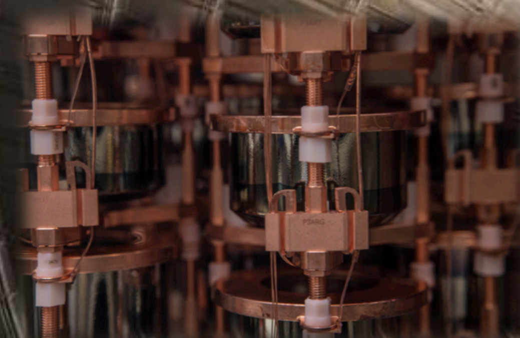
Laboratory-Based Neutrino Mass Measurements

Susanne Mertens
INSS, 2015



Overview

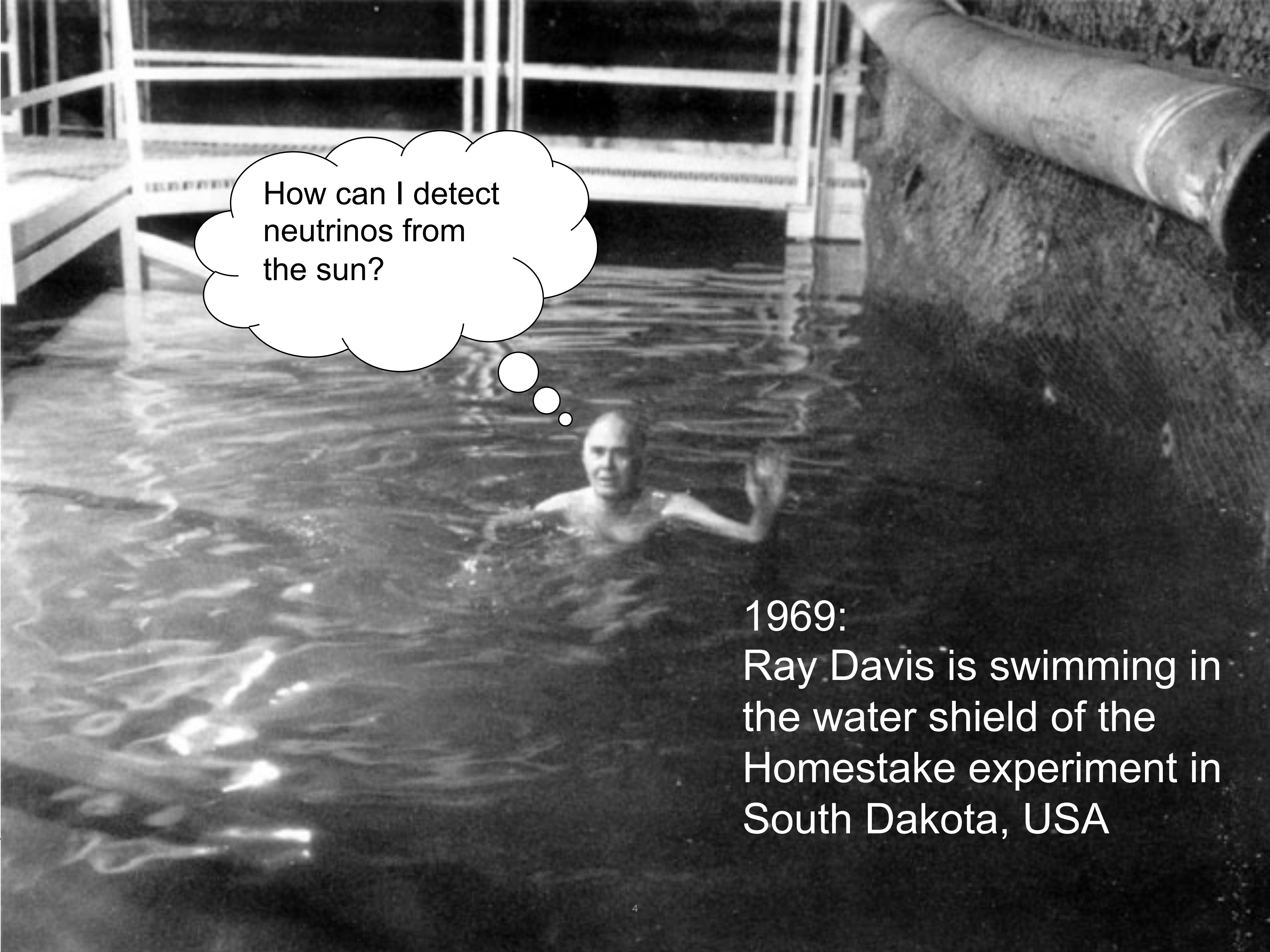
- Intro
- Neutrinoless double beta decay
- Single beta decay

Intro

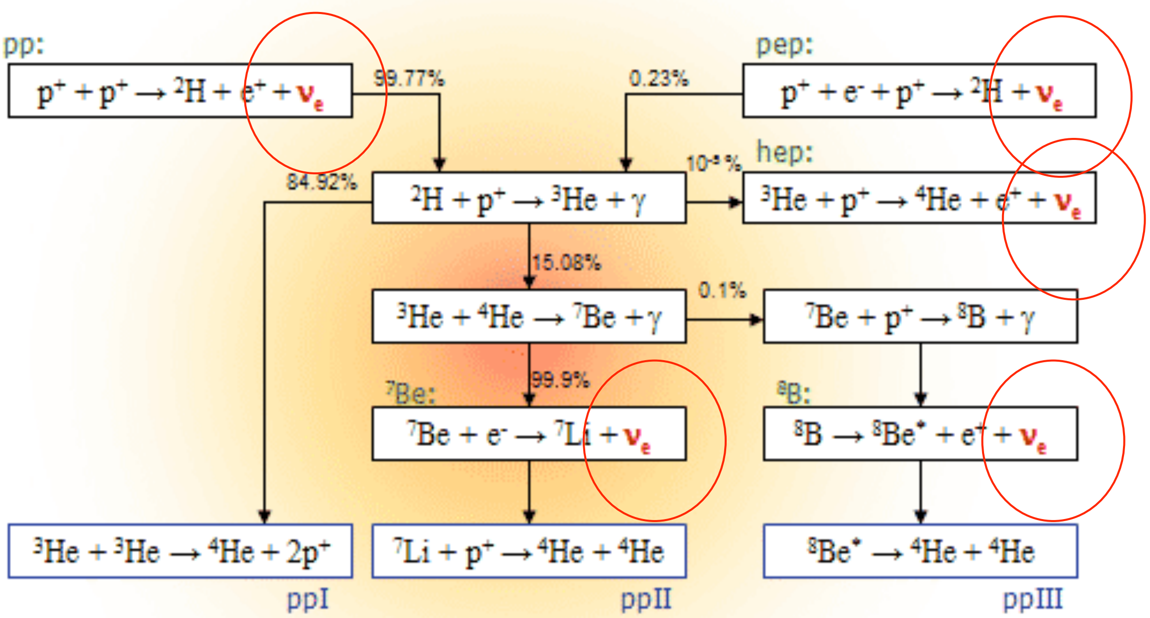
How do we know the neutrino has a mass?

How to incorporate a neutrino mass in the SM?

What are the open questions?


How can I detect neutrinos from the sun?
1969:
Ray Davis is swimming in the water shield of the Homestake experiment in South Dakota, USA

Neutrinos from the sun



- Nuclear fusion processes produce proton-rich nuclei
- On earth 60 Billion neutrinos per cm^2 and second
- **Only electron flavor neutrinos are produced**

Remember:

β^- – decay

$$n \rightarrow p + e^- + \bar{\nu}_e$$

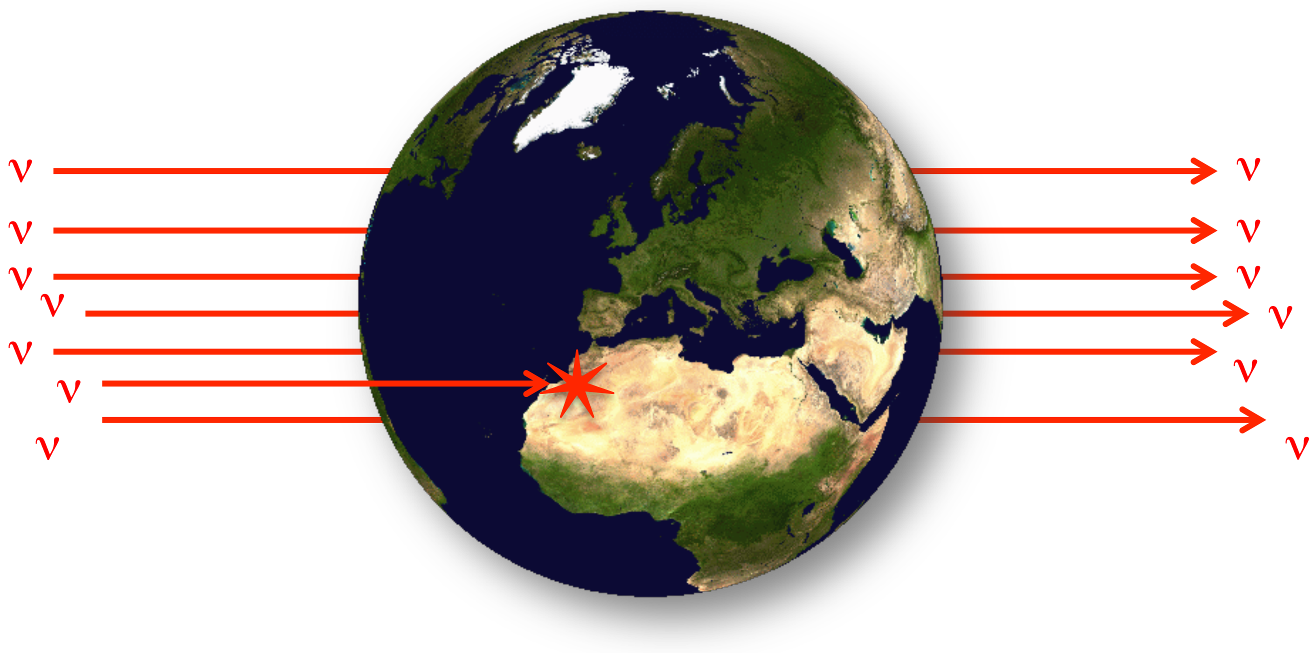
β^+ – decay

$$p \rightarrow n + e^+ + \nu_e$$

Electron capture

$$p + e^- \rightarrow n + \nu_e$$

Why is it so hard to detect them?



- With E_ν = 11 MeV the mean free path in lead is 350 billion kilometer
- In earth ~3 out of 1 billion neutrinos would interact

Inverse beta decay

Can we built a
detector from
neutrons?

$$\nu_e + n \rightarrow p + e$$

Is that possible?

- Yes, this reaction is allowed
- **But free neutrons only live for 15 minutes...**

Inverse beta decay

20 neutrons
17 protons

19 neutrons
18 protons

… A detector
made of
Chlorine?

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

Is that possible ?

- Yes.
- The electron is too low energetic to be detected.
- But the nobel gas argon can be deteted through its decay.

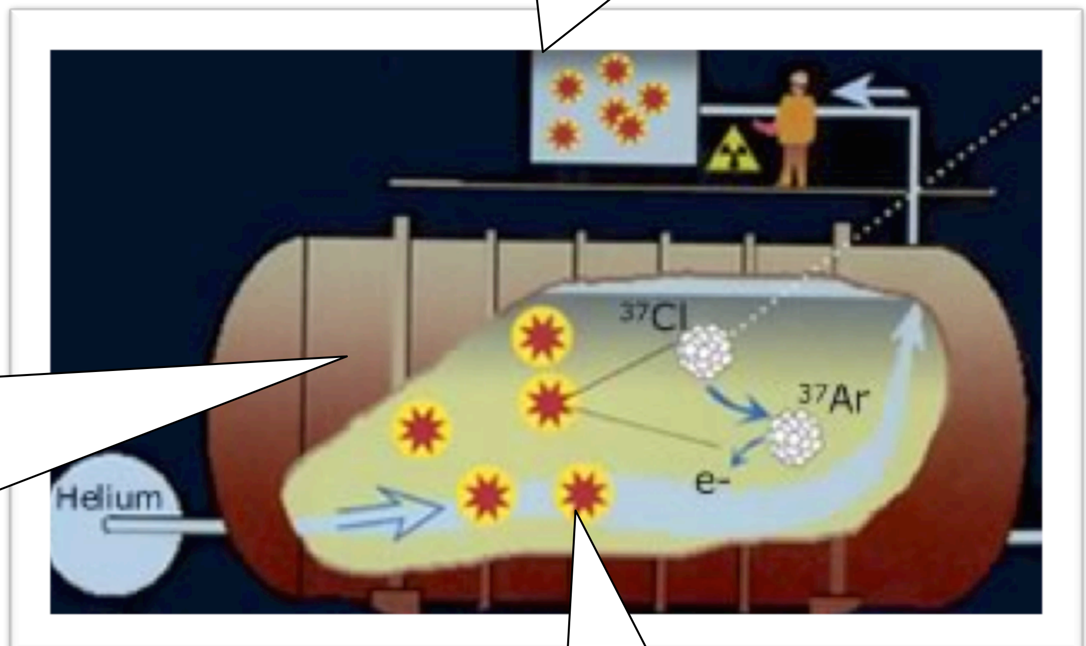
Radiochemical Neutrino Detection

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e$$

$$e + {}^{37}\mathrm{Ar} \rightarrow \nu_e + {}^{37}\mathrm{Cl}^* + \text{Auger electrons}$$

1 neutrino every 2 days

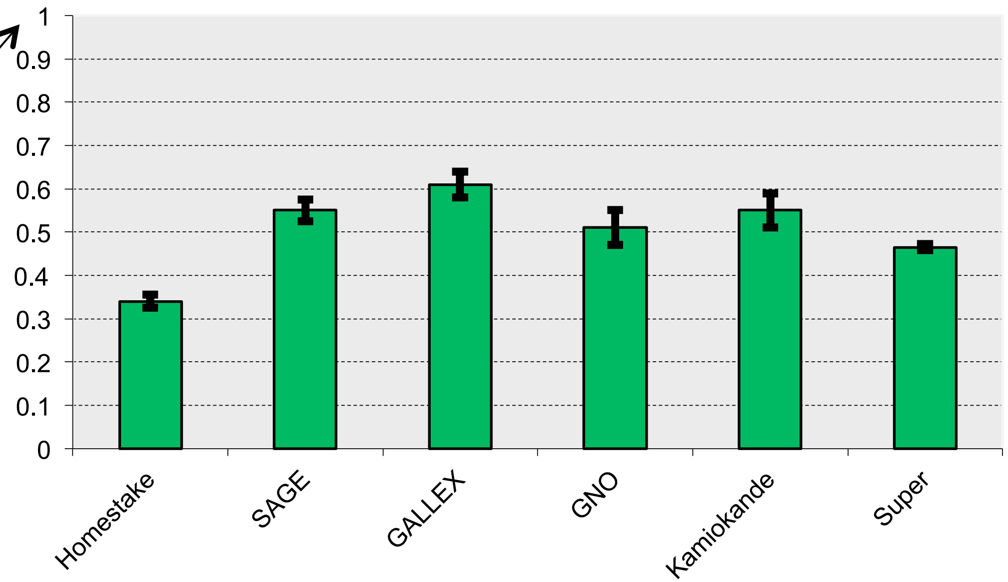
615 t
perchloroethylene



$T_{1/2}$ = 35 days

Solar Neutrino Problem

Prediction of John Bahcall



- …All experiments measure less neutrinos than expected
- What is wrong? The expectation? The measurement?
- Or did the neutrinos change their flavor on the way from the sun to the earth?

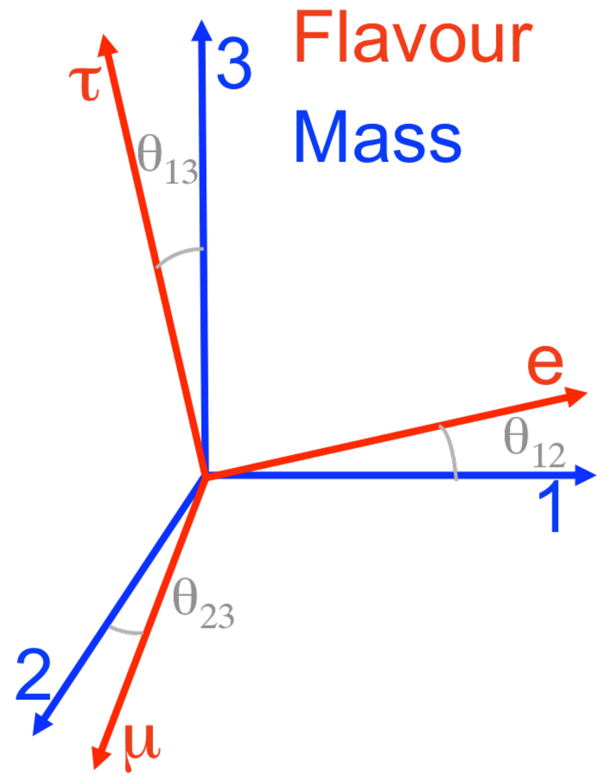
Neutrino Flavours und Masses

A neutrinos with a specific **mass** has no specific **flavour**

… a neutrino with a specific **flavour** has no specific **mass**

Neutrino Flavours und Masses

A **flavour eigenstate** is a quatummechanical superposition of **mass eigenstates**

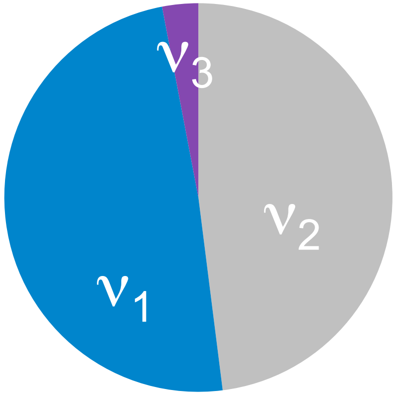


Pontecorvo–Maki–Nakagawa–Sakata Matrix describes the rotation:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino Oscillations

Electron Neutrino



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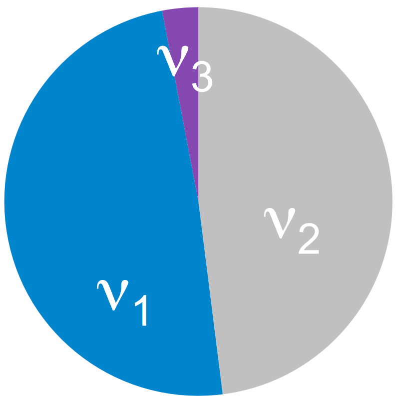
t=0 $$|\nu_e\rangle = U_{e1} \cdot |\nu_1\rangle + U_{e2} \cdot |\nu_2\rangle + U_{e3} \cdot |\nu_3\rangle$$

Neutrino Oscillations

Electron Neutrino

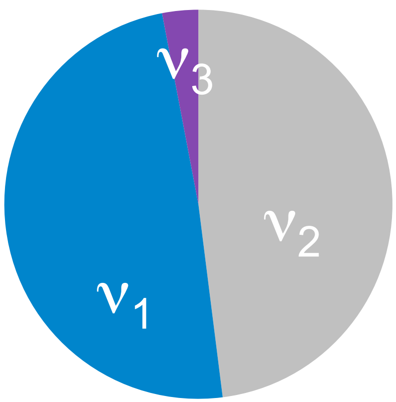


t=0 $$|\nu_e\rangle = U_{e1}\cdot|\nu_1\rangle + U_{e2}\cdot|\nu_2\rangle + U_{e3}\cdot|\nu_3\rangle$$

t>0 $$e^{-i\hat{H}t/\hbar}|\nu_e\rangle = U_{e1}\cdot\boxed{e^{-i\hat{H}t/\hbar}}|\nu_1\rangle + U_{e2}\cdot\boxed{e^{-i\hat{H}t/\hbar}}|\nu_2\rangle + U_{e3}\cdot\boxed{e^{-i\hat{H}t/\hbar}}|\nu_3\rangle$$

Neutrino Oscillations

Electron Neutrino



t=0 $$|\nu_e\rangle = U_{e1}\cdot|\nu_1\rangle + U_{e2}\cdot|\nu_2\rangle + U_{e3}\cdot|\nu_3\rangle$$

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Neutrino Oscillations

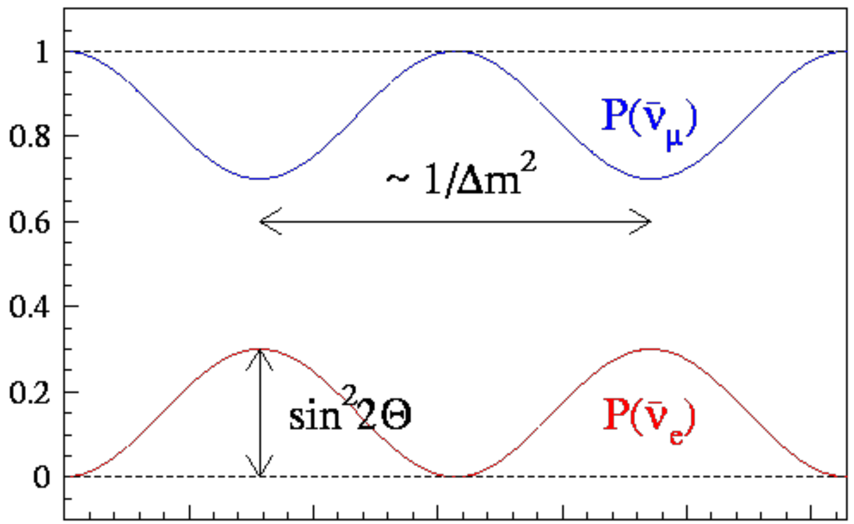
Electron Neutrino **???? Neutrino**

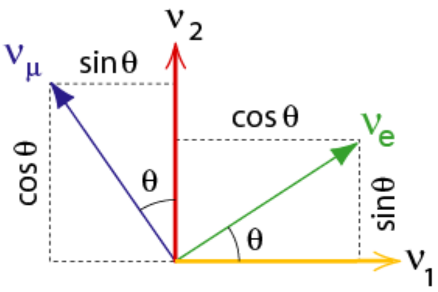
t=0 $$|\nu_e\rangle = U_{e1}\cdot|\nu_1\rangle + U_{e2}\cdot|\nu_2\rangle + U_{e3}\cdot|\nu_3\rangle$$

t>0 $$|\nu_x\rangle = U_{e1}\cdot\boxed{e^{-iE_1t/\hbar}}|\nu_1\rangle + U_{e2}\cdot\boxed{e^{-iE_2t/\hbar}}|\nu_2\rangle + U_{e3}\cdot\boxed{e^{-iE_3t/\hbar}}|\nu_3\rangle$$

$$P = |\langle\nu_e|\nu_x\rangle|^2$$

Neutrino Oscillations (for 2 Flavour)



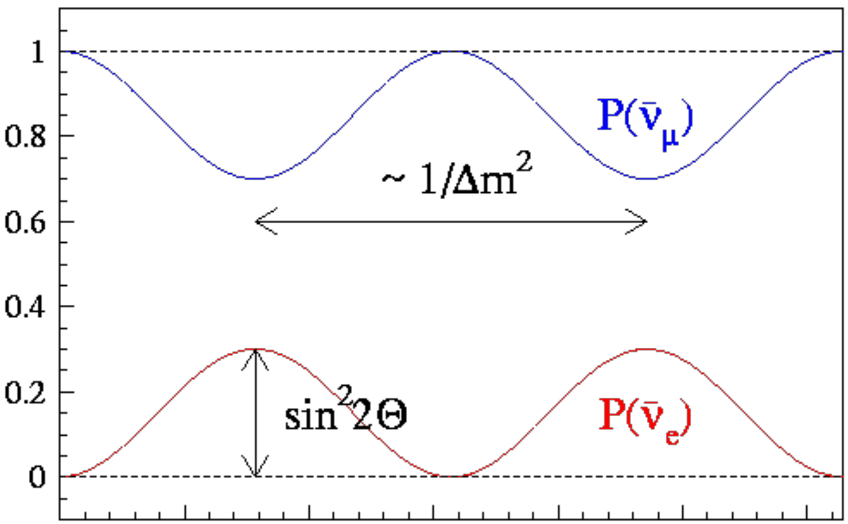


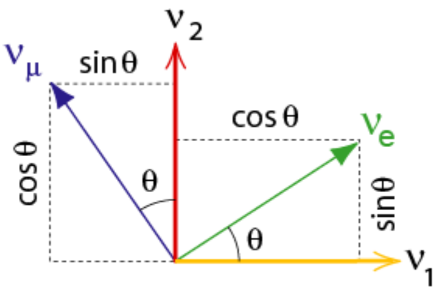
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\boxed{\theta} \cdot \sin^2(\boxed{\Delta m^2} \cdot L_\nu / E_\nu)$$

Amplitude Frequency

$$\Delta m^2 = m_1^2 - m_2^2$$

Neutrino Oscillations (for 2 Flavour)





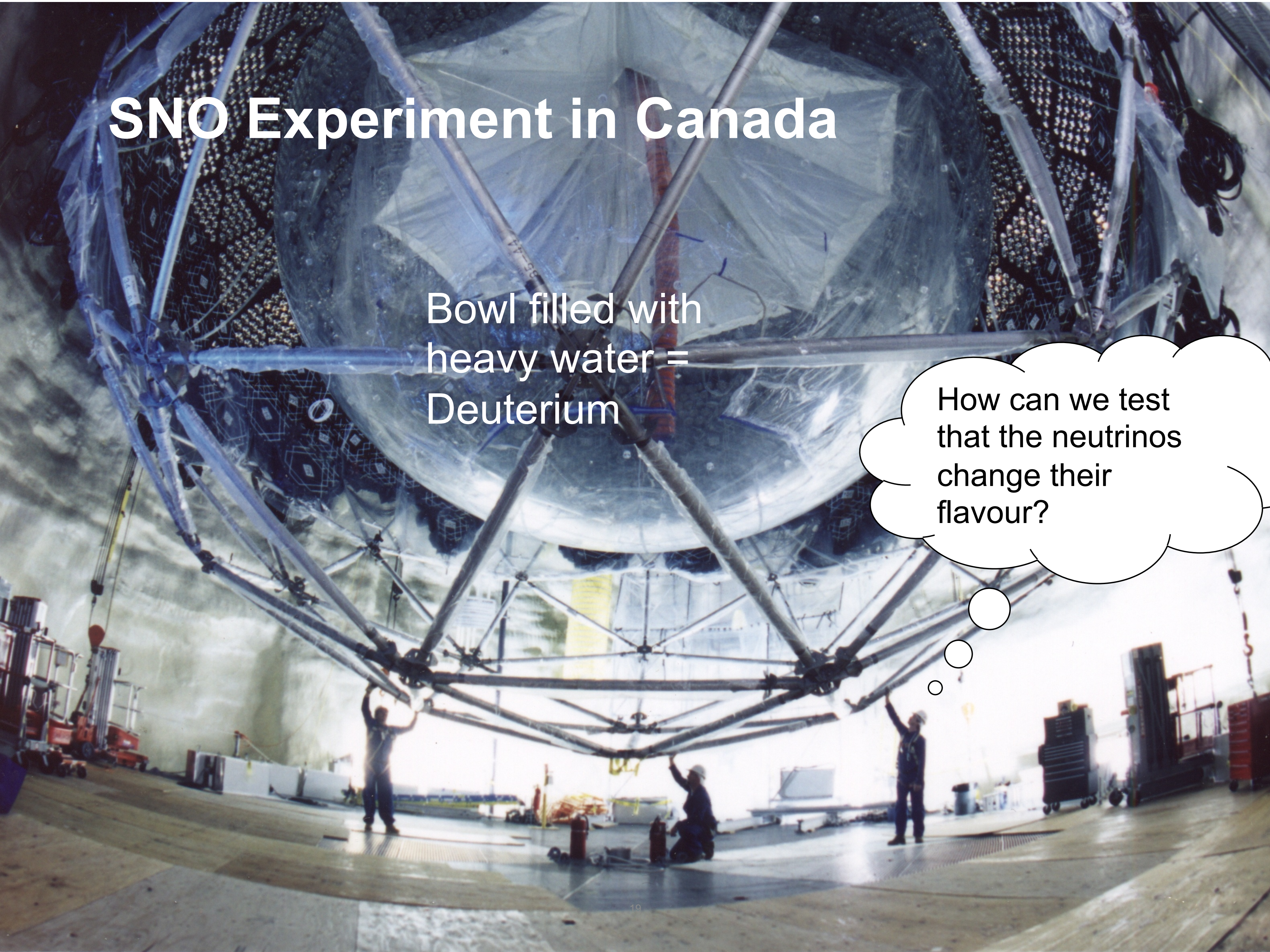
Neutrino oscillations are only possible if at least one neutrino has a mass

$$P(\nu_\mu \to \nu_e) = \sin^2 2\boxed{\theta} \cdot \sin^2(\boxed{\Delta m^2} \cdot L_\nu / E_\nu)$$

Amplitude Frequency

$$\Delta m^2 = m_1^2 - m_2^2$$

SNO Experiment in Canada



Bowl filled with heavy water = Deuterium

How can we test that the neutrinos change their flavour?

Inverser beta decay

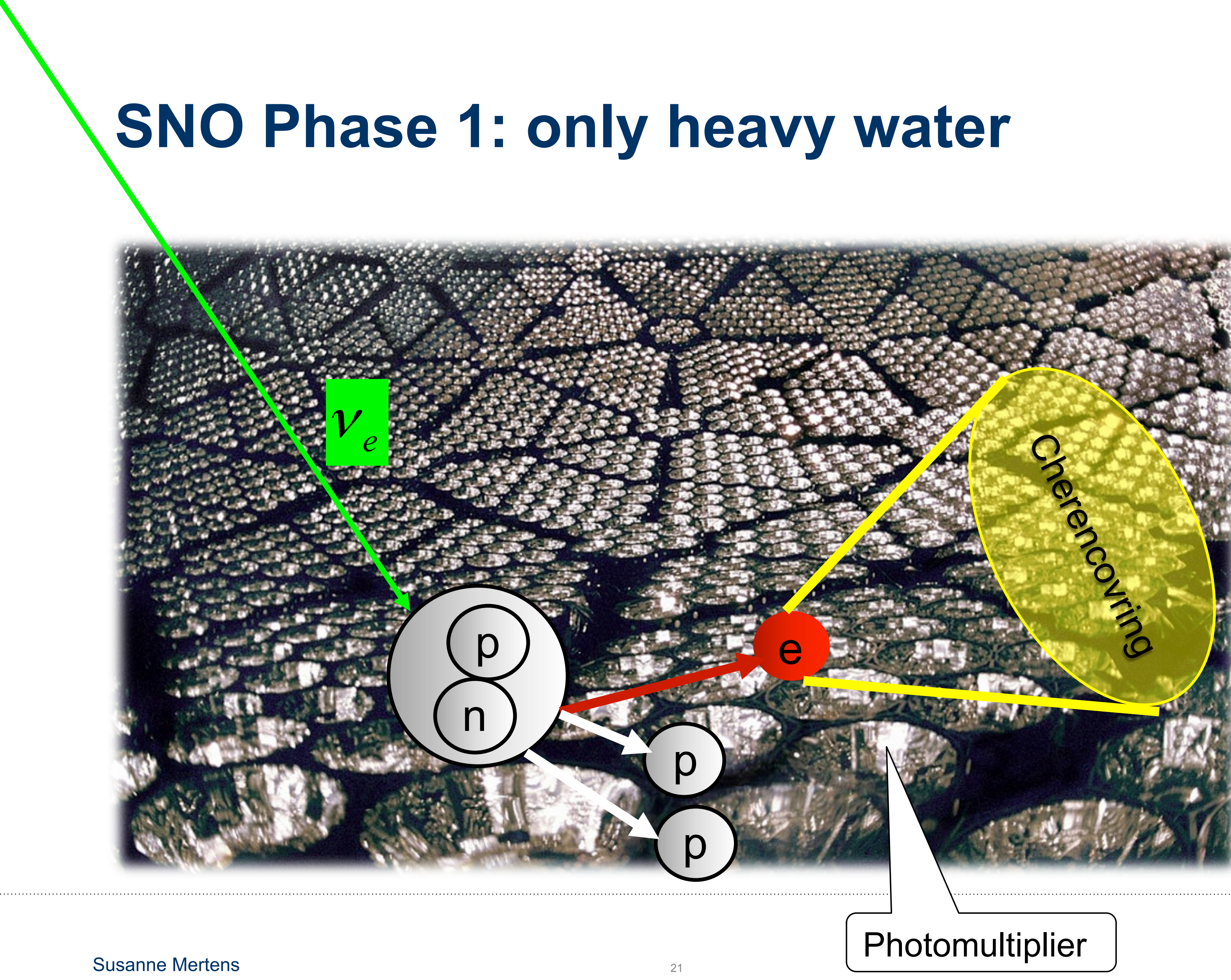
1 neutron
1 proton

$$\nu_e + D \rightarrow p + p + e$$

Is that possible?

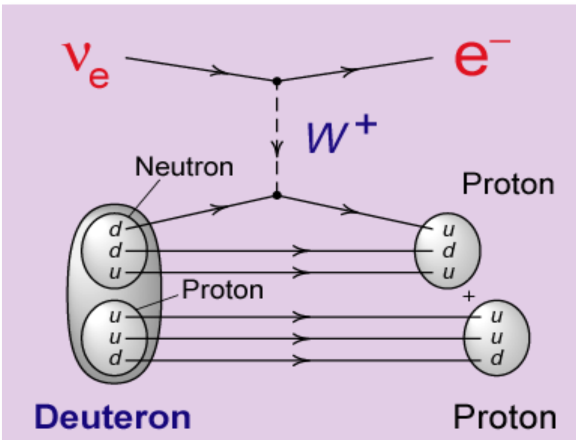
- Yes.
- … and in this case the electron gets so much energy that it can be detected

SNO Phase 1: only heavy water



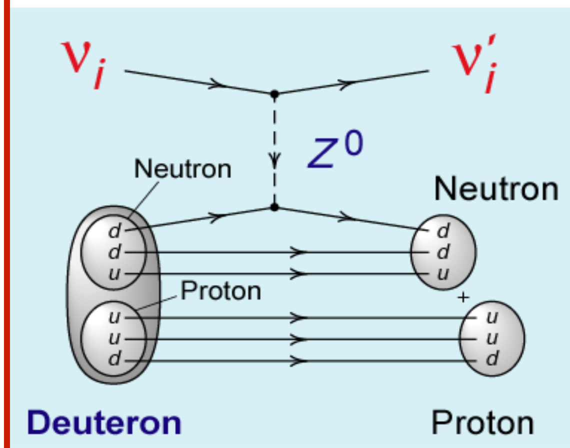
Idea!

charged current (CC)



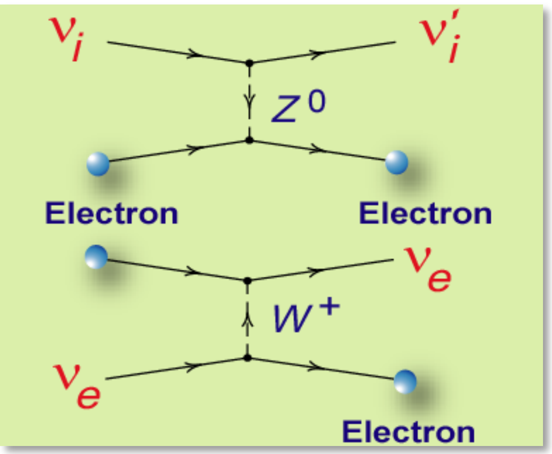
Only ν_e

neutral current (NC)



All Flavours

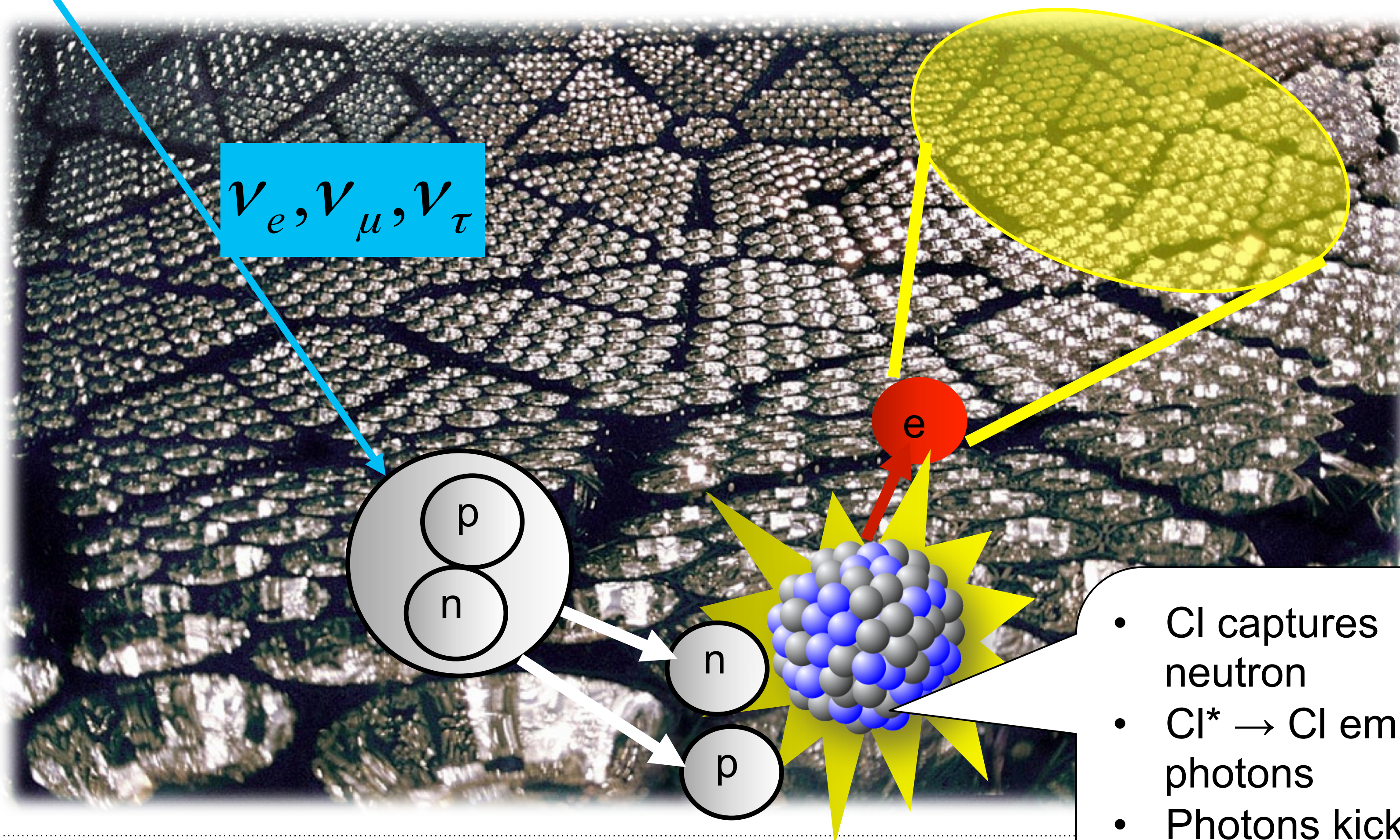
elastic scattering (ES)



mostly ν_e

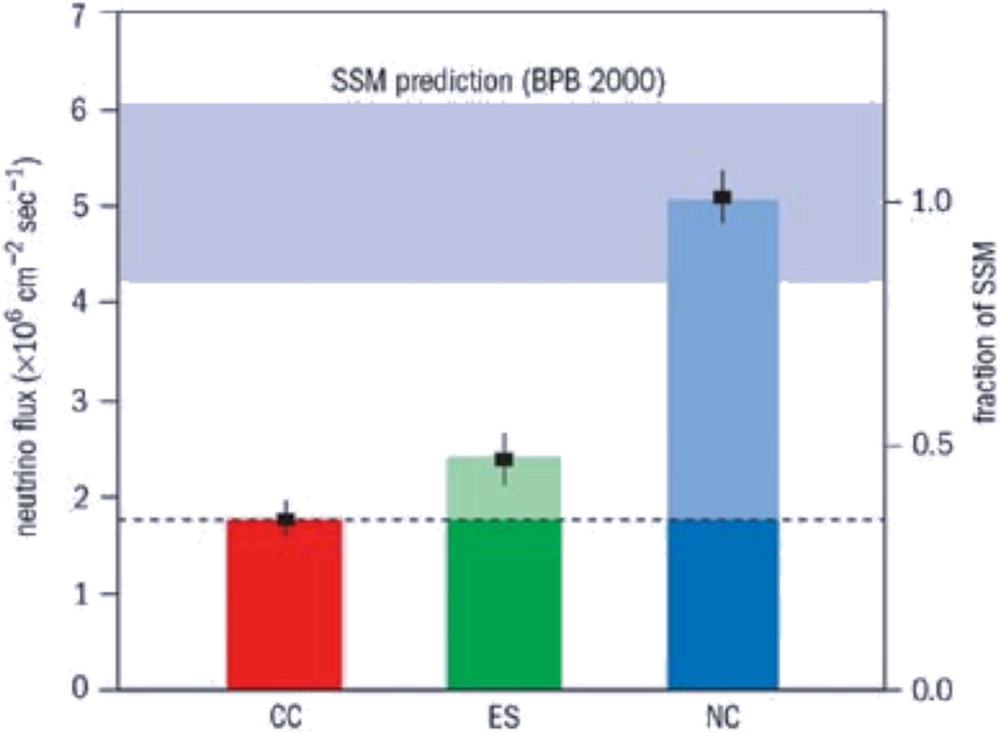
- Scattering via neutral Z-Boson is flavour independent
- This reaction channel measures the entire neutrino flux

SNO Phase 2: with 2t NaCl (Salt)



- Cl captures neutron
- Cl* → Cl emitts photons
- Photons kick electrons out of the atomic shell

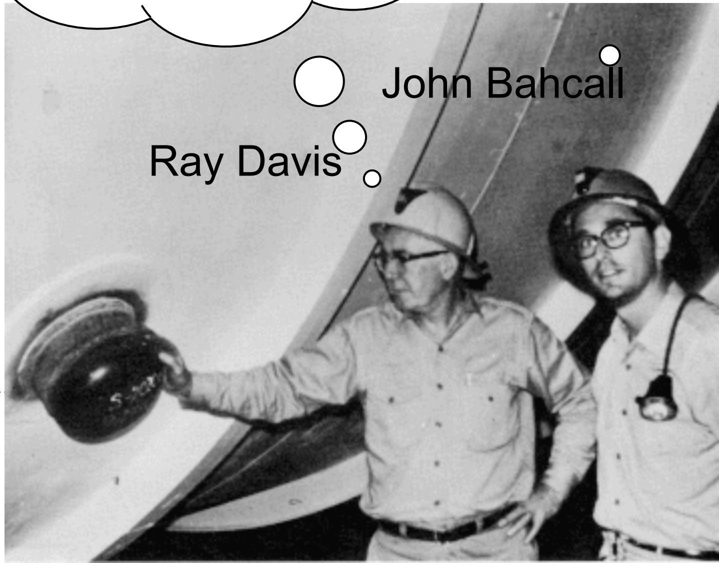
…and what did SNO find?



Only ν_e Mainly ν_e All Flavour

So my calculations were right...

… and my measurements, too



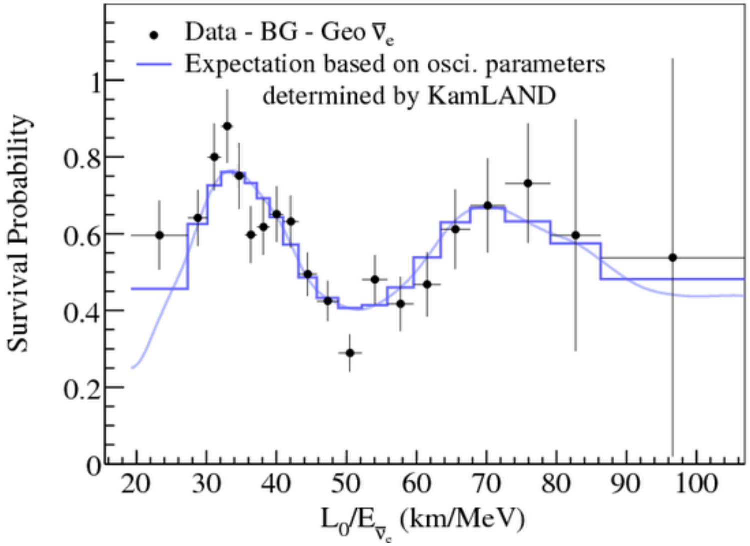
2001 (30 years later)…

Determination of osc. parameters

- 3 angle (Θ_{12}, Θ_{23}, Θ_{13})
- 2 mass differences (Δm^2_{12}, Δm^2_{23})

For two flavour

$$P(\nu_x \rightarrow \nu_y) = \sin^2 2\theta \cdot \sin^2(\Delta m^2 \cdot L_\nu / E_\nu)$$



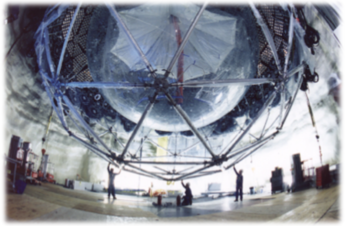
- Position detector at distance L from neutrino source
- Measure P (L/E)
- Extract Θ and Δm^2

Determination of osc. parameters

- 3 angle (Θ_{12}, Θ_{23}, Θ_{13})
- 2 mass differences (Δm_{12}, Δm_{23})

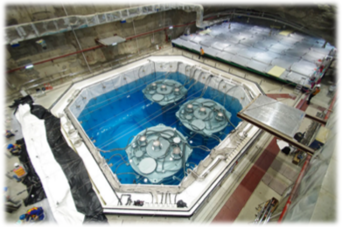
Double Chooz, FR
(Reactor)

SNO, Kanada
(Sun)

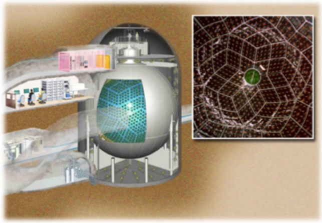


Super K, Japan
(Atmosphere)
T2K, (Accelerator)

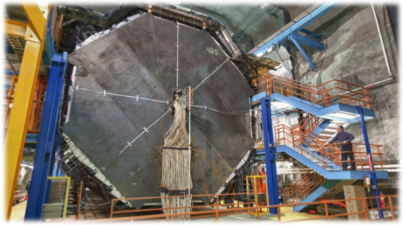
Daya Bay, China
(Reactor)



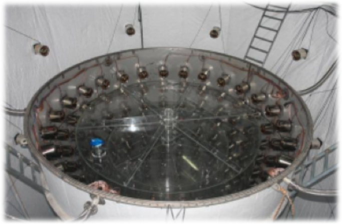
KamLAND, Japan
(Reactor)



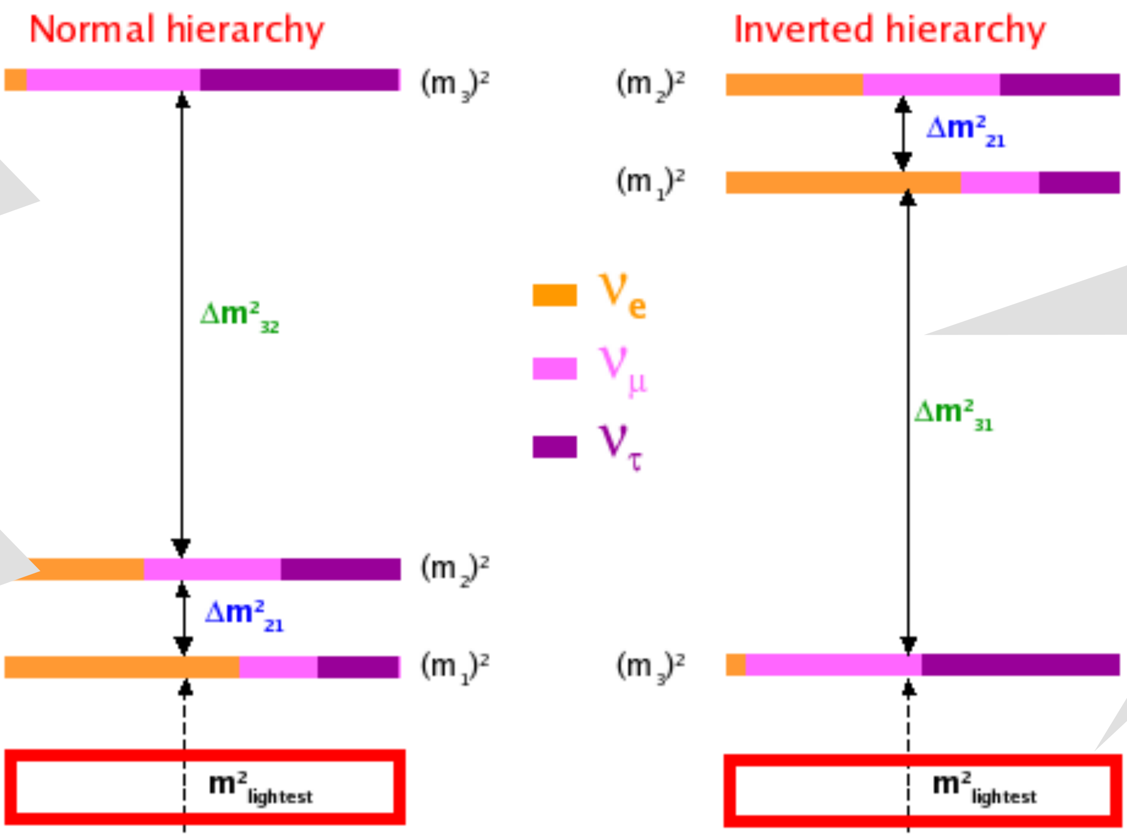
Minos, USA
(Accelerator)



RENO, Korea
(Reactor)



What do we learn about the ν-mass?



we know that there is a large and a small Δm^2

we know m_2 is heavier than m_1 (from matter effects!)

we don't know if m_3 is heavier or lighter than m_1 and m_2 ?

we don't know the absolute mass scale

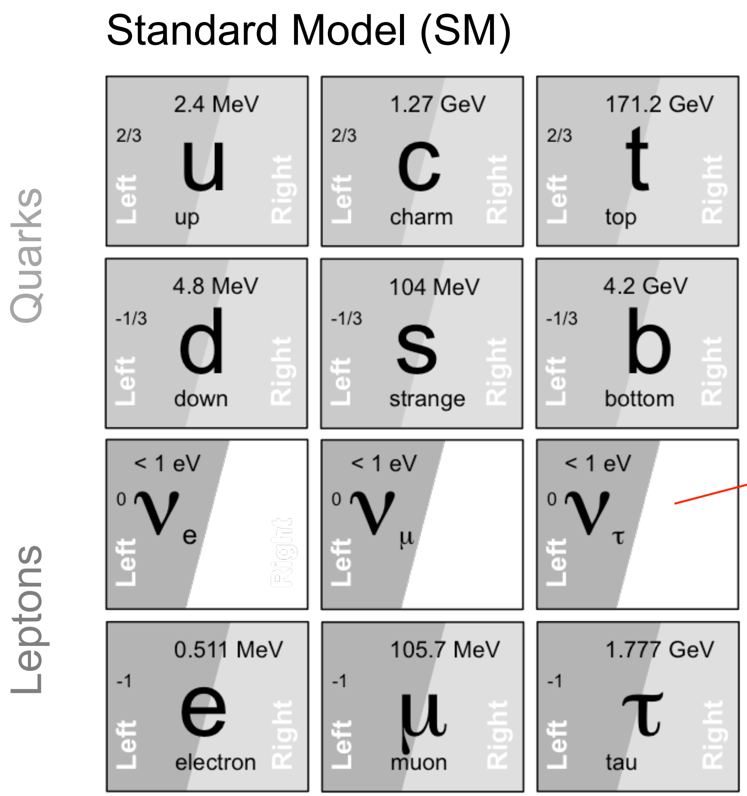
Intro

How do we know the neutrino has a mass?

How to incorporate a neutrino mass in the SM?

What are the open questions?

How to incorporate a ν-mass to the SM

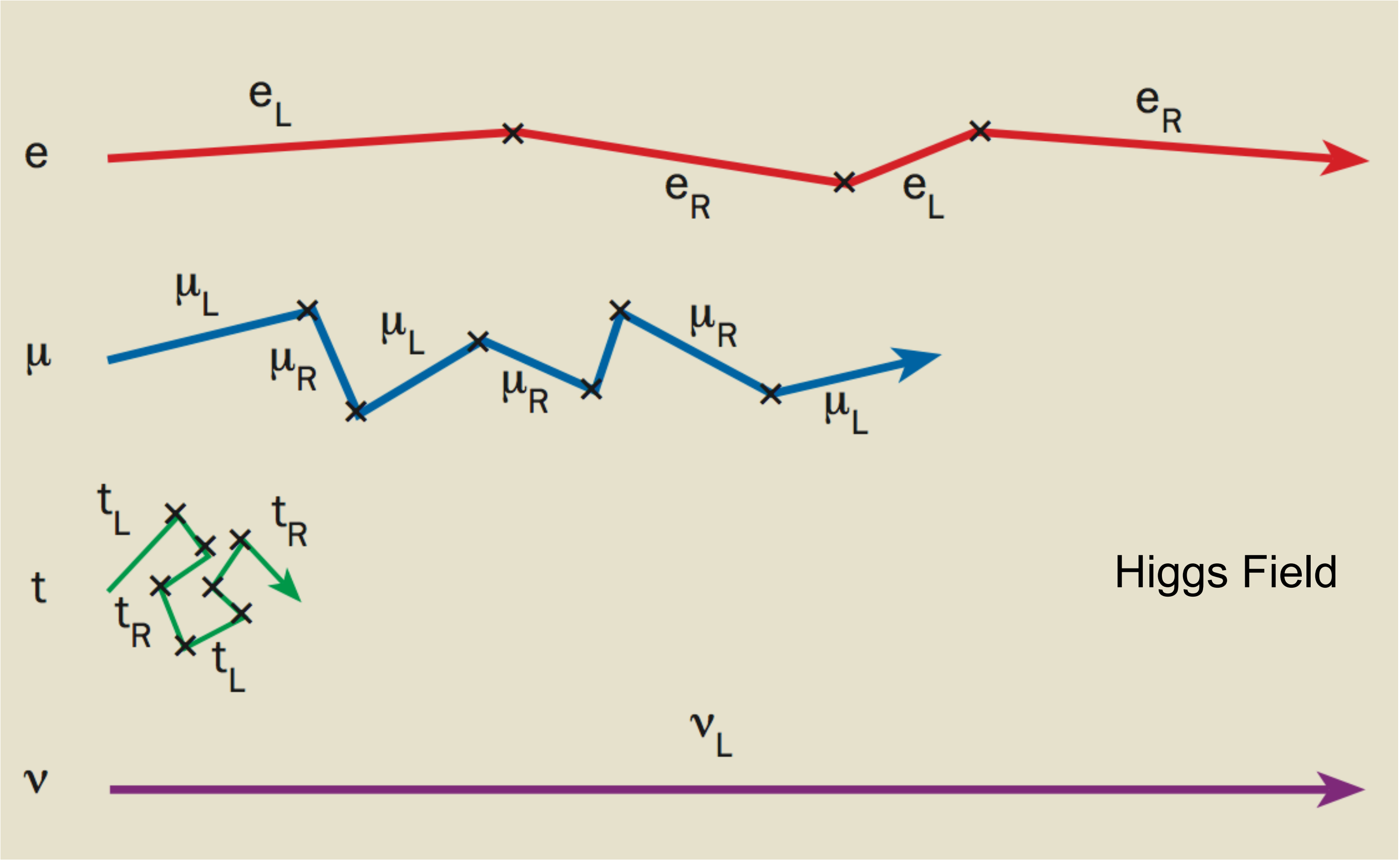


Neutrino mass is not forseen in the SM

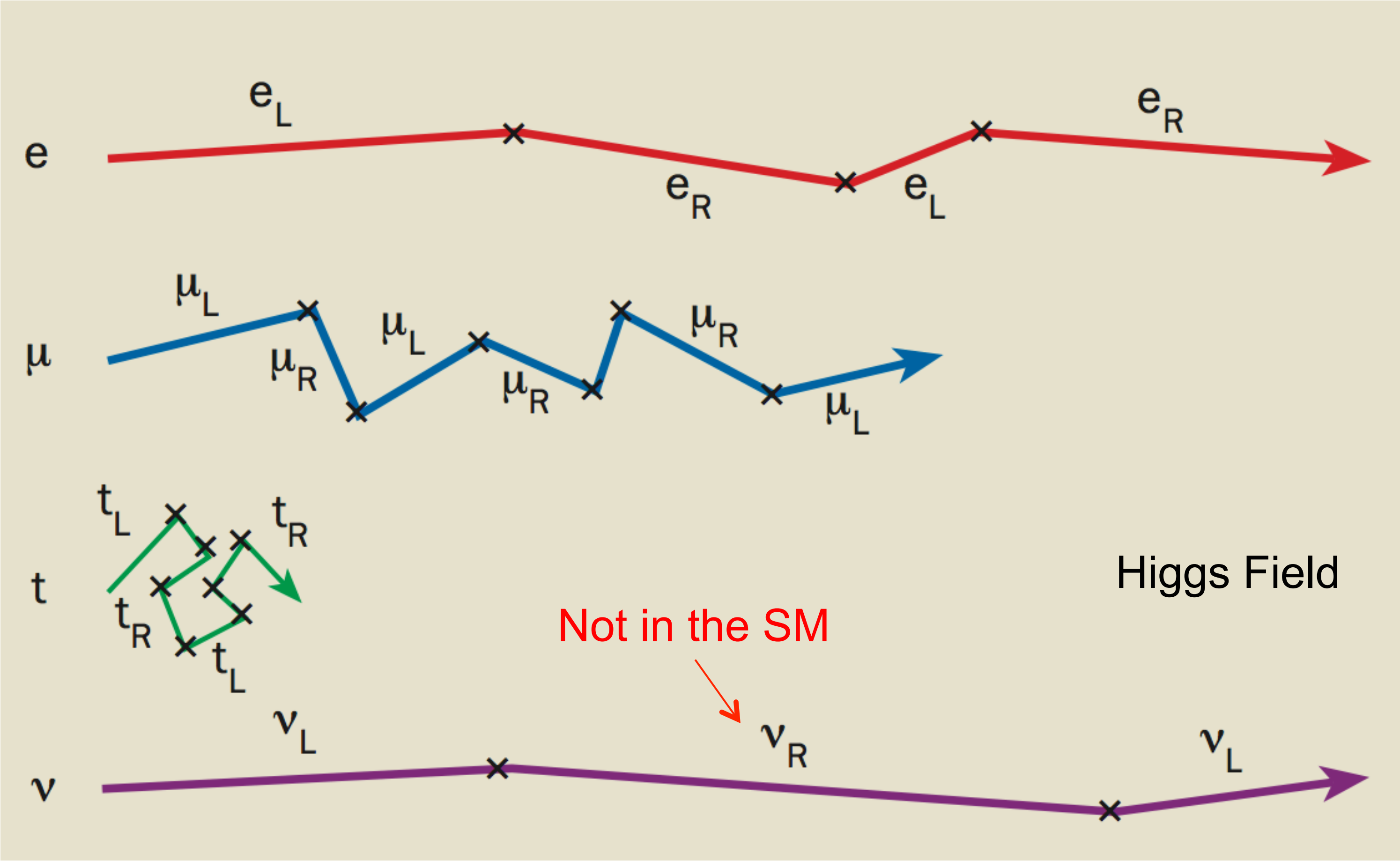
No right-chiral component of the neutrino in the SM

This right-chiral component would not even interact weakly

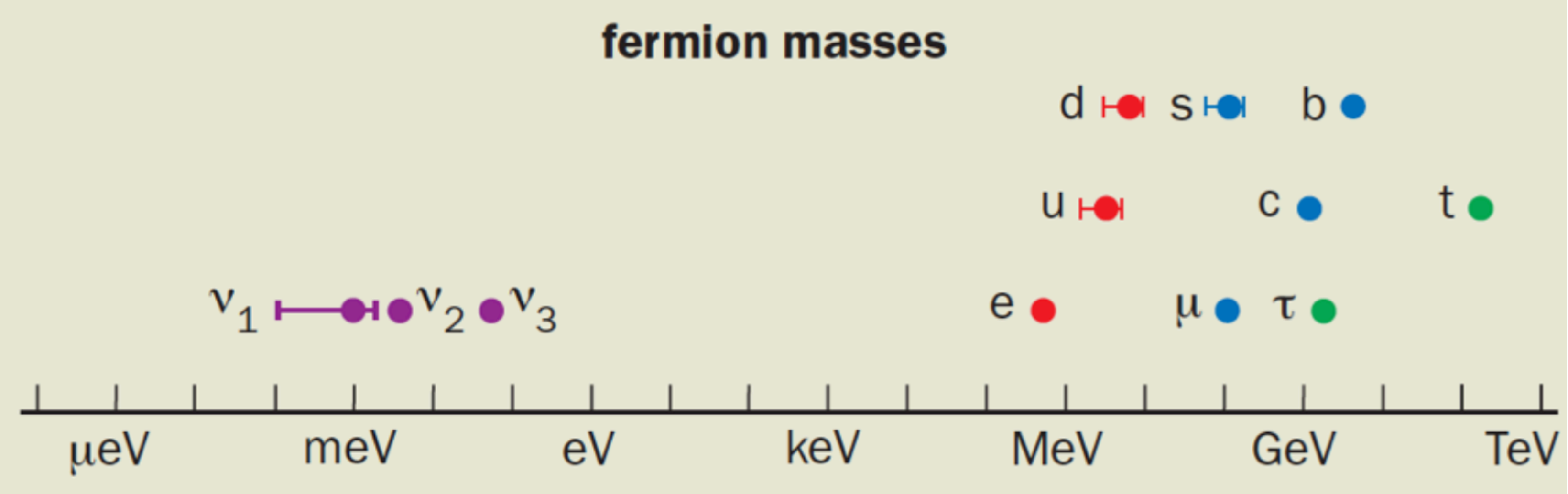
No neutrino mass in the SM

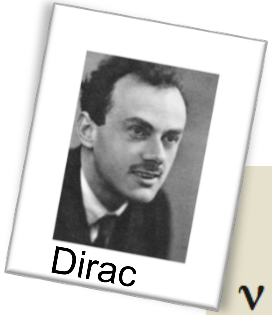


How to incorporate a ν-mass to the SM

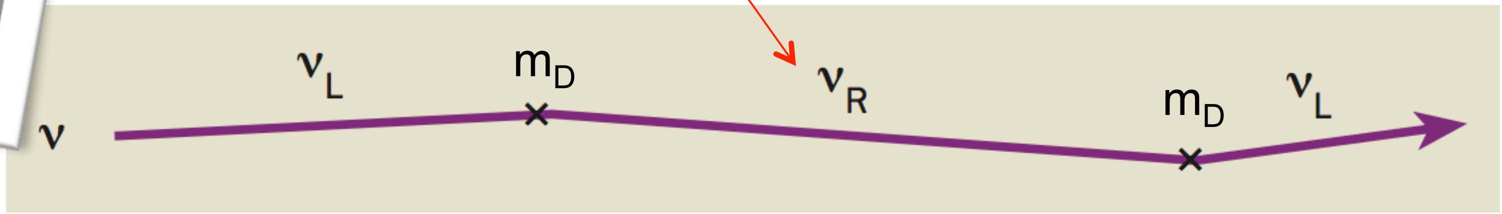


But maybe neutrinos are different…





Not in the SM



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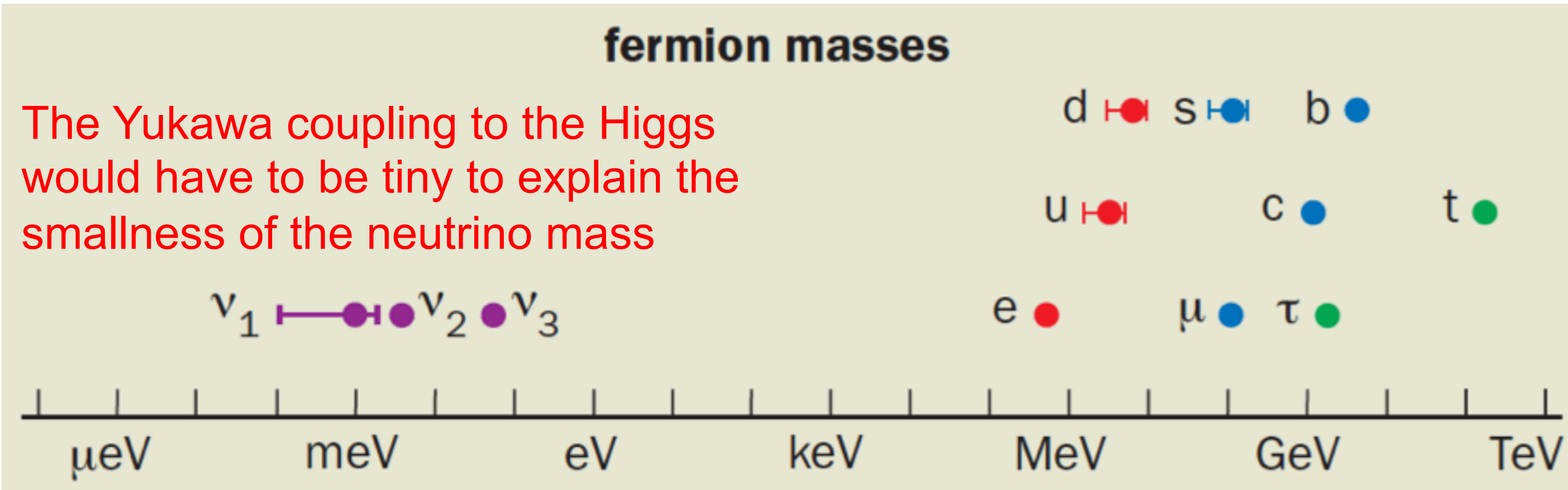
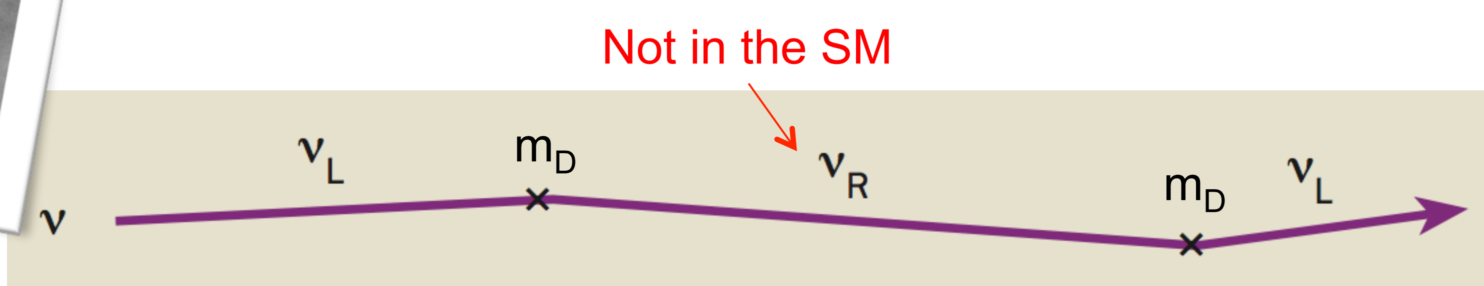
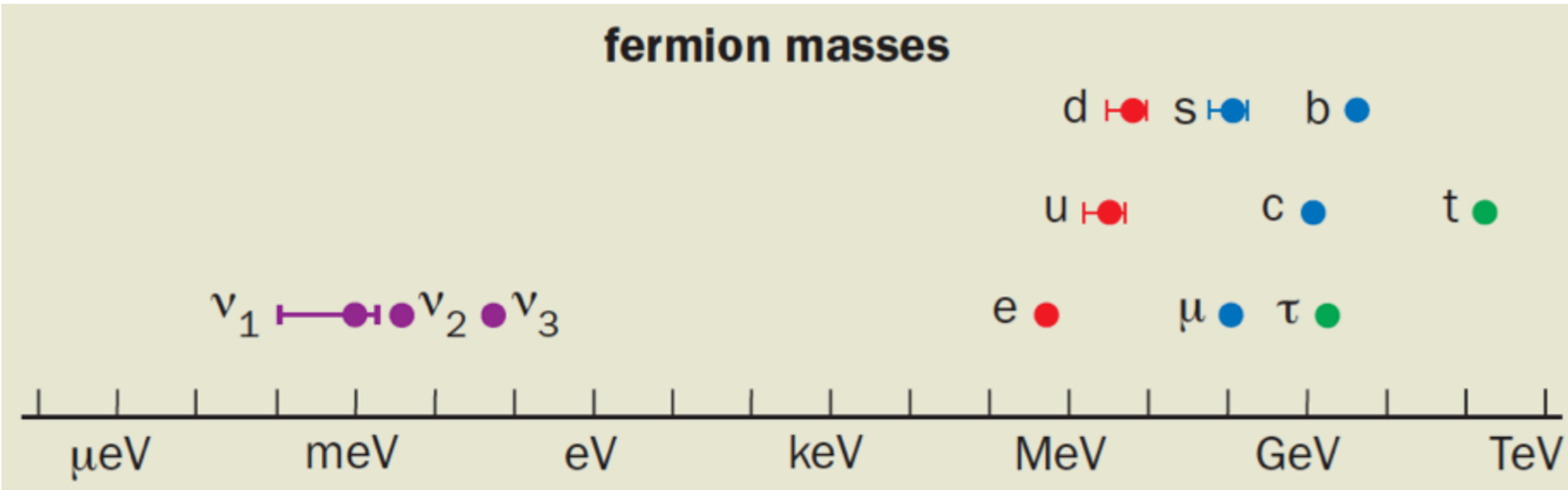
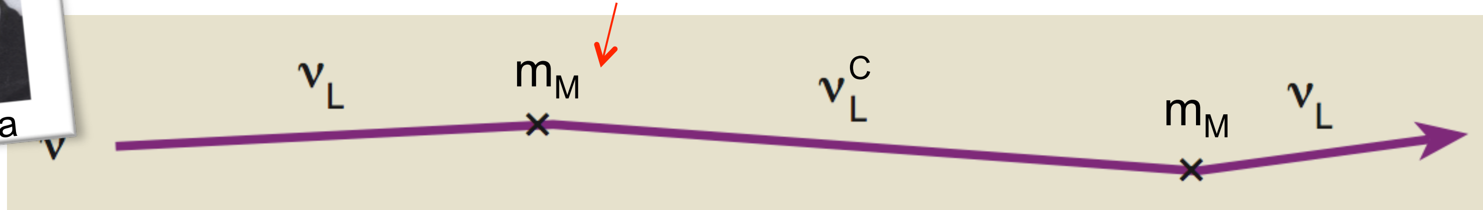




An alternative solution



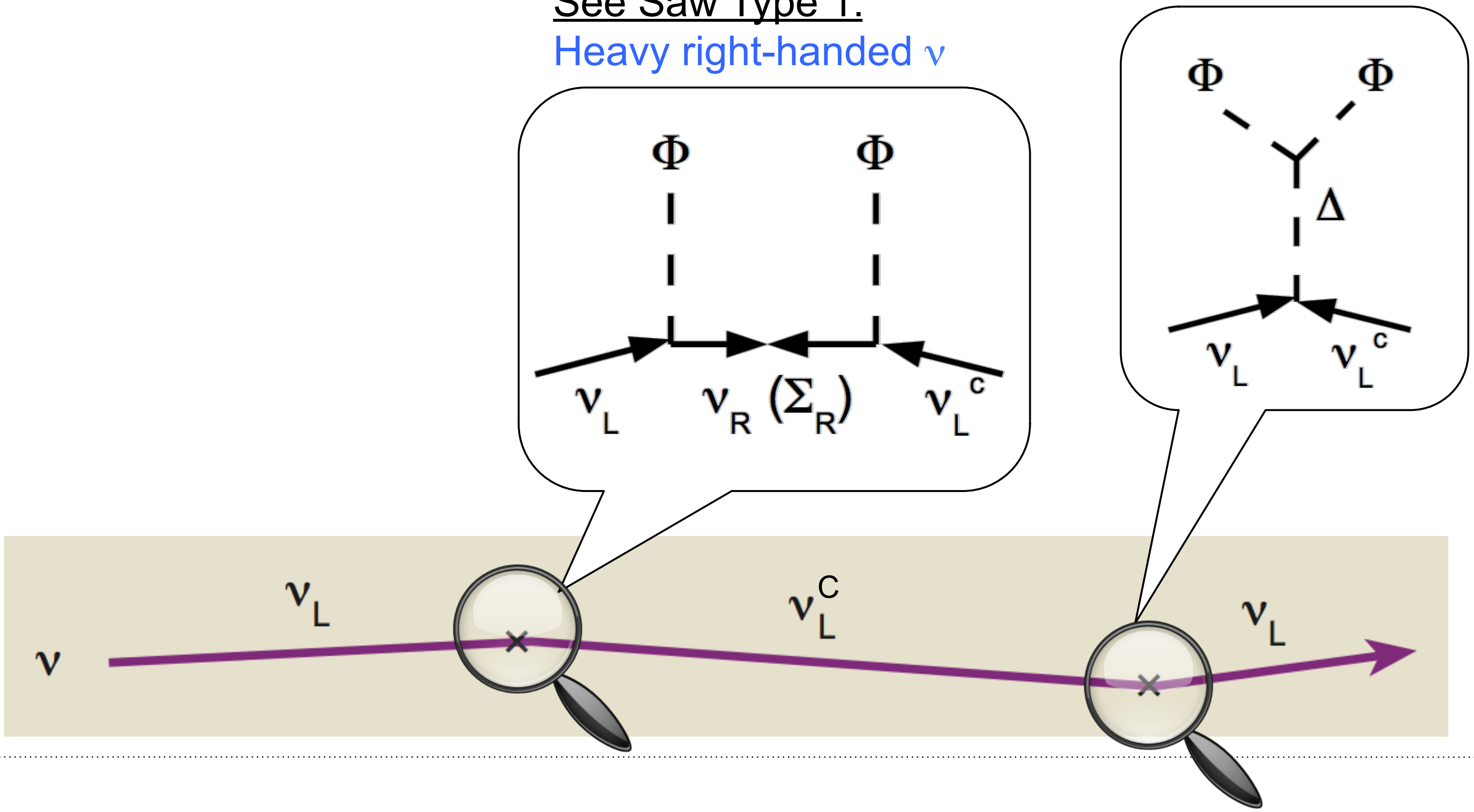
Lepton number violation (not possible in SM)



Possible in an effective theory

See Saw Type 1:
Heavy right-handed ν

See Saw Type 2:
Higgs triplet



The See Saw Mechanism (type 1)

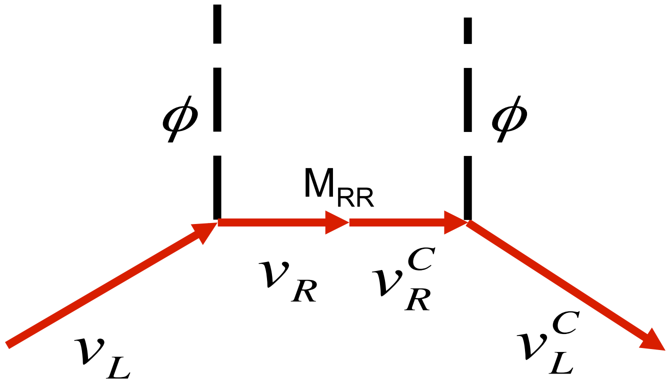
$$L_M = M_{RR}\ \nu_R^C \nu_R$$

- Right-chiral neutrino state carries no charge at all, not even weak charge
- So we can simply "connect" the right-chiral component with its charge conjugate, i.e. introduce a Majorana mass term
- This mass term does not require a higgs mechanism
- This mass could be arbitrarily heavy

The See Saw Mechanism (type 1)

$$L_{D+M} = m \cdot \nu_L \nu_R + m \cdot \nu_L^c \nu_R^c + M_{RR} \nu_R^c \nu_R$$

$$\rightarrow (\nu_L, \nu_R) \begin{pmatrix} 0 & m \\ m & M_{RR} \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

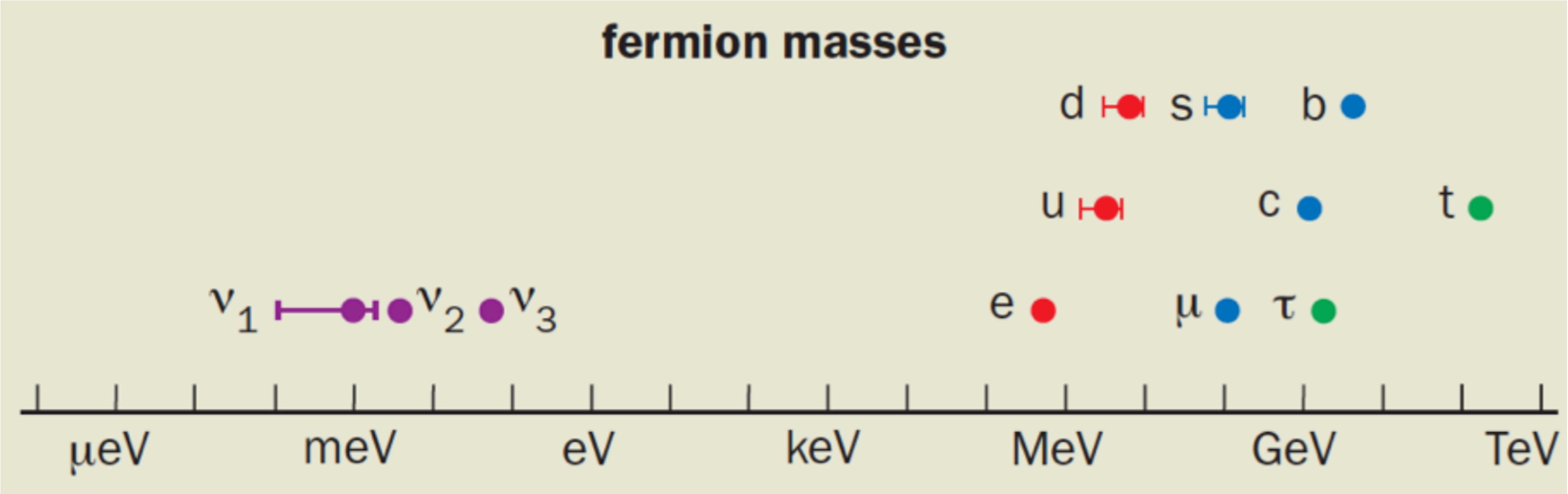


Two mass eigenstates:

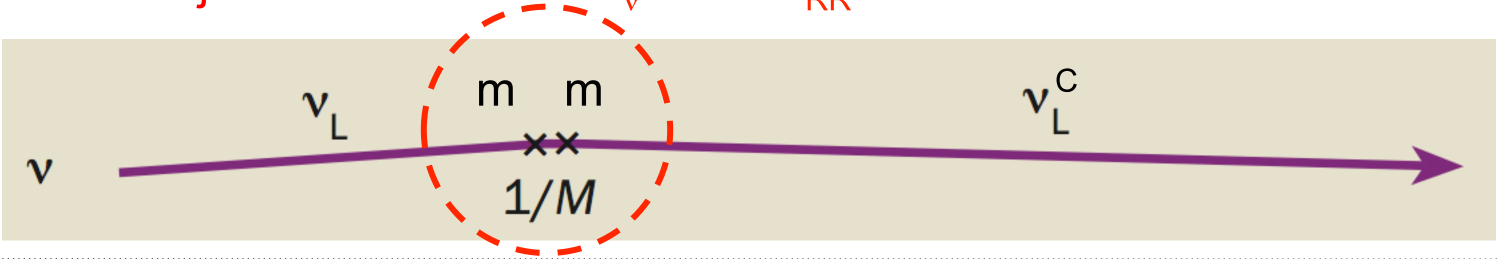
$$m_1 = \frac{m^2}{M_{RR}}, \quad \nu_1 \approx \nu_L$$

$$m_2 = M_{RR}, \quad \nu_2 \approx \nu_R$$

How to incorporate a ν-mass to the SM



Majorana mass term $m_\nu = m^2/M_{RR}$



Intro

How do we know the neutrino has a mass?

How to incorporate a neutrino mass in the SM?

What are the open questions?

Open Questions

- What is the absolute neutrino mass scale ?
- What is the hierarchy of the different mass eigenstates?
- Do neutrinos have Dirac or Majorana nature ?

Why does it (anti-) matter?

- What is the absolute neutrino mass scale ?
- What is the hierarchy of the different mass eigenstates?
- Do neutrinos have Dirac or Majorana nature ?

→ What is the fundamental mass creation mechanism for neutrinos?

→ What is the impact of neutrinos on small scale structure formation in the early universe ?

→ Is lepton number violated → Why is there more matter than anti-matter → why do we exist ?

Overview

- Intro
- Neutrinoless double beta decay
- Single beta decay

Neutrinoless double beta decay

Why do we care whether the neutrino is Dirac or Majorana?

How to test the Majorana vs Dirac nature?

When does $0\nu\beta\beta$ happen?

How often does it happen?

How often does it need to happen so we can say that we found it?

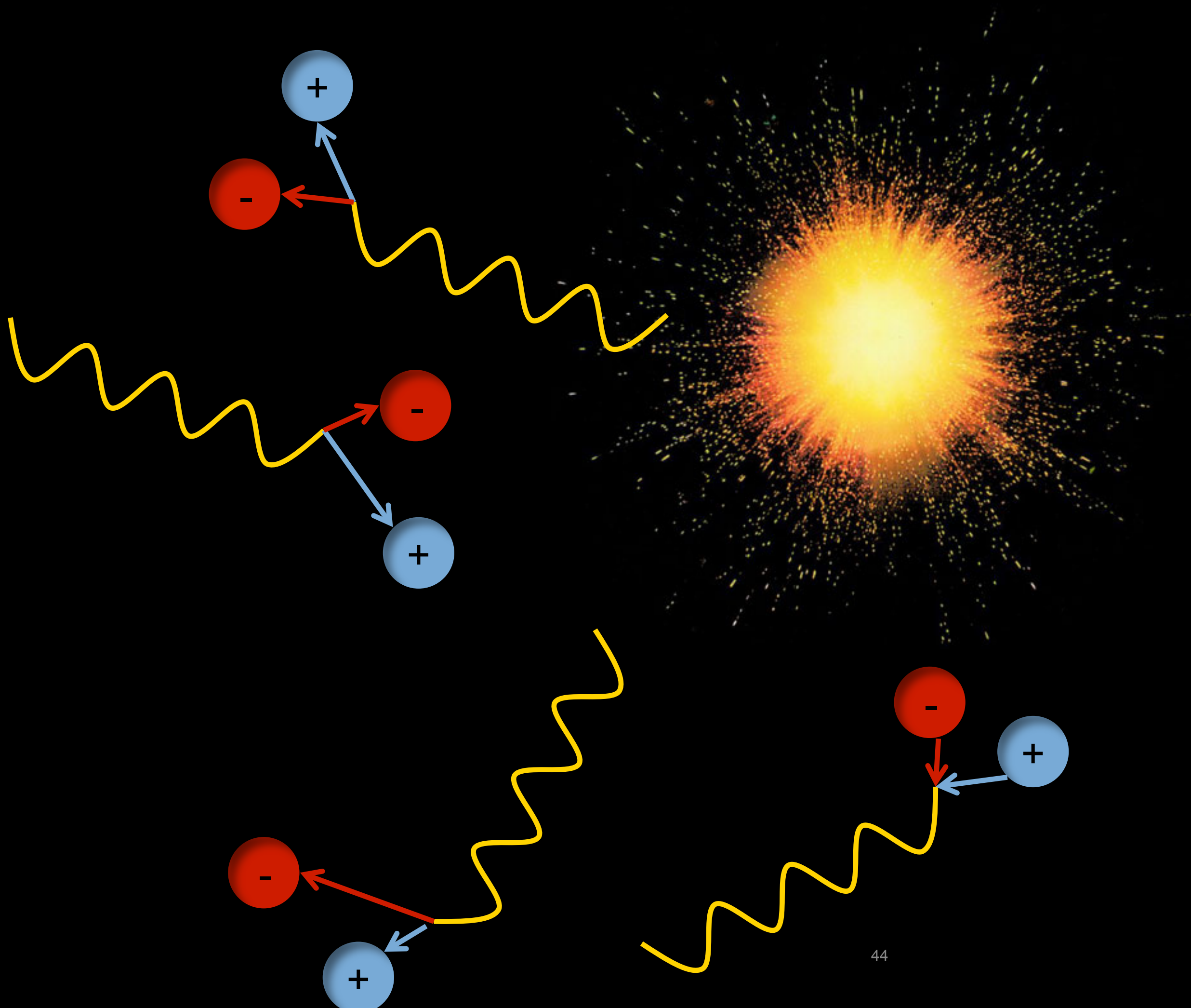
What can we say about the neutrino mass?

Where do we stand experimentally?

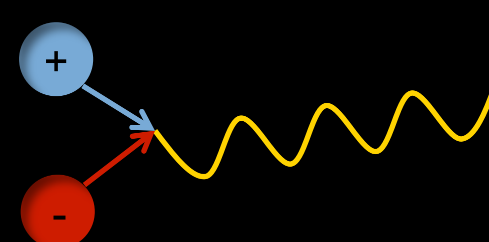
What causes background?

How to realize an experiment?

Why do we exist ?



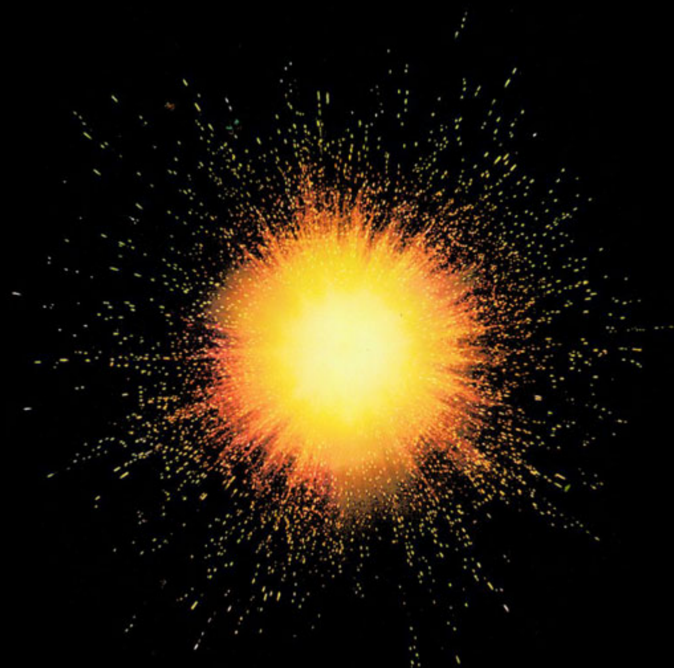
Particles and Anti-particles are produced and annihilated in pairs

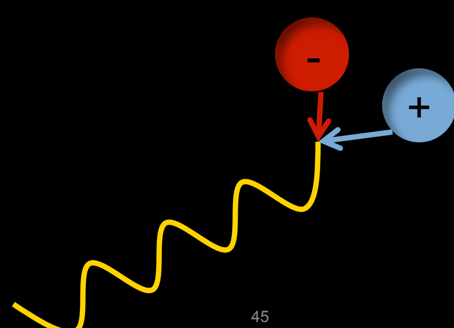


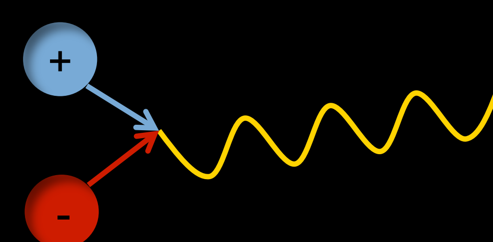
Why do we exist ?

10 s after the Big Bang production freezes out

Expected baryon to photon ratio: 10^{-18}
But observed: 10^{-10}





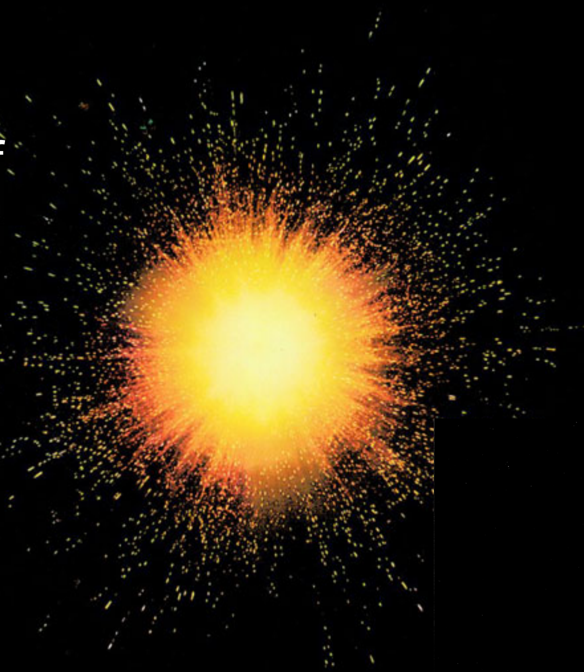


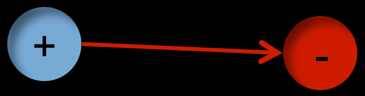
Why do we exist ?

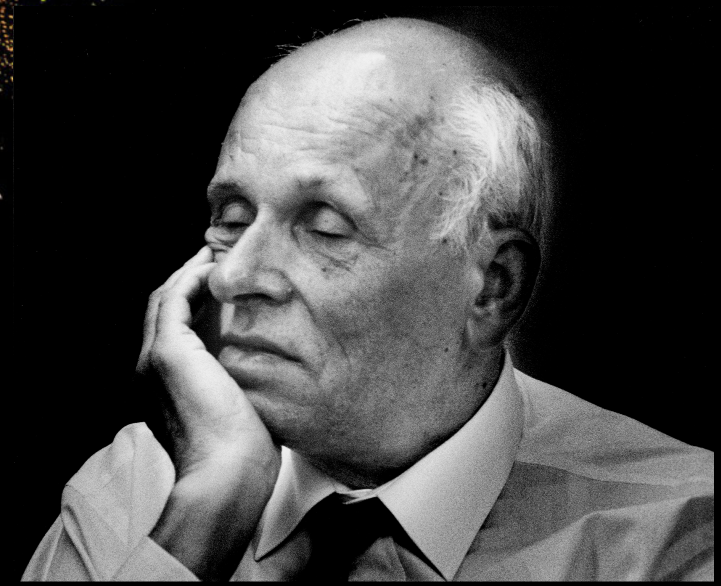
Matter assymetry can dynamically be produced if

… there are processes which violate baryon number

… sphaleron processes connect lepton and baryon number violation







A. D. Sacharow, 1967

Neutrinoless double beta decay

Why do we care whether the neutrino is Dirac or Majorana?

How to test the Majorana vs Dirac nature?

When does $0\nu\beta\beta$ happen?

How often does it happen?

How often does it need to happen so we can say that we found it?

What can we say about the neutrino mass?

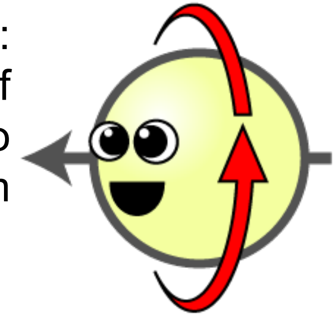
Where do we stand experimentally?

What causes background?

How to realize an experiment?

Dirac vs Majorana

helicity:
projection of
spin onto
momentum



Experiments, so far, tell us:

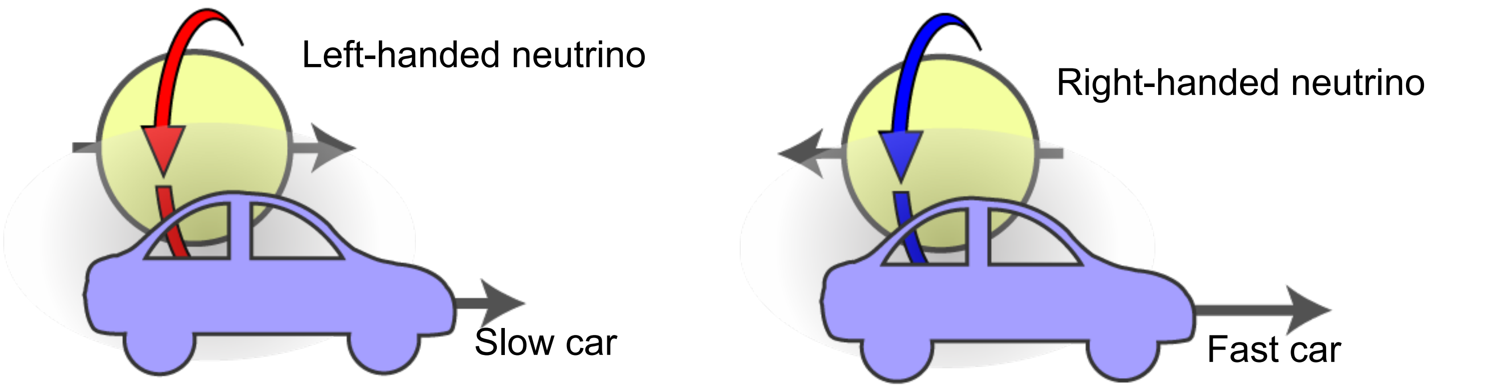
- Neutrinos have left-handed helicity → $p \rightarrow n + e^{+} + \nu_e$
- Antineutrinos have right-handed helicity → $n \rightarrow p + e^{-} + \bar{\nu}_e$

Dirac:
"There is a more fundamental difference between the two"

Majorana:
"That's the only difference"

Gedankenexperiment

Neutrinos have mass, so they can't go as fast as light

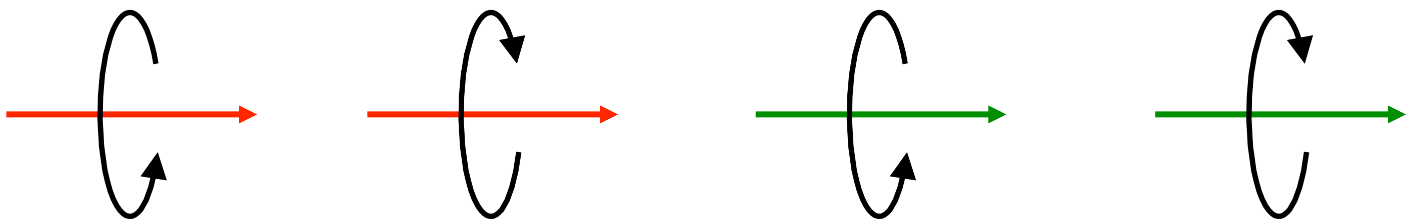


What happens when we flip the helicity of the neutrino?

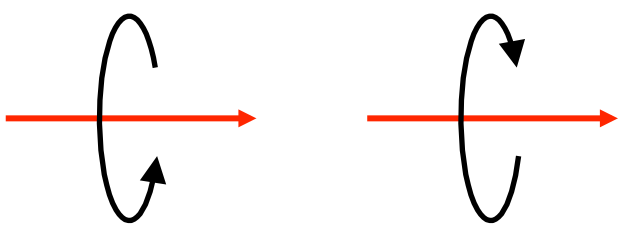
- The neutrino is **not identical** to the known antineutrino (Dirac)
- The neutrino is **identical** to the known antineutrino (Majorana)

Dirac vs Majorana

Dirac:
- 4 neutrino states

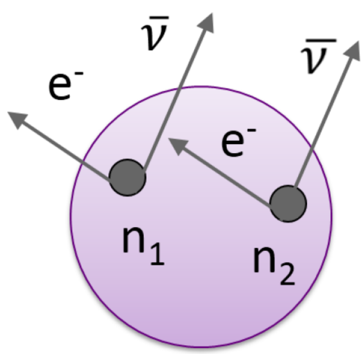


Majorana:
- 2 neutrino states

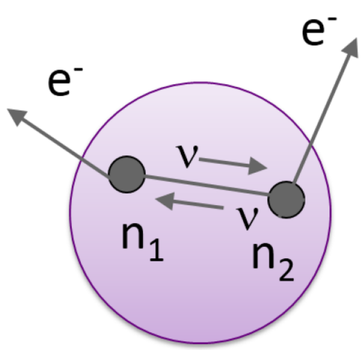


How can we test which one is true?

If neutrino is a Majorana particle (its own antiparticle) then the neutrino emitted by one neutron in a nucleus should be able to interact with another neutron in the nucleus…



2νββ



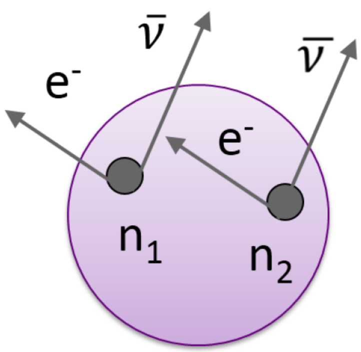
0νββ

$$n \rightarrow p + e + \bar{\nu}_e$$

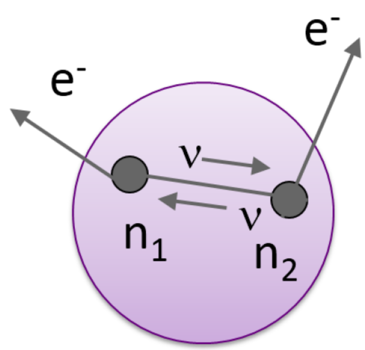
$$\nu_e + n \rightarrow p + e$$

Paradox?

Why — even if they were Majorana particles — do the neutrinos not like to do that ?



2νββ



0νββ

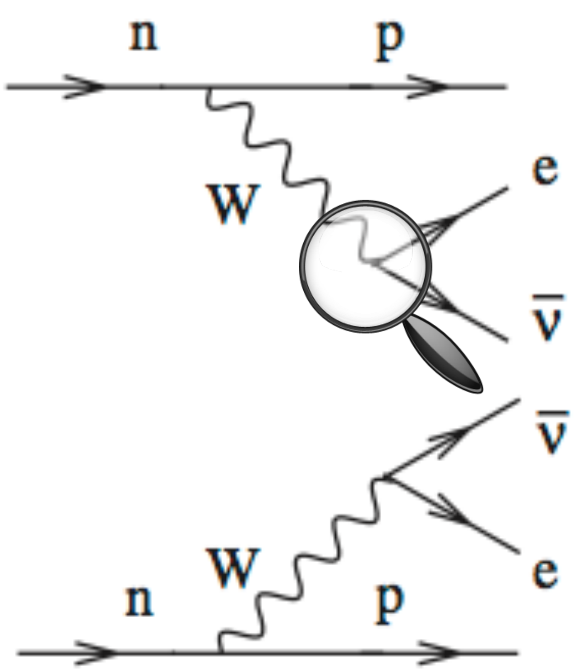
$$n \rightarrow p + e + \bar{\nu}_e$$

$$\nu_e + n \rightarrow p + e$$

Helicity vs Chirality

Helicity	Chirality
$h = \frac{\vec{S} \cdot \vec{p}}{\lvert\vec{p}\rvert}$	$P_L = \frac{1-\gamma^5}{2}$
Weak interaction does not know about helicity	Weak interaction projects out a chiral component of the field
Helicity of massive particle depends on reference frame	Chirality is frame independent
Physical particles occur with a definite helicity in nature	Physical particles have no defined chirality
Property of particle	Property of interaction

Helicity vs Chirality

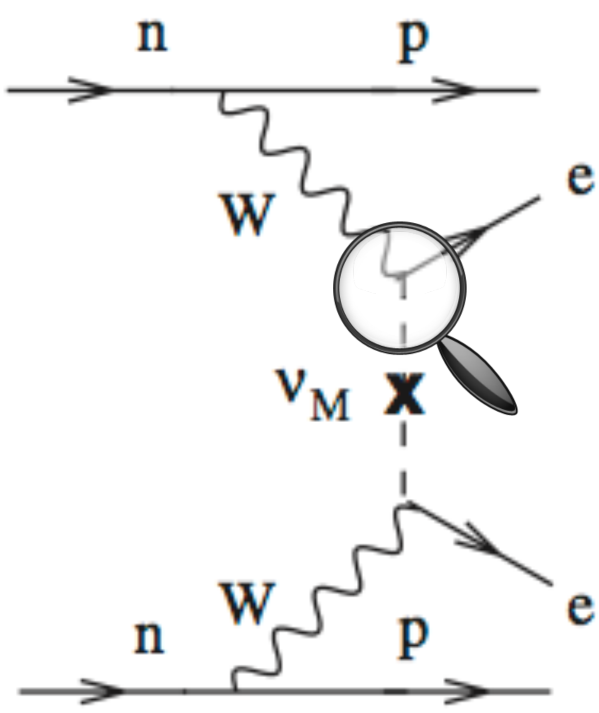


- Projection on right-chiral component of neutrino- (and electron-) field

<u>Massless case:</u>

- The right-chiral component happens to be identical to the right-helicity component of the field
  - The physical neutrino appears only with right-handed helicity

Helicity vs Chirality

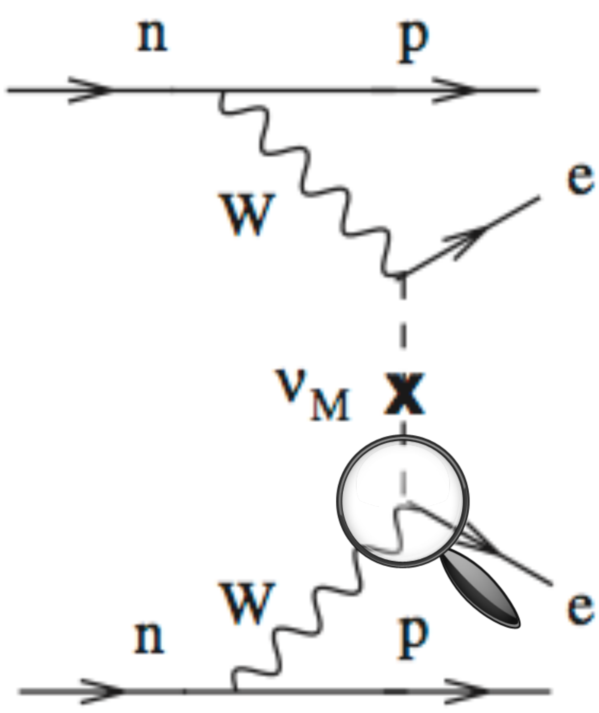


- Projection on right-chiral component of neutrino- (and electron-) field

Massive case:

- The right-chiral component in no longer identical to the right-helicity component of the field
  - The physical neutrino appears mostly with right-handed helicity
  - and a bit O(m/E) of left-handed helicity

Helicity vs Chirality



If the neutrino is a Majorana particle:
The amplitude is suppressed with
the small mass of the neutrino

- Neutrinos from one neutron are mostly right-handed but a little bit left-handed

<u>Massive case:</u>

- At the other interaction vertex the weak interaction projects out the left-chiral component of the field
  - The vertex will absorb with almost no suppression the left-handed helicity neutrino and a O(m/E) fraction of the right-handed helicity neutrino

Neutrinoless double beta decay

Why do we care whether the neutrino is Dirac or Majorana?

How to test the Majorana vs Dirac nature?

When does $0\nu\beta\beta$ happen?

How often does it happen?

How often does it need to happen so we can say that we found it?

What can we say about the neutrino mass?

Where do we stand experimentally?

What causes background?

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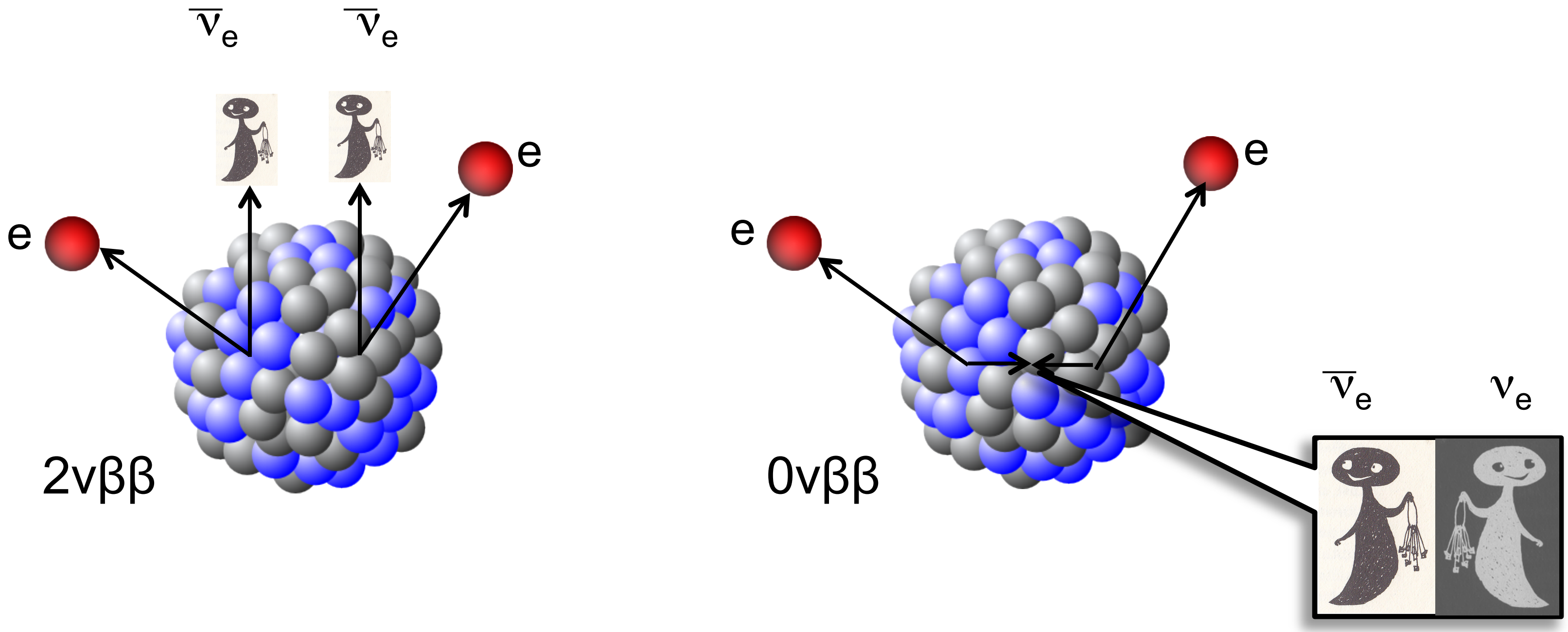
Neutrinoless Double Beta Decay



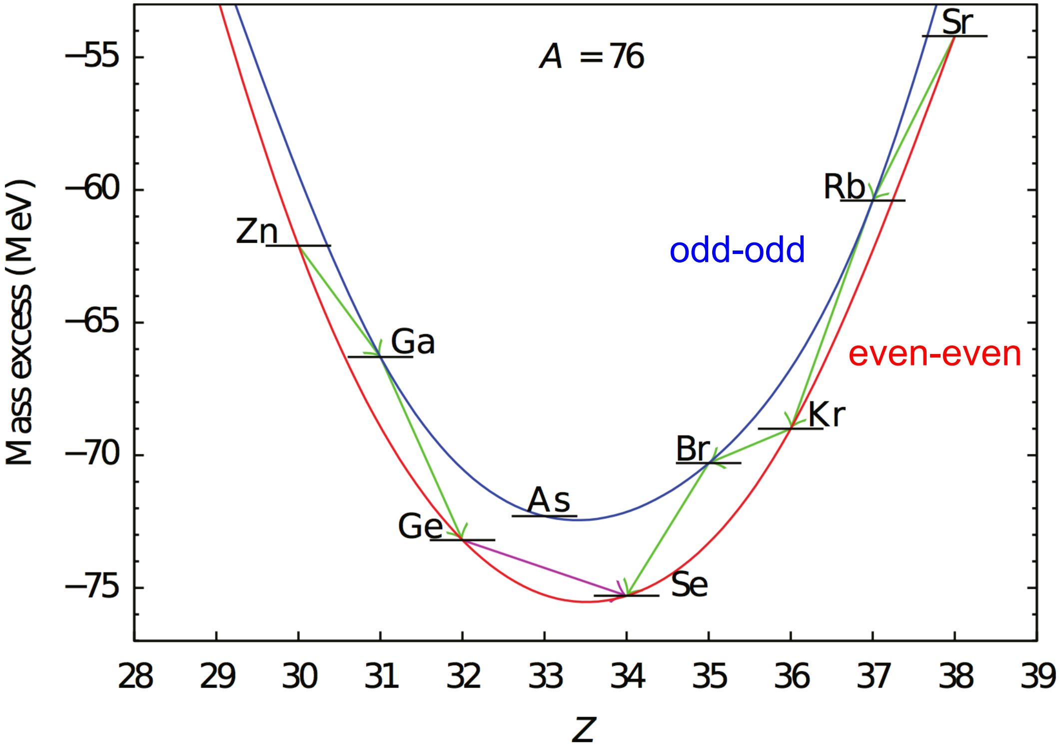
2νββ:

- Two neutrons in one nucleus decay simultaneously
- This has been observed in 11 isotopes
- $T_{1/2} \sim 10^{18\text{-}24}$

Double beta decay (when does it happen?)

Semi-empirical mass formula (Bethe-Weizsäcker formula):

$$E(A,Z) = \underbrace{a_V A}_{\text{Volume}} - \underbrace{a_S A^{2/3}}_{\text{Surface}} - \underbrace{a_C \frac{Z(Z-1)}{A^{1/3}}}_{\text{Coulomb}} - \underbrace{a_A \frac{(A/2-Z)^2}{A}}_{\text{Asymmetry}} + \underbrace{\delta(A,Z)}_{\text{Pairing}}$$



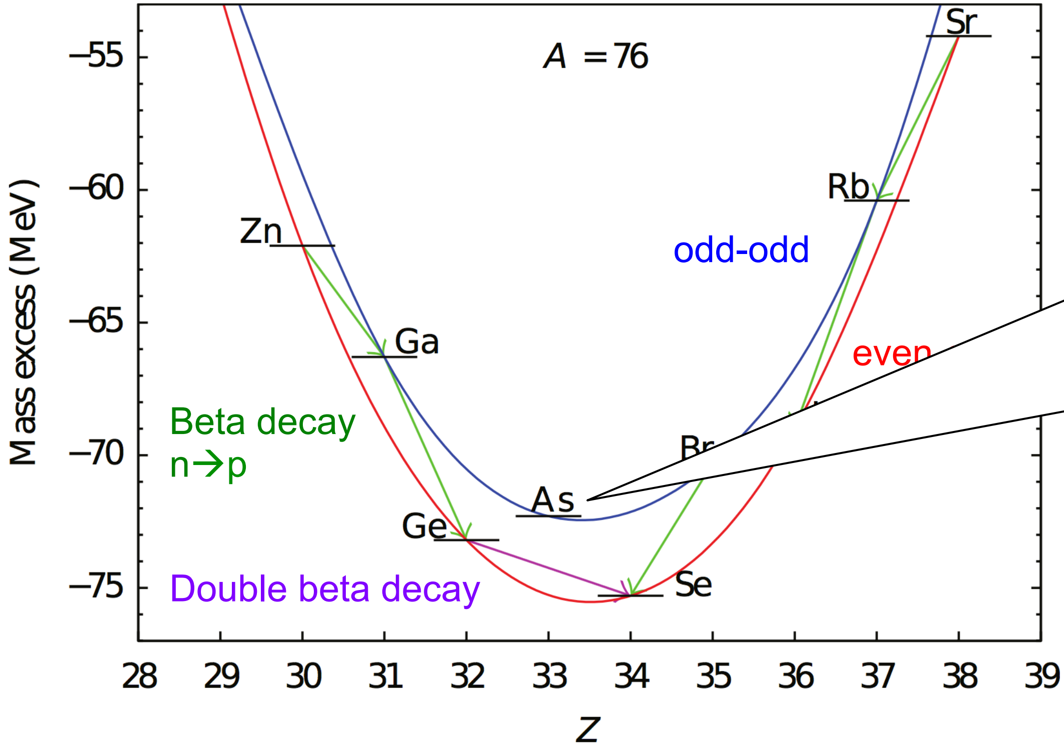
$$\delta(A,Z) = \begin{cases} +\delta_0 & Z,N \quad \text{even} \\ 0 & A = Z+N \quad \text{odd} \\ -\delta_0 & Z,N \quad \text{odd} \end{cases}$$

even-even nuclei are energetically preferred

Double beta decay (when does it happen?)

Semi-empirical mass formula (Bethe-Weizsäcker formula):

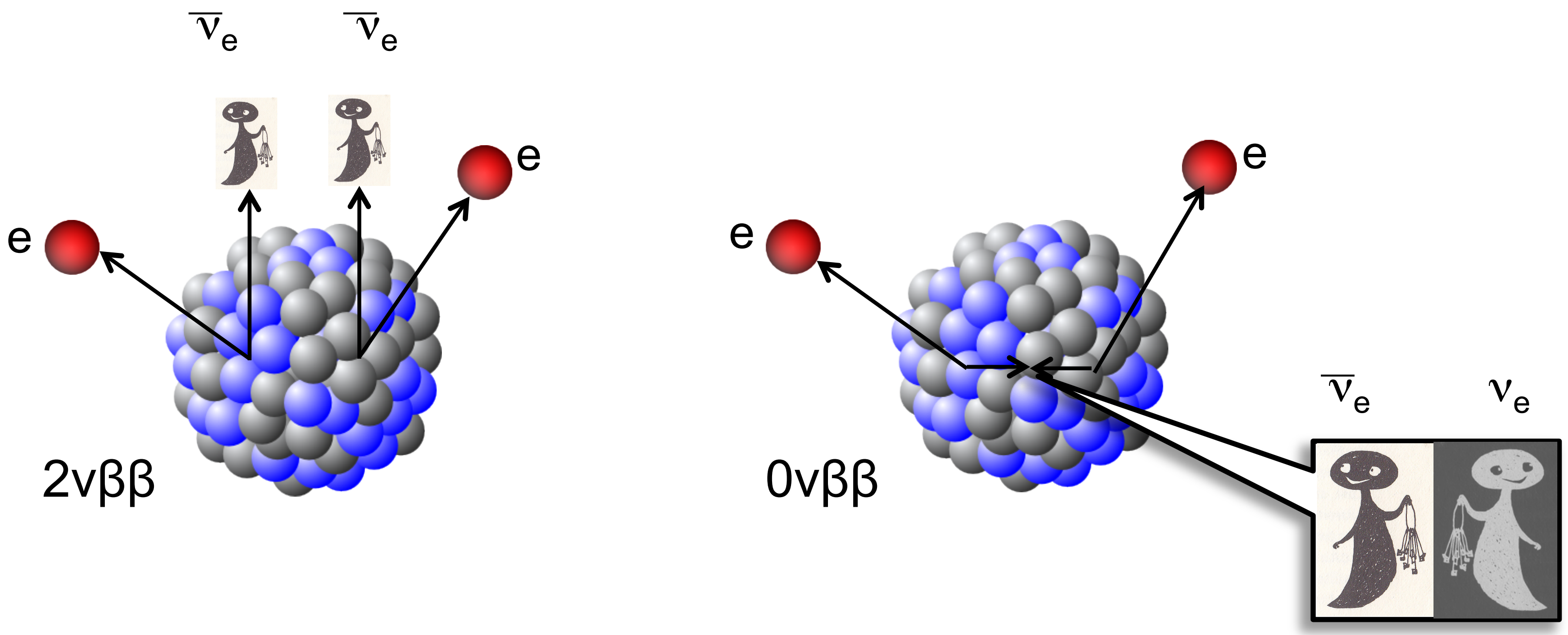
$$E(A,Z) = \underbrace{a_v A}_{\text{Volume}} - \underbrace{a_S A^{2/3}}_{\text{Surface}} - \underbrace{a_C \frac{Z(Z-1)}{A^{1/3}}}_{\text{Coulomb}} - \underbrace{a_A \frac{(A/2-Z)^2}{A}}_{\text{Asymmetry}} + \underbrace{\delta(A,Z)}_{\text{Pairing}}$$



In some cases, the single beta decay is energetically forbidden.

Then double beta decay becomes relevant

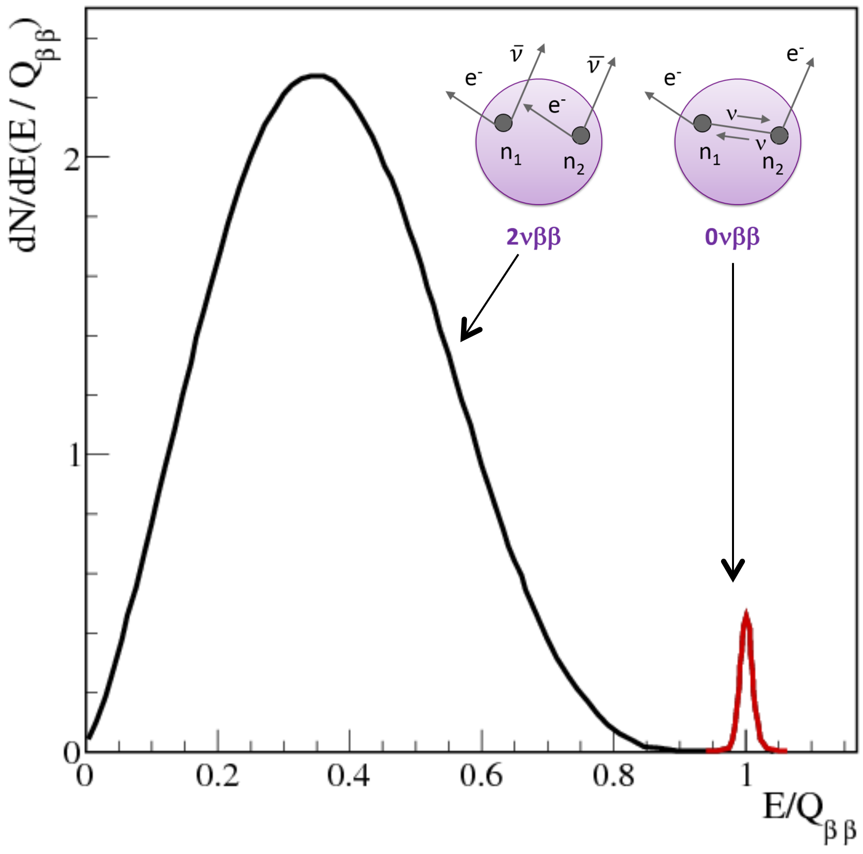
Neutrinoless Double Beta Decay



If 0νββ is discovered:

- The neutrino is a Majorana particle
- Lepton number is violated
- Measure of the neutrino mass

The signature



= Energy of the two electrons/ total energy released in the decay

- 2νββ: neutrinos and electrons share the energy
- 0νββ: the electrons get all the energy

Neutrinoless double beta decay

Why do we care whether the neutrino is Dirac or Majorana?

How to test the Majorana vs Dirac nature?

When does $0\nu\beta\beta$ happen?

How much mass of an isotope do we need?

What can we say about the neutrino mass?

Where do we stand experimentally?

How to achieve low background

Which technology to choose?

The isotopes of choice…

Isotope	$T_{1/2}$ (2ν) (y)
^{48}Ca	$(4.4 \pm 0.6) \cdot 10^{19}$
^{76}Ge	$(1.5 \pm 0.1) \cdot 10^{21}$
^{82}Se	$(0.92 \pm 0.07) \cdot 10^{20}$
^{96}Zr	$(2.3 \pm 0.2) \cdot 10^{19}$
^{100}Mo	$(7.1 \pm 0.4) \cdot 10^{18}$
^{116}Cd	$(2.8 \pm 0.2) \cdot 10^{19}$
^{128}Te	$(1.9 \pm 0.4) \cdot 10^{24}$
^{130}Te	$(1.5 \pm 0.1) \cdot 10^{20}$
^{150}Nd	$(8.2 \pm 0.9) \cdot 10^{18}$
^{238}U	$(2.0 \pm 0.6) \cdot 10^{21}$
^{136}Xe	$(2.1 \pm 0.2) \cdot 10^{22}$

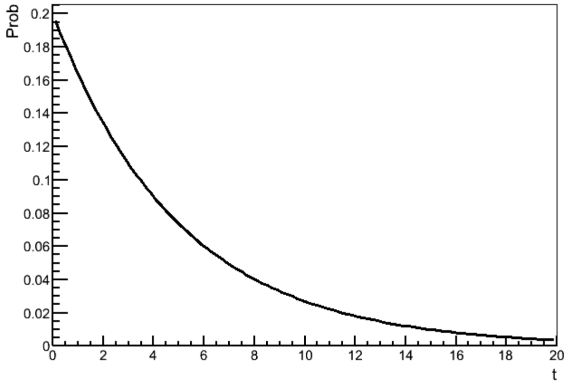
Current best limits on these three isotopes

Isotope	$T_{1/2}$ (0ν) (y)
^{76}Ge	$>3 \cdot 10^{25}$
^{130}Te	$>3 \cdot 10^{24}$
^{136}Xe	$>1 \cdot 10^{25}$

How many $0\nu\beta\beta$ decays occur…

- for 1 t of Ge enriched to 86% ^{76}Ge
- in 1 year
- and if the lifetime of ^{76}Ge was 10^{27} years

Radioactive Decay



The probability to decay at time t is

$$\boxed{p(t) = \frac{1}{\tau} e^{-(t/\tau)}}$$

The probability to decay after a time period t_{exp} is

$$P(t_{\exp}) = \int_{t=0}^{t=t_{\exp}} \frac{1}{\tau} e^{-(t/\tau)} dt$$
$$= 1 - e^{-(t_{\exp}/\tau)}$$

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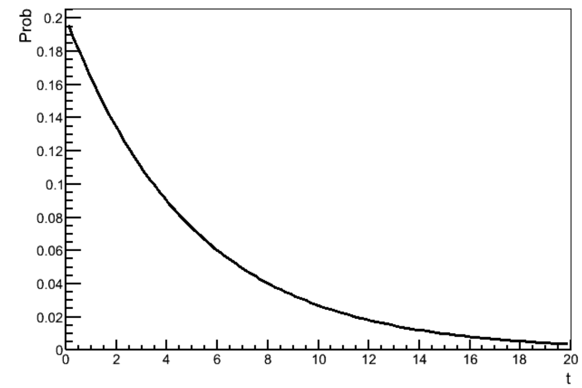
Radioactive Decay



The probability to decay at time t is

$$p(t) = \frac{1}{\tau} e^{-(t/\tau)}$$

It's most likely for the nucleus to decay immediately…why is that, actually?

The probability to decay after a time period t_{exp} is

$$P(t_{\mathrm{exp}}) = \int_{t=0}^{t=t_{\mathrm{exp}}} \frac{1}{\tau} e^{-(t/\tau)} dt$$
$$= 1 - e^{-(t_{\mathrm{exp}}/\tau)}$$

Coins…

Suppose you have a coin

- The probability for head is p = 50% every time you try
- The probability to through "head" at exactly the first try is p(0) = p = 50%
- The probability to through "head" at exactly the second try is p(1) = (1-p)*p = 50%*50% = 25%
- …

Suppose you all through a coin

- 50% of you will get head the first time
- 25% will get head with the second trial
- 12.5% will get head with the third trial
- …

Radioactive isotopes…

Suppose you have one radioactive isotope.

- It has the same probability to decay in every second. That means:
  - It has some probability p to decay in the first second.
  - If it does not decay, then it has again the same probability p to decay in the next second
- $p(0) = p$
- $p(1) = (1-p)p$
- $p(2) = (1-p)(1-p)p$
- So $p(t) = p\,(1-p)^t$

This is an exponential distribution:

$$P(t) = 1/\tau\, e^{(-t/\tau)} = 1/\tau\, (e^{(-1/\tau)})^t = 1/\tau\, (1 - 1/\tau)^t = p(0)\,(1-p(0))^t$$

How many decays do we observe…

$$N_{sig} = \varepsilon_{\det} N_a \left(1 - e^{-\left(t_{\exp}/\tau\right)}\right)$$

$$= \varepsilon_{\det} N_a \left(1 - e^{-\left(\ln(2)\left(t_{\exp}/T_{1/2}\right)\right)}\right)$$

$$= \varepsilon_{\det} \frac{m_{tot}}{m_{iso}} \alpha \left(1 - e^{-\left(\ln(2)\left(t_{\exp}/T_{1/2}\right)\right)}\right)$$

$$\approx \varepsilon_{\det} \frac{m_{tot}}{m_{iso}} \alpha \ln(2) \frac{t_{\exp}}{T_{1/2}}$$

$$\tau = T_{1/2} / \ln(2)$$

$$N_a = \frac{m_{tot}}{m_{iso}} \alpha$$

N_a:	number of isotopes
ε:	detection efficiency
m_{tot}:	total mass
m_{iso}:	mass of atom
α:	enrichment factor
t_{exp}:	measurement time
$T_{1/2}$:	half-life

How many decays do we observe…

detection efficiency

total mass

measurement time

number of signal events

$$N_{sig} \approx 0.99 \cdot \frac{\boxed{1000\,g}}{\frac{75.9}{6 \cdot 10^{23}}\,g} \cdot 0.86 \cdot \ln(2) \cdot \frac{\boxed{1\,y}}{10^{27}\,y} = 5 \text{ decays}$$

mass of germanium atom

enrichment factor

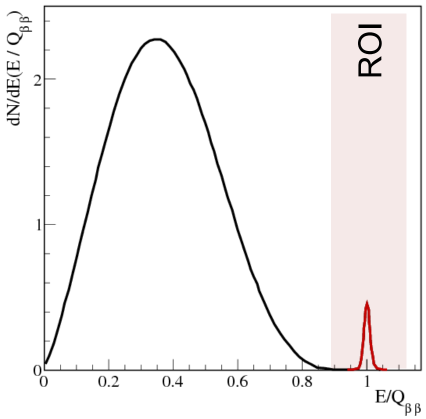
half-life

Signal events vs background events

Number of signal events:

$$N_{sig} \approx \varepsilon_{\det} \frac{m_{tot}}{m_{iso}} \alpha \ln(2) \frac{t_{\exp}}{T_{1/2}}$$

Number of background events:



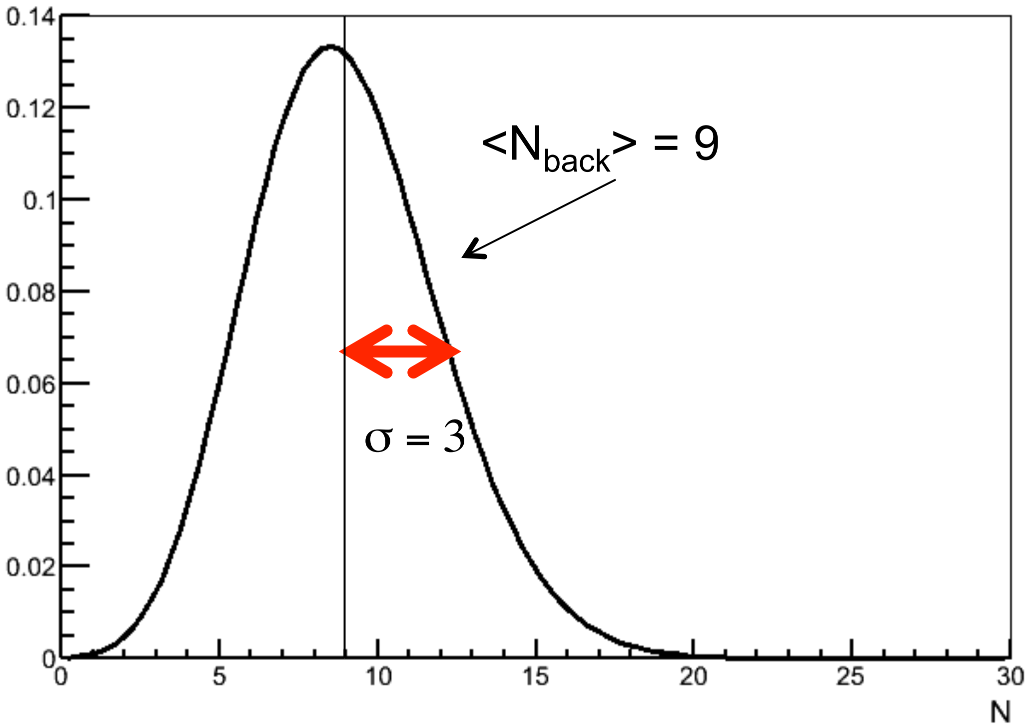
Region of interest
ROI = ΔE

$$N_{back} \approx b \cdot \Delta E \cdot m_{tot} t_{\exp}$$

b: background rate / energy
ΔE: energy resolution
m_{tot}: total mass
t: measurement time

Discovery/Evidence

We have an discovery (evidence) if N_{sig} is more than 5 (3) sigma away from the expected number of background events



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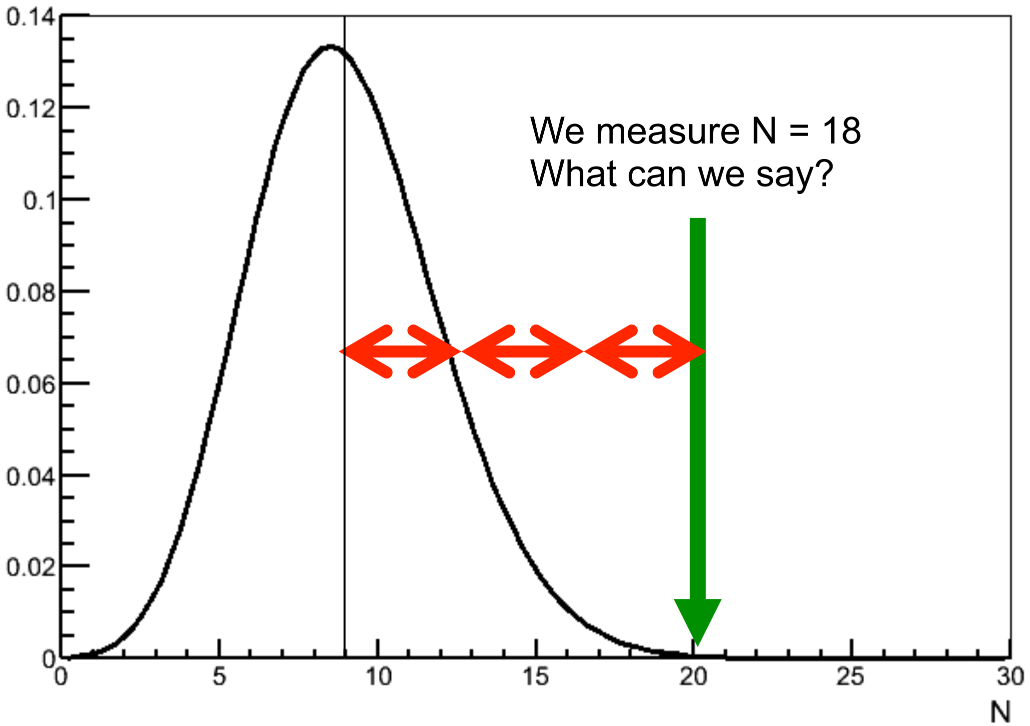
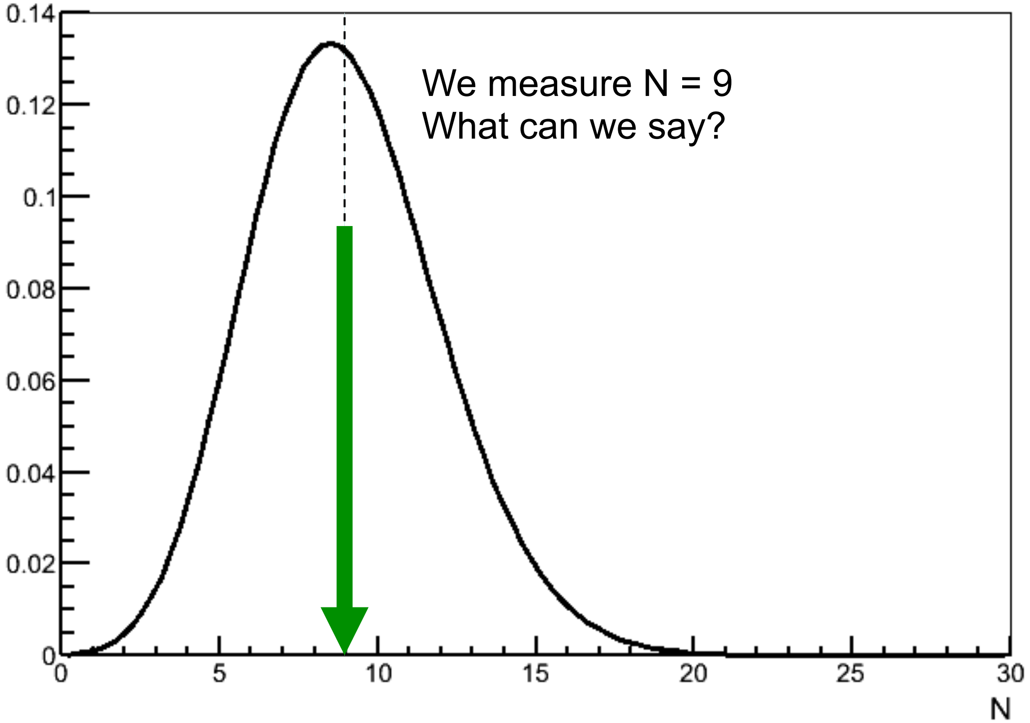


With 3 sigma significance we have found $0\nu\beta\beta$!!!

Exclusion

We can set a 90% exclusion limit if N is less than 3 sigma away from the expected number of background events



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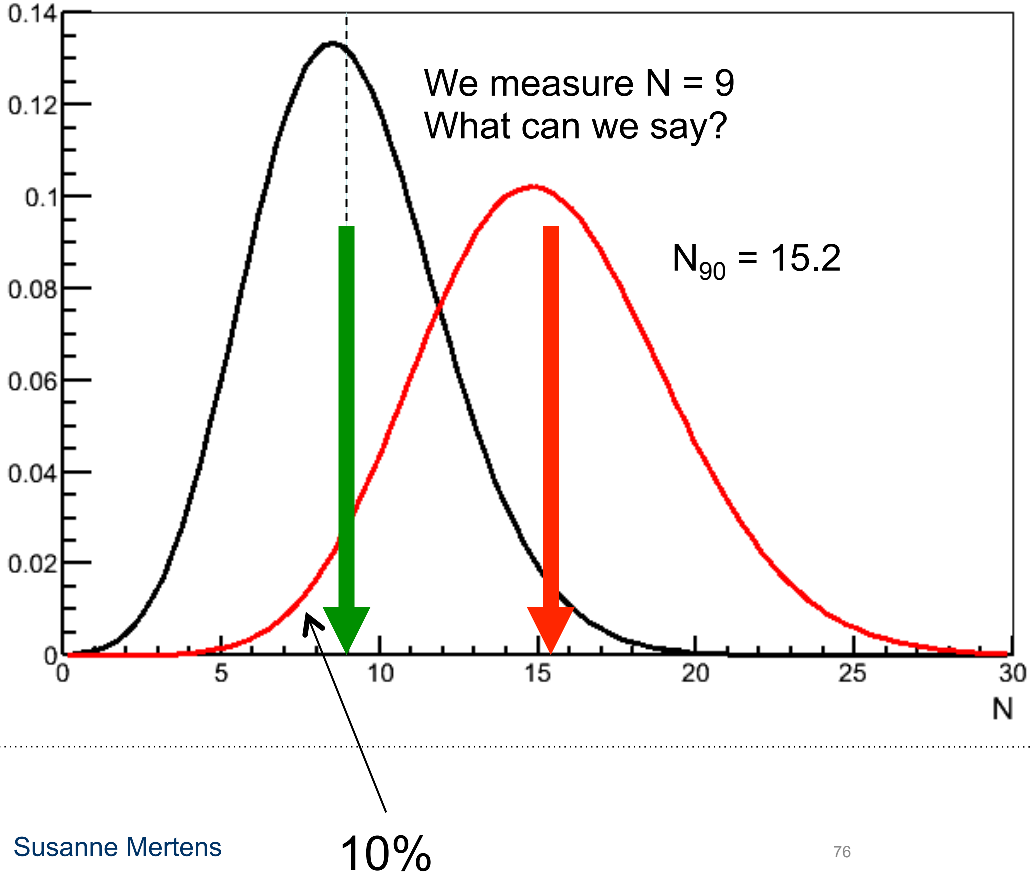
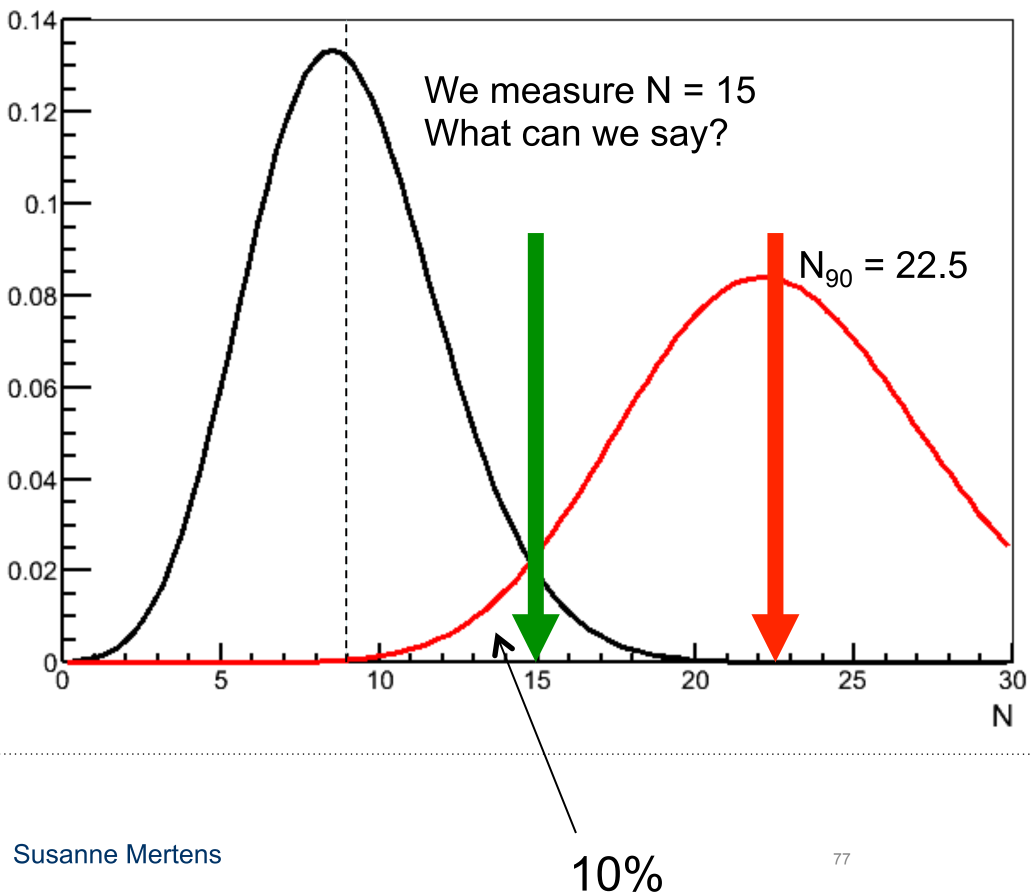


We need find the
$N_{90} = N_{sig,90} + N_{back}$
for which we would have found N in less or equal than 10% of the cases

We can exclude $N_{sig,90}$ with 90% confidence level

Exclusion

We can set a 90% exclusion limit if N is less than 3 sigma away from the expected number of background events



We need find the
$N_{90} = N_{sig,90} + N_{back}$
for which we would have found N in less or equal than 10% of the cases

We can exclude $N_{sig,90}$ with 90% confidence level

The exclusion limit depends on what we measure

Which **exposure** do we need to discover/exclude a **half-life** ?

Number of signal events:

$$\boxed{N_{sig} \approx \varepsilon_{\det} \frac{m_{tot}}{m_{iso}} \alpha \ln(2) \frac{t_{\exp}}{T_{1/2}}}$$

Number of background events: $\boxed{N_{back} \approx b \cdot \Delta E \cdot m_{tot} t_{\exp}}$

Discovery/Evidence

$$\boxed{N_{sig} > 3\sqrt{N_{back}}}$$

Which **exposure** do we need to discover/exclude a **half-life** ?

Number of signal events:

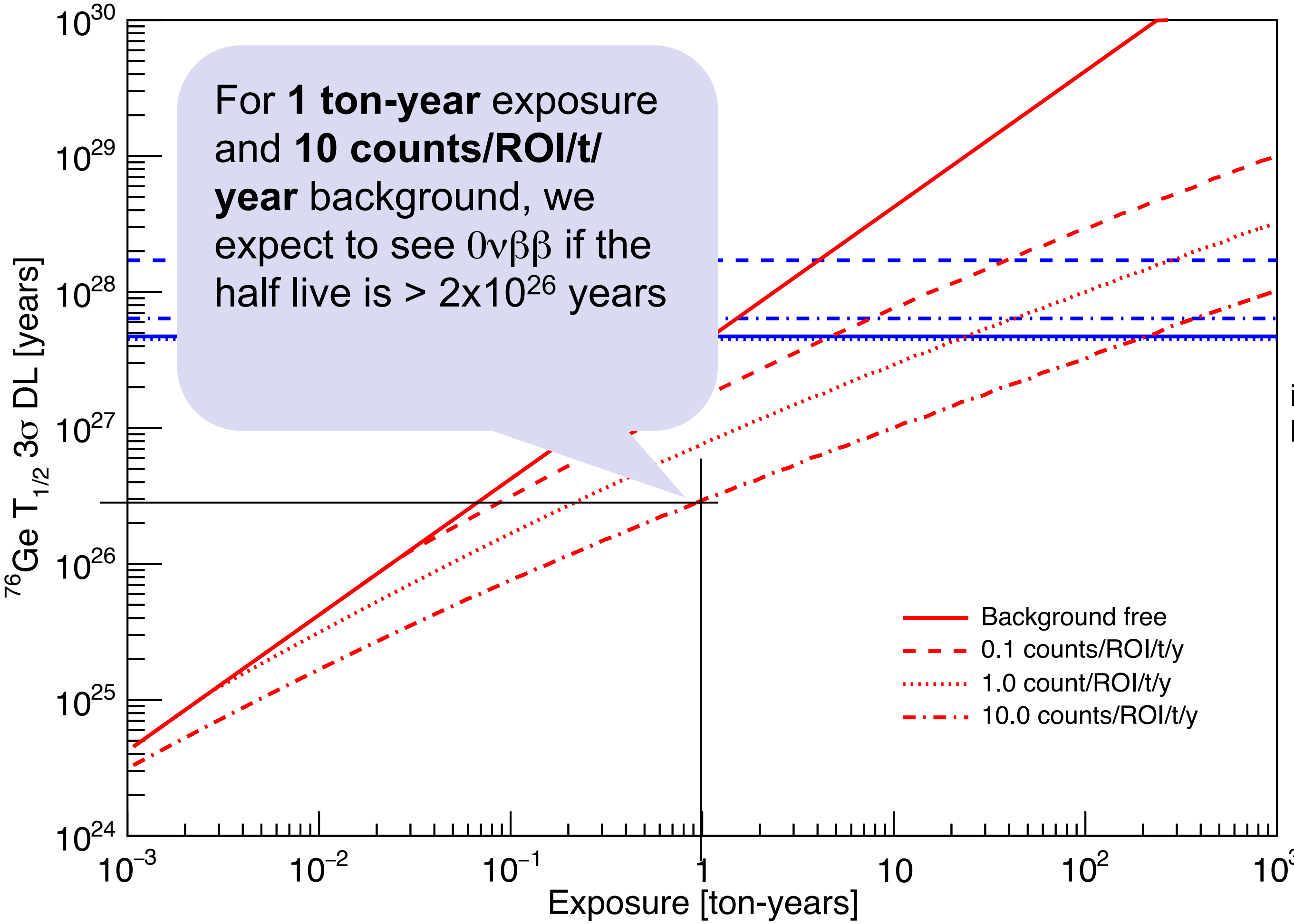
$$\boxed{N_{sig} \approx \varepsilon_{\det} \frac{m_{tot}}{m_{iso}} \alpha \ln(2) \frac{t_{\exp}}{T_{1/2}}}$$

Number of background events: $\boxed{N_{back} \approx b \cdot \Delta E \cdot m_{tot} t_{\exp}}$

Discovery/Evidence

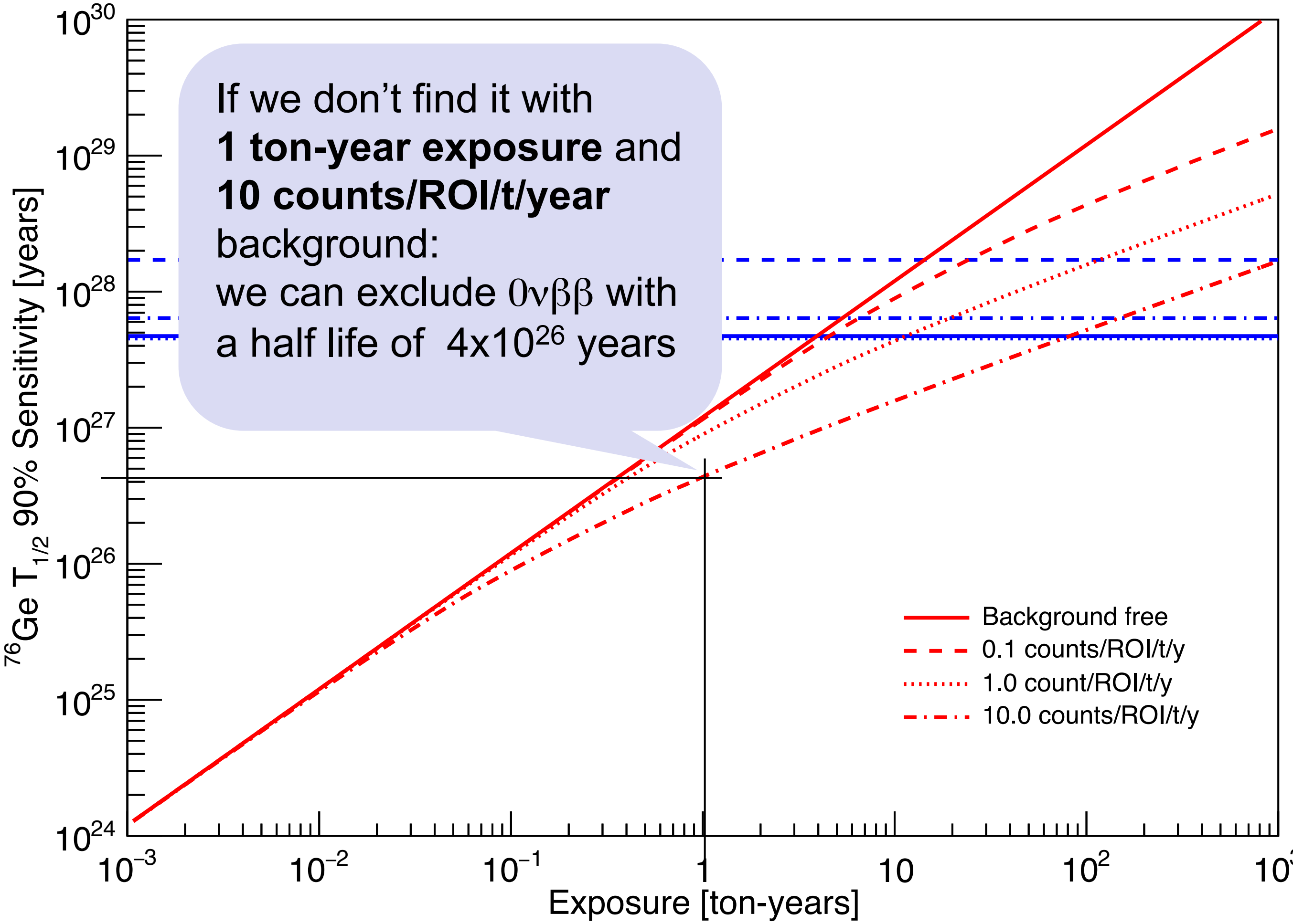
$$\boxed{T_{1/2}(3\sigma\ \mathrm{DL}) \propto \varepsilon_{\det} \sqrt{\frac{t_{\exp} m_{tot}}{b \cdot \Delta E}}}$$

Discovery/Evidence at 3 sigma



ignore blue lines for now

Exclusion at 90%



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Neutrinoless double beta decay

Why do we care whether the neutrino is Dirac or Majorana?

How to test the Majorana vs Dirac nature?

When does $0\nu\beta\beta$ happen?

How much mass of an isotope do we need?

What can we say about the neutrino mass?

Where do we stand experimentally?

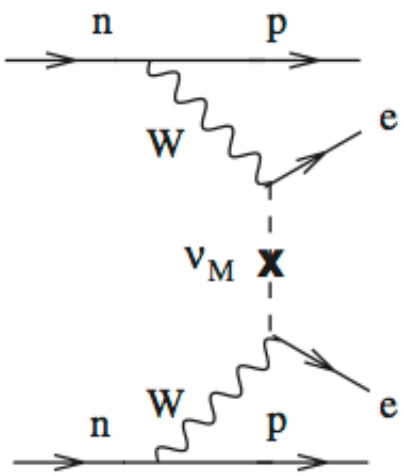
How to achieve low background?

Which technology to choose?

What do we learn about the ν-mass?

$$\frac{1}{T_{1/2}^{0\upsilon}} = G_{0\upsilon} \cdot \left|M_{0\upsilon}\right|^2 \cdot m_{\beta\beta}^2$$

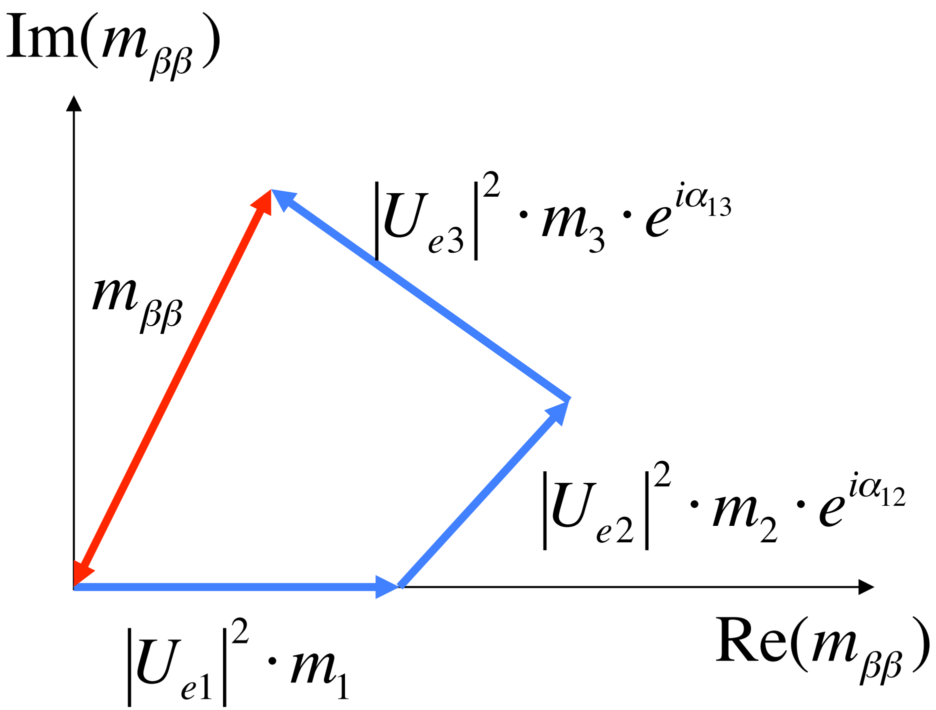
- This is true, if the particle exchanged was only a Majorana neutrino (model-dependence)
- $G_{0\nu}$ = Phase space factor
- $M_{0\nu}$ = nuclear matrix element (large uncertainties!)
- $m_{\beta\beta}$ = majorana mass



$$m_{\beta\beta} = \left| \sum_{j=1}^{3} U_{ej}^2 \cdot m_j \right|$$

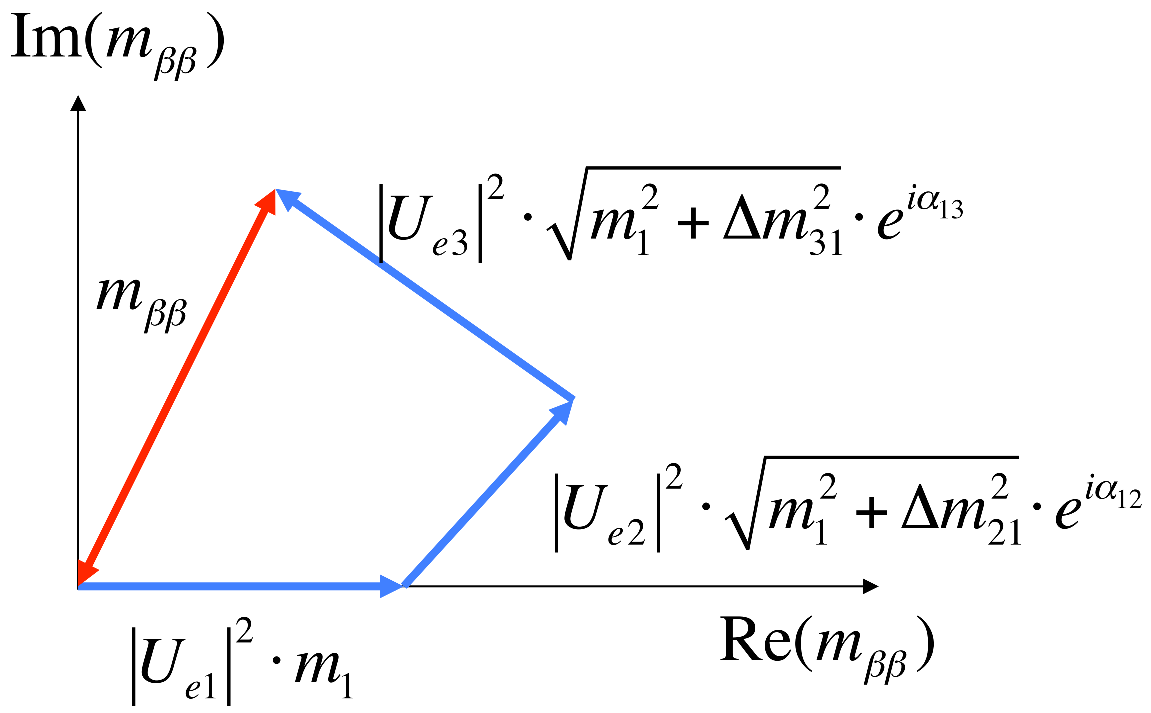
Majorana Mass

$$m_{\beta\beta} = \left| \sum_{j=1}^{3} U_{ej}^2 \cdot m_j \right| = \left| \sum_{j=1}^{3} \left|U_{ej}\right|^2 \cdot m_j \cdot e^{i\alpha_j} \right|$$



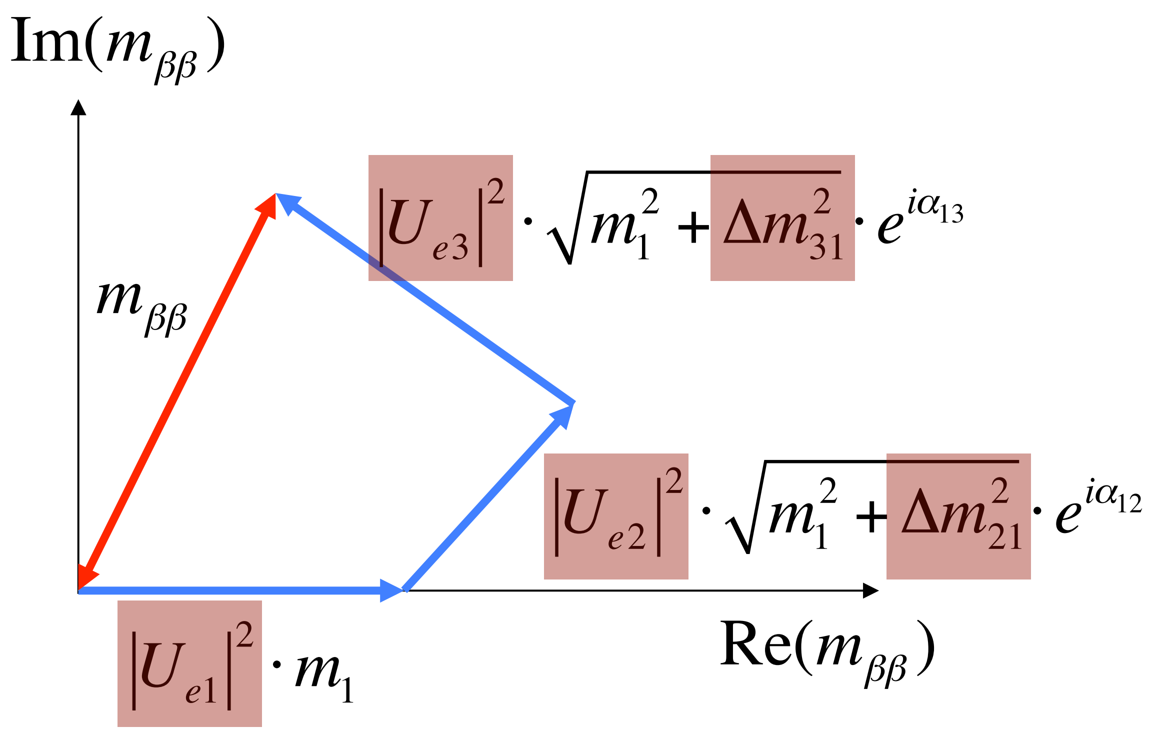
Majorana Mass

$$m_{\beta\beta} = \left| \sum_{j=1}^{3} U_{ej}^2 \cdot m_j \right| = \left| \sum_{j=1}^{3} |U_{ej}|^2 \cdot m_j \cdot e^{i\alpha_j} \right|$$



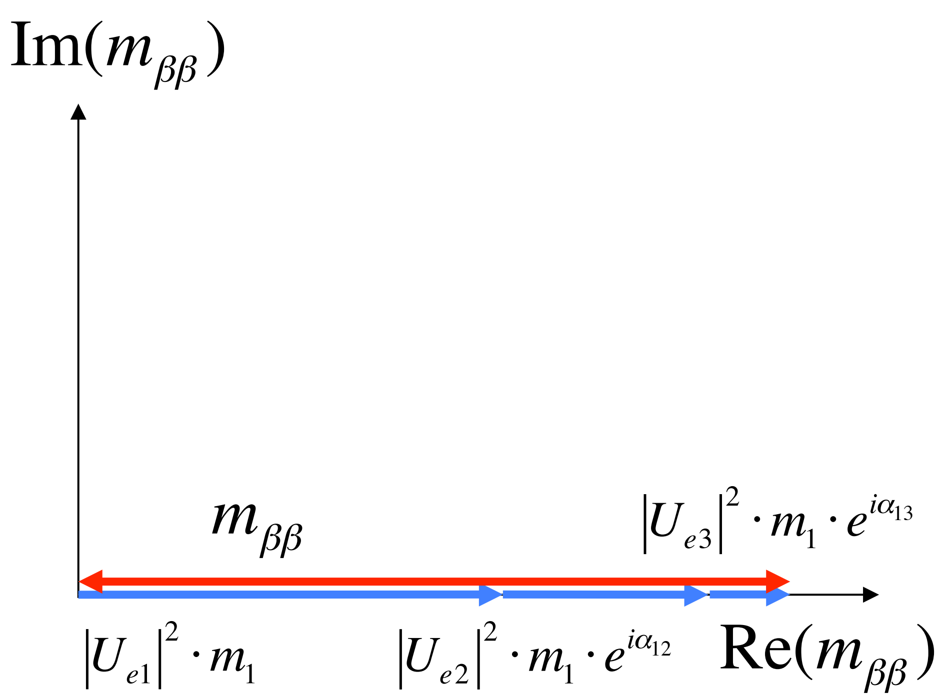
Majorana Mass

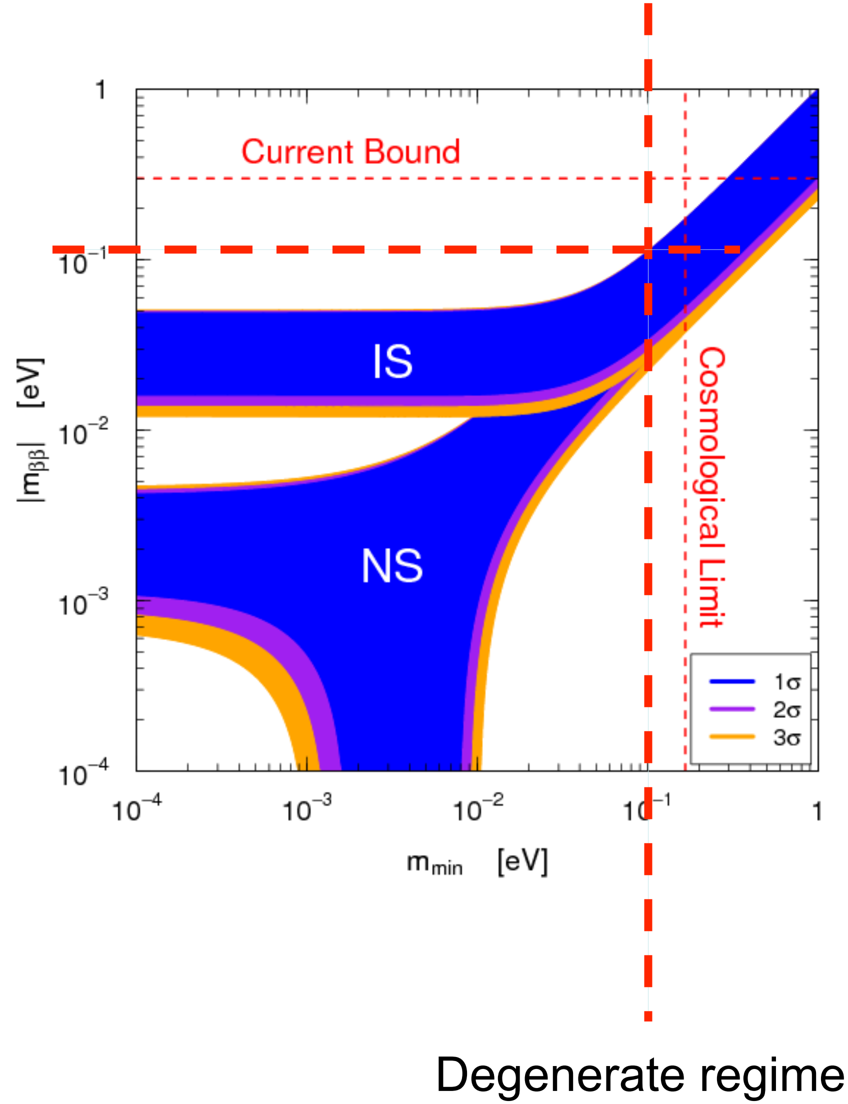
$$m_{\beta\beta} = \left| \sum_{j=1}^{3} U_{ej}^2 \cdot m_j \right| = \left| \sum_{j=1}^{3} \left|U_{ej}\right|^2 \cdot m_j \cdot e^{i\alpha_j} \right|$$



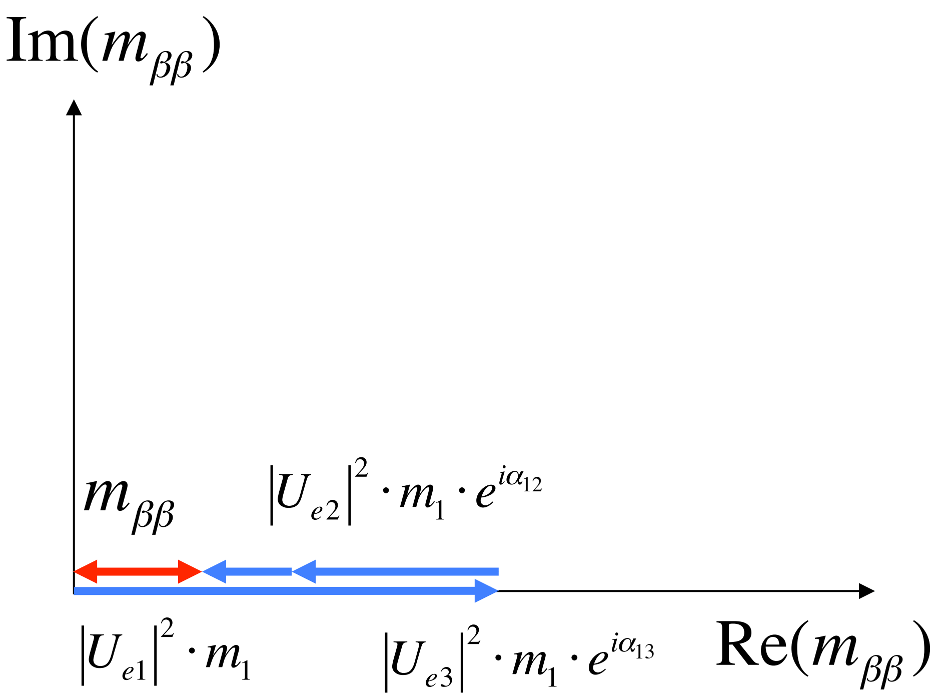
Determined through oscillation experiments

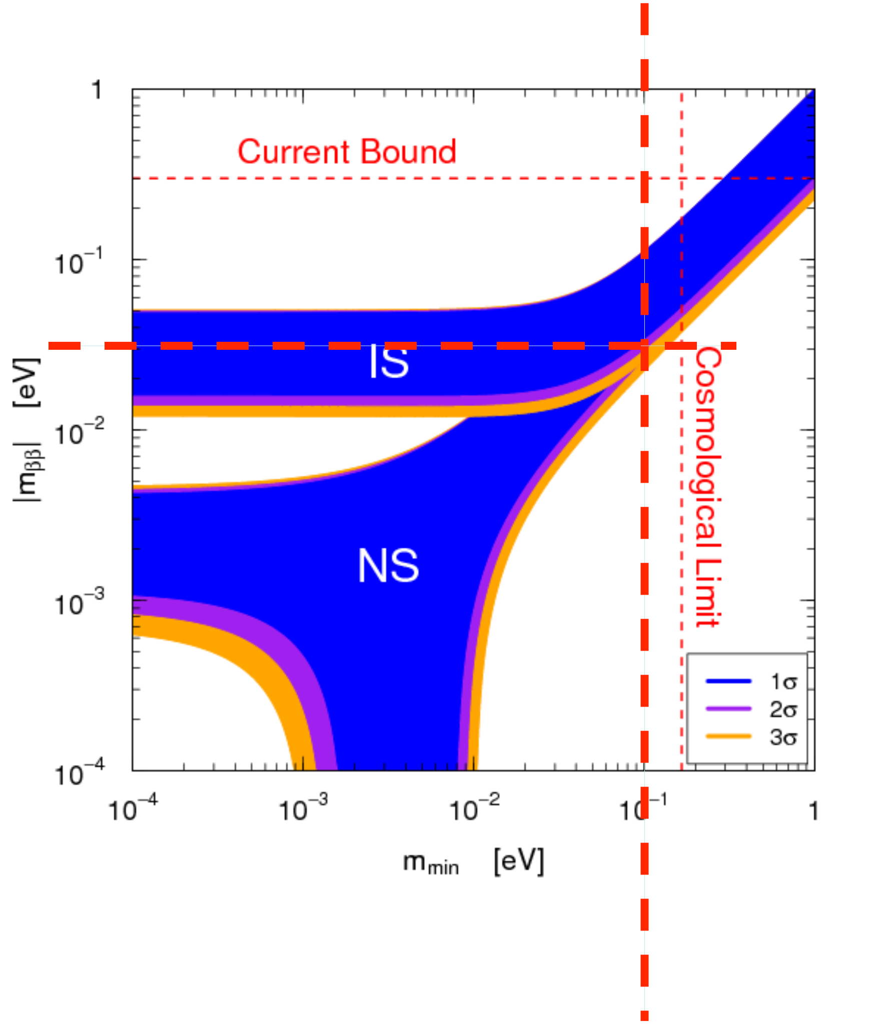
Majorana Mass





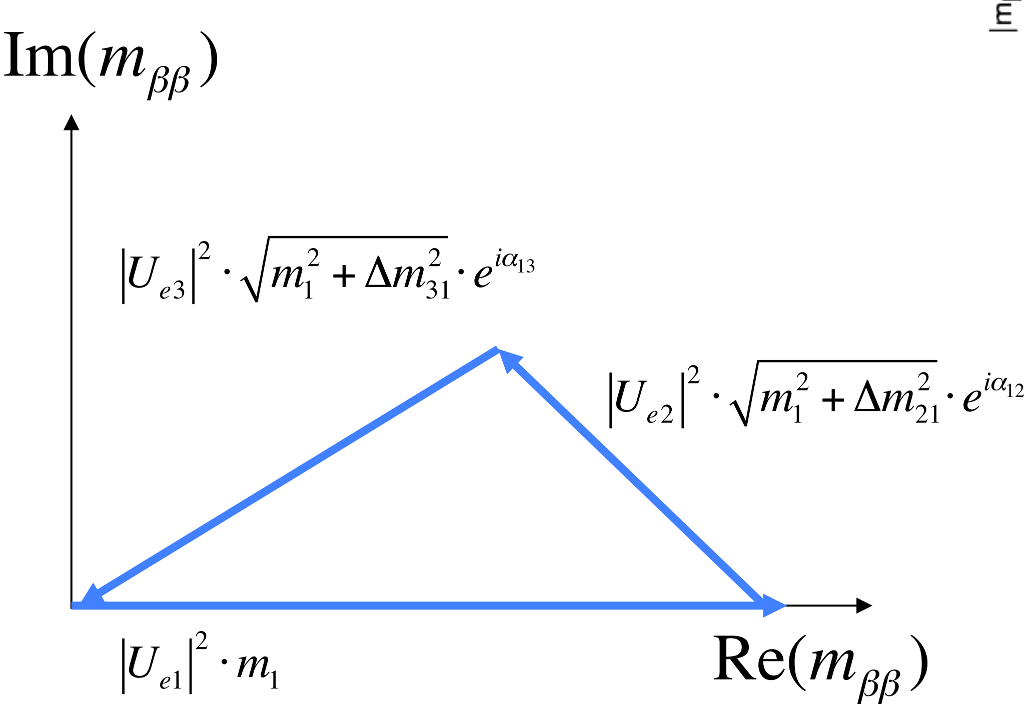
Majorana Mass

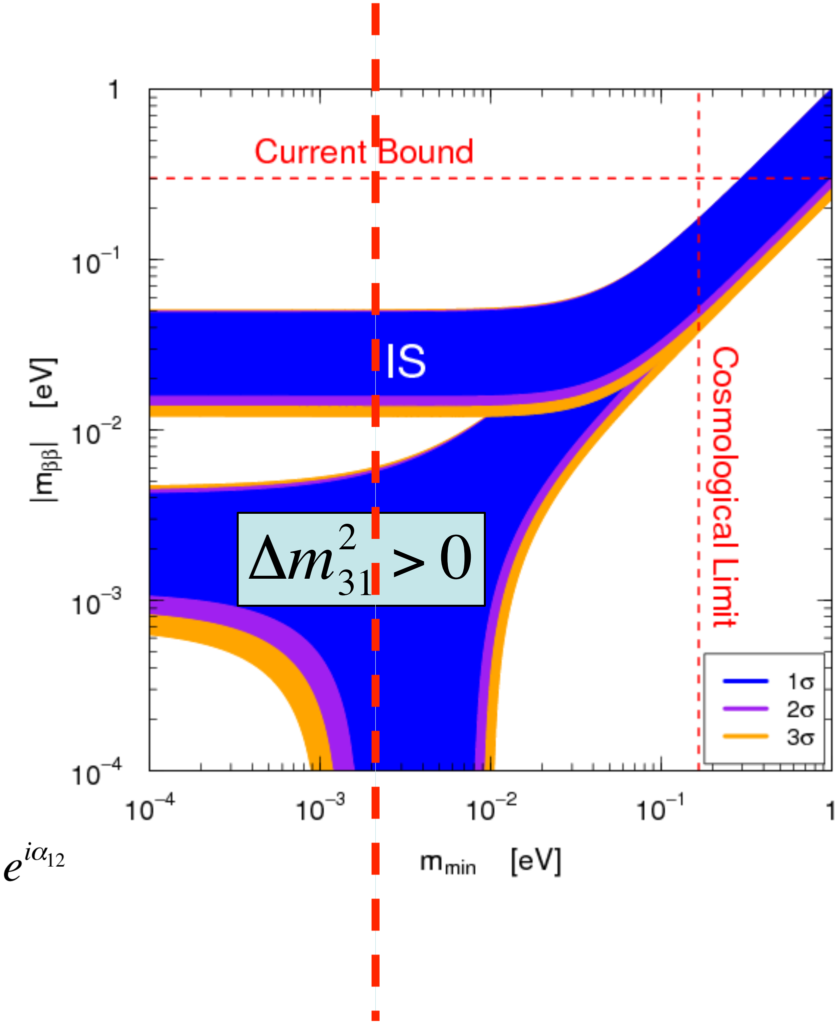




Degenerate regime

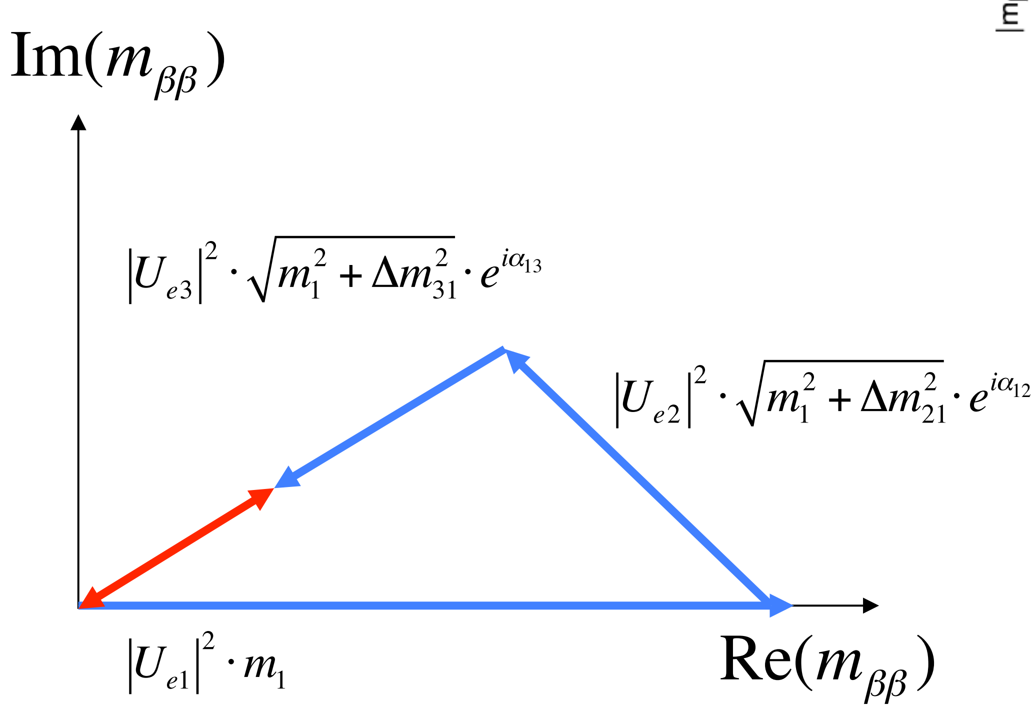
Majorana Mass

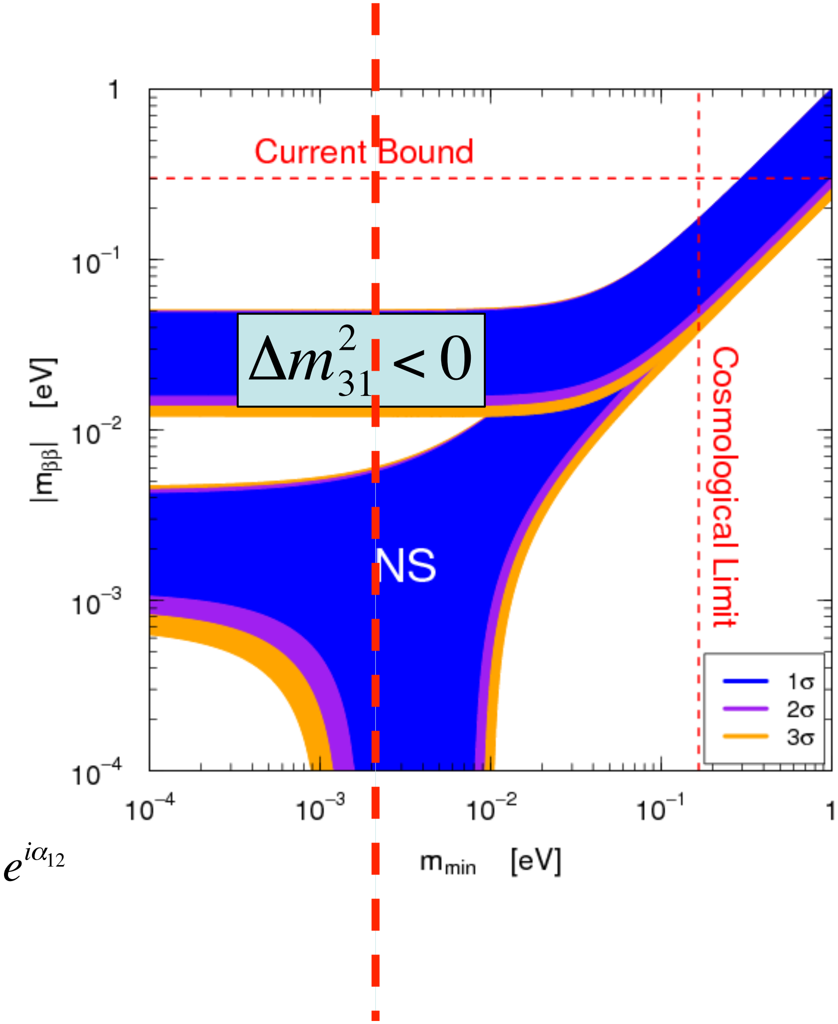




Hierarchical regime
Normal hierarchy

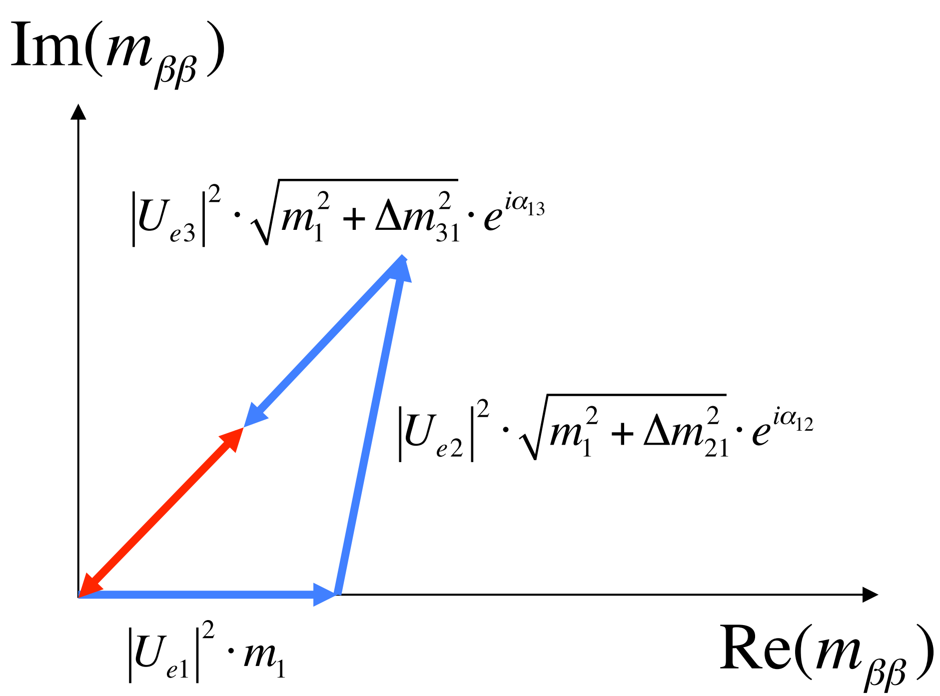
Majorana Mass

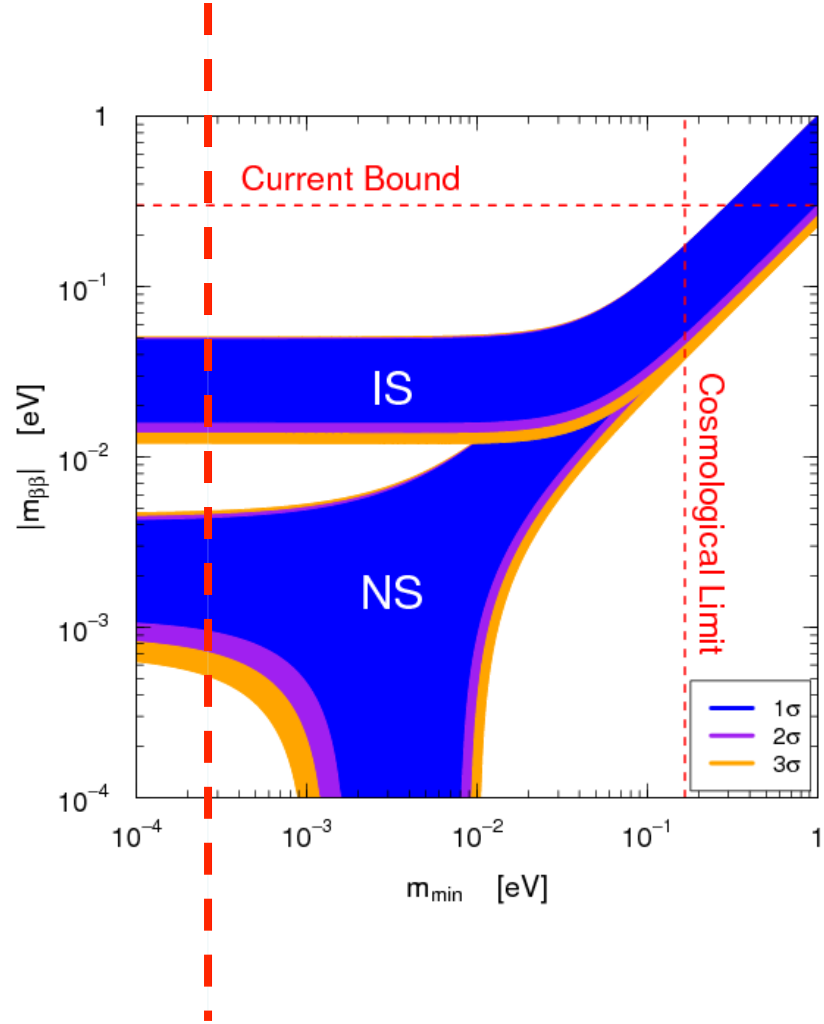




Hierarchical regime
Inverted hierarchy

Majorana Mass





Very small lightest neutrino mass

Neutrinoless double beta decay

Why do we care whether the neutrino is Dirac or Majorana?

How to test the Majorana vs Dirac nature?

When does $0\nu\beta\beta$ happen?

How much mass of an isotope do we need?

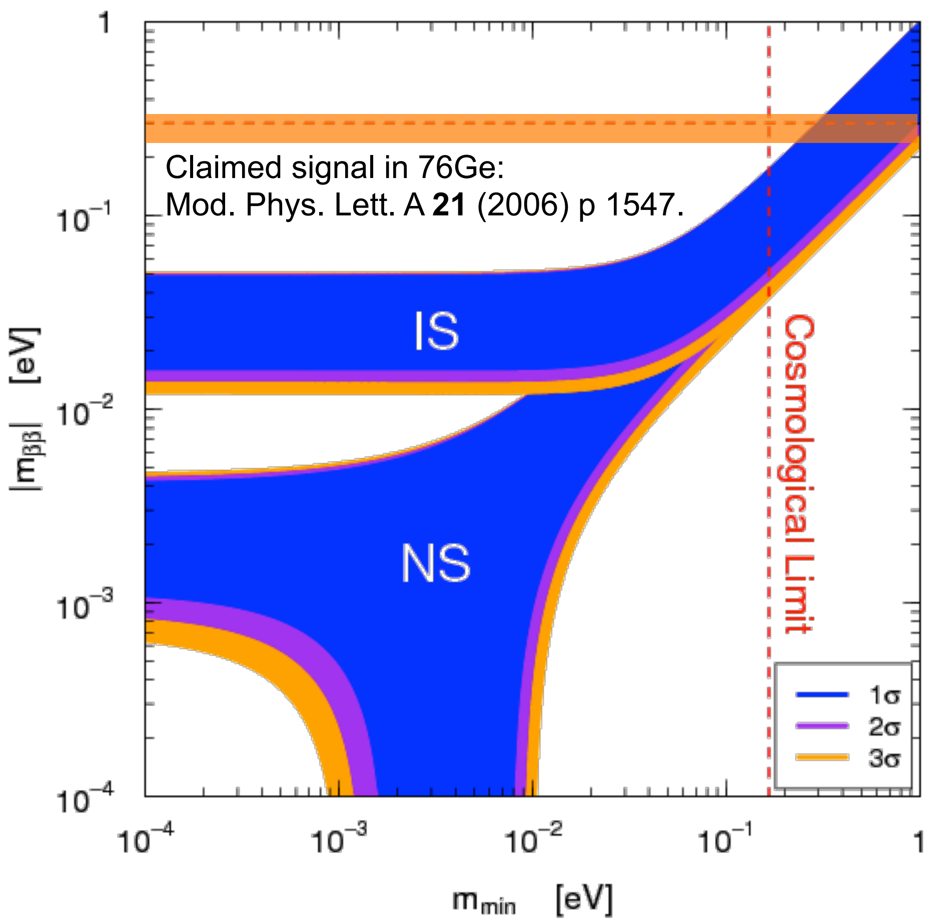
What can we say about the neutrino mass?

Where do we stand experimentally?

How to achieve low background?

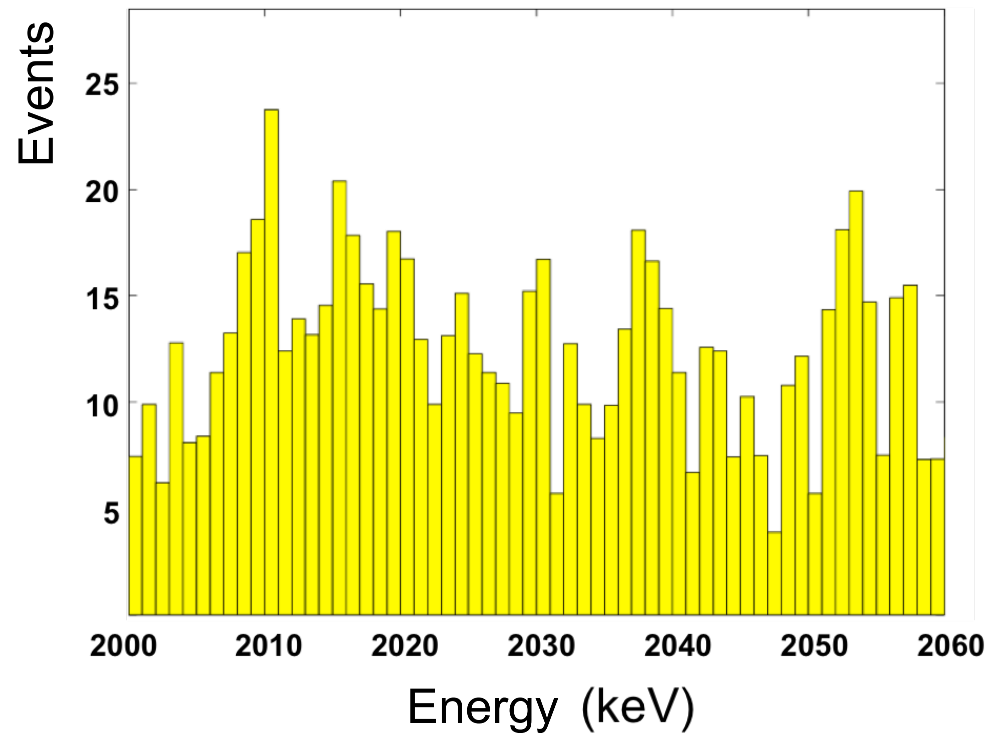
Which technology to choose?

Where do we stand experimentally?



Heidelberg-Moskau Experiment

- 1990-2003
- M = 10.96 kg of Ge detectors
- $^{76}Ge \rightarrow {}^{76}Se + 2\ e^-$
- Q = 2039 keV



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Heidelberg-Moskau Experiment

- 1990-2003
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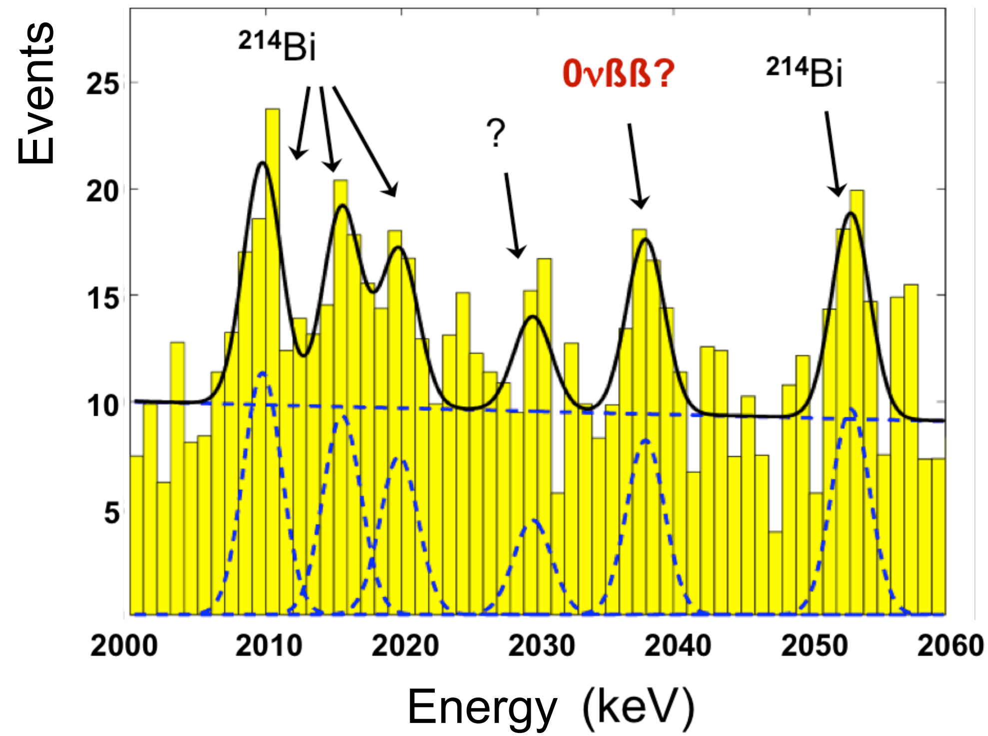
Controversal data analysis by H.V. Klapdor-Kleingrothaus



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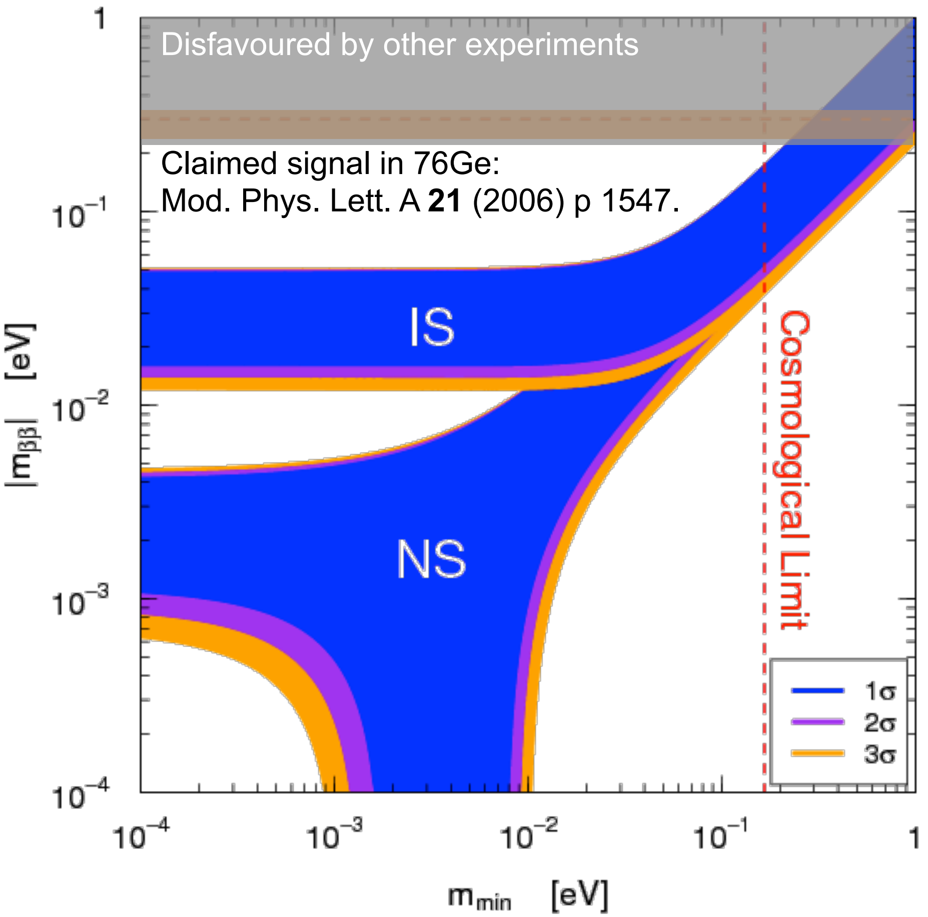
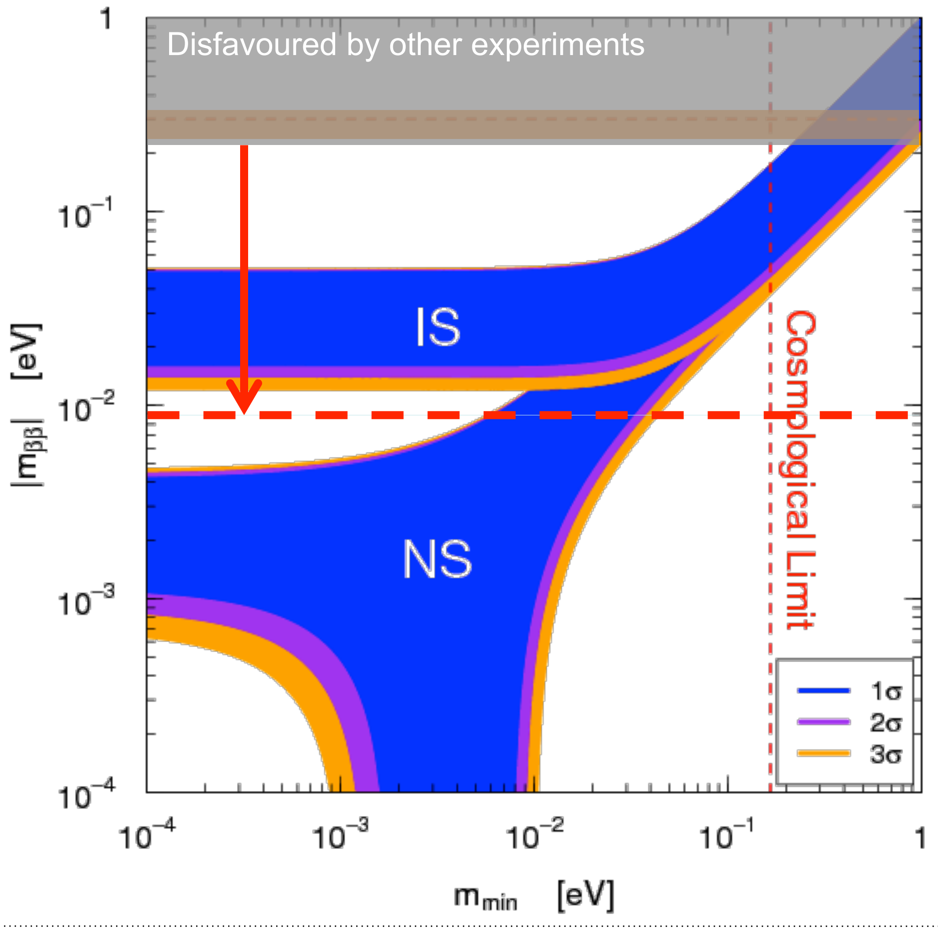
Where do we stand experimentally?

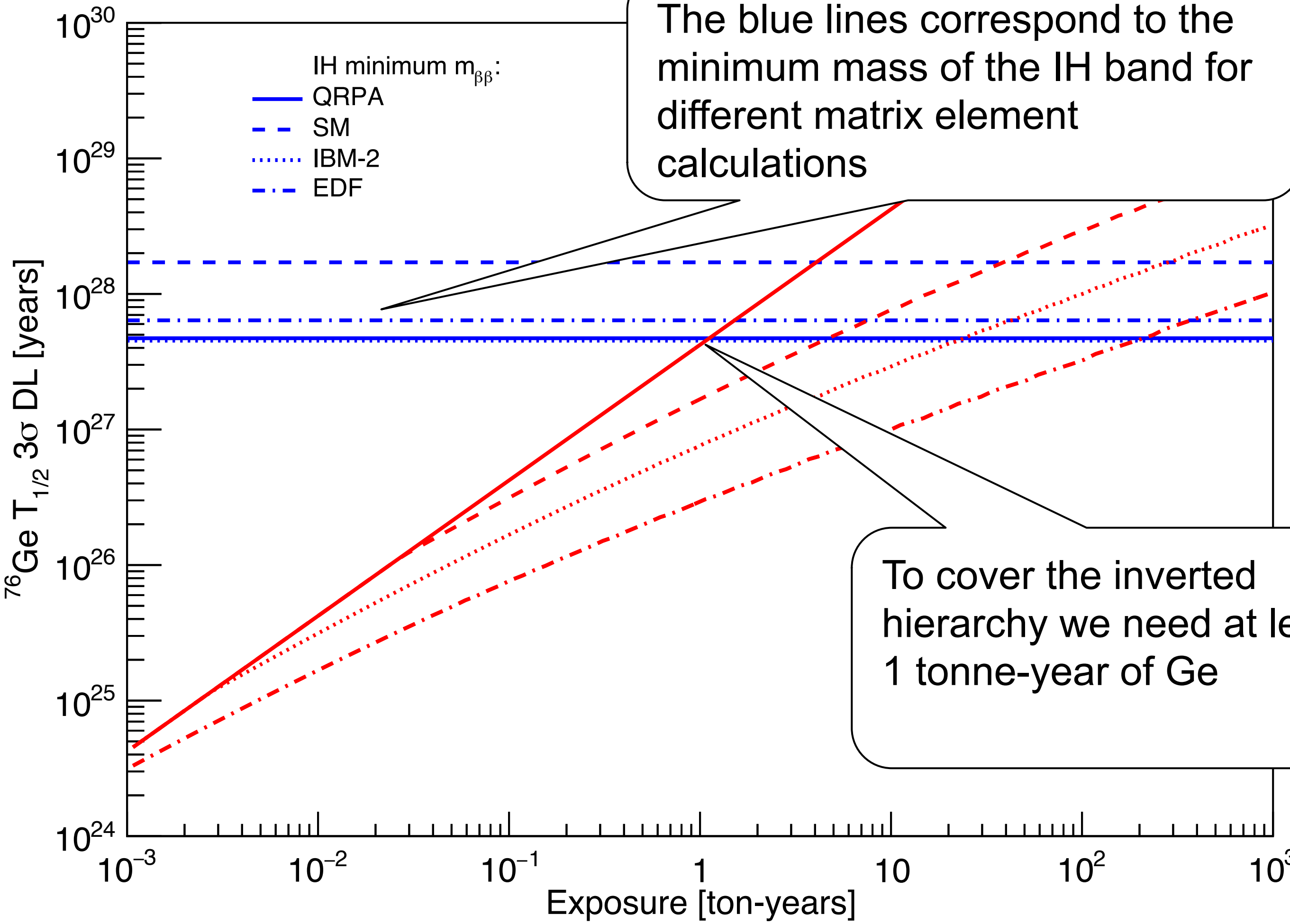


Where do we stand experimentally?



future generation of experiments

Testing the inverted hierarchy



The blue lines correspond to the minimum mass of the IH band for different matrix element calculations

To cover the inverted hierarchy we need at least 1 tonne-year of Ge

$$[T_{1/2}^{(0\nu)}]^{-1} = G_{0\nu} \cdot |\mathcal{M}^{0\nu}|^2 \cdot (m_{0\nu\beta\beta})^2$$

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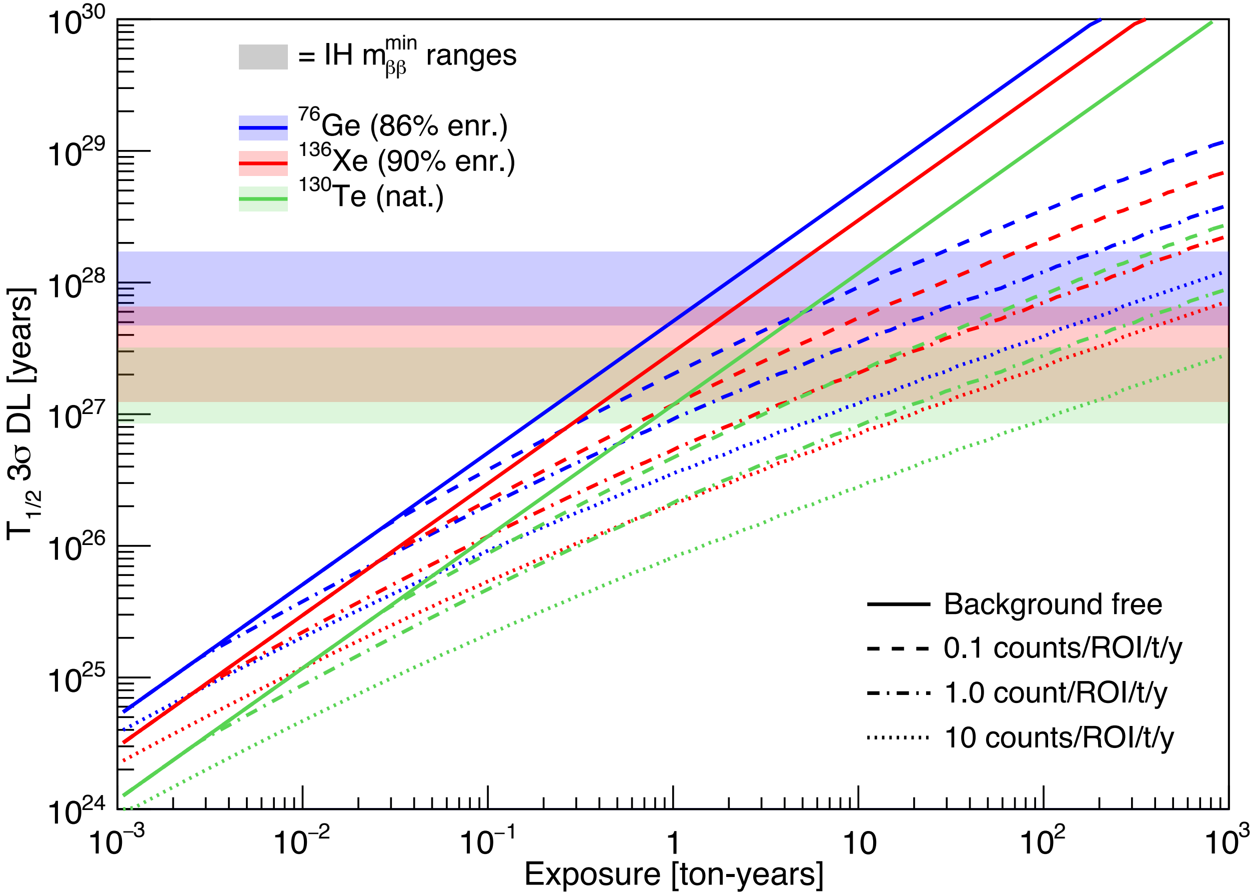
Testing the inverted hierarchy



$$[T_{1/2}^{(0\nu)}]^{-1} = G_{0\nu} \cdot |\mathcal{M}^{0\nu}|^2 \cdot (m_{0\nu\beta\beta})^2$$

What is needed?

- Large mass
  - High isotopic fraction
- Low background
  - Good energy resolution

$$T_{1/2}(3\sigma\ \mathrm{DL}) \propto \varepsilon_{\mathrm{det}} \sqrt{\frac{t_{\exp}\, m_{tot}}{b \cdot \Delta E}}$$

Neutrinoless double beta decay

Why do we care whether the neutrino is Dirac or Majorana?

How to test the Majorana vs Dirac nature?

When does $0\nu\beta\beta$ happen?

How much mass of an isotope do we need?

What can we say about the neutrino mass?

Where do we stand experimentally?

How to achieve low background?

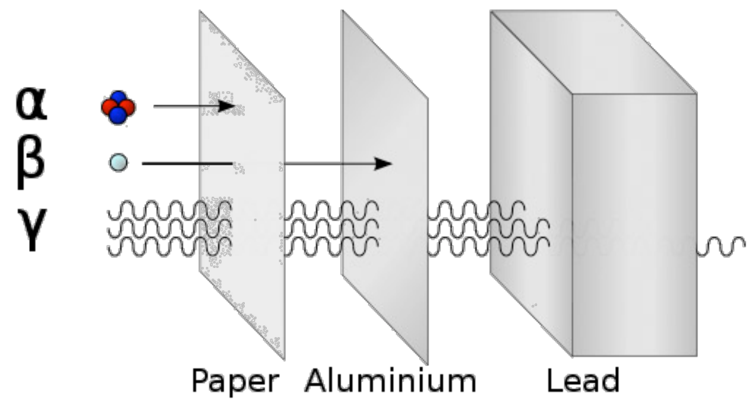
Which technology to choose?

What causes background ?

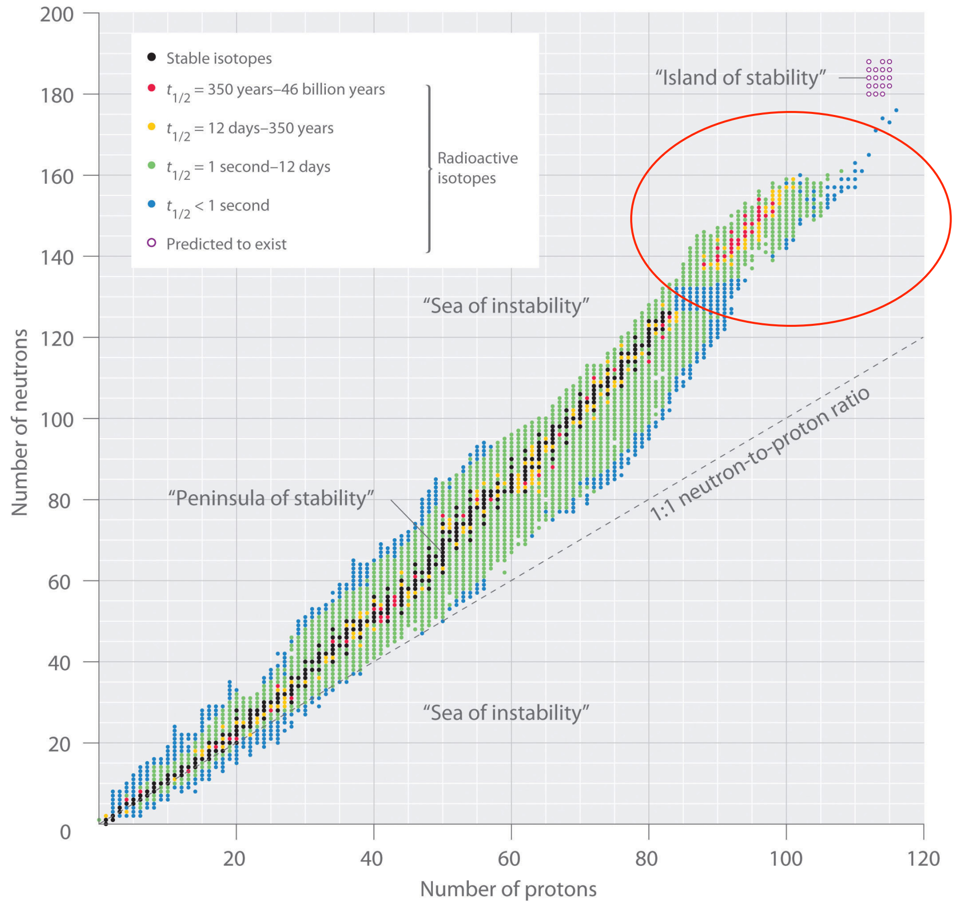
- Anything that deposits energy in the region of interest (ROI) and is indistinguishable from a $0\nu\beta\beta$ is background

- can be alphas, betas, gammas, neutrons, muons, neutrinos or combinations

where do they come from?

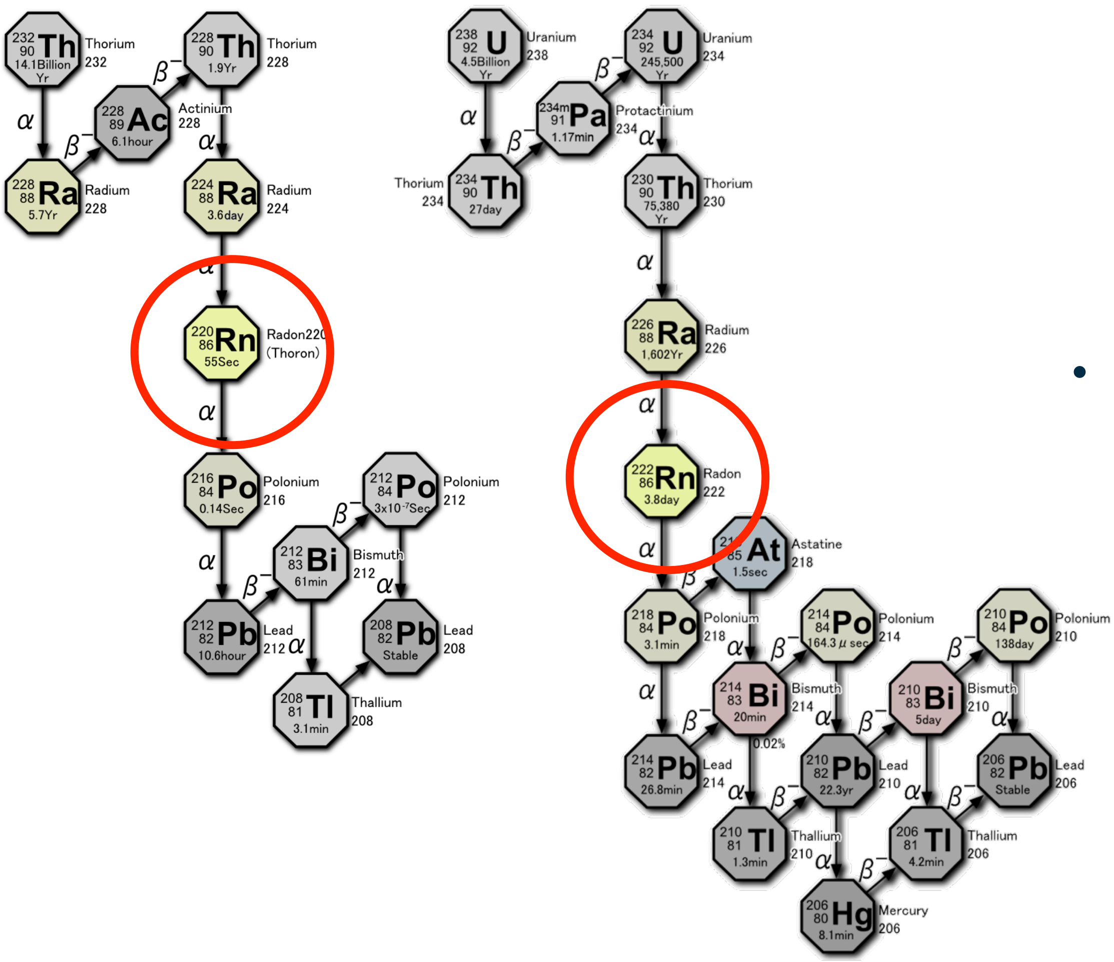


1) Natural Radioactivity



- Primordially created, long-lived (~age of universe) isotopes, U-235, U-238, Th-238, K-40 present in rock etc.

1) Natural Radioactivity



- Primordially created, long-lived (~age of universe) isotopes, U-235, U-238, Th-238, K-40 present in rock etc.
- Radon is everywhere in the air (especially underground)

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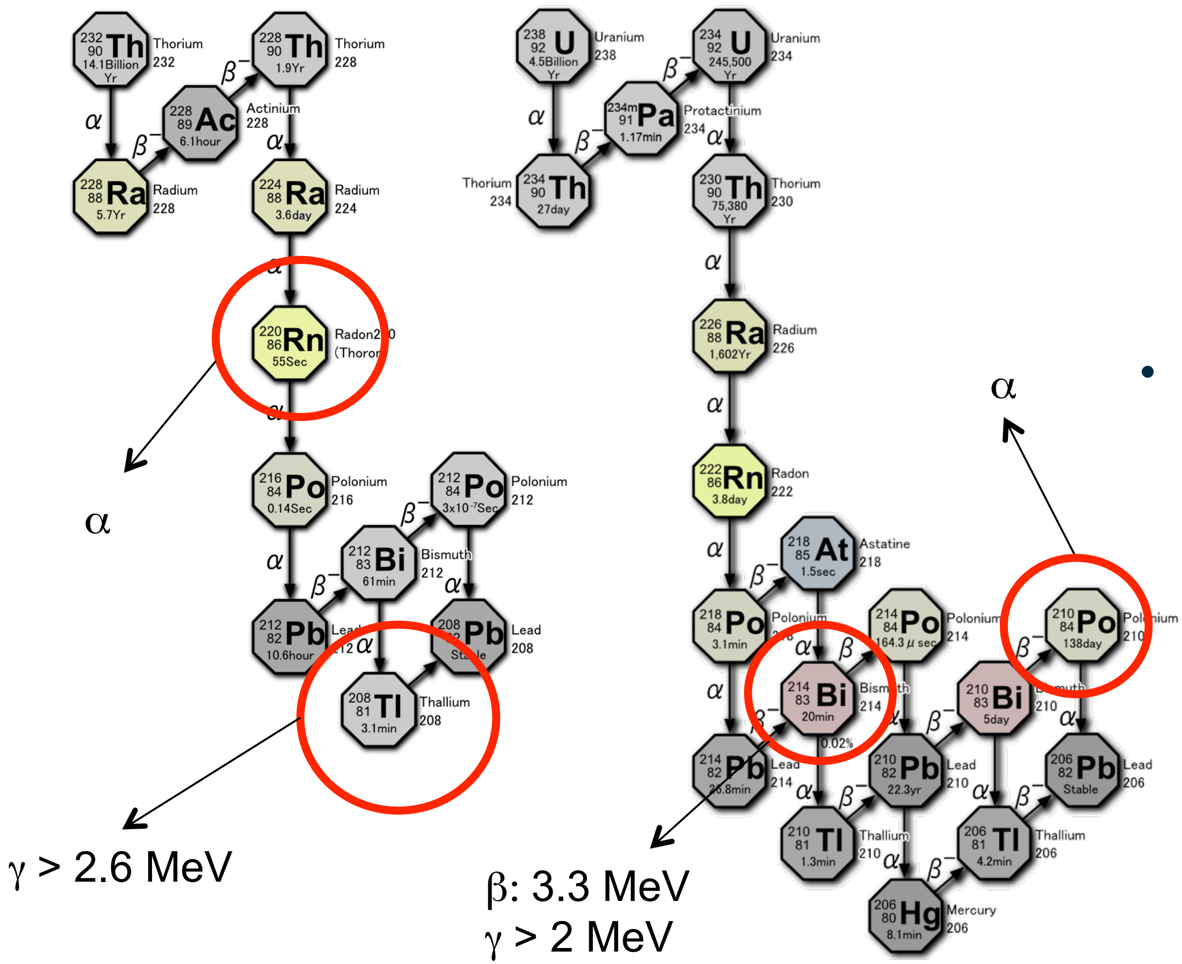
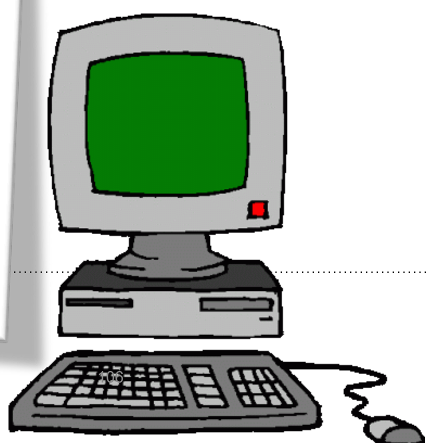


- Primordially created, long-lived (~age of universe) isotopes, U-235, U-238, Th-238, K-40 present in rock etc.
- Radon is everywhere in the air (especially underground)
- alphas, betas, and gammas are produced in the decay

1) Natural Radioactivity → Countermeasures

- Cleanliness
- High purity material
- Shielding
- Analysis cuts



2) Cosmogenic activation

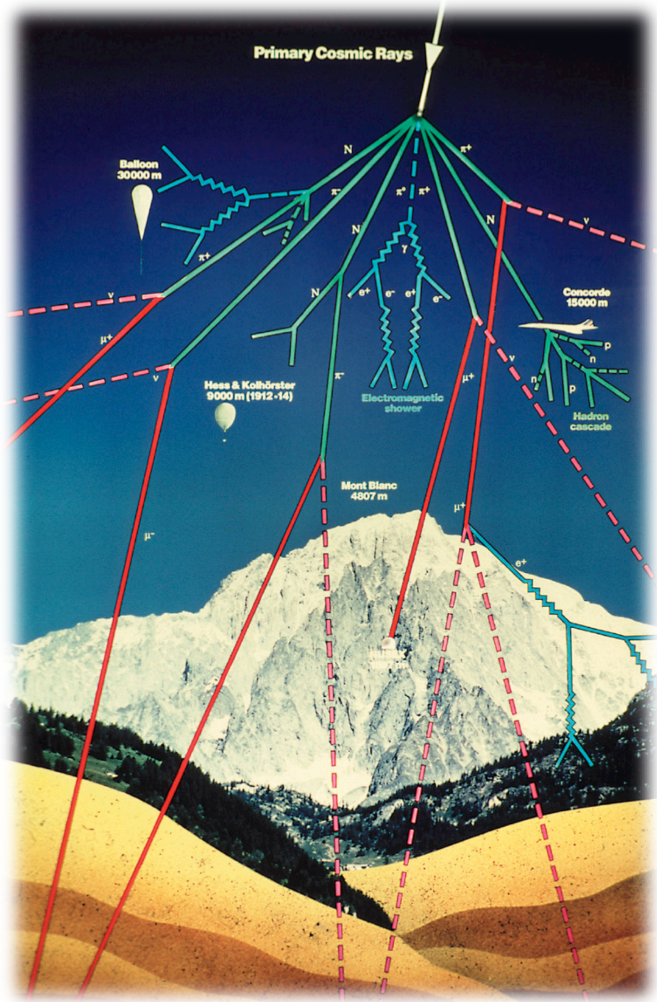
- Cosmogenic activation of medium long lived radioactive isotopes :
- … high energy neutrons and muon break up copper, lead, etc. and make radioactive isotopes (e.g. Ge-68, Co-60)
- … they decay and produce betas and gammas in the ROI

Mitigation:

- Minimize time on surface
- Analysis cuts

3) Muon / Neutron – induced background

- Muon direct hit (not so critical)
- Muon creates high and low energy neutrons in the rock,
  - Neutron excites lead, copper, etc. de-excitation produces gammas
  - Neutron is thermalized and captured (excitation and decay of daughter)
  - Elastic scattering off atoms in detector



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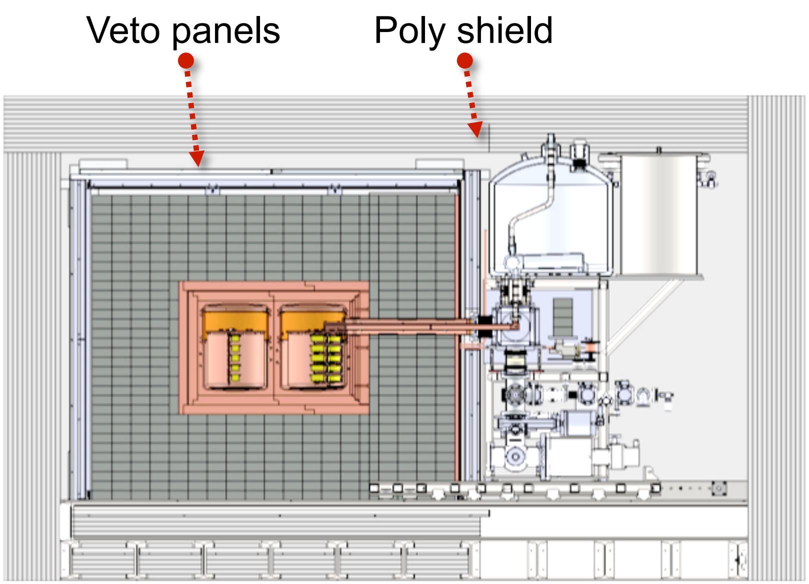
3) Muon / Neutron – induced background → (countermeasure)

- Go underground
- Use a muon veto
- Use Poly-shield to stop/slow down fast neutrons (CH_2, low Z)



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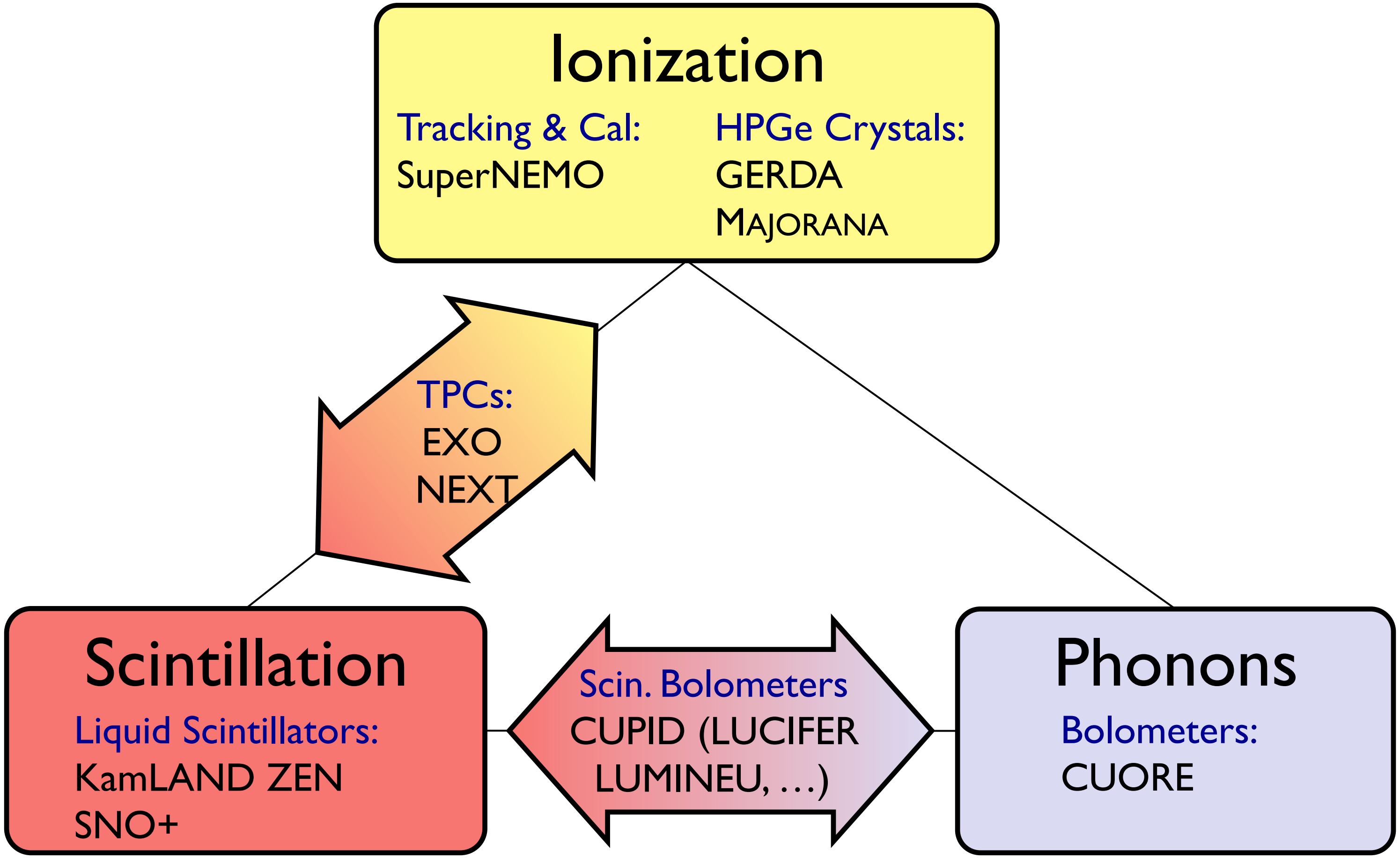
Detection Techniques

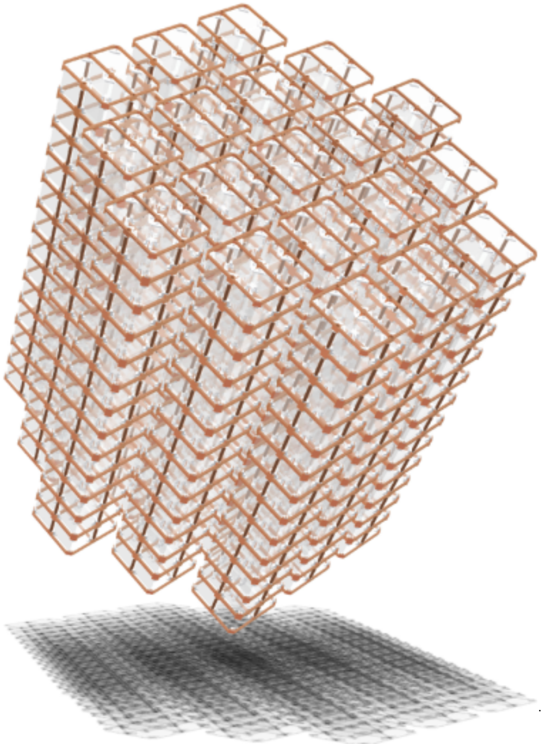


Three Technologies

<u>Bolometer Detector</u>

$^{130}Te \rightarrow {}^{130}Xe + 2\ e^-$

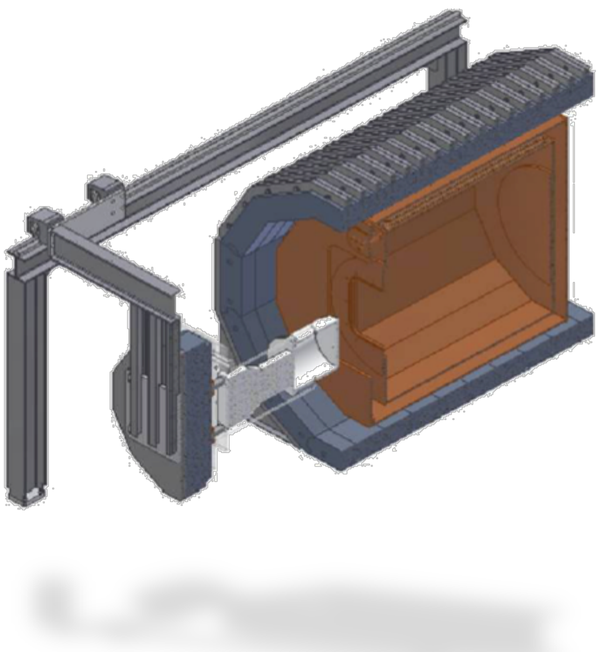
e.g. **CUORE**



<u>Time Projection Chamber</u>

$^{136}Xe \rightarrow {}^{136}Xe + 2\ e^-$

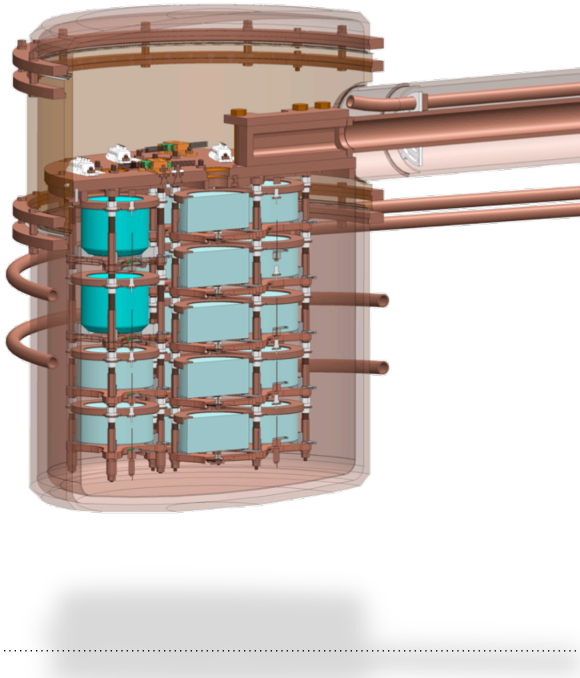
e.g. **EXO**



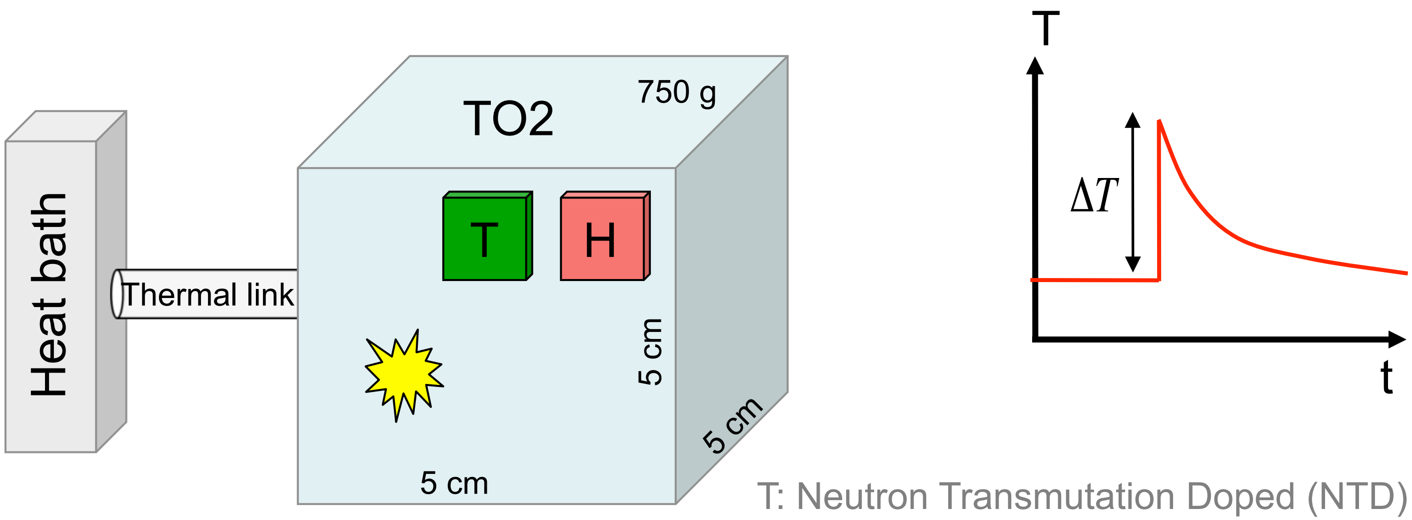
<u>Point Contact Detector</u>

$^{76}Ge \rightarrow {}^{76}Se + 2\ e^-$

e.g. **MAJORANA**



Bolometer Technique (how does it work?)

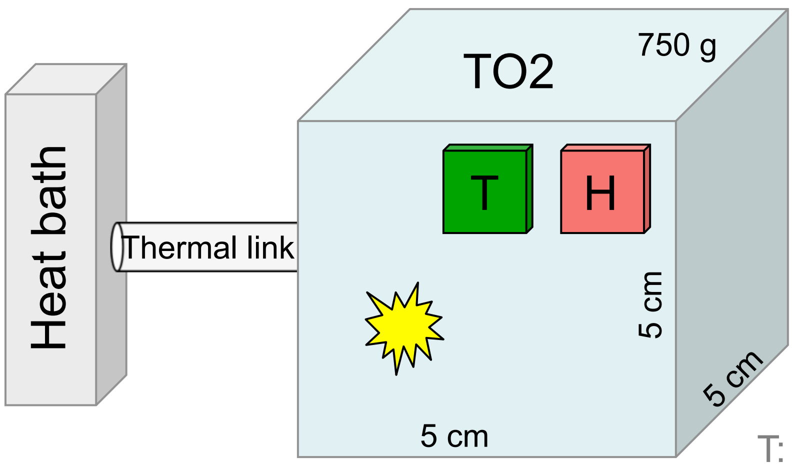


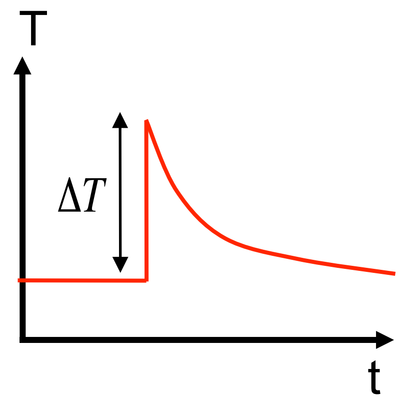
T: Neutron Transmutation Doped (NTD) germanium thermistors
H: Heater (for test signals)

- Electrons create phonons/heat in the tellurium oxide detector
- Heat capacity

Specific heat or heat capacity is the amount of energy needed to raise the temperature by 1 degree Celsius.

Bolometer Technique (how does it work?)





T: Neutron Transmutation Doped (NTD) germanium thermistors
H: Heater (for test signals)

- Electrons create phonons/heat in the tellurium oxide detector
- Small heat capacity: ~$(T/T_D)^3$ (Debye Law)
- Super cold operating temperature: 10 μK
- Temperature change per energy: 10 – 20 μK/MeV
- At $Q_{\beta\beta}$ = 2.5 MeV → ΔT = 50 μK

Heat capacity is the amount of energy needed to raise the temperature by 1 degree Celsius.

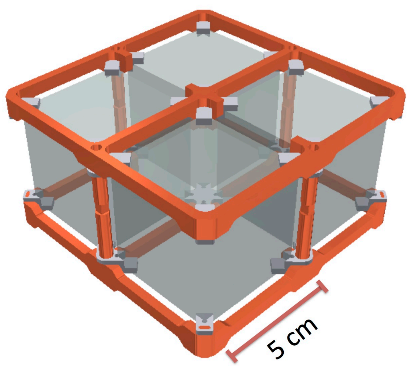
Pros and Cons of $T0_2$ crystals

- High natural abundance of 34.3 %
- Can be enriched
- Bolometers have very good energy resolution
  FWHM = 5 keV @ $Q_{\beta\beta}$ = 2.5 MeV

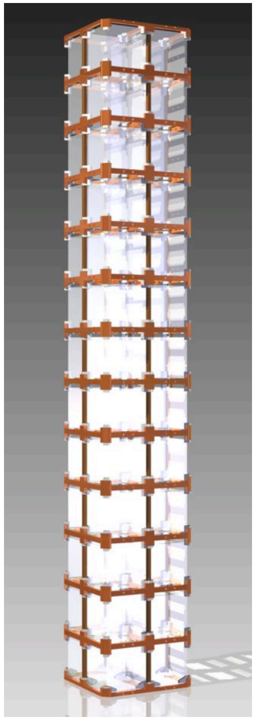
- Ultra-cold (difficult technology)
- Alpha-background

- Large mass ✓
- High isotopic ✓
- Low background
- Good energy resolution ✓

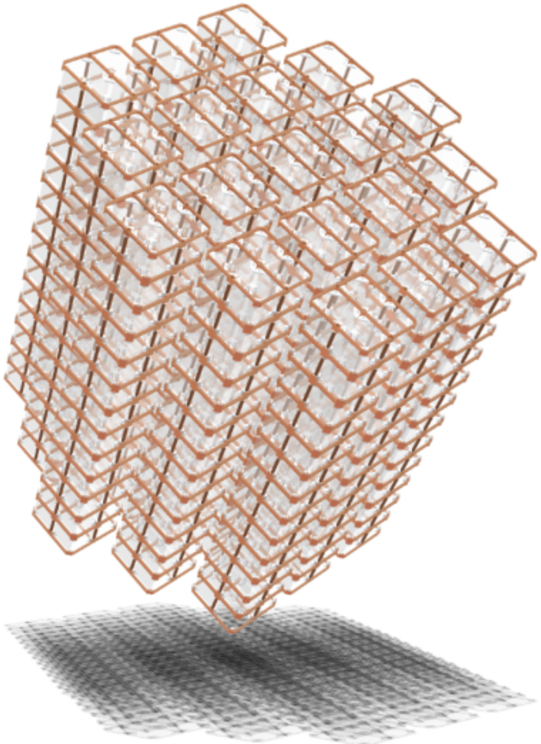
Cryogenic Underground Observatory for Rare Events = CUORE



1 unit = 4 detectors



1 tower = 13 units
Cuoricino
CUORE-0

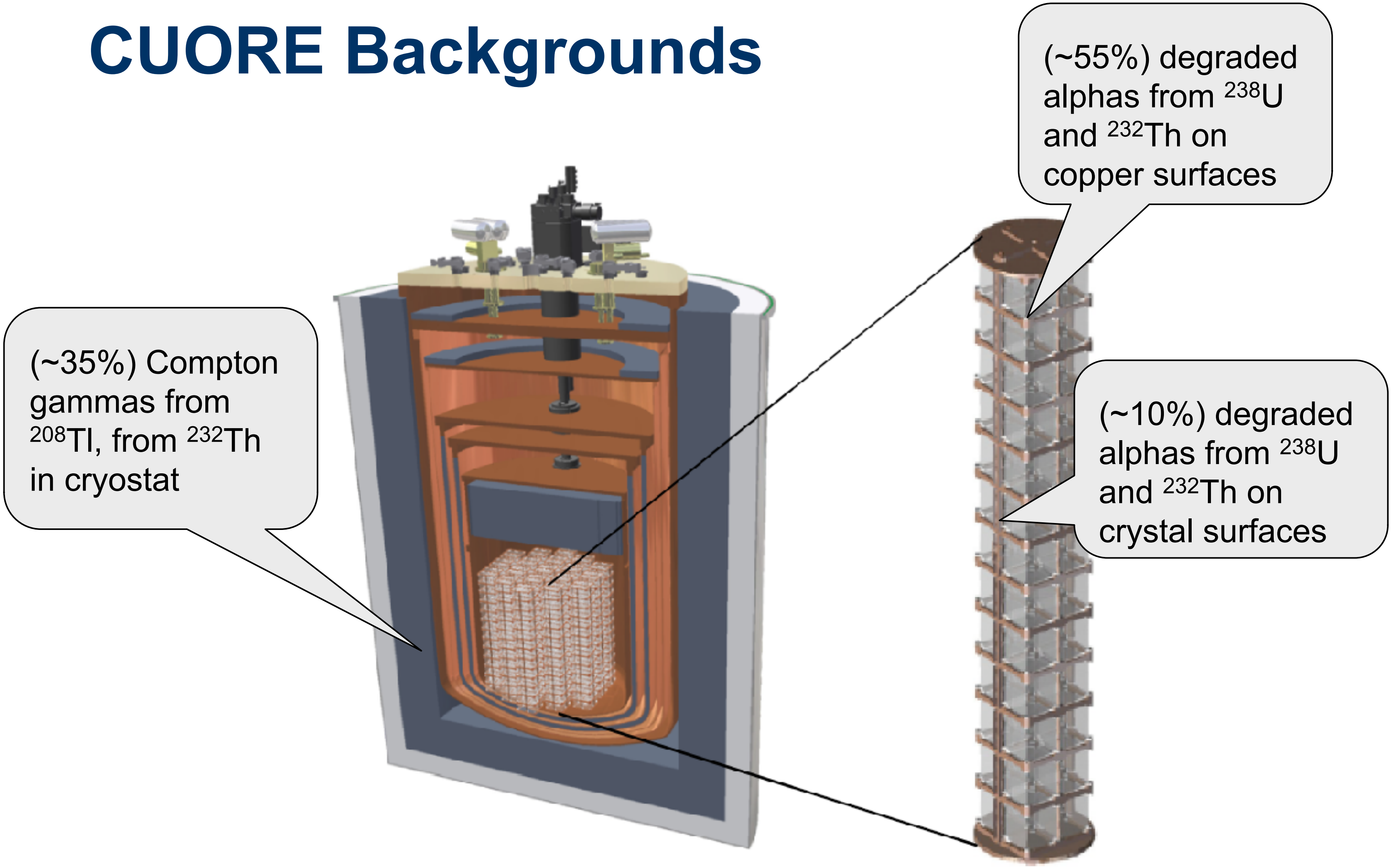


19 towers
988 detectors
CUORE

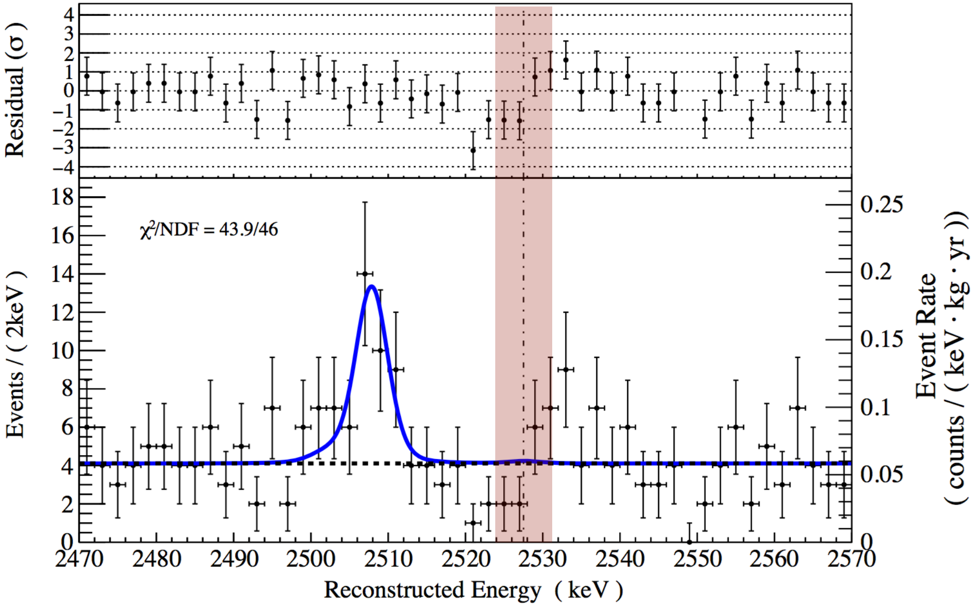
CUORE Setup/Location

Work in the glovebox

CUORE Backgrounds

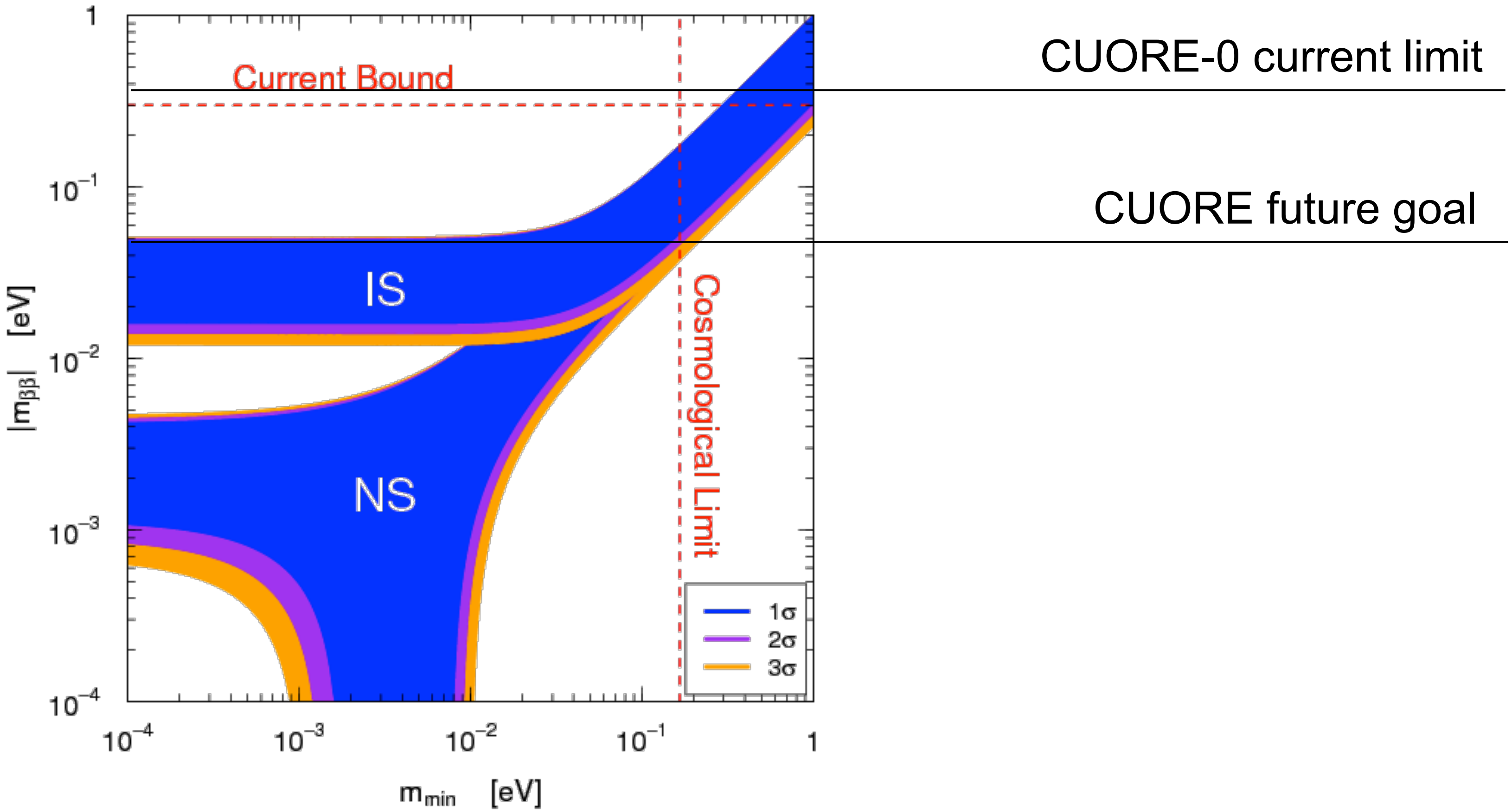


CUORE-0 Results



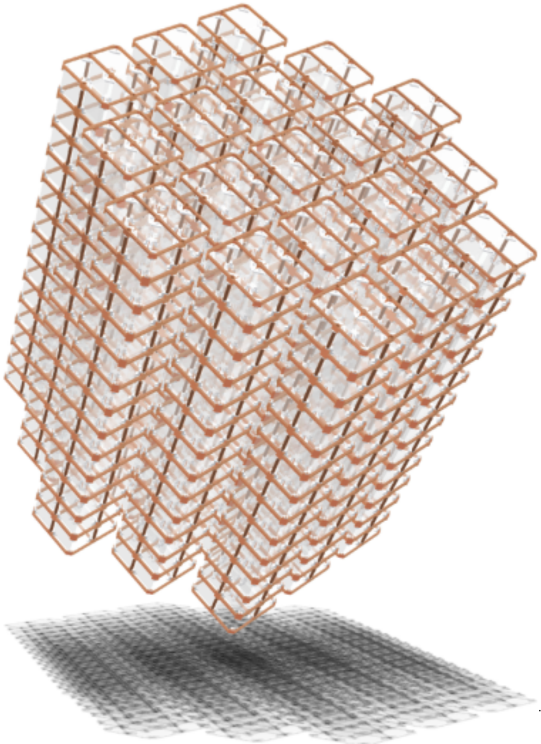
- 32 kg (total)
- 11 kg (effective mass)
- 300 counts/ROI/t/y
- no $0\nu\beta\beta$ found
- $T_{1/2} > 2.7\times10^{24}$ years

CUORE Sensitivity

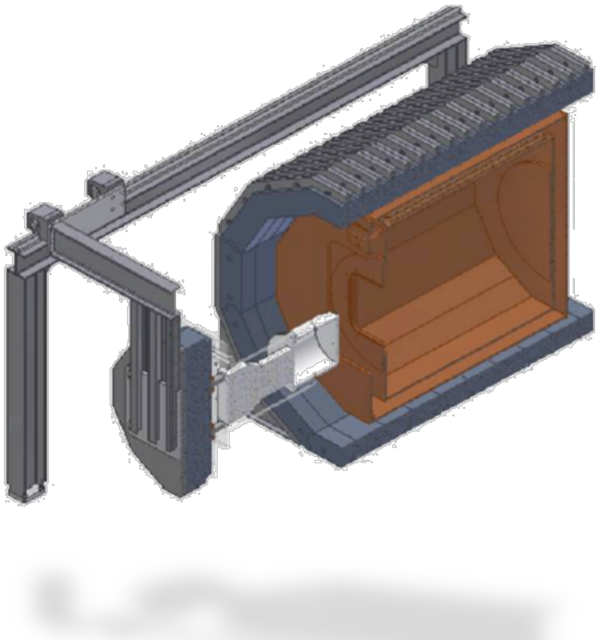


Three Technologies

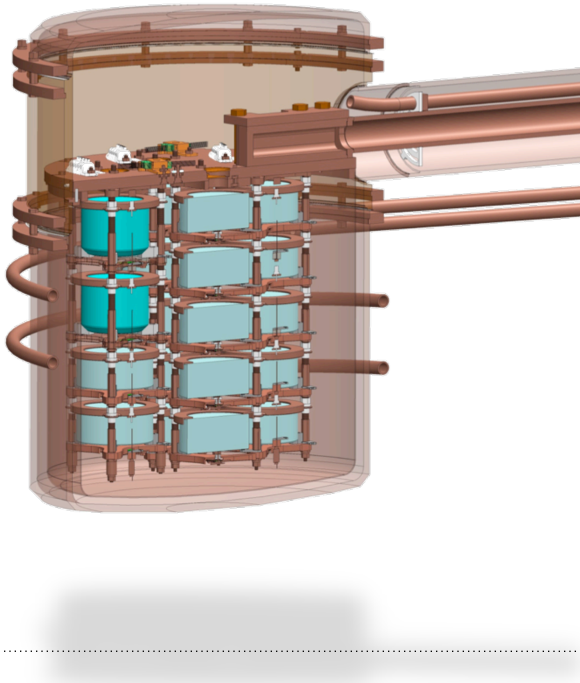
Bolometer Detector
Te-130
e.g. **CUORE**



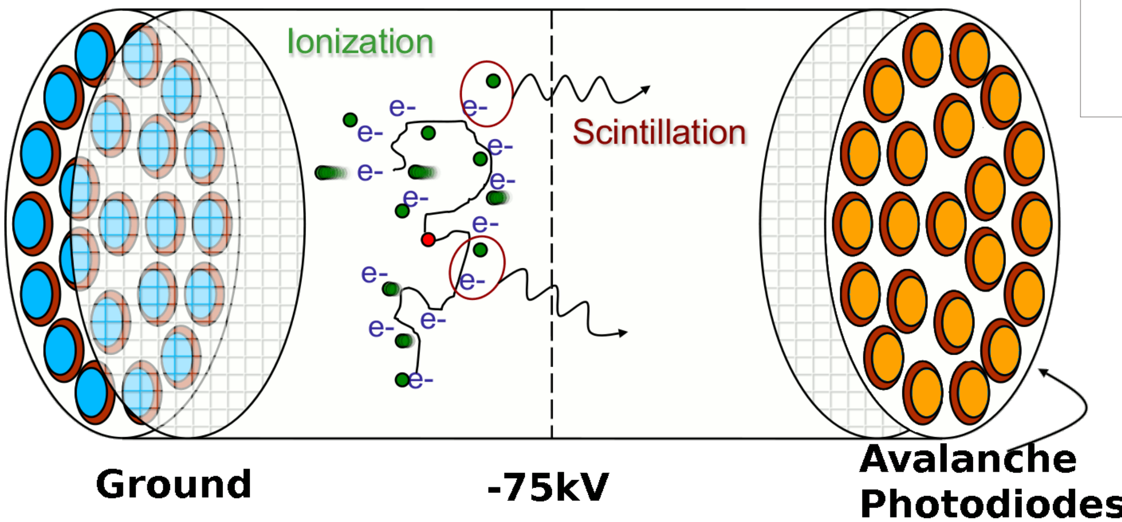
Time Projection Chamber
Xe-136
e.g. **EXO**

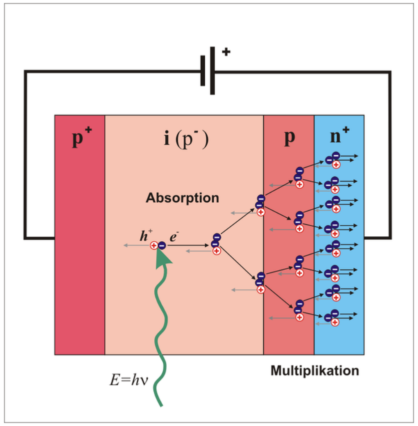


Point Contact Detector
Ge-76
e.g. **MAJORANA**



Time Projection Chamber

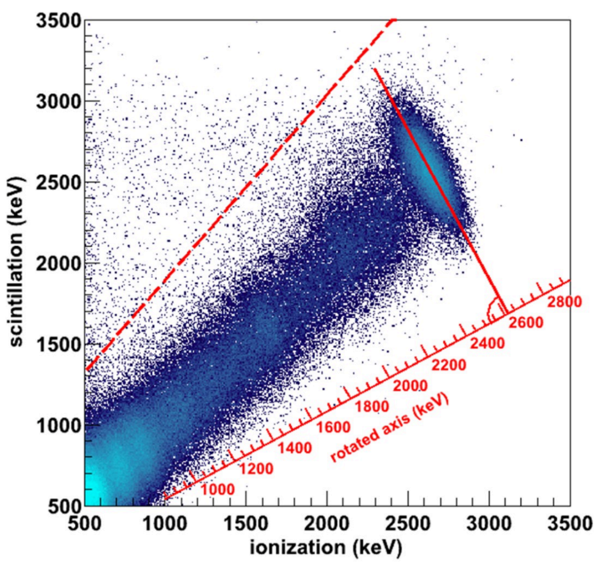


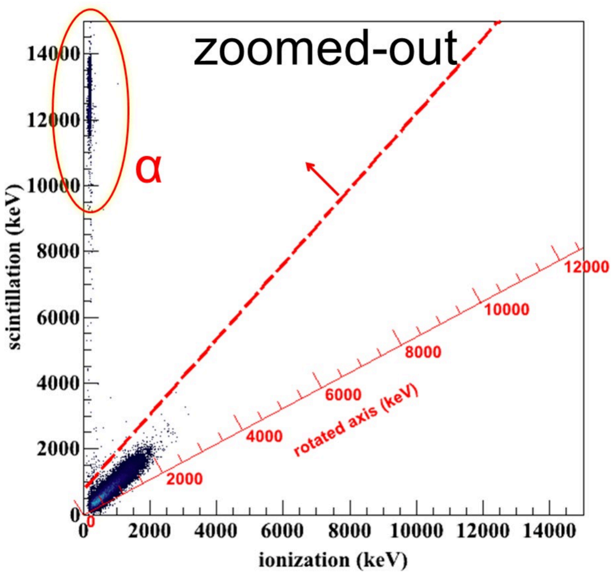


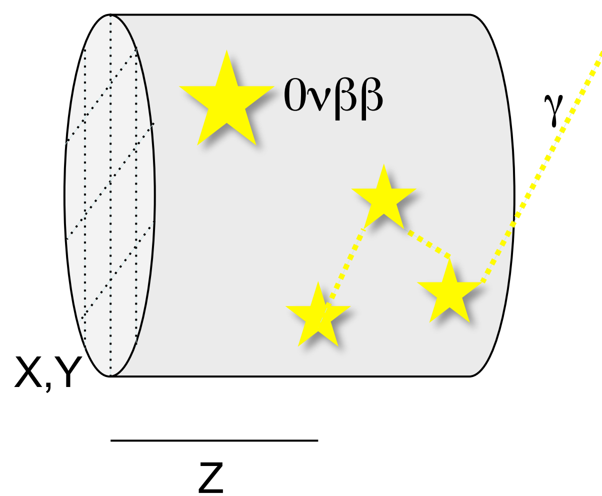
- Electron interacts and ionized LXe → creates secondary electrons
- Electric field guides secondary electrons to wire grid
- Some secondary electrons recombine with the Xe → excited Xe state → scintillation light
- Scintillation light measured by avalanche photodiodes

Ionization + Scintillation

1. Readout of both scintillation and ionization signal → better energy resolution
2. Reject background events characterized by different charge to light collection ratio.
3. Position reconstruction through difference in the arrival time between the scintillation and ionization signals







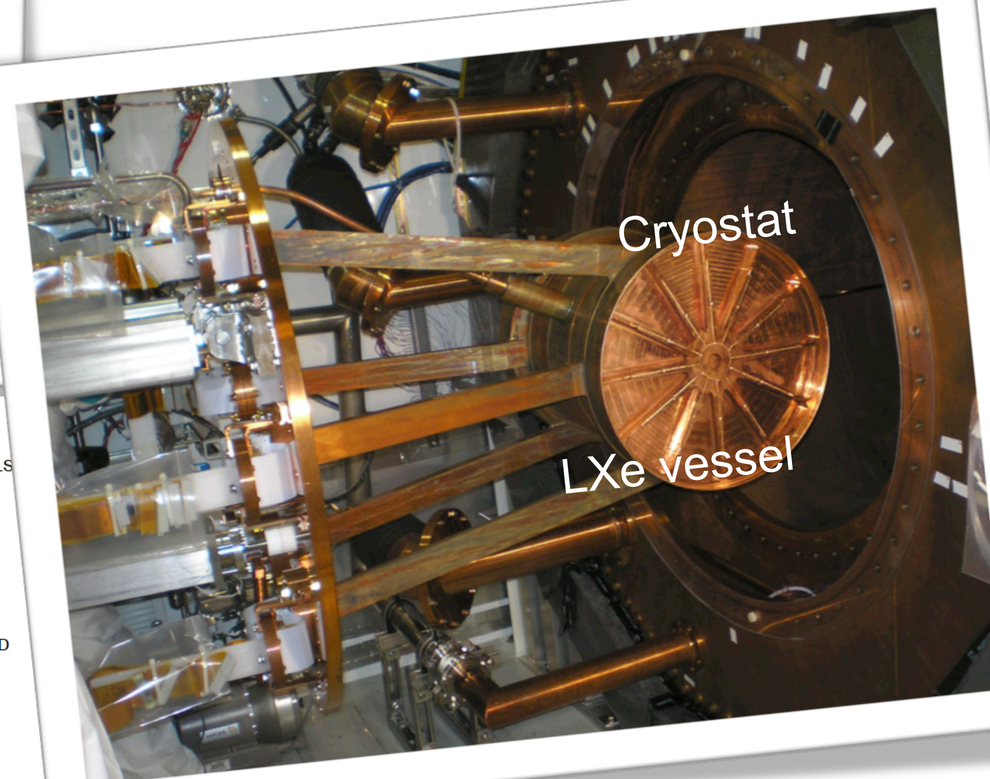
Pros and Cons of TPC with Xe-136

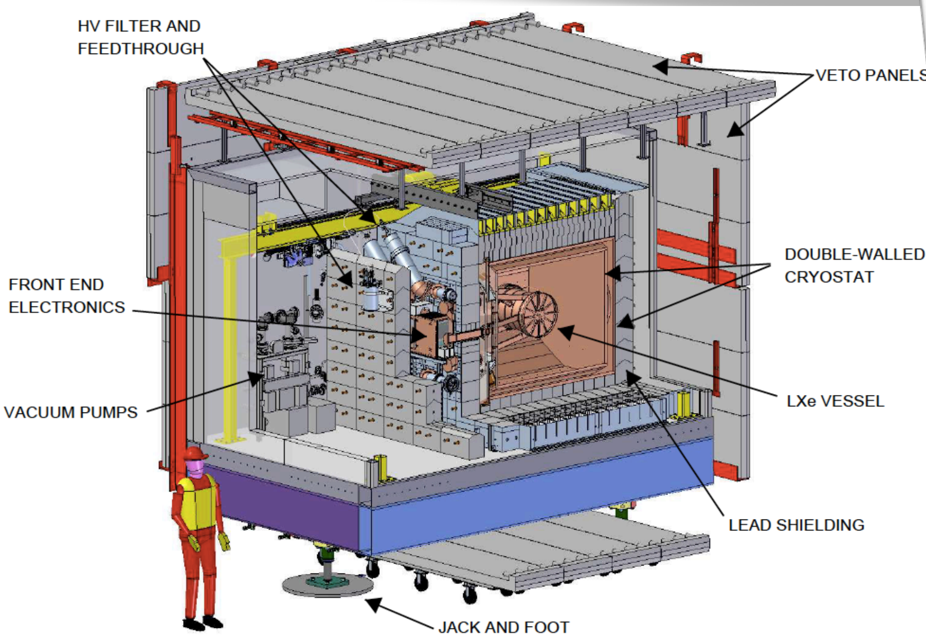
- Liquid Xenon is easy to purity
- The ^{136}Xe isotope can be enriched
- Nobel liquids like liquid Xenon are natural radiation detectors
- Liquid scintillators provide self-shielding
- TPC provides ionization and scintillation signal

- Poor energy resolution of 90 keV @ 2 MeV

- Large mass ✓
- High isotopic ✓
- Low background ✓
- Good energy resolution

EXO Experiment: Setup/Location





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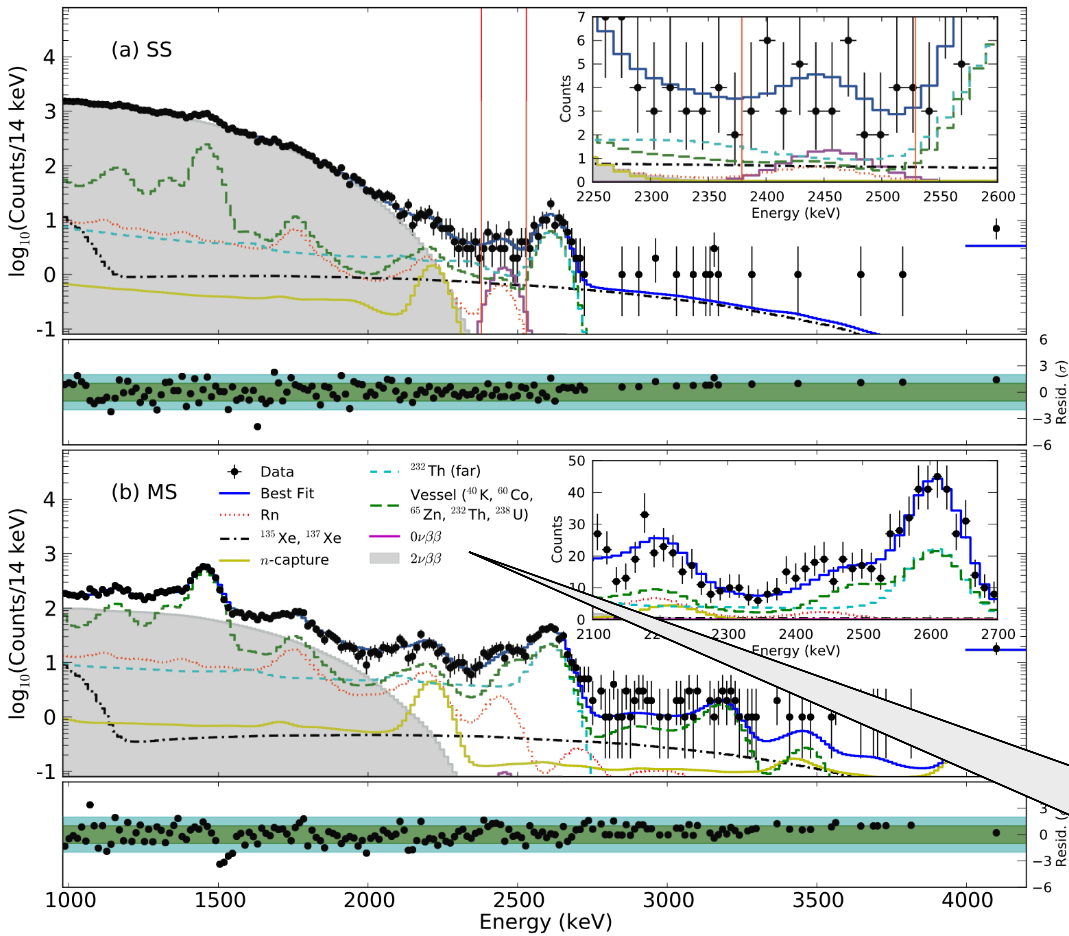
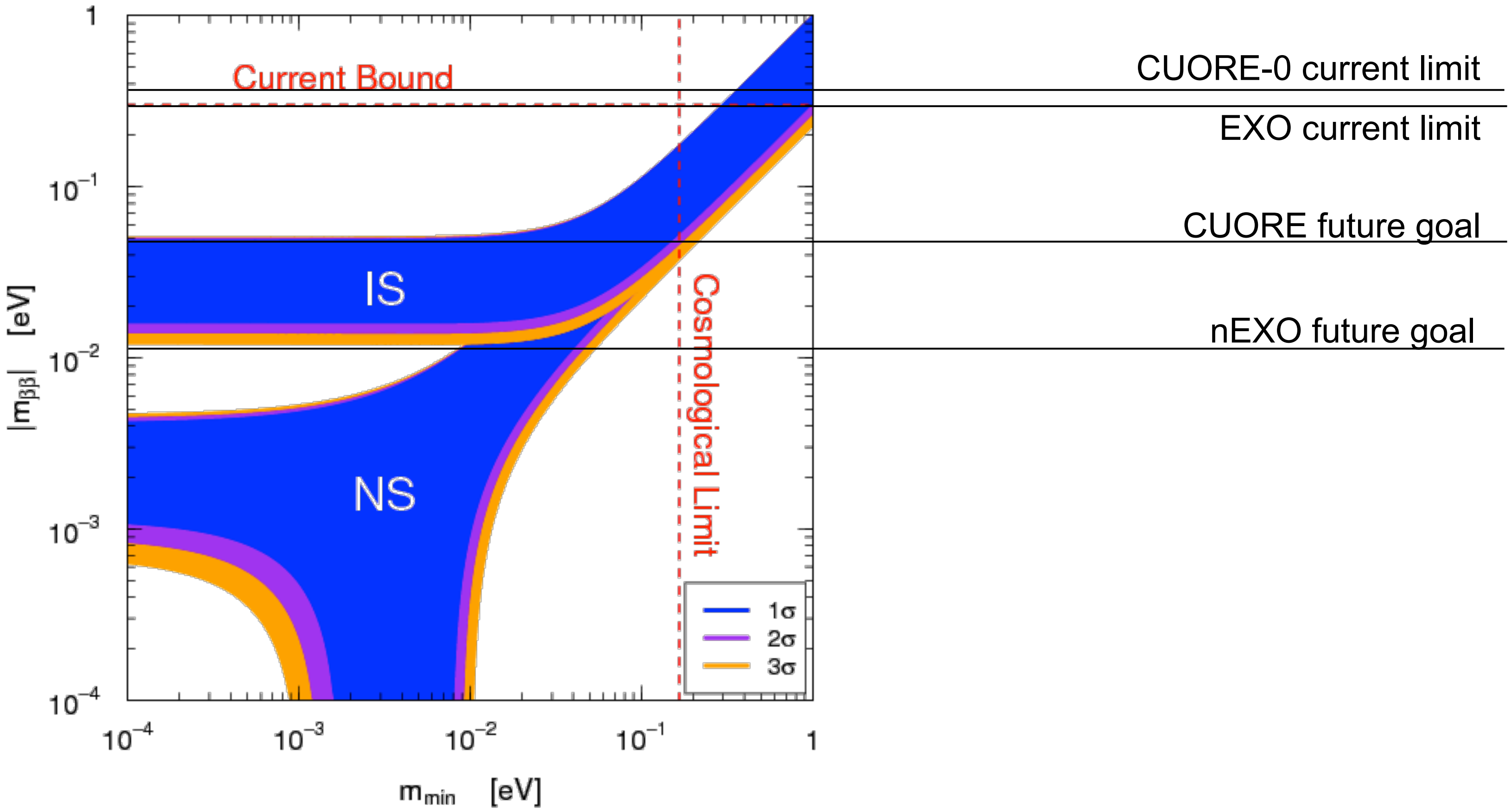
EXO Results



- 170 kg (total)
- 76 kg (effective mass)
- 130 counts/ROI/t/year
- no $0\nu\beta\beta$ found
- $T_{1/2} > 1.1 \times 10^{25}$ years

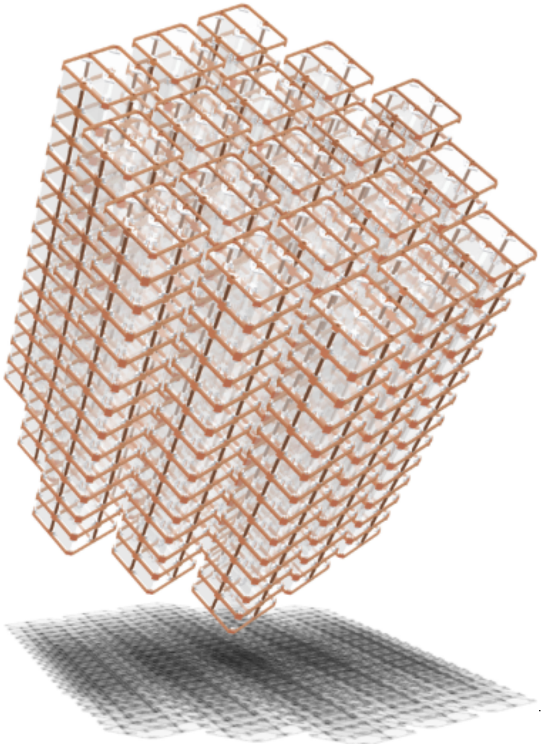
^{232}Th (16.0 counts)
^{238}U (8.1 counts)
^{137}Xe (7.0 counts)

EXO Sensitivity



Three Technologies

Bolometer Detector
Te-130
e.g. **CUORE**



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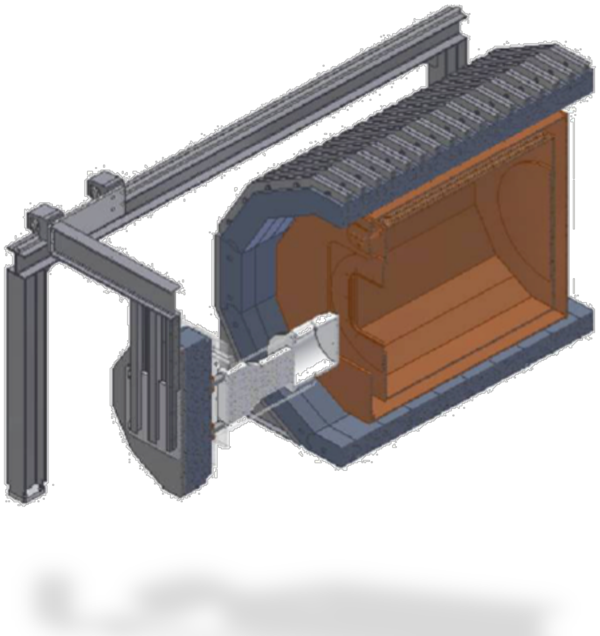

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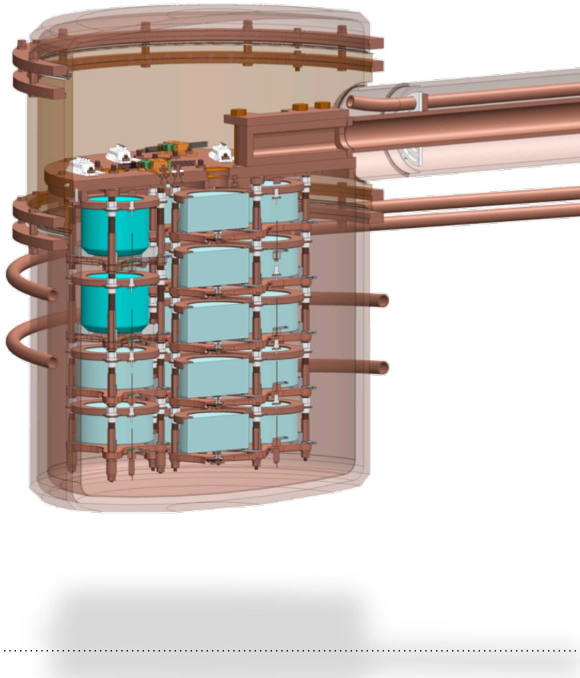
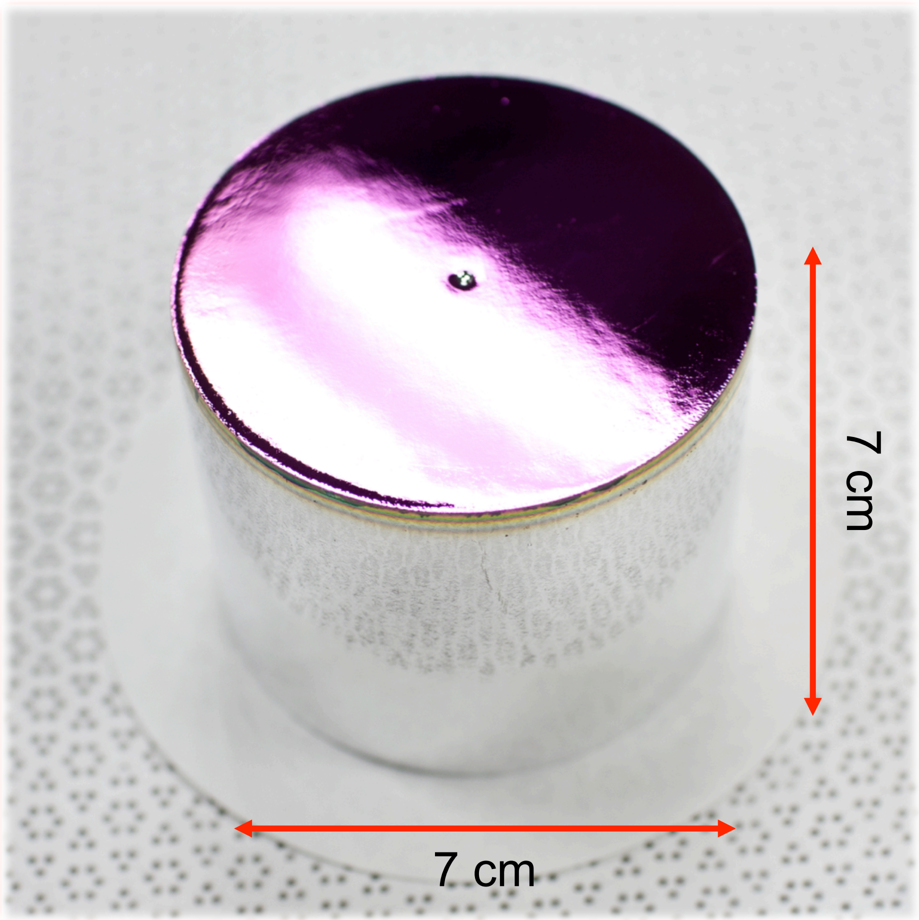


Semiconductor detector



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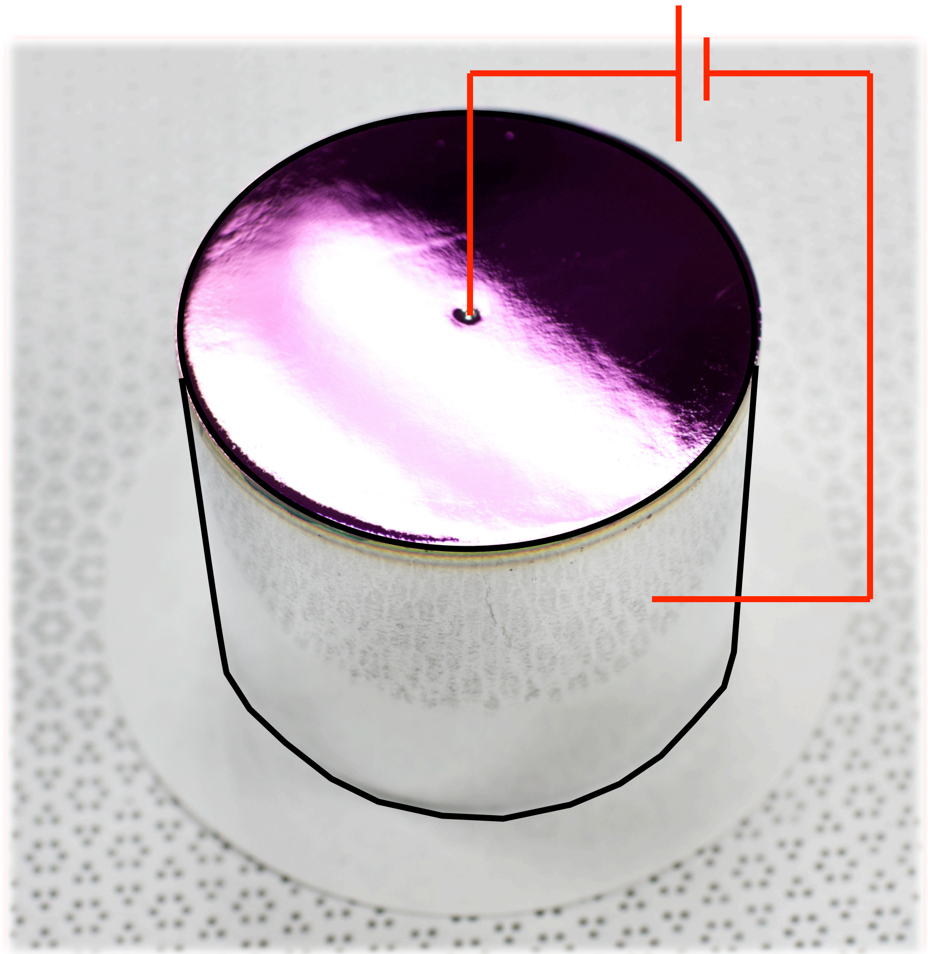
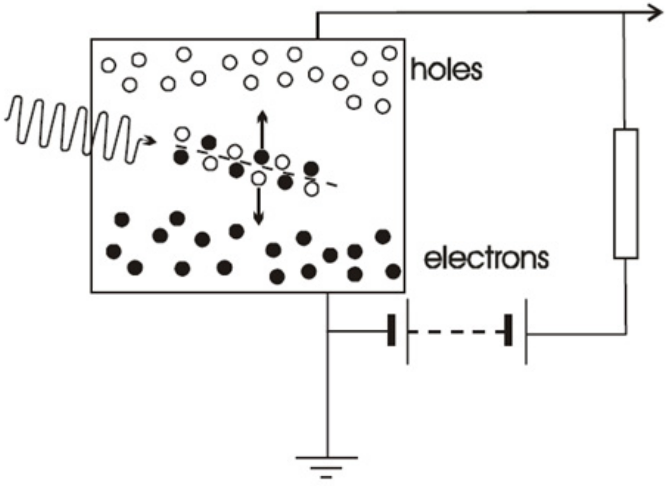
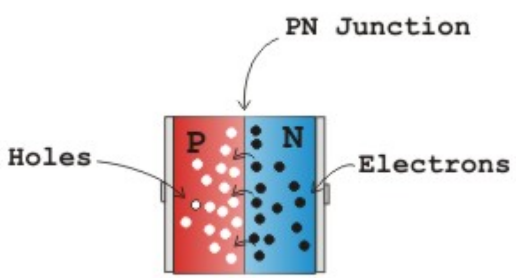
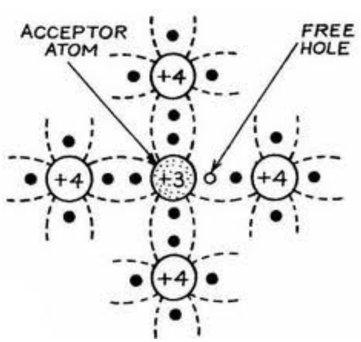
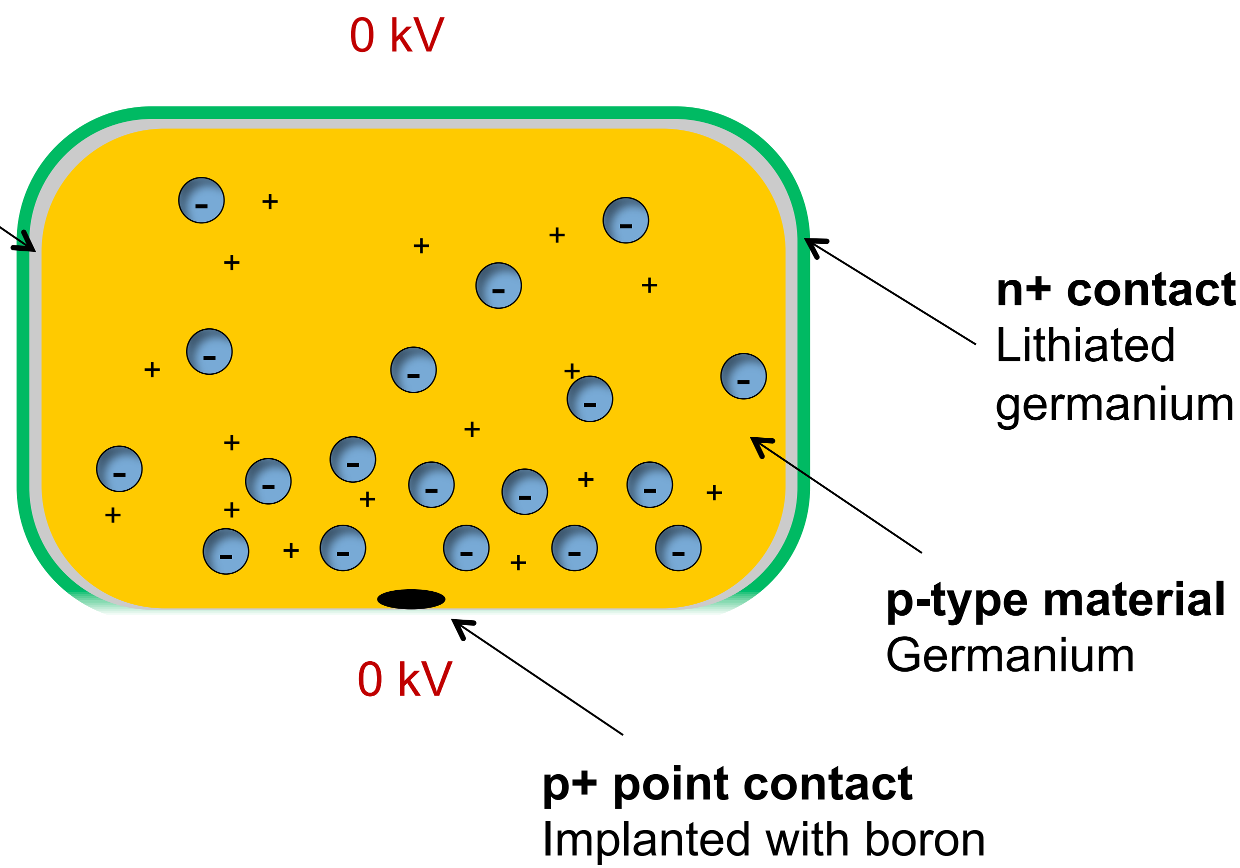




High purity (HP) P-type point contact (PPC) detector







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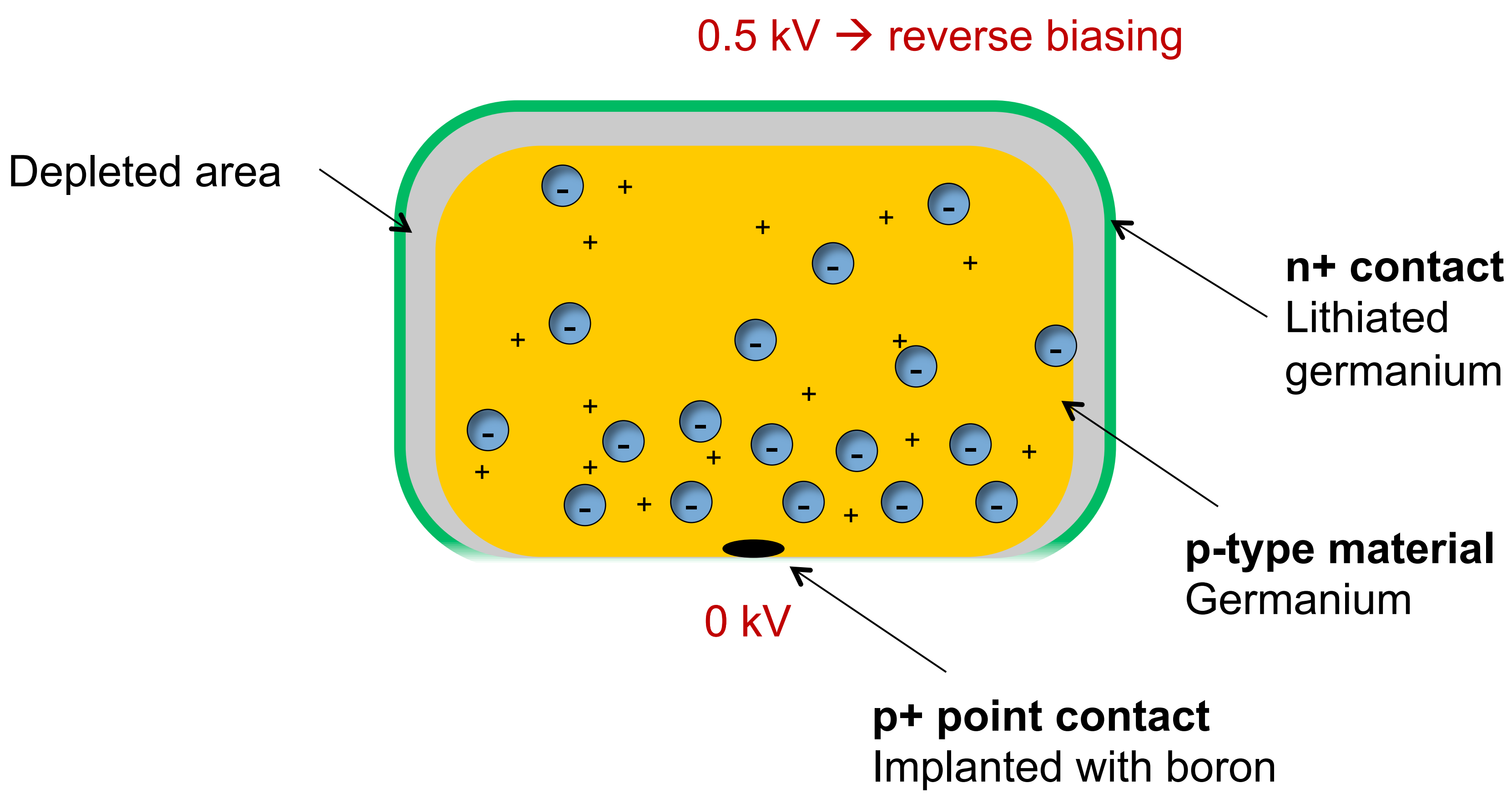

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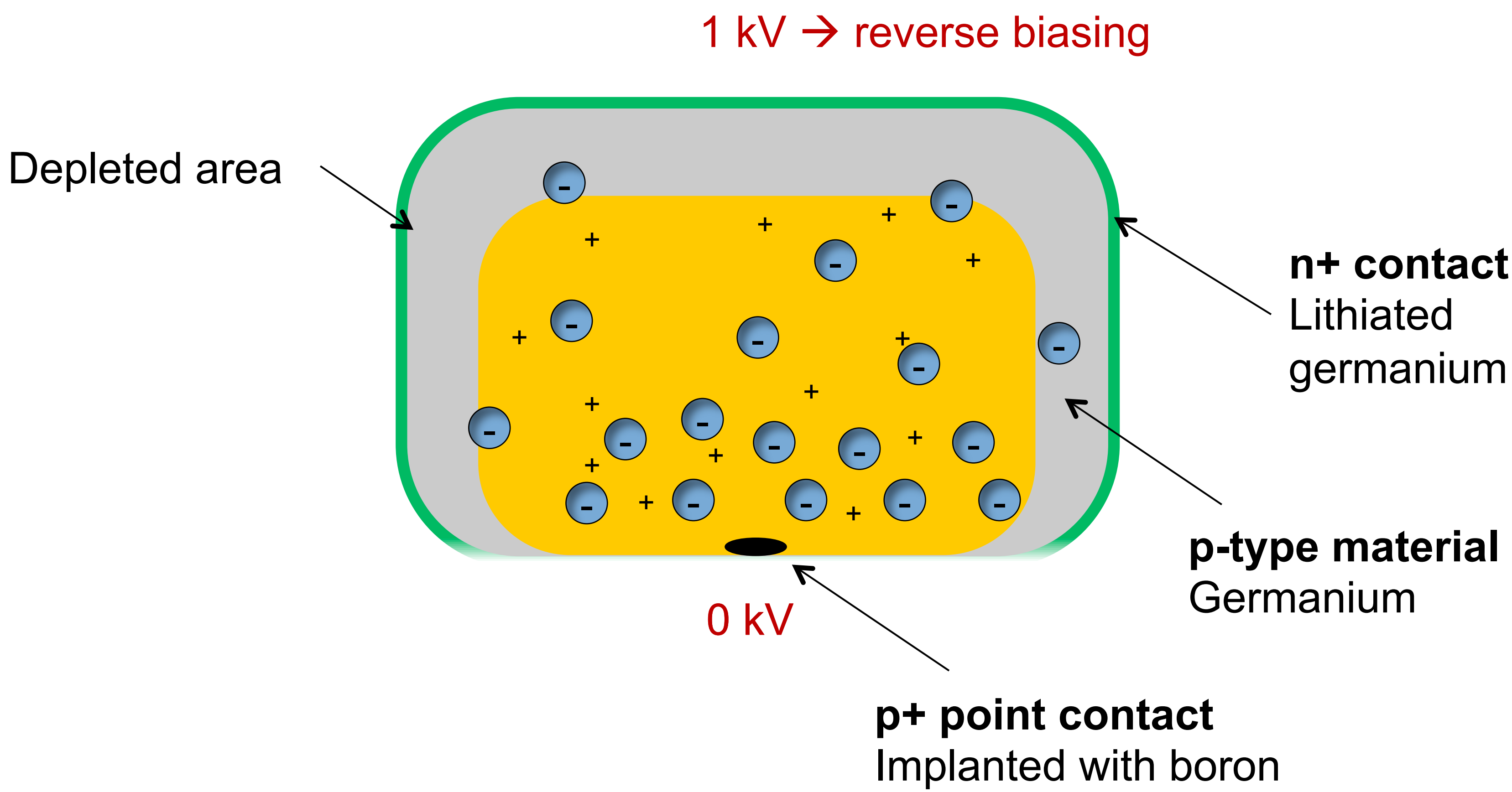
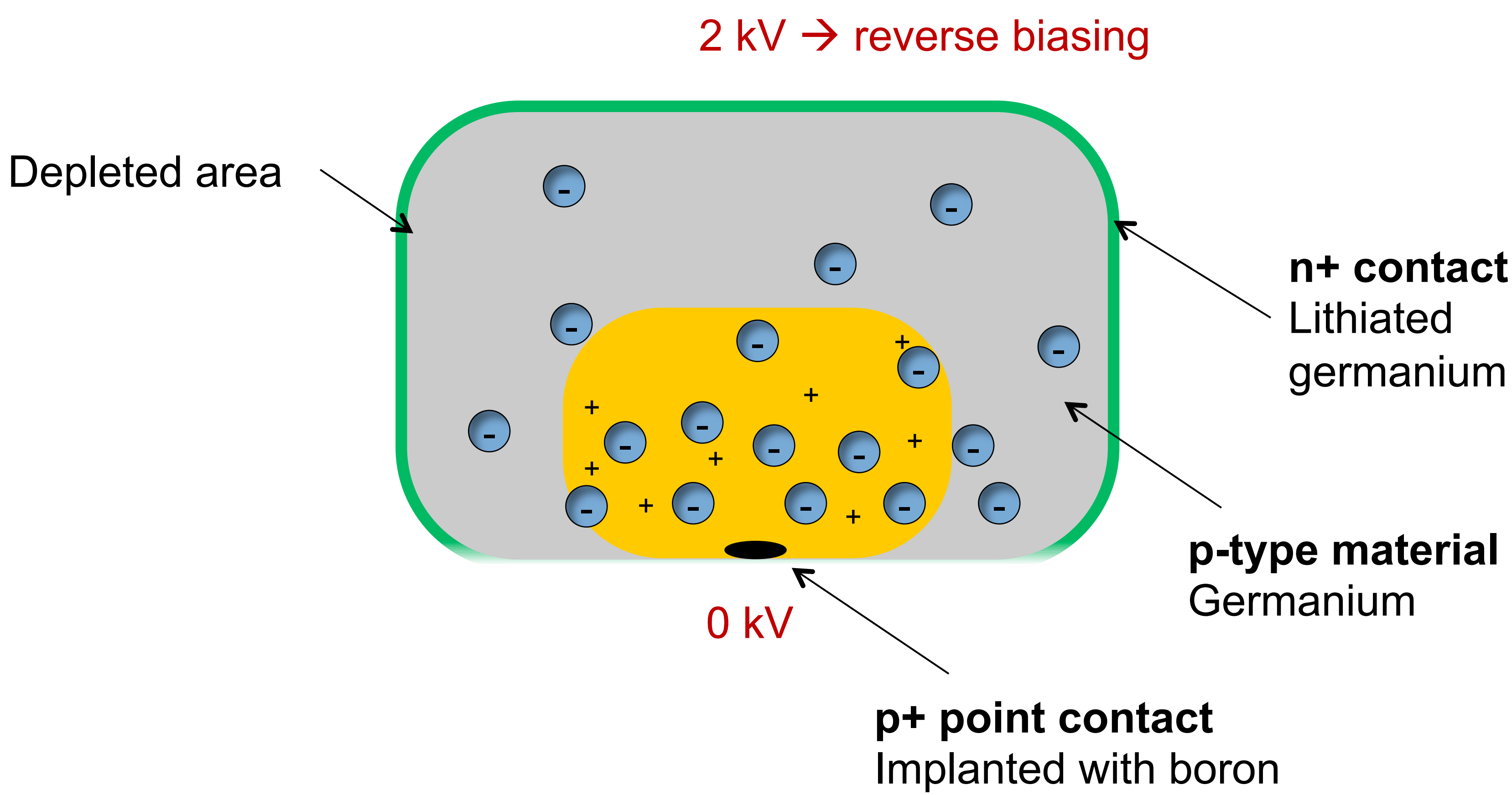


High purity (HP) P-type point contact (PPC) detector



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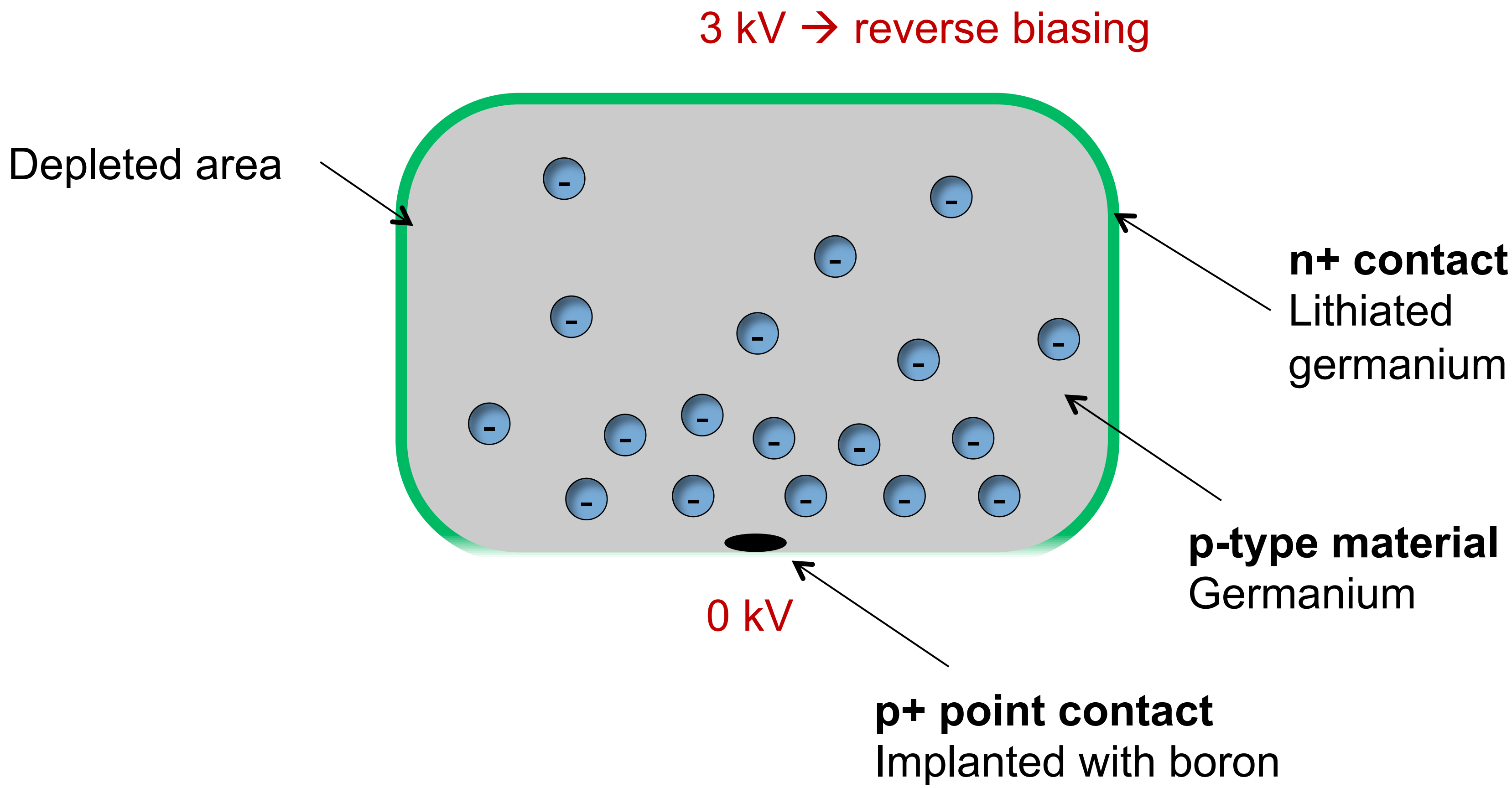

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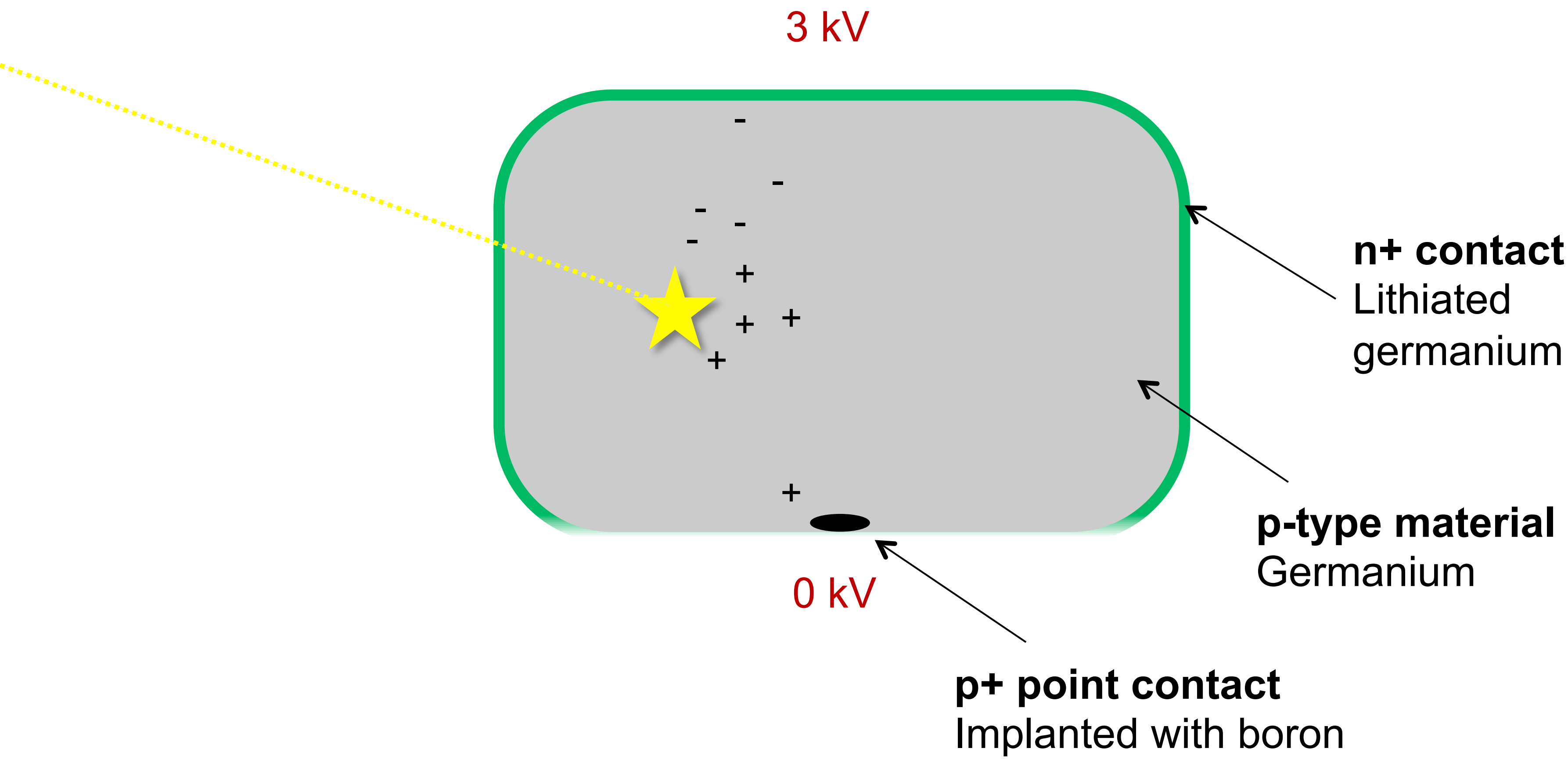
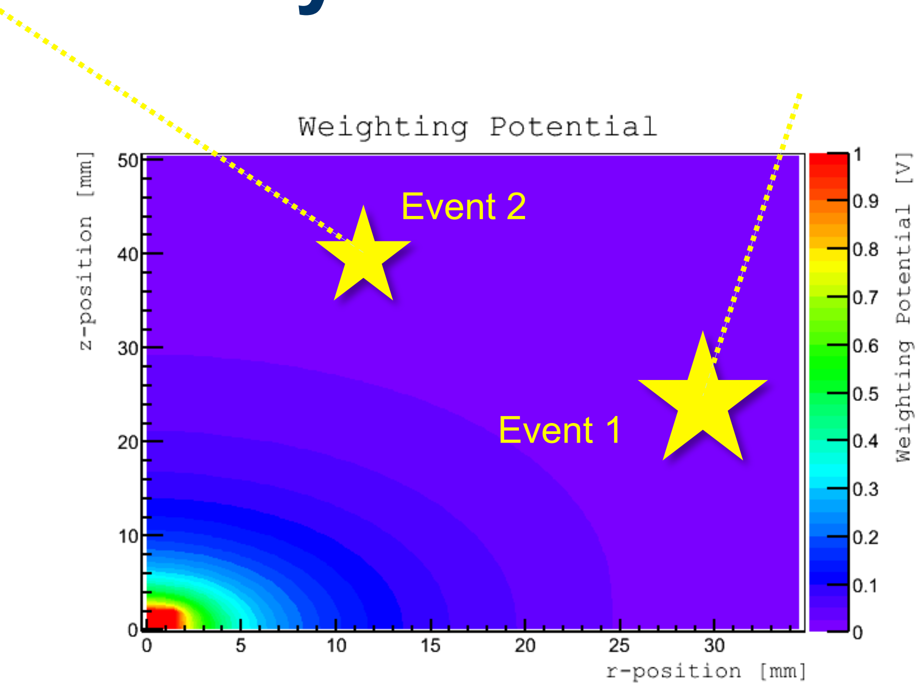
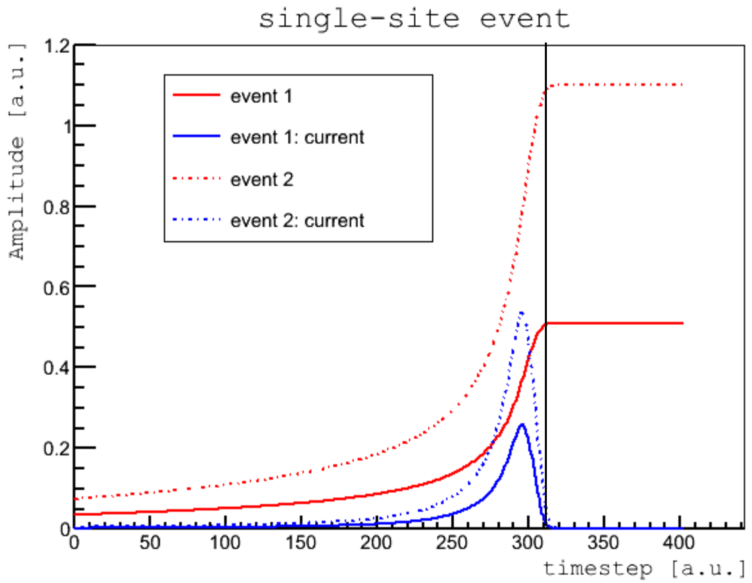


Why Point Contact?

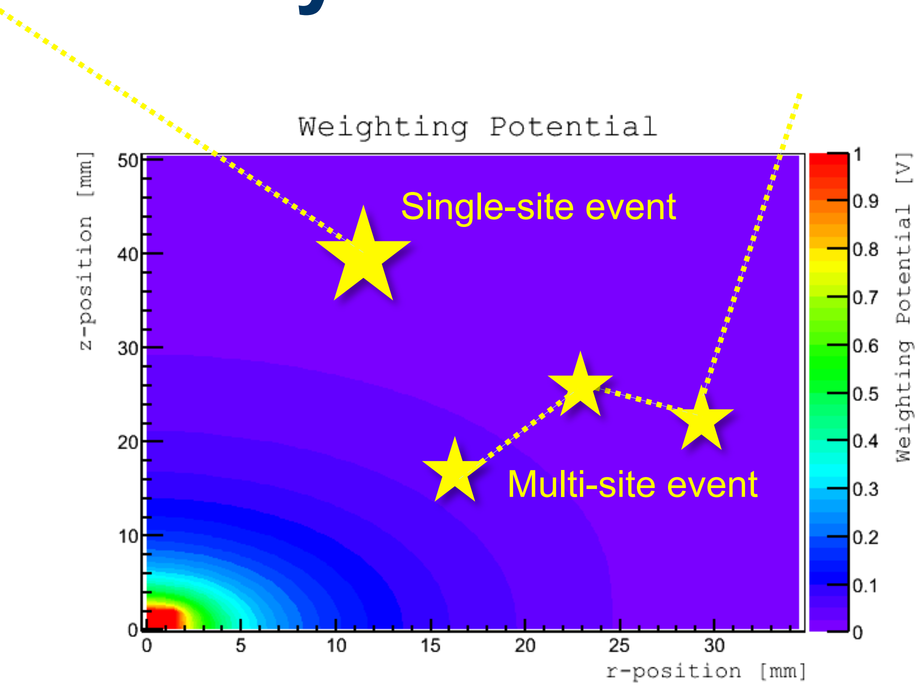
A1 = E1/t
A2 = E2/t

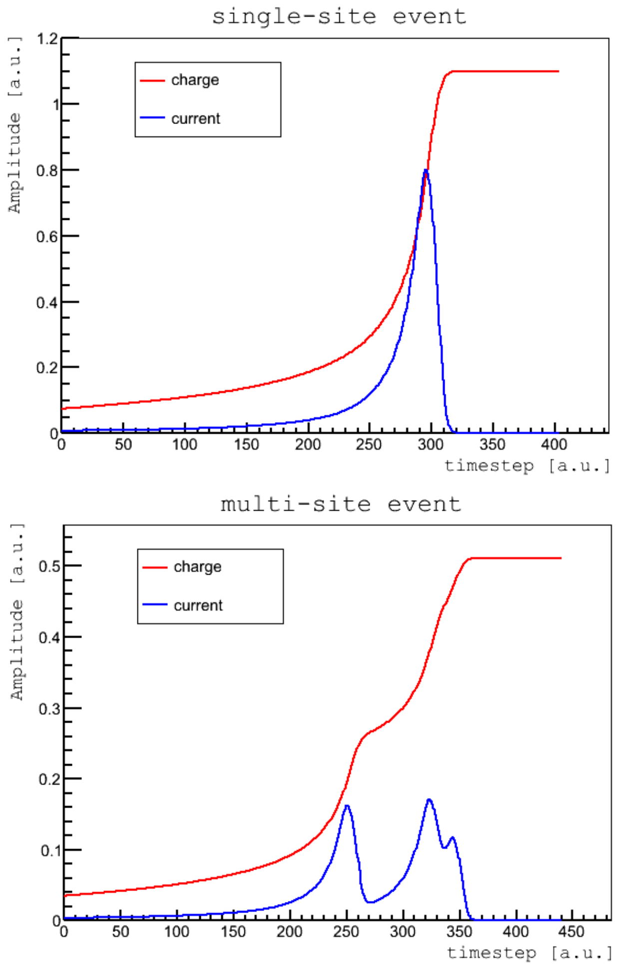




- The charges are only “seen” when they are very close to the point contact
- The rise time of the signal is independent of the creation location
- The ratio of the maximum slope (current) A to the amplitude (charge) E is constant

Why Point Contact?



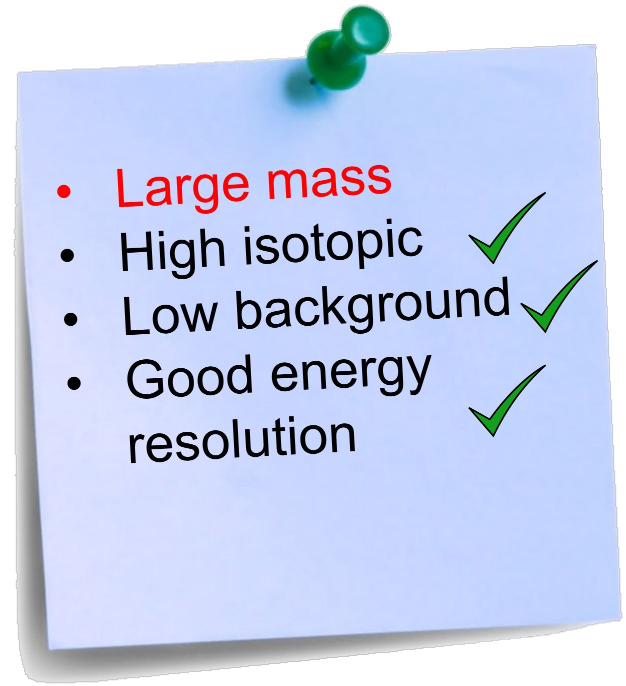


- A/E is different for multi-site events
- Multi-site events are background events

Pros and Cons of ^{76}Ge detectors

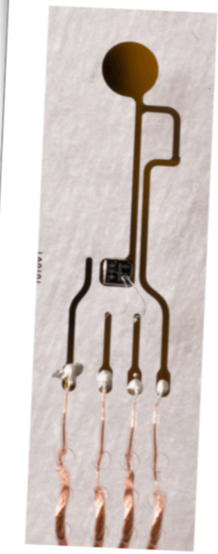
- Very good energy resolution: 4 keV @ 2.039 MeV
- Pulse shape discrimination capability
- Enrichment to 87% is possible

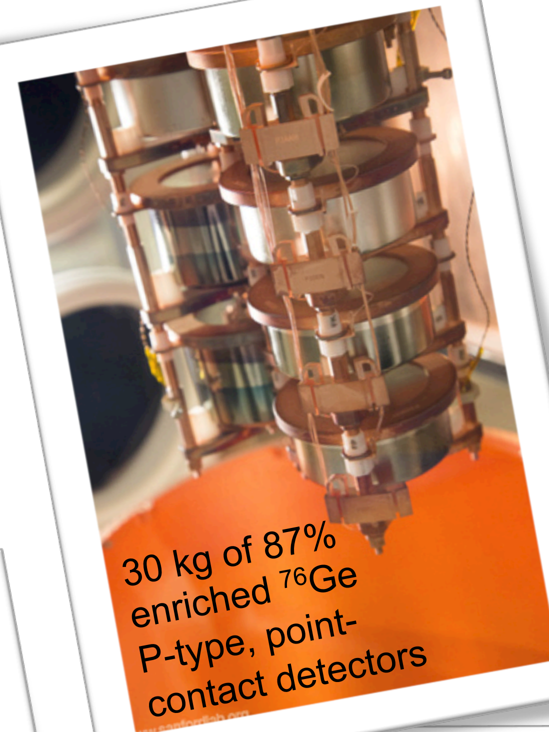
- Ge and the enrichment is expensive

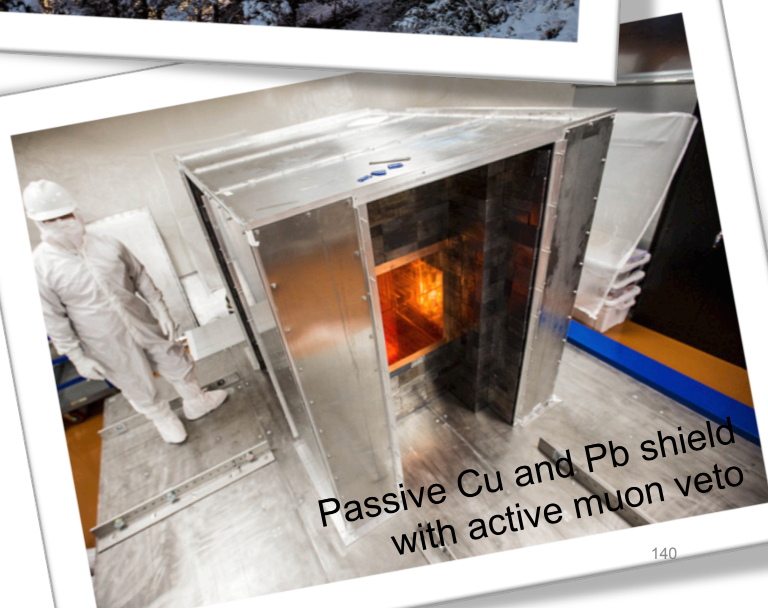


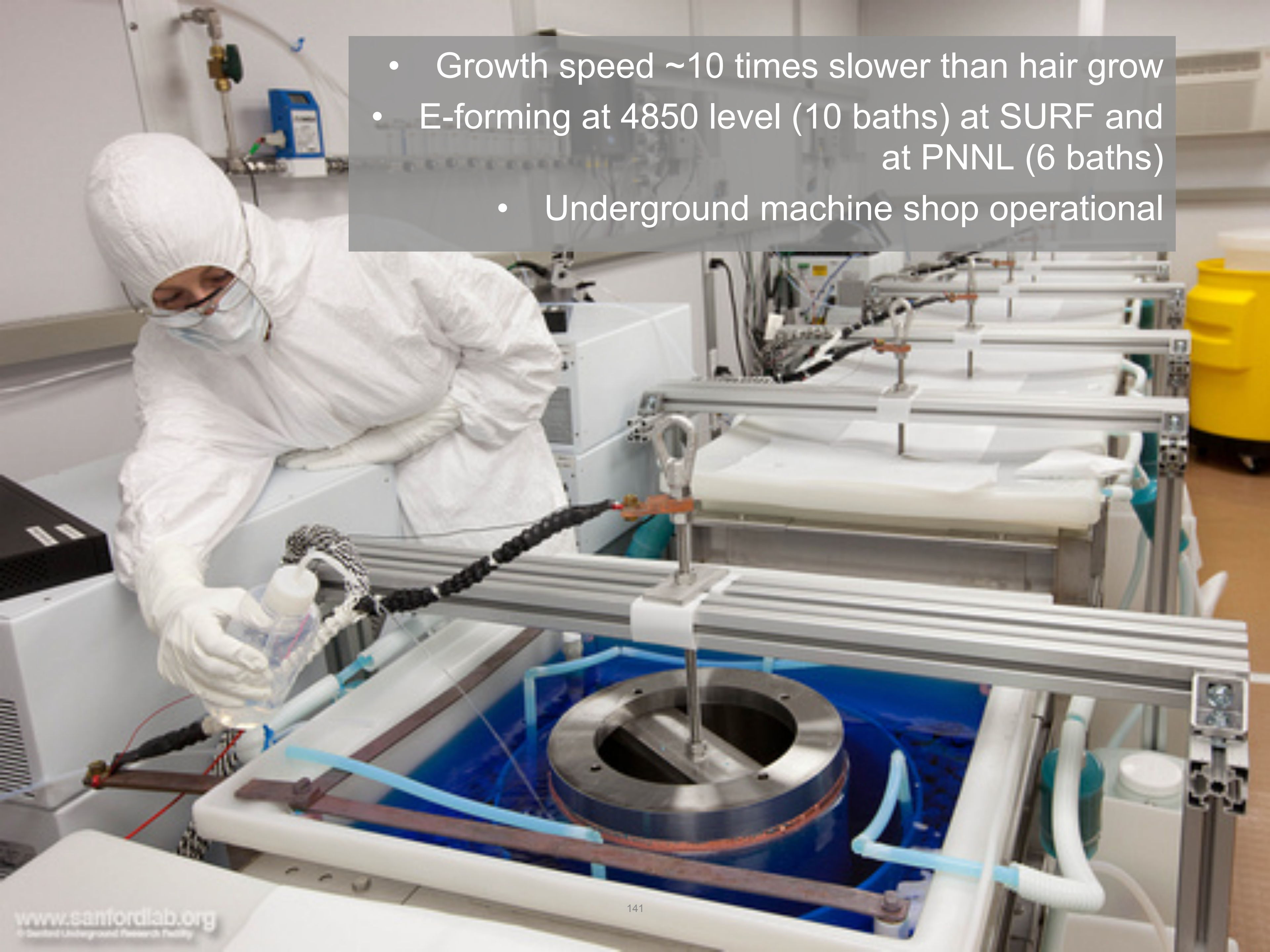
MAJORANA Demonstrator

Low background electronics



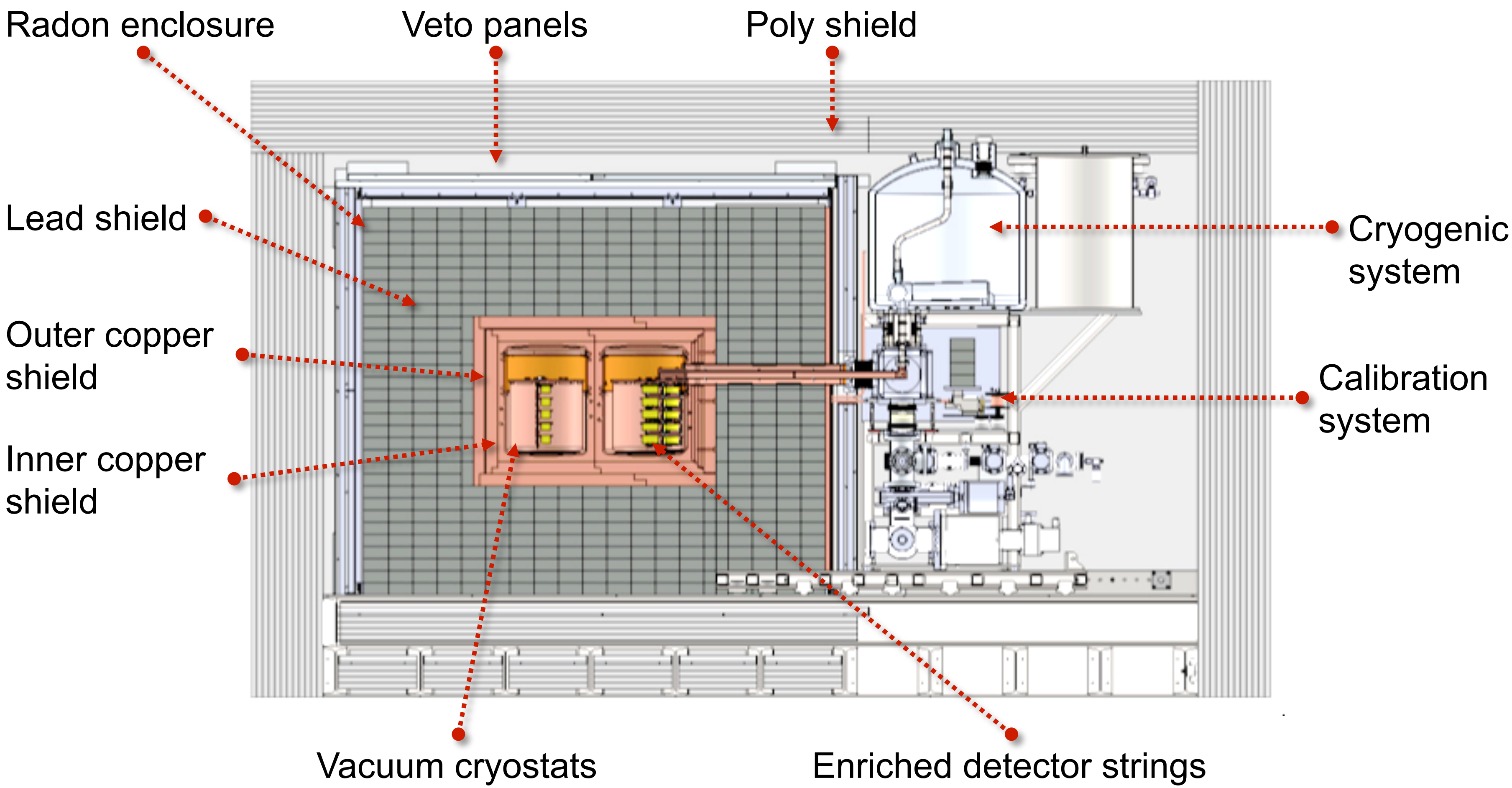






- Growth speed ~10 times slower than hair grow
- E-forming at 4850 level (10 baths) at SURF and at PNNL (6 baths)
- Underground machine shop operational

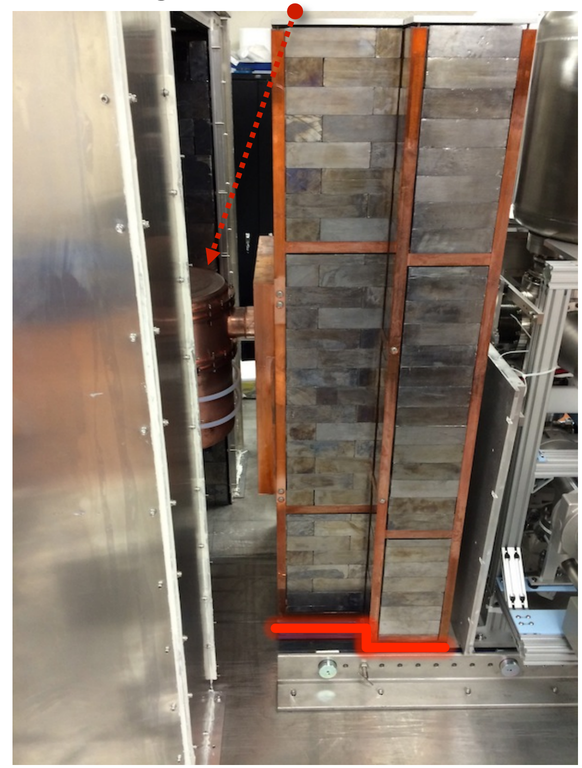
Experimental setup



Lead and Copper Shield

Lead shield

29 detectors at the moment running

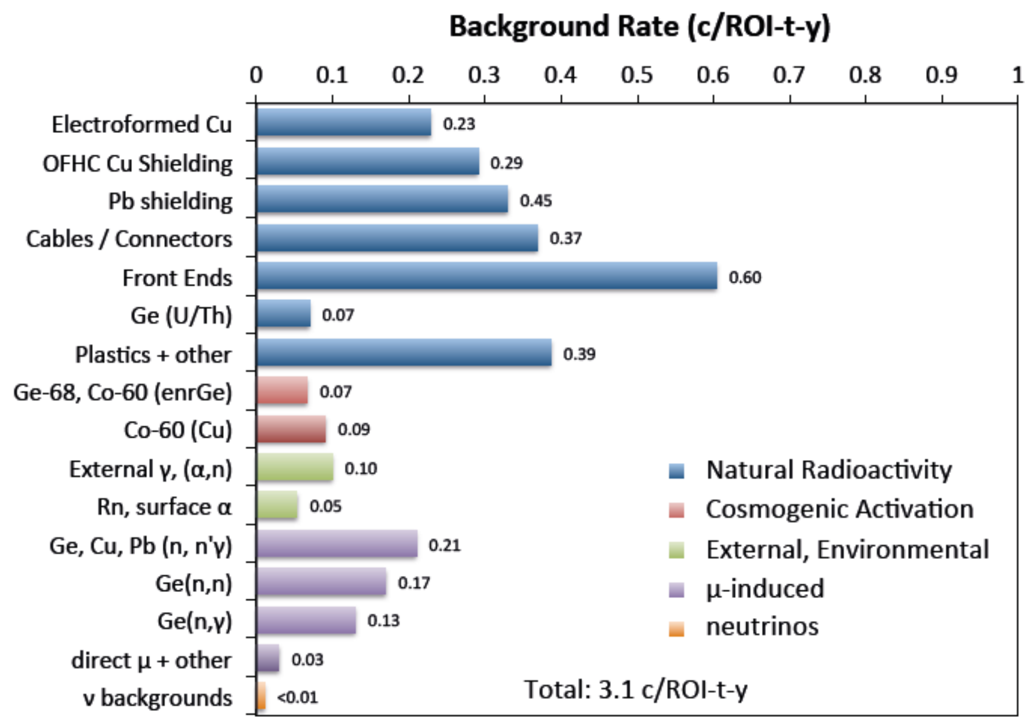


Radon enclosure

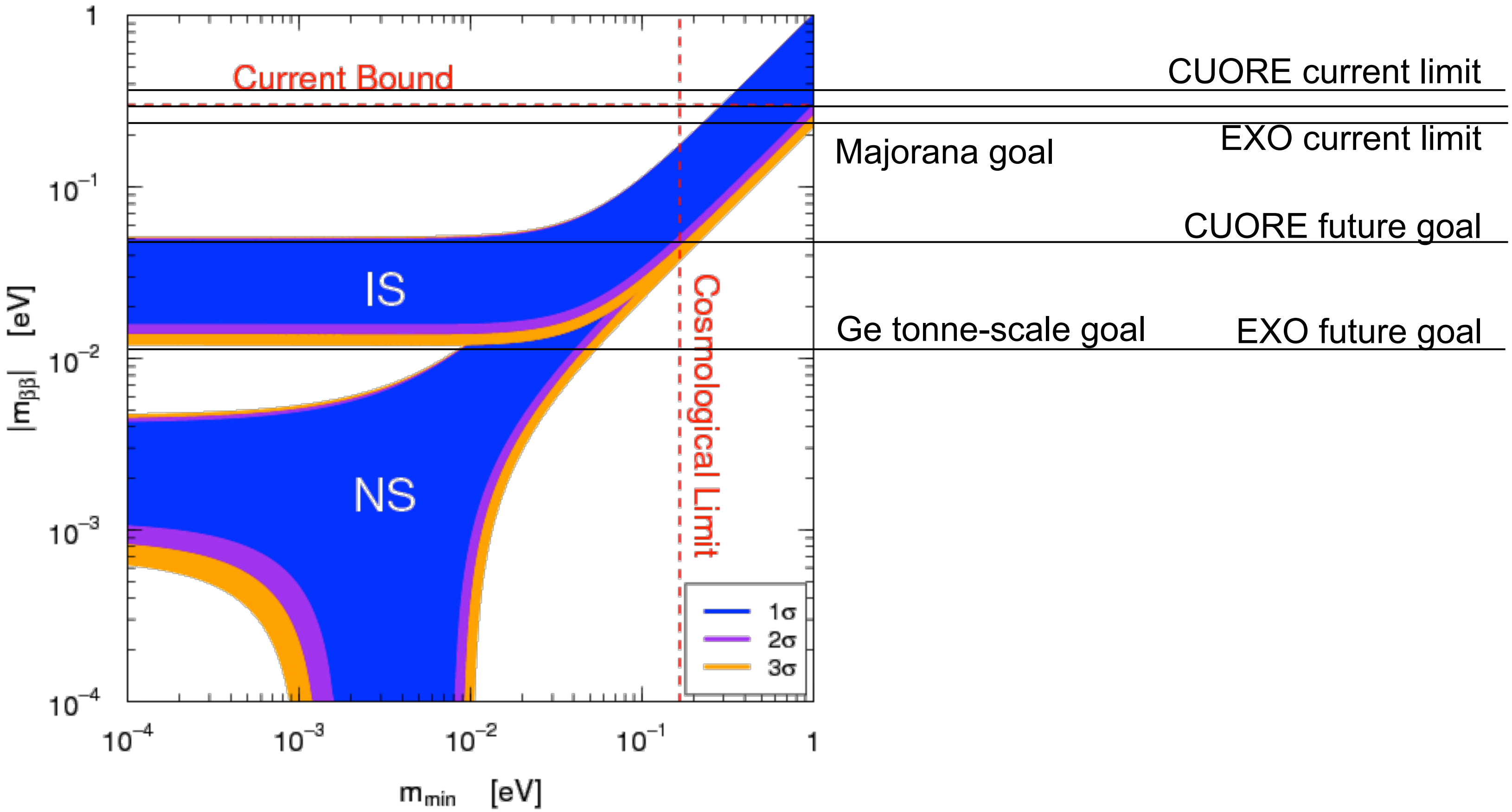
Inner+outer copper shield

MAJORANA Goals

- 30 kg (total)
- 24 kg (effective mass)
- 3 counts/ROI/t/year
- $T_{1/2} > 2.3\mathrm{x}10^{26}$ years



Ge Detector sensitivity



	CUORE-0 CUORE	EXO200/ nEXO	MAJORANA Demonstrator/ 1T Ge
Isotope	130Te	136Xe	76Ge
Background	300 c/t/y/ROI 50 c/t/y/ROI	130 c/t/y/ROI	3 c/t/y/ROI / <1 c/t/y/ROI
Energy resolution	5 keV @ 2.5MeV	88 keV @ 2.1MeV	4 keV @ 2.1MeV
Mass (total)	32 kg/ 206 kg	170 kg/ 5000 kg	30 kg/ 1000 kg
Enrichment	34%	80%	87%
Lifetime Limit	270 10^{25} 10^{26}	1.1 10^{25} 10^{27}	0.23 10^{25} 10^{27}
Critical Point	Alpha background	Energy resolution	Price of Germanium
Upgrades	Second signal/ enrichment	Ba-tagging	Combine with LAr shield (Gerda)

Collaboration	Isotope	Technique	Mass	Status
AMORE	Mo-100	CaMoO4 bolometers + scinillation	5	Construction
CANDLES	Ca-48	CaF	0.	ting
CARVEL	Ca-48	48CaWO	16	
GERDA I	Ge-67	Ge diodes in LAr	15	ete
GERDA II	Ge-67	Point Contact Ge in LAr	20	uction
MAJORANA DEM	Ge-67	Point Contact Ge in LAr	26	uction
1T Ge GERDA+MAJORANA	Ge-67	Best of GERDA + MAJORANA	~10	
NEMO3	Mo-100, Se-82	Foils with tracking	6.9, 0.9	Complete
SuperNEMO Demonstrator	Se-82	Foils with tracking		Construction
SuperNEMO	Se-82	Foils with tracking		R&D
MOON	Mo-100	Mo sheets		R&D
CAMEO	Cd-116	CdWO		R&D
COBRA	Cd-116, Te-130	CdZaTe detectors		Operating/ Construction
CUORICINO	Te-130	TeO bolometer	11	Complete
CUORE-0	Te-130	TeO bolometer	11	
CUORE	Te-130	TeO bolometer	206	
KamLAND-ZEN	Xe-136	2.7% in liquid scint.	370	
KamLAN	Xe-136	2.7% in liquid scint.	~1000	
NEXT-10	Xe-136	High pressure Xe TPC	10	
EXO-200	Xe-136	Xe liquid TPC	160	
nEXO	Xe-136	Xe liquid TPC	~5000	R&D
DCBA		Nd-150	Nd foils & tracking chambers	30	R&D

Crystals: Source = detector

Tracking: Extra observables

Liquid Scint: Self-shielding, scalability

TPC: A bit of everything

Neutrinoless double beta decay

Why do we care whether the neutrino is Dirac or Majorana?
→Lepton number violation → Matter-antimatter asymm.

How to test the Majorana vs Dirac nature?
→ Discovery of $0\nu\beta\beta$ proves the Majorana nature of neutrinos

When does $0\nu\beta\beta$ happen?
→ only possible in 11 isotopes where single beta decay is forbidden

How much mass of the isotope do wee need?
→ 1 tonne-year exposure and < 1 c/t/year/ROI background to cover IH

What can we say about the neutrino mass?
→ model dependence, nuclear matrix elements, complex phases

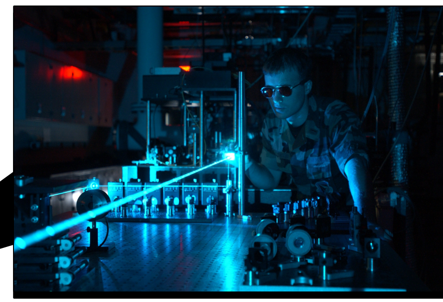
Where do we stand experimentally?
→ $T_{1/2} > 10^{25}$ years
→ $m_{\beta\beta} < 300$ meV

What causes background?
→ natural radioactivity, cosmogentic activation, muons/neutrons

How to realize an experiment?
→ Ionization, Scintillation, Phonons CUORE, EXO, MAJORANA

Helicity confusion

Suppose you want a coffee



“weak interaction force” checks for opacity

ATM only gives you transparent coins

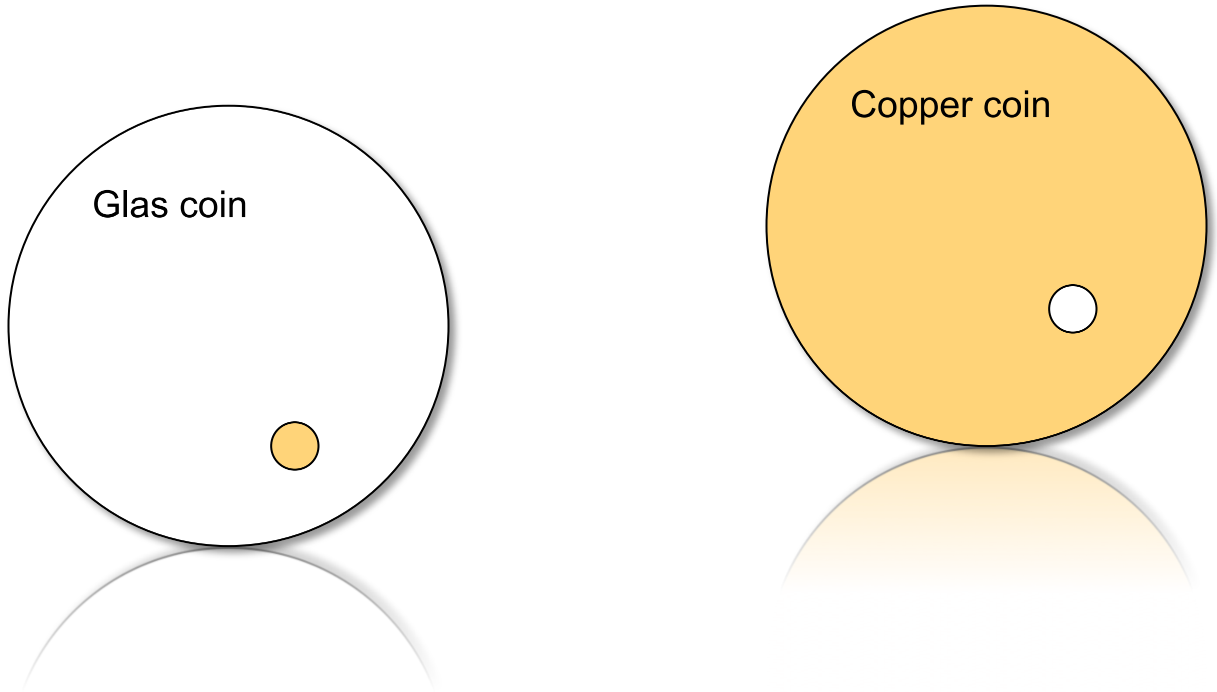
Glas coin

Copp er coin

vending machine only takes opaque coins

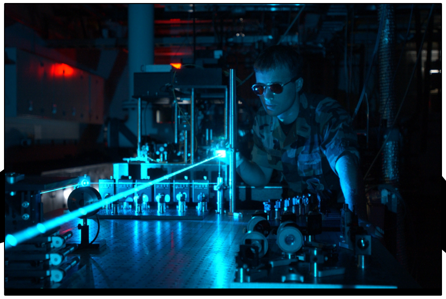
Helicity confusion

The coins have some feature



Helicity confusion

… with ~1% probability you will get one.



“weak interaction force” checks for opacity

returns:
99%: glas
1%: copper

Glas coin

Copper coin

accepts:
99% of copper
1% of glas

Overview

- Intro
- Neutrinoless double beta decay
- Single beta decay

Single Beta Decay

How to measure the neutrino mass directly?

What is actually measured?

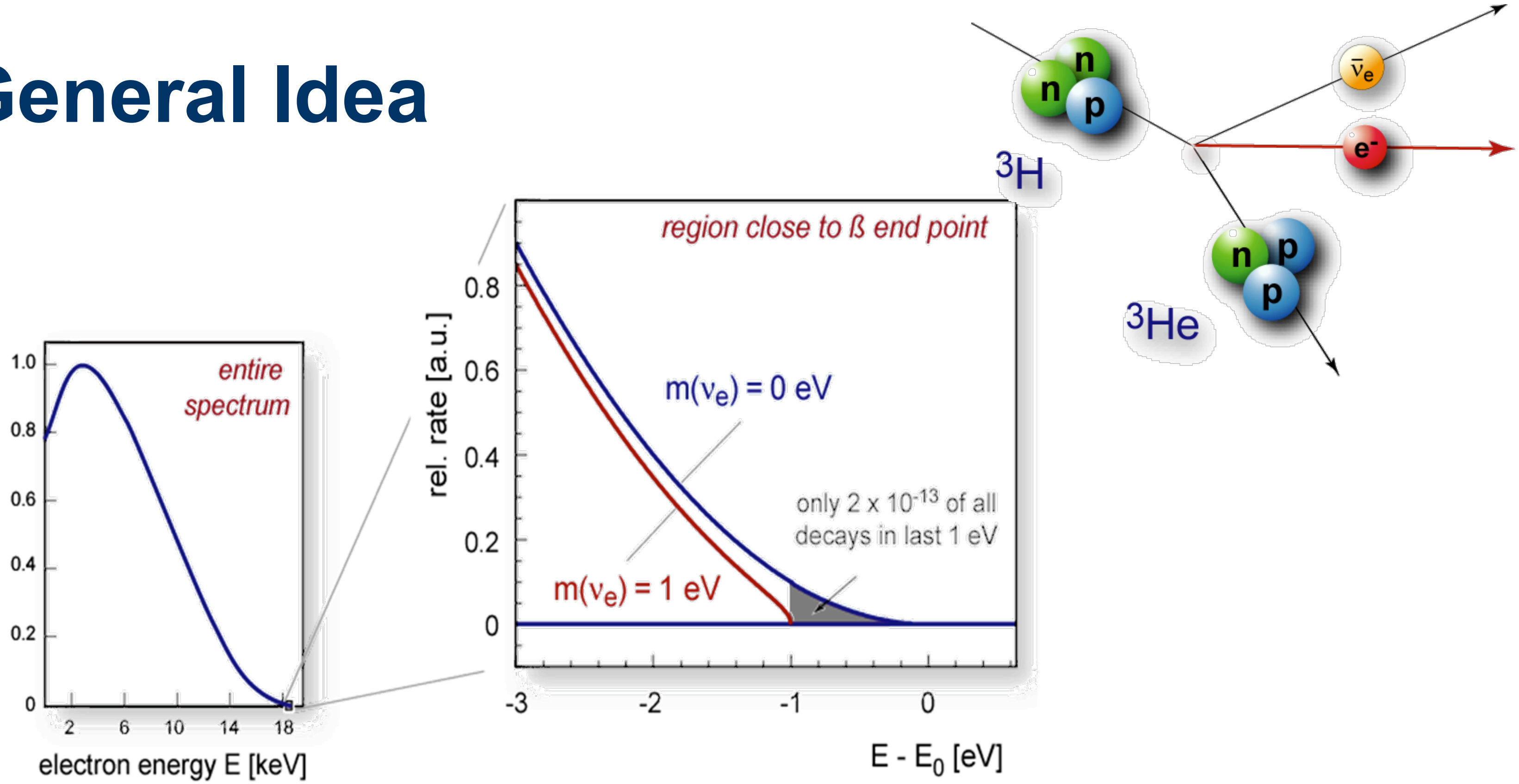
How does it compare to $0\nu\beta\beta$?

Where do we stand experimentally?

How to realize an experiment?

What else can we do with single beta decay?

General Idea

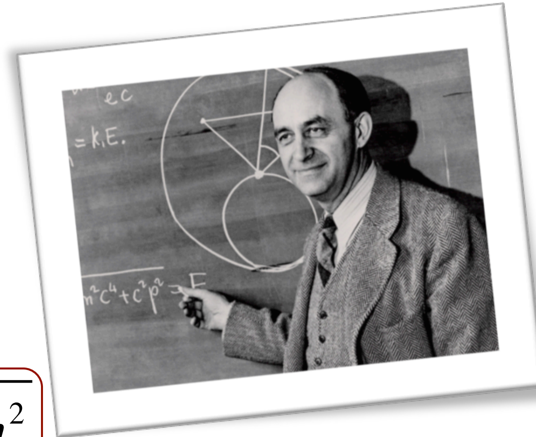


- The electron cannot take all energy that is released in the decay..
- … the neutrino takes at least some of the energy
- Note: signature is the spectral distortion. Endpoint is a free parameter

Single Beta Decay

How to measure the neutrino mass directly?	What is actually measured?	How does it compare to $0\nu\beta\beta$?
Where do we stand experimentally?	How to realize an experiment?	What else can we do with single beta decay?

Fermi Theory



$$\frac{d\Gamma}{dE} = \boxed{C} \cdot \boxed{F(E,Z)} \cdot \boxed{p \cdot (E + m_e) \cdot \left(E_0 - E\right) \cdot \sqrt{\left(E_0 - E\right)^2 - m_\nu^2}}$$

C:

Constant, includes Matrix element, Cabibbo angle, Fermi constant

F: Fermi Function, takes into account the interaction of the electron with the daughter nucleus

Phase Space Factor:

p: Momentum of electron

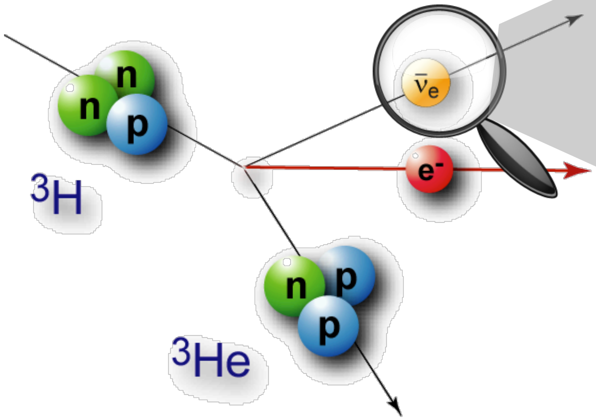
E + m$_e$: Total energy of electron

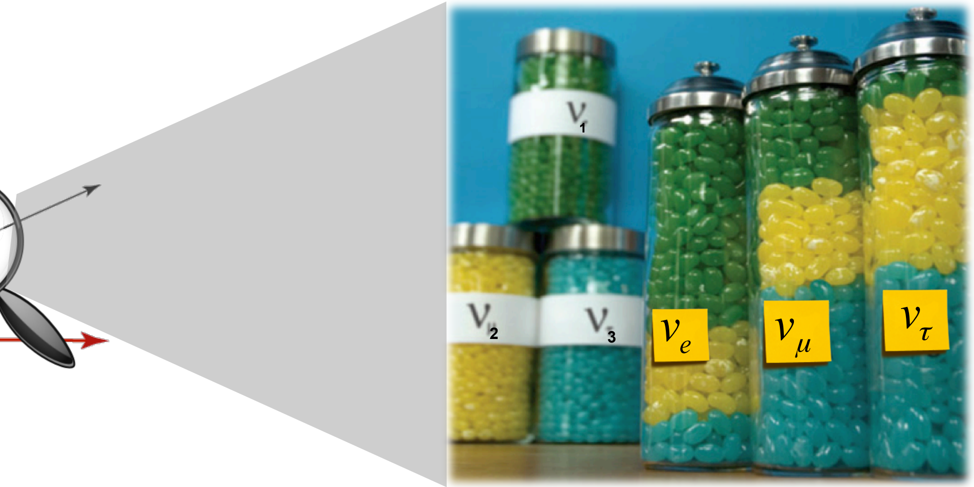
sqrt((E$_0$-E)^2-m$_\nu$$^{2)}$: Momentum of neutrino

E$_0$-E: Total energy of neutrino

E$_0$: Endpoint energy ($E_0 = M_1 - M_2 - m_e$)

Fermi Theory

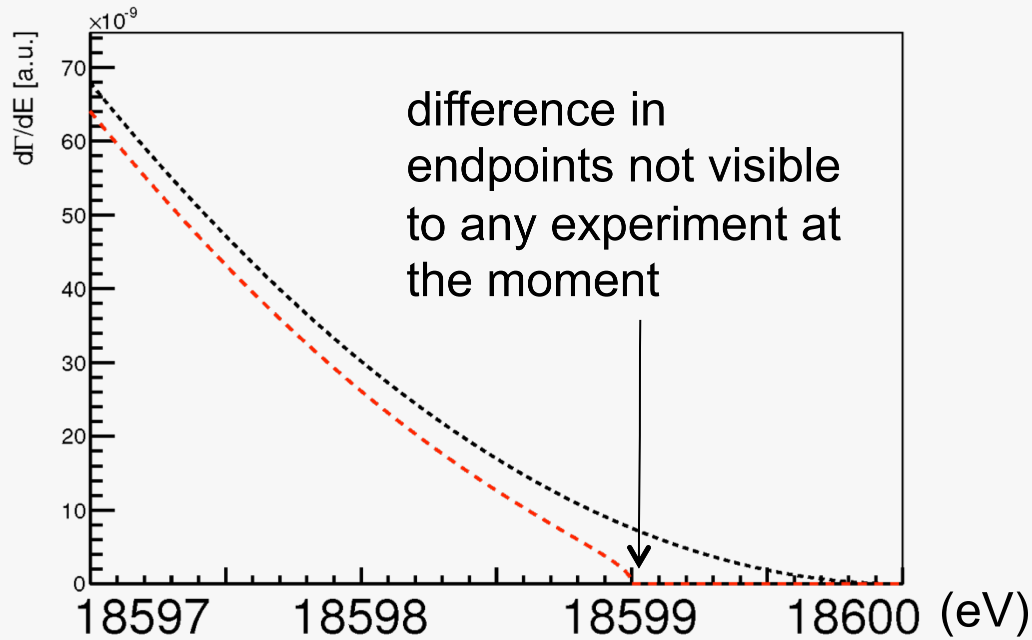




$$\frac{d\Gamma}{dE} = C \cdot F(E,Z) \cdot p \cdot (E + m_e) \cdot (E_0 - E) \boxed{\sum_i |U_{ei}|^2 \sqrt{(E_0 - E)^2 - m_{\nu i}^2}}$$

The beta spectrum is a superposition of spectra

$$\frac{d\Gamma}{dE} = C \cdot F(E,Z) \cdot p \cdot (E + m_e) \cdot (E_0 - E) \boxed{\sum_i |U_{ei}|^2 \sqrt{(E_0 - E)^2 - m_{\nu i}^2}}$$



What is measured instead?

The formula for 1 mass

$$\frac{d\Gamma}{dE} = C \cdot F(E,Z) \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - \boxed{m_\nu^2}}$$

The formula for an effective mass

$$\frac{d\Gamma}{dE} = C \cdot F(E,Z) \cdot p \cdot (E + m_e) \cdot (E_0 - E) \sqrt{(E_0 - E)^2 - \boxed{\sum_i |U_{ei}|^2 m_{\nu i}^2}}$$

… an effective electron anti-neutrino mass or…
… a weighted average of the three neutrino masses or…
… an incoherent sum of neutrino masses

… this is different from $0\nu\beta\beta$

Single Beta Decay

How to measure the neutrino mass directly?

What is actually measured?

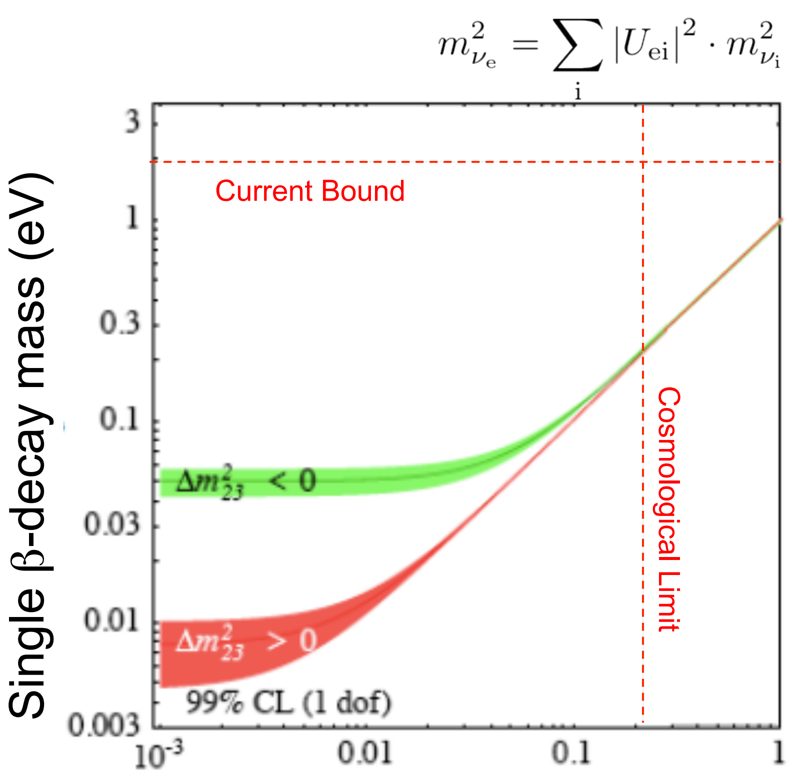
How does it compare to $0\nu\beta\beta$?

Where do we stand experimentally?

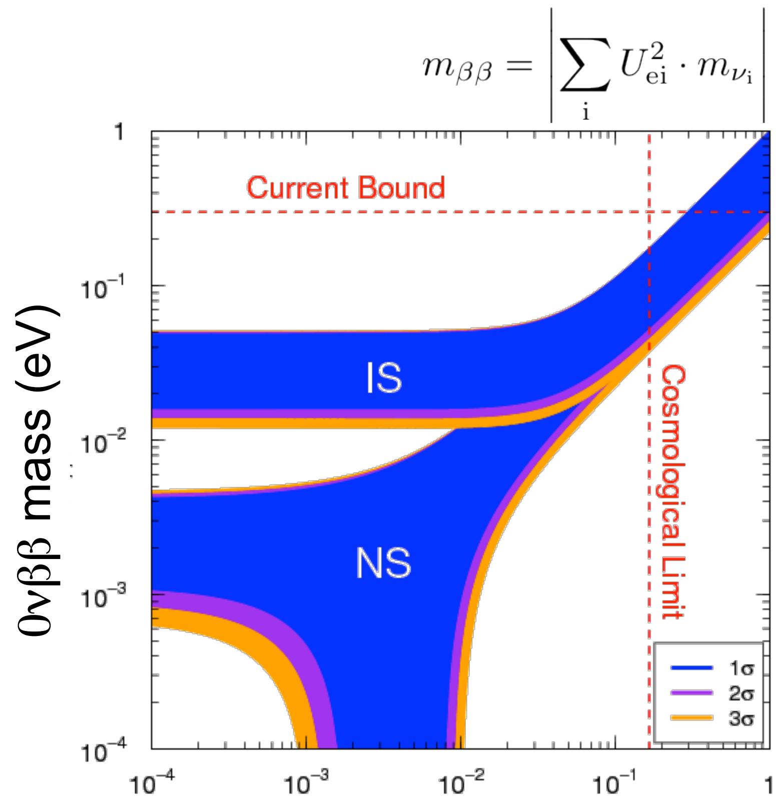
How to realize an experiment?

What else can we do with single beta decay?

Comparison to 0νββ



Lightest neutrino mass (eV)



Lightest neutrino mass (eV)

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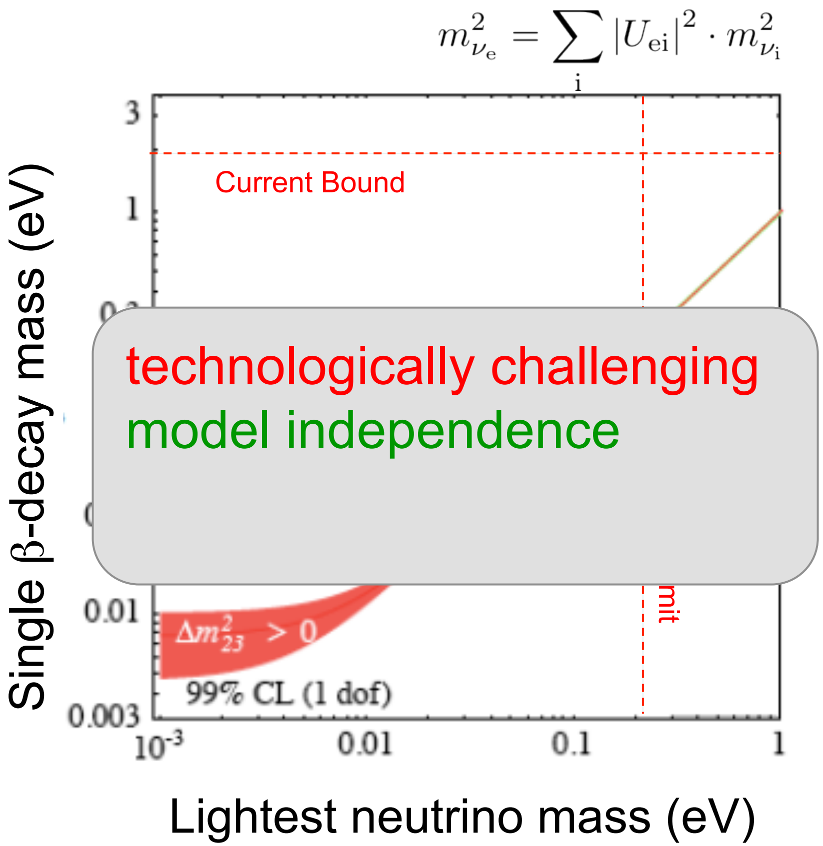

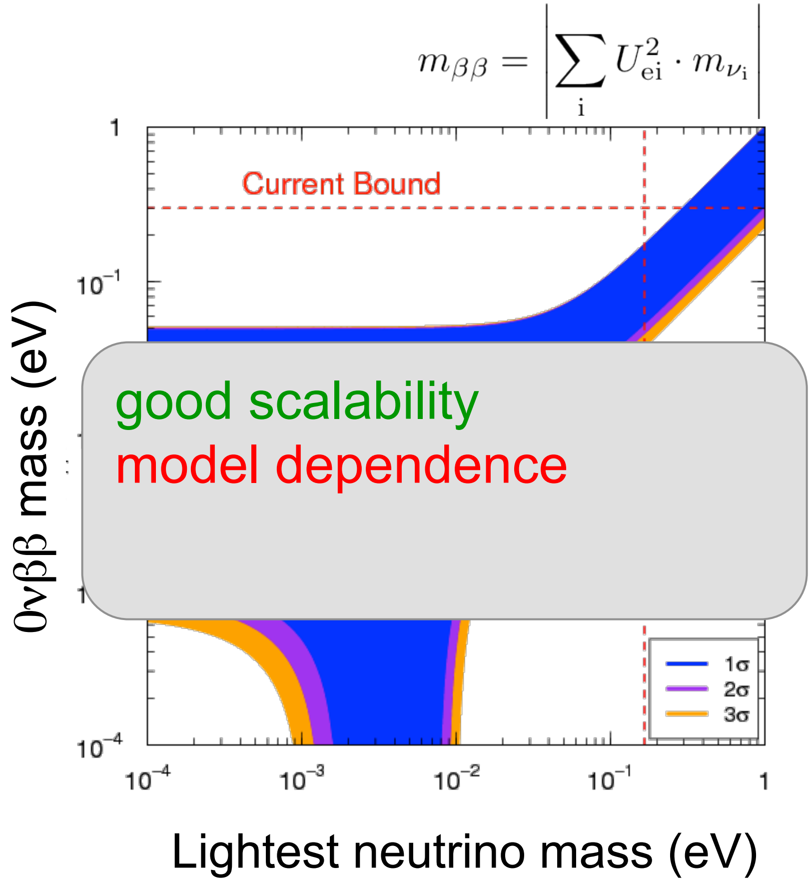

Single Beta Decay

How to measure the neutrino mass directly?

What is actually measured?

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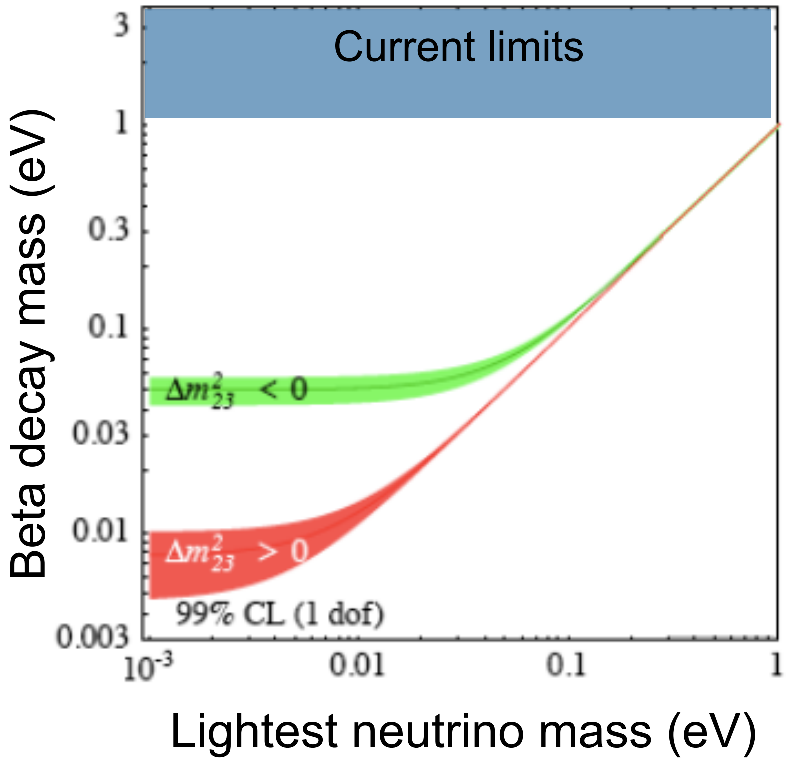
What else can we do with single beta decay?

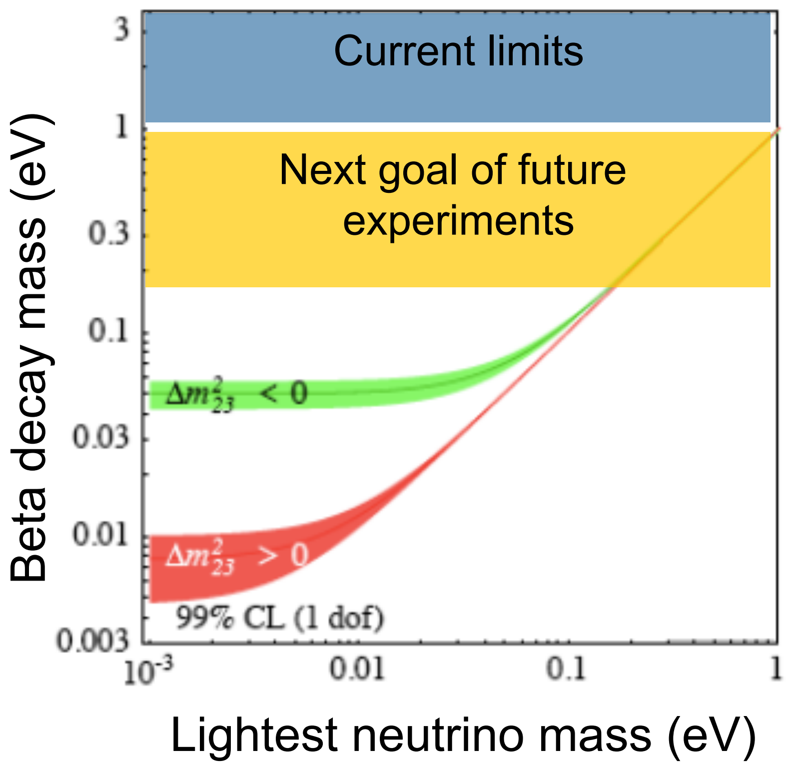
Where do we stand experimentally?



- Neutrinos excluded as Dark Matter

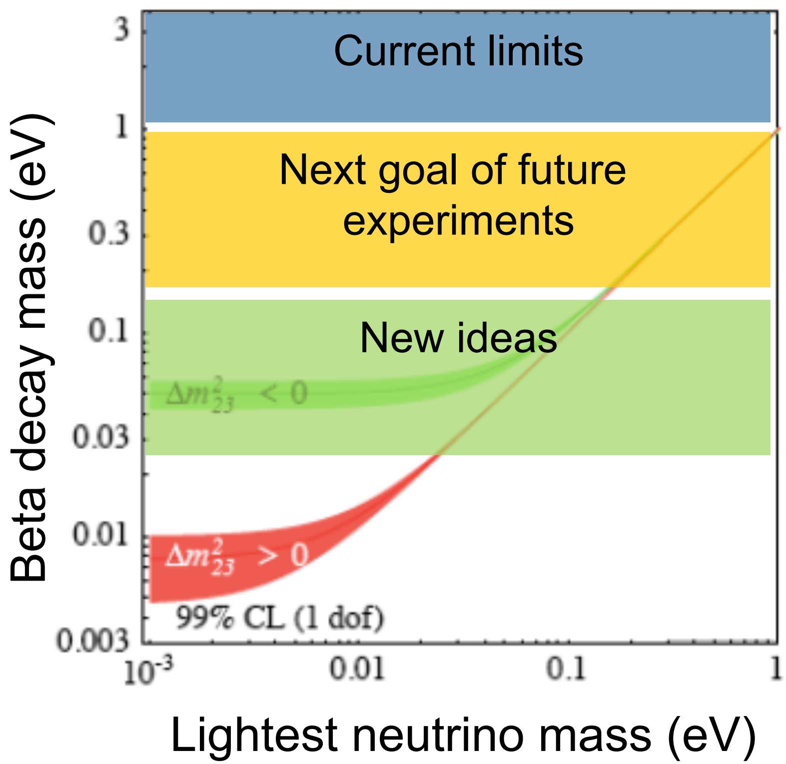
V.N. Aseev et al., Phys. Rev. D 84 (2011) 112003
C. Kraus et al., Eur. Phys. J. C 40 (2005) 447

Where do we stand experimentally?



- Neutrinos excluded as Dark Matter
- Distinquish between hierarchical and degenerate scenario, impact on structure formation

Where do we stand experimentally?



- Neutrinos excluded as Dark Matter
- Distinquish between hierarchical and degenerate scenario, impact on structure formation
- Resolve neutrino mass hierarchy

Single Beta Decay

How to measure the neutrino mass directly?

What is actually measured?

How does it compare to $0\nu\beta\beta$?

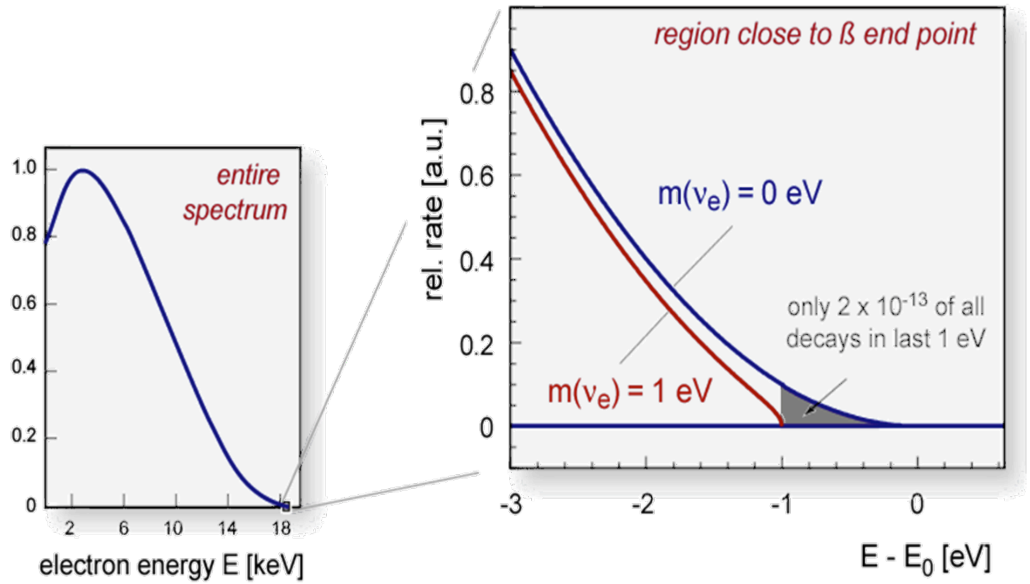
Where do we stand experimentally?

How to realize an experiment?

What else can we do with single beta decay?

Experimental aspects

High statistics
Low systematics

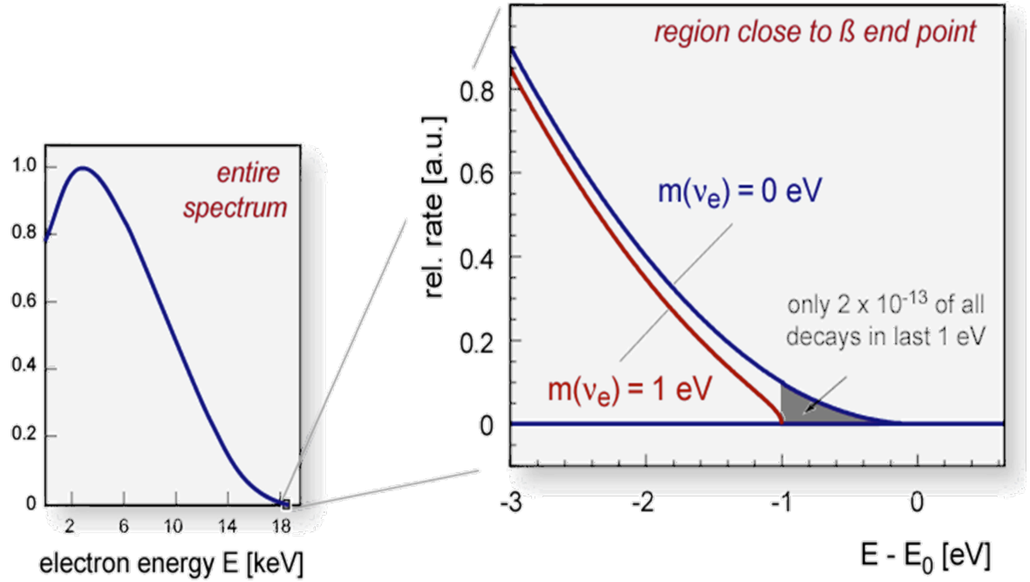


Experimental aspects

Key requirements

- Source isotope
  - short half-life
  - low endpoint
- Instrument
  - Excellent energy resolution
  - Low Background

High statistics
Low systematics



Experimental aspects

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Experimental options

	^{3}H	^{163}Ho
$T_{1/2}$	12.3 years	4500 years
E_0	18.6 keV	2.5 keV
technique	spectrometer frequency	bolometer

Experimental aspects

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Experimental options

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E_0	18.6 keV	2.5 keV
technique	spectrometer frequency	bolometer

KATRIN

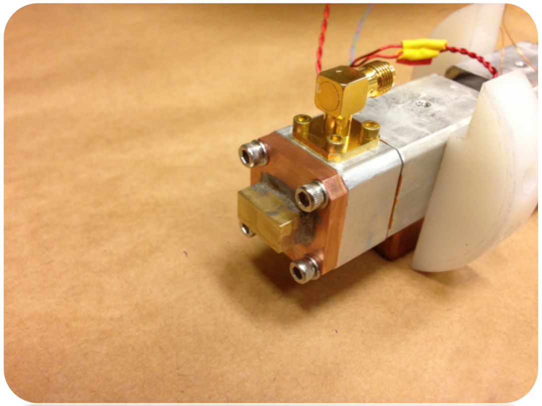
PROJECT 8

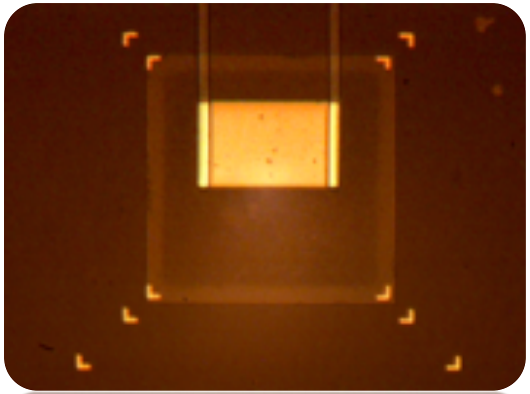
ECHo

HOLMES

NUMECS

3 Experimental Efforts



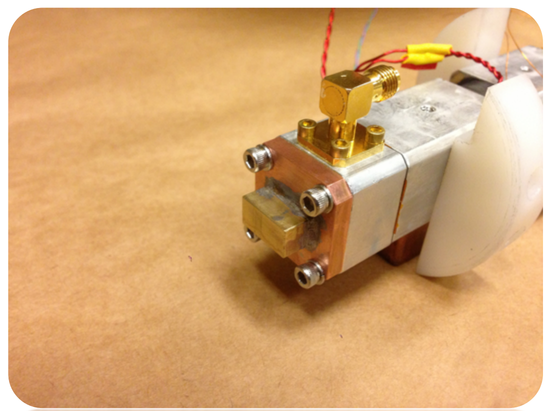


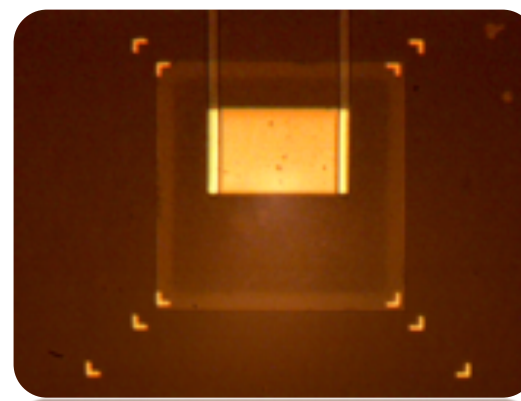
Drexlin, V. Hannen, S. M., C. Weinheimer, Adv. High Energy Physics 2013, Article ID 293986, (2013)

BERKELEY LAB

3 Experimental Efforts

Spectroscopy
(KATRIN)

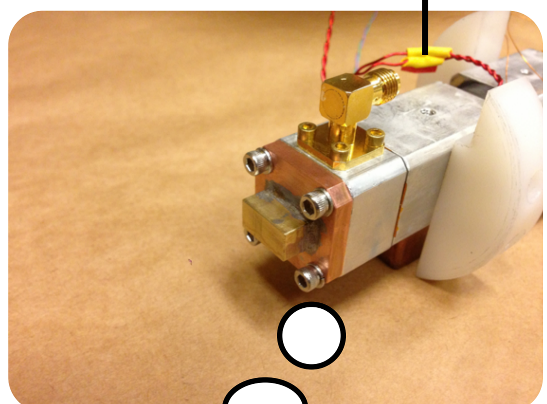


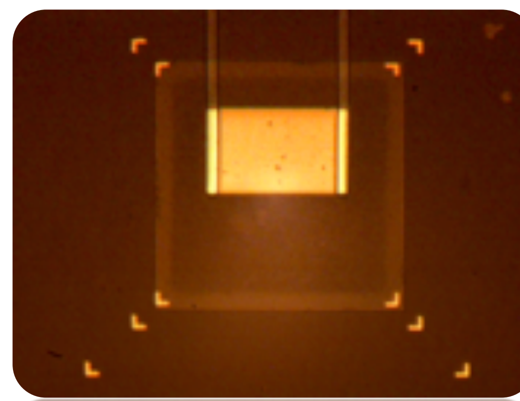


3 Experimental Efforts

Spectroscopy
(KATRIN)

Frequency
(Project 8)

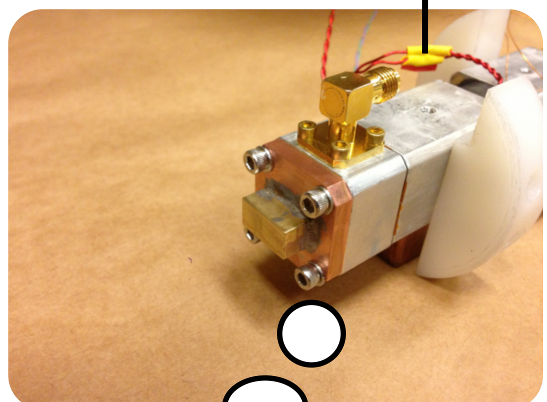




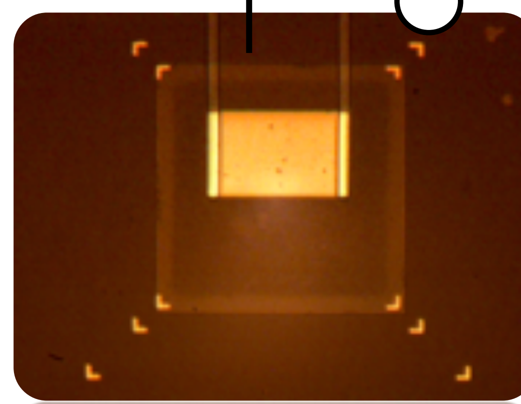
3 Experimental Efforts

Spectroscopy
(KATRIN)

Frequency
(Project 8)



Calorimetry
(HOLMES, ECHo
&NUMECS)

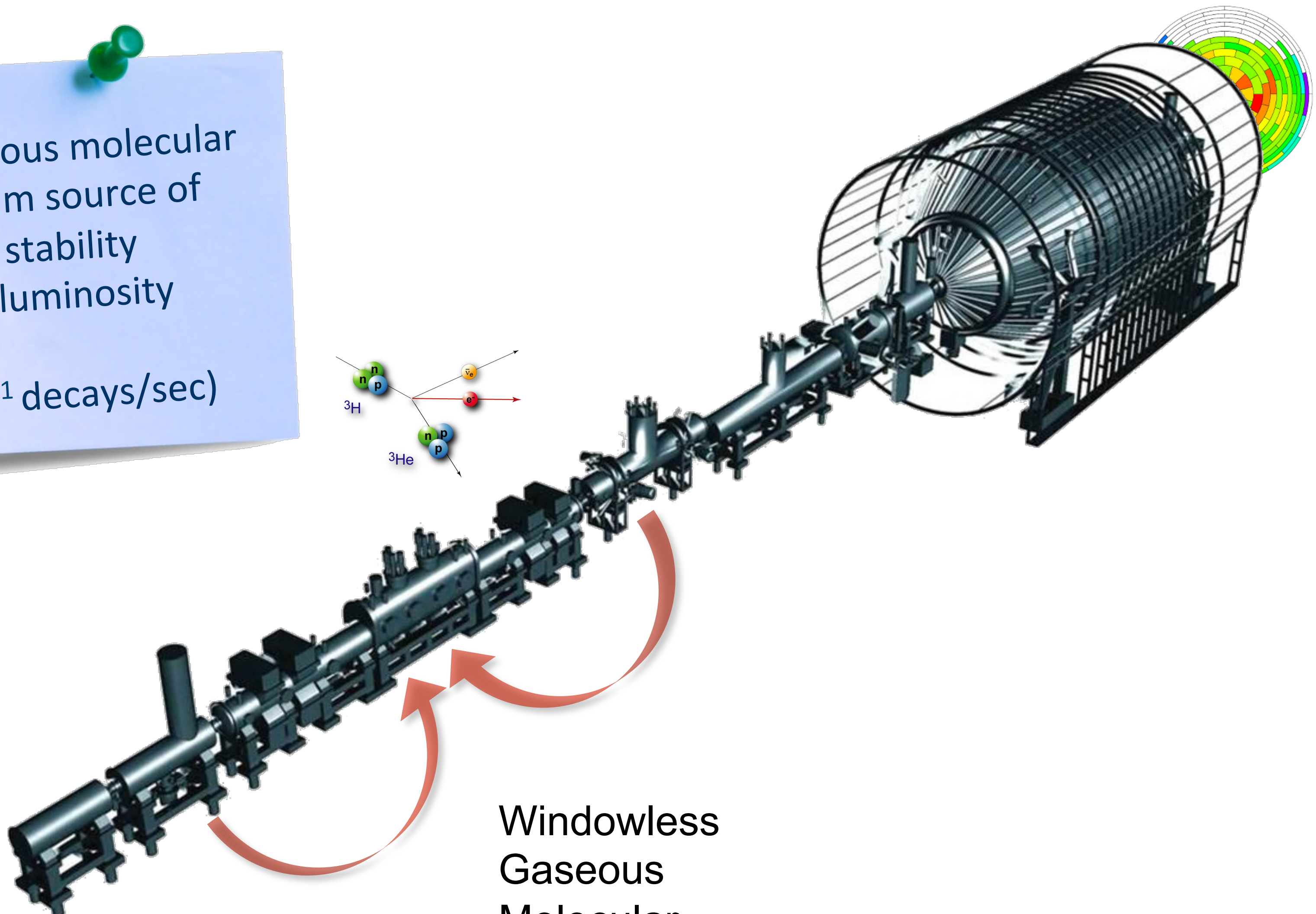


Karlsruhe Tritium Neutrino Experiment

KATRIN Overview

Gaseous molecular tritium source of high stability and luminosity

(10^{11} decays/sec)

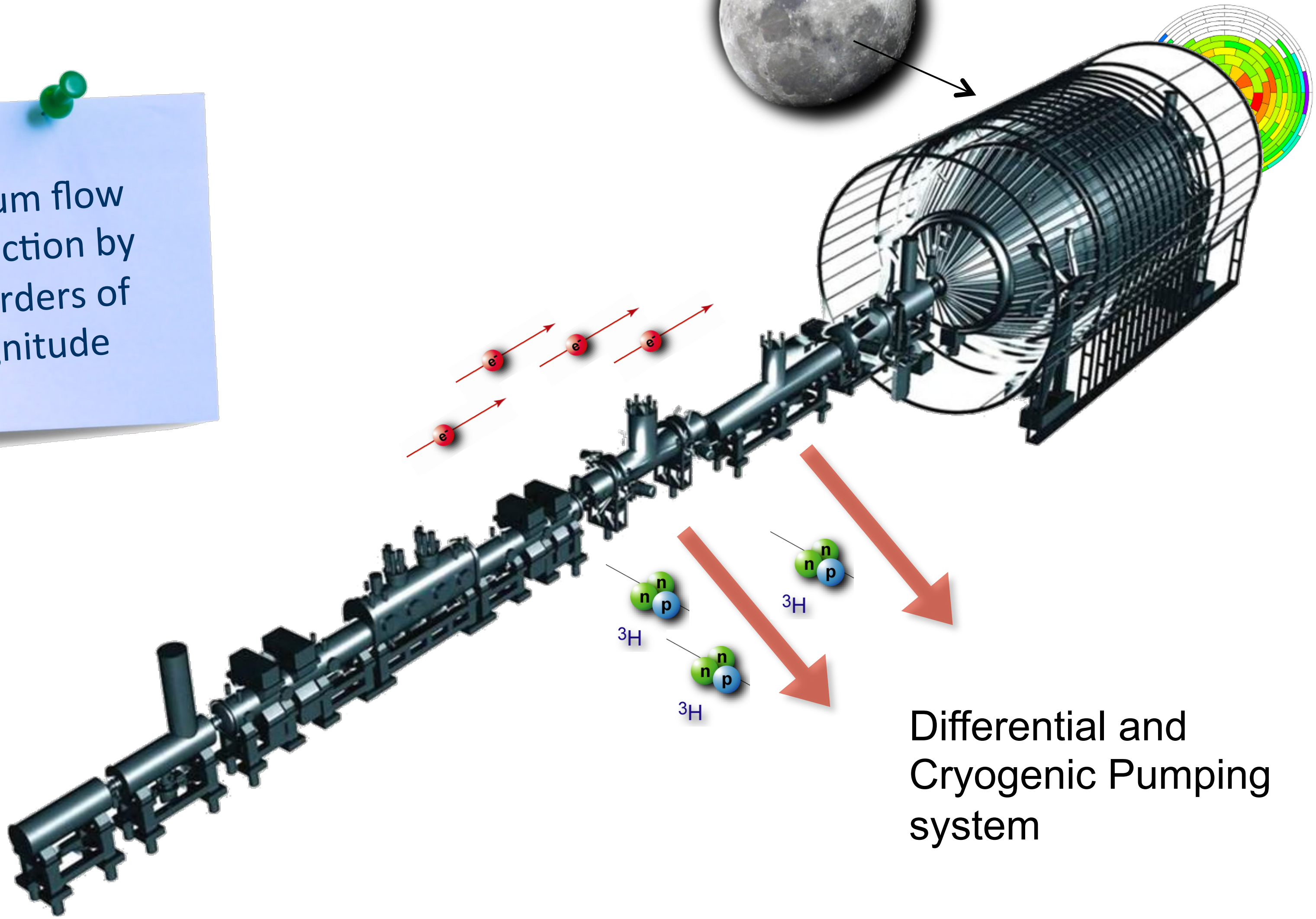


Windowless
Gaseous
Molecular
Tritium Source

KATRIN Overview

Tritium flow reduction by 14 orders of magnitude

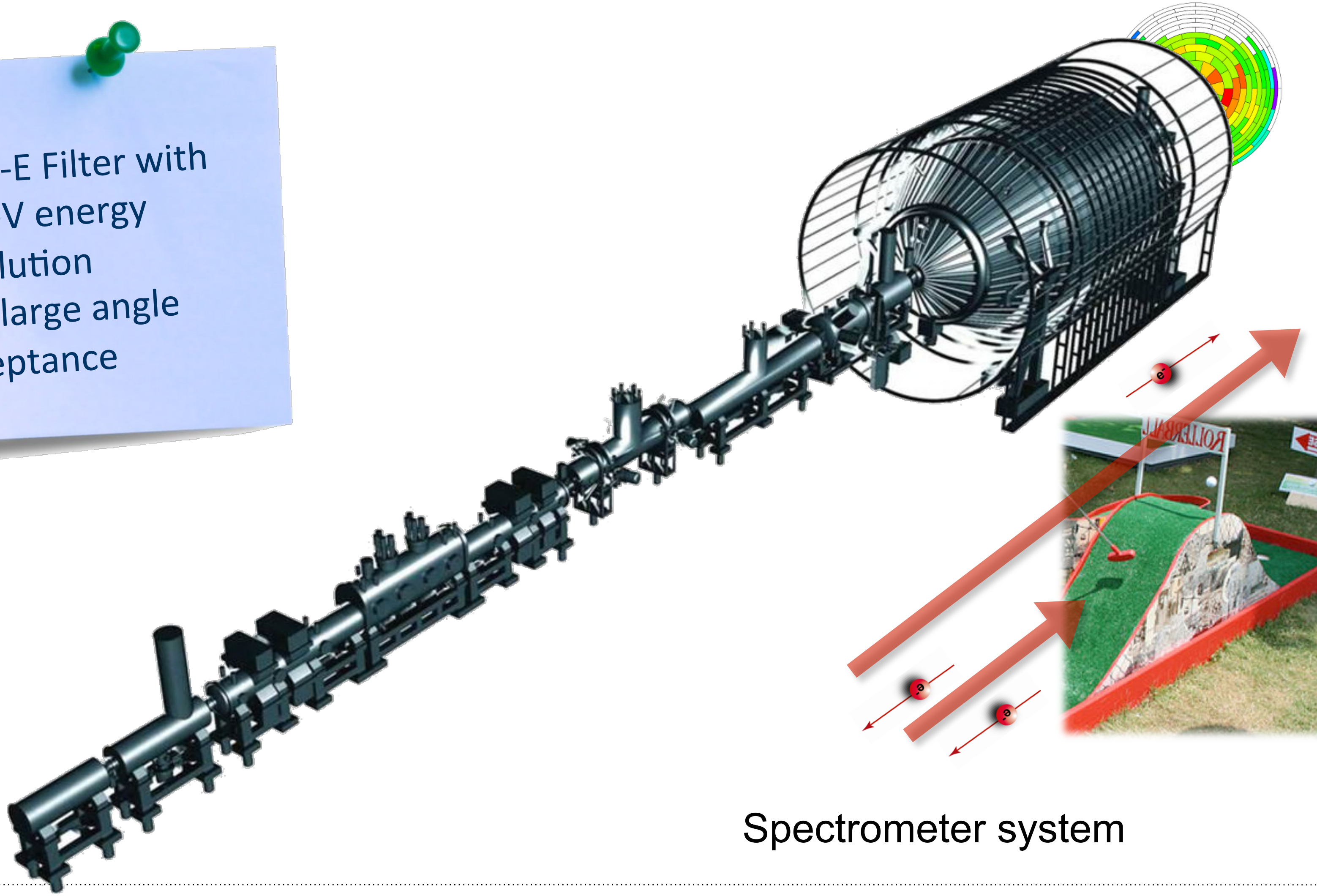
vacuum like on the moon
10^{-11}mbar



Differential and Cryogenic Pumping system

KATRIN Overview

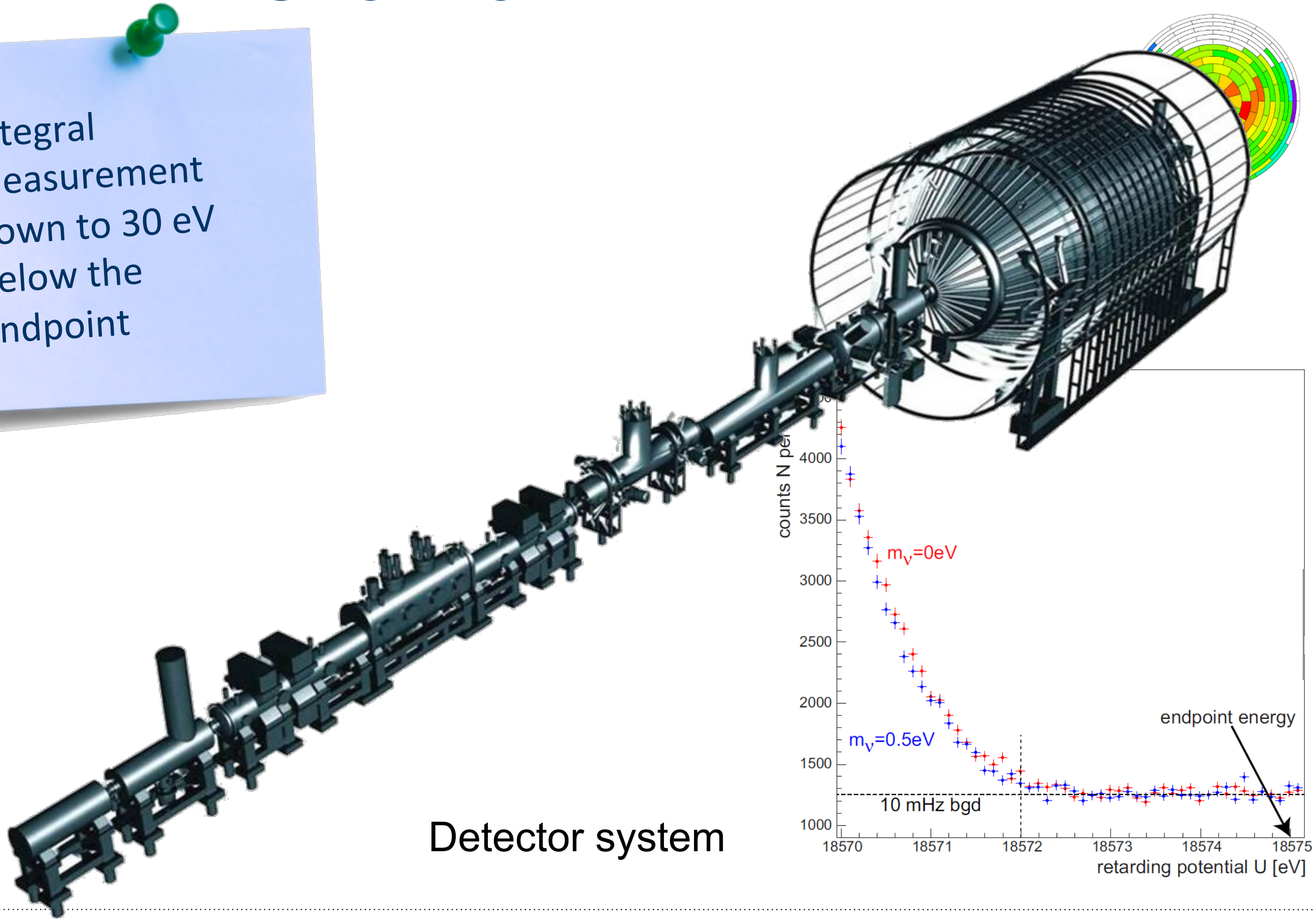
MAC-E Filter with
< 1 eV energy
resolution
and large angle
acceptance



Spectrometer system

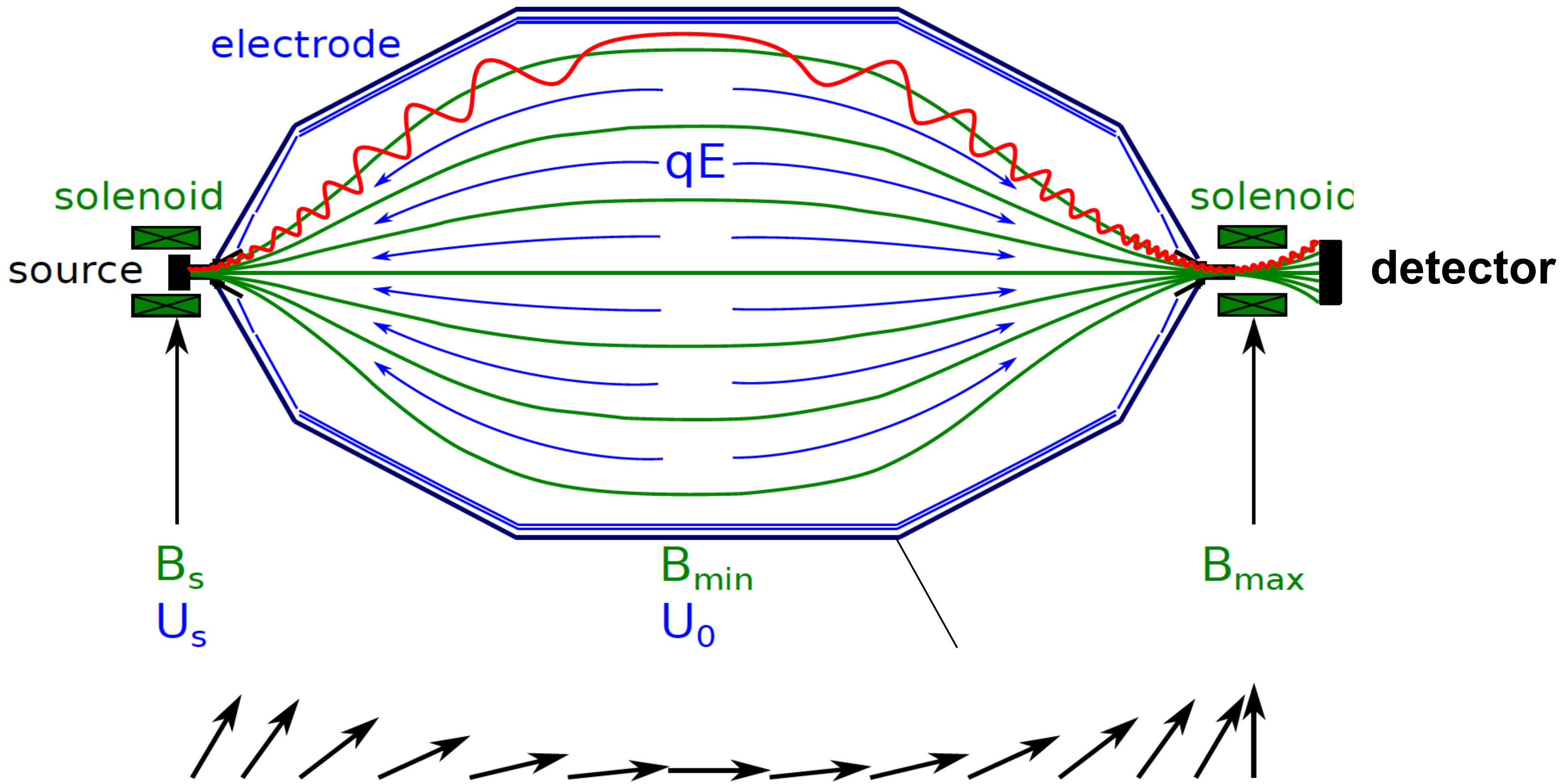
KATRIN Overview

Integral measurement down to 30 eV below the endpoint



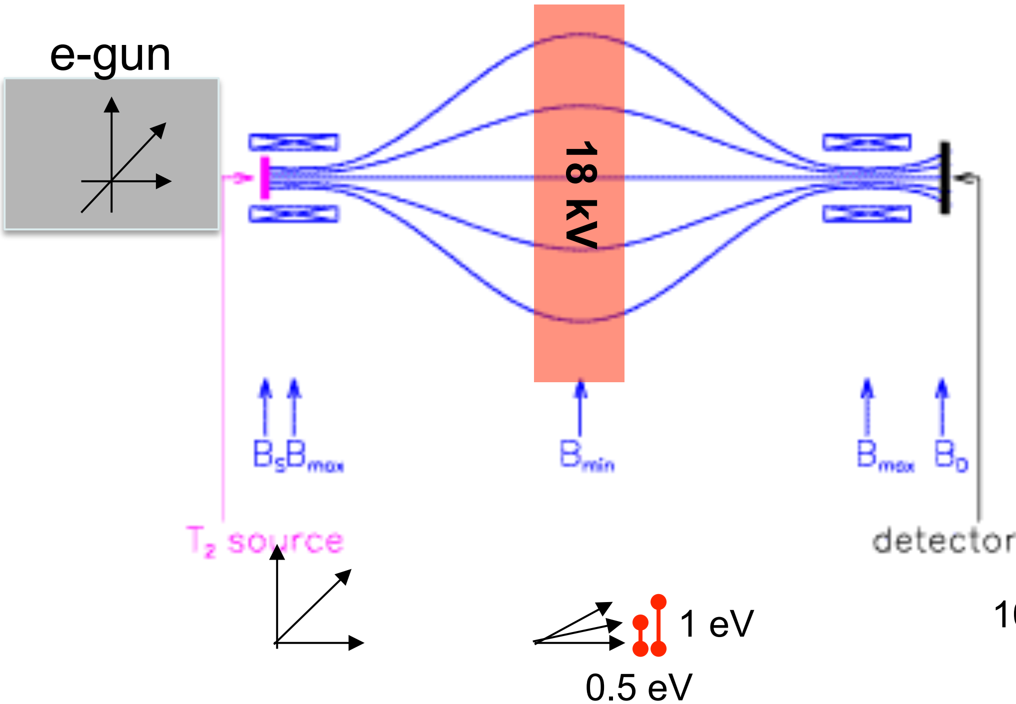
Detector system

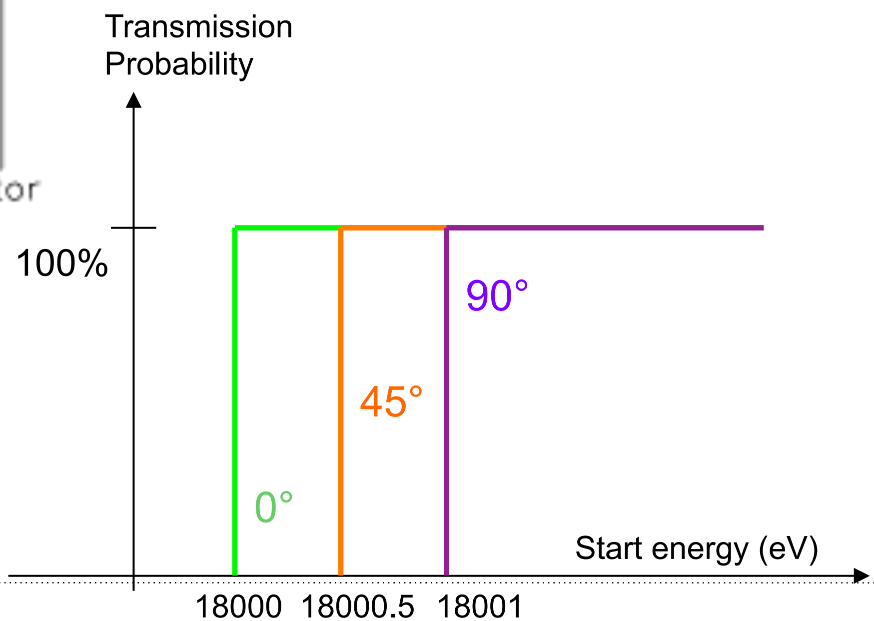
MAC-E-Filter Principle



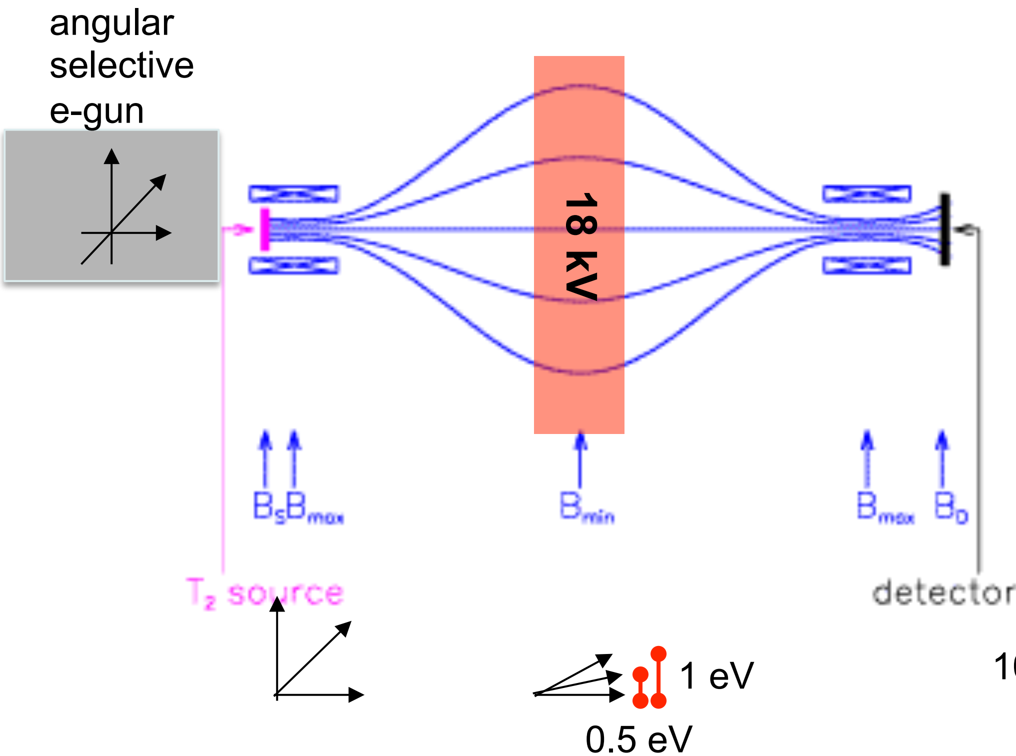
$\mu = E_\perp / B = \text{const.}$

Energy resolution of MAC-E-Filter



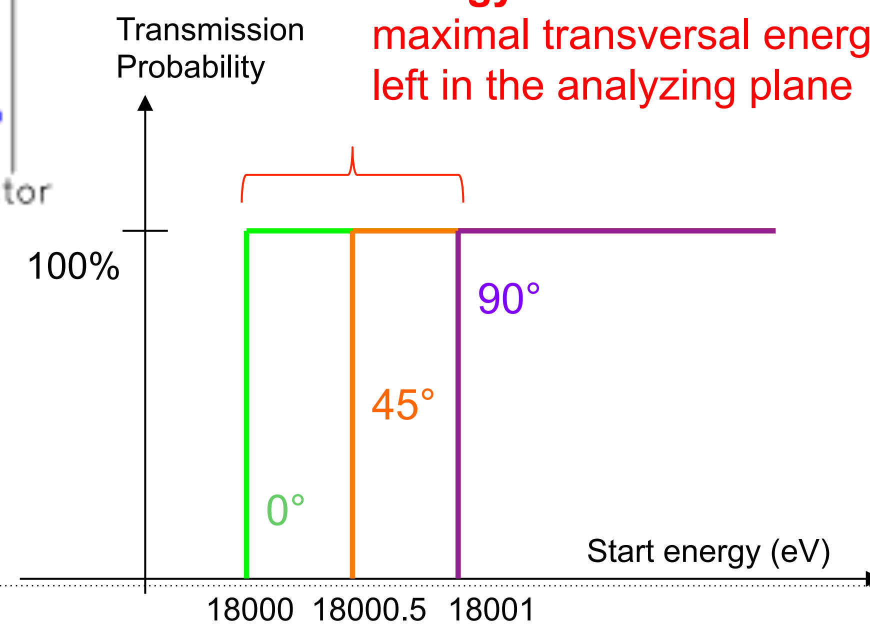


Energy resolution of MAC-E-Filter



$$\frac{\Delta E}{E} = \frac{B_{\min}}{B_{\max}}$$

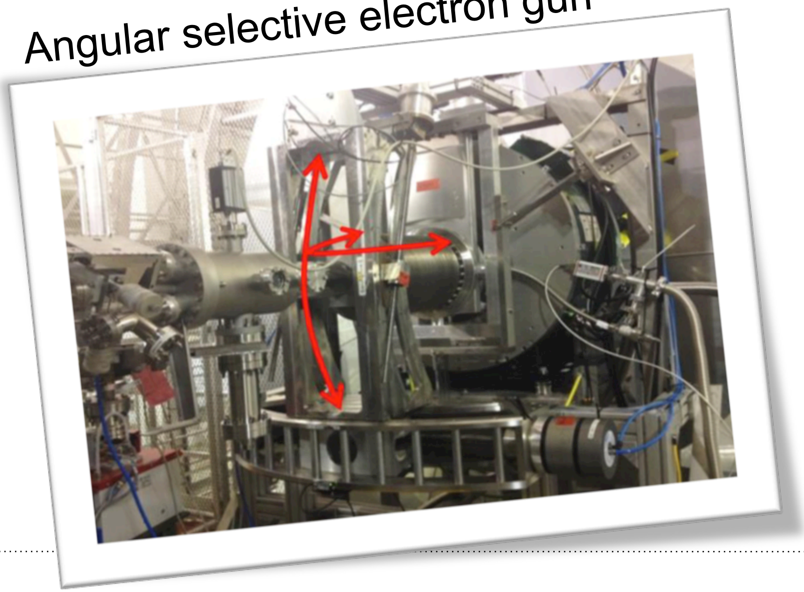
Energy resolution:
maximal transversal energy left in the analyzing plane

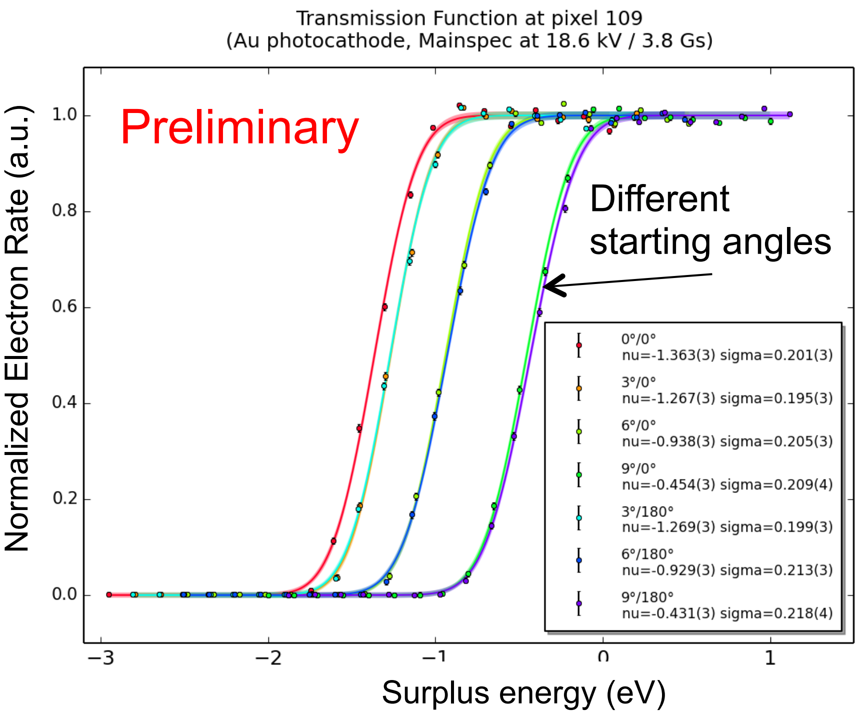


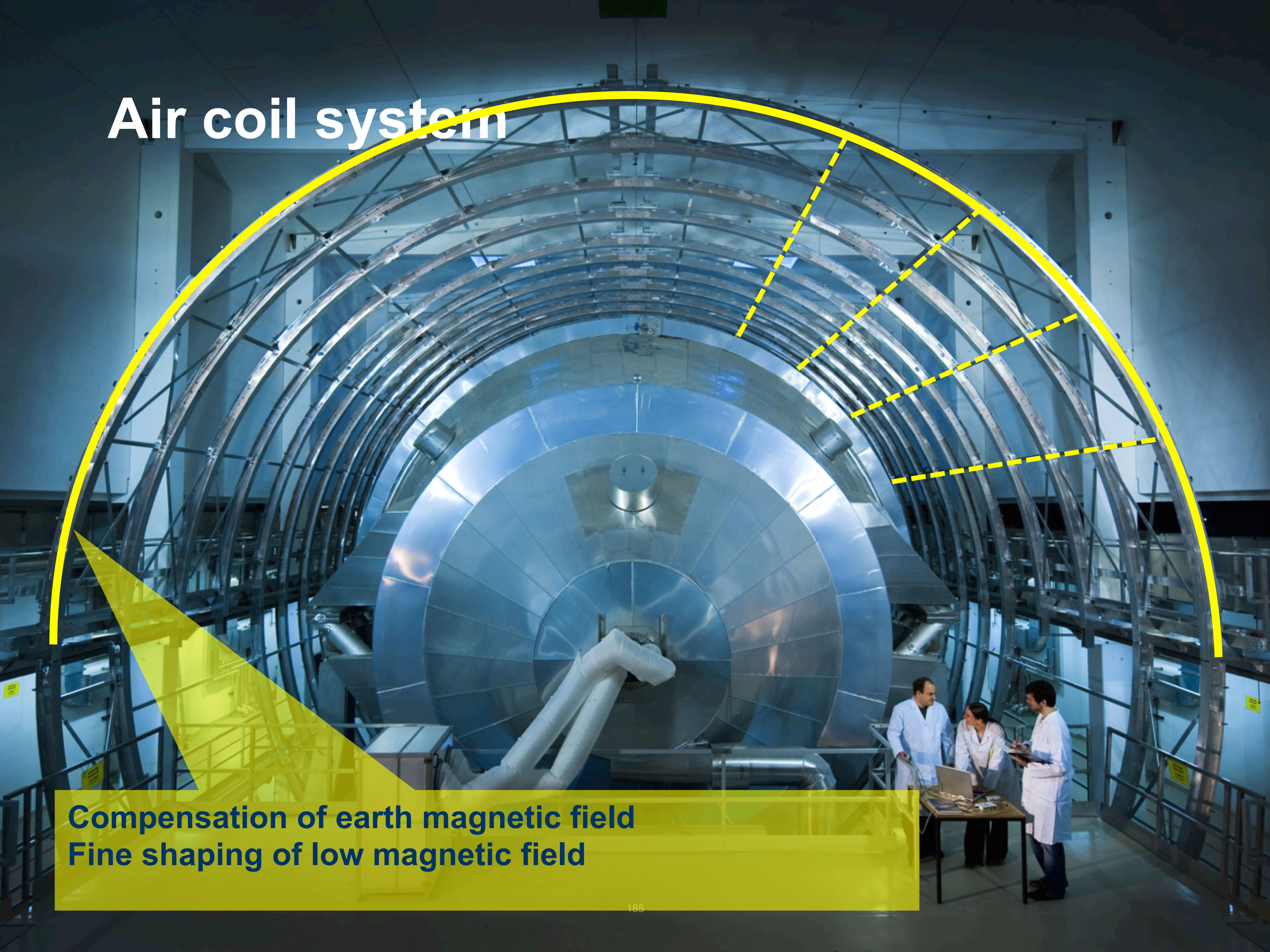
KATRIN Spectrometer measurements

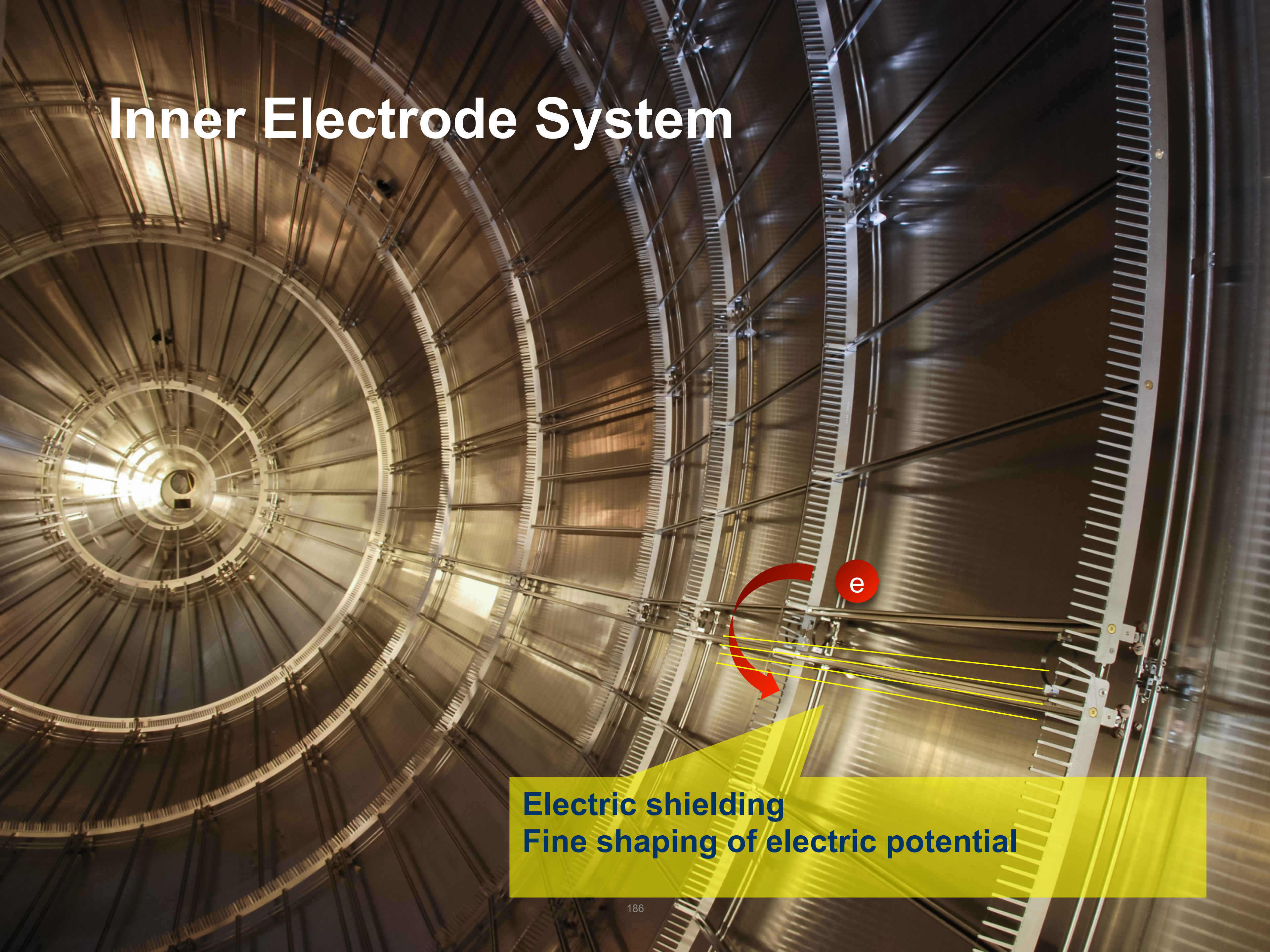
2015: 2nd measurement phase completed

- Spectrometer works as MAC-E Filter

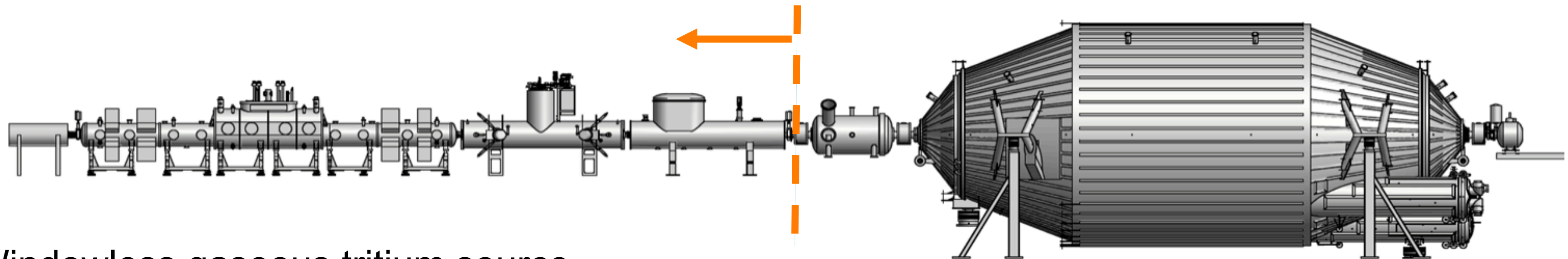





Air coil system
Compensation of earth magnetic field
Fine shaping of low magnetic field


Inner Electrode System
e
Electric shielding
Fine shaping of electric potential

KATRIN Source Status



Windowless gaseous tritium source

→ delivery this year

Differential pumping section

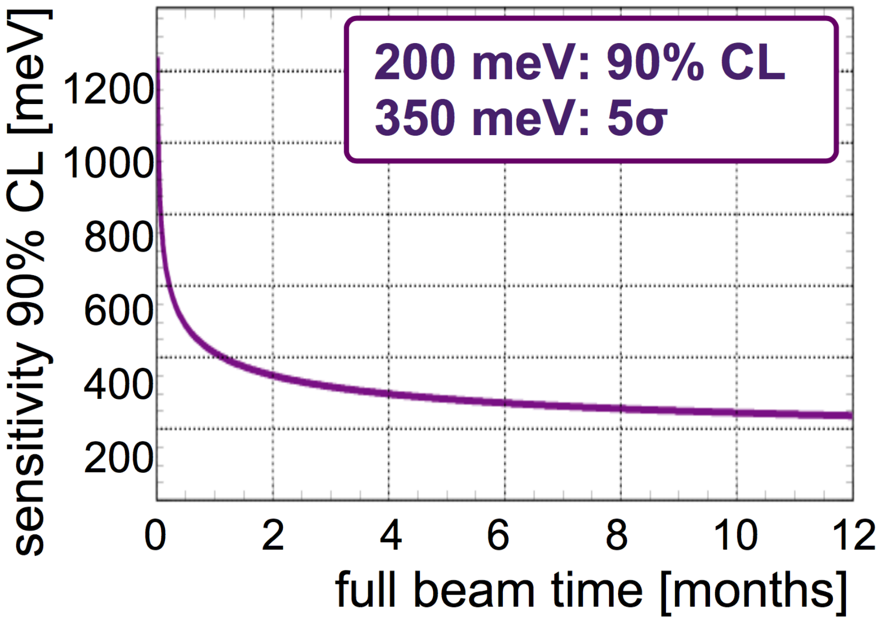
→ Commissioning at KIT

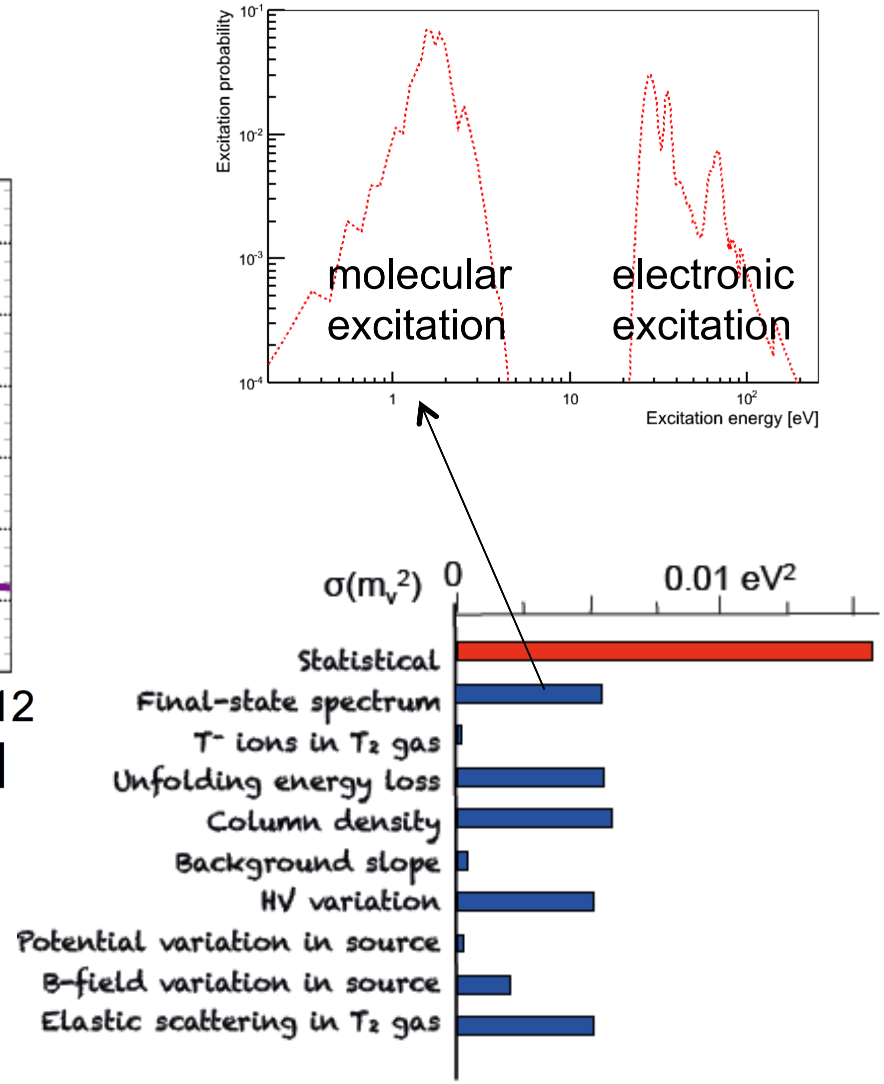
Cryogenic pumping section

→ Delivery this year

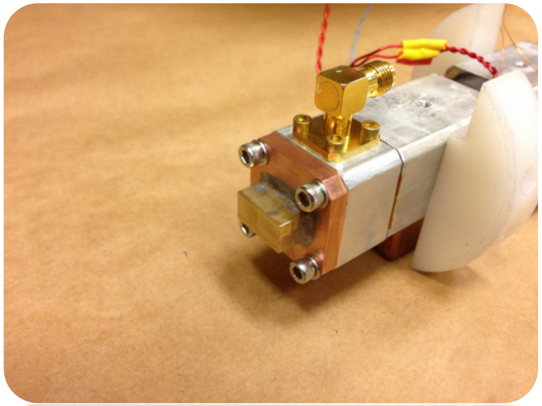
Source System integrated in mid-2016

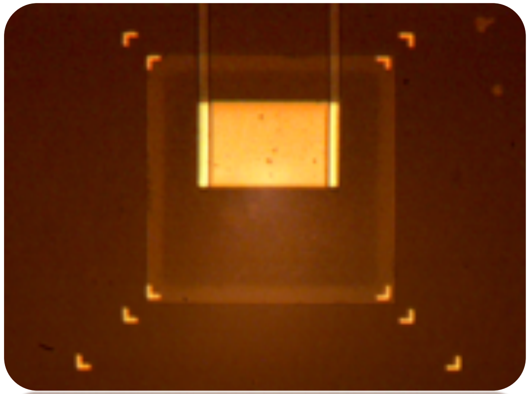
KATRIN Sensitivity





3 Experimental Efforts





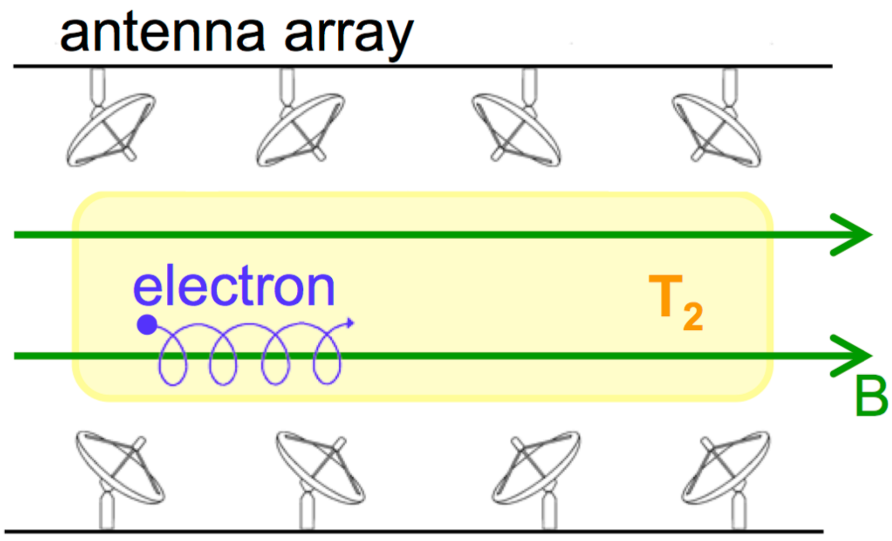
Drexlin, V. Hannen, S. M., C. Weinheimer, Adv. High Energy Physics 2013, Article ID 293986, (2013)

A new kind of energy measurement

UW/Seattle, MIT, UC/Santa Barbara Yale, Pacific NW, Livermore, NRAO, KIT

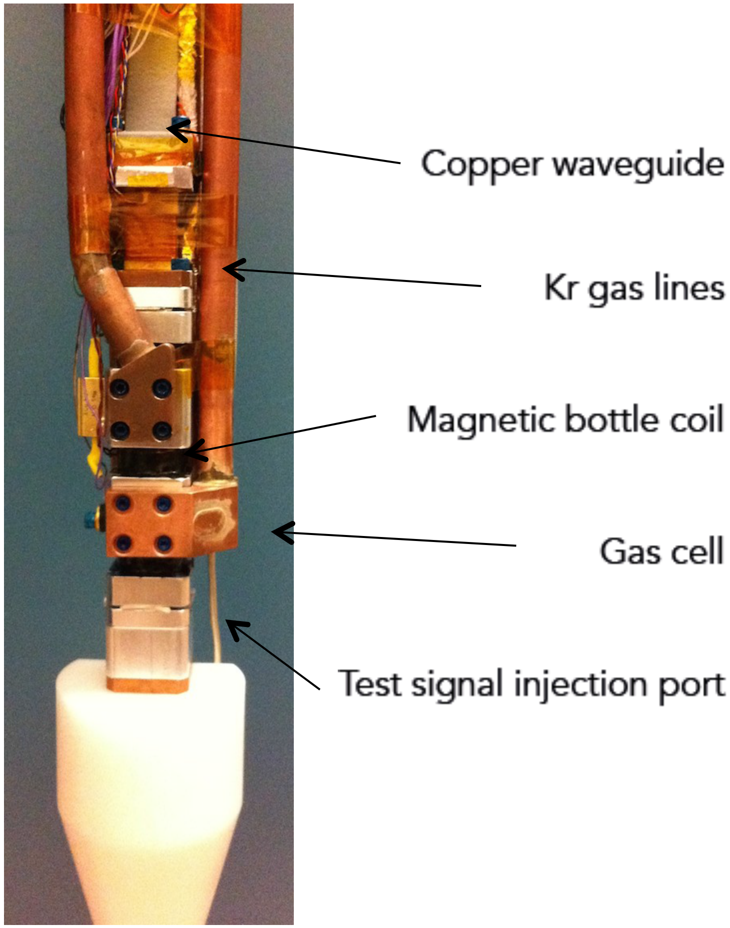
- Use cyclotron frequency to extract electron energy
- Non-destructive measurement of electron energy

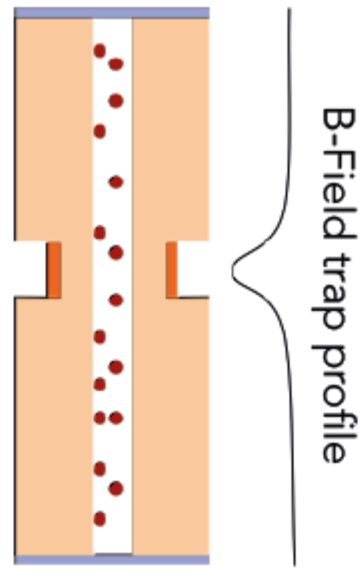
$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$



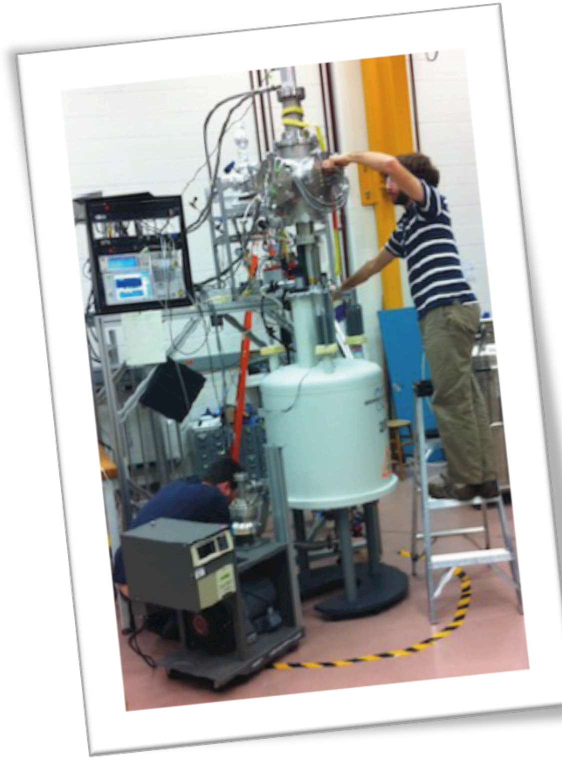
B. Monreal and Joe Formaggio, Phys. Rev D80:051301

PROJECT 8 - Setup

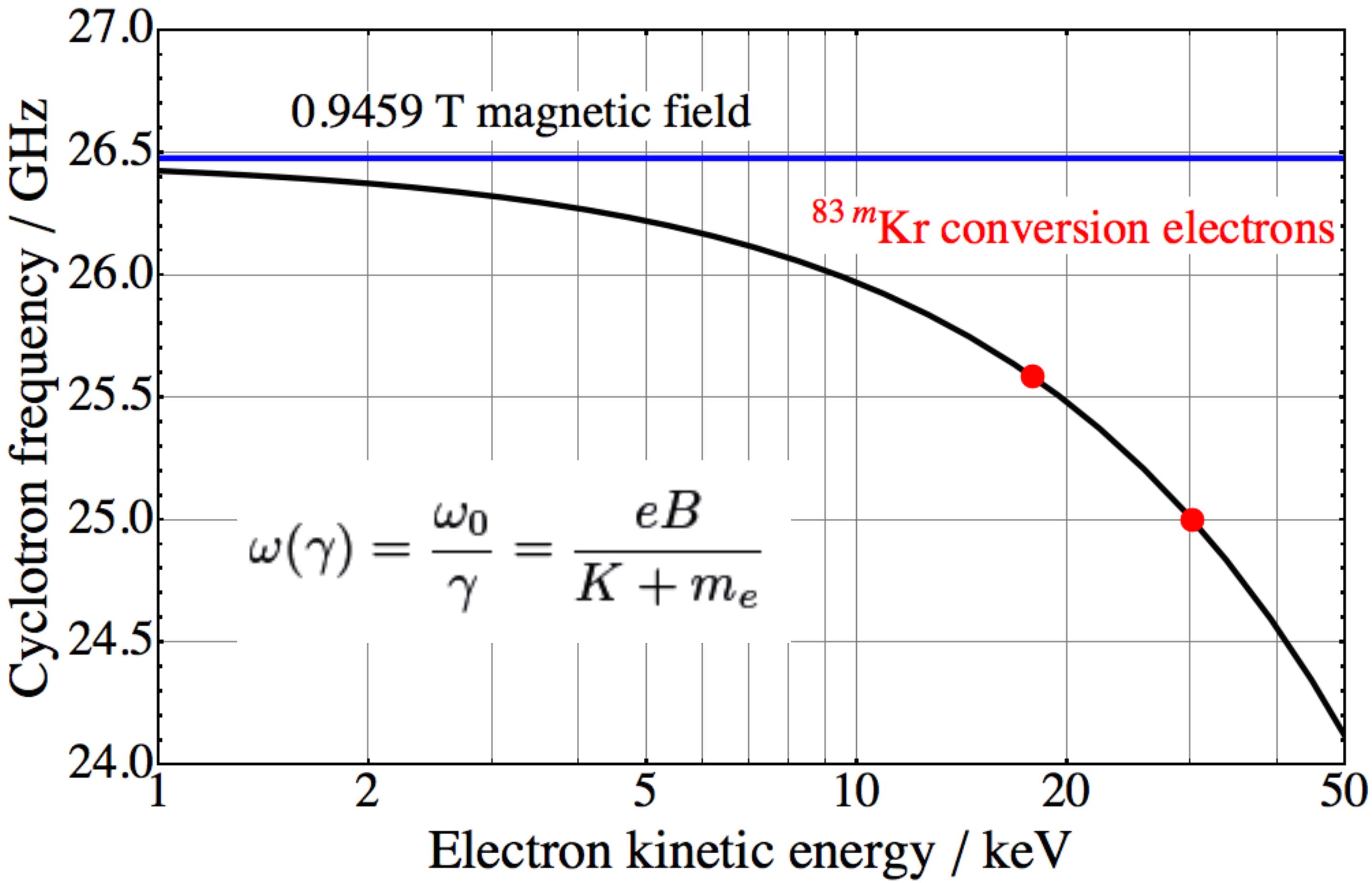




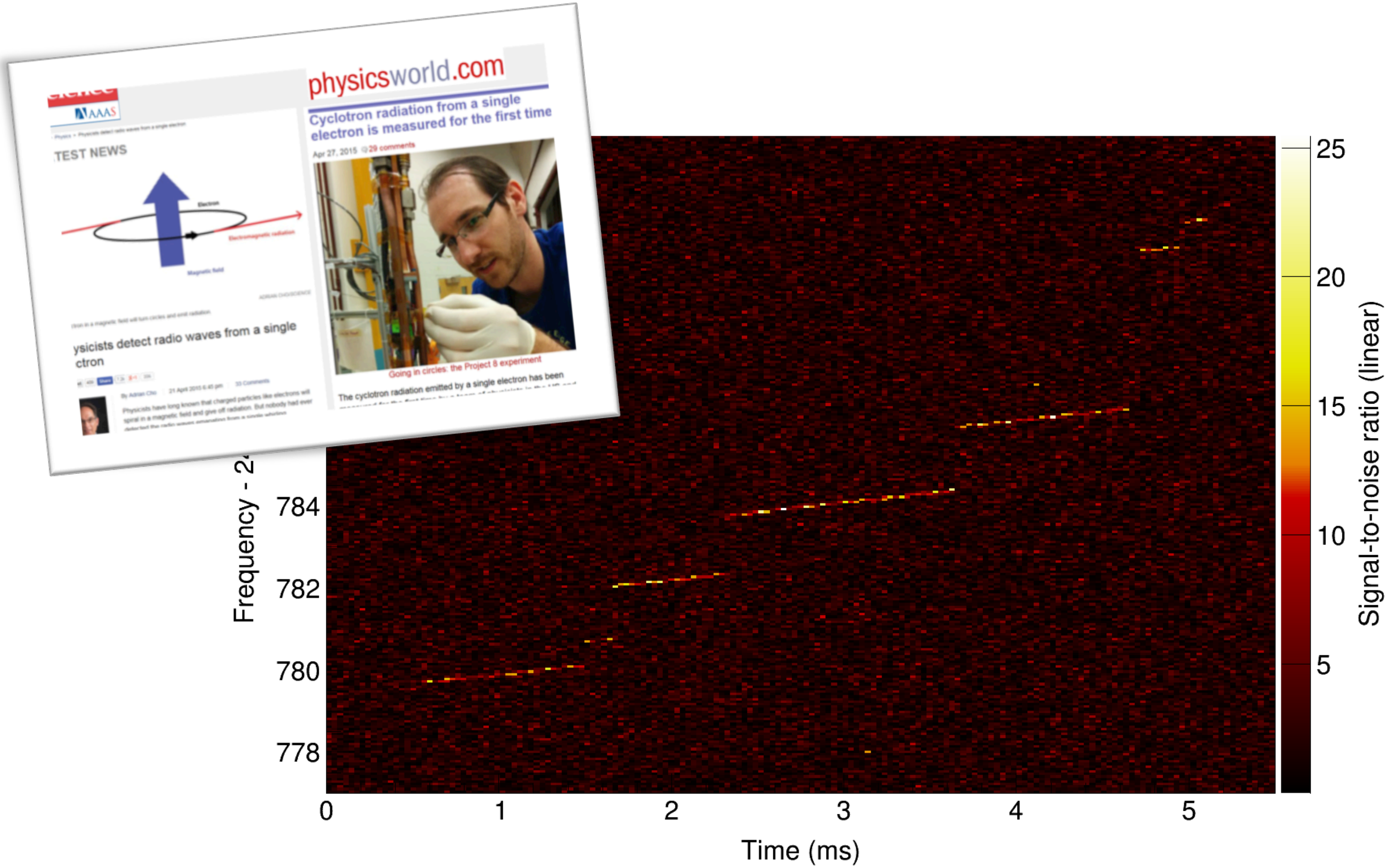
Waveguide
Cut-away



Test measurement with Krypton



First electron detection



D.M. Asner et al., Single electron detection and spectroscopy via relativistic cyclotron radiation,
Phys. Rev. Lett. 114, 162501 (2015)

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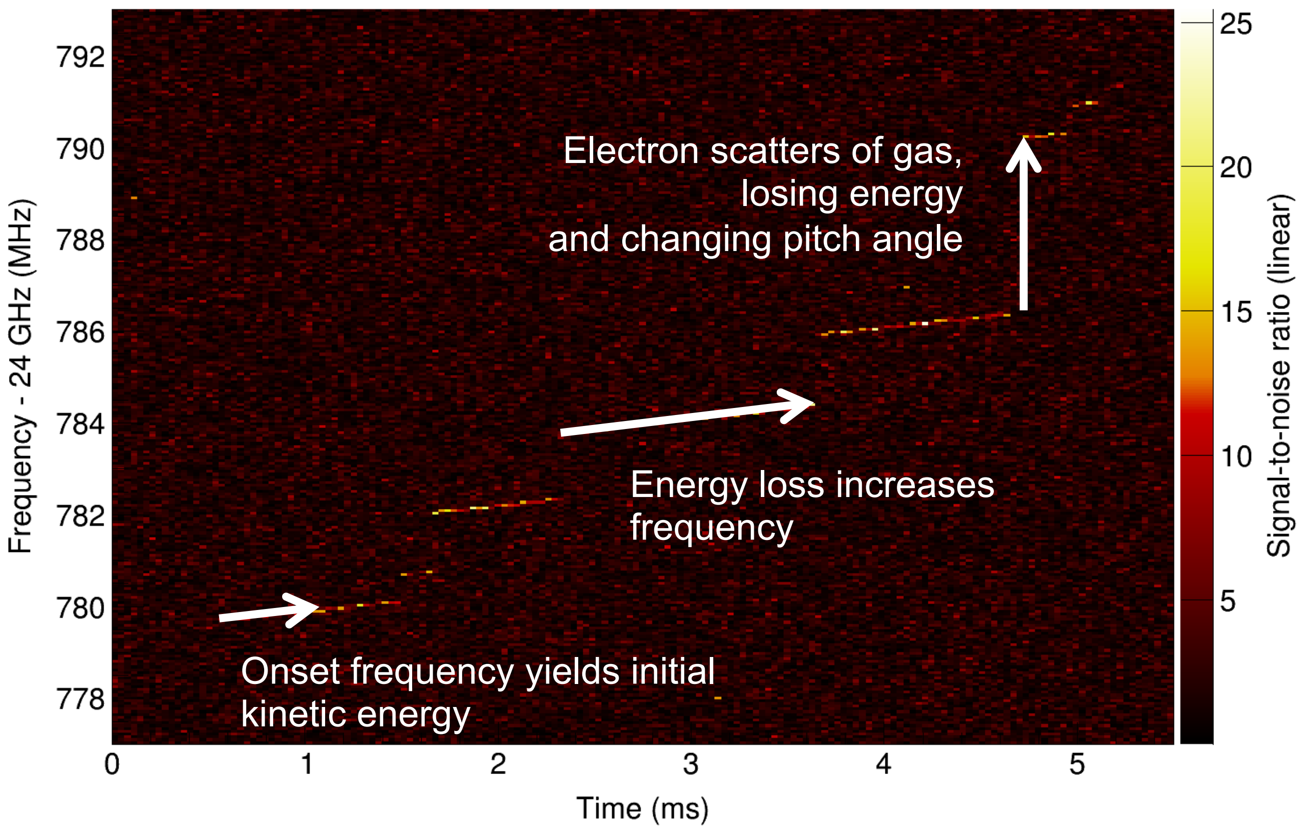
First electron detection



D.M. Asner et al., Single electron detection and spectroscopy via relativistic cyclotron radiation,
Phys. Rev. Lett. 114, 162501 (2015)

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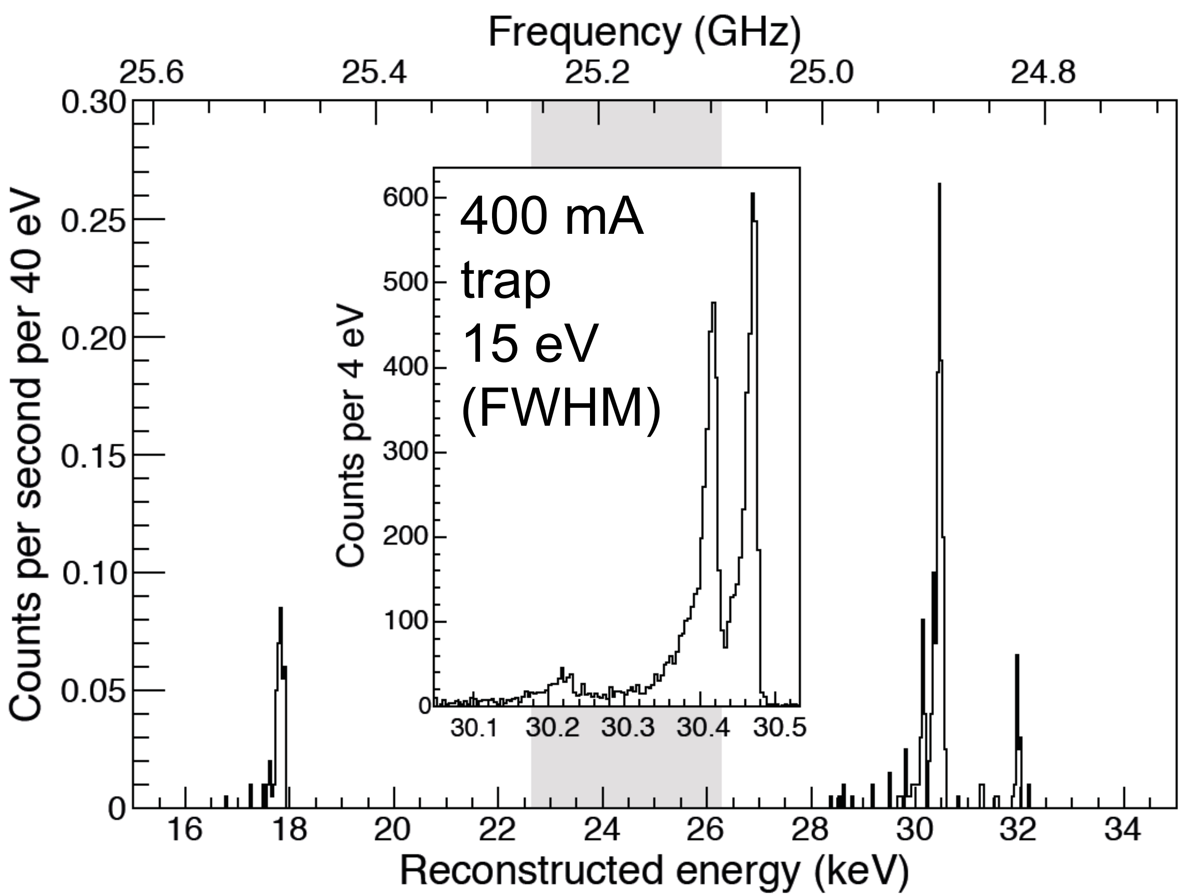
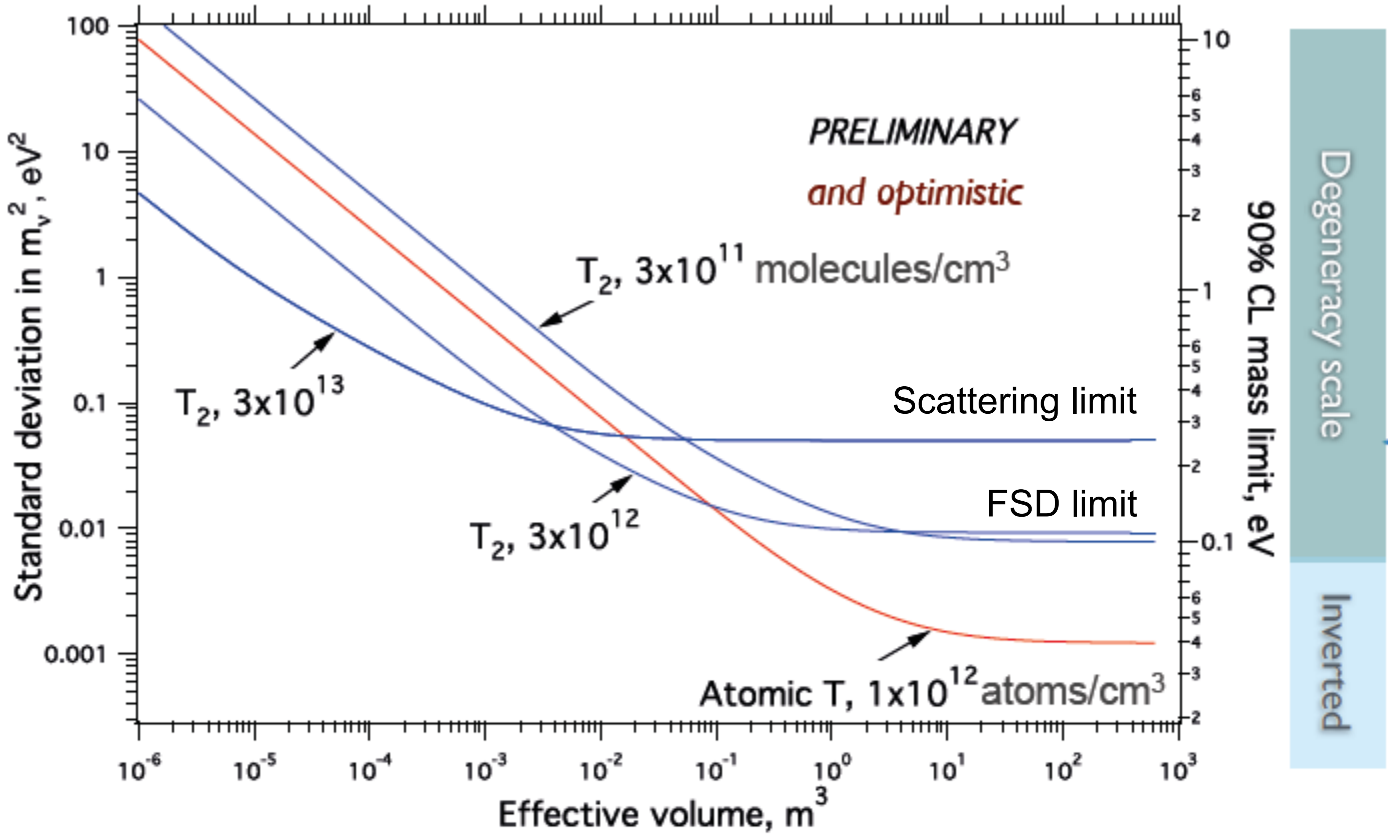
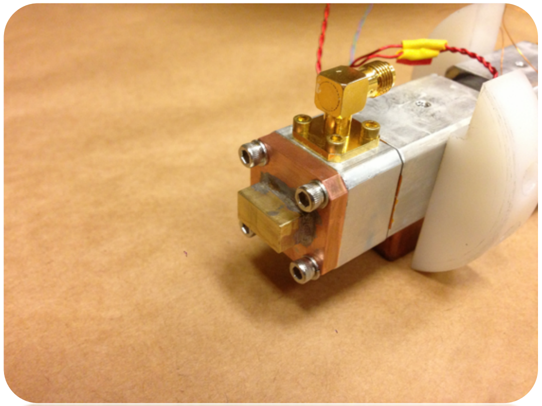


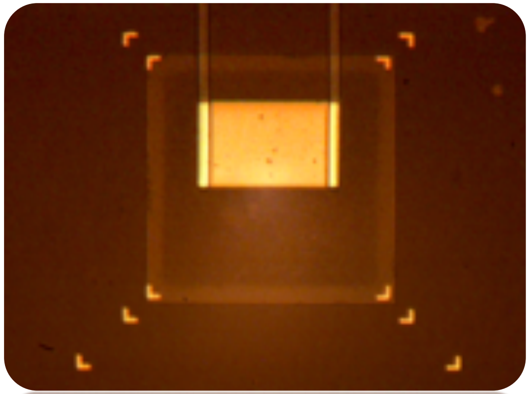
D.M. Asner et al., Single electron detection and spectroscopy via relativistic cyclotron radiation,
Phys. Rev. Lett. 114, 162501 (2015)

Project 8 Sensitivity



3 Experimental Efforts



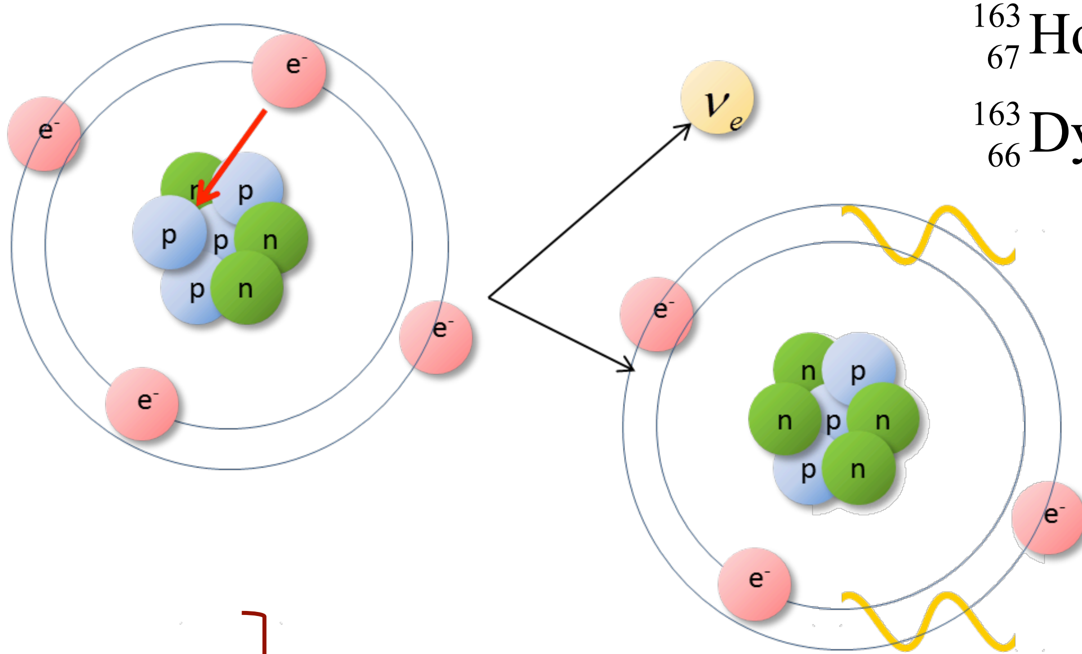


Drexlin, V. Hannen, S. M., C. Weinheimer, Adv. High Energy Physics 2013, Article ID 293986, (2013)

Electron Capture on Holmium

$$^{163}_{67}\mathrm{Ho} \rightarrow {}^{163}_{66}\mathrm{Dy}^* + \nu_e$$

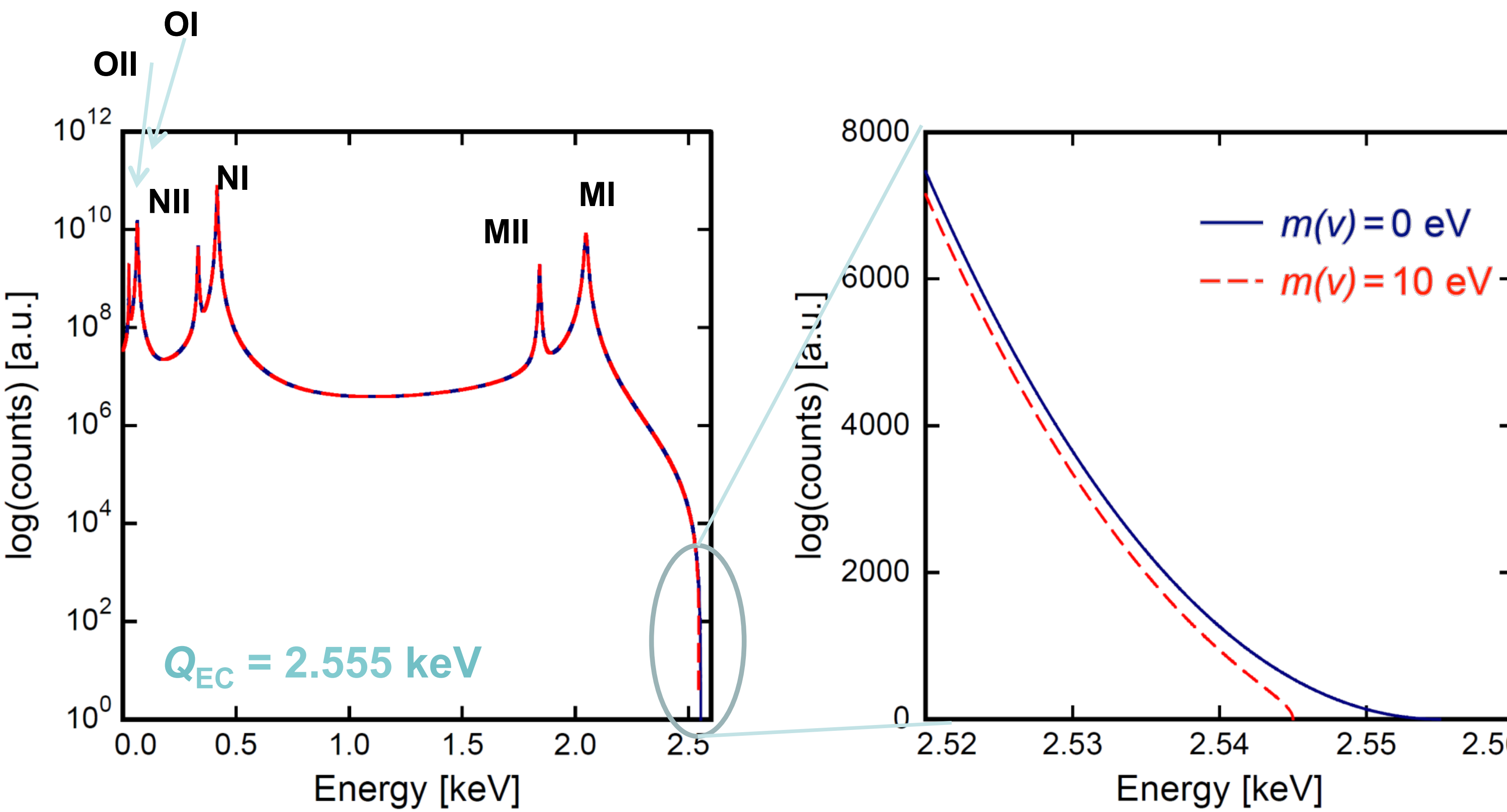
$$^{163}_{66}\mathrm{Dy}^* \rightarrow {}^{163}_{66}\mathrm{Dy} + E_{\mathrm{EC}}$$



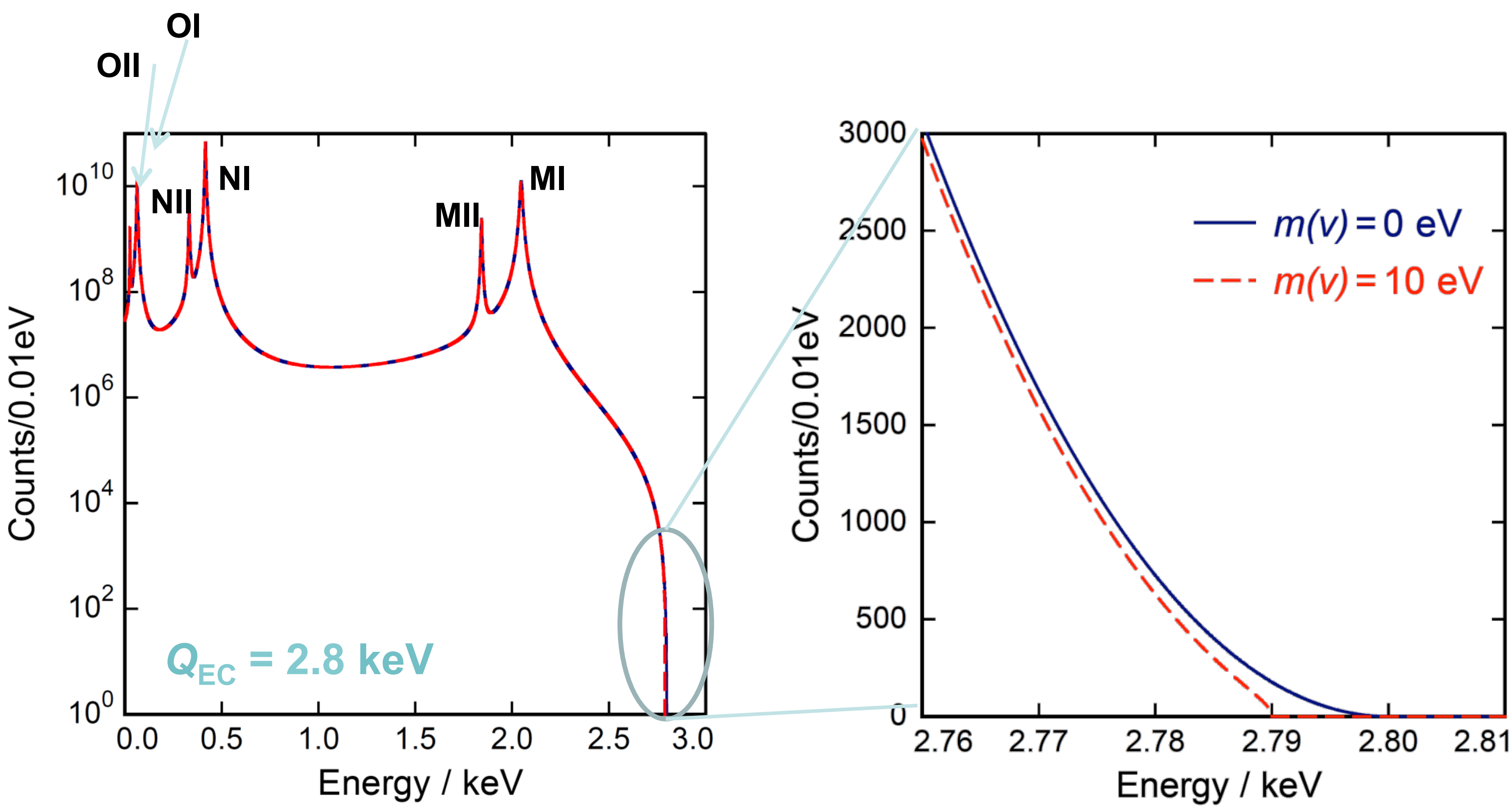
Atomic de-excitation:
- X-ray emission
- Auger electrons

Calorimetric measurement

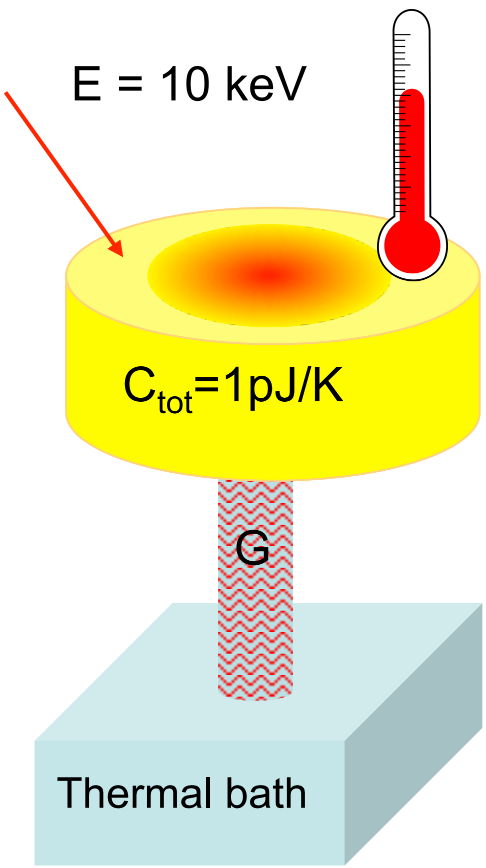
Holmium spectrum

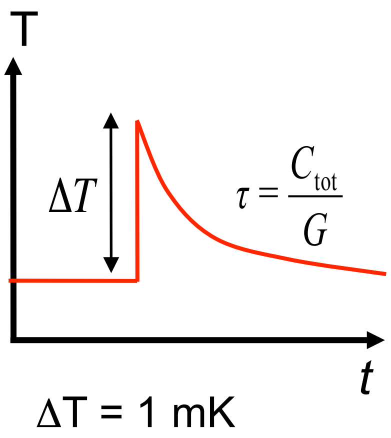


Holmium spectrum



Calorimetric measurement





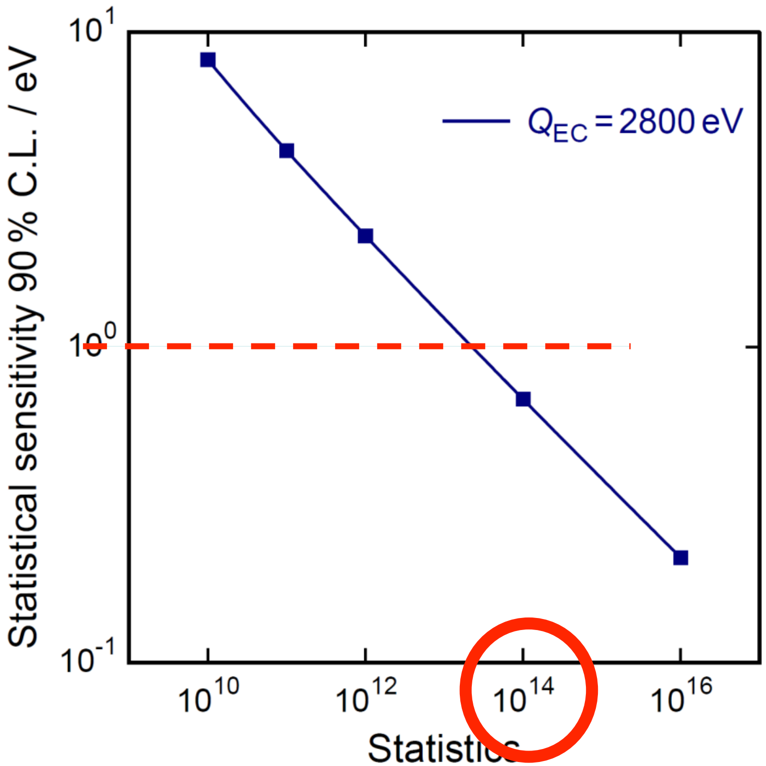
Advantages:

- Source = detector
- All energy is detected

Challenges:

- $\Delta E_{FWHM} < 10$ eV
- $\tau_{risetime} < 1$ μs to avoid background due to pile-up
- Sufficient isotope production
- Scalability

Calorimetric measurement



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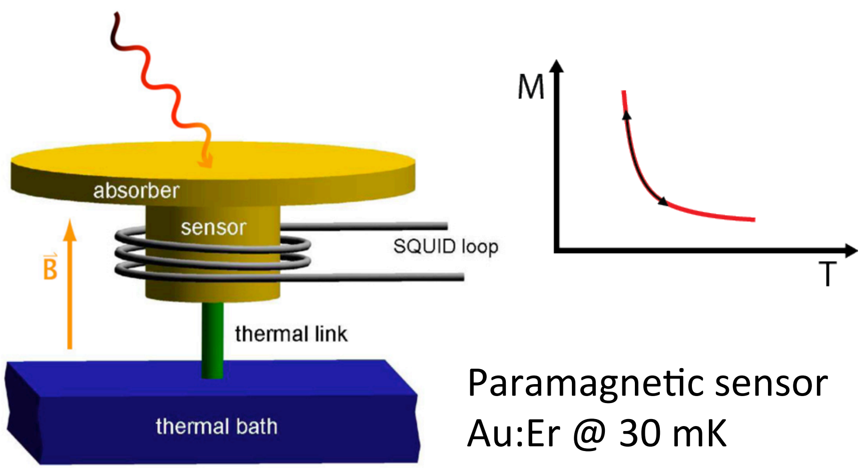
- $\tau_{risetime} < 1$ μs to avoid background due to pile-up
- Sufficient isotope production
- Scalability

10^{14} decays in 1 year
100 per second per detector → 10^5 detectors

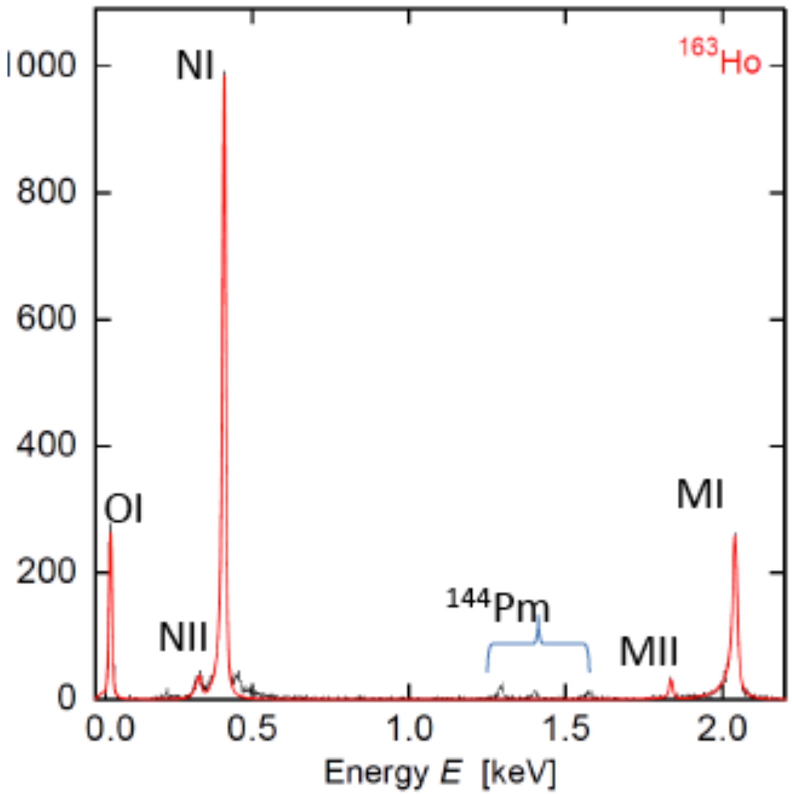
The ECHo Experiment

Heidelberg (Univ., MPI-K),
U Mainz, U Tübingen, TU Dresden
U Bratislava, INR Debrecen,
ITEP Moscow, PNPI St Petersburg,
IIT Roorkee, Saha Inst. Kolkata

- Metallic magnetic calorimeters (MMC)
- Fast rise times (τ = 130 ns), good energy resolutions (7.6 eV @ 6keV) demonstrated



Paramagnetic sensor
Au:Er @ 30 mK



Single Beta Decay

How to measure the neutrino mass directly?

What is actually measured?

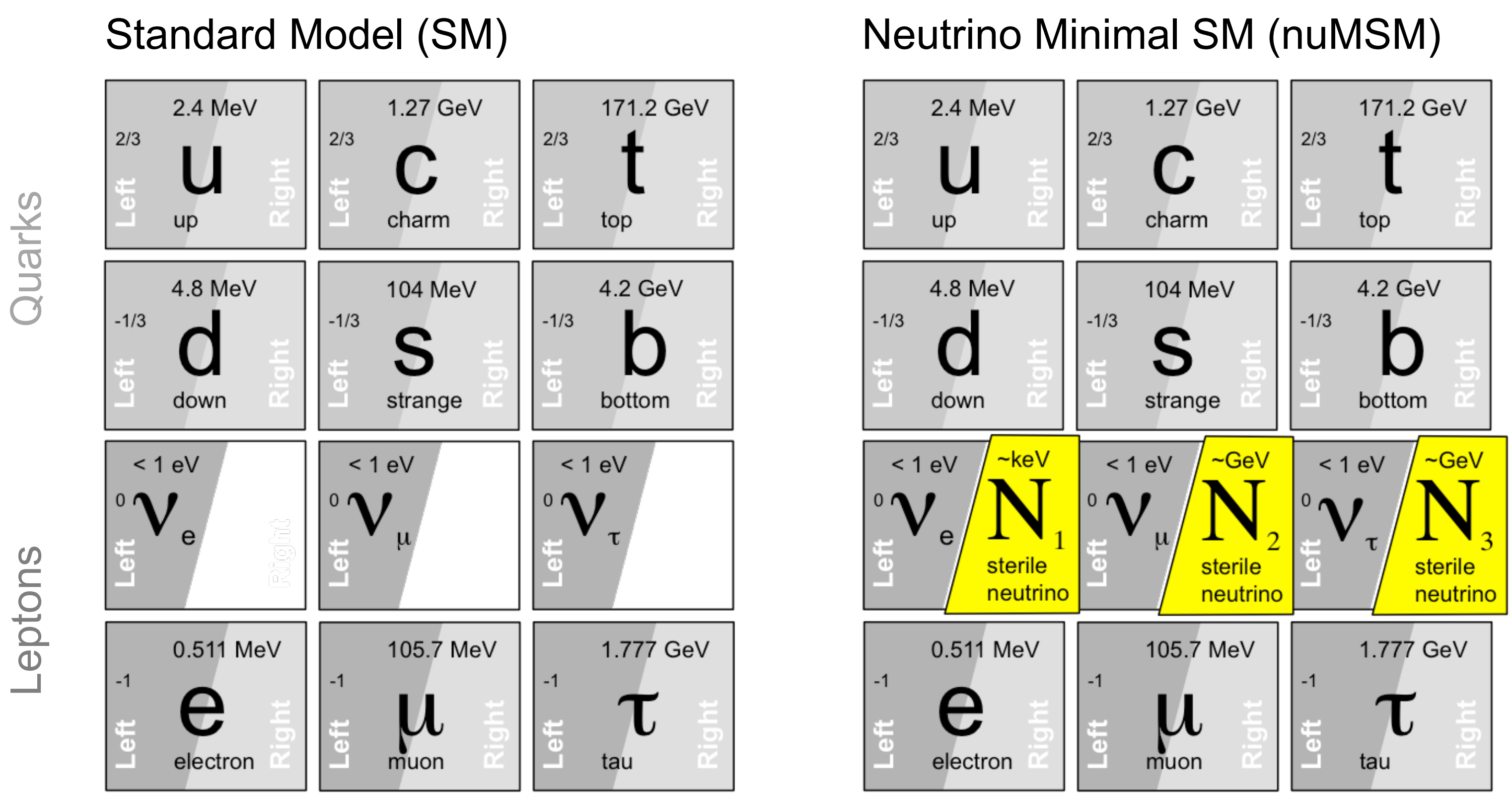
How does it compare to $0\nu\beta\beta$?

Where do we stand experimentally?

How to realize an experiment?

What else can we do with single beta decay?

Sterile Neutrinos



L. Canetti, M. Drewes, and M. Shaposhnikov, PRL **110** 061801 (2013)

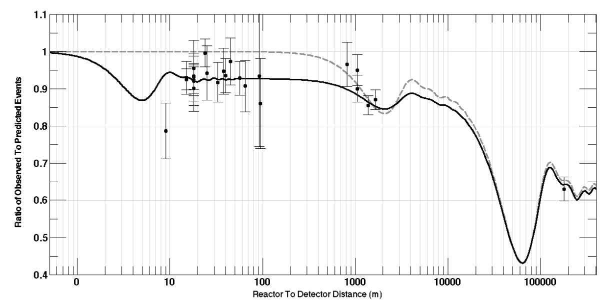
Sterile Neutrinos

Heavy sterile neutrinos (~GeV)

- Lightness of neutrinos via See-saw mechanism

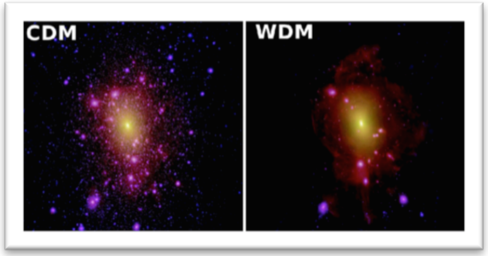
Light sterile neutrinos (~1 eV)

- Reactor anomaly, Gallium anomaly, Short baseline accelerator results



KeV-scale sterile neutrinos (~ 1- 50 keV)

- Warm and cold dark matter candidate



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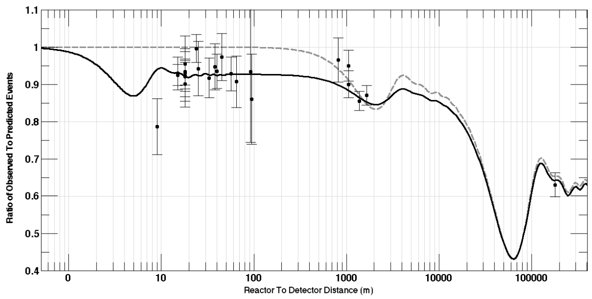

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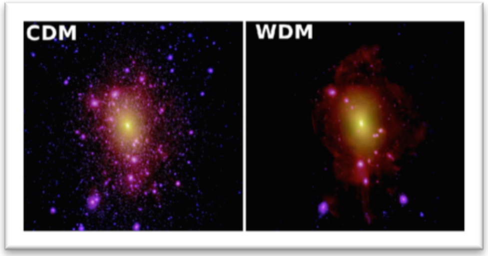
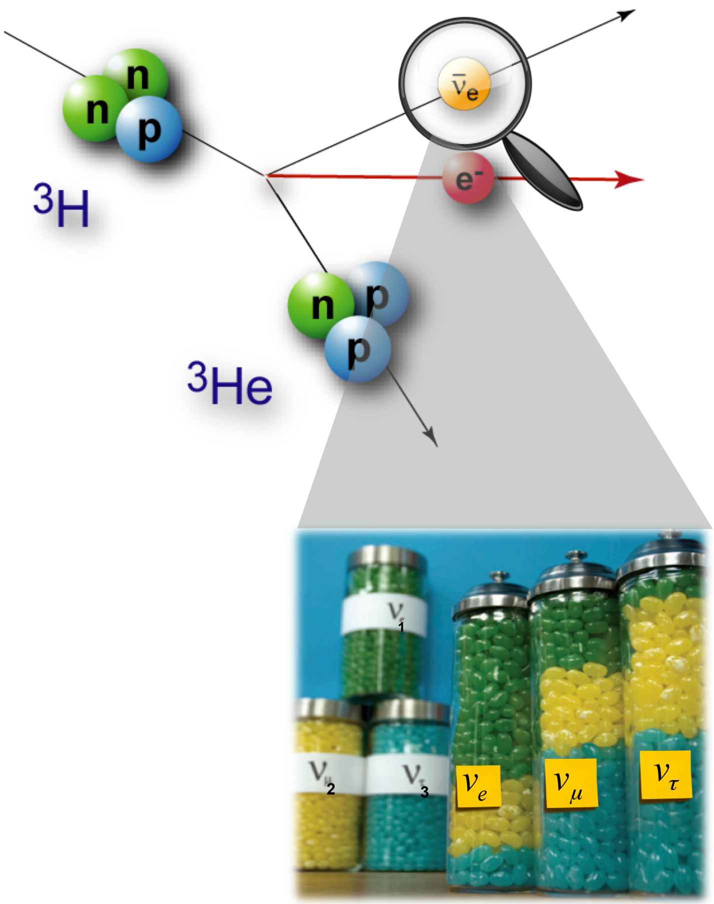
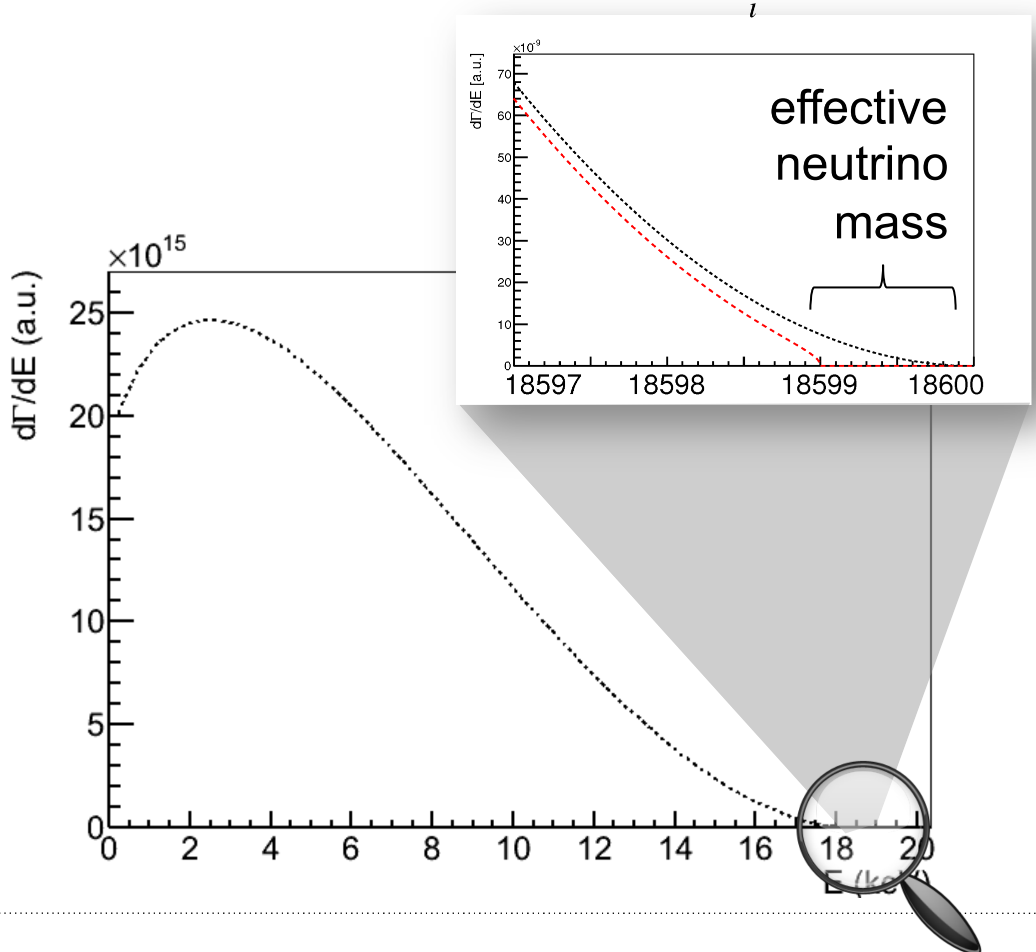


→ Accessible in tritium beta decay

Imprint of sterile ν's on ß-spectrum

$$m_\beta^2 = \sum_i |U_{ei}|^2 m_{\nu i}^2$$





Imprint of sterile ν‘s on ß-spectrum

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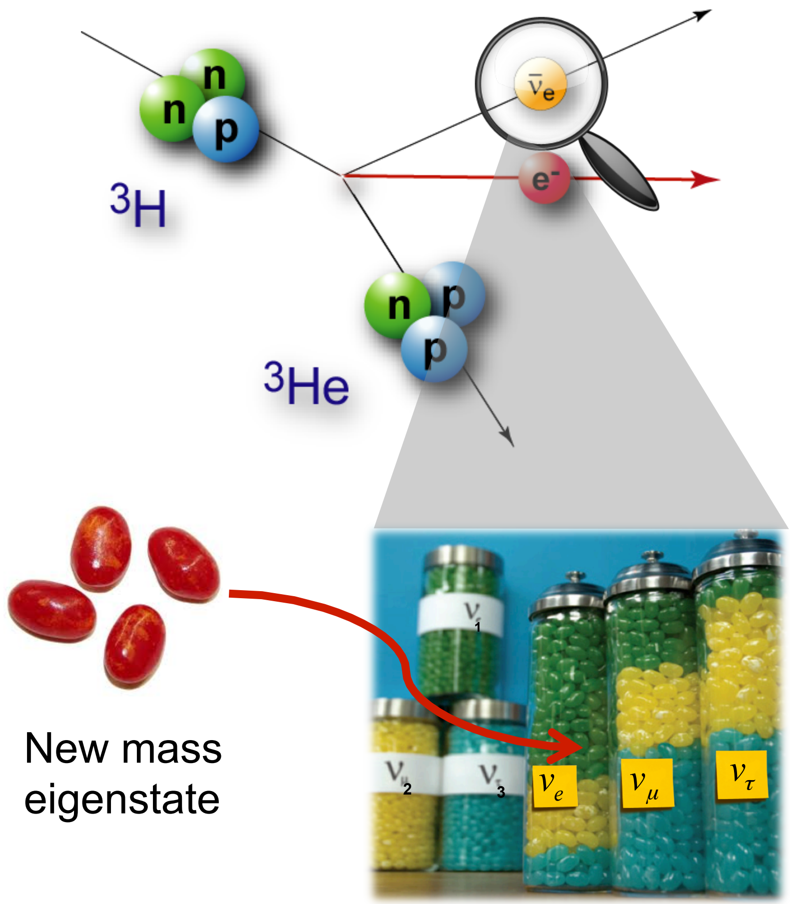
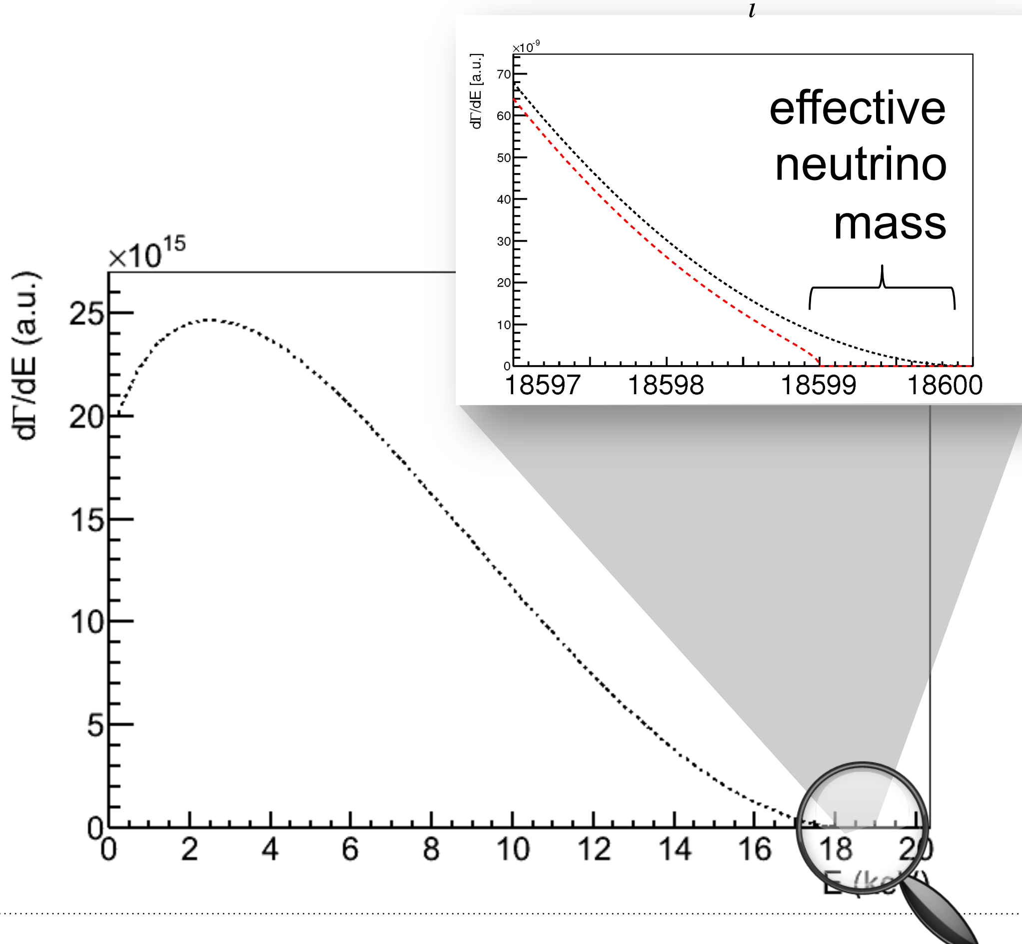
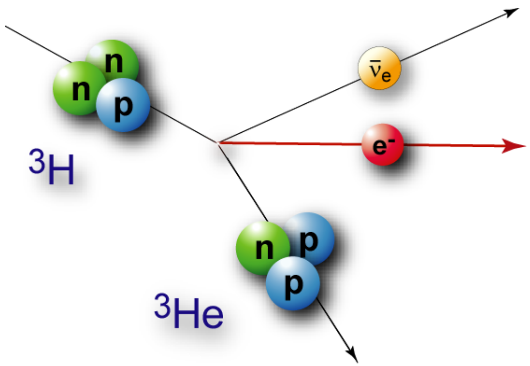
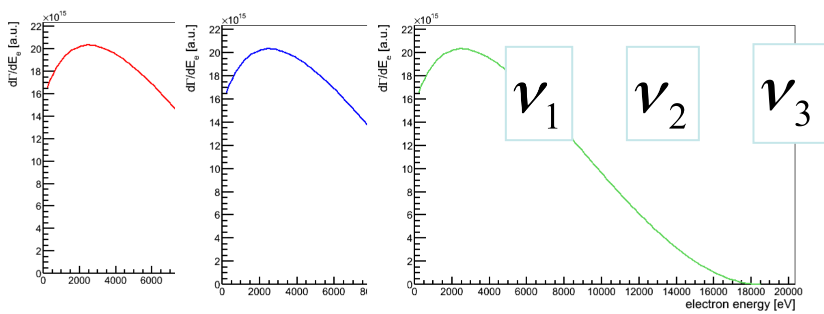




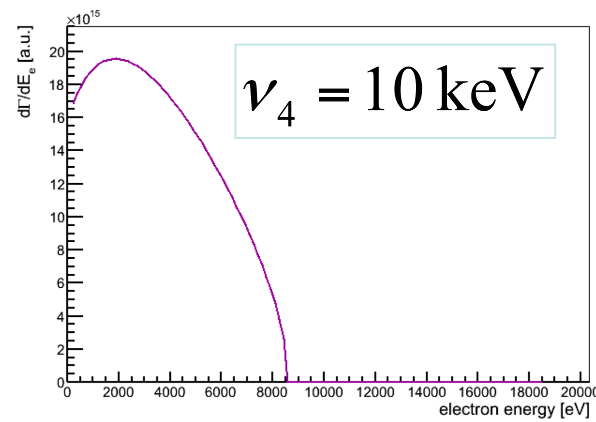
Imprint of sterile ν's on ß-spectrum



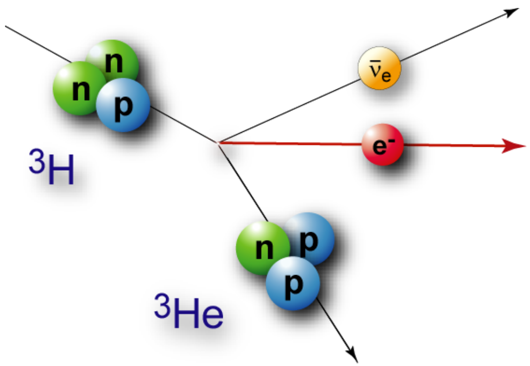
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \boxed{U_{e4}} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & 0 \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & 0 \\ 0 & 0 & 0 & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \boxed{\nu_4} \end{pmatrix}$$



$+ \ |U_{es}|^2$

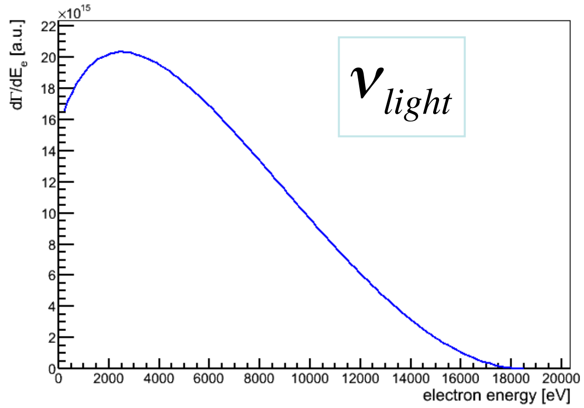


Imprint of sterile ν's on ß-spectrum

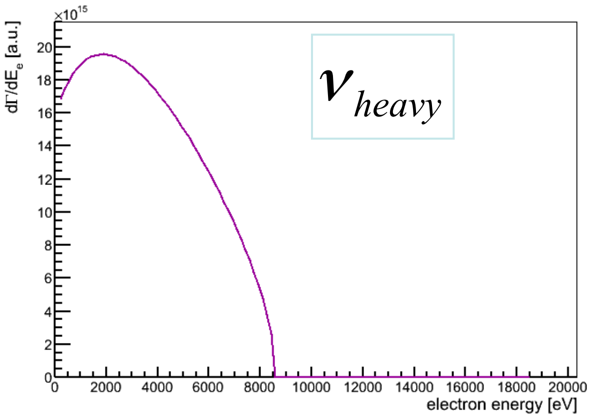


$$\begin{pmatrix} \nu_e \\ \nu_s \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_{light} \\ \nu_{heavy} \end{pmatrix}$$

$\cos^2(\theta)$

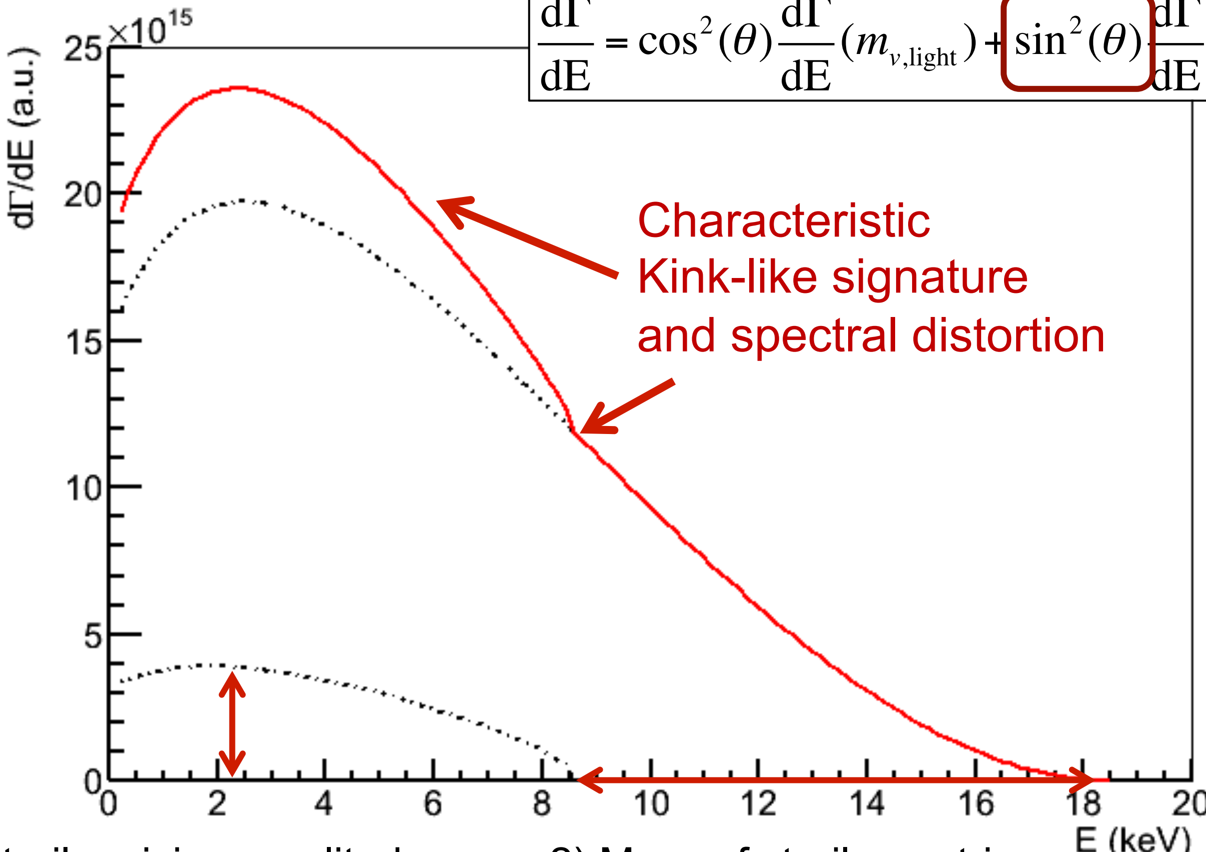


$+ \quad \sin^2(\theta)$



Imprint of sterile ν's on ß-spectrum

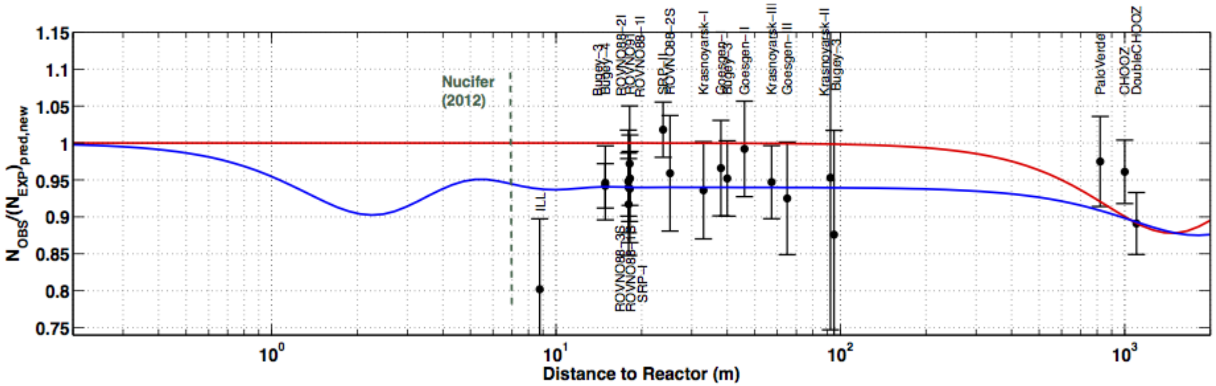
$$\frac{d\Gamma}{dE} = \cos^2(\theta)\frac{d\Gamma}{dE}(m_{\nu,\mathrm{light}}) + \boxed{\sin^2(\theta)}\frac{d\Gamma}{dE}\boxed{(m_{\nu,\mathrm{heavy}})}$$



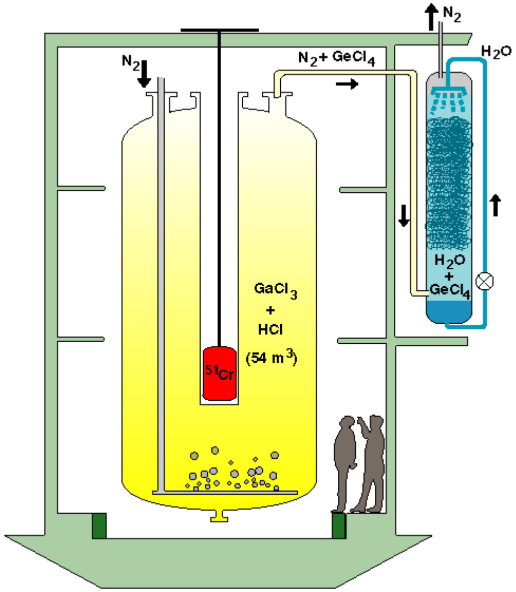
1) Active-to-sterile mixing amplitude

2) Mass of sterile neutrino

Why eV-scale sterile neutrinos?



Reactor anomaly:
6% deficit of measured events compared to prediction



Galium anomaly:
~2.7σ deficit of measured events compared to prediction

G. Mention et al., Phys. Rev. D 83 (2011) 073006
P. Anselmann et al., Phys. Lett. B 357 (1995) 237

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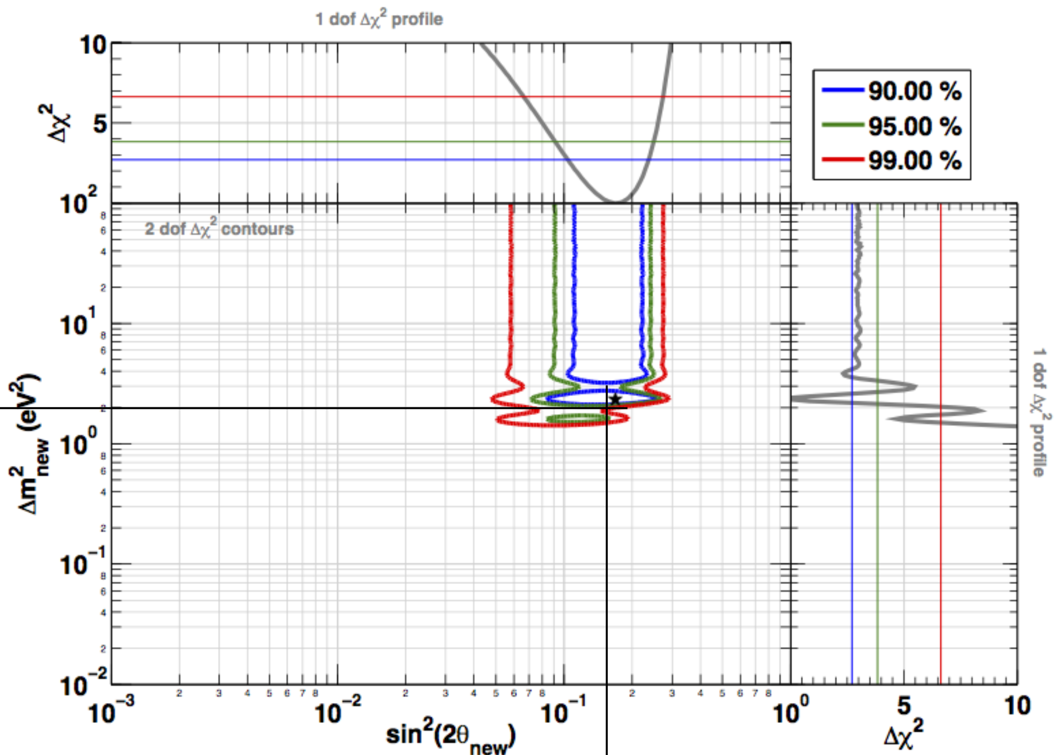
Reactor + Gallium anomaly

...this is where KATRIN measures anyway

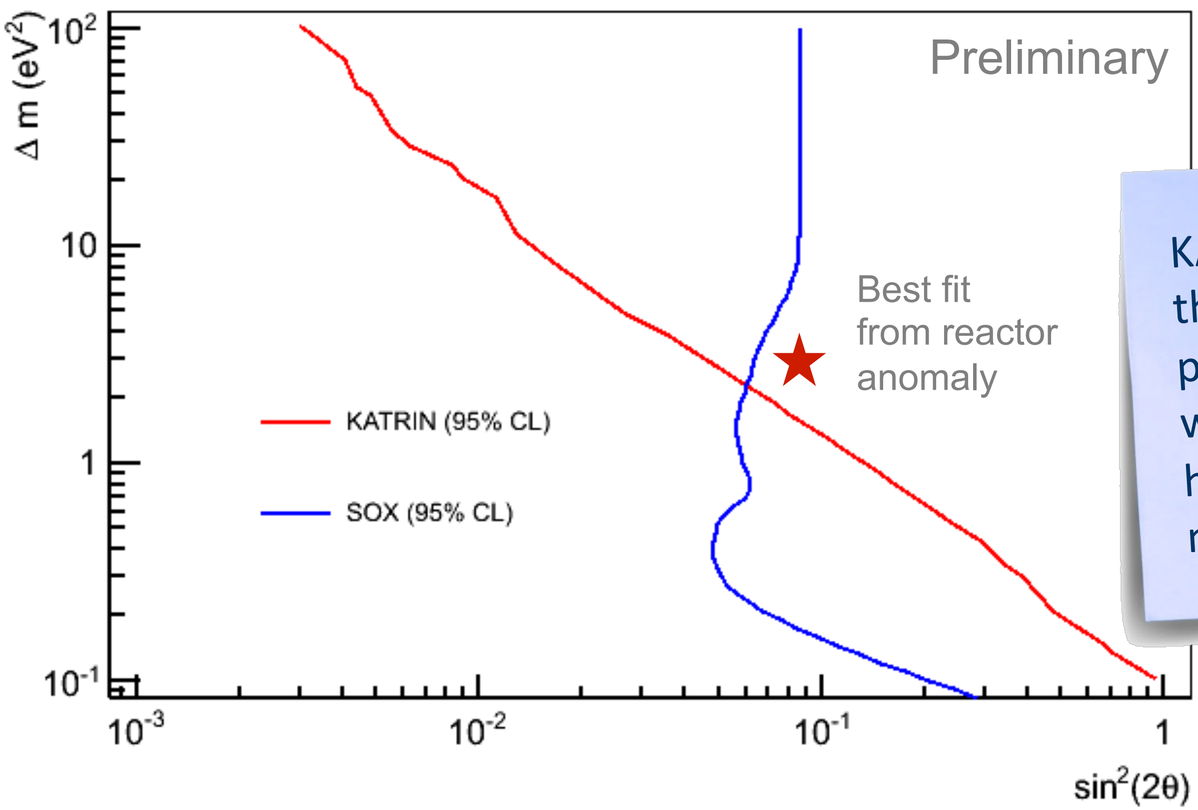


$\Delta m^2 = (2.3 \pm 0.1)\ \mathrm{eV}^2$

$\sin^2(2\theta) = 0.17 \pm 0.04$

Reactor + Gallium combined analysis
“White Paper”, arXiv:1204.5379

eV-Scale Sterile Neutrinos



KATRIN probes the favored parameter space, without any hardware modification

J. A. Formaggio, J. Barret, PLB 706 (2011) 68
A. Esmaili, O.L.G. Peres, Phys. Rev. D 85, 117301
A. Sejersen Riis, S. Hannestad, JCAP02 (2011) 011

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Why keV-Scale Sterile Neutrinos

Sterile Neutrinos in the keV mass range are a candidate for both Warm and Cold Dark Matter

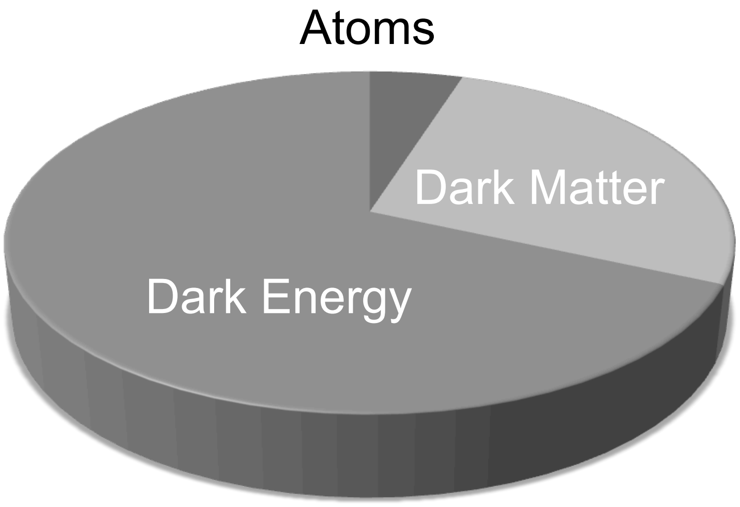
In agreement with cosmological observations from small to large scales

X. Shi, G. M. Fuller 1999 *PRL* **82**

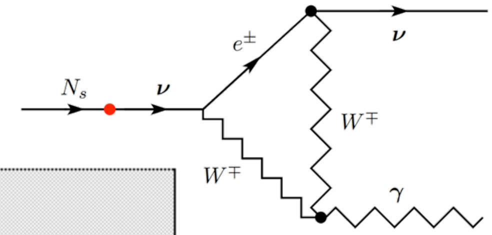
Recent indirect hint from satellite experiments ?

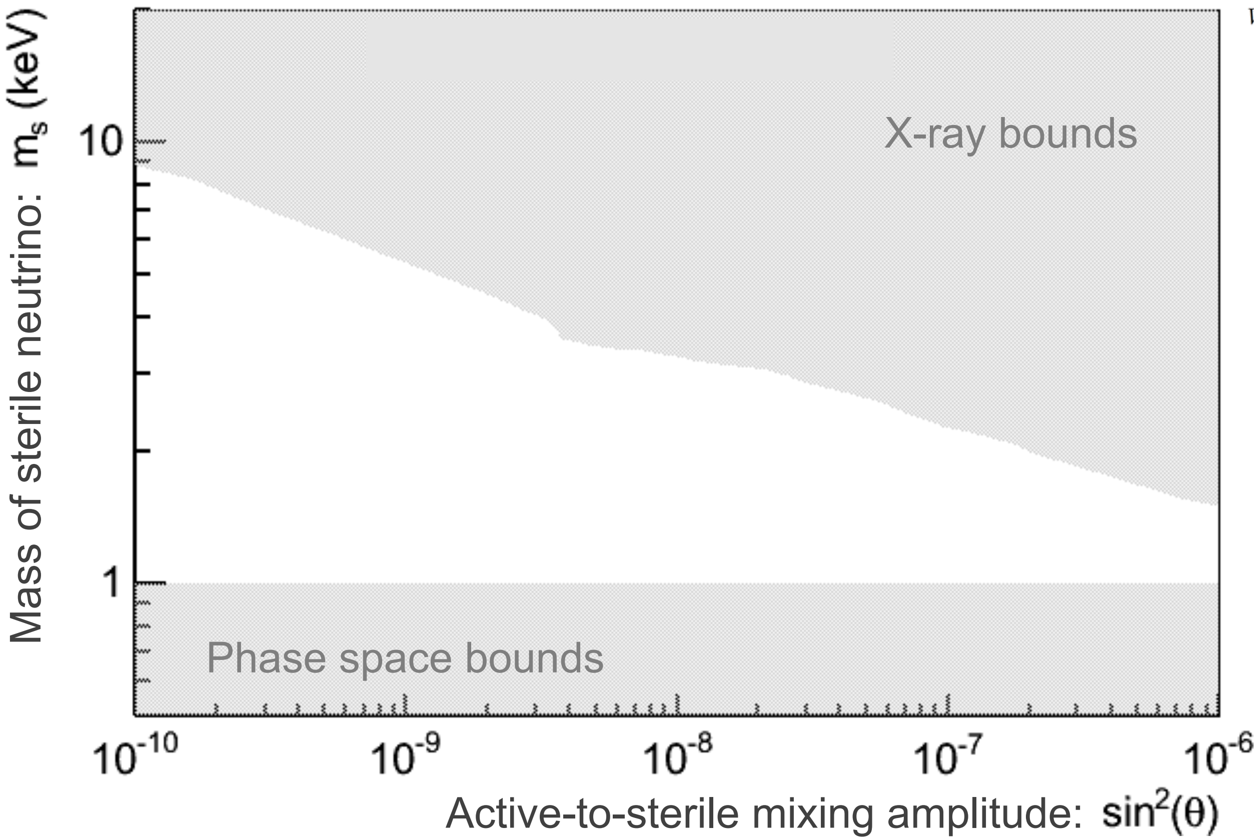
E. Bulbul *et al.* 2014 *ApJ* **789**

Boyarsky *et al.* 2014 *PRL* **113**



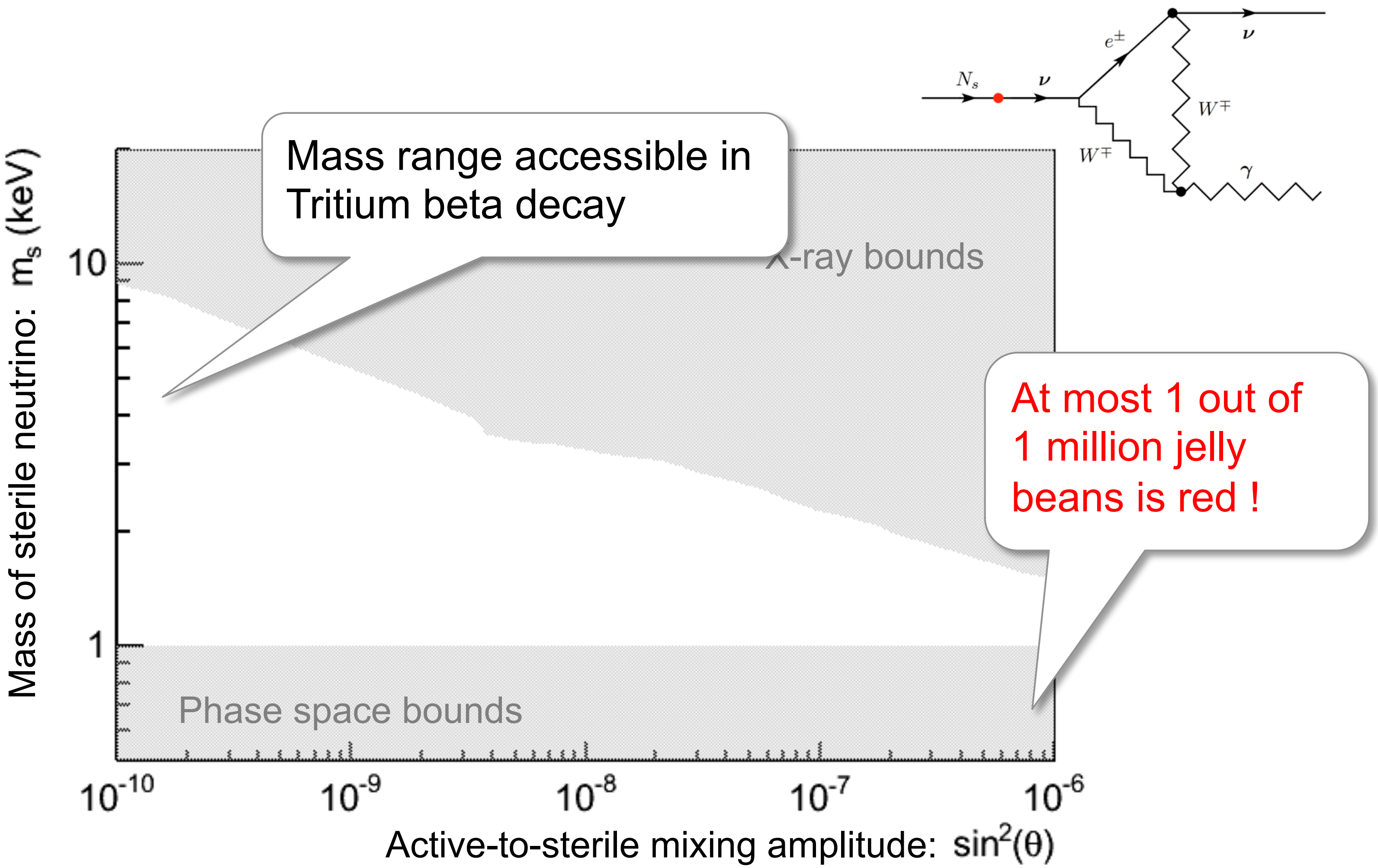
Cosmological constraints





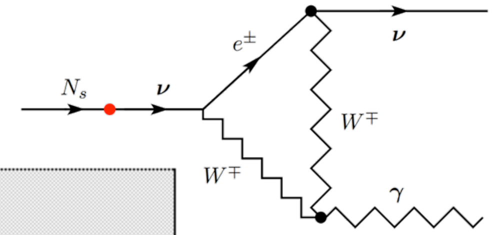
O. Ruchayskiy, A. Ivashko
JHEP **1206** (2012) 100

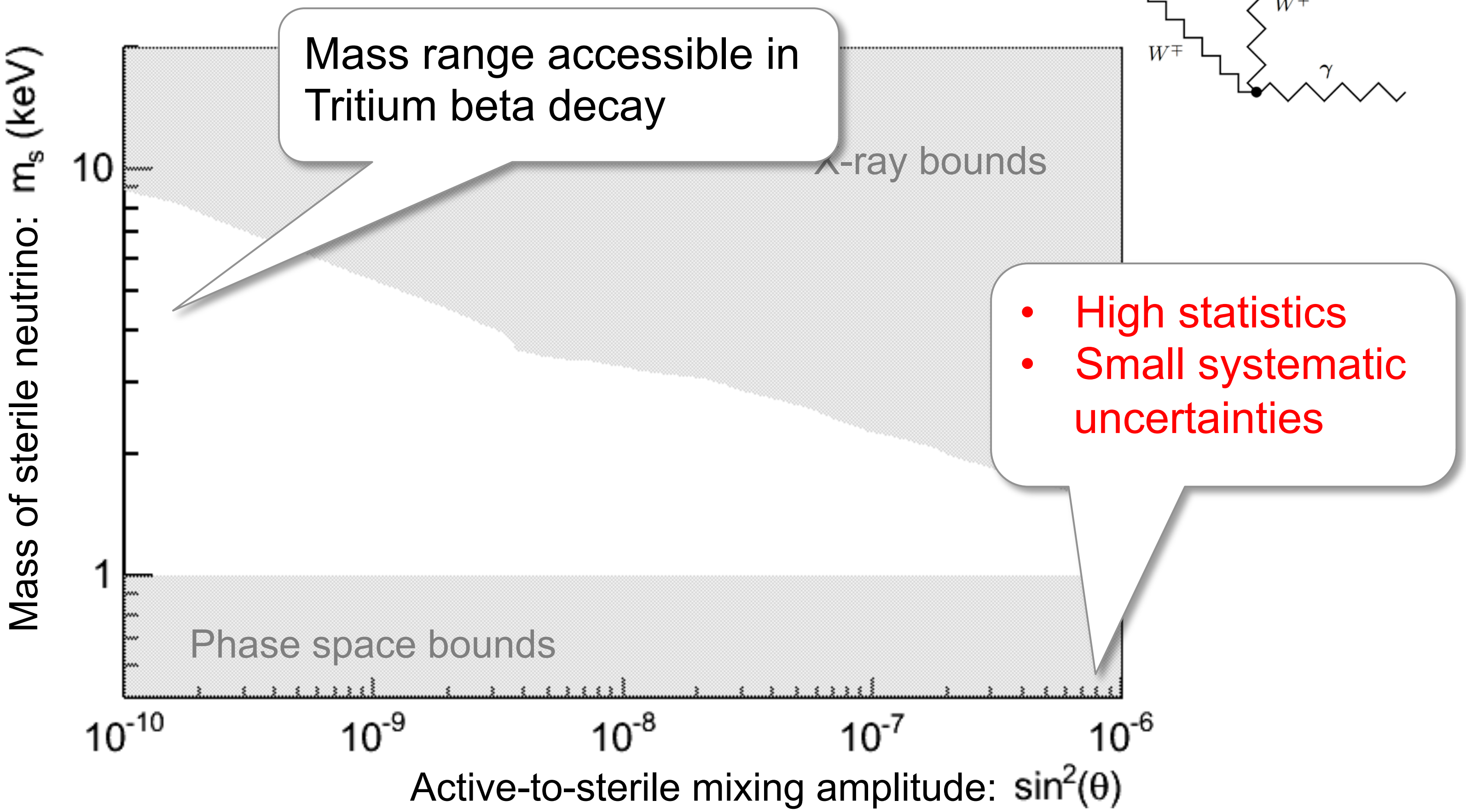
Cosmological constraints



O. Ruchayskiy, A. Ivashko
JHEP **1206** (2012) 100

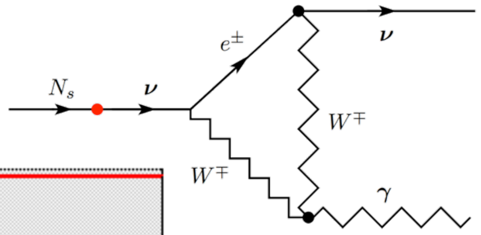
The challenge of sterile ν search

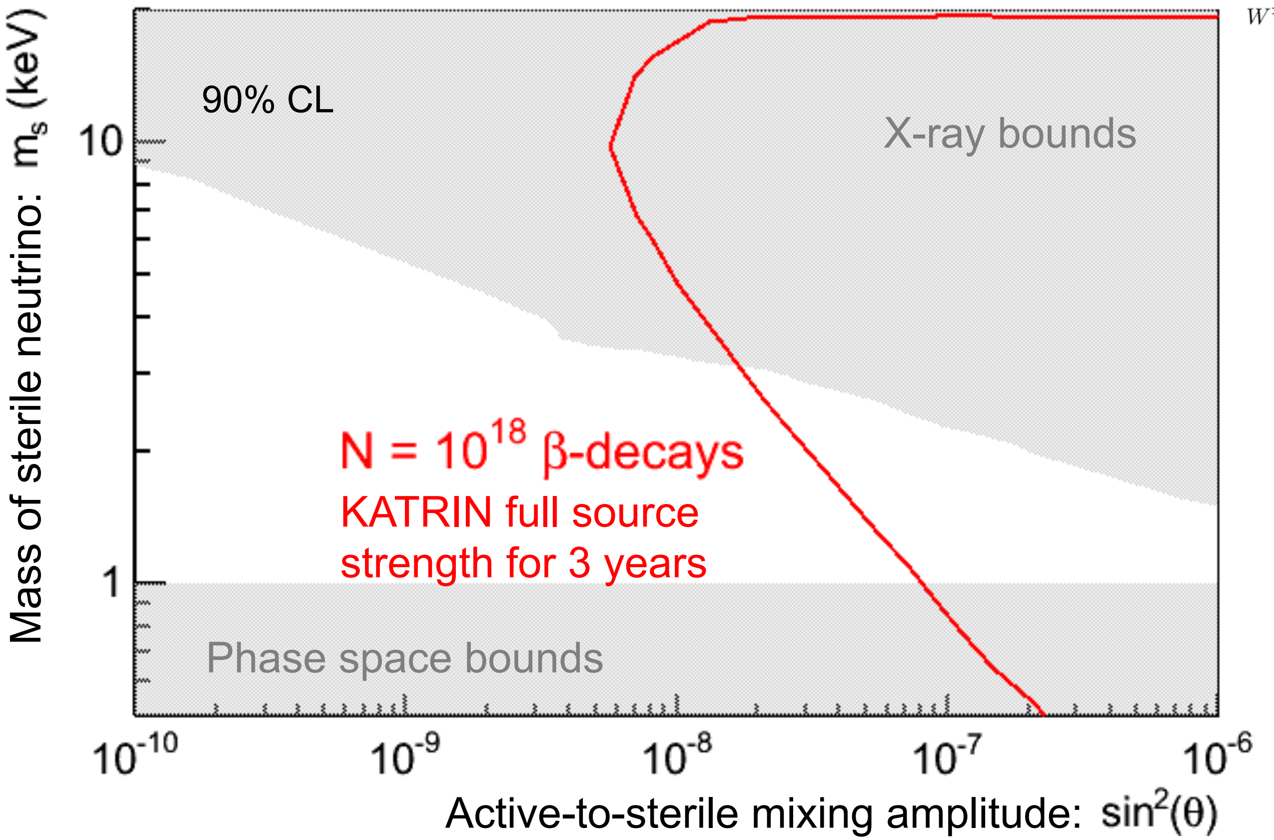




O. Ruchayskiy, A. Ivashko
JHEP **1206** (2012) 100

Statistical sensitivity

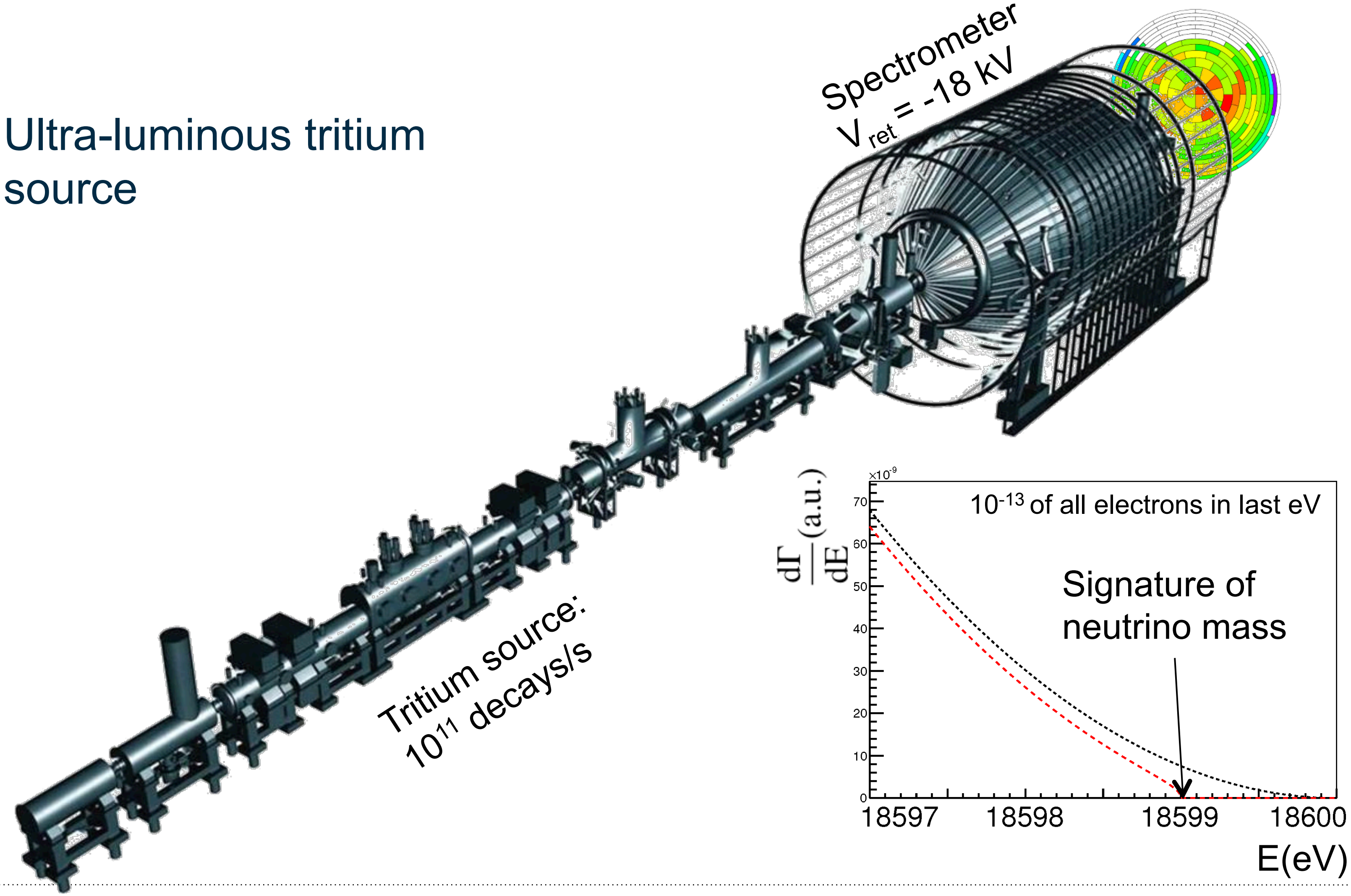




10 mcps

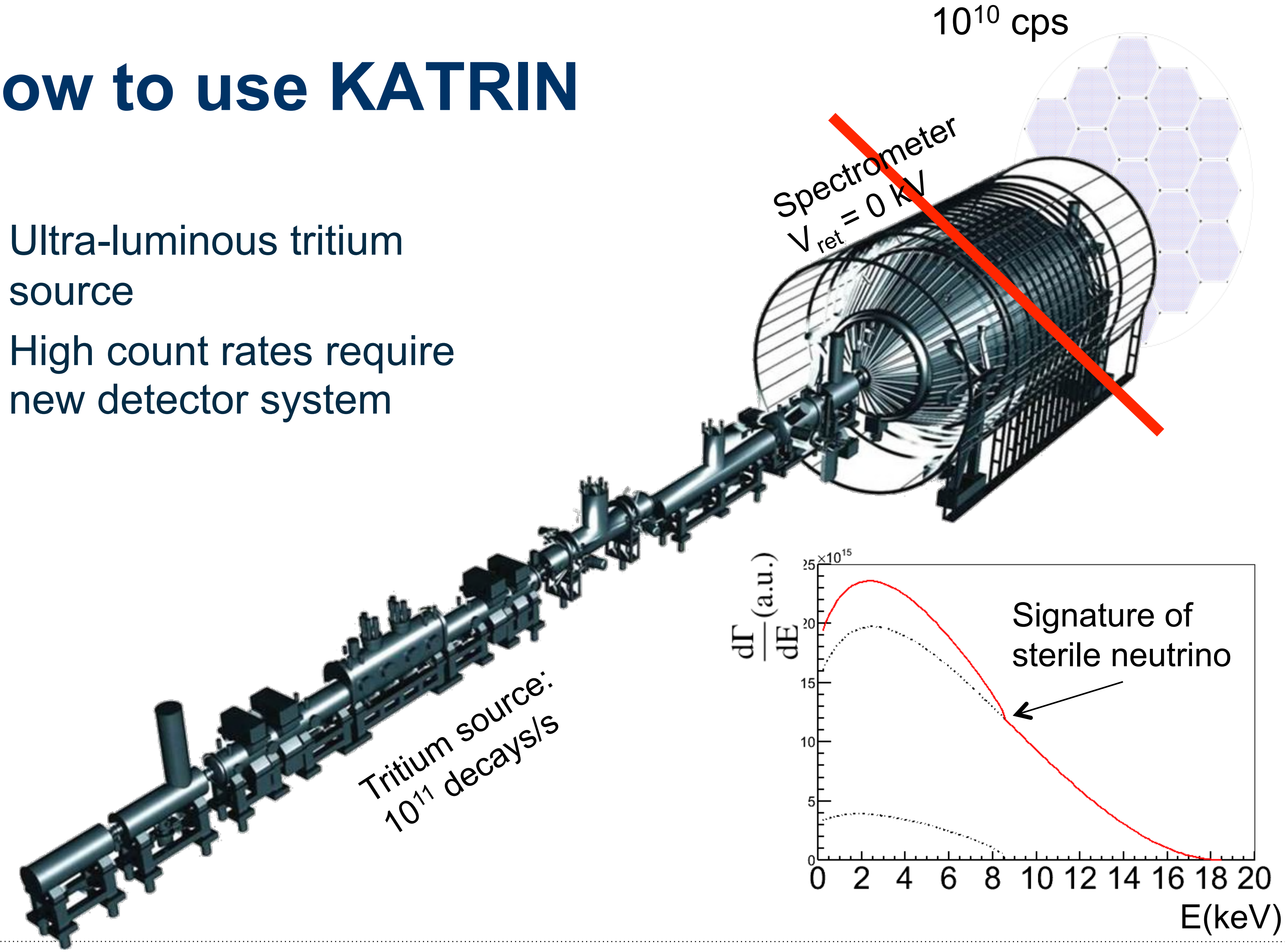
How to use KATRIN

- Ultra-luminous tritium source



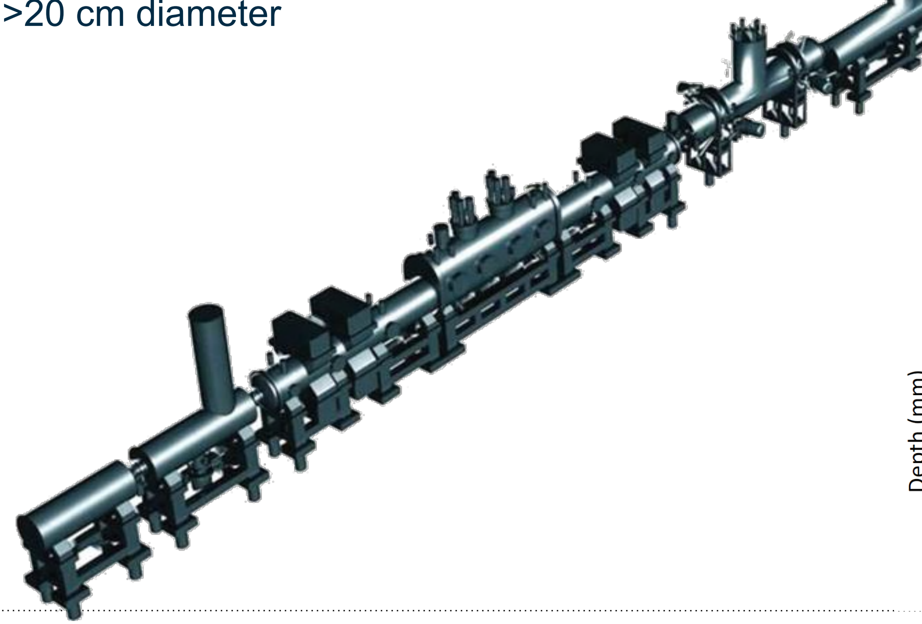
How to use KATRIN

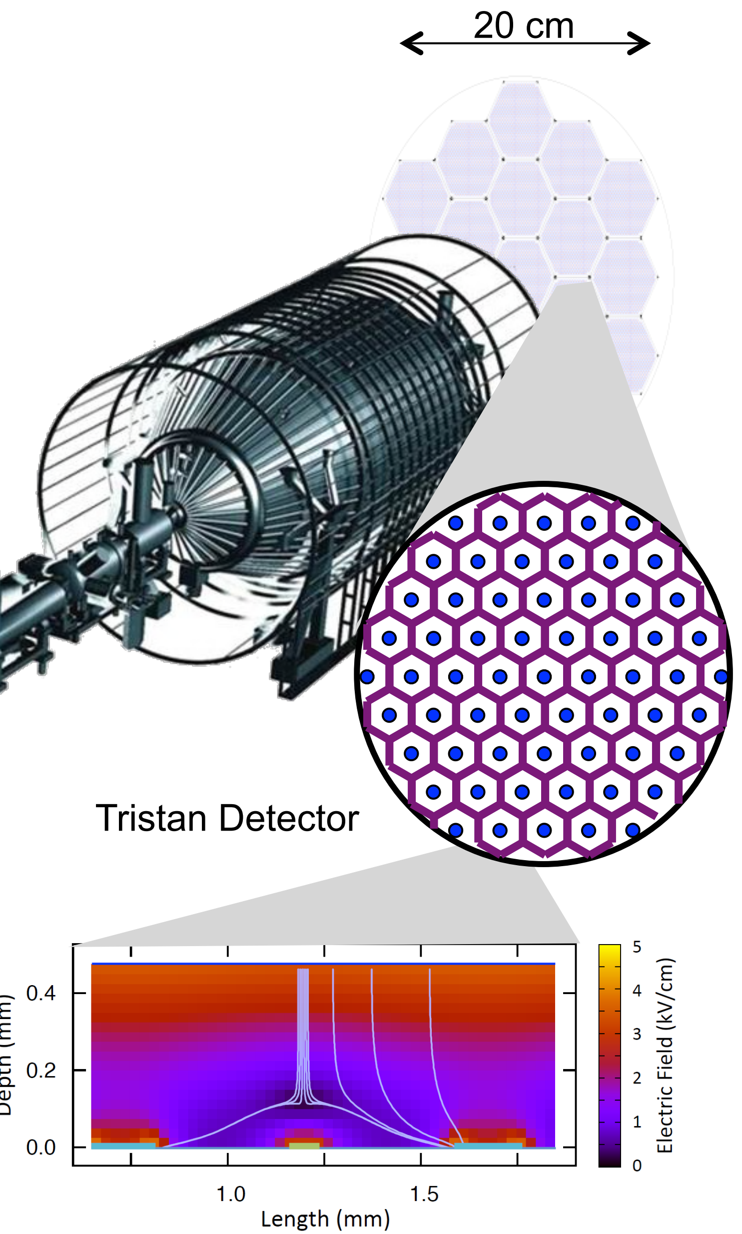
- Ultra-luminous tritium source
- High count rates require new detector system



Novel detector design

- Capability of handling high rates:
  $>10^8$ cnts/s (>10 000 pixel)
- Excellent energy resolution:
  FWHM of 300 eV @ 20 keV
- Large area coverage:
  >20 cm diameter





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Single Beta Decay

How to measure the neutrino mass directly?
→ kinematics of beta decay

What is actually measured?
→ incoherent sum of neutrino masses

How does it compare to $0\nu\beta\beta$?
→ incoherent/ coherent, model dependence

Where do we stand experimentally?
→ best limit 2 eV, next goal 200 meV

How to realize an experiment?
→ ^{3}H, ^{163}Ho,
→ KATRIN, ECHo, Project8

What else can we do with single beta decay?
→ sterile neutrinos, relic neutrinos

Open questions

- Do neutrinos have Dirac or Majorana nature ?

→ $0\nu\beta\beta$ is on its way to find out

- What is the absolute neutrino mass scale ?

→ $0\nu\beta\beta$ and single beta decay are complementary probes

- What is the hierarchy of the different mass eigenstates?

→ Future $0\nu\beta\beta$ and single beta decay experiments can help answering this questions.

→ Complementary with oscillation experiments

Thanks for your attention

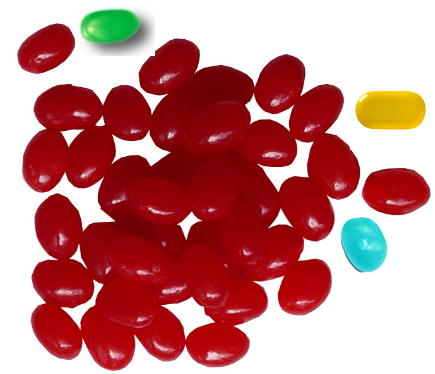
Susanne Mertens
INSS, 2015

Backup

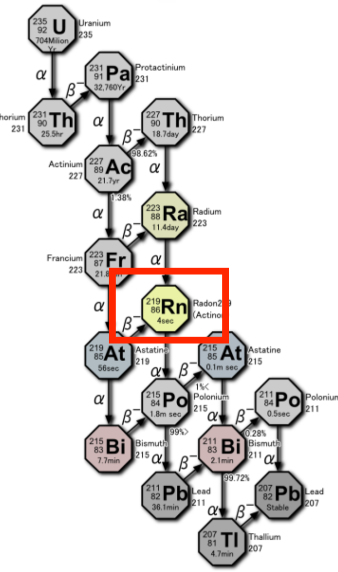
Sterile Neutrinos and Particle Physics

ν_R

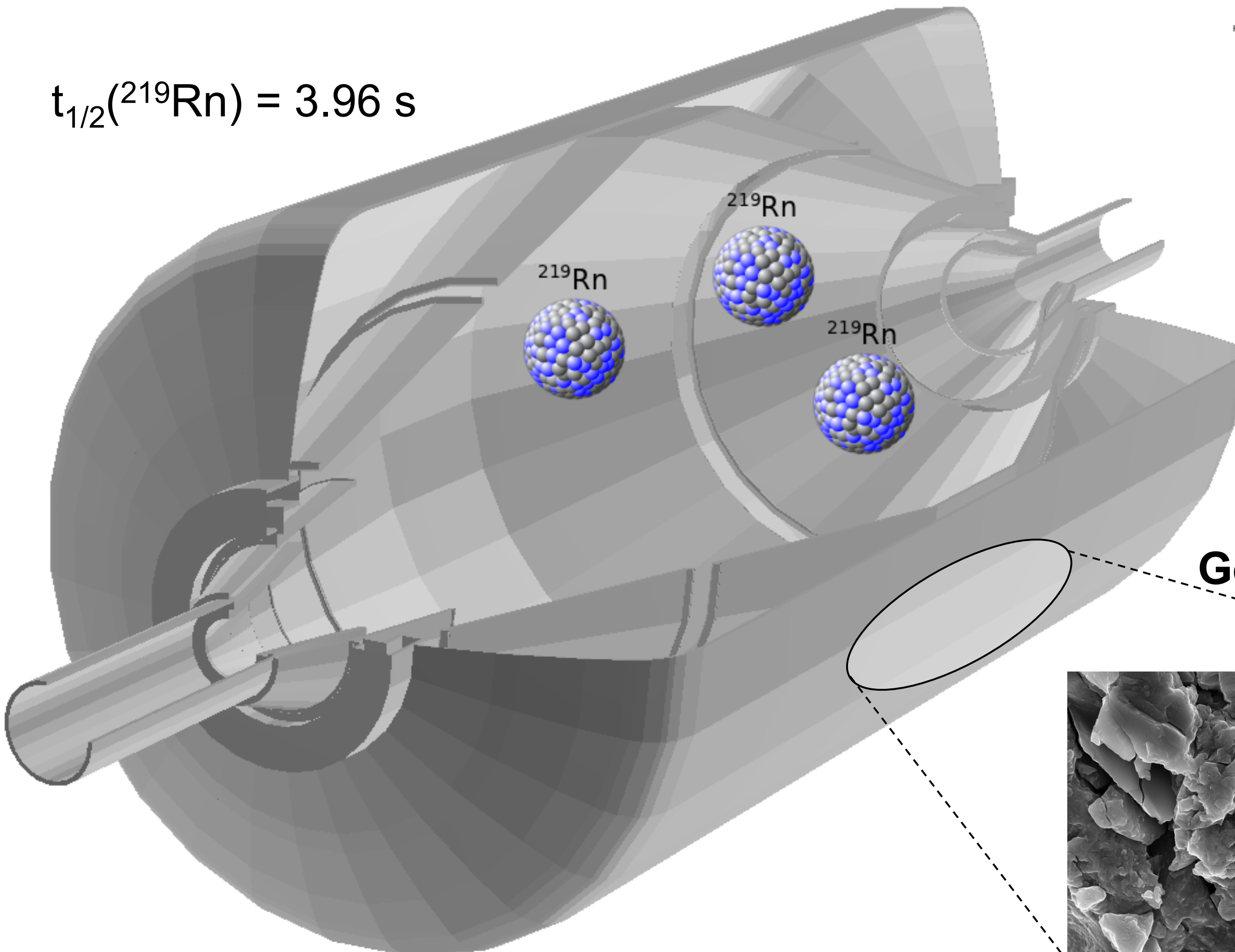
ν_4



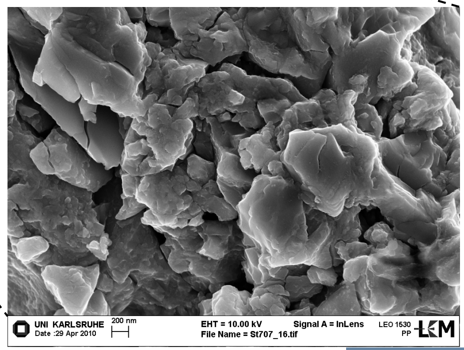
Radon-induced Background



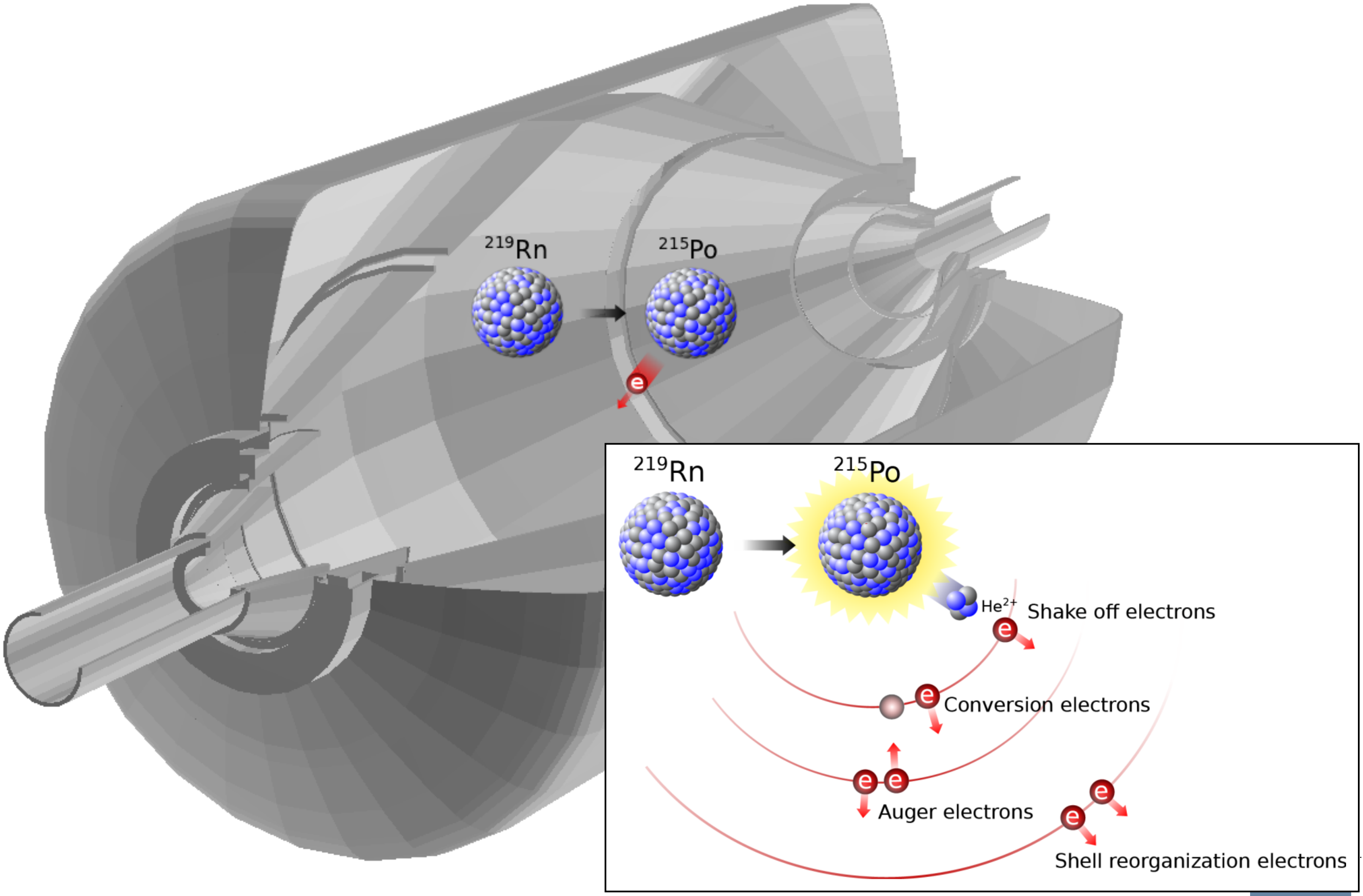
$t_{1/2}(^{219}Rn) = 3.96$ s



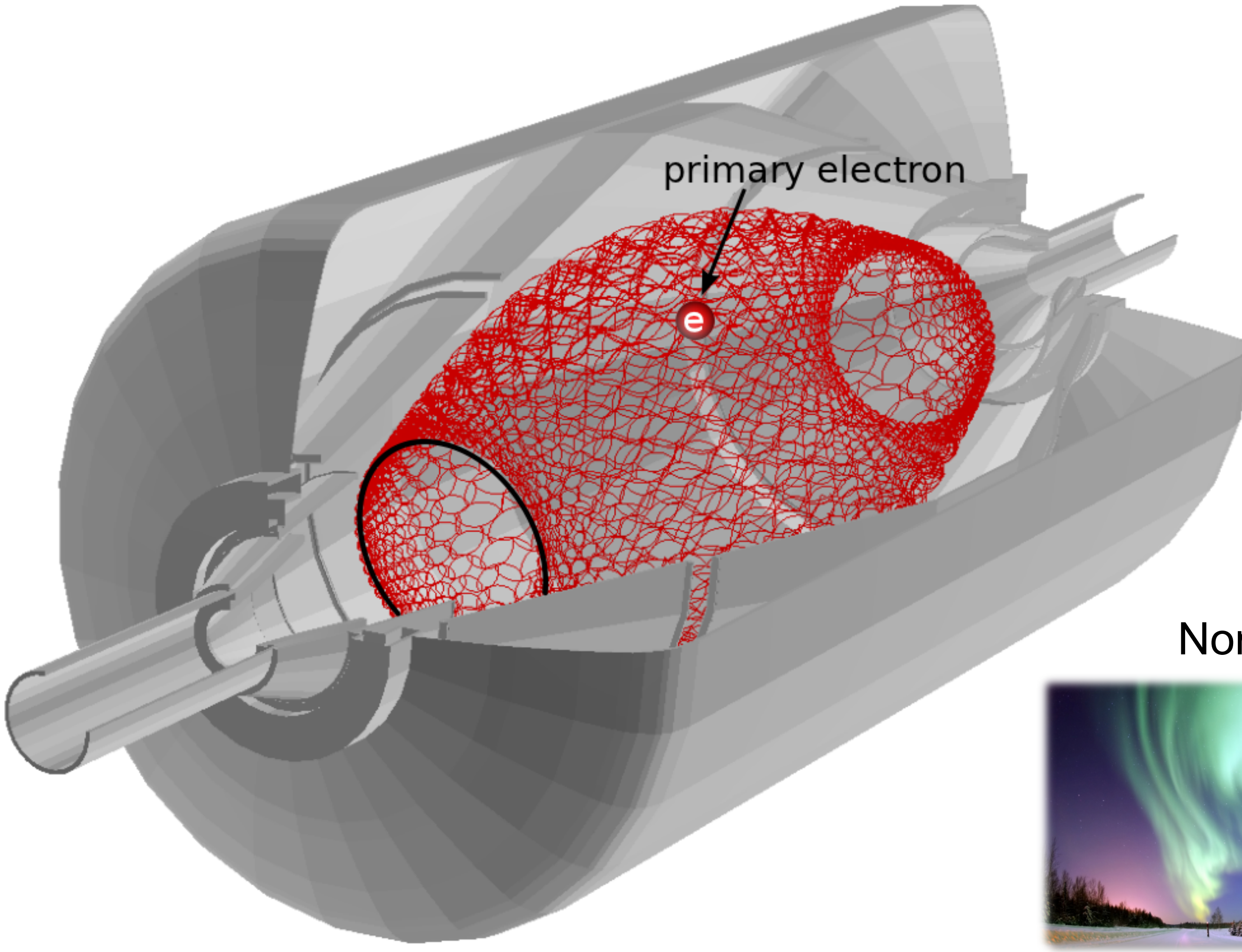
Getter pump



Radon-induced Background

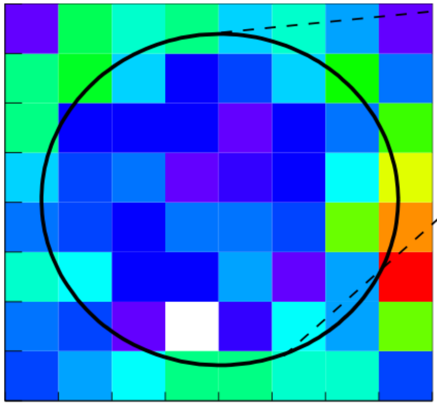


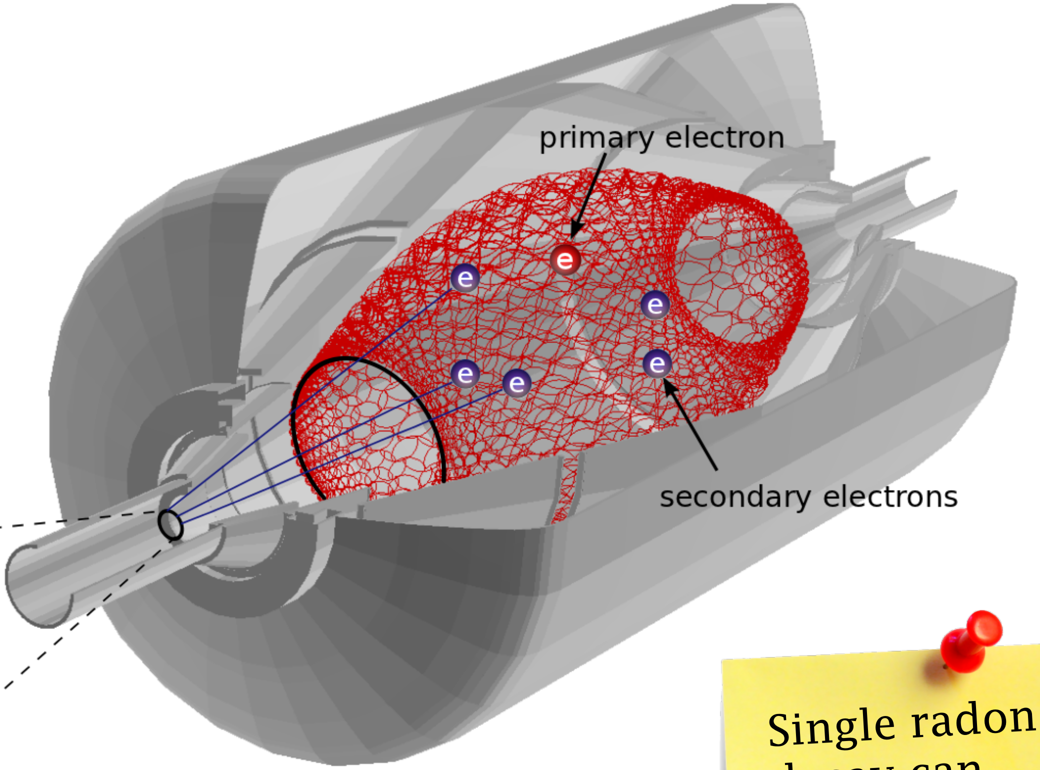
Radon-induced Background



Northern lights

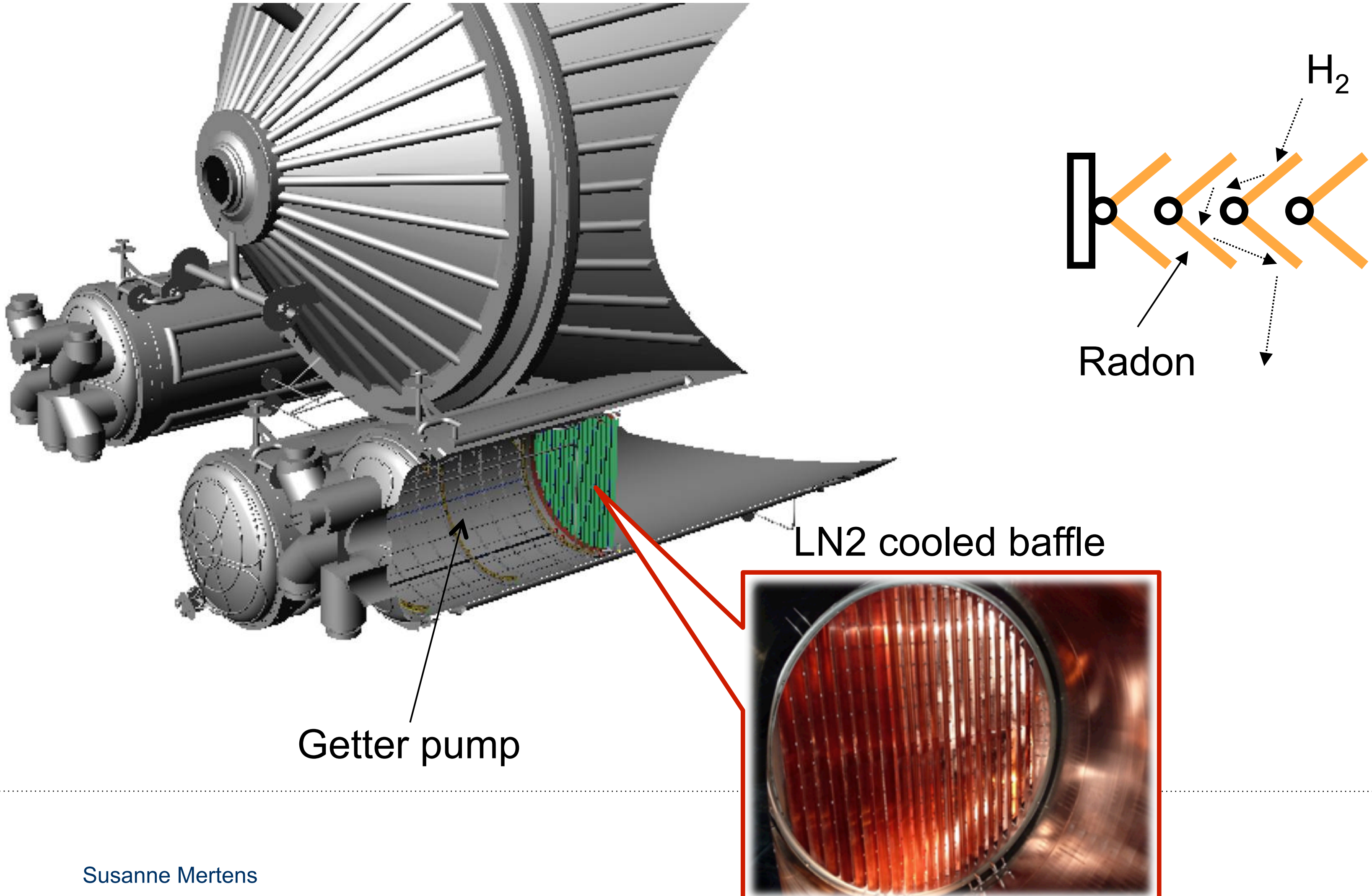
Radon-induced Background





Single radon decay can produce an enhanced background level for up to several hours !!!

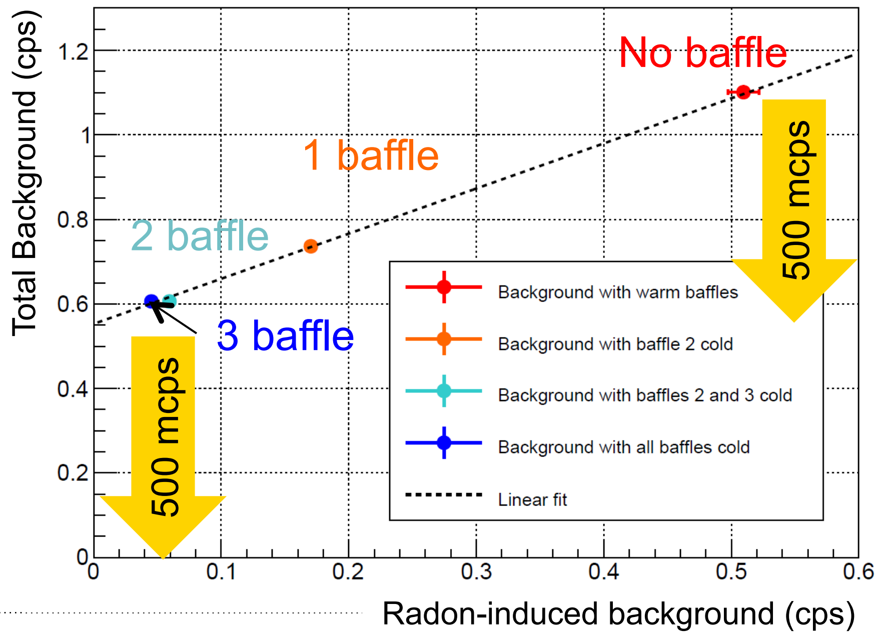
Passive Reduction Technique



KATRIN Spectrometer Status

2015: 2nd measurement phase completed

- ➢ Liquid nitrogen cooled baffles eliminate Radon-induced background with an efficiency of $\varepsilon = (97 \pm 2)\%$
- ➢ Remaining background is under investigation at the moment



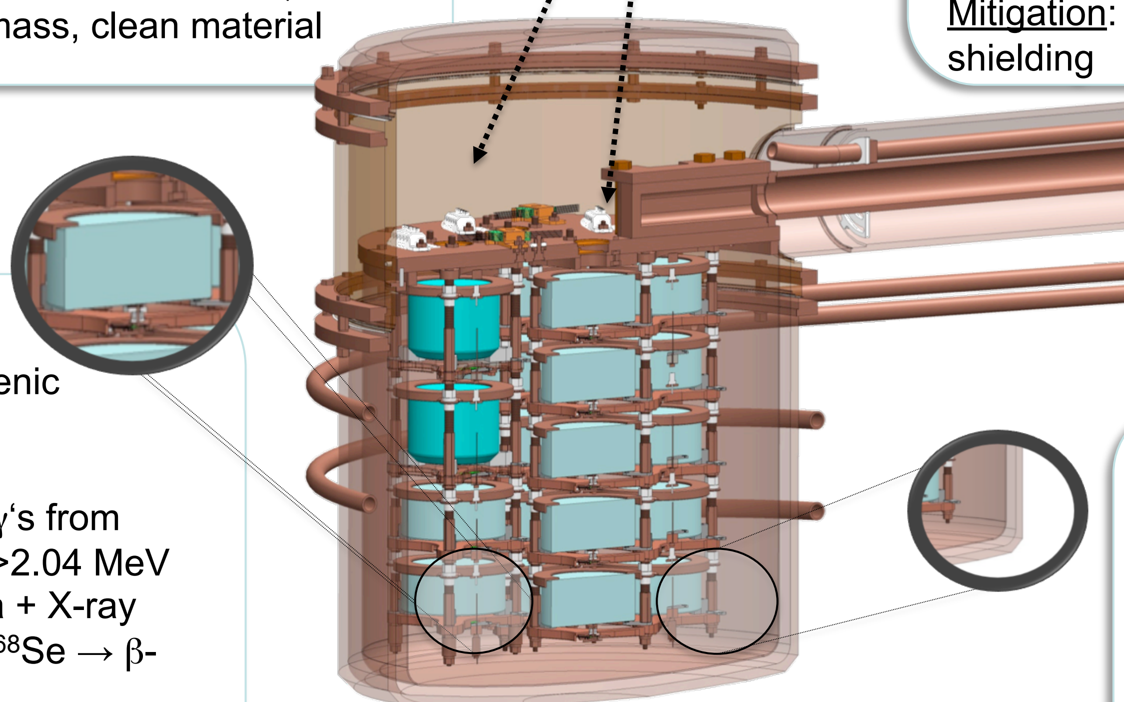
MAJORANA Backgrounds

Uranium and Thorium
Origin: Impurities in surrounding material
Process:
- ^{232}Th chain → ^{208}Tl → 2.615 MeV γ
- ^{238}U chain → ^{214}Bi → >2 MeV γ

Mitigation: Low mass, clean material

Neutrons
Origin: Muons, (α,n) reactions, etc. in rock
Process:
- High energy n: Ge(n,n'γ),
- Low energy n: ^{76}Ge(n,γ)^{77}Ge → β-decay

Mitigation: Underground, shielding



^{60}Co, ^{68}Ge
Origin: Cosmogenic activation
Process:
- Energy of 2 γ's from ^{60}Co-decay >2.04 MeV
- ^{68}Ge → ^{68}Ga + X-ray ($T_{1/2}$ ≈1h)→ ^{68}Se → β-decay + γ's

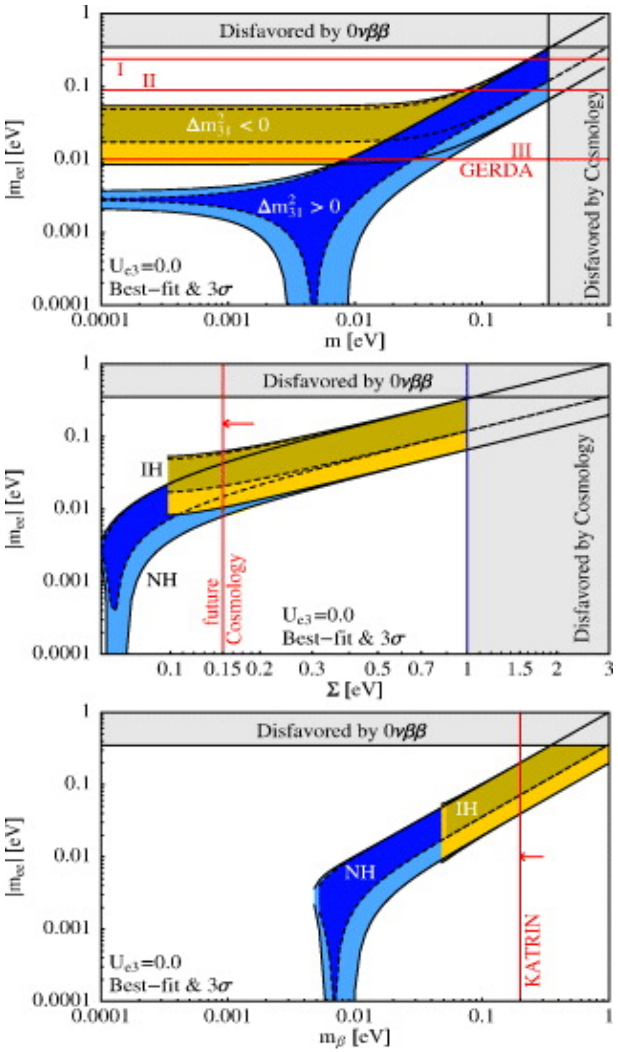
Mitigation: Short exposure times, pulse shape analysis, time correlation cut

Surface Alphas
Origin: Mainly from radon daughters
Process: Penetrate through passivated surface or point contact of detector
Mitigation: Cleanliness, gloveboxes

Others:
- Direct muons
- Neutrinos

Comparison to $0\nu\beta\beta$

- Cosmology
- Beta Decay
- Double Beta Decay



What do we learn about the ν-mass?

$$\frac{1}{T_{1/2}^{0\upsilon}} = G_{0\upsilon} \cdot \left|M_{0\upsilon}\right|^2 \cdot m_{\beta\beta}^2$$

- $G_{0\nu}$ = Phase space factor (depends on isotope)
- $M_{0\nu}$ = nuclear matrix element (depends on isotope, large uncertainties!)
- $m_{\beta\beta}$ = majorana mass

~The larger the matrix element, the smaller the phase space factor
→ No big difference in the lifetime of the different isotopes