Lecture overview

Lecture 1: general principles of neutrino interactions and particle detection

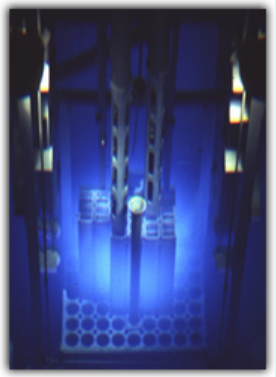
Lecture 2: neutrinos at GeV energies

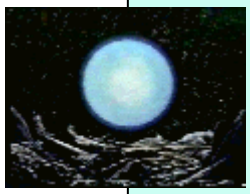
Lecture 3: neutrinos at MeV energies (supernova, solar)

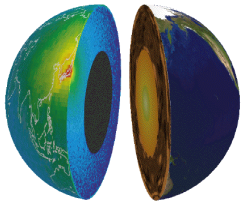
Lecture 4: more neutrinos at MeV energy, and below

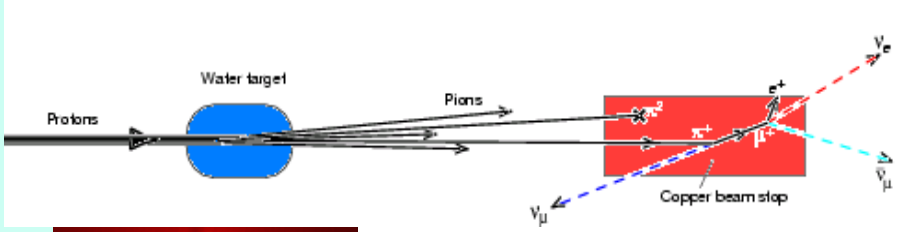
geo, reactor, source neutrinos
stopped-pion neutrinos
detecting *no* neutrinos

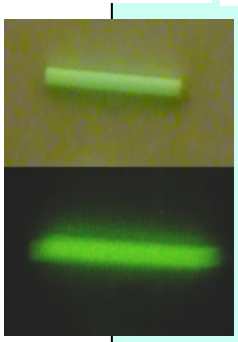
More in the ~ MeV energy range (and below)

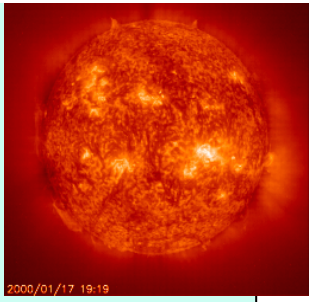










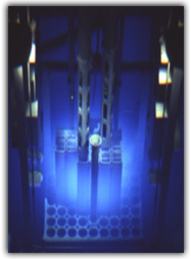


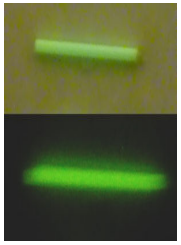
Physics/astrophysics of interest in this energy range (few to few tens of MeV)

Supernova neutrinos: burst and “relic”

Solar neutrinos

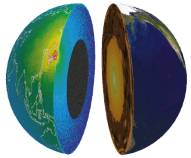
Reactor neutrinos



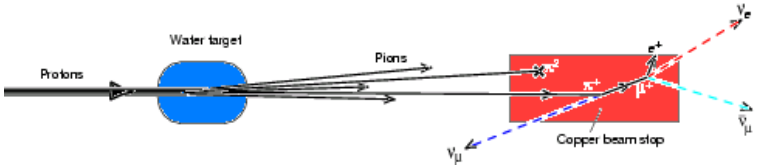


Radioactive sources

Geoneutrinos



Stopped-pion neutrinos



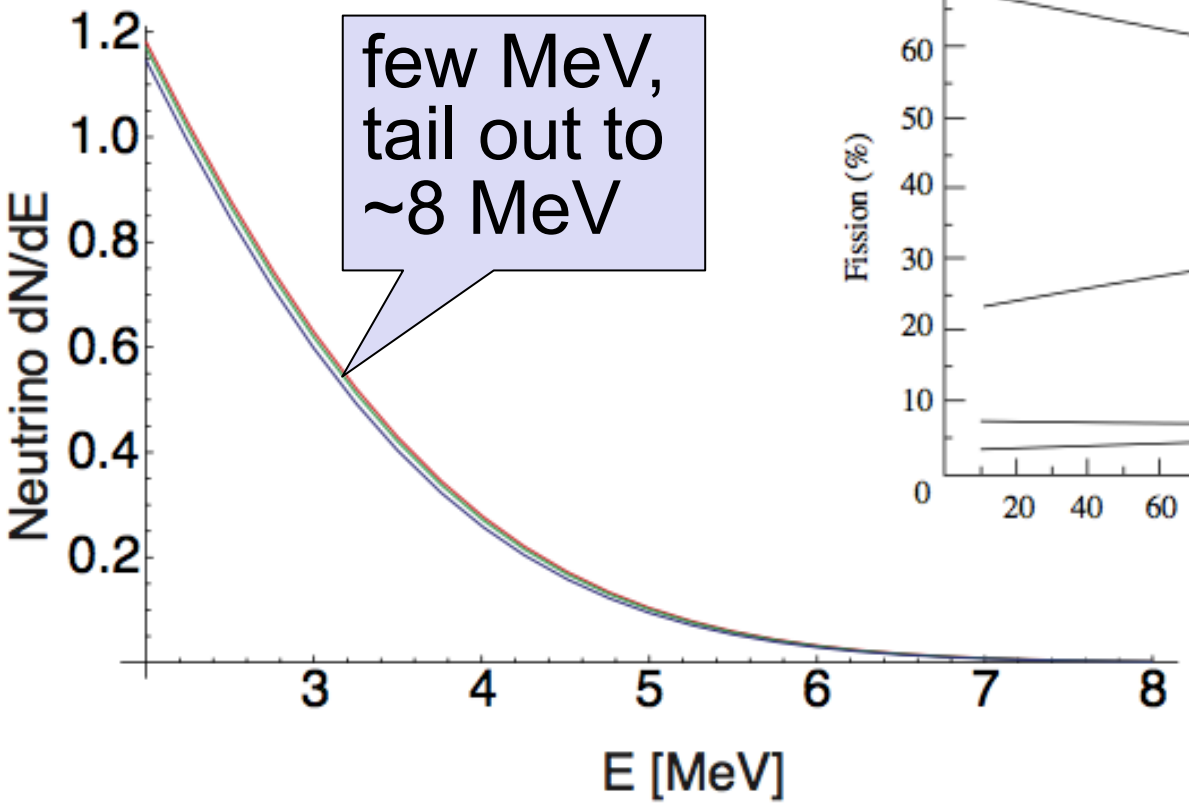
these ones today

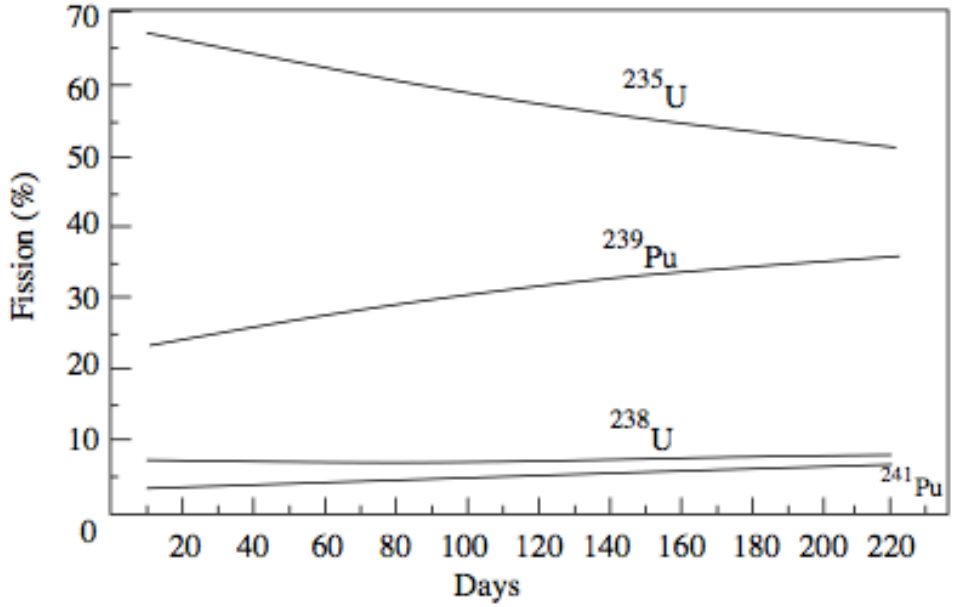
As before, brief mention of physics to motivate detector approaches

Reactor neutrinos

Electron *anti*neutrinos from fission reactions
(neutron-rich nuclei, so $n \rightarrow p + e^- + \bar{\nu}_e$)

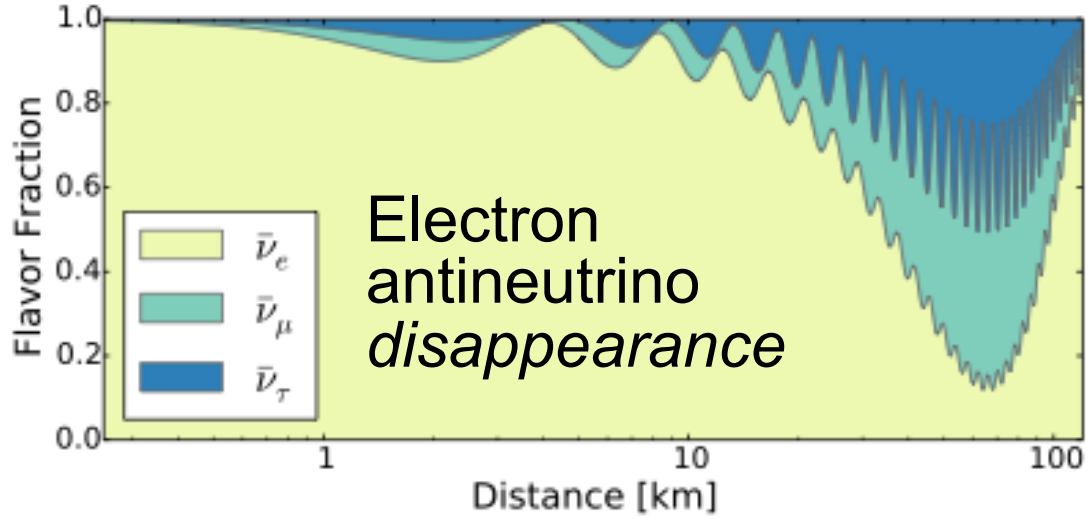
Flux proportional to reactor power,
~6 anti-ν per fission,
2 x 10^{20} anti-ν/s per GW



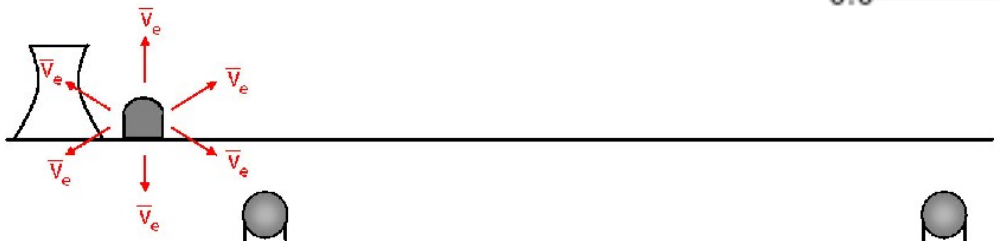


Physics with reactor neutrinos

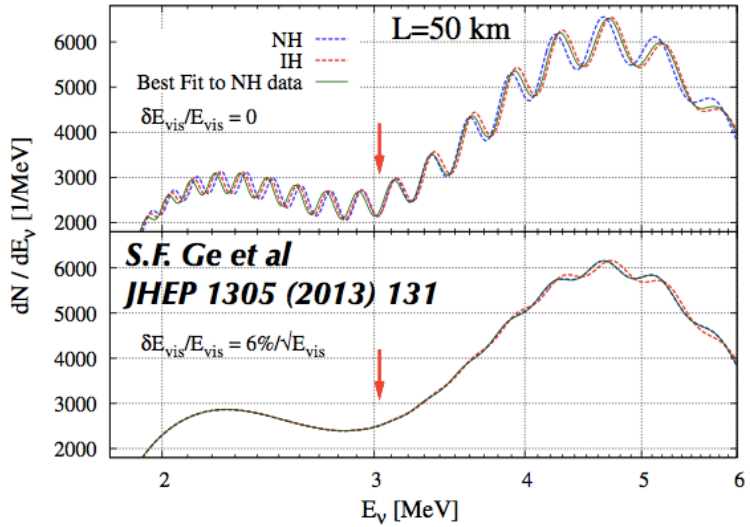
3-flavor oscillations:
13, 12 parameters, mass ordering?

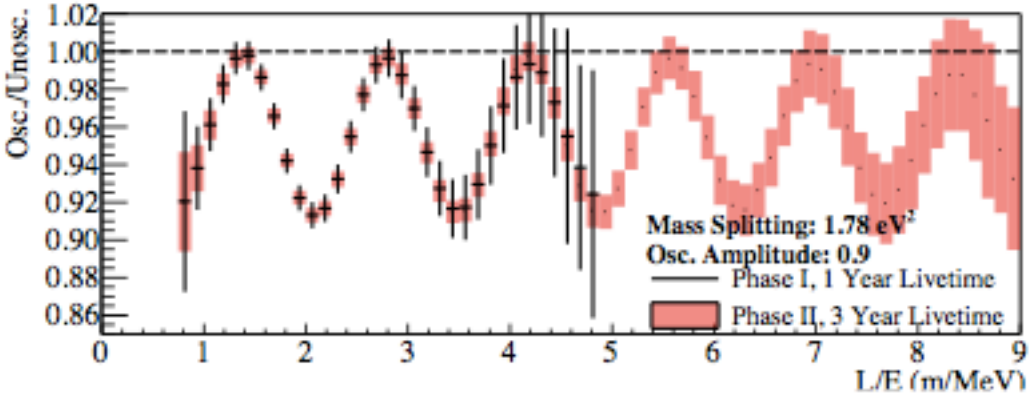


Electron antineutrino *disappearance*



Want near and far detectors





Sterile oscillations
(short baseline, wiggles in same detector)

What do you want in a detector for reactor neutrinos?

Most important information is the ***energy*** (but direction, position info good)

Size	~kton detector mass per 100 events @ 10 kpc
Low energy threshold	~Few MeV at least, <1 MeV best!
Energy resolution & scale	Resolve features in spectrum
Angular resolution	Nice if possible
Position resolution	Intra-detector L evaluation
Low background	BG rate << reactor neutrino rate; overburden good, must be clean
Flavor sensitivity	Nice if possible, but simple disappearance OK

it's all about the backgrounds ...

Scintillation detectors

Lots of photons (hundreds of pe/MeV)
... can achieve **low thresholds** (<1 MeV) and
good energy resolution (3-8%/√E)

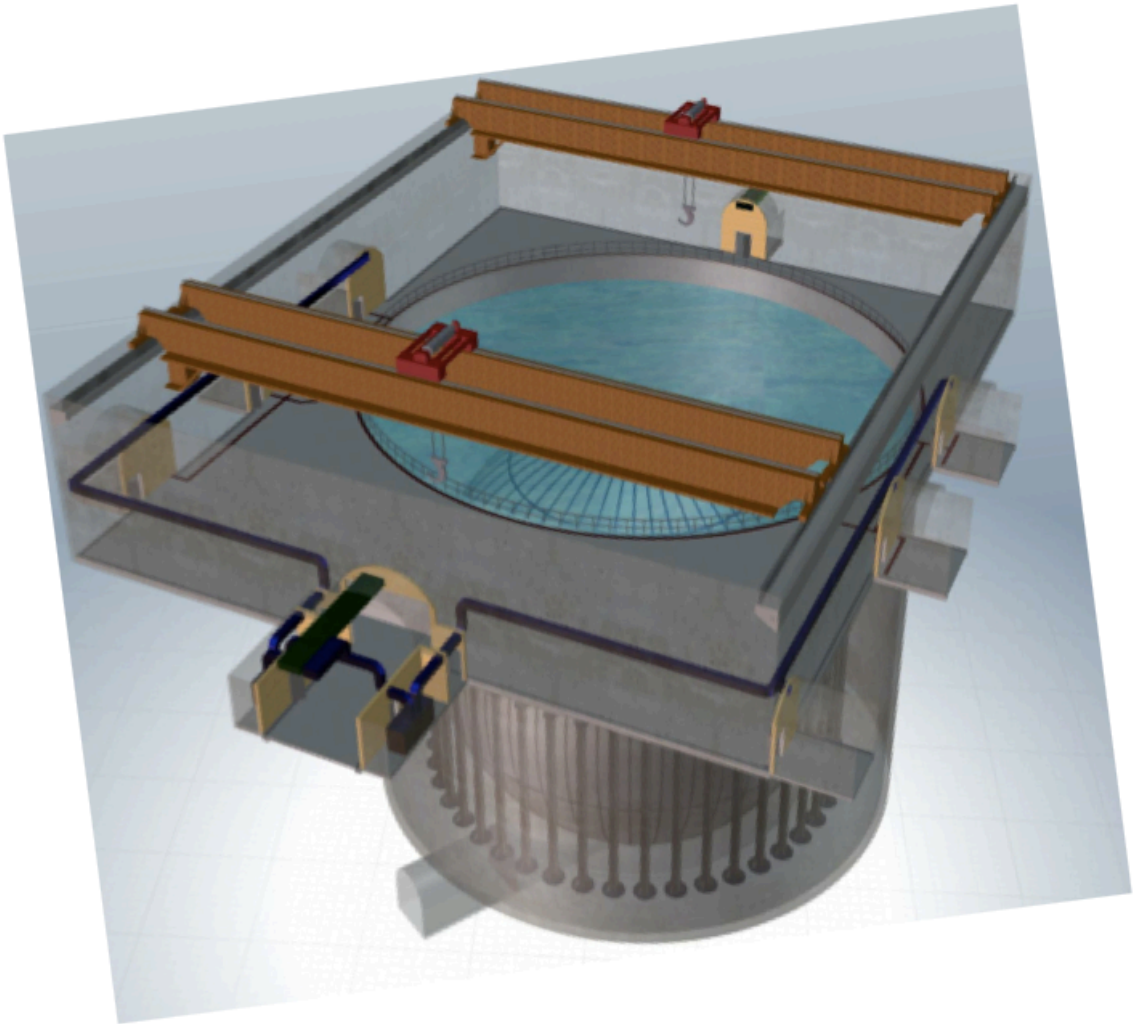
If you have electron antineutrinos > 1.8 MeV,
the standard (& venerable)
background-buster is **inverse beta decay**

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

n capture on protons,
Gd or other nucleus
(10's to 100's of μs delay)
releases gammas

➔ **double-bang pulse**
is clean signature
over background

JUNO, China

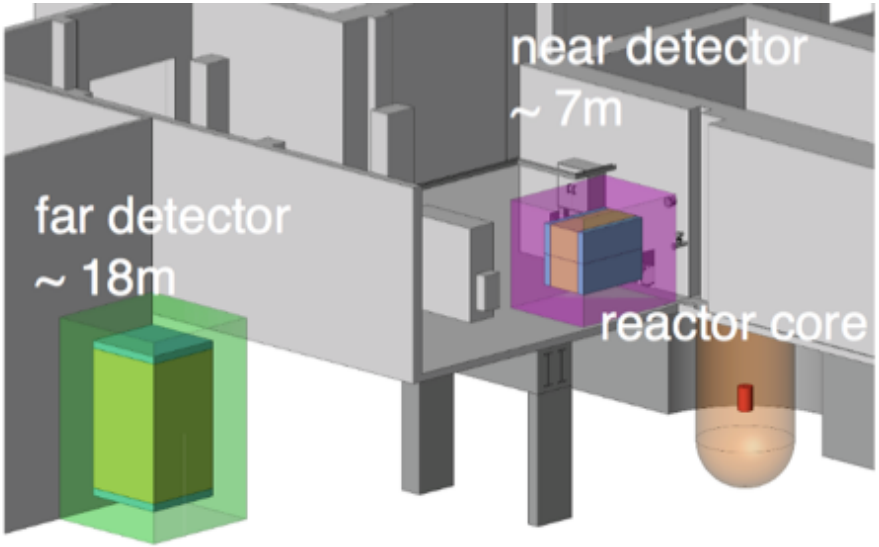


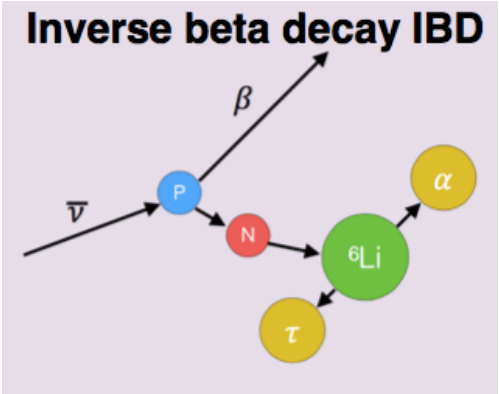
- 700 m overburden
- 20 kt liquid scintillator
- 80% photocoverage
- Aiming for
  1200 pe/MeV,
  3%/√E resolution,
  1% energy scale
  uncertainty

mass ordering, 12 parameters,
(+ natural neutrinos), ...

Some ideas for short-baseline reactor experiments
for sterile oscillation searches (there are many others...)

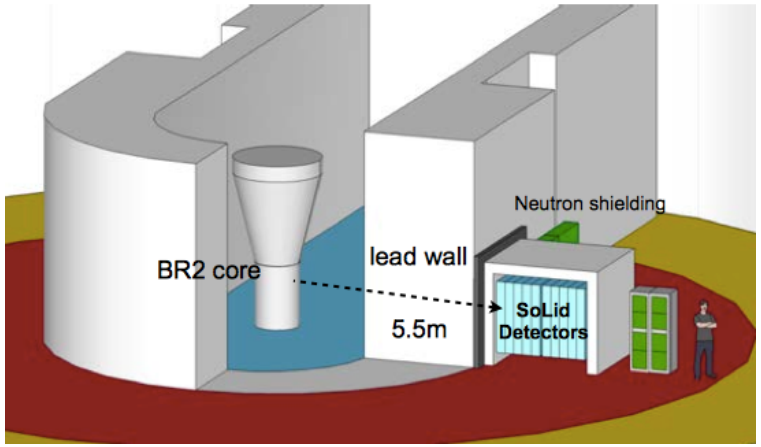
PROSPECT, ORNL

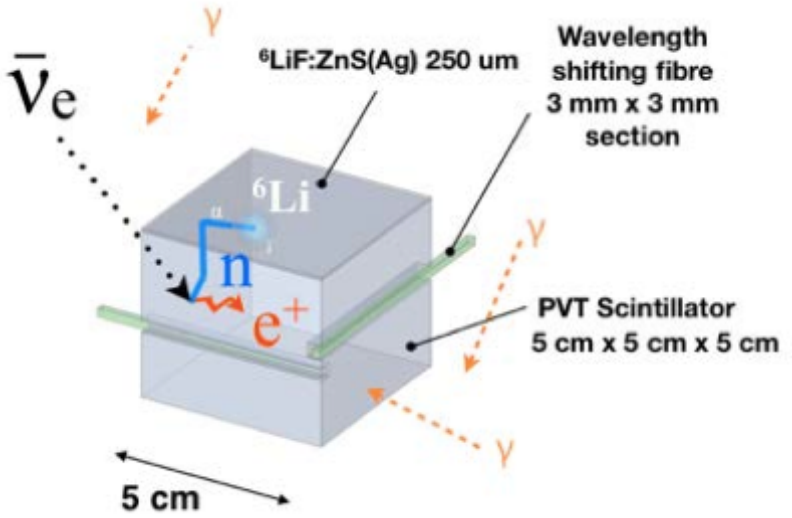




Li-loaded scintillator

SoLiD, Belgium



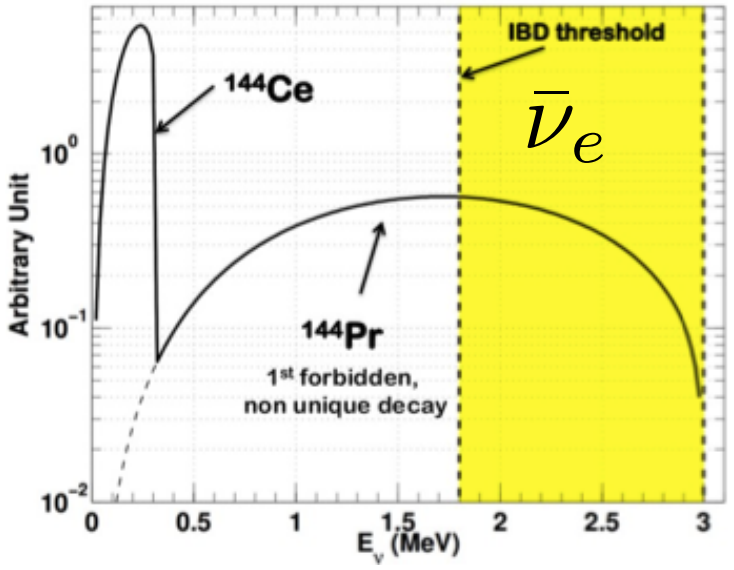


Neutrinos from (artificial) radioactive sources

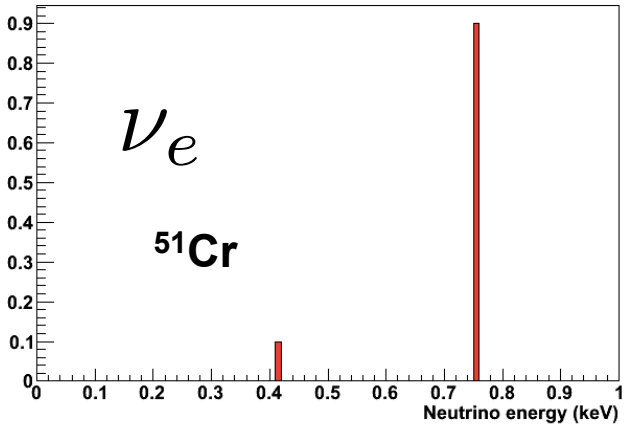
β decay

$^{144}Ce \rightarrow {}^{144}Pr + e^- + \bar{\nu}_e$

$^{144}Pr \rightarrow {}^{144}Nd + e^- + \bar{\nu}_e$

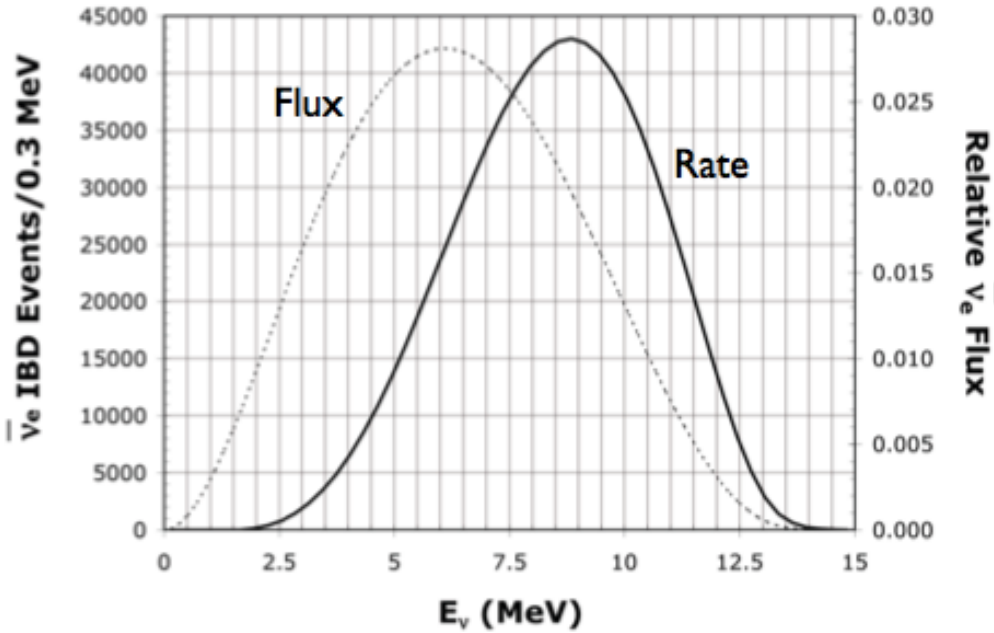


Electron capture

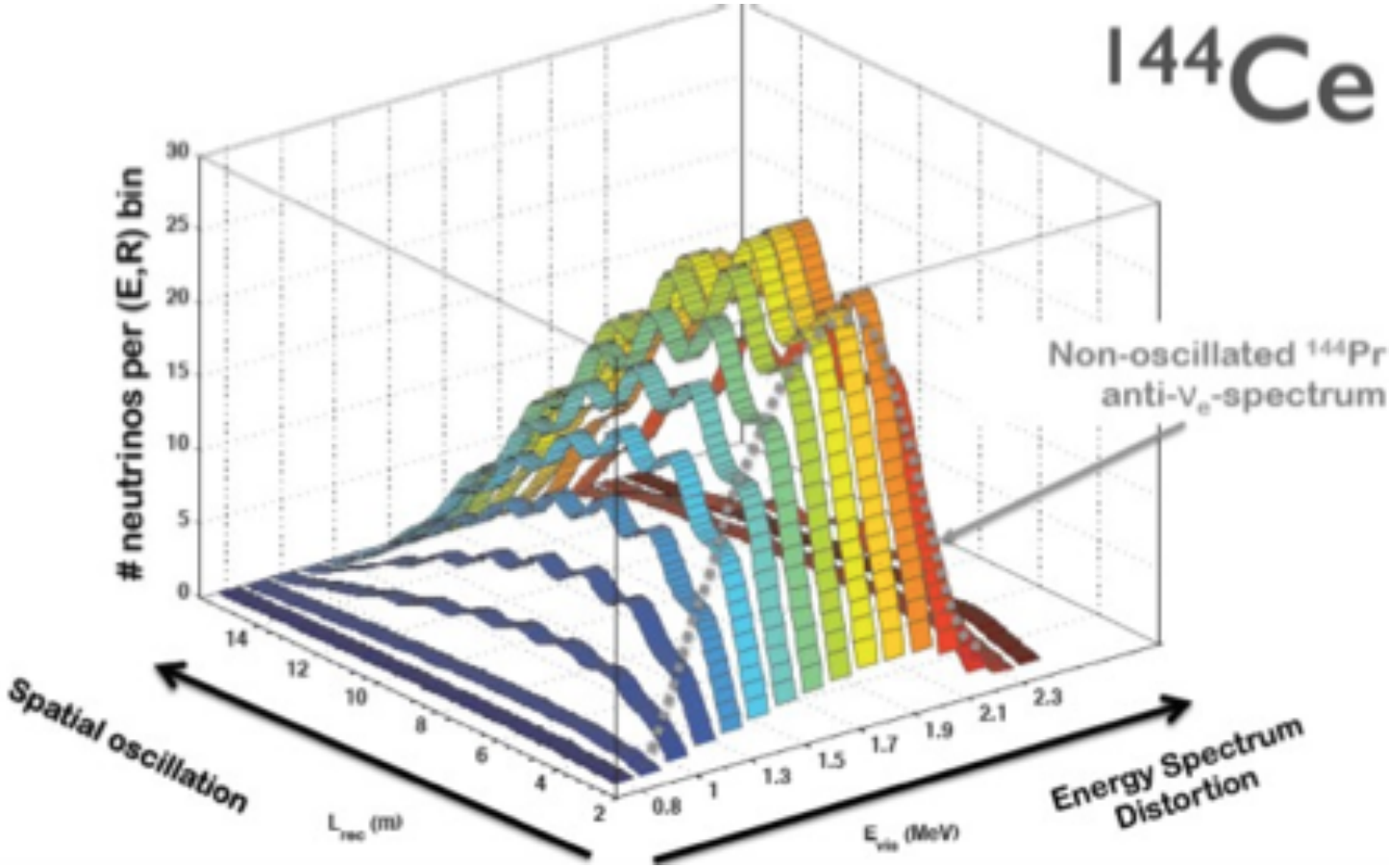


IsoDAR

decay of accelerator-produced ^{8}Li



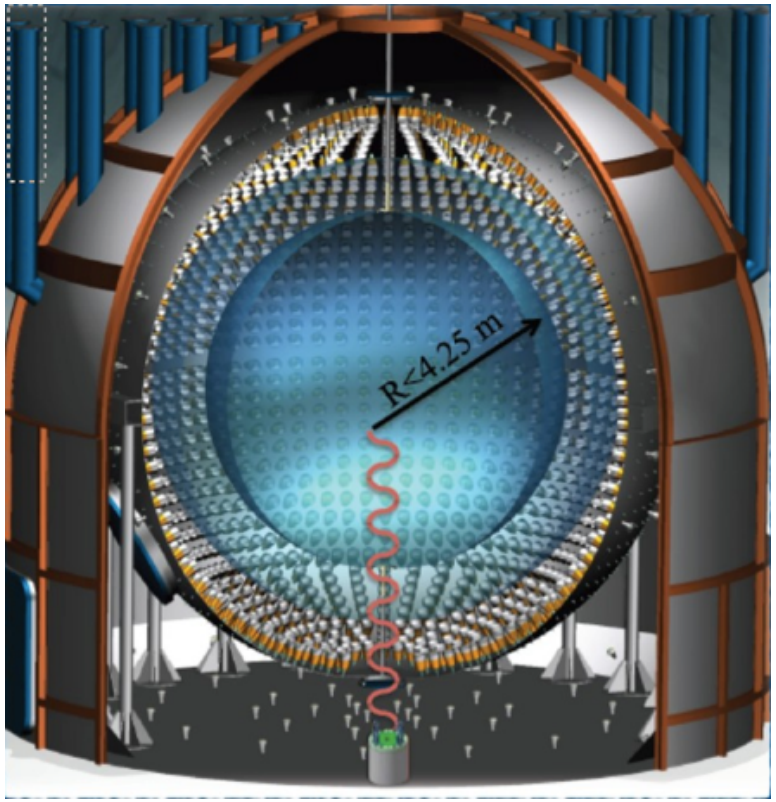
Physics with artificial radioactive sources

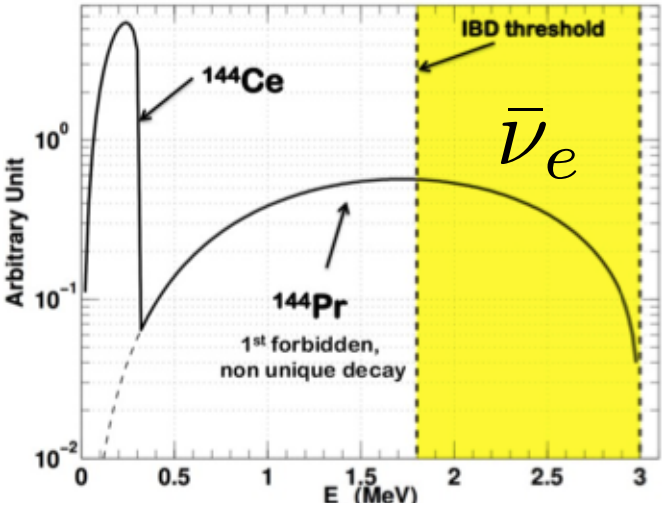


Primarily short-baseline sterile oscillations:
look for wiggles as a function of L, E
on ~meter to tens of meter scale

For antinus above 1.8 MeV ➔ use IBD
For nus below IBD threshold ➔ use ES on electrons
(harder... no tag, xscn down by ~100)

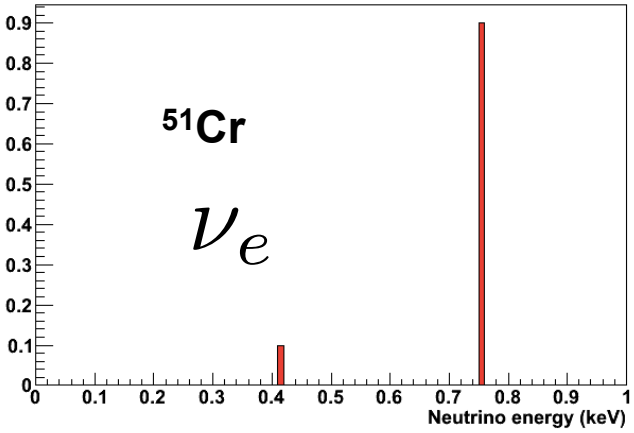
SOX: source deployed below Borexino





IBD for ^{144}Ce,

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



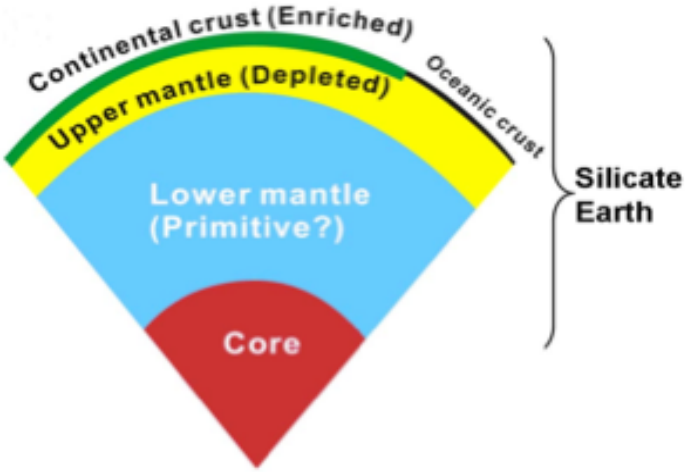
ES for ^{51}Cr

$$\nu + e^- \rightarrow \nu + e^-$$

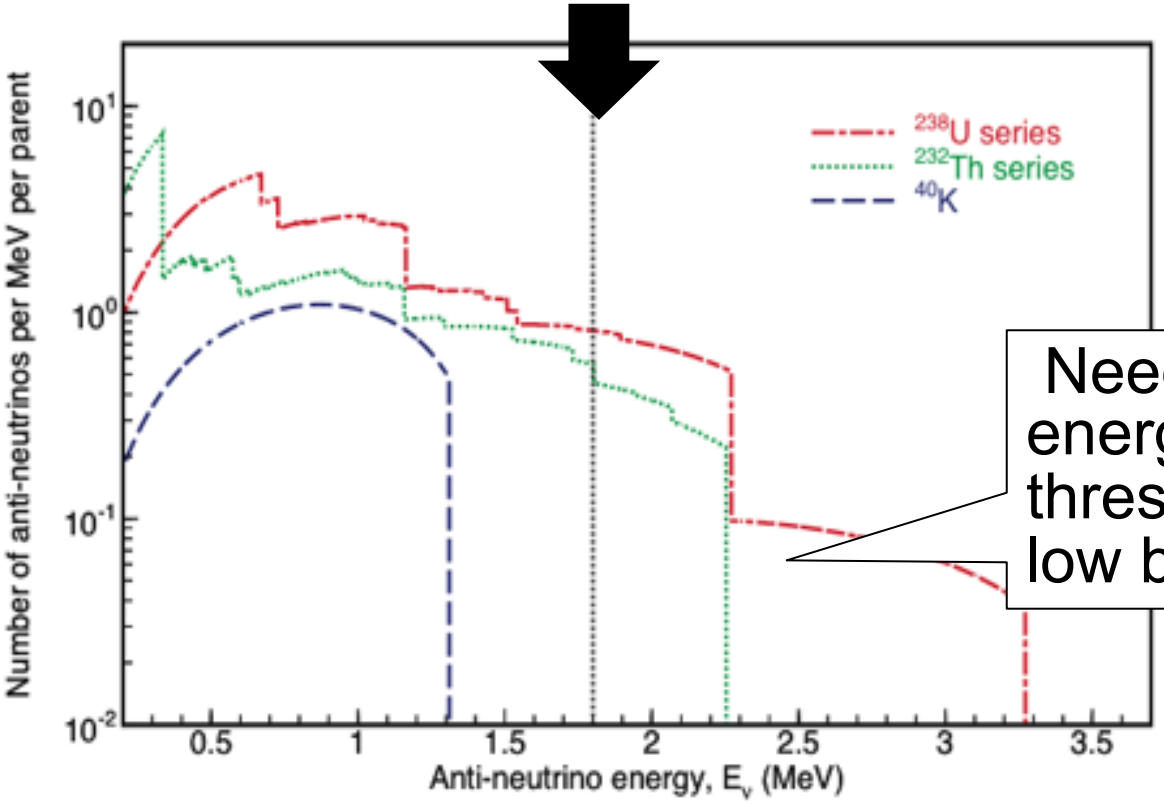
Another approach: CEvNS... will come back to this

Geo-neutrinos

Fraction of Earth's heat from radioactivity is uncertain ... neutrinos can constrain geophysical models

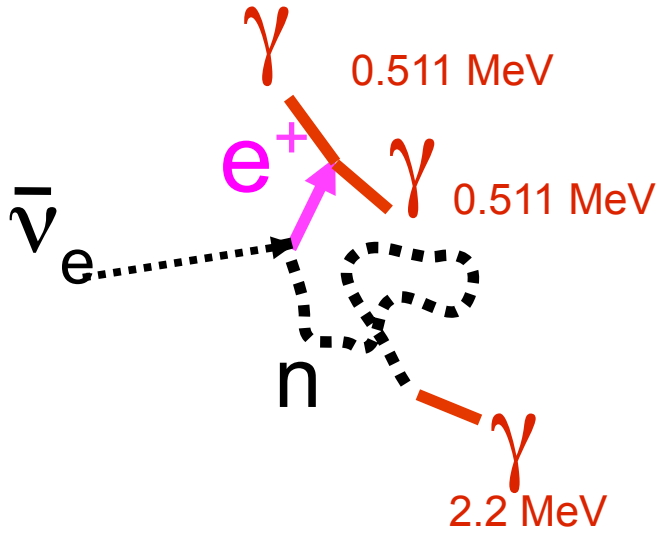


IBD threshold



Need low energy threshold, low bg

Bulk Silicate Earth model:
~1/2 of U, Th, K in crust
~1/2 of U, Th, K in mantle
~no U, Th, K in core

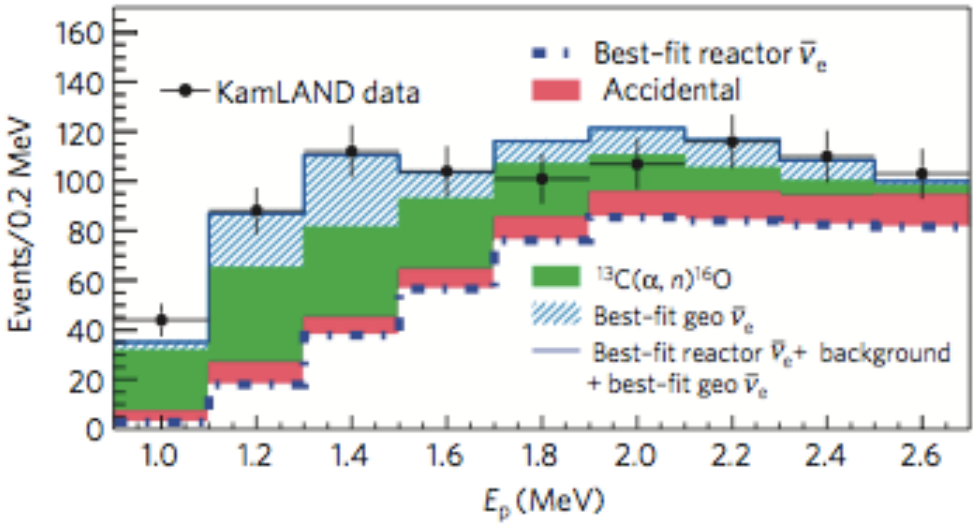


it's all about the backgrounds ...

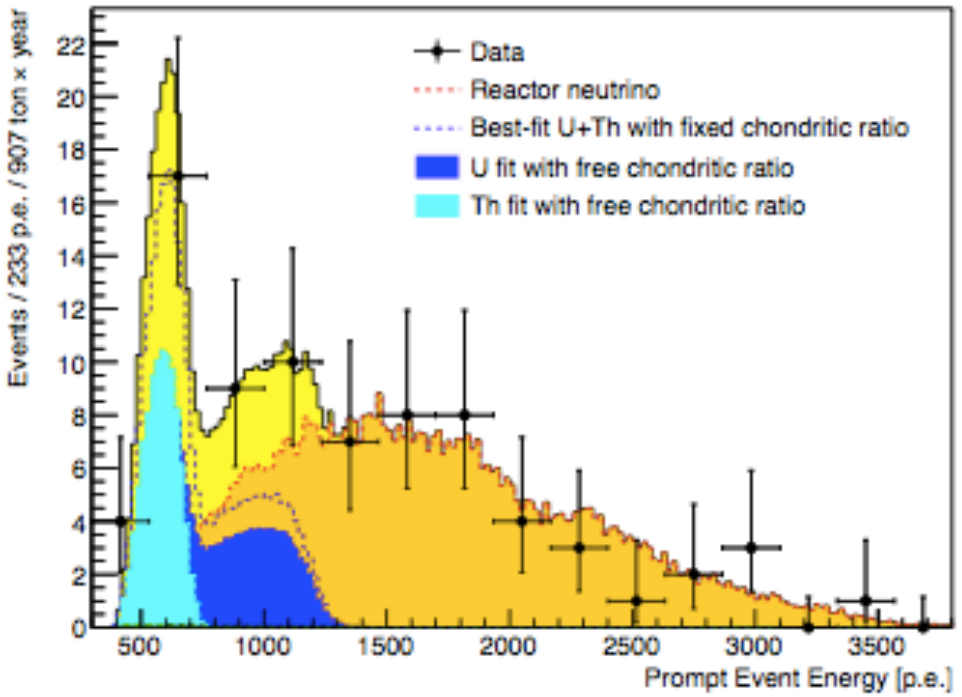
Use IBD "double bang" to select antinues

Geoneutrino measurements

KamLAND

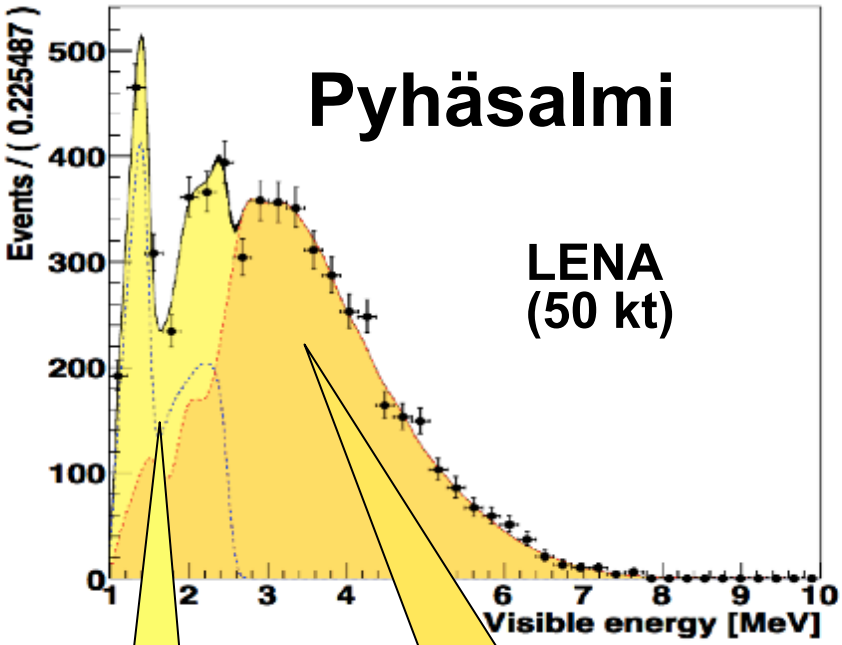


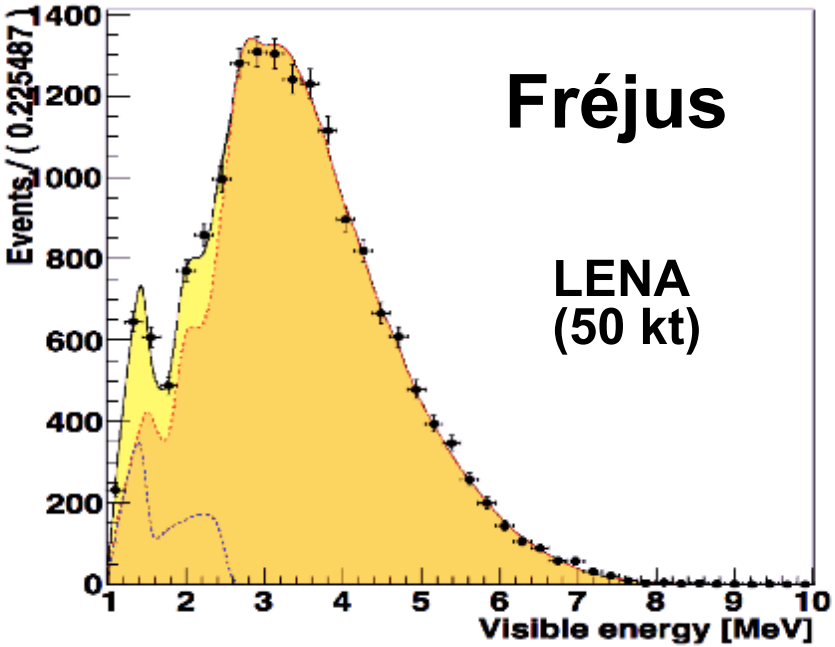
Borexino



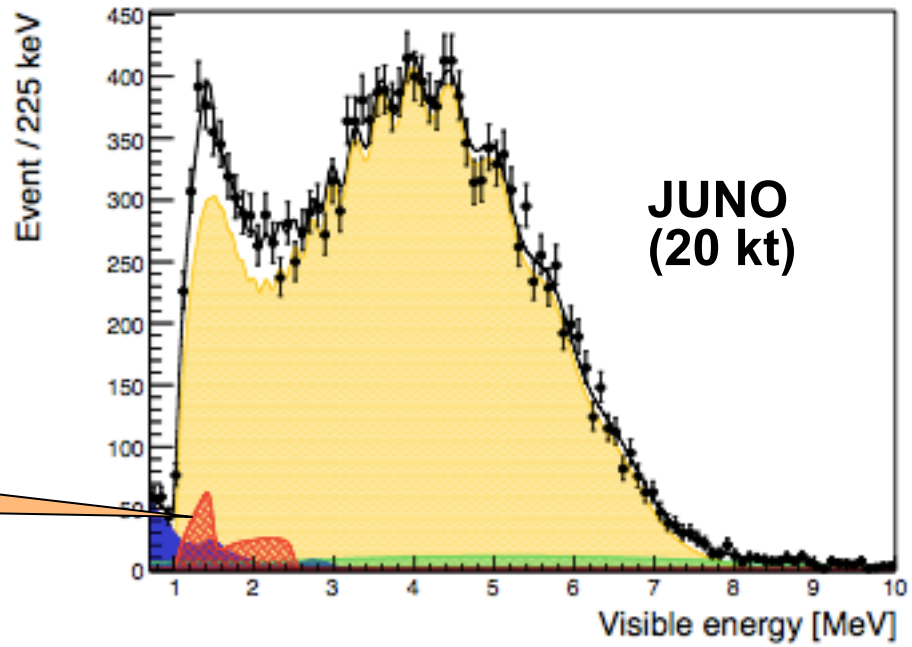
Reactor antineutrino bg is the biggest issue

Future experiments for geoneutrinos





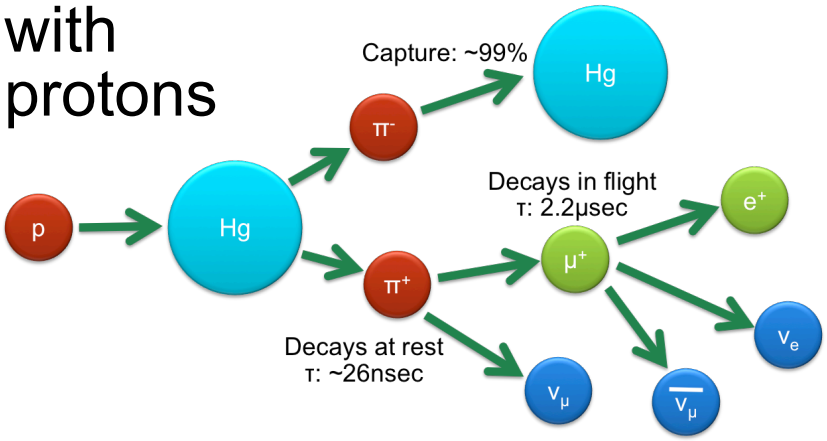
1 year statistics

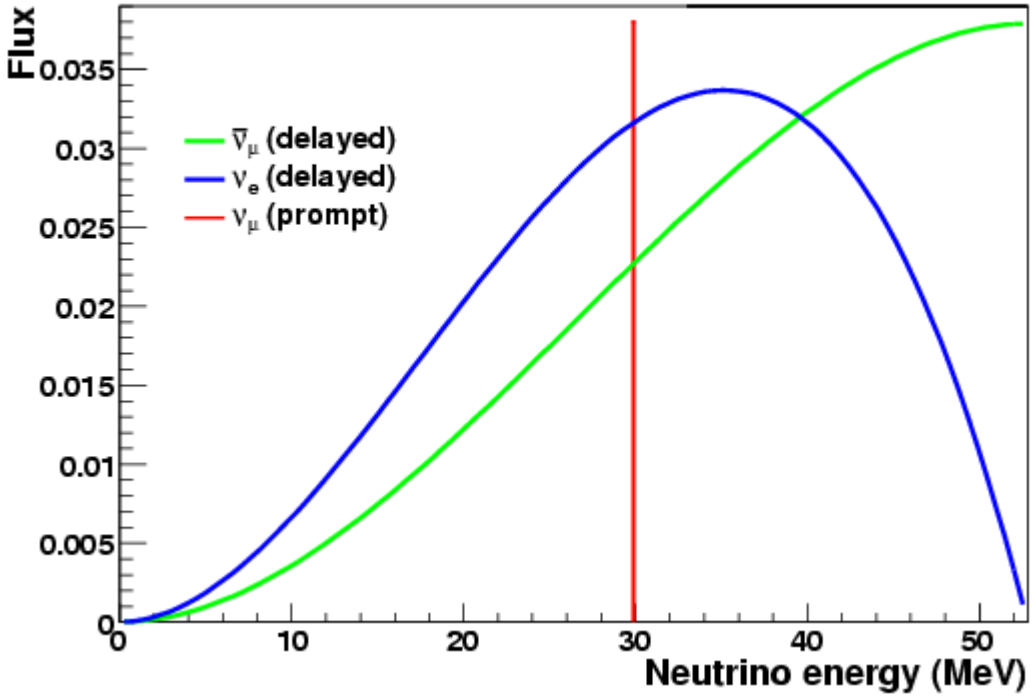


Reactor antineutrinos are problematic!

Stopped-Pion (πDAR) Neutrinos

create with protons





$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

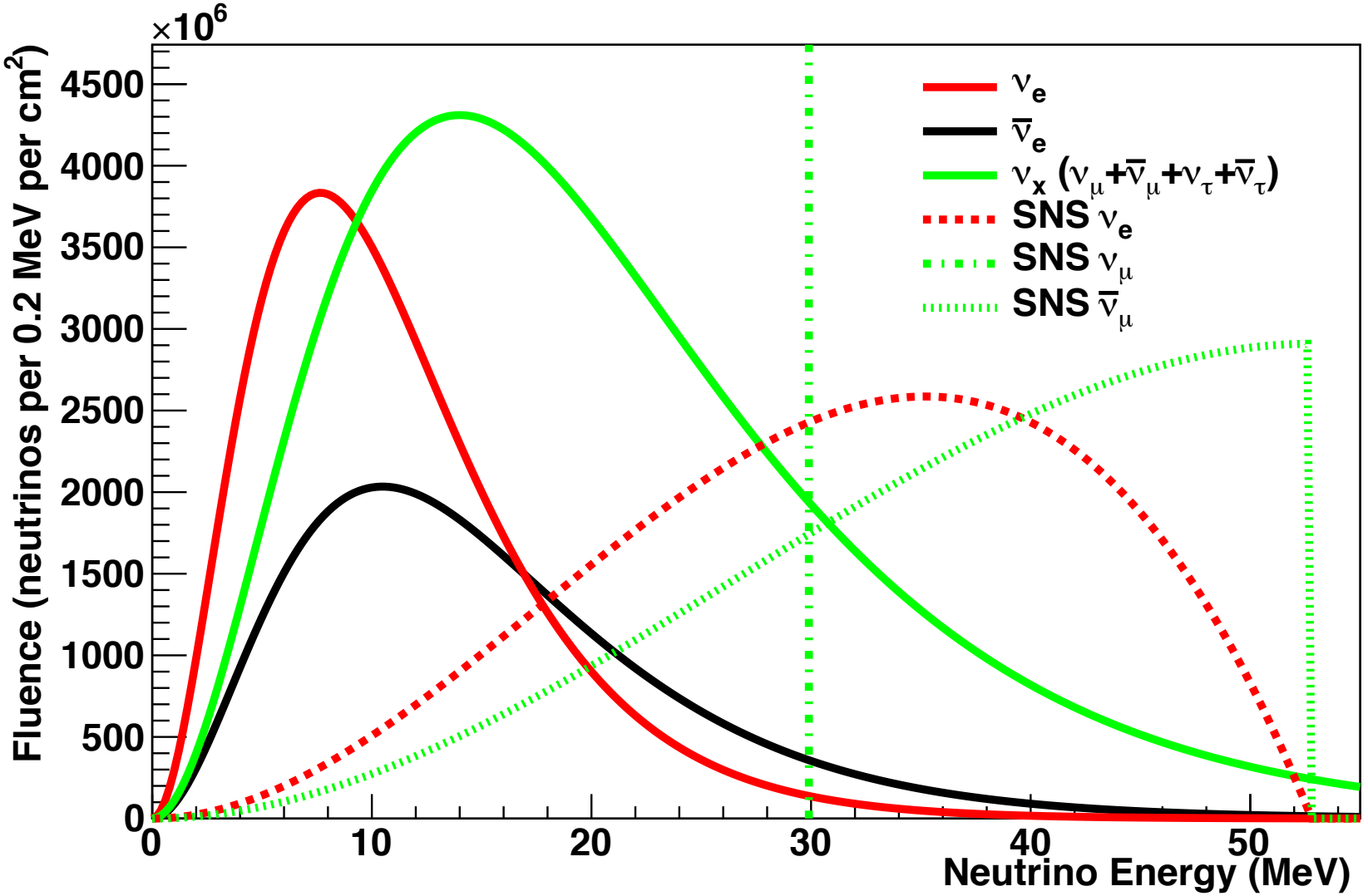
2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

3-body decay: range of energies between 0 and $m_\mu/2$
DELAYED (2.2 μs)

A well understood weak decay

Spectrum overlaps reasonably well with supernova neutrino spectrum



Solid: SN Broken: stopped π

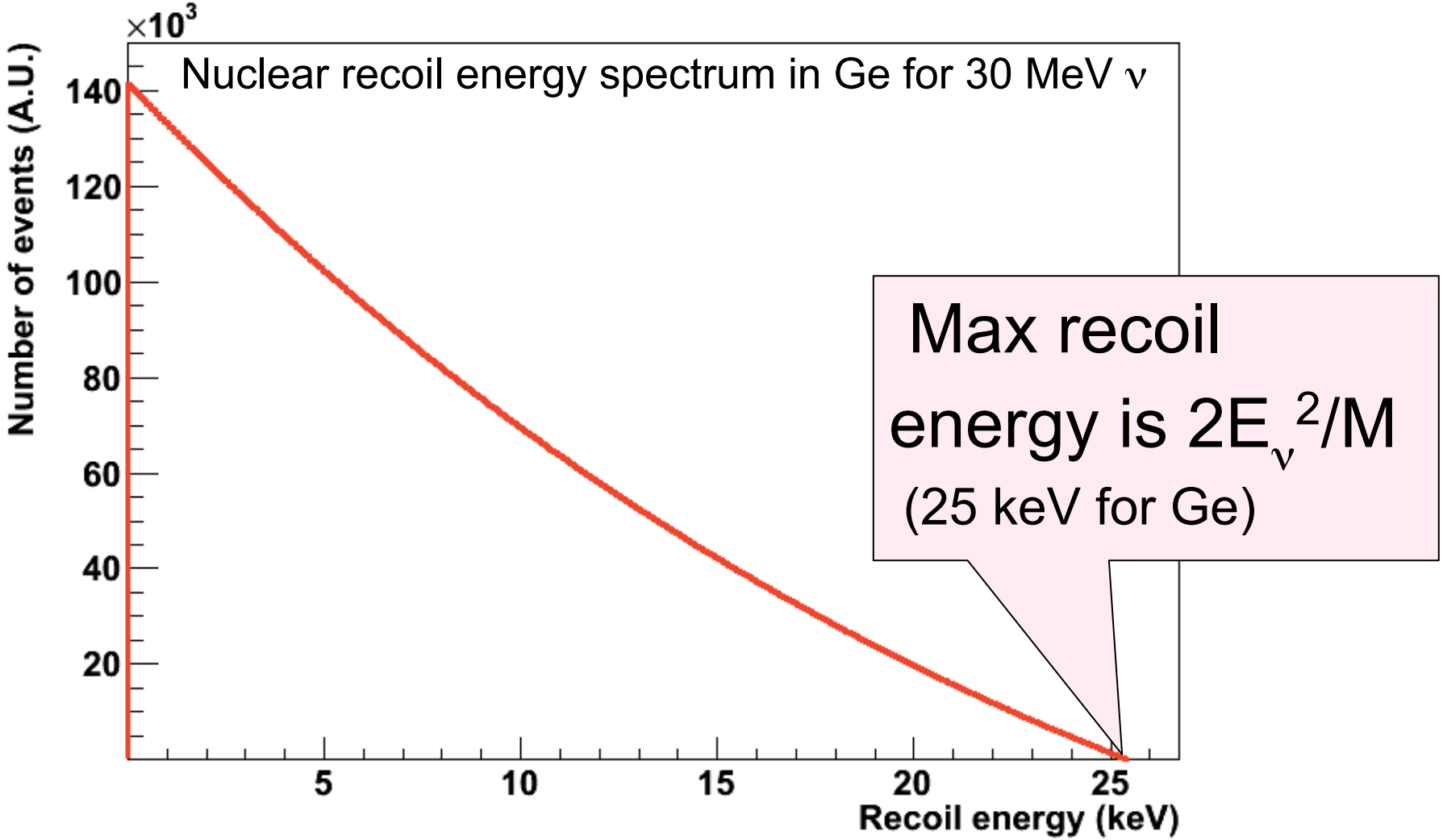
A. Bolozdynya et al., arXiv:1211.5199

Physics with stopped-pion sources

Physics	Experiments	Comments
Sterile neutrino oscillations (LSND-like)	JSNS^2@J-PARC MLF, (OscSNS @ ORNL), liquid scintillator	nuebar appearance w/ IBD, nueCC and NC channels also
Cross sections for supernova neutrinos	(NuSNS, CAPTAIN), COHERENT-NINs	Needed! (C, O, Ar, Pb, Fe) but no active efforts except COHERENT-NINs
CEvNS	COHERENT @ORNL, CENNS@BNB	COHERENT moving ahead rapidly

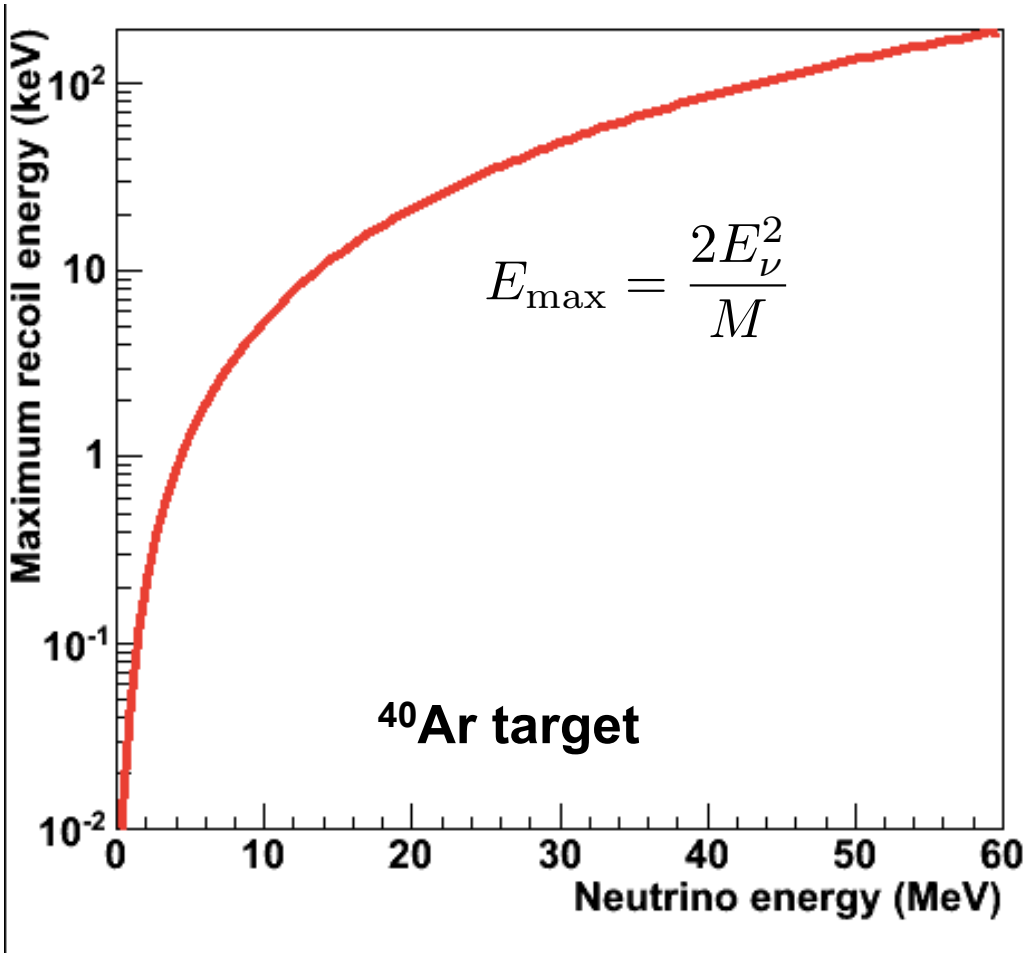
+ 3-flavor CP-violation w/oscillations (DAEδALUS)

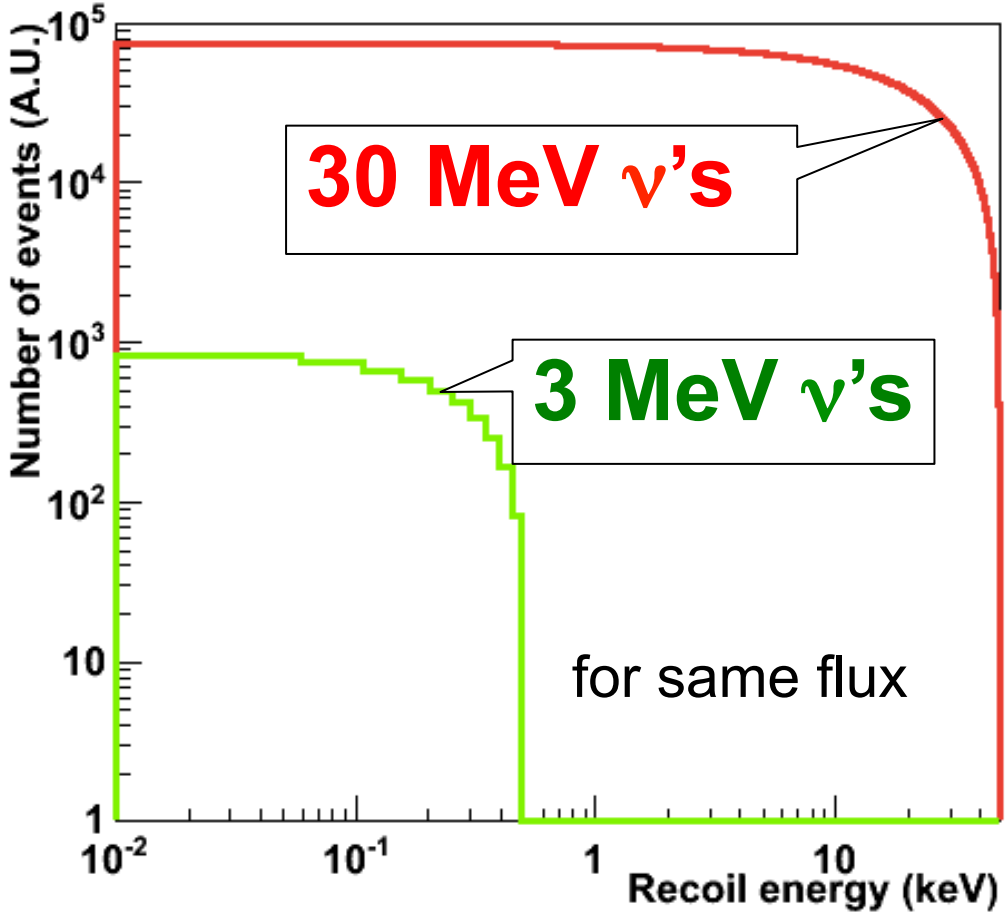
Large cross section, but never observed due to **tiny nuclear recoil energies:**



➔ but **WIMP dark matter detectors** developed over the last ~decade are sensitive to ~ keV to 10's of keV recoils

Both **cross-section and maximum recoil energy increase with neutrino energy**:





Want energy as large as possible while satisfying coherence condition: $Q \lesssim \frac{1}{R}$ (<~ 50 MeV for medium A)

What do you want in a detector for CEvNS?

Need very low energy threshold, background discrimination

Size	always want this, but 10's of kg may be OK!
Low energy threshold	~keV to 10 keV
Energy resolution & scale	Measure in recoil spectrum
Angular resolution	Nice if possible (hard)
Position resolution	Nice if possible, reduces multiple-scatter bg
Timing resolution	Good for pulsed beam
Low background	BG rate << beam event rate; underground location needed, must be clean, particle ID useful for bg rejection (e/γ vs nuclear recoil)
Flavor sensitivity	NC; can't tag flavors (but some CC bg)

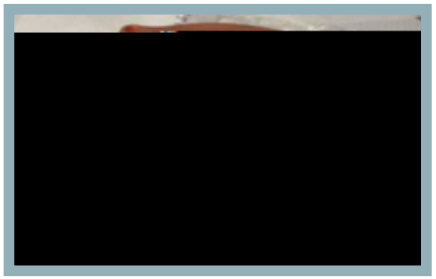
it's all about the backgrounds ...

(Here, actually, a lot of it is about the source...)

Types of detectors for CEvNS (@stopped-π energies)

Scintillating Crystal

- NaI, CsI[Tl]
- good light yield
- low intrinsic background,
- some pulse shape discrimination



Noble Liquid TPC

- can make clean, large volume
- select nuclear recoil w/ ionization & scintillation
- LXe, LAr

Noble Liquid Single Phase

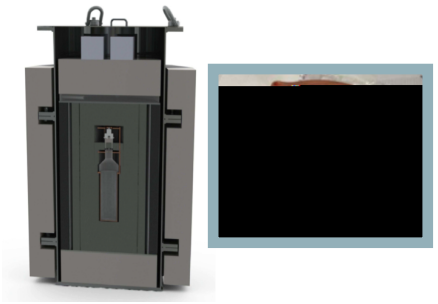
- can make clean, large volume, simple
- select nuclear recoil by scintillation pulse shape
- LNe, LAr

Germanium P-type Point Contact

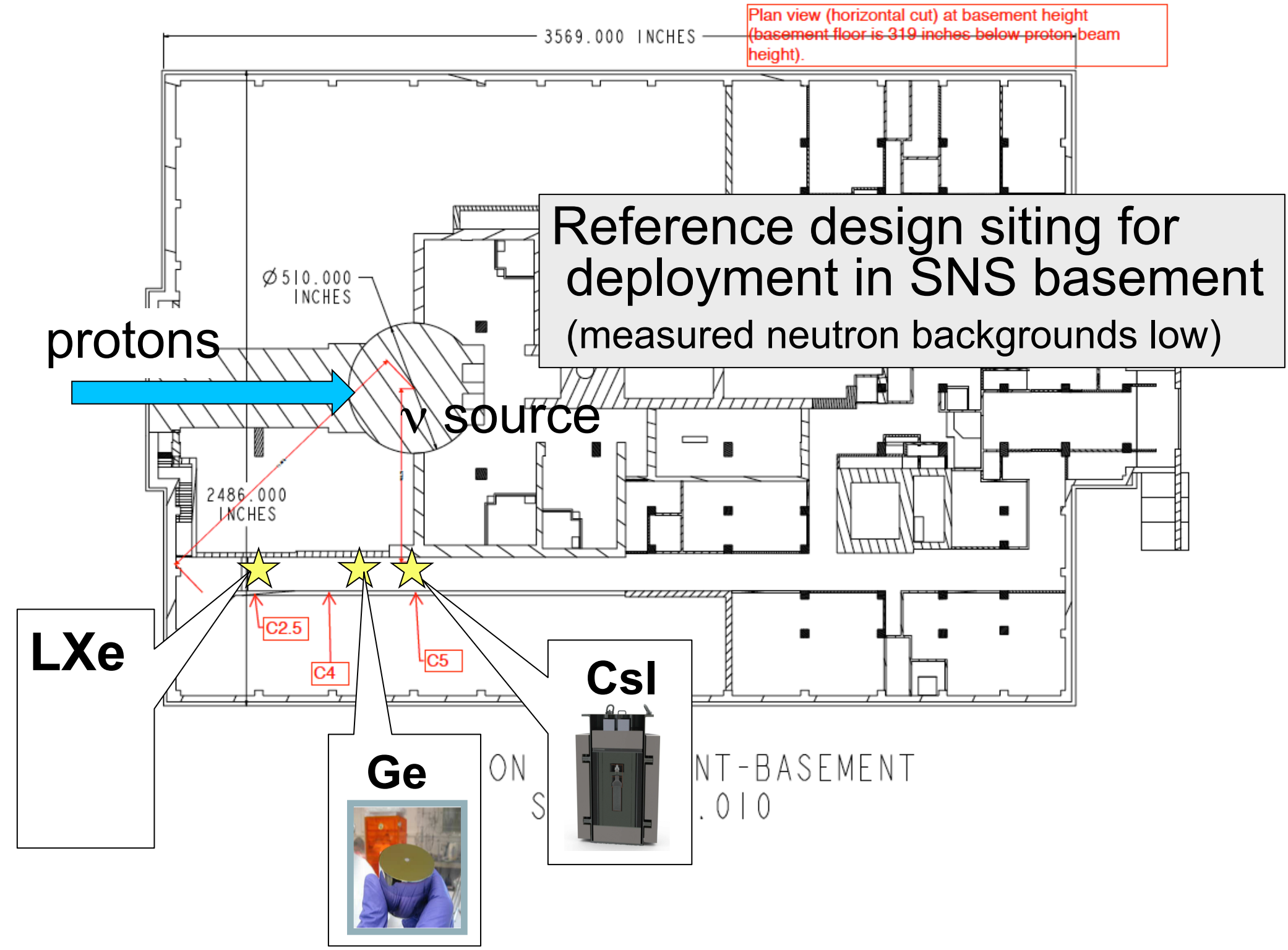
- good energy resolution
- low intrinsic background

... and more... most DM technologies will work @ πDAR energies ...

COHERENT detector subsystems

Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)	COHERENT SNS Spallation Neutron Source
CsI[Na]	Scintillating Crystal	14	20	6.5	
Ge	HPGe PPC	10-20	20	5	
Xe	Two-phase LXe TPC	100	32	4	

(possible future: NaI, Ar,...)



Reference design siting for deployment in SNS basement

(measured neutron backgrounds low)

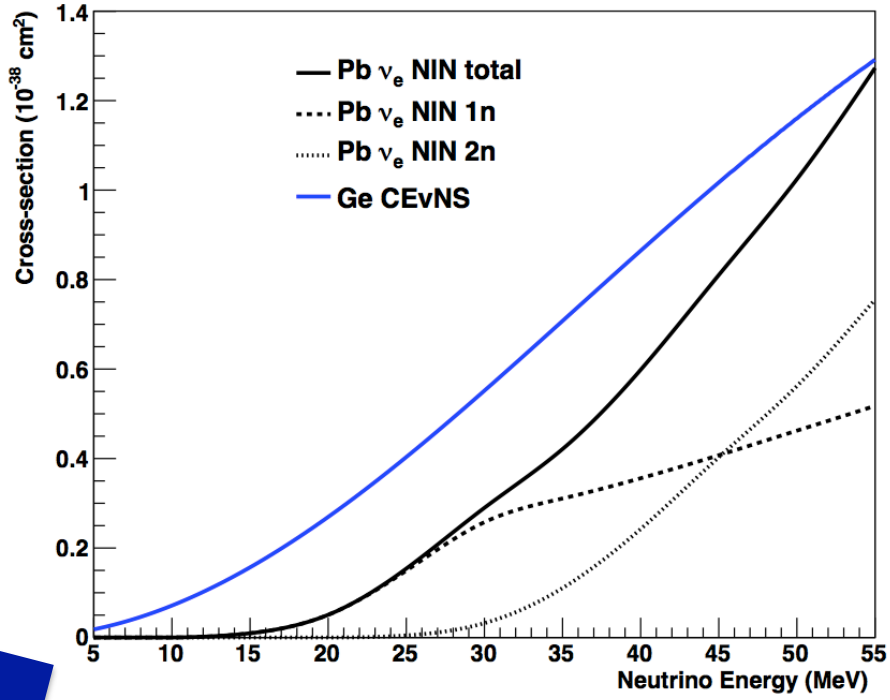
Currently measuring *neutrino-induced neutrons* in lead, (iron, copper), ...

$\nu_e + {}^{208}Pb \rightarrow {}^{208}Bi^* + e^-$ CC

↘ 1n, 2n emission

$\nu_x + {}^{208}Pb \rightarrow {}^{208}Pb^* + \nu_x$ NC

↘ 1n, 2n, γ emission

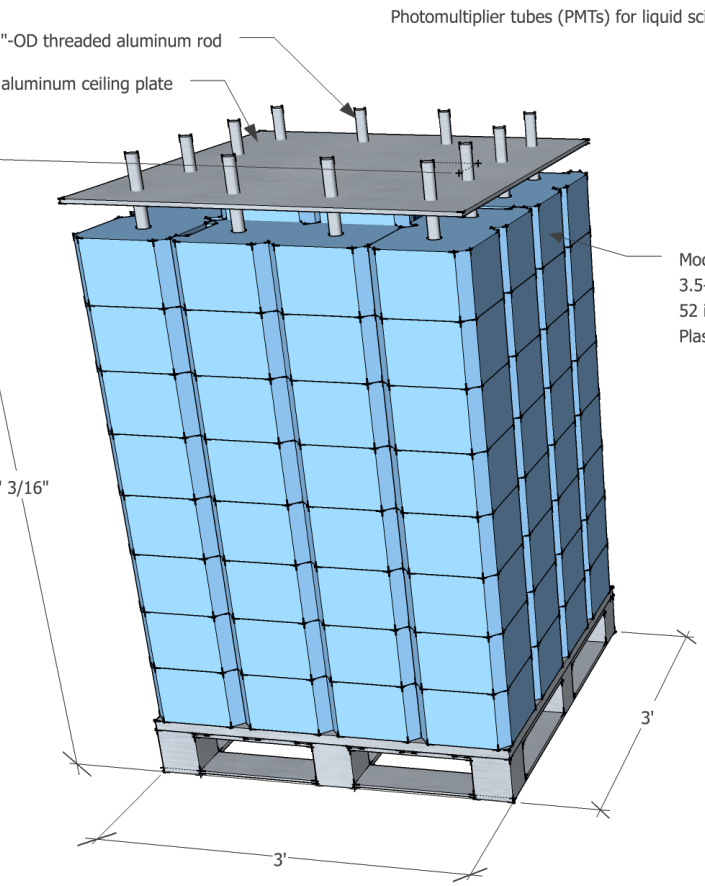


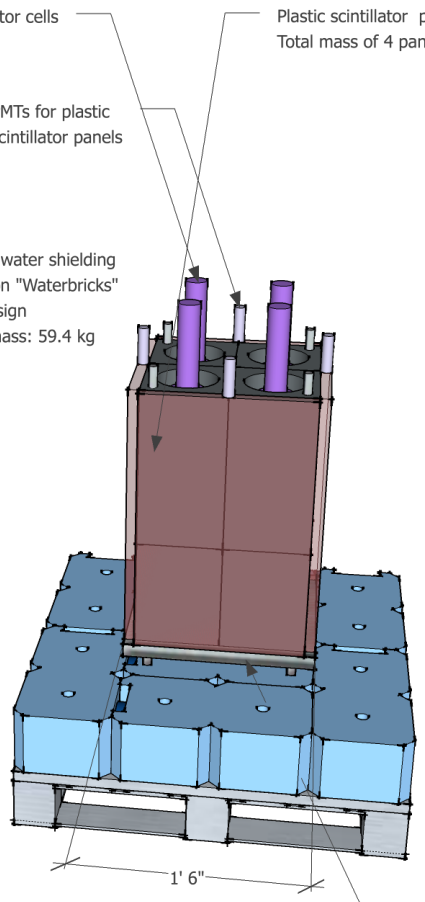
A non-negligible background to CEvNS, especially in lead shield

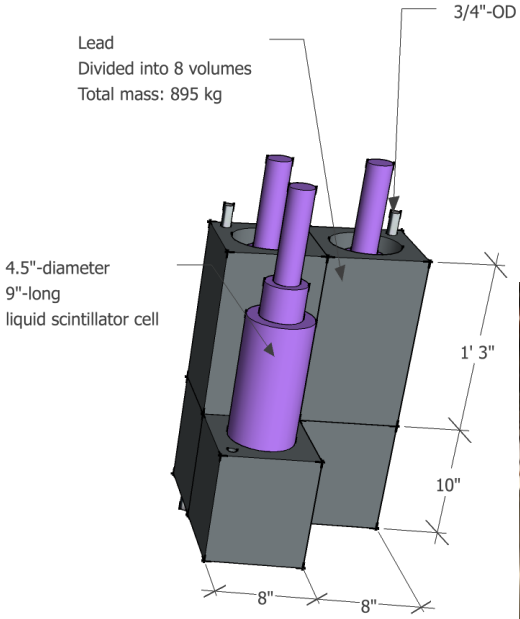
... and interesting in itself! (HALO)

NIN measurement in SNS basement

- Scintillator inside CsI detector lead shield (now)
- Liquid scintillator surrounded by lead (swappable for other NIN targets) inside water shield







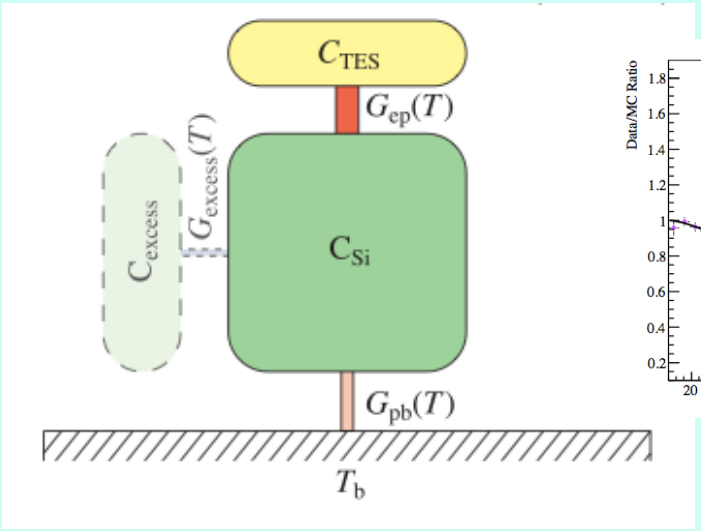
Phil Barbeau

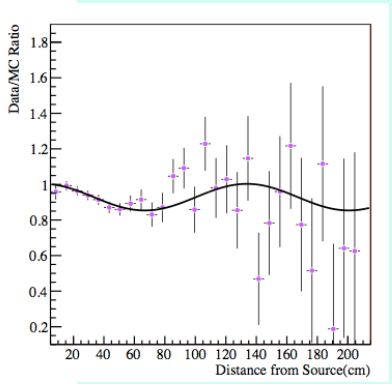
The Low-Energy Recoil Frontier:

There is strong physics motivation to extend recoil energy threshold to sub-keV (reactor & source ν's)

(magnetic moment, sterile osc w/small L, reactor monitoring, astrophysics,...)

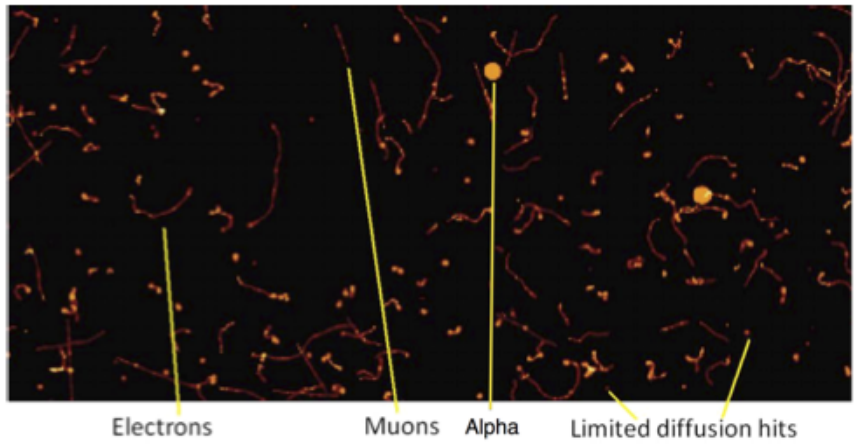
Cryogenic solid-state bolometers (RICOCHET)





J. Formaggio, E. Figueroa-Feliciano, and A. Anderson, PRD D 85, 013009 (2012)

Silicon CCDs (CONNIE)



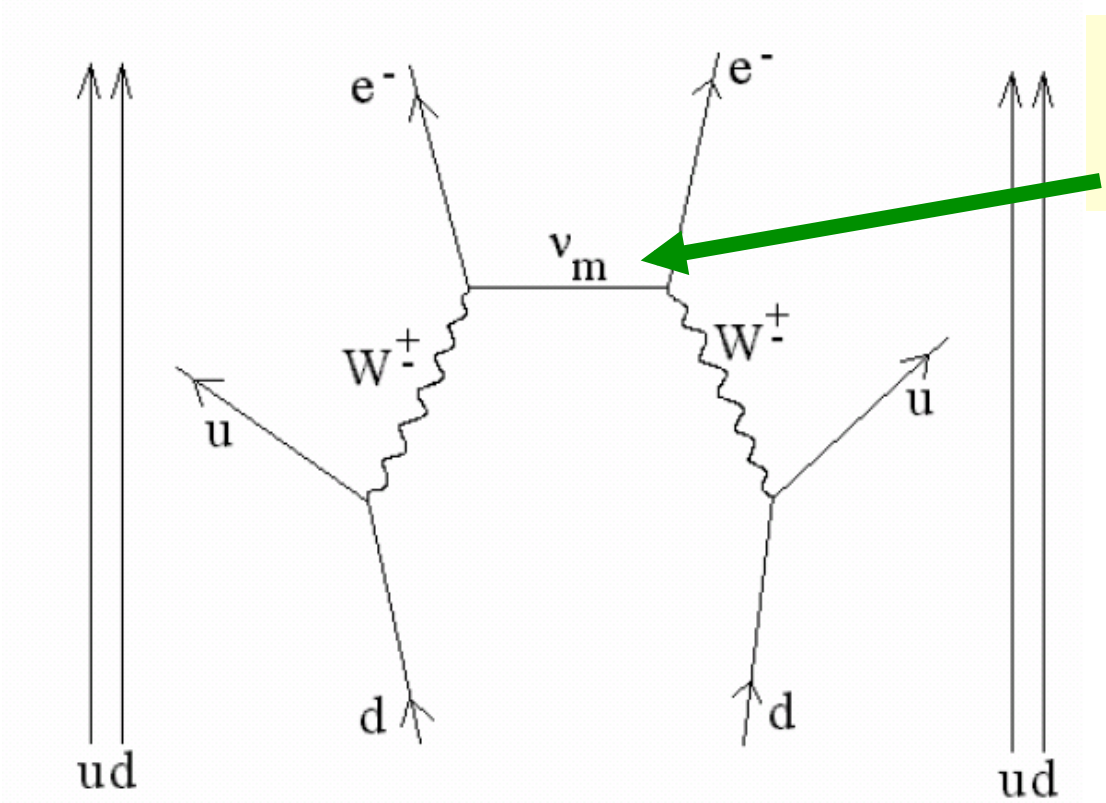
Moroni et al., Phys.Rev. D91 (2015) 7, 072001

(+ Ge PPCs, spherical TPCs, ...)

it's all about the backgrounds ...

How to Detect No Neutrinos

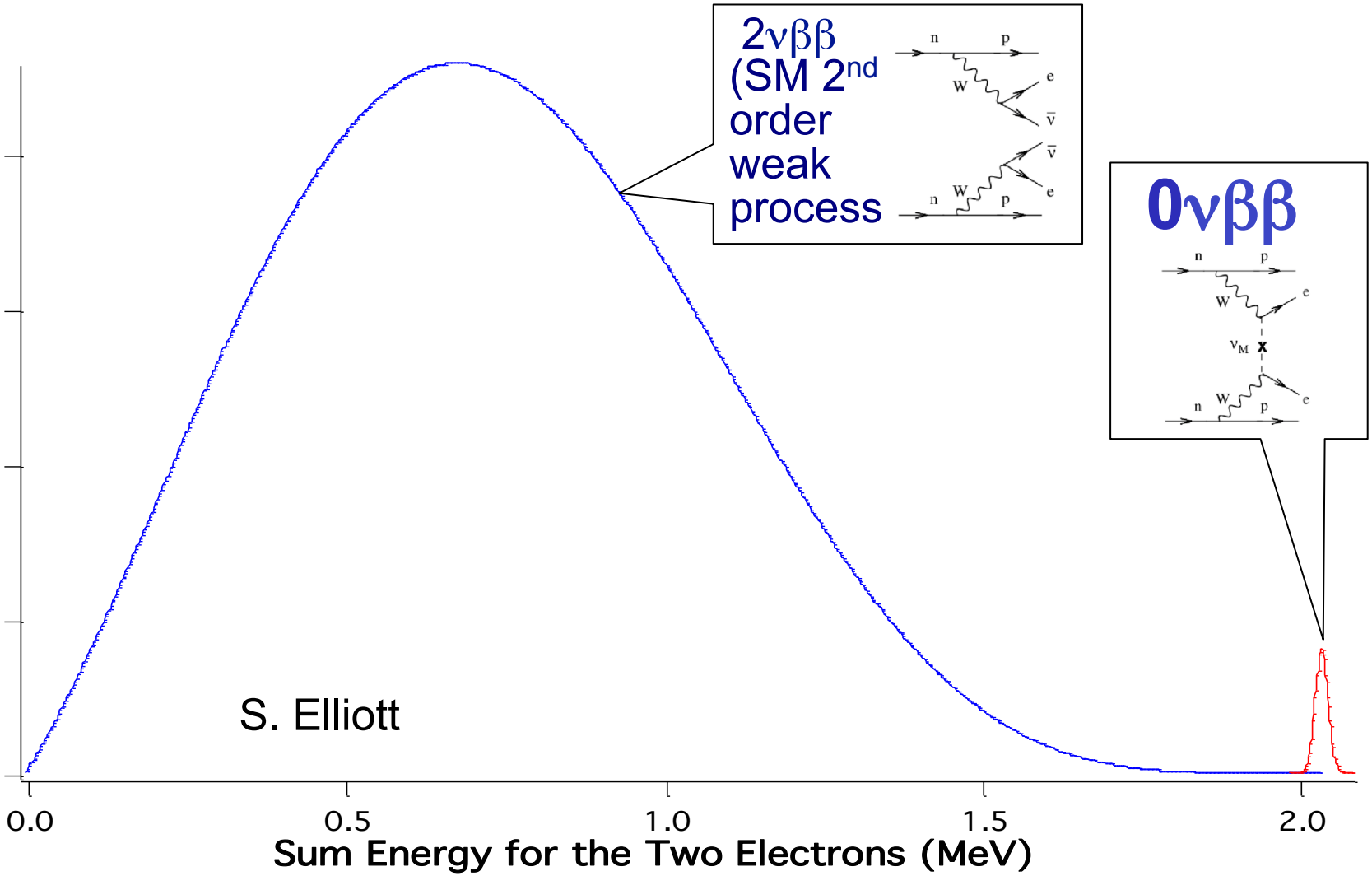
Neutrinoless Double Beta Decay



Only possible for Majorana ν

Look at nuclides for which this is energetically possible, *and* which cannot α, 1β decay

Experimental strategy: look for peak in the two-electron spectrum corresponding to neutrinoless final state



Observed half-life:

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

phase space

matrix element

effective mass

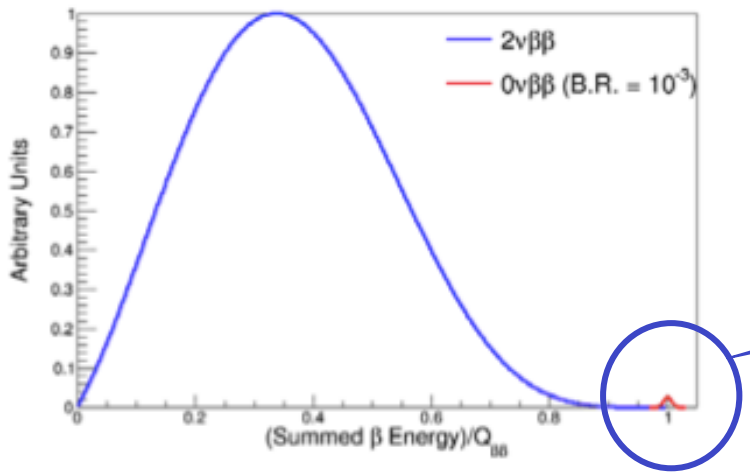
$$\langle m_{\beta\beta} \rangle^2 = |\sum_i U_{ei}^2 \; m_{\nu i}|^2$$

Effective mass depends on the mixing matrix parameters

Experimental sensitivity

$$T_{1/2} > \frac{\ln 2 \ \varepsilon \cdot N_{source} \cdot T}{UL(B(T) \cdot \Delta E)}$$

ε: detection efficiency
N_{source}: number of isotope nuclei
T: observation time
UL(B(T) ΔE): upper limit for expectation
of B background events in ROI of width ΔE



want lots of signal
and no background
in Region of Interest

Go after the numerator:

$$T_{1/2} > \frac{\ln 2 \; \varepsilon \cdot N_{source} \cdot T}{UL(B(T) \cdot \Delta E)}$$

ε: detection efficiency
N_{source}: number of isotope nuclei
T: observation time
UL(B(T) ΔE): upper limit for expectation
of B background events in ROI of width ΔE

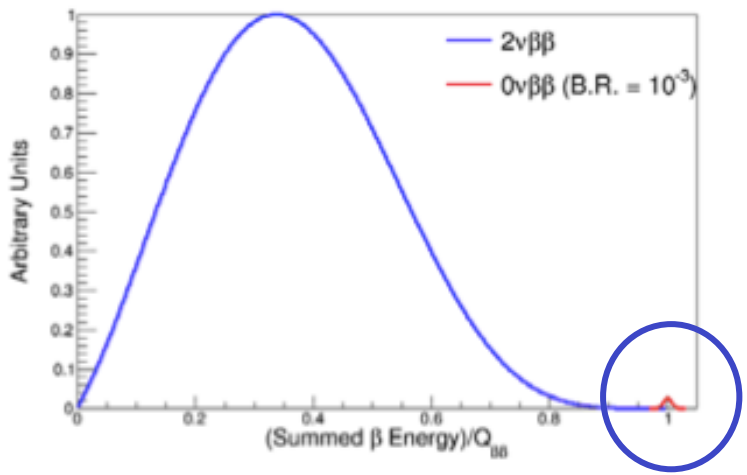
Want lots of candidate isotope!
At lifetime of $10^{26\text{-}27}$ yr ($\langle m_{\beta\beta} \rangle \sim$ 50 meV in IH region)
need ~ 10^4 moles (~ 1 tonne) for 1 count/yr

➔ want high natural abundance

Go after the denominator:

$$T_{1/2} > \frac{\ln 2 \ \varepsilon \cdot N_{source} \cdot T}{UL(B(T) \cdot \Delta E)}$$

ε: detection efficiency
N_{source}: number of isotope nuclei
T: observation time
UL(B(T) ΔE): upper limit for expectation
of B background events in ROI of width ΔE



- Want **small ΔE** to avoid the $2\nu\beta\beta$ "friendly fire" and exclude other background
- Generally want **high Q value** to keep away from background
- Beat down all other background ... ultra-cleanliness, underground location needed

Neutrinoless Double Beta Decay Experiments:
many isotopes and technologies

Experiment	Isotope	Mass	Technique	Status	Location
AMoRE [164, 165]	^{100}Mo	50 kg	$CaMoO_4$ scint. bolometer crystals	Devel.	Yangyang
CANDLES [166]	^{48}Ca	0.35 kg	CaF_2 scint. crystals	Prototype	Kamioka
CARVEL [167]	^{48}Ca	1 ton	CaF_2 scint. crystals	Devel.	Solotvina
COBRA [168]	^{116}Cd	183 kg	^{enr}Cd CZT semicond. det.	Prototype	Gran Sasso
CUORE-0 [151]	^{130}Te	11 kg	TeO_2 bolometers	Constr. (2013)	Gran Sasso
CUORE [151]	^{130}Te	206 kg	TeO_2 bolometers	Constr. (2014)	Gran Sasso
DCBA [169]	^{150}Ne	20 kg	^{enr}Nd foils and tracking	Devel.	Kamioka
EXO-200 [152, 153, 154]	^{136}Xe	200 kg	Liq. ^{enr}Xe TPC/scint.	Op. (2011)	WIPP
nEXO [155]	^{136}Xe	5 t	Liq. ^{enr}Xe TPC/scint.	Proposal	SNOLAB
GERDA [150, 170]	^{76}Ge	~35 kg	^{enr}Ge semicond. det.	Op. (2011)	Gran Sasso
GSO [171]	^{160}Gd	2 t	Gd_2SiO_5:Ce crys. scint. in liq. scint.	Devel.	
KamLAND-Zen [156, 158]	^{136}Xe	400 kg	^{enr}Xe dissolved in liq. scint.	Op. (2011)	Kamioka
LZ [161]	^{136}Xe	600 kg	Two-phase ^{nat}Xe TPC/scint	Proposal	SURF
LUCIFER [172, 173]	^{82}Se	18 kg	ZnSe scint. bolometer crystals	Devel.	Gran Sasso
MAJORANA [147, 148, 149]	^{76}Ge	30 kg	^{enr}Ge semicond. det.	Constr. (2013)	SURF
MOON [174]	^{100}Mo	1 t	^{enr}Mo foils/scint.	Devel.	
SuperNEMO-Dem [162]	^{82}Se	7 kg	^{enr}Se foils/tracking	Constr. (2014)	Fréjus
SuperNEMO [162]	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal (2019)	Fréjus
NEXT [159, 160]	^{136}Xe	100 kg	gas TPC	Devel. (2014)	Canfranc
SNO+ [39, 175, 176]	^{130}Te	800 kg	Te-loaded liq. scint.	Constr. (2013)	SNOLAB

From arXiv: 1310.4340

General NLDBD experiment strategies

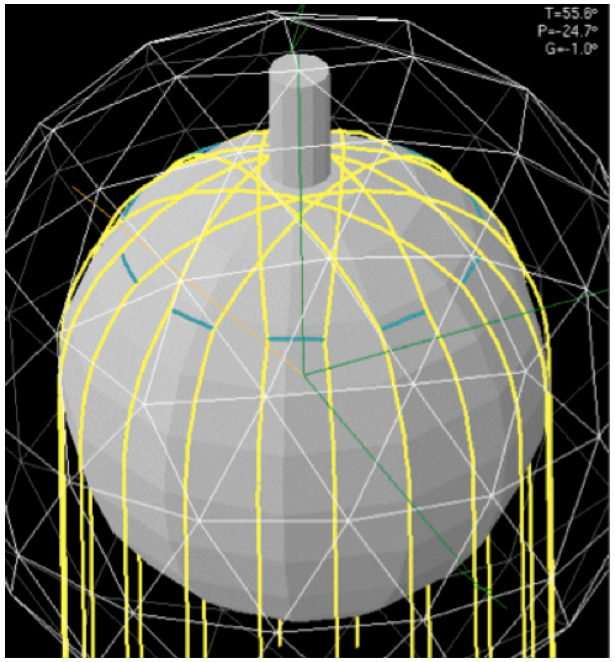
$$T_{1/2} > \frac{\ln 2 \ \varepsilon \cdot N_{source} \cdot T}{UL(B(T) \cdot \Delta E)}$$

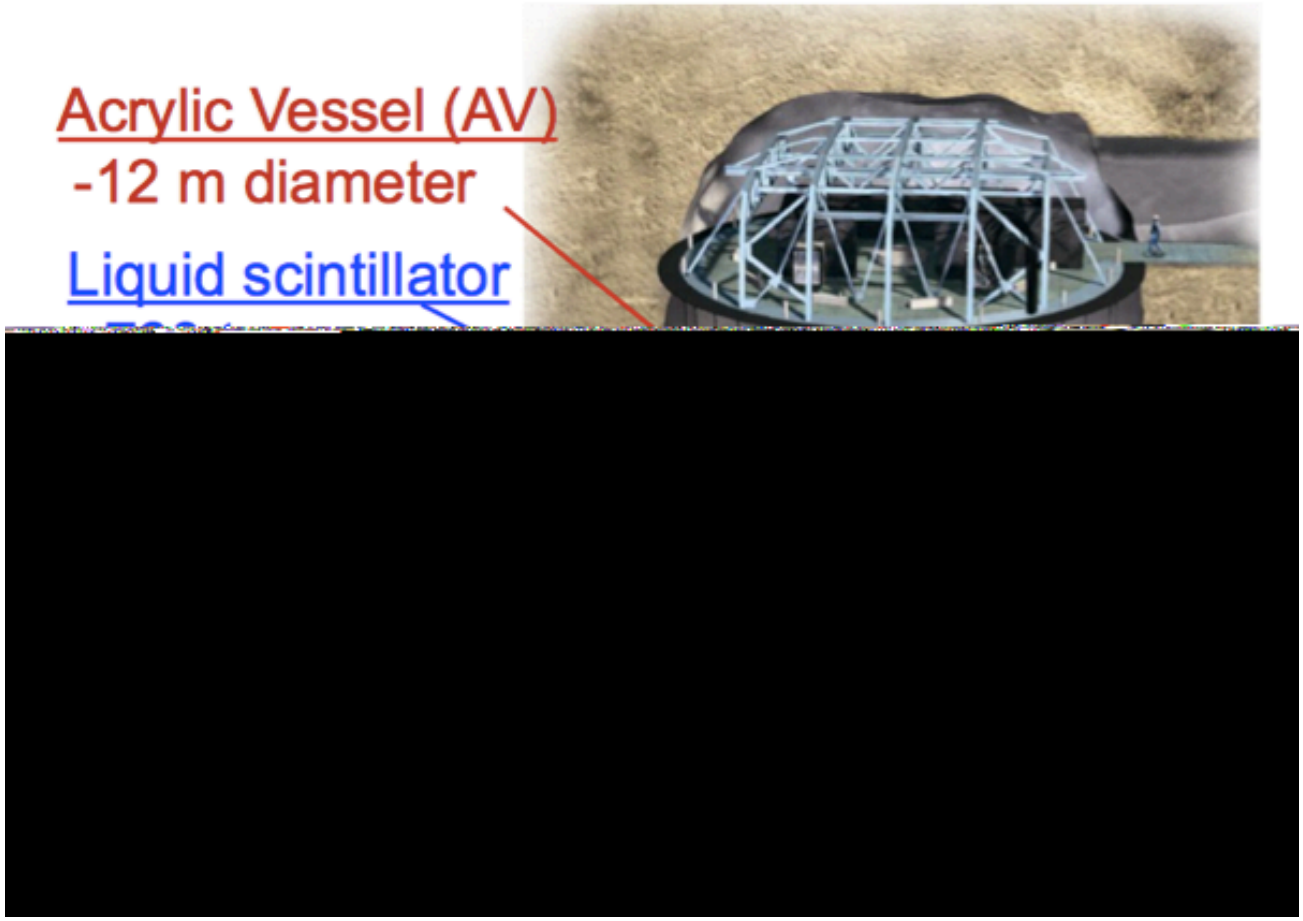
The "Brute Force" Approach	The "Peak-Squeezer" Approach	The "Final-State Judgement" Approach
focus on the numerator with a huge amount of material (often sacrificing resolution)	focus on the denominator by squeezing down ΔE (various technologies)	try to make the background zero by tracking or other technique

...some experiments take hybrid approaches...

Another Brute Force Strategy Example:

SNO+

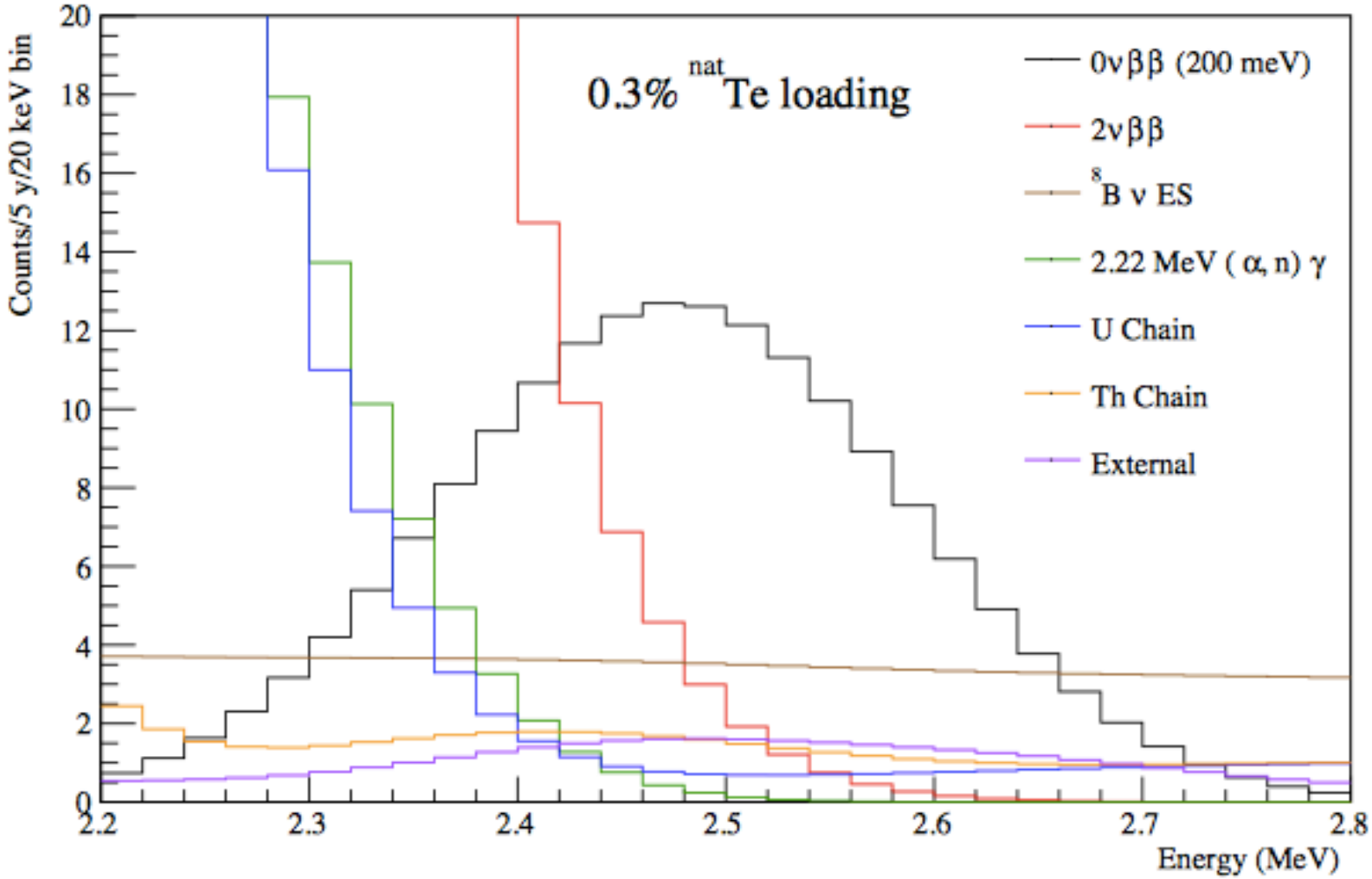




- original plan was to use ^{150}Nd, but switched to ^{130}Te
- 0.3% Te in LAB scintillator (160 kg ^{130}Te)
- very deep location with negligible cosmogenics

Expected spectrum for 5 years of SNO+

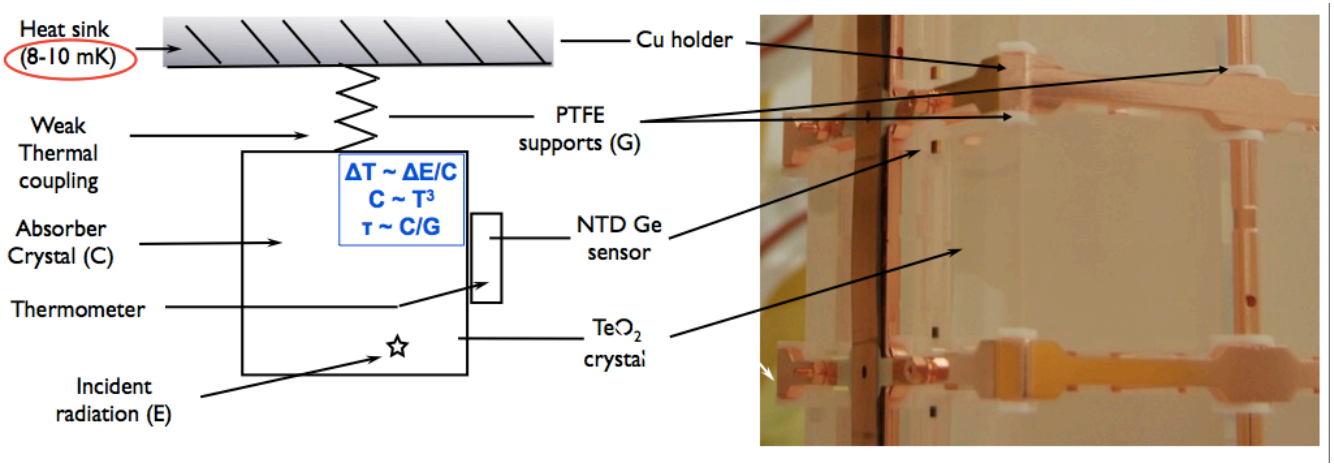
From L. Winslow Nu2014 review talk

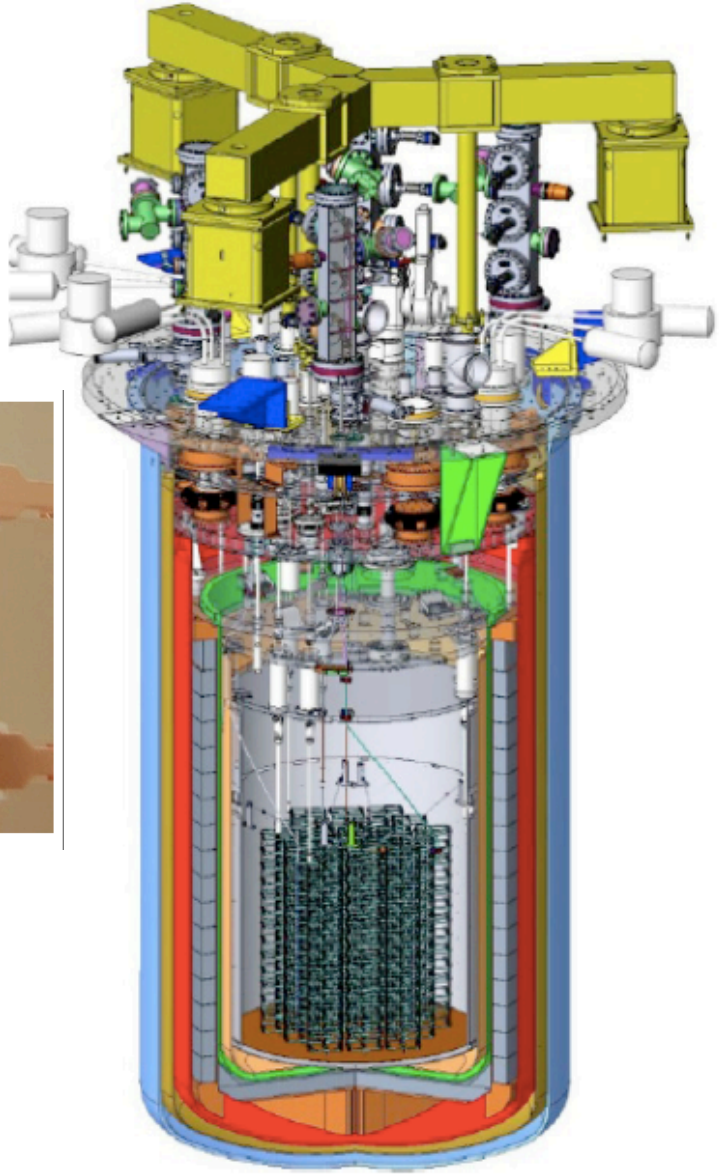


Possible farther future with higher loading, better light collection

A Peak-Squeezer: CUORE

Cryogenic bolometer w/ TeO_2

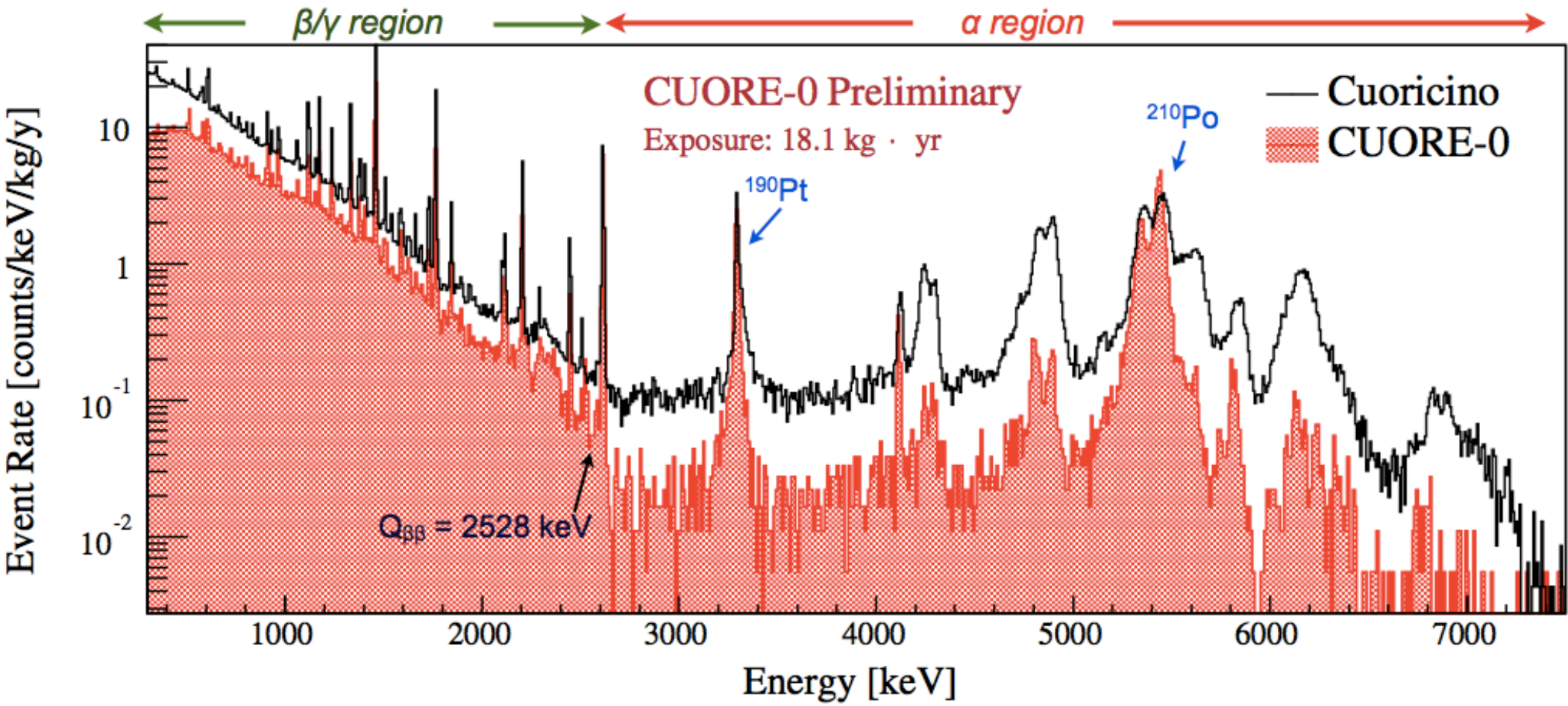




- the source is the detector
- calorimetric approach w/ high intrinsic energy resolution

Cuoricino → CUORE-0 → CUORE

prototype, 2003 | one tower, 11 kg ^{130}Te, 2012 | 19 towers, 2015



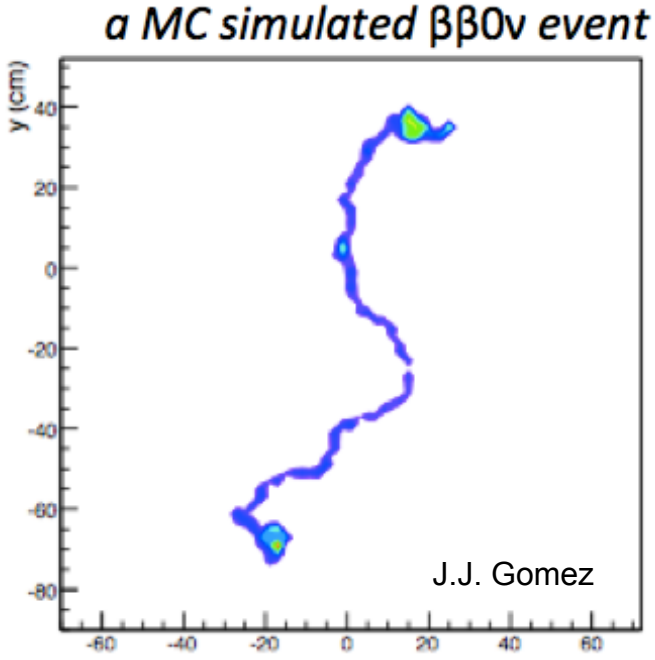
	0νββ region cnts/(keV kg y)	2700-3900 keV	ε(%)
Cuoricino	0.153 ± 0.006	0.110 ± 0.001	83
CUORE-0	**0.063 ± 0.006**	**0.020 ± 0.001**	78

Future bolometer concepts

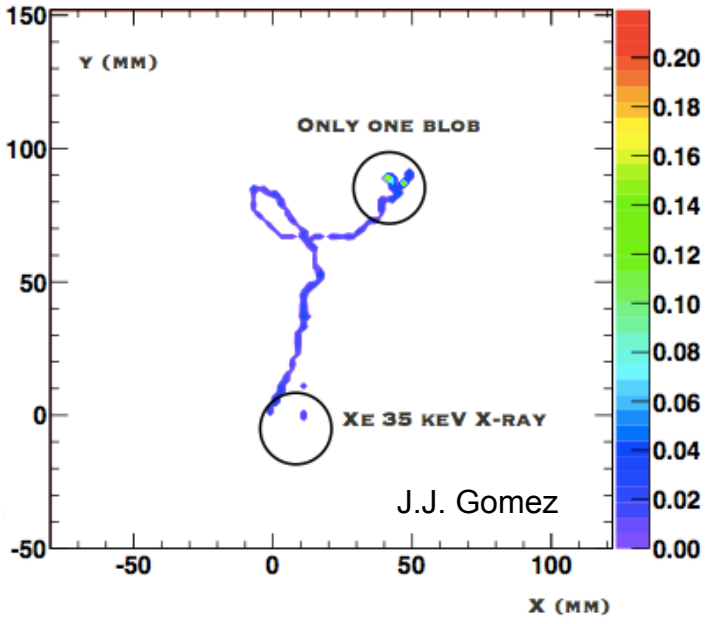
Use scintillation (or Cherenkov) light as well as thermal energy for better background rejection (mitigates surface backgrounds)

Proposals: ZnSe, $ZnMoO_4$, $CaMoO_4$
LUCIFER, LUMINEU, AMoRE

Final-State Judgers: Trackers



Evaluate final-state particles based on their actions

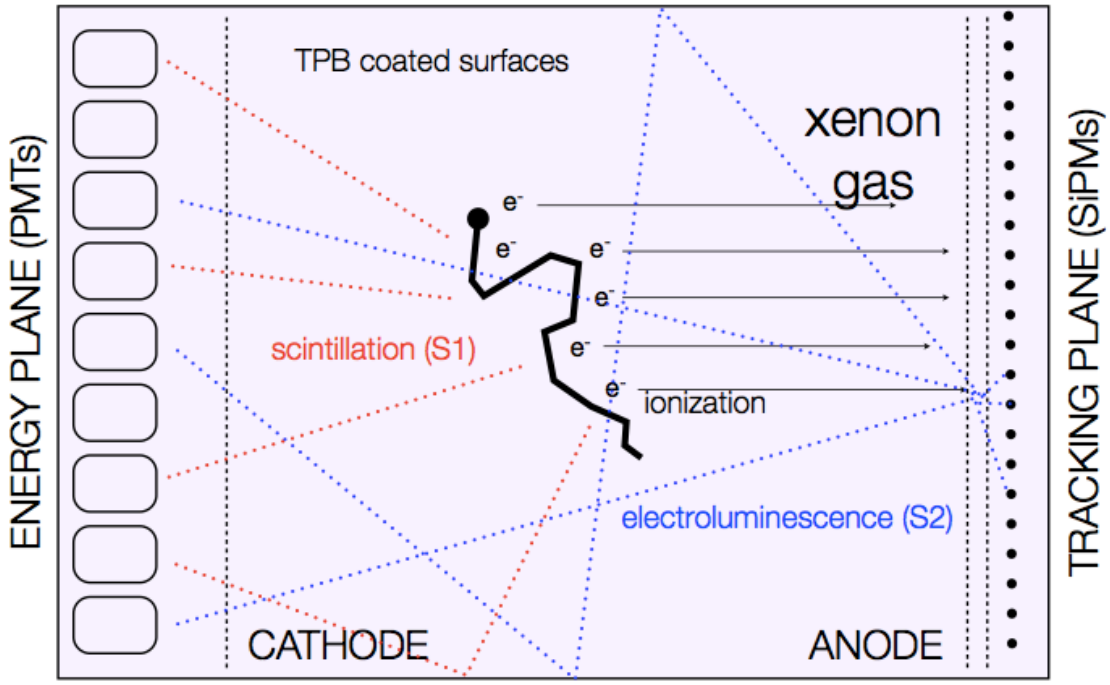


Final-State Judger Example:

NEMO-3

- NEMO-3 Modane Laboratory
- "Camembert" of multiple isotopes:
  foils + tracking
- several $2\nu\beta\beta$ measurements

Final-State Judger Example: NEXT

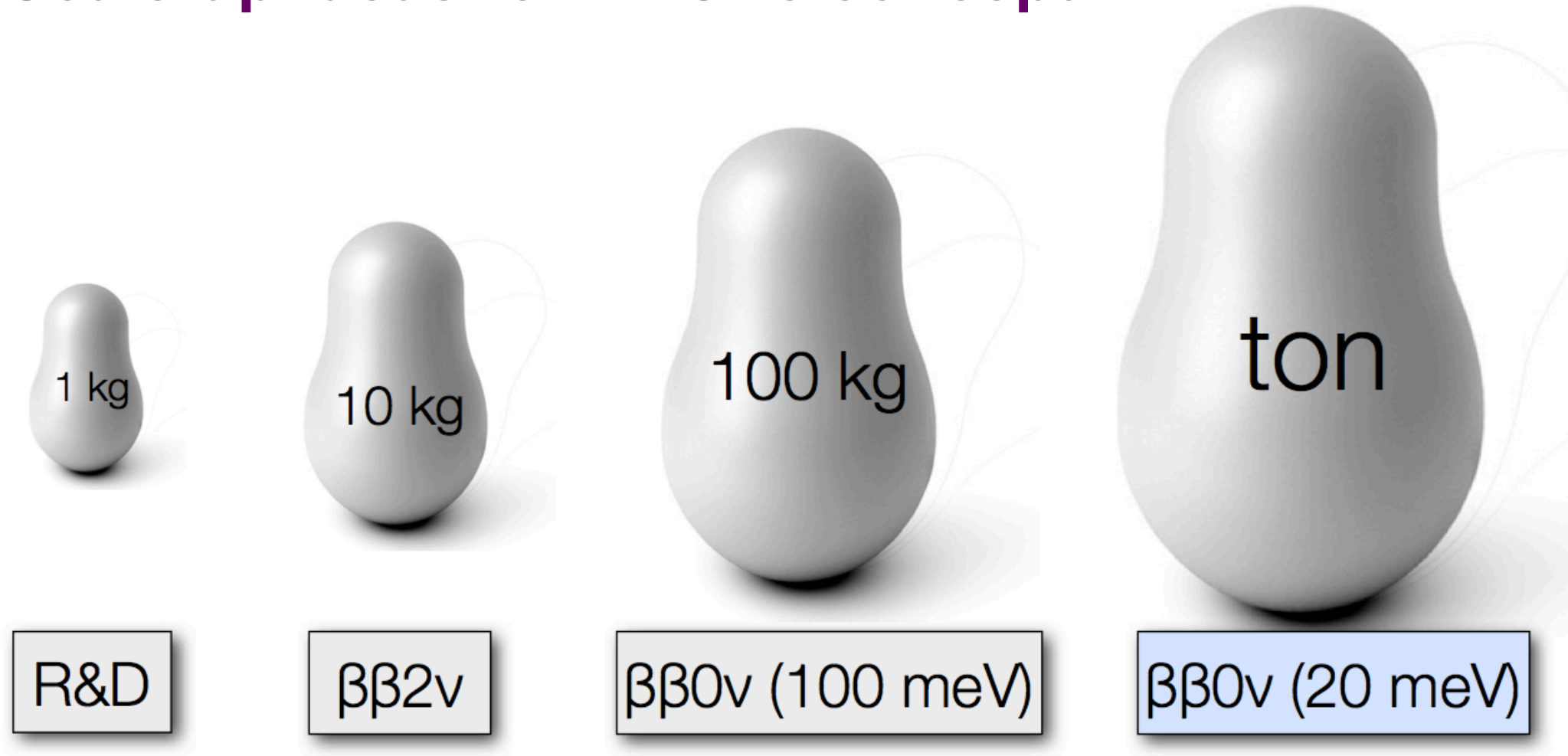


High-pressure xenon gas time projection chamber

- high resolution and tracking,
  very good background rejection
- planned for Canfranc underground lab

1 kg demo @ IPIC

Scale-up ideas for HPGXe concept



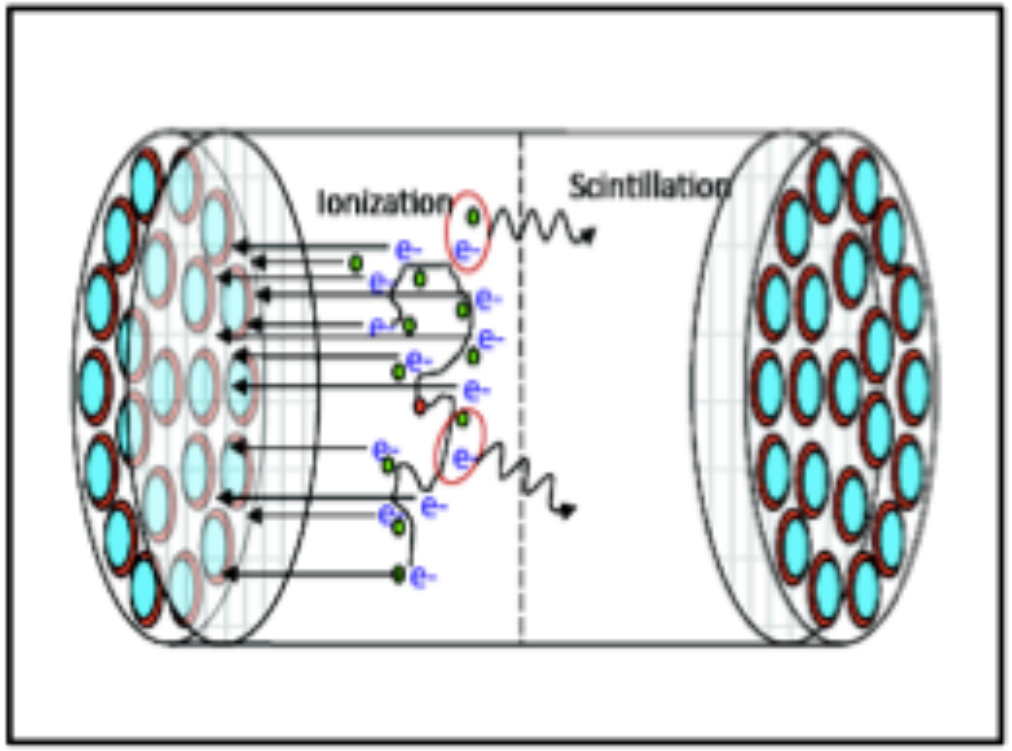
(2008-2013) (2014-2016) (2016-2020?) (2020?)

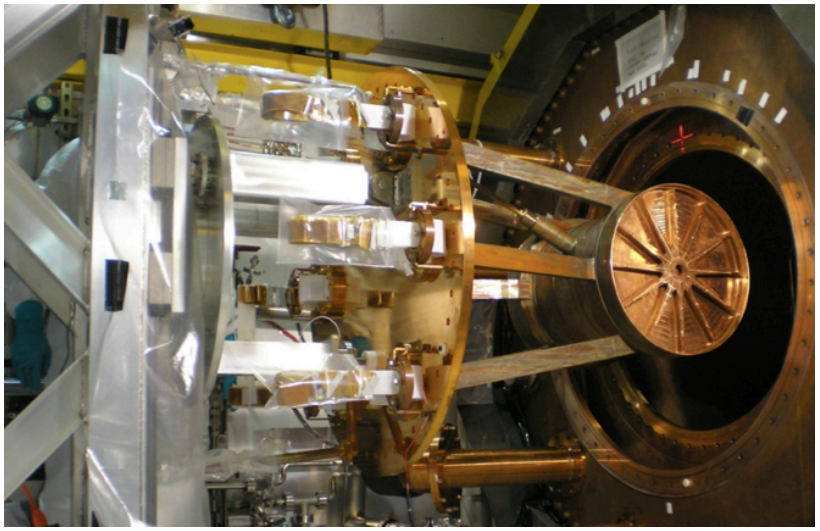
DEMO NEW NEXT MAGIX

J.J. Gomez

EXO

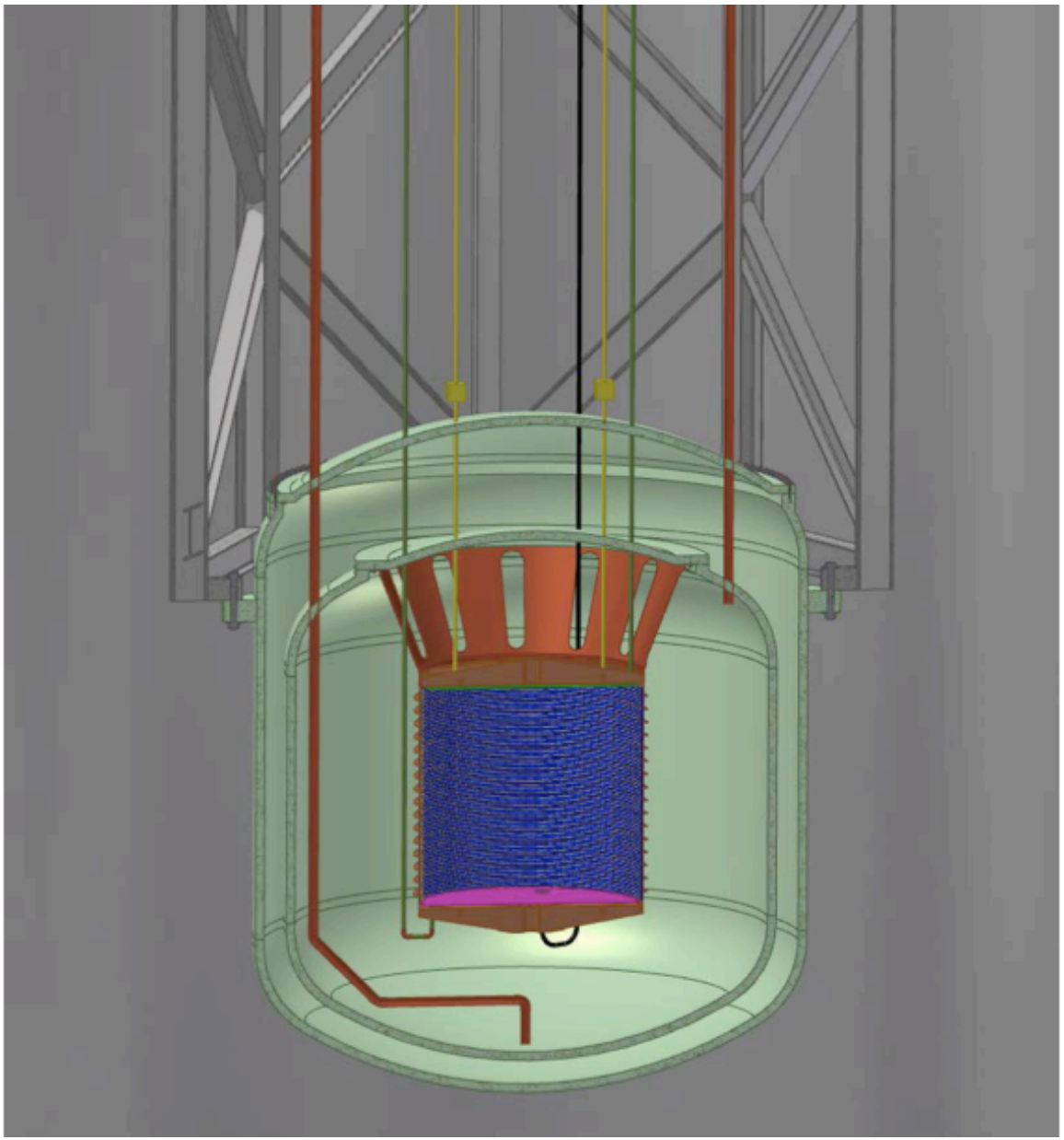
Liquid xenon
TPC





- no tracking, but single (0ν) -vs-multisite (bg) selection
- use scintillation & ionization
- WIPP in New Mexico
- EXO-200: 80.6% enriched ^{136}Xe

nEXO

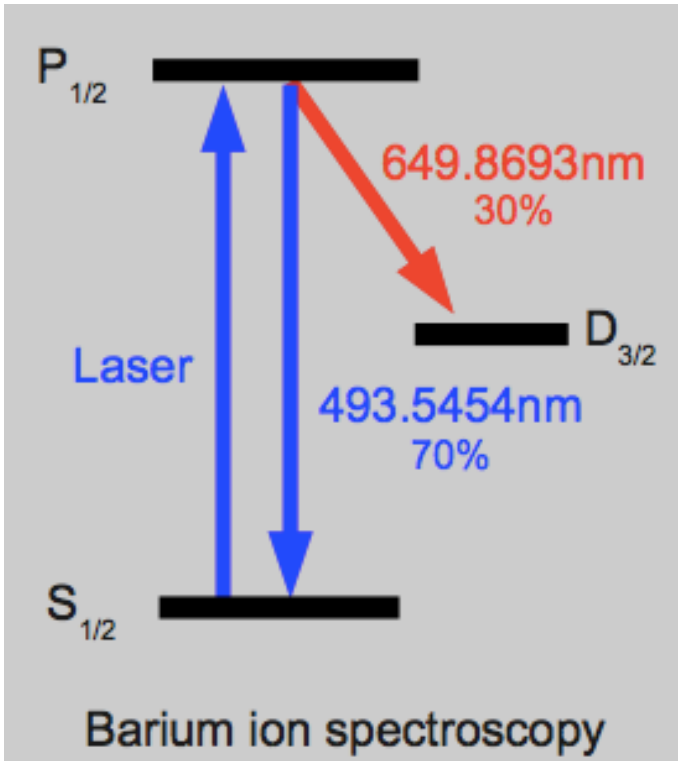


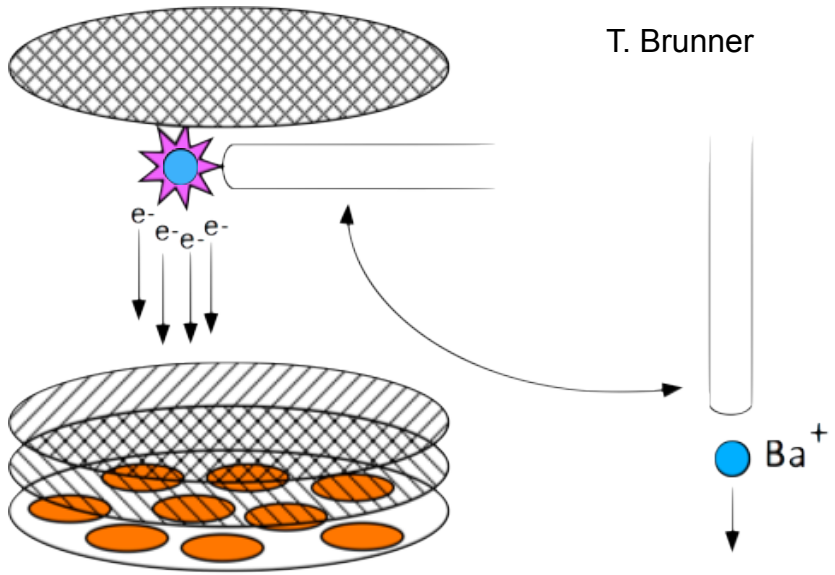
LXe TPC
scale-up
to ~5 tonnes

A possibility for liquid or gaseous xenon upgrades to EXO: (also MAGIX)

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

Barium tagging: identify the barium daughter ion by laser spectroscopy to reduce background



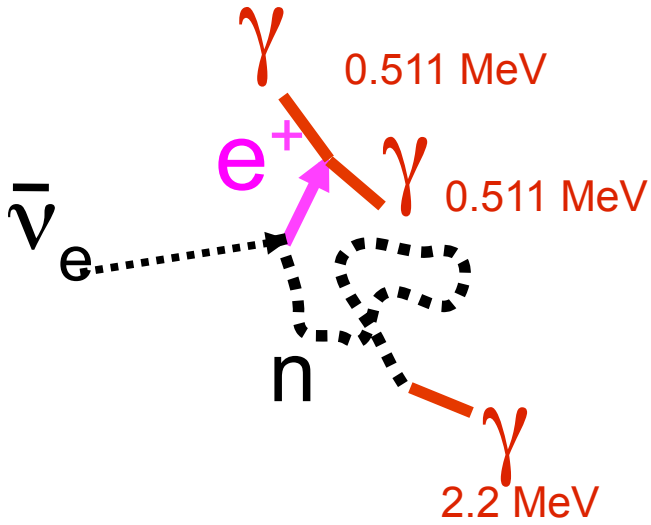


Challenge is to extract the barium ion from liquid or gas... R&D underway

What to take away from this lecture

Reactor, source, geo-neutrinos

- If you have electron antineutrinos >1.8 MeV, **IBD is your friend**
- **Liquid scintillator** works very well (various neutron capture strategies)
- Energy resolution, energy scale matter most



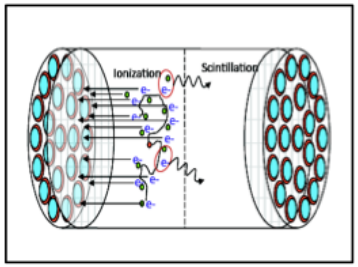
it's all about the backgrounds ...

Stopped-pion neutrinos

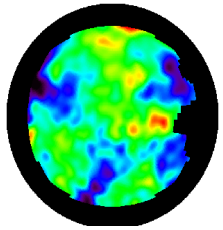
- LSND-style sterile searches possible
- Supernova cross sections (needed! need to grow effort)
- **CEvNS** measurement happening @ SNS!

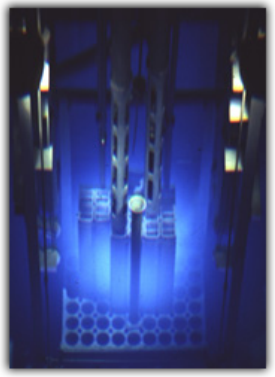
Absence of neutrinos (NLDBD)

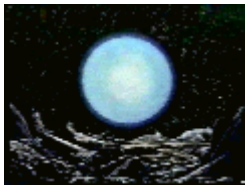
Multiple detection approaches:
more info in S. Mertens lectures

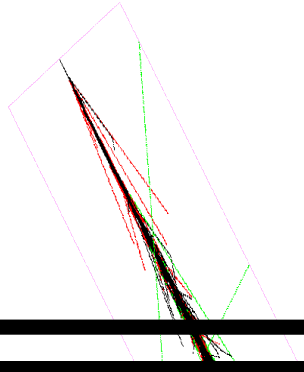
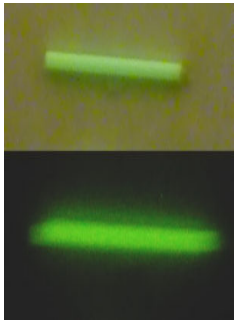
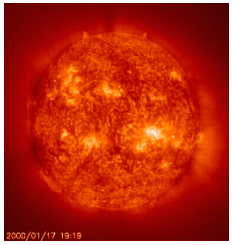
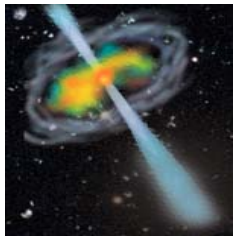
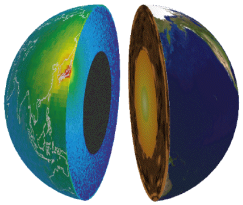
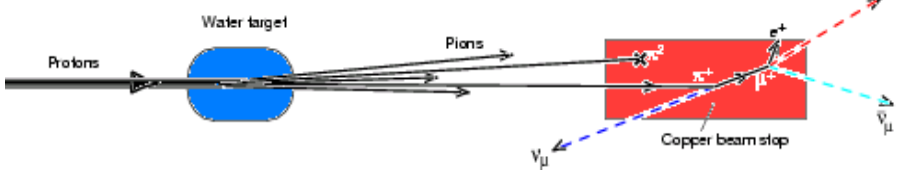


We may never have Geordi's visor, but there are lots of approaches and exciting ideas for the future!









meV eV keV MeV GeV TeV PeV EeV