School and Workshop on Dark Matter and Neutrino Detection

Dark Matter — Direct Detection

Lecture 1

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INTERDISCIPLINARIA DE LAS AMERICAS

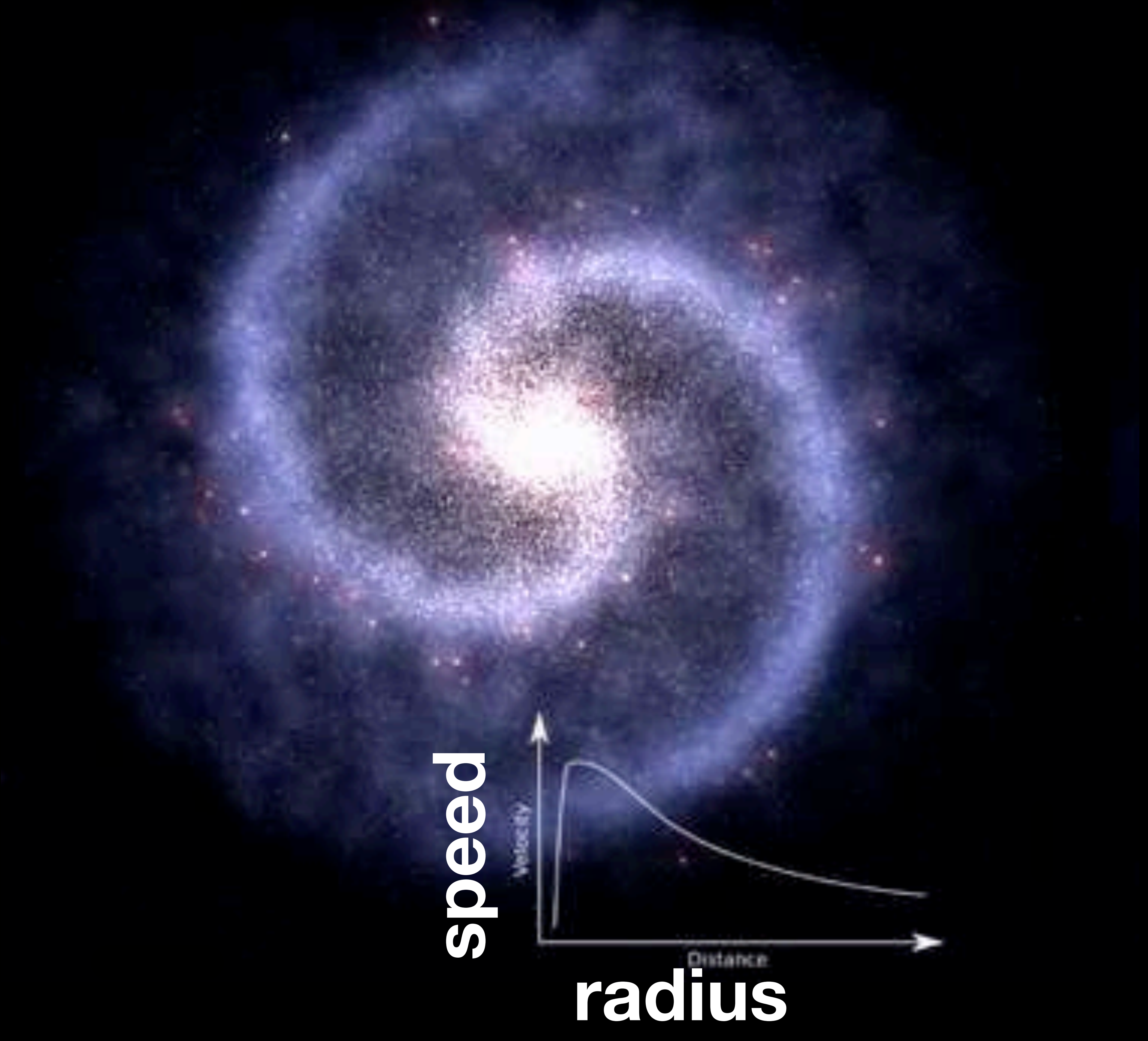
Outline

- Lecture 1:
  - The dark matter problem
  - WIMP and WIMP-like DM detection
- Lecture 2:
  - WIMP detection technologies
  - Current and future limits
- Lecture 3:
  - More 1-10 GeV DM detection technologies
  - To the Neutrino Floor, and beyond!
- Lecture 4:
  - The SuperCDMS Experiment
  - meV - 1GeV direct detection
- Lecture 5:
  - Indirect sterile neutrino detection

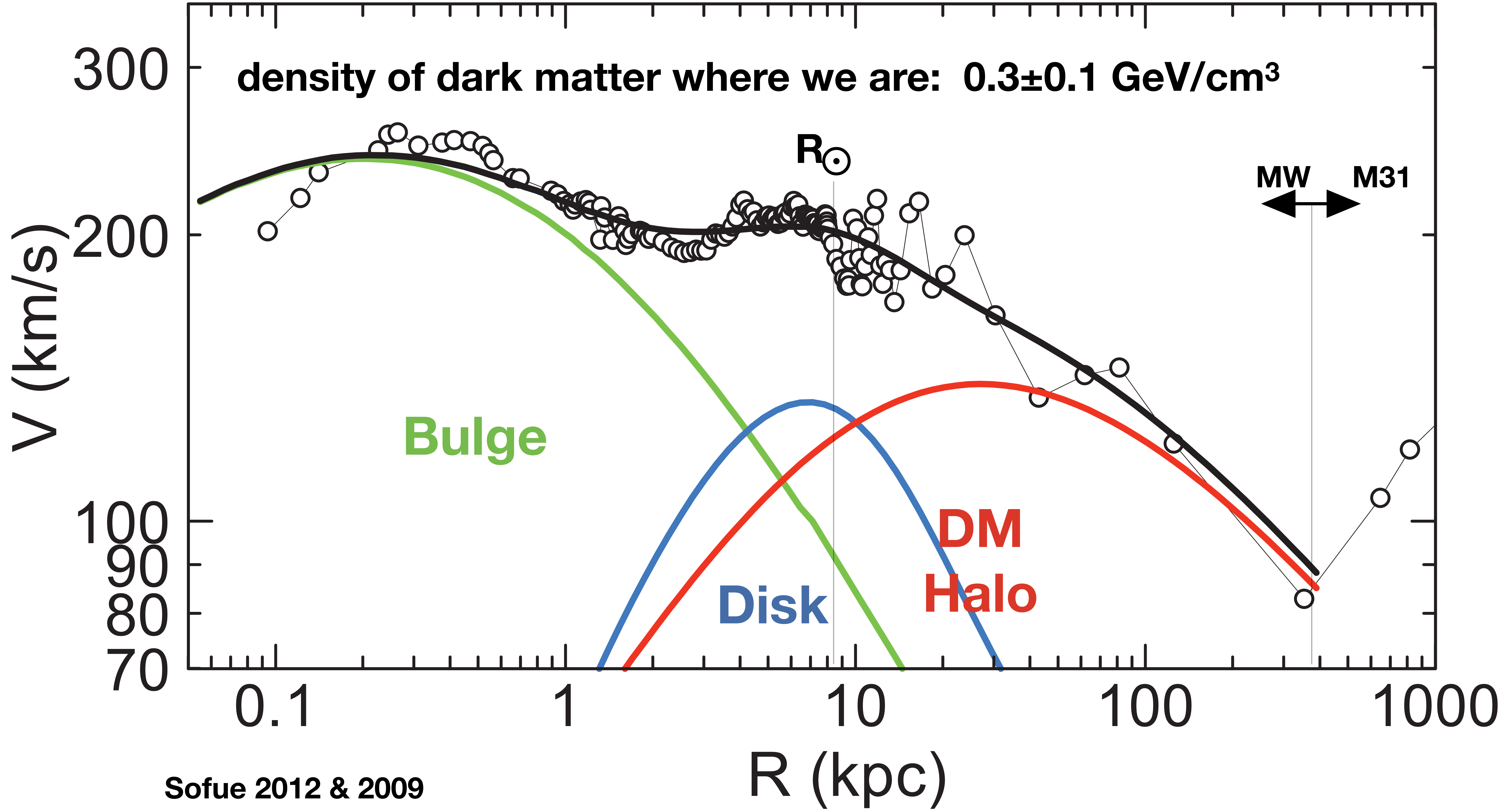
The Dark Matter Problem

Galaxy Rotation Curves

expect slow orbits at high radius

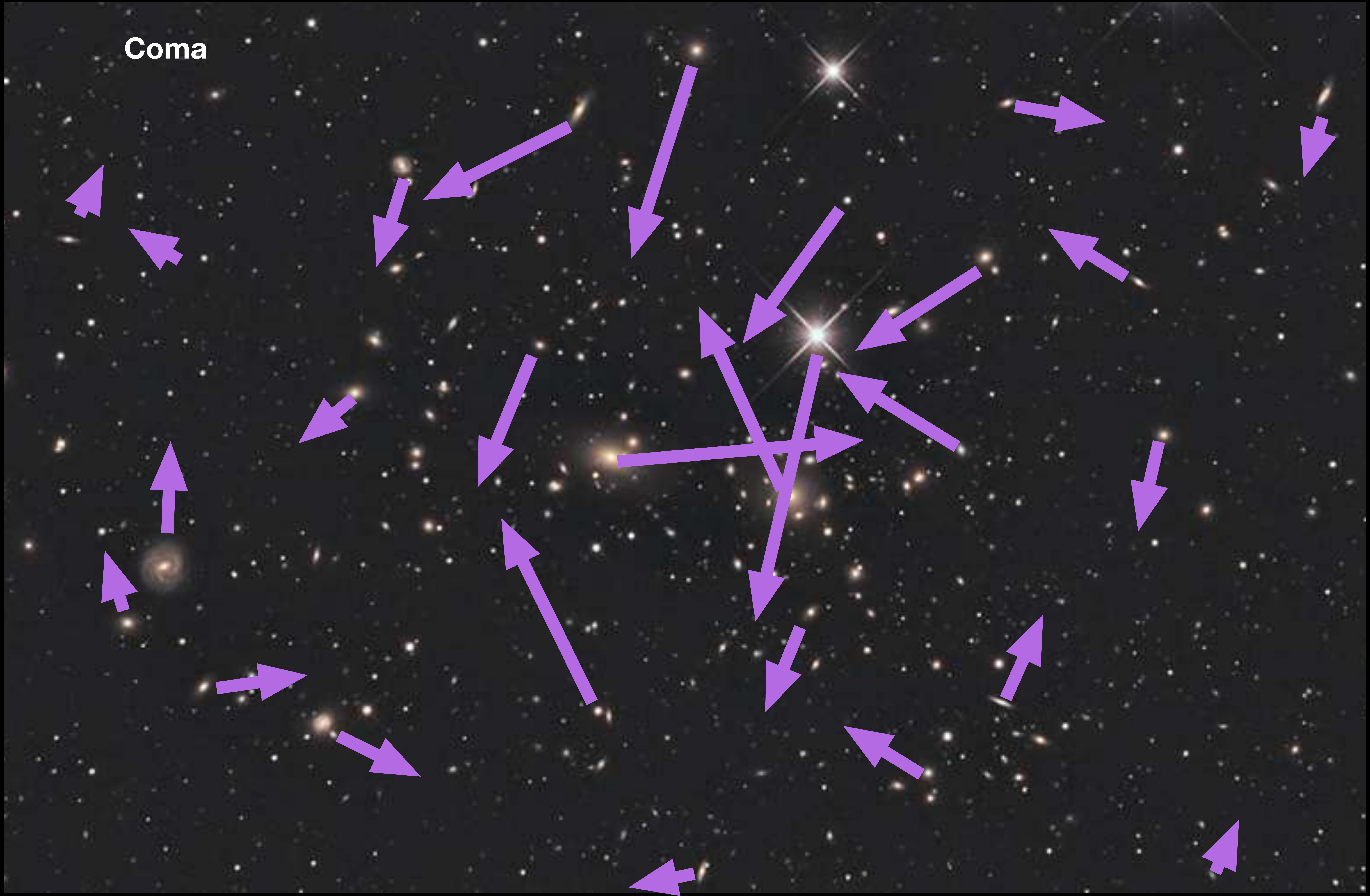


Rotation Curve of the Milky Way

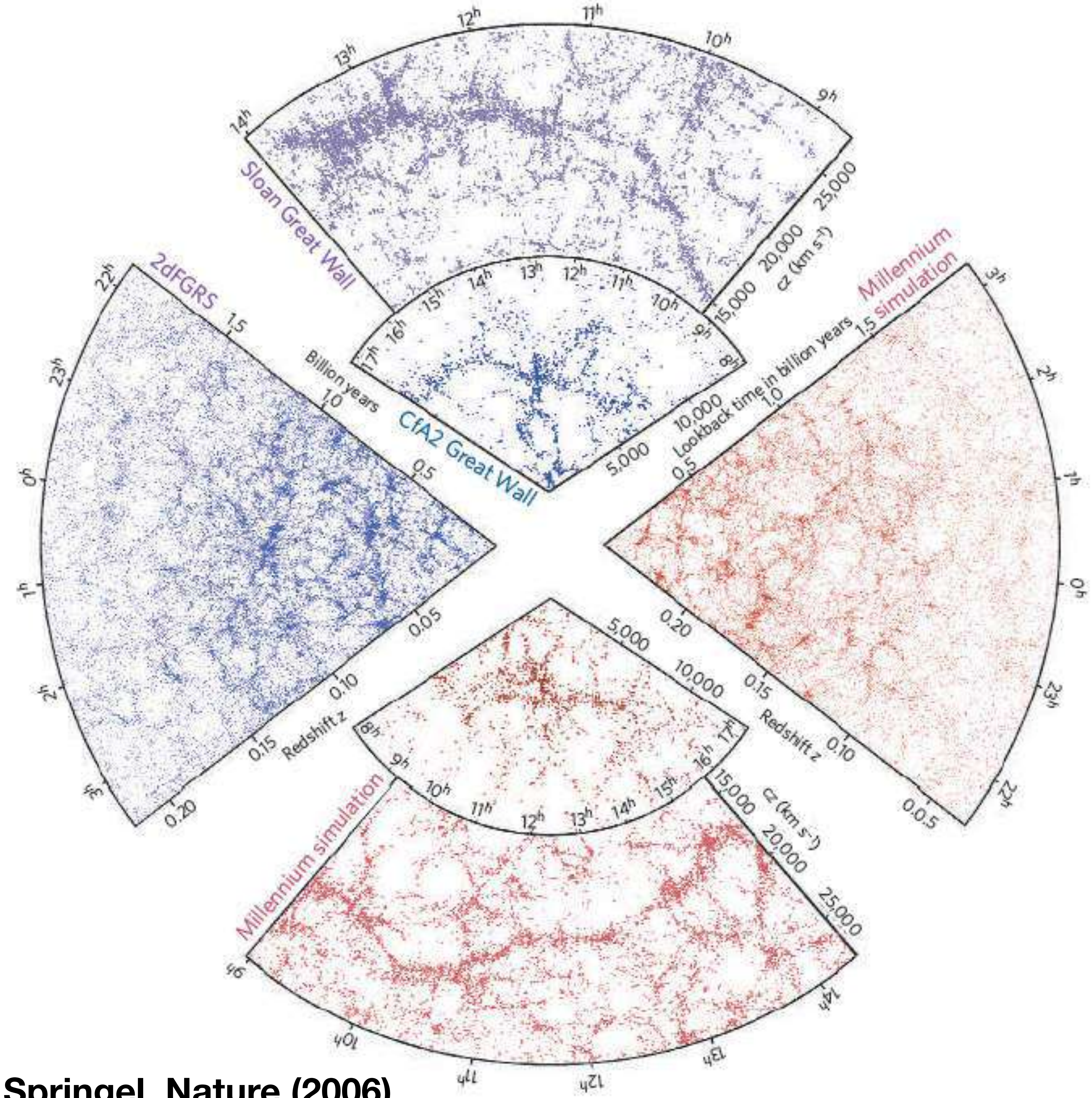


Sofue 2012 & 2009

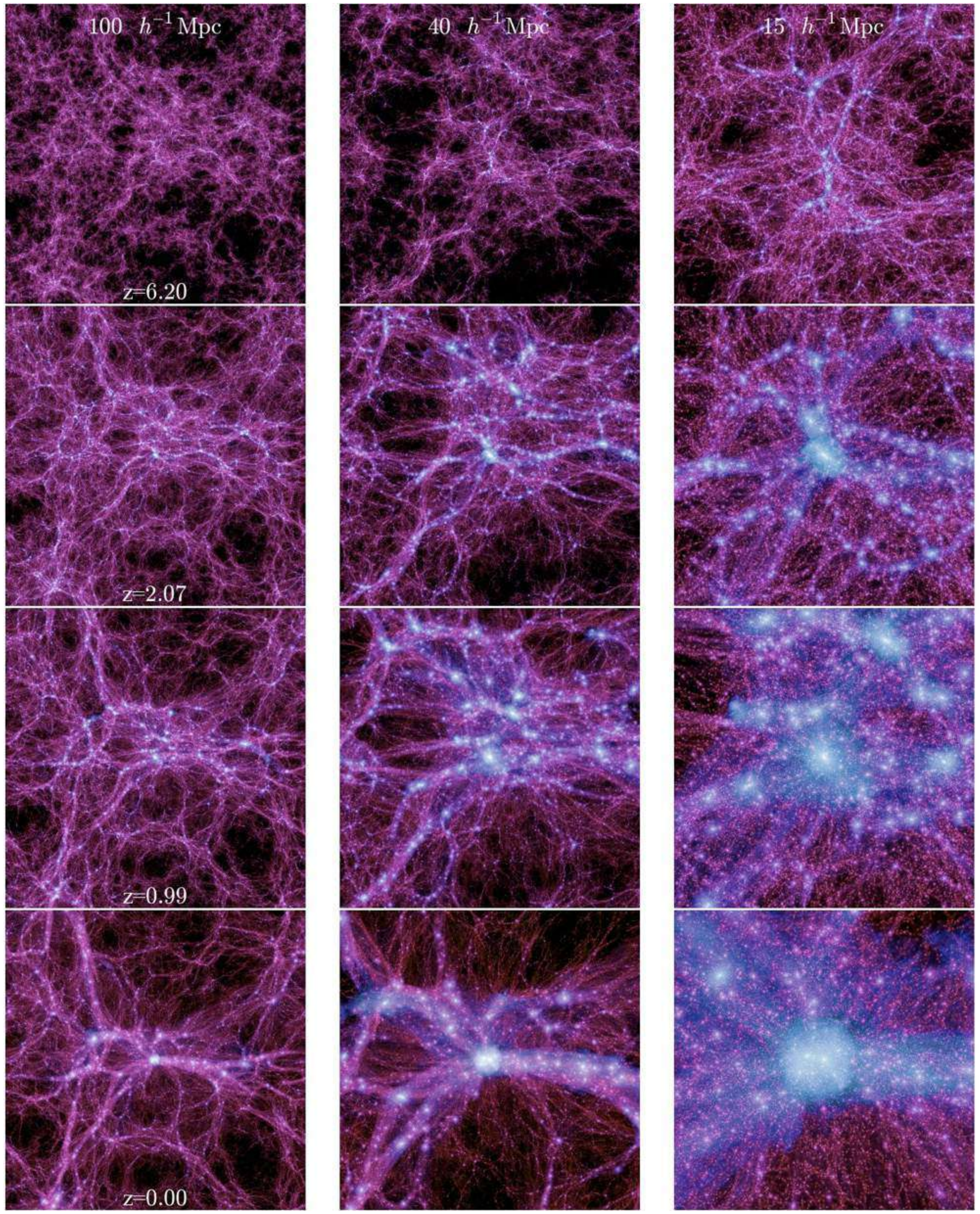
Galaxy Velocities in Clusters



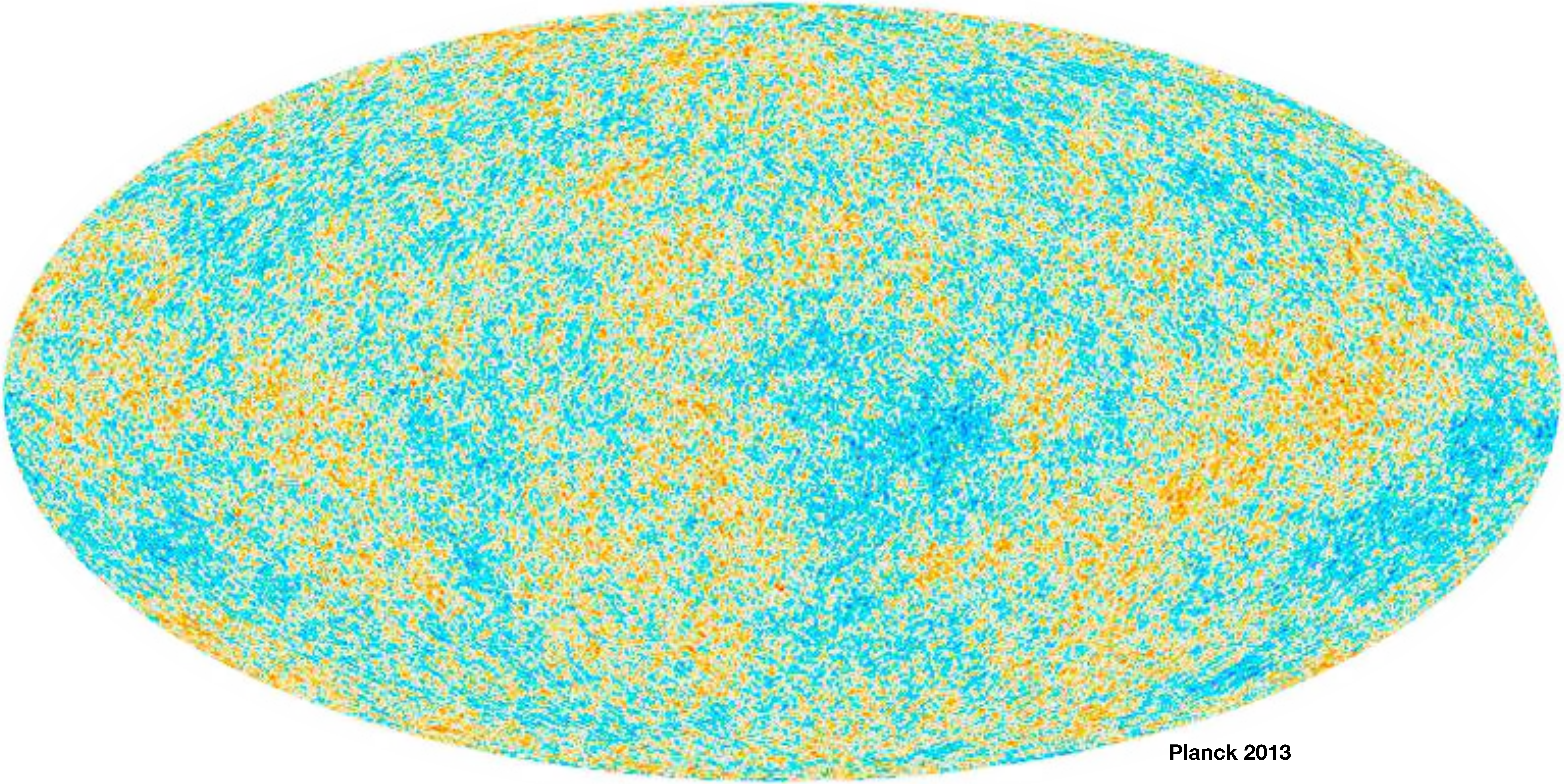
Models of Structure Formation



Springel, Nature (2006)



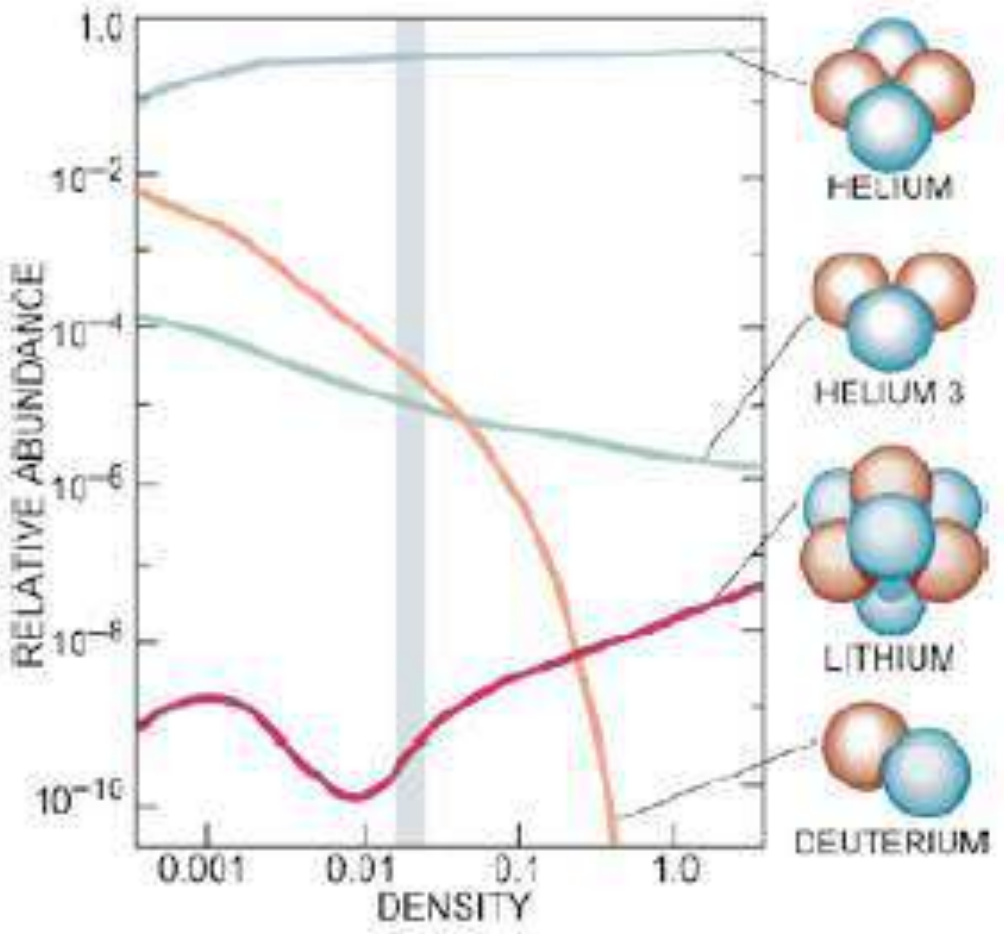
Fits to Cosmic Microwave Background

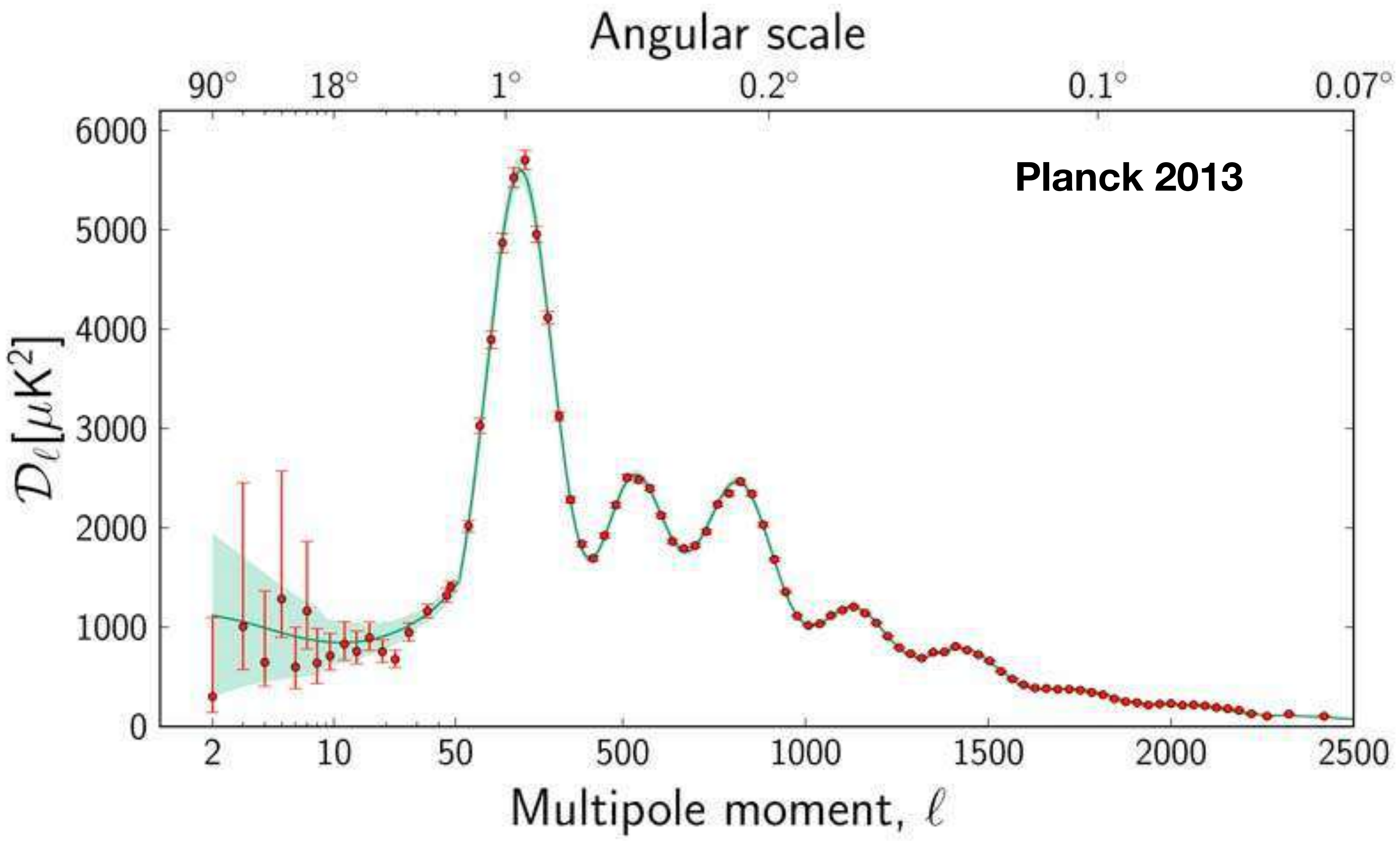


Planck 2013

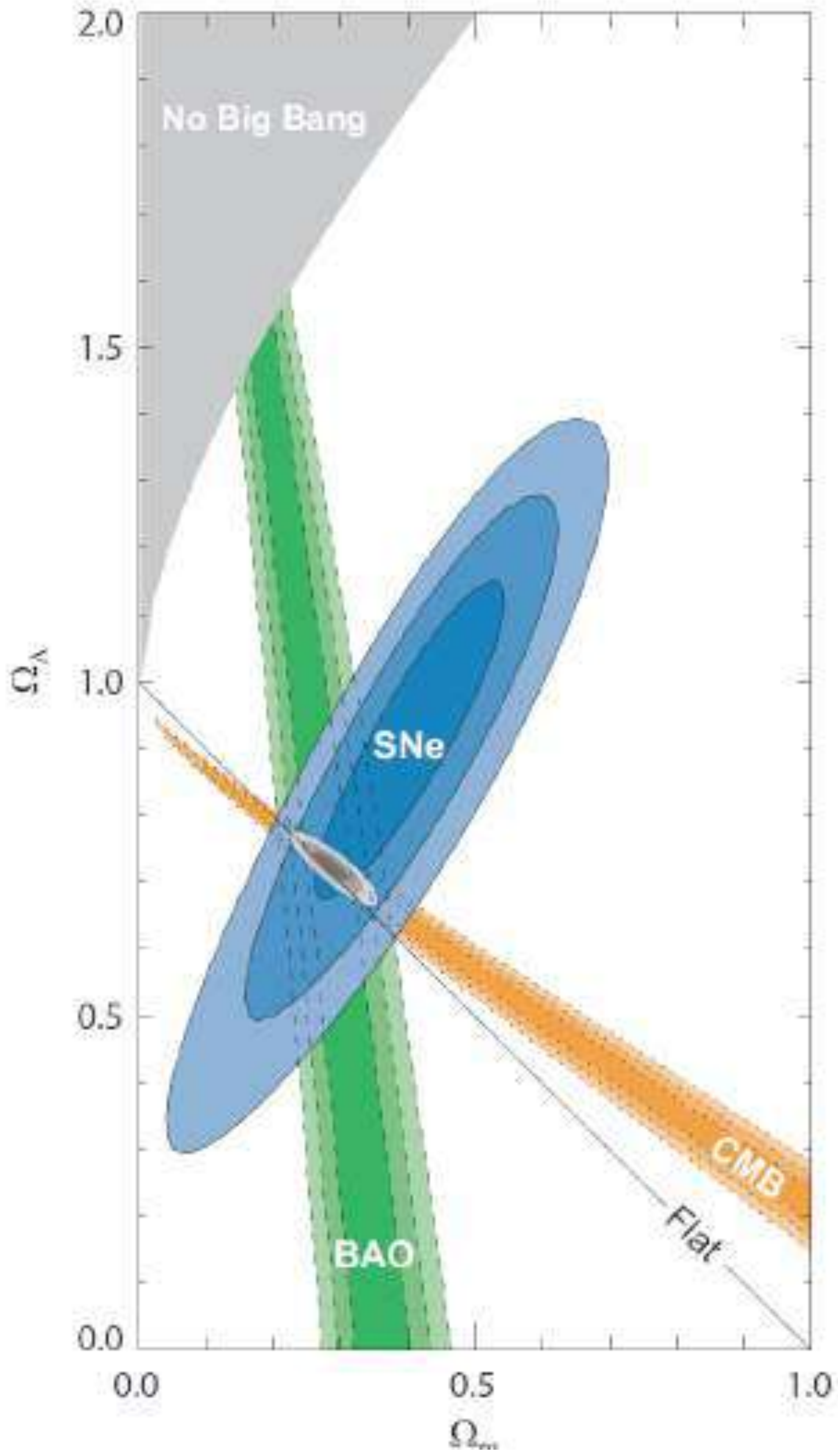
The ΛCDM Model of Cosmology

One model has emerged that fits all the observations with only 6 parameters.

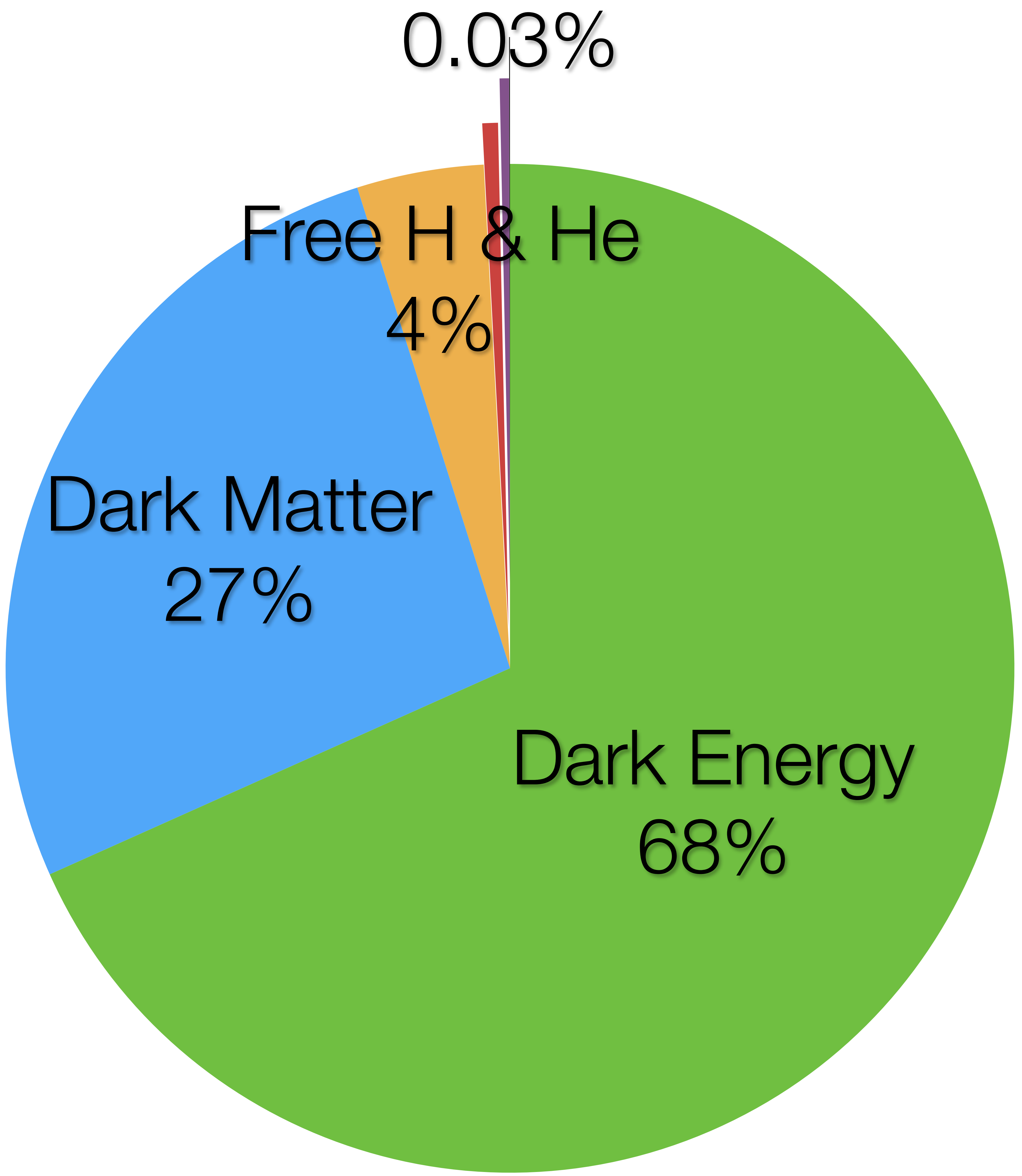




Planck 2013



The ΛCDM Model of Cosmology



We don’t know what 95% of the Universe if made of!

This model raises some truly fundamental physics questions:

What is Dark Matter?

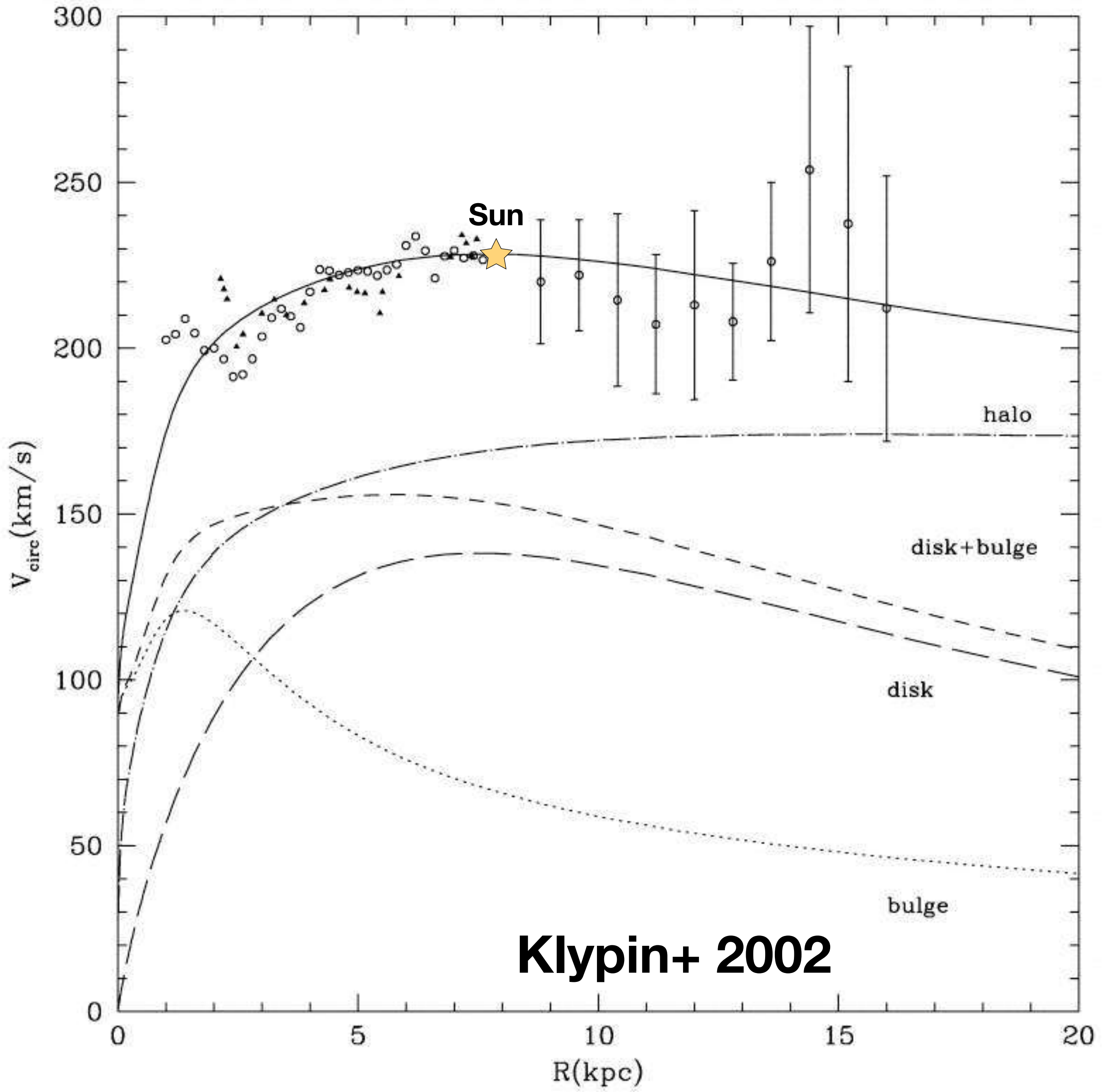
What is Dark Energy?

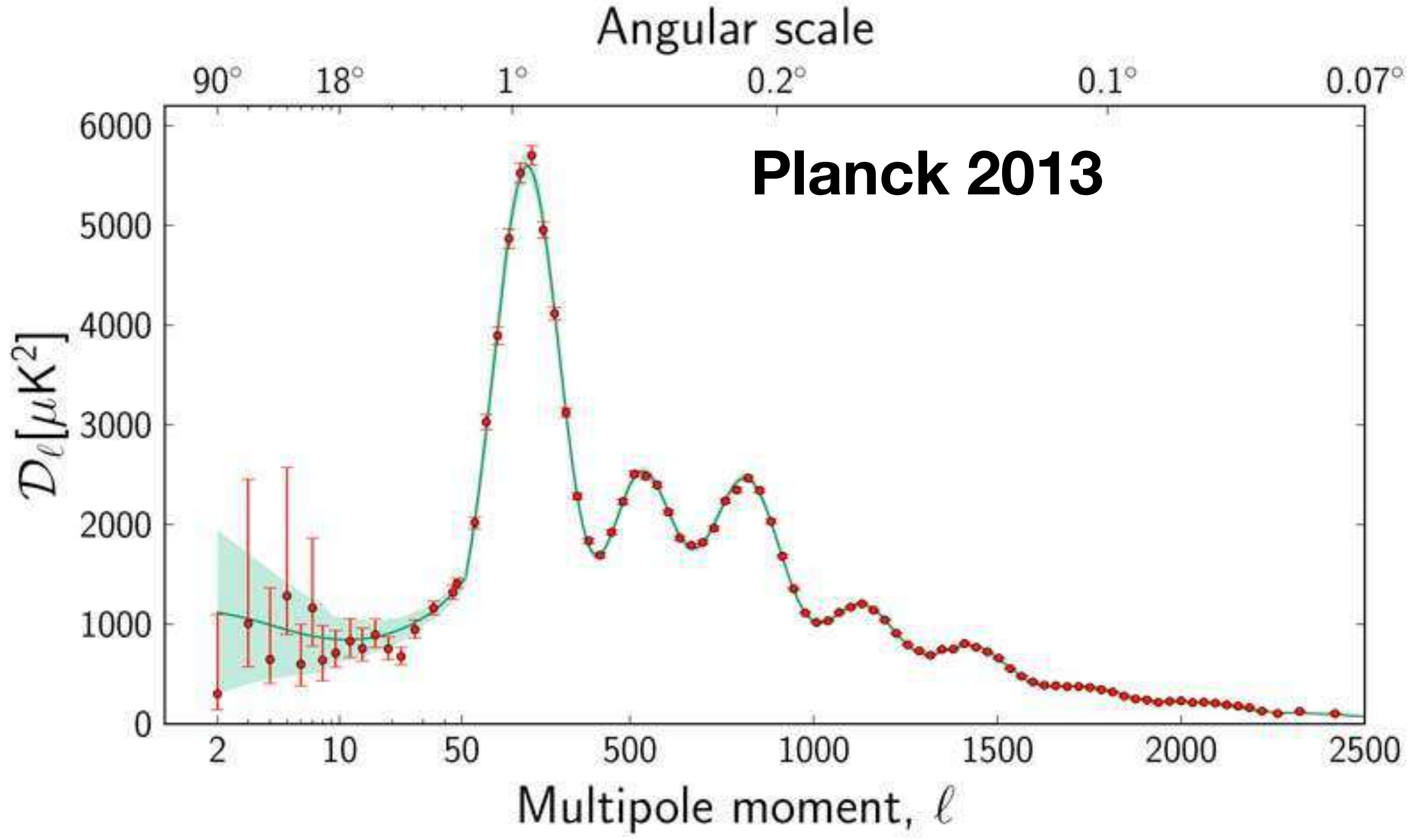
🟢 Dark Energy
🔵 Dark Matter
🟠 Free H & He
🔴 Stars and Gas
🟣 Neutrinos
⚫ Heavy Elements (Us)

We did not know the power of the dark side…

The Nature of Dark Matter

- The Missing Mass Problem:
  - Dynamics of stars, galaxies, and clusters
  - Rotation curves, gas density, gravitational lensing
  - Large Scale Structure formation
- Wealth of evidence for a particle solution
  - MOND has problems with weak lensing and CMB
  - Microlensing (MACHOs) mostly ruled out
- Non-baryonic
  - Height of acoustic peaks in the CMB (Ωb, Ωm)
  - Power spectrum of density fluctuations (Ωm)
  - Primordial Nucleosynthesis (Ωb)
- And STILL HERE!
  - Stable (or extremely long-lived), neutral, non-relativistic
  - Interacts via gravity and (maybe) some sub-weak scale force

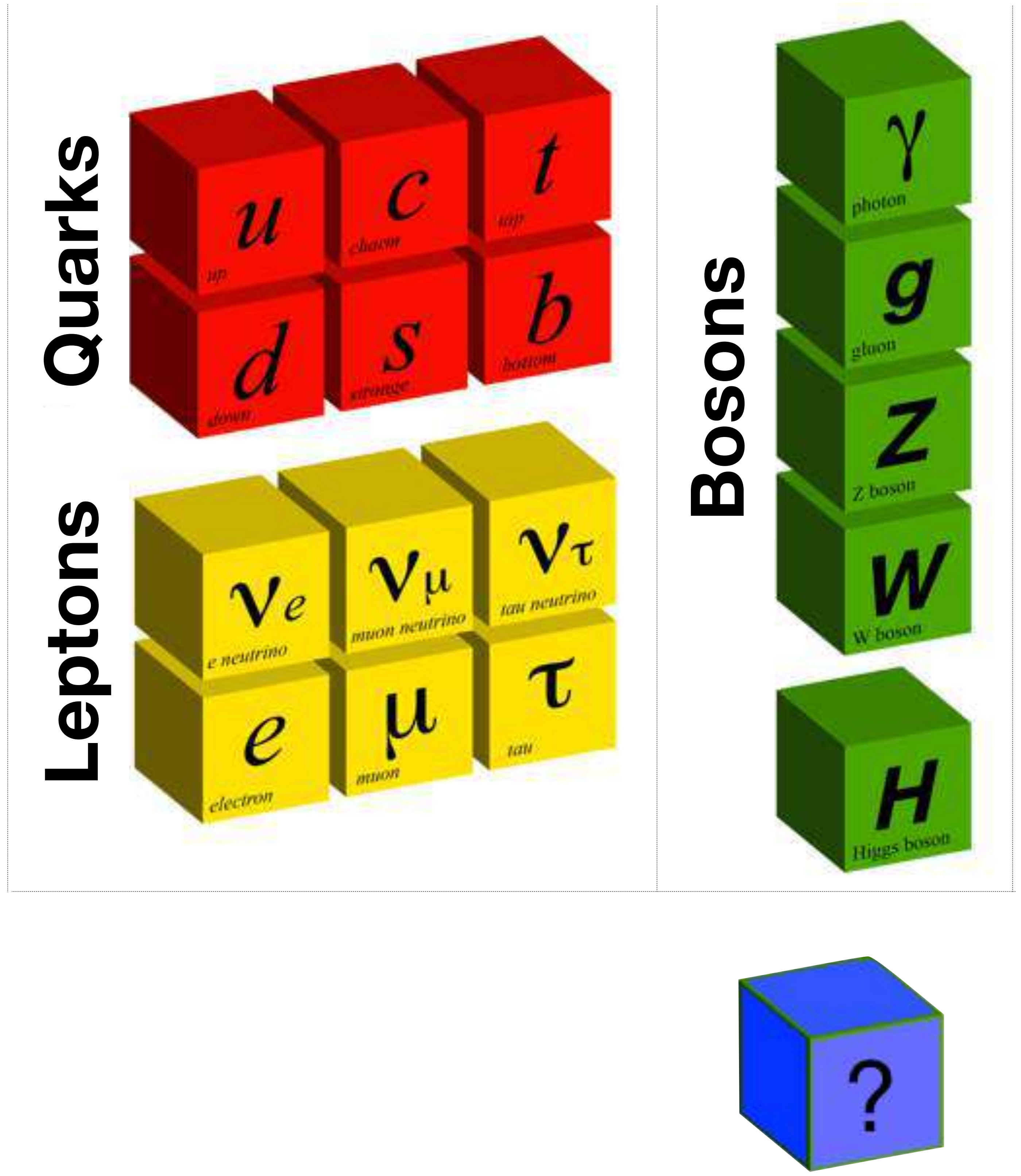




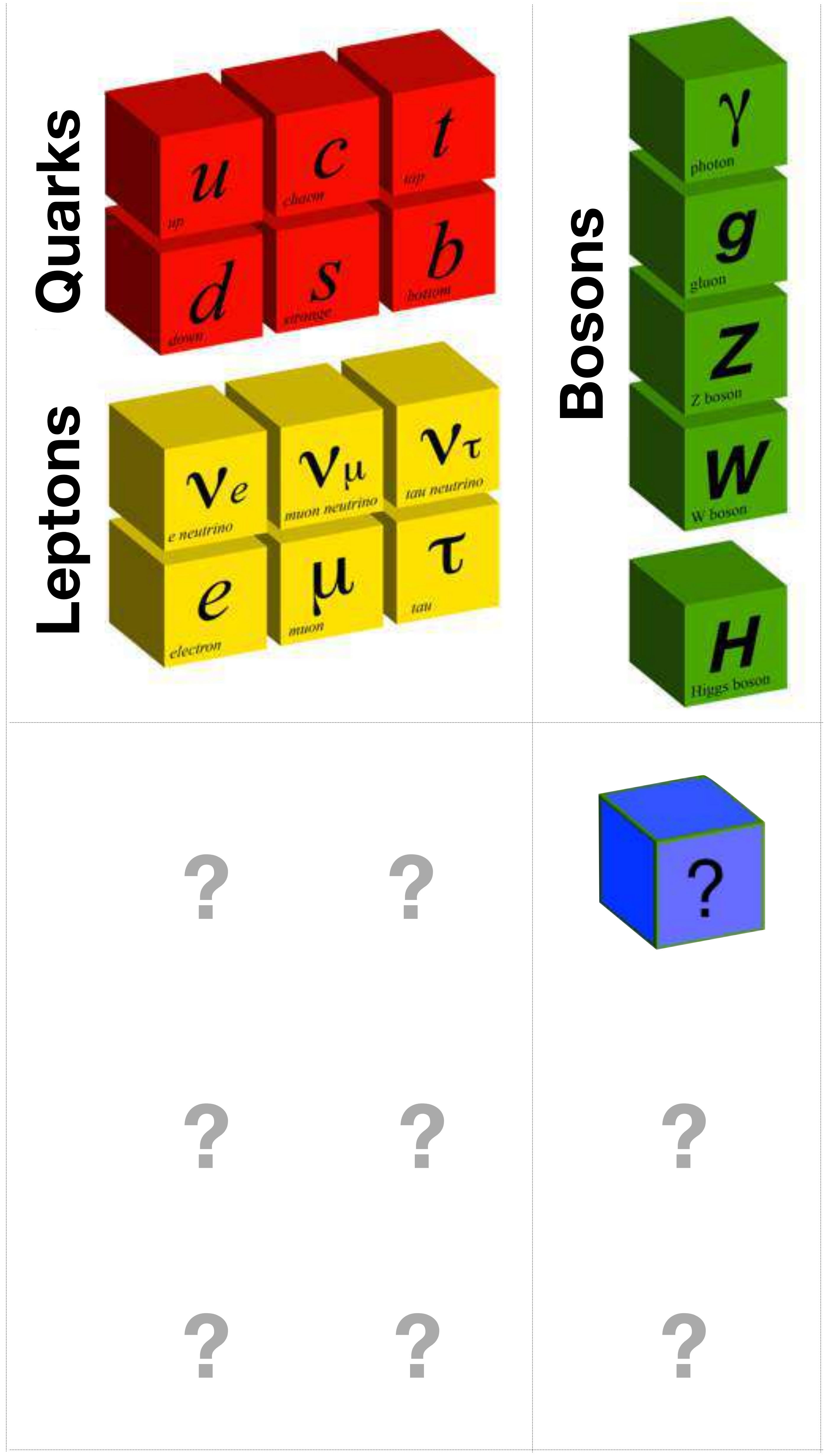
Dark Matter may be a Rosetta Stone!

We know the Standard Model is incomplete.

Where does dark matter fit in?



Dark Matter may be a Rosetta Stone!

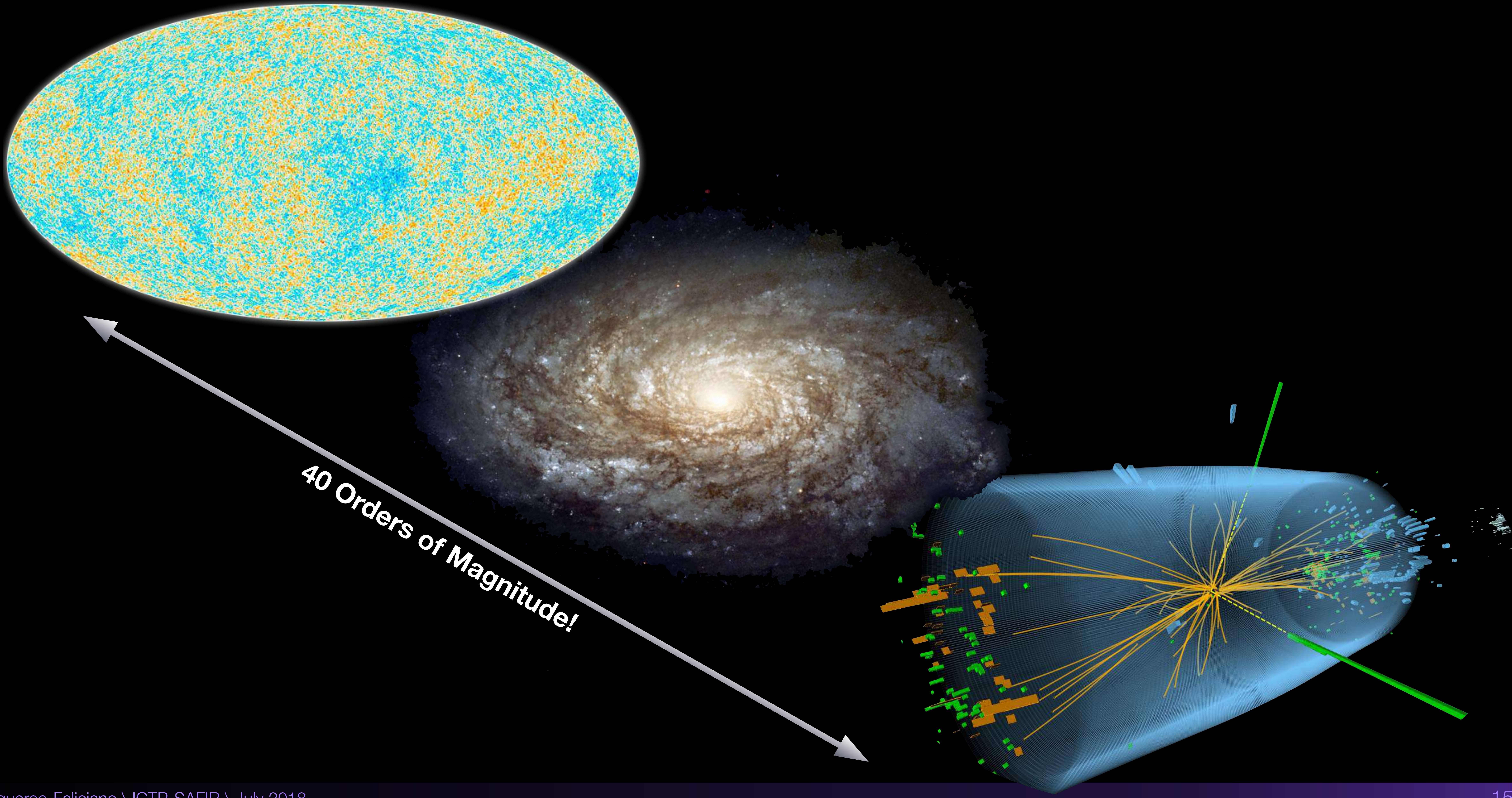


We know the Standard Model is incomplete.

Where does dark matter fit in?

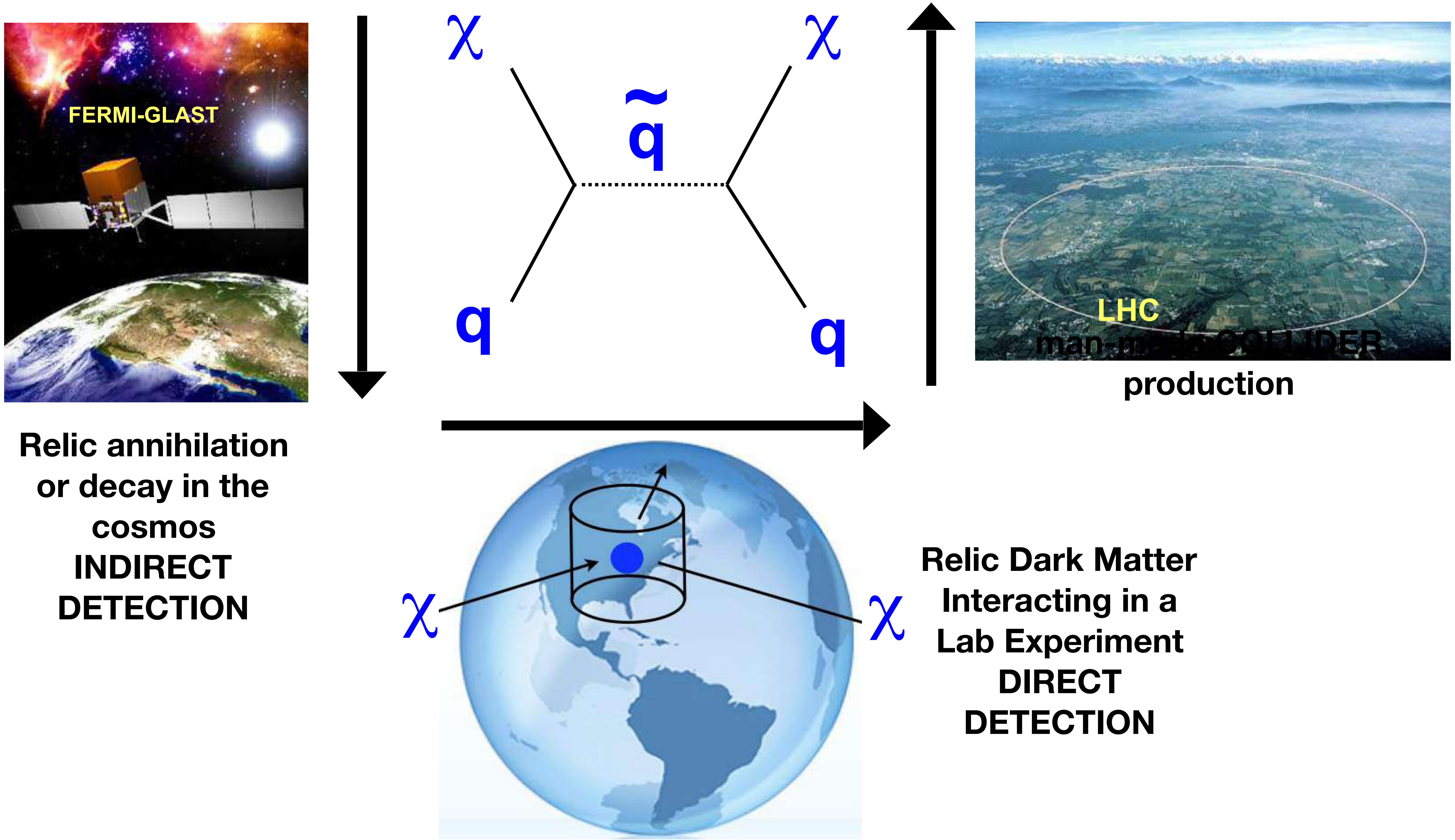
And how does it fit into a more general understanding?

A Beautiful Problem in Physics



40 Orders of Magnitude!

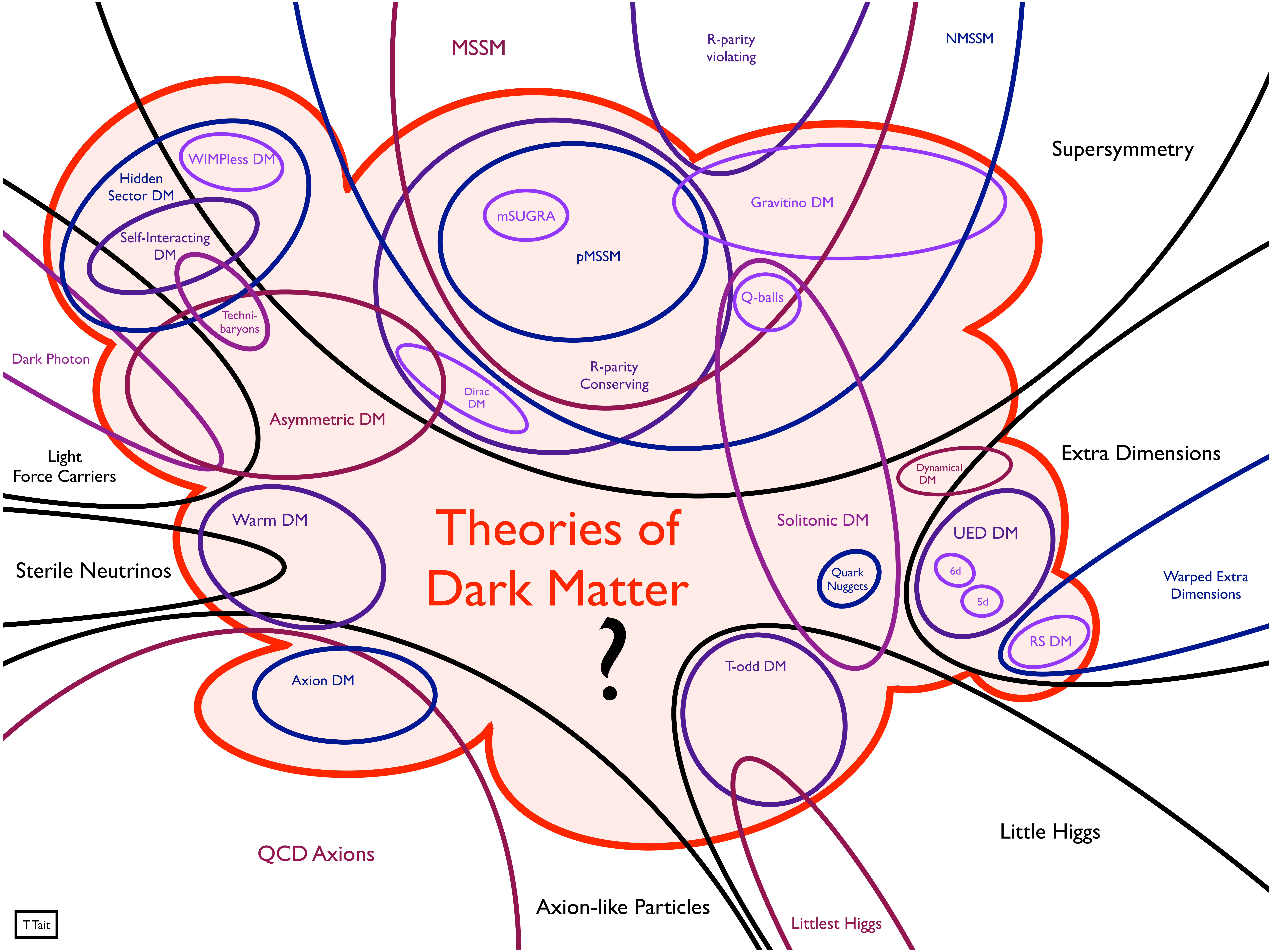
The Hunt for Dark Matter



man-made COLLIDER production

Relic annihilation or decay in the cosmos
INDIRECT DETECTION

Relic Dark Matter Interacting in a Lab Experiment
DIRECT DETECTION



Theories of Dark Matter

?

MSSM

R-parity violating

NMSSM

Supersymmetry

WIMPless DM

Hidden Sector DM

Self-Interacting DM

Techni-baryons

mSUGRA

pMSSM

Gravitino DM

Q-balls

R-parity Conserving

Dirac DM

Dark Photon

Asymmetric DM

Light Force Carriers

Dynamical DM

Extra Dimensions

Warm DM

Solitonic DM

UED DM

Sterile Neutrinos

Quark Nuggets

6d

5d

Warped Extra Dimensions

RS DM

Axion DM

T-odd DM

Little Higgs

QCD Axions

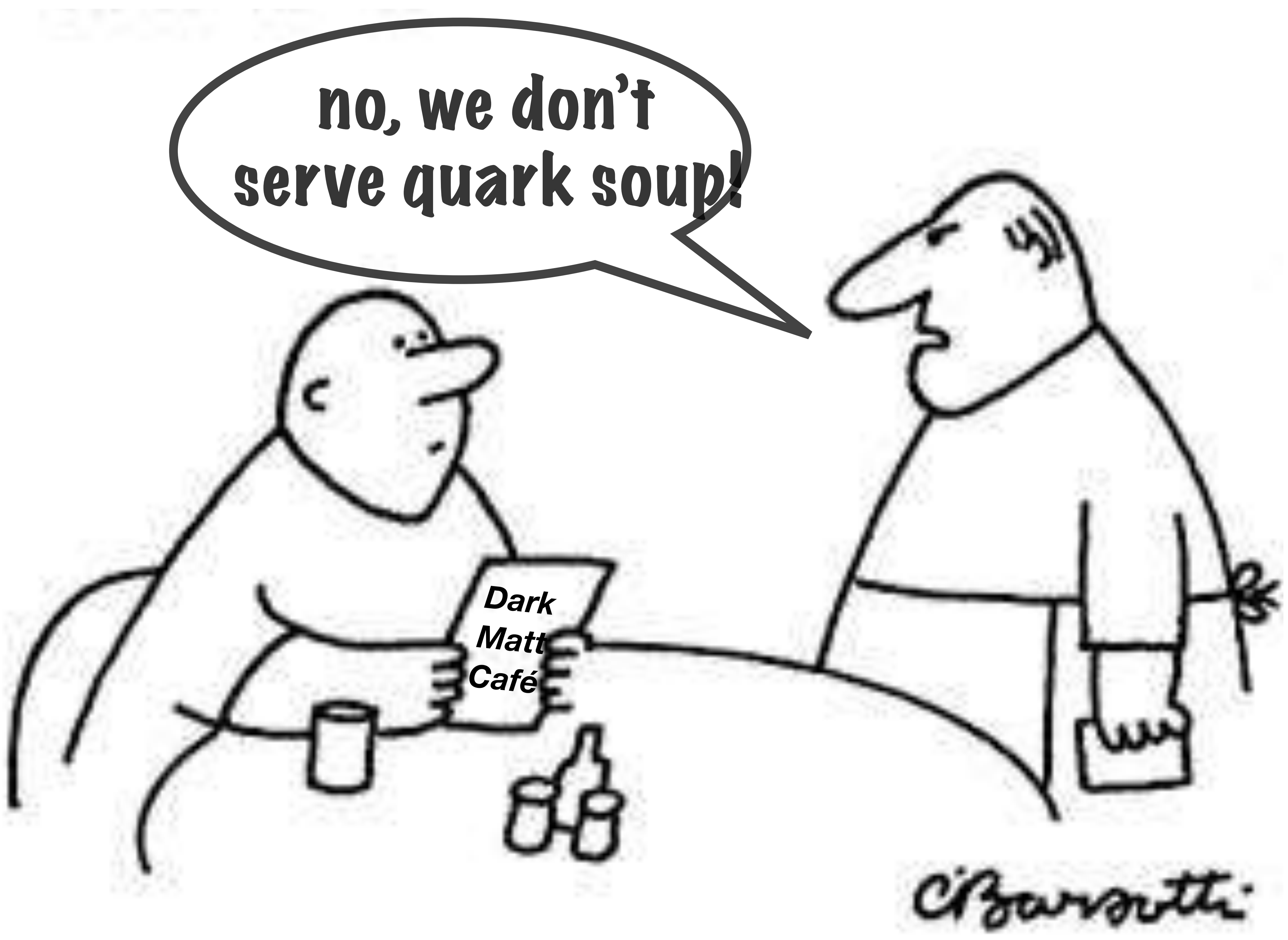
Axion-like Particles

Littlest Higgs

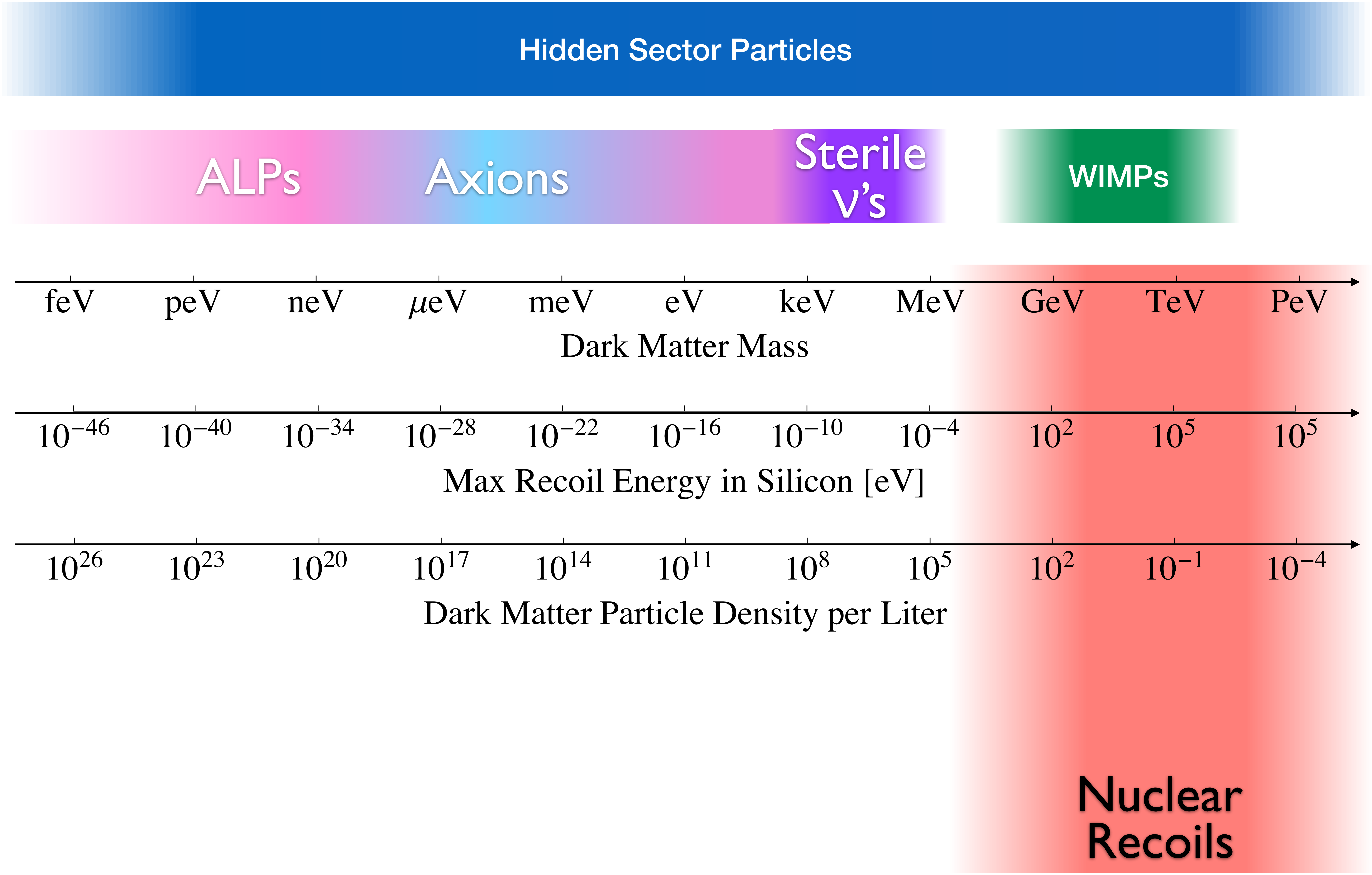
T Tait

Dark Matter Menu

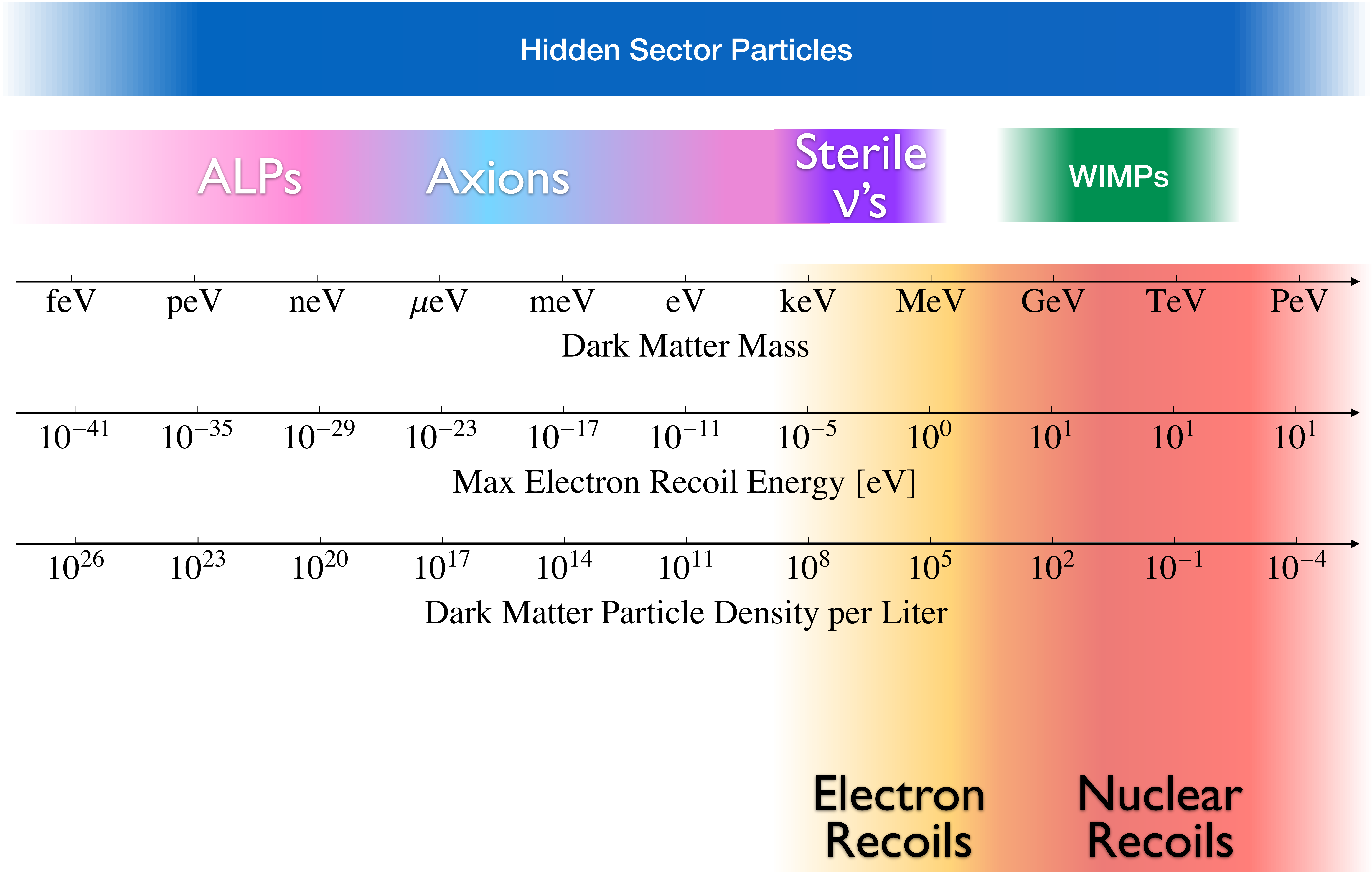
- Axions
- Axion-like Particles
- Hidden Sector Particles
- Sterile Neutrinos
- WIMPs
- SuperWIMPs
- Solitons
- KK excitations
- Gravitinos
- And many more that can fit the bill...



Dark Matter Detection Channels



Dark Matter Detection Channels



Hidden Sector Particles

ALPs

Axions

Sterile ν's

WIMPs

feV peV neV μeV meV eV keV MeV GeV TeV PeV

Dark Matter Mass

10^{-41} 10^{-35} 10^{-29} 10^{-23} 10^{-17} 10^{-11} 10^{-5} 10^{0} 10^{1} 10^{1} 10^{1}

Max Electron Recoil Energy [eV]

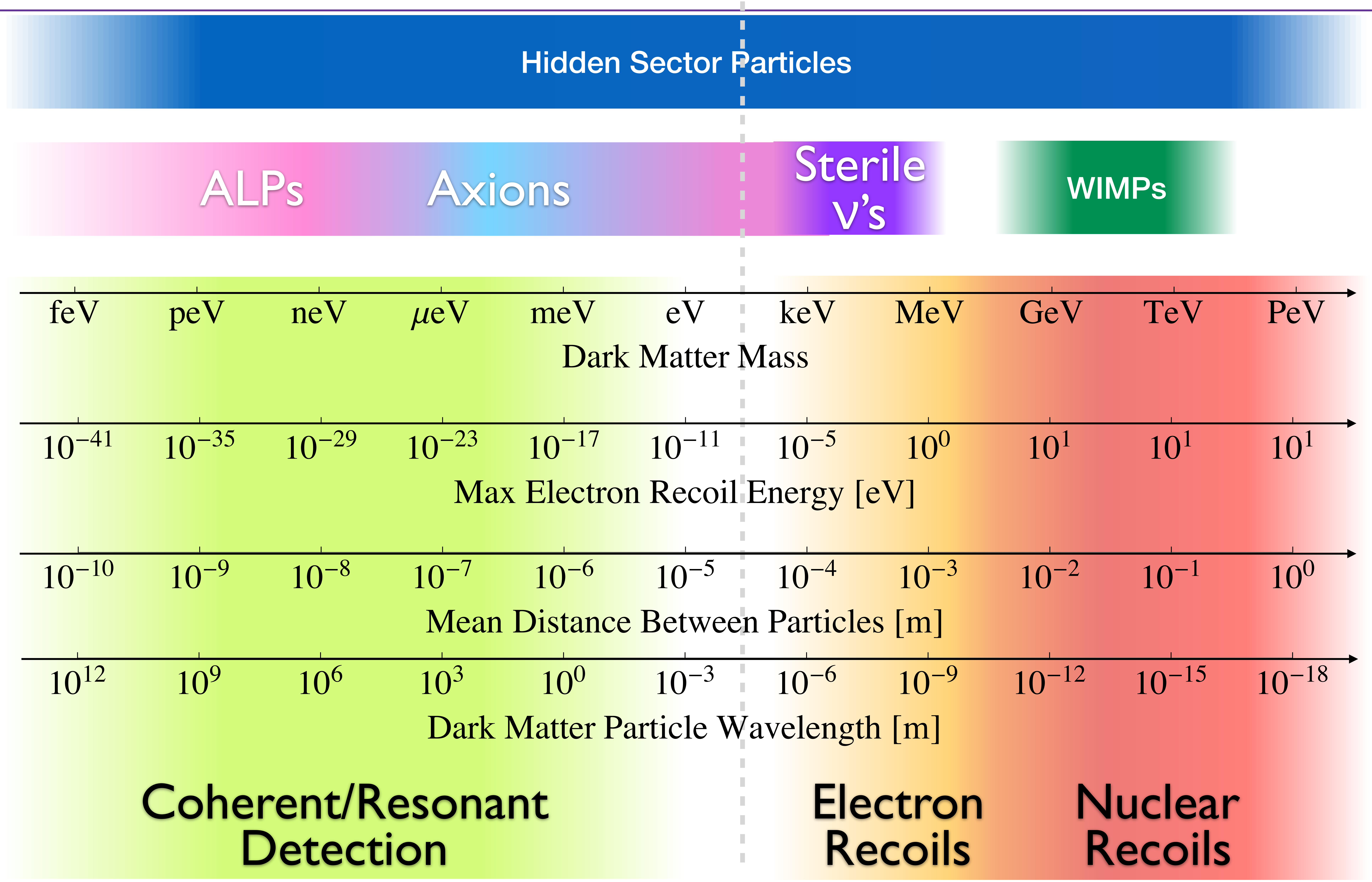
10^{26} 10^{23} 10^{20} 10^{17} 10^{14} 10^{11} 10^{8} 10^{5} 10^{2} 10^{-1} 10^{-4}

Dark Matter Particle Density per Liter

Electron Recoils

Nuclear Recoils

Dark Matter Detection Channels



Hidden Sector Particles

ALPs

Axions

Sterile ν's

WIMPs

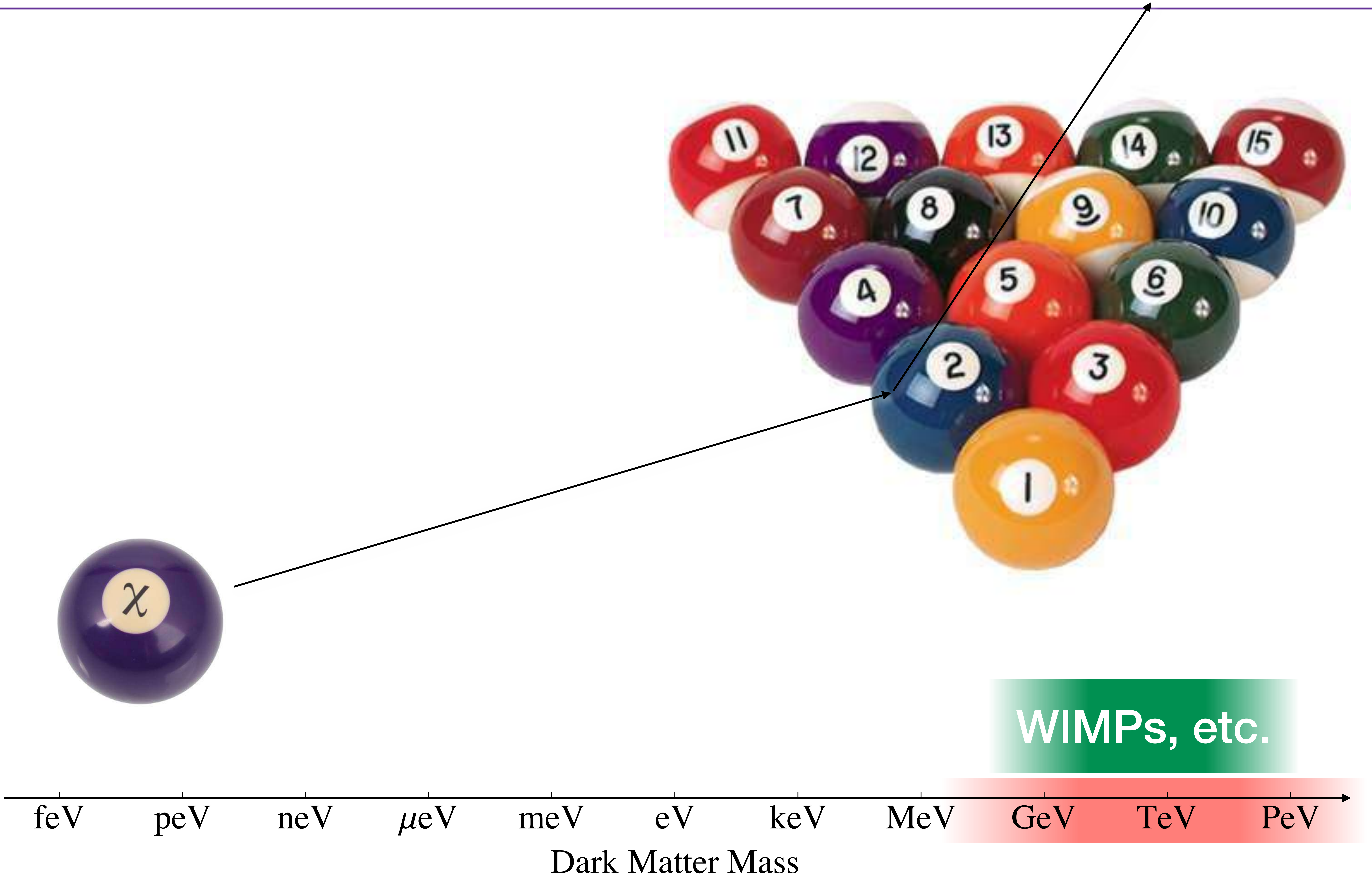
Dark Matter Mass	feV	peV	neV	μeV	meV	eV	keV	MeV	GeV	TeV	PeV
Max Electron Recoil Energy [eV]	10^{-41}	10^{-35}	10^{-29}	10^{-23}	10^{-17}	10^{-11}	10^{-5}	10^{0}	10^{1}	10^{1}	10^{1}
Mean Distance Between Particles [m]	10^{-10}	10^{-9}	10^{-8}	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	10^{0}
Dark Matter Particle Wavelength [m]	10^{12}	10^{9}	10^{6}	10^{3}	10^{0}	10^{-3}	10^{-6}	10^{-9}	10^{-12}	10^{-15}	10^{-18}

Coherent/Resonant Detection

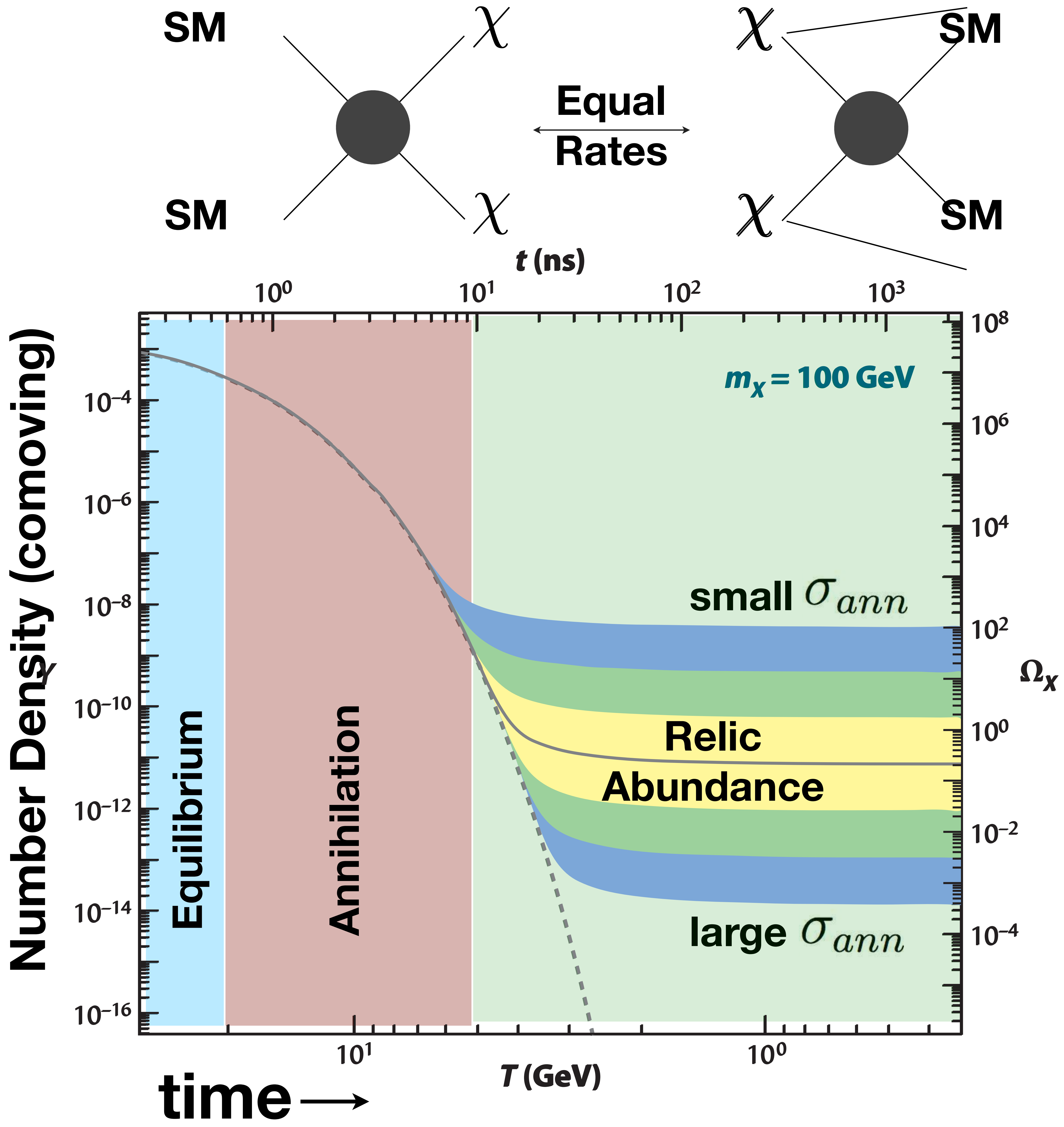
Electron Recoils

Nuclear Recoils

Nuclear Recoils



The WIMP "Miracle"



$$\Omega_{\rm DM} \approx \frac{m_{\rm DM}}{T_f}\,\frac{T_o^3}{\rho_c\,M_{\rm Pl}\,\langle\sigma_{ann}v\rangle}$$

$$m_{\rm DM} \sim 0.1 - 1\,{\rm TeV}$$

$$\sigma_{ann} = \frac{k\alpha^2}{m_{\rm DM}^2}$$

$$\sigma_{ann} \sim 1\,{\rm pb}$$

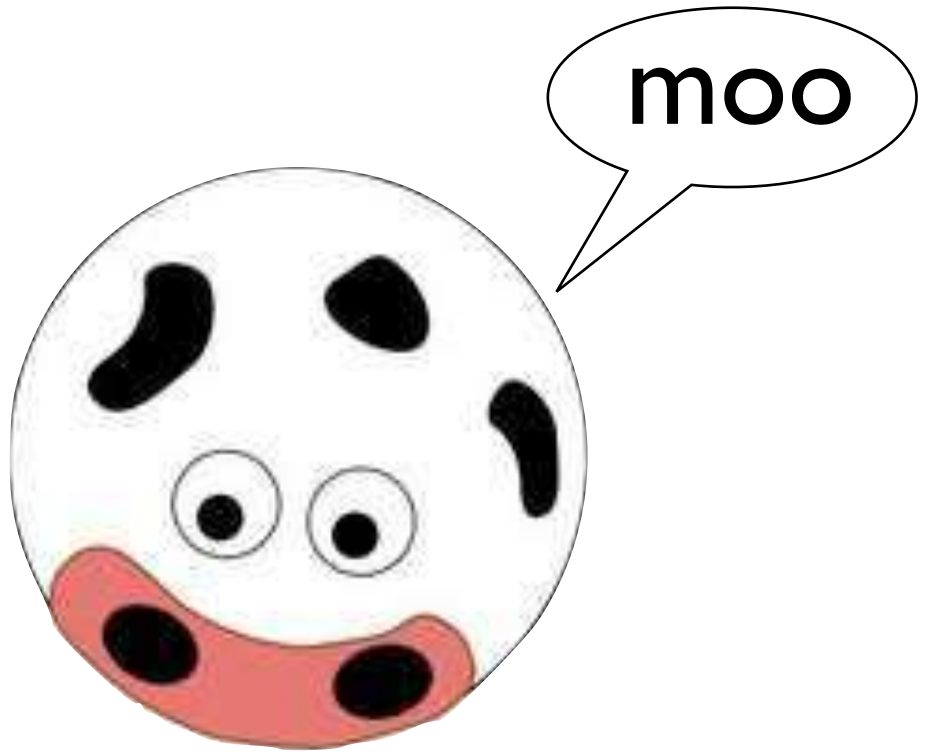
Cosmology Predicts the Weak Scale!

Dark Matter Astrophysics

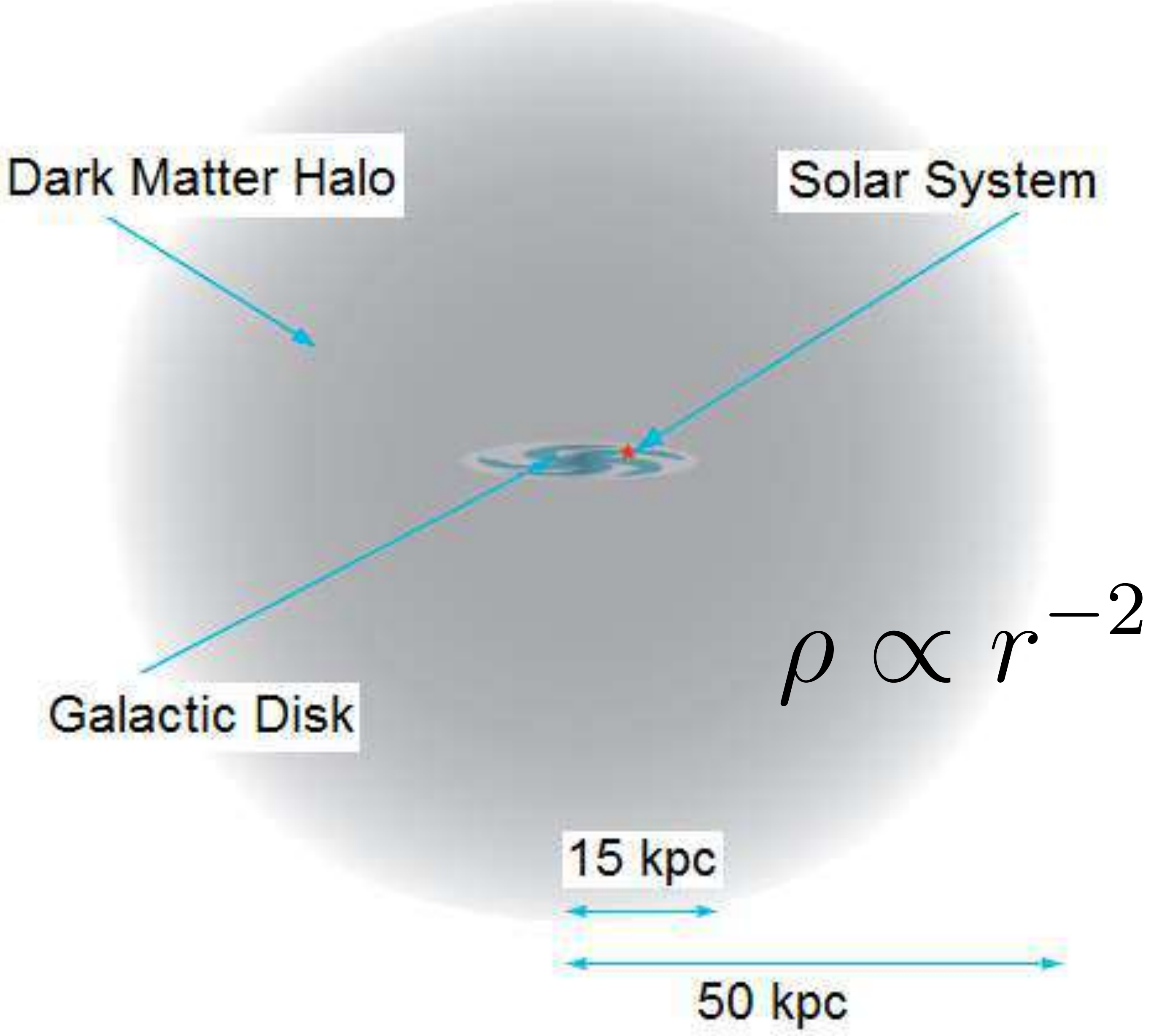
$$f(\vec{v}) = \frac{1}{\sqrt{2\pi}\sigma} exp(-\frac{|\vec{v}|^2}{2\sigma^2})$$

$$\sigma = \sigma_{rms} = \sqrt{\frac{3}{2}} v_0 = 270\,\mathrm{km/s}$$

$$\text{and} \quad v_0 = 220\,\mathrm{km/s}$$

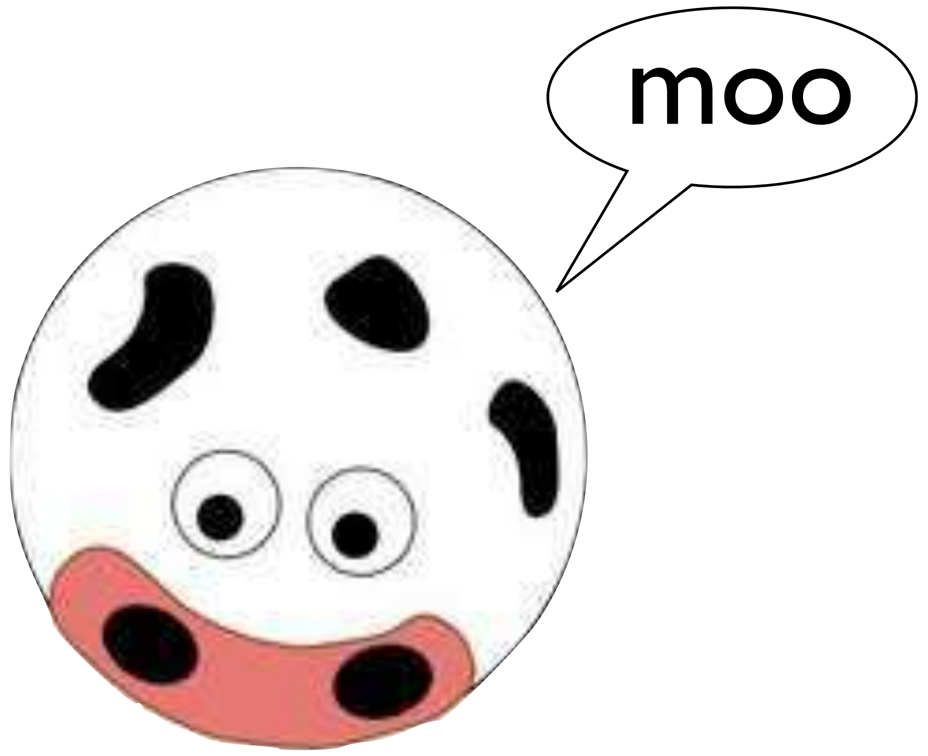


- The dark matter density falls off as r^{-2}
- Particles with speed greater than the local escape velocity are not gravitationally bound. The standard halo extends out to infinite radii and thus the speed distribution in this model must be truncated "by hand". We take v$_{esc}$ = 650 km/s.

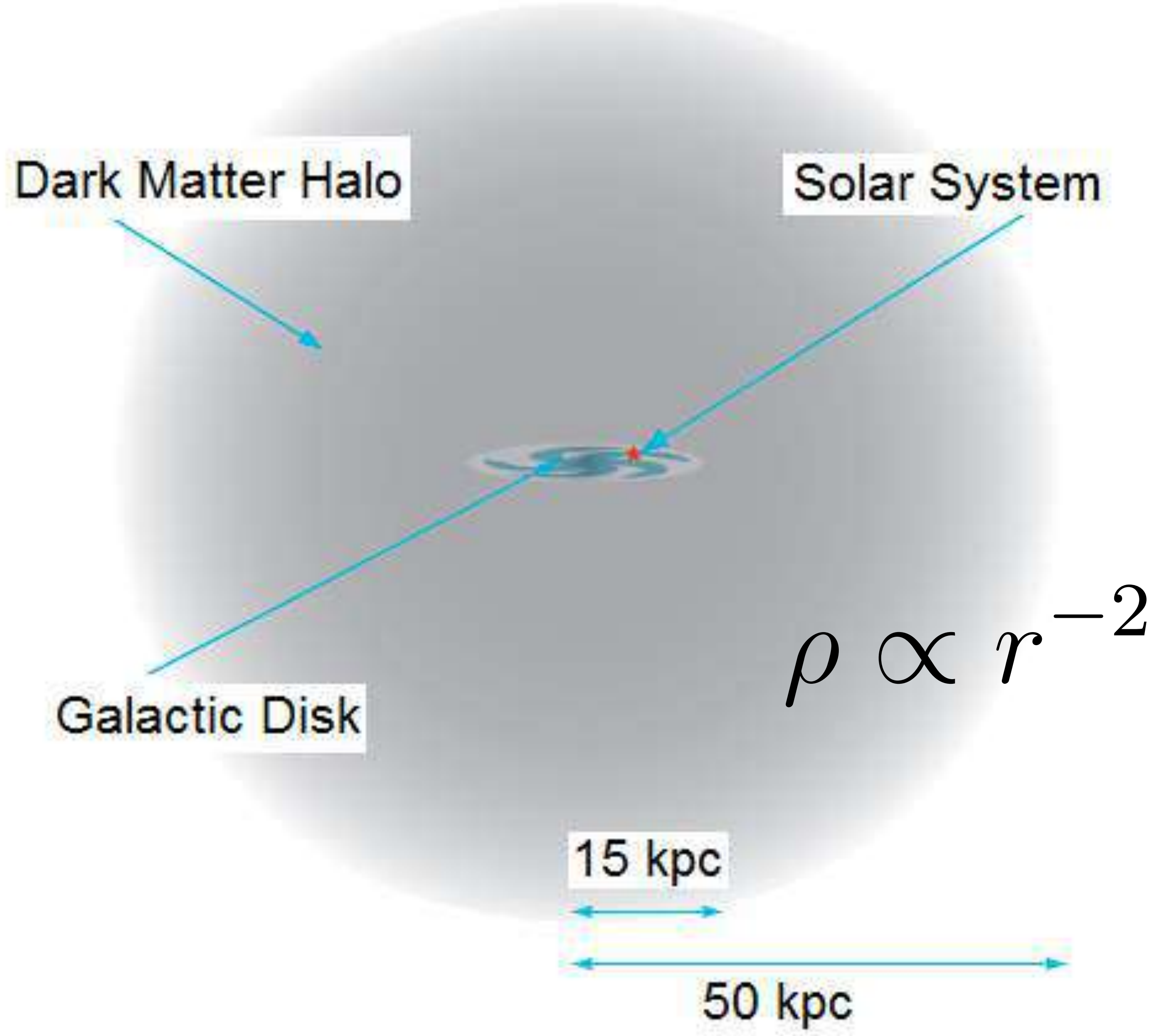


Density of Dark Matter in this Room

- Local dark matter density:
  - ρ_o = 0.3 GeV / cm^3
- Assume mass = 60 GeV/c^2
- Density = 5000 particles/m^3

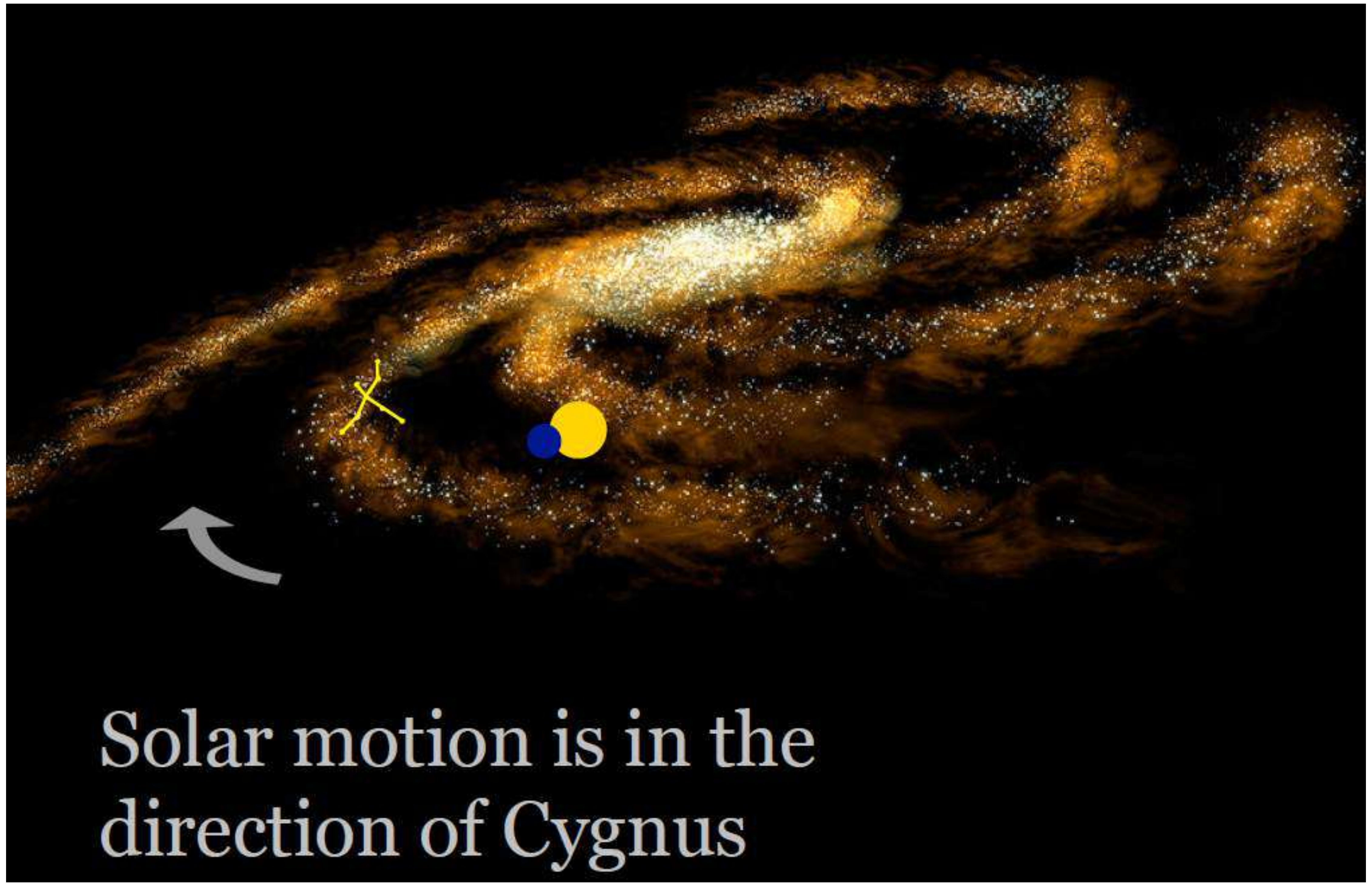


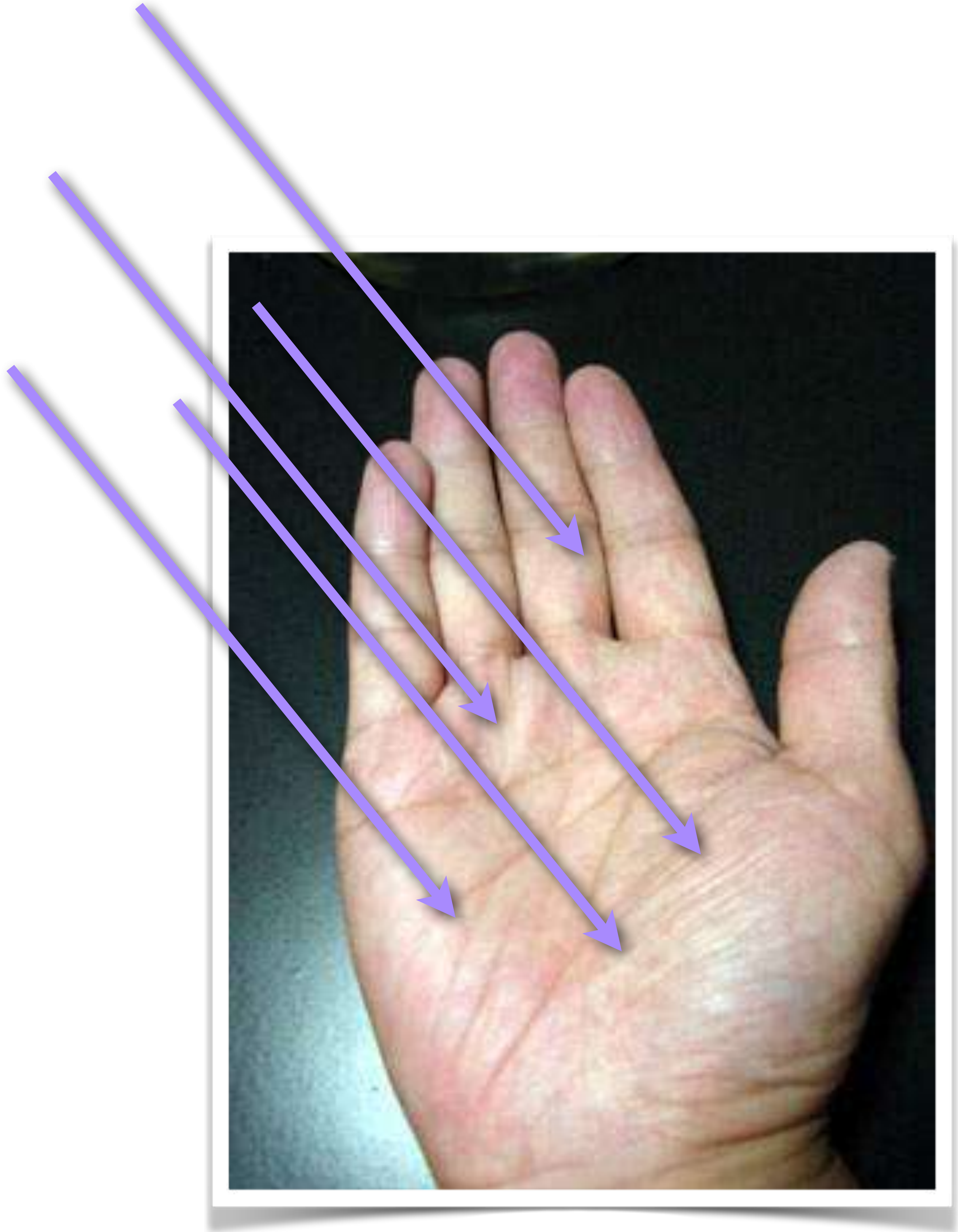
10 WIMPs
on average, inside a 2 liter bottle
(if mass=60 x proton)



$$\rho \propto r^{-2}$$

The Dark Matter Wind





- Dark matter apparently blows from Cygnus
- Our speed relative to the dark matter halo is ~220 km/s
- ~100,000 particles/cm^2/sec
- About 20 million/hand/sec

Principles of Particle Detection

particle theory **nuclear structure** **astrophysics properties**

Interaction Rate
[events/keV/kg/day]

$$\frac{dR}{dE_R} = \frac{\sigma_o}{m_\chi} \frac{F^2(E_R)}{m_r^2} \frac{\rho_o\, T(E_R)}{v_o \sqrt{\pi}}$$

$$m_r = \frac{m_\chi m_N}{m_\chi + m_N}$$

“reduced mass”

Principles of Particle Detection

astrophysics
properties

Interaction
Rate
[events/keV/kg/day]

$$\frac{dR}{dE_R} = \frac{\sigma_o}{m_\chi} \frac{F^2(E_R)}{m_r^2} \boxed{\frac{\rho_o\, T(E_R)}{v_o \sqrt{\pi}}}$$

$$T(E_R) = \frac{\sqrt{\pi}}{2} v_o \int_{v_{\min}}^{\infty} \frac{f_1(v)}{v} dv$$

integral over local WIMP velocity distribution

$$v_{\min} = \sqrt{E_R\, m_N / (2m_r^2)}$$

minimum WIMP velocity for given E_R

$$T(E_R) \simeq \exp(-v_{\min}^2 / v_o^2)$$

for pure Maxwellian case

Principles of Particle Detection

particle theory

nuclear structure

Interaction Rate

[events/keV/kg/day]

$$\frac{dR}{dE_R} = \boxed{\frac{\sigma_o}{m_\chi}} \boxed{\frac{F^2(E_R)}{m_r^2}} \frac{\rho_o\, T(E_R)}{v_o \sqrt{\pi}}$$

These two depend on the interaction type.
Let's look at the standard assumptions, that the interaction is either spin-independent or spin-dependent

Principles of Particle Detection: Spin Independent

nuclear
structure

Interaction
Rate
[events/keV/kg/day]

$$\frac{dR}{dE_R} = \frac{\sigma_o}{m_\chi} \frac{F^2(E_R)}{m_r^2} \frac{\rho_o\, T(E_R)}{v_o\,\sqrt{\pi}}$$

$$F(E_R) = \left[\frac{3J_1(qR_1)}{qR1}\right]^2 \exp\left(-(qs)^2\right)$$

"Woods-Saxon Nuclear Form Factor"
J1 = Bessel function of the first kind, cylindrical harmonic
q = momentum transfered
s = "nuclear skin thickness", or the distance through which the charge density of the nucleus drops to zero (it is not a step function due to quantum mechanics)

Principles of Particle Detection: Spin Independent

particle
theory

Interaction
Rate
[events/keV/kg/day]

$$\frac{dR}{dE_R} = \frac{\sigma_o}{m_\chi} \frac{F^2(E_R)}{m_r^2} \frac{\rho_o\, T(E_R)}{v_o \sqrt{\pi}}$$

$$\sigma_o = \frac{4m_r^2}{\pi} \left[Z f_p + (A - Z) f_n\right]^2$$

$$\sigma_o \simeq \frac{4m_r^2}{\pi} f A^2$$

atomic mass

coupling constant

Enormous enhancement for
heavy nuclei target!

WIMP Spin-Independent Recoil Spectrum

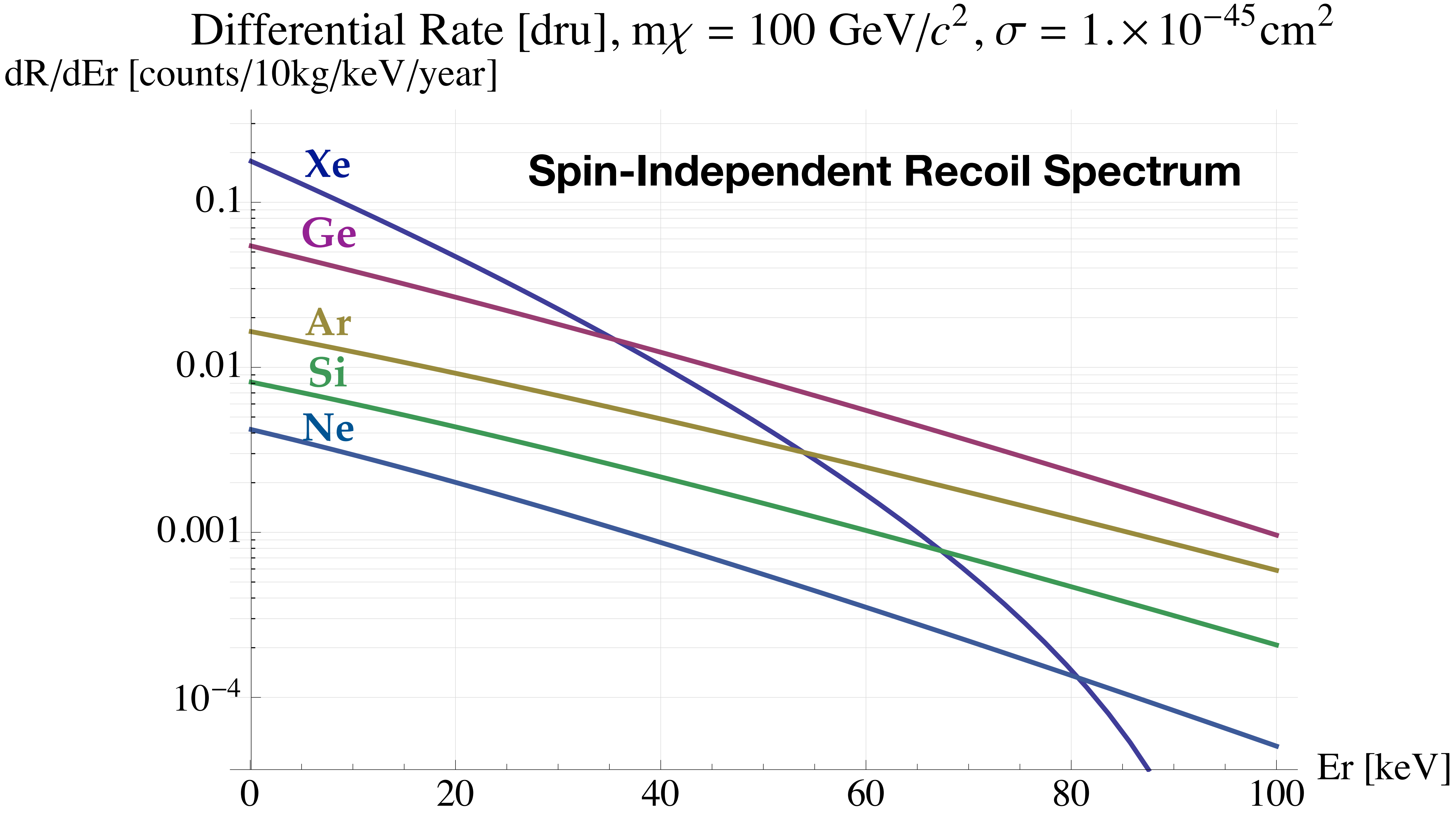
particle theory

nuclear structure

astrophysics properties

Interaction Rate
[events/keV/kg/day]

$$\frac{dR}{dE_R} = \frac{\sigma_o}{m_\chi} \frac{F^2(E_R)}{m_r^2} \frac{\rho_o\, T(E_R)}{v_o \sqrt{\pi}}$$



Principles of Particle Detection: Spin Dependent

nuclear
structure

Interaction
Rate
[events/keV/kg/day]

$$\frac{dR}{dE_R} = \frac{\sigma_o}{m_\chi} \boxed{\frac{F^2(E_R)}{m_r^2}} \frac{\rho_o\, T(E_R)}{v_o \sqrt{\pi}}$$

$$F^2(E_r) = S(E_r)/S(0)$$

$$S(E_r) = a_0^2 S_{00}(E_r) + a_1^2 S_{11}(E_r) + a_0 a_1 S_{01}(E_r)$$

“Spin-dependent Form Factor”

a_0 = isoscalar matrix element

a_1 = isovector matrix element

S_{ij} are obtained from detailed nuclear calculations.

Principles of Particle Detection: Spin Dependent

particle
theory

Interaction
Rate
[events/keV/kg/day]

$$\frac{dR}{dE_R} = \boxed{\frac{\sigma_o}{m_\chi}} \frac{F^2(E_R)}{m_r^2} \frac{\rho_o\, T(E_R)}{v_o\,\sqrt{\pi}}$$

- Dominated by unpaired nucleons
- For spinless nuclides, SD cross section = 0
- For zero momentum transfer collisions (extremely soft bumps) the cross section is approximately:

$$\sigma_o = \frac{32(J+1)}{\pi \underset{\uparrow}{J}} \underset{\uparrow}{G_F^2}\, m_r^2\, (a_p\langle S_p\rangle + \underset{\uparrow}{a_n}\langle \underset{\uparrow}{S_n}\rangle)^2$$

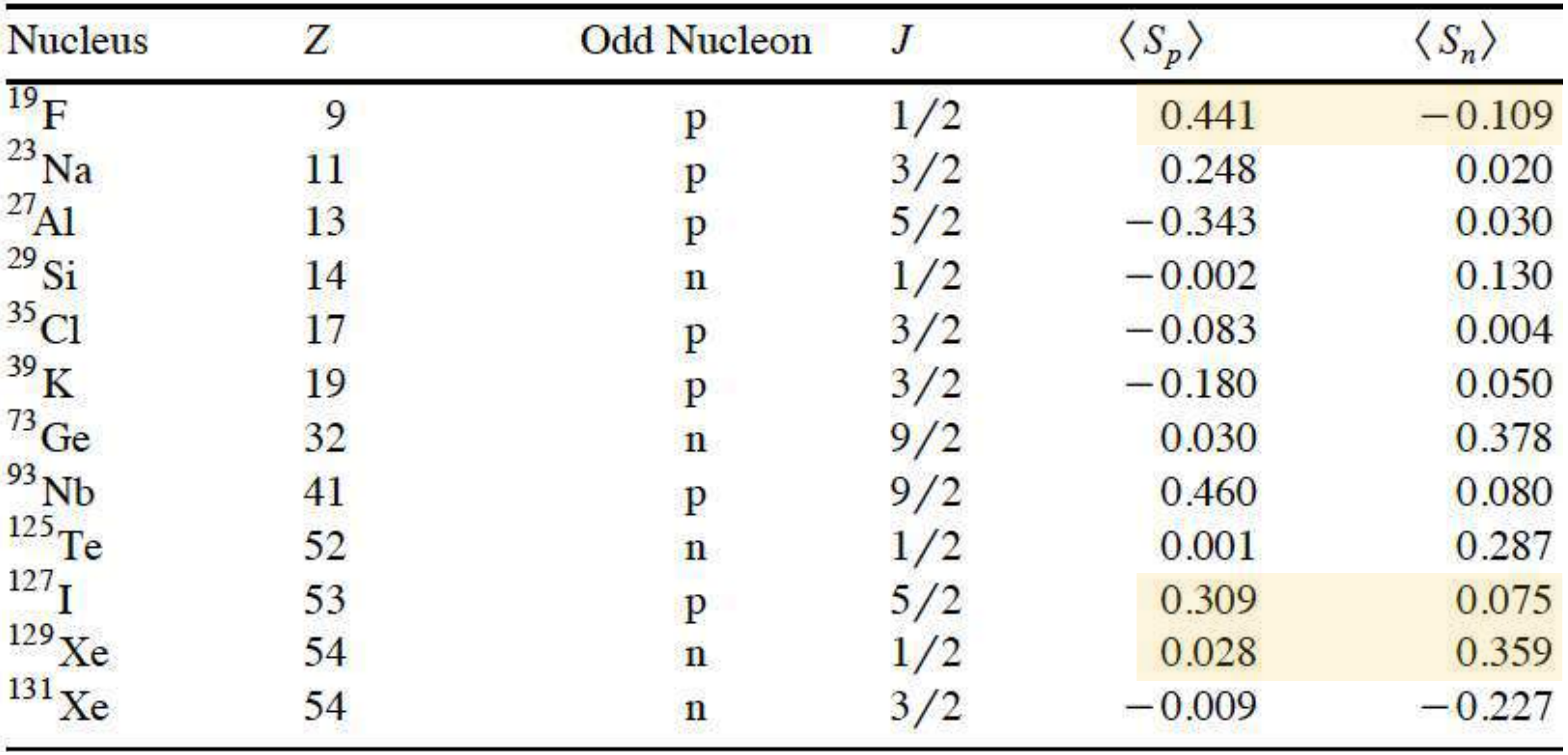
Nuclear Angular Momentum Fermi constant Coupling constant Spin

Principles of Particle Detection: Spin Dependent

$$\sigma_o = \frac{32(J+1)}{\pi J} G_F^2 \, m_r^2 \, (a_p \langle S_p \rangle + a_n \langle S_n \rangle)^2$$

Nuclear Angular Momentum Fermi constant Coupling constant Spin

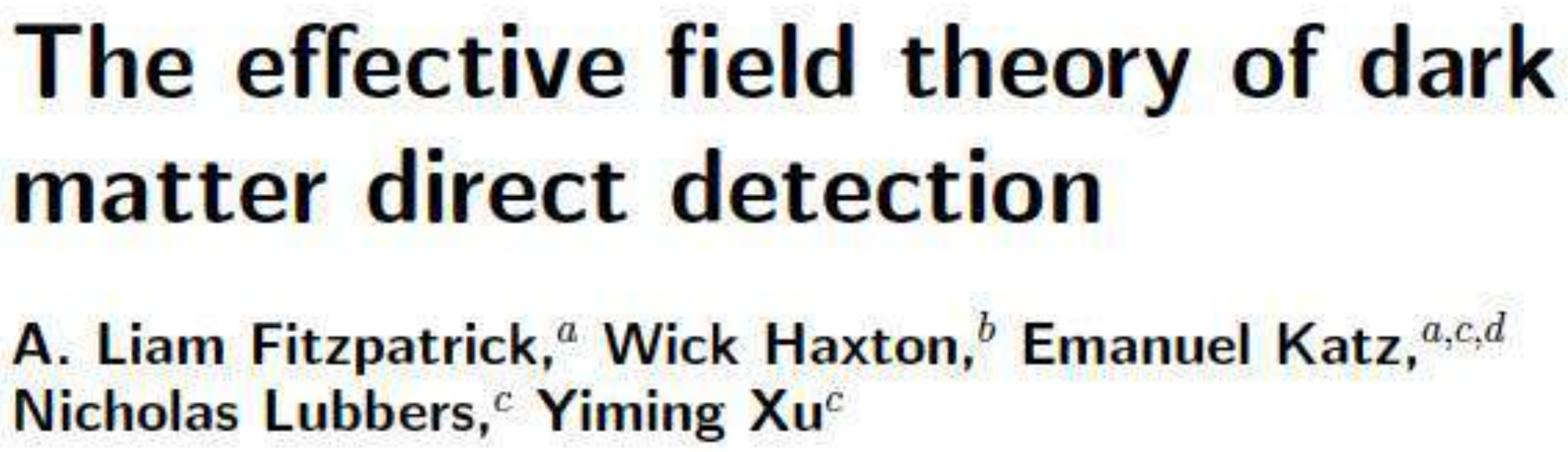
Tovey et al. Physics Letters B 488 (2000) 17-26



Nucleus	Z	Odd Nucleon	J	$\langle S_p \rangle$	$\langle S_n \rangle$
^{19}F	9	p	1/2	0.441	−0.109
^{23}Na	11	p	3/2	0.248	0.020
^{27}Al	13	p	5/2	−0.343	0.030
^{29}Si	14	n	1/2	−0.002	0.130
^{35}Cl	17	p	3/2	−0.083	0.004
^{39}K	19	p	3/2	−0.180	0.050
^{73}Ge	32	n	9/2	0.030	0.378
^{93}Nb	41	p	9/2	0.460	0.080
^{125}Te	52	n	1/2	0.001	0.287
^{127}I	53	p	5/2	0.309	0.075
^{129}Xe	54	n	1/2	0.028	0.359
^{131}Xe	54	n	3/2	−0.009	−0.227

WIMP-Nucleus Interaction: maybe not so simple?

- Effective Field Theory contains 14 operators, which combine such that the WIMP-nucleon cross section depends on six independent nuclear response functions:
  - One “Spin independent”
  - Two “Spin Dependent”
  - Three “Velocity-Dependent”
- Two pairs of these interfere, so there are *eight independent parameters* that can be probed



The effective field theory of dark matter direct detection

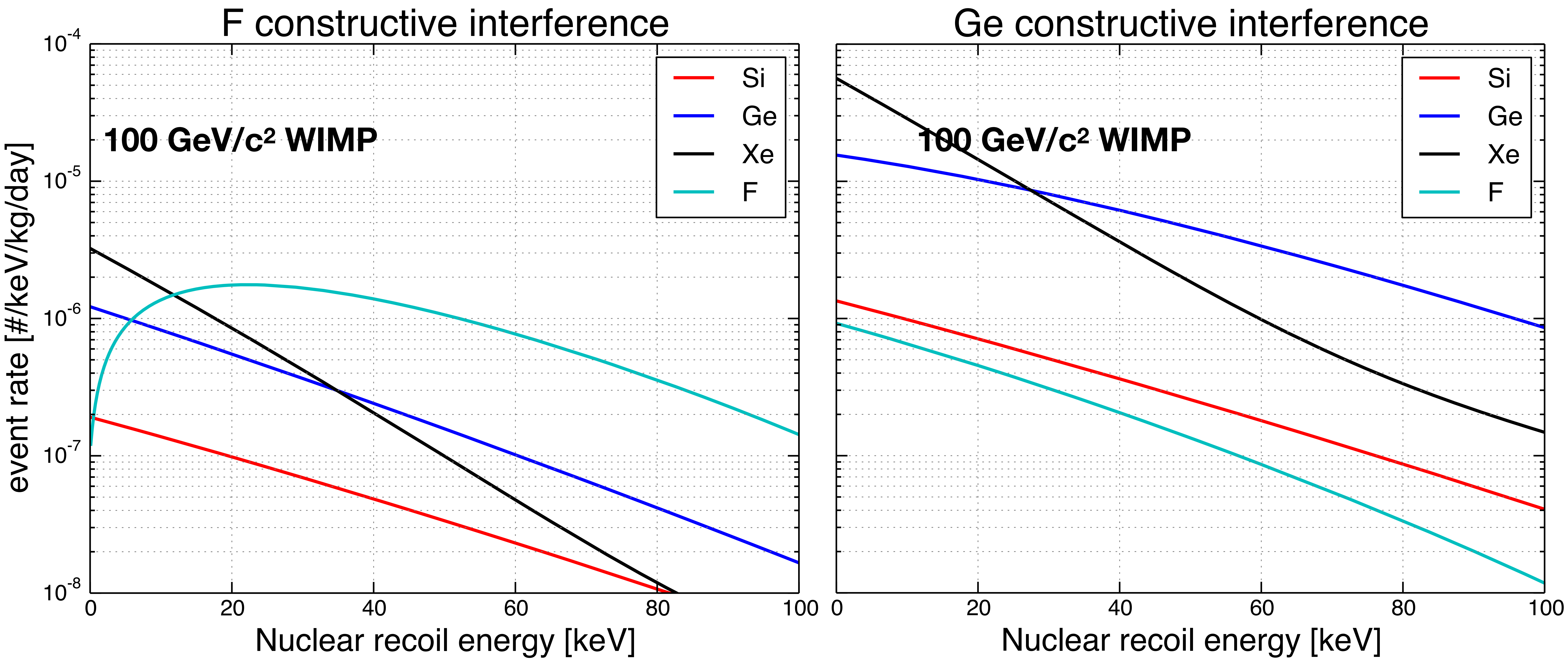
A. Liam Fitzpatrick,[a] Wick Haxton,[b] Emanuel Katz,[a,c,d]
Nicholas Lubbers,[c] Yiming Xu[c]

http://arxiv.org/abs/1211.2818
http://arxiv.org/abs/1308.6288
http://arxiv.org/abs/1405.6690
http://arxiv.org/abs/1503.03379

Dark Matter Could Look Different in Different Targets

- EFT Operators can interfere, generating not only different rates between targets, but different spectral shapes
- A robust dark matter direct detection program with different target materials will be needed to nail down which operators are contributing to any detected signal

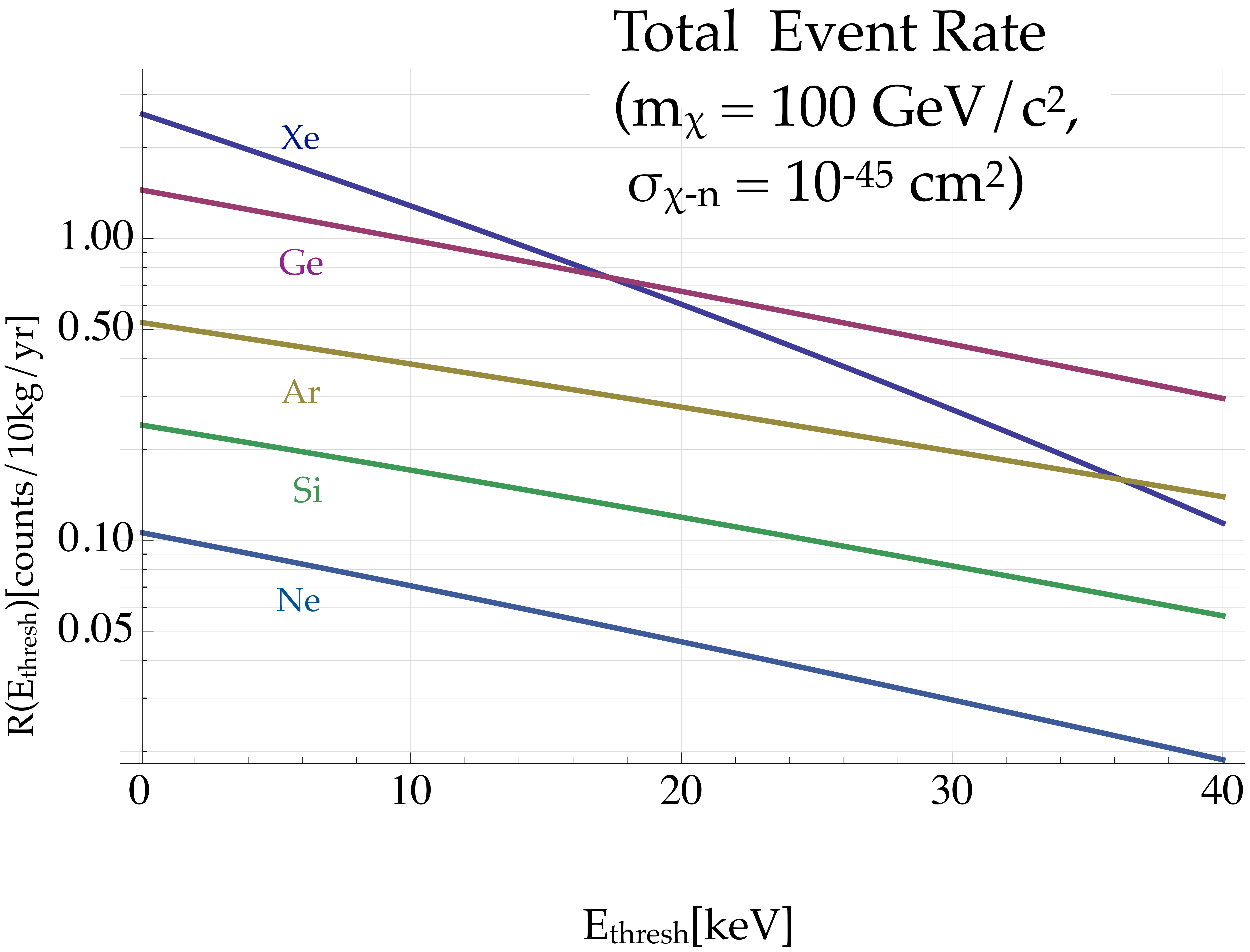
- Take home message: *We will need multiple targets to map out the physics of WIMP-nucleon interactions!*



Designing an Ideal WIMP Detector

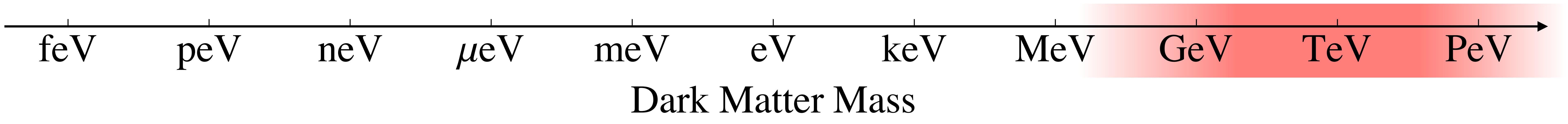
The Event Rates are Extremely Low!

- Elastic scattering of WIMP deposits small amounts of energy into a recoiling nucleus (~few 10s of keV)
- Featureless exponential spectrum with no obvious peak, knee, break…
- Event Rate is very, very low
- Radioactive background of most materials is higher than the event rate.

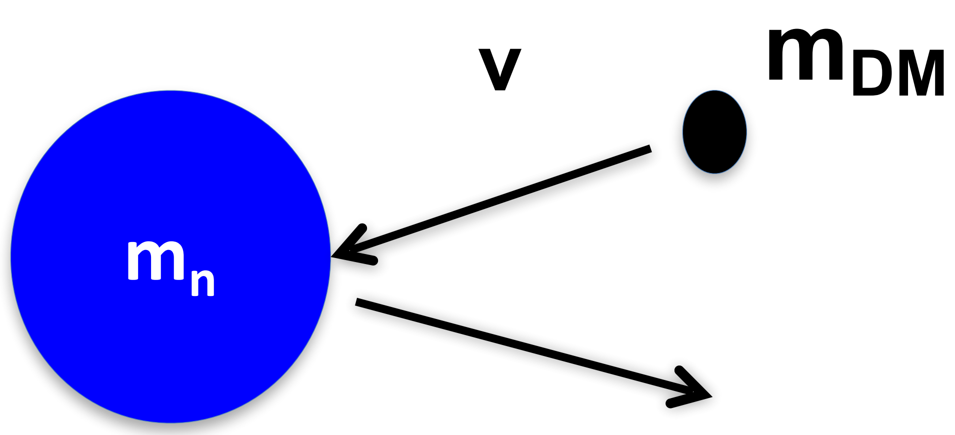


Nuclear Recoil Direct Detection Requirements

1: Large Exposure (Mass x Time)

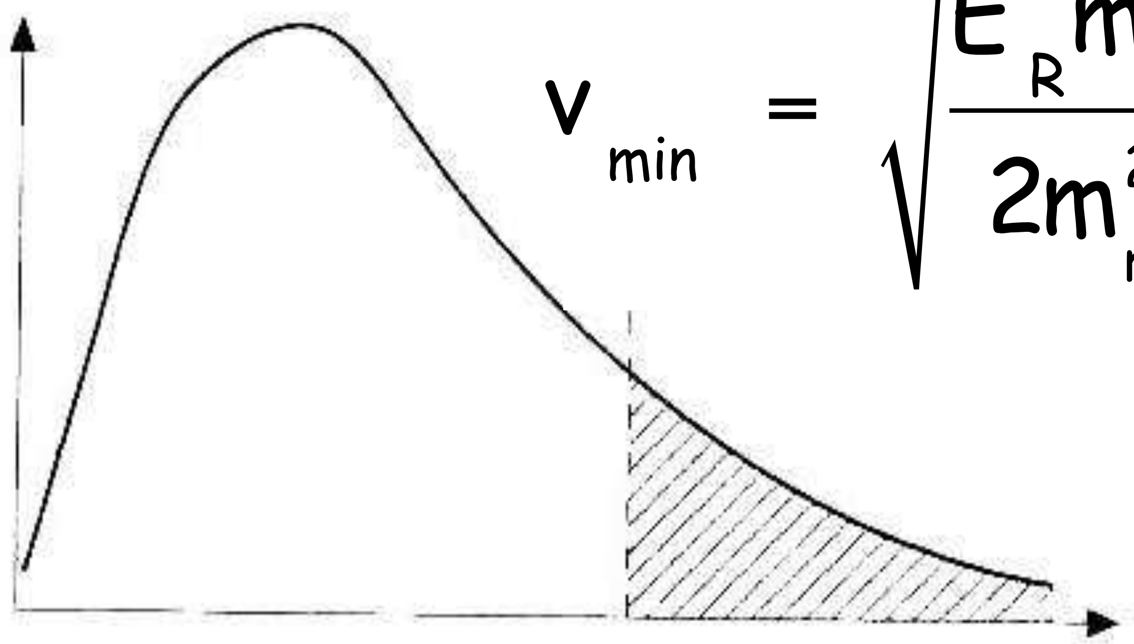


The low-mass WIMP challenge

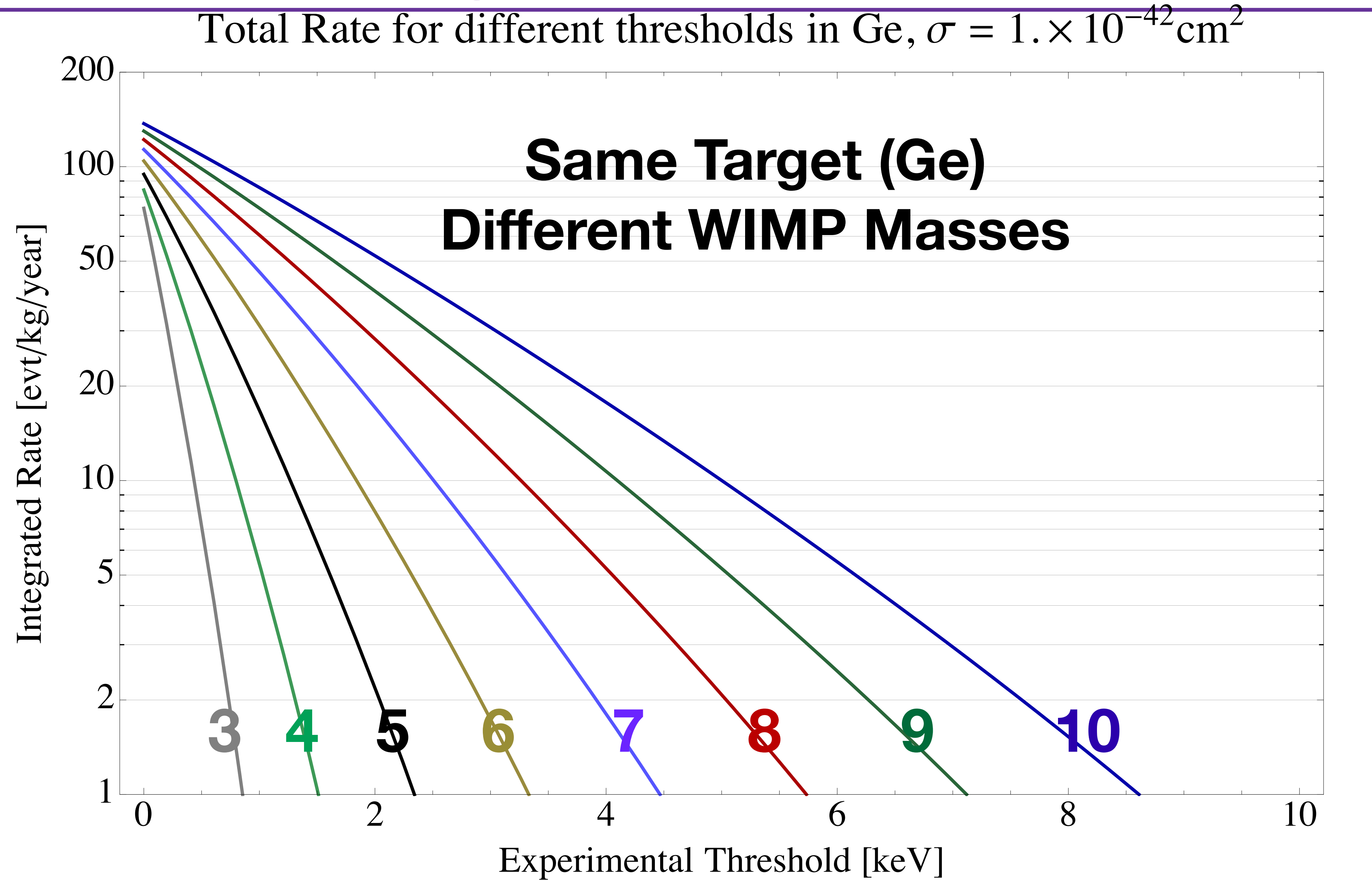


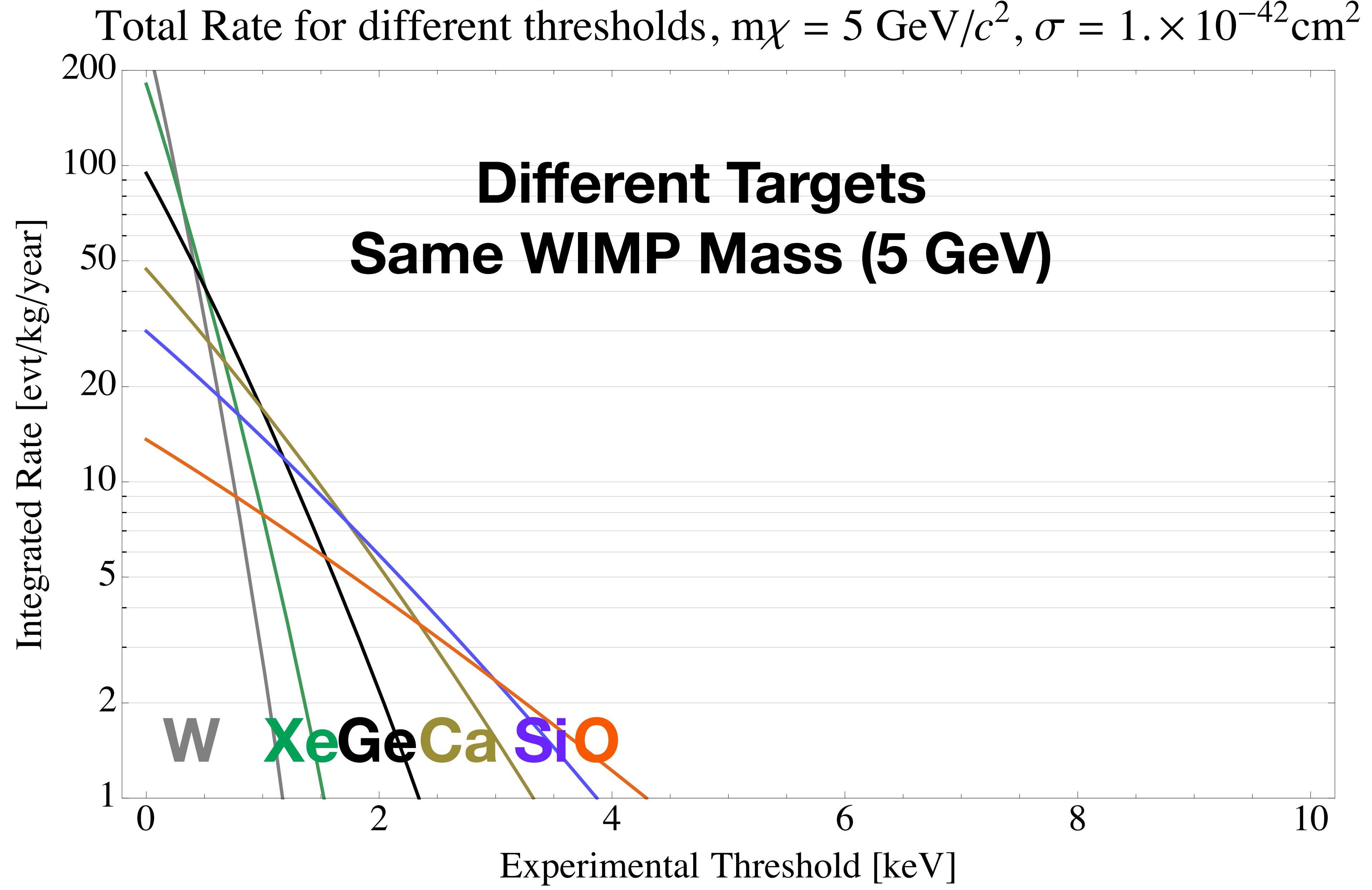
$$\Delta E = \frac{\Delta P^2}{2M_n} \lesssim \frac{2M_{DM}^2 v^2}{M_N}$$

A WIMP must have a minimum velocity to produce a recoil of a specific energy

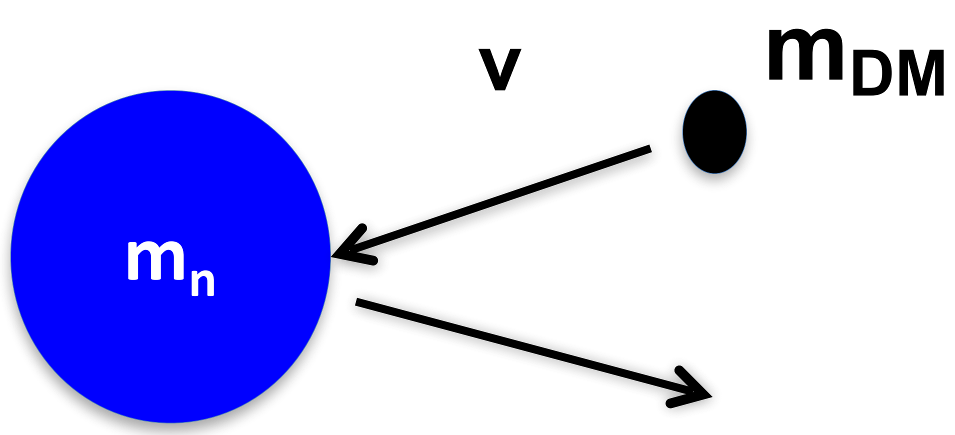


$$v_{min} = \sqrt{\frac{E_R m_N}{2m_r^2}}$$





The low-mass WIMP challenge below 5 GeV



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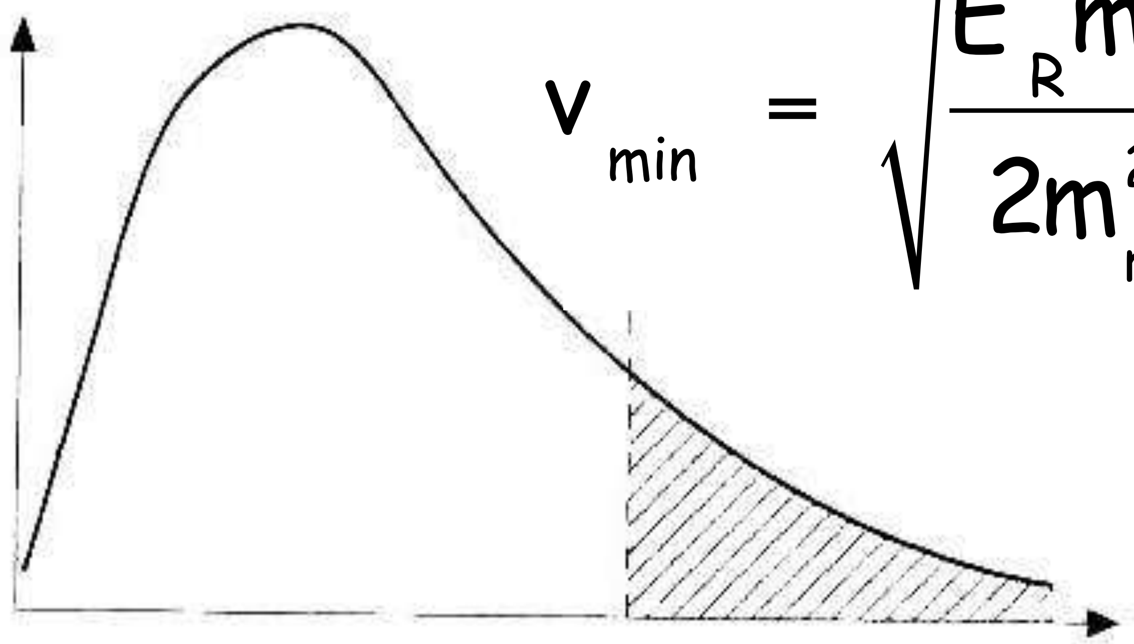

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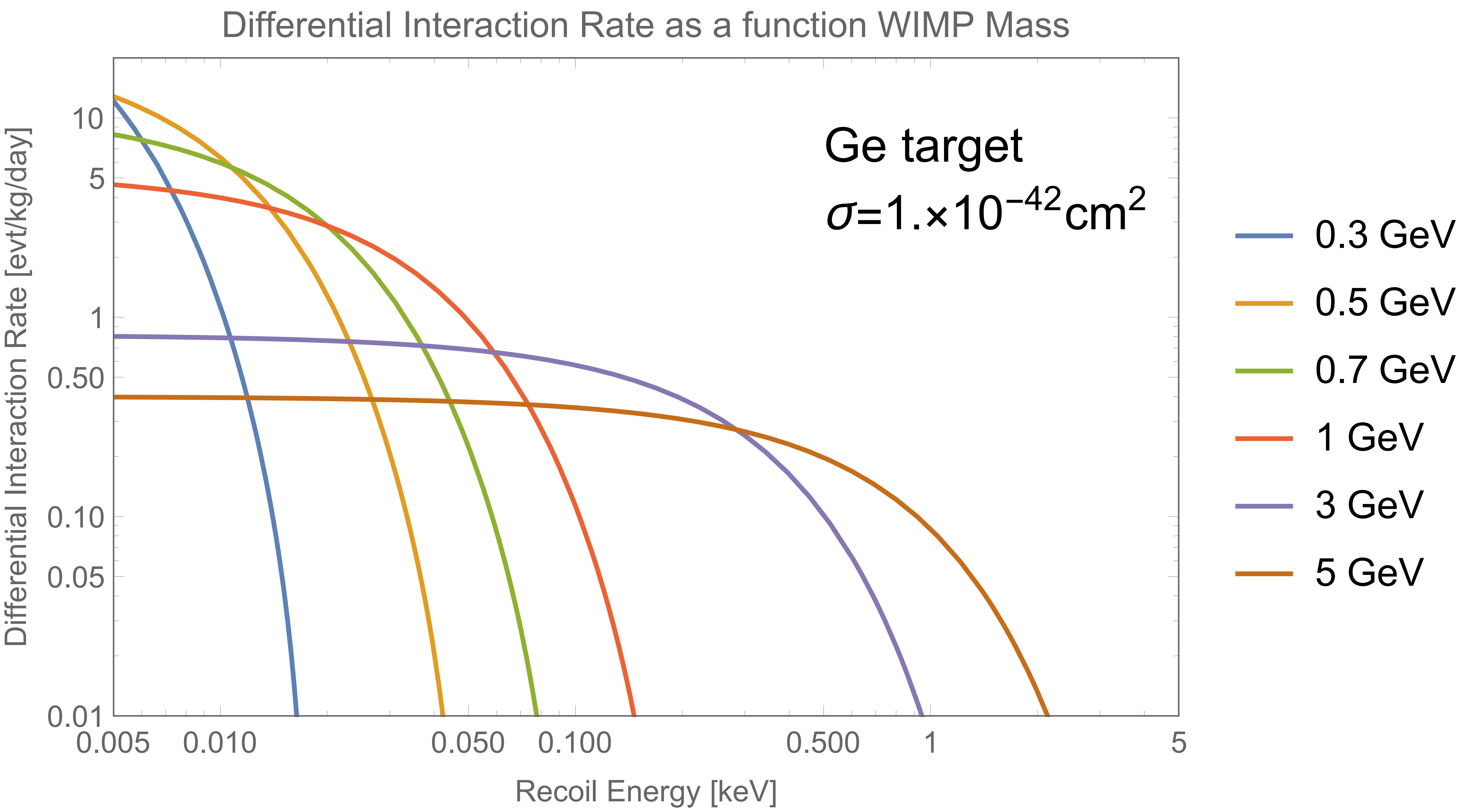
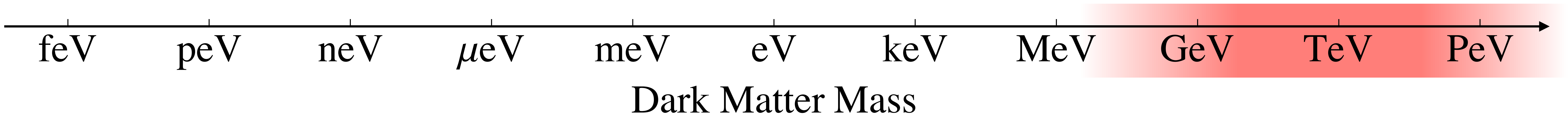


Nuclear Recoil Direct Detection Requirements

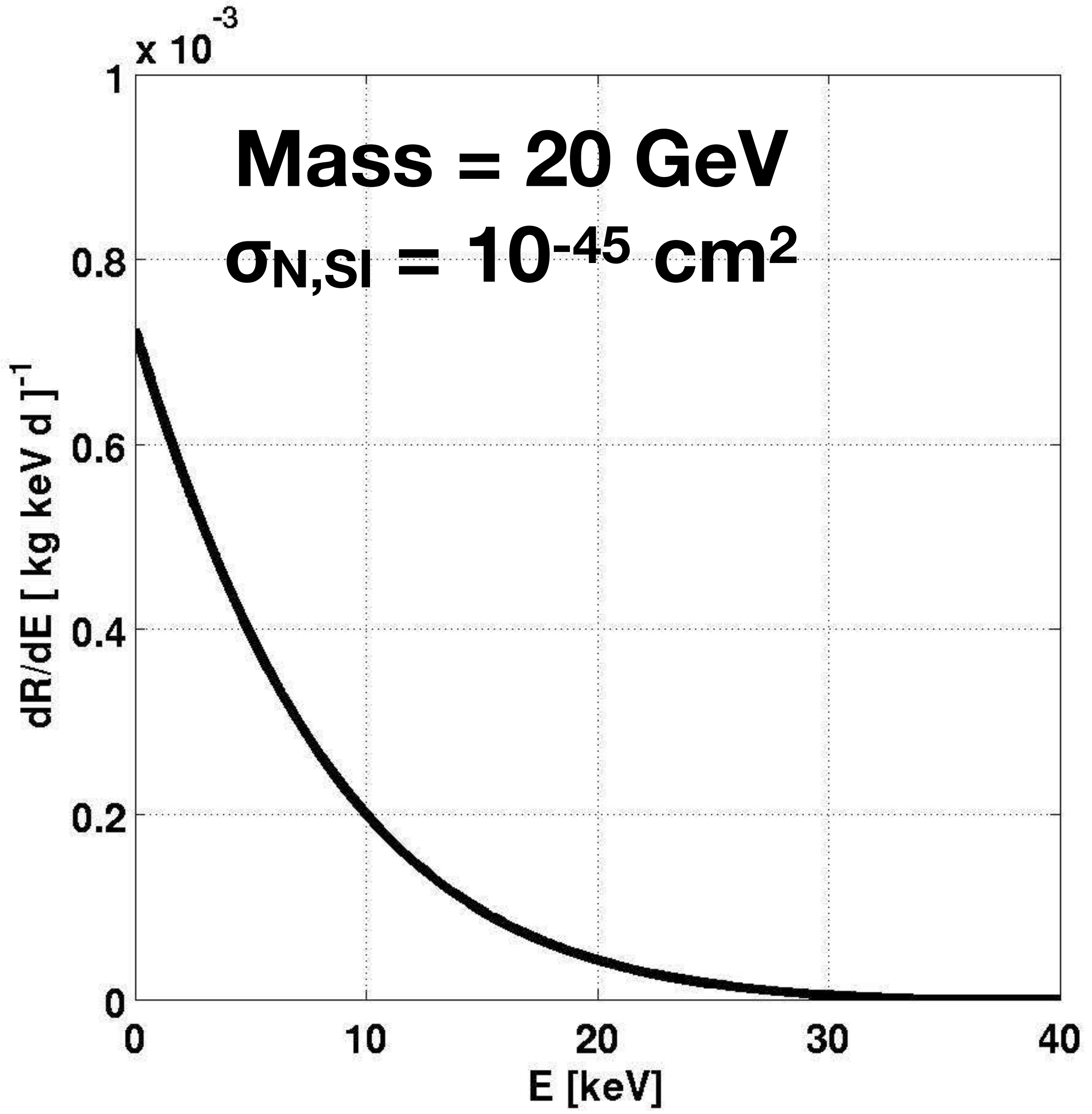
1: Large Exposure (Mass x Time)

2: Low Energy Threshold

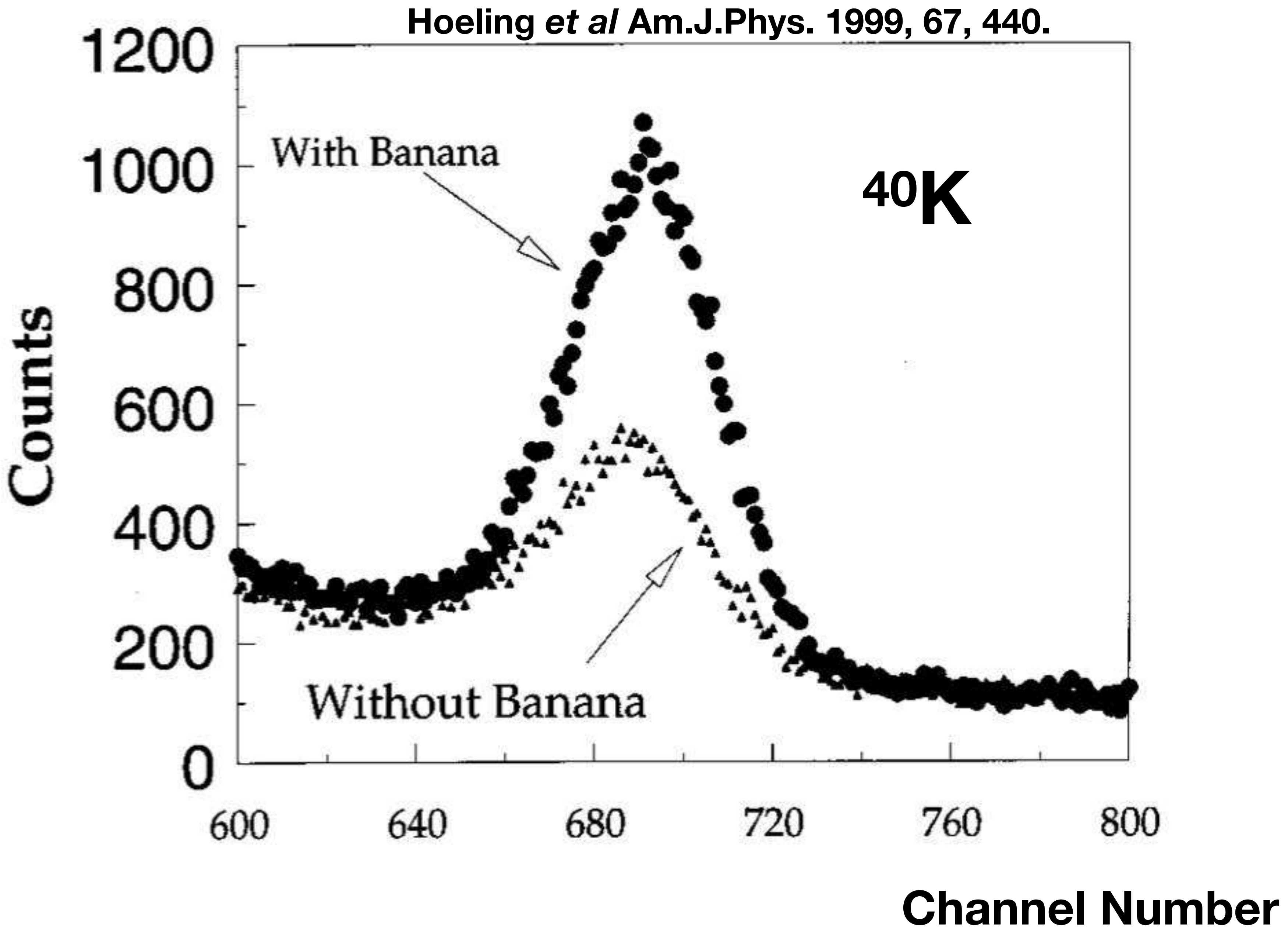


The Event Rates are Extremely Low!

Expected WIMP Spectrum



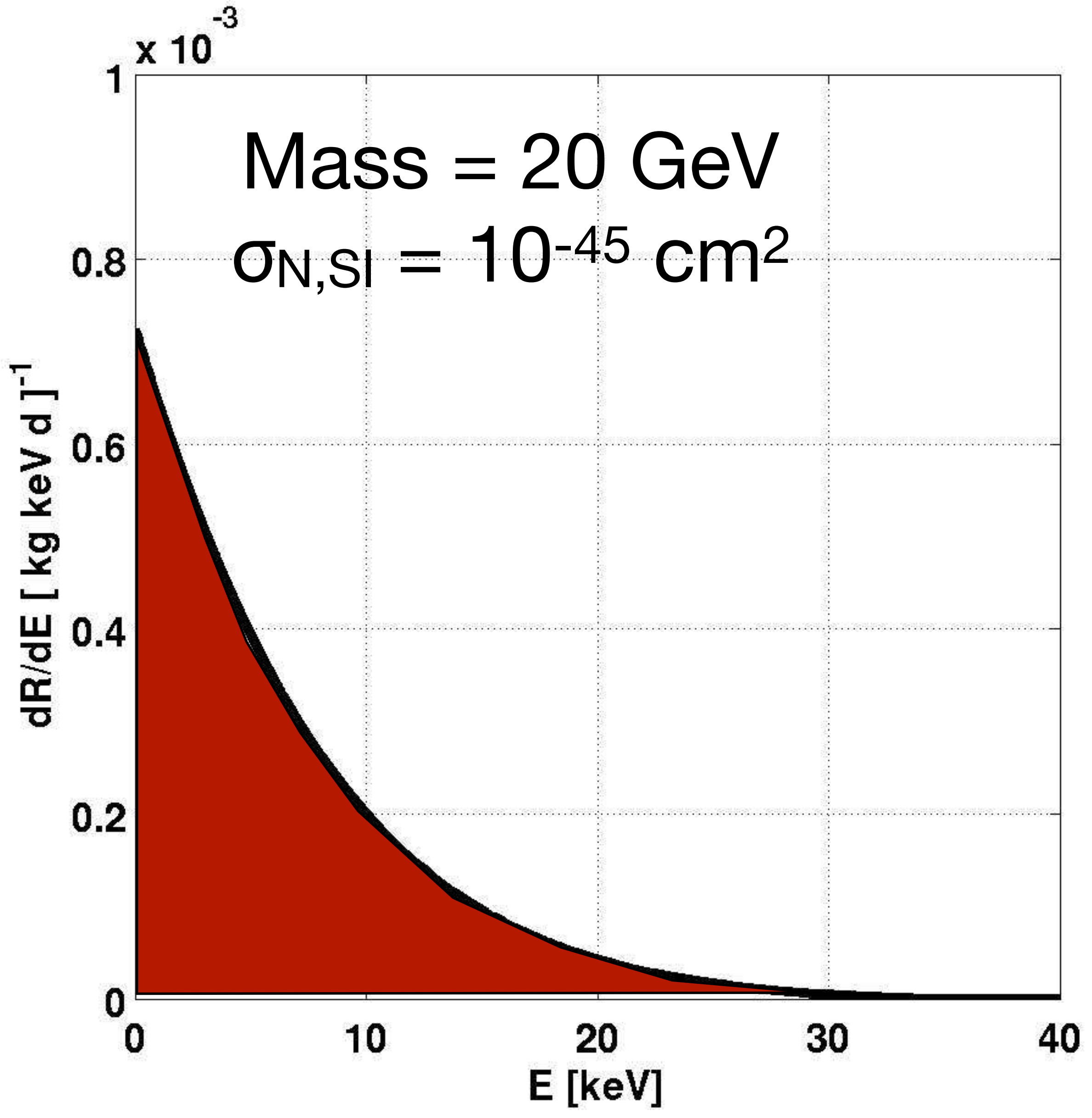
Measured Banana Spectrum



The Event Rates are Extremely Low!

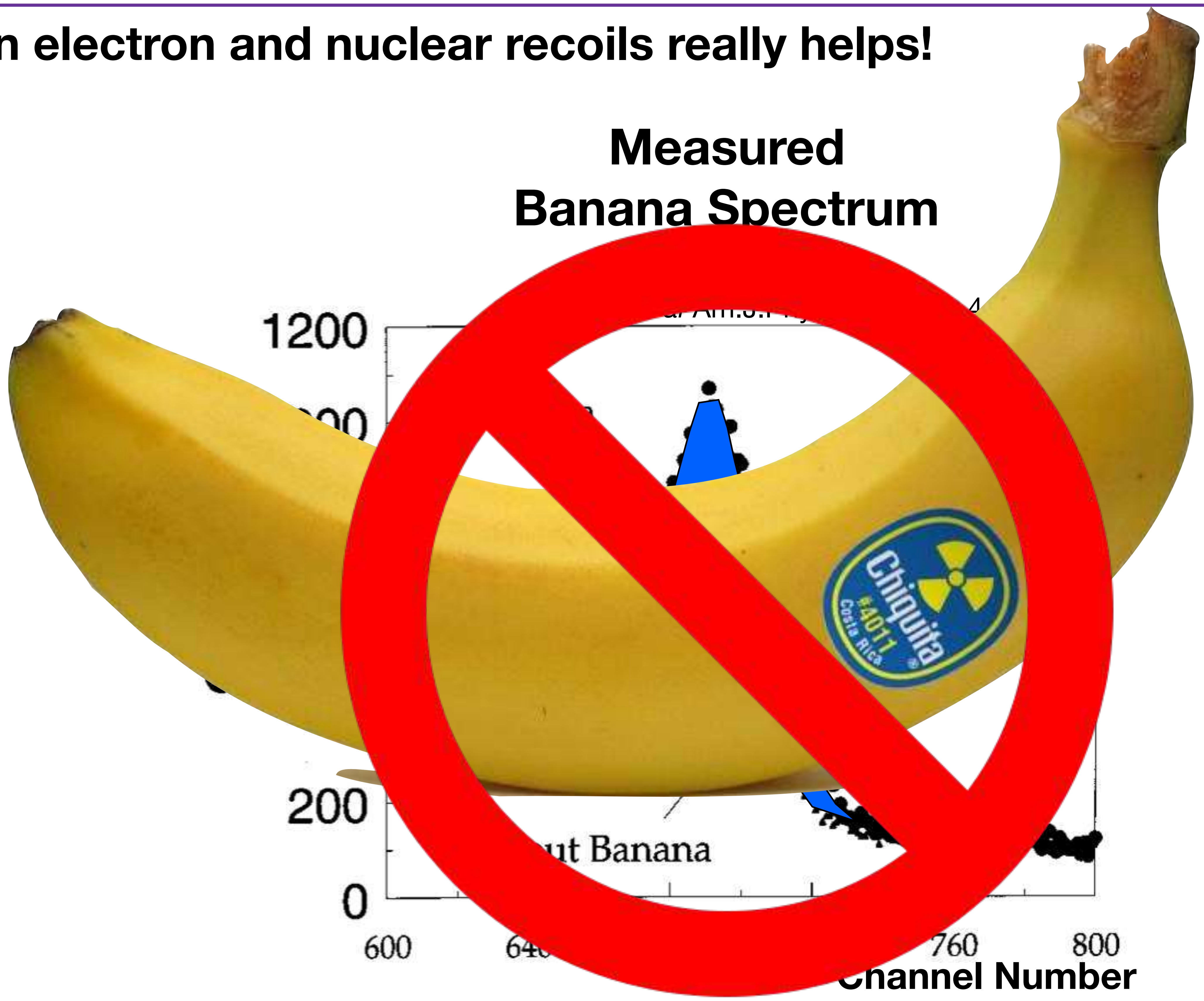
Discrimination between electron and nuclear recoils really helps!

Expected WIMP Spectrum



Mass = 20 GeV
$\sigma_{N,SI} = 10^{-45}$ cm^2

Measured Banana Spectrum



~1 event per kg per year

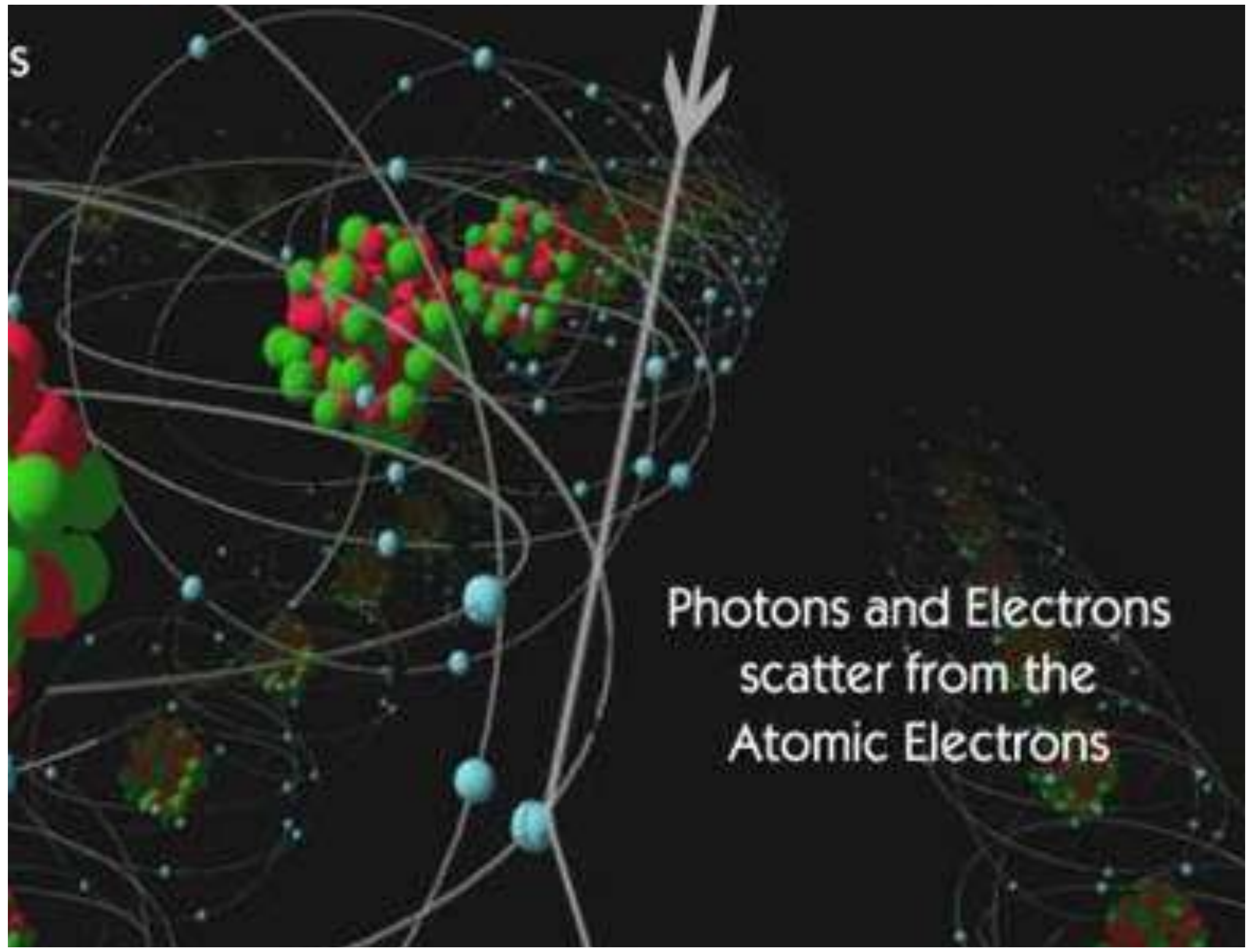
~100 events per kg per second

(Nuclear Recoils)

(Electron Recoils)

Typical backgrounds

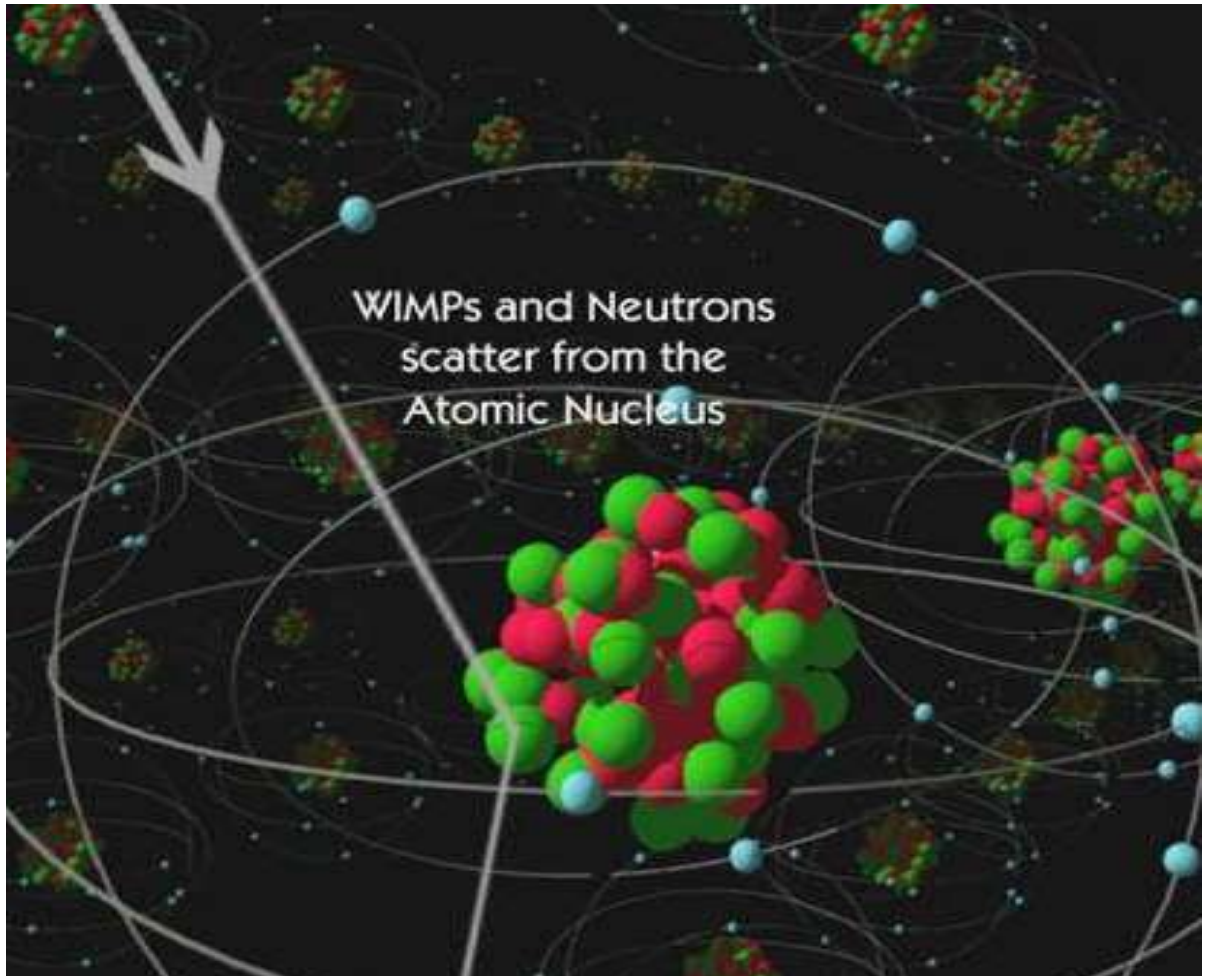
Most backgrounds are from trace radioactivity (U, Th, K contamination) or induced by cosmic rays (cosmogenic background)



ELECTRON RECOILS (ER)

Gamma: Most prevalent background

Beta: on the surface or in the bulk



NUCLEAR RECOILS (NR)

Neutron: NOT distinguishable from WIMPS

Alphas: almost always a surface event

Recoiling parent nucleus: yet another surface event

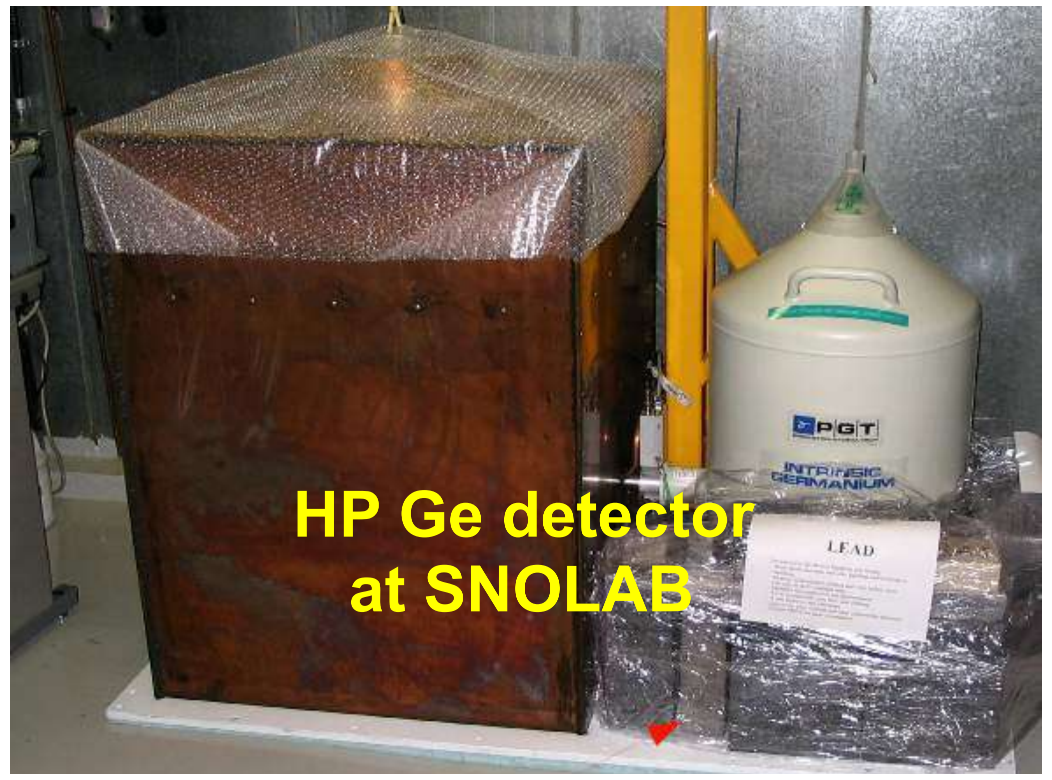
Managing backgrounds (in 5-steps)

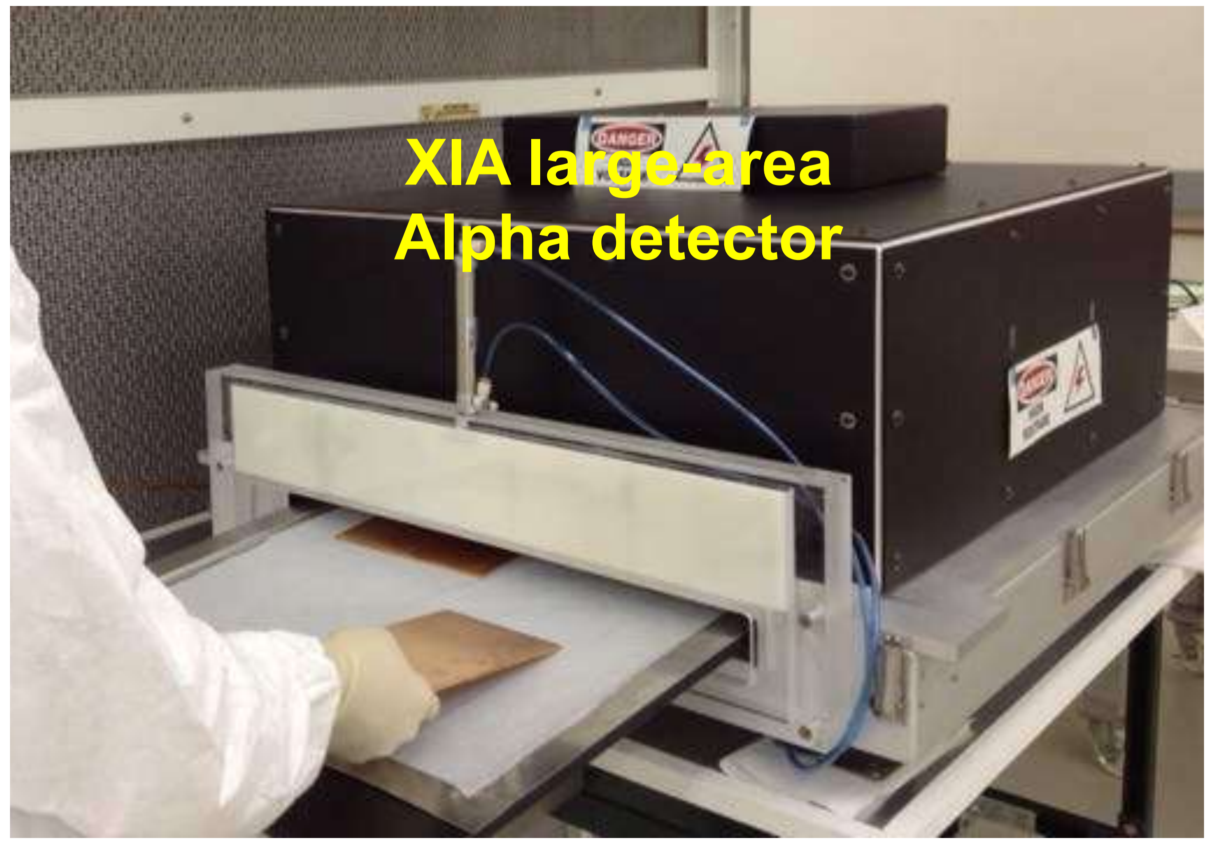
1. Choose highly radiopure materials for your detector and experimental setup. Build it in a state-of-the art clean lab (class ~1000 or better is often used).

1a) Screening and material assay

Materials used for dark matter (and some neutrino) experiments must be thoroughly screened for radioactivity before use.


MWPC
(Beta Cage)


HP Ge detector
at SNOLAB


XIA large-area
Alpha detector


ICP Mass Spectrometer at
LNGS

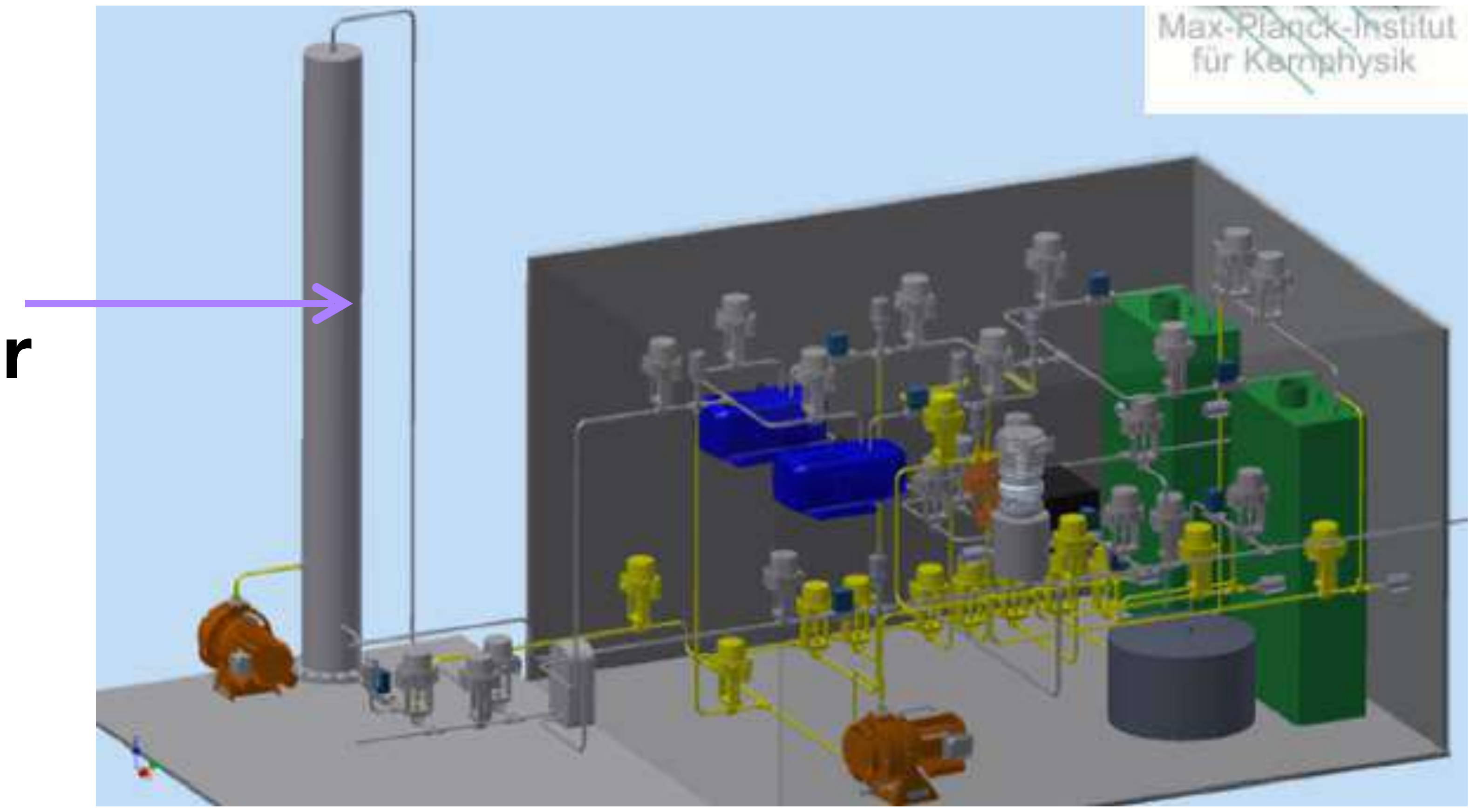
In many cases one is looking for isotope contamination at the level of parts per billion (ppb).

The demands on radiopurity are so high that one needs a detector that is almost as well shielded and low in background as the dark matter detector itself!

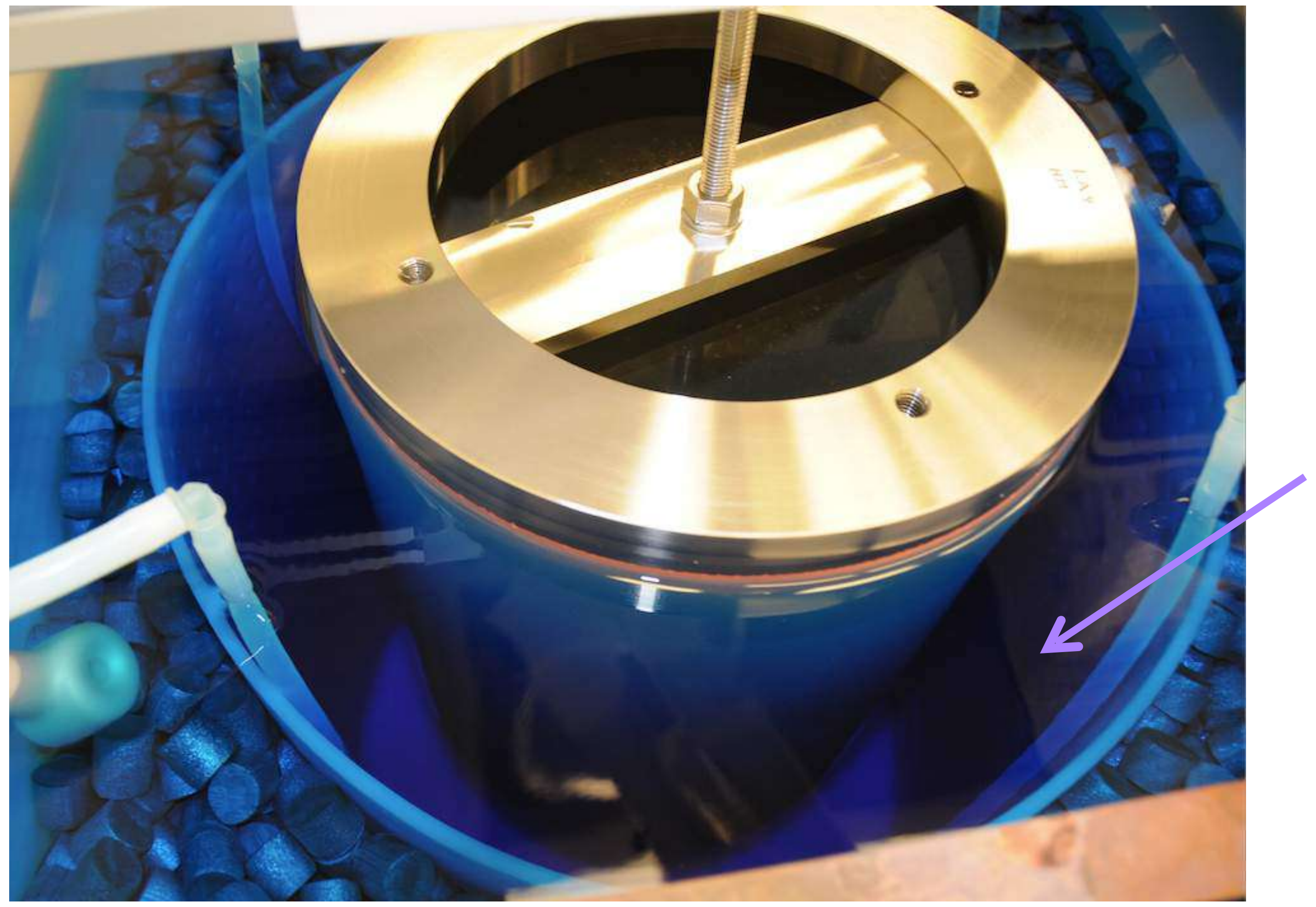
1b) If you can't find it build it

If the materials you come across aren't clean enough then build, extract or purify it yourself

Kr and Rn purification schematic for Xenon 1T



Distillation tower (at Fermilab) for extracting Ar depleted in 39Ar from natural gas wells

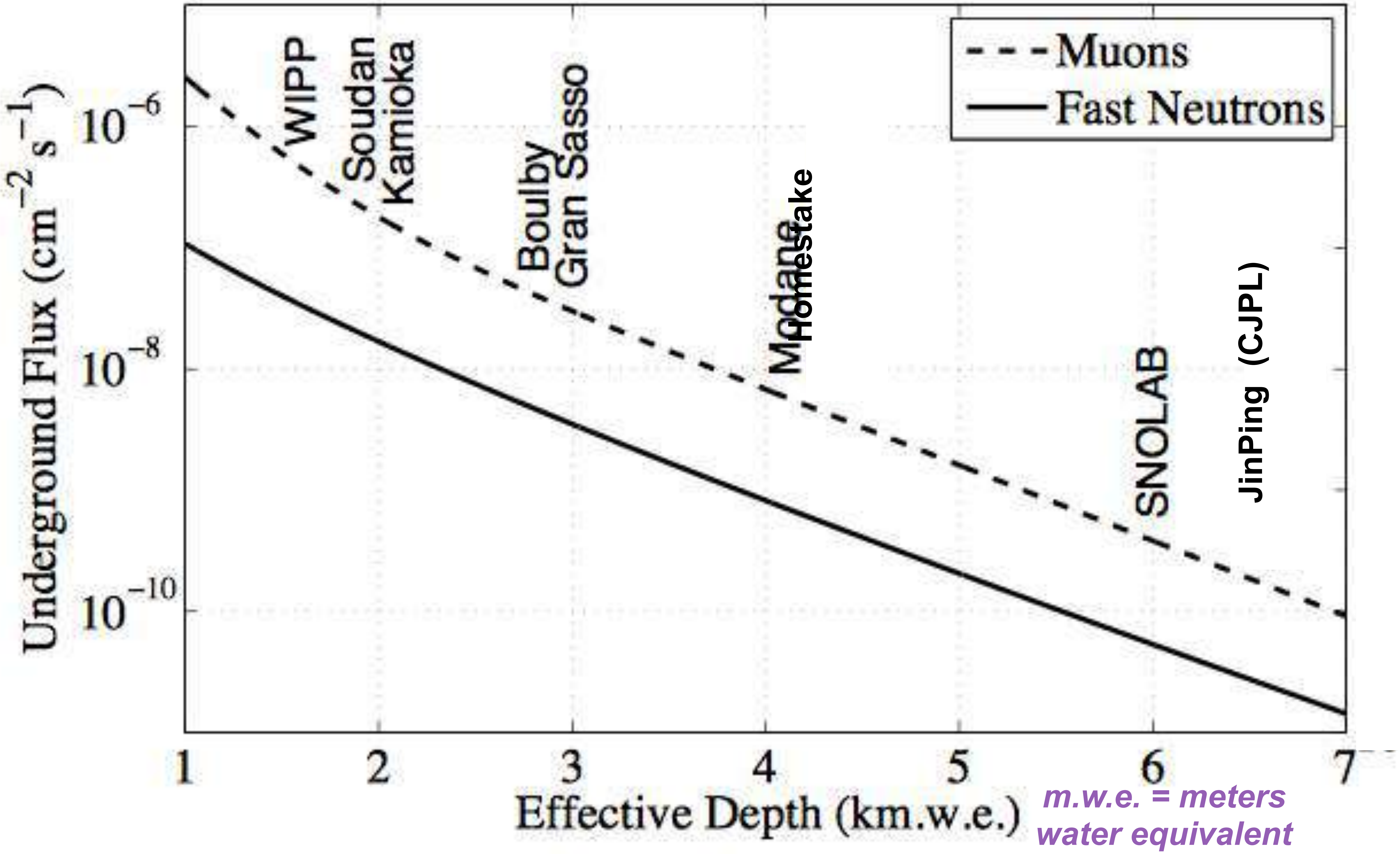


Copper electroforming setup at PNNL

Managing backgrounds (in 5-steps)

1. Choose highly radiopure materials for your detector and experimental setup. Build it in a state-of-the art clean lab (class ~1000 or better is often used).
2. Cosmic muons produce fast neutrons via spallation. These are difficult to shield against and are a source of irreducible background. Go deep underground where the fast neutron flux is reduced.

2) Where to locate your experiment



m.w.e. = meters water equivalent

Most experiments use the earth as shielding from muons. The lower the muon rate, the lower the fast neutron rate.

Managing backgrounds (in 5-steps)

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2. Cosmic muons produce fast neutrons via spallation. These are difficult to shield against and are a source of irreducible background. Go deep underground where the fast neutron flux is reduced.

3. Unless you bury your detector 2 km deep in pristine glacial ice, you will have significant background from radioactivity.   Surround your radiopure experiment with several tons of radiopure shielding.

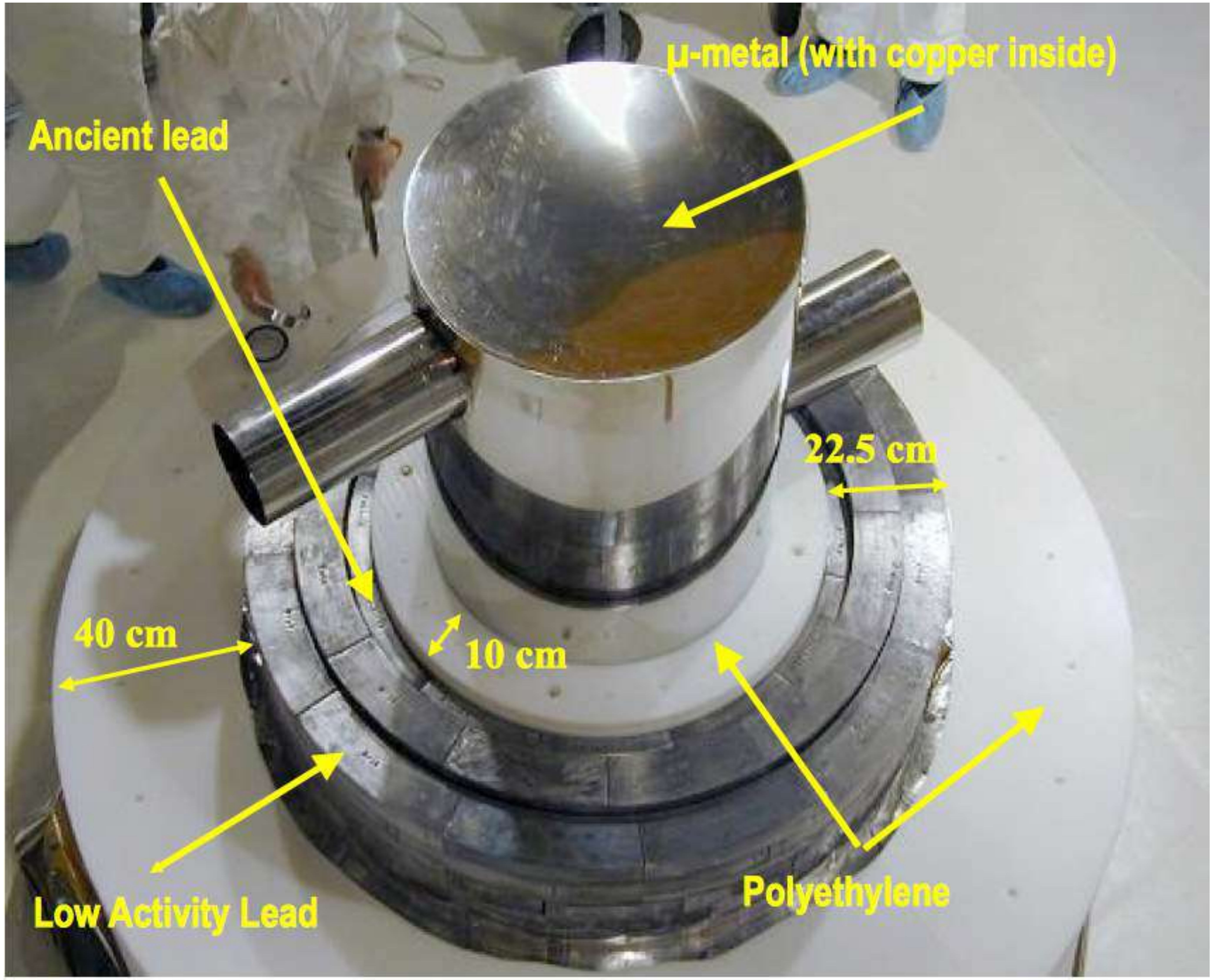
3a) Passive Shielding

Trace U/Th/K and other isotopes in cavern walls and surroundings produce a constant flux of gammas and neutrons (via spontaneous fission or α,n)

Lead shields against gammas; *~22 cm drops the gamma rate by ~10^6*

Ancient lead or copper shields against ^{210}Pb, and its daughters, found in standard lead

Polyethylene or water moderates radiogenic and cosmogenic neutrons so that they produce recoils below the experimental threshold; *0.5 m of poly reduces the neutron scattering rate by ~10^4*



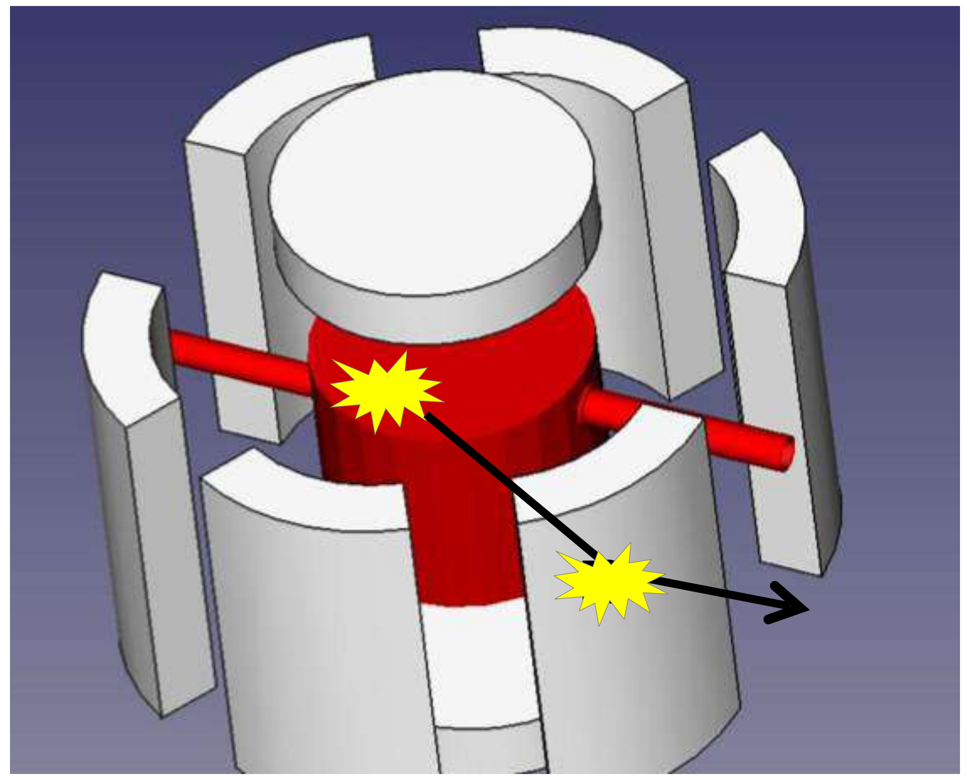
SuperCDMS passive shielding

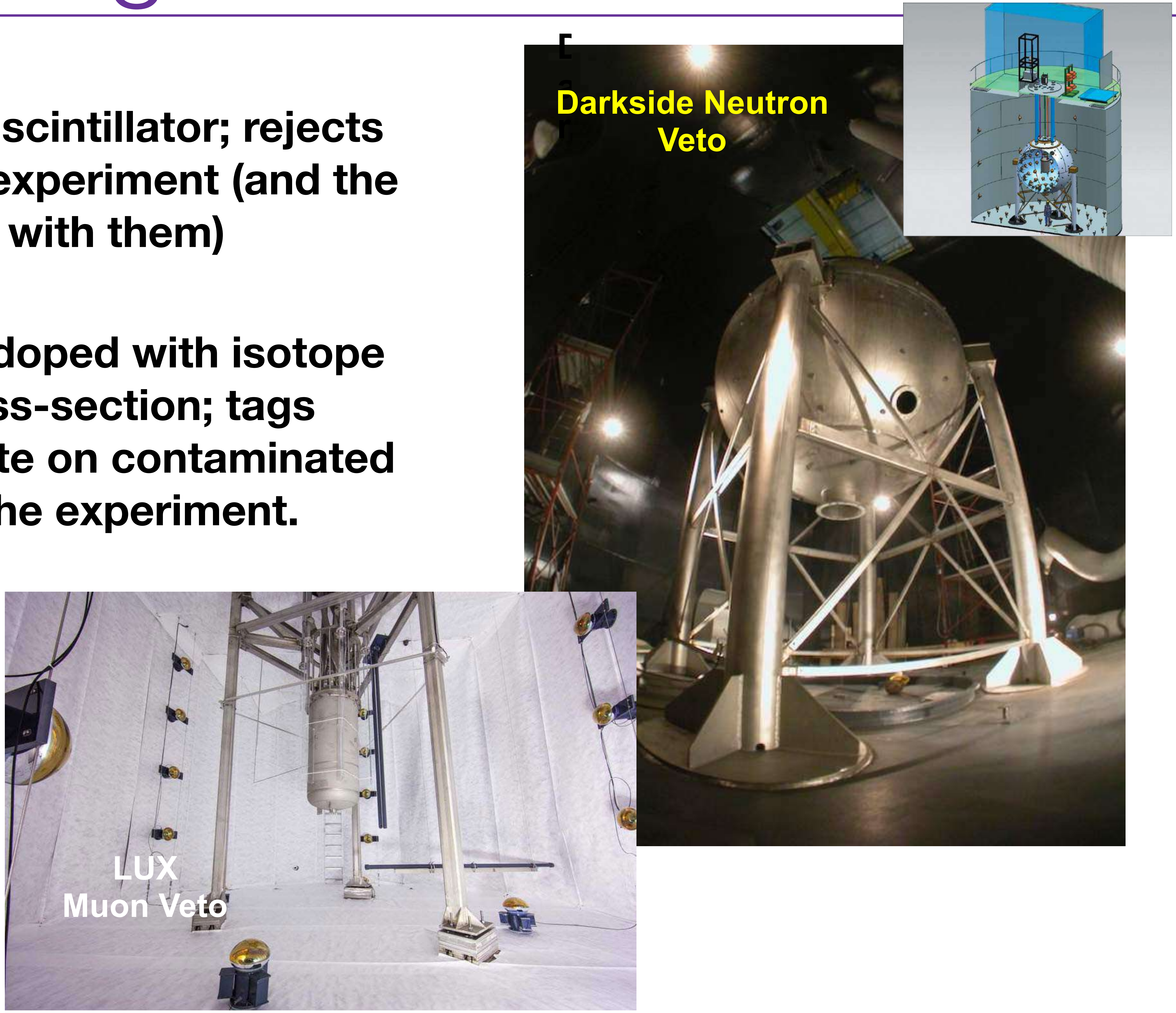
3b) Active Shielding

Muon Veto: water cherenkov or scintillator; rejects muons passing through or near experiment (and the fast neutrons that come with them)

Neutron Veto: liquid scintillator doped with isotope w/ high neutron capture cross-section; tags radiogenic neutrons that originate on contaminated material close to or within the experiment.

SuperCDMS neutron veto schematic





Managing backgrounds (in 5-steps)

1. Choose highly radiopure materials for your detector and experimental setup. Build it in a state-of-the art clean lab (class ~1000 or better is often used).

2. Cosmic muons produce fast neutrons via spallation. These are difficult to shield against and are a source of irreducible background. Go deep underground where the fast neutron flux is reduced.

3. Unless you bury your detector 2 km deep in pristine glacial ice, you will have significant background from radioactivity. Surround your radiopure experiment with several tons of radiopure shielding

4. You will likely still have O(10^6) more ER than expected WIMP scatters in your detector, so make sure your experiment has some ability to distinguish ER from NR - at the level of one part in 10^6 or 10^7 if you can manage it.

Managing backgrounds (in 5-steps)

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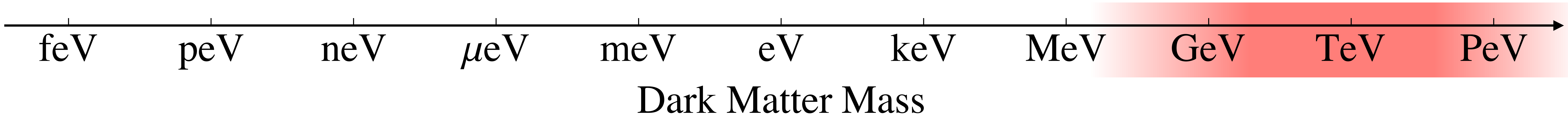
5. A team of talented students and postdocs who fine-tune rejection of background and maximize signal acceptance will extract the most out of the data.

Nuclear Recoil Direct Detection Requirements

1: Large Exposure (Mass x Time)

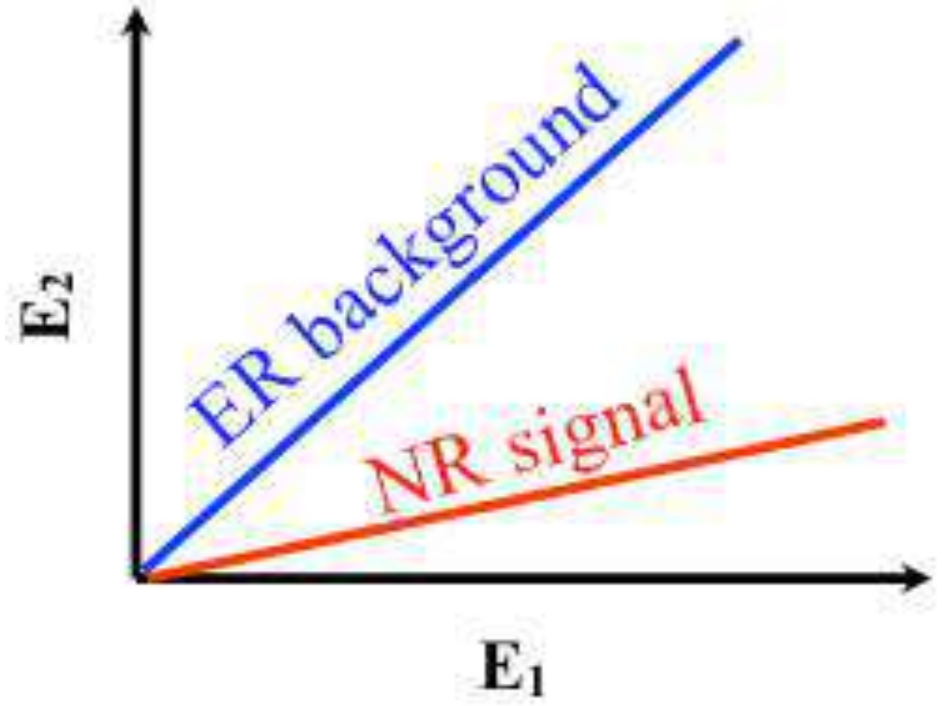
2: Low Energy Threshold

3: Low Backgrounds

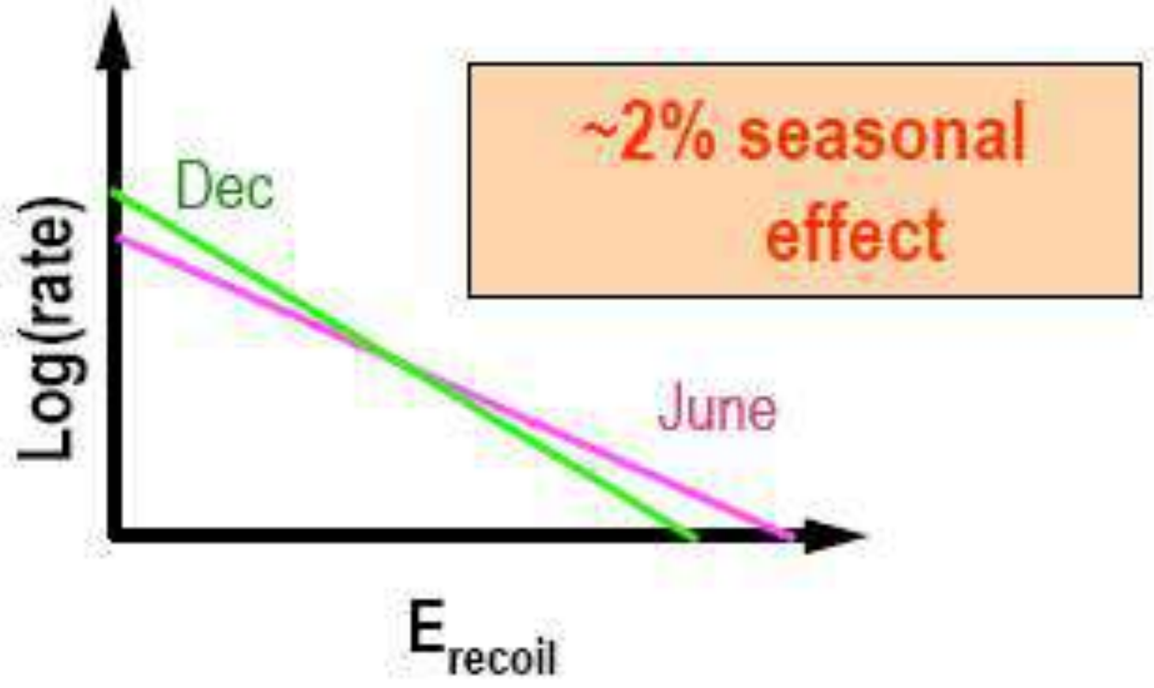


Separating Signal from Background…

- By Detector **Response**
  - Obtain particle identification from the physics of the detector response to different types of particle interactions.

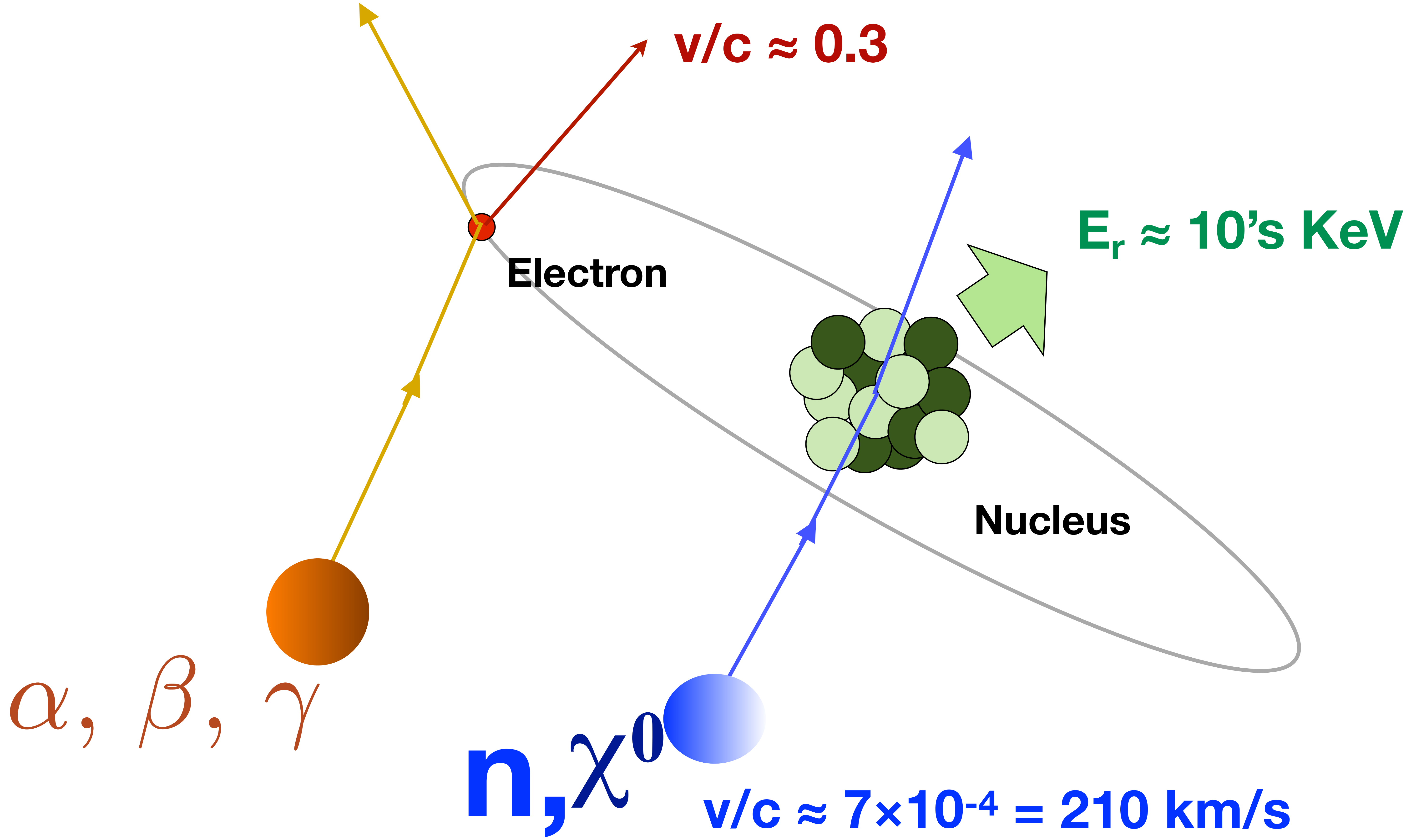


- By **Astrophysical** Modulation
  - Annual Modulation in the WIMP recoil spectrum. Earth's velocity through the galactic halo is max in June, min in December (DAMA/LIBRA).
  - Daily modulation of the incident WIMP direction. Measure the direction of the short track produced by nuclear recoil. (DM-TPC)
- Can be Event-by-Event or Statistical

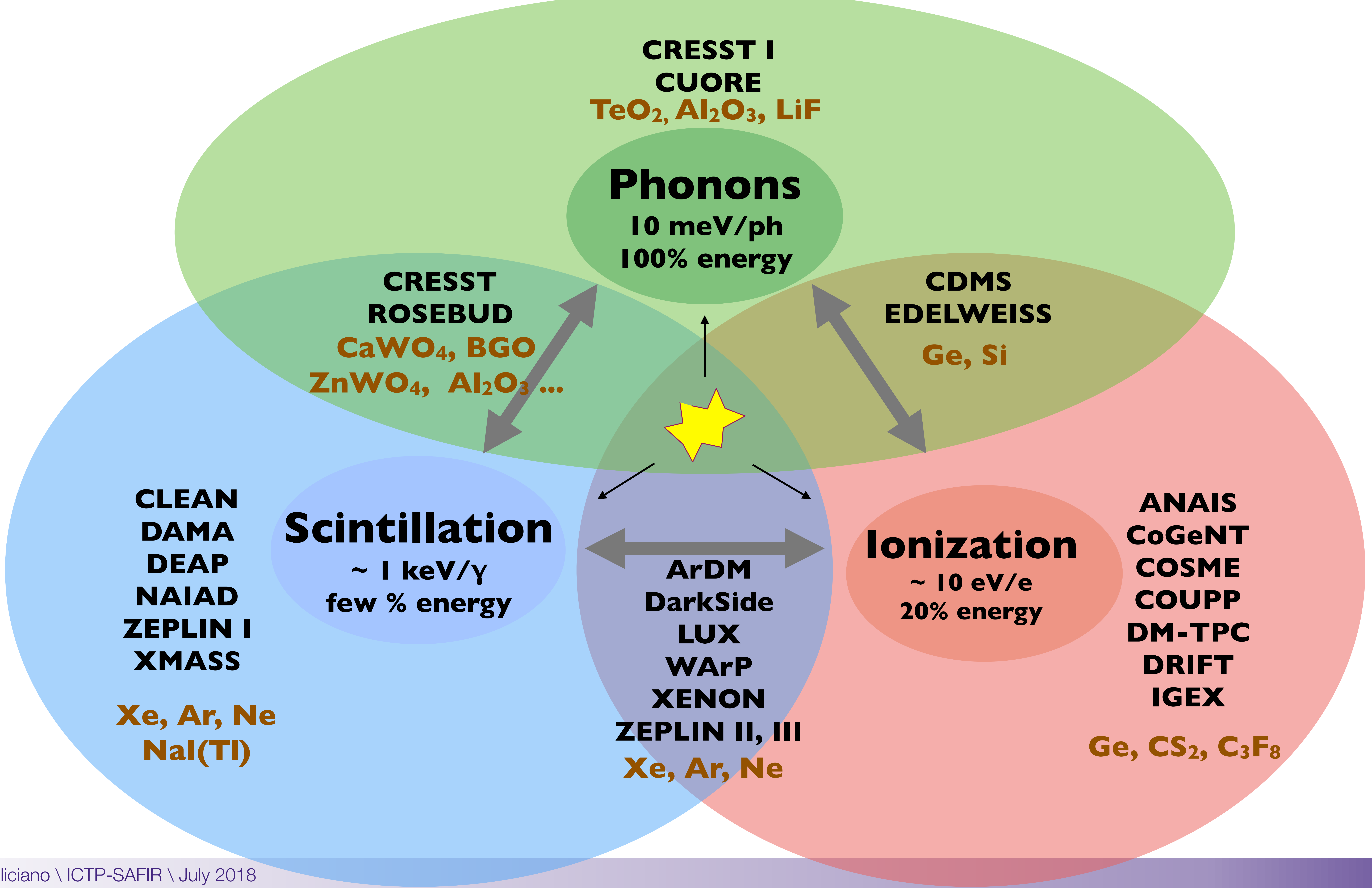


Particle ID through Detector Response

Different Response to Electron Recoils and Nuclear Recoils Allows Discrimination



Particle ID Through Detector Response



CRESST I
CUORE
TeO_2, Al_2O_3, LiF

Phonons
10 meV/ph
100% energy

CRESST
ROSEBUD
$CaWO_4$, BGO
$ZnWO_4$, Al_2O_3 ...

CDMS
EDELWEISS
Ge, Si

CLEAN
DAMA
DEAP
NAIAD
ZEPLIN I
XMASS
Xe, Ar, Ne
NaI(Tl)

Scintillation
~ 1 keV/γ
few % energy

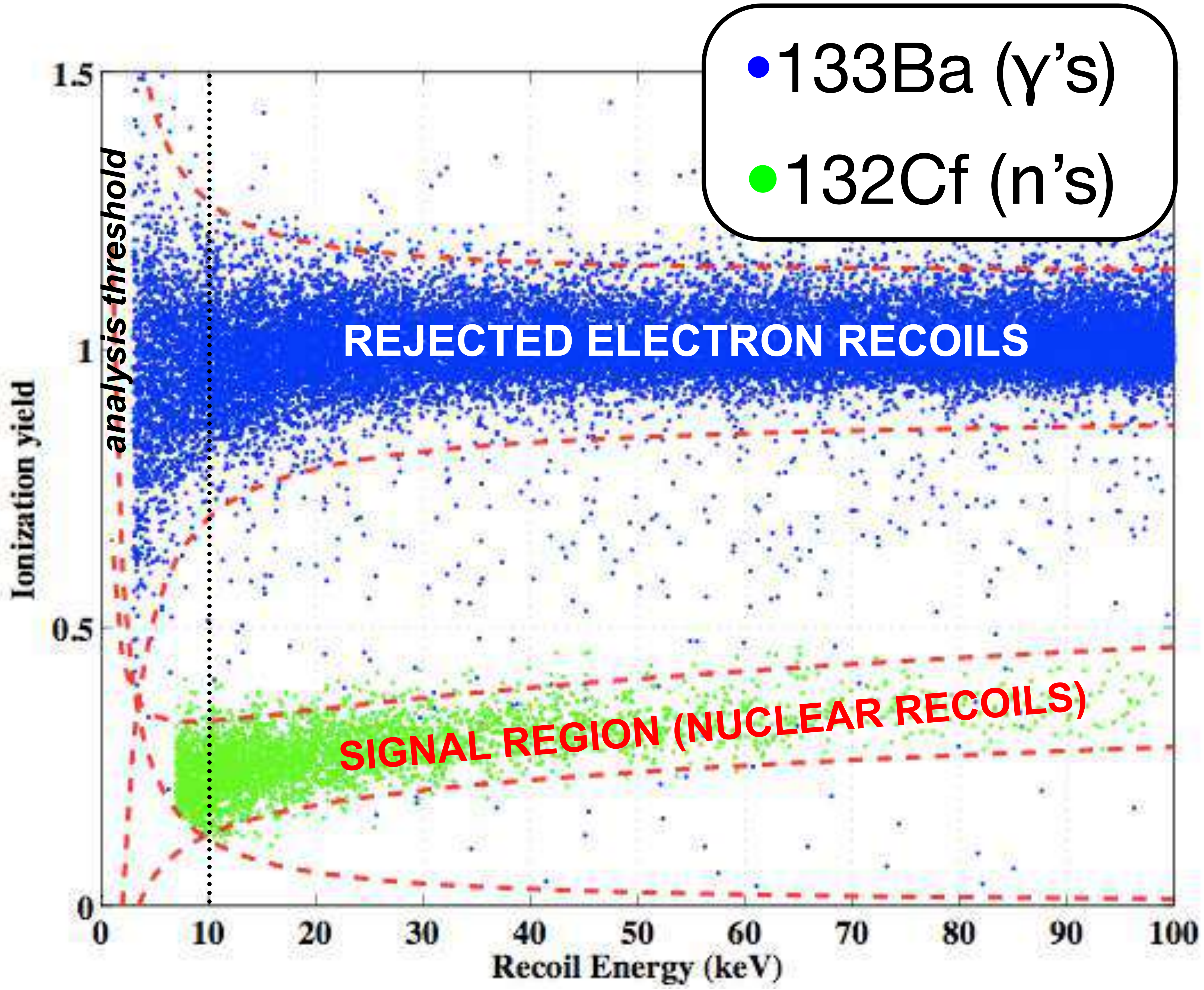
ArDM
DarkSide
LUX
WArP
XENON
ZEPLIN II, III
Xe, Ar, Ne

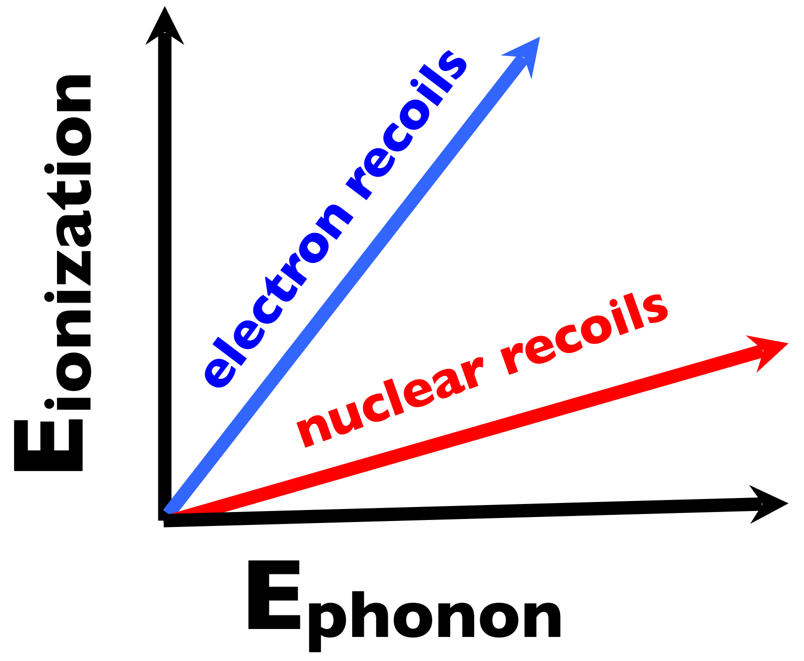
Ionization
~ 10 eV/e
20% energy

ANAIS
CoGeNT
COSME
COUPP
DM-TPC
DRIFT
IGEX
Ge, CS_2, C_3F_8

Textbook example with CDMS

“Some discrimination parameter” (ionization yield in this case)





$$\text{ionization yield} = \frac{E_{ionization}}{E_{phonon}}$$

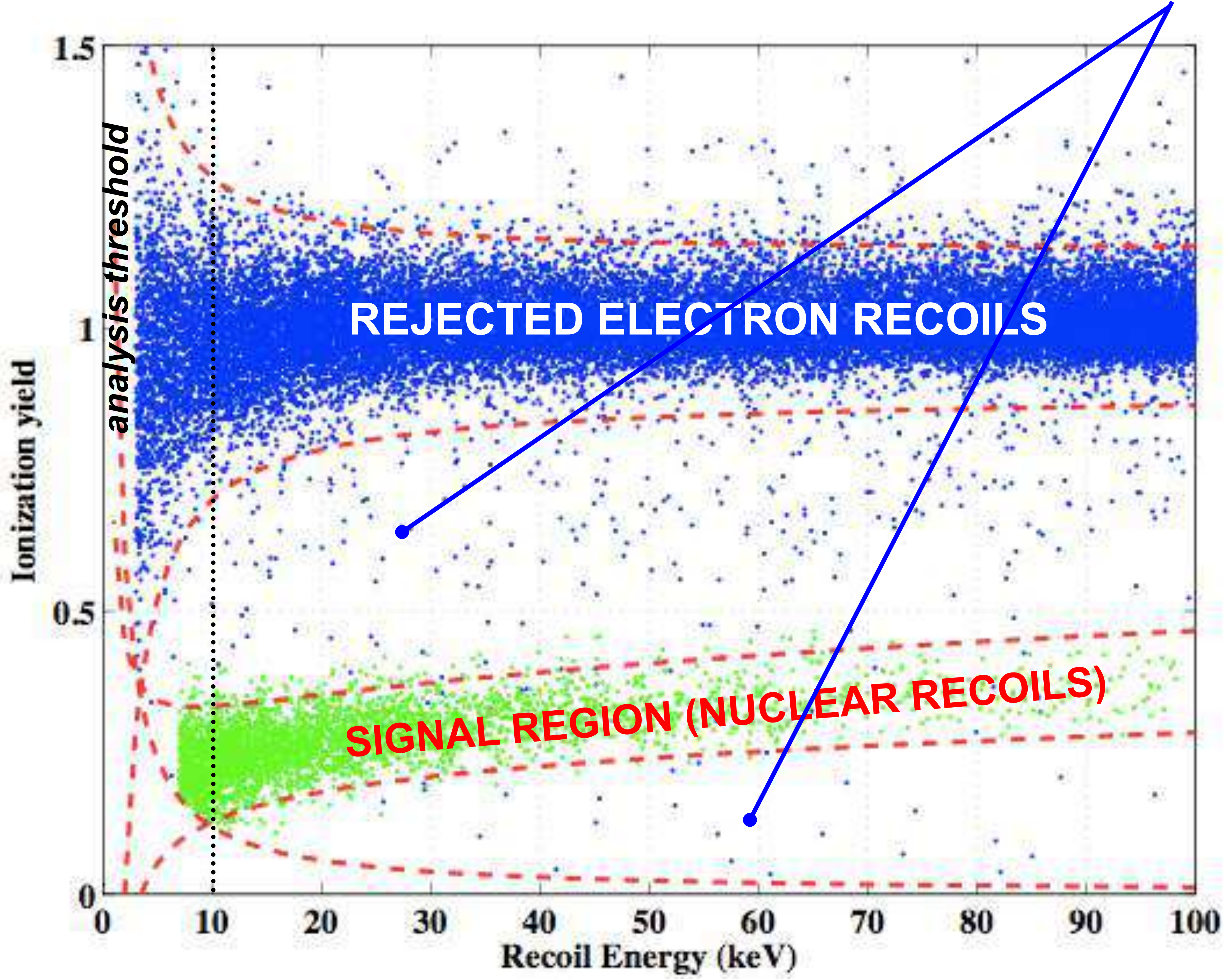
$1:10^4$ rejection of gammas based on ionization yield alone

Experiments that measure more than one of the products of a recoil exploit the fact that ER’s and NR’s deposit different fractions of the recoil energy in the form of HEAT, IONIZATION and SCINTILLATION.

Textbook example with CDMS

“Some discrimination parameter” (ionization yield in this case)

1:10^4 sounds great, BUT wait! What are these events?



SURFACE EVENTS (betas, alphas, recoiling parent nuclei and x-rays) are a near-universal problem in direct detection.

FIDUCIALIZATION of the target volume is necessary to reject these events. So ideally, your detector needs to be able to determine the position of an event as well as its energy.

Experiments that measure more than one of the products of a recoil exploit the fact that ER’s and NR’s deposit different fractions of the recoil energy in the form of HEAT, IONIZATION and SCINTILLATION.

Other ways of attaining Particle Identification

- Pulse-Shape Discrimination
  - e.g., scintillation timing (DEAP/CLEAN, DarkSide, etc…)
- Nuclear-recoil-only trigger mechanism
  - (a la COUPP, PICASSO, PICO…)
- Self-Shielding (XMASS)
- Others...

End of Lecture 1