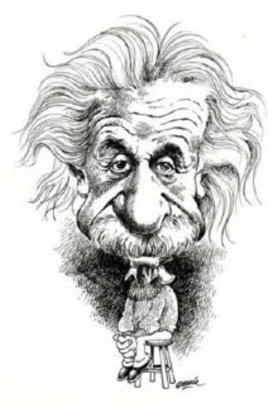
Old and New Ideas in Dark Matter Detection



&

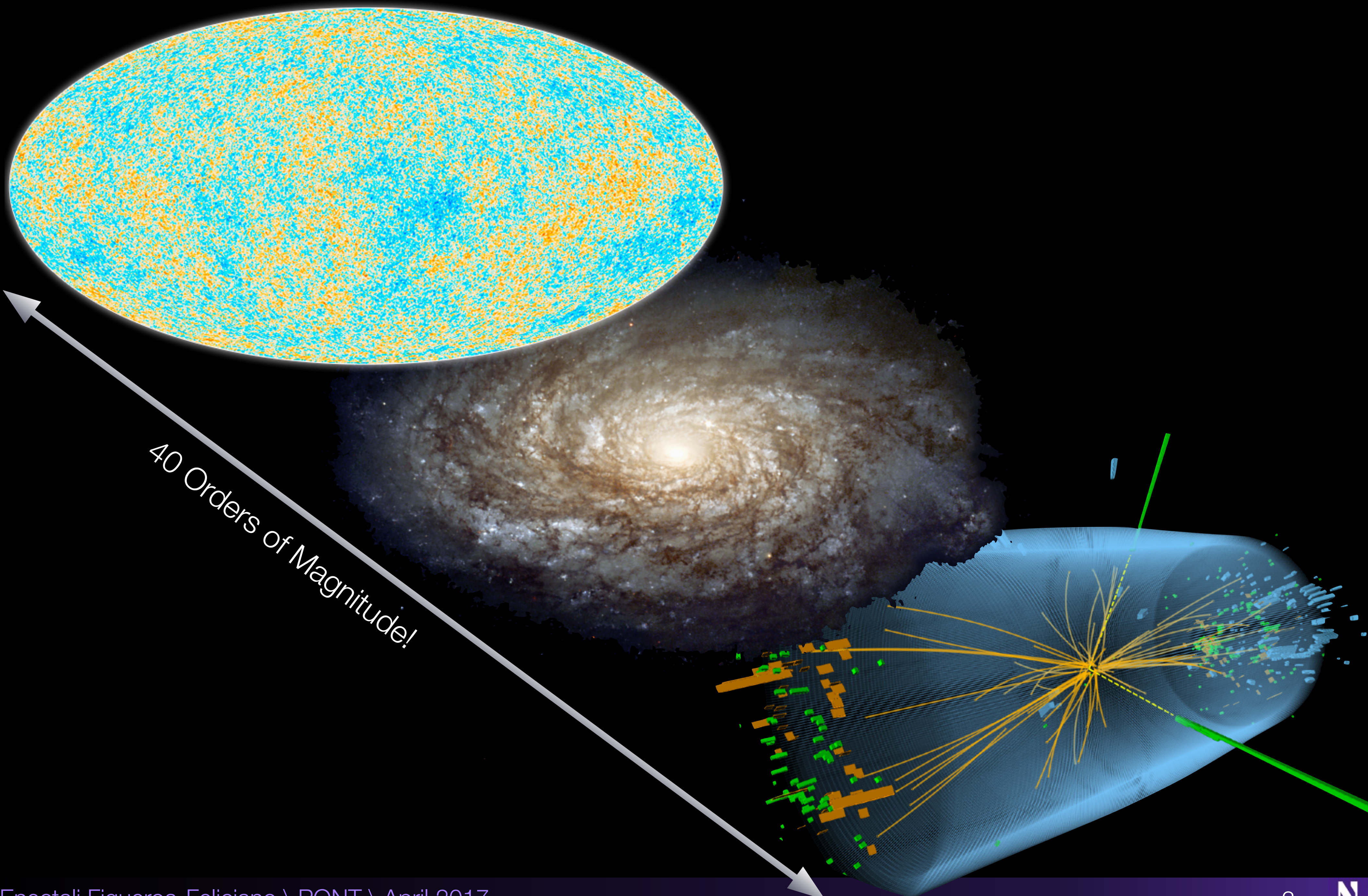
Enectalí Figueroa-Feliciano

Northwestern

Outline

- The Dark Matter Problem
- Dark Matter Detection Strategies
- Direct Detection Experiments
    - Nuclear Recoils
    - Electron Recoils
    - Coherent/Resonant Effects
- Indirect Detection with Micro-X
- Conclusions

Dark Matter: A Beautiful Problem in Physics




The Hunt for Dark Matter
AMS-02
CALET
ALICE
CMS
ATLAS
LHC
LHCb
Chandra,
XMM-Newton
Micro-X
Production in
Colliders
Direct
Detection
Indirect
Detection
FERMI,
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HESS, VERITAS,
Magic
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Single
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IceCube
1.5 kilometers
2.5 kilometers
Astrophysics
Measurements


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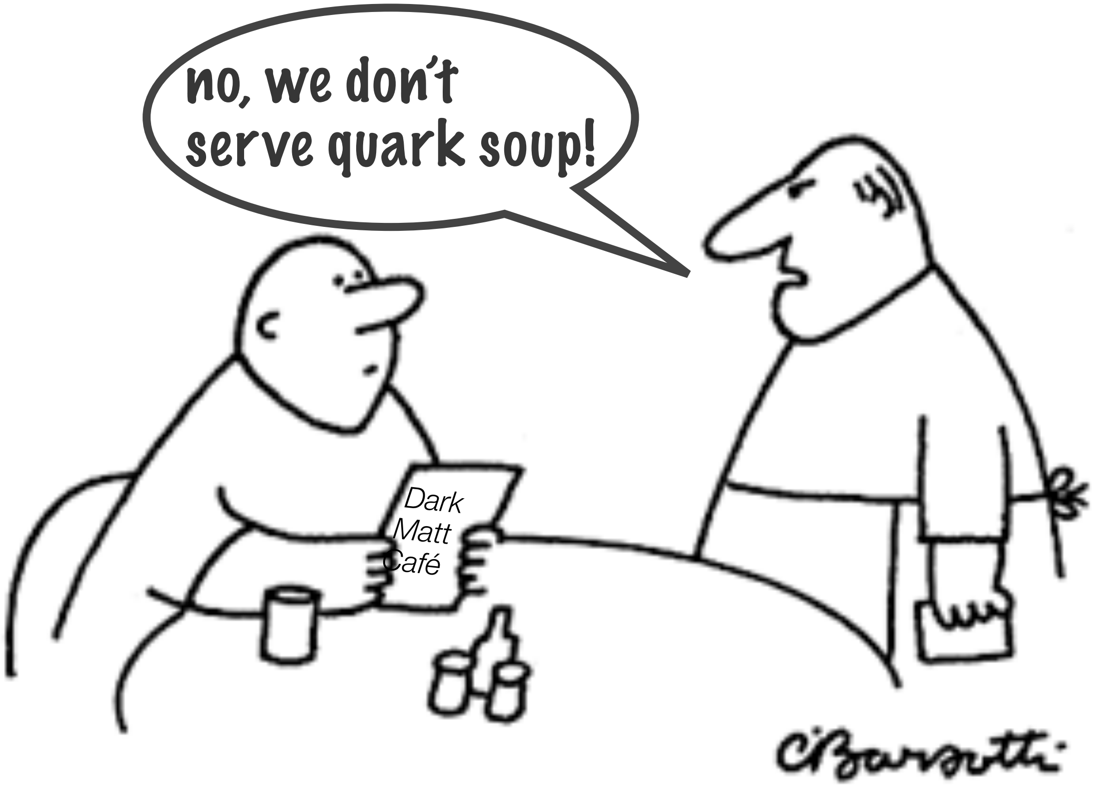
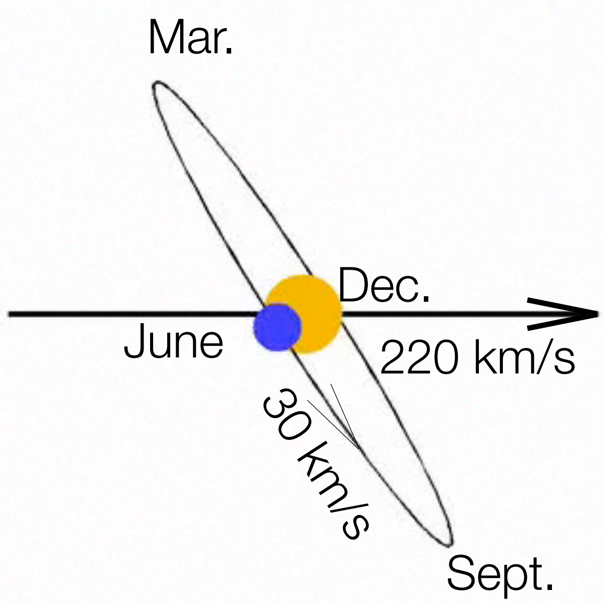
Dark Matter Menu

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



Annual Modulation: "Model-Independent" Search

Target: Ge
σ_{SI} = 1x10^{-4} pb
M_χ = 10 GeV/cm^2



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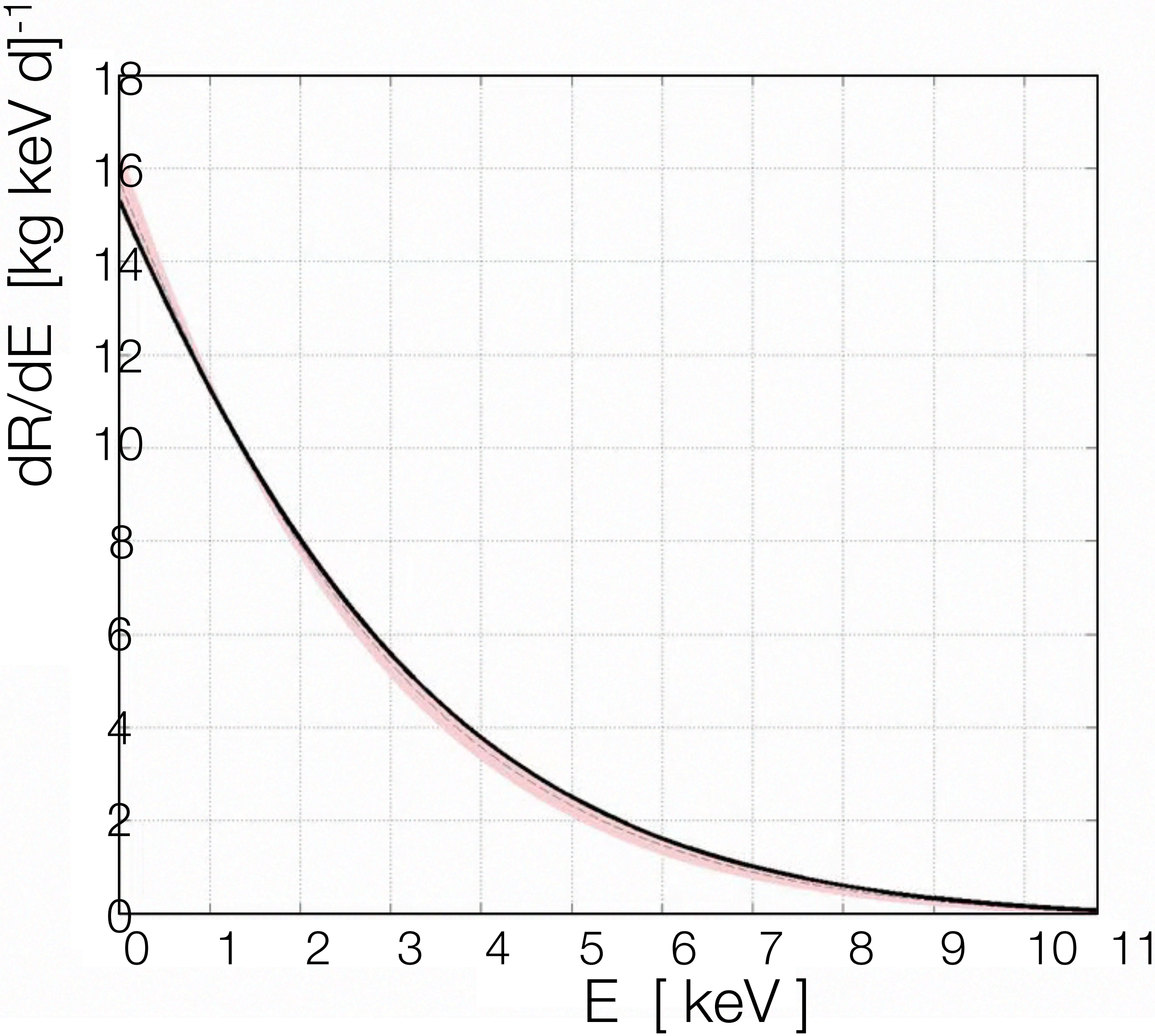

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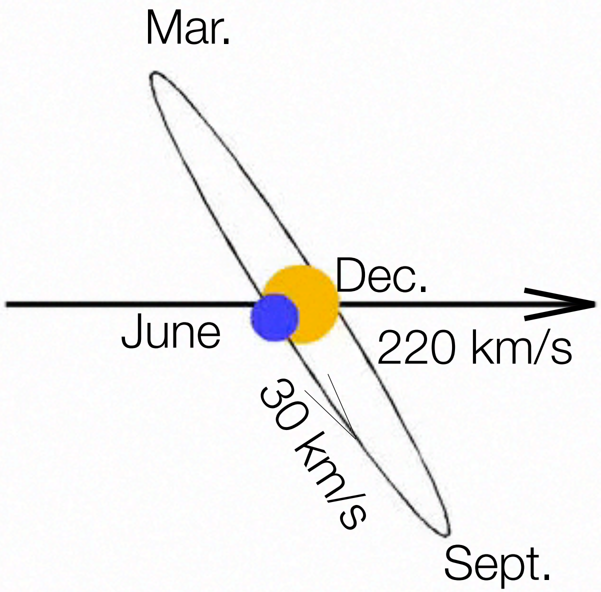
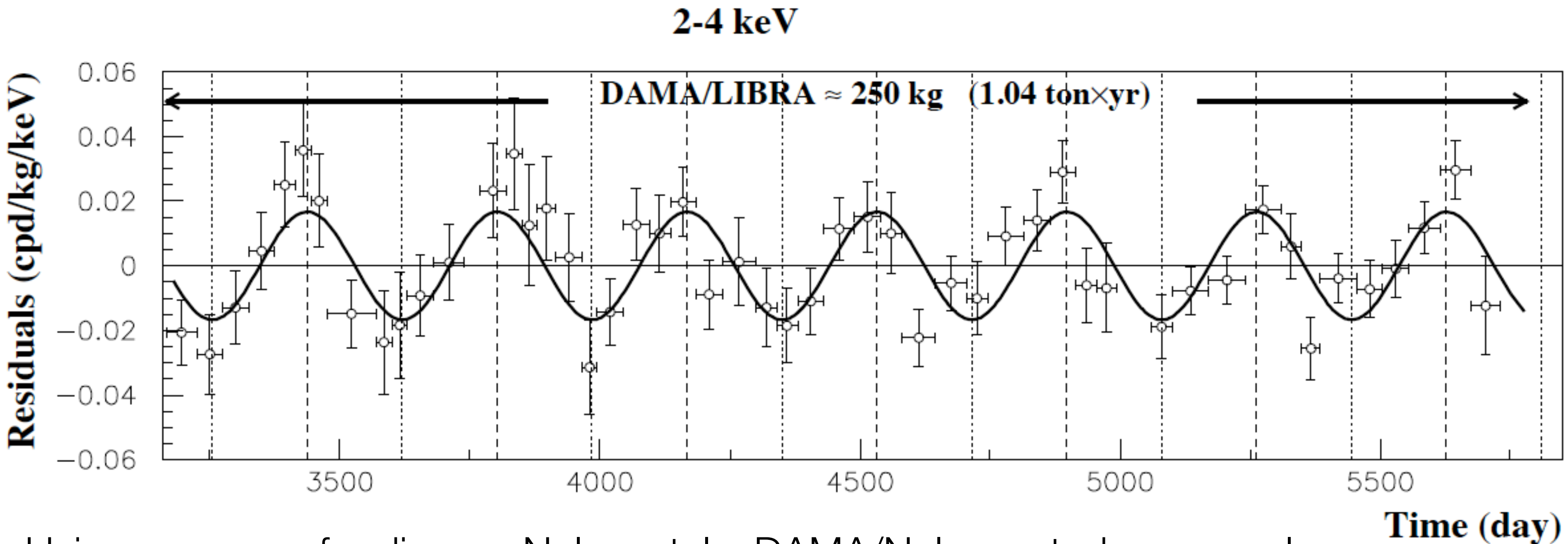
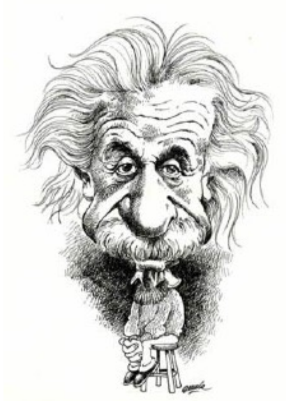


DAMA/LIBRA



- Using an array of radiopure NaI crystals, DAMA/NaI reported an annual modulation in event rate consistent with dark matter, observed over 7 annual cycles.
- In 2008, follow-up experiment, DAMA/LIBRA, confirms the annual modulation. Together the DAMA experiments now report an effect with a statistical significance of 9.3σ with a 1.33 ton-yr exposure over 14 annual cycles. A phase-2 program with lower-energy thresholds is currently taking data.
- To date no other experiments have confirmed this signal, yet several efforts are ongoing to directly test this. A viable dark matter model that explains this data (and its non-detection in other experiments) has not been found.

Eur. Phys. J. C (2010) 67: 39–49
Eur. Phys. J. C (2013) 73:2648



Checking DAMA with NaI Detectors

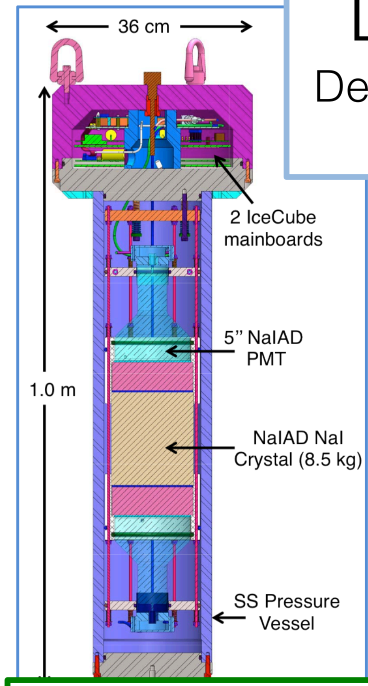
Northern Hemisphere	Gran Sasso **DAMA/LIBRA** 250 kg running	Boulby **DM-Ice North** 37 kg R&D 250 kg planned	Canfranc **ANAIS** 37 kg R&D 250 kg planned	Y2L **KIMS** 45 kg R&D 200 kg planned	Gran Sasso **SABRE** R&D	Kamioka **PICO-LON** **KamLAND-PICO** R&D
Southern Hemisphere		South Pole **DM-Ice** 17 kg running 250 kg planned			Stawell **SABRE** Lab completion 2017	rock ice

Ultra-pure crystal development underway by DM-Ice, KIMS, ANAIS, SABRE, and PICO-LON collaborations

South Pole offers:

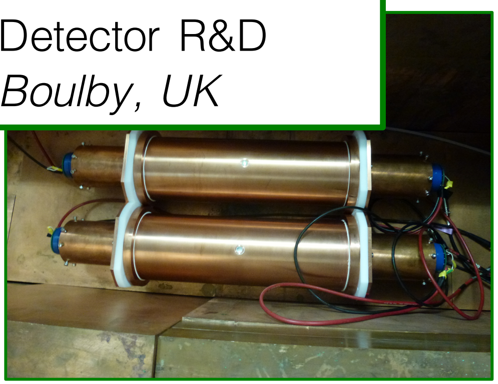
- Ultra-clean and ultra-stable environment
- Seasonal variation unambiguously different from dark matter modulation
- IceCube offers muon monitoring and veto as well as experience
- NSF-run South Pole Station for logistical support

DM-Ice and COSINE



DM-Ice17
Determine feasibility
South Pole

DM-Ice37 ✓
Detector R&D
Boulby, UK

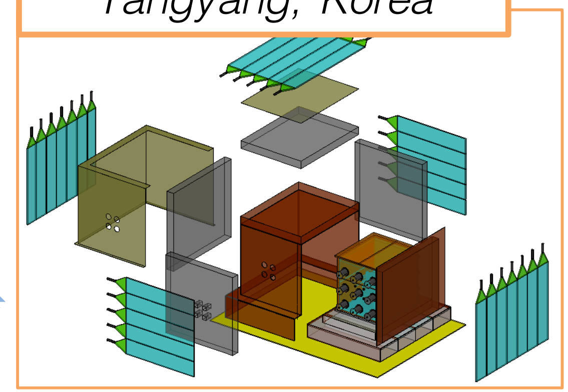


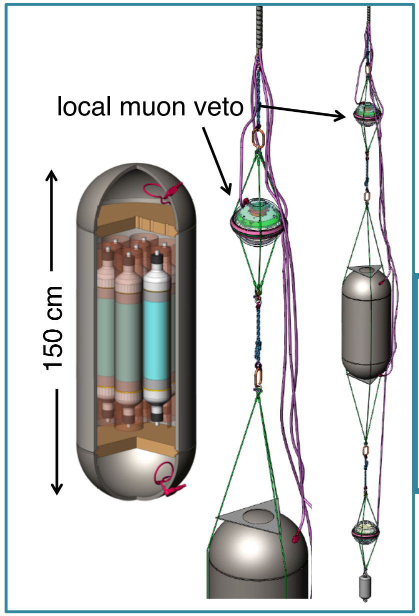
DM-Ice + KIMS

COSINE-100
Set initial limits
Yangyang, Korea

Currently running

COSINE-200
Set definitive limits
Yangyang, Korea

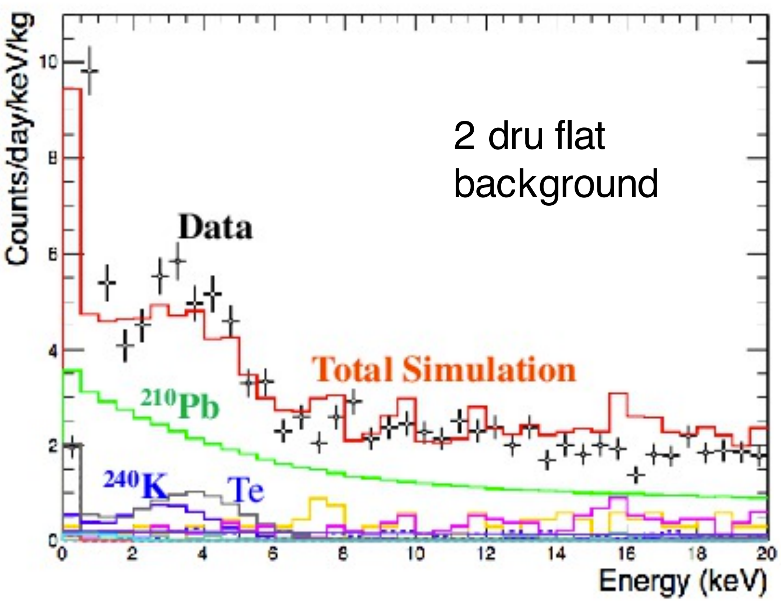


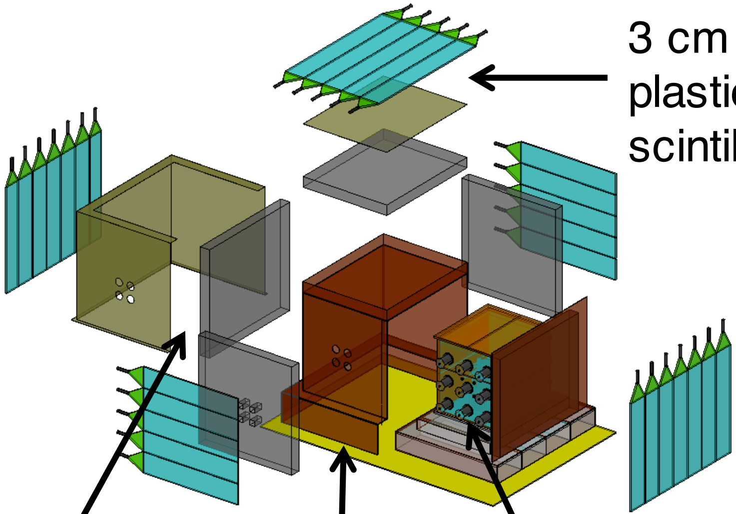


COSINE-200 South
Determine source of modulation
South Pole

COSINE-100

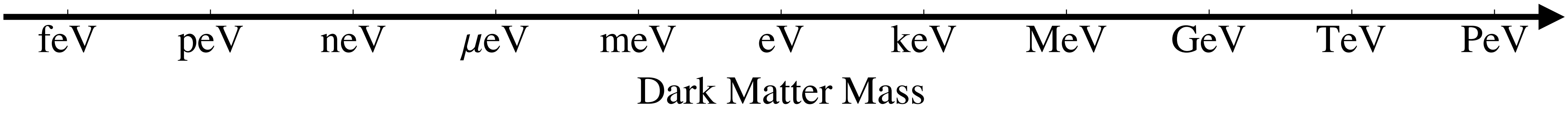
- Started running September 2016
- 8 crystals for a total of 106 kg
- Including DM-Ice37 crystals
- Low background, high QE 3” PMTs
- Active and passive shielding
- 2 years to reach DAMA sensitivity





Dark Matter Detection Strategies

Dark Matter Detection Strategies



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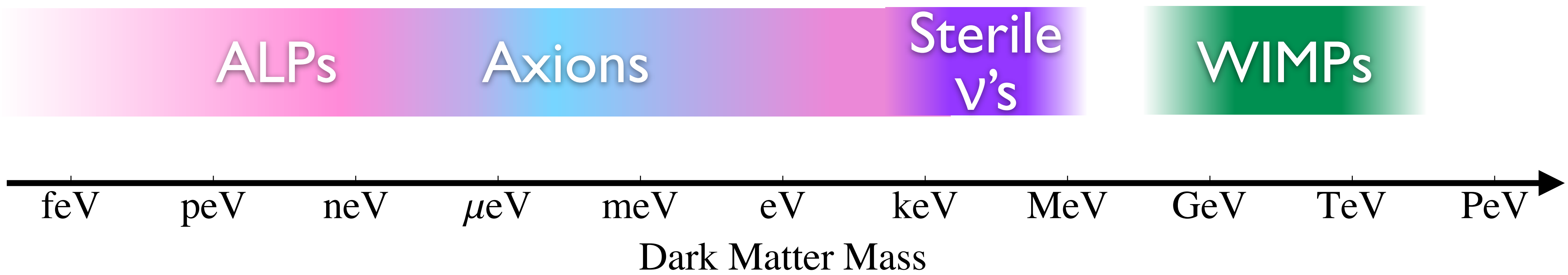

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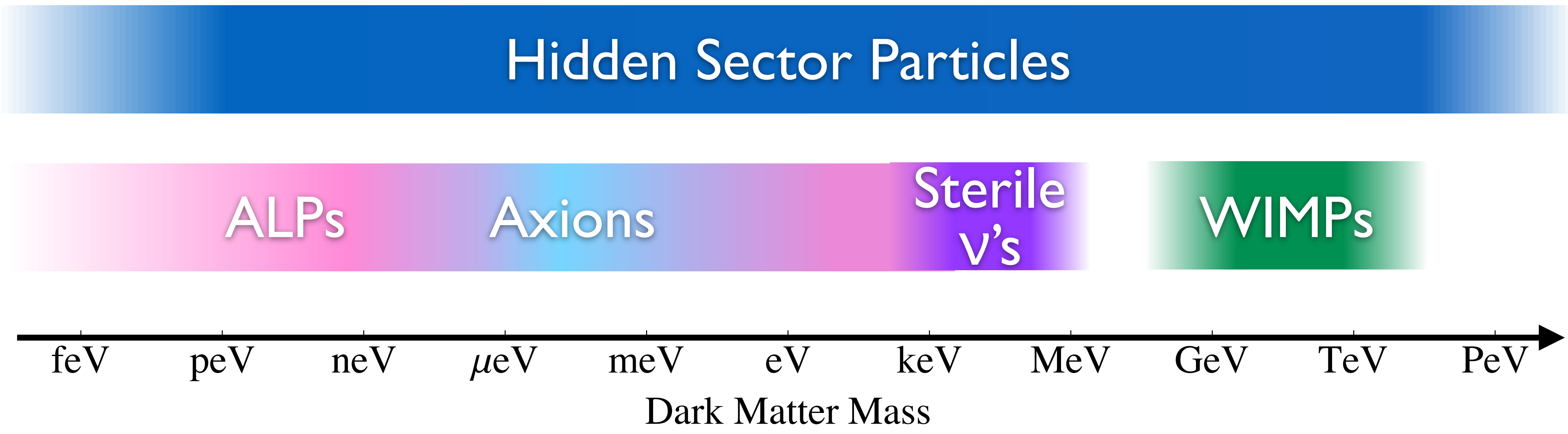

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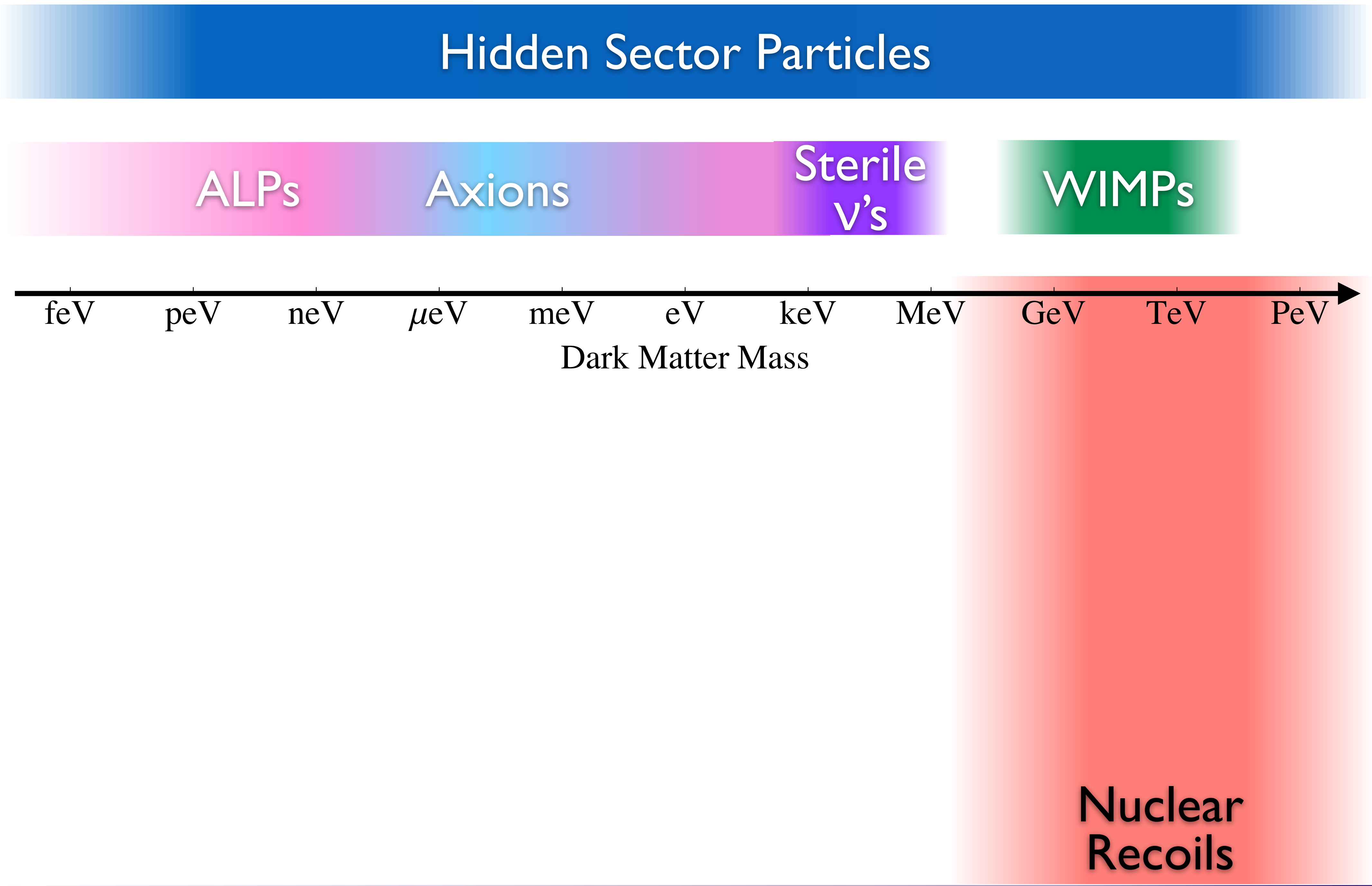

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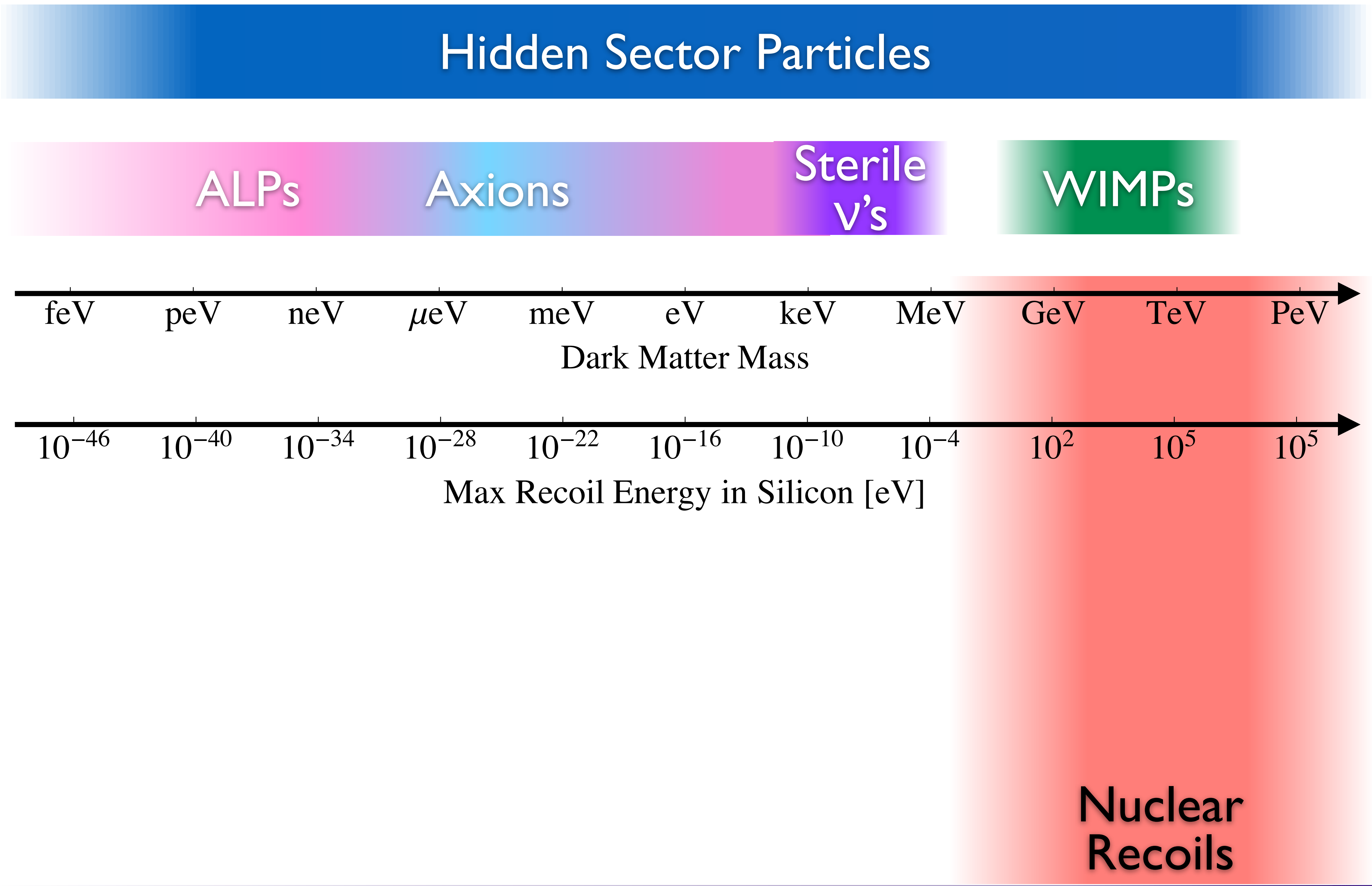

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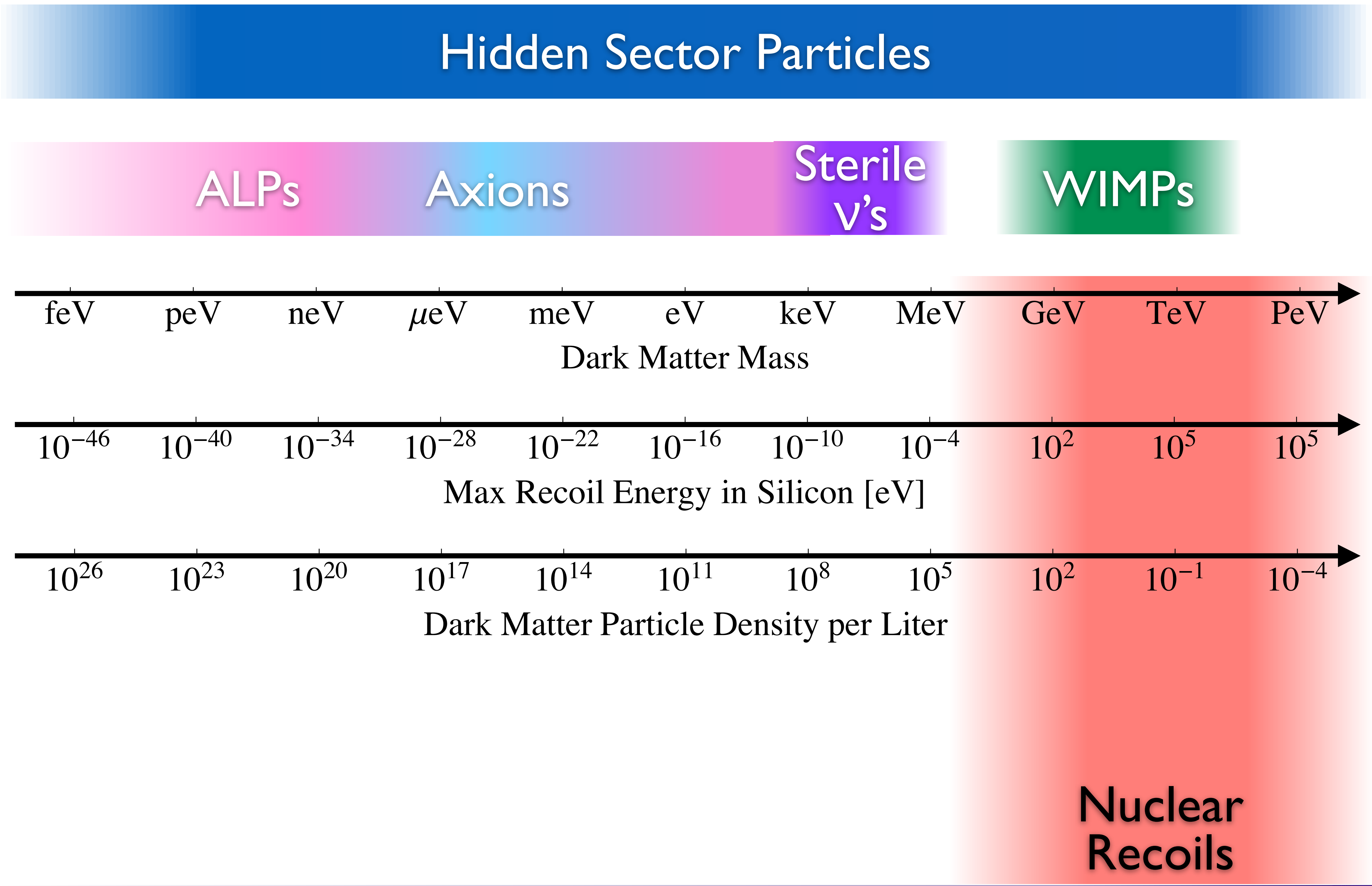

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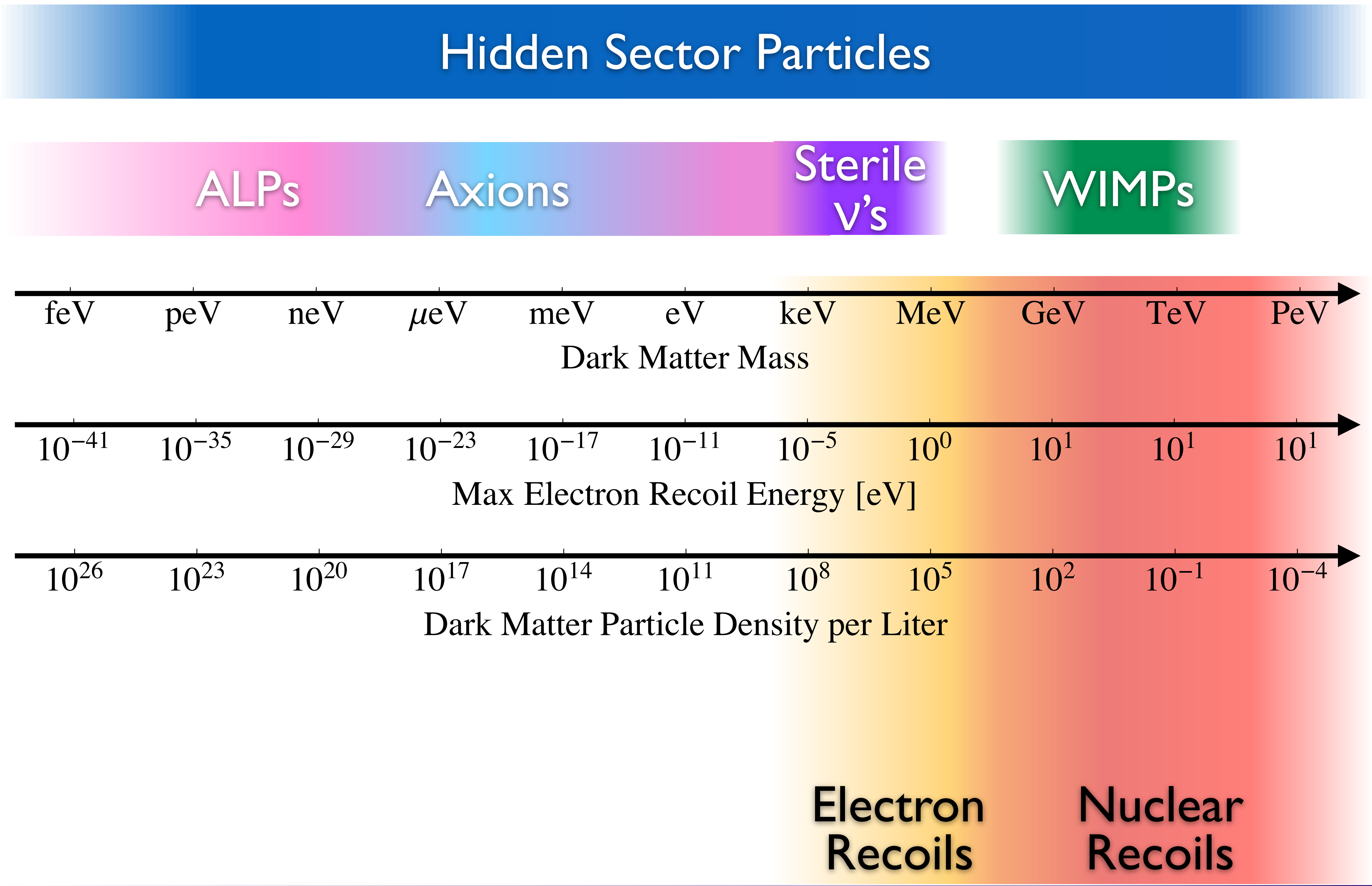

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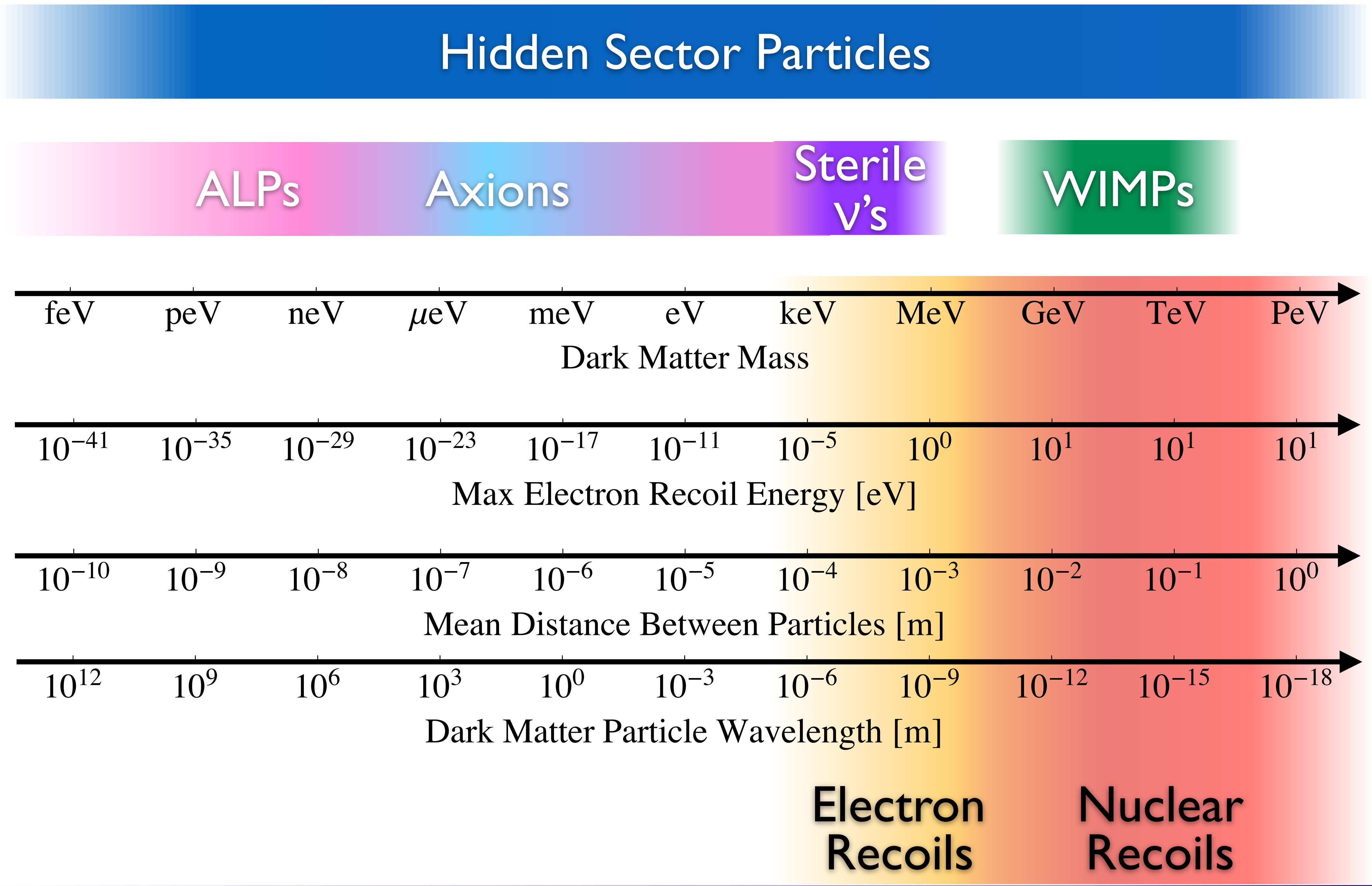

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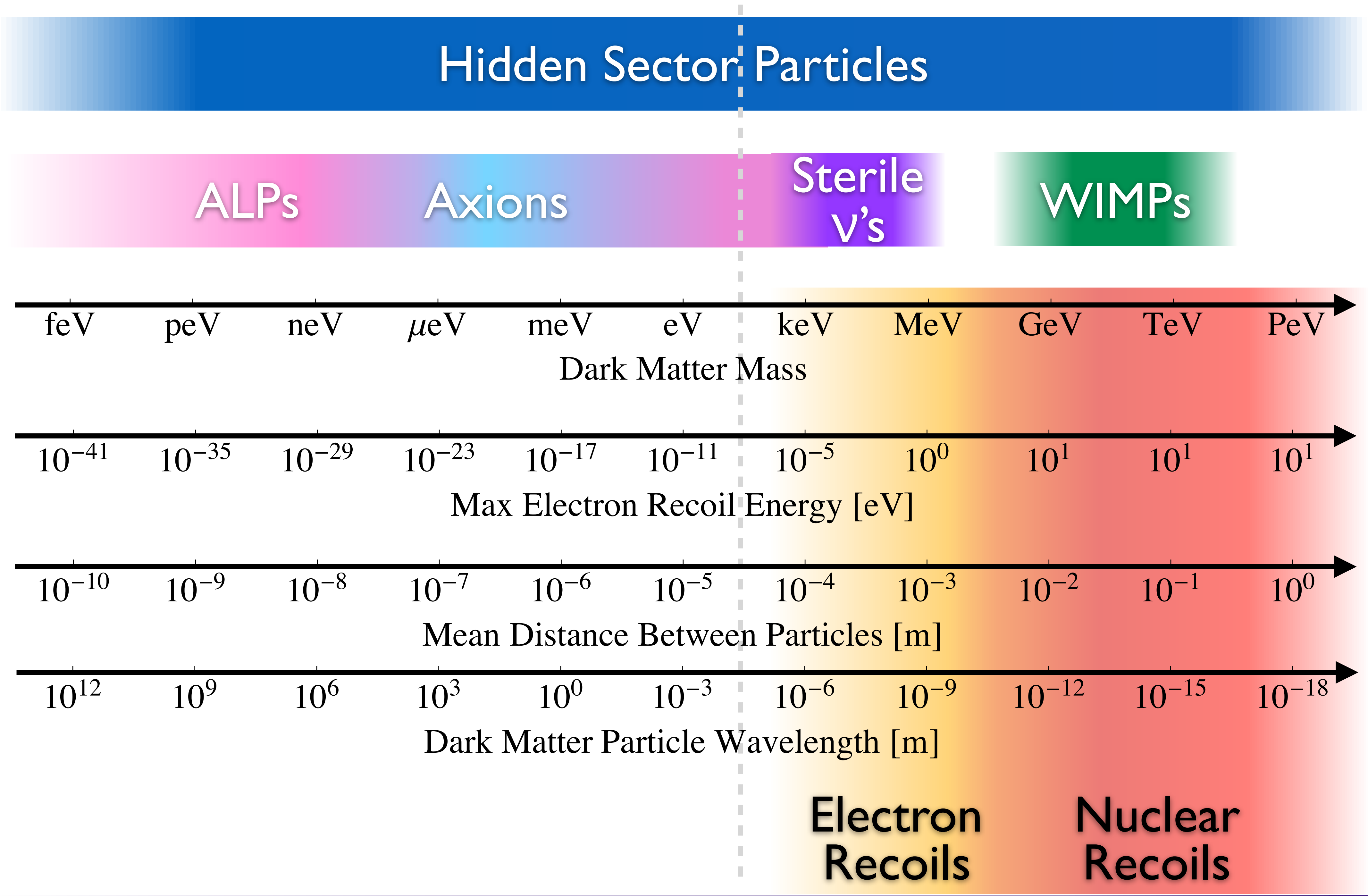

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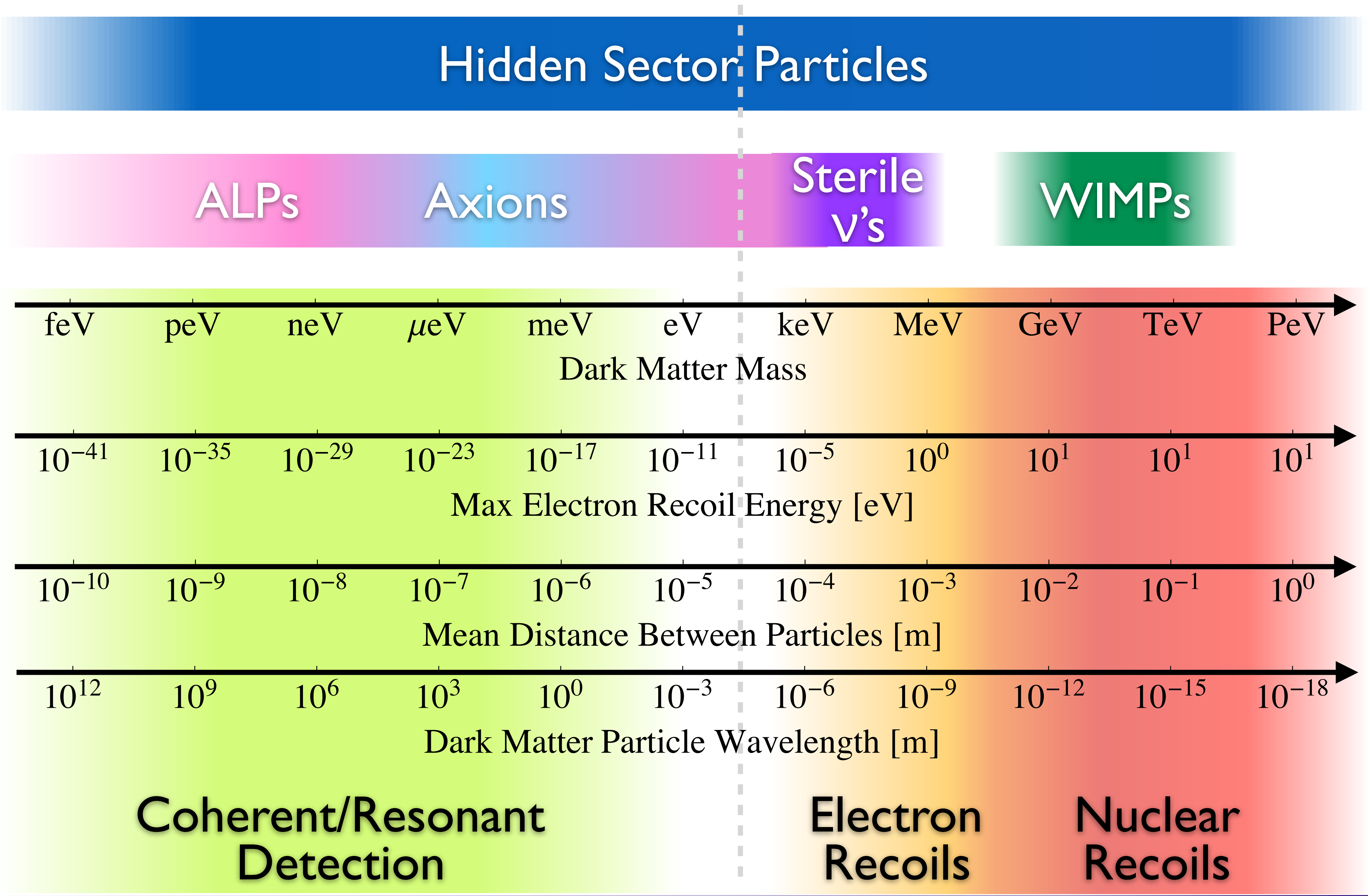
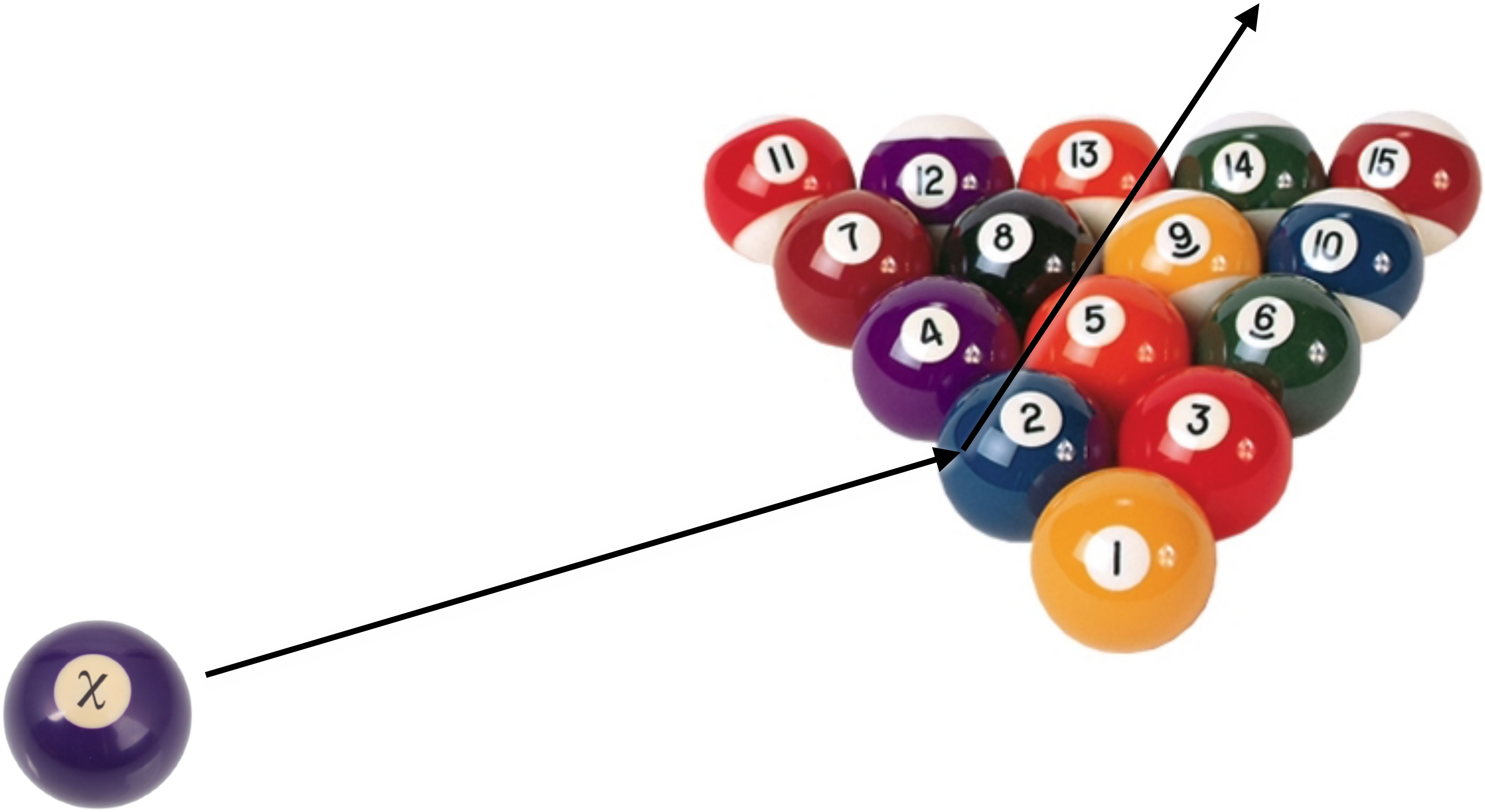
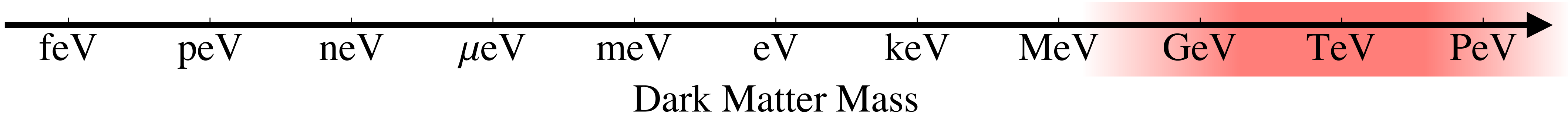
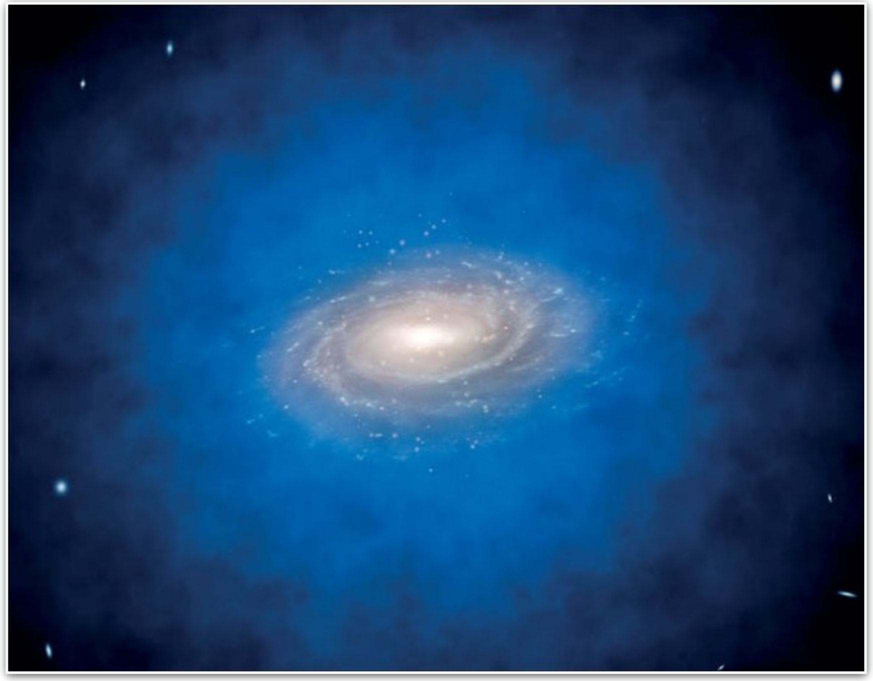


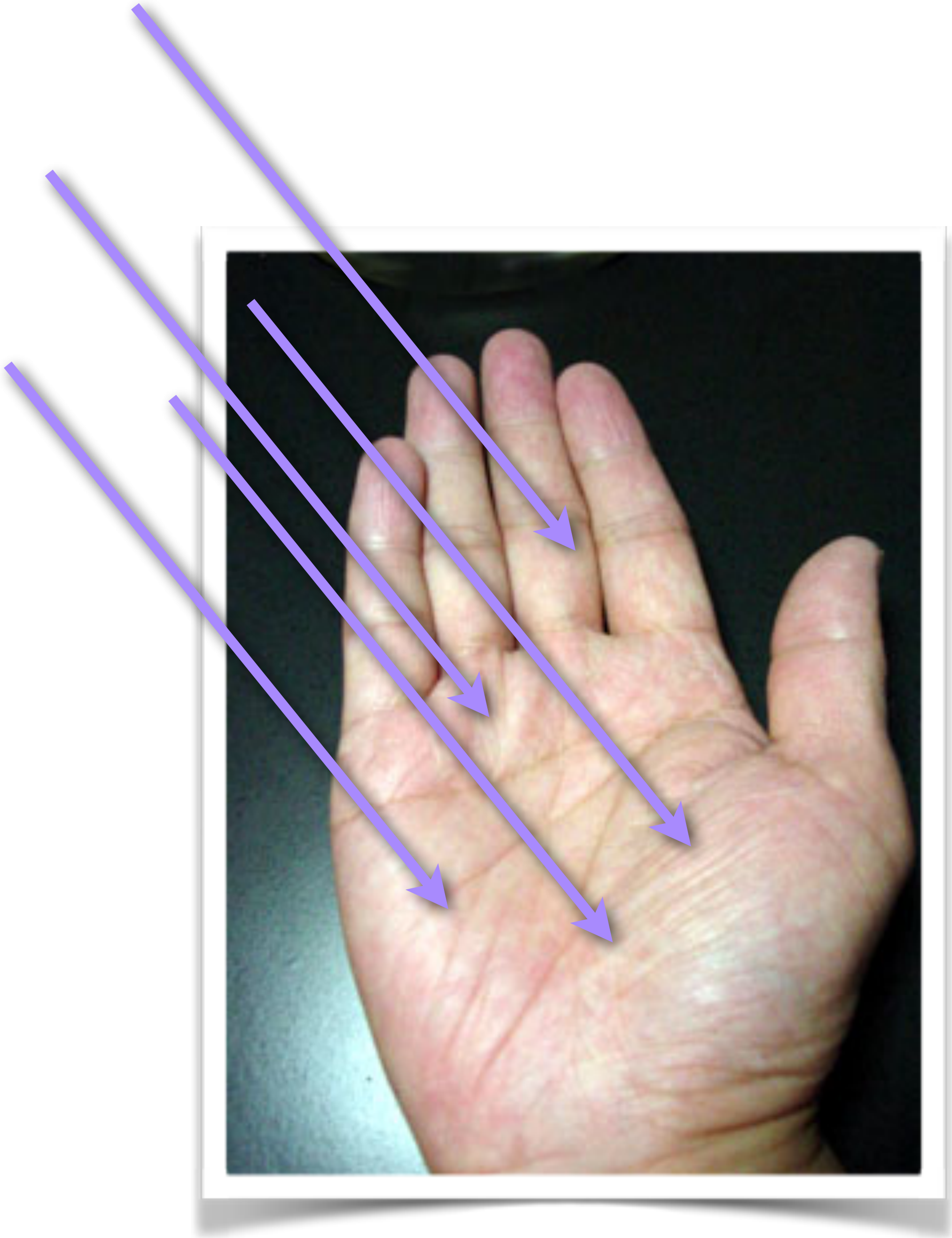
Nuclear Recoils





Dark Matter in the Lab





- Assume a Maxwell-Boltzmann velocity distribution for the dark matter halo
- Density: 0.3 GeV/cm^3
- Mass: assume 60 GeV/c^2
- Relative velocity ~220 km/s
- ~100,000 particles/cm^2/sec
- About 20 million/hand/sec

Interaction Rate [events/keV/kg/day]

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

$$F(E_R) \simeq \exp\left(-E_R \, m_N \, R_o^2/3\right)$$

"form factor" (quantum mechanics of interaction with nucleus)

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

"reduced mass"

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

integral over local WIMP velocity distribution

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

minimum WIMP velocity for given E_R

Principles of Particle Detection

particle theory

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particle theory — nuclear structure

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integral over local WIMP velocity distribution

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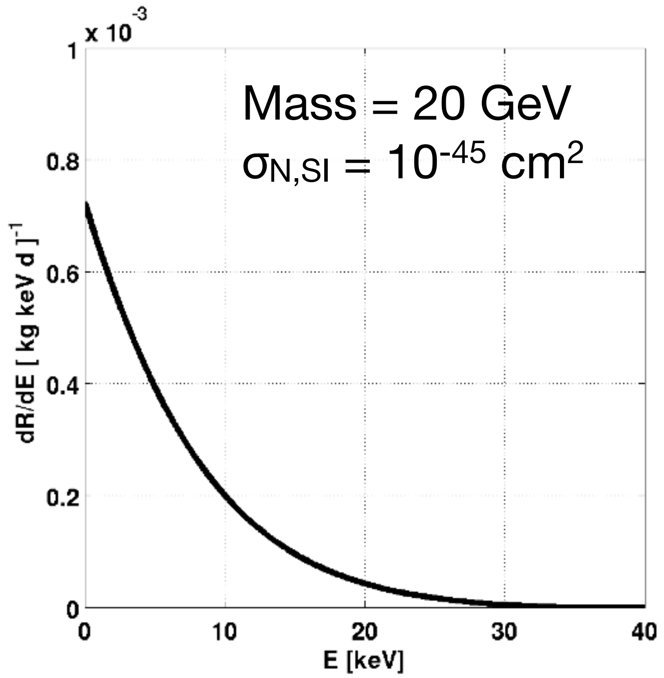
minimum WIMP velocity for given E_R

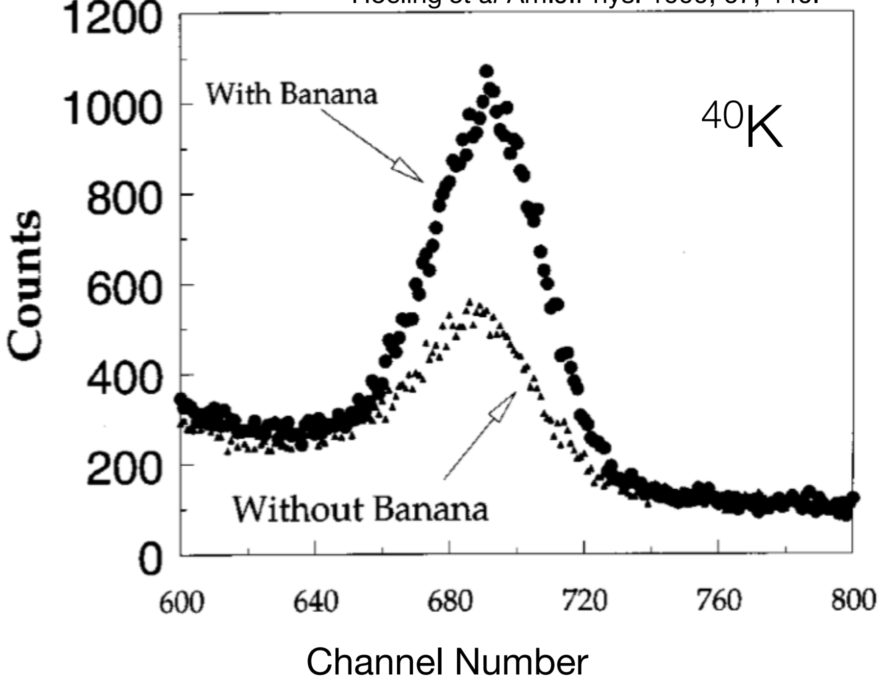
The Interaction Rate is Extremely Low!

Expected
WIMP Spectrum



Measured
Banana Spectrum

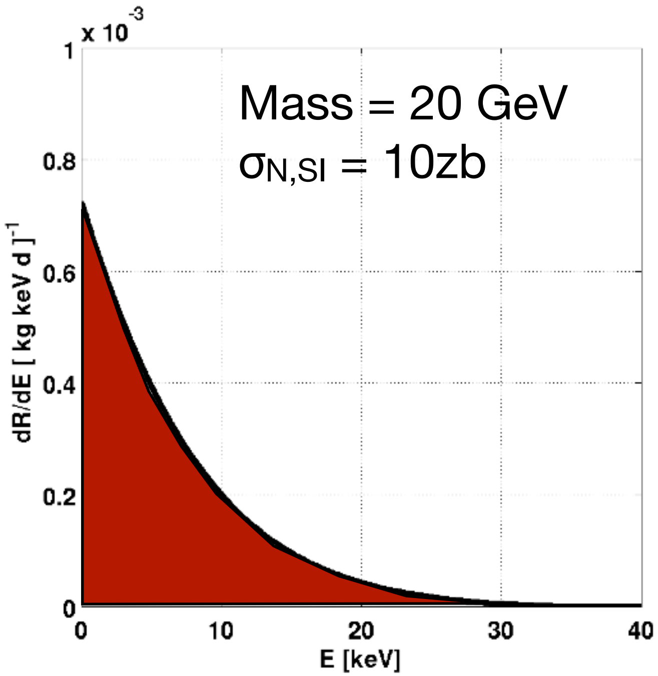
Hoeling *et al* Am.J.Phys. 1999, 67, 440.



But the Interaction Rate is Extremely Low!

Discrimination between electron and nuclear recoils really helps!

Expected
WIMP Spectrum



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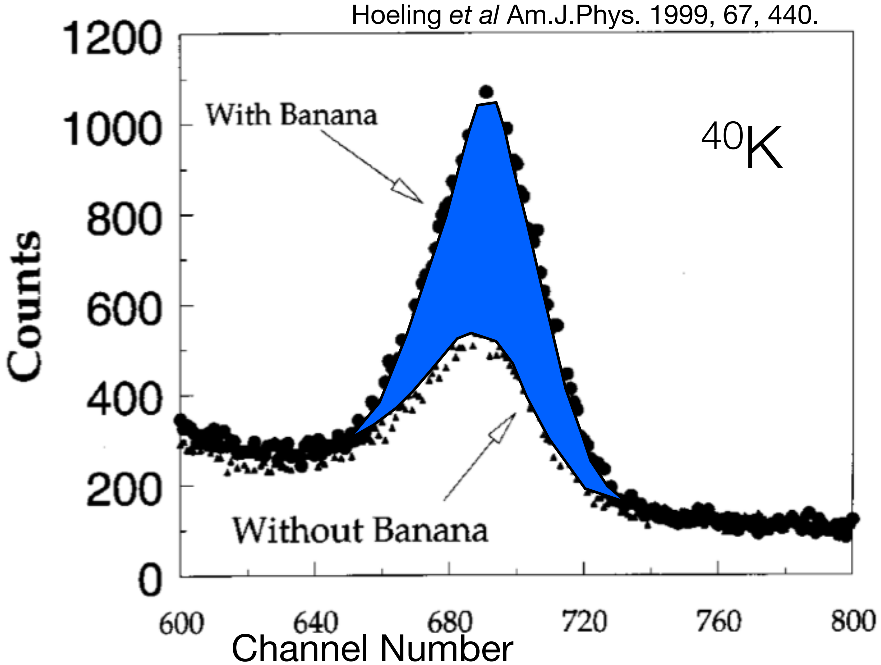

~1 event per kg per **year**

(Nuclear Recoils)

~100 event per kg per **second**

(Electron Recoils)

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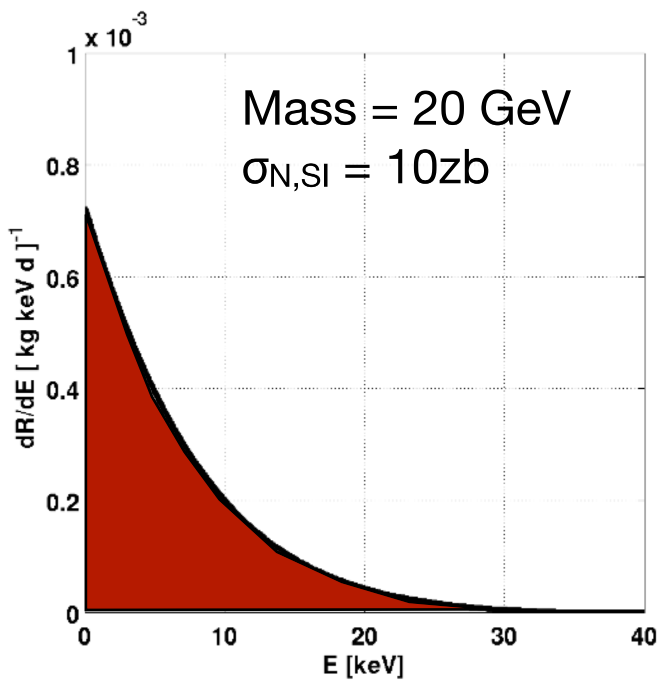
Expected
WIMP Spectrum



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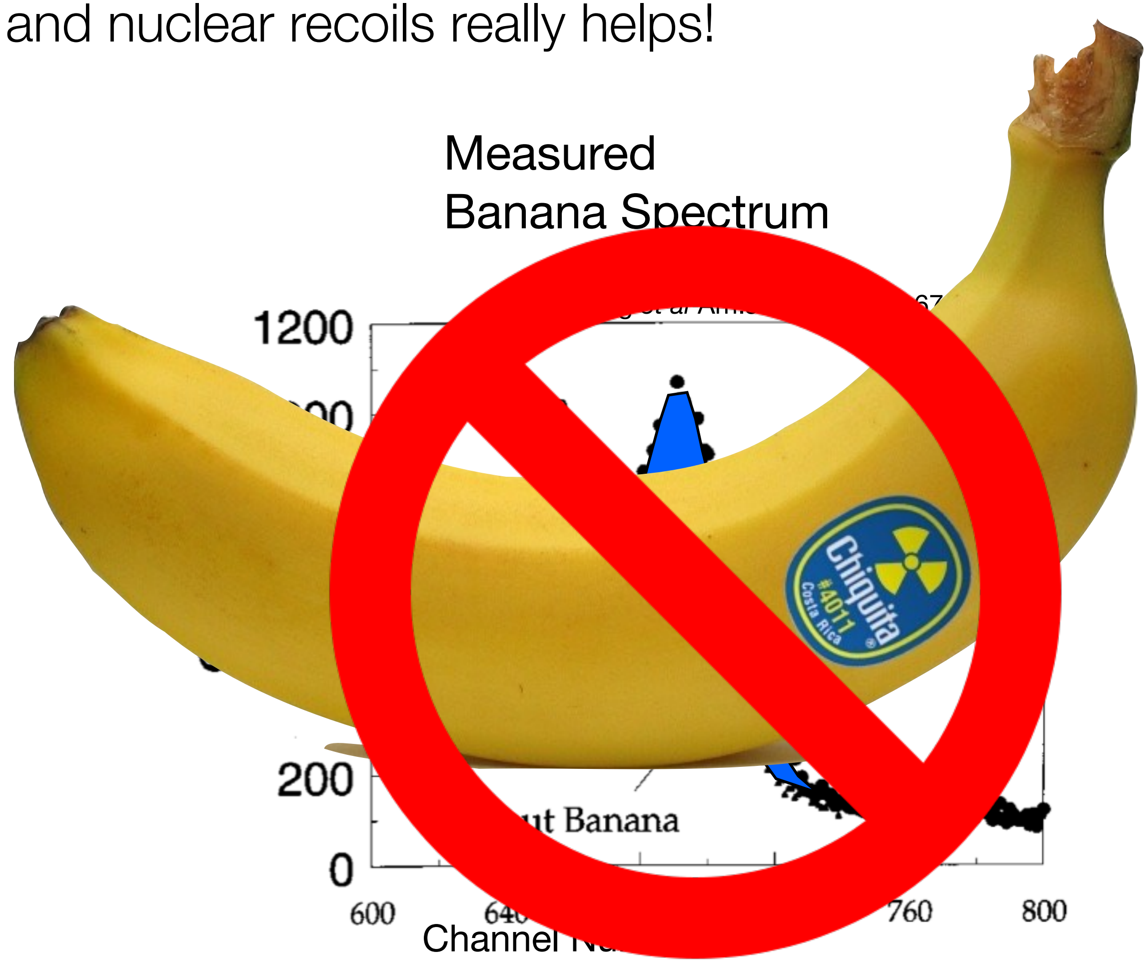

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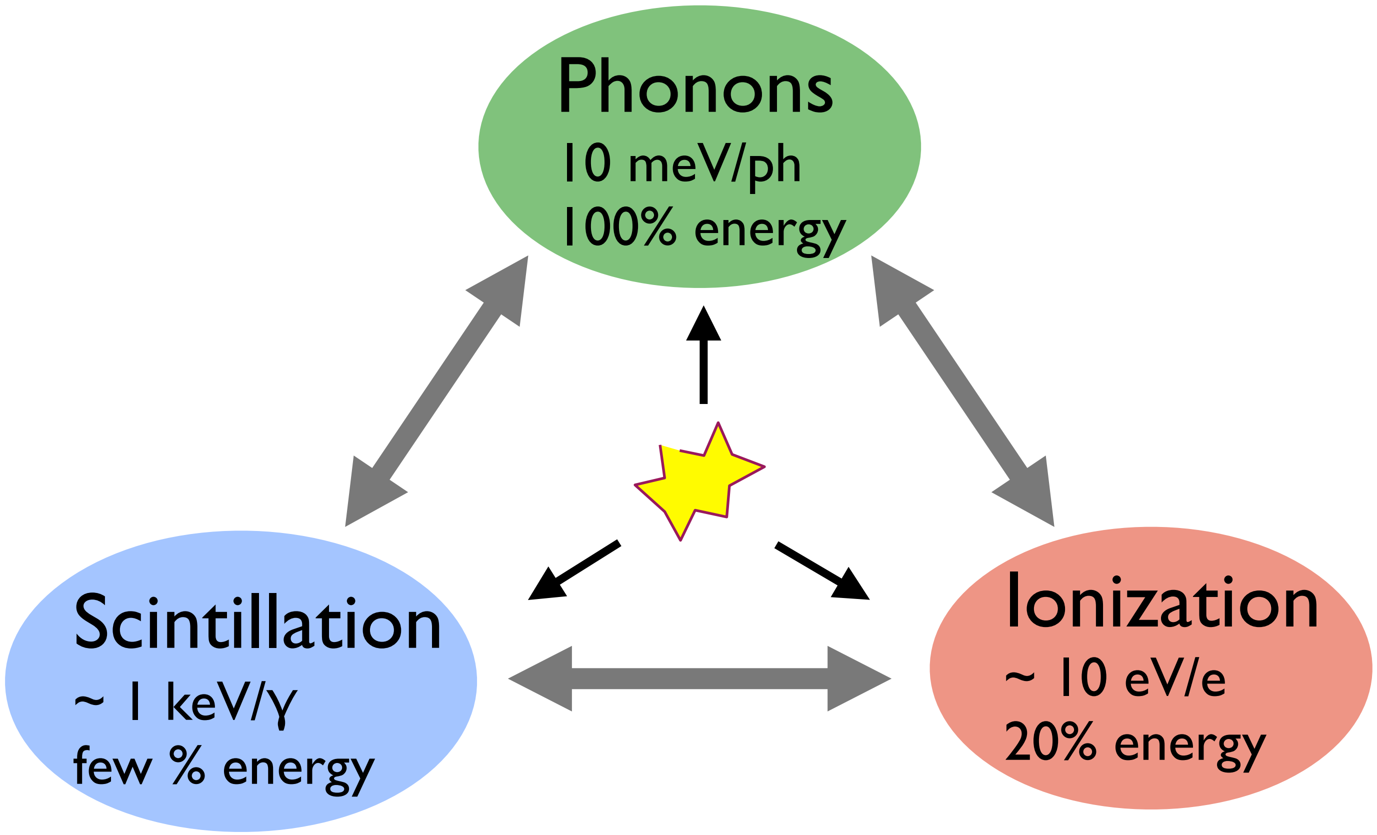
Particle ID Through Detector Response



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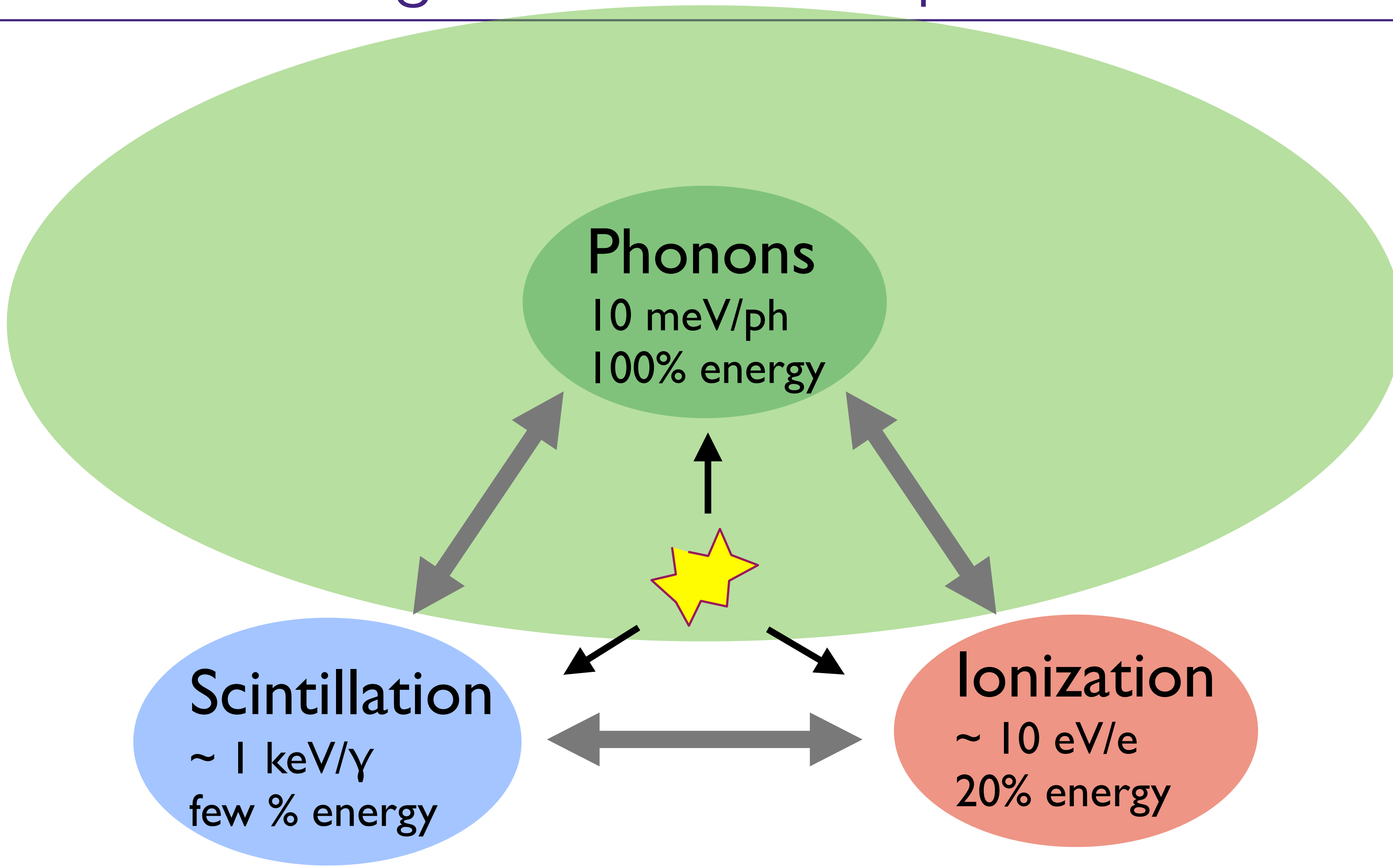

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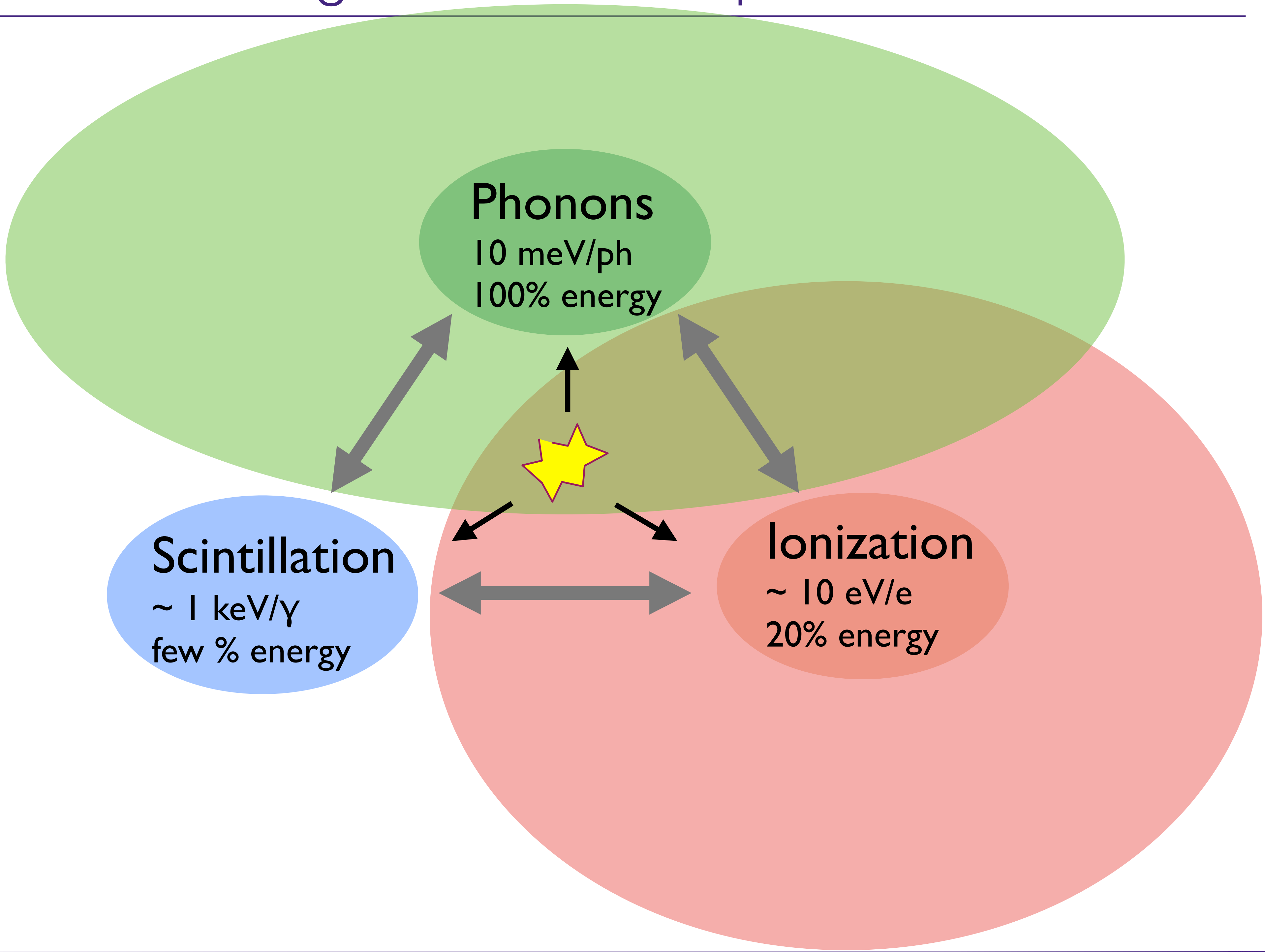

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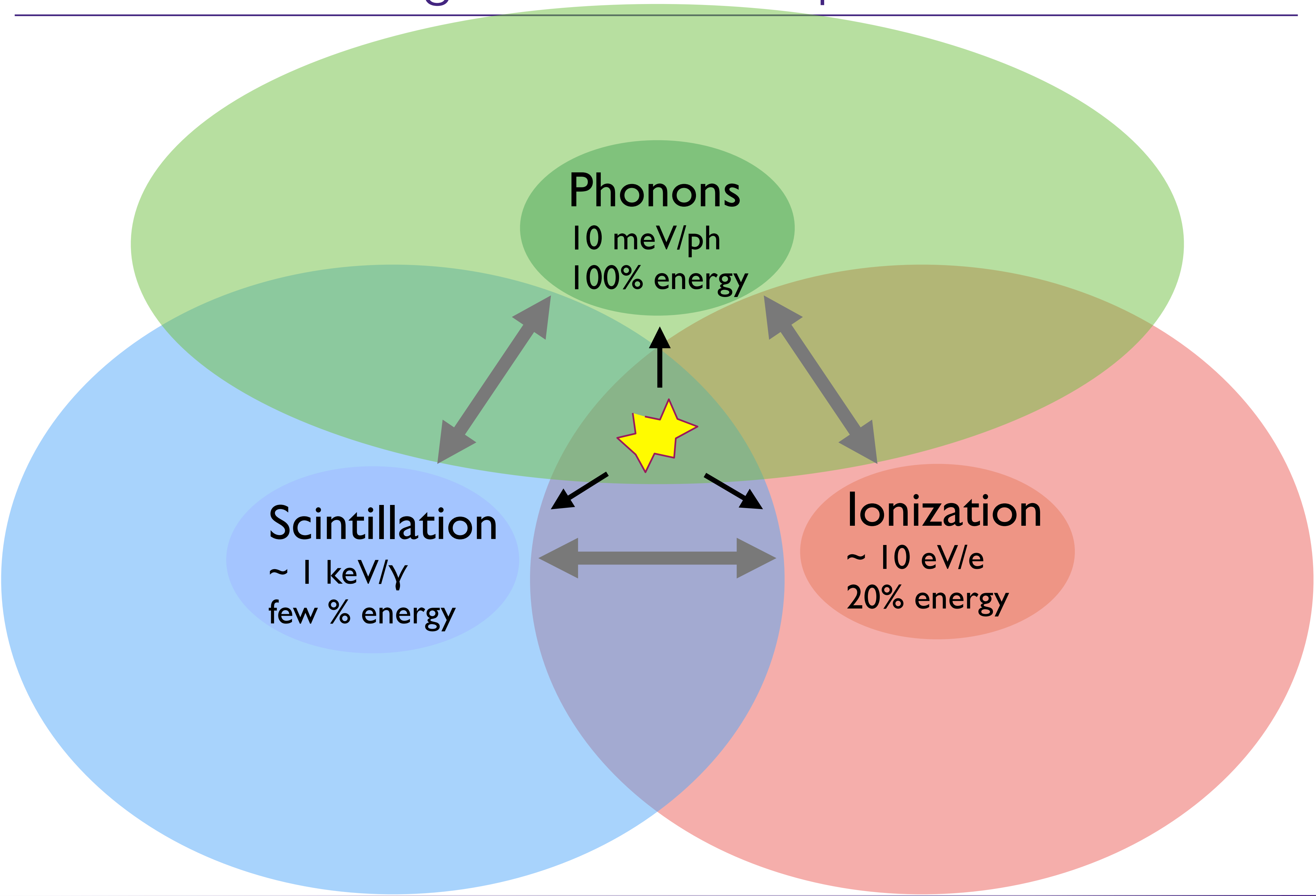

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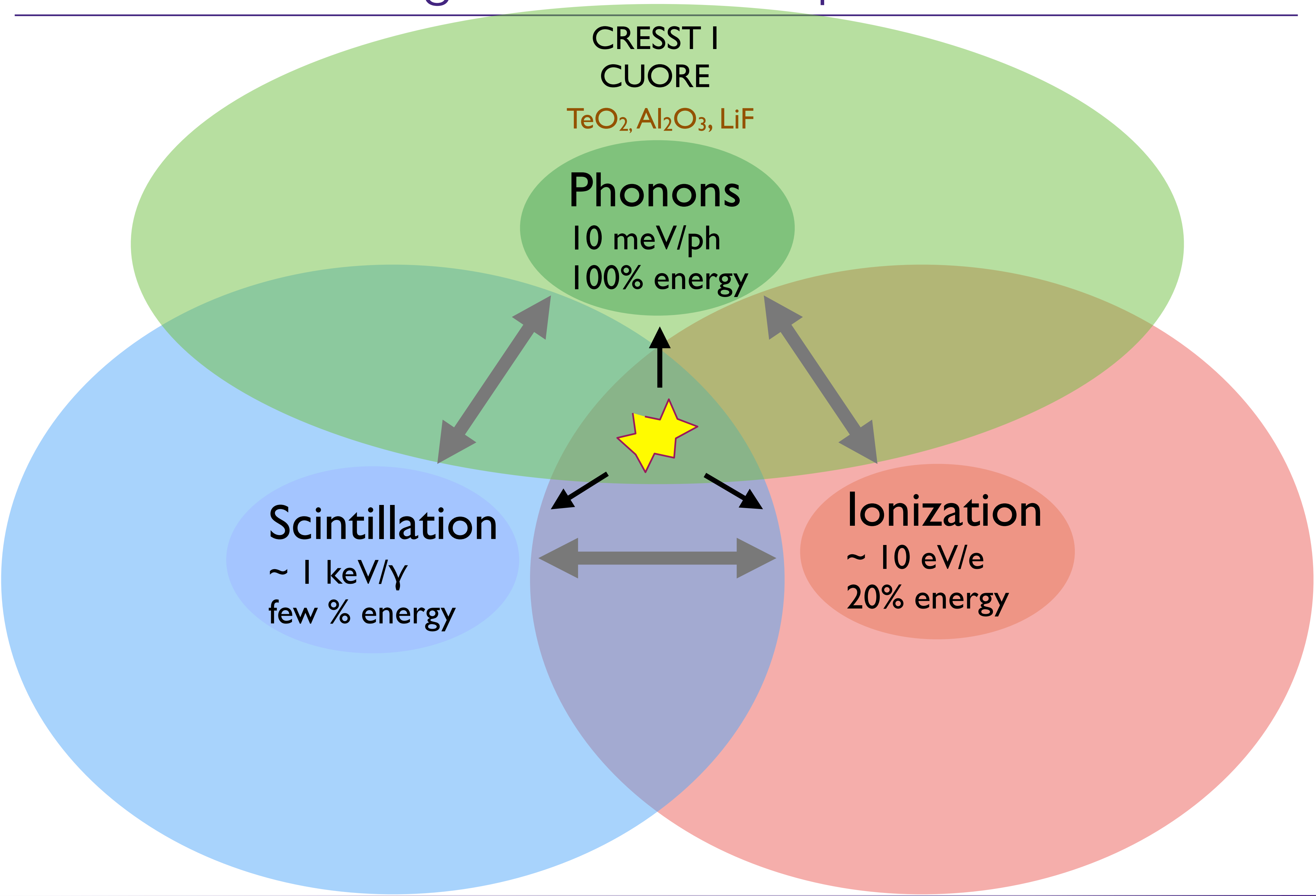

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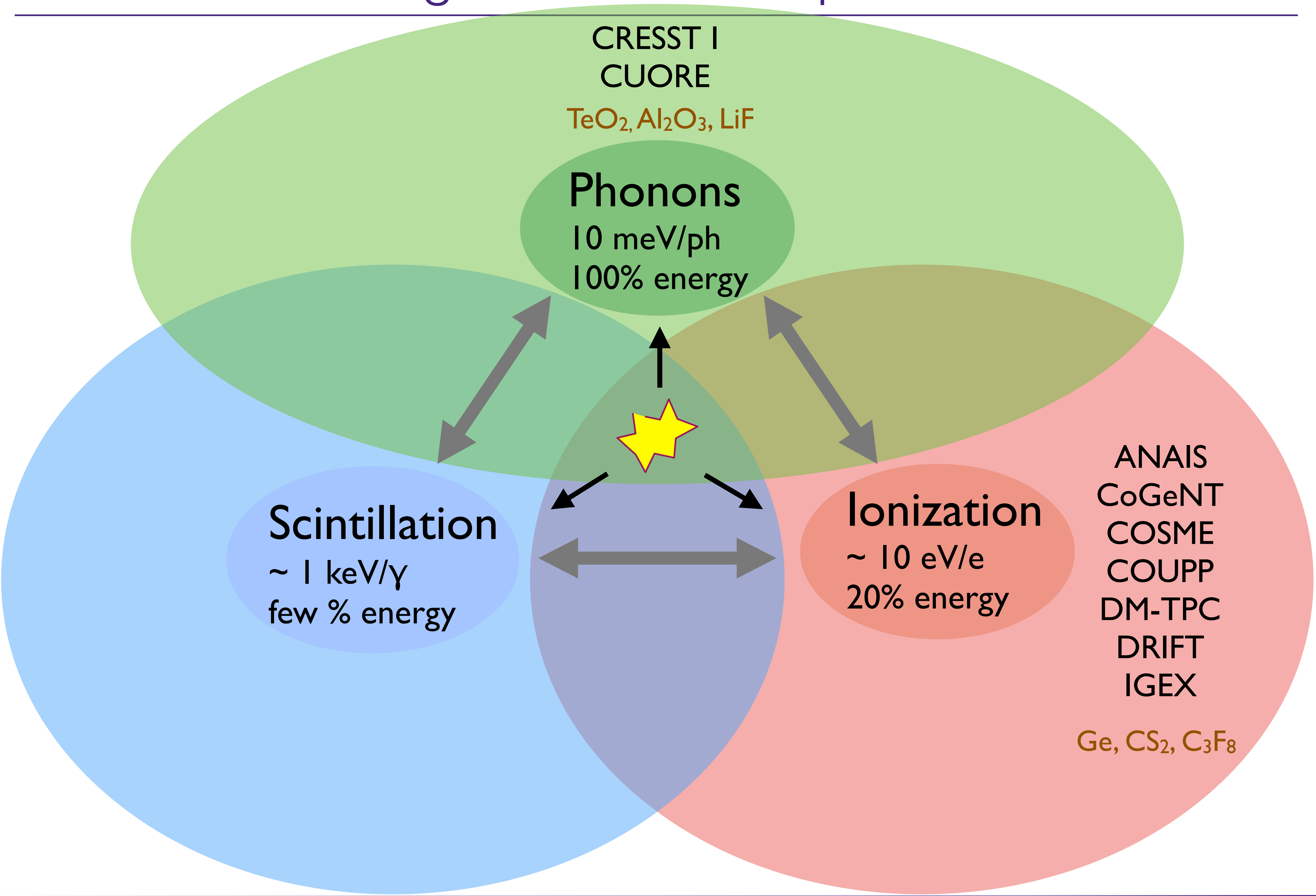

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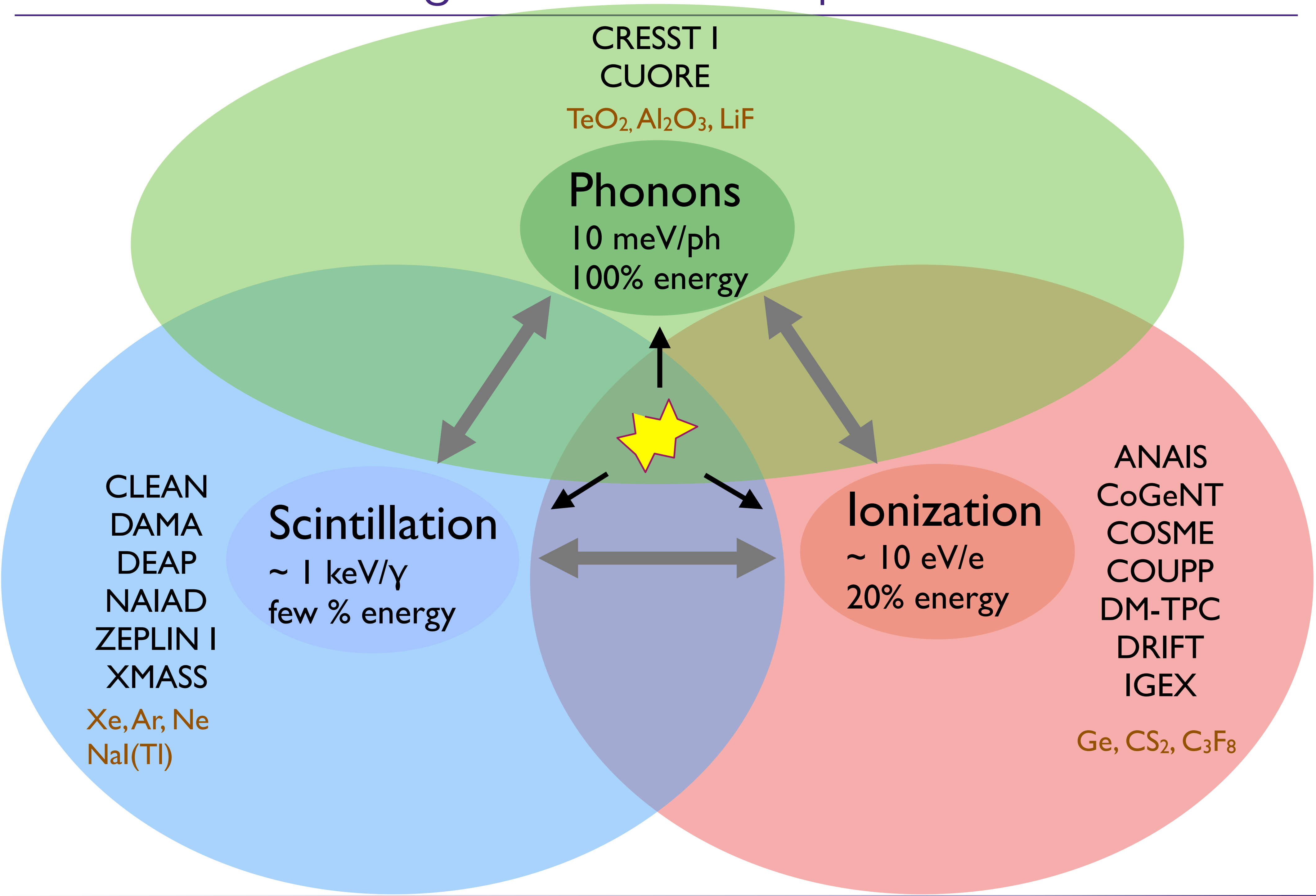

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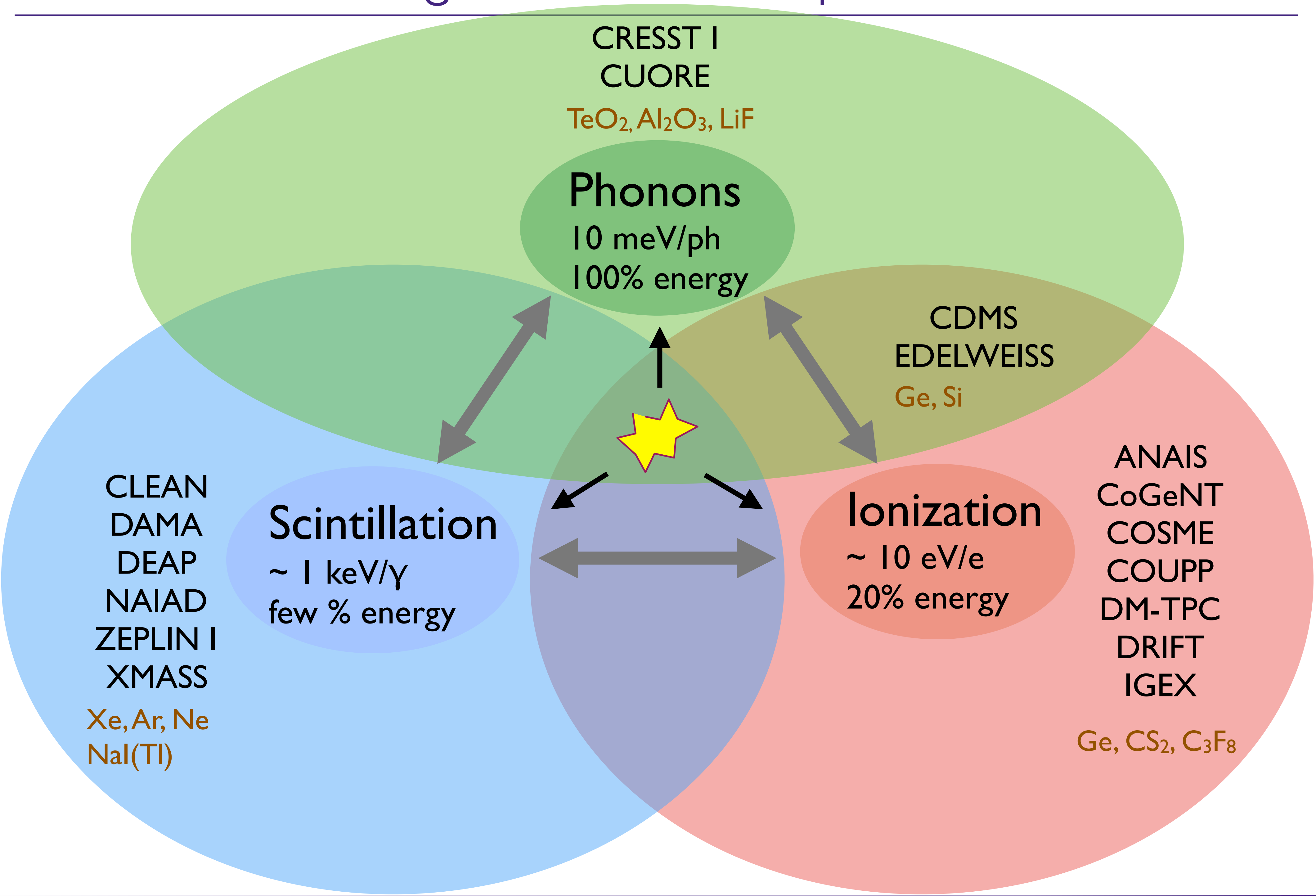

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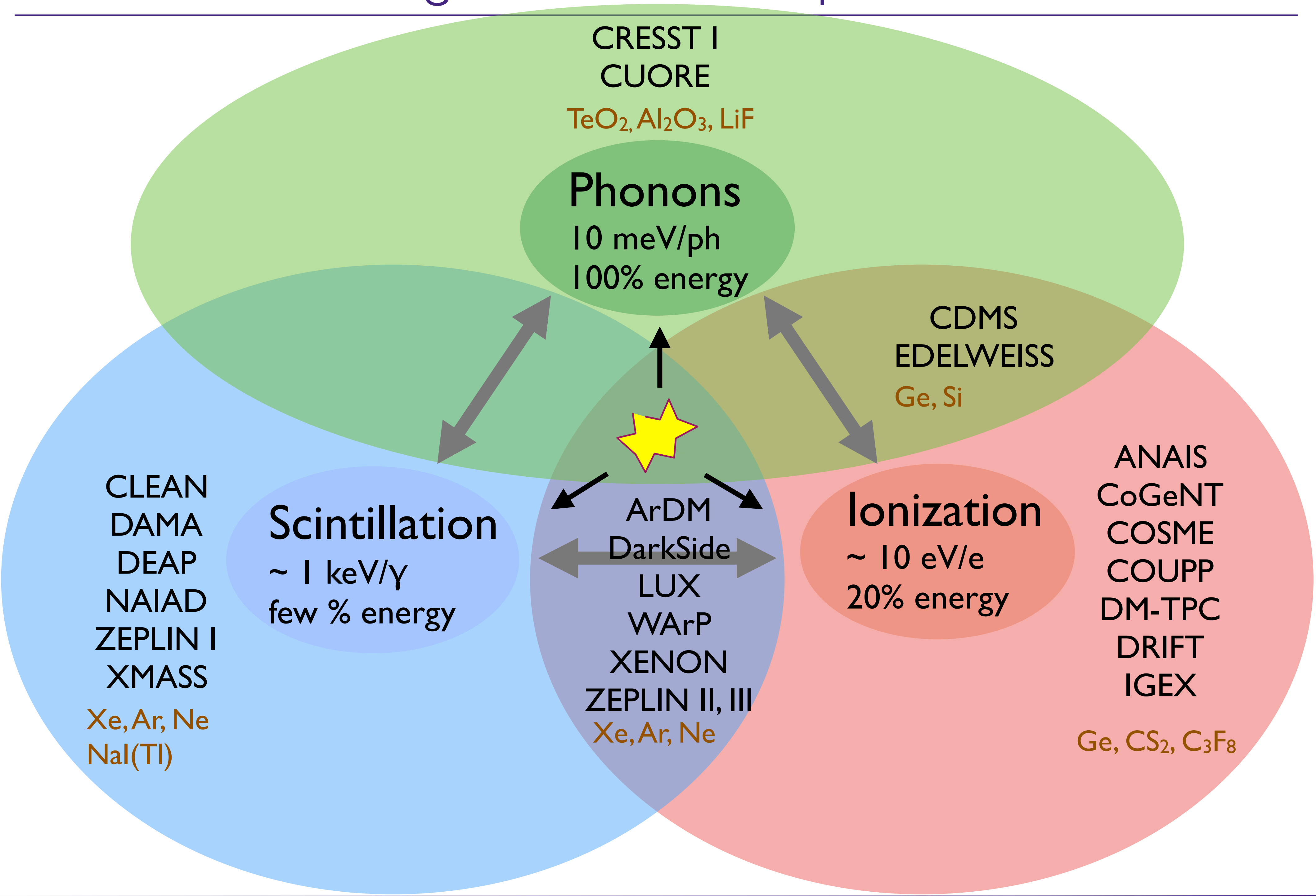

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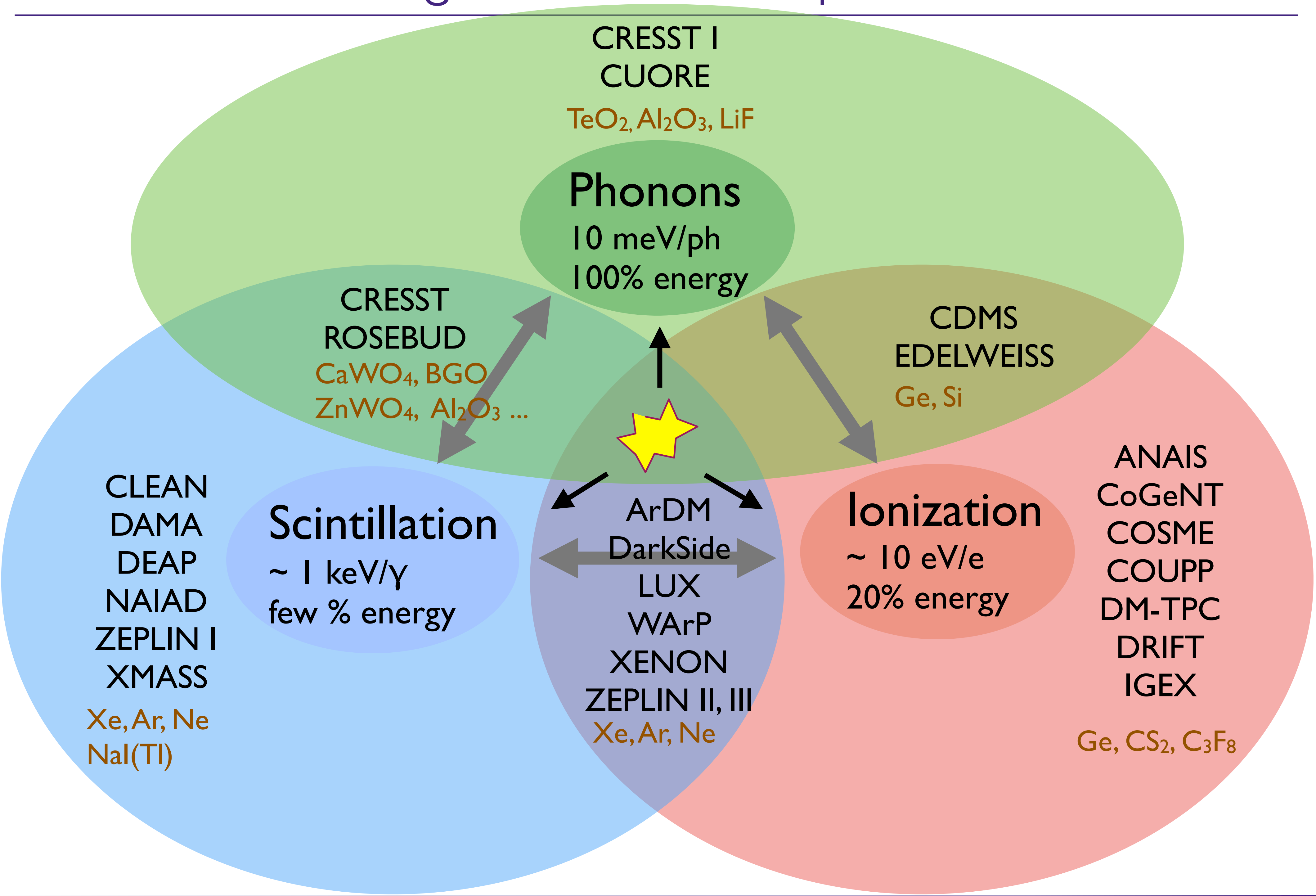
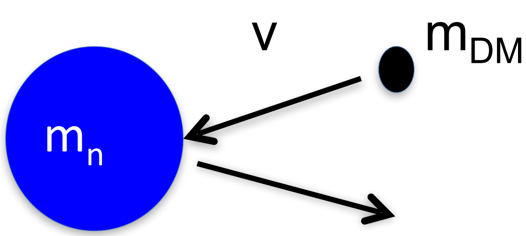


Thinking outside the Triangle…

- Scintillation Timing (DEAP/CLEAN, DarkSide, etc…)
- Signal Modulation (DAMA/LIBRA, DRIFT, DM-TPC, etc...)
- Nuclear-recoil-only trigger mechanism
  - (a la COUPP, PICASSO, PICO…)
- Self-Shielding (XMASS)
- Others...

The low-mass WIMP challenge



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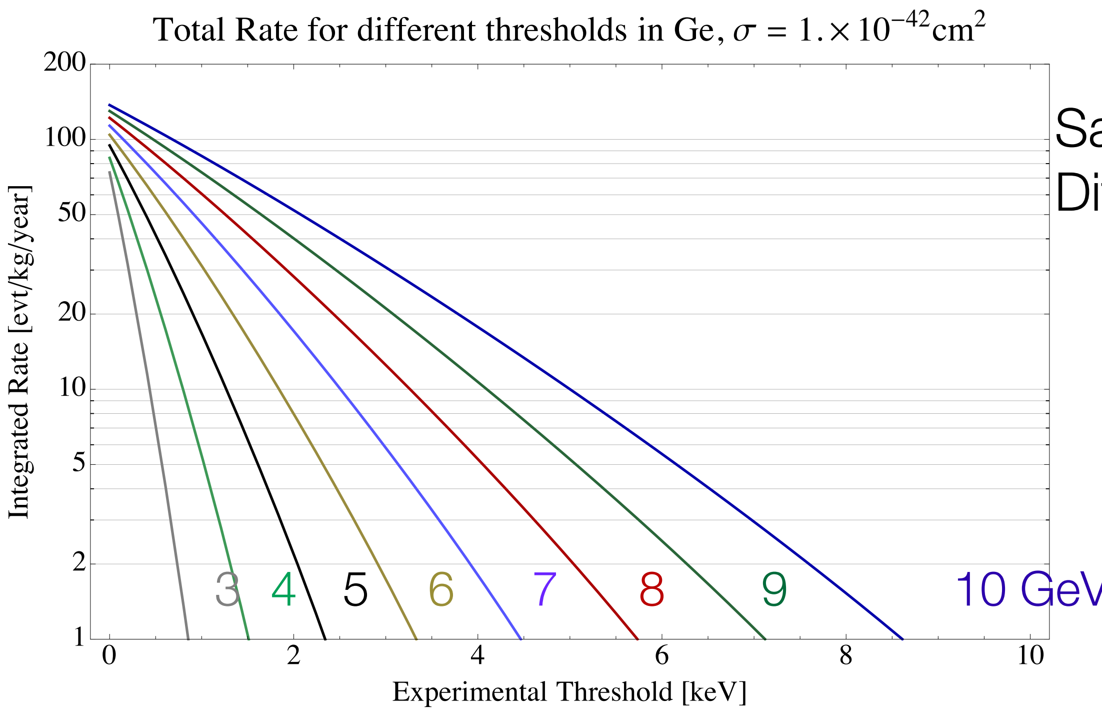
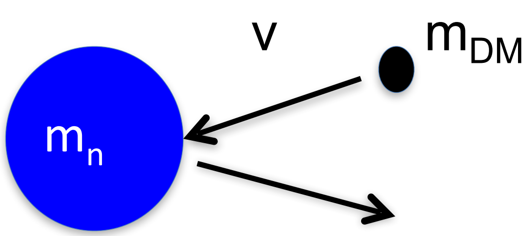


Sar
Diff

The low-mass WIMP challenge



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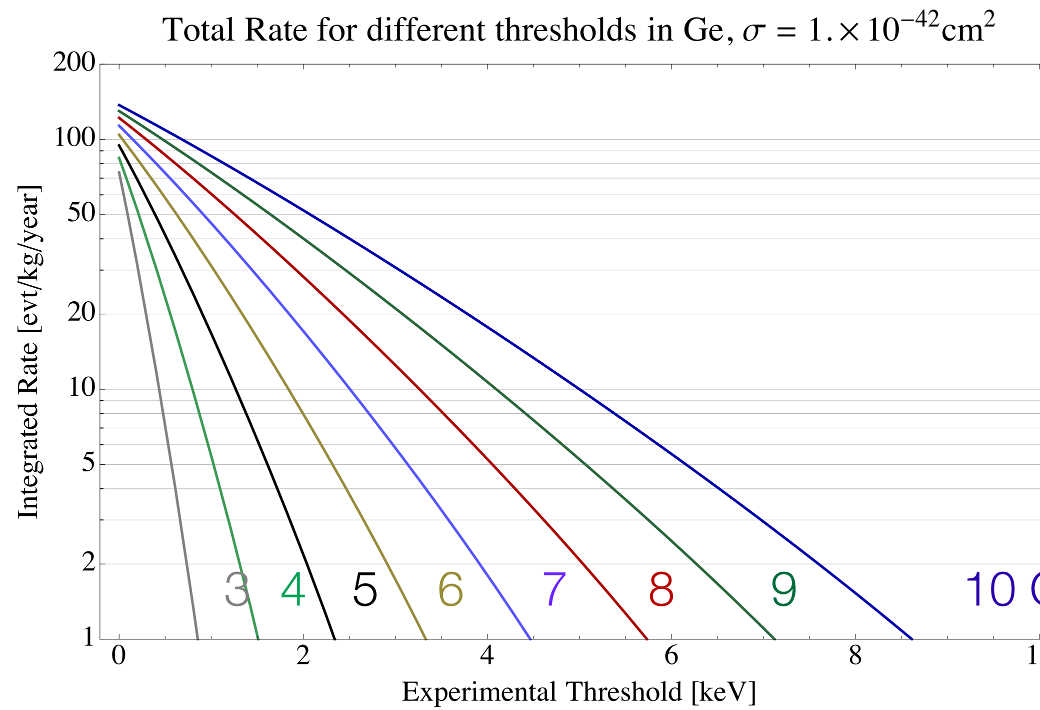

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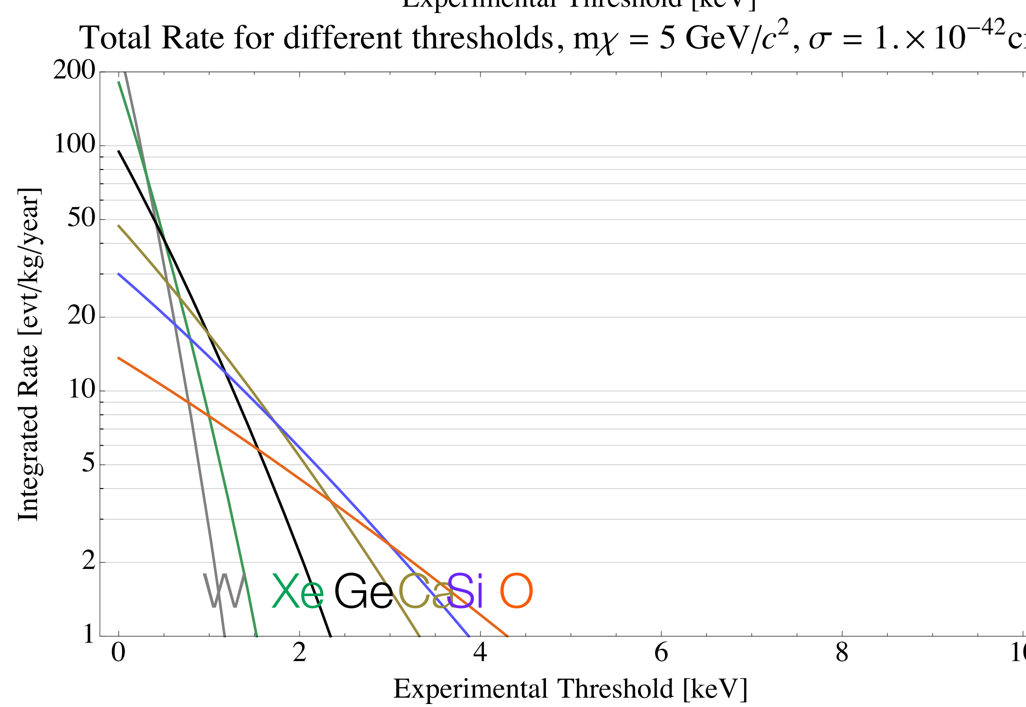


Differ
Same

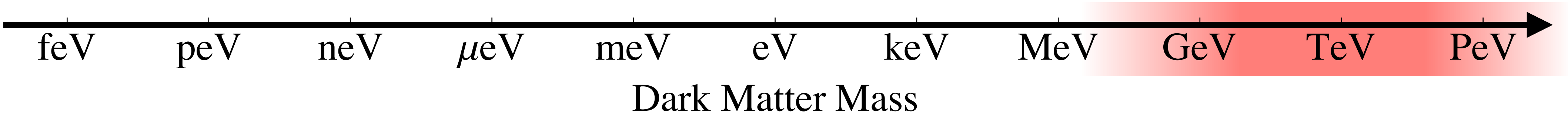
Summary of Nuclear Recoil Direct Detection Requirements

1: Large Exposure (Mass x Time)

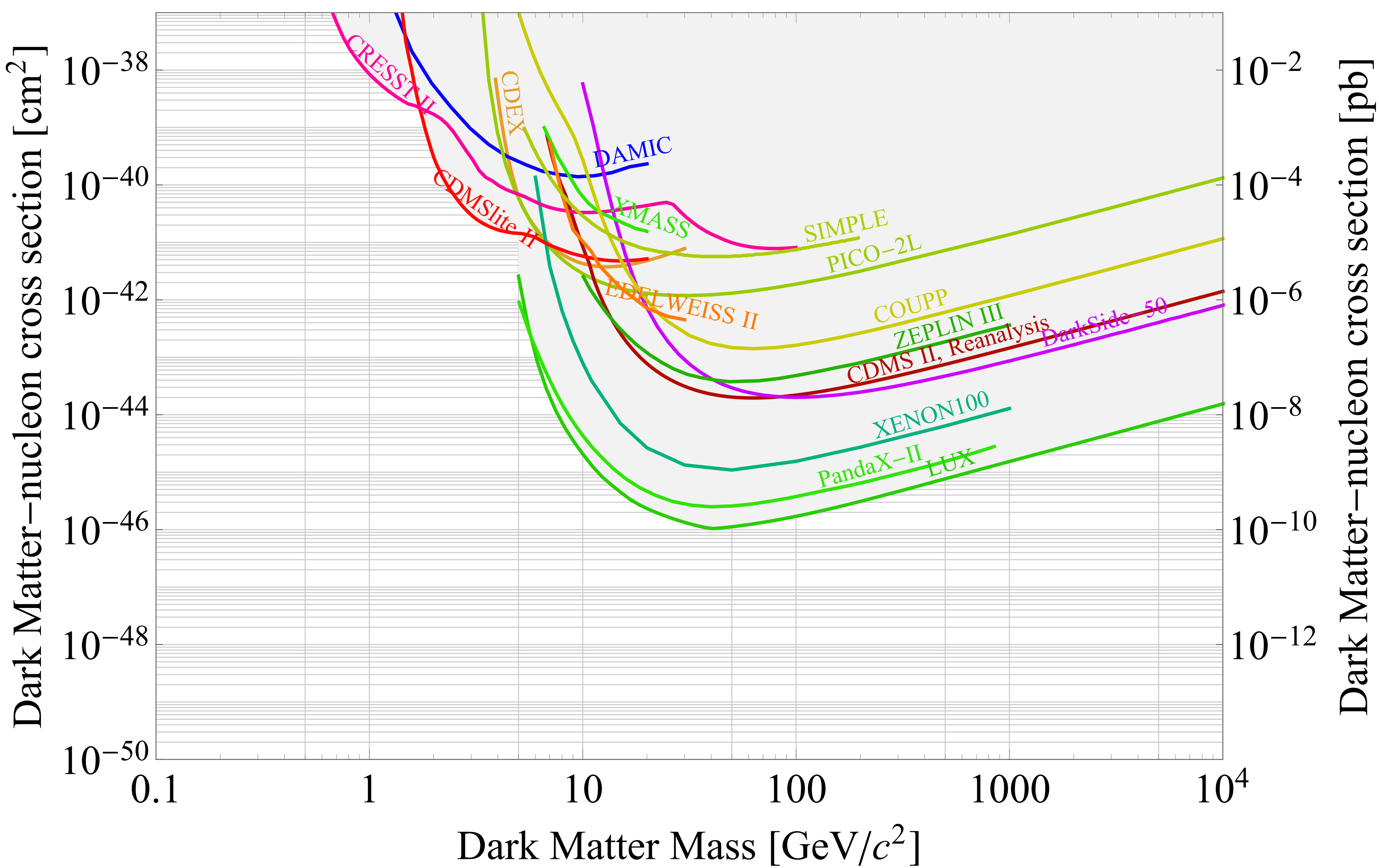
2: Low Background Rate

3: Discrimination between Signal and Backgrounds

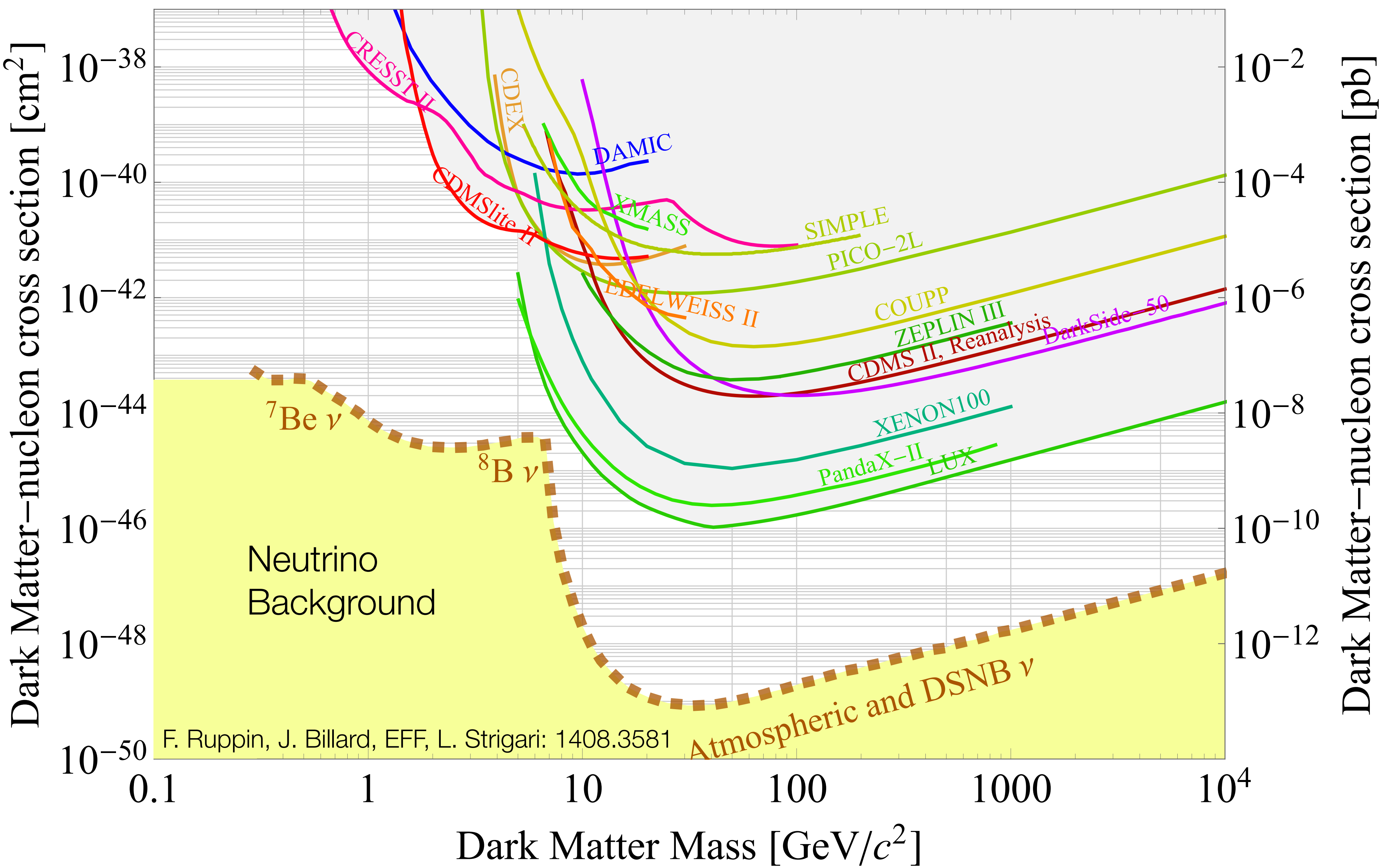
4: Low Energy Threshold



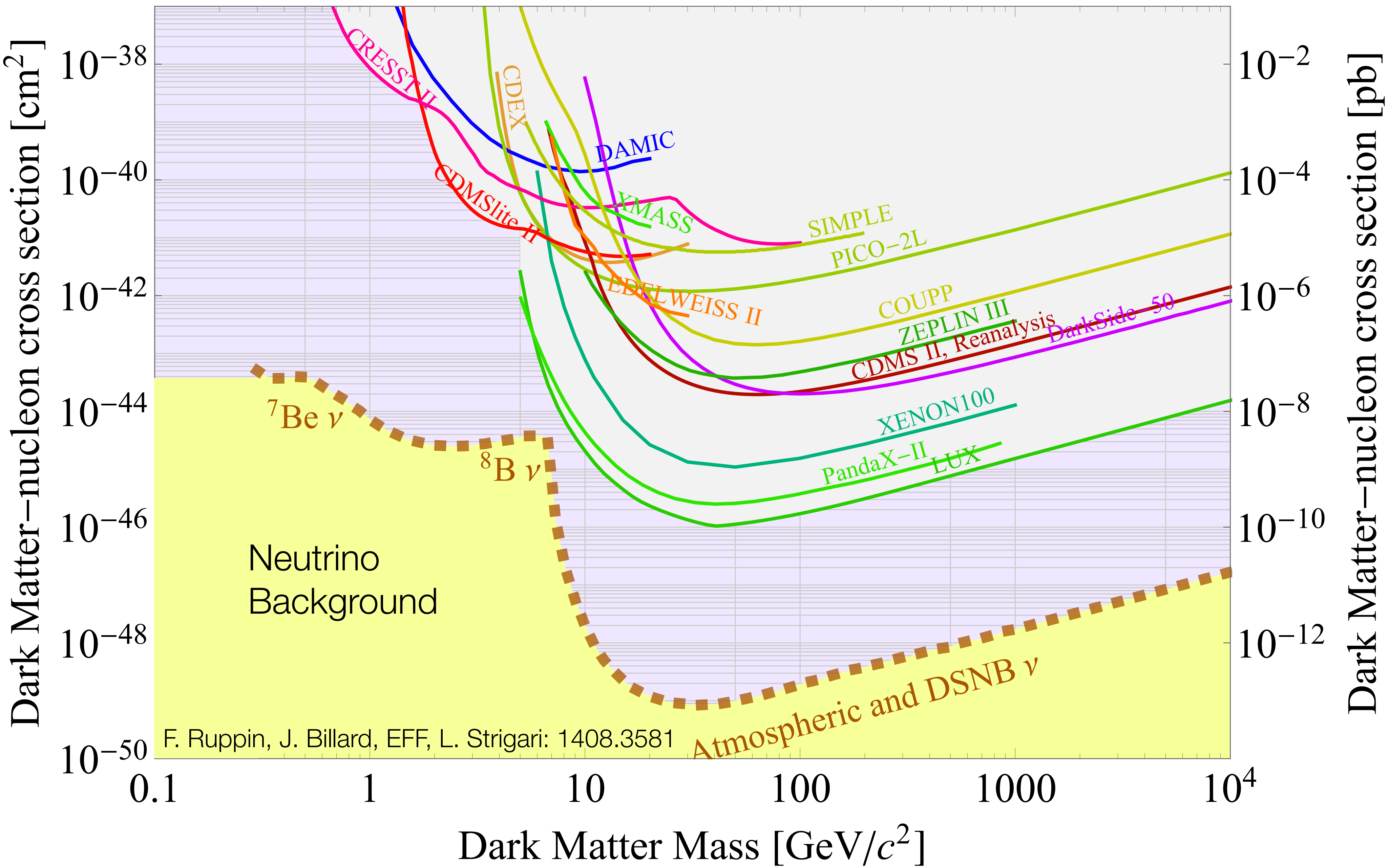
Current Limits



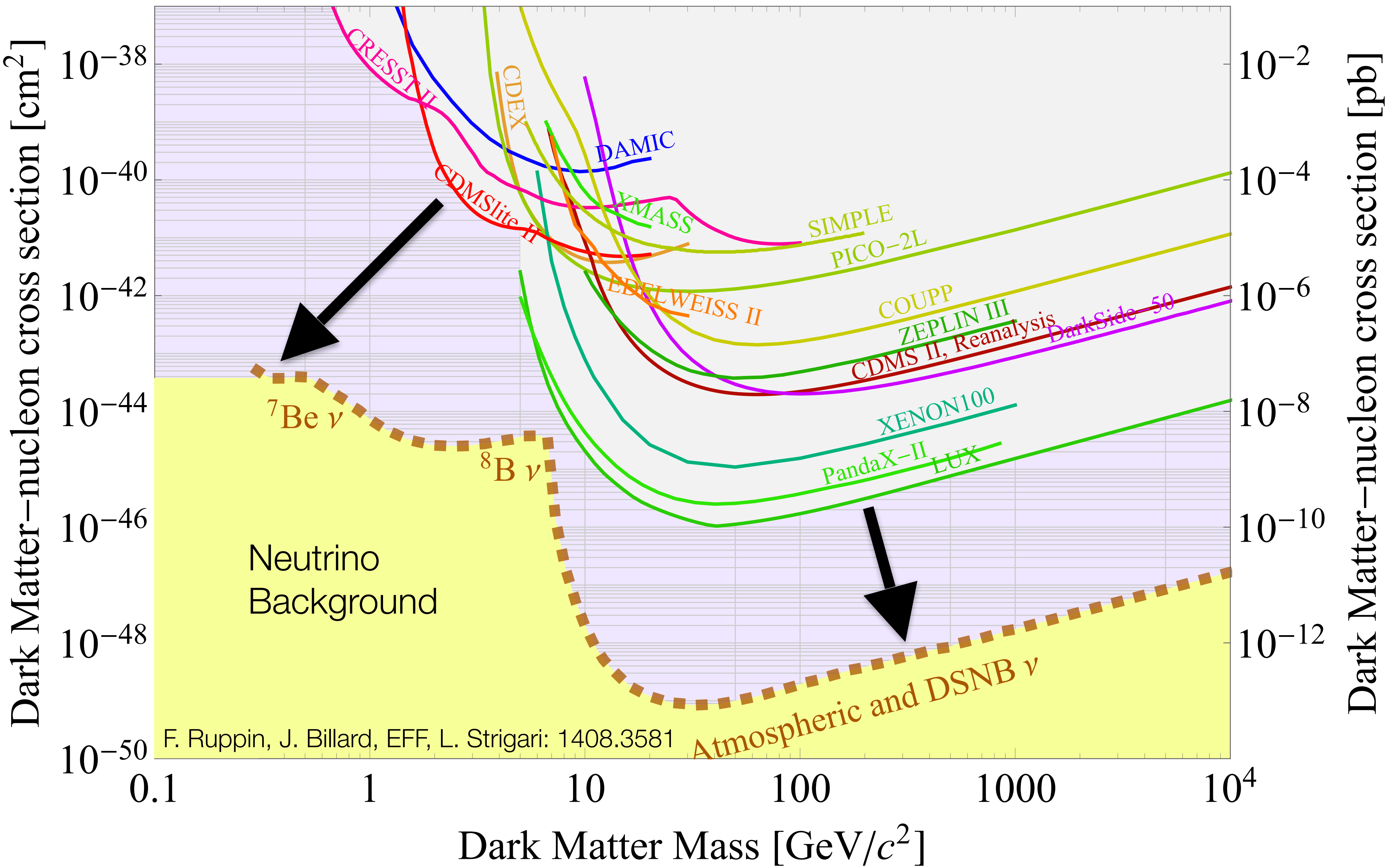
To Neutrinos, and Beyond!



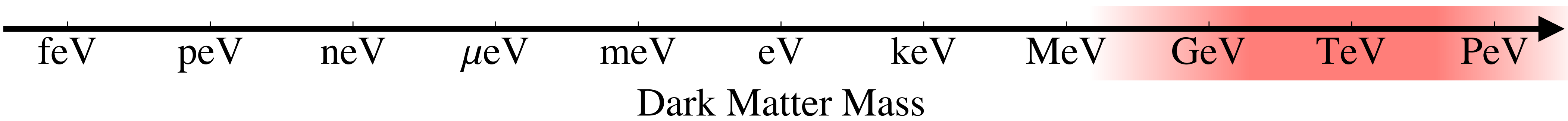
To Neutrinos, and Beyond!



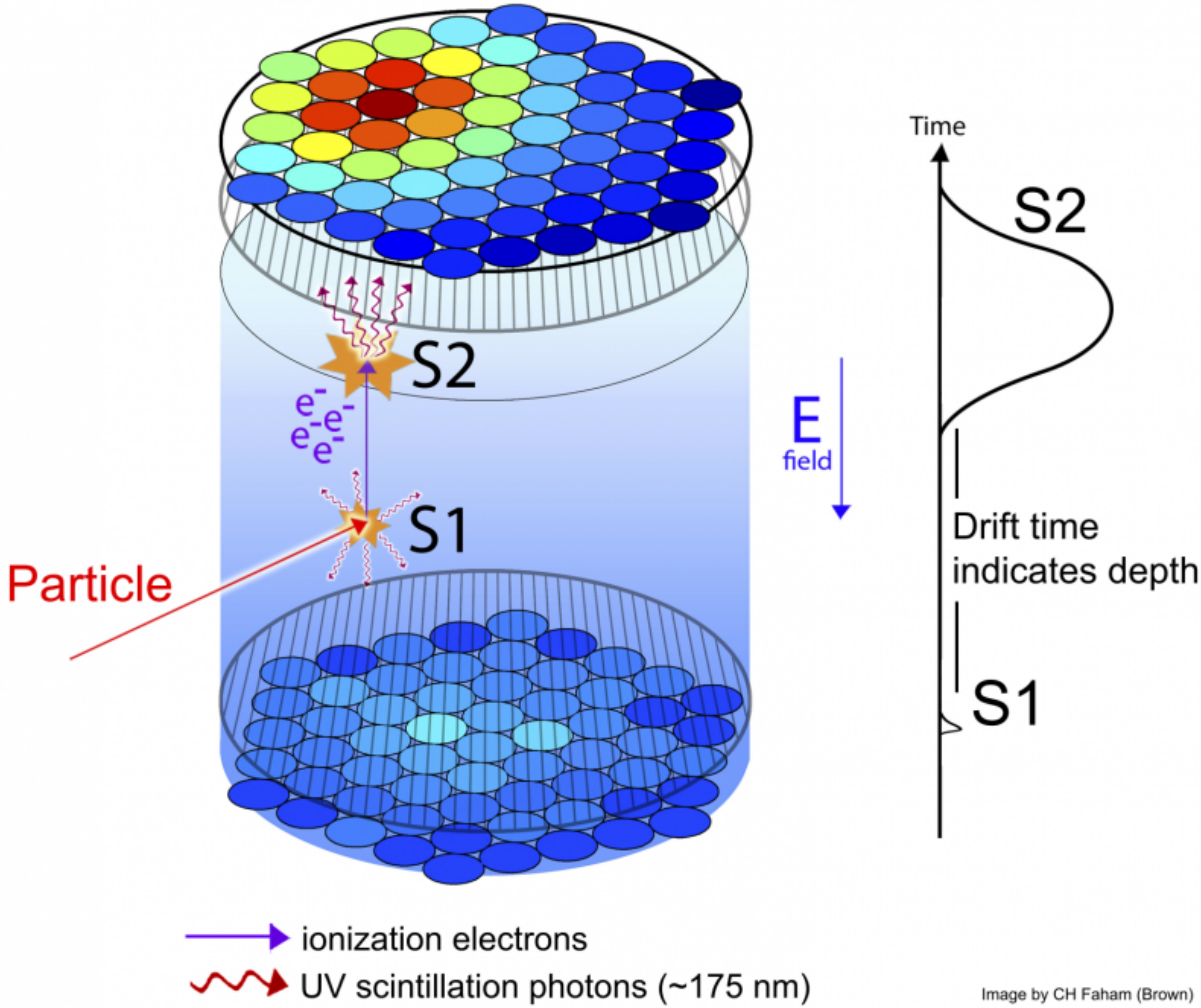
To Neutrinos, and Beyond!

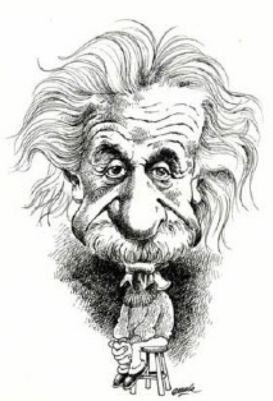


Nuclear Recoil Detection Technologies



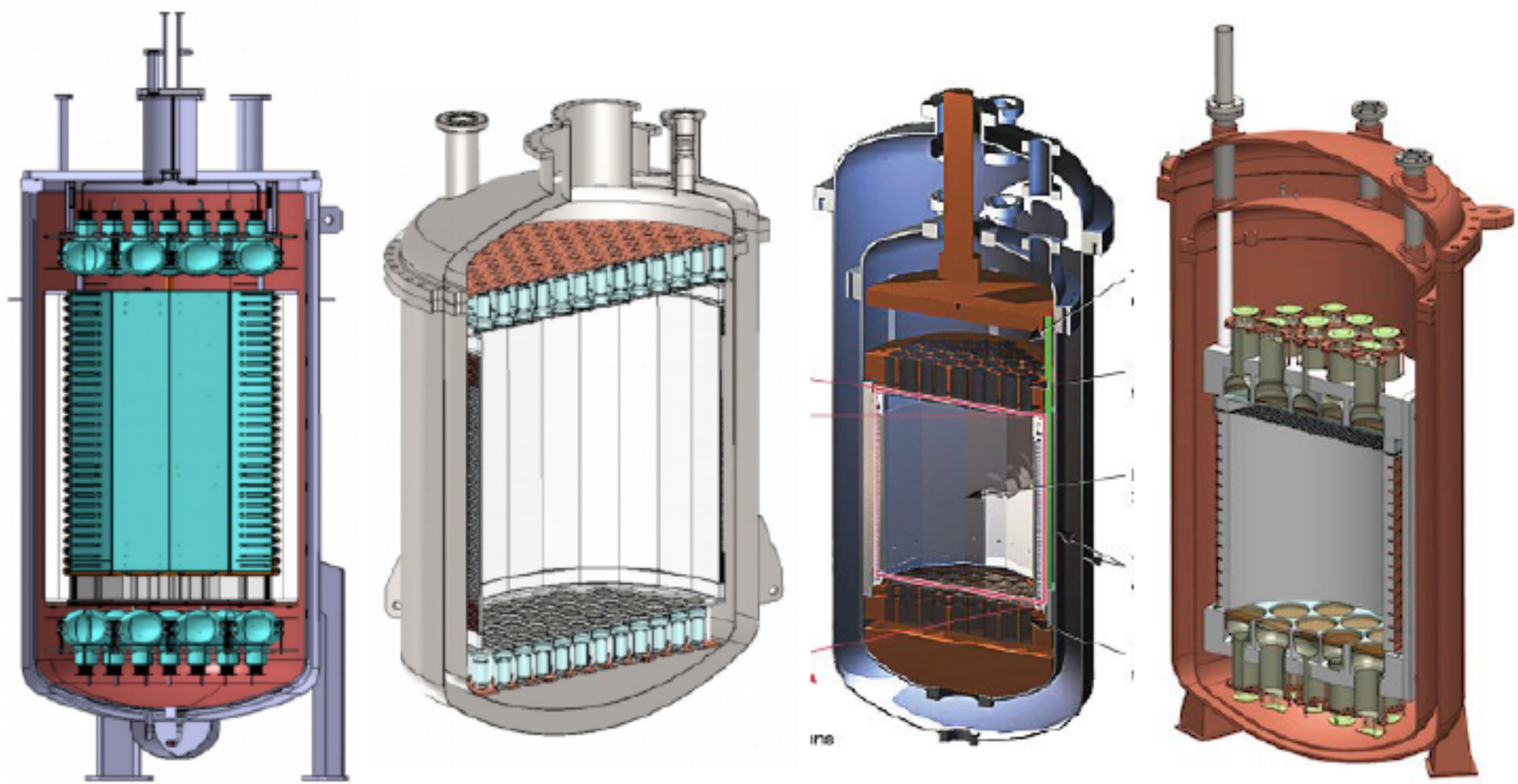
Noble Liquid Time-projection Chambers





Noble Liquid Time Projection Chambers

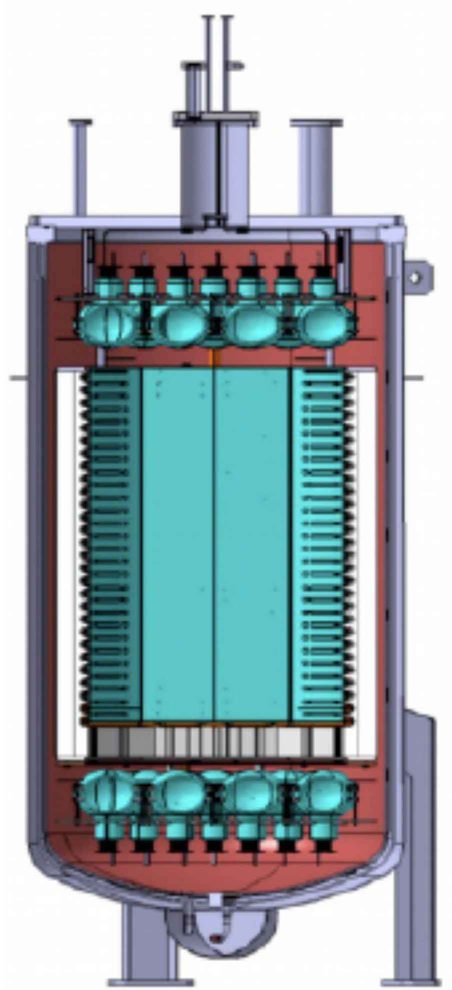
NOT TO SCALE!



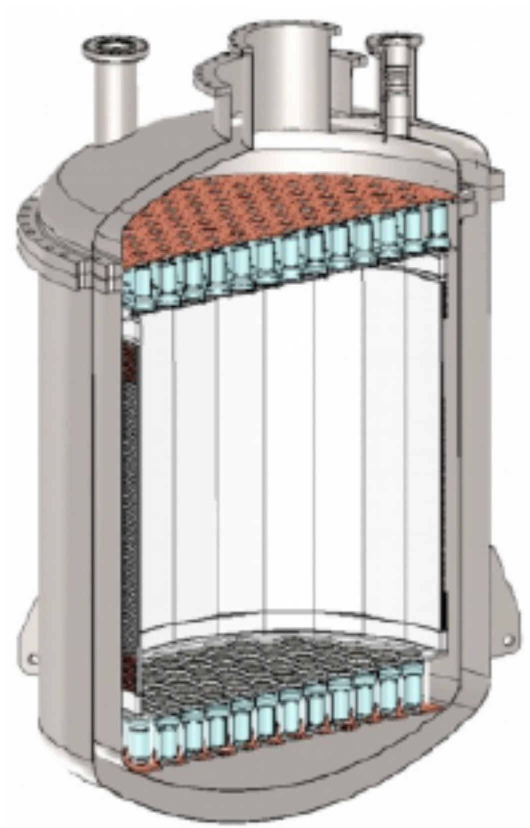
Noble Liquid Time Projection Chambers

NOT TO SCALE!

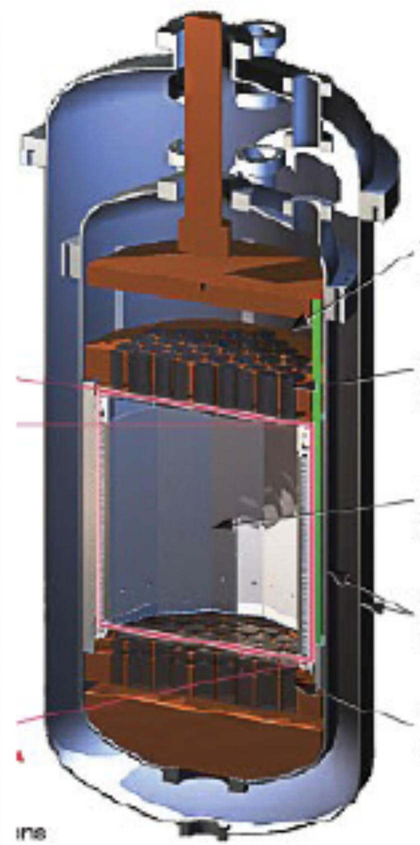
ArDM



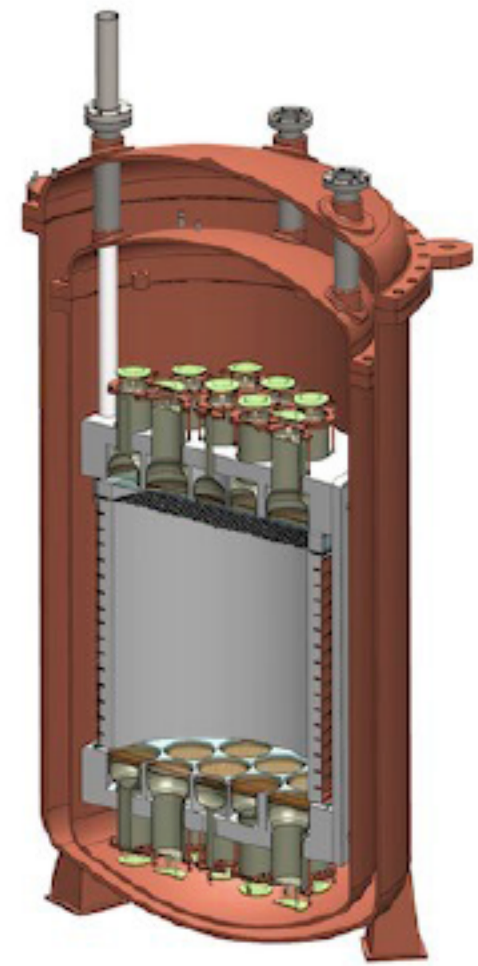
XENON1T



LUX

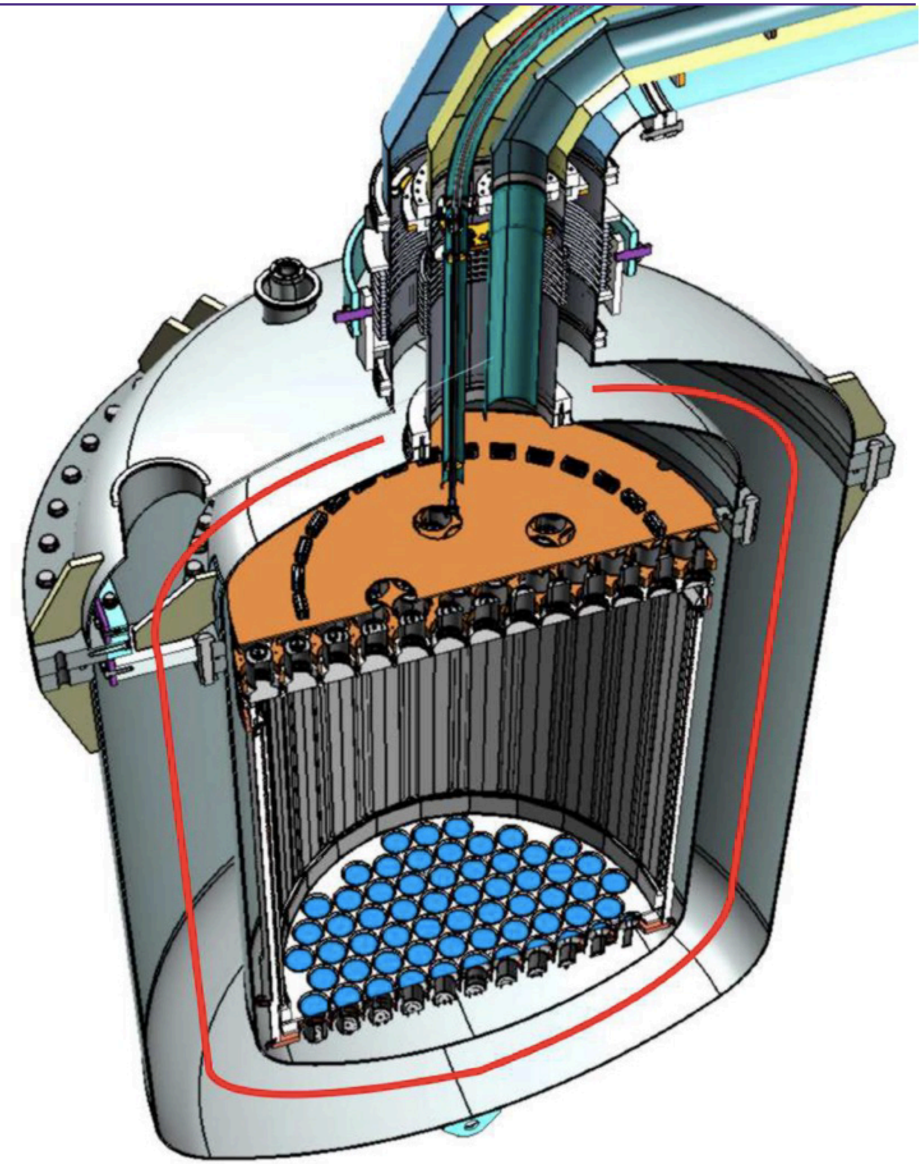


DarkSide-50



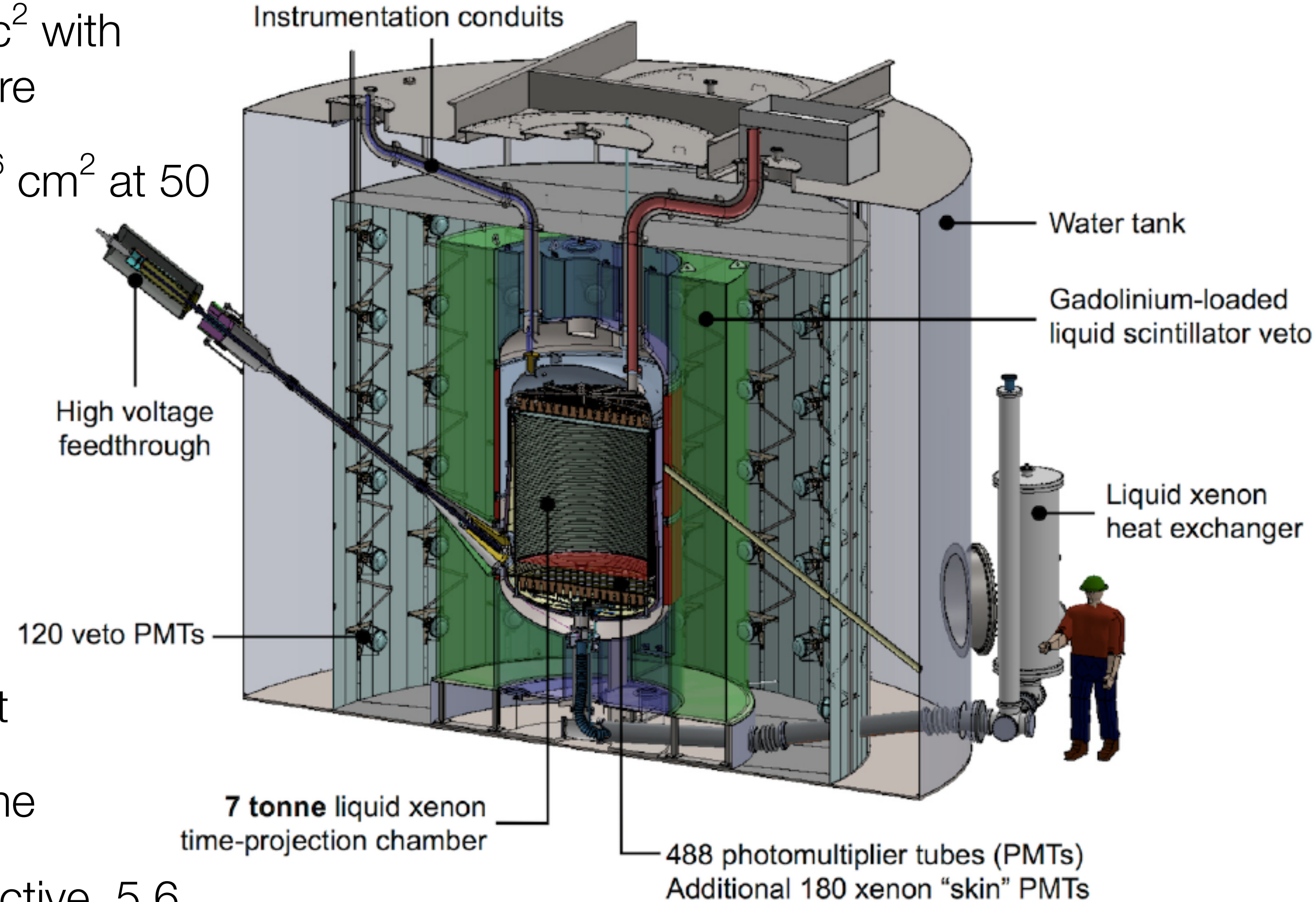
The XENON Dark Matter Program

- XENON1T
  - 3.5 tons of XENON
  - 2 tons active
  - taking data now
  - first science results soon
- XENONnT
  - 7.5 tons of XENON
  - 6 tons active
  - Starts in 2019



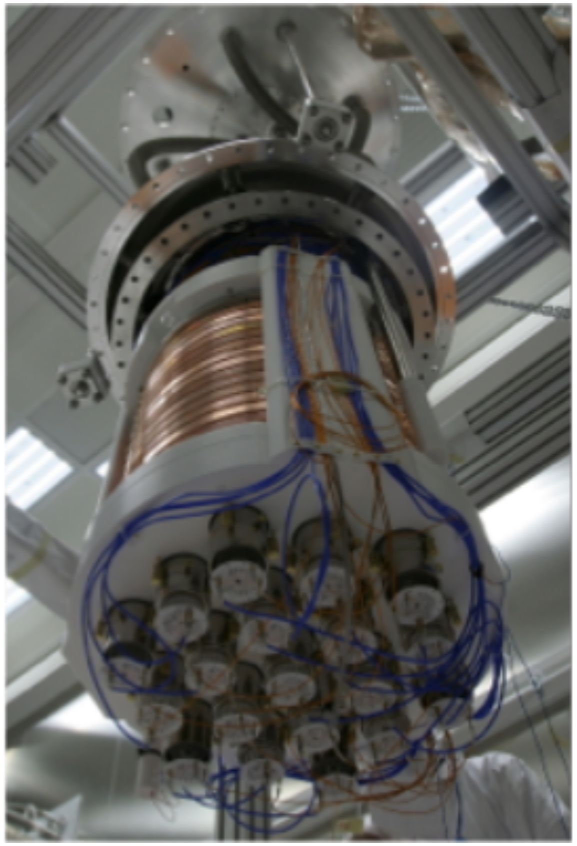
LUX and LZ Programs

- LUX
  - Current best limits for WIMP masses above 5 GeV/c^2 with 33,500 kg-day exposure
  - WIMP limit at 1.1×10^{-46} cm^2 at 50 GeV/c^2
- LZ
  - Funded G2 Experiment
  - 50 x LUX fiducial volume
  - 10 Ton Xenon, 7 Ton Active, 5.6 Ton fiducial
  - Begin taking data in 2019

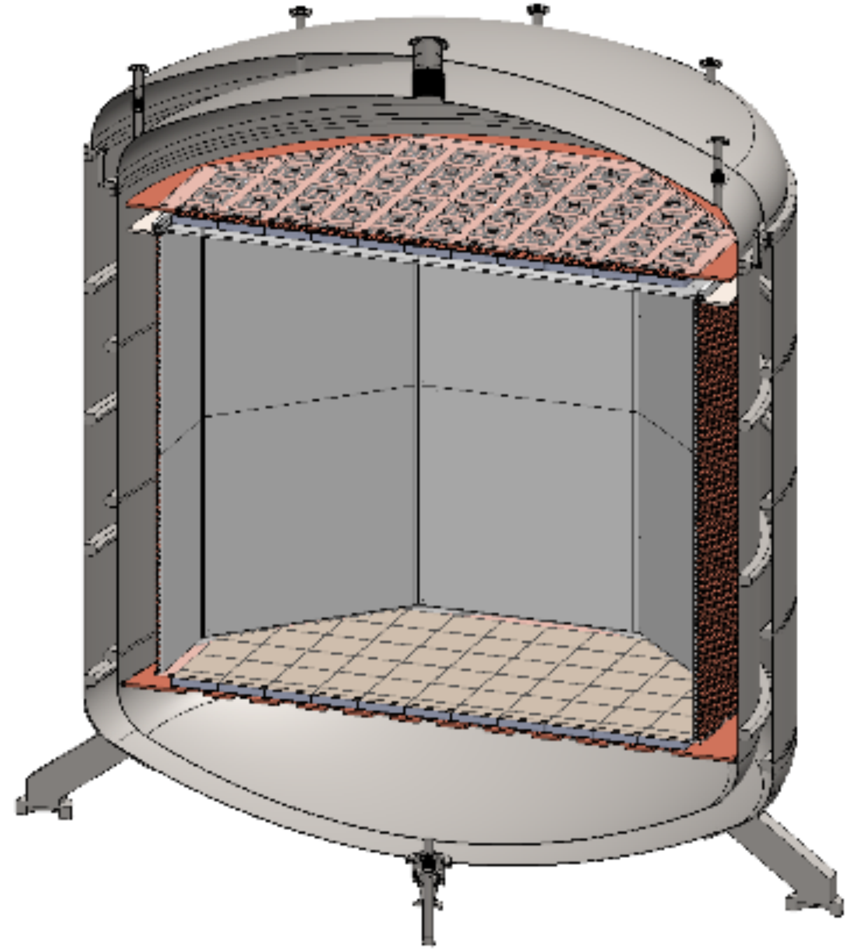


The DarkSide Program

DarkSide-50



DarkSide-20k

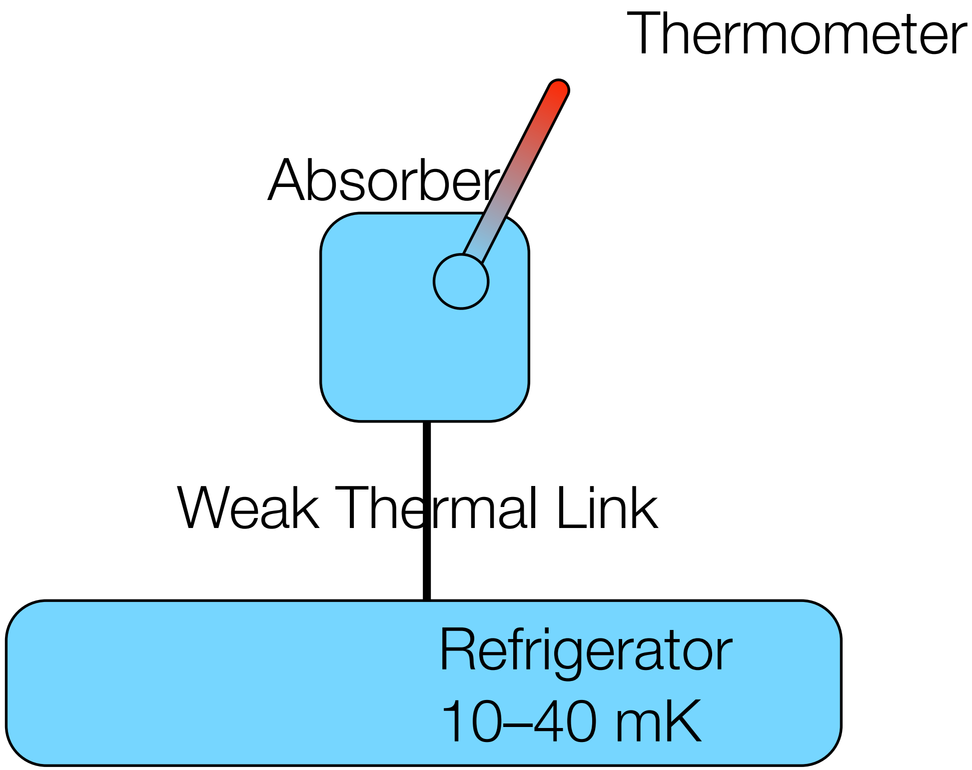


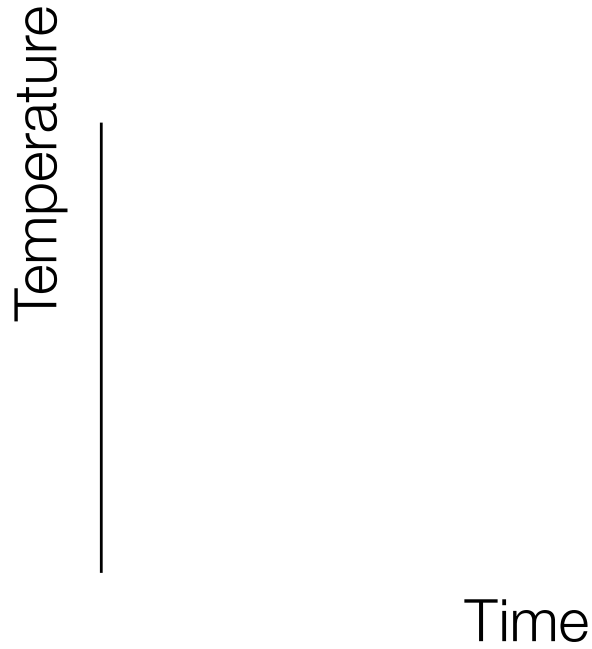
- 46 kg active Ar, 36.9 kg Fiducial
- Active neutron veto (borated liqud scintillator)
- Using underground Ar obtained 300x less ^{39}Ar events that atmospheric Ar

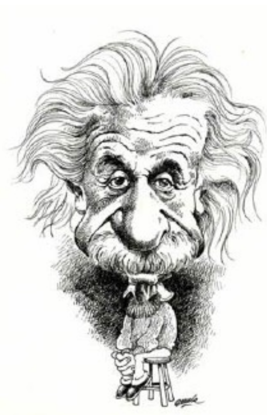
- 30Ton Ar, 20 Ton fiducial
- 100 Ton-yr background-free exposure
- Gd-loaded Water Cherenkov active veto
- Timeline: TBD

Cryogenic Crystal Detectors

The Phonon Channel

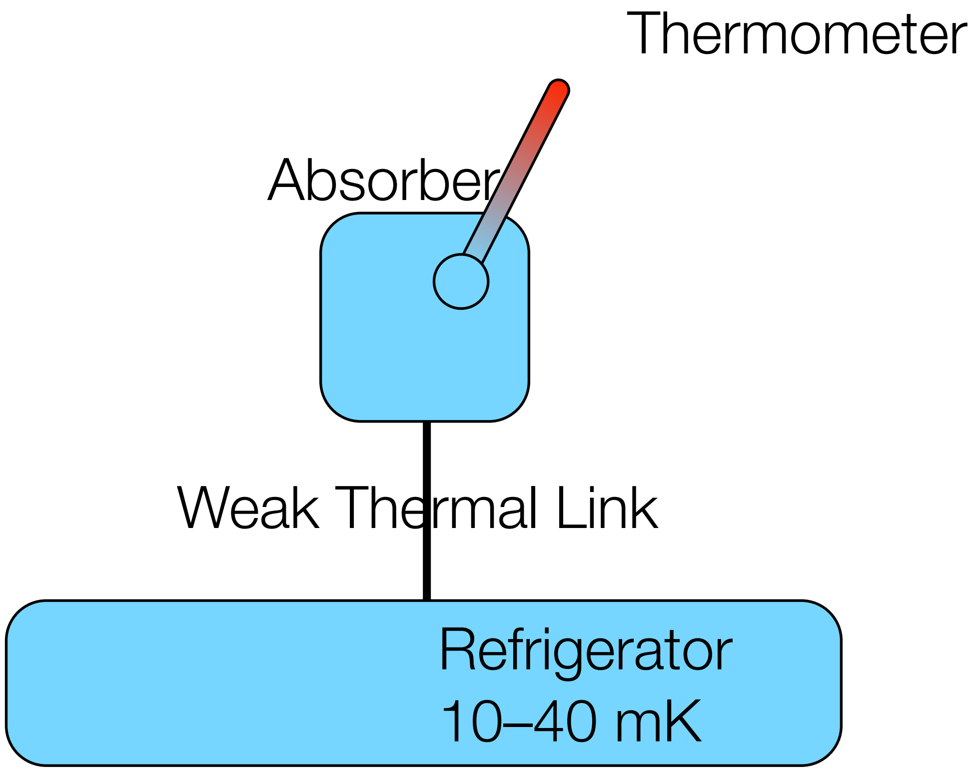


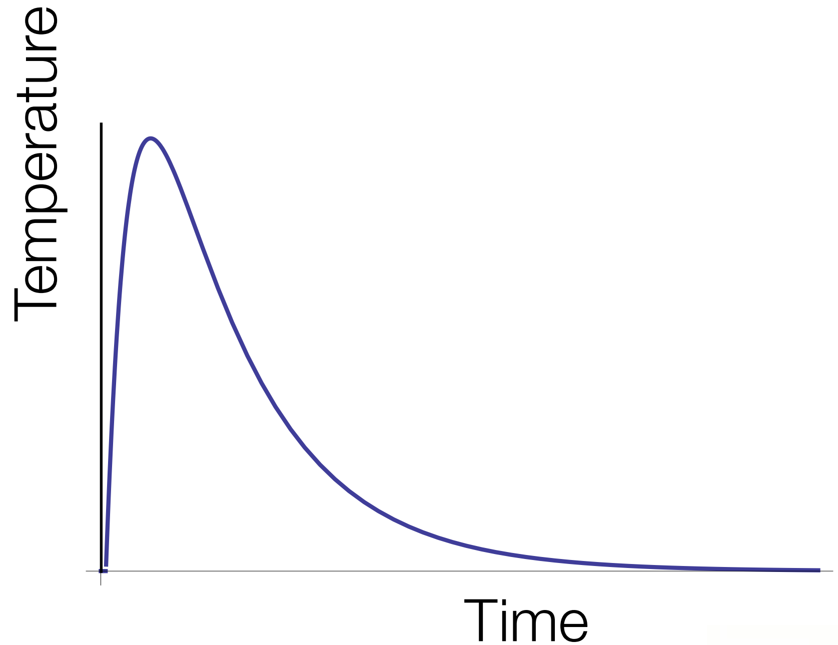


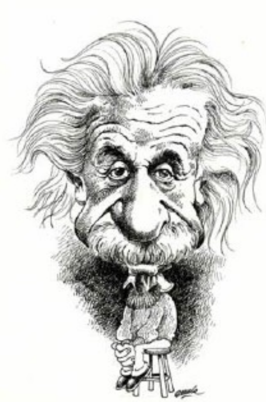


Cryogenic Crystal Detectors

The Phonon Channel

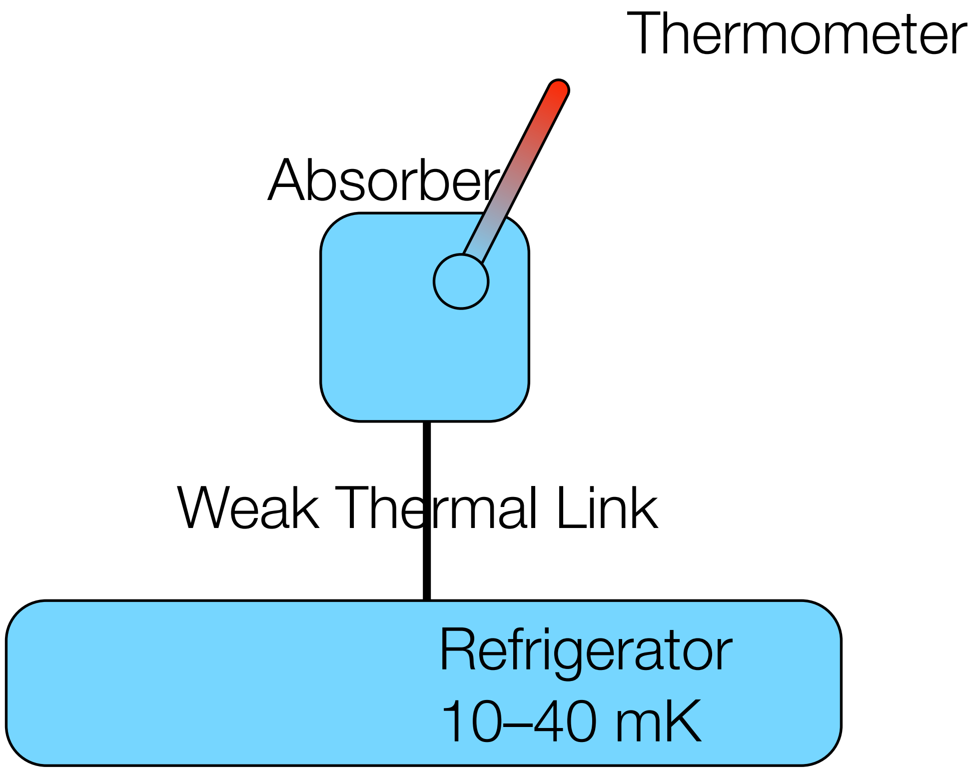


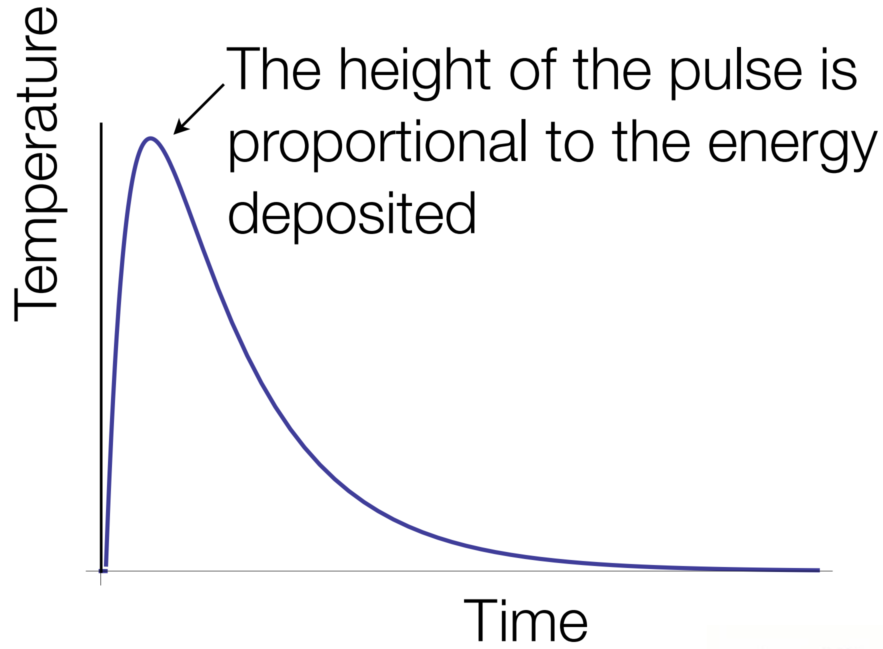


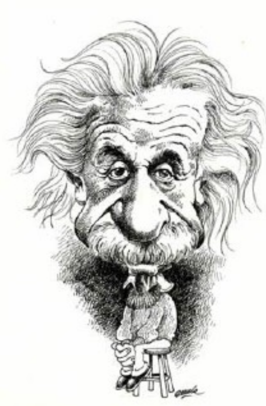


Cryogenic Crystal Detectors

The Phonon Channel



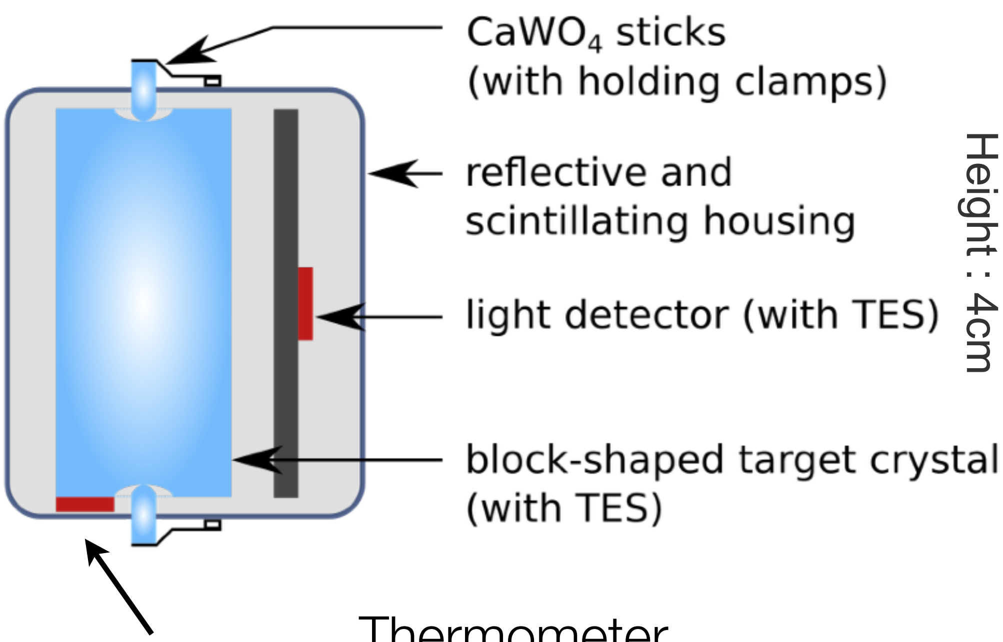


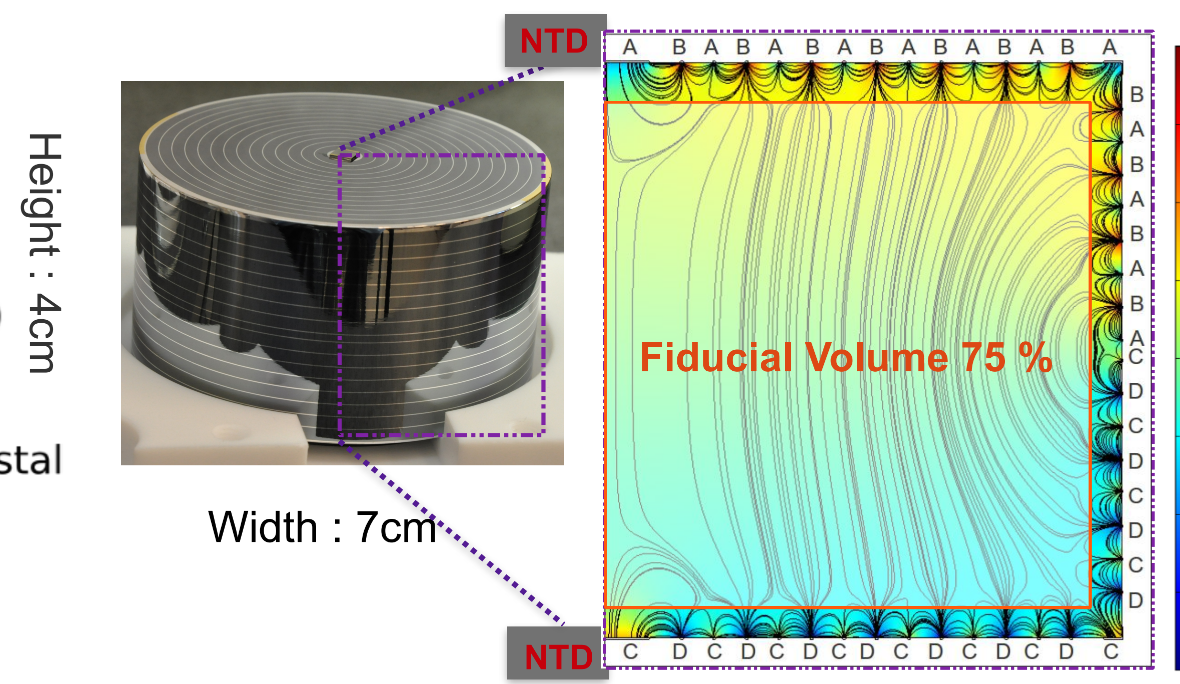


CRESST and EDELWEISS

- CRESST: phonon + light
- Current Experiment: CRESST Phase 2 ongoing
- New CRESST Phase III detectors focused on low-mass WIMPs

- EDELWEISS: phonon + charge
- 36 x 800 g detectors installed in cryostat; results later this year
- New runs with better sensitivity to light WIMPS using High Voltage operation coming soon.



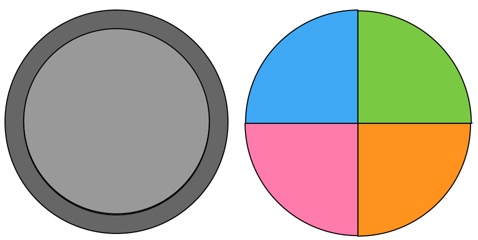


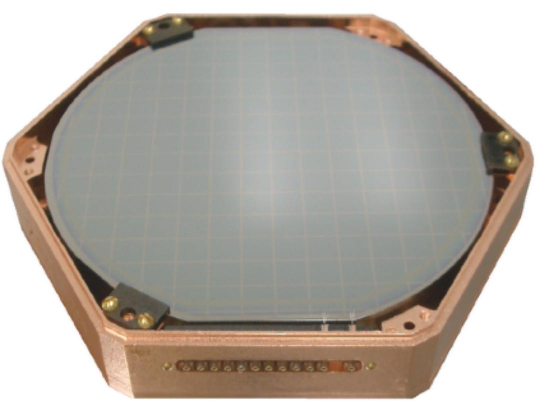
SuperCDMS SNOLAB

CDMS II

4.6 kg Ge (19 x 240 g)
1.2 kg Si (11 x 106g)
3” Diameter
1 cm Thick

2 charge + 4 phonon

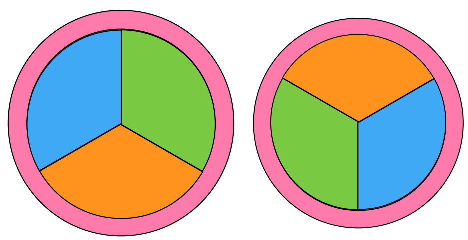


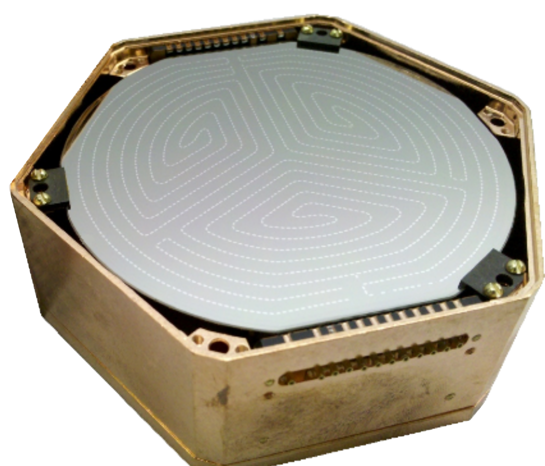


SuperCDMS Soudan

9.0 kg Ge (15 x 600g)
3” Diameter
2.5 cm Thick

2 charge + 2 charge
4 phonon + 4 phonon

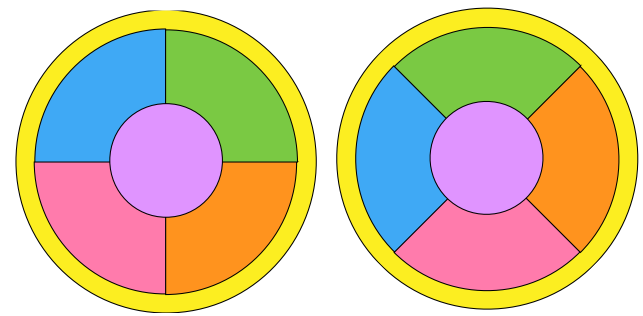


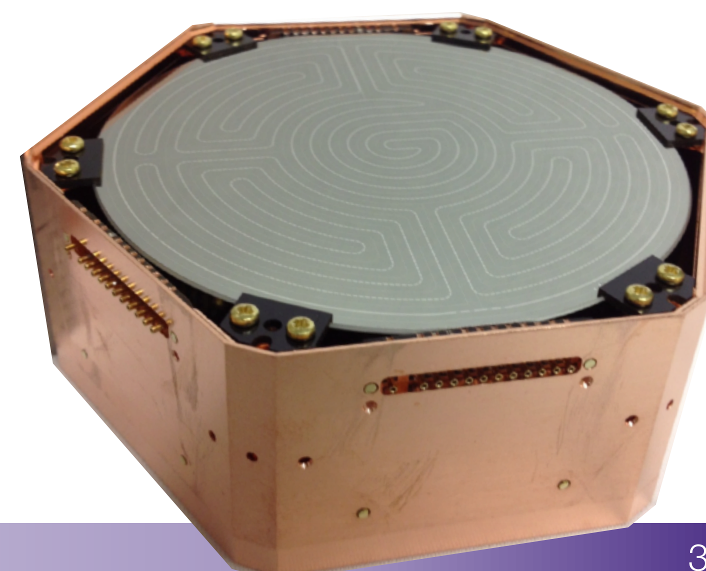


SuperCDMS SNOLAB

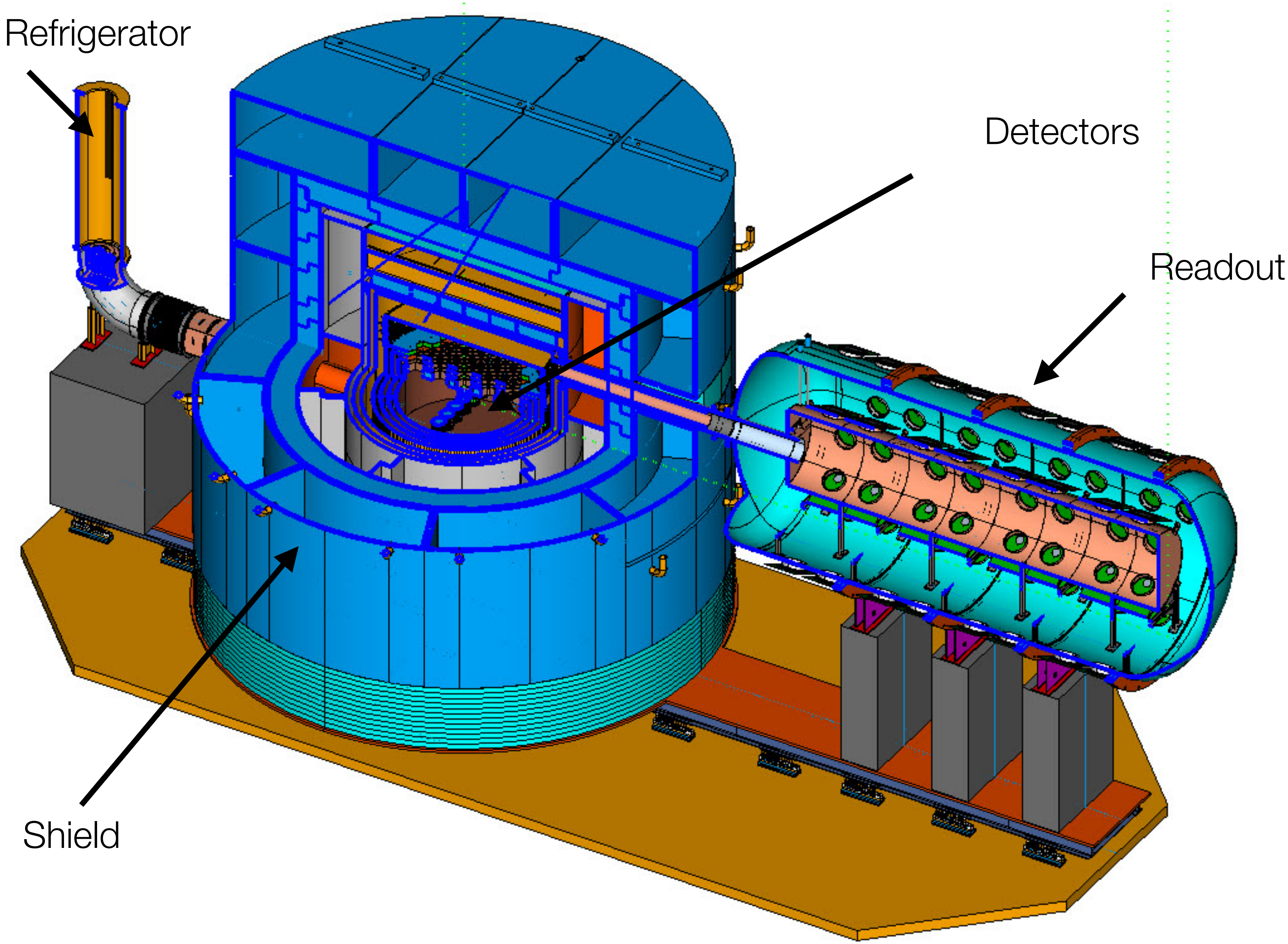
Funded G2 Experiment
Data Taking in 2020
25 kg Ge (18 x 1.4 kg)
3.6 kg Si (6 x 0.6 kg)
4” Diameter
3.3 cm Thick

2 charge + 2 charge
6 phonon + 6 phonon

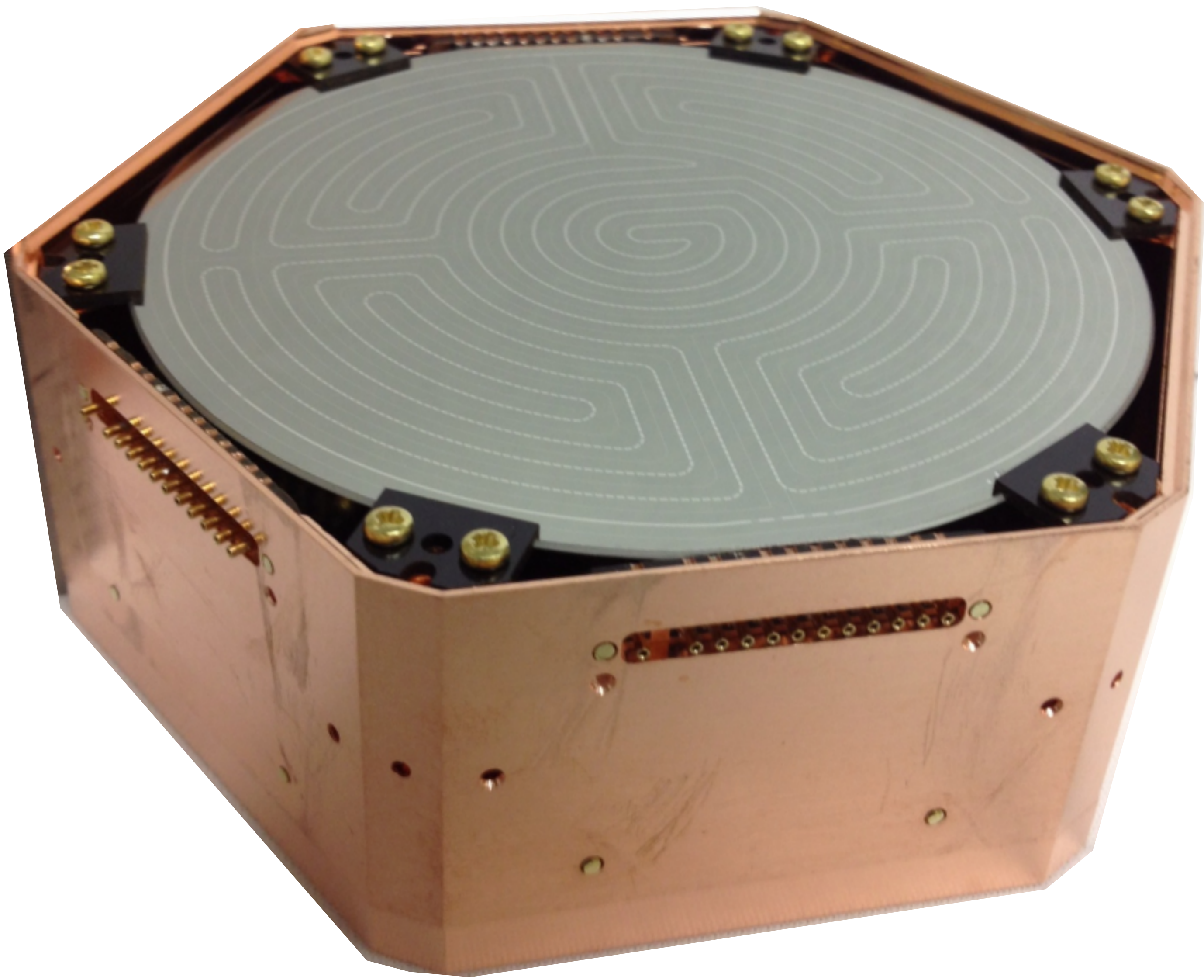




SuperCDMS SNOLAB @ the Ladder Lab

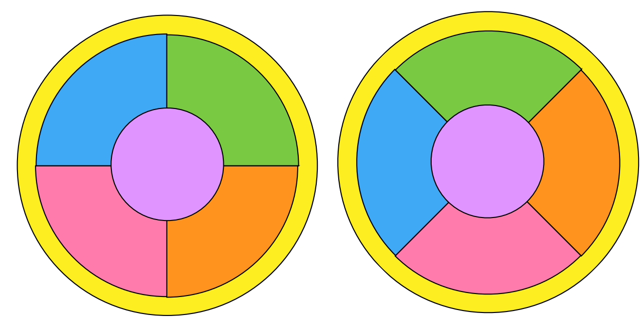


SuperCDMS Detectors: iZIPs

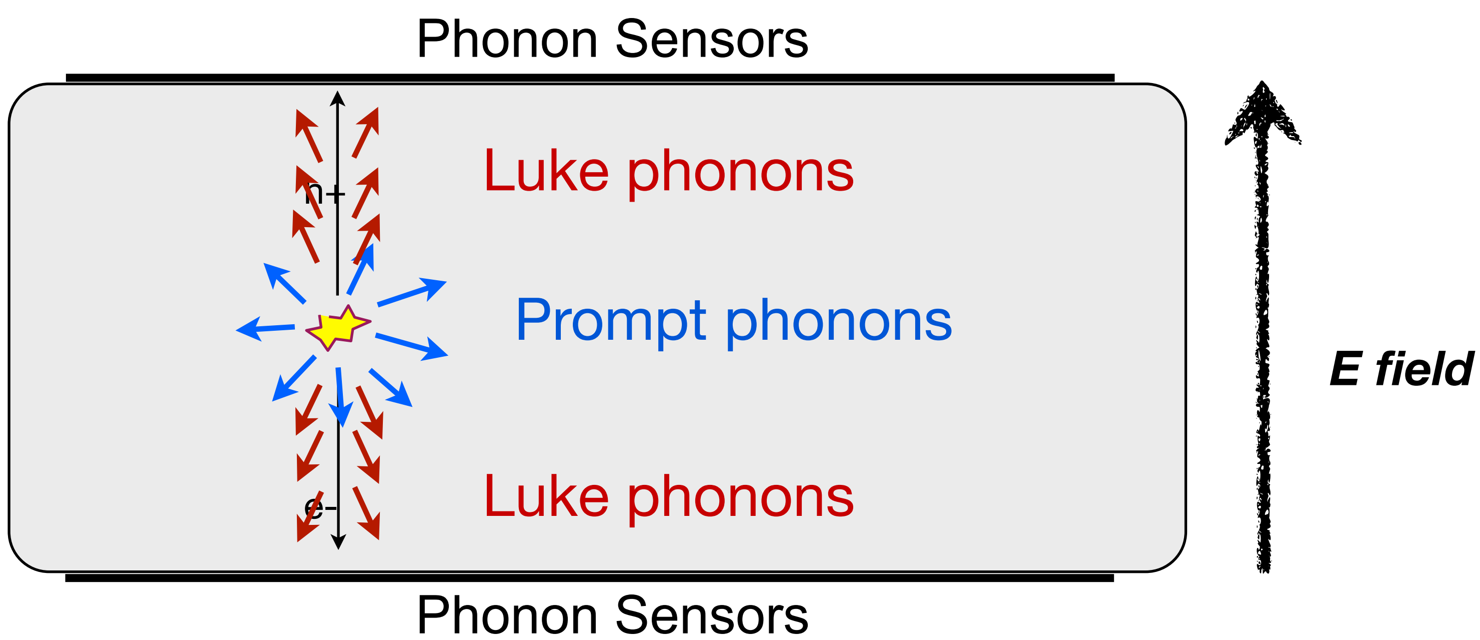


Ge (1.4 kg)
Si (0.6 kg)
4” Diameter
3.3 cm Thick

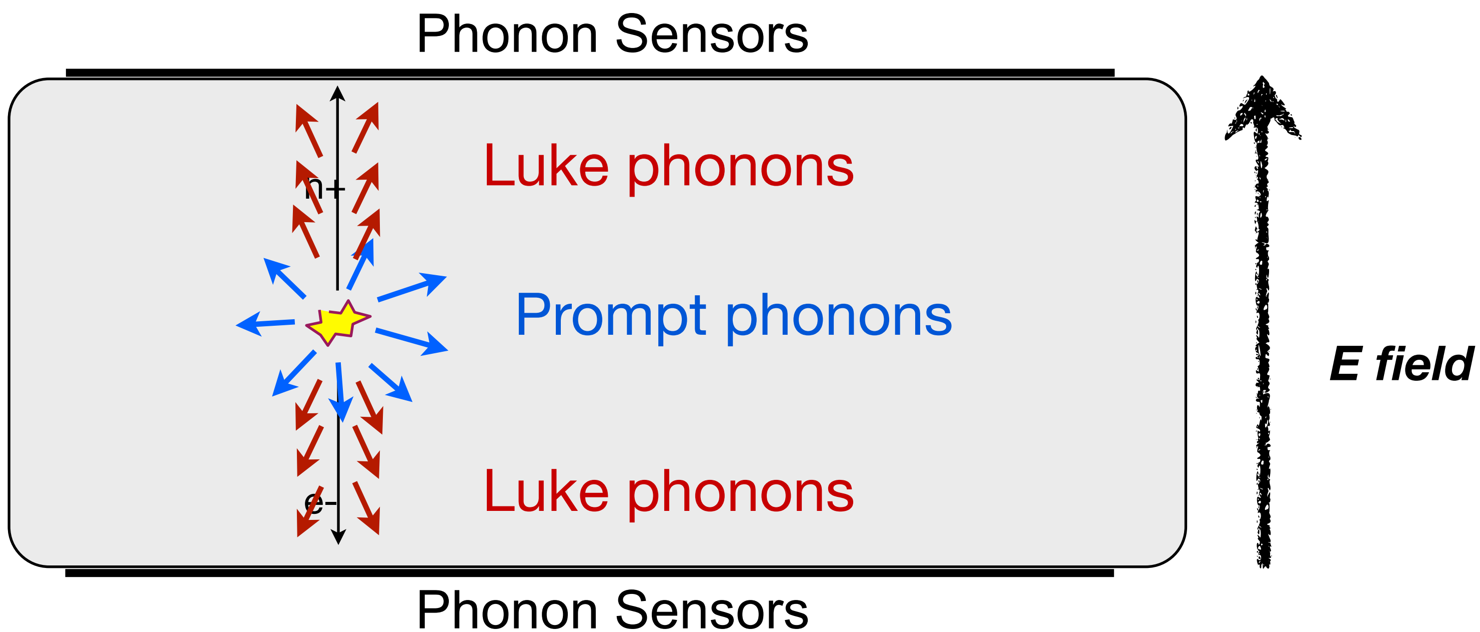
2 charge + 2 charge
6 phonon + 6 phonon



SuperCDMS High-Voltage Operation



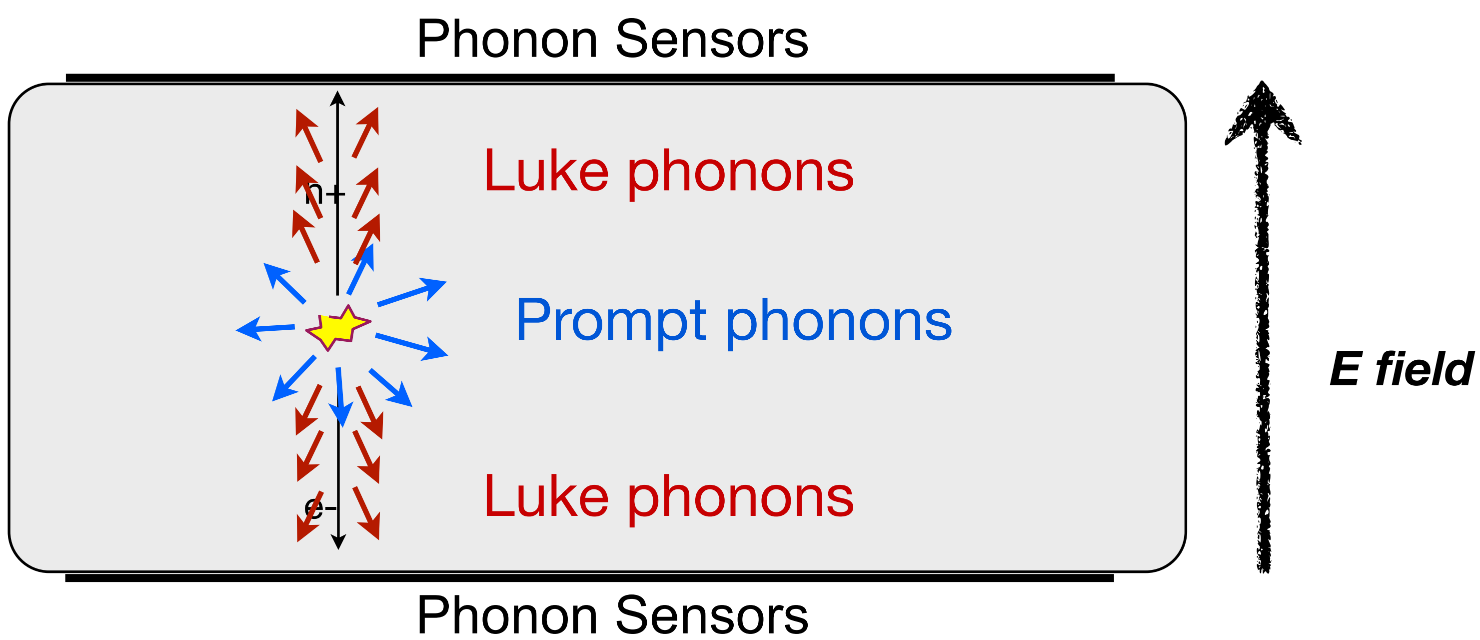
SuperCDMS High-Voltage Operation



$$\text{Phonon energy} = E_{recoil} + E_{Luke}$$
$$= E_{recoil} + n_{eh}\, e^{-}\, \Delta V$$

SuperCDMS High-Voltage Operation

Phonon sensors measure amount of charge produced:
Phonon-based charge amplification!



$$\text{Phonon energy} = E_{recoil} + E_{Luke}$$
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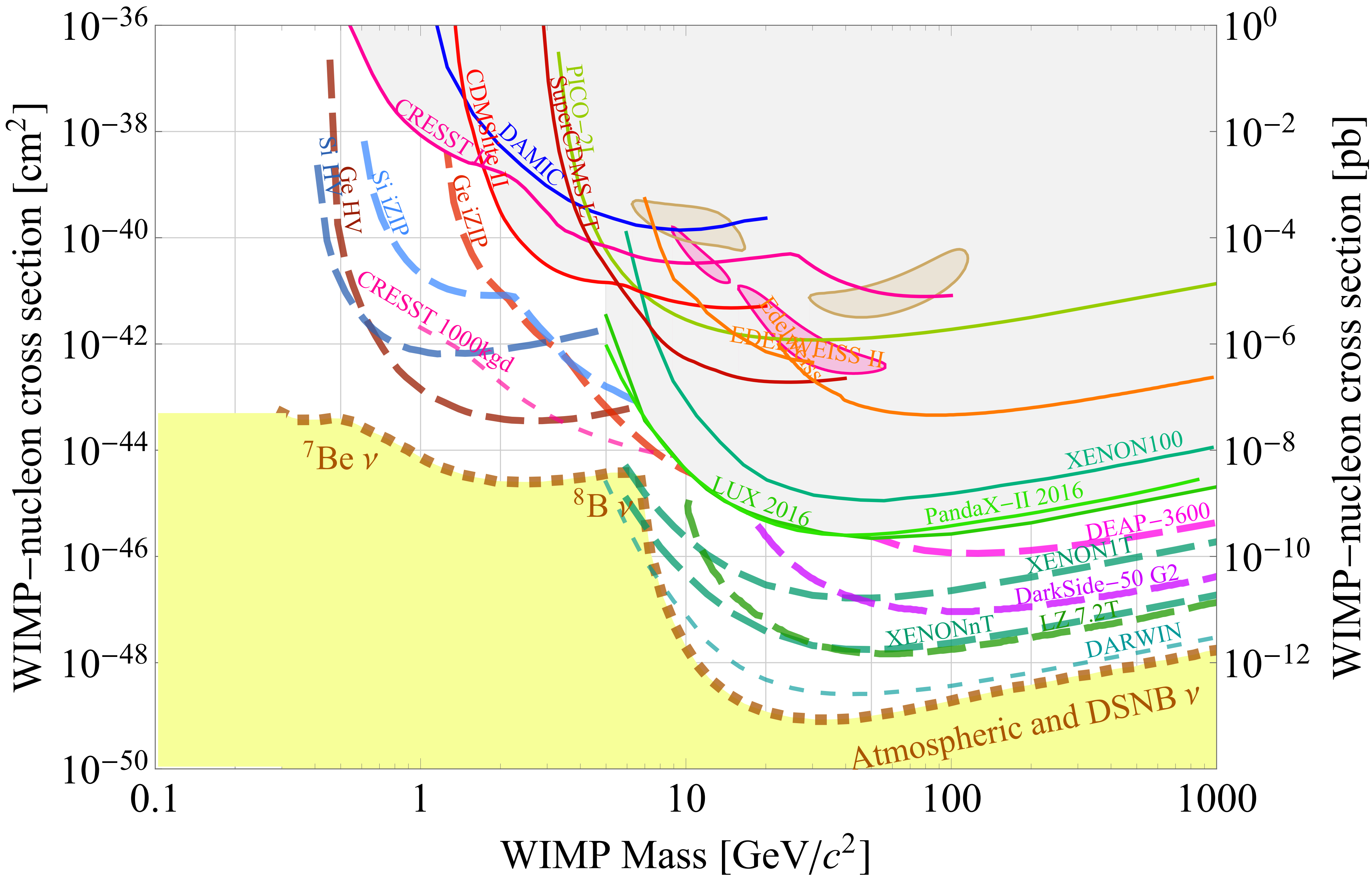
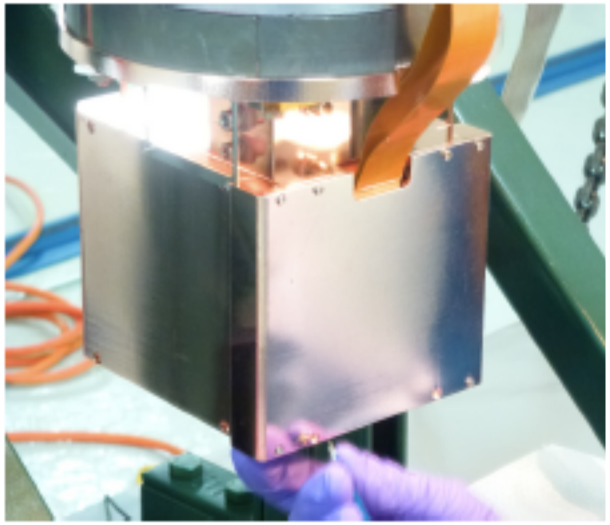
To Neutrinos, and Beyond!



Other Nuclear Detection Technologies

- Bubble Chamber Experiments
  - PICO
    - Best Spin-Dependent Sensitivity
    - (currently running at SNOLAB)
  - Xenon Bubble Chamber
- Silicon CCDs: DAMIC
- Directional Detection Experiments
  - DRIFT, DMTPC, NEWAGE, MIMAC
- New Ideas
  - DNA and/or organic detectors?
  - Molecular dissociation / inelastic collisions?



Other Nuclear Detection Technologies

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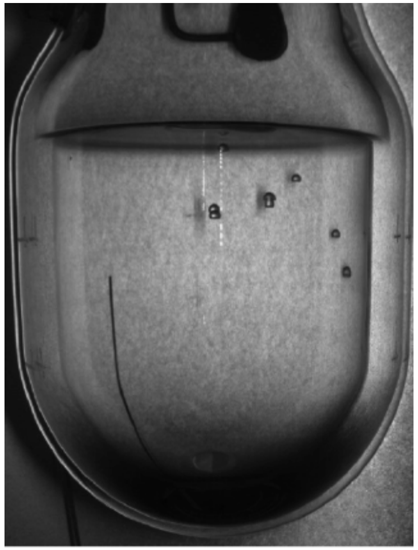
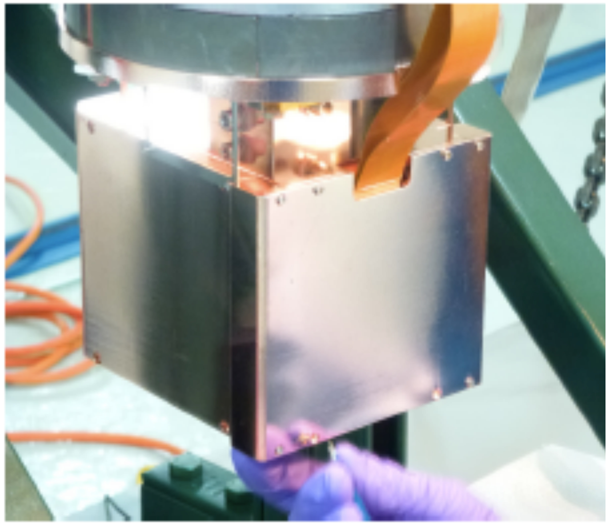
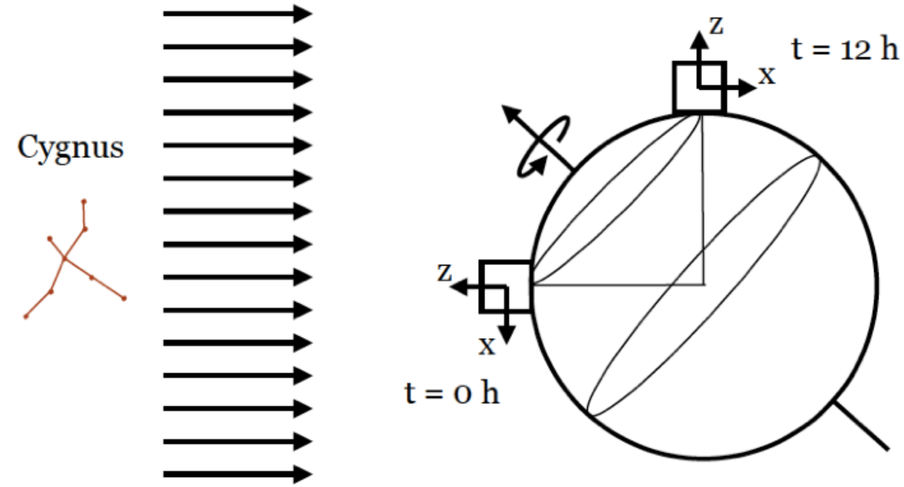
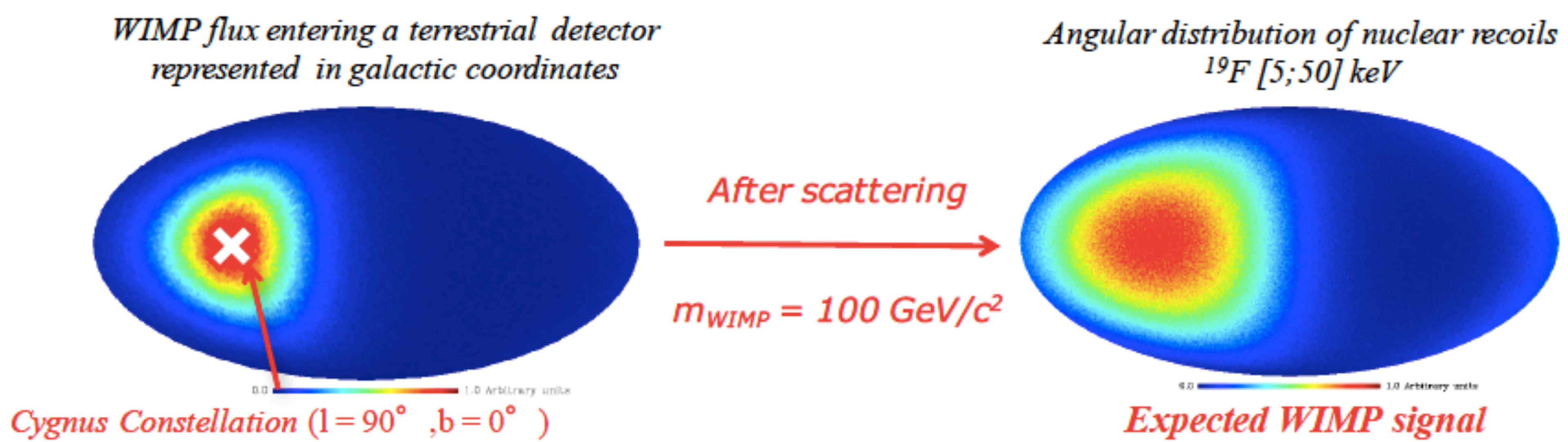




Directional Detection

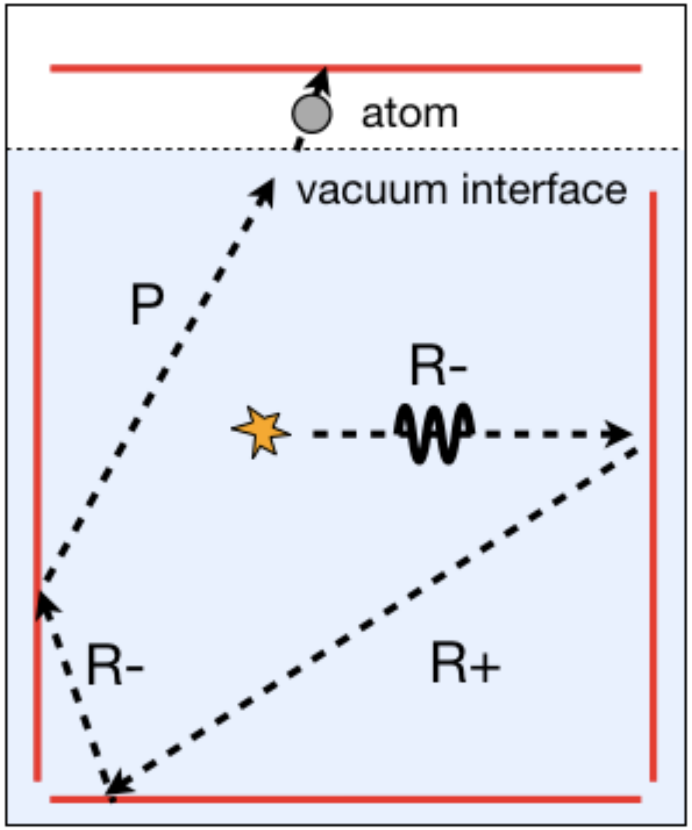
- Thanks to the rotation of the Solar System around the galactic center, we expect a « wind of WIMPs » coming from constellation Cygnus at l=90 and b=0
- The expected WIMP signal has a strong dipole feature which cannot be mimicked by any backgrounds
- Unambiguous dark matter signature !

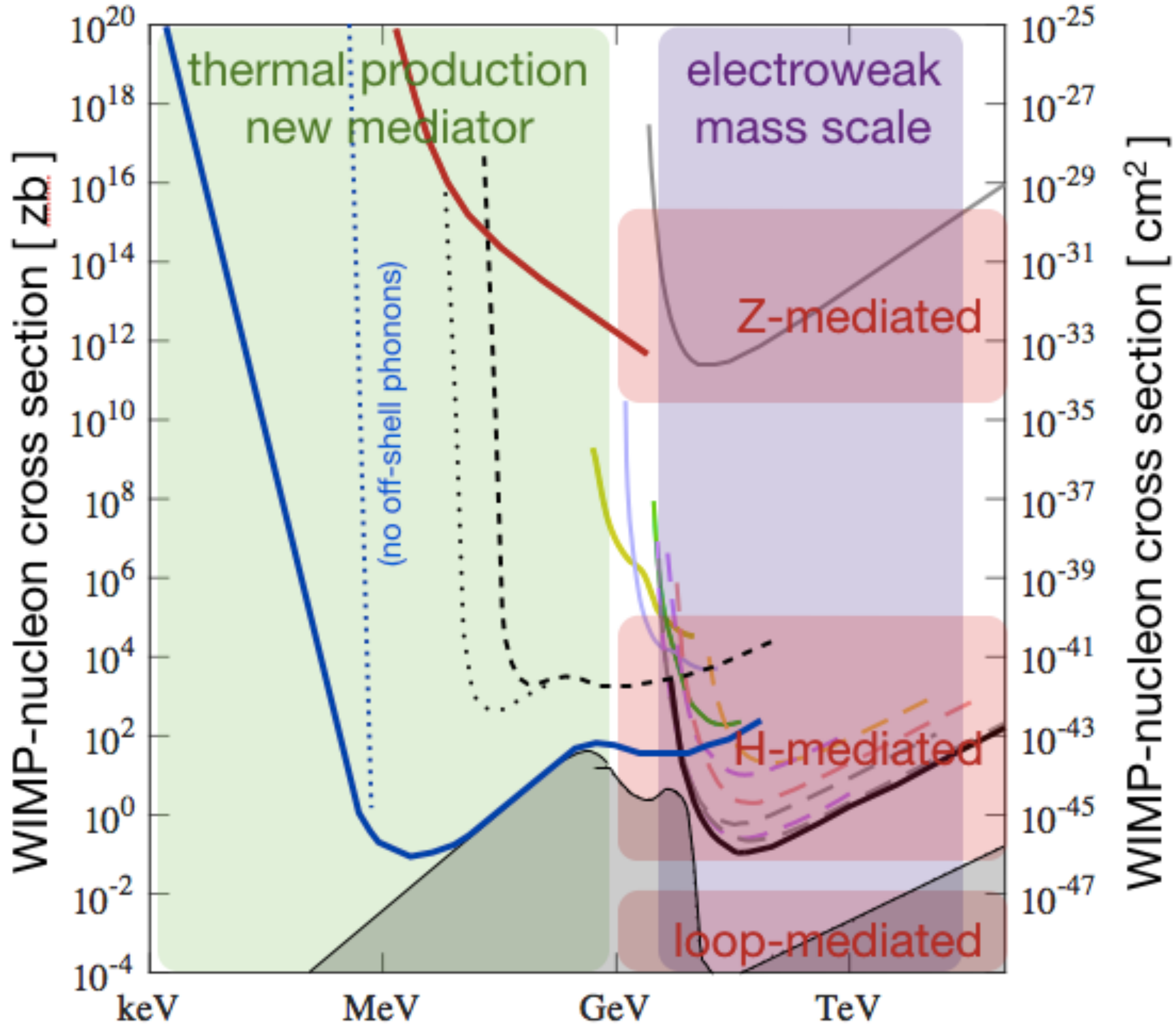




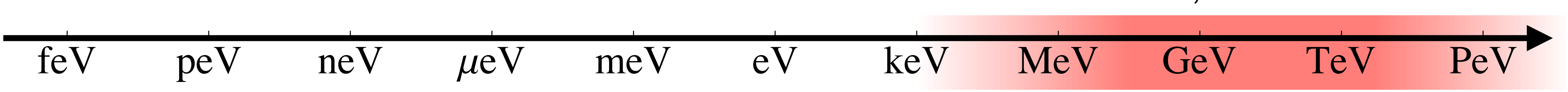
Directional Detection

Liquid Helium Detectors: Nuclear Recoils for MeV DM!

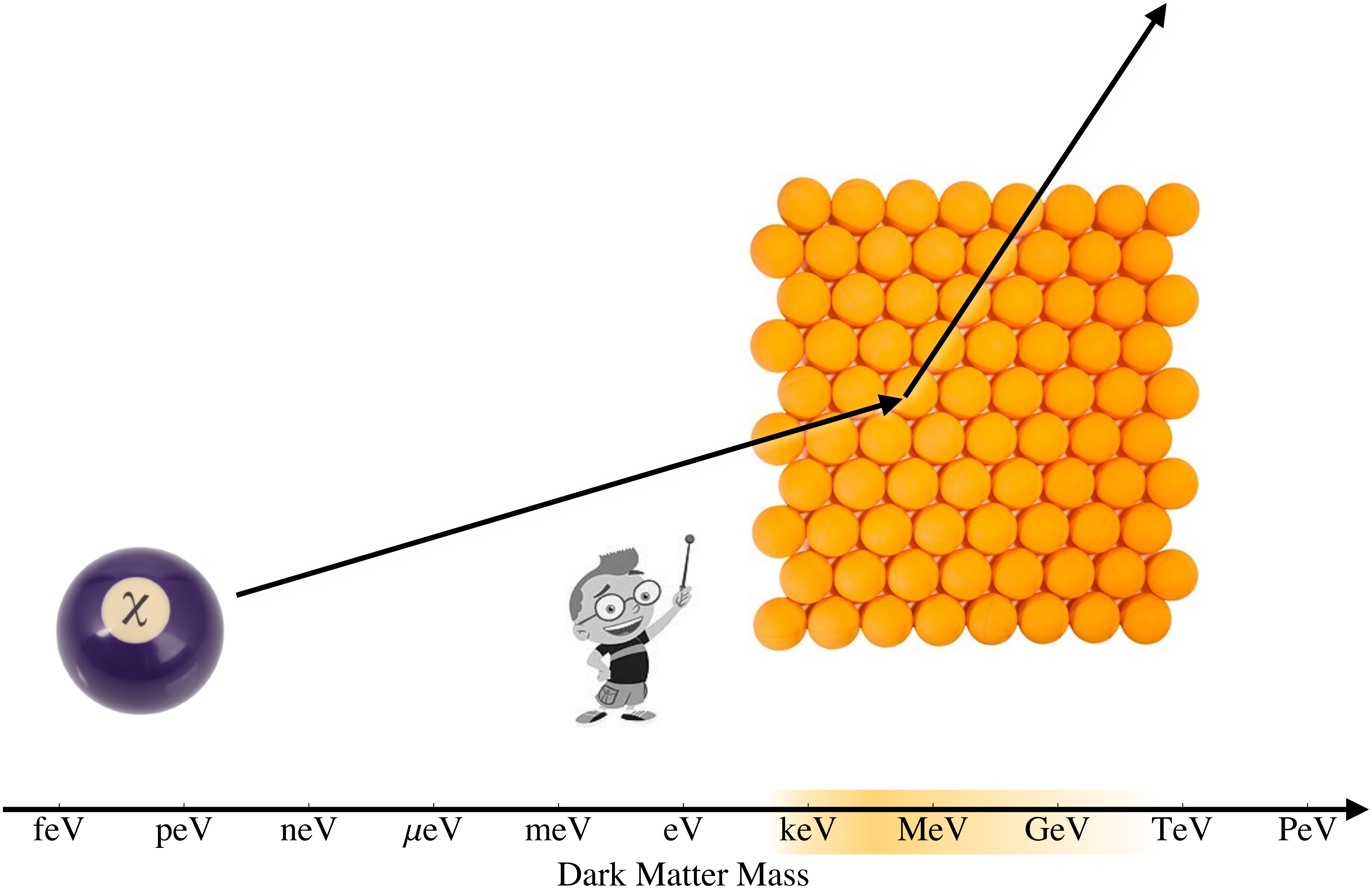




Slide from Scott Hertel, U. Massachusetts



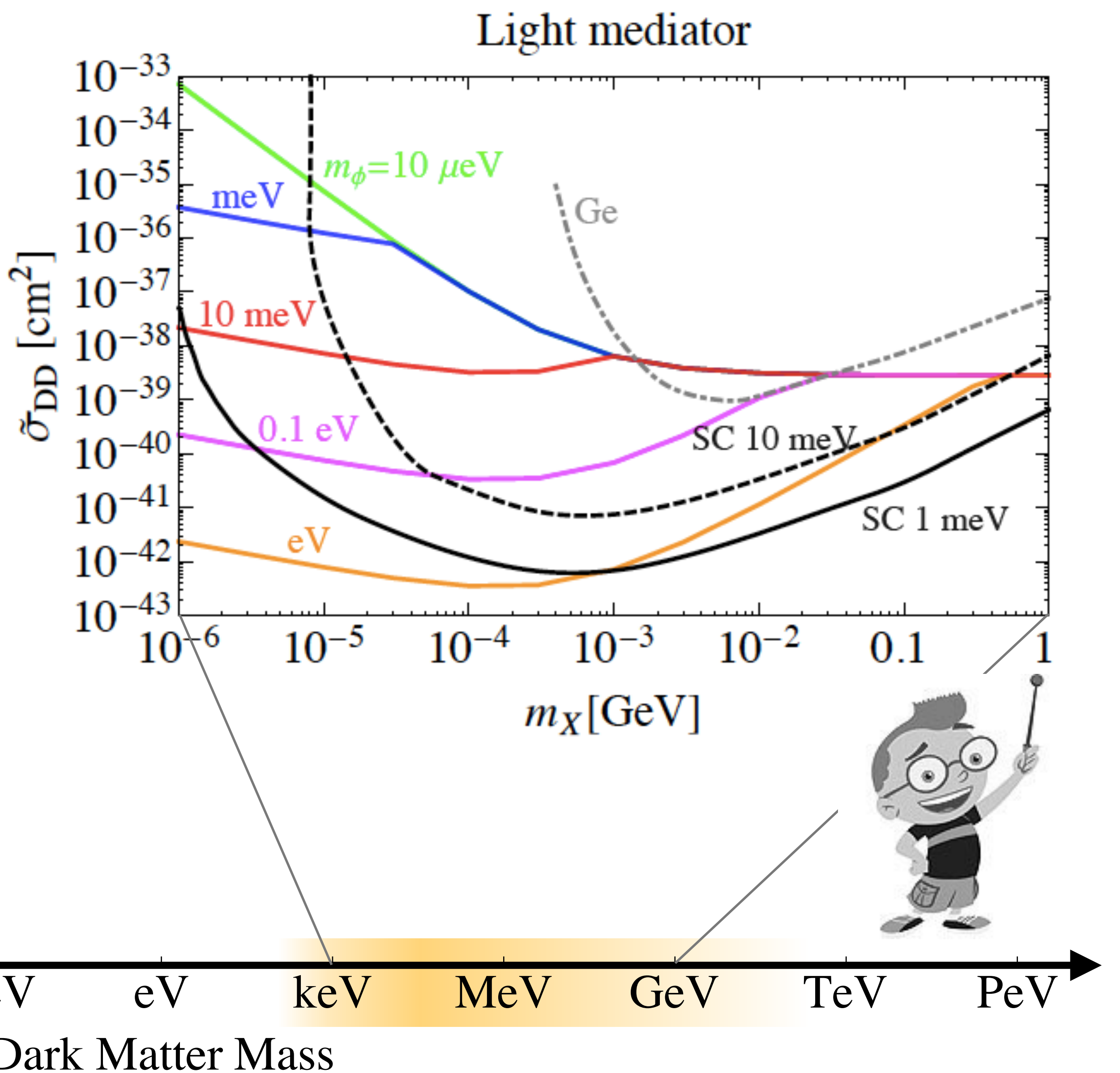
Electron Recoils



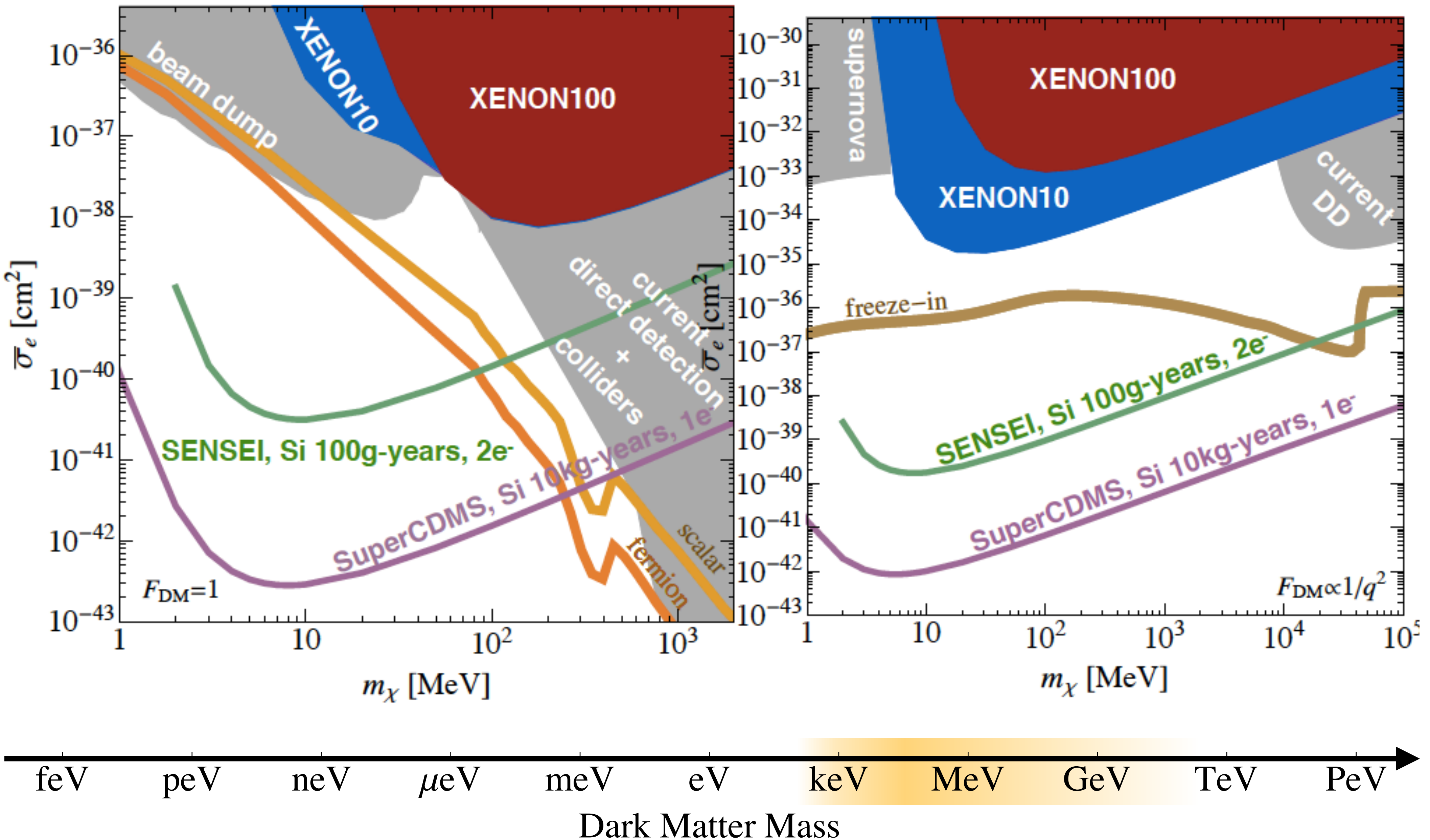
How do we look for DM with electron recoils?

- Pretty much all experiments that look for nuclear recoils also see electron recoils!
- Single electron sensitivity expected in both liquid noble and crystal experiments.
- The main issues are threshold, fiducialization, and lowering backgrounds.
- Using materials with a band gap or even quasiparticles in superconductors can drastically reduce the threshold!

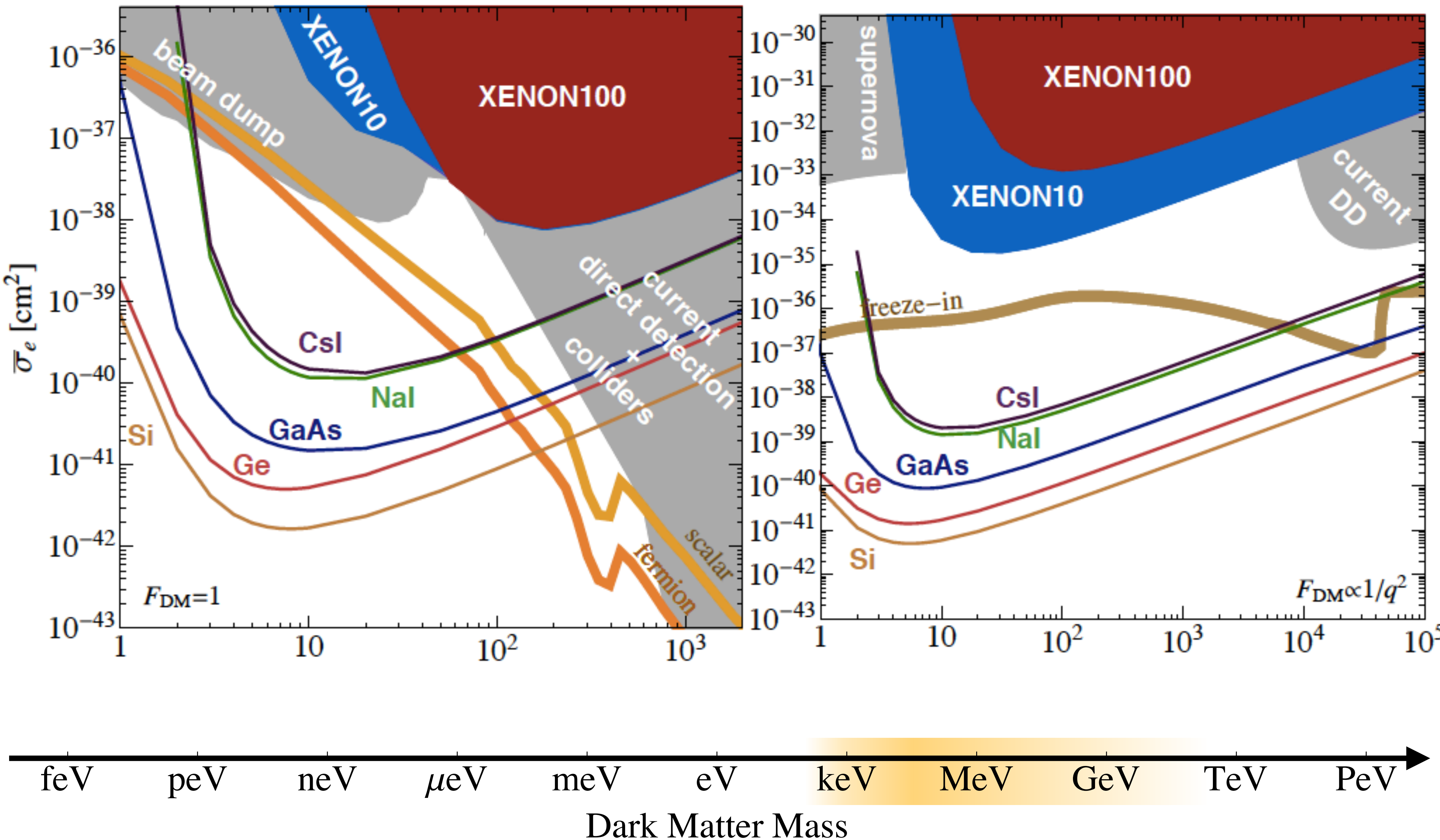
Hochberg et al. 1504.07237
see also Essig et al. 1108.5383



Electron Recoils with Silicon Detectors

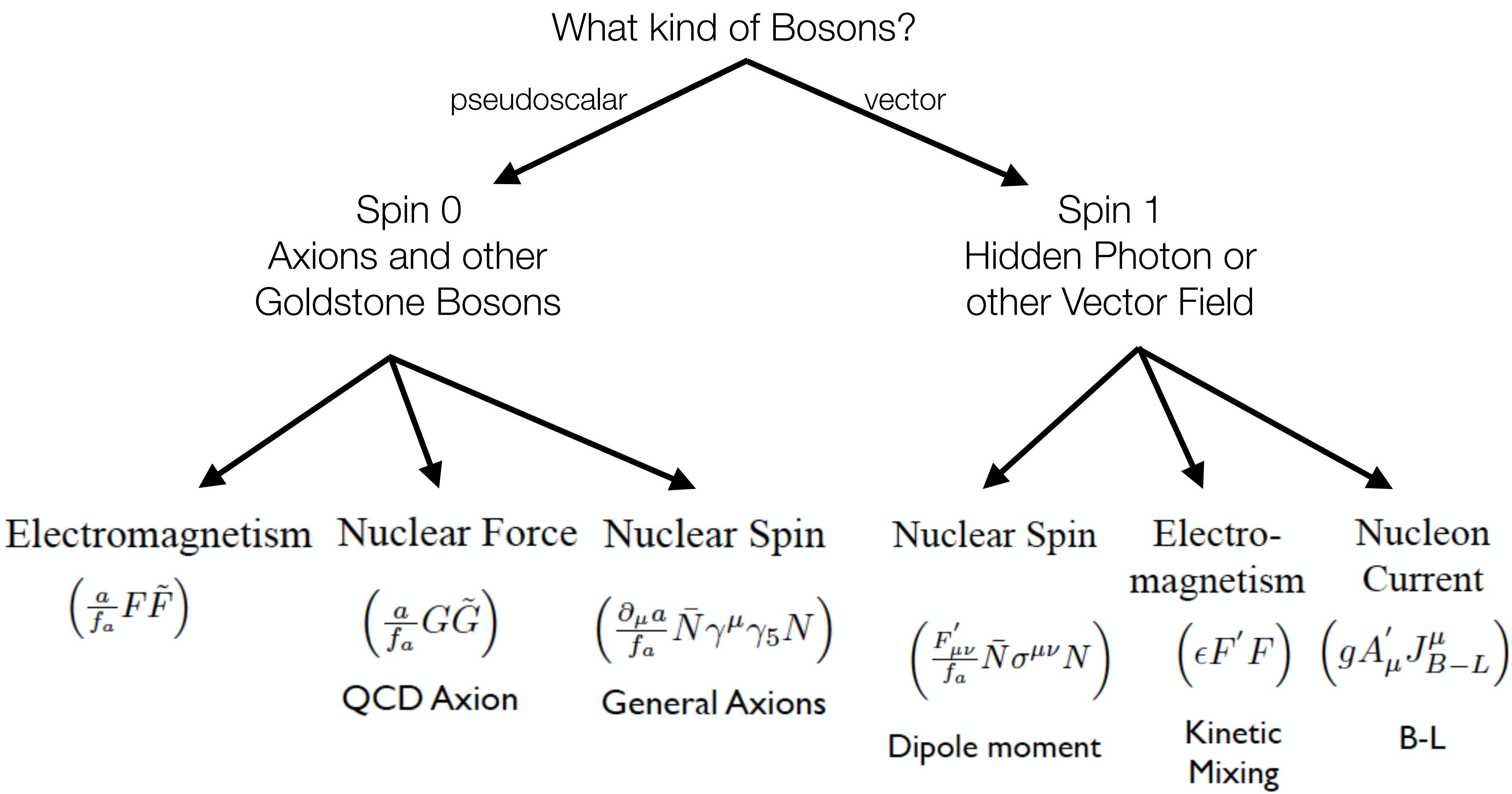


Electron Recoils with Scintillators

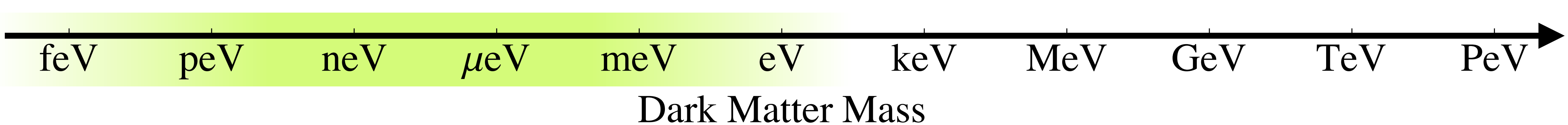


Coherent / Resonant Detection

Bosonic Dark Matter



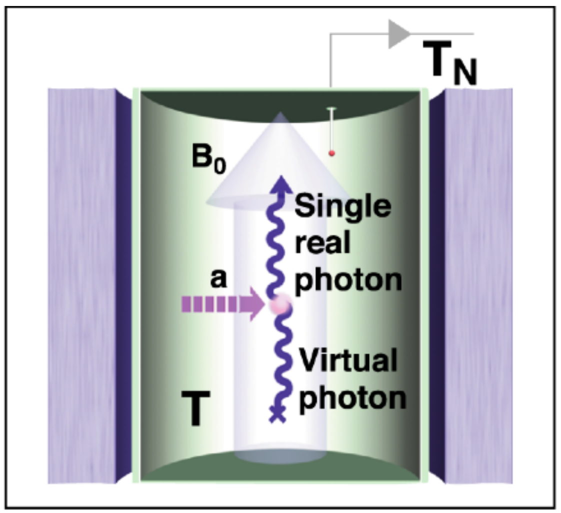
Slide From Surjeet Rajendran

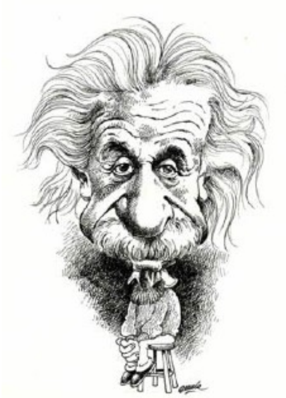


The Axion Dark Matter eXperiment (original concept from P. Sikivie)

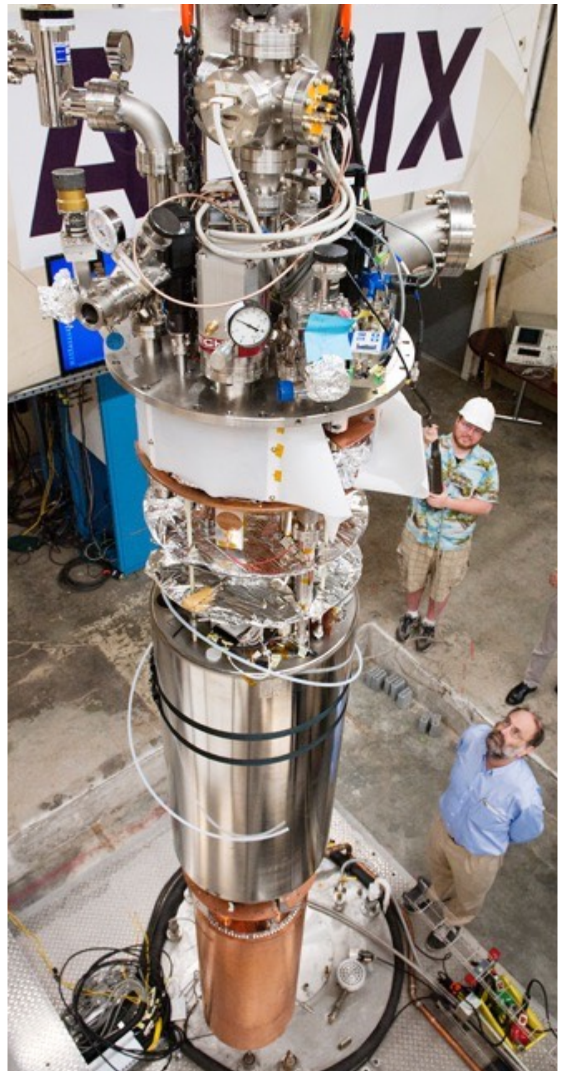
G2 Funded Experiment

Halo axions convert into microwave photons inside a RF cavity threaded by a strong magnetic field

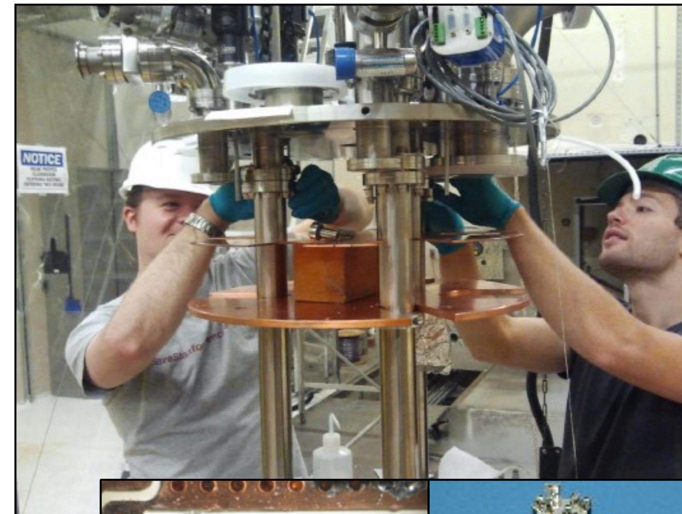


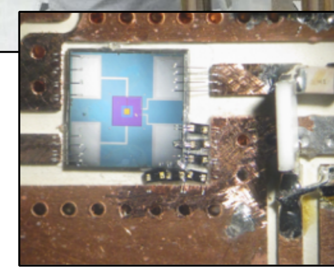


ADMX is sensitive to sub-yoctowatts of microwave power



New ADMX experiment insert fabricated and being assembled

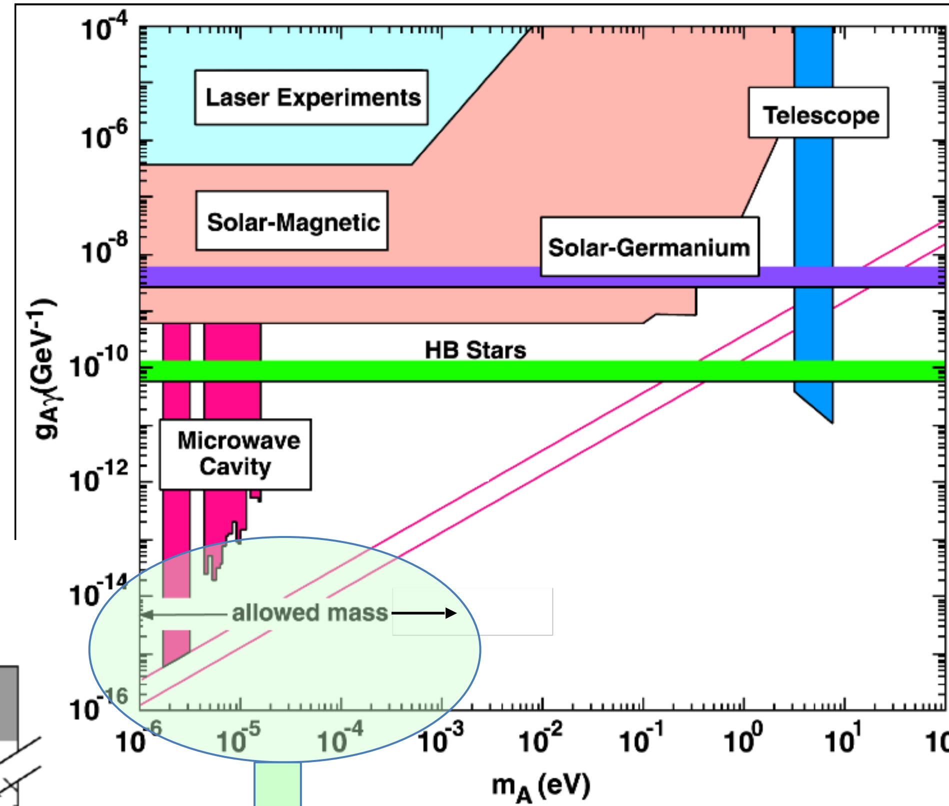




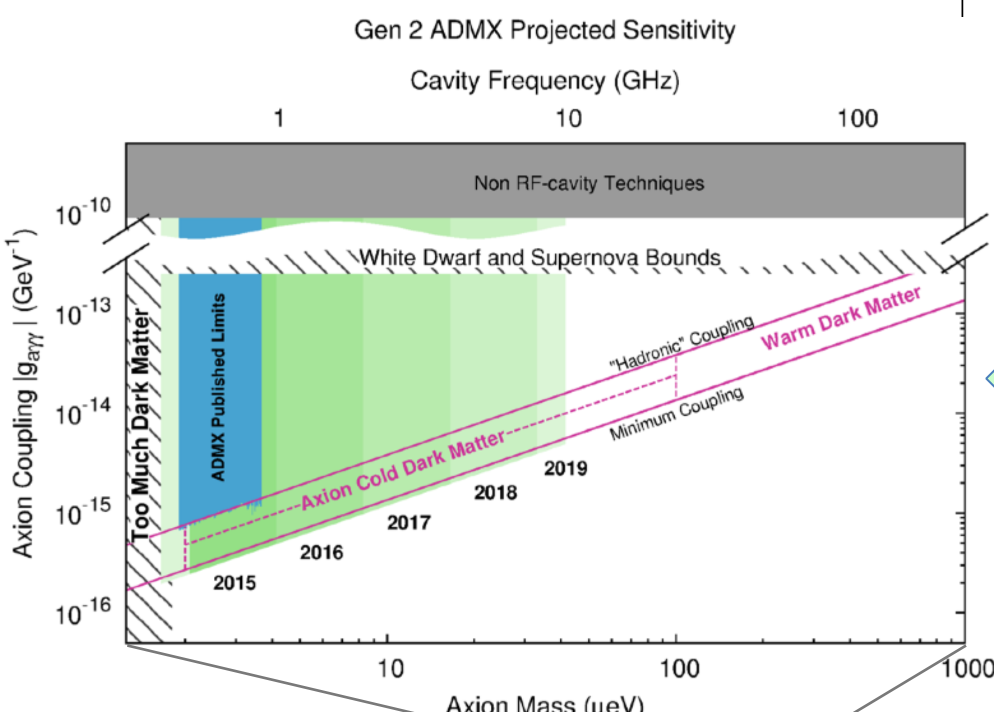
Dilution refrigerator and quantum-limited amplifiers provide sensitivity for the ADMX “Definitive Search”

G2 ADMS Search Capability

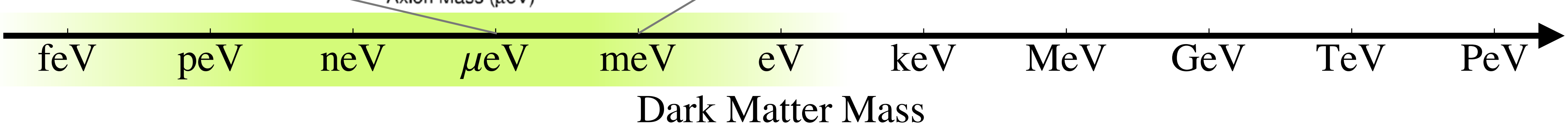
U. Washington, LLNL, U. Florida, U.C. Berkeley, National Radio Astronomy Observatory, Sheffield U., Yale U., U. of Colorado
(+ new collaborators soon)



The dilution refrigerator in ADMX significantly speeds the dark-matter search, so that …

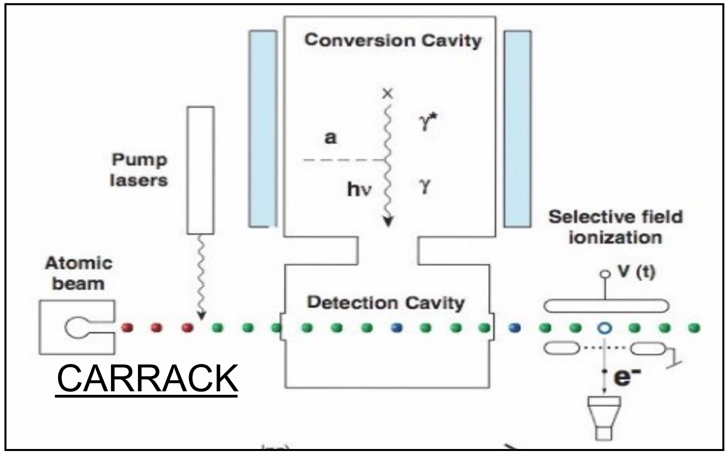


… ADMX has the sensitivity to either detect the dark-matter QCD axion or reject the hypothesis at high confidence. This is called the "Definitive Search".

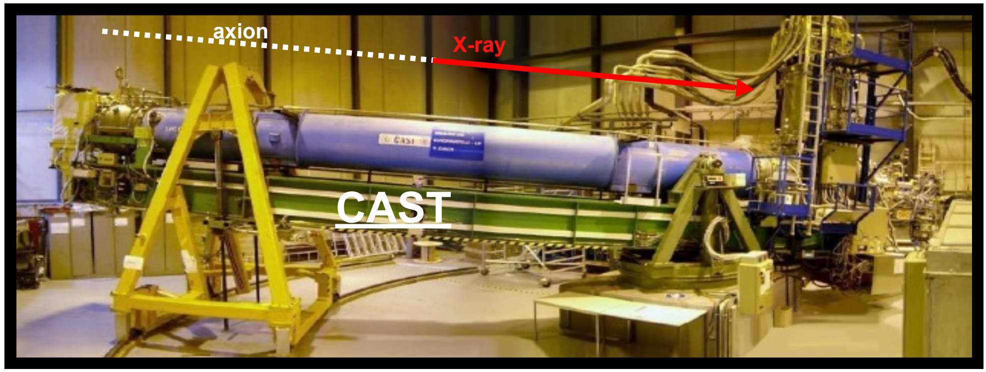


Variety of Experiments

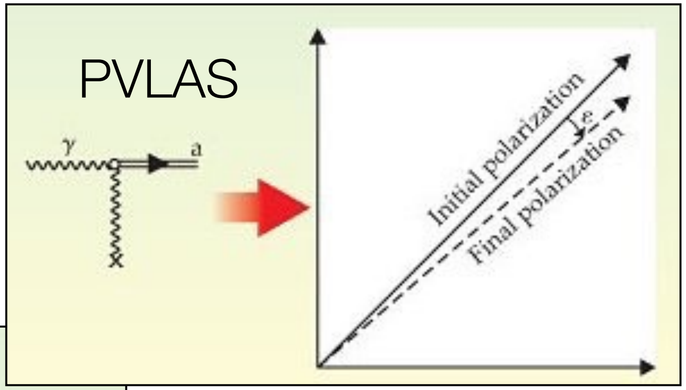
- Microwave Cavities
  - Low noise amplifiers (ADMX) and Rubidium Atoms (CARRACK)
  - Look for dark matter axions (low mass) converting to photons in B-Field

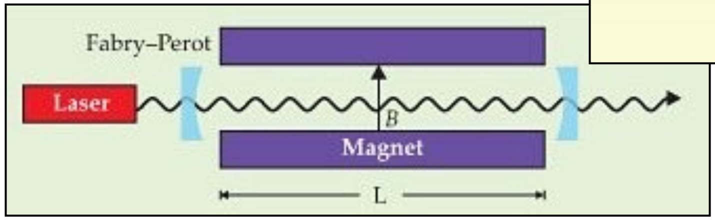


- Solar Observatories
  - X-Ray (CAST) and Germanium detectors
    - Look for axions generated from the sun
    - Higher coupling required than for DM axions.



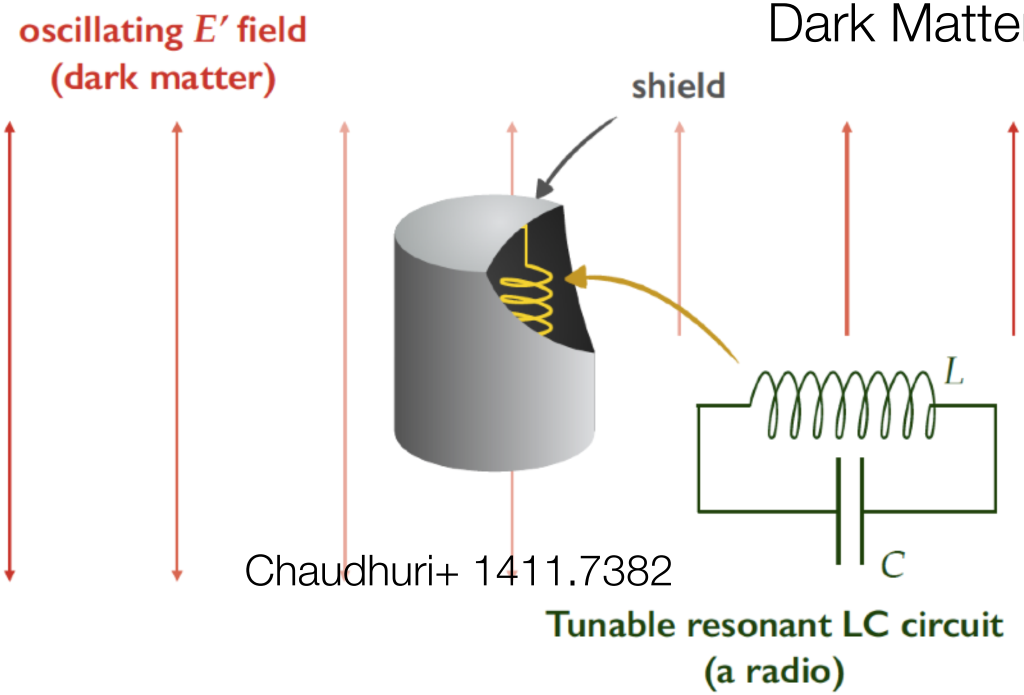
- Lab experiments
  - Photon regeneration and polarization changes (PVLAS)
    - Look for production of axions from light passing through B-field
    - Higher coupling required.
    - Ultralight axions (nano-eV)
  - ALPS II (light shining through wall)
  - (NMR / LC Circuit)



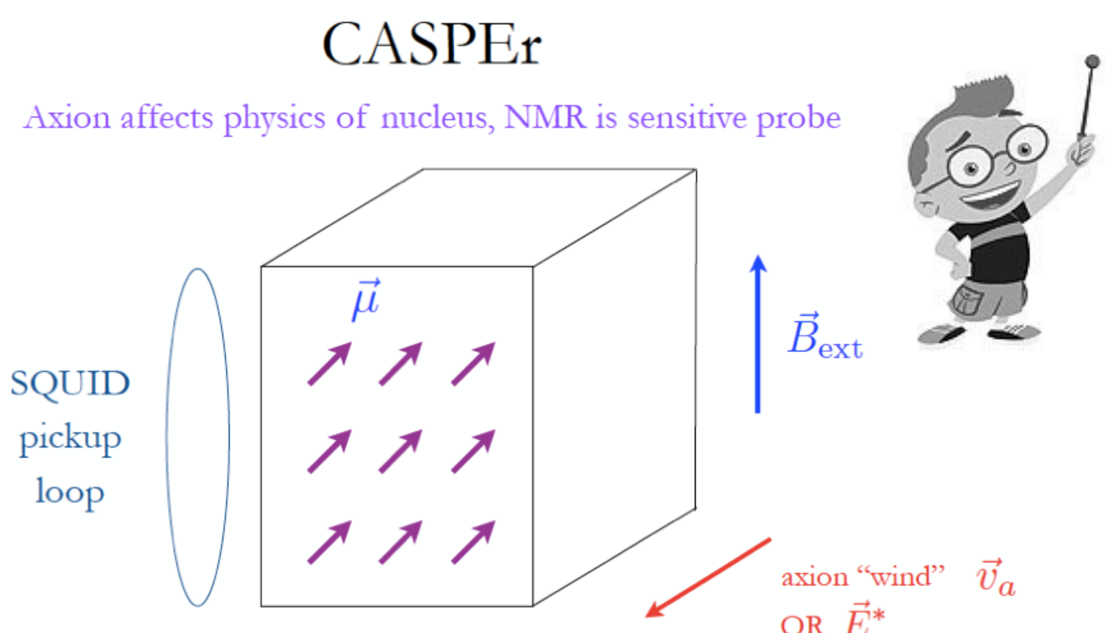


New Ideas to search for Hidden Photons

Dark Matter Radio Station

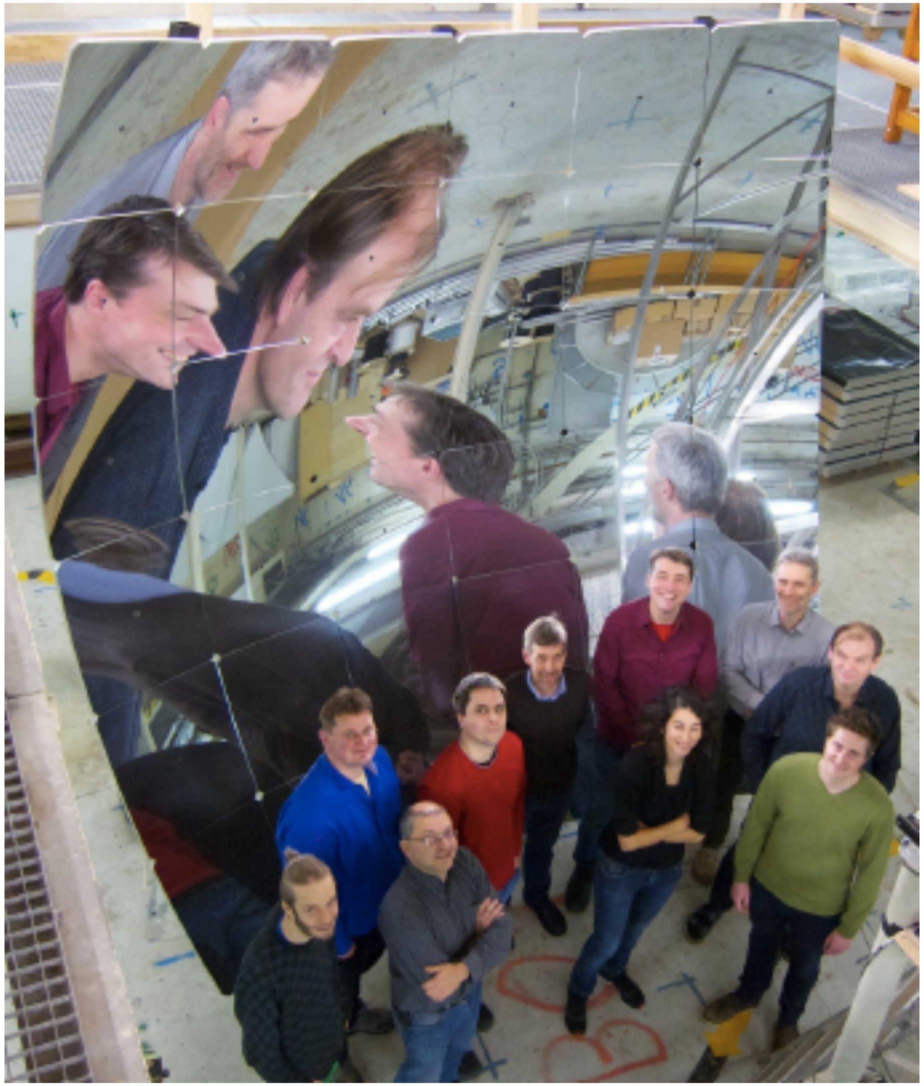


Chaudhuri+ 1411.7382

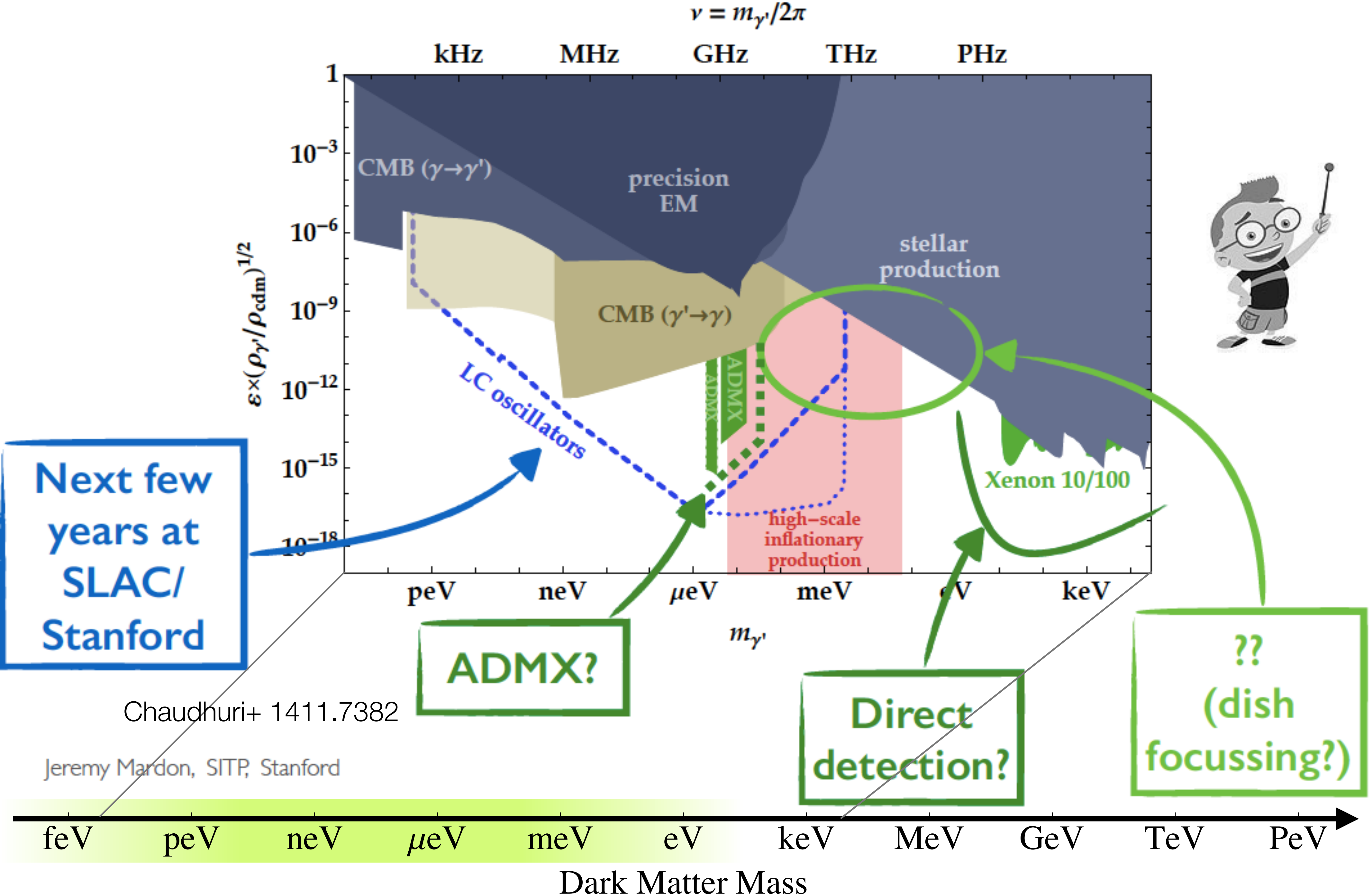


Budker+ 1306.6089

Search for Hidden Photons with a large Spherical Mirror



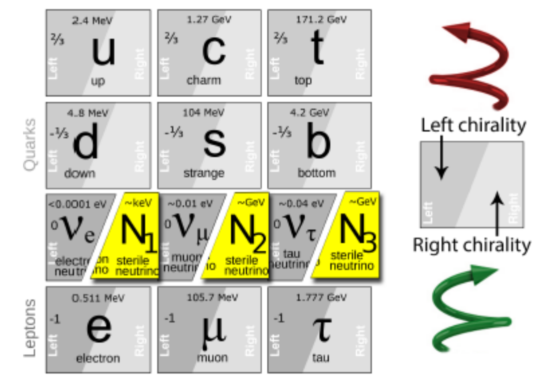
Hidden Photon Searches



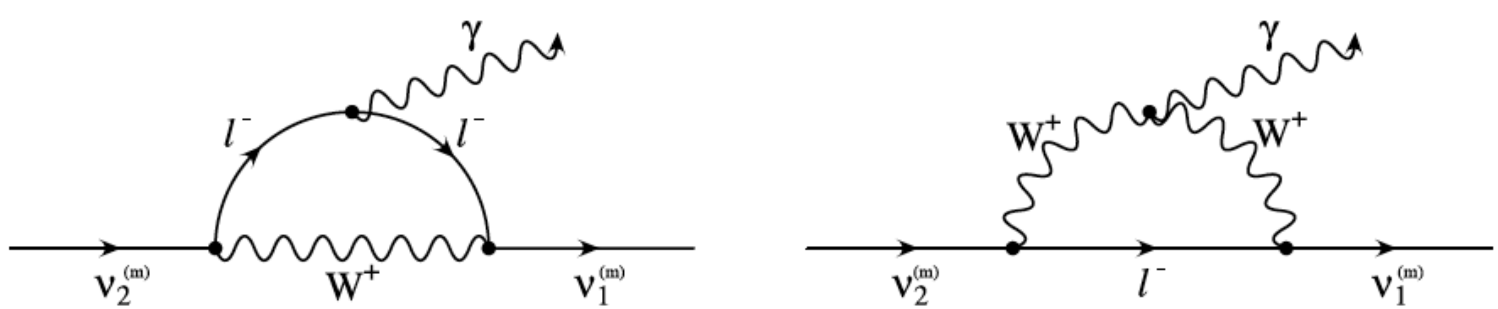
Indirect Detection of Sterile Neutrinos

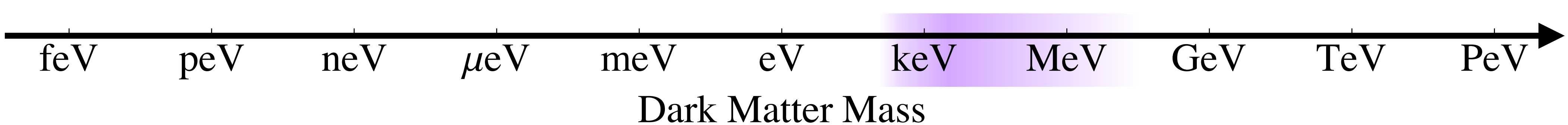
- Sterile neutrinos are a natural way of giving the known neutrino species mass. IF sterile neutrinos exist, and one of them has a mass between a few keV and 100 keV, it could constitute some or all of the dark matter.

- Sterile neutrinos may decay to a photon and active neutrino via loop-suppressed processes.



$$\Gamma = \frac{9\alpha G_F^2 m_s^5 \sin^2 2\theta}{1024\pi^4}$$
$$= (1.38 \times 10^{-29}\ \mathrm{s}^{-1}) \left(\frac{\sin^2 2\theta}{10^{-7}}\right) \left(\frac{m_s}{1\ \mathrm{keV}}\right)^5$$

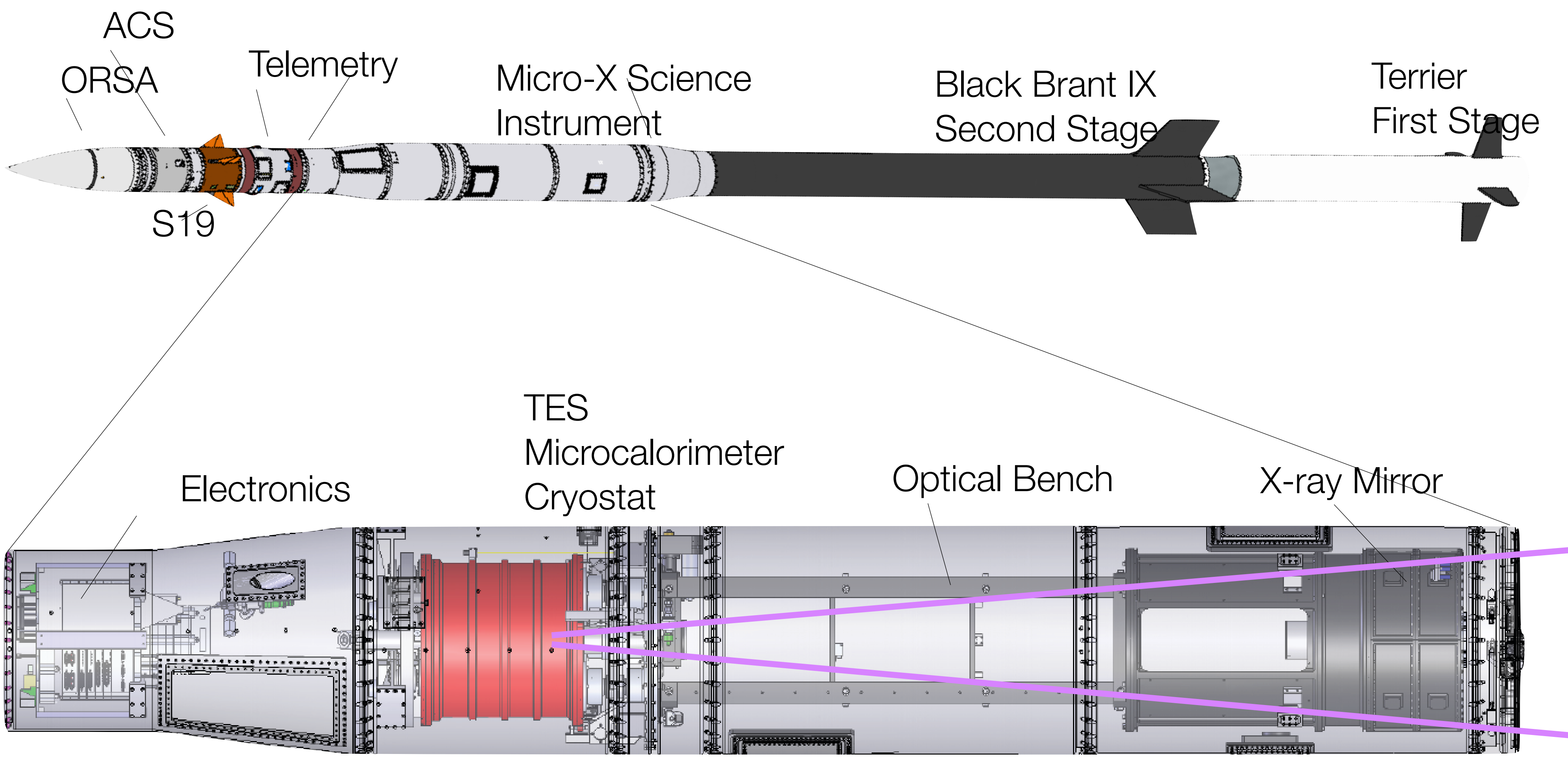




Sounding Rocket Payloads

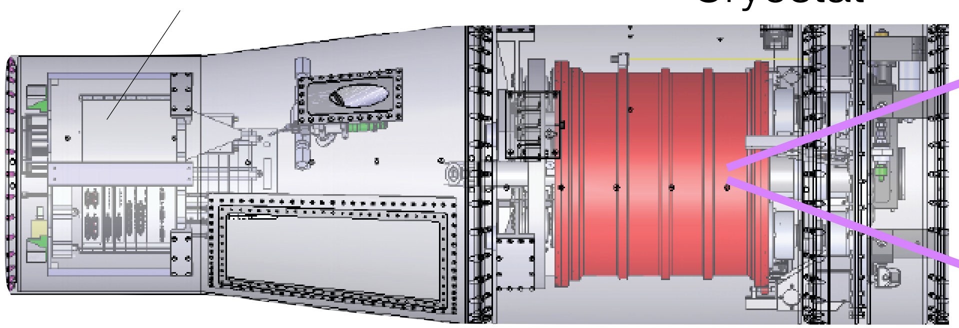
- 300 seconds of on-target data above 169 km
- High resolution X-ray microcalorimeter with ~1cm^2 area and large ~steradian FOV
- Flights from White Sands Missile Range in New Mexico and Woomera Range in Australia

The Micro-X Sounding Rocket



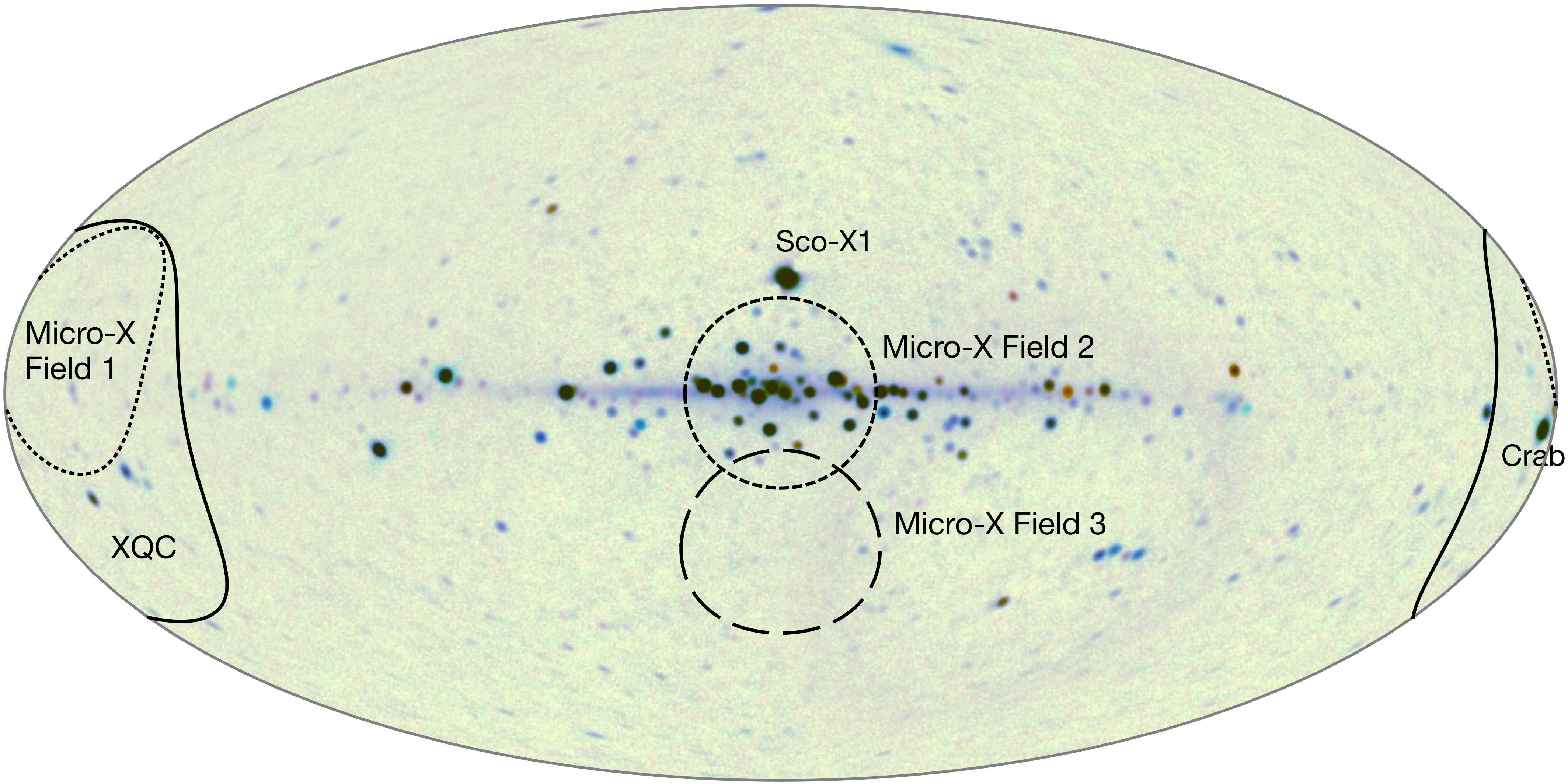
The Micro-X Sounding Rocket

- Payload under development. First flight less than a year away!
- TES Microcalorimeter array with 128 pixels, each with a 0.9mm x 0.9mm x (3μm Bi + 0.7μm Au) absorber
- Baseline energy resolution is 3-4 eV FWHM, flat out to 6-7 keV.
- 0.38 steradian FOV ~ 1200 arcmin radius, expect to increase to 1 sr in the future.

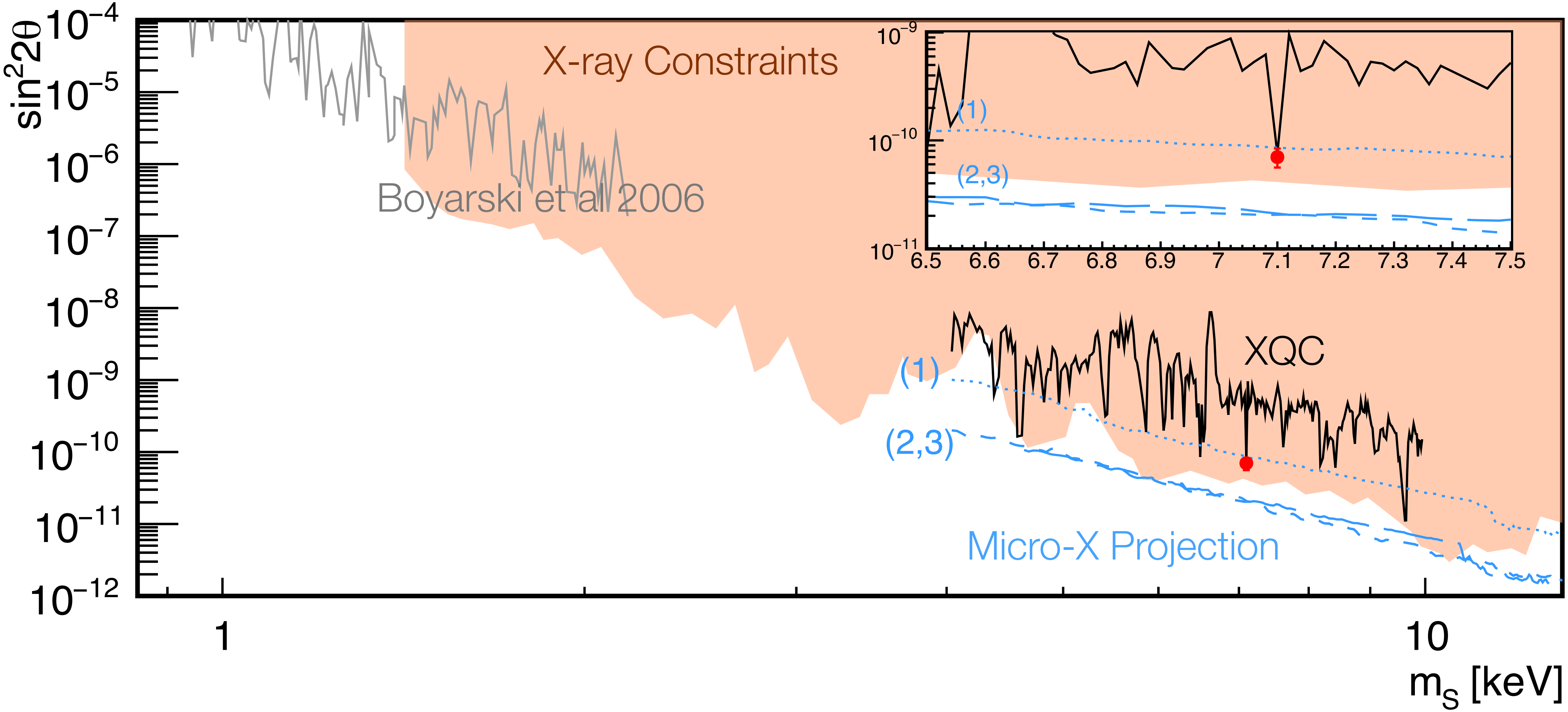


- For sterile neutrino searches, we will fly the payload without the mirror to obtain a large FOV and thus greater grasp:
  - With mirror, grasp = 38 cm^2 deg^2
  - Without mirror, grasp = 1256 cm^2 deg^2

FOV for Micro-X GC Observation

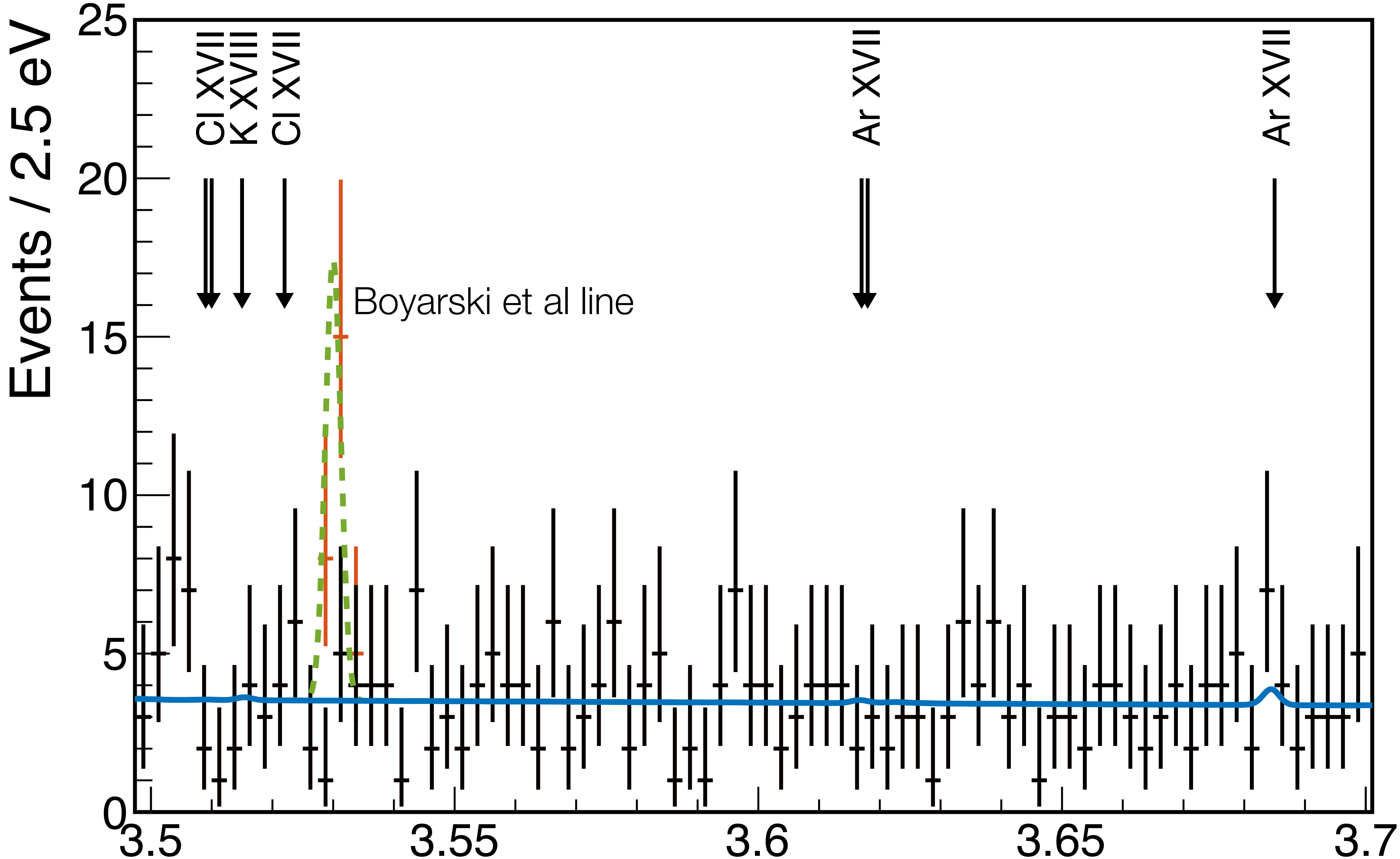


Sterile Neutrino Bounds



E.F.F. et al, ApJ 814:82, 2015
arXiv:1506.05519

Mock Micro-X GC Observation



E.F.F. et al, ApJ 814:82, 2015
arXiv:1506.05519

Conclusions

- The next ten years will be very exciting for dark matter direct detection. Various G2 Experiments will come online, covering a lot of new parameter space.
- Although WIMPs remain a very interesting dark matter candidate, other scenarios are gaining traction in the theoretical community, while new ideas for direct searches have been proposed and are gaining momentum.
- Sterile Neutrino indirect searches with the Micro-X Payload will obtain world-leading sensitivity and be a definitive test of the 3.5 keV line.
- Both Old and New approaches are important!