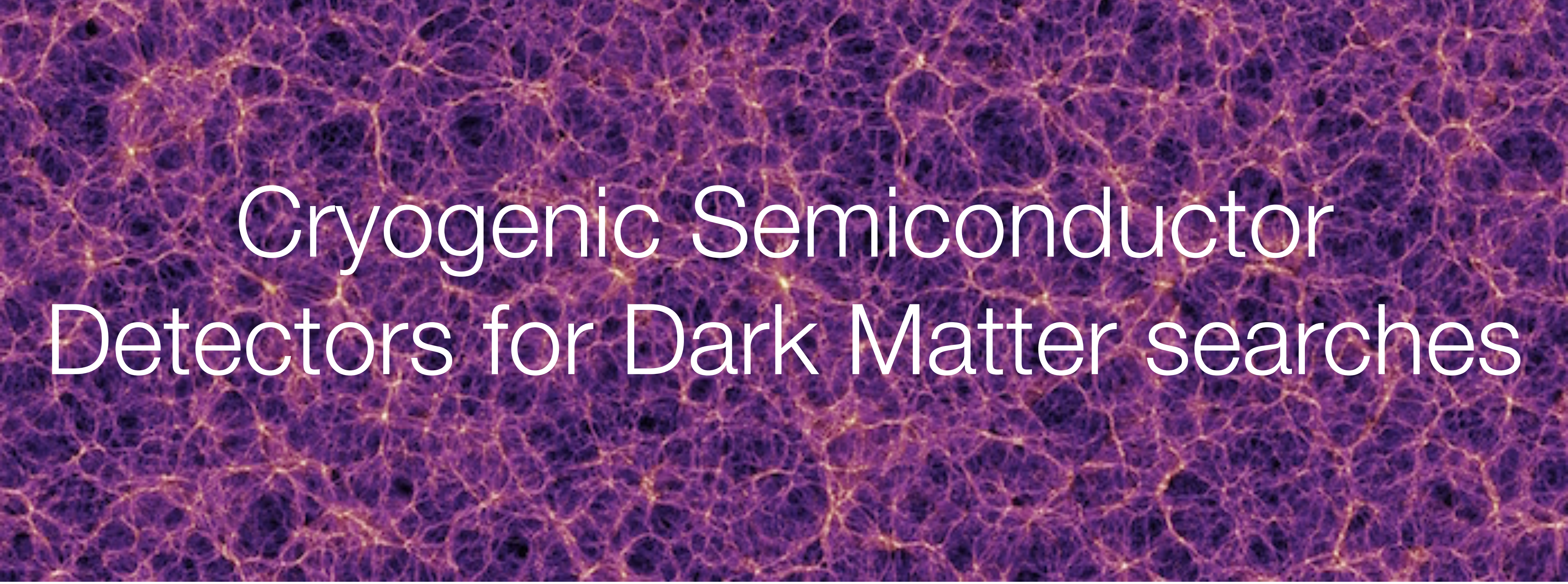
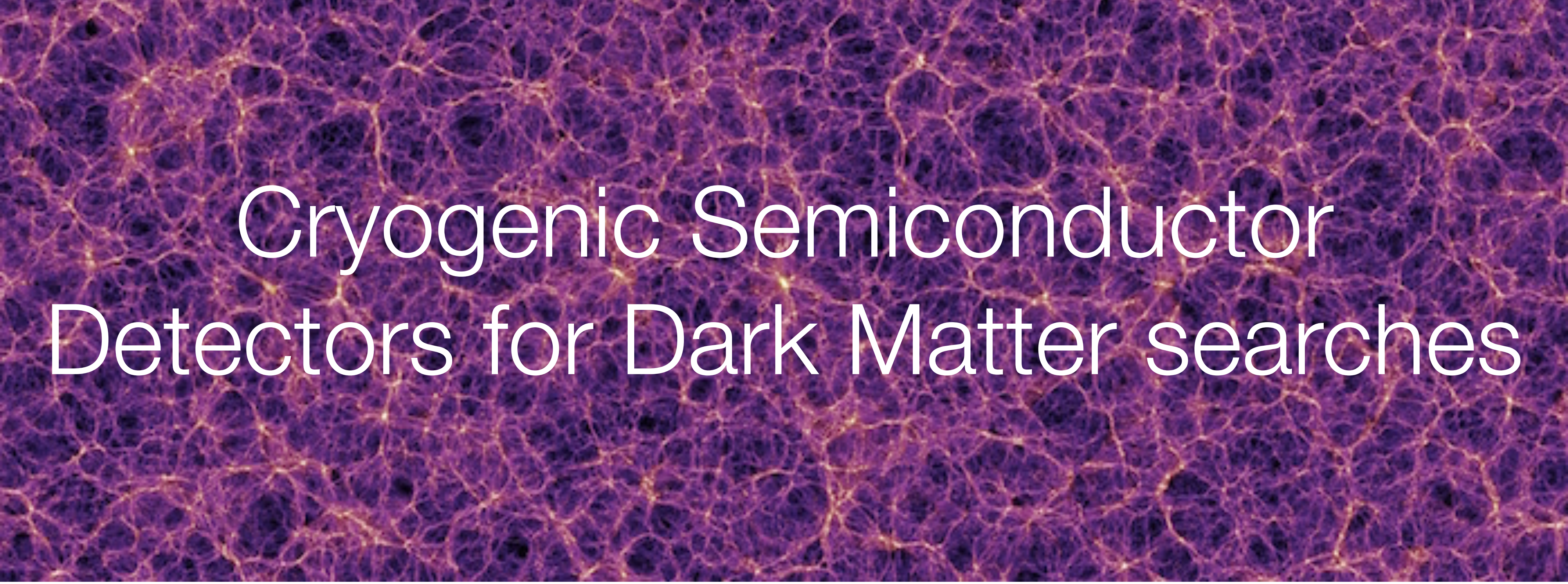


Cryogenic Semiconductor Detectors for Dark Matter searches

Enectalí Figueroa-Feliciano

Northwestern



Cryogenic Semiconductor Detectors for Dark Matter searches

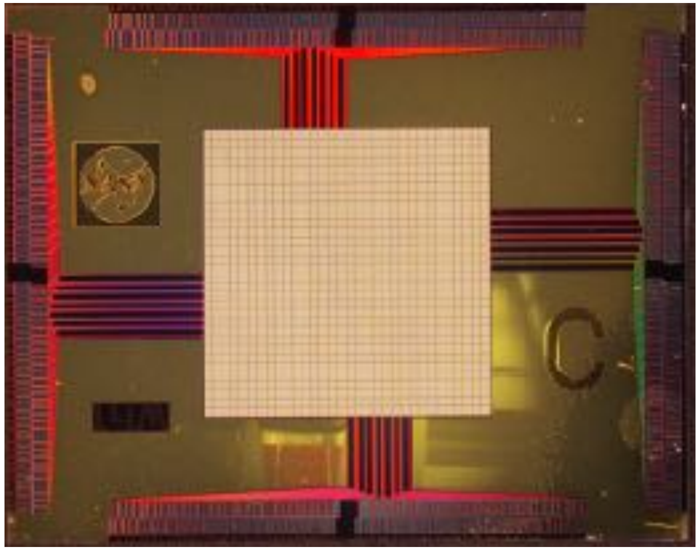
Enectalí Figueroa-Feliciano
Northwestern

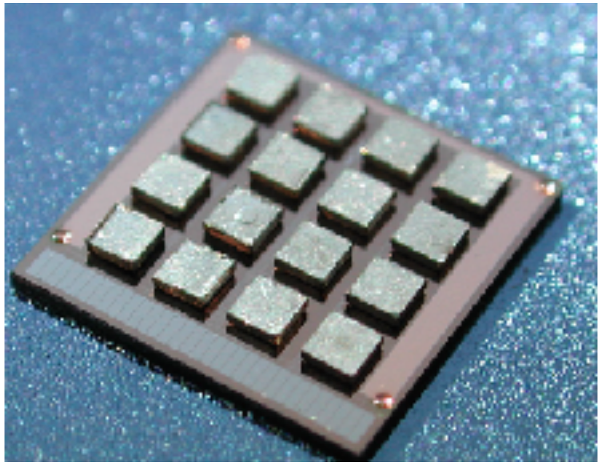
Outline

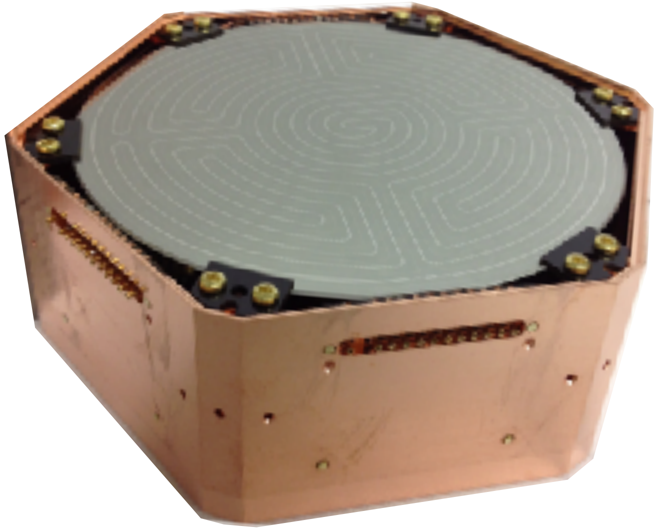
- Cryogenic Crystal Detector Basics
- Applications
    - Dark Matter: Direct Detection
    - Dark Matter: Indirect Detection
    - Neutrino Physics

Cryogenic Crystal Detectors are used in…

- Astrophysics
  - mm to gamma-ray energies
- Particle Physics
  - Dark Matter Detectors
  - Neutrino Physics
- Materials-analysis
- Others!

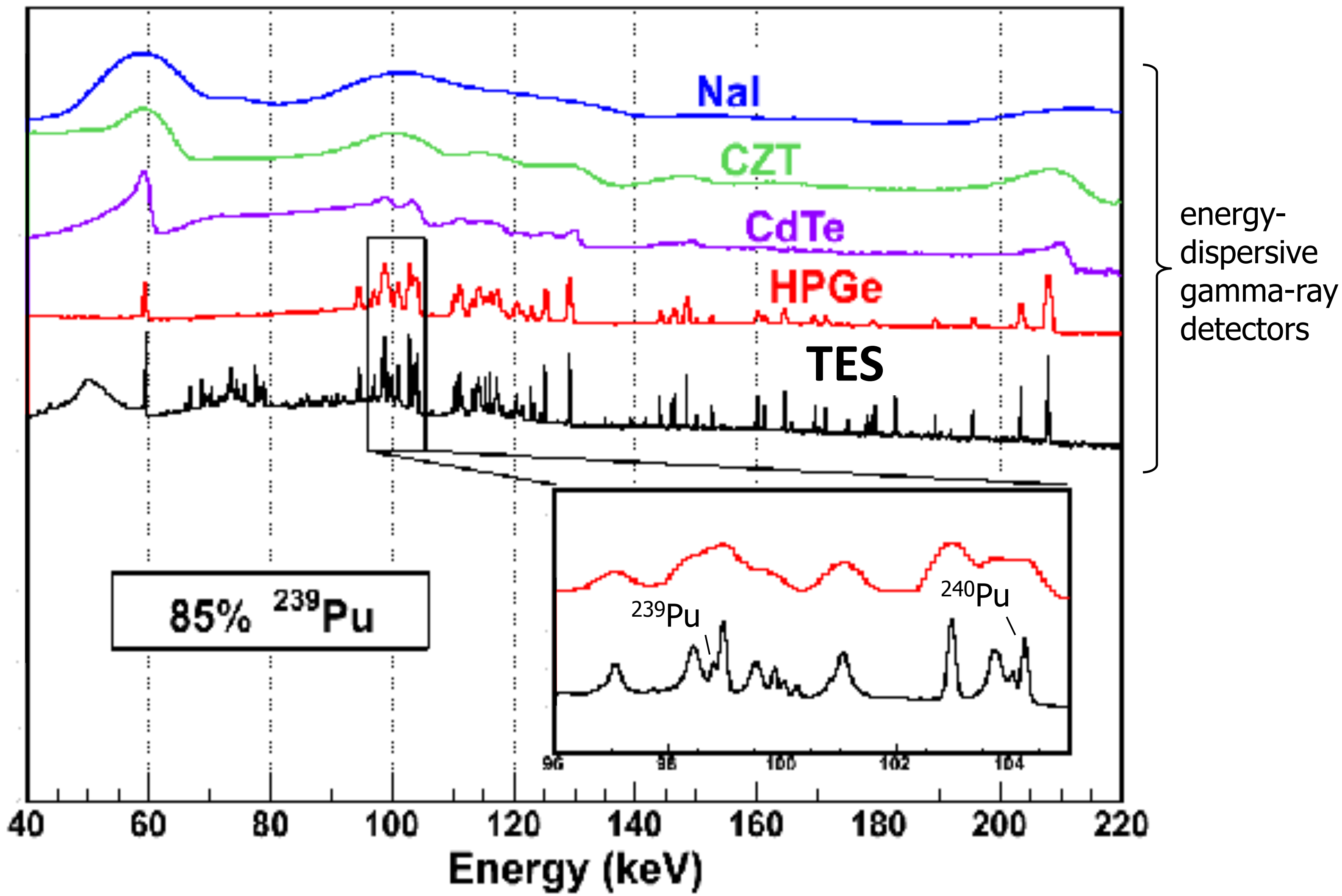






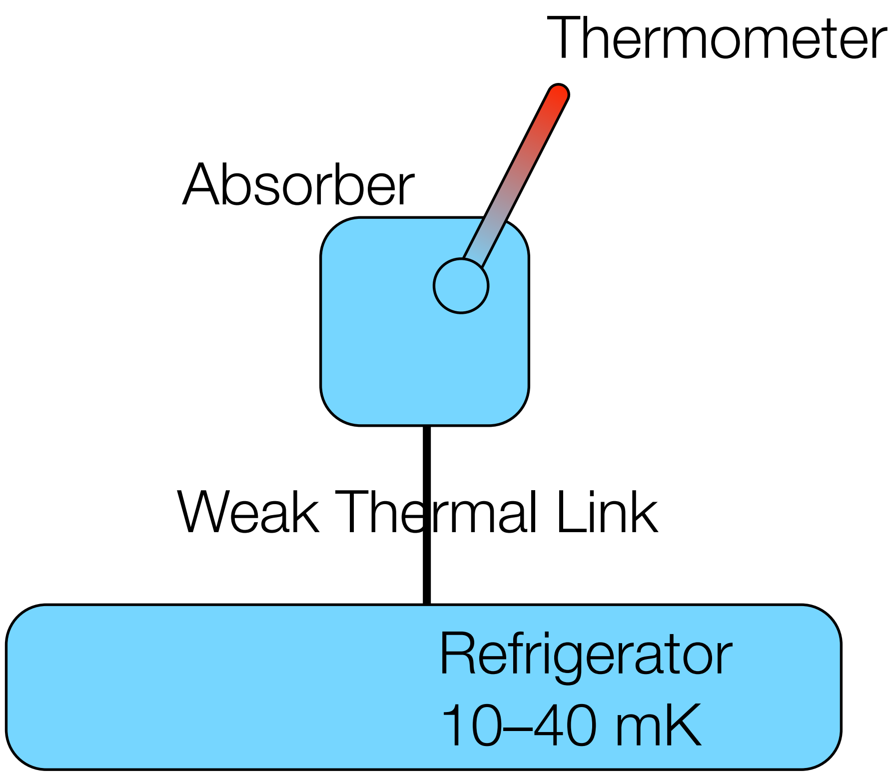
Why Use Cryogenic Detectors?

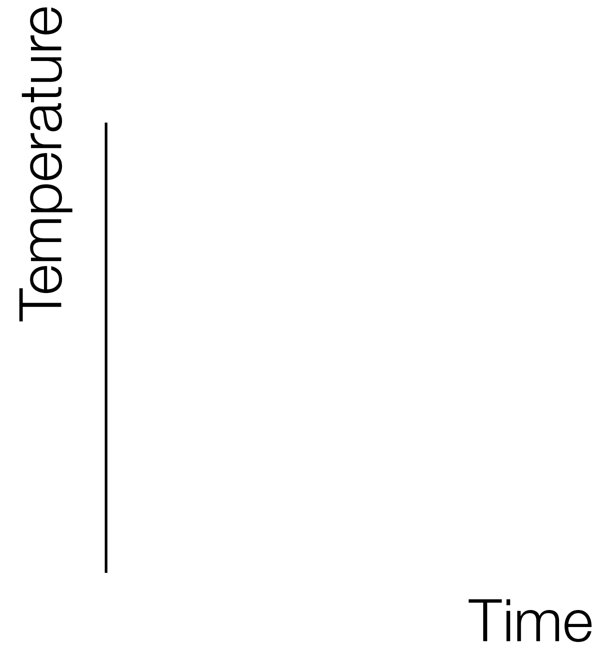
Cryogenic microcalorimeters can provide a unique combination of energy sensitivity, low thresholds, and efficiency



Cryogenic Crystal Detectors

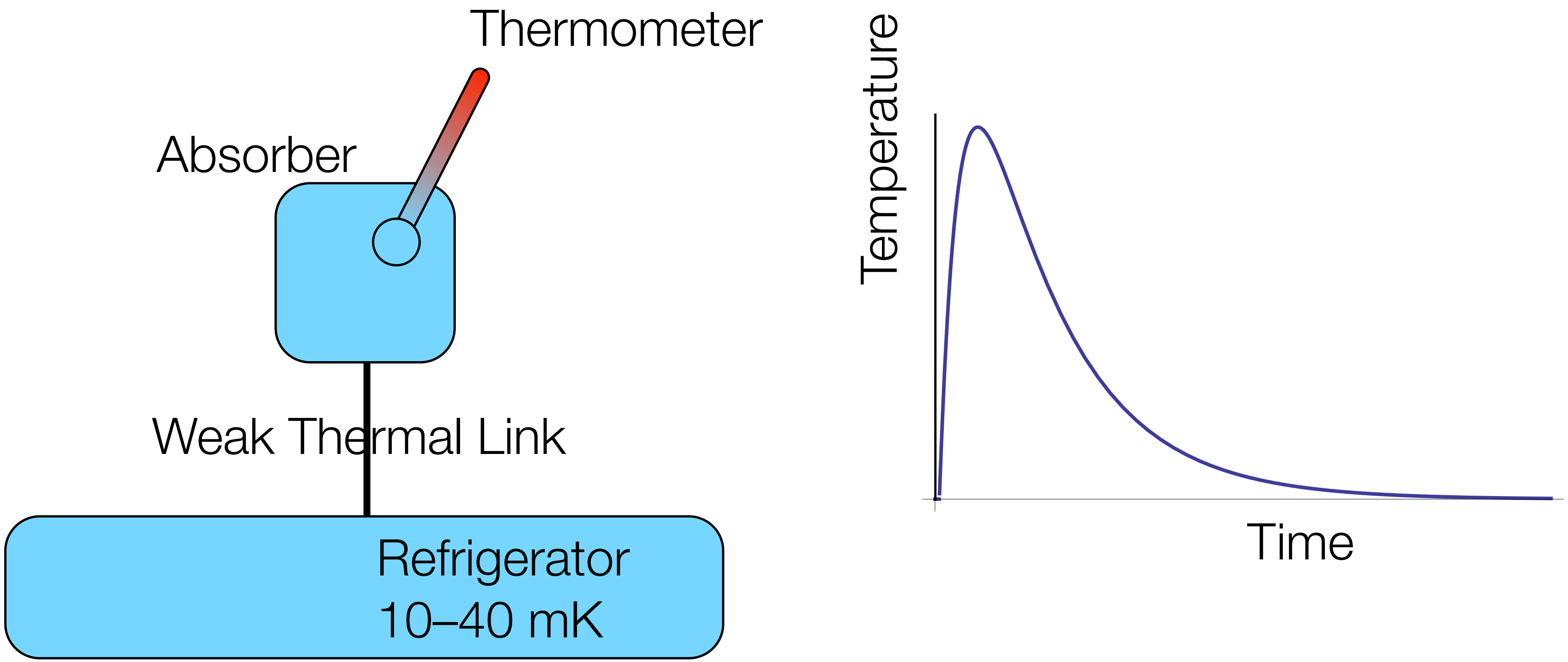
The Phonon Channel





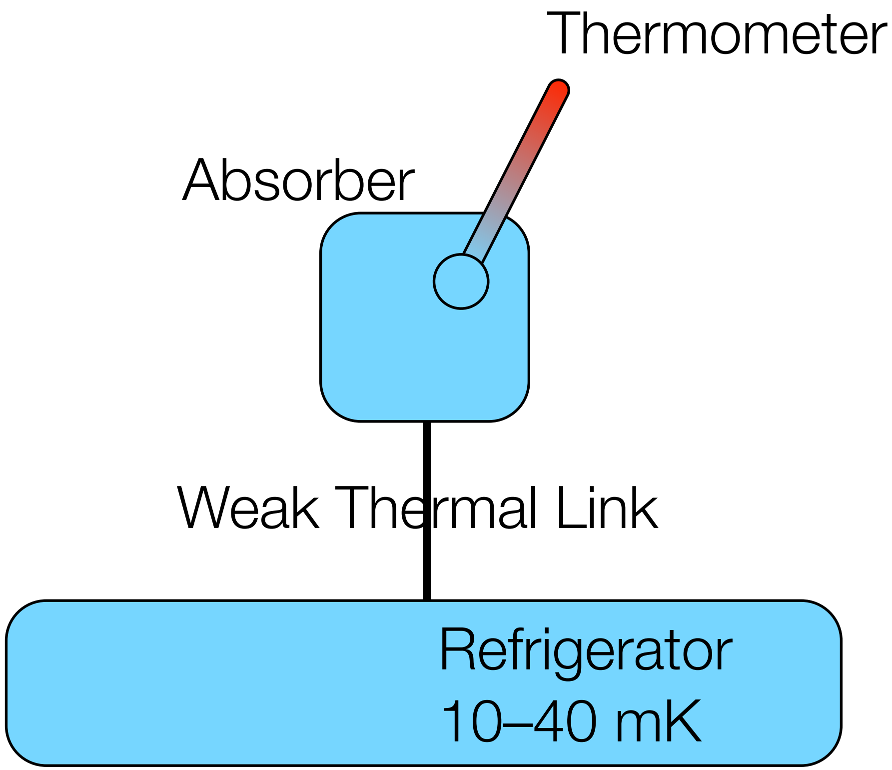
Cryogenic Crystal Detectors

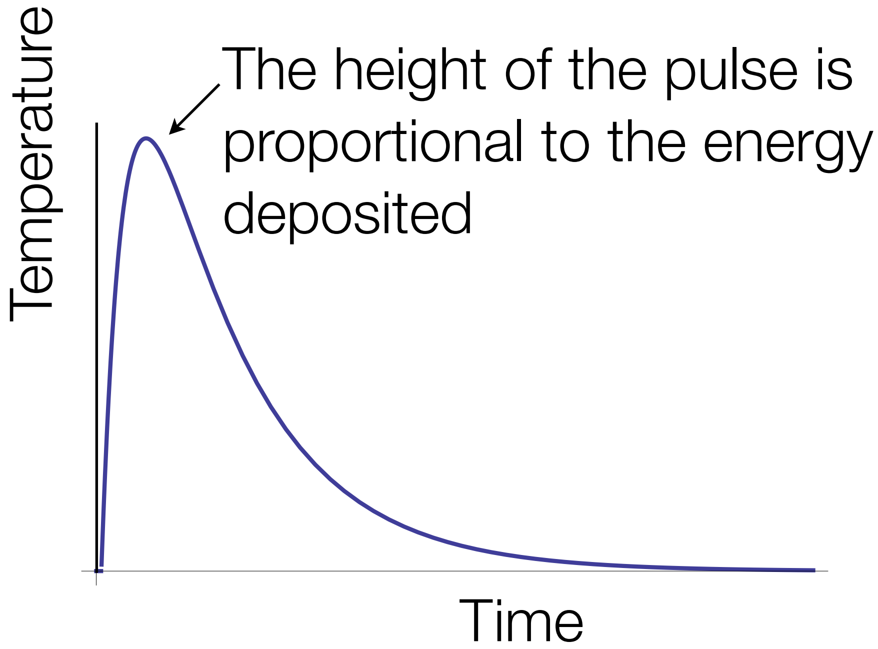
The Phonon Channel



Cryogenic Crystal Detectors

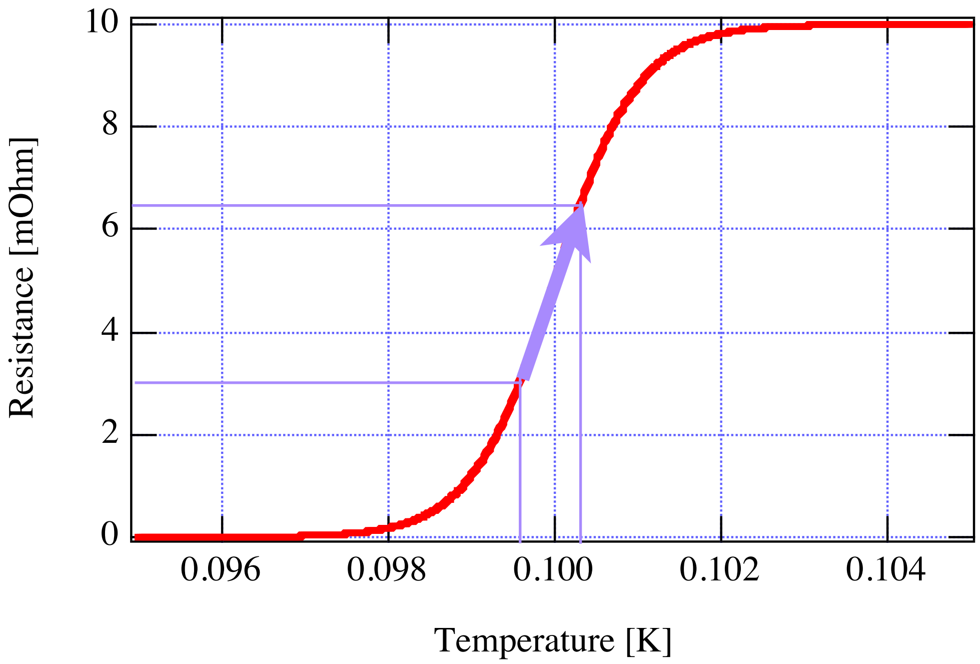
The Phonon Channel





Microcalorimeters 101: Transition-Edge Sensros

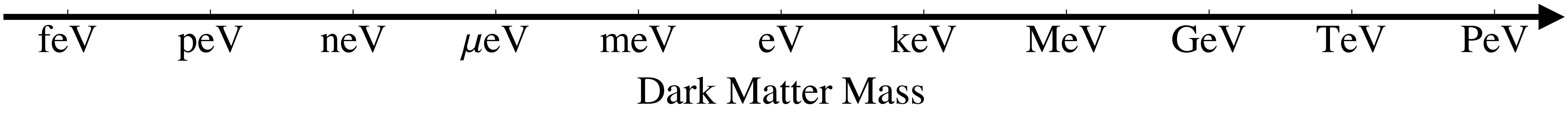
- Refrigerator temperature has to be close to absolute zero
- Thermometer is a Superconducting Transition-Edge Sensor (TES)
- Readout is done with Superconducting Quantum Interference Devices (SQUIDs)



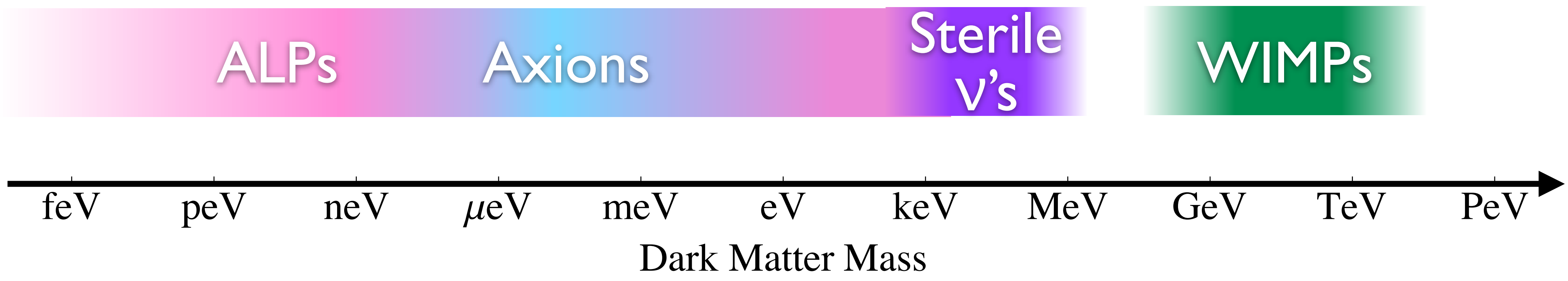
Dark Matter:
Direct Detection

Dark Matter Detection Channels

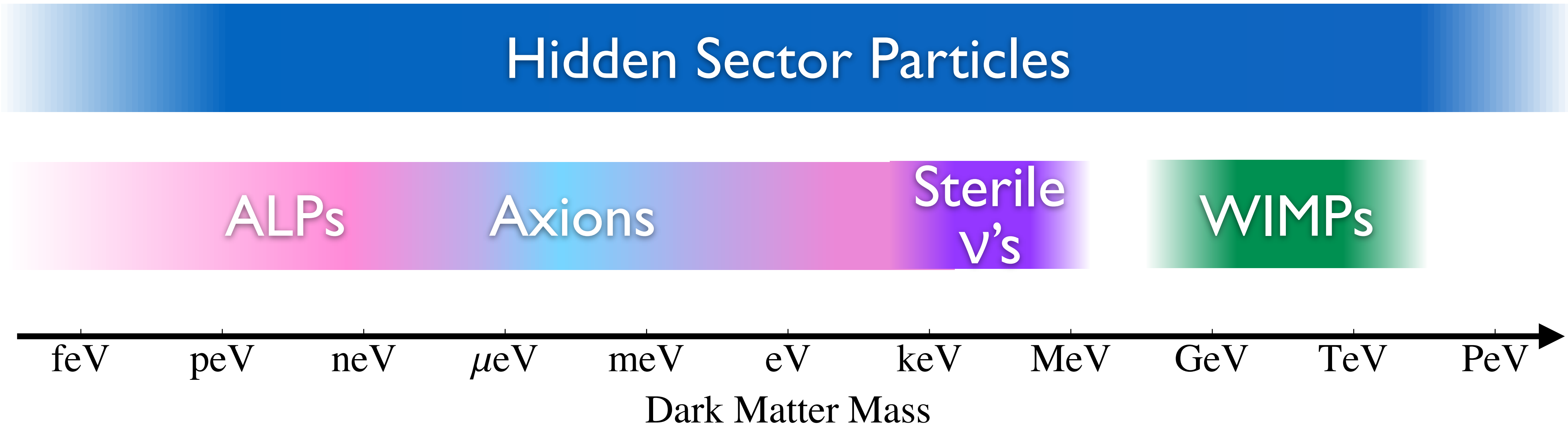
Dark Matter Detection Channels



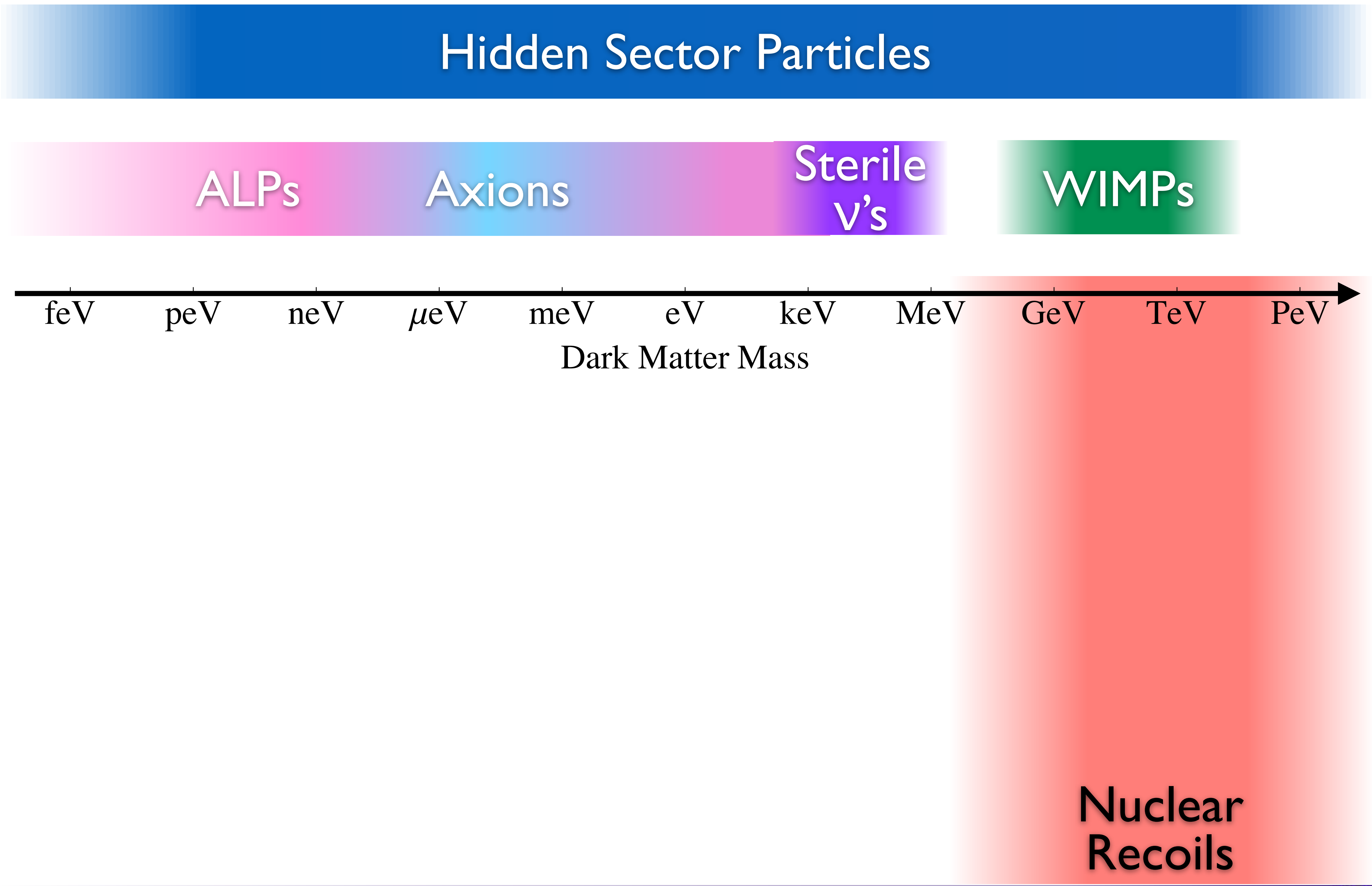
Dark Matter Detection Channels



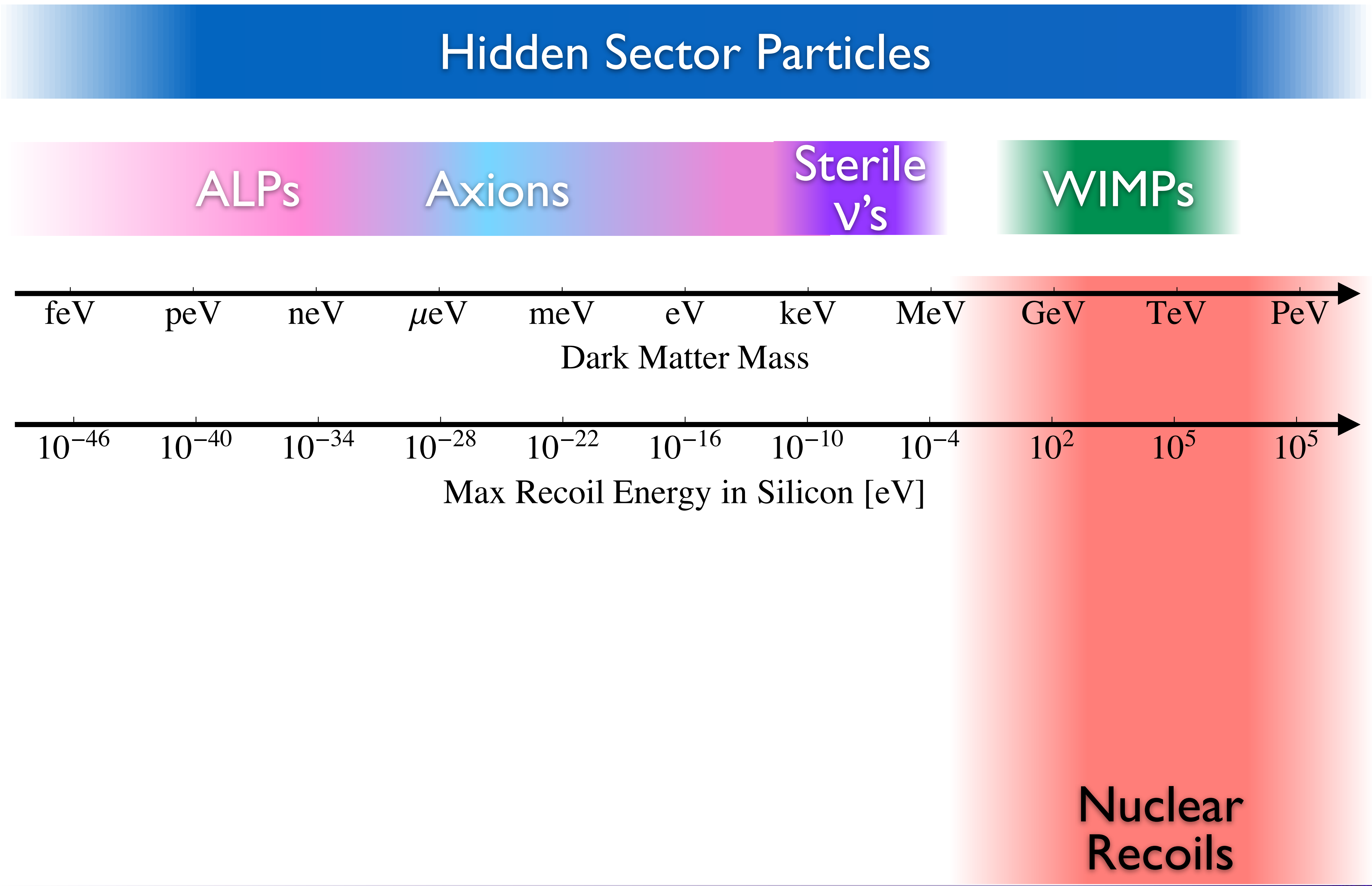
Dark Matter Detection Channels



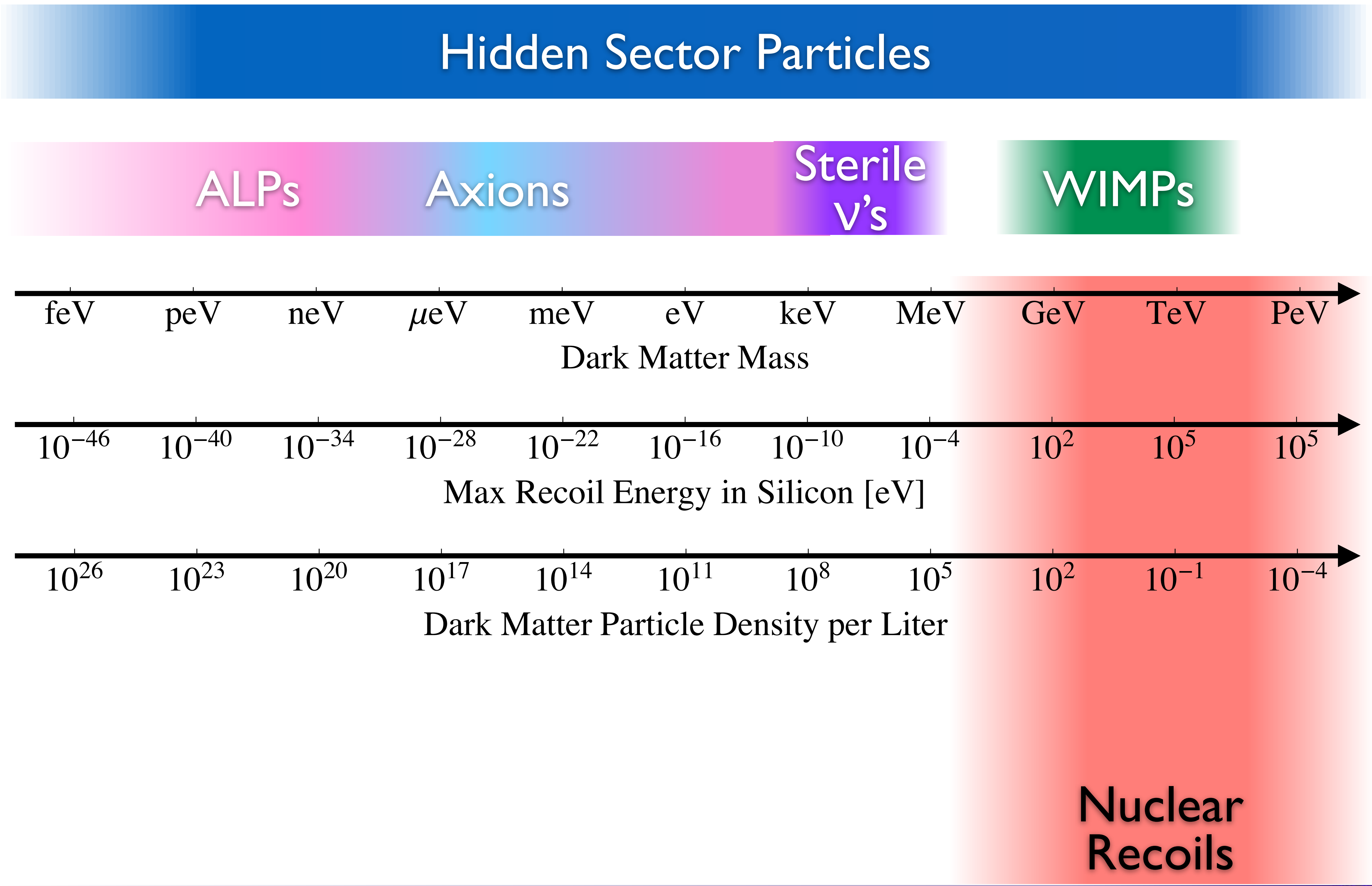
Dark Matter Detection Channels



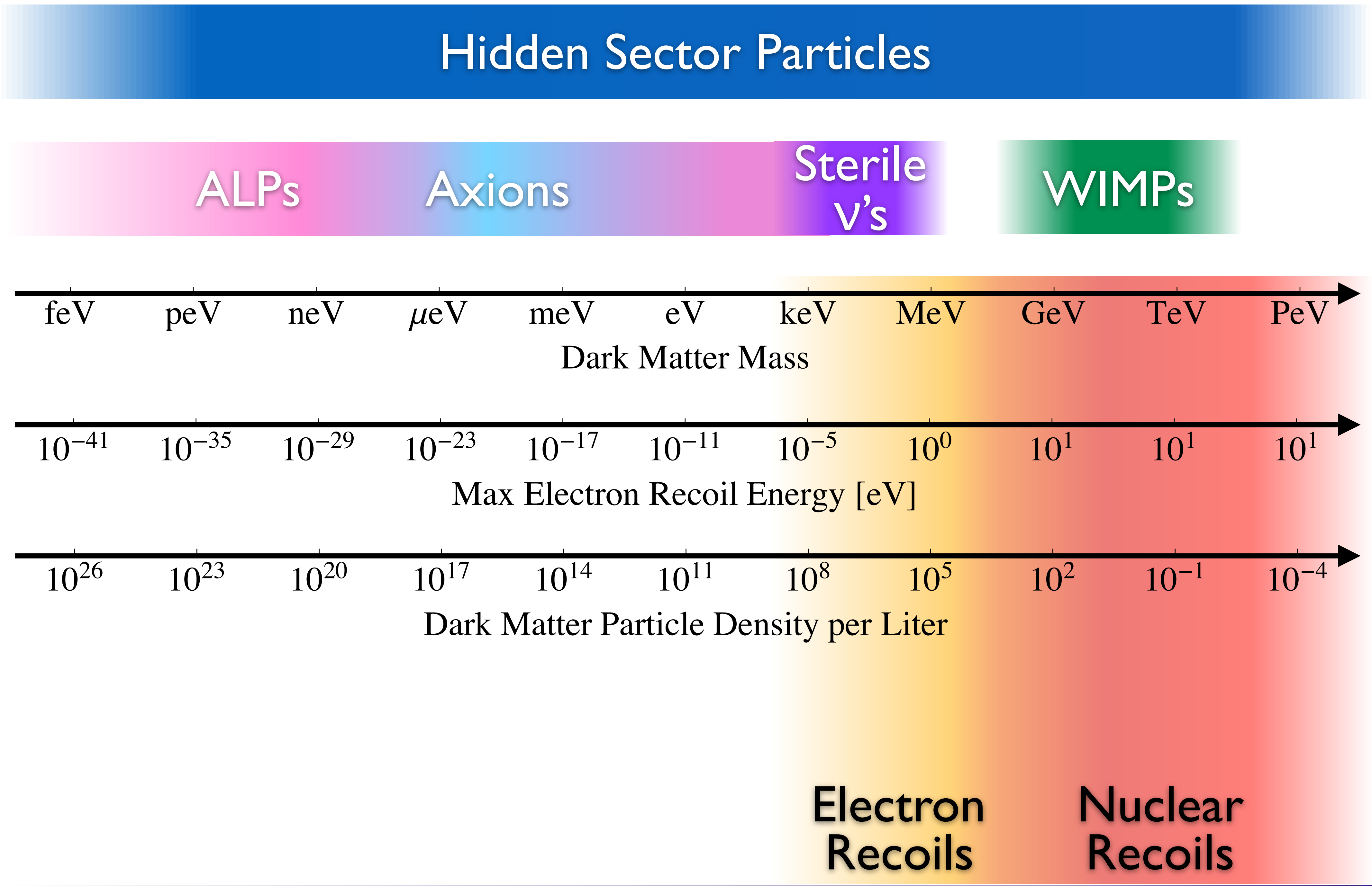
Dark Matter Detection Channels



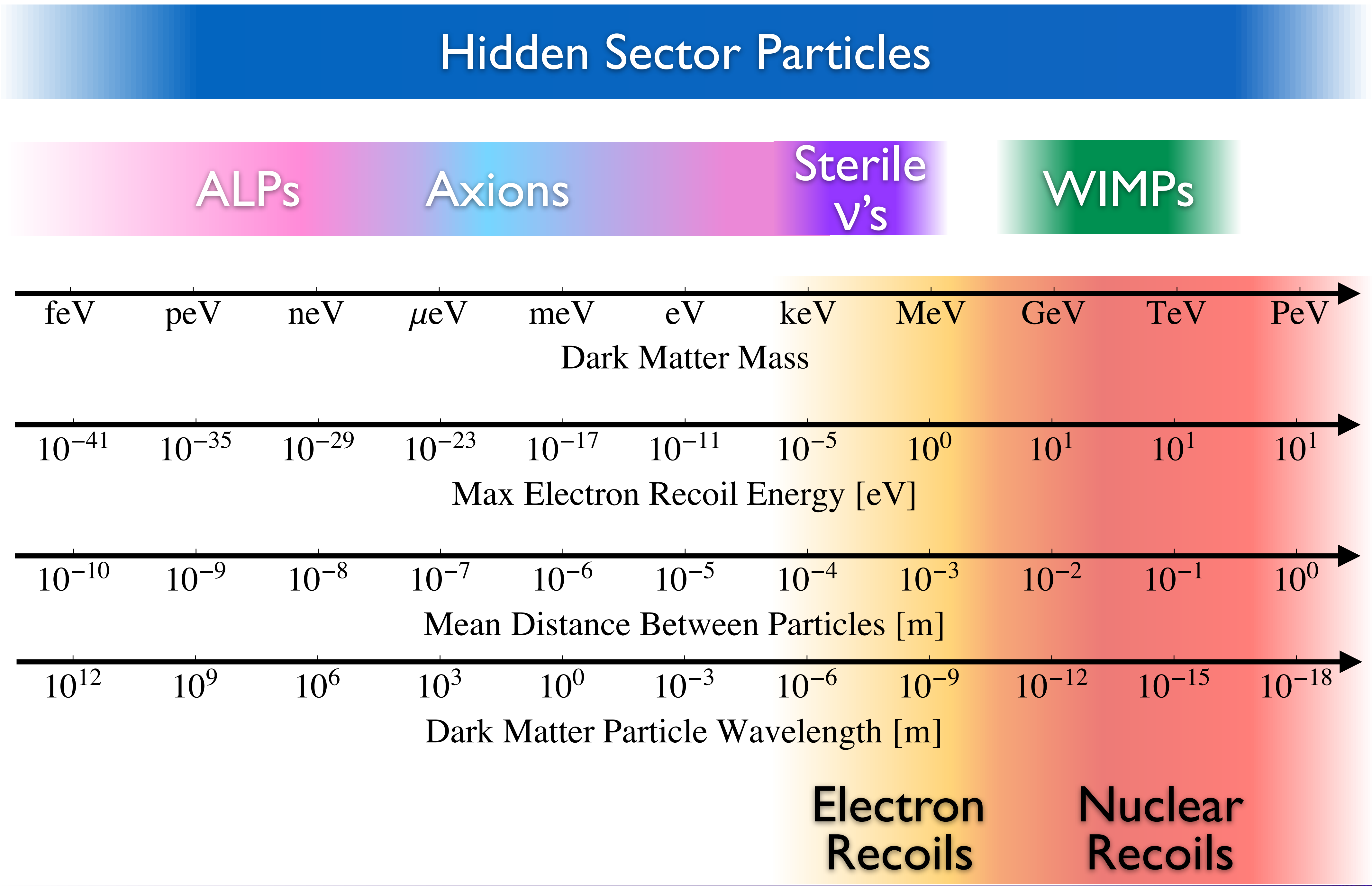
Dark Matter Detection Channels



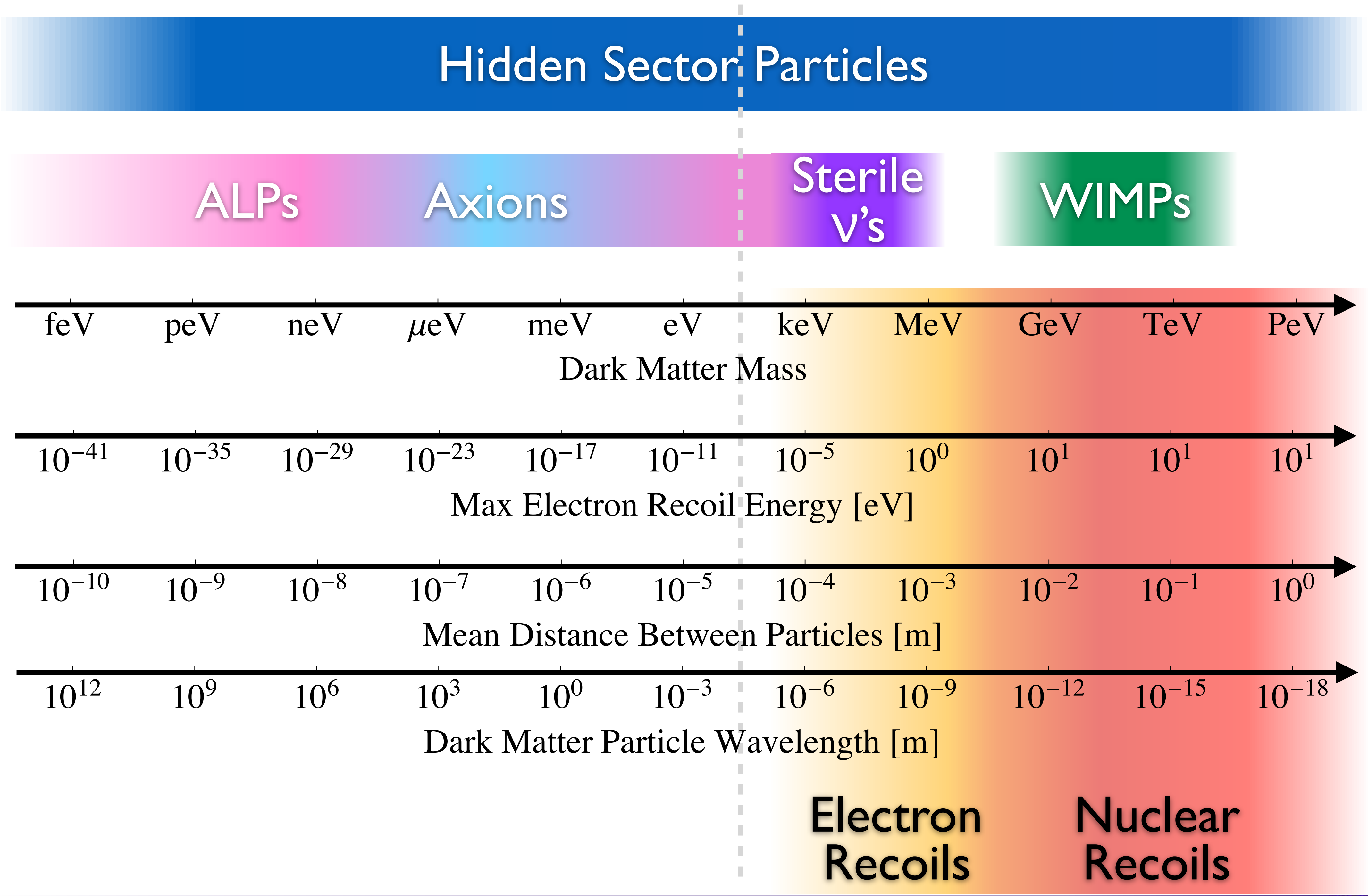
Dark Matter Detection Channels



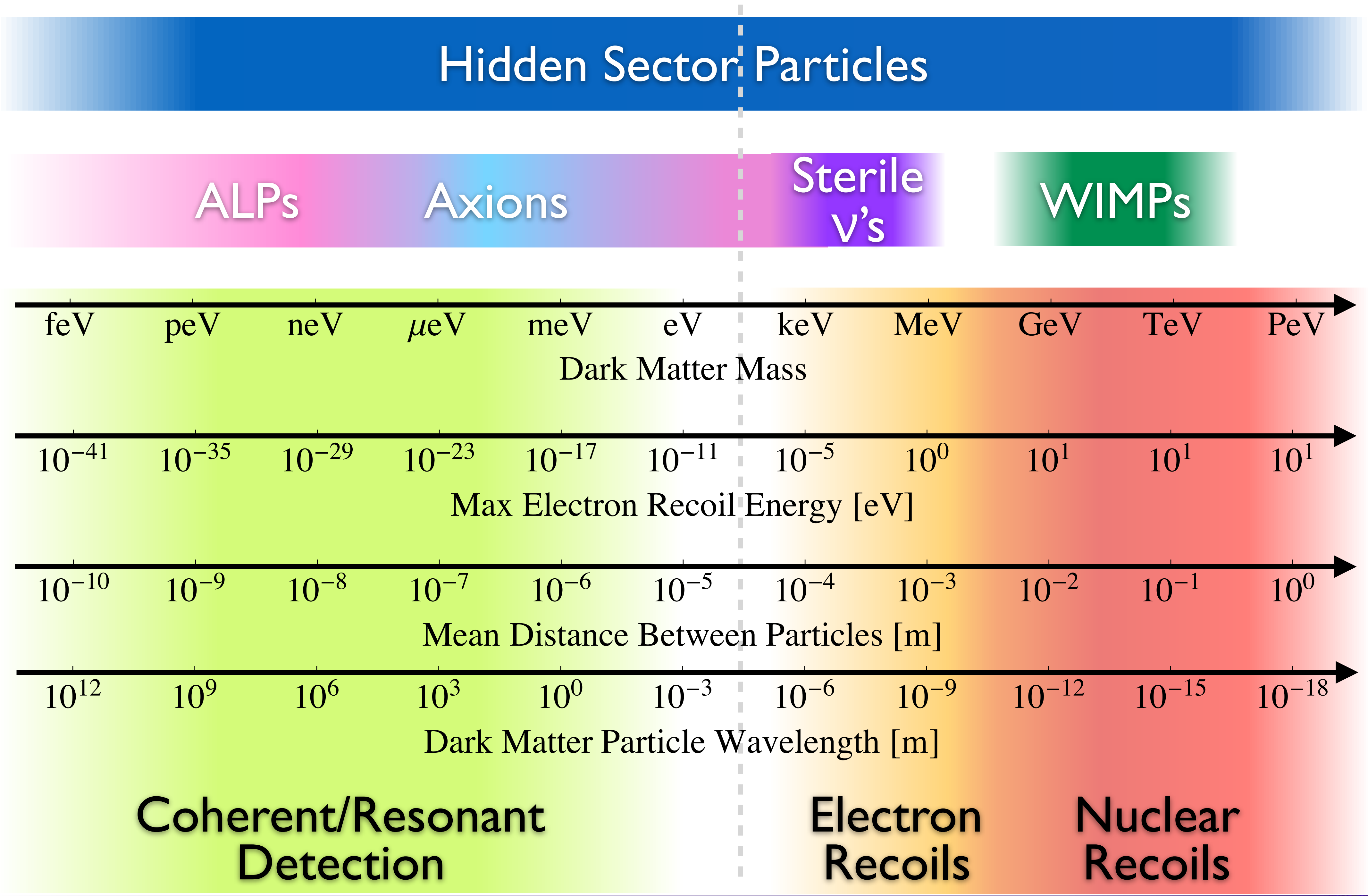
Dark Matter Detection Channels



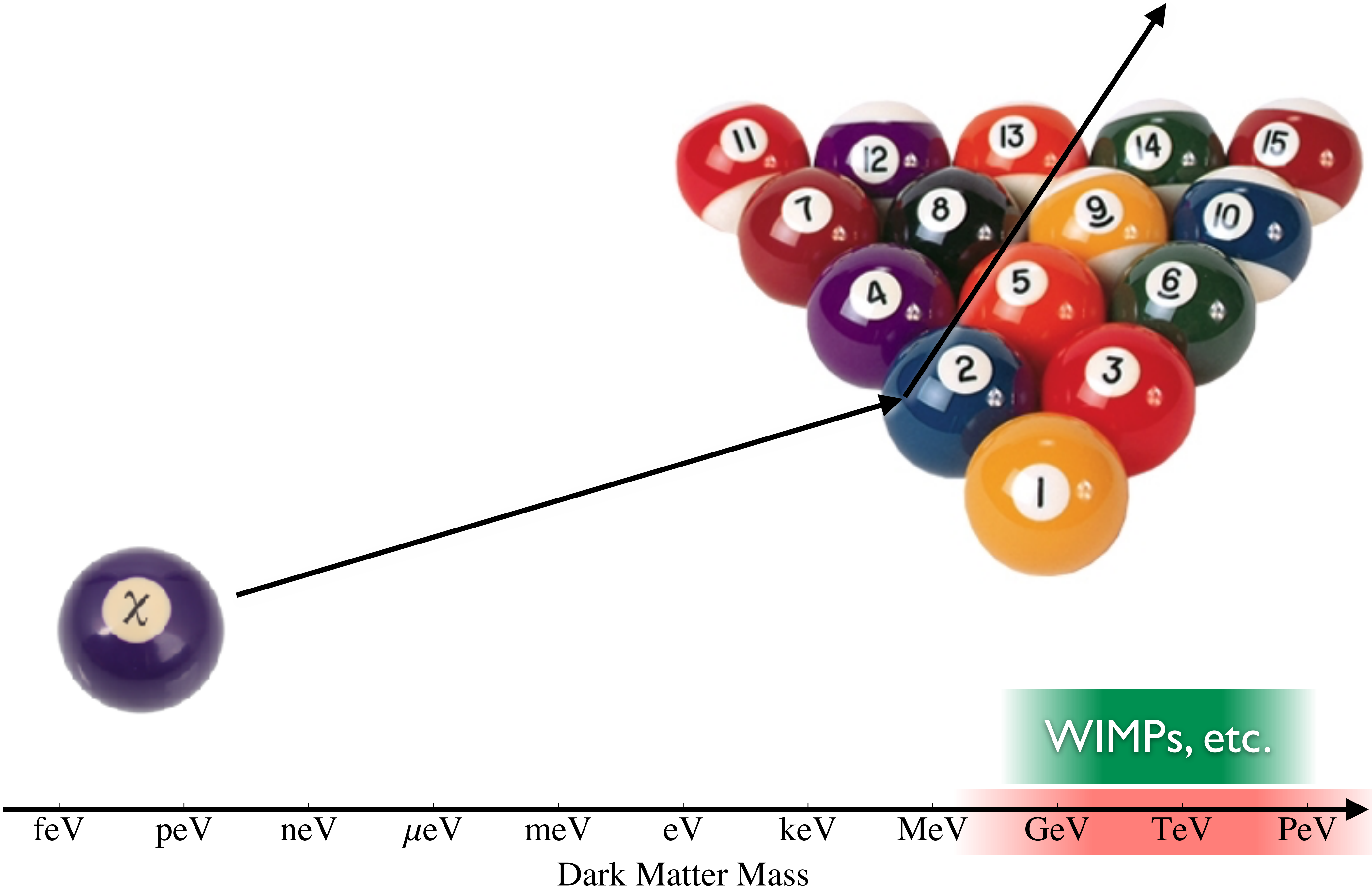
Dark Matter Detection Channels



Dark Matter Detection Channels



Nuclear Recoils



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

particle
theory

Interaction
Rate
[events/keV/kg/day]

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

particle theory

nuclear structure

Interaction Rate [events/keV/kg/day]

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

Principles of Particle Detection

	particle theory	nuclear structure	astrophysics properties

Interaction Rate [events/keV/kg/day]

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

Principles of Particle Detection

particle theory | nuclear structure | astrophysics properties

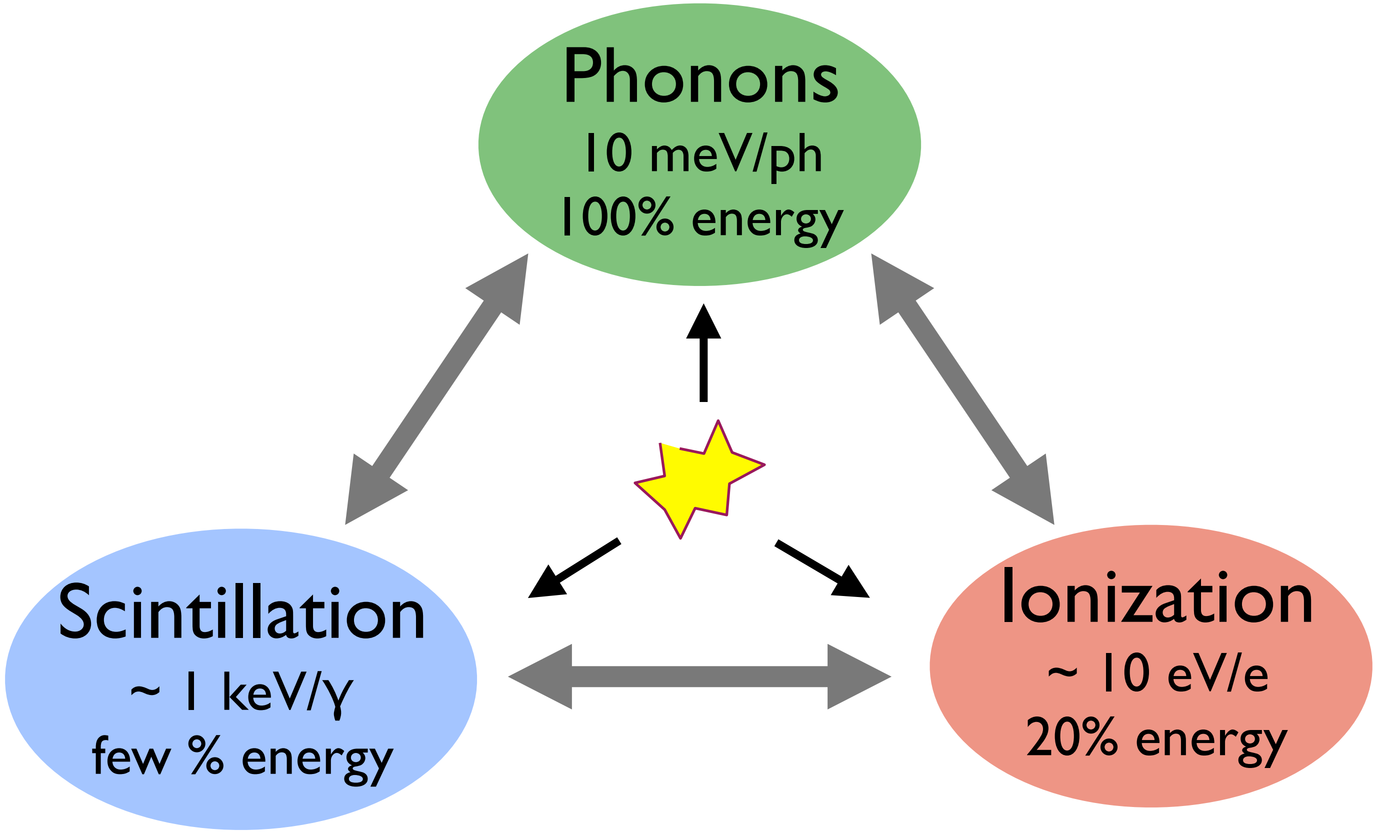
Interaction Rate [events/keV/kg/day]

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

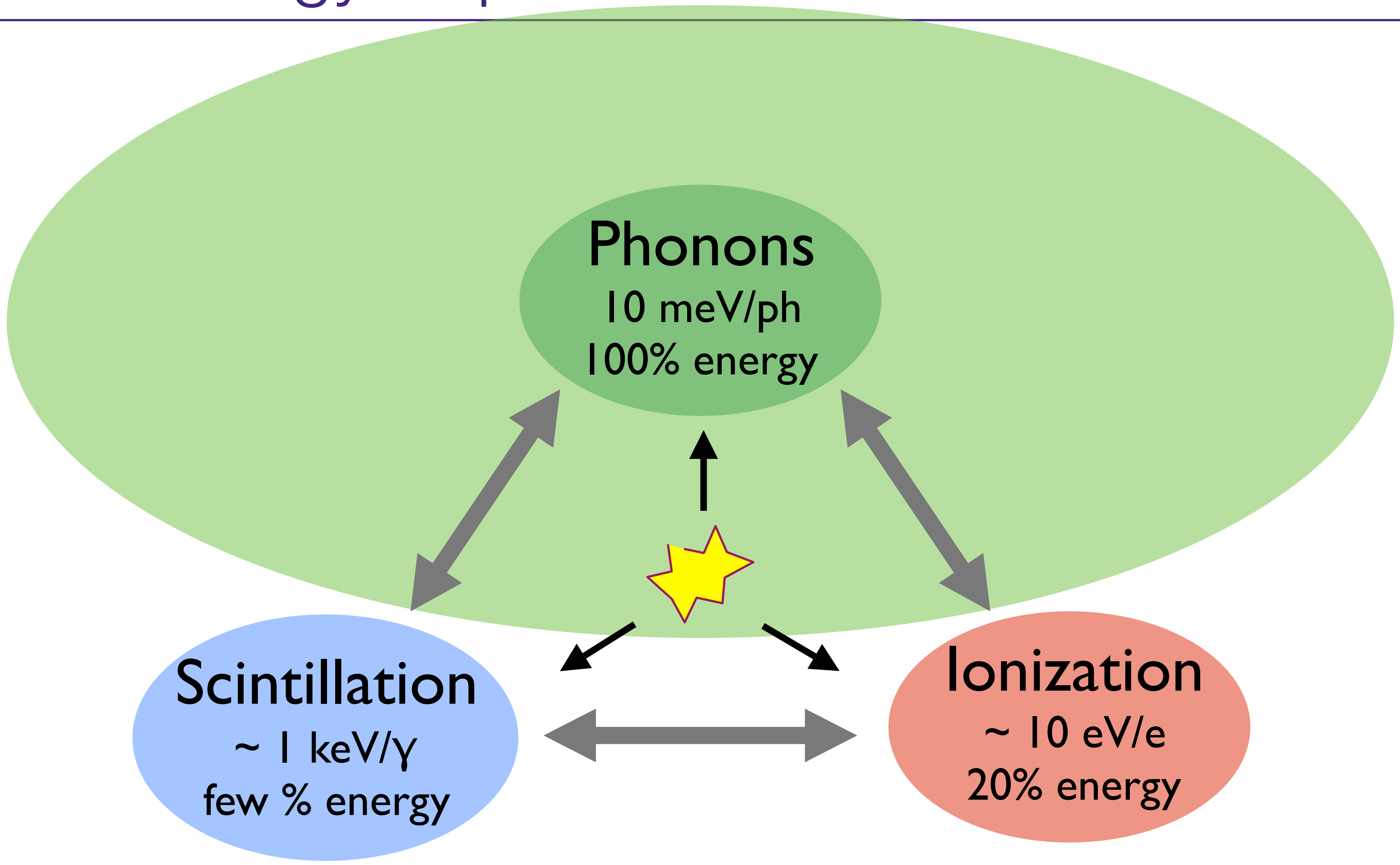
$$m_r = \frac{m_\chi m_N}{m_\chi + m_N}$$

“reduced mass”

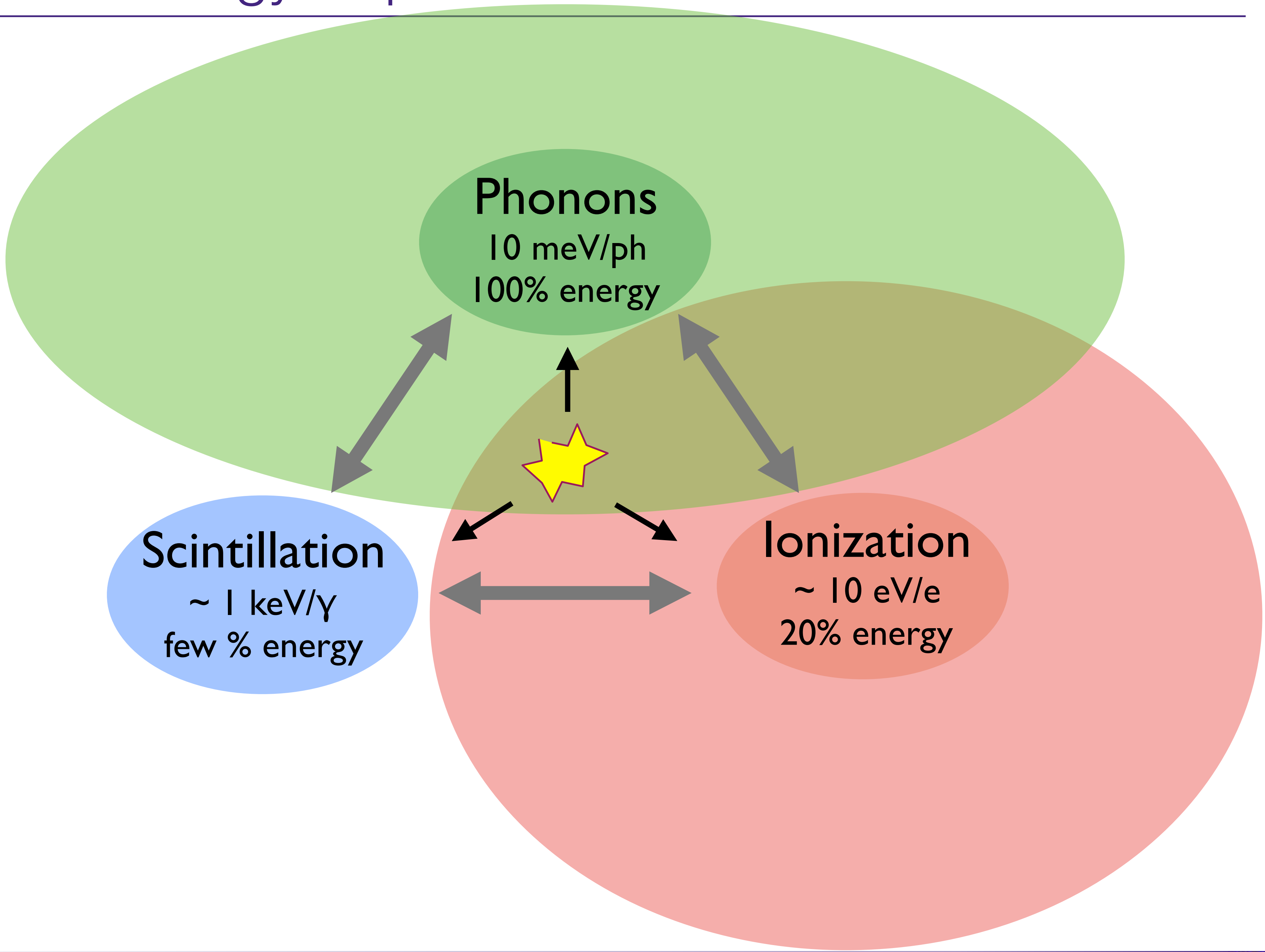
Different Energy Deposition Channels



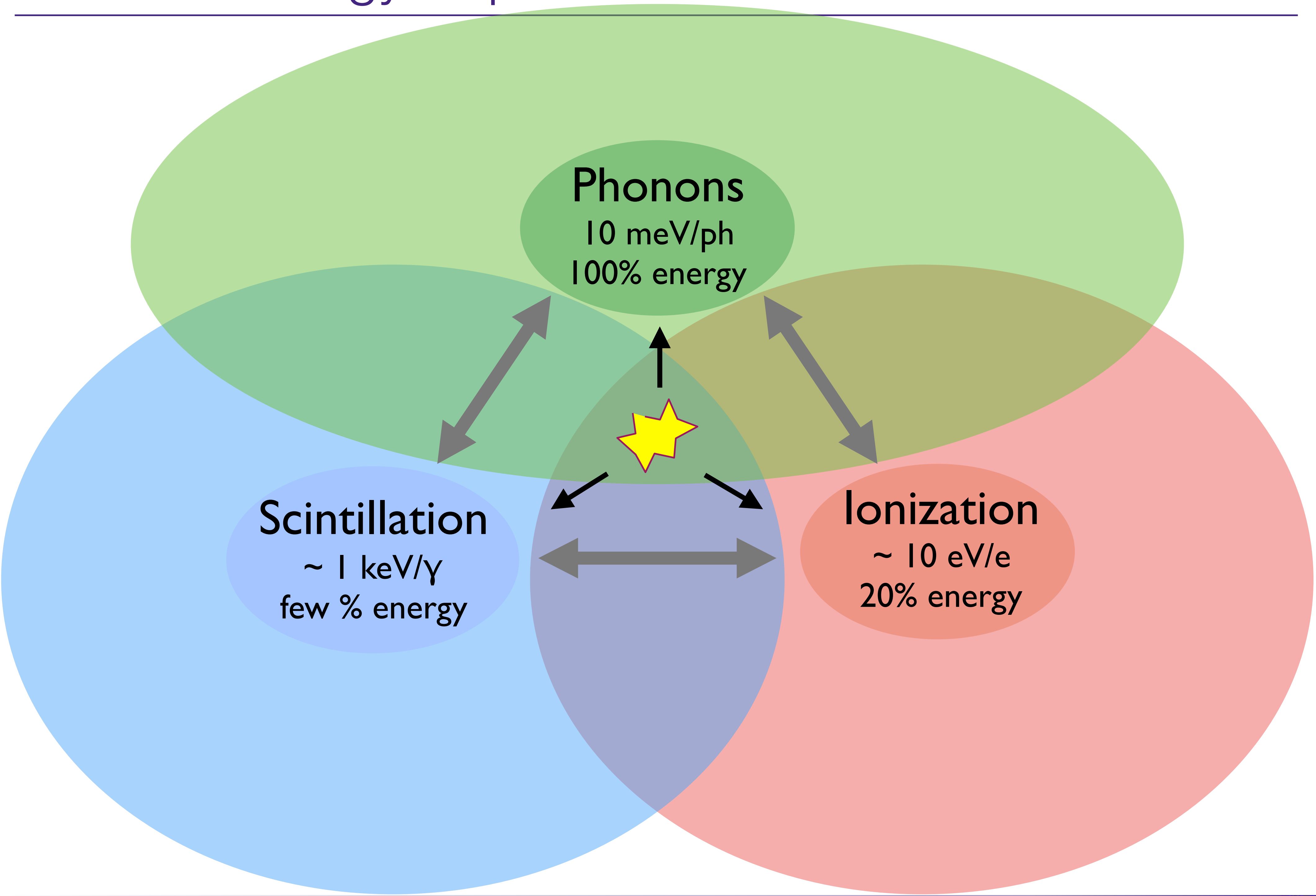
Different Energy Deposition Channels



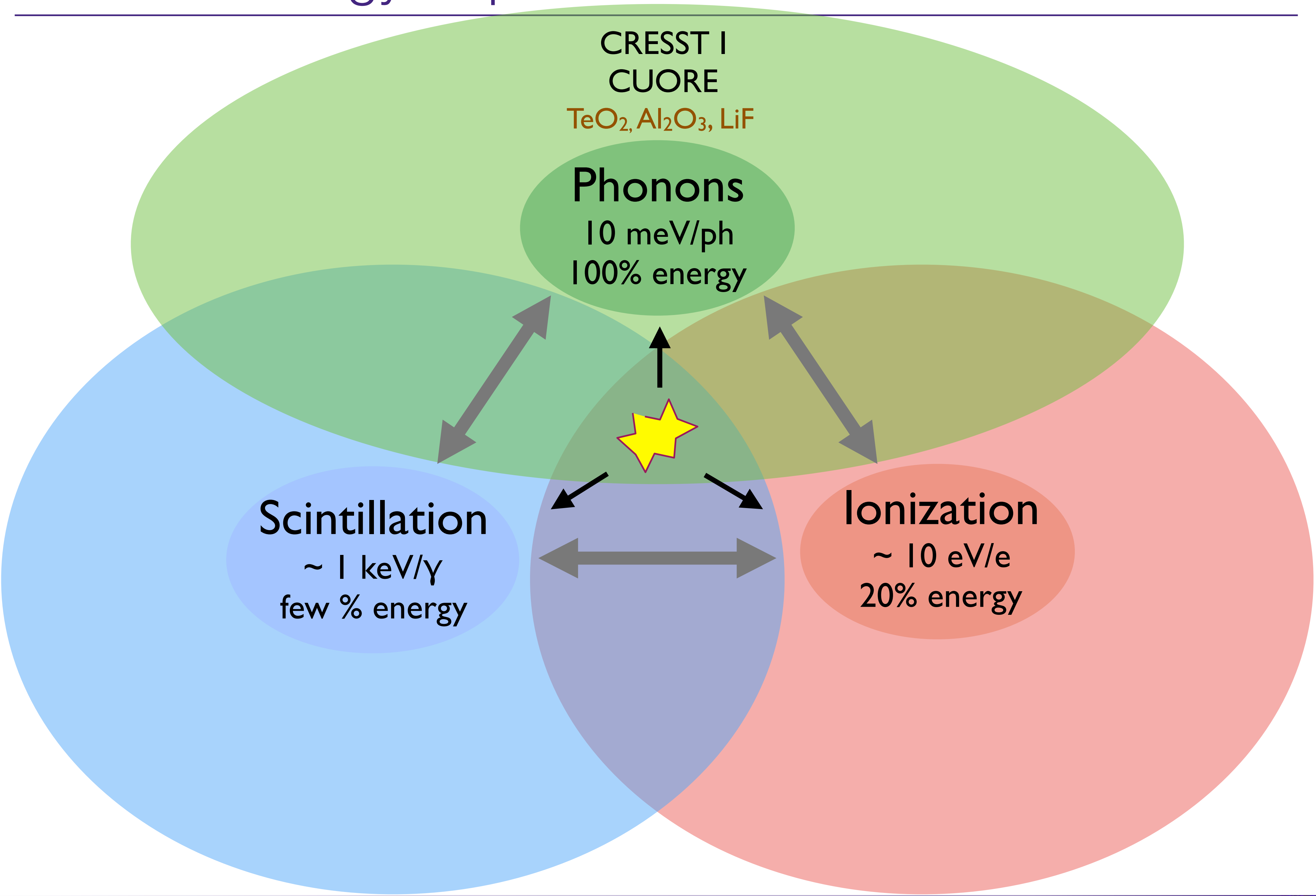
Different Energy Deposition Channels



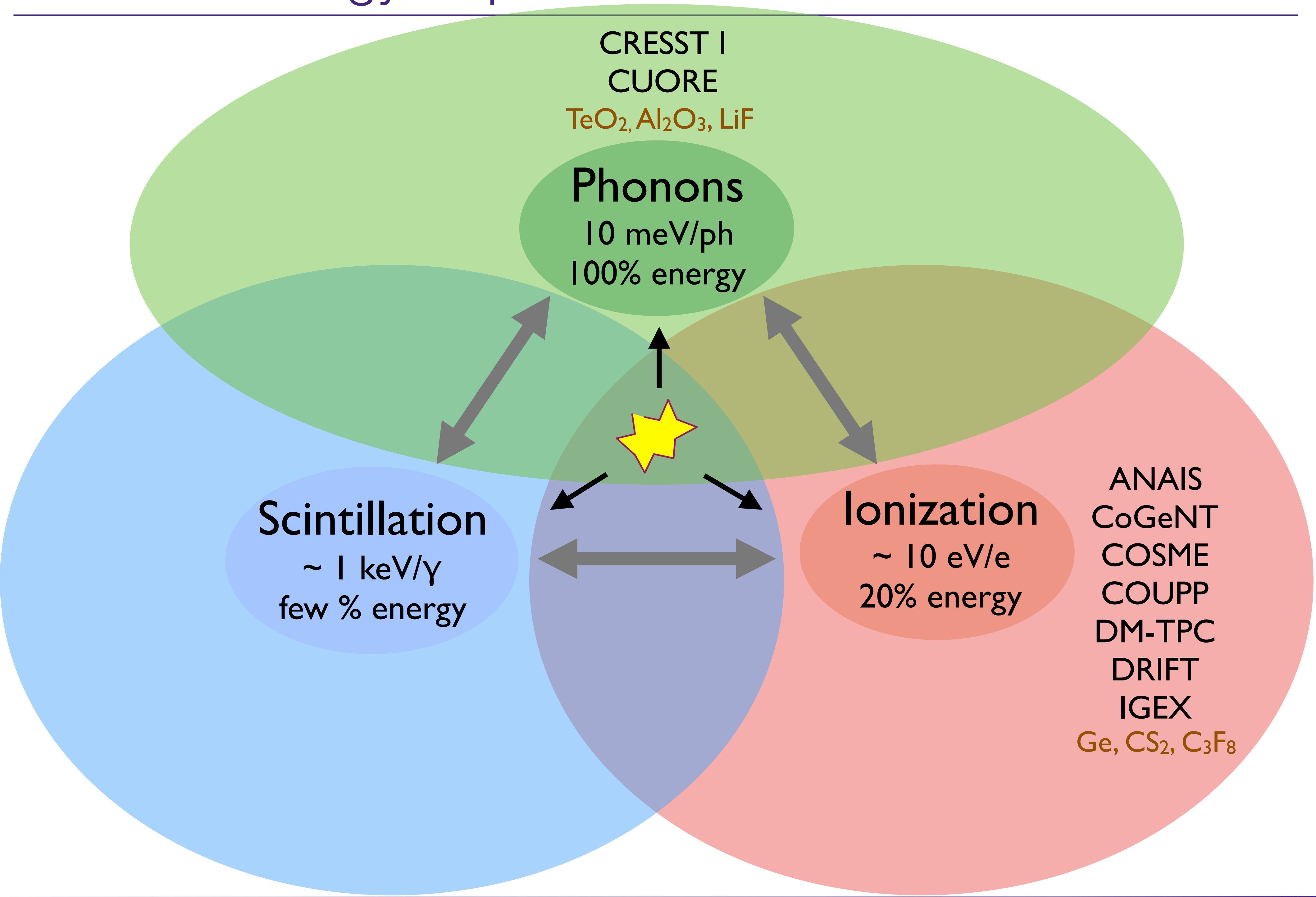
Different Energy Deposition Channels



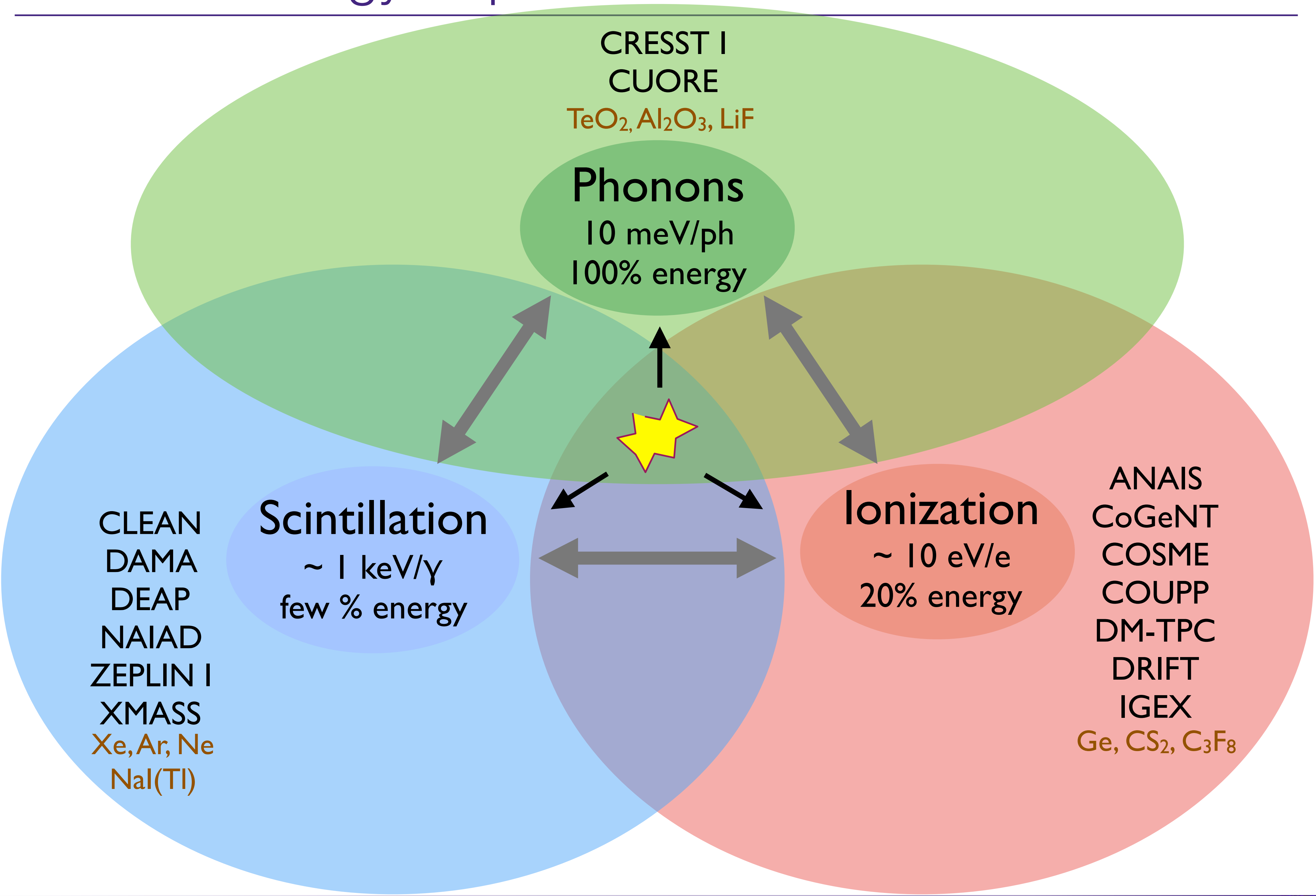
Different Energy Deposition Channels



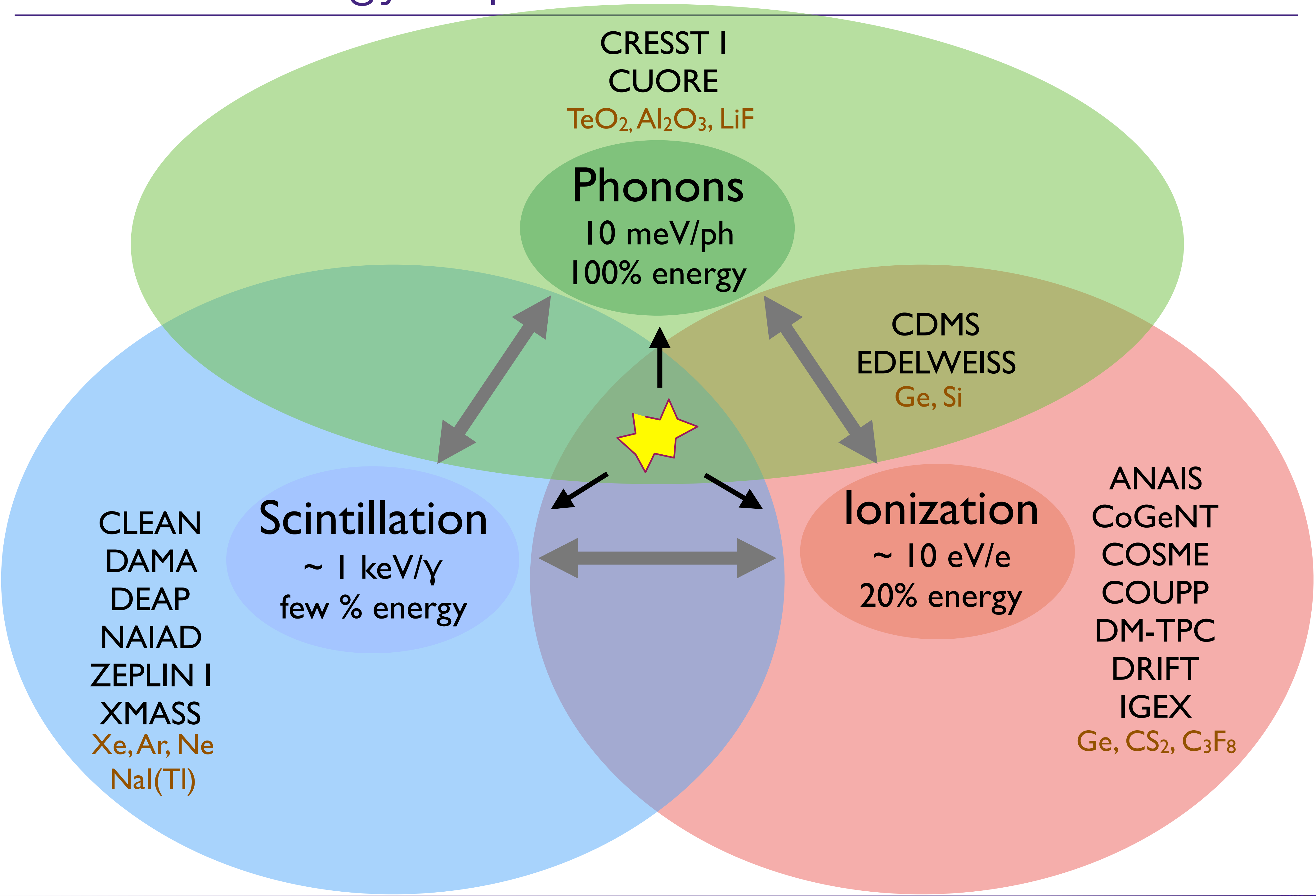
Different Energy Deposition Channels



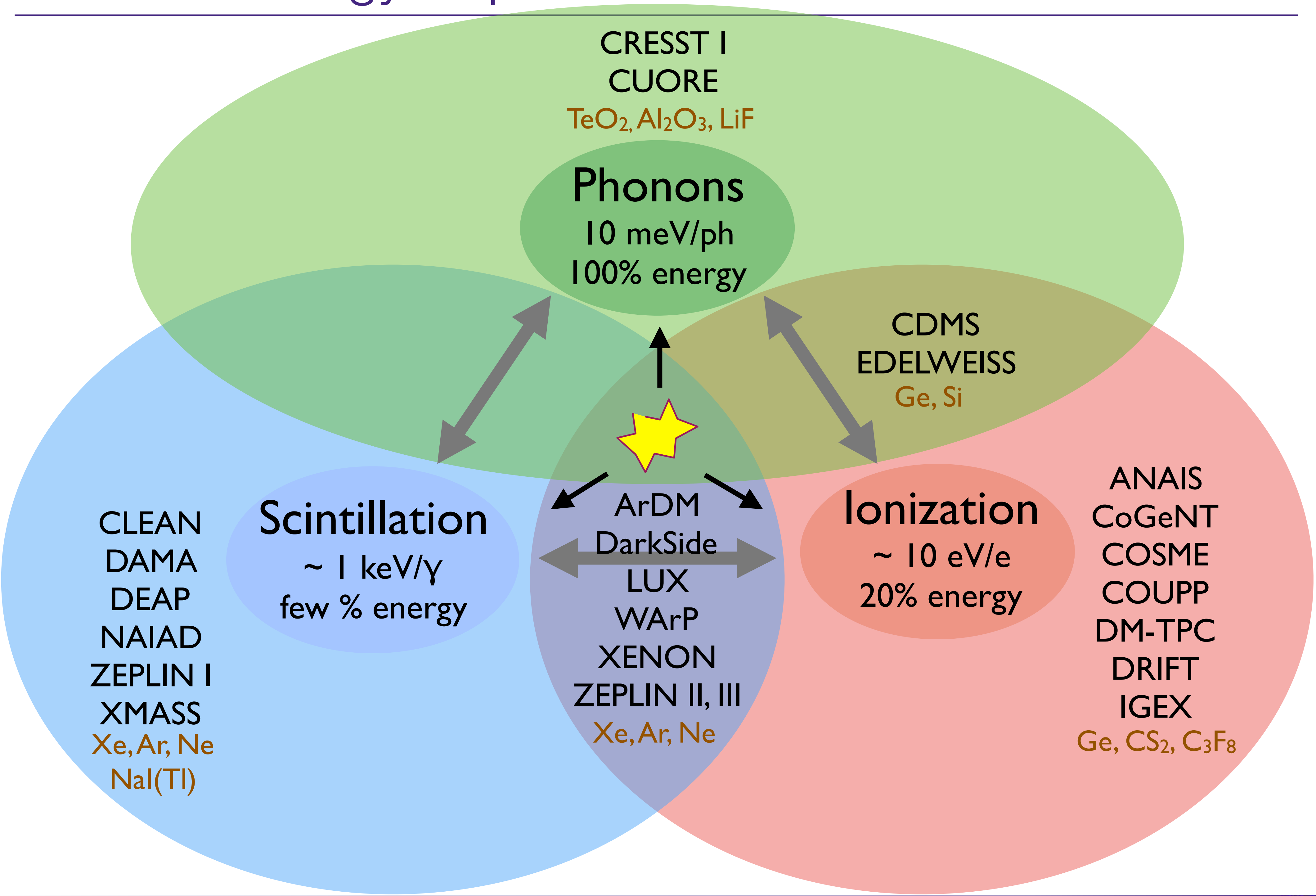
Different Energy Deposition Channels



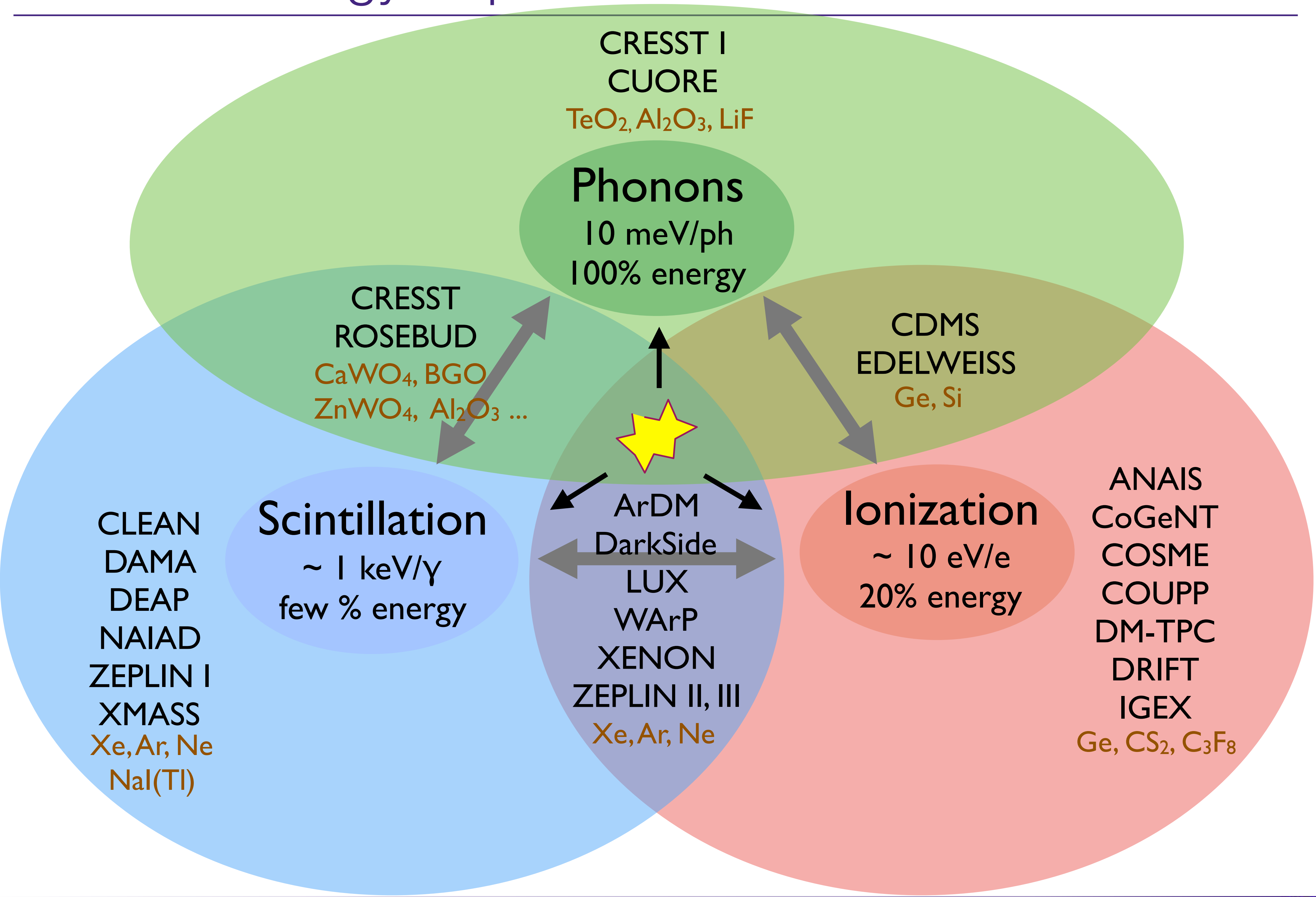
Different Energy Deposition Channels



Different Energy Deposition Channels



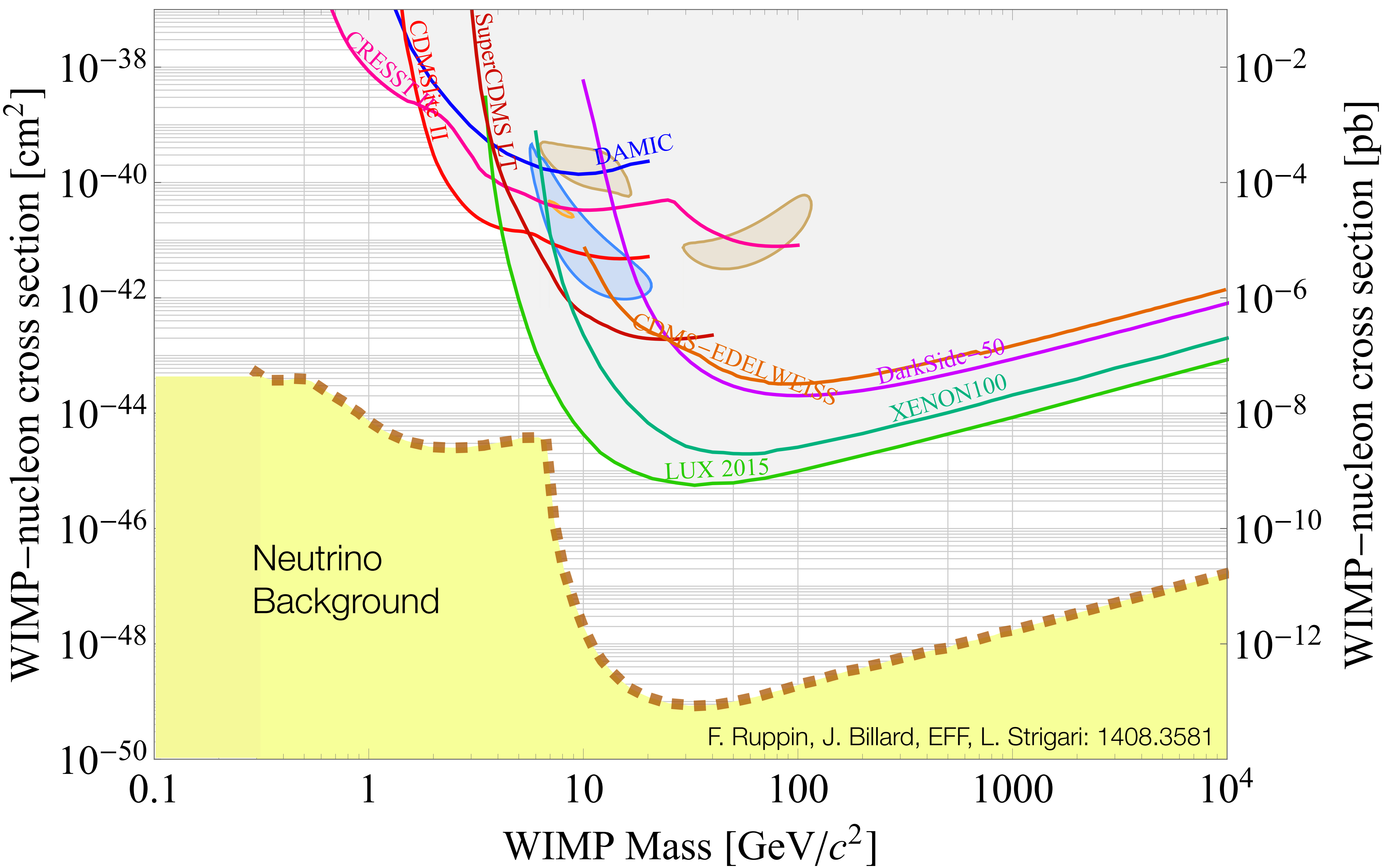
Different Energy Deposition Channels



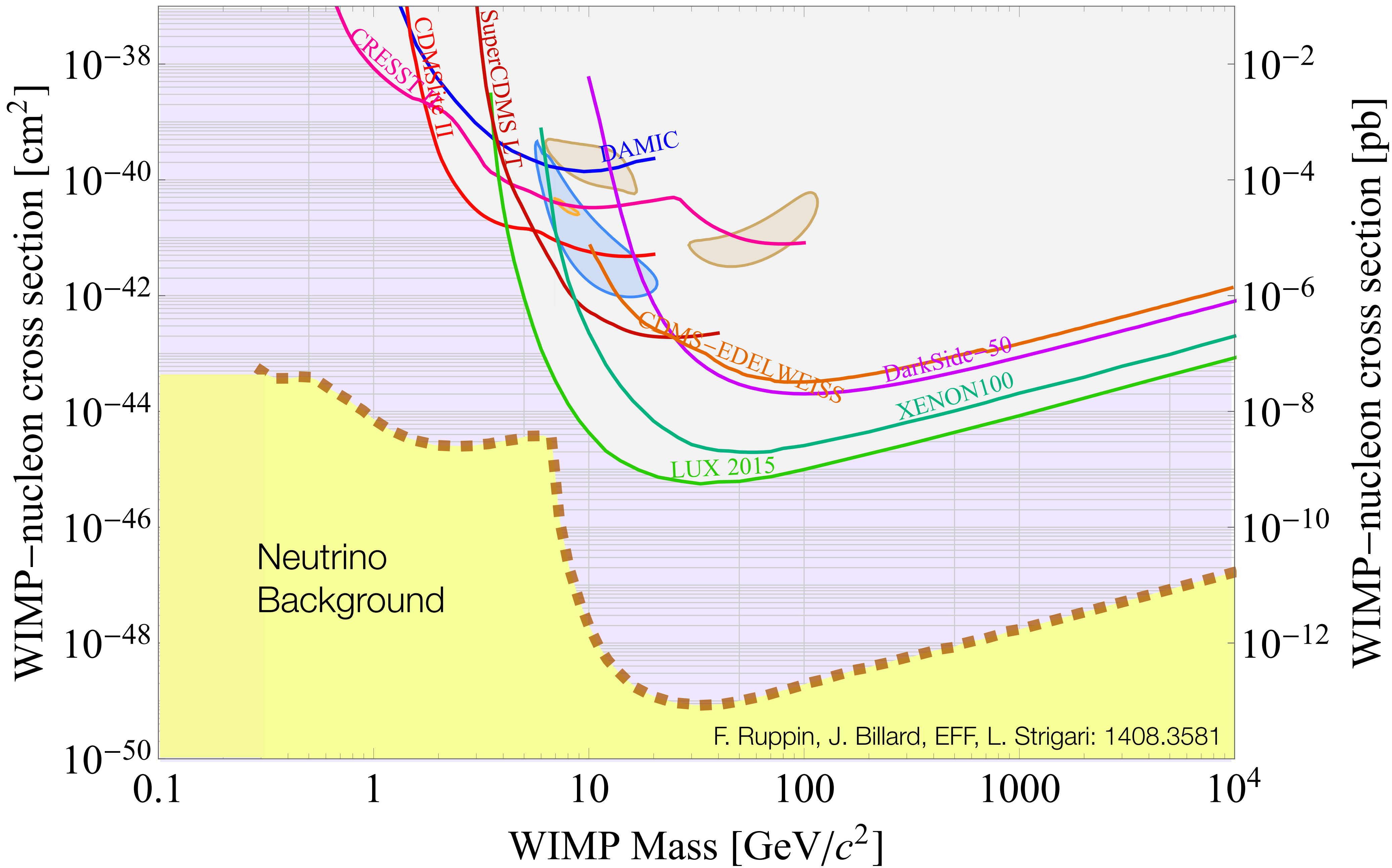
Other ways of attaining Particle Identification

- 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...

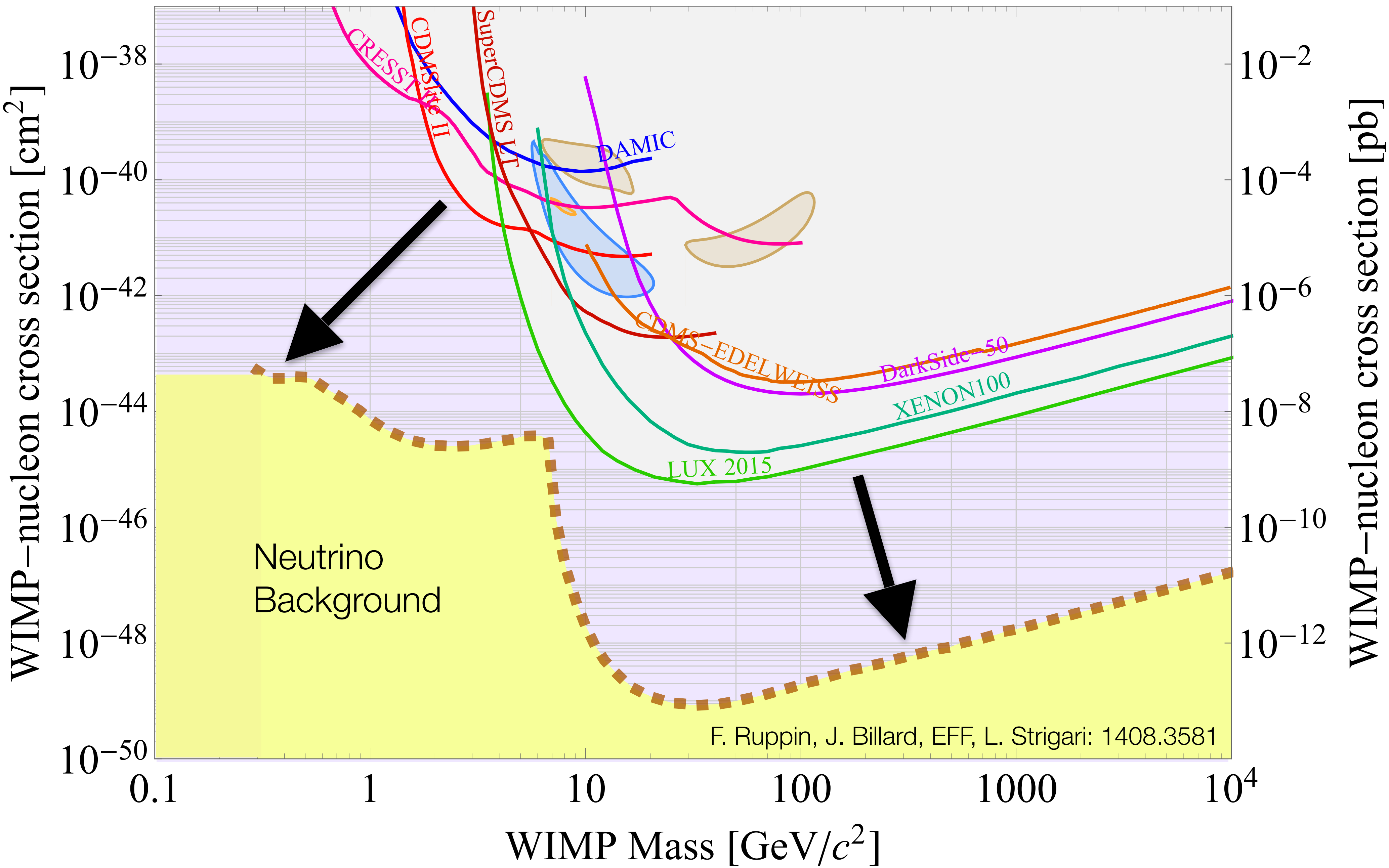
To Neutrinos, and Beyond!



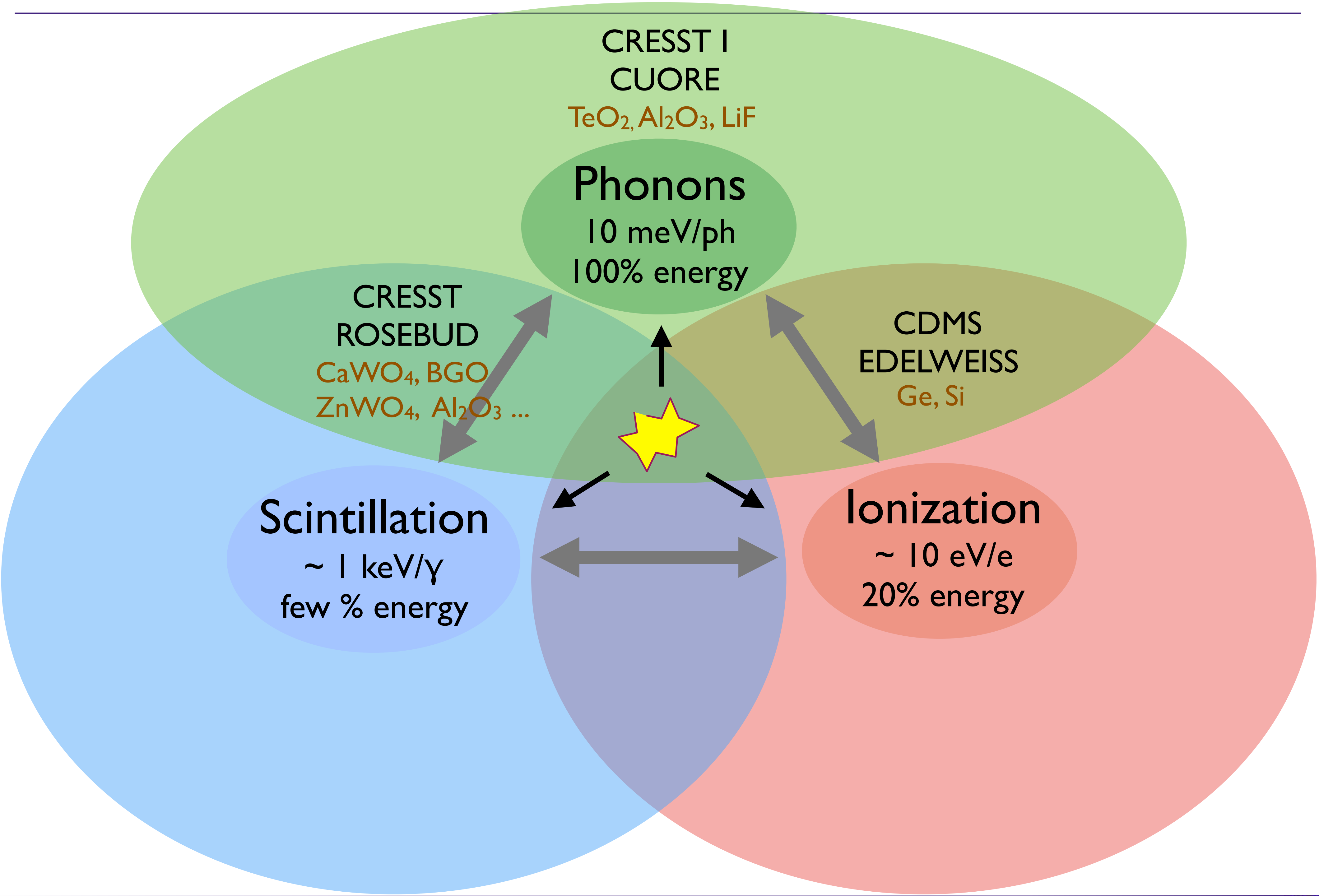
To Neutrinos, and Beyond!



To Neutrinos, and Beyond!



Cryogenic Crystal Detectors: Looking for Low-mass WIMPs

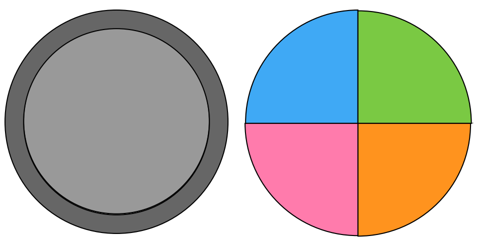


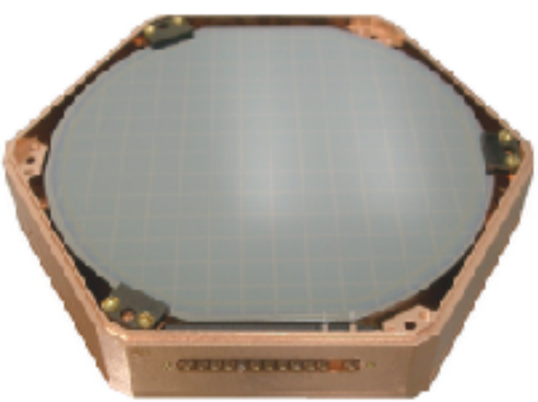
SuperCDMS SNOLAB

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

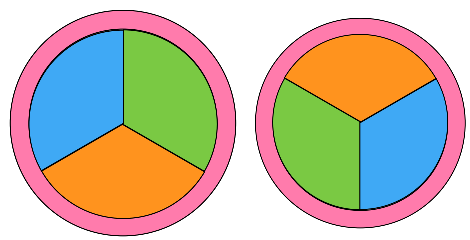


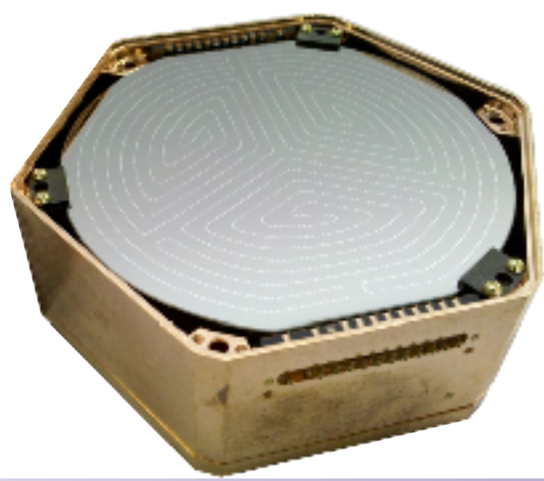


SuperCDMS Soudan

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

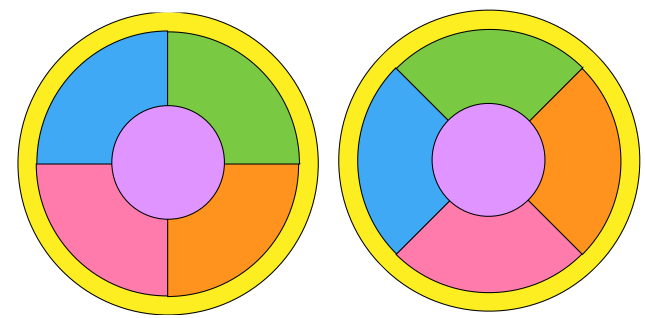
2 charge + 2 charge
4 phonon + 4 phonon

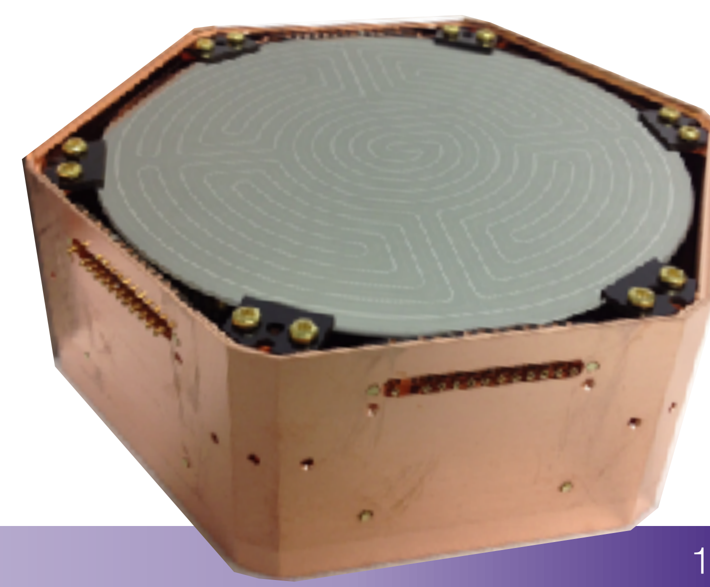




SuperCDMS SNOLAB

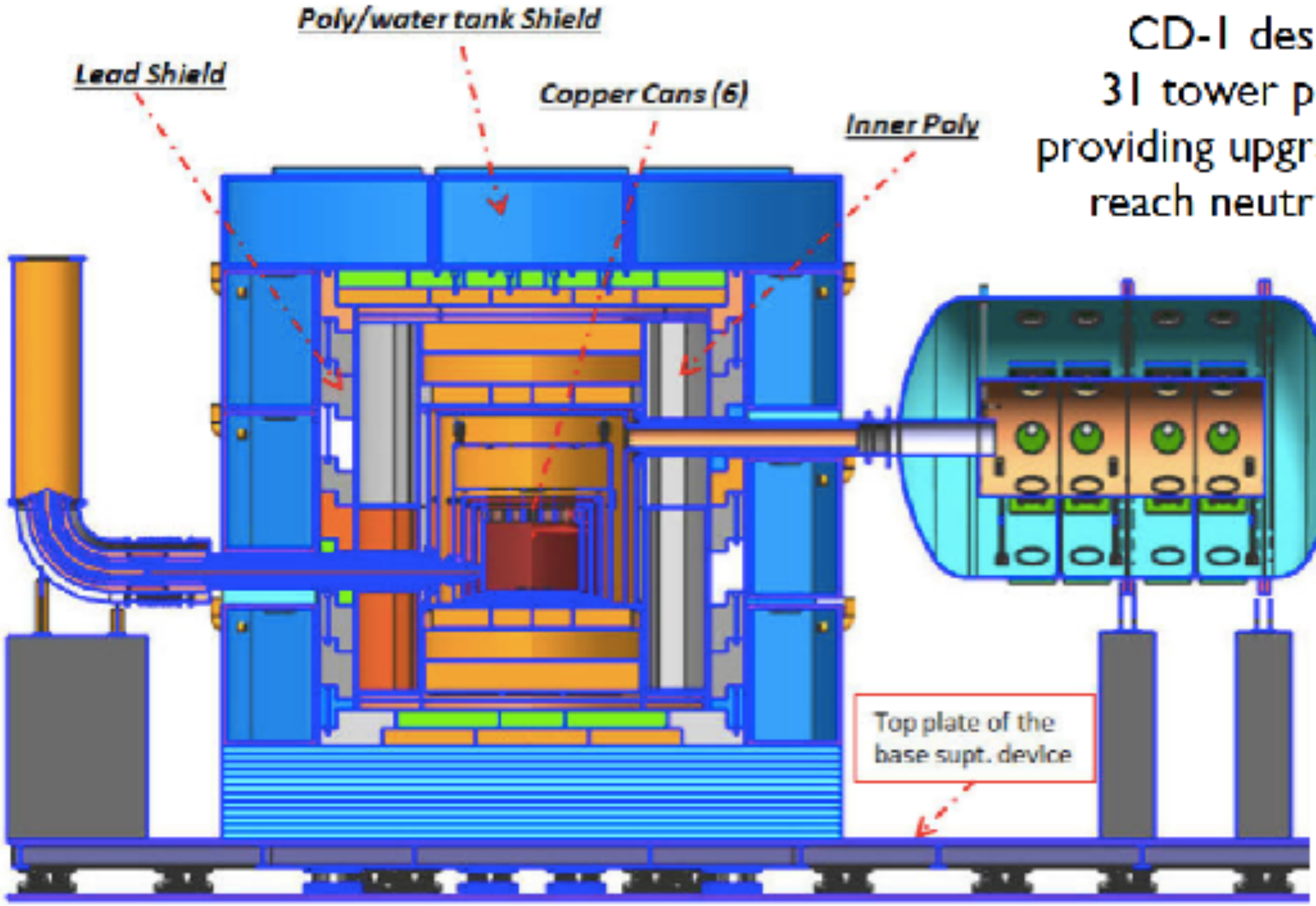
Funded G2 Experiment
Data Taking in 2020
30 kg Ge (22 x 1.4 kg)
5 kg Si (8 x 0.6 kg)
4” Diameter
3.3 cm Thick
2 charge + 2 charge
6 phonon + 6 phonon



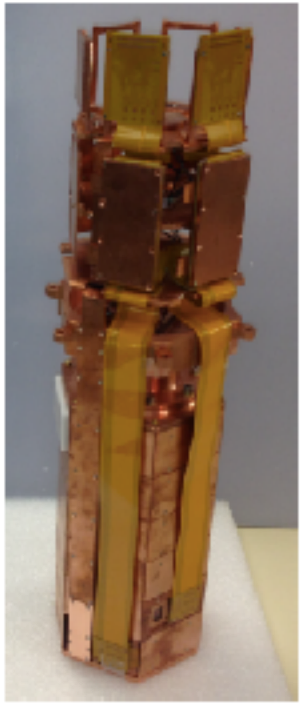


SuperCDMS SNOLAB @ the Ladder Lab

- Passive Shielding or Active neutron shield (under consideration) to achieve 0.1 /kg/keV/day background rate on Ge Towers. Much cleaner cryostat than CDMS II @ Soudan

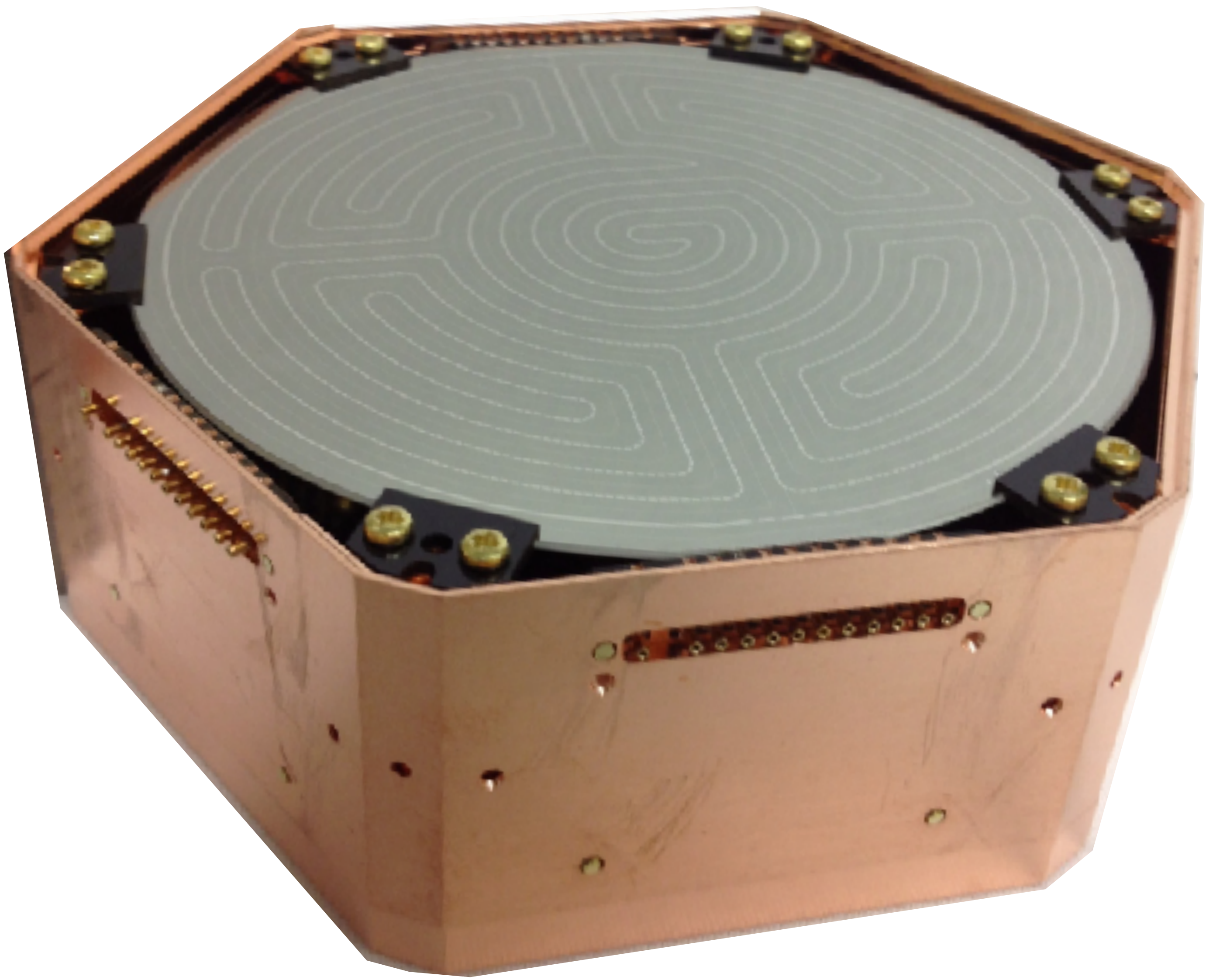


CD-1 design has 31 tower positions, providing upgrade path to reach neutrino floor



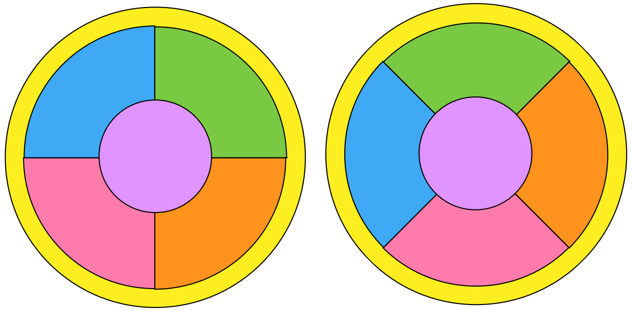
Detector Payload:
- 3 Ge iZIP towers (50 kg)
- 1 Si iZIP tower (4 kg)
- 1 HV tower:
  - 4 Ge (5.6 kg)
  - 2 Si (1.4 kg)

SuperCDMS Detectors: iZIPs



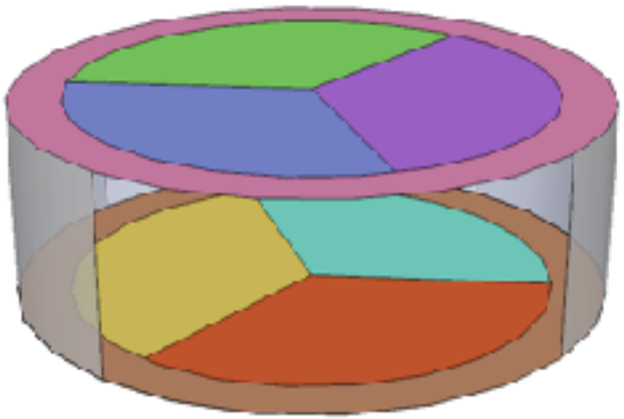
Ge (1.4 kg per detector)
Si (0.6 kg per detector)
4” Diameter
3.3 cm Thick

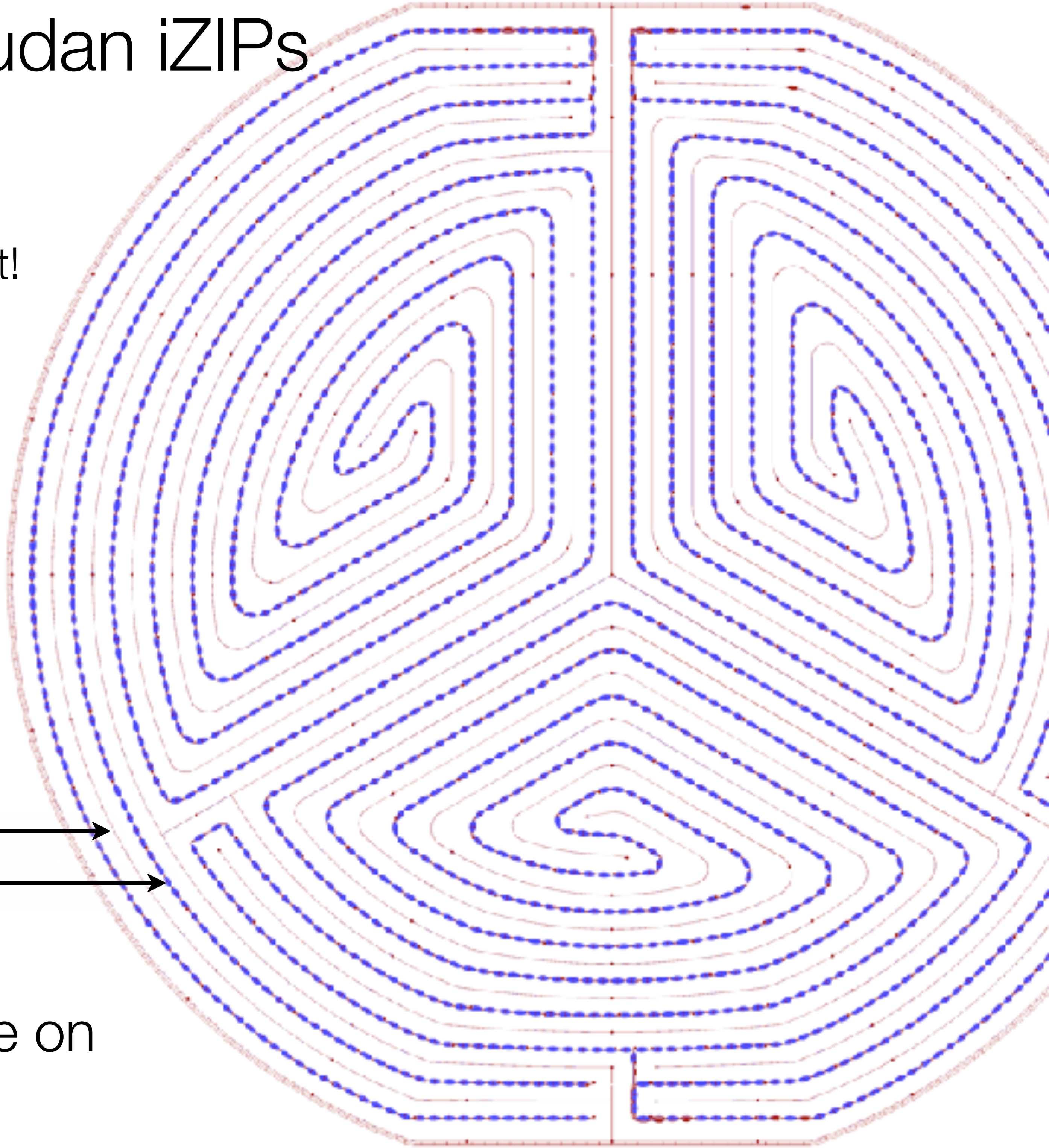
2 charge + 2 charge
6 phonon + 6 phonon



SuperCDMS Soudan iZIPs

8 phonon channels +
4 charge sensors =
Lots of information per event!

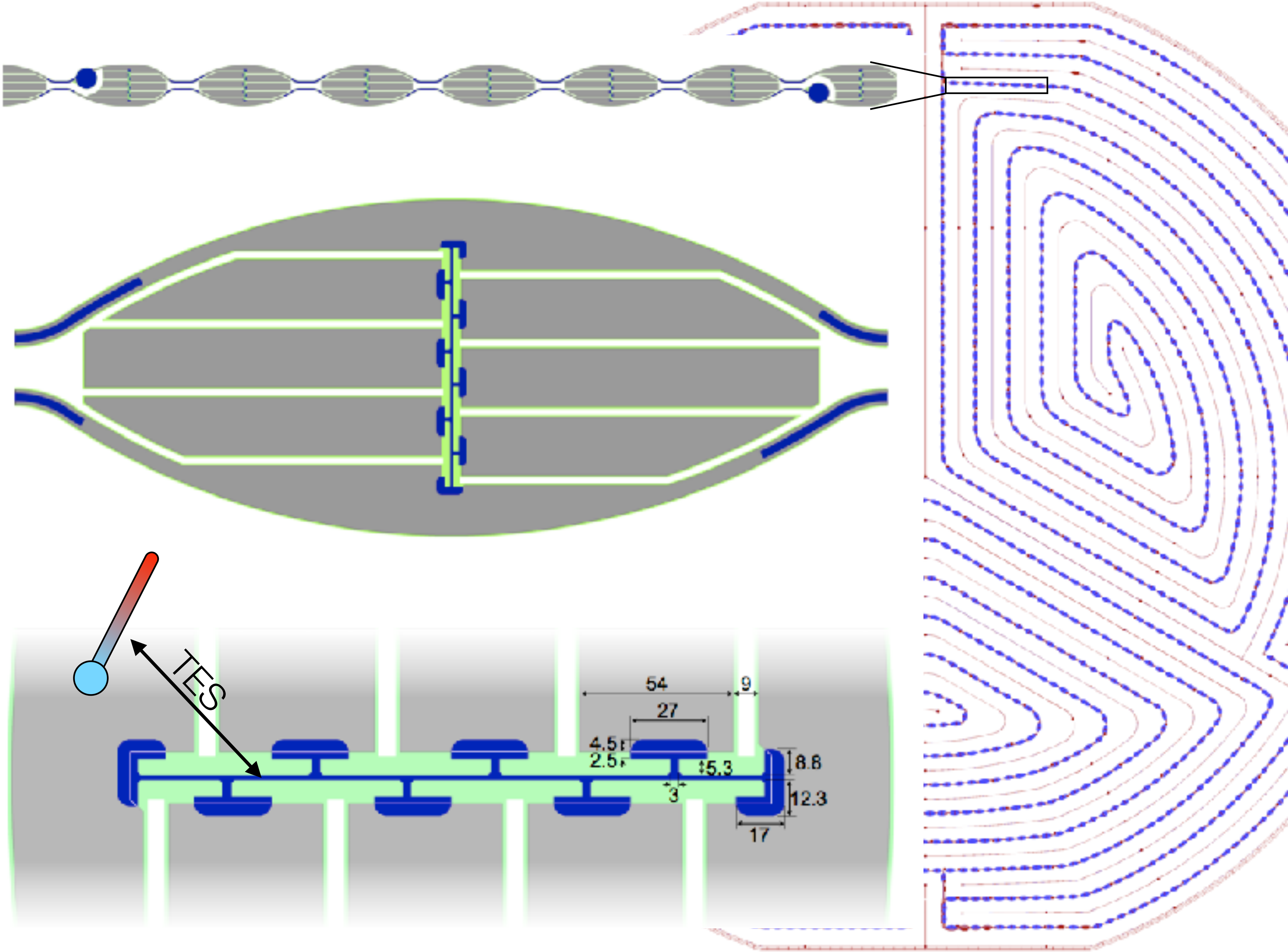




phonon sensor (grounded)

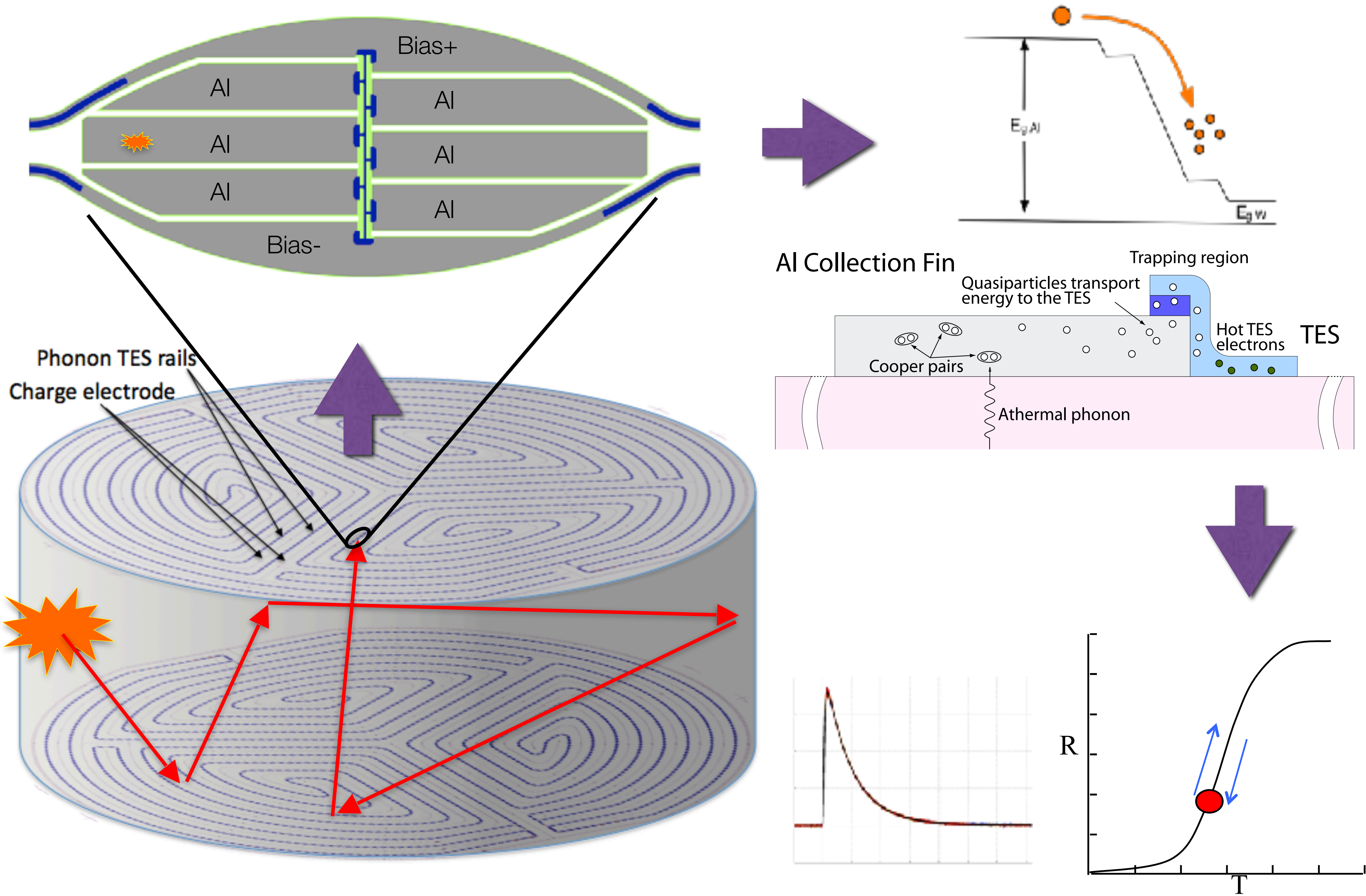
charge sensor (biased)

"interwoven"
phonon *and* charge on each side!



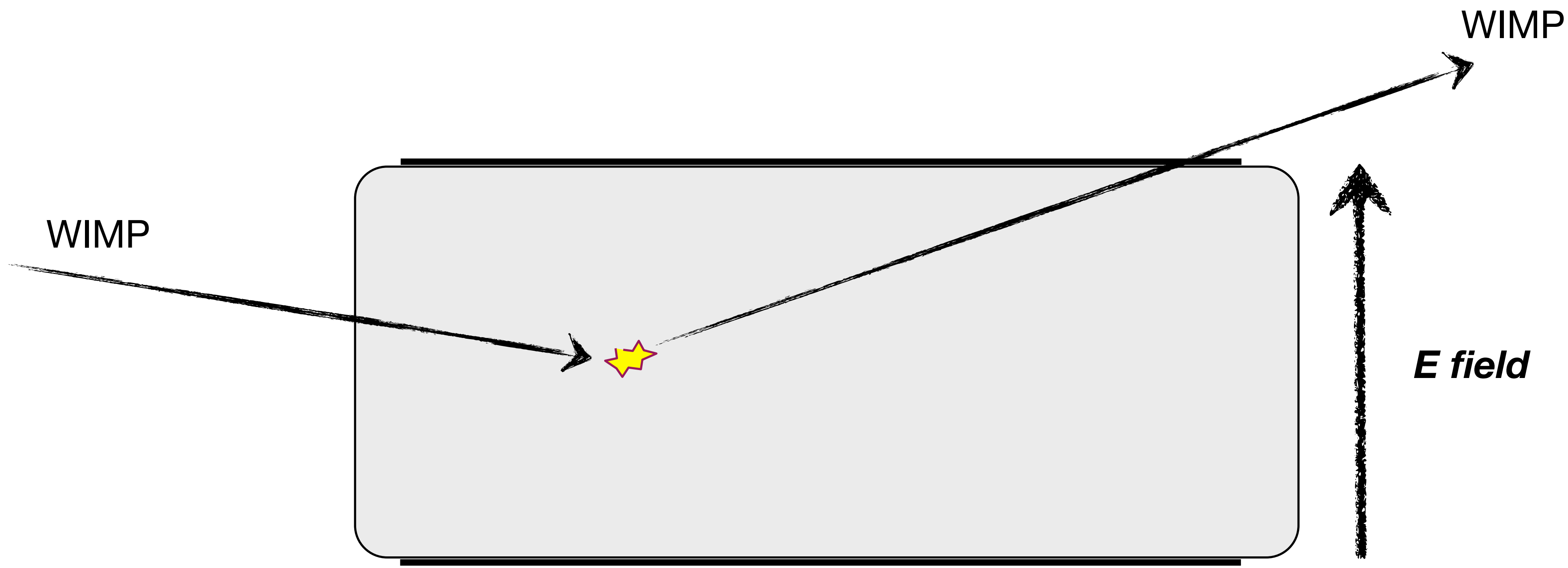
TES
54
9
27
4.5
2.5
5.3
3
8.8
12.3
17

Getting Energy to the Athermal Phonon Sensors



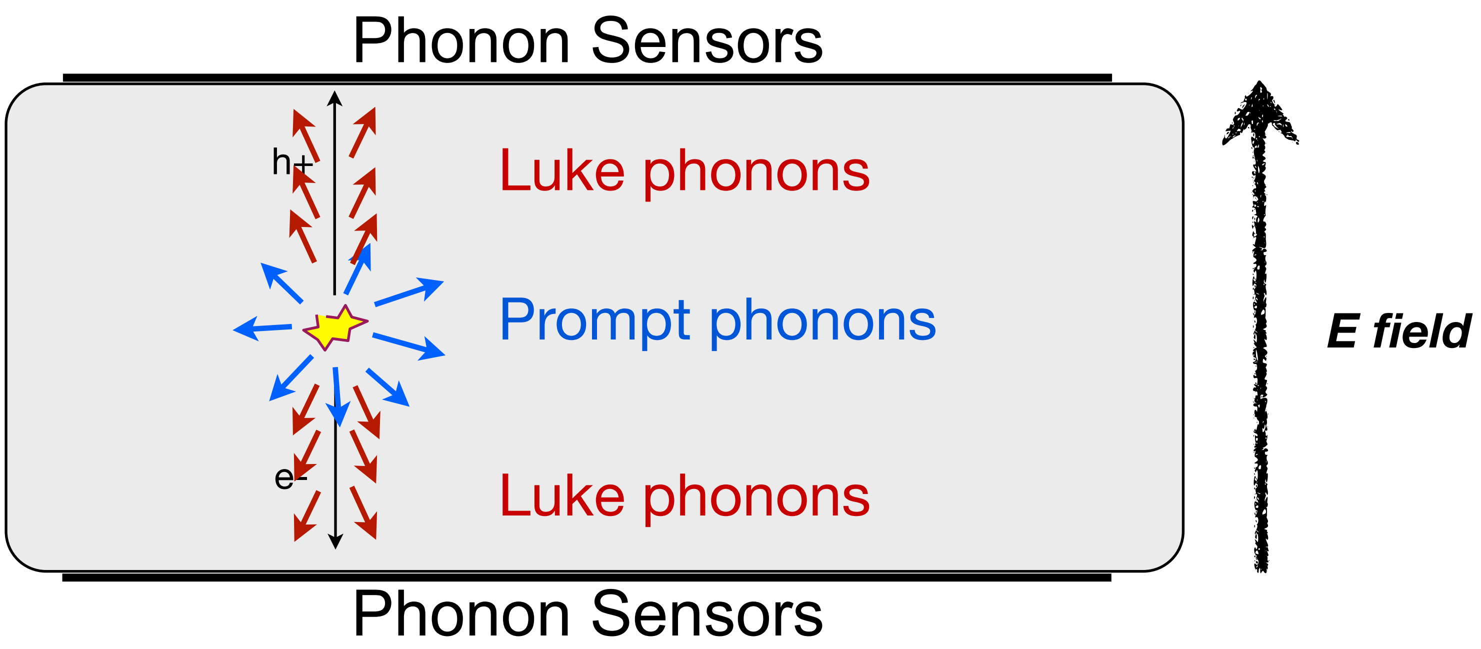
SuperCDMS High-Voltage Operation

CDMSlite: CDMS low ionization threshold experiment

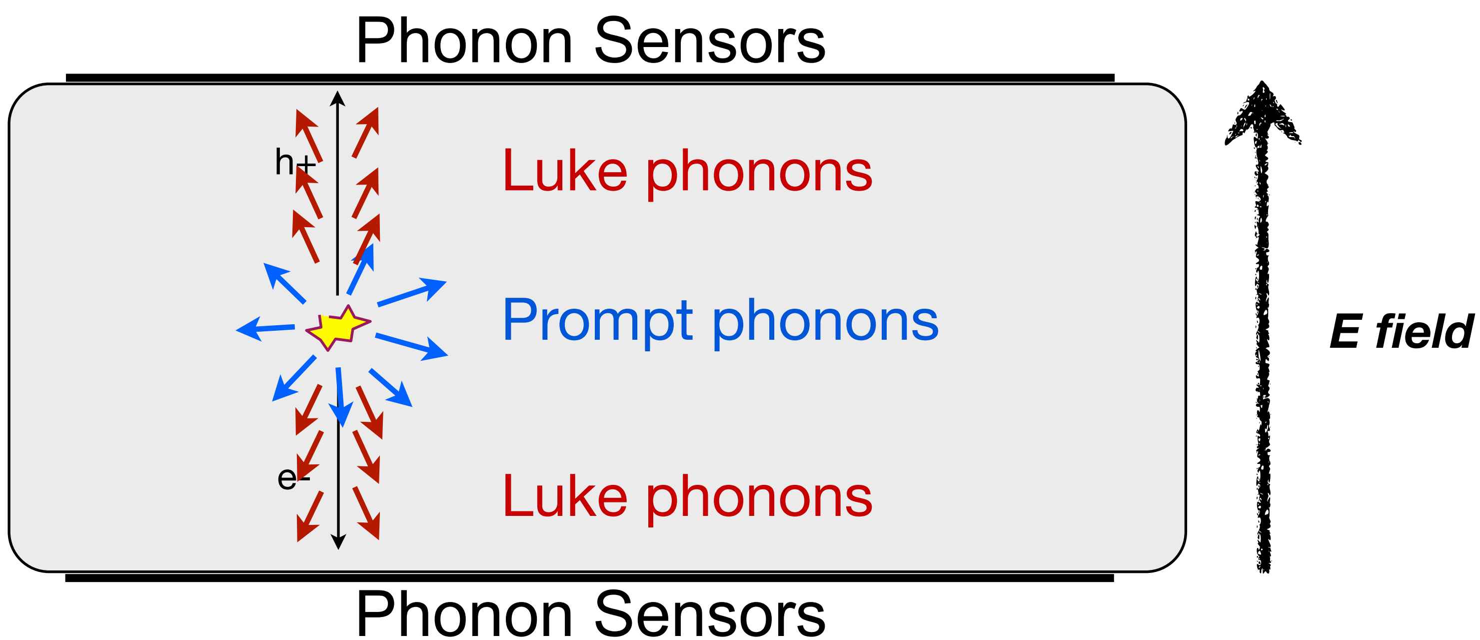


SuperCDMS High-Voltage Operation

SuperCDMS High-Voltage Operation



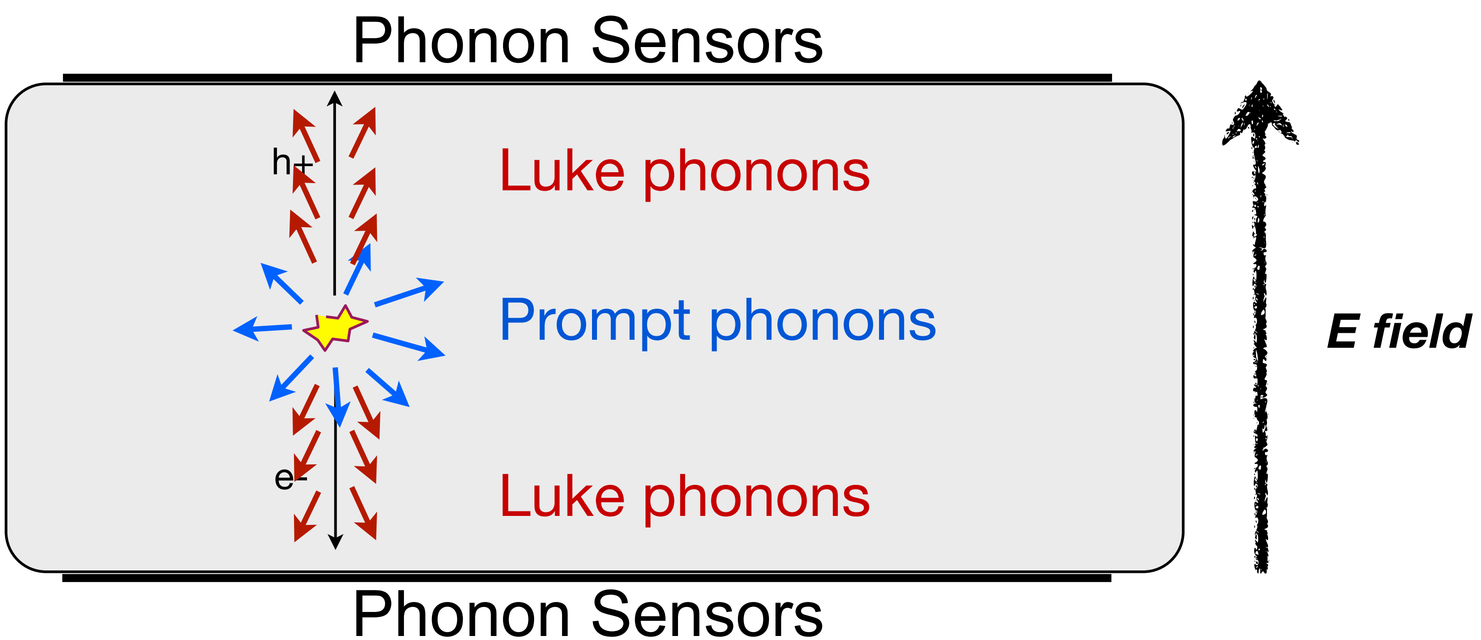
SuperCDMS High-Voltage Operation



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

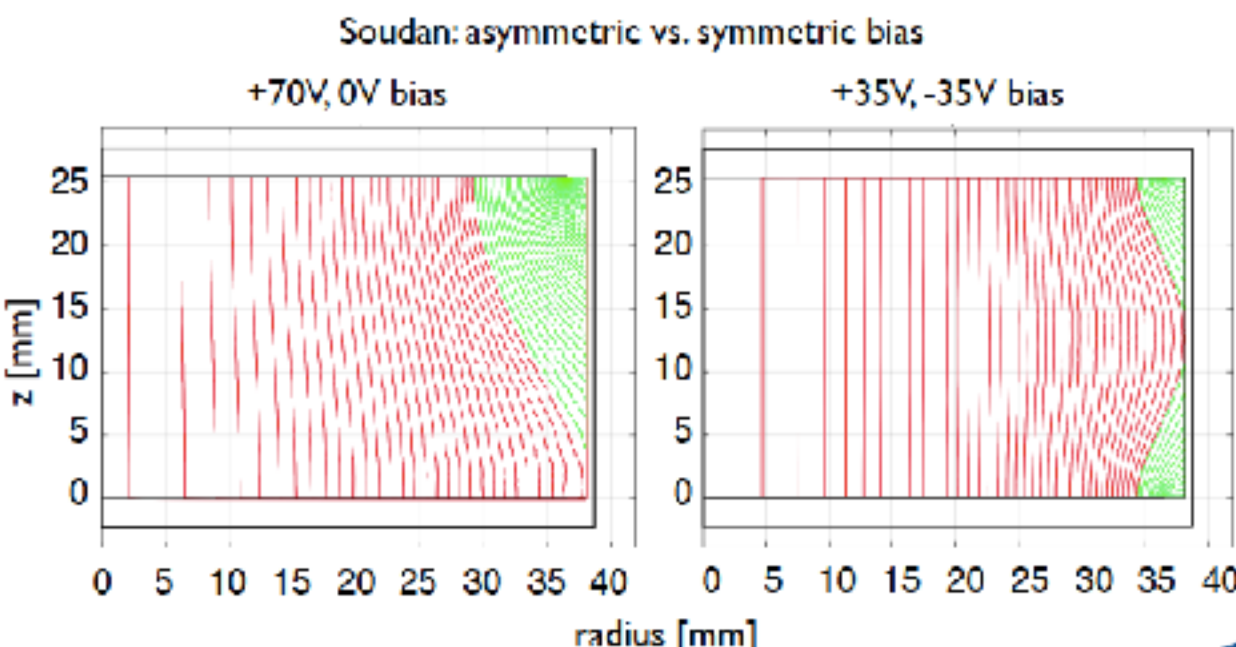
SuperCDMS High-Voltage Operation

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



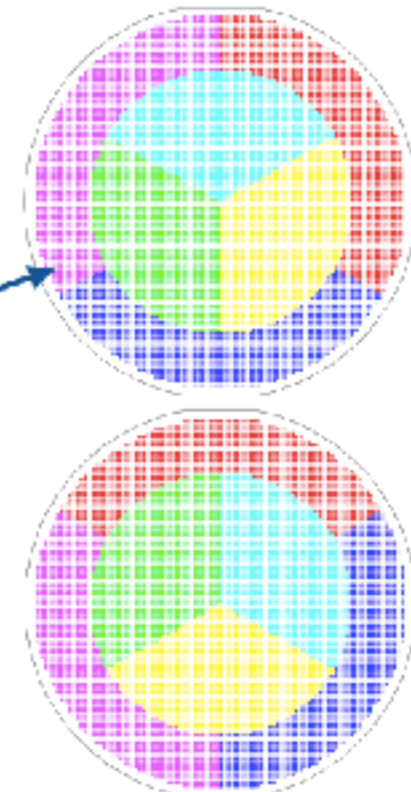
$$\text{Phonon energy} = E_{recoil} + E_{Luke}$$
$$= E_{recoil} + n_{eh}\, e^{-}\, \Delta V$$

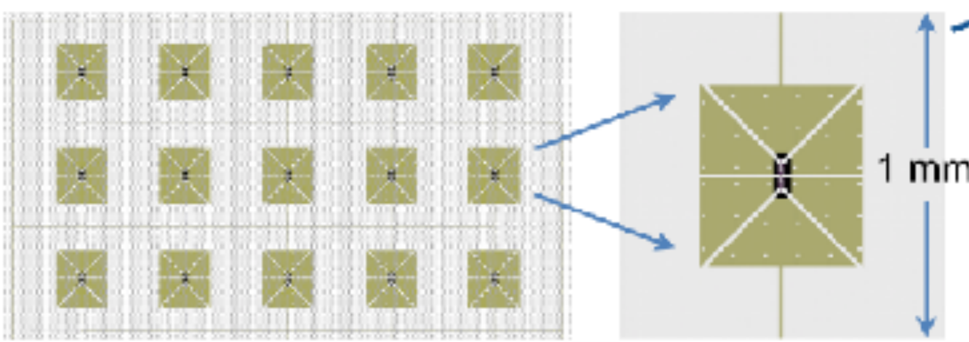
SuperCDMS SNOLAB HV Detector Design



Symmetric HV bias at +/- 50V to maximize fiducial volume

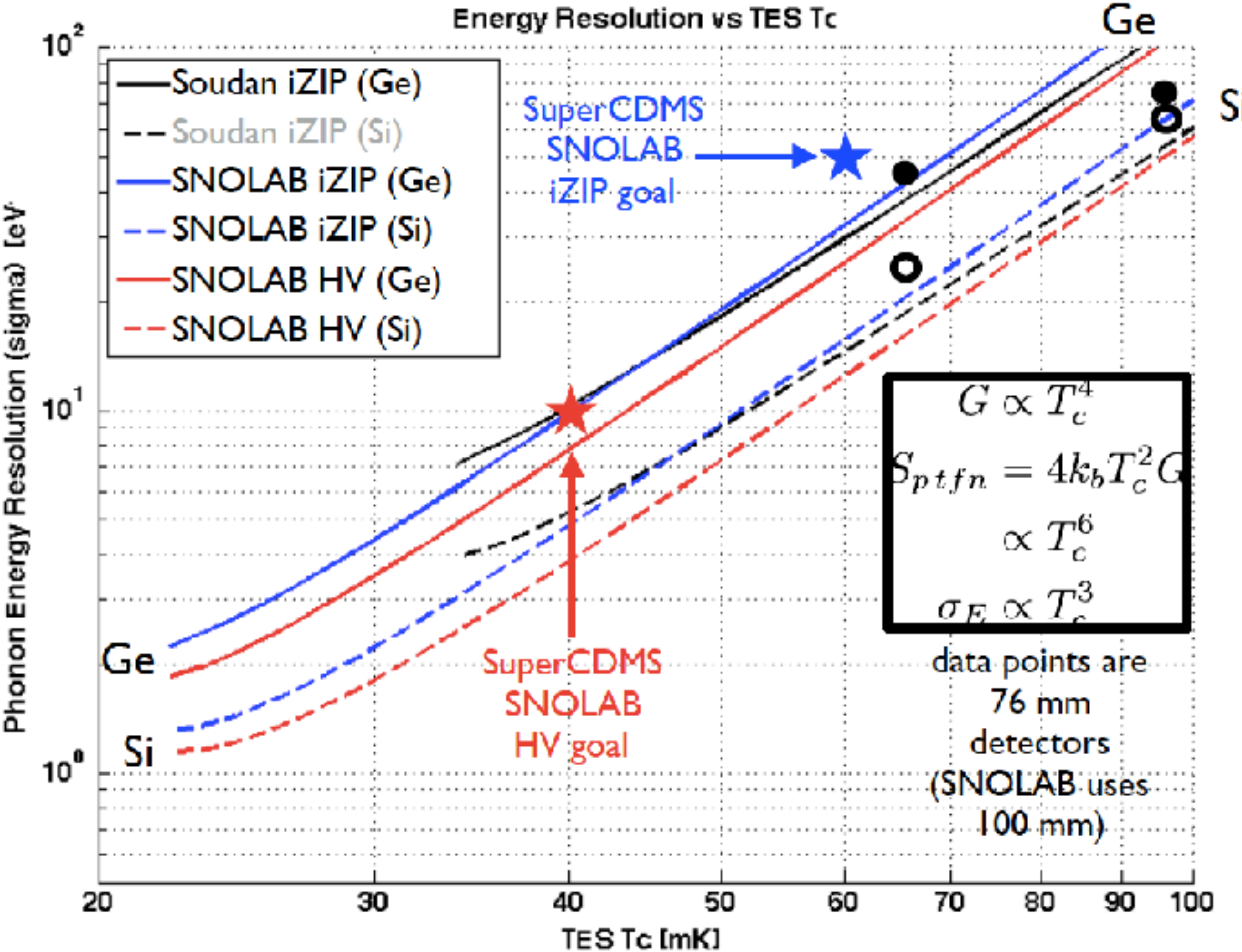
maximize phonon radial position reconstruction information





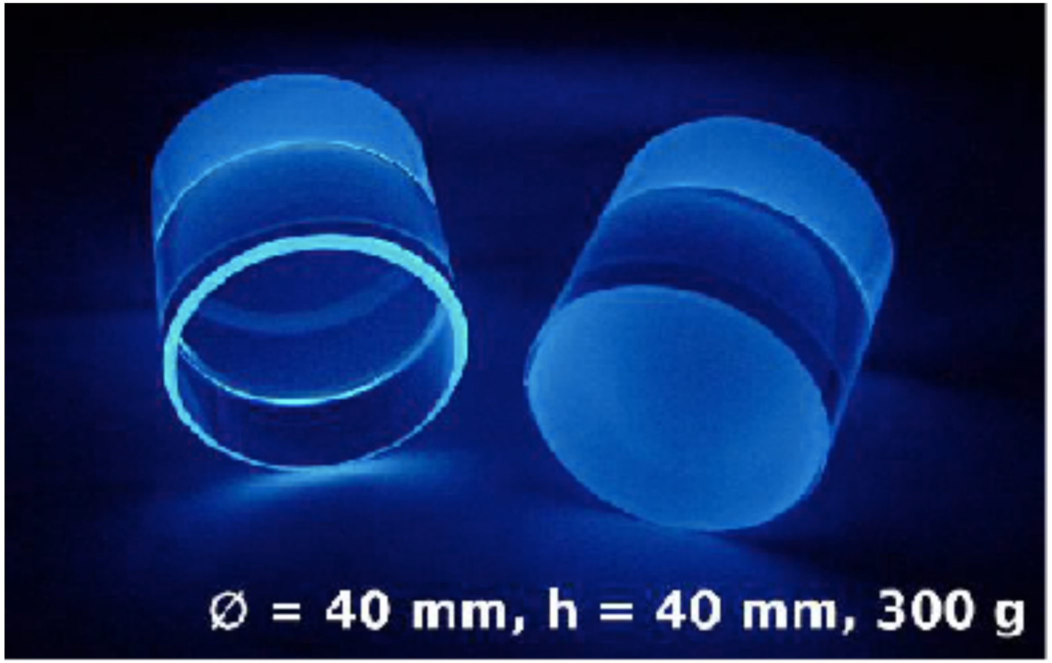
Uniform coverage phonon sensors to maximize energy collection

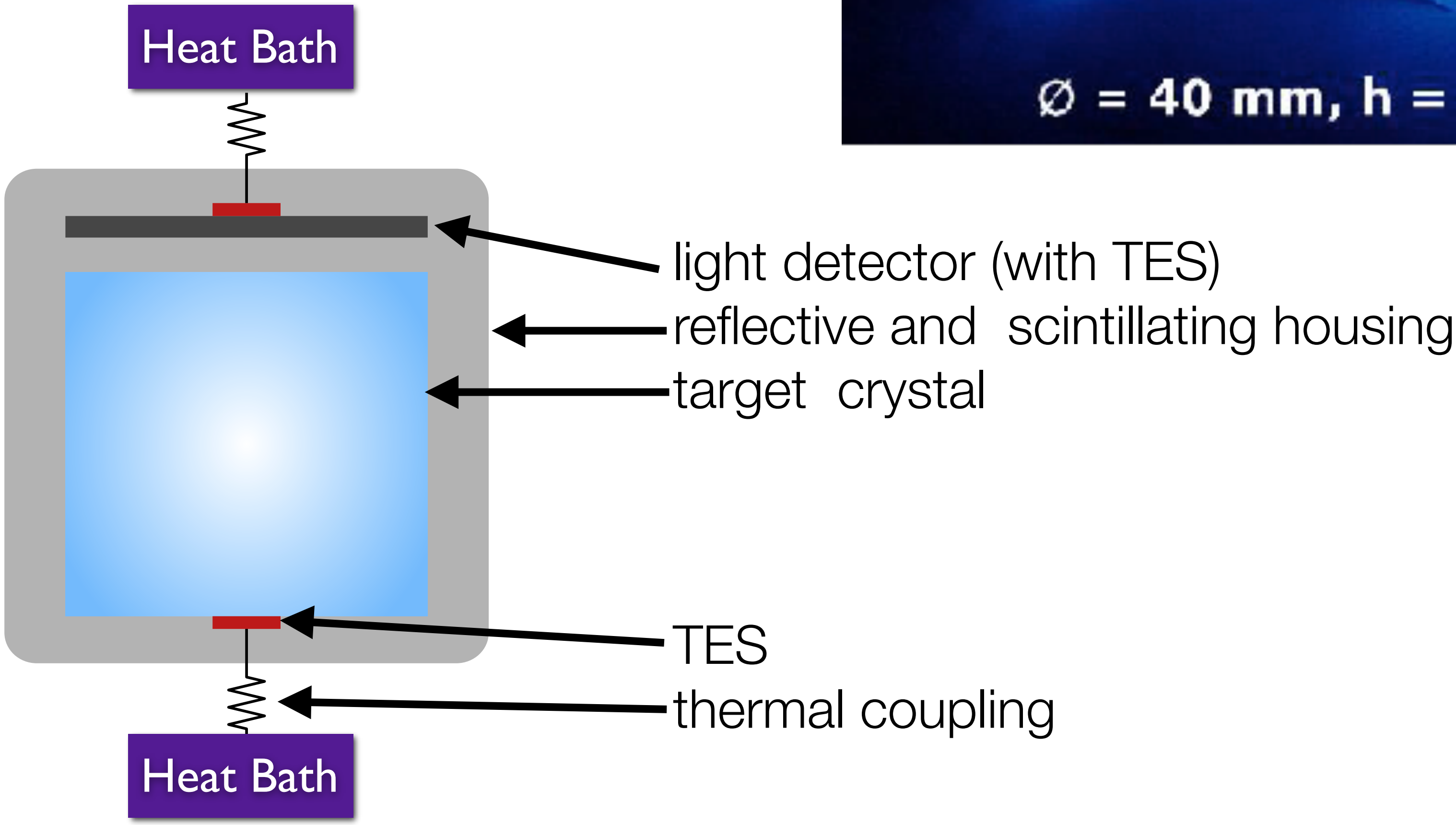
Better Phonon Sensitivity with Lower T_c!



CRESST

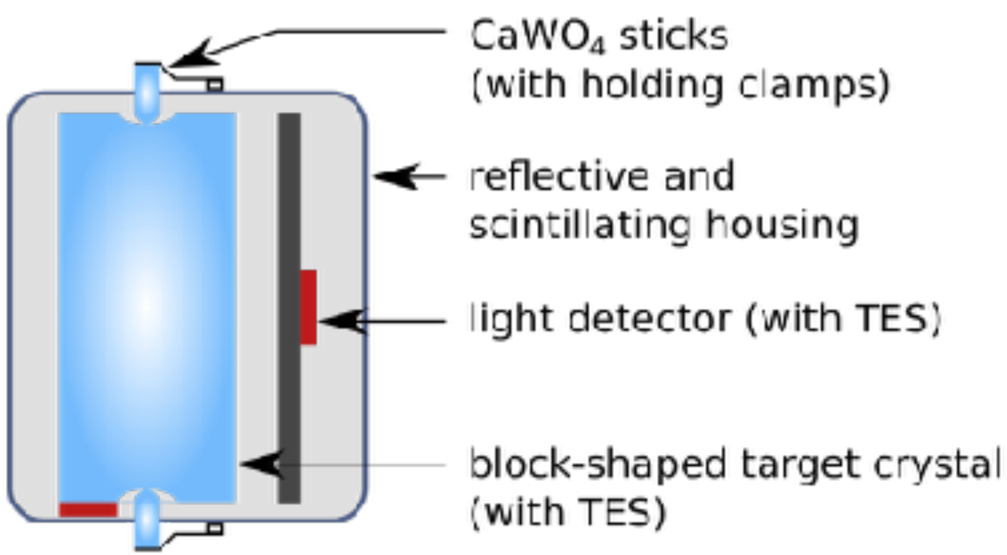
- CRESST: phonon + light
- Current Experiment: CRESST Phase 2 ongoing
- New CRESST Phase III detectors focused on low-mass WIMPs

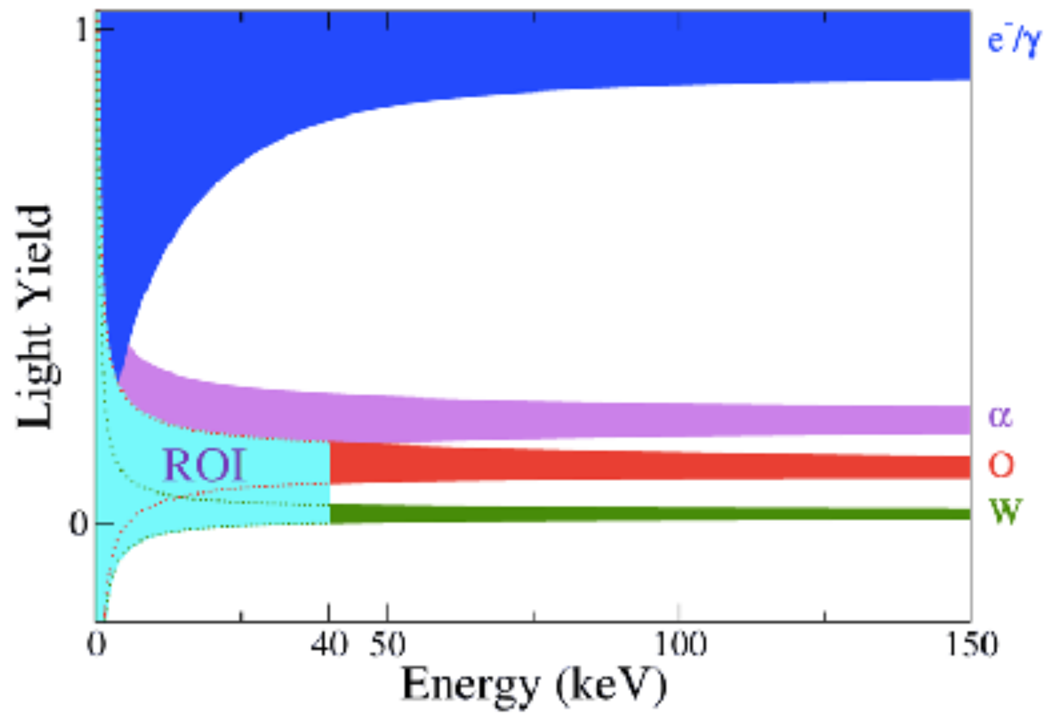




CRESST

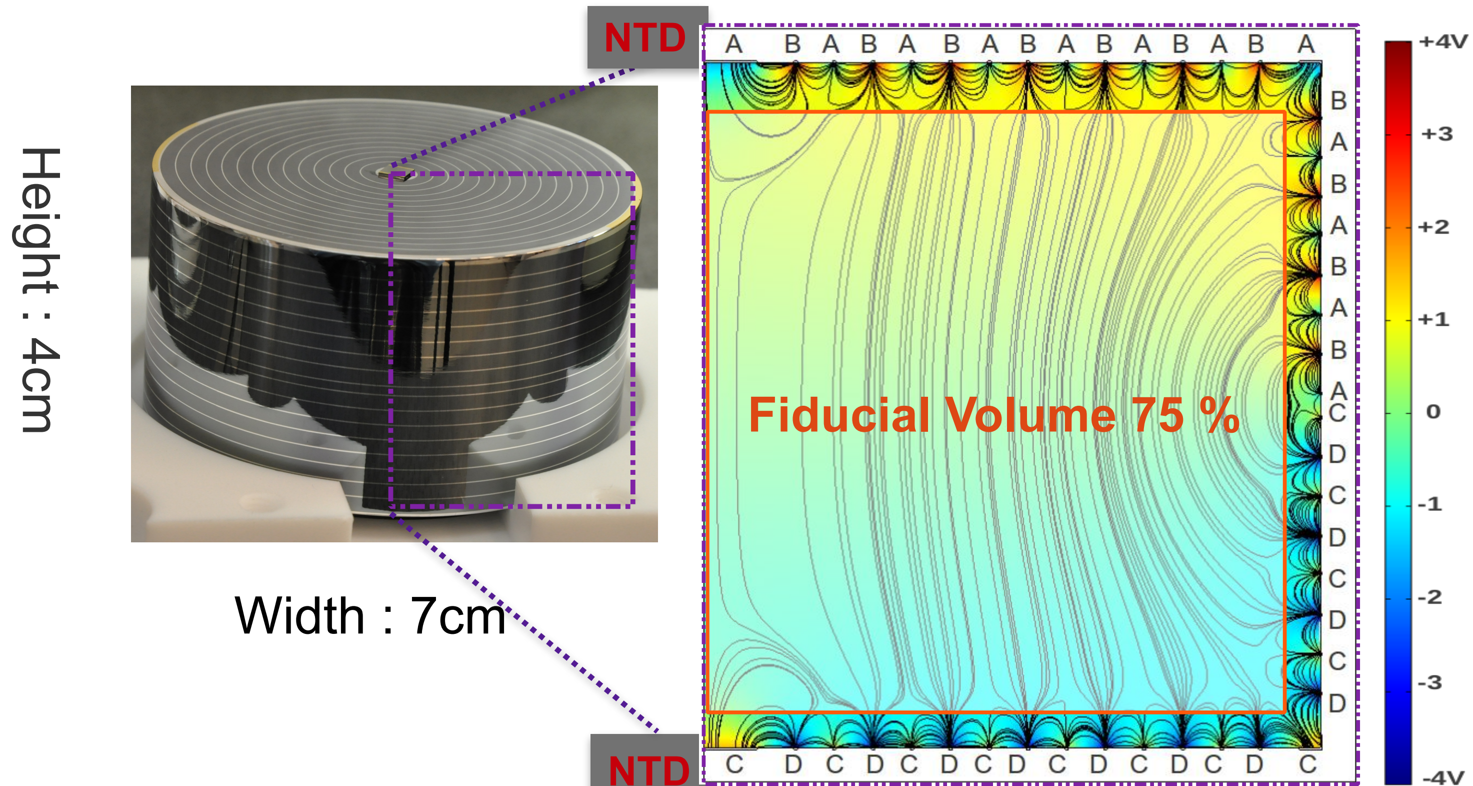
- New CRESST Phase III detectors focused on low-mass WIMPs
- Design Goal: Threshold of 100 eV. How? Smaller Crystals!
- Going from 250g in CRESST II to 24g in CRESST III



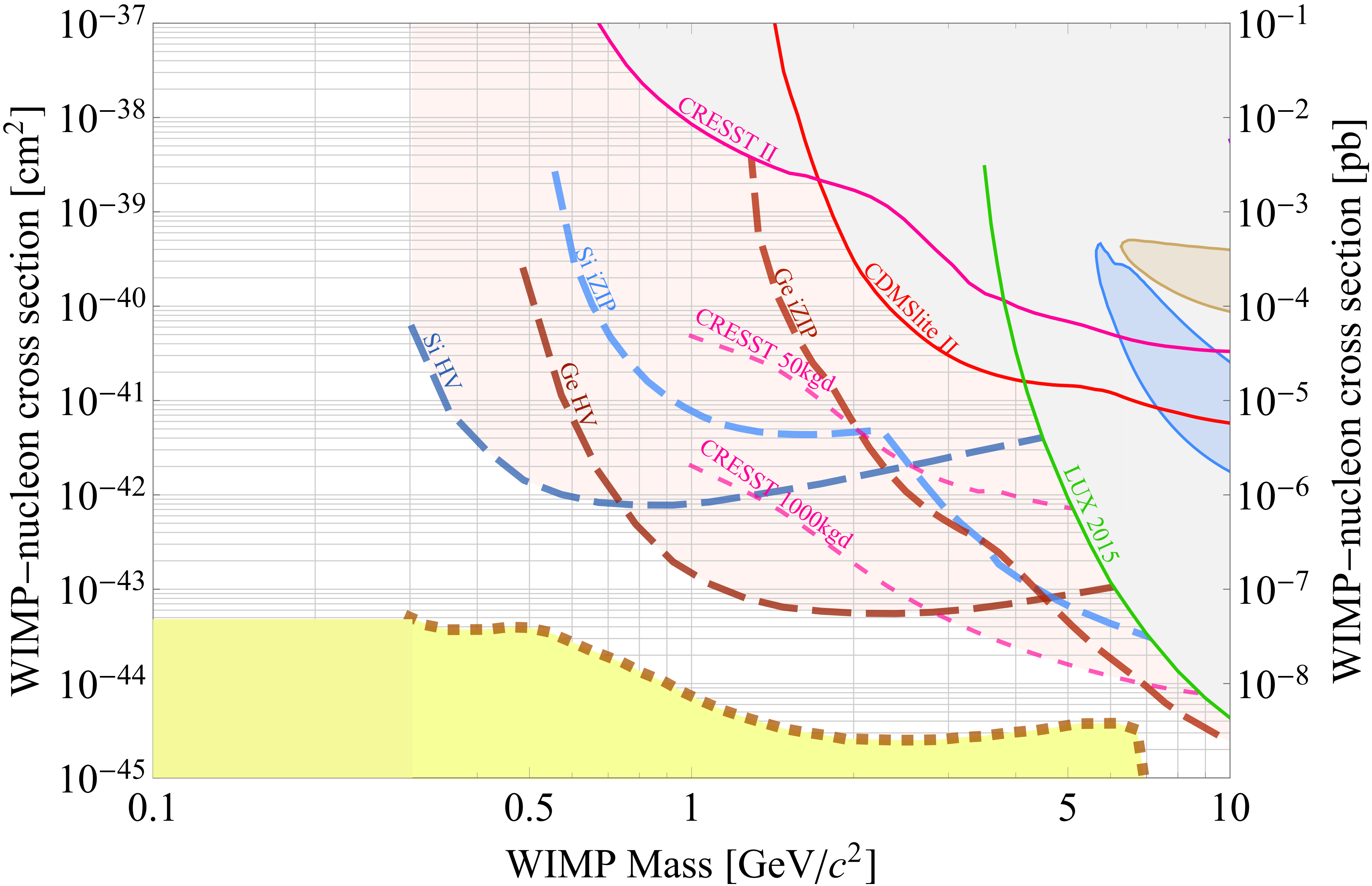


EDELWEISS

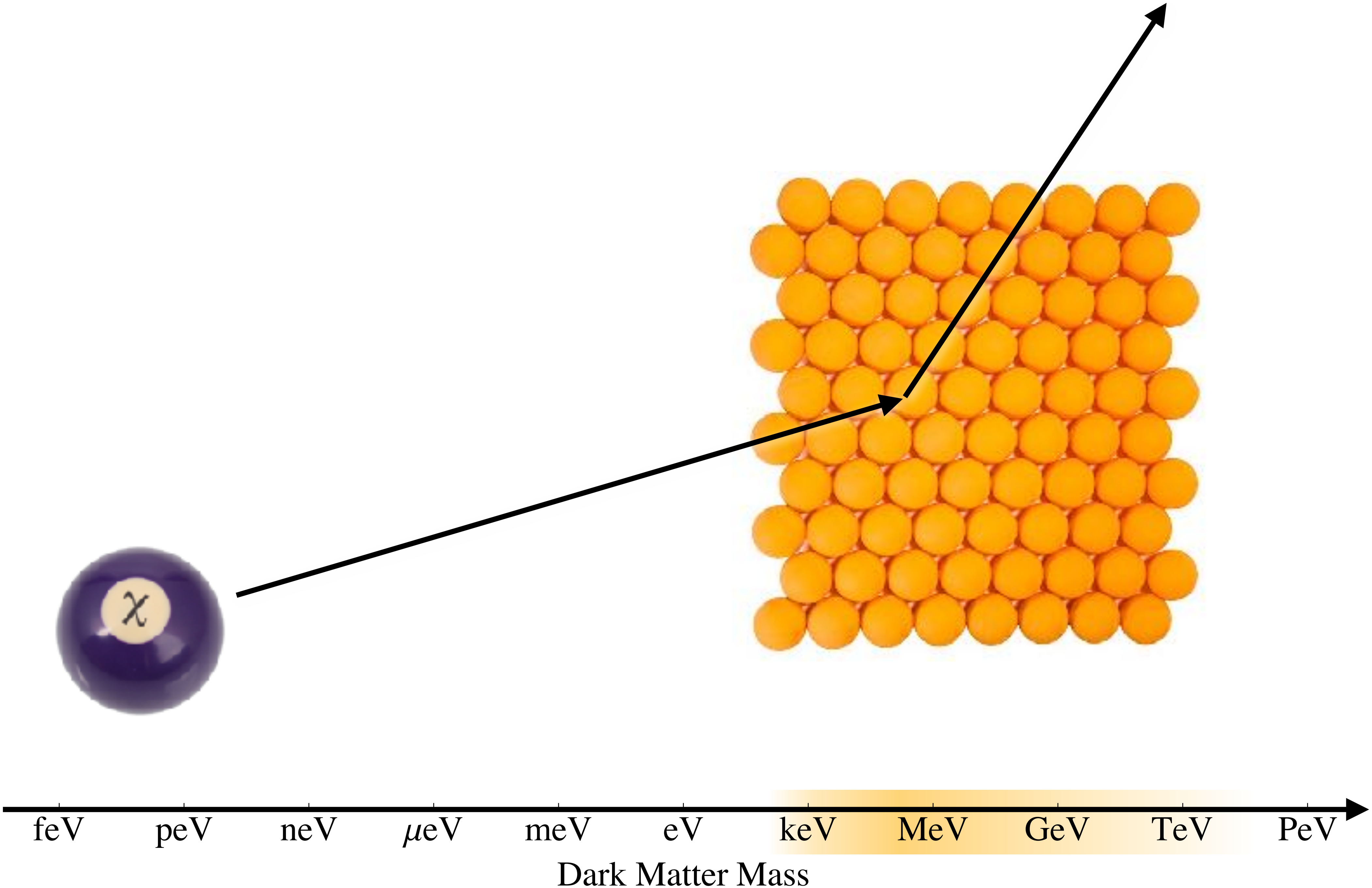
- EDELWEISS: phonon + charge
- 36 x 800 g detectors installed in cryostat; results later this year
- New runs with better sensitivity to light WIMPS using High Voltage operation coming soon.



To the Neutrino Background… and Beyond!

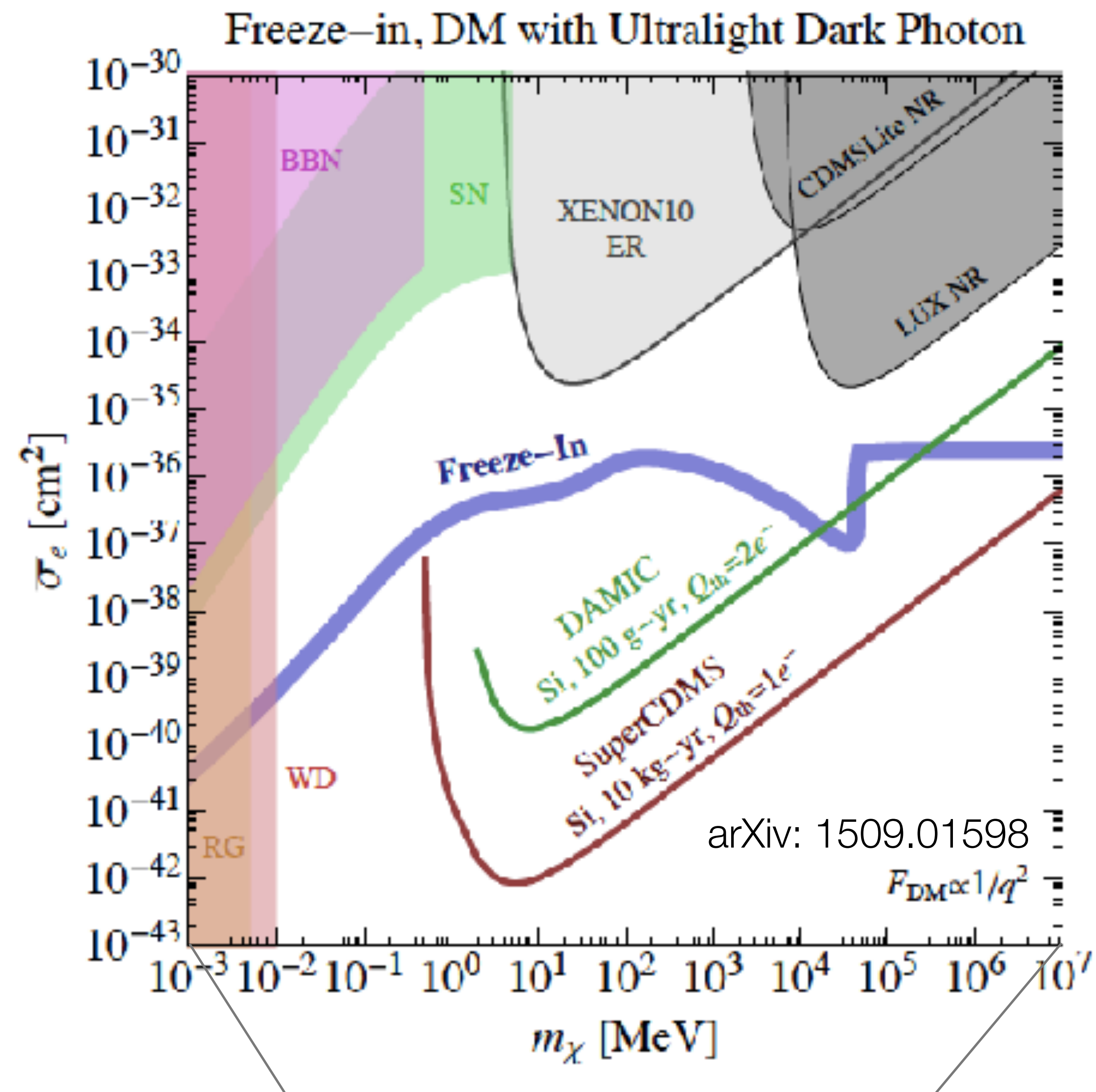


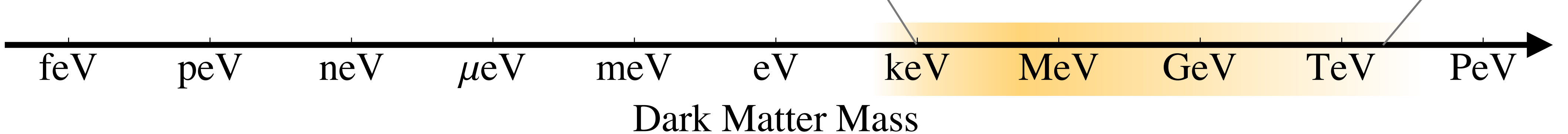
Electron Recoils



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, dark currents, and lowering backgrounds.
- Using materials with a band gap or even quasiparticles in superconductors can drastically reduce the threshold!





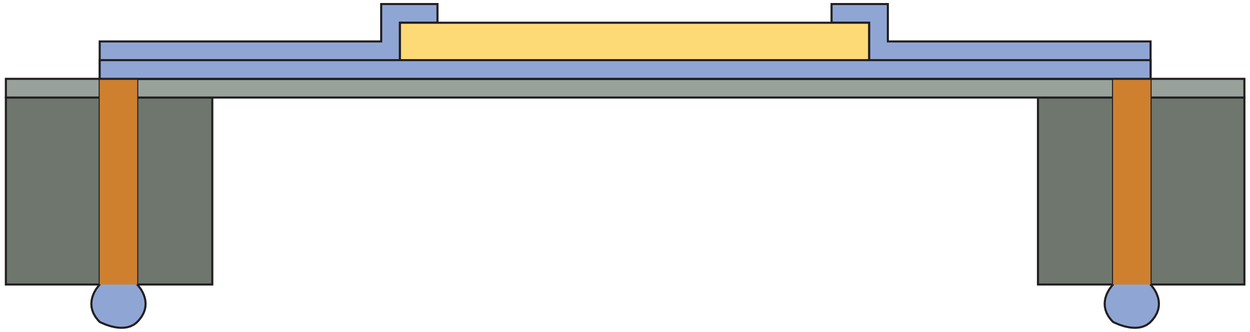
X-ray Astrophysics

Requirements

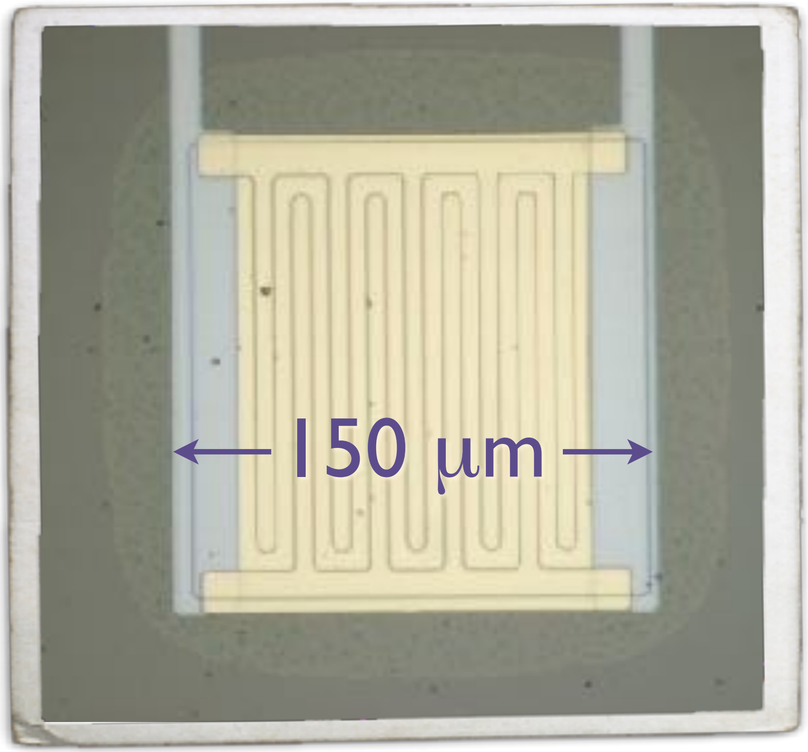
- High Energy Resolution
- High Quantum Efficiency
- High Count Rate
- Close-packing of pixels
- Large Arrays (megapixels desired)

Anatomy of an X-ray TES

Side View



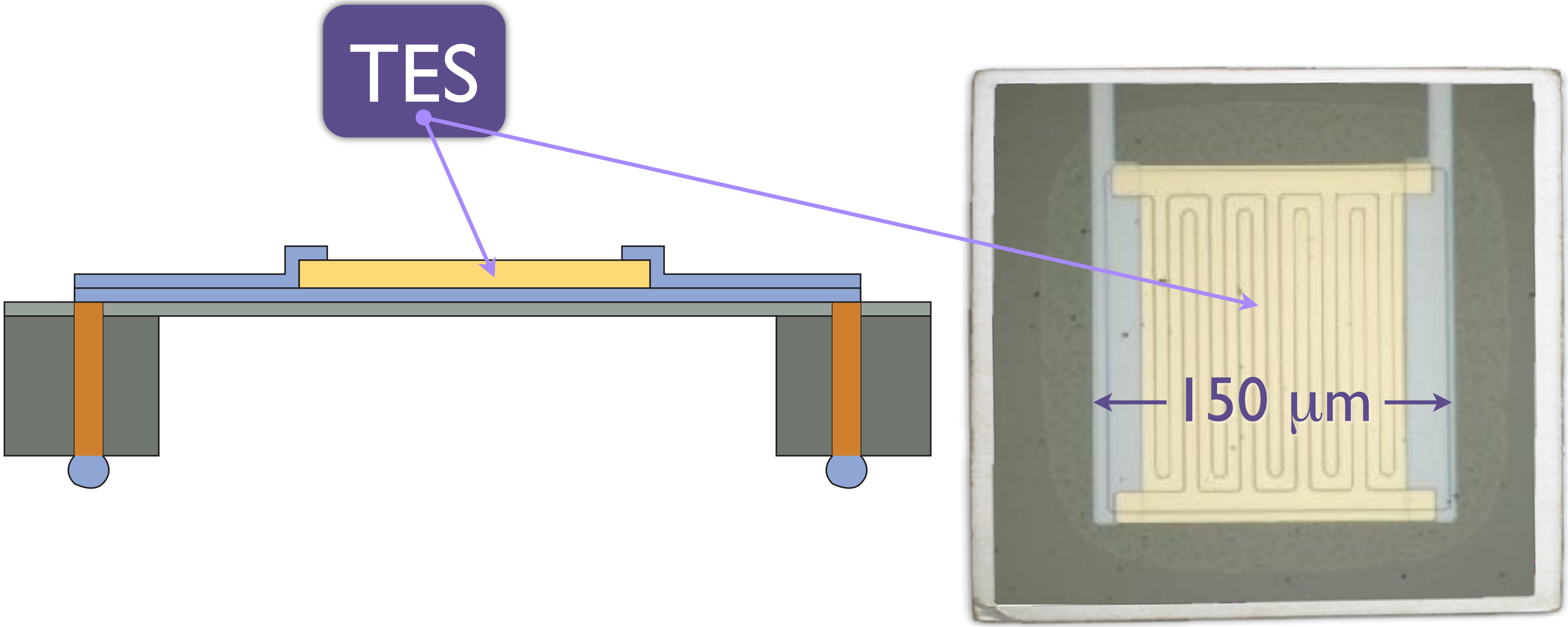
Top View



Anatomy of an X-ray TES

Side View

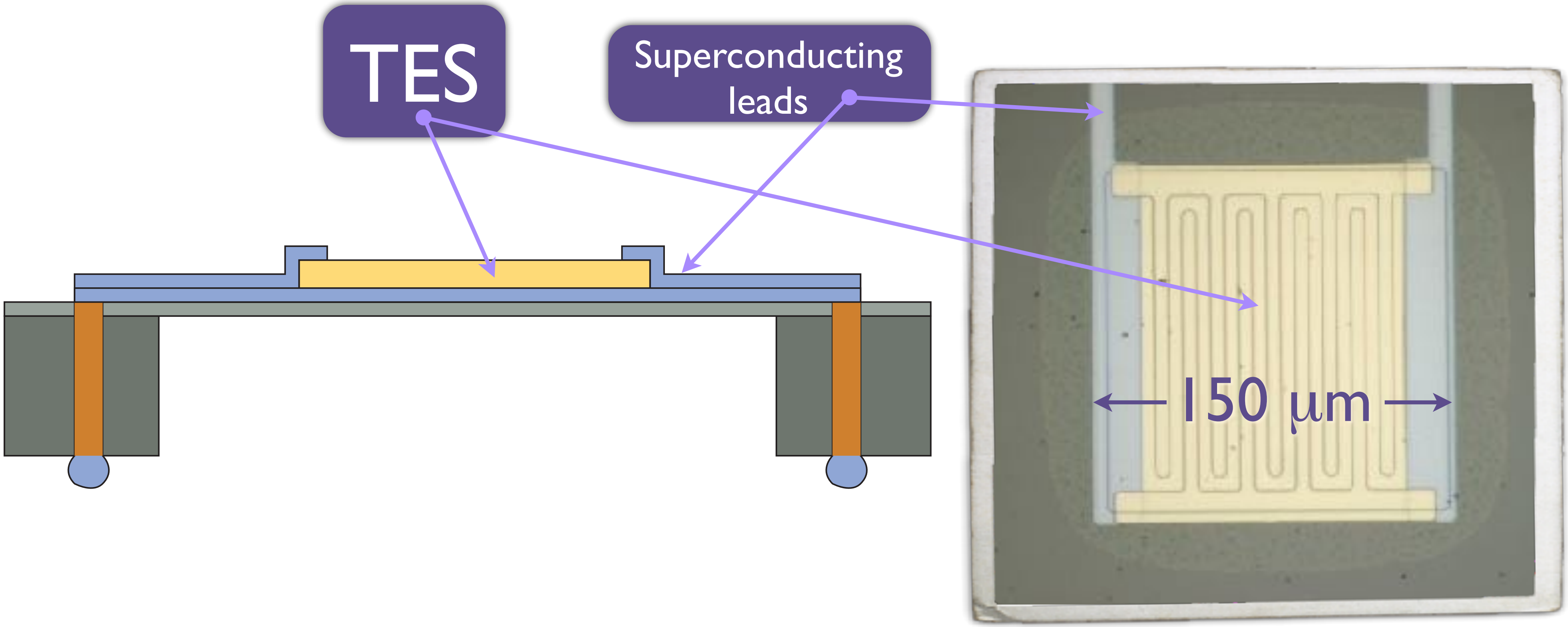
Top View



Anatomy of an X-ray TES

Side View

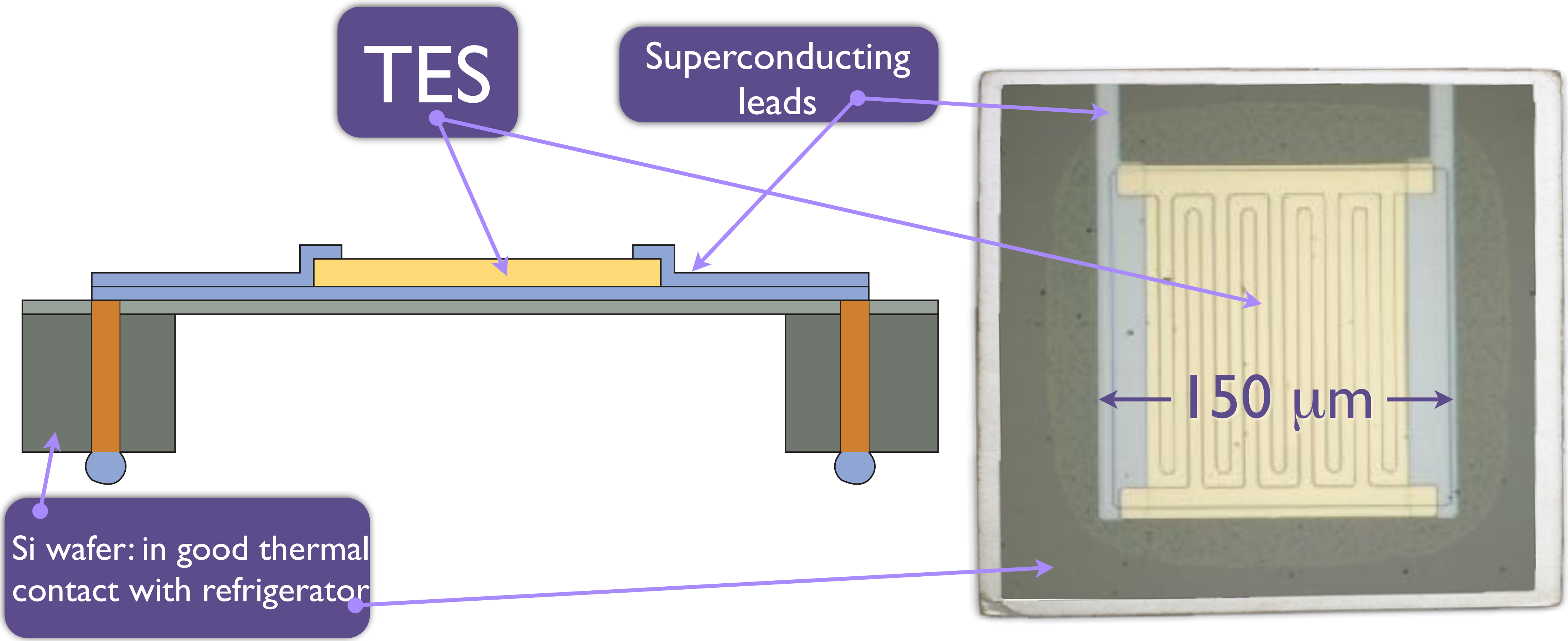
Top View



Anatomy of an X-ray TES

Side View

Top View



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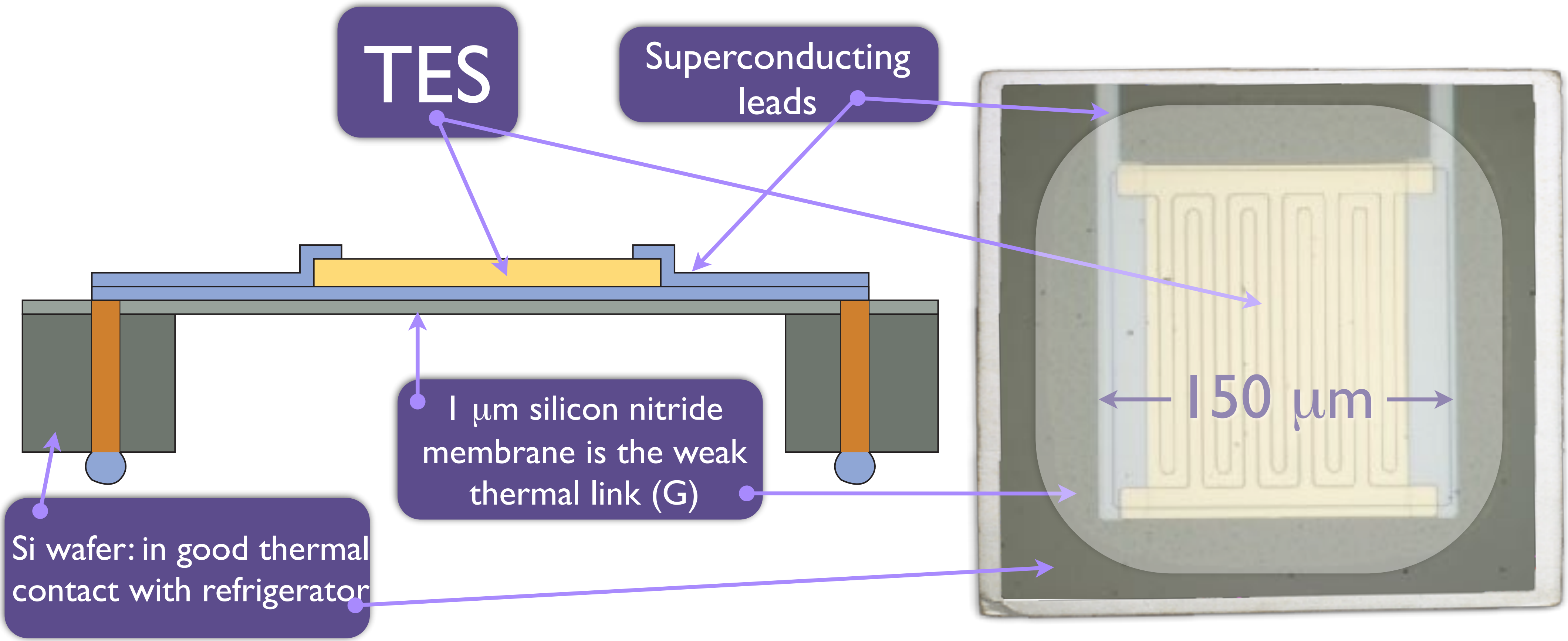
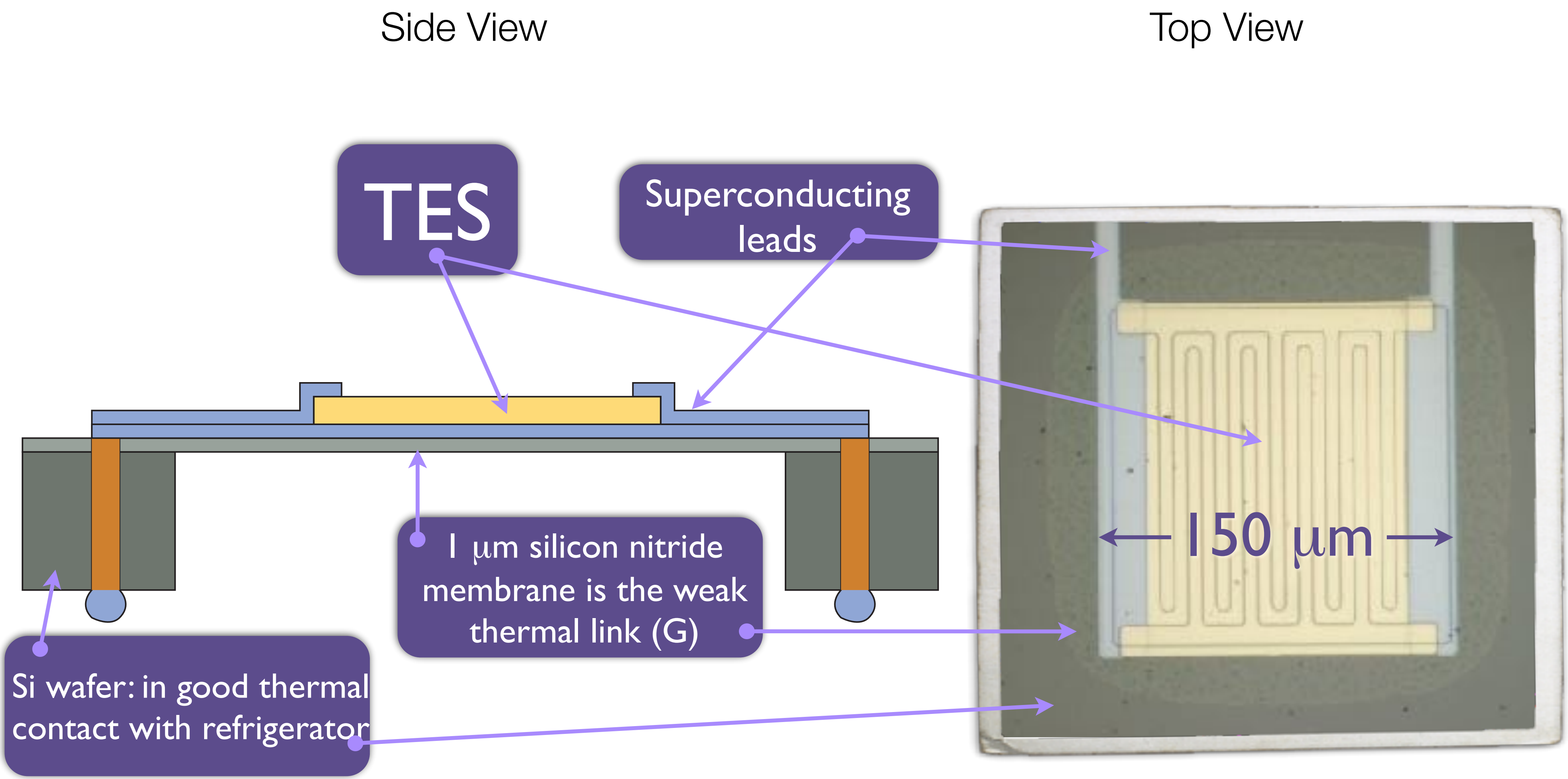
Top View



Anatomy of an X-ray TES



Anatomy of an X-ray TES

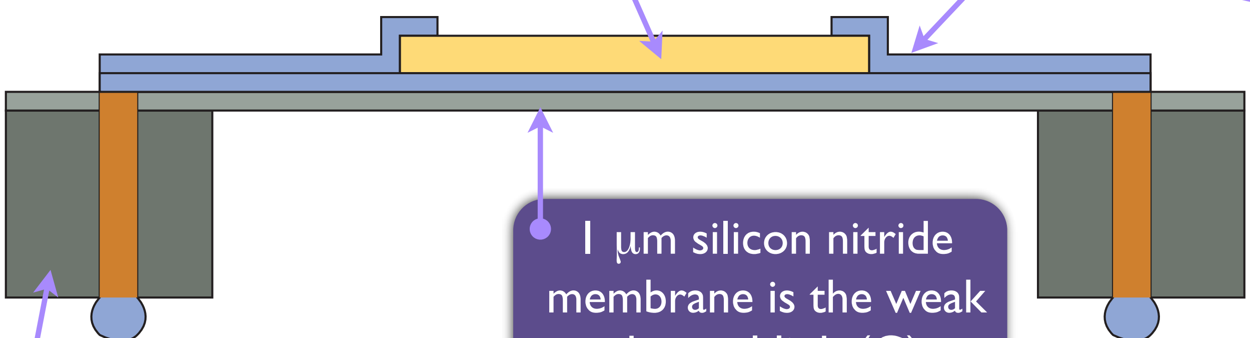
A 300-nm-thick TES has low x-ray stopping efficiency:

58 % @ 1.5 keV
22% @ 6 keV

Side View

TES

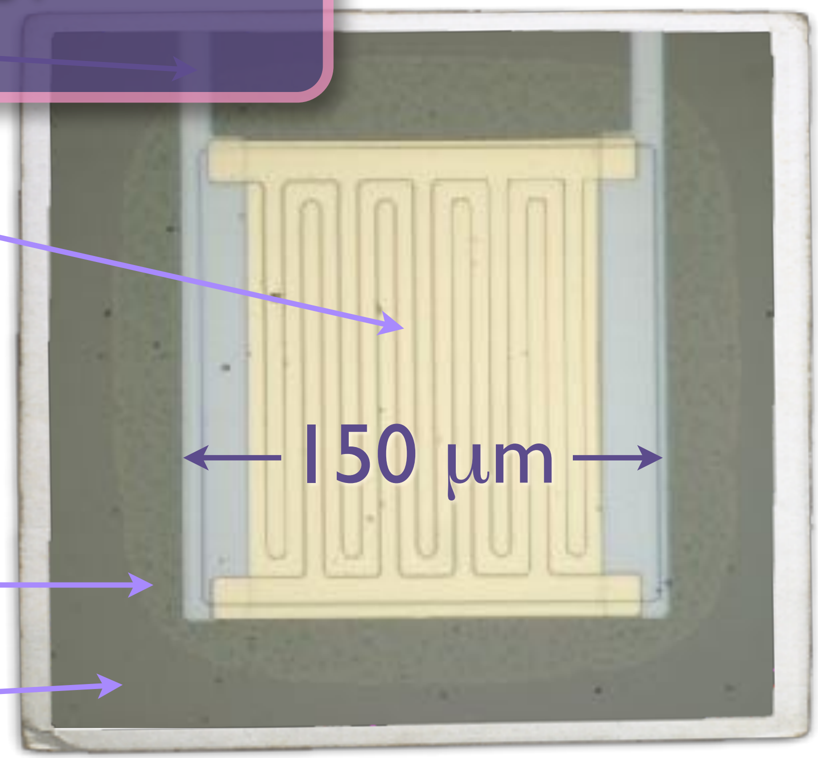
Supe ng
leads



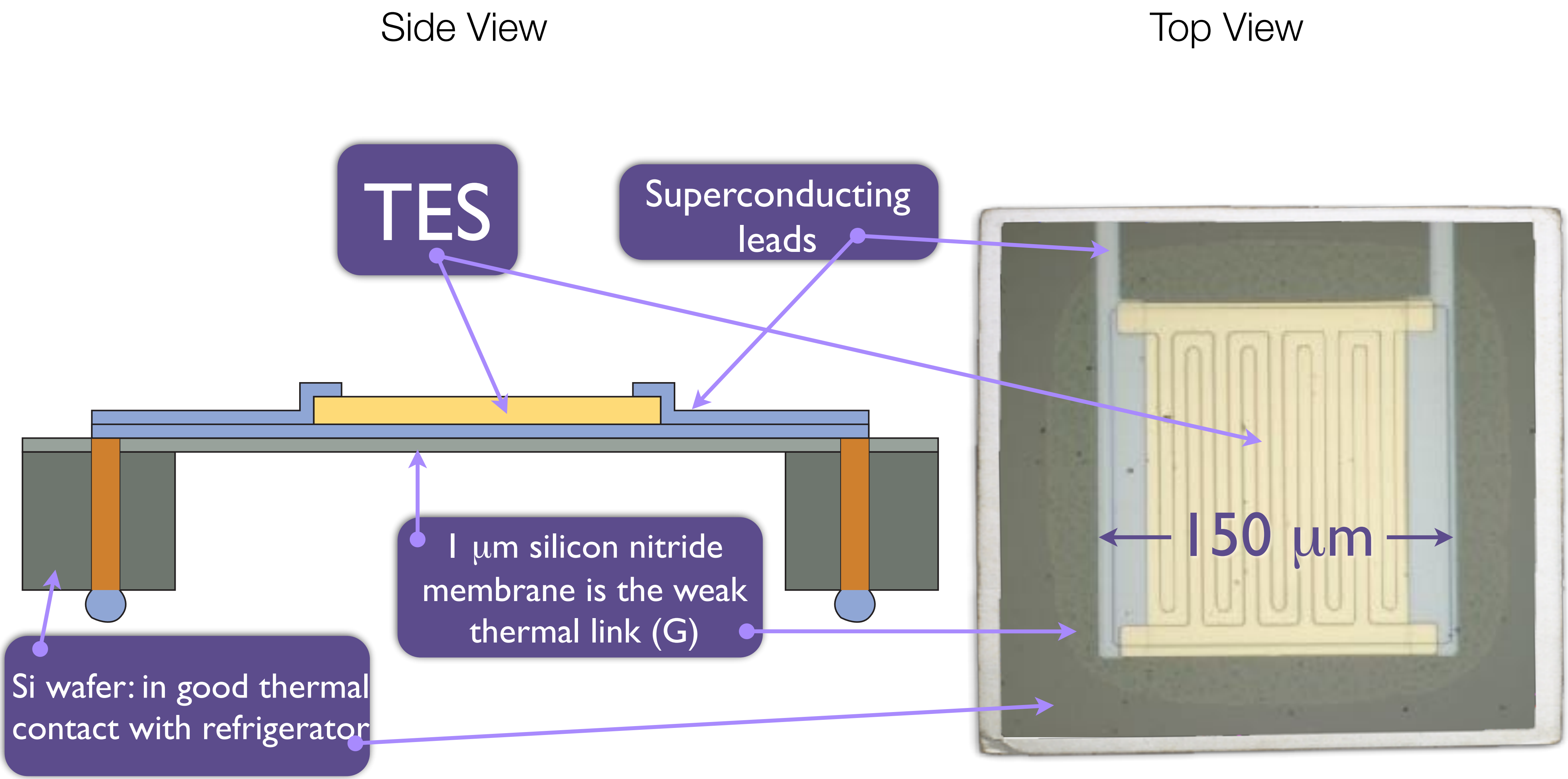
1 μm silicon nitride membrane is the weak thermal link (G)

Si wafer: in good thermal contact with refrigerator

Top View



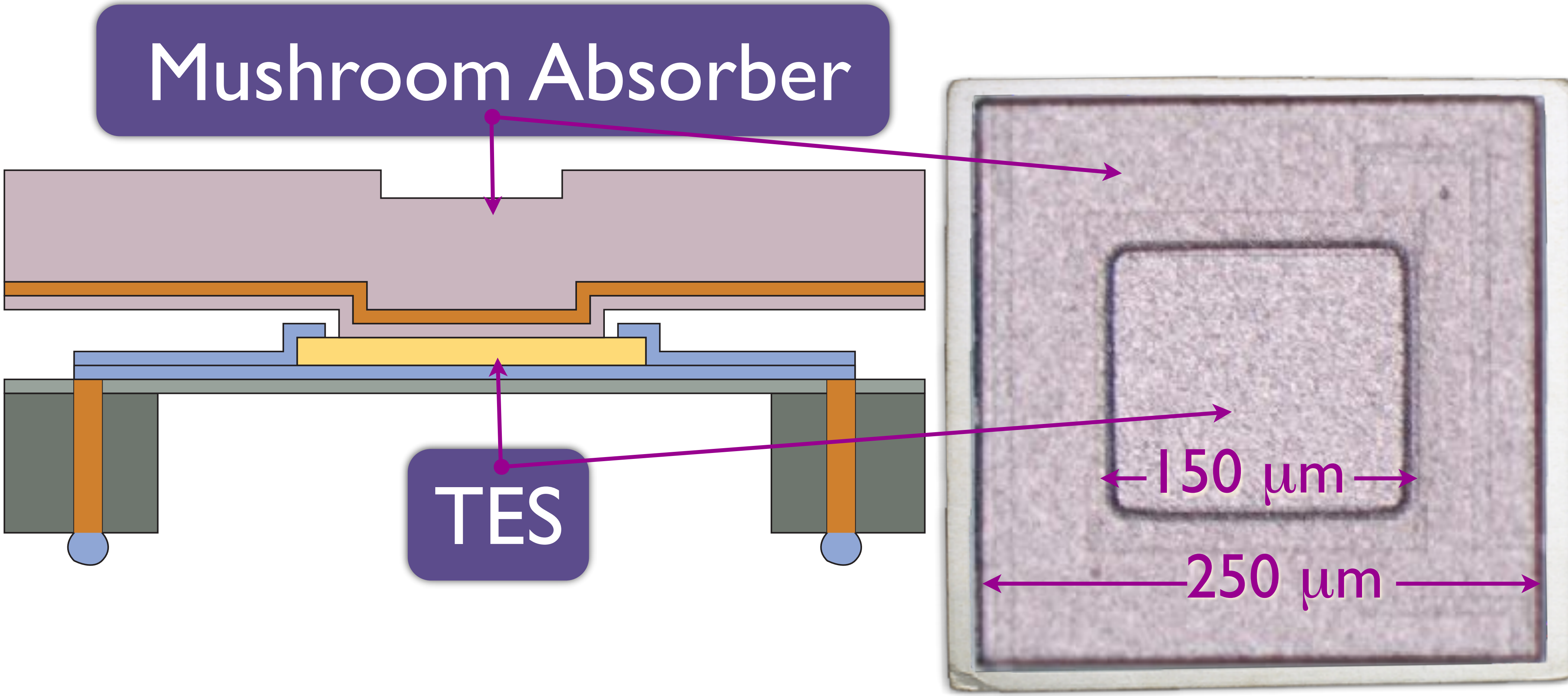
Anatomy of an X-ray TES



X-ray TESs

Side View

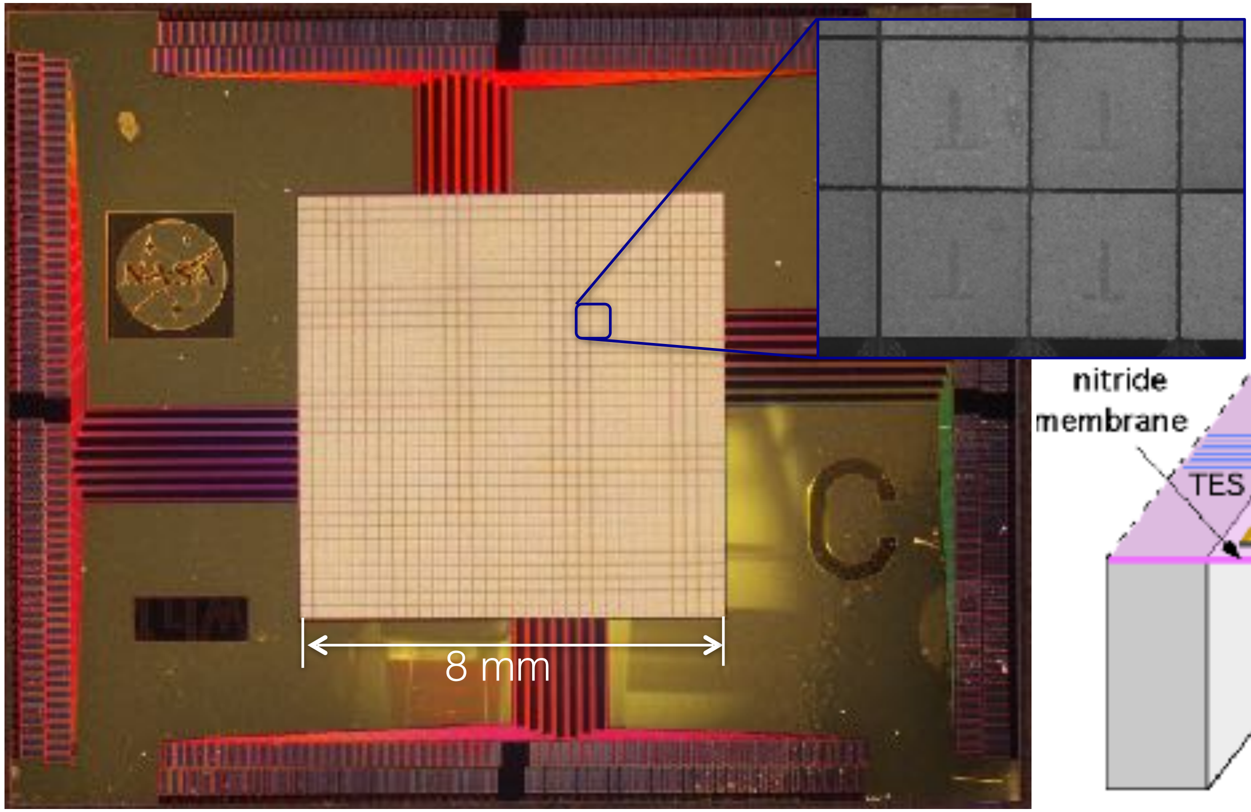
Top View



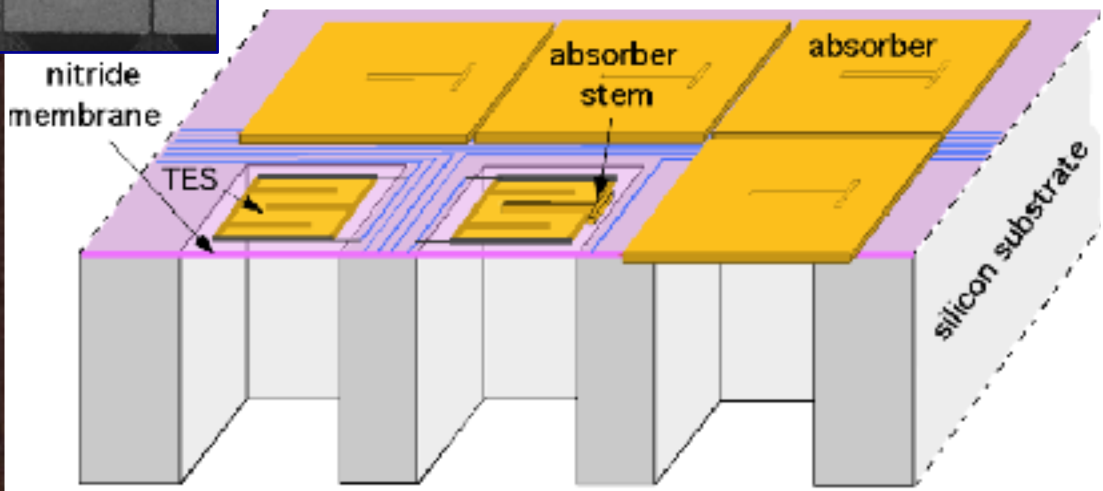
Transition-edge sensor arrays

- NASA Goddard Space Flight Center TES Arrays
  - Mo/Au Bilayer, target T_C ~ 90 mK, suspended on SiN (~ 1 μm).
  - Au/Bi electroplated absorbers, microstrip wiring, Cu backside layer for heat sinking.
  - Prototype 32x32 array (250 μm pitch) will be used for initial Athena technology demonstrations.

Fully wired 32x32 array (8x8 mm^2) with
64 pixels connected to bond pads on each side



Array cross-section



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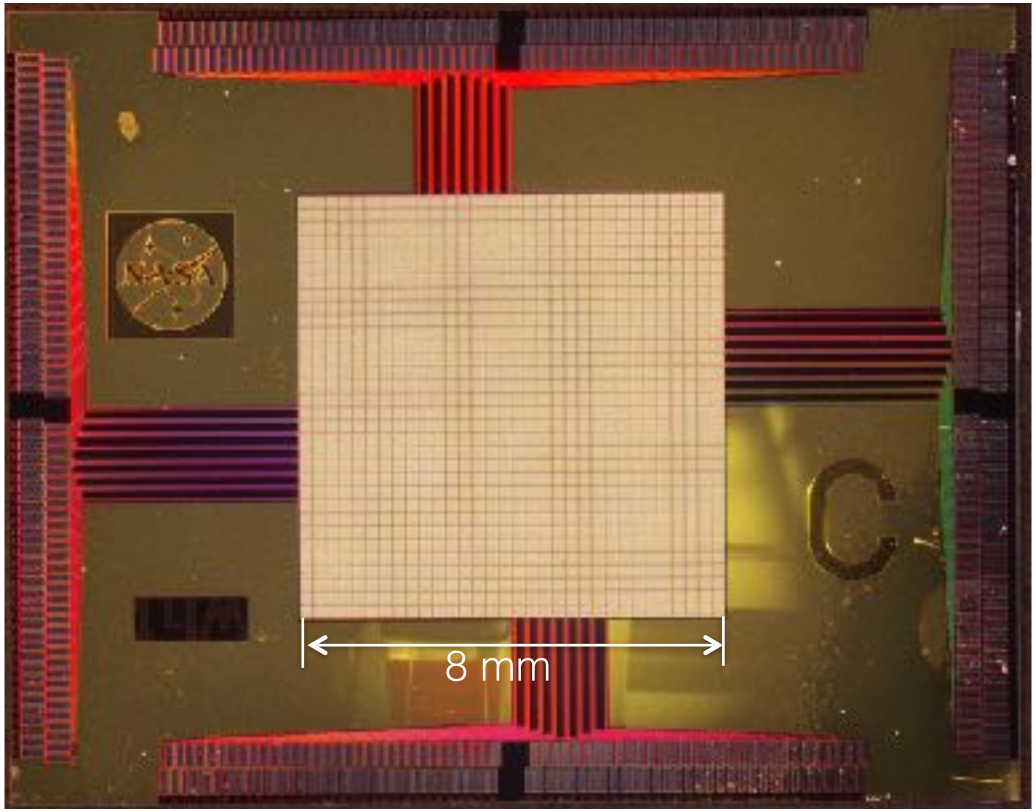
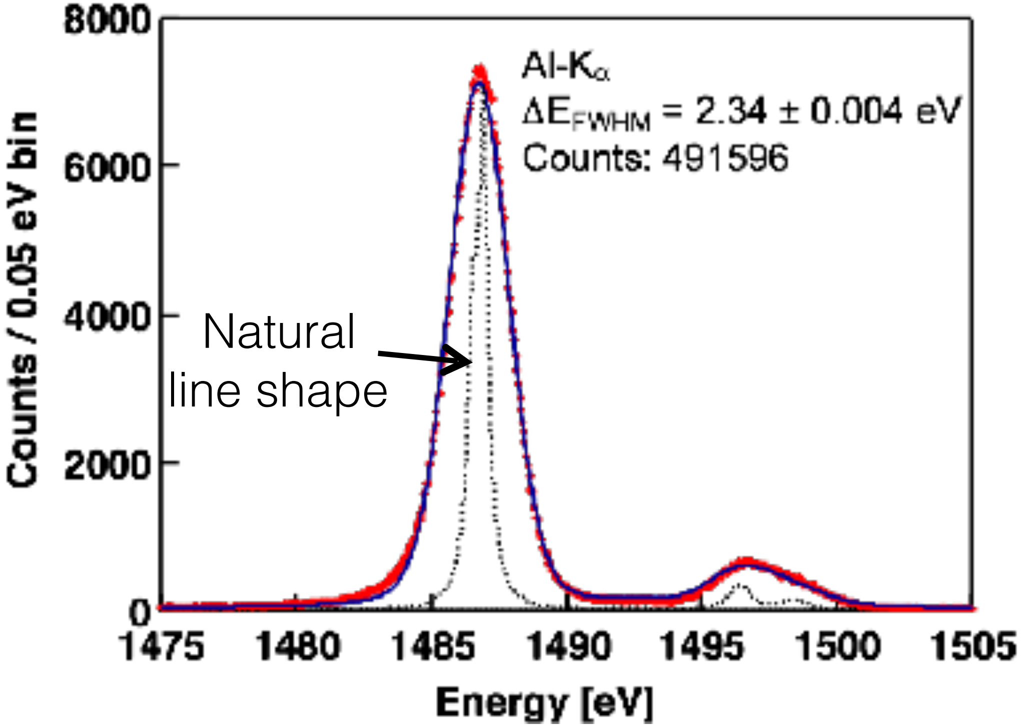


Combined spectrum from 26 pixels simultaneously read out (multiplexed)

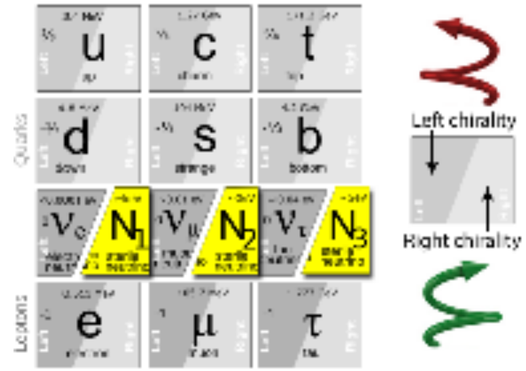


Dark Matter:
Indirect Detection

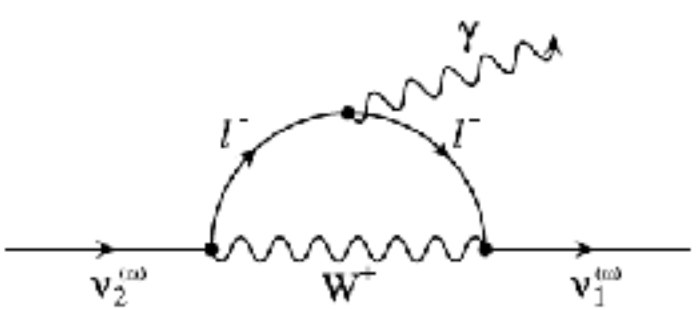
Sterile Neutrinos

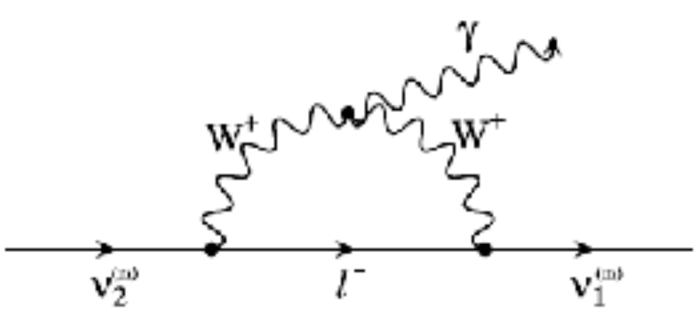
- Sterile neutrinos are a natural way of giving the known neutrino species mass. IF sterile neutrinos exist, and one of them has a mass between a few keV and 100 keV, it could constitute some or all of the dark matter.

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



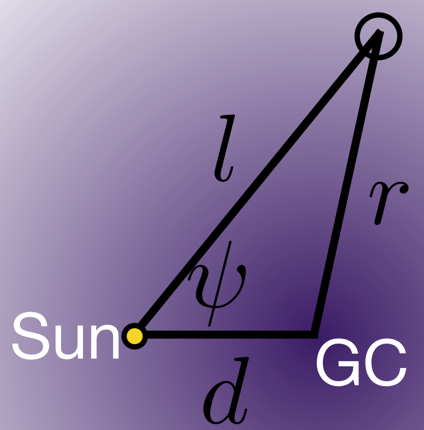
$$\Gamma = \frac{9\alpha G_F^2 m_s^5 \sin^2 2\theta}{1024\pi^4}$$
$$= (1.38 \times 10^{-29}\ \mathrm{s}^{-1}) \left(\frac{\sin^2 2\theta}{10^{-7}}\right) \left(\frac{m_s}{1\ \mathrm{keV}}\right)^5$$

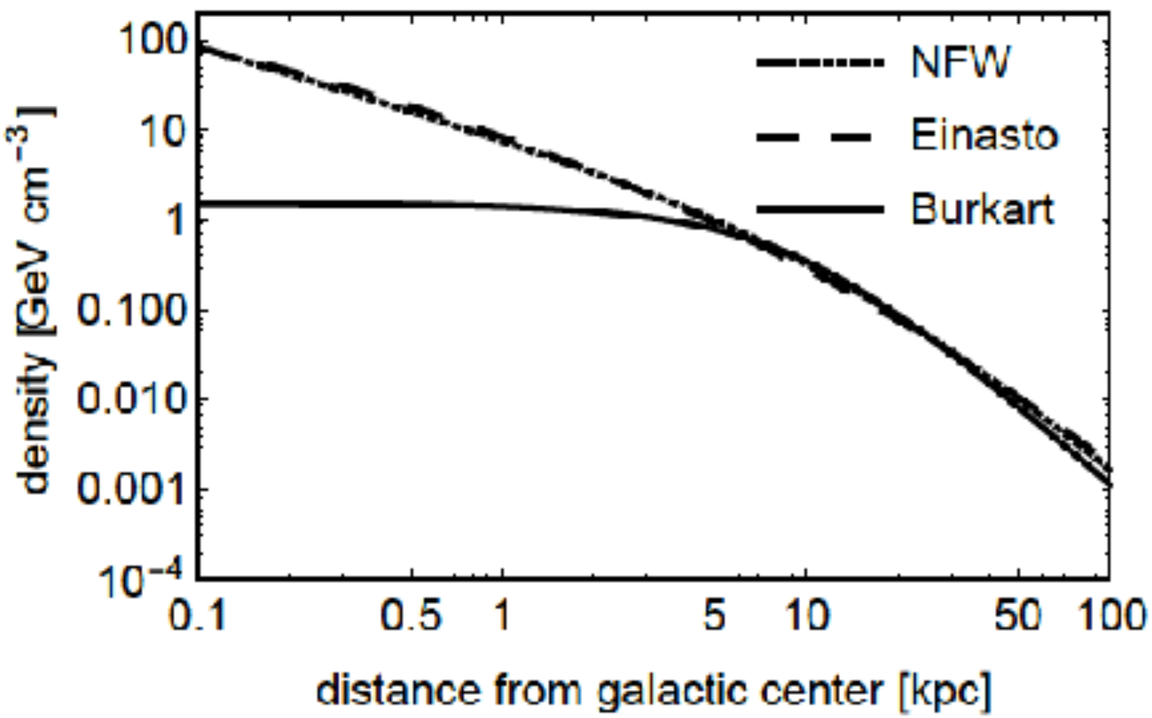




MW Sterile Neutrino Signal - FOV is important!

- The signal from sterile neutrino decay would be a line at half the energy of the sterile neutrino.



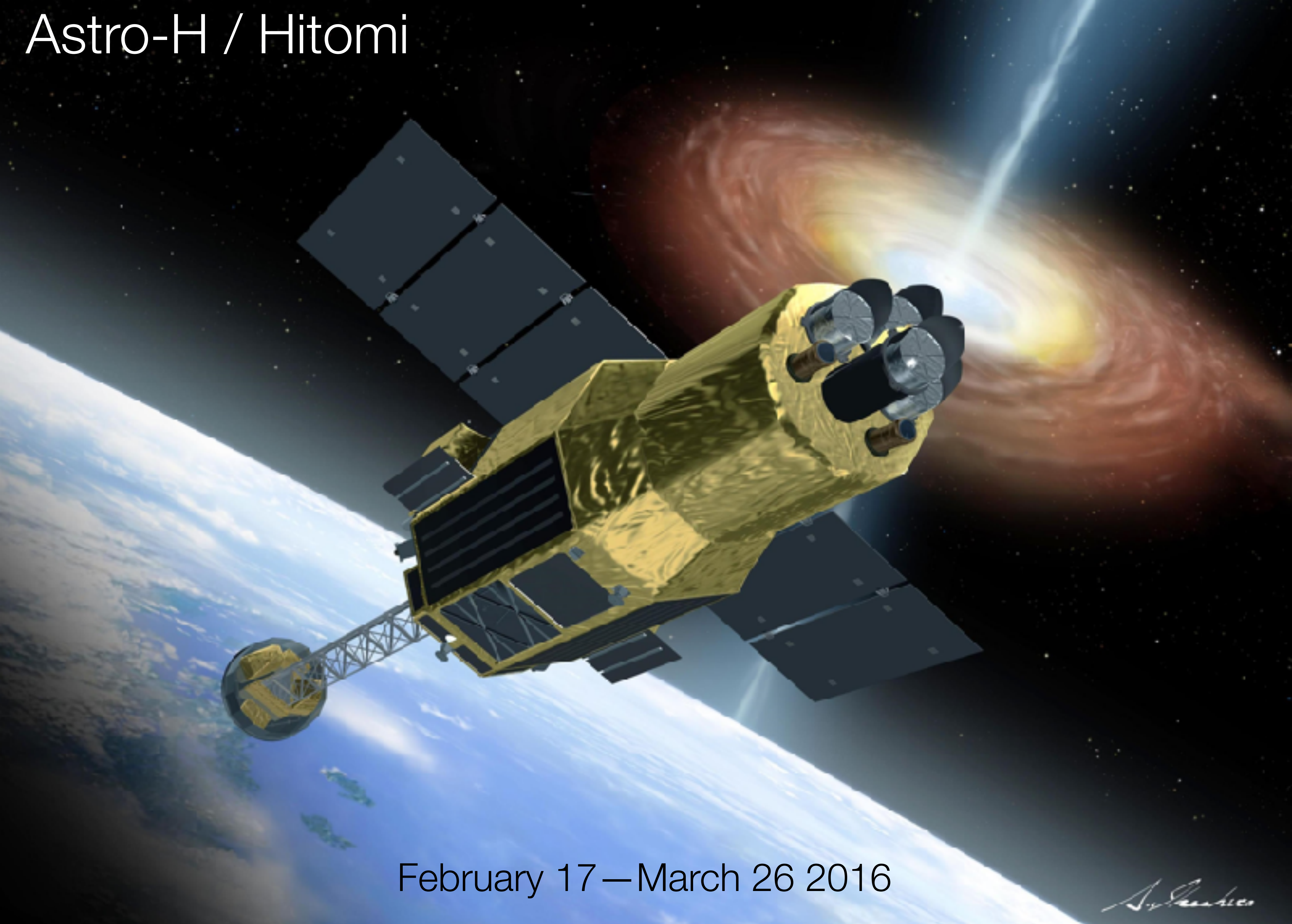


$$\mathcal{F} = \frac{\Gamma}{m_s}\frac{1}{4\pi}\int_{FOV}\int_0^\infty \rho(r(\ell,\psi))\, d\ell\, d\Omega$$

$$r(\ell,\psi) = \sqrt{\ell^2 + d^2 - 2\ell d\cos\psi}$$

- The flux goes as the number of dark matter particles in your FOV. Estimates depend on assumed MW DM profile.

Astro-H / Hitomi

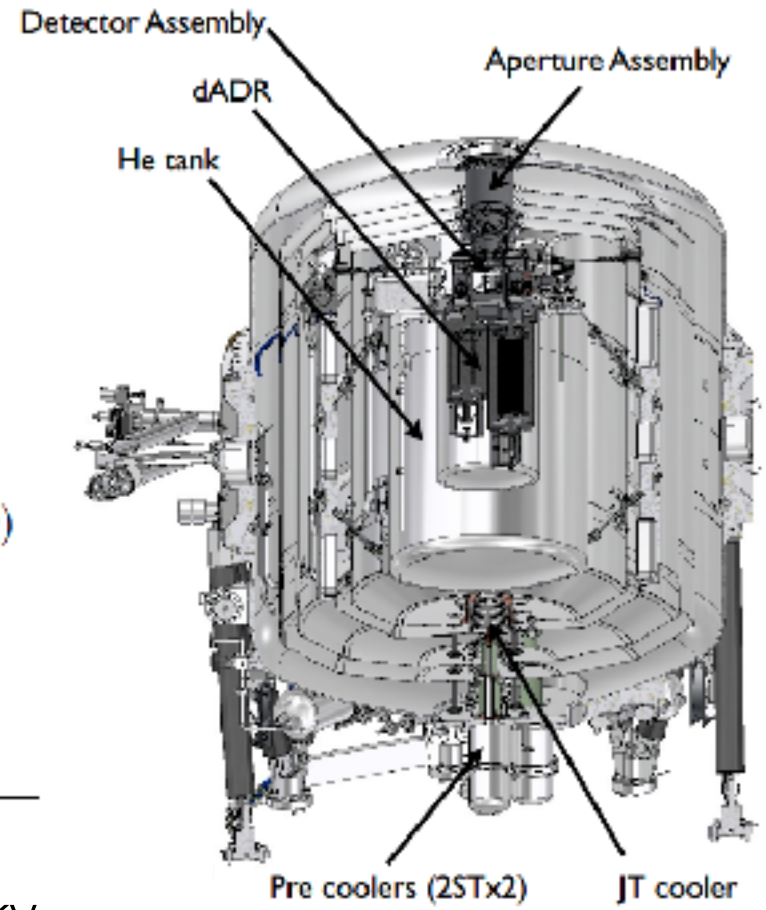


February 17 — March 26 2016

Astro-H Soft X-ray Spectrometer (SXS)

Table 1. *ASTRO-H* SXS key requirments

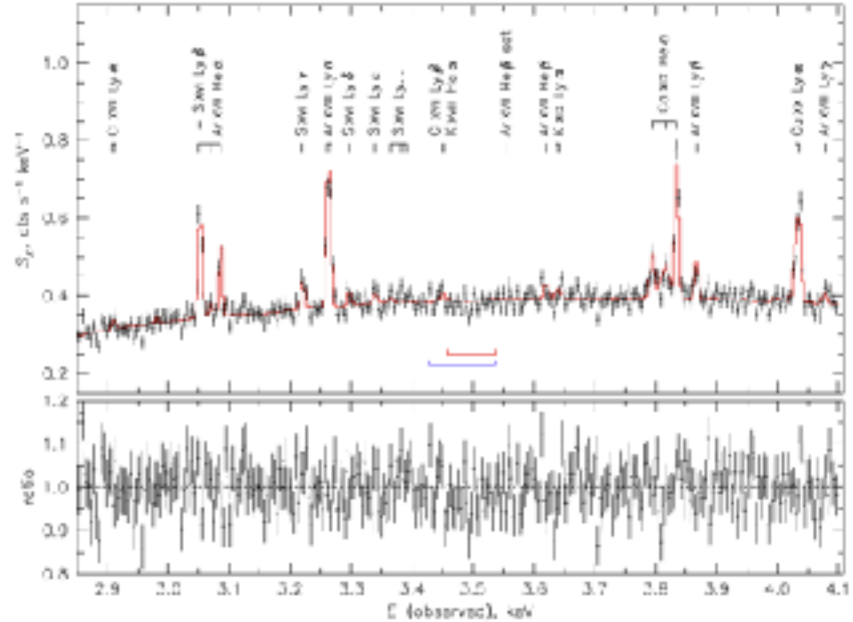
	Requirement	Goal
Energy range	0.3 - 12 keV	
Effective area at 1 keV	160 cm^2	
Effective area at 6 keV	210 cm^2	
Energy resolution	7 eV	4 eV
Array format	6×6	
Field of view	$2.9' \times 2.9'$	
Angula resolution	1.7'(HPD)	1.3' (HPD)
Lifetime	3 years	5 years
Time assignment resolution	80 μs	
Maximum counting rate	150 c s^{-1} pixel^{-1}	
Energy-scale calibration accuracy	2 eV	1 eV
Line-spread-function calibration accuracy	2 eV	1 eV

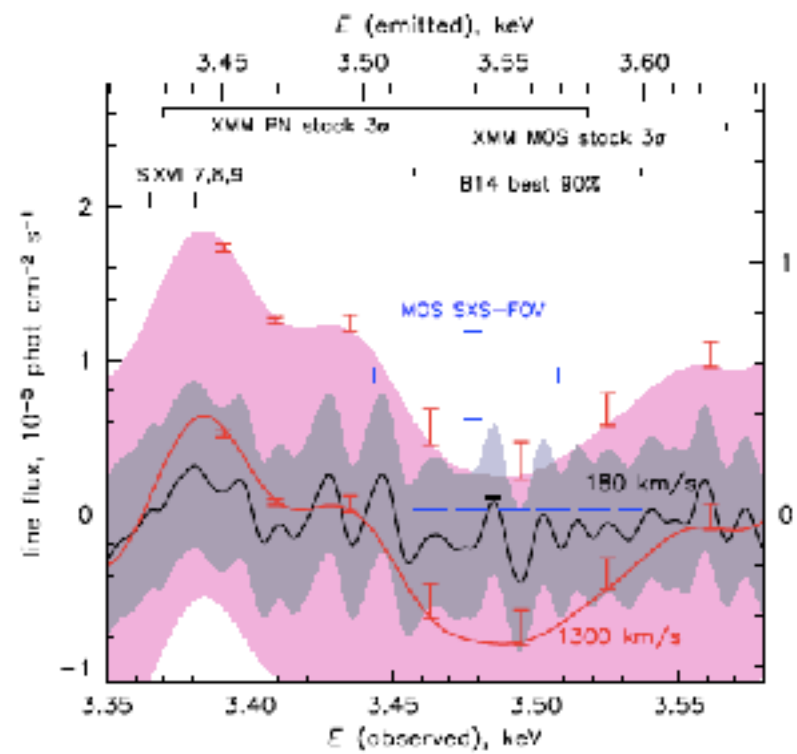


- The FOV limited its ability to look for the all-sky signal expected from sterile neutrino decay in the Milky Way (although it was certainly going to look!)
- Extragalactic sources from galaxy clusters to dwarf spheroidals were better fits to its FOV.

Astro-H SXS Microcalorimeter Perseus Simulation

arXiv:1607.07420





- Although Hitomi did make an observation of Perseus, it was through the gate valve filter and for a short exposure, so the "effective" exposure at 3.5 keV will be only about 8% of the desired 1Ms observation.
  - Baseline Effective Area: ~200 cm^2
  - Gate Valve Closed Area: ~70 cm^2
  - Raw exposure: 230 ks
- Not sensitive enough to conclusively settle the issue!

Sounding Rocket Payloads for Sterile Neutrino Searches

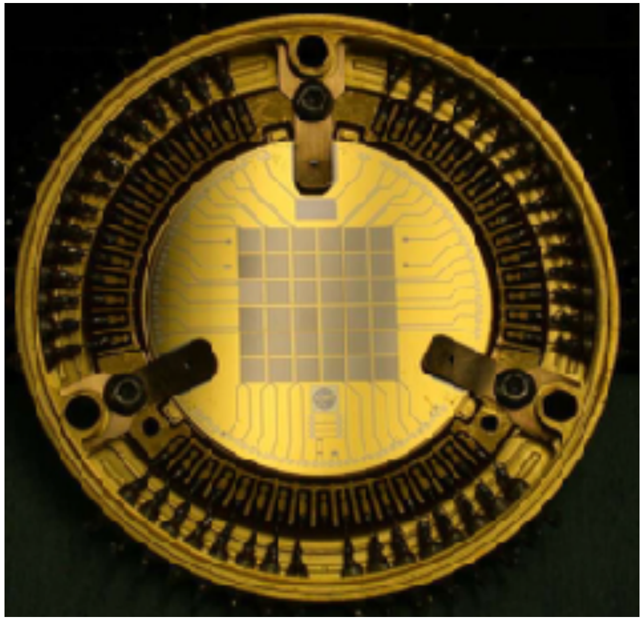
E.F.F. et al, ApJ 814:82, 2015
arXiv:1506.05519

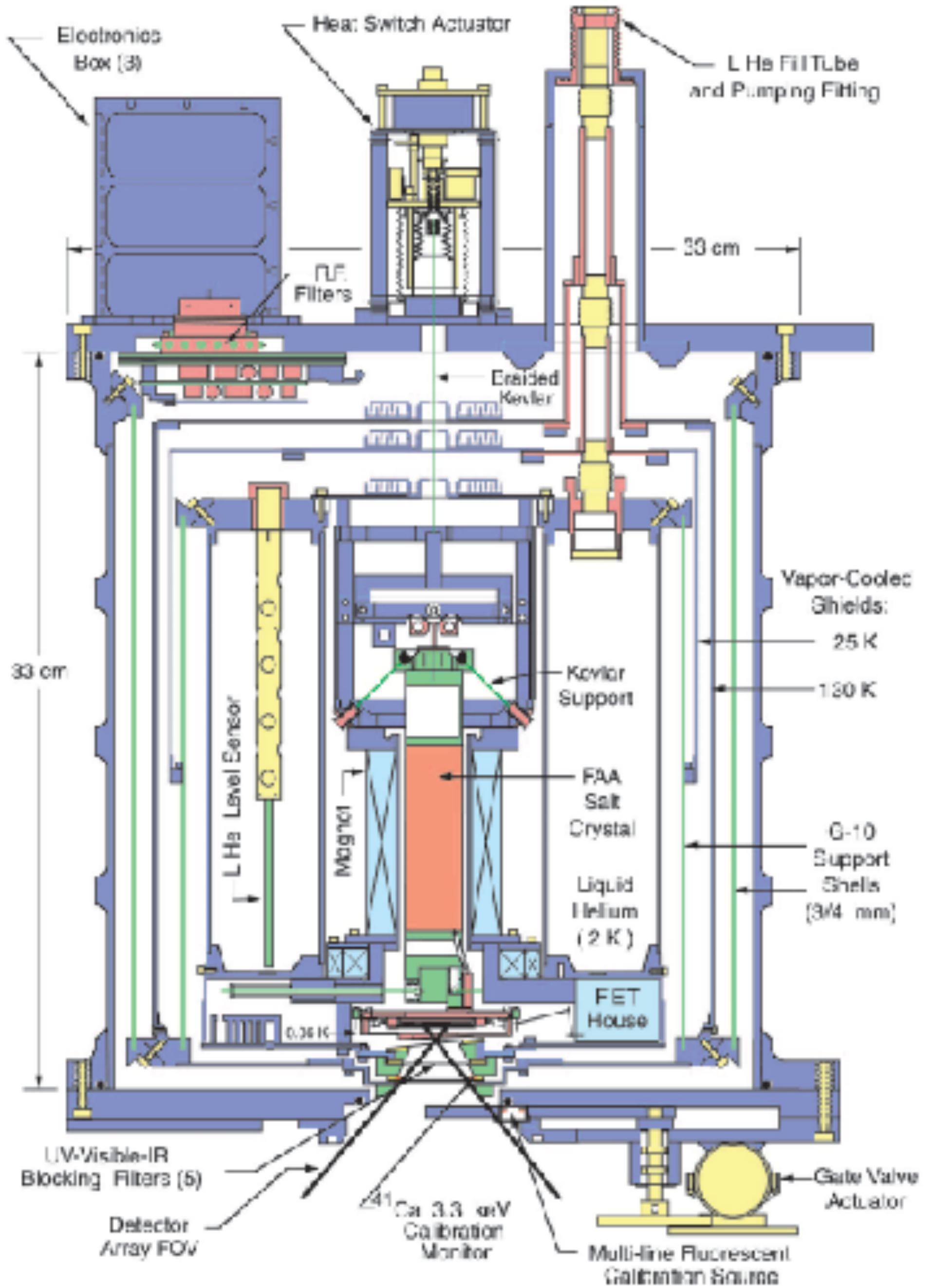
Sounding Rocket Payloads

- 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 XQC Rocket Payload

- Mature flight system flown 6 times between 1995 and 2014
- Si Thermistor Microcalorimeter array with 36 pixels, each with a 2mm x 2mm x 0.96μm HgTe absorber on a 14μm Si substrate
- Baseline energy resolution is 11 eV FWHM, 23 eV FWHM at 3.53 keV.
- 1 steradian FOV ~ 1900 arcmin radius

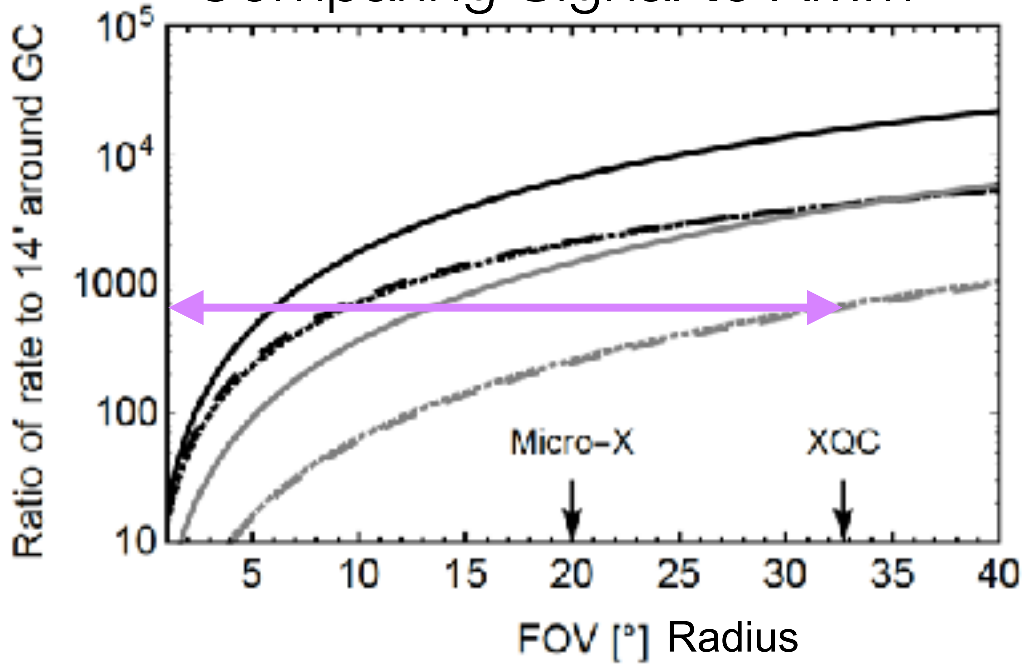




Analysis of XQC Data

- Analyzed data from 5th flight of XQC, which flew Nov 6 2011.
- 1 steradian FOV centered on Galatic coords l=165, b=-5, close to Galactic anti-center.
- About 300 seconds of on-target data were acquired at altitudes above 160 km, of which 200 s of data on 29 pixels were analyzed. After quality cuts, the effective exposure is 106 s.
- Future analysis of entire XQC data set from all flights will increase the exposure by a factor of about 5.

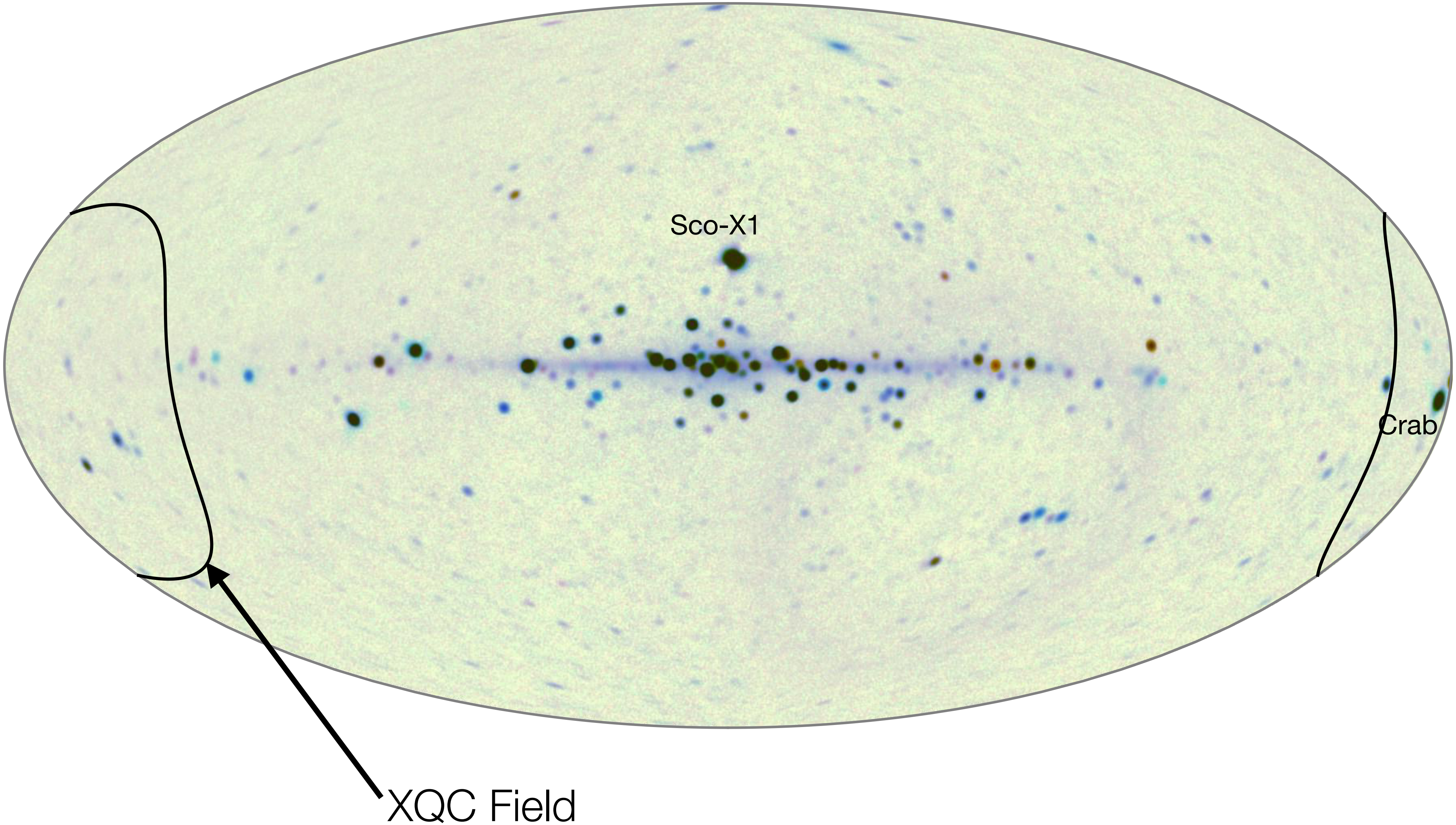
Comparing Signal to XMM



Dotted: NFW
Dashed: Einasto
Solid: Burkart

Black: Galactic Center
Gray: XQC Field

All-sky X-ray map from the MAXI/GSC on International Space Station



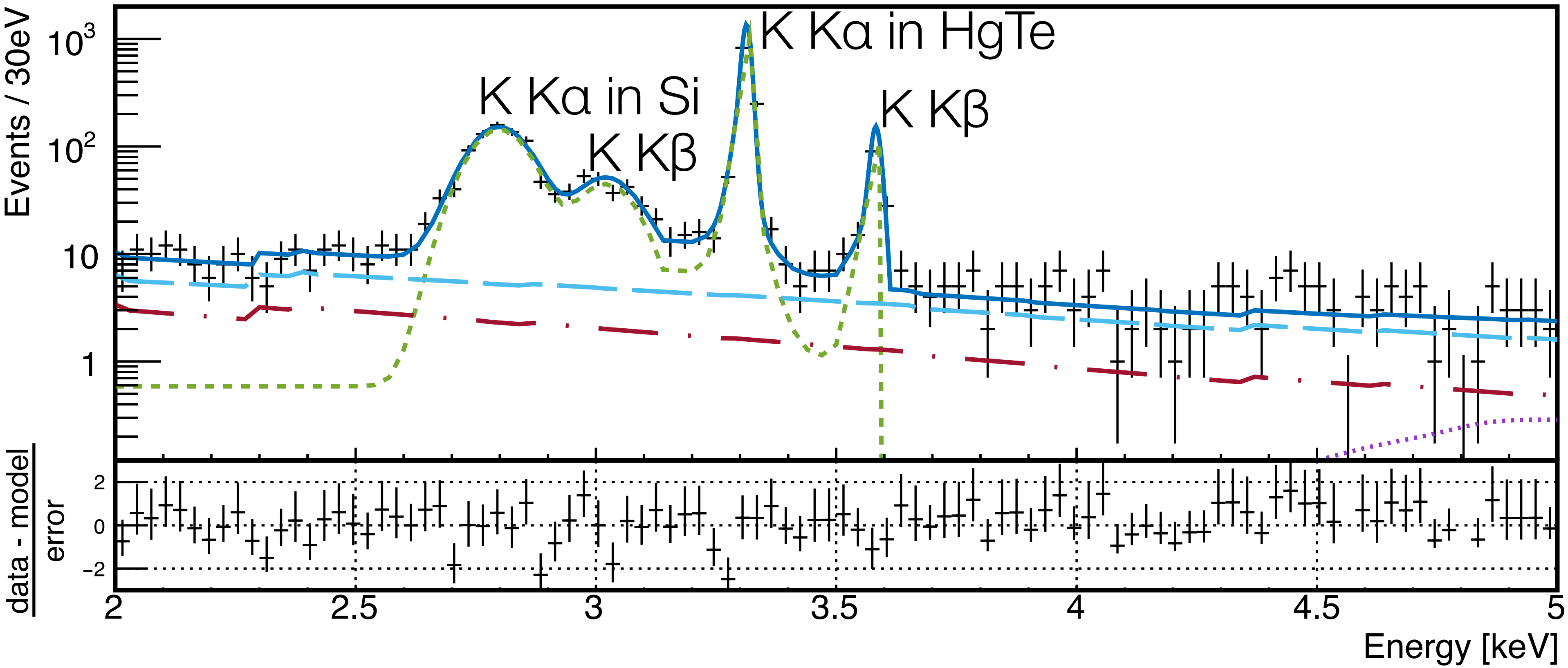
Fit to XQC Data

Diffuse X-ray Background (Hickox & Markevitch 2006)

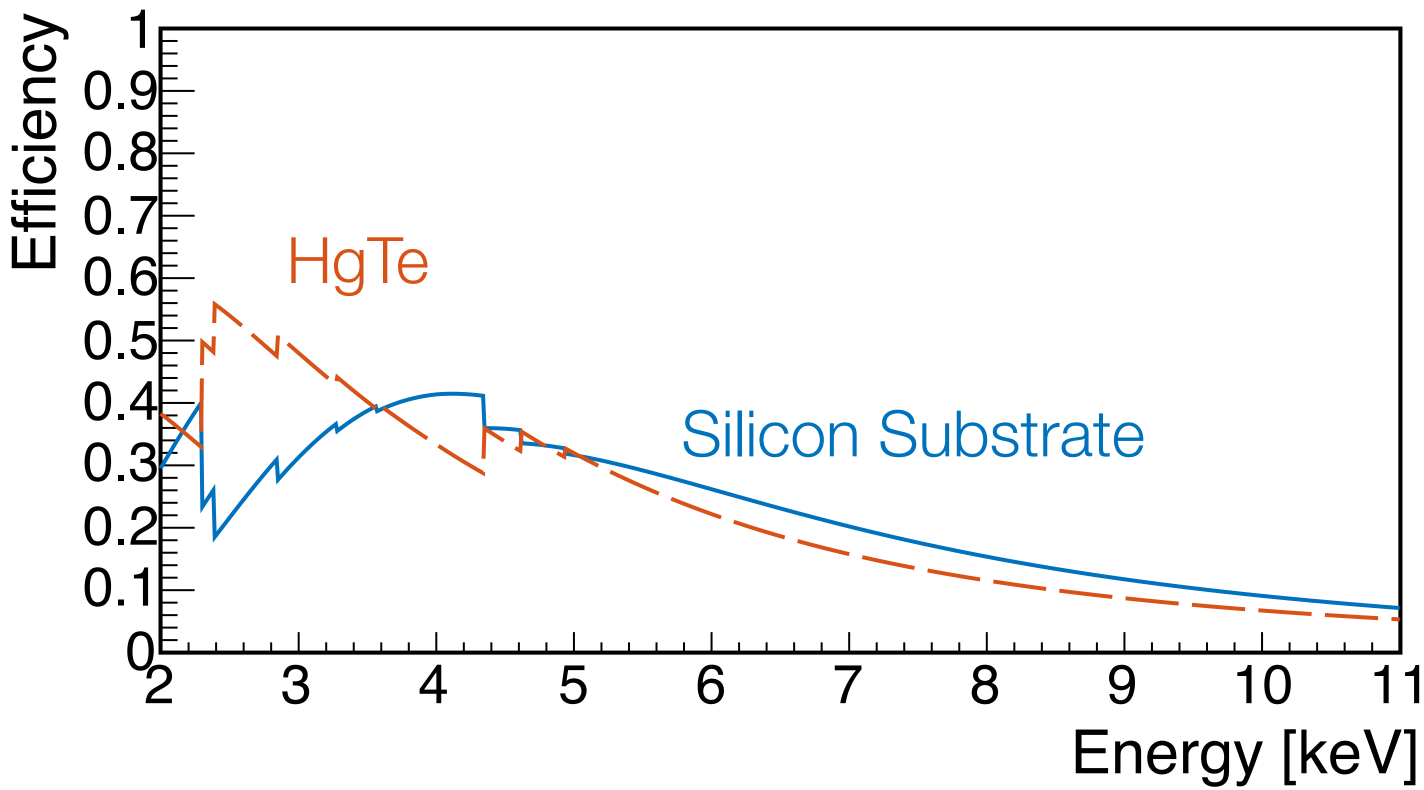
Crab (Mori et al 2004)

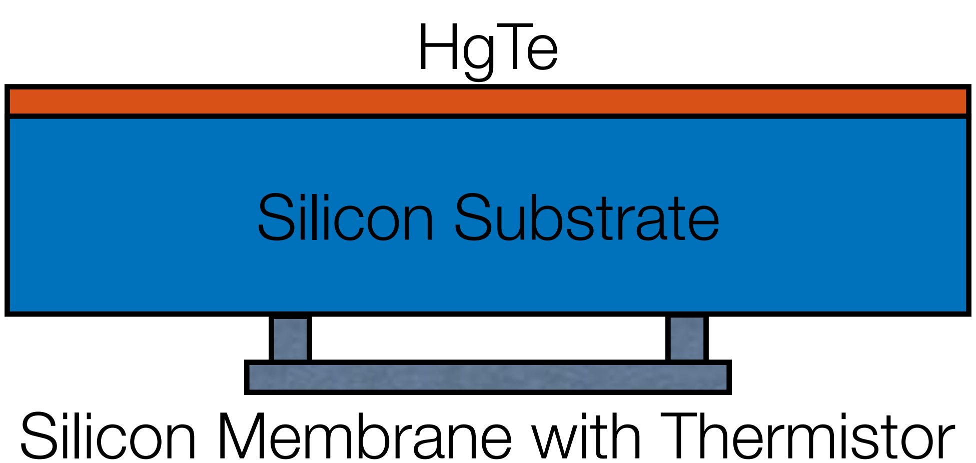
Calibration Source (model from pre-flight calibration data)

Cosmic Rays (GEANT4 simulation)

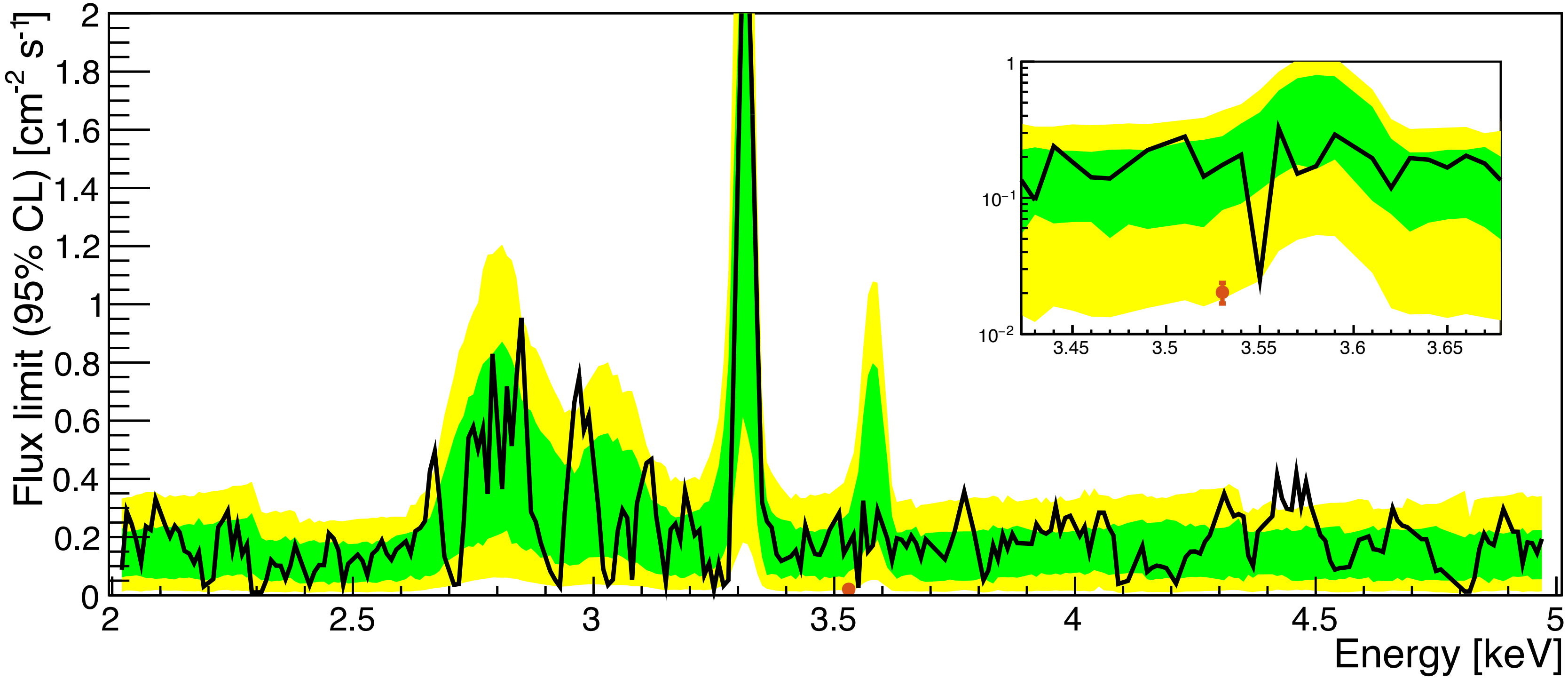


X-rays hit both the HgTe absorber and its Si substrate



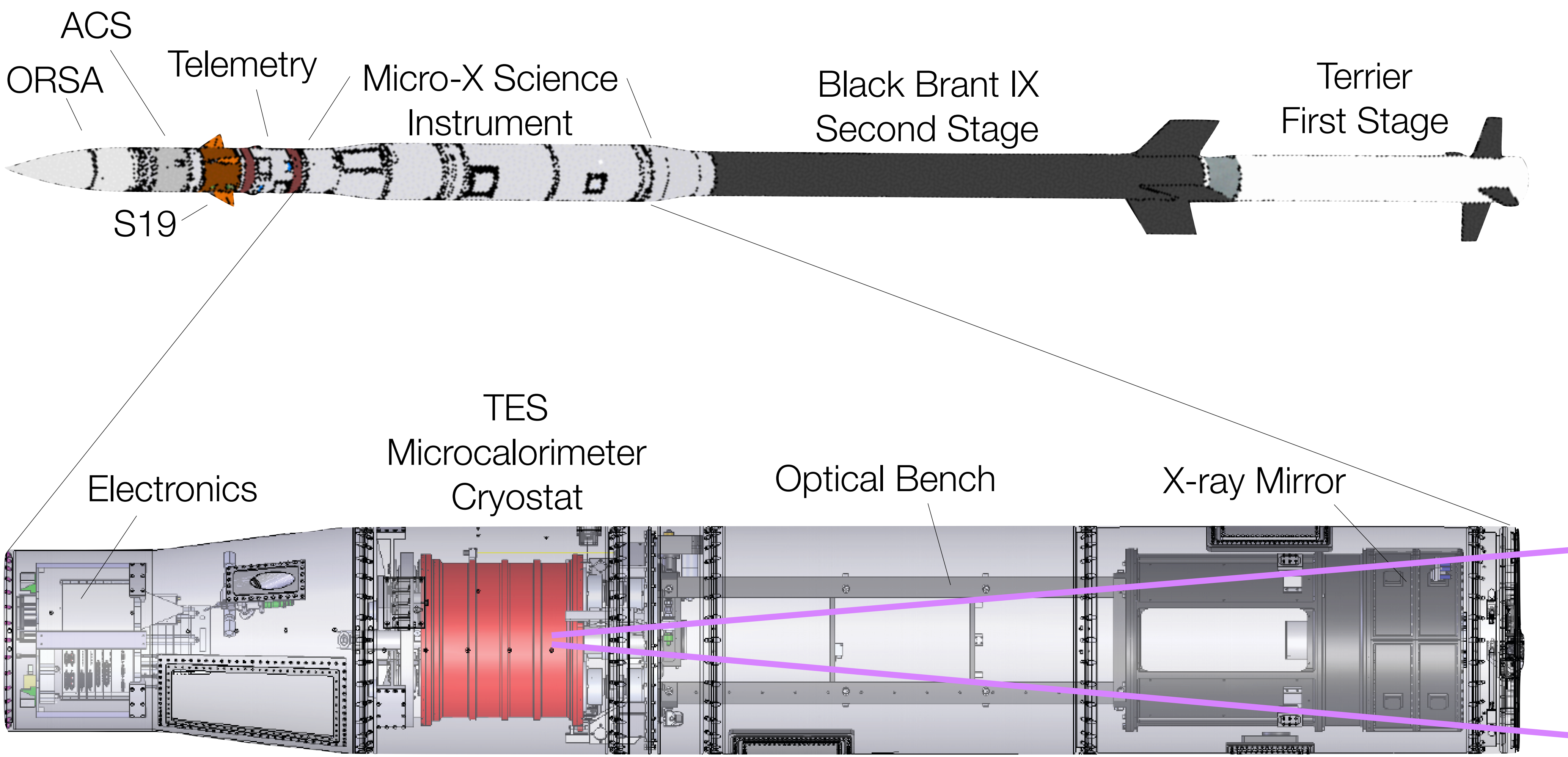


XQC Analysis Results



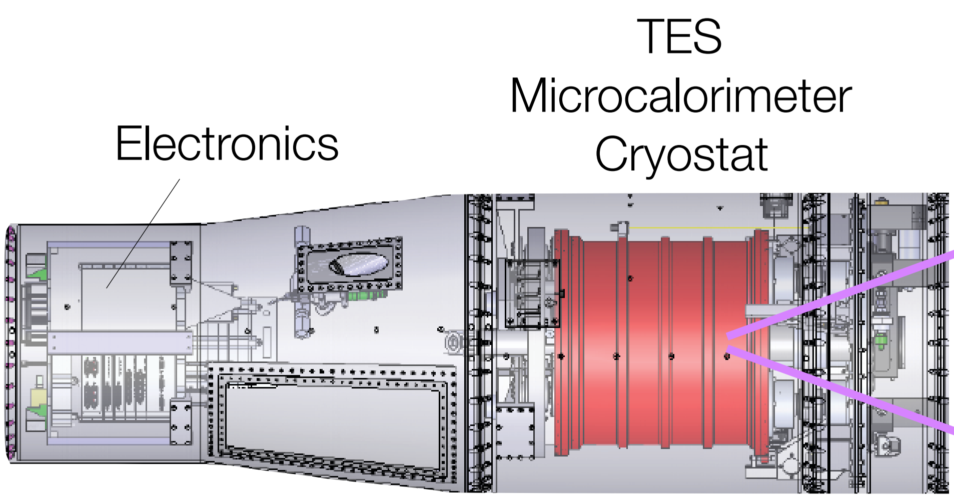
- Not sensitive enough to rule out Boyarski's MW detection claim… will analyze existing archival data to gain a factor of around 5 in exposure

The Micro-X Sounding Rocket



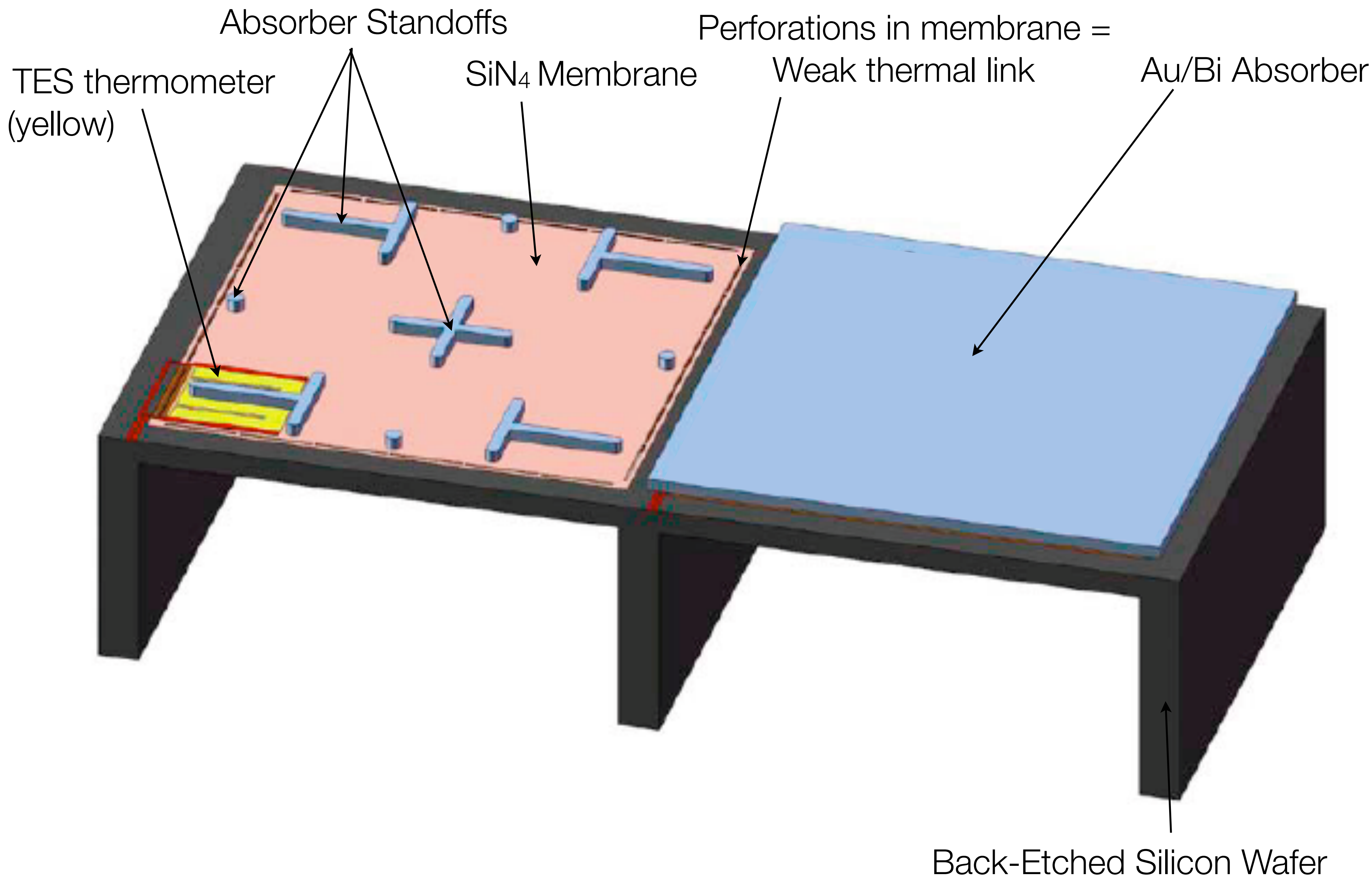
The Micro-X Sounding Rocket

- 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.



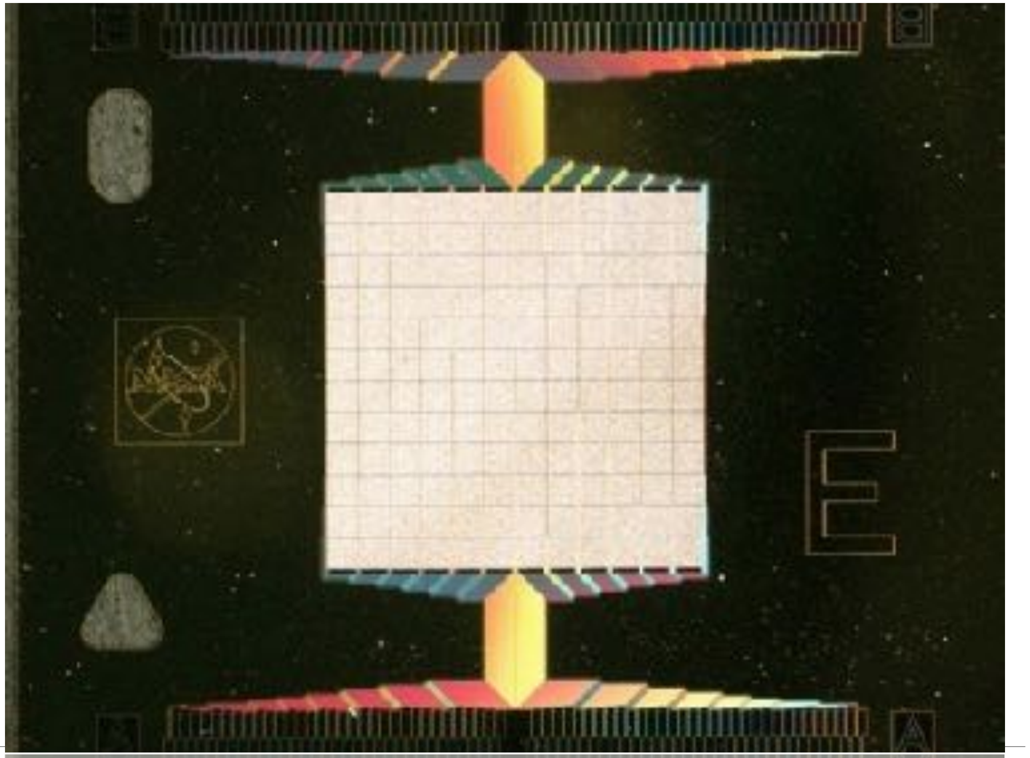
- For sterile neutrino searches, we will fly the payload without the mirror to obtain a large FOV and thus greater grasp:
  - With mirror, grasp = 38 cm^2 deg^2
  - Without mirror, grasp = 1256 cm^2 deg^2

Microcalorimeters for Micro-X



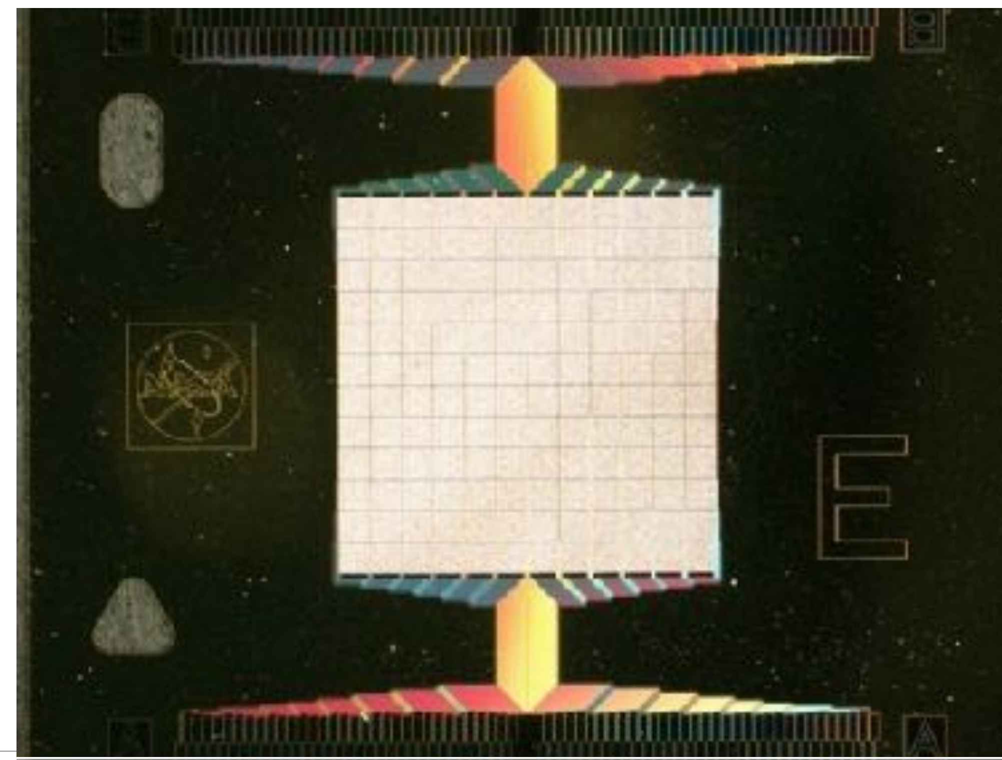
Micro-X Microcalorimeter Array

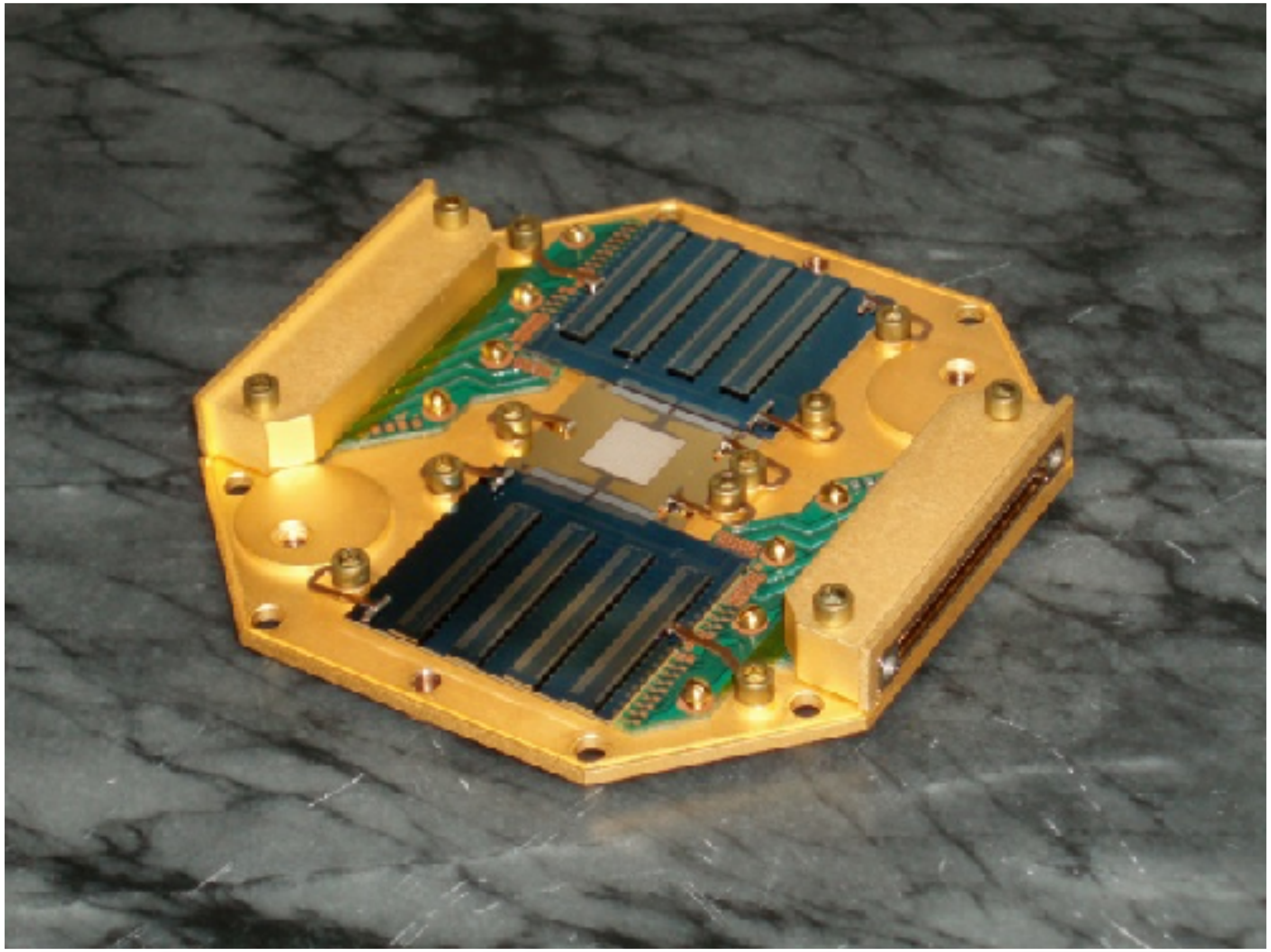
Pixel array:
12 x12 = 7.2mm / side



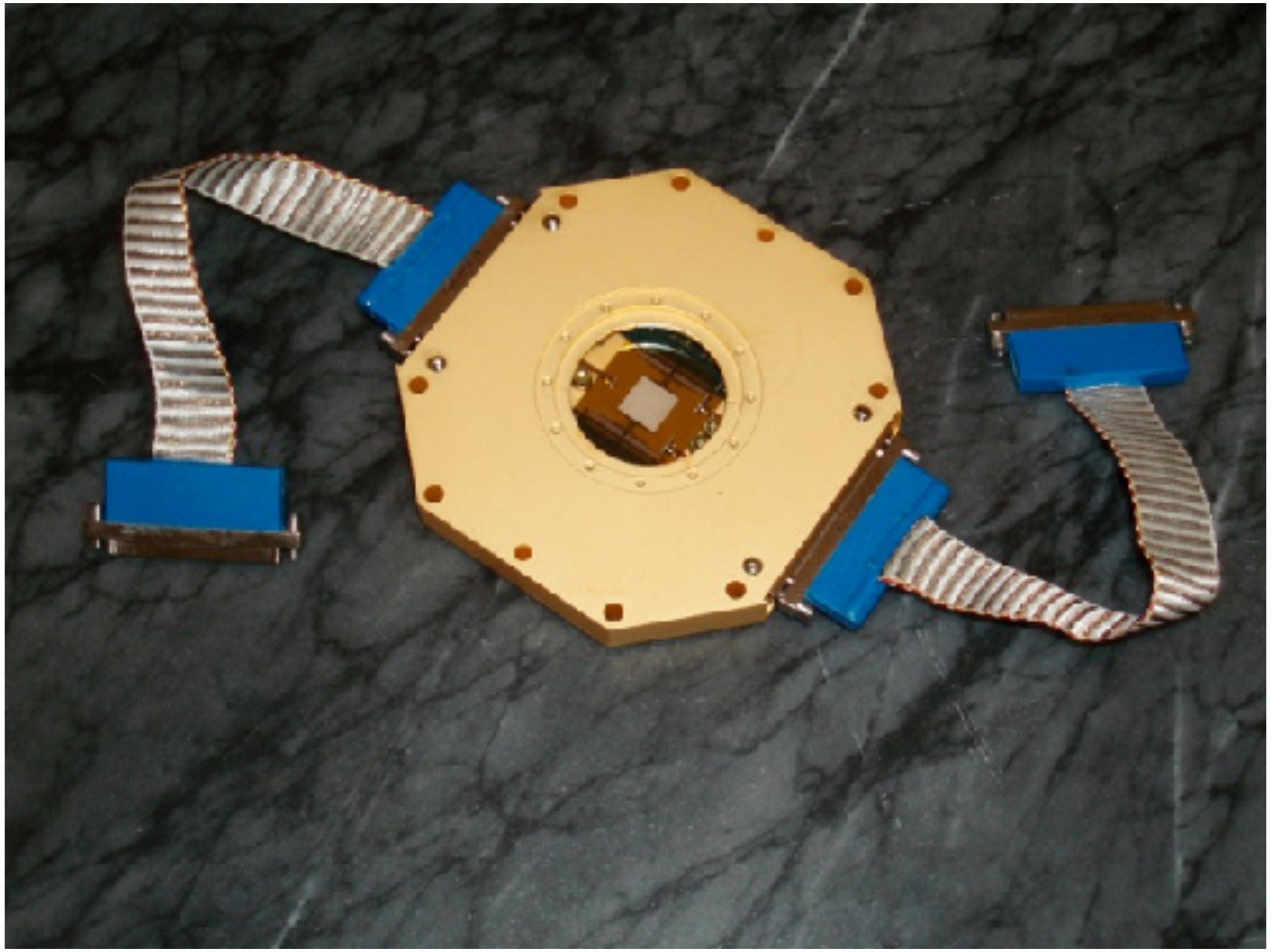
Micro-X Microcalorimeter Array

Pixel array:
12 x12 = 7.2mm / side

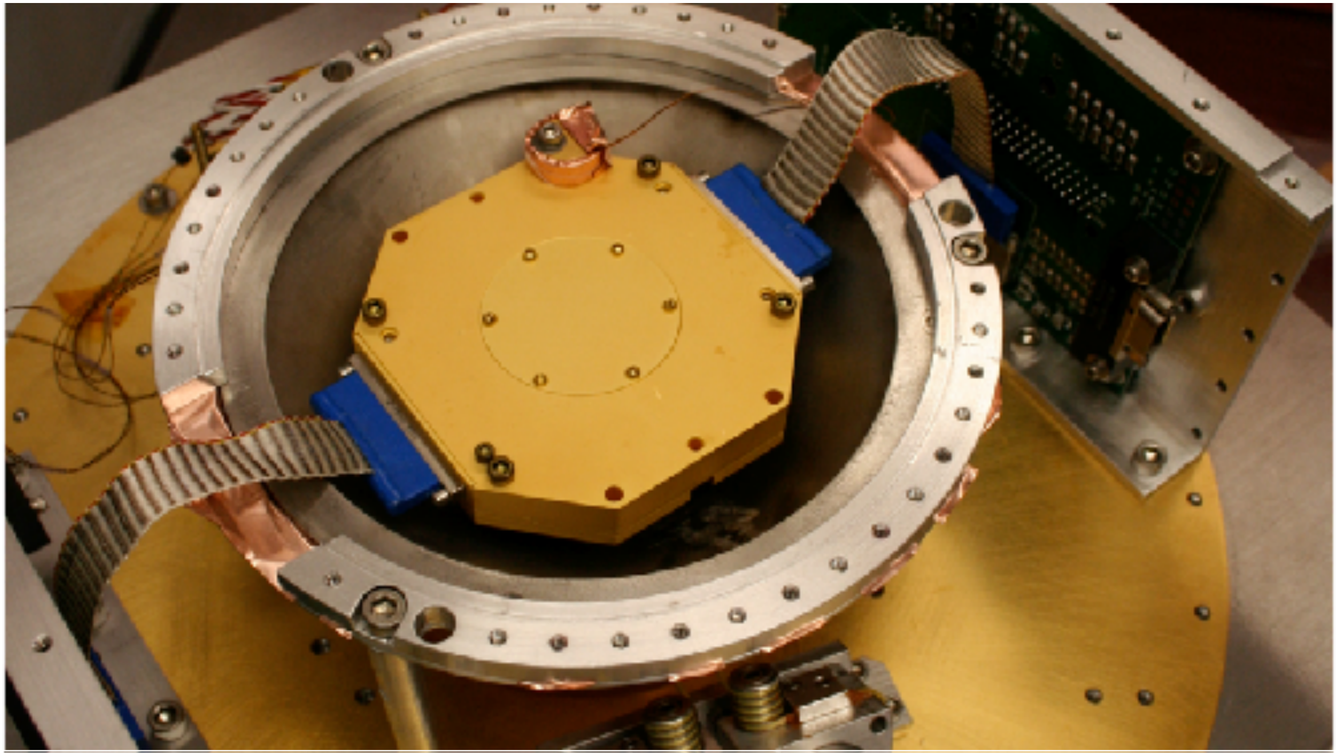




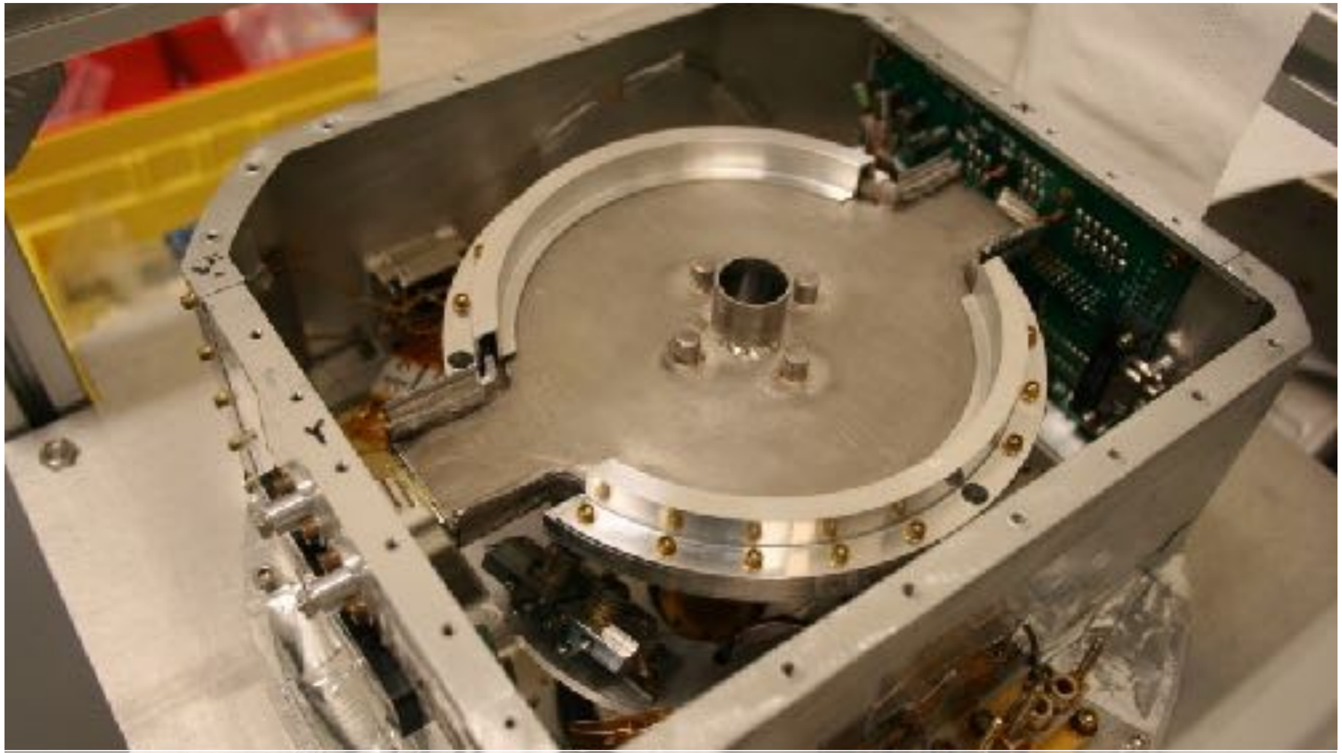
Micro-X Focal Plane



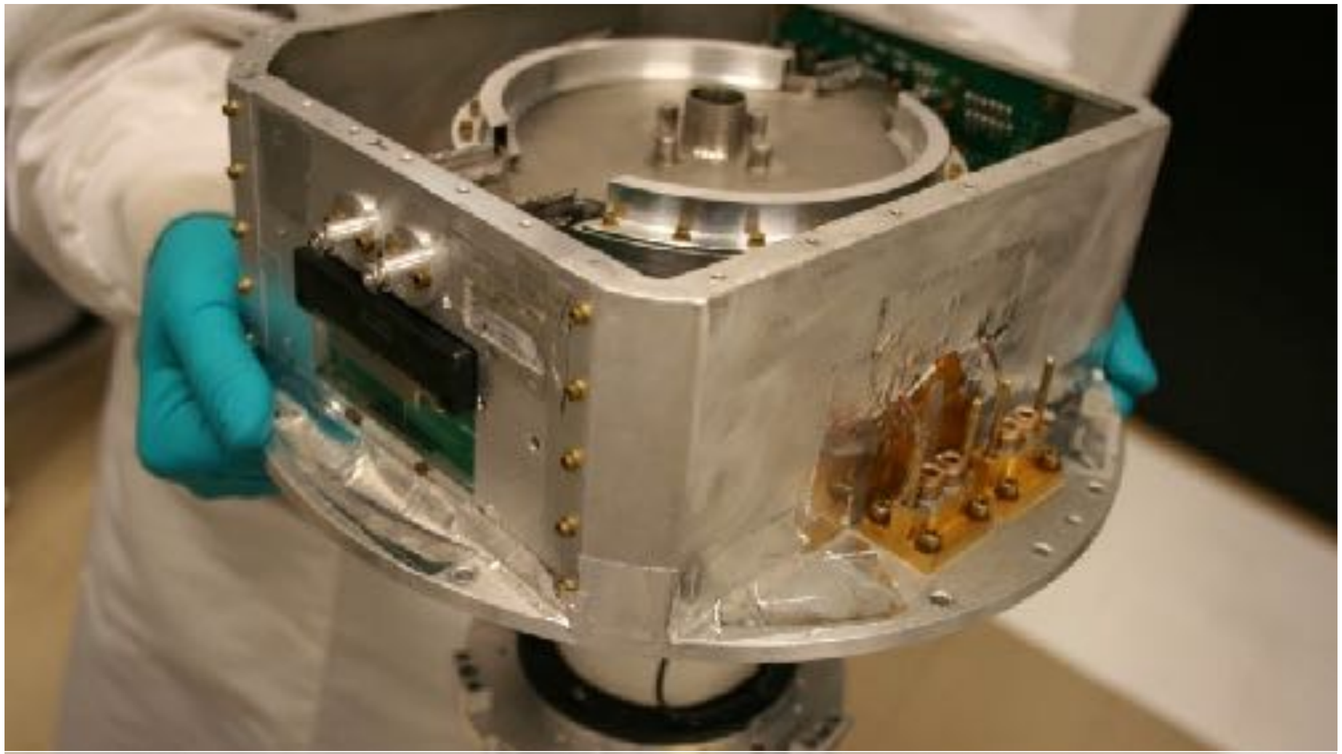
Micro-X Focal Plane



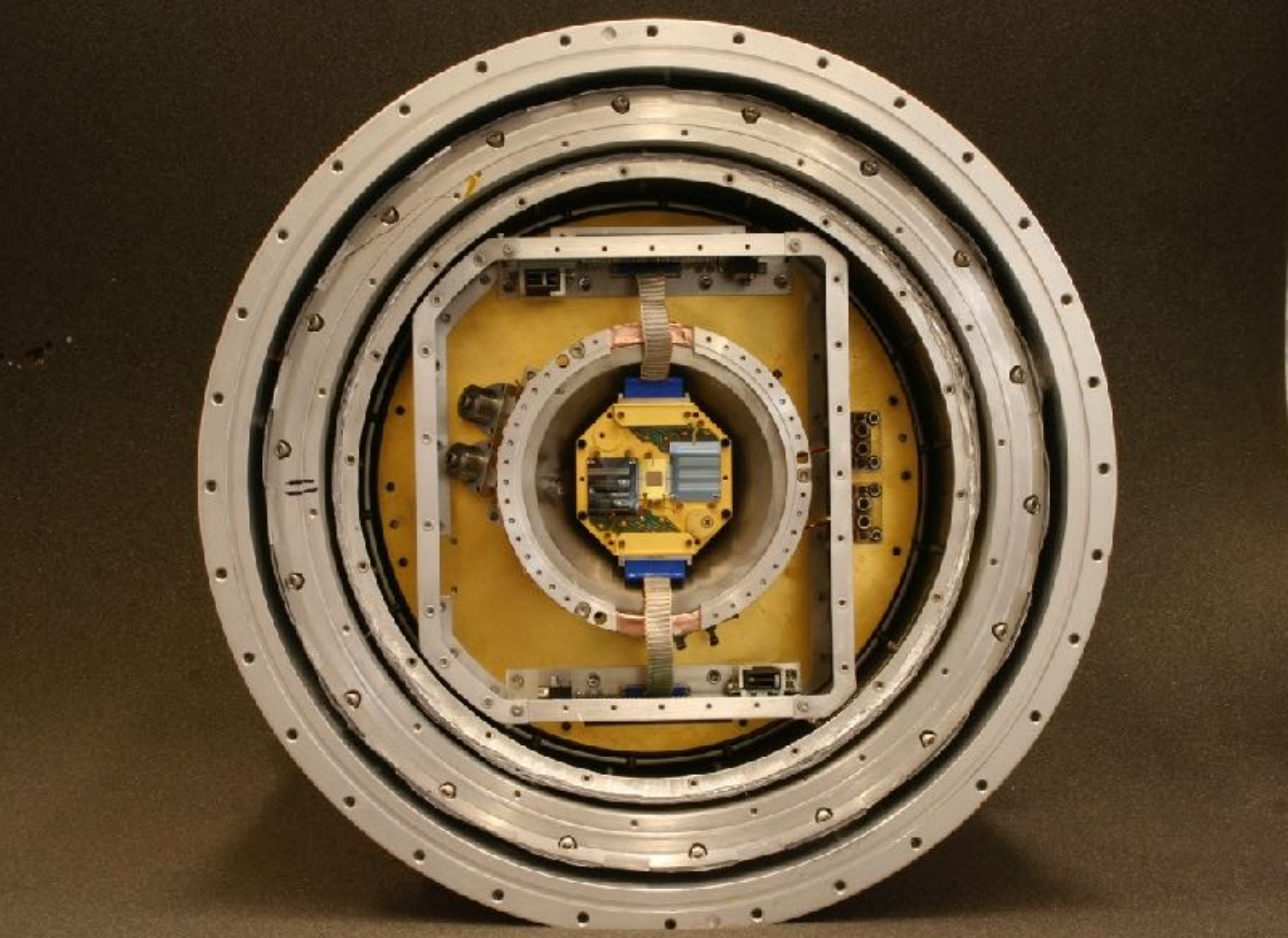
Focal Plan inside Superconducting Shield

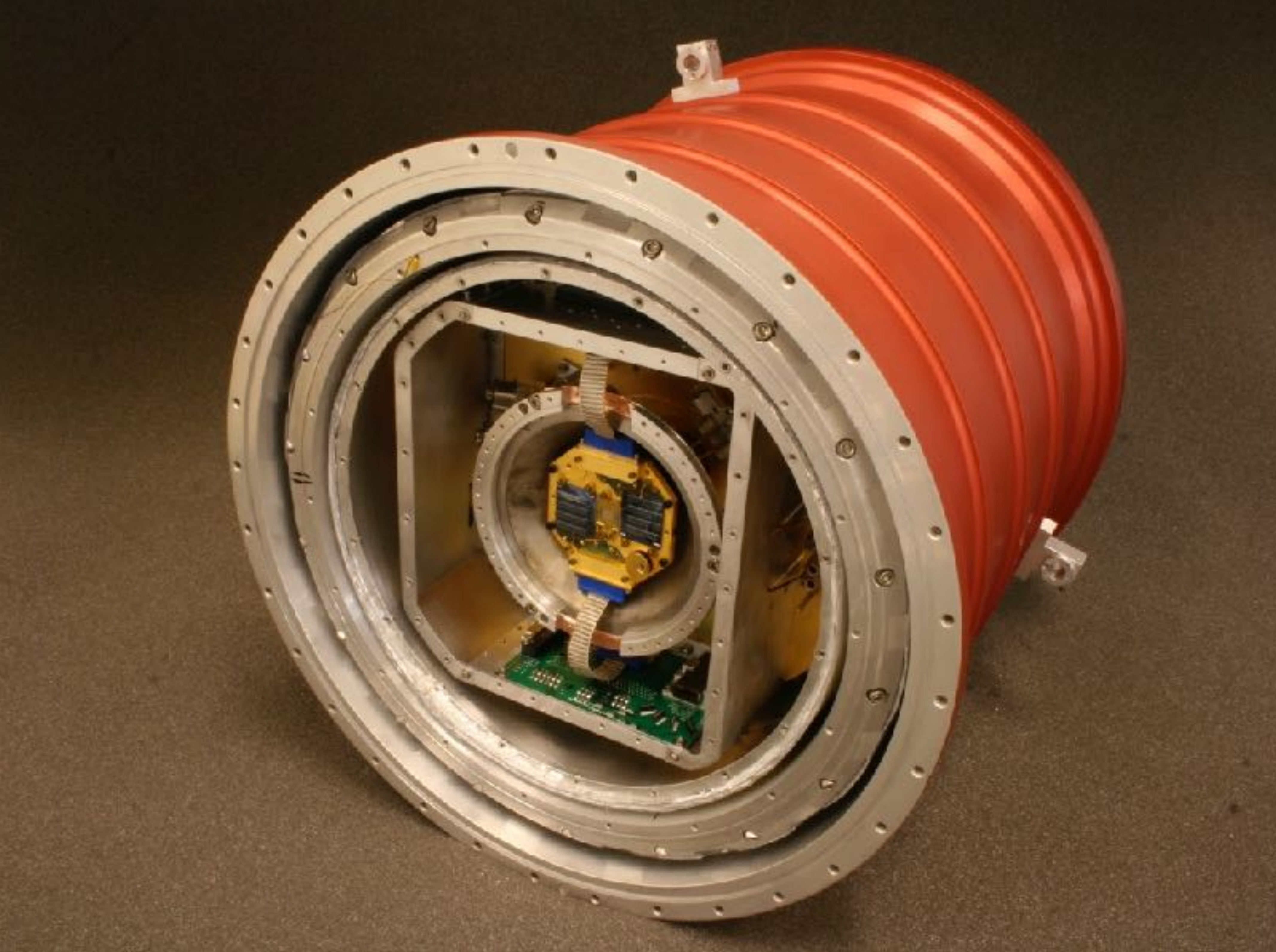


Superconducting Shield



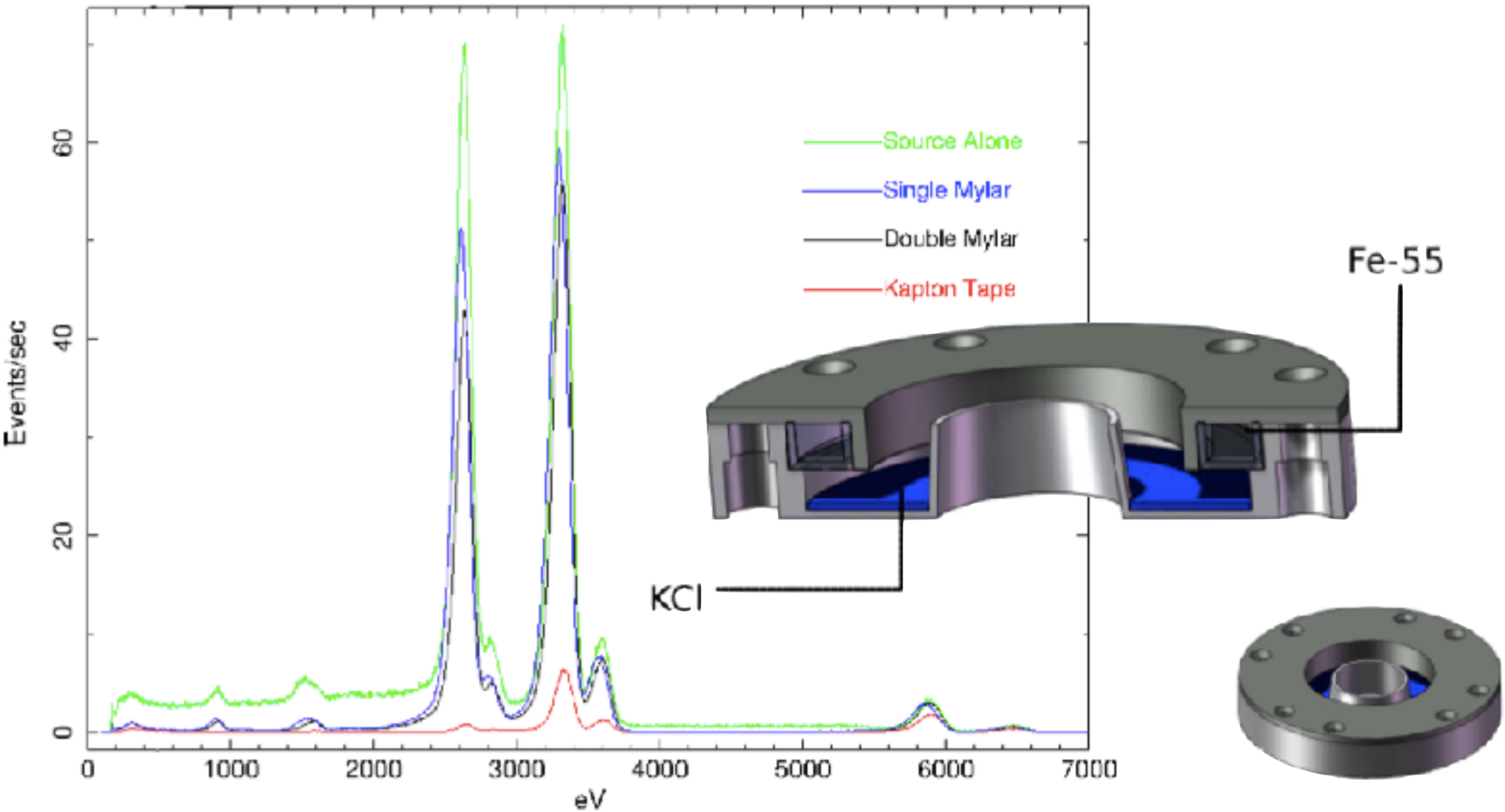
Micro-X Insert



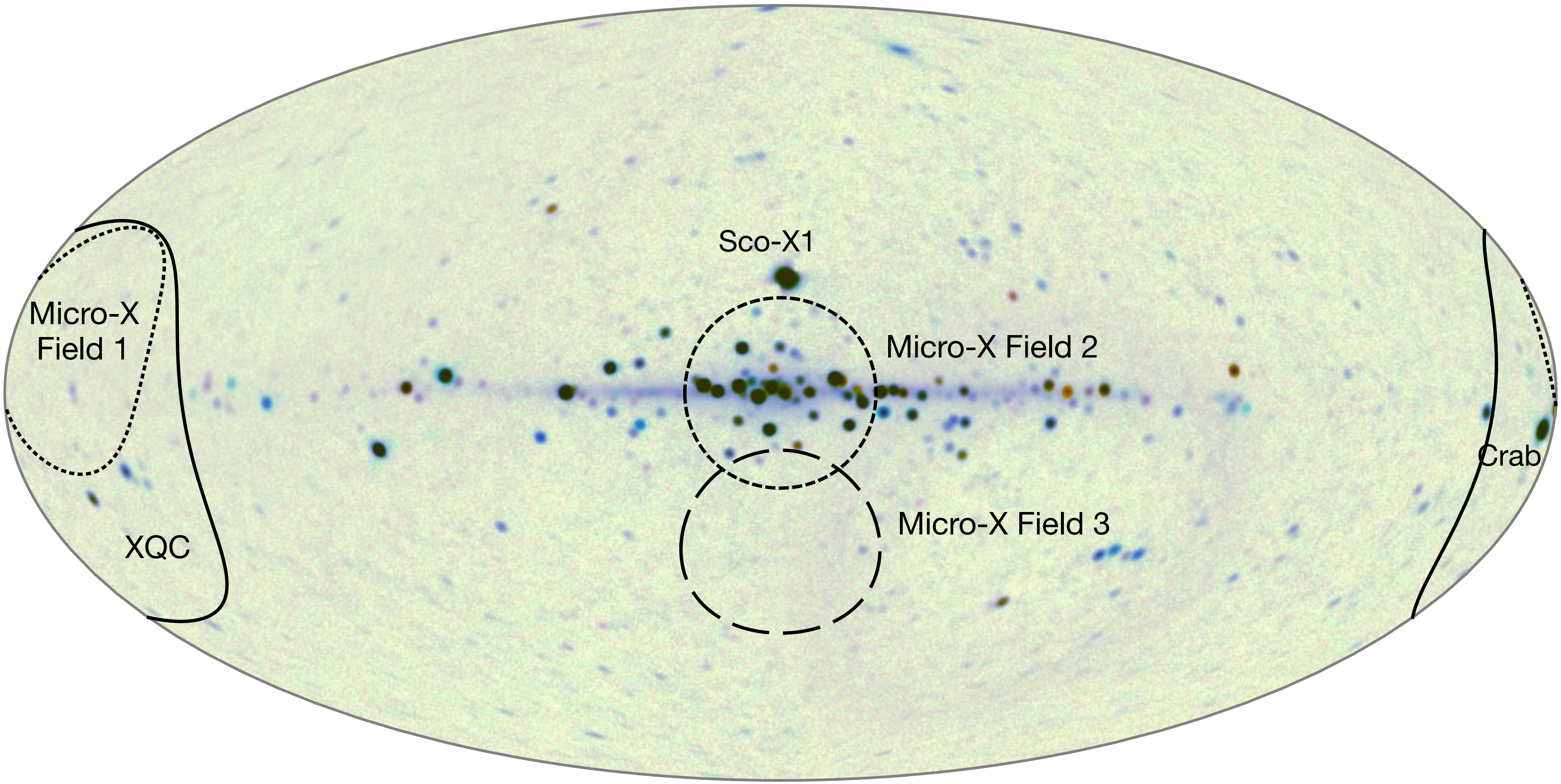


In-flight Calibration

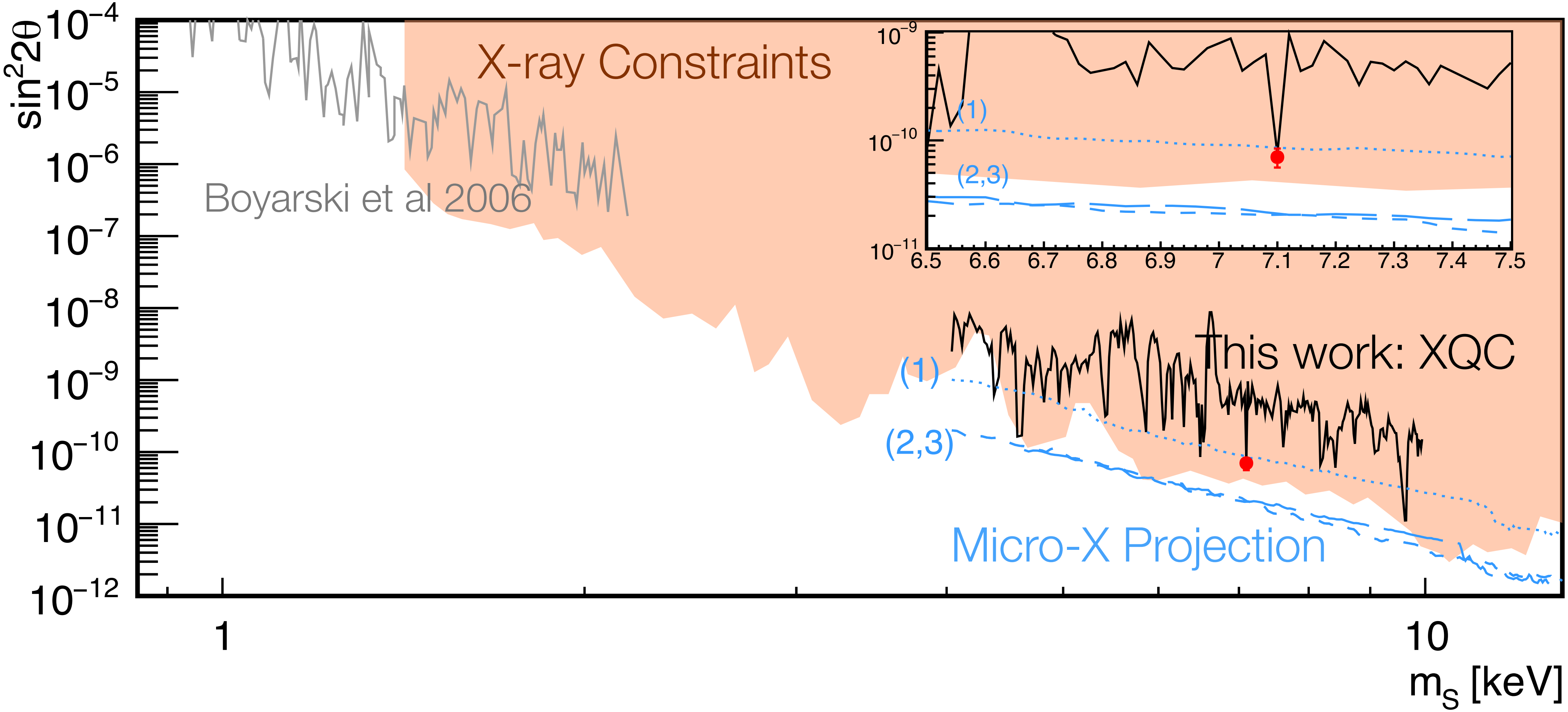
Custom-designed gain calibration source provides counts above the science spectral band.
Target rate is 1 count/sec/pixel.



FOV for Micro-X GC Observation

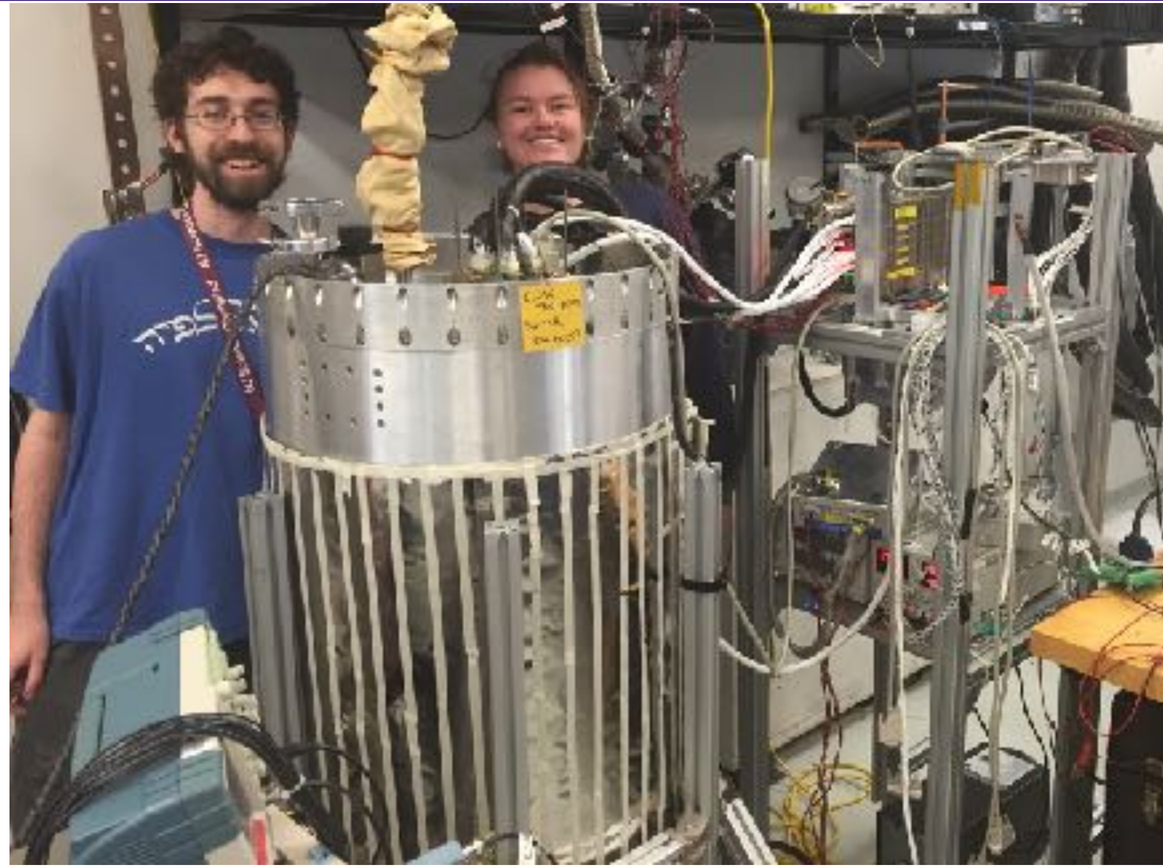


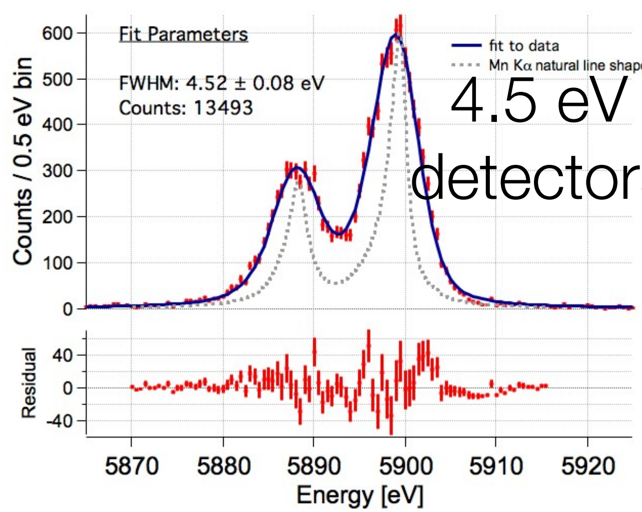
Sterile Neutrino Bounds



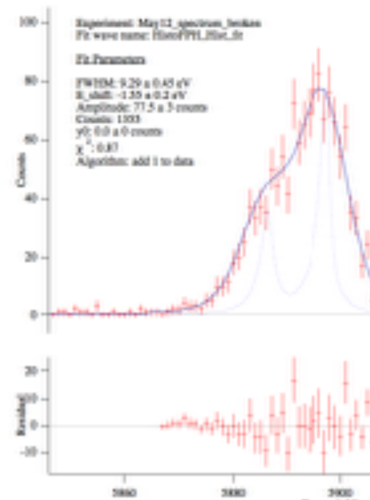
Current Micro-X Status Report

- The payload has passed all functional tests, including vibration tests, SQUID multiplexing and ADR control
- Micro-X is undergoing Detector Qualification Testing at NASA Goddard Space Flight Center
- We expect a launch later this year, first dark matter observation in 2018, either from White Sands or Australia





4.5 eV detectors



Currently hunting down electronics noise

Hydra Concept Complex TES

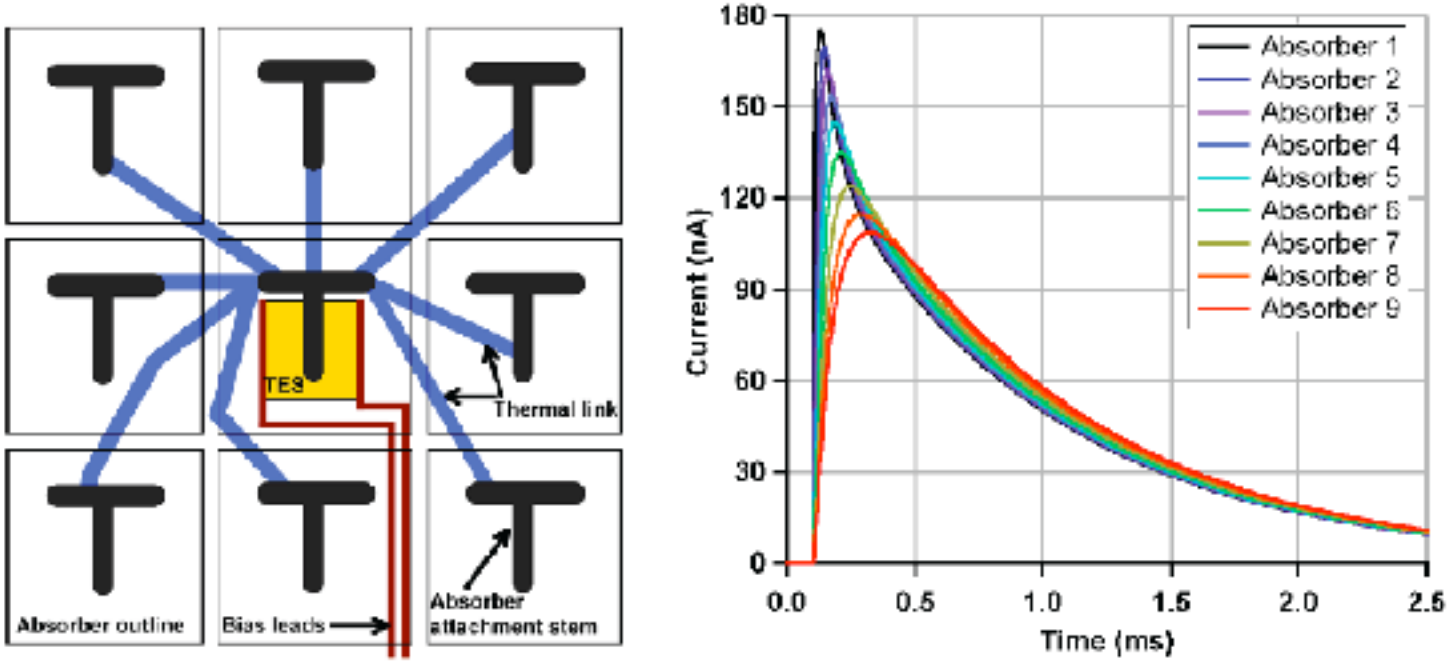
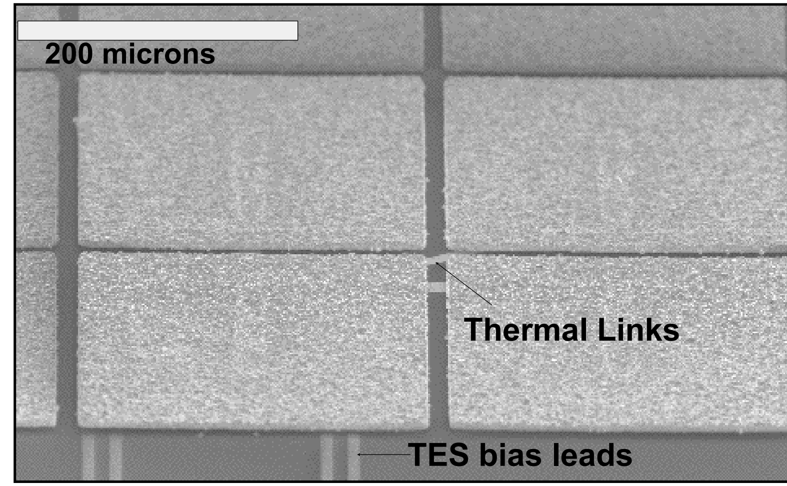


Figure 4. *Left:* Schematic diagram of the Hydra concept, showing nine absorbers, each with a different thermal conductance, connected to a single TES. Each absorber is supported above the TES and solid substrate using small stem contact regions (shown as "T" shapes here). *Right:* Simulated 9-pixel Hydra noise-less pulse shapes for a photon energy of 100eV. Absorber 1 is the most strongly coupled absorber to the TES.

Proc. SPIE 8443, Space Telescopes and Instrumentation 2012: Ultraviolet to Gamma Ray, 844316 (September 7, 2012); doi:10.1117/12.926851

Hydra Fabrication

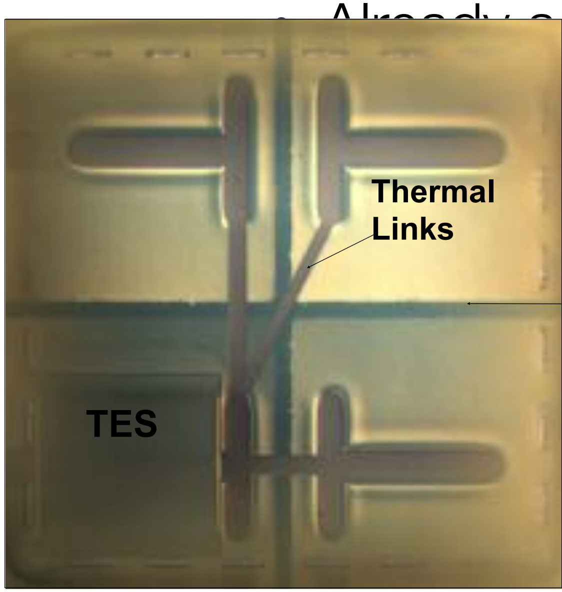


SEM of 4 Hydra absorbers from wafer 2

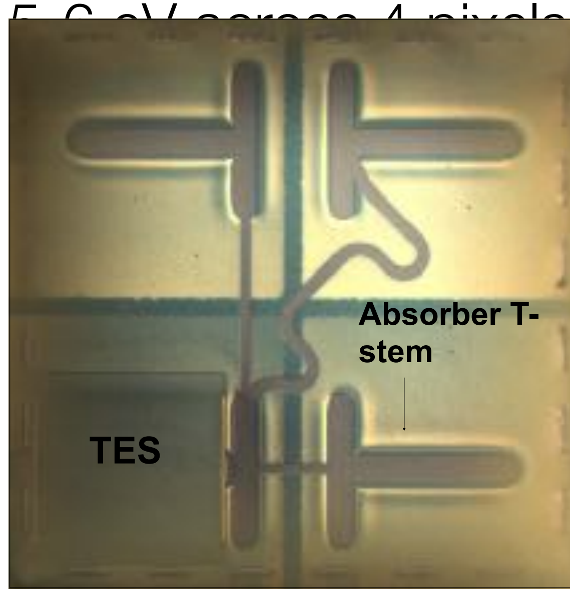
- Different combinations of Glink and Gbath to investigate energy resolution, position sensitivity and speed.
- Already achieved 5-6 eV across 4 pixels with 630 μs decay at ... ergy.

Back view shows links and 'T'-Stems through the Si-N membrane

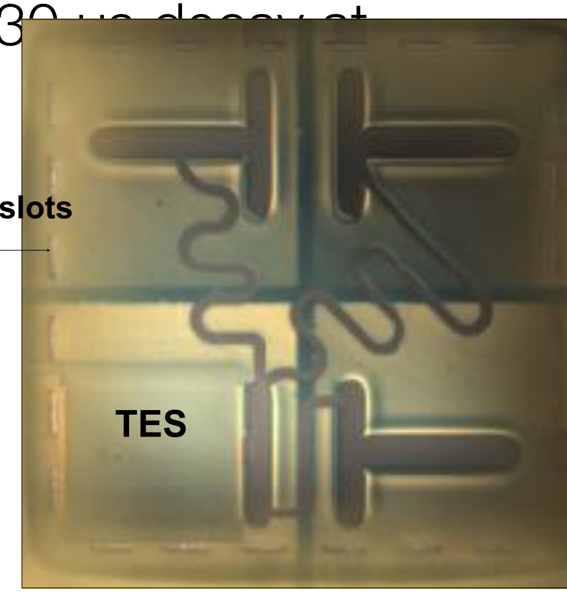
Fast G_{link}'s



Medium G_{links}'s



Slow G_{links}'s



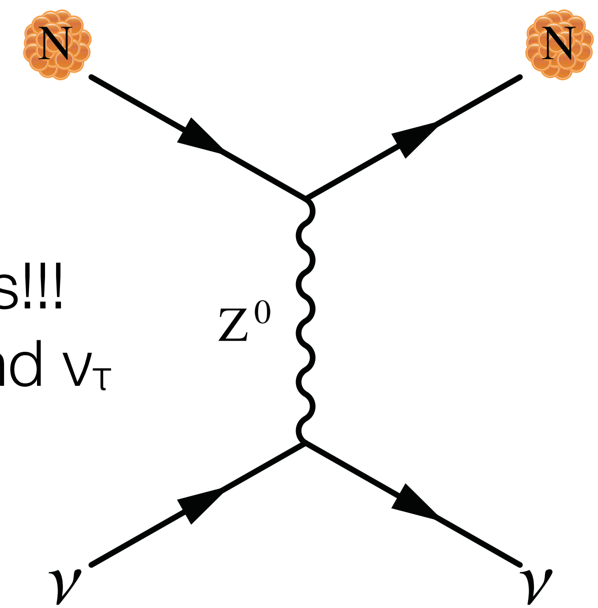
Neutrino Physics

Coherent Elastic ν-Nucleus Scattering

$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} Q_W^2 M_A \left(1 - \frac{M_A T}{2E_\nu^2}\right) F(q^2)^2$$

- σ: Cross Section
- T: Recoil Energy
- E_ν: Neutrino Energy
- G_F: Fermi Constant
- Q_W: Weak Charge
- M_A: Atomic Mass
- F: Form Factor

No flavor-specific terms!!!
Same rate for ν_e, ν_μ, and ν_τ



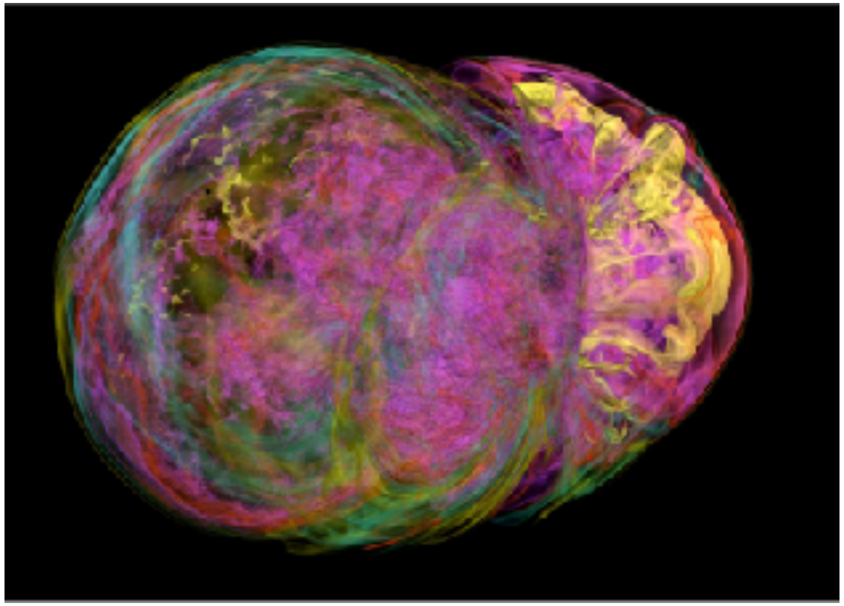
VOLUME 55, NUMBER 1 PHYSICAL REVIEW LETTERS 1 JULY 1985

Bolometric Detection of Neutrinos

Blas Cabrera, Lawrence M. Krauss, and Frank Wilczek
Department of Physics, Stanford University, Stanford, California 94305
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 01238
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106
(Received 14 December 1984)

CEνNS as a Probe

- Channel opens new doors for a variety of physics
    - Physics of supernovae (and detection)
    - Probe into the form factors of nuclei at very small Q^2 that are otherwise difficult to probe.
    - Sensitive to non-standard-model couplings
    - Renewed interest in nuclear proliferation monitoring



Neutrino Sources

4 sources to consider:

- The Sun + other cosmic sources
- Electron-capture sources
- Reactors
- Decay-at-rest sources

Neutrino Sources

arXiv:1402.7137
1408.3581
1409.0050

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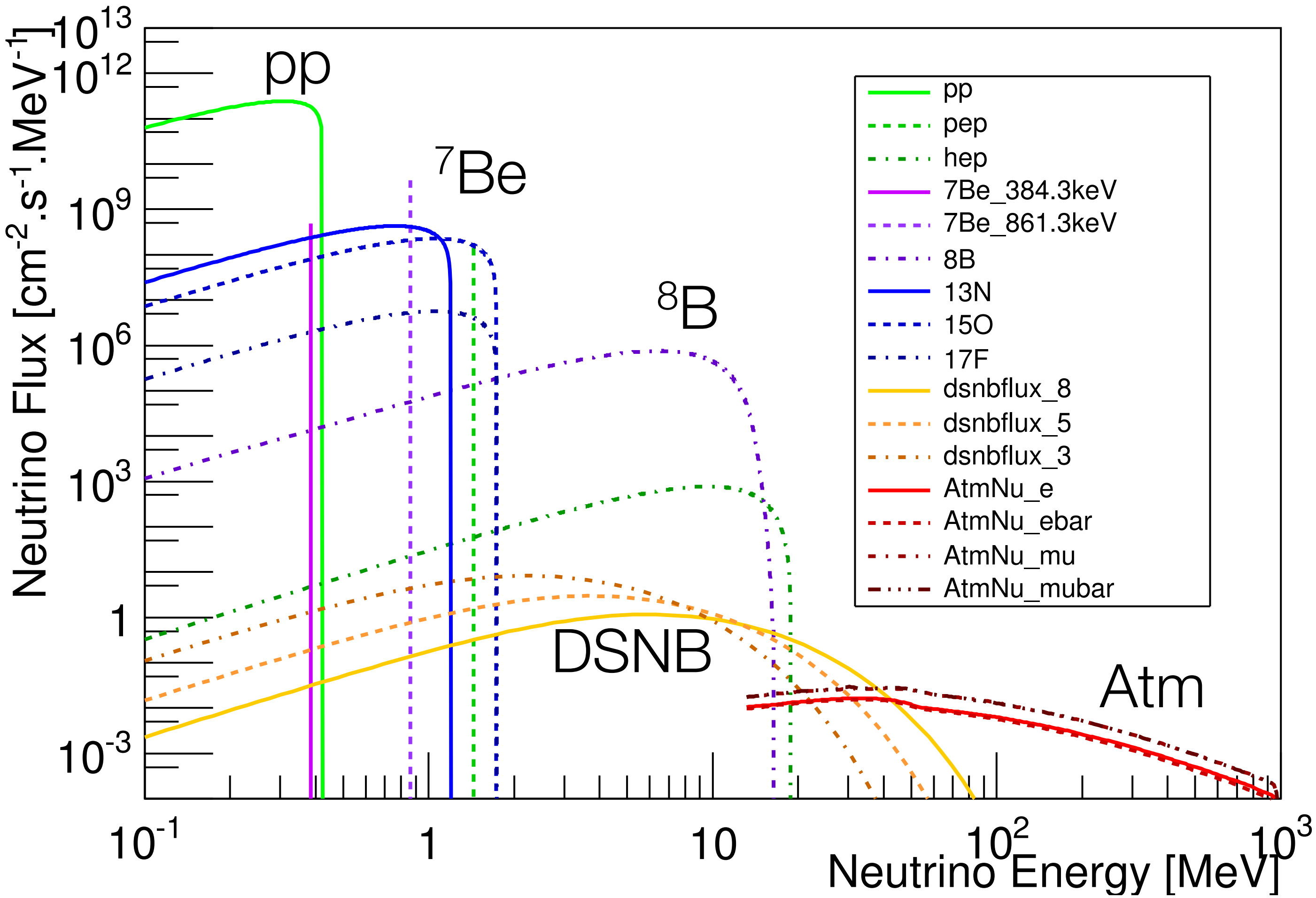

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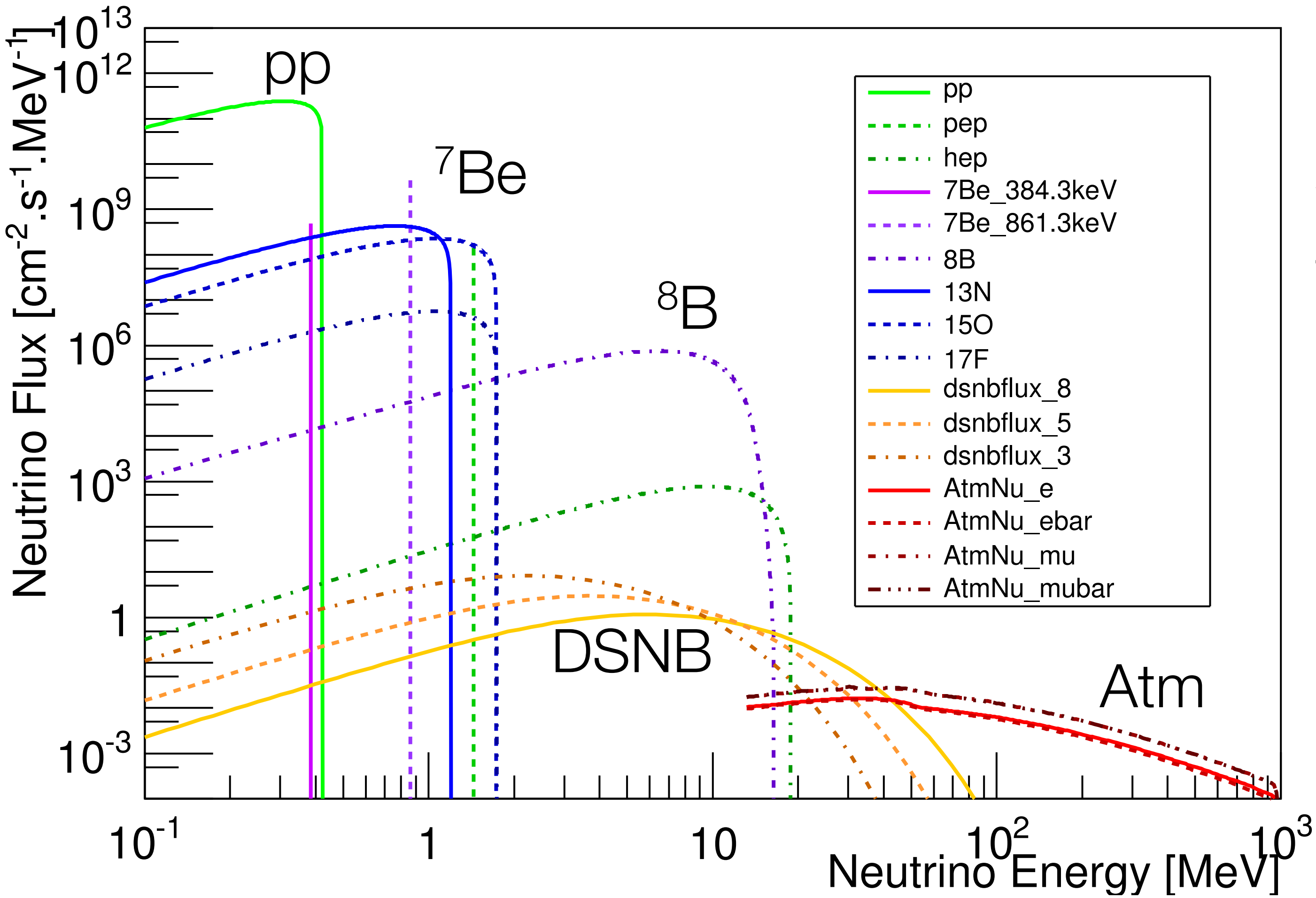
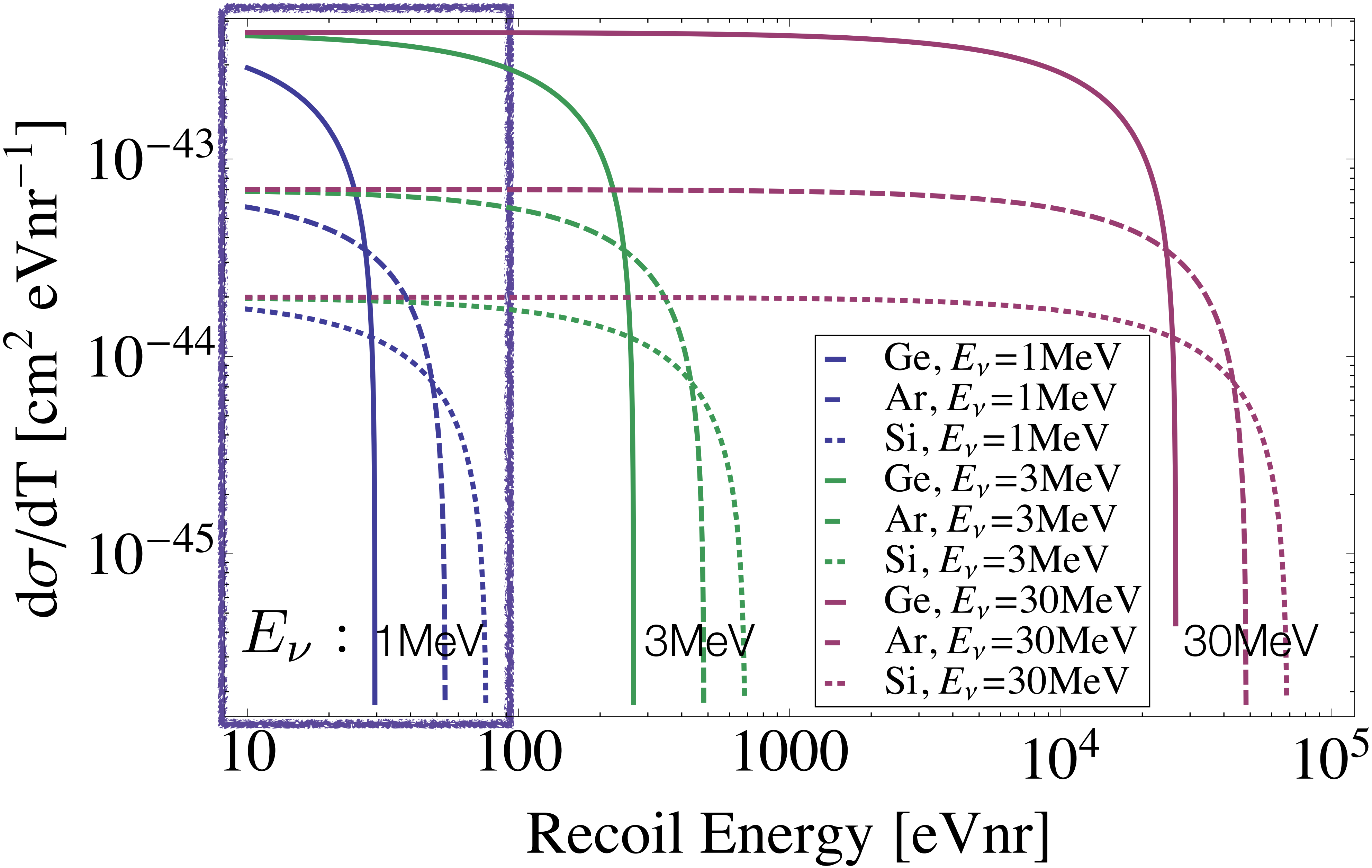


G2 Dark Matter Experiments (SuperCDMS SNOLAB and possibly LZ) will be able to detect the Solar ^{8}B CE**ν**NS signal!

Small number of events, but expect a positive CE**ν**NS detection in the next ~5 years…

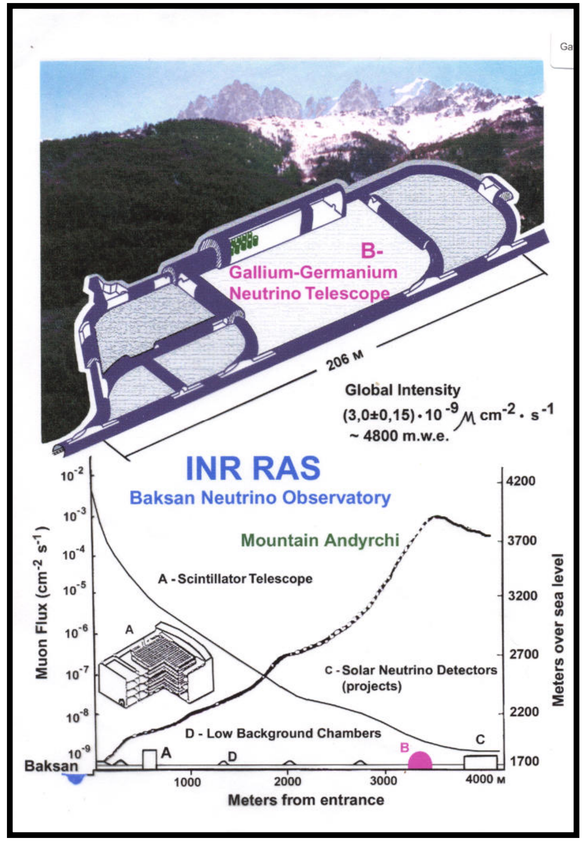
Ricochet: CEvNS with ~1 MeV neutrinos

Need Thresholds of 10's of eV!



Ricochet Source ~1 MeV neutrino sources

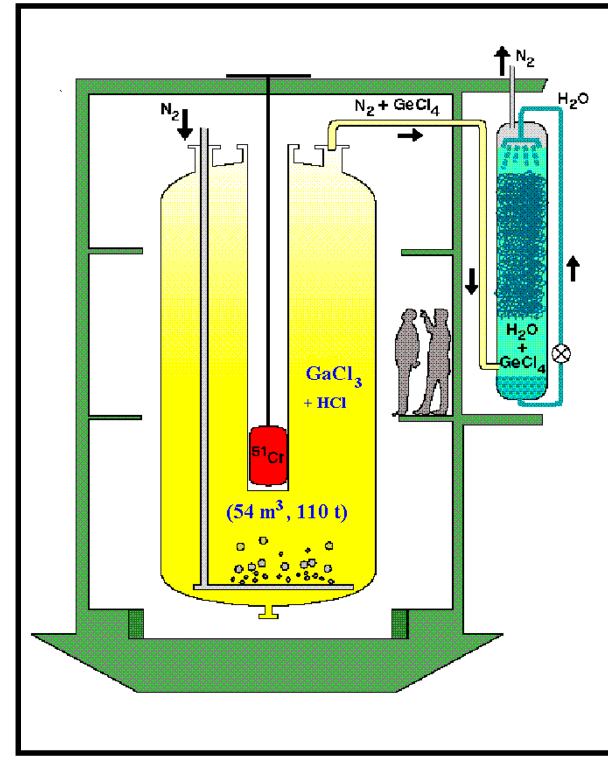
- Ideal mono-energetic sources have been constructed for experiments previously (SAGE, GALLEX), of order 1 MCi activity.
- Jon Link will talk about the ^{51}Cr program
- A Ricochet detector at SOX might also be an interesting possibility.



SAGE

$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$

Use of ^{37}Ar and ^{51}Cr



Gallex/GNO

$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$

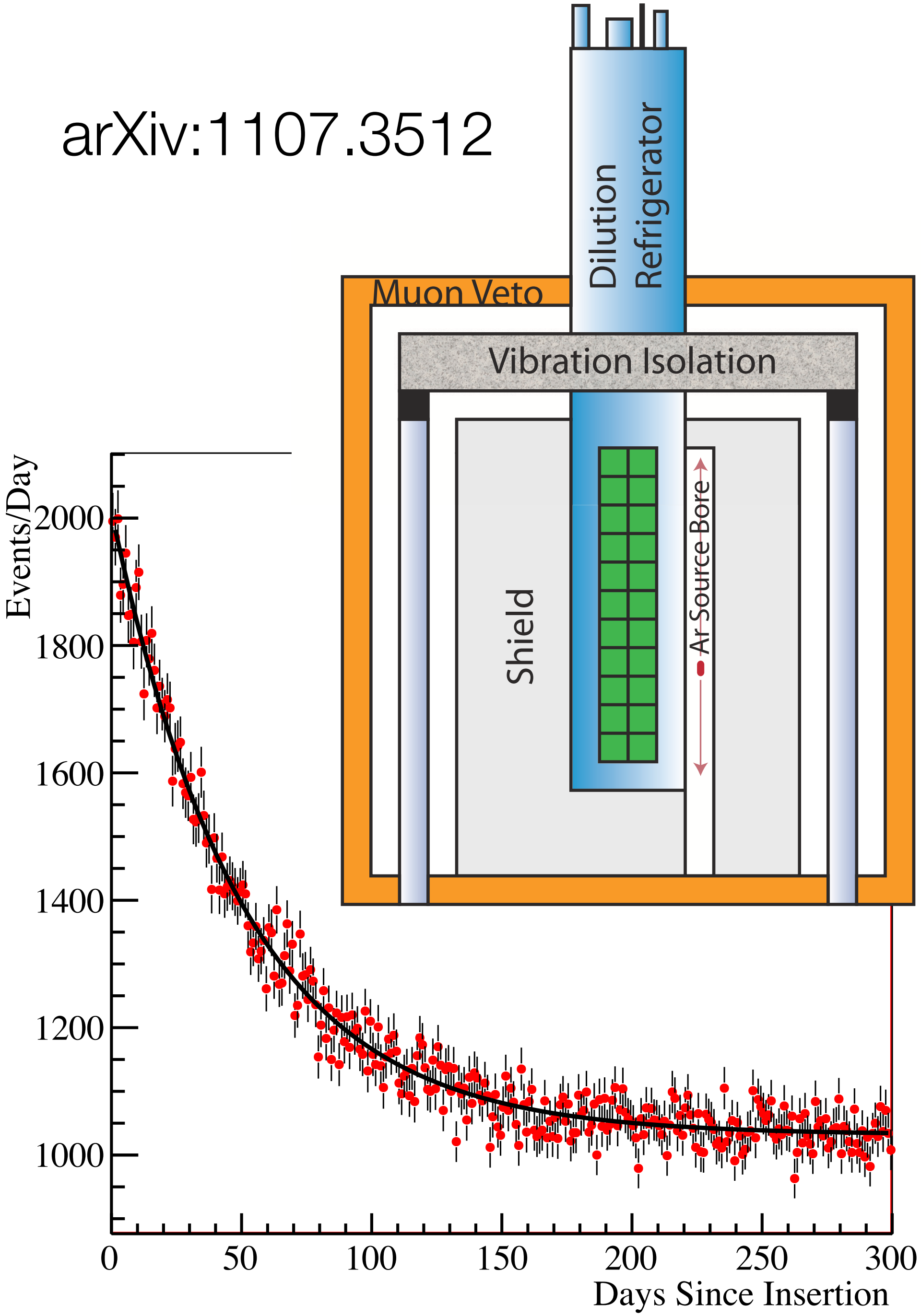
Use of ^{51}Cr

Source	Half-Life	Progeny	Production	E_ν
^{37}Ar	35.04 days	^{37}Cl	^{40}Ca(n,α)^{37}Ar	811 keV (90.2%), 813 keV (9.8%)
^{51}Cr	27.70 days	^{51}V	n capture on ^{50}Cr	747 keV (81.6%), 427 keV (9%), 752 keV (8.5%)
^{65}Zn	244 days	^{65}Cu	n capture on ^{64}Zn	1343 keV (49.3%), 227 keV (50.7%)

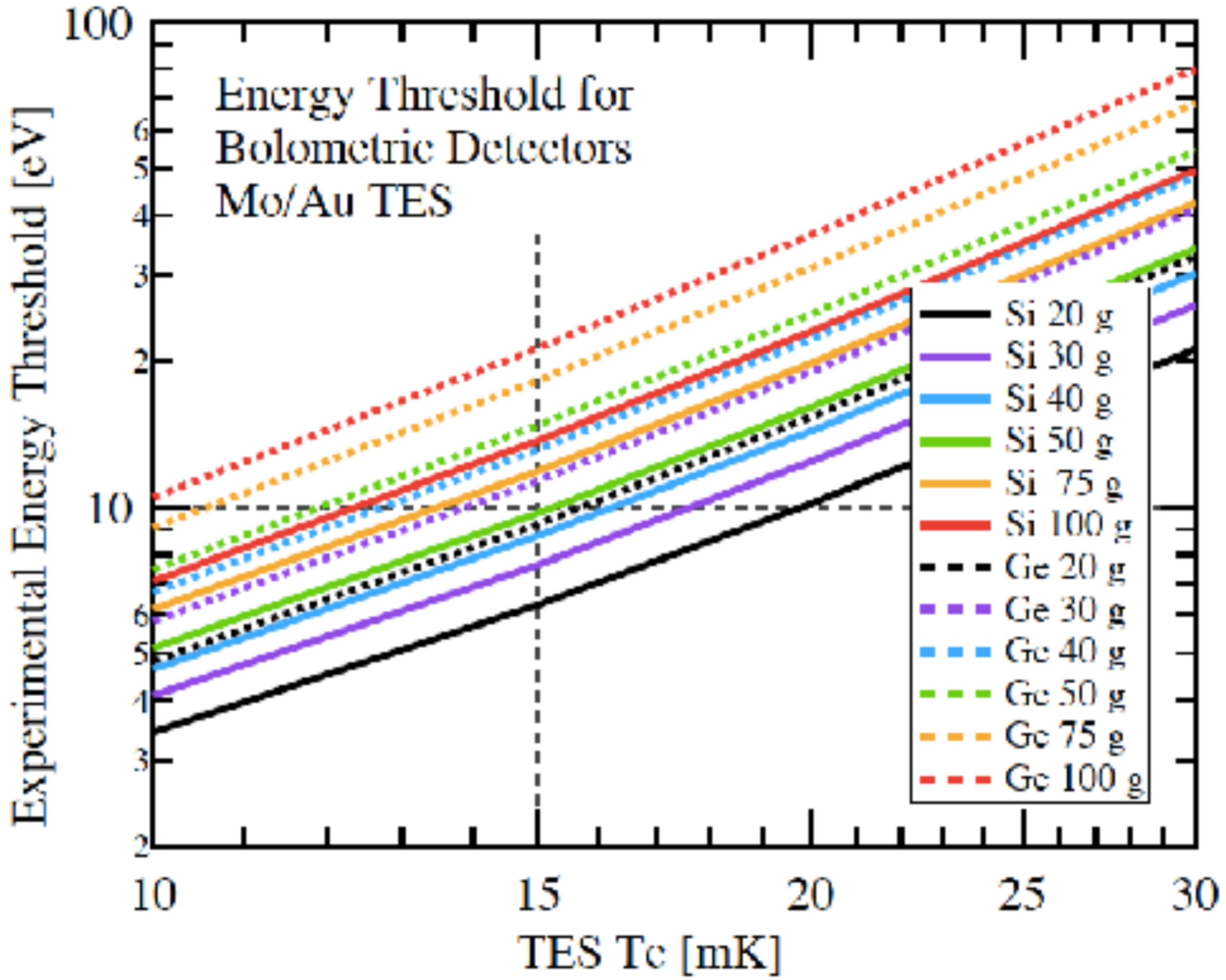
Ricochet Phase 2: CEvNS with ~1 MeV neutrinos

arXiv:1107.3512

- Array of 10,000 elements with ^{37}Ar or ^{51}Cr source just outside shield (10 cm closest distance).
- Measuring time of 300 days (for ^{37}Ar, equivalent of 50 days signal, 250 days background).
- Background rate of 1 event/kg/day in energy region of interest
- R&D needed, would be a "smoking gun" experiment done if charged current experiments saw a signal.



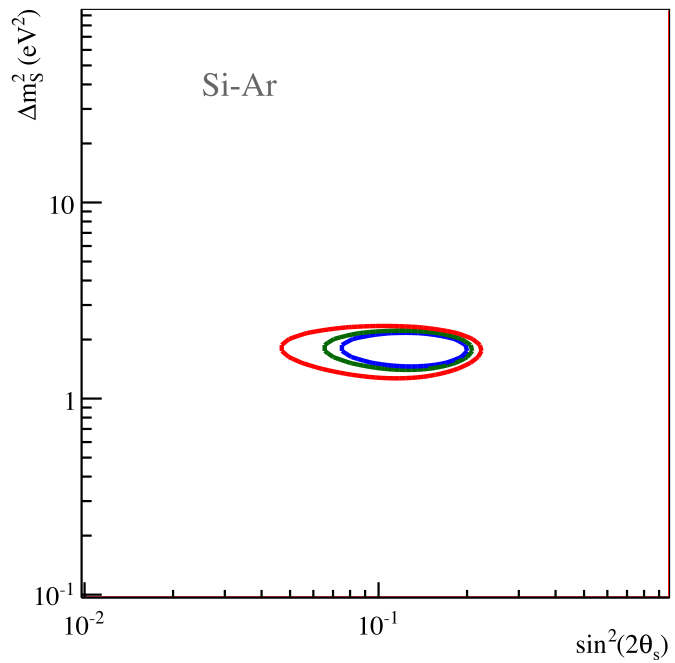
Detector Design - Merge Micro-X and SuperCDMS

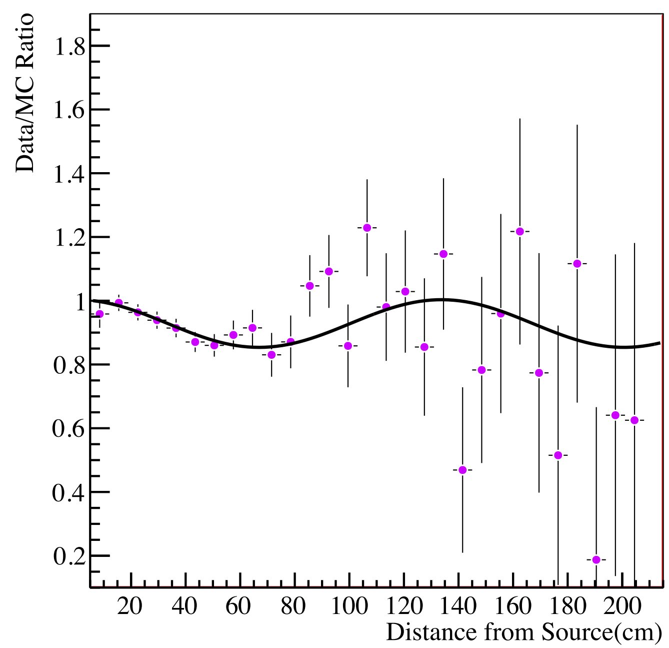


Ricochet Phase 2: CEνNS with ~1 MeV neutrinos

- Sensitivity study performed on 10,000 element array (500 kg Si, 200 kg Ge), ^{37}Ar or ^{51}Cr source.
- Assumed 300 day measuring time with background rate of 1 event/kg/day.
- Analysis on shape + rate (bulk result from shape)
- Mock signal also tested.

arXiv:1107.3512





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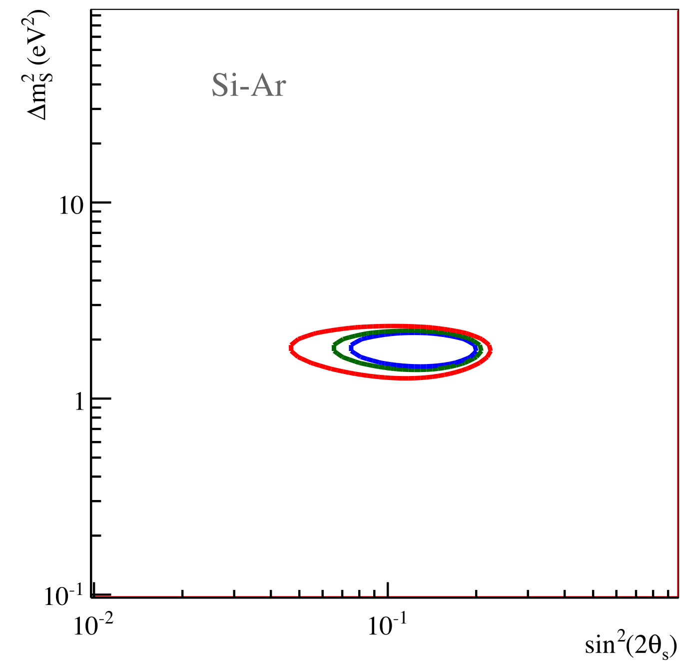
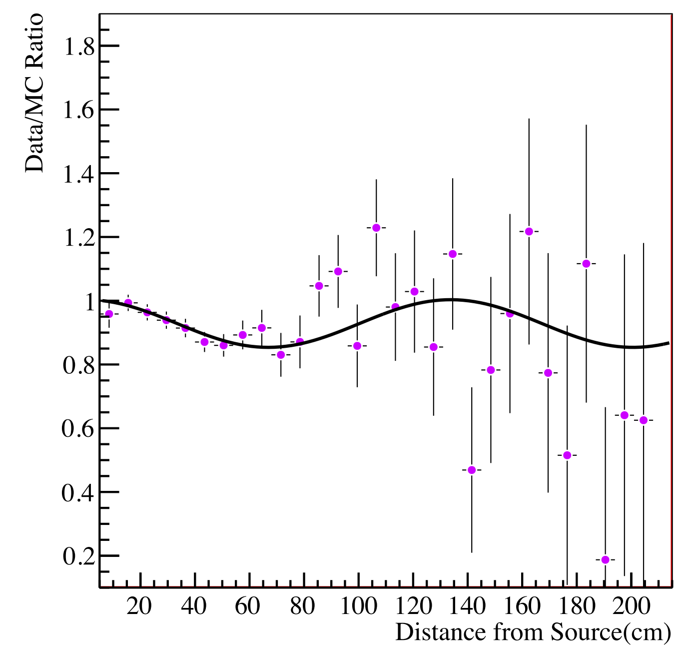
<u>Alternate Measurements</u>

coherent scattering measurement

$\sin^2\theta_W$ measurement

dark matter detection





Conclusions

- Cryogenic TES-based detectors are a powerful technology with many scientific applications.
- Astronomy, Particle Astrophysics, and Material's Analysis are the main uses right now.
- Other uses are waiting to be pursued!