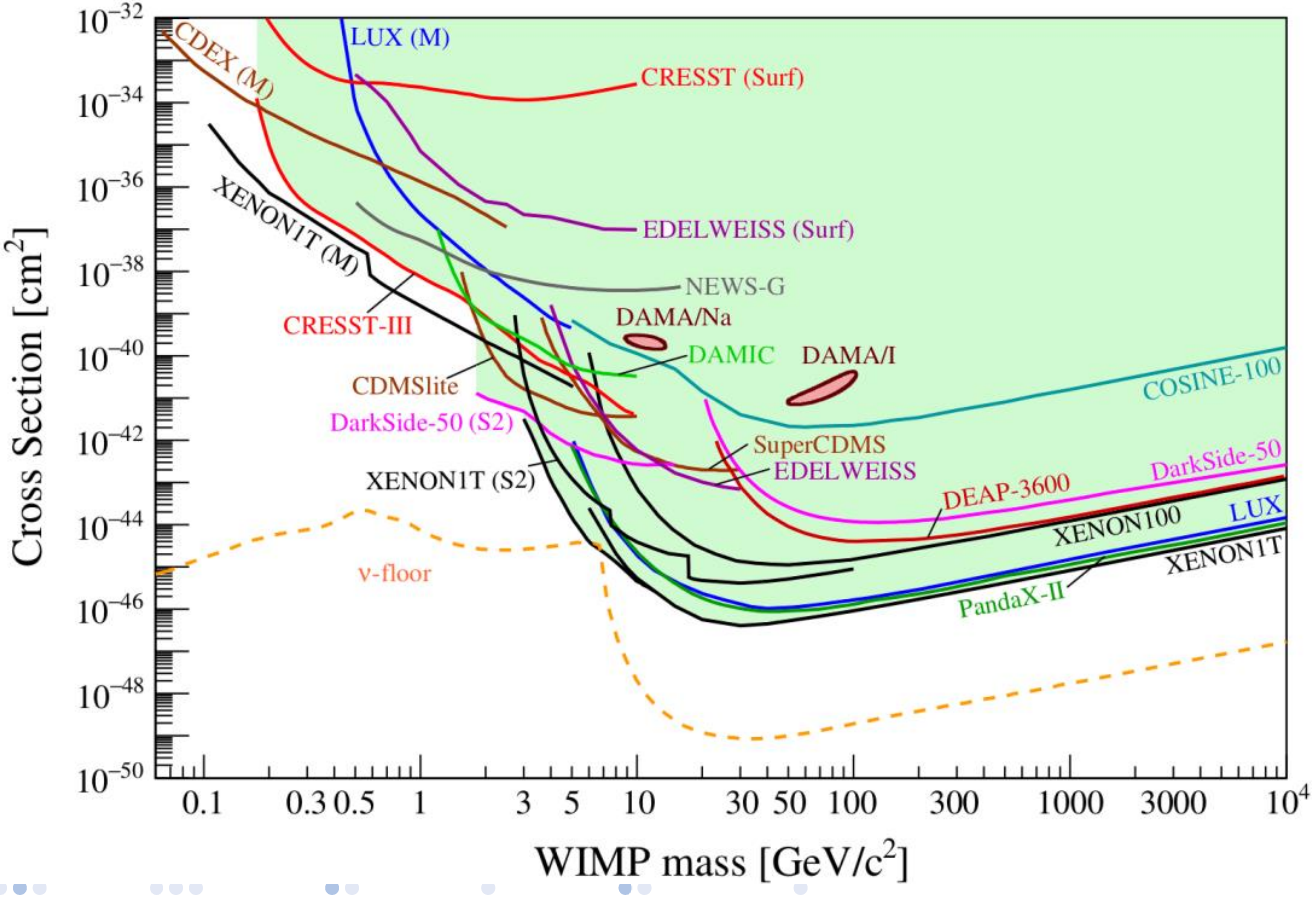
12/SEP/2023

Introduction To Dark Matter

Matthew Stukel (with slides from Pierre Gorel and Pietro Giampa)



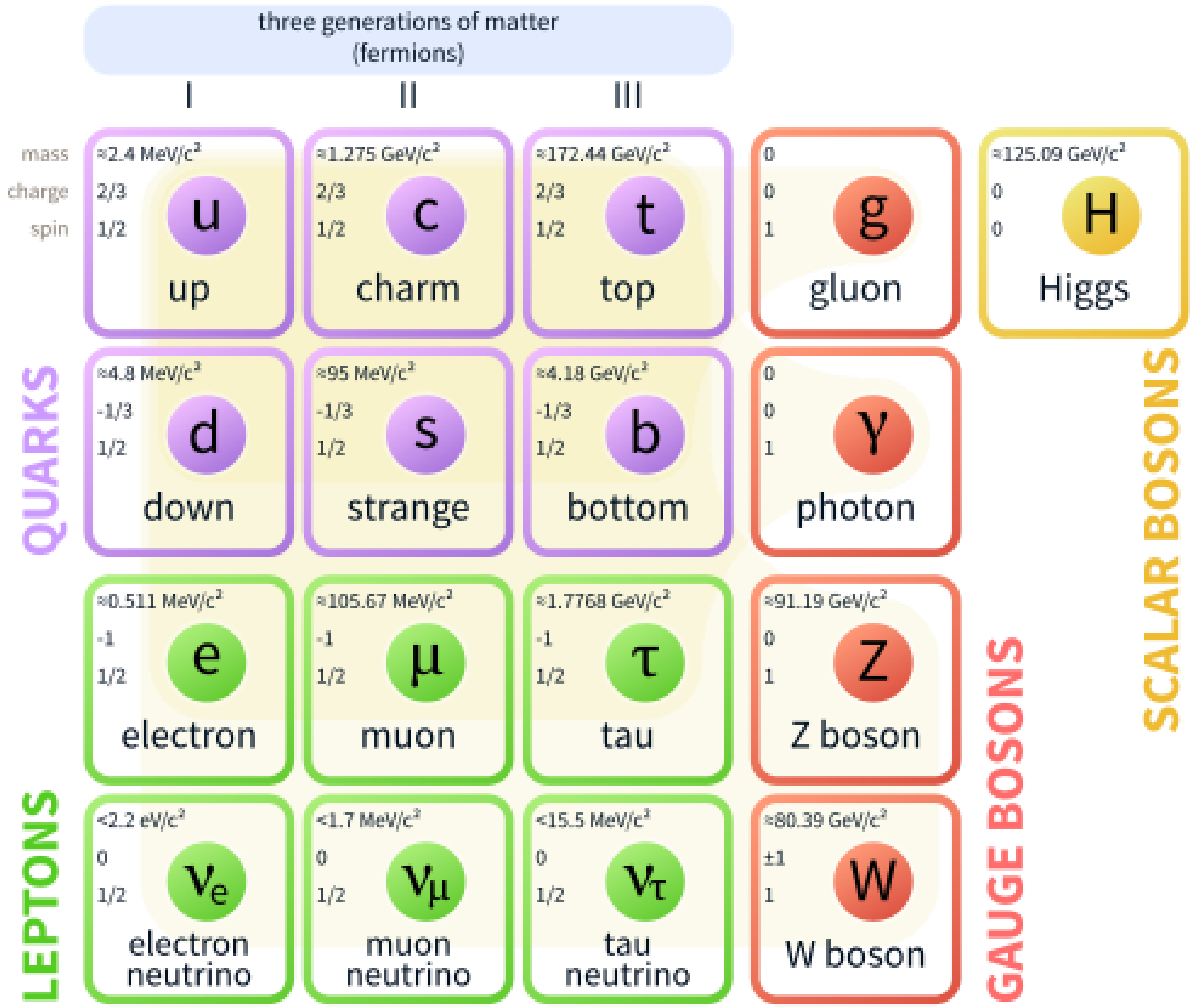
Cross Section [cm^2]
WIMP mass [GeV/c^2]
CDEX (M)
LUX (M)
CRESST (Surf)
XENON1T (M)
EDELWEISS (Surf)
NEWS-G
CRESST-III
DAMA/Na
DAMIC
DAMA/I
CDMSlite
COSINE-100
DarkSide-50 (S2)
SuperCDMS
EDELWEISS
XENON1T (S2)
DEAP-3600
DarkSide-50
XENON100
LUX
XENON1T
PandaX-II
ν-floor

Outlook

- Evidence for dark matter
- Searching for dark matter
- Dark matter backgrounds
- Dark matter detection

Evidence For Dark Matter

Standard Model of Elementary Particles



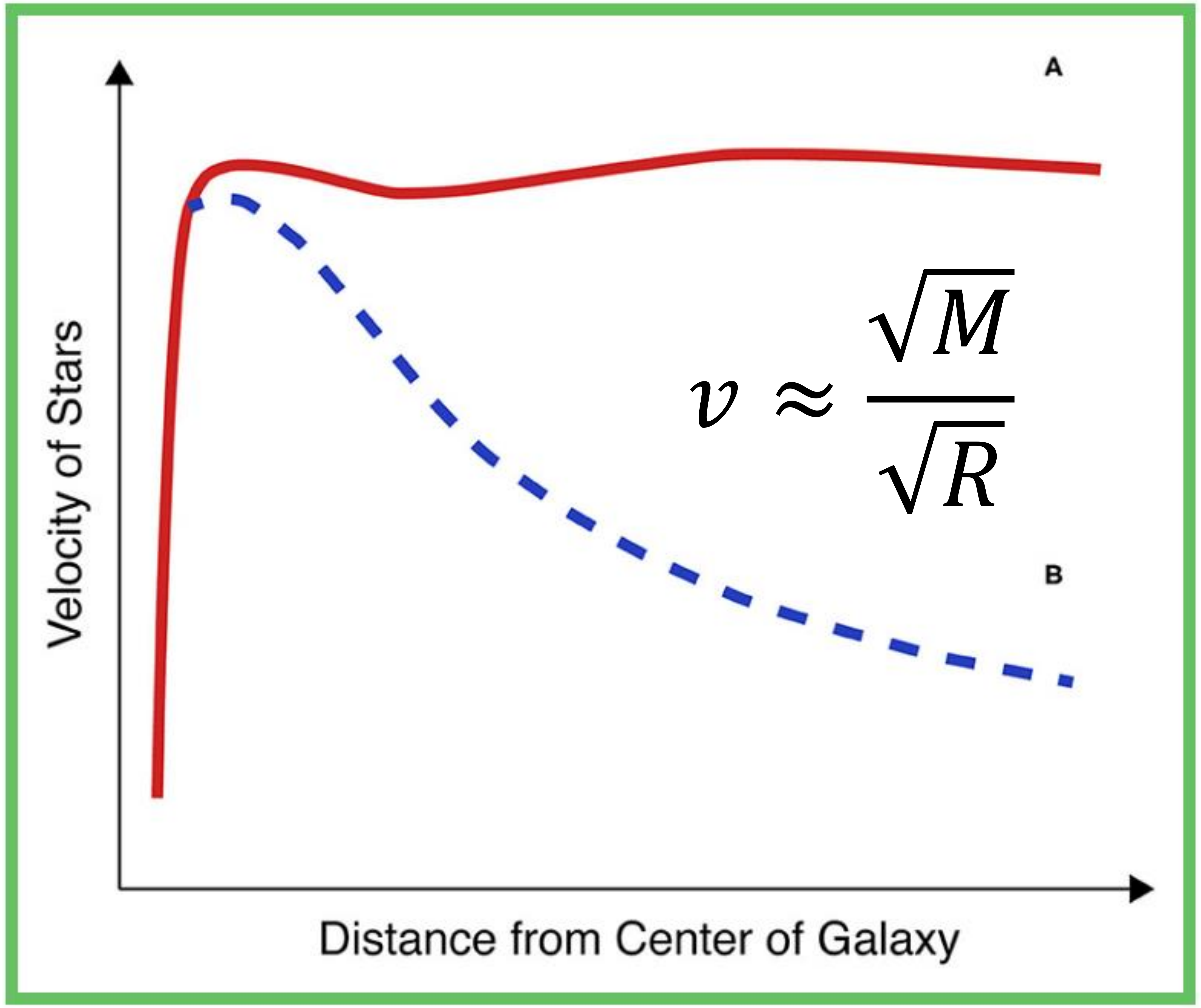
- **Electromagnetism:** Light, Technology, communications
- **Weak Force:** Radioactive Decay, Medical isotopes, geological dating, security
- **Strong Force:** Nuclear reactor, fusion and fission
- But what if there was something beyond?????????

Evidence 1: Galactic Rotation Curves

- Fritz Zwicky, 1933, found a large discrepancy between the mass of the COMA cluster from the **Virial Theorem** vs. the observable mass
  - Dunkle Materie
- Horace Babcock, Franz Kahn, Lodewijk Woltjer and Arrigo Finzi would find similar evidence
- Vera Rubin observed the rotation curve of spiral galaxie (such as Andromeda), found that the rotation velocity of the galaxy did not decrease as the distance of the galaxy increased

$$2 < T > = - < U >$$

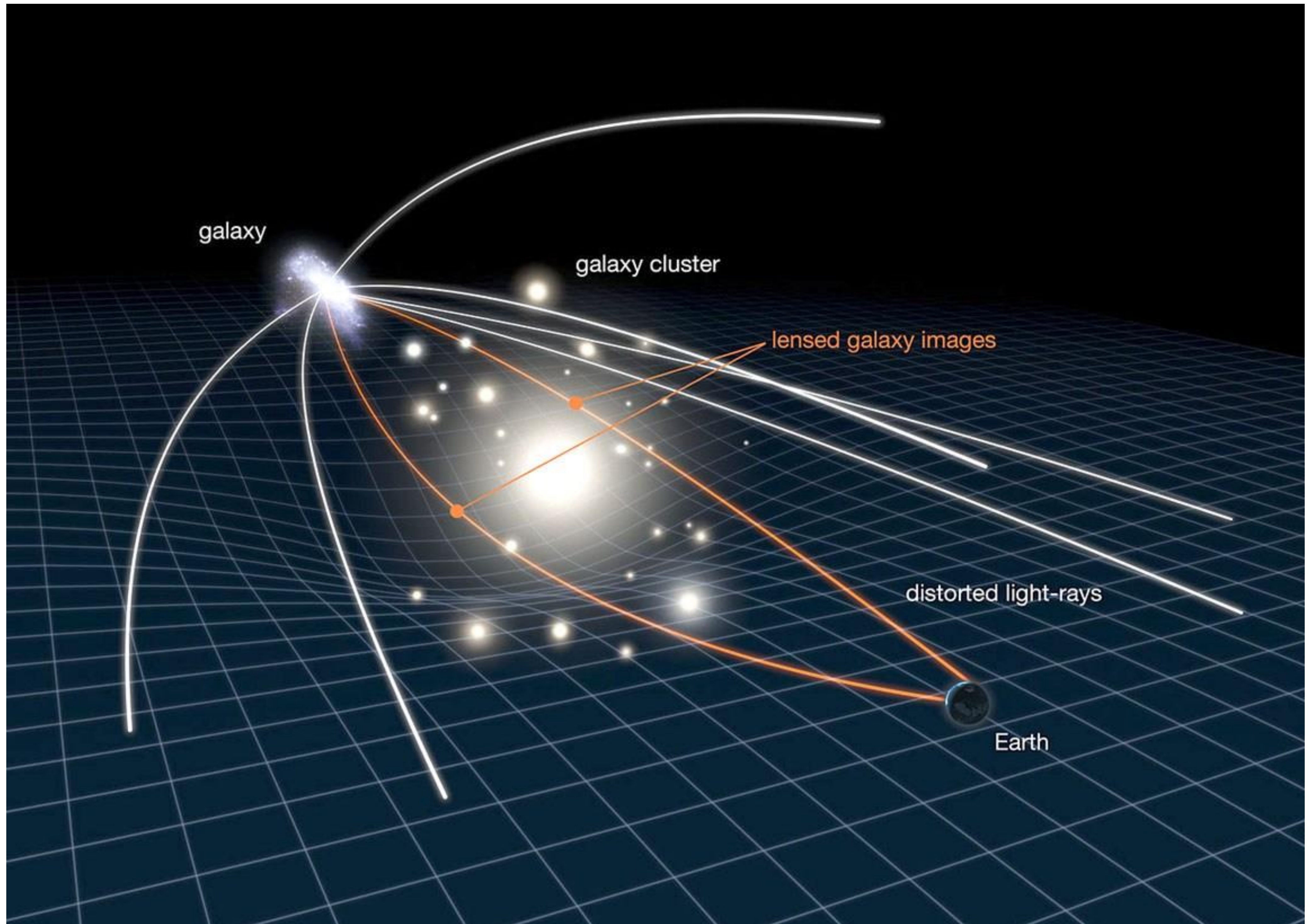
$$2\left(\frac{1}{2} M_{Tot} v^2\right) = -\frac{G M_{TOT}^2}{2 R_{TOT}}$$



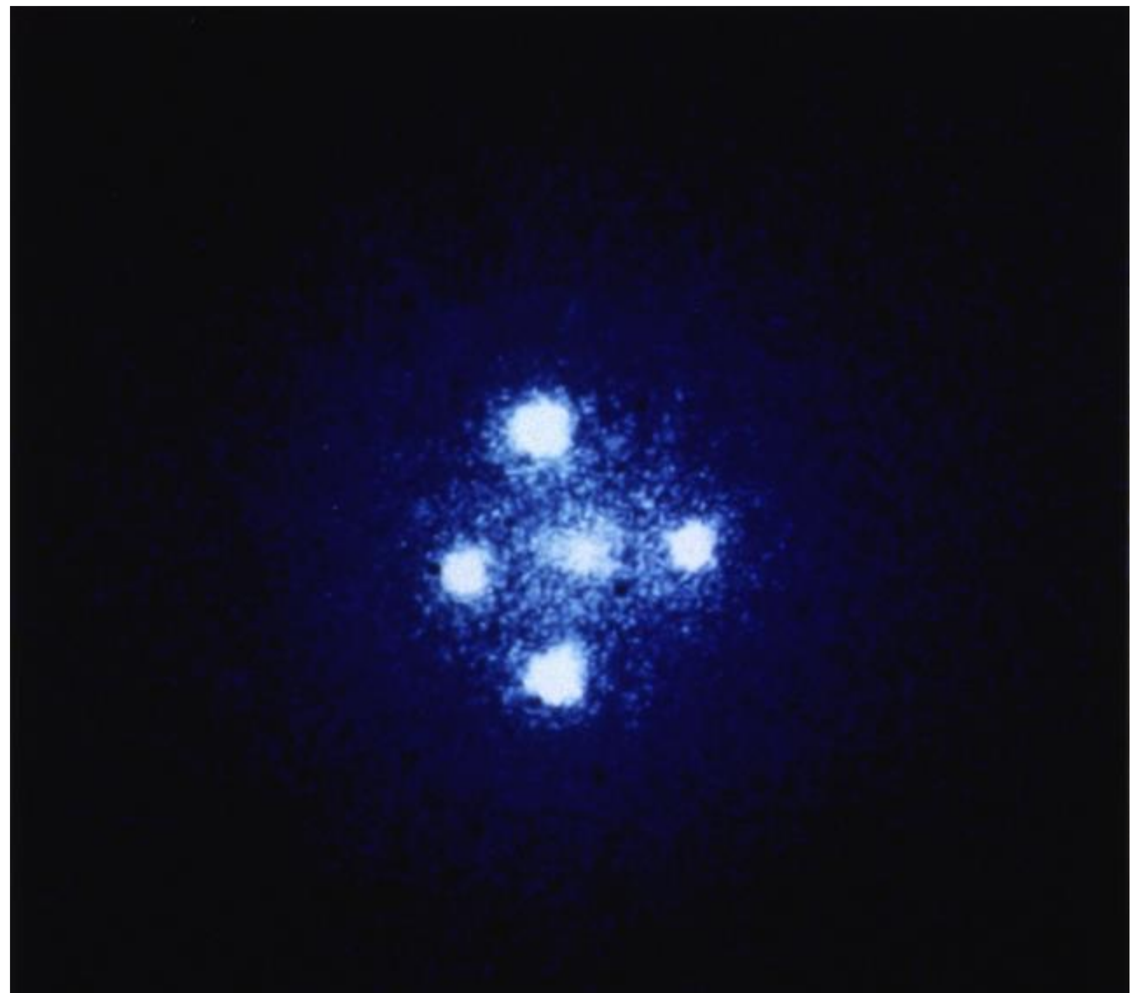
$$v \approx \frac{\sqrt{M}}{\sqrt{R}}$$

Evidence 2: Gravitational lensing

- Significant mass between the source and the observer will bend light
- This will lead to stretched or bigger images
  - Einstein Cross image of a quasar
- If we know how much material is in the way you can calculate the expected bending
- More bending then expected means unseen mass



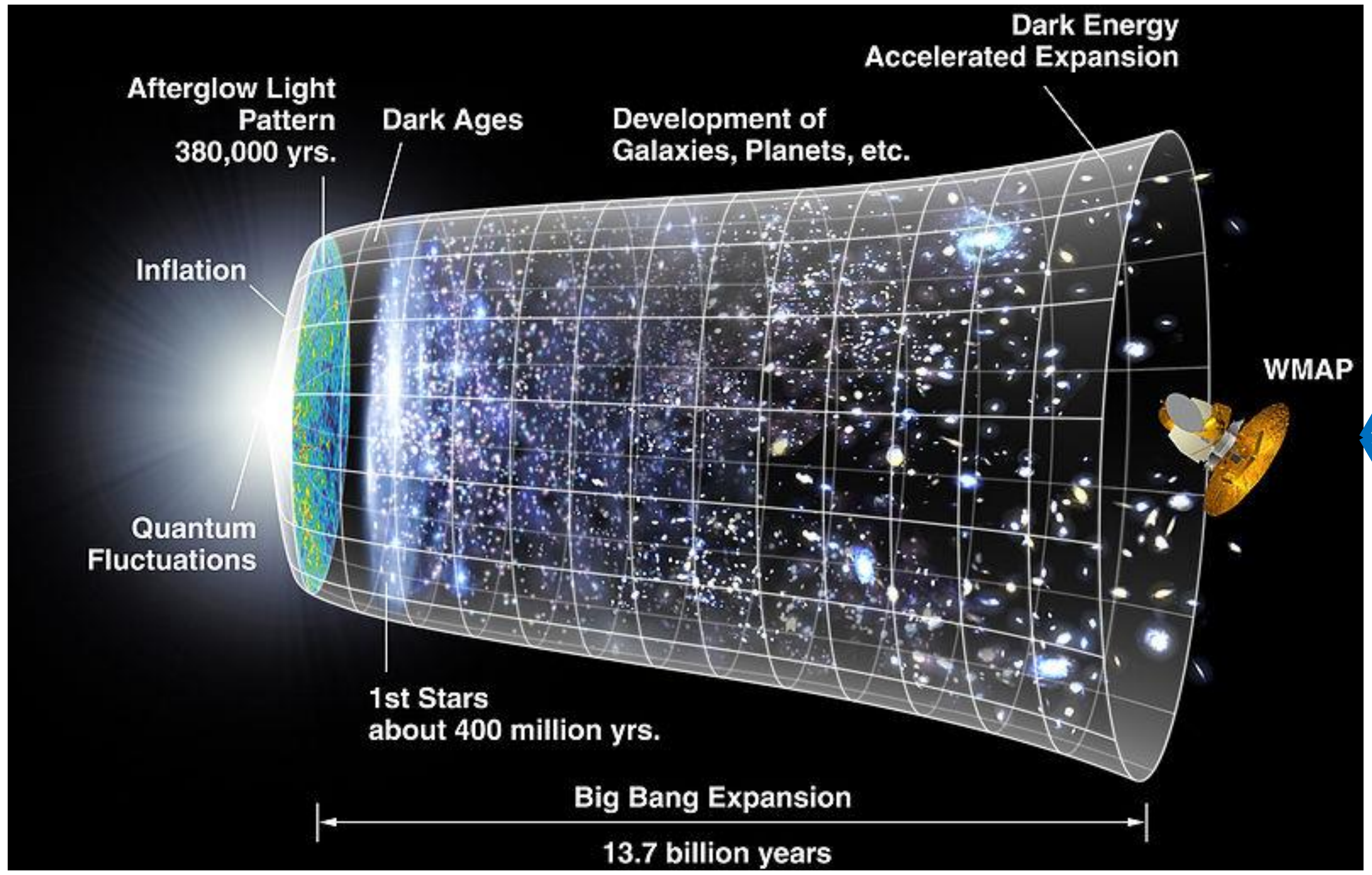
Credit: NASA/ESA

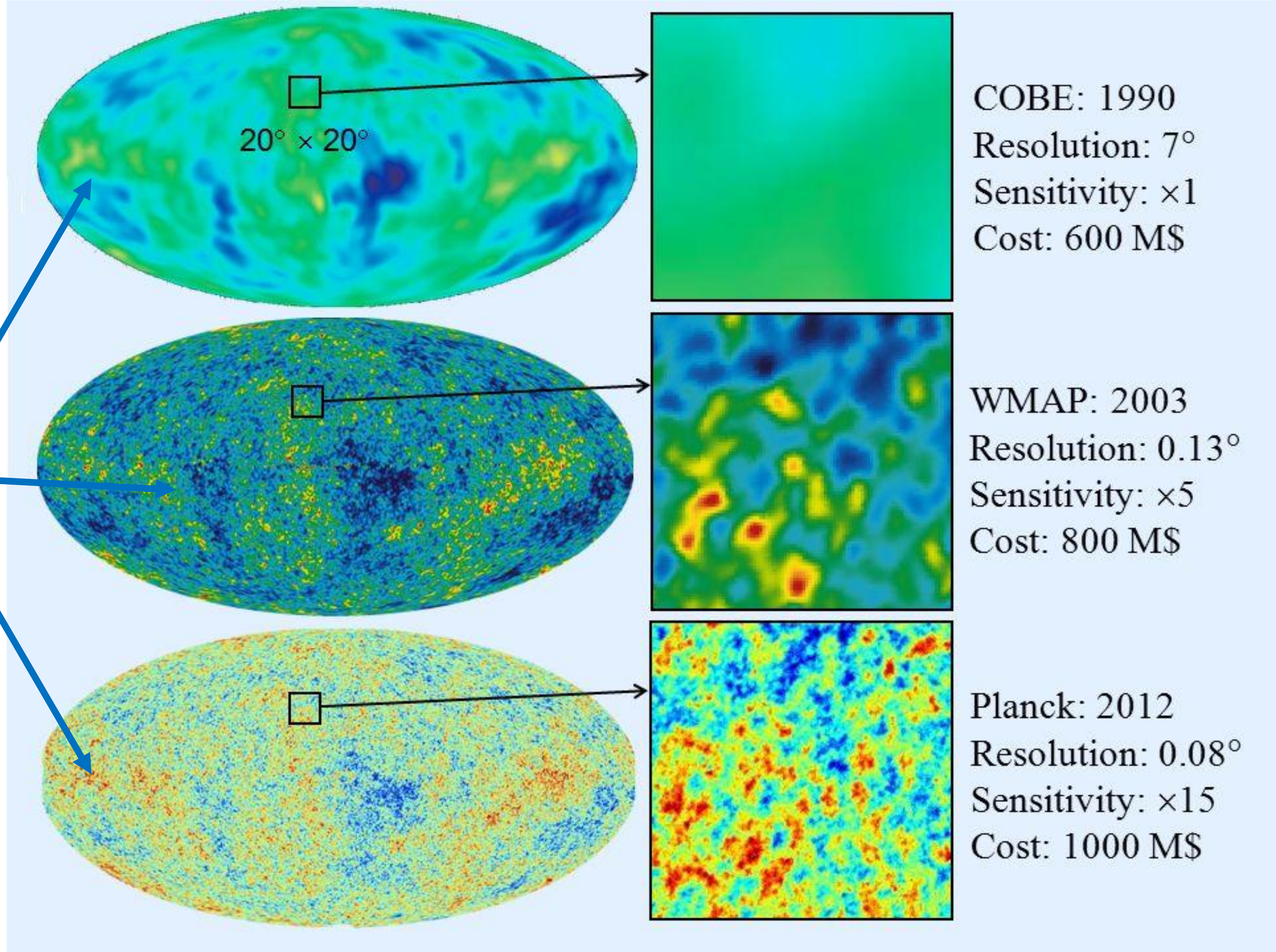


Credit: NASA/ESA

Credit: NASA/ESA

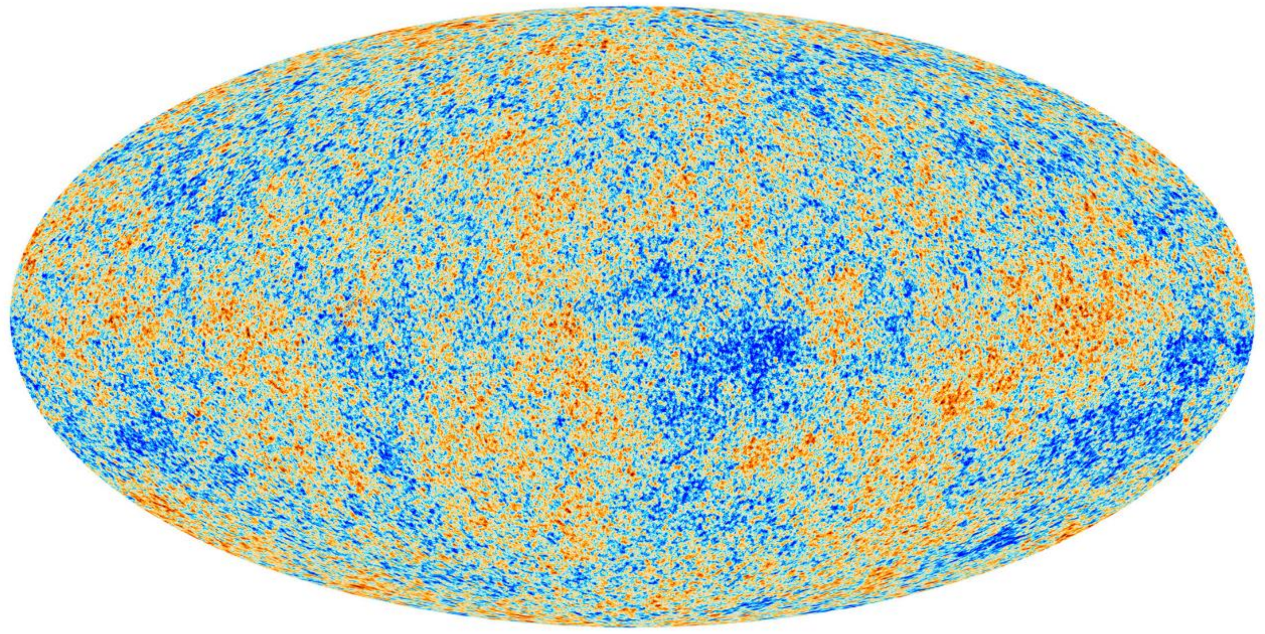
Evidence 3: Cosmic Microwave Background

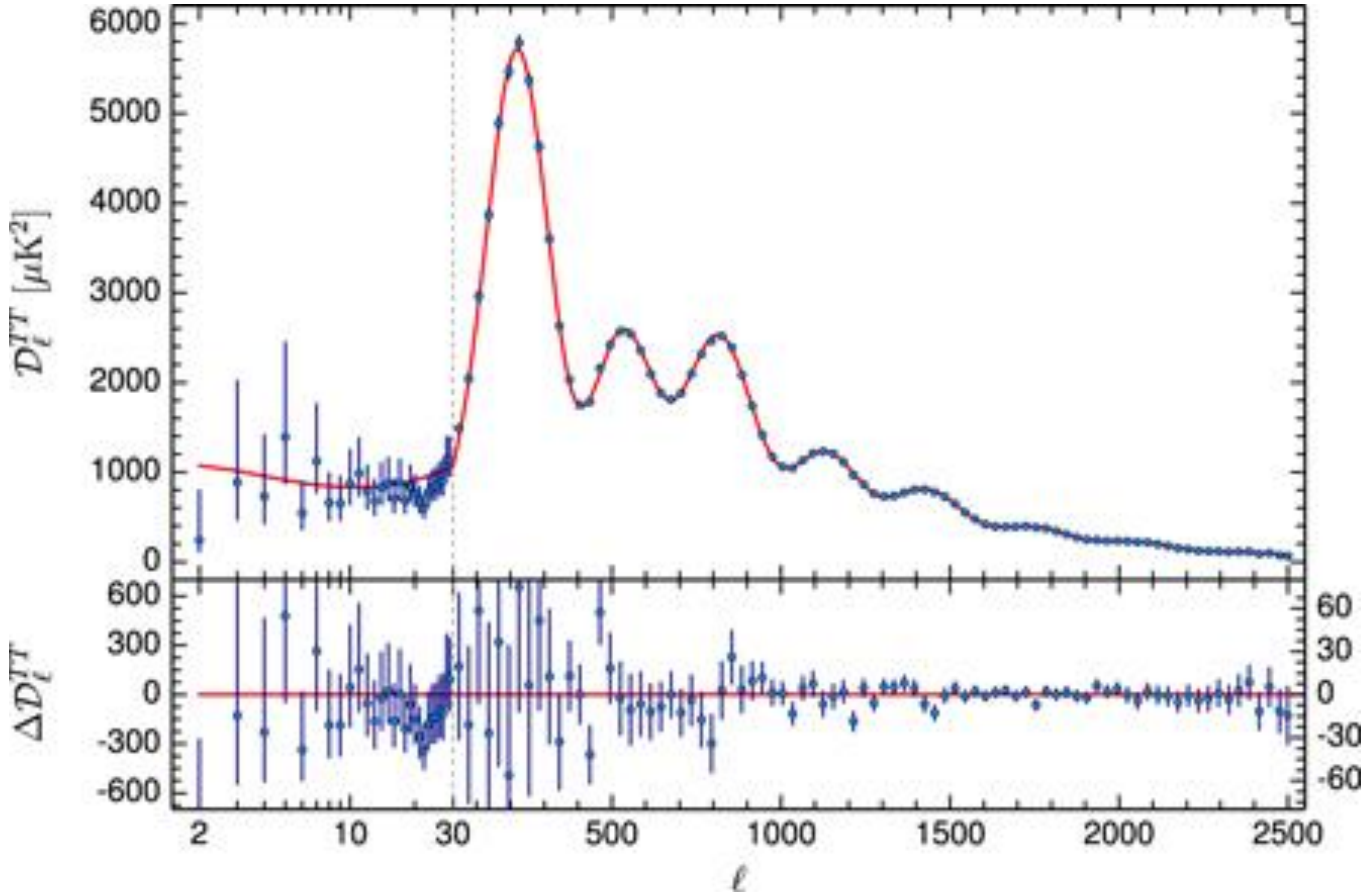




- The early universe started with a rapid inflation into a hot, dense, smooth and homogeneous plasma. Matter and E&M radiation scattered off each other
- Rapid expansion made elements (H, He) with which the photons did not interact
- The CMB is a snapshot of these old, free traveling photons.

Energy Content From the CMB





https://phys.libretexts.org/Courses/University_of_California_Davis/UCD%3A_Physics_156_-_A_Cosmology_Workbook/Workbook/27%3A_Cosmic_Microwave_Background_Anisotropies

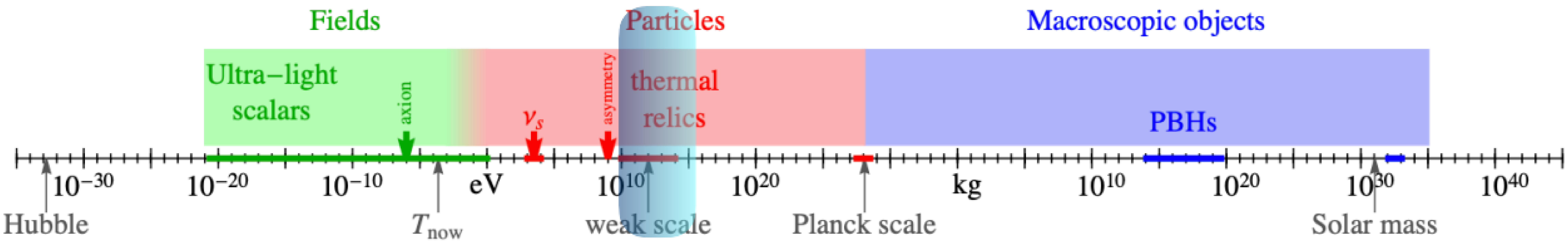
- The most accurate map of the CMB comes from the Planck experiment.
- “How do you measure the roughness of the ocean”
- A six-parameter ΛCDM model was shown to be very consistent with this data.
  - Dark Matter Density = 26%
  - Matter Density = 5%
  - Age of the Universe = 13.9 billion years
  - Curvature = Flat
  - Scalar Spectral Index = 0.96 (density changes with scale, < 1 means inflation)
  - Reionization Optical Depth = 0.006 (when reionization occurs, no more dark ages
- Dark energy, Hubble constant

Properties of Dark Matter?????

Properties of Dark Matter

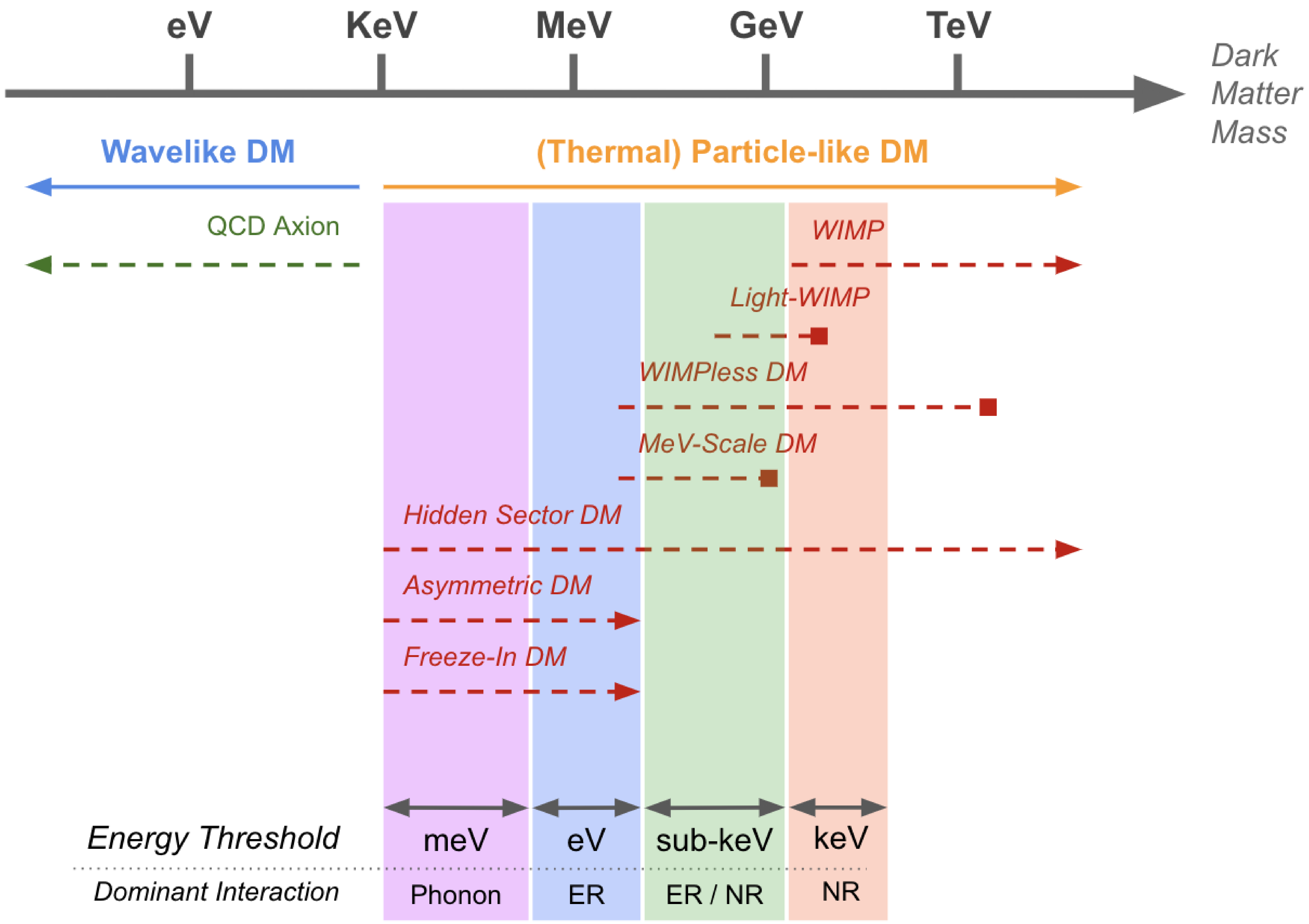
- Weakly interacting (No light)
- Non-relativistic (Cold)
- Stable (On a cosmological scale)
- Massive (interacts gravitationally)

The Search Begins



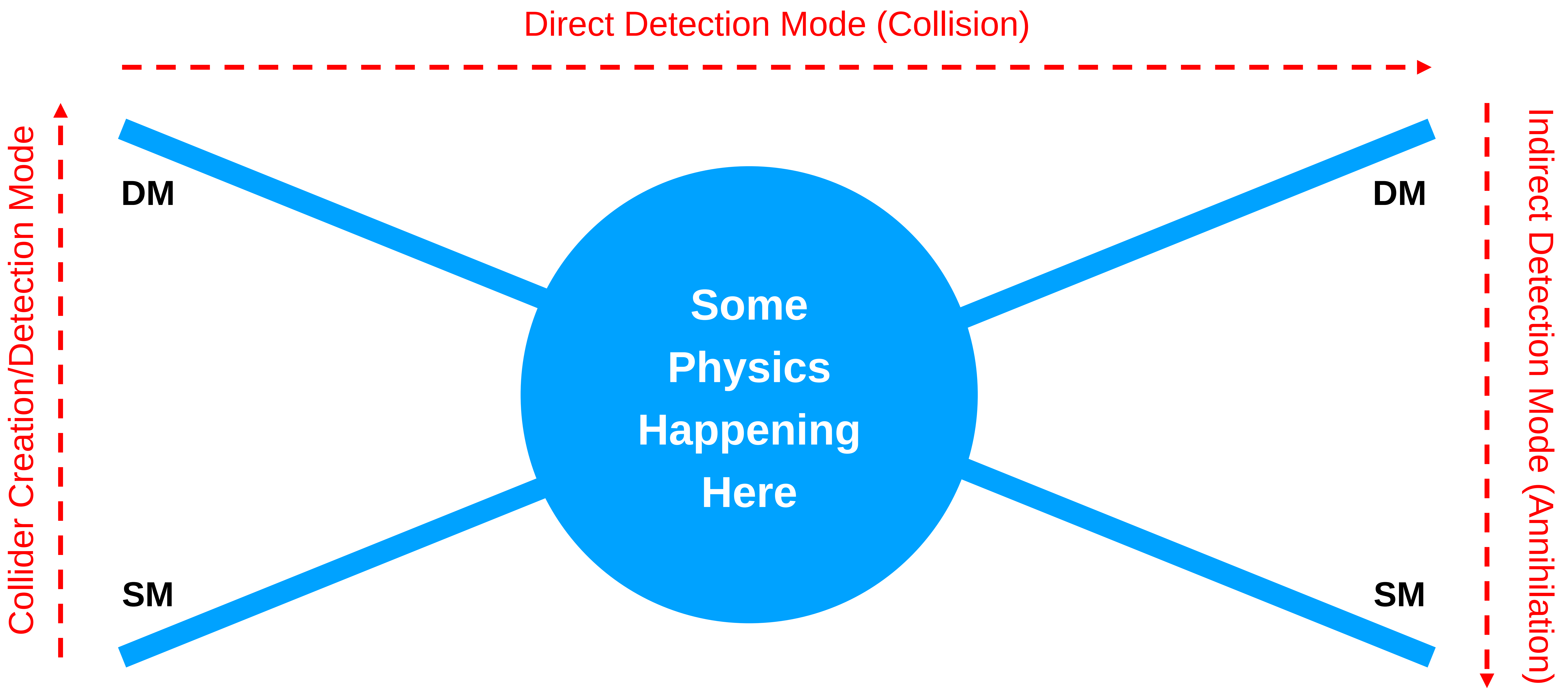
- MOND
- MACHO

The Search Begins

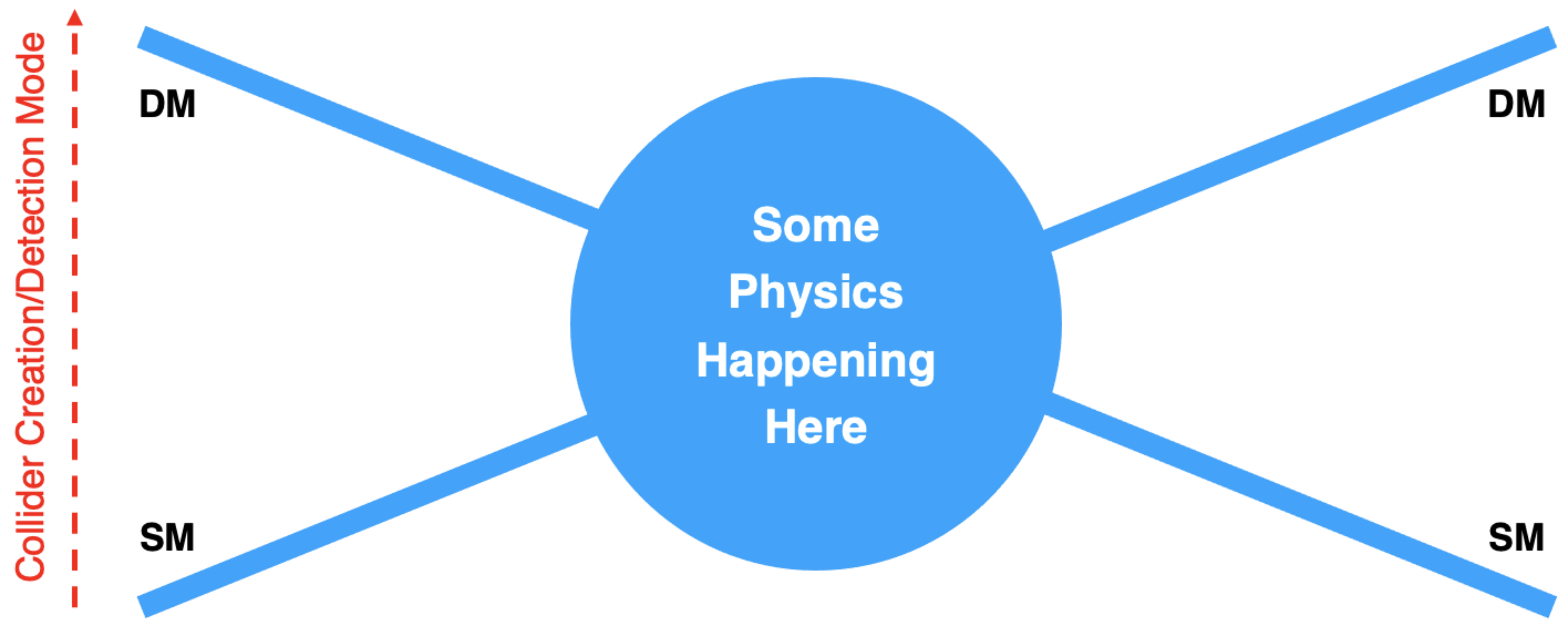


Searching For Dark Matter

Dark Matter Detection Methods

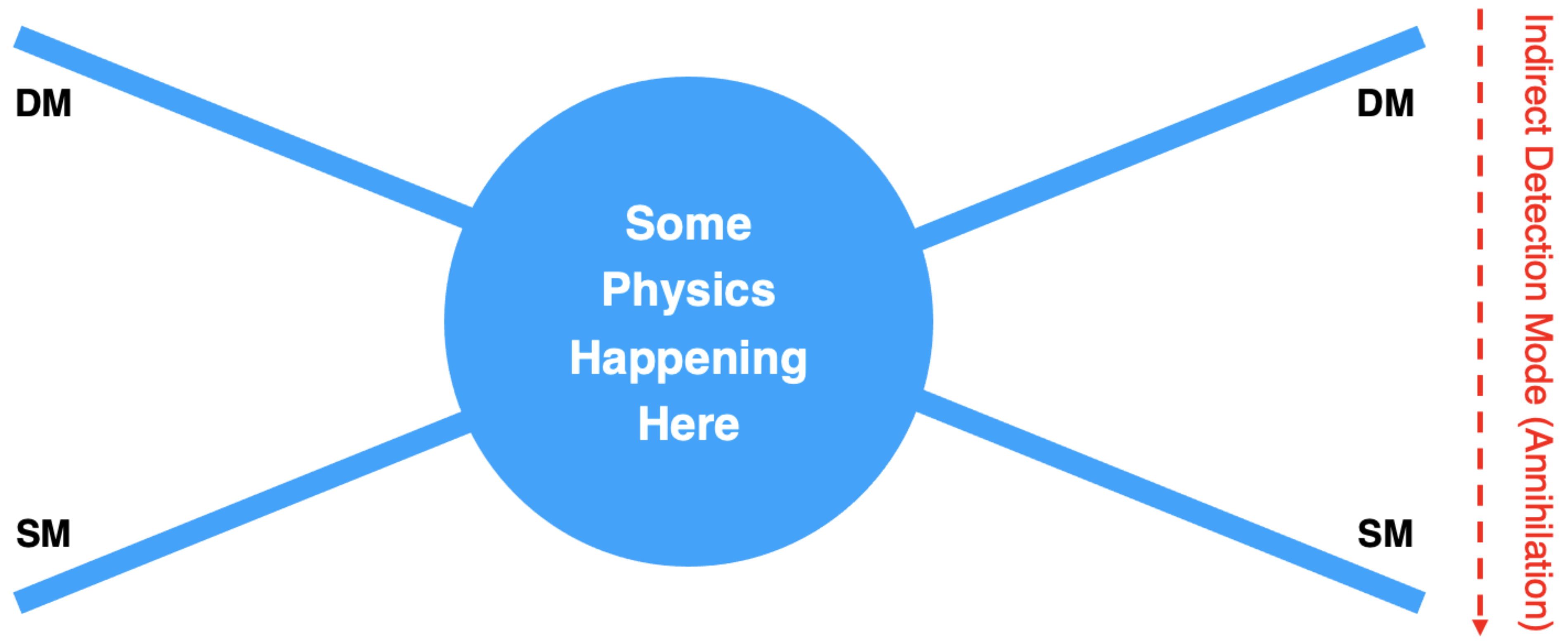


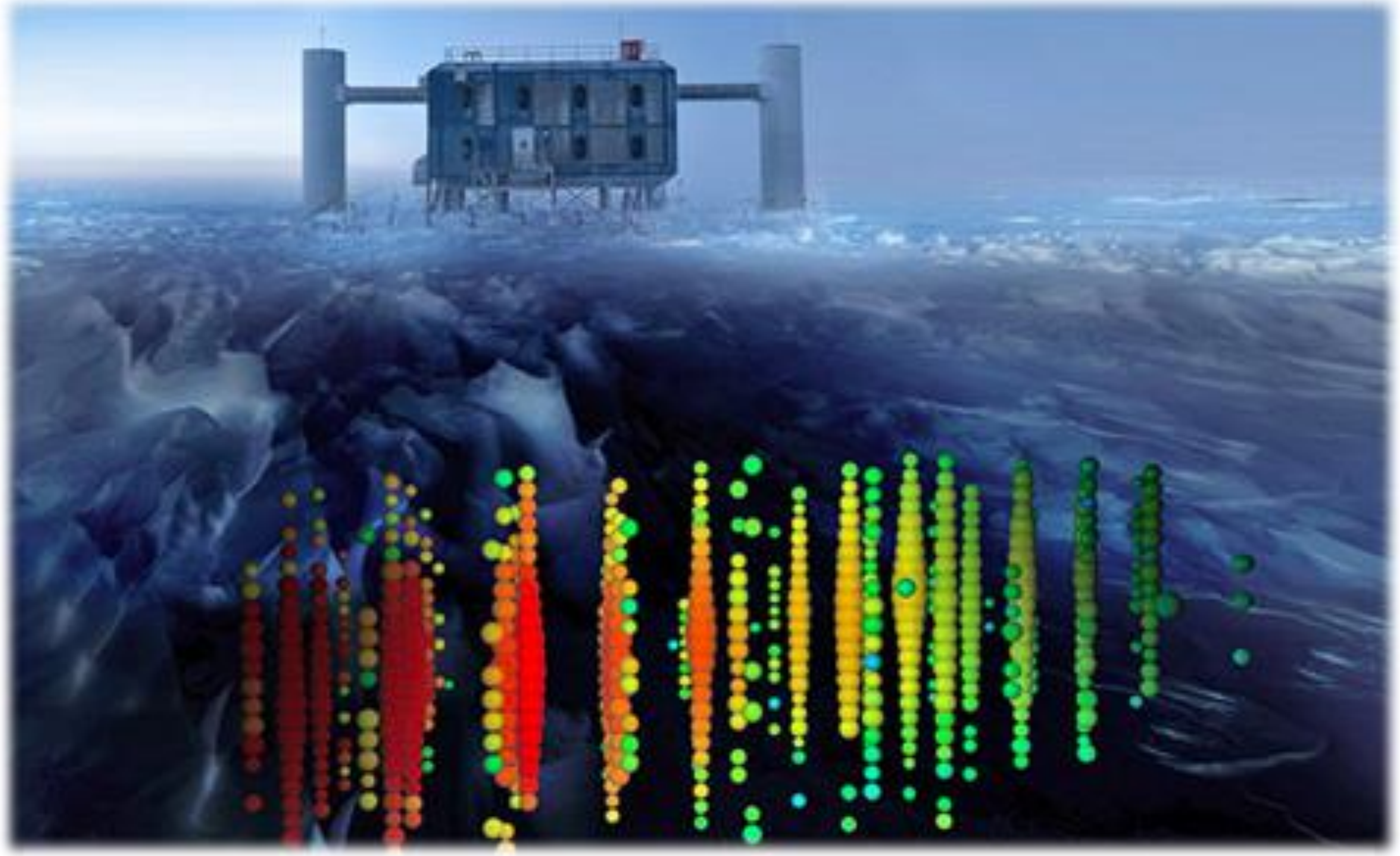
Dark Matter Detection Methods



Colliding Standard Model Particles at very high energies to recreate the early conditions of the universe and generate Dark Matter particles.

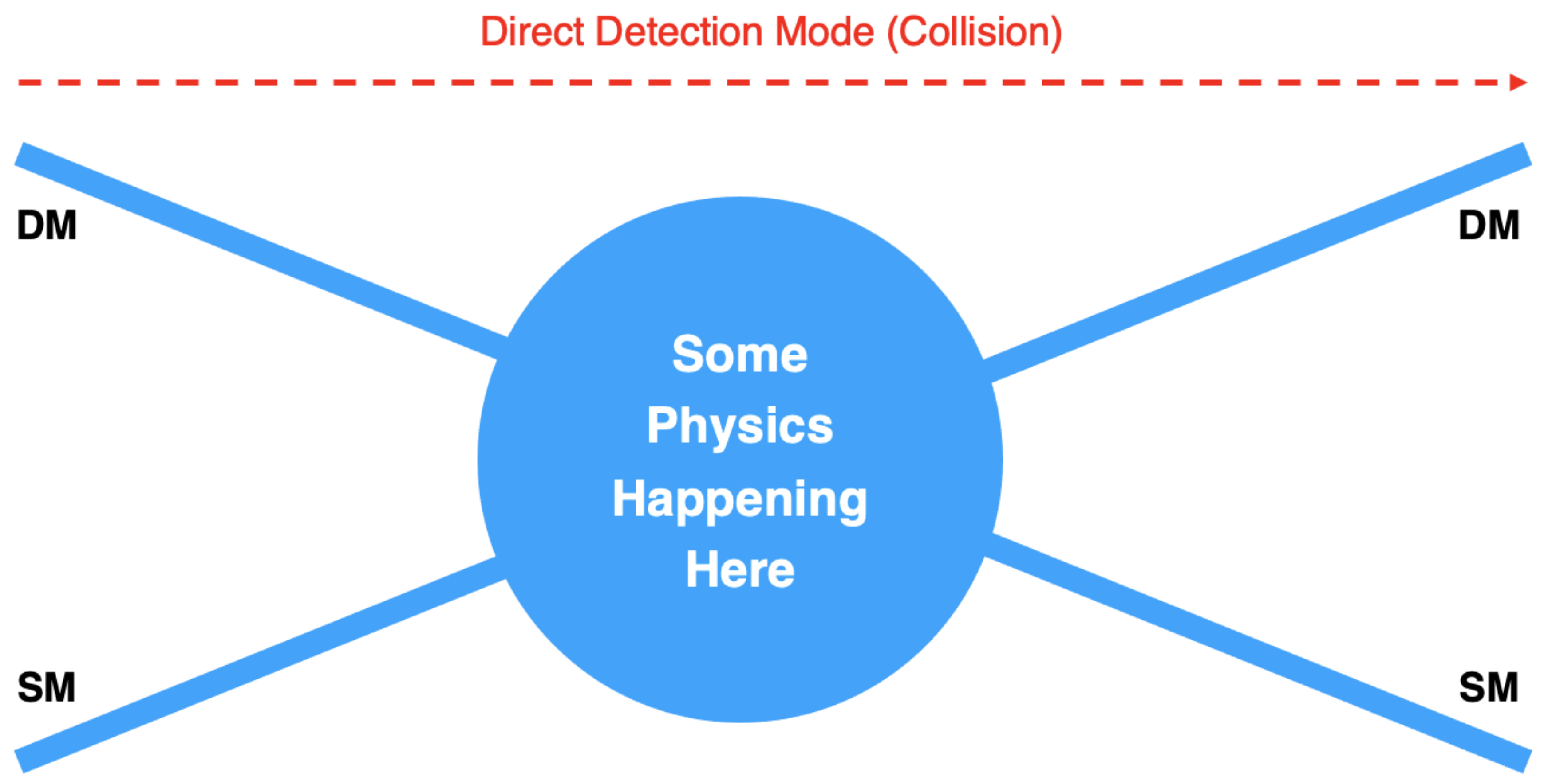
Dark Matter Detection Methods





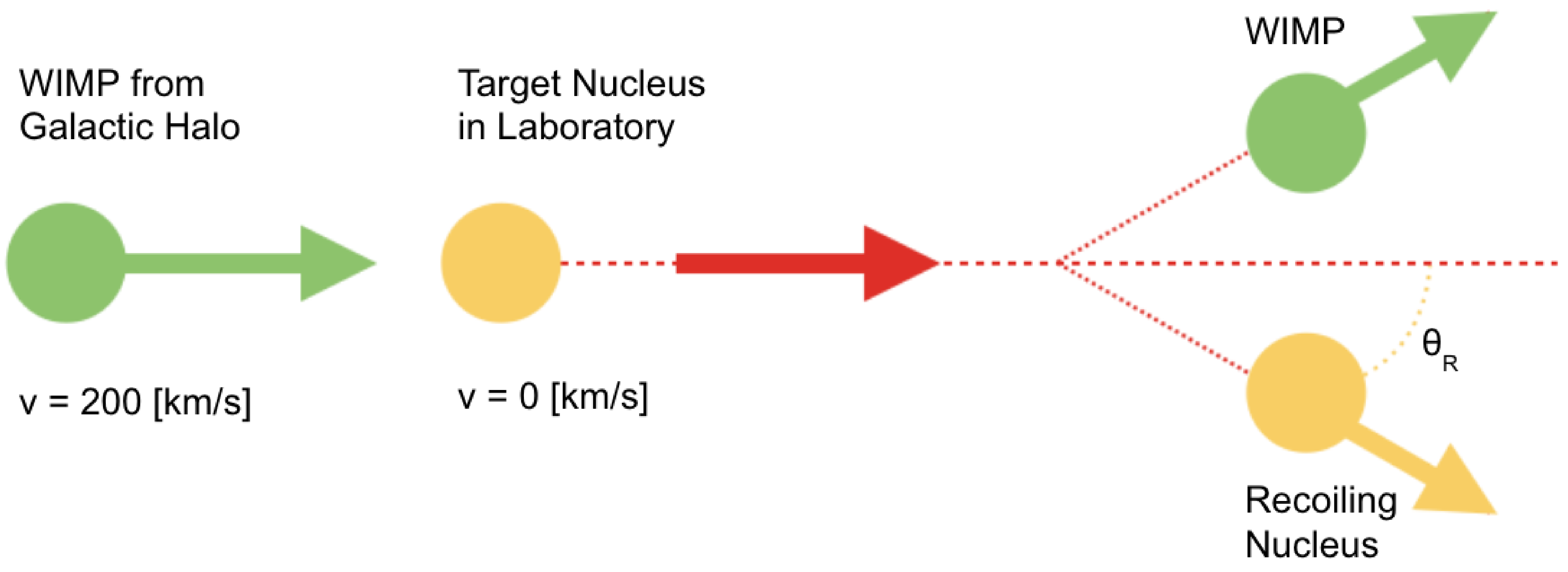
Look for Standard Model particles produced by the annihilation of Dark Matter particles in deep space. This requires detectors with very large masses and very specific detector capabilities.

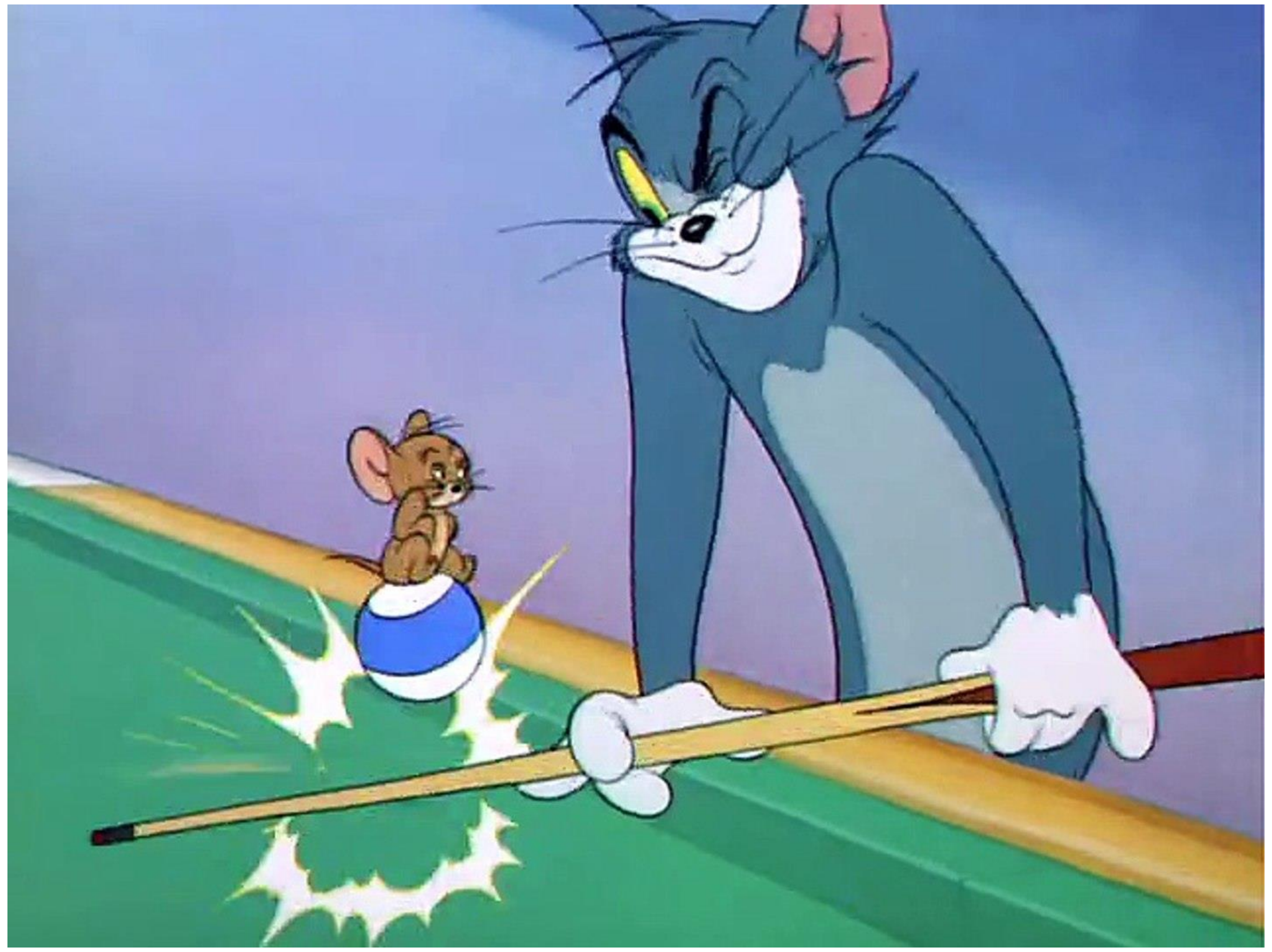
Dark Matter Detection Methods



Coherent elastic scattering or quasi-elastic scattering between Dark Matter particle and ordinary matter. Detector size and capabilities depends on the Dark Matter candidate we are looking for.

Direct Detection Method





- Elastic Scatter of WIMP off a nucleus:
  - Can occur via **spin-dependent** or **spin-independent** channels.
  - Need to distinguish this event from an overwhelming number of **background events**.

Standard Halo Model

The energy spectrum and the expected rate depend on details of the WIMP distribution in the Dark Matter Halo.

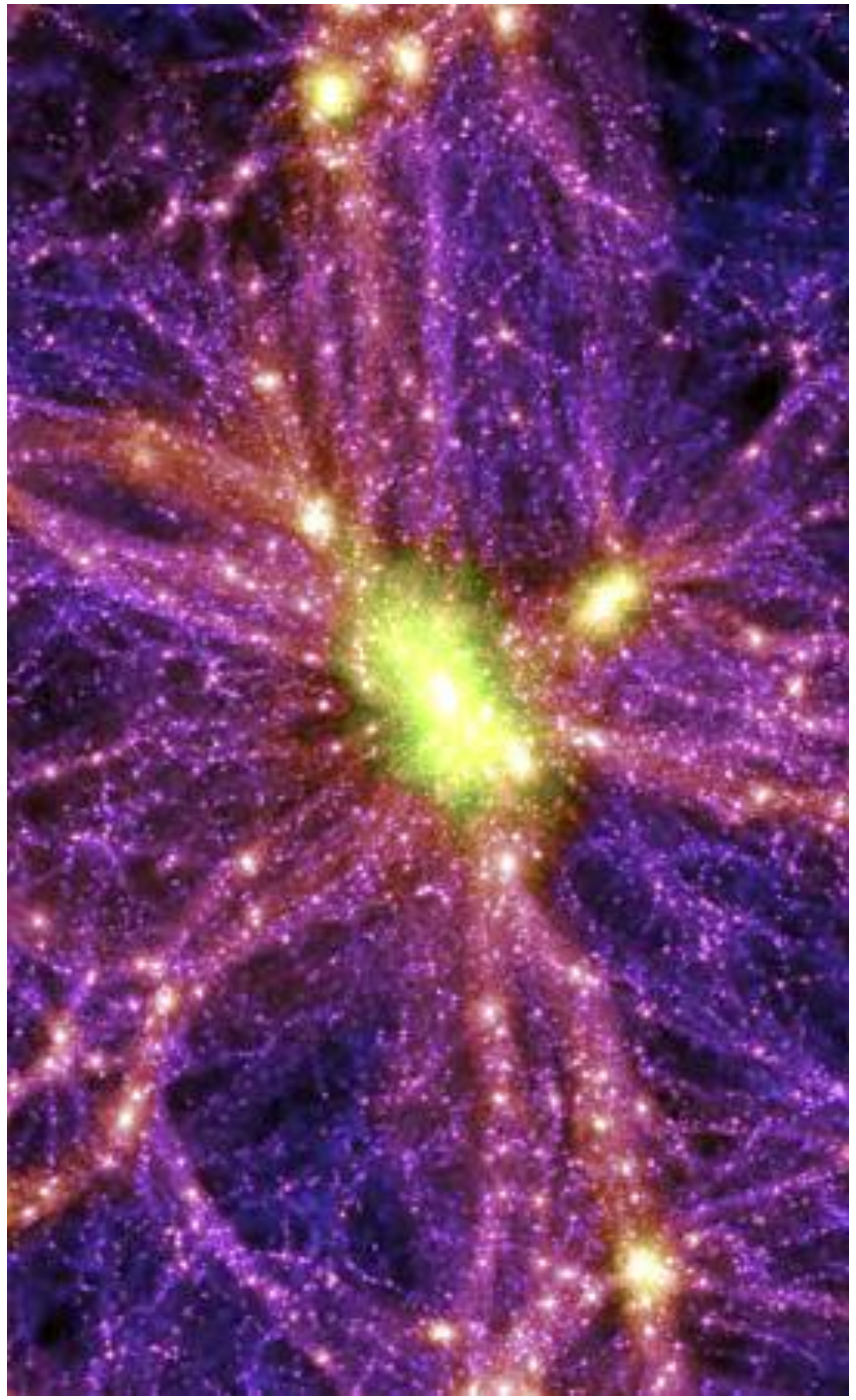
Local Dark Matter Density:

$$\rho_0 = \rho(r = R_0) = 0.3 \text{ [GeV/cm}^3\text{]}$$

Speed Distribution - Isotropic, Maxwellian:

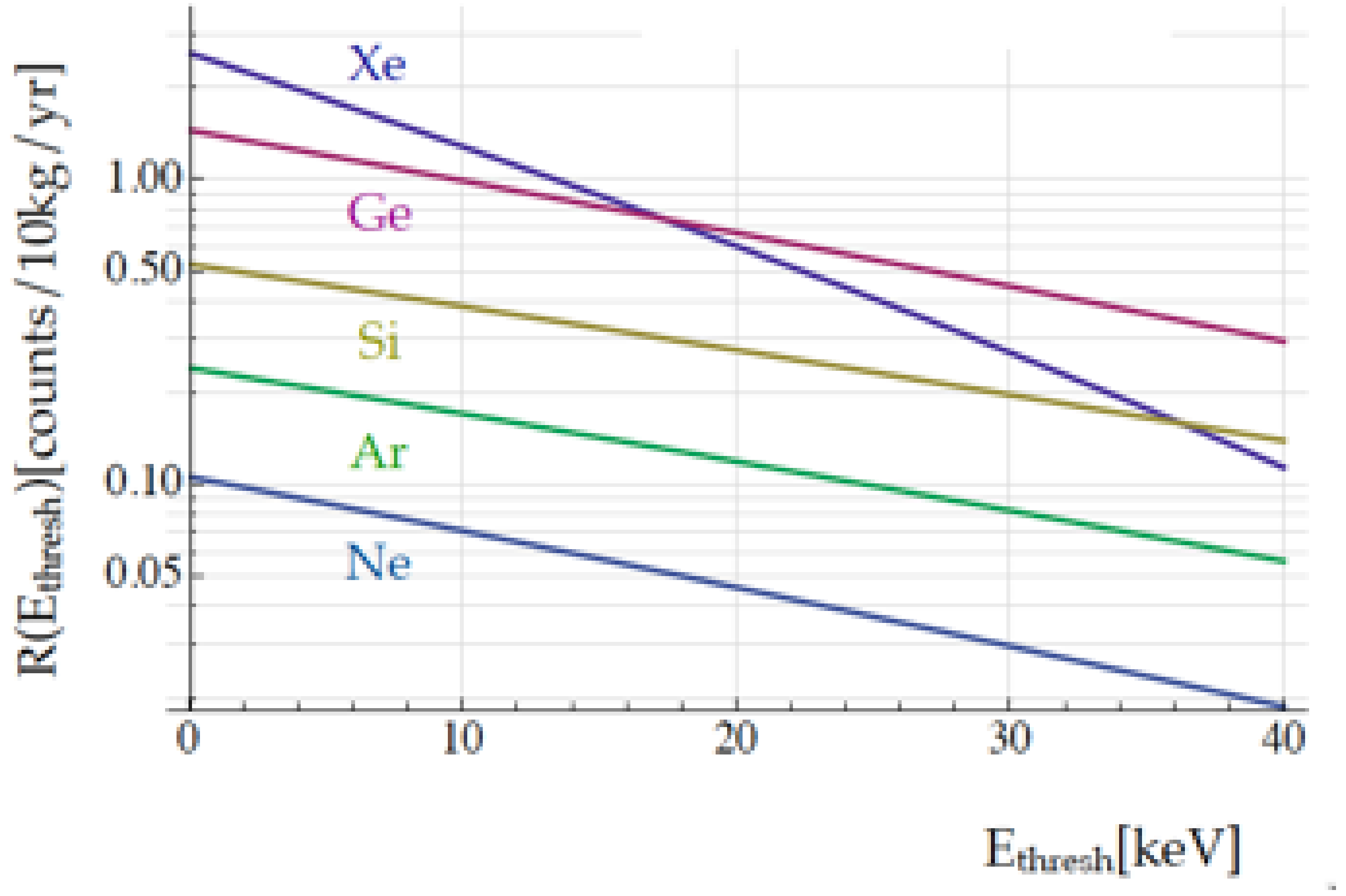
$$f(\vec{v}) = \frac{1}{\sqrt{2\pi\sigma}} exp\left(-\frac{|\vec{v}|^2}{2\sigma^2}\right)$$

Particles with speed greater than the local escape speed are not gravitationally bound. The standard halo model extends out to infinite radii and thus the speed distribution in this model must be truncated “by hand”, v_{esc} = 544 [km/s].

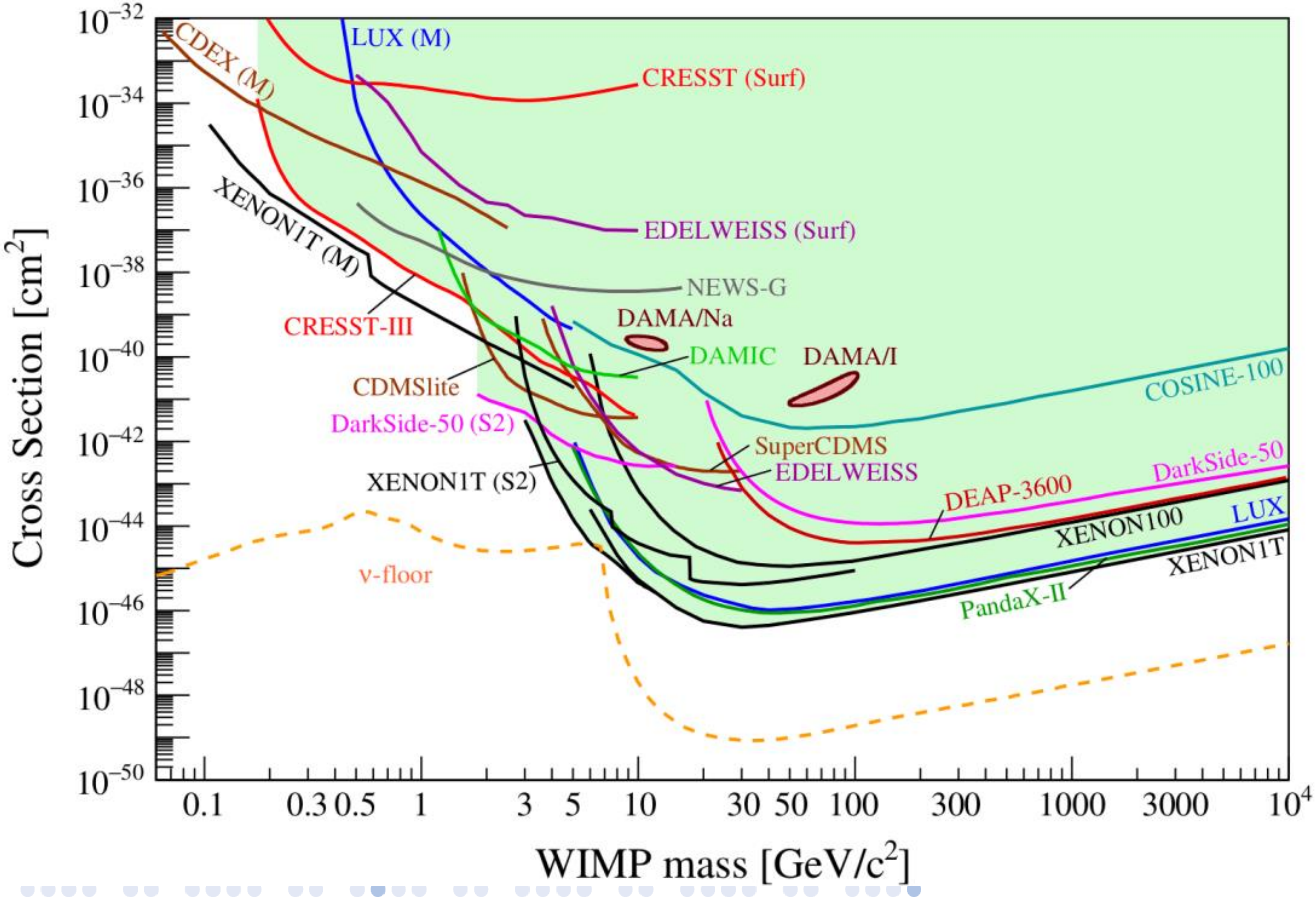


Direct Detection Method Review

- Elastic Scattering of Dark Matter deposits small amounts of energy into recoiling nucleus (~few 10s of keV).
- Featureless exponential spectrum with no obvious peak, knee, break …….
- Event rate is very, very low.
  (requires inputs from astro, particle and nuclear physics).
- Radioactive background of most materials is much higher than the expected event rate.

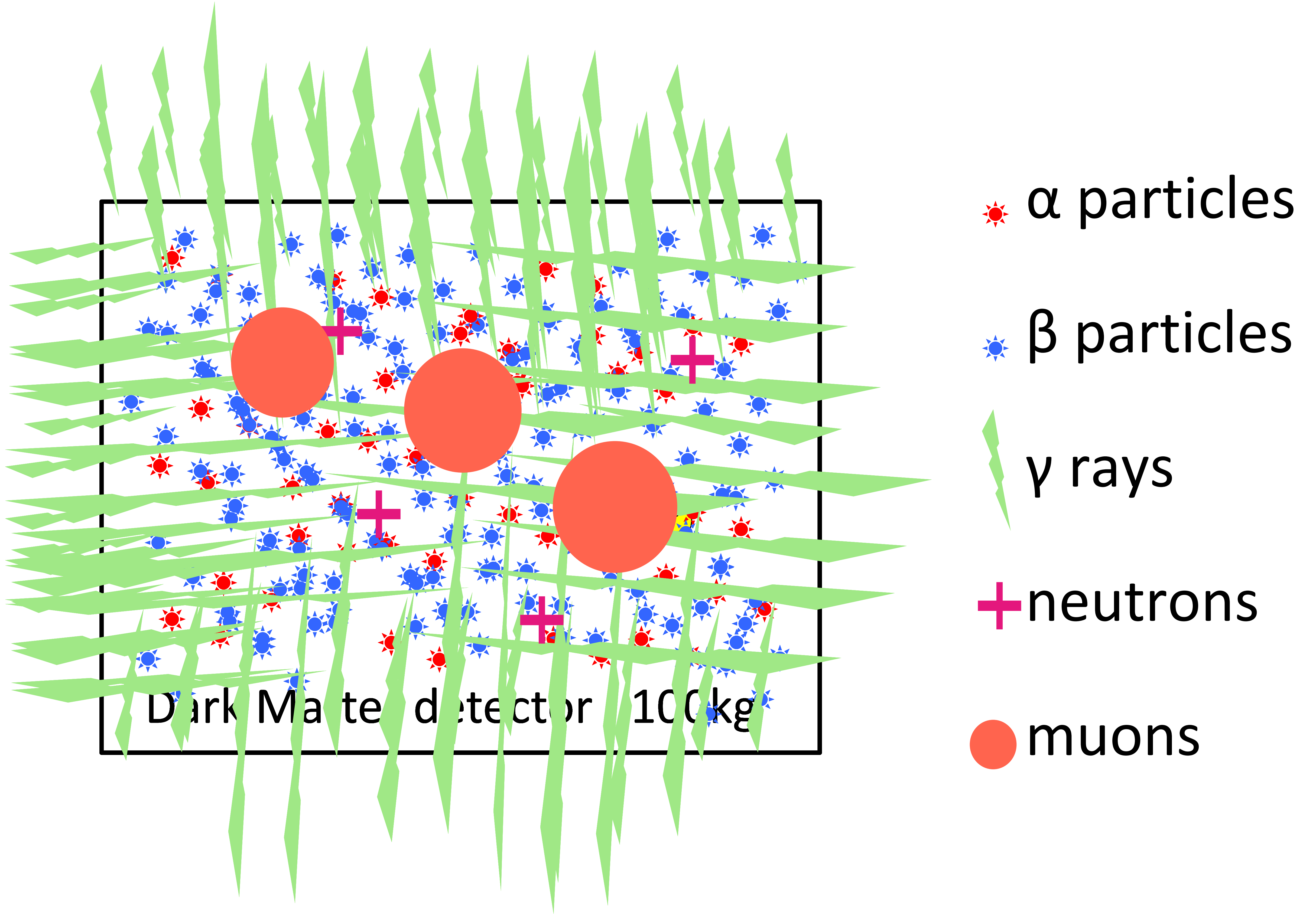


Direct Detection Method Review



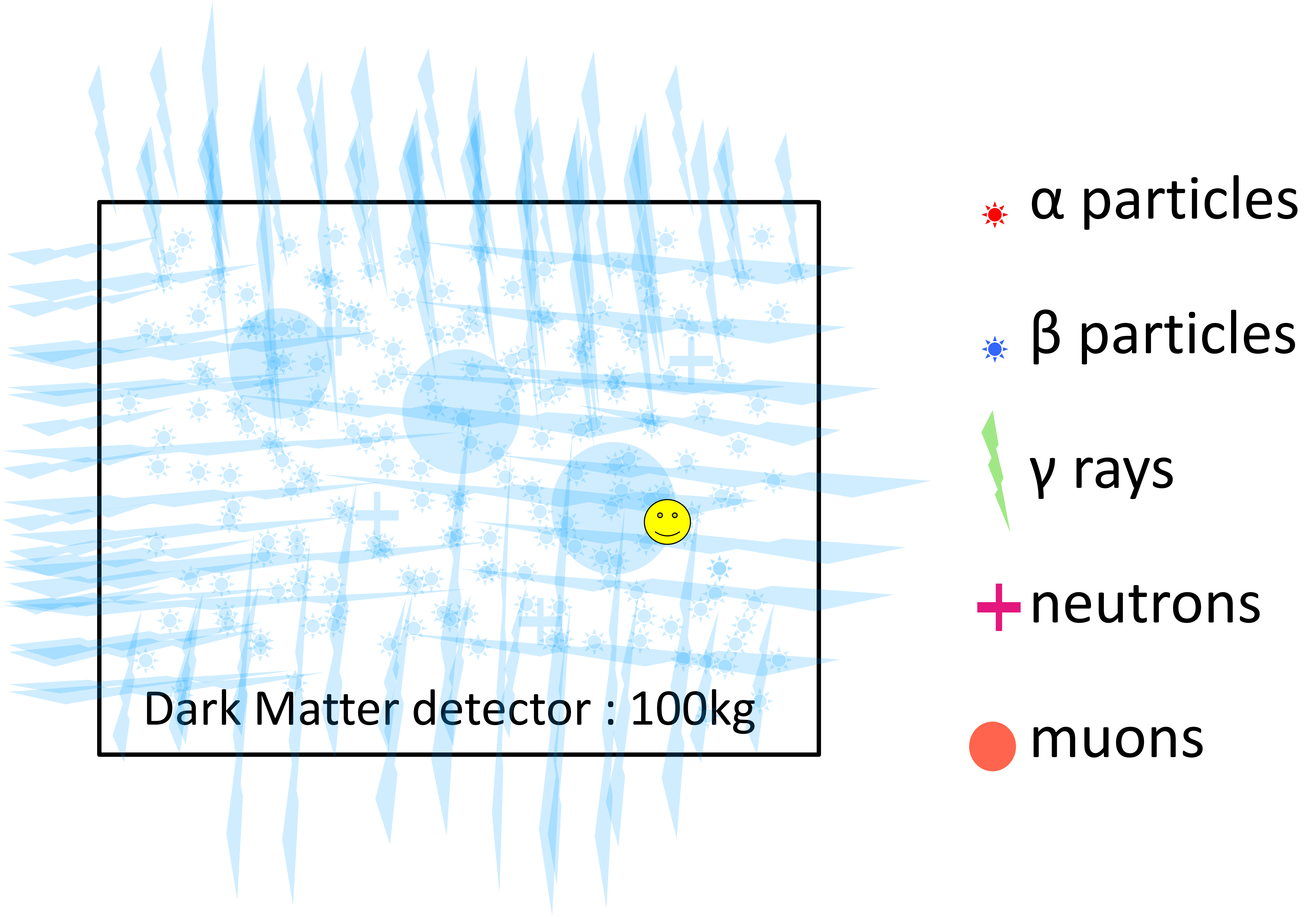
Dark Matter Detection Backgrounds

Dark matter detector: very sensitive… to background

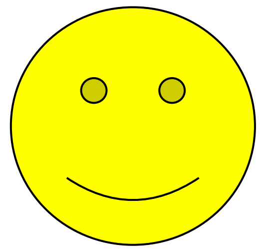


Where is ~~Waldo~~ the dark matter event?

Background will make it impossible to detect the signal

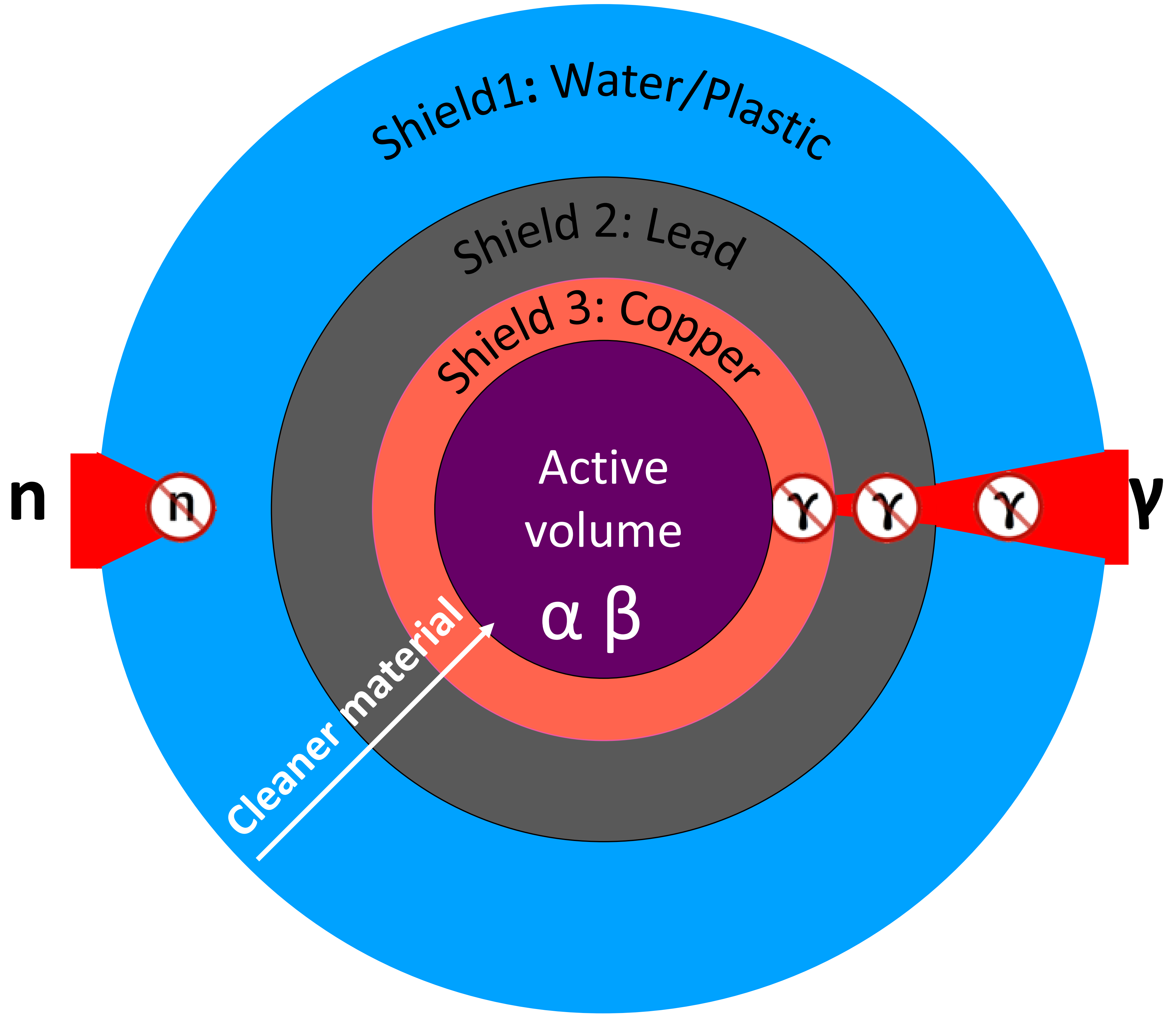


Where is ~~Waldo~~ the dark matter event?



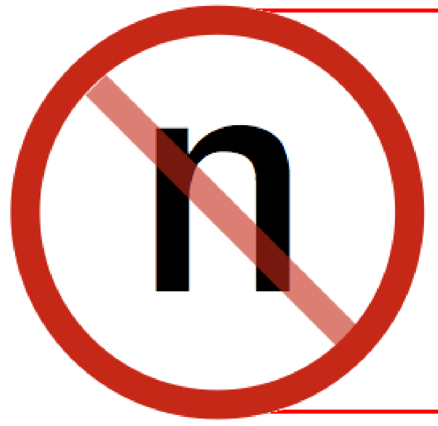
Multiple background suppression

Passive shielding (external Background)



Discrimination
(Internal background)

- Active veto
- Energy
- Position
- Pulse shape
- …

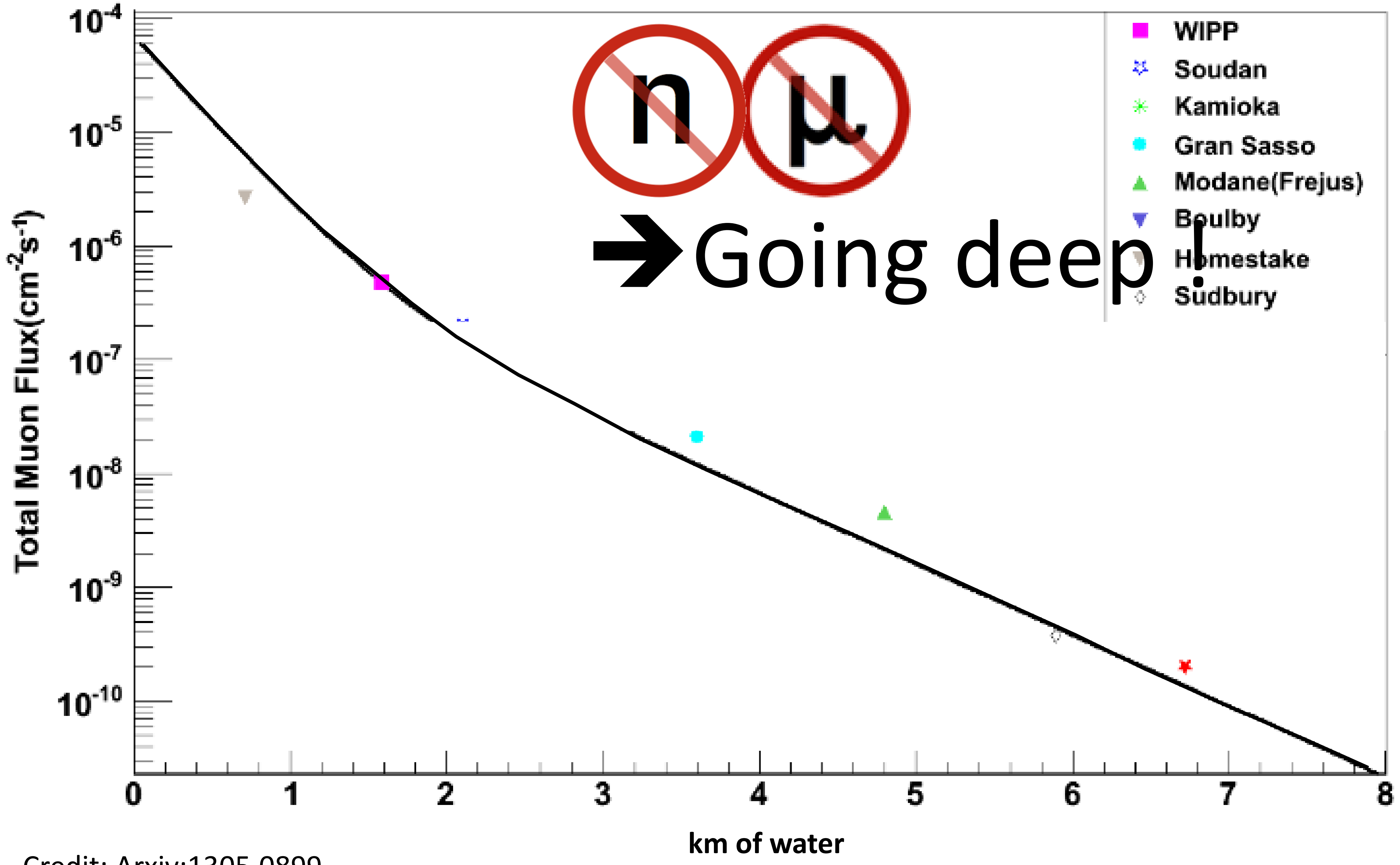


Neutrons mimicking WIMP signal
=> All sources need to be removed or shielded

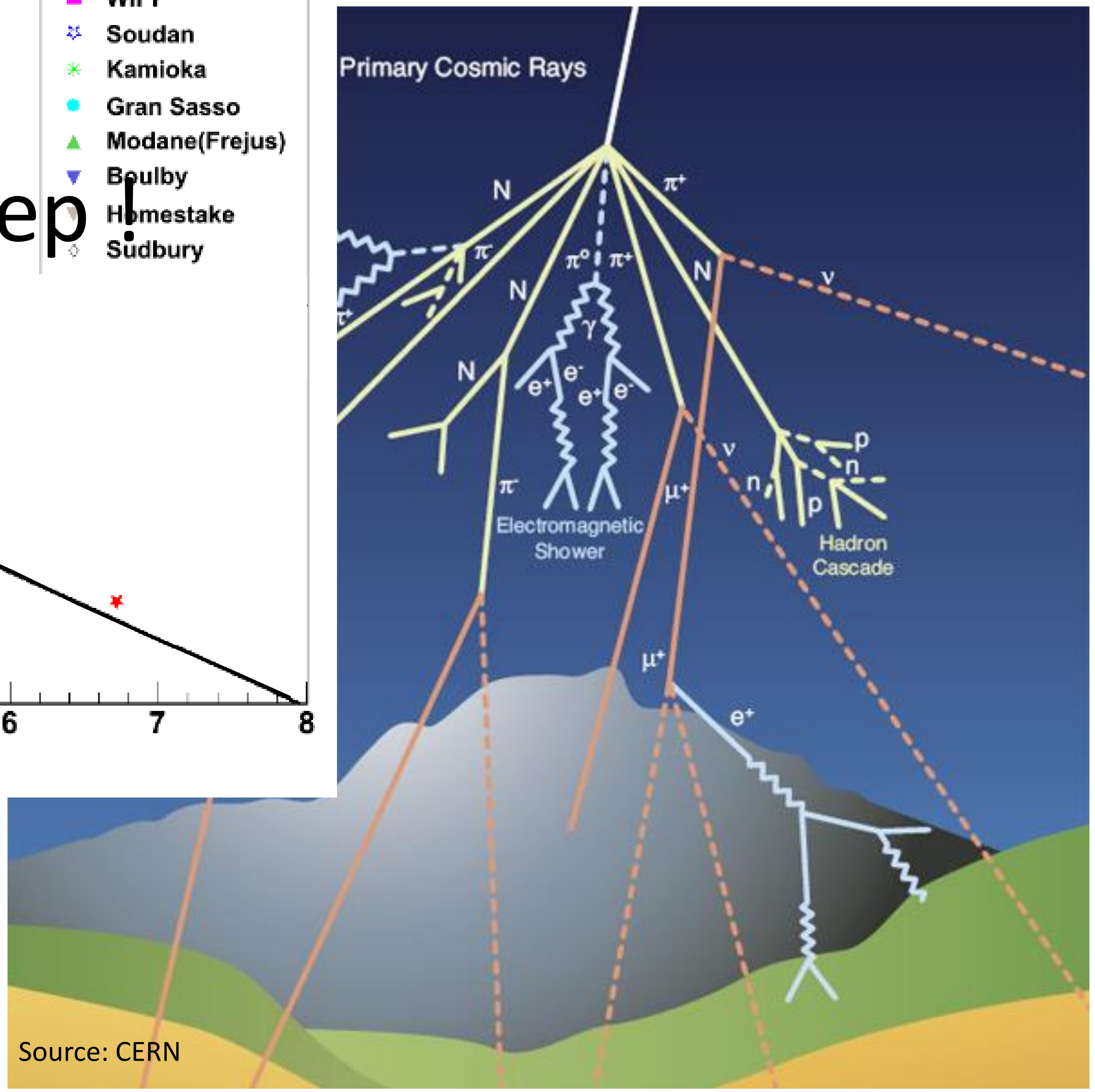
Muons: creating neutrons everywhere

~~n~~ ~~μ~~

➔Going deep !



Credit: Arxiv:1305.0899

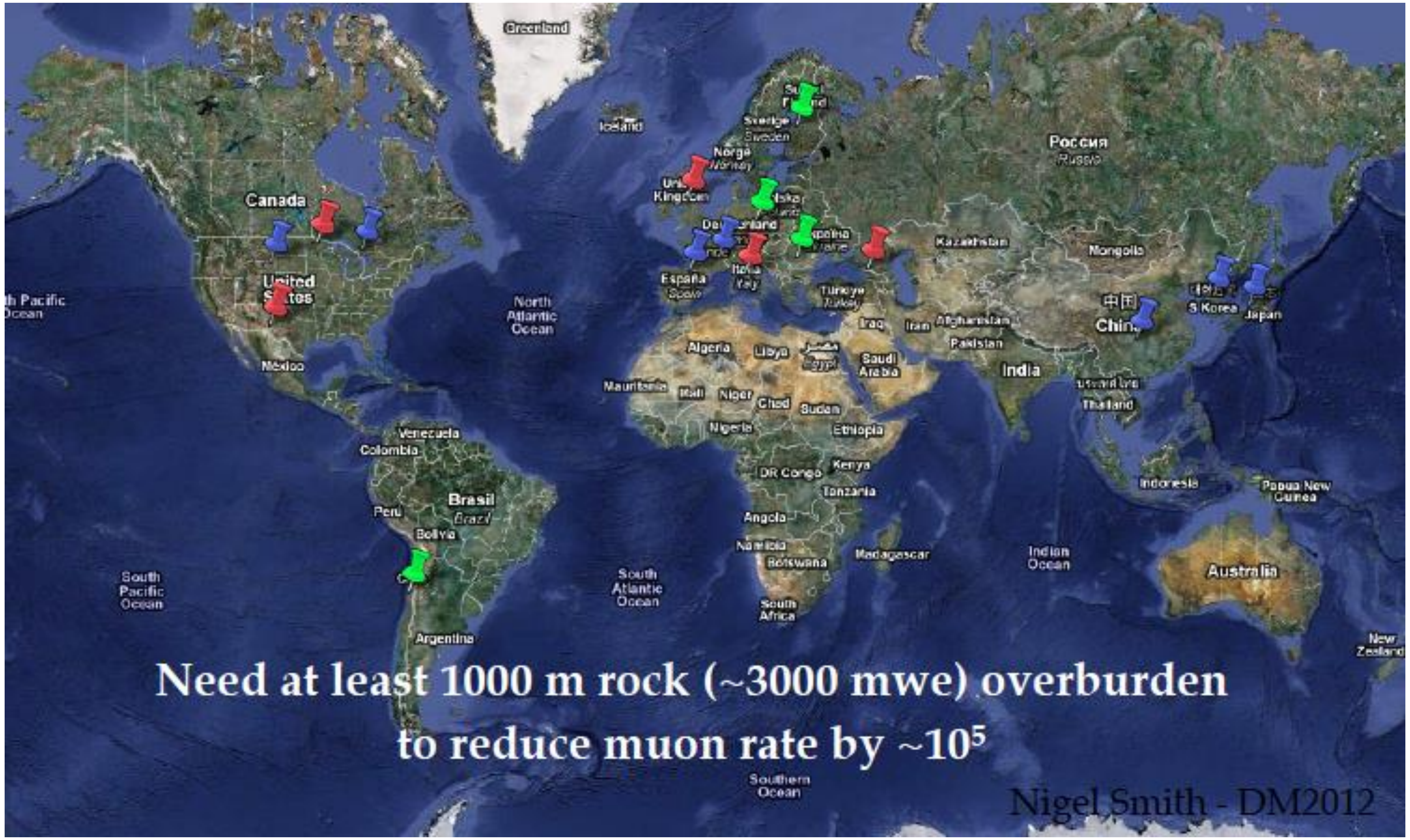


Source: CERN

High energy muons travel deep

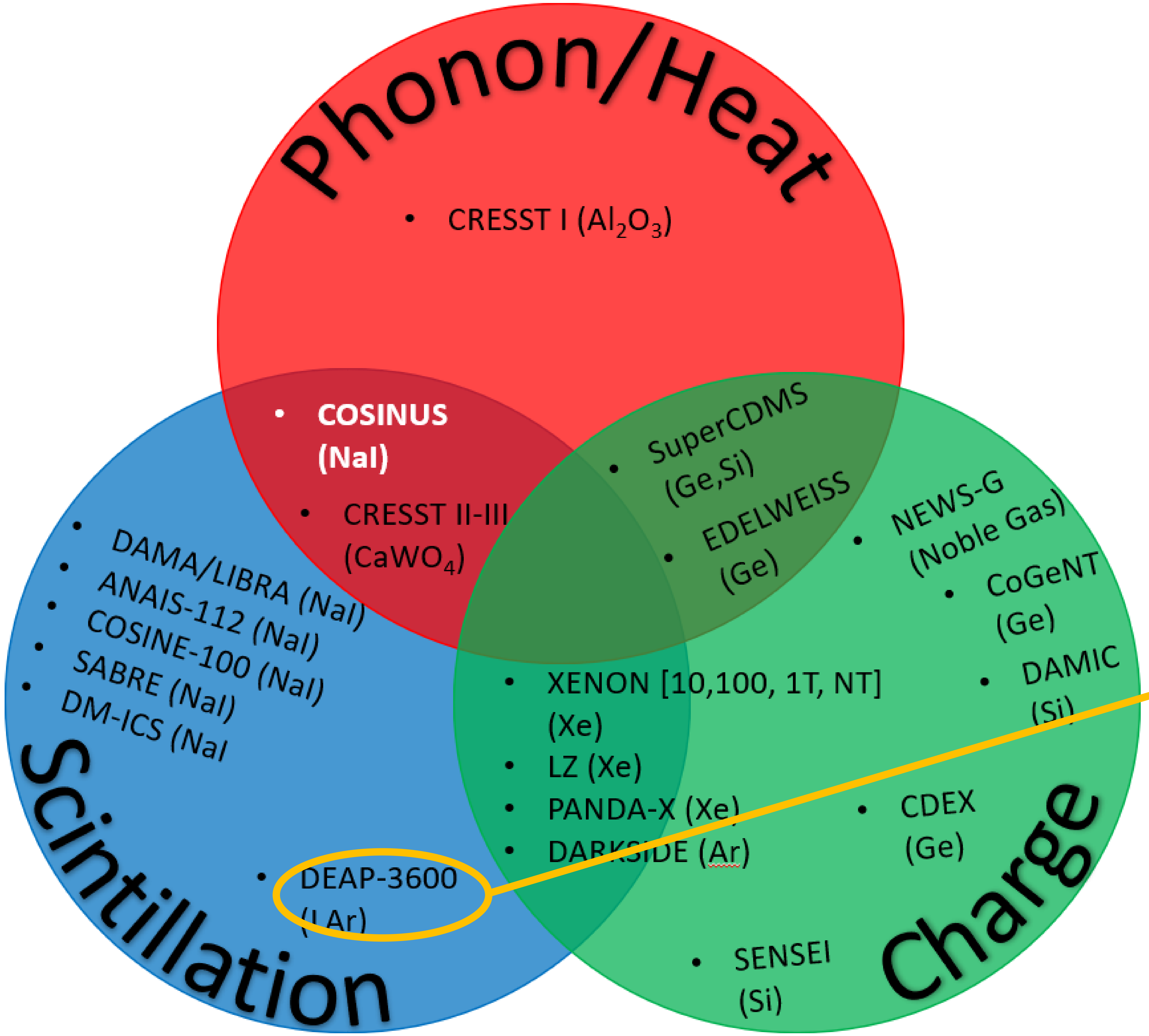
Production of unstable isotopes
=> Neutrons (spallation)

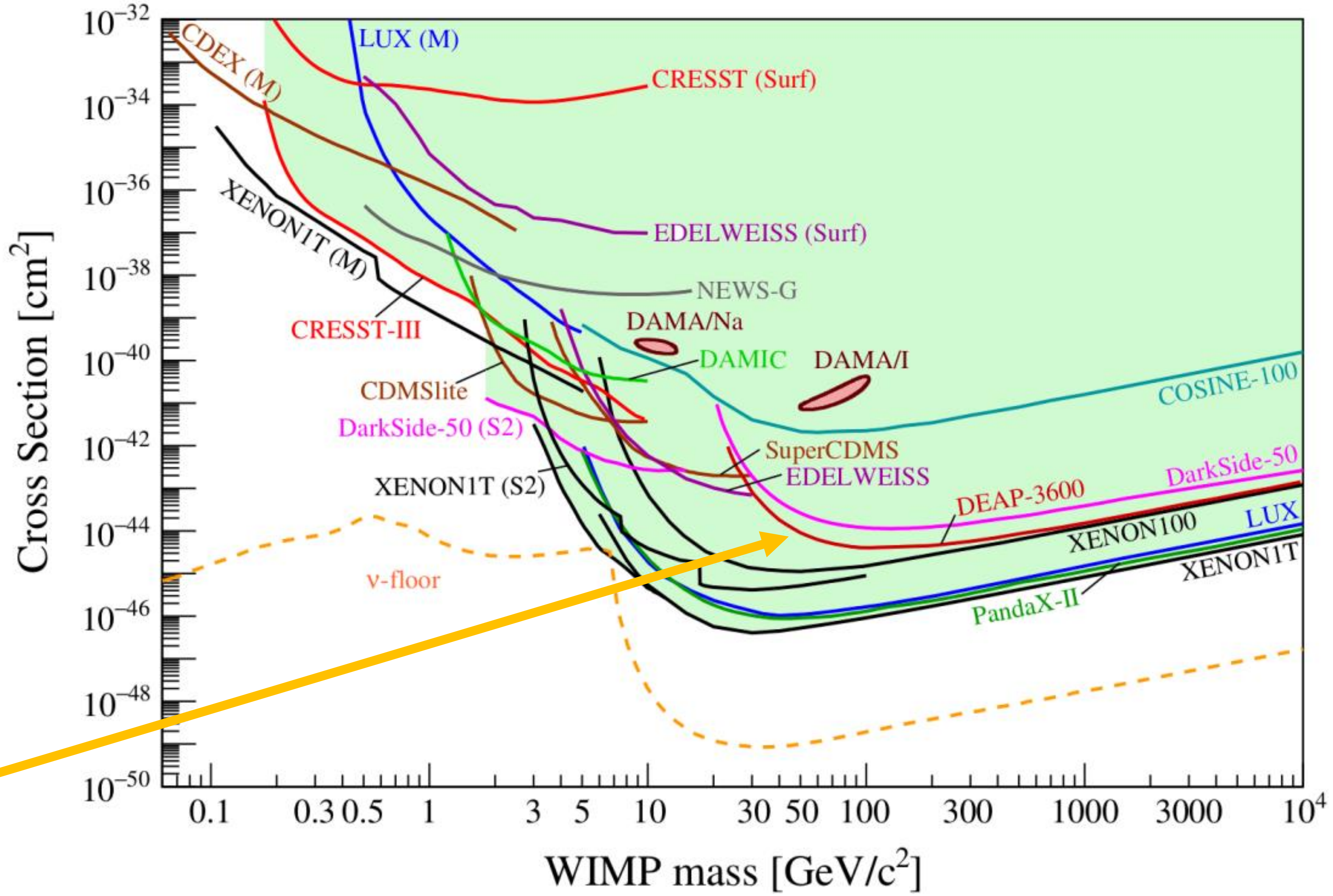
Underground Facilities To The Rescue



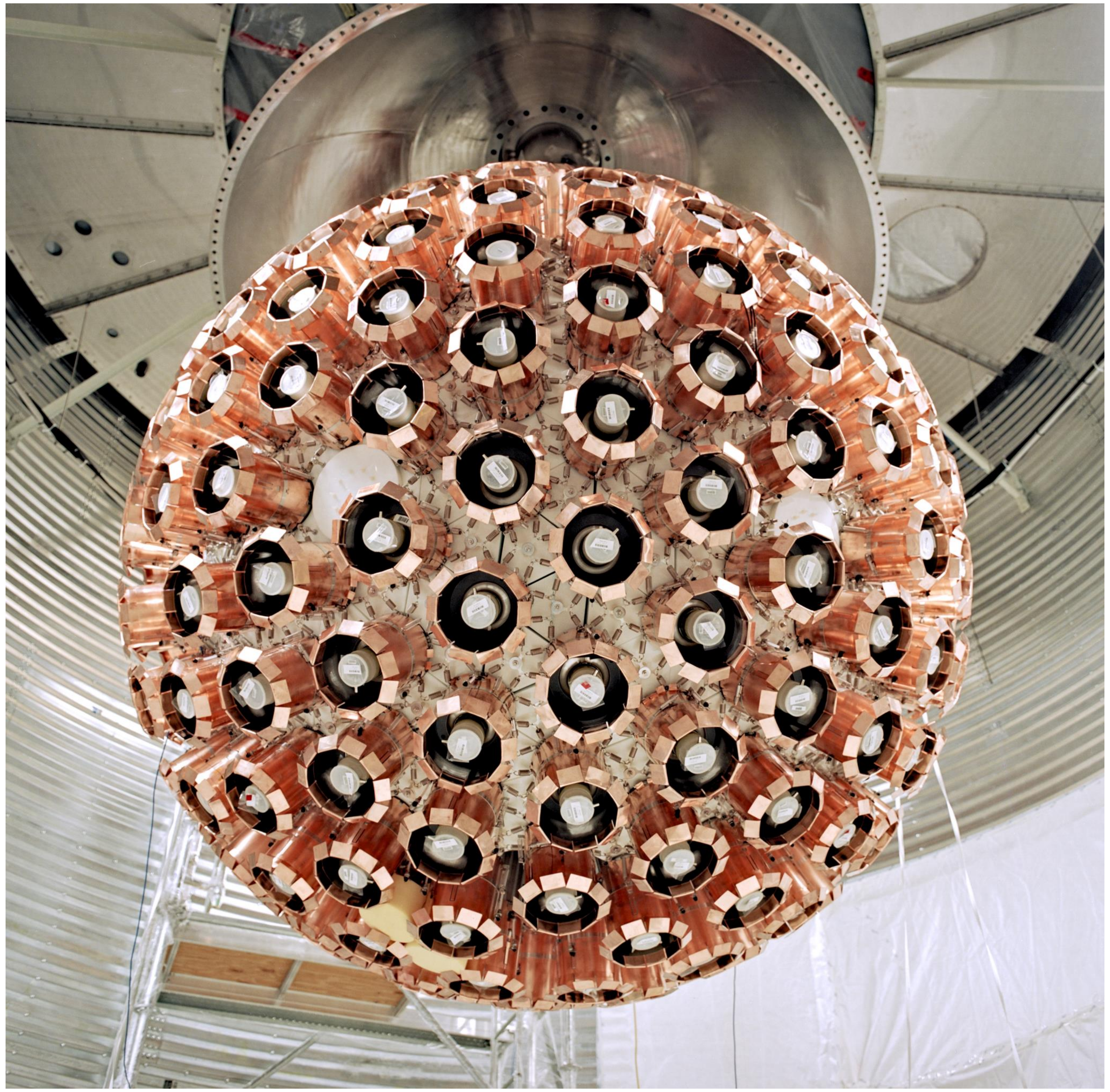
Dark Matter Detection Experiments

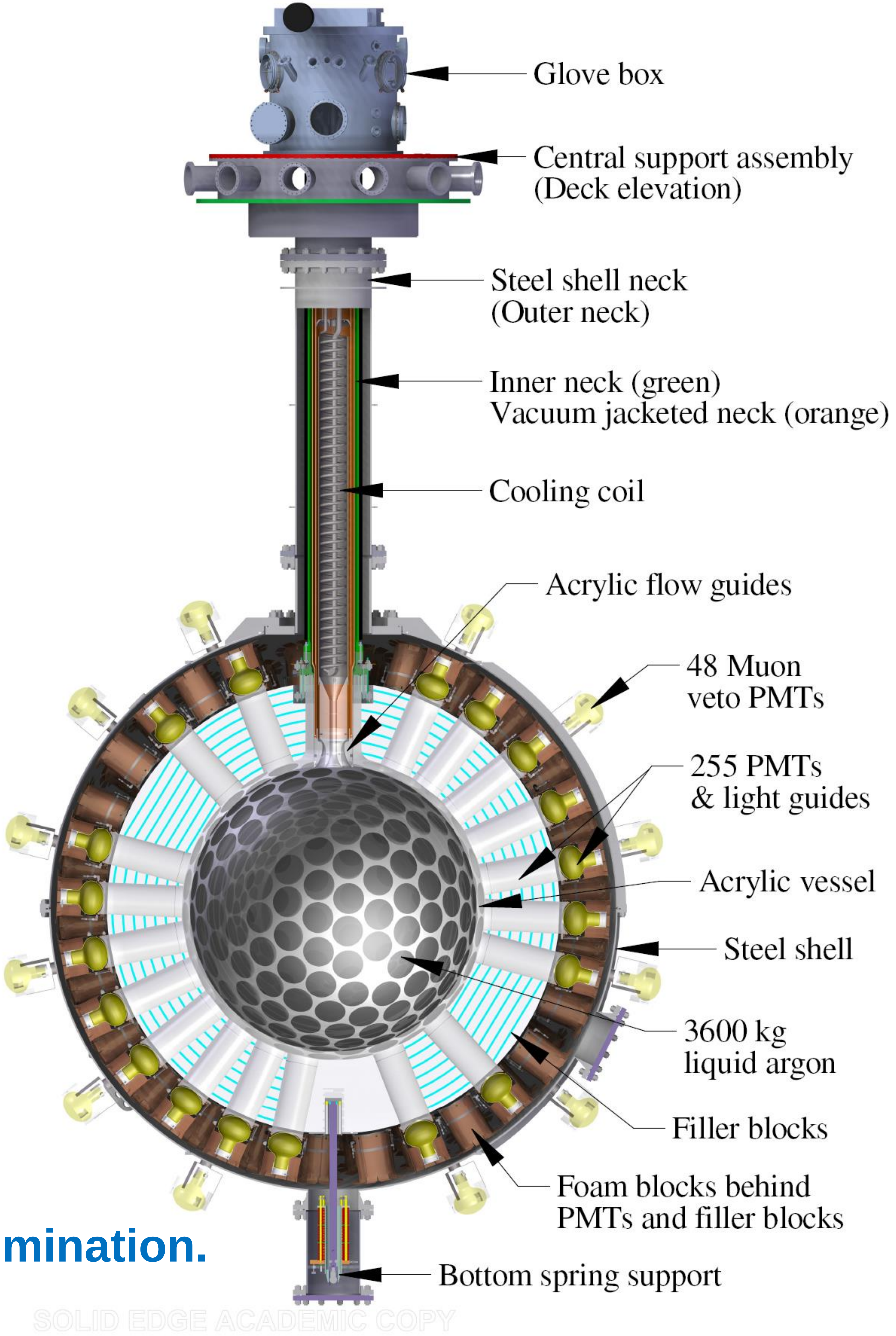
Direct Detection DM Experiments





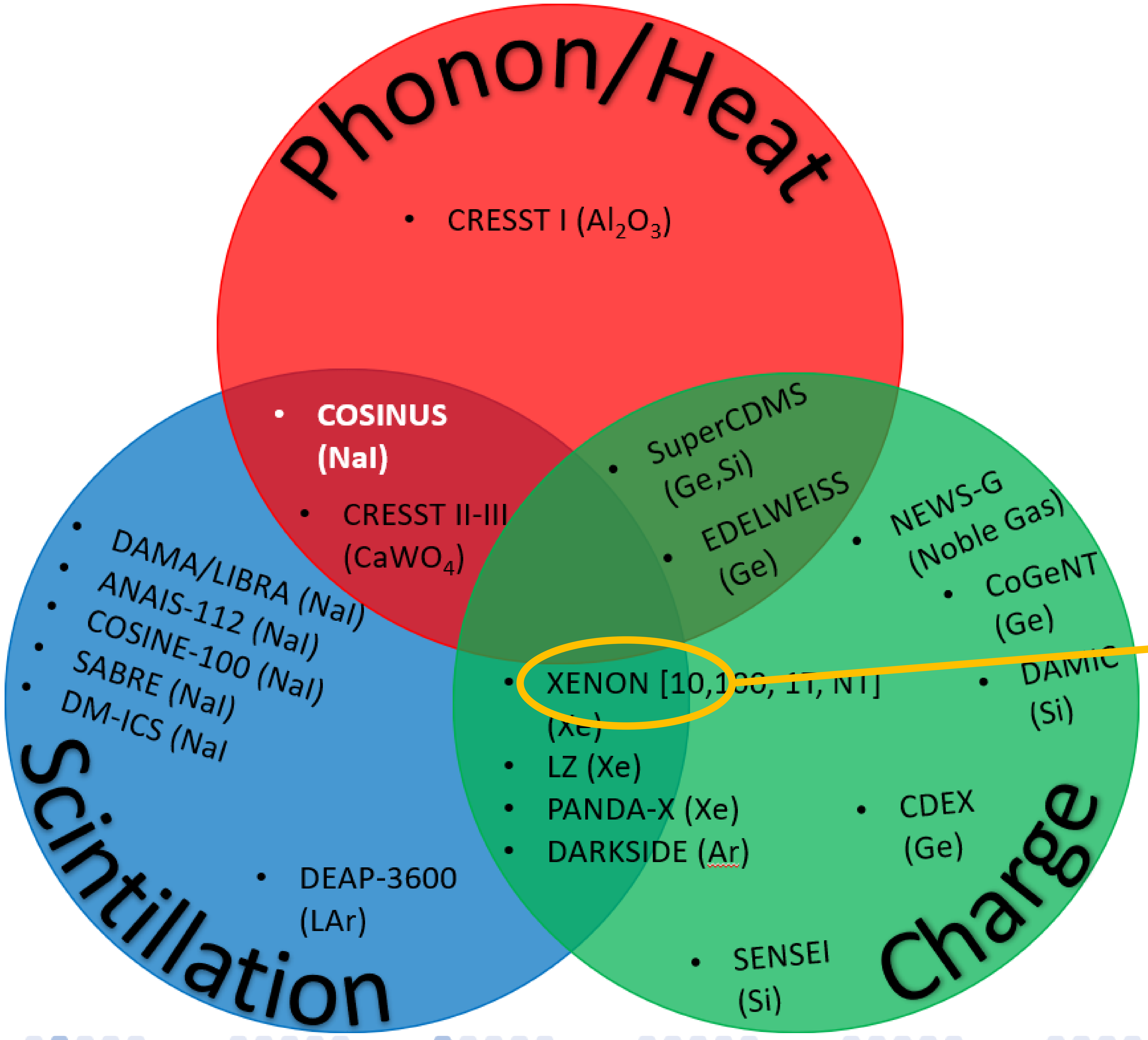
DEAP-3600

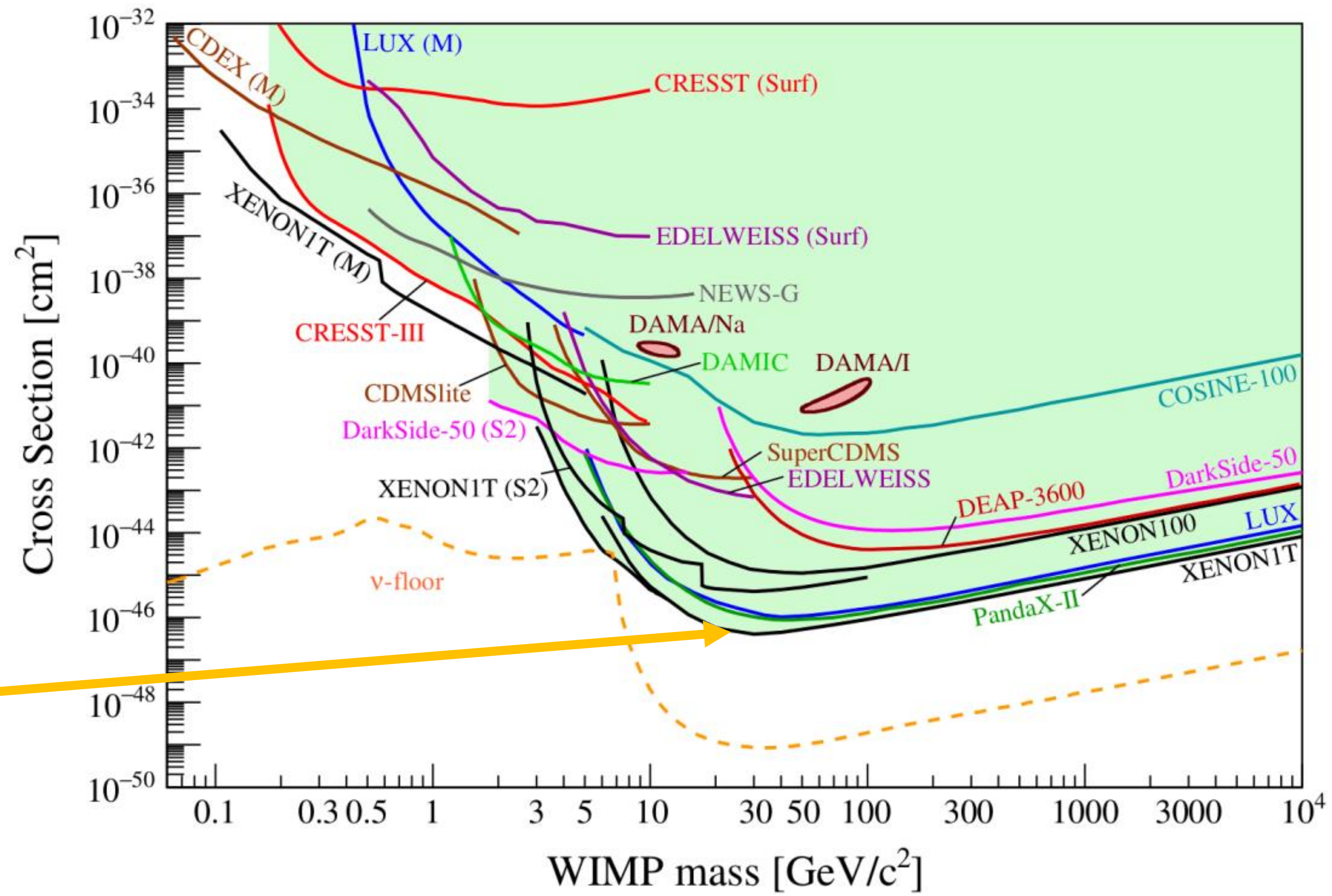




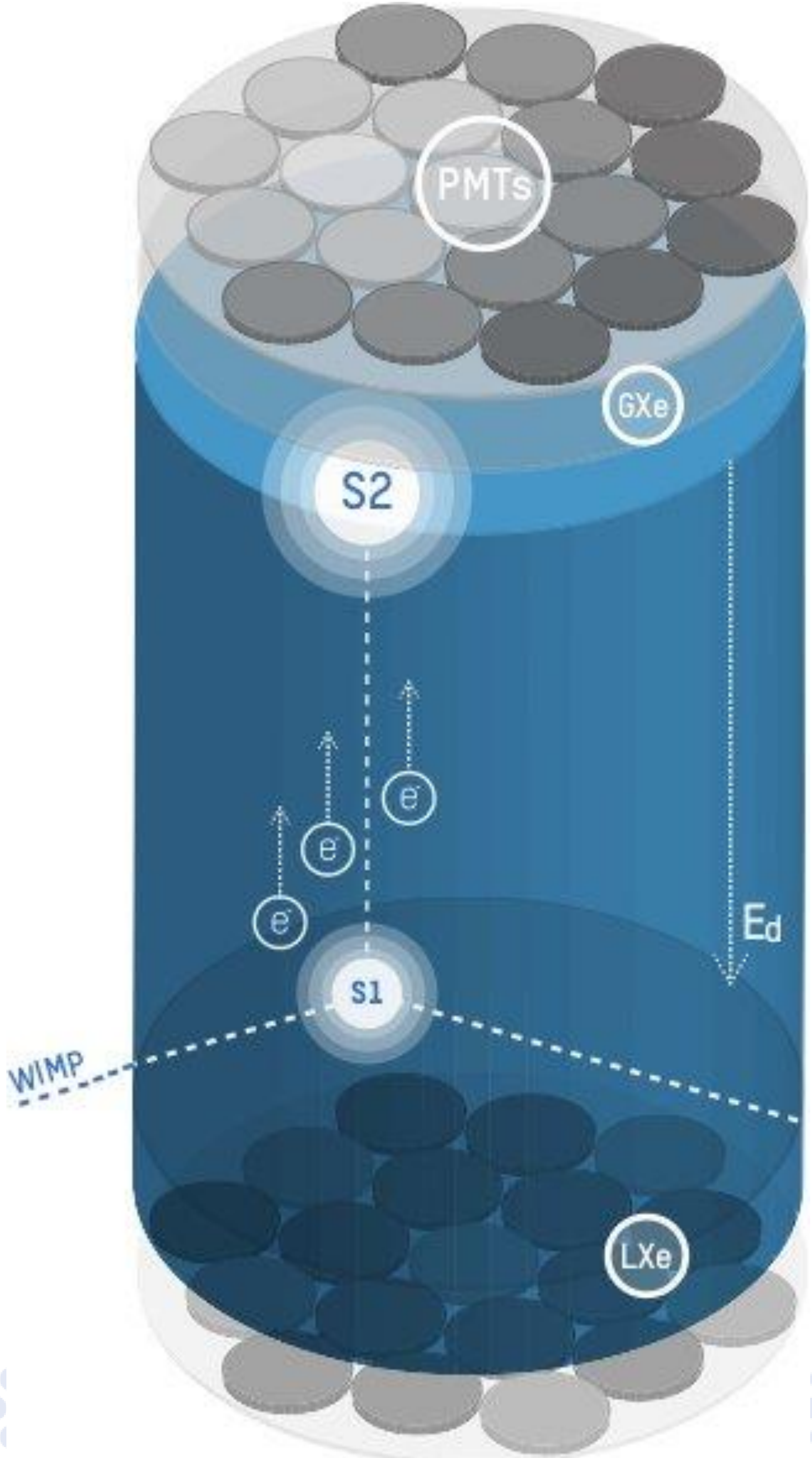
- **Single phase (scintillation)**
- **Argon because has the power of Pulse-Shape discrimination.**

Direct Detection DM Experiments



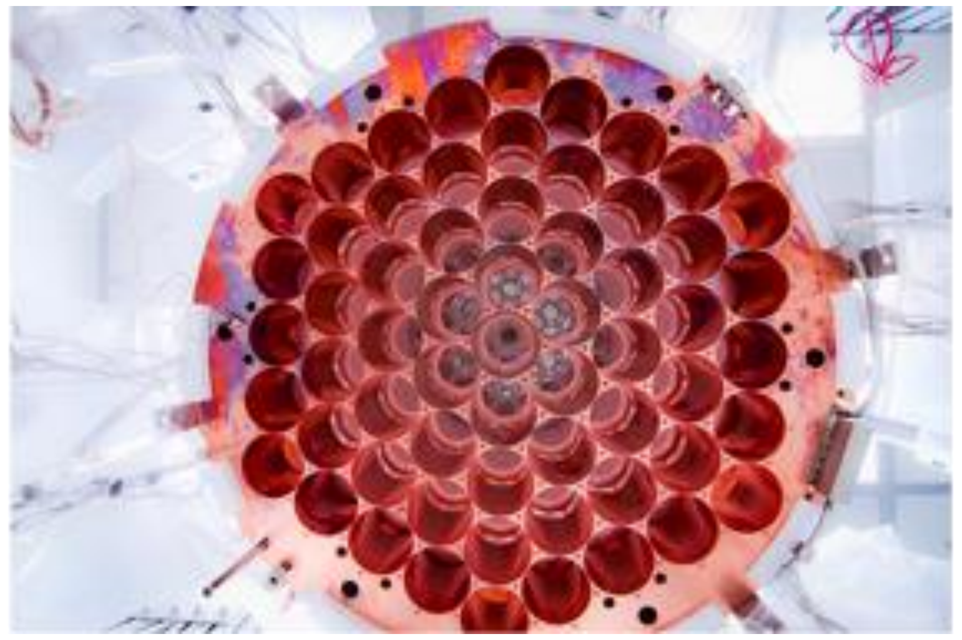
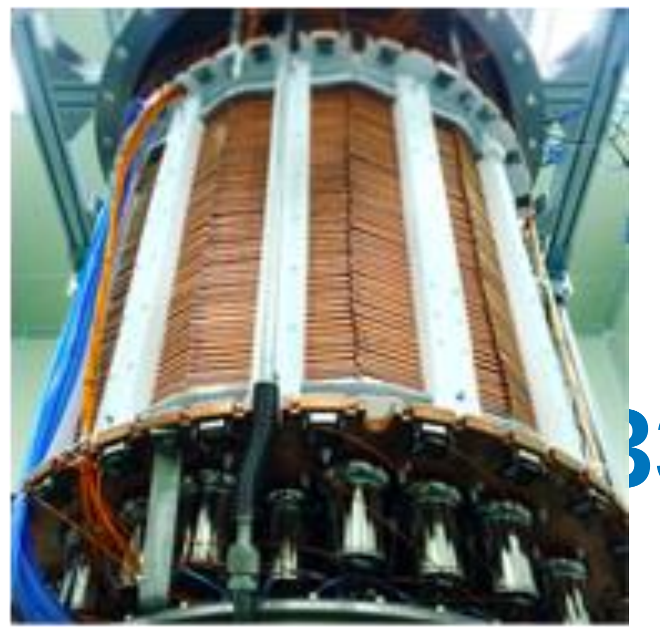


XENON-nT

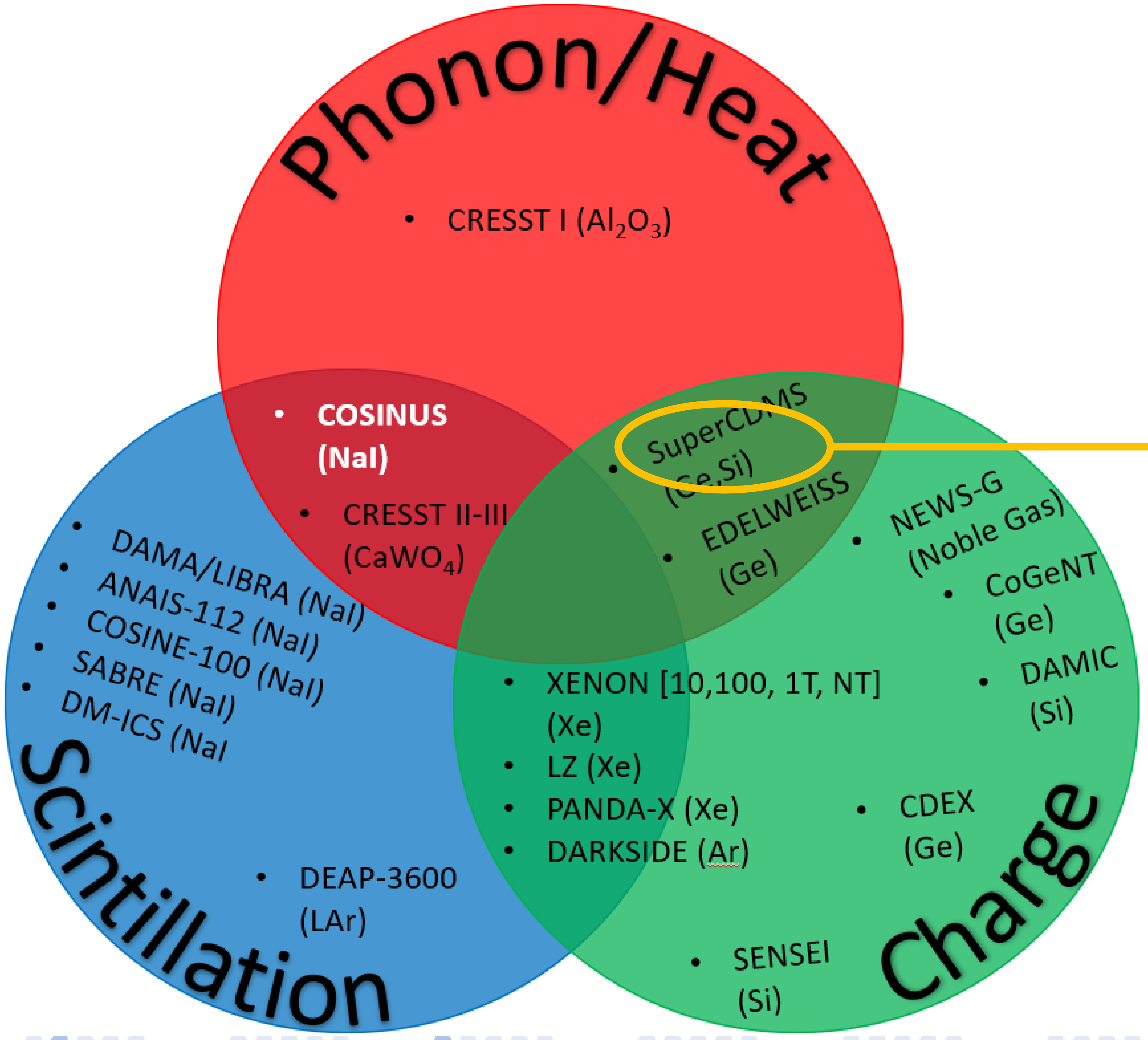


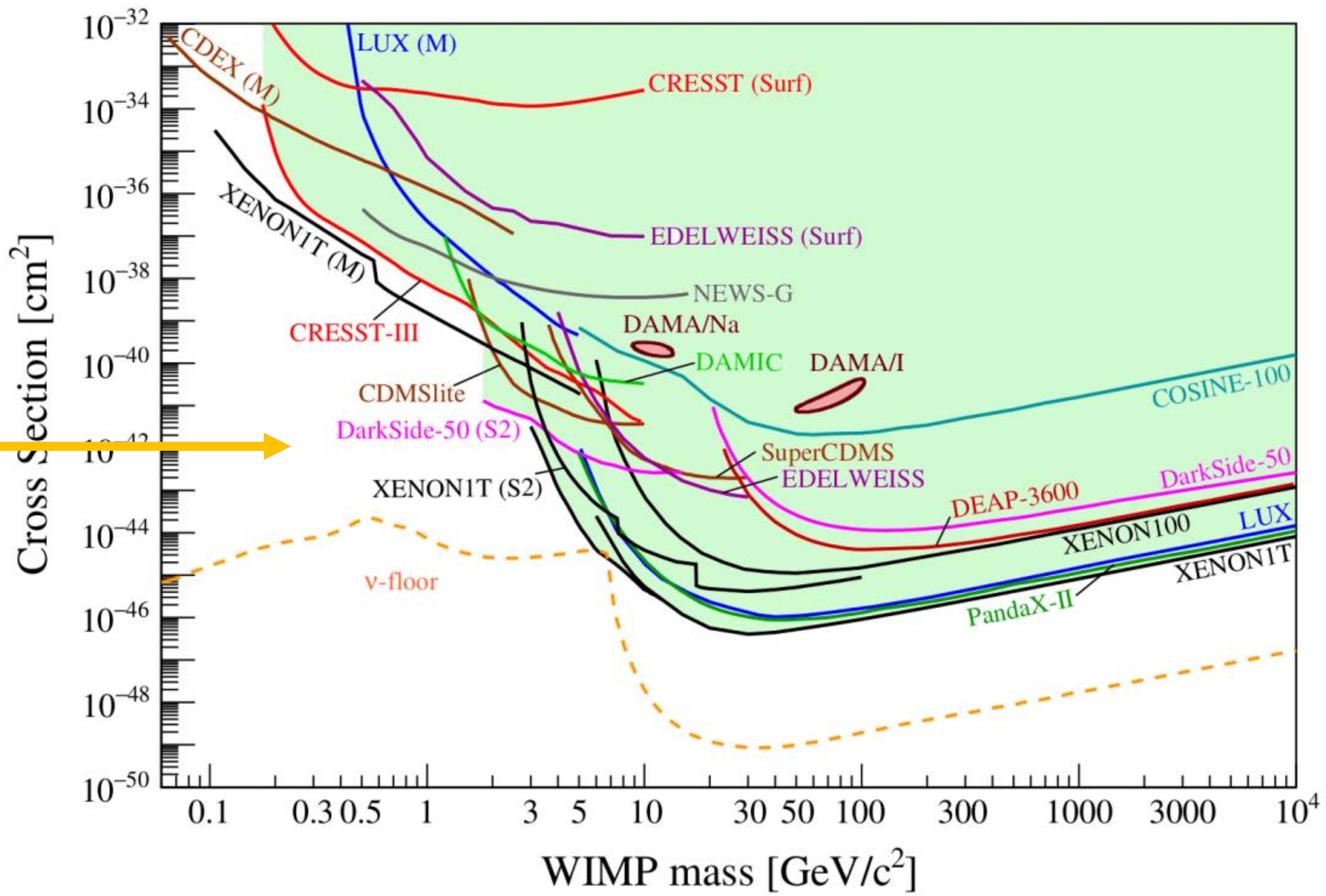
- Dual-phase (Scintillation and Ionization)
- S2 Gives x-y position, drift time gives z.
- Ratio of S2/S1 main discriminator for nuclear and electron recoils.
- Low threshold, few keVs.
- Recently detected solar neutrinos



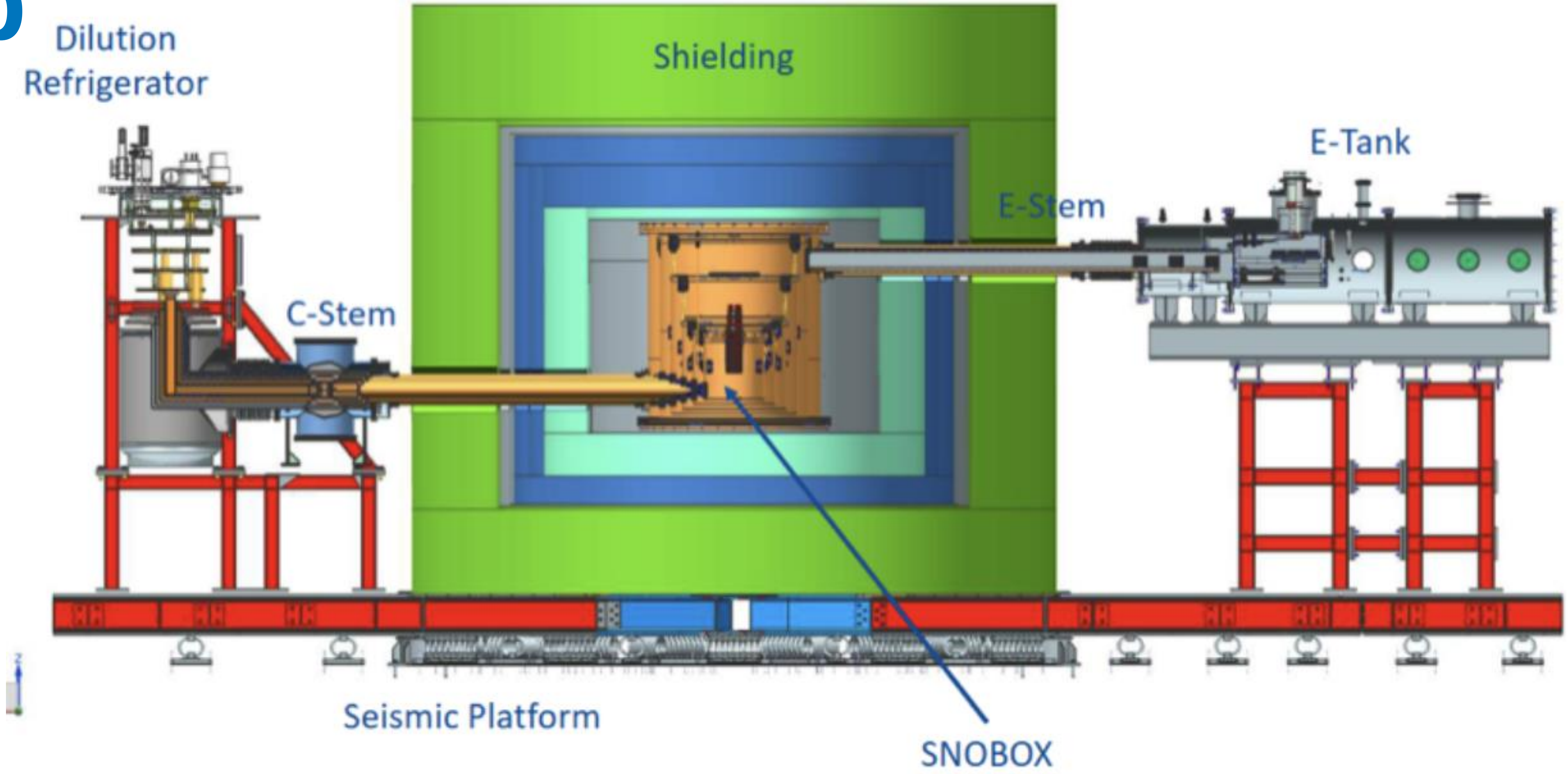



Direct Detection DM Experiments



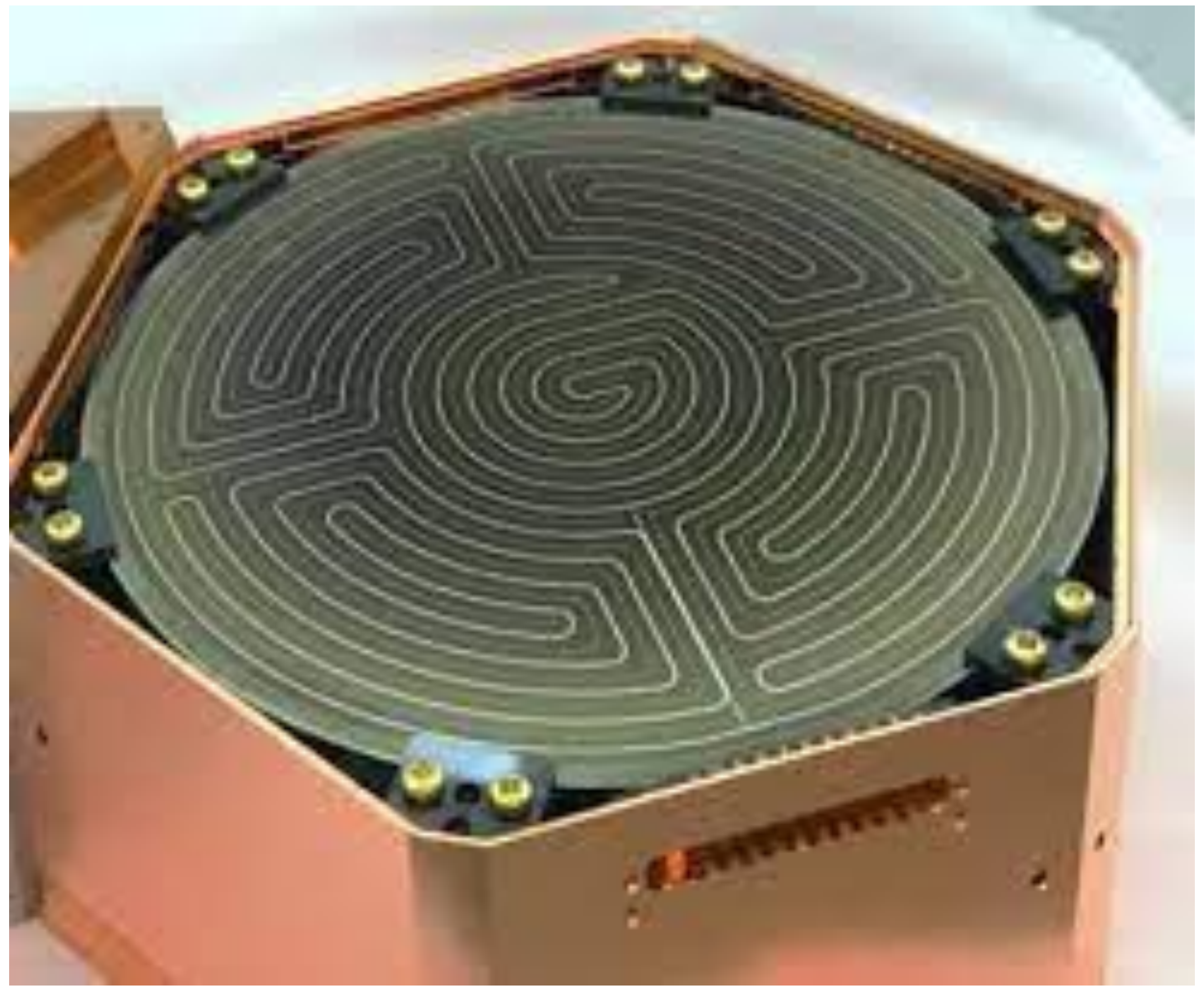


SuperCDMS Experimental Setup

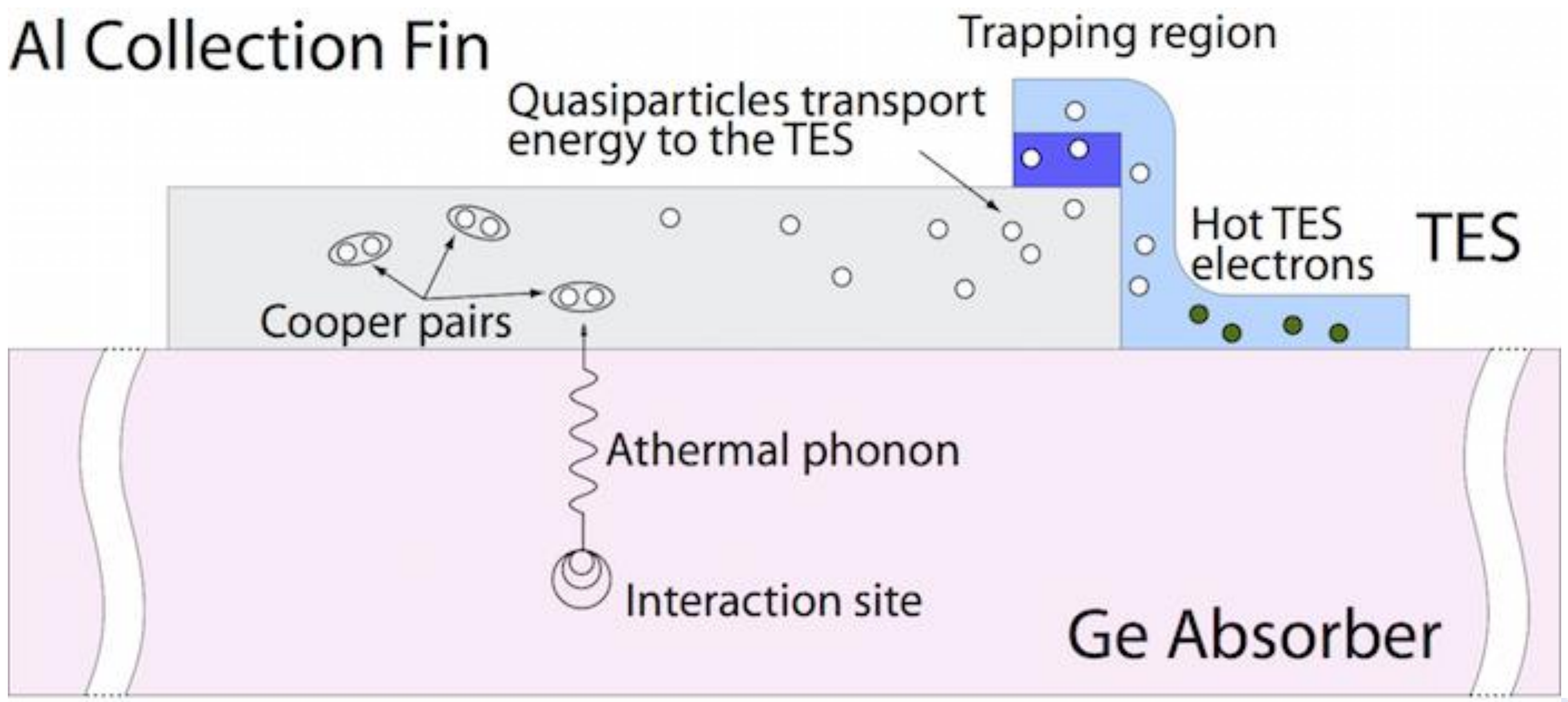


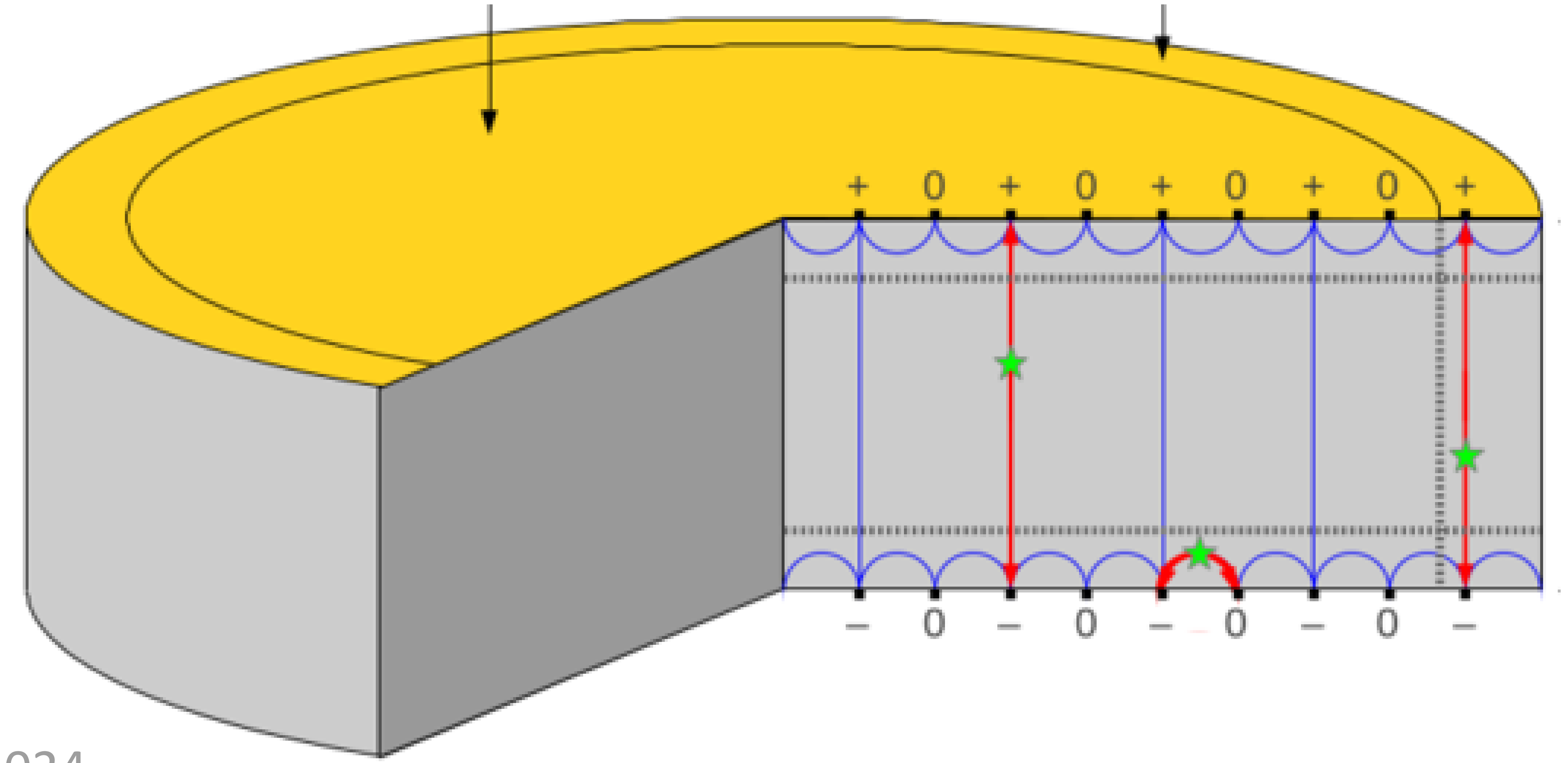
- Four towers (6 detectors each) will be used in the initial physics run, 30 kg total
- Towers will consist of Si and Ge targets iZIP (x12) and HV (x12) detectors

SuperCDMS Detectors

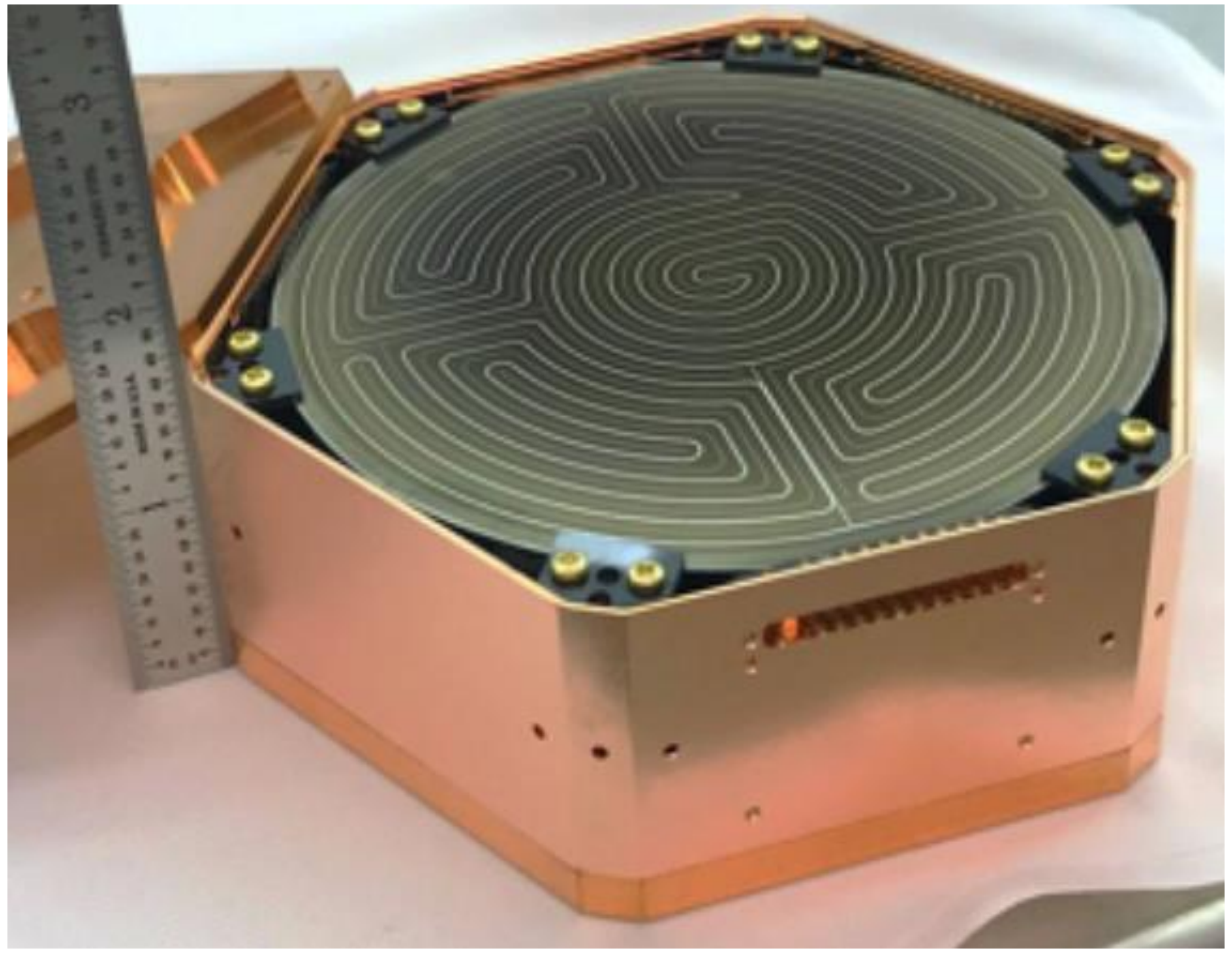


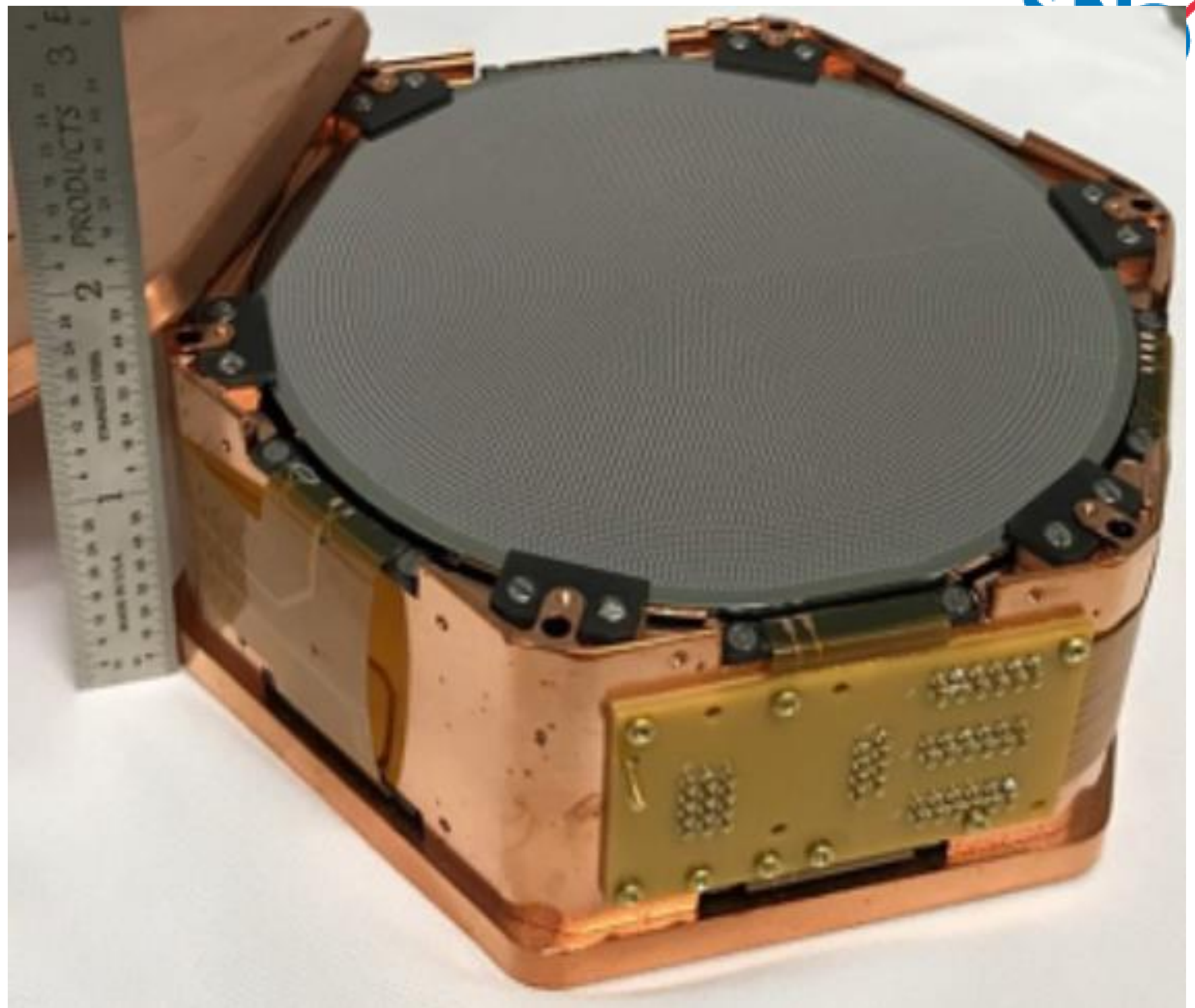
- Upgrade from CDMS and SuperCDMS Soudan (bigger and higher purity)
- Si(0.6 kg)/Ge (1.4 kg) cryogenic detectors
- Measure of **heat (phonon)** and **ionization**
- Heat is measured through Quasi-particle trap assisted electrothermal Feedback Transition Edge sensors
- Charge is measured through interleaved electrodes





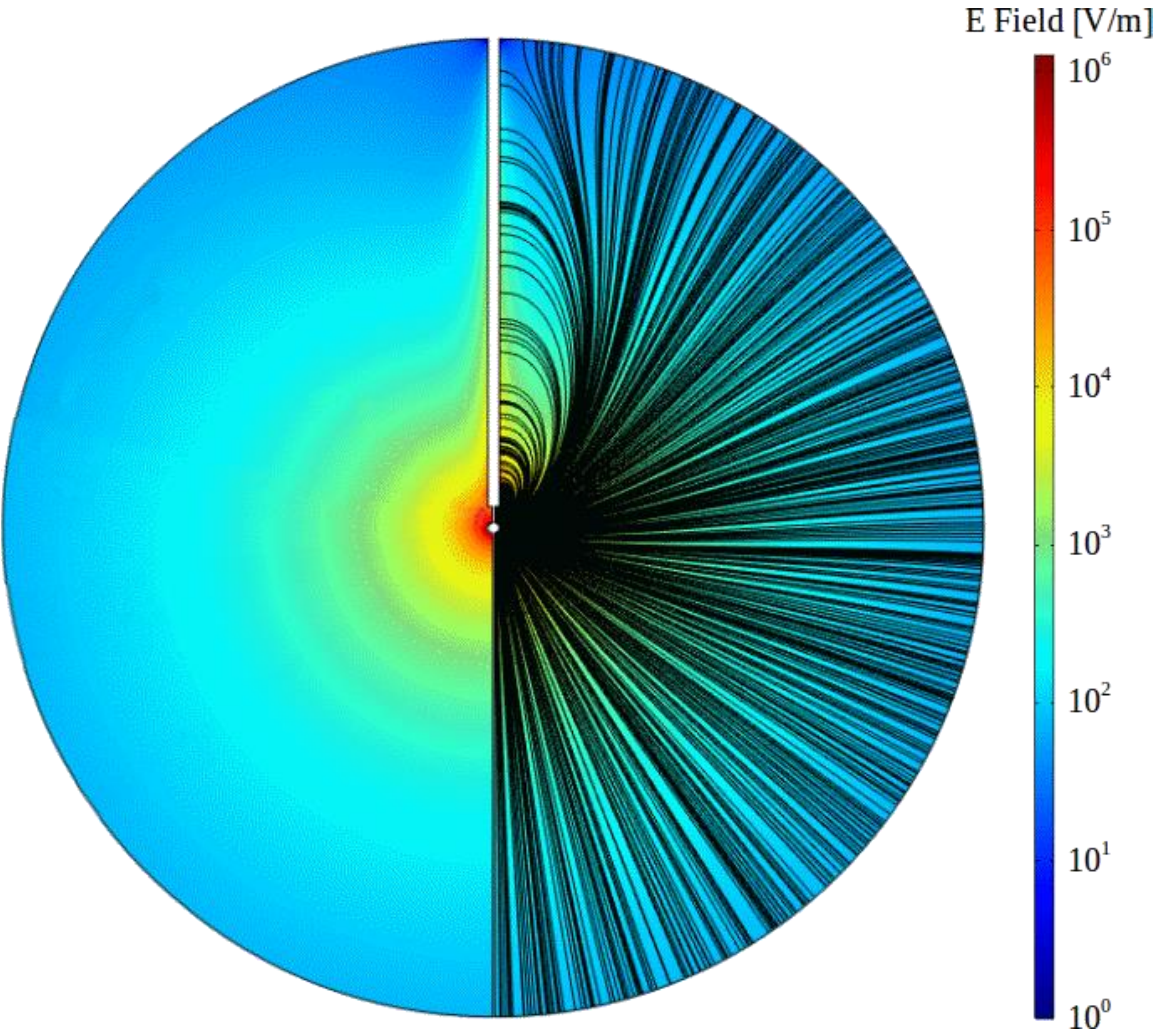
iZIP and HV SuperCDMS Detectors

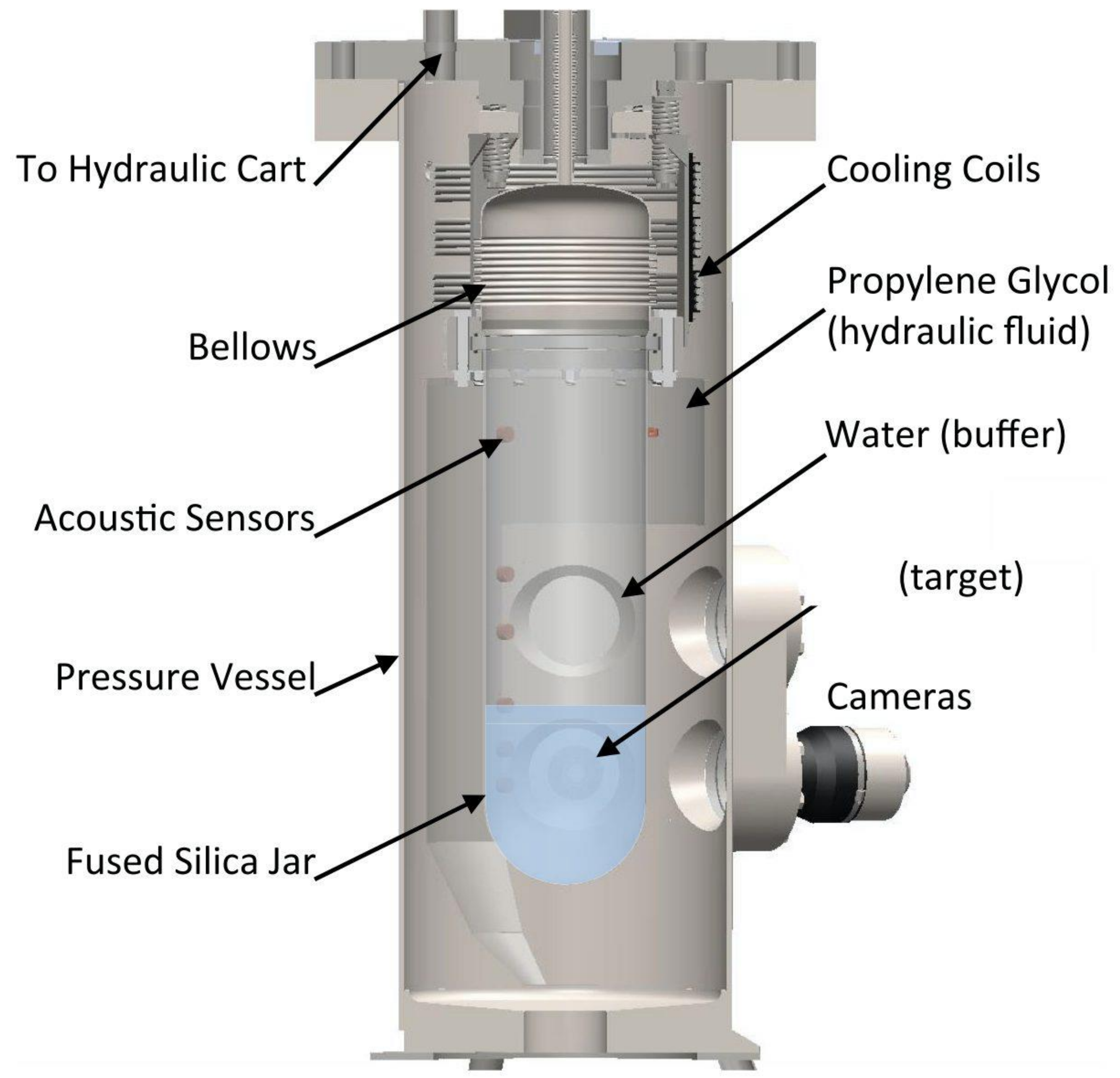


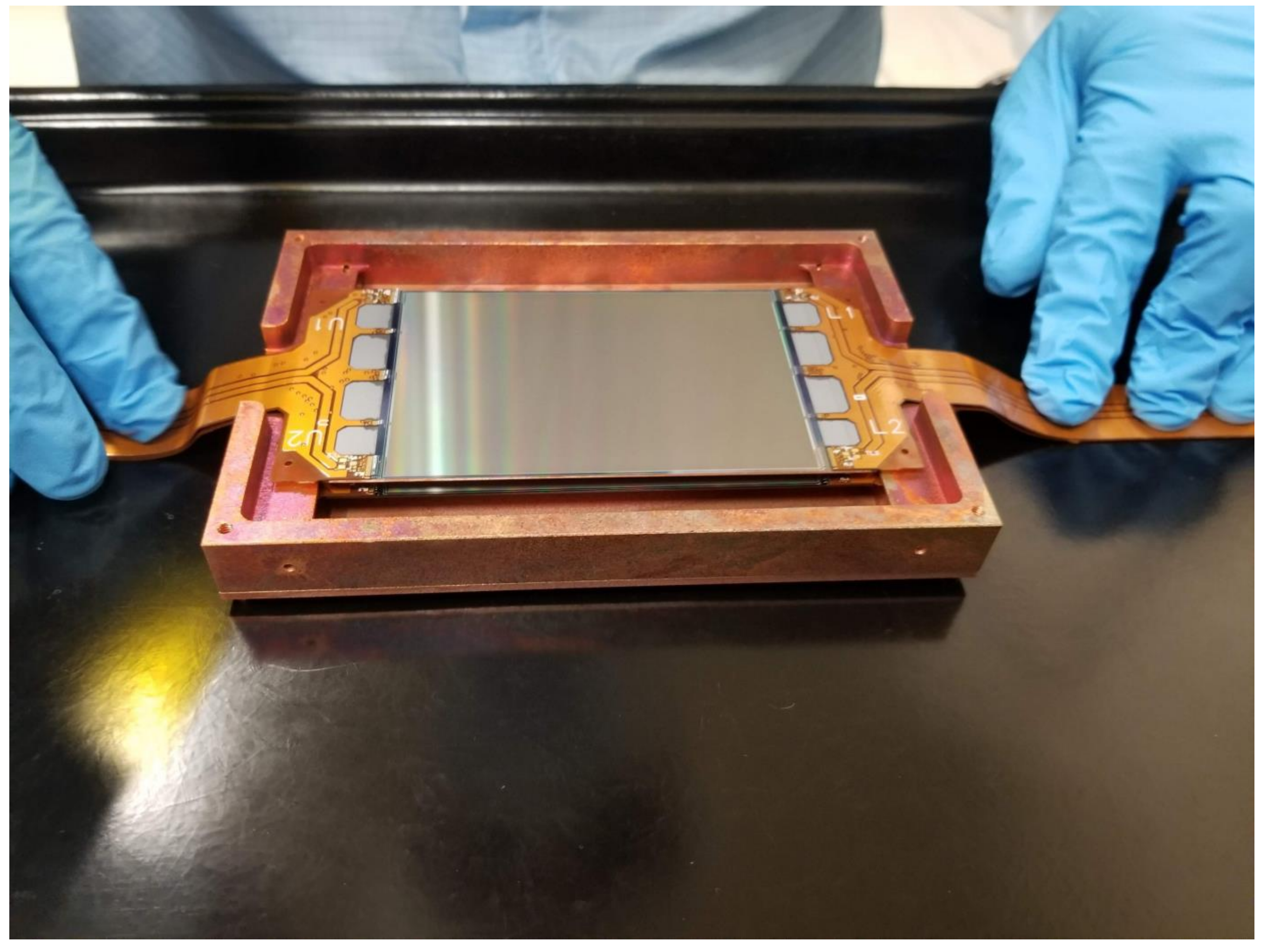


	iZIP		HV	
	Ge	Si	Ge	Si
Number of detectors	10	2	8	4
Total exposure [kg·yr]	45	3.9	36	7.8
Phonon resolution [eV]	33	19	34	13
Ionization resolution [eV_{ee}]	160	180	–	–
Voltage Bias ($V_+ - V_-$) [V]	6	8	100	100

Other DM Experiments at SNOLAB





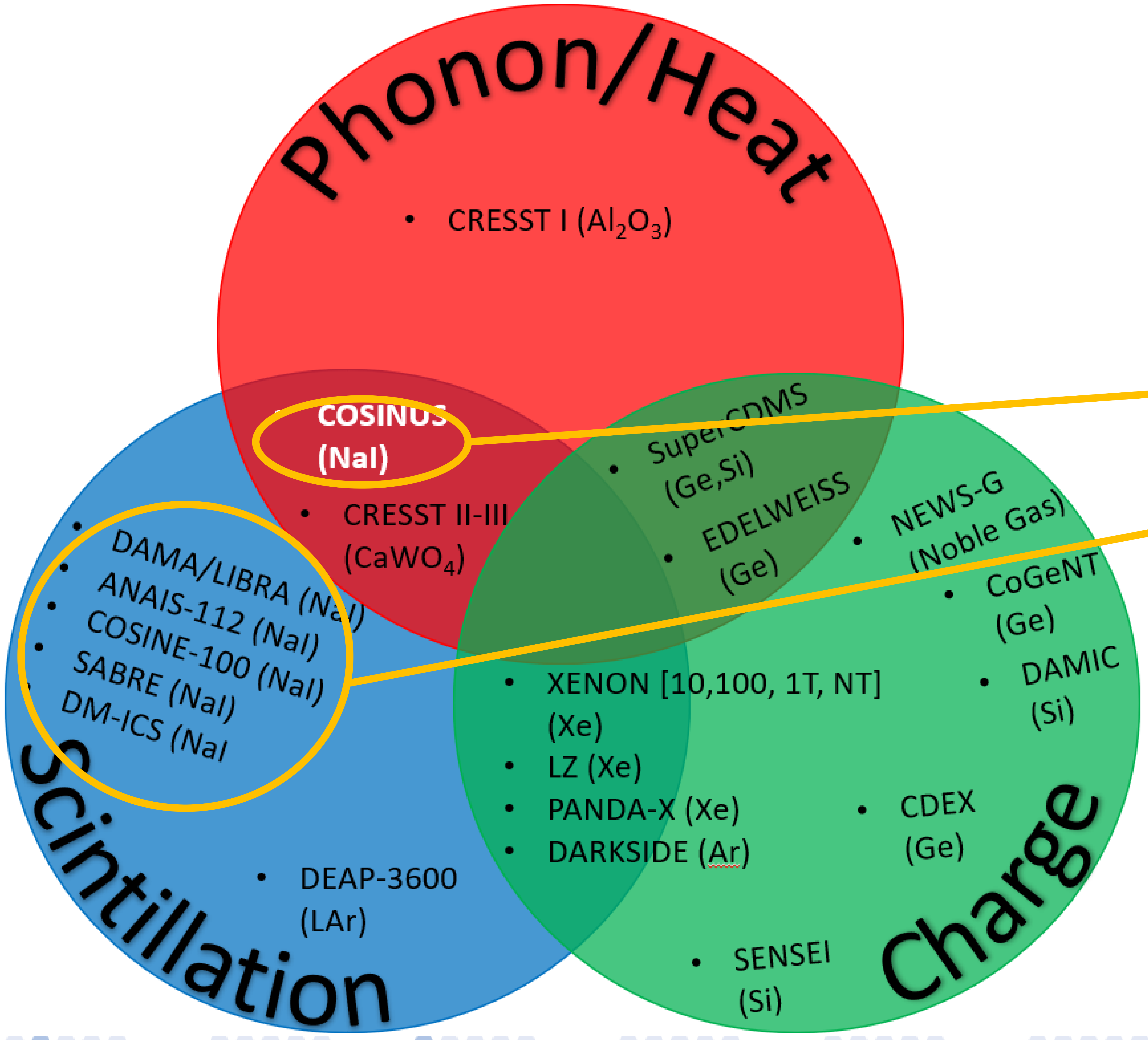


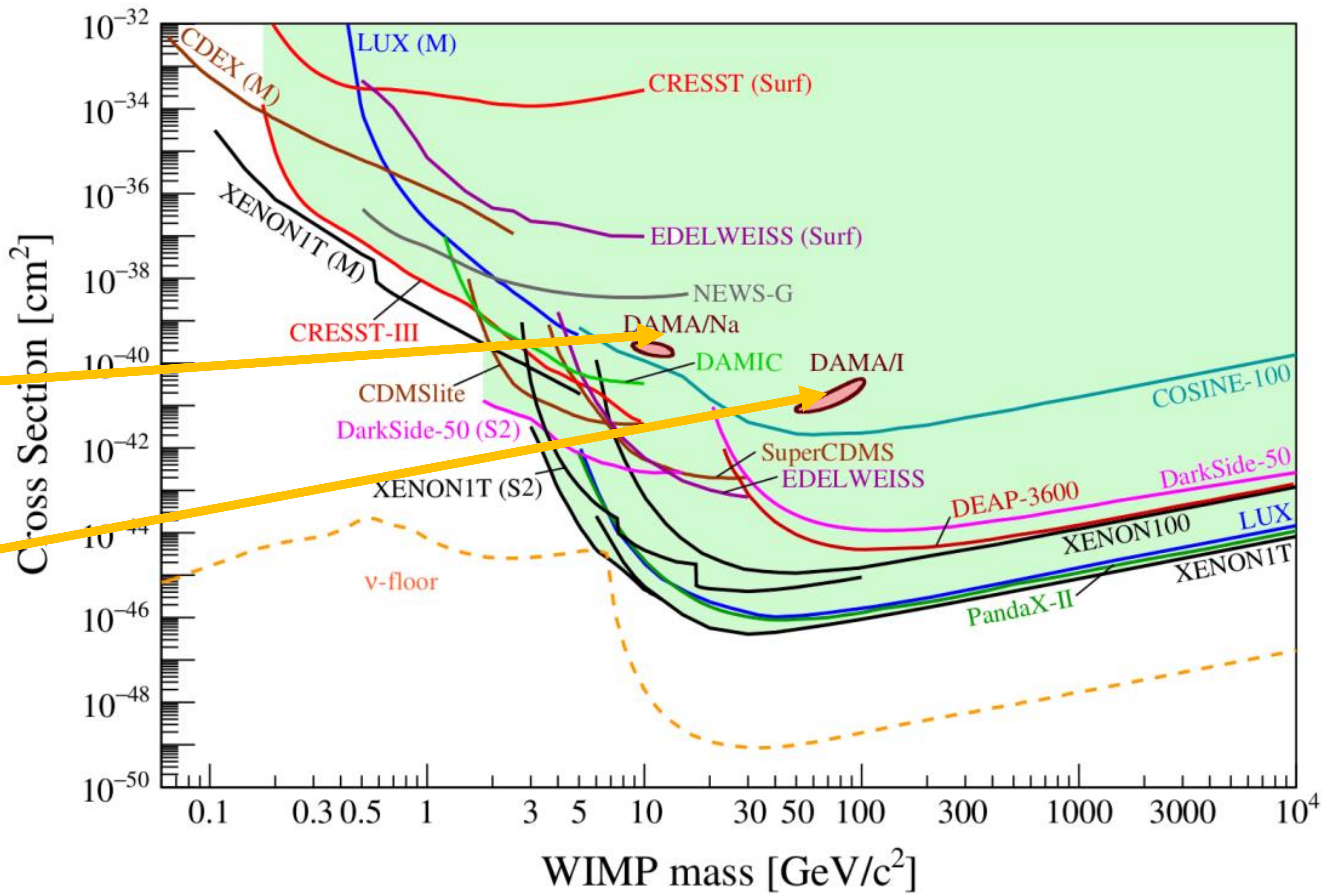
- <u>NEWS-G:</u> Charge measurements with gas
- Talk to: Pierre Gorel

- <u>PICO (40 or 500):</u> Superheated bubbles
- Talk to: Ian Lawson

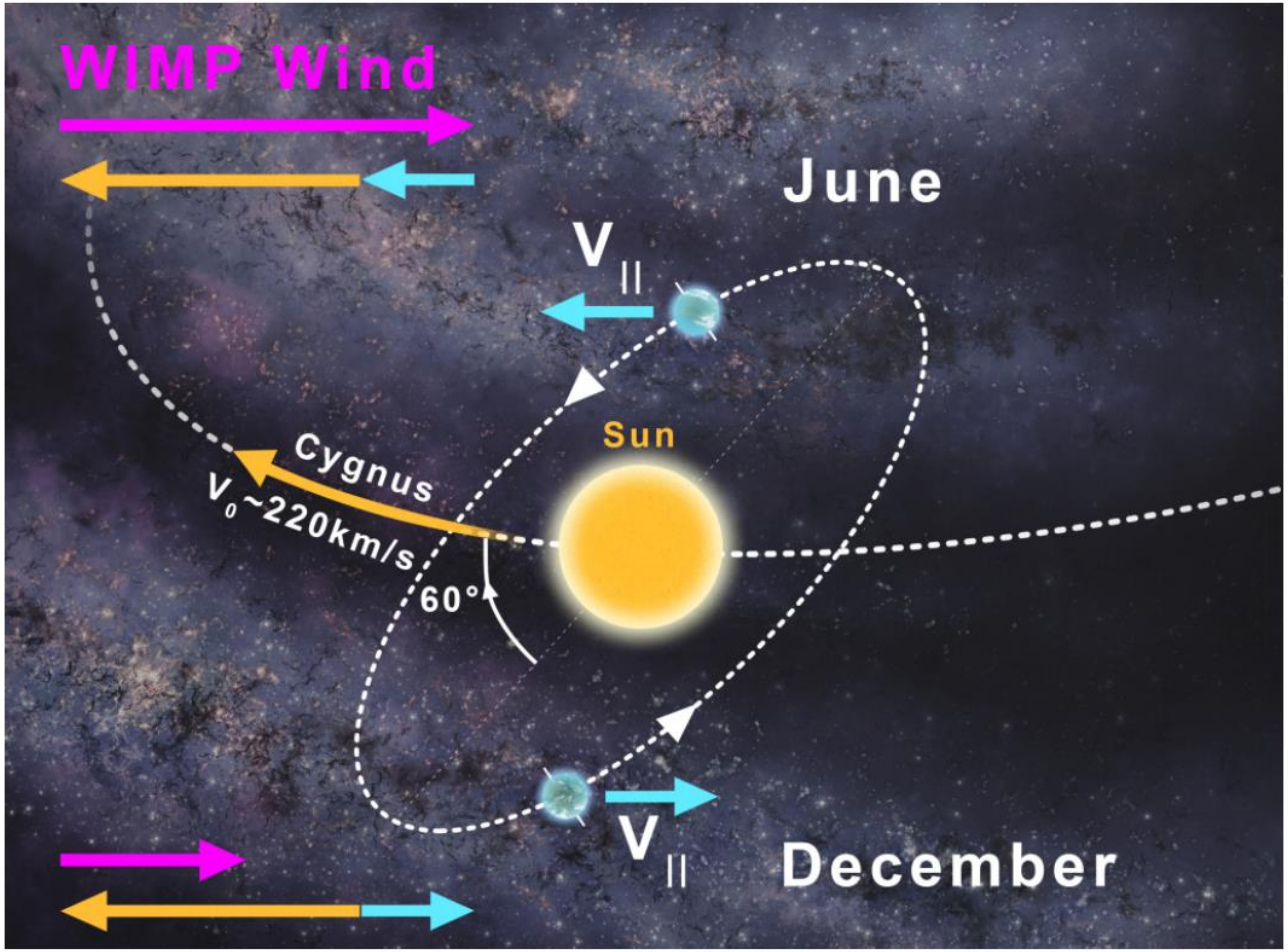
- <u>DAMIC or SENSEI:</u> CCD based
- Talk to: Ian Lawson

Direct Detection DM Experiments



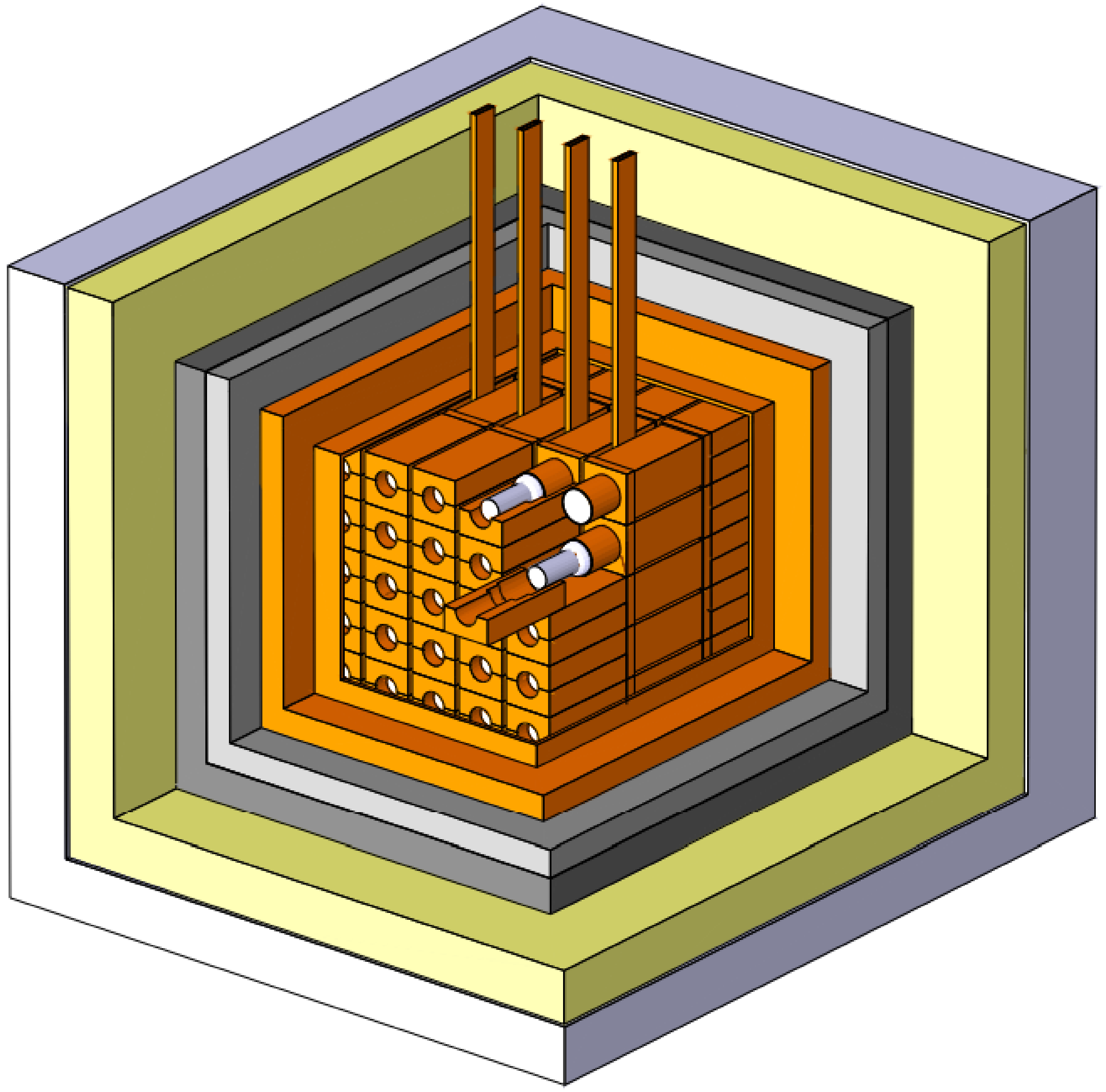


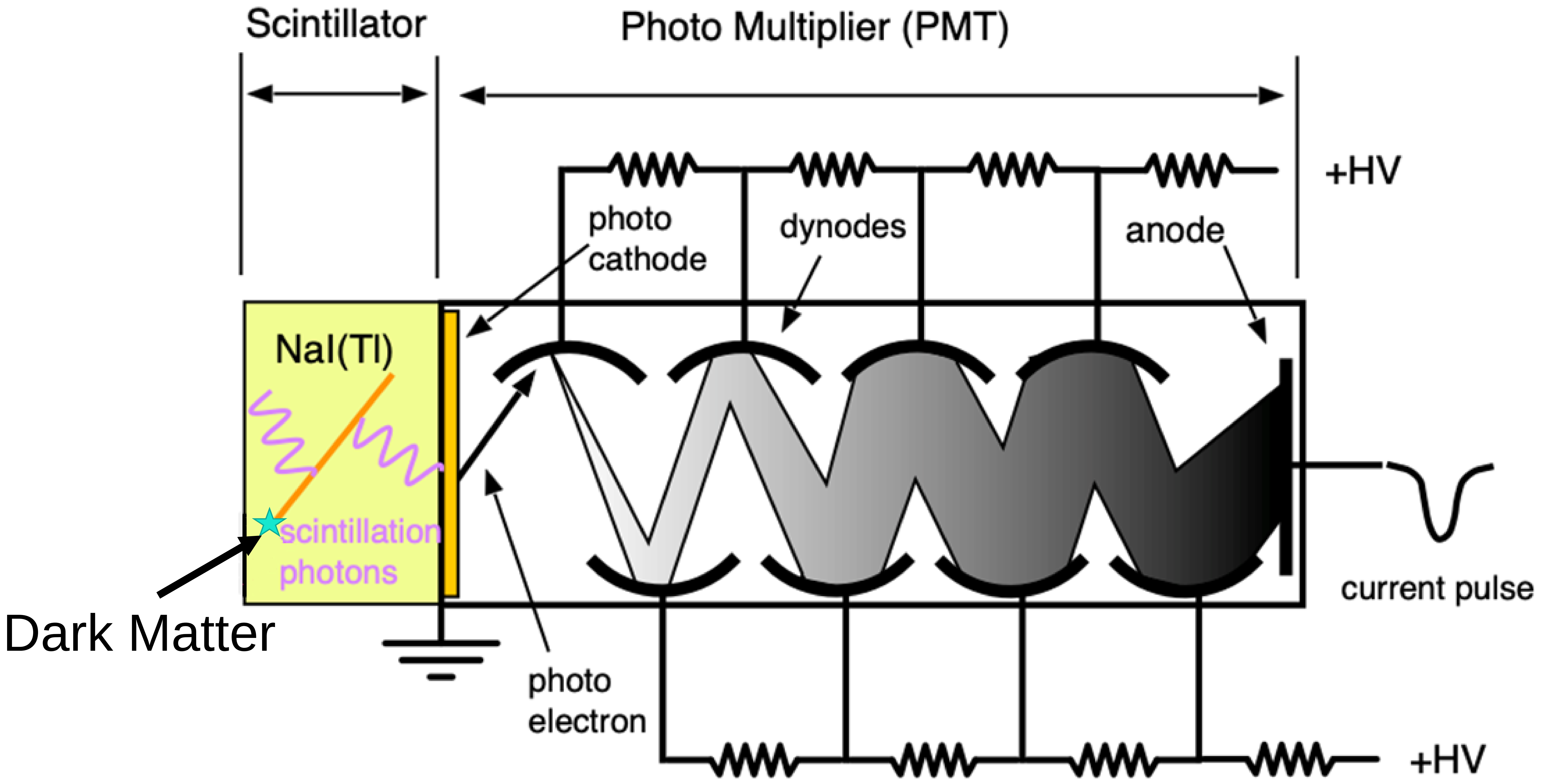
Direct Detection: Annual Modulation



- The sun moves through the galactic dark matter halo
- The earths rotates around the sun
- Induces a change in the dark matter flux throughout the year
- <u>Unique</u> and <u>detectable</u> signal for dark matter
  - Period of one year
  - Peaks around June 2^{nd}
  - Signal expected in low energy region (O(keV))

DAMA/LIBRA Experiment



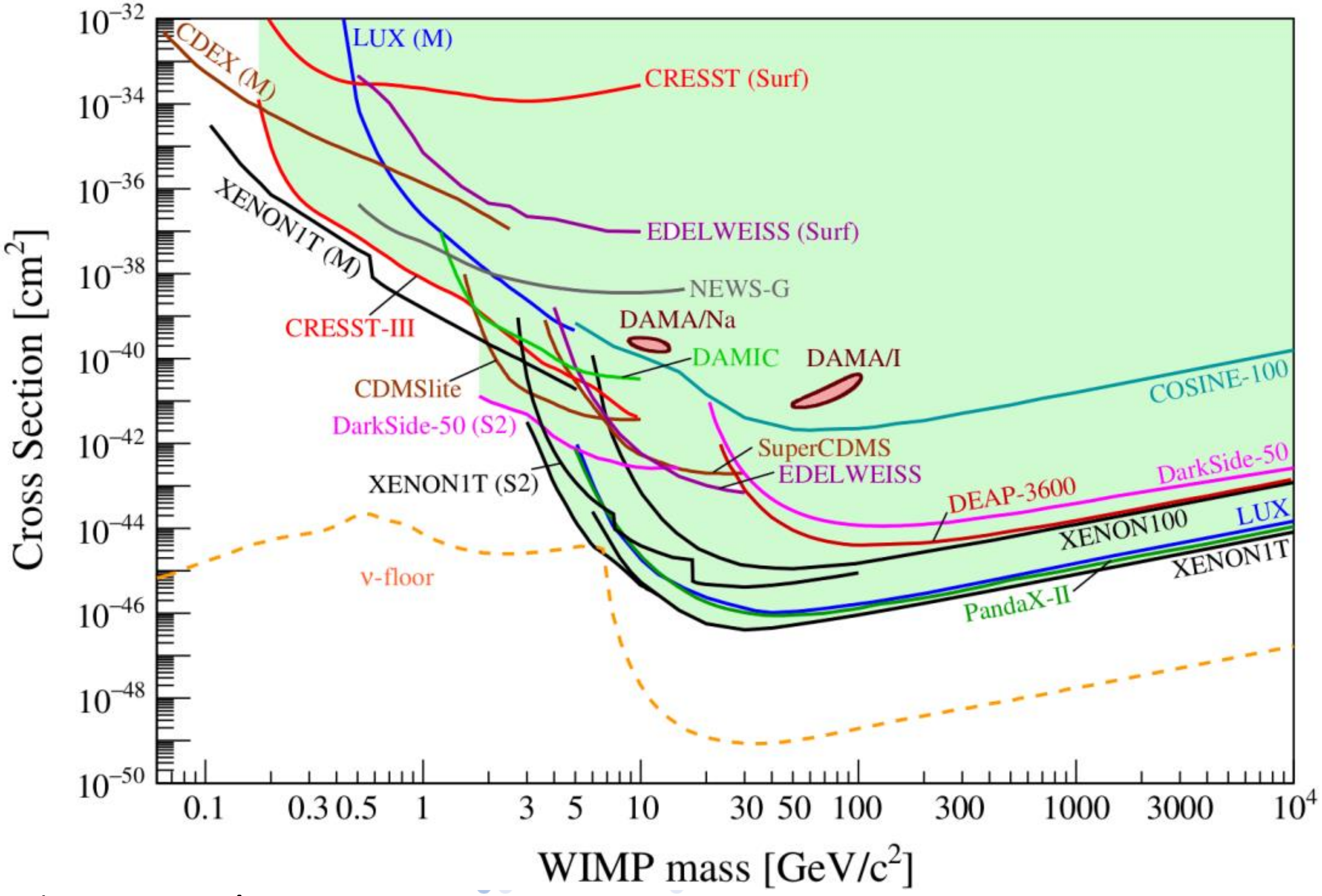


- The DAMA detector consists of 25 highly radiopure NaI(Tl) crystals. (~10 kg each)
- Search for dark matter model-independent annual modulation signature
- <u>Single-channel Experiment</u> -> Scintillation light from NaI(Tl)

DAMA/LIBRA Results

- The DAMA collaboration has detected a peculiar annual modulation signal since 1997
- Signal is consistent with WIMP dark matter halo predictions (0.75 keV threshold shown)
  - Statistics: >13σ
  - Period: 0.999 +/- 0.001
  - Phase: 25th May +/- 5 days
  - Non-dark matter explanation: No

Complications with DAMA



- Incompatibility with **every other experiment**

https://arxiv.org/abs/21

Response of DAMA

SNOLAB

About interpretation and comparisons

See e.g.: Riv.N.Cim.26 ono.1(2003)1, IJMPD13(2004)2127, EPJC47(2006)263, IJMPA21(2006)1445, EPJC56(2008)333, PRD84(2011)055014, JMPA28(2013)1330022

...models...

- Which particle?
- Which interaction coupling?
- Which EFT operators contribute?
- Which Form Factors for each target-material?
- Which Spin Factor?
- Which nuclear model framework?
- Which scaling law?
- Which halo model, profile and related parameters?
- Streams?
- ...

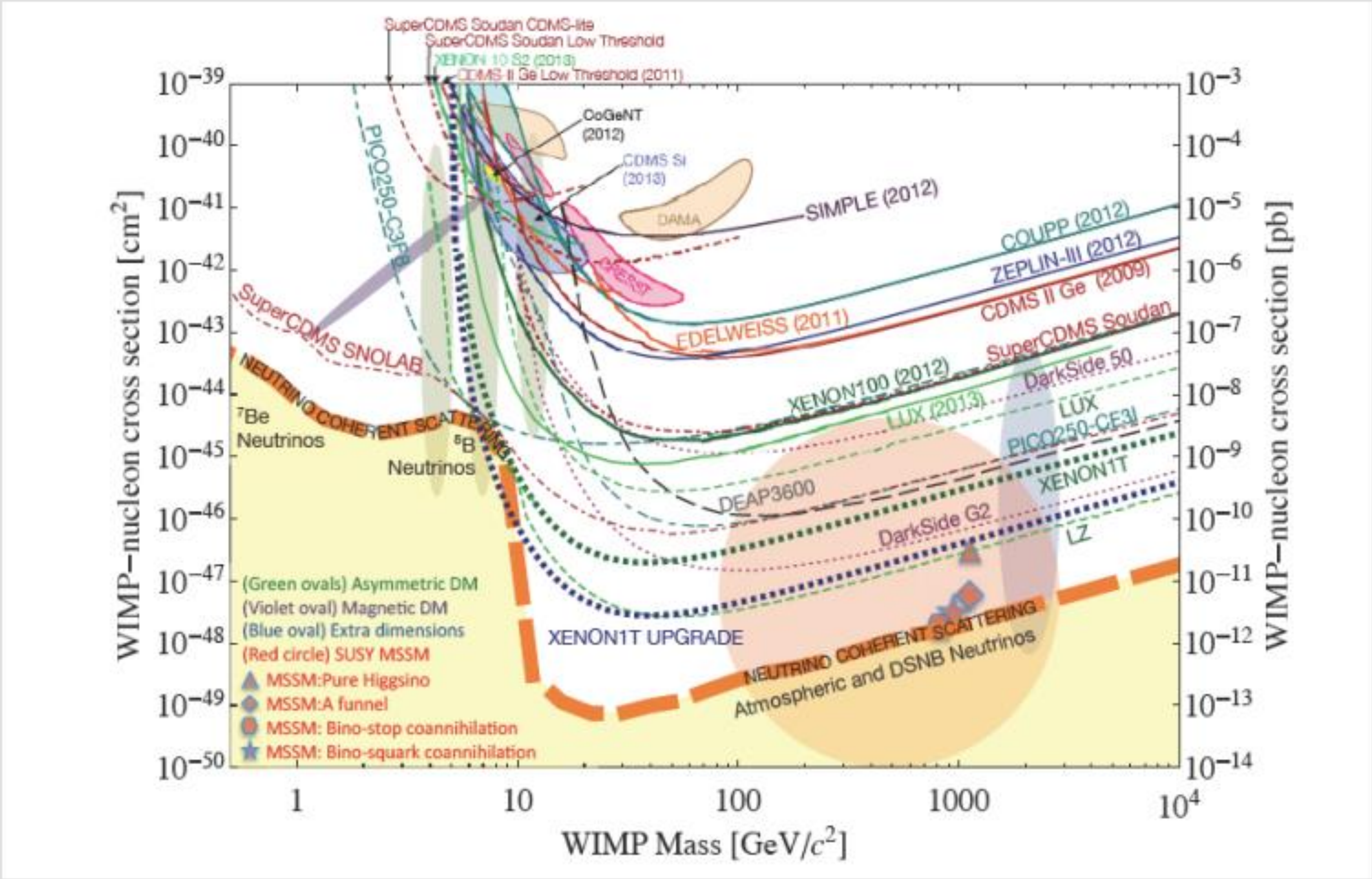
...and experimental aspects...

- Exposures
- Energy threshold
- Detector response (phe/keV)
- Energy scale and energy resolution
- Calibrations
- Stability of all the operating conditions.
- Selections of detectors and of data.
- Subtraction/rejection procedures and stability in time of all the selected windows and related quantities
- Efficiencies
- Definition of fiducial volume and non-uniformity
- Quenching factors, channeling
- ...

Uncertainty in experimental parameters, as well as necessary assumptions on various related astrophysical, nuclear and particle-physics aspects, affect all the results at various extent, both in terms of exclusion plots and in terms of allowed regions/volumes. Thus comparisons with a fixed set of assumptions and parameters' values are intrinsically strongly uncertain.

No experiment can - at least in principle - be directly compared in a model independent way with DAMA so far

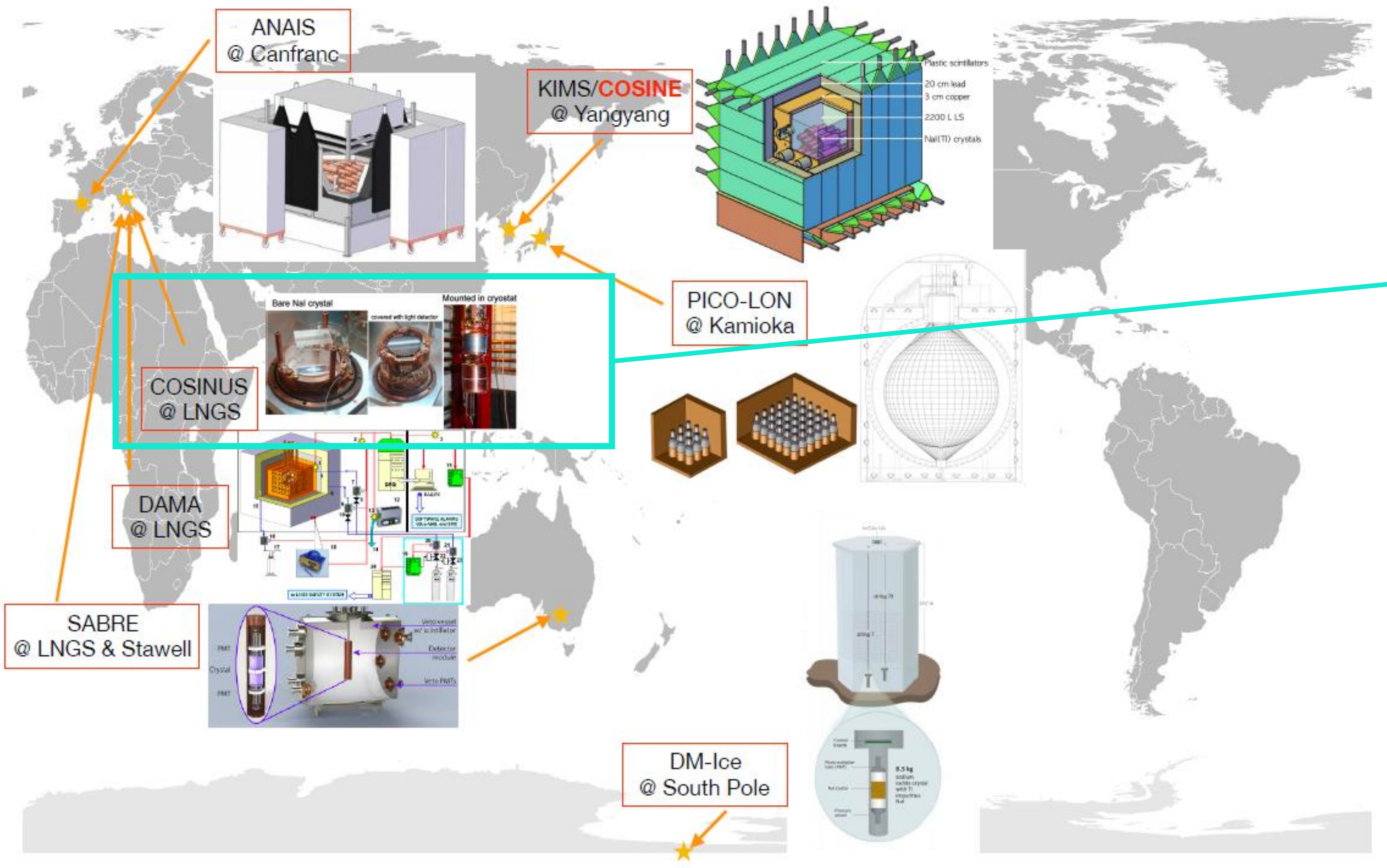
Is it an "universal" and "correct" way to approach the problem of DM and comparisons?



No, it isn't. This is just a largely arbitrary/partial/incorrect exercise

https://agenda.infn.it/getFile.py/access?contribId=34&sessionId=1&resId=0&materialId=slides&confId=15474

Global Efforts using NaI(Tl)



The best one

Conclusions & Outlook

- Plenty of observational evidence (galactic, cluster, universe)
- Dark matter does not produce light, interacts gravitationally and is non-relativistic
- Many theories of dark matter
- Many experimental searches for dark matter
- Hopefully we find it soon