

Dark Matter Experiments - I

Maxime Pierre

Some context about me:

- ✦ Post-doctoral researcher at Nikhef, working on the XENONnT dark matter direct detection experiment
- ✦ Did my Ph.D. in France on: “*Neutrinoless double beta decay search in the XENONnT Dark Matter direct detection experiment*”

What I will not do:

- ✦ List and explain in details all the ongoing effort to search for Dark Matter

What I would like to do:

- ✦ Give you the keys to understand the challenges associated with the detection of Dark Matter and general overview of the current experimental strategy

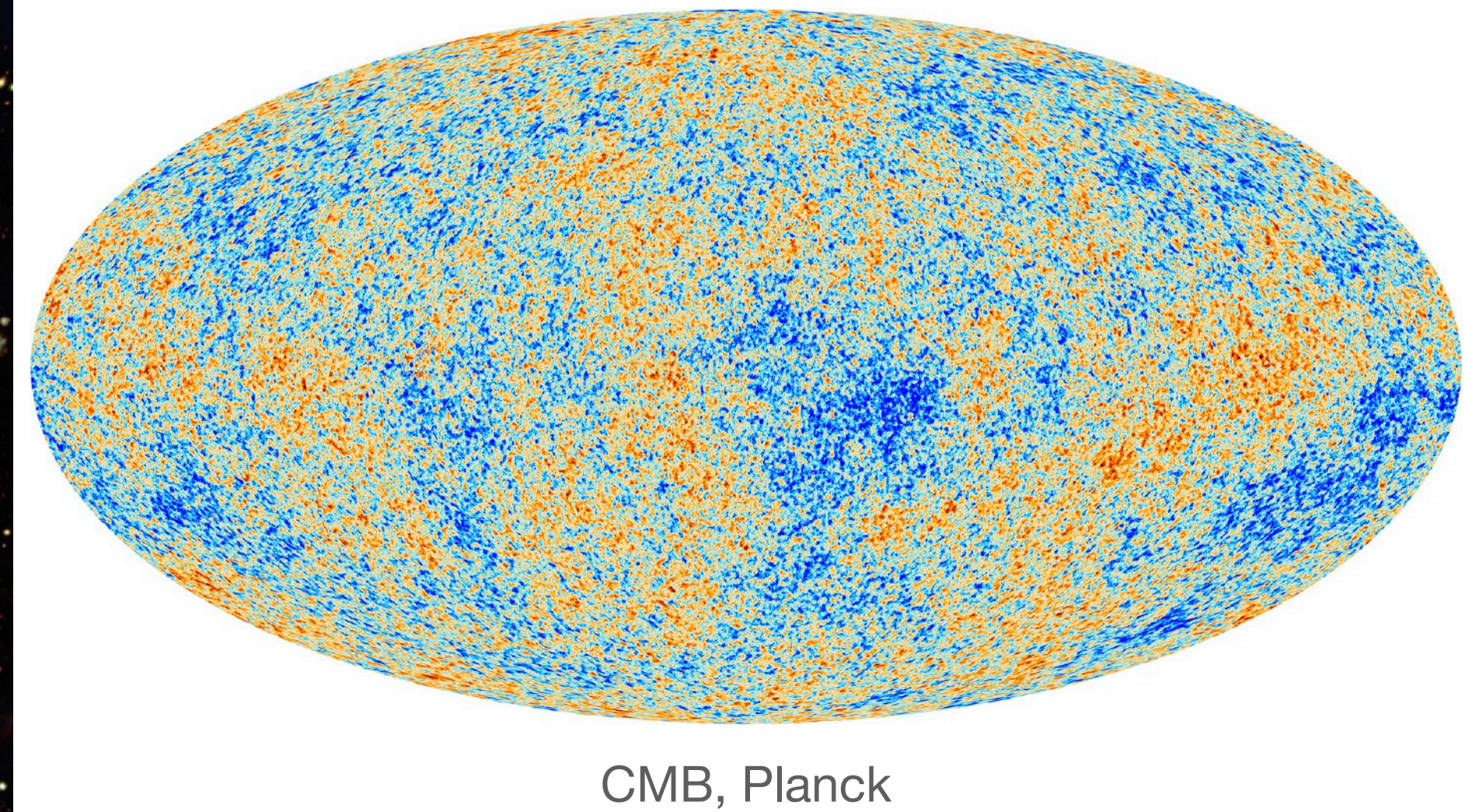
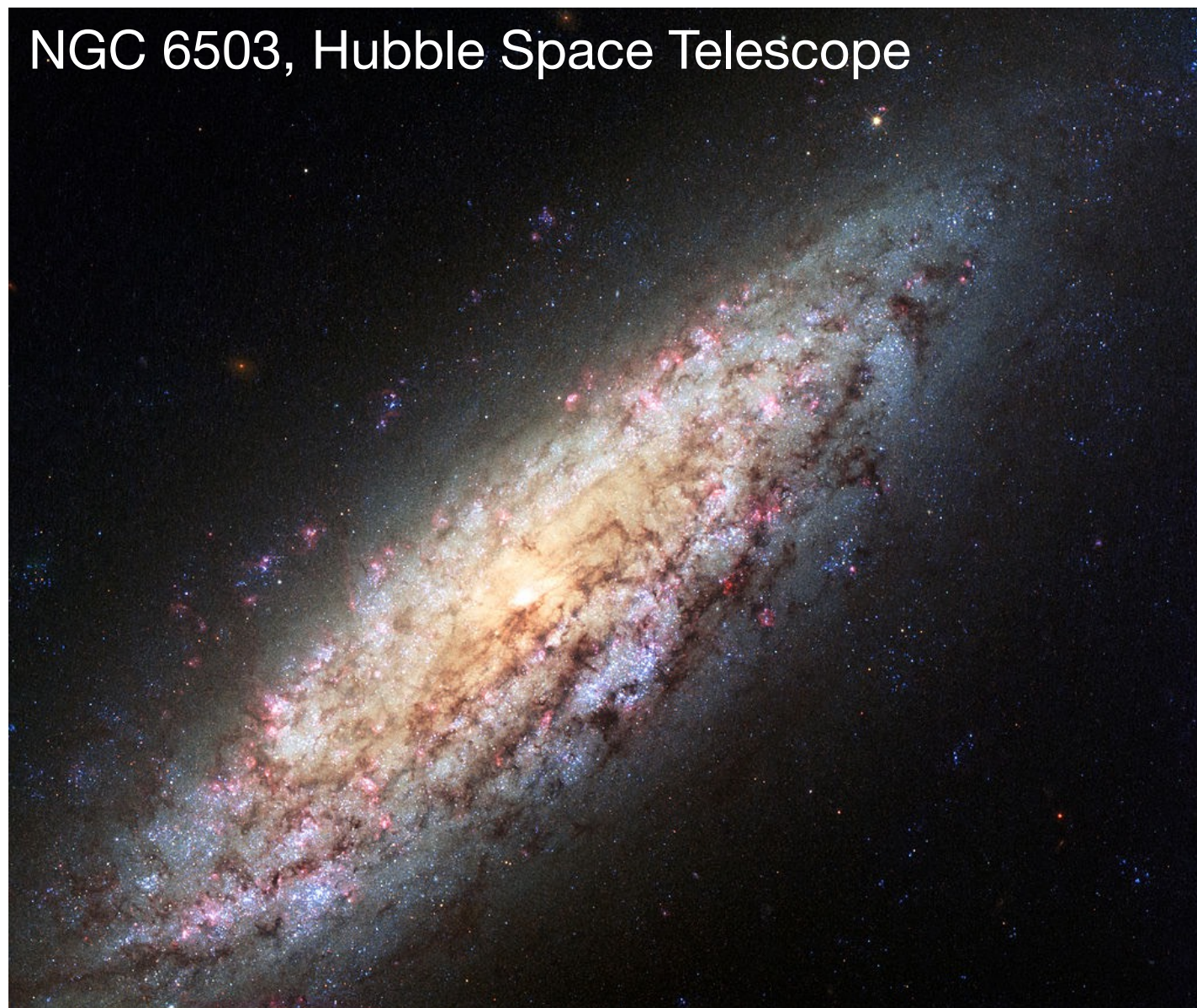
A visualization of the cosmic web, showing a complex network of dark matter filaments and galaxy clusters. The background is a dark, textured surface with numerous small, bright yellow and orange points representing galaxies. The filaments are thin, dark lines that connect the clusters, forming a web-like structure. The overall color palette is dark, with shades of black, grey, and brown, punctuated by the bright colors of the galaxies.

Who know nothing about Dark Matter?

Dark Matter, Why?

4

Evidence of a missing mass at different scale of the Universe



CMB, Planck

20-60 kpc

2-10 Mpc

4 Gpc

arXiv:2406.01705

Dark Matter

~500 pages!!!

I will obviously not cover everything

Marco Cirelli

*Laboratoire de Physique Théorique et Hautes Énergies (LPTHE),
CNRS & Sorbonne Université, 4 Place Jussieu, Paris, France*

Alessandro Strumia

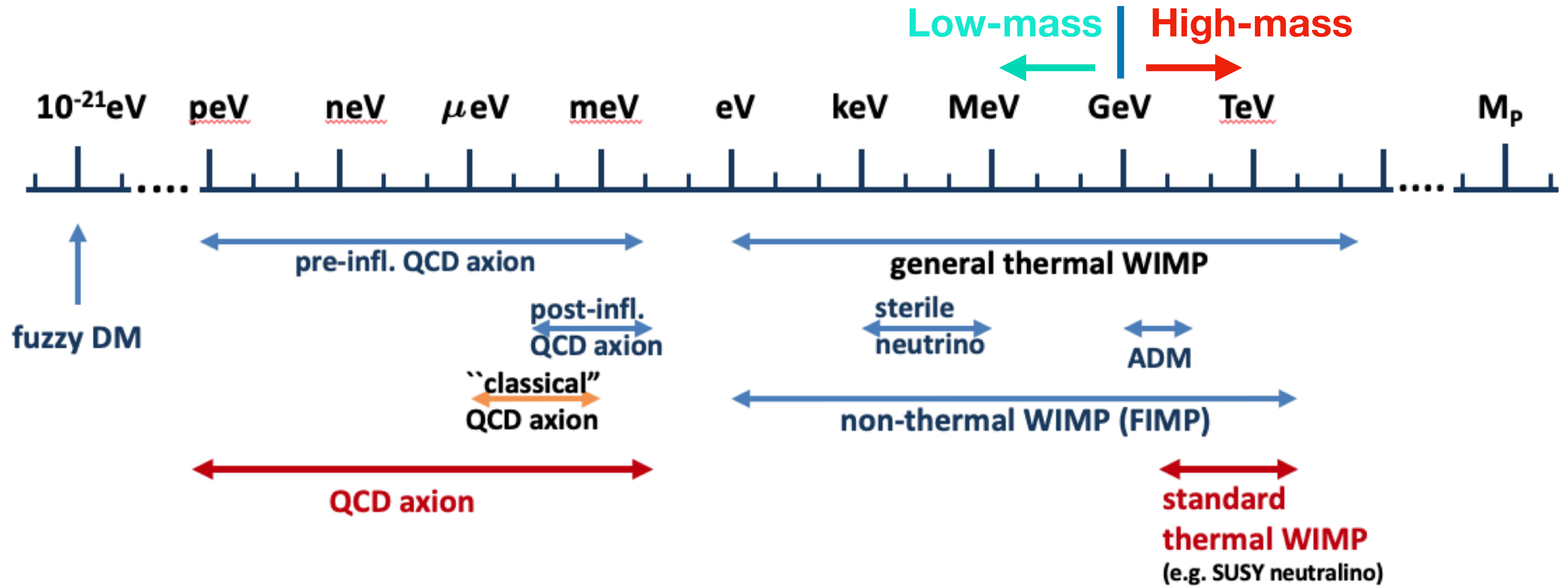
Dipartimento di Fisica dell'Università di Pisa, Italia

Jure Zupan

Department of Physics, University of Cincinnati, Cincinnati, Ohio 45221, USA

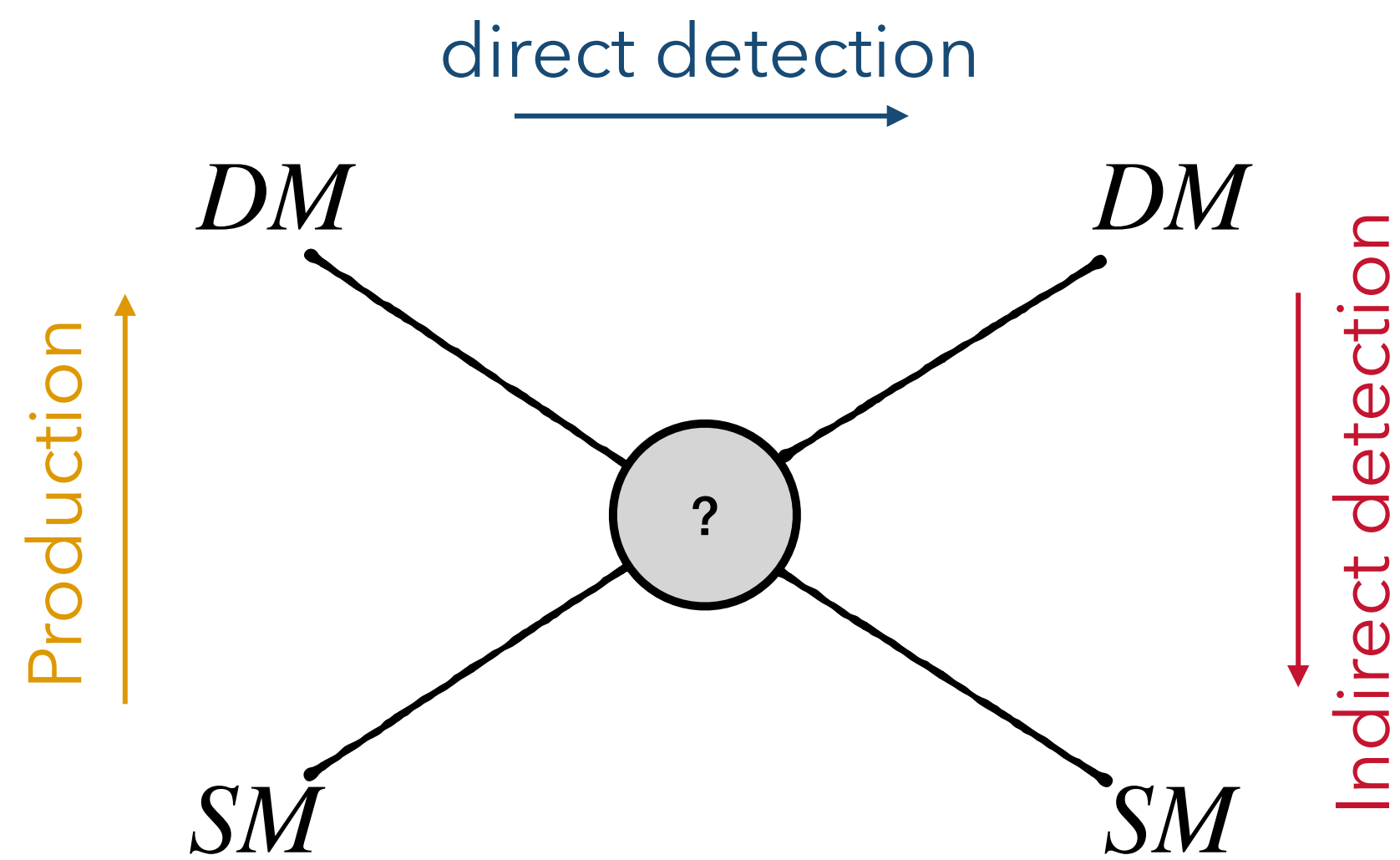
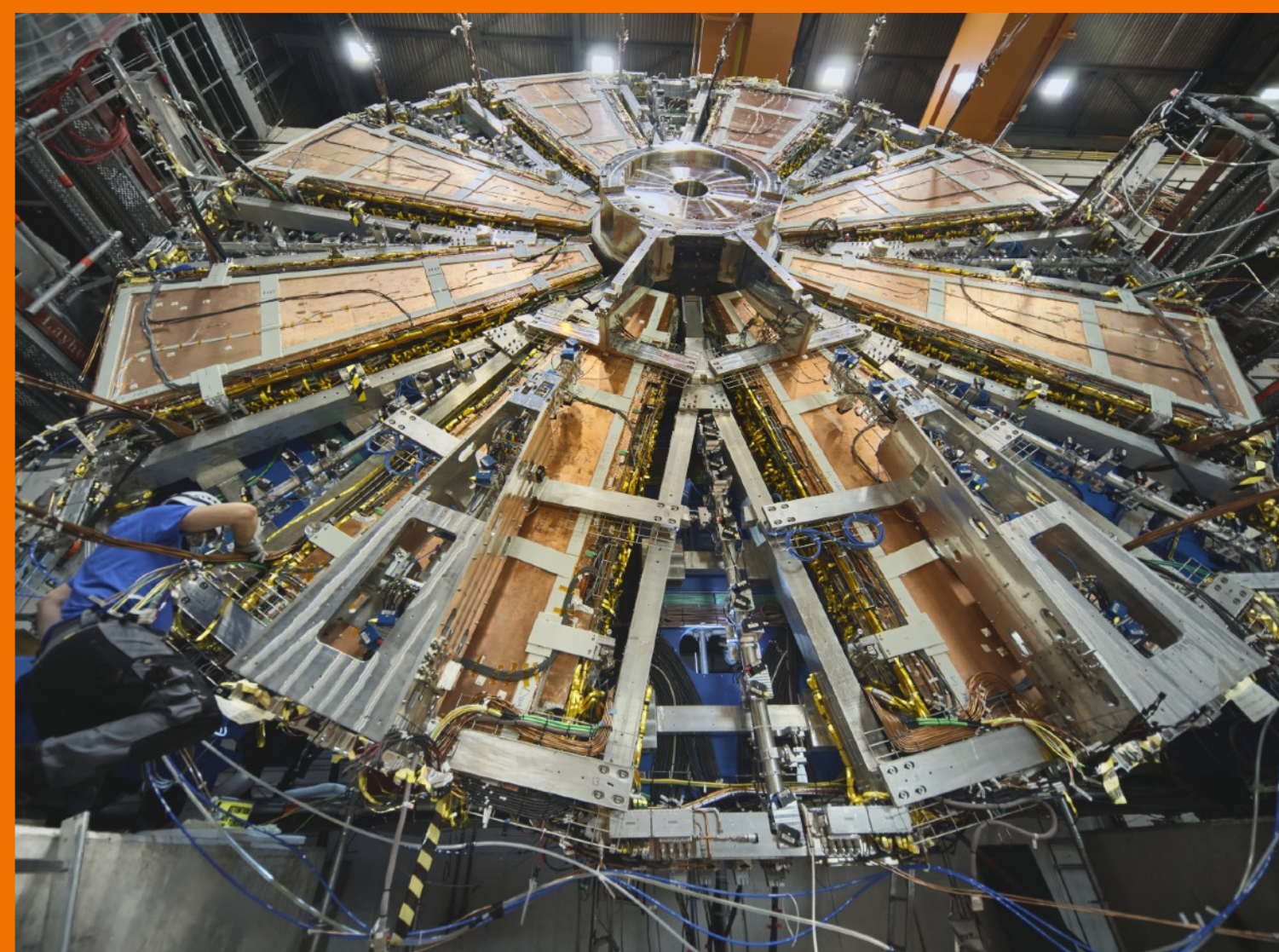
Abstract

We review observational, experimental and theoretical results related to Dark Matter.



How to explore the (very very large) Dark Matter realm?

Will Focus on WIMPs searches



Lecture 1 - Dark Matter Direct Detection part 1

Direct Detection Principle

Low-background Experiments

Experimental Landscape

Lecture 2 - Dark Matter Direct Detection part 2

Case Example: XENONnT

Application to Neutrino Physics

Lecture 3 - Dark Matter Production

Dark Matter Indirect Detection

1

Direct Detection Principle

Main strategy used to search for Dark Matter Direct Detection

2

Low-background Experiments

Main Requirements/Characteristics required to search for DM Direct Detection
Detection Technology

3

Experimental Landscape

Overview of the current experimental Landscape for Dark Matter Direct Detection

The background of the slide is a detailed visualization of the cosmic web, showing a complex network of dark matter filaments and galaxy clusters. Numerous bright, yellowish-white points of light, representing galaxies, are scattered throughout the dark, textured fabric of the universe.

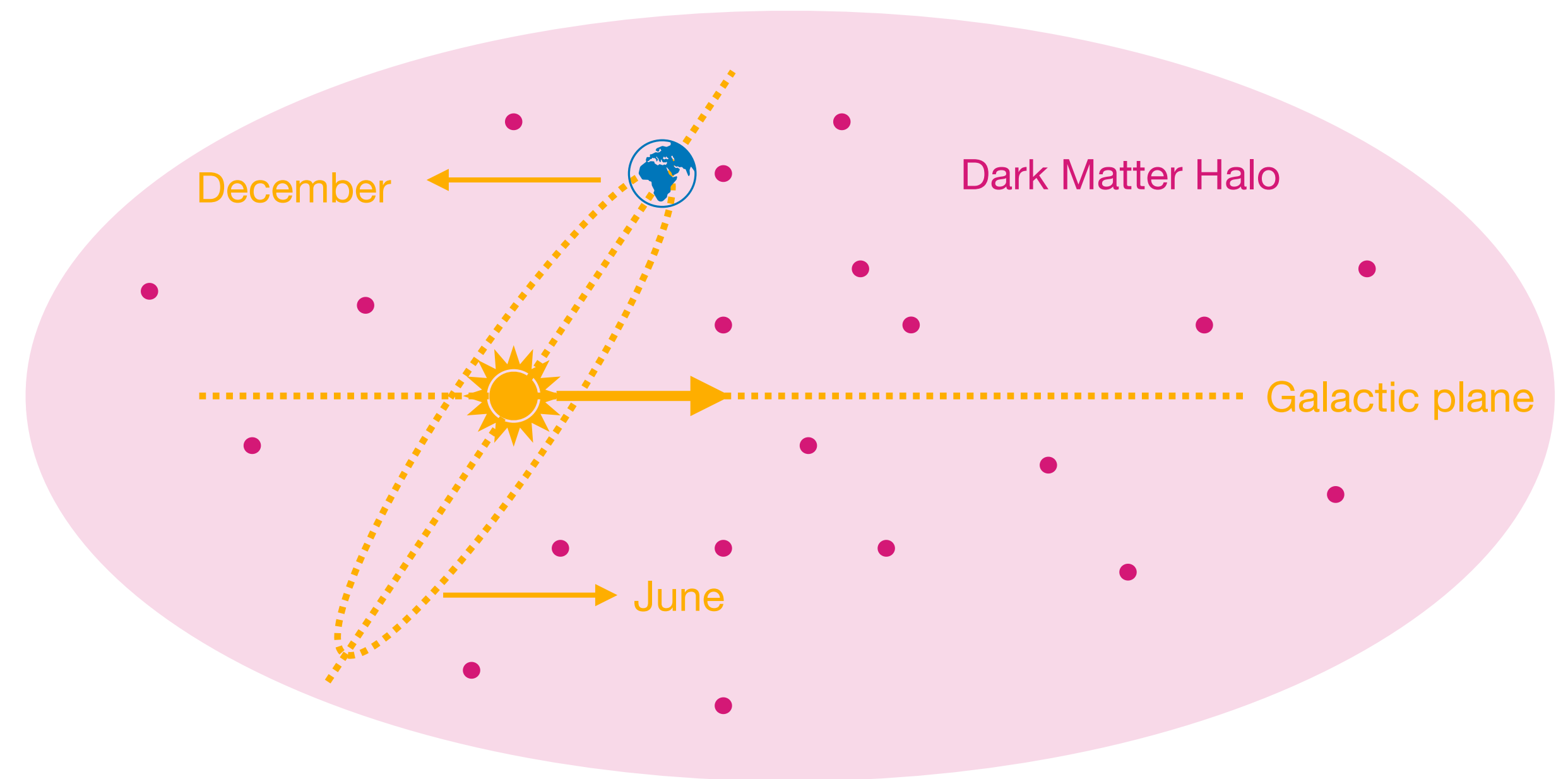
Direct Detection Principle

Direct Detection Principle

11

Dark Matter in the Milky Way:

- ✦ Ground based experiment looks for scatter of galactic DM particles with target material.
 - ▶ Sun rotation around galactic center
 - ▶ Earth going through DM Halo
 - ▶ Dark Matter “Wind”



1 minute discussion:

Do you know what are the main properties of DM we can infer from astronomical observations?

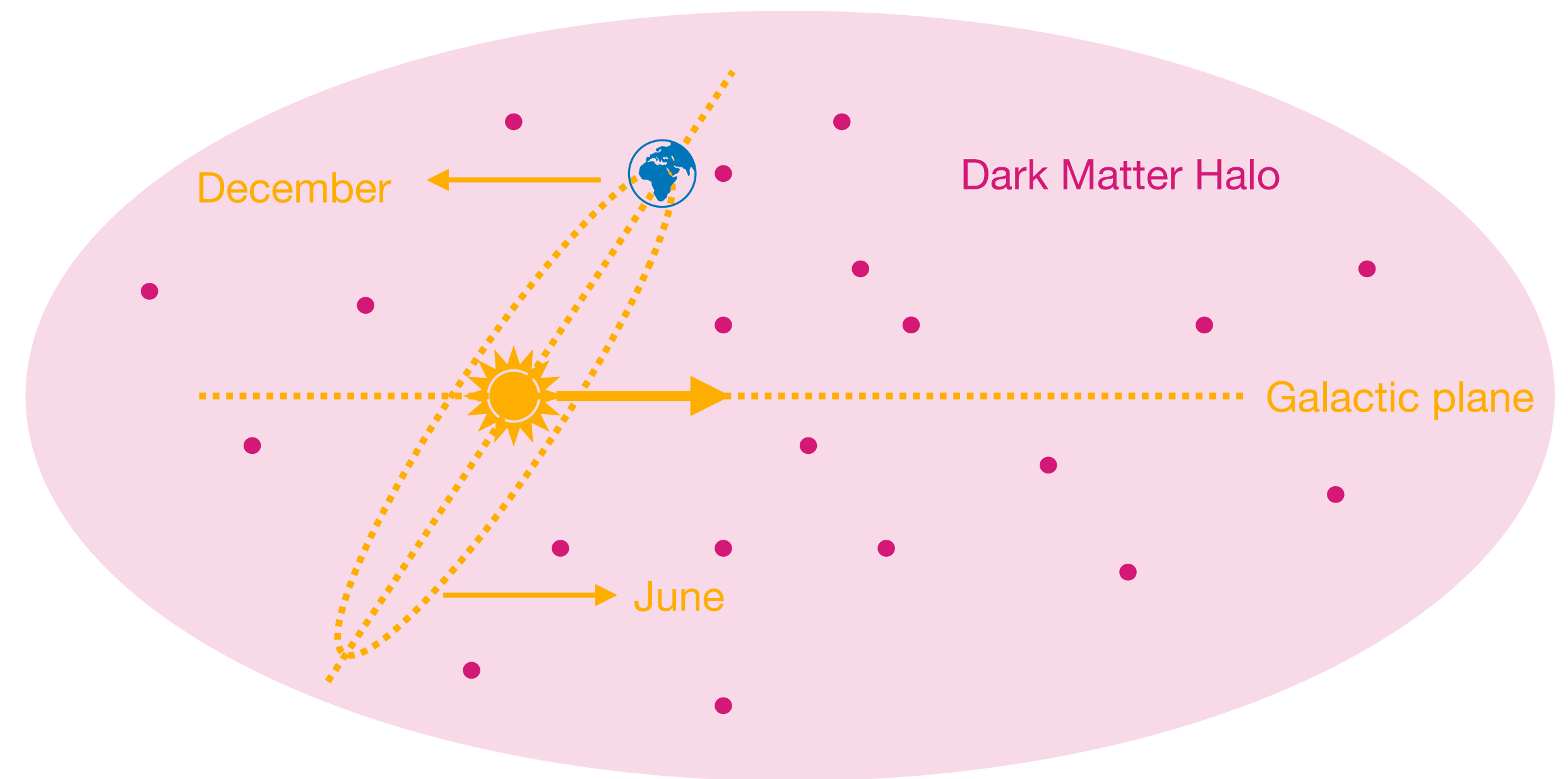
Direct Detection Principle

12

Dark Matter in the Milky Way:

- ✦ Ground based experiment looks for scatter of galactic DM particles with target material.
 - ▶ Sun rotation around galactic center
 - ▶ Earth going through DM Halo
 - ▶ Dark Matter “Wind”

Learn more about it during
Felix Kahlhoefer Lecture



1 minute discussion:

Do you know what are the main properties of DM we can infer from astronomical observations?

Stable (long-lived)

Cold/large mass mass compared to SM particles

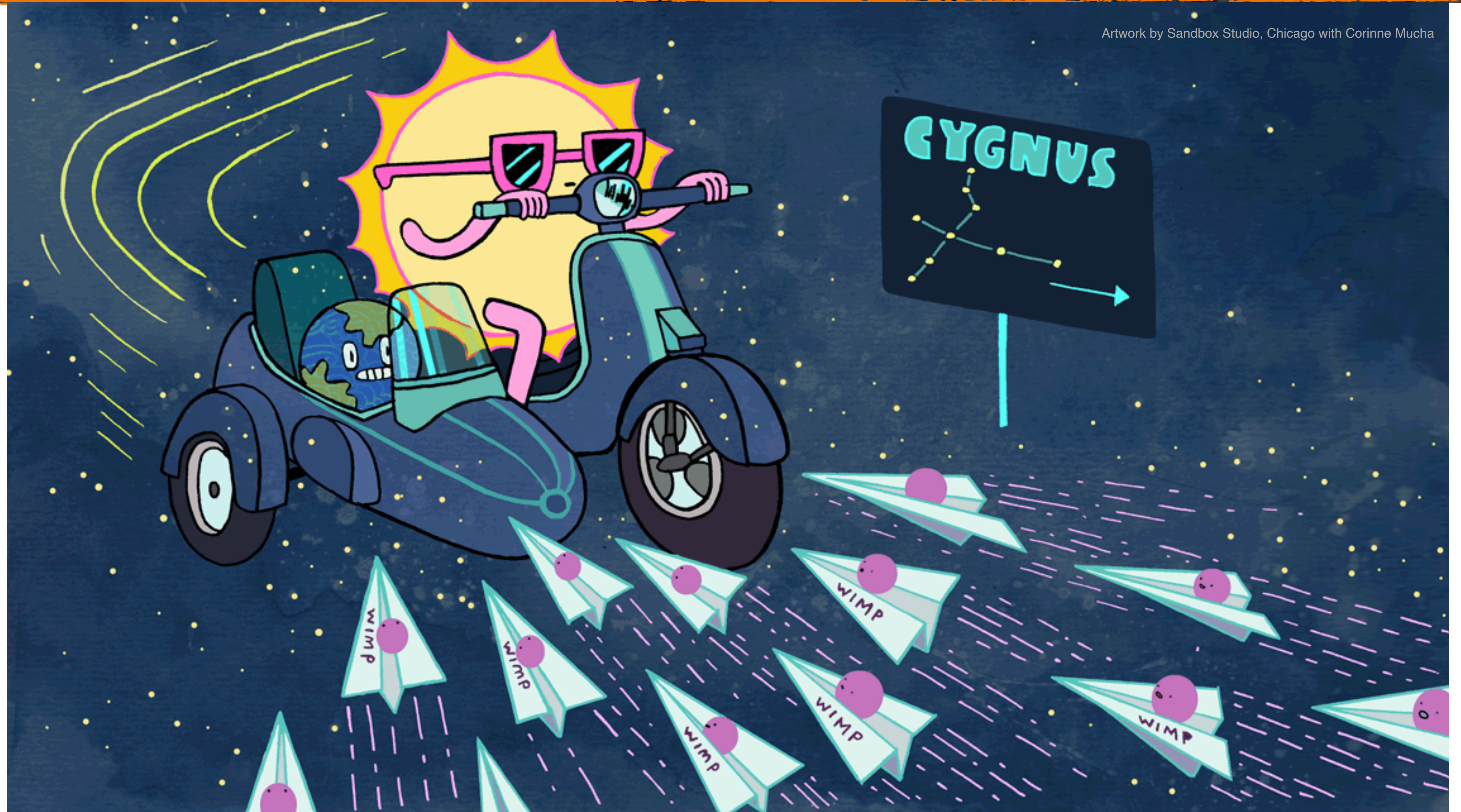
$\Omega = 0.26$

Invisible (no charge)

Weakly Interacting with SM and itself

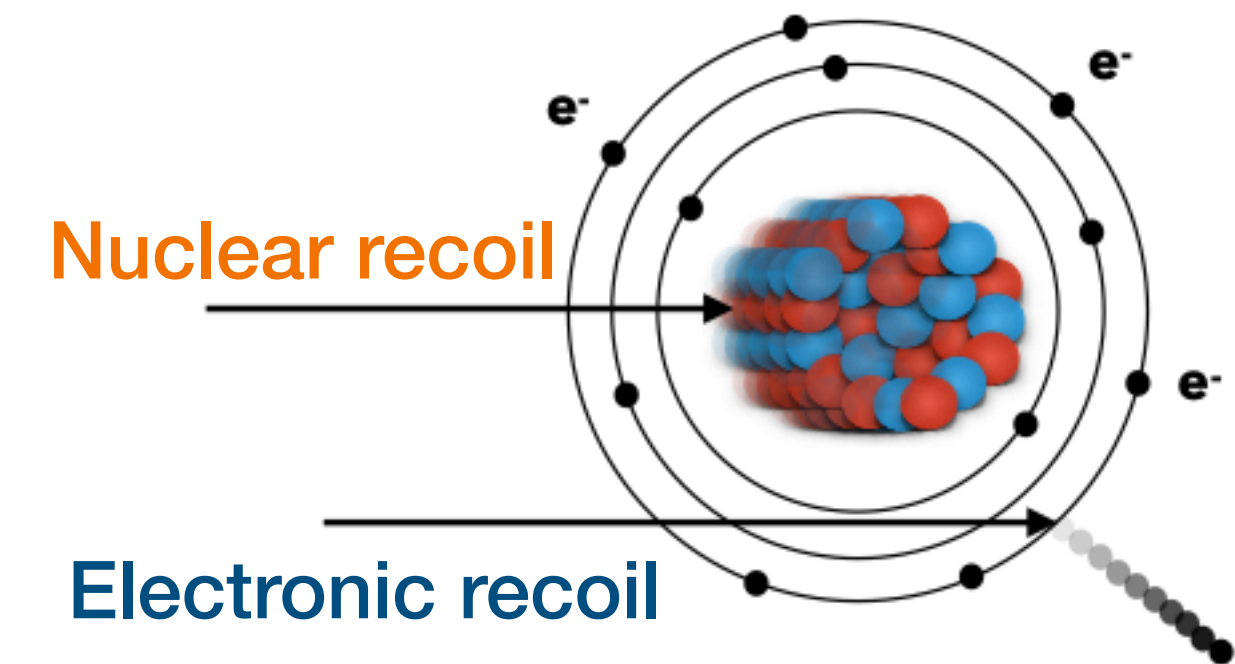
Massive

Dark Matter - Direct Detection Principle 13

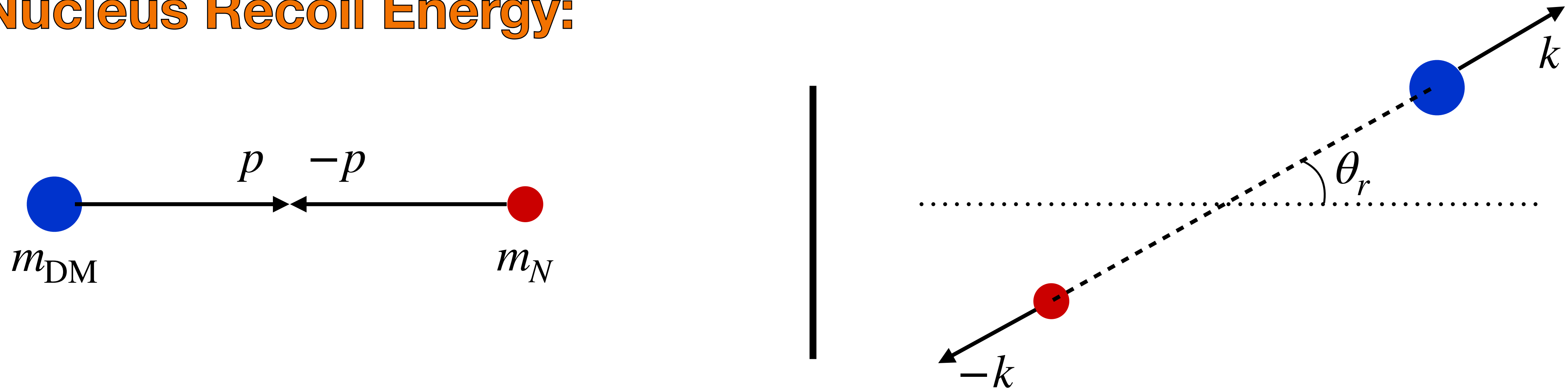


Dark Matter Signature:

- ✱ Try to measure the interaction of a DM particle in the form of:
 - ▶ Scattering on Nucleus
 - ▶ Scattering on Electron
 - ▶ Others (Absorption, Inelastic,...)



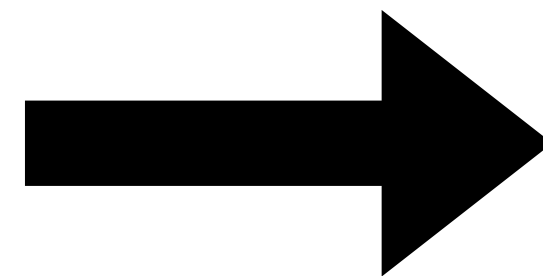
DM-Nucleus Recoil Energy:



- ✦ Use energy and momentum conservation with non-relativistic DM in center of mass frame:

Momentum: $\vec{p} = \mu \vec{v}$

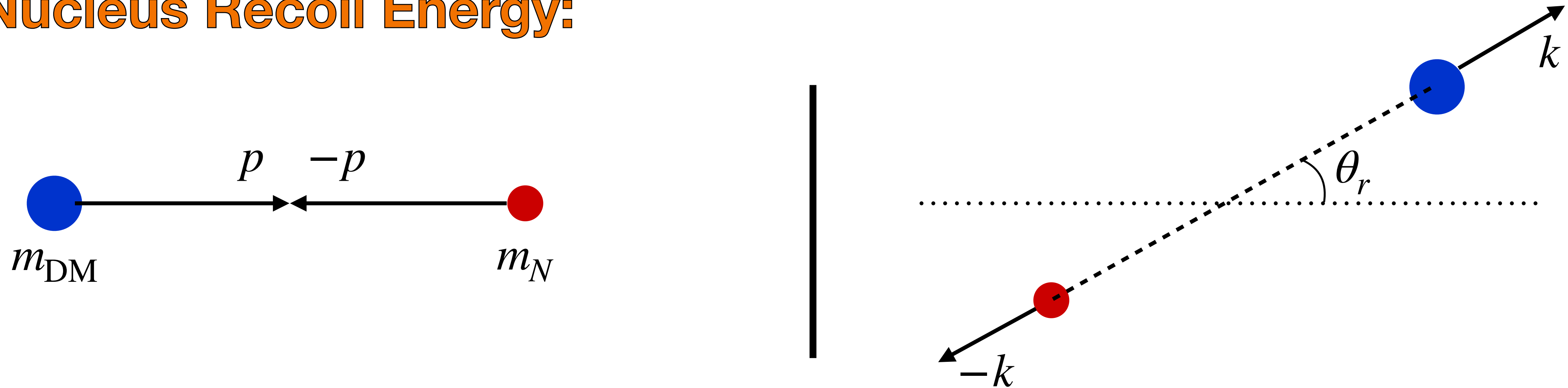
With reduced mass: $\mu = \frac{m_{\text{DM}} m_N}{m_{\text{DM}} + m_N}$



Momentum transfer: $\vec{q} = (\vec{k} - \vec{p})$

with: $\vec{q} = \begin{pmatrix} \mu v \cos \theta_r \\ \mu v \sin \theta_r \end{pmatrix} - \begin{pmatrix} \mu v \\ 0 \end{pmatrix}$

DM-Nucleus Recoil Energy:



- Use energy and momentum conservation with non-relativistic DM in center of mass frame:

Momentum transfer: $\vec{q} = (\vec{k} - \vec{p})$

with: $\vec{q} = \begin{pmatrix} \mu v \cos \theta_r \\ \mu v \sin \theta_r \end{pmatrix} - \begin{pmatrix} \mu v \\ 0 \end{pmatrix}$

Recoil energy: $E_r = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N} (1 - \cos \theta_r)$

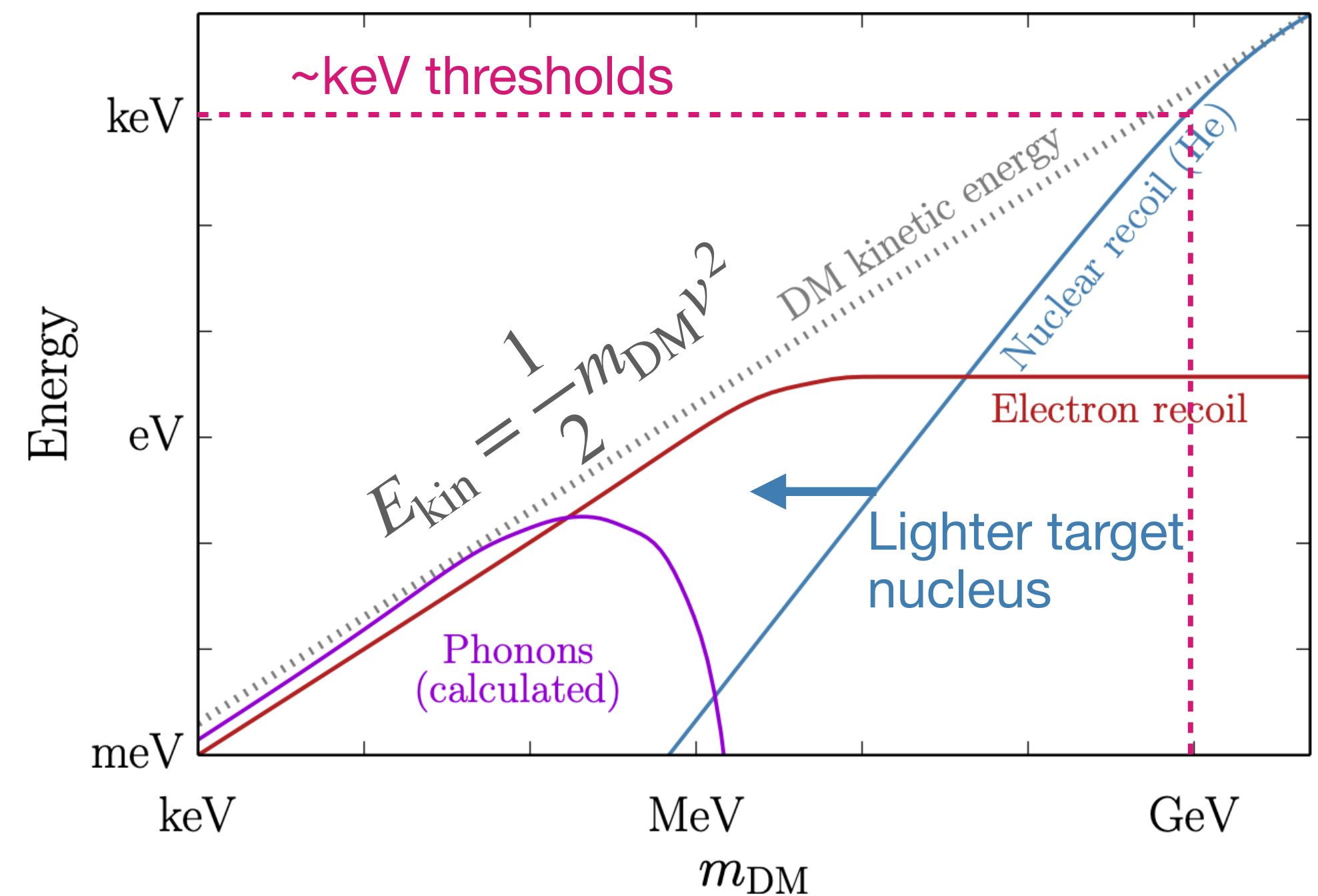
*Trigonometric transformations

$E_r = E_{\text{kin}} \frac{4m_{\text{DM}} \cdot m_N}{(m_{\text{DM}} + m_N)^2} \cos^2 \theta_r$

DM-Nucleus Recoil Energy:

- From energy and momentum conservation with non-relativistic DM:

$$E_r = E_{\text{kin}} \frac{4m_{\text{DM}} \cdot m_N}{(m_{\text{DM}} + m_N)^2} \cos^2 \theta_r$$



Recoil Rate:

- ✱ Expected event rate of WIMP-Nucleus scattering in a detector

$$\frac{dR}{dE_R} = \text{Number density of DM} \\ \times \text{Flux} \\ \times \text{Number of target nuclei} \\ \times \text{Differential cross-section}$$

Recoil Rate:

- ✦ Expected event rate of WIMP-Nucleus scattering in a detector
- ✦ Parameters that can impact the recoil rate expected in your experiment

► Astrophysics

► Detector physics

► Particle physics

► Nuclear physics

$$\frac{dR}{dE_R} = \text{Number density of DM} \times \text{Flux} \times \text{Number of target nuclei} \times \text{Differential cross-section}$$

The diagram illustrates the components of the recoil rate equation $\frac{dR}{dE_R}$. It shows the equation with various terms highlighted in colored circles and labeled with arrows:

- $\frac{dR}{dE_R}$ is labeled "Recoil rate".
- ρ_0 is labeled "WIMP density".
- M_T is labeled "Target mass".
- m_N is labeled "Nucleus mass".
- m_χ is labeled "WIMP mass".
- The integral $\int_{v_{\min}}^{v_{\text{esc}}} dv f(v) v$ is labeled "WIMP velocity distribution".
- The differential cross-section $\frac{d\sigma_{\chi-N}}{dE_r}$ is labeled "Interaction cross section".

The equation is written as:

$$\frac{dR}{dE_R} = \frac{\rho_0 M_T}{m_N m_\chi} \int_{v_{\min}}^{v_{\text{esc}}} dv f(v) v \frac{d\sigma_{\chi-N}}{dE_r}$$

Unknown parameter we are looking for

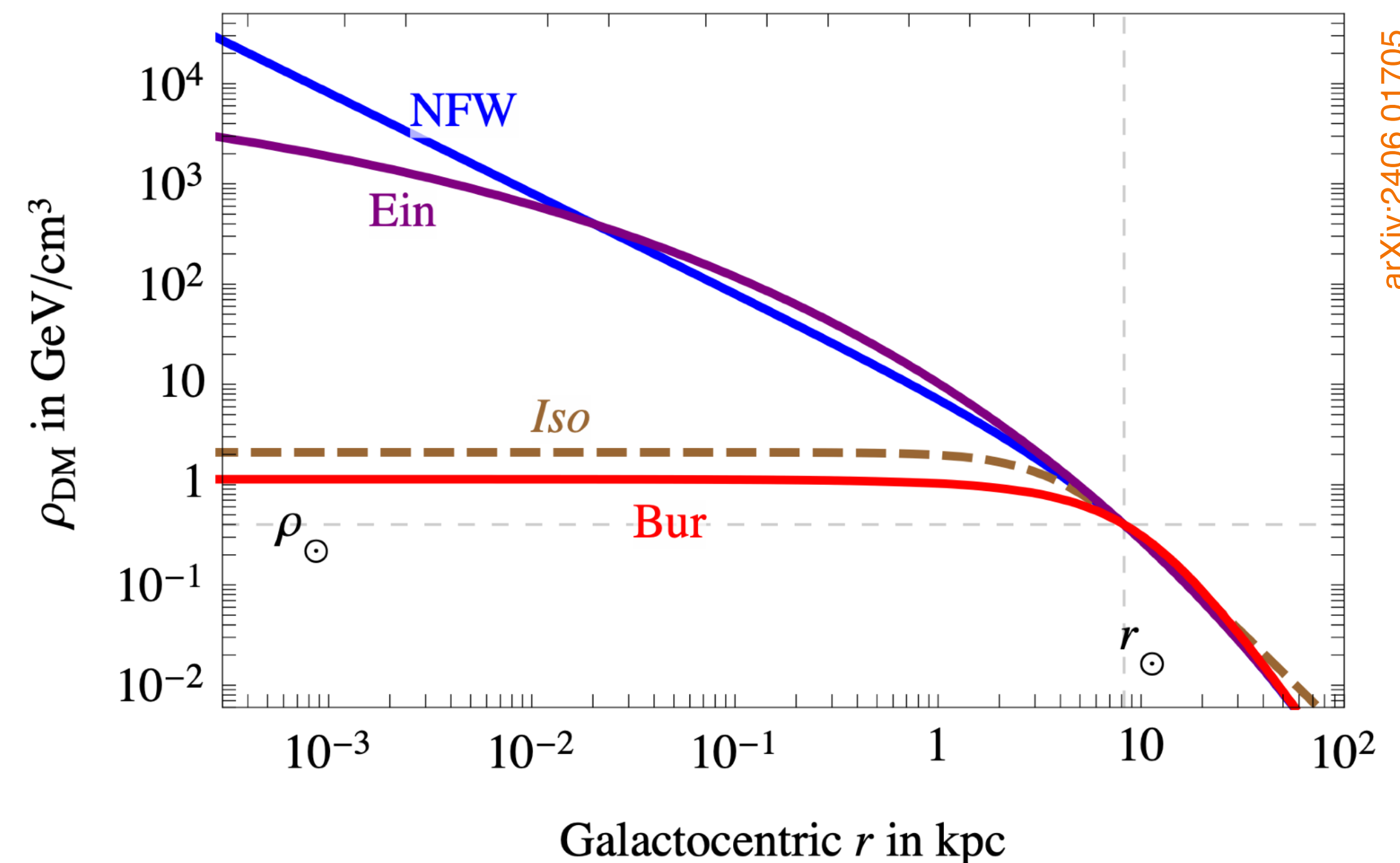
Dark Matter Halo Model:

- Local DM density and velocity distribution plays a major role!

Recent results $\rho_0 = 0.30 - 0.40 \text{ GeV/cm}^3$

Historically $\rho_0 = 0.30 \text{ GeV/cm}^3$

$$\frac{dR}{dE_R} = \frac{\rho_0 M_T}{m_N m_\chi} \int_{v_{\min}}^{v_{\text{esc}}} dv f(v) v \frac{d\sigma_{\chi-N}}{dE_r}$$



Dark Matter Halo Model:

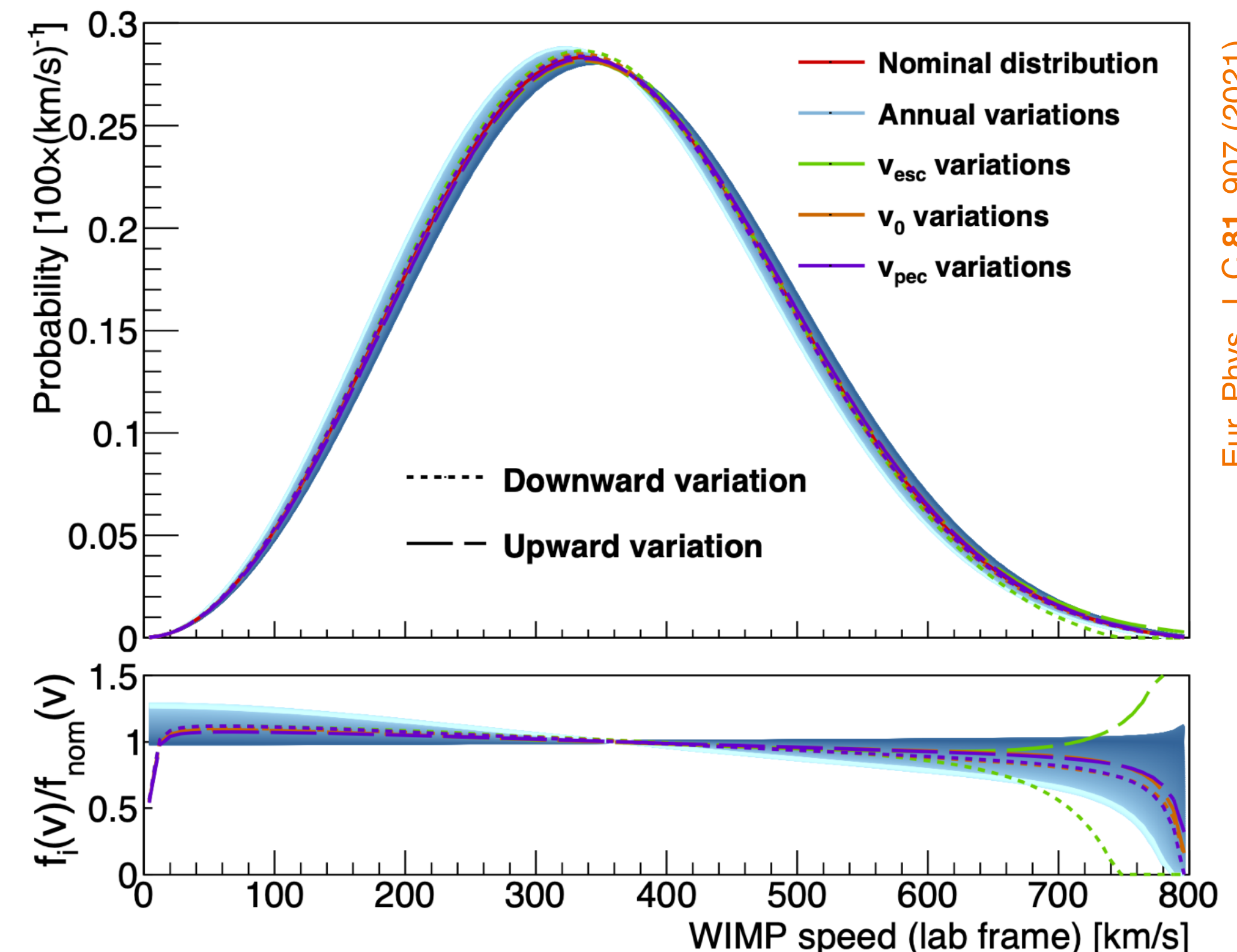
- Local DM density and velocity distribution plays a major role!

Recent results $\rho_0 = 0.30 - 0.40 \text{ GeV/cm}^3$

Historically $\rho_0 = 0.30 \text{ GeV/cm}^3$

- Annual modulation of the WIMP velocity expected
 - DM signature we can look for.

$$\frac{dR}{dE_R} = \frac{\rho_0 M_T}{m_N m_\chi} \int_{v_{\min}}^{v_{\text{esc}}} dv f(v) v \frac{d\sigma_{\chi-N}}{dE_r}$$



Dark Matter Halo Model:

- Local DM density and velocity distribution plays a major role!

Recent results $\rho_0 = 0.30 - 0.40 \text{ GeV/cm}^3$

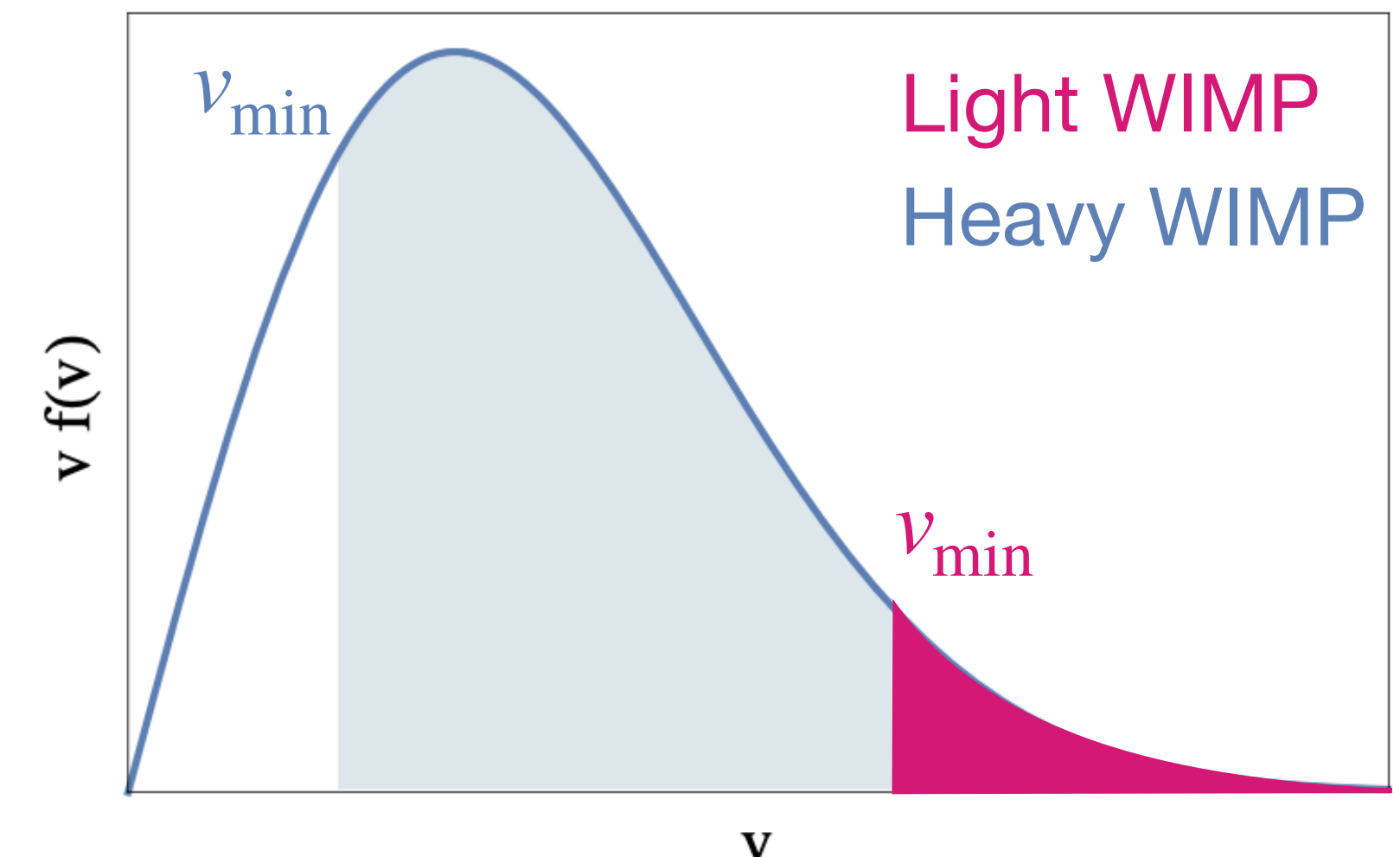
Historically $\rho_0 = 0.30 \text{ GeV/cm}^3$

- Annual modulation of the WIMP velocity expected
 - DM signature we can look for.
- Boundary on DM velocity

$$\frac{dR}{dE_R} = \frac{\rho_0 M_T}{m_N m_\chi} \int_{v_{\min}}^{v_{\text{esc}}} dv f(v) v \frac{d\sigma_{\chi-N}}{dE_r}$$

$$v_{\text{esc}} \approx 544 \pm 35 \text{ km/s}$$

$$v_{\min} = \frac{m_\chi + m_N}{m_\chi} \sqrt{\frac{E_R}{2m_N}}$$



Interaction Cross section:

$$\frac{dR}{dE_R} = \frac{\rho_0 M_T}{m_N m_\chi} \int_{v_{\min}}^{v_{\text{esc}}} dv f(v) v \frac{d\sigma_{\chi-N}}{dE_r}$$

- ✦ Unknown Interaction mechanism
- ✦ Interactions involve nuclear spin, giving Spin-Dependent (SD) scattering, or they do not, giving Spin-Independent (SI)

$$\frac{d\sigma_{\chi-N}}{dE_r} = \frac{m_N}{2v^2 \mu^2} \left[\sigma_0^{\text{SI}} F_{\text{SI}}^2(E_r) + \sigma_0^{\text{SD}} F_{\text{SD}}^2(E_r) \right]$$

Helm form factor

$\propto A^2 \rightarrow$ Coherent enhancement of the cross section

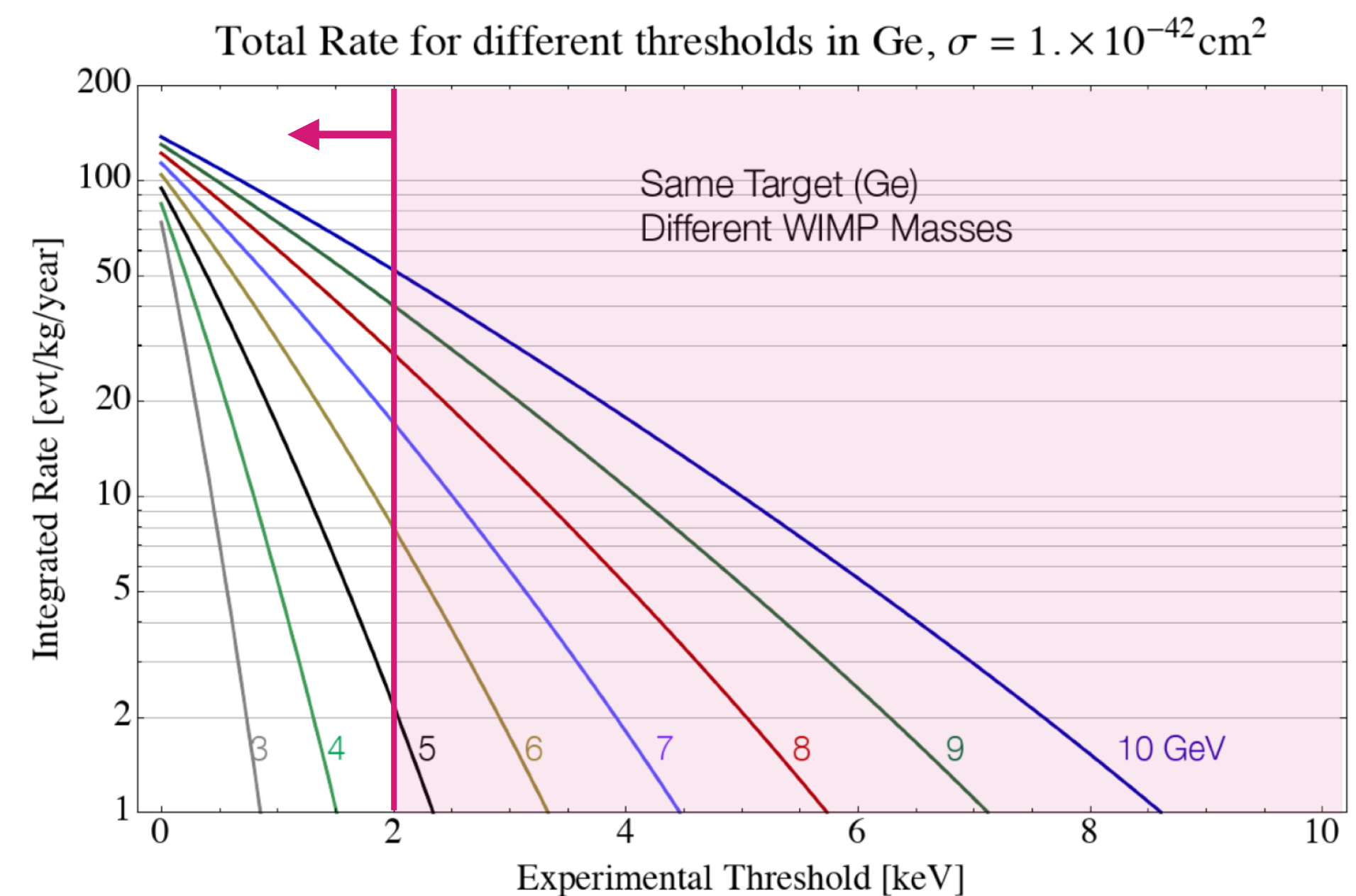
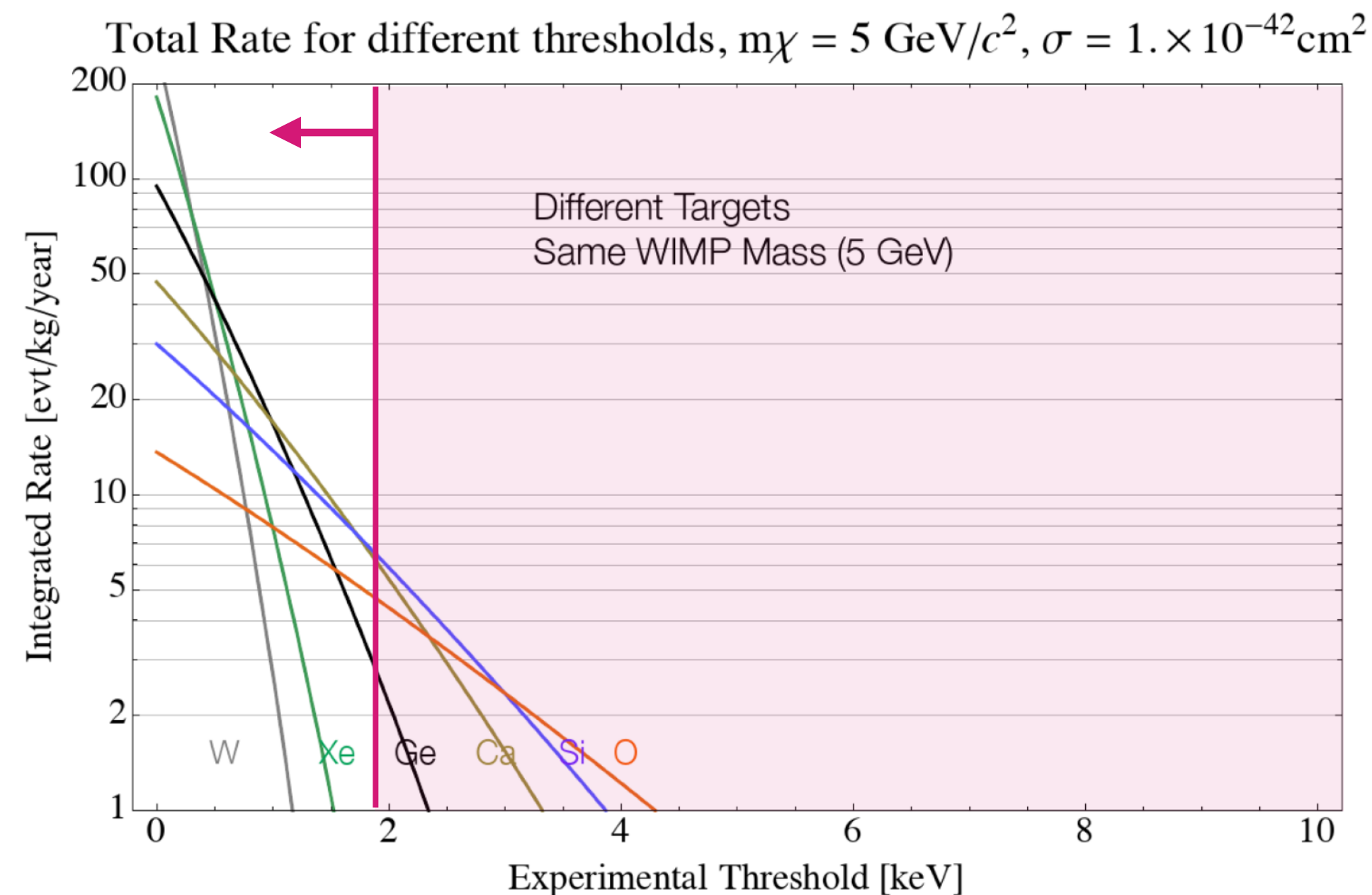
σ_0 : cross section at zero momentum transferred

F: Form factor describing how the WIMP interferes with the nucleon structure of the nucleus

Detector Physics dependencies

- ✦ Target mass scalability
- ✦ Target nucleus mass, A, spin
- ✦ Energy threshold of the detector

$$\frac{dR}{dE_R} = \frac{\rho_0 M_T}{m_N m_\chi} \int_{v_{\min}}^{v_{\text{esc}}} dv f(v) v \frac{d\sigma_{\chi-N}}{dE_r}$$



From energy recoil spectra to expected number of WIMP-N events

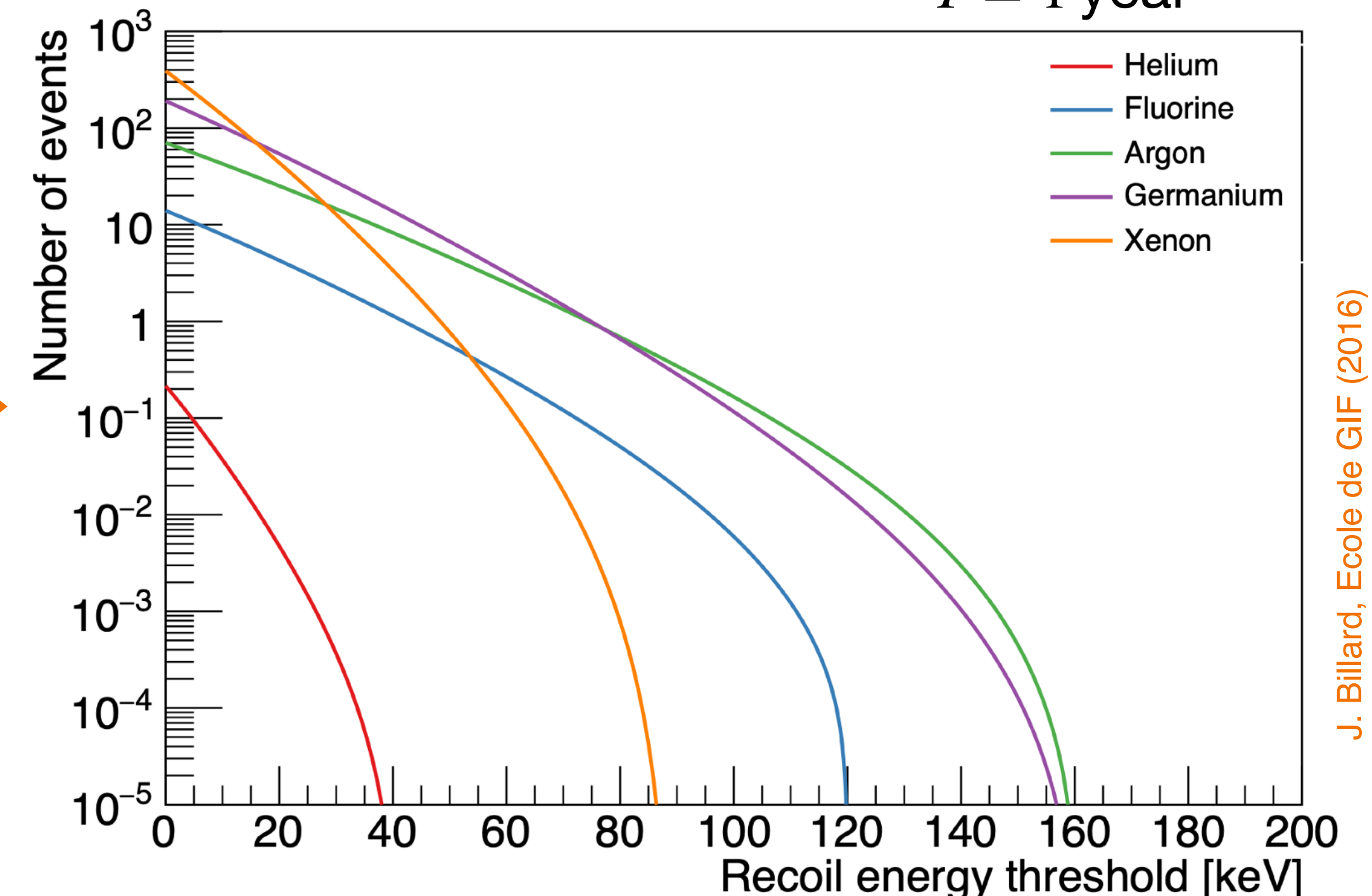
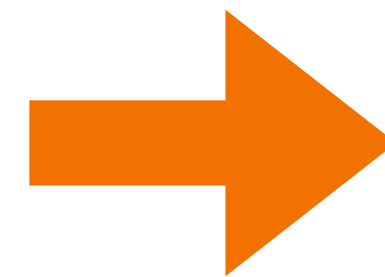
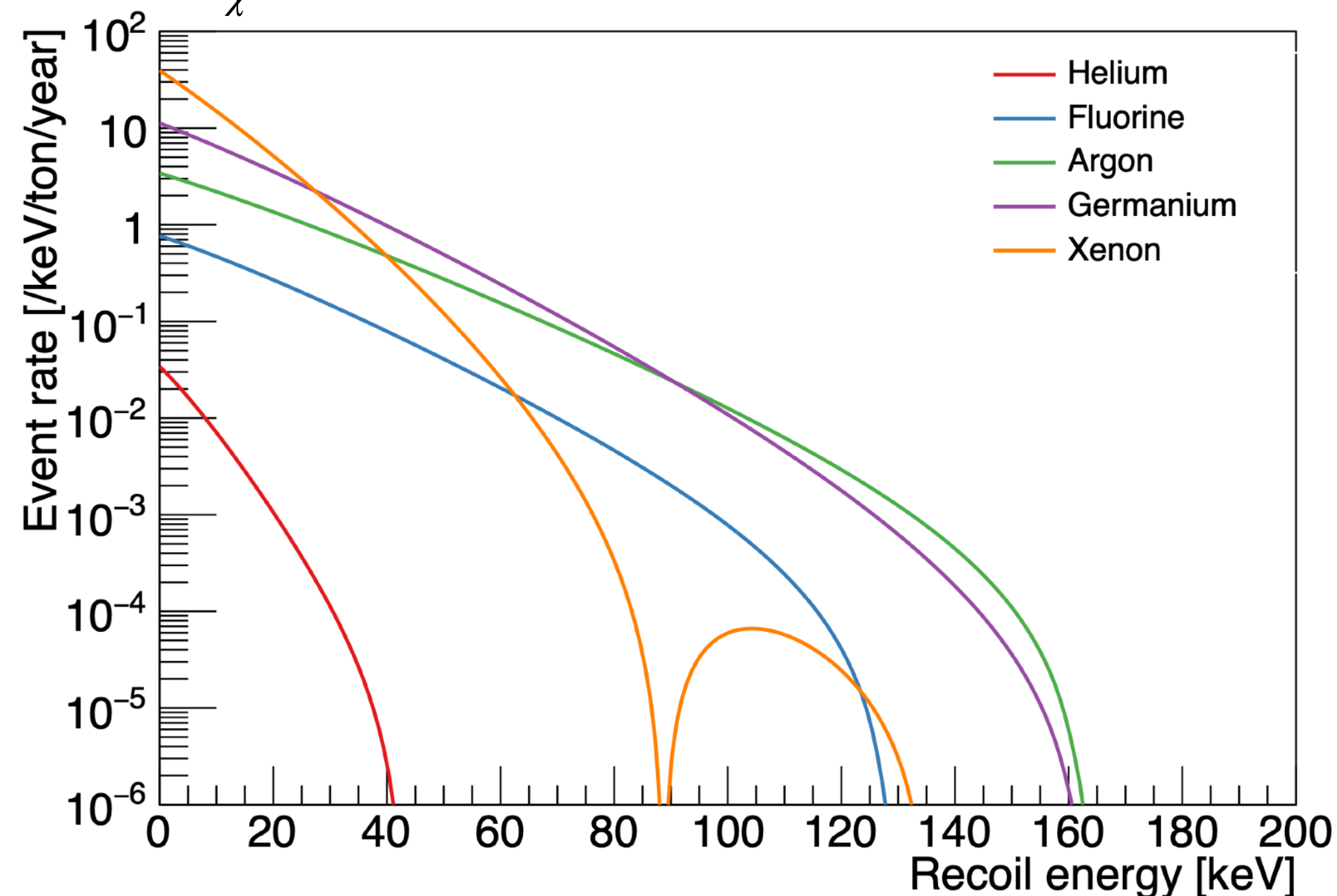
$$\mu_\chi = M_T T \int_{E_{\text{th}}} \frac{dR}{dE_R} \left(\sigma^{SI}, m_\chi \right) dE_R$$

$$\sigma^{SI} = 50 \text{ GeV}$$

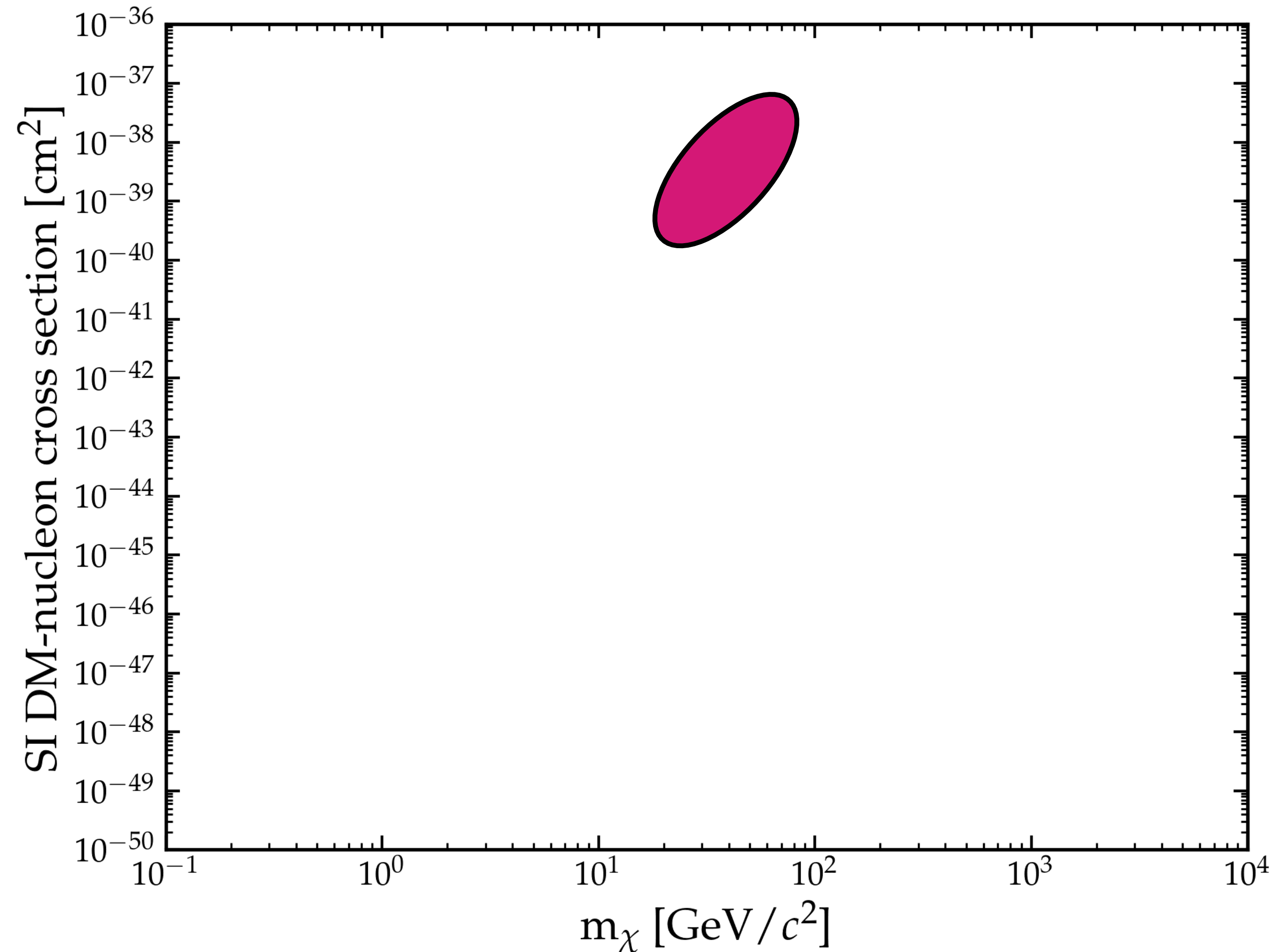
$$m_\chi = 10^{-45} \text{ cm}^2$$

$$M_T = 1 \text{ tonne}$$

$$T = 1 \text{ year}$$



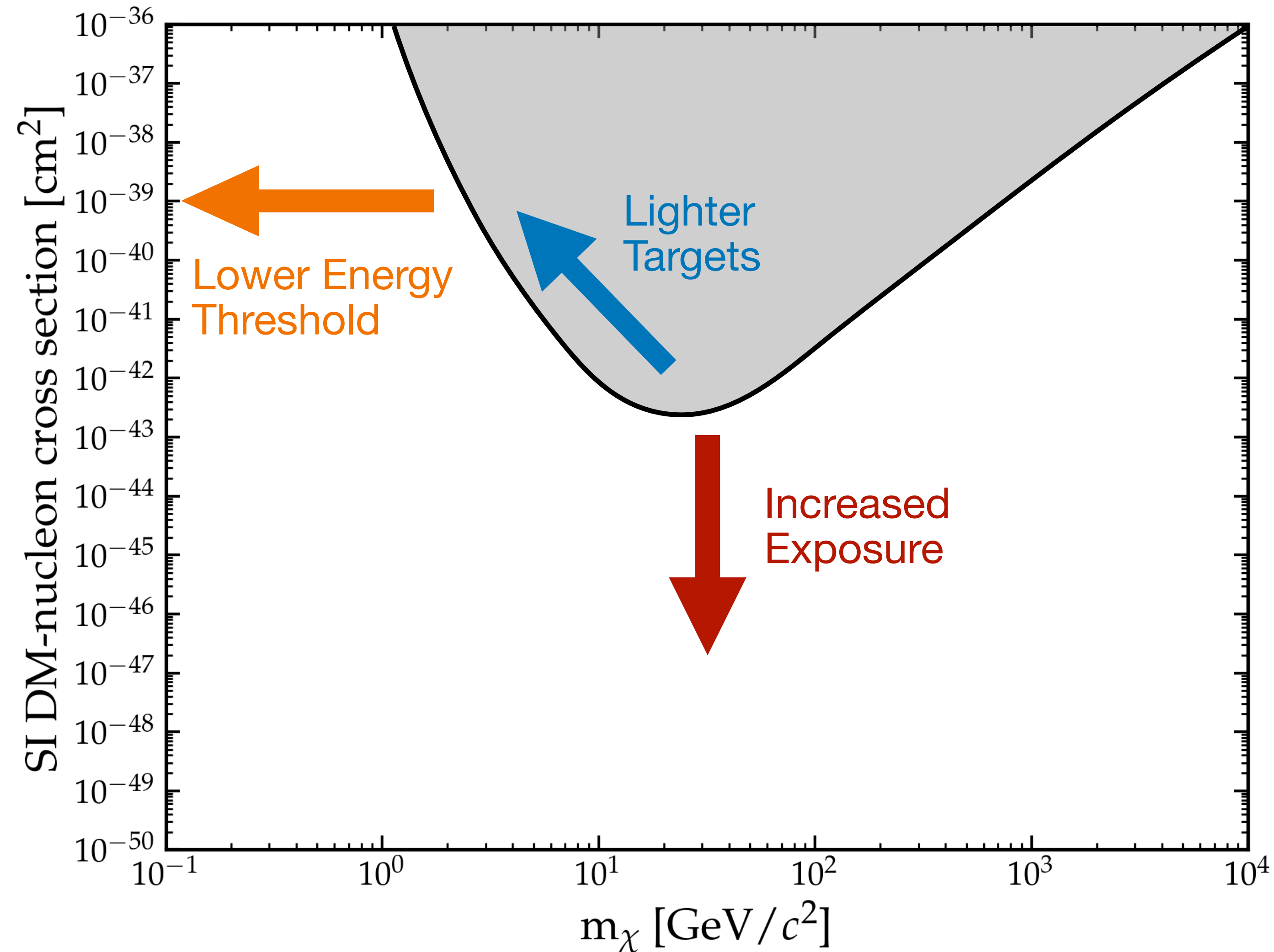
Exclusion/Discovery Plot:



✱ Signal contour

✱ Limit curve (90% C.L.)

Exclusion/Discovery Plot:

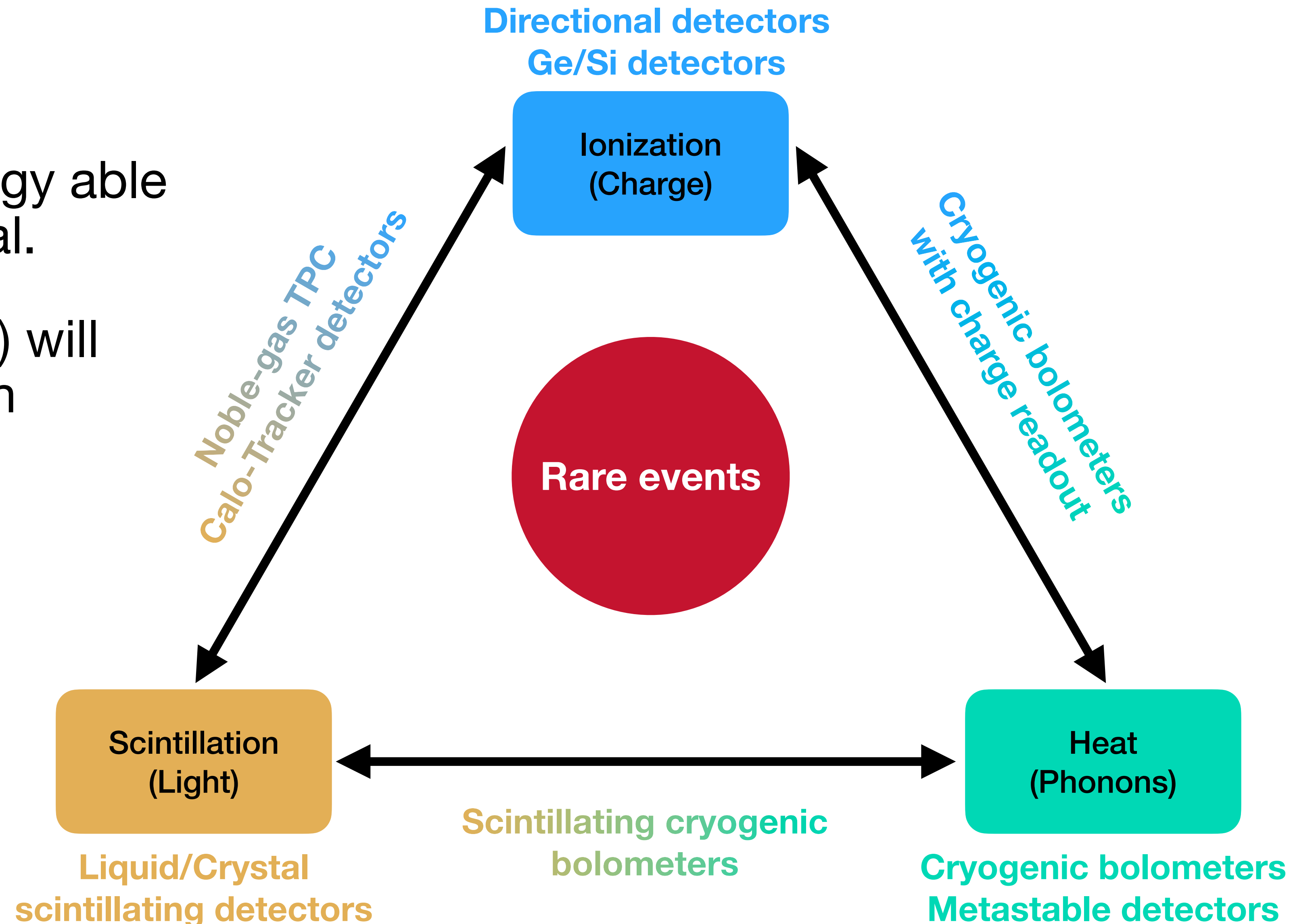


✱ Signal contour

✱ Limit curve (90% C.L.)

What do we measure?

- ✦ Need a detection technology able to identify the sparse signal.
- ✦ Recoiled nucleus (electron) will deposit energy in detection medium via:
 - Charge
 - Heat
 - Light



When a (DM) particle scatters off a target nucleus (or electron), the recoiling particle deposits energy in the detection medium via three channels:



Scintillation

(Light)

Photons emitted by de-excitation of target atoms. Detect by PMTs or SiPMs.



Ionization

(Charge)

e-ion pairs created by ionising interactions. Collected by electrodes under E_{field} or in CCDs.

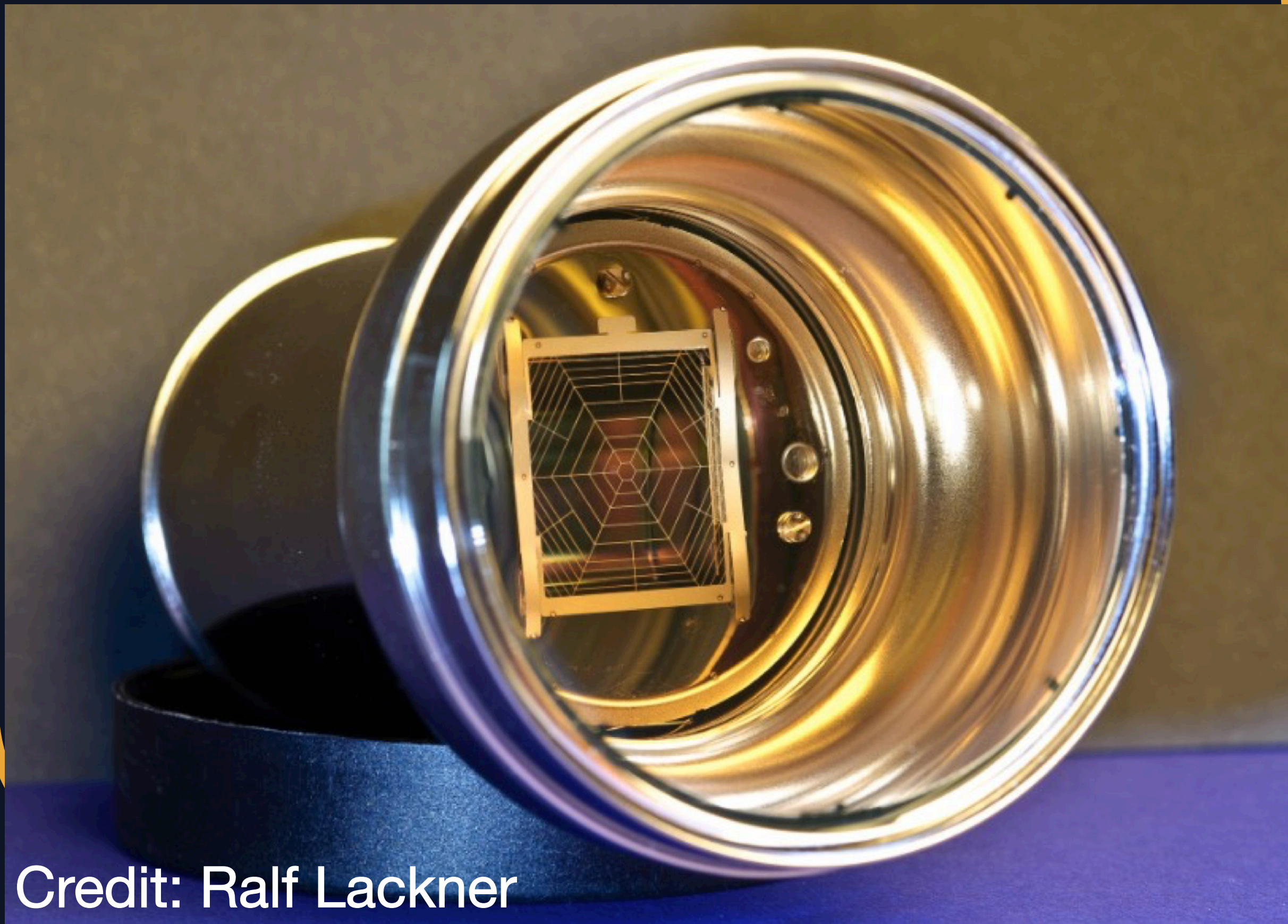


Phonons

(Heat)

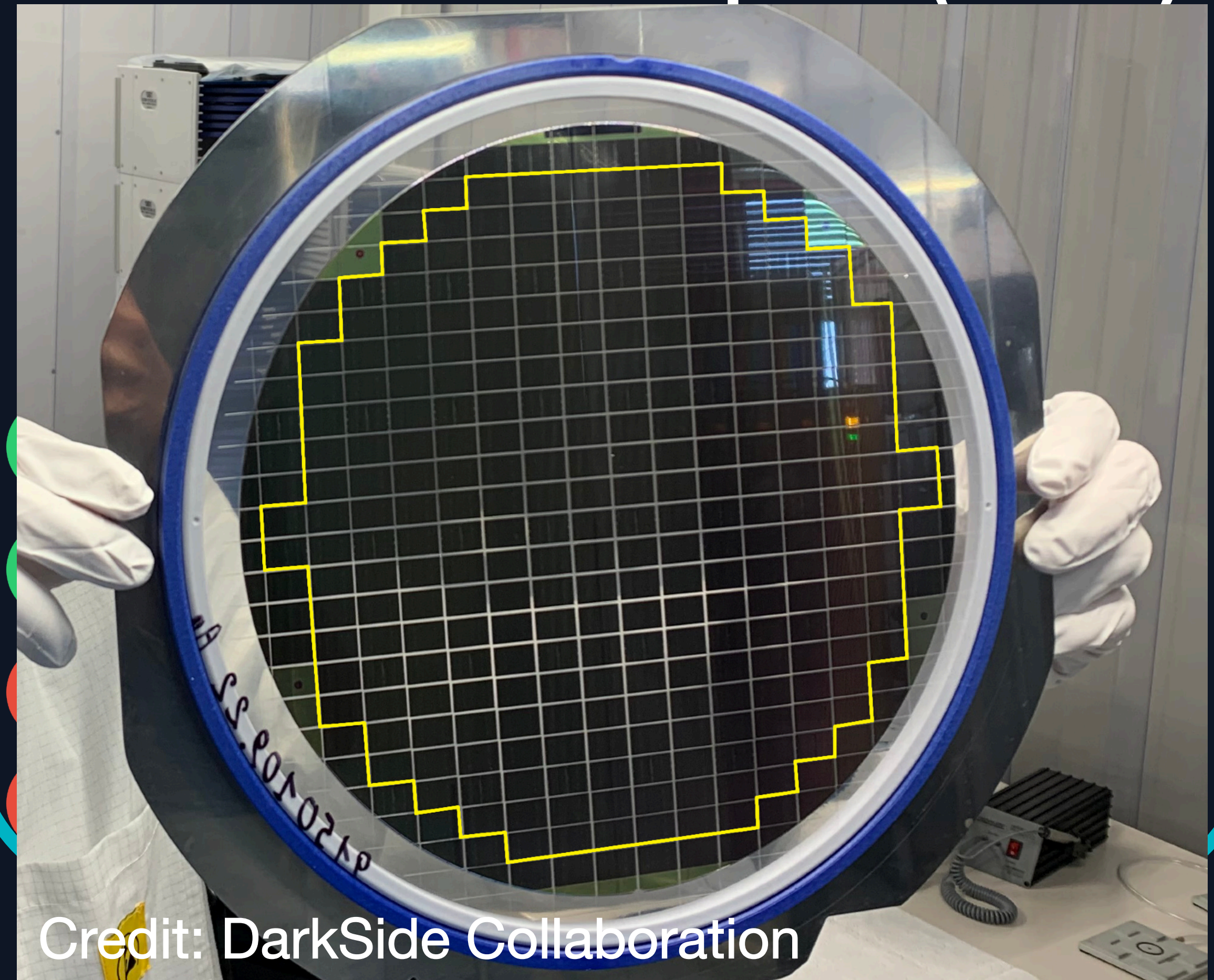
“Vibrations” from energy deposition. Measured by transition-edge sensors or NTDs at mK temperatures.

Photomultiplier Tubes (PMTs)



Credit: Ralf Lackner

Silicon Photomultipliers (SiPMs)



Credit: DarkSide Collaboration

Used in: XENONnT, LZ, PandaX (PMTs) — DarkSide-20k (SiPMs) — DEAP-3600, DAMA/LIBRA (PMTs)

Photomultiplier Tubes (PMTs)

Photons hit a photocathode, ejecting electrons via photoelectric effect. Electrons are multiplied through a dynode chain (gain $\sim 10^6 - 10^7$), producing a measurable current pulse

- ✓ High gain, single-photon sensitivity
- ✓ Large active area, mature technology
- ✗ Radioactive impurities (glass body)
- ✗ Bulky; limited QE at specific wavelengths

Silicon Photomultipliers (SiPMs)

Array of micro-avalanche photodiode (APD) operated in Geiger mode above breakdown voltage. Provide analog photon-counting.

- ✓ Very low radioactivity
- ✓ Compact, low voltage
- ✗ Dark count rate (thermal noise)
- ✗ After-pulsing and cross-talk between cells

Used in: XENONnT, LZ, PandaX (PMTs) — DarkSide-20k (SiPMs) — DEAP-3600, DAMA/LIBRA (PMTs)

Direct Charge collection

Drifted electrons are collected directly on electrodes or pixel arrays, and the induced current is measured. Used in semiconductor detectors (Ge, Si, CCDs), bolometers, single-phase TPCs.

- ✓ Fine segmentation gives spatial resolution and tracking
- ✓ Can reach single-electron sensitivity
- ✗ Electronic noise limits threshold in large detectors
- ✗ No intrinsic amplification

Electroluminescence

Drifted electrons are extracted from liquid in a thin gas layer, where a strong E_{field} accelerates them and induces proportional scintillations photons production, that can be measured by light sensors.

- ✓ High gain ($\sim 100 - 1000$ photons/e-)
- ✓ Hit pattern gives position information
- ✗ Require stable liquid-gas Interface and HV delivery/control
- ✗ Sensitive to impurities

Direct collection: EDELWEISS, SuperCDMS, DAMIC-M, SENSEI — Electroluminescence: XENONnT, LZ, PandaX-4T (dual-phase TPCs)

Transition Edge Sensors (TES)

Superconducting thin films (e.g. W) poised at a knife-edge transition. A tiny heat pulse can make the metal lose its superconducting properties and thus a resistance jump.

- ✓ Extremely low threshold ($\sim 10\text{--}100$ eV)
- ✓ High energy resolution, phonon pulse shape info
- ✗ Operates at mK

Neutron Transmutation Doped (NTD) Thermistors

Temperature-sensitive resistors, glued to a detector crystal. Made of Ge (or other) doped to make their electrical resistance drop sharply as temperature rises.

- ✓ Simple fabrication, robust and reproducible
- ✓ Flexible absorber choice (Ge, CaWO_4 ,)
- ✗ Slower response than TES ($\sim \text{ms}$ vs $\sim \mu\text{s}$)
- ✗ Operated at mK

The background of the slide is a detailed visualization of the cosmic web, showing a complex network of dark matter filaments and galaxy clusters. Numerous bright, yellowish-white points of light, representing galaxies, are scattered throughout the dark, textured space. The overall tone is dark and scientific.

Low-Background Experiments

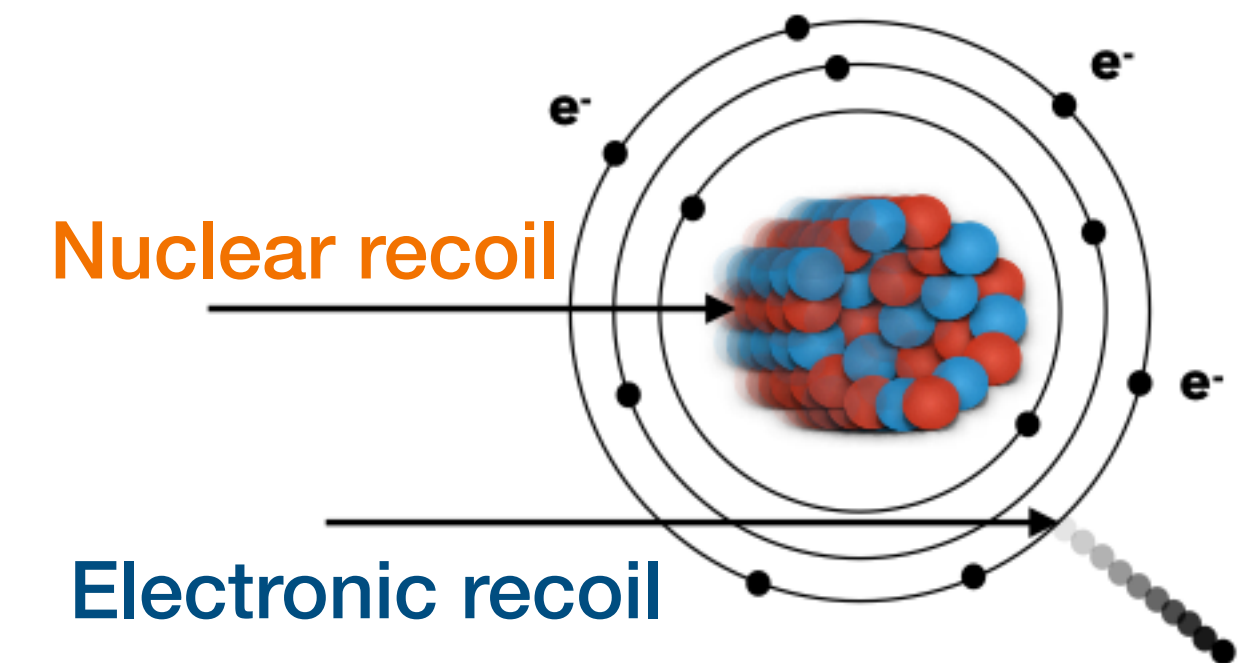
Searching for a sparse signal

- ✦ **Background** mitigation strategy
- ✦ Discrimination power (signal/background)
- ✦ Large exposure
- ✦ Low energy threshold (low-WIMP mass)

**Unwanted physical process,
mimicking the signature of your signal**

Signal of Interest:

- ✦ WIMP scattering-off a target nuclei (Nuclear Recoil)



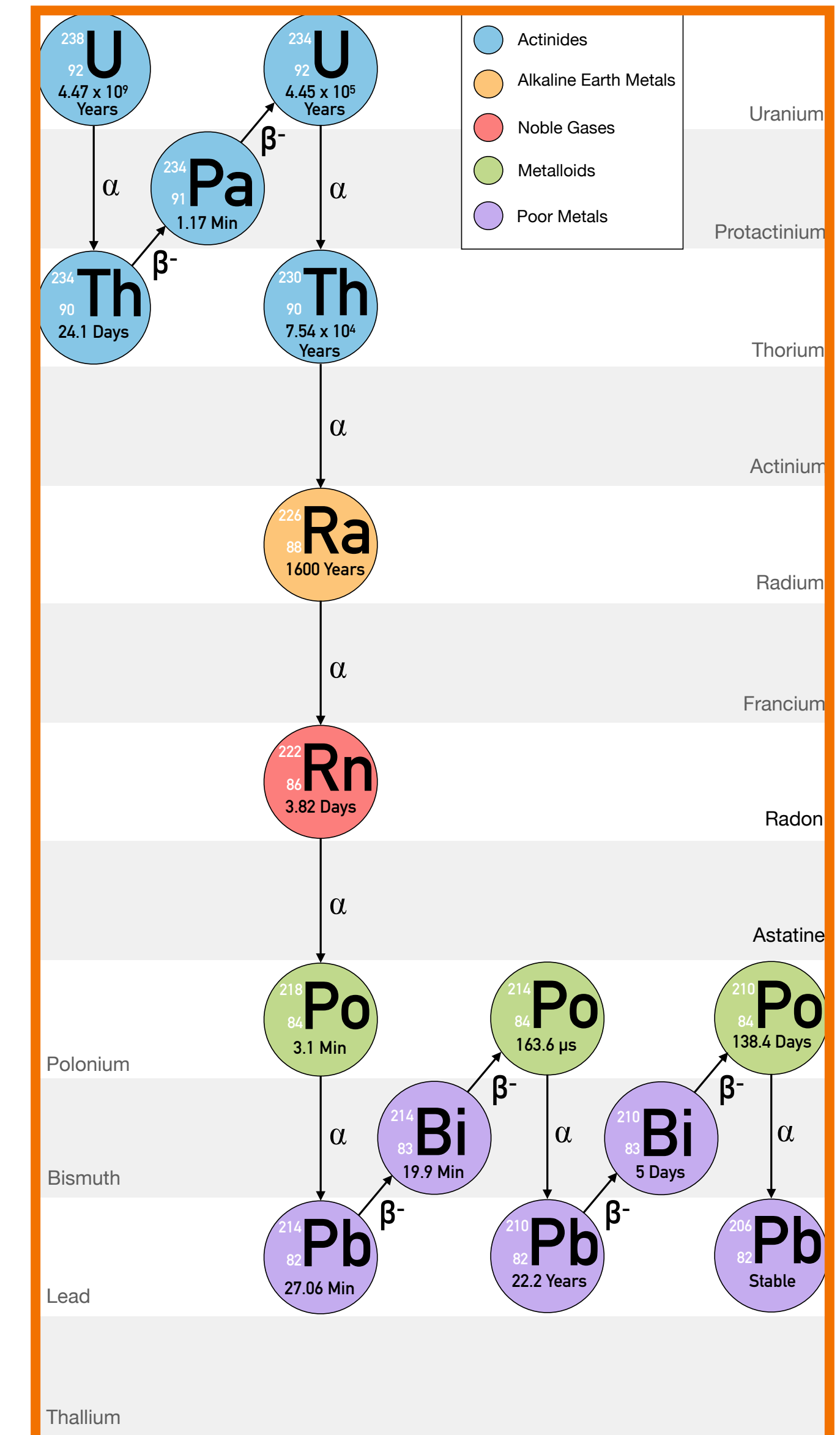
Type of background:

- ✦ Interaction producing a (nuclear) recoil in the same energy range than WIMP
 - ▶ External backgrounds
 - ▶ Cosmogenic backgrounds
 - ▶ Internal backgrounds

External/Internal to the target material

Radiogenic Background Source:

- ✦ Radiogenic contaminant naturally present in all materials → Including the detector itself and its environment!
 - ▶ Primordial decay chains (^{238}U , ^{235}U , ^{232}Th), with α , β , γ emission, and neutron production via (α , n) reaction or fission [ER & NR]
 - ▶ Other Isotopes: ^{60}Co , ^{137}Cs , ^{40}K , ... [ER]
- ✦ Decay product can induce electronic or nuclear recoil in the detection medium.



Mitigation Strategy:

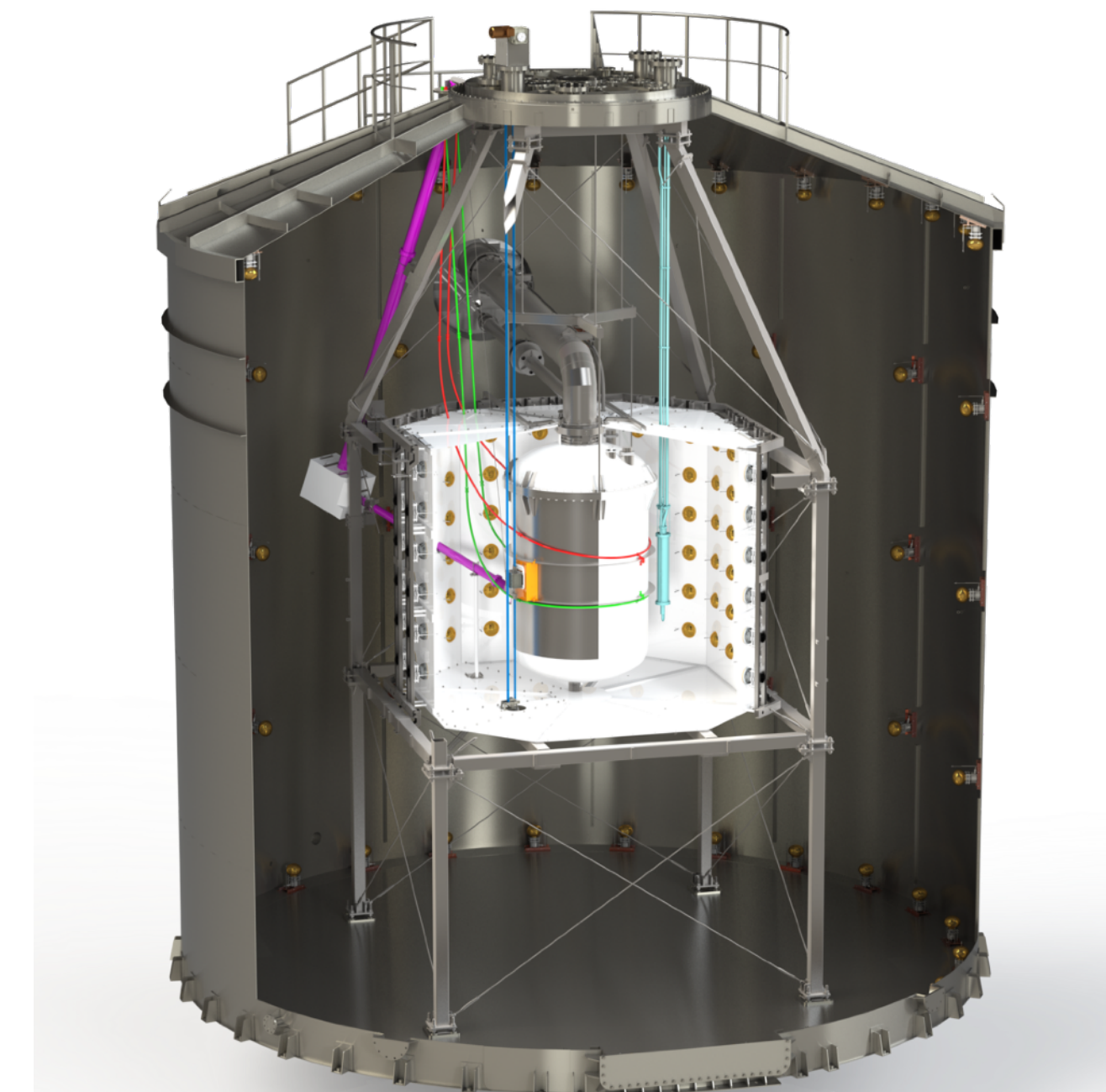
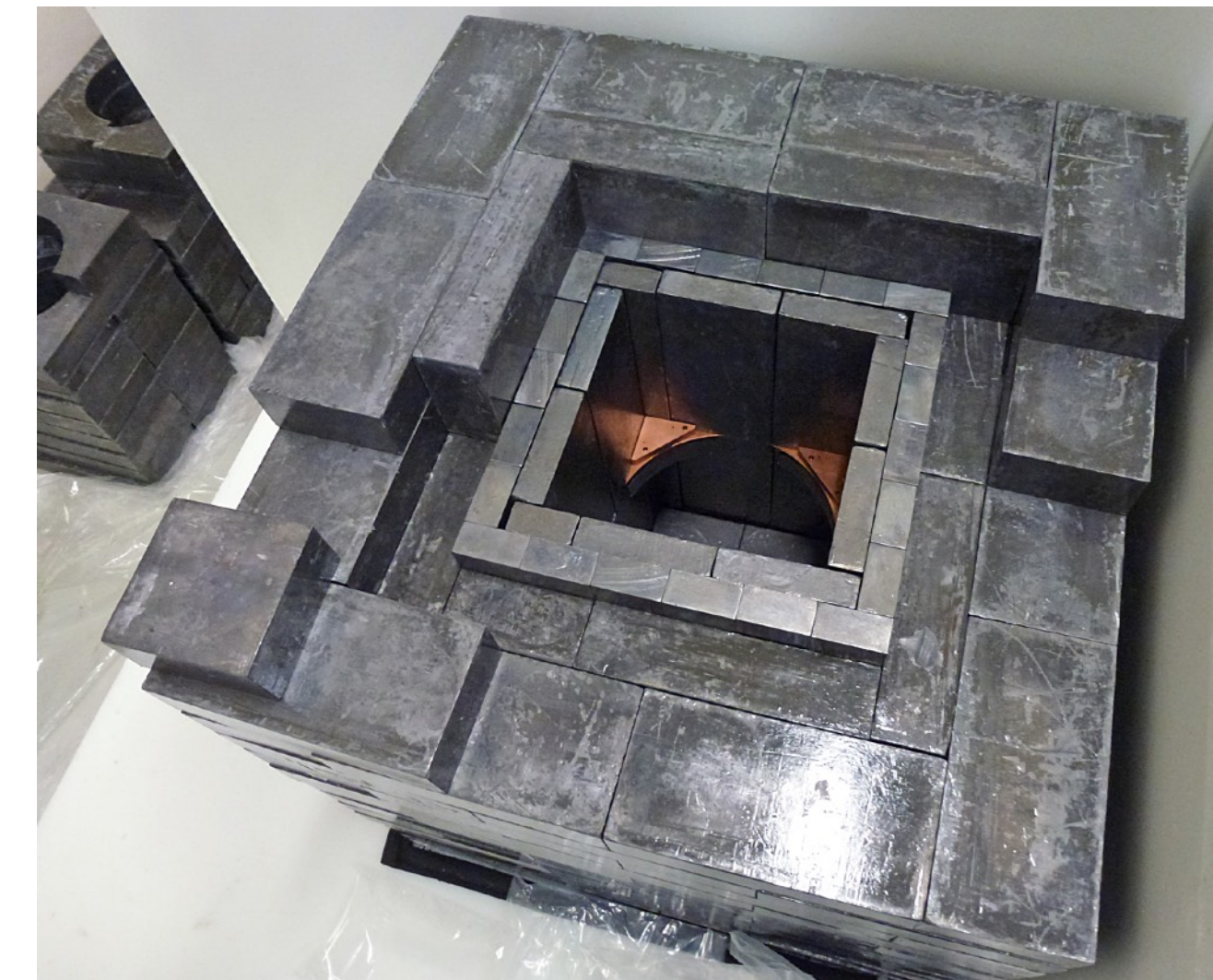
- ✦ Detector Material Selection
 - ▶ Screening campaign of material samples to select the most radio pure and allow background modelling.



HPGe array - Modane

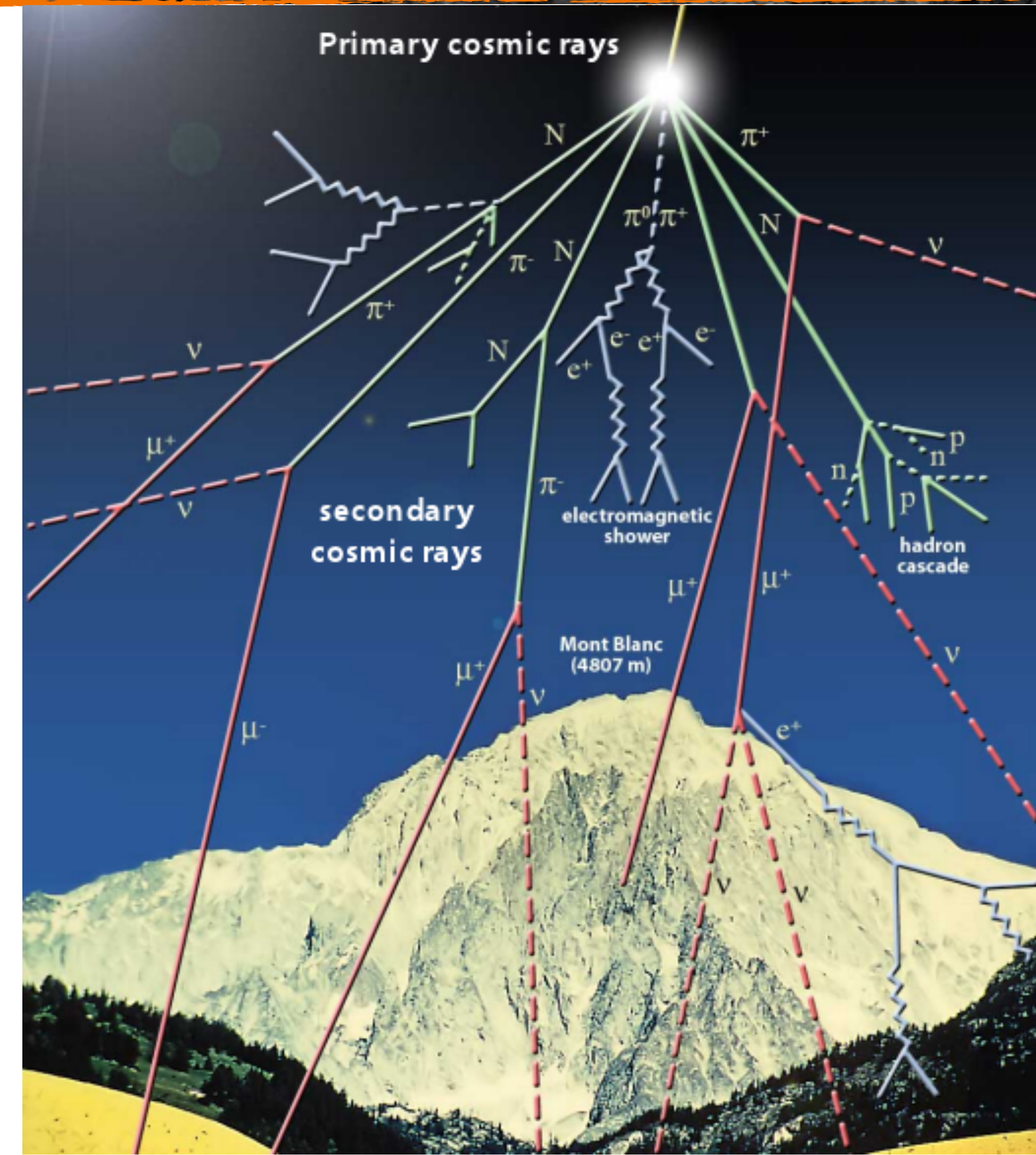
Mitigation Strategy:

- ✦ Detector Material Selection
 - Screening campaign of material samples to select the most radio pure and allow background modelling.
- ✦ Detector Shielding
 - Passive Shielding: Material, like **Archaeological Lead**, to suppress
 - Active Shielding: Instrumented shielding volume, such as **Cherenkov Water Tank**
 - **Self-Shielding**: Part of detection medium as shielding → require position reconstruction.

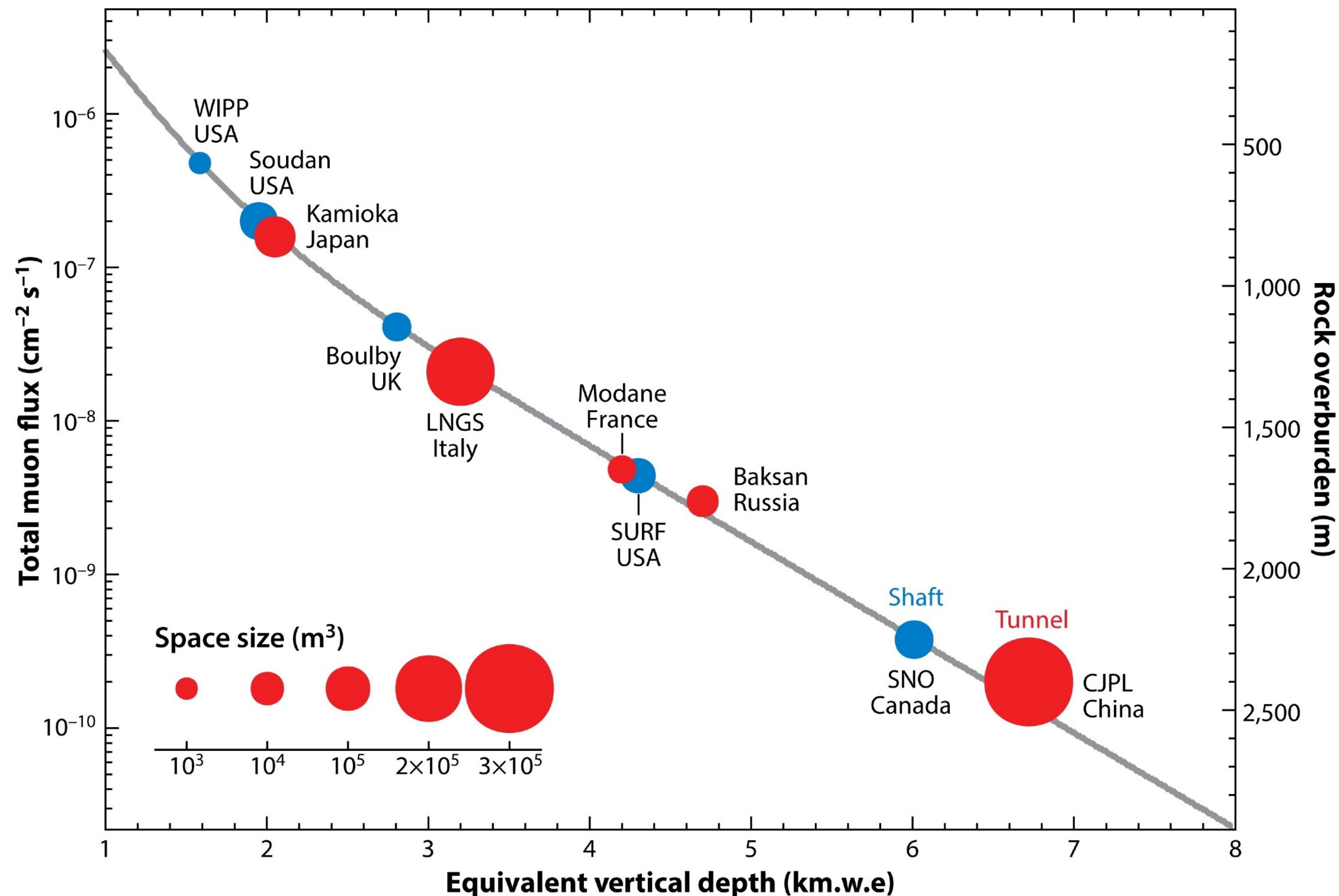


Cosmogenic Background Source:

- ✱ Muons produced by cosmic ray shower in the atmosphere
 - ▶ Can produce Muon-induced neutrons via hadronic process when interacting with the matter [NR]
 - ▶ Cosmogenic activation (via spallation, fragmentation, capture...): ^3H , ^{60}Co , ^{32}Si , ^{39}Ar , ... [ER]
- ✱ Relevant underground but also above ground!



Mitigation Strategy:



- ✱ Operate experiment in deep Underground Laboratory (UL)
 - Use Earth as shielding to reduce Muon flux



LNGS



CJPL



Canfranc



Modane

Intrinsic Background Source:

- ✱ Radiogenic component naturally present in the target/detection medium (^{136}Xe , ^{42}Ar , ^{85}Kr ,...)
- ✱ Radon (^{222}Rn) Emanation: Recoil/Diffusion of Radon in material following alpha decay of Radium ^{226}Ra

Natural xenon composition

Isotope	Abundance [%]	Decay mode	Half-life [years]
^{124}Xe	0.09	$2\nu\text{ECEC}$	$(1.1 \pm 0.2_{\text{stat}} \pm 0.1_{\text{sys}}) \times 10^{22}$
^{126}Xe	0.09	stable	-
^{128}Xe	1.92	stable	-
^{129}Xe	26.4	stable	-
^{130}Xe	4.08	stable	-
^{131}Xe	21.2	stable	-
^{132}Xe	26.9	stable	-
^{134}Xe	10.4	stable	-
^{136}Xe	8.87	$2\nu\beta\beta$	$(2.165 \pm 0.016_{\text{stat}} \pm 0.059_{\text{sys}}) \times 10^{21}$

TAKE ACTION ON RADON

Radon is an invisible, radioactive gas that comes from the ground

Radon is the **2nd LEADING CAUSE** of LUNG CANCER

3000+ PEOPLE/YEAR die from radon-induced LUNG CANCER

Radon is in ALL buildings

The only way to know how much radon is in your home is to TEST

Radon is easy to TEST and easy to REDUCE

HOW TO REDUCE RADON IN YOUR HOME

HIRING a certified professional LOWERS RADON BY UP TO **90%**

INCREASING home ventilation LOWERS RADON BY **25-50%**

SEALING cracks LOWERS RADON BY **13%**

Recent research found that **ONLY 29% OF CANADIANS** with high RADON in their home took action to REDUCE it!

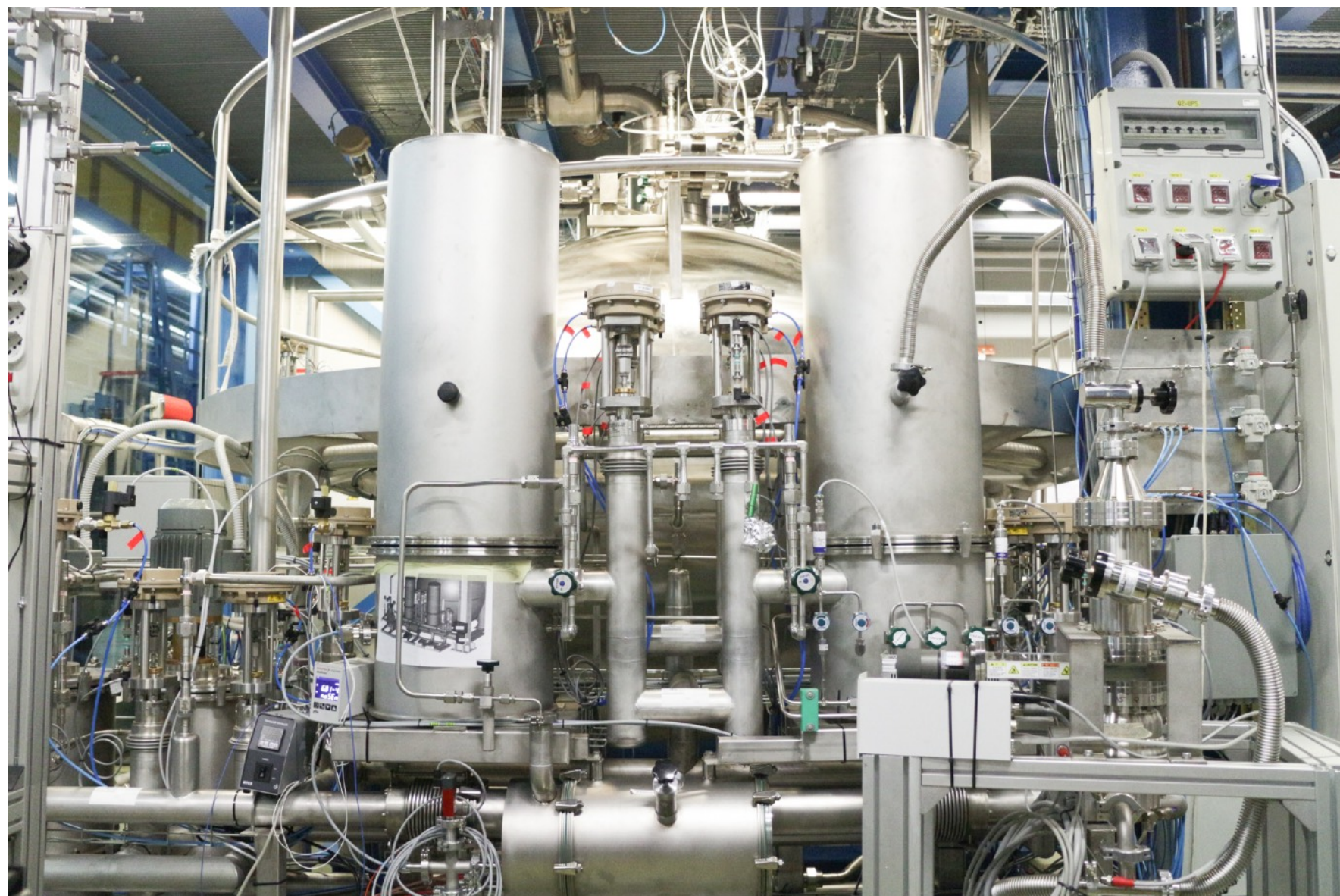
TEST and REDUCE RADON to protect against lung cancer

www.takeactiononradon.ca

Canada

Mitigation Strategy:

- ✦ Selection/Production of pure target/detection medium
- ✦ Offline/Online Purification system
- ✦ Surface Coating to limit radon emanation



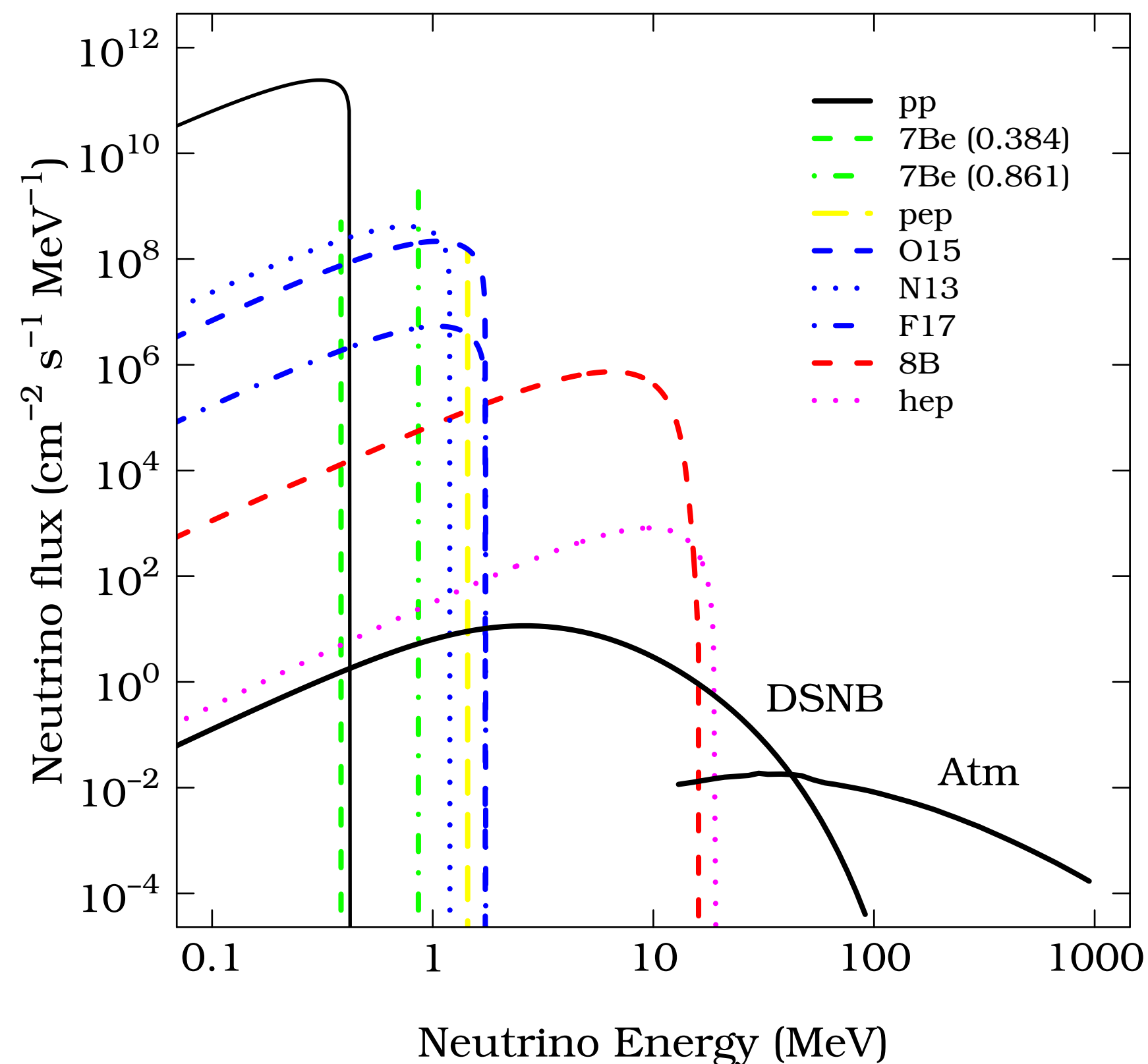
Liquid Xenon purification unit used in XENONnT for online purification

Seruci-0 cryogenic distillation column

Ar production



Ultimate source of Background?



✦ Neutrino from the sun or the atmosphere

▶ Neutrino-electron elastic scattering [ER]

▶ Coherent Elastic neutrino-Nucleus Scattering (CEvNS) [NR]

✦ Shielding and Veto system impossible...

Neutrino fog

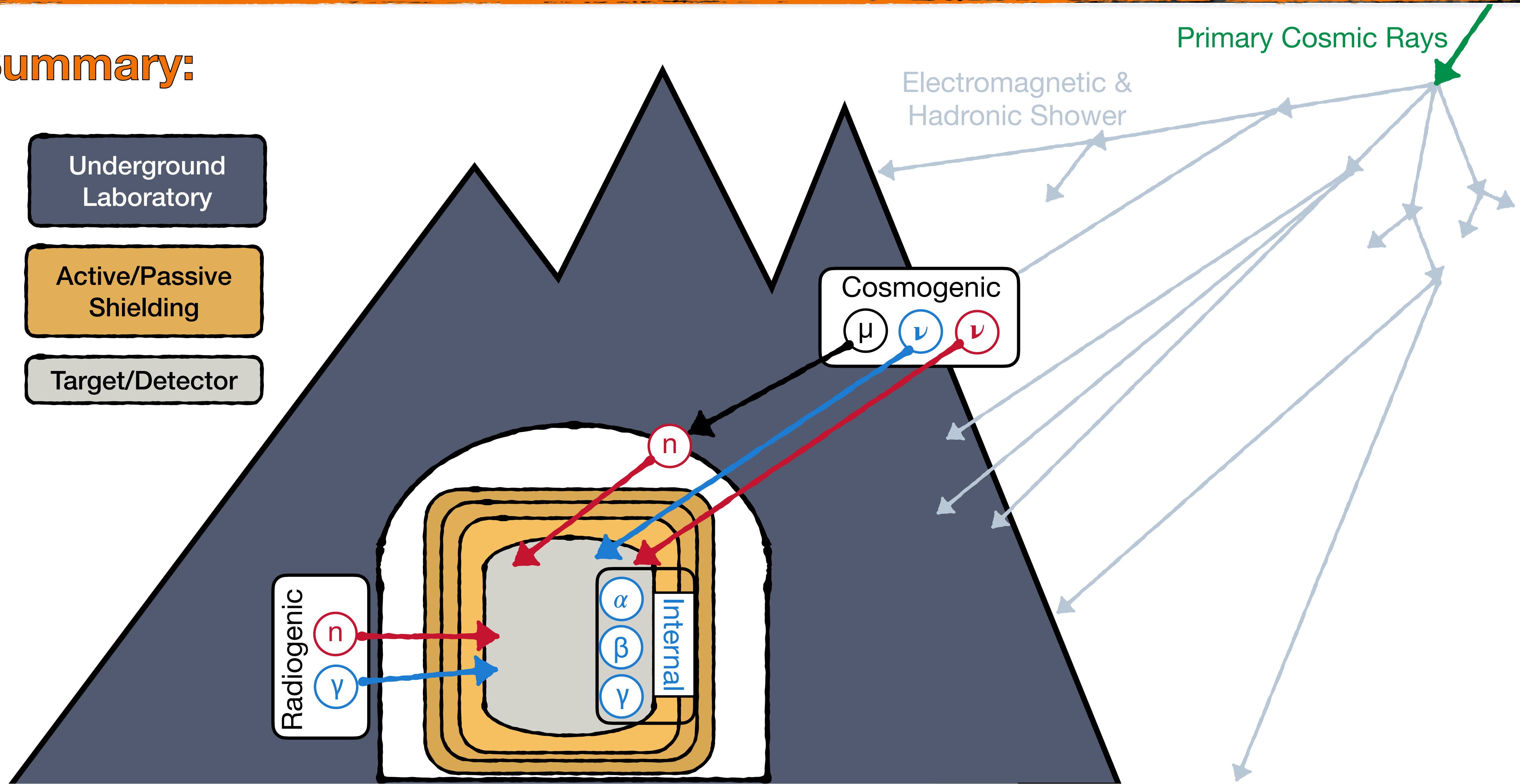
One way to work-around:

✦ Directionality: we know where they are coming from.

Background Mitigation Strategy

44

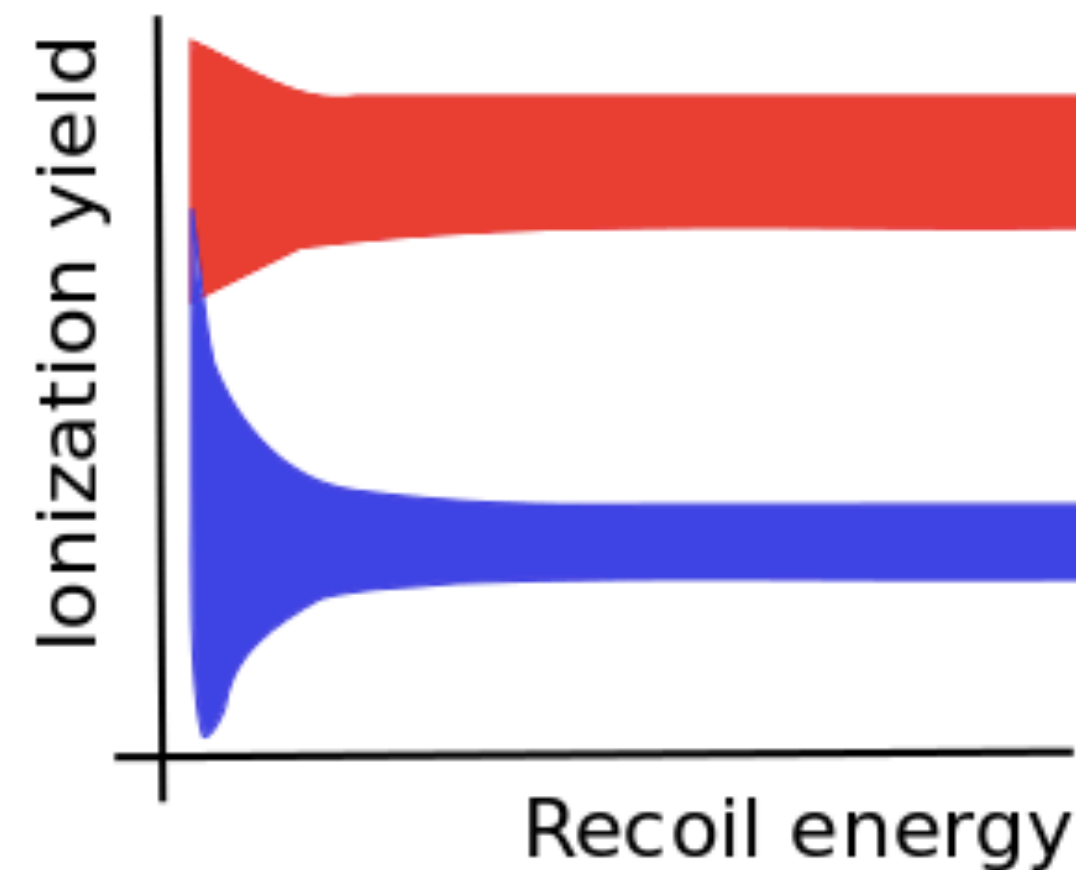
Summary:



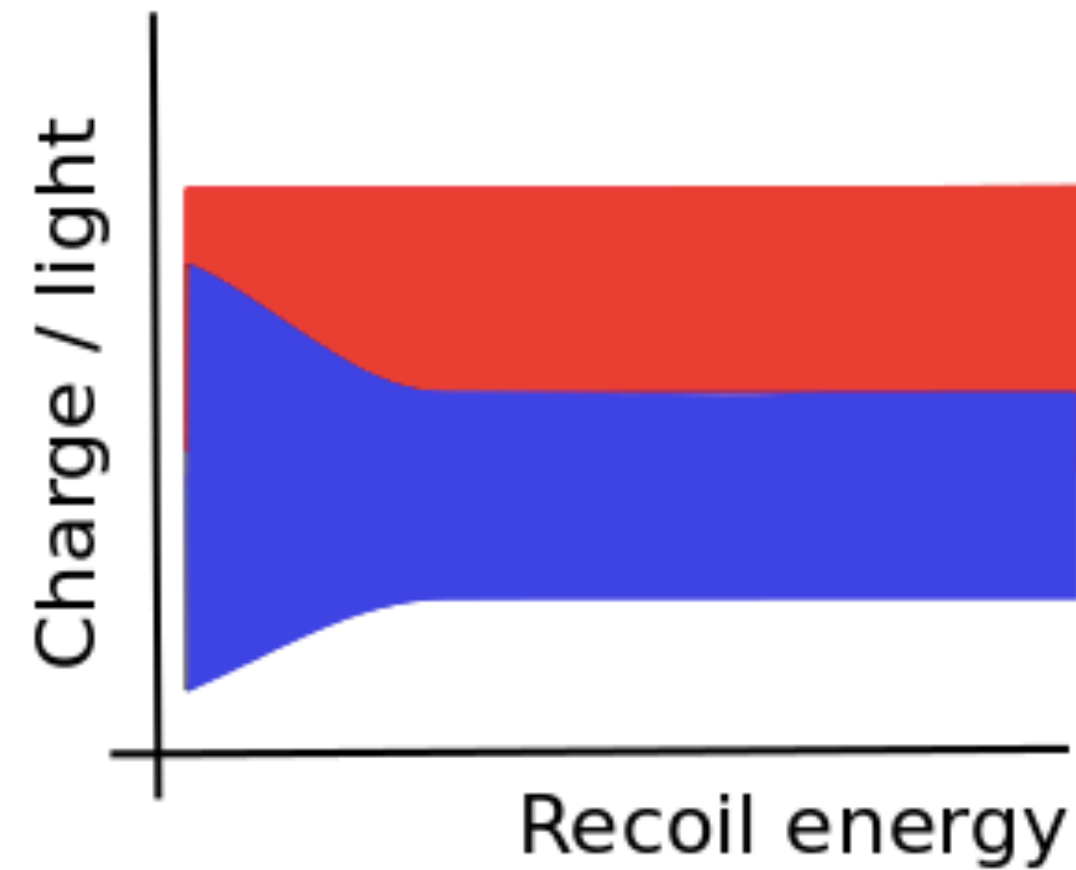
Can we further suppress backgrounds in our detector?

- ✦ Use differences in detector response to particle (γ, α, n, β) or interaction (ER/NR) type
 - Combination of multiples energy deposition channel (Light, Charge, Heat)
 - Pulse Shape Discrimination (PSD)
- ✦ Use calibration data to study detector response to signal/background events

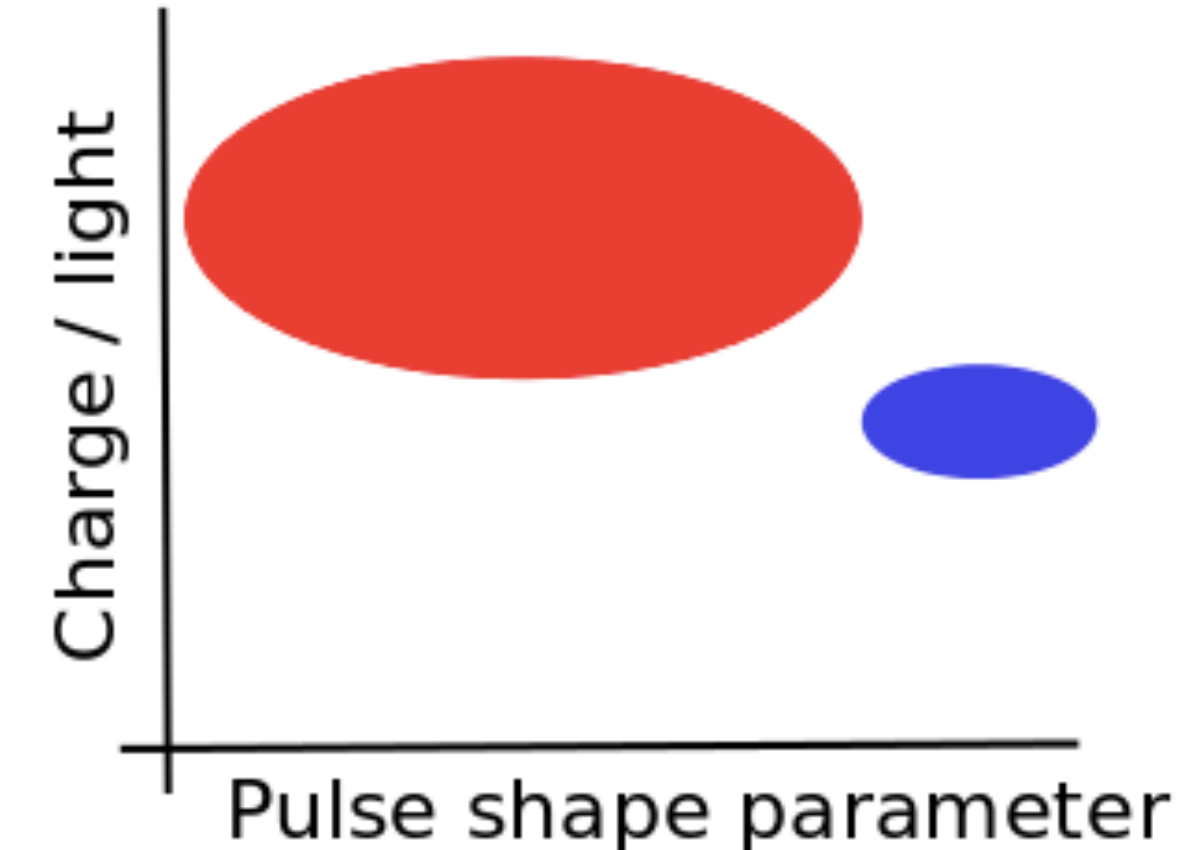
Cryogenic Germanium detector



Liquid Xenon detector

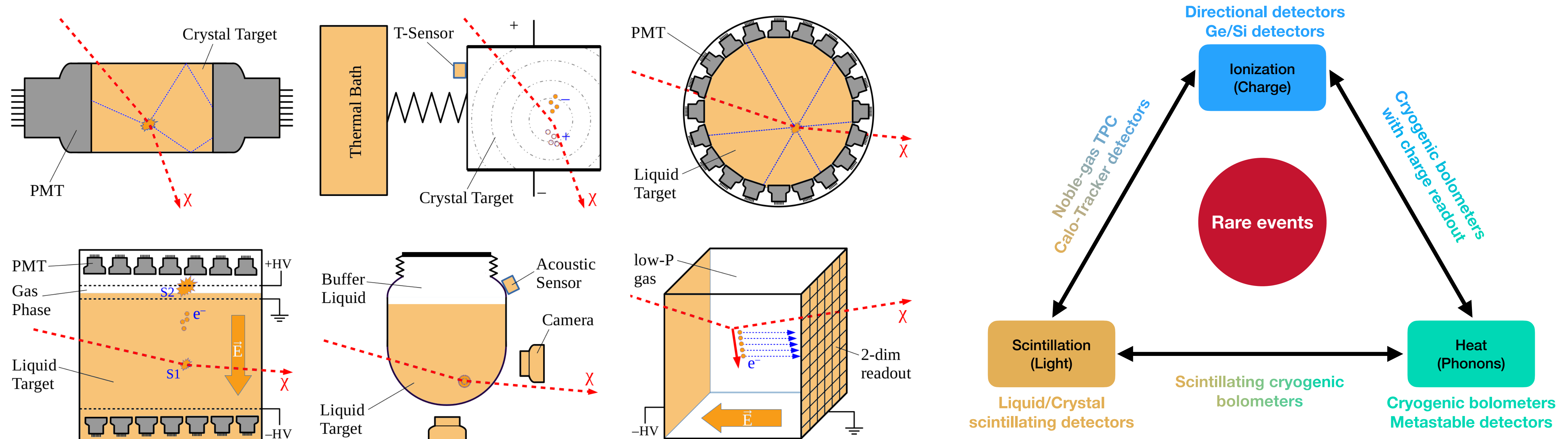


Liquid Argon detector



Large diversity of detector to face the challenges of DM detection

- ✦ Different detection techniques with different goals (low-/high-mass DM)
- ✦ Detector choice associated with Pro and Cons

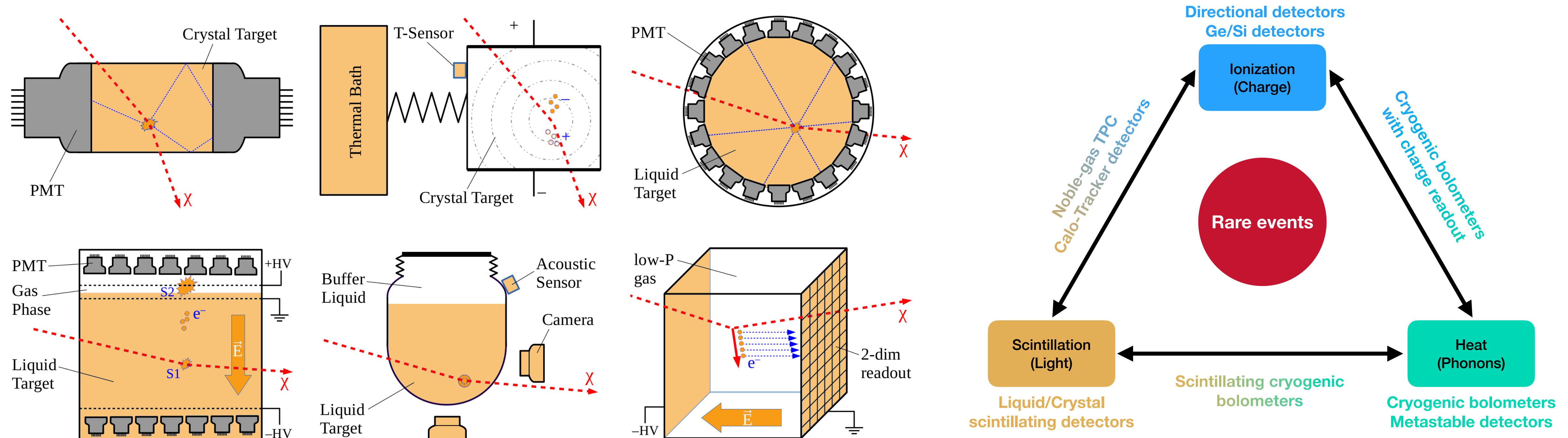


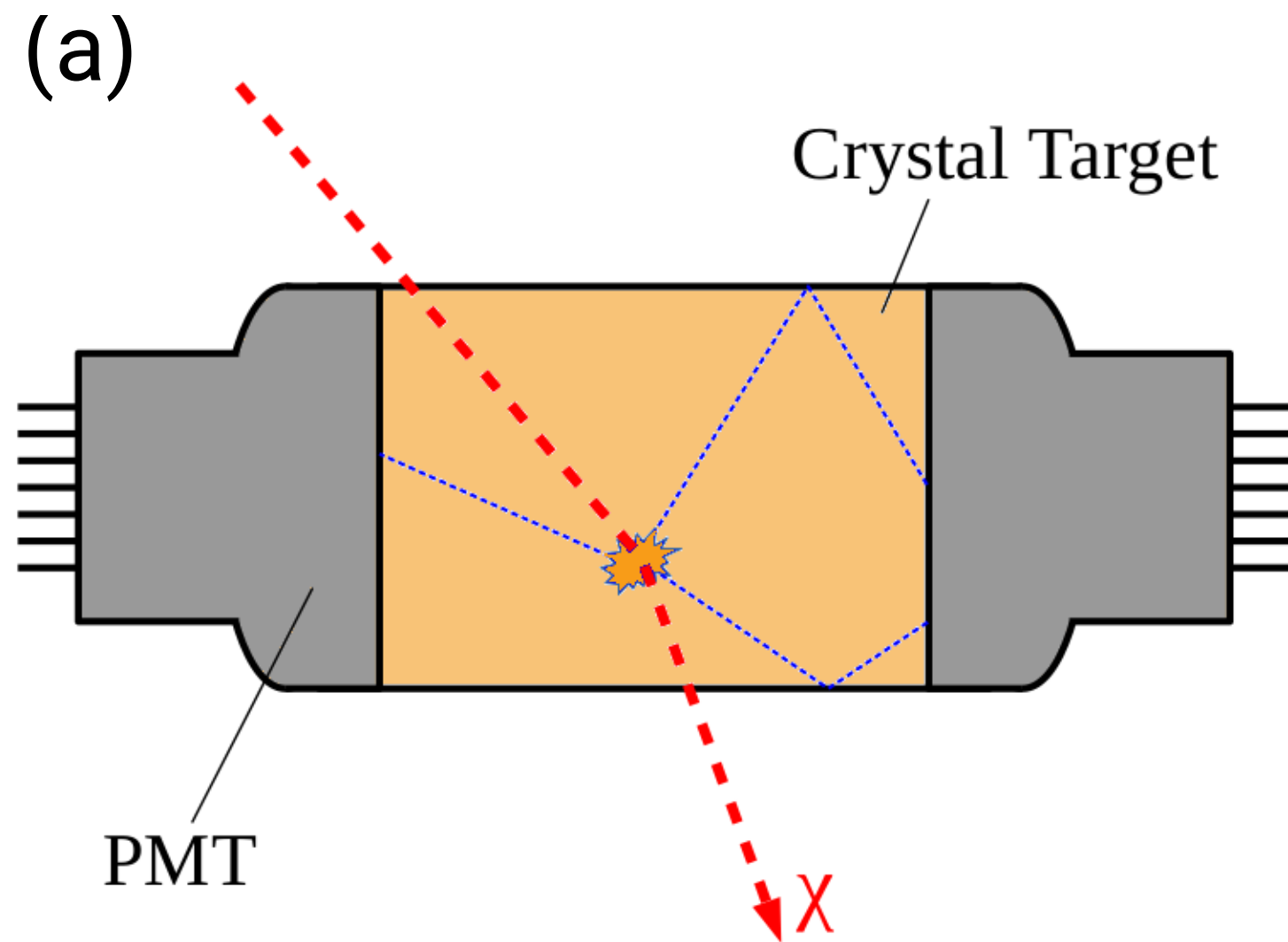
The background of the slide is a detailed visualization of the cosmic web, showing a complex network of dark matter filaments and galaxy clusters. Numerous bright yellow and orange points, representing galaxies, are scattered throughout the dark, textured space. The text "5 min break, question?" is centered in the middle of the image in a bold, orange font with a white outline.

5 min break, question?

Large diversity of detector to face the challenges of DM detection

- ✦ Different detection techniques with different goals (low-/high-mass DM)
- ✦ Detector choice associated with Pro and Cons





- ✦ Target: NaI and CsI
- ✦ Target mass $\sim \mathcal{O}(100)$ kg
- ✦ Energy Threshold $\sim \mathcal{O}(1)$ keV
- ✦ Detection channel: **Light**

Mostly used for annual modulation searches

Strength

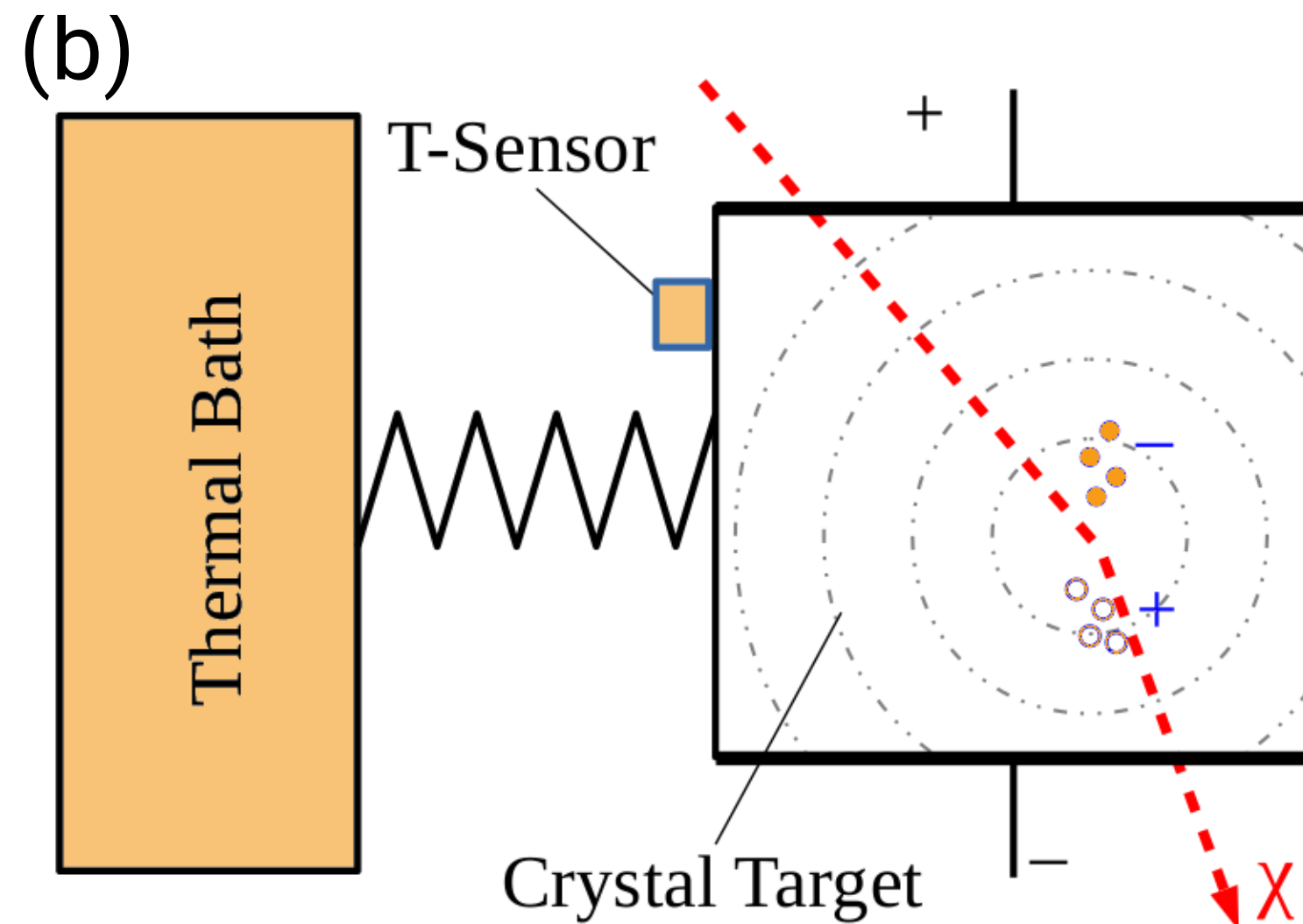
Mature technology, can operate stably for long periods of time

High mass number, boost SI sensitivity

Weakness

Comparatively high intrinsic background

No Fiducialisation or ER/NR discrimination



- ✦ Target: Ge, Si, and CaWO_4
- ✦ Target mass $\sim \mathcal{O}(1)$ kg
- ✦ Energy Threshold $\sim \mathcal{O}(10-100)$ eV
- ✦ Detection channel: Heat, (and Light, or Charge)

Efficient to search for low-mass WIMP

Strength

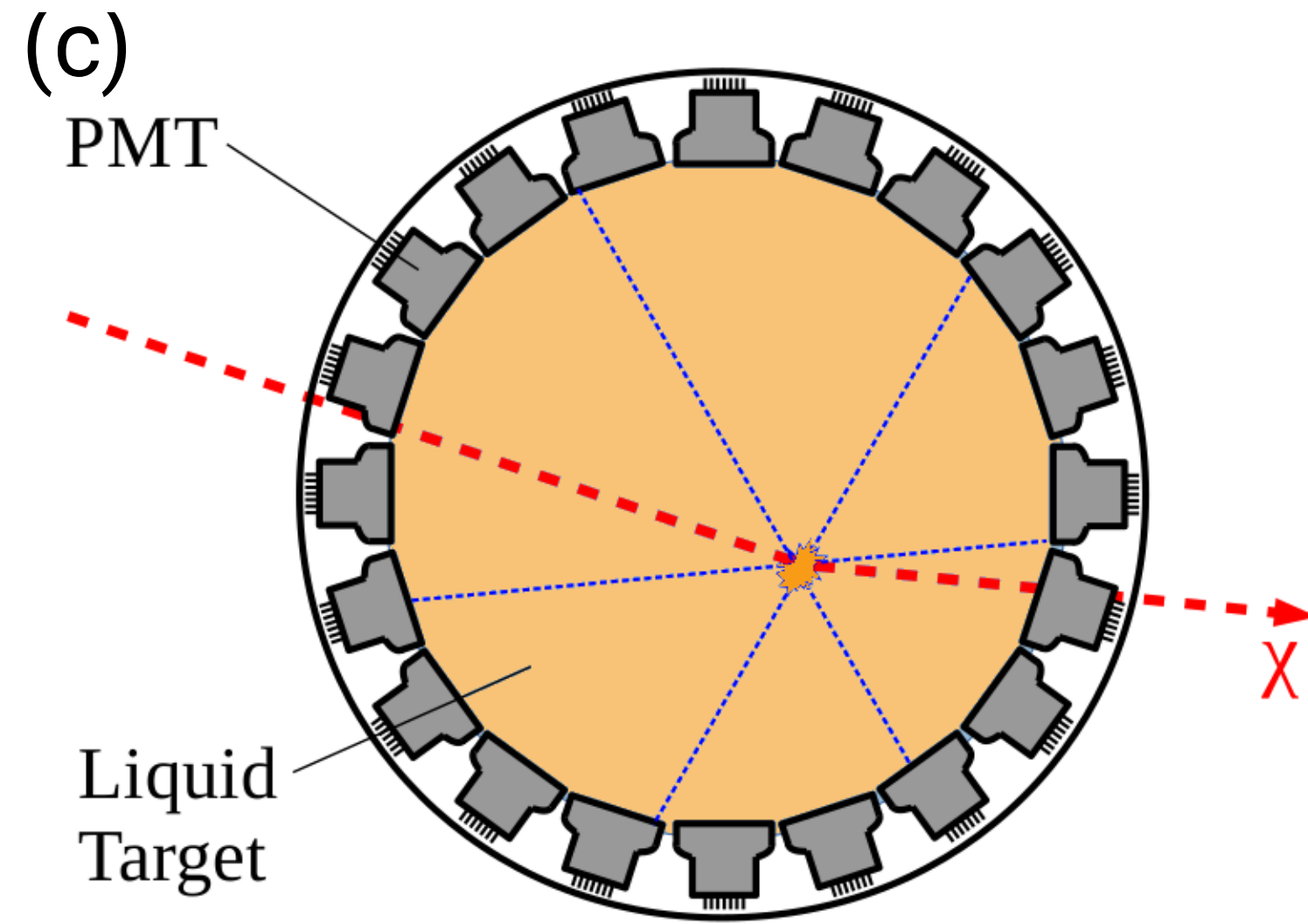
Excellent energy resolution and low energy threshold

Two detection channel to allow background rejection + PSD

Weakness

Cryogenic detectors (< 50 mK)
Target mass scalability is challenging

Presence of an “unkown” (structural stress?) background at low-energy (LEE - phonon)



- ✦ Target: Ar and Xe
- ✦ Target mass $\sim \mathcal{O}(1000)$ kg
- ✦ Energy Threshold $\sim \mathcal{O}(1)$ keV
- ✦ Detection channel: **Light**

Efficient to search for high-mass WIMP

Strength

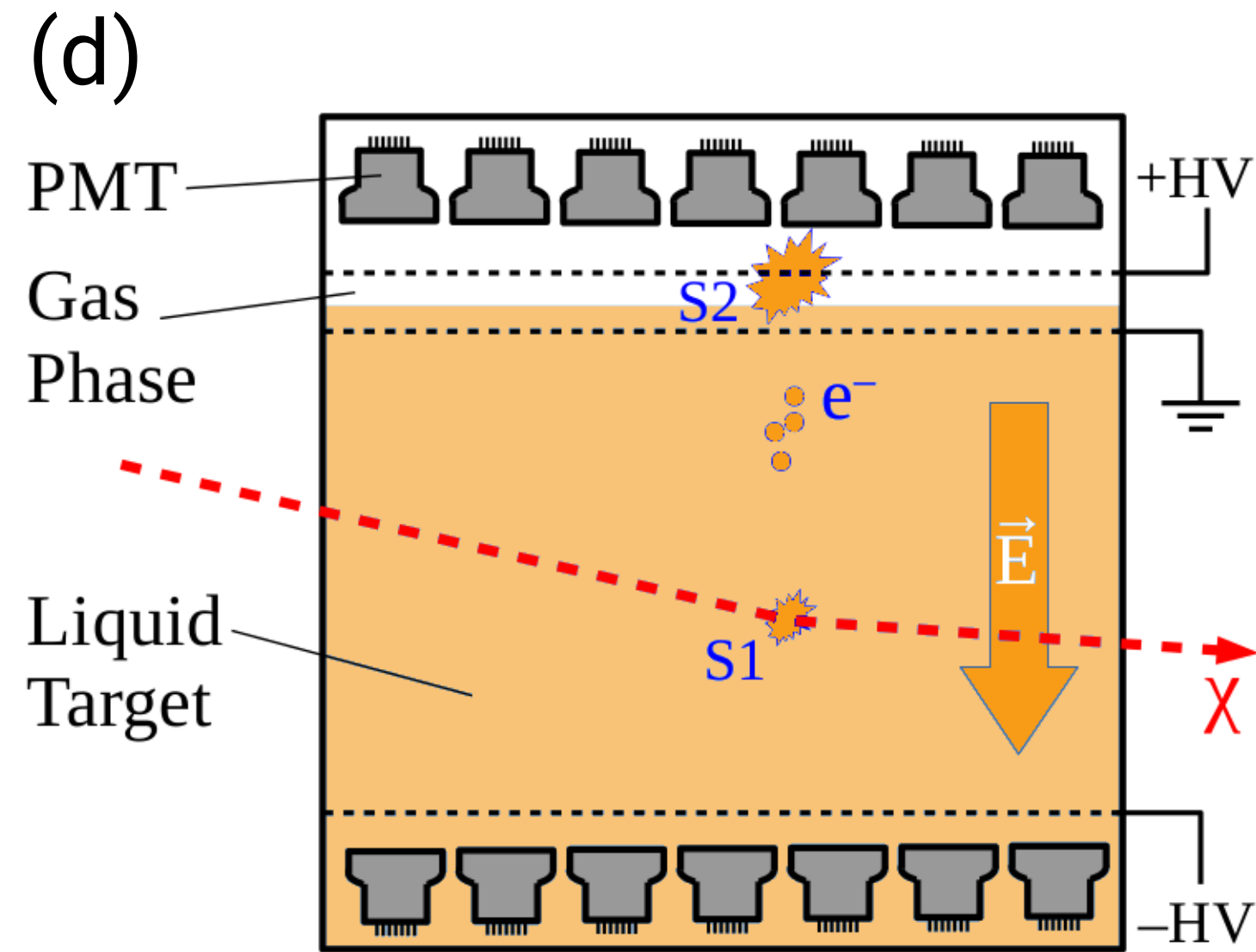
Target mass scalability
Position reconstruction for fiducialisation
Background discrimination for Ar

Weakness

Only one detection channel
Background discrimination not as efficient as the next type of detection technique...

Time Projection Chambers (Double phase)

52



- ✦ Target: Xe and Ar
- ✦ Target mass $\sim \mathcal{O}(10\,000)$ kg
- ✦ Energy Threshold $\sim \mathcal{O}(1)$ keV
- ✦ Detection channel: **Light** and **Charge**

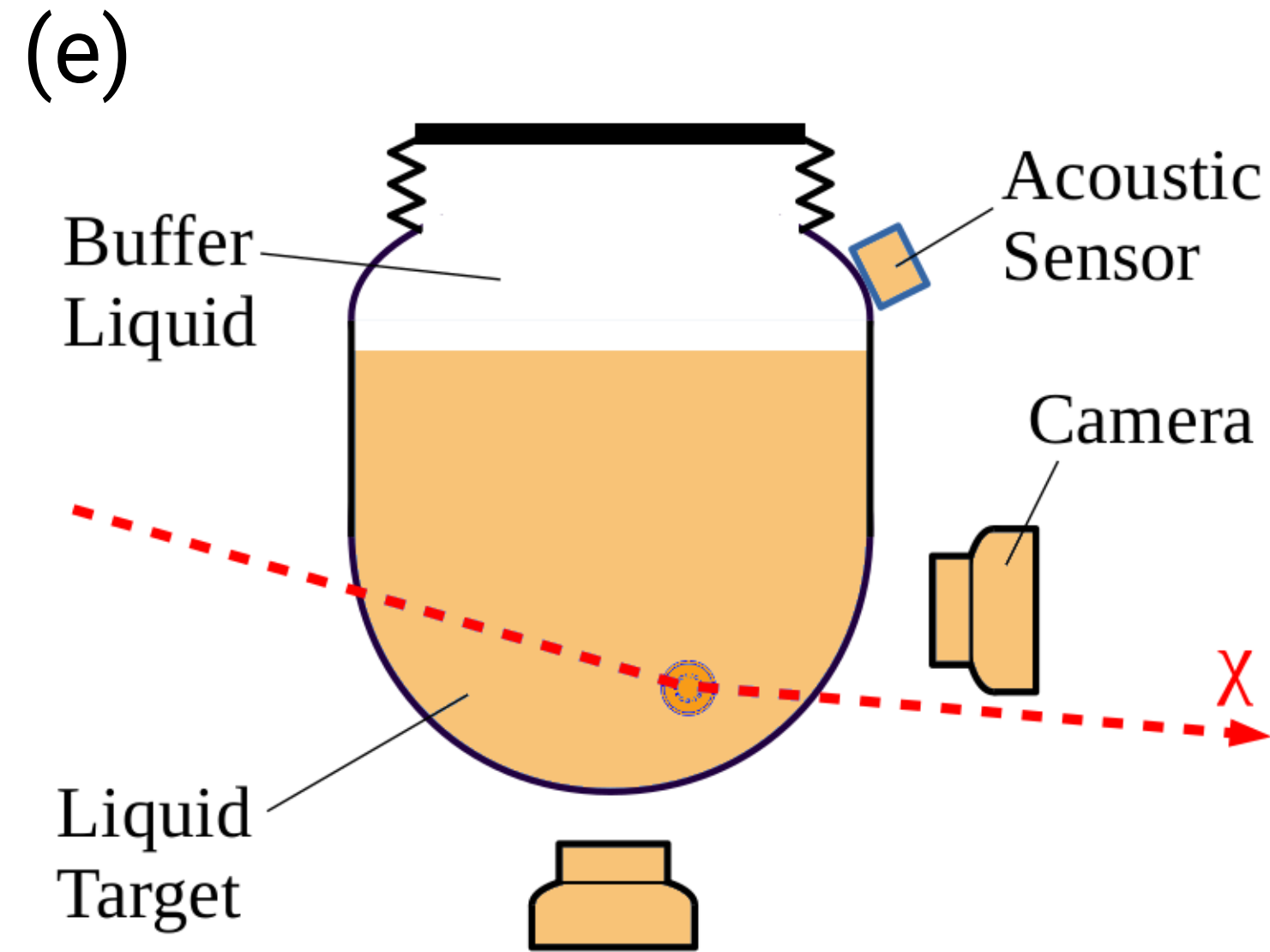
Leading technology for high-mass WIMP search

Strength

Target mass scalability
Position reconstruction for fiducialisation
Background discrimination with light and charge channel

Weakness

Energy threshold too high for low-mass WIMP search...
But there is some work-around possible (Ionization-only, Migdal effect)



- ✦ Target: Superheated (Kept at a temperature just above their boiling point) fluids, C_3F_8
- ✦ Target mass $\sim \mathcal{O}(10)$ kg
- ✦ Energy Threshold $\sim \mathcal{O}(1)$ keV
- ✦ Detection channel: **Optical** and **Acoustic (!)**

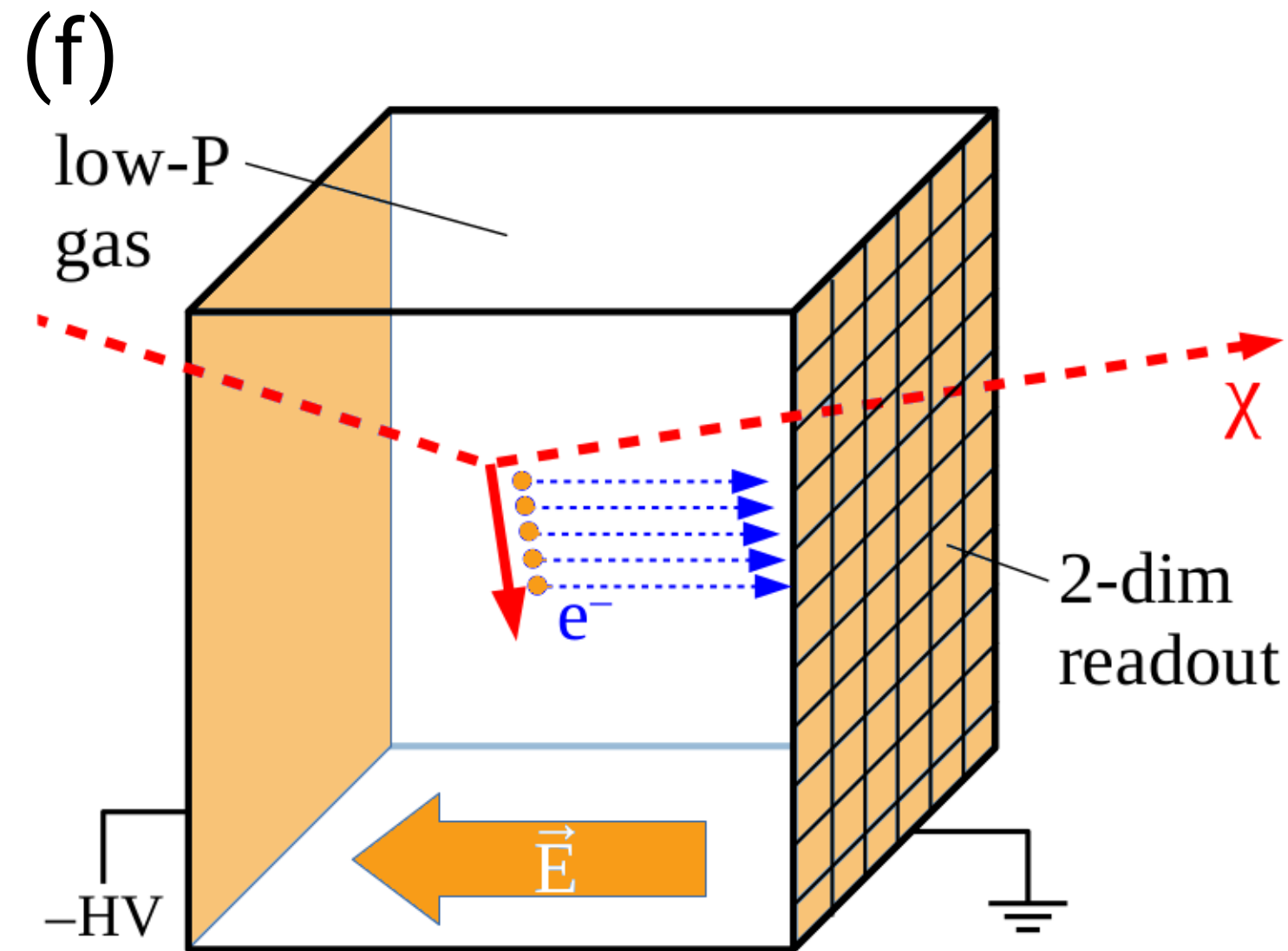
Contain ^{19}F , best sensitivity for SD WIMP-proton coupling

Strength

Can be tuned to be only sensitive to nuclear recoils (dE/dx of the recoiling particle)
Position reconstruction for fiducialisation

Weakness

Need to change the pressure inside to remove bubbles after each event $\rightarrow$ dead time and difficult calibration



- ✦ Target: Low-pressure gas, such as CF_4 , can use a mixture of gases also (Ne, CH_4 ,...)
- ✦ Target mass $\sim \mathcal{O}(0.1)$ kg
- ✦ Energy Threshold $\sim \mathcal{O}(1-10)$ keV
- ✦ Detection channel: **Charge**

Can be used to search WIMPs in the neutrino fog, and sensitive to SD WIMP-proton coupling

Strength

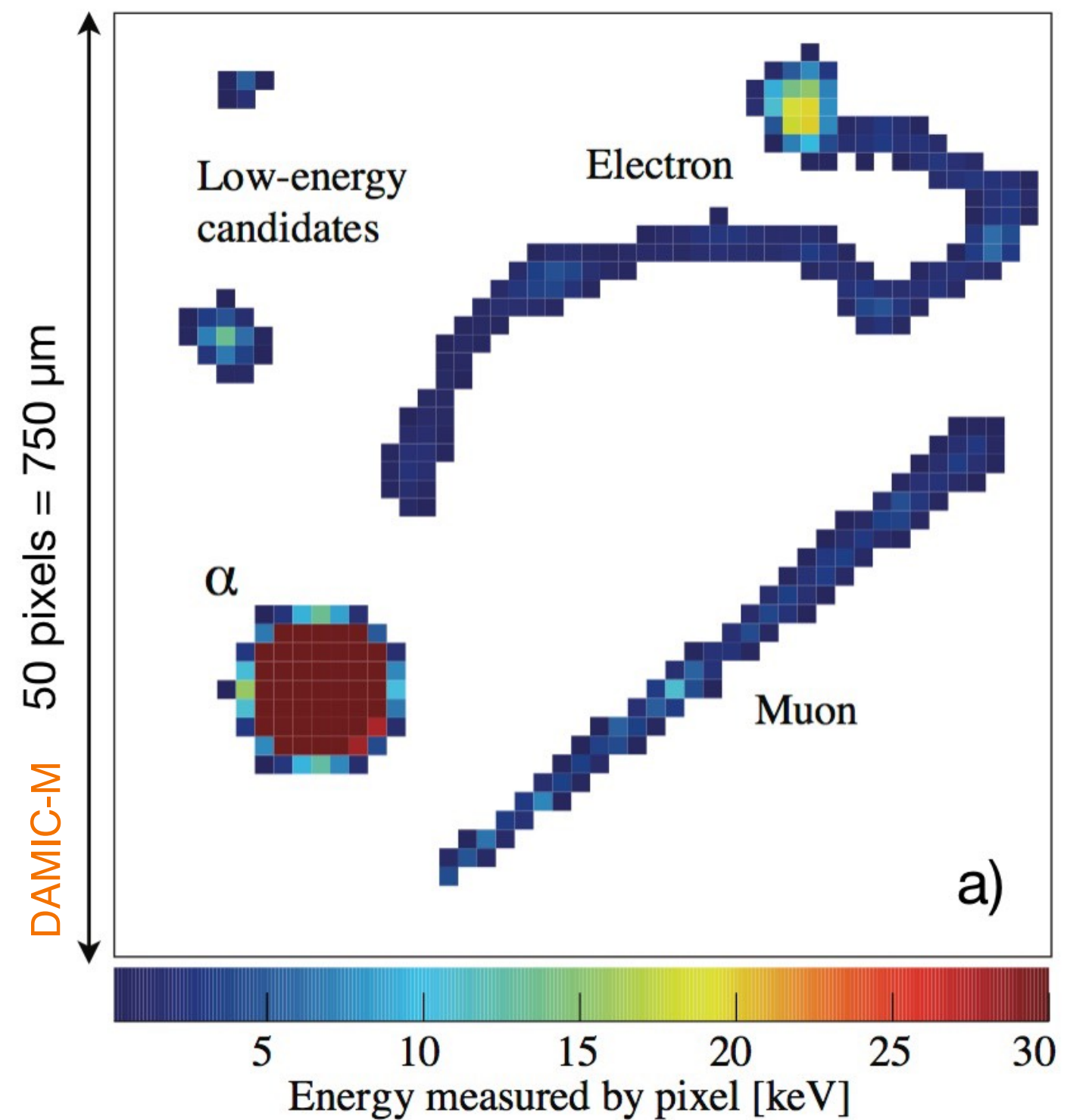
Track reconstruction of the deposited energy
Electronic background rejection (longer range, lower ionisation density)

Weakness

Small target mass, scalability is challenging
No self-shielding

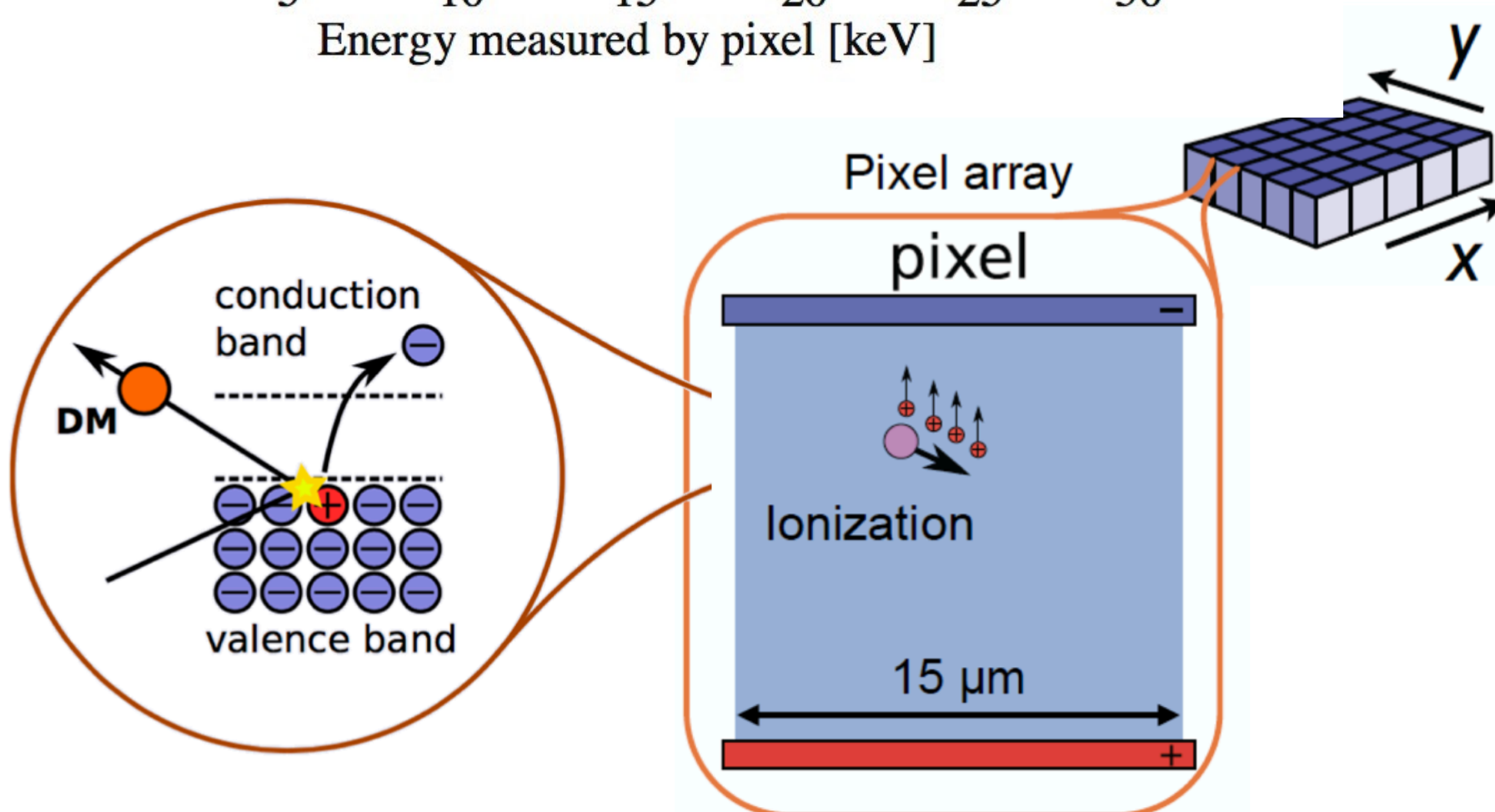
Charged Coupled Devices (CCDs)

55



- ✦ Target: Ge and Si
- ✦ Target mass $\sim \mathcal{O}(1)$ kg
- ✦ Energy Threshold $\sim \mathcal{O}(1-10)$ eV
- ✦ Detection channel: Charge

DM-electron scattering



Strength

Excellent spatial resolution for particle identification
Very low-energy threshold (Ge: 2.9 eV, Si: 3.6 eV), aim for low-mass WIMP

Weakness

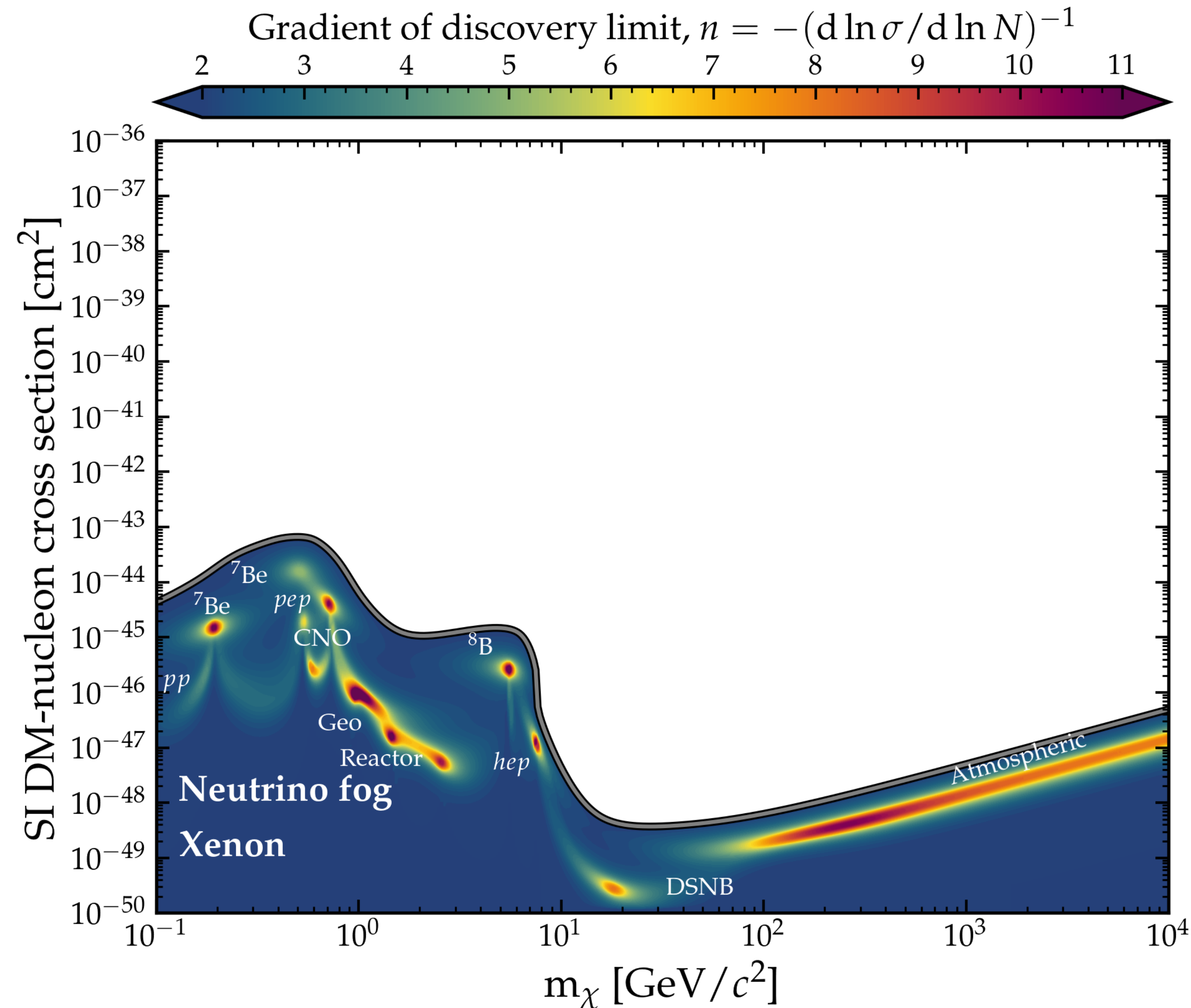
Small target mass, scalability is challenging
Presence of an “unkown” background at low-energy (not LEE! From charge here)

Experimental Landscape

How those detection technologies are actually used in the field to search for Dark Matter?

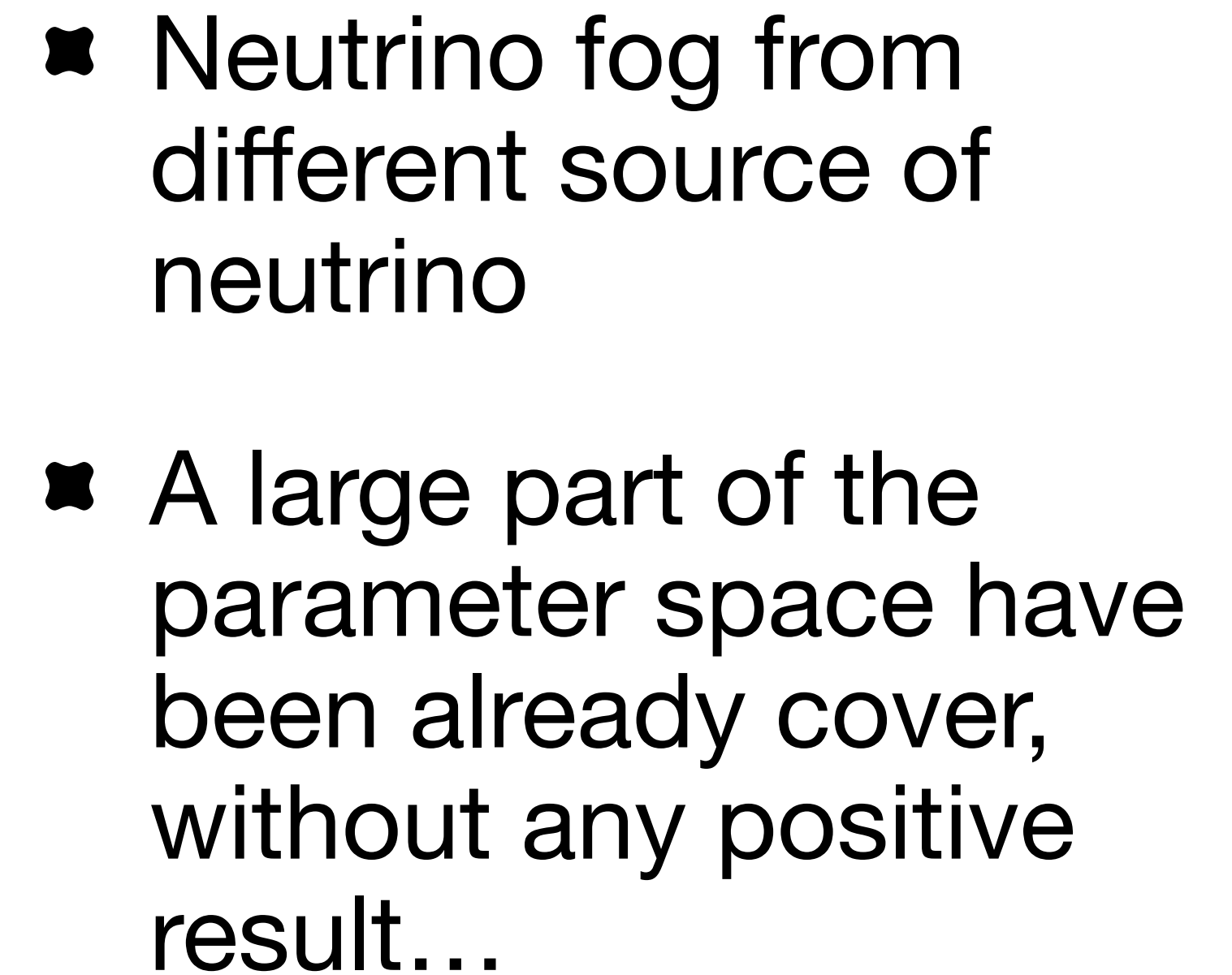
Direct Detection Landscape

57



- ✱ Neutrino fog from different source of neutrino

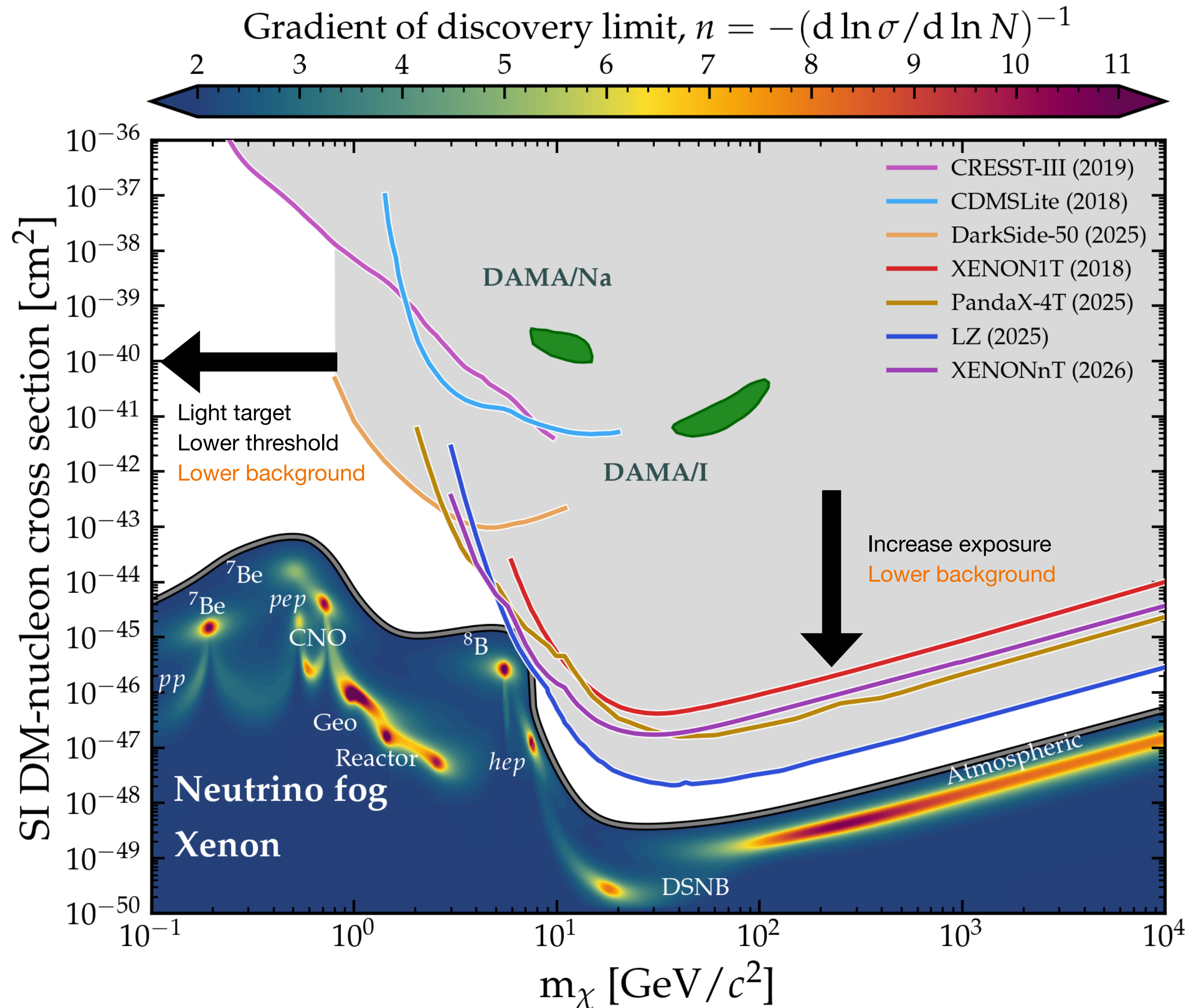
57



- ✖ Neutrino fog from different source of neutrino
- ✖ A large part of the parameter space have been already cover, without any positive result...

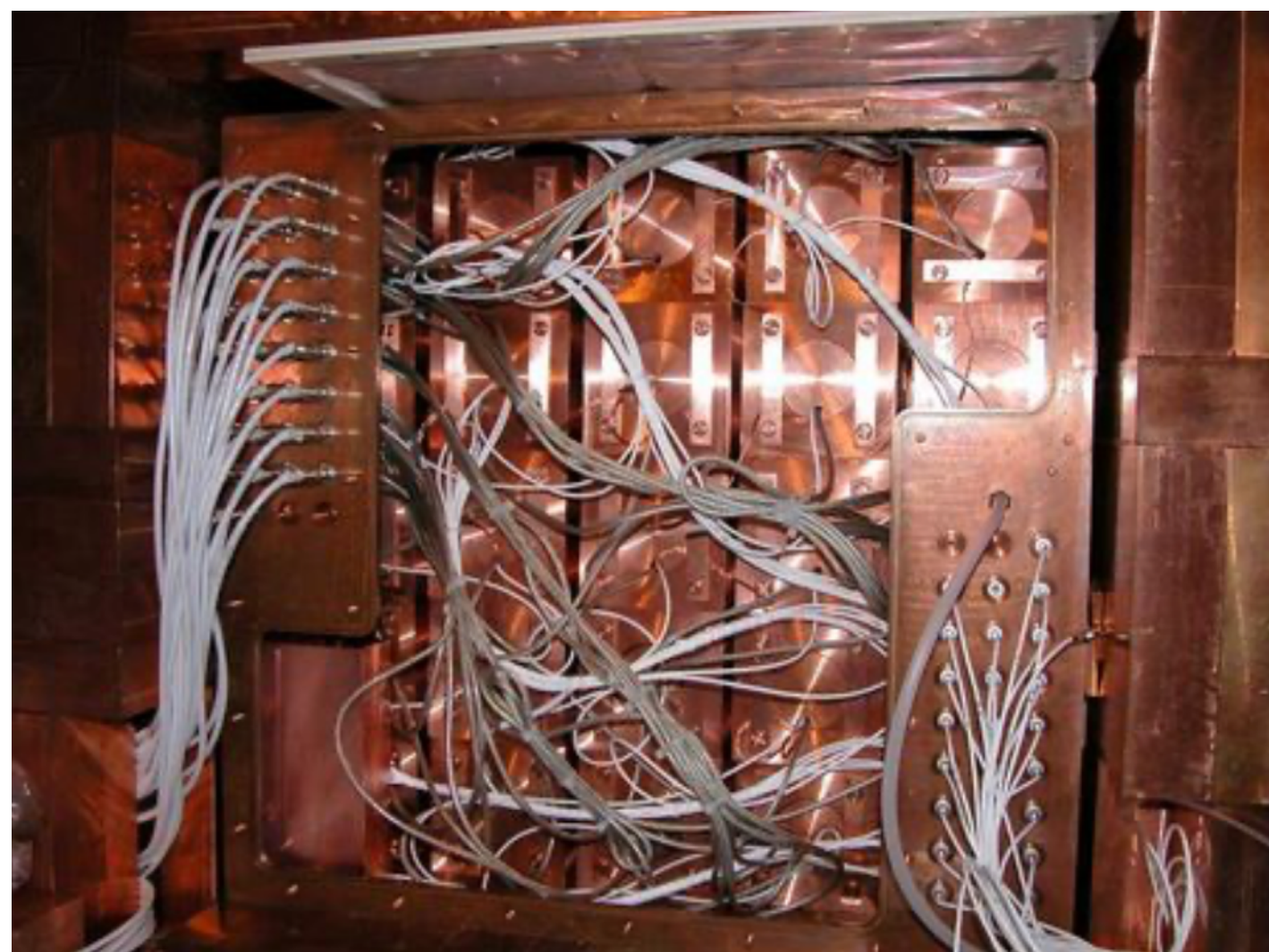
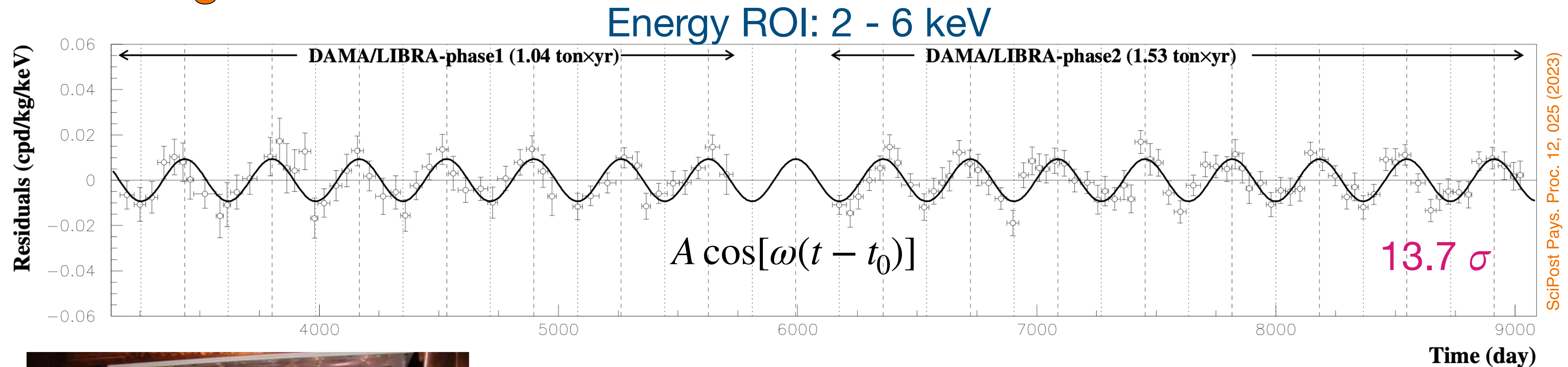
Direct Detection Landscape

57

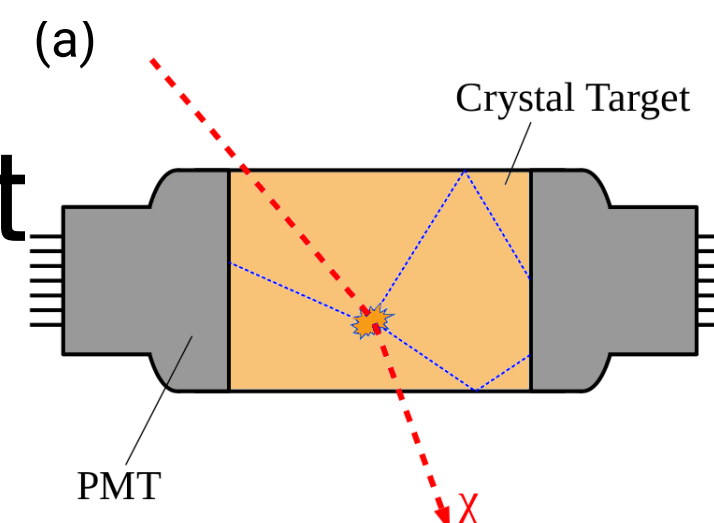


- ✖ Neutrino fog from different source of neutrino
- ✖ A large part of the parameter space have been already cover, without any positive result...
- ✖ **Well, is it really true?**

Clear Signal Modulation:



- ✦ ~ 250 kg NaI(Tl) scintillating crystals taking data in the underground laboratory of Gran Sasso in Italy for ~ 22 years
- ✦ Observe annual modulation signal consistent with WIMP hypothesis

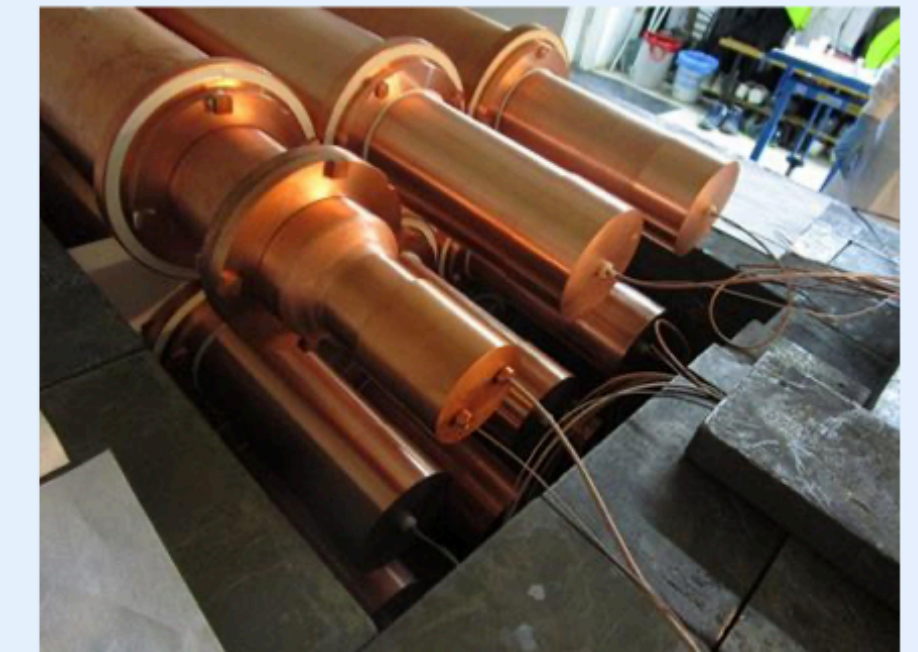
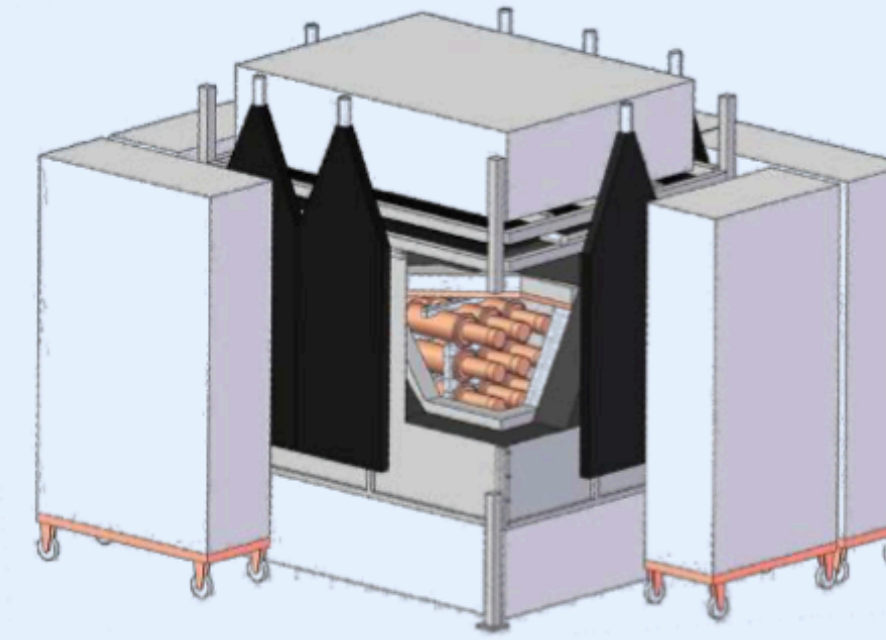


- ✱ But DAMA results is in strong tension with result from many other DM direct detection experiments with better sensitivity.
- ✱ What is the source of the annual modulation signal seen in DAMA?
 - ▶ Unknown source of backgrounds? (^{40}K ?)
 - ▶ Modulation seen in the 3 keV energy bin, close to the energy threshold from the detector (2 keV) → hard to control systematics. Upgraded version of DAMA currently running with lower energy thresholds.
 - ▶ Dark Matter?

A Series of experiments are running/or under development to test DAMA results

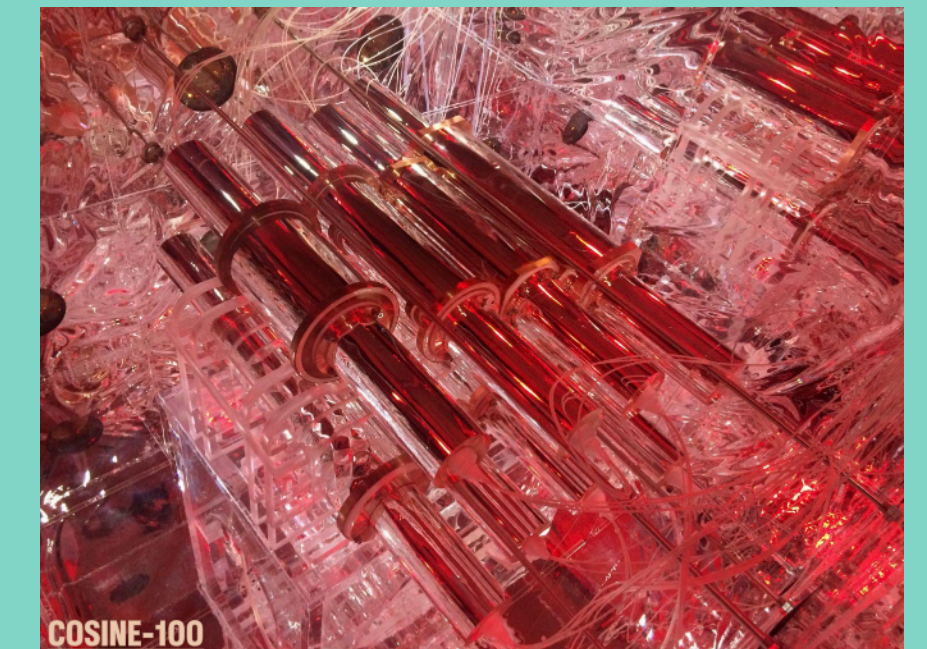
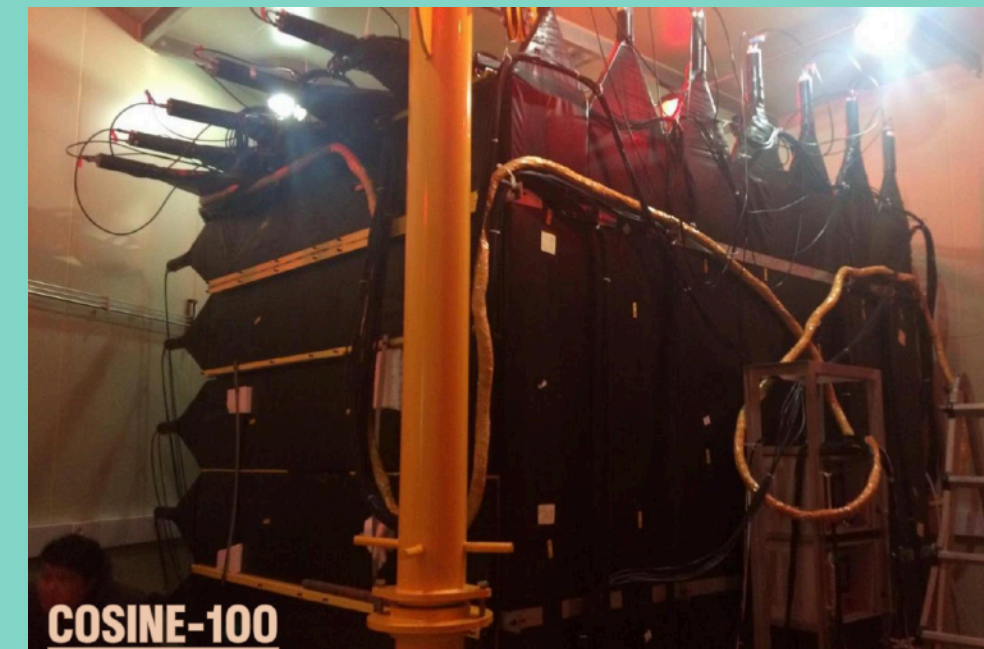
ANAIS-112

- ✦ 9 Ultrapure NaI(Tl) crystals (total: 112.5 kg)
- ✦ Operating in Canfranc UL (Spain)
- ✦ Preliminary 6 year results incompatible with the DAMA/LIBRA result at $\sim 4\sigma$



COSINE-100

- ✦ 5 Ultrapure NaI(Tl) crystals (total: 61.3 kg)
- ✦ Operating in Yangyang UL (Korea)
- ✦ 3 year results compatible with null and DAMA results (lack of stat.)



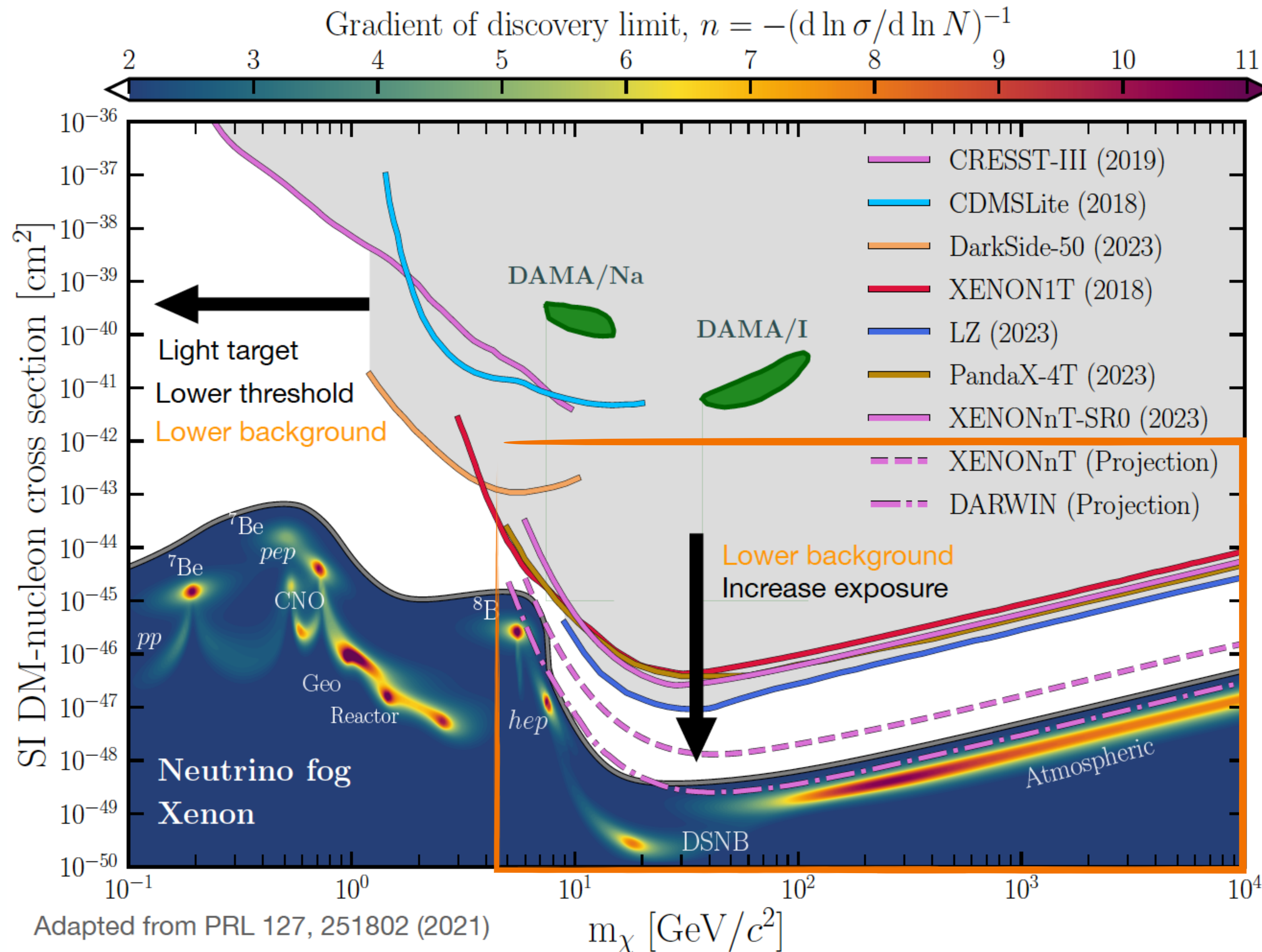
SABRE

R&D Ongoing

- ✦ 2x Ultra-low background NaI(Tl): North (LNGS - Italia), South (SUPL - Australia)

Direct Detection Landscape

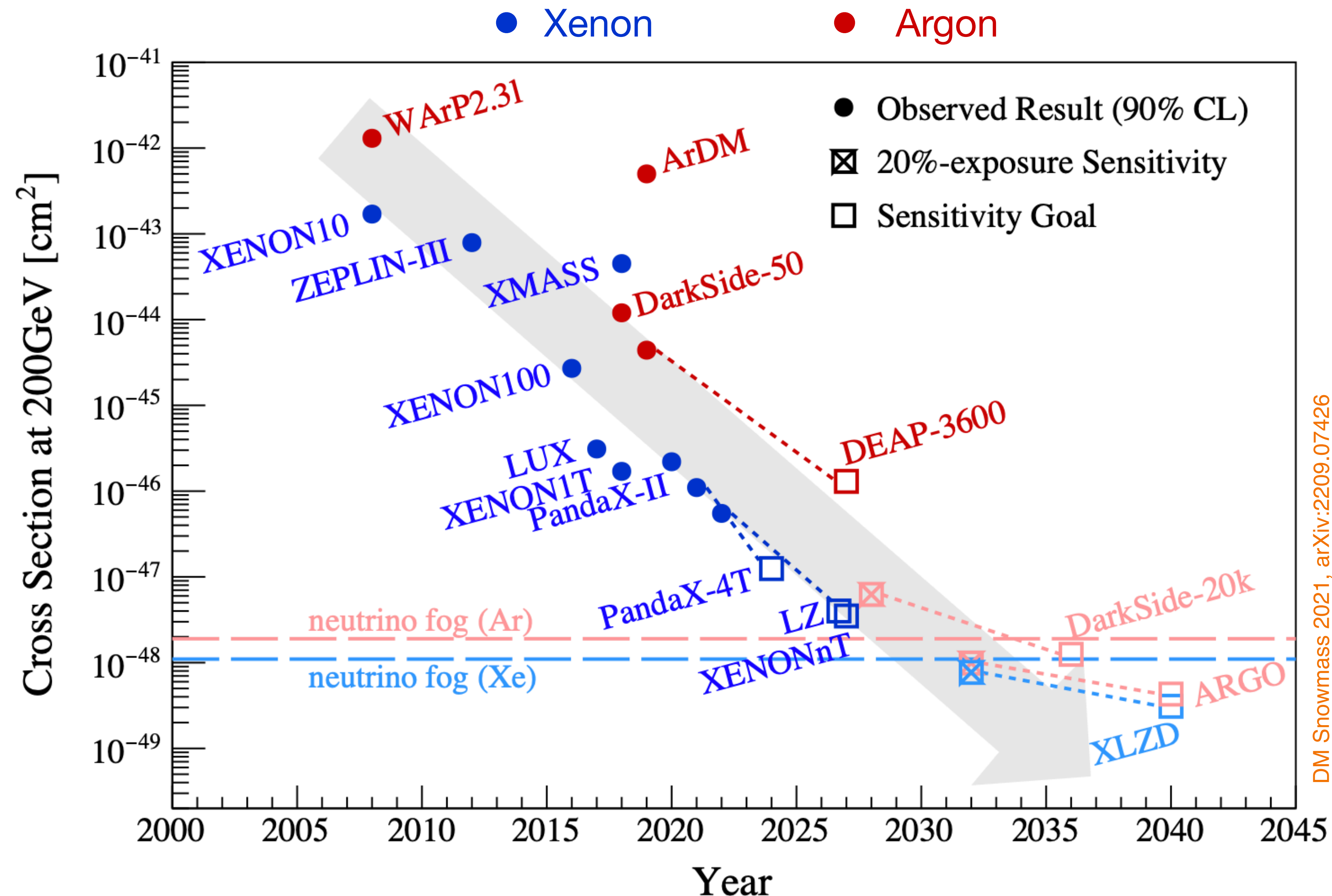
61



✱ Noble gases experiments are leading the race for high-mass WIMP search

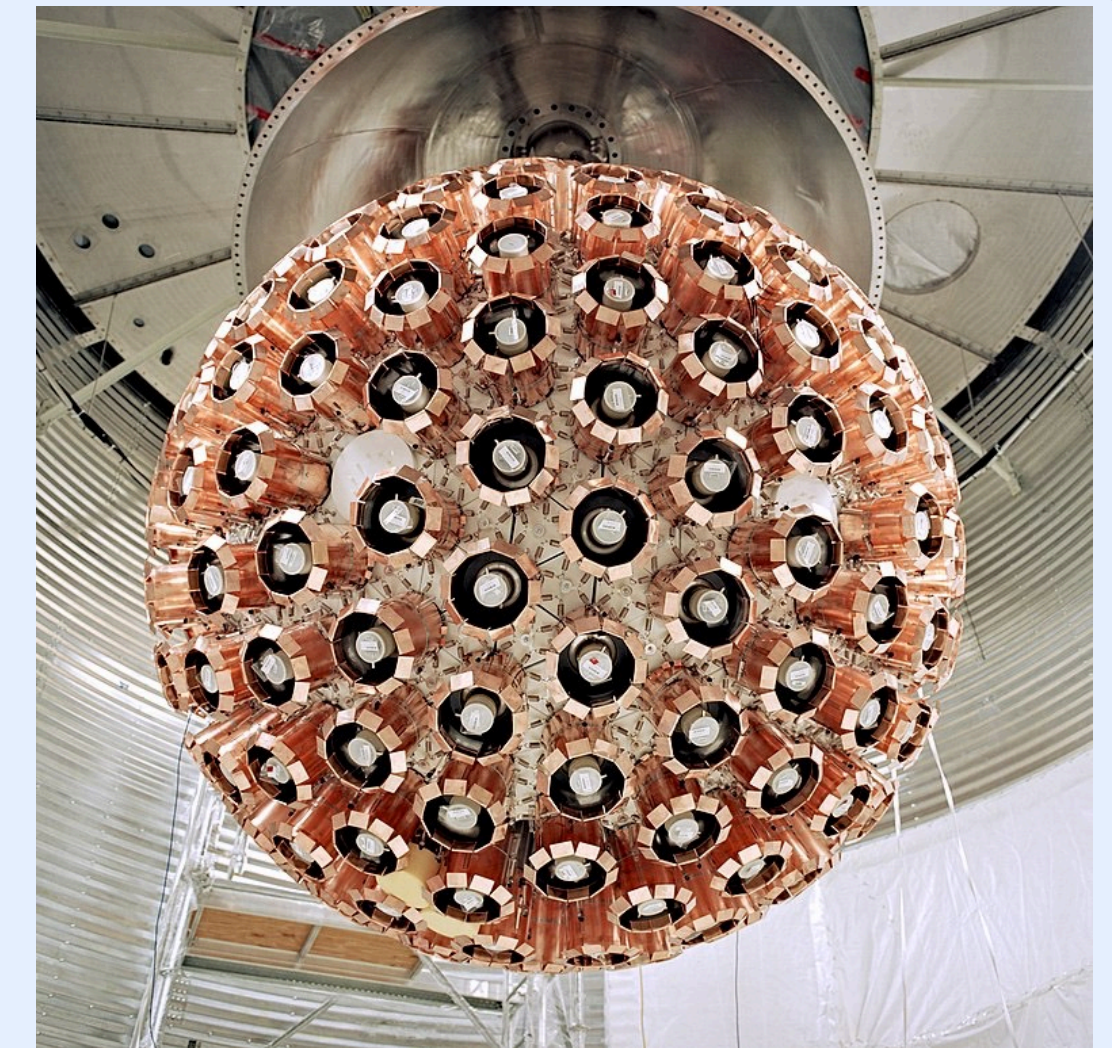
Wild race:

- ✦ Noble gases experiments are leading the race for high-mass WIMP search
- ✦ Reaching multiple tonne of noble element as target

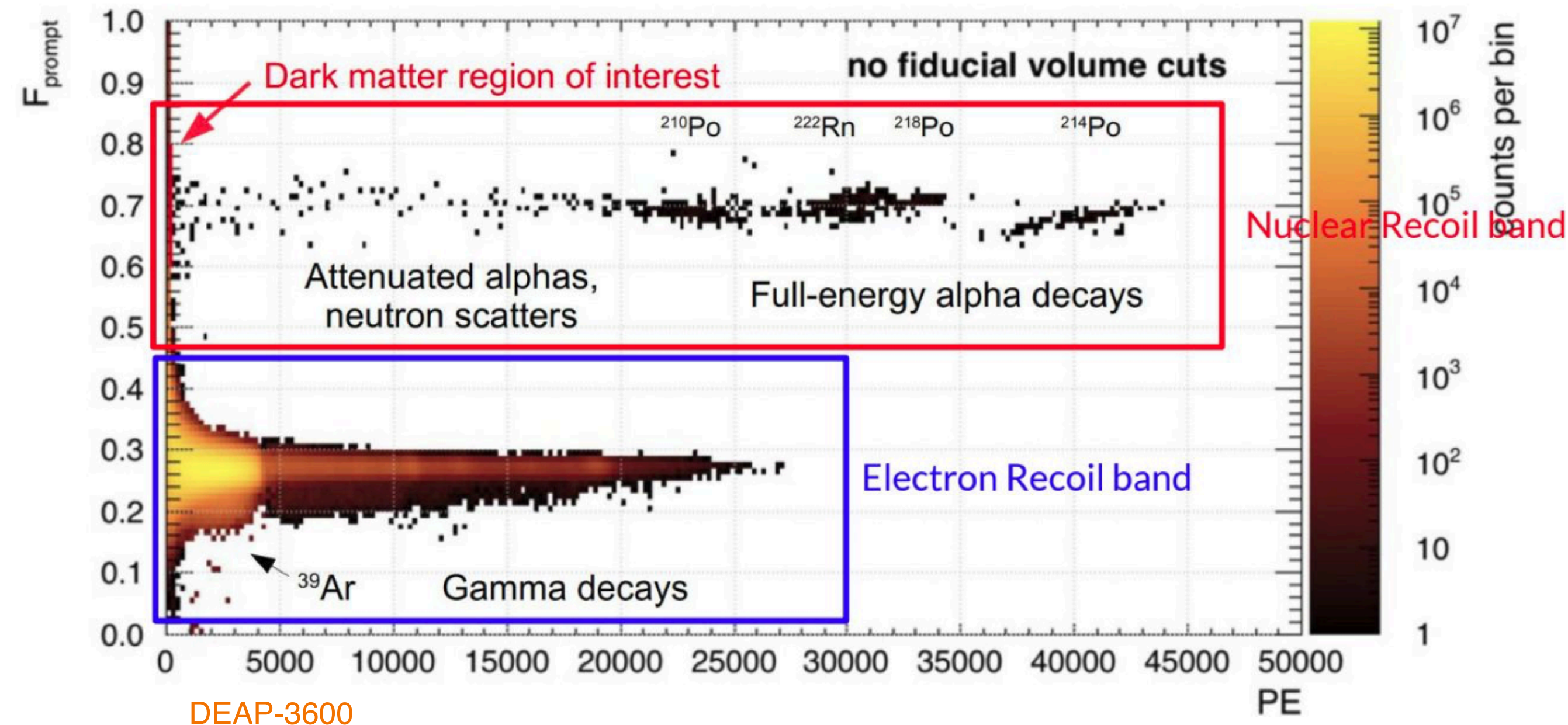


DEAP-3600

- ✦ 3.3 tonnes of liquid argon target | liquid scintillator detector
- ✦ Operating in SNOLAB UL (Canada)
- ✦ No WIMP-like signal find in the 1st year dataset
- ✦ 3 year dataset soon, and upgrade ongoing



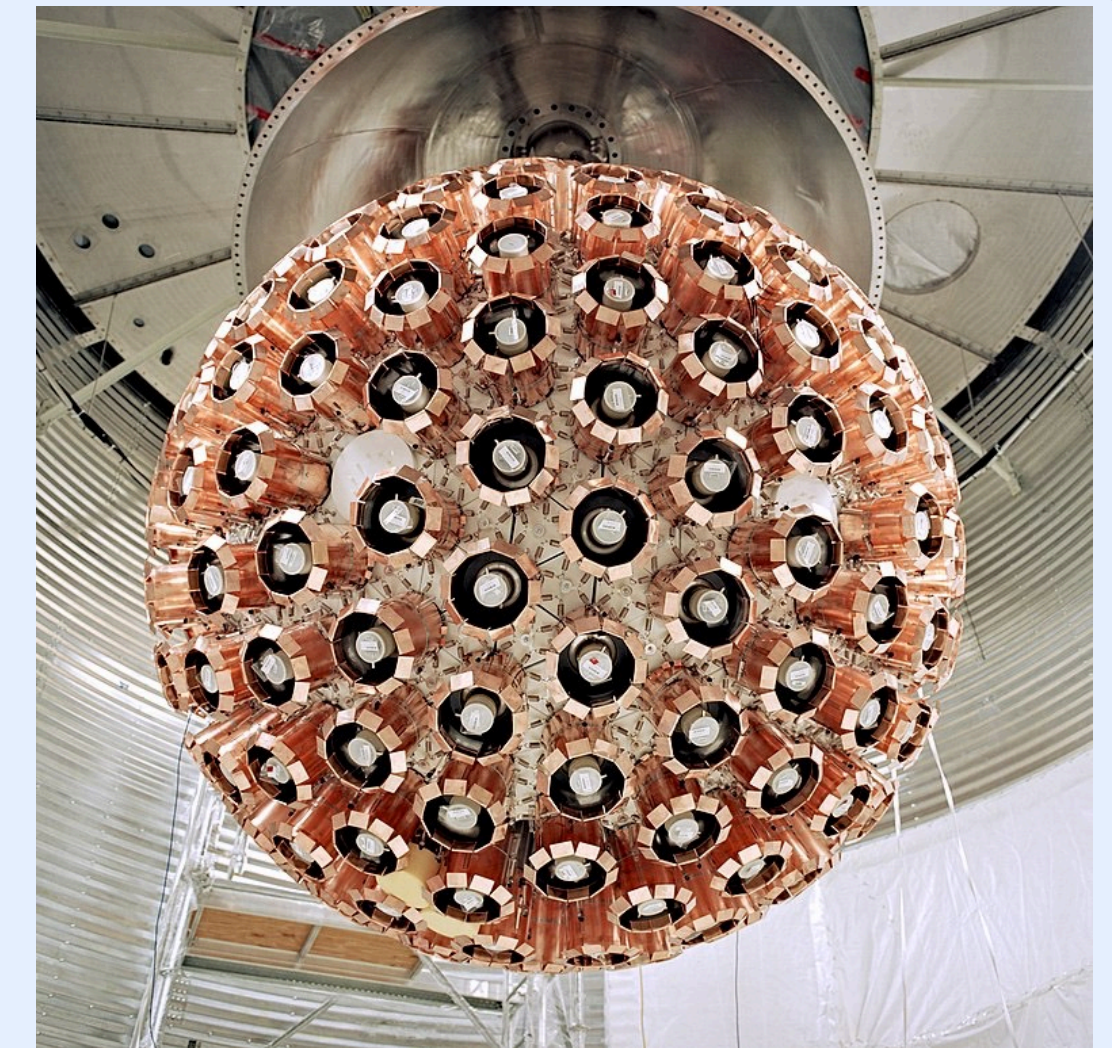
**Excellent ER/NR
discrimination**



DEAP-3600

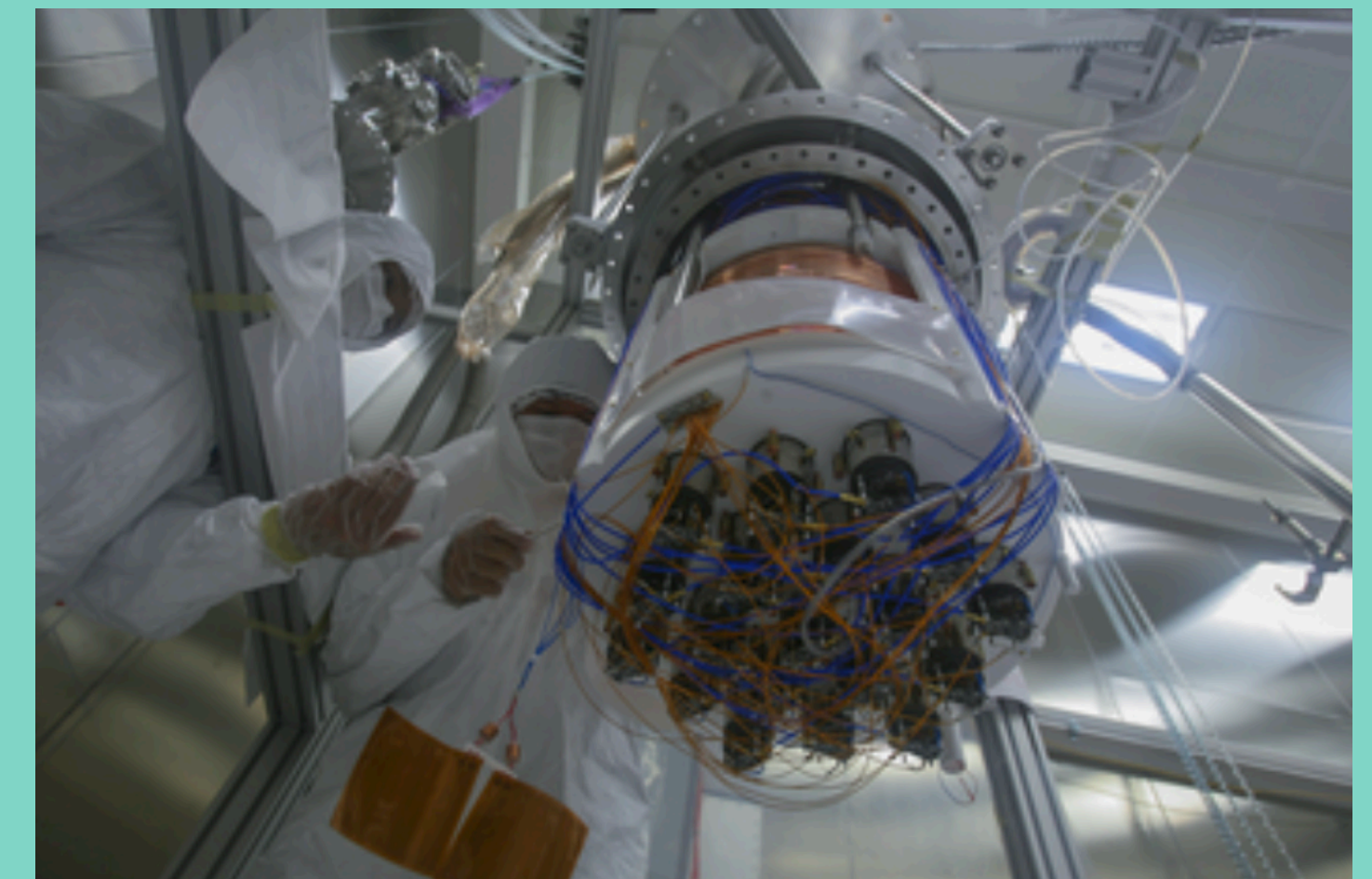
DEAP-3600

- ✦ 3.3 tonnes of liquid argon target | liquid scintillator detector
- ✦ Operating in SNOLAB UL (Canada)
- ✦ No WIMP-like signal find in the 1st year dataset
- ✦ 3 year dataset soon, and upgrade ongoing



DarkSide-50

- ✦ ~46 kg of liquid argon active mass | dual-phase TPC
- ✦ Operational in LNGS UL (Italy) between 2013-2019
- ✦ Ongoing transition → DarkSide-20k



Xenon dual-phase TPC

65

LZ



XENONnT



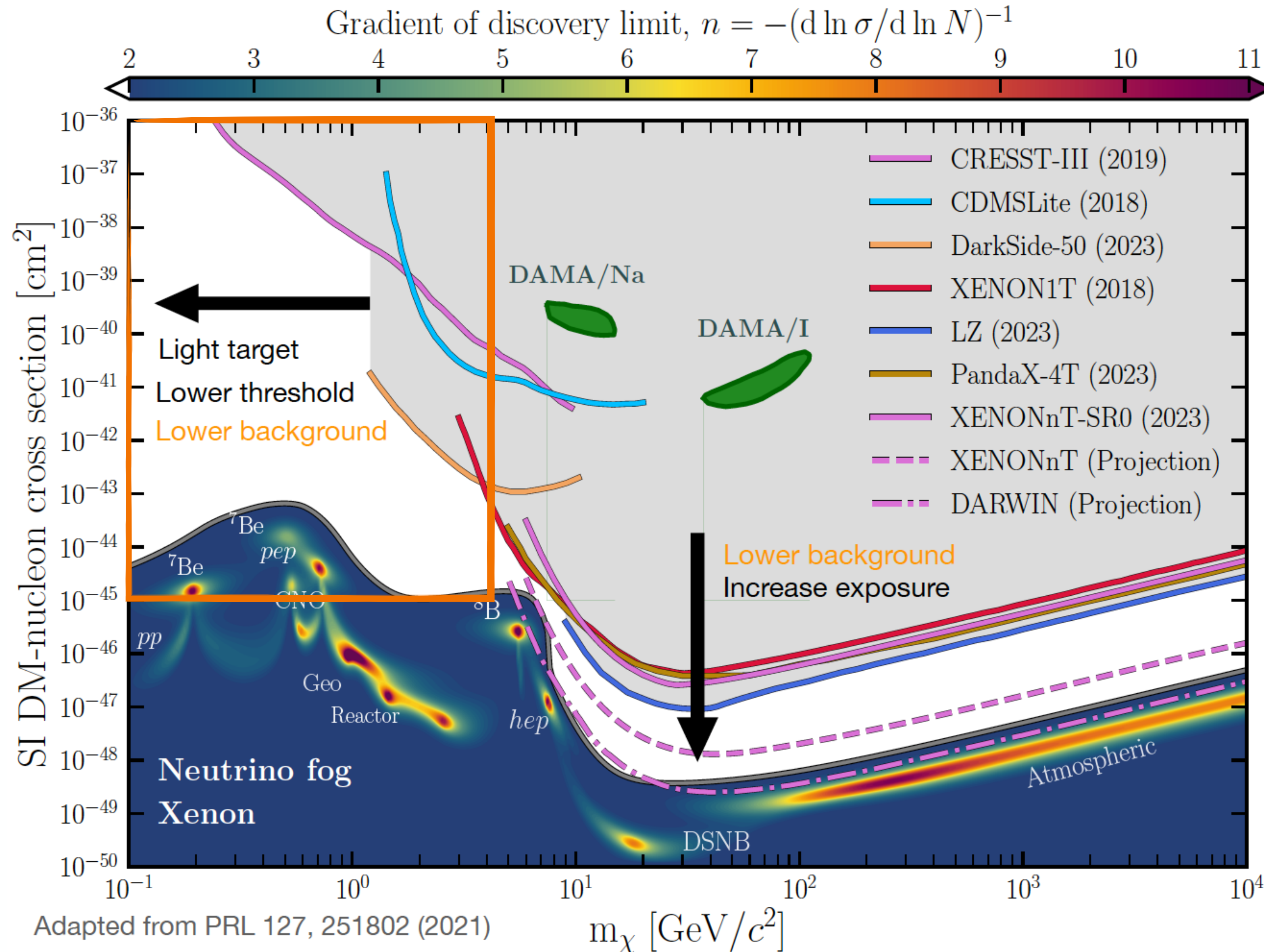
PandaX-4T



Will be discussed in further detail tomorrow

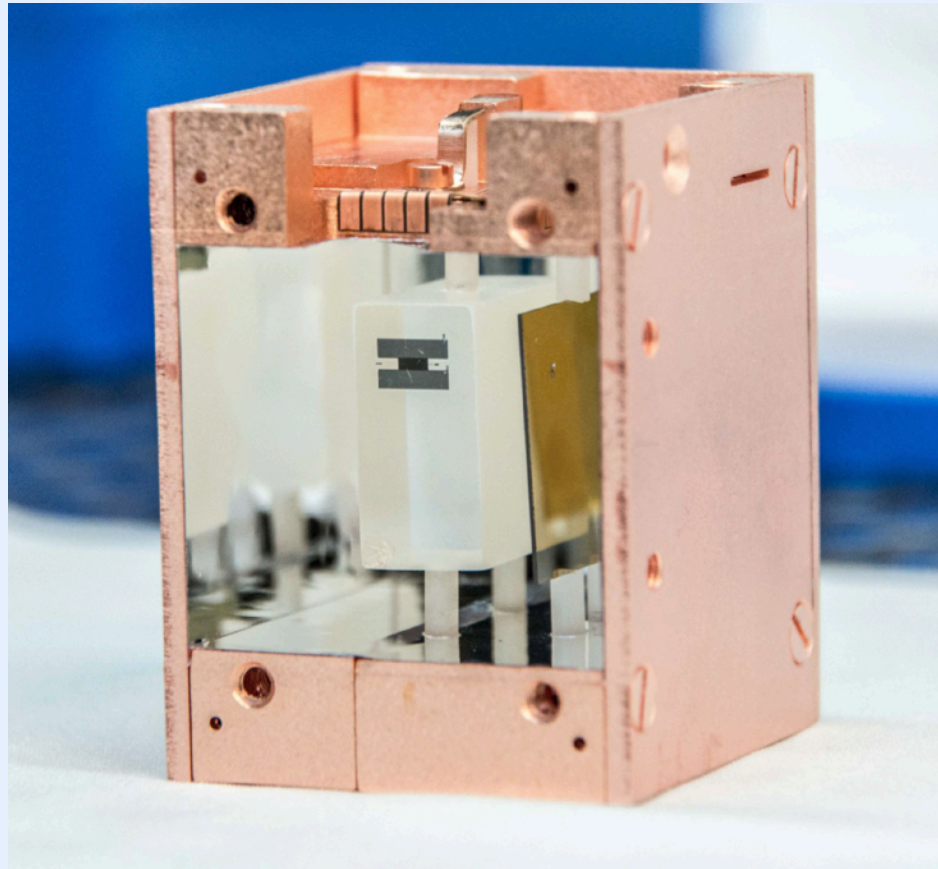
Direct Detection Landscape

66



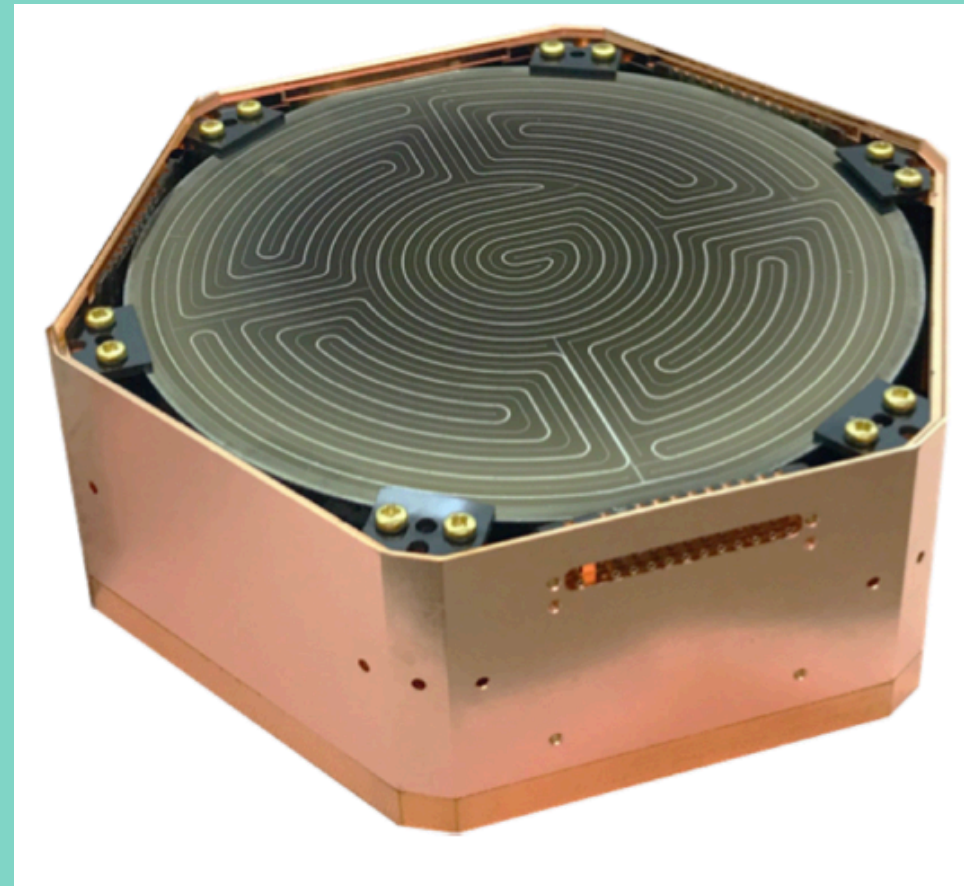
✱ Low-mass WIMP kingdom: cryogenic bolometers and CCDs

CRESST-III



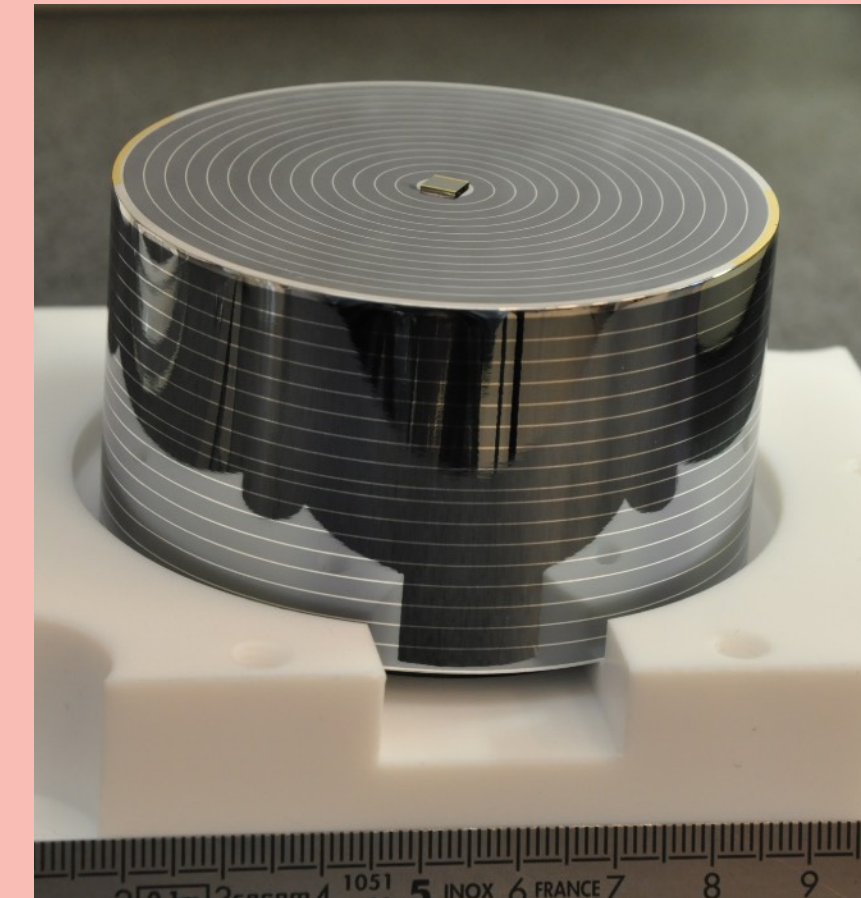
- ✦ ~24 g Scintillating crystal CaWO_4
- ✦ Result from 1st run operating at LNGS
- ✦ Limitation by Low-Energy Excess (LEE)

SuperCDMS



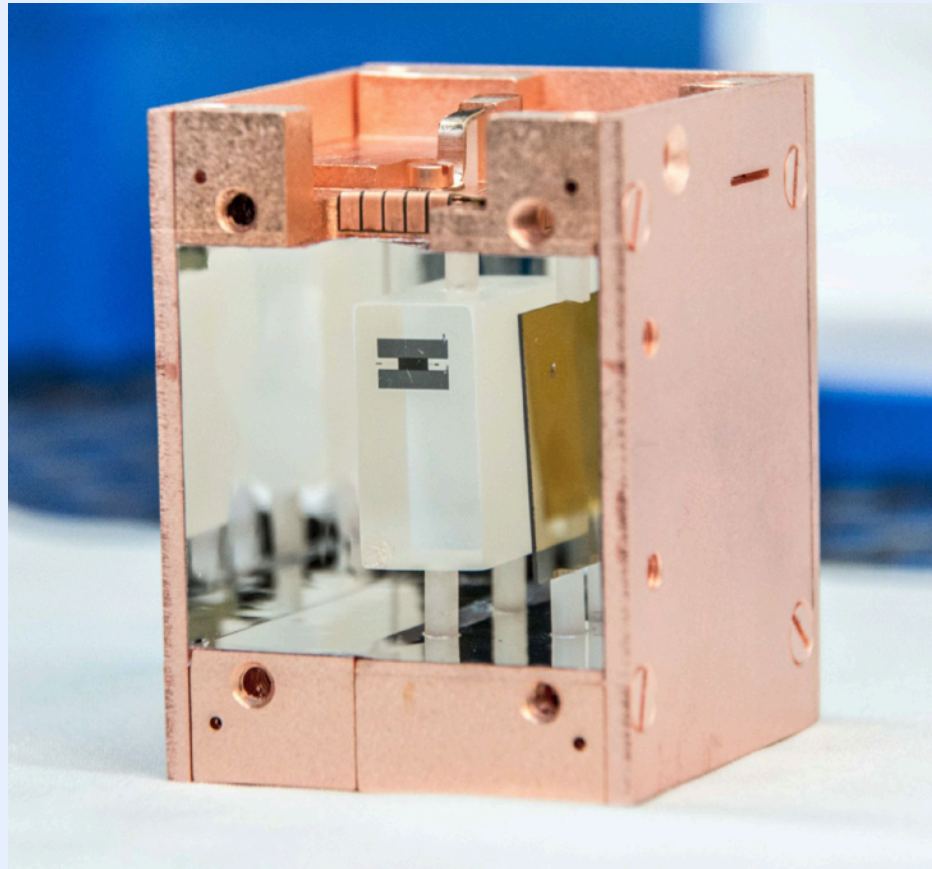
- ✦ Ge and Si cryogenic semiconductor
- ✦ Will operate at SNOLAB
- ✦ Commissioning in 2025

EDELWEISS-III

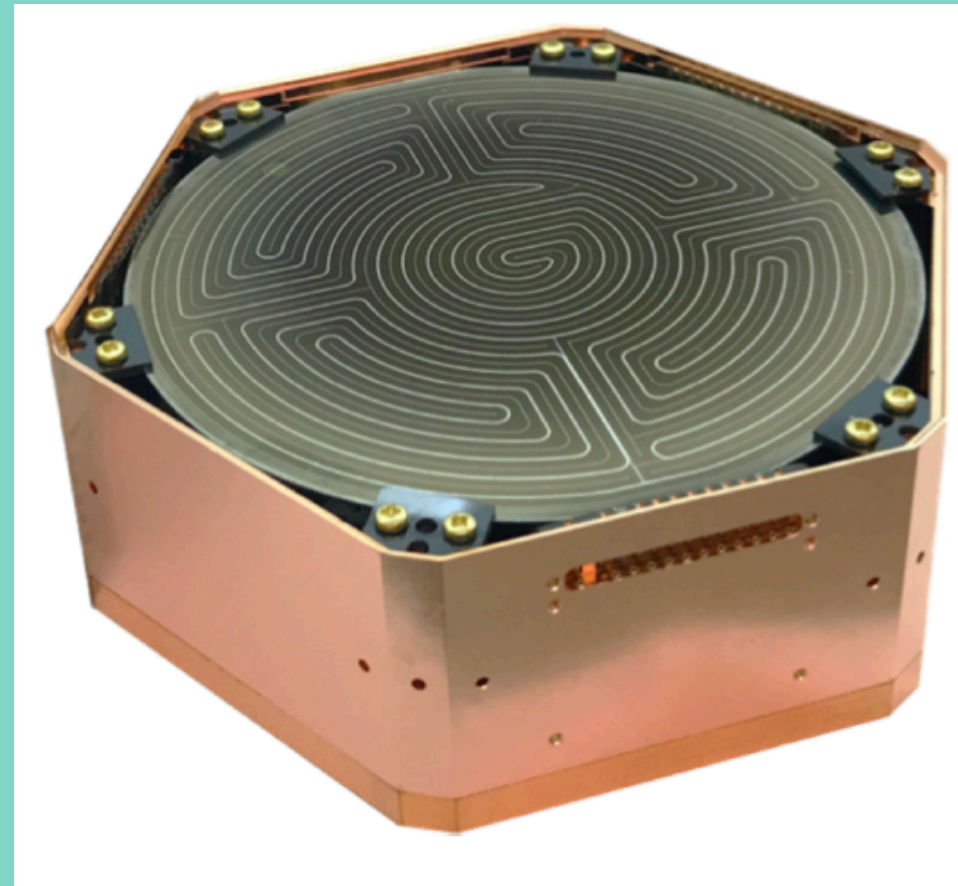


- ✦ Ge cryogenic semiconductor
- ✦ Operated at Modane
- ✦ 2014-2015: 582 kg-days exposure

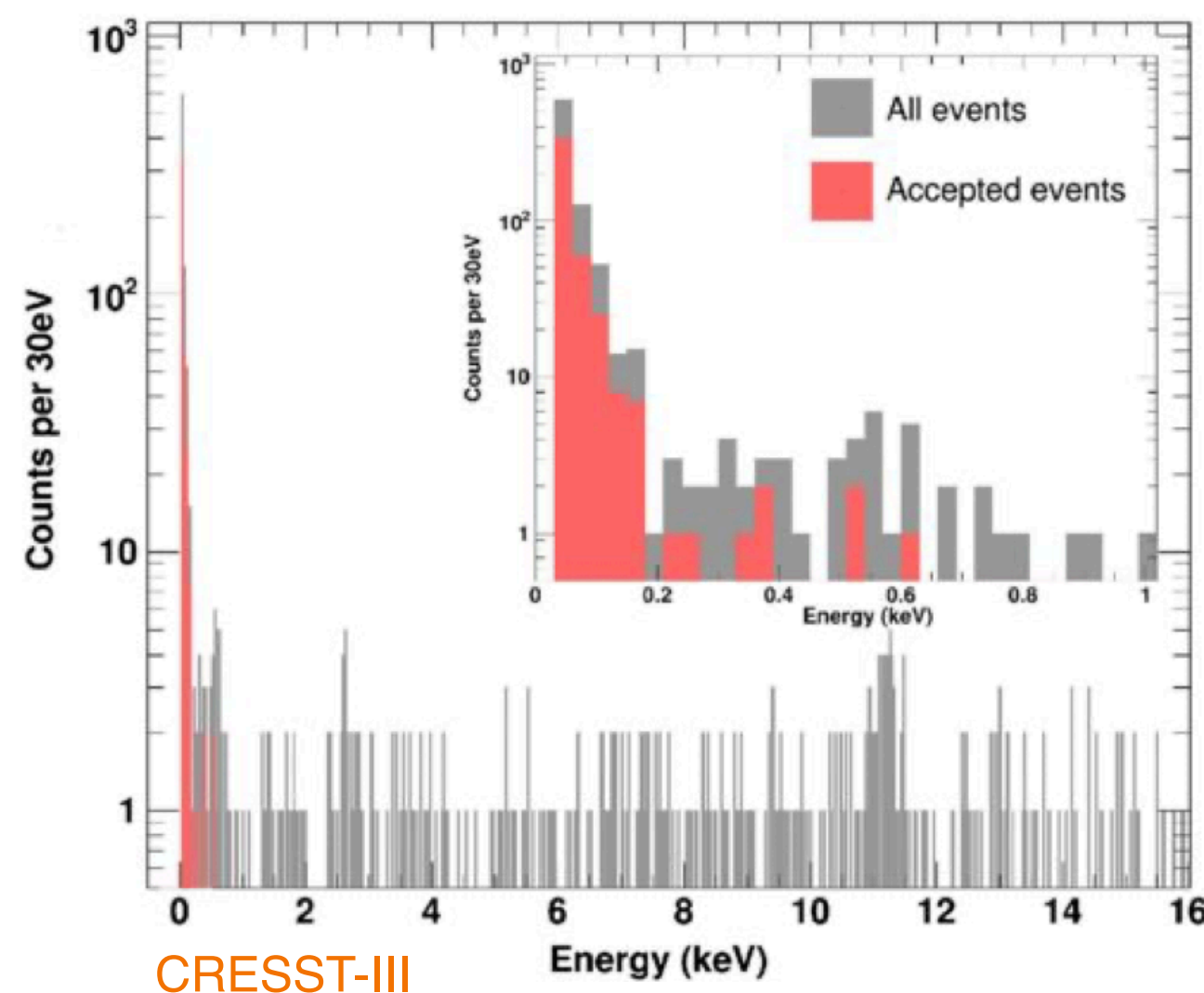
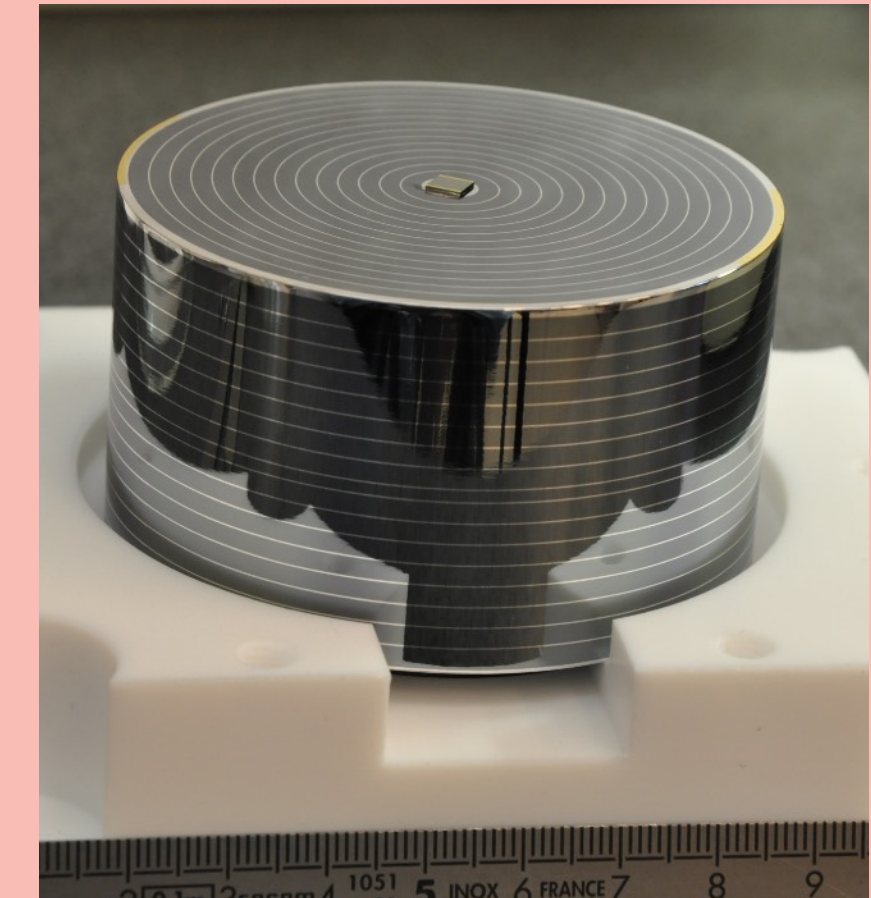
CRESST-III



SuperCDMS



EDELWEISS-III



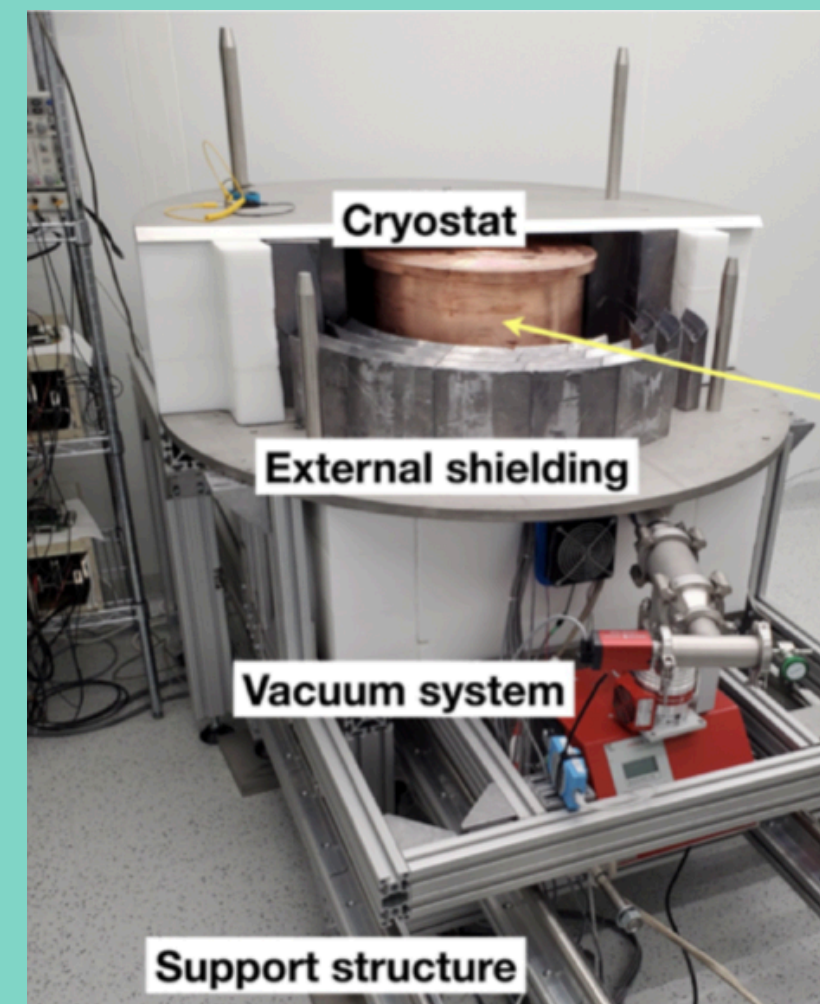
- ✱ Limitation by Low-Energy Excess (LEE)
 - Unknown source of backgrounds impacting currently all detector based on this technology
 - A lot of effort from the community to identify and mitigate the LEE. Potentially from structural stress.

DAMIC



- ❖ ~6g CCDs (7)
- ❖ Operate at SNOLAB
- ❖ Multiple results already published

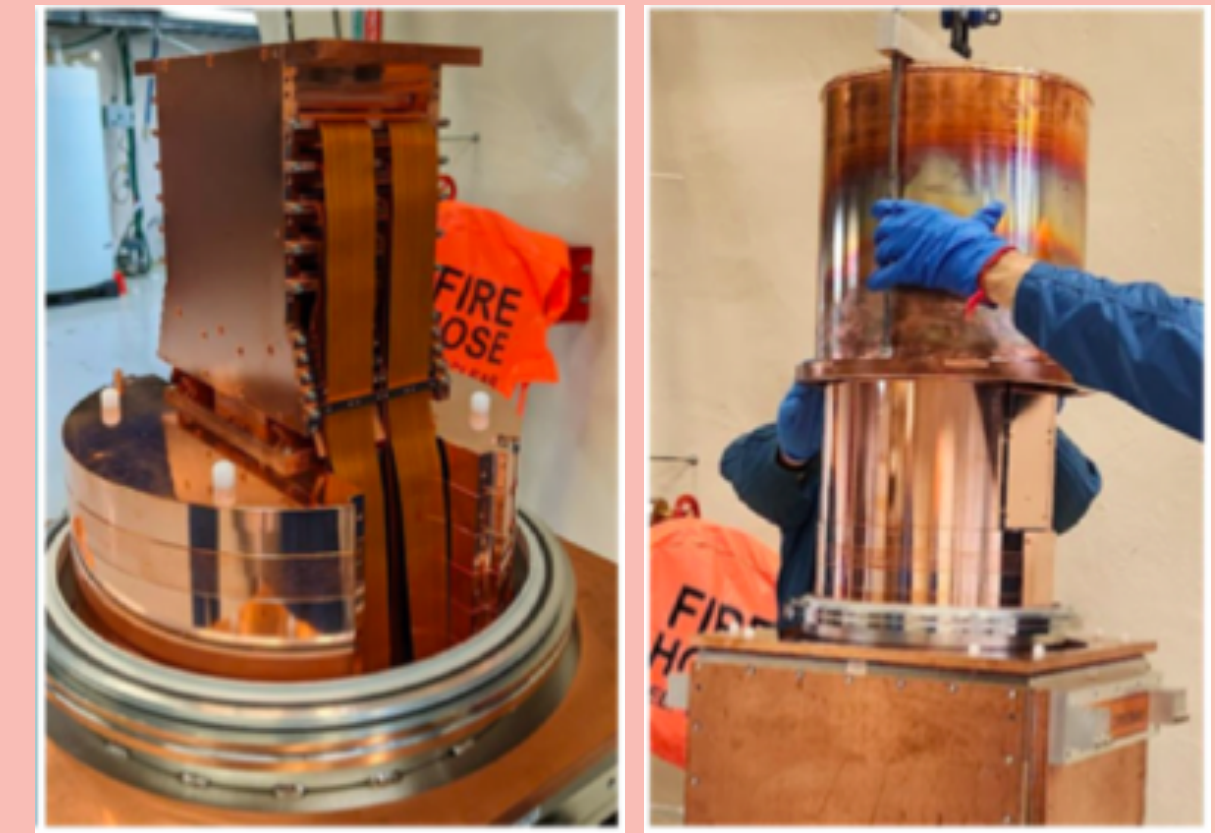
DAMIC-M



K. Schöffner, TAUP 2023I

- ❖ ~13g CCDs, two for the first run
- ❖ Operate at Modane
- ❖ Construction phase towards the kg scale

SENSEI



K. Schöffner, TAUP 2023I

- ❖ Different phase, now reaching ~40g per CCDs (19)
- ❖ Operate at SNOLAB
- ❖ Science run ongoing

arXiv:2406.01705

Experiment	Location	Data Taking	Readout	Target	Home	Ref.
DARKSIDE-20K	Gran Sasso, Italy	2023	scint.+ioniz. (~ 85 K)	20 t Ar	web	[378]
SBC	SNOLAB, Canada	2028	scint. bubble chamb. (~ 100 K)	10 kg Ar	talk	[379]
ARGO	SNOLAB, Canada	2029	scint.+ioniz. (~ 85 K)	300 t Ar	web	web
DARKSIDE-LM			scint.+ioniz. (~ 85 K)	1.5 t Ar	web	[380]
LZ-HYDROX	Sanford, SD	202x	ioniz.+scint. (174 K)	5.5 t Xe + 2 kg H ₂	web	LOI
DARWIN/XLZD	undetermined	2027/28	scint.+ioniz. (~ 170 K)	40/60 t Xe	web	[381]
PANDAX-xT	Jinping, China	202x	scint.+ioniz. (~ 170 K)	43 t Xe	web	[382]
QUEST-DMC			quasipart. (~ 100 μ K)	1 cm ³ ³ He	paper	[383]
DELIGHT	Vue-des-Alpes, Switz.	202x	phon.+roton (~ 20 mK)	10 l ⁴ He	web	[384]
HERALD		202x	phon.+roton (~ 50 mK)	~ 1 kg ⁴ He	web	[385]
SUPERCDMS SNOLAB	SNOLAB, Canada	2023	ath. phon.[+ioniz.] (15 mK)	11[+14] kg Ge	web	[386]
			ath. phon.[+ioniz.] (15 mK)	2.4[+1.2] kg Si		
DAMIC-M	Modane, France	2025	ioniz. (~ 120 K)	0.7 kg Si	web	[387]
OSCURA	SNOLAB, Canada	2029	ioniz. (~ 130 K)	10 kg Si	web	[388]
CDEX-50	Jinping, China	202x	ioniz. (~ 90 K)	~ 300 kg Ge	web	talk
EDELWEISS-CRYOSEL	Modane, France	202x	ath. phon. (~ 10 mK)	~ 30 g Ge	web	[389]
CDEX-300	Jinping, China	2027	ioniz. (~ 90 K)	~ 300 kg Ge	web	LOI
CDEX-1T	Jinping, China	2033	ioniz. (~ 90 K)	~ 1 t Ge	web	LOI
CDEX-10T	Jinping, China	2040	ioniz. (~ 90 K)	~ 10 t Ge	web	LOI
COSINE-200	Yemilab, South Korea	2024	scint. (~ 300 K)	~ 200 kg NaI(Tl)	web	talk
COSINUS	Gran Sasso, Italy	2024	scint. (~ 10 mK)	~ 1 kg NaI(Tl)	web	[390]
SABRE	Gran Sasso, Italy	2024	scint. (~ 300 K)	50 kg NaI(Tl)	web	[339]
	SUPL, Australia	2023	scint. (~ 300 K)	50 kg NaI(Tl)	web	
PICOLON	Kamioka, Japan	202x	scint. (~ 300 K)	54 $\rightarrow$ 250 kg NaI(Tl)	paper	[391]
KAMLAND-PICO	Kamioka, Japan	203x	scint. (~ 300 K)	1000 kg NaI(Tl)	paper	[391]
DMICE-250	South Pole		scint. (~ 260 K)	~ 200 kg NaI(Tl)	talk	talk
PICO-40L	SNOLAB, Canada	2023	bubble chamber (~ 290 K)	~ 50 kg C ₃ F ₈	web	[392]
PICO-500	SNOLAB, Canada	202x	bubble chamber (~ 290 K)	360 kg C ₃ F ₈	web	[393]
MOSCAB	Gran Sasso, Italy	202x	bubble chamber (~ 290 K)	2 $\rightarrow$ 25 l C ₃ F ₈	paper	[348]
MIMAC	Grenoble, France		ioniz. (~ 300 K)	CF ₄ +CHF ₃	paper	[352]
NEWS-G : ECUME	SNOLAB, Canada		ioniz. (~ 300 K)	~ 2 kg CH ₄	web	[335]
NEWS-G : DARKSPHERE	Boulby, UK		ioniz. (~ 300 K)	27 kg He+C ₄ H ₁₀	web	[335]
CYGN0	Gran Sasso, Italy	2024	ioniz. (~ 300 K)	1 m ³ He+CF ₄	web	[354]
CYGNUS	multiple sites		ioniz. (~ 300 K)	10 ³ m ³ He+SF ₆ /CF ₄	web	[355]
SNOWBALL			supercooled liq. (~ 250 K)	1 kg H ₂ O	talk	[394]
ALETHEA			scint.+ioniz. (~ 4 K)	10 kg He	paper	[395]
TESSERACT			ath. phon.	Al ₂ O ₃ , GaAs, He	web	LOI
SPLENDOR			ioniz	Eu ₅ In ₂ Sb ₆ , EuZn ₂ P ₂	poster	LOI
WINDCHIME			accelerometers		paper	[266]

Planned future, and R&D project for direct detection experiment, few examples

Final test for DAMA results

Next generation of Noble gases TPC to reach the neutrino fog

Directionality to overcome it

Exploring the low-mass DM realm