# Dark Matter Experiments - I

Maxime Pierre

BND Graduate School — Blankenberge 2024

# Avant-propos



## 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 status 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*

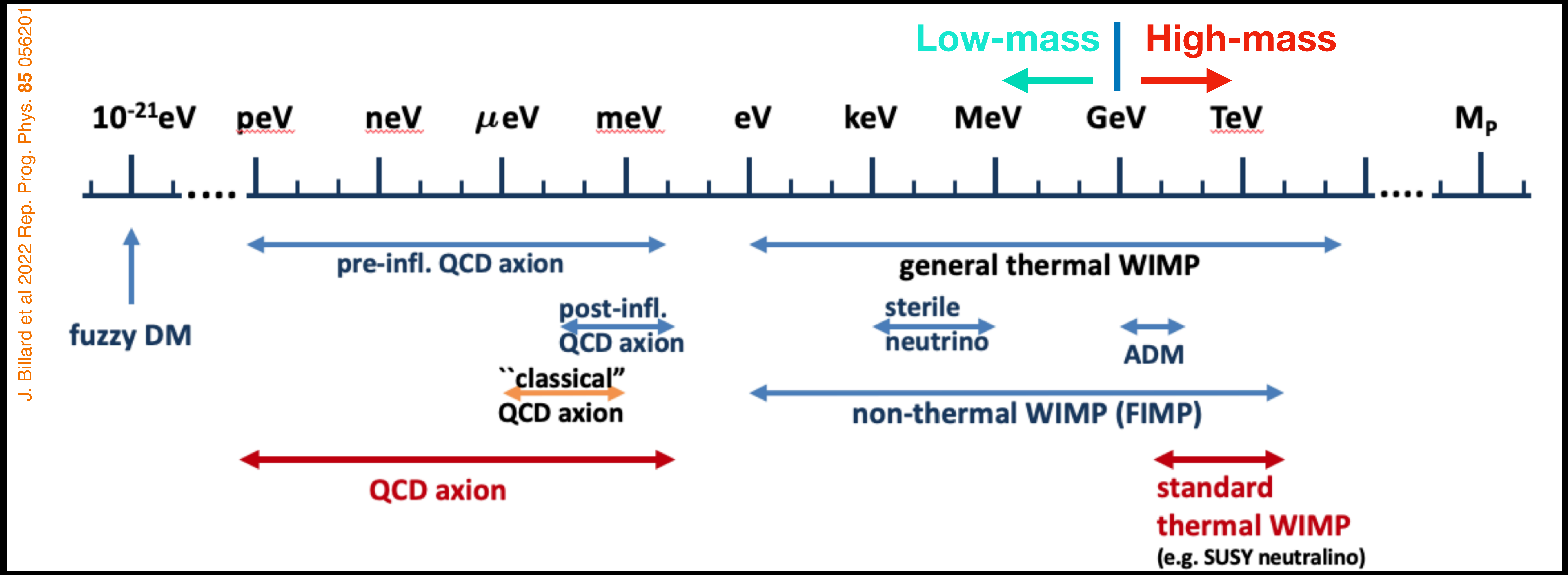
**Jure Zupan**

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

**Abstract**

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

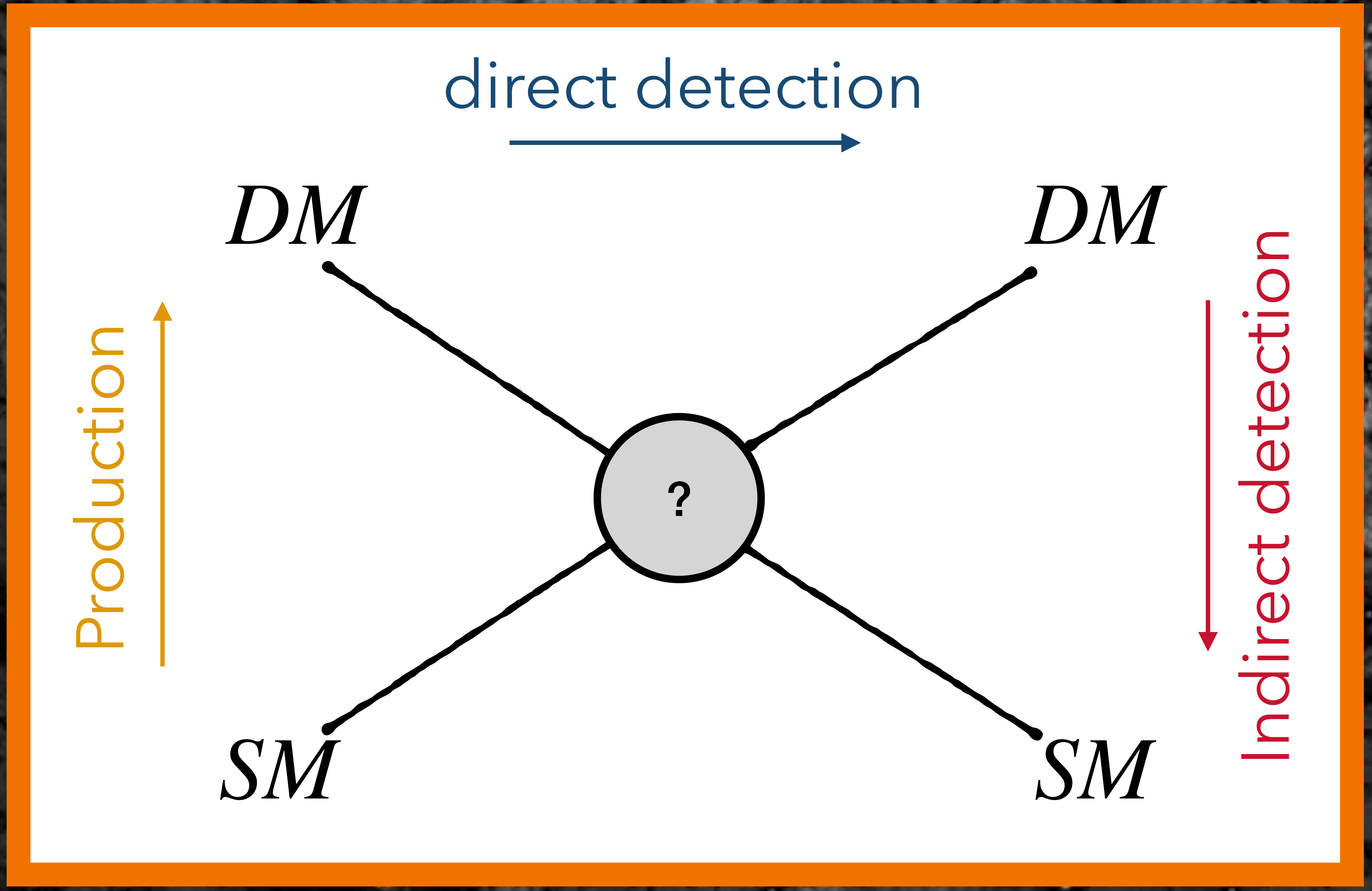
Version 0, November 11, 2011 – Version 1, June 3, 2024 – Version 2, July 31, 2024




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

Will Focus on WIMPs searches


© PHOTOTHEQUE IN2P3 /


direct detection
DM
DM
Production
?
Indirect detection
SM
SM

# Overview



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

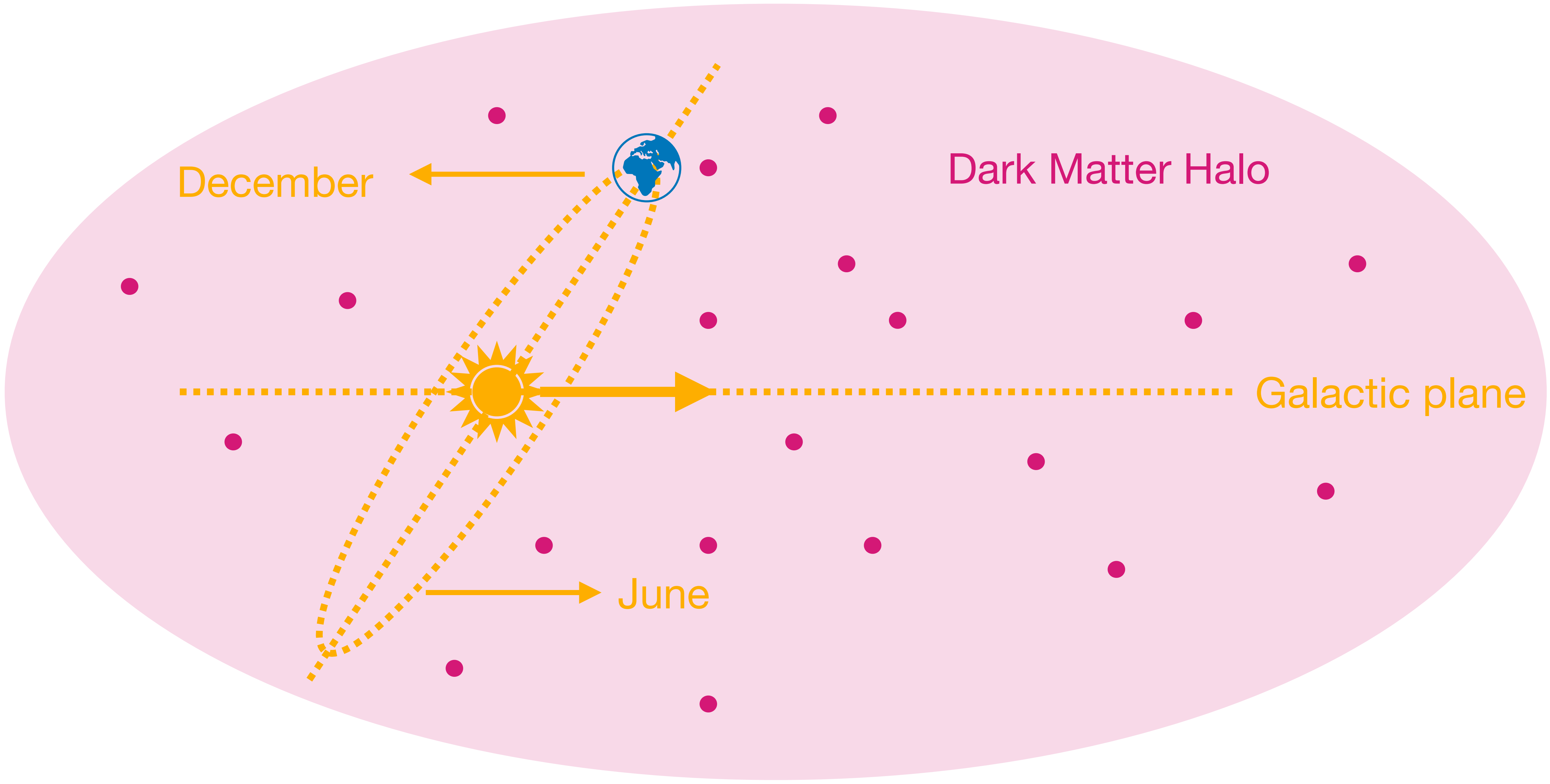
3. Experimental Landscape

   Overview of the current experimental Landscape for Dark Matter Direct Detection


Direct Detection Principle

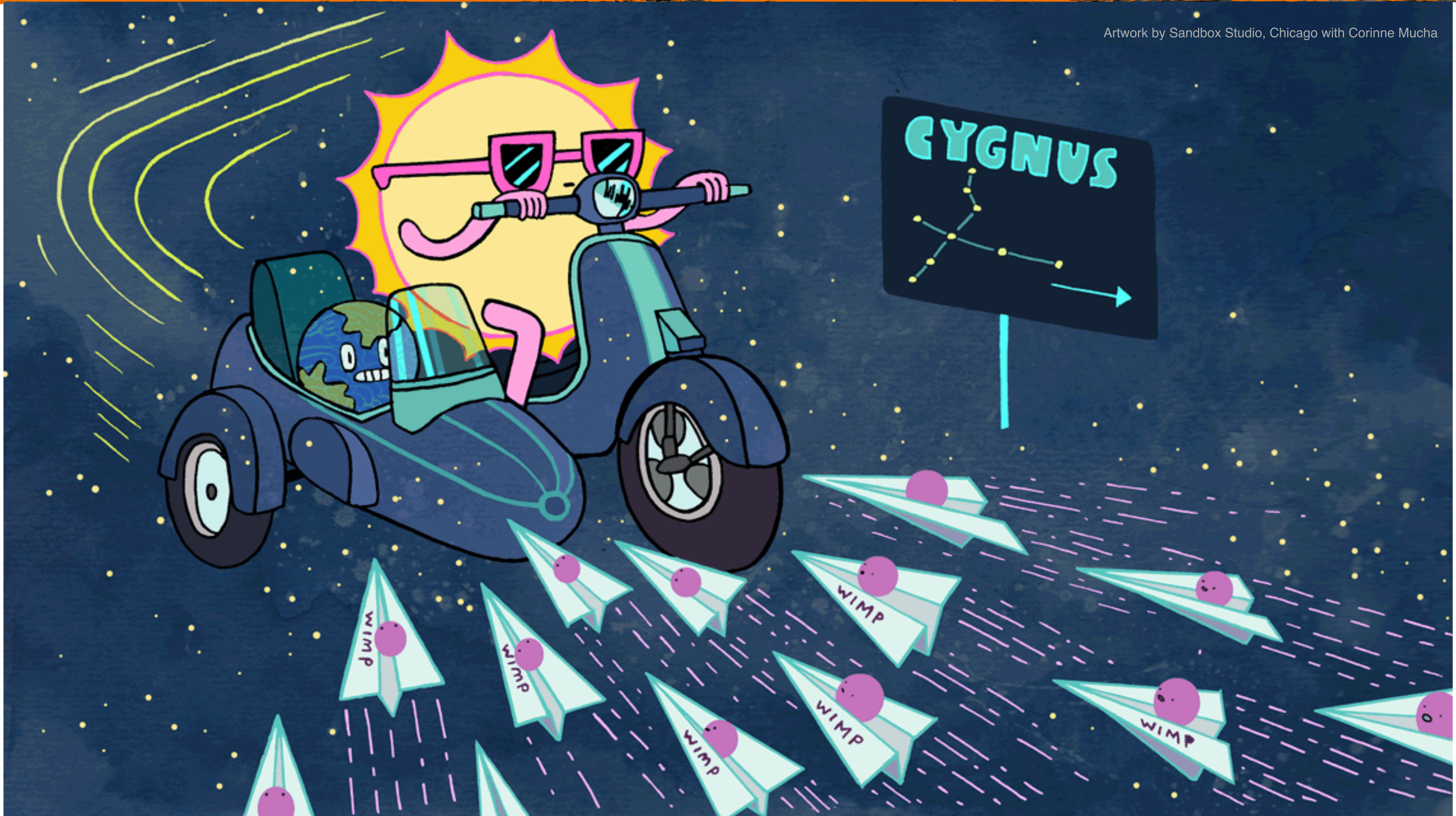
## Dark Matter in the Milky Way:

- 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”



# Dark Matter - Direct Detection Principle



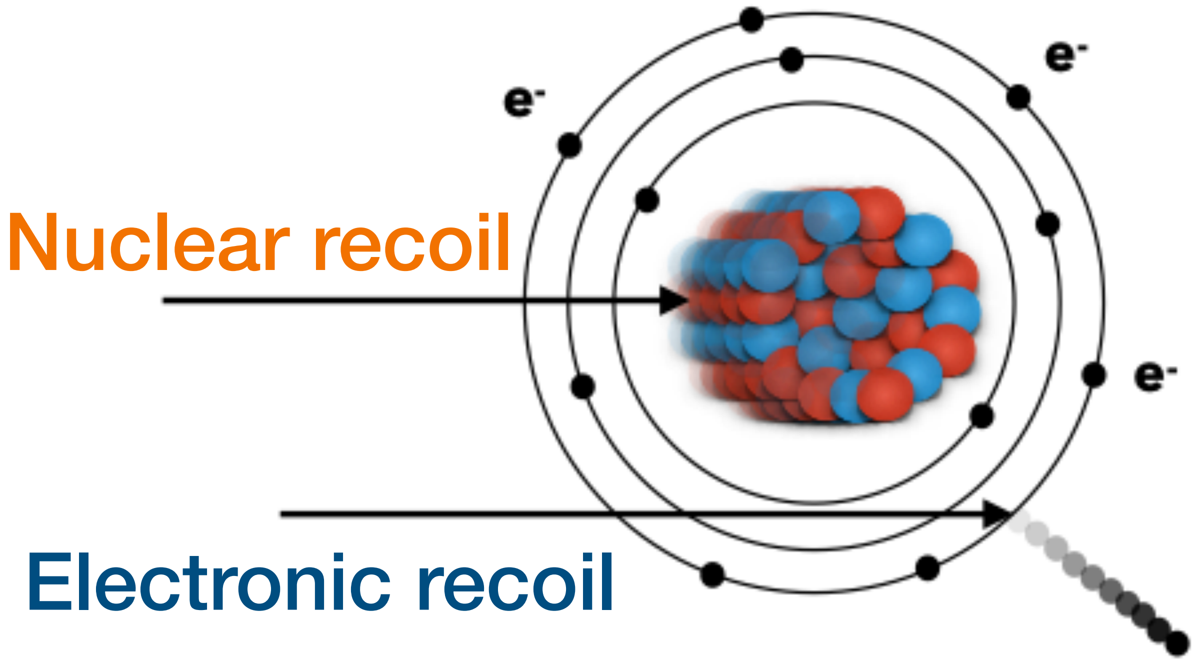


# Direct Detection Principle



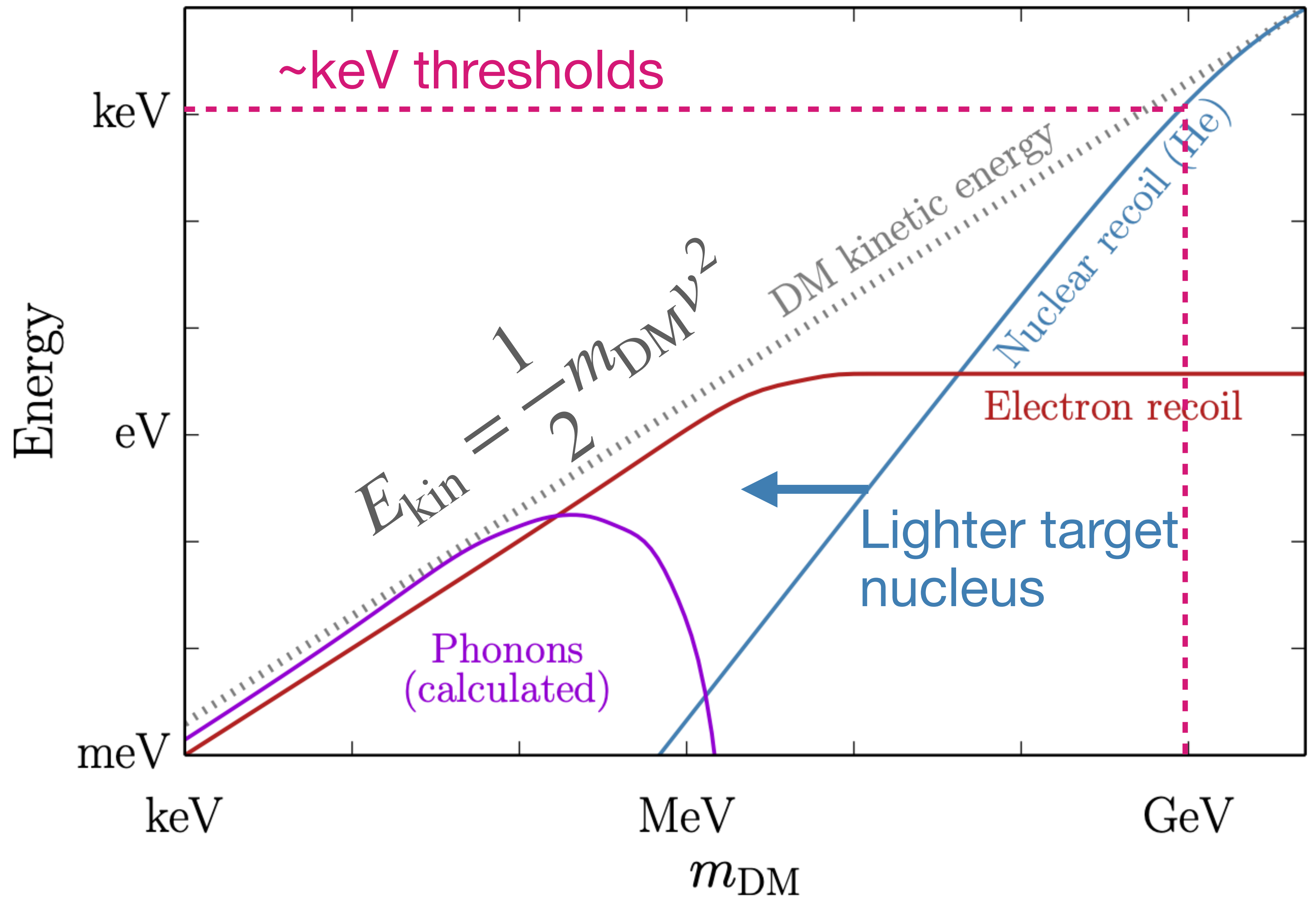
## Dark Matter Signature:

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




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

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



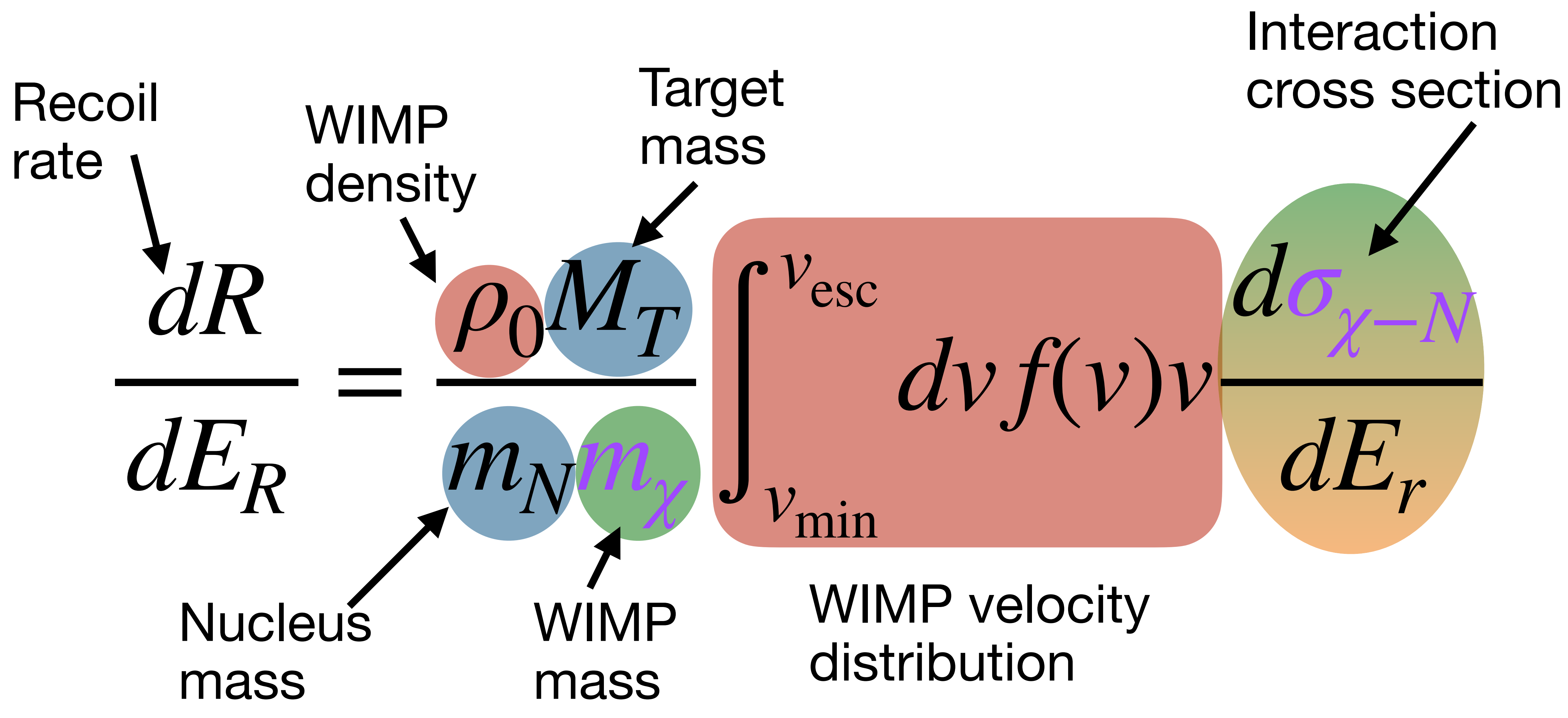

T. Lin, TASI lectures, arXiv:1904.07915

# Direct Detection Principle



## How Challenging is it?

- 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




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

Unknown parameter we are looking for

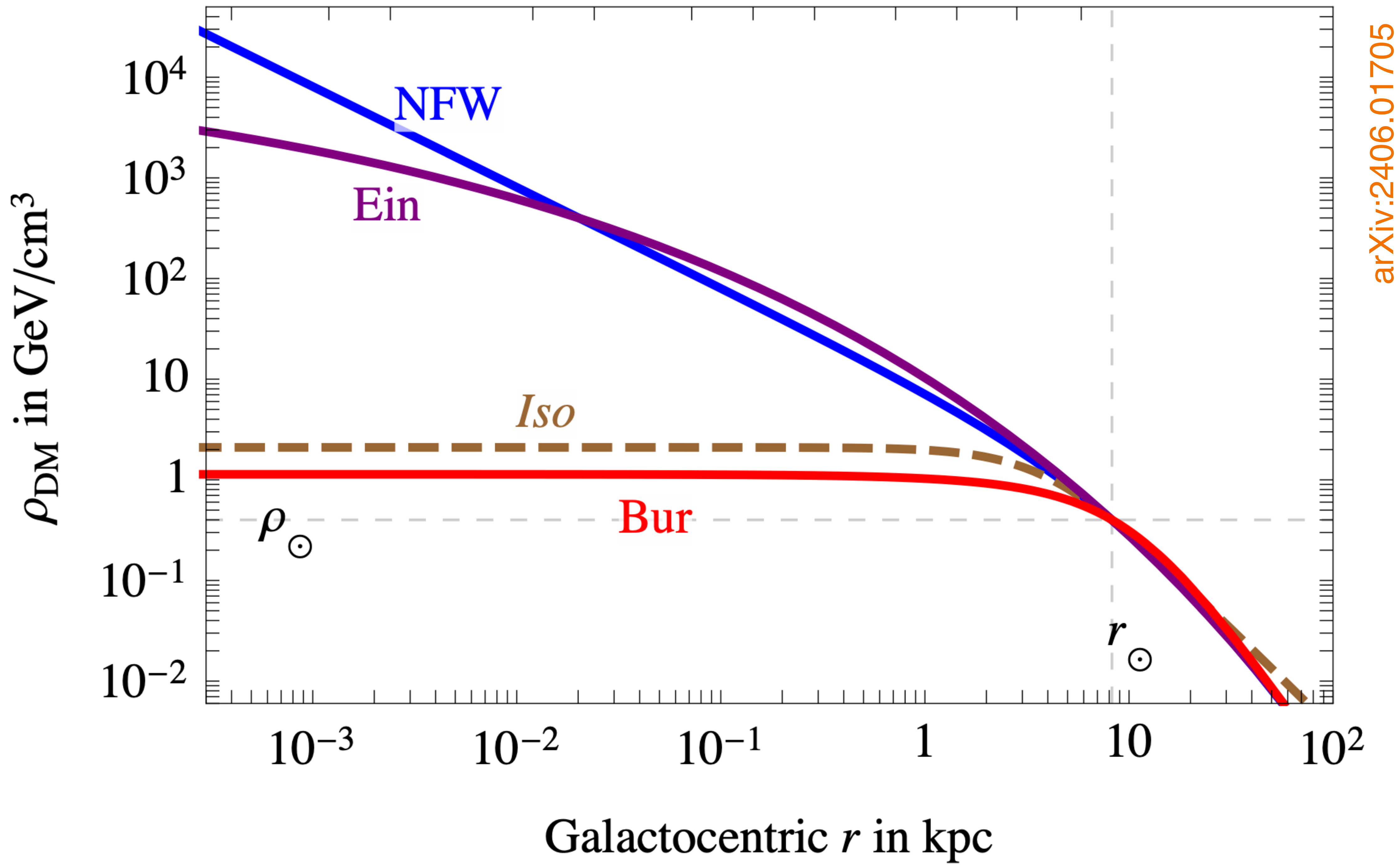
# Direct Detection Principle



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

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



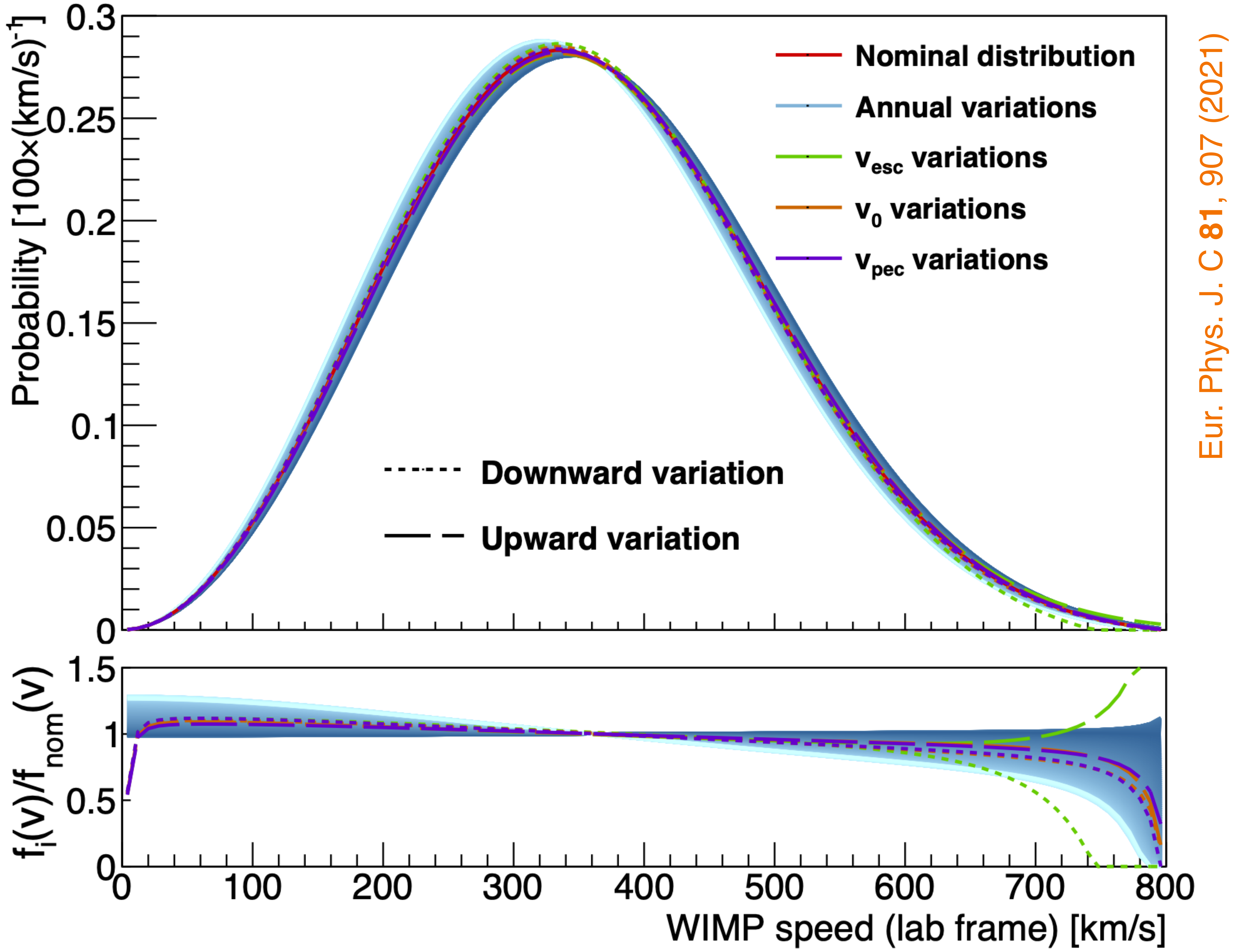

arXiv:2406.01705

# Direct Detection Principle

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

## 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.




Eur. Phys. J. C 81, 907 (2021)

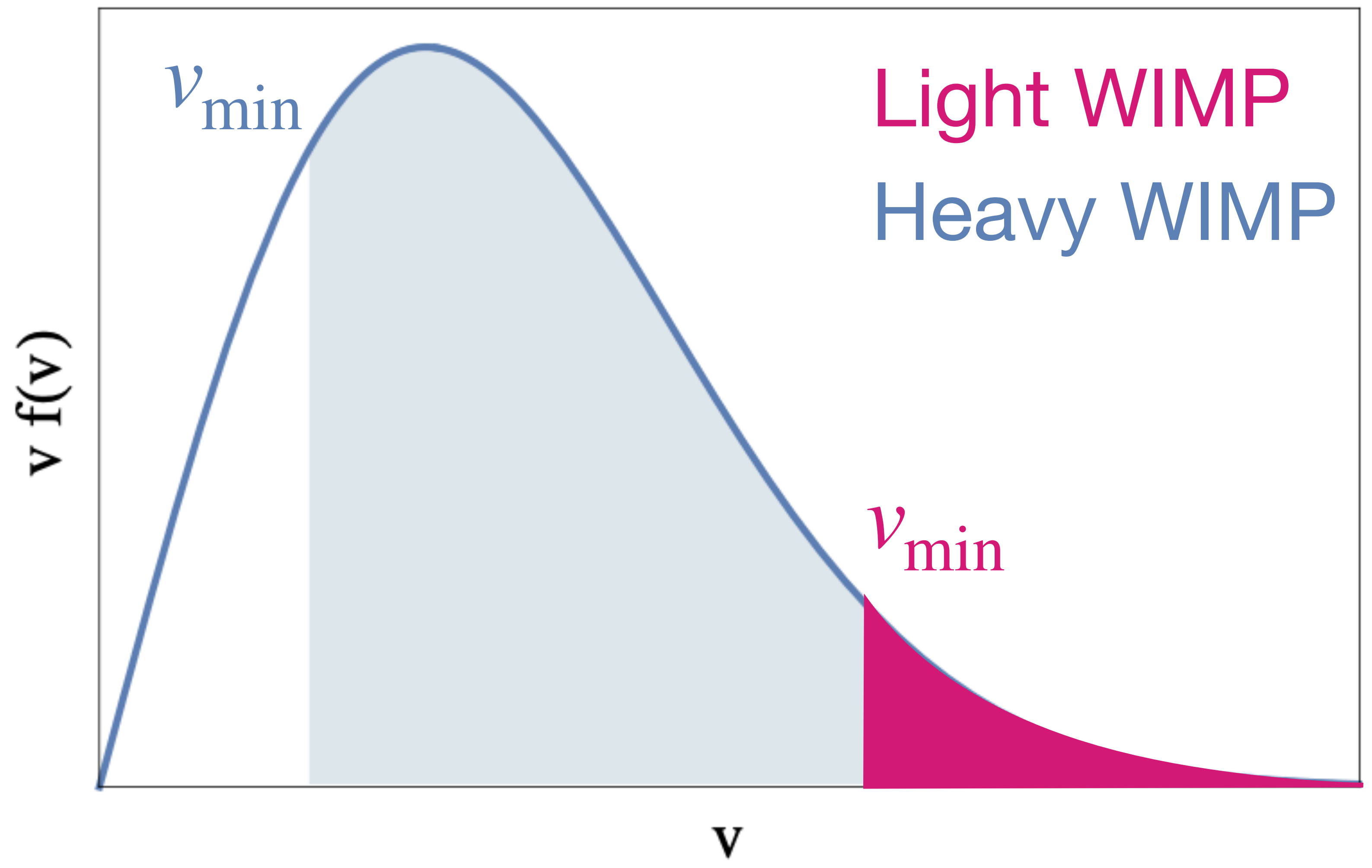
## Dark Matter Halo Model:

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

- 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

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

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




M. Lisanti, TASI lectures, arXiv:1603.03797

# Direct Detection Principle



## Interaction Cross section:

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

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

Helm form factor

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

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

$\sigma_0$: cross section at zero momentum transferred

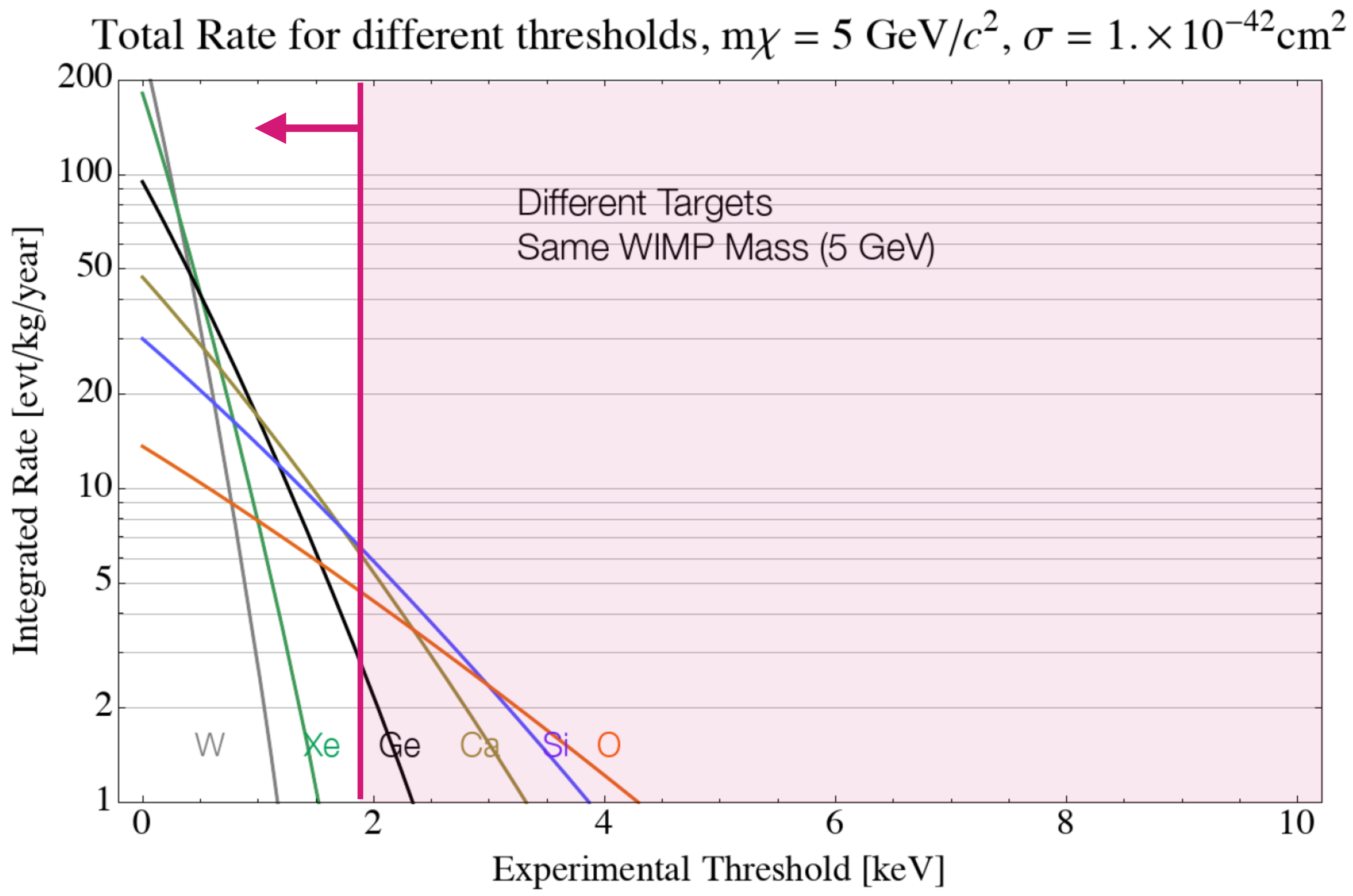
F: Form factor describing how the WIMP interferes with the nucleon structure of the nucleus

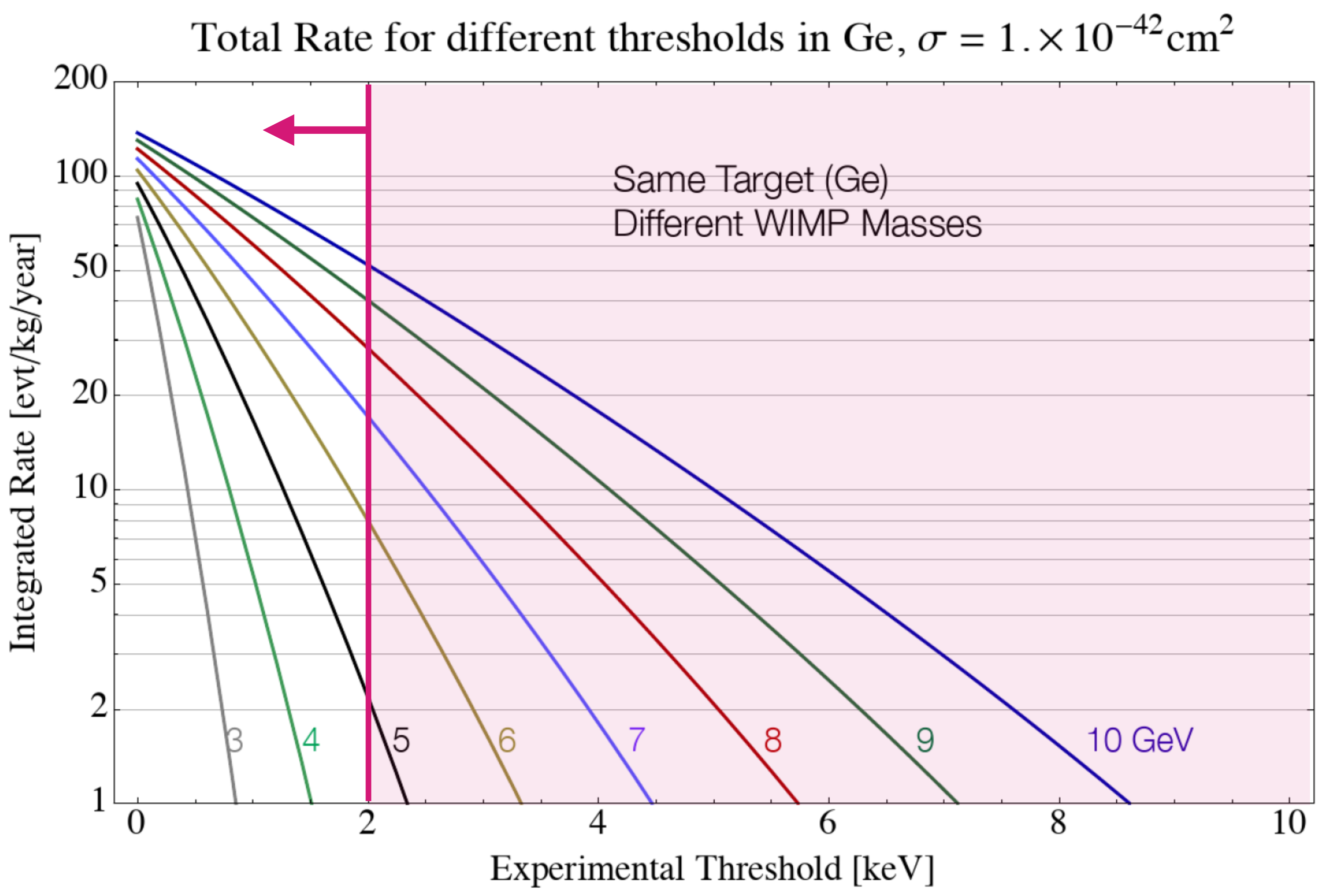
# Direct Detection Principle

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

## Detector Physics dependencies

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



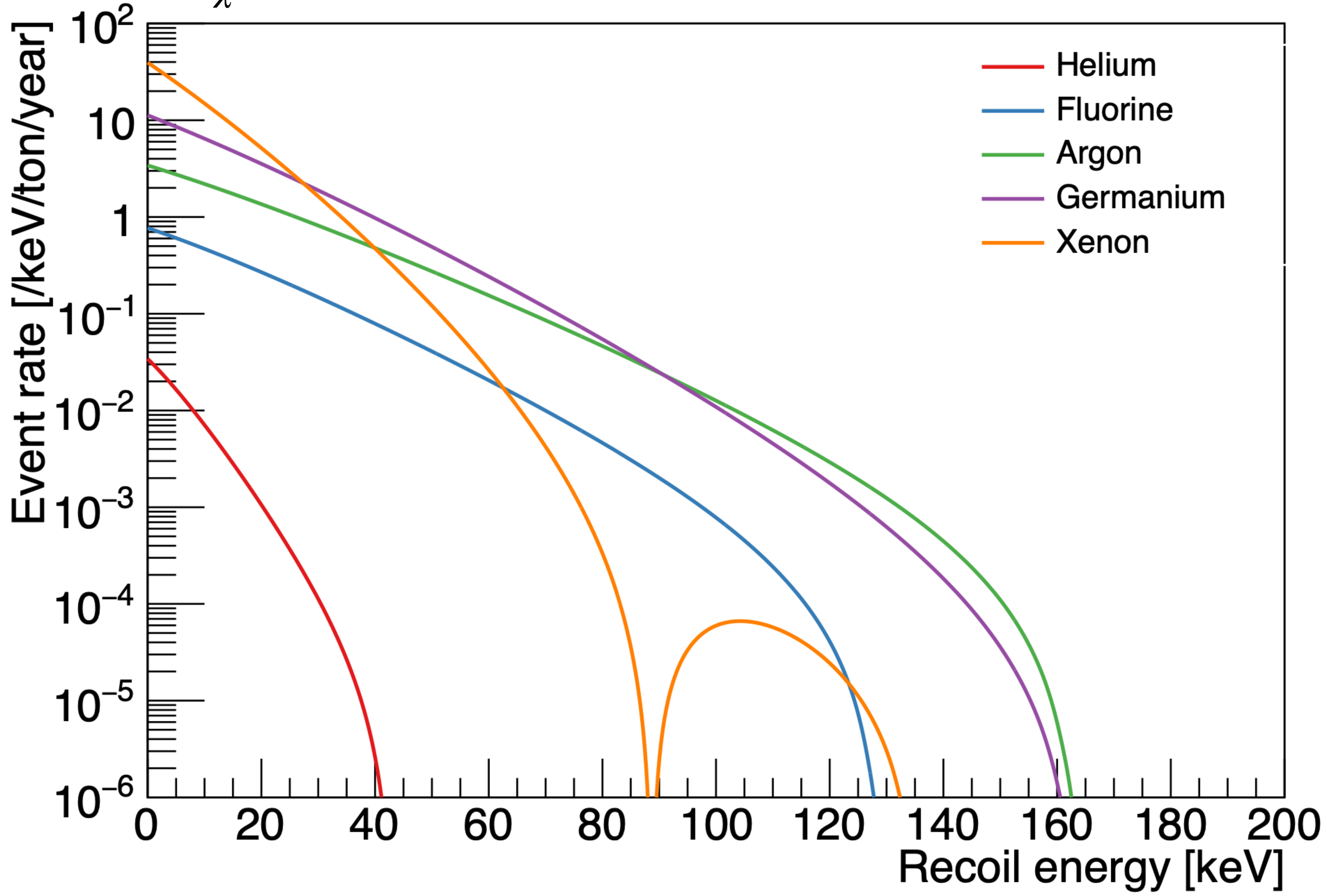

J. Cooley, SciPost Phys. Lect. Notes 55 (2022)

# Direct Detection Principle

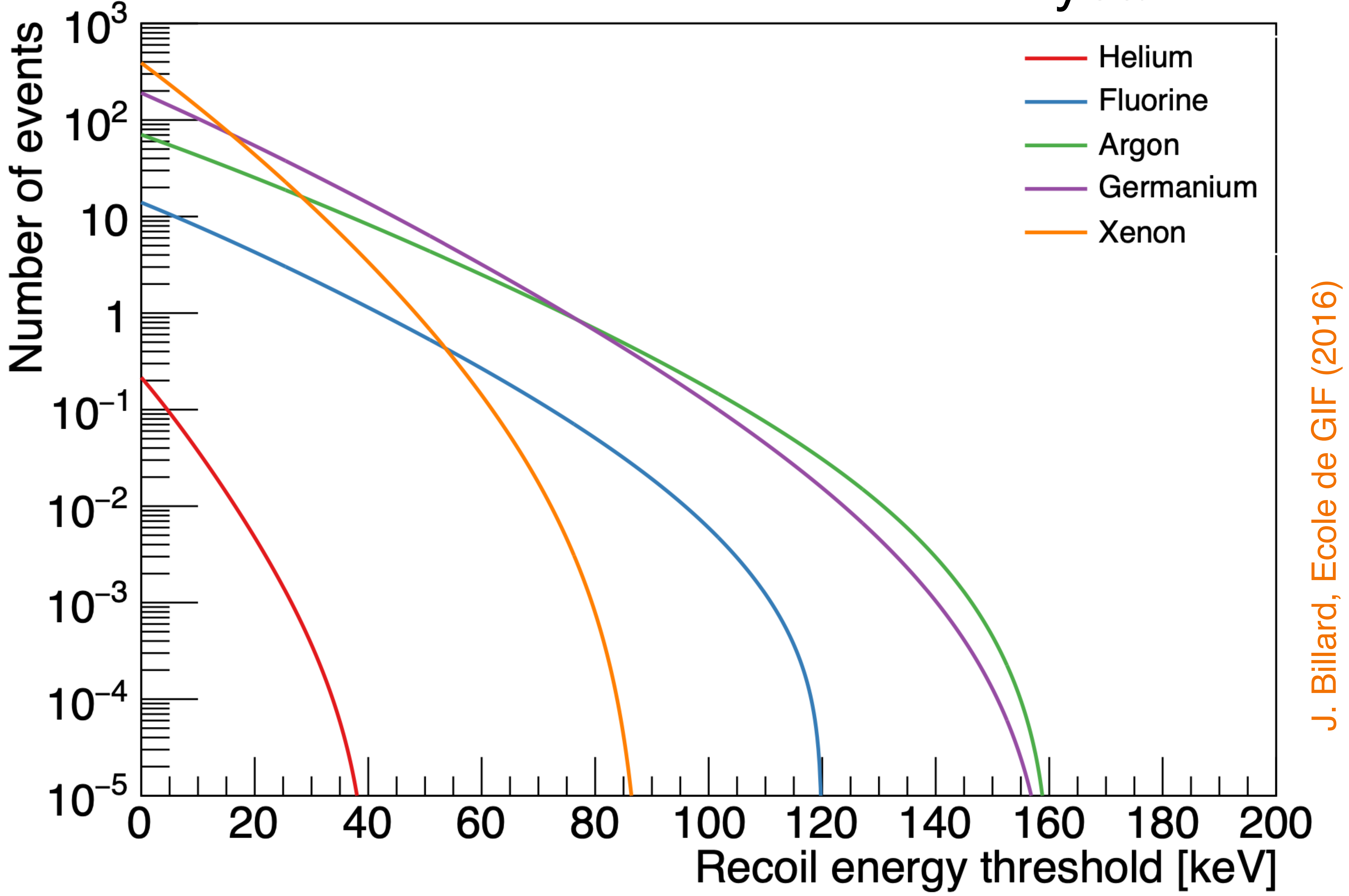
## From energy recoil spectra to expected number of WIMP-N events

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

$\sigma^{SI} = 50\,\mathrm{GeV}$
$m_\chi = 10^{-45}\,\mathrm{cm}^2$



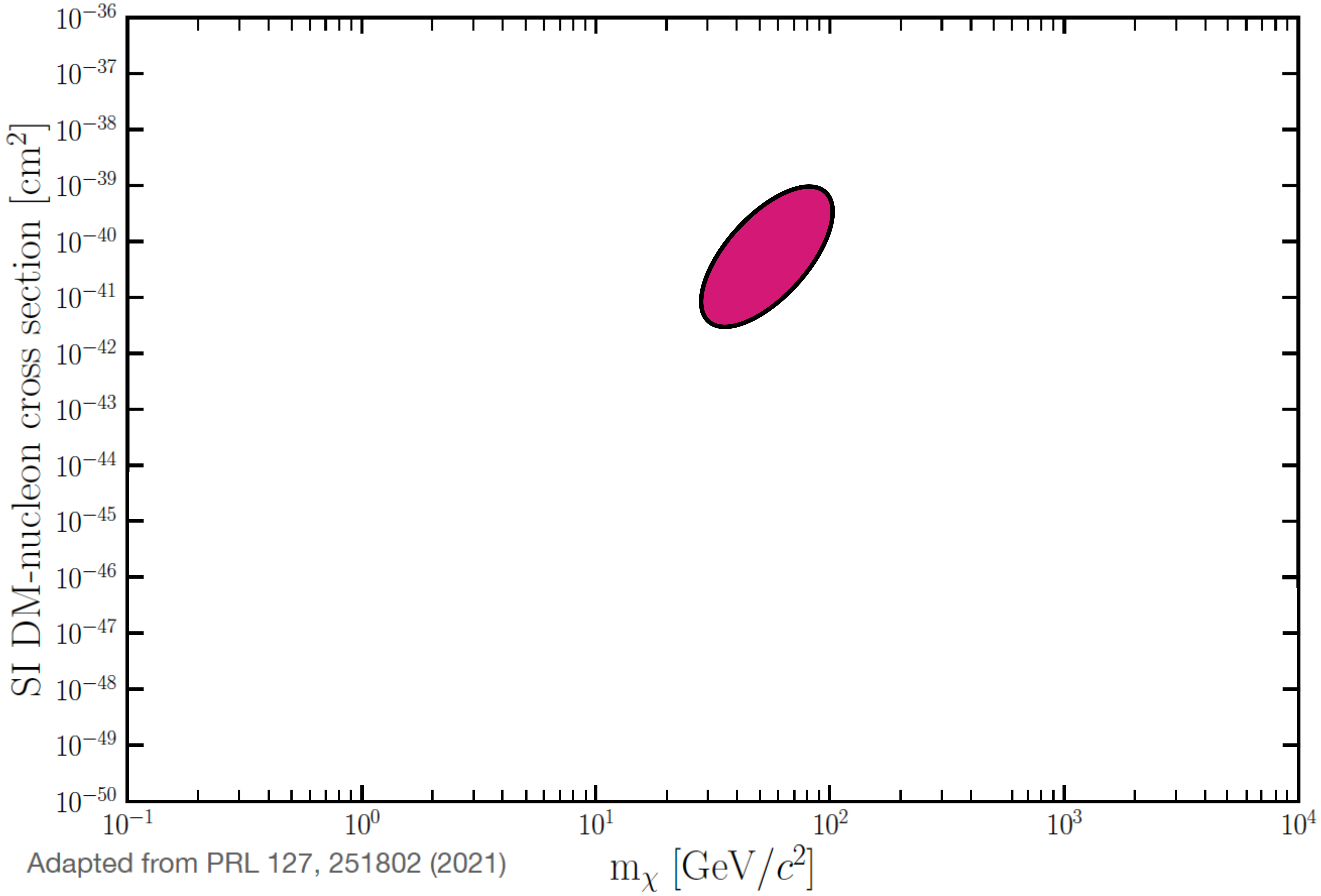

$M_T = 1\,\mathrm{tonne}$
$T = 1\,\mathrm{year}$




J. Billard, Ecole de GIF (2016)

# Direct Detection Principle

## Exclusion/Discovery Plot:

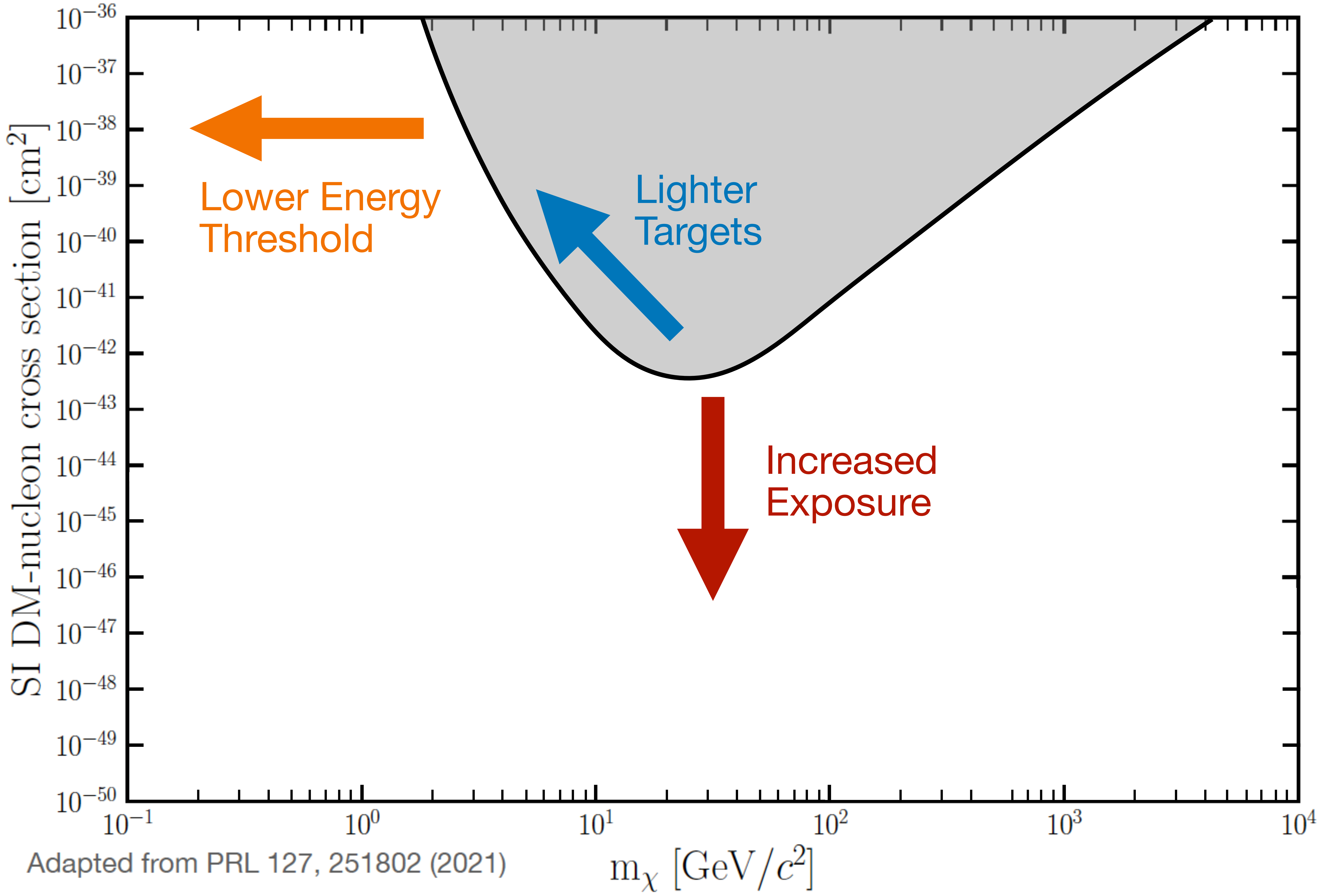



Adapted from PRL 127, 251802 (2021)

- Signal contour
- Limit curve (90% C.L.)

# Direct Detection Principle

## Exclusion/Discovery Plot:



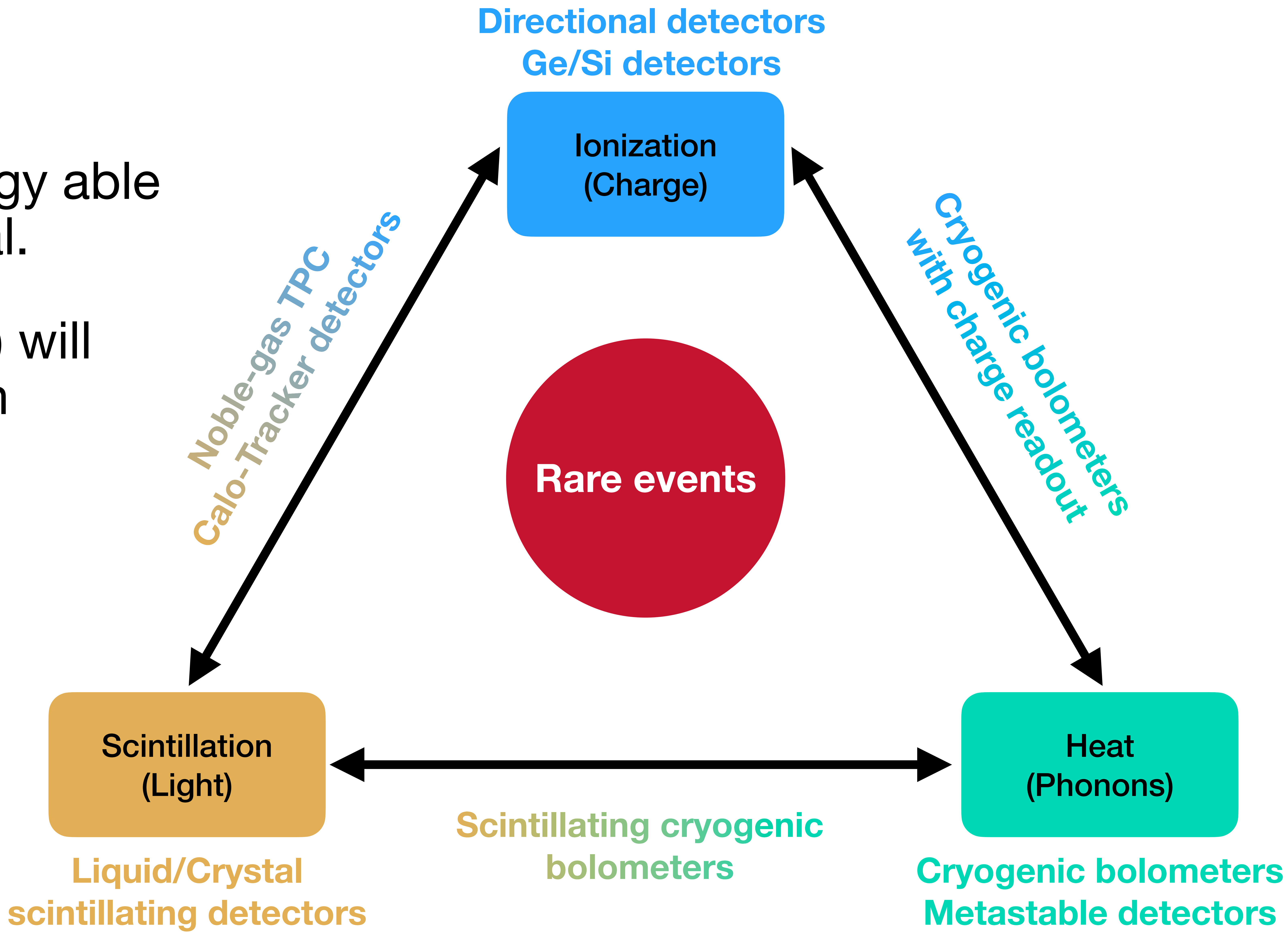

Adapted from PRL 127, 251802 (2021)

- Signal contour
- Limit curve (90% C.L.)

# Direct Detection Principle

## 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



# Direct Detection Principle



## Summary:

- Direct Detection of Dark Matter involve
  - Recent results
  - Historically

# Low-Background Experiments

# Features of a Low-background experiment



## Searching for a sparse signal

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

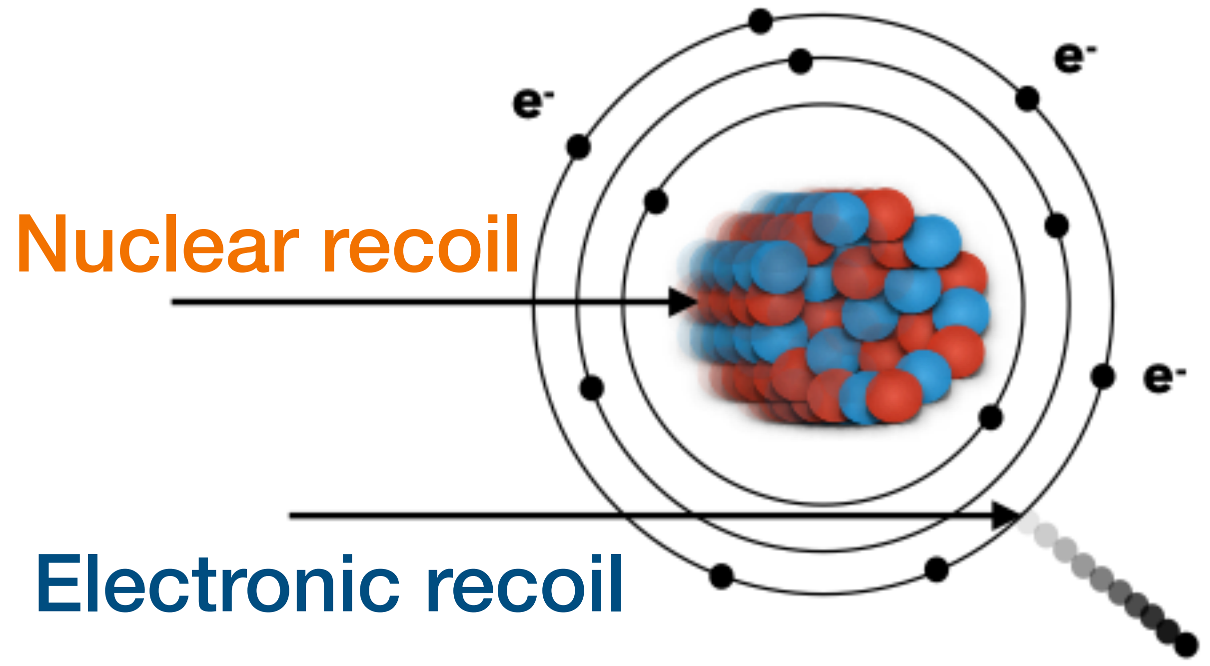
**Unwanted physical process, mimicking the signature of your signal**

# Background Identification



## 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

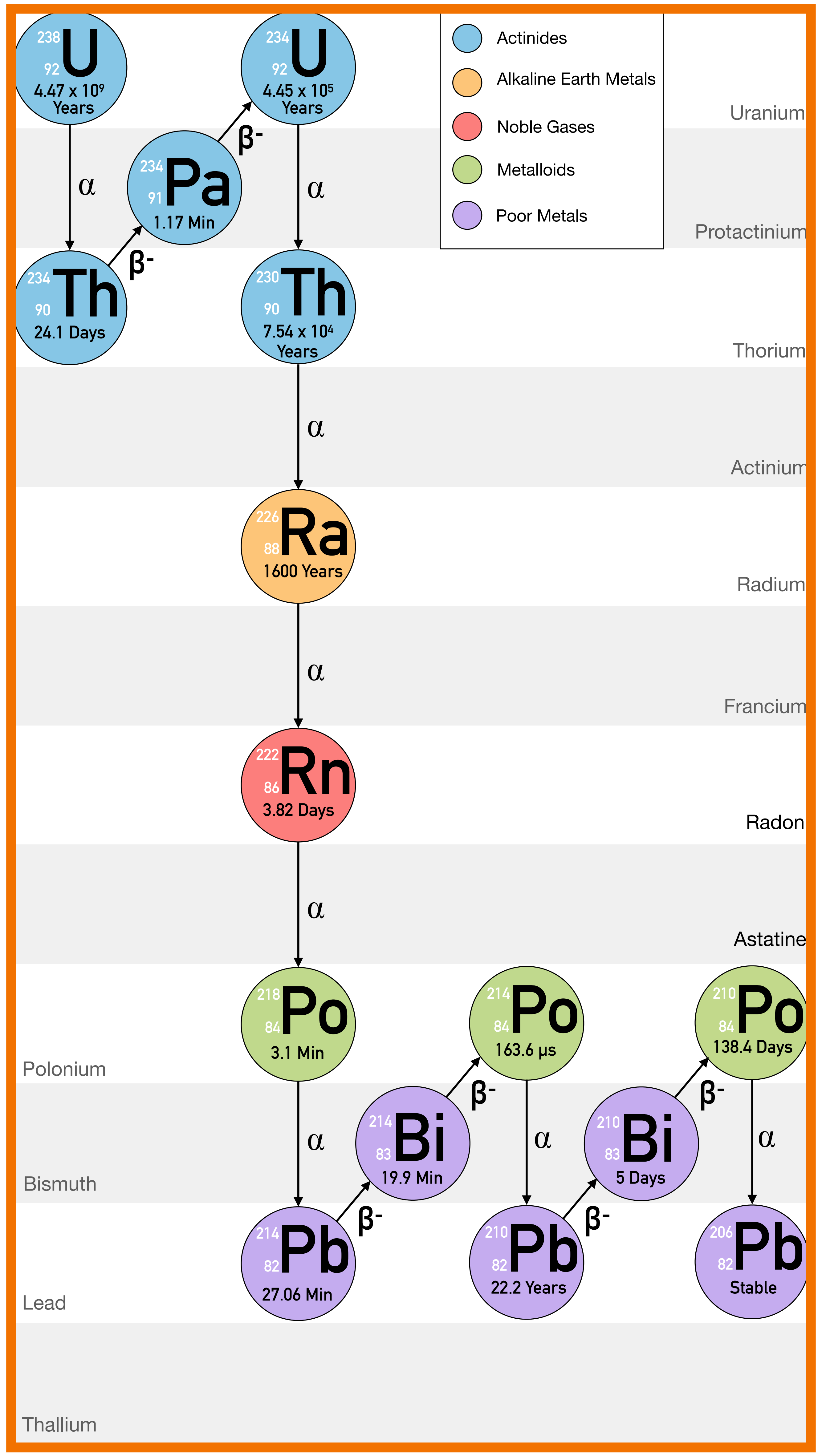
External/Internal to the target material

# Background Source - Radiogenic



## 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.



# Background Source - Radiogenic 

## Mitigation Strategy:

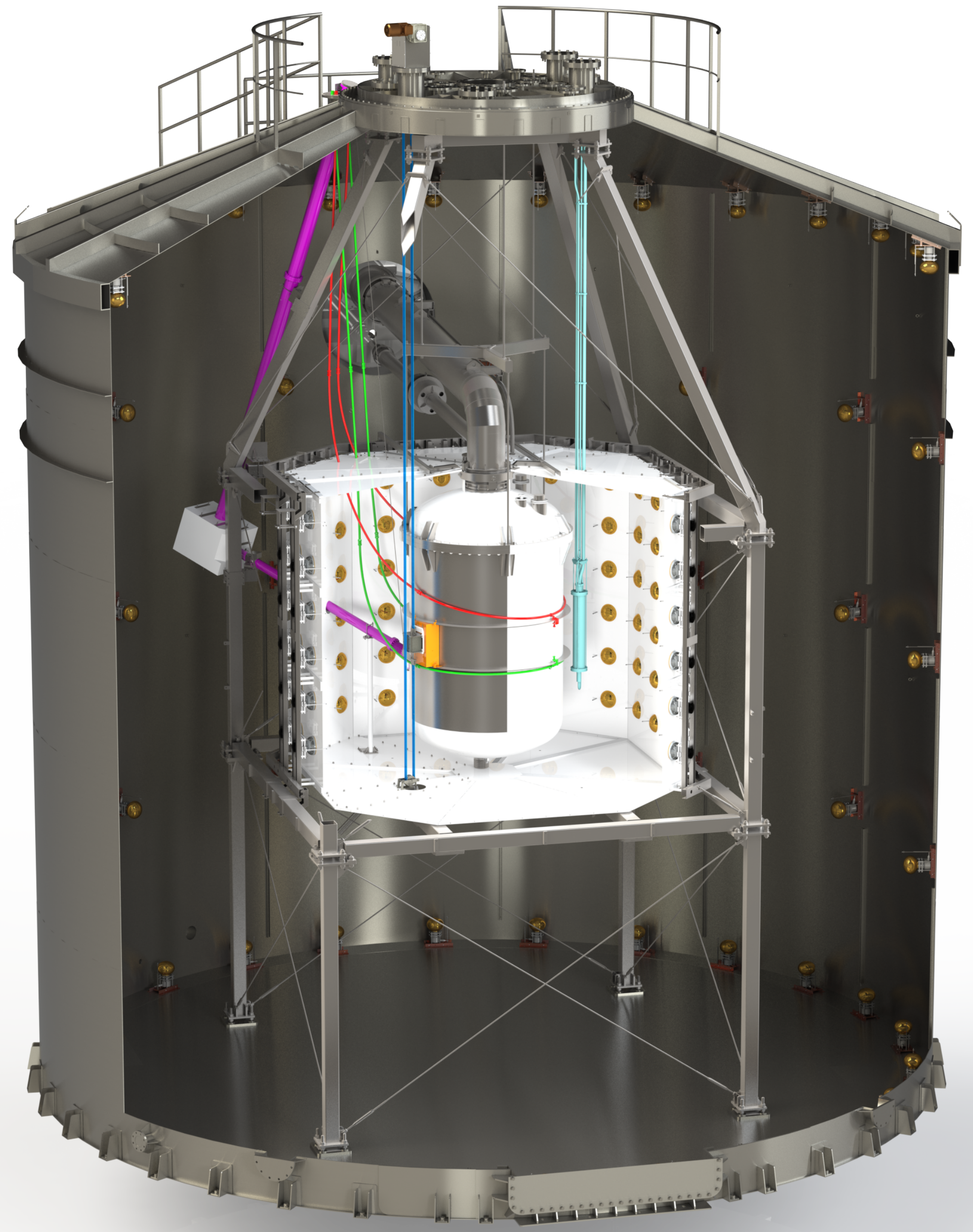
- Detector Material Selection
    - Screening campaign of material samples to select the most radio pure and allow background modelling.

HPGe array - Modane

# Background Source - Radiogenic 

## Mitigation Strategy:

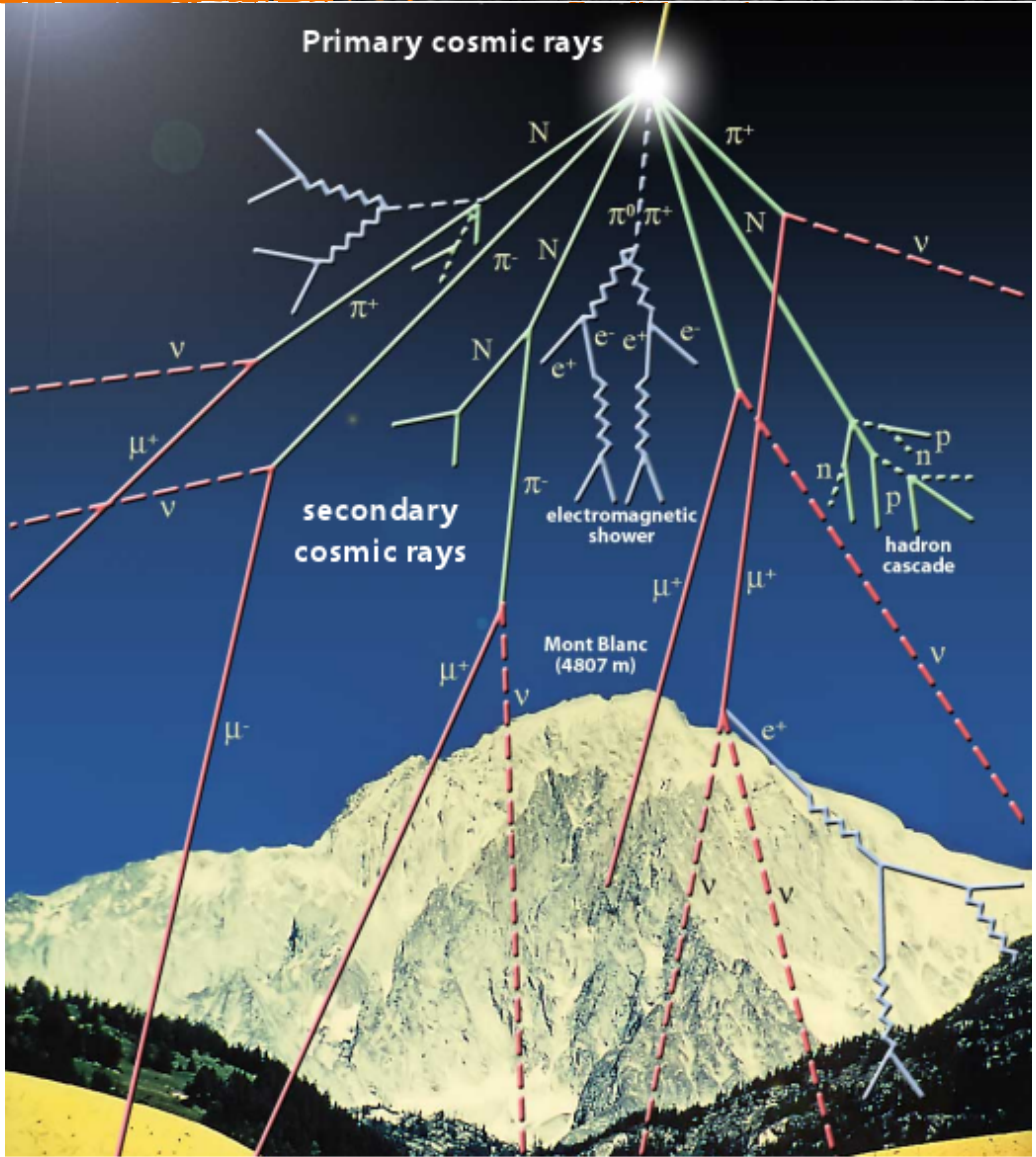
- Detector Material Selection
  - Screening campaign of material samples to select the most radio pure and allow background modelling.
- Detector Shielding
  - Passive Shielding: Material, like Archaeological Lead, to suppress
  - Active Shielding: Instrumented shielding volume, such as Cherenkov Water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



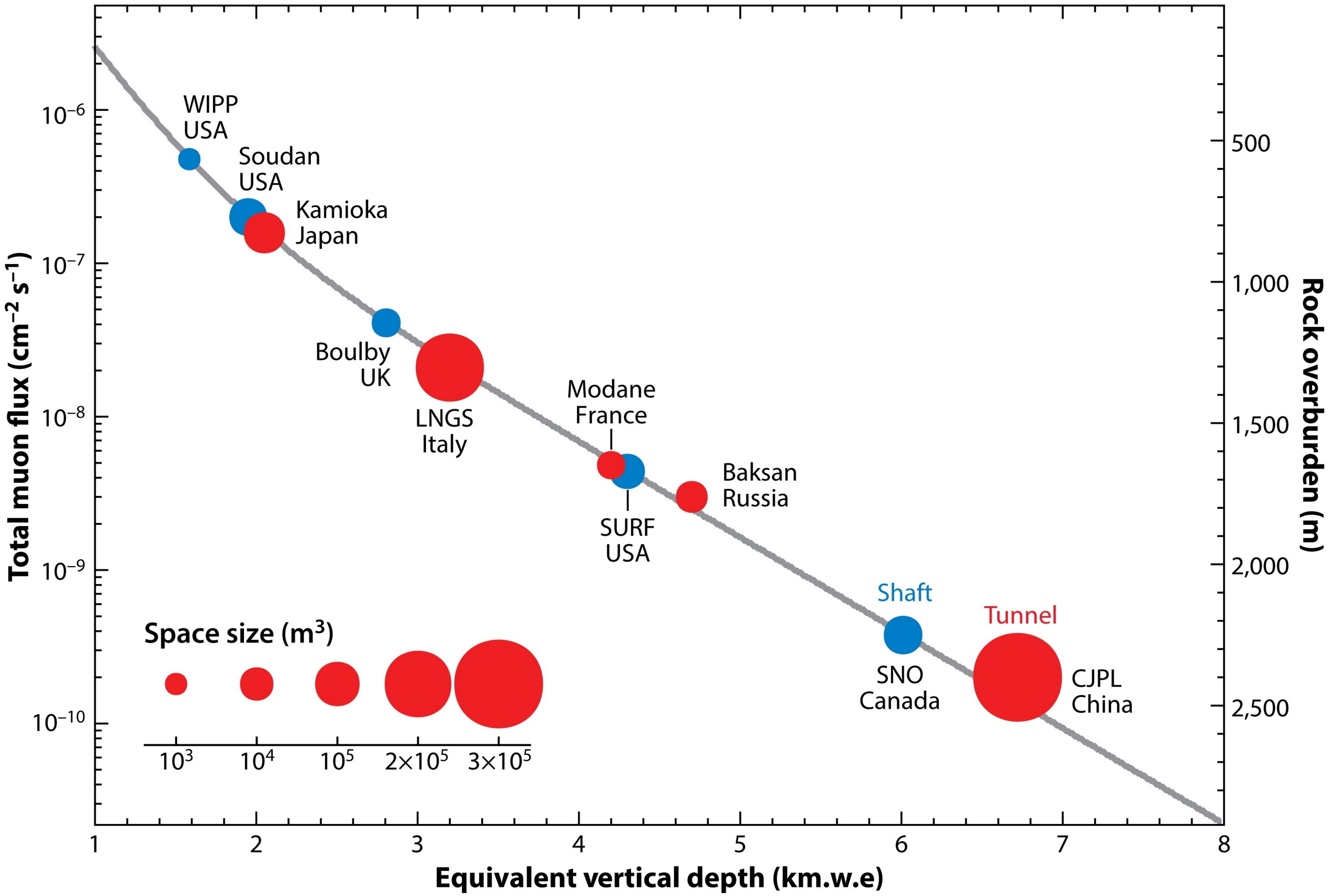
# Background Source - Cosmogenic

## 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… ): $^{3}H$, $^{60}Co$, $^{32}Si$, $^{39}Ar$, … [ER]
- Relevant underground but also above ground!



# Mitigation Strategy:




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

## 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

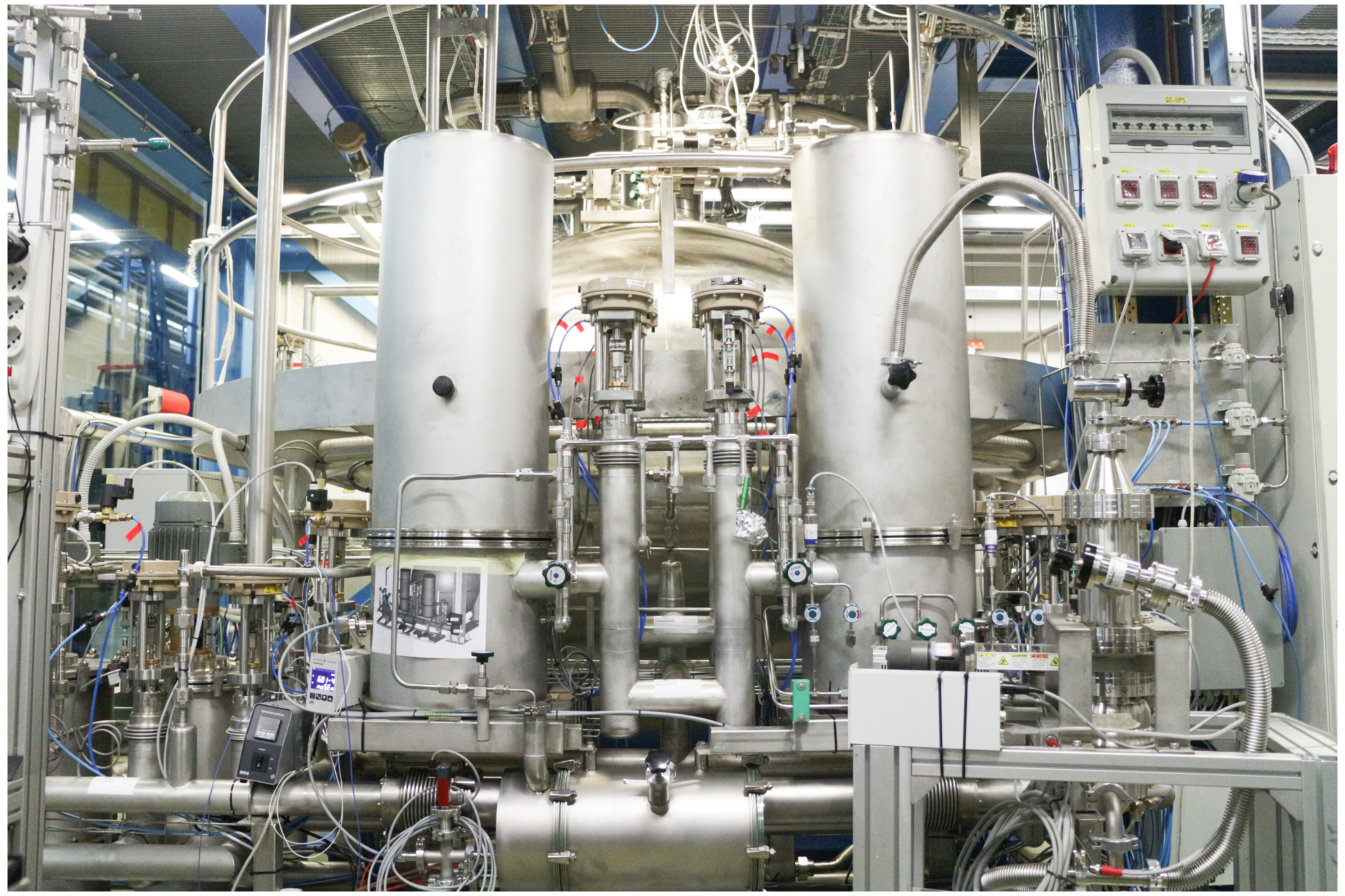
| Isotope | Abundance [%] | Decay mode | Half-life [years] |
|---|---|---|---|
| $^{124}$Xe | 0.09 | $2\nu$ECEC | $(1.1 \pm 0.2_{\text{stat}} \pm 0.1_{\text{sys}}) \times 10^{22}$ |
| $^{126}$Xe | 0.09 | stable | - |
| $^{128}$Xe | 1.92 | stable | - |
| $^{129}$Xe | 26.4 | stable | - |
| $^{130}$Xe |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

# Background Source - Intrinsic



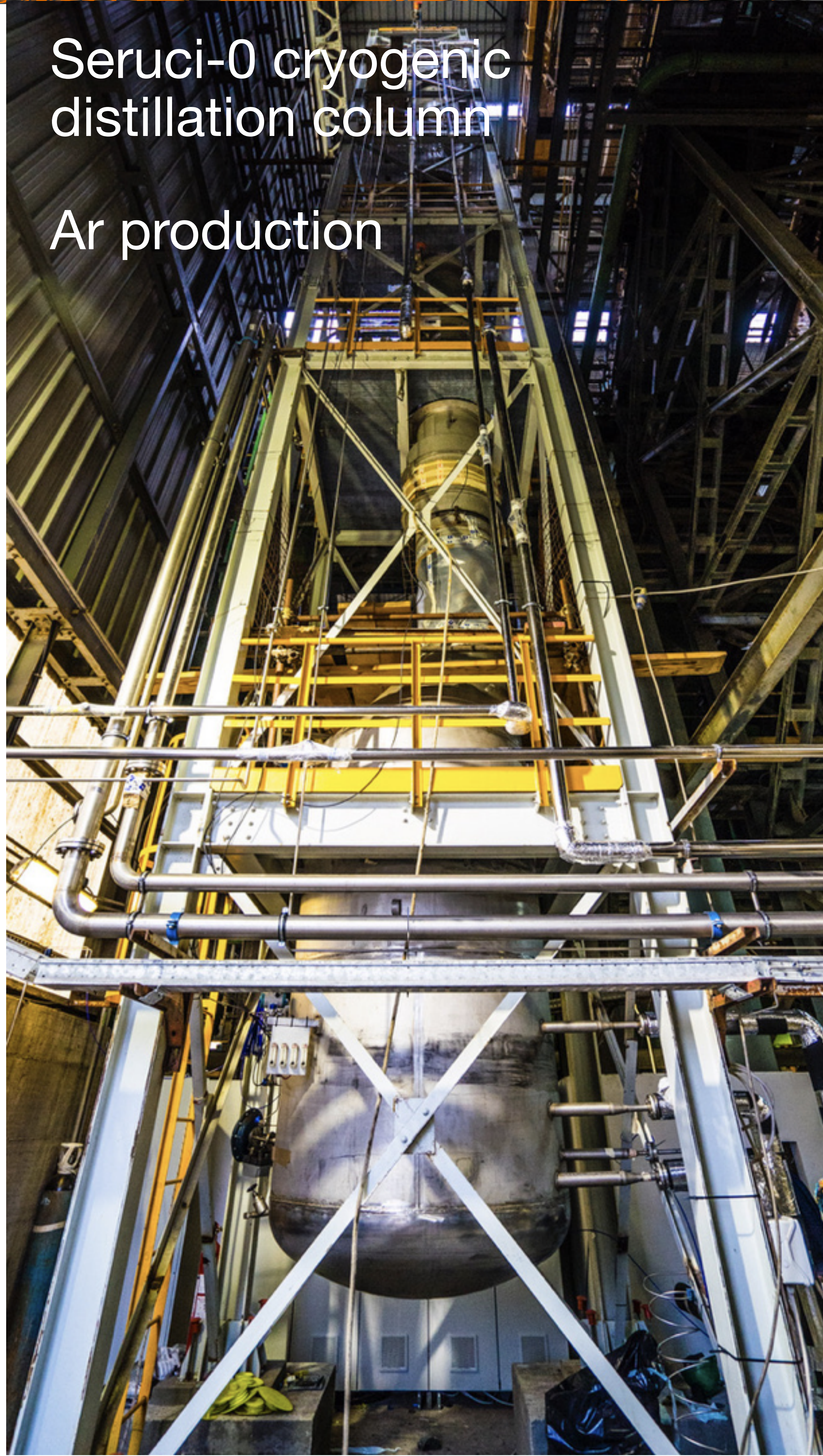
## Mitigation Strategy:

- 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

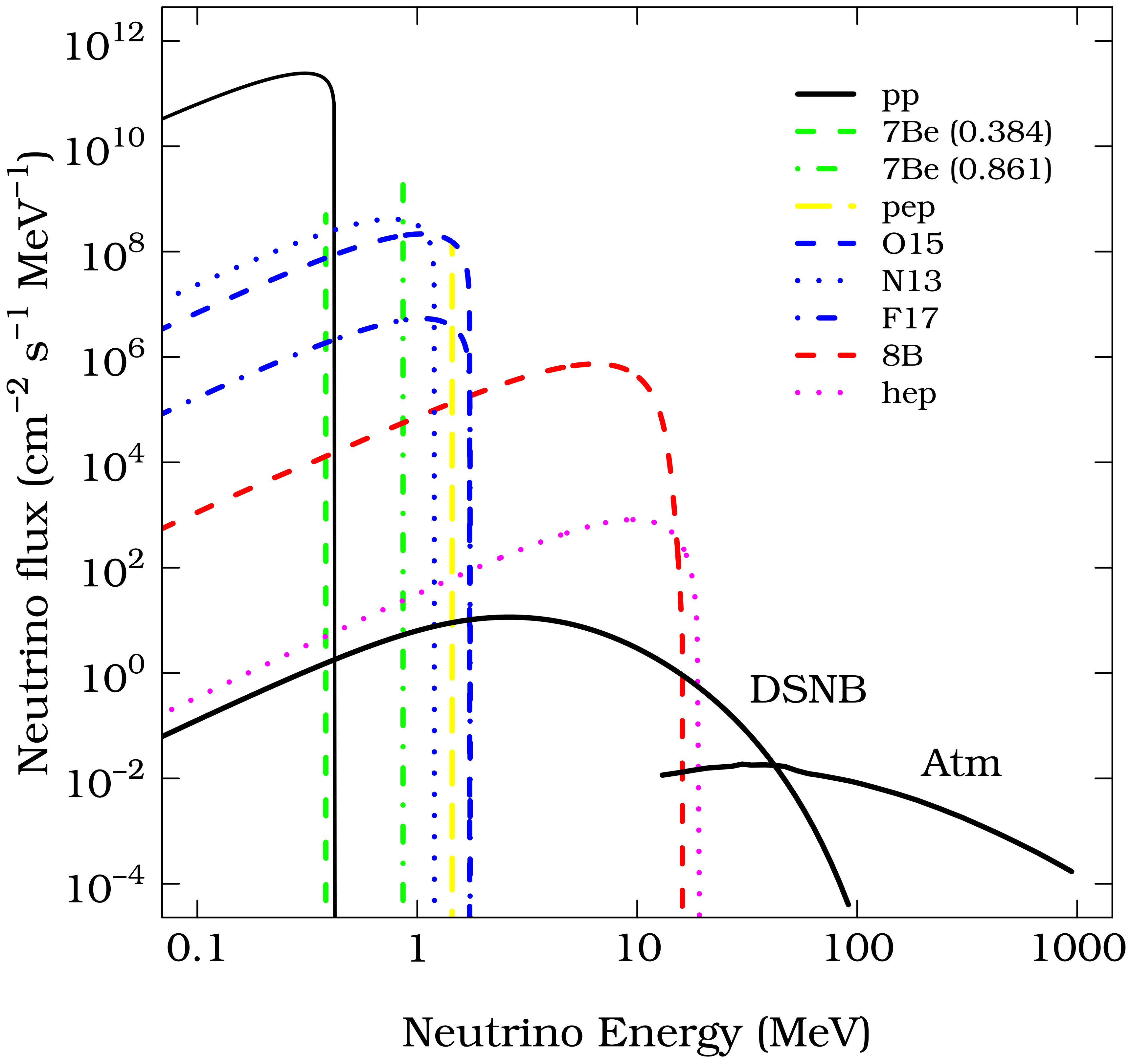
Journal of Physics: Conference Series 1468 (2020) 012234



# Background Source - Solar Neutrinos



## 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**

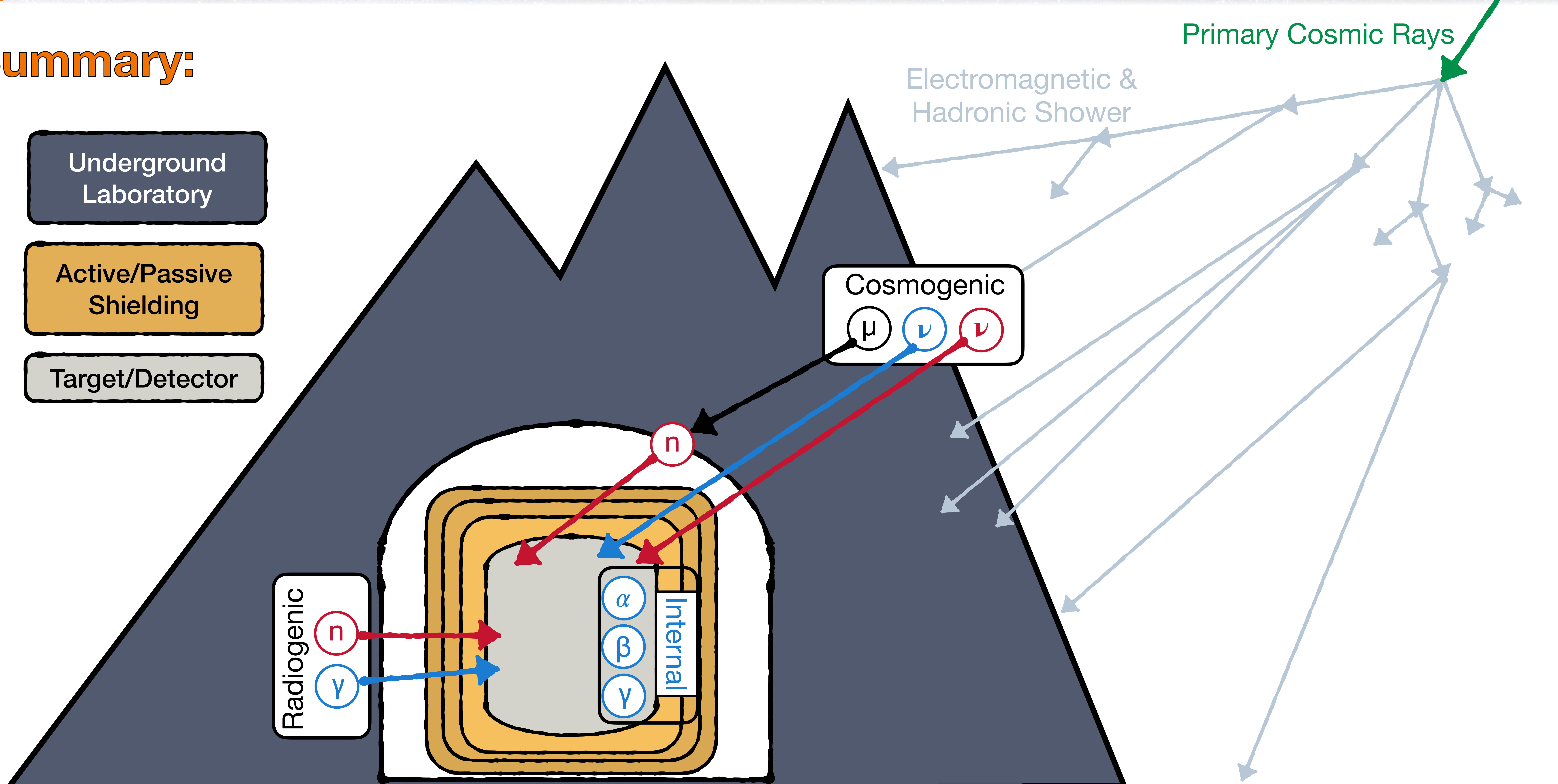
## One way to work-around:

- Directionality: we know where they are coming from.

# Background Mitigation Strategy



## Summary:

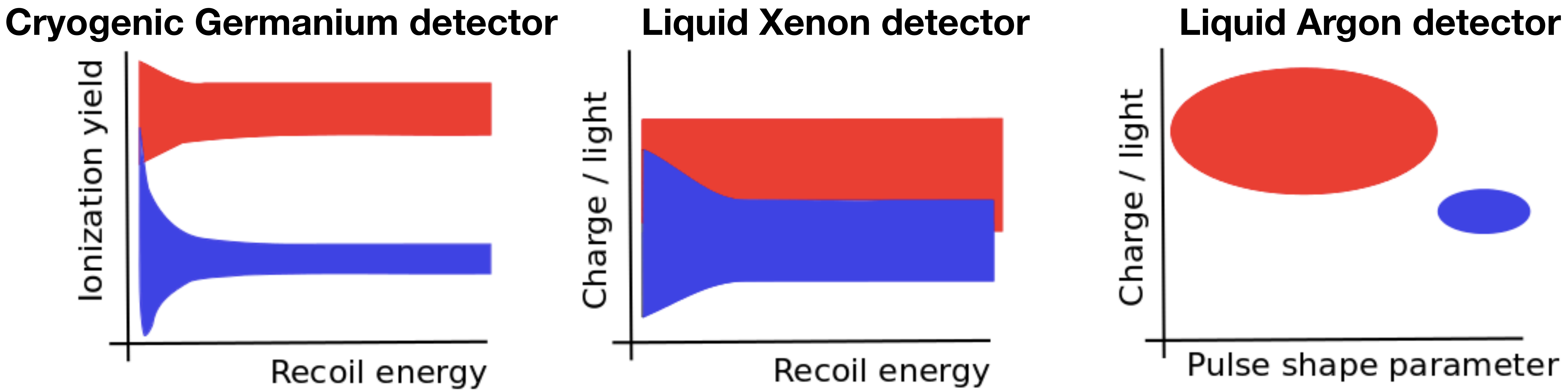


# Background Discrimination



## Can we further suppress backgrounds in our detector?

- Use differences in detector response to particle (ɣ,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



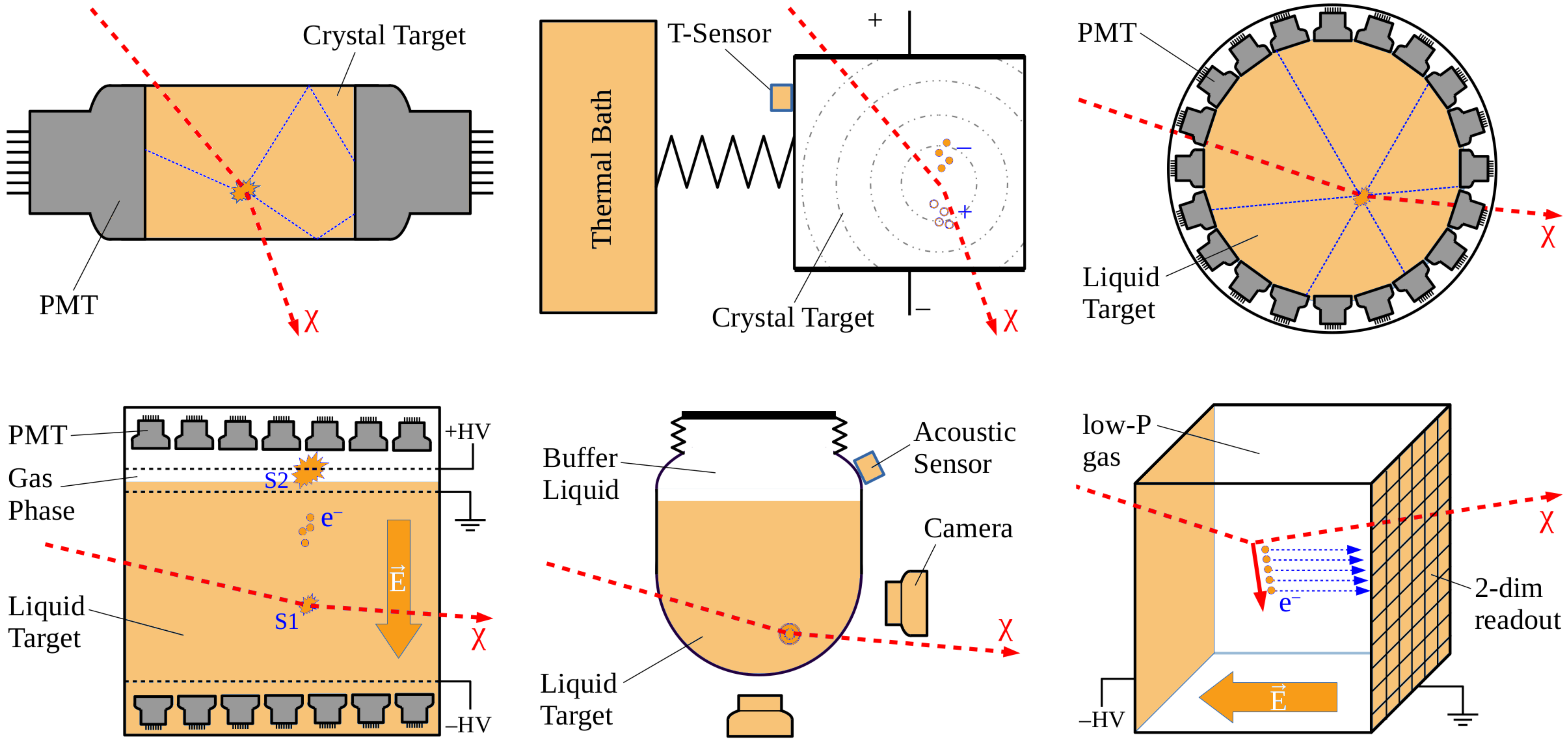

J. Phys. G: Nucl. Part. Phys. **43** 013001

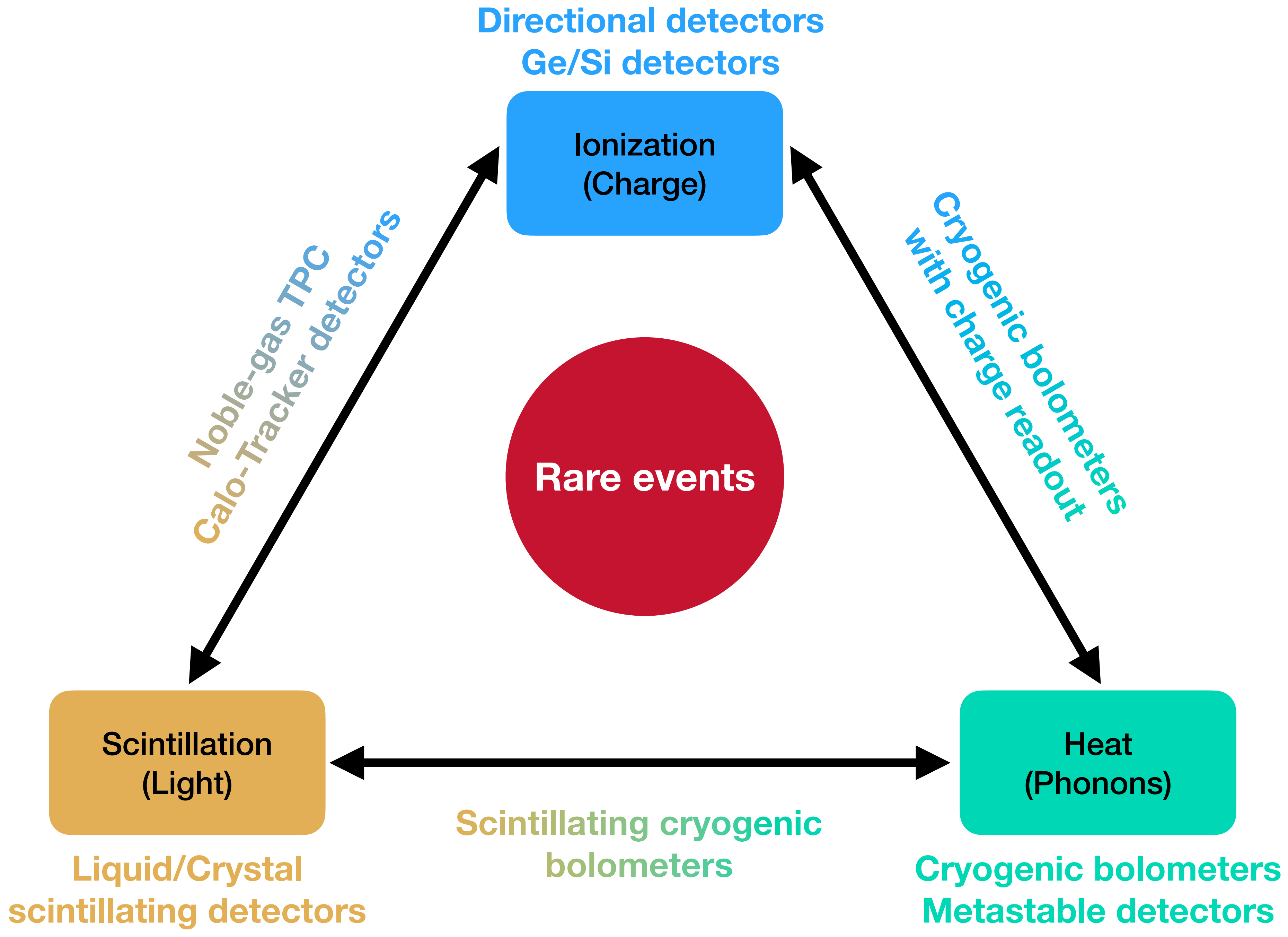
# Detection Techniques

## 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

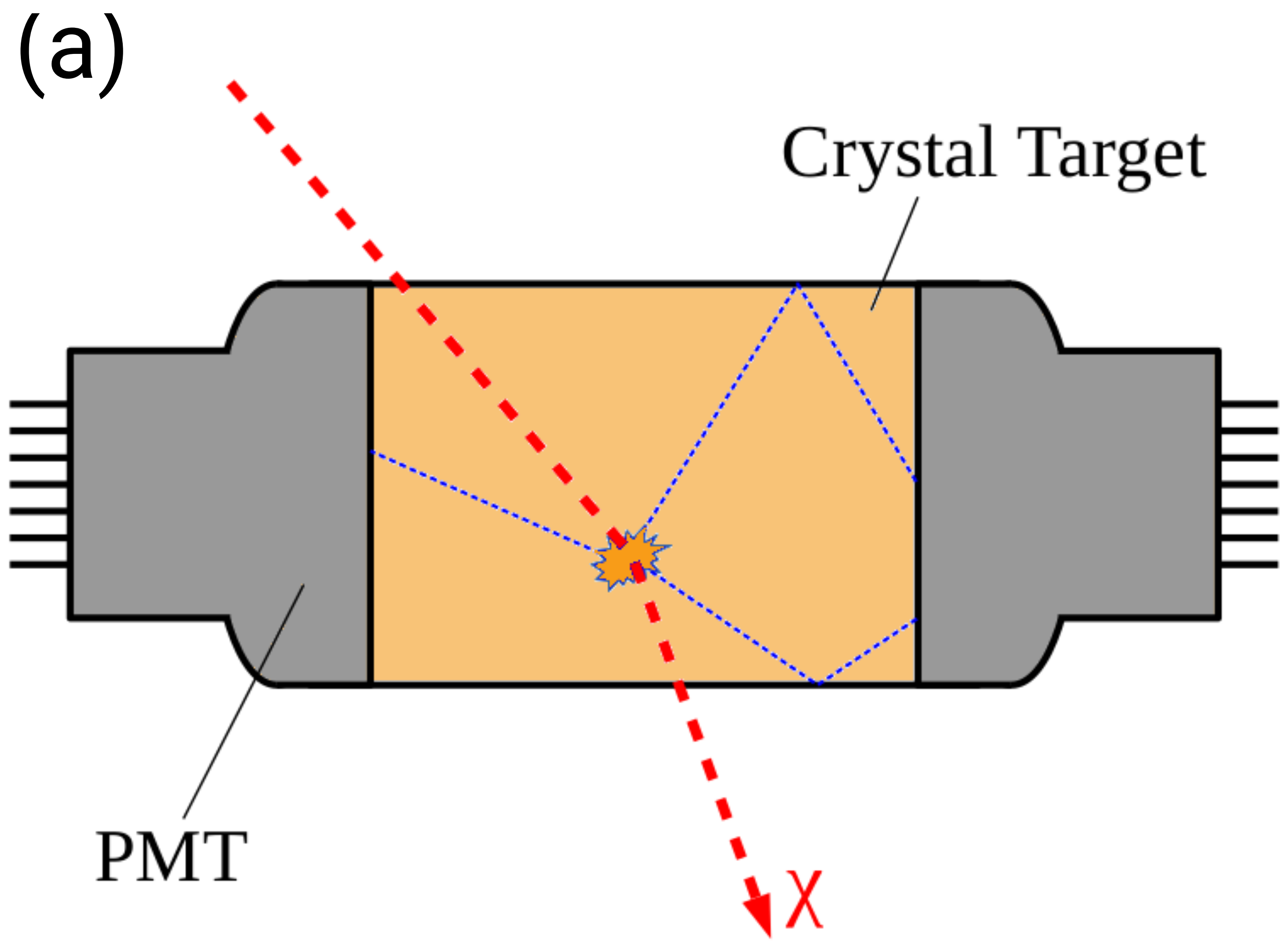
J. Billard et al 2022 Rep. Prog. Phys. **85** 056201




5 min break, question?

# High-Purity Scintillator Crystals




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

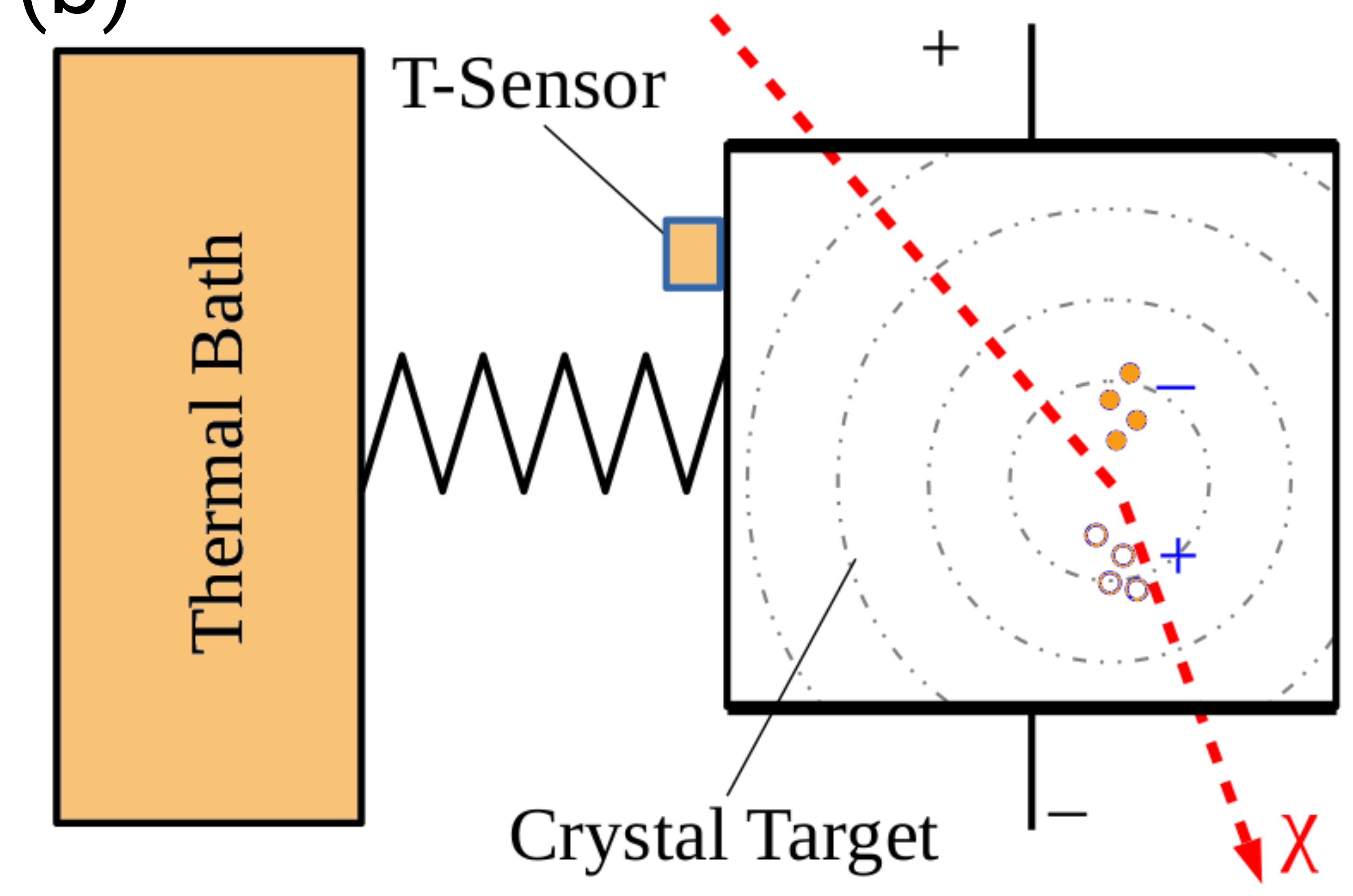
**Mostly used for annual modulation searches**

| **Strength** | **Weakness** |
|---|---|
| Mature technology, can operate stably for long periods of time | Comparatively high intrinsic background |
| High mass number, boost SI sensitivity | No Fiducialisation or ER/NR discrimination |

# Cryogenic Bolometers



(b)



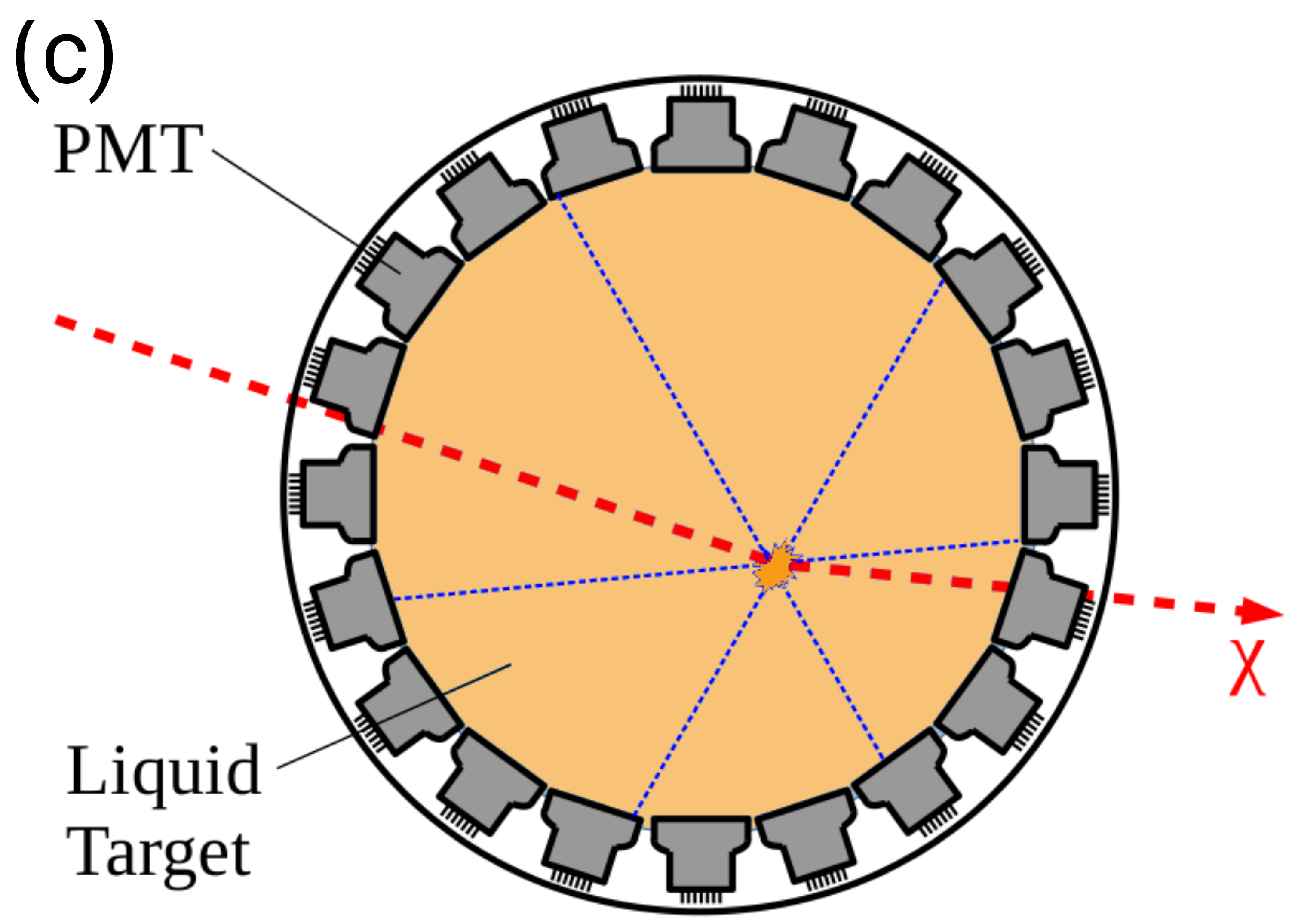

- Target: Ge, Si, and $CaWO_4$
- Target mass ~$\mathcal{O}$(1) kg
- Energy Threshold ~$\mathcal{O}$(10-100) eV
- Detection channel: Heat, (and Light, or Charge)

| Strength | Weakness |
|---|---|
| Excellent energy resolution and low energy threshold | Cryogenic detectors (< 50 mK) |
| Two detection channel to allow background rejection + PSD | Target mass scalability is challenging |
| | Presence of an “unkown” (structural stress?) background at low-energy (LEE - phonon) |

**Efficient to search for low-mass WIMP**

# Noble Liquid Scintillators



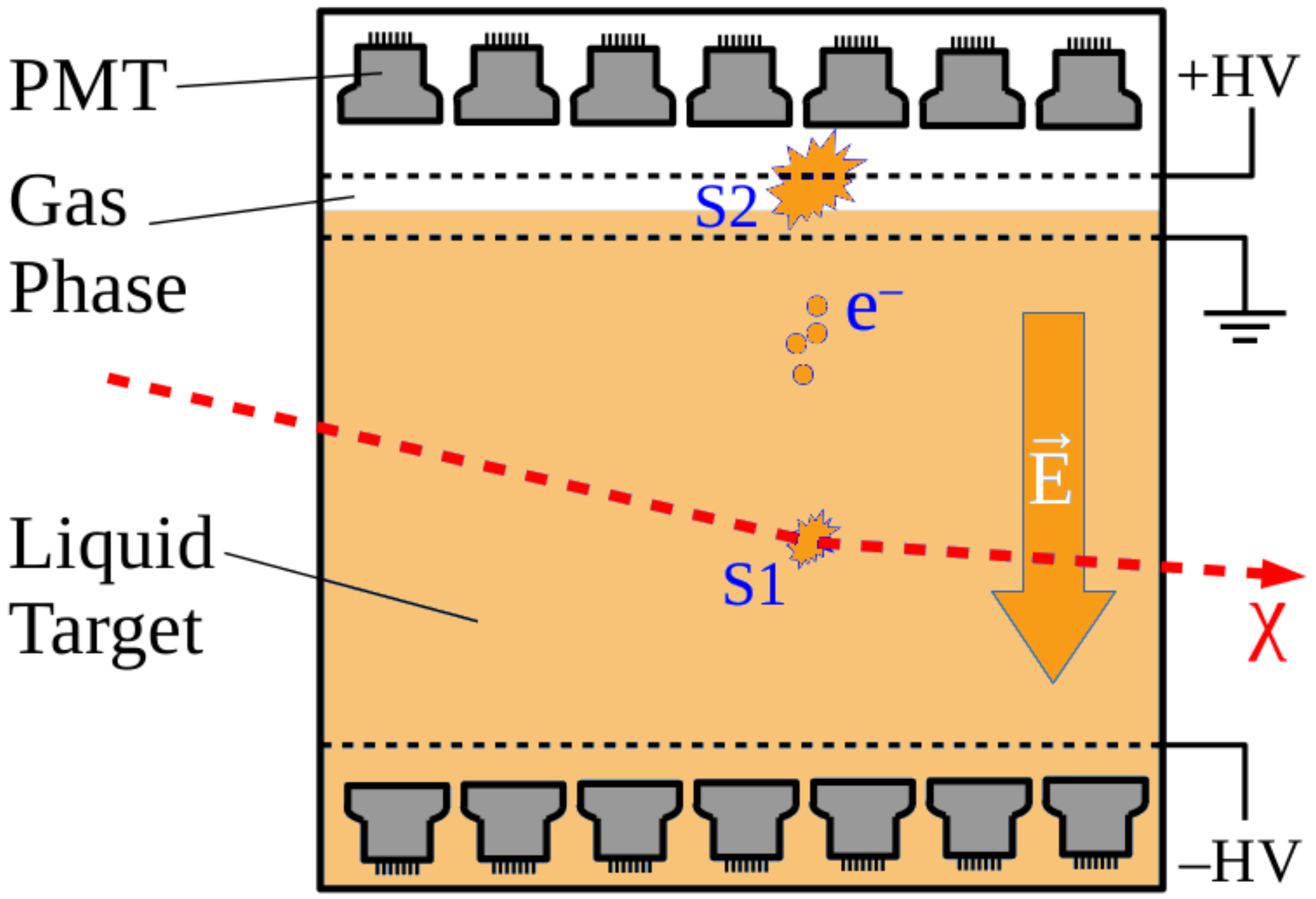



- Target: Ar and Xe
- Target mass ~$\mathcal{O}(1000)$ kg
- Energy Threshold ~$\mathcal{O}(1)$ keV
- Detection channel: Light

**Efficient to search for high-mass WIMP**

| Strength | Weakness |
| --- | --- |
| Target mass scalability | Only one detection channel |
| Position reconstruction for fiducialisation | Background discrimination not as efficient as the next type of detection technique… |
| Background discrimination for Ar | |

(d)



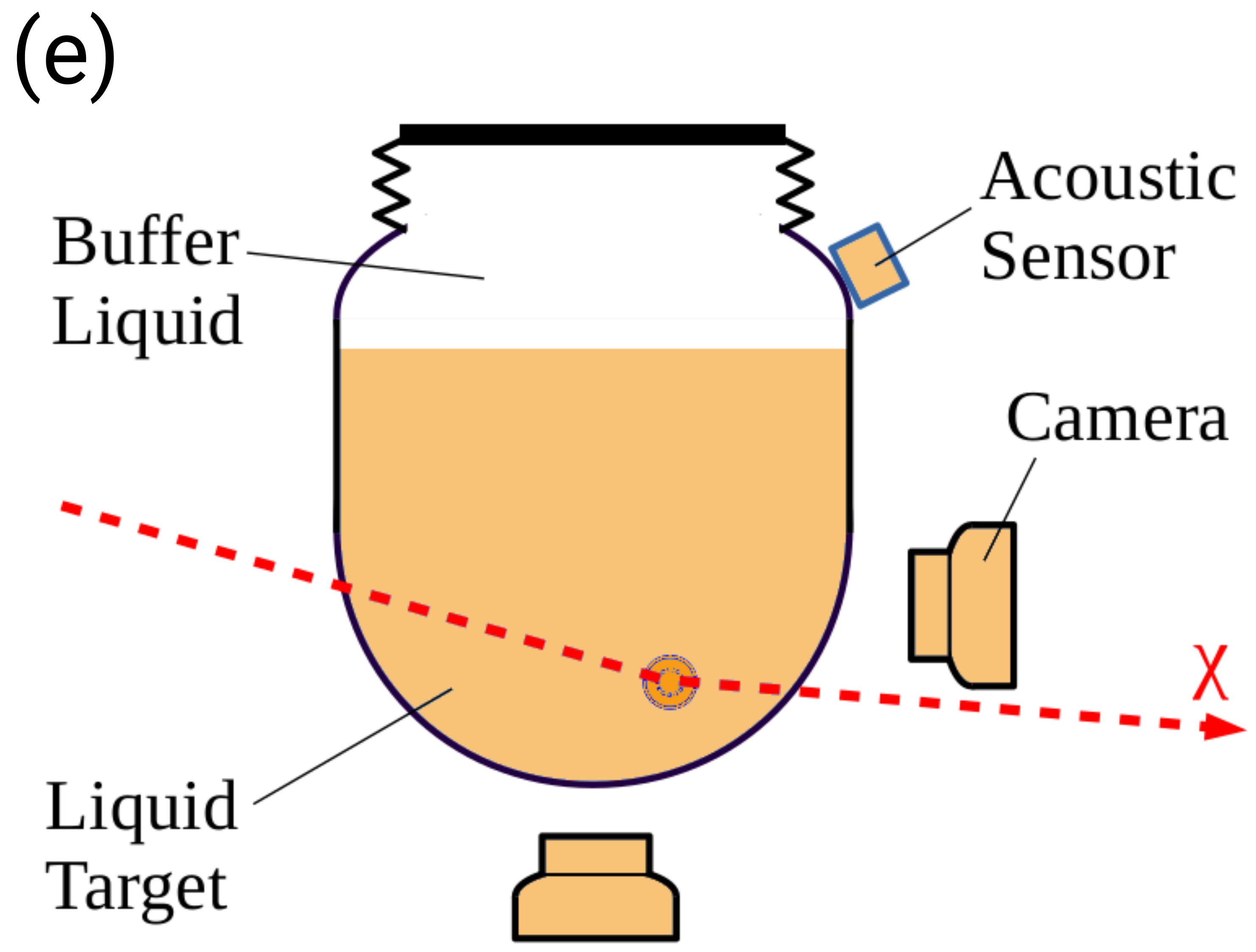

- Target: Xe and Ar
- Target mass ~$\mathcal{O}$(10 000) kg
- Energy Threshold ~$\mathcal{O}$(1) keV
- Detection channel: Light and Charge

| Strength | Weakness |
|---|---|
| Target mass scalability | Energy threshold to high for low-mass WIMP search… |
| Position reconstruction for fiducialisation | But their is some work-around possible (Ionization-only, Migdal effect) |
| Background discrimination with light and charge channel | |

**Leading technology for high-mass WIMP search**

# Bubble Chambers





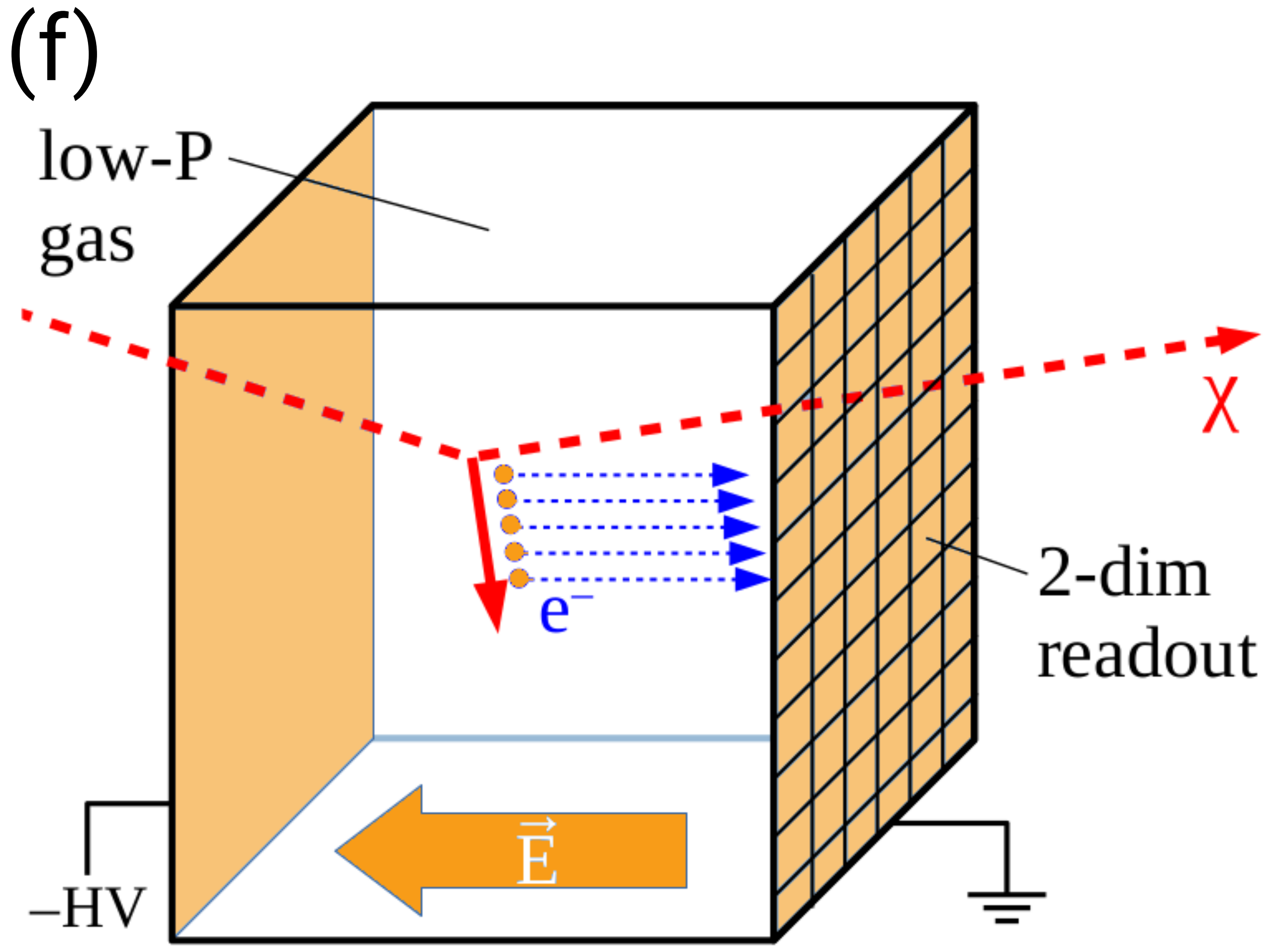

- Target: Superheated (Kept at a temperature just above their boiling point) fuilds, $C_3F_8$
- Target mass ~$\mathcal{O}(10)$ kg
- Energy Threshold ~$\mathcal{O}(1)$ keV
- Detection channel: Optical and Acoustic (!)

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

| **Strength** | **Weakness** |
| --- | --- |
| Can be tuned to be only sensitive to nuclear recoils (dE/dx of the recoiling particle)<br><br>Position reconstruction for fiducialisation | Need to change the pressure inside to remove bubbles after each event → dead time and difficult calibration |

# Low-Pressure Gas TPC



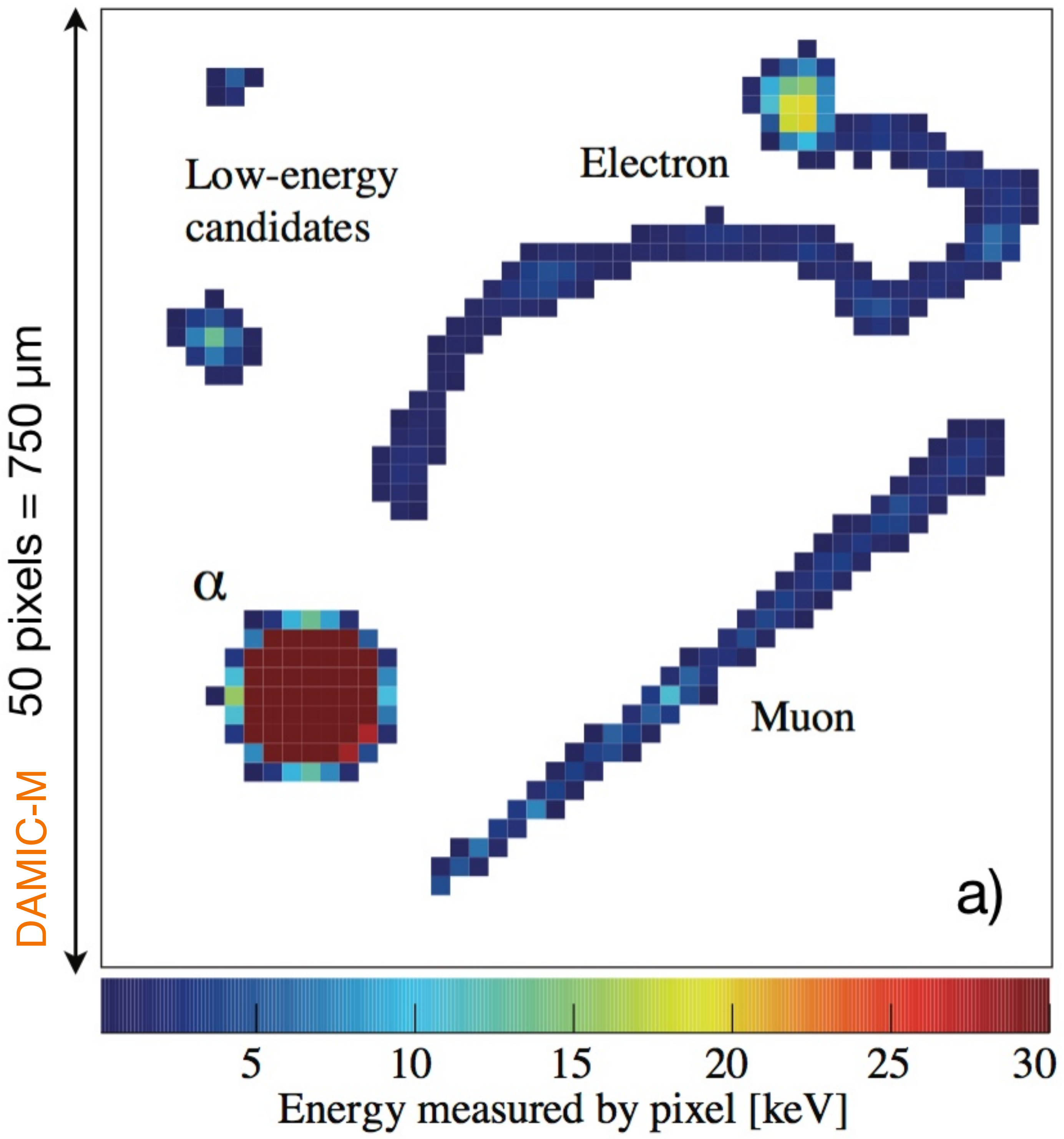



- Target: Low-pressure gas, such as $CF_4$, can use a mixture of gases also (Ne, $CH_4$,…)
- Target mass ~$\mathcal{O}(0.1)$ kg
- Energy Threshold ~$\mathcal{O}(1\text{-}10)$ keV
- Detection channel: Charge

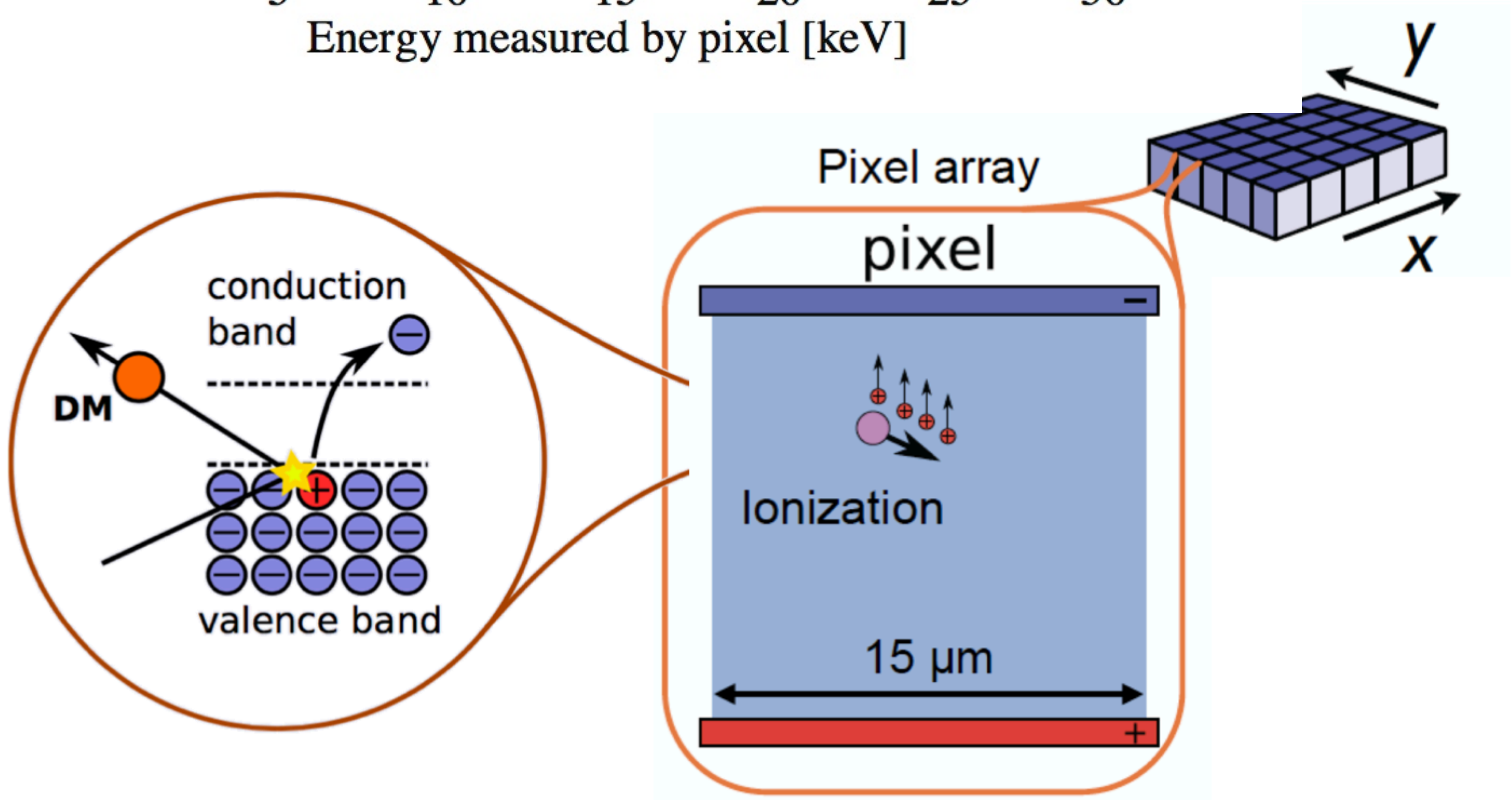
**Can be used to search WIMPs in the neutrino fog, and sensitive to SD WIMP-proton coupling**

| Strength | Weakness |
|---|---|
| Track reconstruction of the deposited energy | Small target mass, scalability is challenging |
| Electronic background rejection (longer range, lower ionisation density) | No self-shielding |

# Charged Coupled Devices (CCDs)




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




## DM-electron scattering

| Strength | Weakness |
|---|---|
| Excellent spatial resolution for particle identification | Small target mass, scalability is challenging |
| Very low-energy threshold (Ge: 2.9 eV, Si: 3.6 eV), aim for low-mass WIMP | Presence of an “unkown” background at low-energy (not LEE! From charge here) |

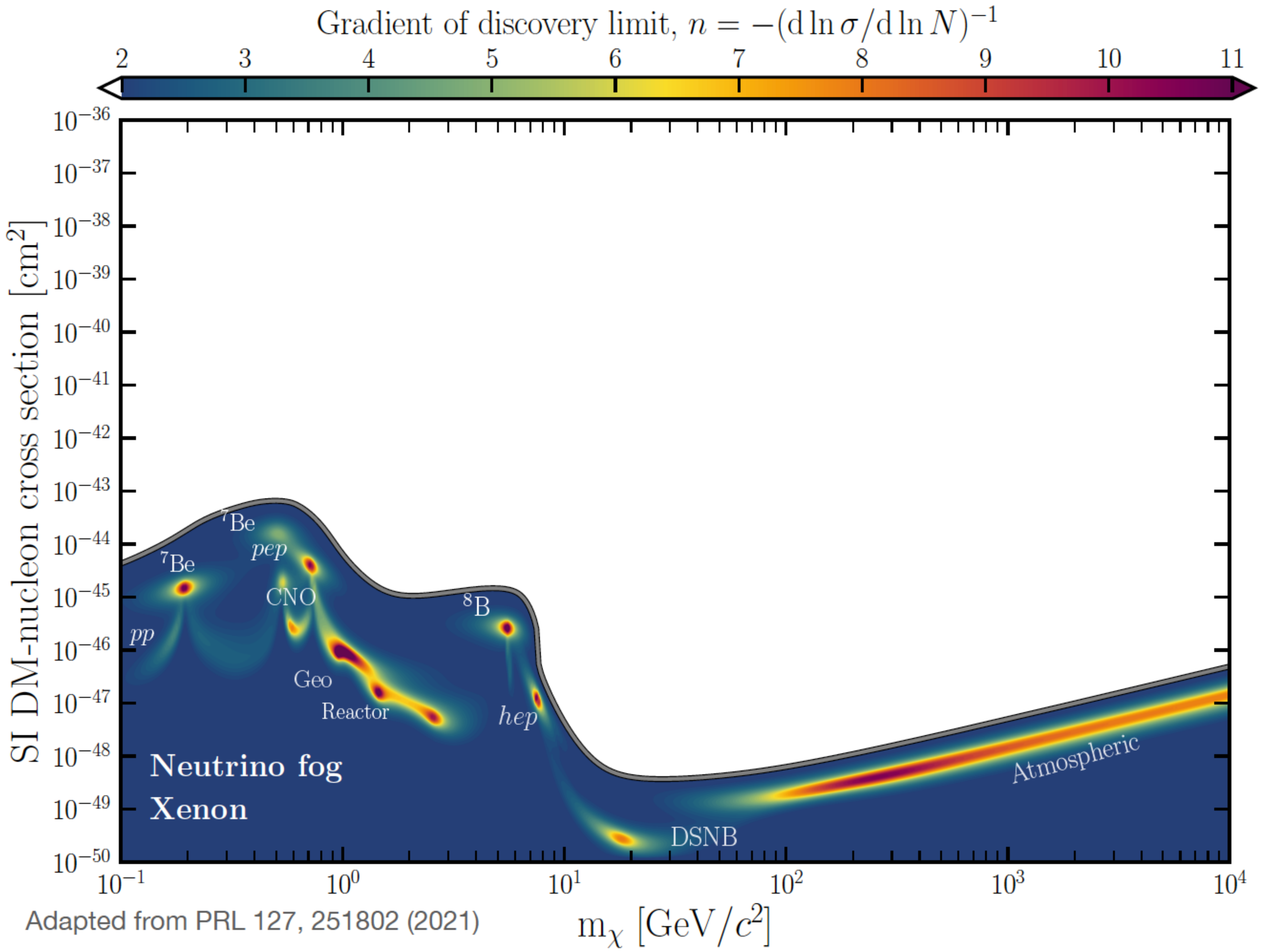
Credits: A. Botti, P. Privitera

# Experimental Landscape

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

# Direct Detection Landscape



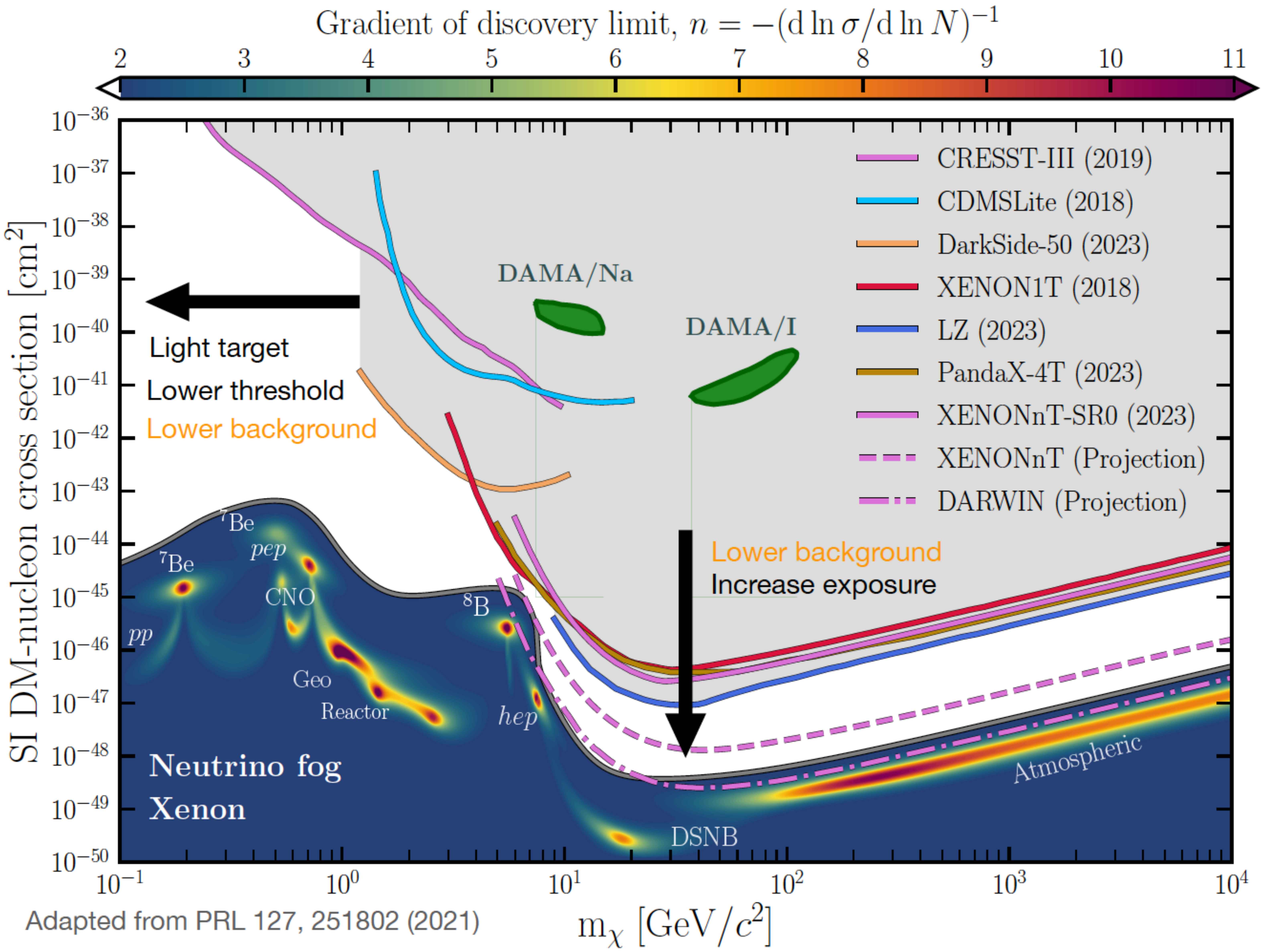



Adapted from PRL 127, 251802 (2021)

- Neutrino fog from different source of neutrino

# Direct Detection Landscape

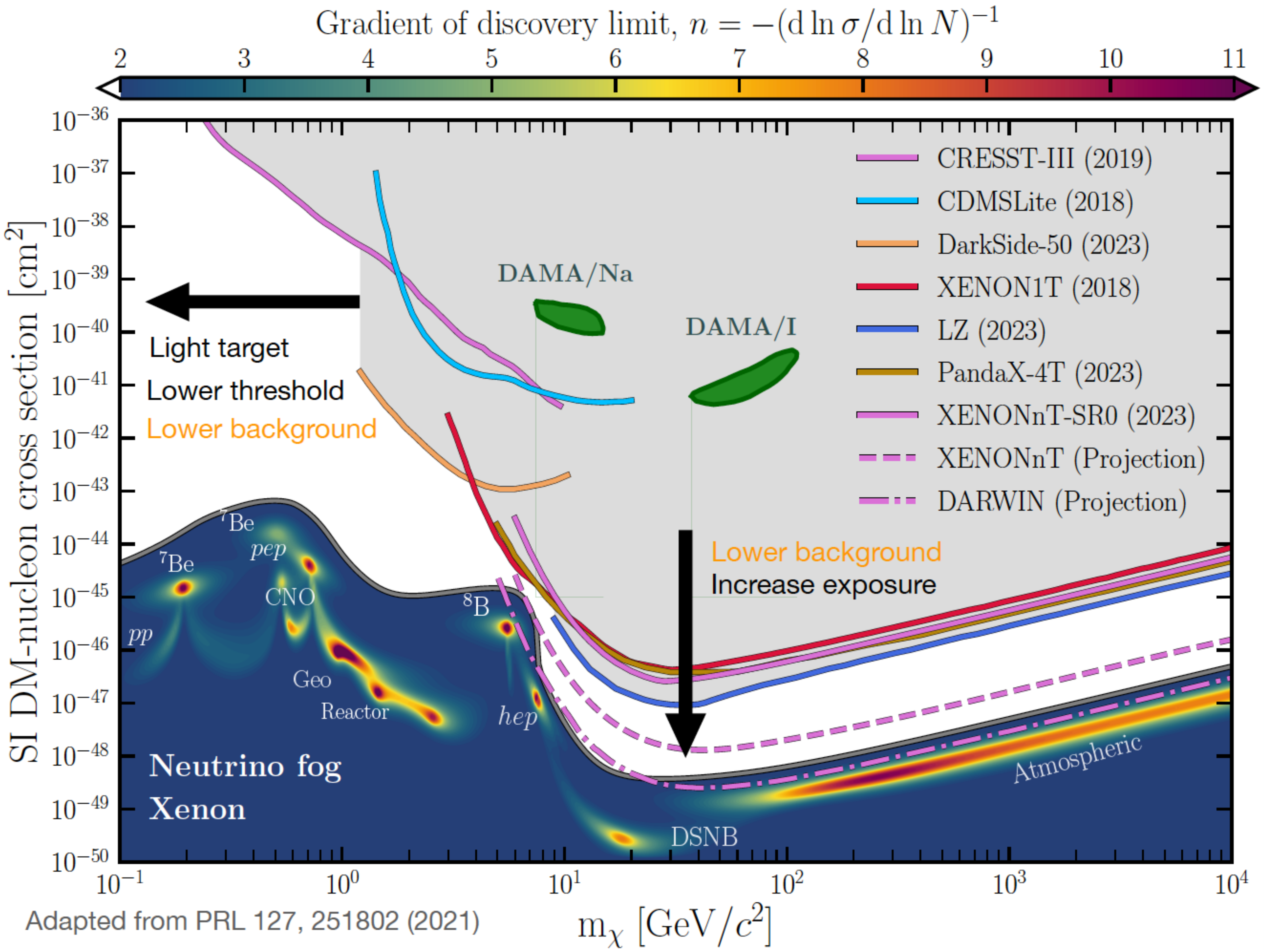





Adapted from PRL 127, 251802 (2021)

- 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

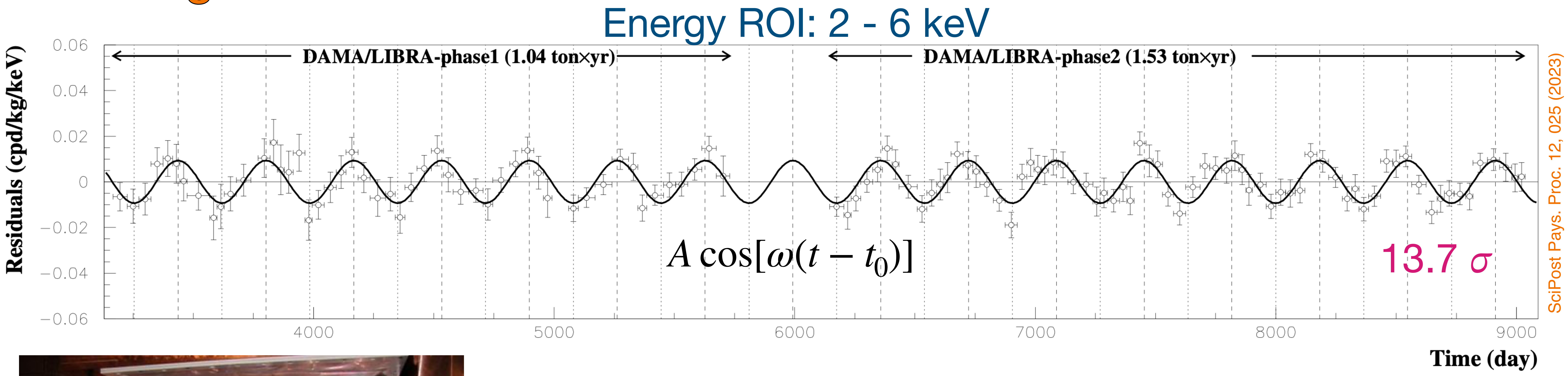


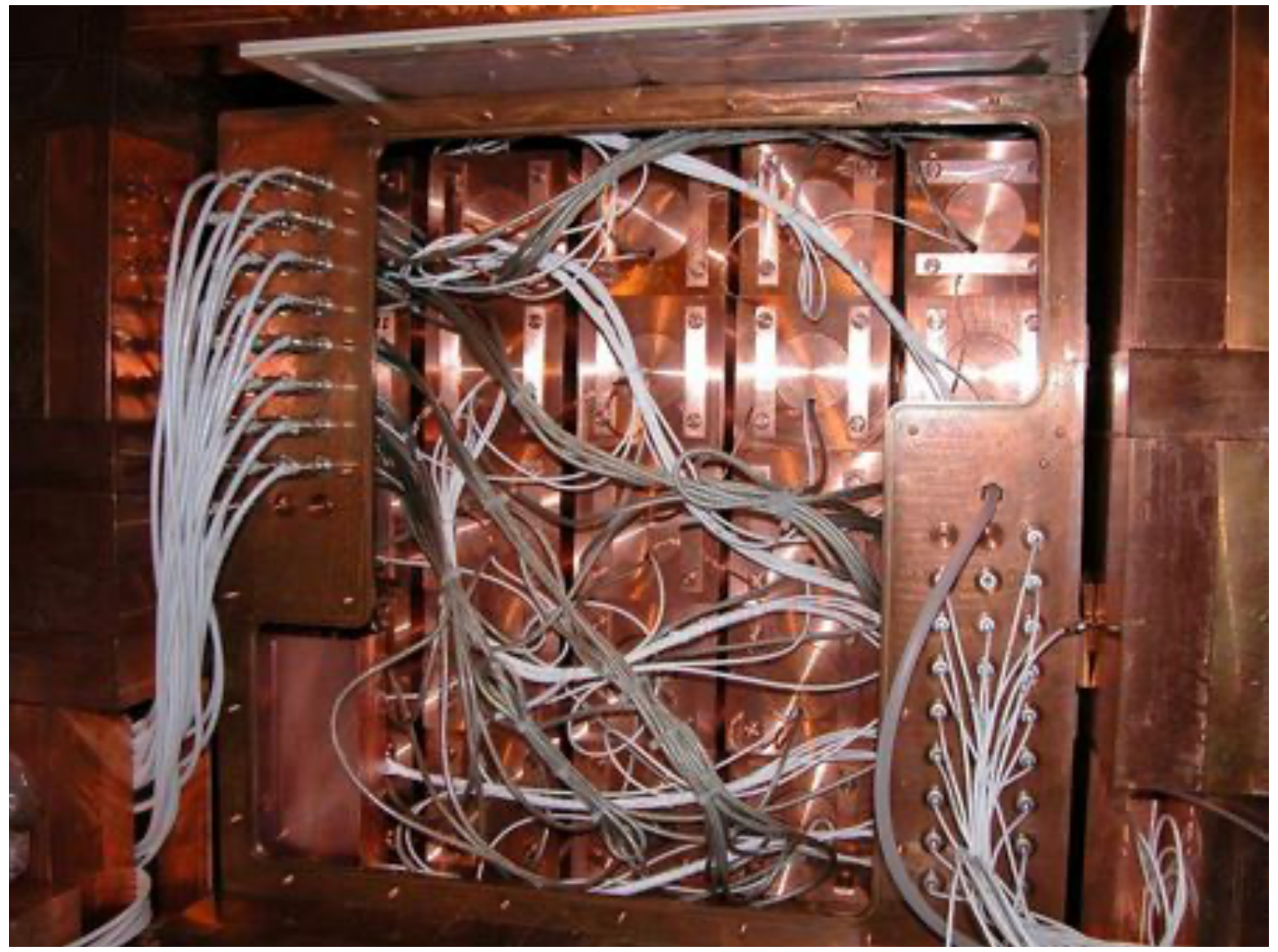

Adapted from PRL 127, 251802 (2021)

- 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?**

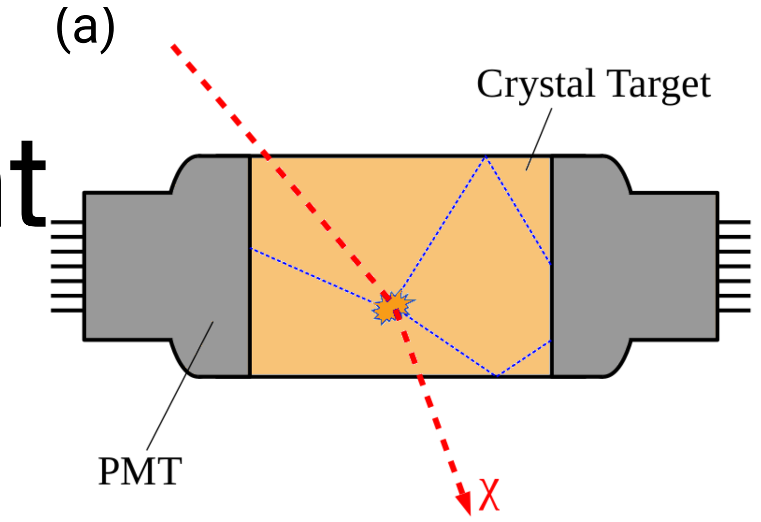
# DAMA DISCOVERY!

## 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



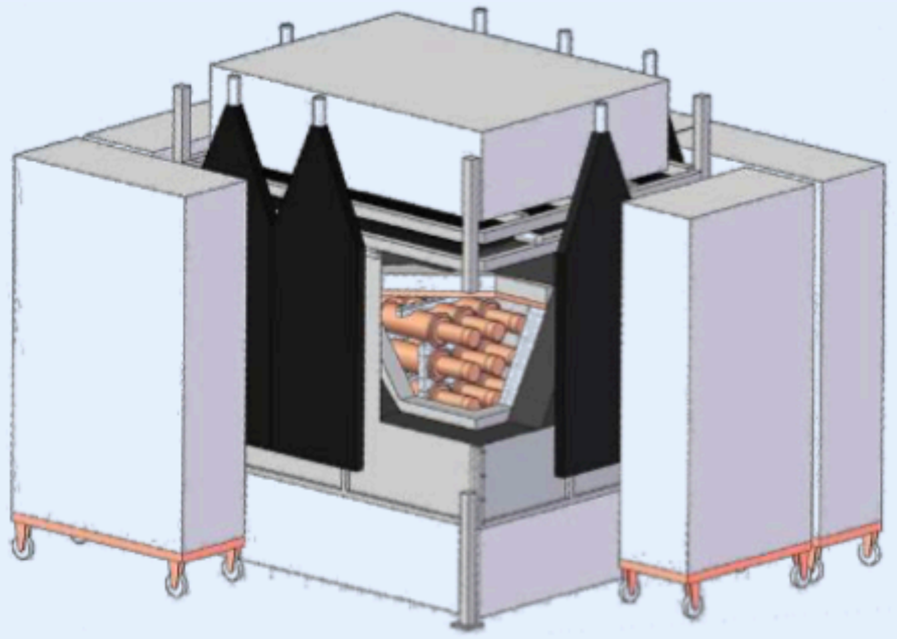
# DAMA/LIBRA DISCOVERY?

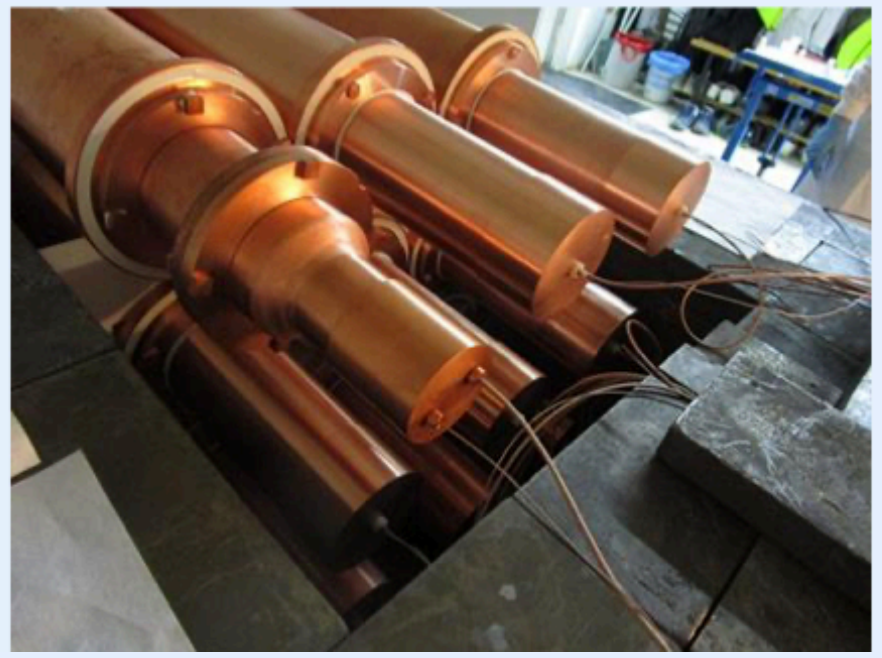


- But DAMA results is in strong tension with result from many other DM direct detection experiments with better sensitivity.
- What is the source of the annual modulation signal seen in DAMA?
  - Unknown source of backgrounds? ($^{40}K$?)
  - Modulation seen in the 3 keV energy bin, close to the energy 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**

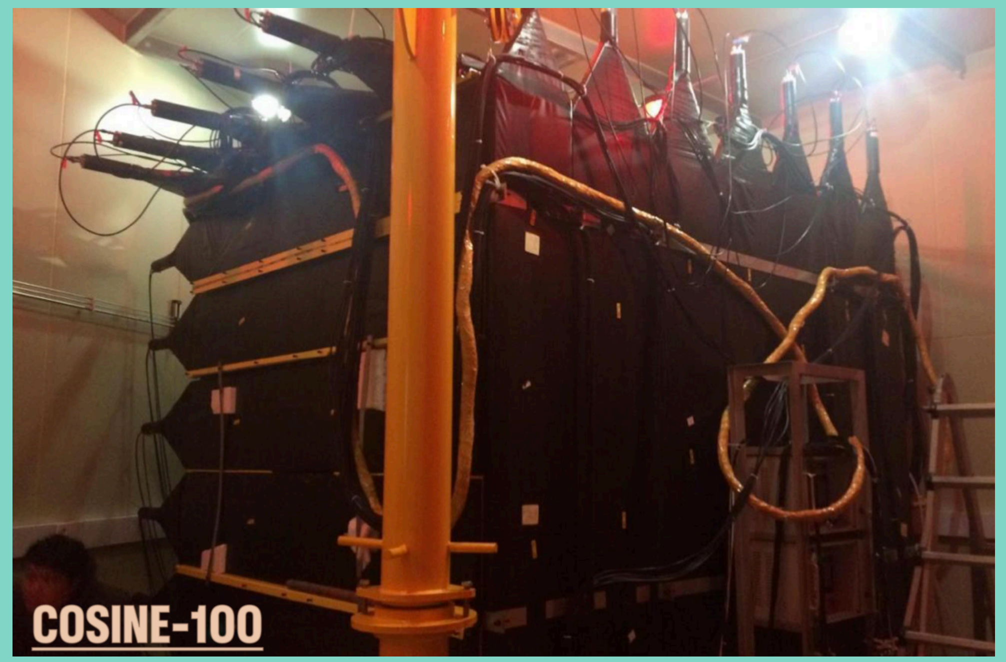
## ANAIS-112





- 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 ~4$\sigma$

## COSINE-100





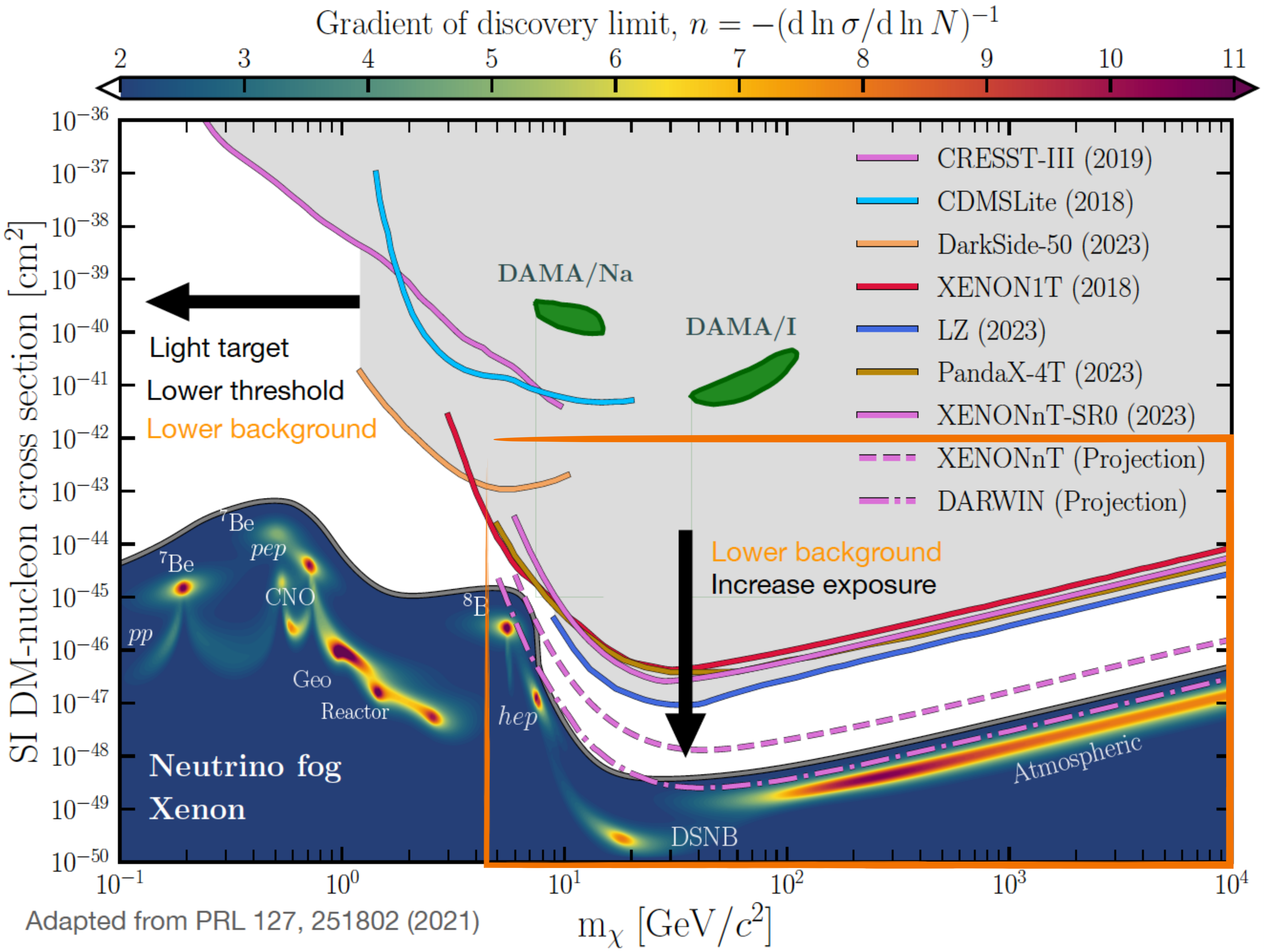
- 5 Ultrapure NaI(Tl) crystals (total: 61.3 kg)
- Operating in Yangyang UL (Korea)
- 3 year results compatible with null and DAMA results (lack of stat.)

## SABRE

**R&D Ongoing**

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

# Direct Detection Landscape



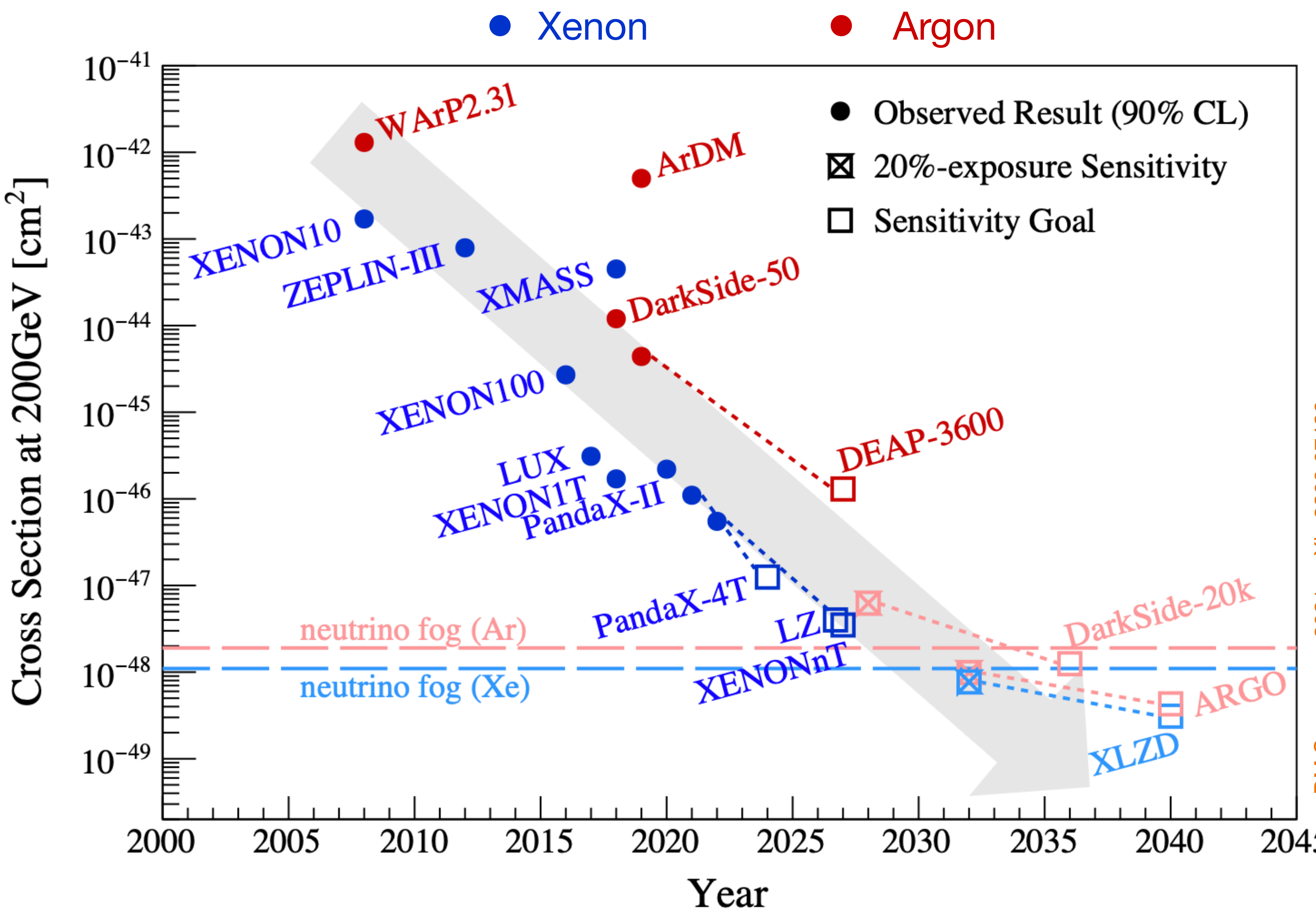

Adapted from PRL 127, 251802 (2021)

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

# Long history

## Wild race:

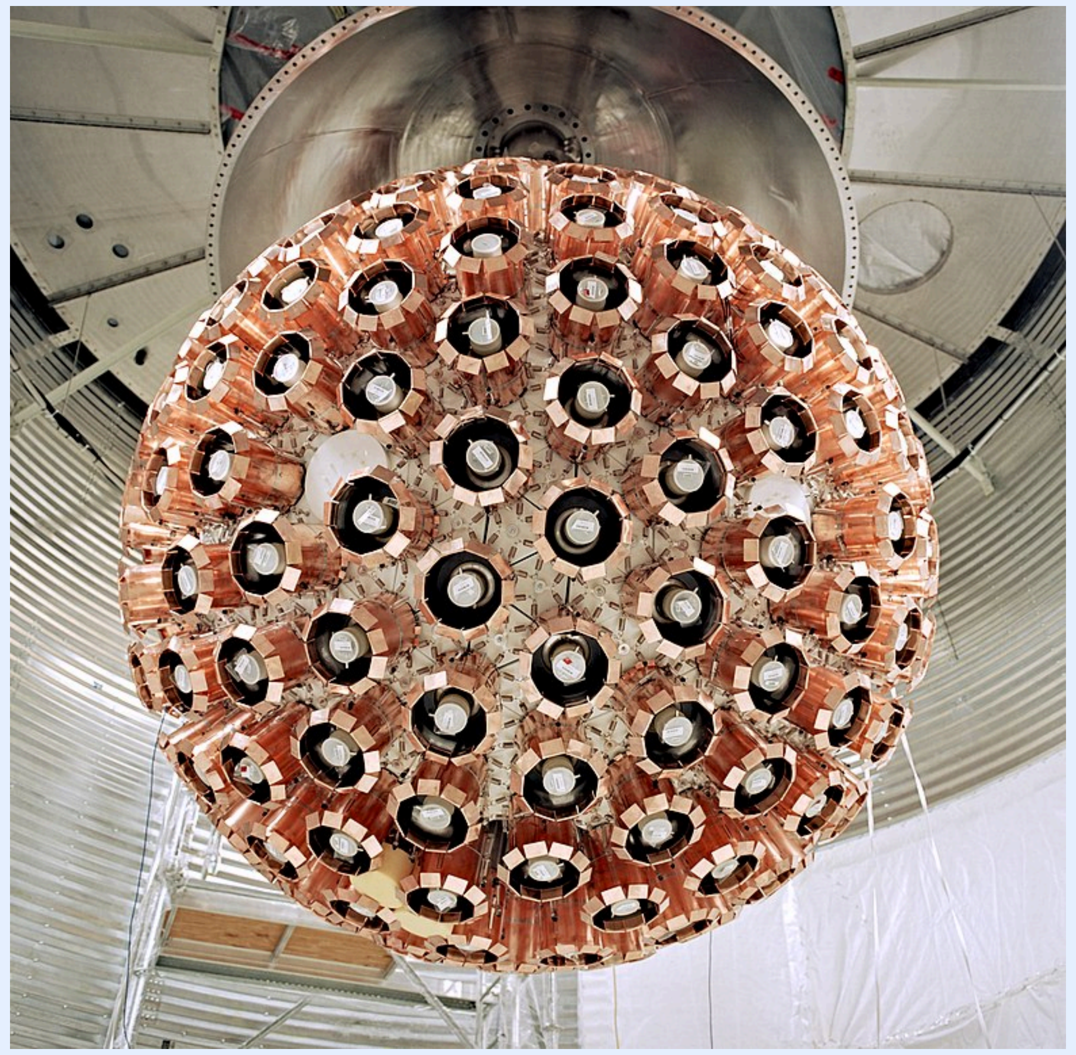
- Noble gases experiments are leading the race for high-mass WIMP search
- Reaching multiple tonne of noble element as target



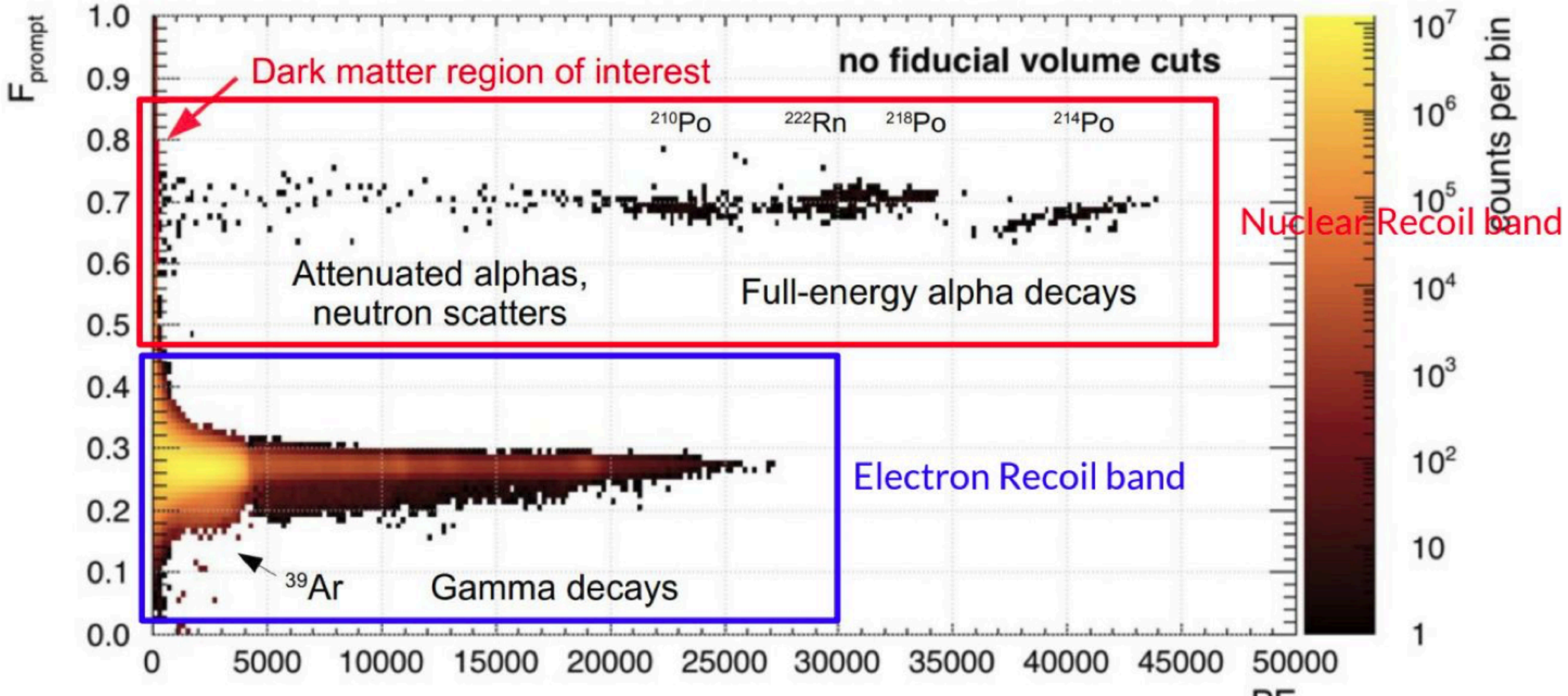

DM Snowmass 2021, arXiv:2209.07426

## 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**



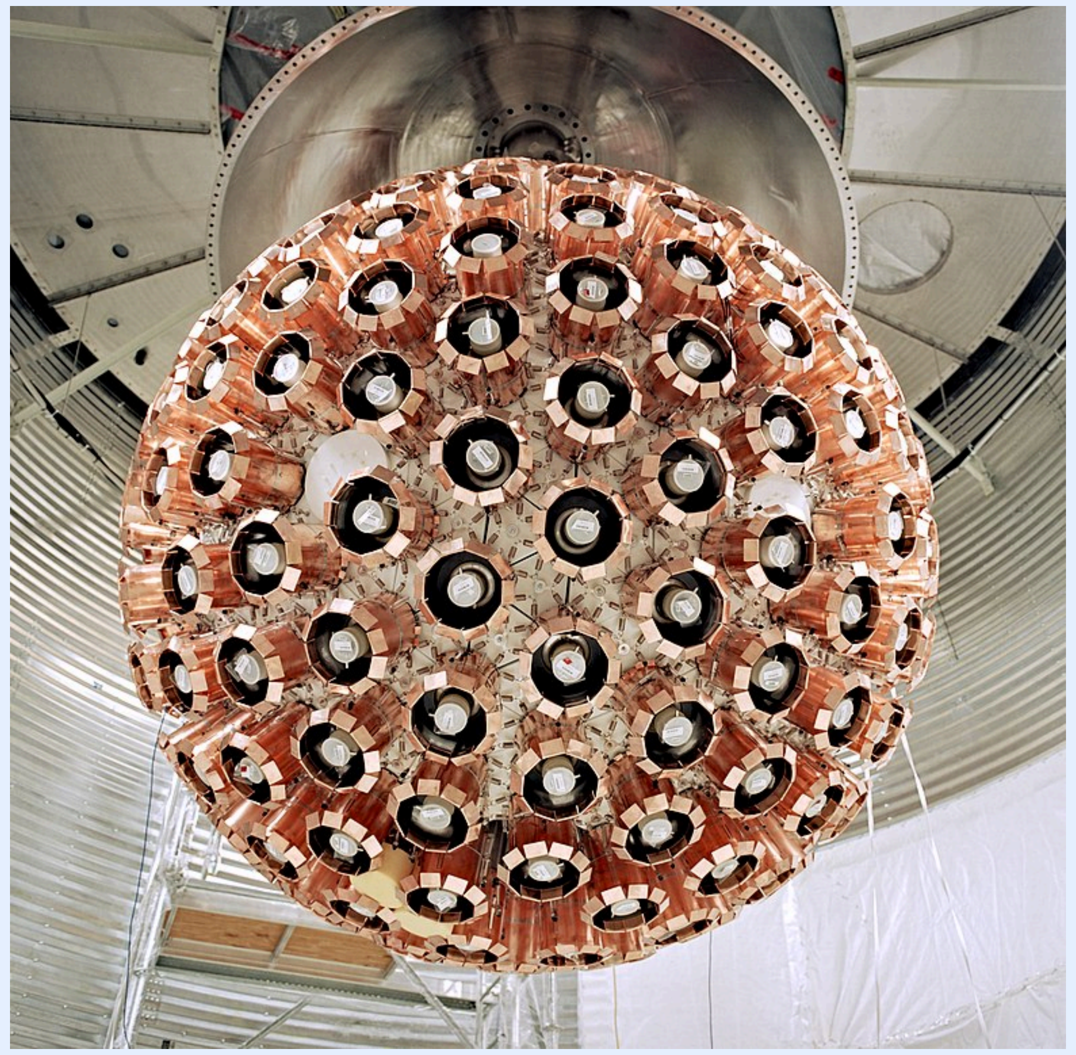

DEAP-3600

# Argon experiments



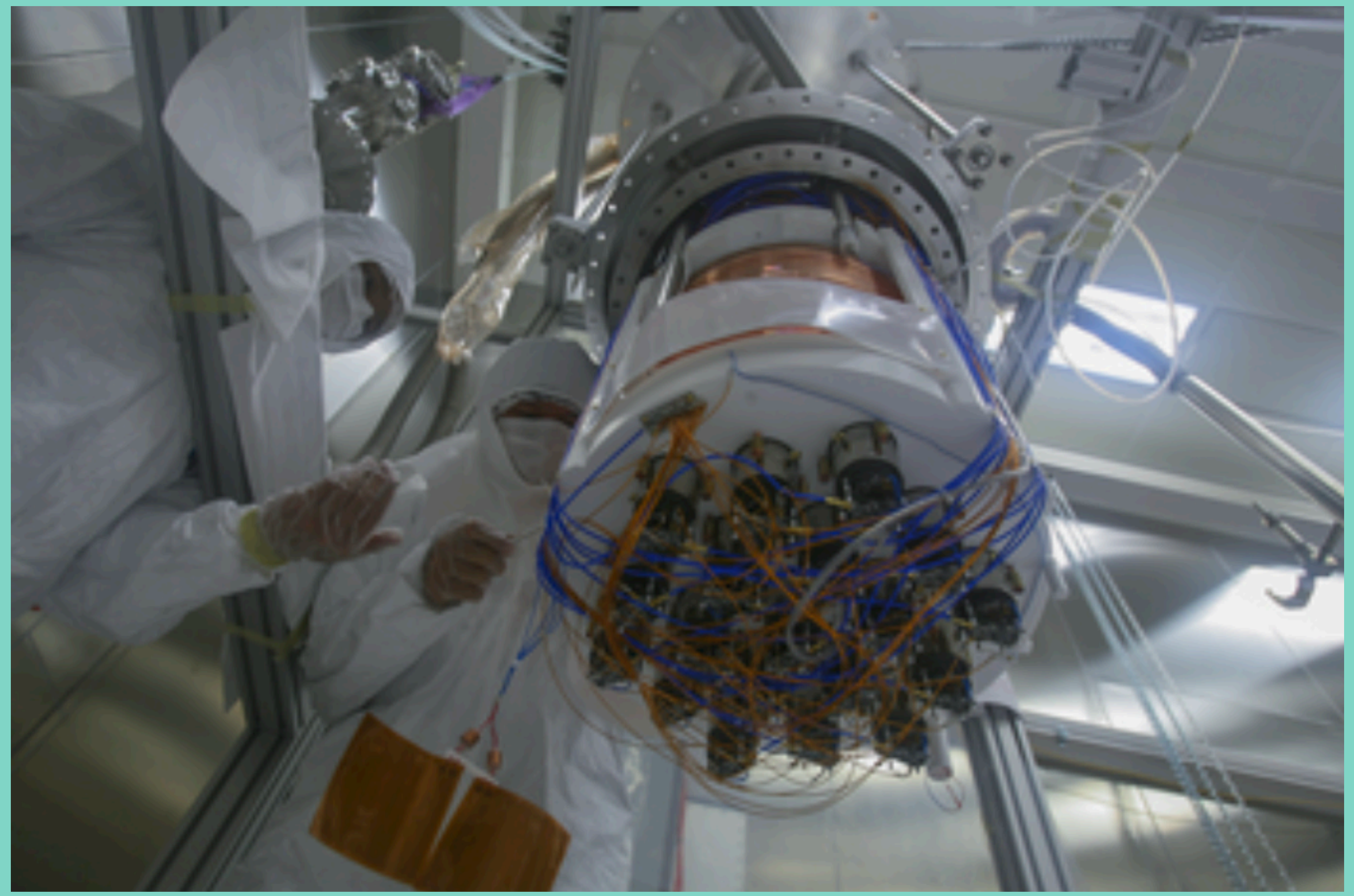
## DEAP-3600

- 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

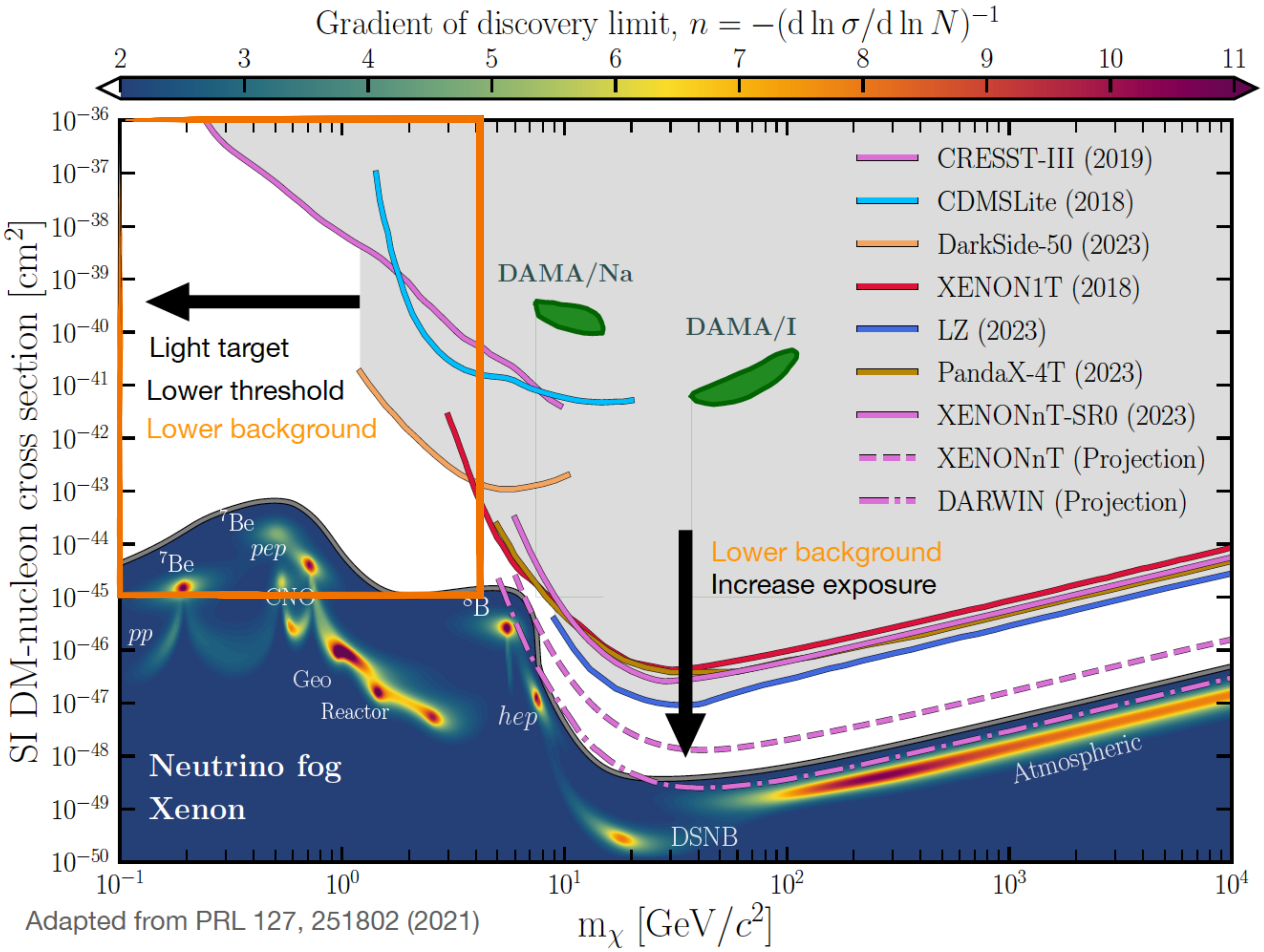
**LZ**

**XENONnT**

**PandaX-4T**

**Will be discussed in further detail tomorrow**

# Direct Detection Landscape

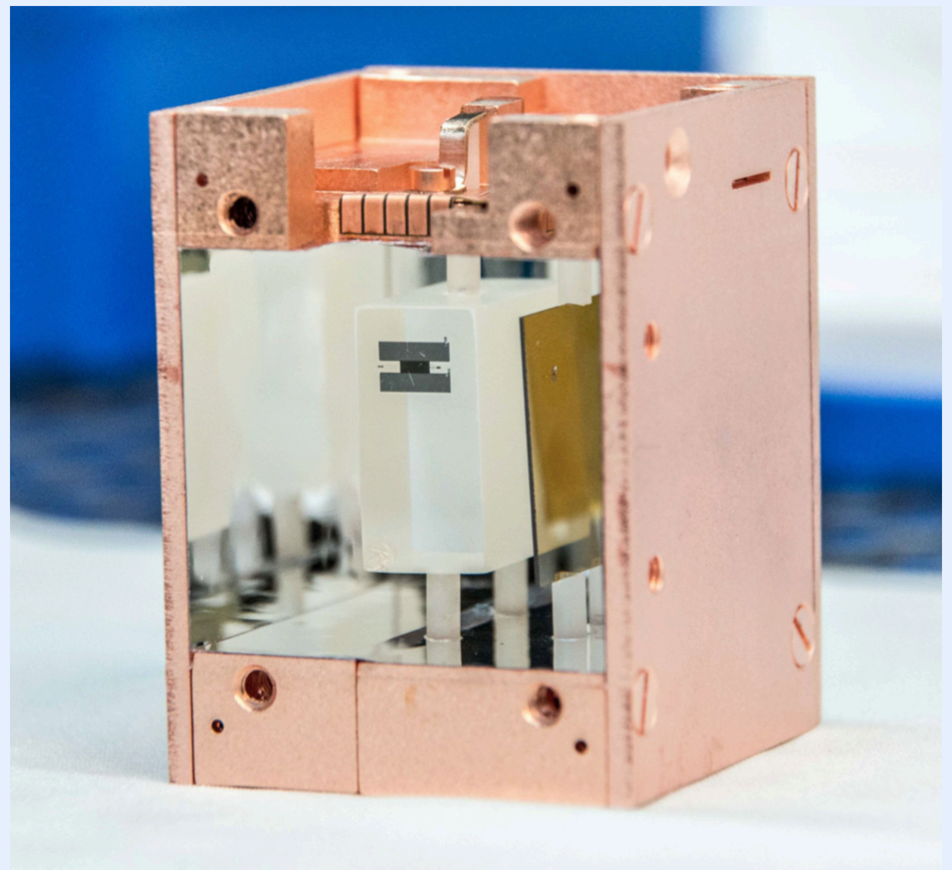



Adapted from PRL 127, 251802 (2021)

- Low-mass WIMP kingdom: cryogenic bolometers and CCDs

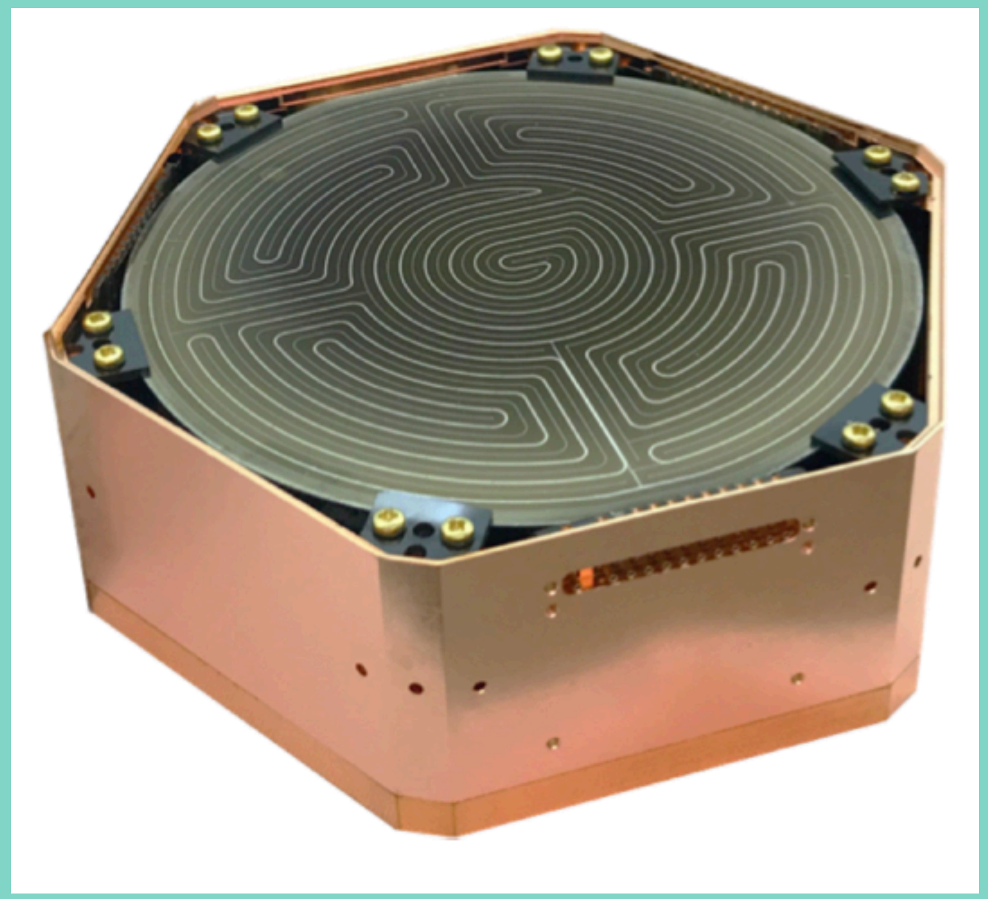
# CRESST-III | SuperCDMS | EDELWEISS-III 

## CRESST-III



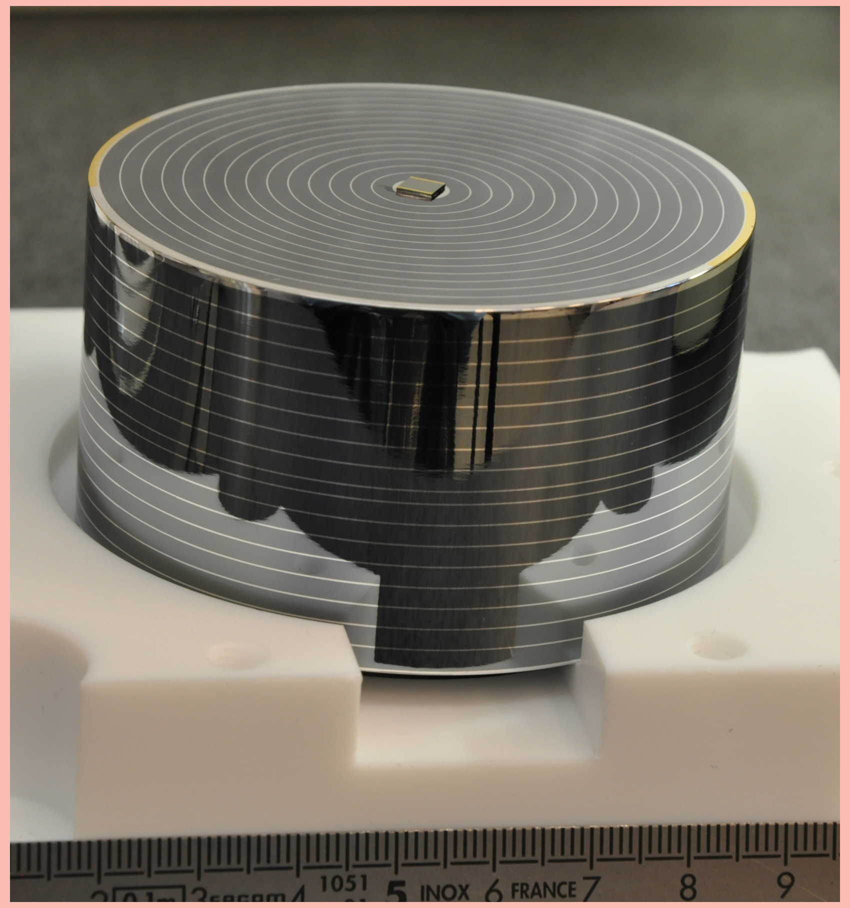
- ~24 g Scintillating crystal $CaWO_4$
- Result from 1st run operating at LNGS
- Limitation by Low-Energy Excess (LEE)

## SuperCDMS



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

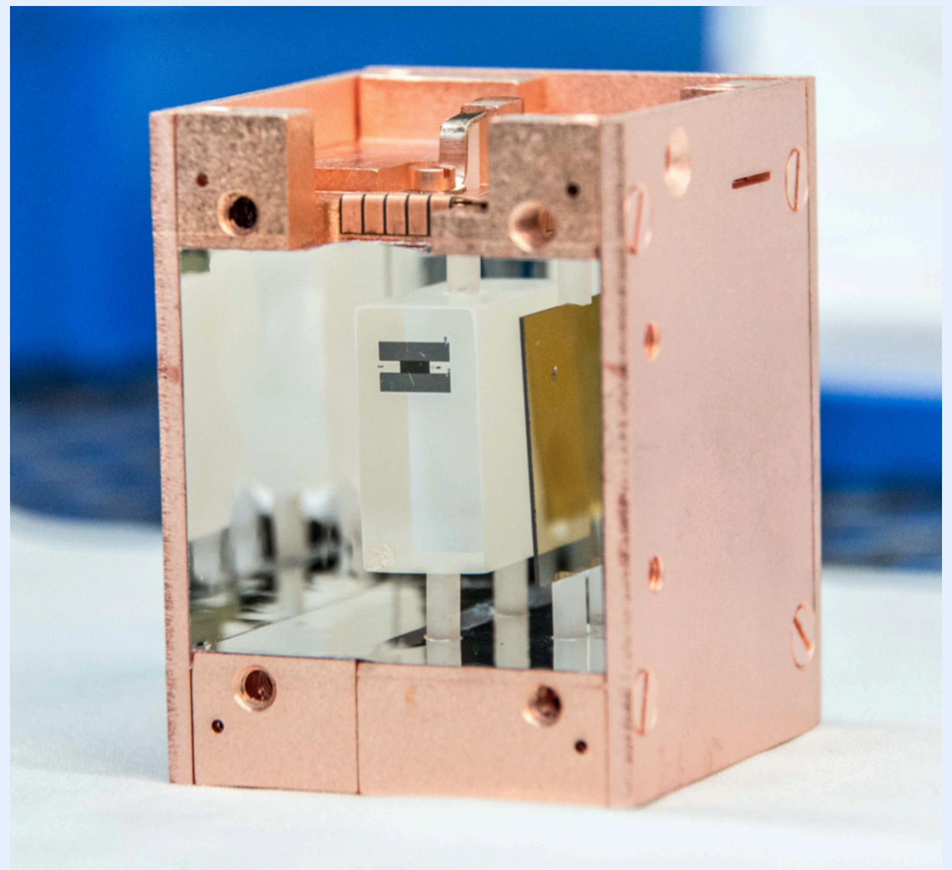
## EDELWEISS-III



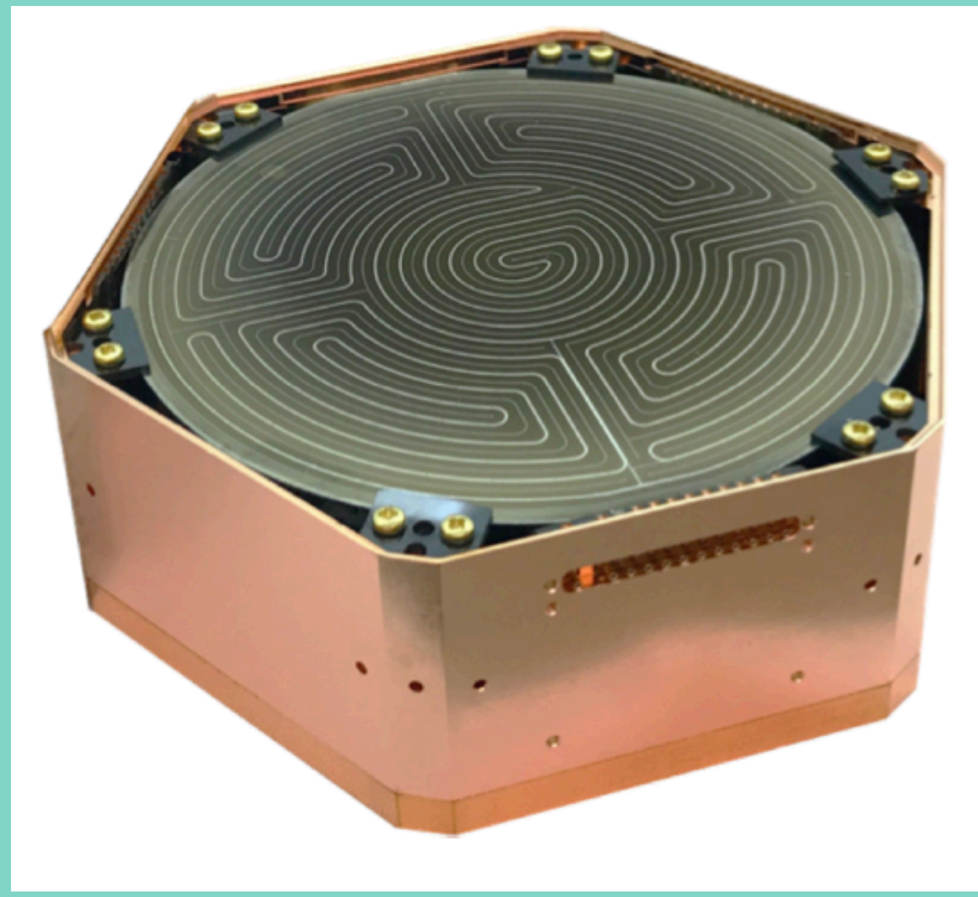
- Ge cryogenic semiconductor
- Operated at Modane
- 2014-2015: 582 kg-days exposure

# CRESST-III | SuperCDMS | EDELWEISS-III

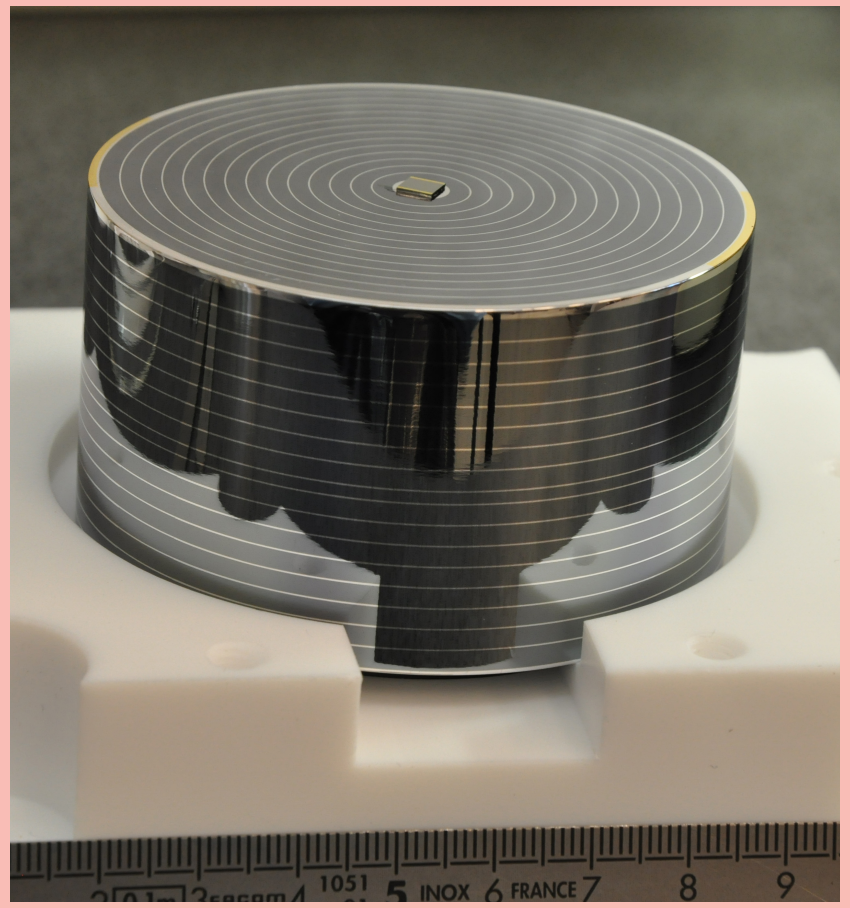
## CRESST-III

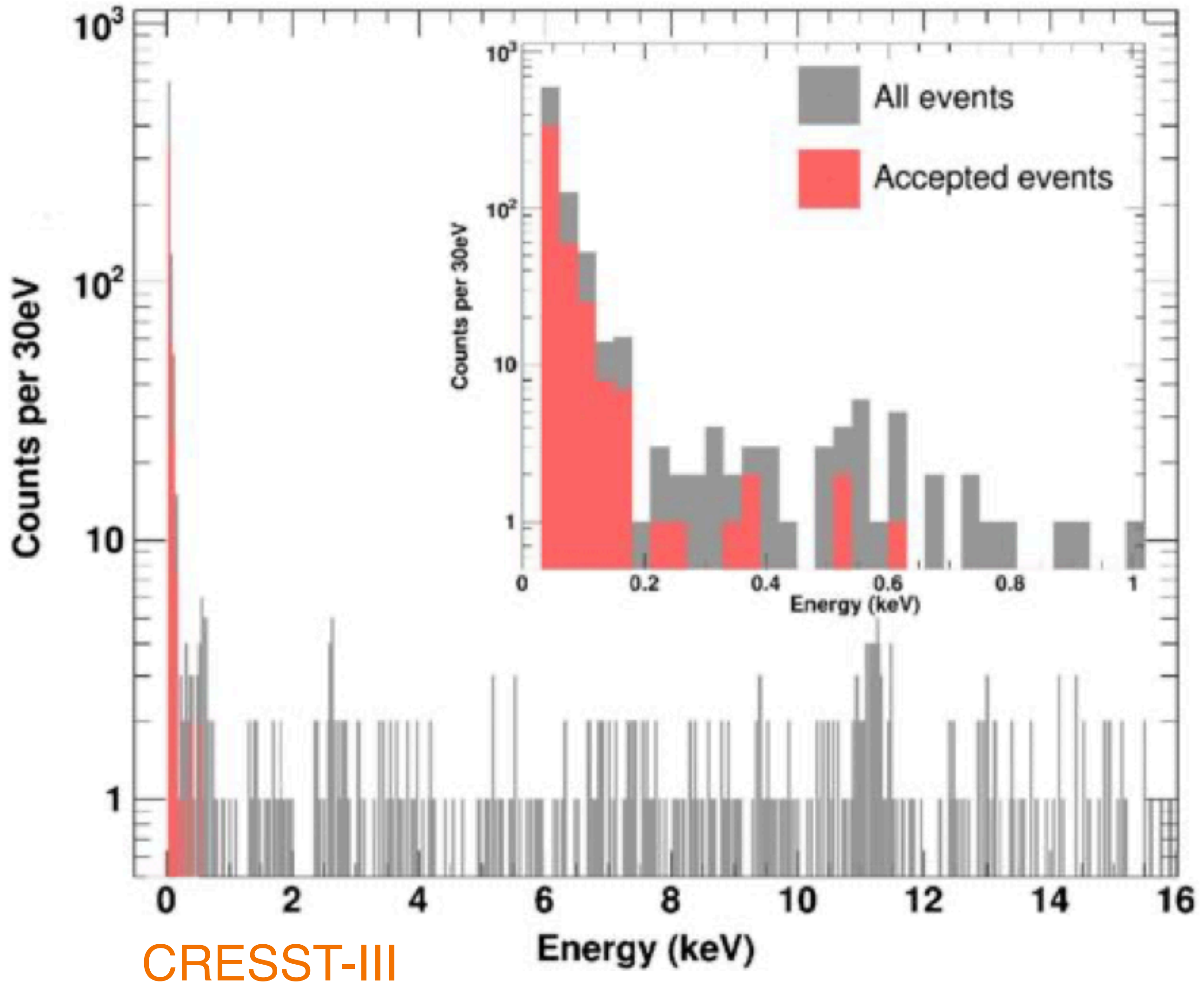


## SuperCDMS



## EDELWEISS-III





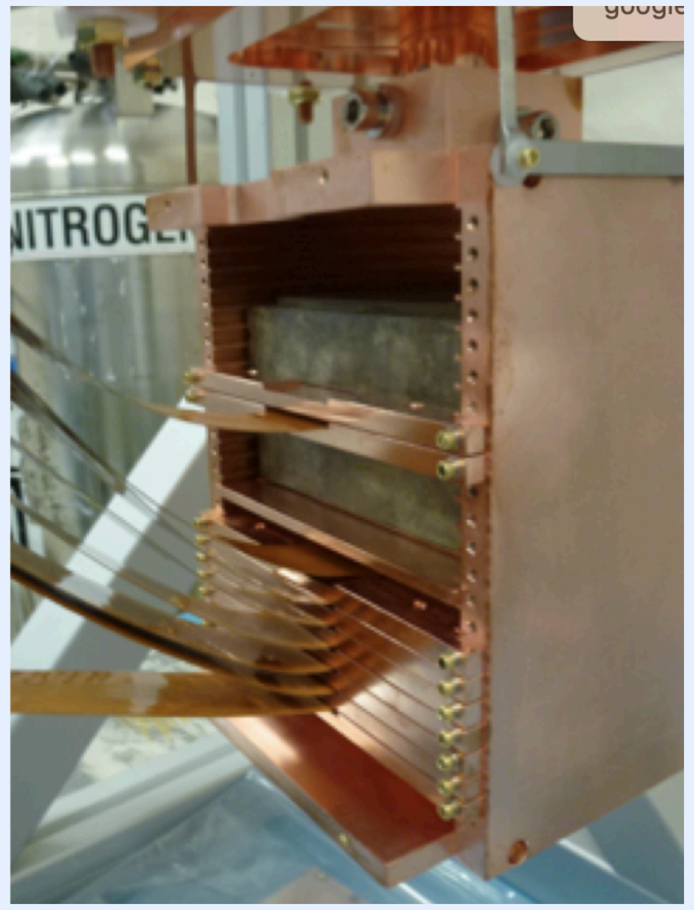

CRESST-III

- 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/DAMIC-M/SENSEI

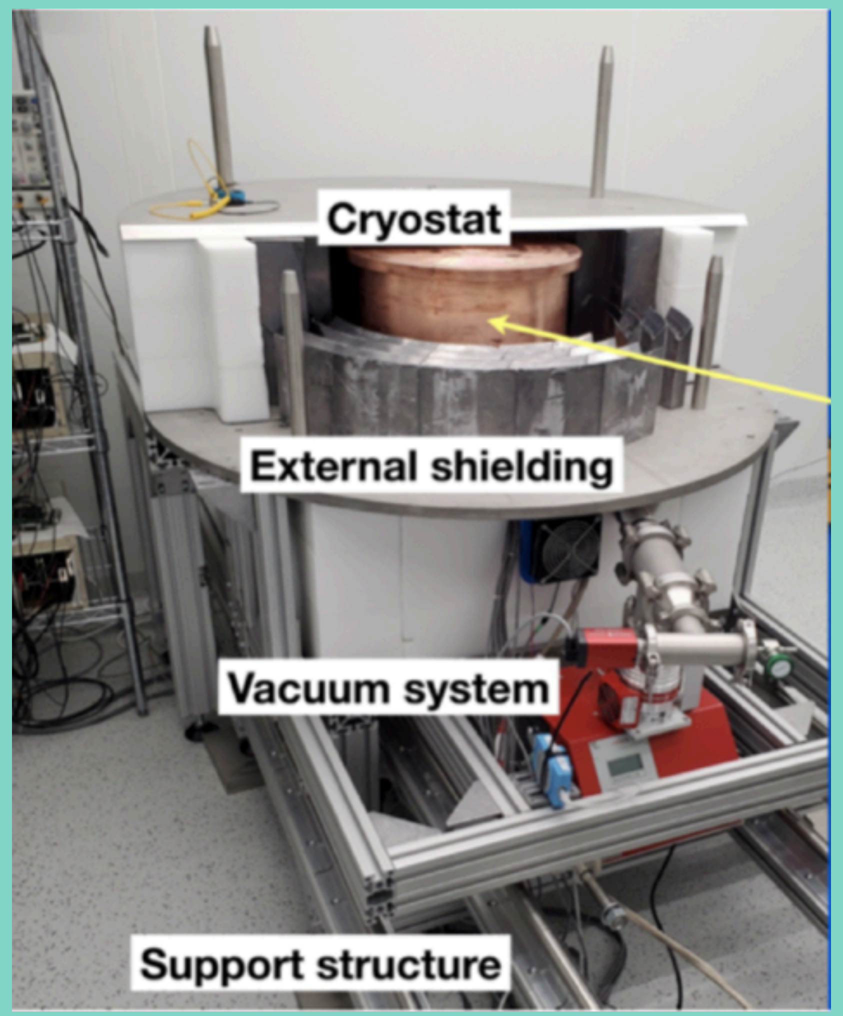


## DAMIC




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

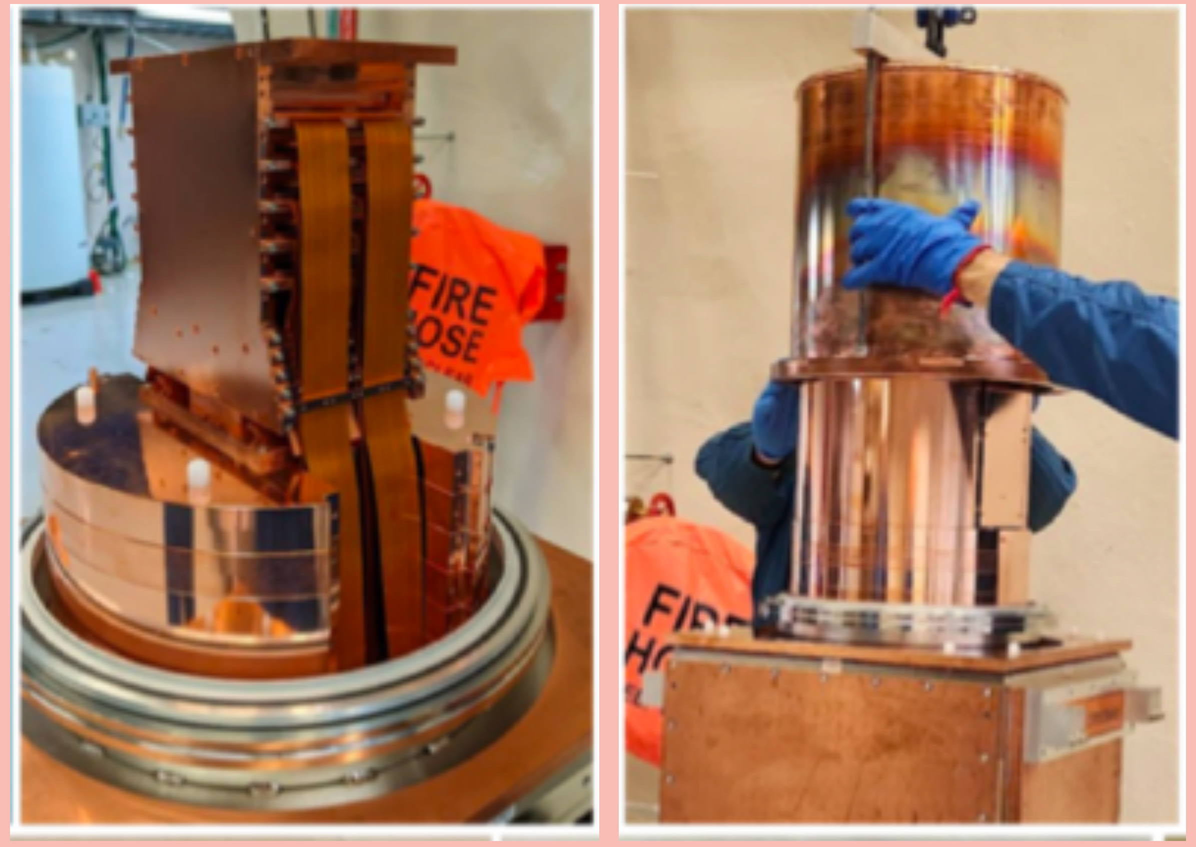
## DAMIC-M




K. Schäffner, TAUP 2023I

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

## SENSEI



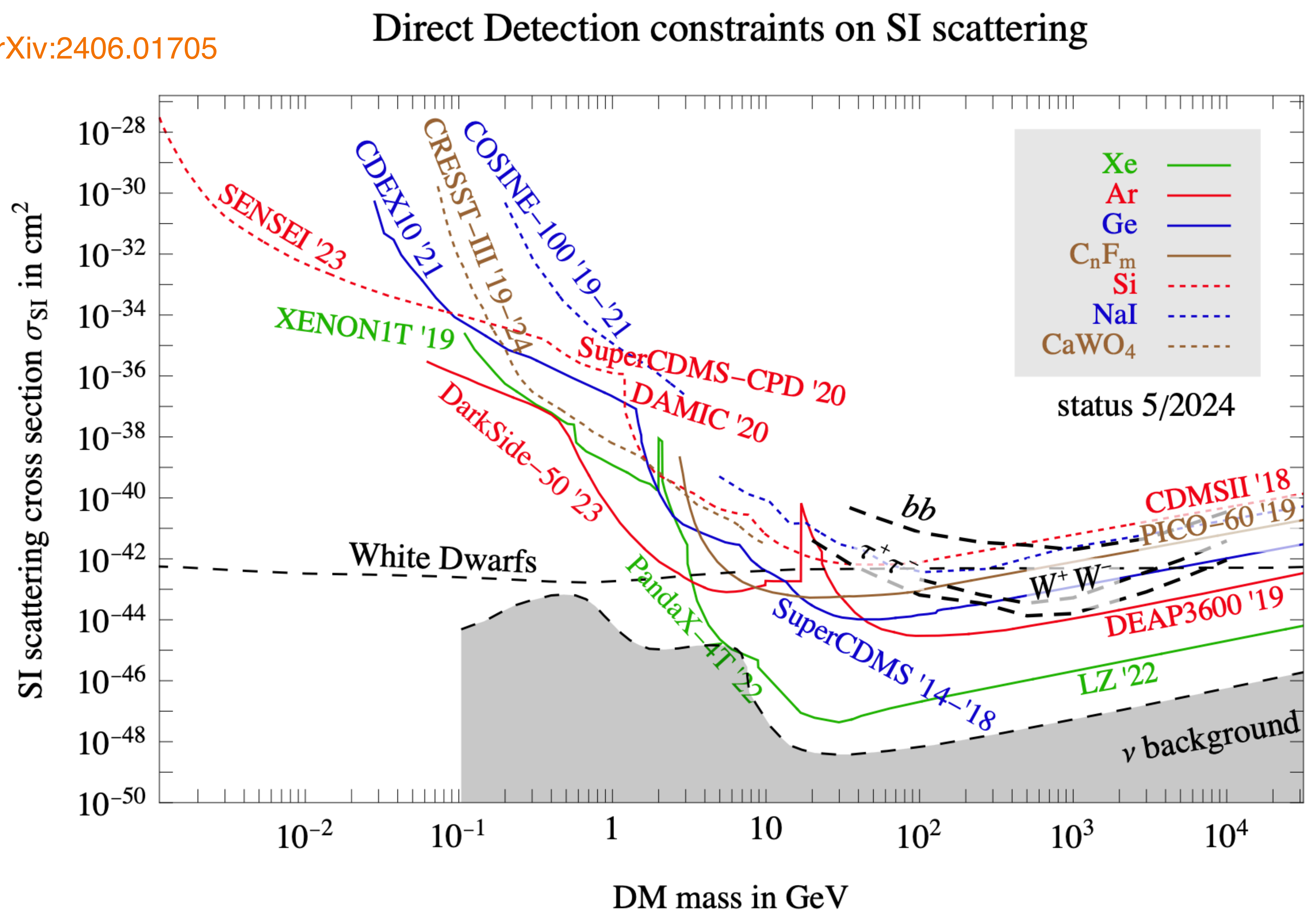
K. Schäffner, TAUP 2023I

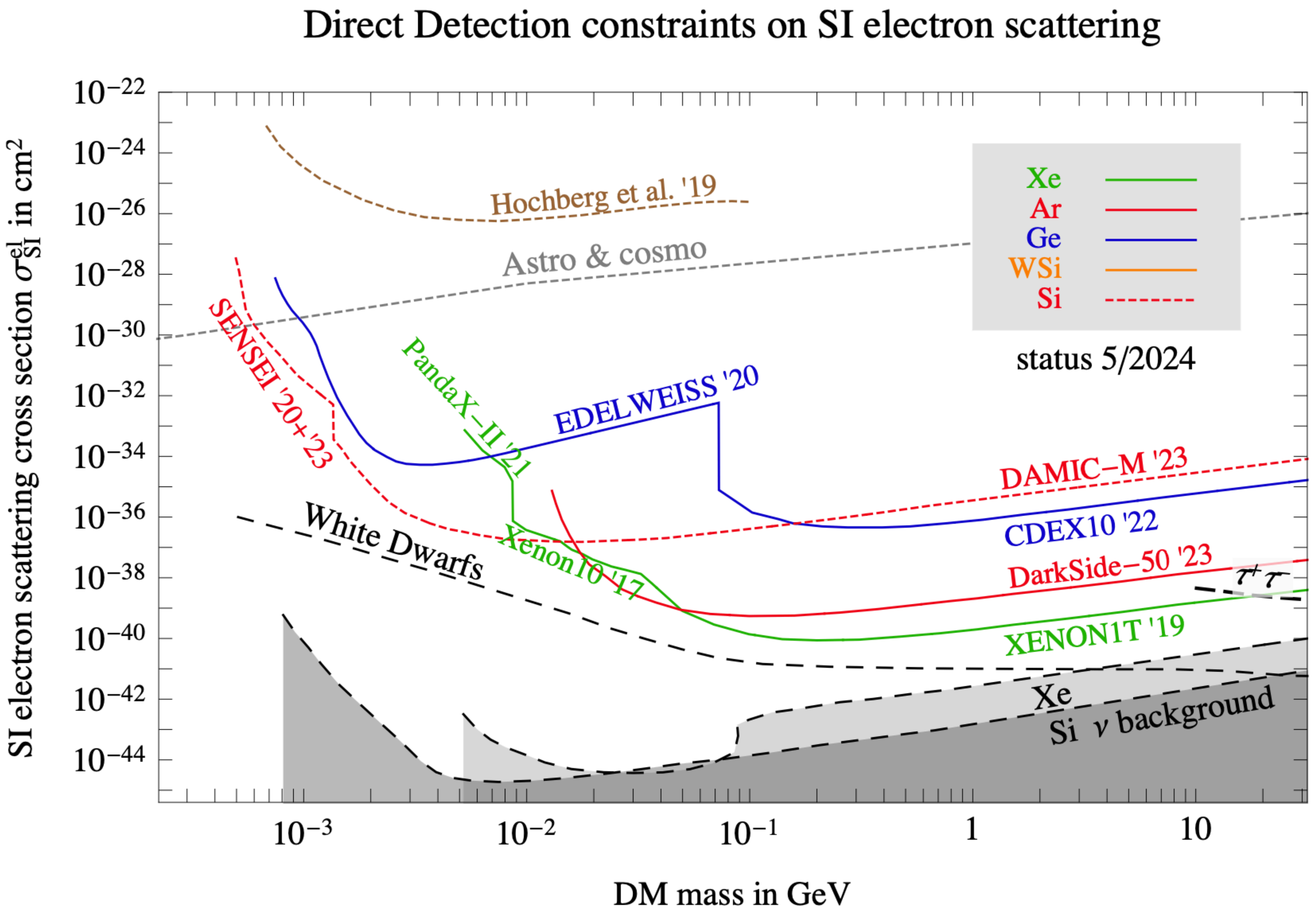
- Different phase, now reaching ~40g per CCDs (19)
- Operate at SNOLAB
- Science run ongoing

# Current State of the Art*



arXiv:2406.01705



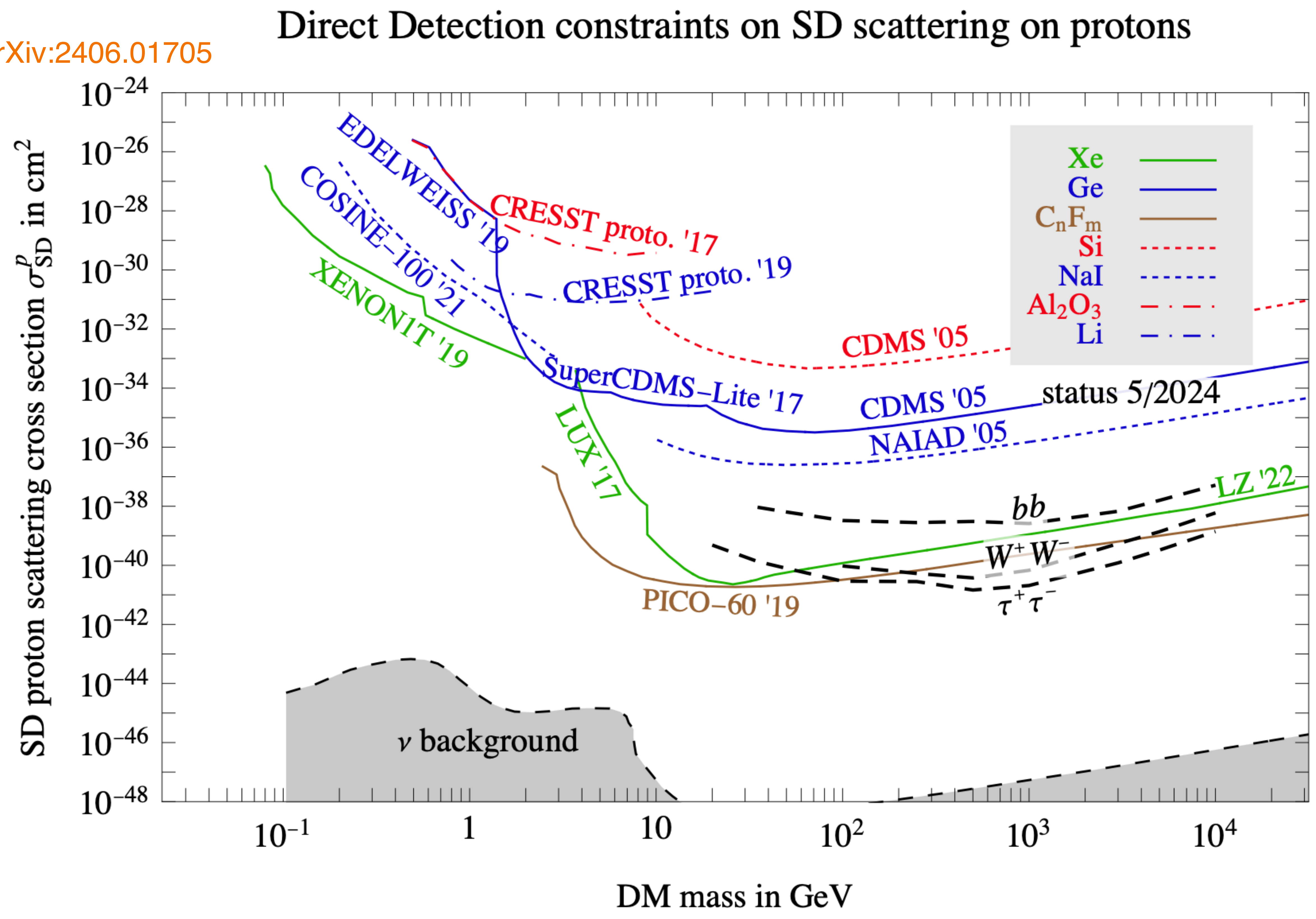



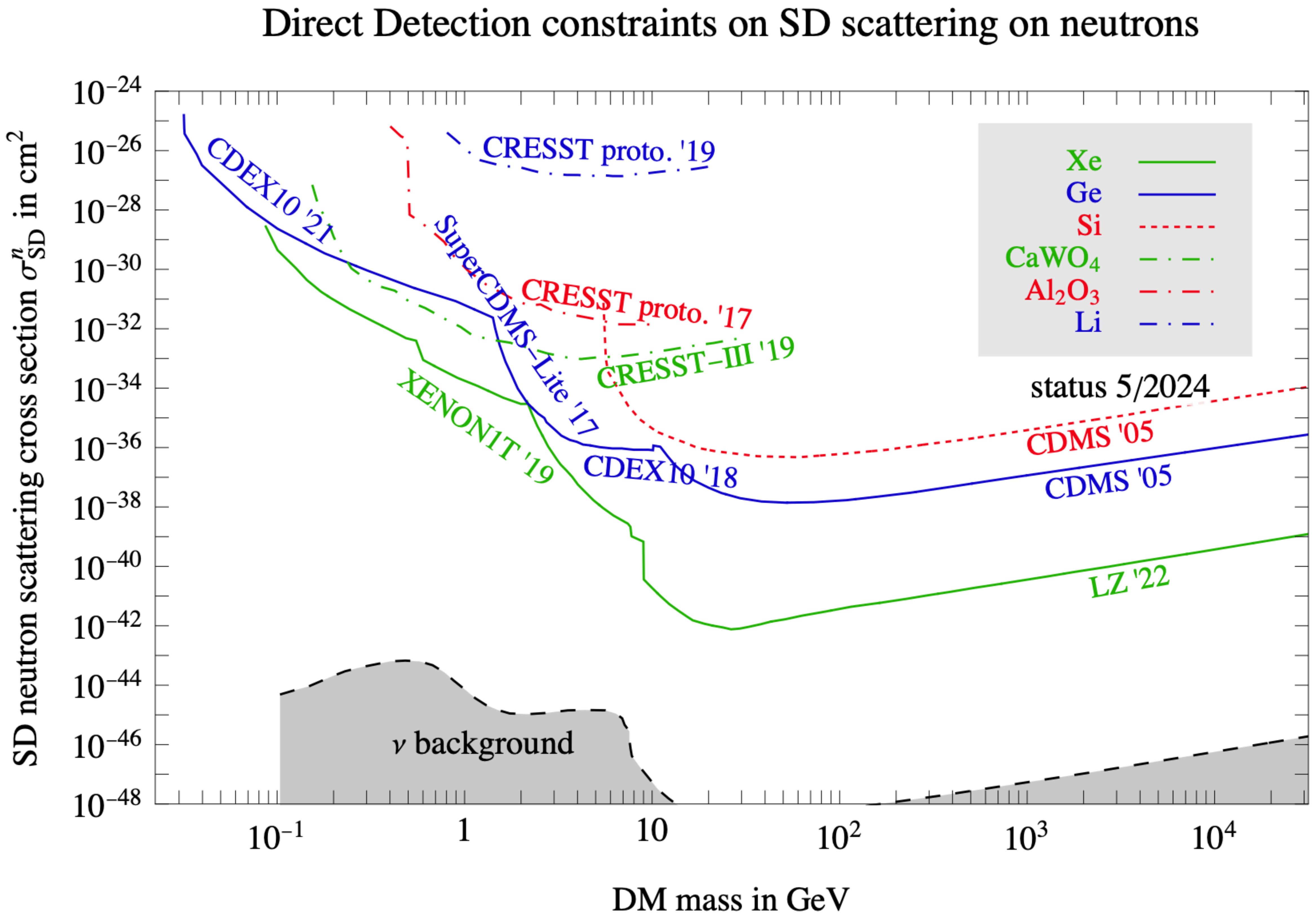

**Noble gases experiment are also in the competition for low-mass DM search**

# Current State of the Art*



arXiv:2406.01705




**Noble gases experiment are also in the competition for low-mass DM search**

# Future perspective



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 $\mu$K) | 1 $cm^3$ $^3He$ | paper | [383] |
| DELight | Vue-des-Alpes, Switz. | 202x | phon.+roton (~ 20 mK) | 10 l $^4He$ | web | [384] |
| HeRALD | | 202x | phon.+roton (~ 50 mK) | ~ 1 kg $^4He$ | web | [385] |
| SuperCDMS SNOLAB | SNOLAB, Canada | 2023 | ath. phon.[+ioniz.] (15 mK)<br>ath. phon.[+ioniz.] (15 mK) | 11[+14] kg Ge<br>2.4[+1.2] kg Si | web | [386] |
| 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<br>SUPL, Australia | 2024<br>2023 | scint. (~ 300 K)<br>scint. (~ 300 K) | 50 kg NaI(Tl)<br>50 kg NaI(Tl) | web<br>web | [339] |
| PICOLON | Kamioka, Japan | 202x | scint. (~ 300 K) | 54 → 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 $C_3F_8$ | web | [392] |
| PICO-500 | SNOLAB, Canada | 202x | bubble chamber (~ 290 K) | 360 kg $C_3F_8$ | web | [393] |
| MOSCAB | Gran Sasso, Italy | 202x | bubble chamber (~ 290 K) | 2 → 25 l $C_3F_8$ | 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+$C_4H_{10}$ | web | [335] |
| CYGNO | 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 $H_2O$ | talk | [394] |
| ALETHEA | | | scint.+ioniz. (~ 4 K) | 10 kg He | paper | [395] |
| TESSERACT | | | ath. phon. | $Al_2O_3$, GaAs, He | web | LOI |
| SPLENDOR | | | ioniz | $Eu_5In_2Sb_6$, $EuZn_2P_2$ | 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**