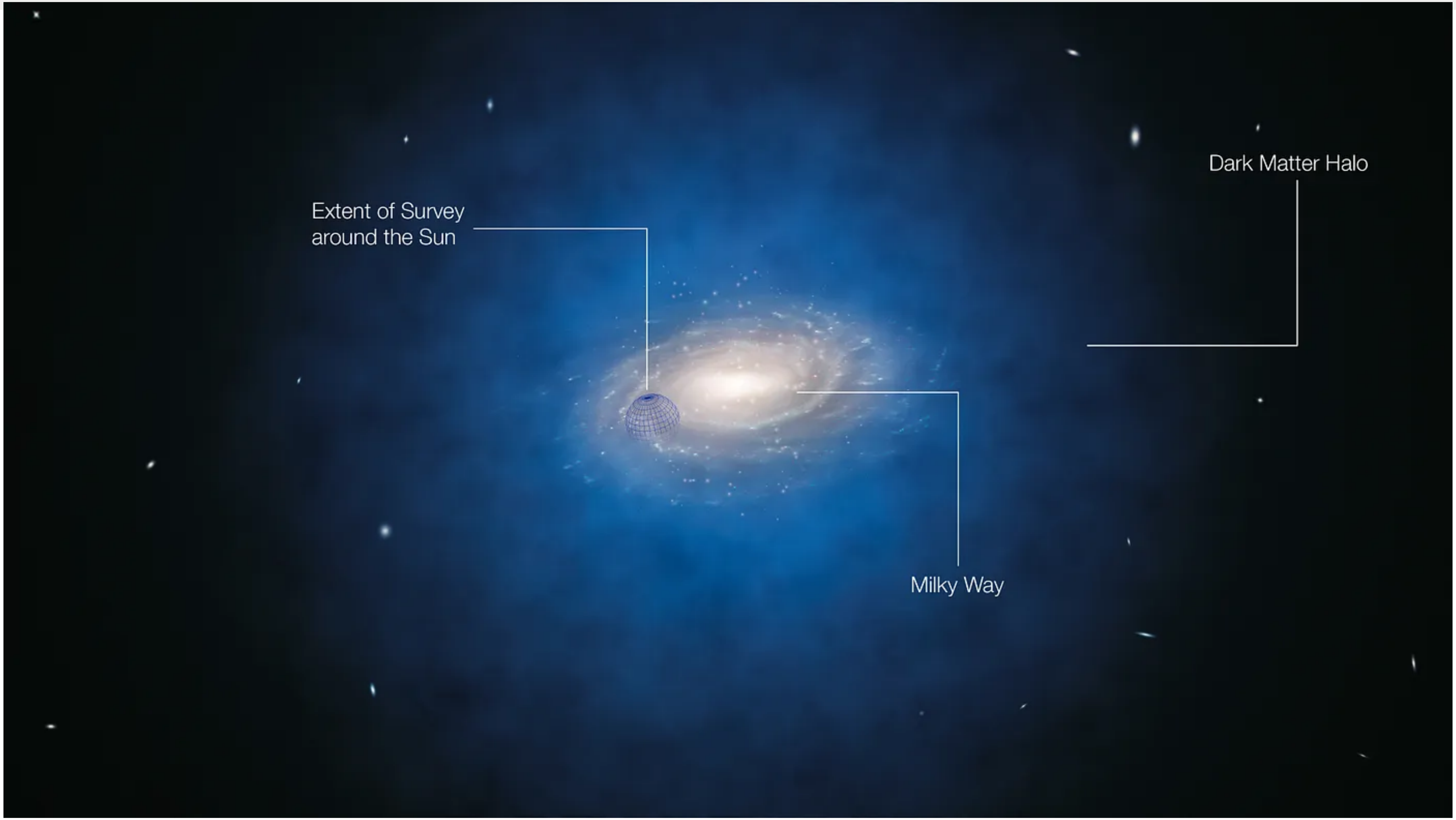
Dark Matter Direct Detection

Davide Franco

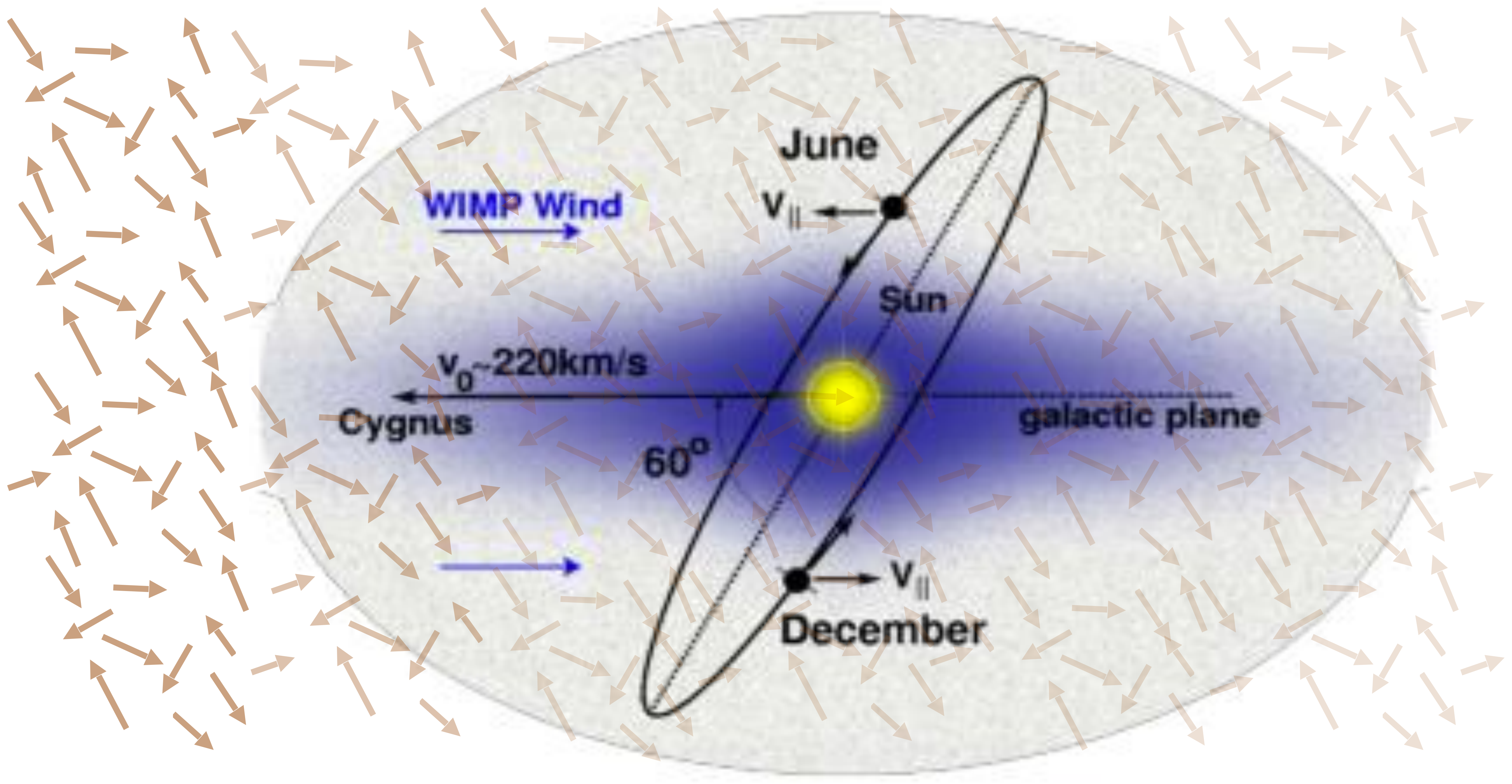
Laboratoire AstroParticule et Cosmologie

Halo des WIMPs

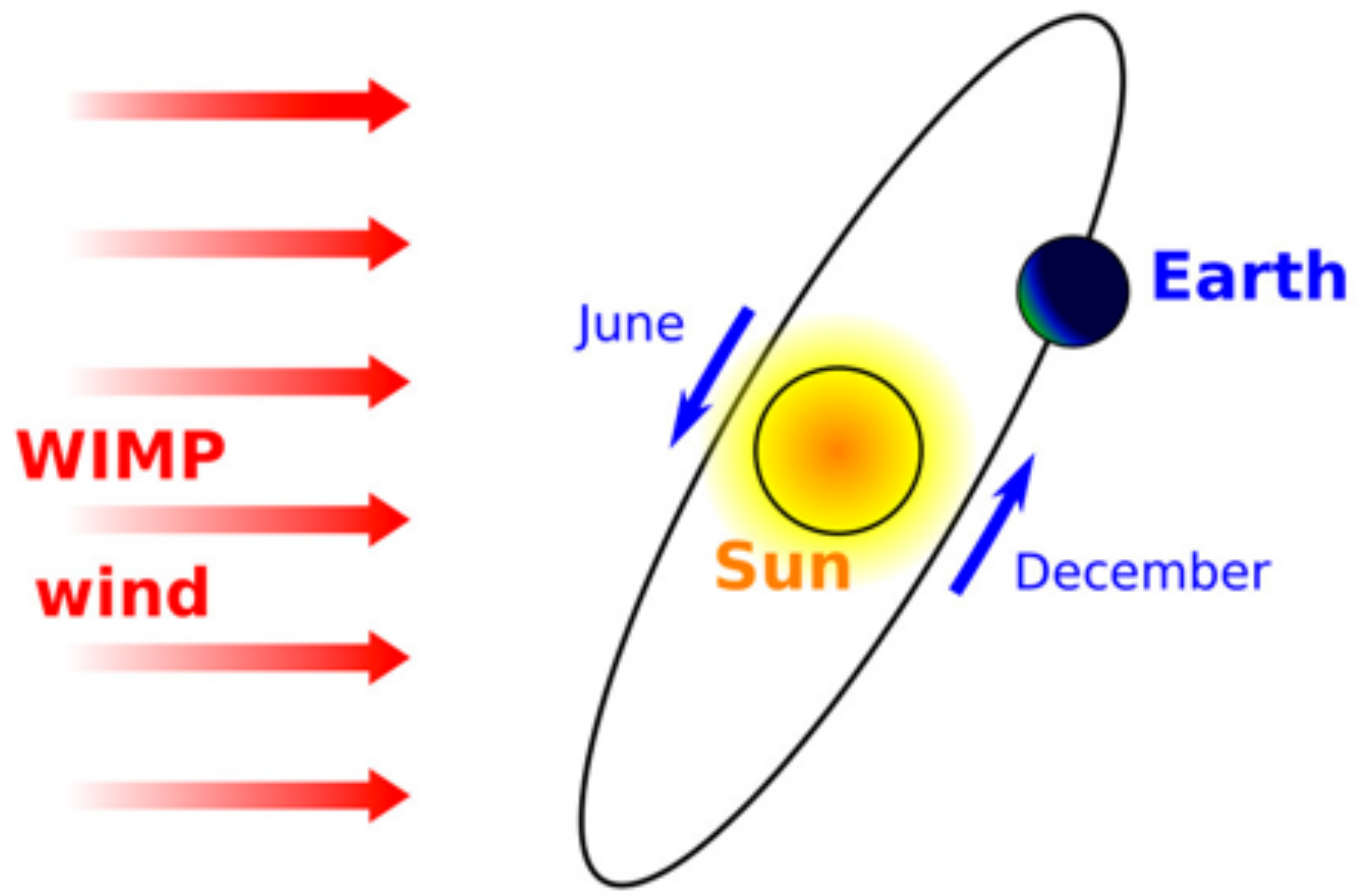


The WIMP halo

With respect to the galactic center

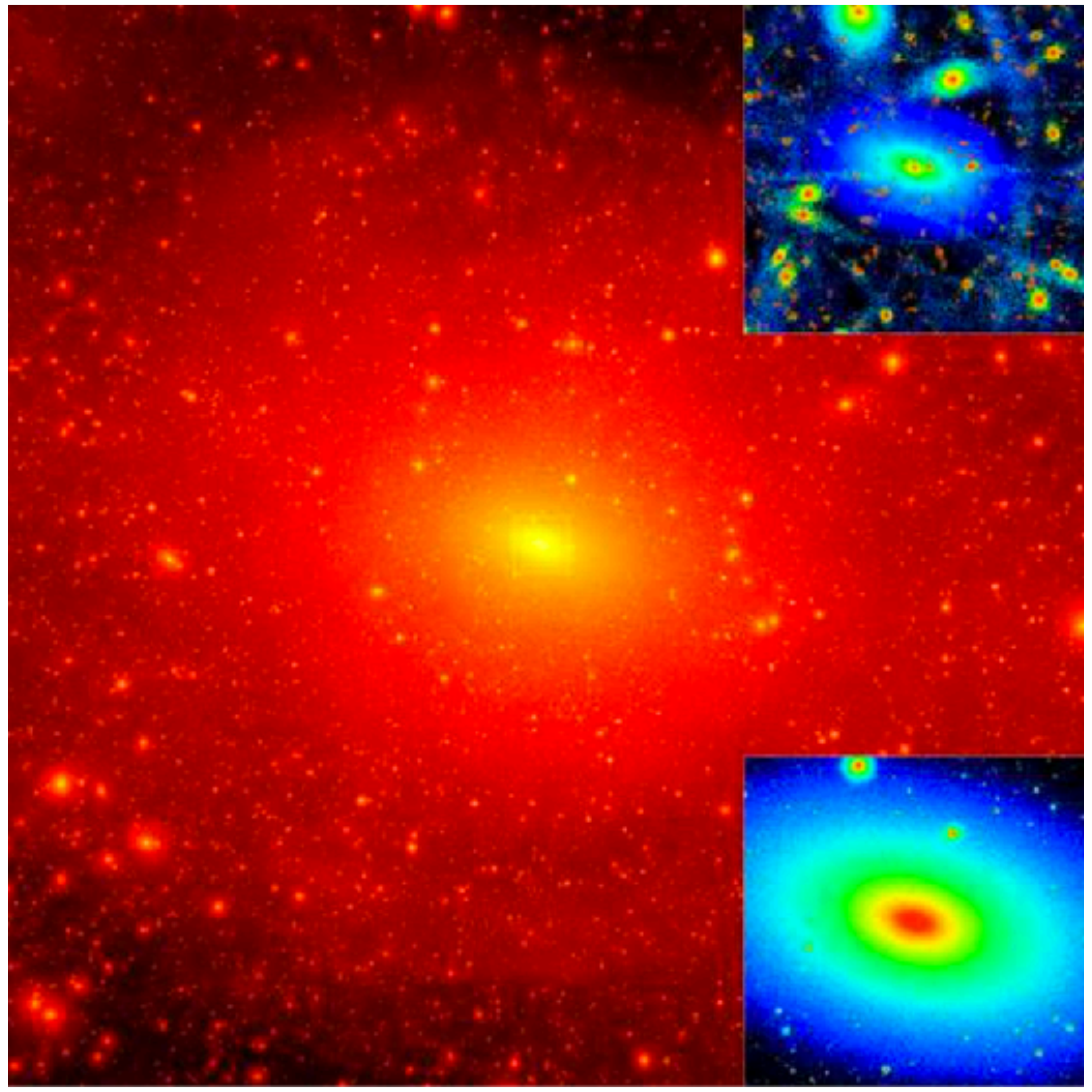


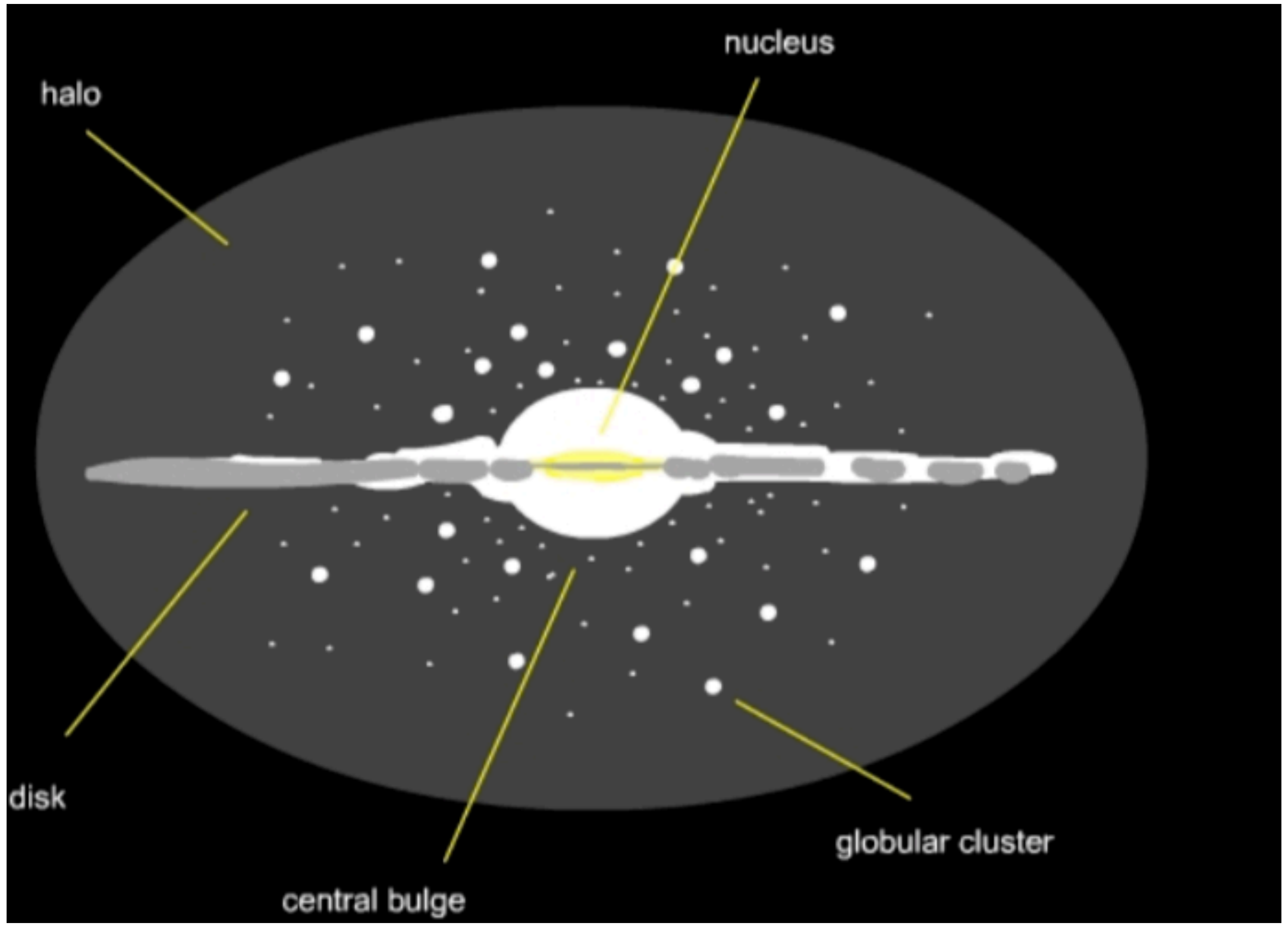
With respect to the Earth



The stationary Halo?

"Standard" galaxy structure:
- baryonic component in central bulge and spiral disk
- embedded in a fairly smooth **spherical** and **stationary** halo of dark matter particles





The Halo parameters

- **Density** ~ 0.3 GeV/cm³

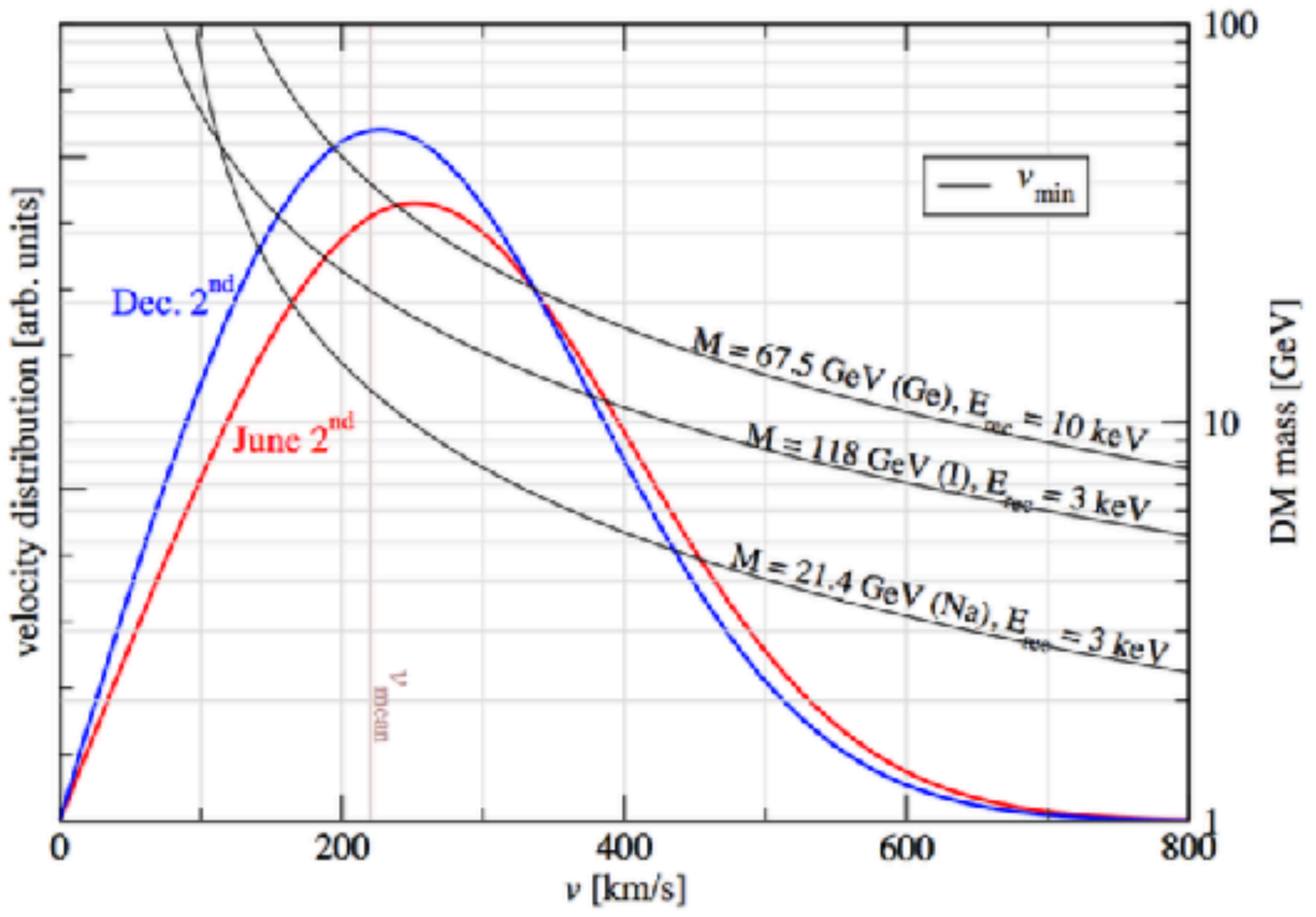
$$\rho(r) \propto 1/r^2$$

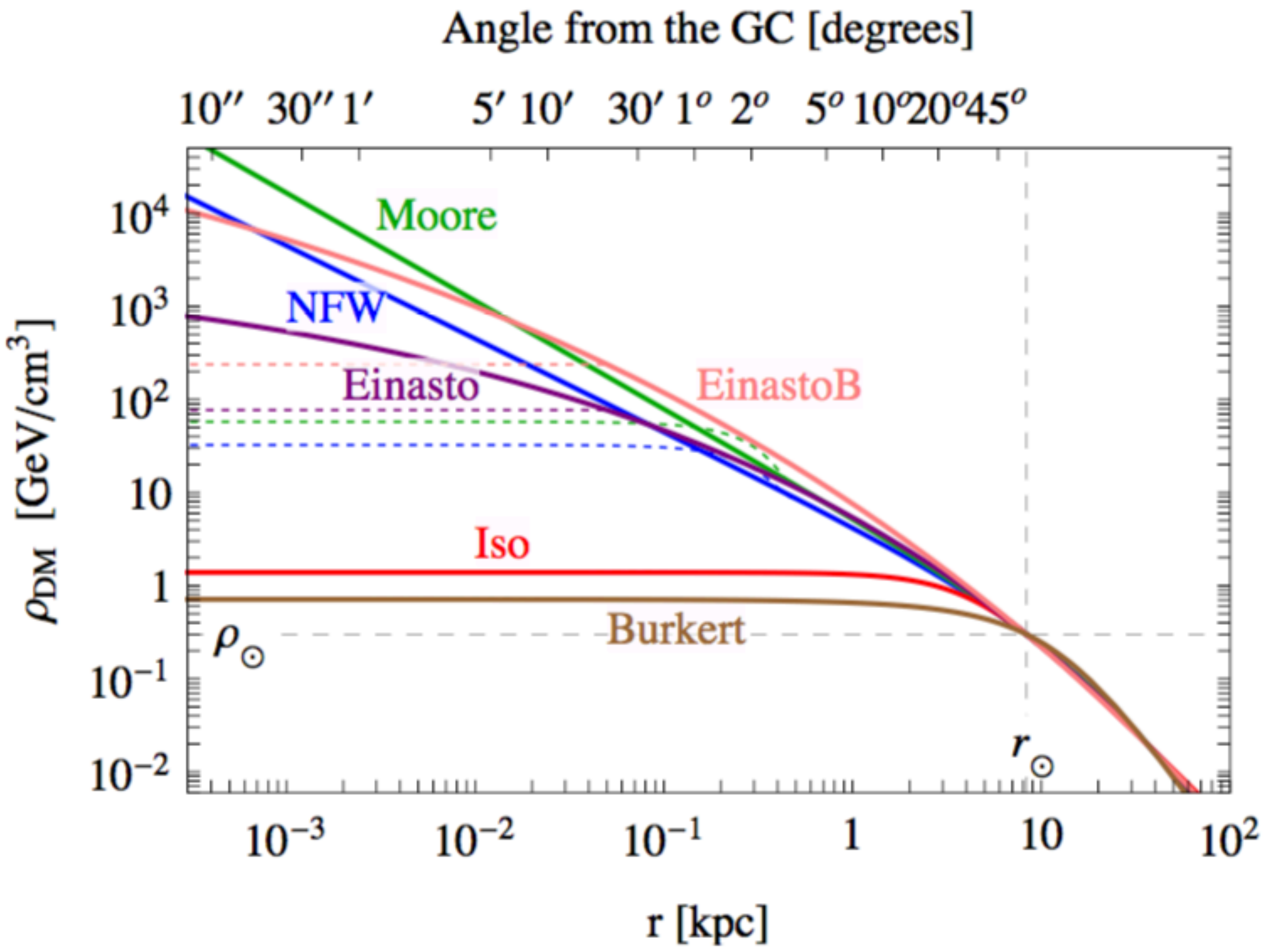
- non-rotating isothermal **sphere** with an isotropic Maxwell-Boltzmann velocity **distribution**:

$$f(\mathbf{v}) = \begin{cases} \frac{1}{N_{esc}} \left(\frac{3}{2\pi\sigma_v^2}\right)^{3/2} e^{-3\mathbf{v}^2/2\sigma_v^2} & : |\mathbf{v}| < v_{esc} \\ 0 & : \text{otherwise} \end{cases}$$

- σ_v is the rms velocity **dispersion**
- v_{esc} the **escape** velocity ~544 km/s
- v_0 the most **probable** velocity

$$v_0 = \sqrt{2/3}\sigma_v \approx 235 \text{ km/s}$$





2.1 DM density distribution

For the galactic distribution $\rho(r)$ we list the functional forms considered more plausible:

$$
\begin{aligned}
\text{NFW}: \quad \rho_{\rm NFW}(r) &= \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2} \\
\text{Einasto}: \quad \rho_{\rm Ein}(r) &= \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\} \\
\text{Isothermal}: \quad \rho_{\rm Iso}(r) &= \frac{\rho_s}{1+(r/r_s)^2} \\
\text{Burkert}: \quad \rho_{\rm Bur}(r) &= \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)} \\
\text{Moore}: \quad \rho_{\rm Moo}(r) &= \rho_s \left(\frac{r_s}{r}\right)^{1.16}\left(1+\frac{r}{r_s}\right)^{-1.84}
\end{aligned} \tag{2.1}
$$

The Dark Matter Halo: Density and Flux

The expected WIMP flux on Earth can be estimated, under the assumption that Milky Way's dark matter is made of WIMPs

Standard value: ρ_c ~ **0.3 GeV/cm³** **(±0.1 GeV/c³)** at the Sun location (with large uncertainties!)

Authors	Date	Ref.	$\rho_\odot$ [GeV/cm³]
Turner	1986	[21, 22]	0.28
Flores	1988	[23]	$0.3 \to 0.43$
Kuijken & Gilmore	1991	[24]	0.42 (±20%)
Widrow et al.	2008	[25]	0.304 ± 0.053
Catena & Ullio	2009	[26]	0.385 ± 0.027 0.389 ± 0.025
Weber & de Boer	2009	[27]	$0.2 \to 0.4$
Salucci et al.	2010	[28]	$0.43 \pm 0.11 \pm 0.10$
McMillan	2011	[29]	0.40 ± 0.04
Garbari et al.	2011	[30]	$0.11^{+0.34}_{-0.27}$ $1.25^{+0.30}_{-0.34}$
Iocco et al.	2011	[31]	$0.2 \to 0.56$
Bovy & Tremaine	2012	[32]	0.3 ± 0.1
Zhang et al.	2012	[33]	0.28 ± 0.08
Piffl et al.	2014	[34]	0.59 (±15%)

Equivalent to
- $10^6\ M_\odot/kpc^3$
- 1 WIMP of 100 GeV/c² mass in a coffee cup

WIMP flux on the Earth assuming WIMP mass of 100 GeV

$$\phi_\chi = \rho_\chi / M_\chi <v> \;=\; 0.3\ \text{GeV/cm}^3 / 100\ \text{GeV} \times 220\ \text{km/s} \approx \mathbf{6.6 \times 10^4\ cm^{-2}\ s^{-1}}$$

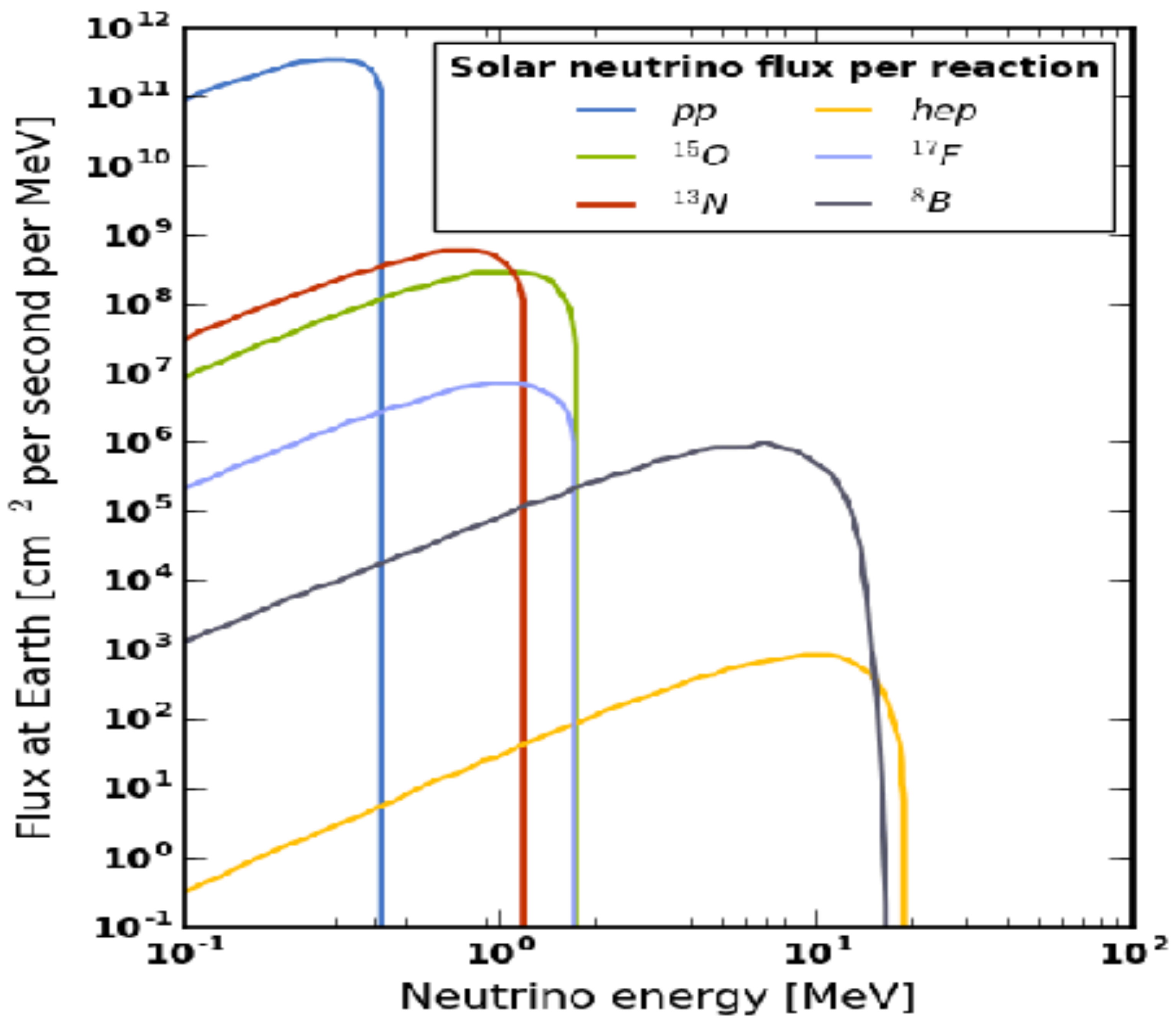
Dark Matter vs Neutrino Flux

$\varphi_\chi \approx$ **6.6 x 10^4 cm^{-2} s^{-1}**

The flux is rather large. A fraction of WIMPs should elastically scatter off nuclei, inducing some nuclear recoils.

- Can we detect the energy deposited by nuclear recoils?
- Is this fraction of events sufficiently large to be "measured" in a detector?

Comparing with solar neutrinos

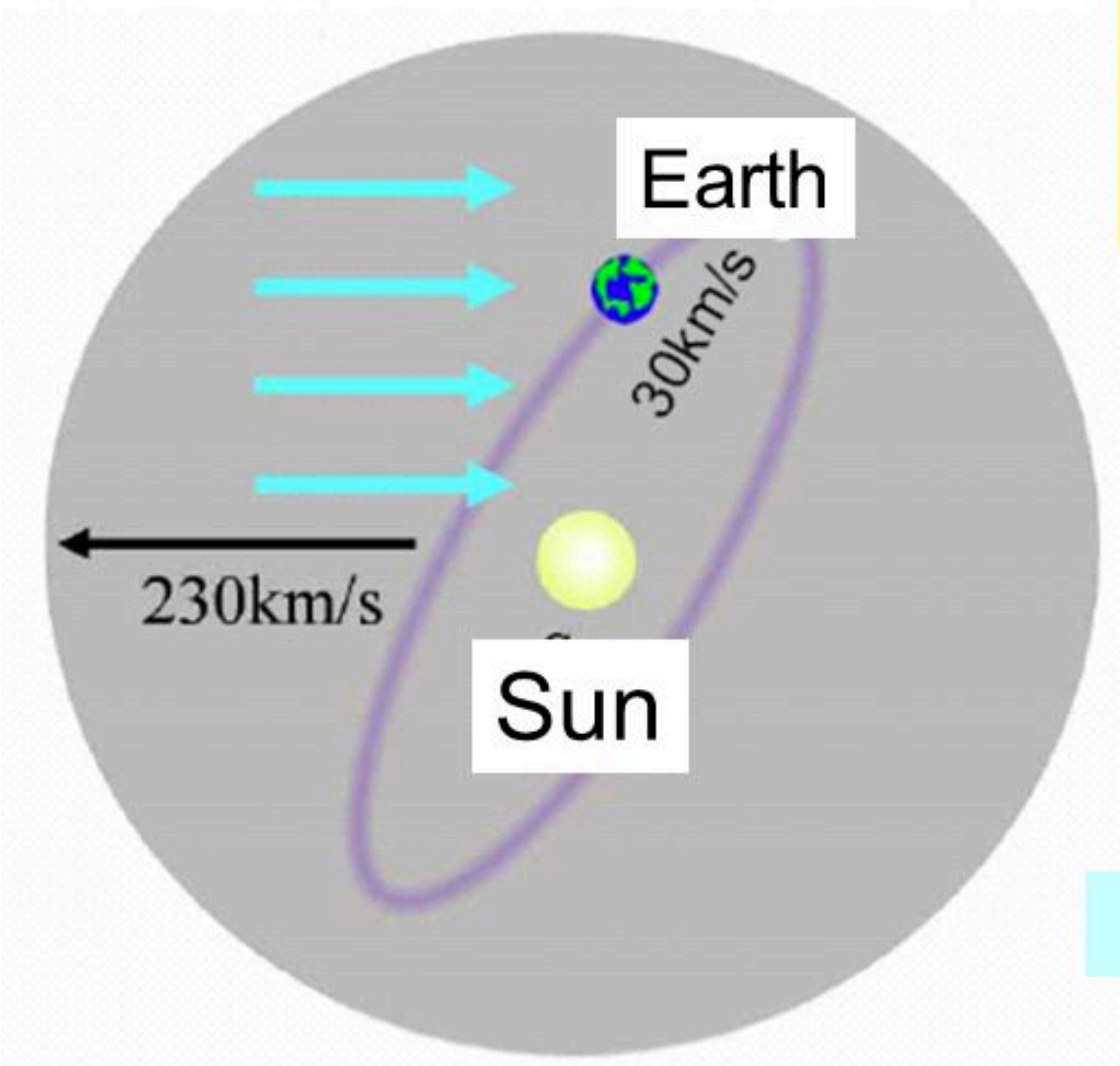


Expected rate assuming nucleus with atomic mass A = 100, scattering cross-section 10^{-38} cm^2

$$R = \frac{N_A}{A} \times \phi_\chi \times \sigma \quad \sim 0.13 \text{ events/kg/year}$$

Earth motion wrt galactic center

Motion of WIMPs around us



WIMPs are randomly moving with Maxwell distribution <v>~270km/sec

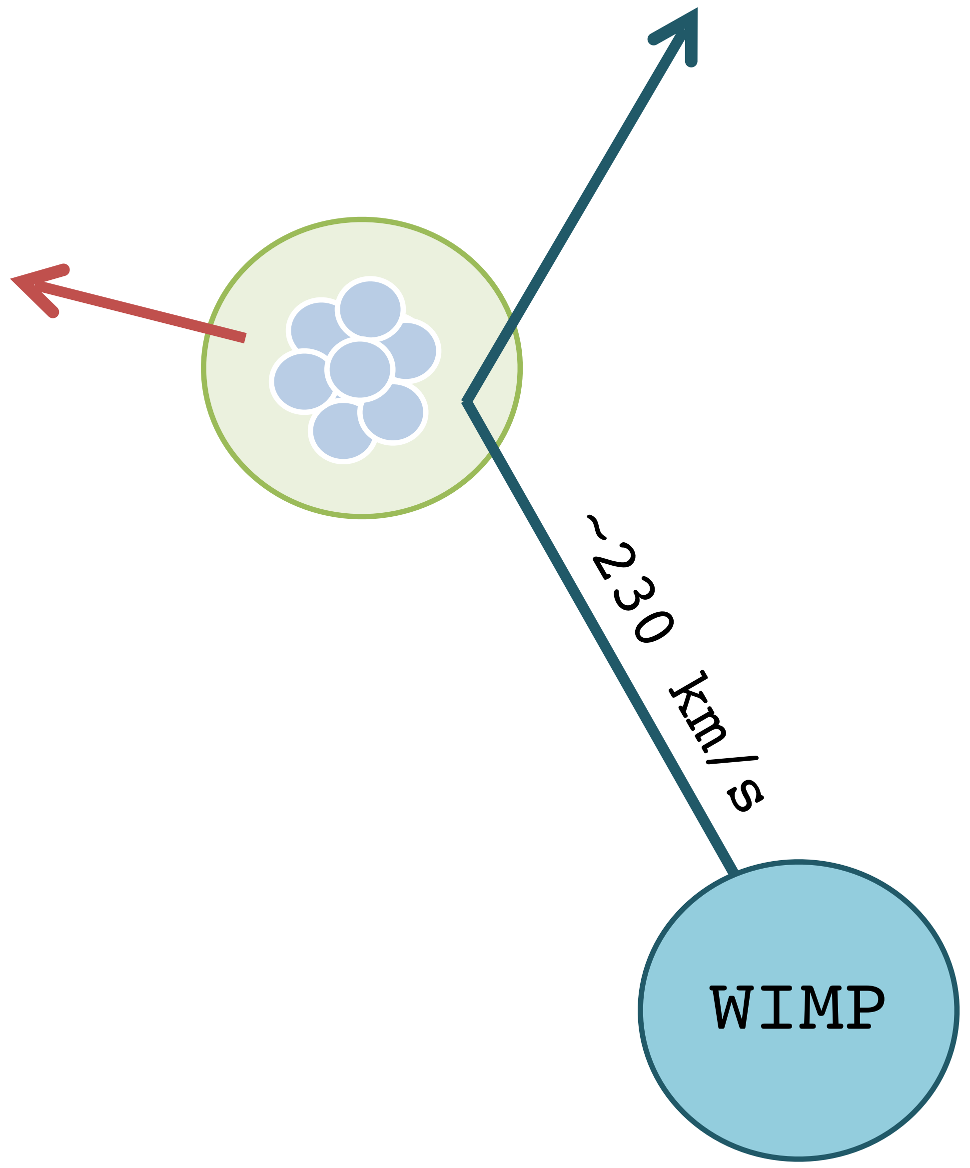
The solar system is moving at ~230km/sec.
The earth is moving at ~30km/sec.
The earth is rotating.

Annual, sidereal modulation

"Wind" of Dark Matter

DM density ~0.3GeV/cc
100GeV WIMPs ➔ 1 WIMP / 7cm cubic, $\Phi=10^5/cm^2/sec$

$$\frac{dR}{dE}(E,t) = \frac{\rho_0}{m_\chi \cdot m_A} \cdot \int v \cdot f(\mathbf{v},t) \cdot \frac{d\sigma}{dE}(E,v)\, \mathrm{d}^3v$$



ρ_0: local dark matter density

m_a: nucleus mass

m_χ: WIMP mass

$d\sigma/dE$: differential cross section

$f(v,t)$: WIMP velocity distribution

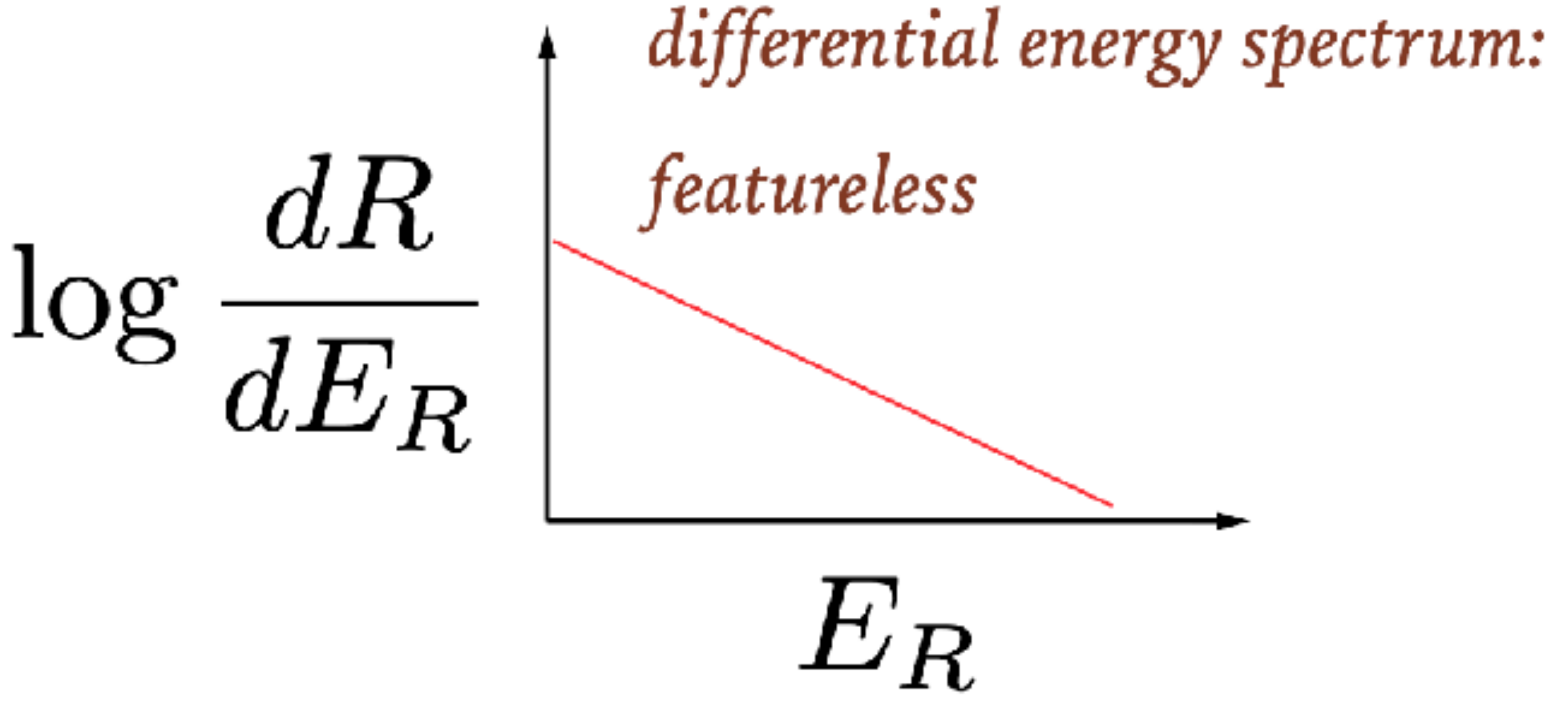
v: dark matter velocity wrt detector rest frame

- The differential event rate for simplified WIMP interaction (a detector stationary in the galaxy) is given by:

$$\frac{dR}{dE_R} = \frac{R_0}{E_0 r} e^{-E_R/E_0 r}$$

- $\frac{dR}{dE_R}$: event rate
- E_R: recoil energy
- R_0: total event rate
- E_0: most probable incident energy (Maxwell-Boltzman distribution)
- r: kinematic factor

$$r = \frac{4M_\chi M_N}{(M_\chi + M_N)^2}$$



- The total event rate is given by

$$\int_0^\infty \frac{dR}{dE_R} dE_R = R_0$$

and the mean recoiling energy

$$< E_R > = \int_0^\infty E_R \frac{dR}{dE_R} dE_R = E_0 r$$

From Jodi Cooley's slides

A quantitive example

- Assuming that WIMP and nucleus masses are identical:

$$m_\chi = m_\mathrm{N} = 100\ \mathrm{GeV/c^2}$$

→ kinematic factor: $$r = \frac{4 m_\chi m_\mathrm{N}}{(m_\chi + m_\mathrm{N})^2} = 1$$

- Assuming stationary DM halo, Sun moves through the halo:

→ mean WIMP velocity relative to target $v \approx 220\ \mathrm{km/s} = 0.75 \times 10^{-3}\ c$

$$\langle E_R \rangle = E_0 = \frac{1}{2}\, m_\chi v^2$$

$$\langle E_R \rangle = \frac{1}{2}\, 100\ \frac{\mathrm{GeV}}{\mathrm{c}^2}\ (0.75 \times 10^{-3}\ c)^2$$

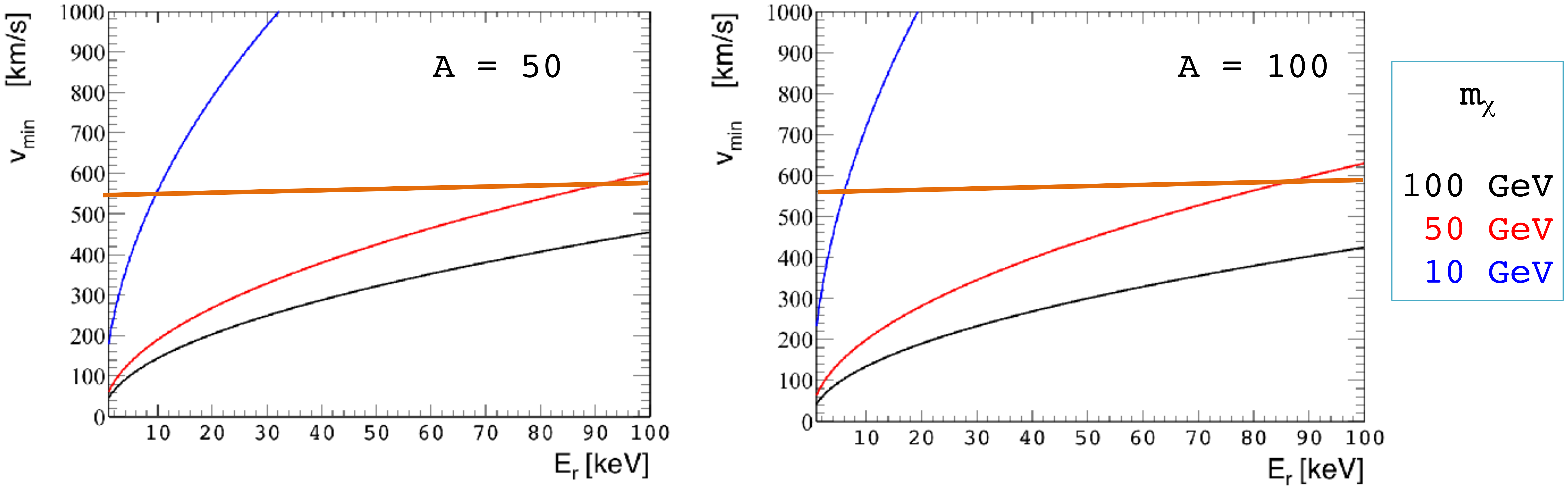
→ Mean recoil energy deposited in a detector:

$$\langle E_R \rangle = 25\ \mathrm{keV}$$

- Minimal velocity = the velocity that is required to produce a recoil energy E_R

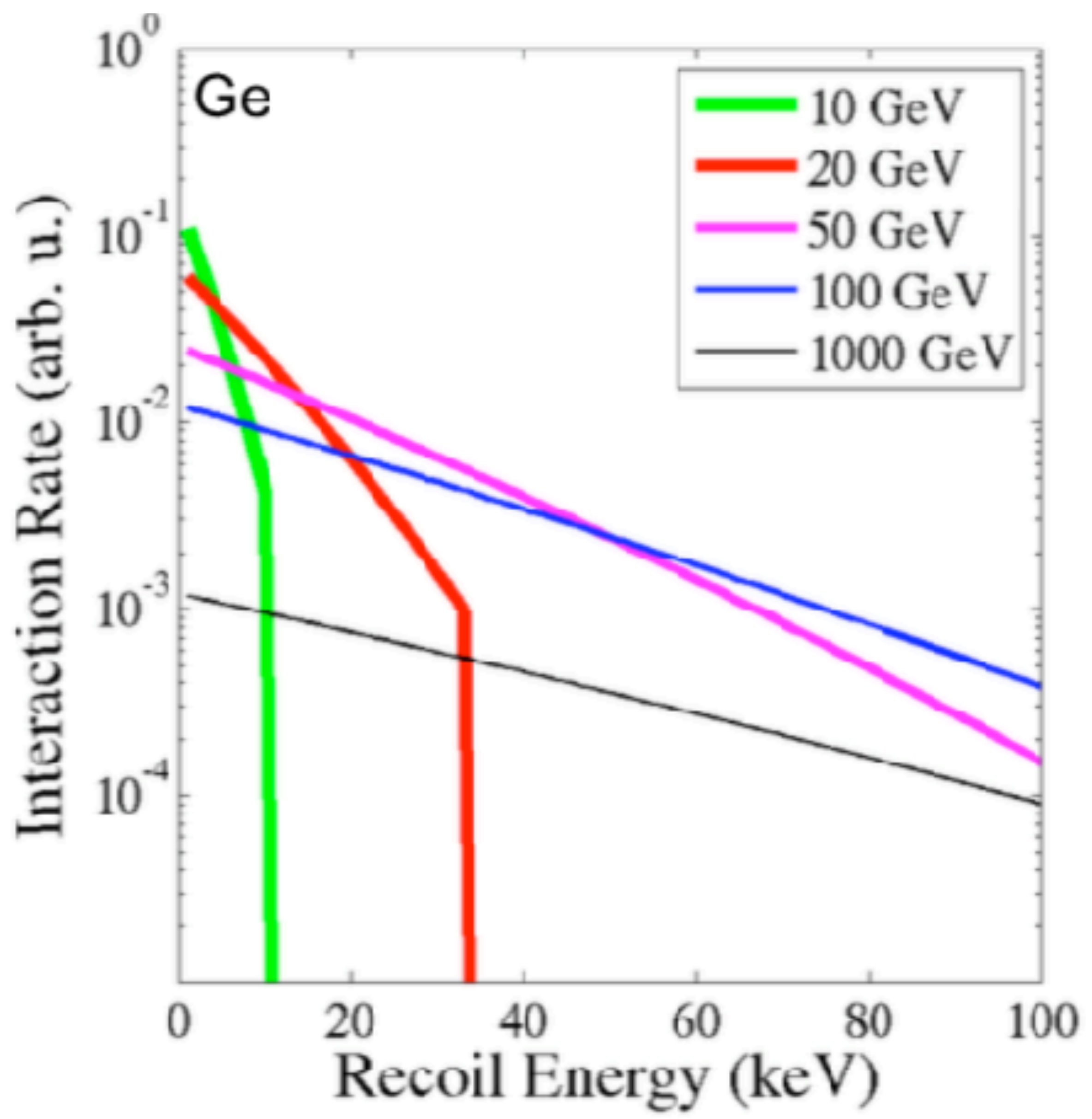
$$v_{min} = \sqrt{\frac{2E_R}{r \cdot m_\chi}} = \sqrt{\frac{E_R m_N}{2\mu^2}} = \frac{m_\chi + m_N}{m_\chi}\sqrt{\frac{E_R}{2m_N}}$$

with $r = 4m_\chi m_N/(m_\chi + m_N)^2$. the Kinematic factor



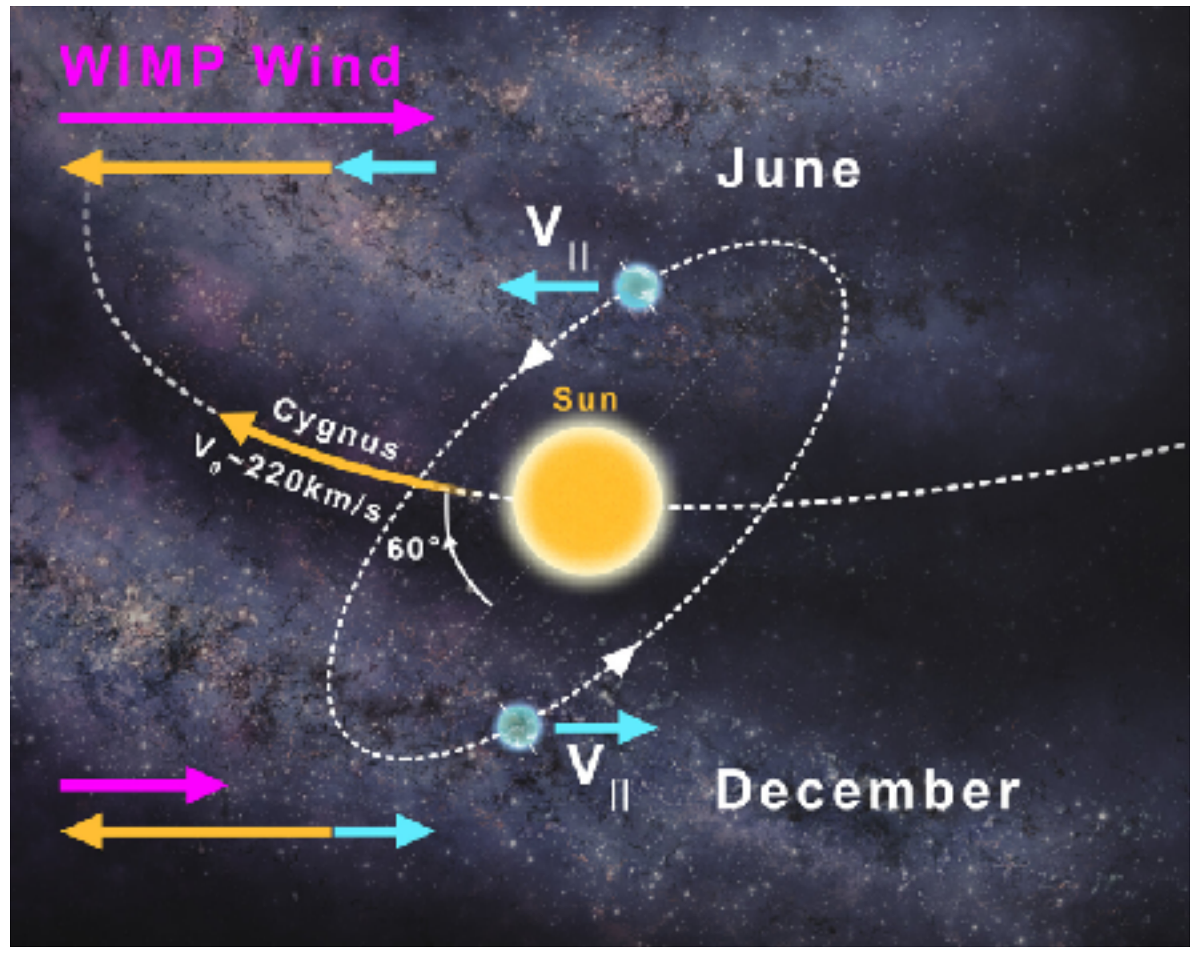
Escape Velocity

$$\frac{dR}{dE_R} = \frac{k_0}{k_1(v_{esc},0)} \frac{R_0}{E_0 r} \left(e^{-\frac{E_R}{E_0 r}} - e^{-\frac{(v_{esc})^2}{v_0^2}} \right)$$



Earth Velocity

$$v_E \simeq 244 + 15 \sin(2\pi y) \text{ km s}^{-1}$$



The ~6% velocity modulation gives rise to a **~3% modulation in rate**

Cross Section

Spin-Independent

- Mediated by scalar or vector couplings
- Coherent scattering on all nucleons → cross section scales as A^2
- Dominant in detectors with heavy targets (Xe, I, W)

$$\sigma_0^{SI} = \frac{4}{\pi}\mu^2[Zf_p + (A-Z)f_n]^2$$

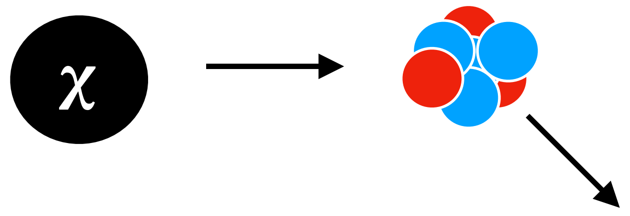
Spin-Dependent

- Mediated by axial-vector couplings
- Sensitive only to unpaired nucleon spins → no coherence, no A^2
- Favours targets with high nuclear spin (e.g., ^{19}F, ^{127}I, ^{129}Xe)

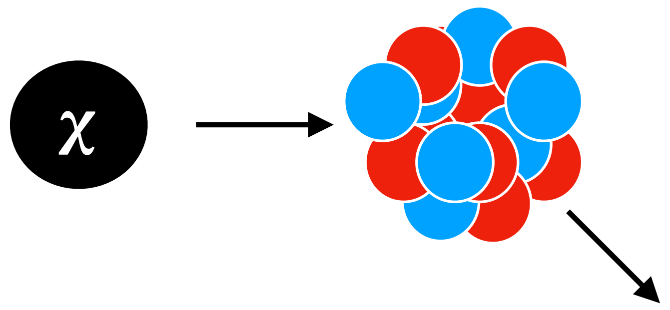
$$\sigma_0^{SD} = \frac{32}{\pi}G_F^2\mu_N^2\frac{J+1}{J}[a_p\langle S_p\rangle + a_n\langle S_n\rangle]^2$$

Form Factor

$\lambda \gtrsim 2R$ → coherent scattering

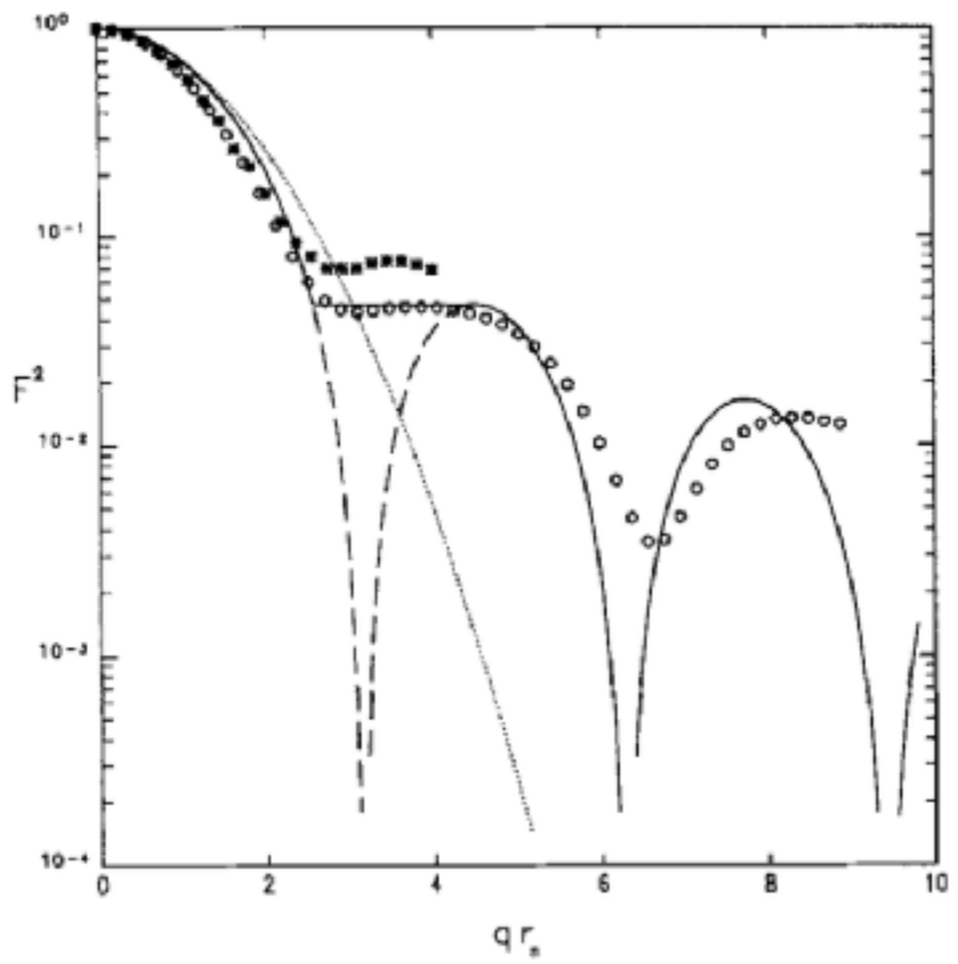


$\lambda \lesssim 2R$ → incoherent scattering ($F^2(q) < 1$)



WIMP de Broglie wavelength
λ (100 GeV) ≈ 12 fm

Nuclear radii:
R(^{28}Si) ≈ 3.6 fm
R(^{40}Ar) ≈ 4.1 fm
R(^{132}Xe) ≈ 6.6 fm



Form Factor

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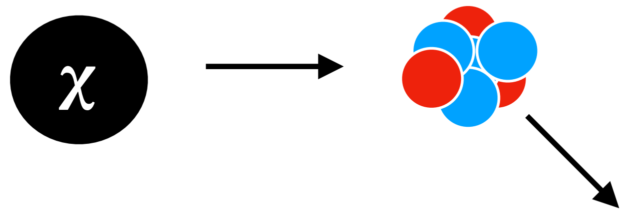

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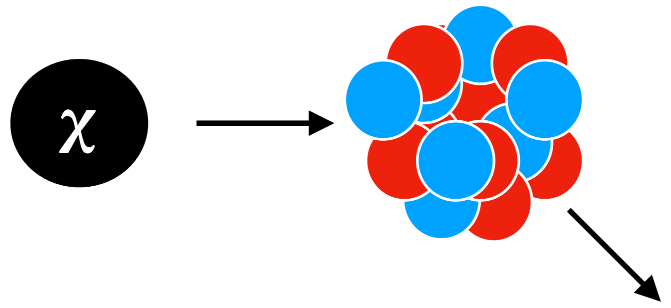

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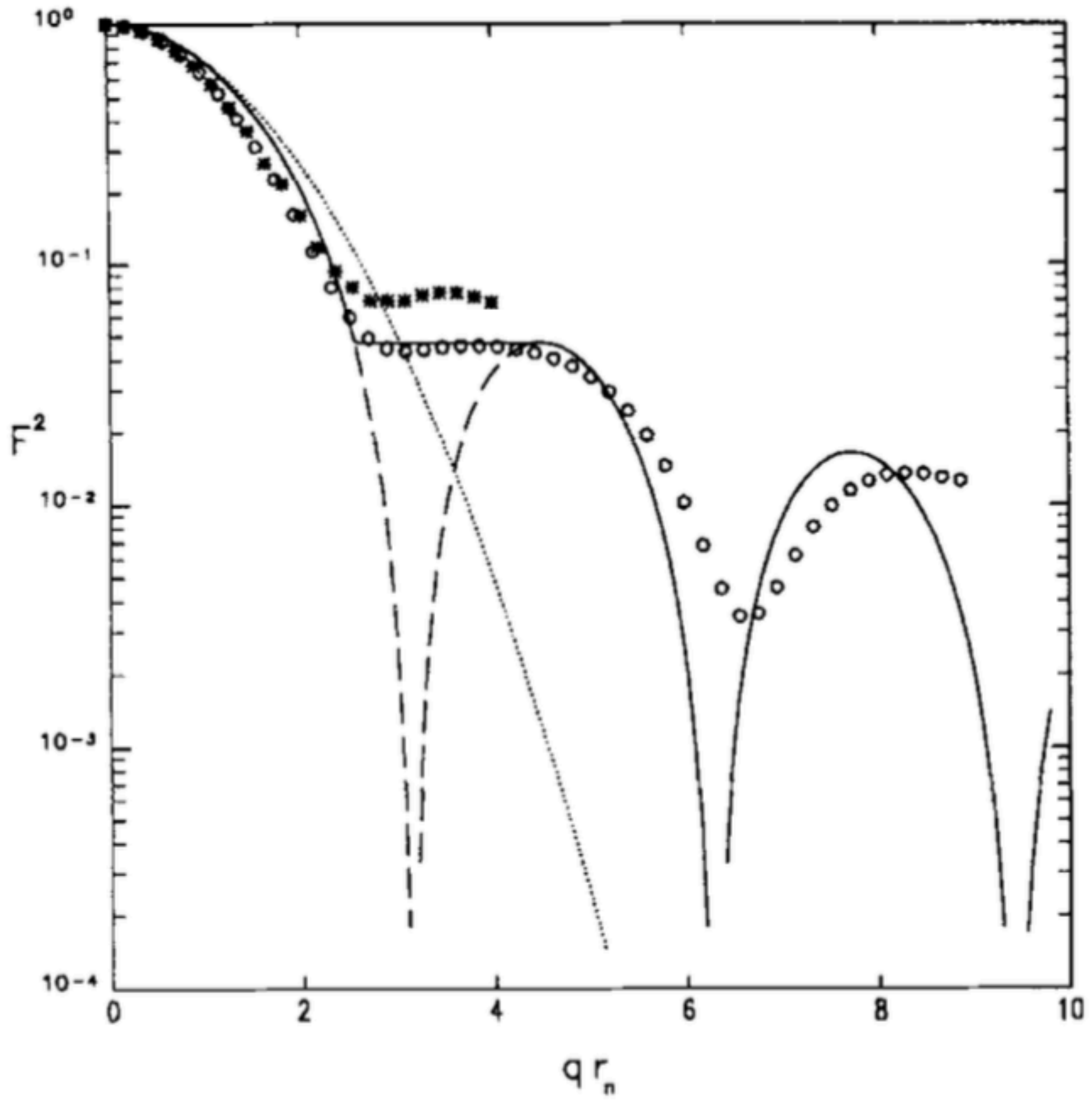
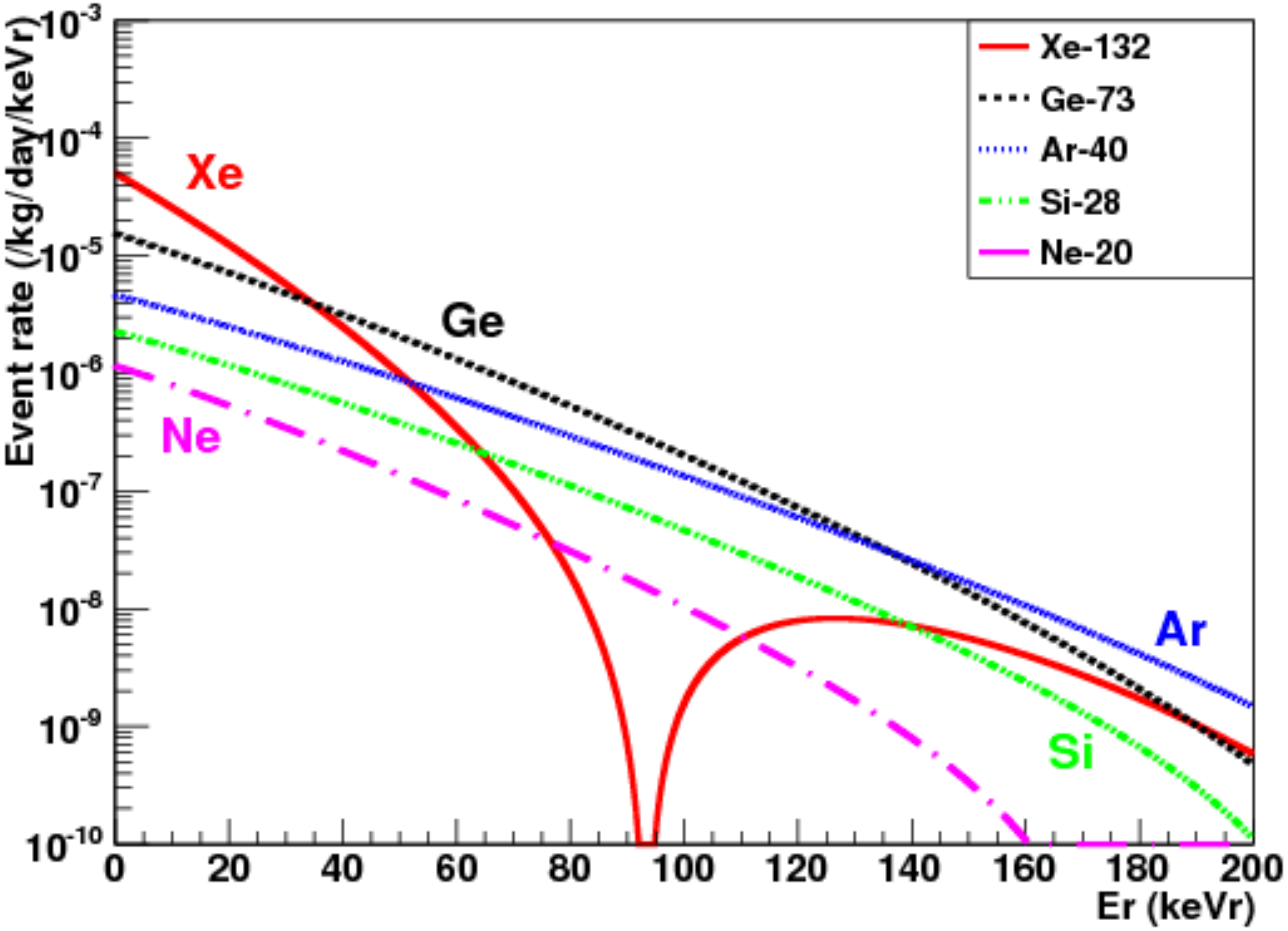




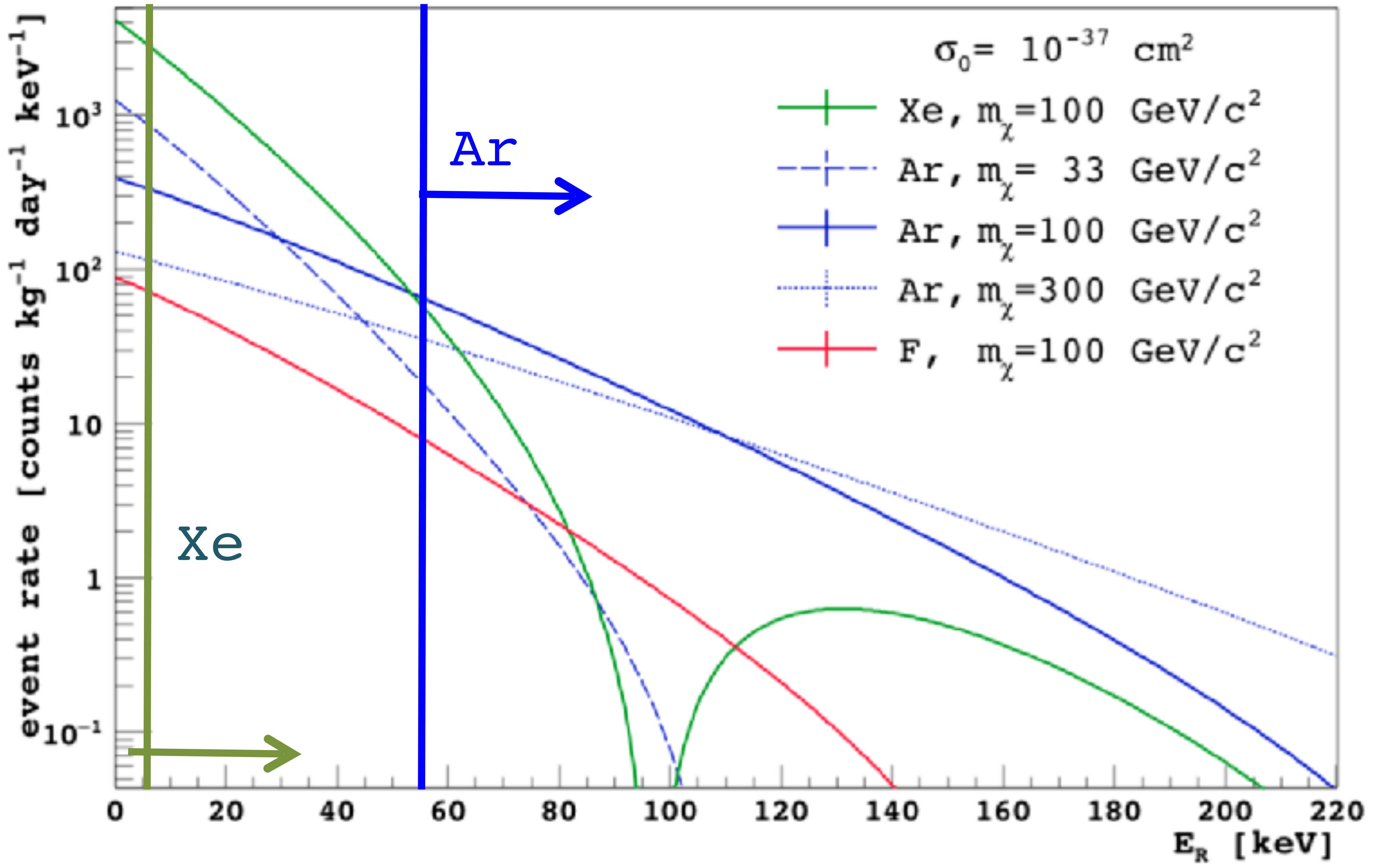
Which target to use?

High-A Target:
- higher cross section
- Lower nuclear recoil energy

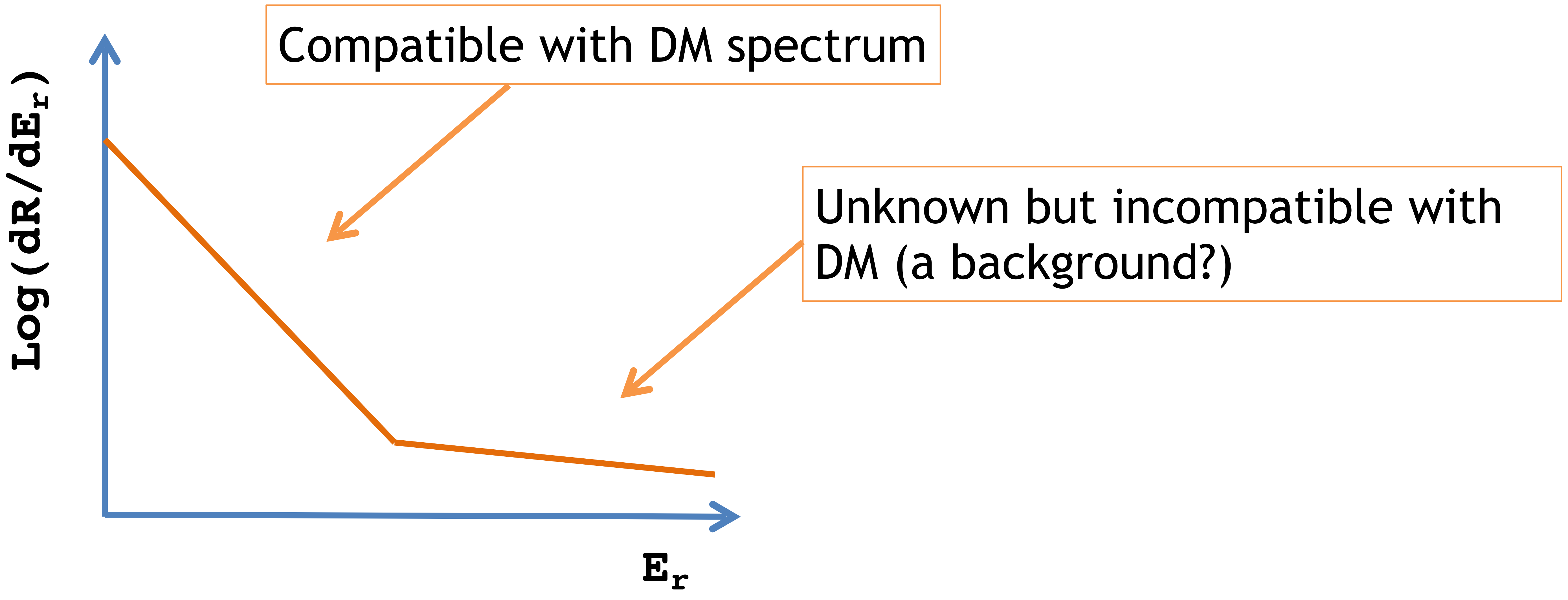
Which is better?

Low-A Target:
- lower cross section
- higher nuclear recoil energy

Depends on the detector threshold

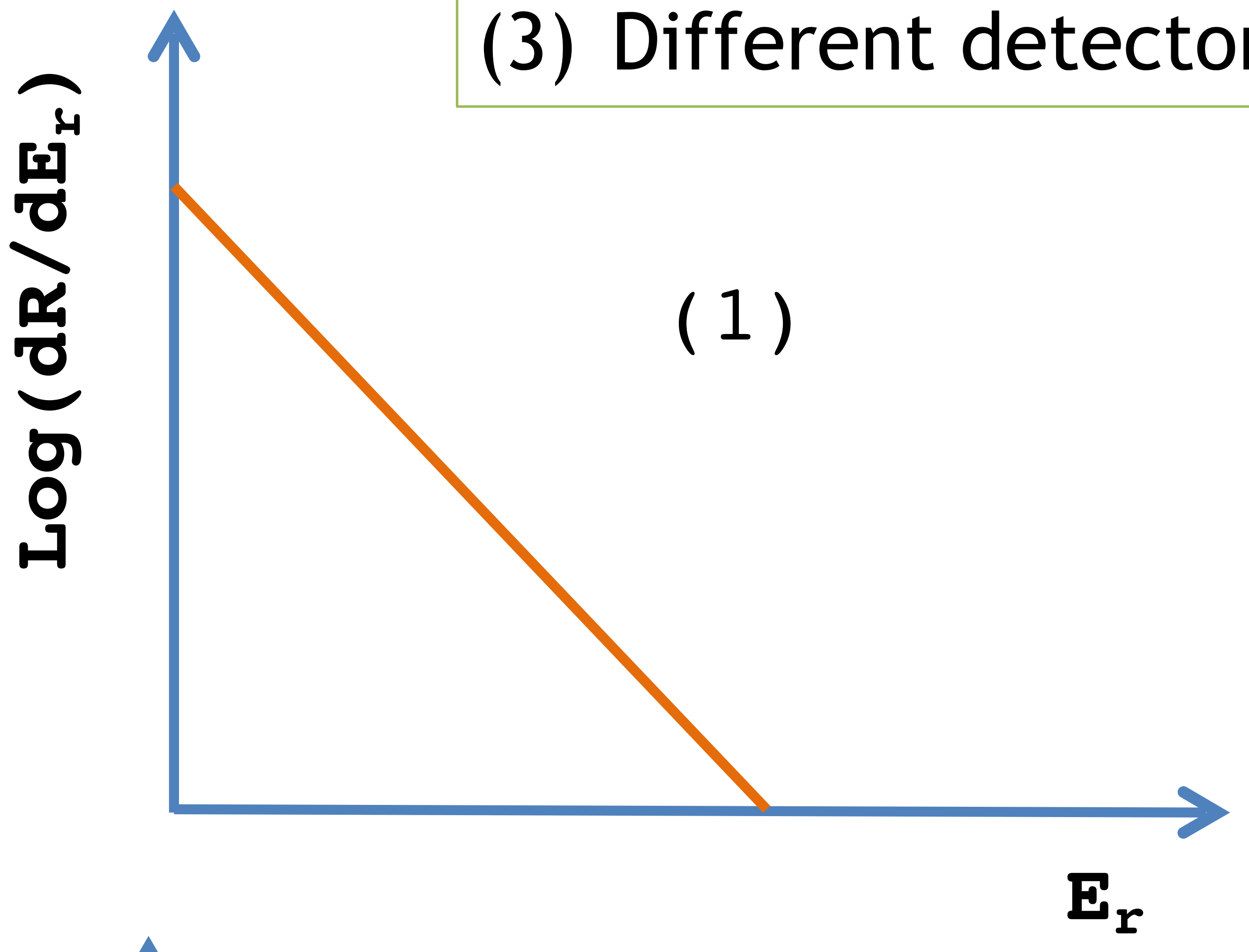


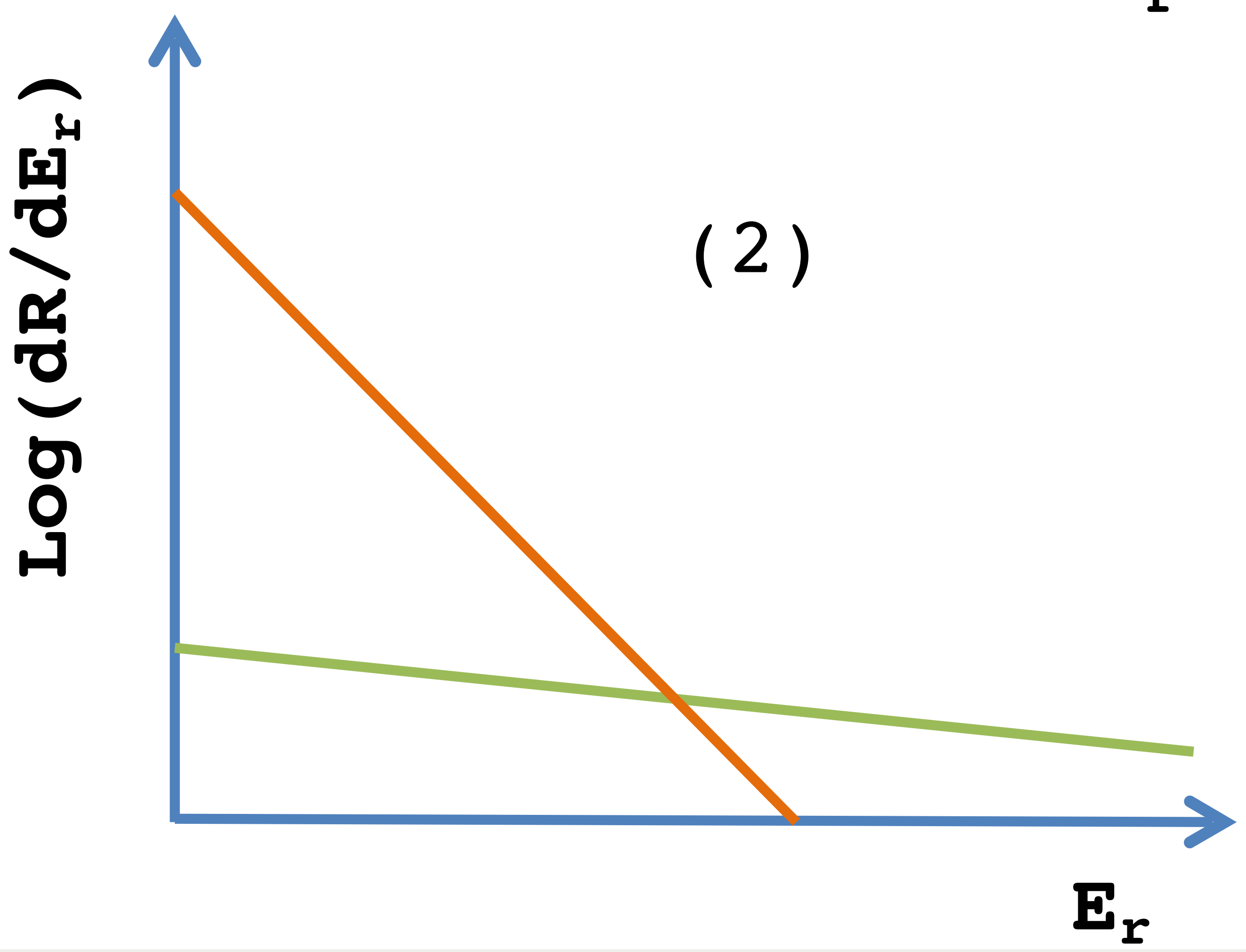
Suppose that a detector observes a spectrum like this:

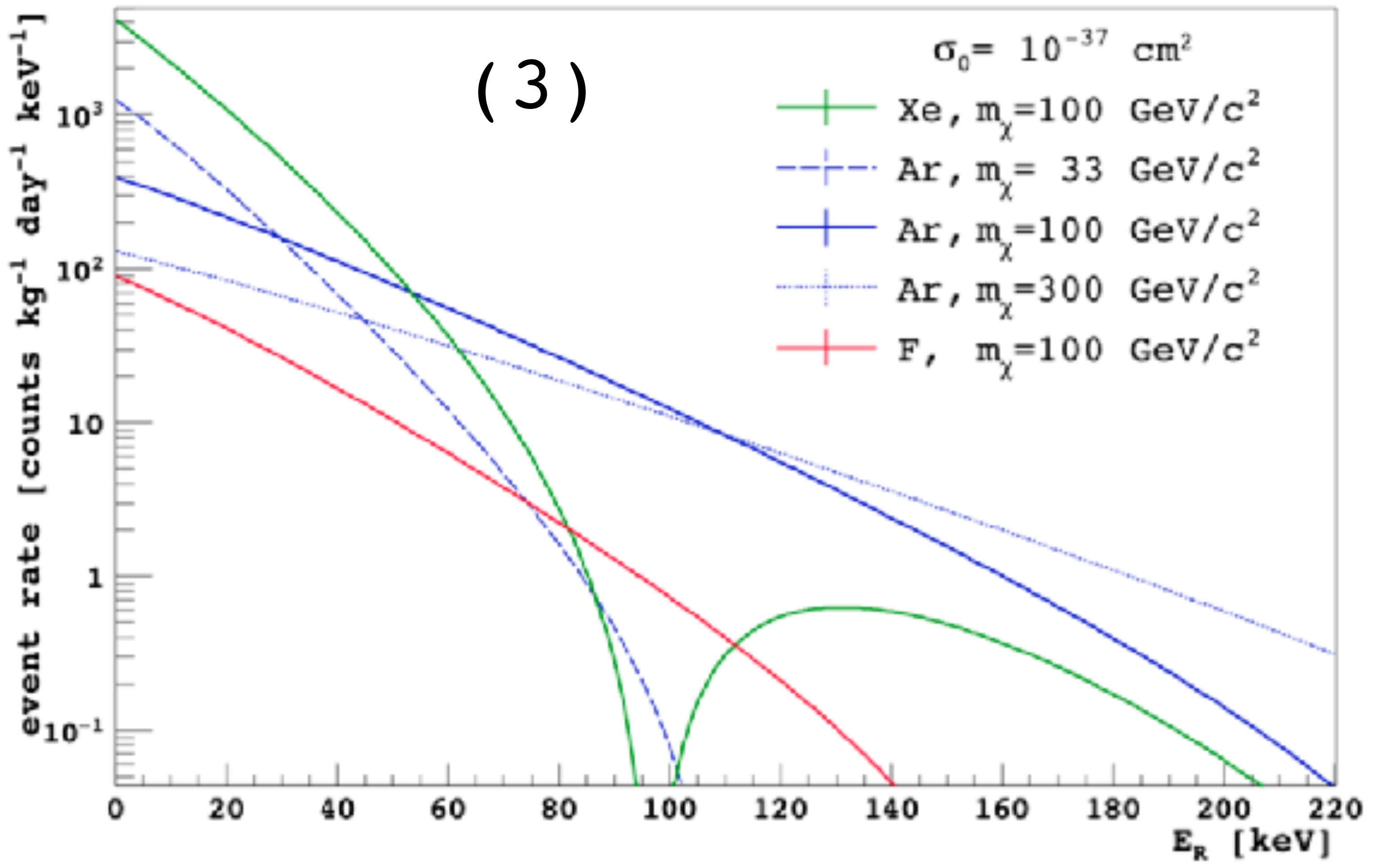


how can we claim for a dark matter evidence?

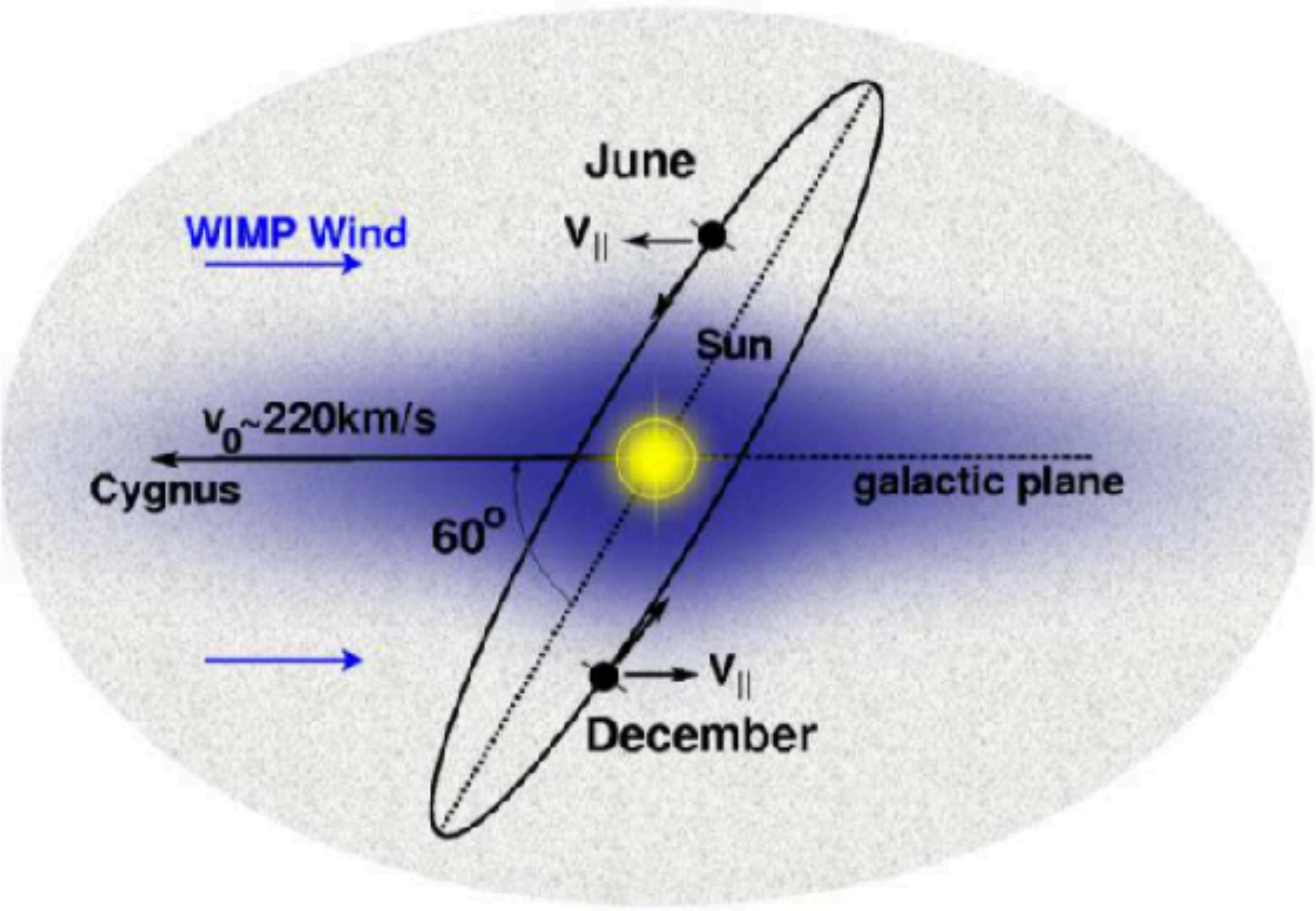
Three options:
(1) There is no background
(2) Background is very well known
(3) Different detectors provide compatible excesses



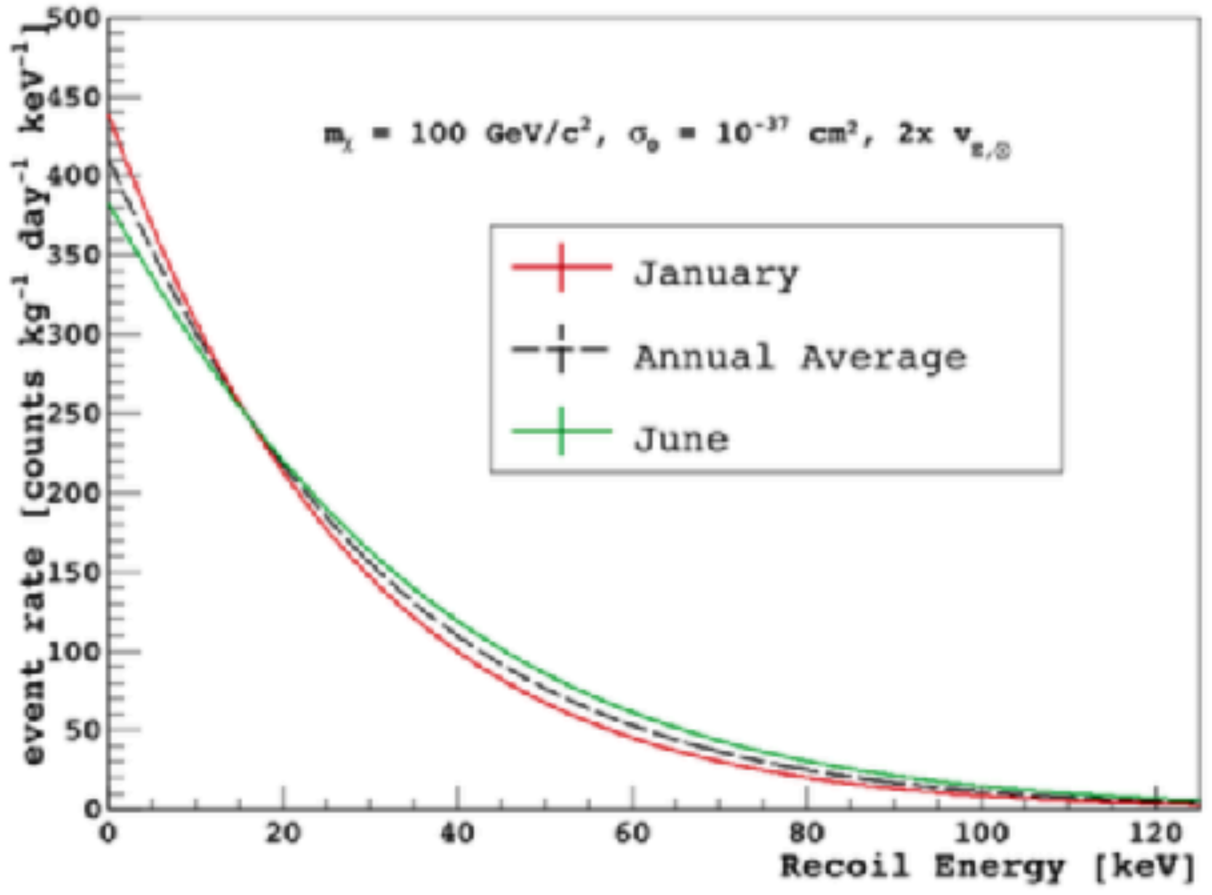




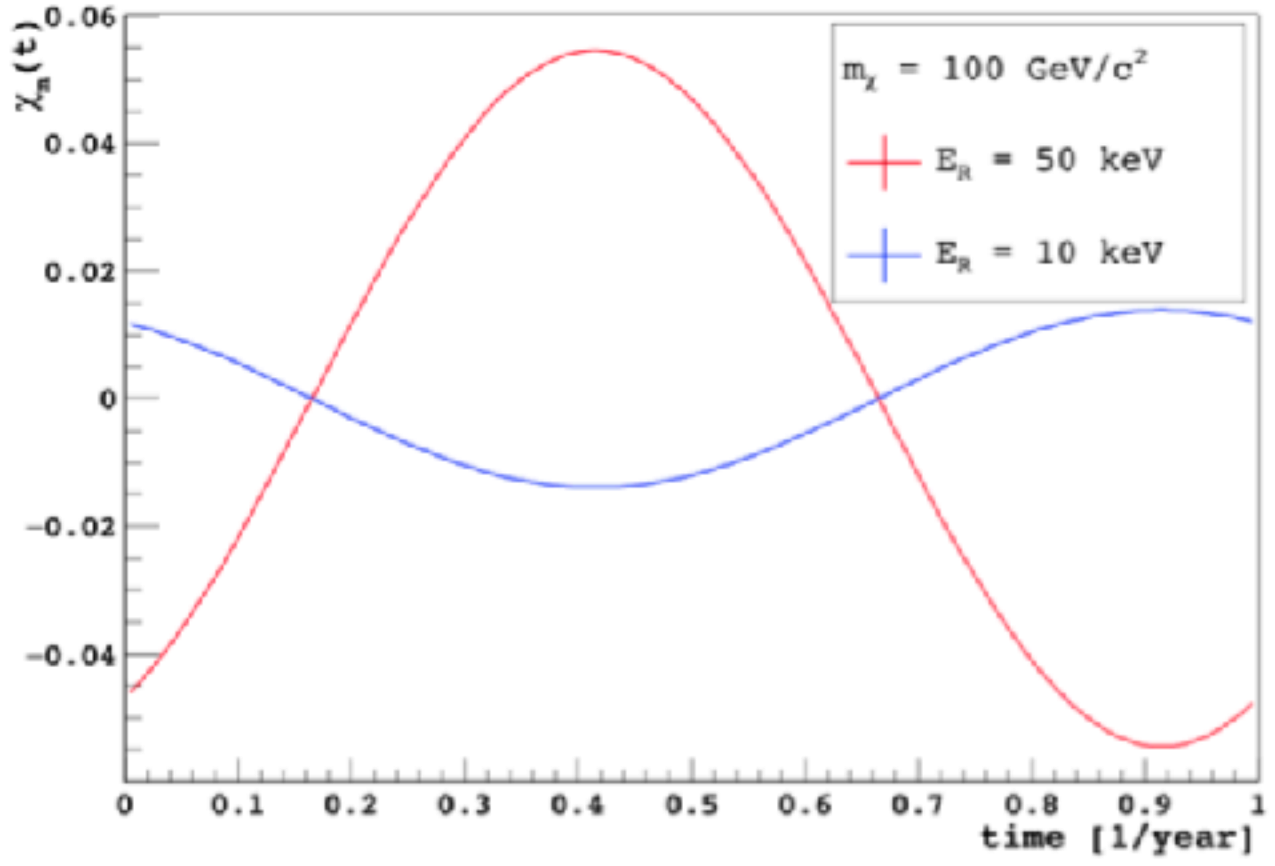
Signatures: Annual Modulation



$$\frac{dR}{dE_R}(E_R,t) \simeq \frac{dR}{dE_R}(E_R)\left[1+\Delta(E_R)\cos\frac{2\pi(t-t_0)}{T}\right]$$



(a) Seasonal variation of $\frac{dR}{dE}$(t)



(b) Amplitude of the modulation

Signatures: Directionality

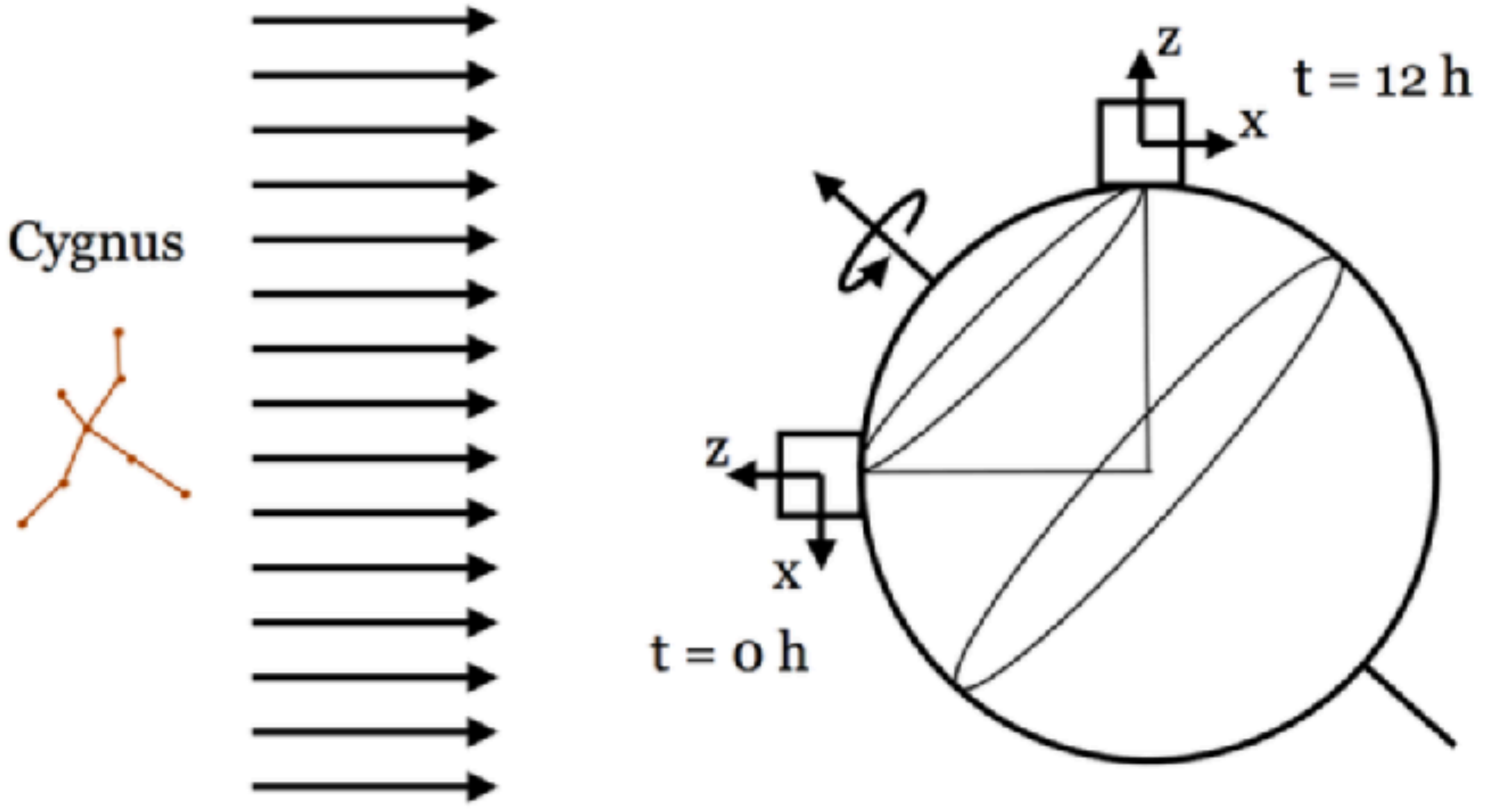


Fig. 1.8 The daily rotation of the Earth introduces a modulation in recoil angle, as measured i laboratory frame. [48]

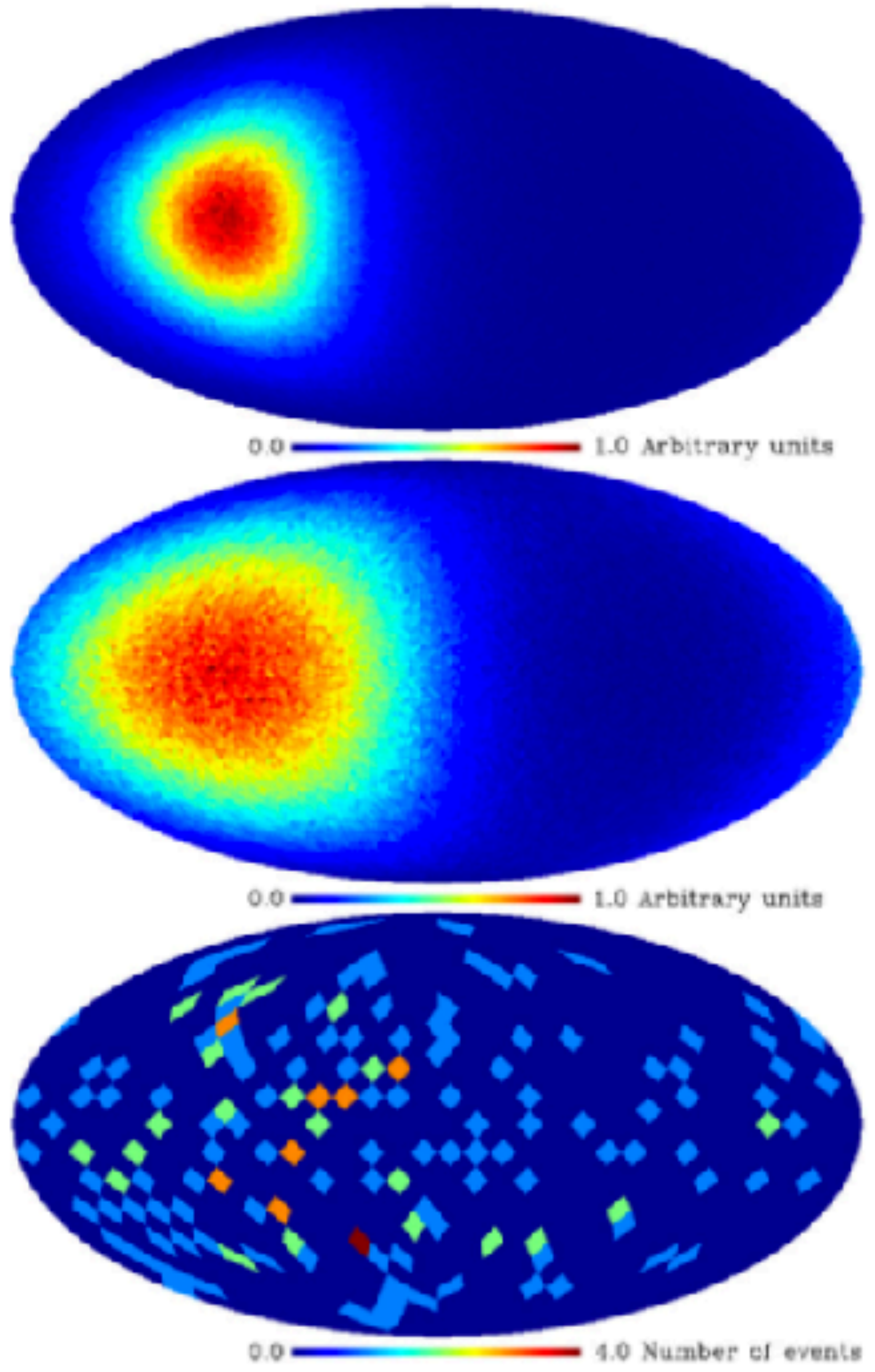


Figure from J. Billard *et al.* 2010

- WIMP flux in the case of an isothermal spherical halo
- WIMP-induced recoil distribution
- A typical simulated measurement:
  100 WIMP recoils and
  100 background events
  (low angular resolution)

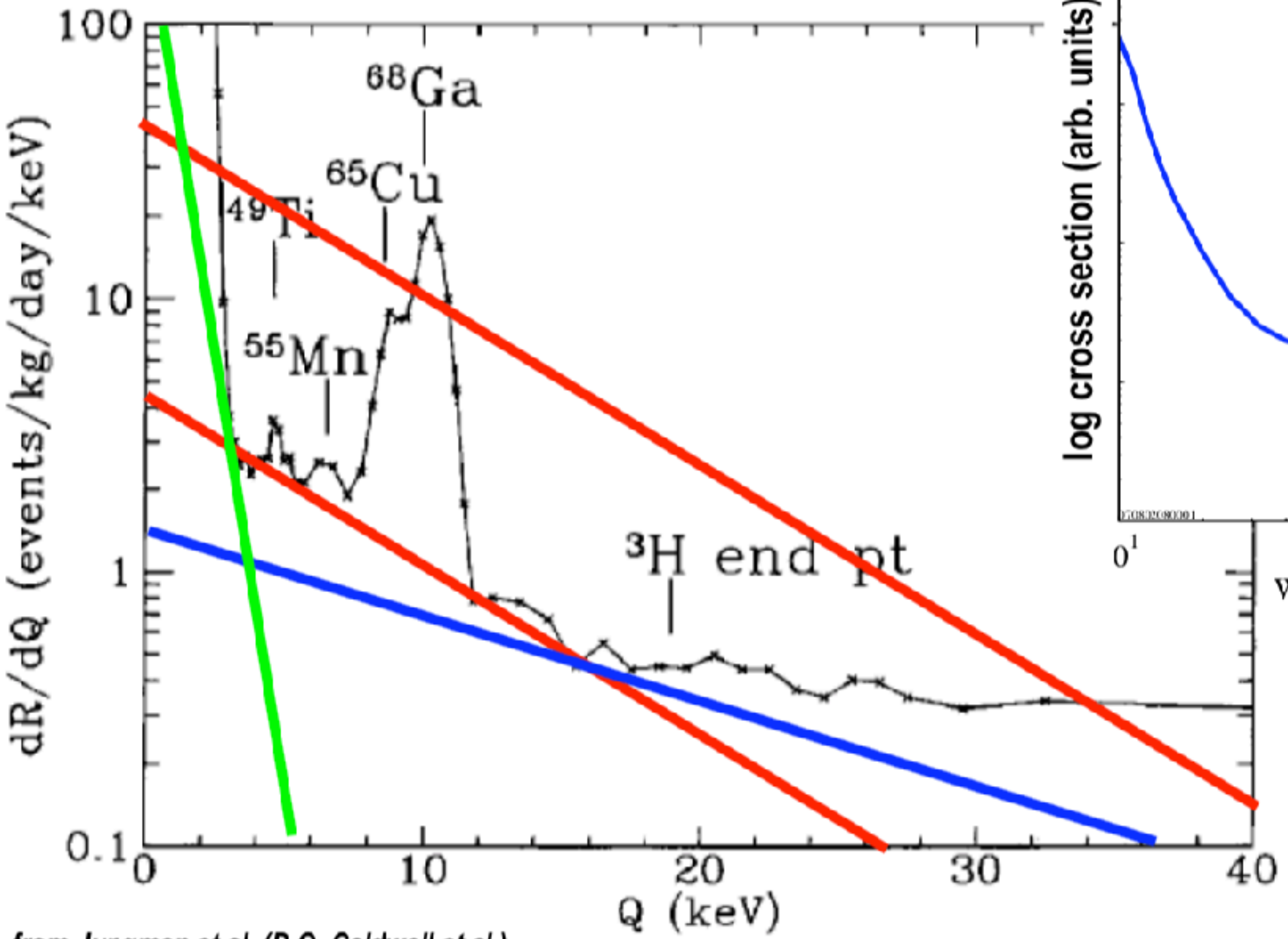
Signatures: Summary

Signature	Pros	Cons	Solution
Rate/Spectrum	"simplest"	Background?	Multi-target
Seasonal modulations	Smoking gun: background should be constant	Cosmogenic background is not constant	Repeating the experiment in the two hemispheres
Directionality	Background has not a preferred "direction" Recoils from dark matter have a "preference" towards Cygnus direction	Needs of some tens of events. Gaseous detectors can not reach large masses Liquid and solid detectors have to prove the existence of this signature	New technologies able to explore directionality with very large target masses

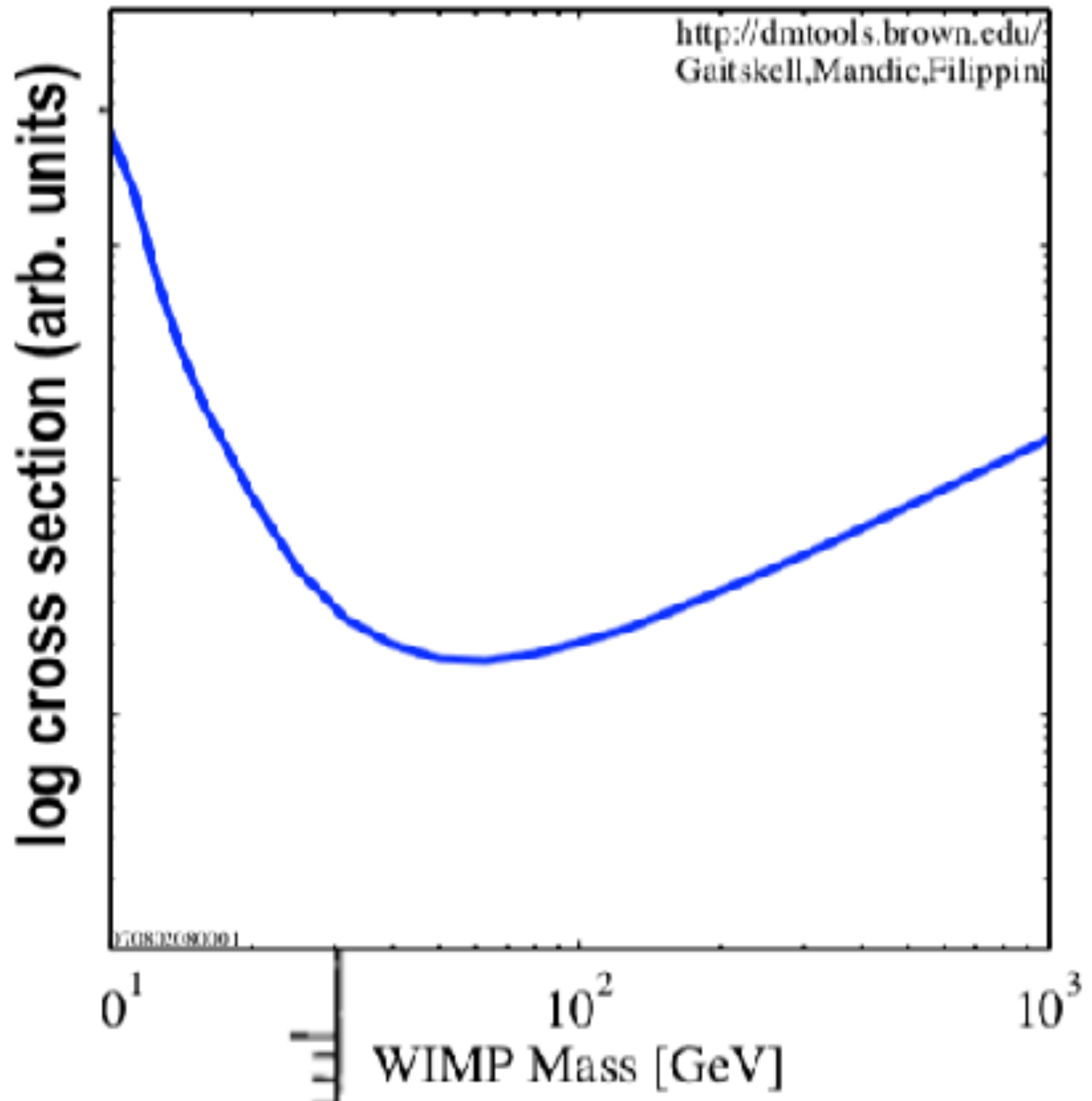
Pioneering experiments

Year (pub.)	Experiment	Technology	Primary Goal	Typical SI Limit [cm^2]
1987	Homestake NaI	NaI(Tl) scintillators	WIMP search	~10^{-34}
1990	UC Irvine / UKDMC	NaI(Tl), pulse shape discr.	WIMP search	~10^{-35}
1992	Heidelberg-Moscow	HPGe semiconductor diodes	$0\nu\beta\beta$ (^{76}Ge) + WIMP	~10^{-36}
1993	IGEX	HPGe detectors	$0\nu\beta\beta$ (^{76}Ge) + WIMP	~10^{-36}
1995	EDELWEISS (proto)	Cryogenic Ge bolometers	WIMP search	~10^{-37}
1996	DAMA/NaI	NaI(Tl) array	Annual modulation (WIMP)	~10^{-37}
1999	CDMS (Stanford)	Ge/Si bolometers + ionization	WIMP search	~10^{-38}
1998	CRESST-I	Sapphire bolometers (phonons only)	WIMP search	~10^{-37}
2002	ZEPLIN-I	Liquid xenon scintillation	WIMP search	~10^{-36}

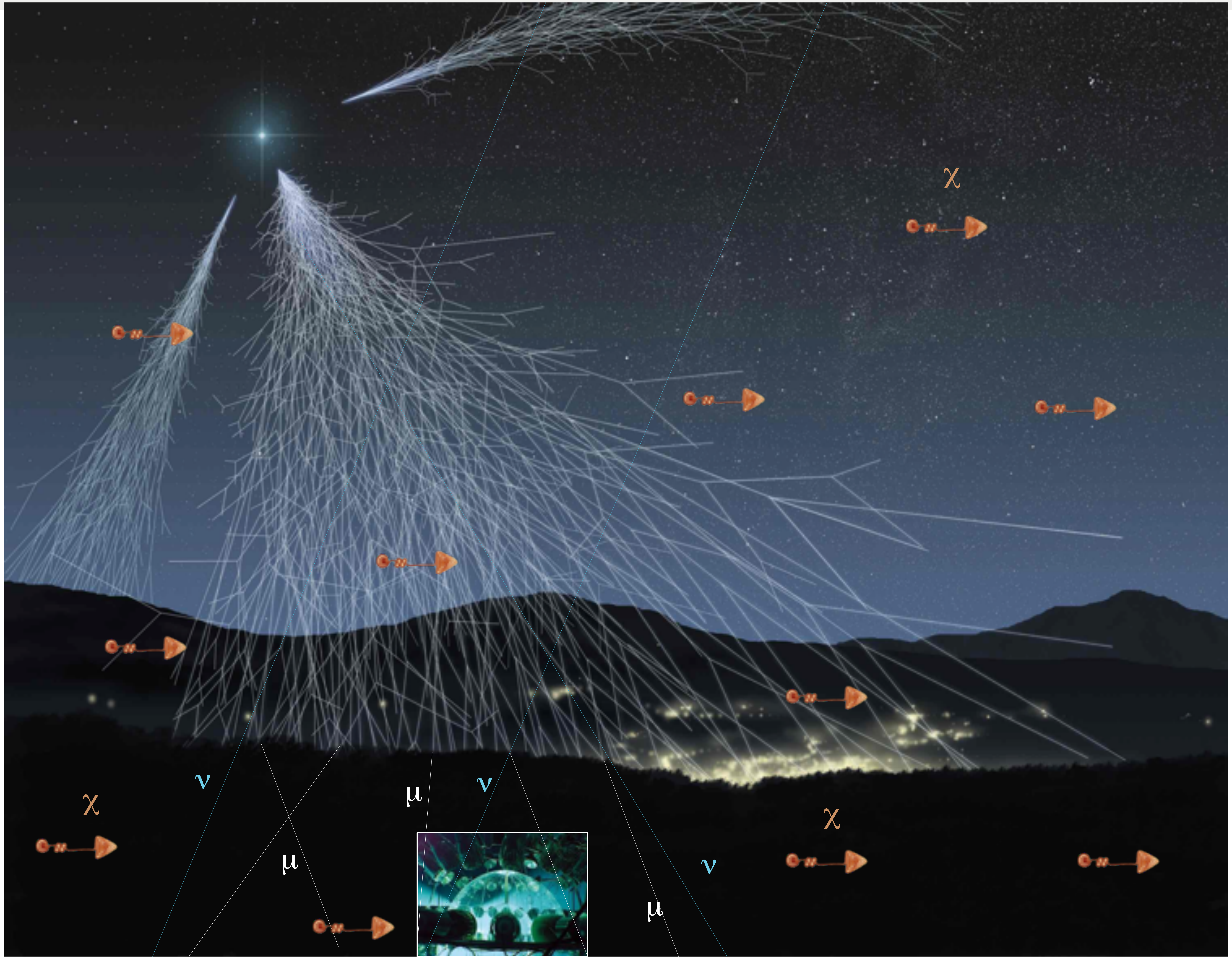
- **Germanium ionization detector (UCSB/UCB/LBL)**



from Jungman et al. (D.O. Caldwell et al.)



Expected signal and background

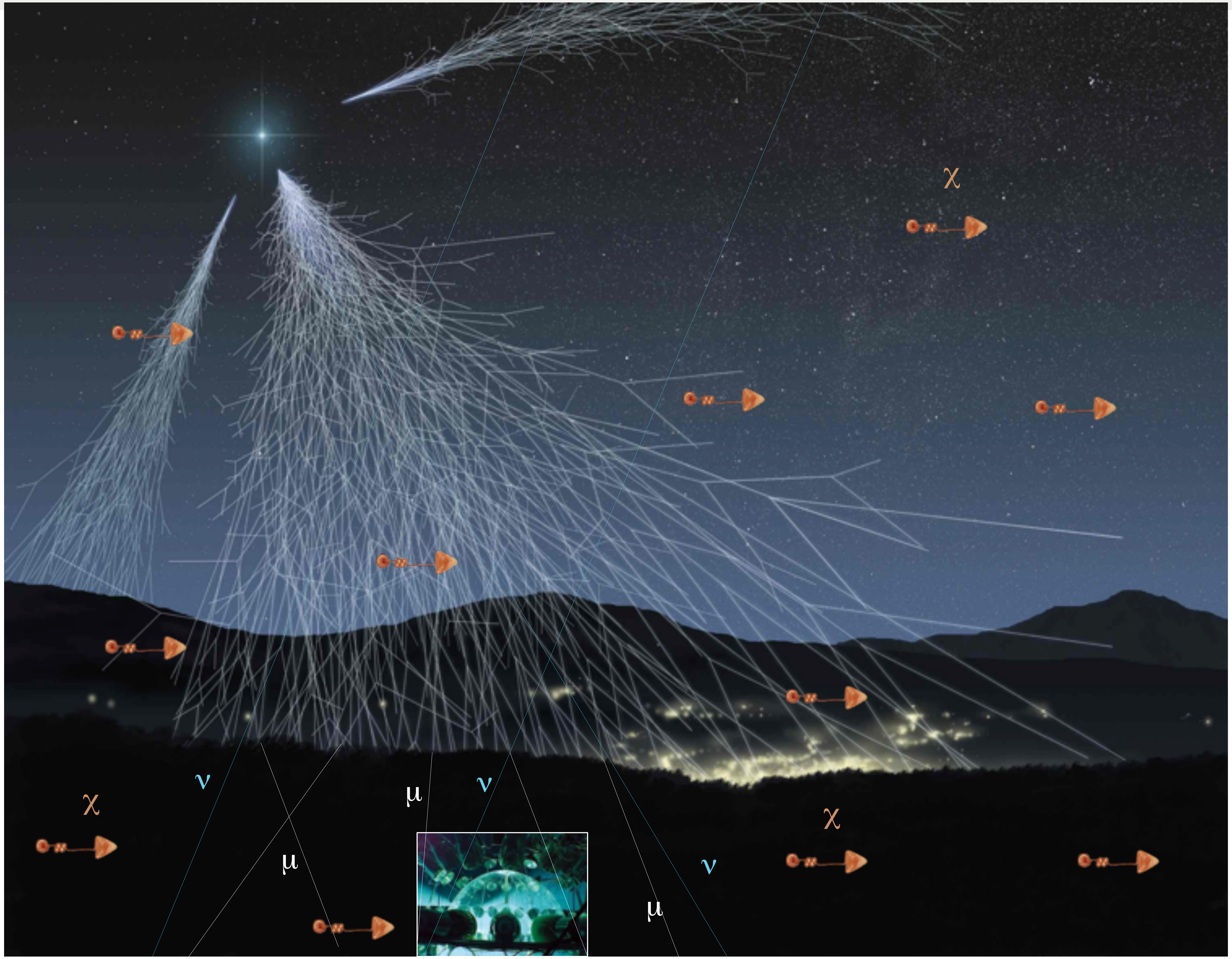


Searching for just a **handful of WIMP interactions** in **multi-tonne** targets, over **several years**

To compare with:

- Cosmic background at surface: ??? events / m² / s
- Radioactivity in rock: ??? events / kg / s
- Radioactivity in water: ??? events / liter / s
- Radioactivity in air: ??? events / m³ / s

Expected signal and background

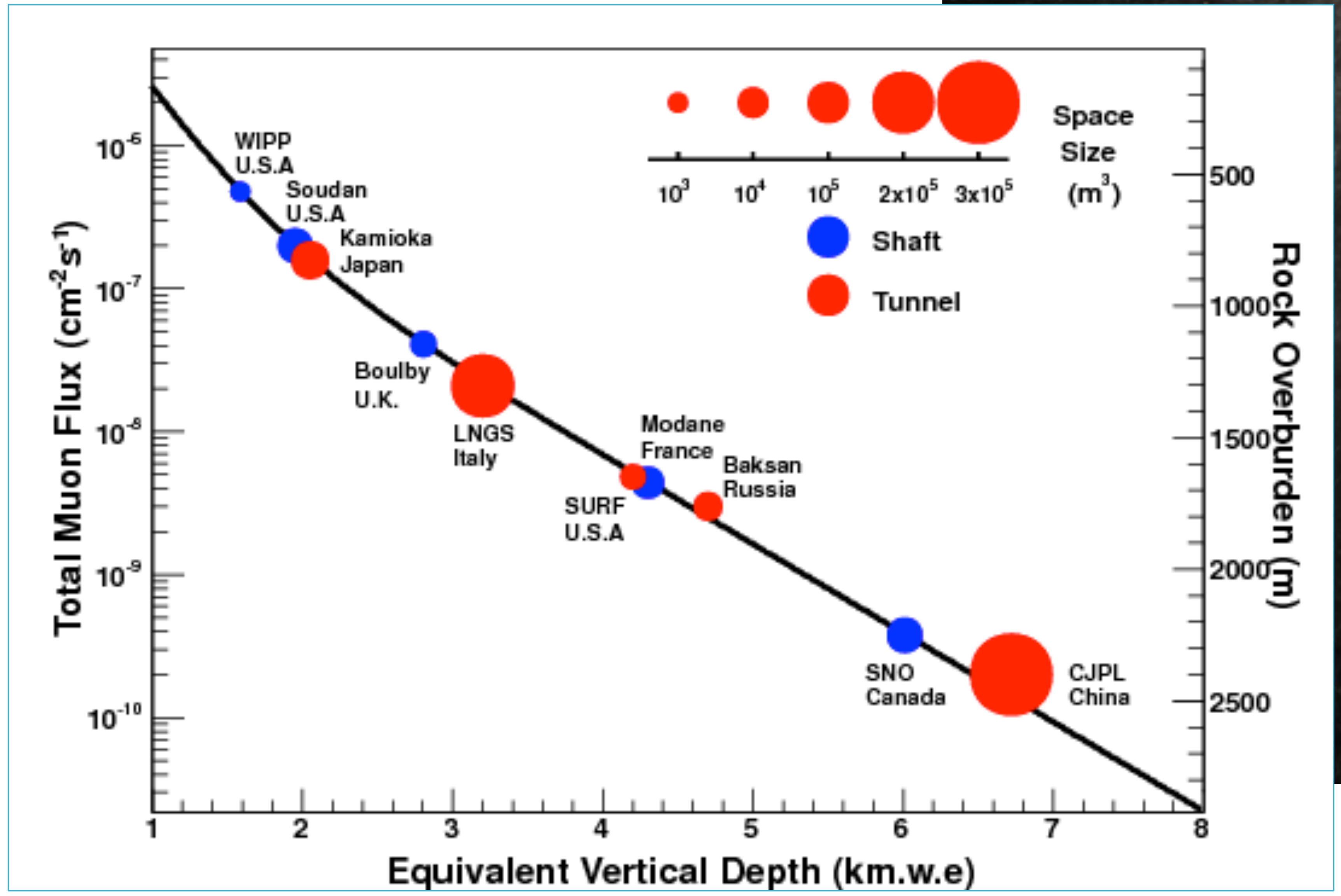


Searching for just a **handful of WIMP interactions** in **multi-tonne** targets, over **several years**

To compare with:

- Cosmic background at surface: **100** events / m^2 / s
- Radioactivity in rock: **1,000** events / kg / s
- Radioactivity in water: **10** events / liter / s
- Radioactivity in air: **10** events / m^3 / s


ZEPLIN
DRIFT
SuperCDMS
CoGeNT
EDELWEISS
DEAP
CLEAN
Picasso
COUPP
DAMIC
LUX
LZ
ArDM
Rosebud
ANAIS
XENON
CRESST
DAMA / LIBRA
Darkside
KIMS
XMASS
NEWAGE
PandaX
CDEX
DM-Ice

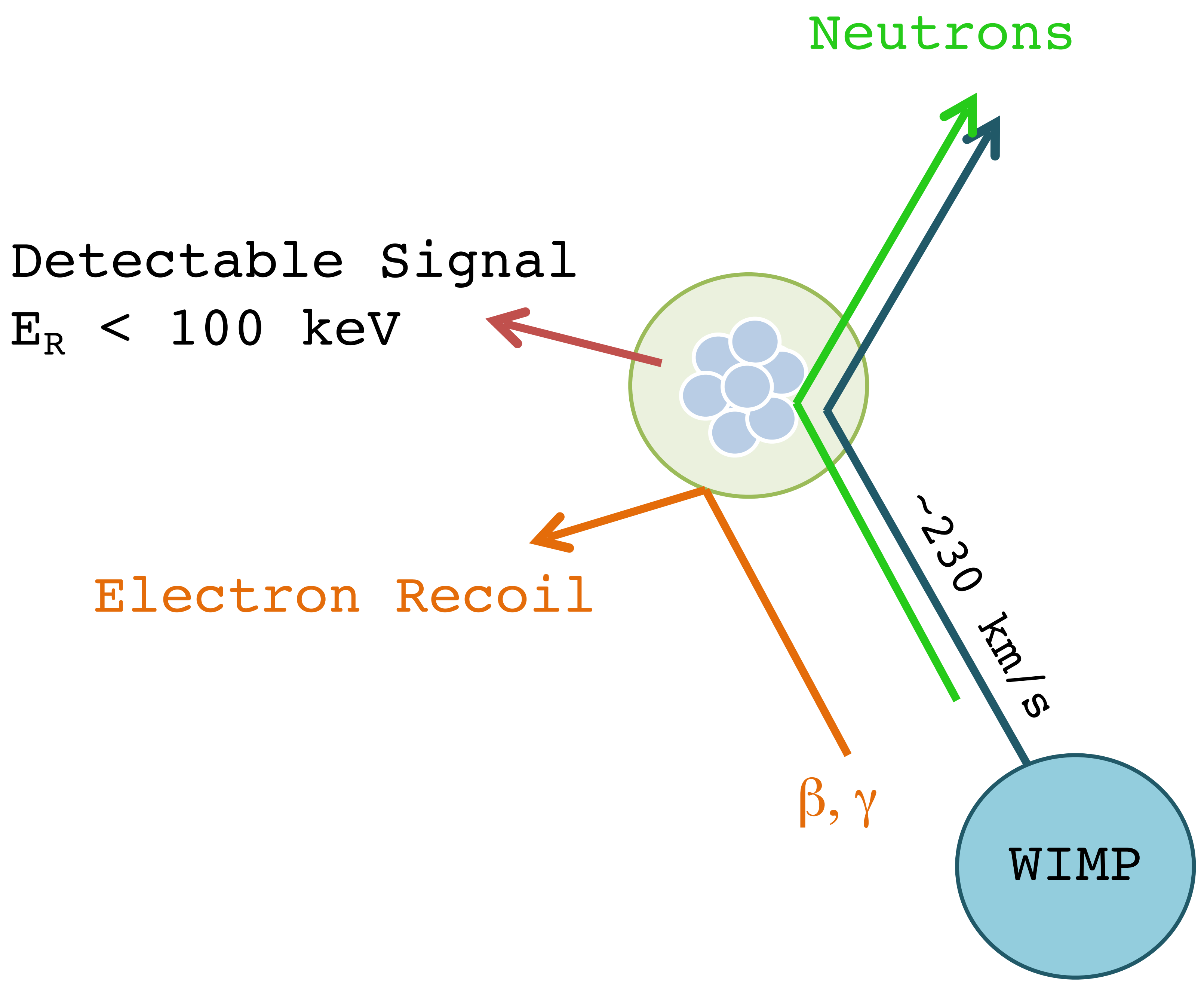

Total Muon Flux ($cm^{-2}s^{-1}$)
Equivalent Vertical Depth (km.w.e)
Rock Overburden (m)
Space Size (m^3)
10^3 10^4 10^5 $2x10^5$ $3x10^5$
Shaft
Tunnel
WIPP U.S.A
Soudan U.S.A
Kamioka Japan
Boulby U.K.
LNGS Italy
Modane France
Baksan Russia
SURF U.S.A
SNO Canada
CJPL China

Expected Backgrounds

Cosmic rays and cosmogenic isotopes

Natural (^{238}U, ^{232}Th, ^{235}U, ^{222}Rn,…) and anthropogenic (^{85}Kr, ^{137}Cs,…) **radioactivity**

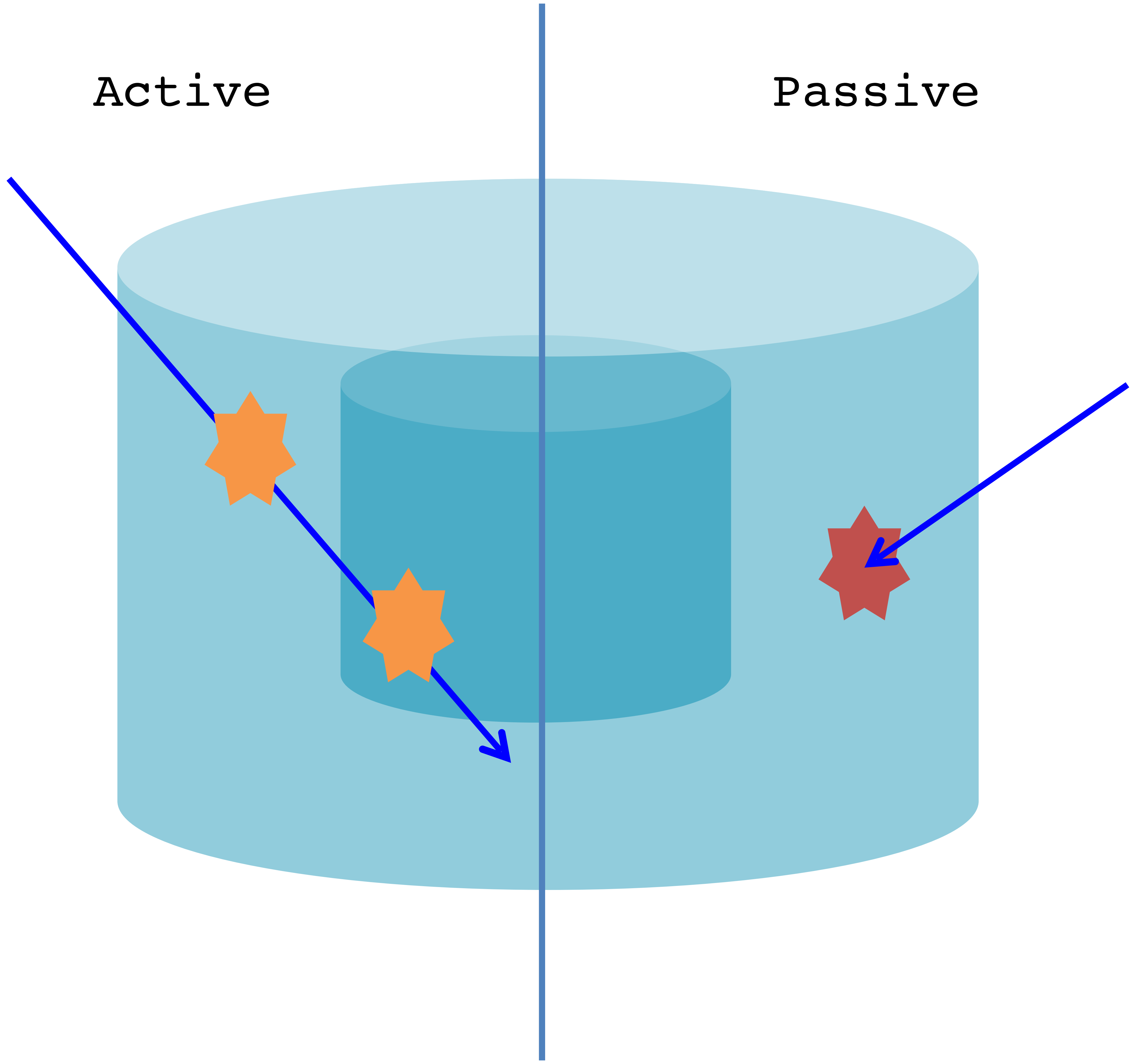
Neutrinos (solar, atmospheric, diffuse supernovae)



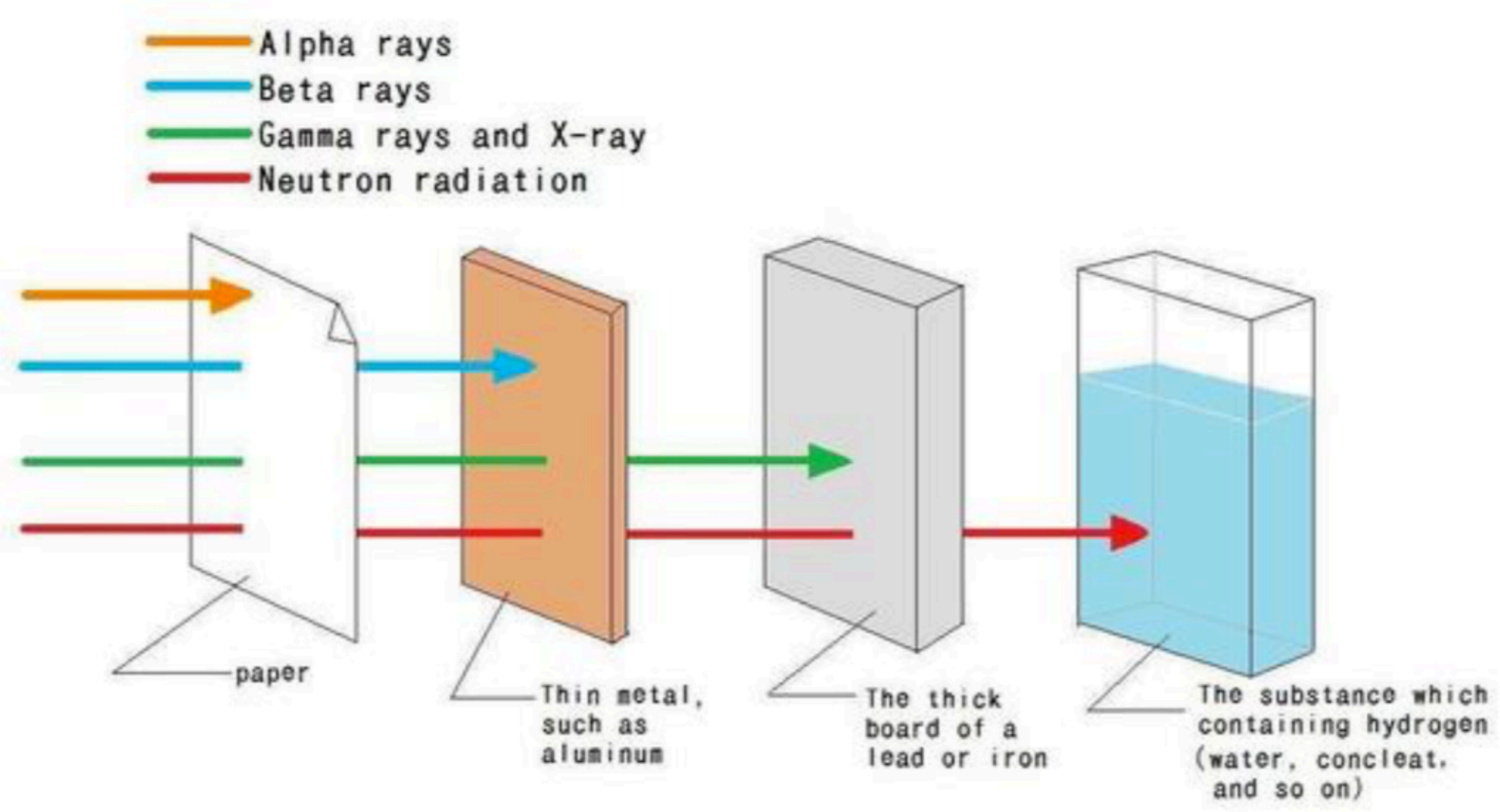
WIMP detector requirement:
- Large mass
- Low energy threshold
- Ultra-low background
- Signal/background discrimination

Either **background free** or perfectly constrained background

Or **clear signature** (annual modulation, directionality)


Active
Passive

Passive Shielding: Attenuation Lengths

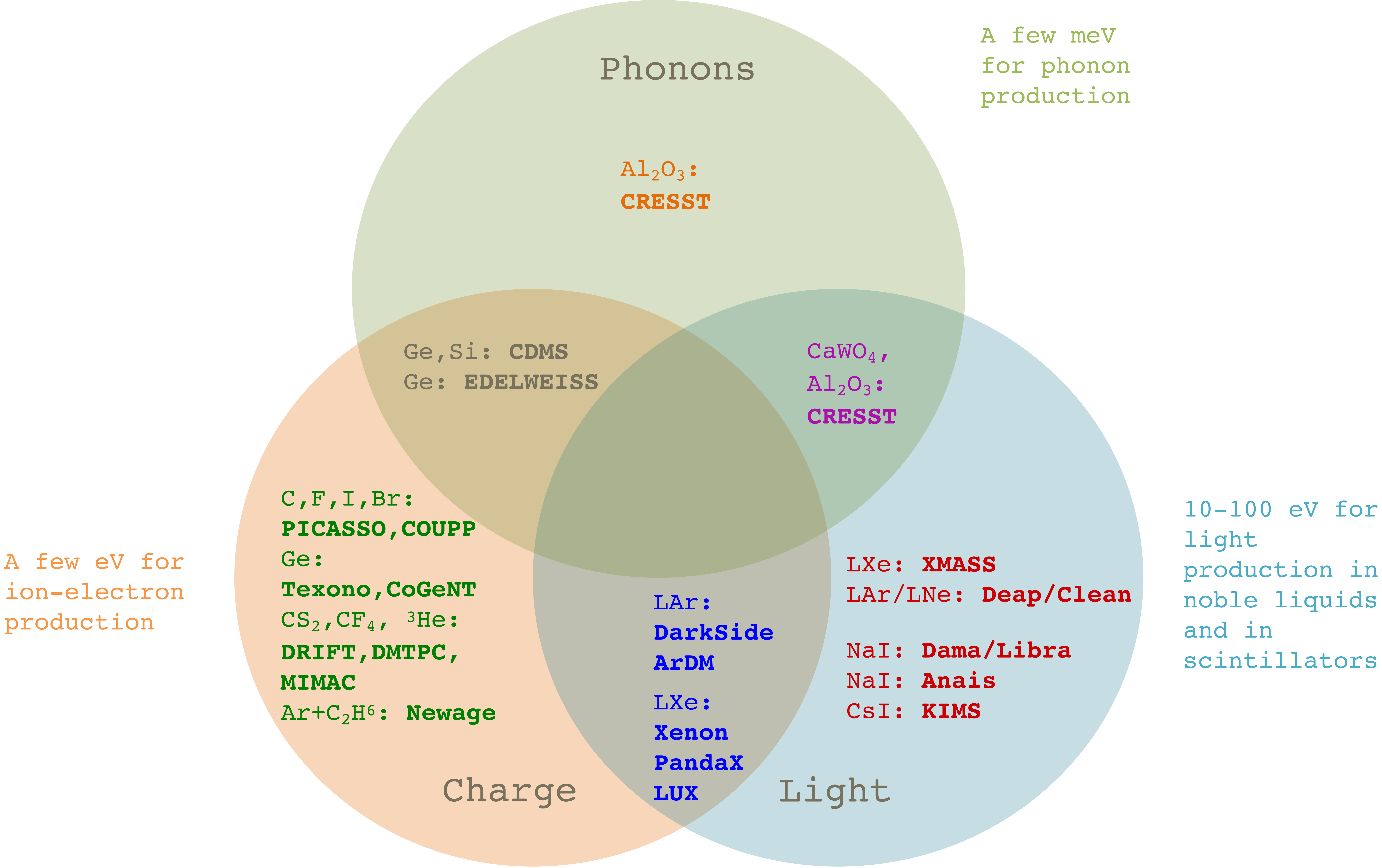


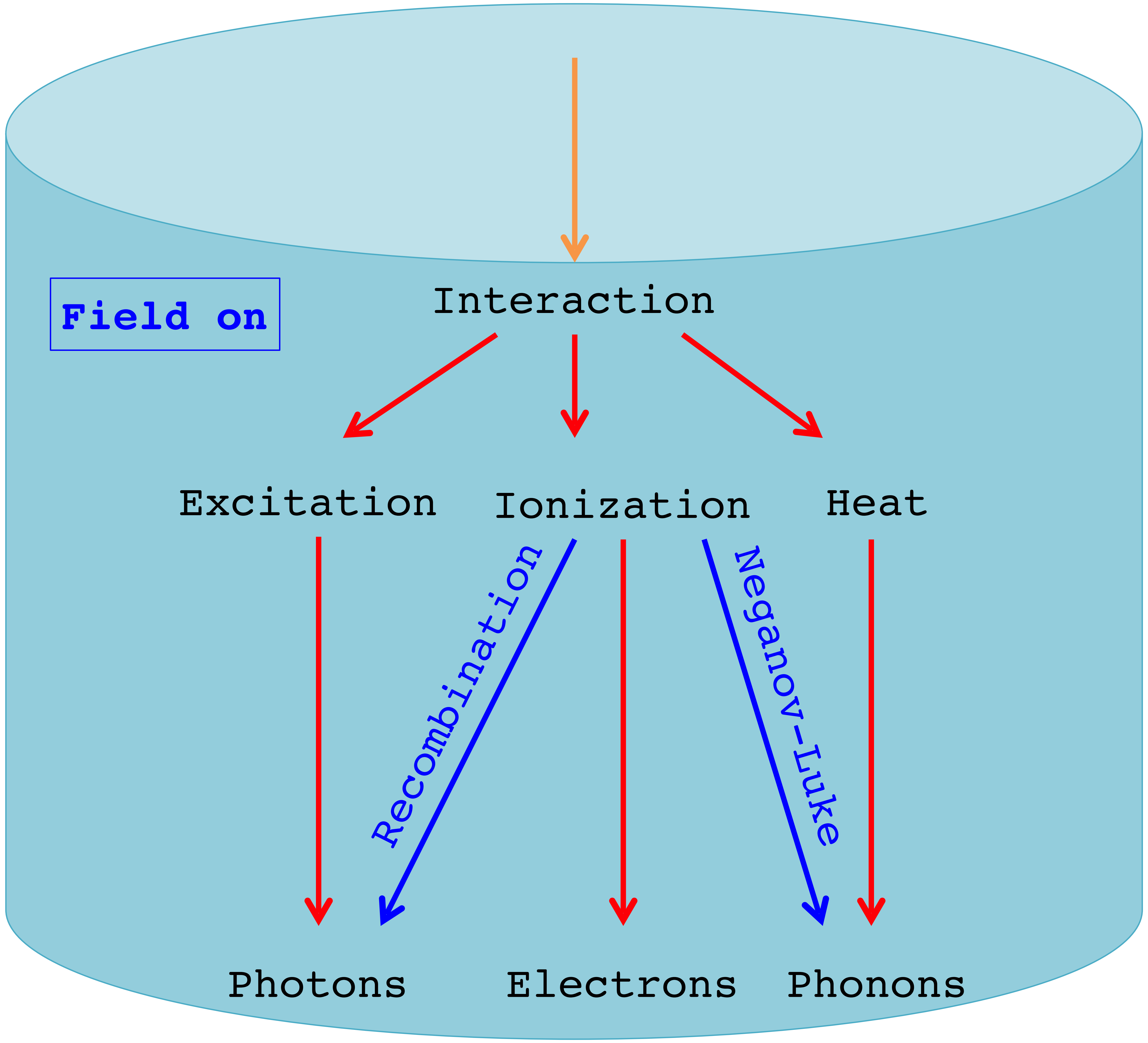
- muons – can not be stopped

Radiopurity: the Roman lead

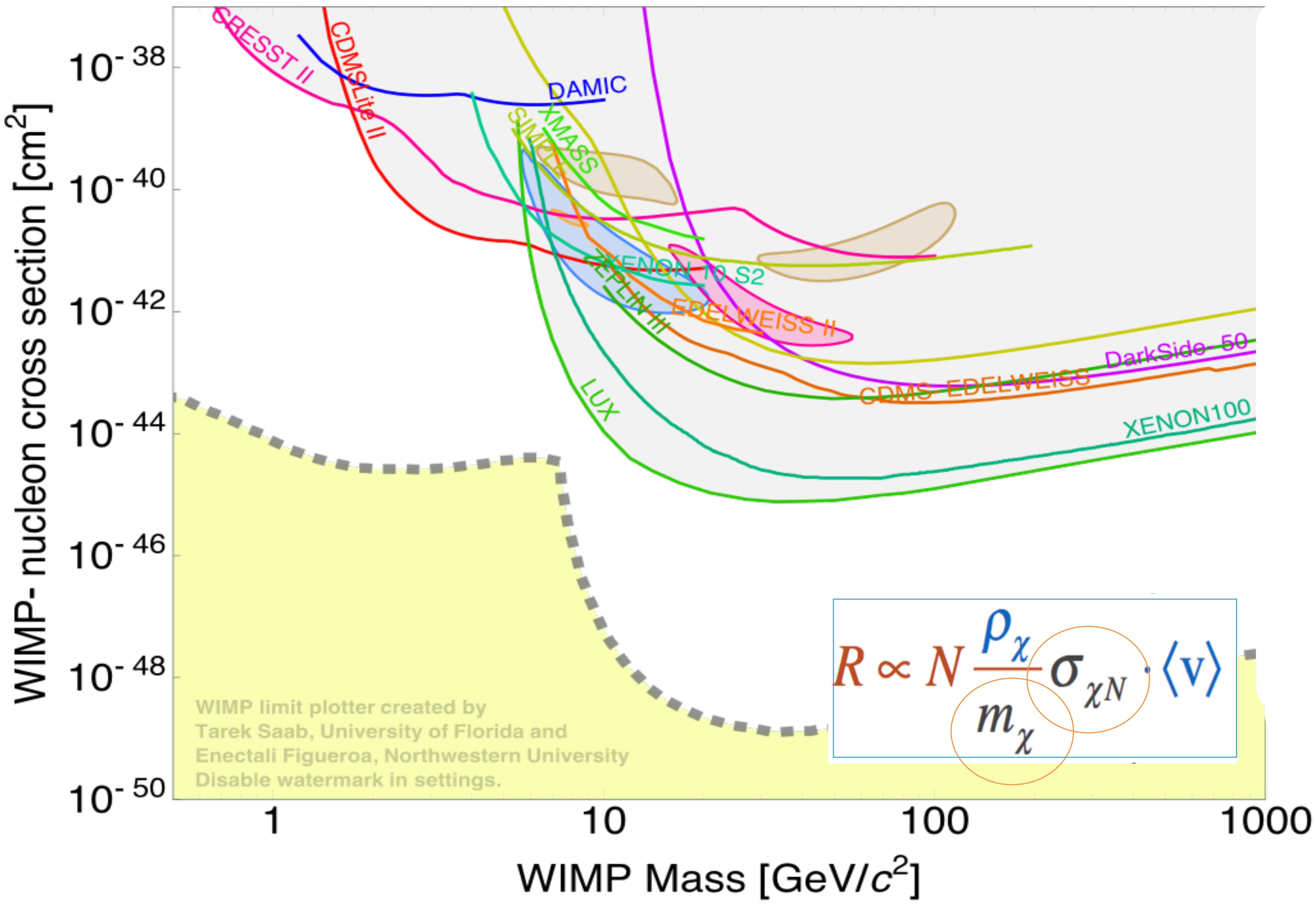
- Lead is ideal for shielding due to its high density and atomic number, but modern lead contains radioactive Pb-210.
- Ancient lead, however, is free from Pb-210 thanks to its 22.3-year half-life.
- A Roman shipwreck near Sardinia yielded ~1000 lead ingots (33 kg each);
- 150 were donated to INFN for use at LNGS, preserving the original Roman inscriptions.

Direct Detection Techniques



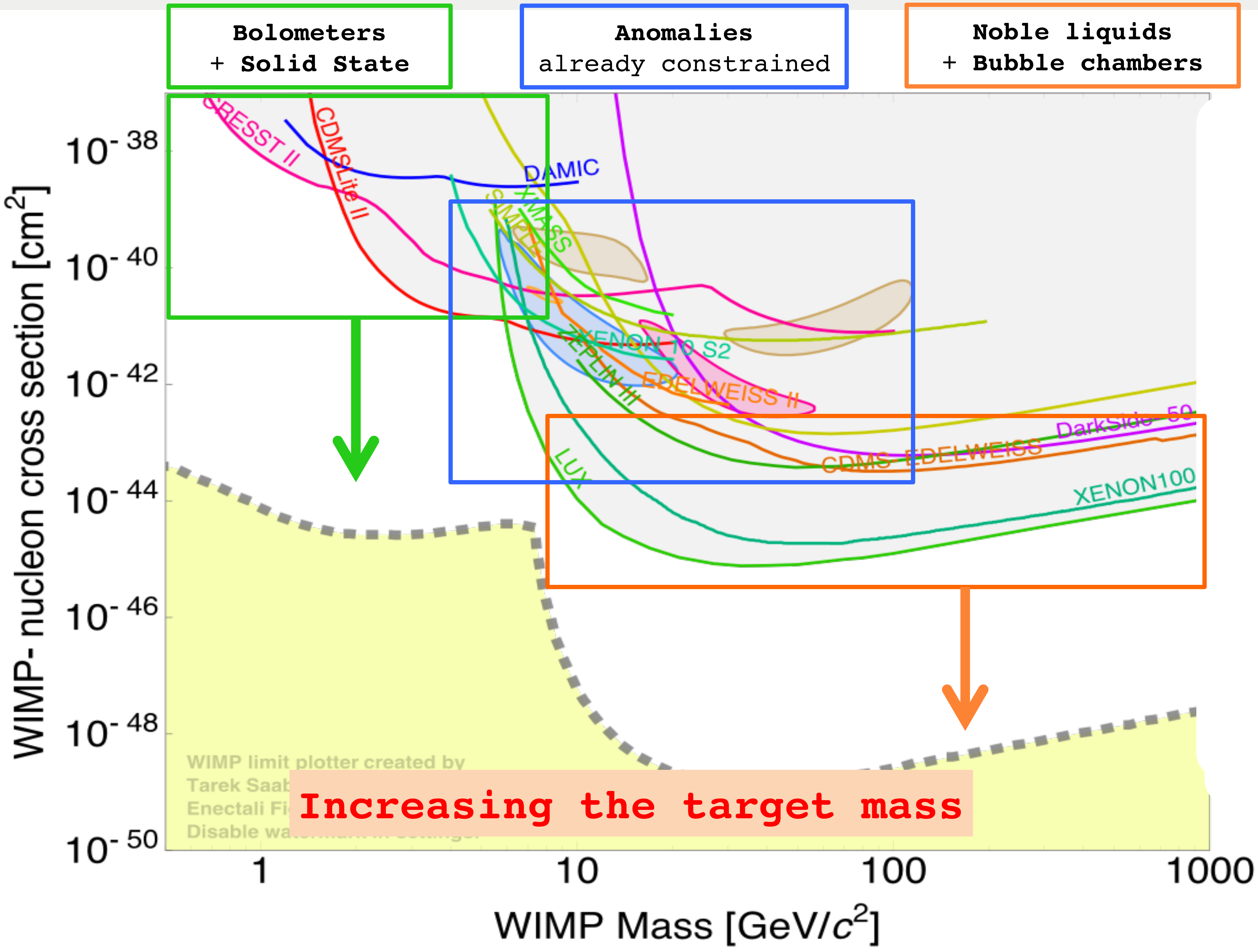

Field on
Interaction
Excitation
Ionization
Heat
Recombination
Neganov-Luke
Photons
Electrons
Phonons

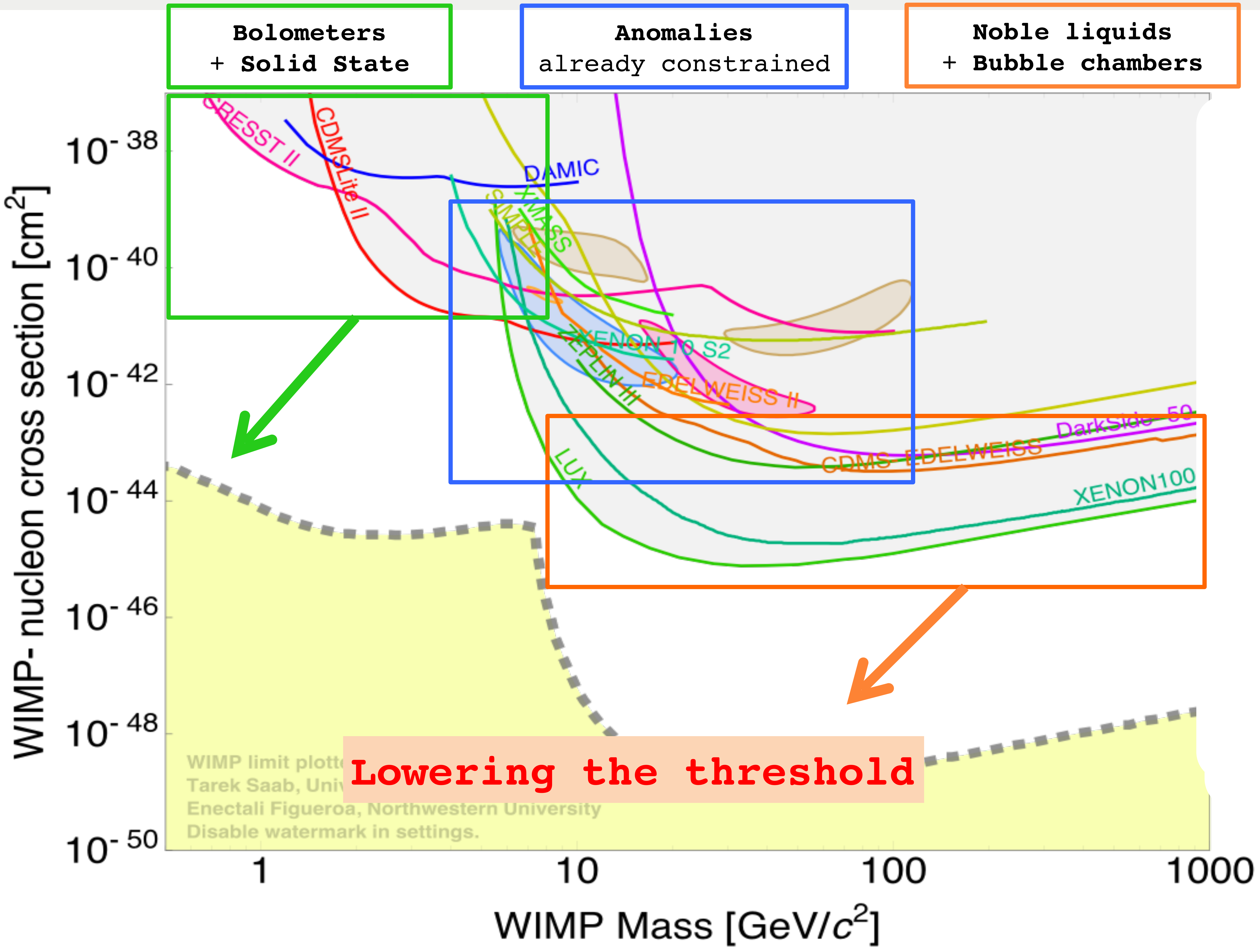
The Sensitivity



$$R \propto N \frac{\rho_\chi}{m_\chi} \sigma_{\chi N} \cdot \langle v \rangle$$

The Sensitivity




Bolometers
+ Solid State
Anomalies
already constrained
Noble liquids
+ Bubble chambers
CRESST II
CDMSLite II
DAMIC
XENON10 S2
ZEPLIN III
EDELWEISS II
LUX
DarkSide-50
CDMS-EDELWEISS
XENON100
Lowering the threshold
WIMP- nucleon cross section [cm^2]
WIMP Mass [GeV/c^2]
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-50}
1
10
100
1000
Enectali Figueroa, Northwestern University
Disable watermark in settings.

A few fundamental concepts

Quenching factor: ratio between observed energy and deposited energy

Yields (light yield, phonon yield, ionization yield): number of quanta per unit of energy

Trigger: set of criteria that must be fulfilled for acquiring an event

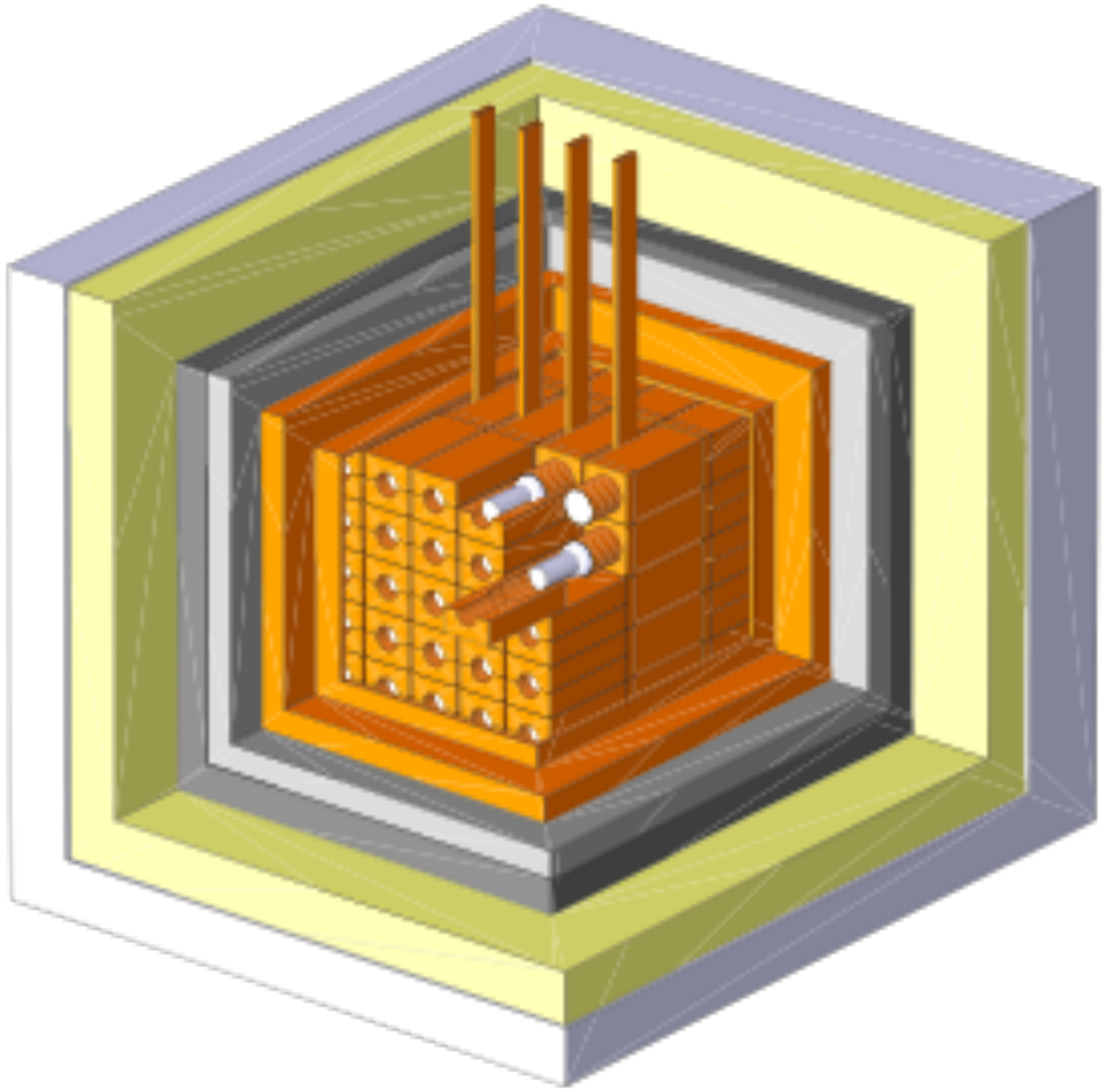
Trigger threshold: minimum energy required to “trigger” the detector

Analysis threshold: minimum energy used in the analysis

The DAMA observation

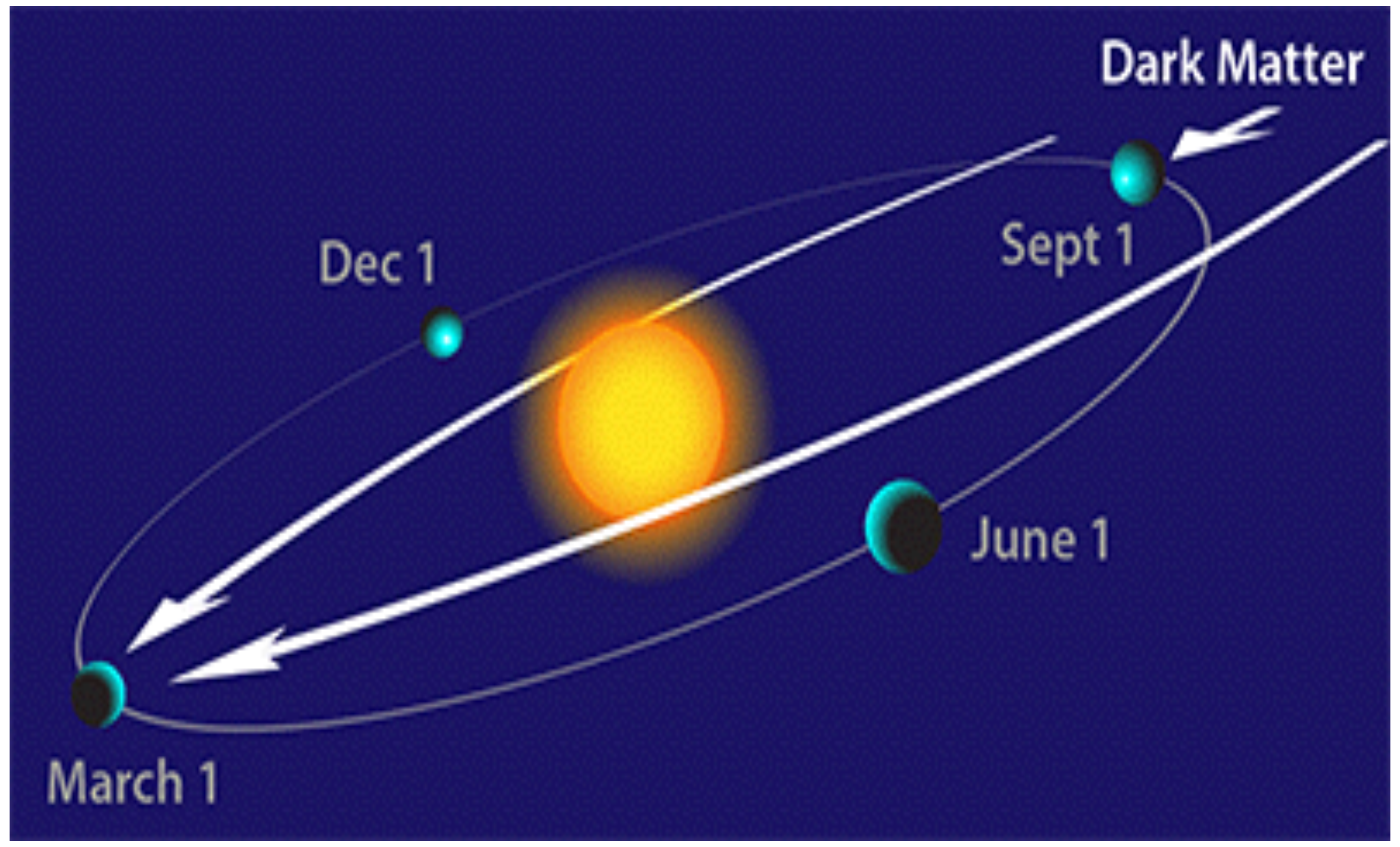
High purity NaI(Tl) crystals

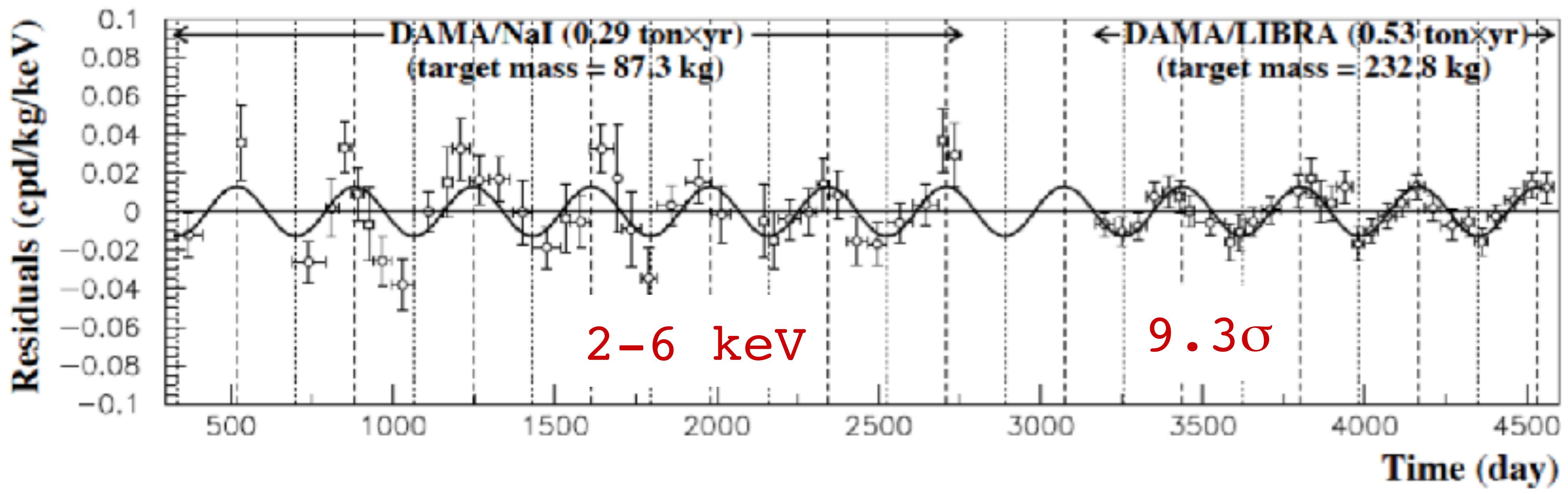
- OFHC copper
- Low radioactivity lead
- Cu/Pb etched with acid in clean room
- Polyethylene/paraffin-Cadmium
- Flushed with HP N2 Gas
- No muon veto (no active shielding).



Characteristics
- Operating at room temperature
- High density (3-5 g/cm^3): **large stopping power**
- High light yield: **low thresholds** ~O(keV)
- **Limited crystal size** (several cm^3): several detectors for large masses
- **Limited background rejection** (only multiple crystal cut)

The DAMA observation





Target: ~250kg NaI(Tl)

- Signal: Annual modulation
  - Modulating: ~0.0112 (12) cpd/keV/kg
  - Signal region: 2-6 keV_{ee}
  - Non-modulating: ~ 1 cpd/keV/kg
  - No modulation above 6 keV.
- **~9.3σ significance 14 cycles (2013)**
- **Is this signal from dark matter interactions?**

The DAMA observation

The annual modulation observed by DAMA-LIBRA is **consistent with motion of Sun-Earth system through dark matter halo:**

- The **amplitude** is ~1%.
- The **period** is one year.
- The rate is maximum on day 144 ± 7 d (May 24). This is **within uncertainty of June 2**, the expected peak rate in dark matter.

Results are inconsistent with experiments using other targets. (LUX, XENON, CDMS)

Alternative explanations:

- Muon flux modulates due to the changing temperature of the atmosphere. Muon induced signal? The phase is slightly different

- Neutrinos also modulate (due to the Sun-Earth distance). Combination of muon-induced and neutrino flux?

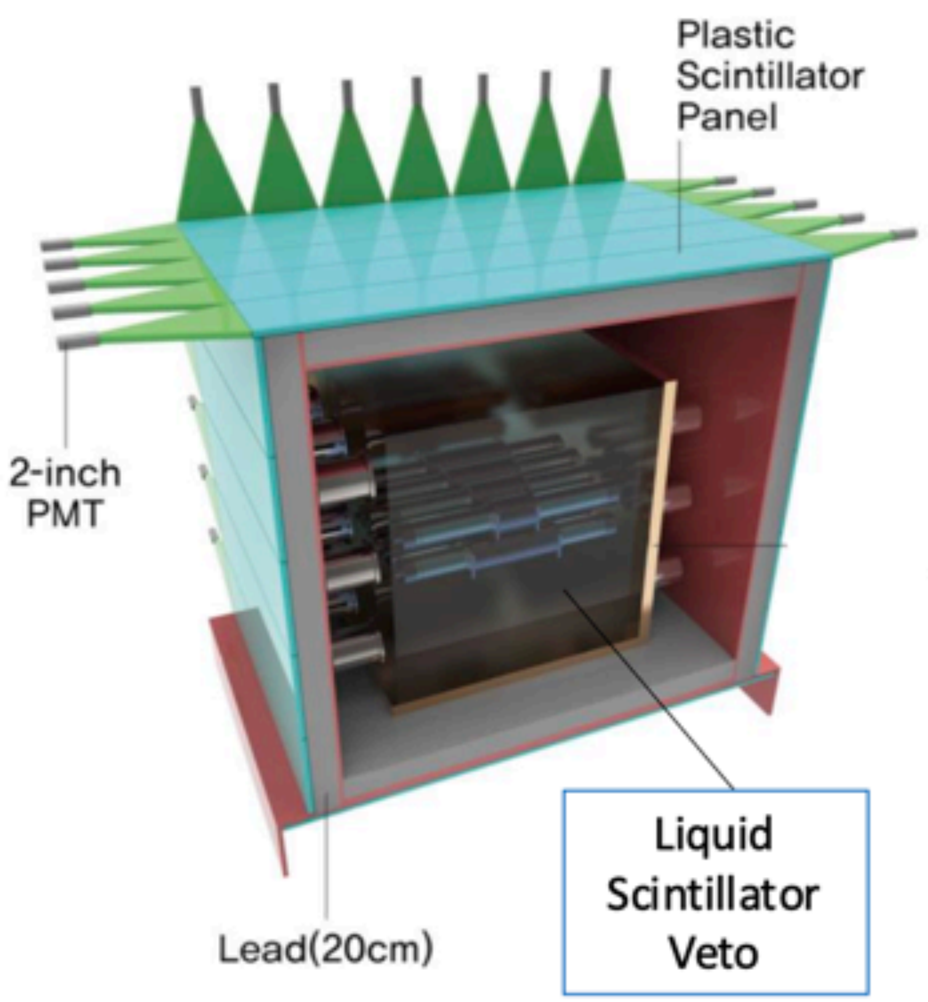
- Varying rates of background neutrons?

- Experimental effects?

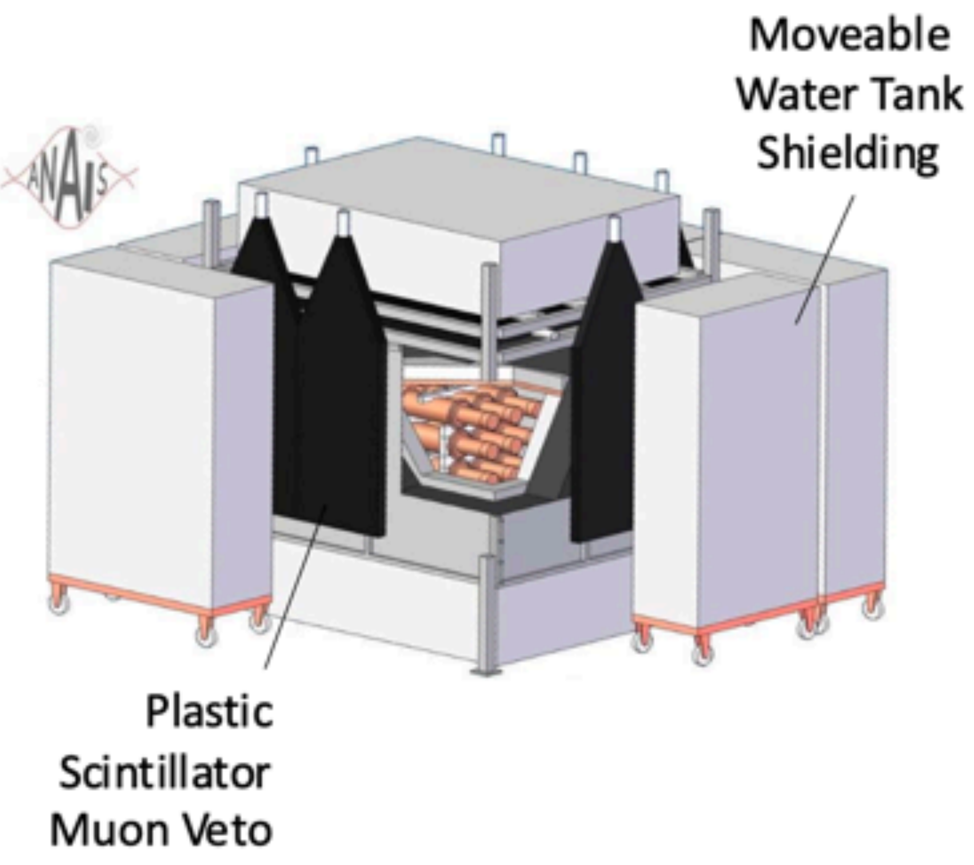
Rejecting the DAMA claim

Combined analysis by COSINE-100 and ANAIS-112

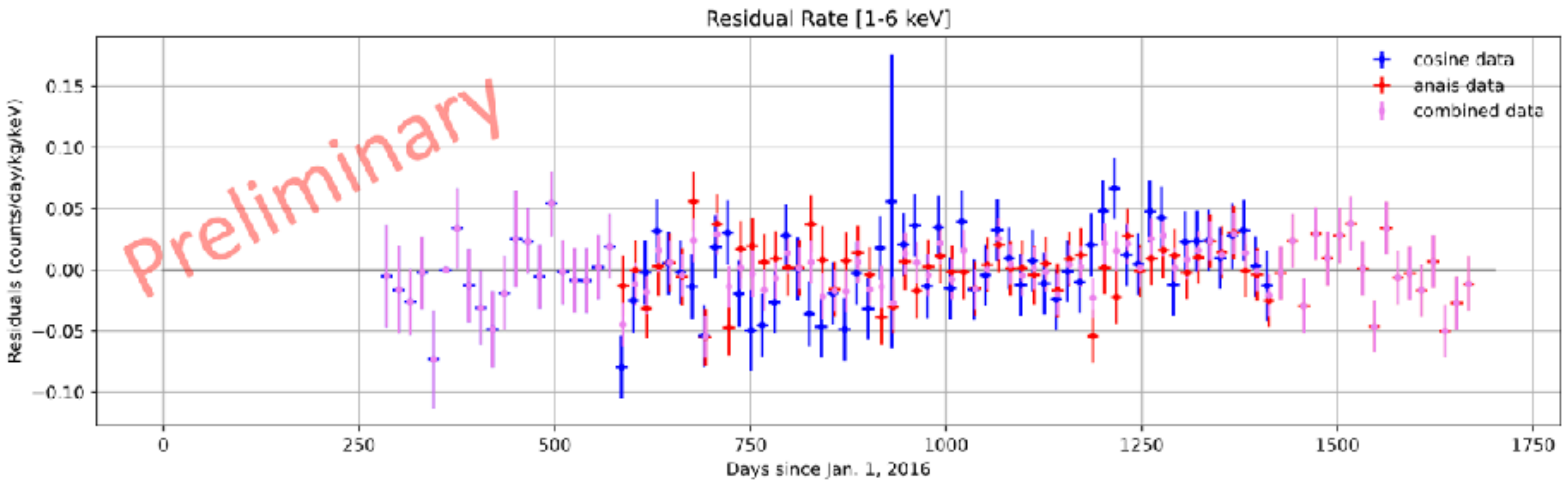
COSINE-100 | **ANAIS-112**

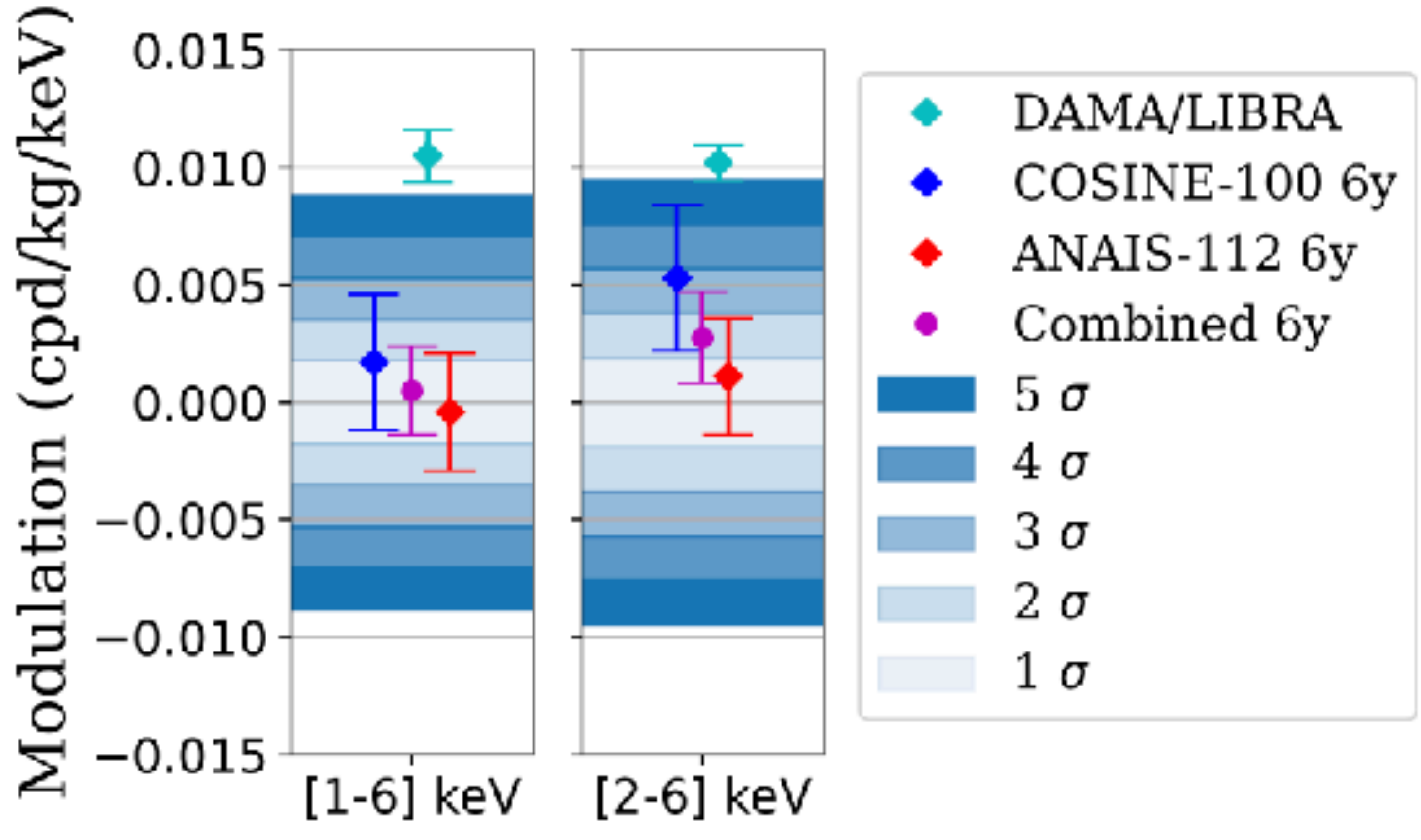


COSINE-100		ANAIS-112
Yangyang, South Korea	Location	Canfranc, Spain
September 2016	Comissioning	August 2017
61.3 kg 5 detectors	Active NaI(Tl) Mass	112.5 kg 9 detectors
~85%, 95% at 1.0, 1.5 keV	Efficiency	~25%, 80% at 1.0, 1.5 keV



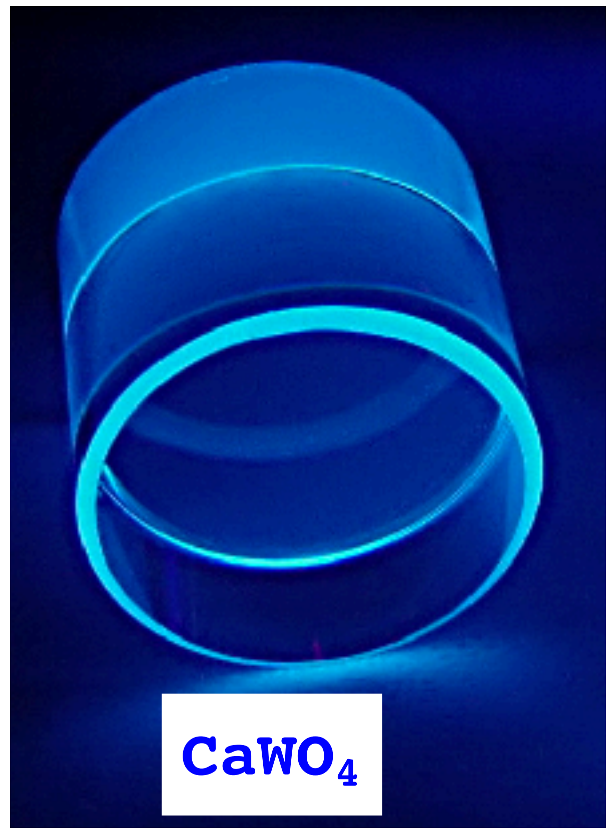
arXiv:2503.19559





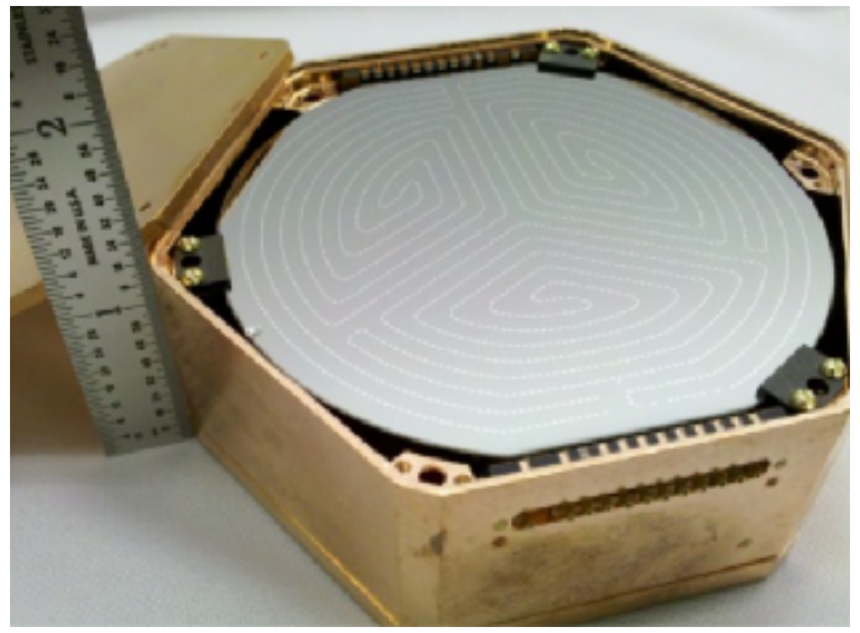
Characteristics
- Operating at **mK temperature**
- Excellent **energy resolution**
- Good radio-purity
- Very low thresholds **>0.2 keV**
- **Limited crystal sizes** (100 g – 1.4 Kg)
- **Good discrimination with phonon vs light/charge**
- Slow response: **not (yet) active vetoes**

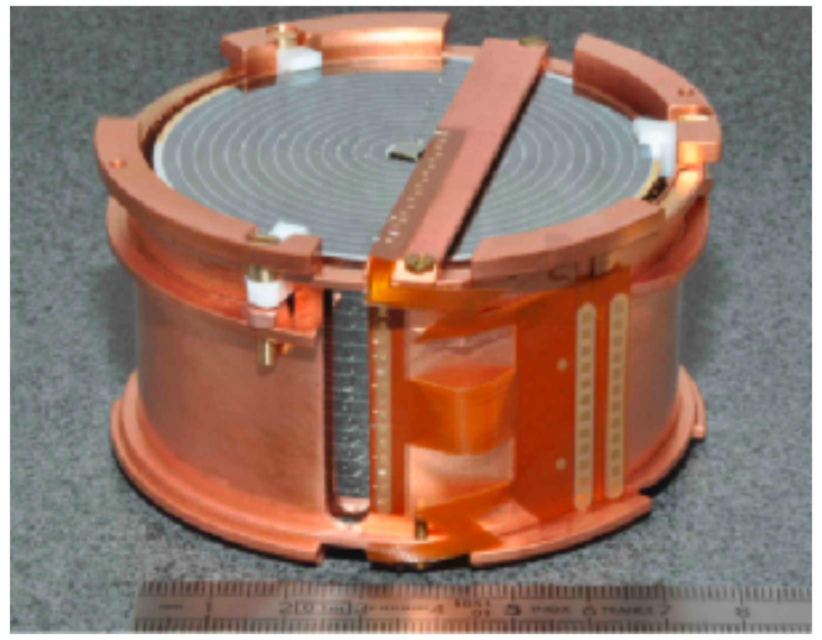
Phonon vs **Light**



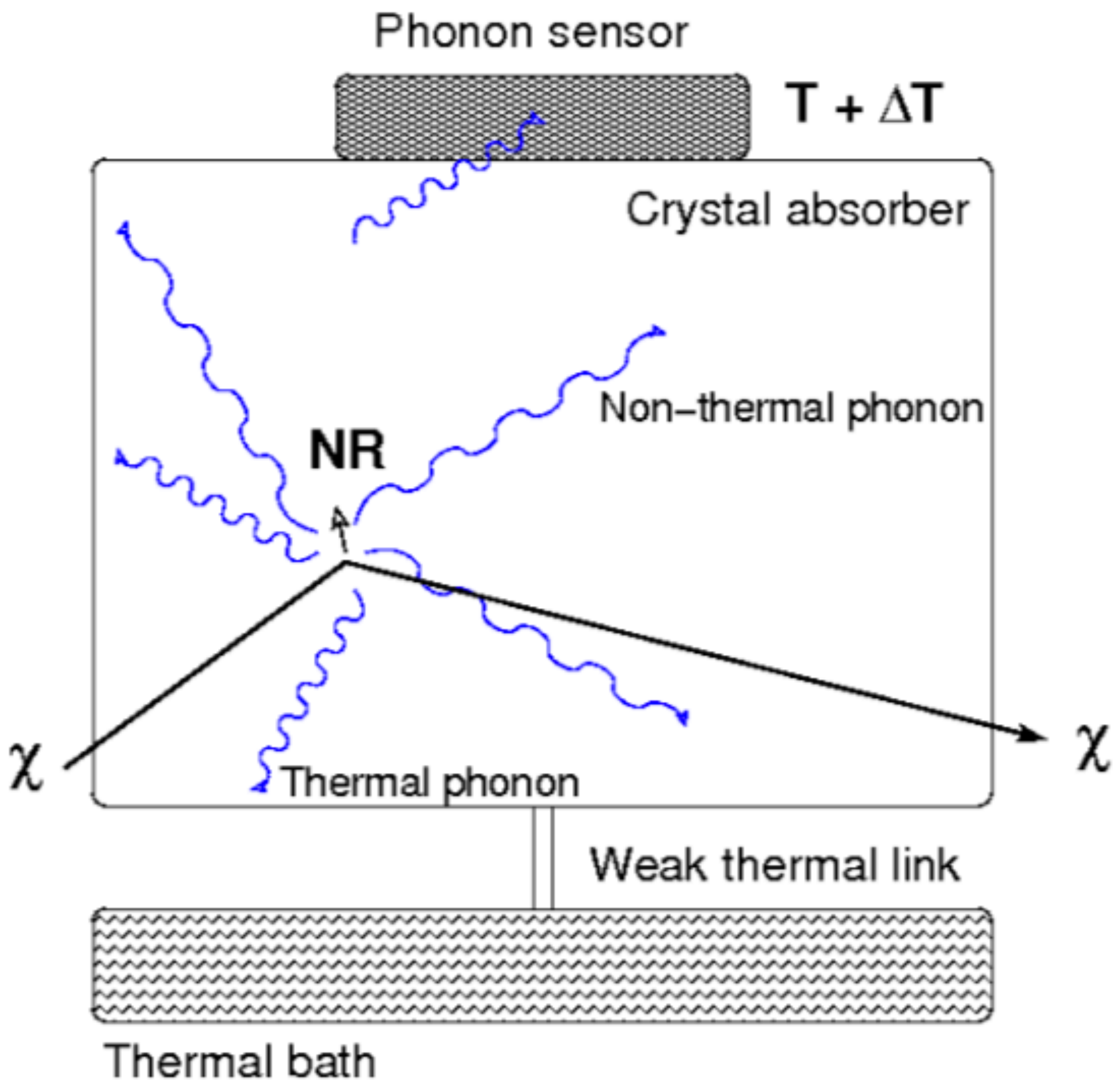
CRESST-II

Phonon vs **Charge**





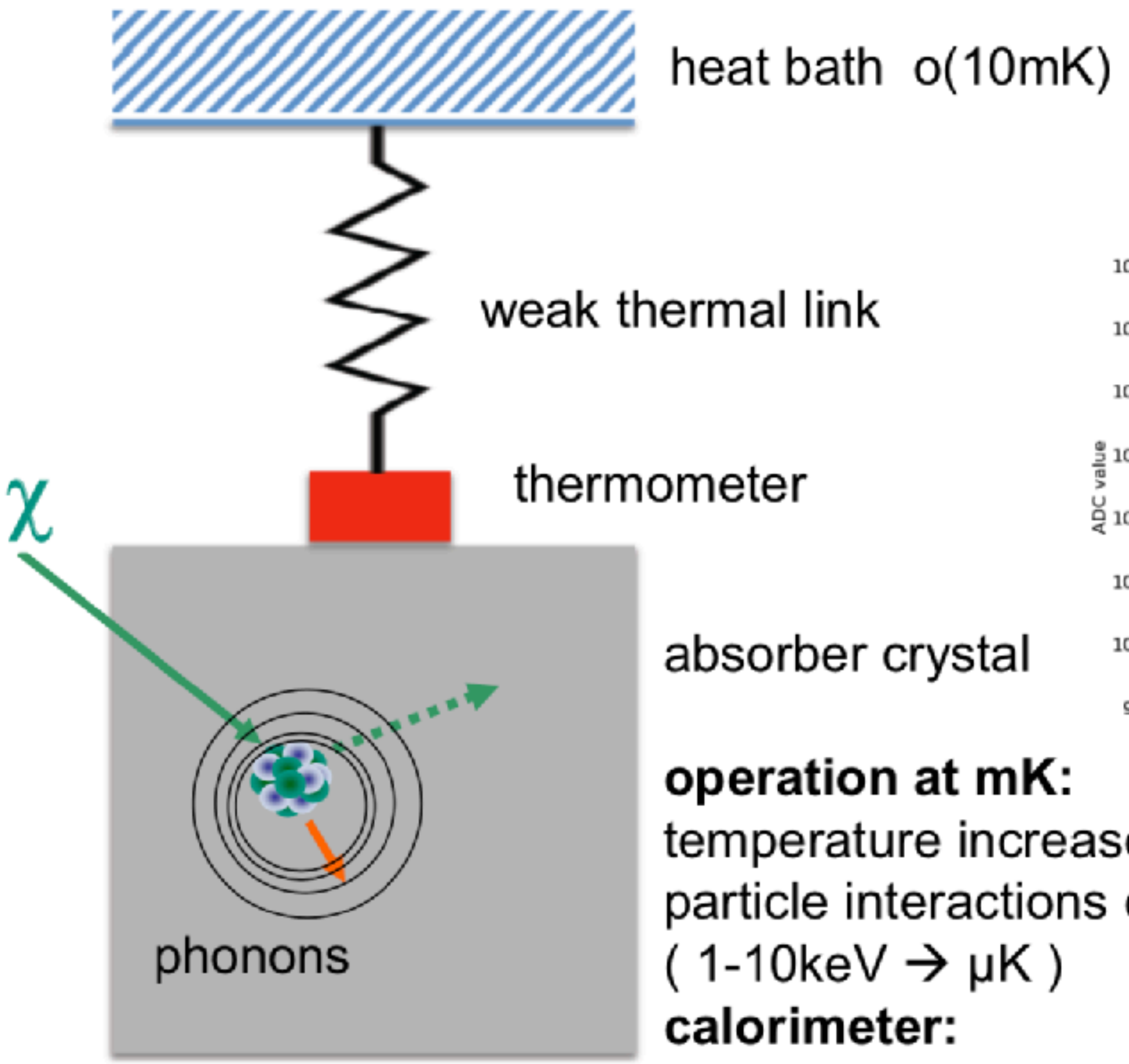
SuperCDMS: Ge, Si
EDELWEISS-III: Ge

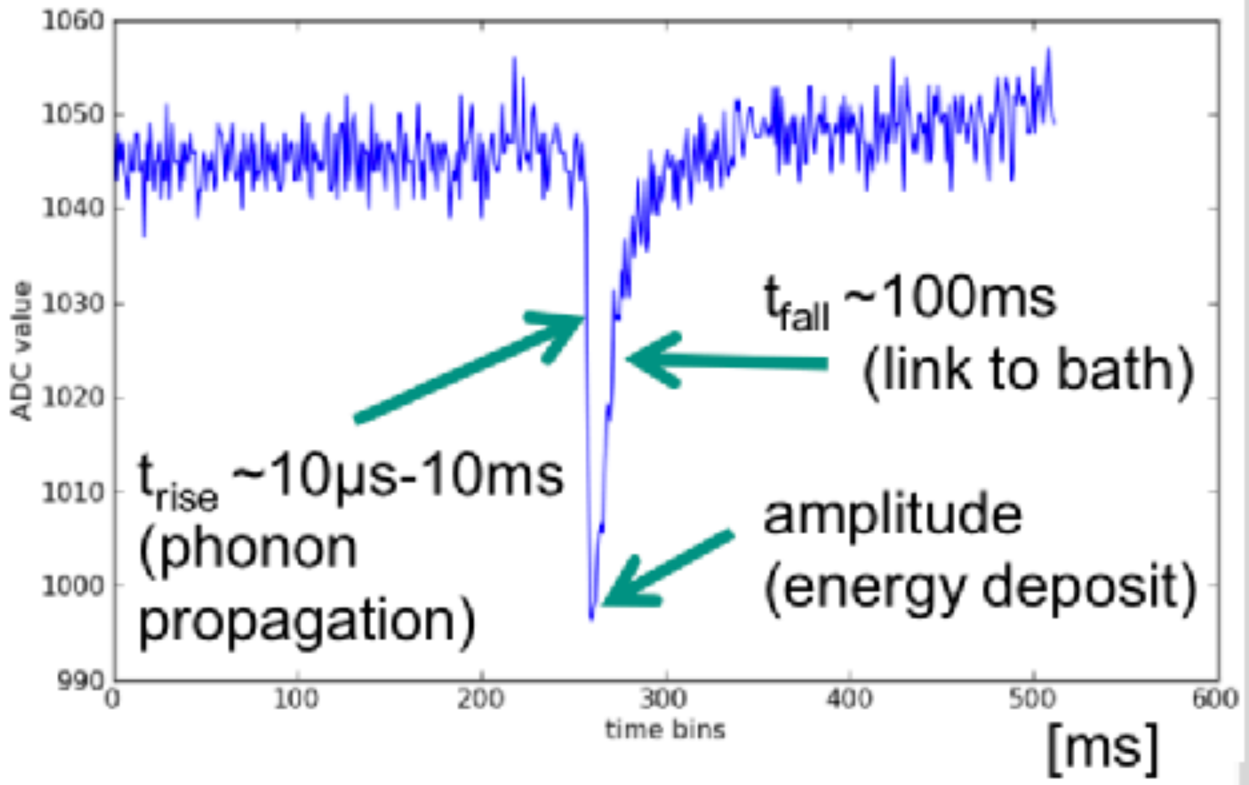


- Crystals at (10 – 100) mK
- Temperature rise:
  $\Delta T = E/C(T)$
  E.g. Ge at 20 mK, $\Delta T = 20\,\mu$K for few keV recoil
- Measurements of ΔT
  NTD: neutron transmutation-doped Ge sensors
  TES: Transition edge sensors
- Discrimination: combination with light or charge read-out

$$\Delta T = \frac{E}{C(T)} \cdot \exp(-t/\tau)$$

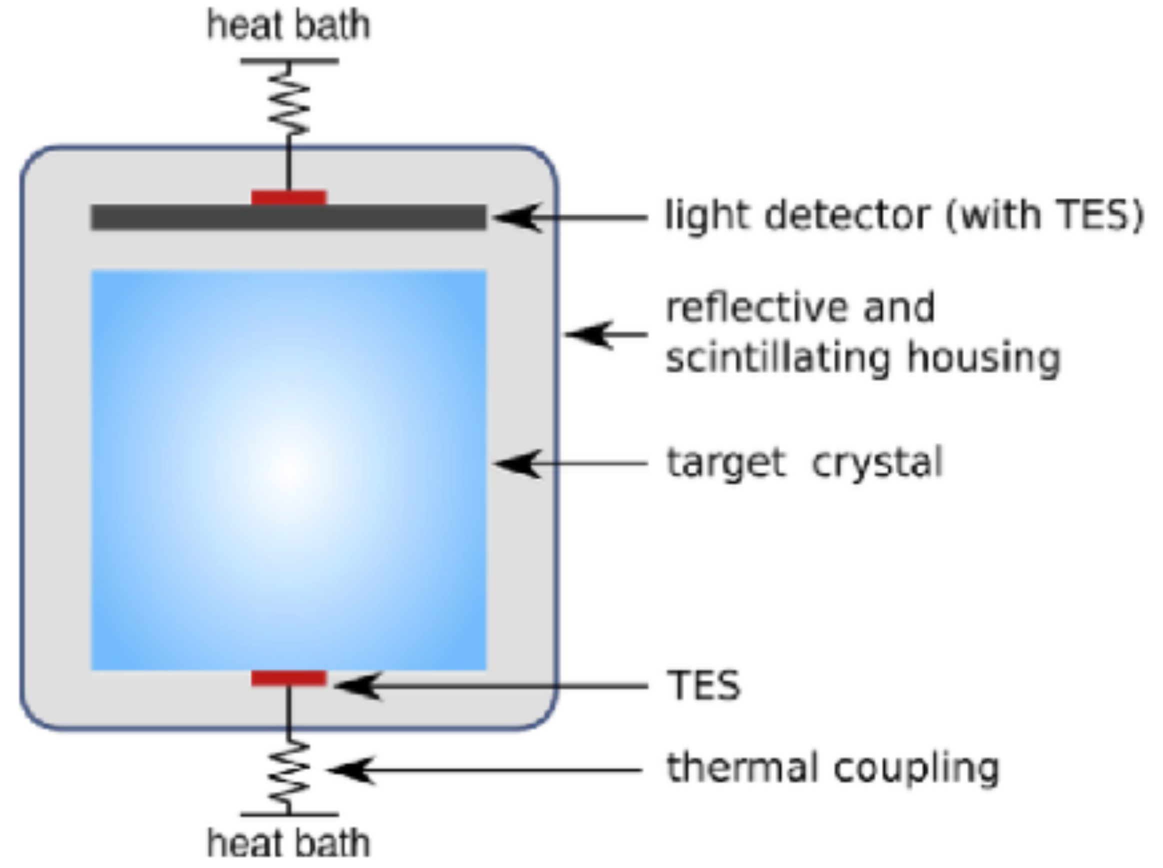
Cryogenic detectors (crystals)





operation at mK:
temperature increase from particle interactions can be measured!
(1-10keV → μK)
calorimeter:
direct measurement of total energy deposit!

6 Klaus Eitel -- Andes workshop 2017

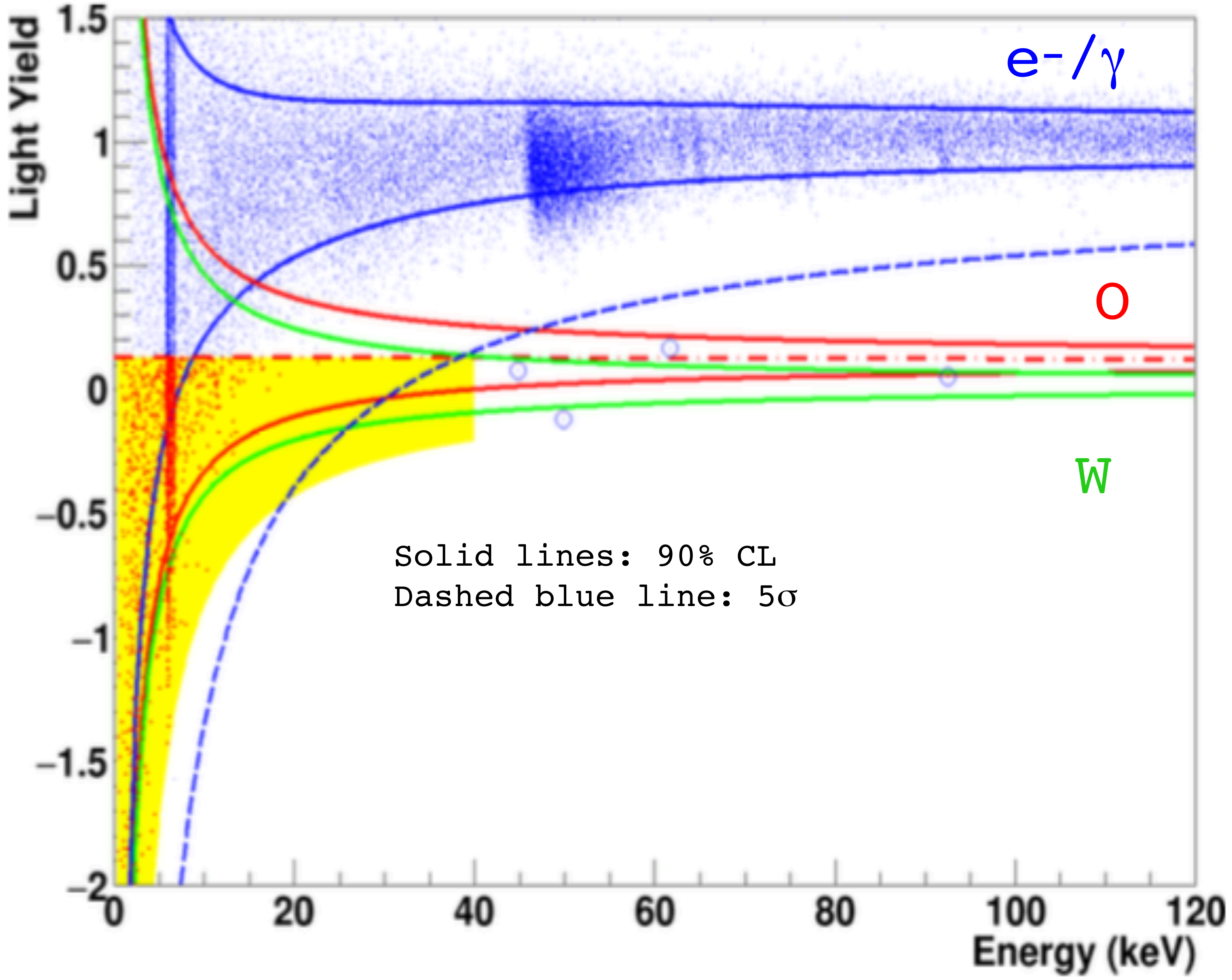


CRESST II Phase 2
arXiv:1509.01515
Exposure: 52 kg day
Threshold: **0.3 keV**
Background level: 8.5 /(keV kg day)

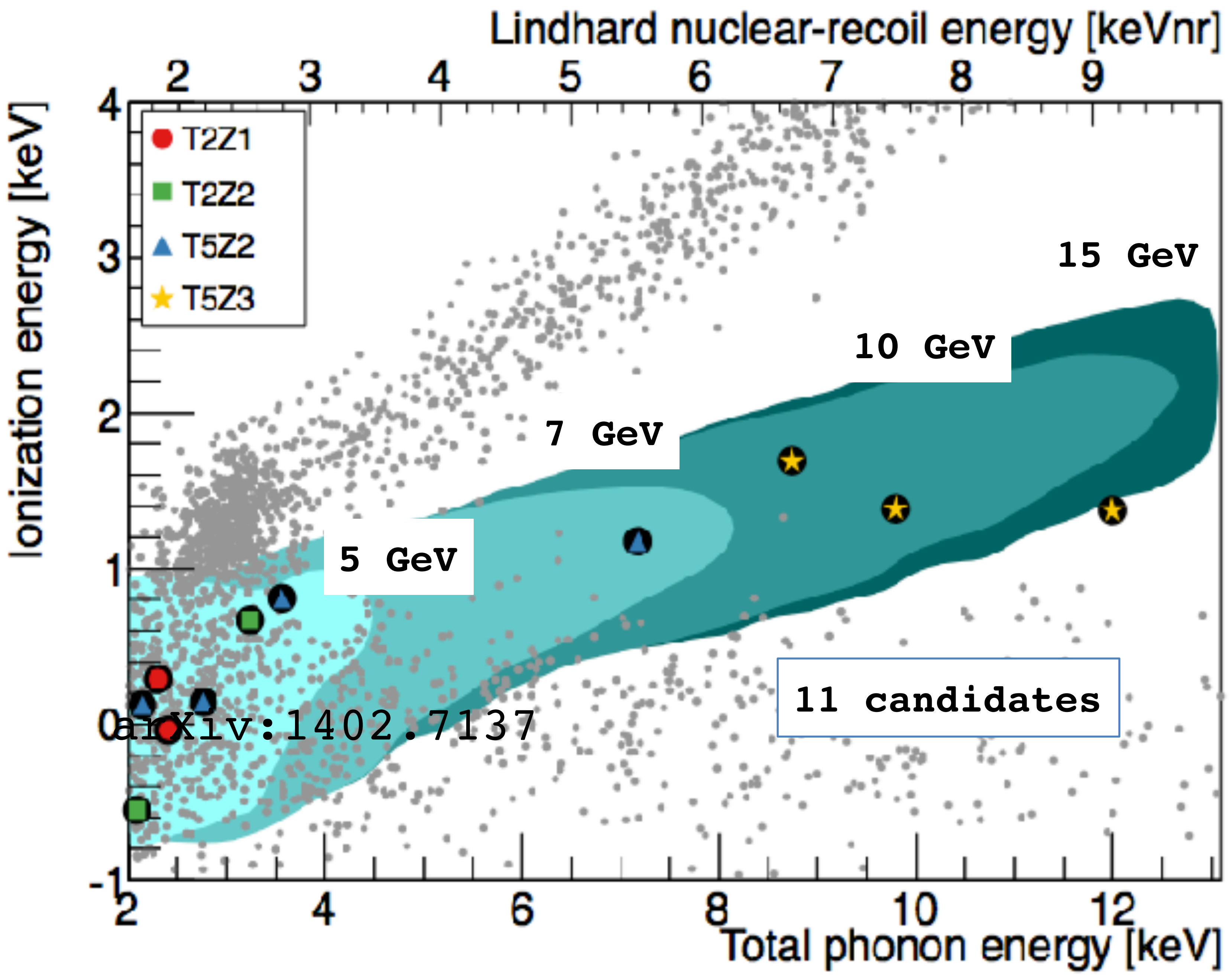
249 g $CaWO_4$ crystals operating at ~10 mK at LNGS
Several passive shieldings + active muon veto

Deposited energy converted mainly in phonons -> **Reconstructed energy**

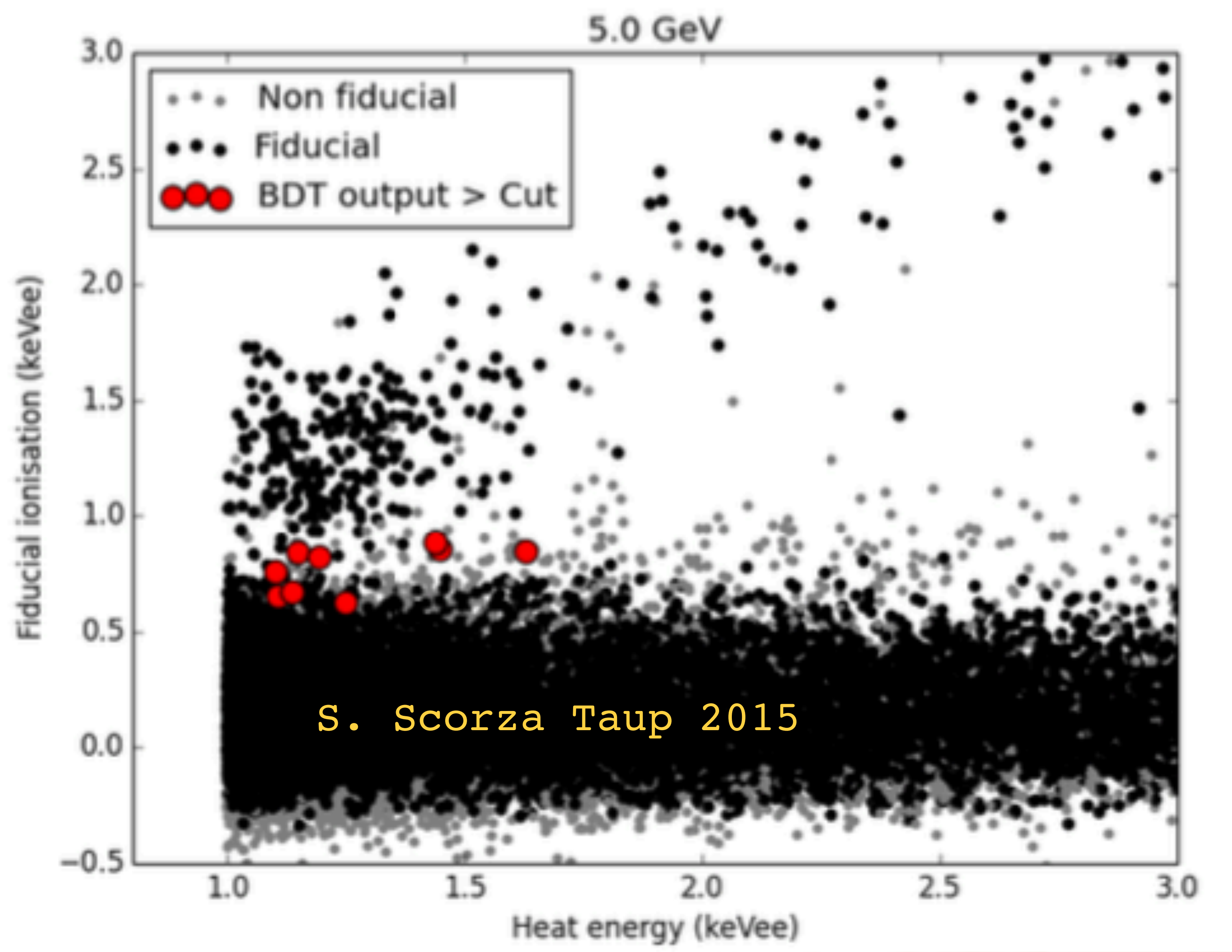
Small fraction into scintillation light -> **Particle discrimination**



SuperCDMS at SOUDAN
- 15x0.6 kg iZIP Ge at 50 mK
- Exposure: **577 kg day**
- Energy RoI: **1.6 – 10 keV$_{nr}$**
- Efficient surface background rejection

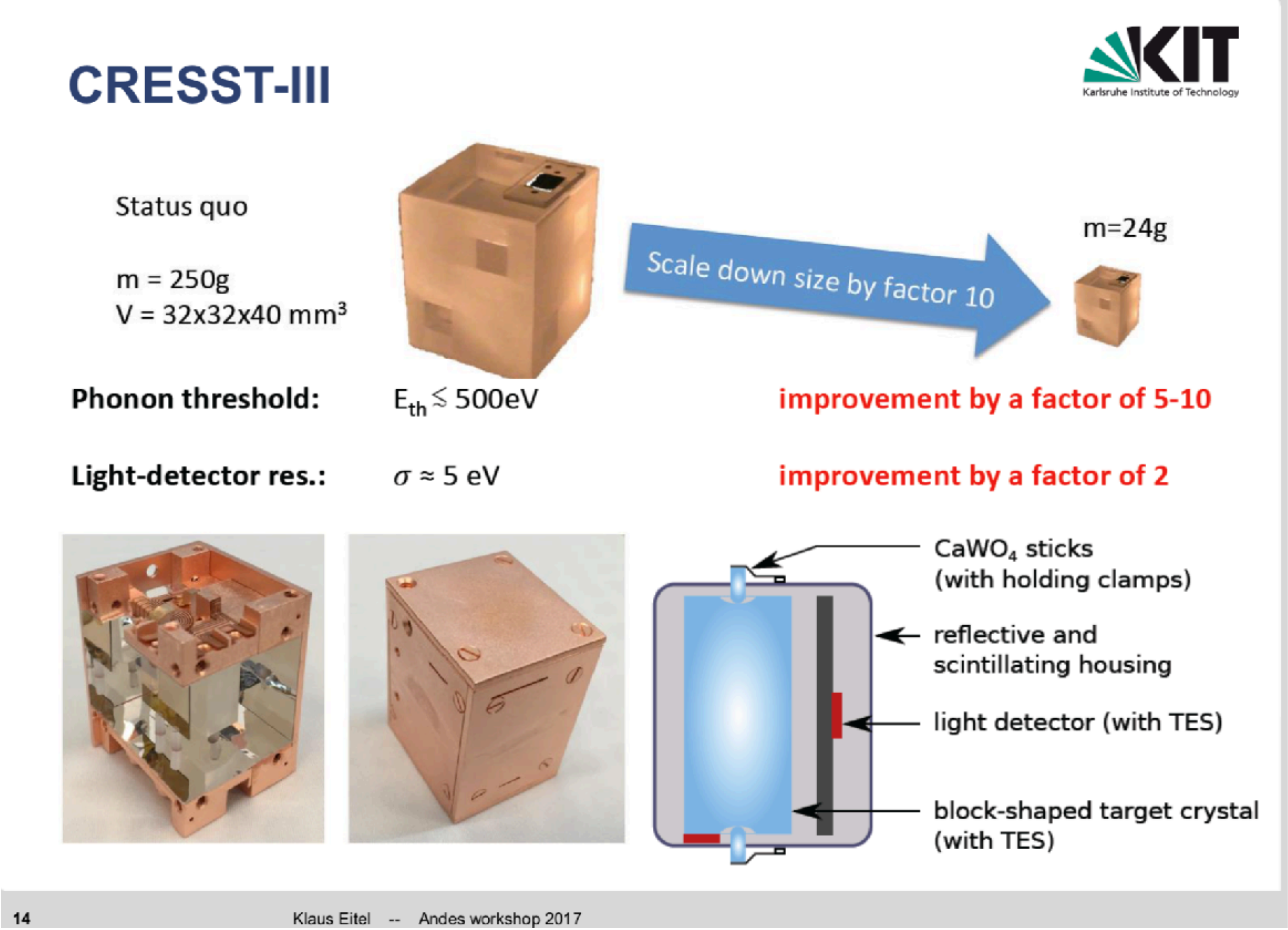


EDELWEISS at LSM
- 8x0.8 kg HP Ge at 18 mK
- Exposure: **582 kg day**
- Energy RoI: **1 – 15 keV$_{ee}$**
- Surface background rejection with Boosted Decision Tree



Example at 5 GeV WIMP mass:
9 events in 4 detectors at 1keV$_{ee}$

Improving capacitance



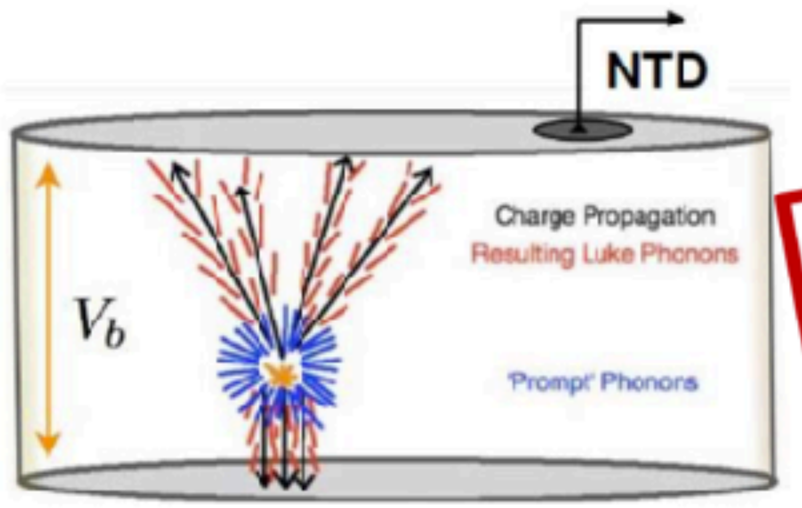
The Neganov-Luke effect

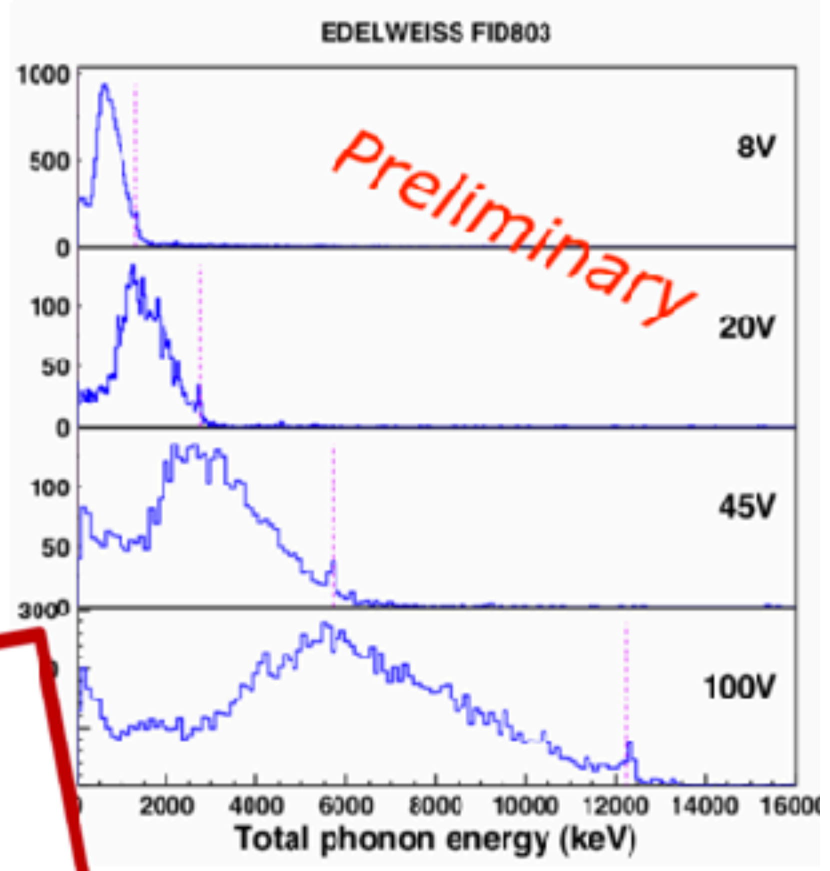
Edelweiss

Applying high voltage

Neganov-Luke:

$$E_t = E_r + \frac{1}{3\,eV} E_Q \Delta V$$



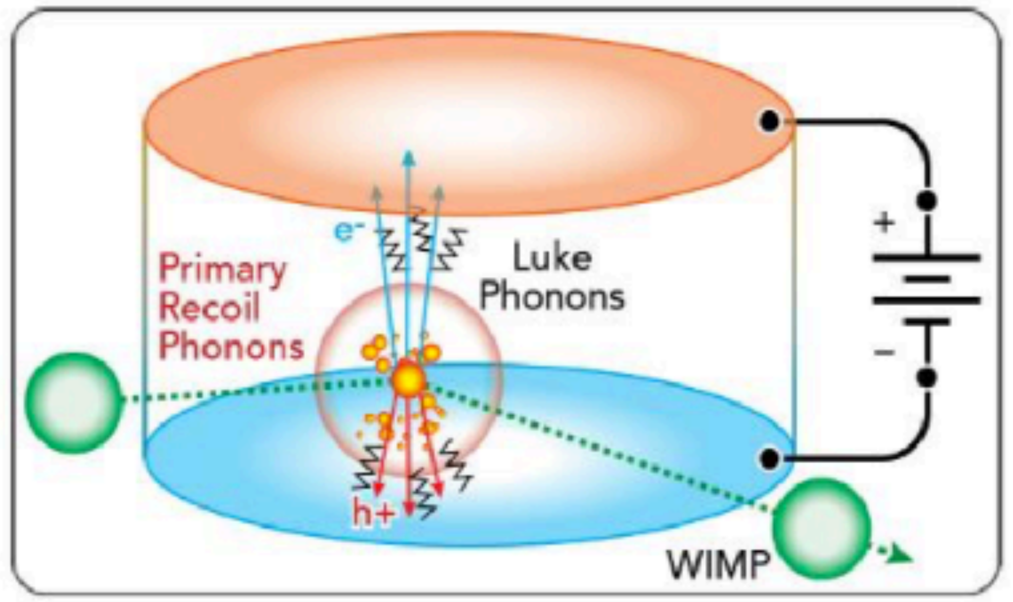


first measurements in LSM with FID800 in NL-mode ^{133}Ba calib 356keV line

→ up to 100V working → NL boost 35
→ sensitivity to low mass WIMPs (~1GeV/c^2)

→ BUT: no electron/gamma suppression

CDMS Lite



making use of Neganov-Luke effect:

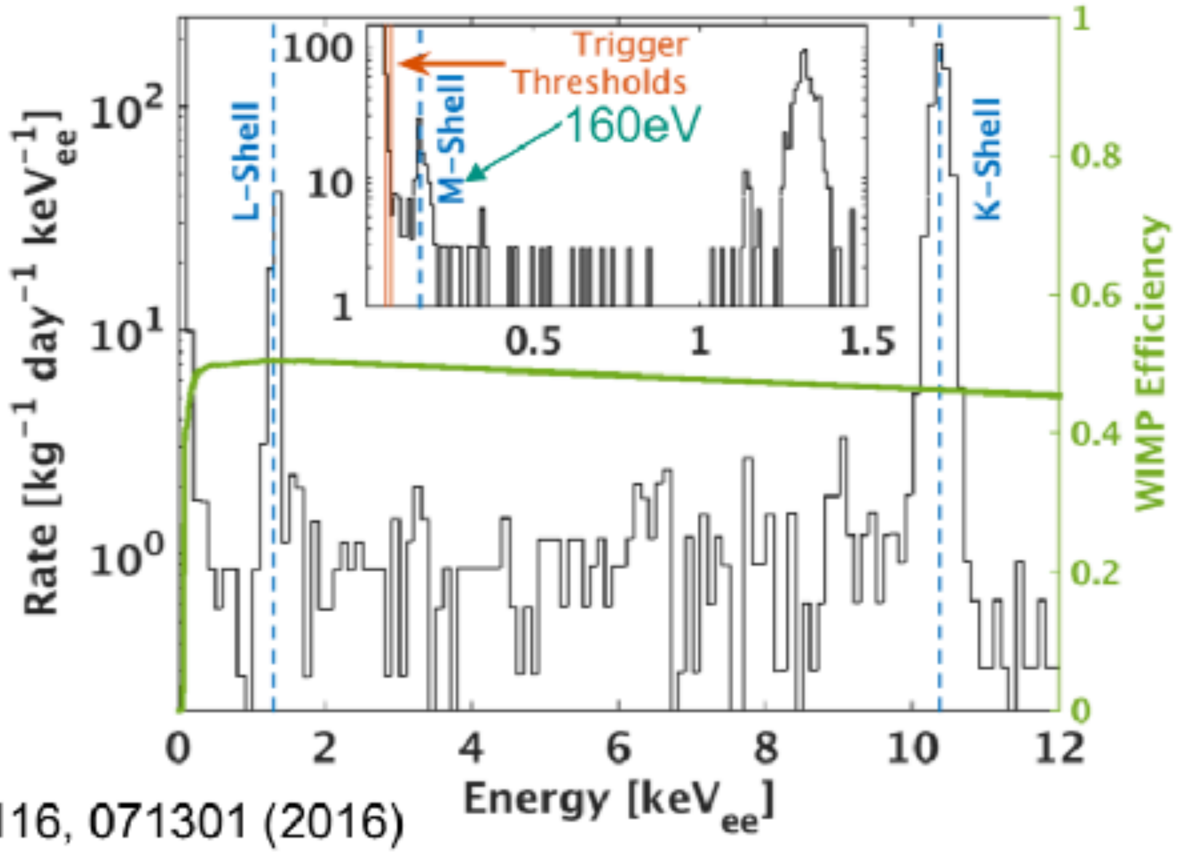
$$E_t = E_r + \frac{1}{3\,eV} E_Q \Delta V$$

with V=70V amplification of heat signal ~24
→ effective lowering the threshold

NL amplification:

- allows $E_{thr} \approx 50eV$
- opens window into ~GeV range

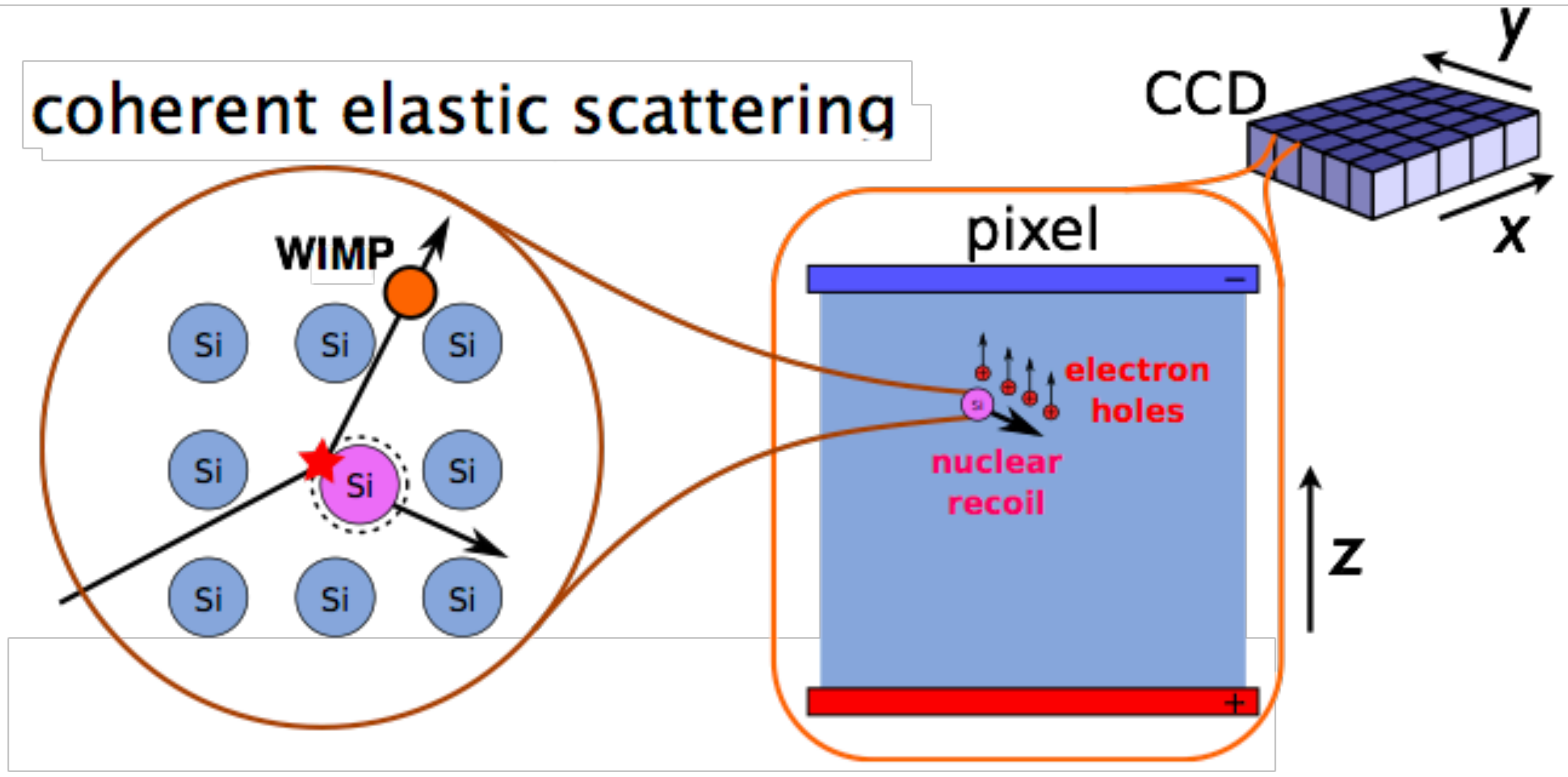
- loss of PID
- needs careful energy calib.



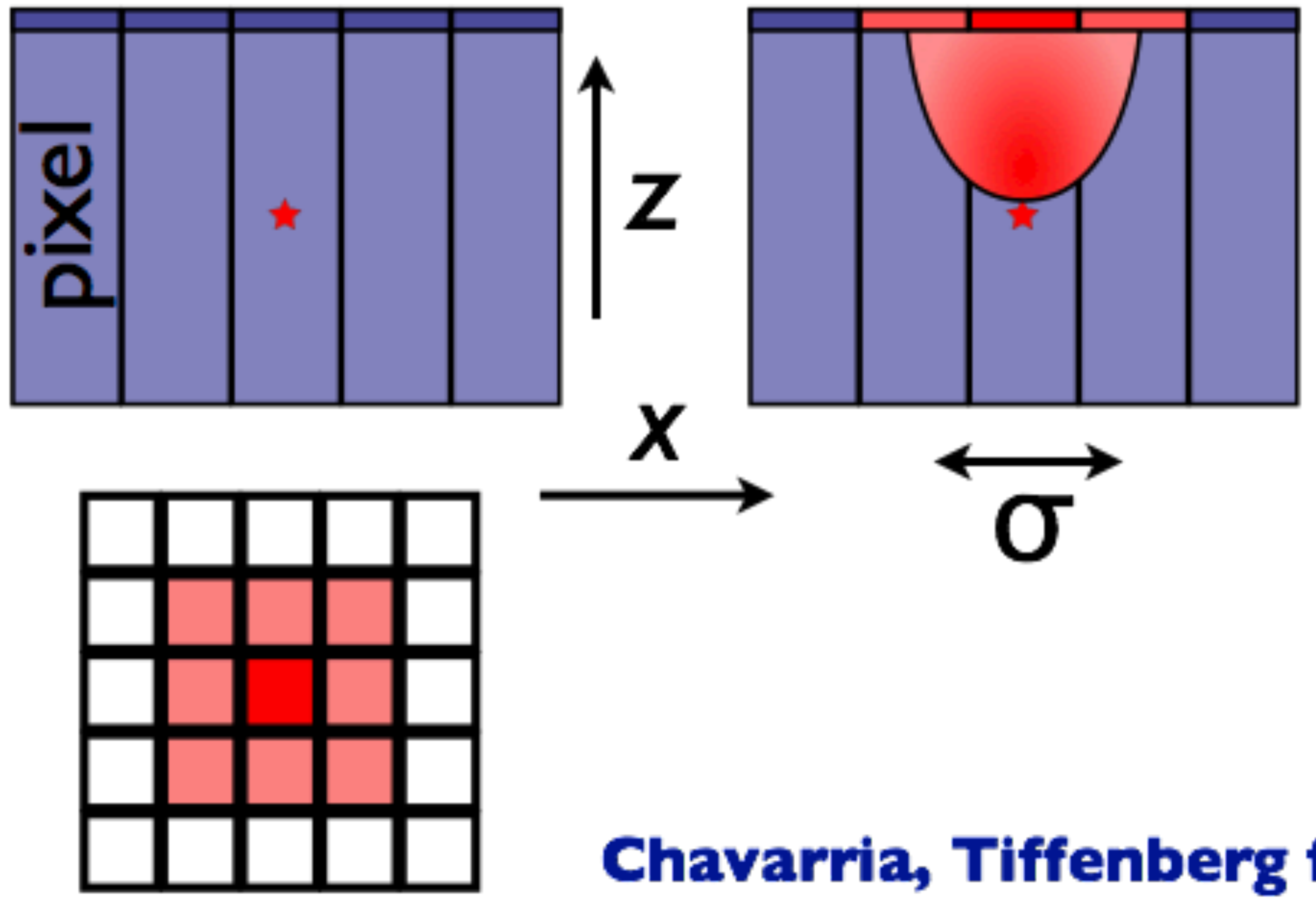
PRL 116, 071301 (2016)

Slides by Klaus Eitel

CCDs as dark matter detectors



The **interaction** of a DM particle in the target (nucleus or **electron**) leads to **ionization**, 3.6 eV/e–h pair
Si band gap: 1.2 eV



Charge carriers are **drifted** along z direction and collected at CCD gates

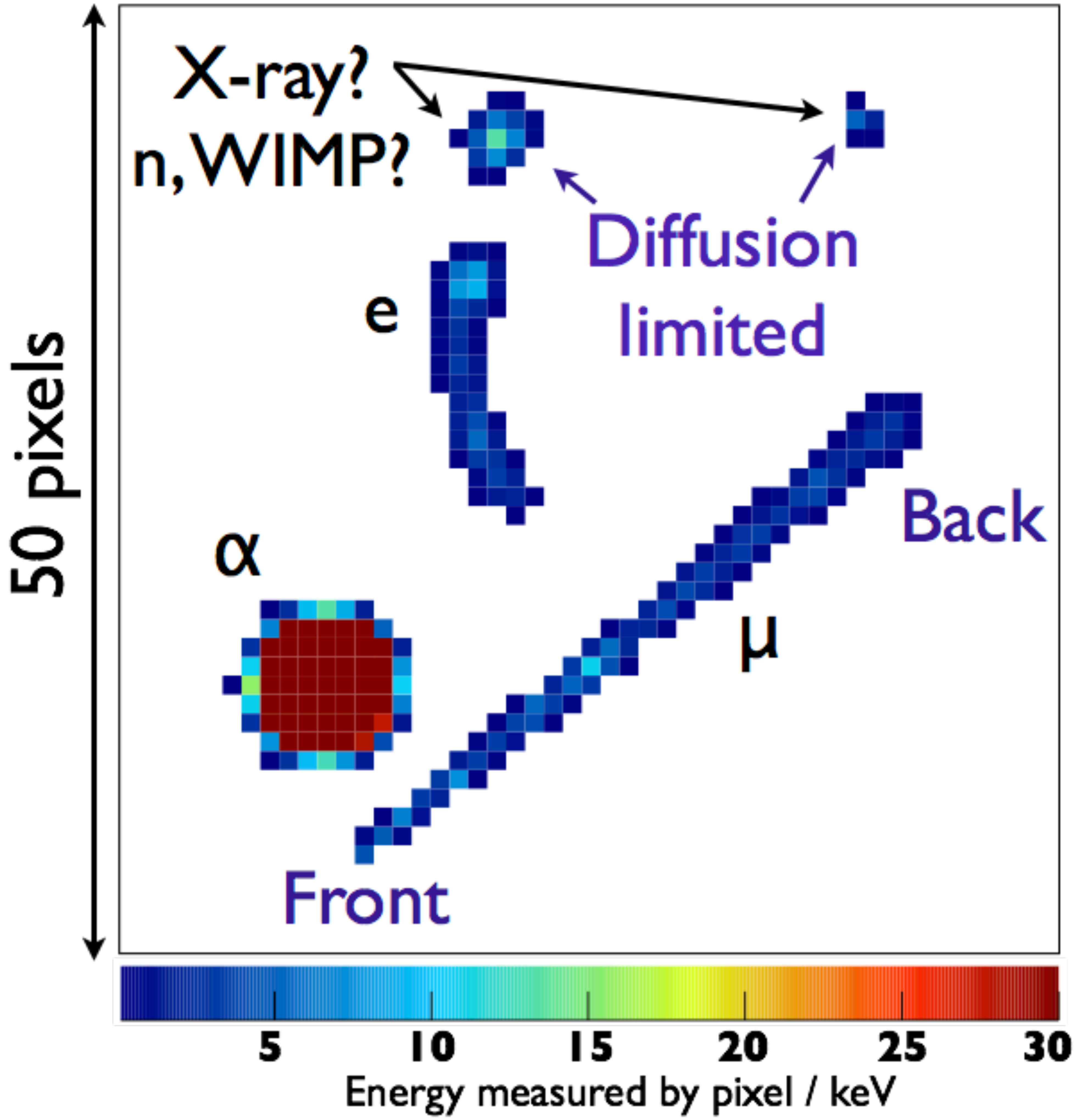
Charge **diffuses** as it travels

We fit to the radial spread of the cluster to estimate its **position in z** within the CCD bulk

Chavarria, Tiffenberg for Damic Collab., Phys. Procedia, 2014

x

Particles detected (at ground level)



Low energy electrons and nuclear recoils: **diffusion limited clusters**

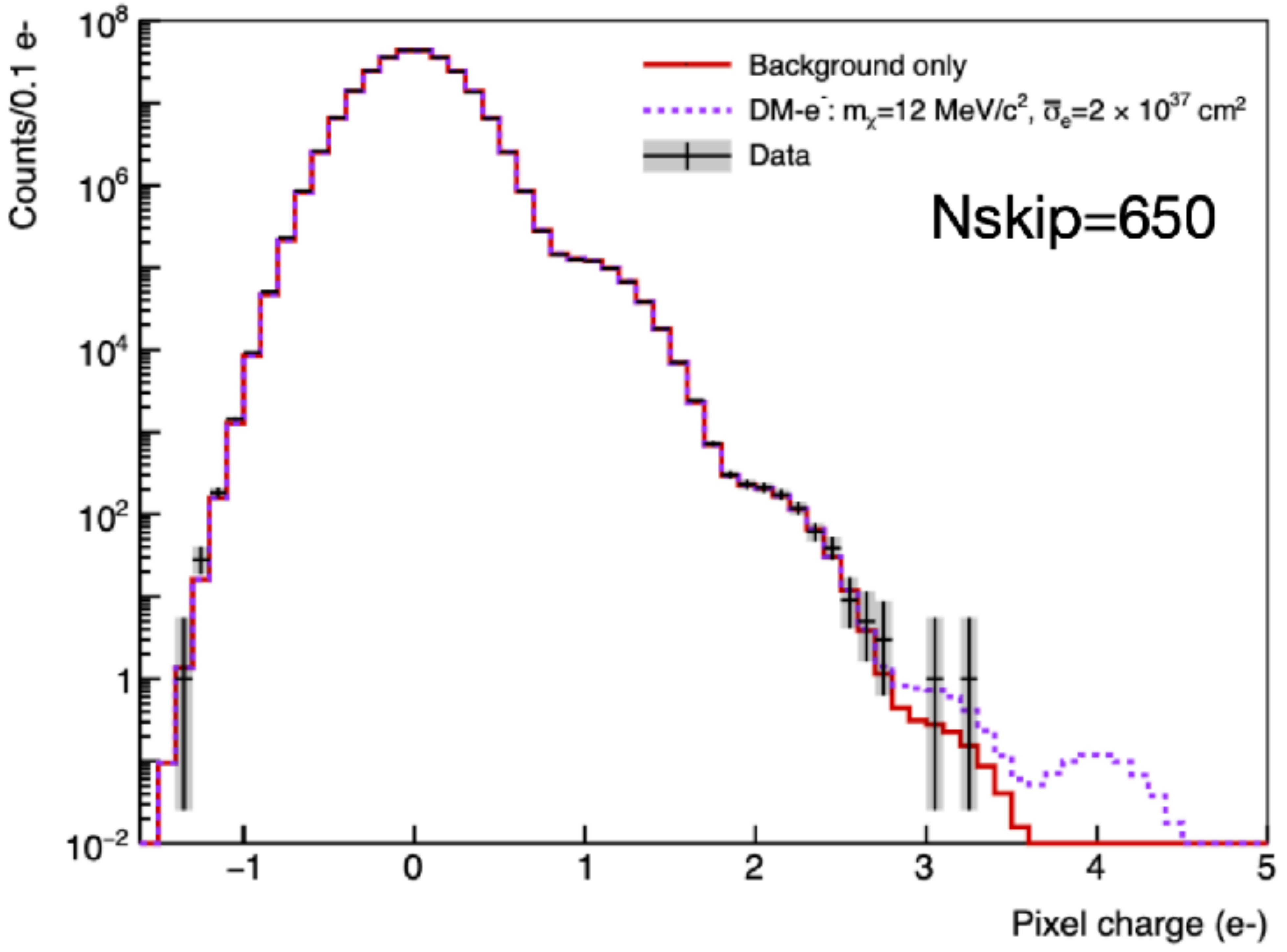
(their spatial extension is dominated by charge diffusion)

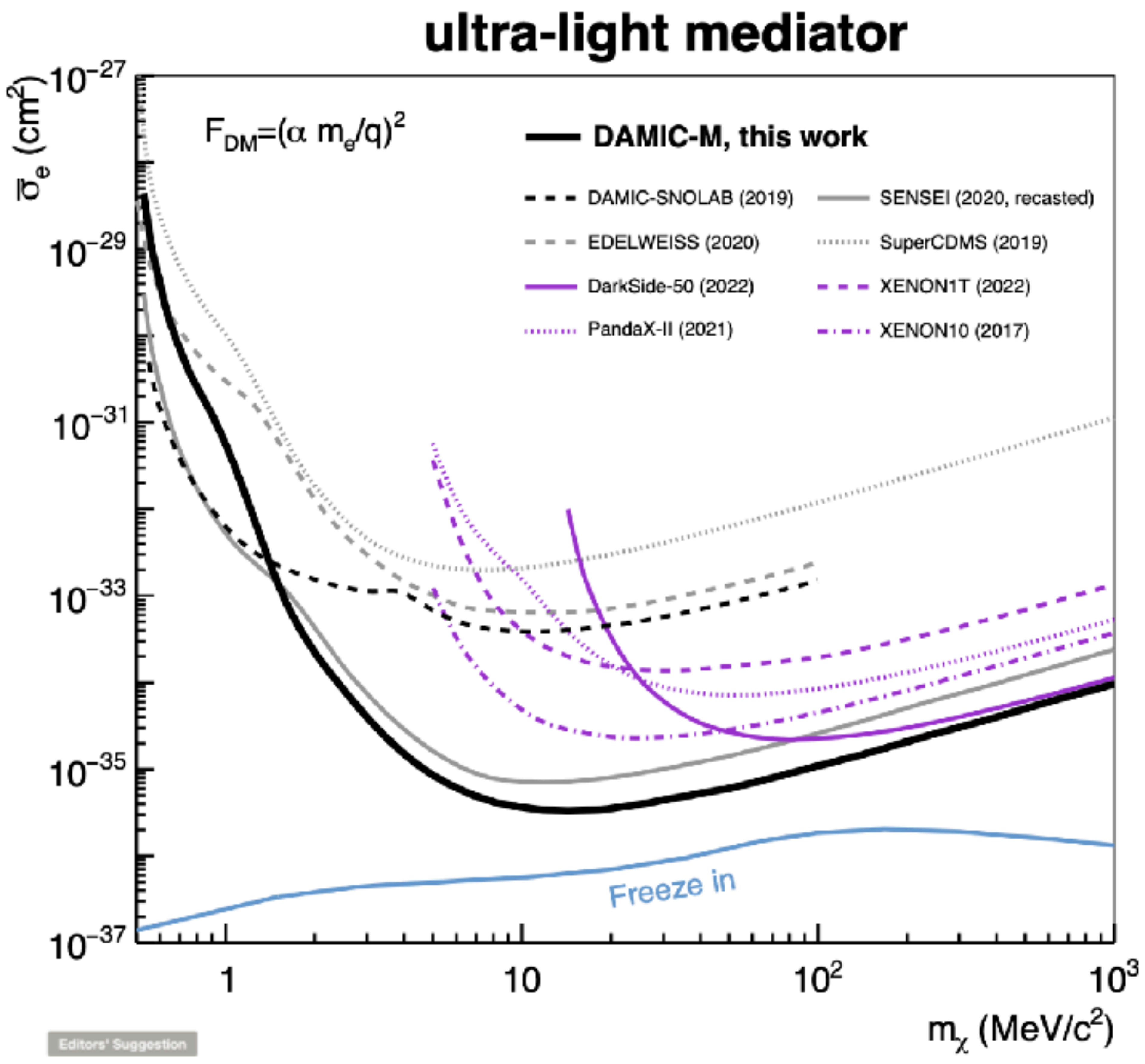
Higher energy **electrons** (Compton, β decay): extended tracks

α particles in the bulk or from the back: large round structures

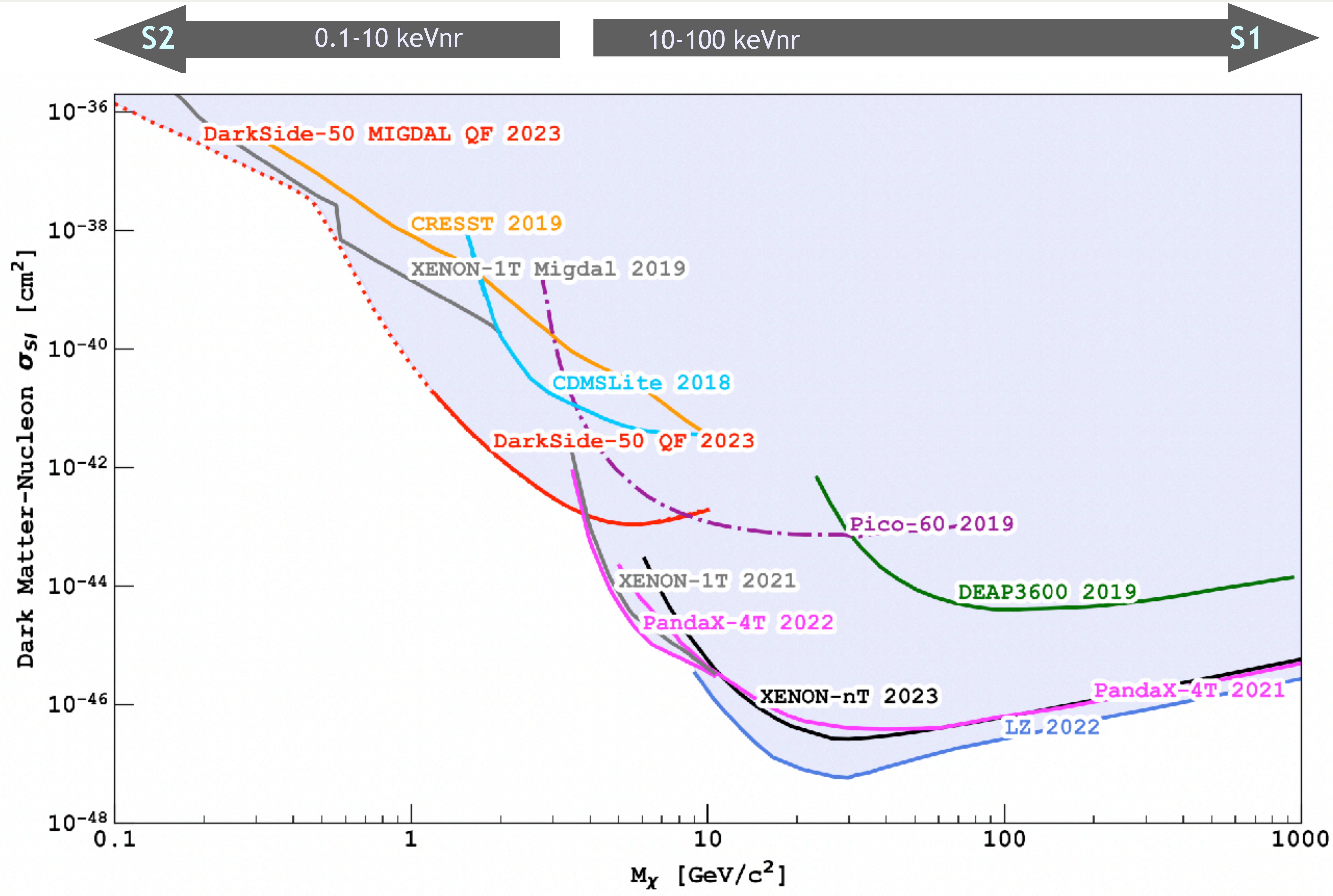
cosmic **muons**: orientation of the track is evident

CCD camera: DAMIC-M

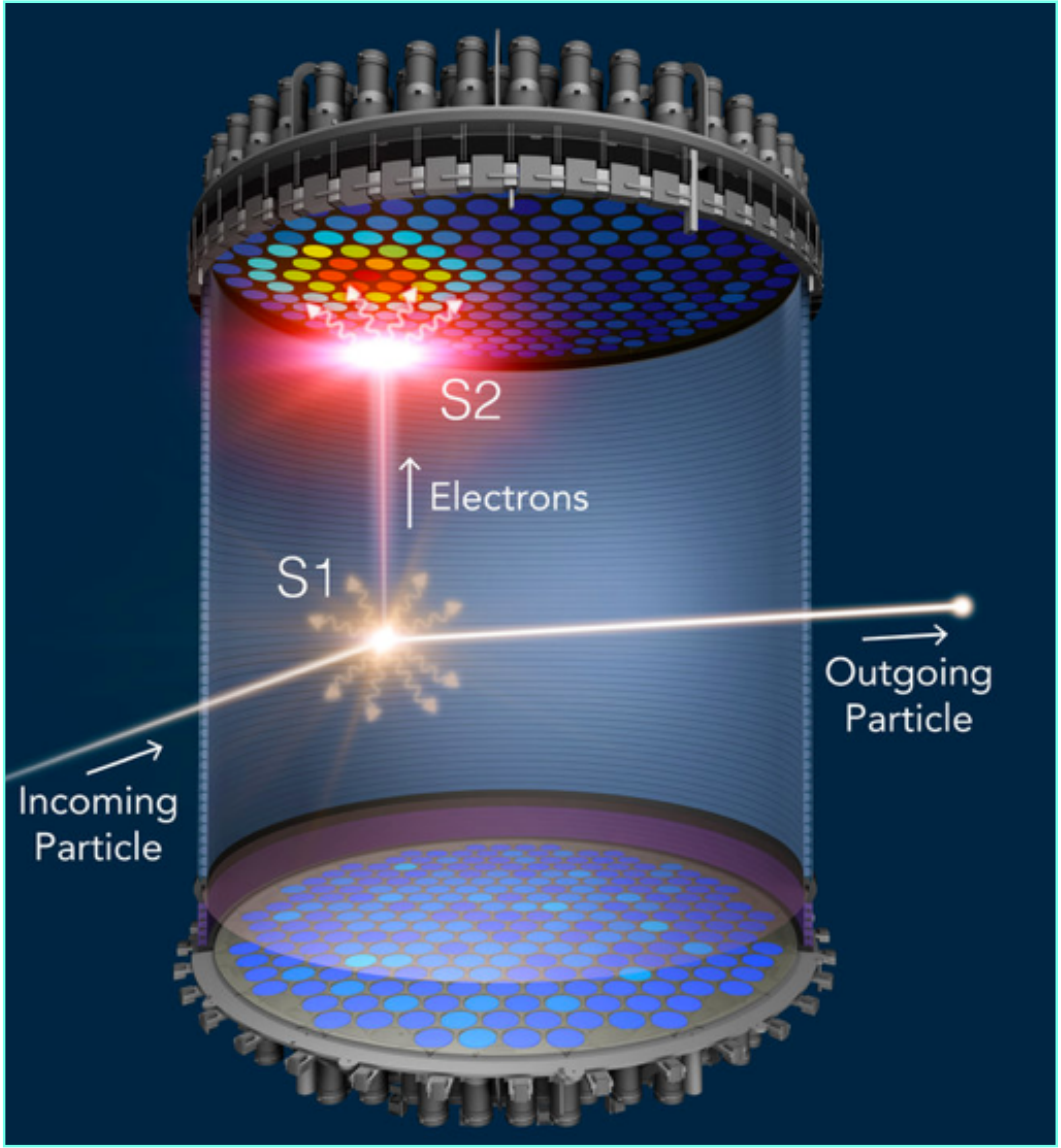




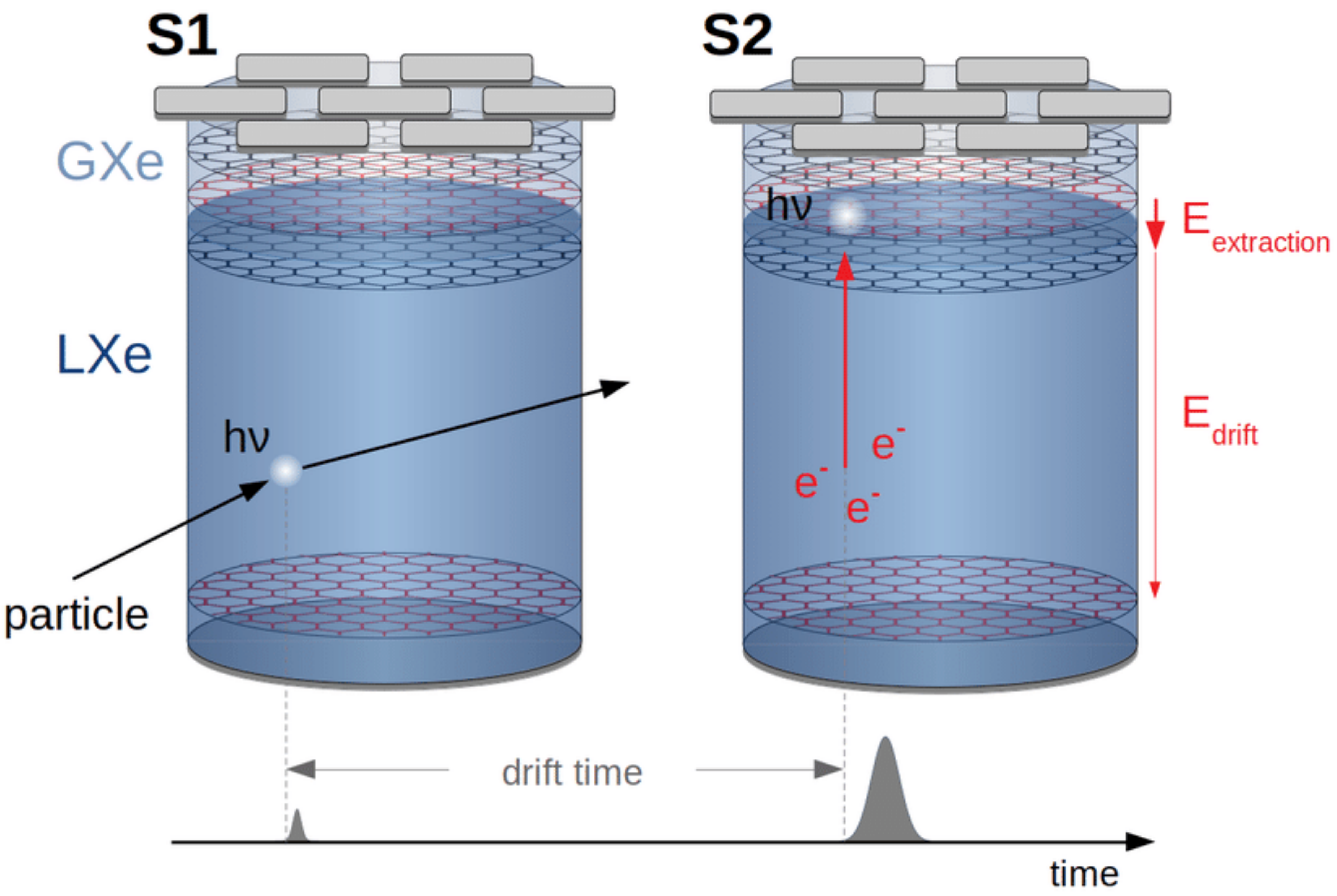
Why looking at very low-mass WIMPs?



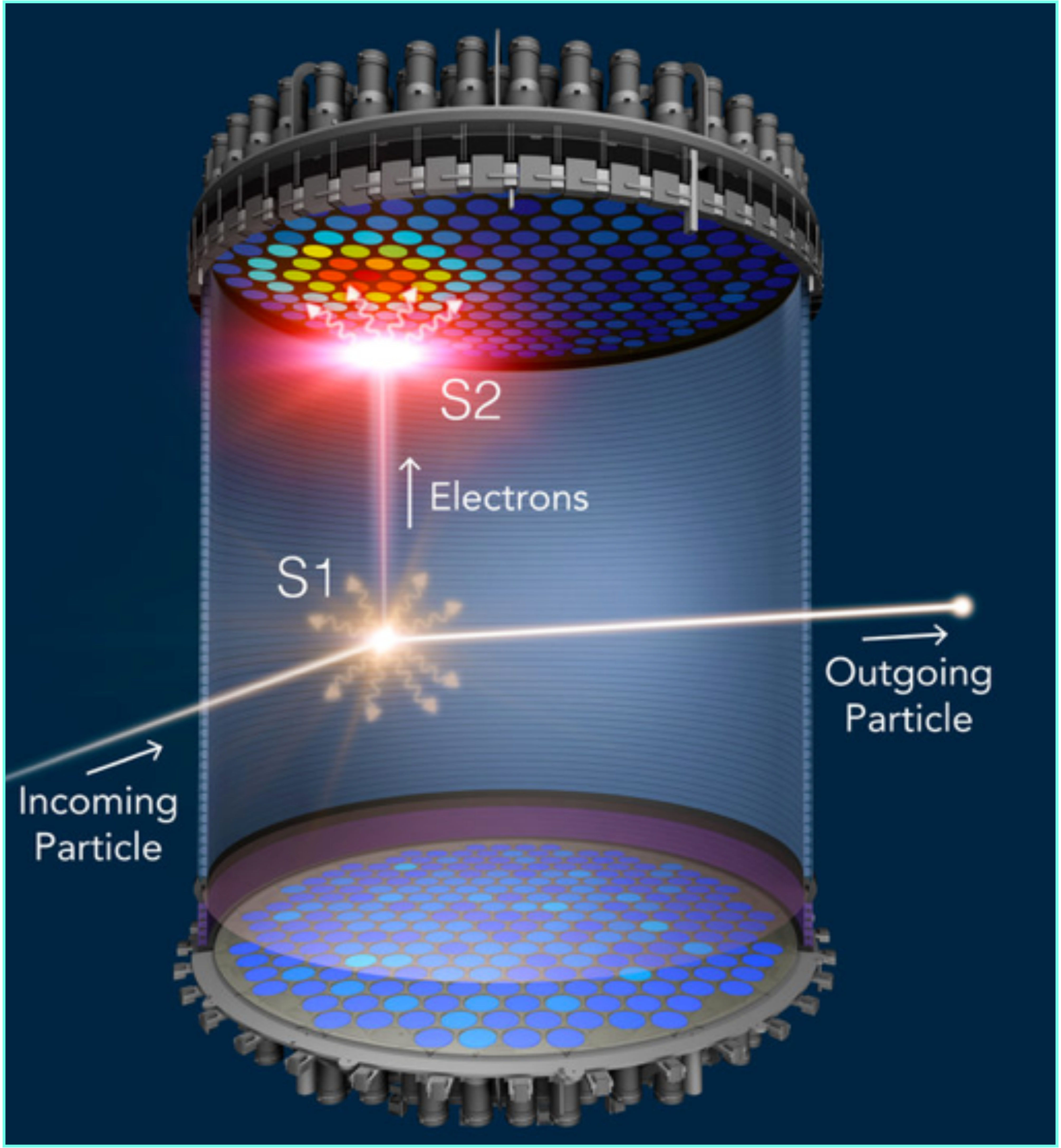
Dual-Phase Time Projection Chambers



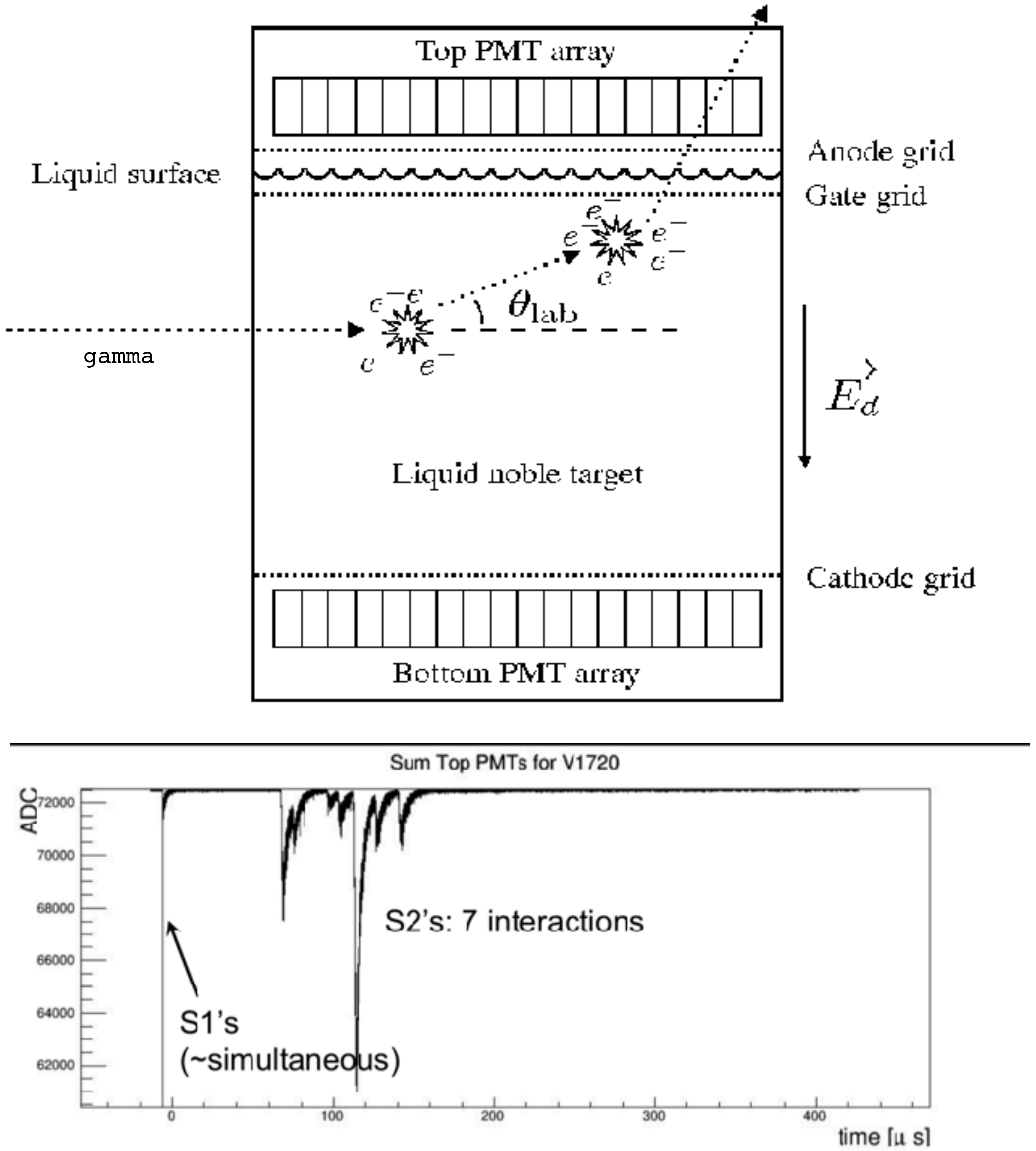
Excellent topology reconstruction



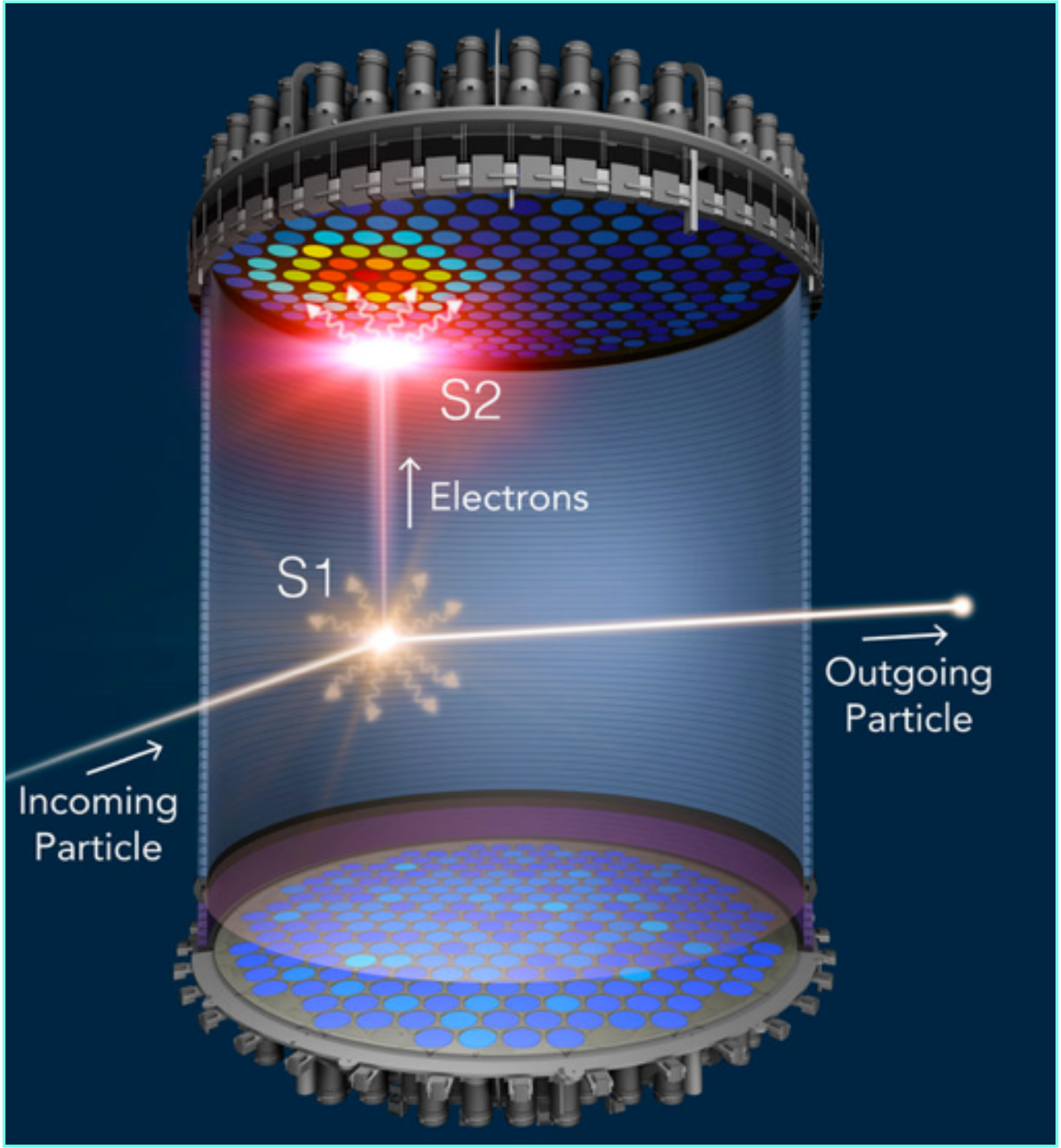
Dual-Phase Time Projection Chambers



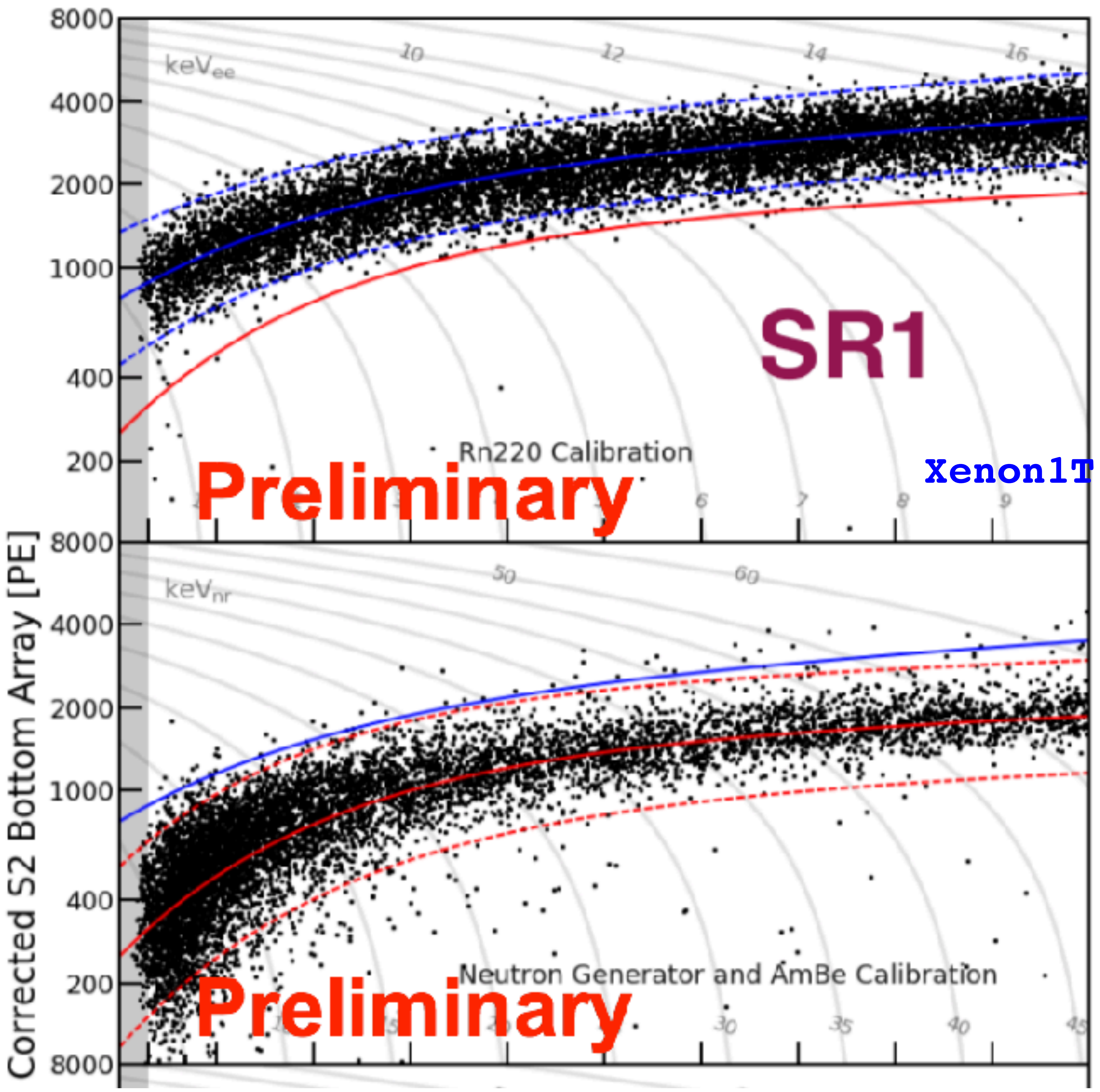
Rejection of multiple scattering particles



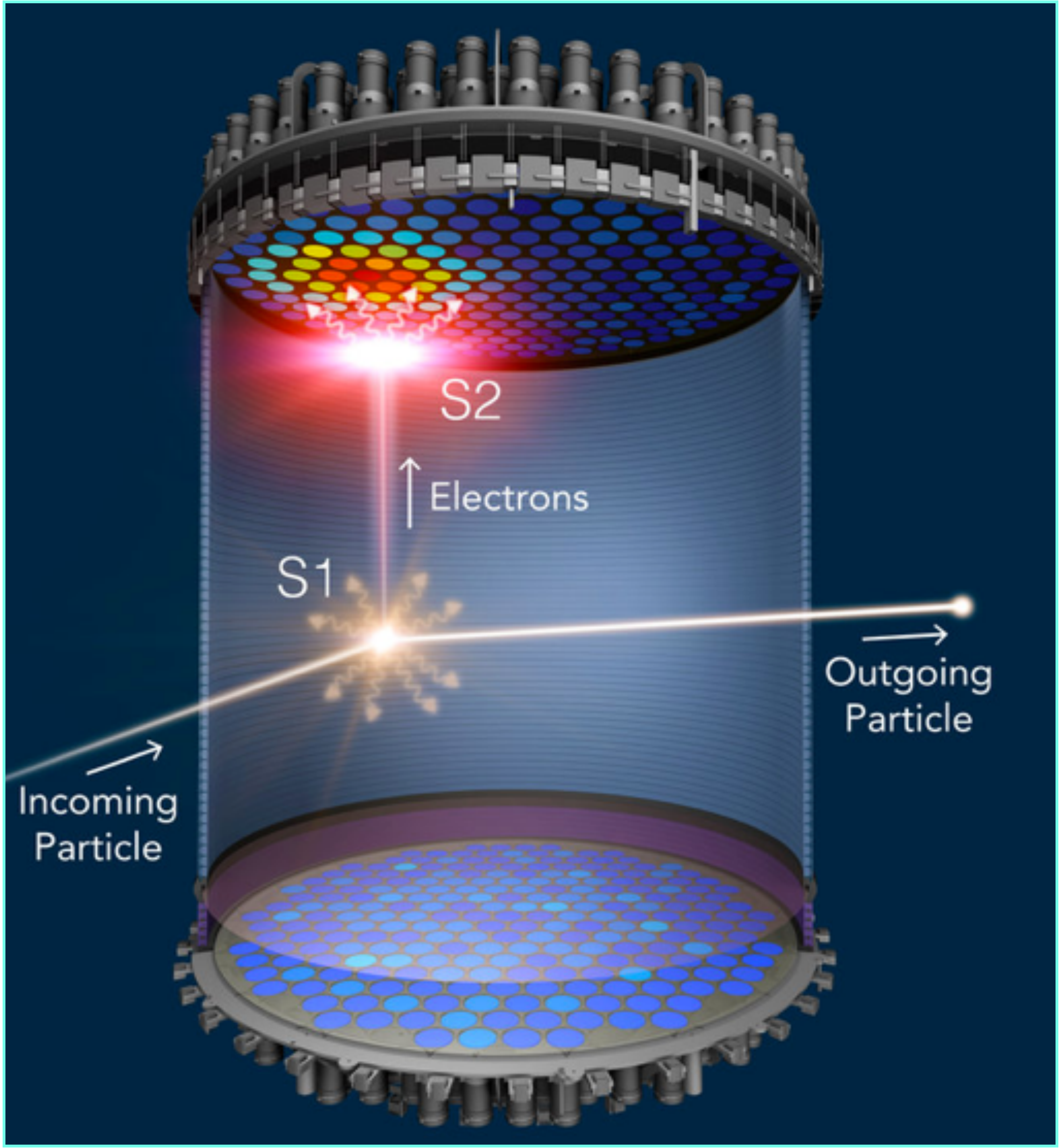
Dual-Phase Time Projection Chambers



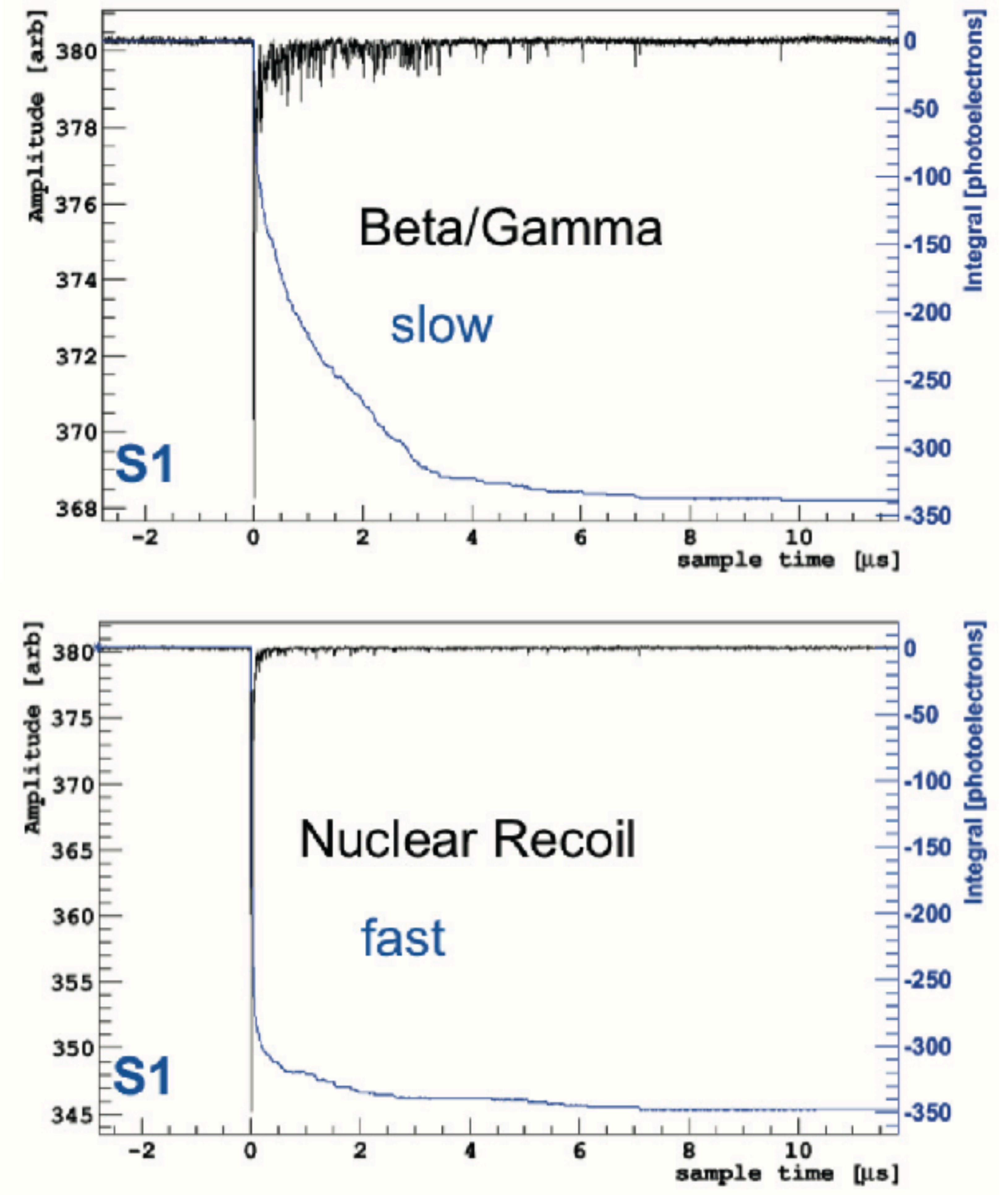
Electron to nuclear recoil discrimination



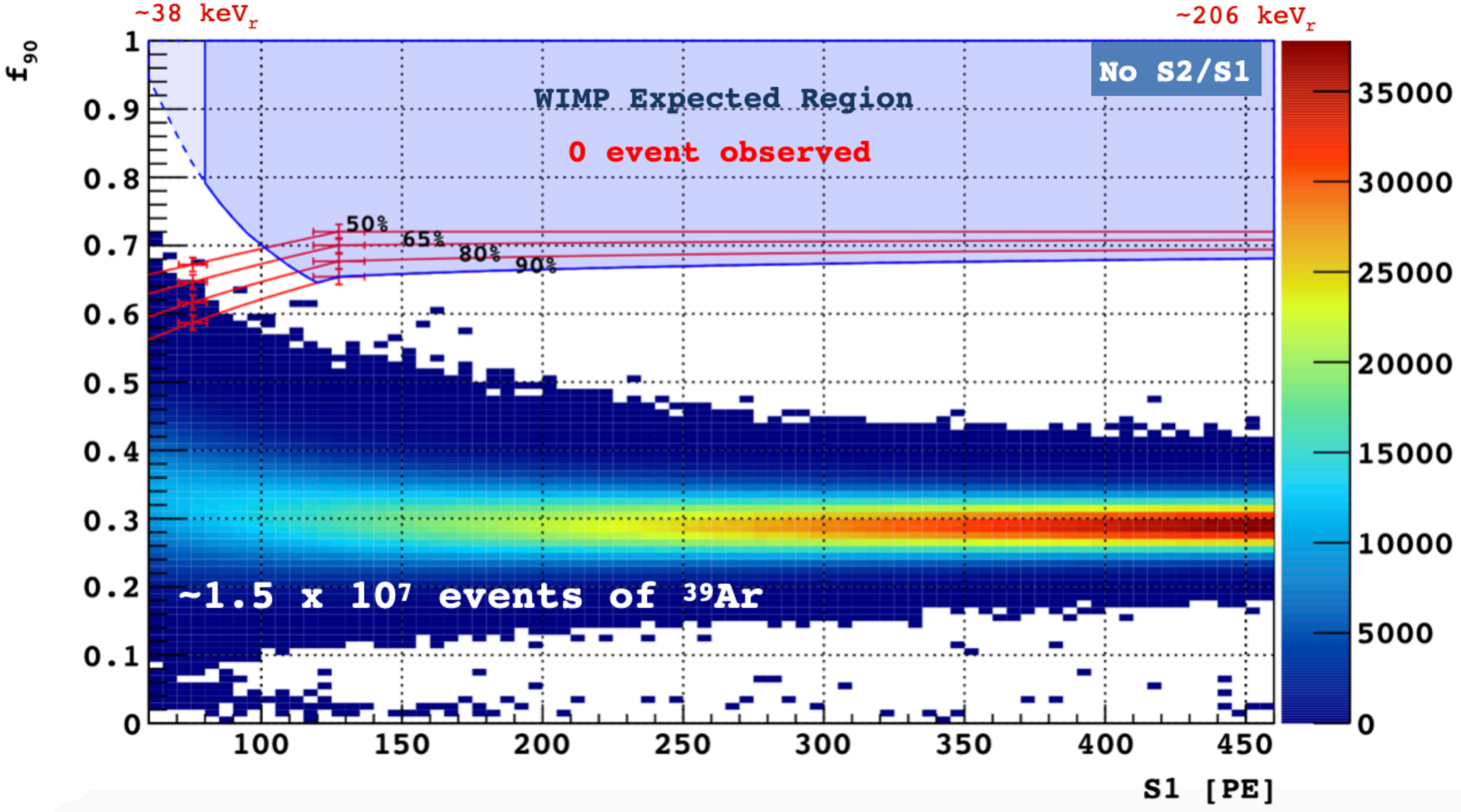
Dual-Phase Time Projection Chambers



Liquid Argon



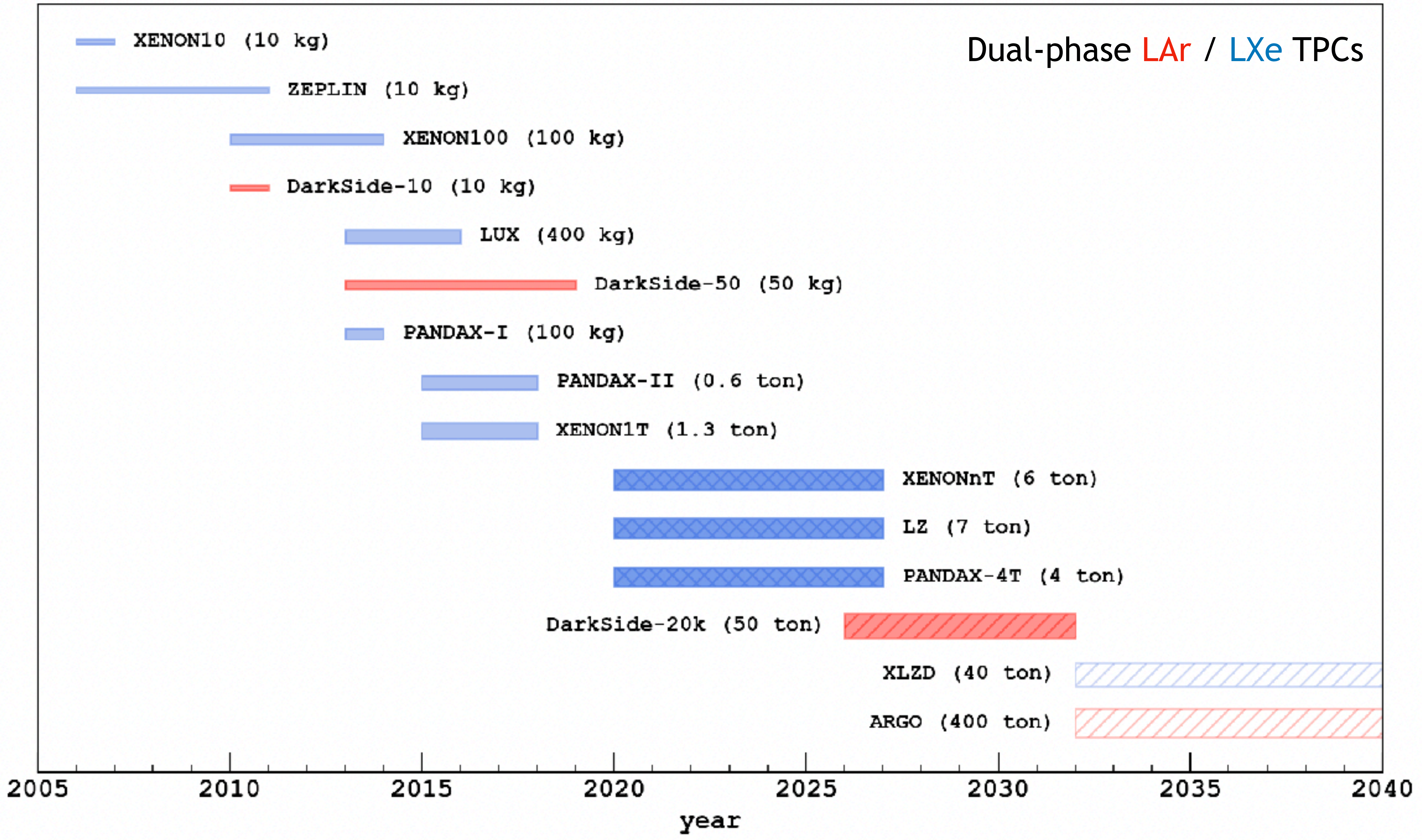
Grâce à la discrimination basée sur la forme de l'impulsion de scintillation, il est possible d'**identifier une interaction nucléaire parmi 100 millions d'interactions électroniques.**



Dual-Phase Noble Liquid TPCs for Dark Matter Search

Noble Liquids

- **Noble**
  => no radiochemical impurities
- **Scalable**
  => O(10-100 ton)
- High **scintillation** yield (x 4 organic scintillator)
  => high resolution
- Excellent particle **identification**
  => background suppression
- High **ionization** yield
  => very low energy thresholds
- Low electron **diffusion** and mobility
  => accurate event topology in a TPC

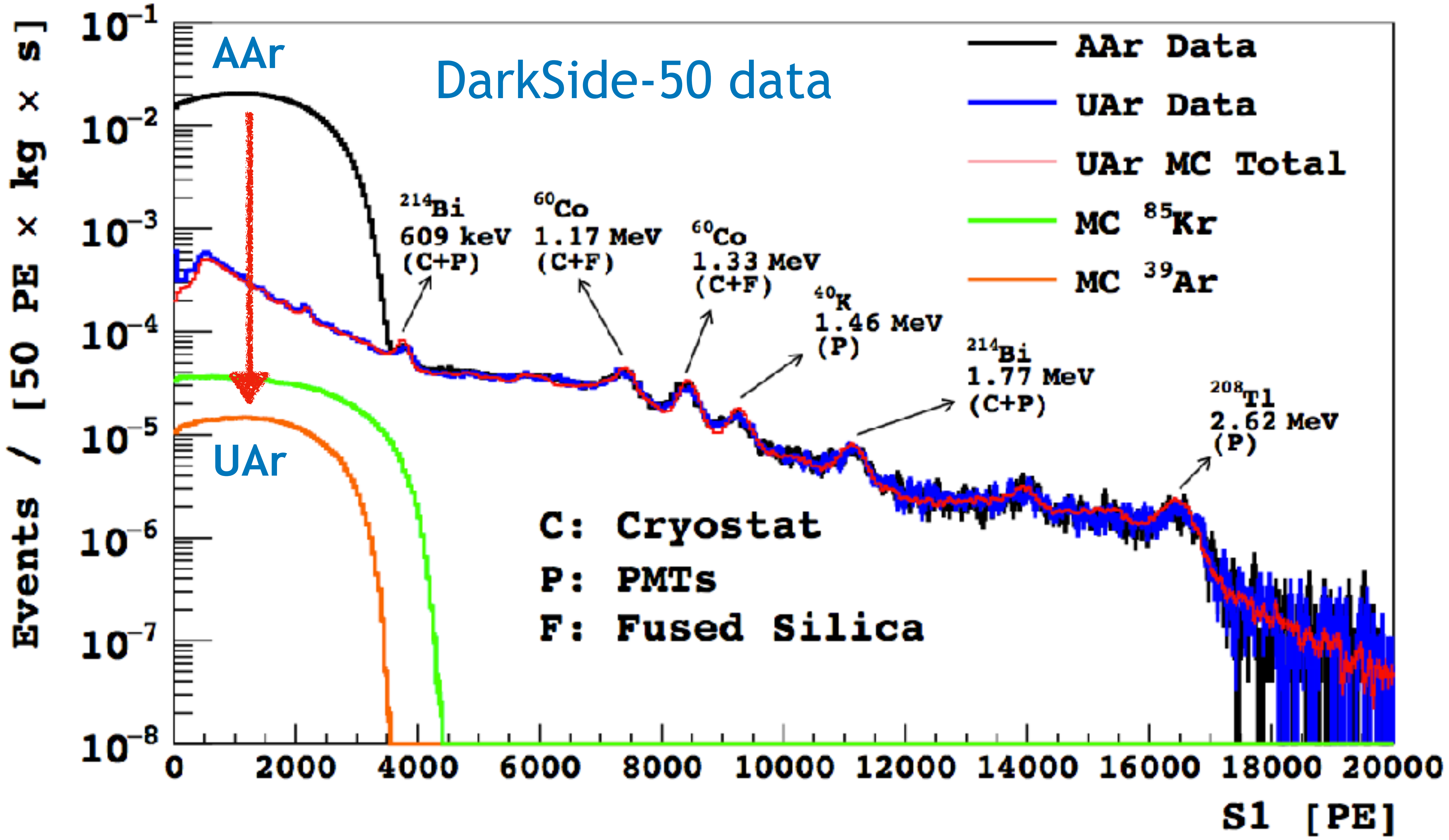


Noble Liquids: Xenon vs Argon

	LAr	LXe
WIMP SI cross section	**Limited to large masses (M_χ > 10 GeV)**	**Sensitive also to low masses**
WIMP SD cross section	**Not accessible**	**Accessible**
Radio-purity	^{39}Ar contamination	**Intrinsically pure**
Density	1.4 g/cm^3	**3.1 g/cm^3**
Temperature	**87.2 K** (close to nitrogen)	166.4 K
S1 Pulse Shape Discrimination	**Yes (singlet ~7 ns; triplet ~1600 ns)**	Very limited (singlet: ~2 ns; triplet: ~27 ns)
Cost and availability	**Generically cheap** (~$/kg) + **extra costs** for underground extraction **Abundant**	**Expensive** (~kDollar/kg) **Limited** world production

Why ~~not~~ liquid argon?

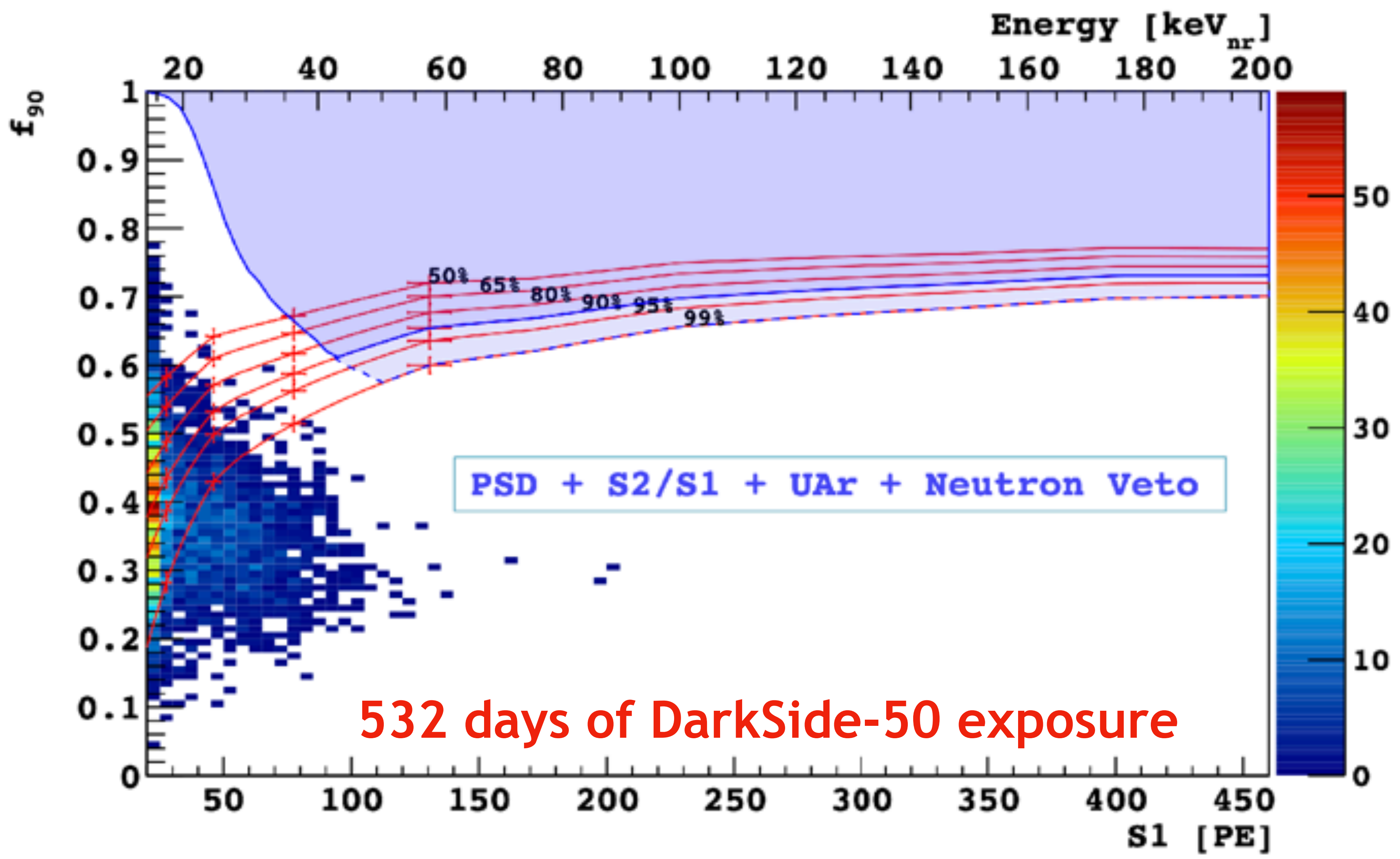
Underground Argon



^{39}Ar reduction factor in UAr: ~1400

Cosmogenic ^{39}Ar in **atmospheric argon** is the primary background (~1 Bq / kg)

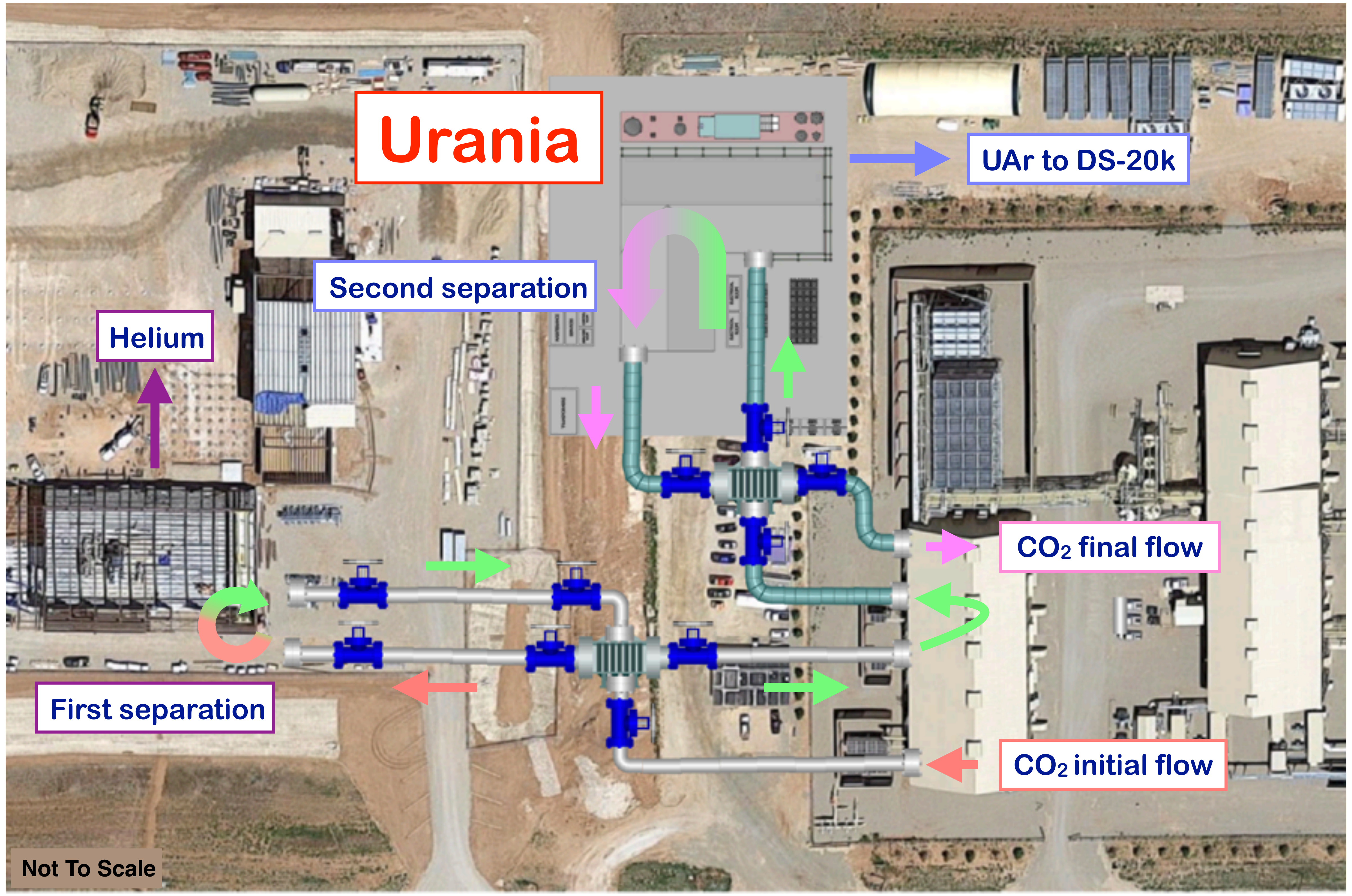
Argon extracted from deep underground is naturally shielded against cosmic rays



URANIA

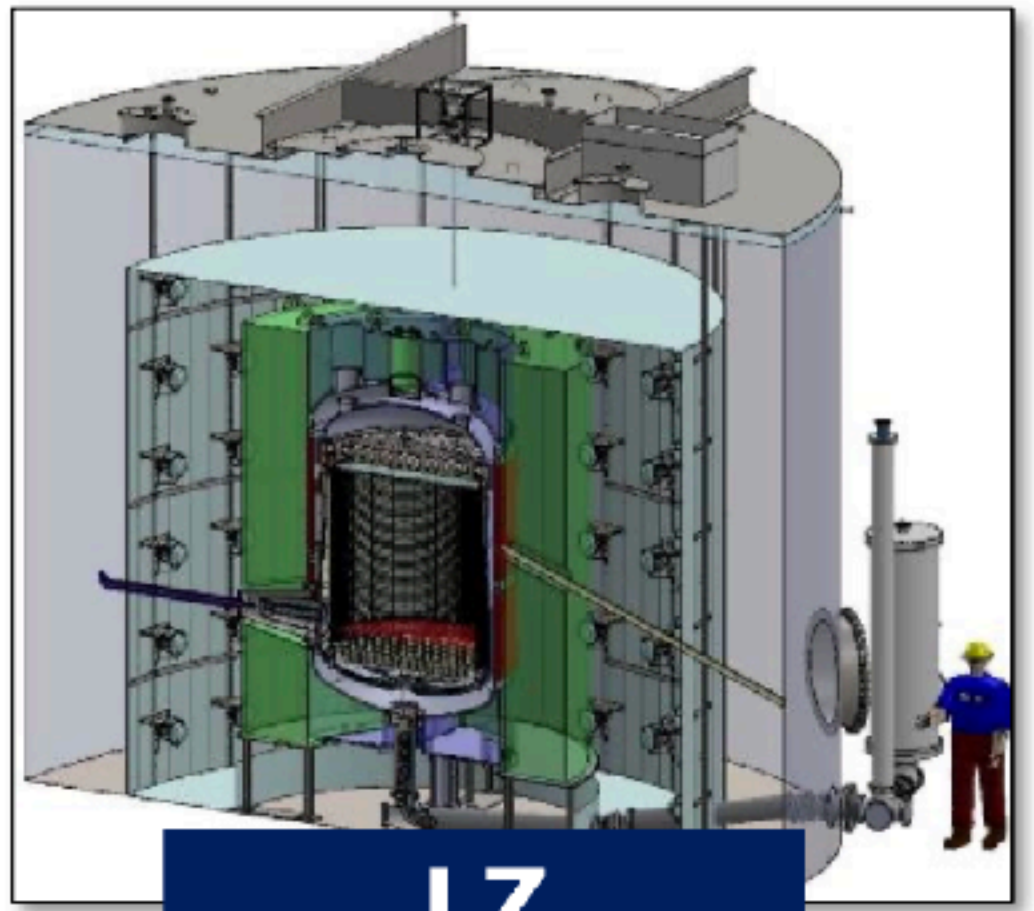
Expansion de l'usine à échelle industrielle à Cortez, pour atteindre une capacité de 250 kg/jour d'argon souterrain

Pureté initiale : 99,99%



- **Multi-tonne scale xenon experiments**

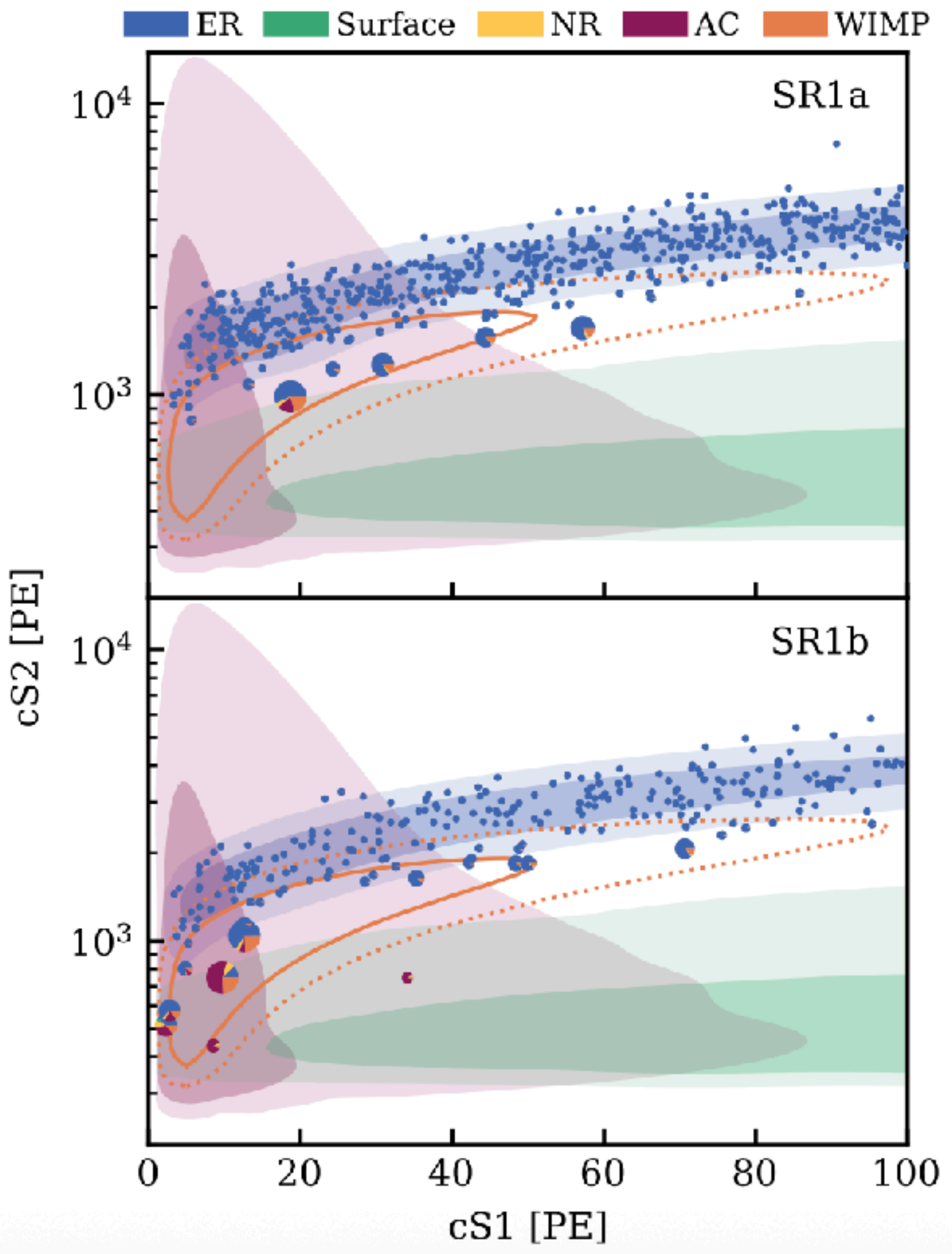
Experiment	Sensitive Volume	Fiducial Volume	Expected exposure	Expected Sensitivity
PandaX-4T	4 tonne	2.8 ton	5 tonne-year	10^{-47} cm^2
XENONnT	6 tonne	5 ton	20 tonne-year	2×10^{-48} cm^2
LZ	7 tonne	5.6 ton	20 tonne-year	2×10^{-48} cm^2


LZ

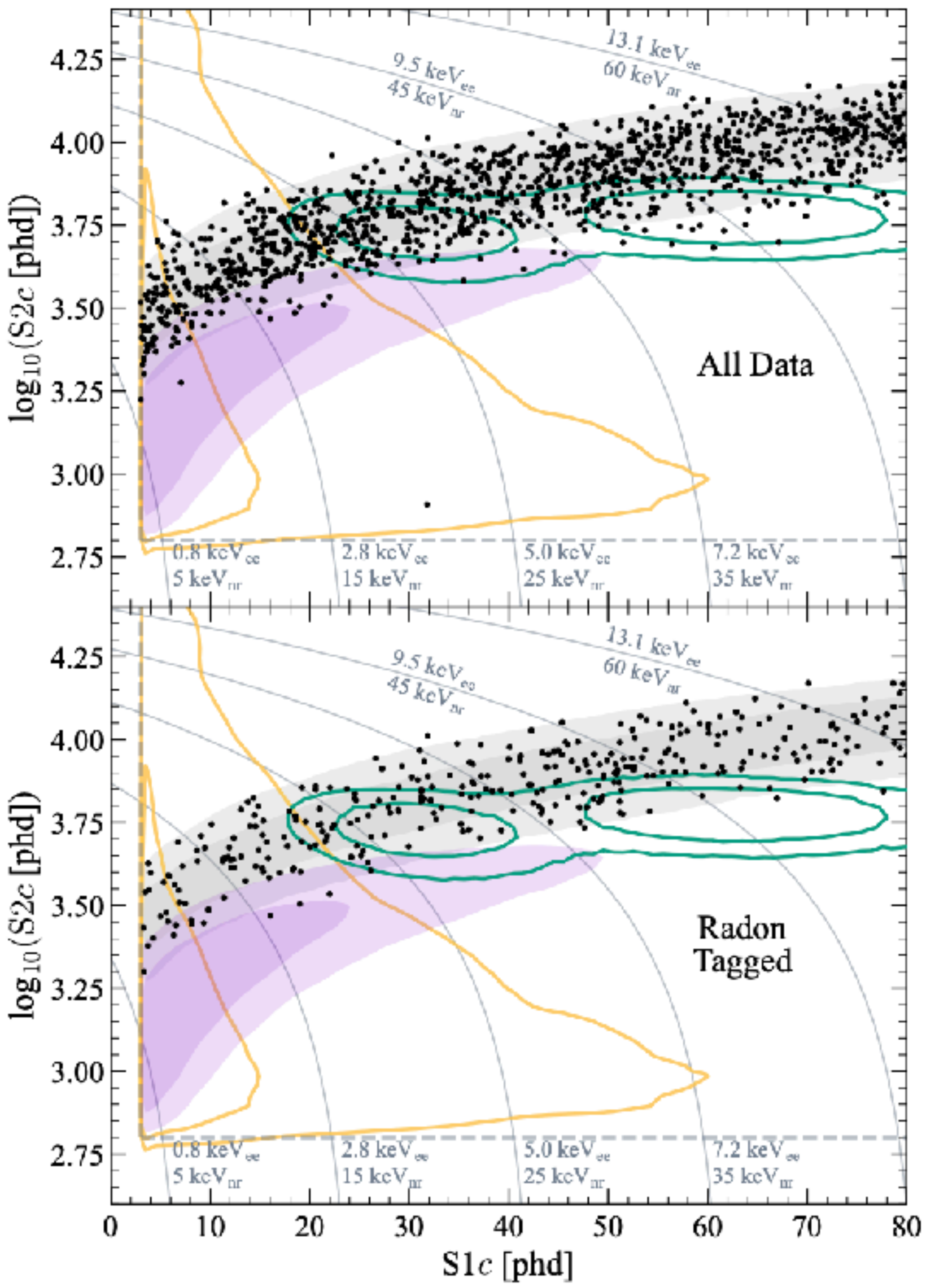

XENONnT


PandaX-4T

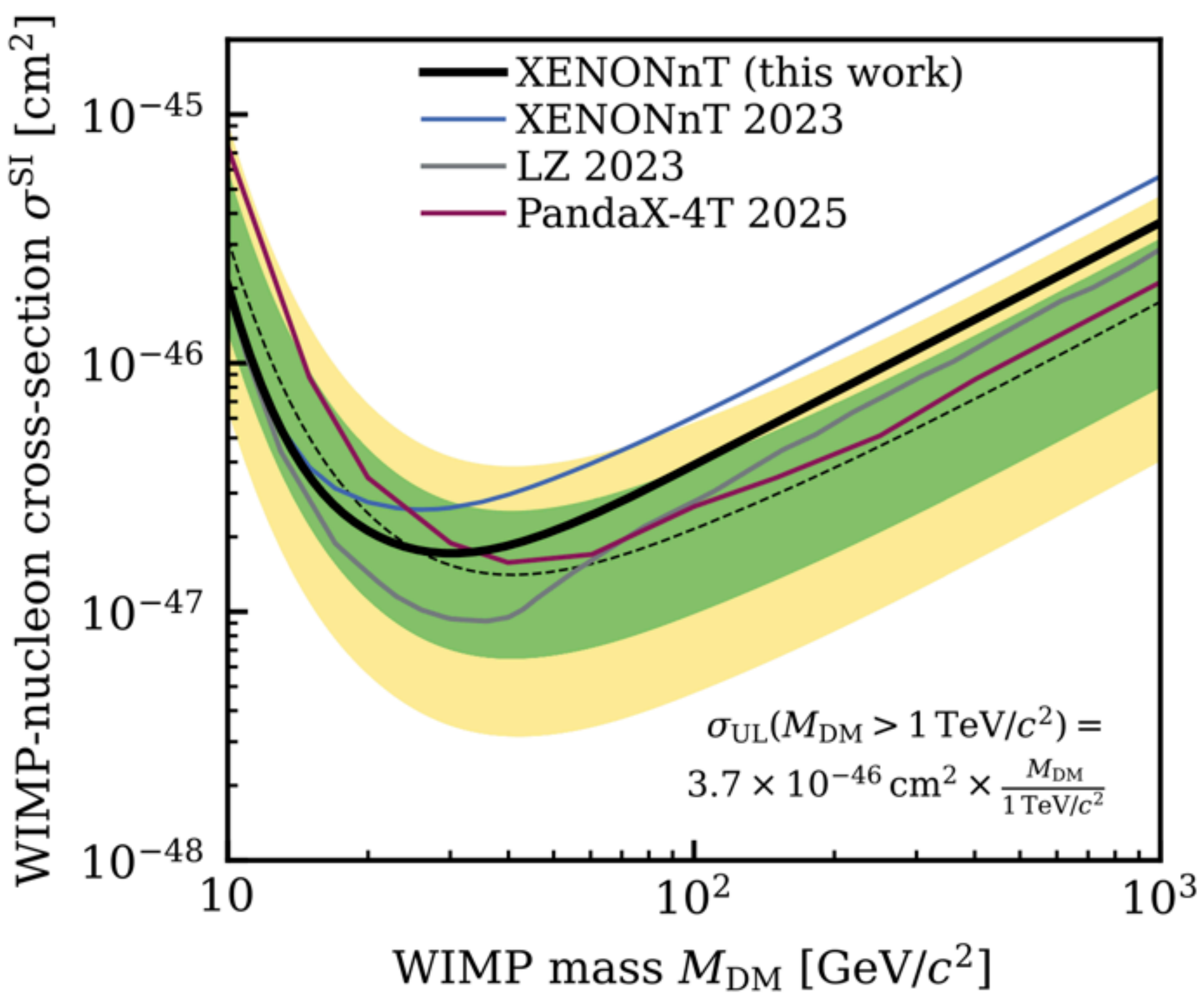
XENONnT

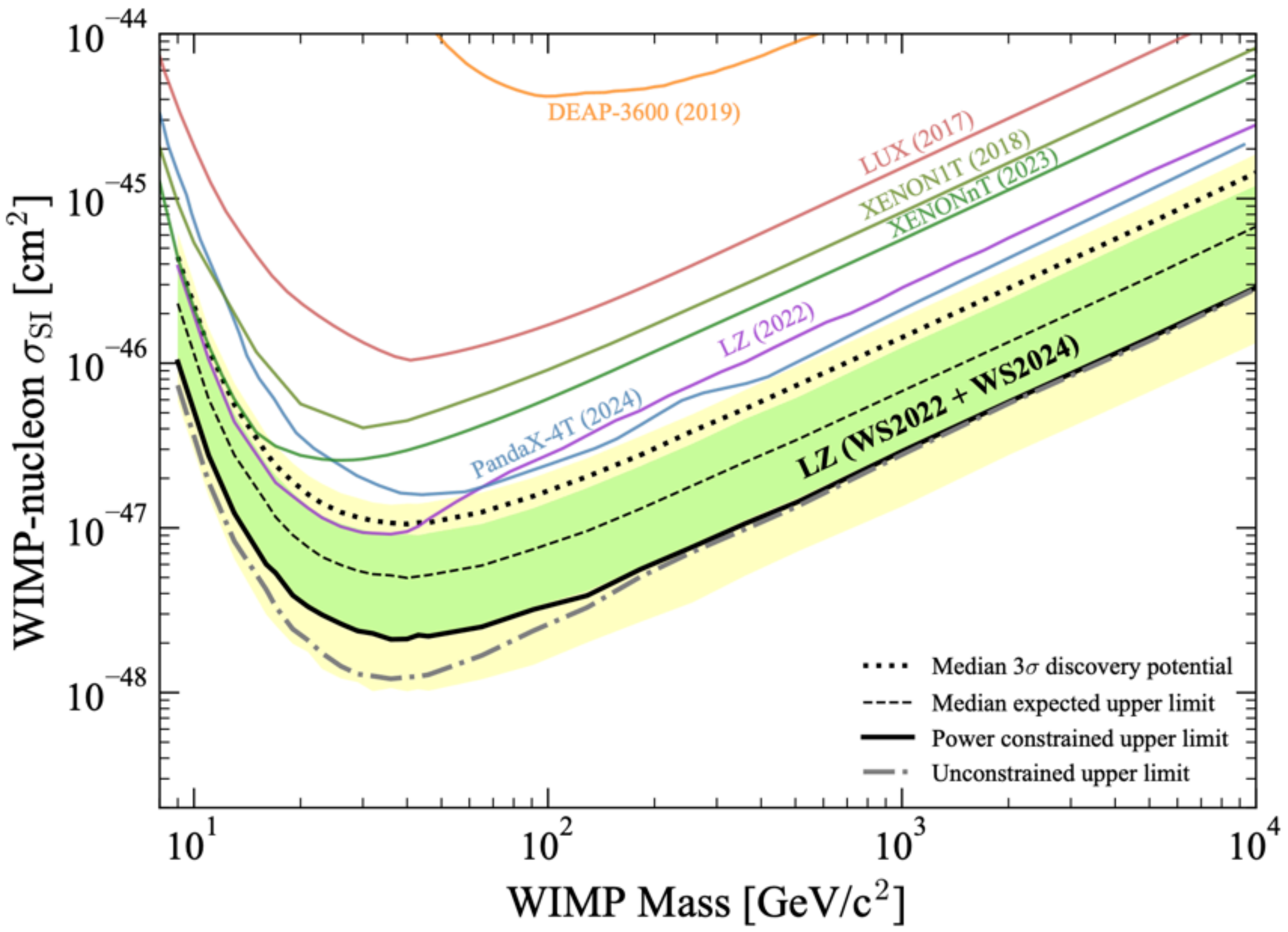

ER
Surface
NR
AC
WIMP
SR1a
SR1b
cS2 [PE]
cS1 [PE]

LZ


All Data
Radon Tagged
log10(S2c [phd])
S1c [phd]

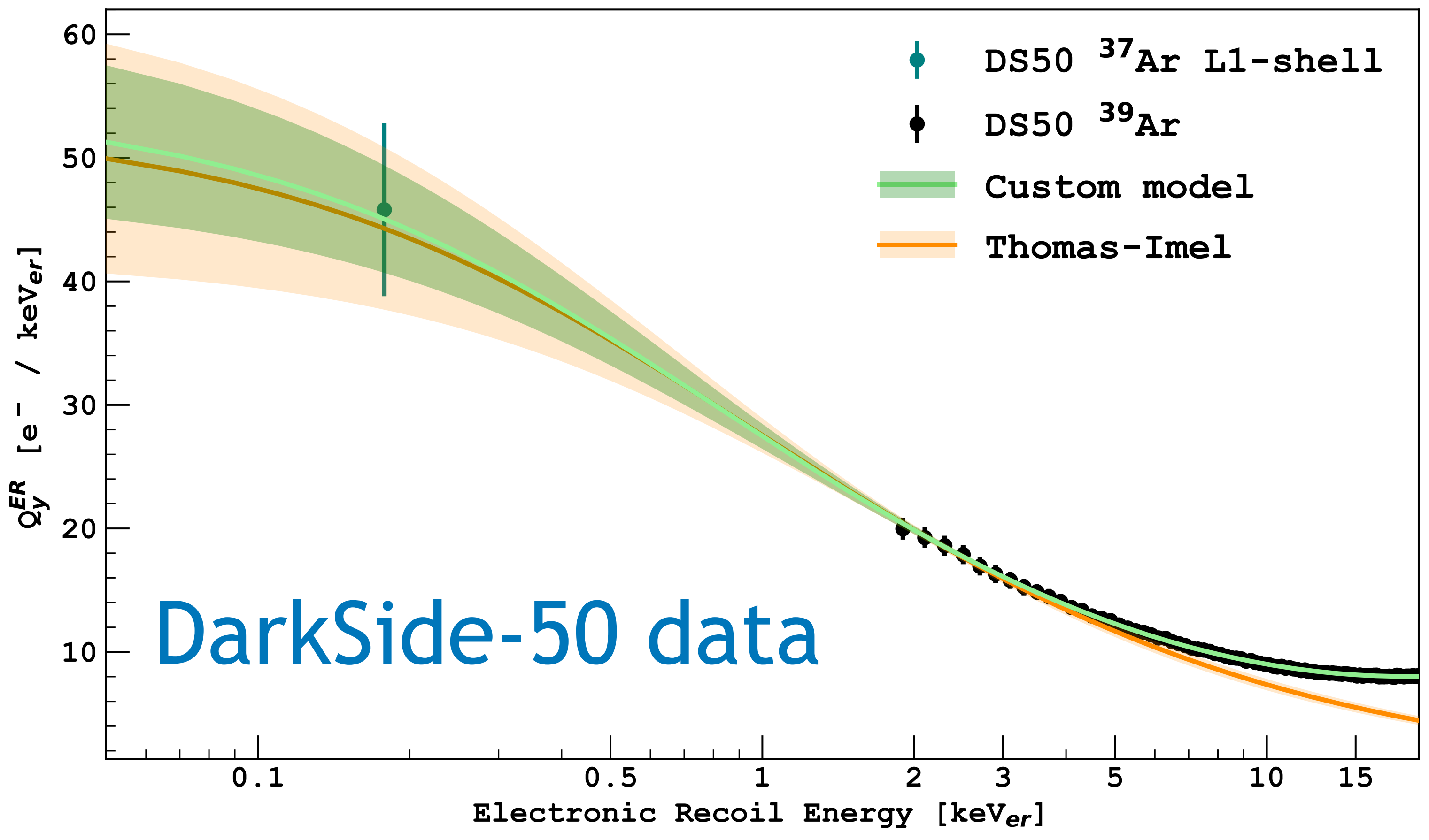
The High-Mass Sensitivity

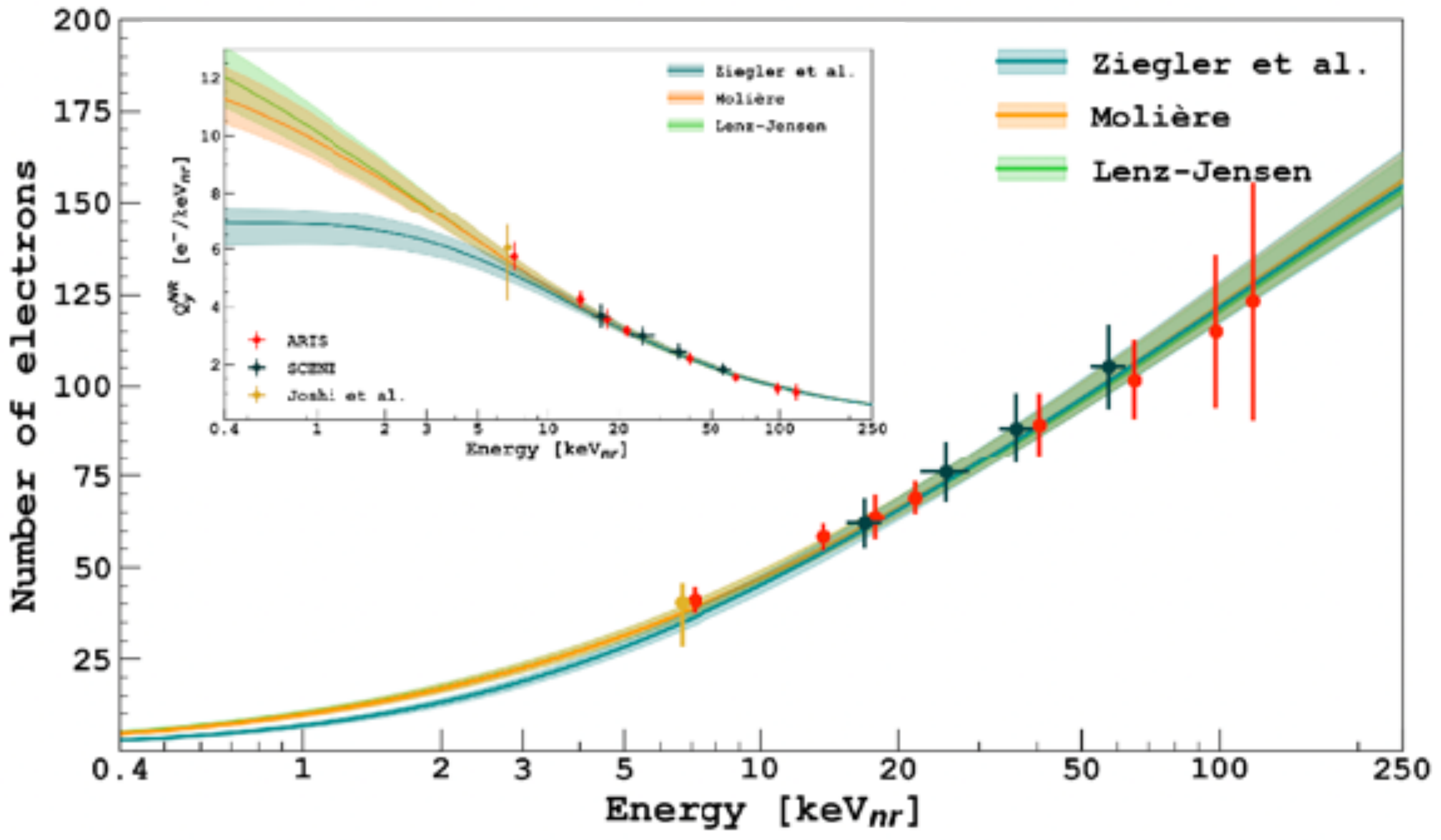




Lowering the energy threshold

Low-energy calibration





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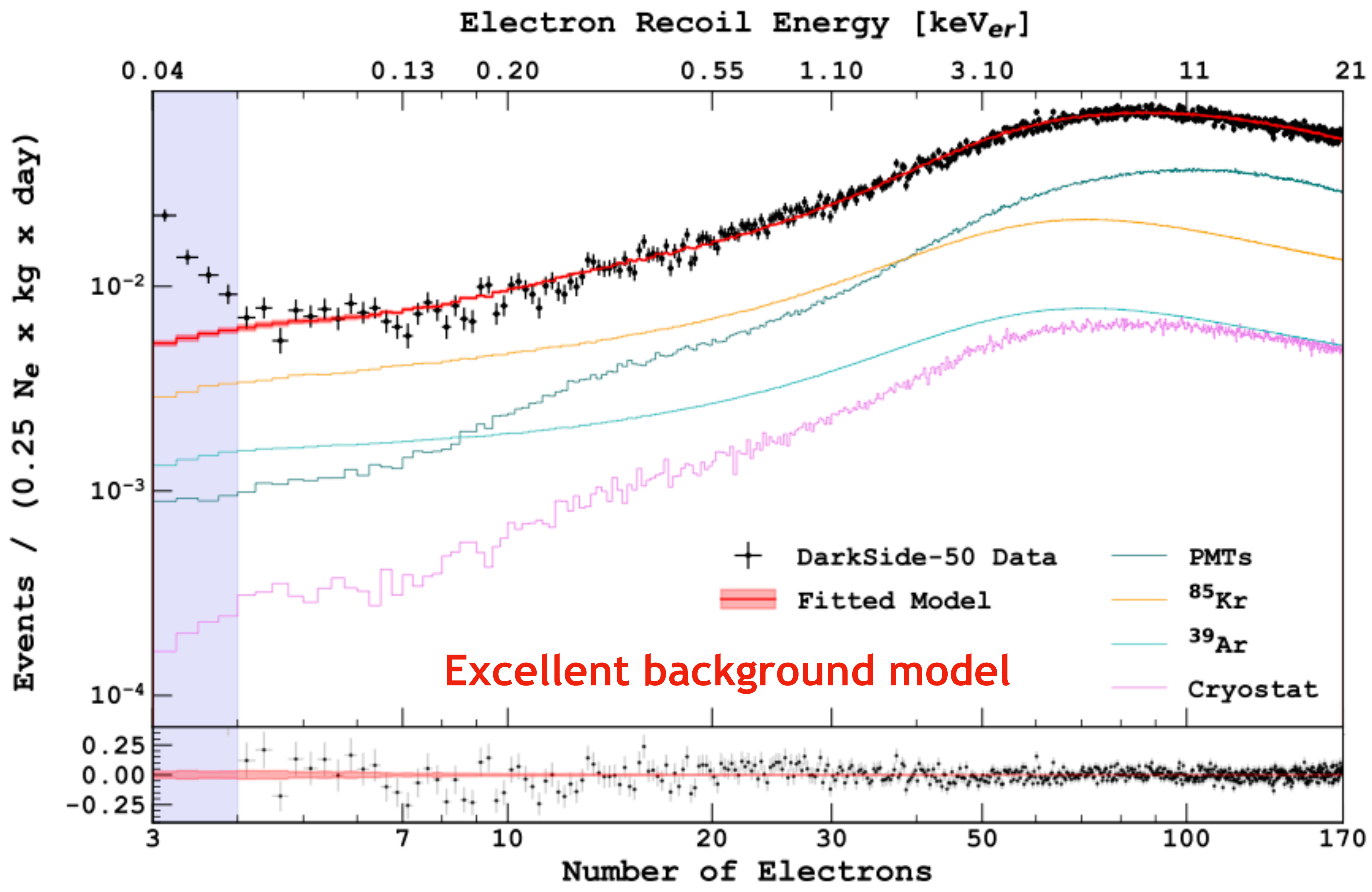
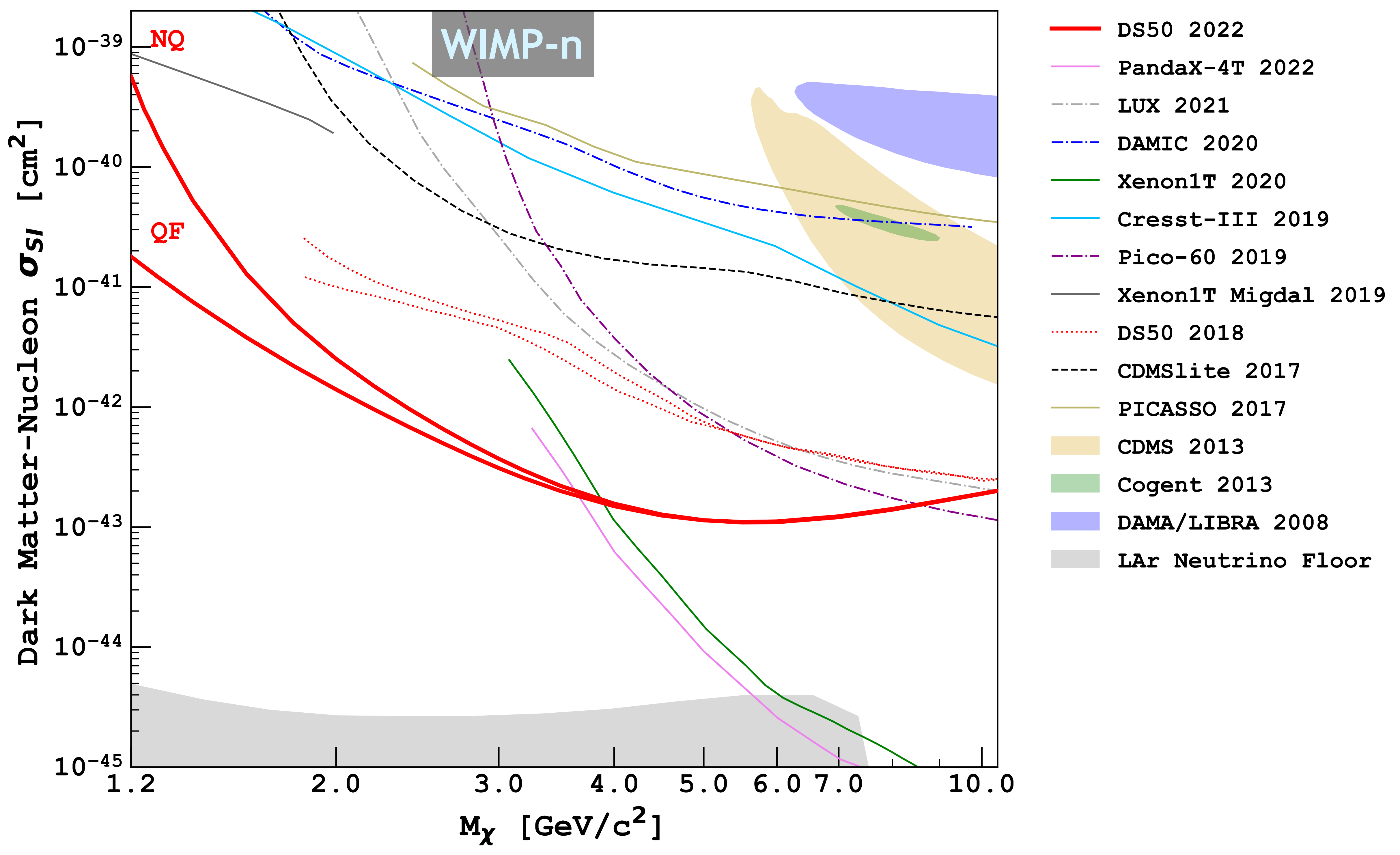
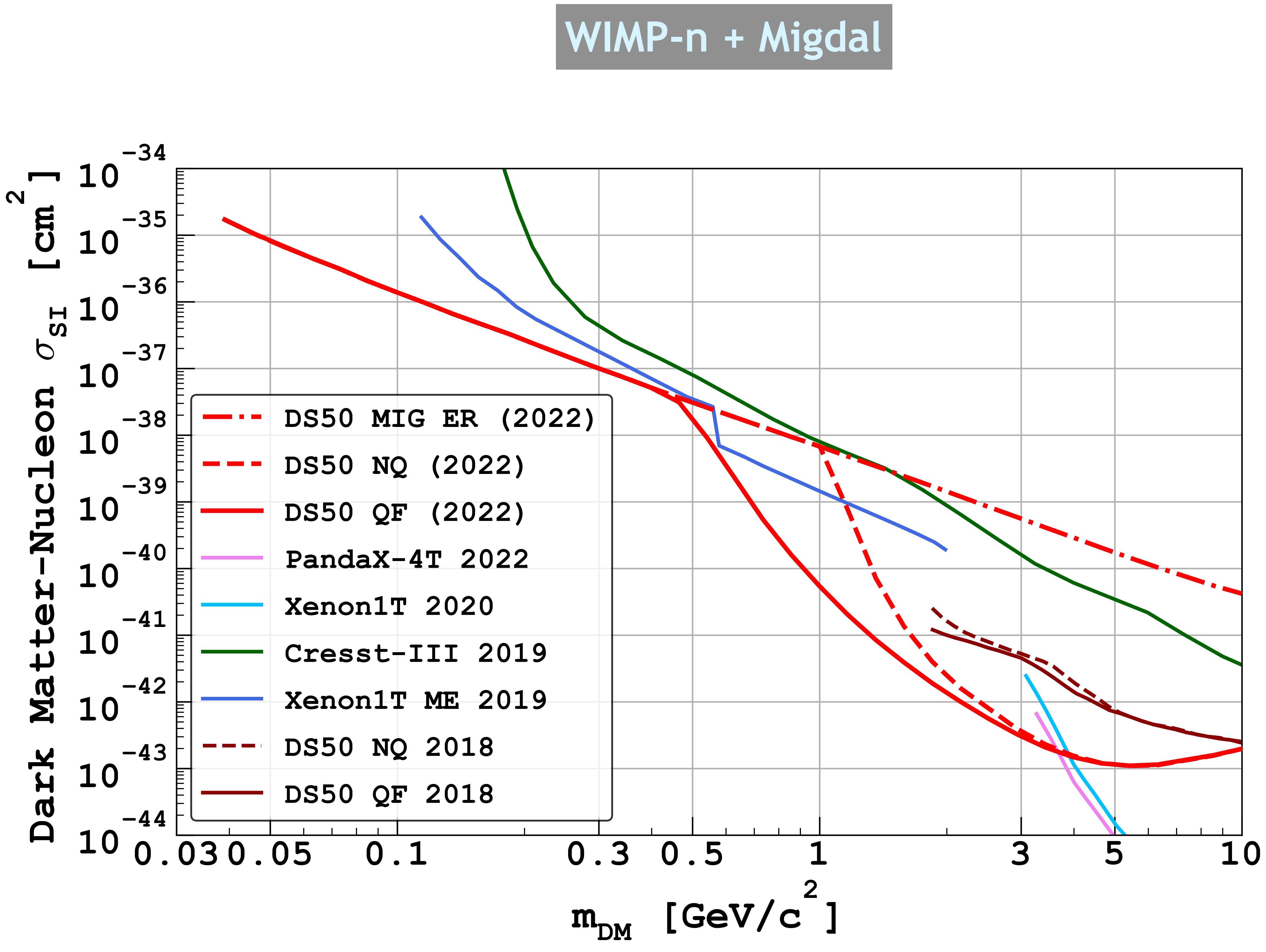
- Scintillation (S1)
  - Detection efficiency (g1) ~ 16%
- Ionization (S2)
  - Efficiency to extract 1 e- in the gas pocket ~ 100%
  - Amplification factor (g2) = ~23 pe / e-





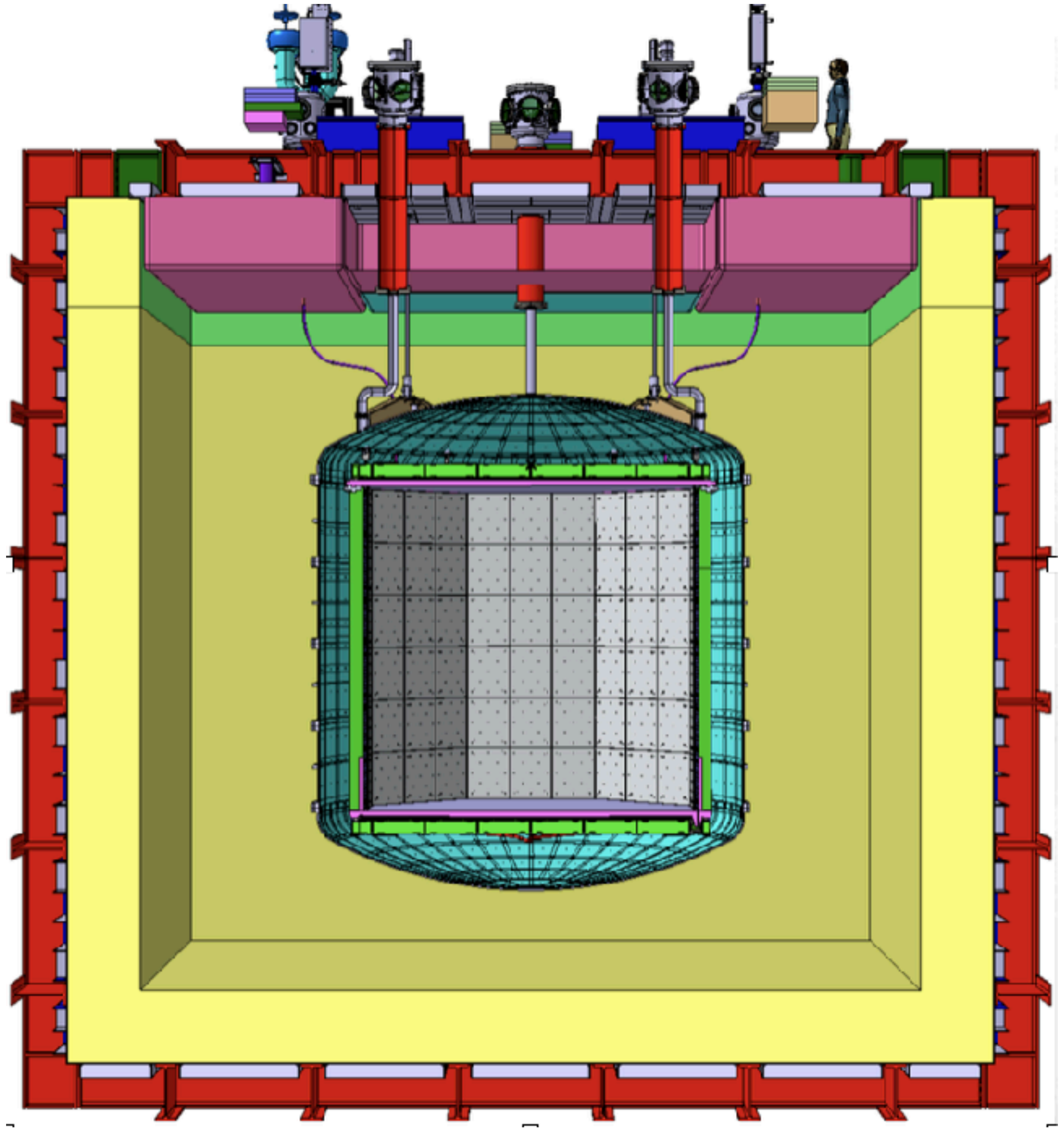


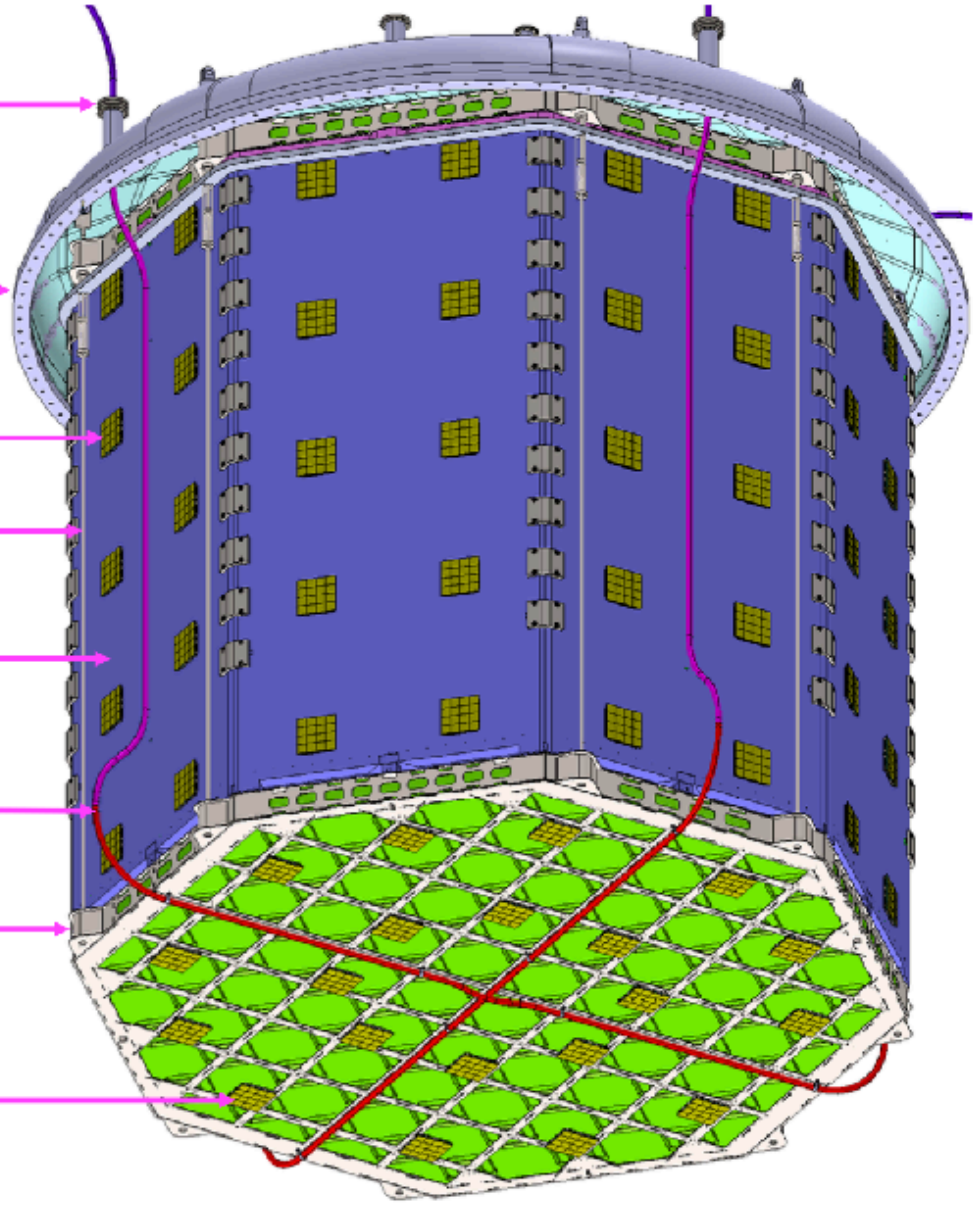
DarkSide-50, Phys. Rev. D 107 (2023) 063001

DarkSide-50, Phys. Rev. Lett. 130 (2023) 101002

DarkSide-50, Phys. Rev. Lett. 130 (2023) 101001

50 tonnes d'argon souterrain





Conclusions

Dark matter is one of the main mysteries of the universe

- Dark matter is a cross-disciplinary topic of interest to cosmology, astrophysics, particle physics, and nuclear physics.
- There are multiple lines of evidence supporting the existence of dark matter, although some doubts remain (modification of the law of gravity?).
- Detectors are becoming increasingly sensitive: in the next five years, sensitivity is expected to improve by more than a factor of 10.