Experimental Searches for

Dark Matter

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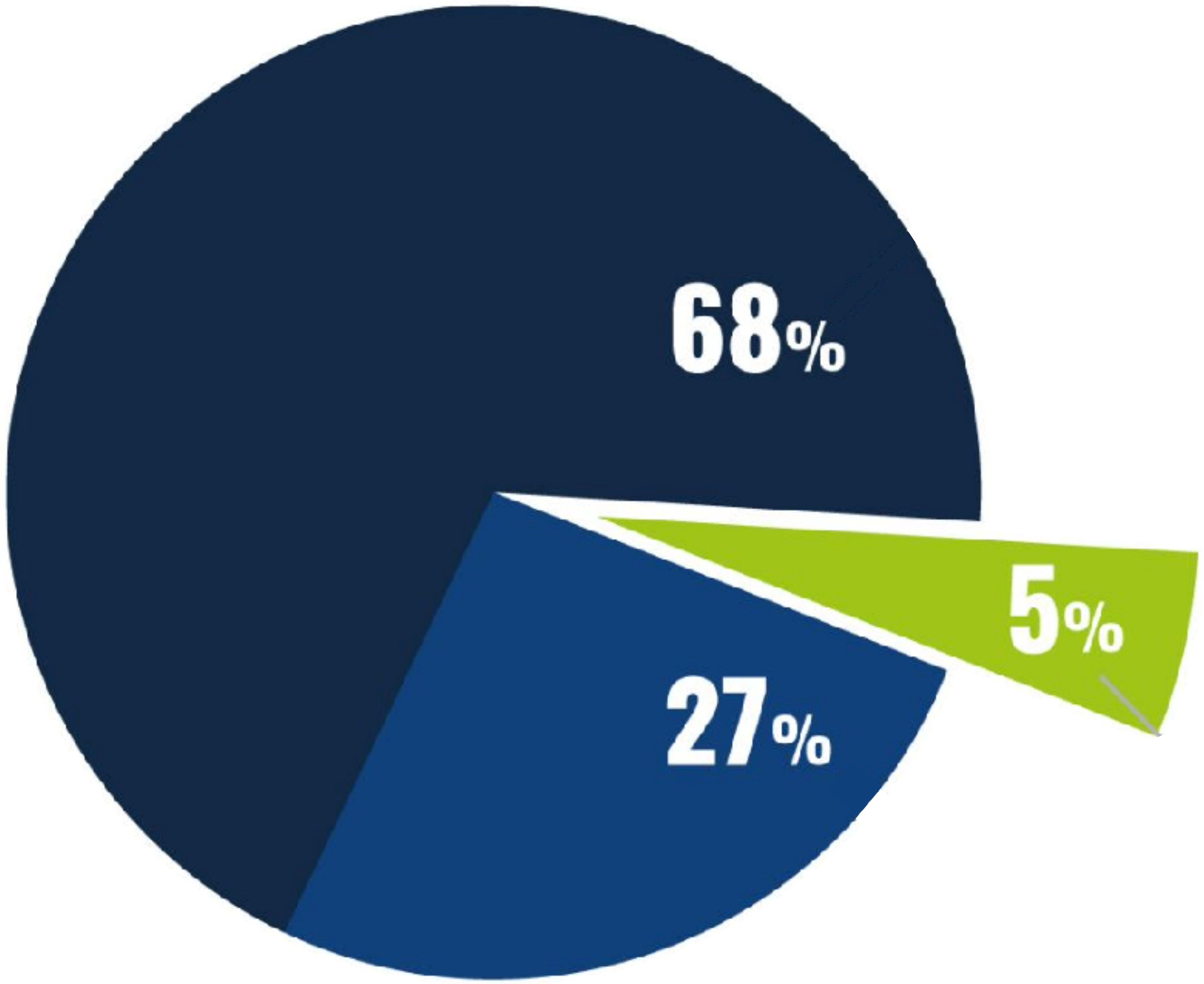
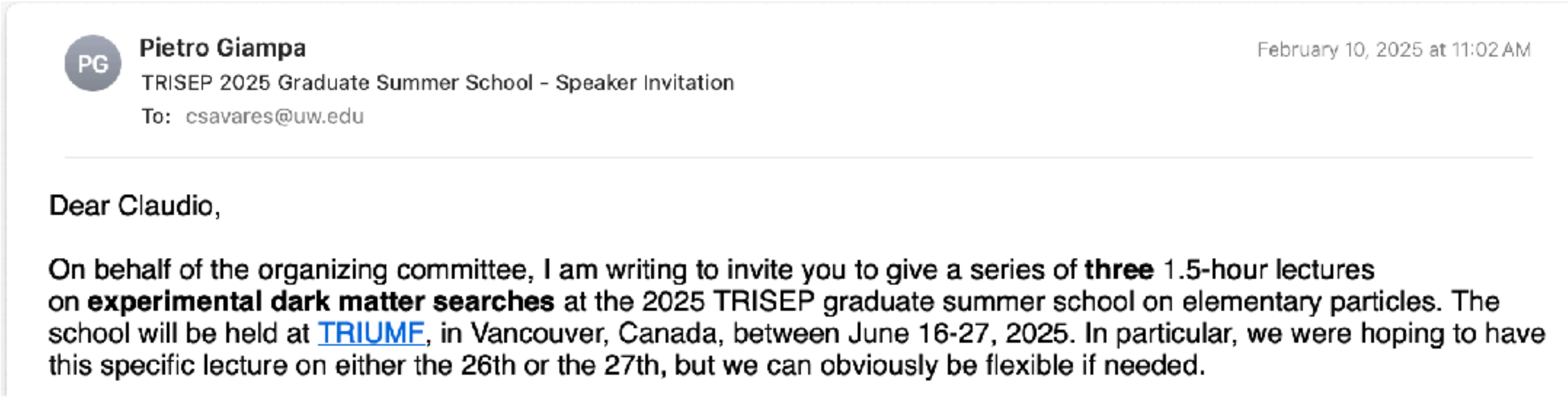
TRISEP, Vancouver, June 26th and 27th, 2025





Pietro Giampa

February 10, 2025 at 11:02 AM

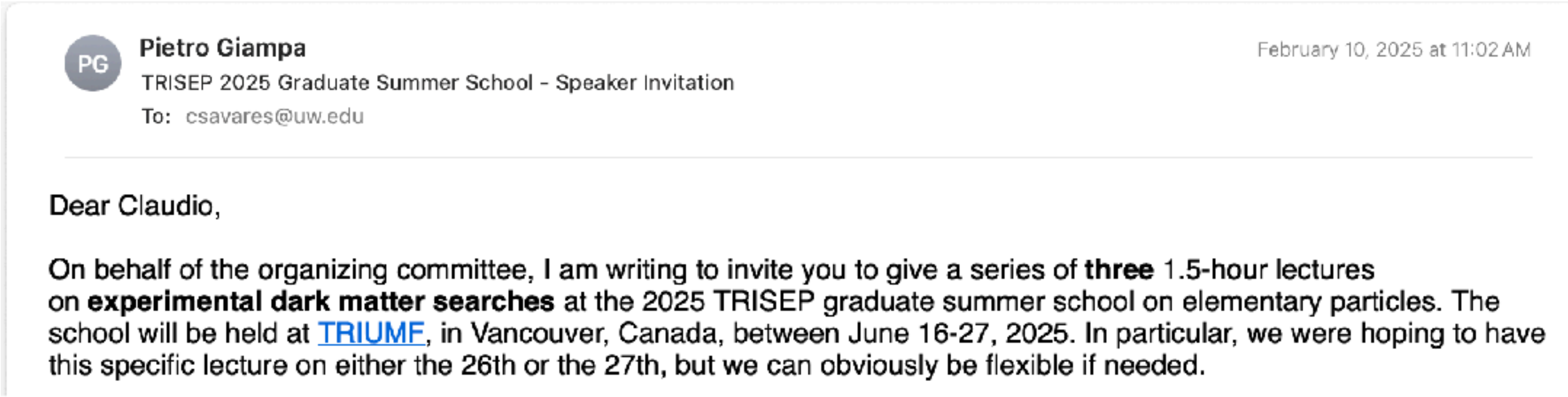
TRISEP 2025 Graduate Summer School - Speaker Invitation

To: csavares@uw.edu

Dear Claudio,

On behalf of the organizing committee, I am writing to invite you to give a series of **three** 1.5-hour lectures on **experimental dark matter searches** at the 2025 TRISEP graduate summer school on elementary particles. The school will be held at TRIUMF, in Vancouver, Canada, between June 16-27, 2025. In particular, we were hoping to have this specific lecture on either the 26th or the 27th, but we can obviously be flexible if needed.

...



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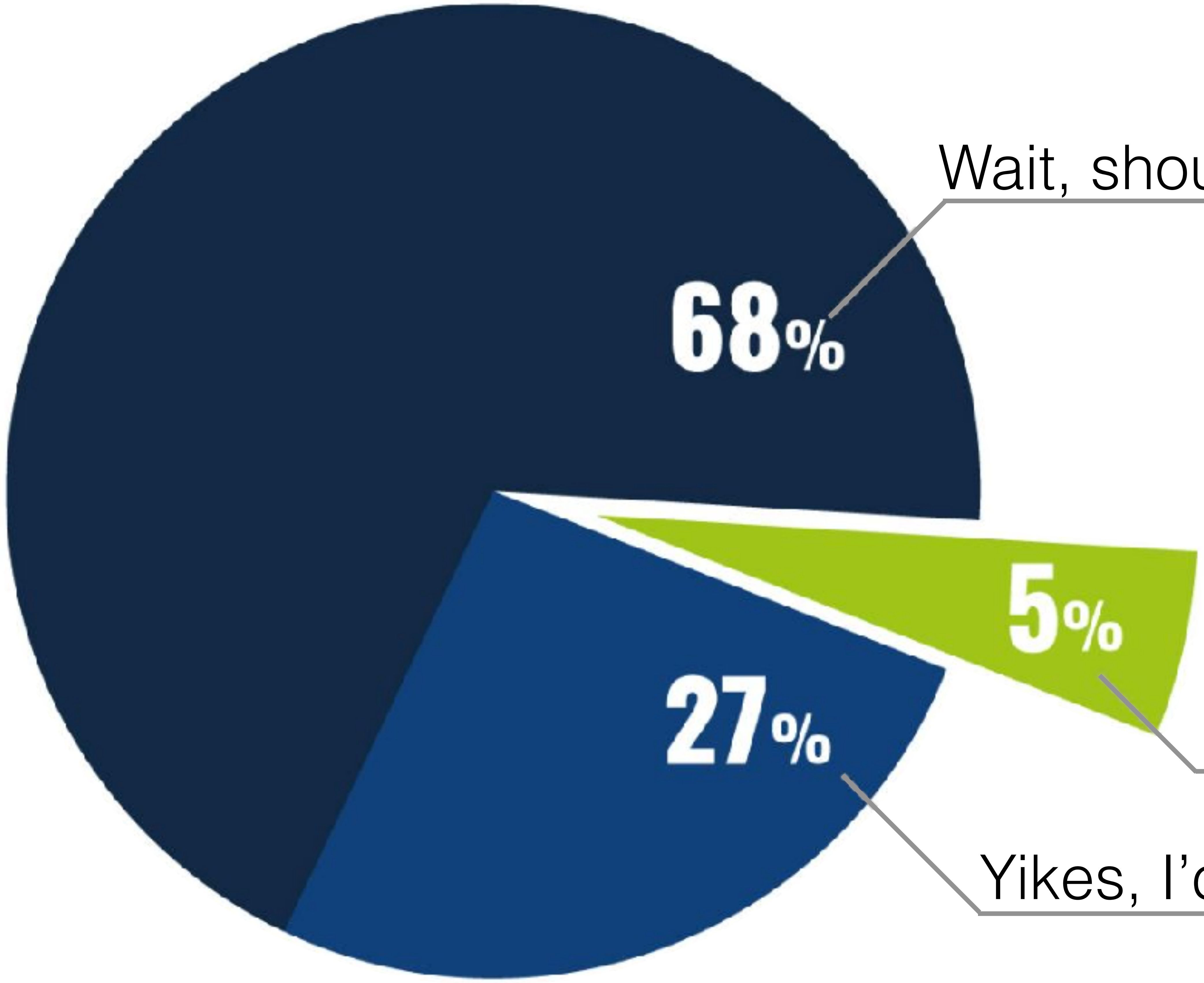


Wait, should I cover this stuff too?!

I am an expert in this field!

Yikes, I'd better find some reviews about this topic

Overview

1. **Dark Matter 101**
   - History
   - Evidence
   - What do we know

2. **Dark Matter Candidates**
   - Non-particle DM
   - Particle DM
     - Axion-like
     - WIMP-like

3. **Experimental Search Channels**
   - Production
   - Indirect Detection
   - Direct Detection

4. **Direct Searches**
   - Axion Detection
   - WIMP Detection
     - WIMP signal
     - Current landscape
     - Heavy DM experiments
     - Light DM experiments

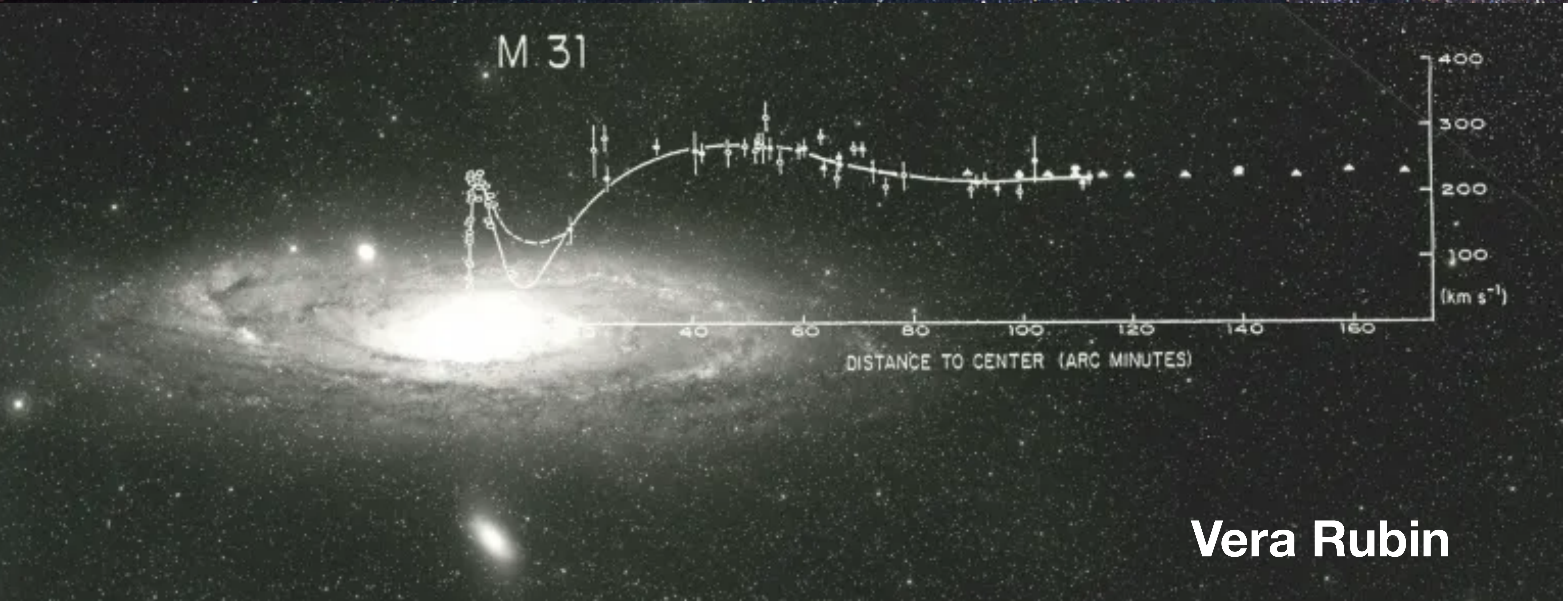
Evidence

First hints - Coma Cluster

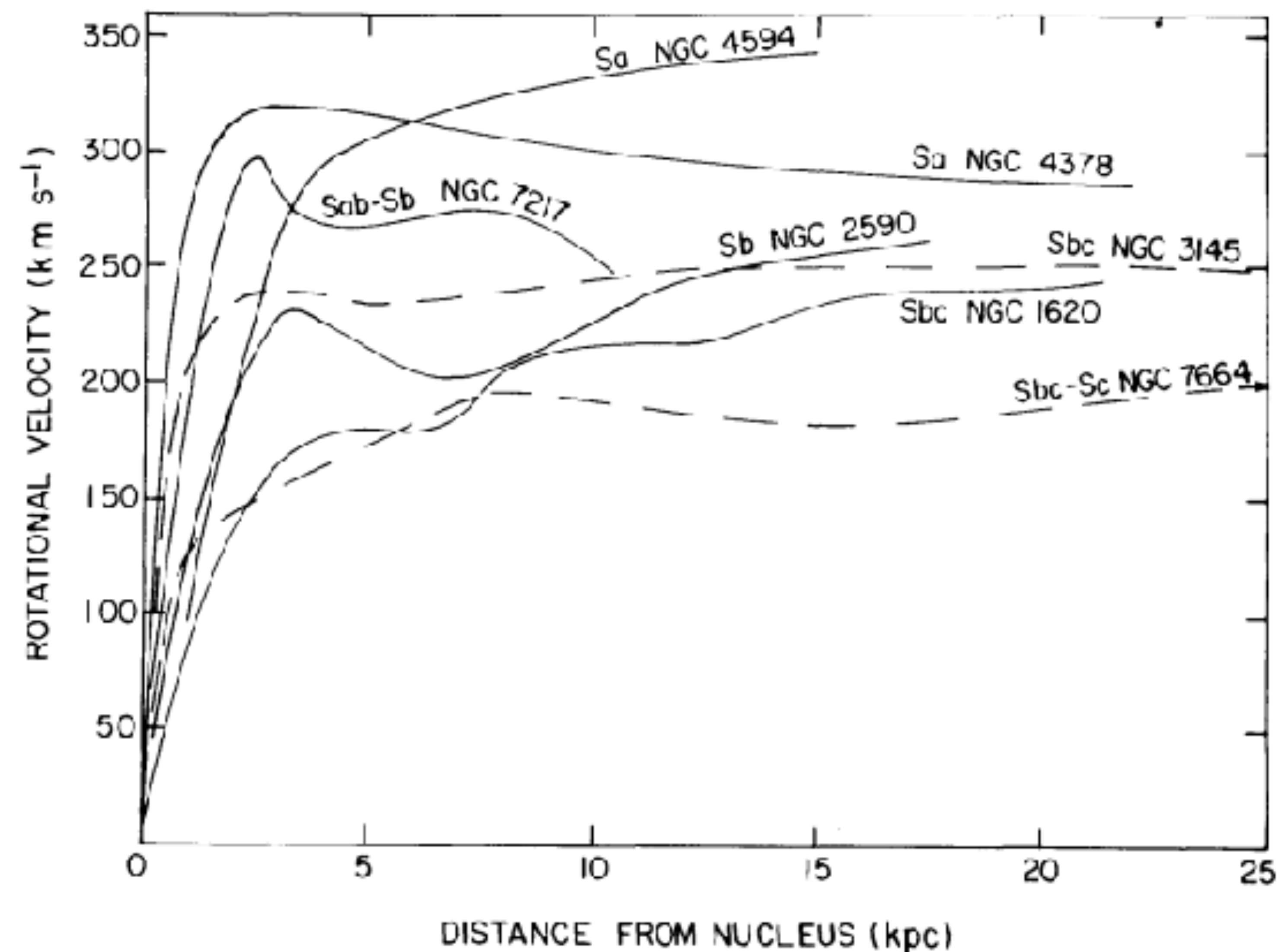
Fritz Zwicky - 1933

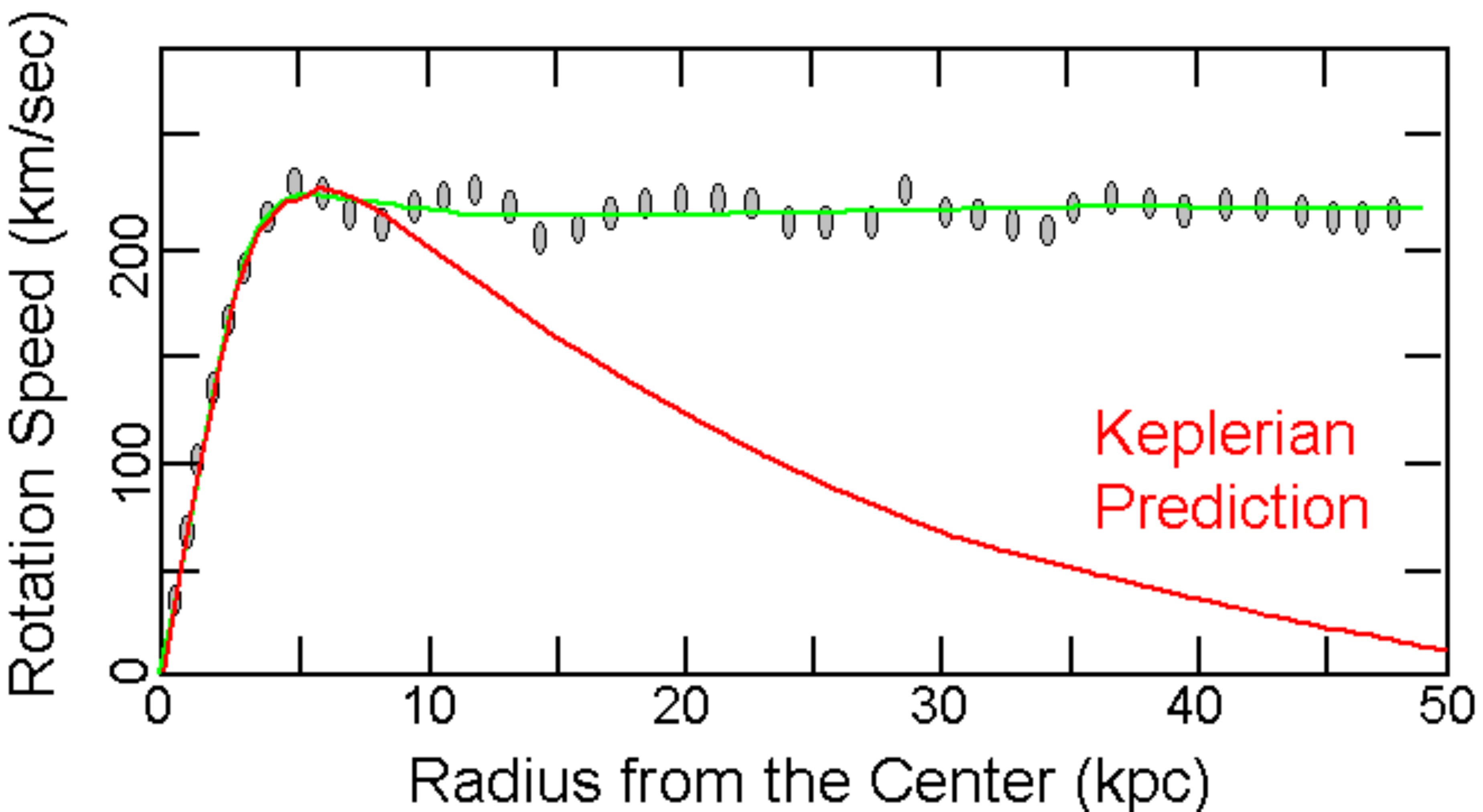
- Luminosity to infer total mass of the cluster
- Prediction of average galaxy velocity
- Emission spectra red\blue shift to measure velocities
- Discrepancy in velocities and mass!
- Dunkle Materie

First hints - Galactic Rotation Curves



Vera Rubin

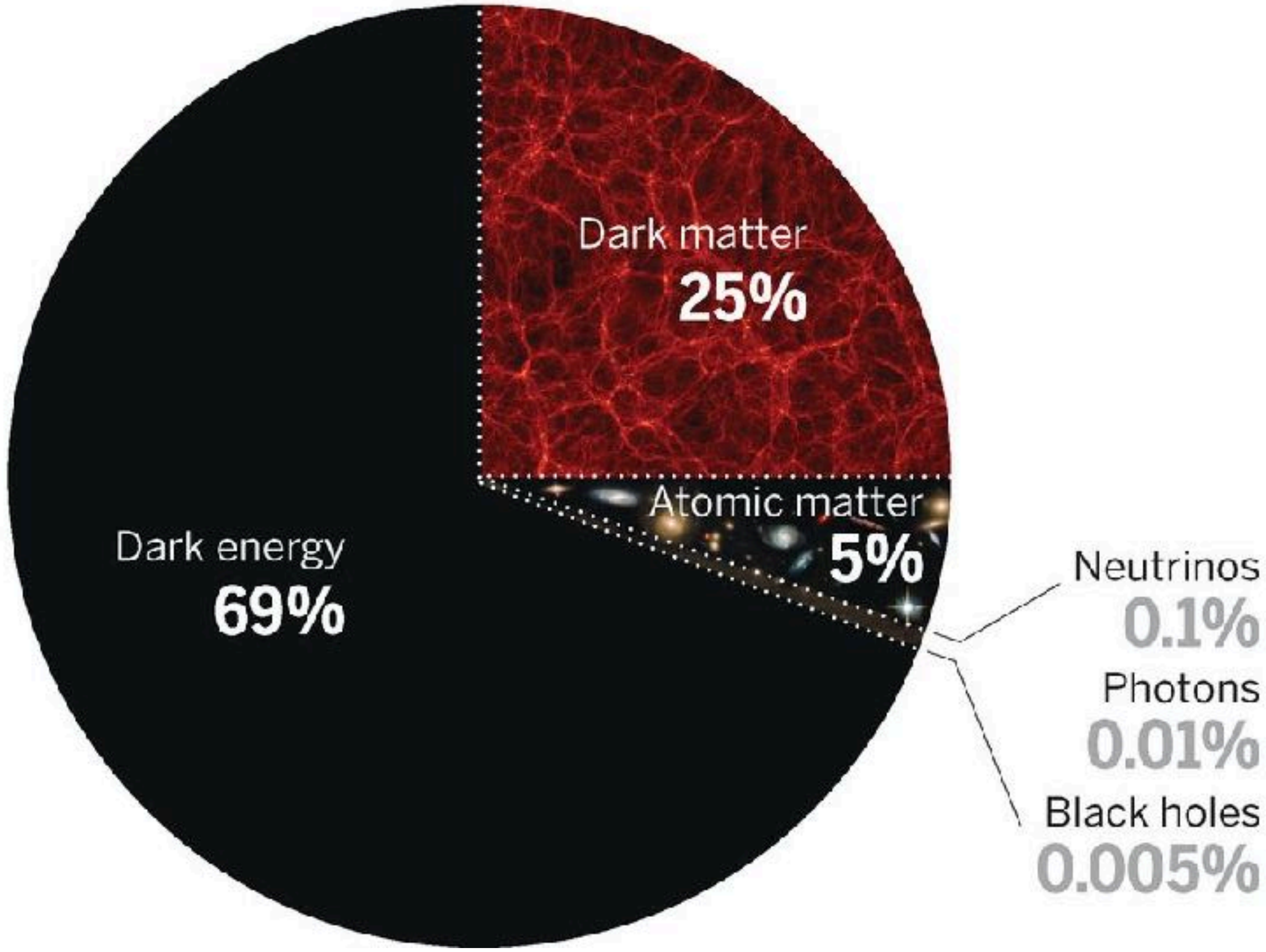



Observed *vs.* Predicted Keplerian

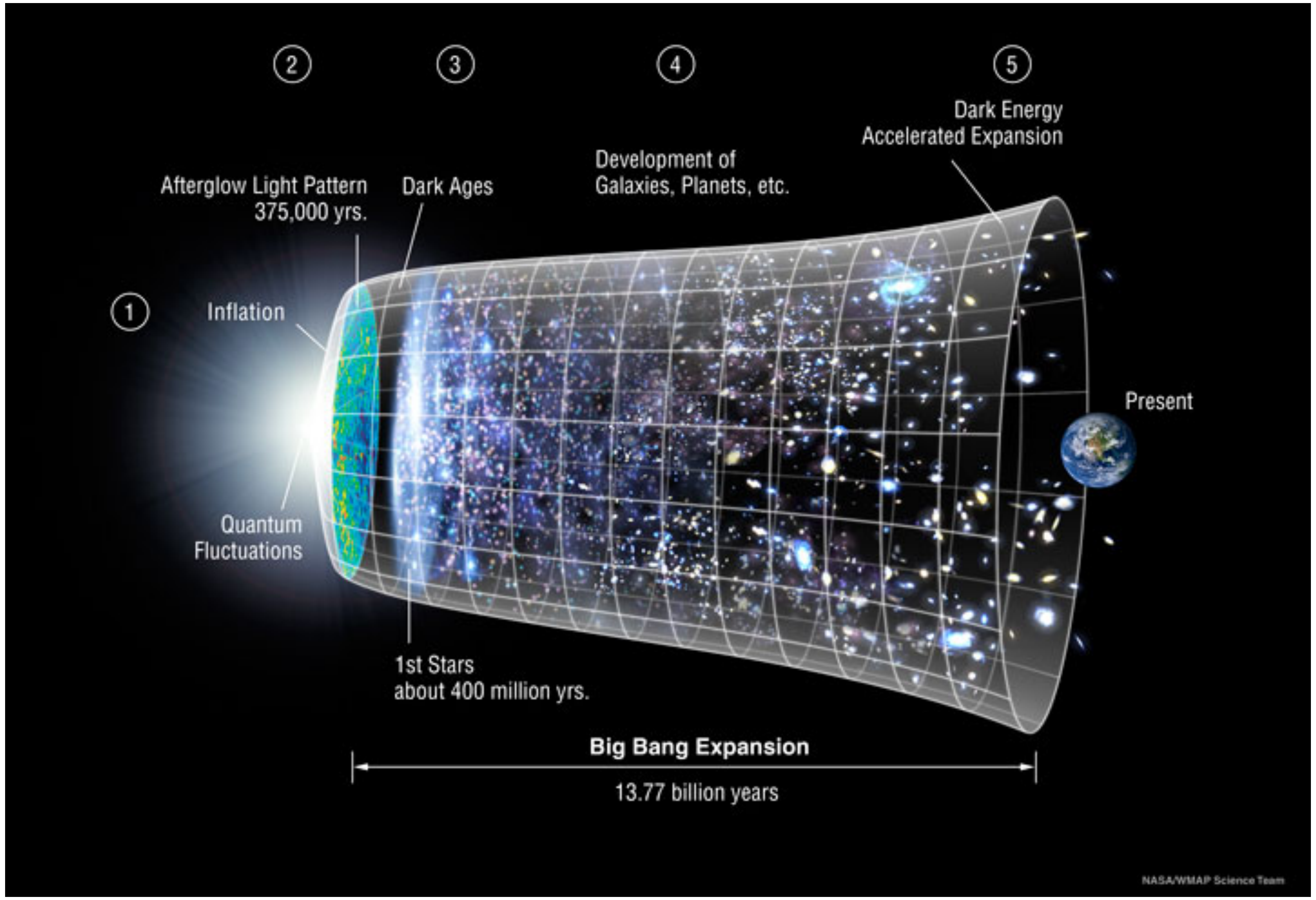
- Luminosity to infer mass profile of the galaxy
- Prediction of stars' velocity
- Emission spectra red\blue shift to measure rotation velocity

The ΛCDM Universe

Matter+Energy in the Universe

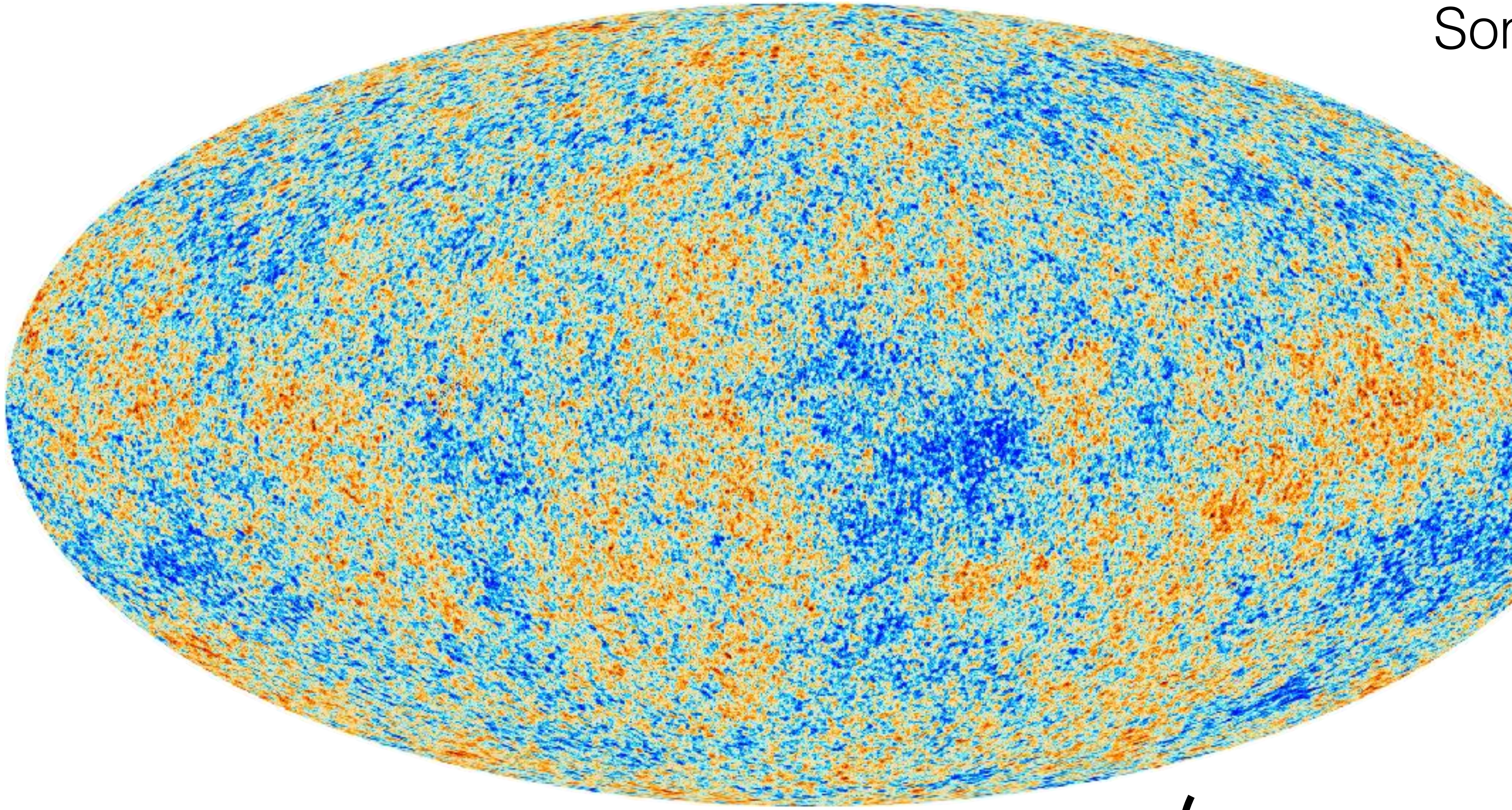


- Baryonic Matter
- **Dark Matter**
- Dark Energy

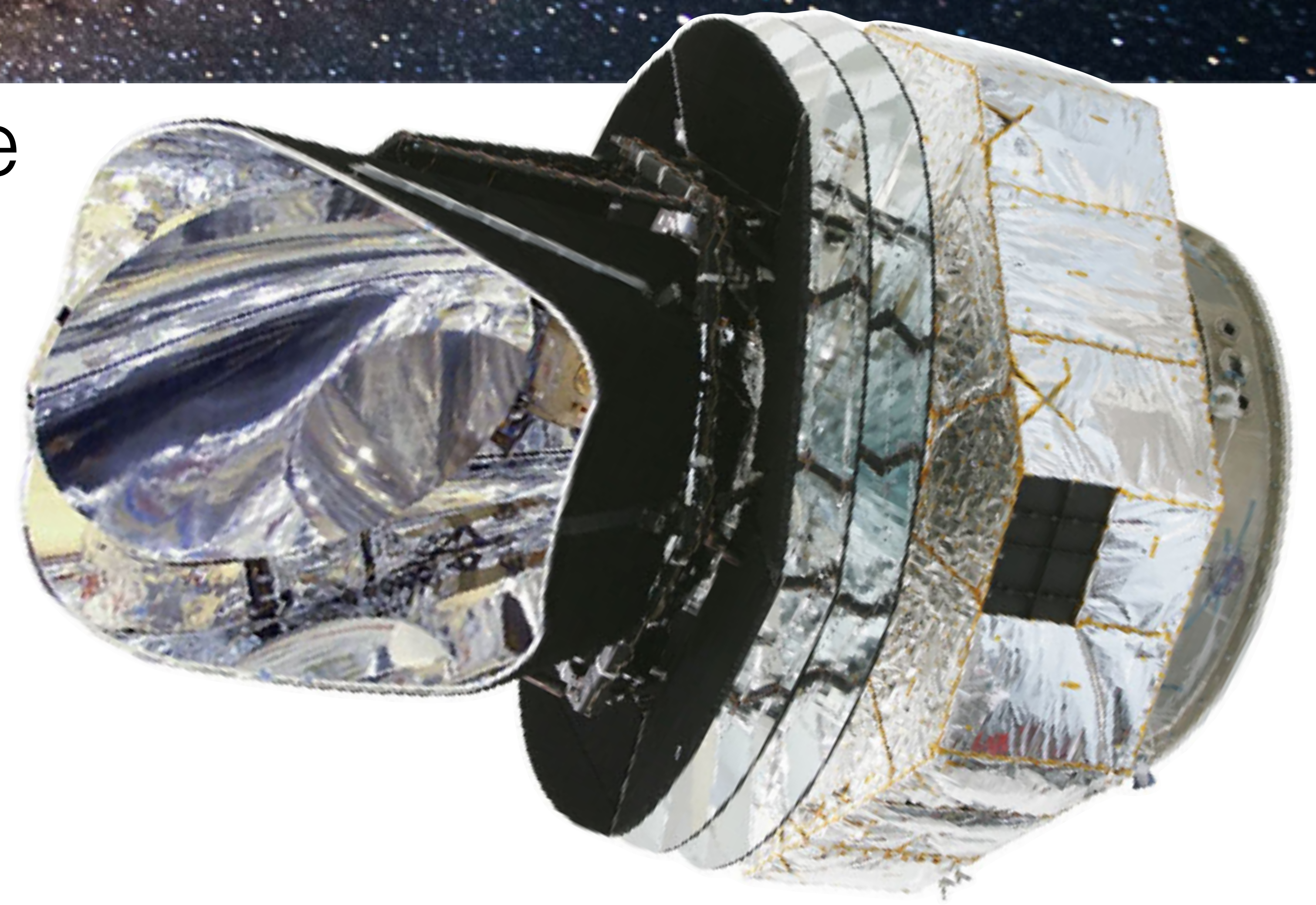


- Big Bang
- Inflation?
- CMB era
- Re-ionization…

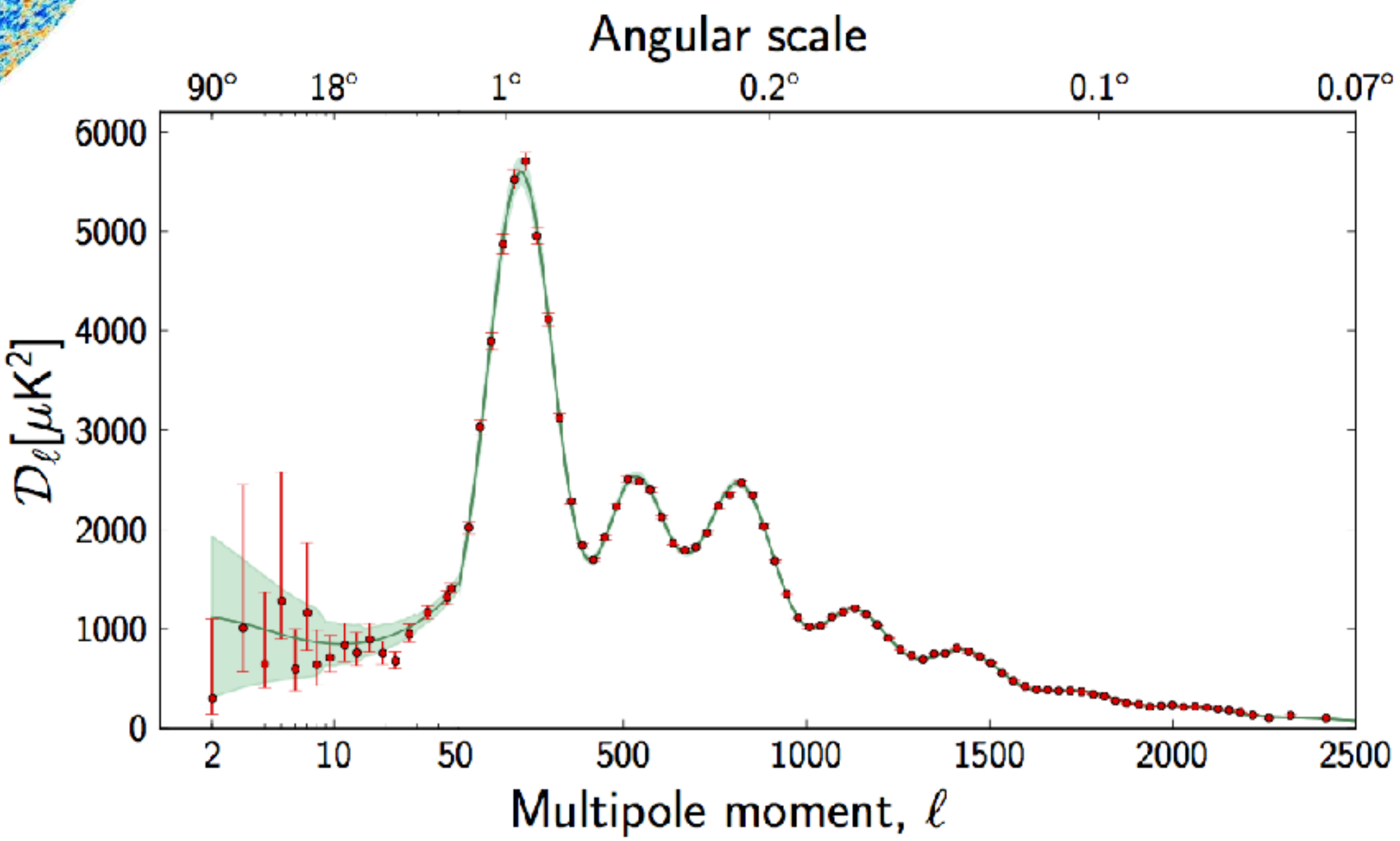
Evidence - CMB



Some cool science

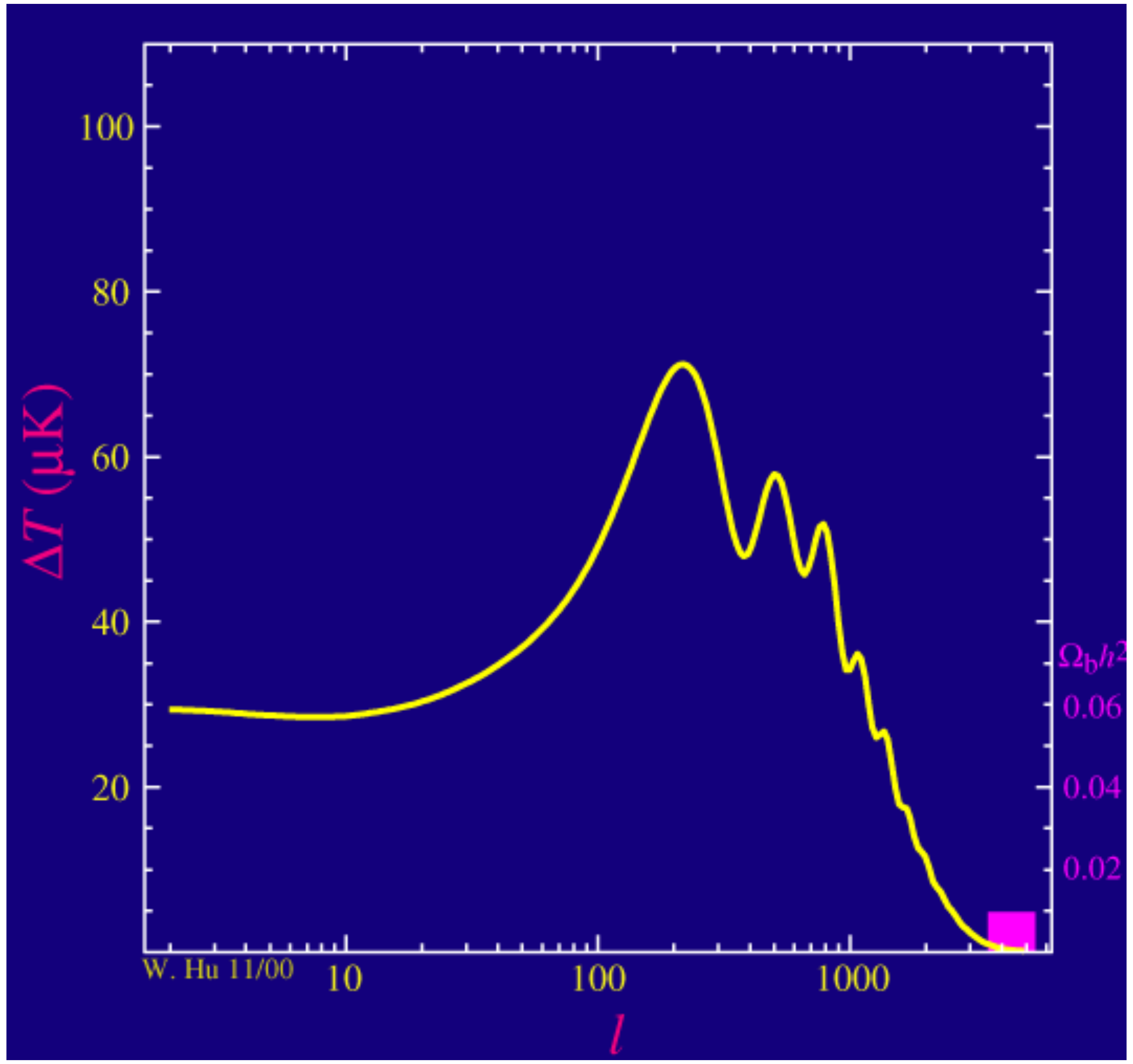


Some cool math

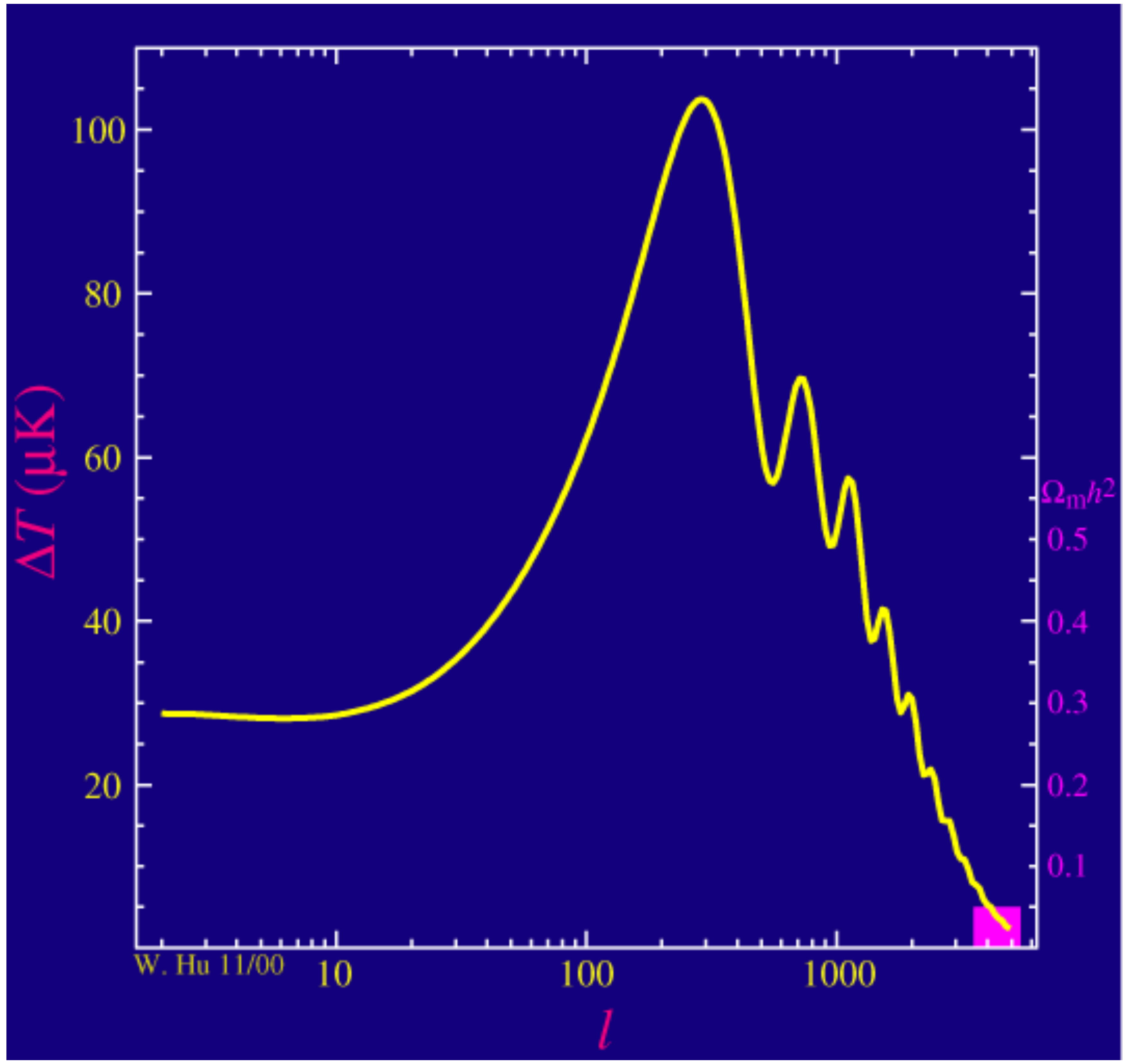


Evidence - CMB

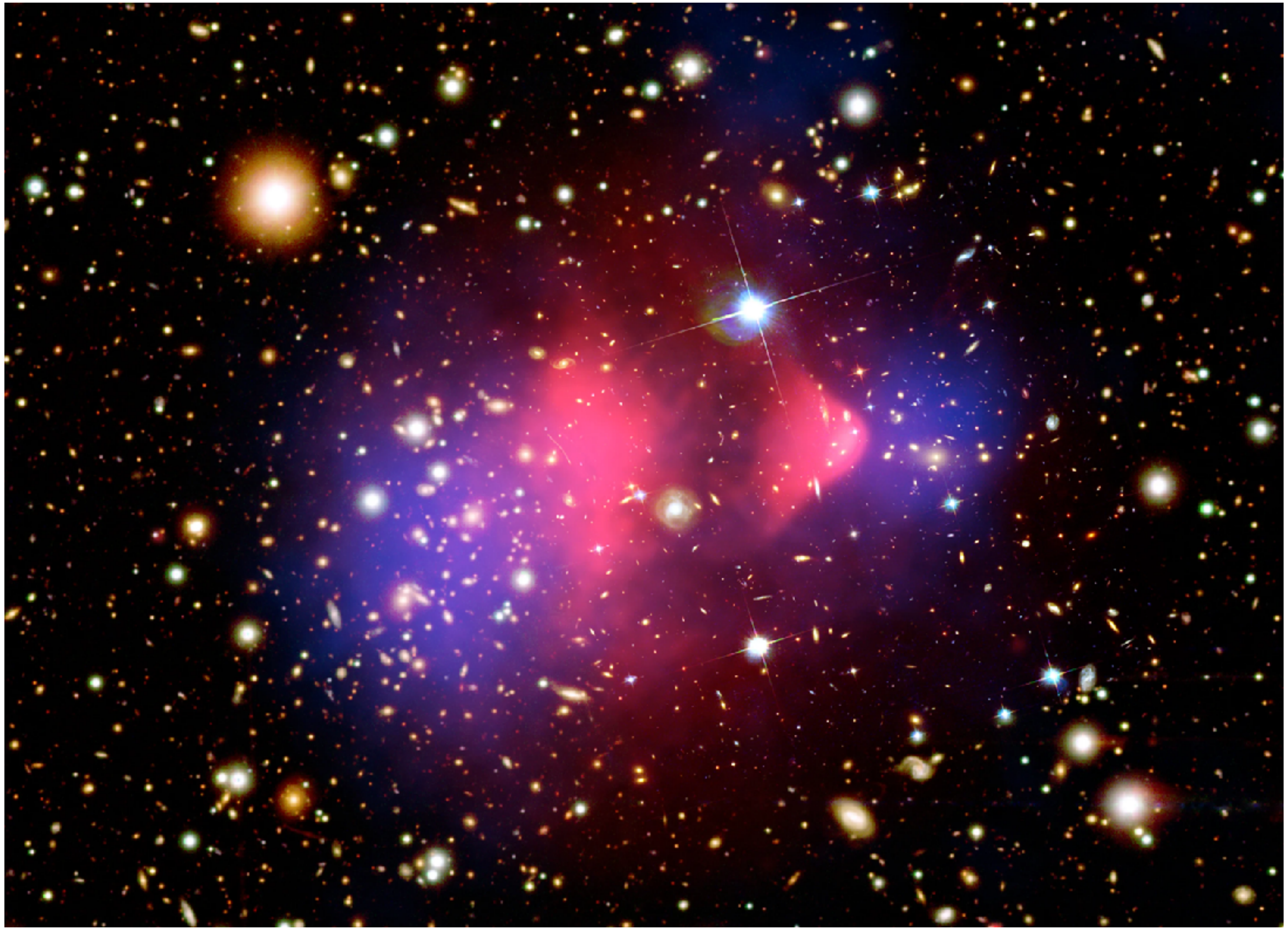
Baryons



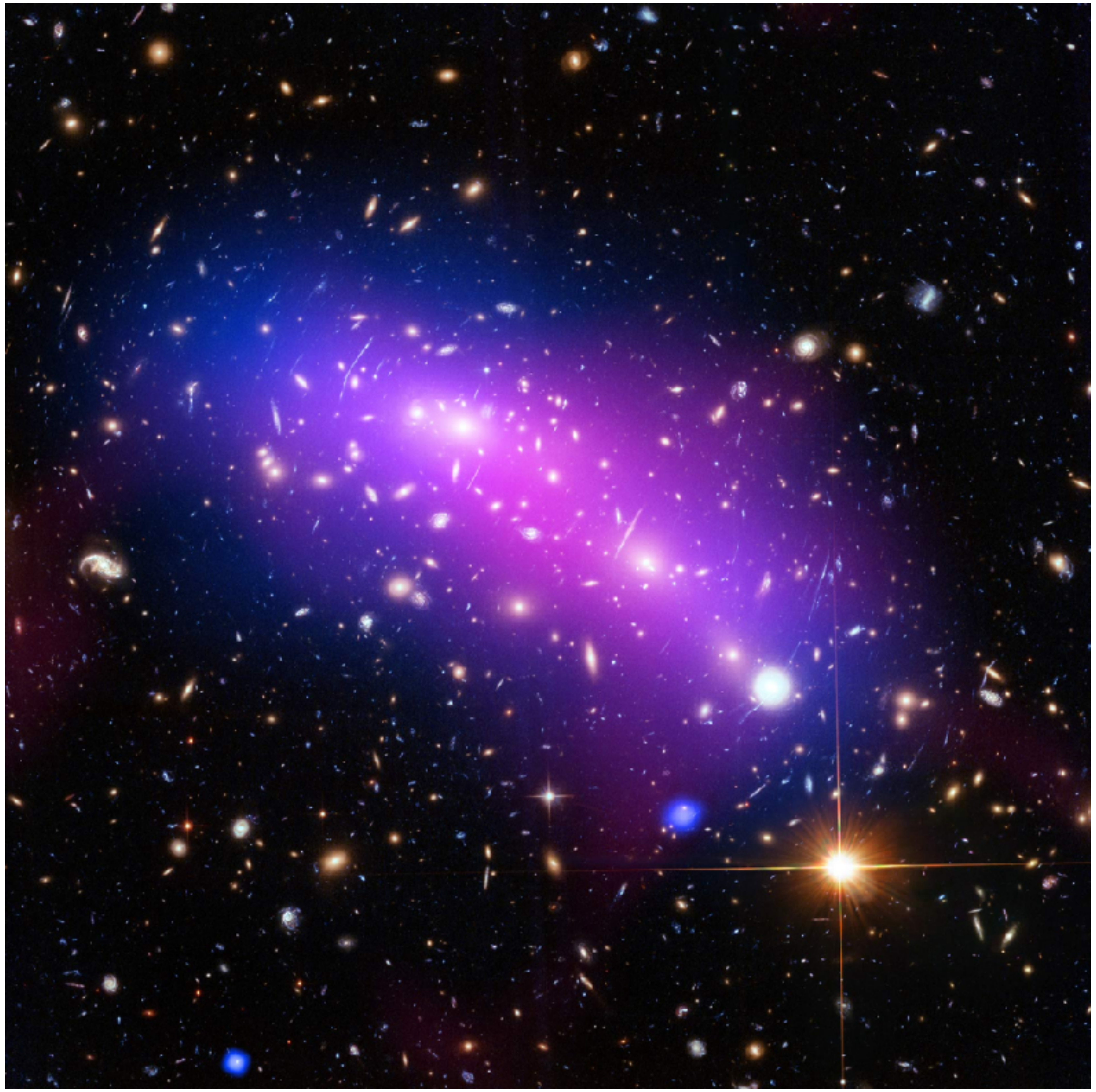
Total Matter



Evidence - Gravitational Lenses



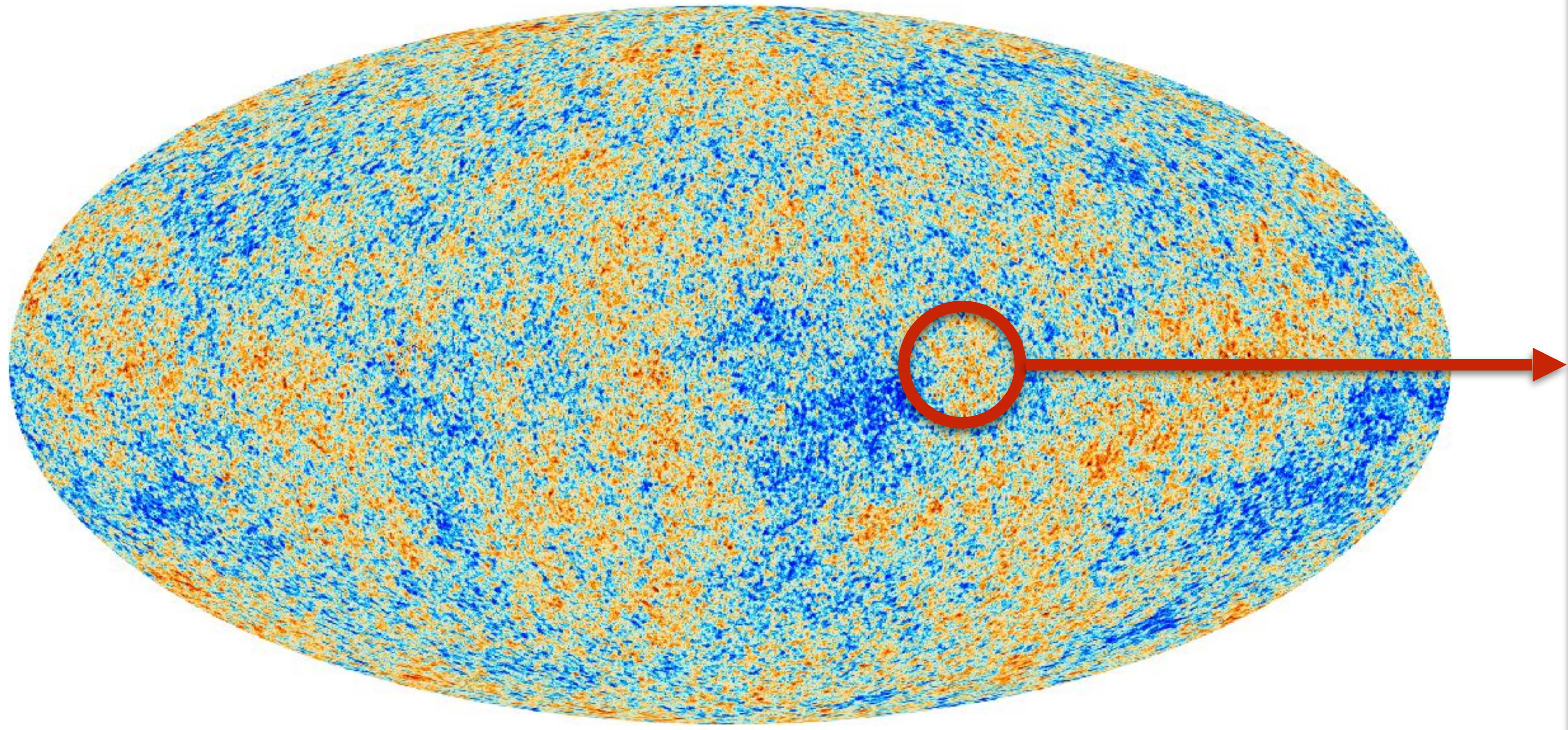
Bullet Cluster



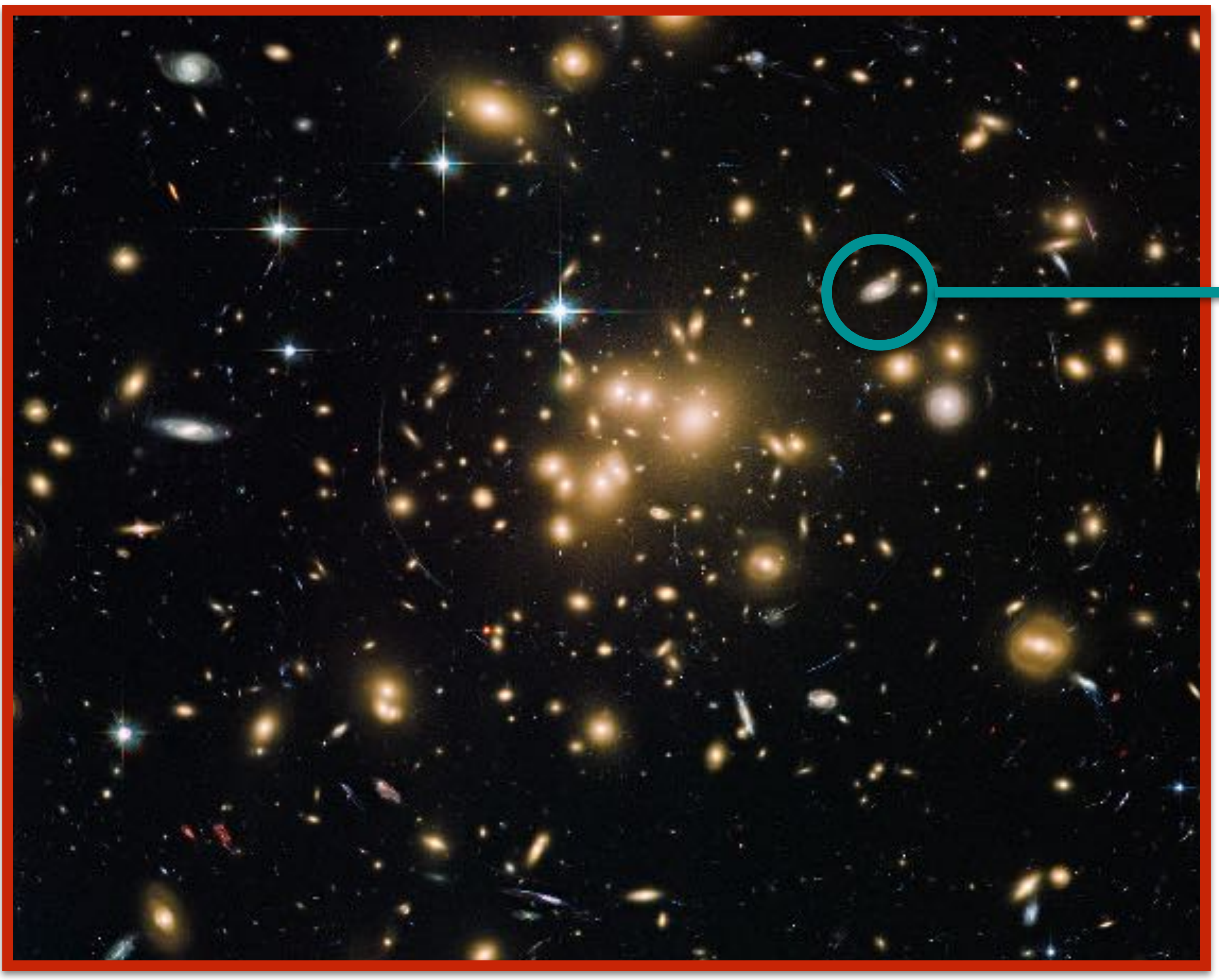
MACS J0416.1-2403

Observations at all scales

CMB



Galactic clusters



Galaxies

Multipole expansion

CMB thermal anisotropies

Galaxy velocities

Gravitational lensing (Bullet)

Rotation curves

Gravitational lensing

Compelling evidence at all scales

Recap of properties

Invisible (i.e. does NOT absorb and/or emit light)

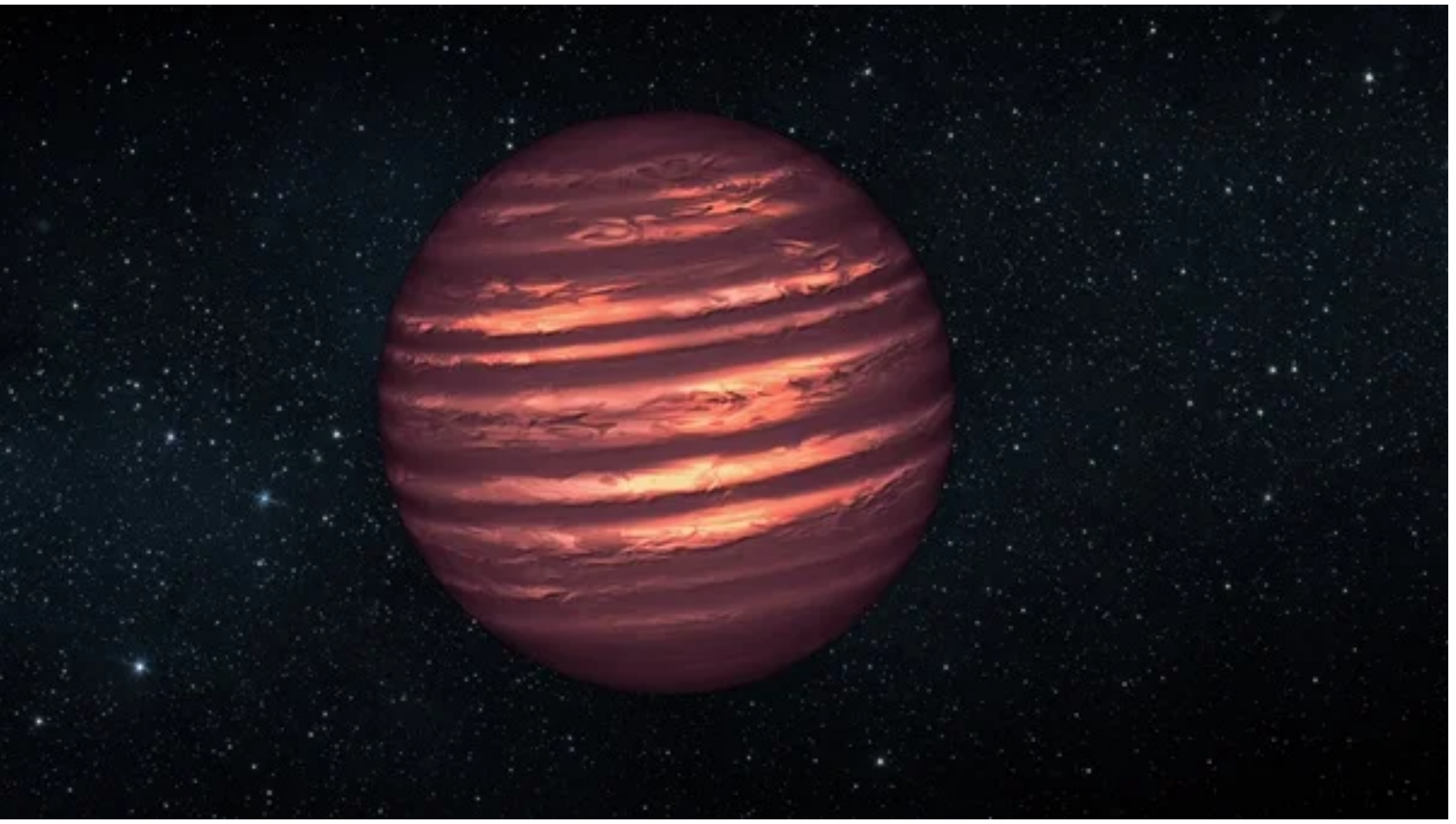
Has Mass and interacts with other matter through gravity

Does not interact (much) with normal matter with EM/weak/strong forces

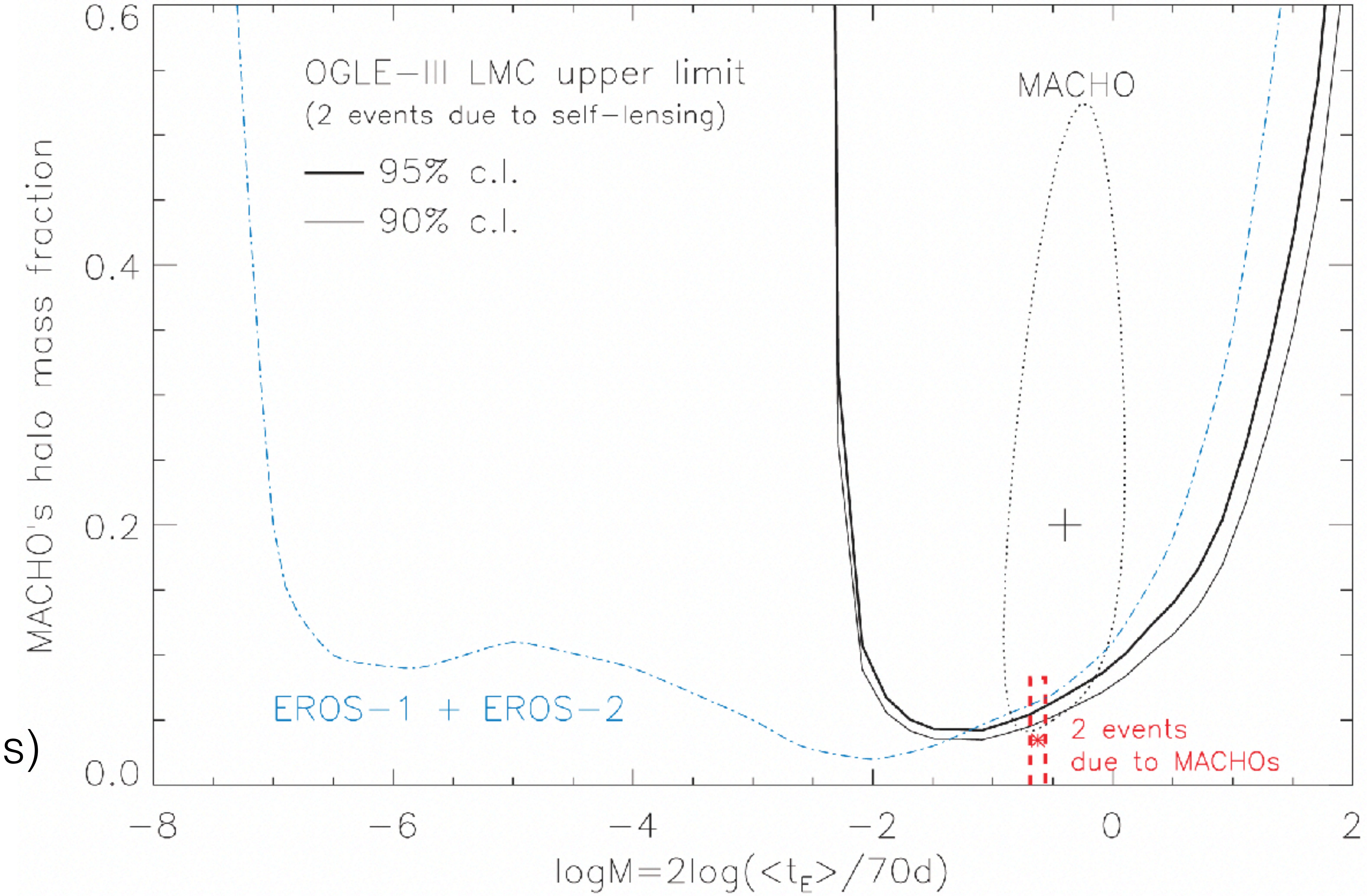
DM Candidates

Non-particle DM Candidates

MACHOs

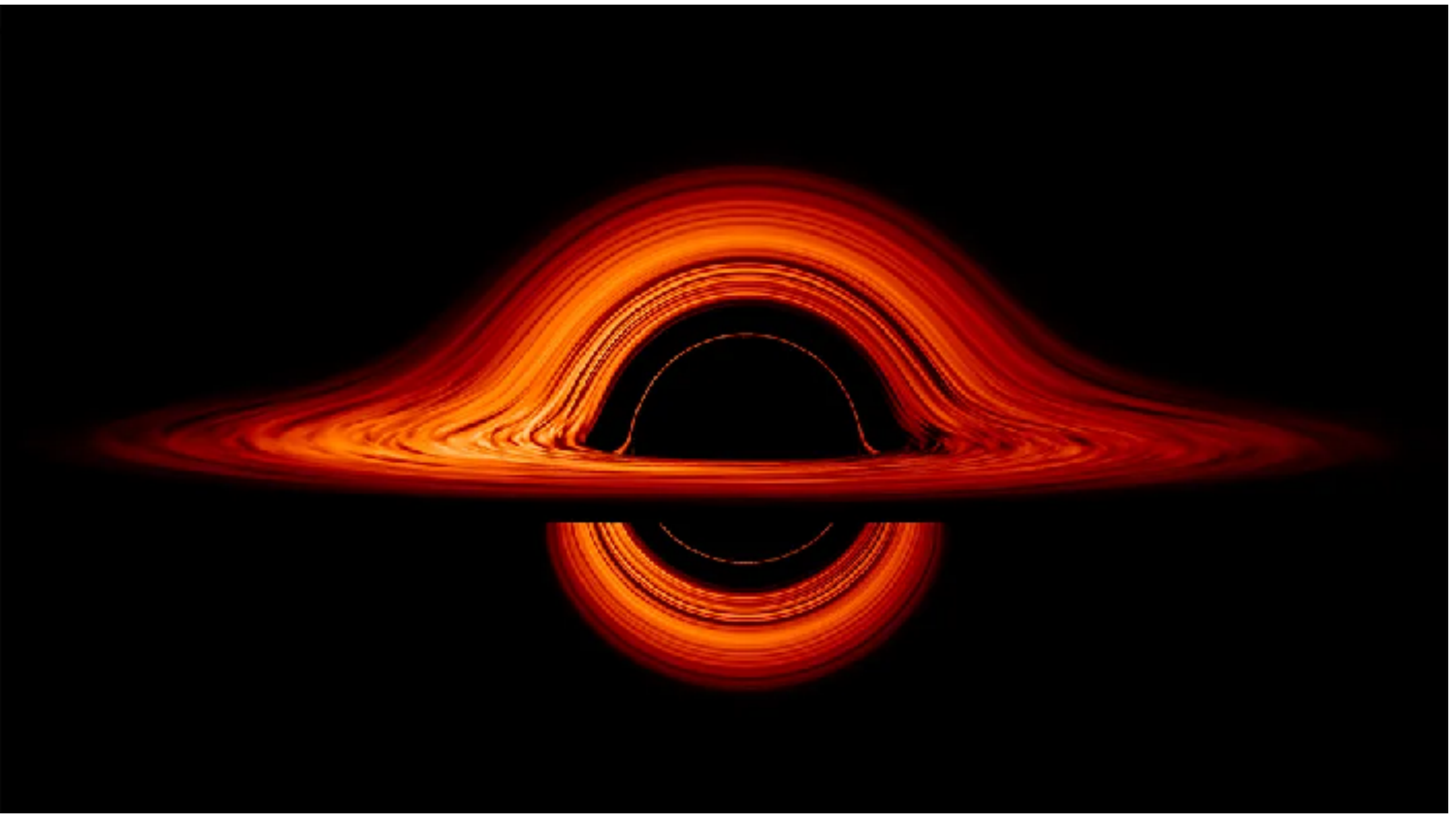


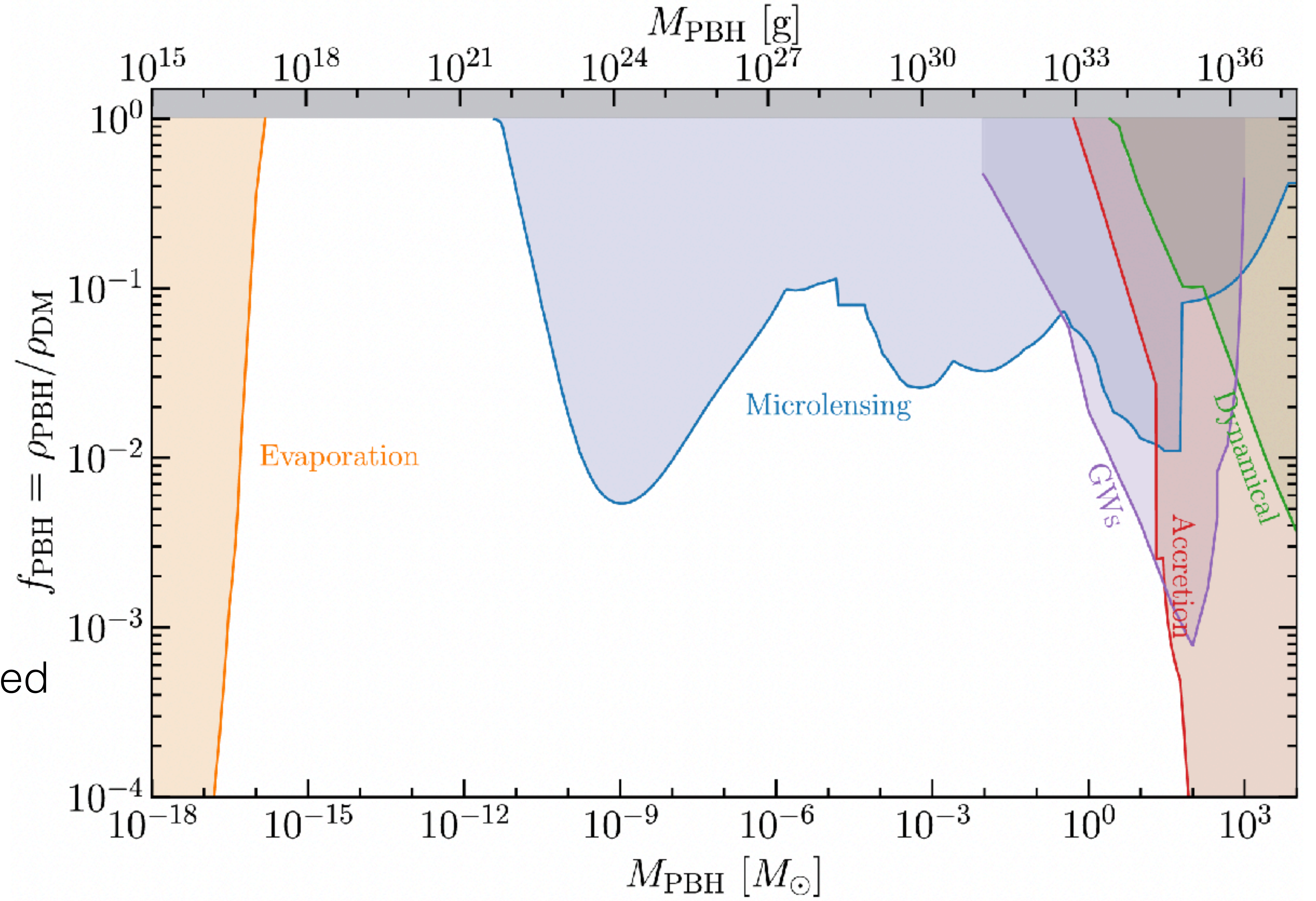
- **MA**ssive **C**ompact **H**alo **O**bjects
- Non-luminous astronomical body (planets, black/red dwarfs, black holes)
- Search by gravitational lensing by several experiments (OGLE, MACHO)



MACHOs excluded in (10^{-7} - 30) $M_\odot$ range

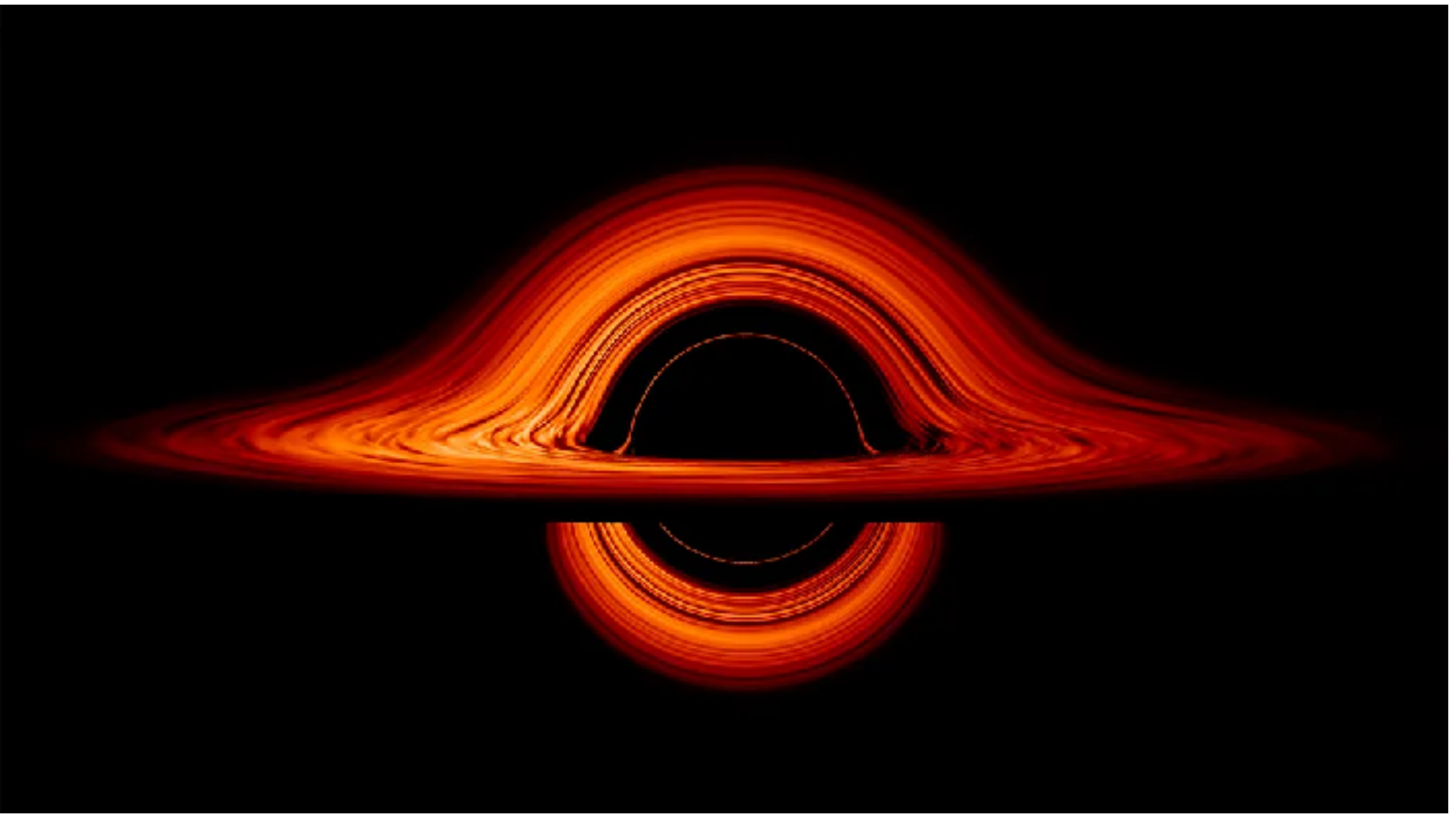
PBHs



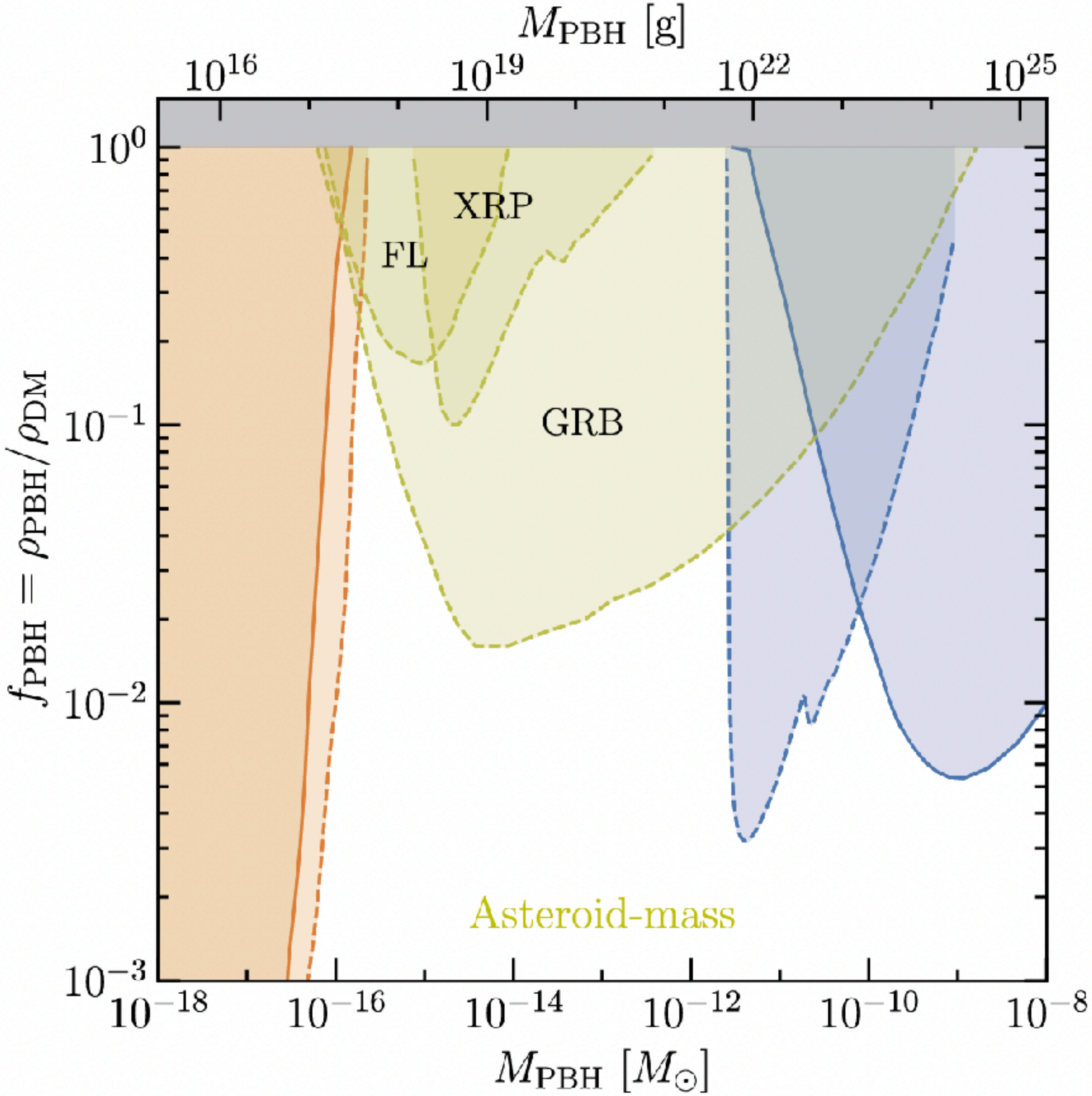


- **P**rimordial **B**lack **H**oles
- Generated right after the Big Bang
- PBH $<10^{-15}$ M$_\odot$ evaporating - excluded by X/γ ray observations
- PBH 10^{-12} - 10^{3} M$_\odot$ excluded by microlensing + GW + Effects on binaries

PBHs - Future Constraints

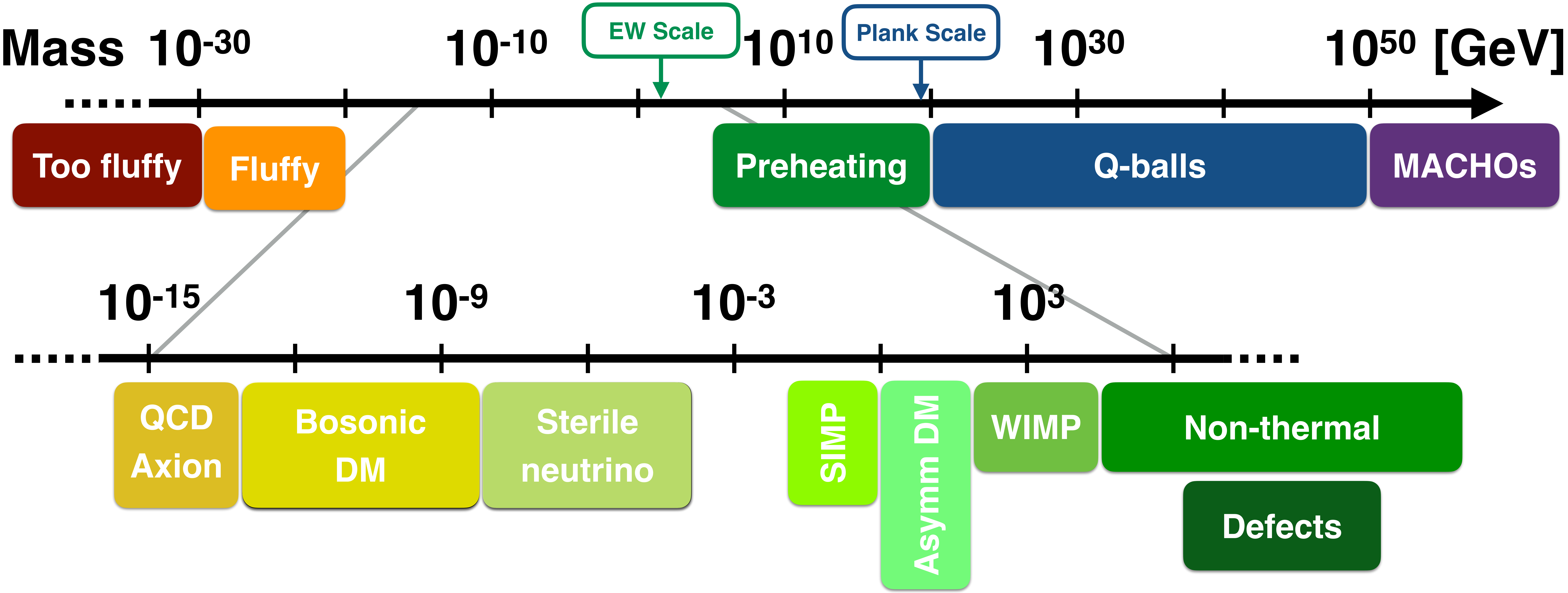


- **P**rimordial **B**lack **H**oles
- Generated right after the Big Bang
- PBH 10^{-16} - 10^{-12} $M_\odot$ window will be closed by observation of micro-lensing of X-rays emitted by pulsars and γ-rays from Gamma Ray Bursts



Particle DM Candidates

Where should we look?



EW Scale

Plank Scale

Mass 10^{-30} 10^{-10} 10^{10} 10^{30} 10^{50} [GeV]

Too fluffy

Fluffy

Preheating

Q-balls

MACHOs

10^{-15} 10^{-9} 10^{-3} 10^{3}

QCD Axion

Bosonic DM

Sterile neutrino

SIMP

Asymm DM

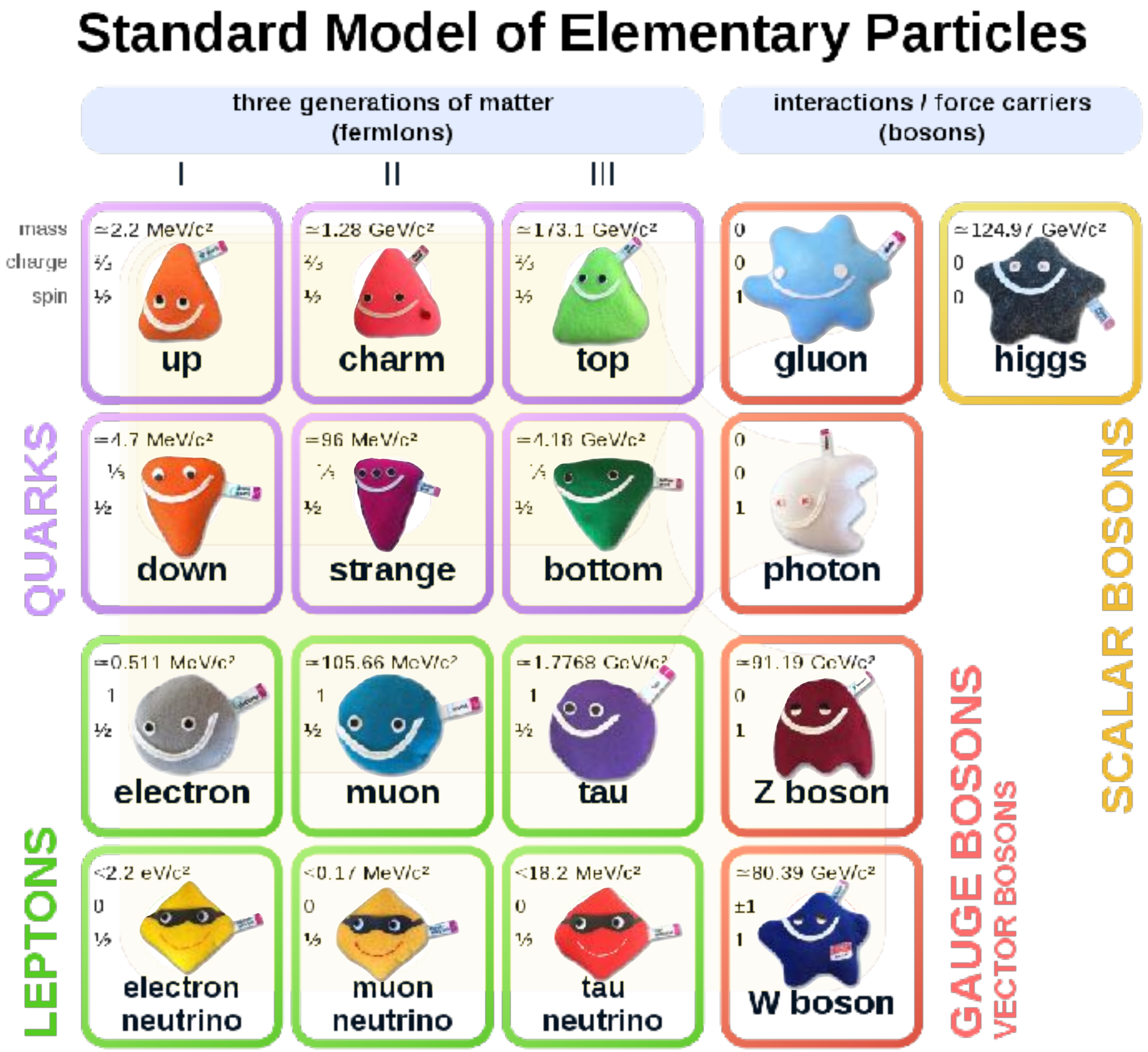
WIMP

Non-thermal

Defects

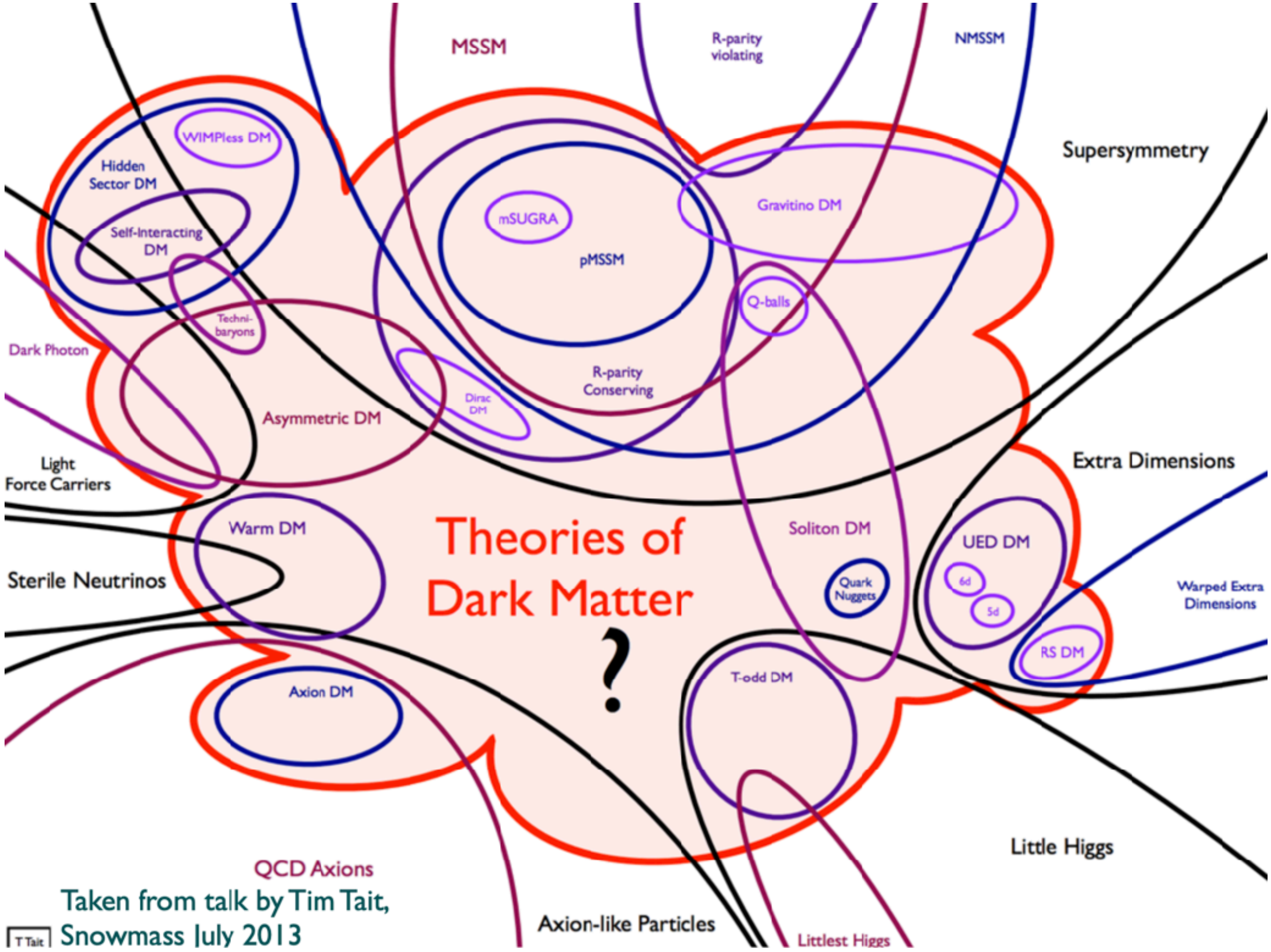
~70 orders of magnitude!

What are we looking for?



?!

How do we fit DM in our framework of particle physics?



Taken from talk by Tim Tait, Snowmass July 2013

massive, cold, neutral, weakly interacting

The Axion

- Originally invented to solve a completely unrelated problem - the **Strong CP Problem**
- Later recognized to be a viable DM candidate
- Considerable experimental efforts are now being made to search for axions

The strong CP problem

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4}G^{a}_{\mu\nu}G^{a\mu\nu} + \sum_{j=1}^{n}\left[\bar{q}_j\gamma^{\mu}iD_{\mu}q_j - (m_j q^{\dagger}_{Lj}q_{Rj\,+\,\text{h.c.}})\right] + \theta\underbrace{\frac{g^2}{32\pi^2}G^{a}_{\mu\nu}\widetilde{G}^{a\mu\nu}}_{\text{CP-violating non-perturbative term}}$$

Purely Strong Force parameter

QCD Observables depend on the physical angle: $\bar{\theta} = \theta - \underbrace{\arg\left(m_u, m_d, m_c, m_s, m_t, m_b\right)}_{\text{Parameters from EW symmetry breaking}}$

A non-zero angle induces measurable effects such as electron and neutron Electric Dipole Moments (EDM):

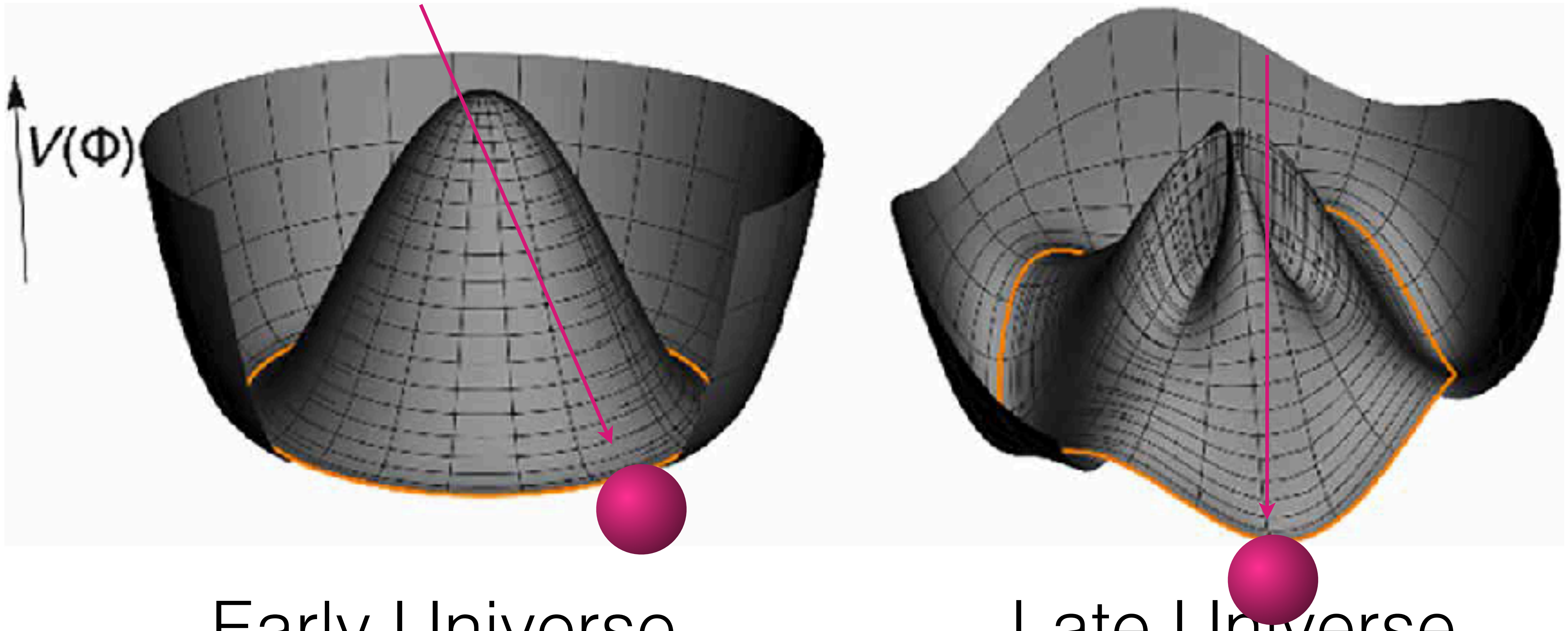
$$\begin{array}{r}\text{Theory}\\ \text{Experiment}\end{array}\begin{cases} d_n \sim 3\times 10^{-16}\times\bar{\theta}\;\; e\cdot cm \\ d_n < 1.8\times 10^{-26}\;\; e\cdot cm\end{cases} \Longrightarrow \bar{\theta} \lesssim 5\times 10^{-11}\ \text{rad}$$

Why that small? This angle could take any value

Peccei-Quinn Axions

True Nambu-Goldstone Boson ($m = 0$)

Pseudo Nambu-Goldstone Boson ($m \neq 0$)



Early Universe (T > T$_{QCD}$)

Late Universe (T « T$_{QCD}$)

Spontaneous Symmetry Breaking

$$m_a = (5.700{\pm}0.007){\times}10^{-6}\,\text{eV}\left(\frac{10^{12}\,\text{GeV}}{f_a}\right)$$

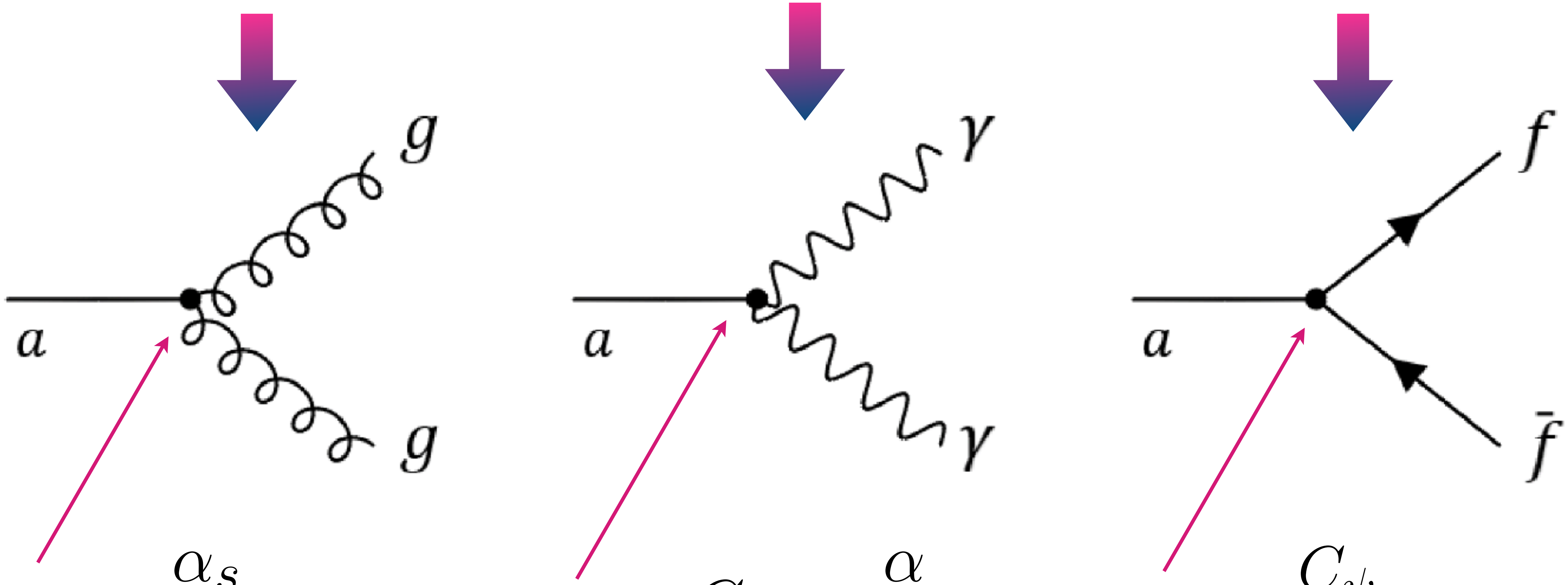
- Introduce a new global symmetry U(1)$_{PQ}$ - Sombrero potential
- Equivalent to introducing a new boson field (like the Higgs) - the axion $a = \bar{\theta} f_a$
- Early Universe - a can take any value along the minima circle
- Late Universe - after QCD phase transition (baryogenesis) - the potential deforms - discrete minima with one at $\bar{\theta} = 0$
- Axion field trapped in a well $V(a) \simeq 1/2\, m_a^2 a^2$ where m_a is the mass of the axion field

Axion Interactions

$$\mathcal{L} \supset \frac{g_{agg}}{4} a G_{\mu\nu} \widetilde{G}^{\mu\nu} + \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \widetilde{F}^{\mu\nu} + \frac{g_{a\psi\psi}}{2} \partial_\mu a \overline{\psi} \gamma^\mu \gamma_5 \psi$$

Axion Interactions

$$\mathcal{L} \supset \frac{g_{agg}}{4} a G_{\mu\nu}\widetilde{G}^{\mu\nu} + \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\widetilde{F}^{\mu\nu} + \frac{g_{a\psi\psi}}{2}\partial_\mu a \overline{\psi}\gamma^\mu\gamma_5\psi$$



$$g_{agg} = \frac{\alpha_s}{2\pi f_a}$$

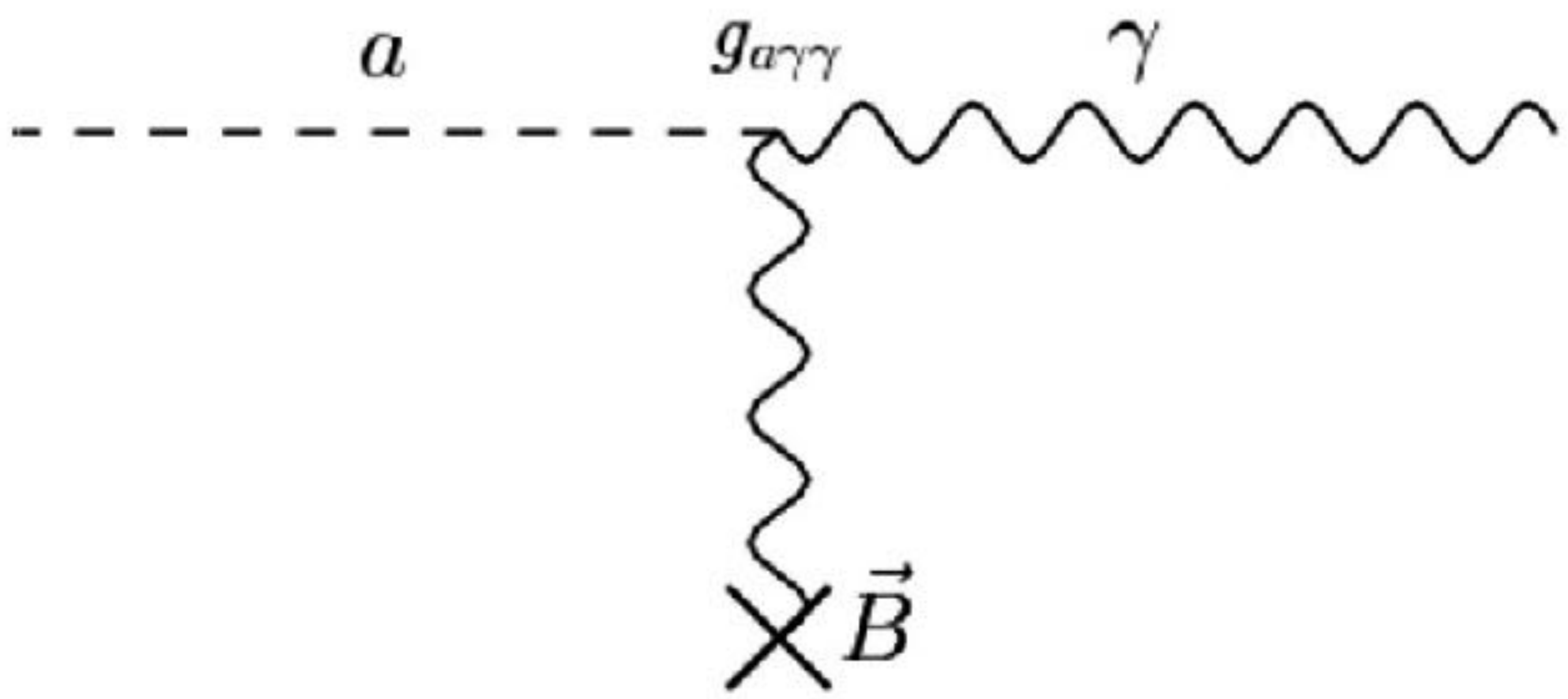
$$g_{a\gamma\gamma} = C_{a\gamma\gamma}\frac{\alpha}{2\pi f_a}$$

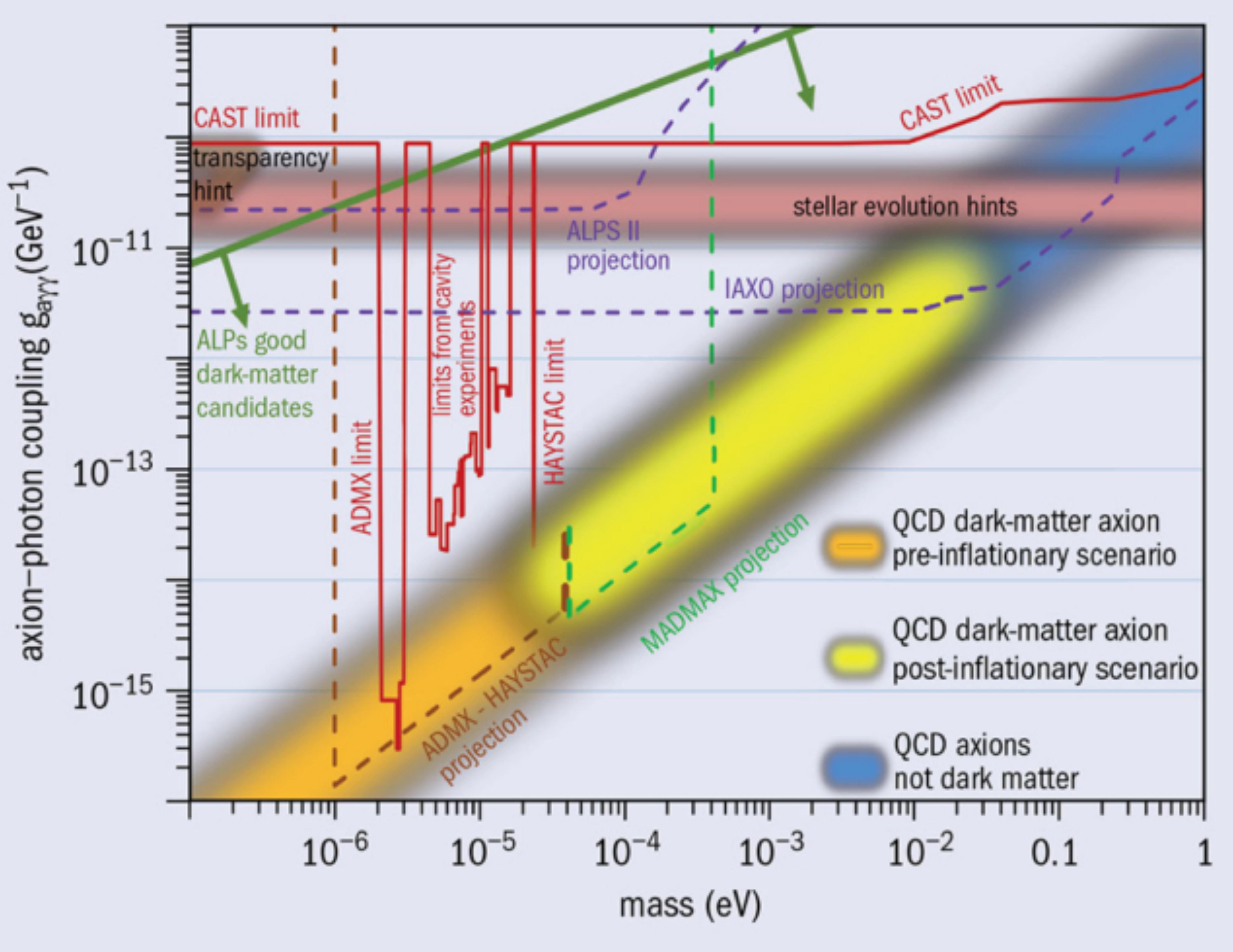
$$g_{a\psi\psi} = \frac{C_\psi}{f_a}$$

Interactions and Parameter Space

$$\mathcal{H} \supset g_{a\gamma\gamma}\sqrt{\frac{\varepsilon_0}{\mu_0}}\int a\,\mathbf{E}\cdot\mathbf{B}\,dV$$

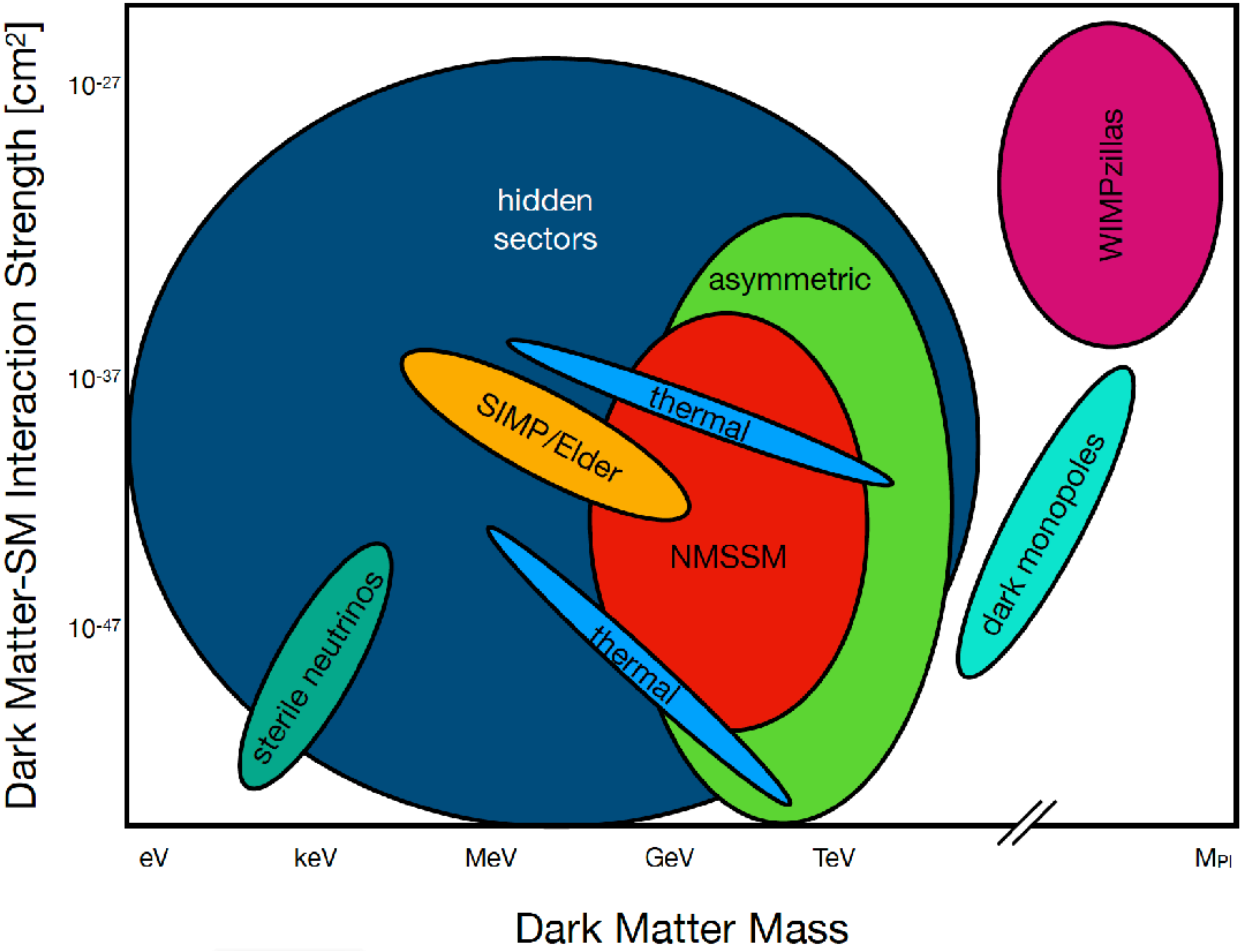
← Low-energy Hamiltonian





$$\left.\begin{array}{l} m_a \propto \dfrac{1}{f_a} \\[2ex] g_{a\gamma\gamma} \propto \dfrac{1}{f_a} \end{array}\right\} m_a \propto g_{a\gamma\gamma}$$

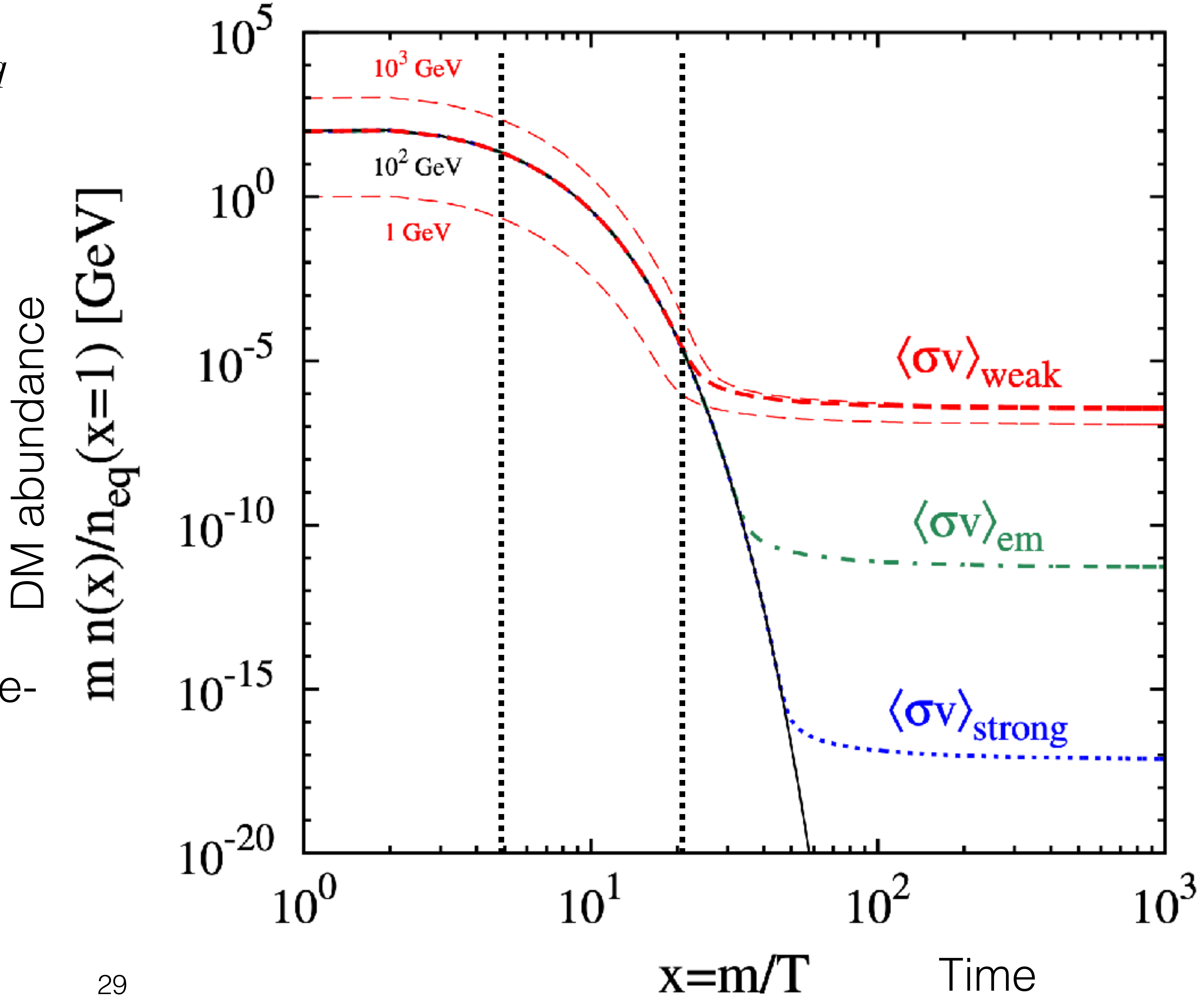
WIMP-like Candidates



- **W**eakly **I**nteracting **M**assive **P**articles
- Umbrella term for different models
- Originally referring to supersymmetry

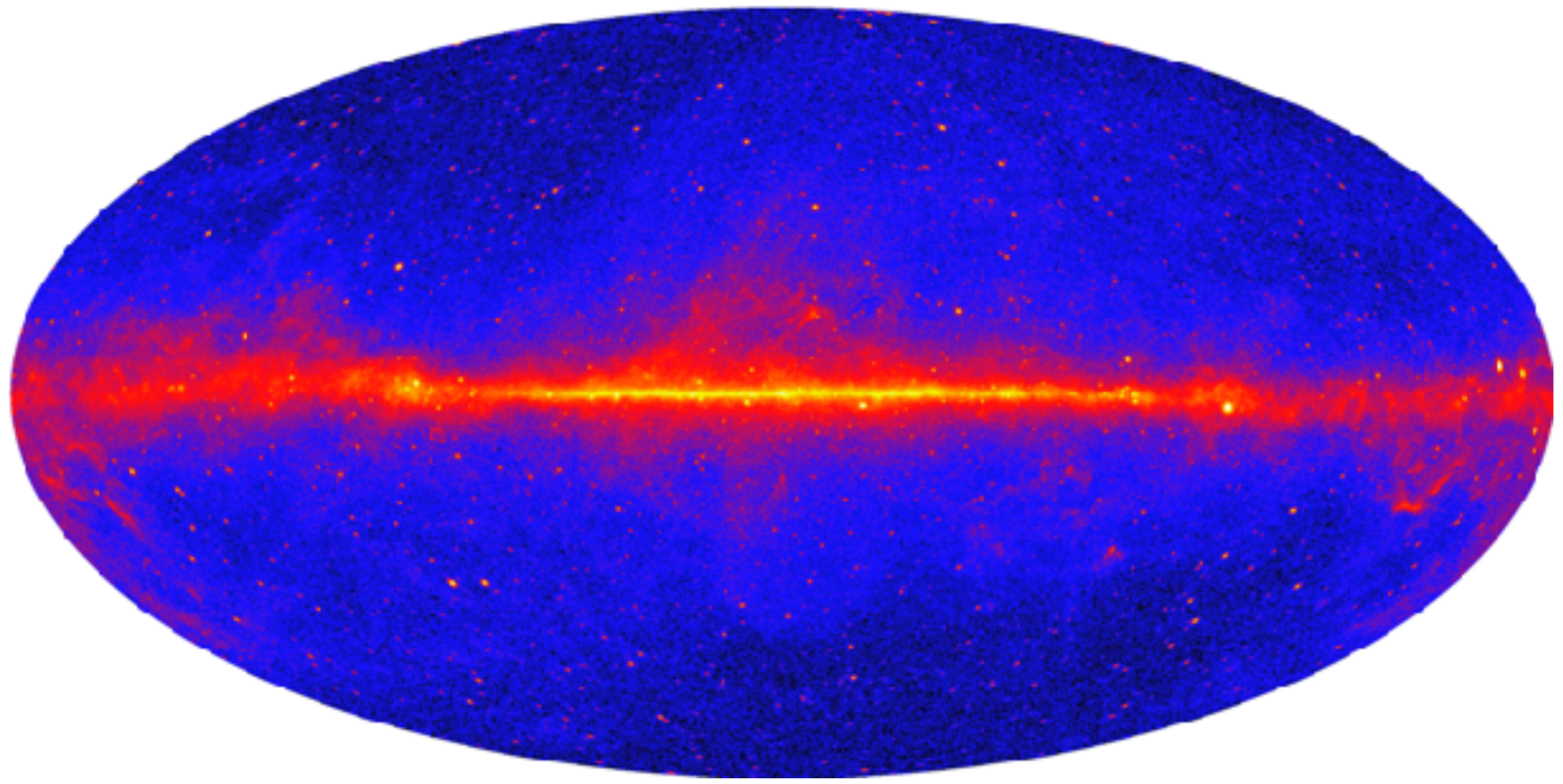
WIMP Thermal Production

- Equilibrium: $T \gg m_\chi$ and $\Gamma_{ann} = \langle \sigma_{ann} v \rangle n_{eq}$
  $\chi\bar{\chi} \leftrightarrow e^+e^-, q\bar{q}, W^+W^-, HH, \ldots$
- Cool-down: $T \sim m_\chi \Rightarrow \Gamma_{\text{prod}} \sim e^{-m_\chi/T}$ and WIMP density is diluted by the expansion
- Freeze-out: $T \ll m_\chi \Rightarrow \Gamma_{\text{prod}} \sim 0$ and $\Gamma_{\text{ann}} < H$
- Weaker cross-sections produce higher freeze-out abundances
- WIMP Miracle: $\langle \sigma_{ann} v \rangle : \Omega_{DM} \sim 0.3$ and $\sigma_{ann} \sim \sigma_{weak} \Rightarrow$ WIMPs can be observed!

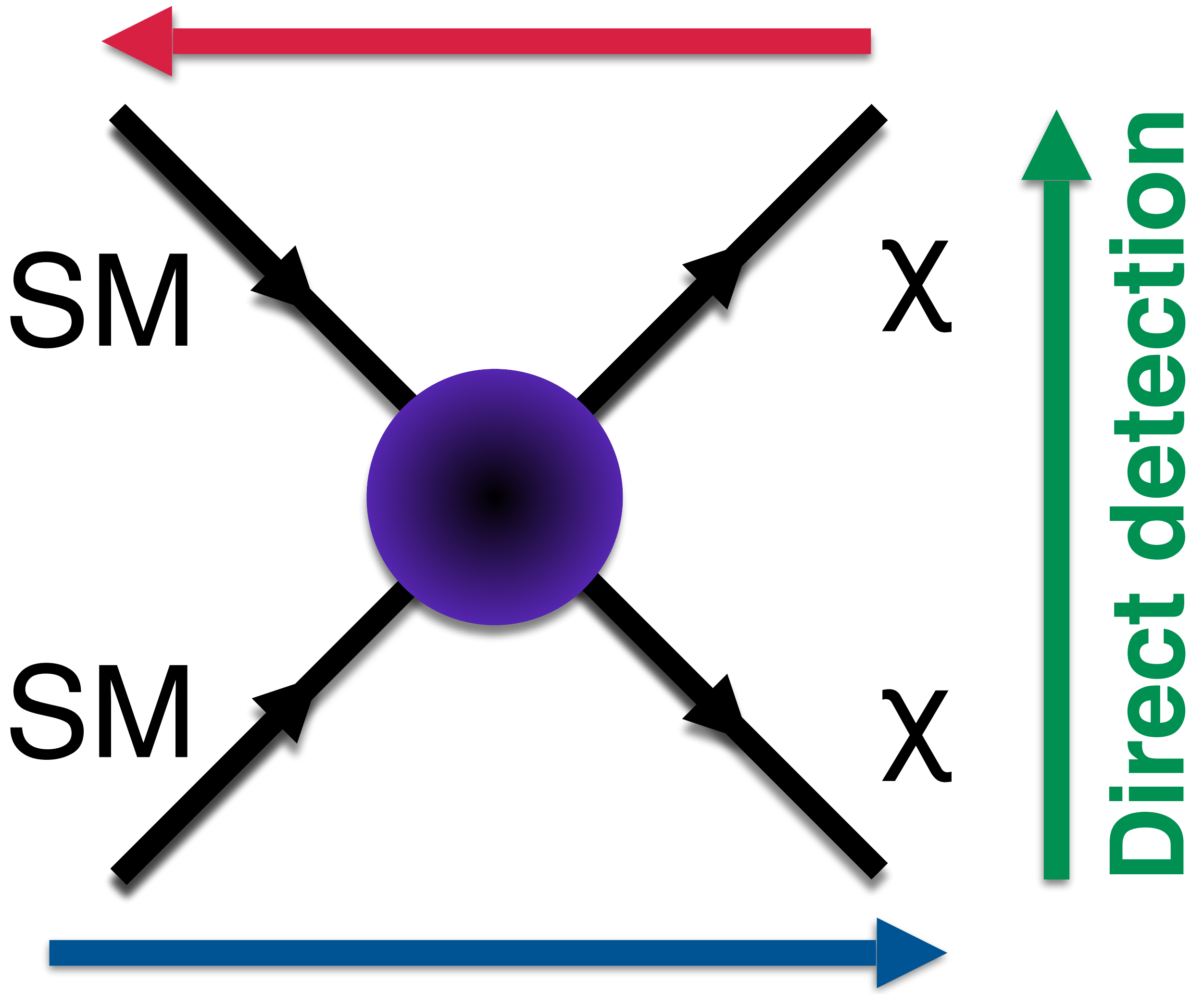


Experimental Search Techniques

How to?



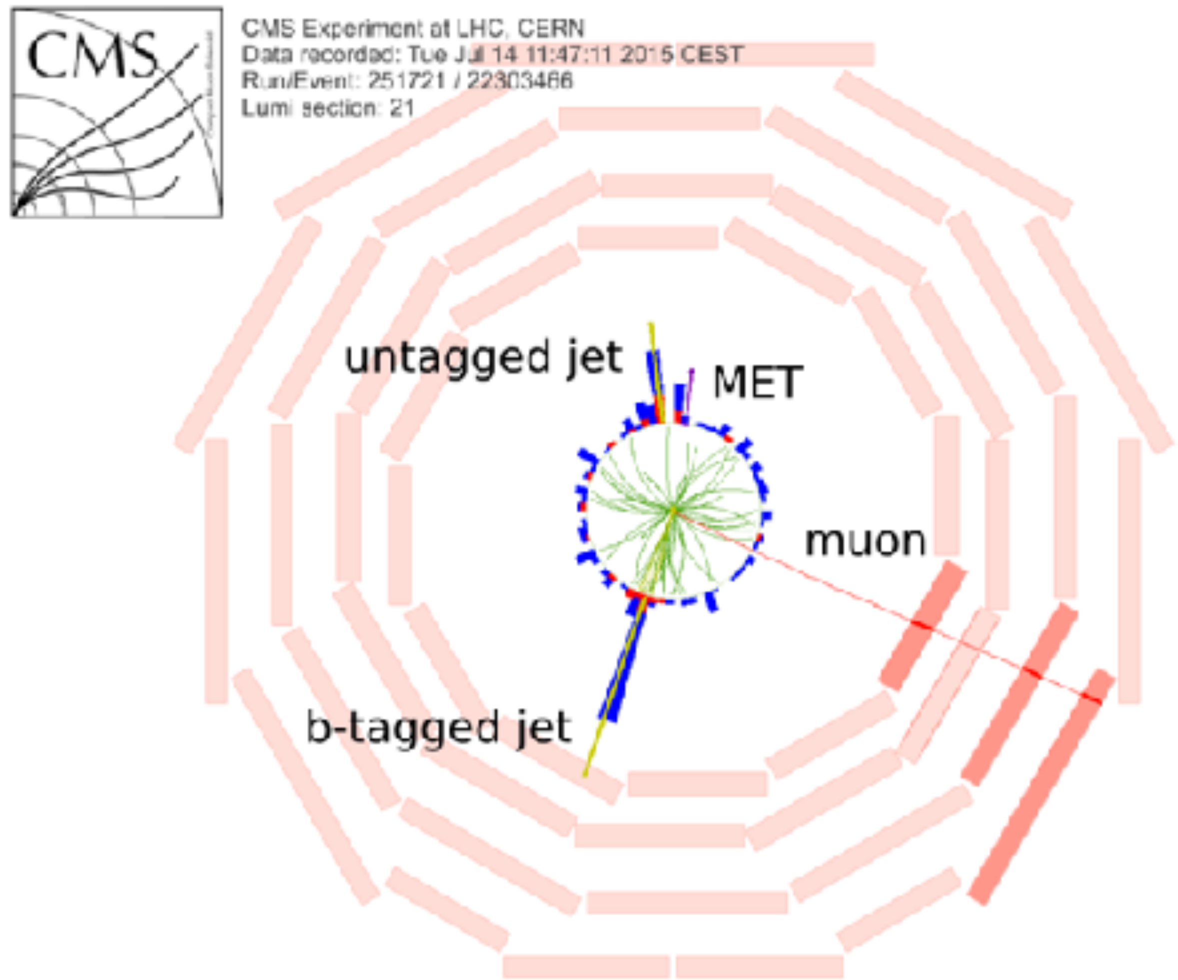
Indirect detection

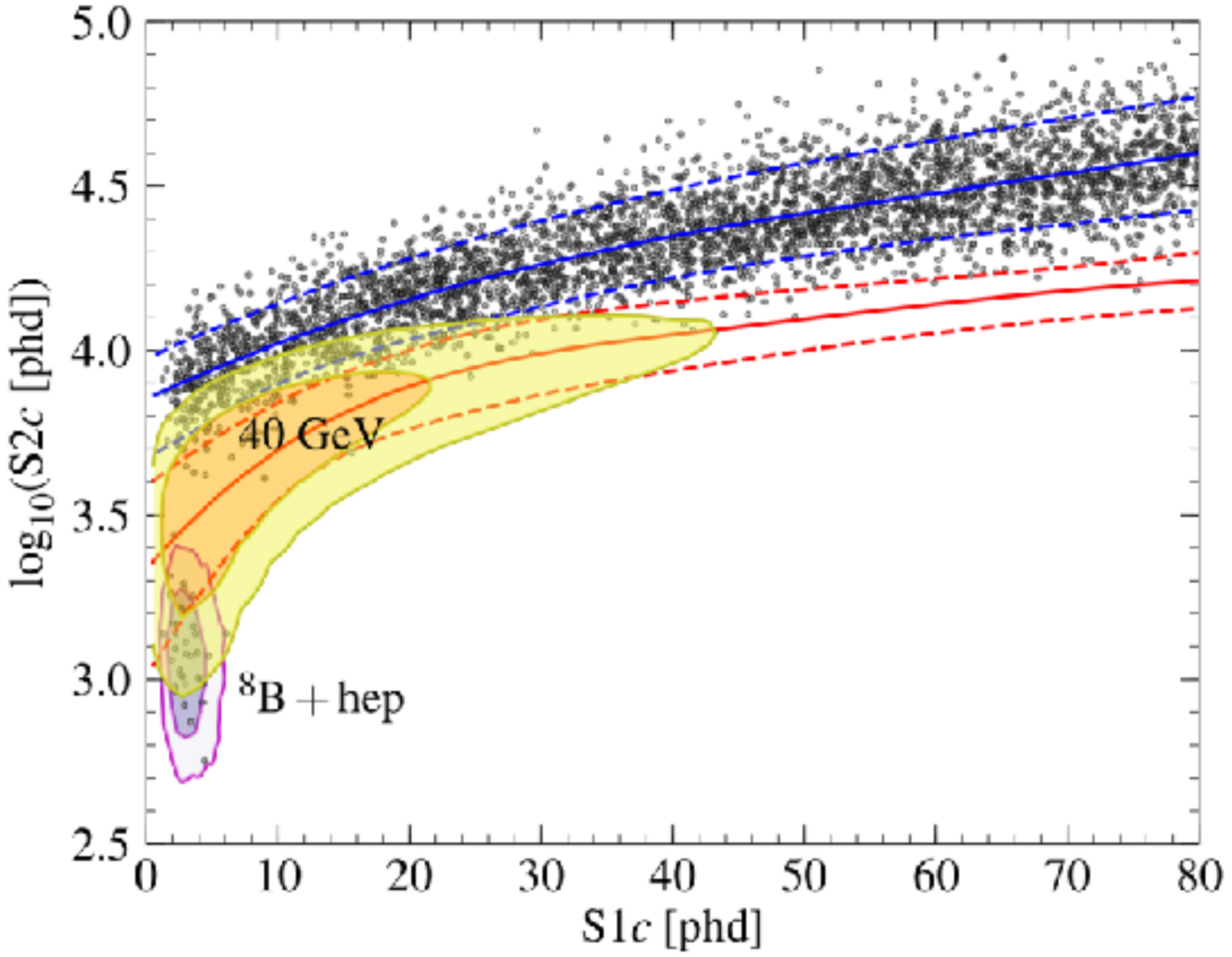


Direct detection

Production

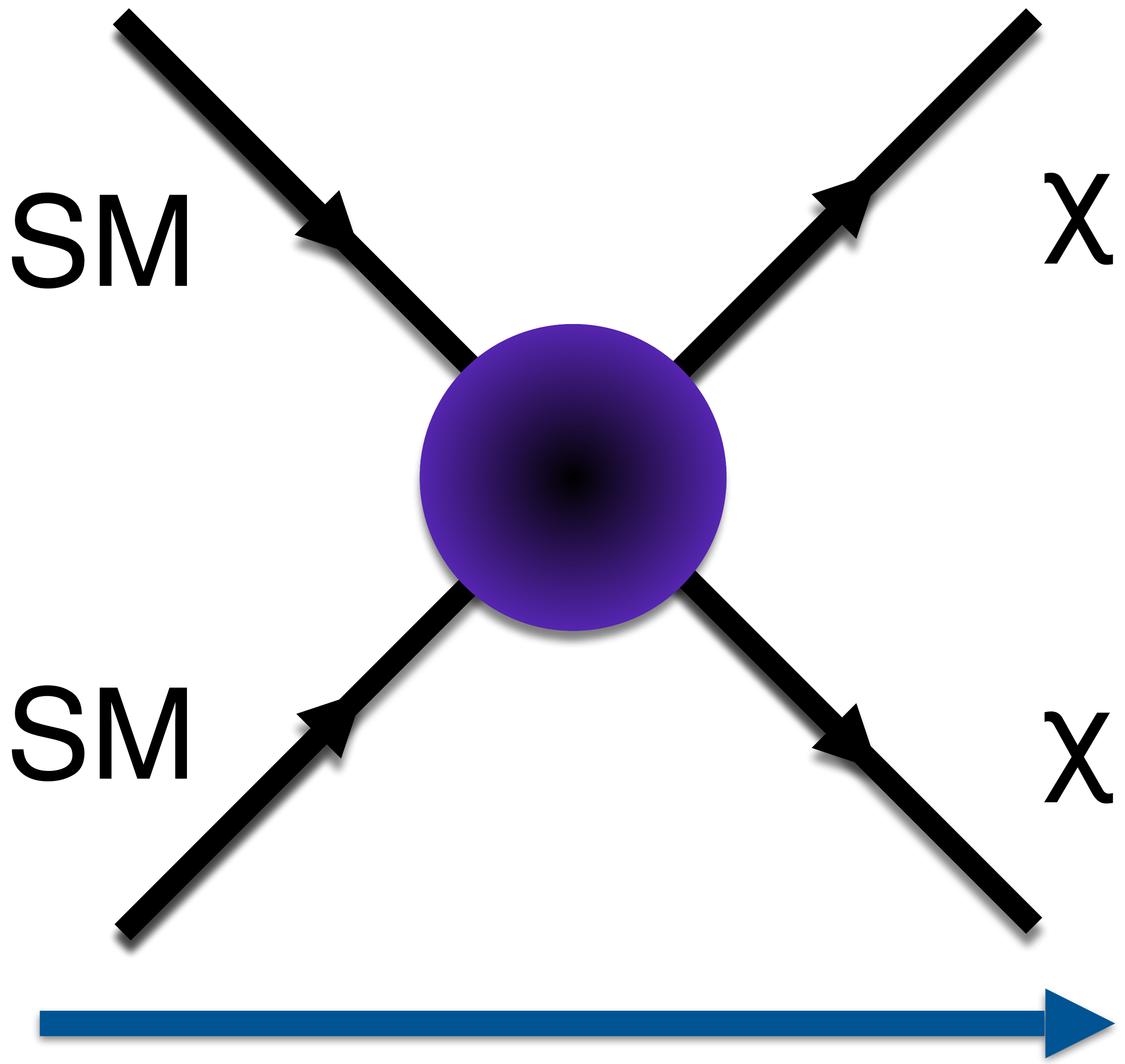
- Annihilation in SM particles
- Universe is our lab! ✔
- Mostly space-based detectors ✘
- Background fluxes difficult to predict ✘





- Scattering with SM particles
- Spans over many orders of magnitude in mass ✔
- Depends on local ρ_{DM} ✘
- Rare events and huge bkg ✘

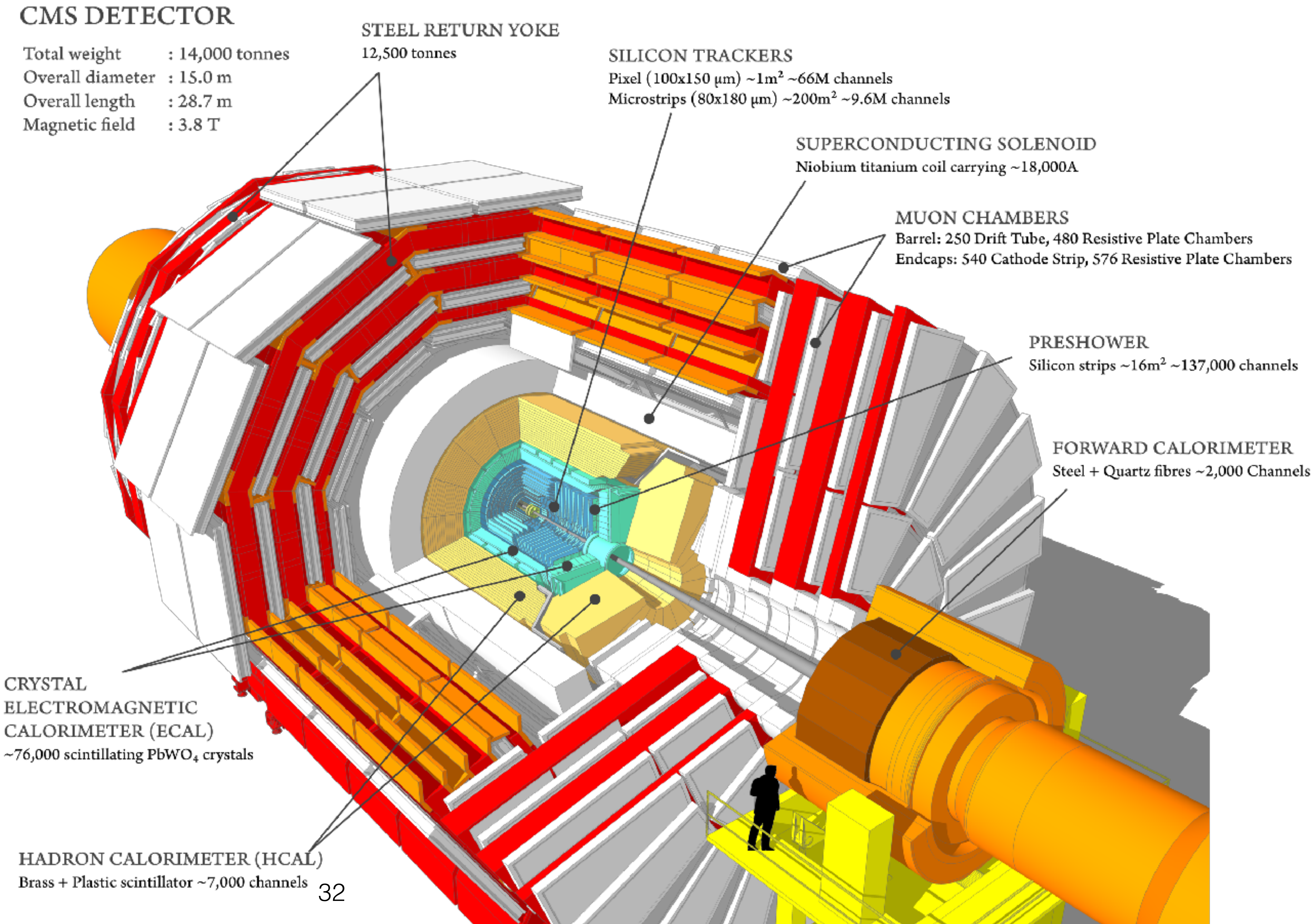
Production



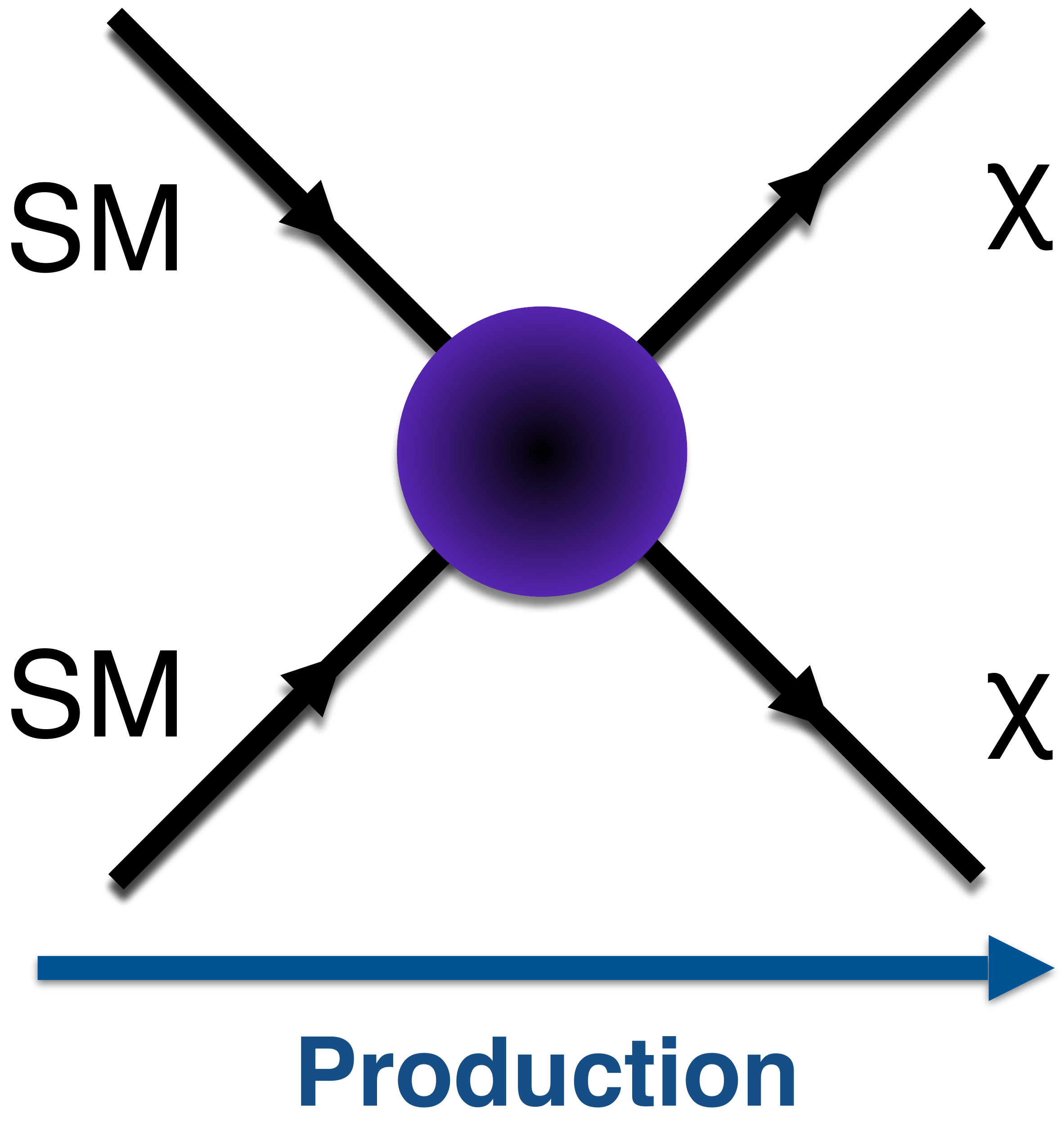
Production

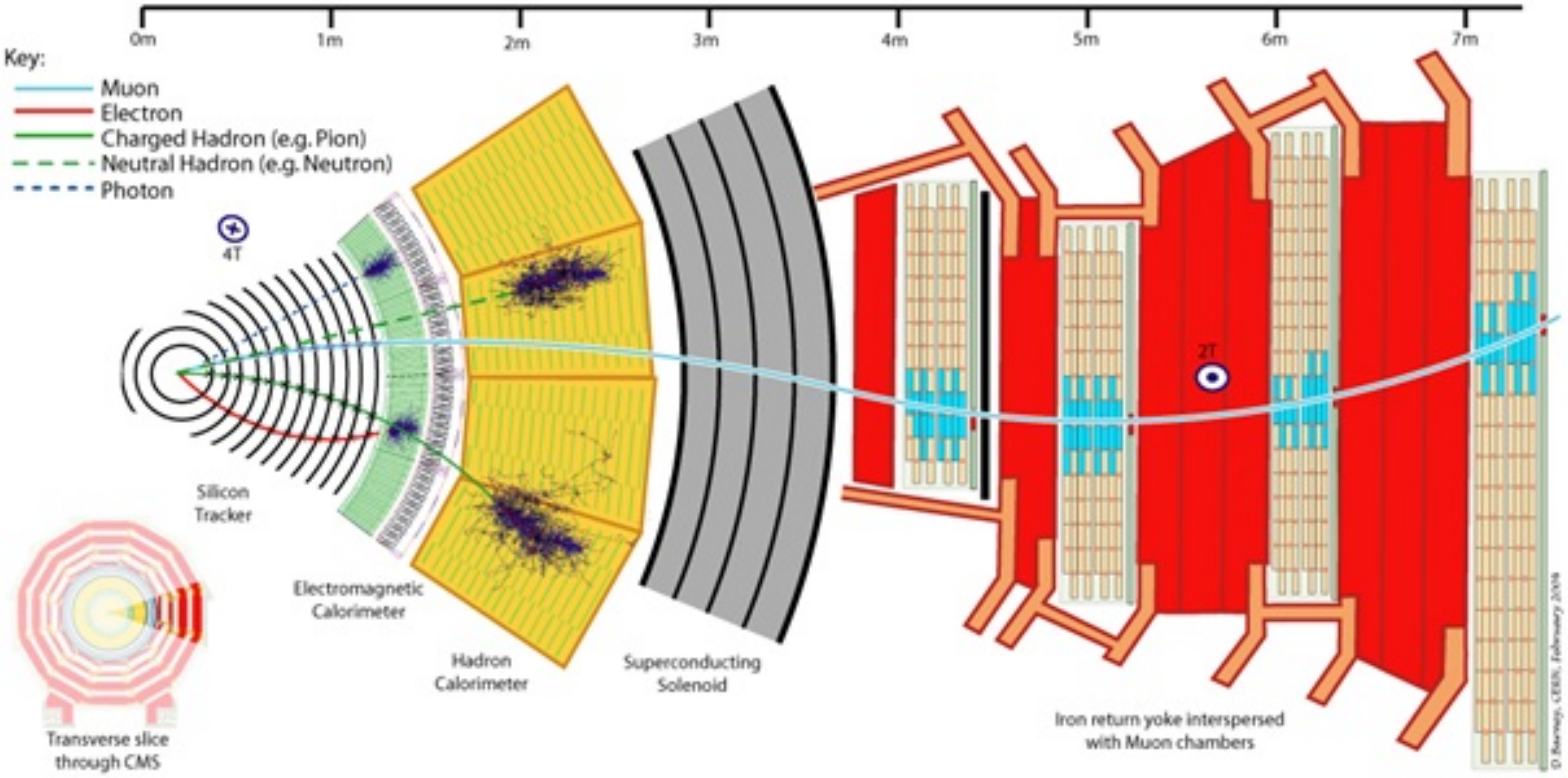
~10^9 pp collisions/s @13TeV

4 experiments at collision points



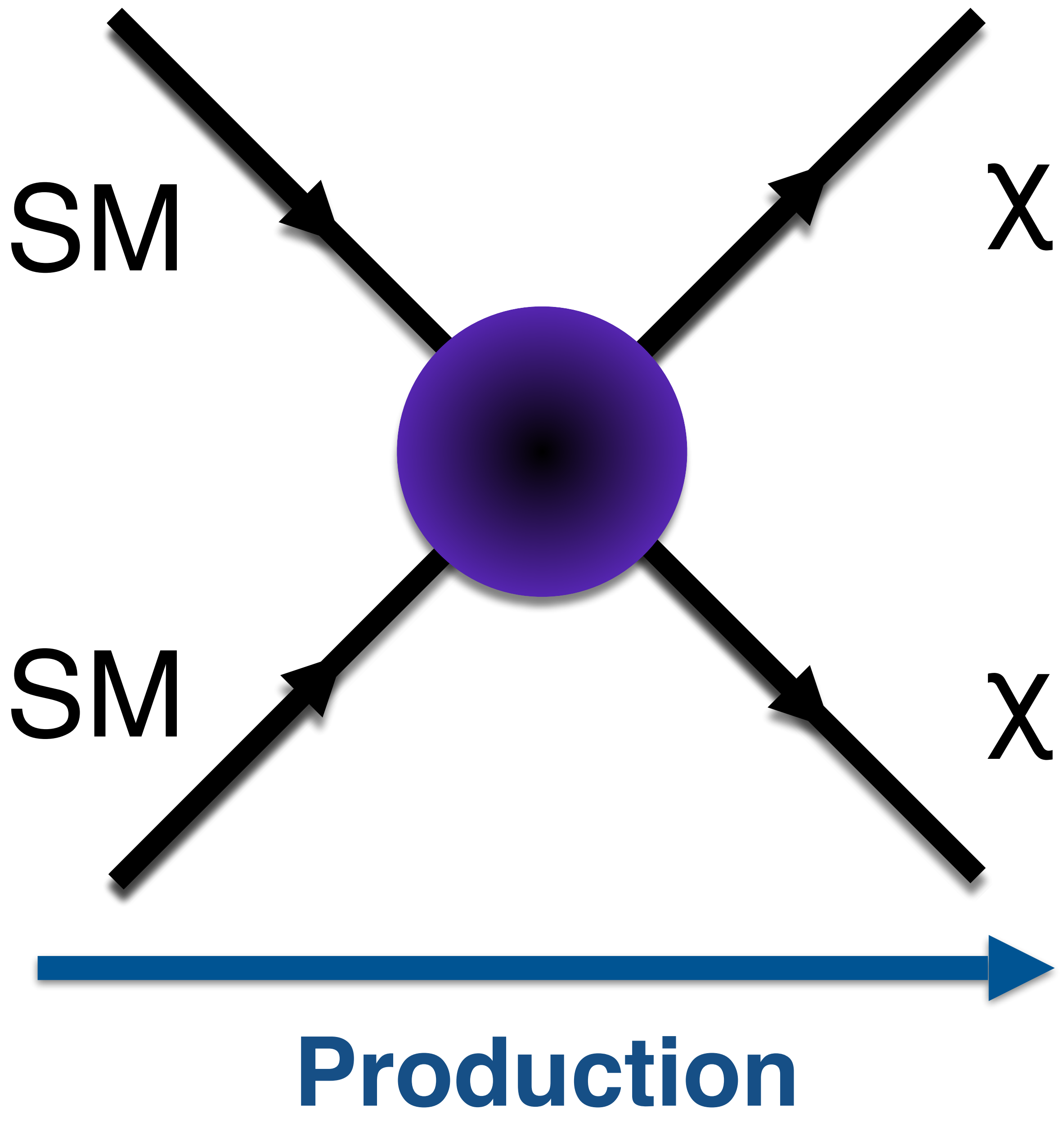
Production

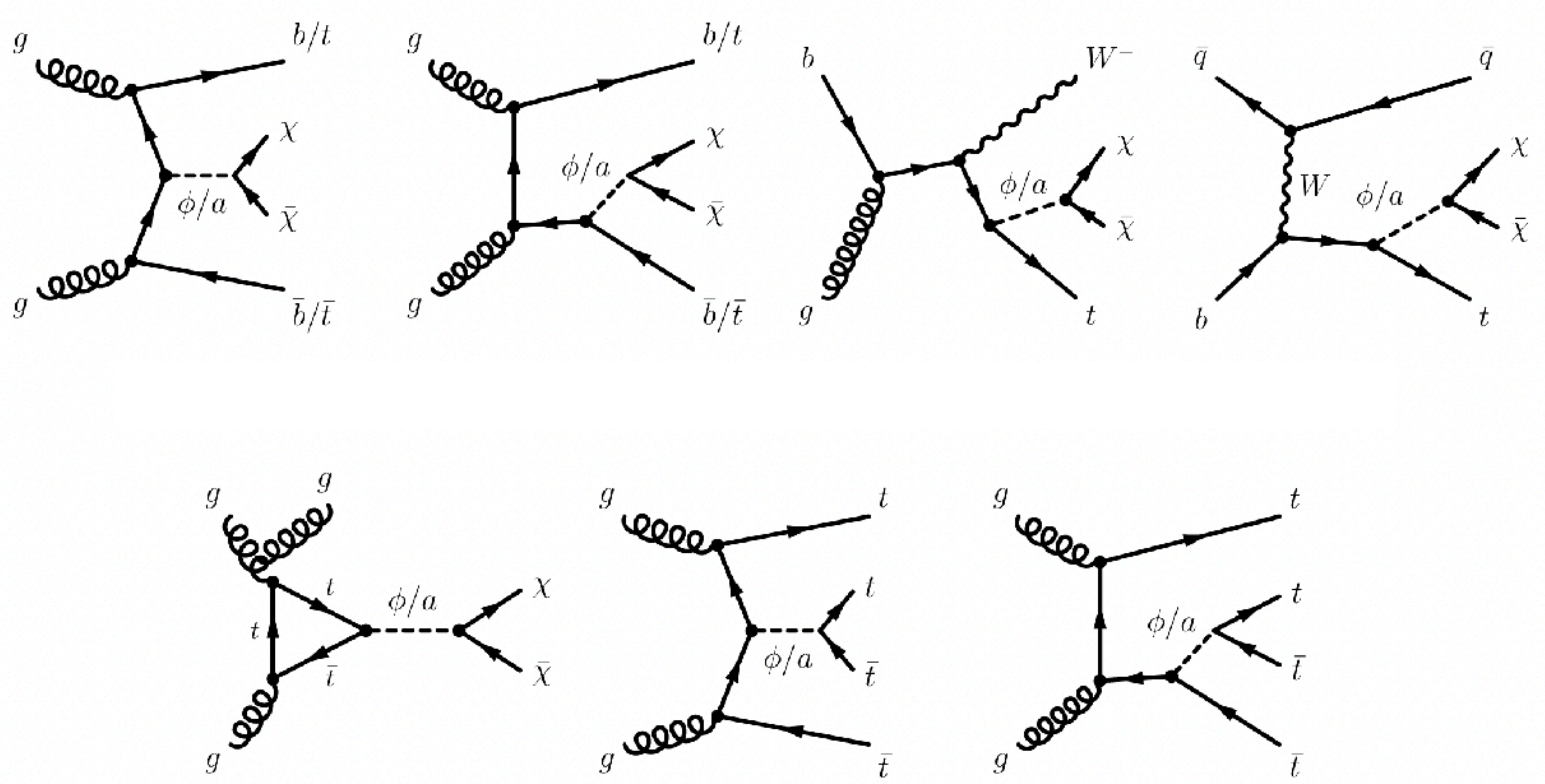




- ~4π detectors to record ~all particles produces in each collision
- Particle identification + energy/momentum reconstruction
- Virtually only DM (and neutrinos) escape undetected

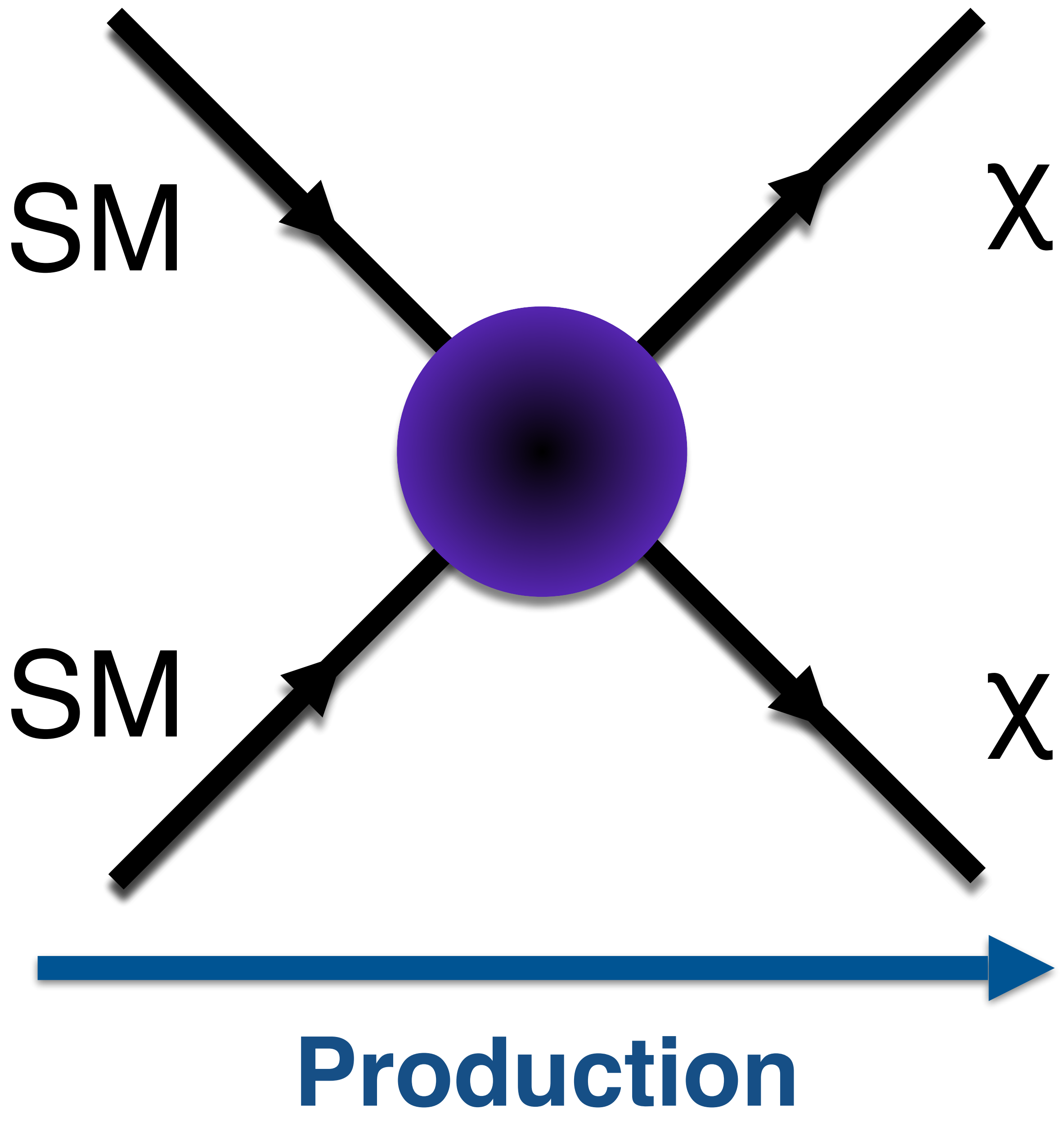
Production



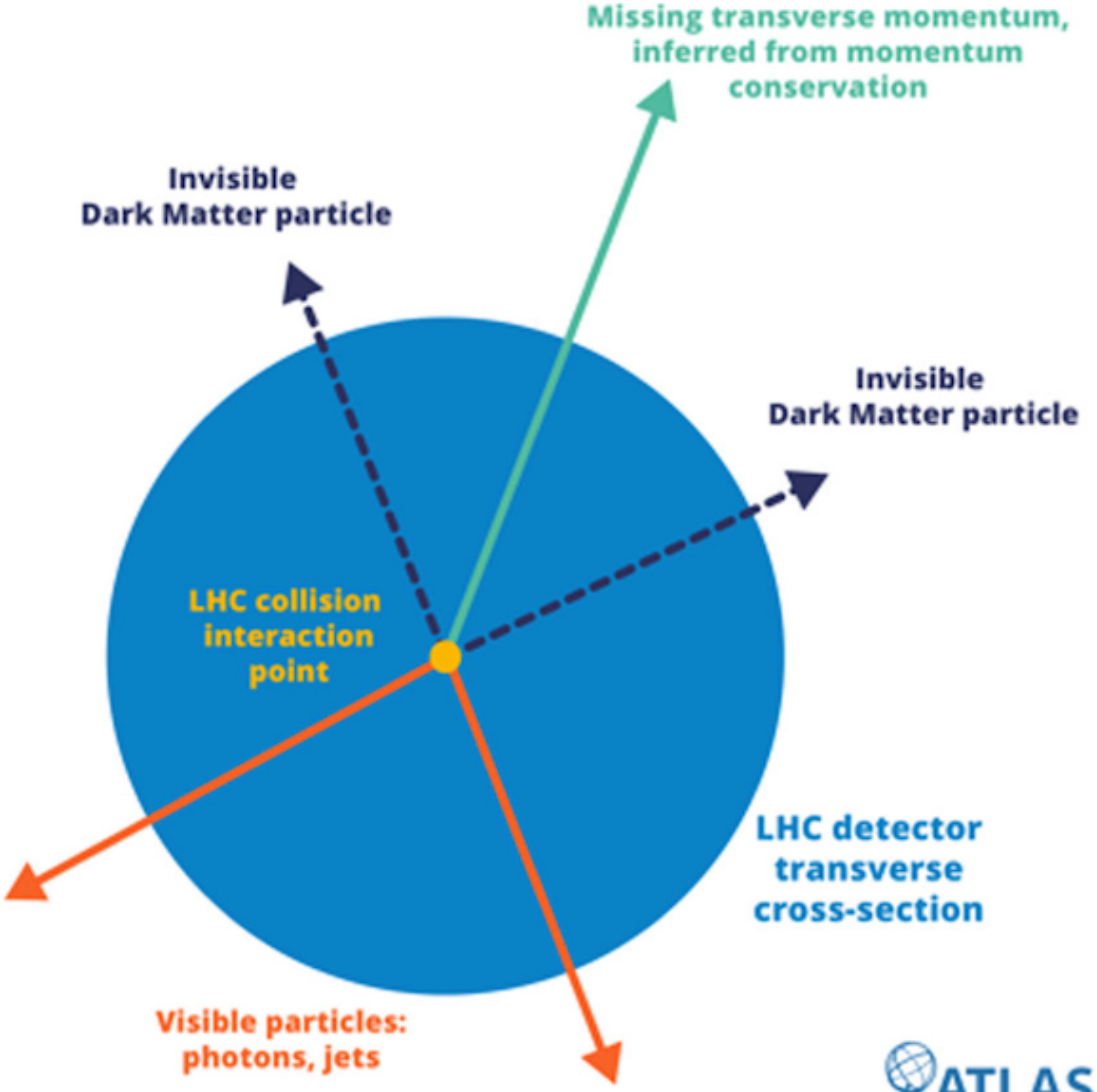


- Simplified models: SM + 1 mediator + 1 DM Dirac fermion
- Visible models: mediator is produced, then decays to SM
- Semi-visible models: mediator is produced, then decays to DM

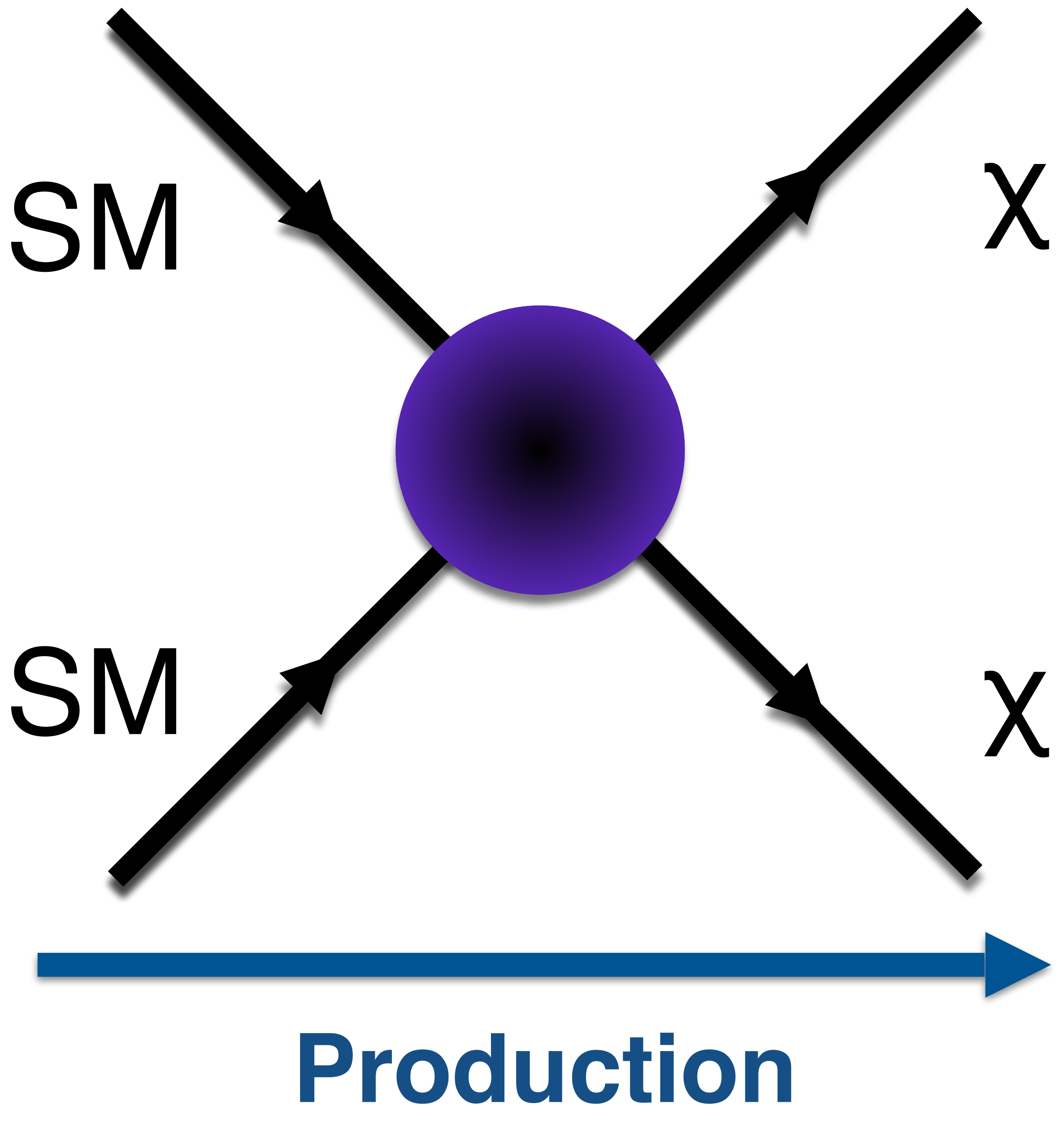
Production


SM
SM
χ
χ
Production

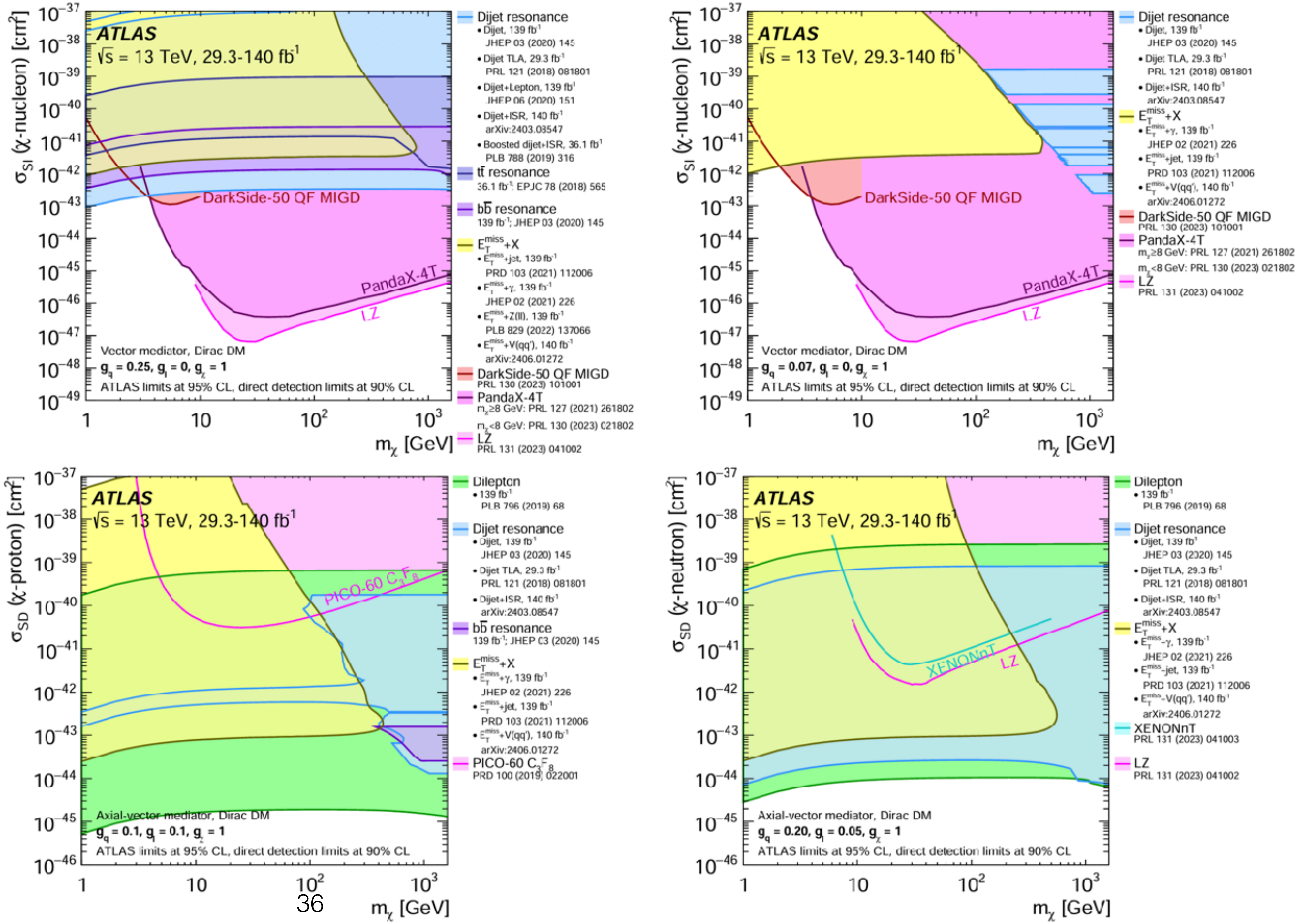

ALICE
CMS
ATLAS
LHCb


Missing transverse momentum, inferred from momentum conservation
Invisible Dark Matter particle
Invisible Dark Matter particle
LHC collision interaction point
LHC detector transverse cross-section
Visible particles: photons, jets

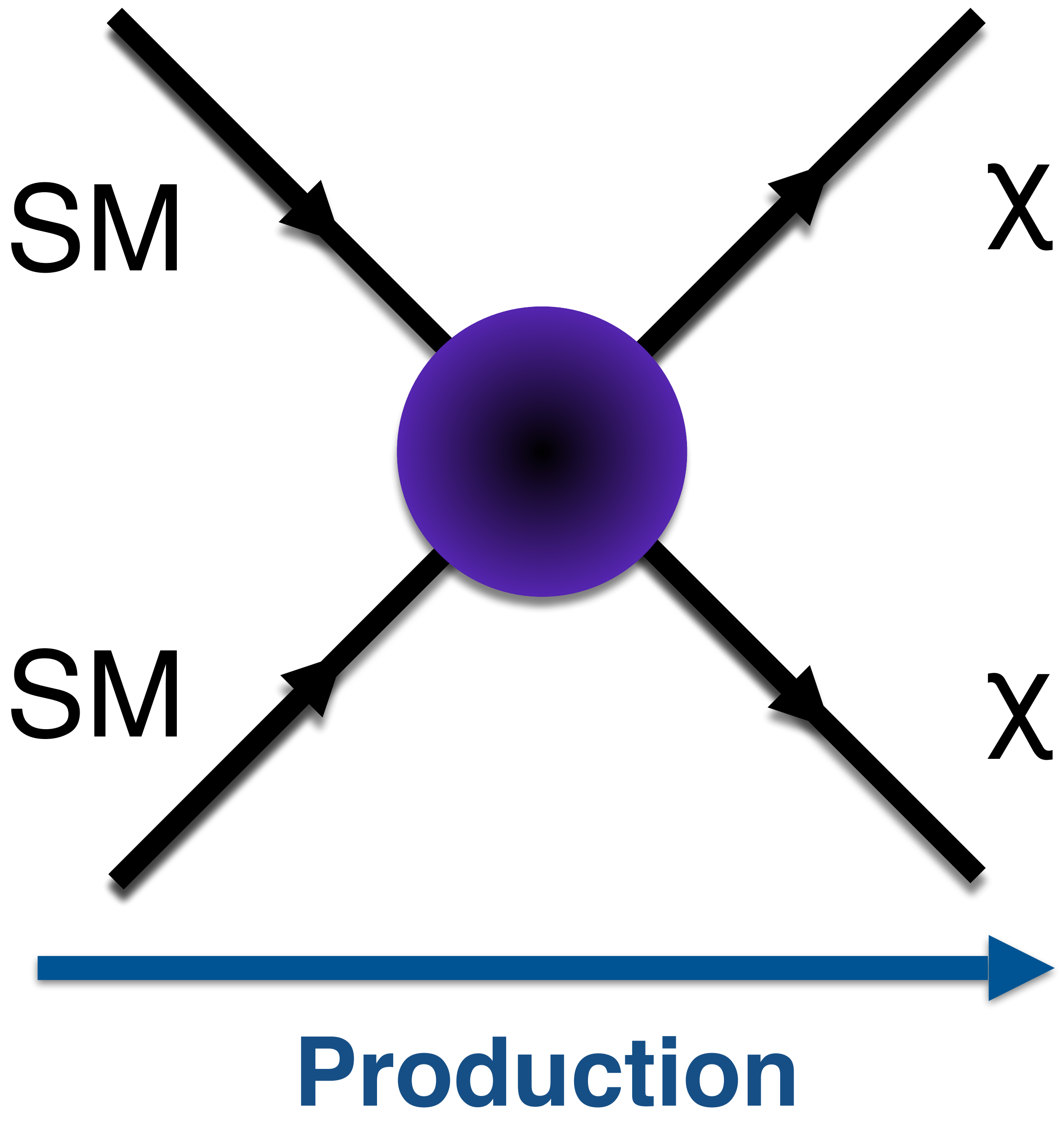
Recent Limits



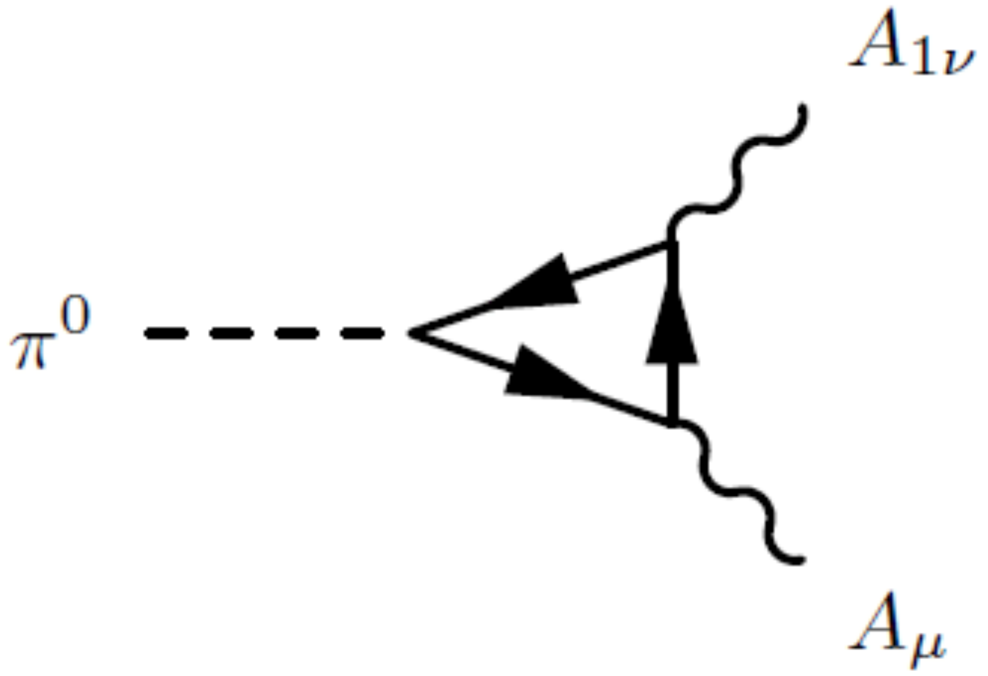
- No positive observations
- Upper limits on the DM-nucleon interaction cross-section

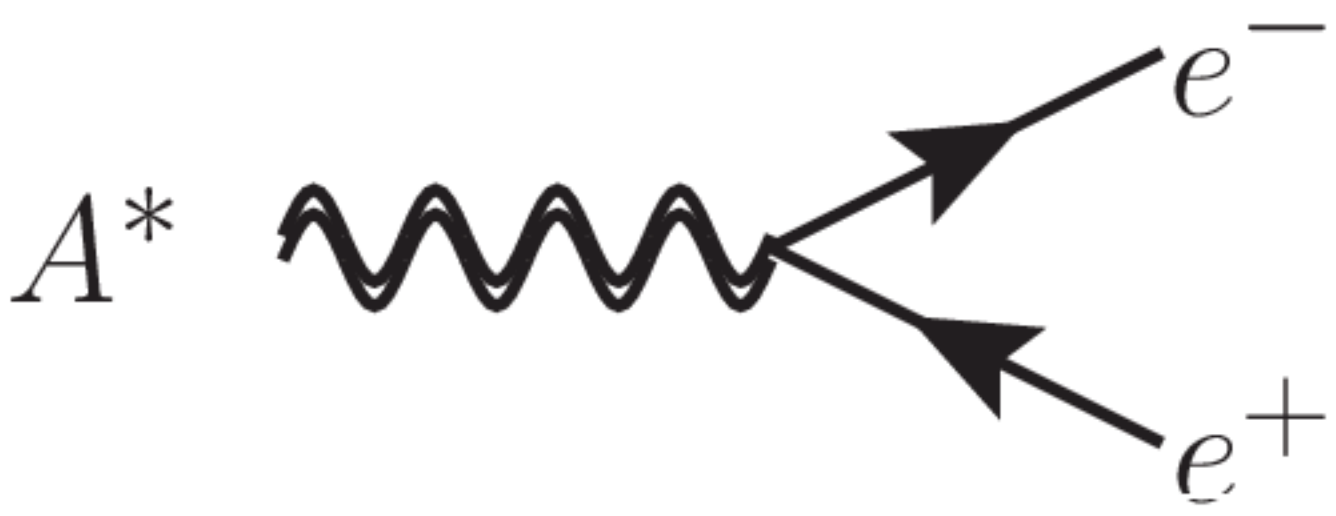


A Lighter Dark Sector

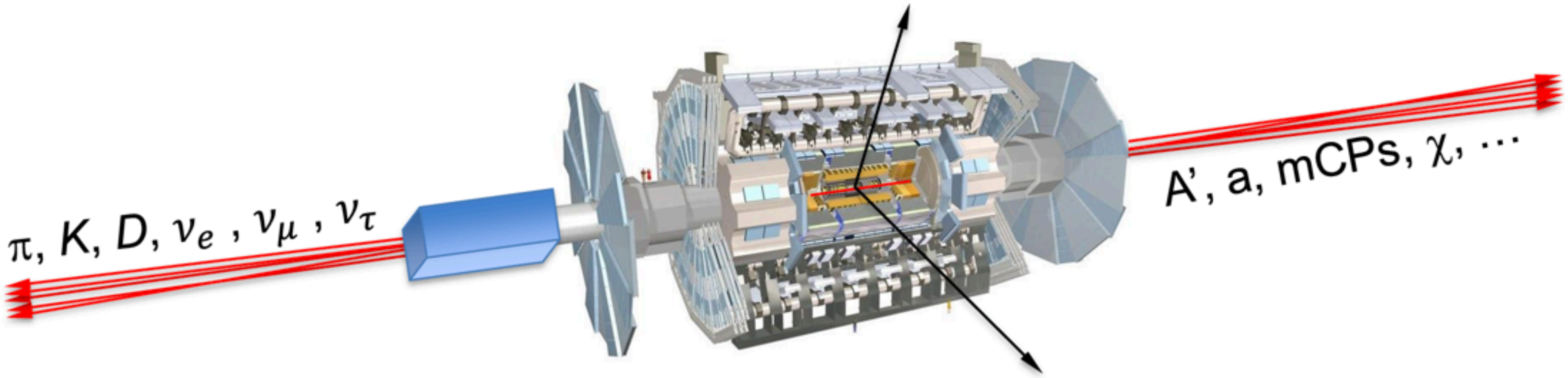


- What if DM is light, with mass ~MeV to GeV?
- Example: dark photon A_1 with ~100 MeV mass
- Produced from decay of neutral particles: $H \to \gamma A_1$

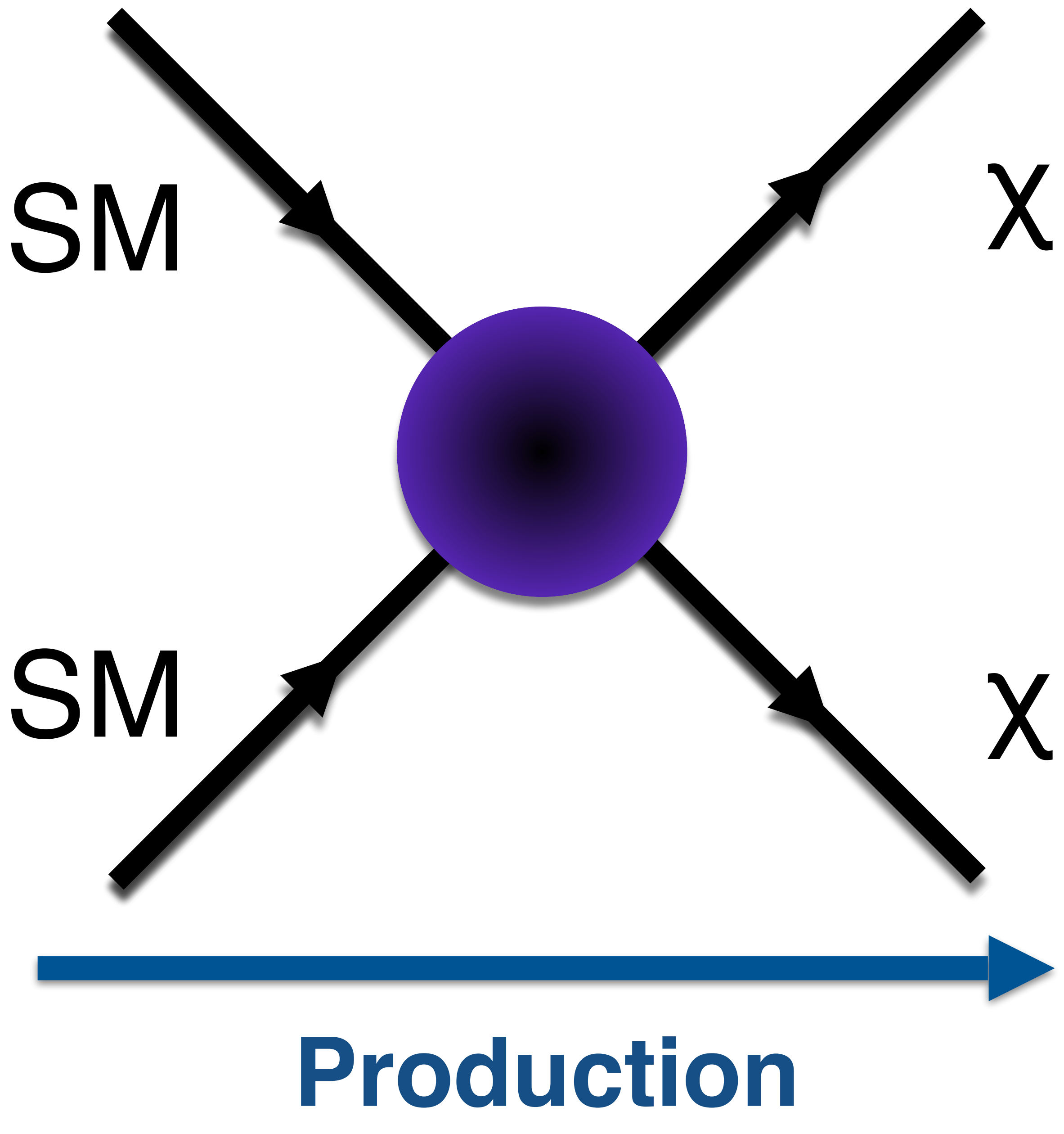




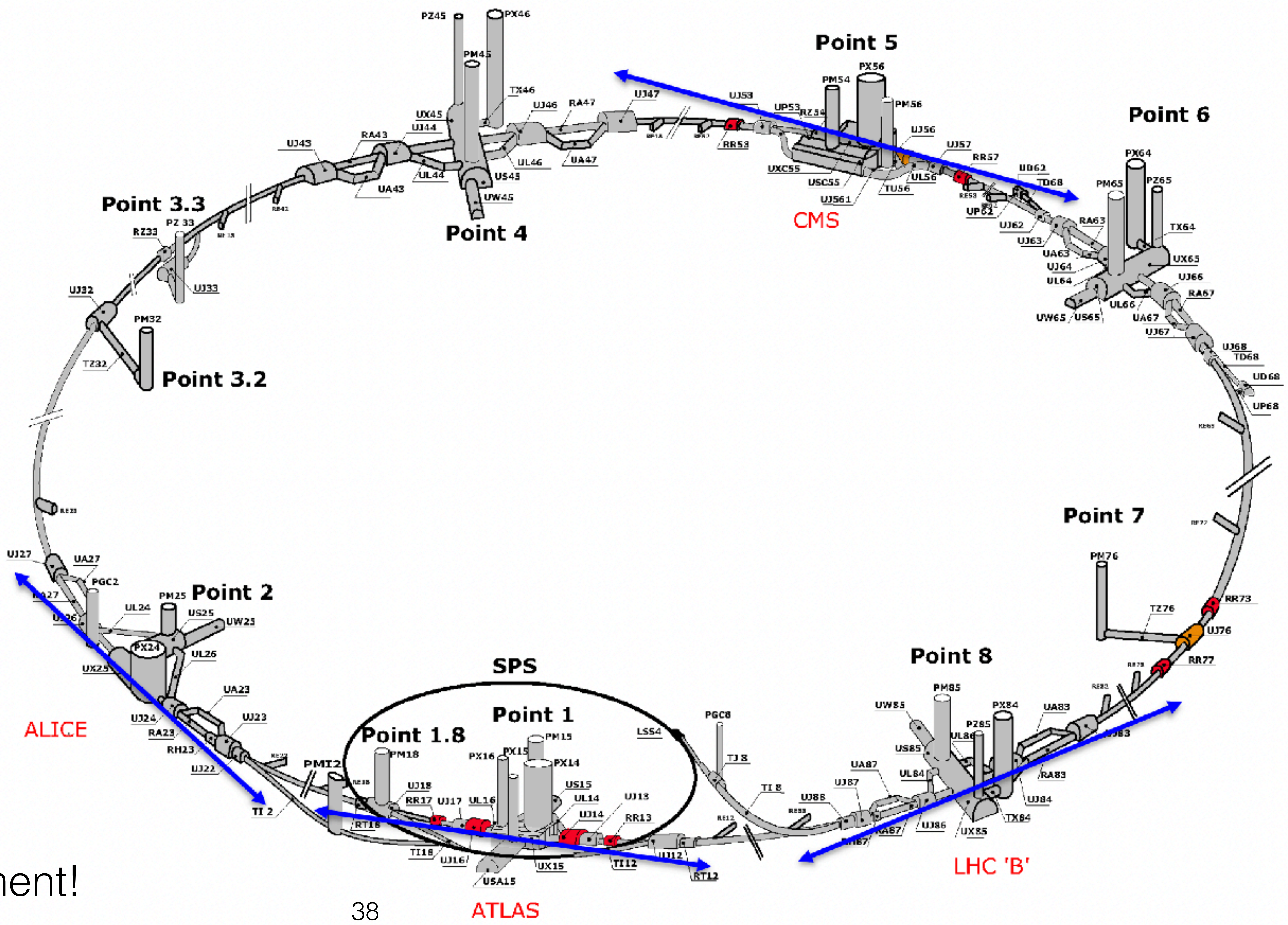
- But H is rarely produced and A_1 has a low mass.
- π^0 production cross-section (~100 mb) is 10^{12} times the Higgs'.
- New search: $\pi^0 \to \gamma A_1$, then $A_1 \to e^+e^-$
- But light particles are produced mostly along the beam axis



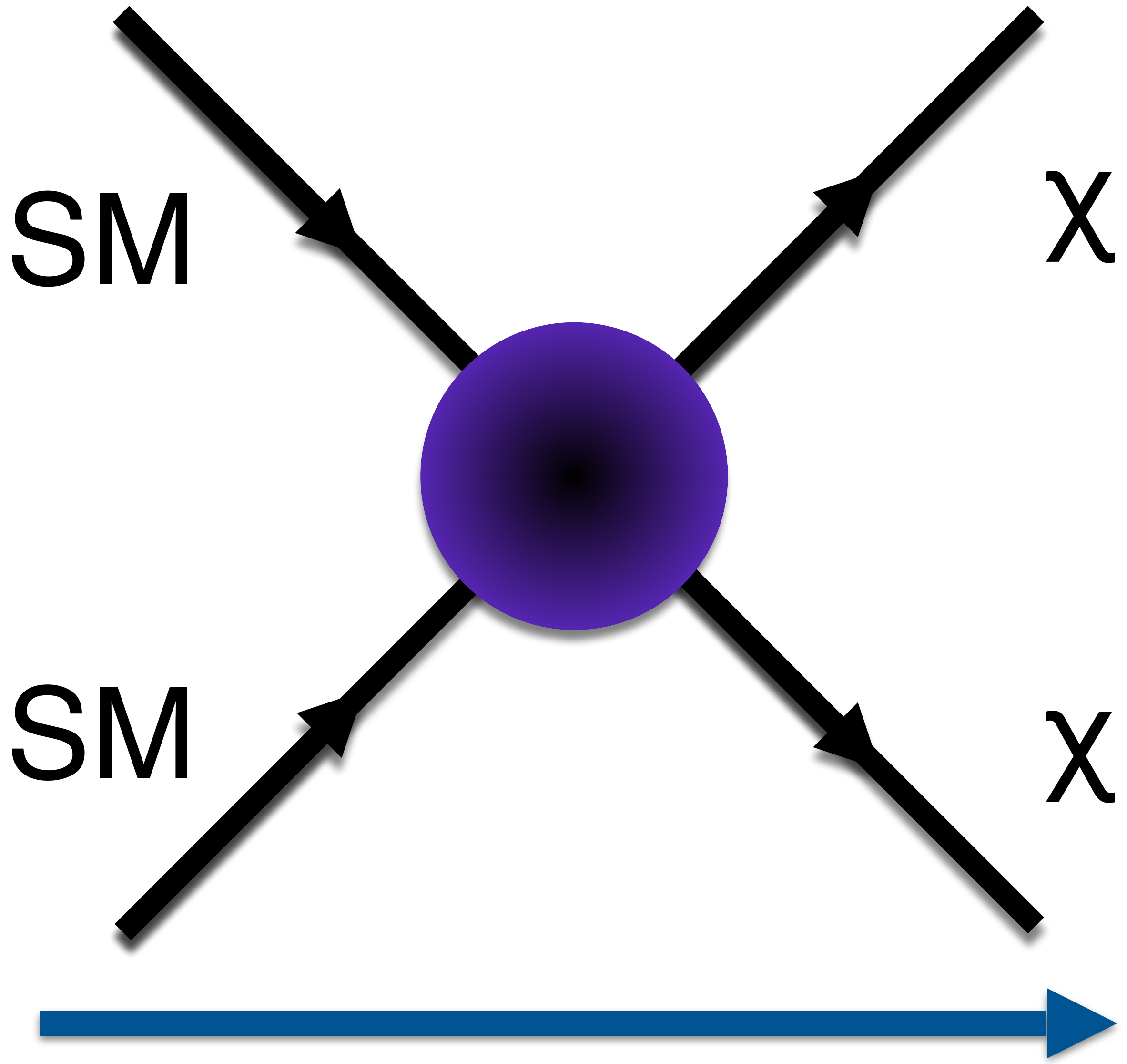
A Lighter Dark Sector



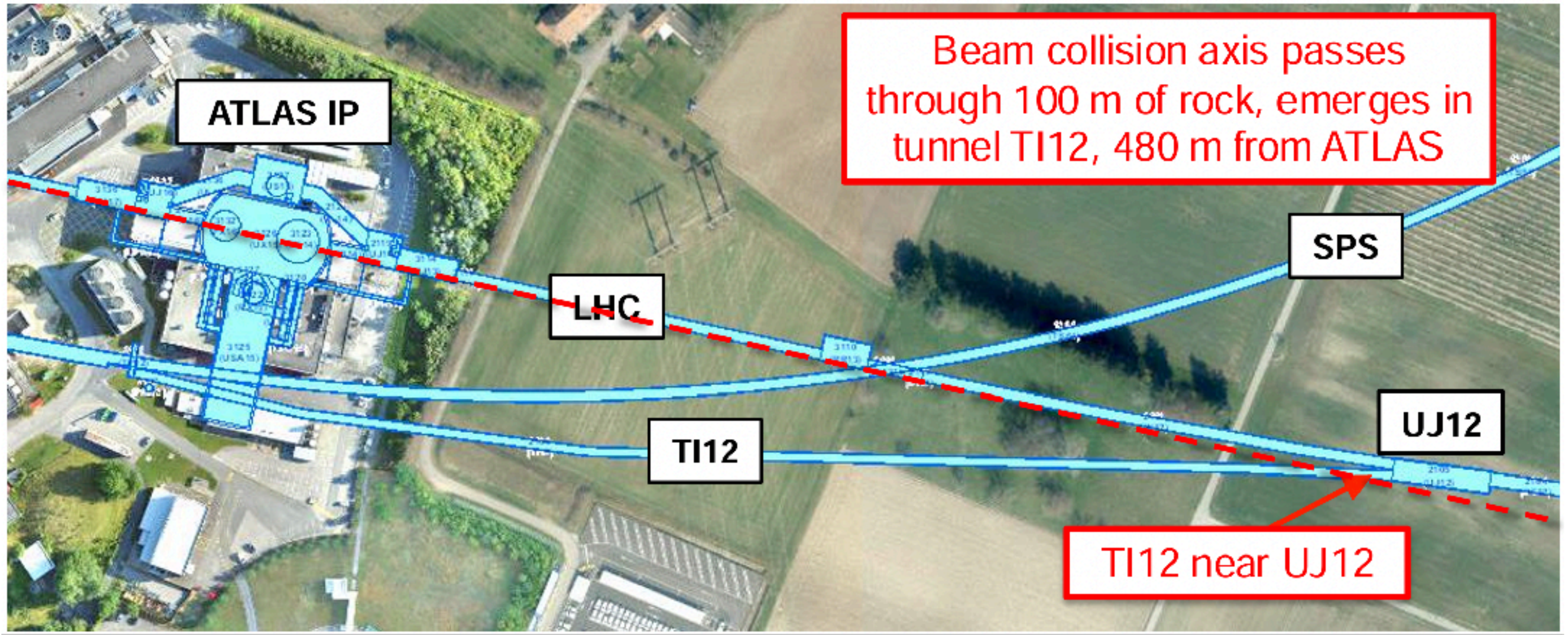
- Exploit LHC circular geometry
- Place experiments along the blue tangent lines
- DM particles don't care about traveling through rock and cement!



A Lighter Dark Sector



Production



Beam collision axis passes through 100 m of rock, emerges in tunnel TI12, 480 m from ATLAS

TI12 near UJ12

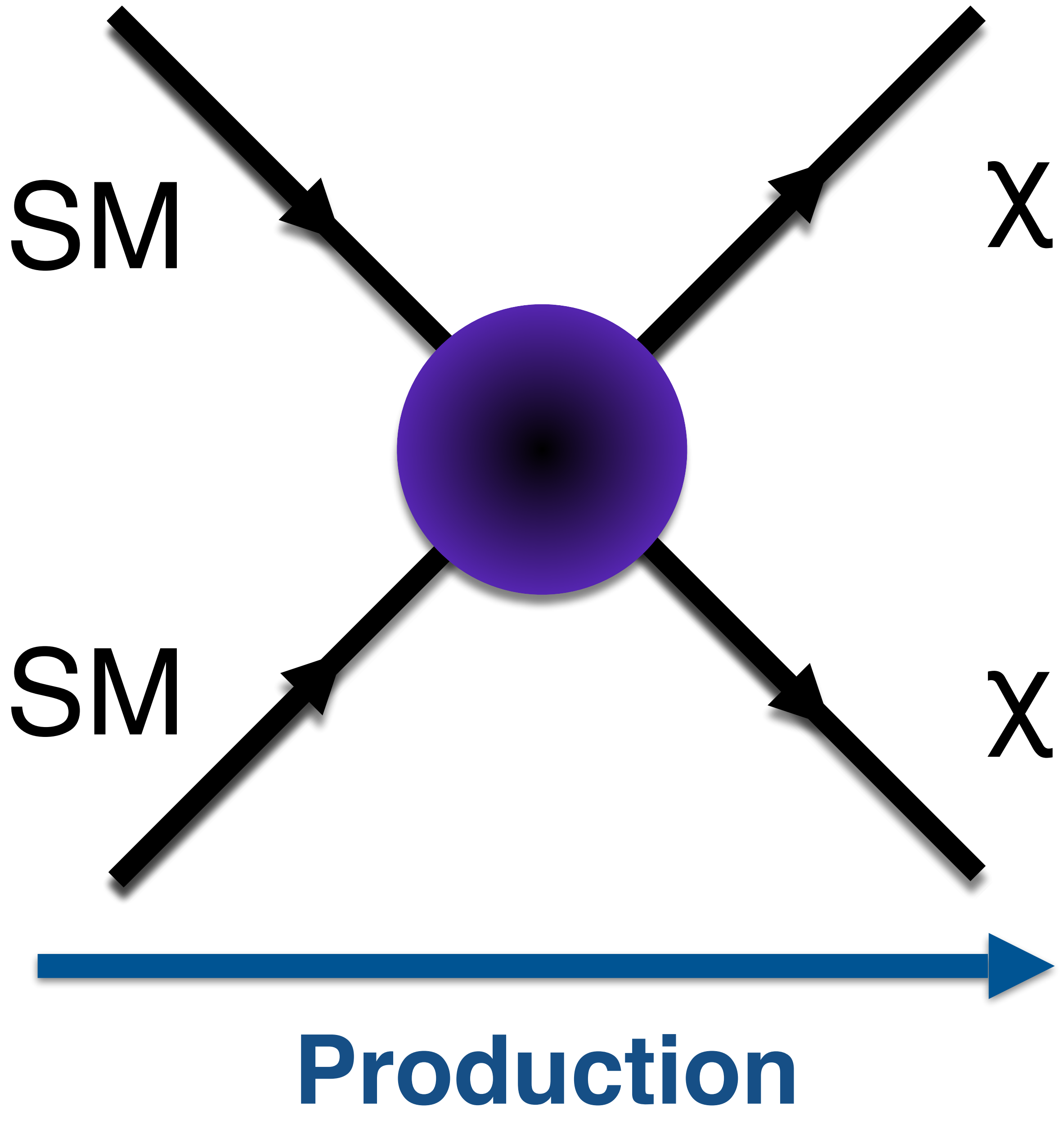
The view in UJ12 looking west in 2018

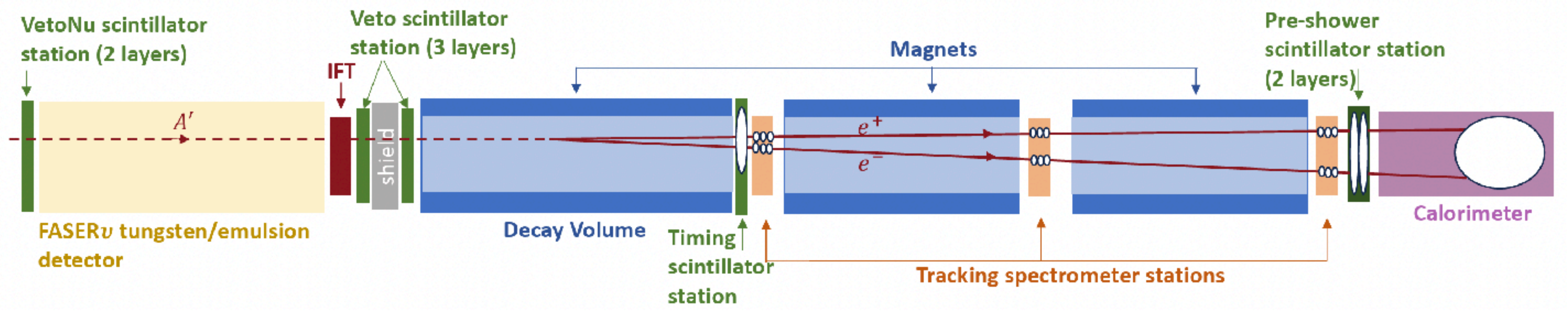
Beam collision axis: dark matter, new particles could be streaming through this tunnel!

LHC beamline

- Exploit LHC circular geometry
- Place experiments along the blue tangent lines
- DM particles don't care about traveling through rock and cement!

Faser



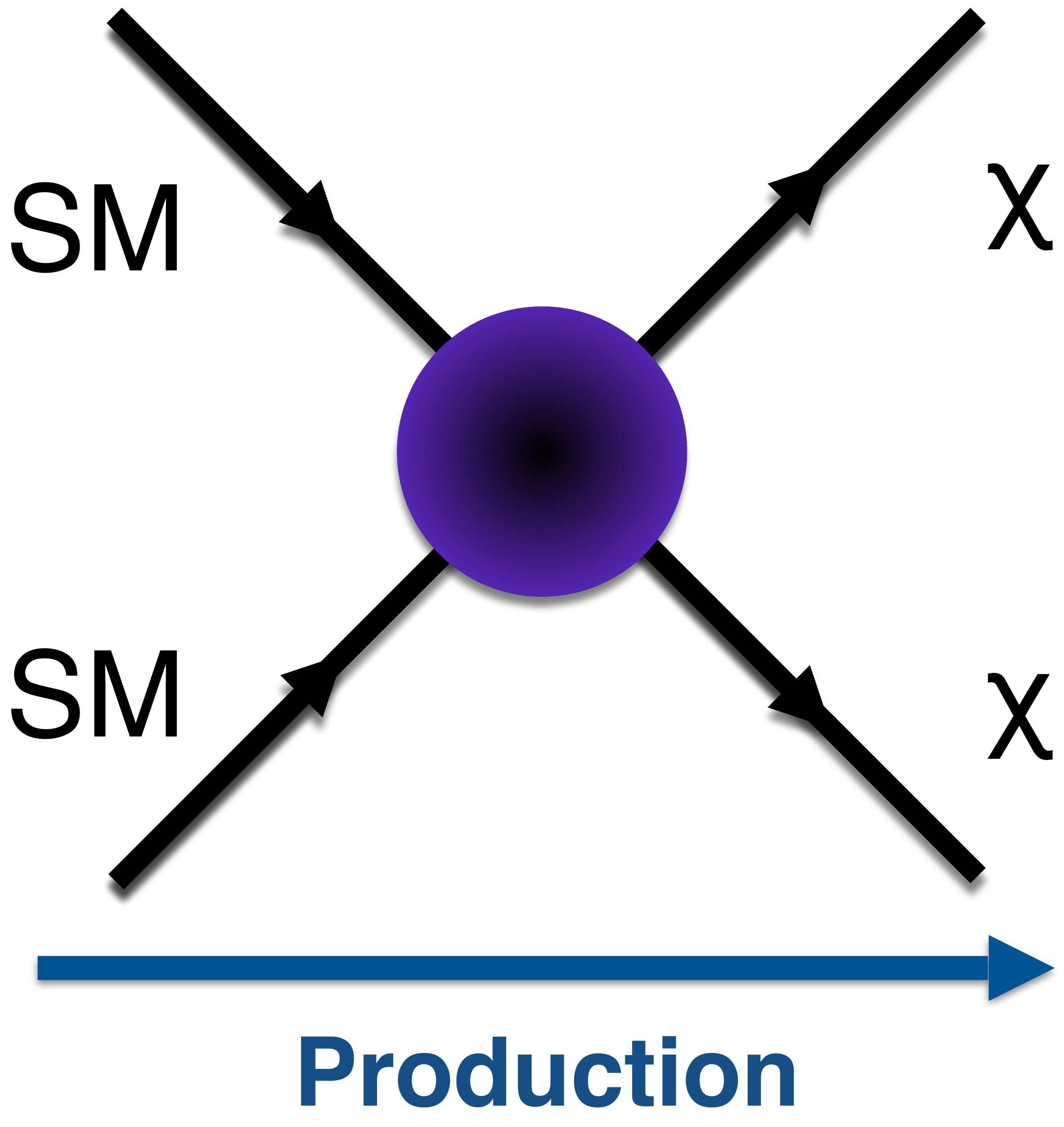


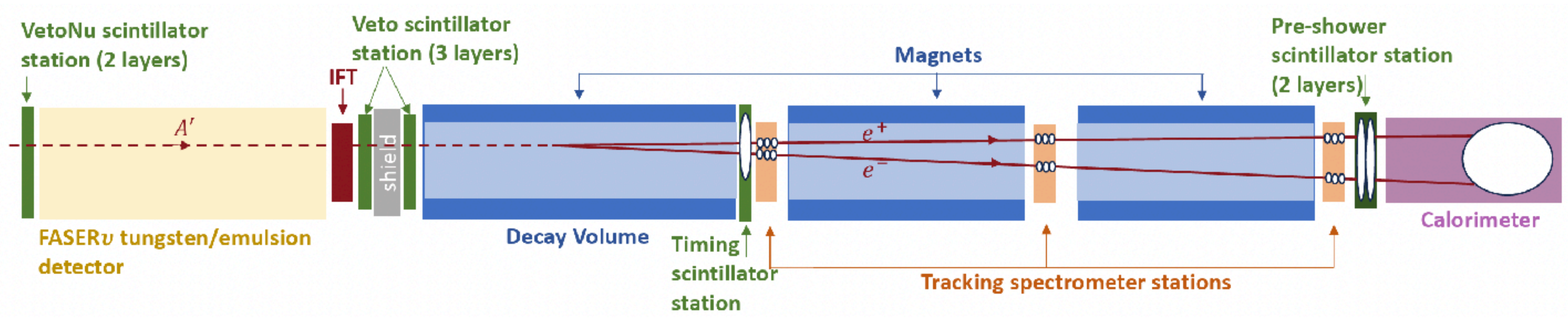
- Experimental Signature: no charged particle in the upstream veto scintillator detectors + two very energetic charged tracks in downstream trackers.

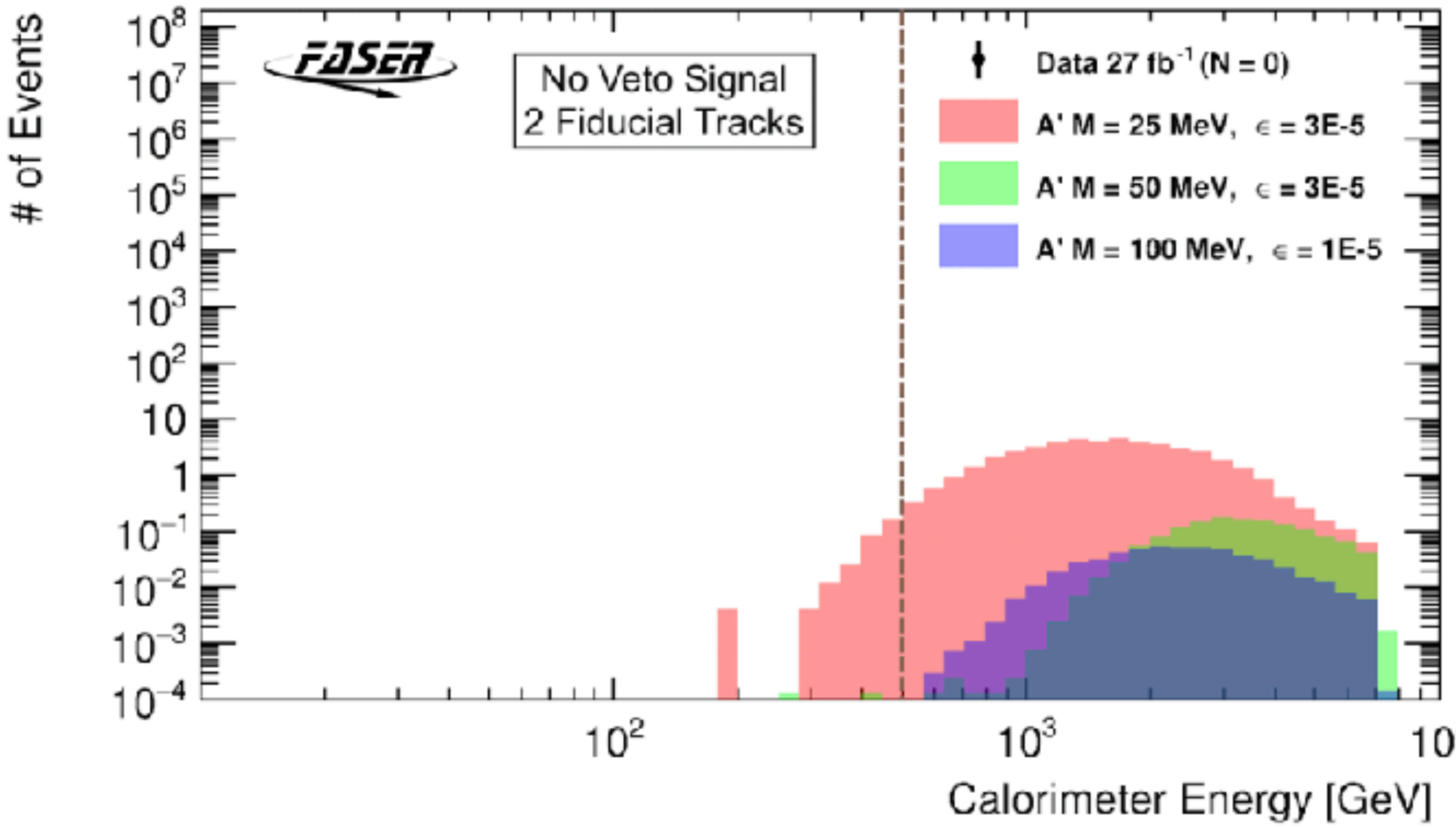
- Exploit LHC circular geometry
- Place experiments along the blue tangent lines
- DM particles don't care about traveling through rock and cement!

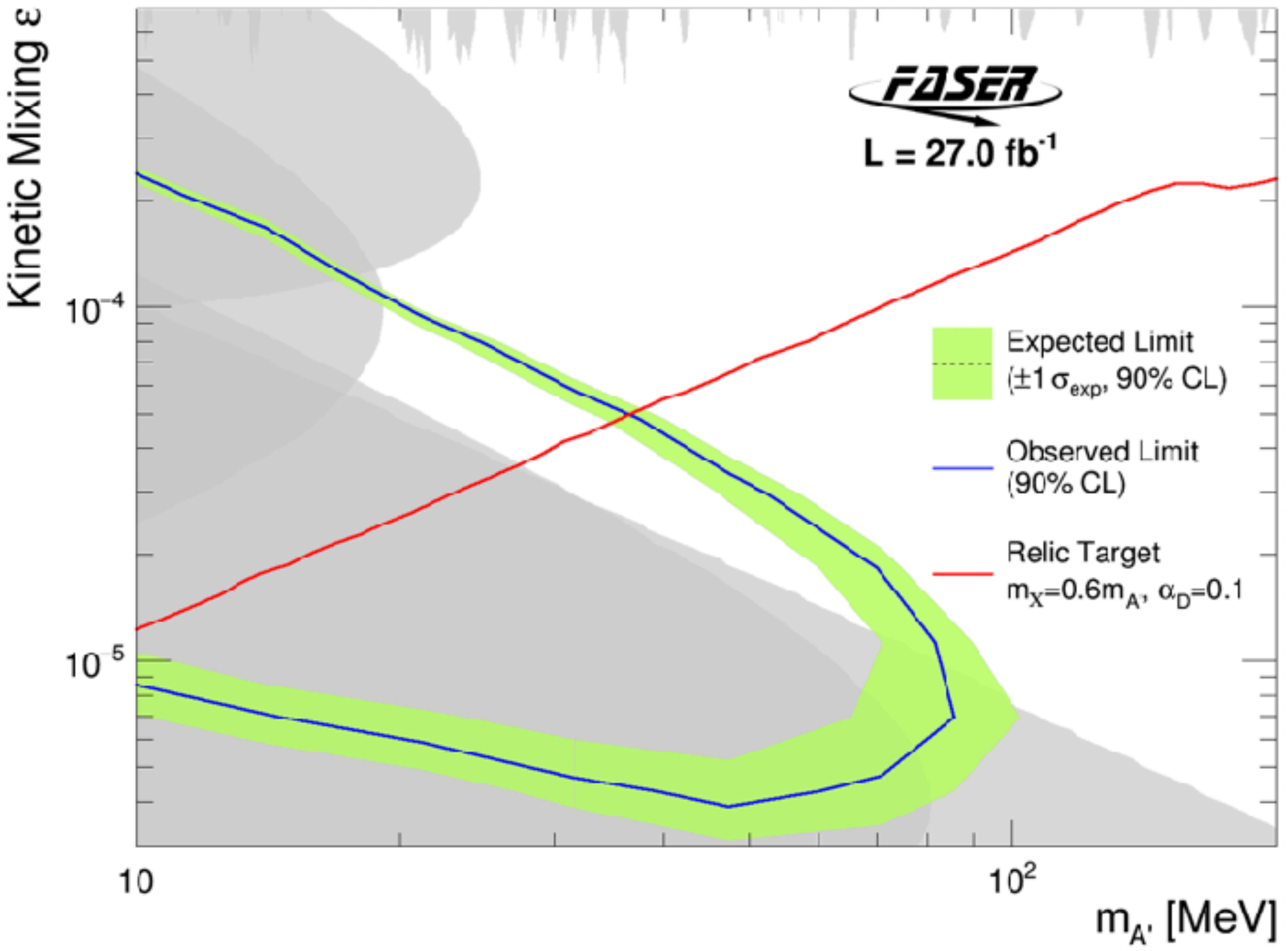
Small, cheap, and high impact!

Faser







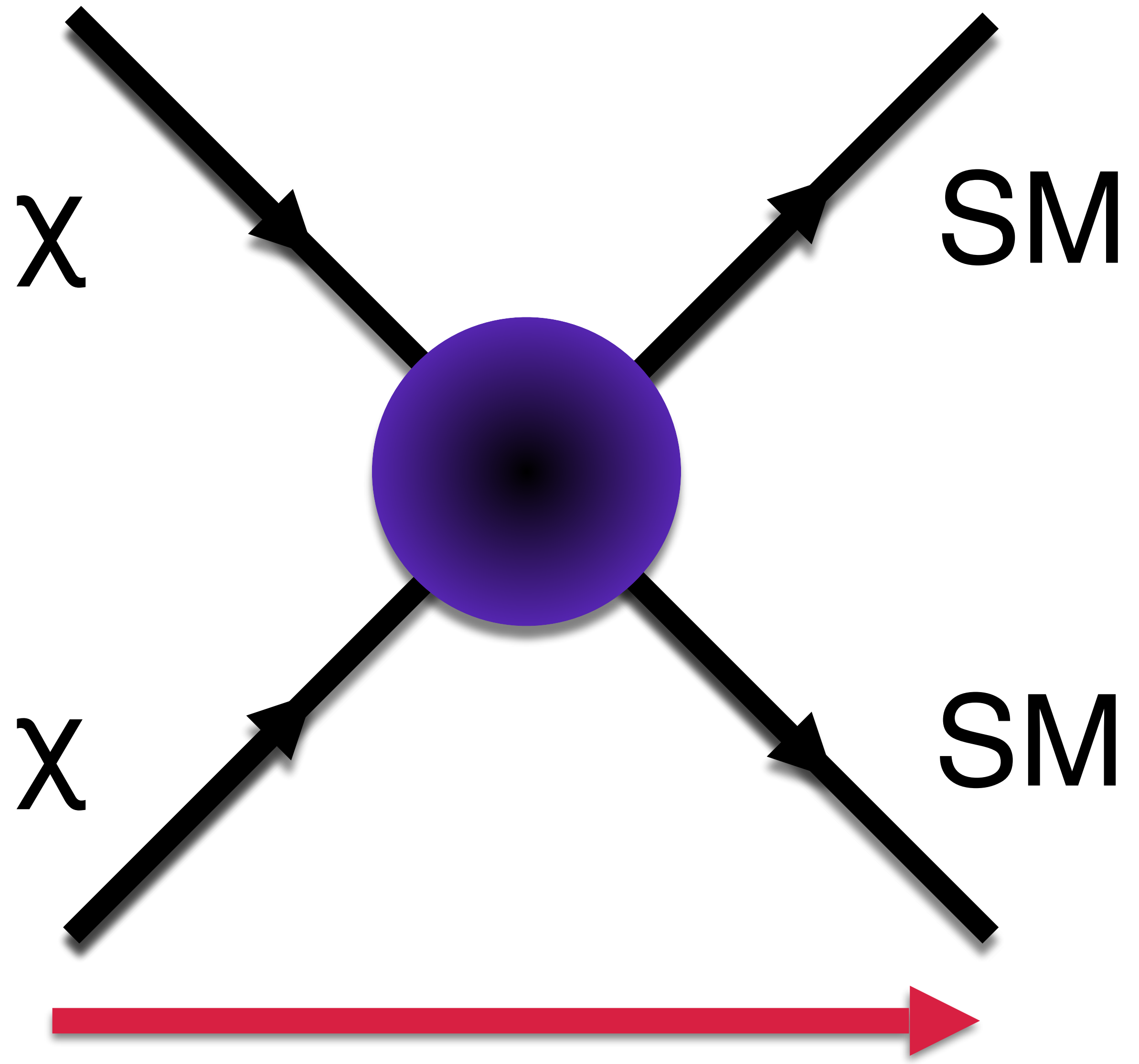


- Observed events: 0
- Expected Bkg: $(2.3 \pm 2.3) \times 10^{-3}$ events.
- New world-leading constraints to dark photon models!

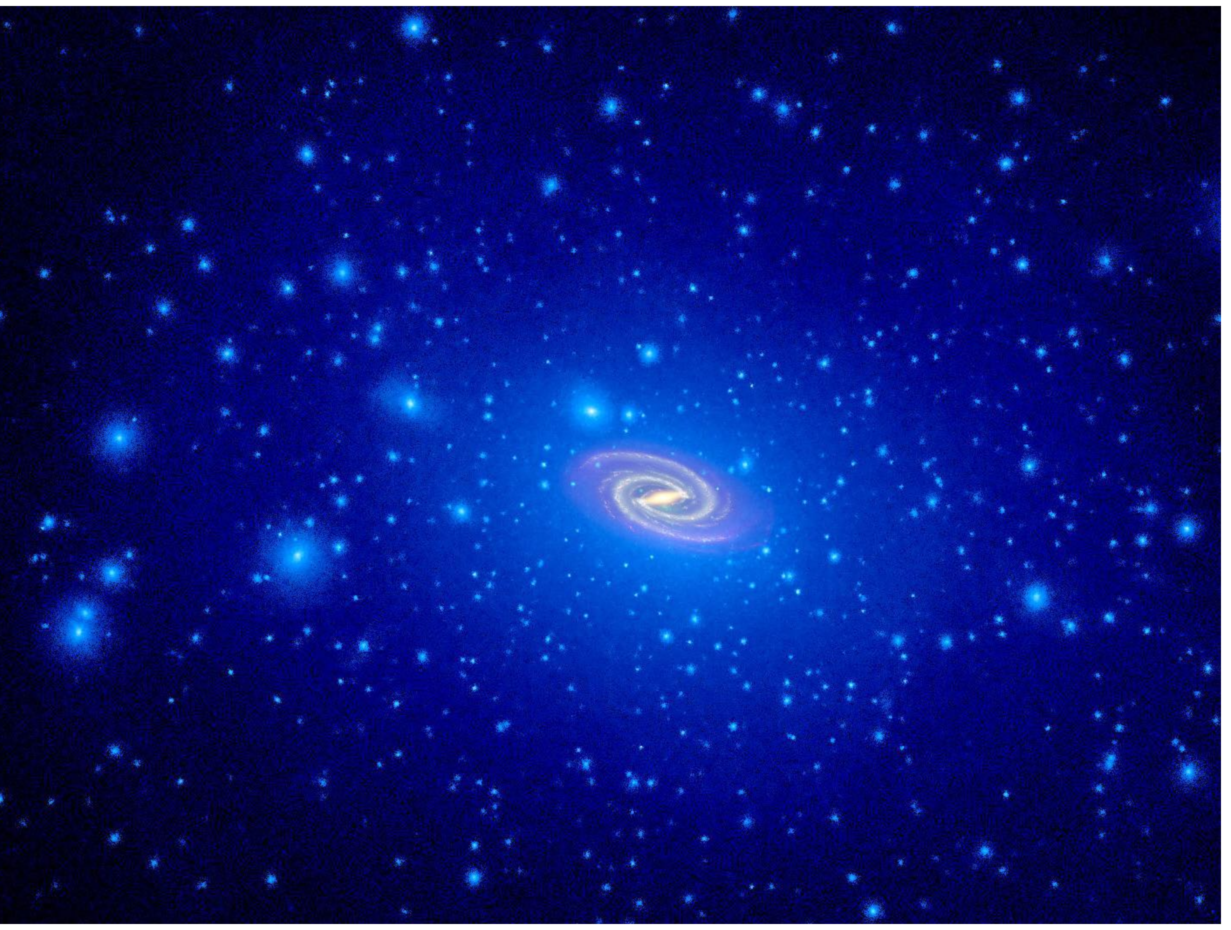
CDM in the Milky Way

Simulations with Cold Dark Matter agree with observations

Indirect detection

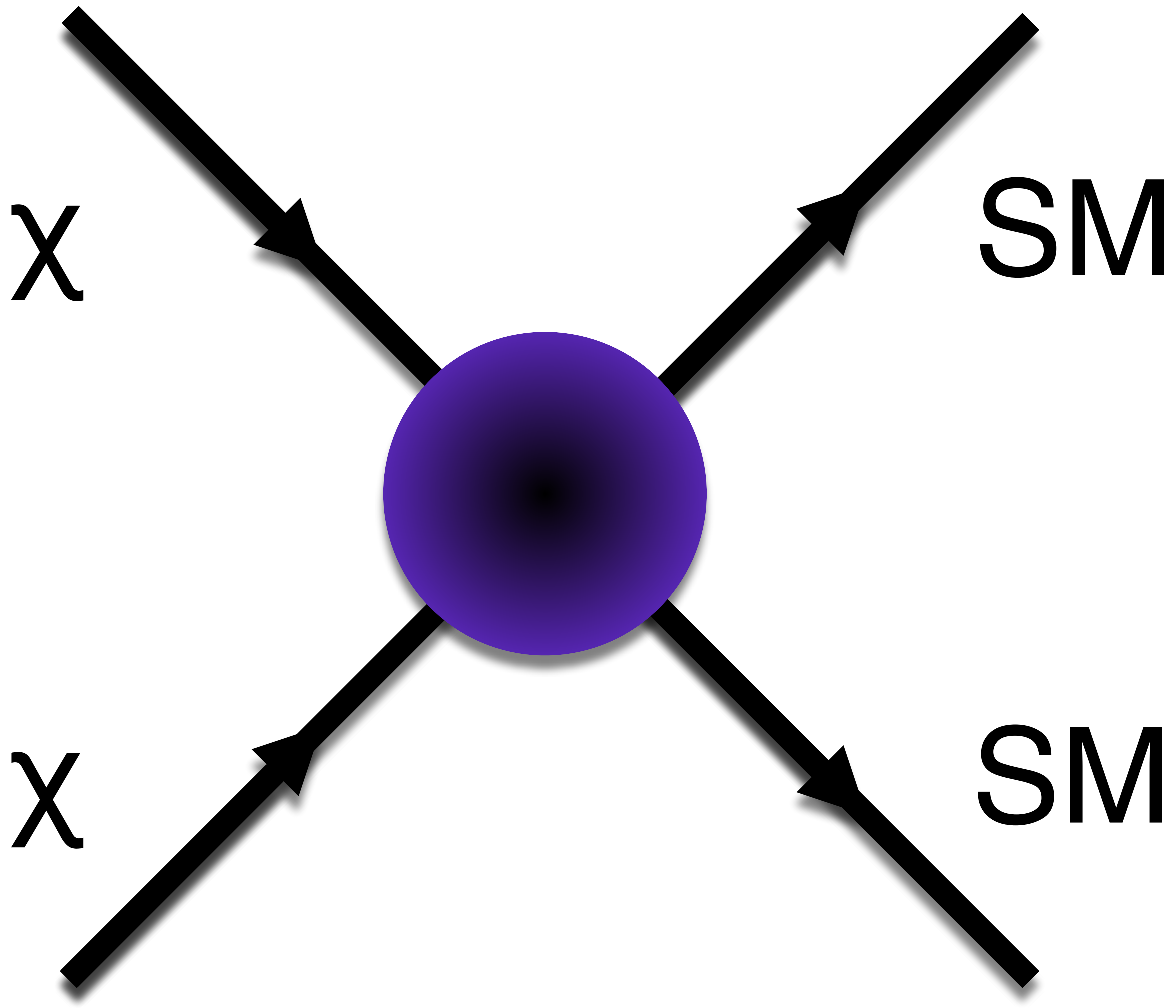


Indirect detection

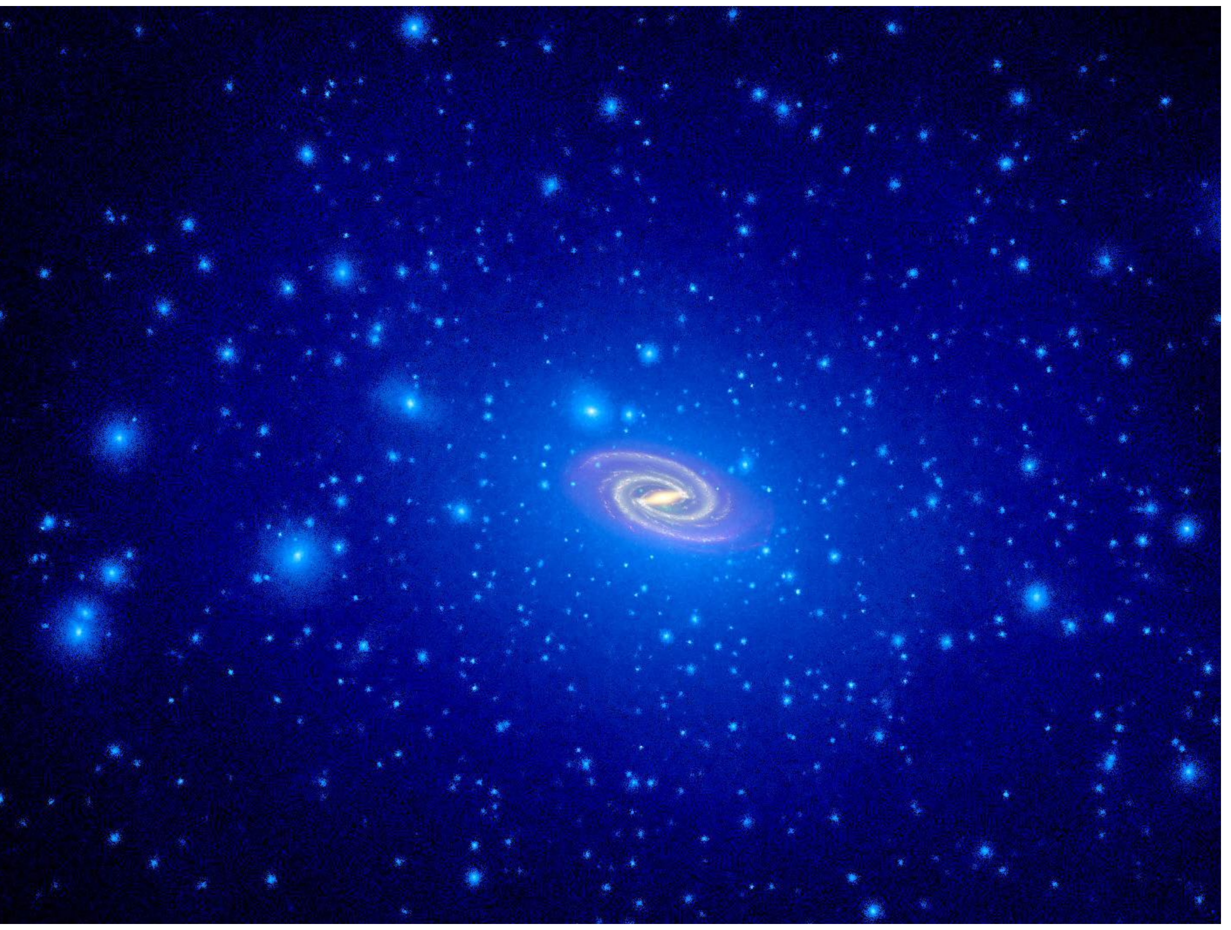


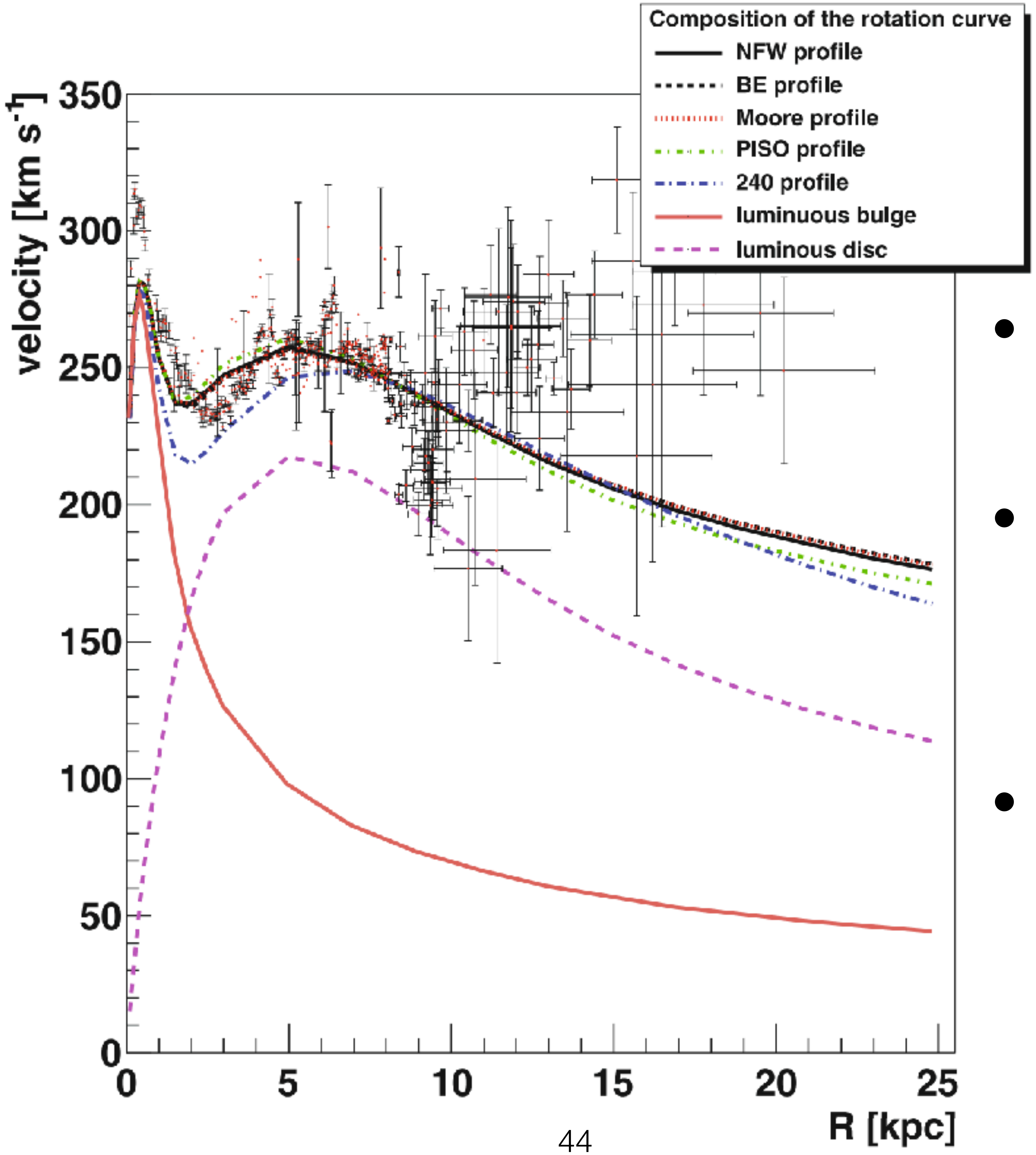
- If DM undergoes self-interaction (self-annihilation), we can look for SM products of such reactions
- We do not produce the DM
- Need to find regions of the cosmos with a high DM density, where the $\chi\overline{\chi} \rightarrow e^+e^-, \gamma\gamma, q\overline{q}, ZZ, W^+W^-$ reactions occur at a rate high enough (decay $\chi \rightarrow SM$ is also an option)
- But the resulting flux of annihilation products decreases as the square of the distance, so can't go look too far from home!
- Extra-galactic sources are generally regarded as too distant, within the Milky Way is the most promising

The Milky Way



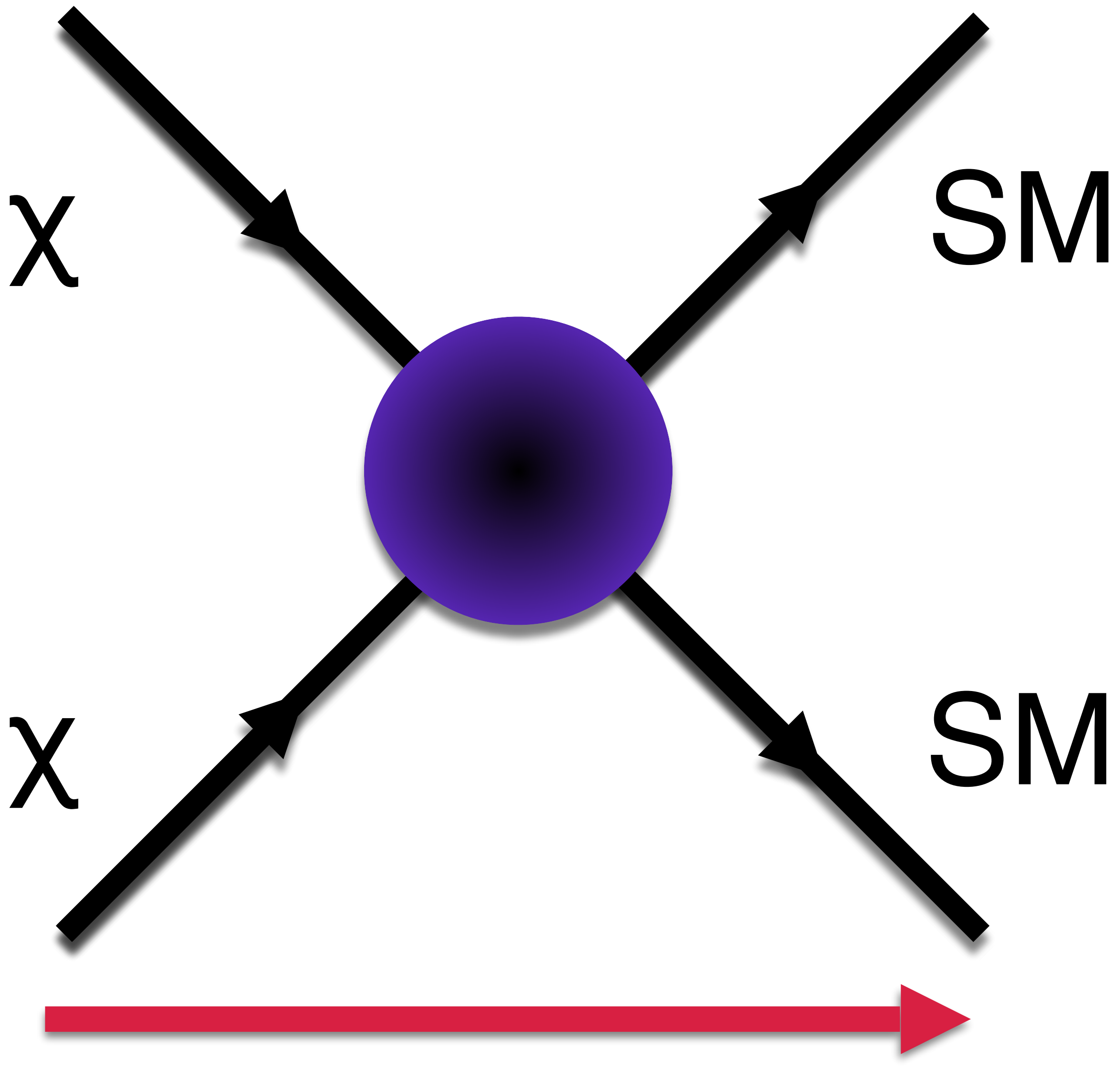
Indirect detection





- Milky Way rotation curve
- Fits obtained with different models of the DM density profile
- Models obtained by numerical simulation of galactic structure formation and evolution

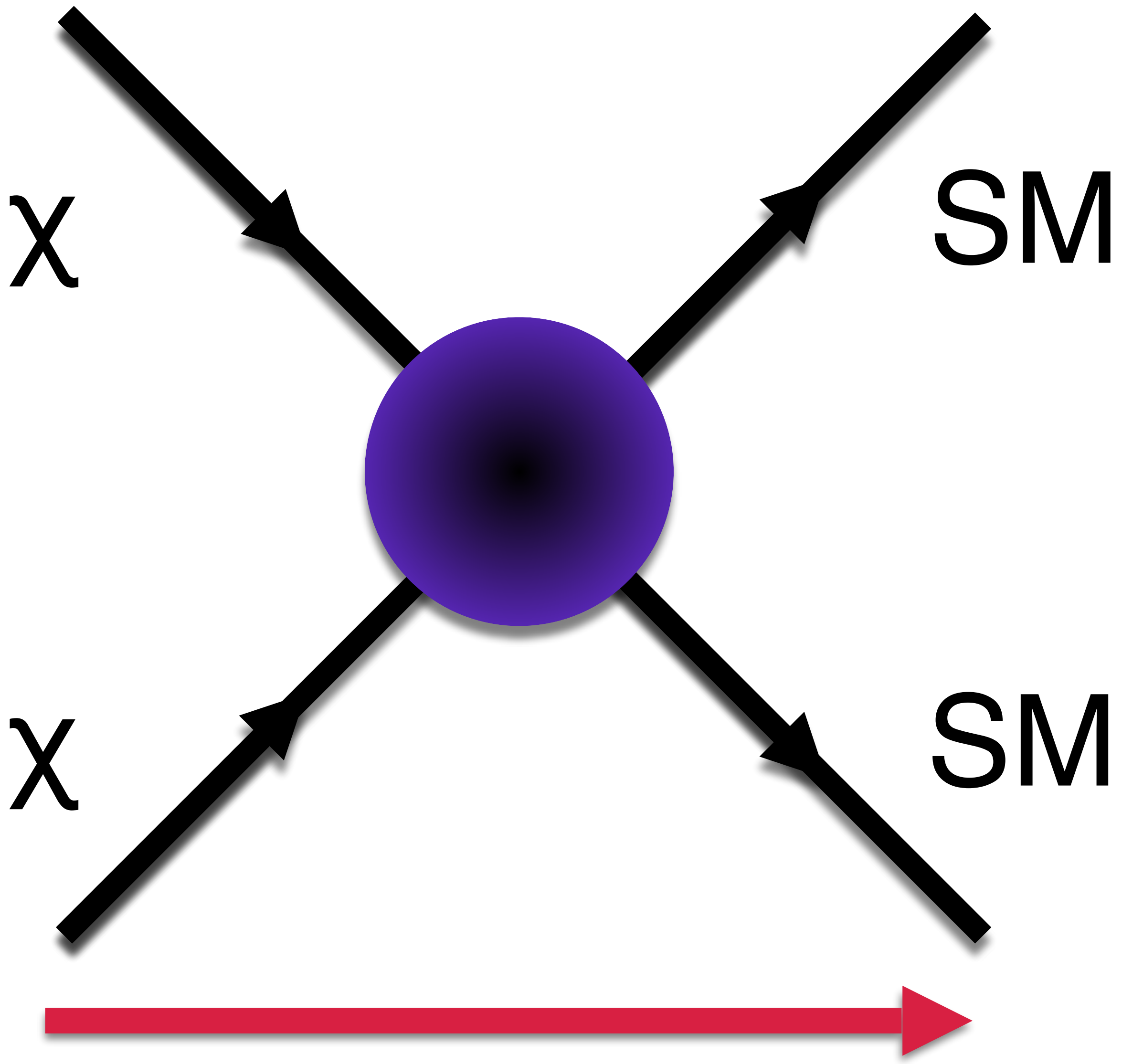
Indirect detection



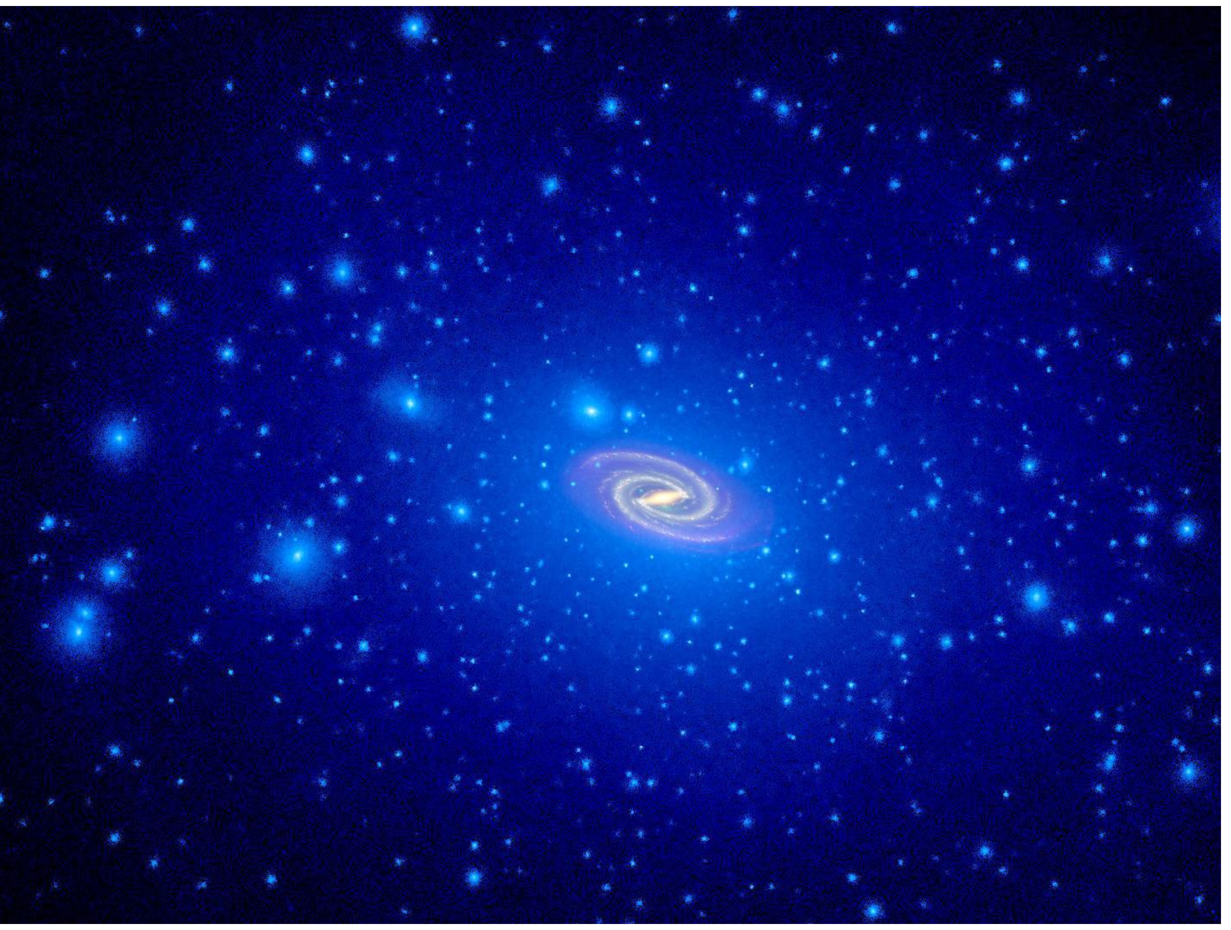
Indirect detection

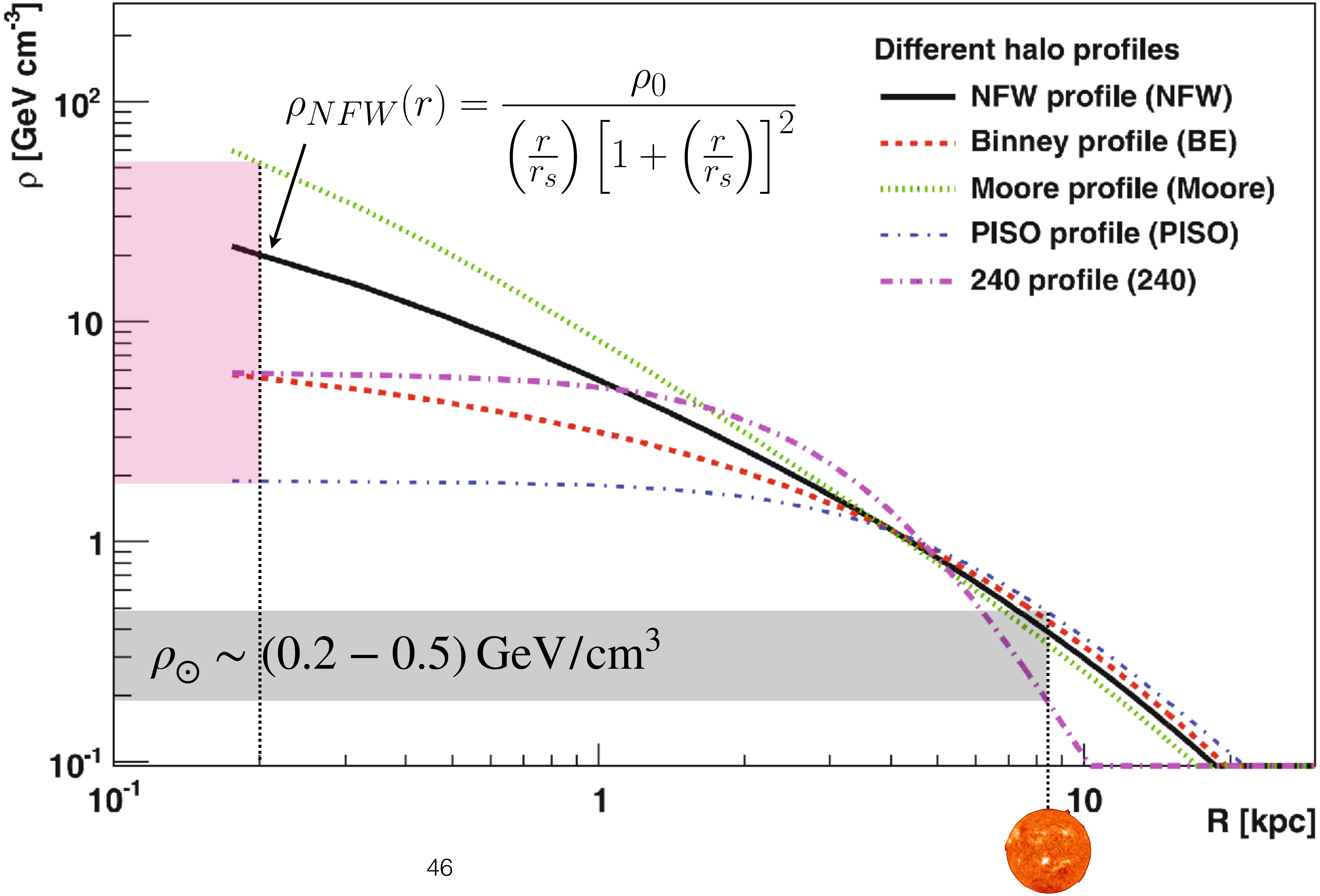
- Smooth component of DM halos can be approximated to a spherically symmetric distribution
- This does not account for sub-halos, but is sufficient for this discussion

Galactic Nucleus



Indirect detection

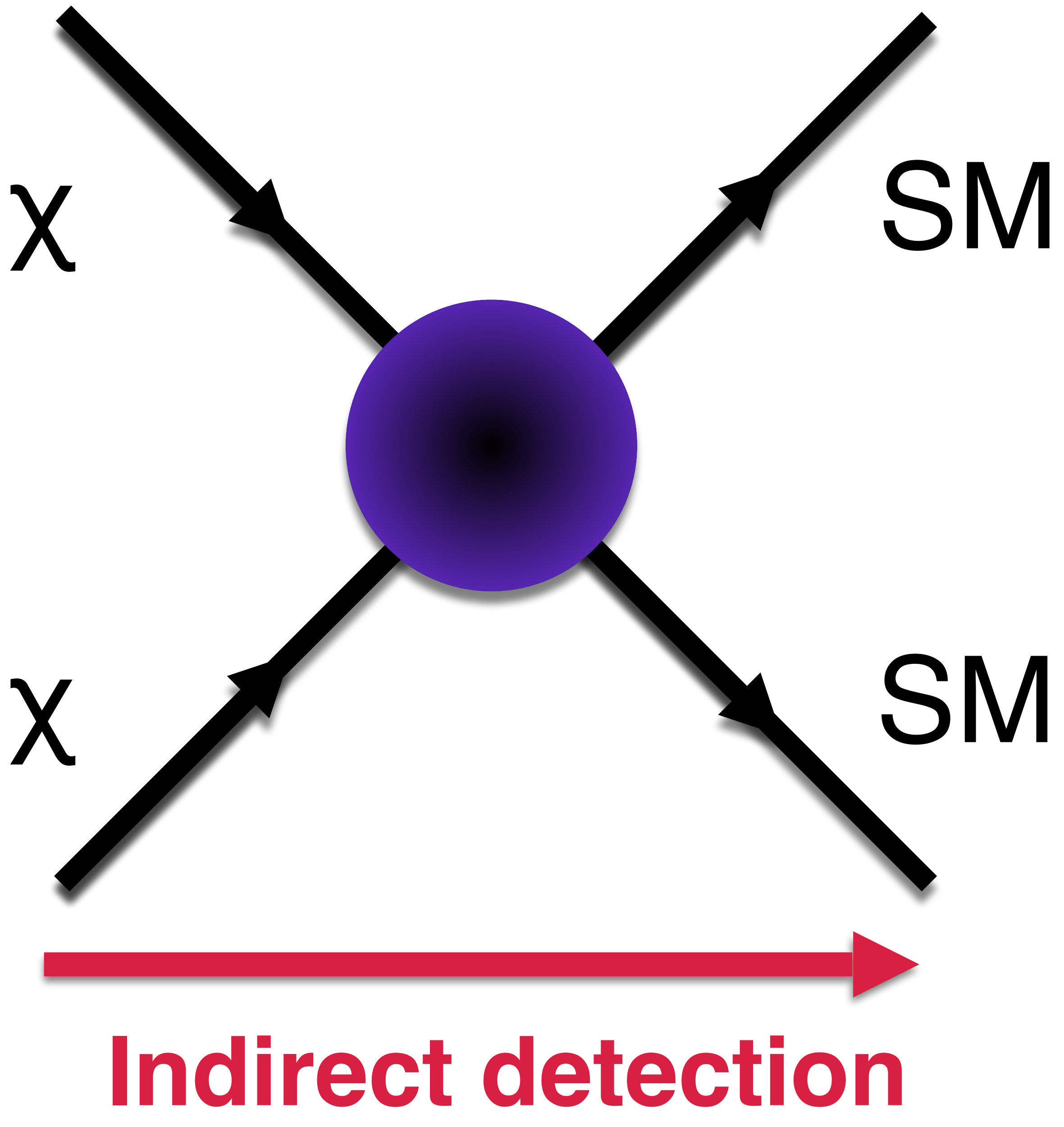


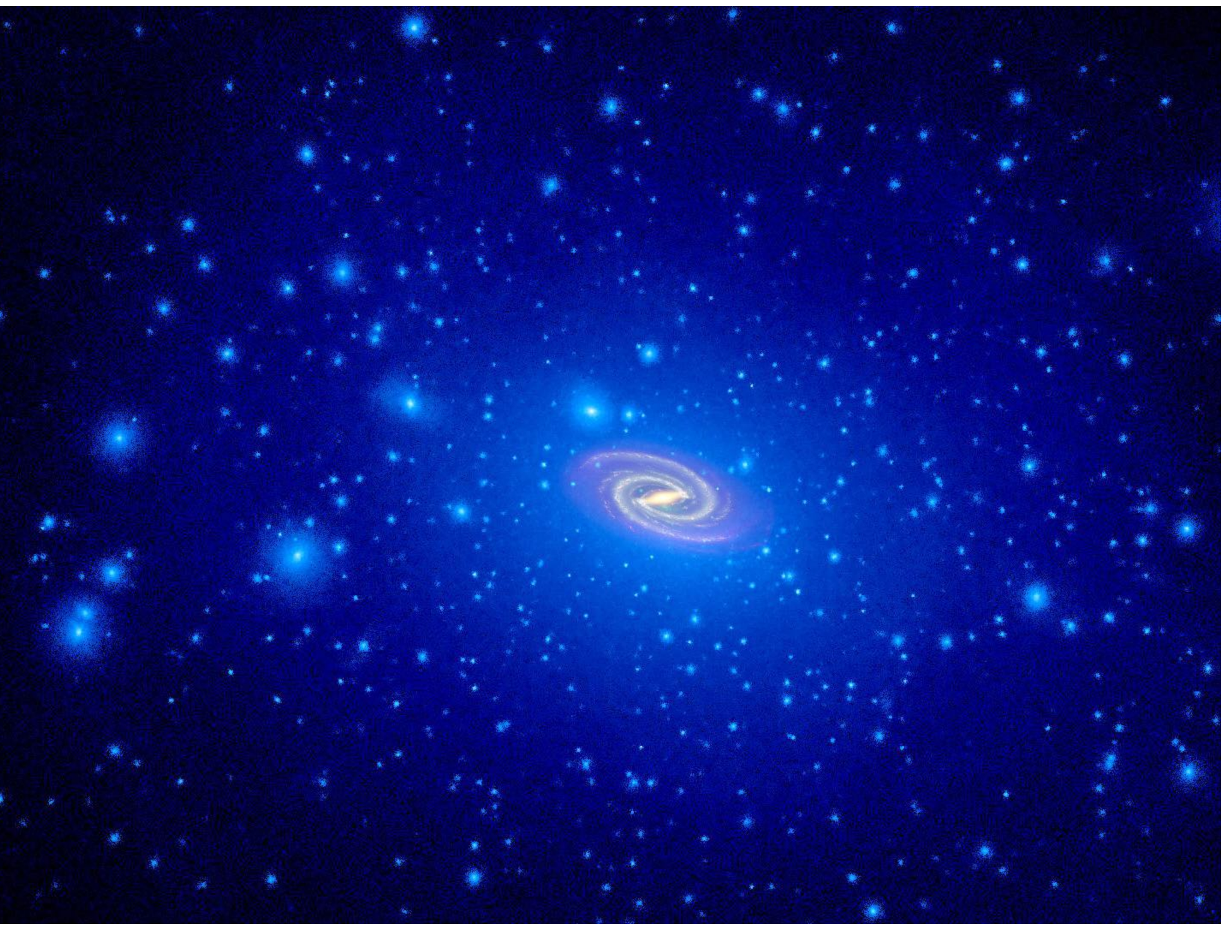


$$\rho_{NFW}(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)\left[1+\left(\frac{r}{r_s}\right)\right]^2}$$

$$\rho_\odot \sim (0.2 - 0.5)\,\mathrm{GeV/cm^3}$$

Expected flux





Differential Intensity:

Particles per area, time, solid angle, and energy

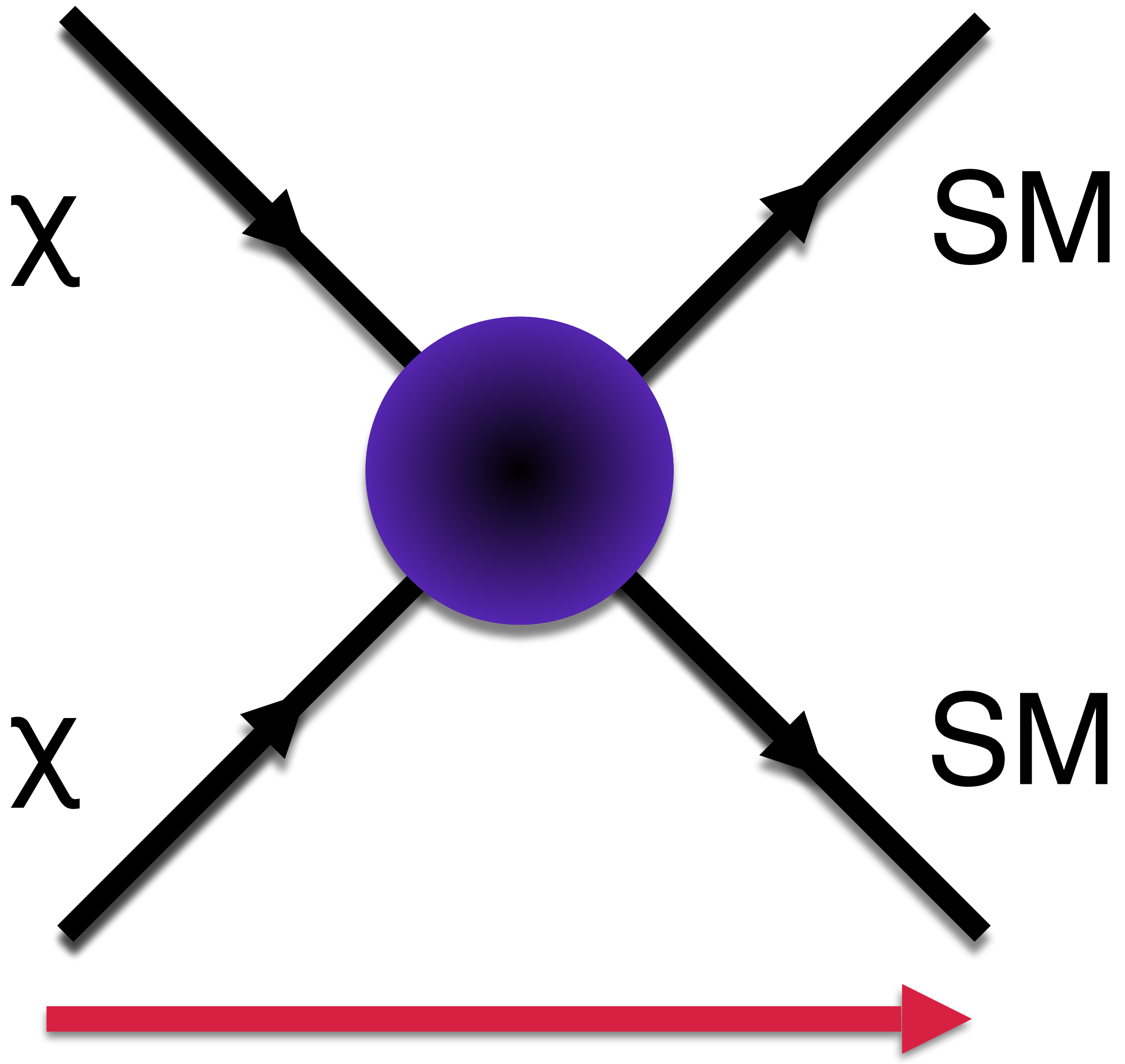
Average of σ and relative velocity over thermal distribution

$$\frac{dN_{\mathrm{ann}}}{dA\,dt\,d\Omega\,dE} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_\chi^2}\frac{dN_x}{dE}J_{\mathrm{ann}}(\psi)$$

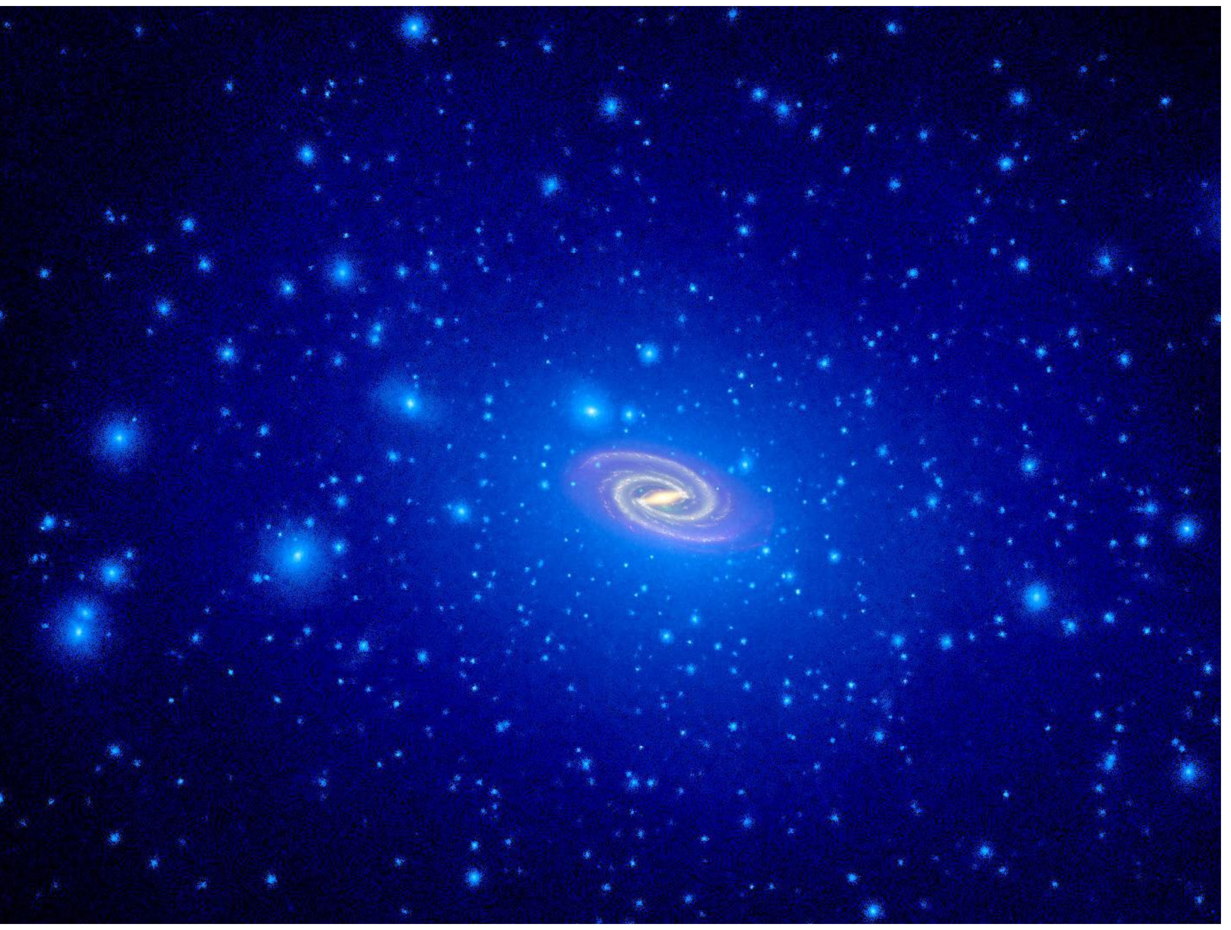
Energy spectrum for particle x

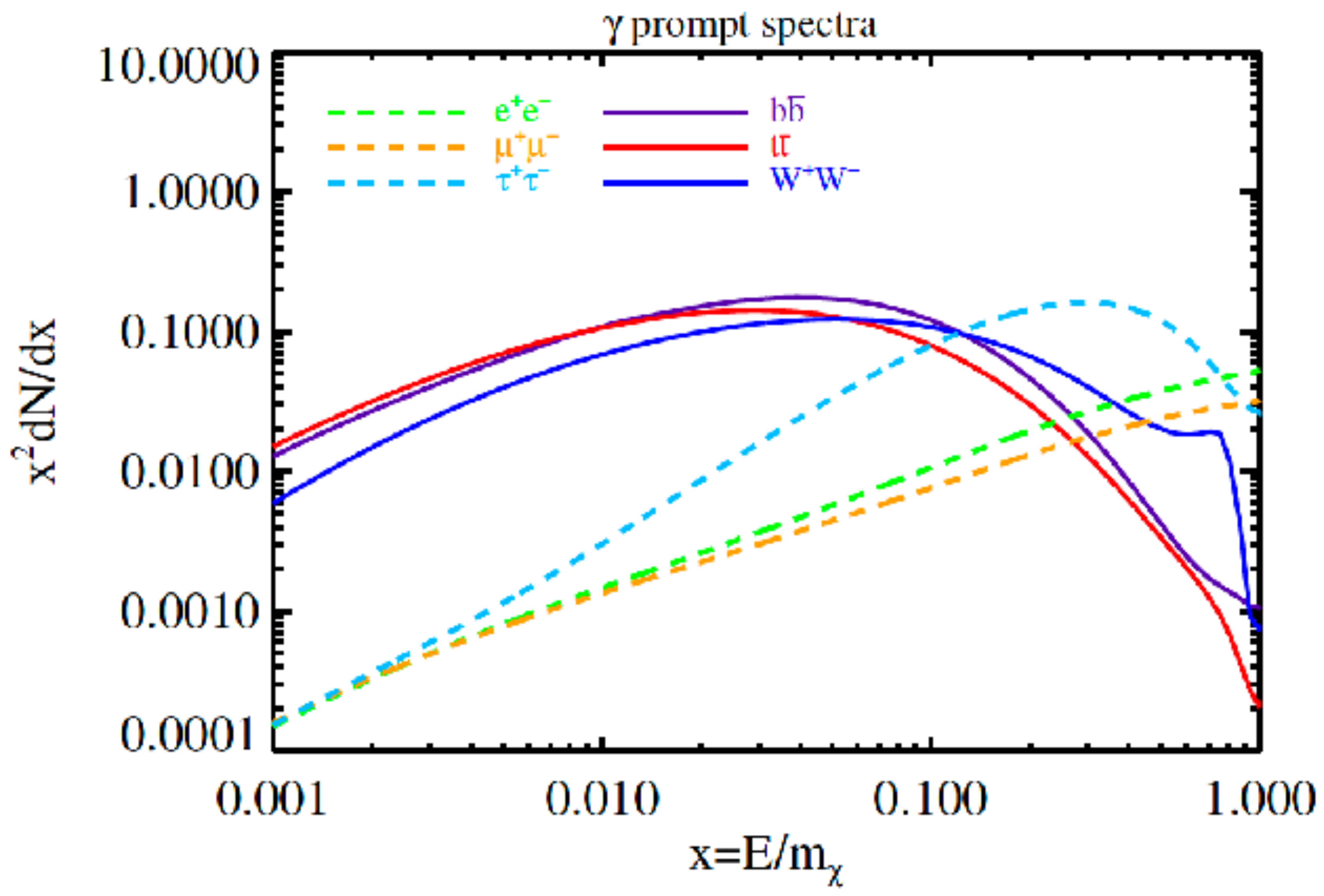
J-factor - summarizes information on DM spatial distribution

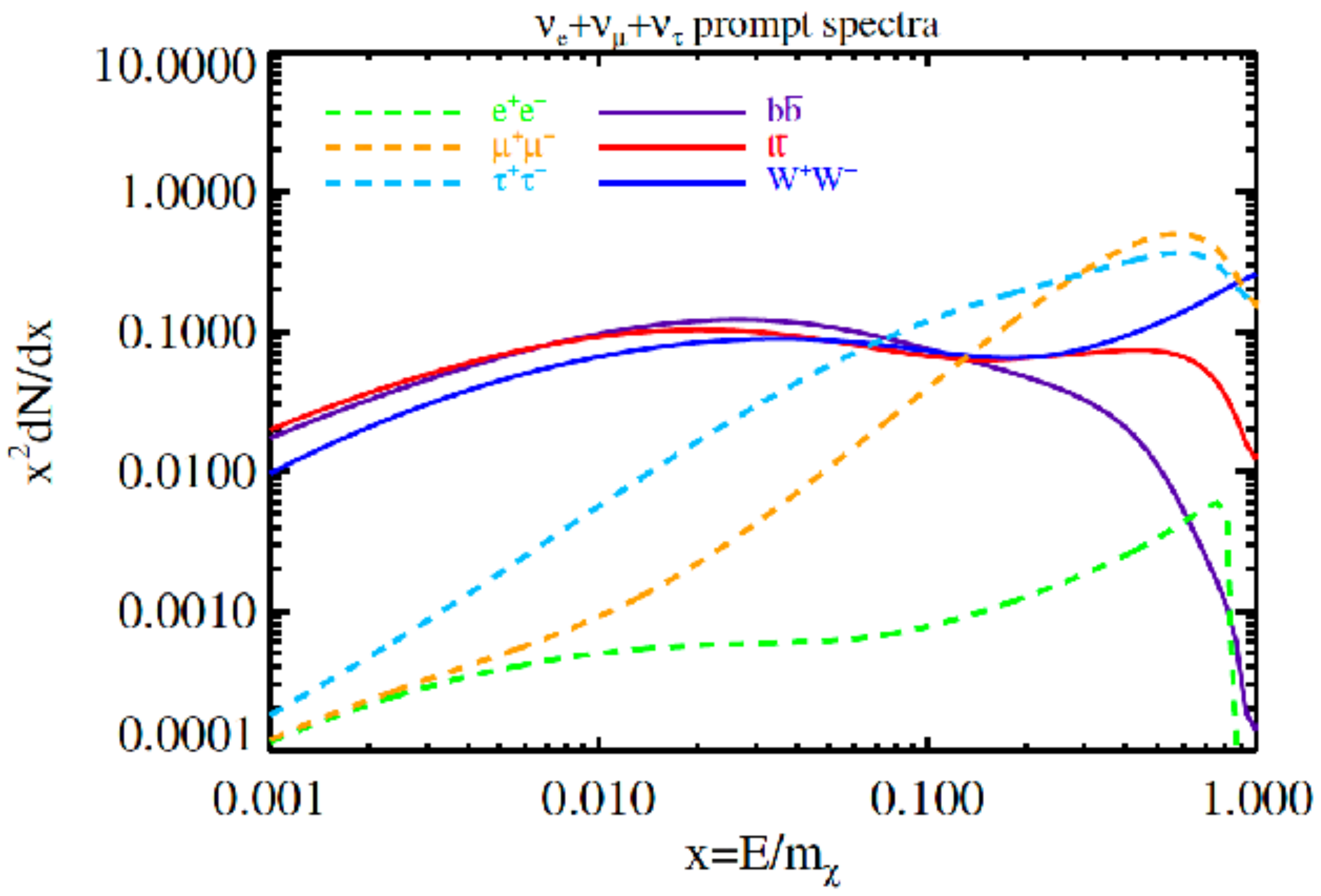
Energy Spectra

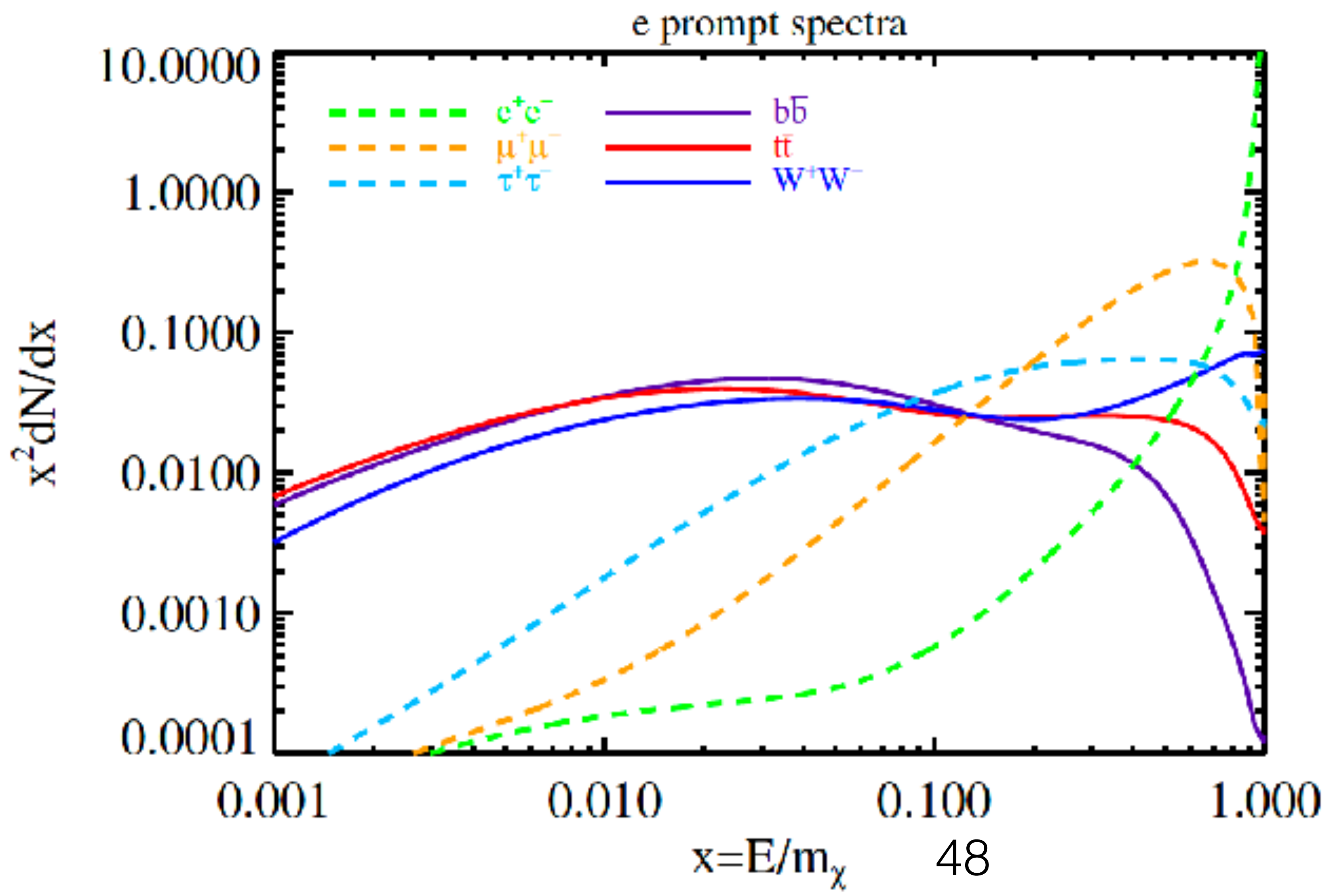


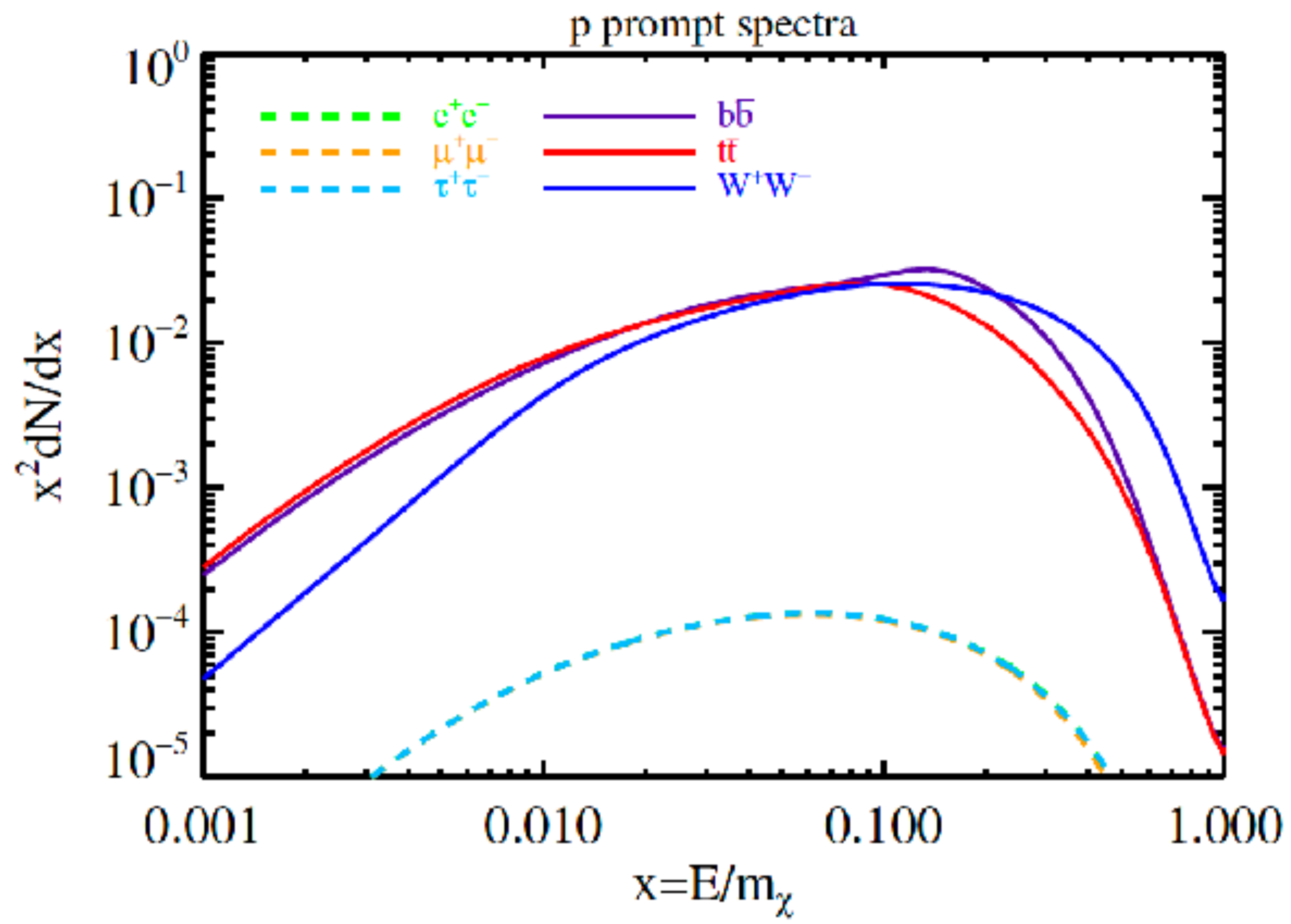
Indirect detection



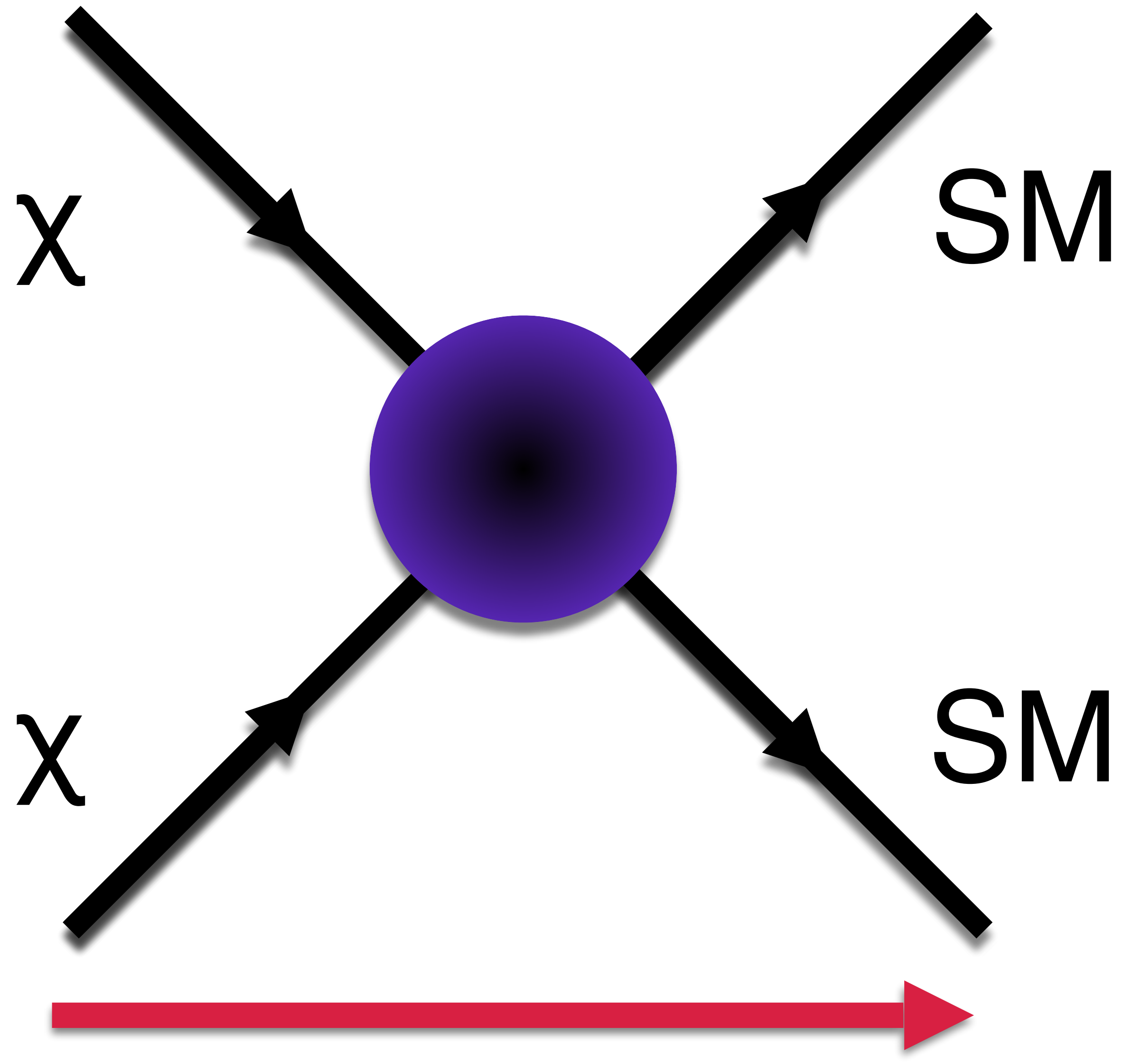

γ prompt spectra


$\nu_e+\nu_\mu+\nu_\tau$ prompt spectra

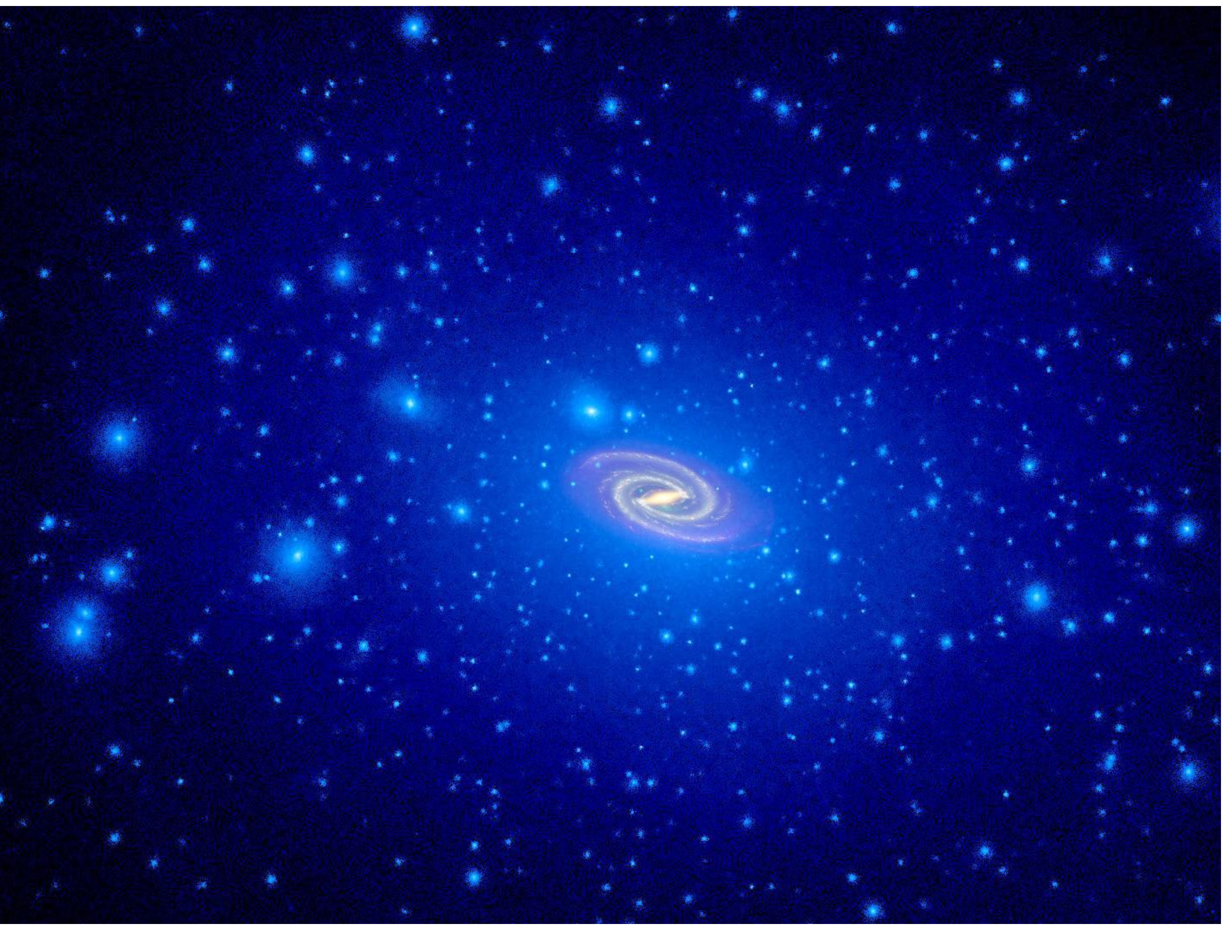

e prompt spectra


p prompt spectra

J-factor



Indirect detection



$$J_{\text{ann}}(\psi) = \int_{\text{los}} \rho^2(\psi, l)dl$$

Direction in the sky

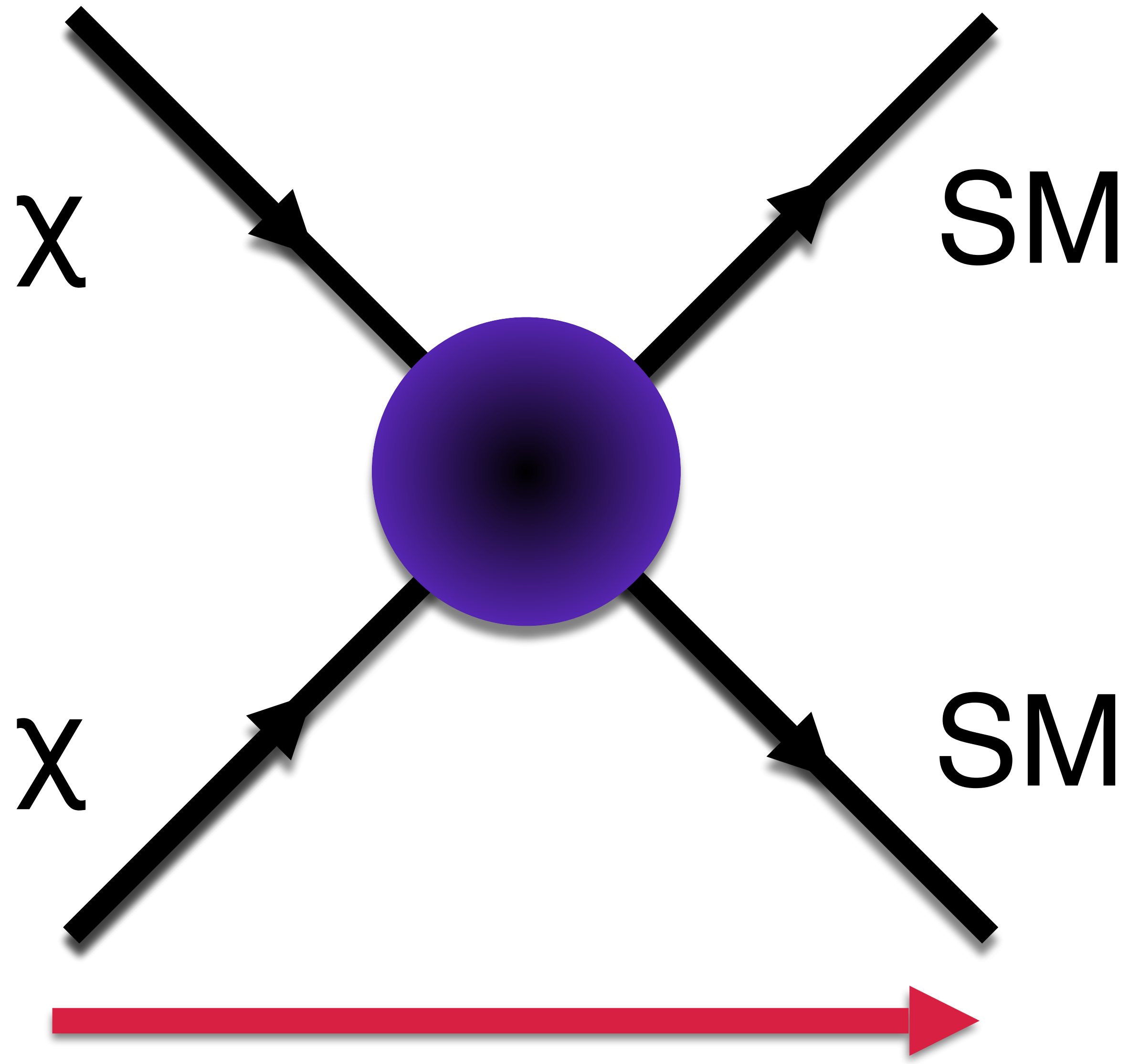
Line of sight

Distance along los

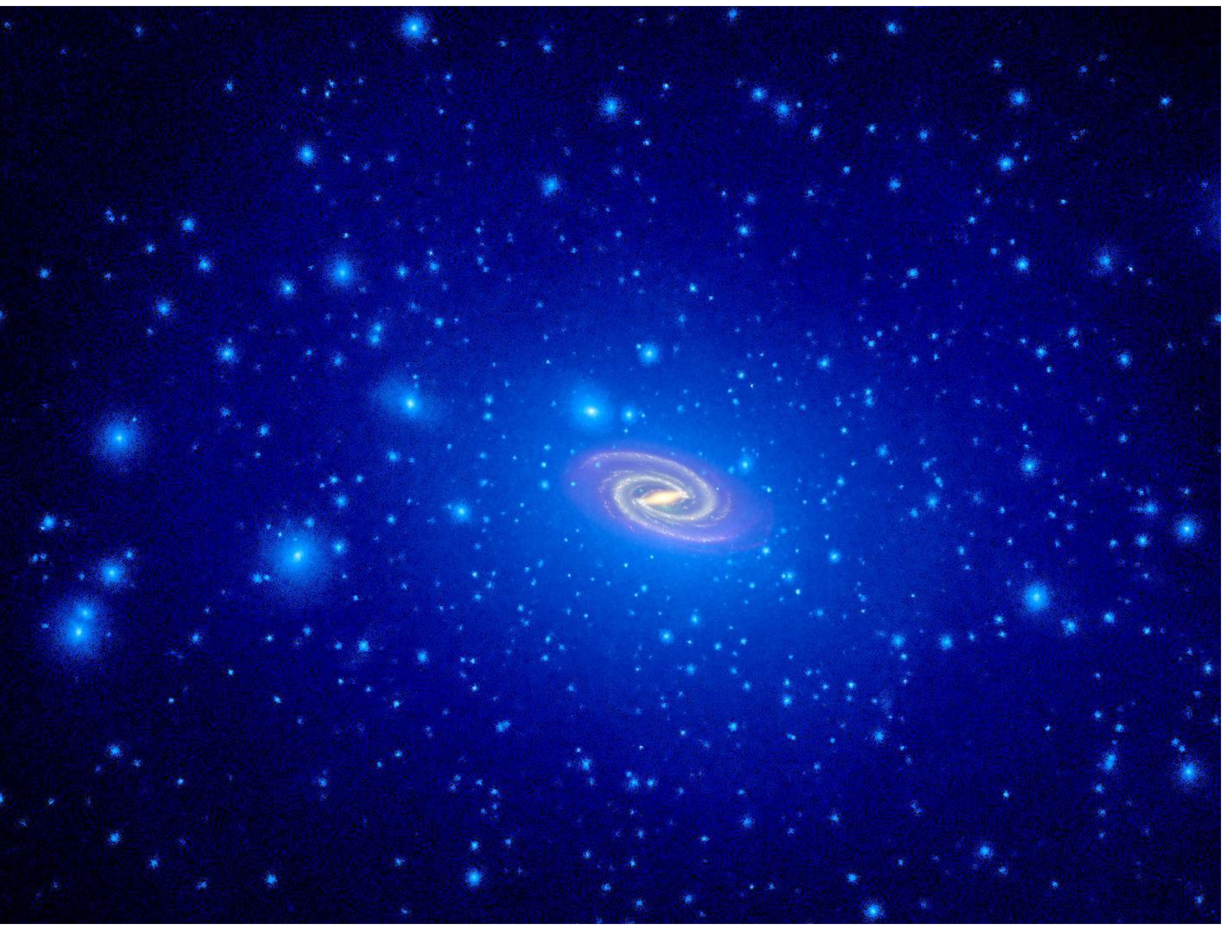
Target	$\log_{10}(J_{\text{ann}})$
Galactic Center	21.5
Dwarf galaxies (best)	19
Galaxy clusters (best)	18

← Highest!

Detection channels

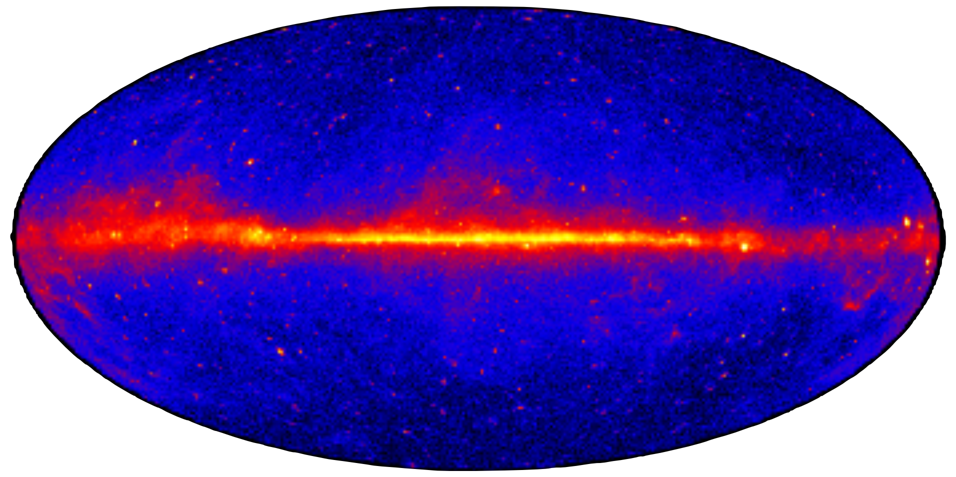


Indirect detection



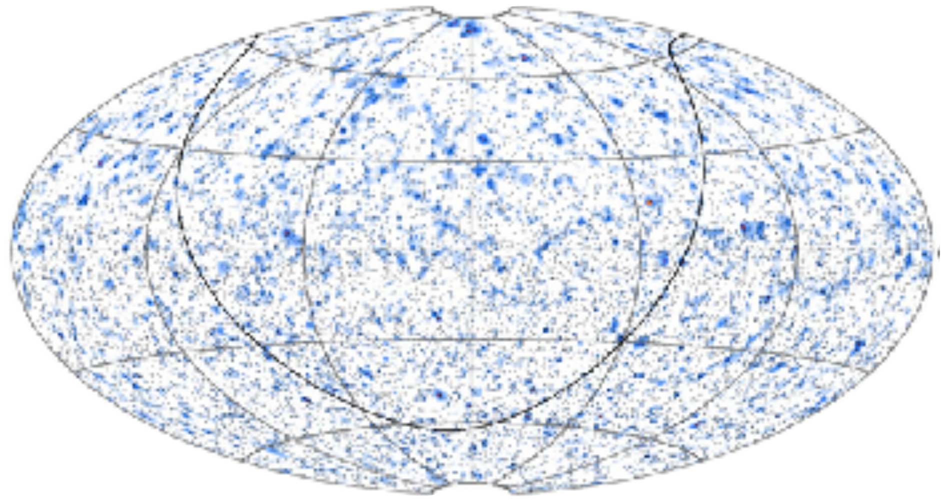
Particles from the cosmos constantly bombard the Earth.

Some of these messengers might be delivering information on DM.



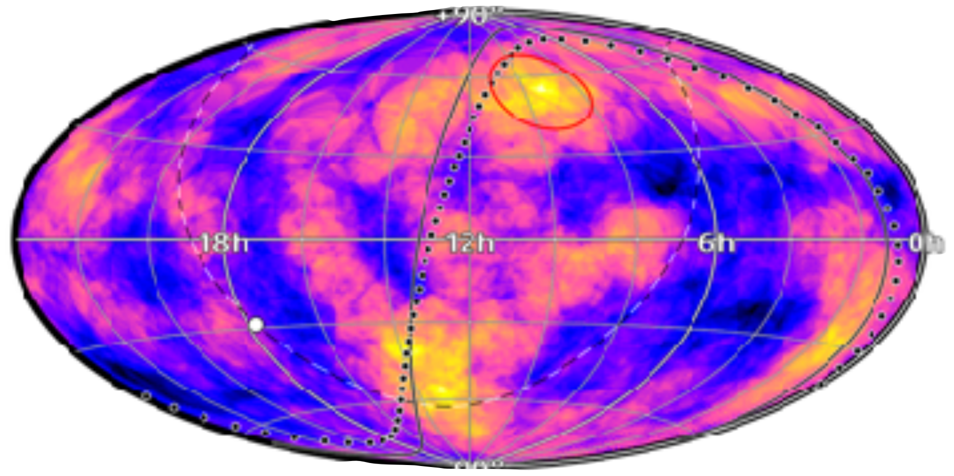
Gamma Rays

- Point back to source ✓
- Spectral signatures ✓
- High backgrounds ✗
- Attenuation ✗



Neutrinos

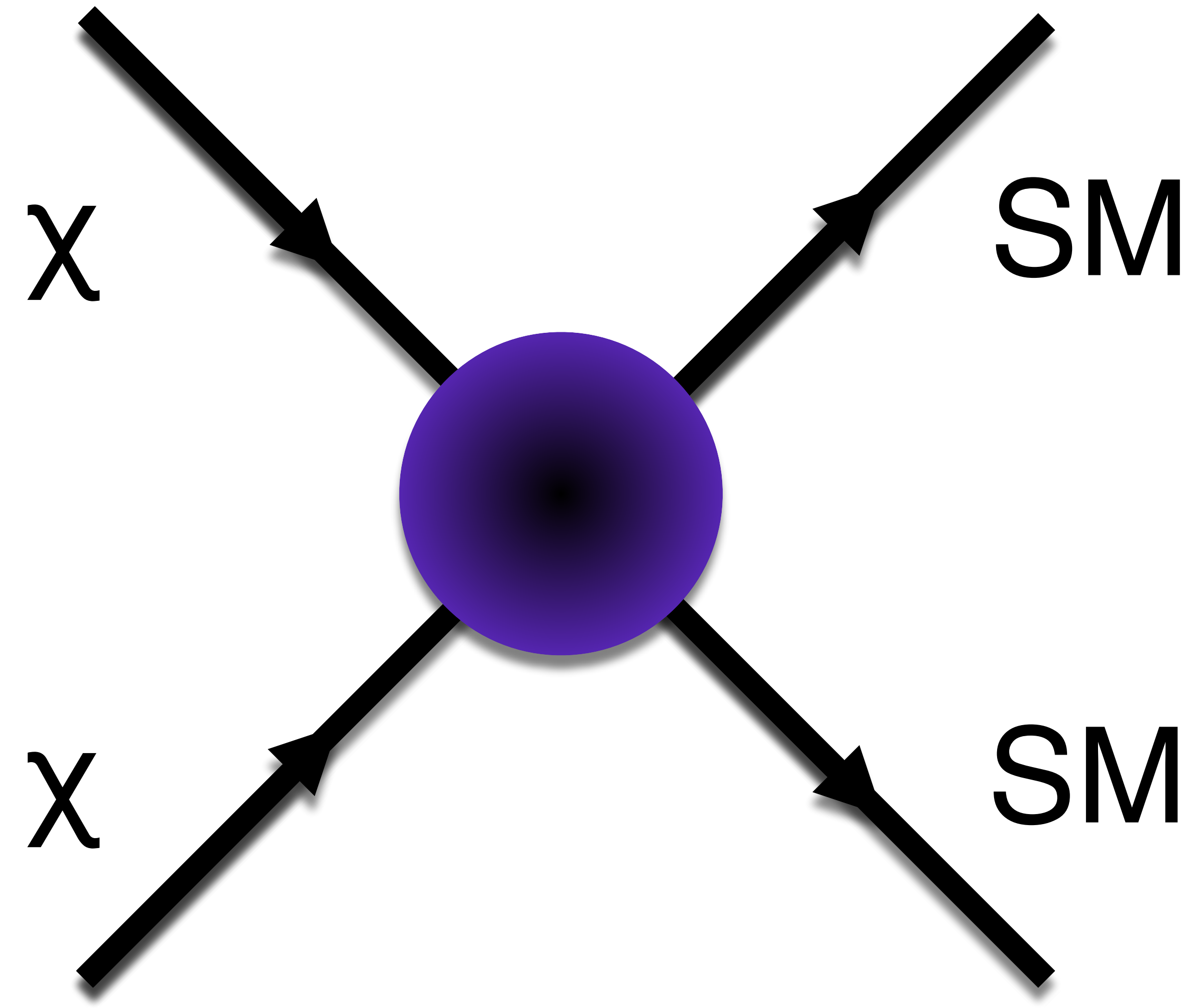
- Point back to source ✓
- Spectral signatures ✓
- High backgrounds ✗
- Low Statistics ✗



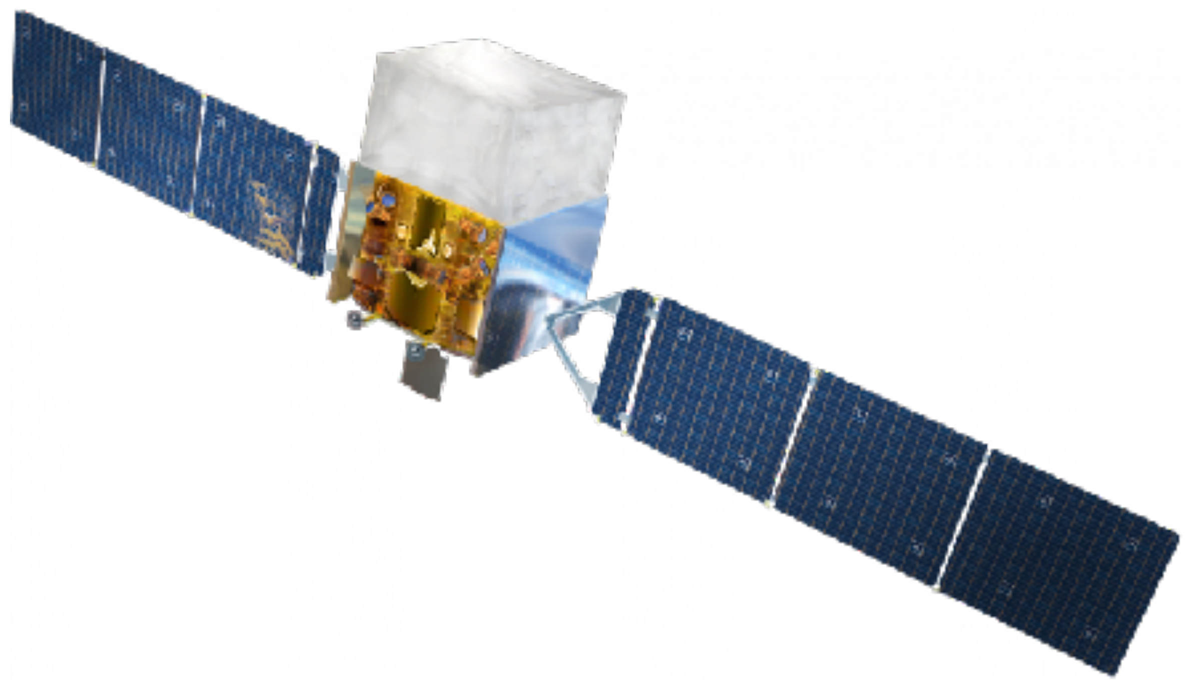
Cosmic Rays

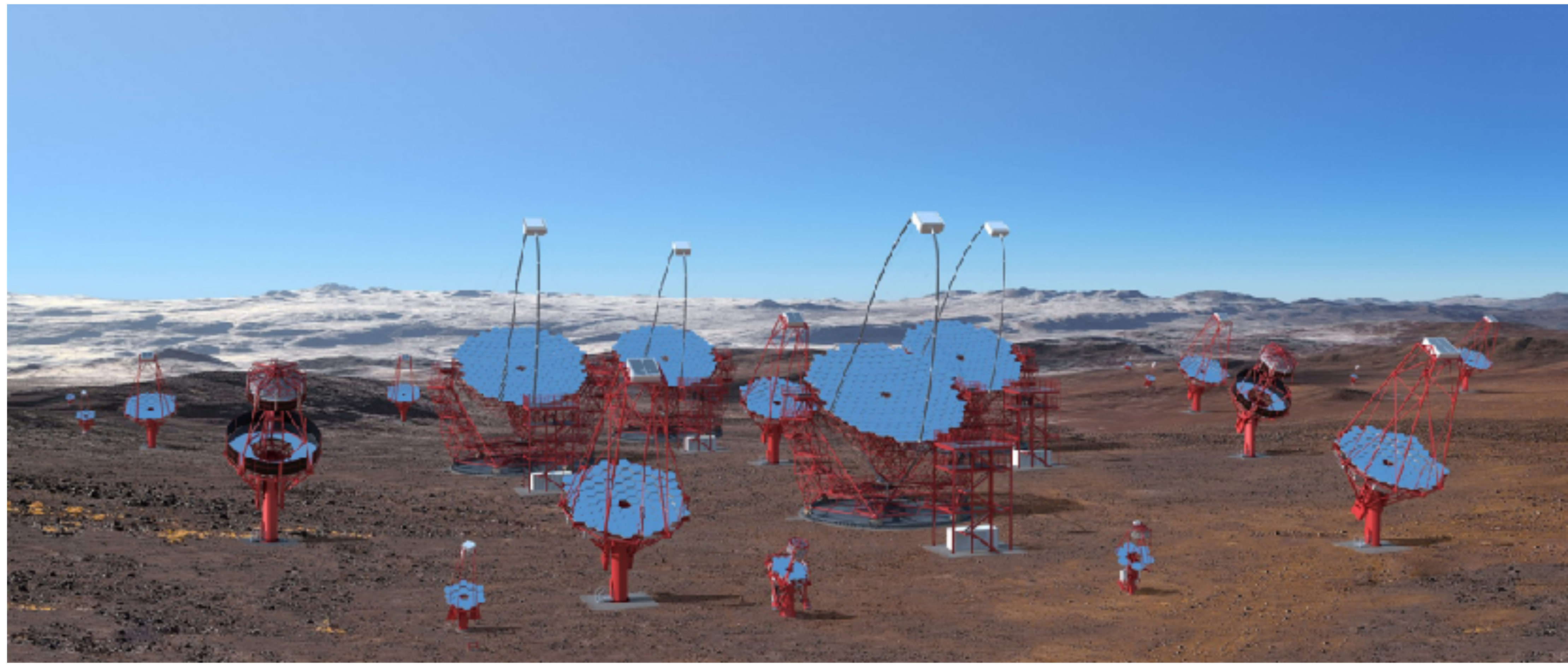
- Not point back to source ✗
- Spectral signatures ✓
- Low Bkg (for antimatter) ✓
- Diffusion ✗

γ-ray telescopes

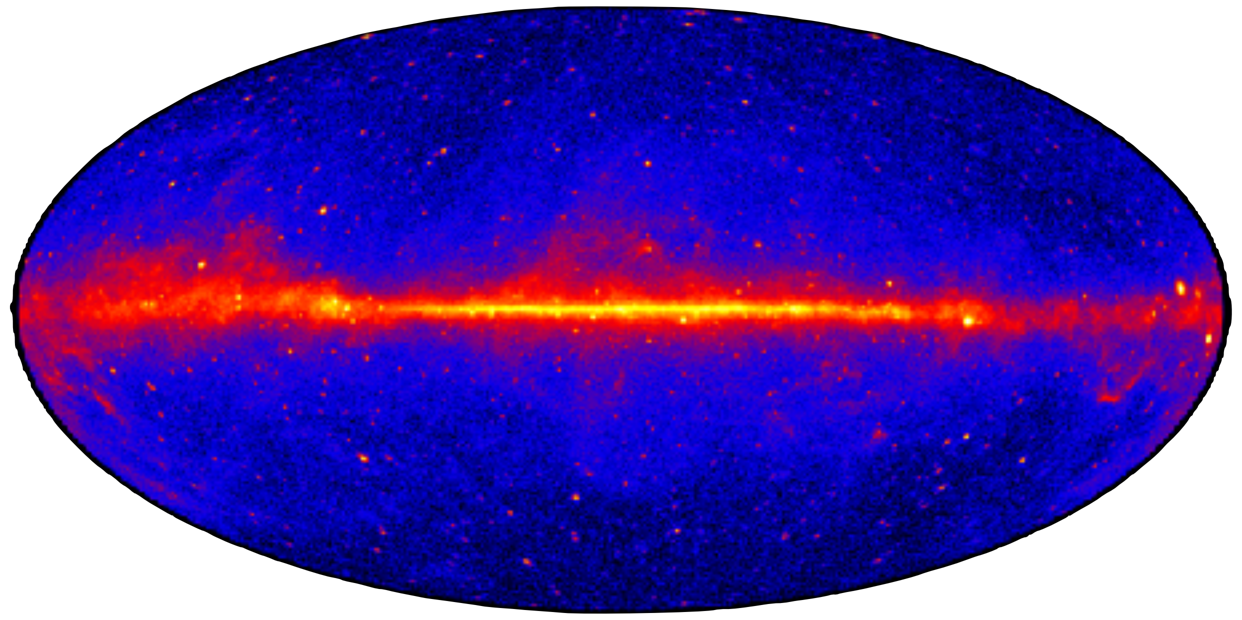


Indirect detection



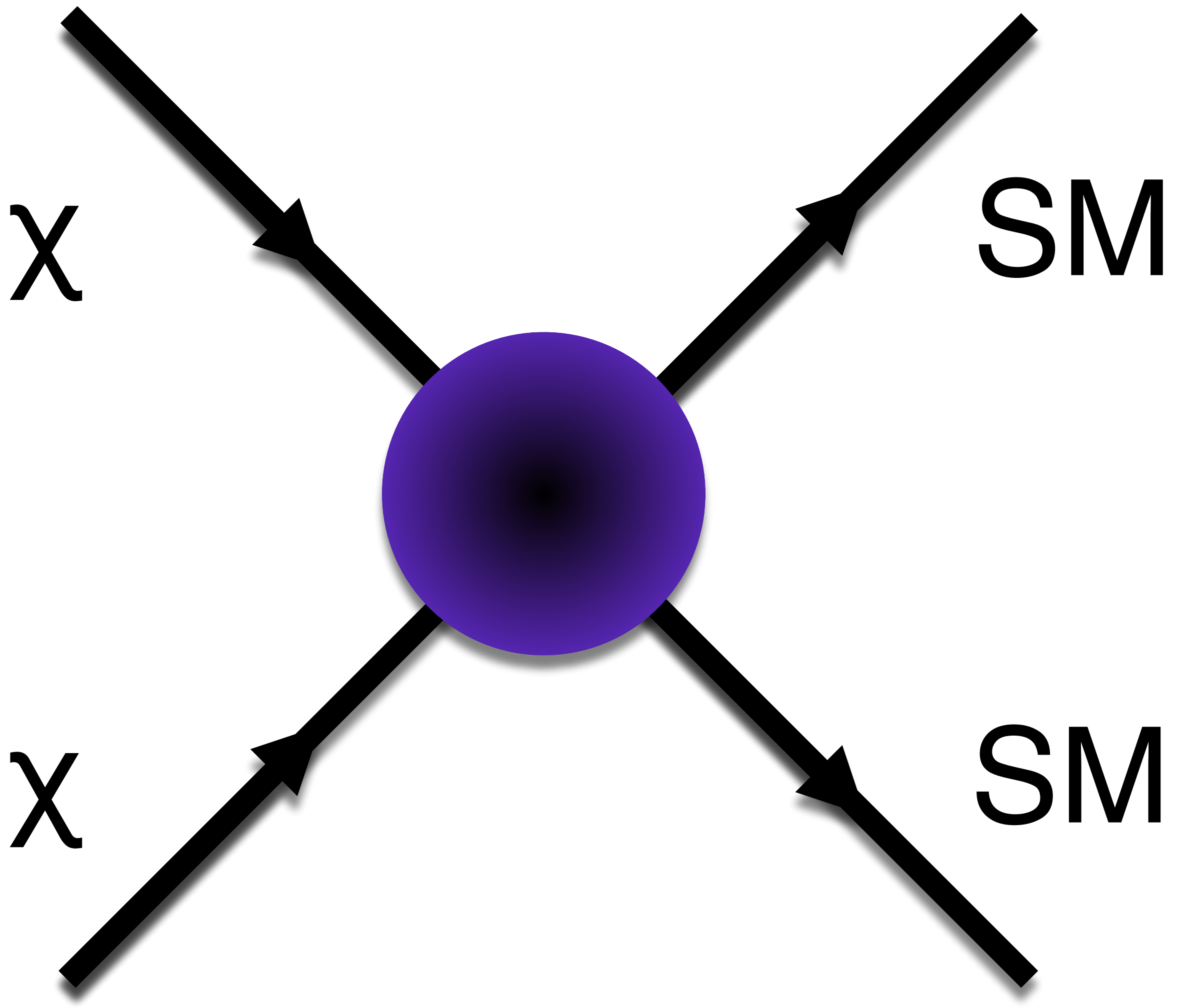


- Earth Atmosphere opaque to γ ⇒ Satellite-based telescope (Fermi LAT)
  - $E_\gamma \sim (0.02 - 300)\,\mathrm{GeV}$, Field of View ~2.4 sr
- γ flux quickly falls with energy ⇒ Ground based Cherenkov telescopes for high energy γ
  - Many arrays: HESS, MAGIC, VERITAS, CTA…
  - $E_\gamma \sim (50 - 100{,}000)\,\mathrm{GeV}$, Field of View ~$5^\circ - 10^\circ$
  - Can reject hadronic cosmic rays, but not leptons (e^-e^+)

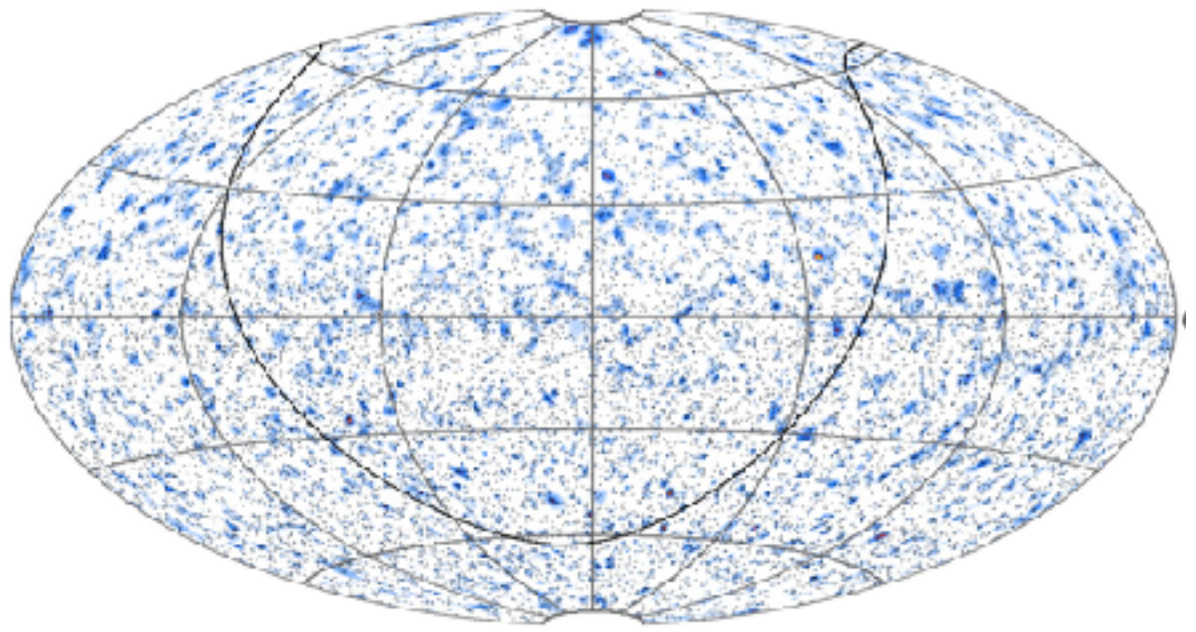


Map of the γ sky

ν-telescopes - Ice Cube



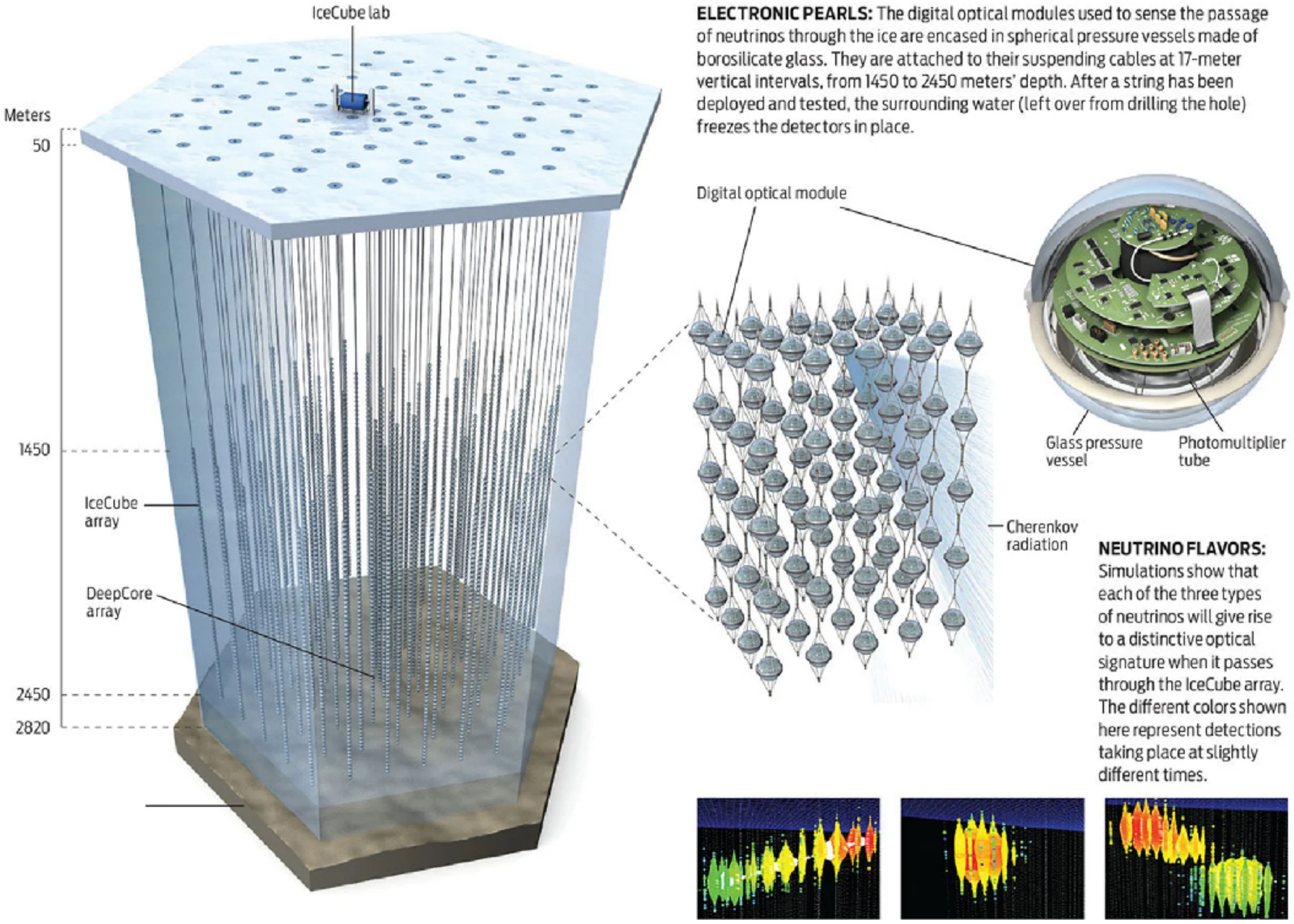
Indirect detection



Map of the ν sky

- Loc: South Pole
- Volume: ~1 km^3
- E_{th}: ~100 GeV
- Cherenkov Light from ν conversions

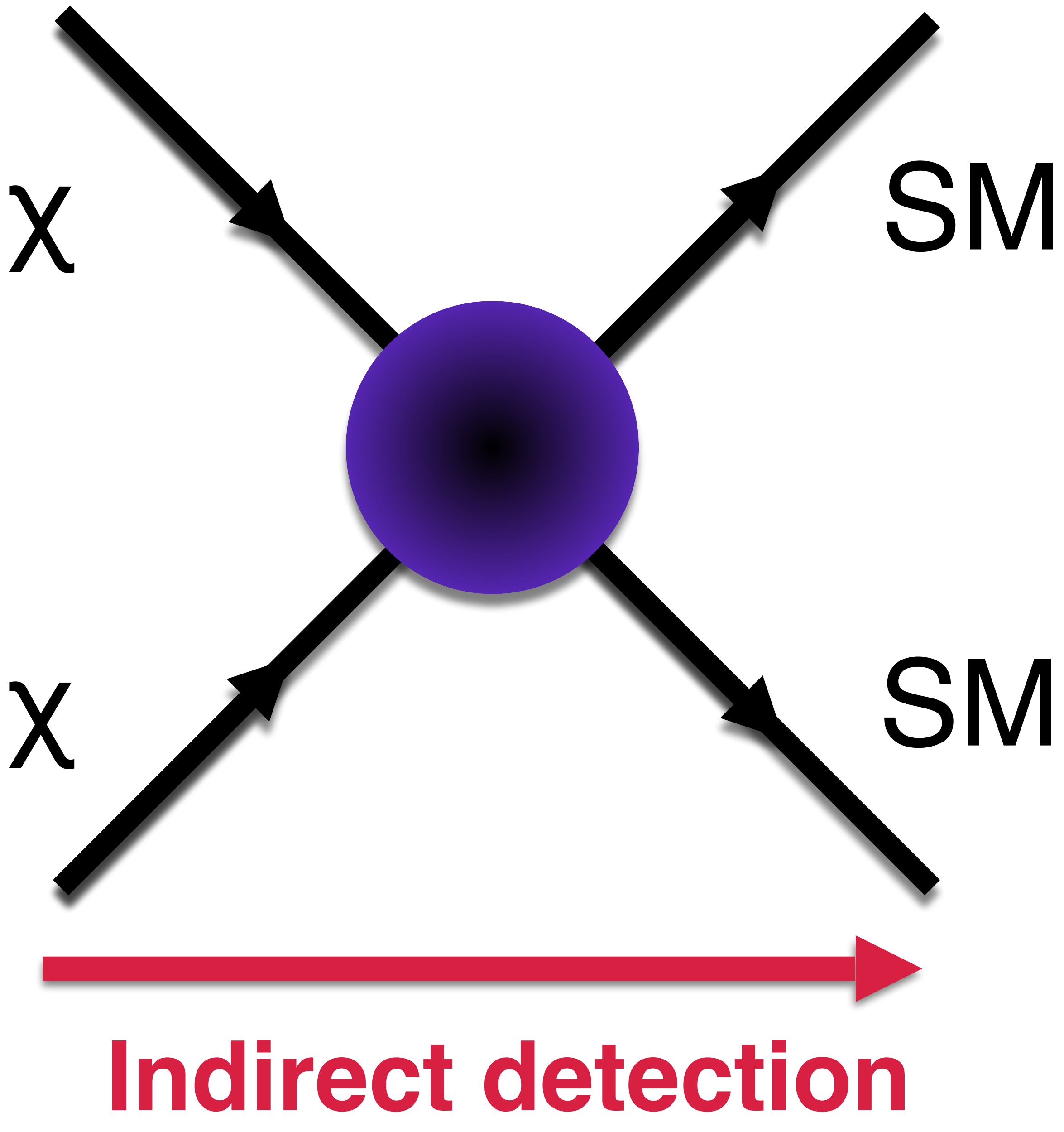
- Also more experiments under the sea: Antares, Km3Net, P-One…



ELECTRONIC PEARLS: The digital optical modules used to sense the passage of neutrinos through the ice are encased in spherical pressure vessels made of borosilicate glass. They are attached to their suspending cables at 17-meter vertical intervals, from 1450 to 2450 meters' depth. After a string has been deployed and tested, the surrounding water (left over from drilling the hole) freezes the detectors in place.

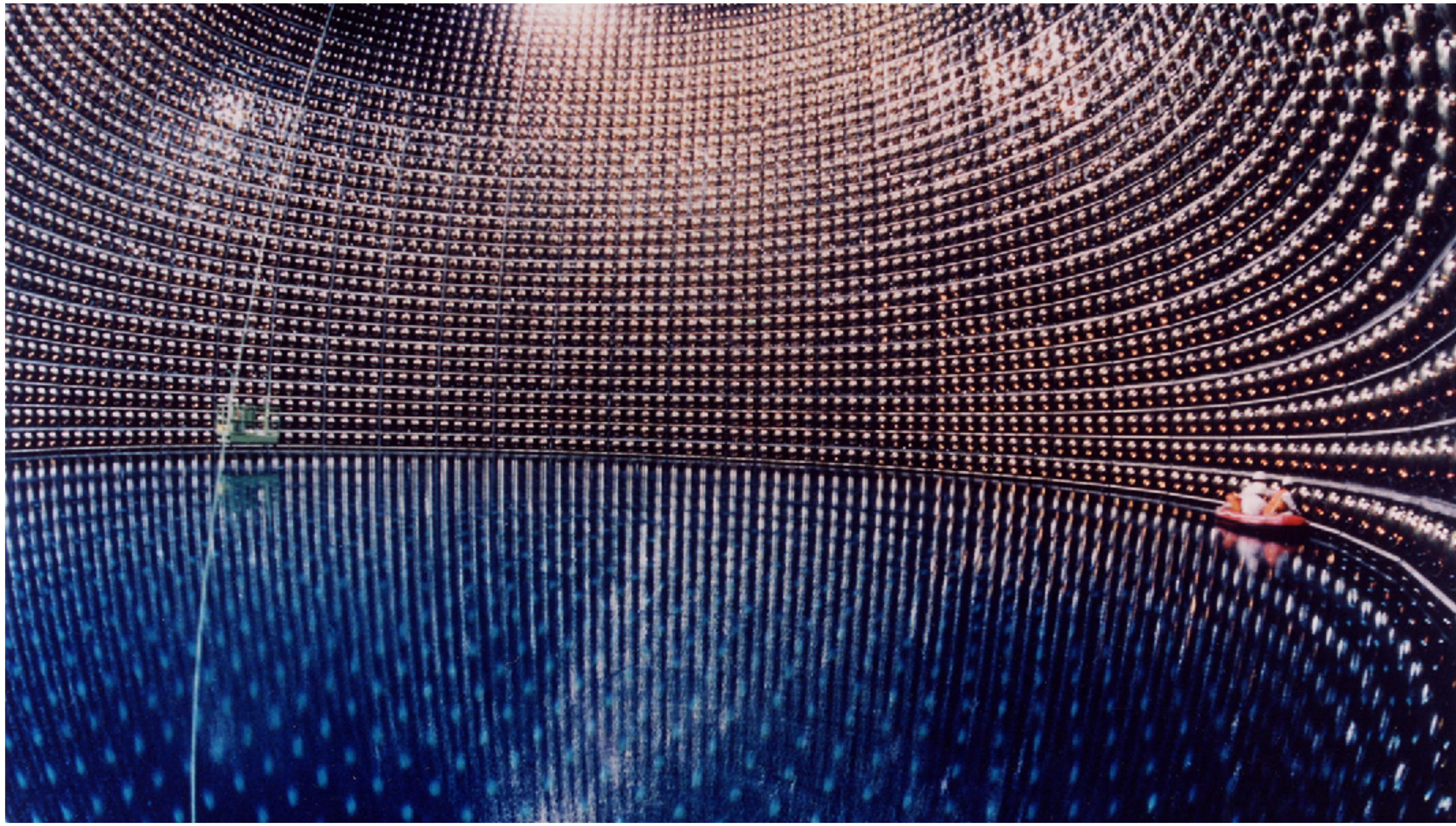
NEUTRINO FLAVORS: Simulations show that each of the three types of neutrinos will give rise to a distinctive optical signature when it passes through the IceCube array. The different colors shown here represent detections taking place at slightly different times.

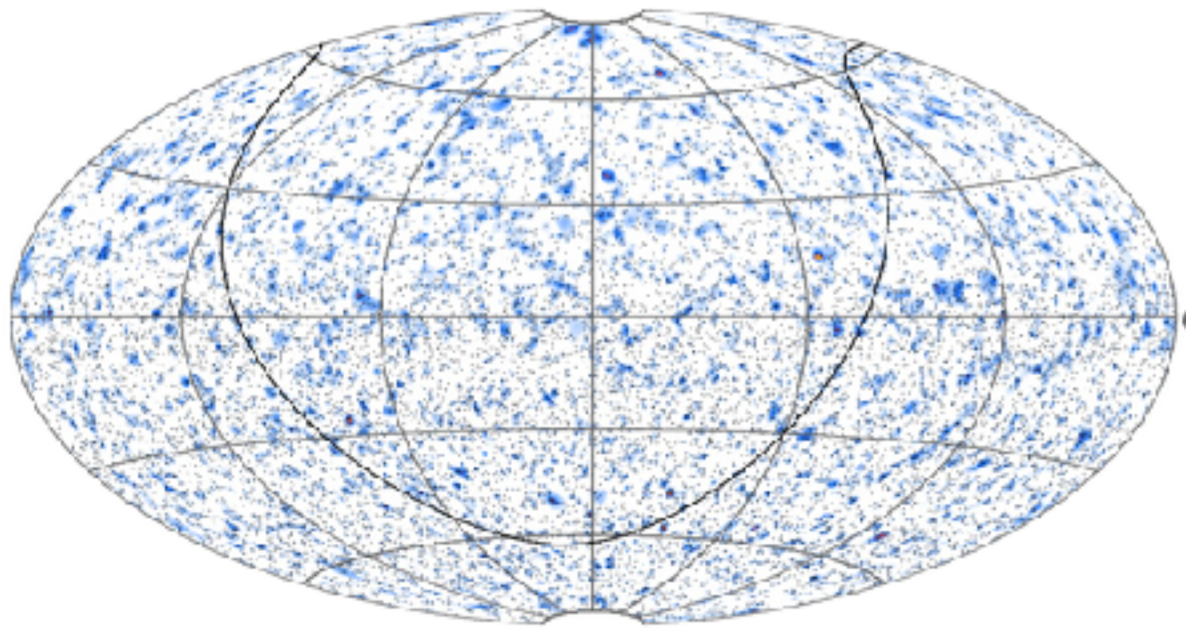
ν-telescopes - Super Kamiokande



Indirect detection

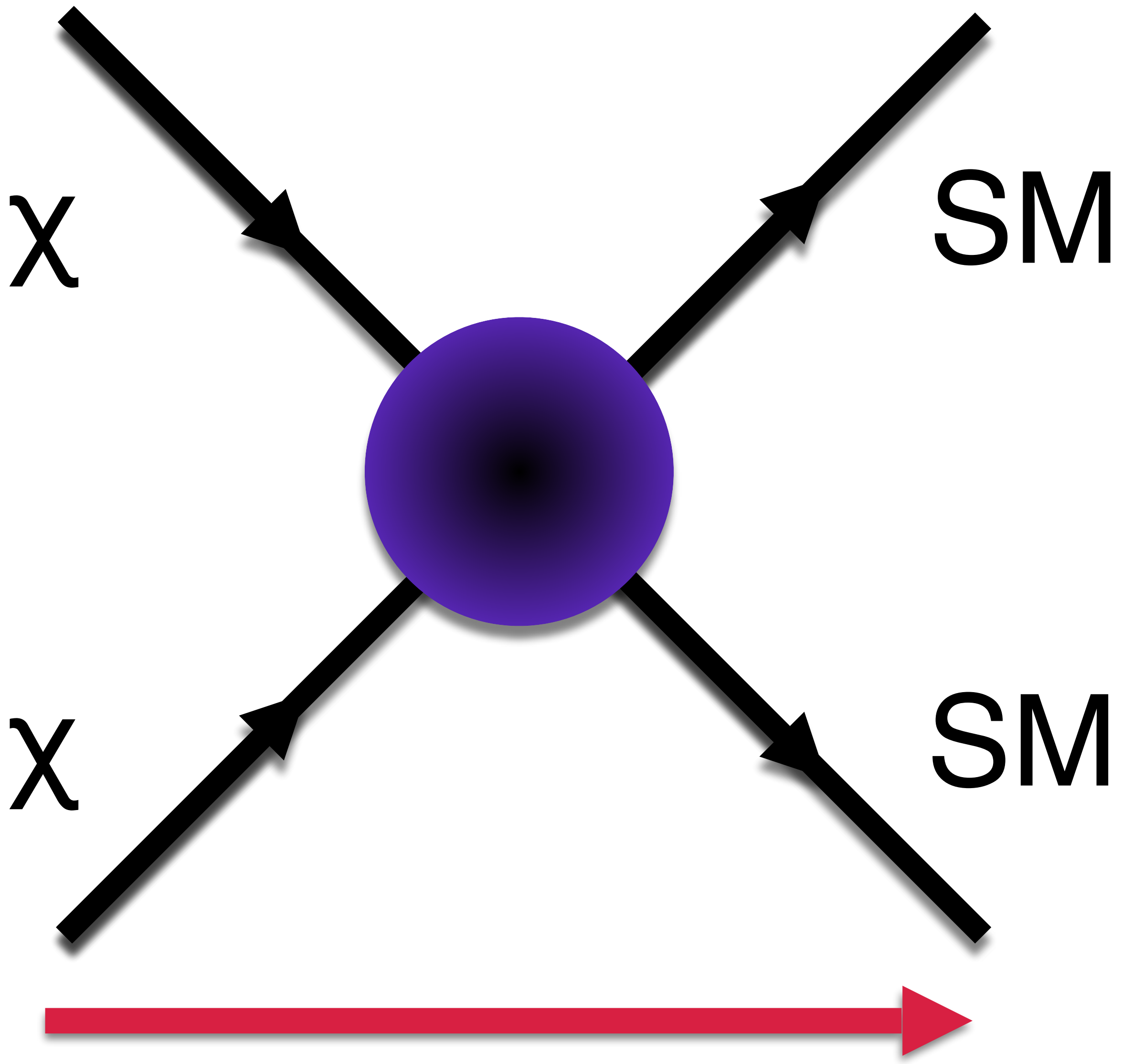
- Loc: Kamioka (JP)
- Mass: ~50,000 t
- E_{th}: ~5 MeV
- Cherenkov Light from ν conversions
- Hyper-Kamiokande (~258,000 t) under construction



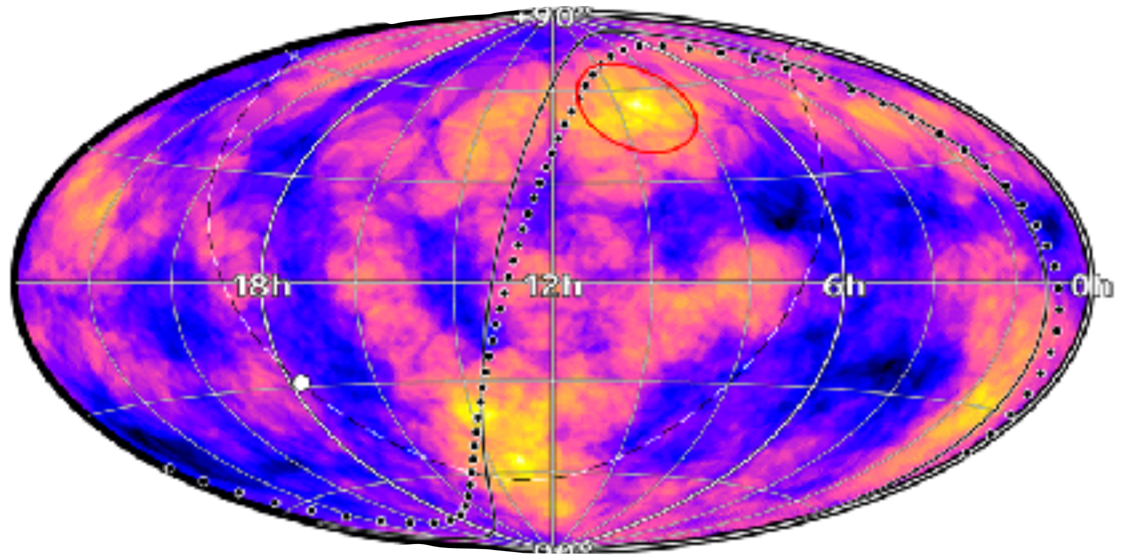


Map of the ν sky

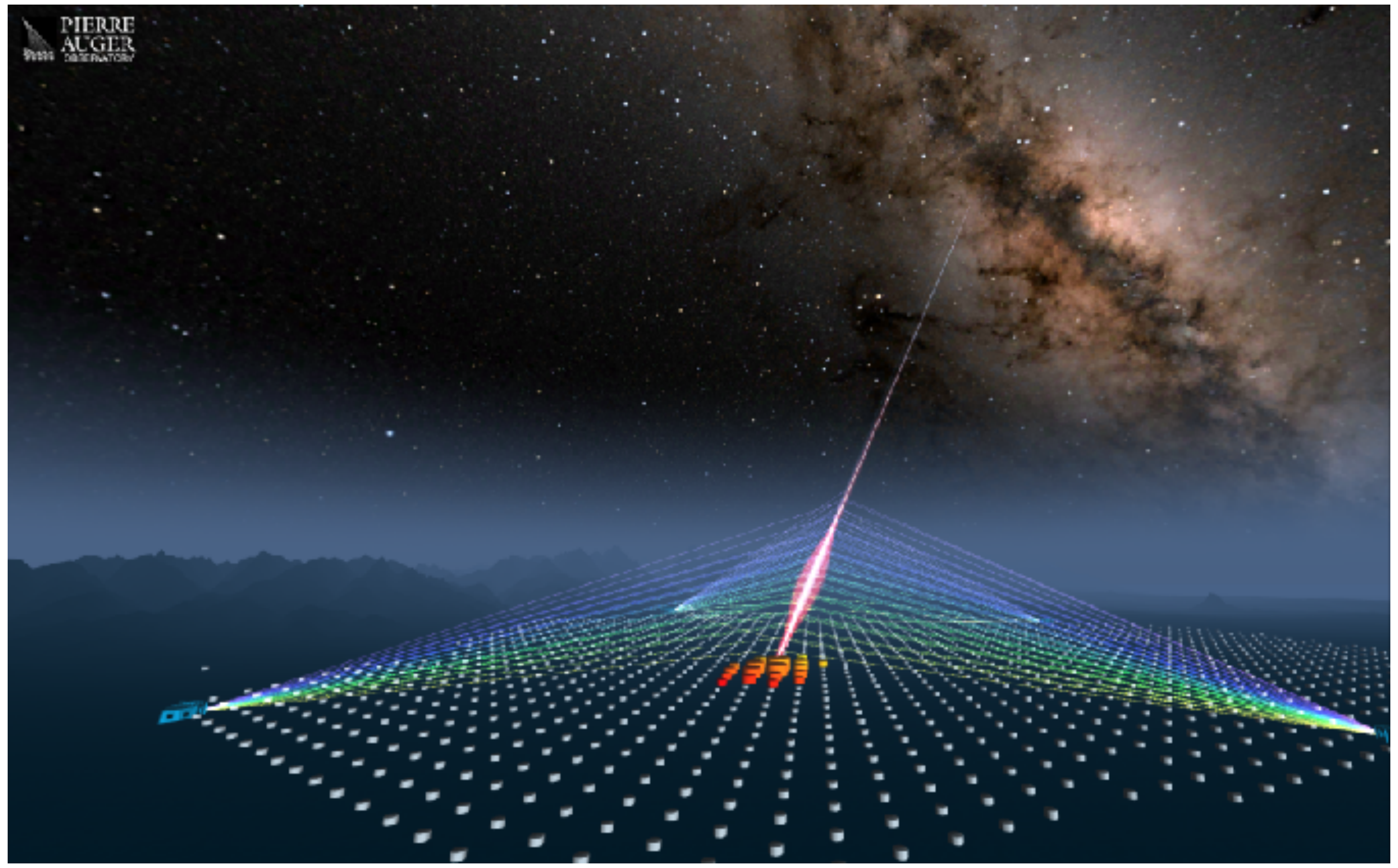
Cosmic Rays telescopes



Indirect detection

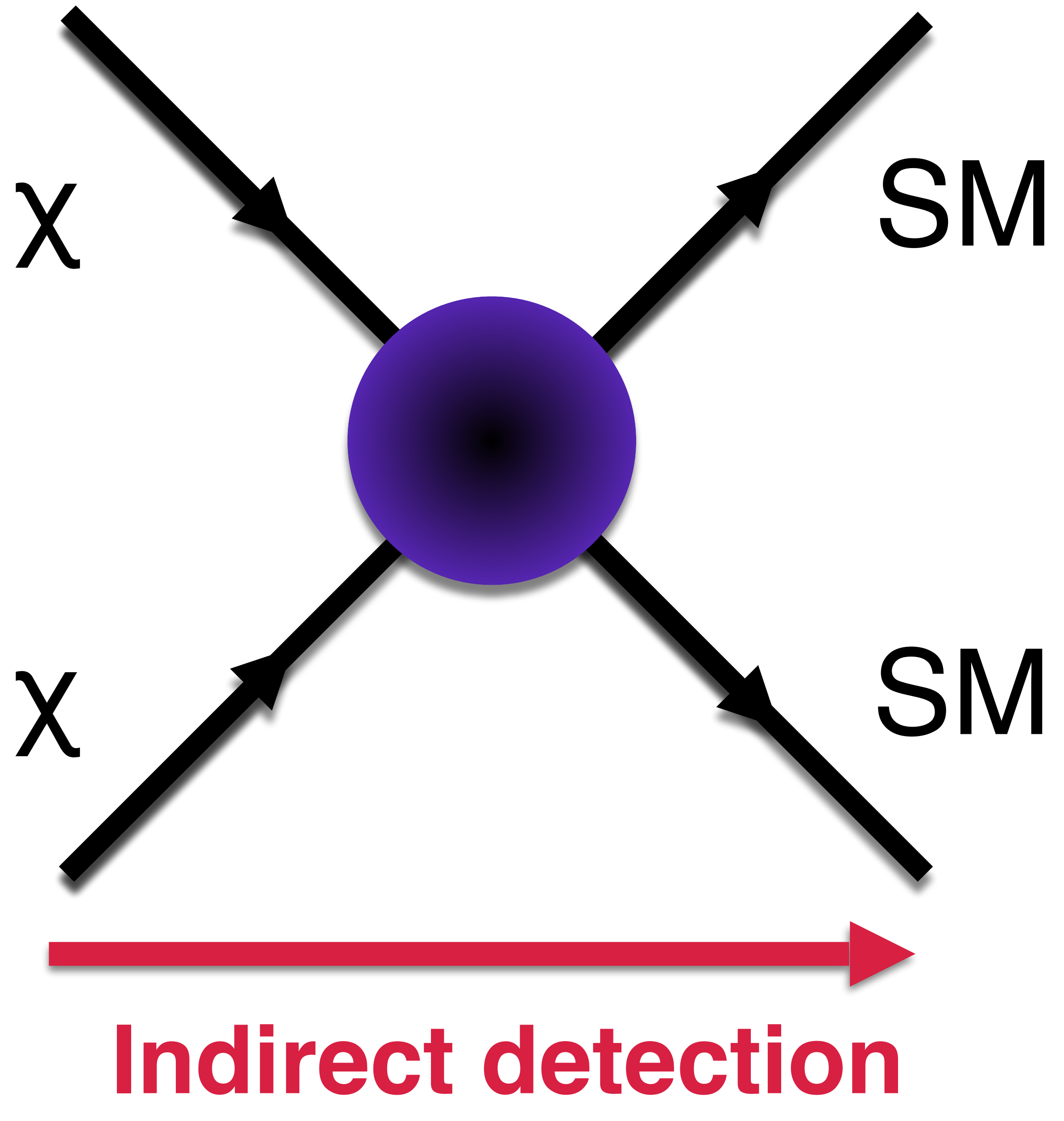


Cosmic ray sources

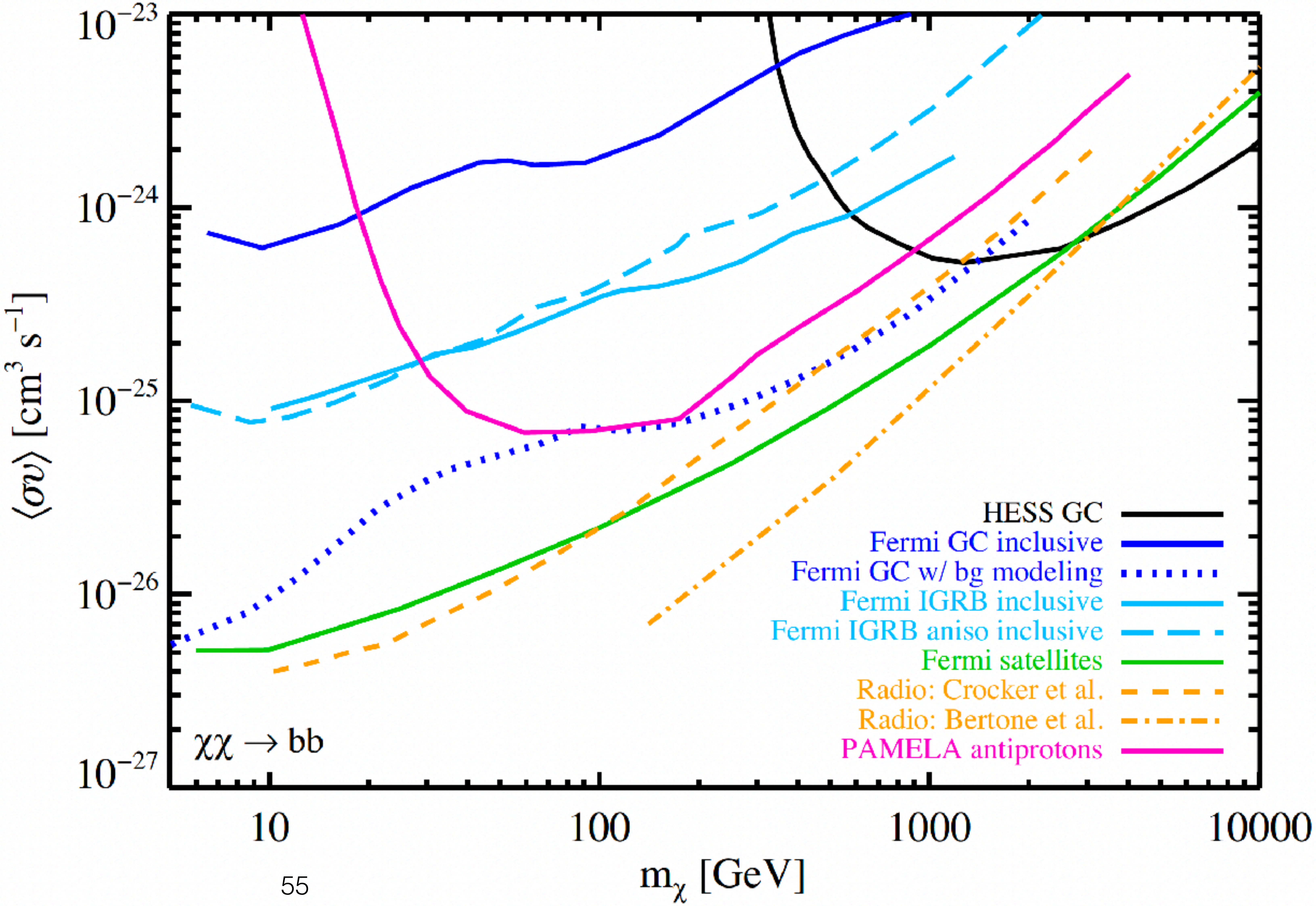


- Earth Atmosphere absorbs primary cosmic rays ⇒ AMS-02 on ISS
  - $E \sim (0.1 - 500)\,\mathrm{GeV}$
- Flux quickly falls with energy ⇒ Ground based observatories for high energy cosmic rays
  - Pierre Auger Observatory
  - Cherenkov water tanks + atmospheric fluorescence telescopes
  - $E > 10^{18}\,\mathrm{eV} = 10^{9}\,\mathrm{GeV}$

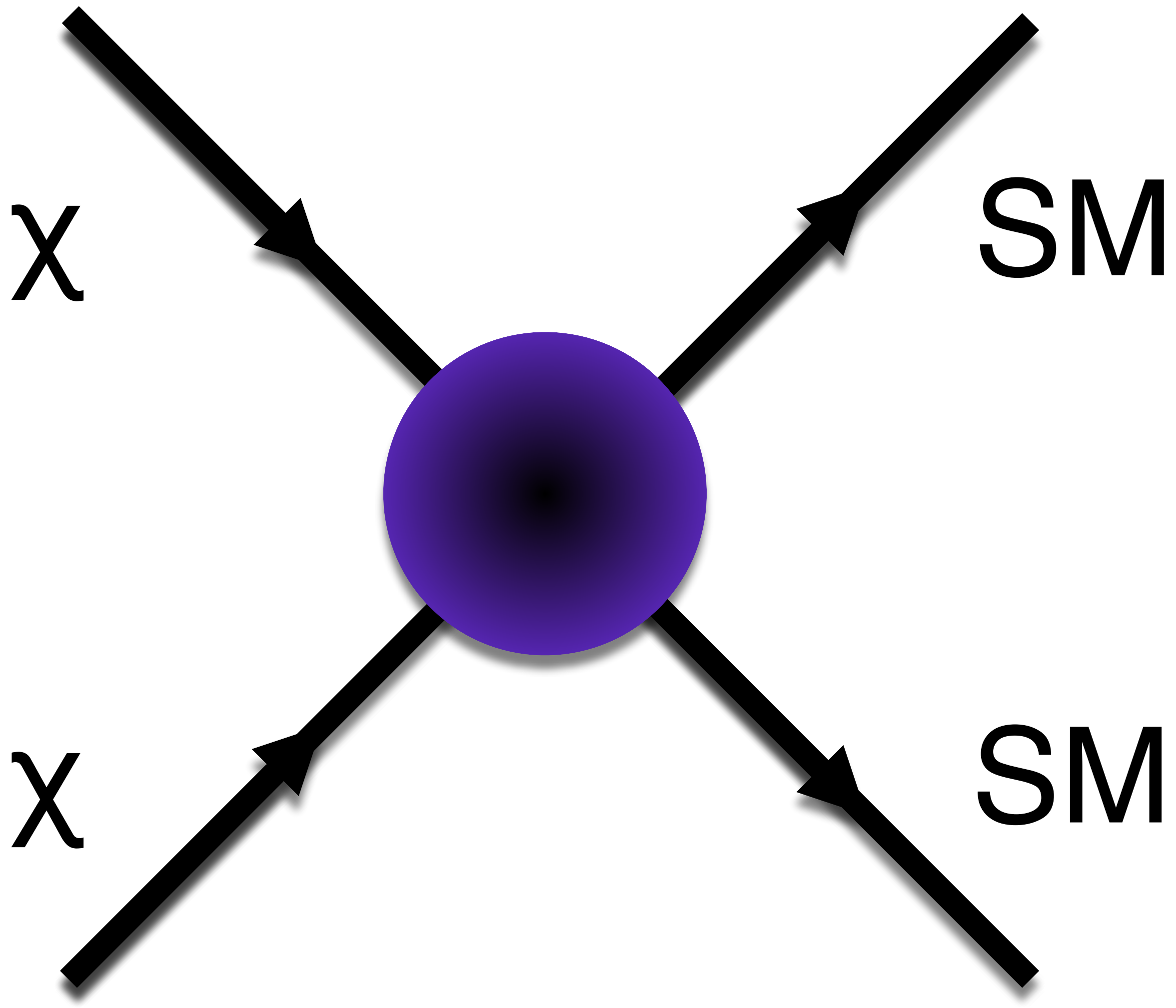
Status



- Current and future sensitivity to s-wave DM annihilation to quarks and gauge bosons
- More info on the Snowmass-2021 topical white paper (2209.07426)

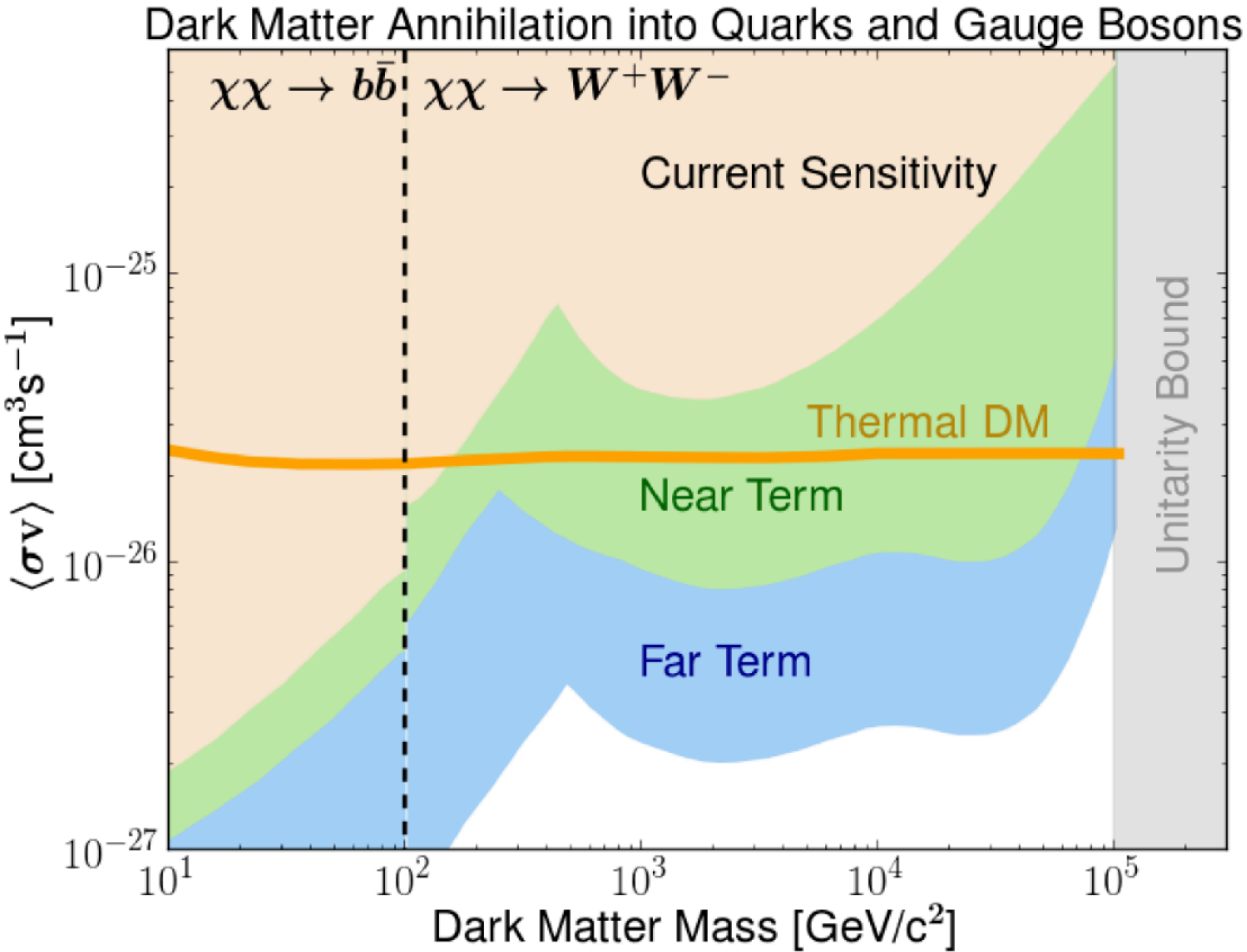


Perspectives

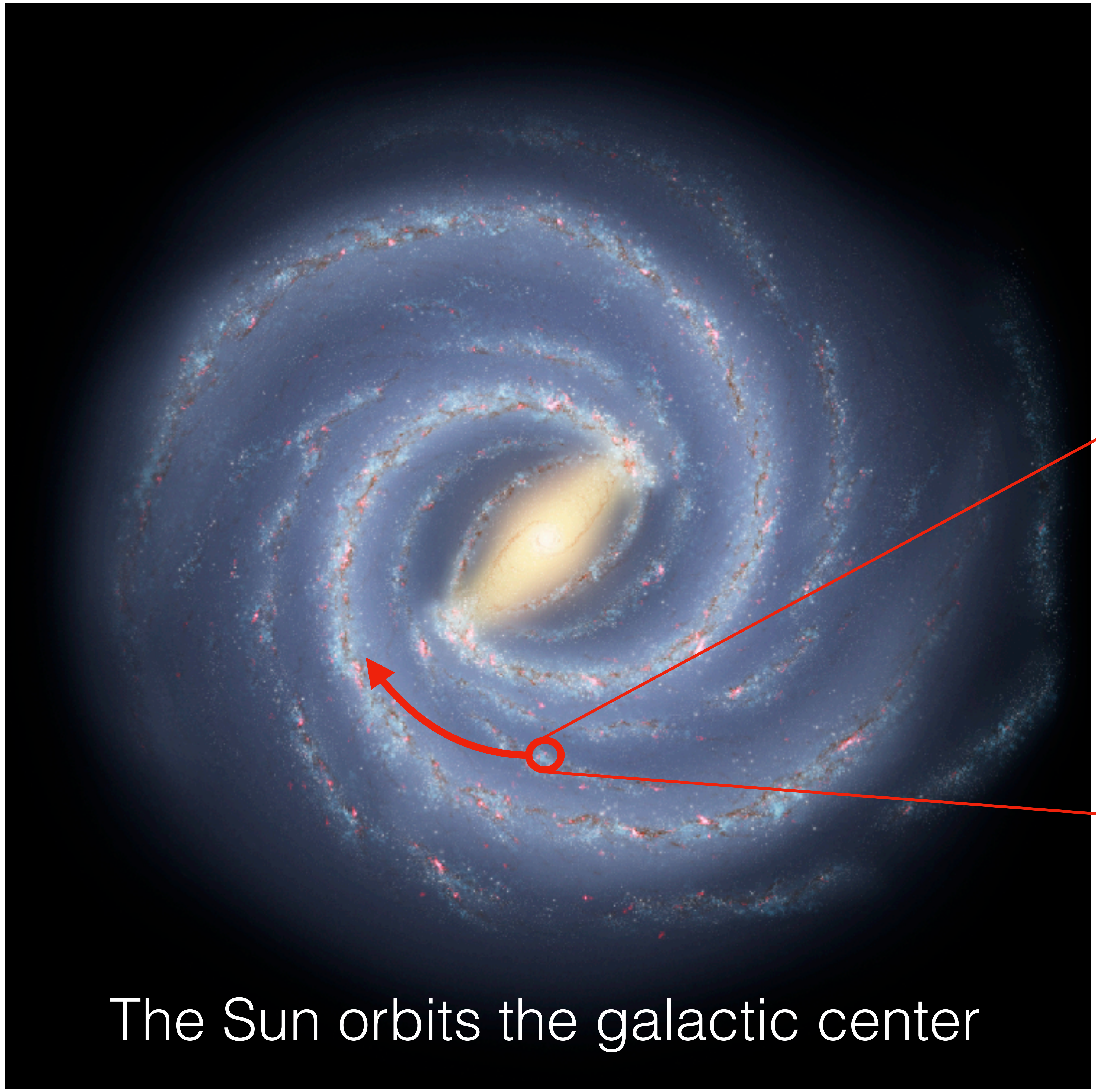


Indirect detection

- Current and future sensitivity to s-wave DM annihilation to quarks and gauge bosons
- More info on the Snowmass-2021 topical white paper (2209.07426)

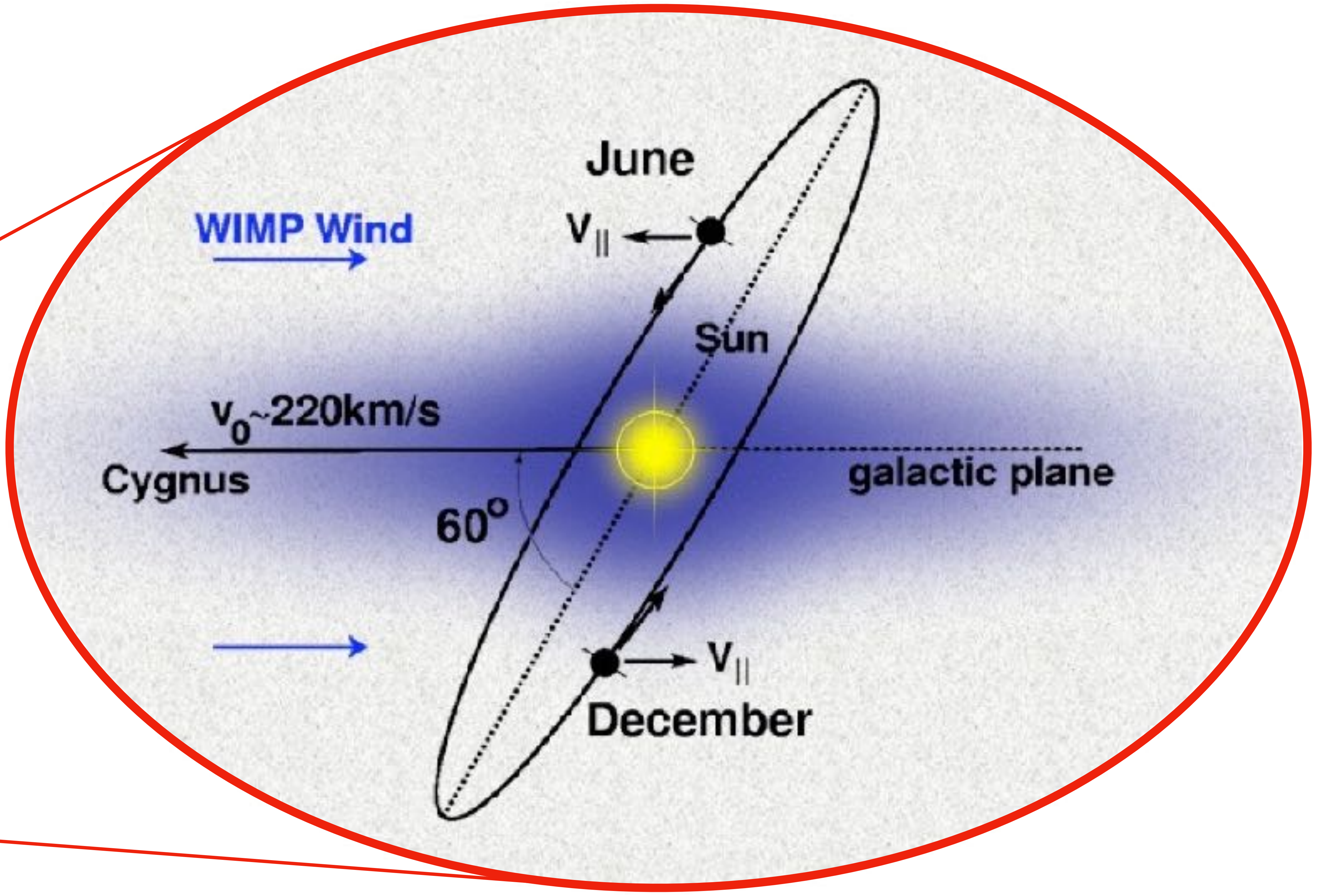


WIMP Wind



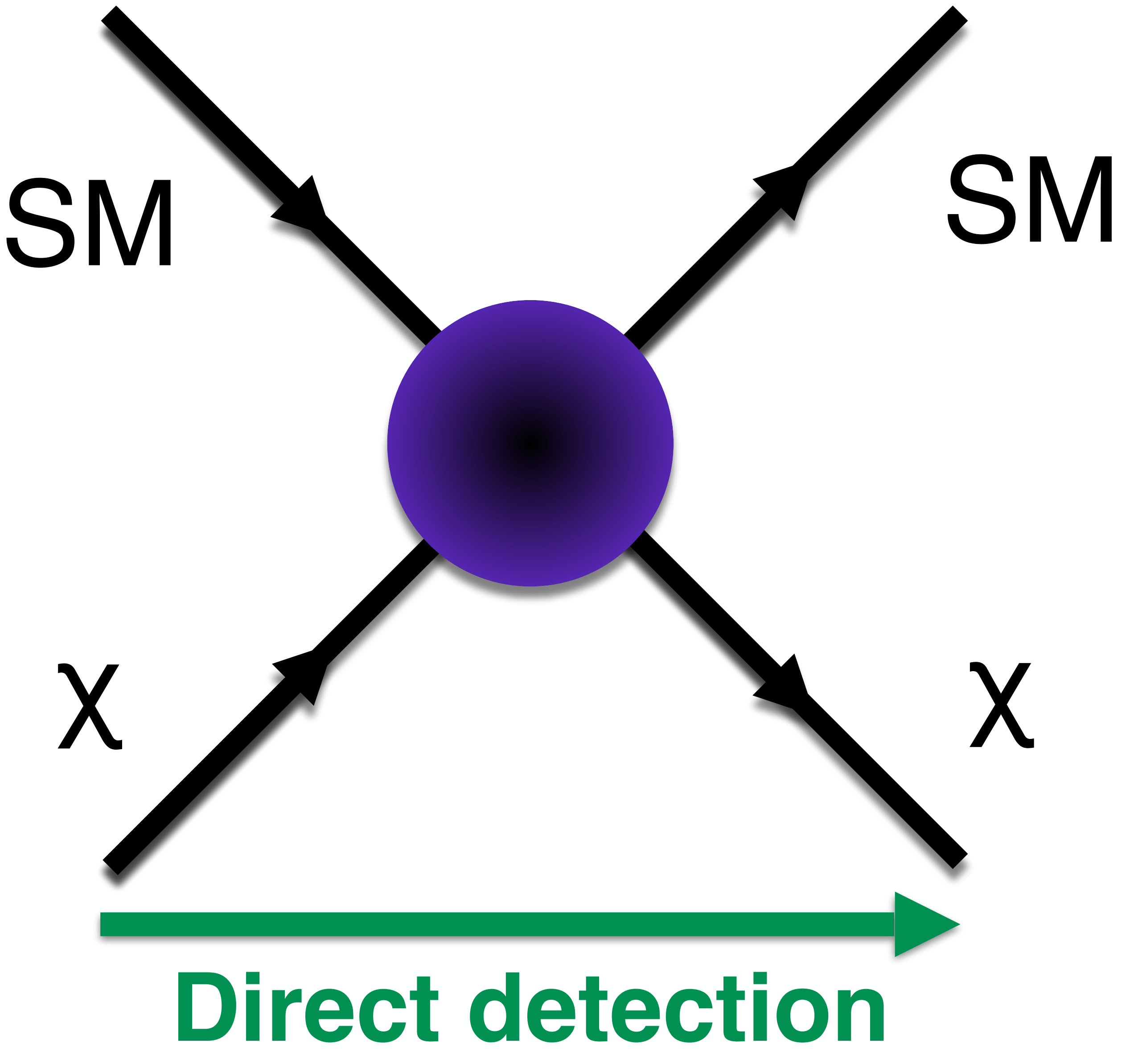
The Sun orbits the galactic center

“Gas” of WIMPs

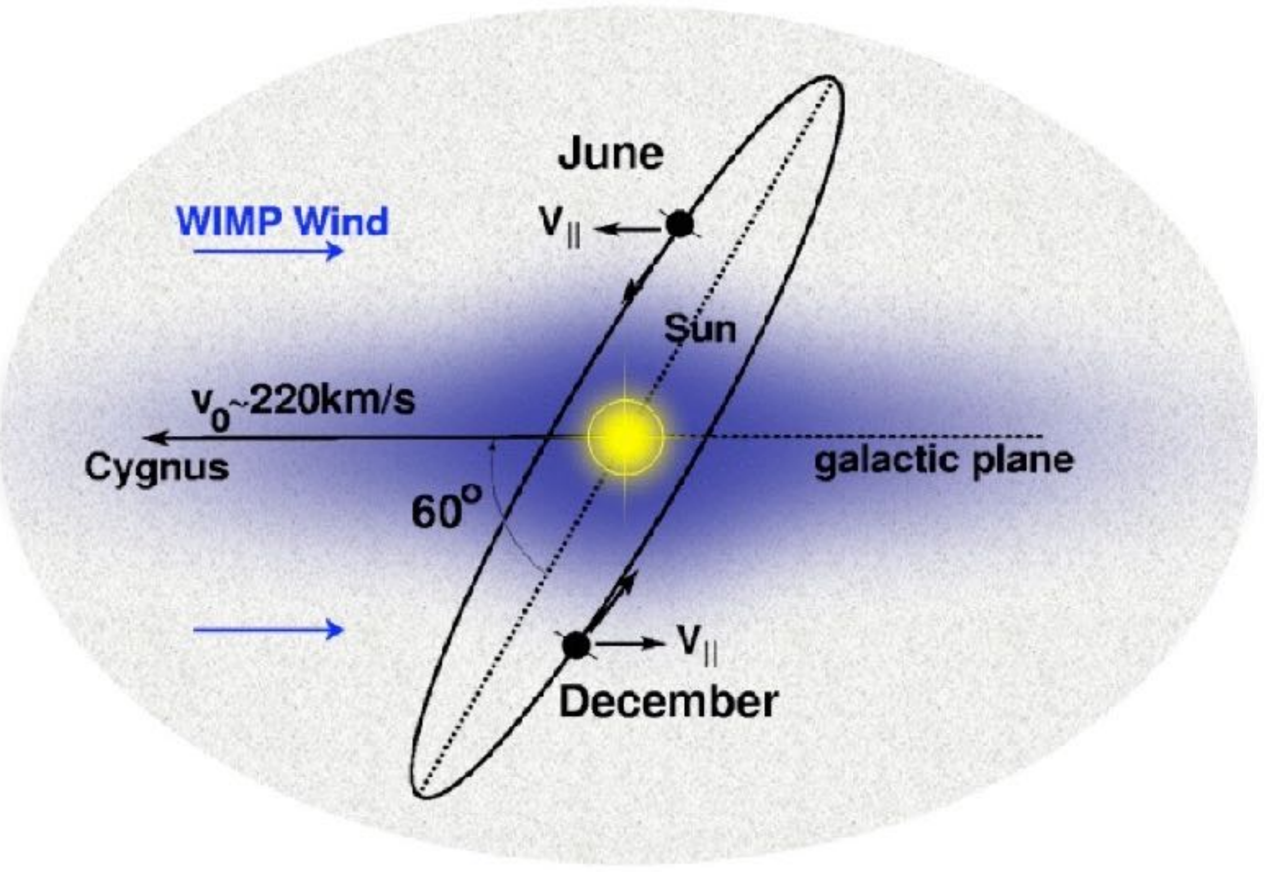


The Sun moves through a WIMP “gas”
“WIMP wind” on Earth

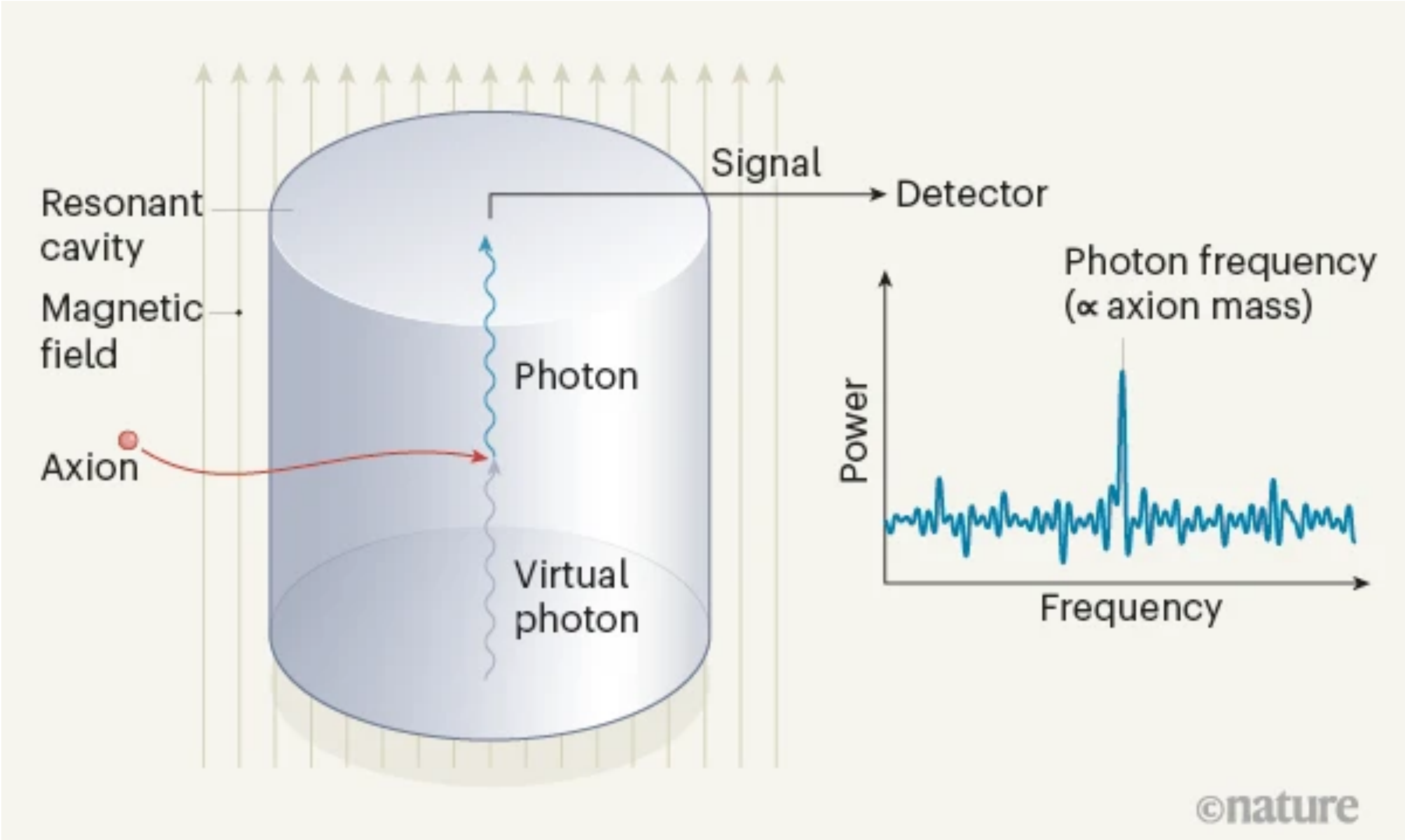
Direct Detection



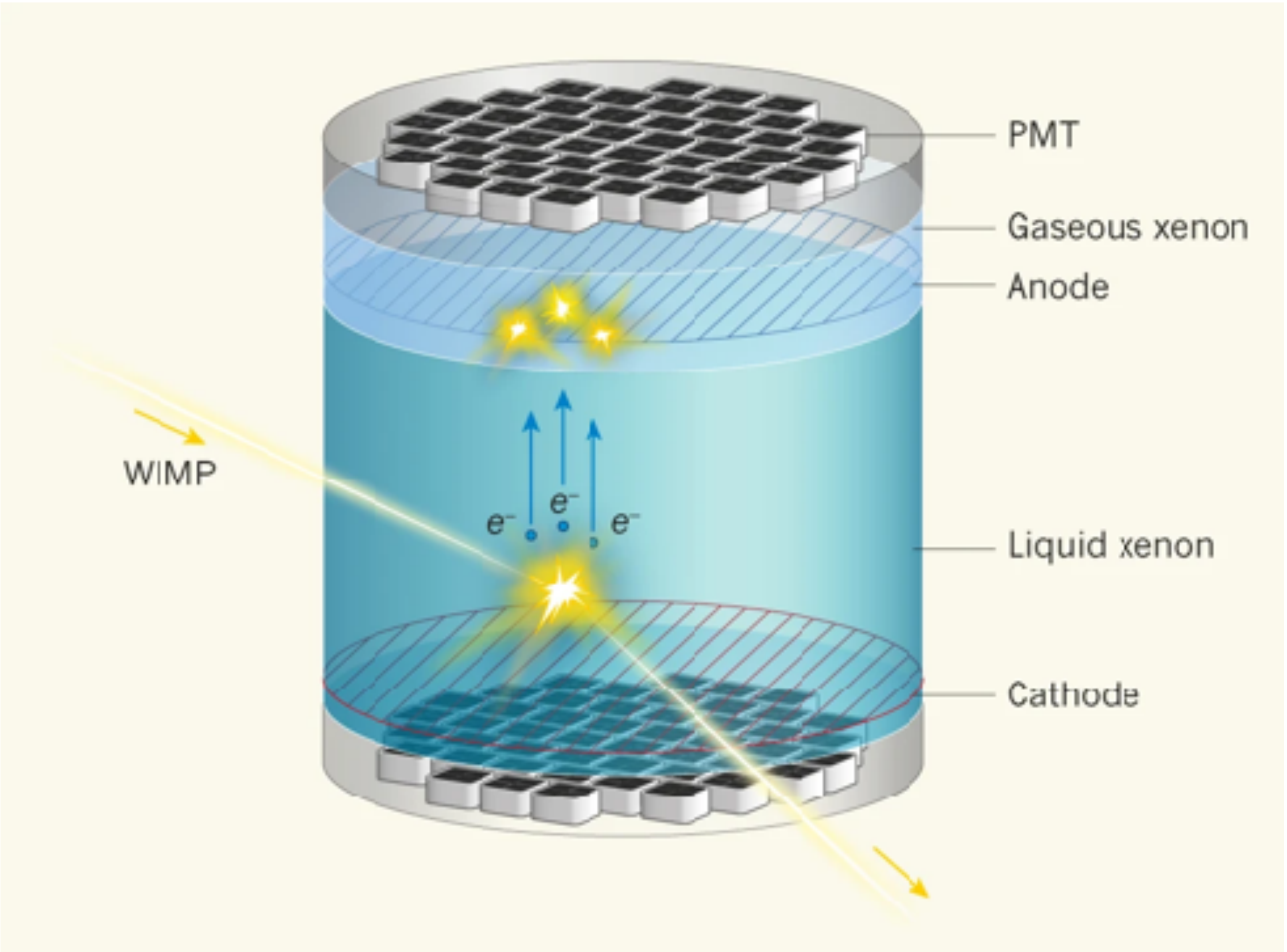
- If DM has any coupling (other than gravity) to the SM, we can look for DM particles interacting in detectors here on Earth!
- We do not produce the DM - traveling through a gas of DM right now
- Direct searches are branched in 2 main sub-fields:



Axion-like particles (ALPs)



WIMP-like particles



Direct Detection

Axion Detection

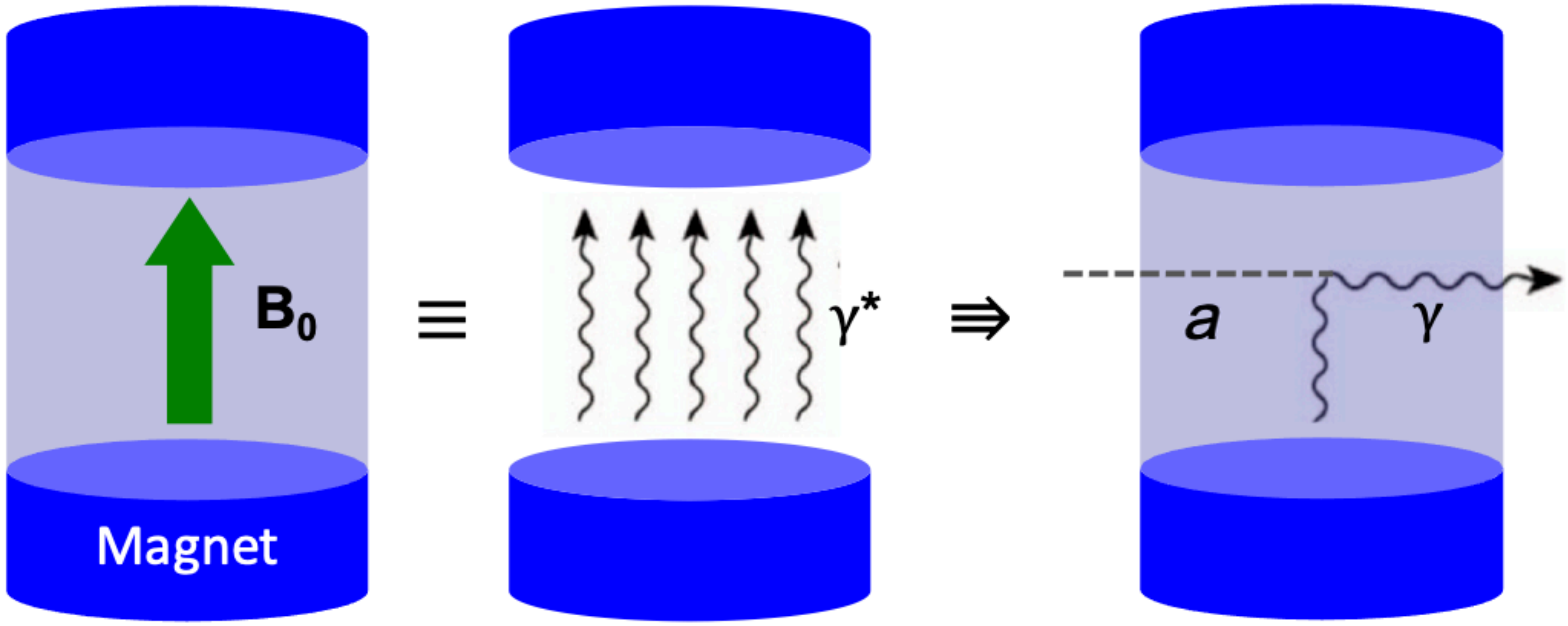
$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \widetilde{F}^{\mu\nu}$$ → Euler-Lagrange Equations → Modified Maxwell Equations

$$\nabla \cdot \mathbf{E} = \rho - g_{a\gamma\gamma} \nabla a \cdot \mathbf{B}$$

$$\nabla \times \mathbf{B} = -\dot{\mathbf{E}} + \mathbf{j} + g_{a\gamma\gamma}(\dot{a}\mathbf{B} + \nabla a \cdot \mathbf{E})$$

De Broglie wavelength of ~1μeV axion: ~1 km → $\nabla a \sim 0$ in detectors of size ~1m →

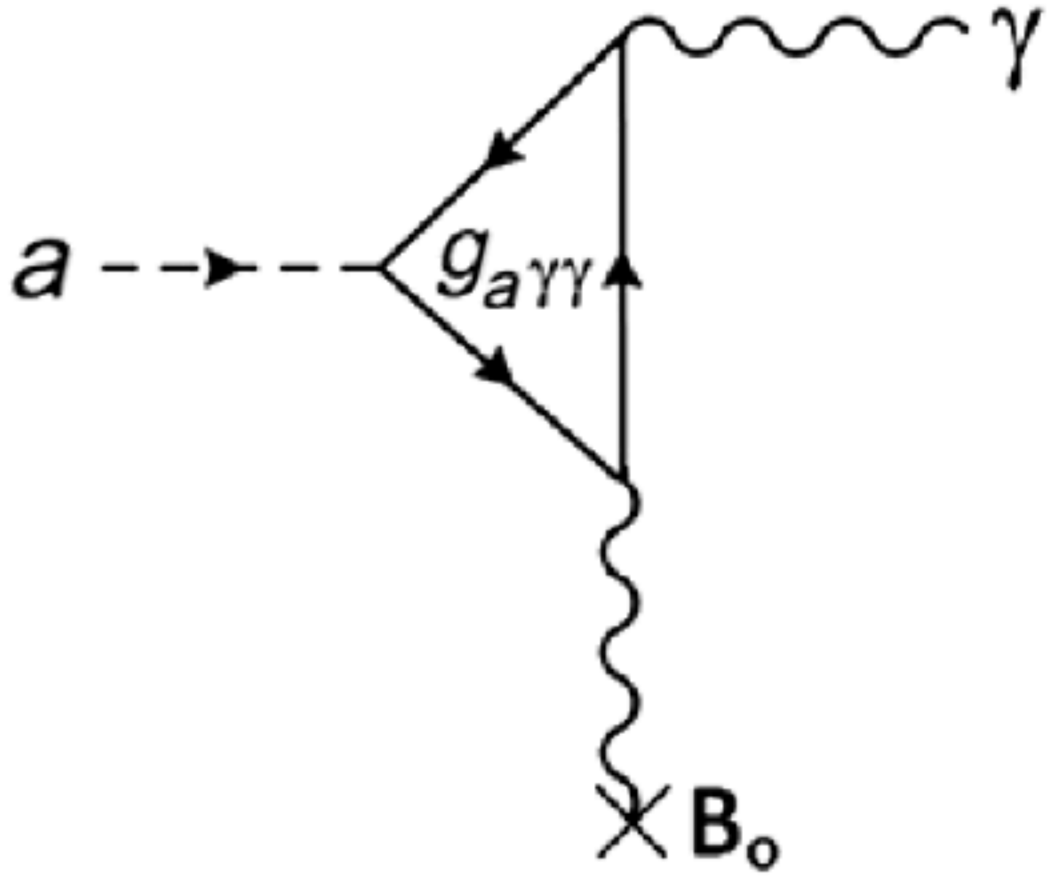
$$\nabla \times \mathbf{B} = -\dot{\mathbf{E}} + \mathbf{j} + g_{a\gamma\gamma}\dot{a}\mathbf{B}$$



Classical EM field

Sea of virtual photons

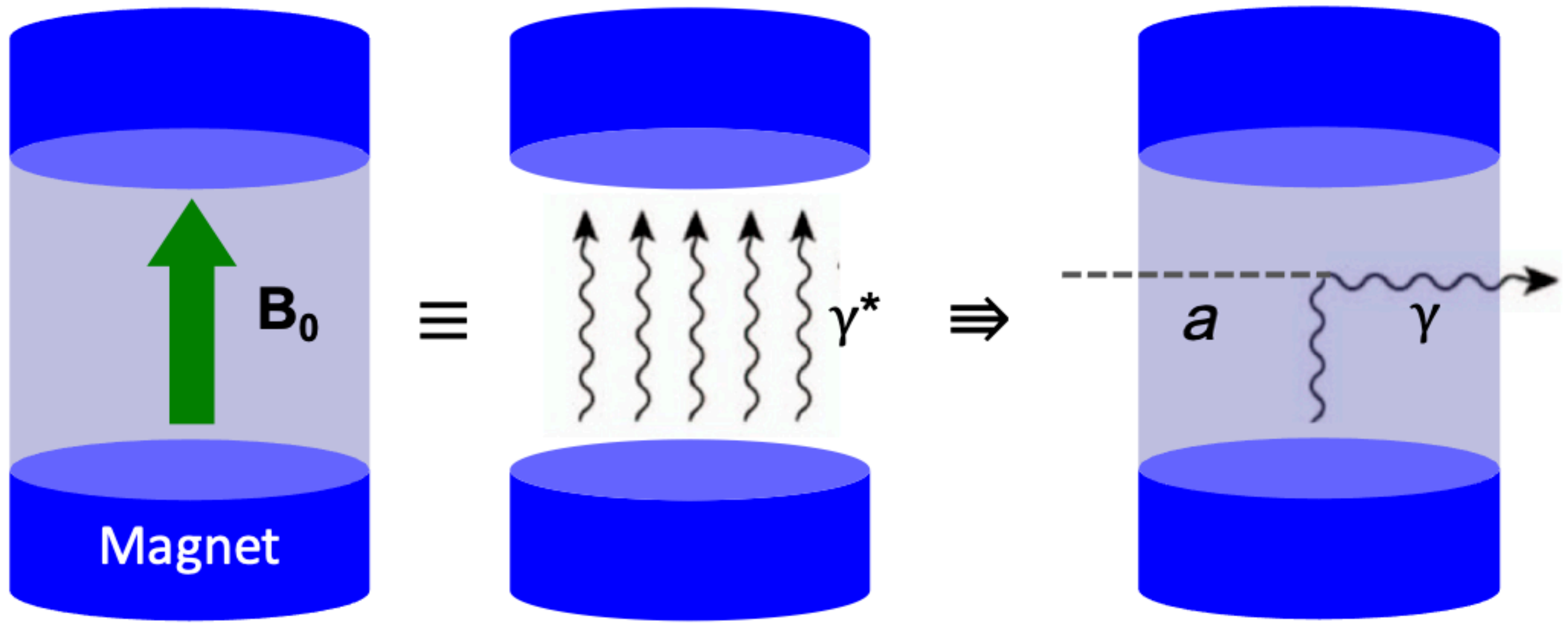
Axion-photon interaction



Additional source term for EM waves (i.e. photons)

Haloscopes

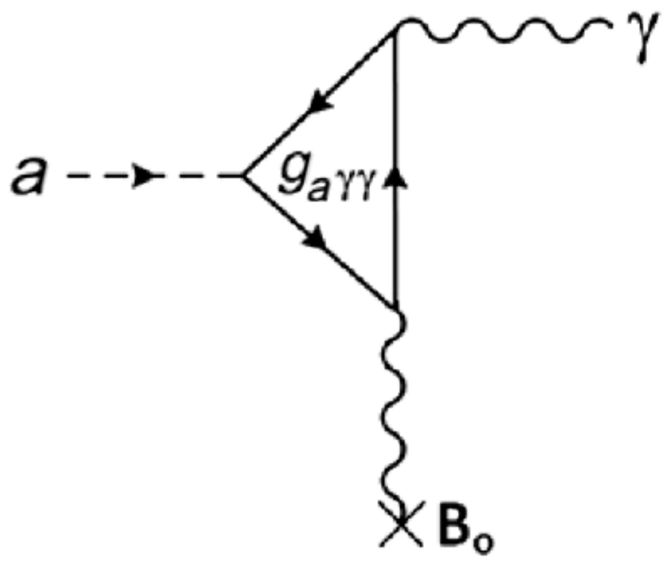
$$P_{a\gamma\gamma} = 5{\times}10^{-23} W \left(\frac{C_\gamma}{0.75}\right)^2 \left(\frac{\rho}{0.45\,\mathrm{GeV/cm^3}}\right) \left(\frac{m_a/h}{1\,\mathrm{GHz}}\right) \left(\frac{B}{10\,\mathrm{T}}\right)^2 \left(\frac{V}{30\,\mathrm{L}}\right) \left(\frac{G}{0.5}\right) \left(\frac{Q_c}{10^5}\right)$$



Classical EM field

Sea of virtual photons

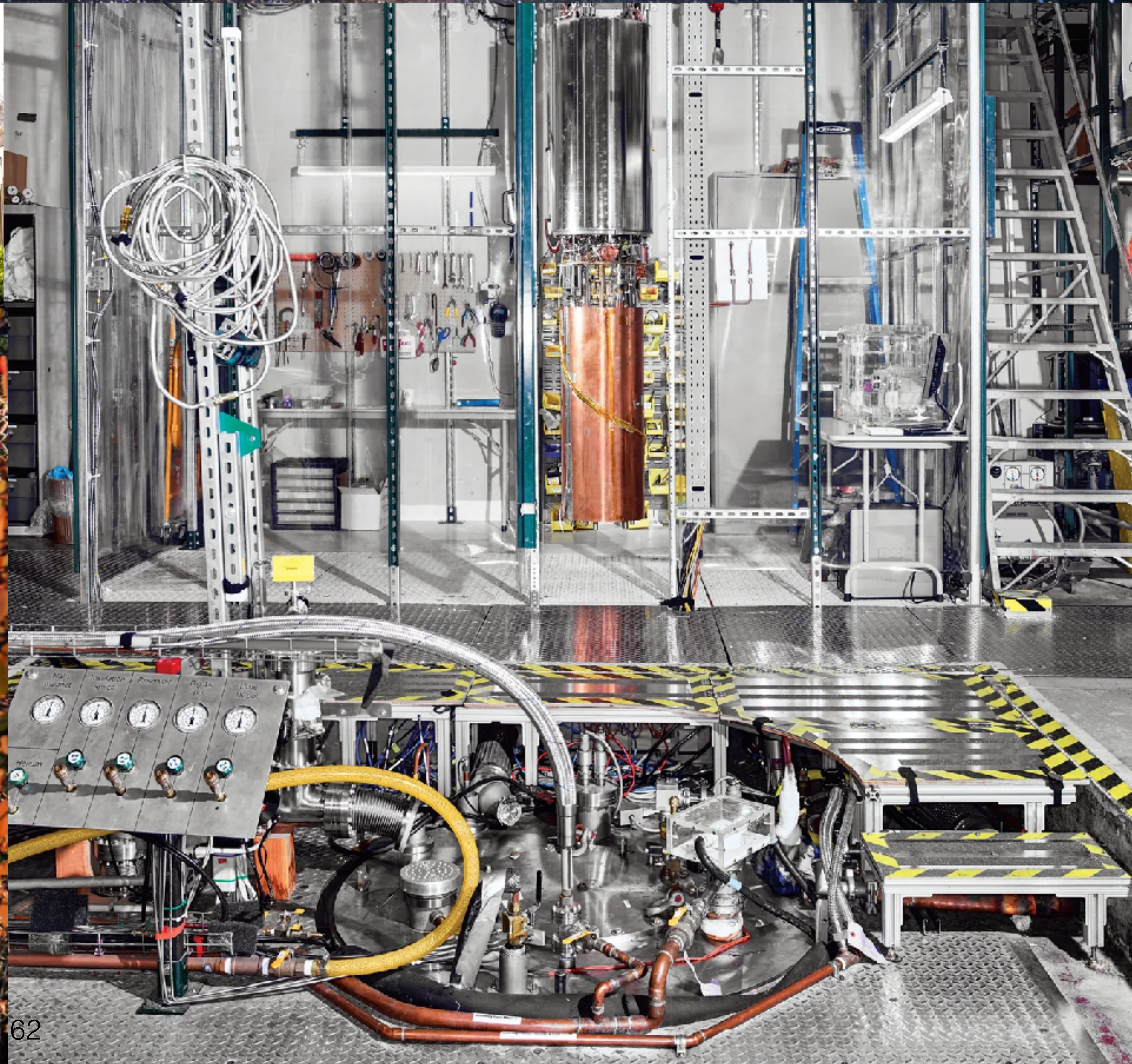
Axion-photon interaction



C_γ - axion-photon coupling
G - photon-cavity coupling
Q_c - cavity quality factor

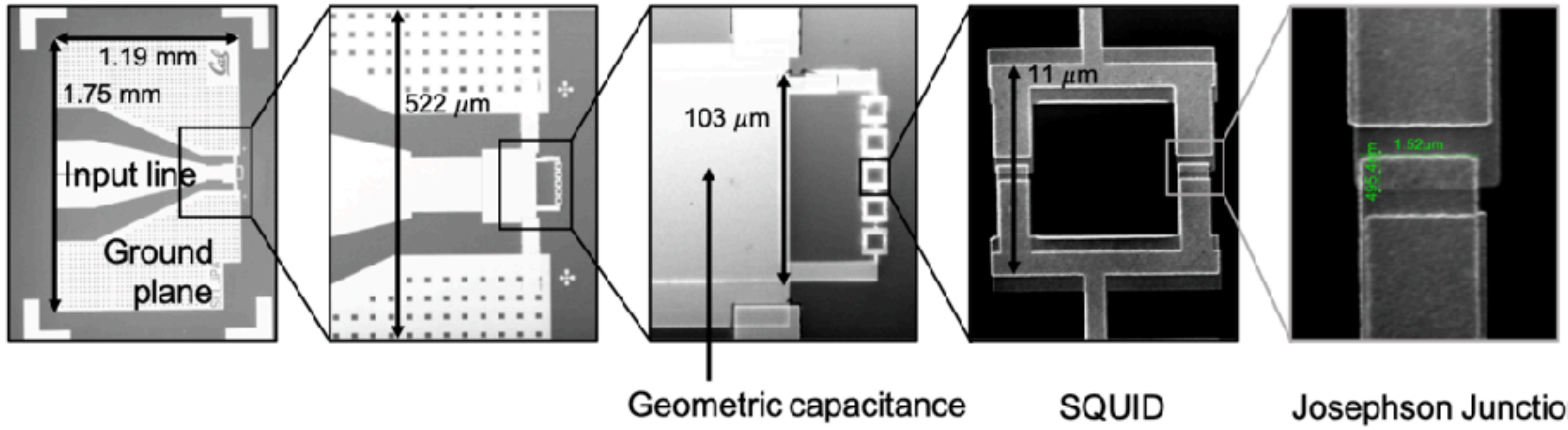
- Microwave resonant cavities immersed in a static magnetic field
- B provides a sea of virtual photons to convert the oscillating axion field into a microwave photon
- The cavity can be tuned to resonate at a precise frequency. If no microwave is detected, tune on next frequency - scan of parameter space.

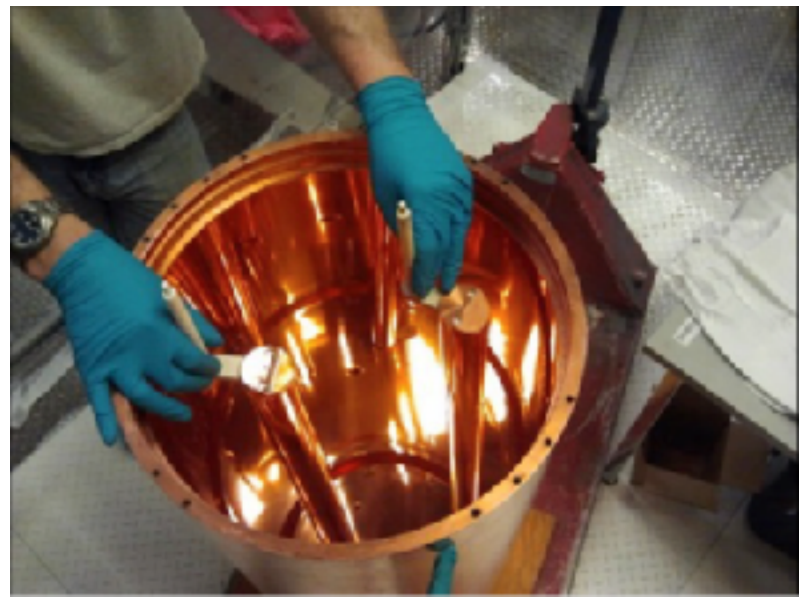
ADMX

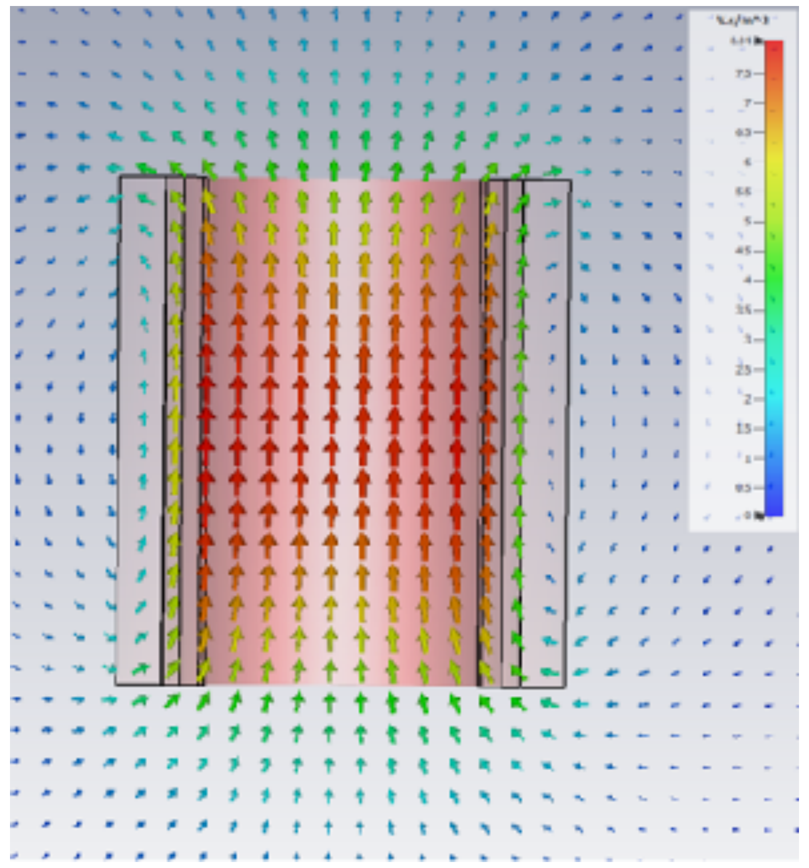


ADMX

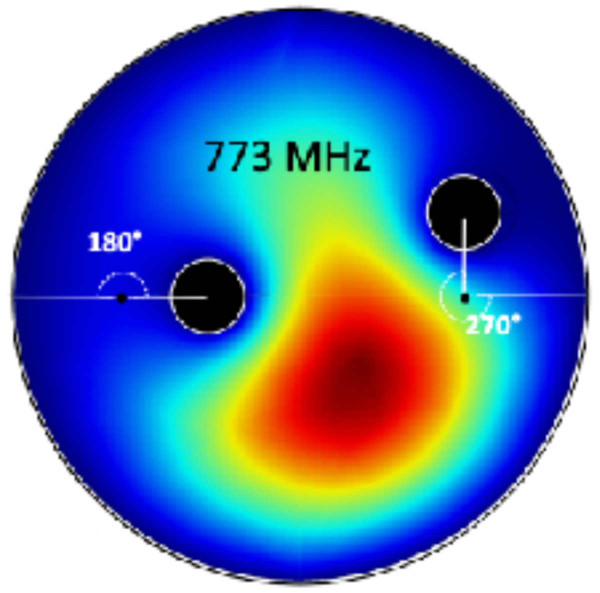
- **A**xion **D**ark **M**atter e**X**periment
- ~8T superconducting solenoid magnet
- Cylindrical Cavity
  - Volume: ⌀ x H: (0.59 x 3) m^3 = 136 L
  - OFHC annealed copper
  - Resonance frequencies: (580 - 890) MHz
  - Quality factor: ~(40,000 - 80,000)
  - Temperature: ~(100 - 250) mK
- Readout: JPA amplifier based on SQUIDs

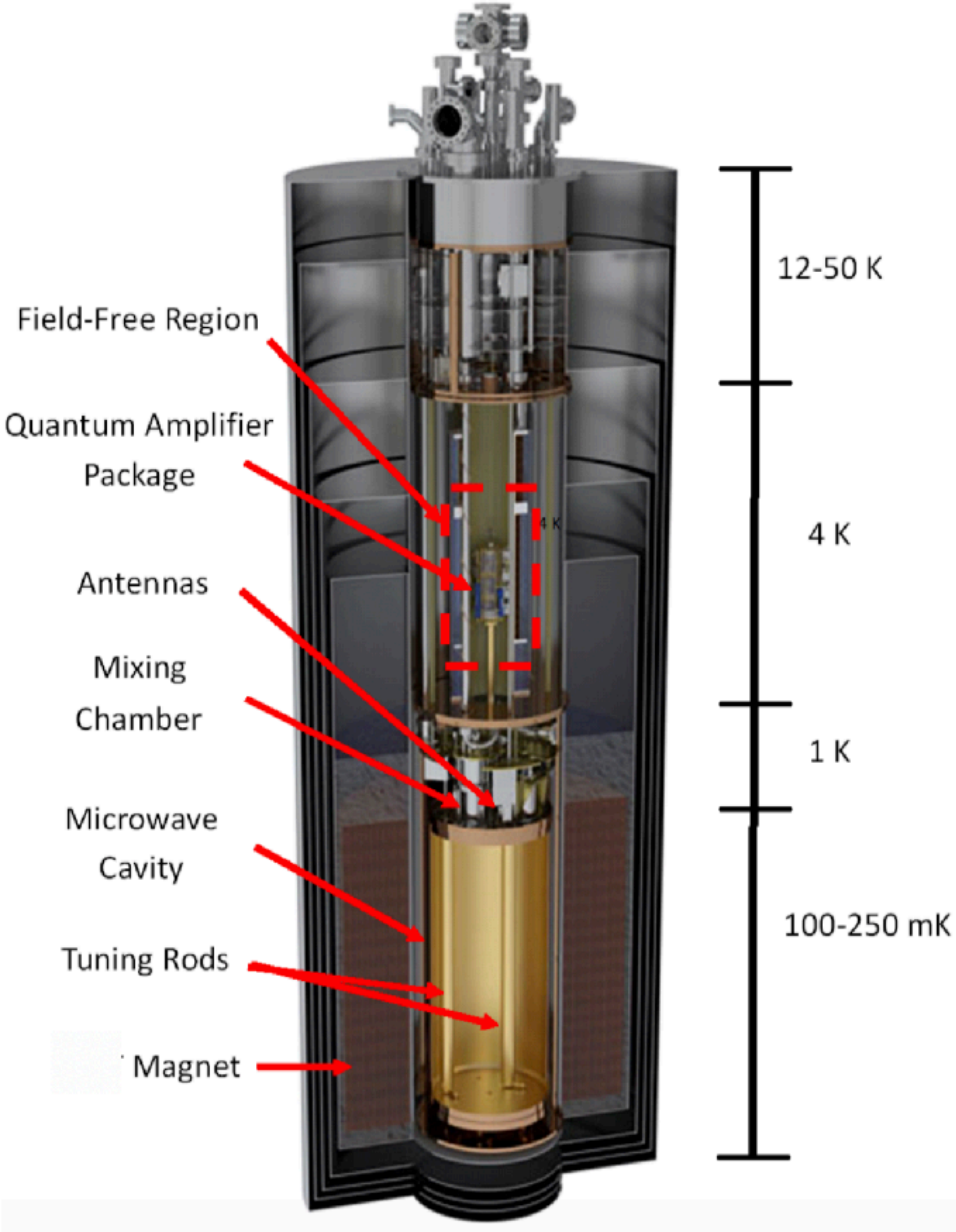






TM$_{010}$ E-Field for Cavity Cross Section



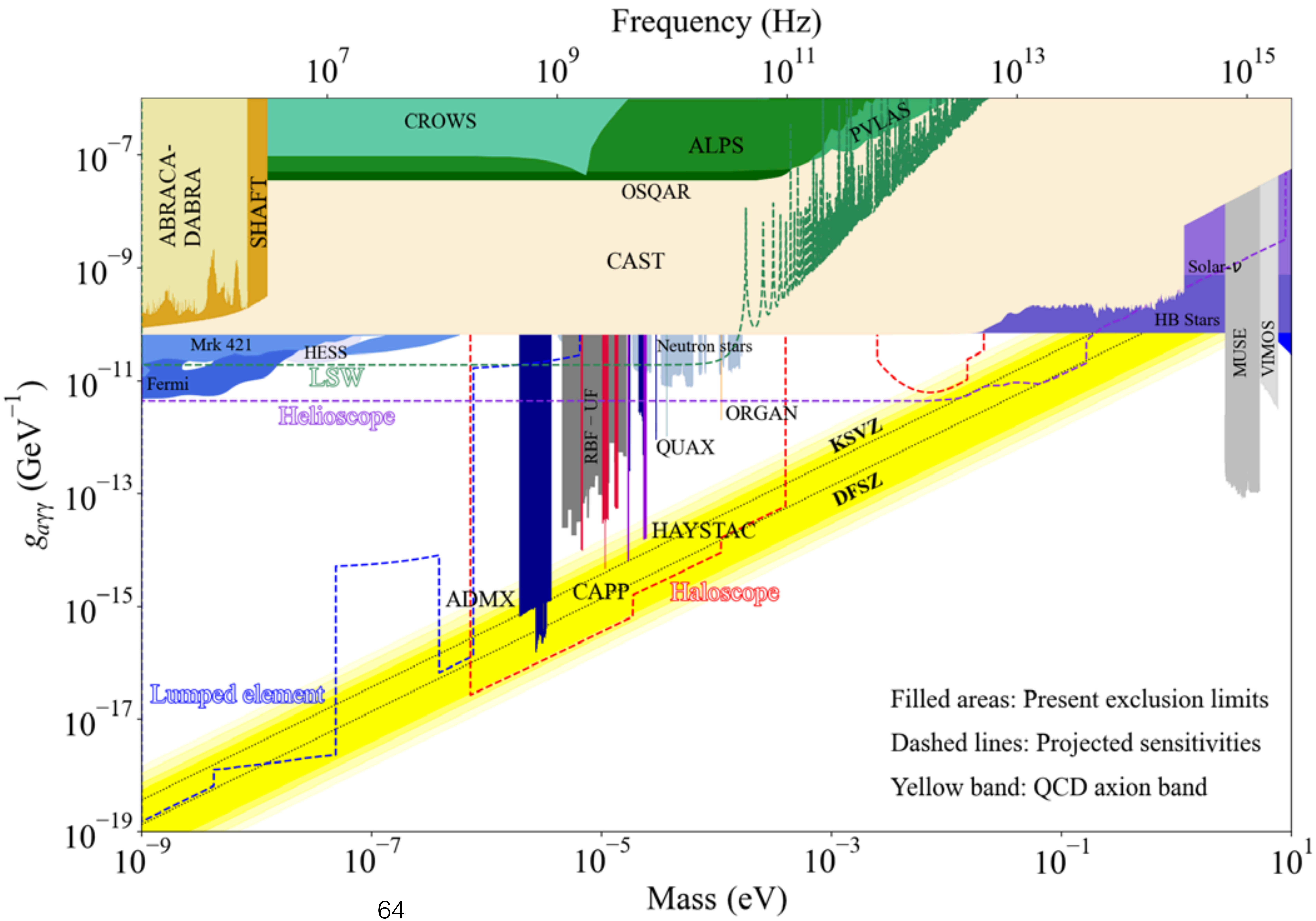


Current limits

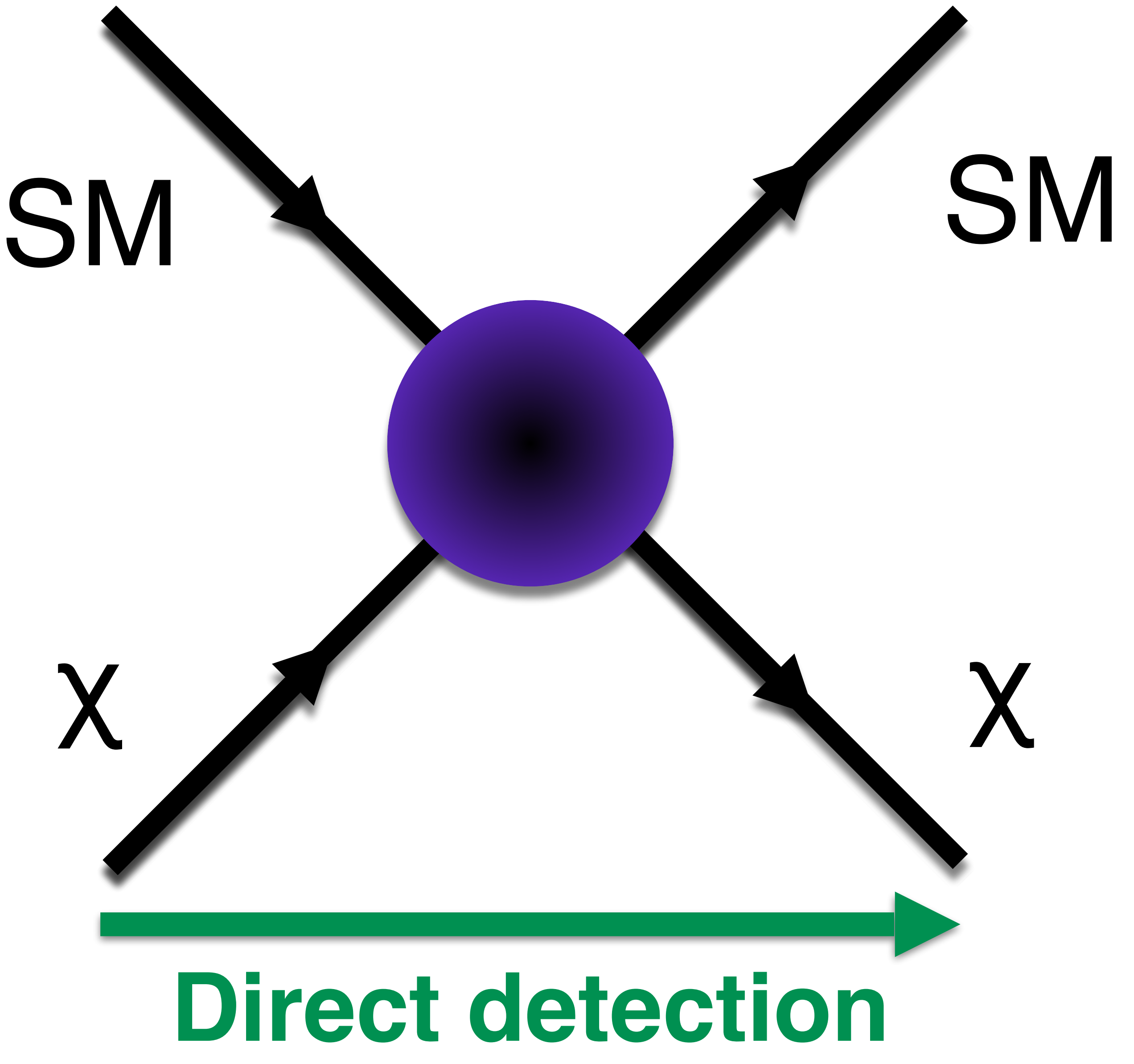
- ADMX is currently scanning the parameter space down to the QCD axion band

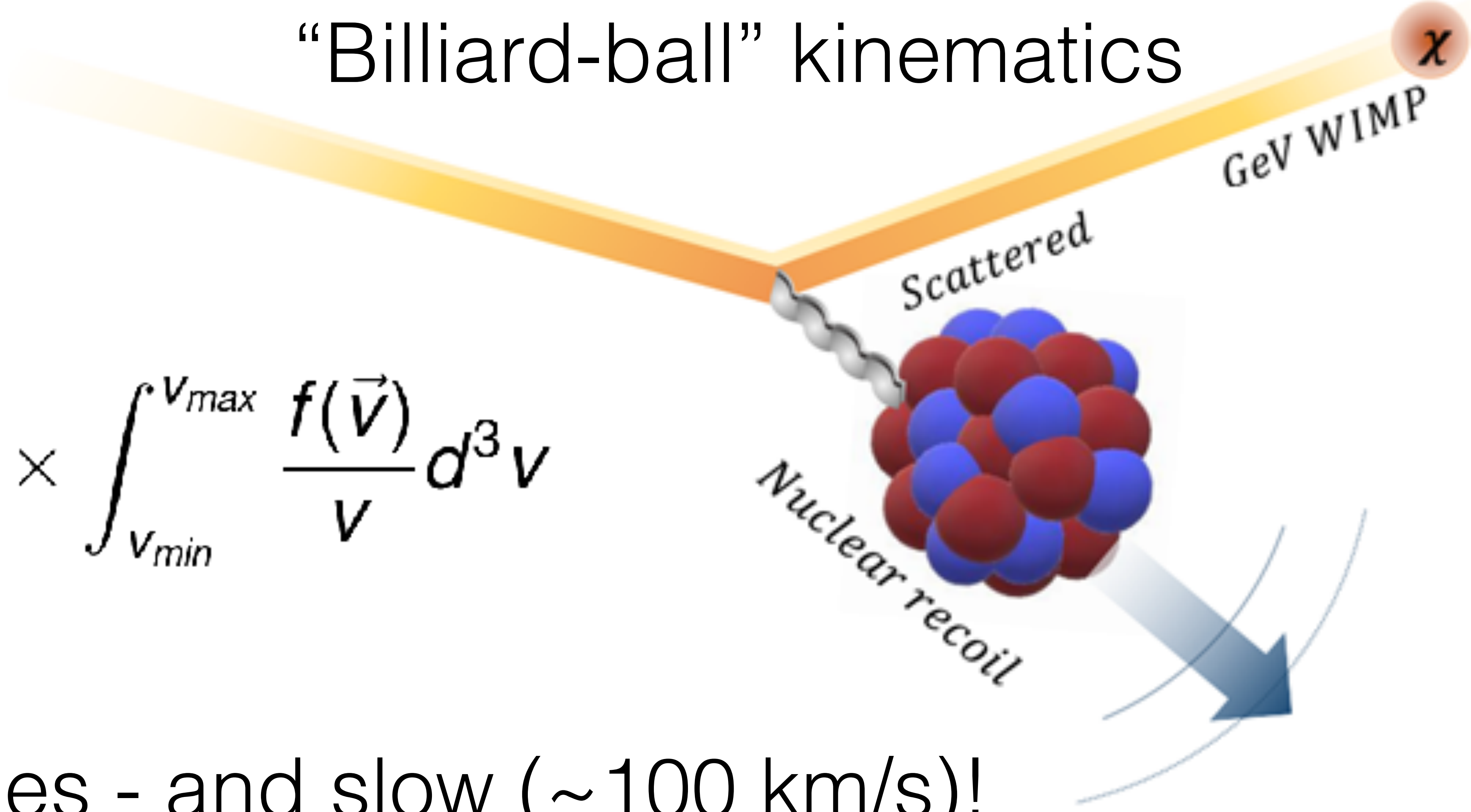
- Many more haloscopes are or will be online to explore more parameter space

- New ideas (helioscopes, lumped elements) to access new regions inaccessible to haloscopes.



WIMP-like Direct Detection



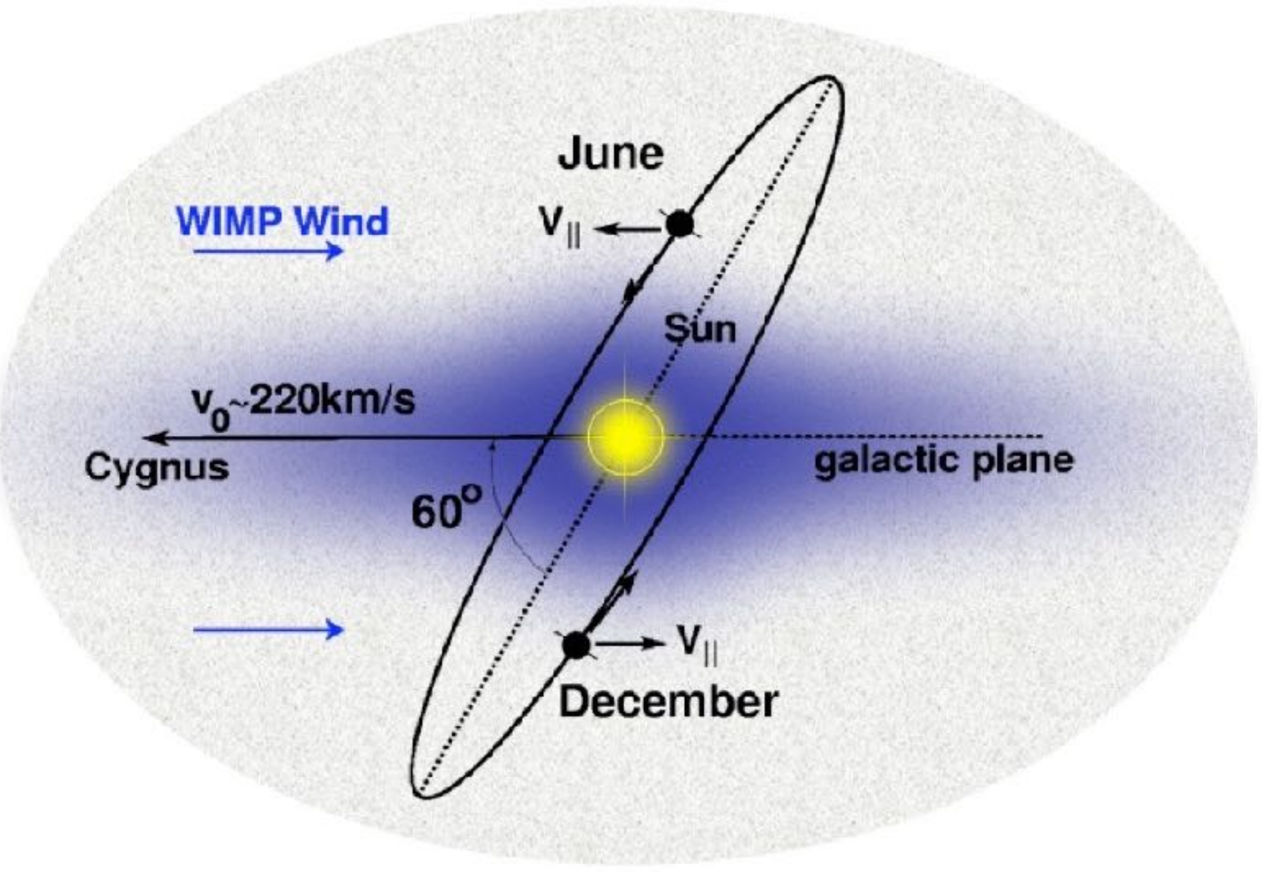

“Billiard-ball” kinematics

$$\frac{dR}{dE_r} = \frac{MT}{2m_W\mu_N^2} \times \sigma_{Wn} \times \frac{\mu_N^2}{\mu_p} A^2 \times F^2(E_r) \times \rho_0 \times \int_{v_{min}}^{v_{max}} \frac{f(\vec{v})}{v} d^3v$$

- DM are heavy (1-100,000 GeV) particles - and slow (~100 km/s)!
- Non-relativistic kinematics

- De Broglie wavelength: $\lambda = h/(mv)$ of a 100 GeV WIMP ~20 fm
- Nucleus size ~ 1-10 fm ⇒ WIMPs interact with the whole nucleus

- A WIMP will scatter off a nucleus and make it recoil
- We want to detect such nuclear recoil! How to predict the signal spectrum?



Simple Setup

Rate of DM-Nuclei scatters $\longleftarrow \; R = N_{\mathrm{T}} \, \Phi_\chi \, \sigma \; \longrightarrow$ DM-Nuclei Scattering Cross Section

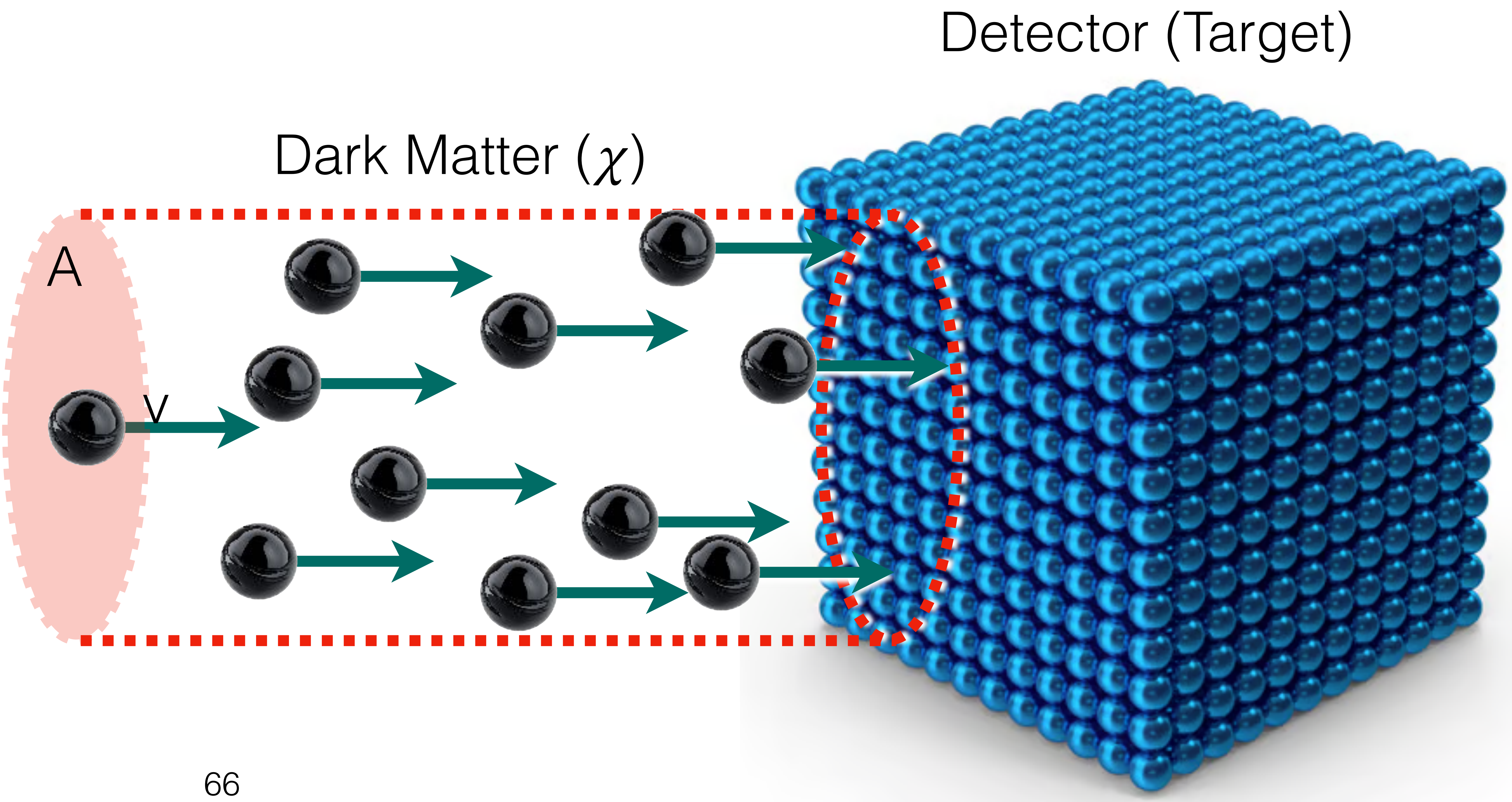
N_{T} $\swarrow$ Number of target nuclei

Φ_χ $\searrow$ DM Flux

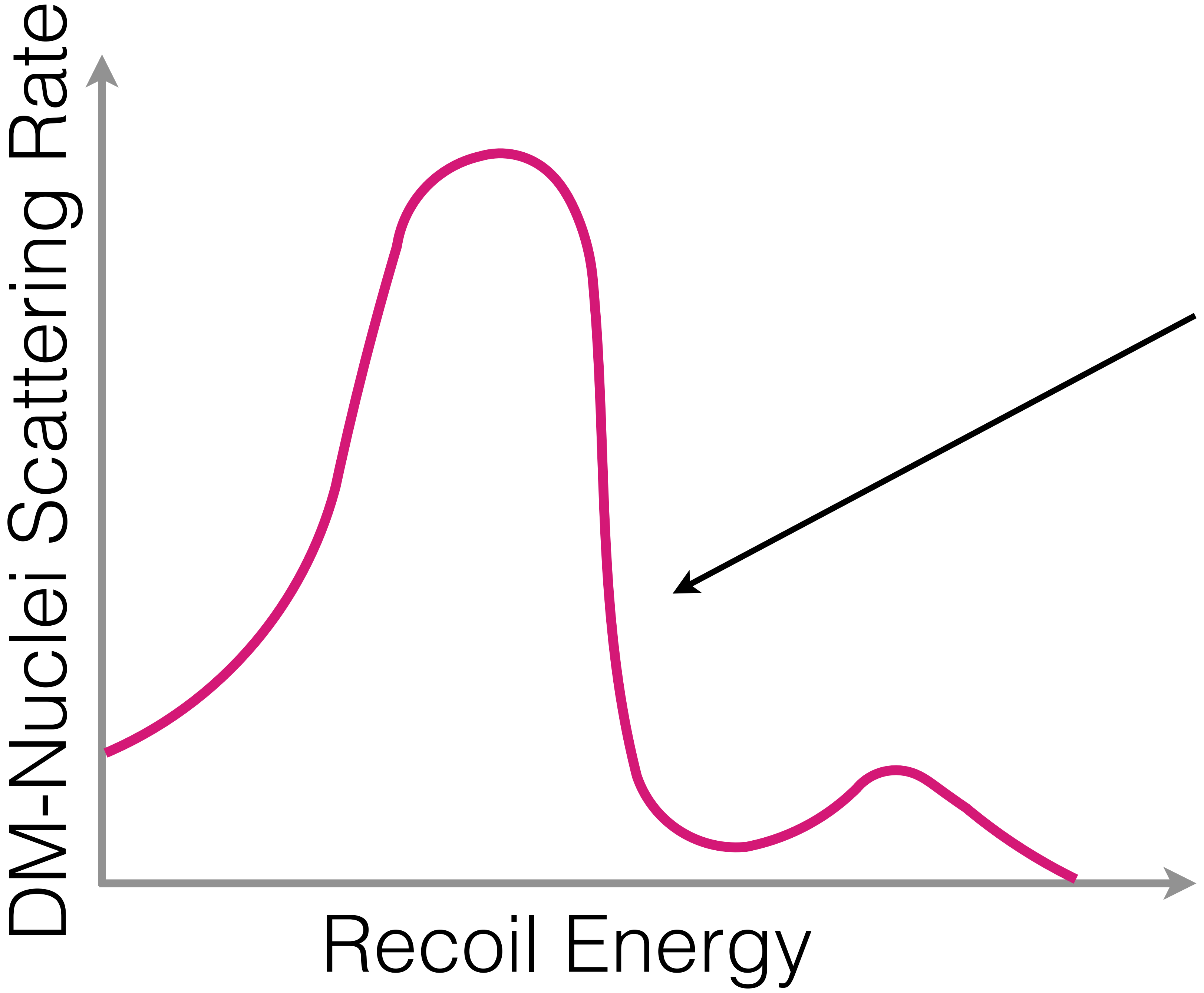
$$\Phi_\chi = \frac{N_\chi}{A\,t} = \frac{n_\chi\,V}{A\,t} = \frac{\rho_\chi}{m_\chi}\,v$$

$$N_{\mathrm{T}} = \frac{M}{m_{\mathrm{N}}}$$

$$R = \frac{M}{m_{\mathrm{N}} m_\chi} \rho_\chi\, v\, \sigma$$



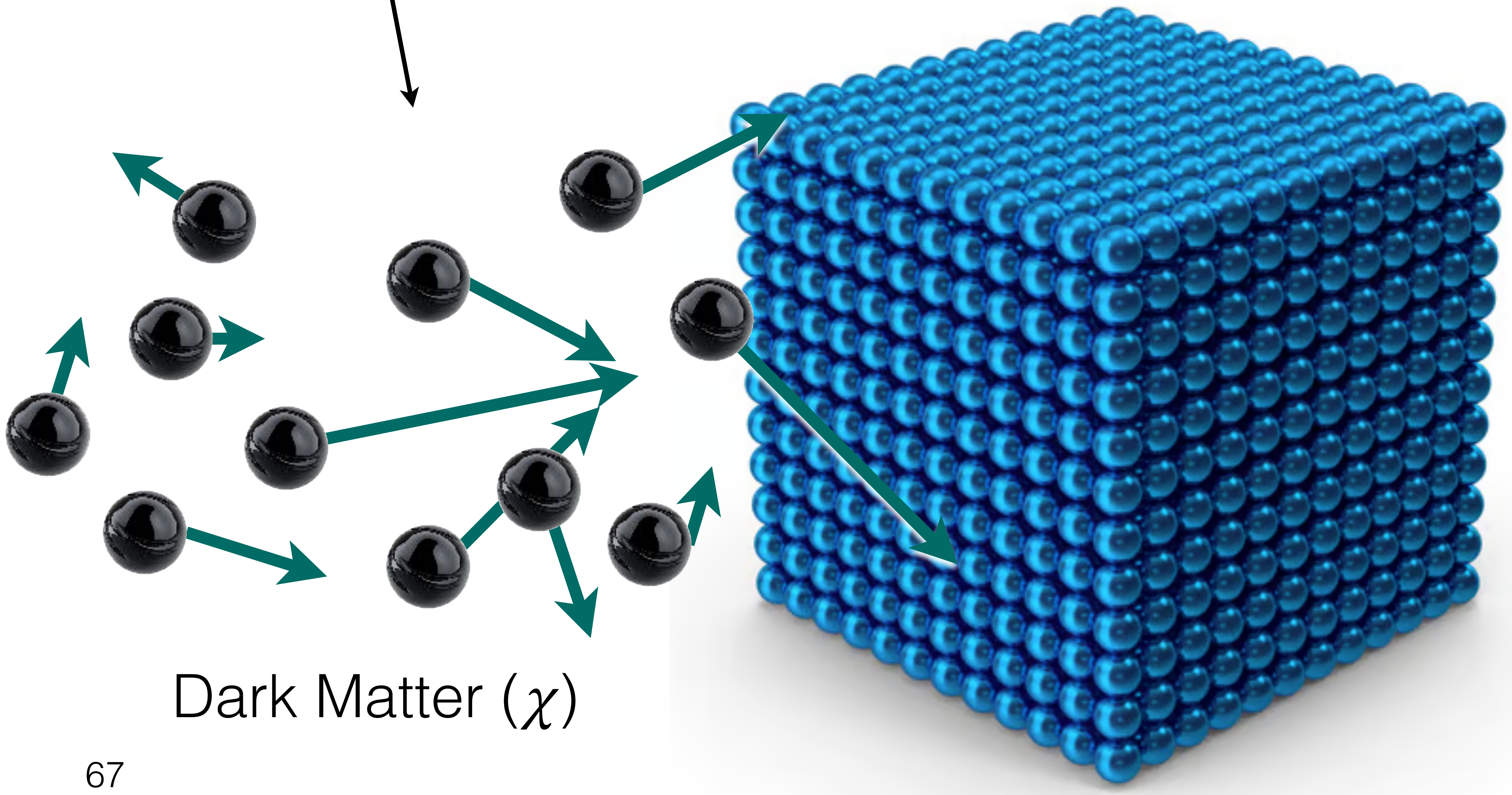
Some more nuance



$$\frac{dR}{dE_R} = N_\mathrm{T}\int_{v_\mathrm{min}}^{\infty}\Phi(v)\frac{d\sigma_N}{dE_R}(v, E_R)\,dv$$

Differential DM-Nuclei Scattering Cross Section

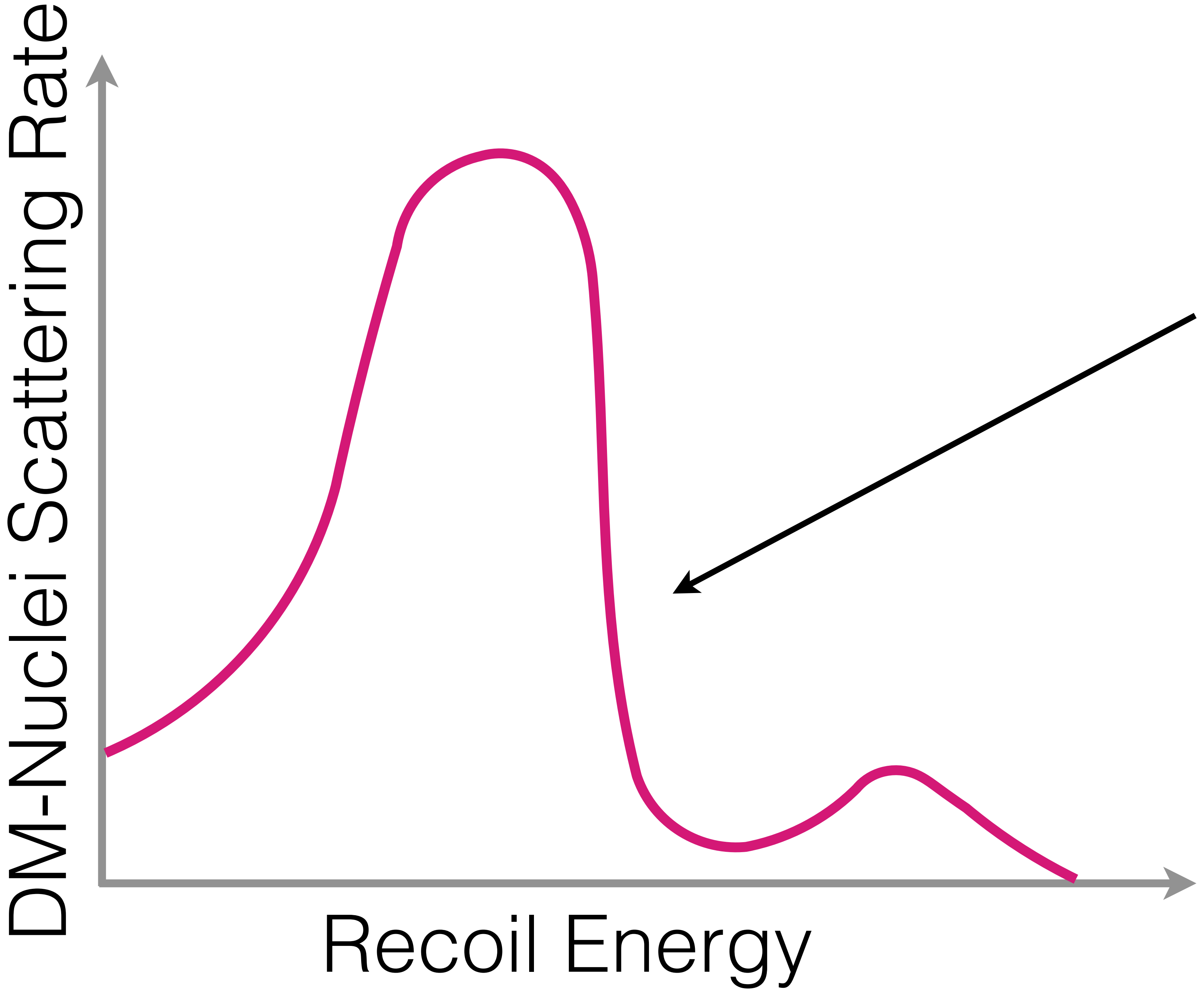
Detector (Target)



Dark Matter (χ)

- DM particles behave as a rarefied perfect gas
- Velocity distribution $f(v)$ can be inferred with some statistical mechanics

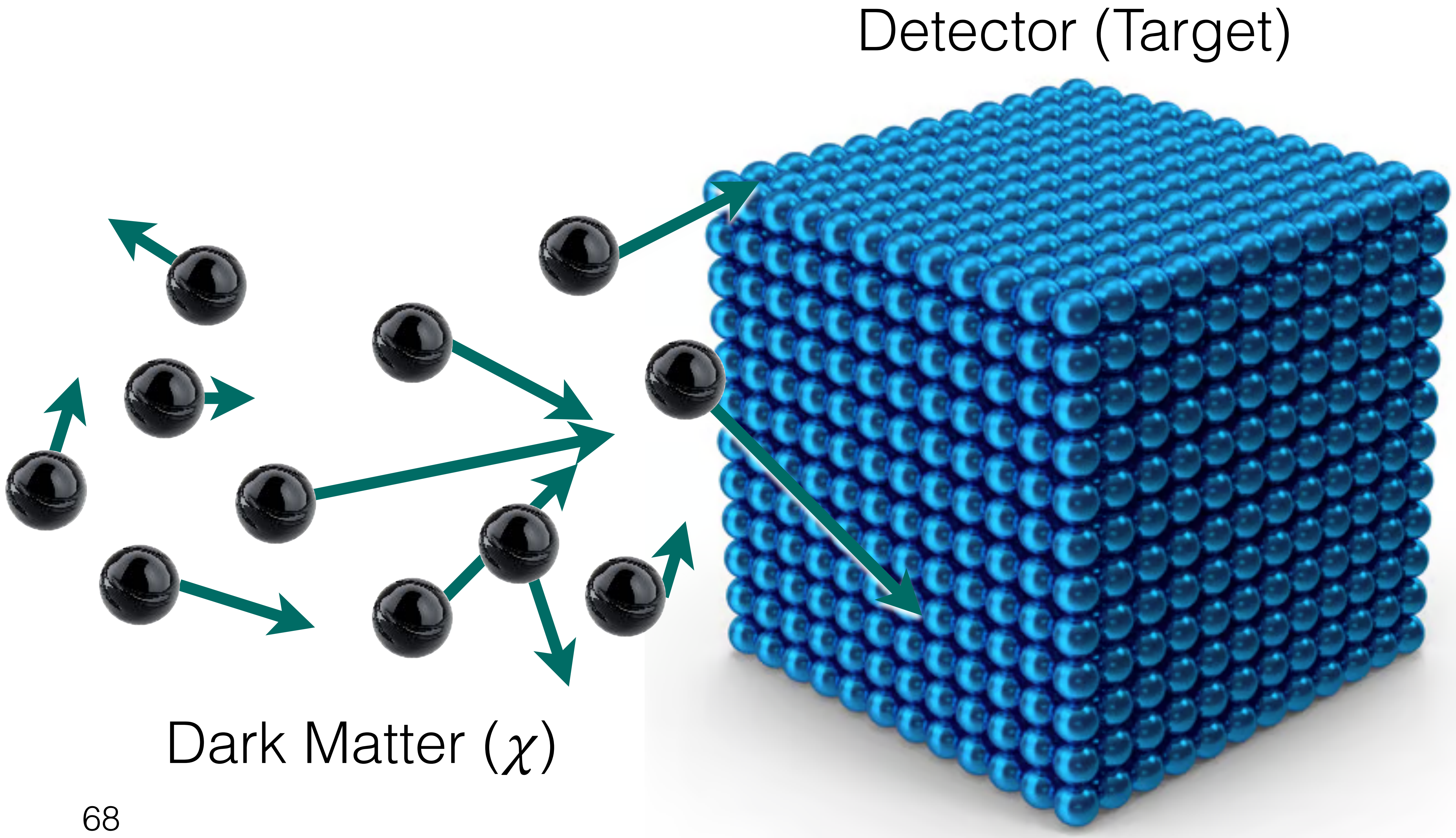
Some more nuance



$$\frac{dR}{dE_R} = \frac{M}{m_\chi m_N}\rho_\chi \int_{v_{\min}}^{\infty} v f(v) \frac{d\sigma_N}{dE_R}(v, E_R)\, dv$$

$$f(v) = \exp\left(-\frac{3v^2}{2\sigma^2}\right)$$

$$\int_0^\infty f(v)\, dv = 1$$



A closer look at the cross section

$$\frac{d\sigma_N}{dE_R} = \left(\frac{d\sigma_N}{dE_R}\right)_{SI} + \left(\frac{d\sigma_N}{dE_R}\right)_{SD} = \frac{1}{E_R^{\max}}\left[\sigma_0^{SI} F_{SI}^2(E_R) + \sigma_0^{SD} F_{SD}^2(E_R)\right]$$

Nuclear form factors

Nuclear Physics Realm

$$E_R^{\max} = \frac{2\mu^2 v^2}{m_N} \longrightarrow \frac{d\sigma_N}{dE_R} = \frac{m_N}{2\mu^2 v^2}\left[\sigma_0^{SI} F_{SI}^2(E_R) + \sigma_0^{SD} F_{SD}^2(E_R)\right]$$

Particle Physics Realm

$$\mathcal{L} \supset \alpha_q^A (\overline{\chi}\gamma^\mu\gamma_5\chi)(\overline{q}\gamma_\mu\gamma_5 q)$$

Axial q-current, DM Spin-1/2 Fermion

$$\mathcal{L} \supset \alpha_q^S \overline{\chi}\chi\overline{q}q + \alpha_q^V \overline{\chi}\gamma^\mu\chi\overline{q}\gamma_\mu q$$

Scalar-scalar Vector-vector

$$\mathcal{L} \supset \alpha_q^A \epsilon^{\mu\nu\rho\sigma}(B_\rho \overleftrightarrow{\partial} B_\nu)(\overline{q}\gamma^\sigma\gamma_5 q)$$

Axial q-current, DM Spin-1 Boson

Spin Dependent

$$\frac{d\sigma_N}{dE_R} = \frac{m_N}{2\mu^2 v^2}\left[\sigma_0^{SI} F_{SI}^2(E_R) + \boxed{\sigma_0^{SD}}\,\boxed{F_{SD}^2(E_R)}\right]$$

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

$$\frac{S(E_R)}{S(0)}$$

Expectation Value of protons’ and neutrons’ spins in the nucleus

J - Total angular momentum of the nucleus

Interference Form Factor

Isoscalar Form Factor

Isovector Form Factor

$$S(E_R) = a_0^2\, S_{00}(E_R) + a_0\, a_1\, S_{01}(E_R) + a_1^2\, S_{11}(E_R)$$

Iso-scalar/vector Couplings →
$$\begin{cases} a_0 = a_p + a_n \\ a_1 = a_p - a_n \end{cases}$$

Proton/neutron Couplings
$$\begin{cases} a_p = \sum_{q=u,d,s} \frac{\alpha_q^A}{\sqrt{2}G_F}\Delta_q^p \\ a_n = \sum_{q=u,d,s} \frac{\alpha_q^A}{\sqrt{2}G_F}\Delta_q^n \end{cases}$$

$$\left(\frac{d\sigma_N}{dE_R}\right)_{SD} = \frac{16 m_N}{\pi v^2} G_F^2 \left[a_p\langle S_p\rangle + a_n\langle S_n\rangle\right]^2 \frac{J+1}{J}\,\frac{S(E_R)}{S(0)}$$

Spin Independent σ_0

$$\frac{d\sigma_N}{dE_R} = \frac{m_N}{2\mu^2 v^2}\left[\sigma_0^{SI} F_{SI}^2(E_R) + \sigma_0^{SD} F_{SD}^2(E_R)\right]$$

$$\sigma_0^{SI} = \frac{4\mu^2}{\pi}\left\{\left[\overbrace{Zf_p + (A-Z)f_n}^{\text{Scalar contribution}}\right]^2 + \frac{1}{256}\left[\overbrace{\alpha_u^V(A+Z) + \alpha_d^V(2A-Z)}^{\text{Vector contribution}}\right]^2\right\}$$

Proton/neutron couplings

Up/Down quarks couplings

$$f_p \approx f_n \;\Rightarrow\; \sigma_0^{SI} = \frac{4\mu^2}{\pi} f_p^2 A^2$$ for the scalar contribution

- Coherent enhancement factor (A^2) ⇒ Usually the scalar SI contribution dominates over all others for nuclei with A>20

SI Form Factor

$$\frac{d\sigma_N}{dE_R} = \frac{m_N}{2\mu^2 v^2}\left[\sigma_0^{SI} F_{SI}^2(E_R) + \sigma_0^{SD} F_{SD}^2(E_R)\right]$$

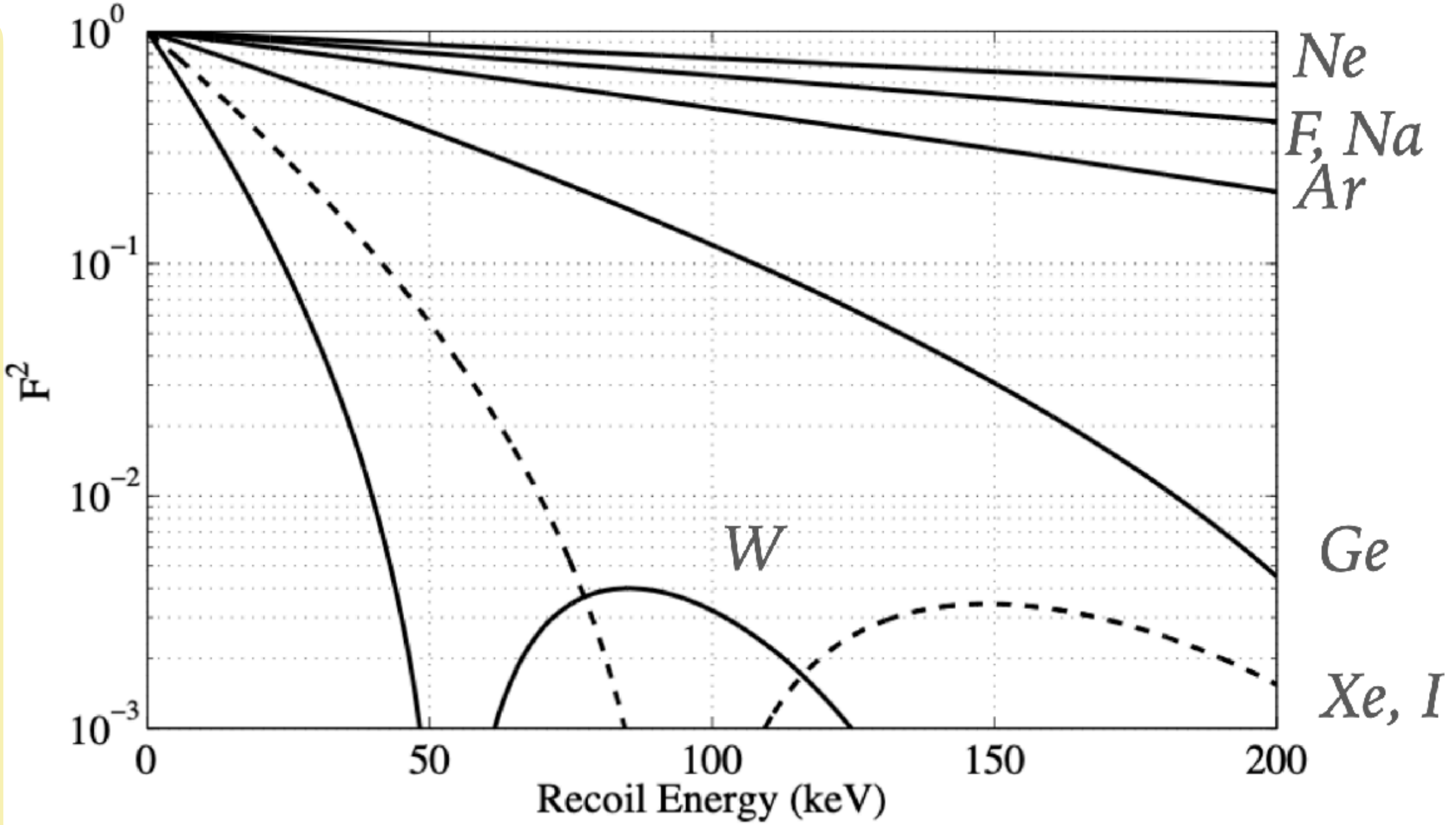
Woods-Saxon Form Factor

$$F_{SI}^2(E_R) = \left(\frac{3j_1(qR_1)}{qR_1}\right)^2 e^{-q^2 s^2/2}$$

Momentum transfer $q = \sqrt{2m_N E_R}$

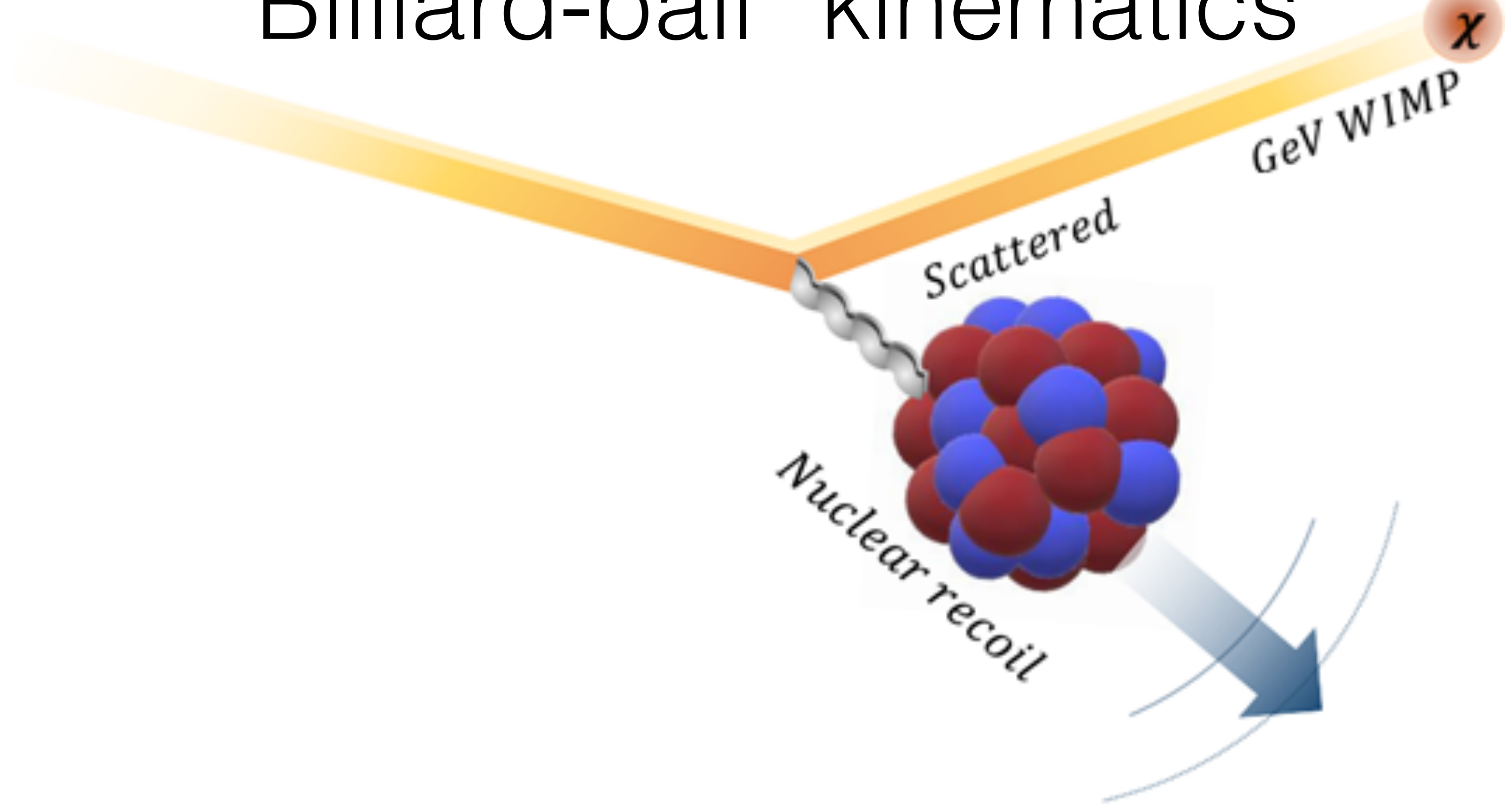
Bessel Function $j_1(x) = \frac{sin(x)}{x^2} - \frac{cos(x)}{x}$

Nucleus size And skin thickness
$$\begin{cases} R_1 = \sqrt{R^2 - 5s^2} \\ R = 1.2\, A^{1/2}\,\mathrm{fm} \\ s \approx 1\,\mathrm{fm} \end{cases}$$



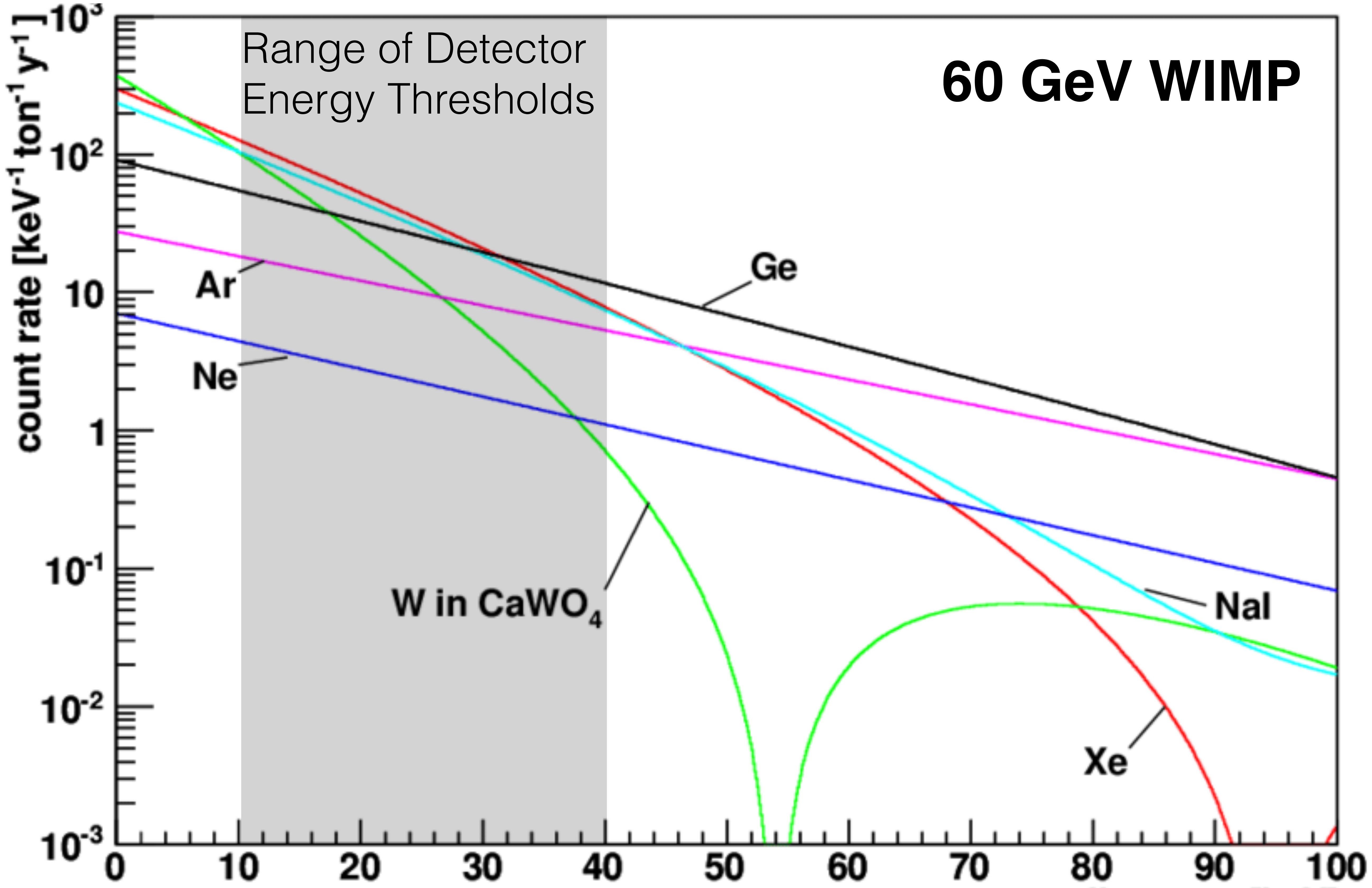
The WIMP Signal

“Billiard-ball” kinematics



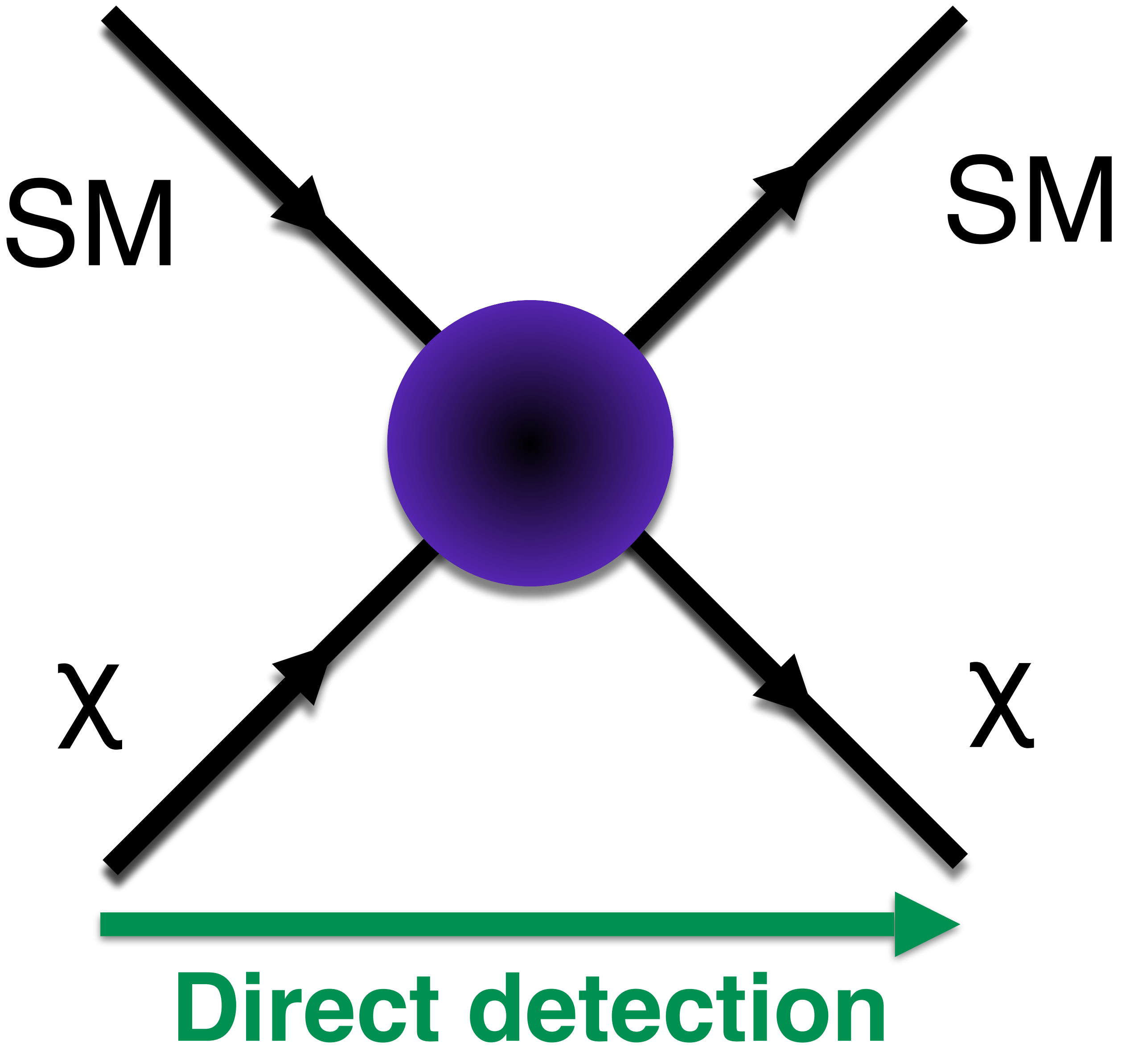
$$\frac{dR}{dE_r} = \frac{MT}{2m_W\mu_N^2} \times \boxed{\sigma_{Wn}} \times \frac{\mu_N^2}{\mu_p} A^2 \times \boxed{F^2(E_r)} \times \boxed{\rho_0 \times \int_{v_{min}}^{v_{max}} \frac{f(\vec{v})}{v} d^3v}$$

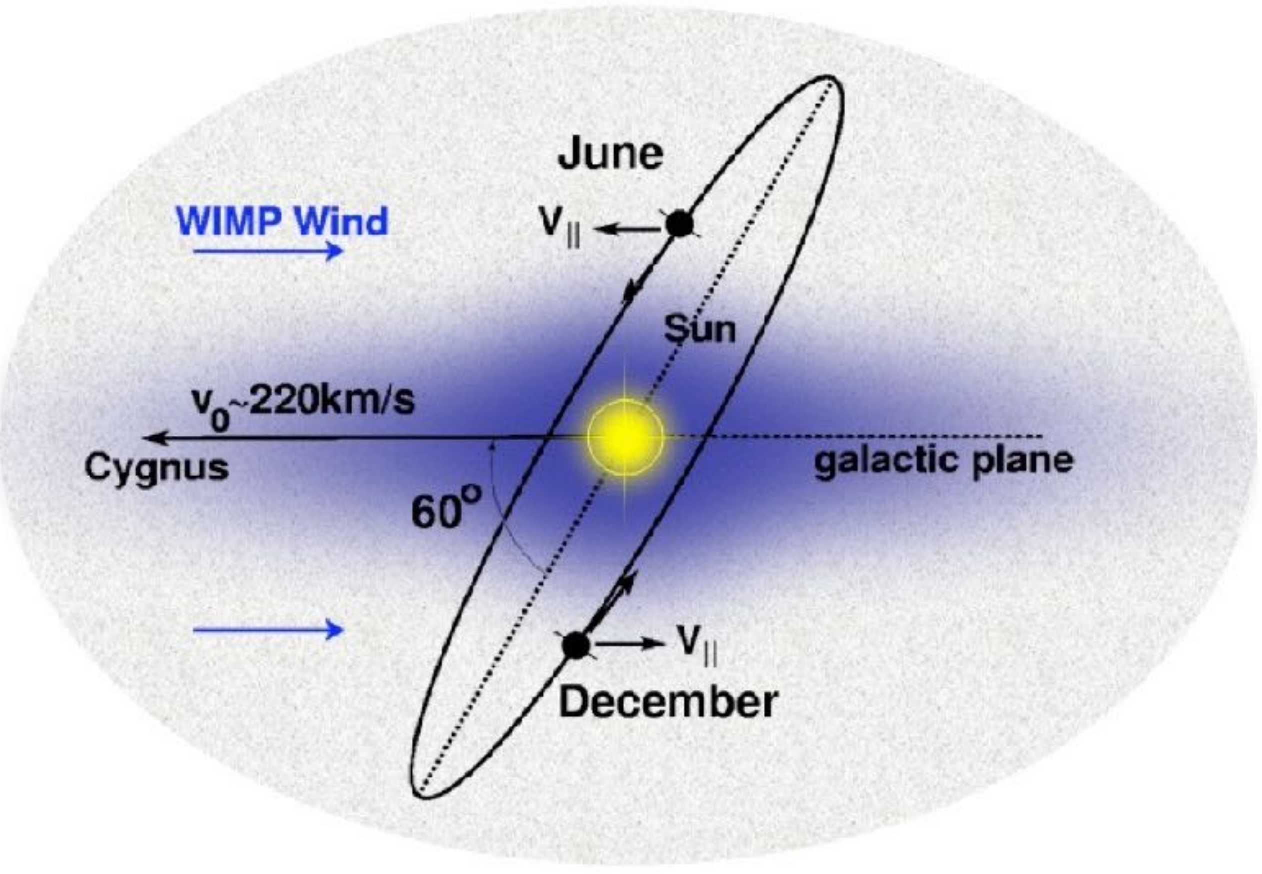
Particle physics **Nuclear physics** **Astrophysics**

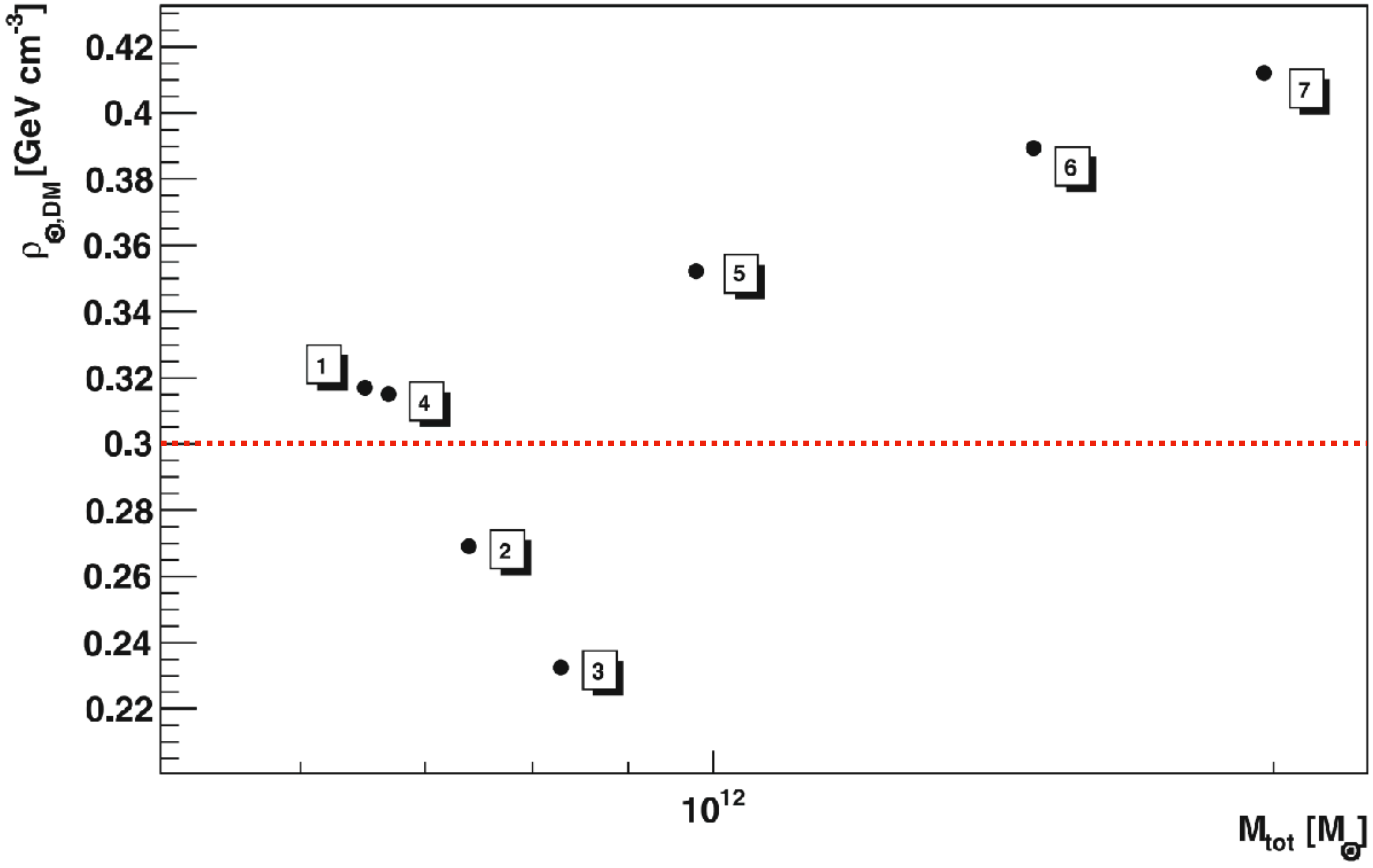


- **Signal: nuclear recoils (NR)**
- **Rate ~exponential in obs. energy**
- Spectra are generally steeper for heavier nuclei because of the form factor
- Max momentum transfer when $M_\chi = M_N$
  - Light DM best coupled to light targets
- Best to optimize detectors for low energy

DM Local Density

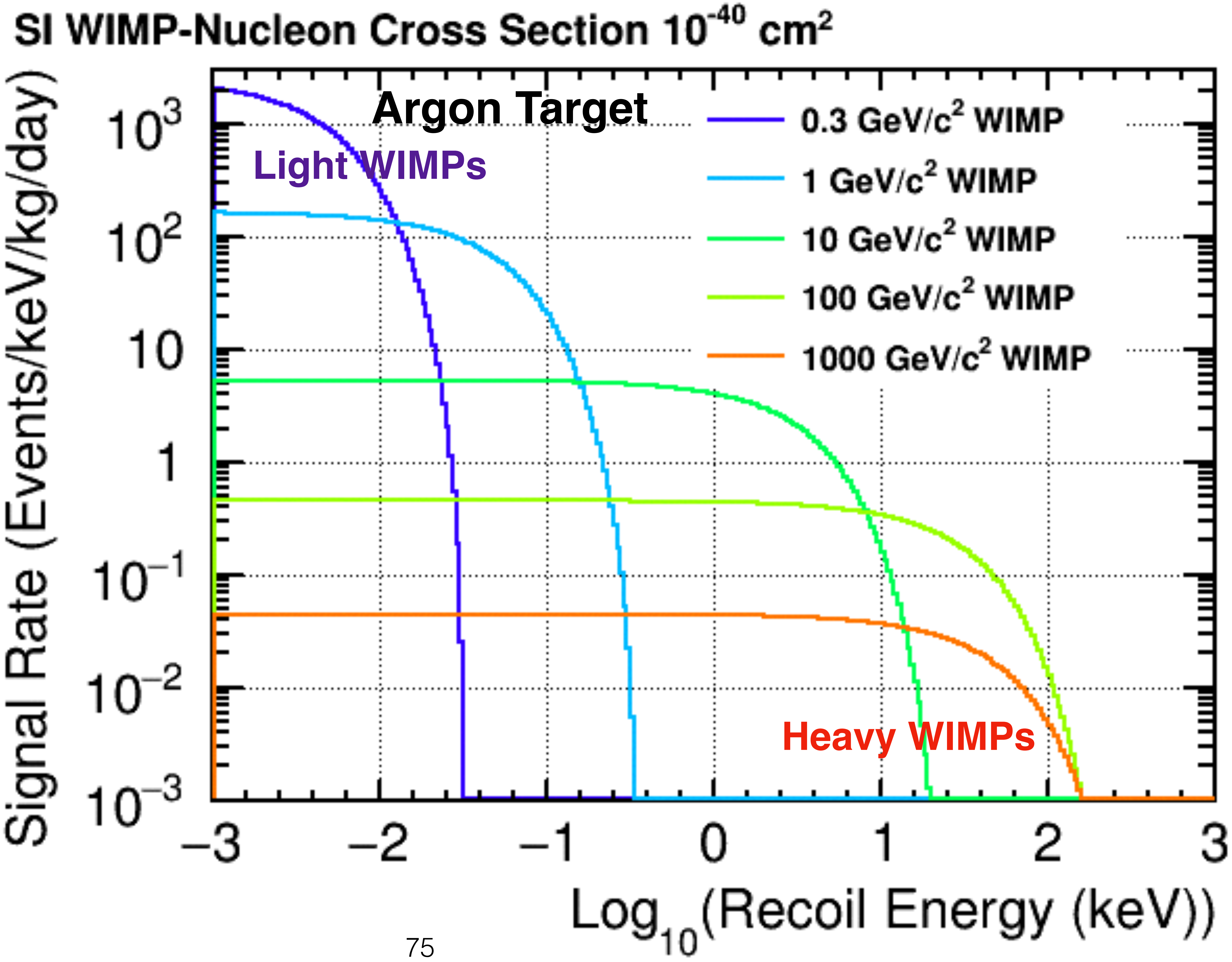






DM Spectra vs DM mass

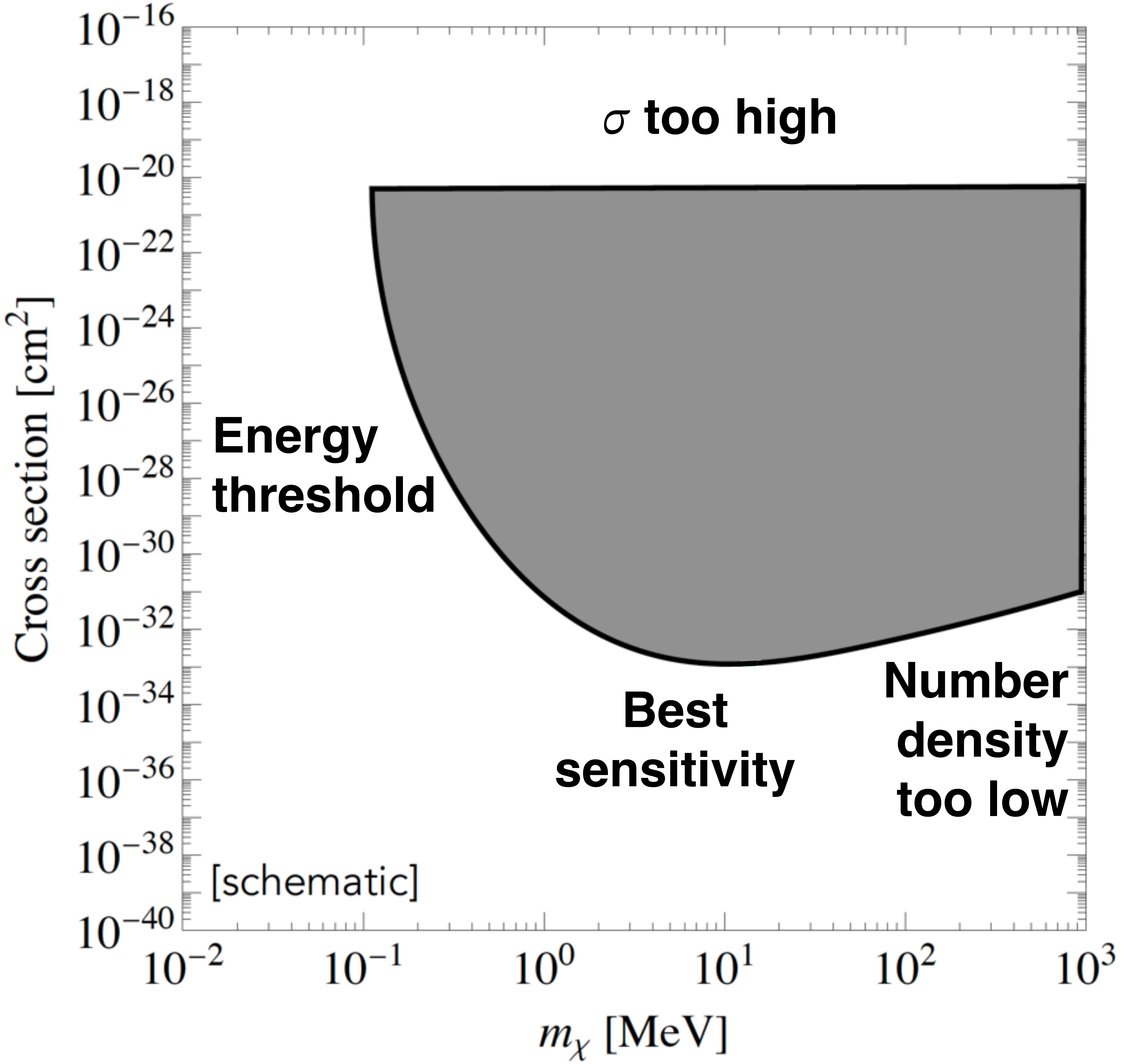
High number density
High Event Rates
Low recoil energies



Low number density
Low Event Rates
High recoil energies

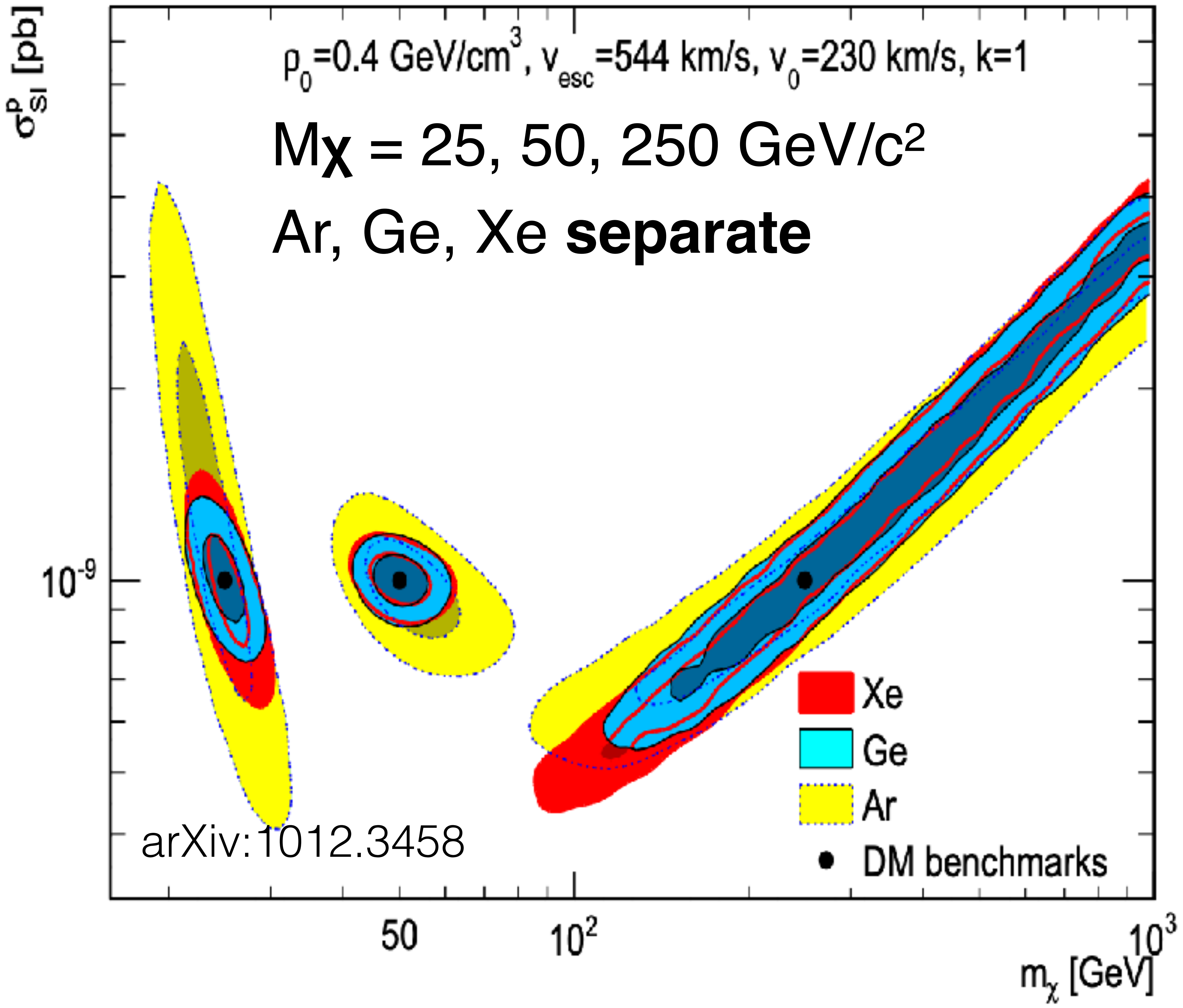
Setting Limits

- Experiment up and running
- Accrue exposure (mass x time) - i.e. wait…
- Analyze data
- No events or no excess above expected background
- Draw limits of WIMP cross-section vs mass
- Best sensitivity depends on:
  - Target atomic mass
  - Detector energy threshold
  - In general different across technologies and detectors



Target complementarity

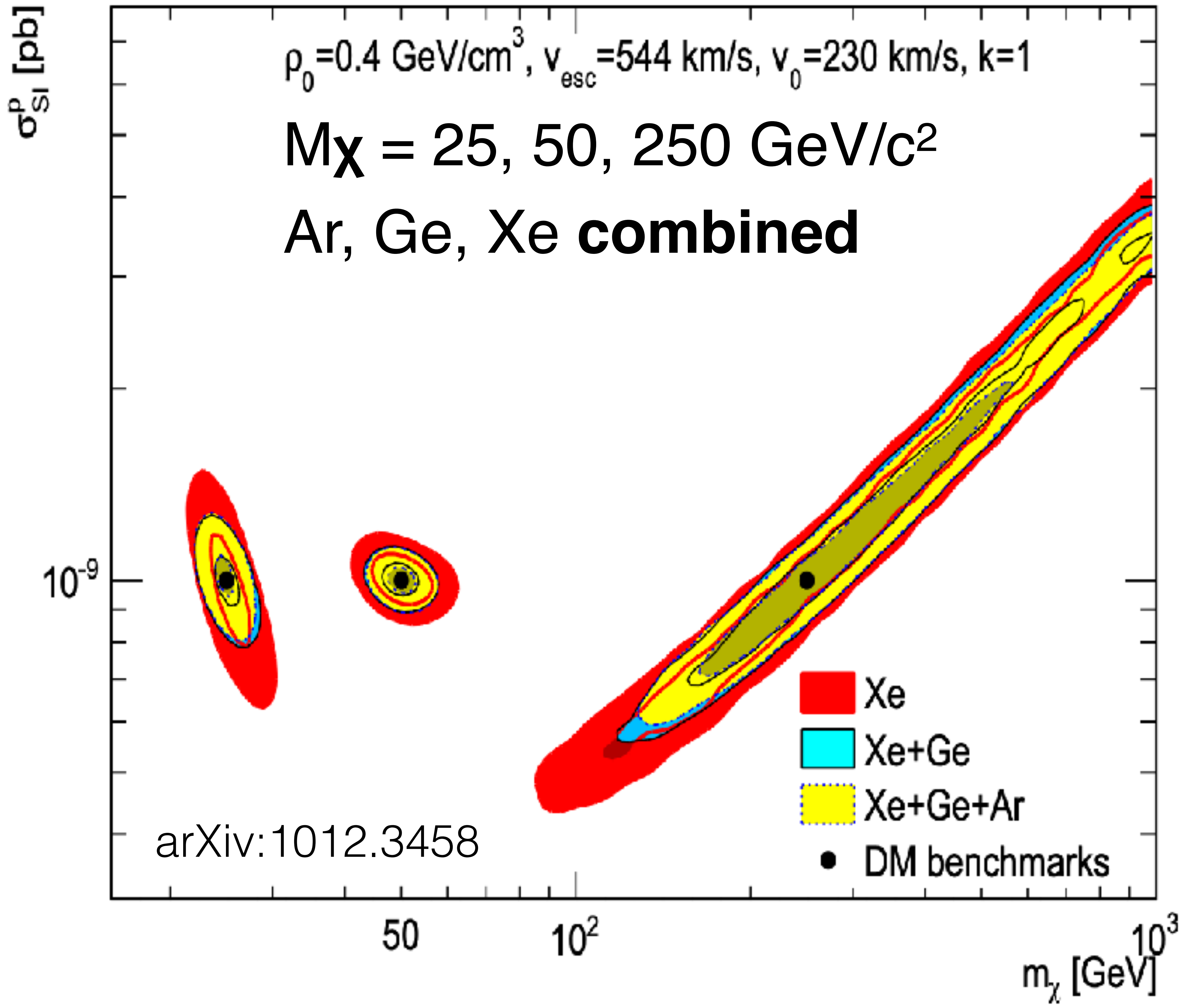
What if we observe something?



M**χ** = 25, 50, 250 GeV/c²

Ar, Ge, Xe **separate**

arXiv:1012.3458



M**χ** = 25, 50, 250 GeV/c²

Ar, Ge, Xe **combined**

arXiv:1012.3458

A positive observation with more than one target will help constraining M**χ** and σ

Experimental Techniques for WIMP-like DM

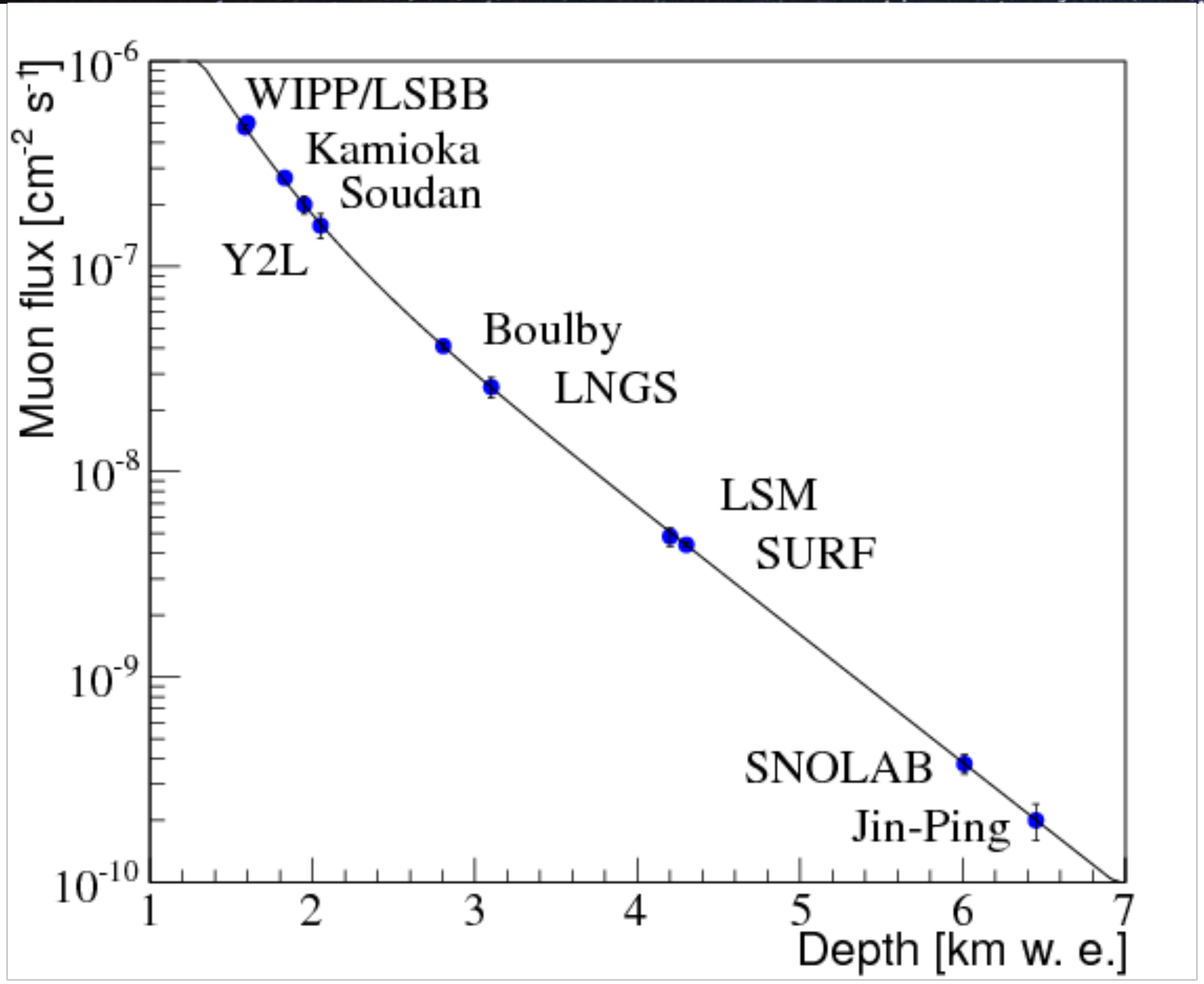
Backgrounds

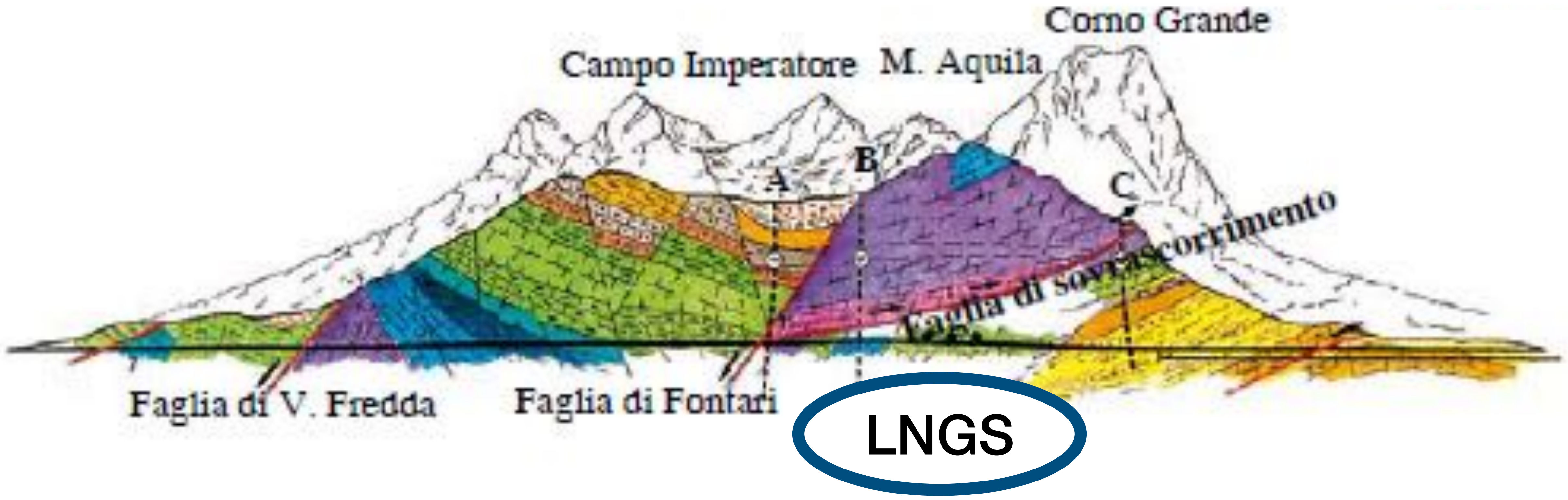
Backgrounds - Cosmogenic

- Cosmic rays on the atmosphere
- Secondary muons arrive at surface
- Flux at sea level ~10,000 / m^2 min
- Also, activation of materials
- Neutron generation

- Need a better shield than the atmosphere…
- Rock efficiently absorbs neutrons

Underground laboratories





- Handful of laboratories around the world
- Depth between 800 m and 2400 m
- Muon flux reduction factor ~(10^6 -10^8)

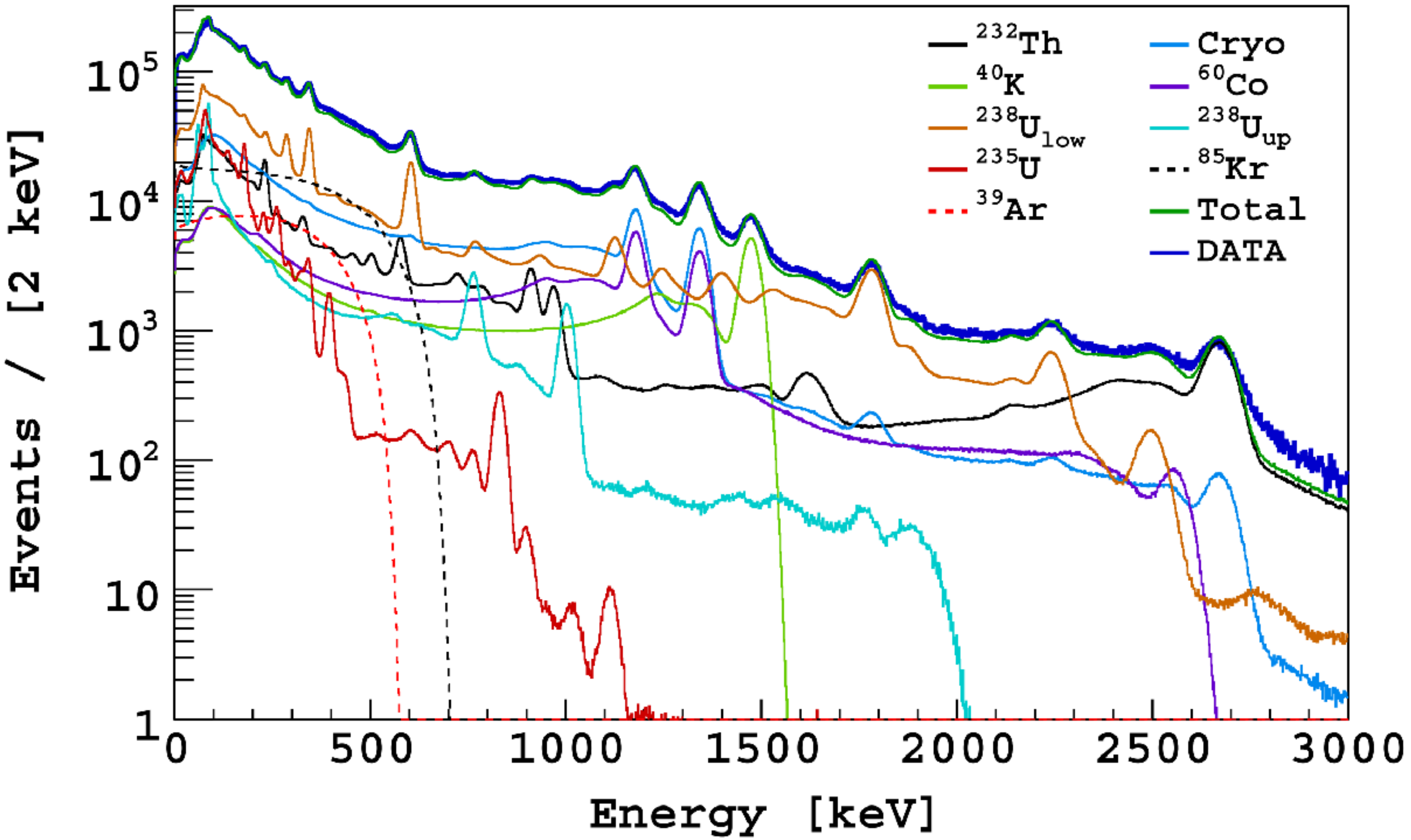
Backgrounds - Radiogenic

- All materials contain traces of radioactive isotopes

- Natural: U and Th chains, K-40
- Human-made: Co-60, Cs-137, Eu-155, etc

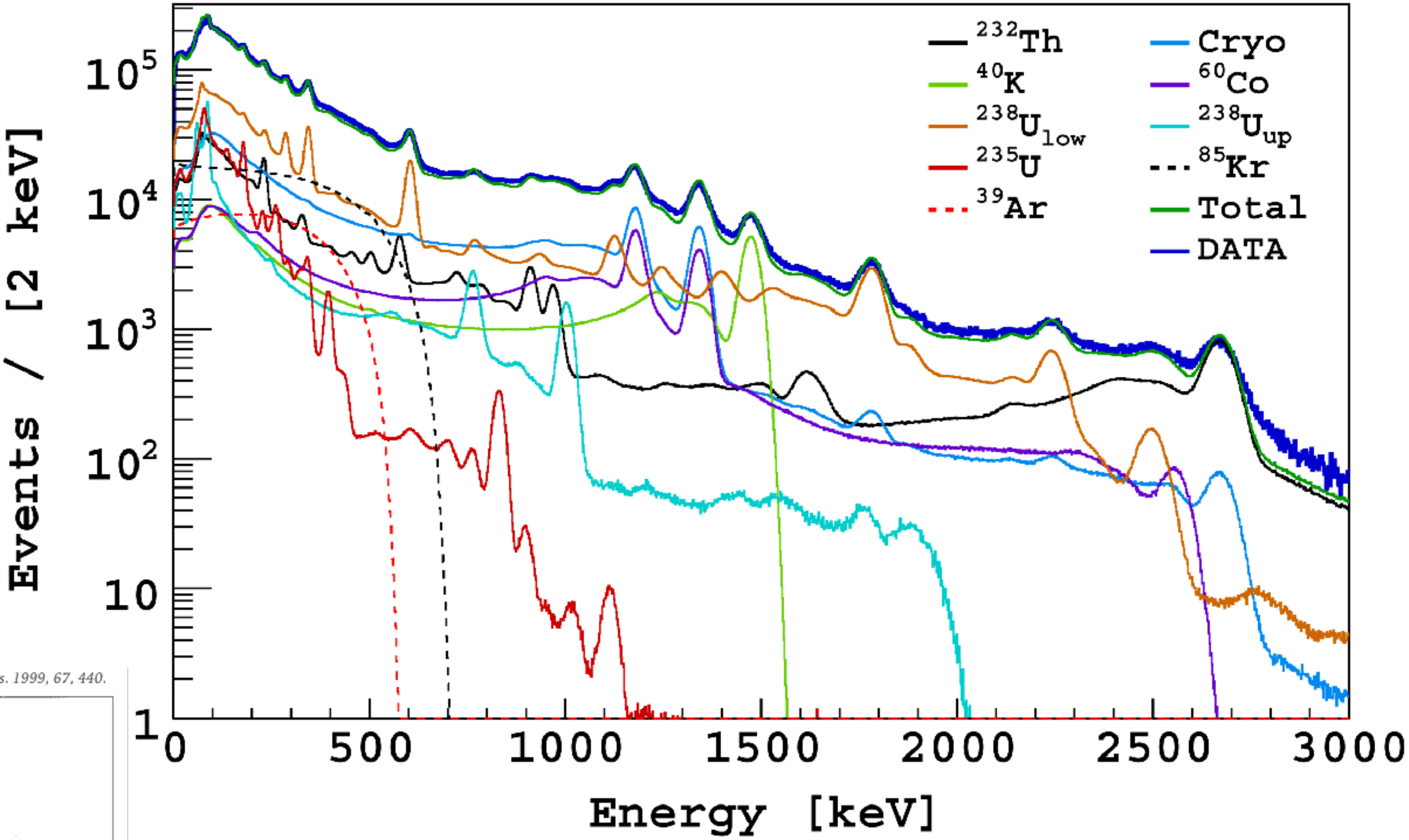
- Activities up to ~100 Bq

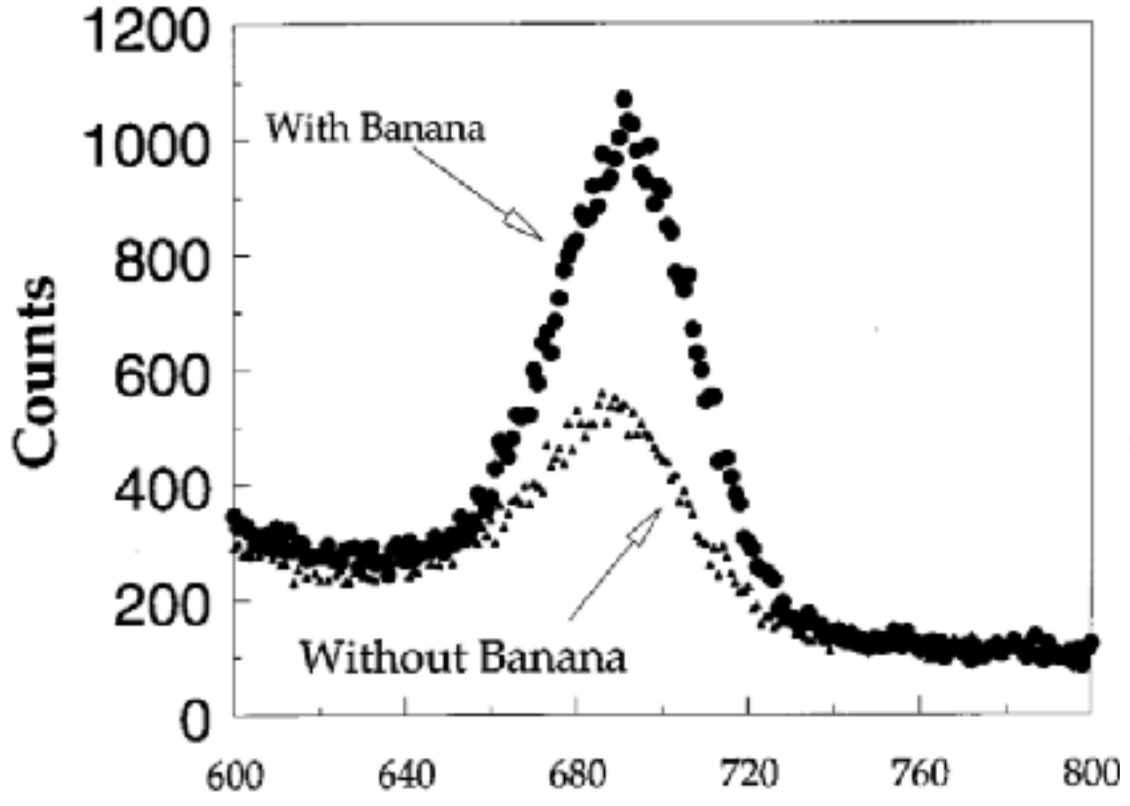
- Worst background: NEUTRONS! Only interact with nuclei - mimic WIMP signal

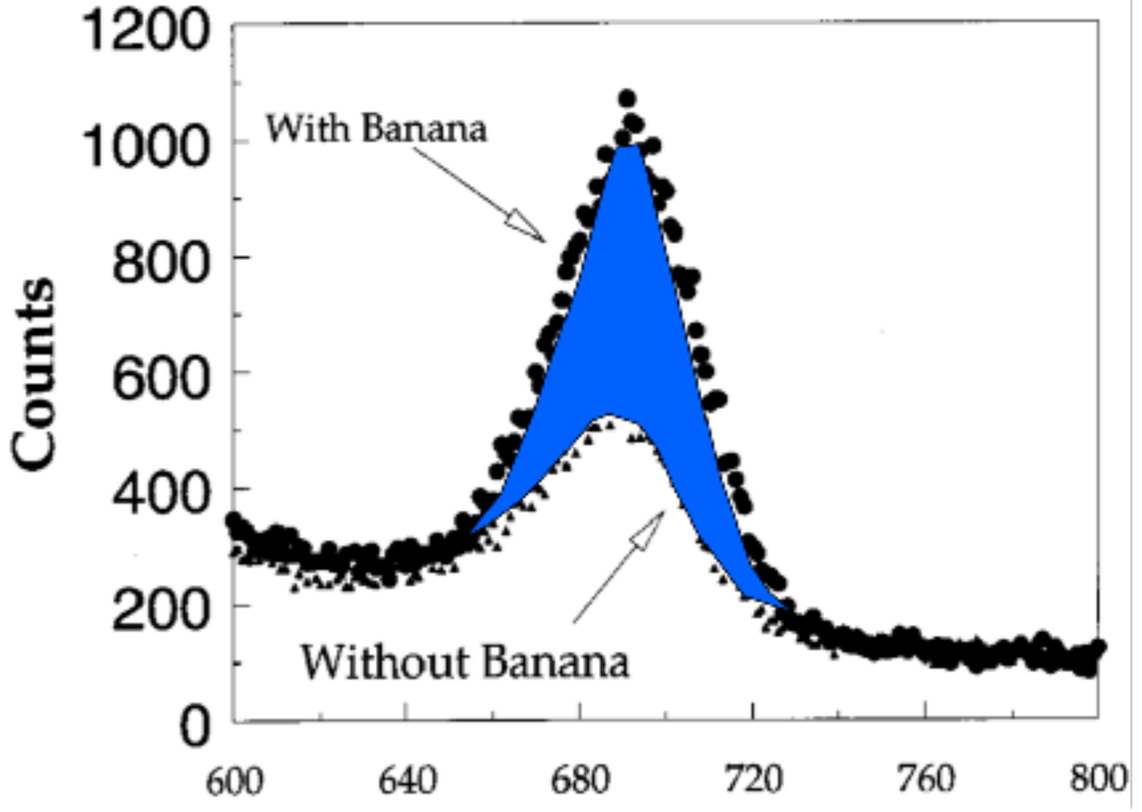


Backgrounds - Radiogenic

- All materials contain traces of radioactive isotopes
- Natural: U and Th chains, K-40
- Human-made: Co-60, Cs-137, Eu-155, etc
- Activities up to ~1 Bq/kg

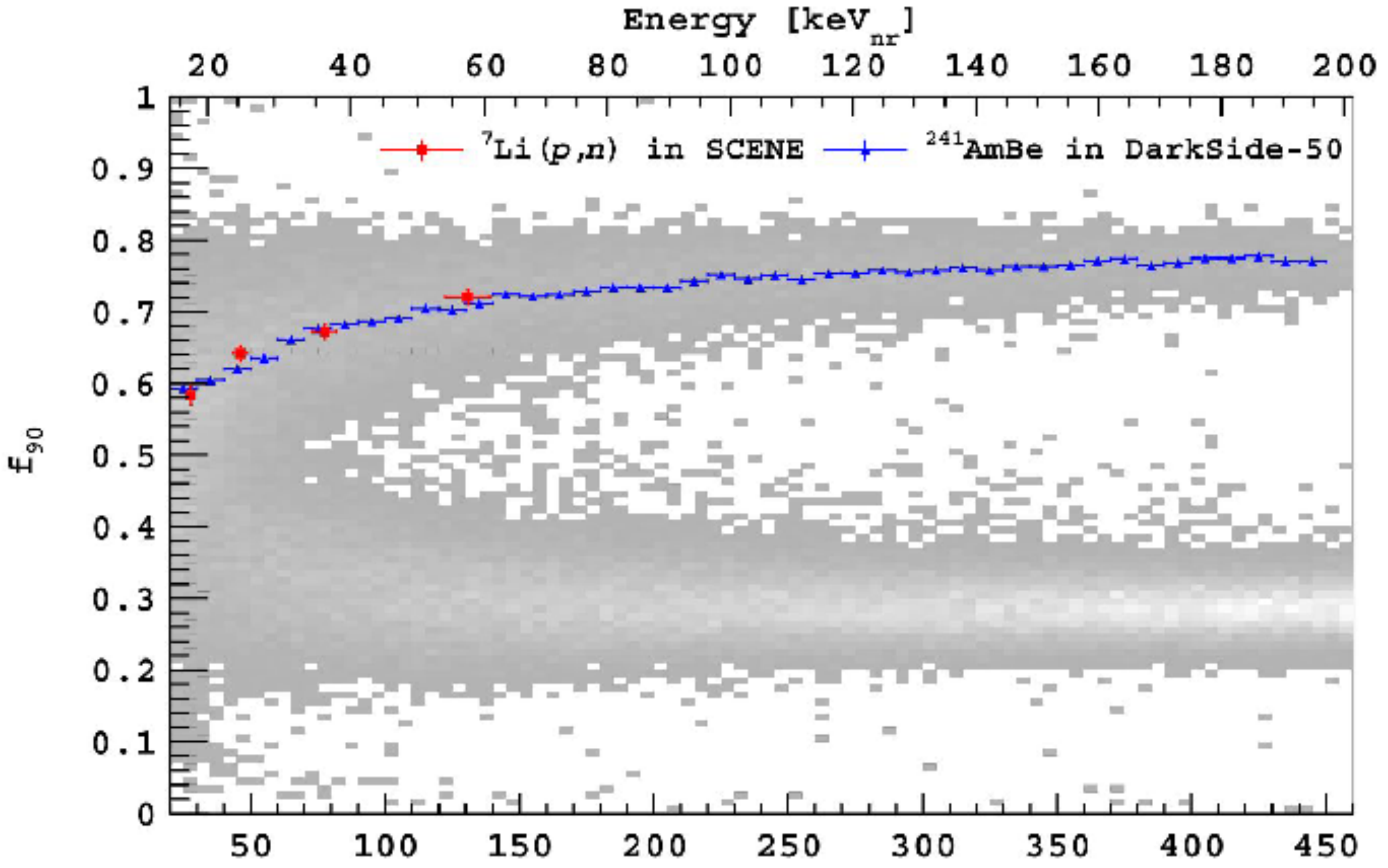


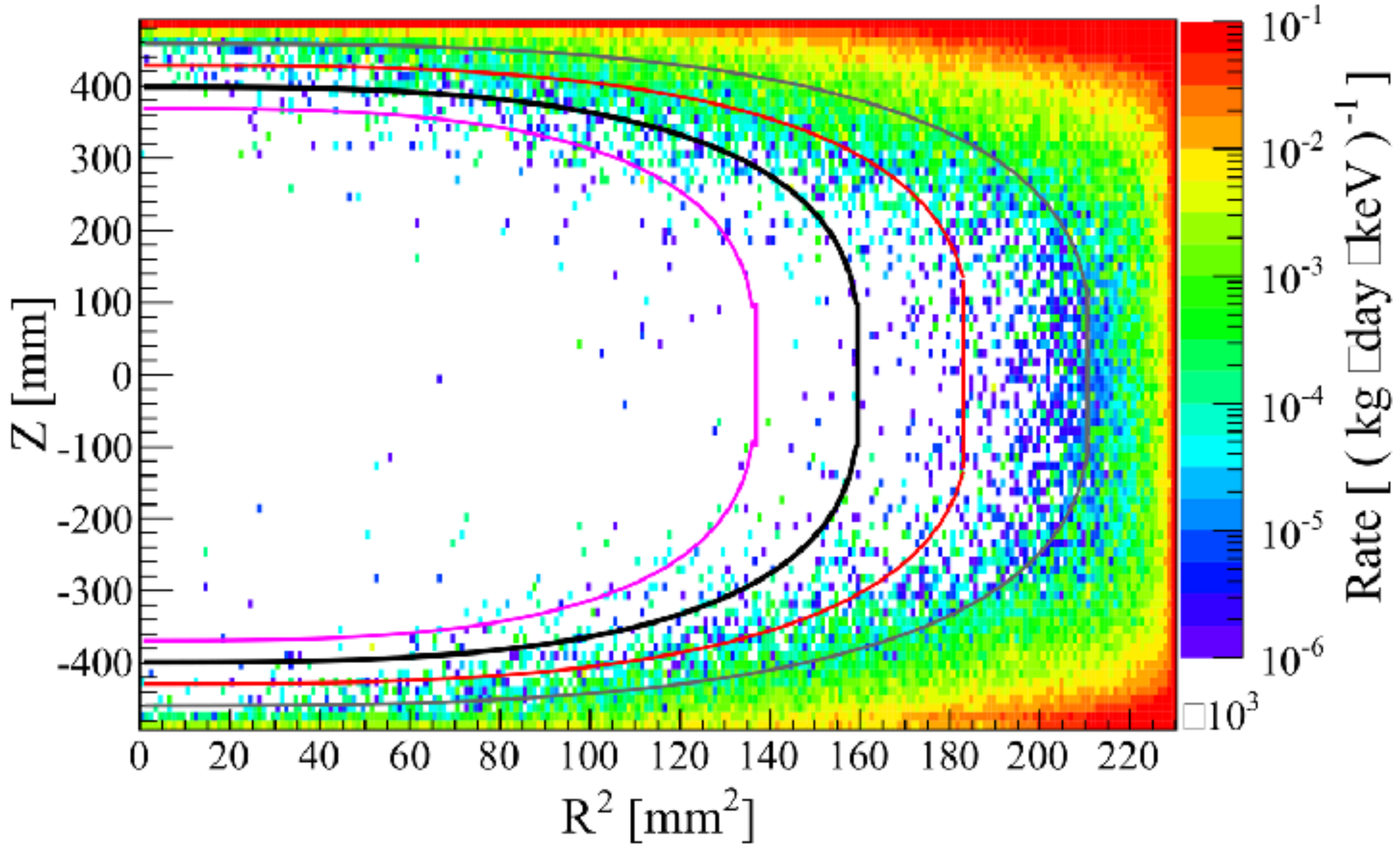

Hoeling et al Am.J.Phys. 1999, 67, 440.


Hoeling et al Am.J.Phys. 1999, 67, 440.

DM Experiments can be blinded by a single banana (K-40)

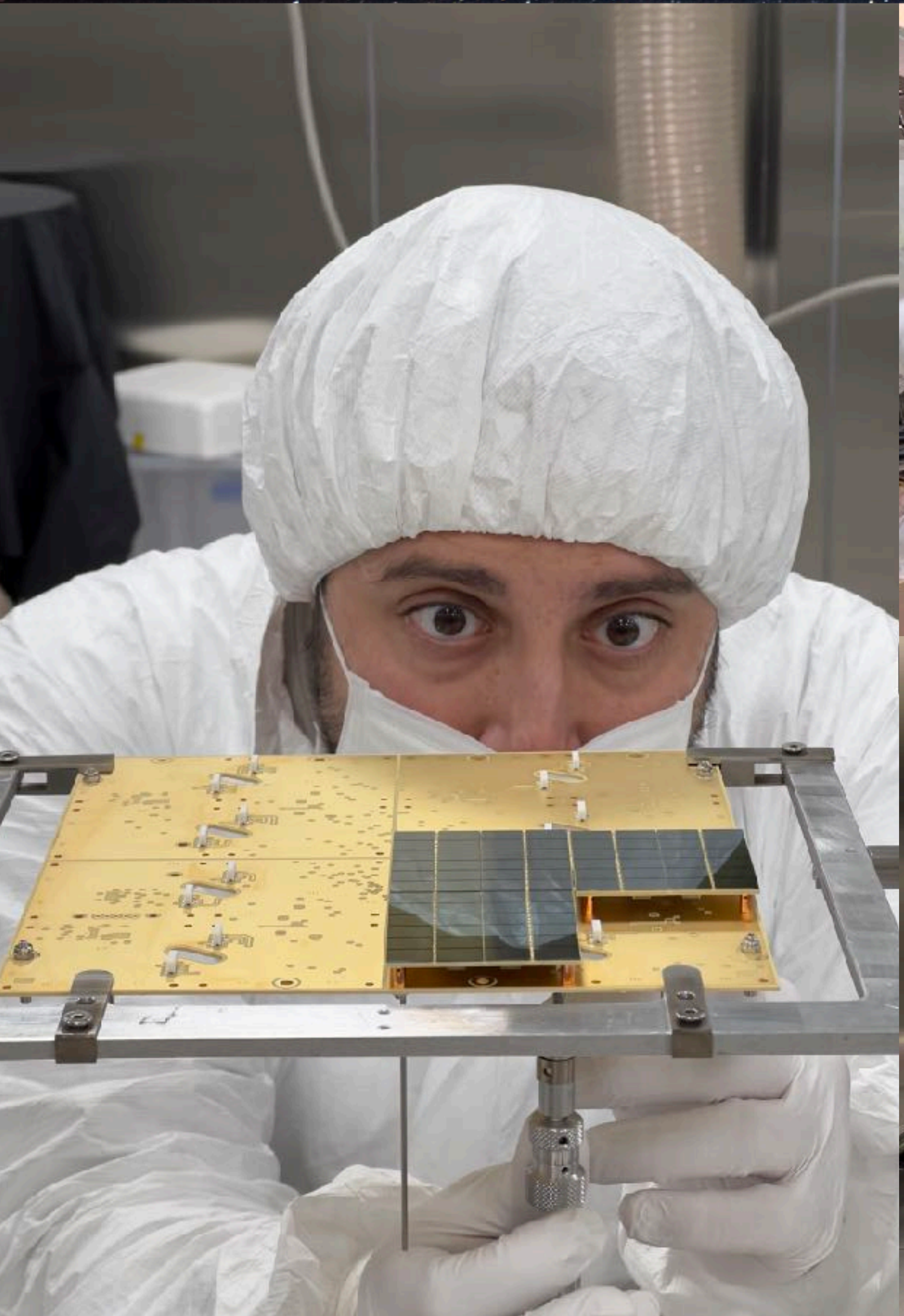
Countering Radioactivity

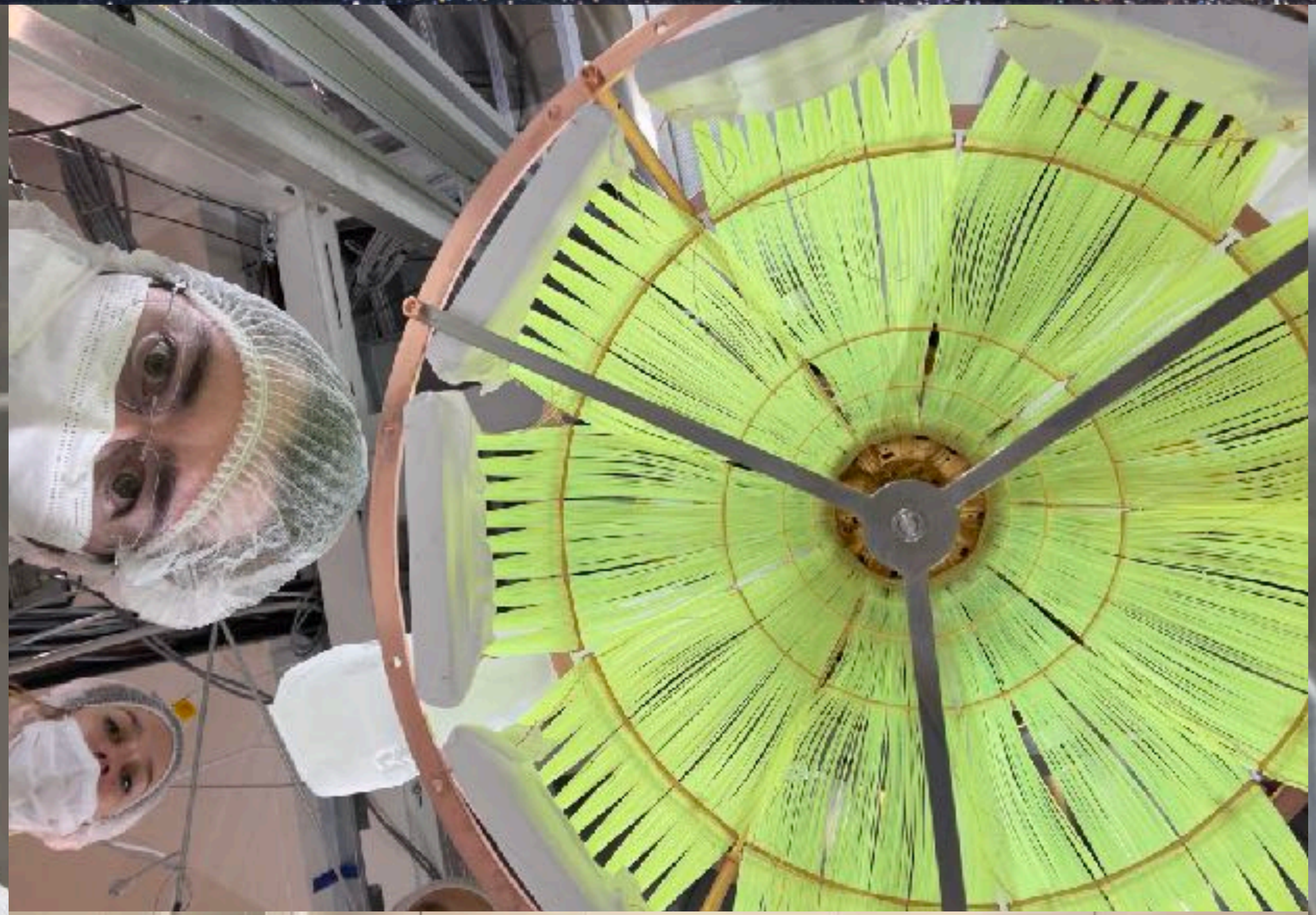




- Material assay and selection + cleaning
- Particle identification: ER/NR
- Fiducialization: surface events

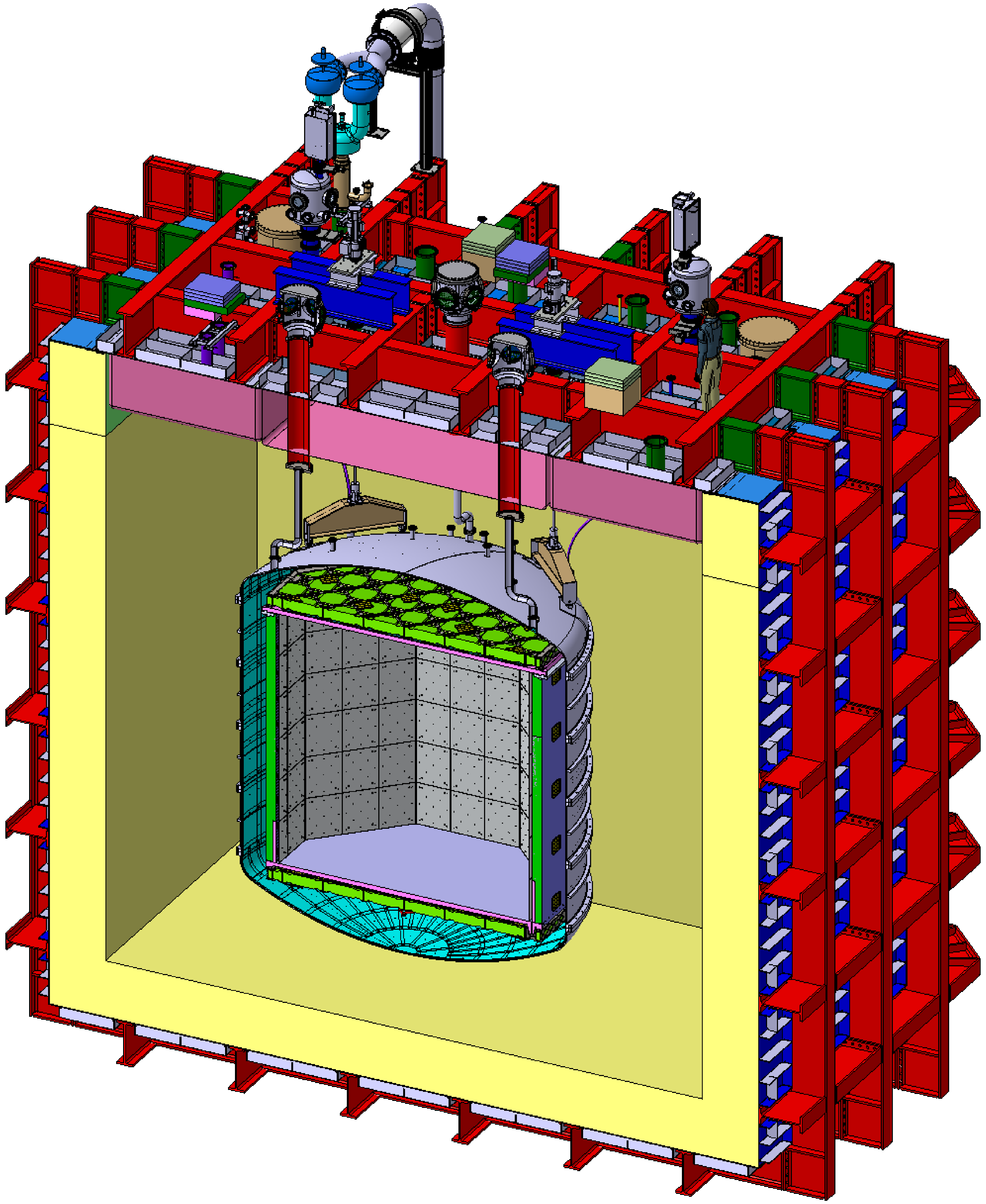
Build it clean!





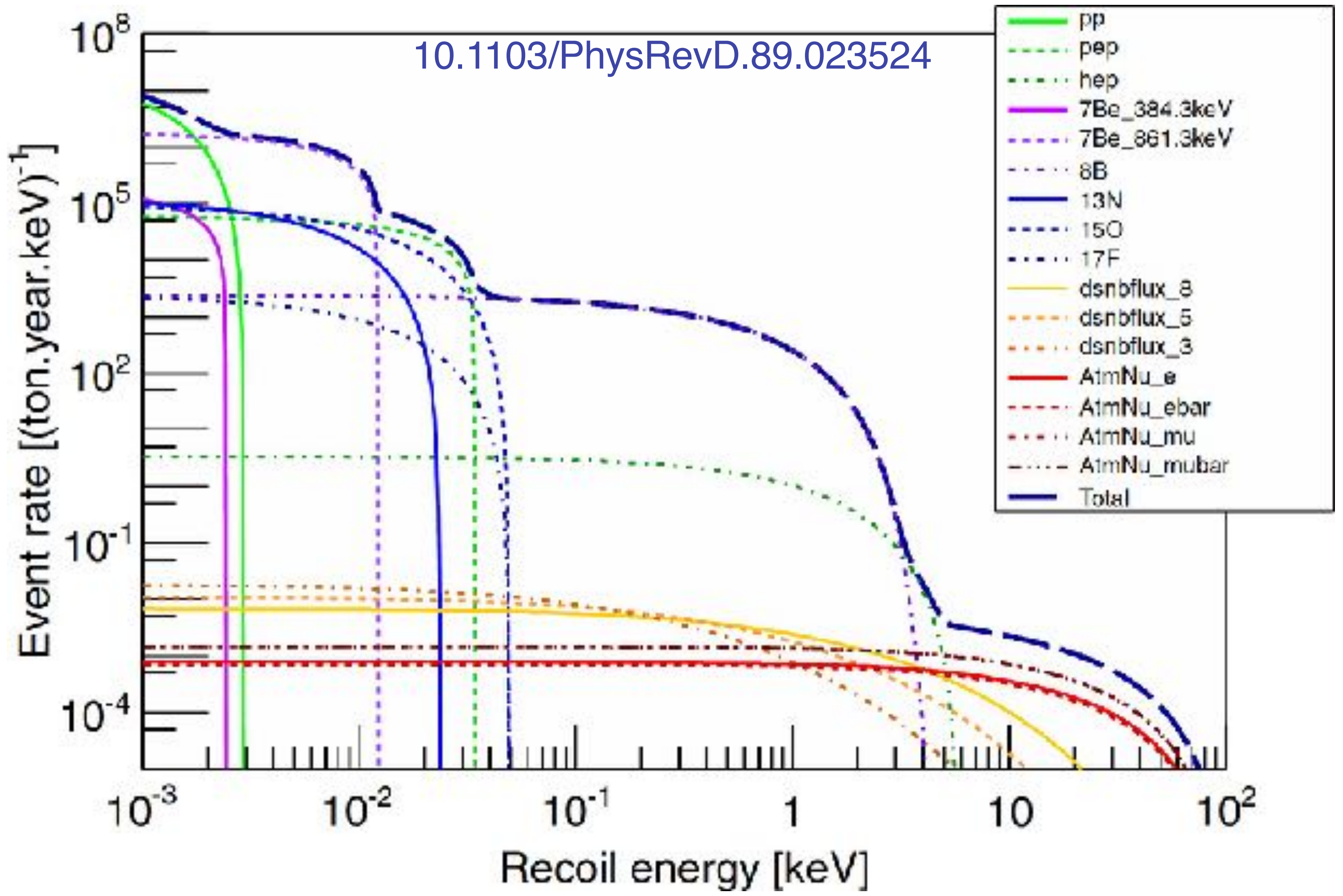
Onion Experiments

- Concentric Detectors of increasing radiopurity
- Outer layers provide passive shielding from external radioactivity
- Active Veto systems to tag and reject residual activity
  - Muon Veto - Usually Water Cherenkov detector
  - Neutron Veto - Based on capture of neutrons to produce gammas (easy to tag)
  - DM Detector - Tag and Reject a variety of bkgs



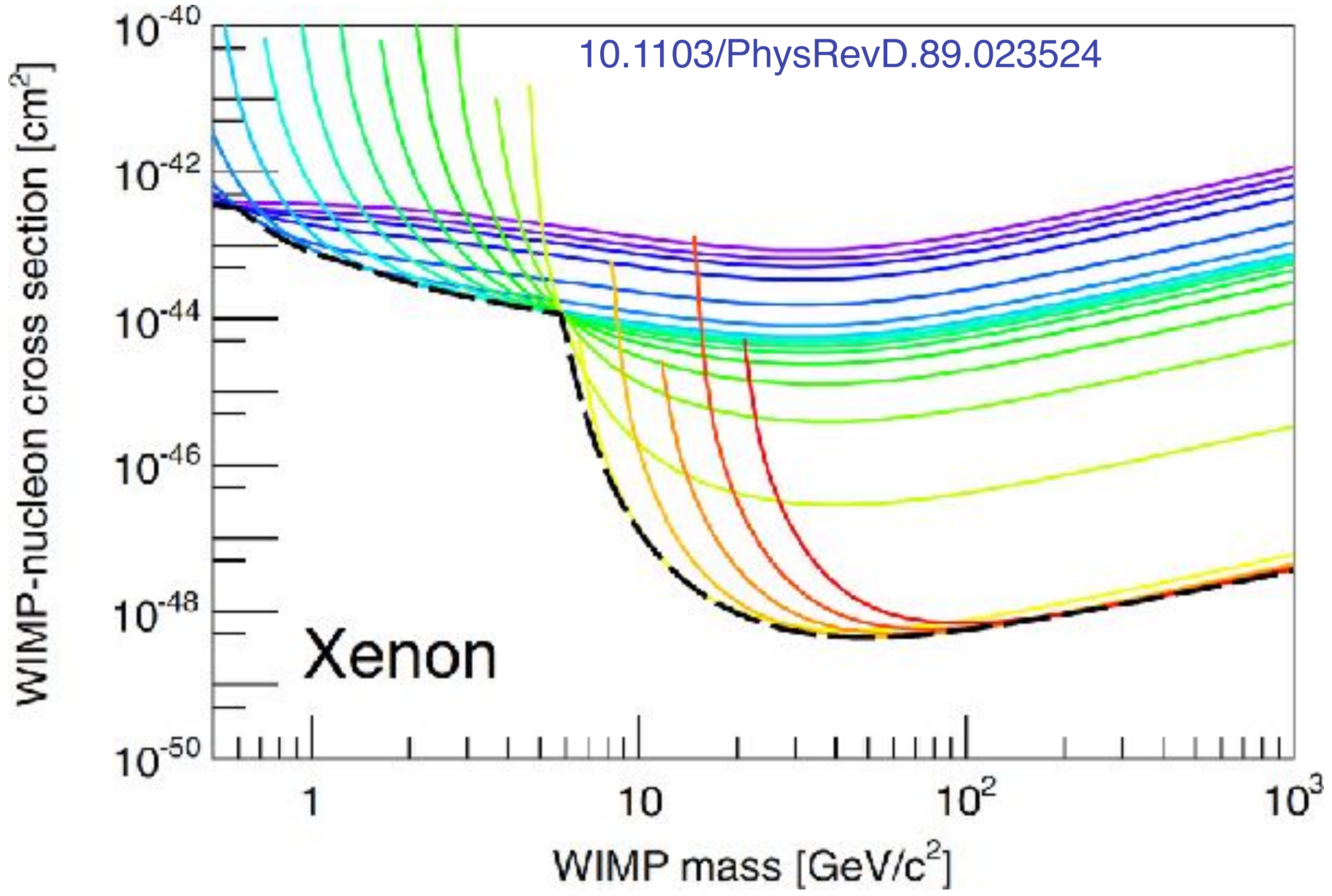
Neutrinos

CEvNS



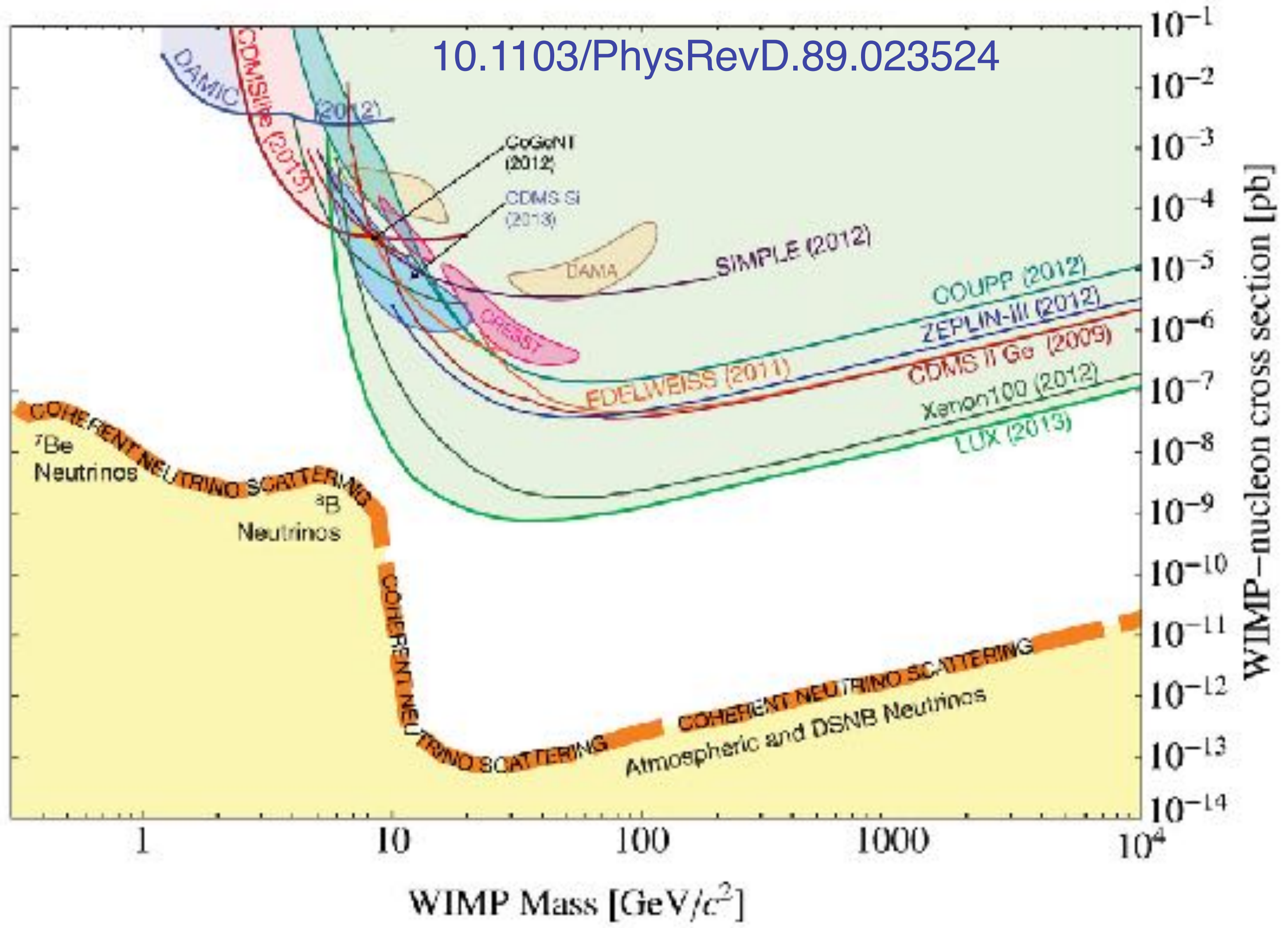
- Neutrinos neutral current
- Coherent scattering on nuclei
- ^{8}B at low energies
- Atmospheric ν at high energies

Sensitivity vs E_{th}



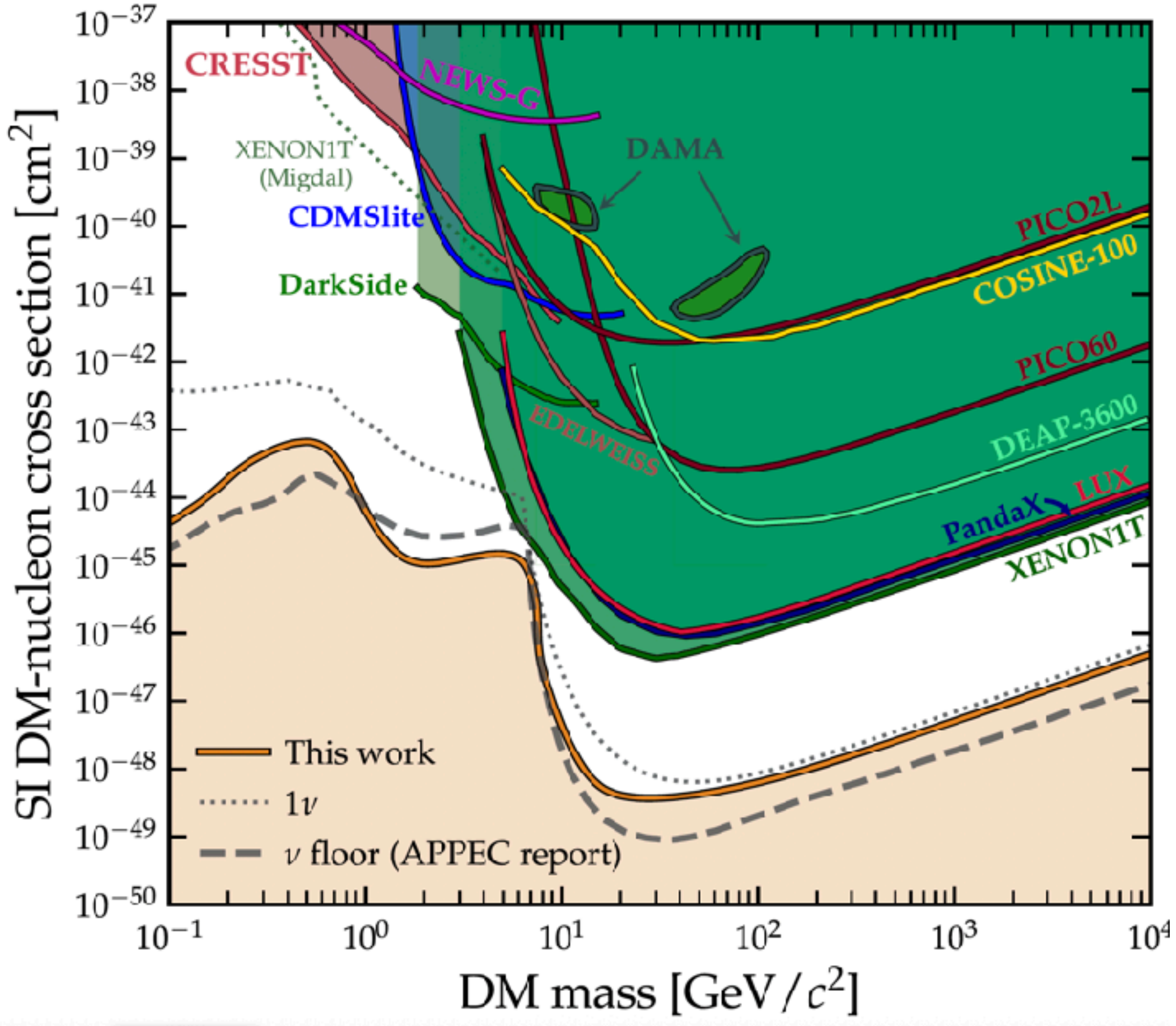
- Background-free sensitivity for exposures reaching 1 event
- Different energy thresholds
- Envelope forms the neutrino floor

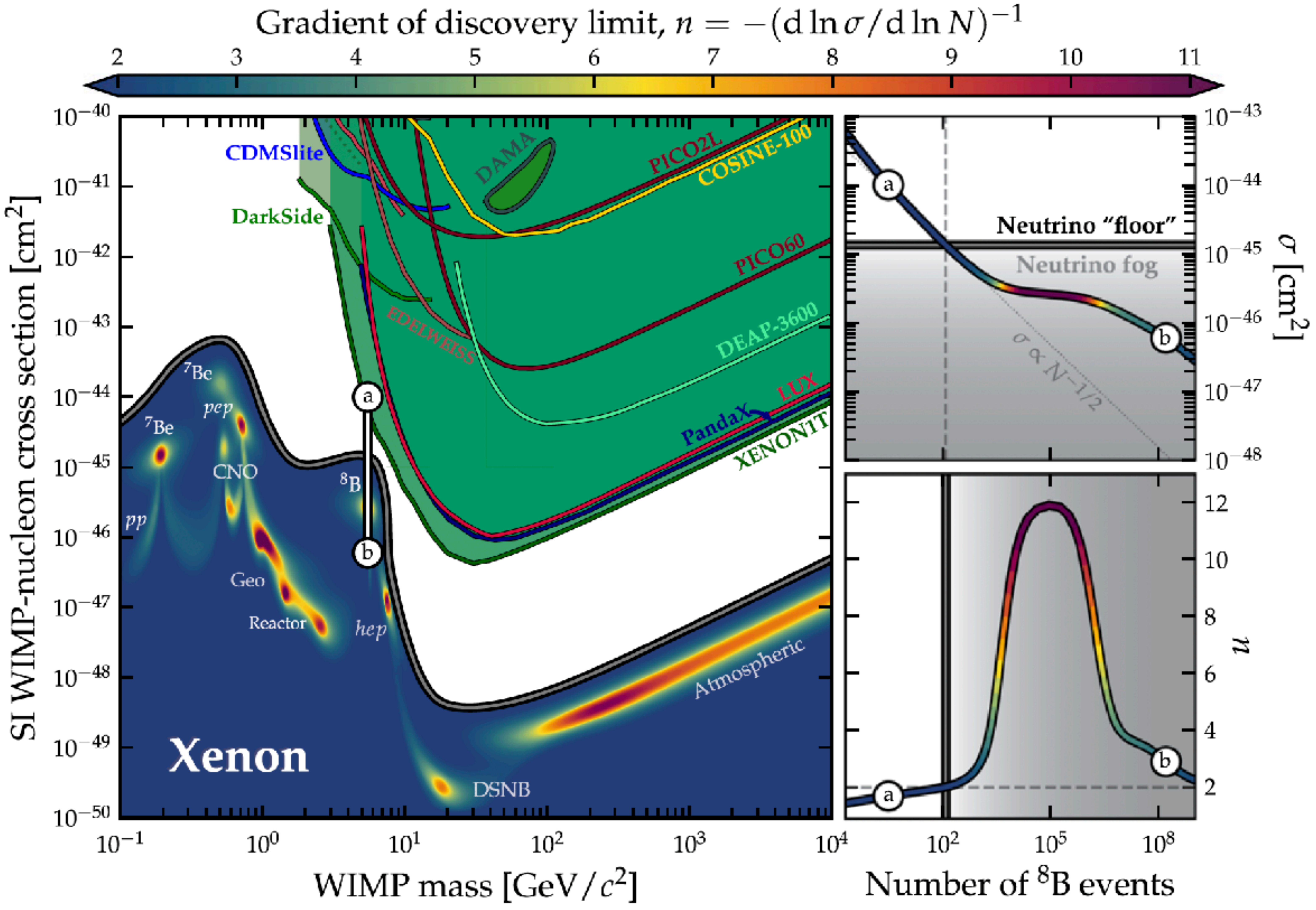
Neutrino floor



- Hard limit on experimental sensitivity for any detector
- How to go beyond?
  - Modulation
  - Directionality

Neutrinos


SI DM-nucleon cross section [cm^2]
DM mass [GeV/c^2]
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10^{-1}
10^0
10^1
10^2
10^3
10^4
CRESST
NEWS-G
XENON1T (Migdal)
DAMA
CDMSlite
DarkSide
PICO2L
COSINE-100
PICO60
DEAP-3600
EDELWEISS
LUX
PandaX
XENON1T
This work
1ν
ν floor (APPEC report)


Gradient of discovery limit, $n = -(\mathrm{d}\ln\sigma/\mathrm{d}\ln N)^{-1}$
2
3
4
5
6
7
8
9
10
11
SI WIMP-nucleon cross section [cm^2]
WIMP mass [GeV/c^2]
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10^{-1}
10^0
10^1
10^2
10^3
10^4
CDMSlite
DarkSide
DAMA
PICO2L
COSINE-100
PICO60
EDELWEISS
DEAP-3600
LUX
PandaX
XENON1T
^{7}Be
^{7}Be
pep
pp
CNO
^{8}B
Geo
Reactor
hep
Atmospheric
DSNB
Xenon
a
b
Neutrino "floor"
Neutrino fog
$\sigma \propto N^{-1/2}$
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
σ [cm^2]
12
10
8
6
4
2
n
10^2
10^5
10^8
Number of ^{8}B events

Detector Technologies

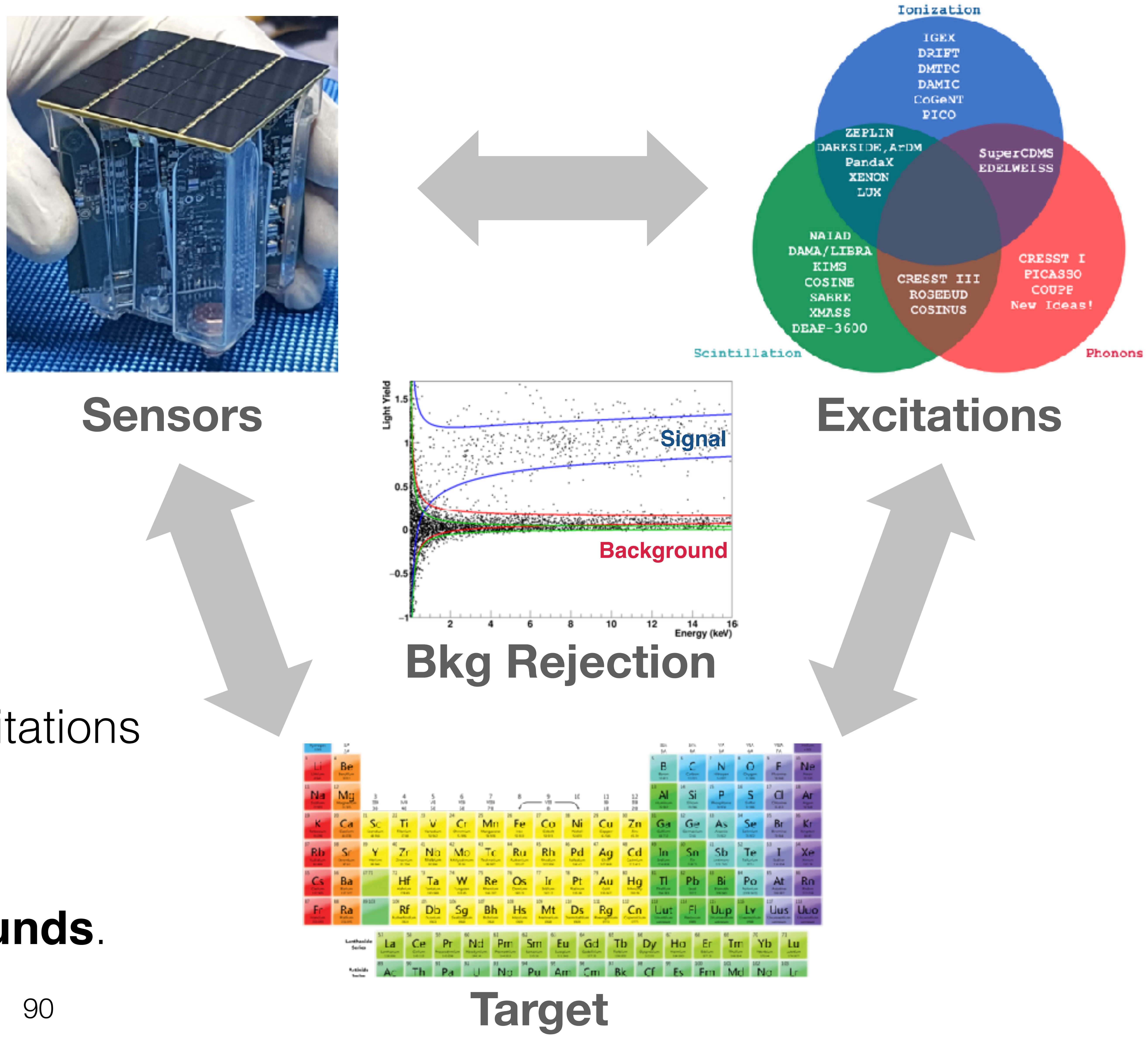
Recipe for a DM detector

1. Find a **suitable target** that:
    - maximizes DM interaction probability
    - maximizes energy deposition

2. Choose **target excitations** (signal) that:
    - Are efficiently produced by energy deposits
    - Travel efficiently within the target, even for macroscopic distances

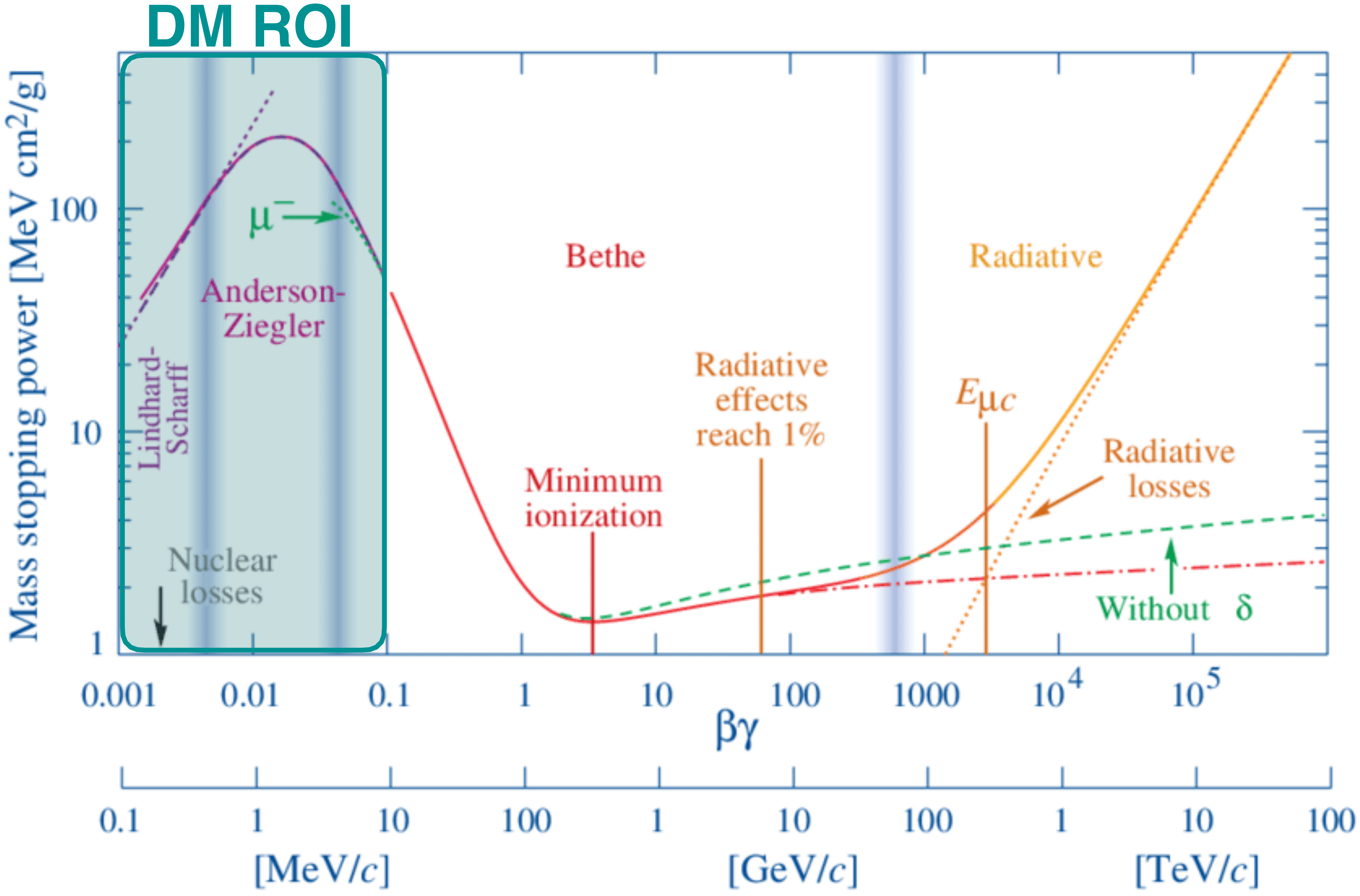
3. Develop **sensors** that:
    - Have high efficiency to the chosen target excitations
    - Do not produce instrumental noise

4. Target excitations and sensors **reject backgrounds**.

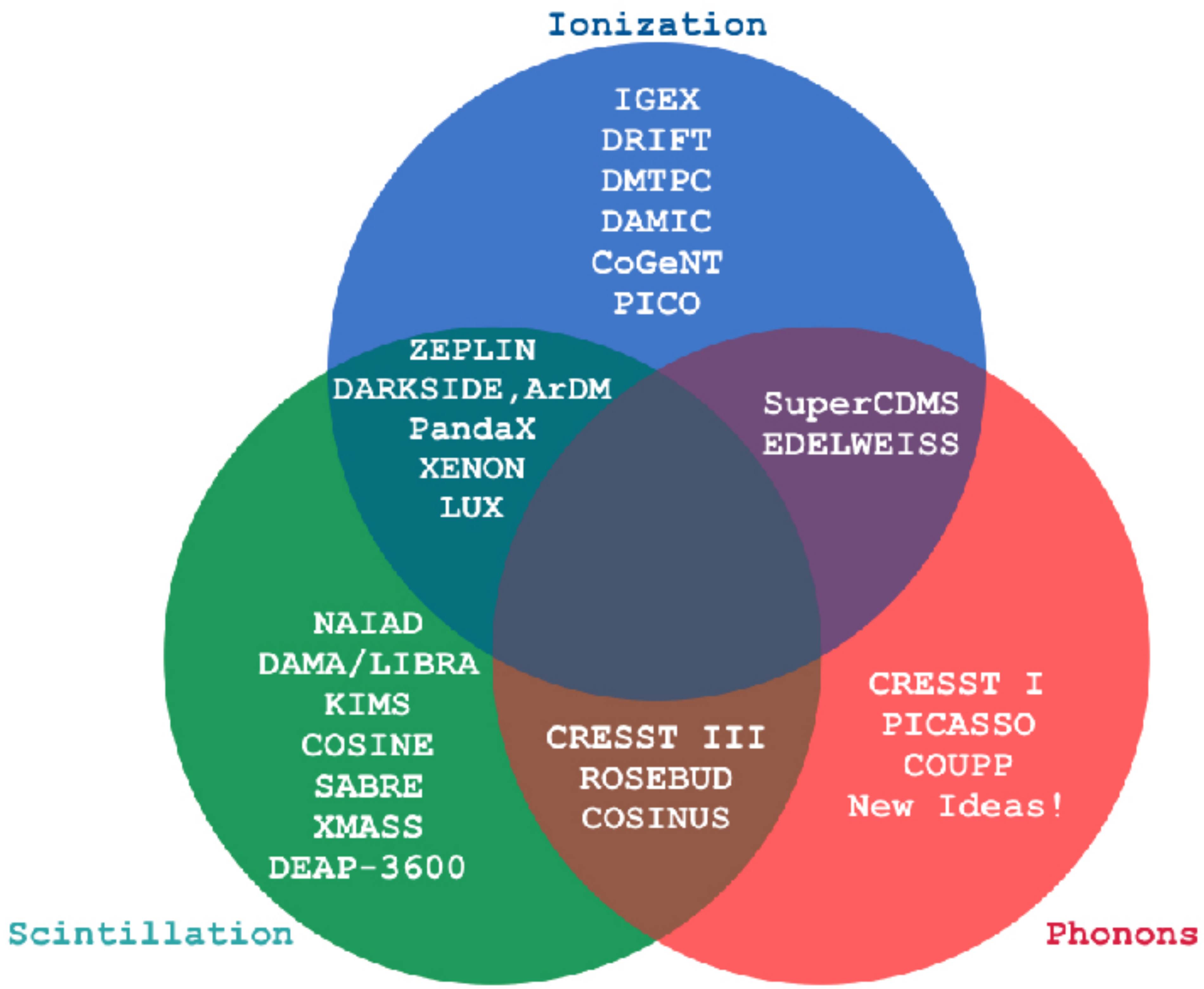


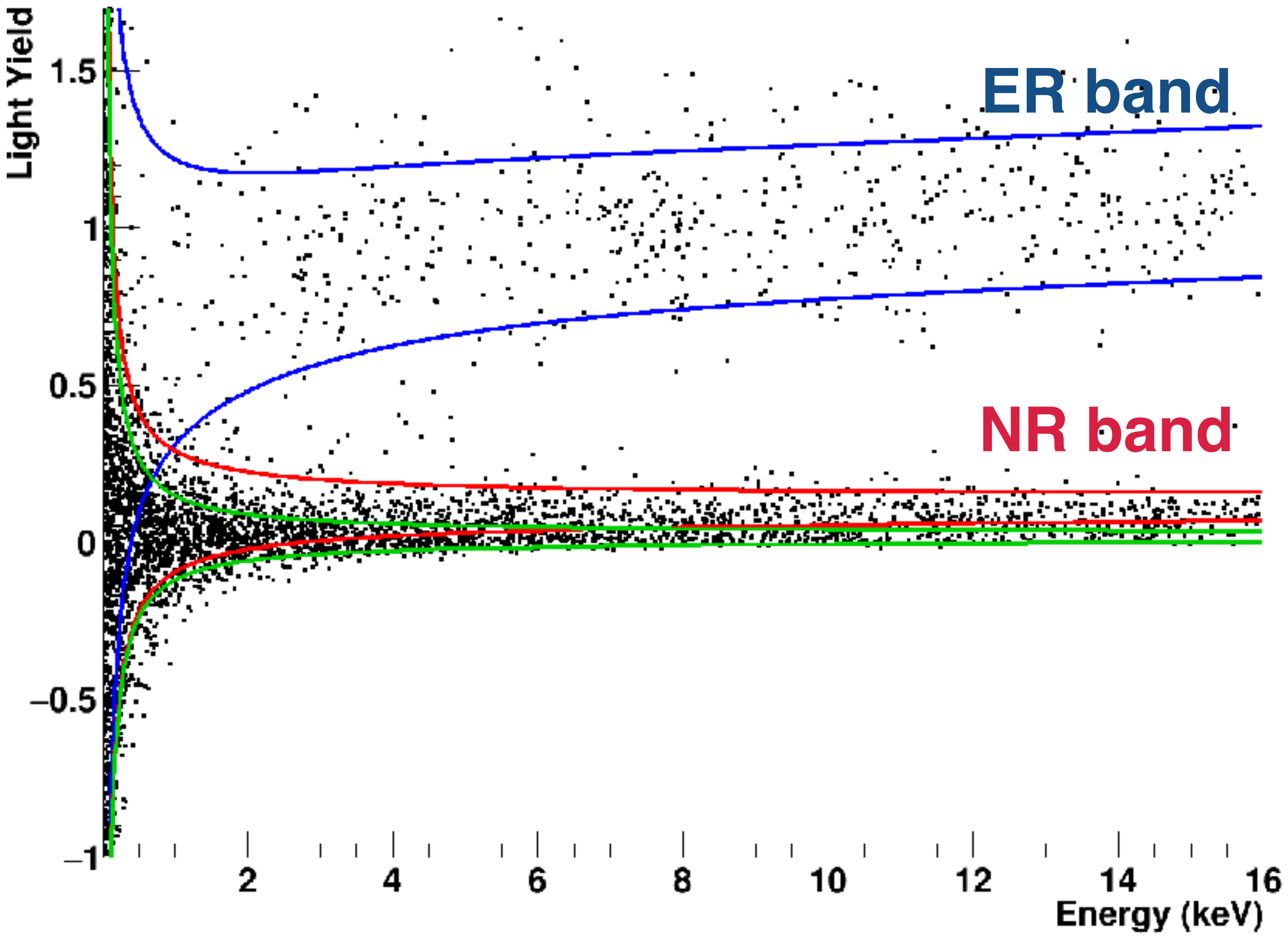
Energy Loss

- Energy loss mechanisms in matter depend on energy scale
- ROI for DM induced NR < 100 keV
- Lindhard regime: adiabatic overlap of electron shells
- Energy losses as HEAT (nuclear quenching)



WIMP detection

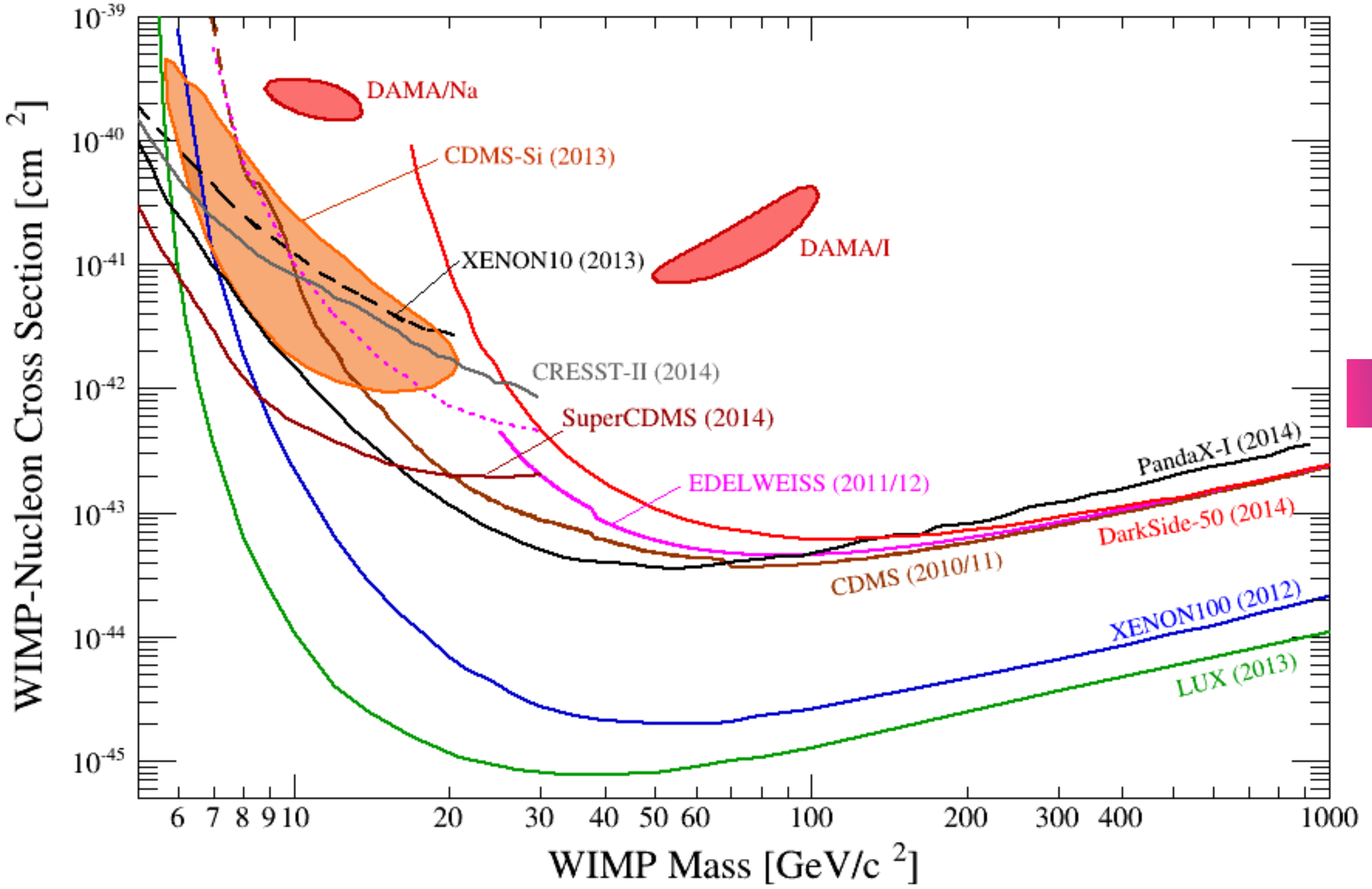




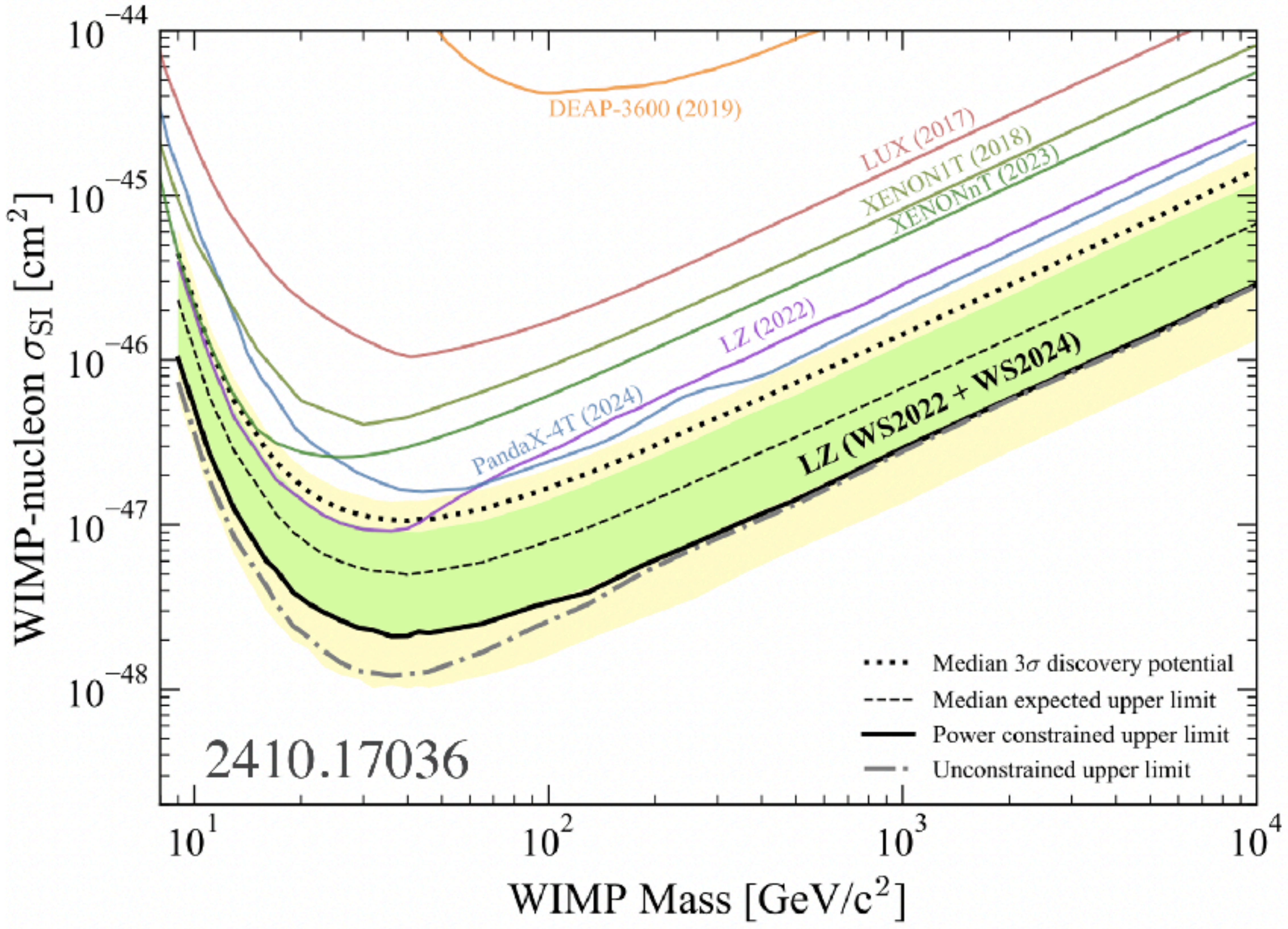
- Variety of experiments exploiting all channels
- Phonon observation requires cryogenics

- Sensitivity to 2 excitation channels
- ER/NR discrimination ⇒ background rejection

10 years of field development

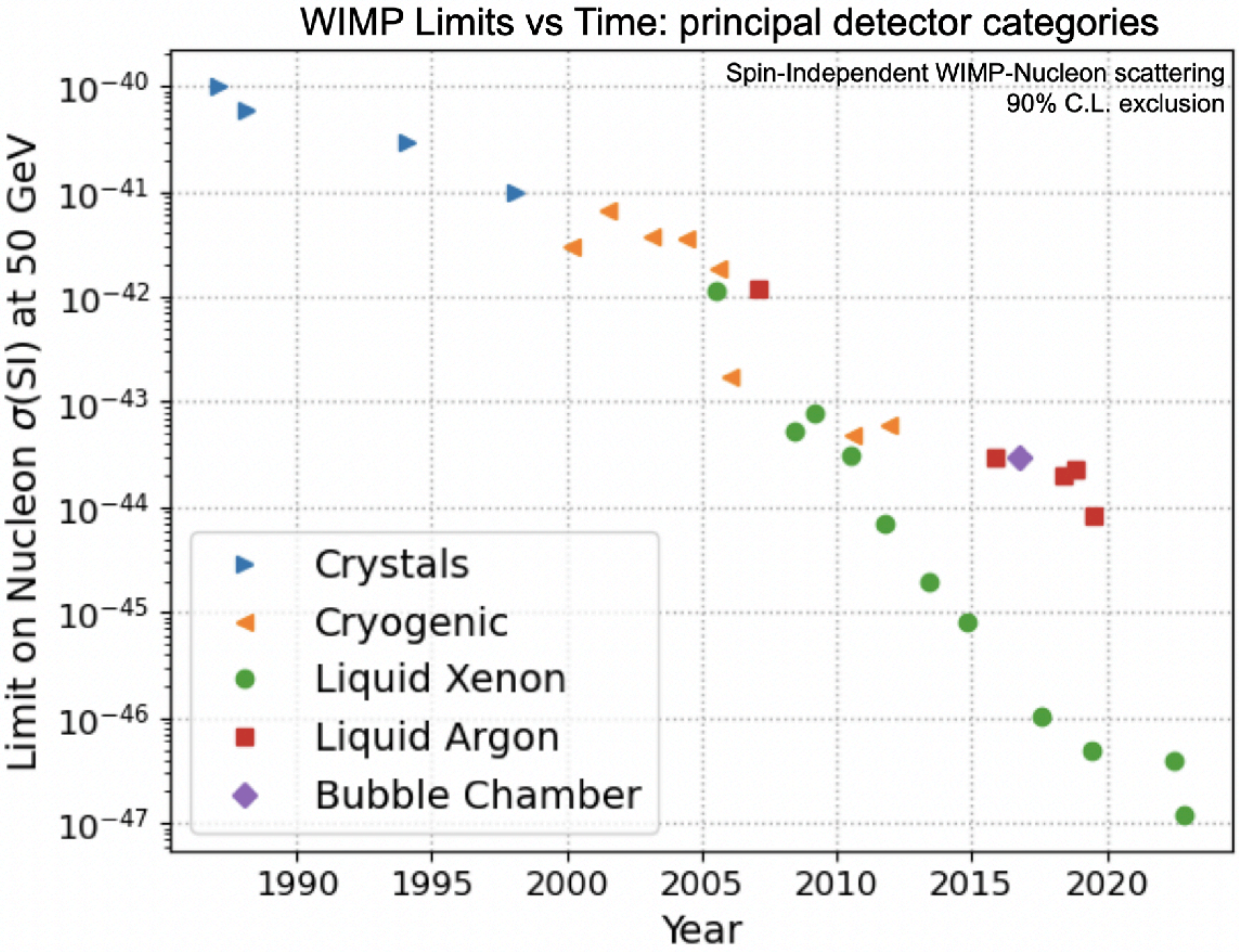


- Many different technologies
  - Scintillating crystals
  - Bolometers
  - Charge collection (Si, Ge)
  - Noble Element Dual Phase TPC



- Only 1 technology leading for heavy WIMPs
  - Noble Element Dual Phase TPC
- 3 orders of magnitude gain
- New exciting exploration at low masses!

Time Progression

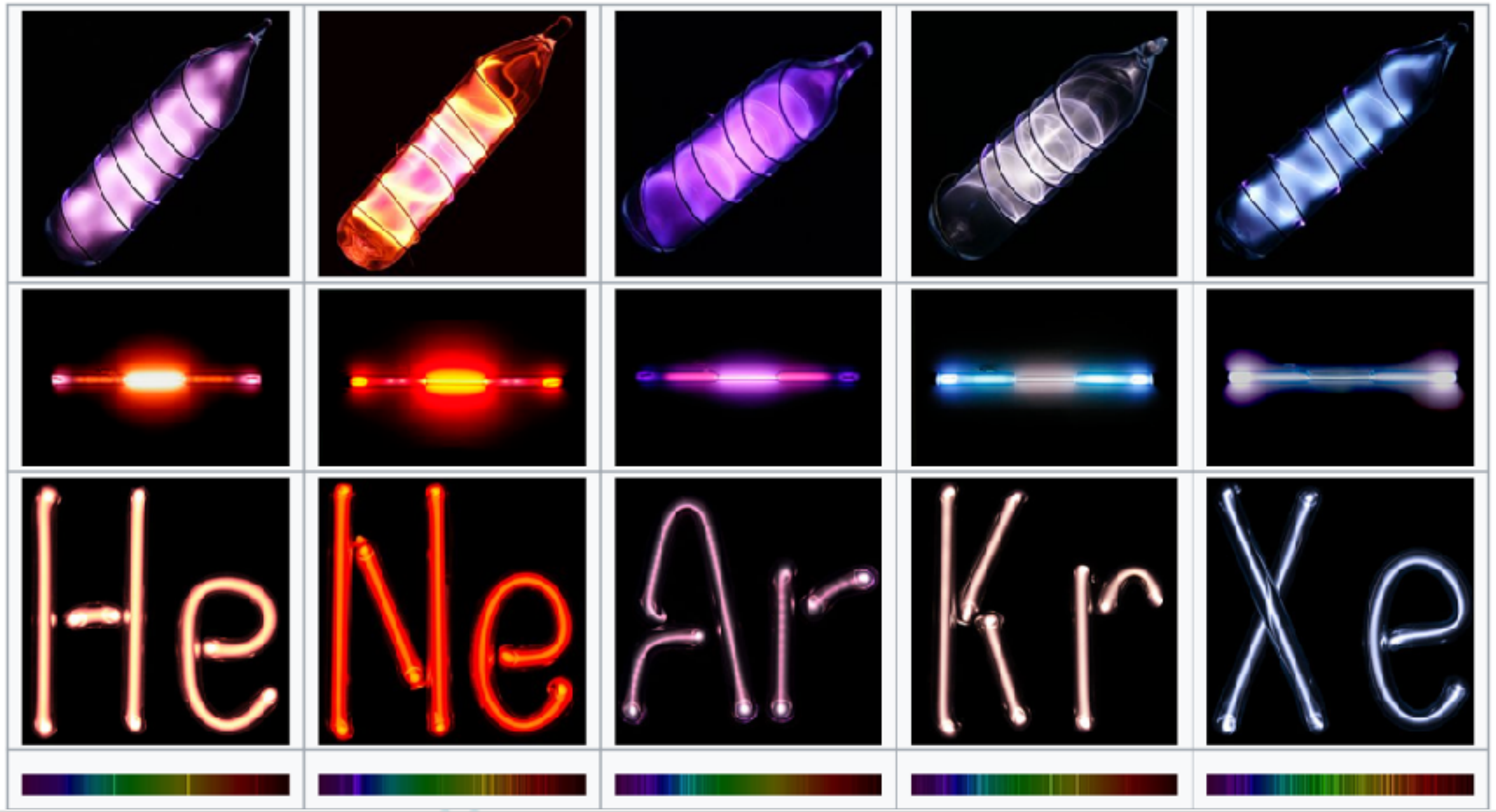


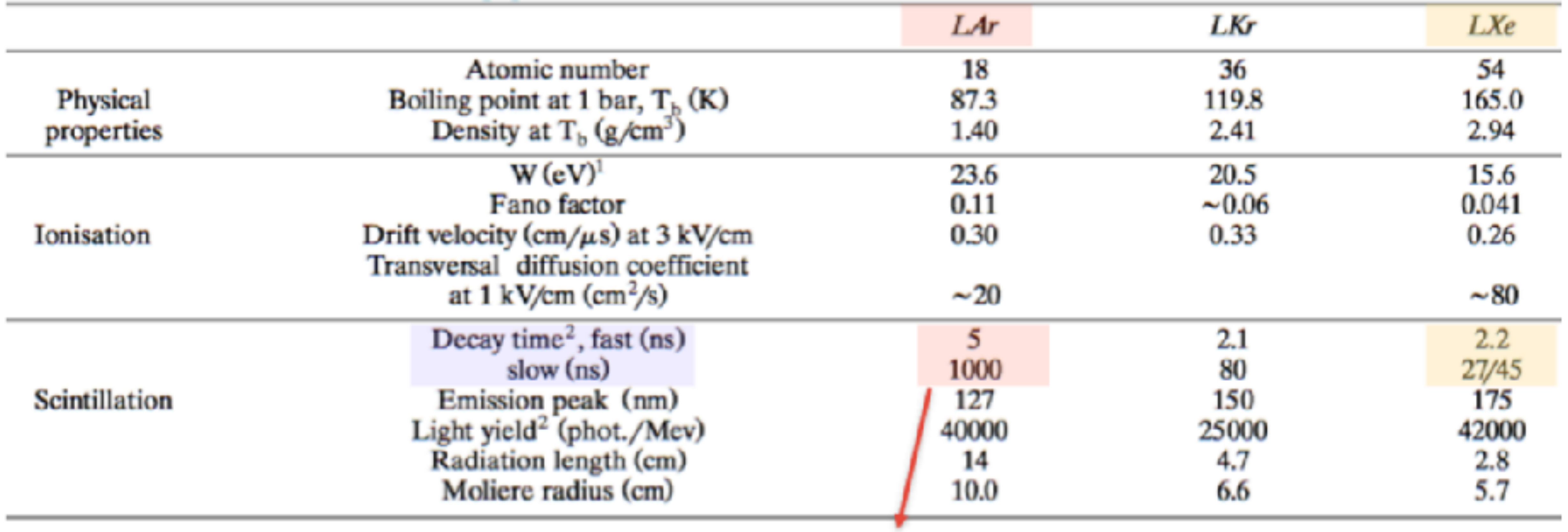
Noble Elements

Liquefied noble elements

- WIMP DM signal: nuclear recoils (NR)
- Electron Recoils (ER) are background

- High density ✔
  - Self screening
  - Good scalability
- Easy(-ish) purification, also online ✔
- Target Excitation:
  - Scintillation ✔
  - Ionization ✔
- ER (background) rejection ✔
- NR quenching at low energies ✘





		LAr	*LKr*	*LXe*
Physical properties	Atomic number	18	36	54
	Boiling point at 1 bar, T_b (K)	87.3	119.8	165.0
	Density at T_b (g/cm^3)	1.40	2.41	2.94
Ionisation	W (eV)^1	23.6	20.5	15.6
	Fano factor	0.11	~0.06	0.041
	Drift velocity (cm/μs) at 3 kV/cm	0.30	0.33	0.26
	Transversal diffusion coefficient at 1 kV/cm (cm^2/s)	~20		~80
Scintillation	Decay time^2, fast (ns)	5	2.1	2.2
	slow (ns)	1000	80	27/45
	Emission peak (nm)	127	150	175
	Light yield^2 (phot./Mev)	40000	25000	42000
	Radiation length (cm)	14	4.7	2.8
	Moliere radius (cm)	10.0	6.6	5.7

Excellent discrimination power!

Single phase detectors

- High active mass
- Simple design
- 4π coverage, high light yield
- Bonus (for LAr): ER rejection via PSD on scintillation light
- No claim of observation

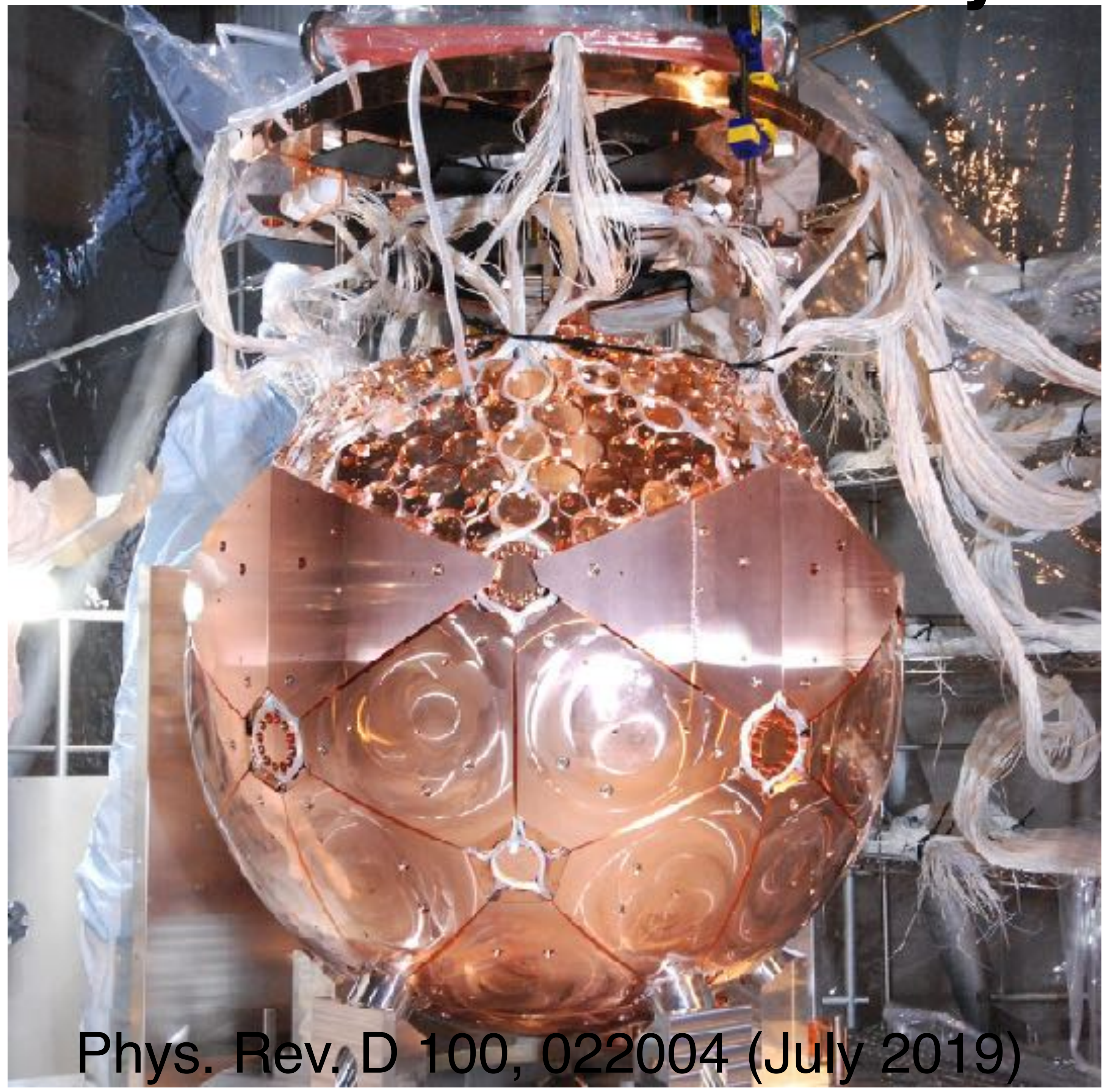
@SNOLAB

Phys. Rev. D 100, 022004 (July 2019)

DEAP-3600

- 3279 (824) kg of active (fid.) mass
- 5 cm acrylic vessel, 255 PMTs
- Cherenkov muon veto (300t H_2O)

@Kamioka Observatory

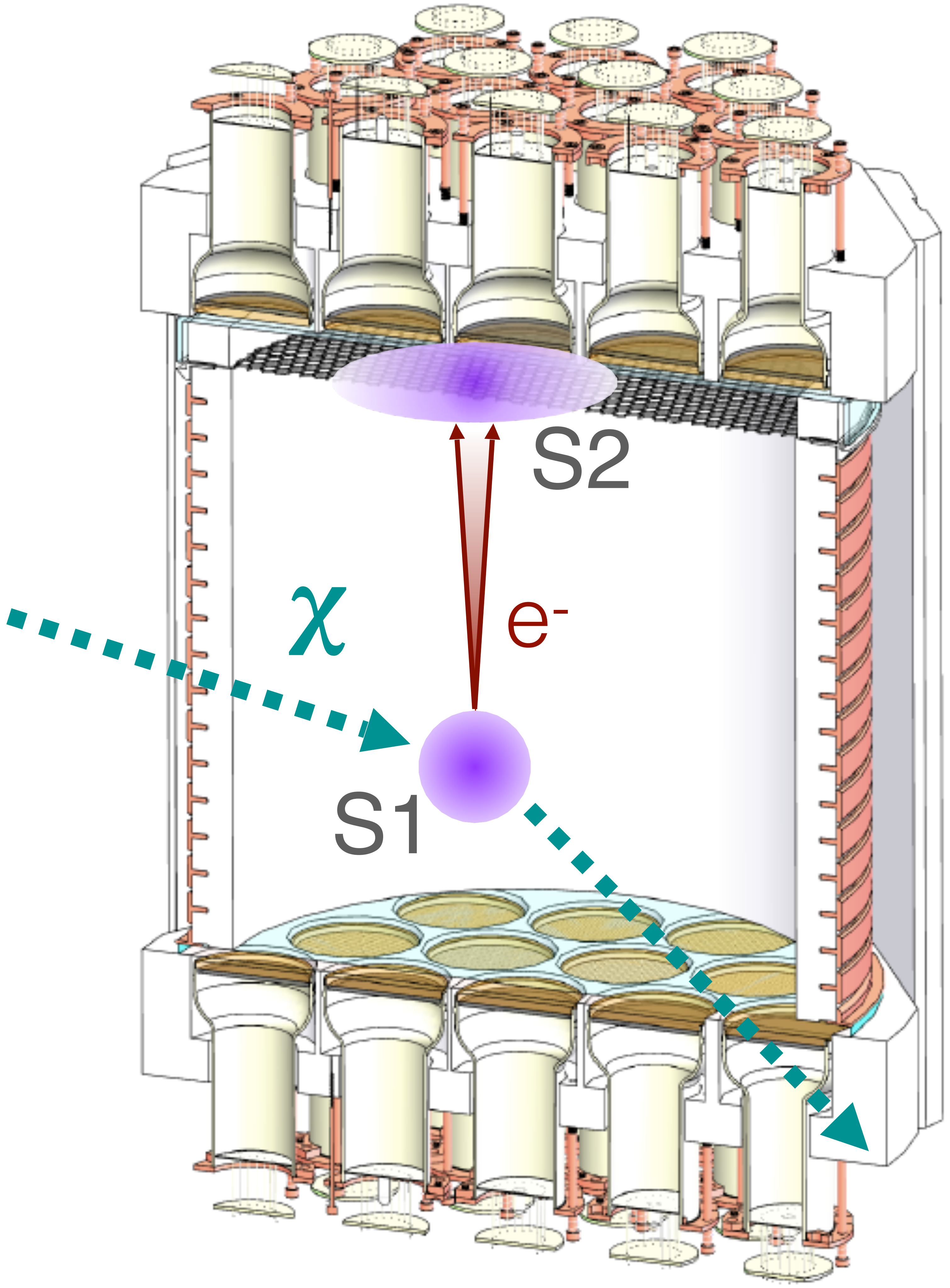


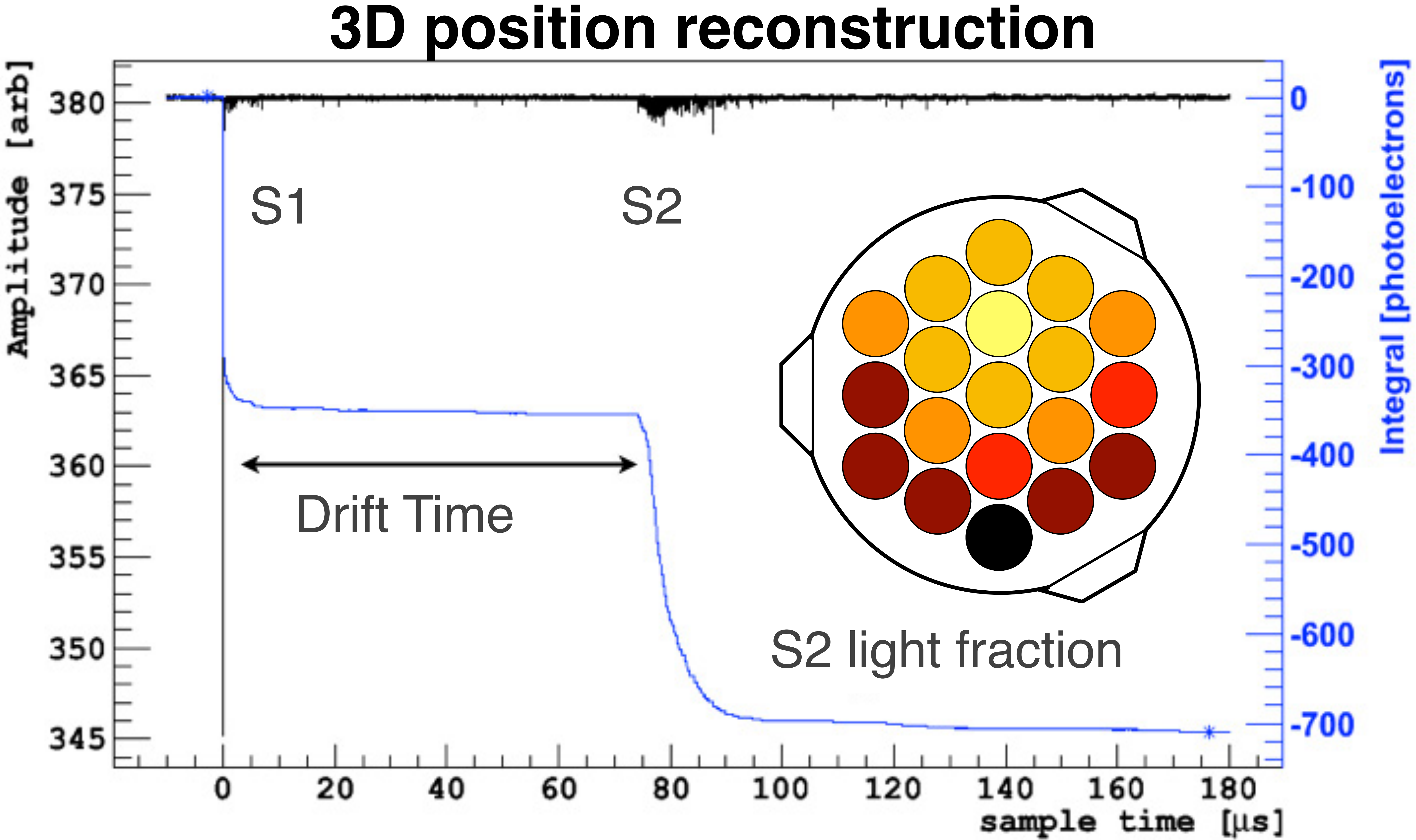
Phys. Rev. D 100, 022004 (July 2019)

XMASS-I

- 832 (97) kg of active (fid.) mass
- 642 2”-PMTs
- Cherenkov muon veto

Dual-phase TPCs





- Z from S1-S2 time difference
- XY from S2 light distribution
- Definition of a Fiducial Volume

- Rejection of multiple scattering
- ER rejection by S2/S1 (10^2 - 10^3)

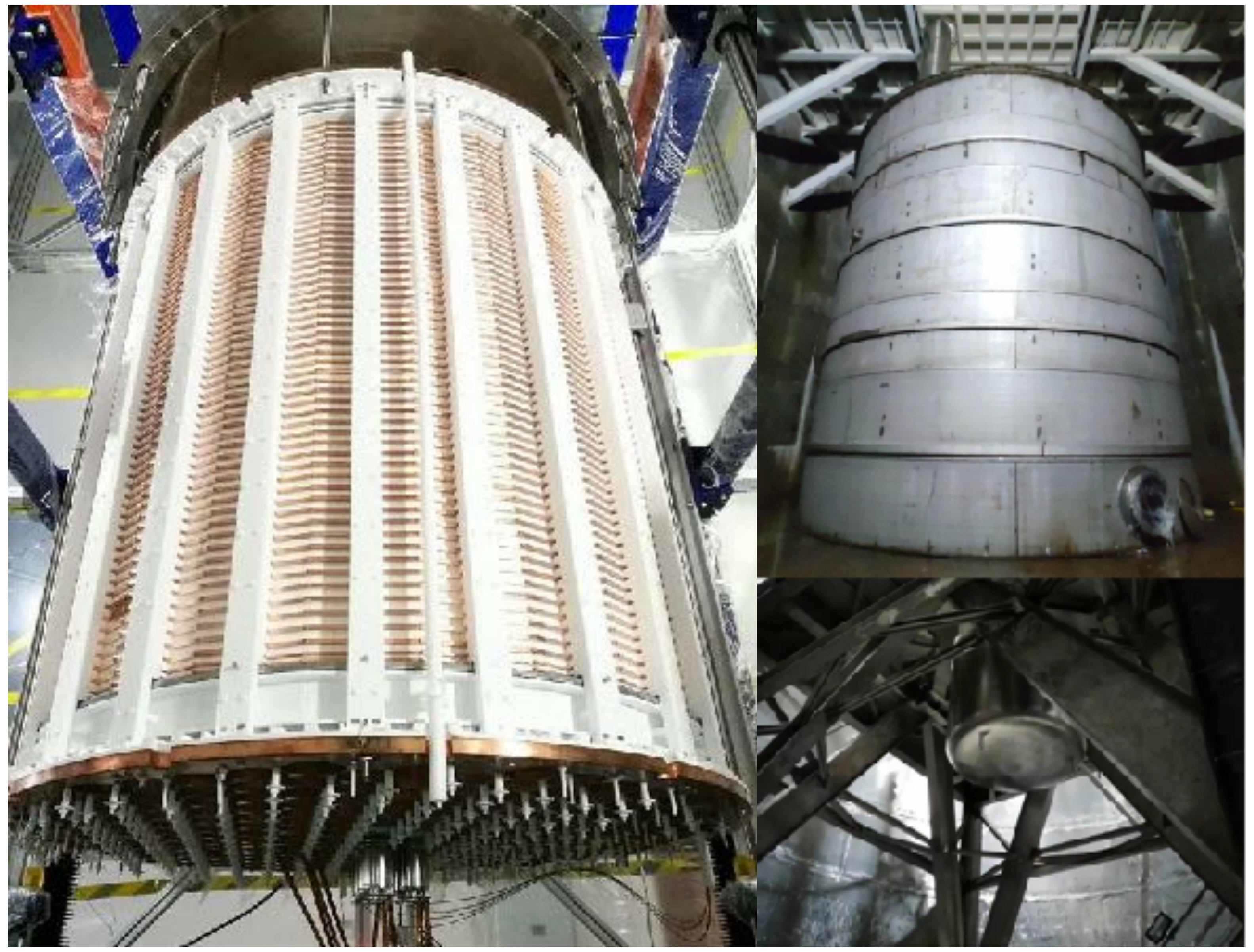
LXe Dual-Phase TPCs

LZ (2020)

- 7 (5.6) t active (fiducial) mass
- Skin detector (LXe) for ɣ tagging
- Outer detector (LScint+Gd) for μ and n tagging

XENON-nT (2019)

- 5.9 t active mass
- Neutron veto (H_2O+Gd) for μ and n tagging
- Cherenkov muon veto (H_2O)

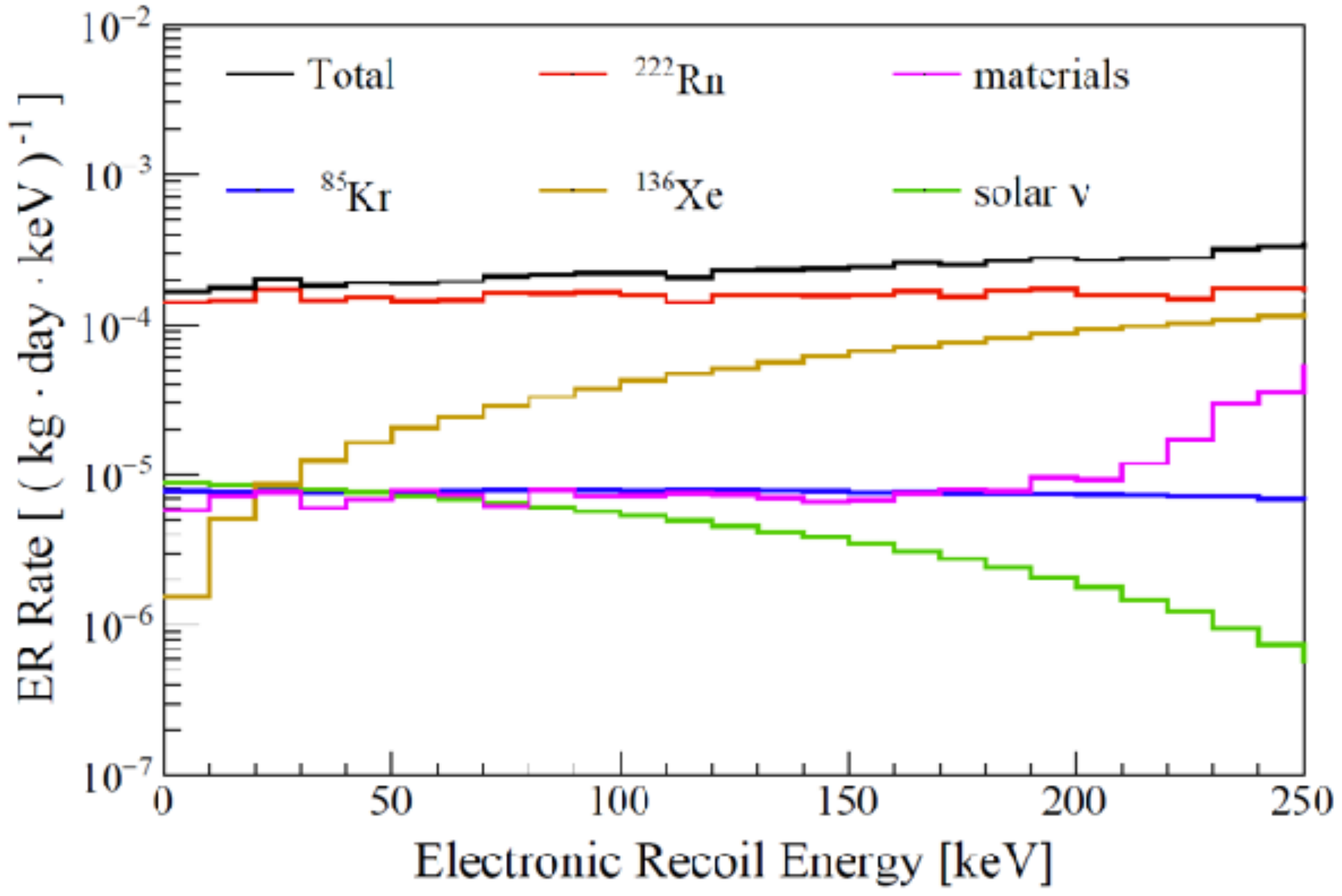


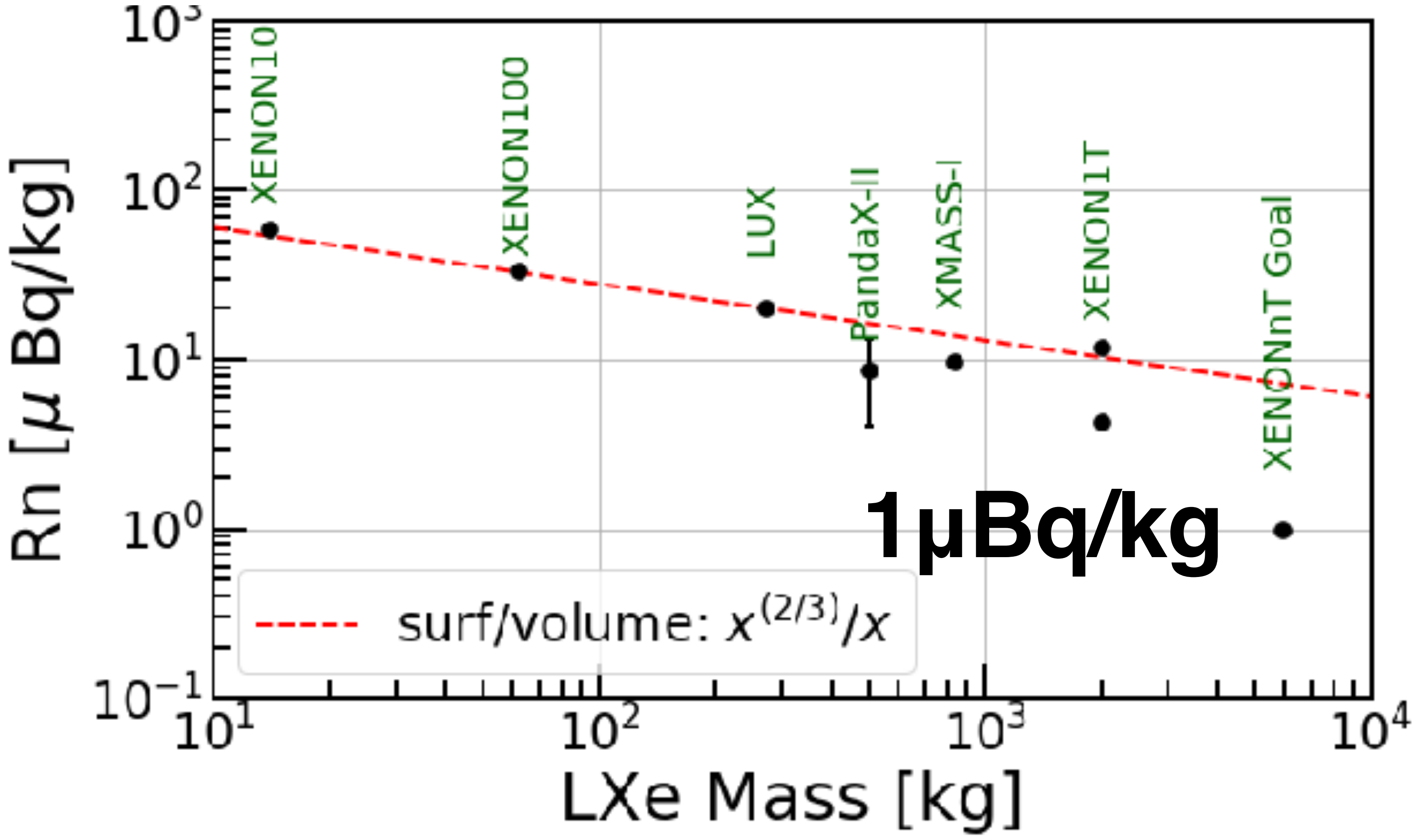
PandaX-xT (2019)

- 4 t active mass
- Immersed in a 900m^3 ultra-pure water tank

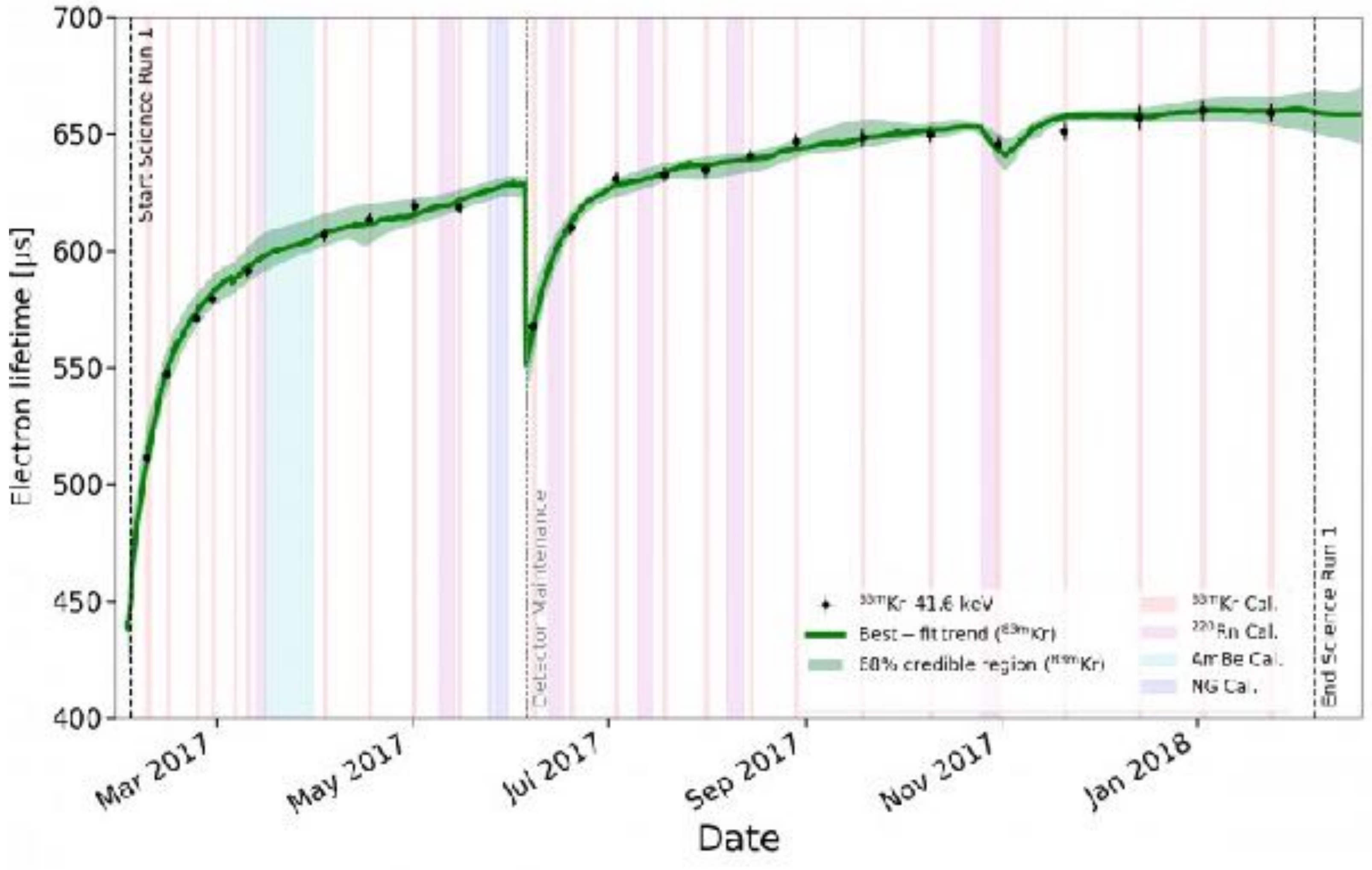
G2: LXe challenges

Radon elimination



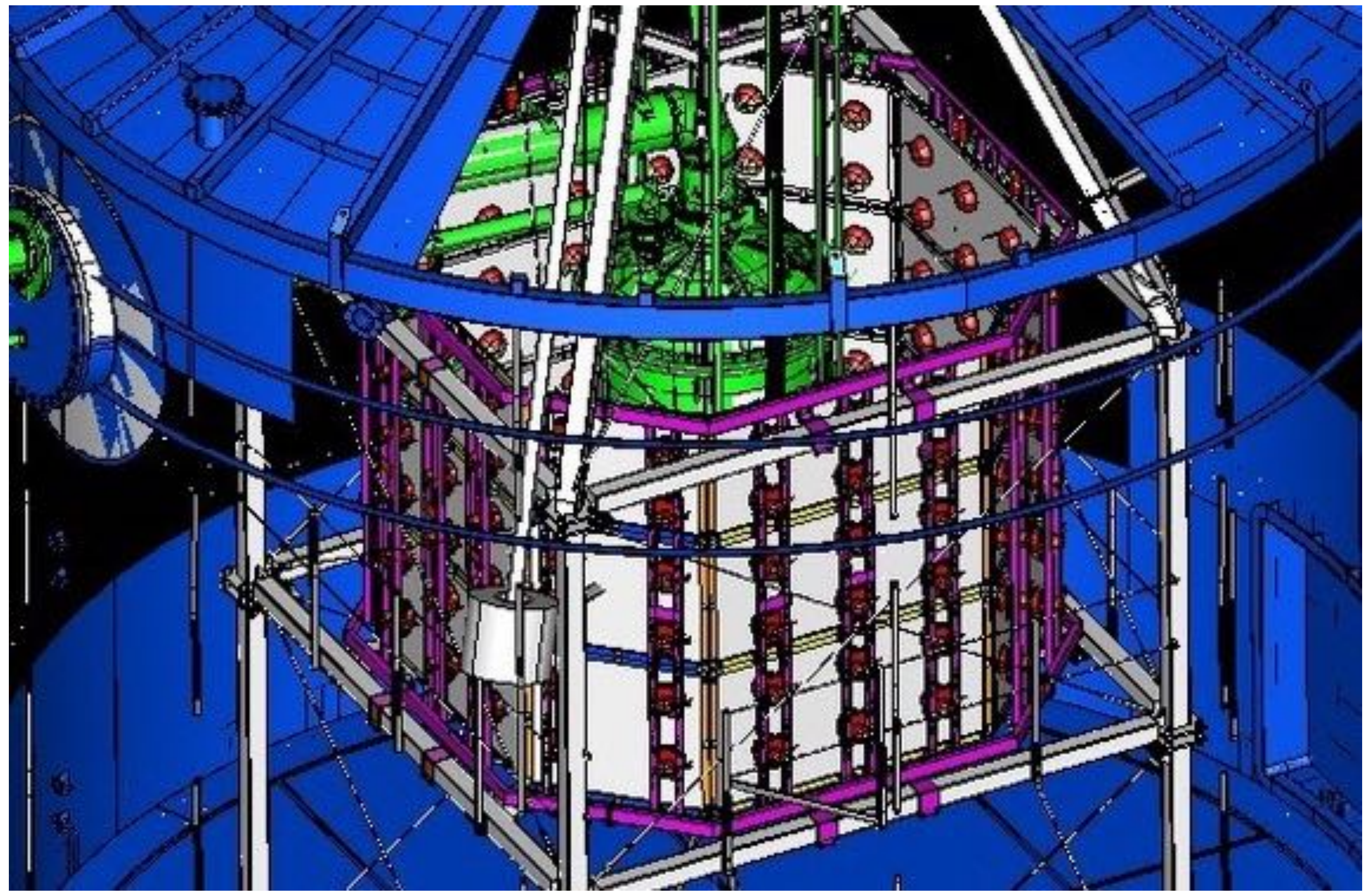


Purification for e- lifetime



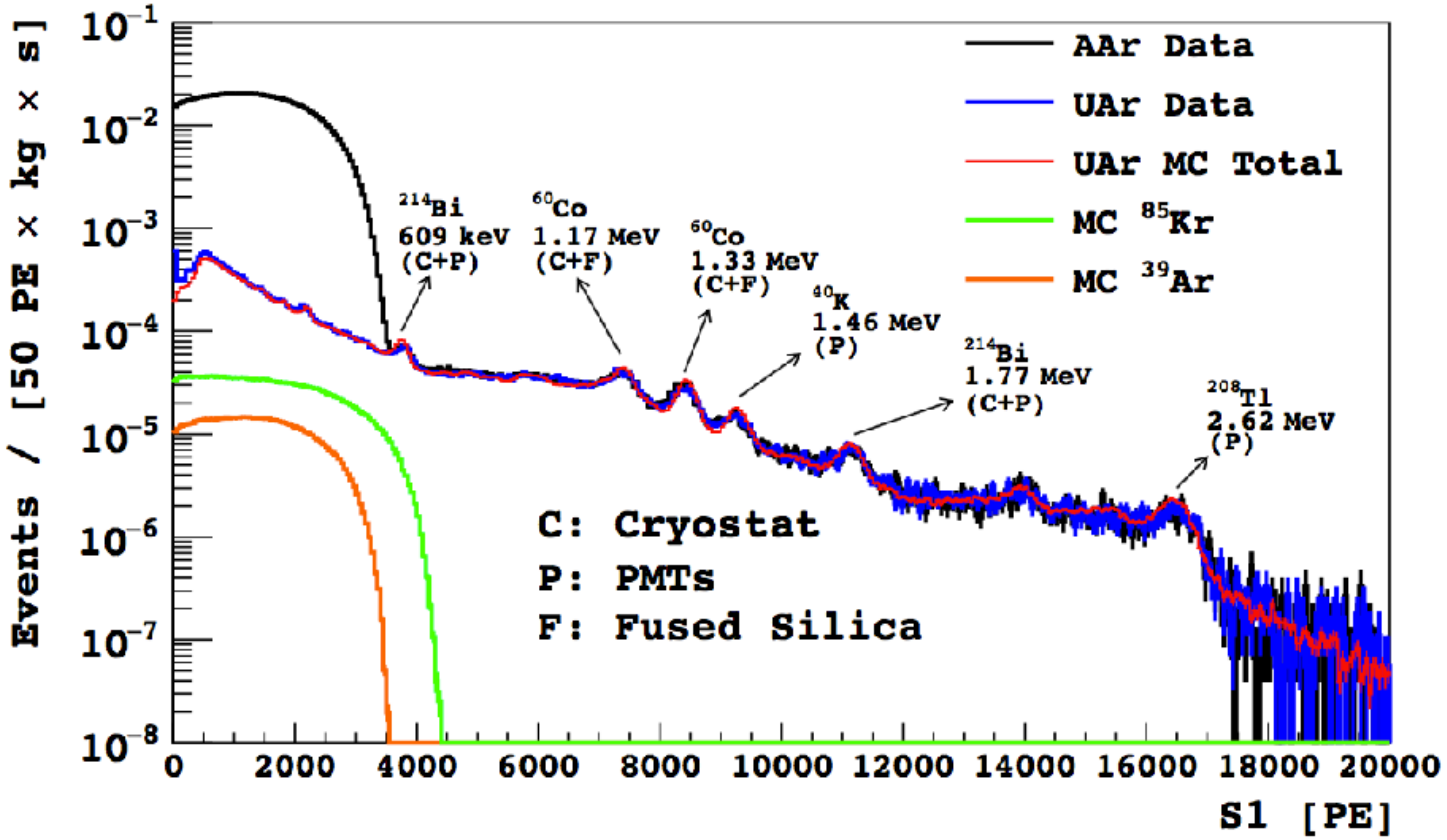
- Outgassing: electronegative impurities (O_2)
- Recirculation speed needs a boost
- Liquid purification: 5L/min of LXe > 2500SLPM of GXe

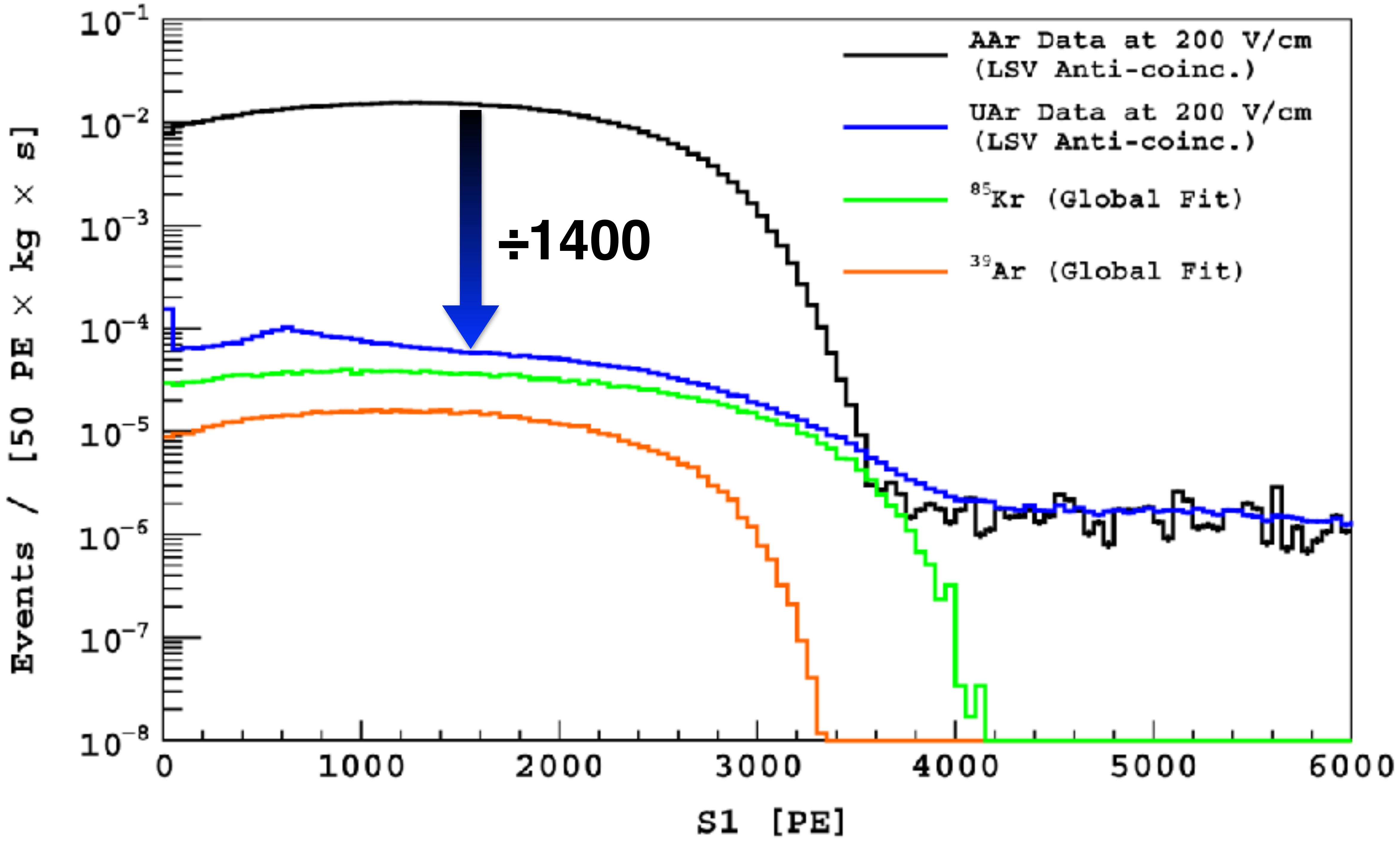
Neutron tagging



- Fission from U,Th + (α,n)
- ~7n/20ty expected
- n capture on Gd+(H_2O or LS)
- Tagging efficiency > 85%

Challenges of using argon: ^{39}Ar

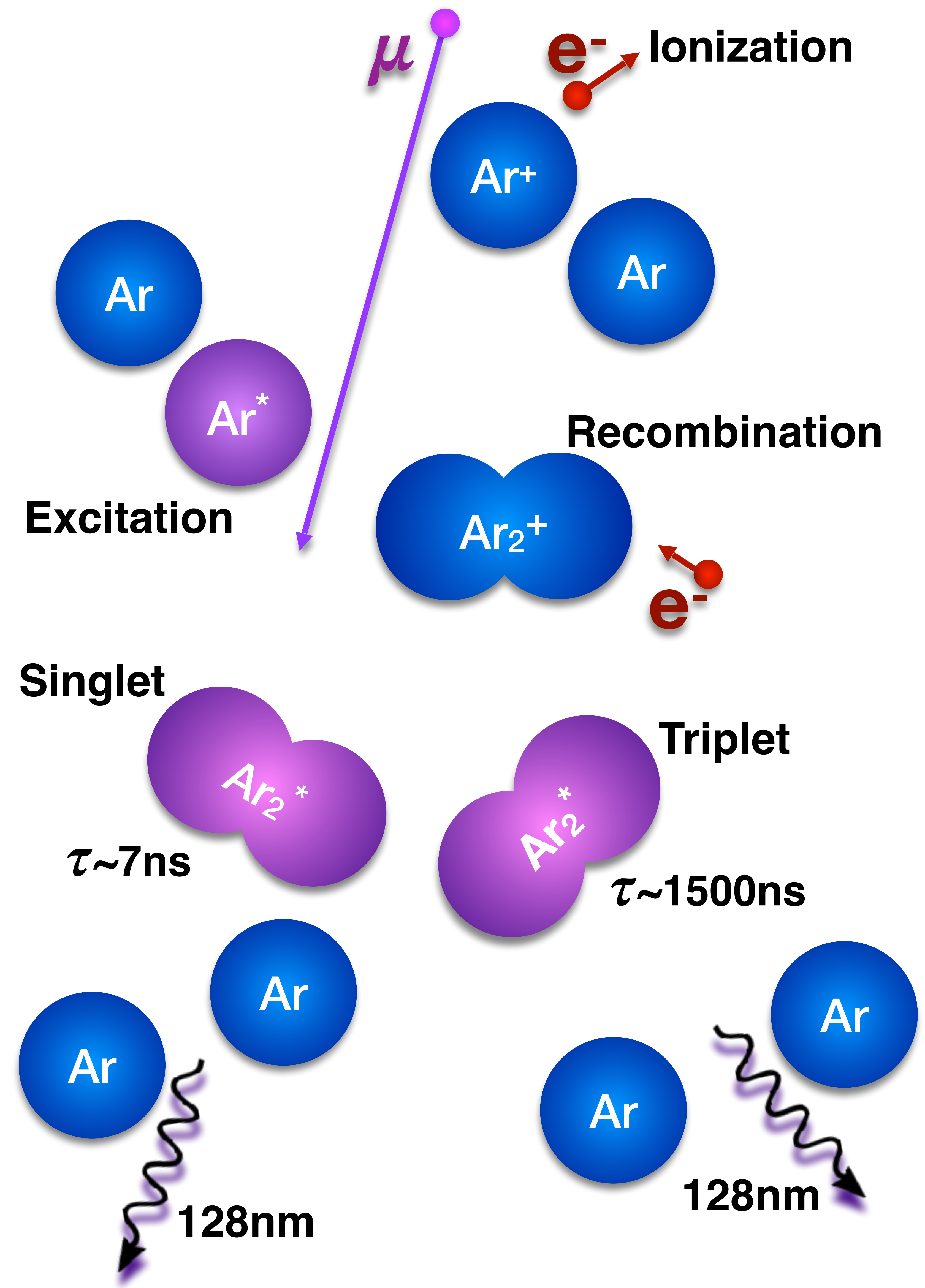


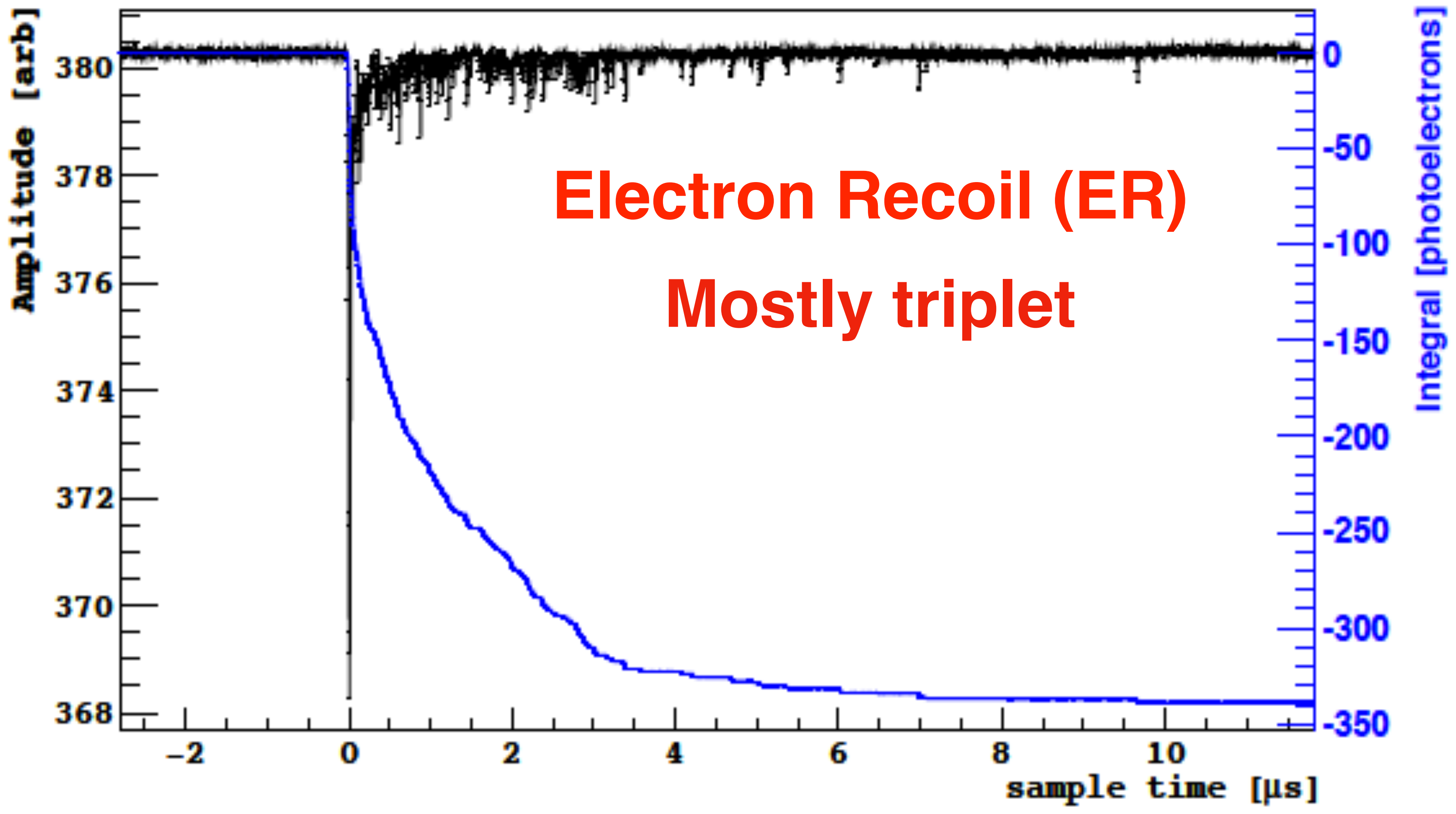


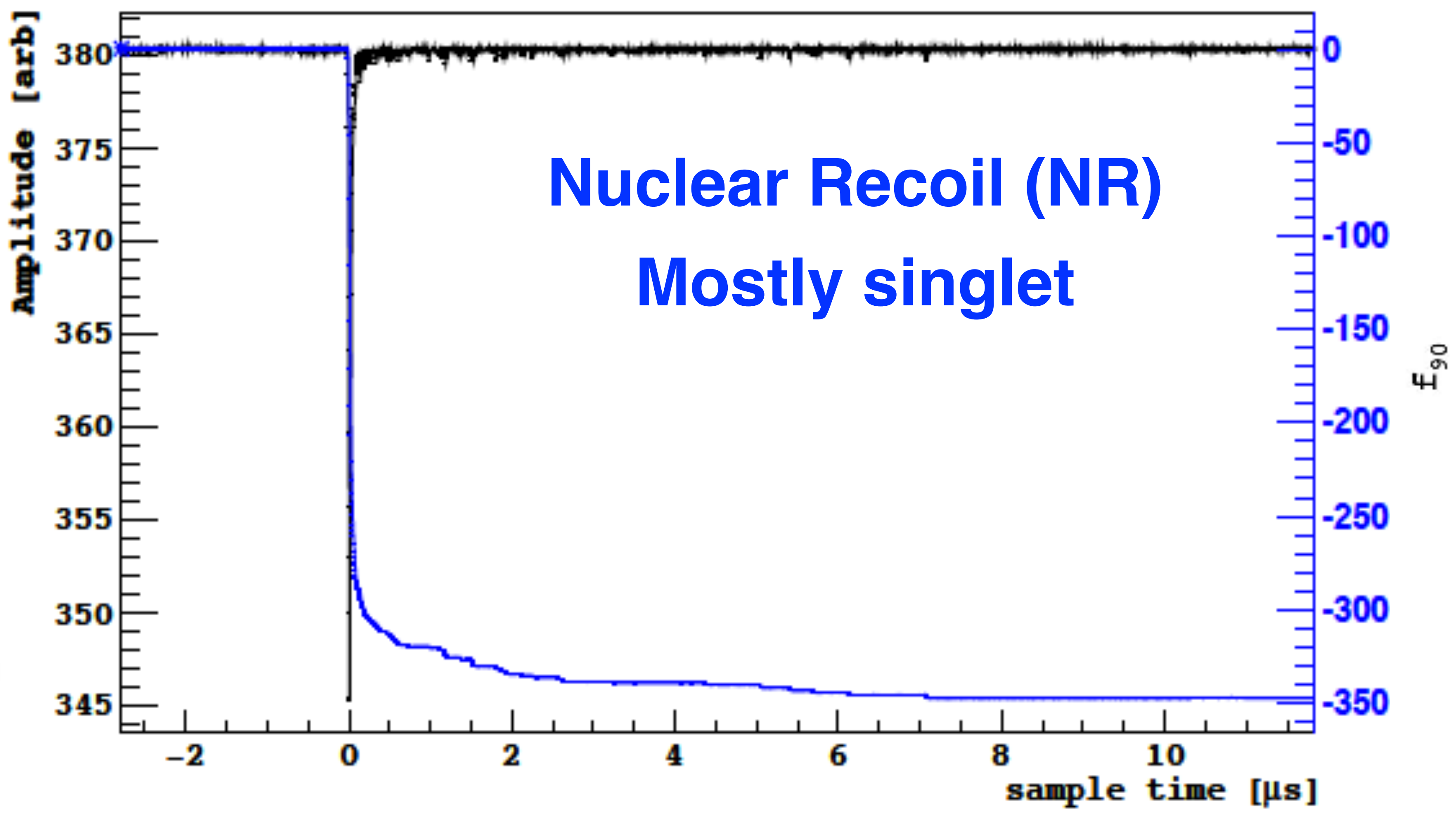
- ^{39}Ar is a cosmogenic isotope
- β-decay with 565 keV endpoint and ~269y of half life
- ~1Bq/kg in atmospheric Ar
- Rejection possible with PSD, but there's pile-up!

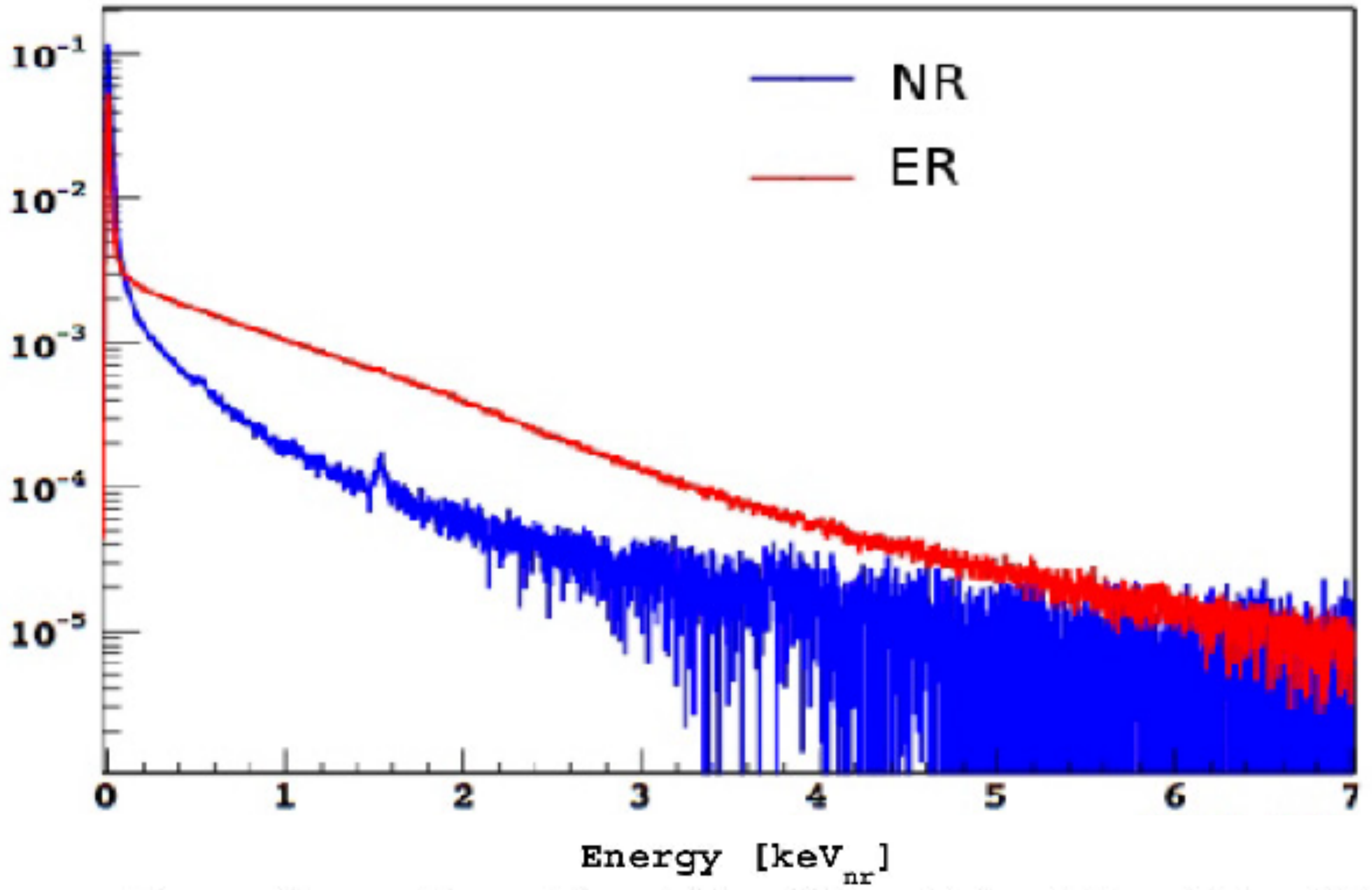
- No activation in Ar from deep gas reservoirs (UAr)
- Suppression factor ~1400 demonstrated in DS-50
- Possibly higher depletion factor

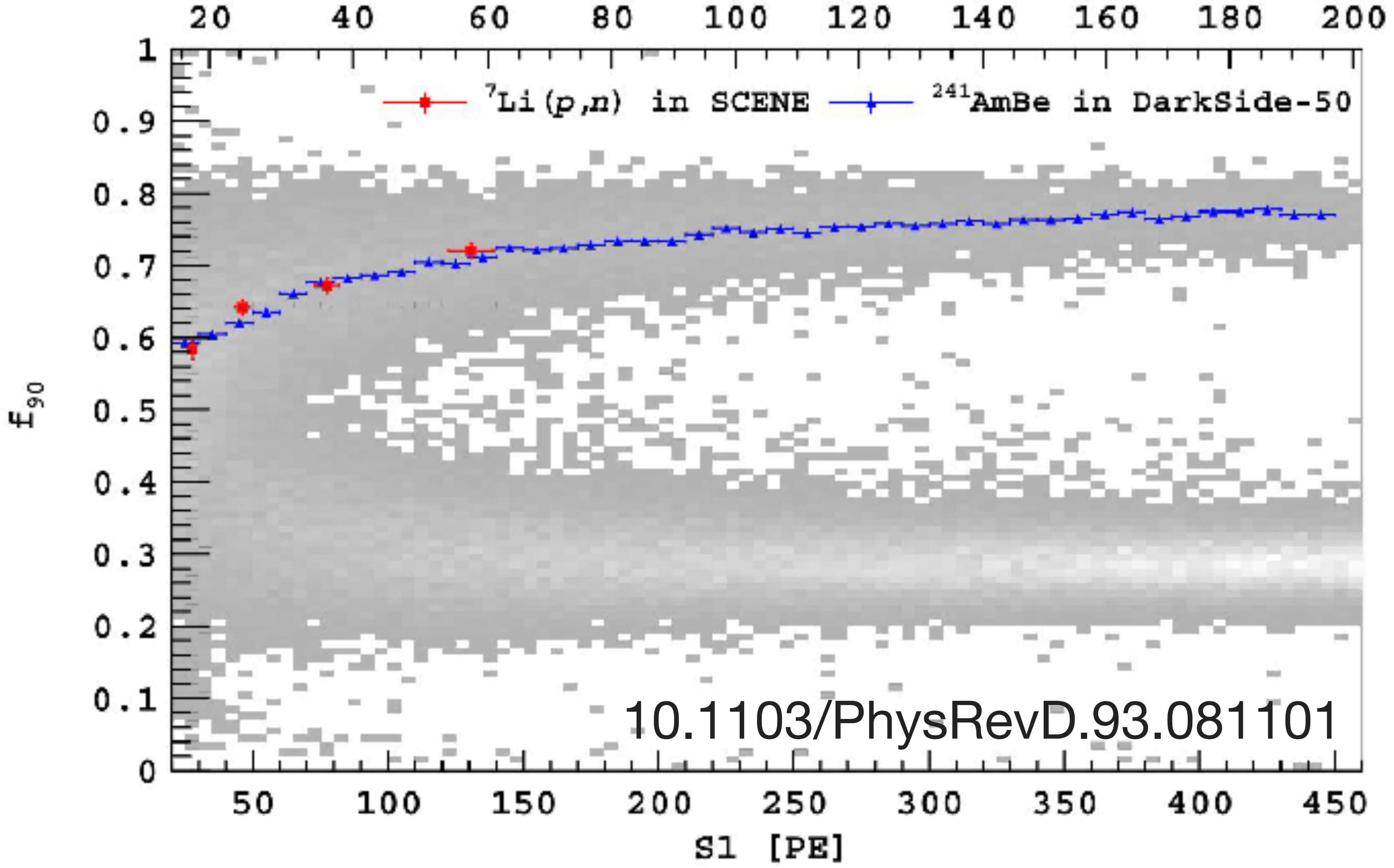
ER rejection in LAr











10.1103/PhysRevD.93.081101

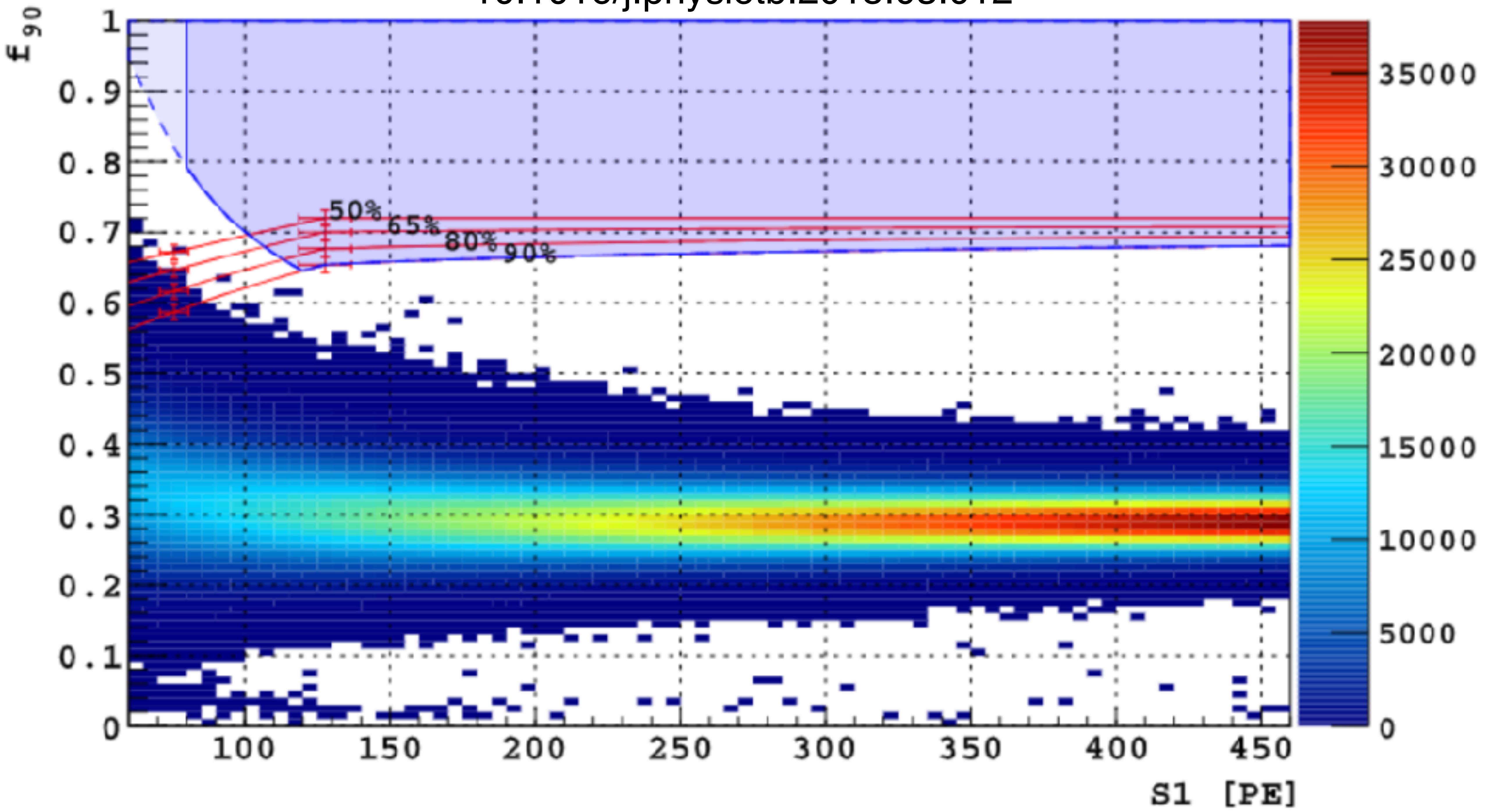
β,γ → ER $\quad\nu$, n, WIMPs → NR

$$f_{prompt} = \frac{\text{prompt light}}{\text{total light}}$$

ER rejection in LAr

DarkSide-50

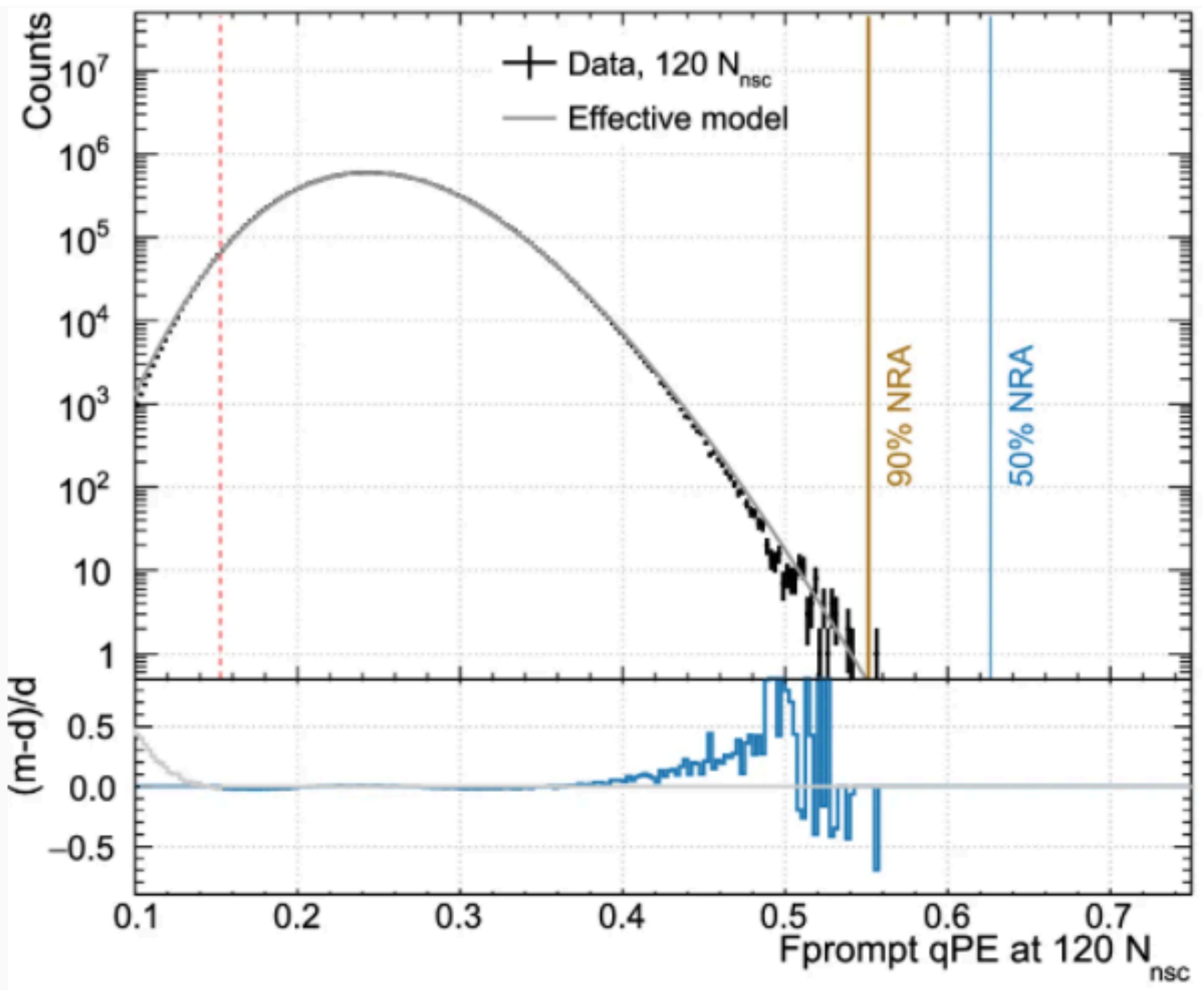
10.1016/j.physletb.2015.03.012



β,γ rejection better than 1.5x10^7

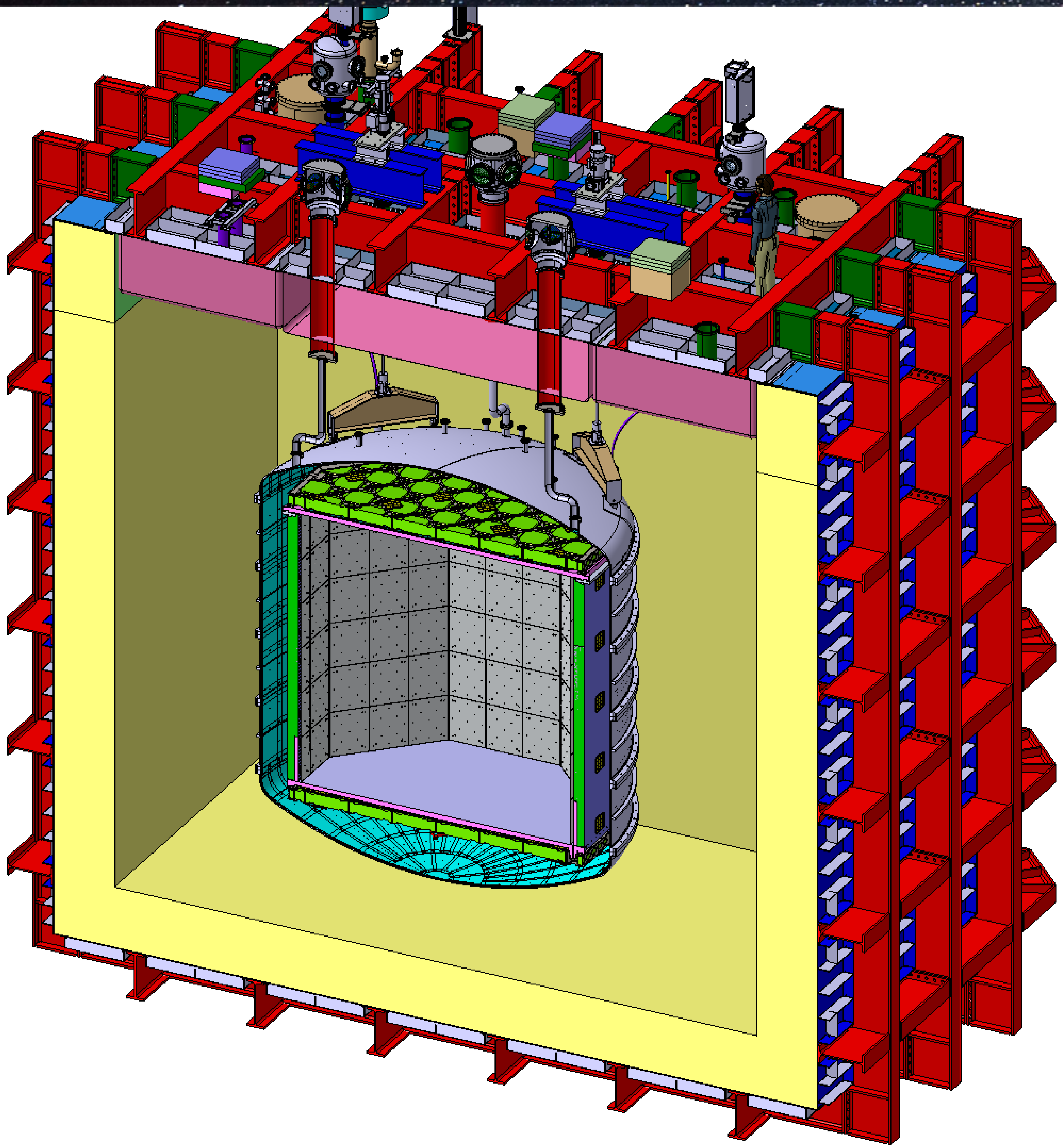
DEAP-3600

Eur. Phys. J. C 81,823 (2021)



β,γ rejection better than 10^8

DarkSide-20k overview



Nested detectors structure:

- ProtoDUNE-like cryostat (8x8x8m^3) - Muon veto
- Ti vessel separating AAr from underground UAr.
- Neutrons and γ veto
- WIMP detector: dual-phase TPC hosting 50t of LAr
- Fiducial mass: 20 tonnes

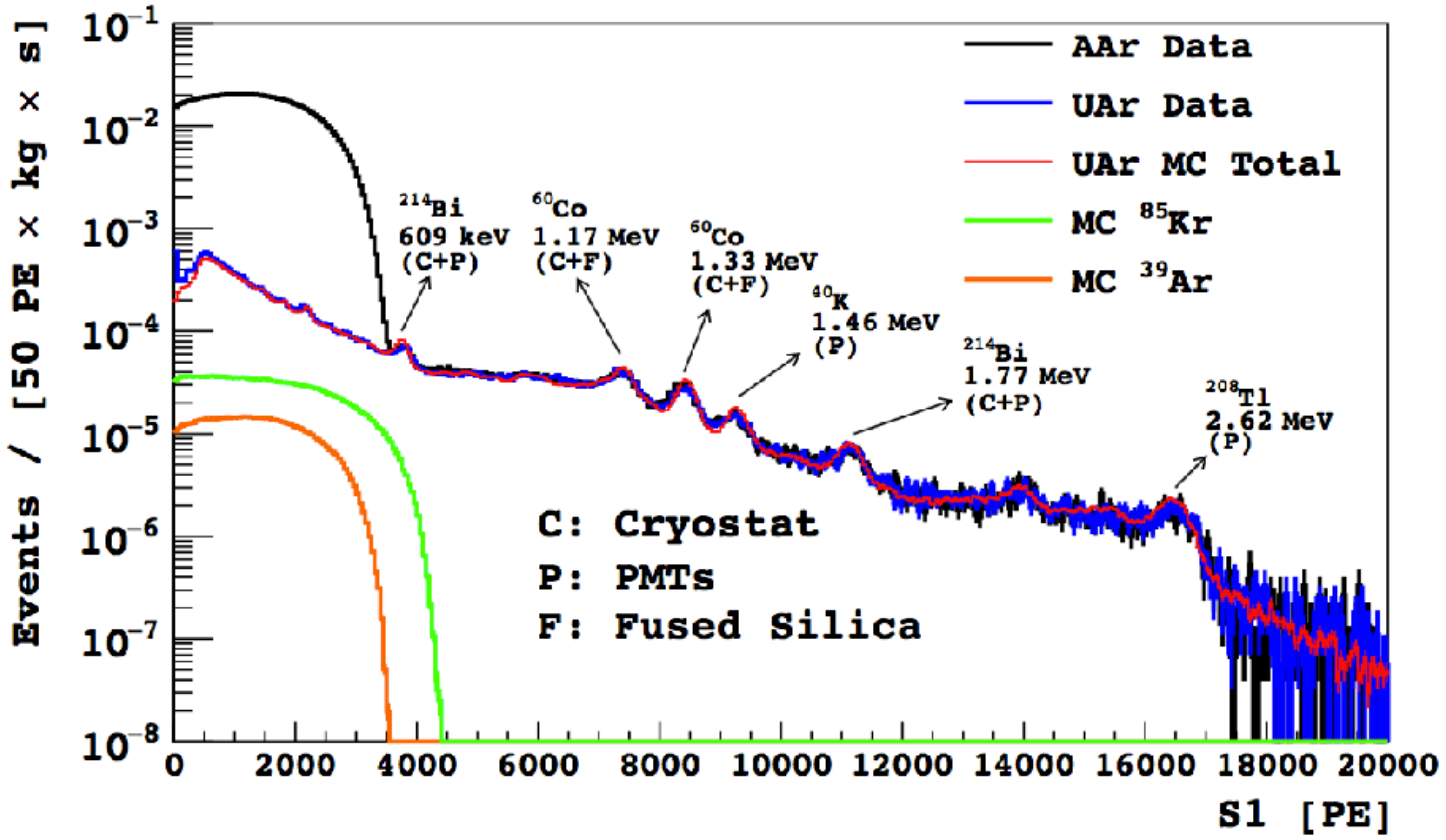
Multiple detection channels for bkg supression:

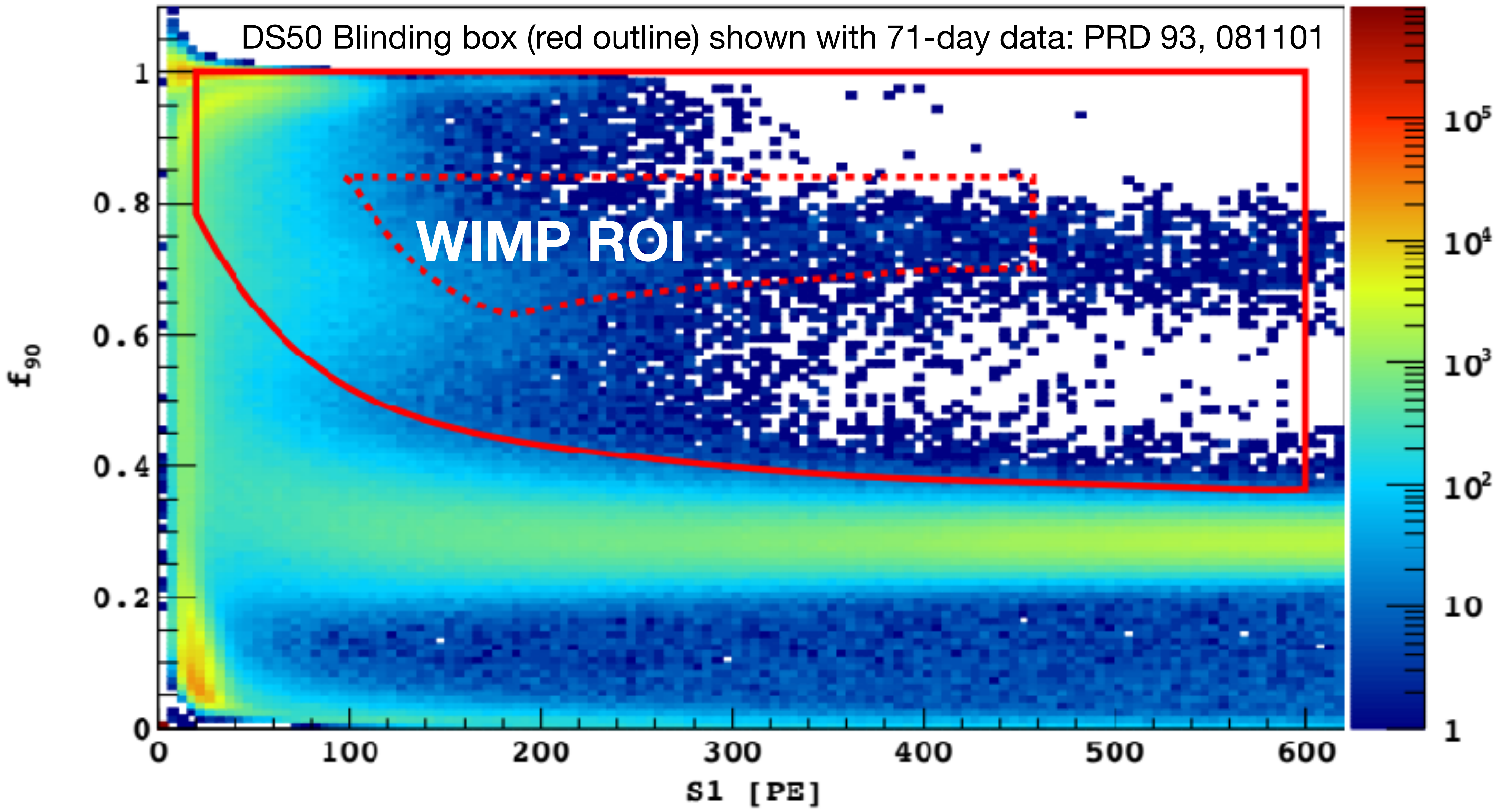
- Neutron after cuts: < 0.1 in 10 y
- β and γ after cuts: < 0.1 in 10 y
- CEνNS: 3.2 in 10 y

Position reconstruction resolution:

- ~ 1 cm in XY
- ~ 1 mm in Z

Backgrounds and Mitigation Strategies




DS50 Blinding box (red outline) shown with 71-day data: PRD 93, 081101

Electron Recoils (ER)

^{39}Ar β decays → Use of UAr, PSD

γ decays from U,Th chains + non actinides (^{40}K, ^{60}Co, ^{137}Cs) → Material selection, PSD

Surface events Position reconstruction

Radon progeny → Surface cleaning

Rn abatement

Nuclear Recoils (NR)

Radiogenic neutrons, mainly from (α,n) reactions.

→ Material selection, Neutron Veto

Cosmogenic neutrons, from materials activation due to residual muon flux → Muon Veto

Atmospheric neutrinos → Irreducible

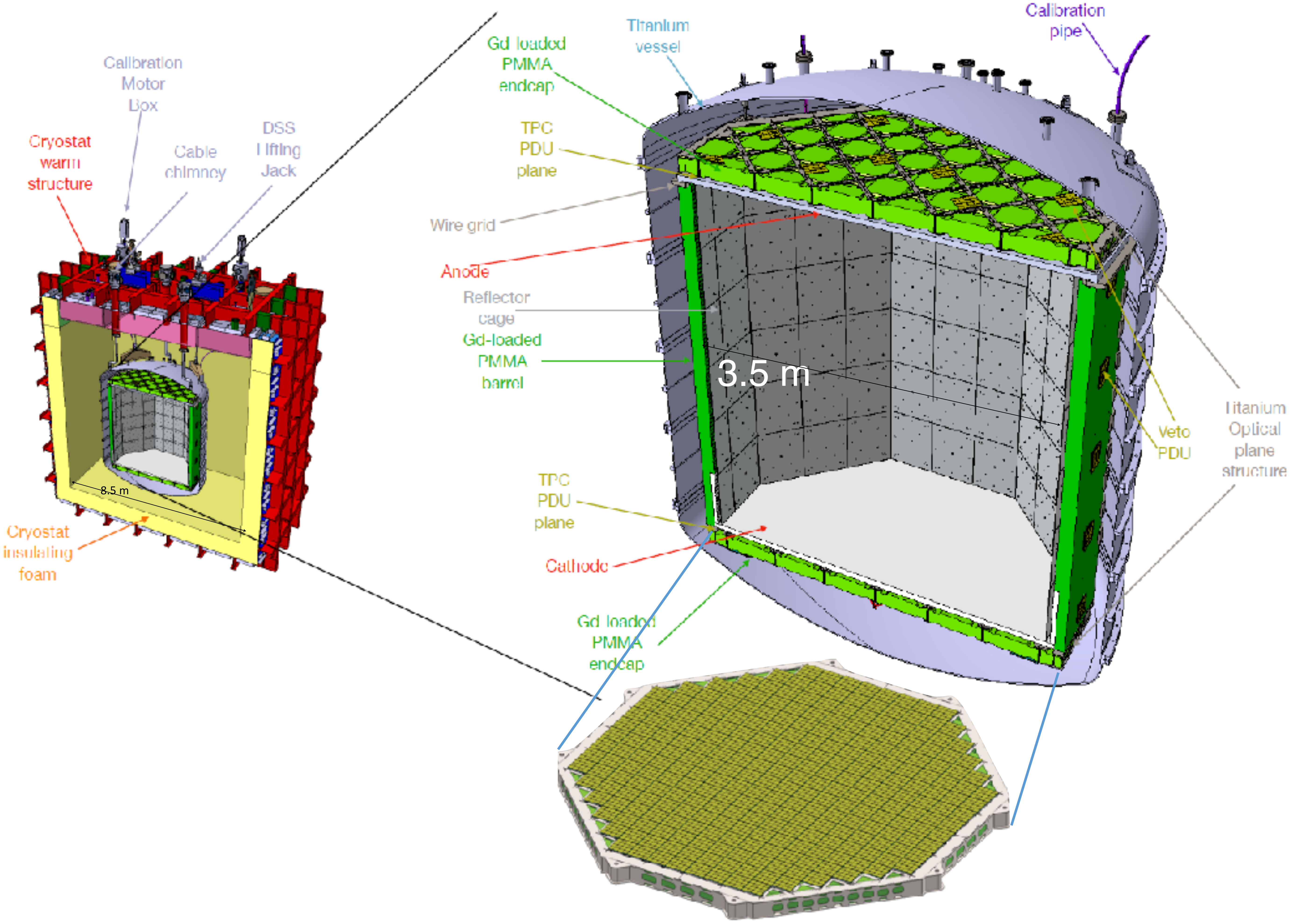
Inner detector

- Integration of **TPC** and **VETO** in a single object

- **TPC Vessel:**
  - top and bottom: transparent pure acrylic
  - lateral walls: Gd-loaded acrylic + reflector + WLS
  - anode, cathode and field cage made with conductive paint (Clevios)
- **TPC readout:** 21m^2 cryogenic SiPMs

- **Veto:**
- TPC surrounded by a single phase (S1 only) detector in UAr
- TPC lateral walls + additional top&bottom planes in Gd loaded acrylic (PMMA)
  - ○ to thermalize n (acrylic is rich in Hydrogen)
  - ○ neutron capture releases high energy γ
- **Veto readout:** 5 m^2 cryogenic SiPMs

99 t UAr held in Ti vessel



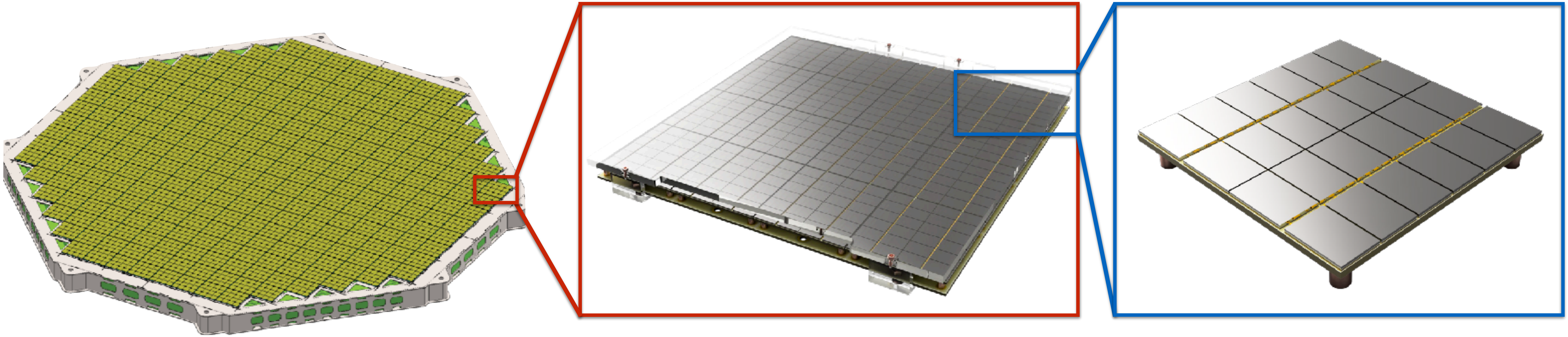
TPC photo-detection system

Photo-detection system

TPC optical plane

Photo-Detection Unit

Tile



TPC planes area: 21m^2

2100 readout channels

Organized in 528 PDUs

100% coverage of TPC top and bottom

16 tiles arranged in 4 readout channels

SiPM bias distribution

cryogenic pre-amplifiers bias

Signal transmission

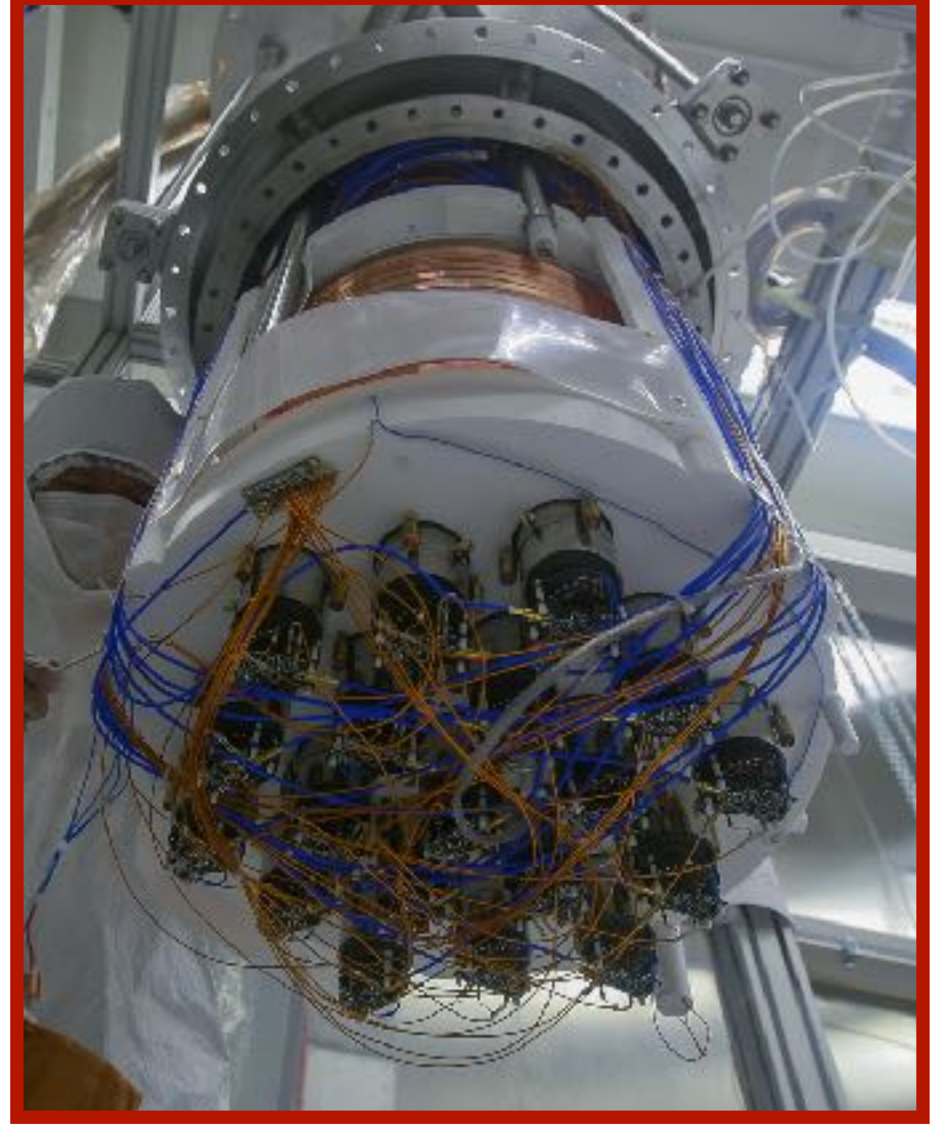
Channels switch-on/off

Photosensor

Array of 24 SiPMs

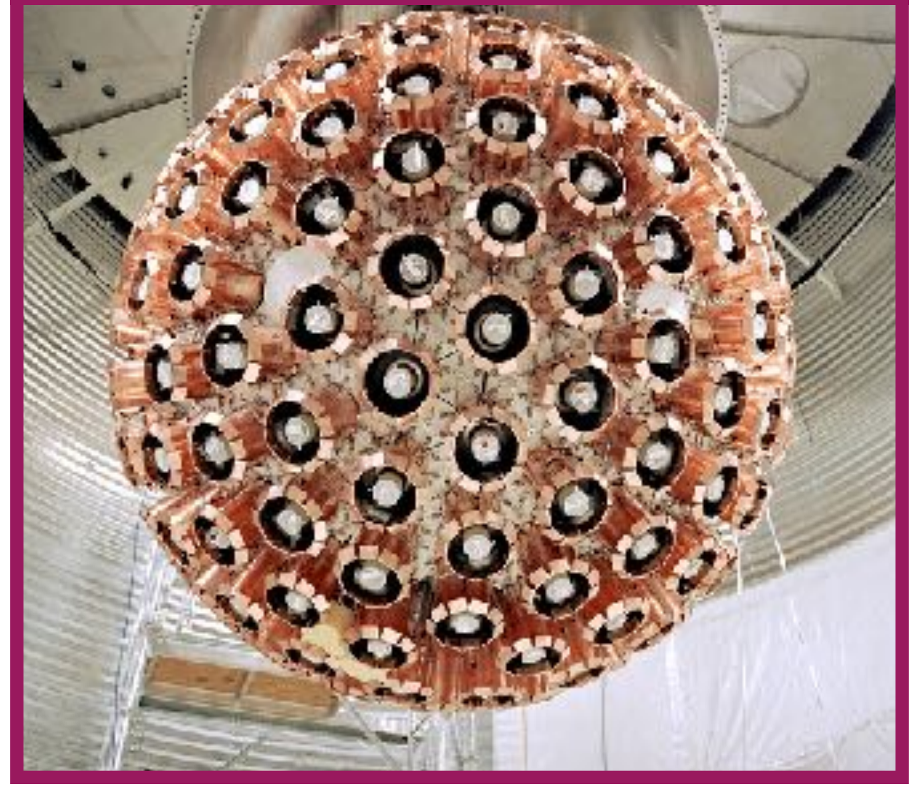
Signal pre-amplification

International Collaborations


DarkSide-50 @ LNGS


ArDM @ Canfranc


MiniClean @ Snolab

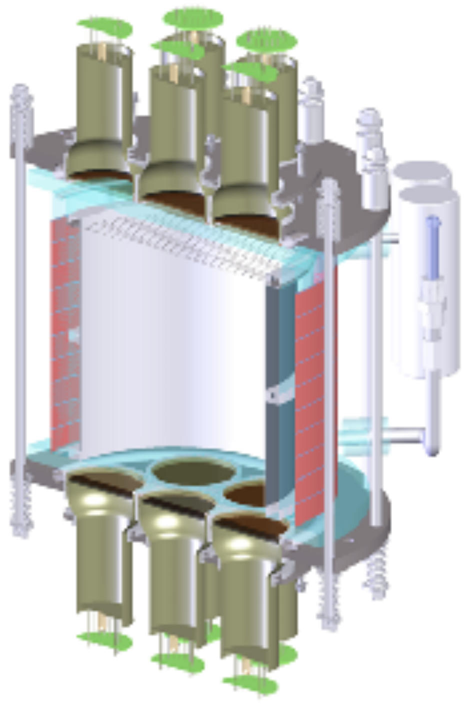

DEAP @ Snolab

>400 scientists, >100 institutions distributed across 13 countries

ASTROCENT
Budker Institute of Nuclear Physics
BROOKHAVEN NATIONAL LABORATORY
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
CPPM
ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich
FONDAZIONE BRUNO KESSLER
Fermilab
GSSI
Instituto de Física
INFN
IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY
NATIONAL RESEARCH CENTER "KURCHATOV INSTITUTE"
LPNHE PARIS
Politechnika Łódzka
POLITECNICO MILANO 1863
Novosibirsk State University *THE REAL SCIENCE
Pacific Northwest NATIONAL LABORATORY
SAPIENZA UNIVERSITÀ DI ROMA
ROMA TRE UNIVERSITÀ DEGLI STUDI
SNOLAB MINING FOR KNOWLEDGE CREUSER POUR TROUVER... L'EXCELLENCE
US UNIVERSITY OF SUSSEX
TIFPA Trento Institute for Fundamental Physics and Applications
TRIUMF
TUM
THE UNIVERSITY OF CHICAGO
UMASS
UNIVERSITÉ DE SHERBROOKE
WARWICK THE UNIVERSITY OF WARWICK
araid FUNDACIÓN AGENCIA ARAGONESA PARA LA INVESTIGACIÓN Y EL DESARROLLO

Multi-decade experimental programmes

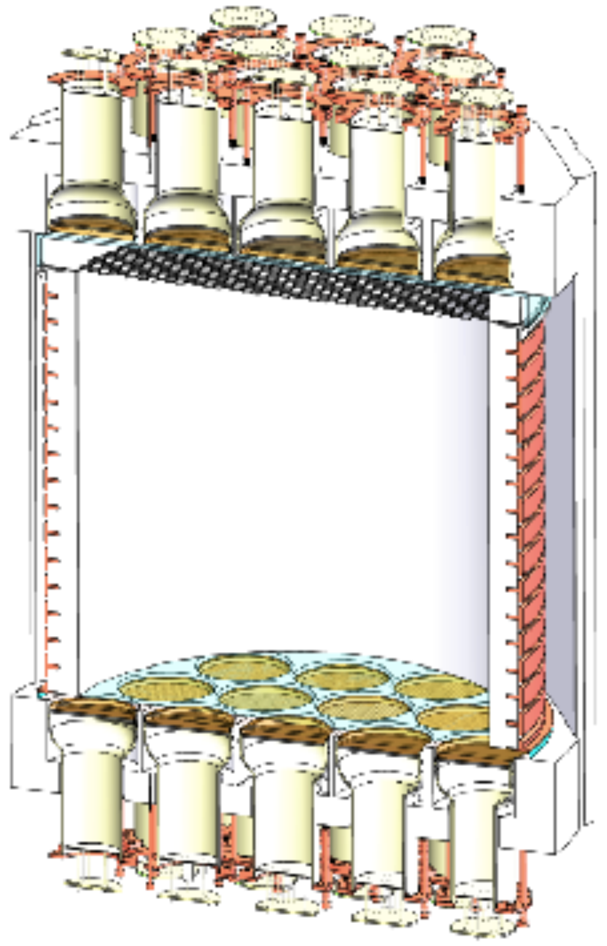
2012



DarkSide-10

- First prototype
- Helped to refine TPC design
- Demonstrated a light yield >9PE/keV$_{ee}$

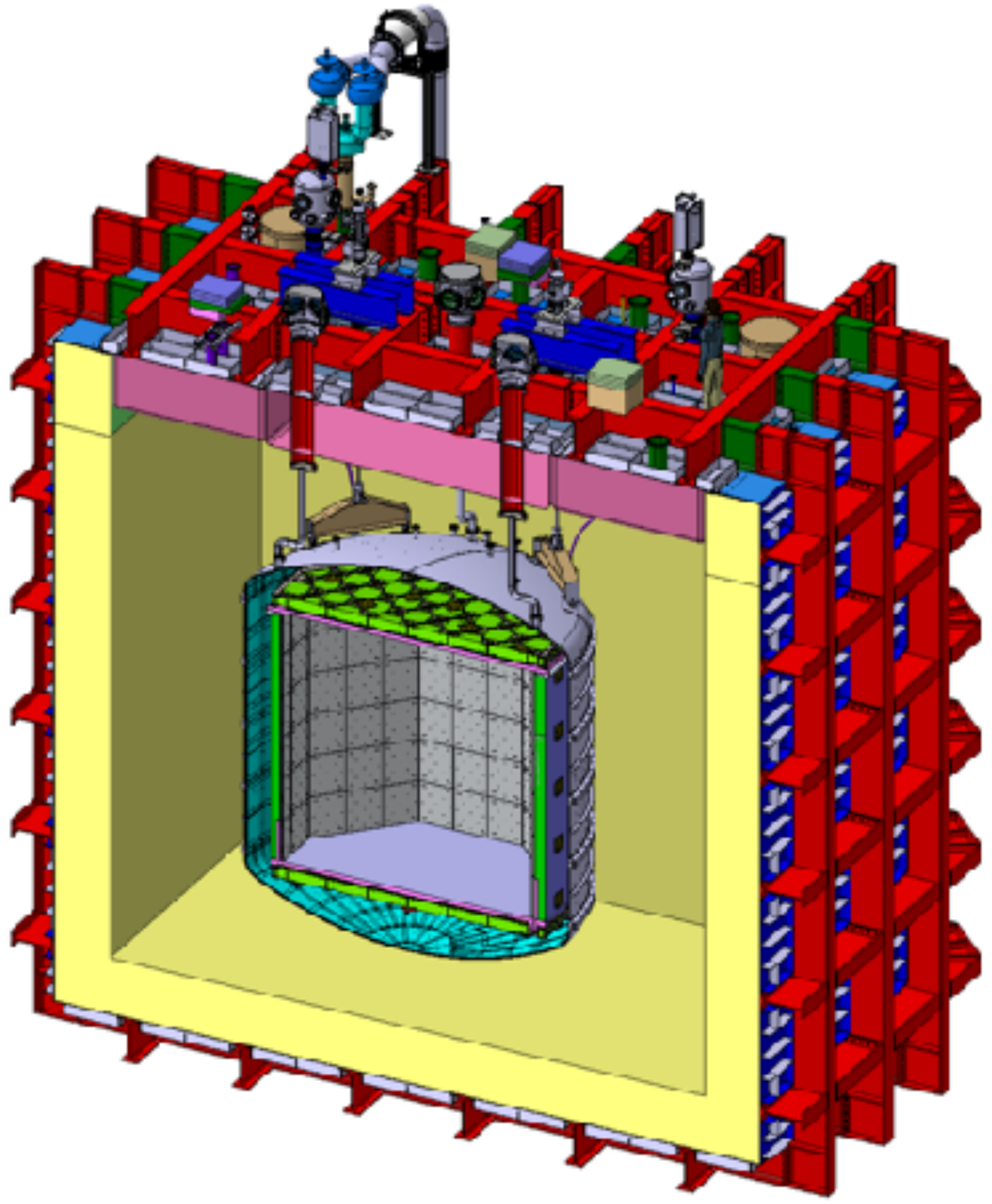
2013 - 2018



DarkSide-50

- Science detector
- Demonstrated the use of UAr
- First background-free results
- Best limits for low mass WIMP searches

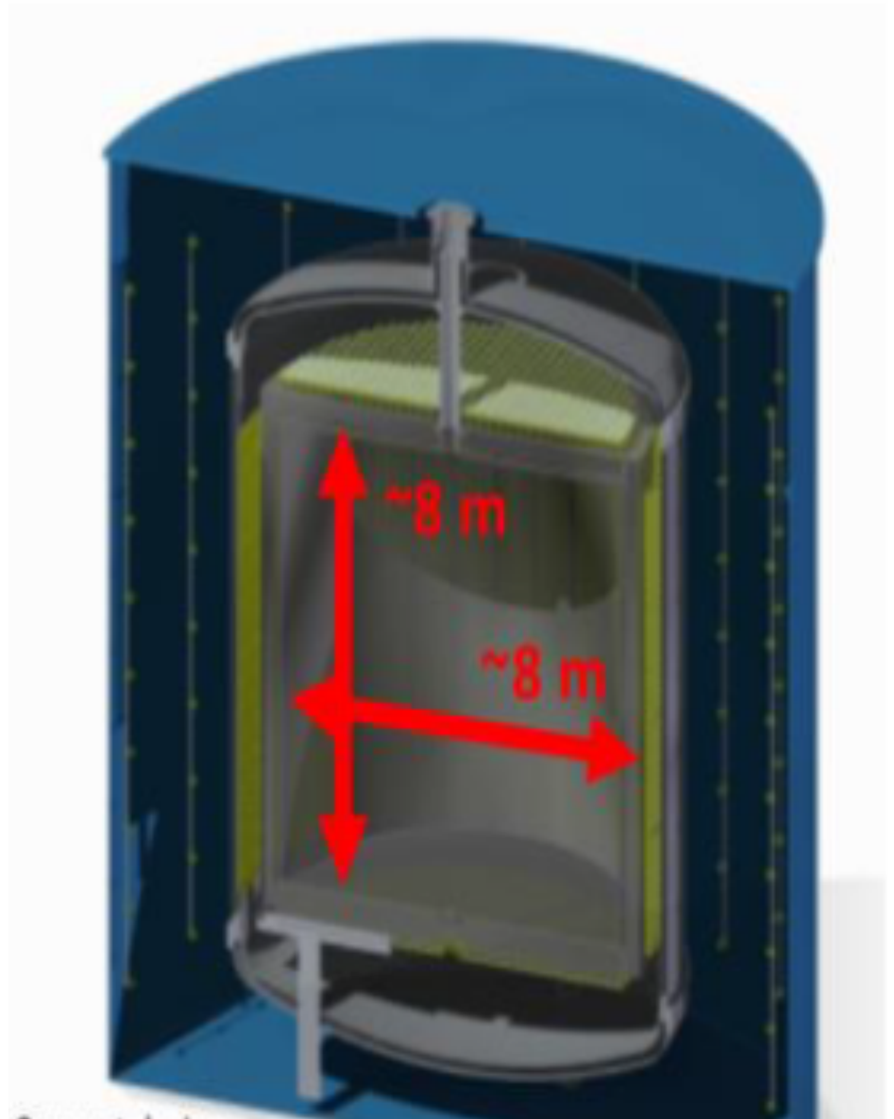
2025 - 2035



DarkSide-20k @ LNGS

- Novel technologies
- First peek into the neutrino fog
- Nominal exposure: 200 t y

2030s - ...



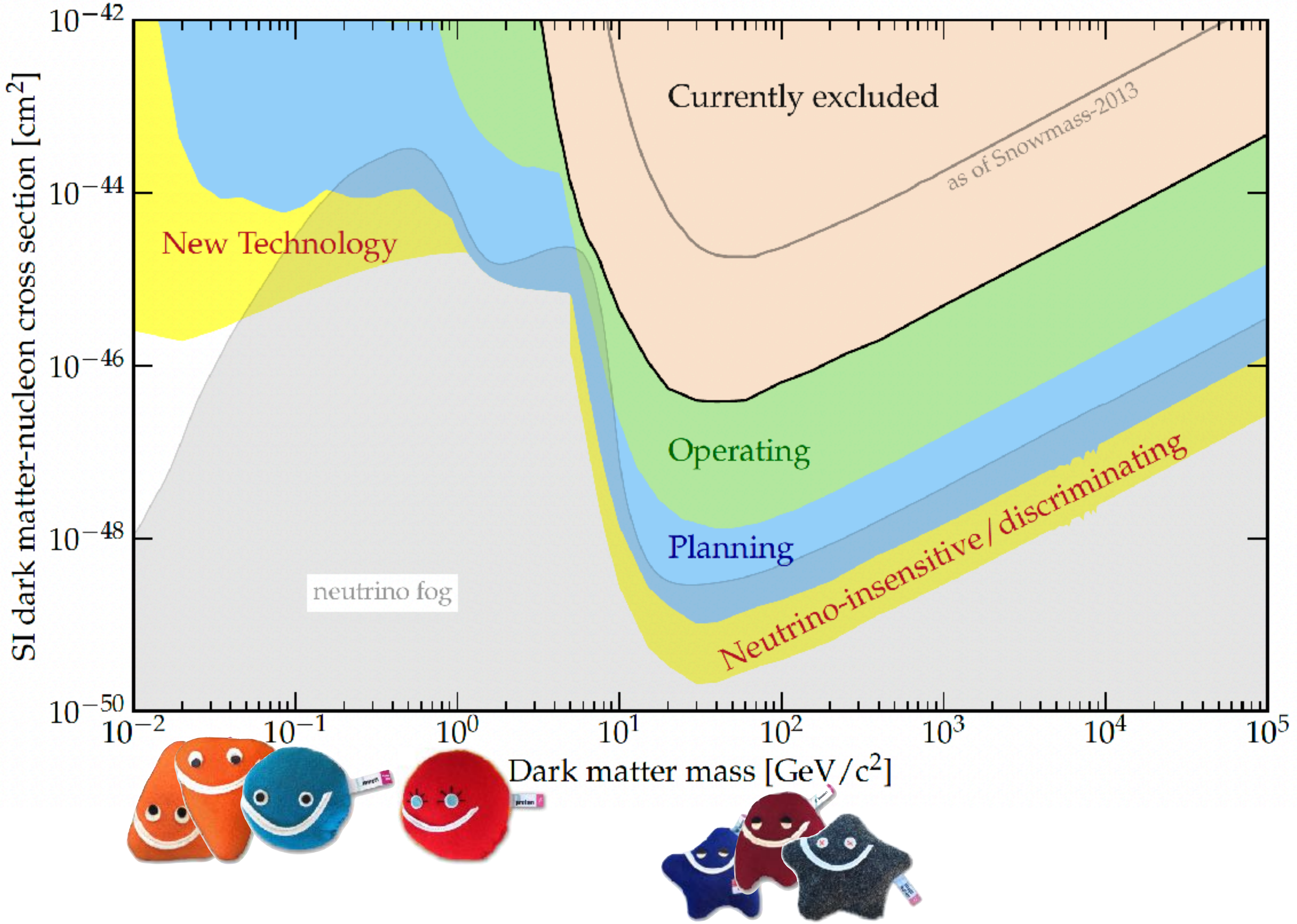
Concept design
from Mark Boulay

Argo @ SNOLAB

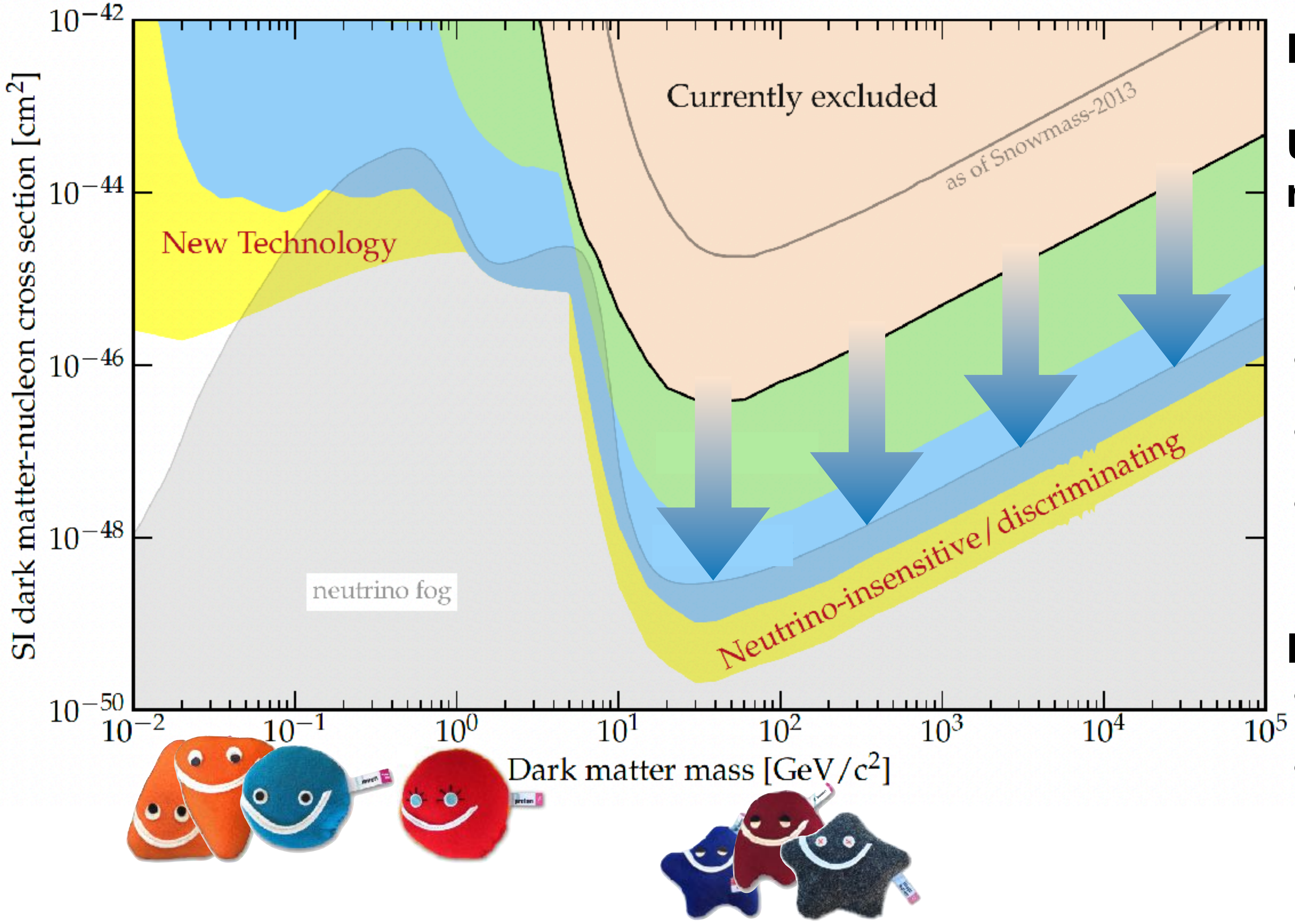
- Ultimate LAr DM detector
- Push well into the neutrino fog
- Nominal exposure: 3000 t y

Low Mass Frontier

SnowMass 2021 report



SnowMass 2021 report



DEEP FRONTIER

Under construction or running

- XENON-nT
- LZ
- PandaX-4T
- DarkSide-20k

Planned

- XLZD
- Argo

SnowMass 2021 report

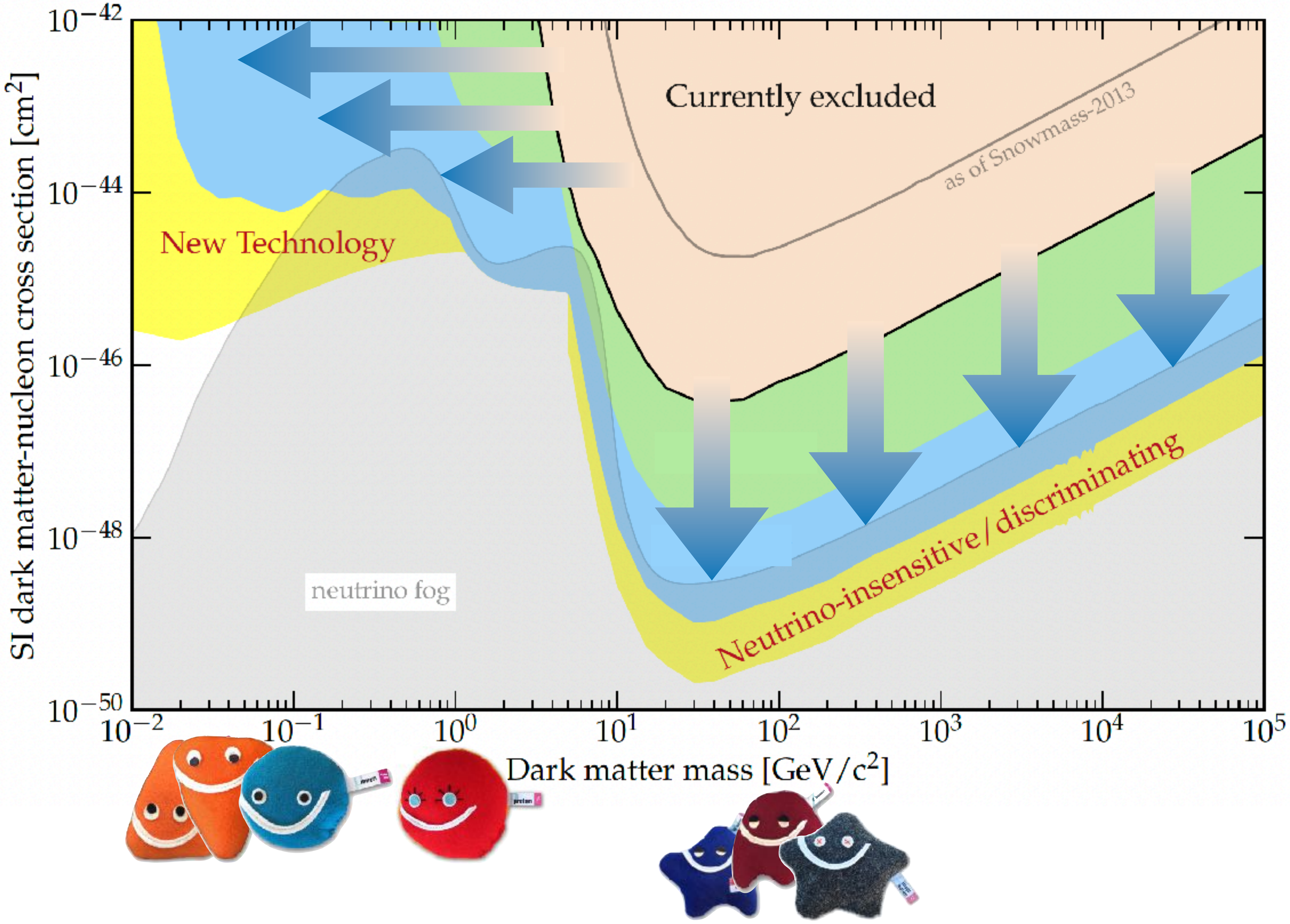
LIGHT FRONTIER

Proven targets and technologies

- Noble element TPC
- Charge+Phonon

R&D, Concepts

- Tesseract
- Scintillating Bubble Chambers
- Charge readouts
- Phonon readouts



DEEP FRONTIER

Noble element TPC

Under construction or running:

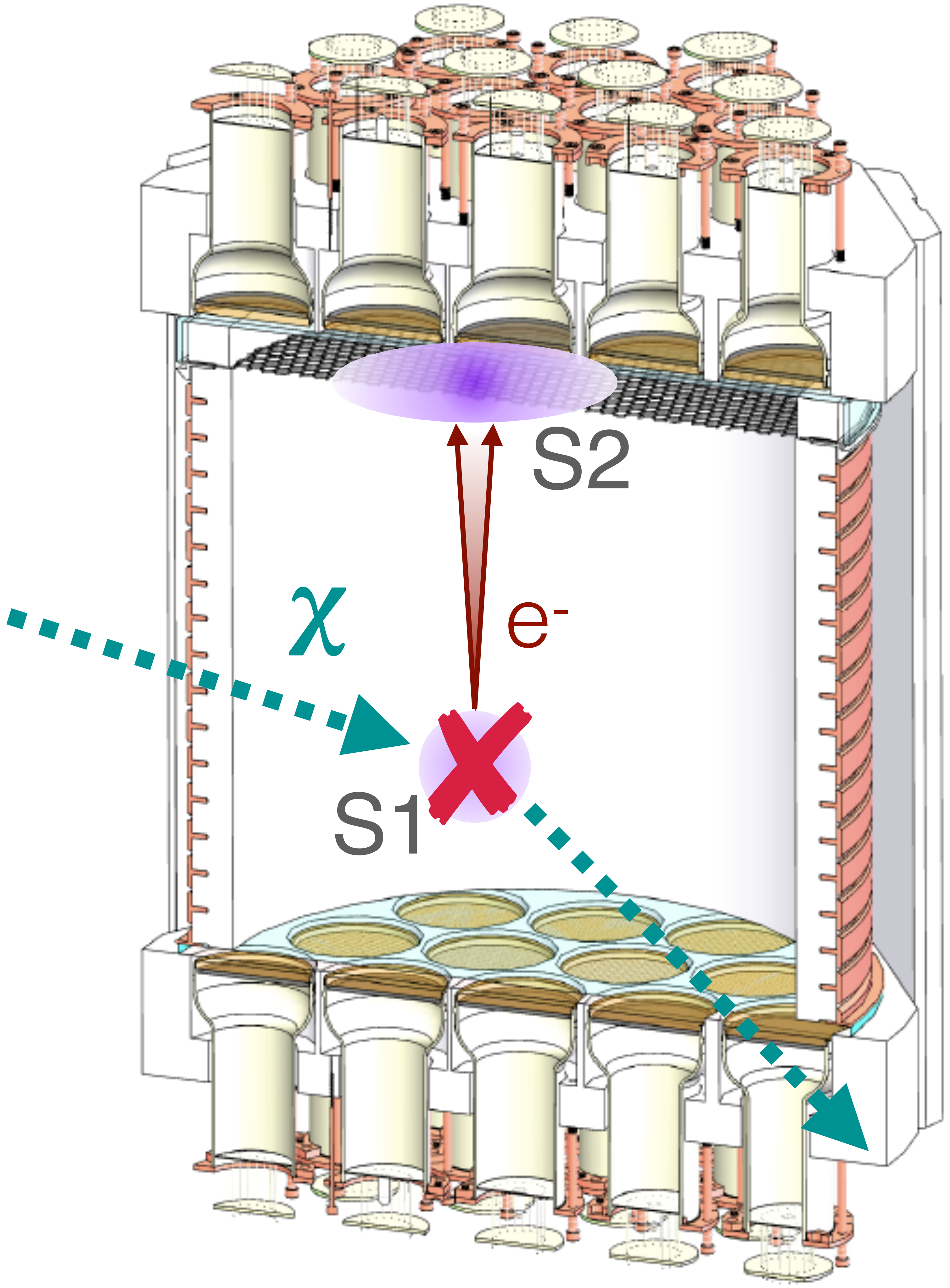
- XENON-nT
- LZ
- PandaX-4T
- DarkSide-20k

Planned:

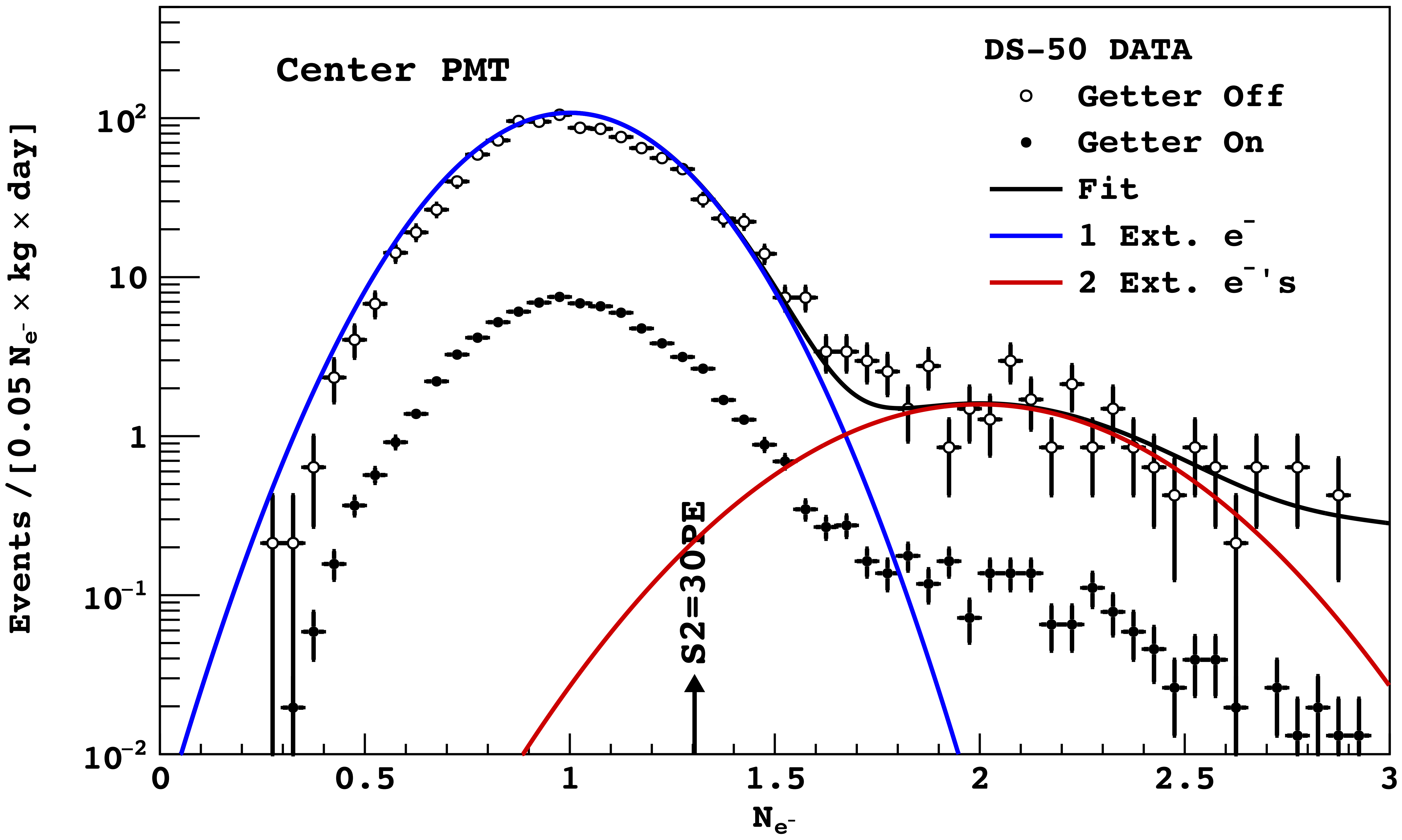
- XLZD
- Argo

Light Dark Matter with Noble Elements

Lower the threshold

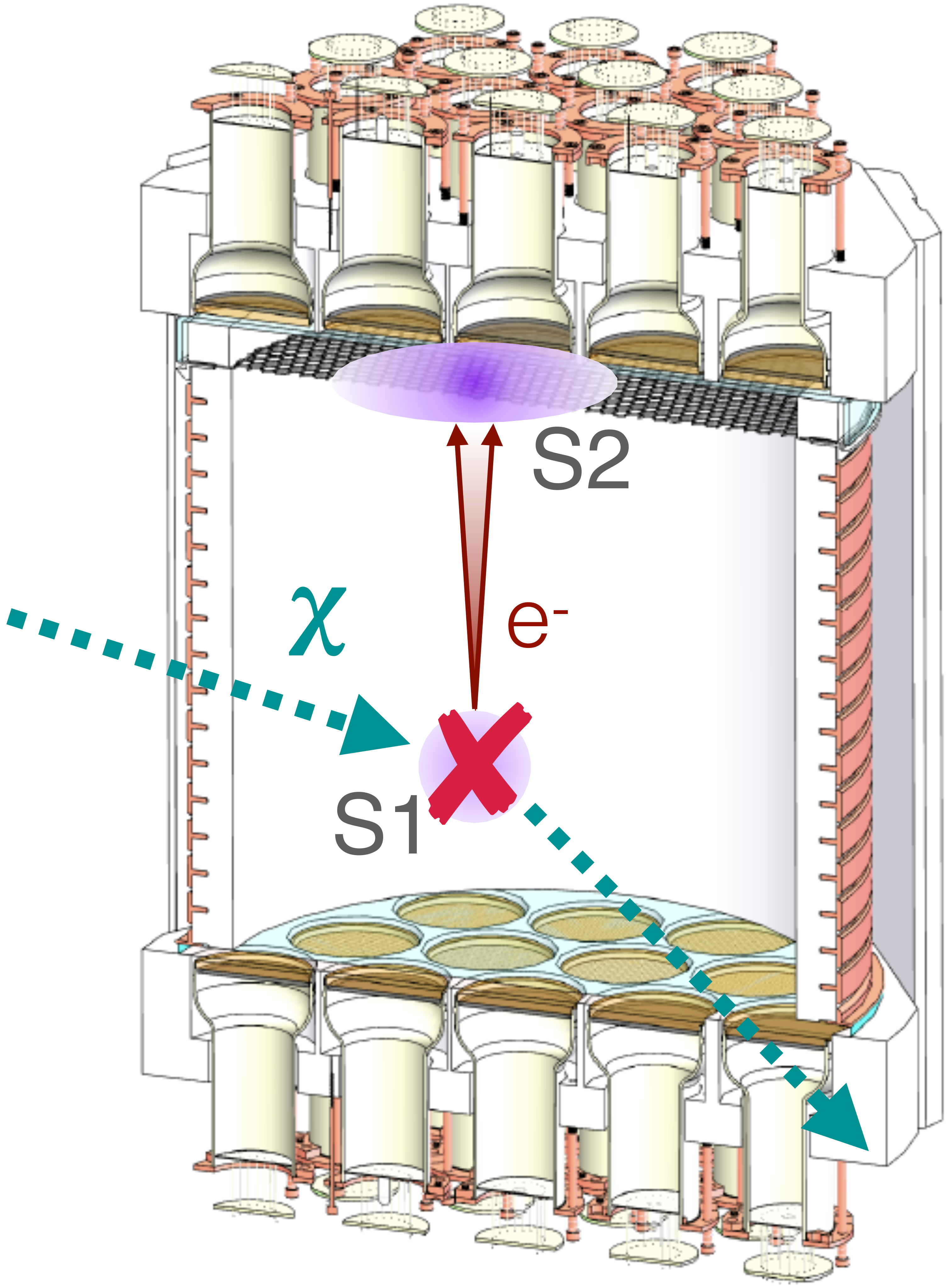


Lower the energy threshold ⇒ Look at the S2 only events

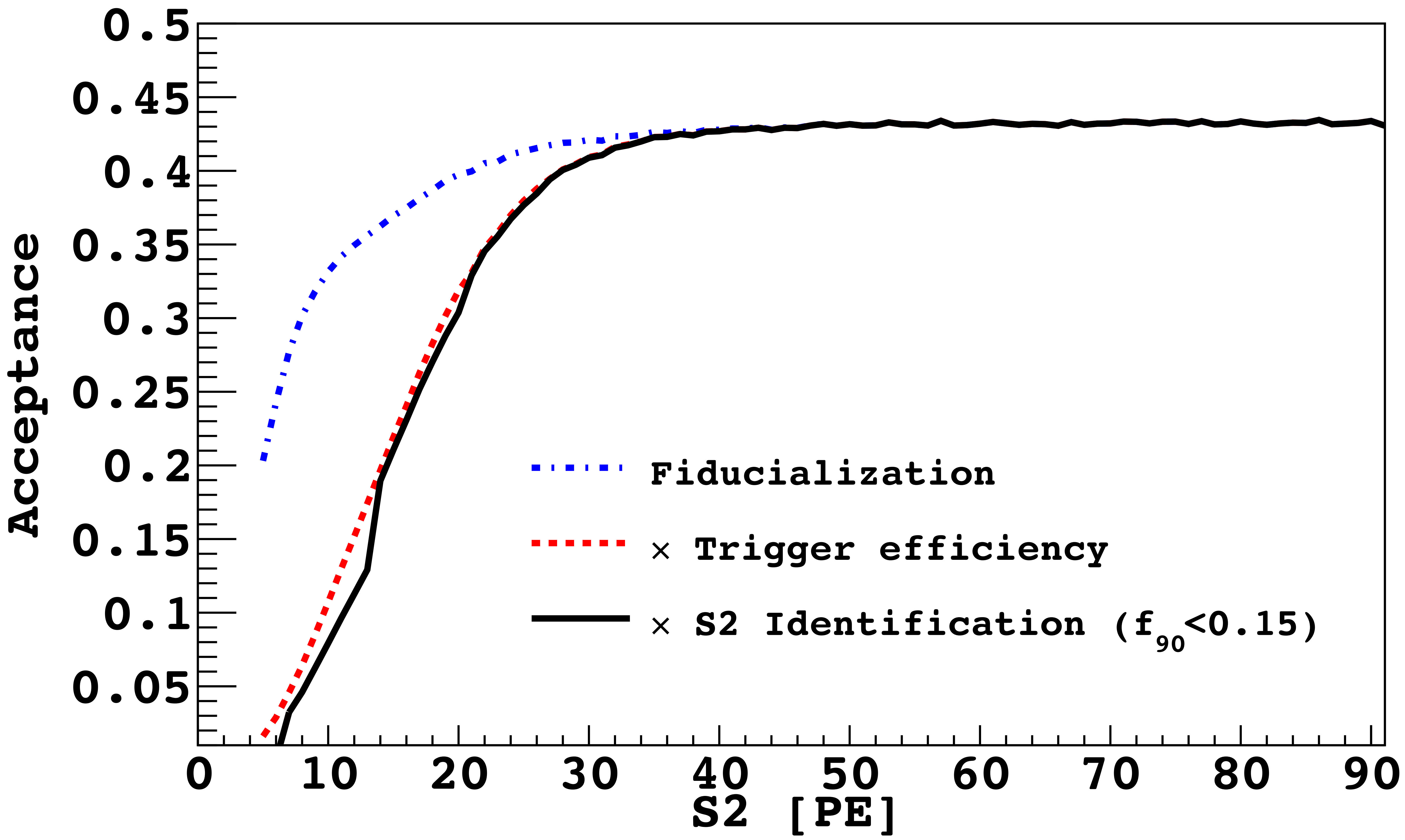


- S2 >> S1 (23ph/e- in DS50)
- 100% S2 identif. eff. > ~30PE
- 100% Trigger eff. > ~40PE
- Thresholds: <0.1keV$_{ee}$, 0.4keV$_{nr}$

Lower the threshold

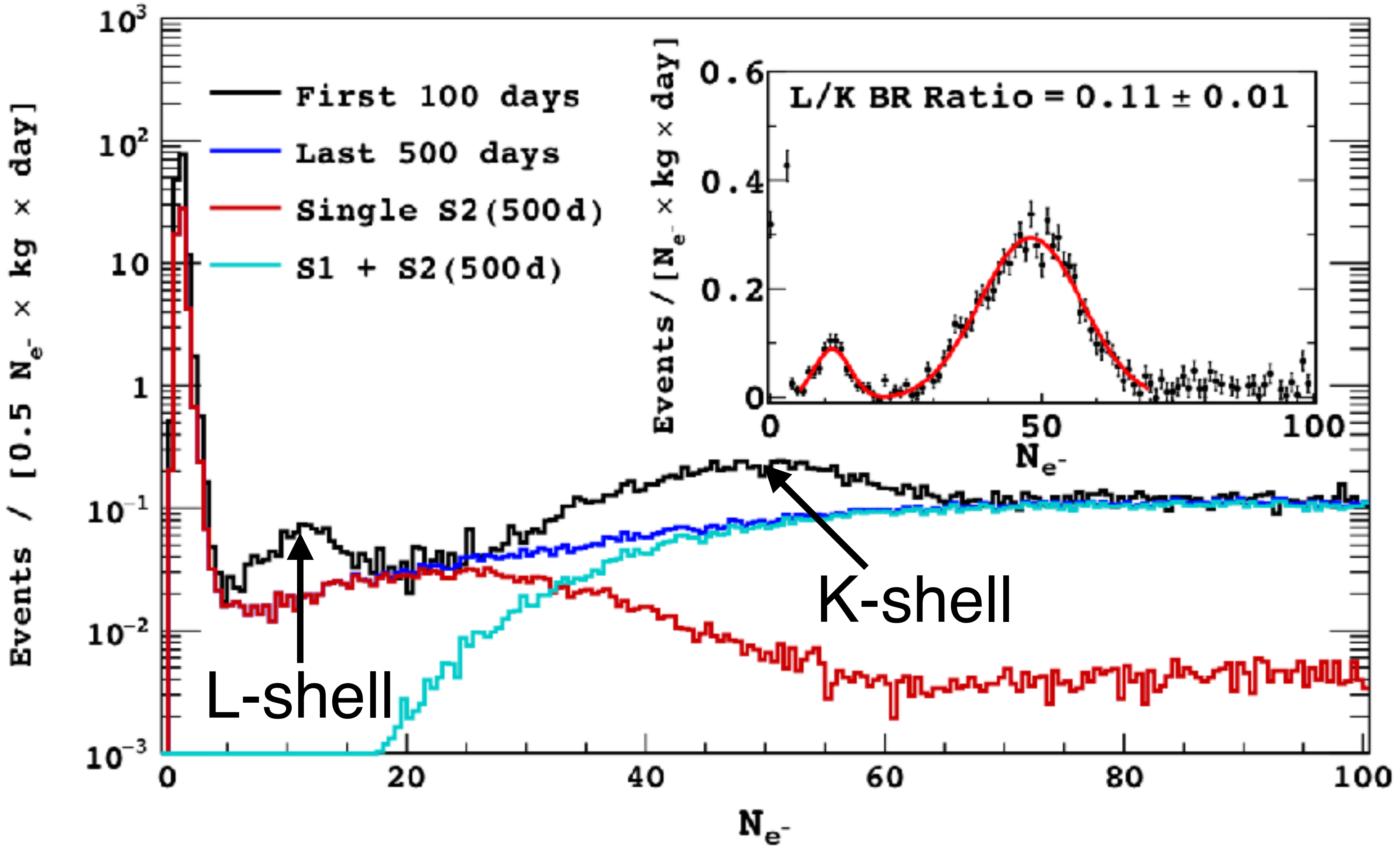


Lower the energy threshold ⇒ Look at the S2 only events



- S2 >> S1 (23ph/e^- in DS50)
- 100% S2 identif. eff. > ~30PE
- 100% Trigger eff. > ~40PE
- Thresholds: <0.1keV_{ee}, 0.4keV_{nr}

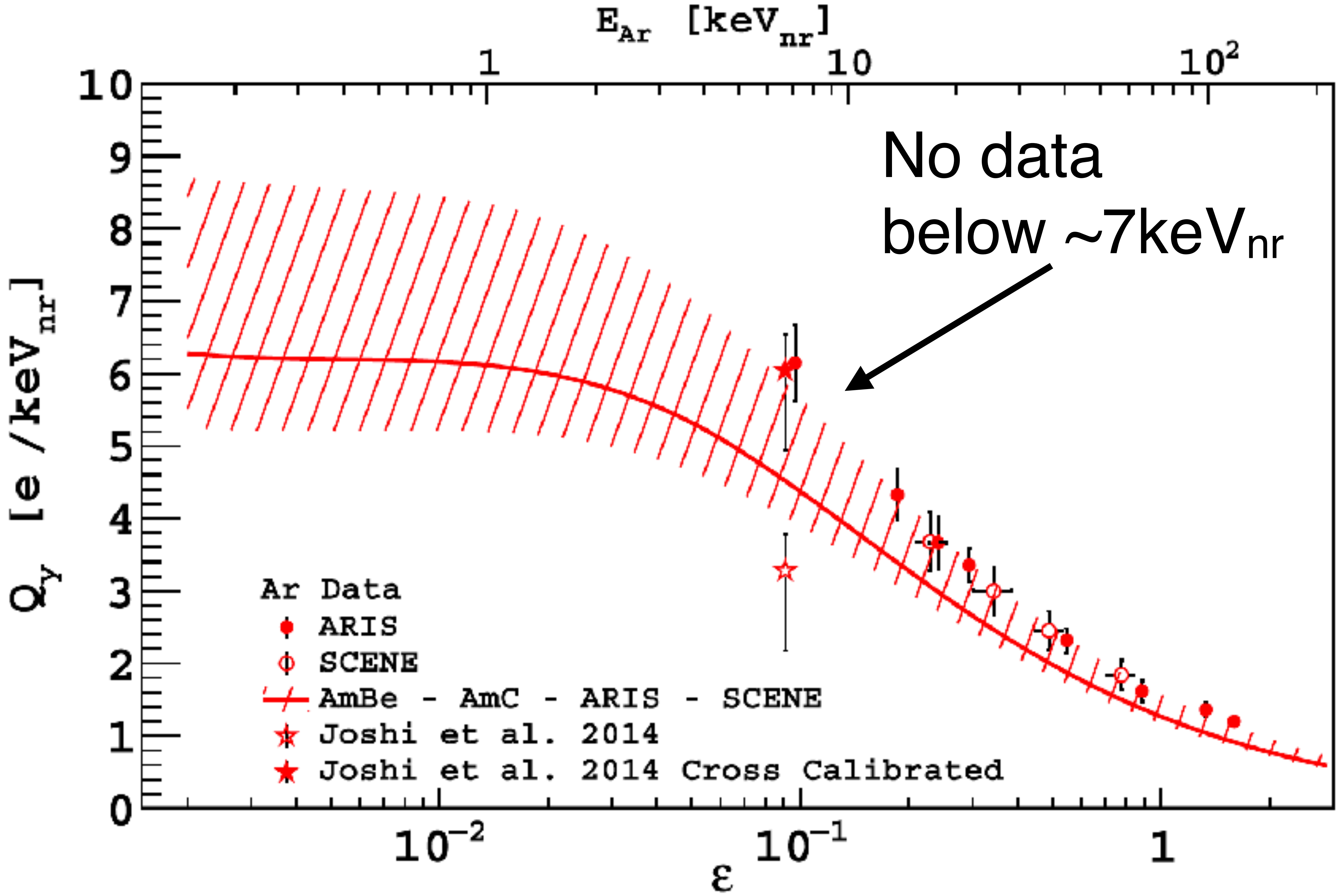
ER and NR energy scales



K-shell

L-shell

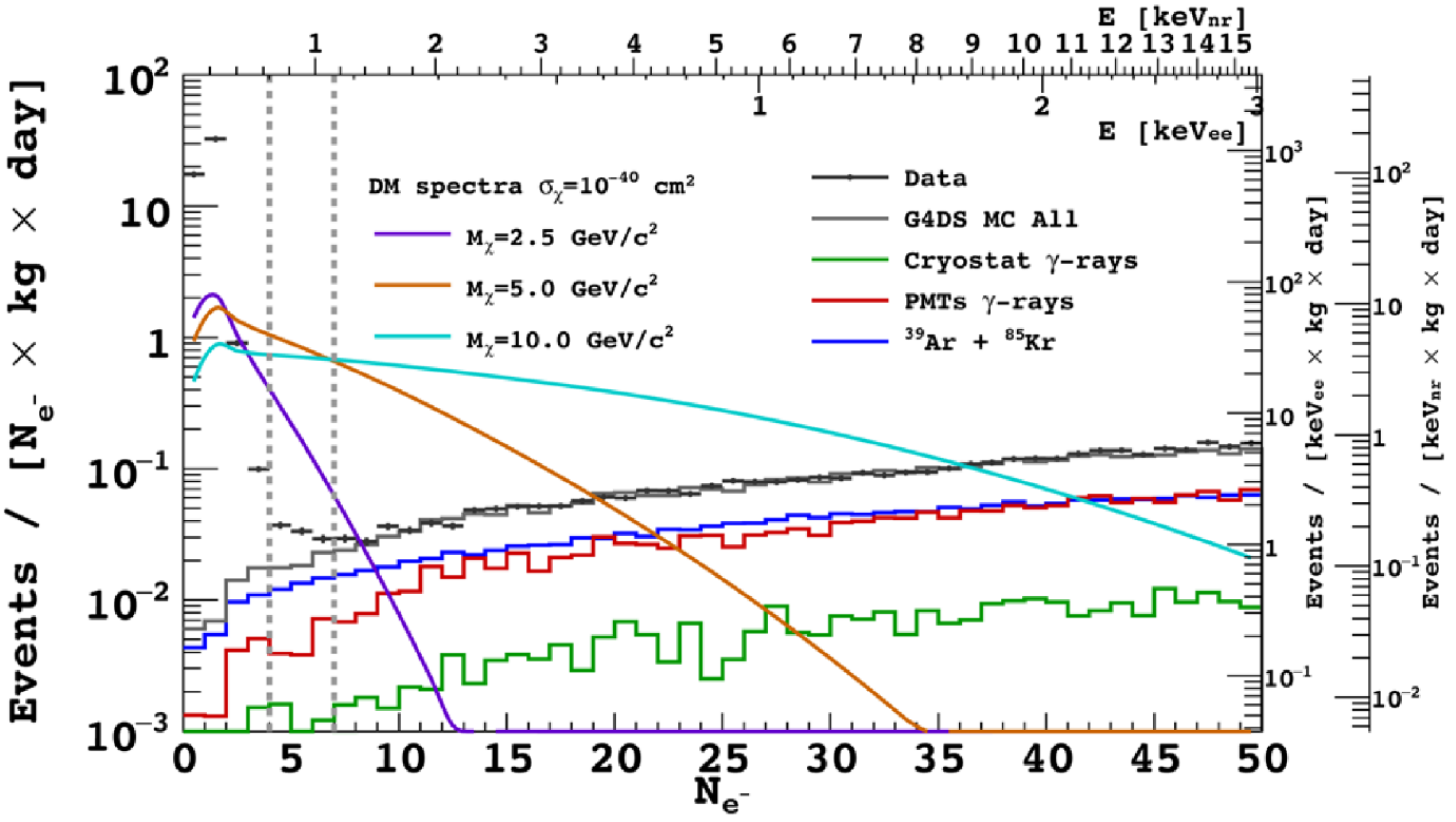
- First 100 days UAr dataset
- ER calibration from ^{37}Ar EC ($t_{1/2}$ = 35d)
- ^{37}Ar lines:
  E = 0.27 keV → Ne = 11
  E = 2.82 keV → Ne = 48



No data below ~7keV_{nr}

- MC template fit (red line) to DS50 AmBe and Am^{13}C neutron spectra data
- Uncertainty red band from deviations wrt external neutron calibrations (ARIS, SCENE)

Results from DS50 (2018)



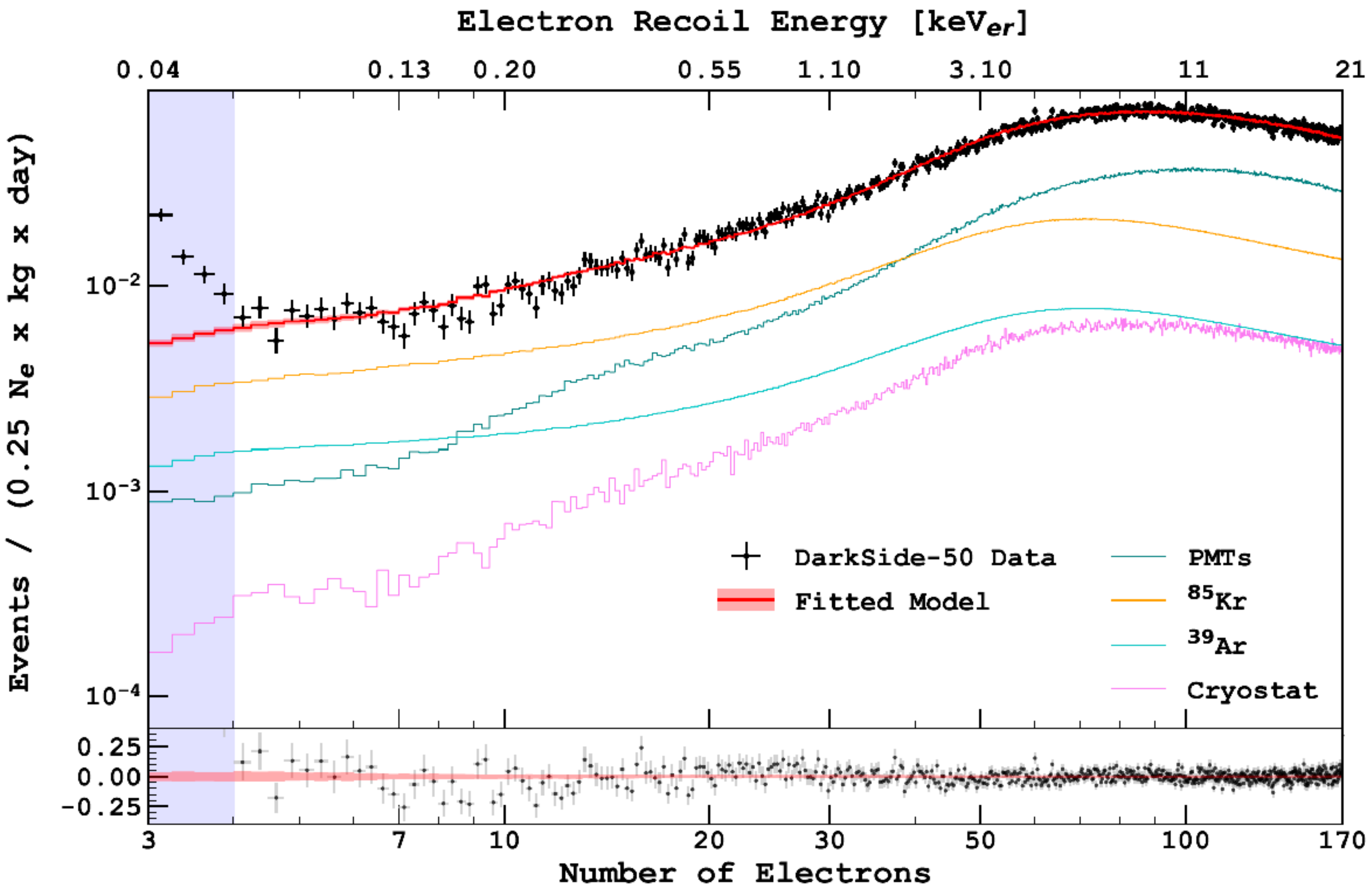
Expected BKGs

- ^{39}Ar + ^{85}Kr β spectra
- Compton continuum (PMTs + Cryostat)

Unexpected BKGs

- 1-4e$^-$ events

Results from DS50 (2022)



Re-analysis + extended dataset

- New event selection
- Extended ROI
- New ^{39}Ar and ^{85}Kr β-spectra
- High statistics MC for γ events from PMTs and Cryostat
- ER and NR internal calibration

A treasure trove of new limits

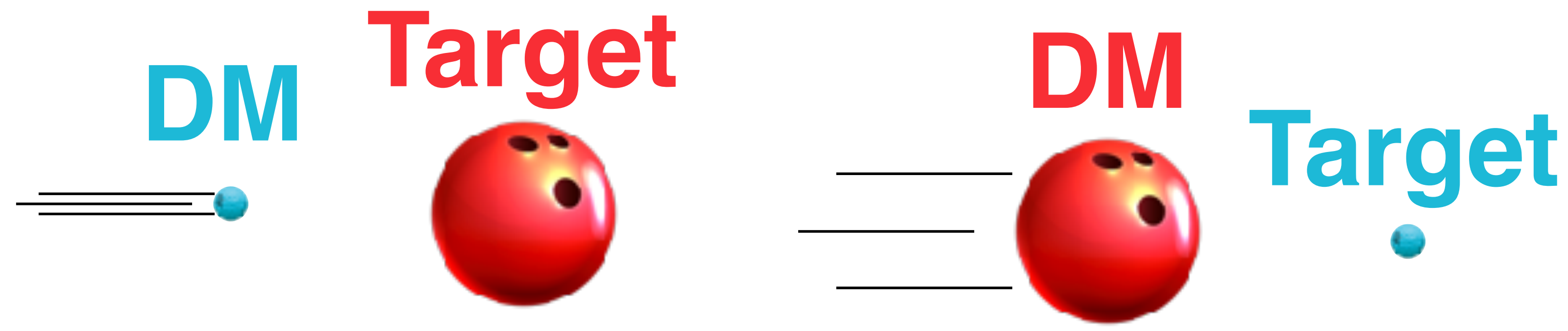
- DS-50 demonstrated the feasibility of LDM searches with dual-phase LAr TPCs.
- Use of ionization signals only: $E_{th} = 0.05\,\mathrm{keV_{ee}}$ with 100% trigger efficiency.
- Many models probed and world-leading limits.

Other Technologies

A kinematics approach to DM

Kinematics

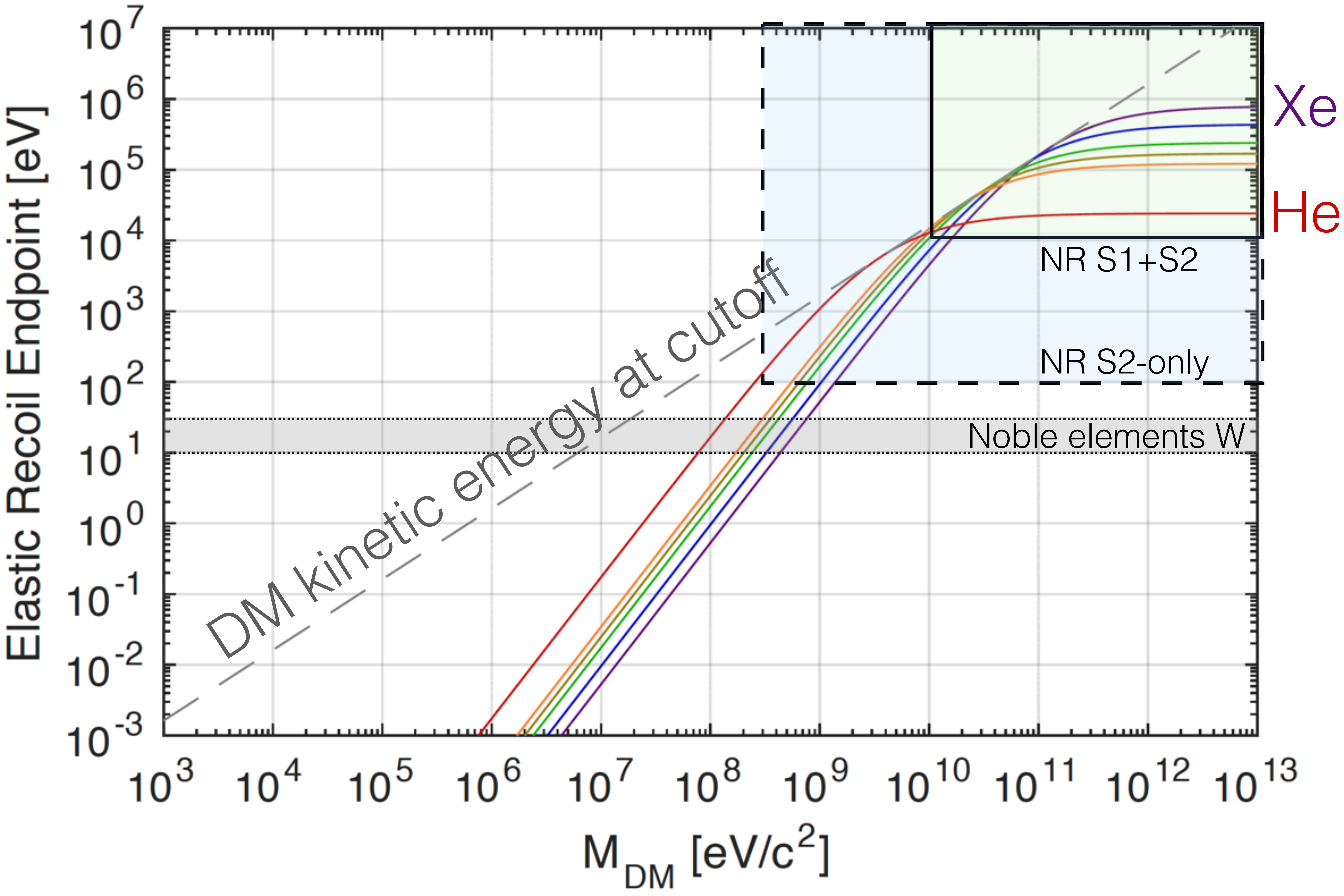
- Momentum transfer is maximal when $M_{DM} = M_{SM}$



Inefficient p-transfer

Nuclear Recoils

- Noble element TPCs (S1+S2): E_{th} ~ 10keV$_{nr}$, M_{DM} > 10GeV/c^2
- Noble element TPCs (S2-only): E_{th} ~ 0.5keV$_{nr}$, M_{DM} > 1GeV/c^2
- Rate enhancement by coherent scattering (A^2)
- Nuclear recoils quenching



A kinematics approach to DM

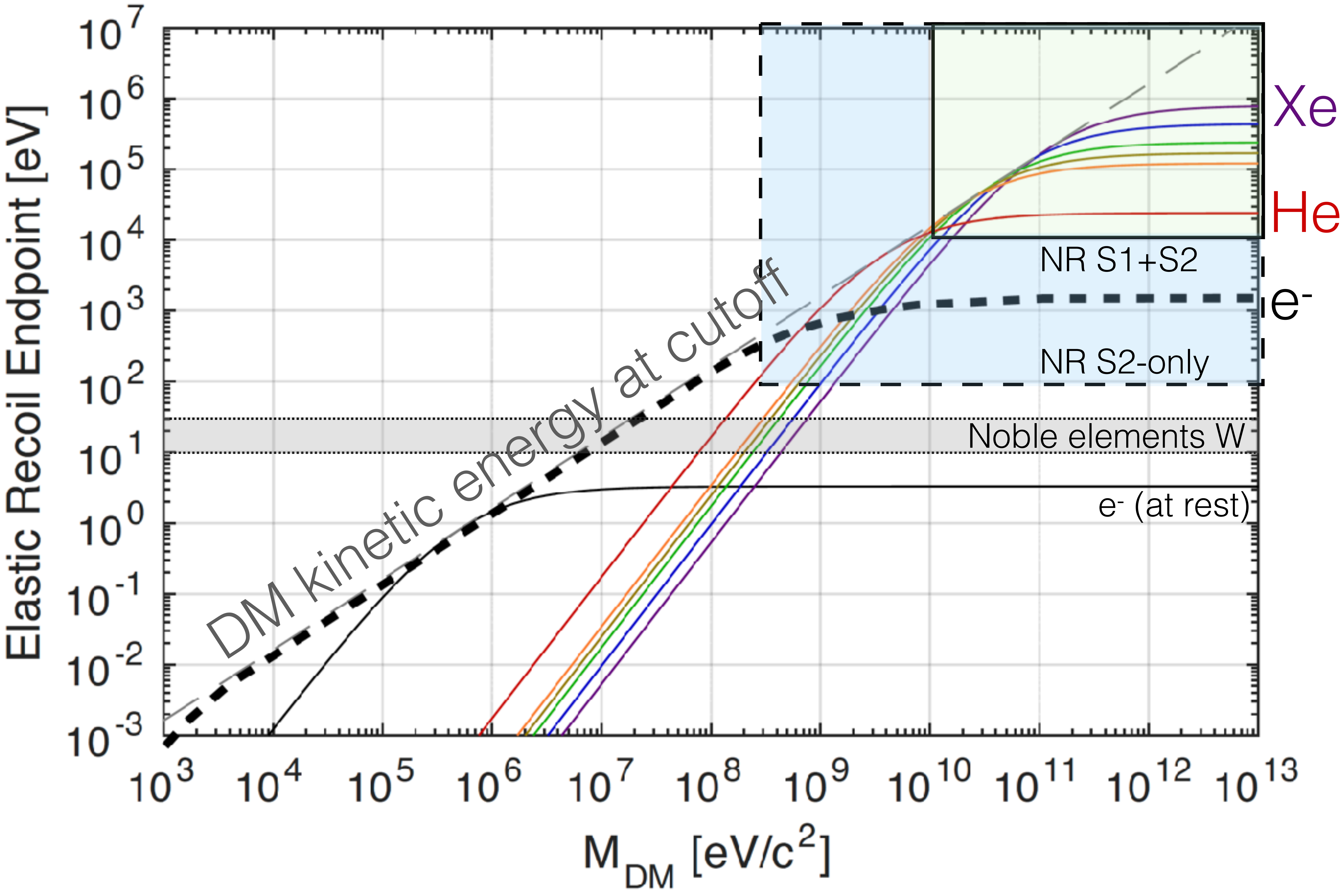
Kinematics

- Momentum transfer is maximal when $M_{DM} = M_{SM}$

Inefficient p-transfer

Electron Scattering

- Initial E and p electron distribution: full energy transfer possible over wide mass range. $E_{th} \sim 50eV_{ee}$, $M_{DM} > 10MeV/c^2$
- Rate suppression
- No quenching, more efficient transfer of KE into a signal



A kinematics approach to DM

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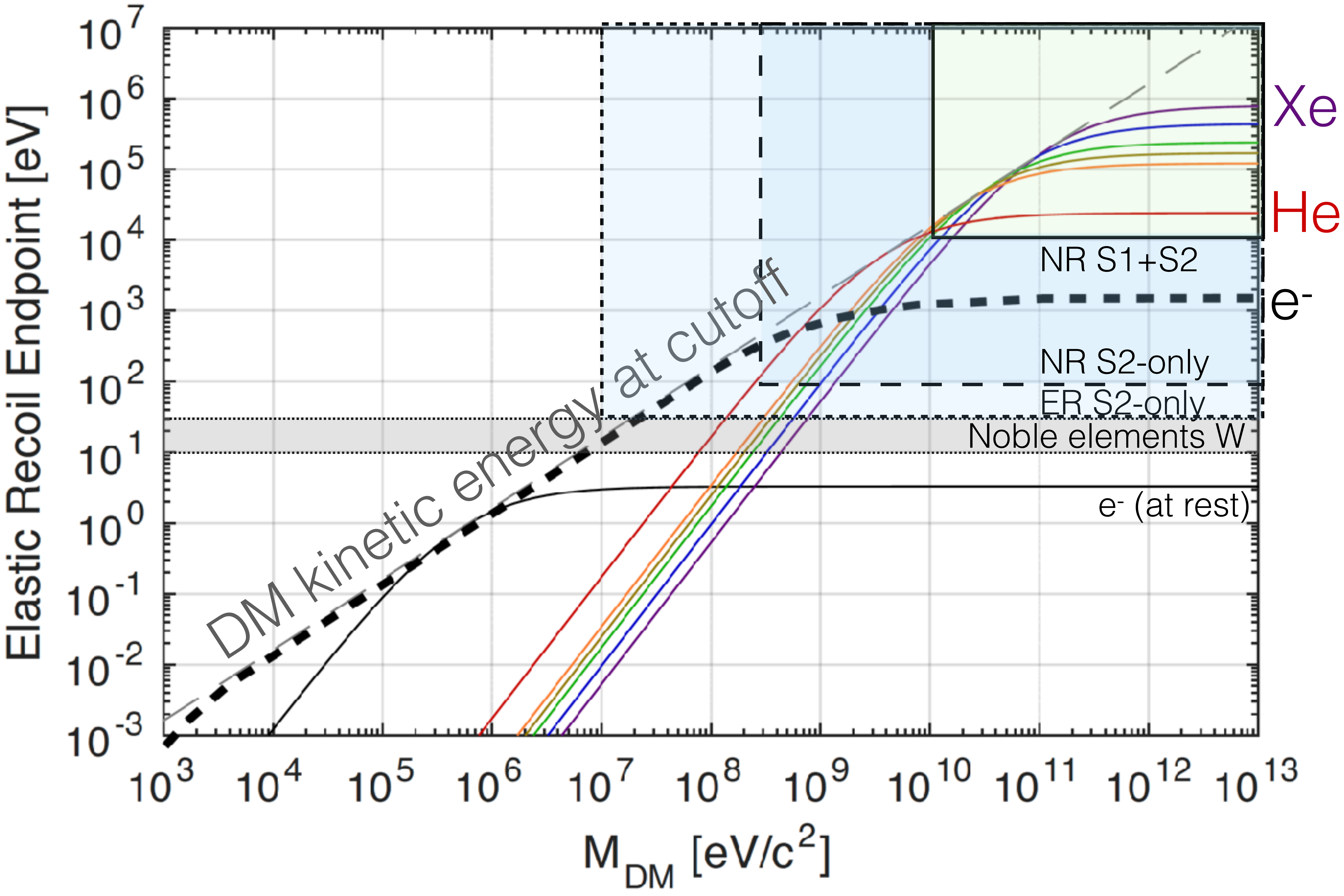
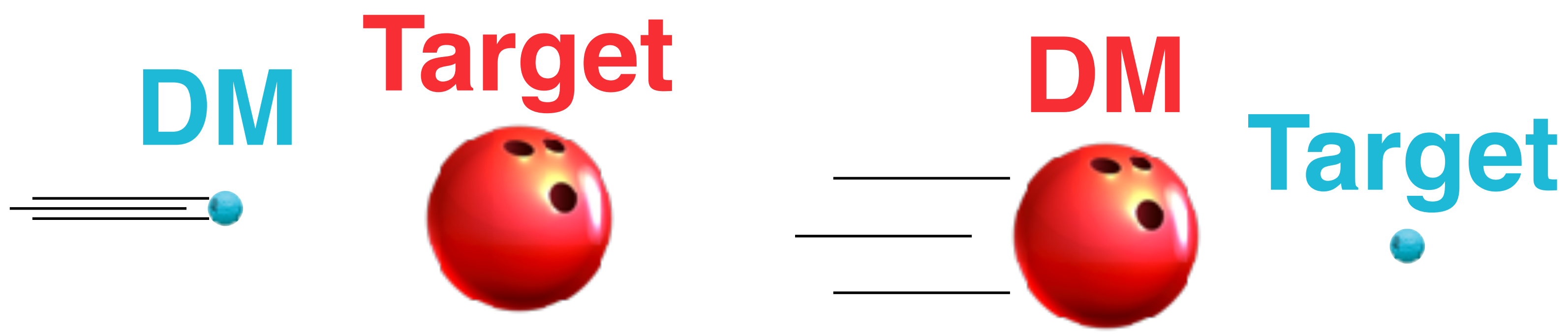


A kinematics approach to DM

Kinematics

- Momentum transfer is maximal when $M_{DM} = M_{nucleus}$

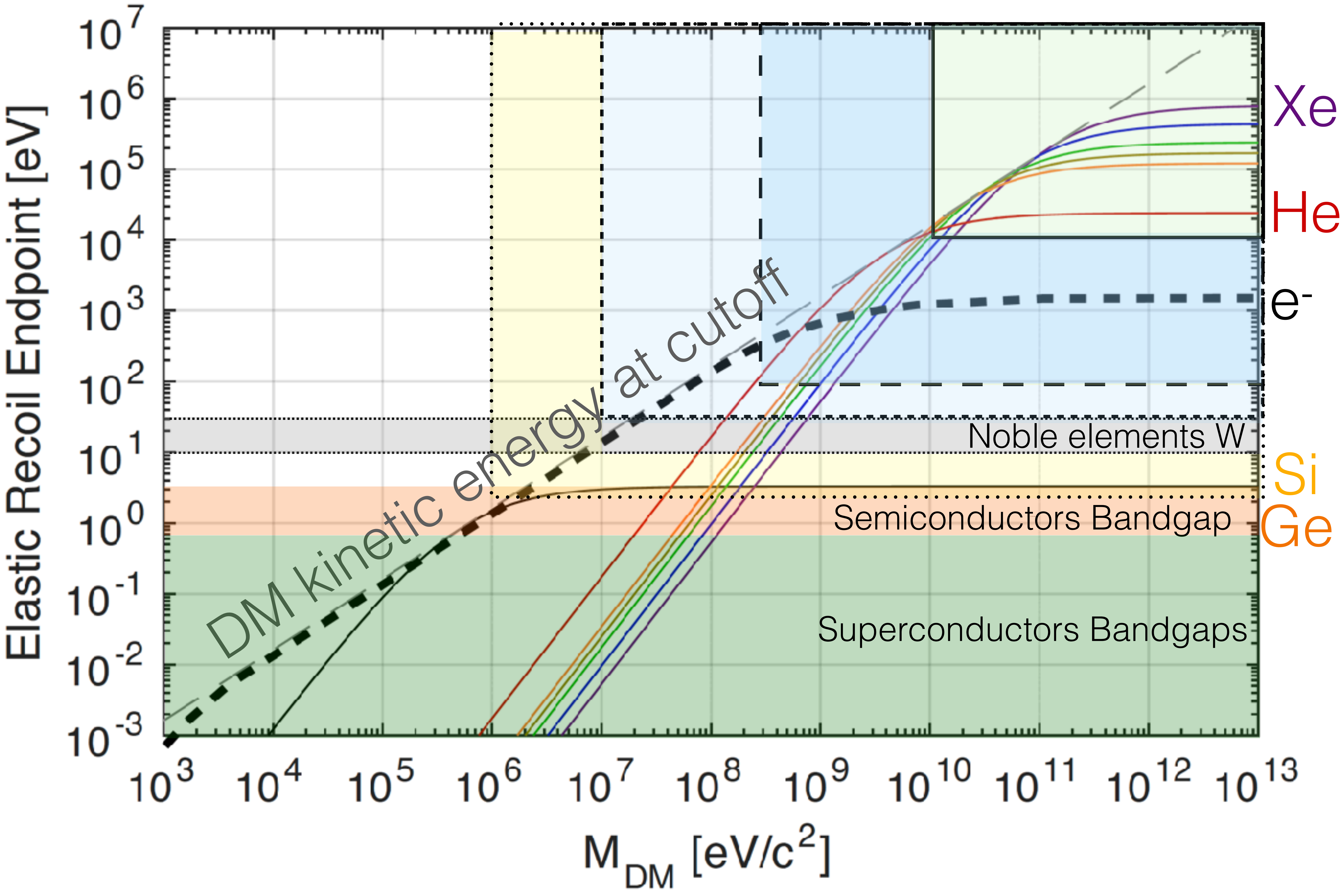


Inefficient p-transfer

Electron Scattering

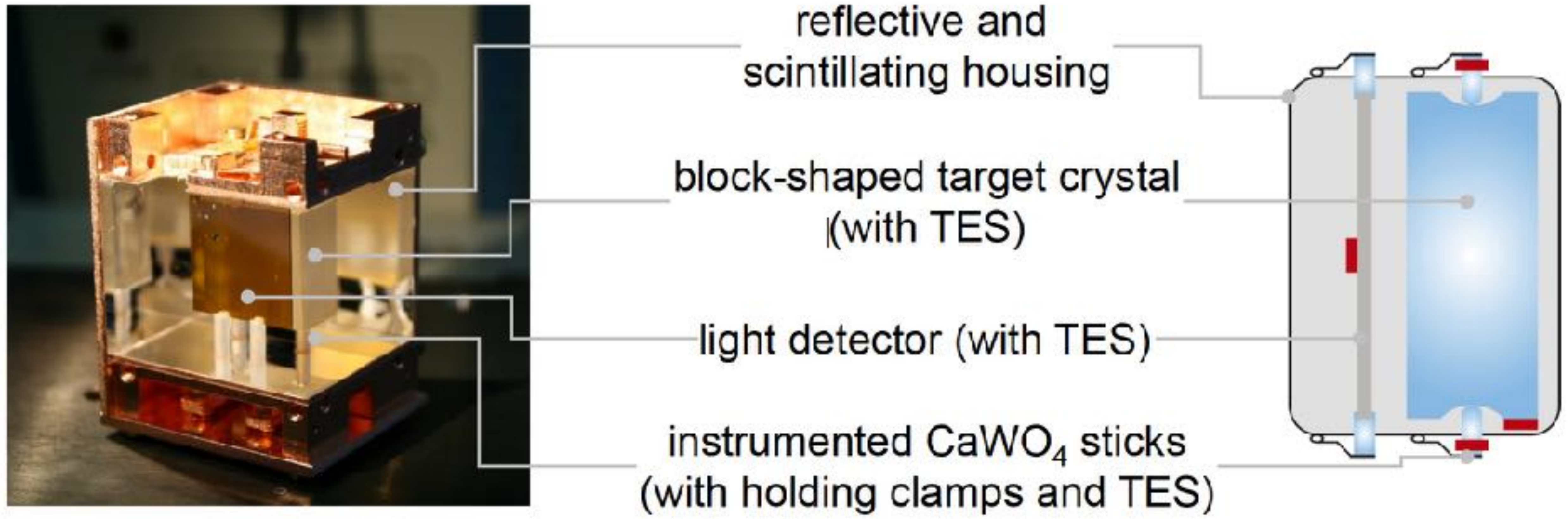
- Bandgap << Noble elements W
- More charge per unit of energy $E_{th} \sim 10eV_{ee}$, $M_{DM} > 1MeV/c^2$

- Large rate suppression



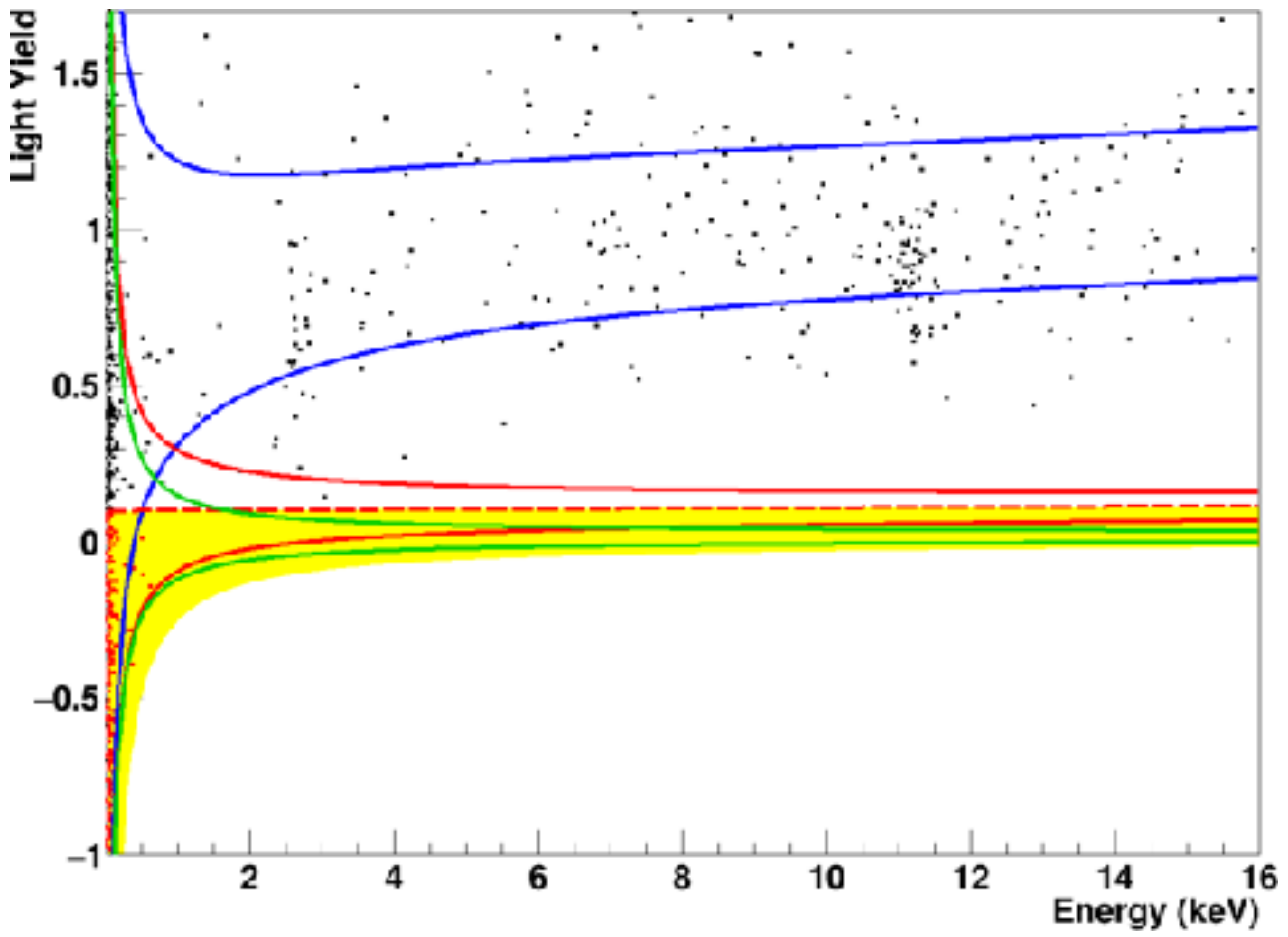
Cryogenic detectors

Phonons + Scintillation

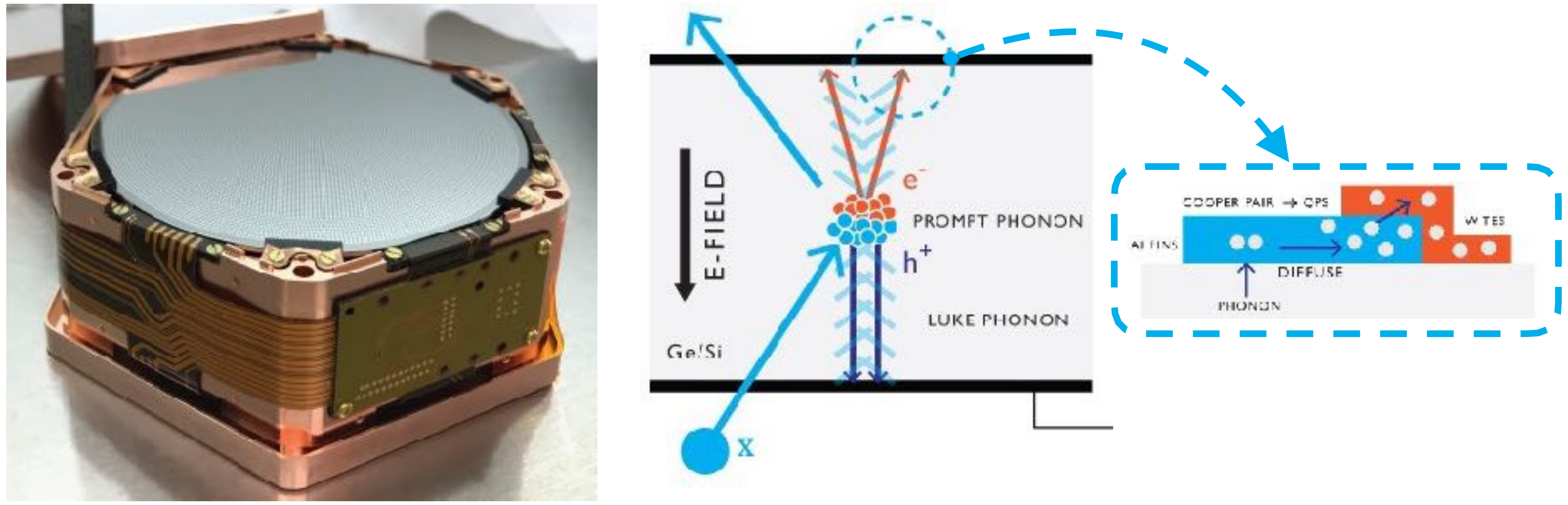


CRESST-III detector module

- $CaWO_4$ crystal: T~10mK
- TES readout
- 24g: 1keV ~ 1μK
- Goal: E_{th} ~ 100eV
- Low bkg: 3/keV/kg/d



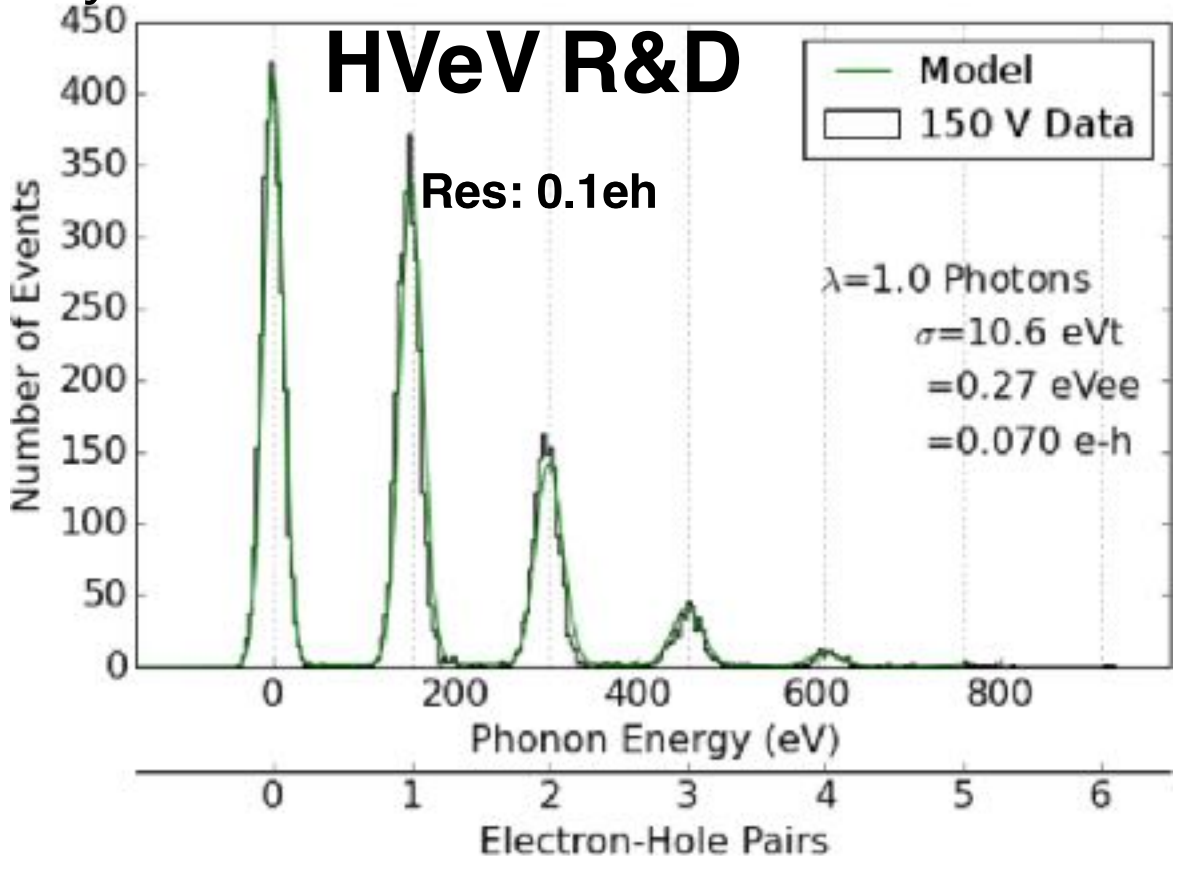
Phonons + Ionisation



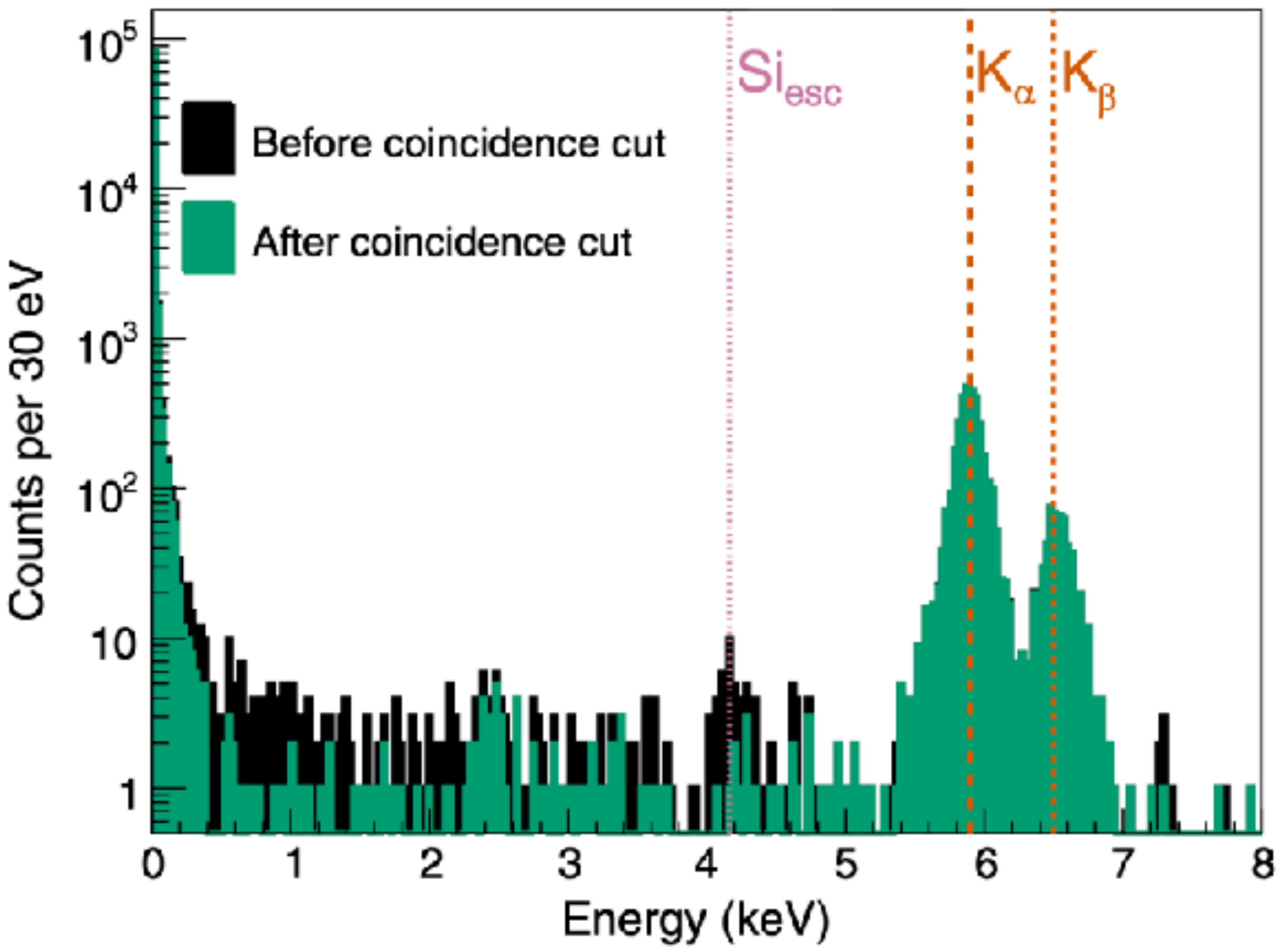
SuperCDMS HV/iZIP/ detector

- Ge or Si crystal: T~15mK
- TES readout
- Prompt phonons
- HV: Luke phonons (low E_{th})
- iZIP: ER/NR discrimination

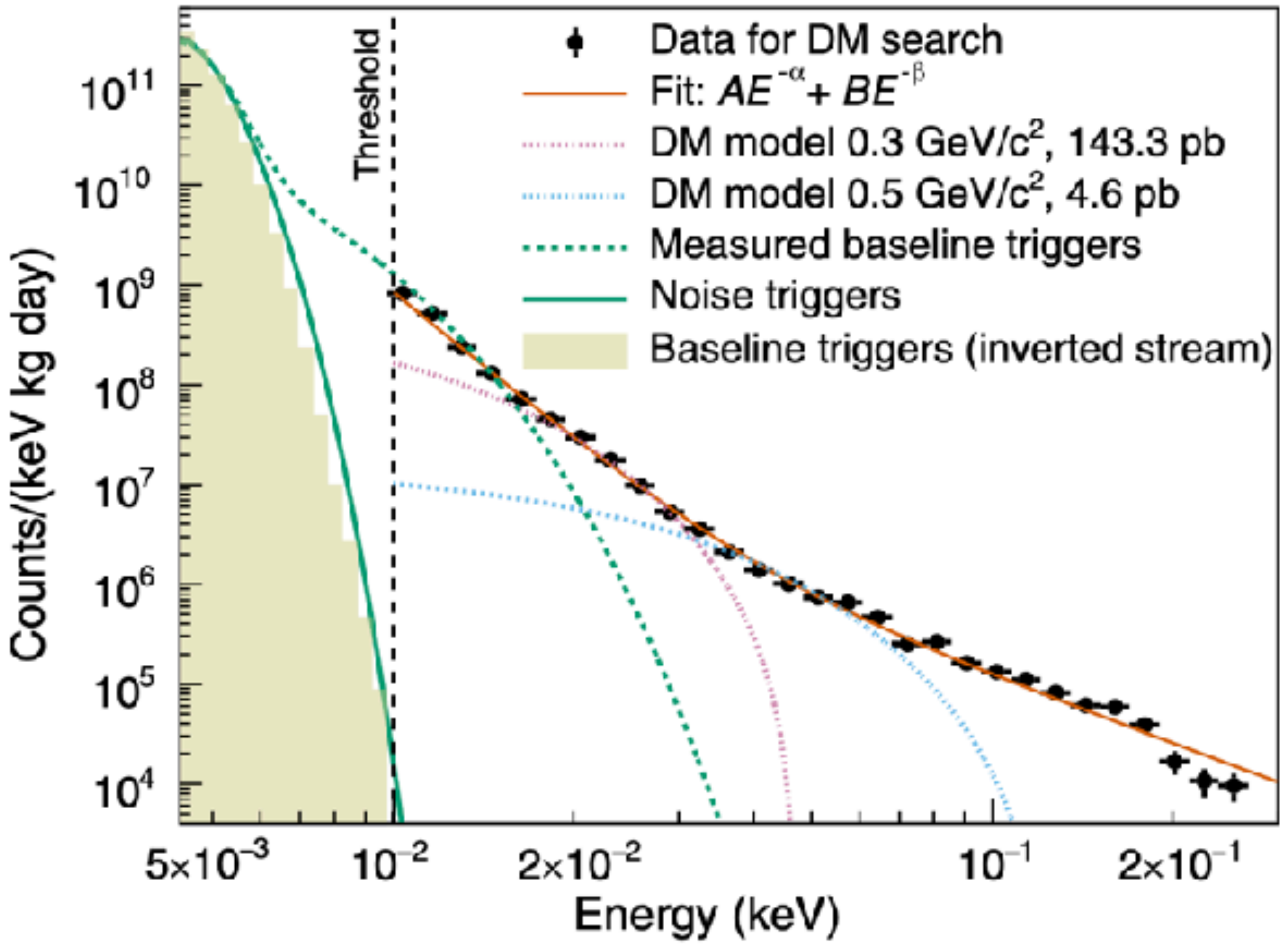
Phys. Rev. Lett. 121, 051301



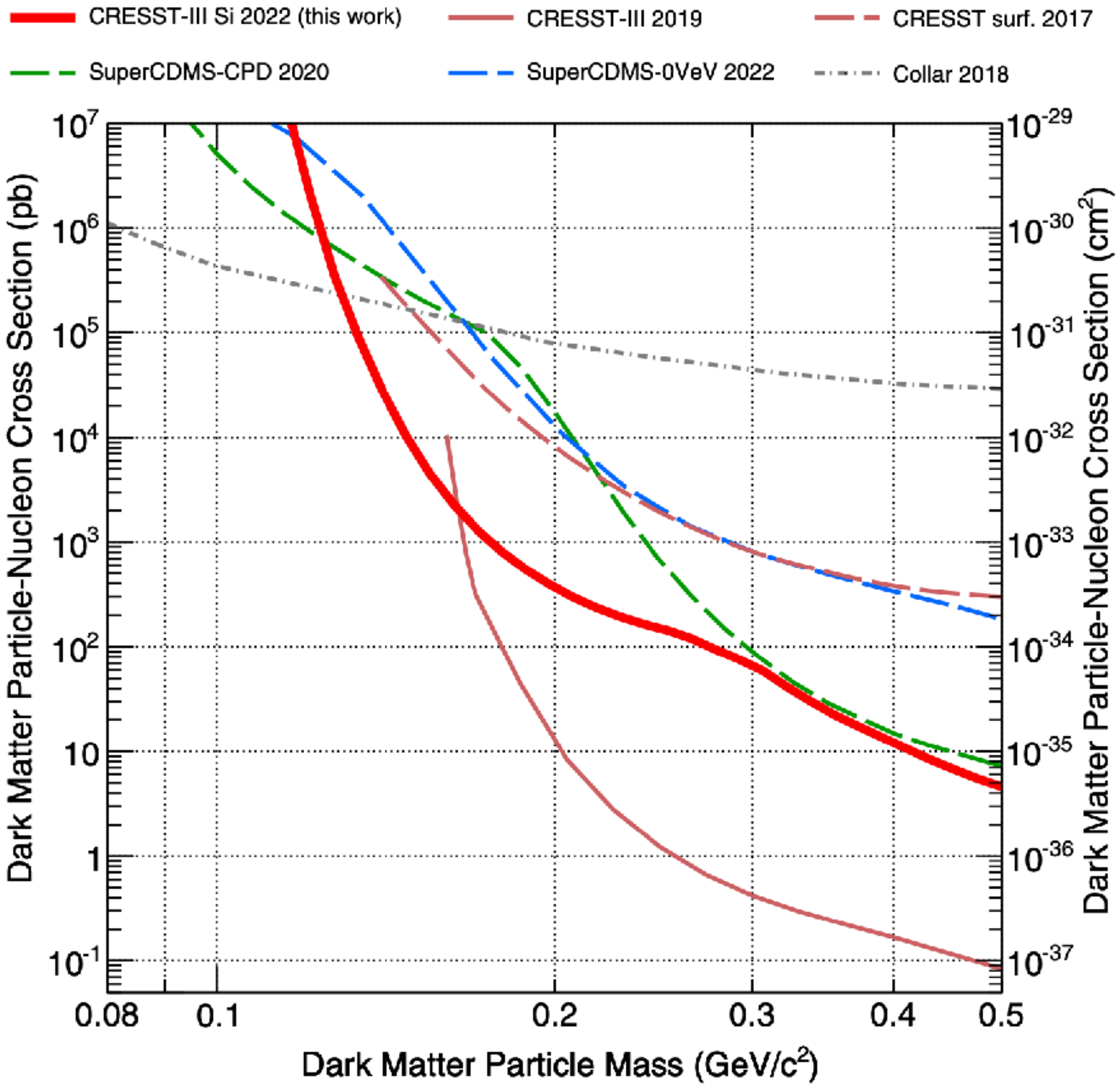
CRESST-III



Si_esc
K_α
K_β
Before coincidence cut
After coincidence cut
Counts per 30 eV
10^5
10^4
10^3
10^2
10
1
0
1
2
3
4
5
6
7
8
Energy (keV)

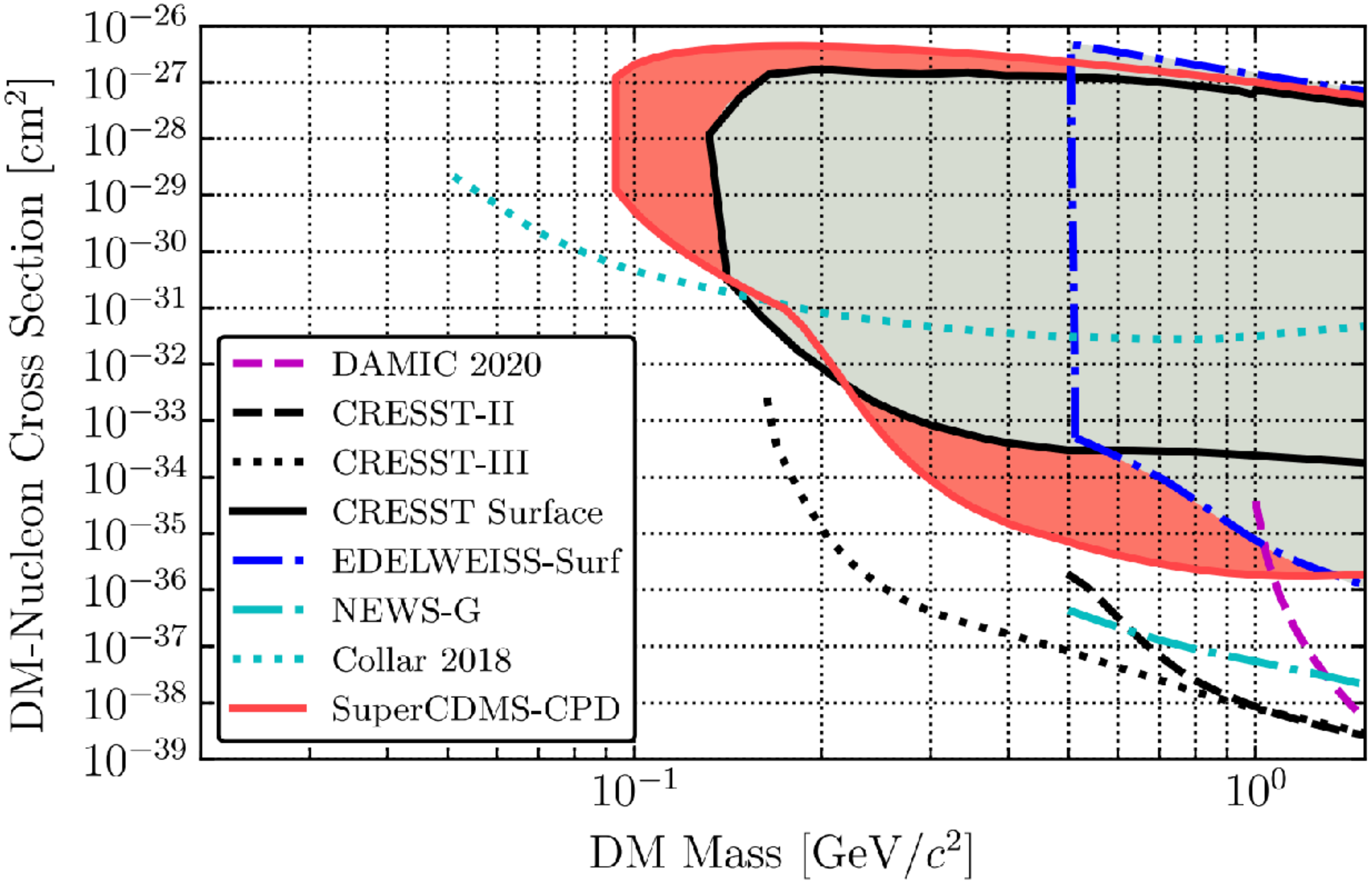


Threshold
Data for DM search
Fit: AE^-α + BE^-β
DM model 0.3 GeV/c², 143.3 pb
DM model 0.5 GeV/c², 4.6 pb
Measured baseline triggers
Noise triggers
Baseline triggers (inverted stream)
Counts/(keV kg day)
10^11
10^10
10^9
10^8
10^7
10^6
10^5
10^4
5×10^-3
10^-2
2×10^-2
10^-1
2×10^-1
Energy (keV)



CRESST-III Si 2022 (this work)
CRESST-III 2019
CRESST surf. 2017
SuperCDMS-CPD 2020
SuperCDMS-0VeV 2022
Collar 2018
Dark Matter Particle-Nucleon Cross Section (pb)
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^-1
Dark Matter Particle-Nucleon Cross Section (cm²)
10^-29
10^-30
10^-31
10^-32
10^-33
10^-34
10^-35
10^-36
10^-37
0.08
0.1
0.2
0.3
0.4
0.5
Dark Matter Particle Mass (GeV/c²)

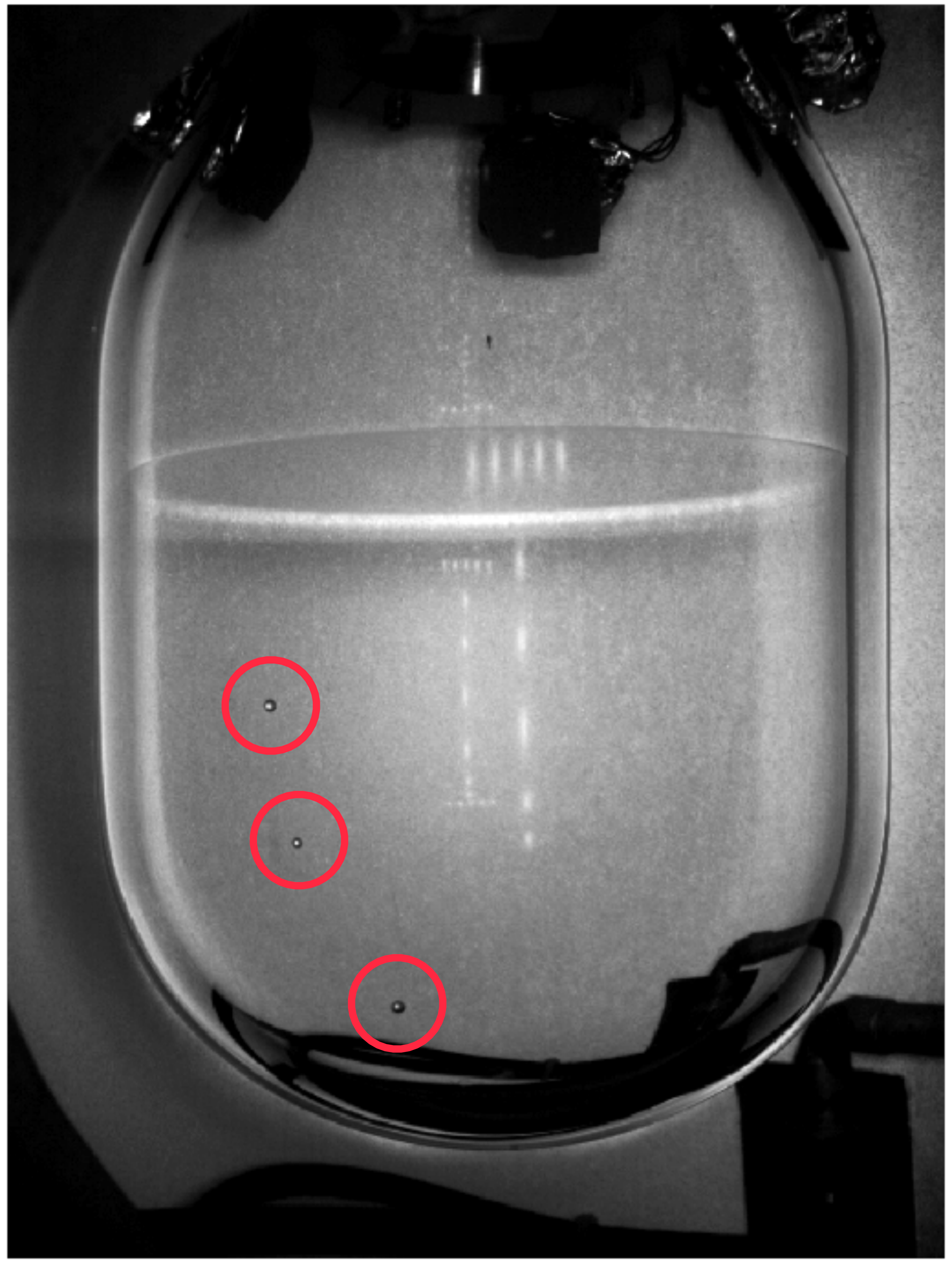
SuperCDMS


DM-Nucleon Cross Section [cm^2]
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-1}
10^{0}
DM Mass [GeV/c^2]
DAMIC 2020
CRESST-II
CRESST-III
CRESST Surface
EDELWEISS-Surf
NEWS-G
Collar 2018
SuperCDMS-CPD

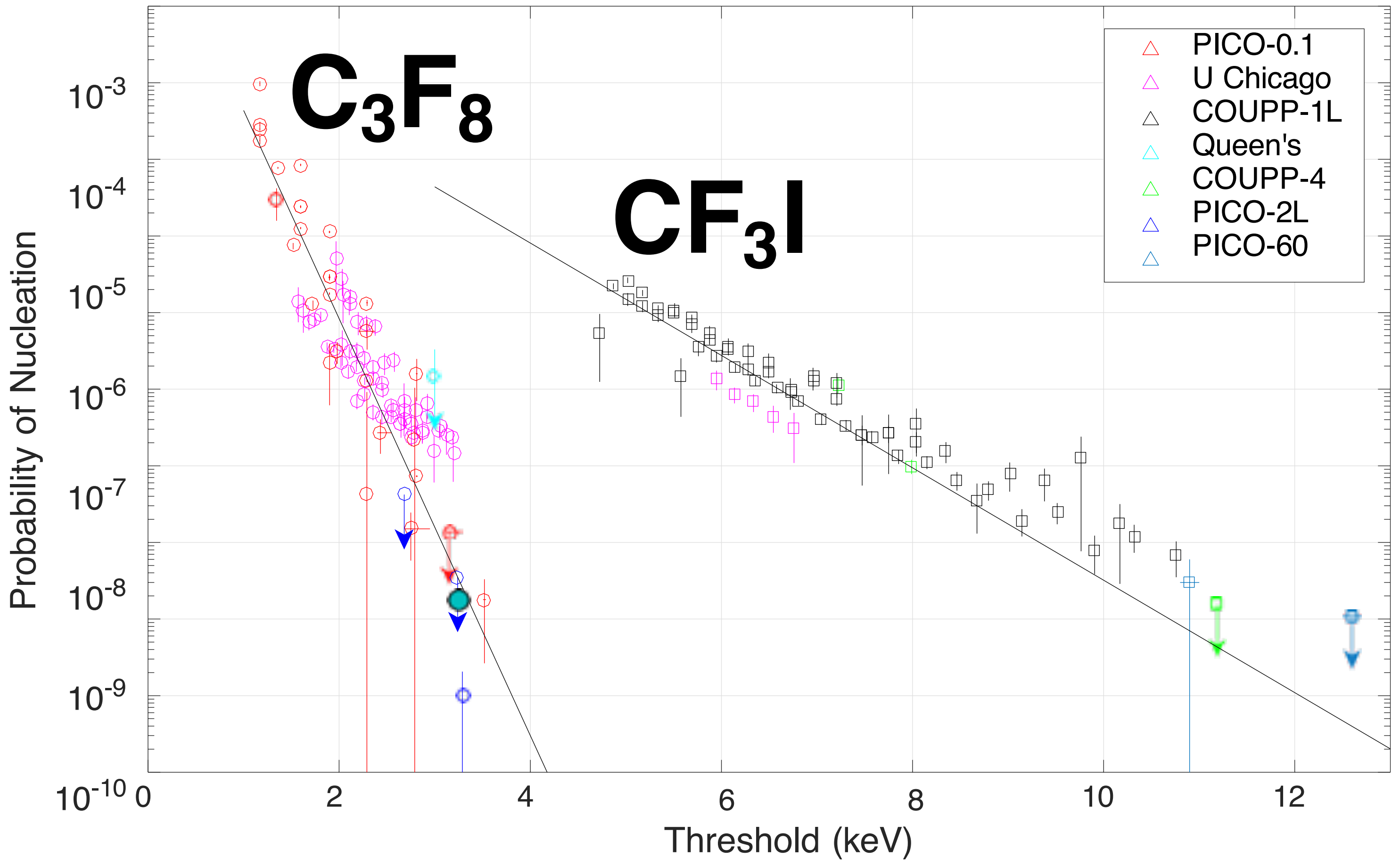
Bubble chambers: PICO

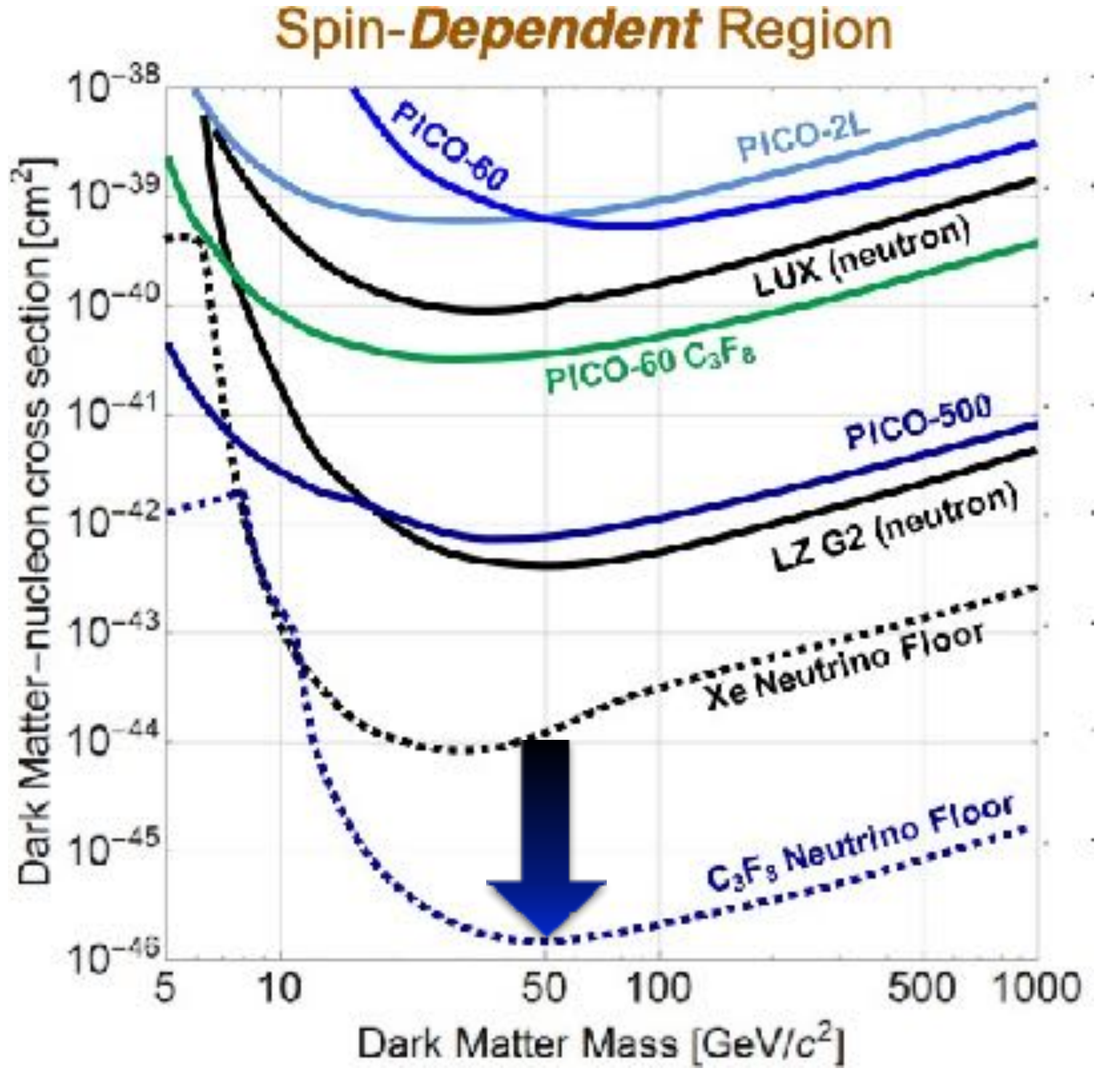
- Active target: C_3F_8 (currently)
- Superheated active fluid. Control by temperature and pressure.
- Energy Deposition by particle interactions triggers formation of a bubble.
- Bubble observed with cameras and acoustic sensors.
- Appealing technology: MS vetoing, ER rejection, Low E_{th}
- C_3F_8 neutrino floor lower than Xe

Multiple scattering vetoing

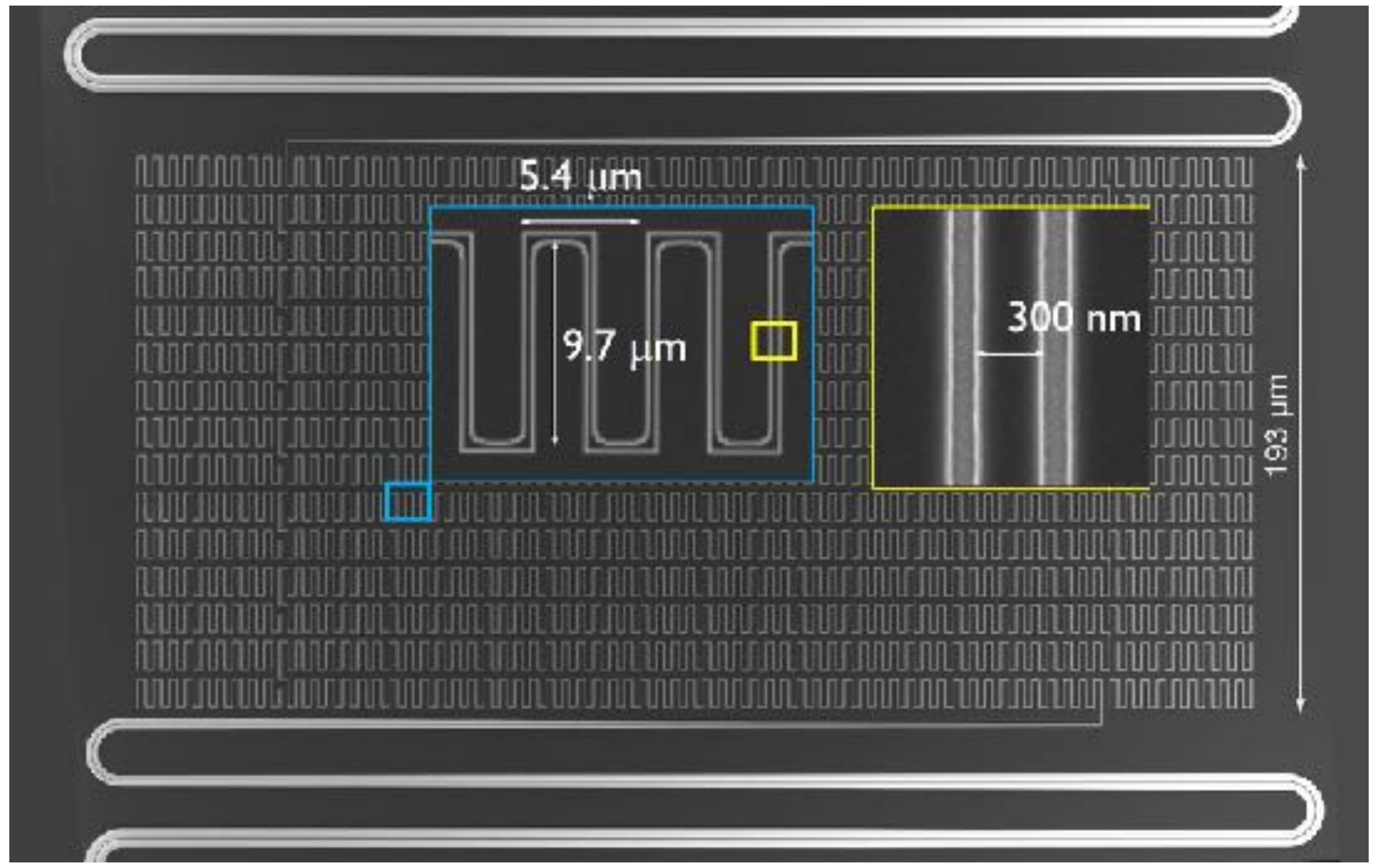


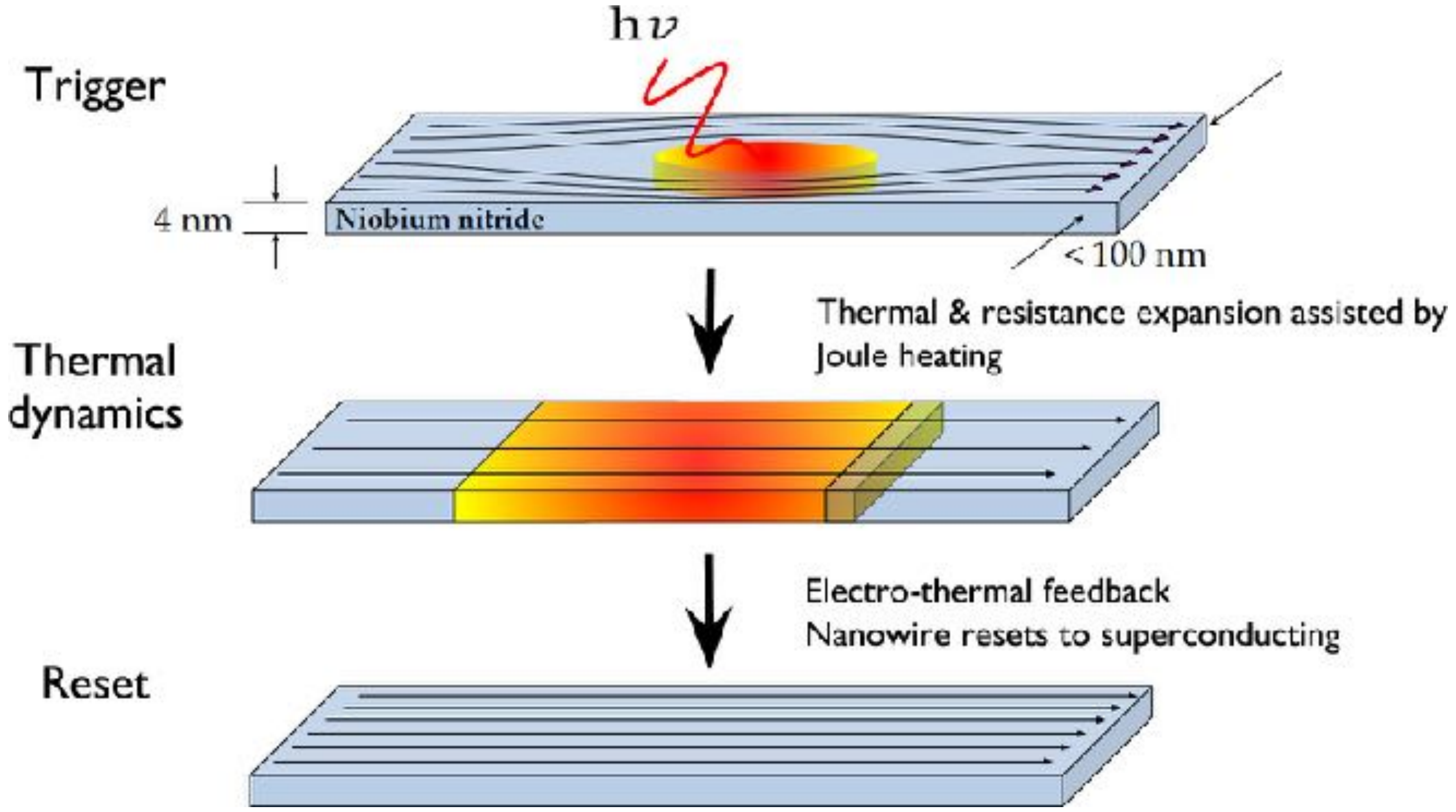
ER rejection (no nucleation)



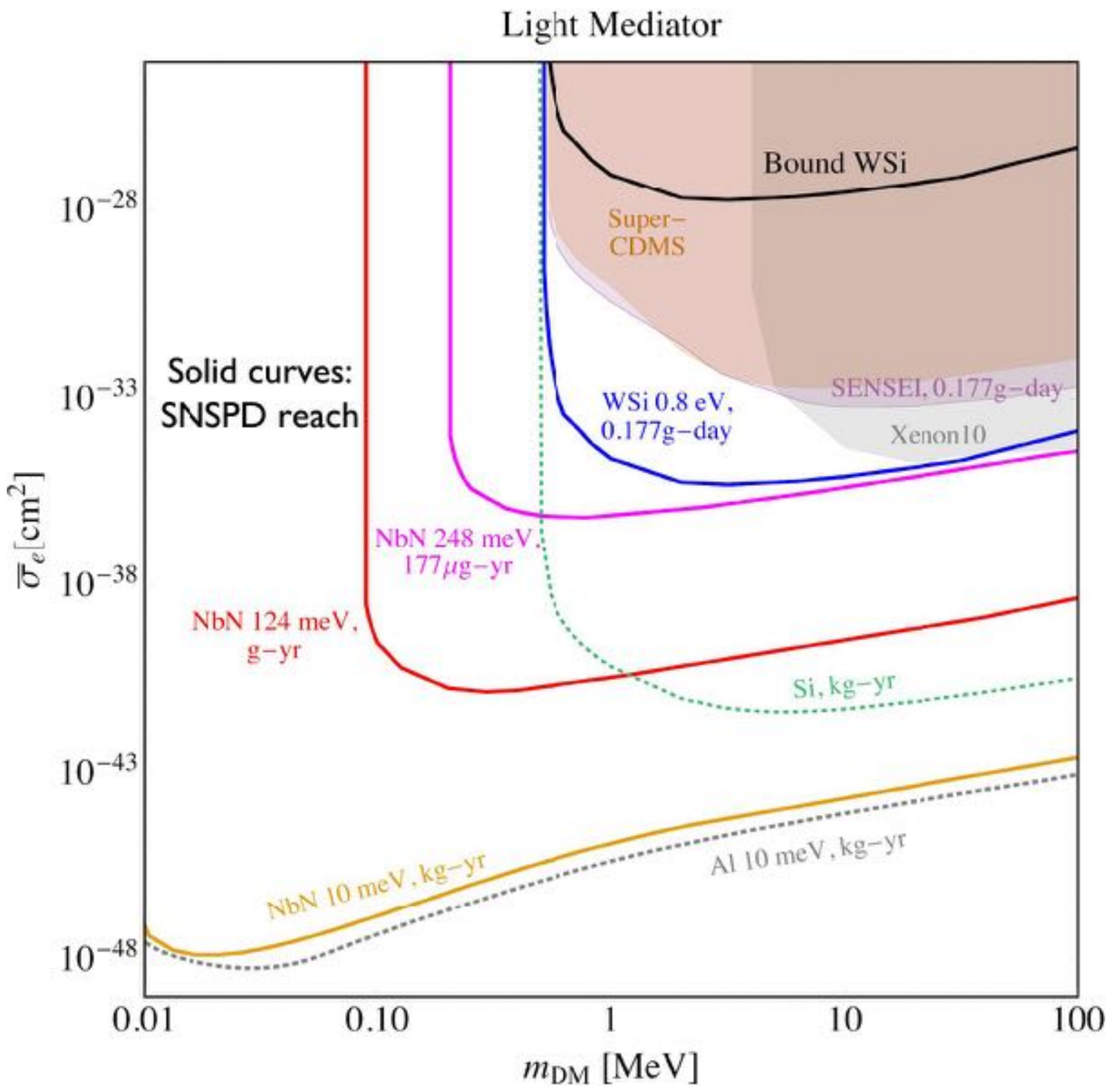


Superconducting nano-wires

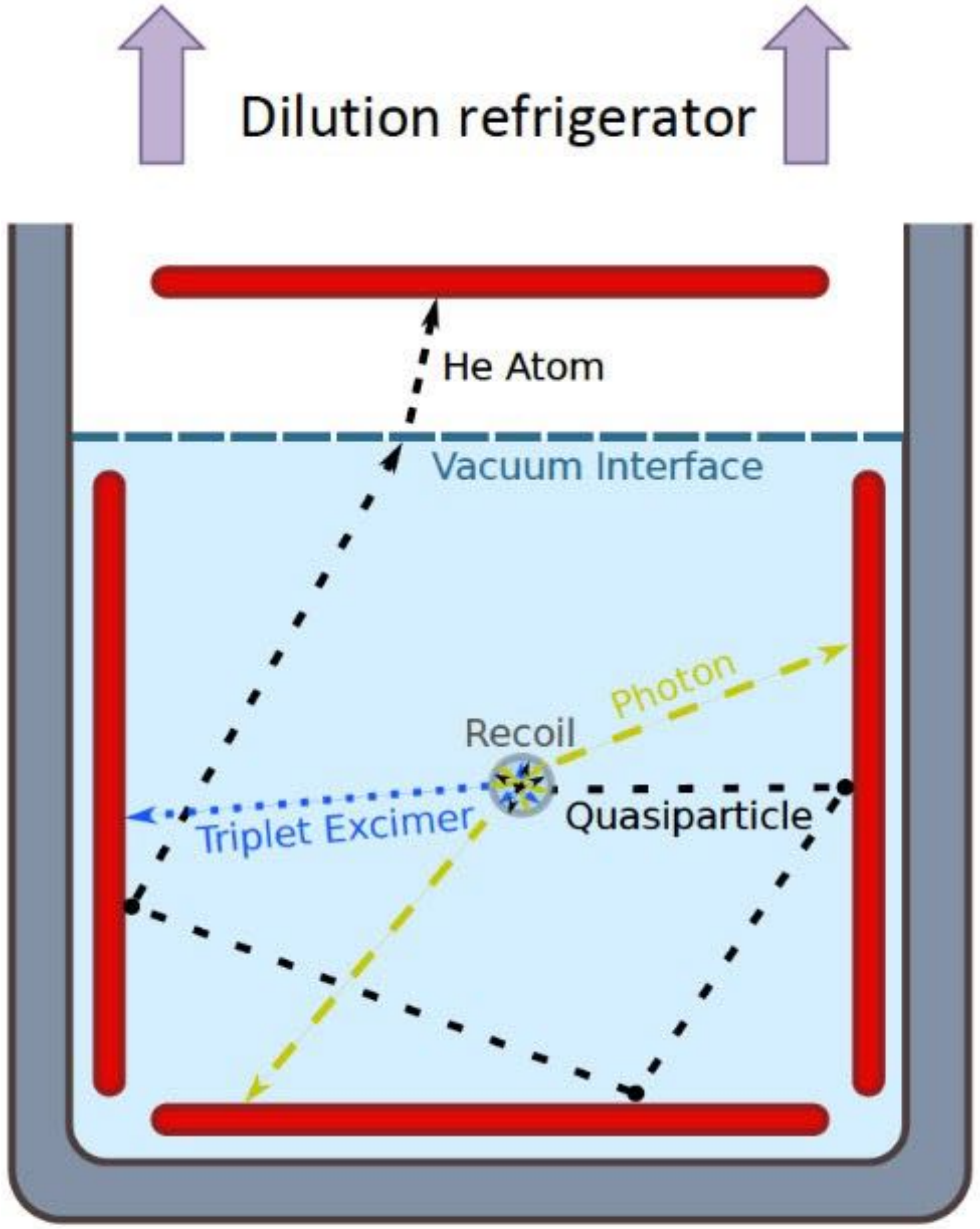




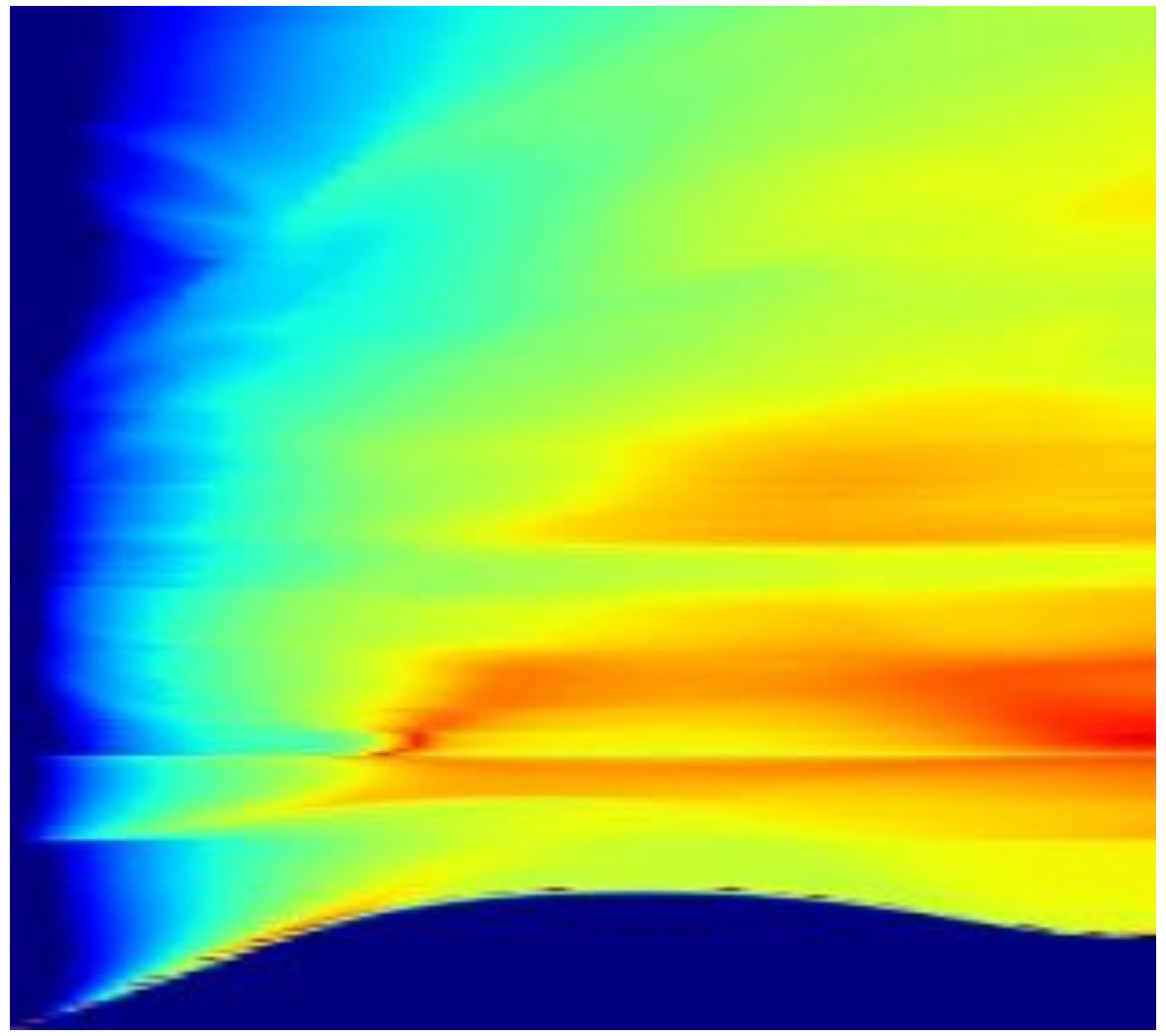
- meV gap, low E_{th}
- Production relatively easy and reliable
- Low dark counts
- Competitive limits with very small exposures



HeRALD

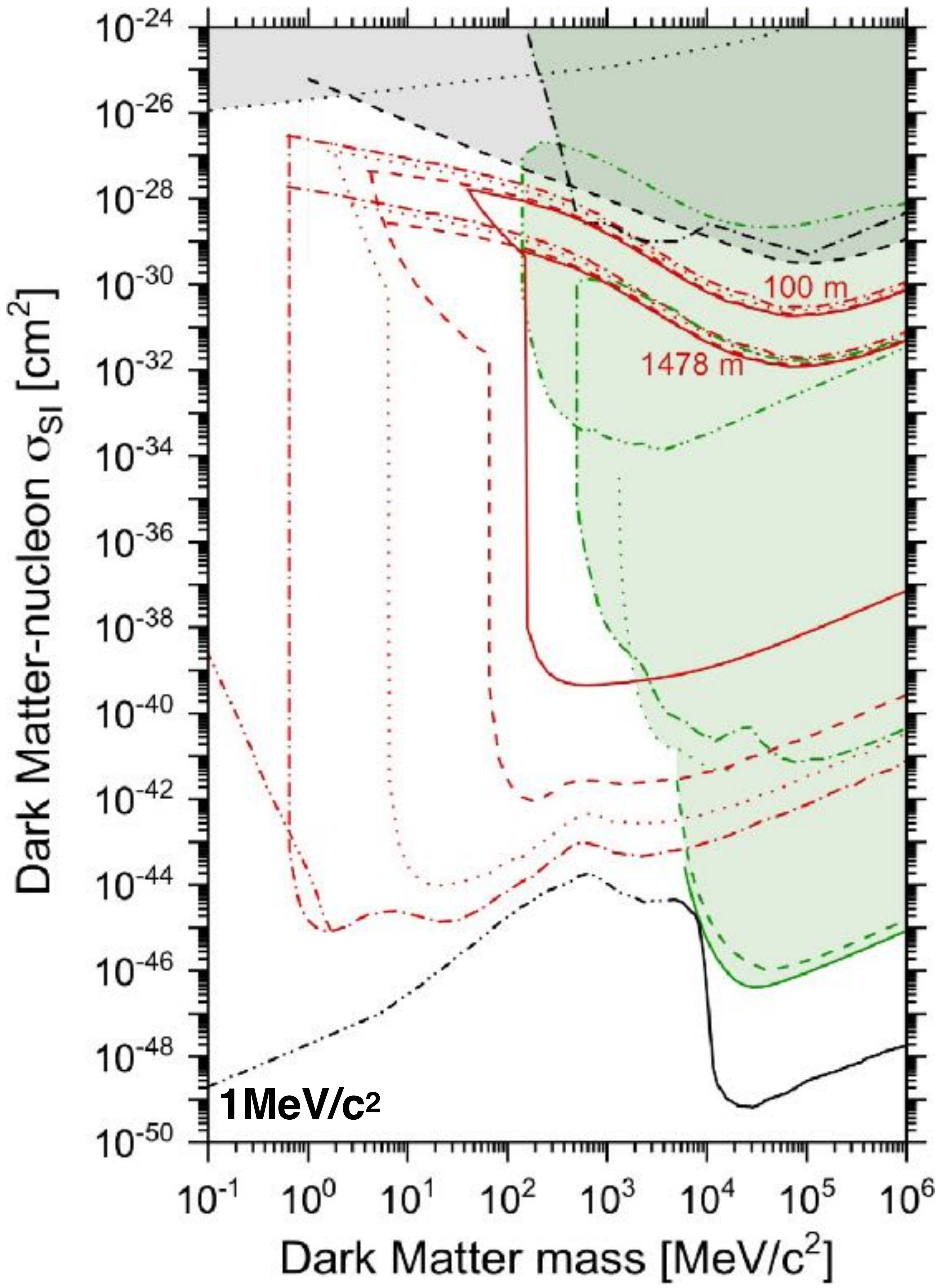


Excitation diagram of ^{4}He



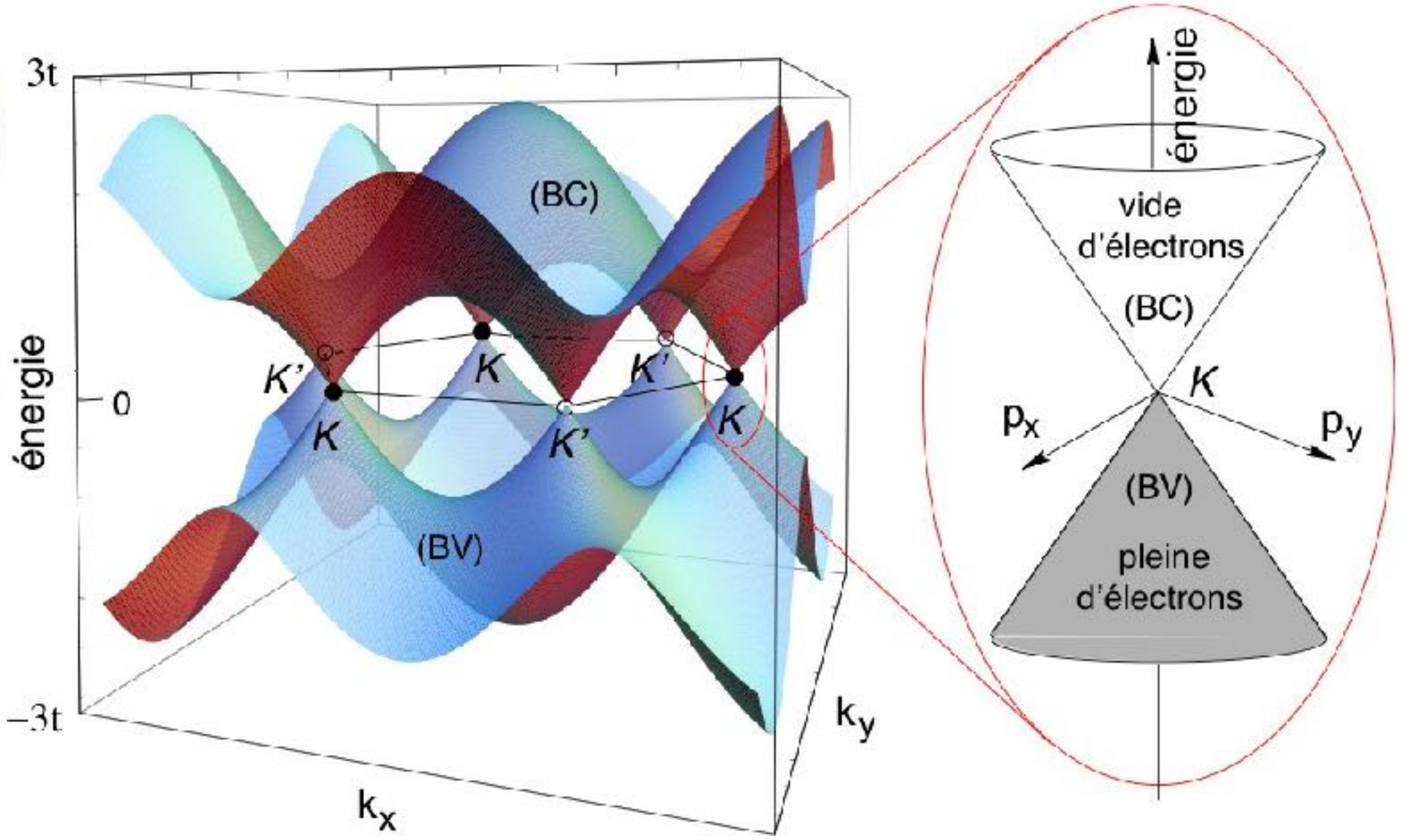
Excitation:

- ~meV Vibrations (phonons, rotons)
- Singlet UV (16 eV) photons
- Triplet Kinetic Excitations



A zoo of New Ideas

- Crystal defects or color centers
- Diamond detectors
- Paleo-detectors
- Dirac materials
- Molecular gases
- Many many others!



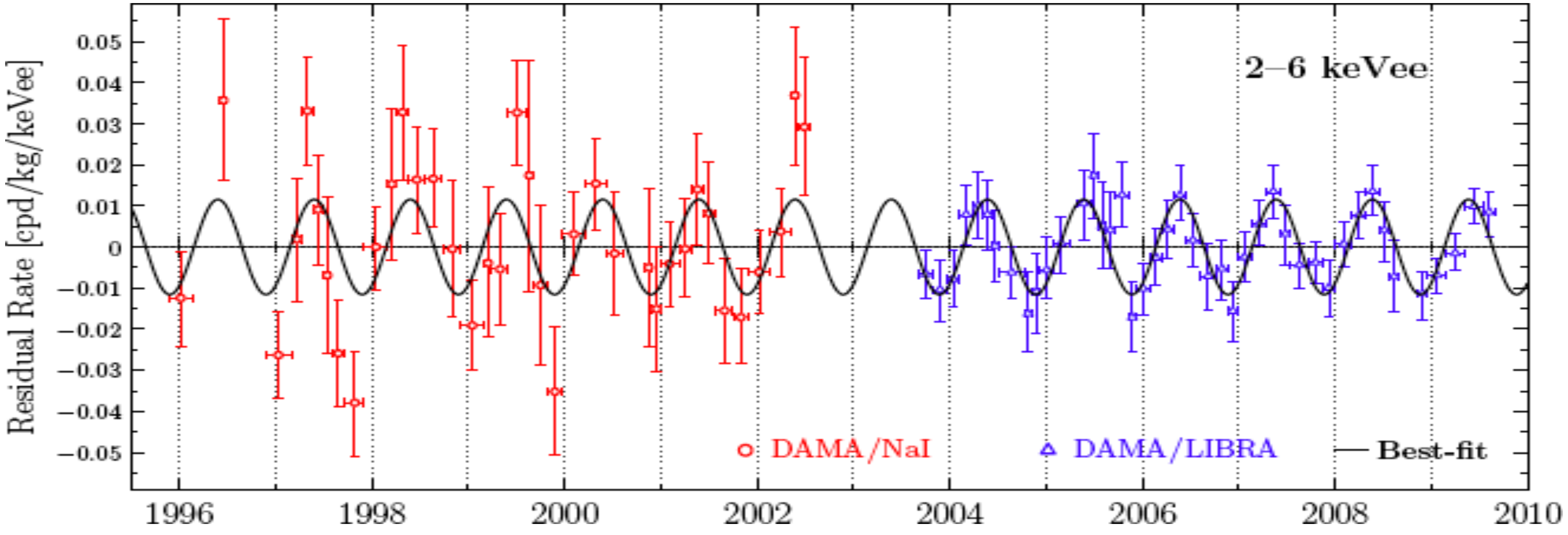
Conclusions

- Multi-tonne experiments are taking data
- Noble liquid technology is leading the way for direct searches at high masses
- Next-gen experiment are being designed and will push the search down to the neutrino floor
- In the next 10 years all the heavy WIMP parameter space will have been explored
- Next efforts to be on unambiguous experimental signatures: modulation and directionality
- The search for DM in the low mass regime is gaining momentum
- A lot of new ideas there!

Backup

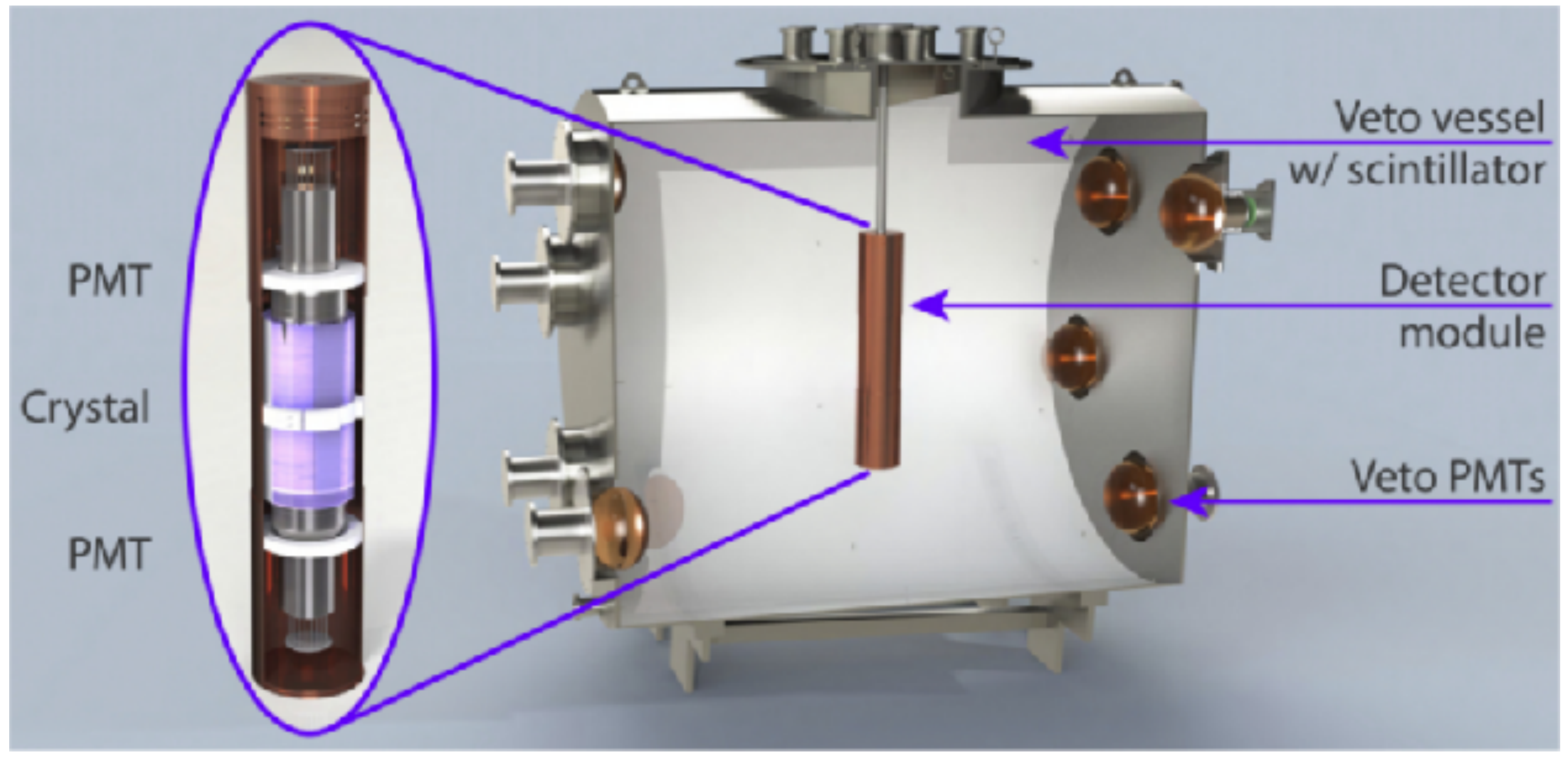
Modulation with SABRE

The long standing modulation: DAMA/LIBRA

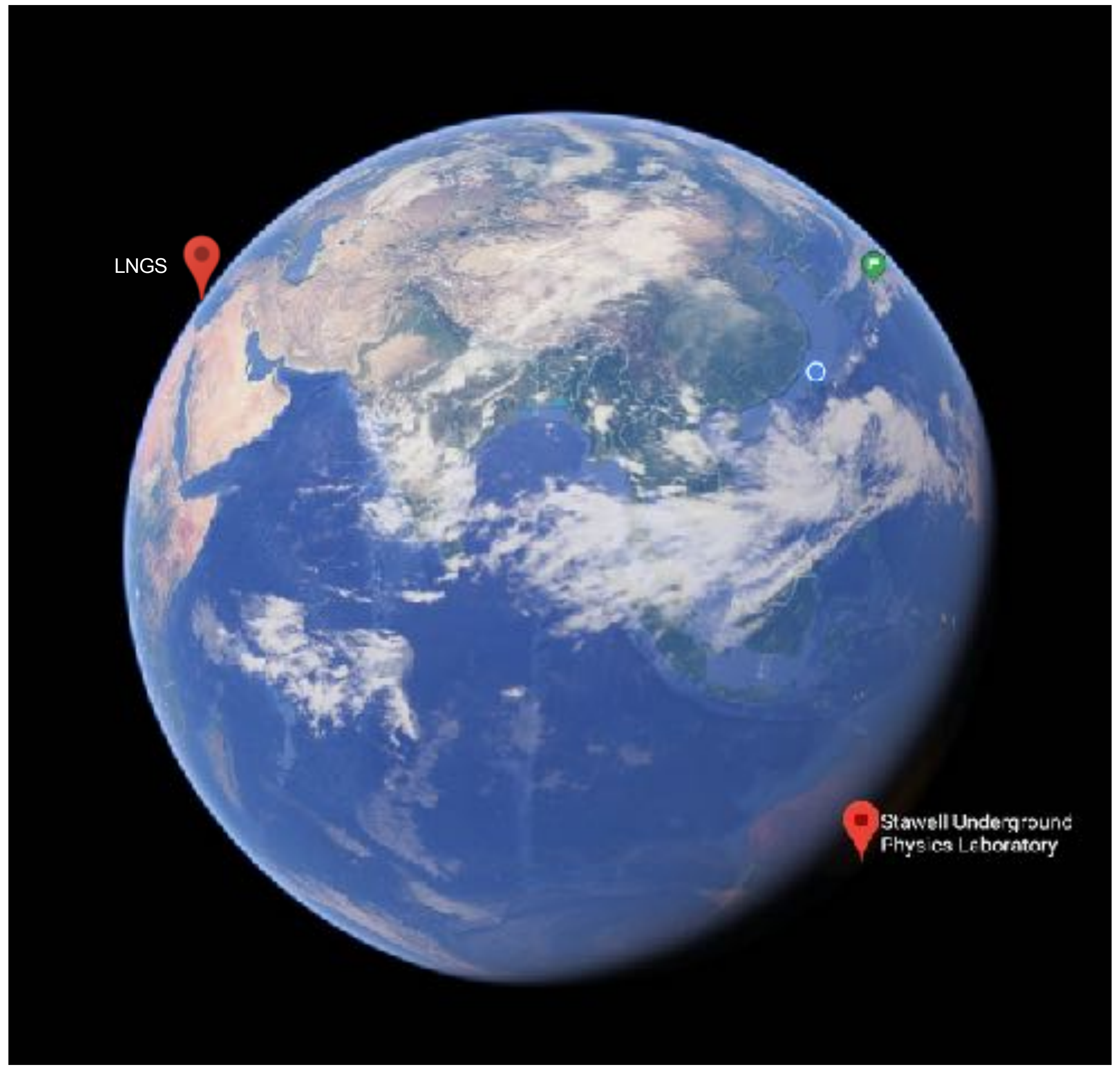


- Exposure: 1.13 ton × year (6y)
- Sensitive mass: about 250 kg of radio-pure NaI(Tl) crystals
- Statistical significance: 9.5σ in (1 - 6)keV and 12.9σ in (2 - 6)keV

SABRE Proof of Principle



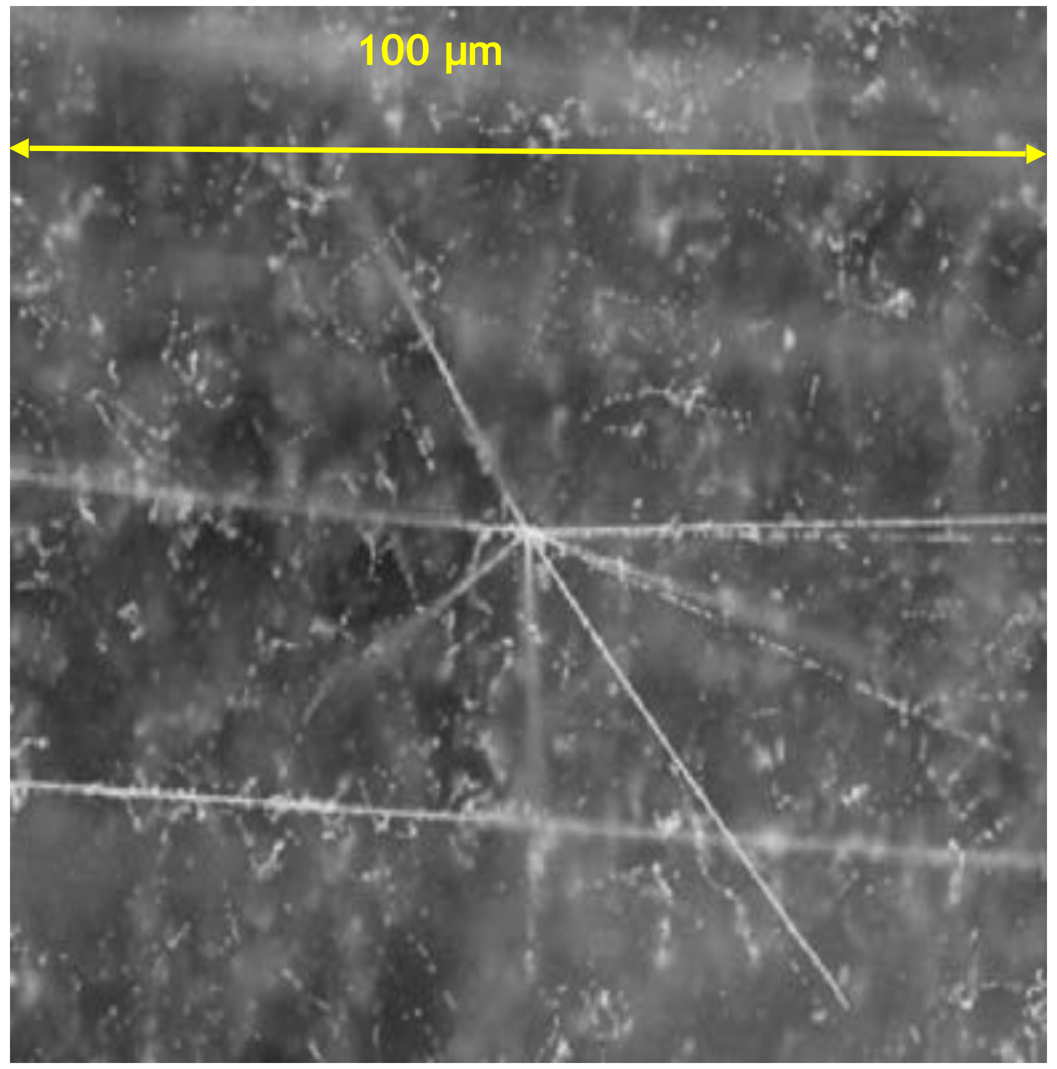
SABRE



- Active background rejection
- Low energy threshold
- Hemispheres: seasonal effects
- High purity crystals

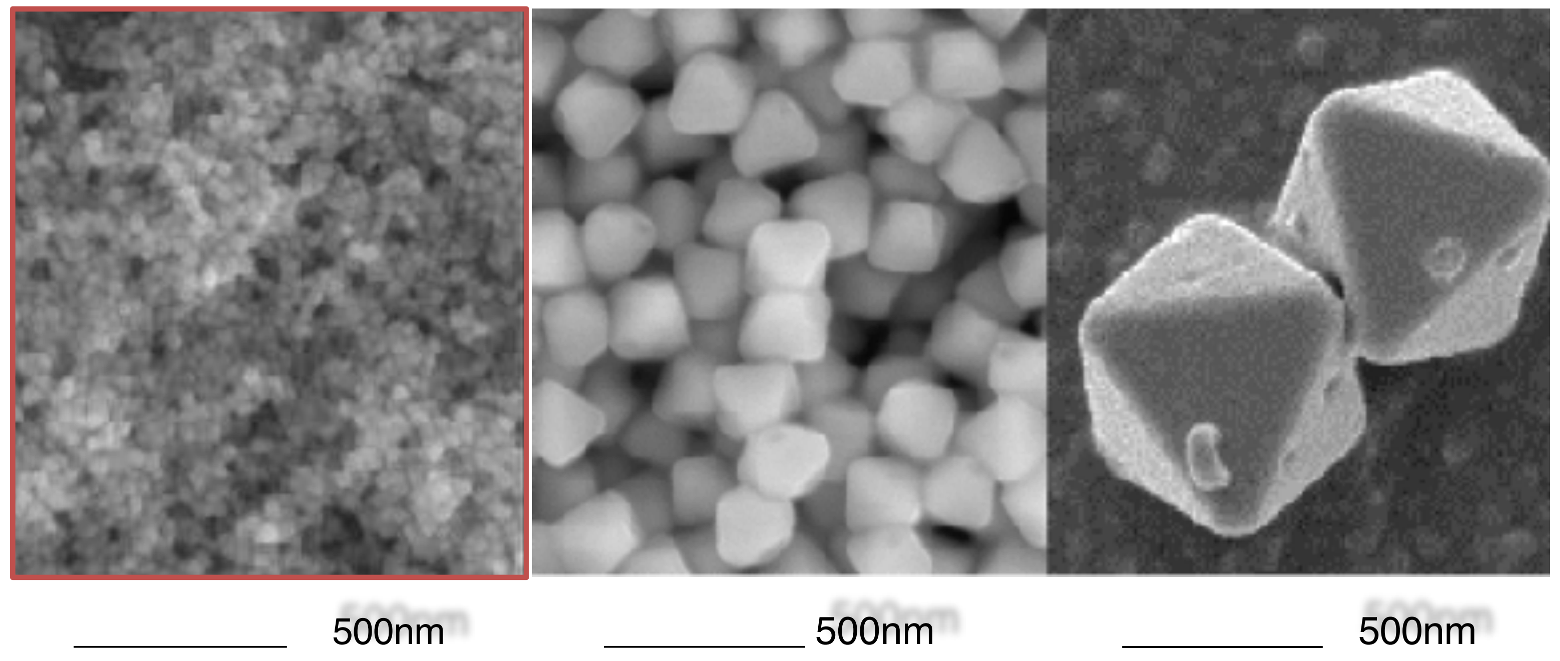
Directionality with NEWSdm

Nuclear emulsion



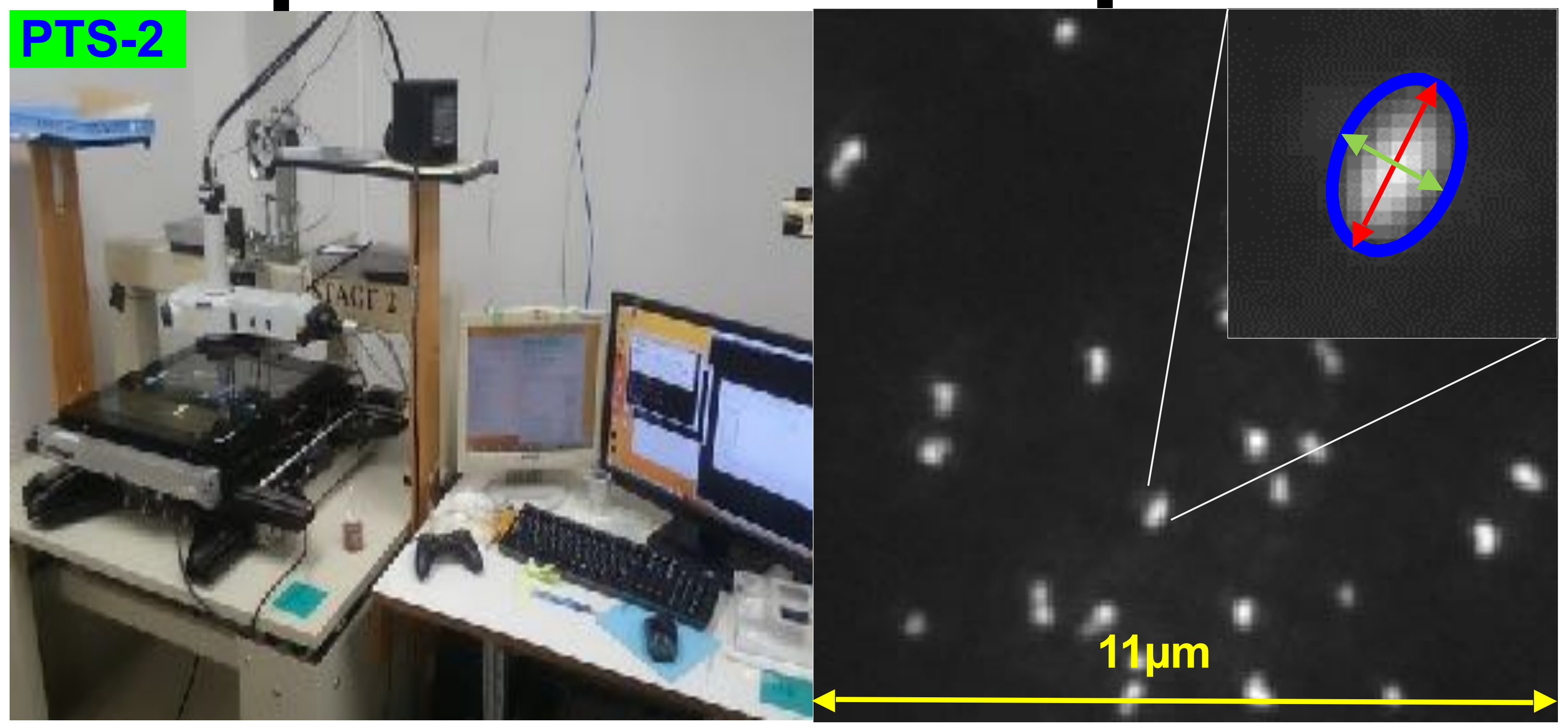
- Solid state detector ~3g/cm^3
- Target: C, N, O, Ag, Br
- High spatial resolution
- 4π tracking
- Large scalability: OPERA (20t)

Crystal growth



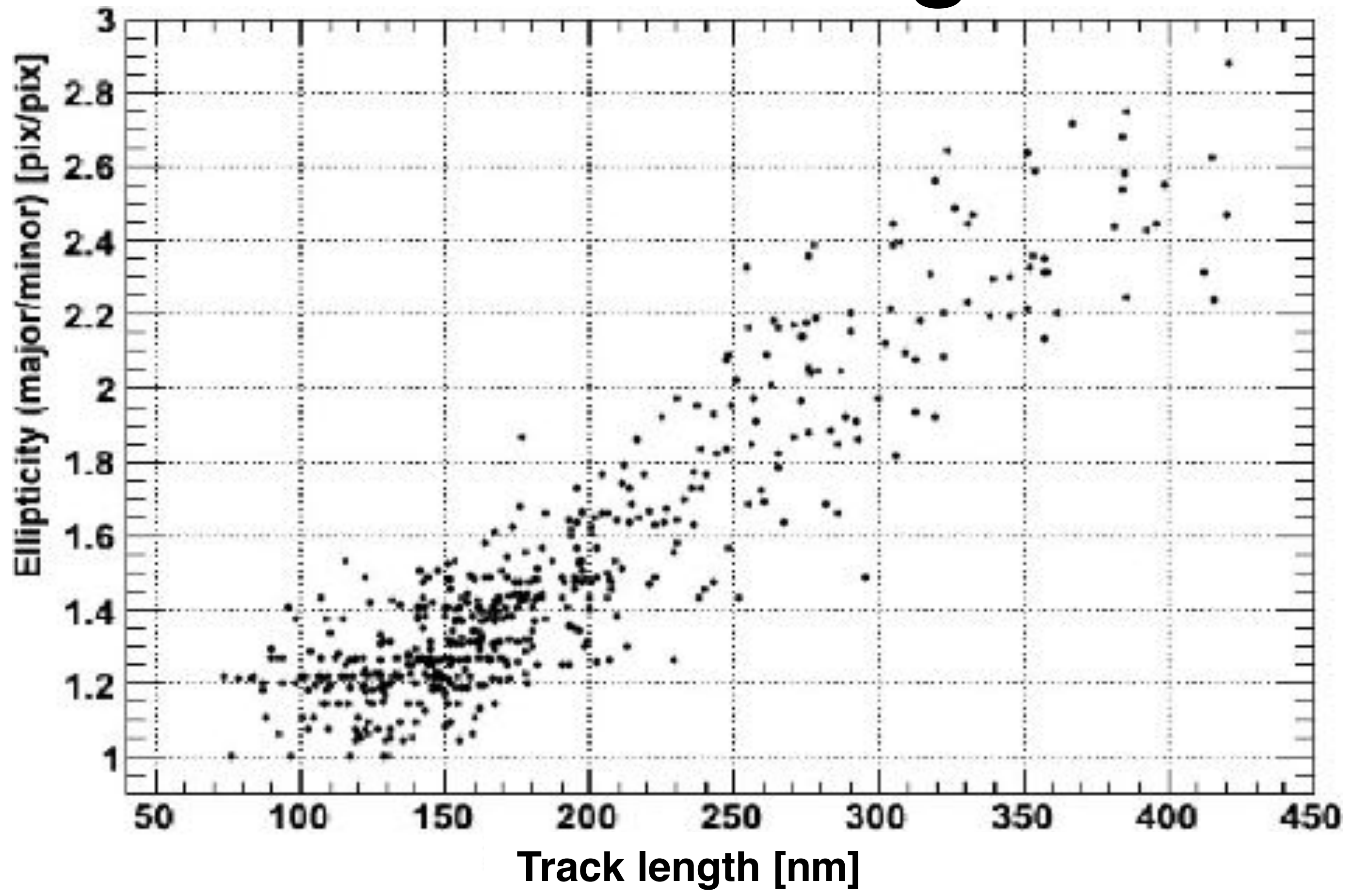
M_W~10GeV/c^2 NR track≪200nm

Tracks scanning with optical microscopes

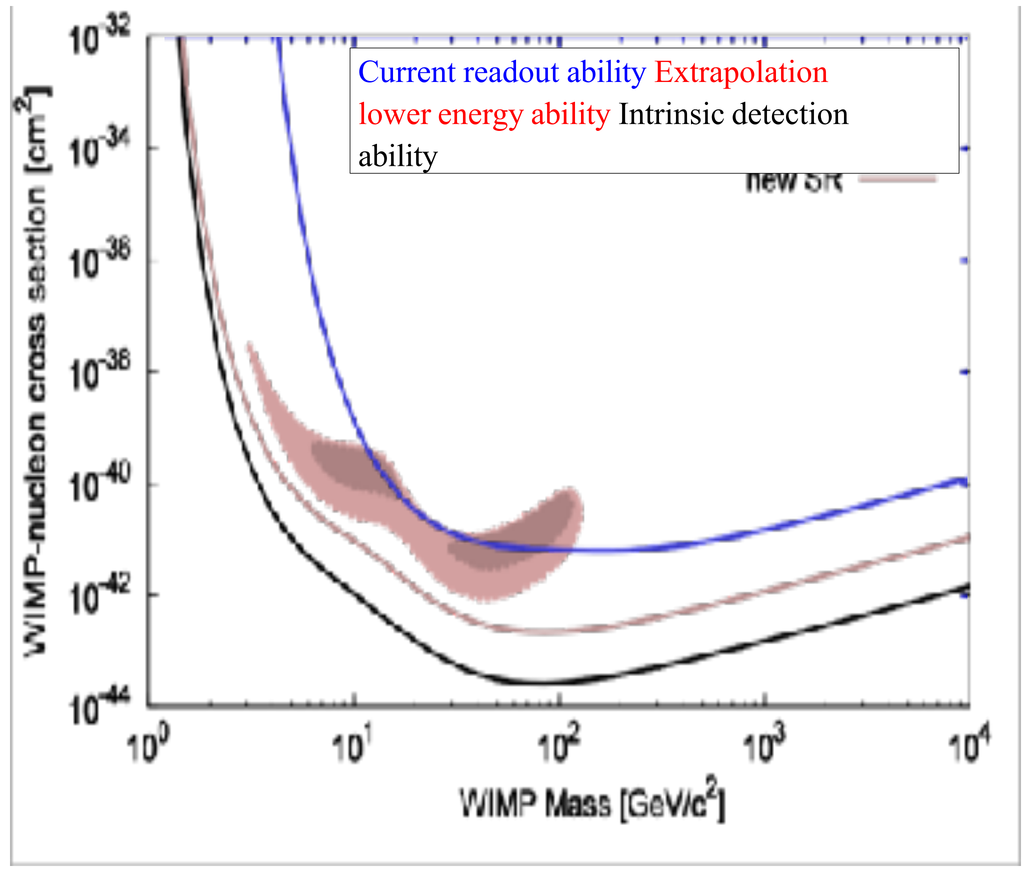


Current scan speed: 30g/y

Current microscope could select >100 nm length tracks



10 kg y sensitivity (No bkg)



Q-balls

Aggregates of elementary particles (bosons) from the Dark Sector (like supersymmetric DM)

Extraction

Picture of the extraction plant used to procure DS50 UAr target (<0.5kg/d)

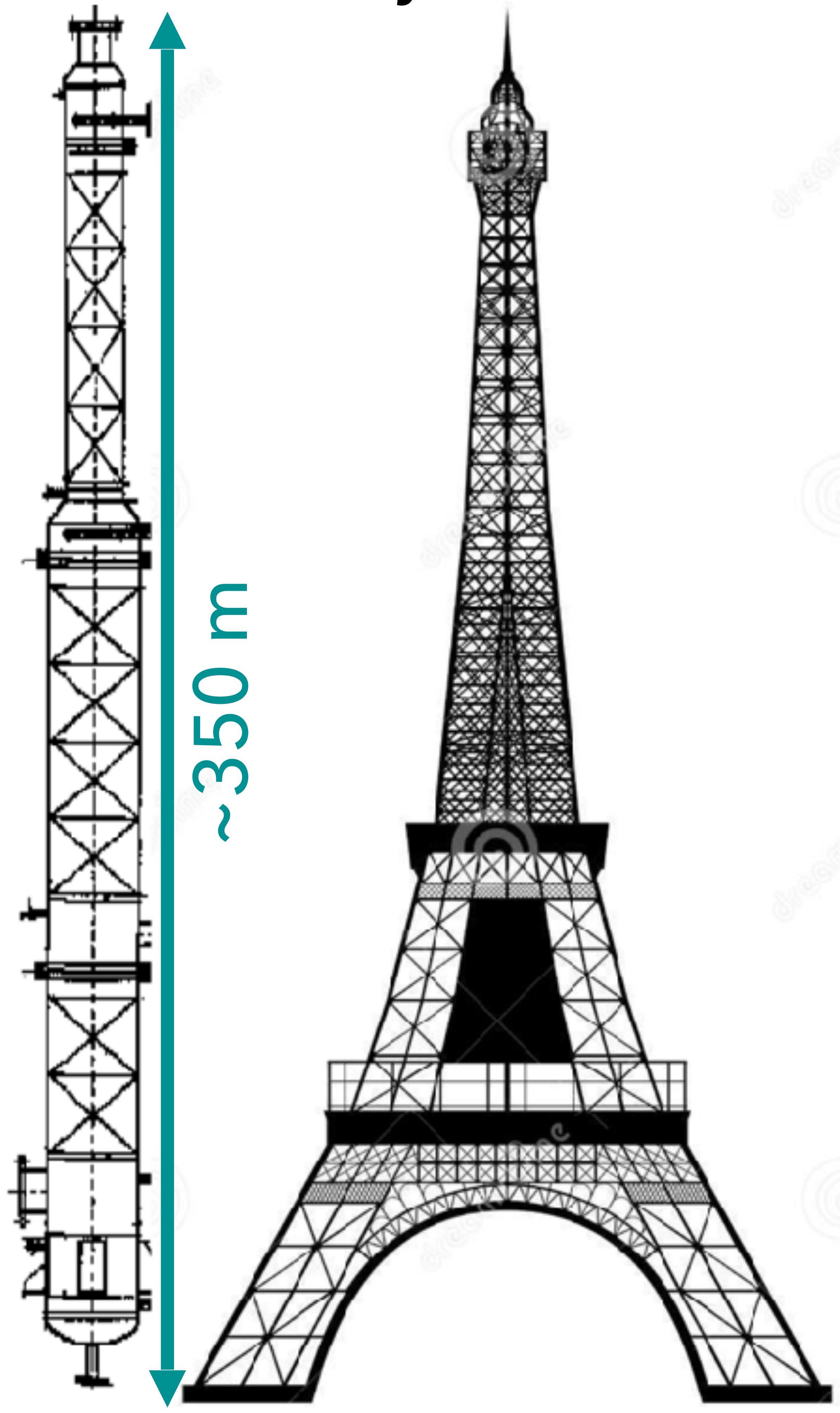
- CO_2 well in Cortez, CO, USA;
- Industrial scale extraction plant;
- Plant has been shipped to Colorado;
- Civil work ongoing;
- Expected argon purity at outlet: 99.99%;
- UAr extraction rate: 250-330 kg/day;

Purification

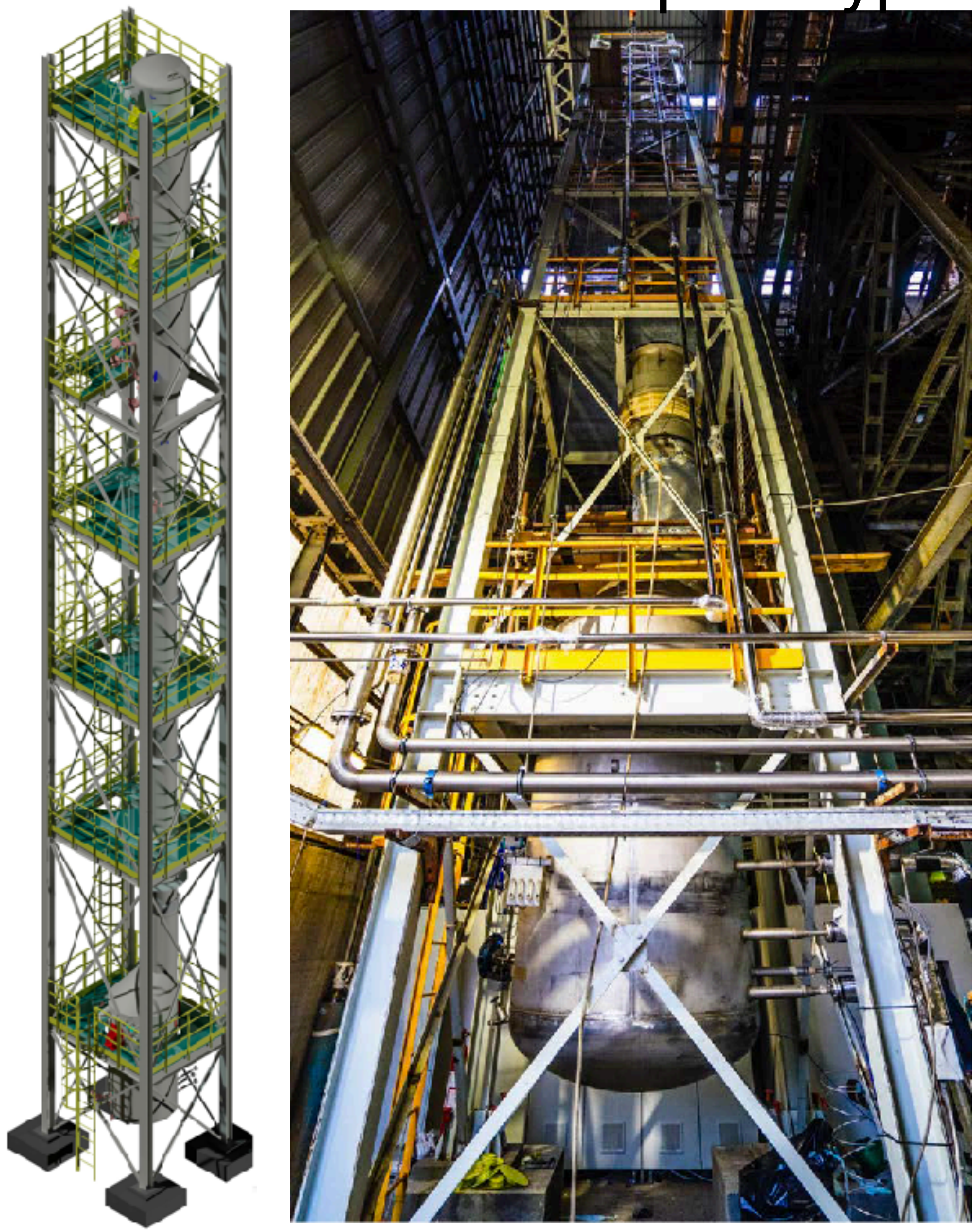
ARIA: UAr distillation plant

- Cryogenic distillation column in Sardinia (Italy).
- Installed in the shaft of a coal mine
- Three sections: bottom reboiler, 28 central modules (12 m each), top condenser
- Chemical purification rate: 1 t/day
- First module operated according to specs with nitrogen in 2019 (Eur. Phys. J. C (2021) 81:359)
- Run completed with Ar at the end of 2021: results to be published soon.
- Full assembly to start in 2023

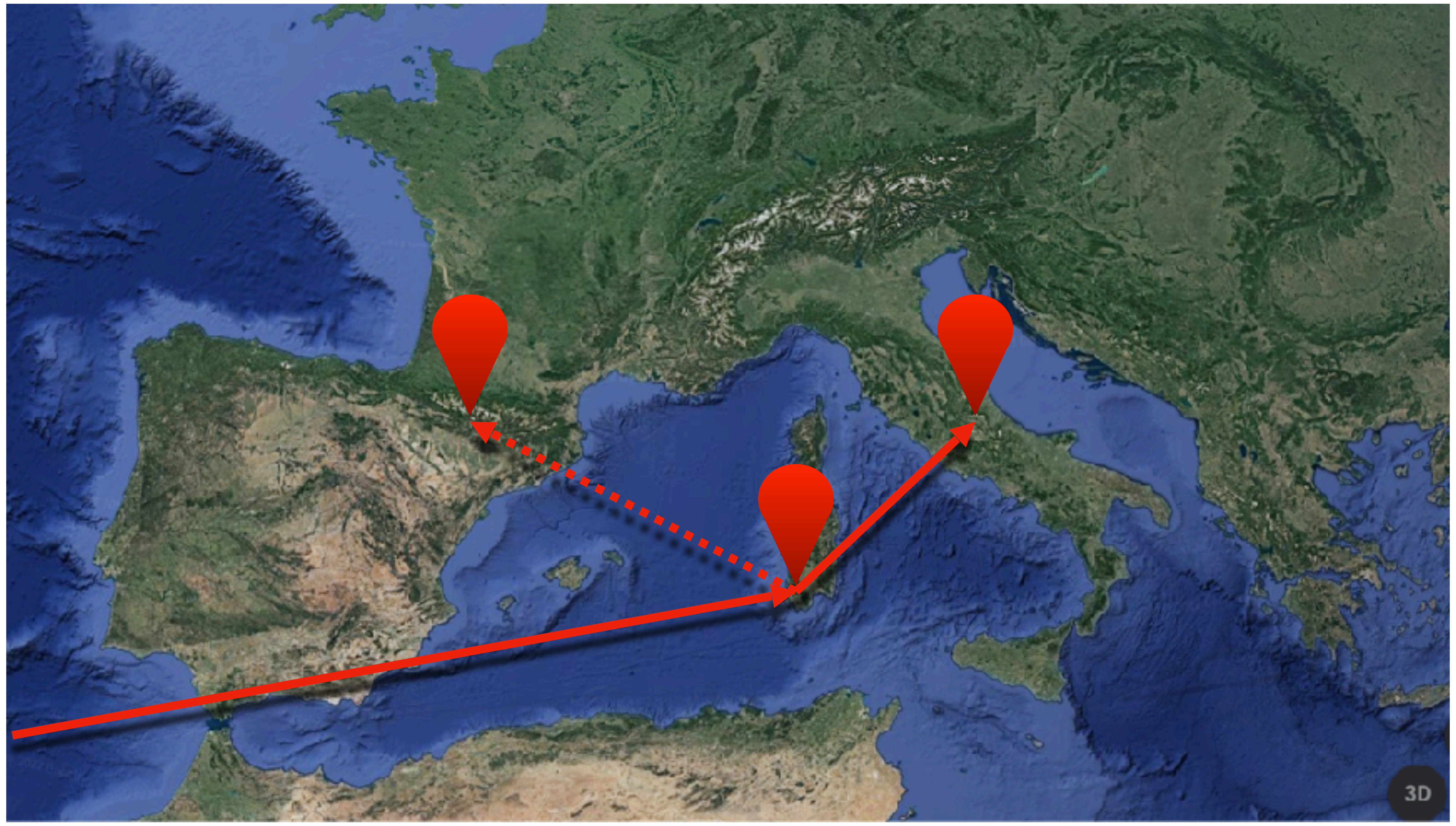
Sketch of ARIA when fully assembled

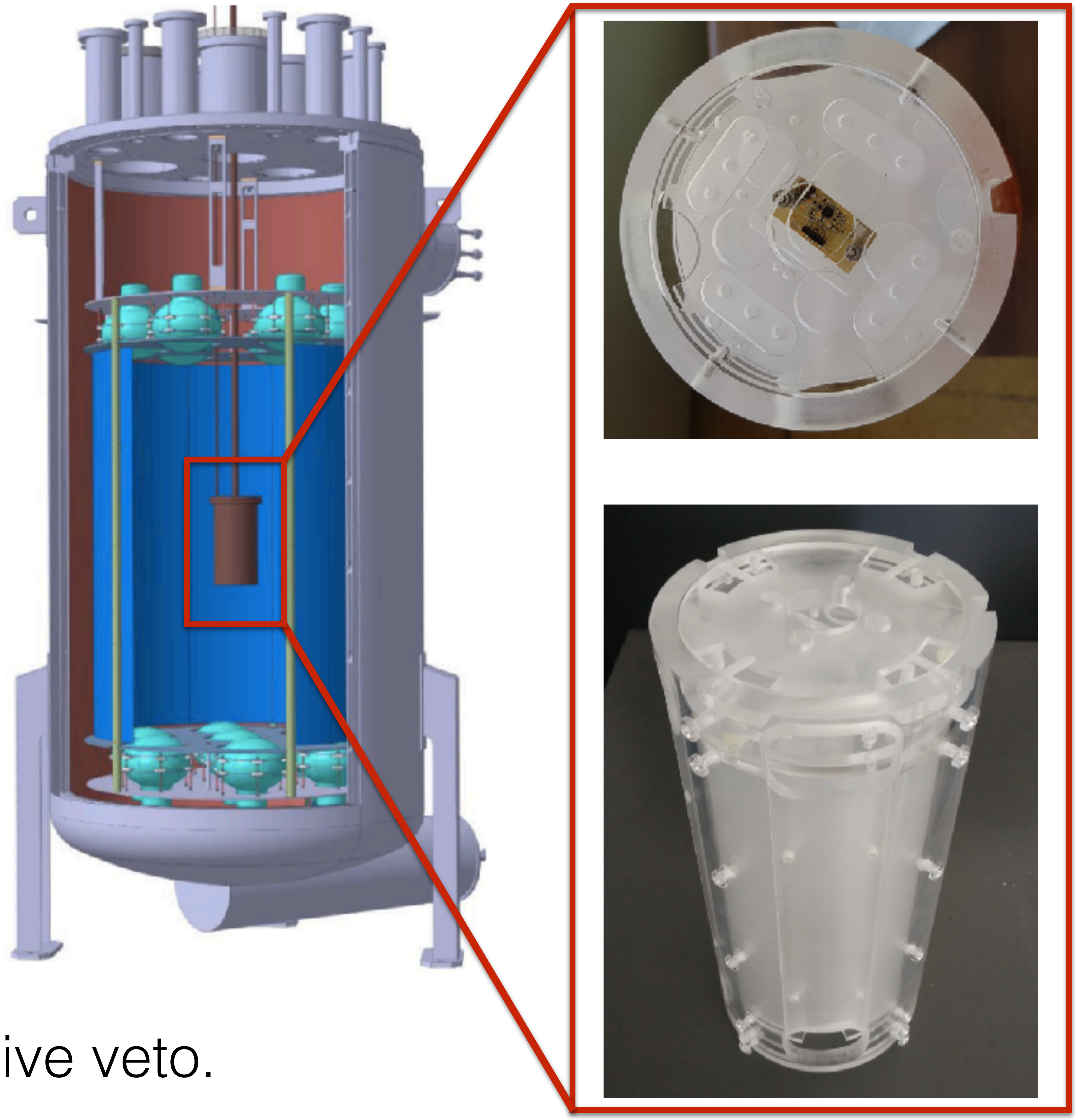


Drawing and picture of ARIA distillation column prototype



Assaying





DArT : Measurement of the activity of the ^{39}Ar

- LSC, Canfranc, Spain
- Single-phase inner detector for 1.42 kg of liquid UAr
- Will be installed inside ArDM detector, acting as an active veto.
- ^{39}Ar depletion factor sensitivity: U.L. 90% CL. 6×10^4 (2020 JINST 15 P02024).