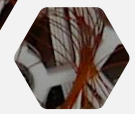
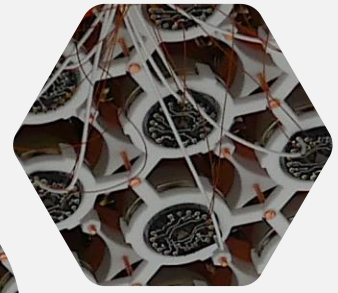
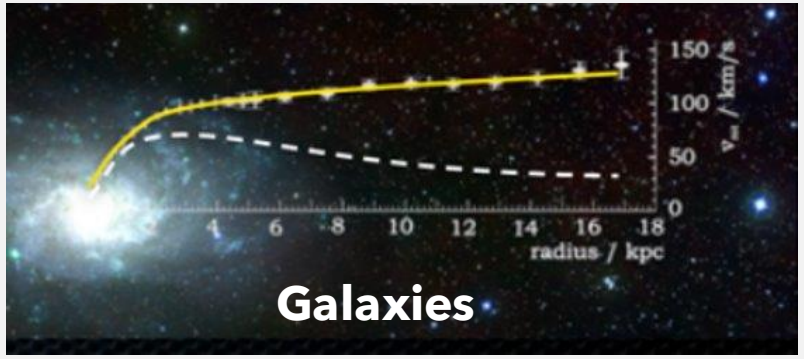


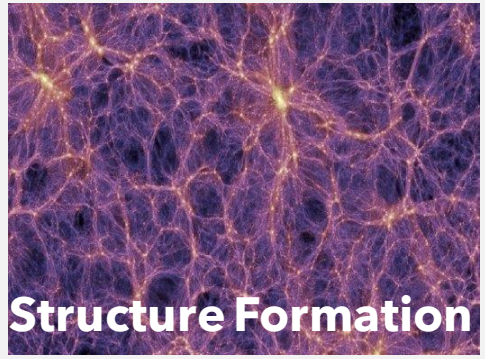


Dark Matter:
Looking beyond the Lamp Post

Jacques Pienaar
25 September 2023

Evidence for Missing Mass

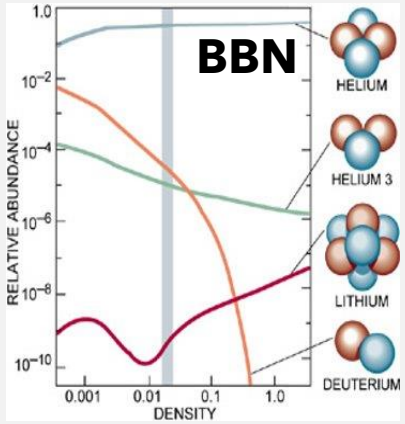


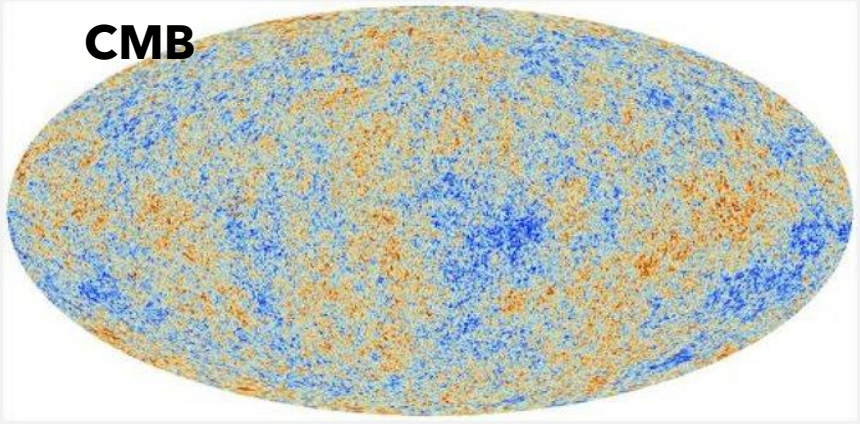


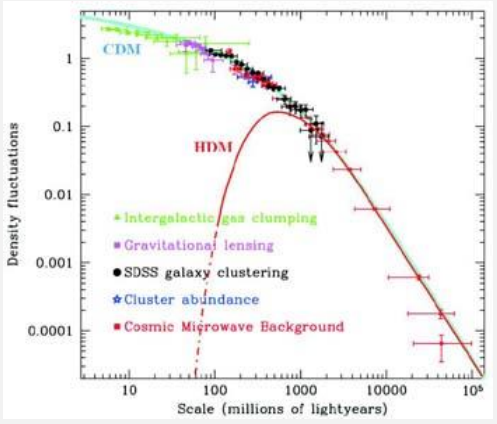
Evidence for Dark Matter

- At various length scales
- Throughout the lifetime of the universe

Motivates terrestrial based search via direct detection

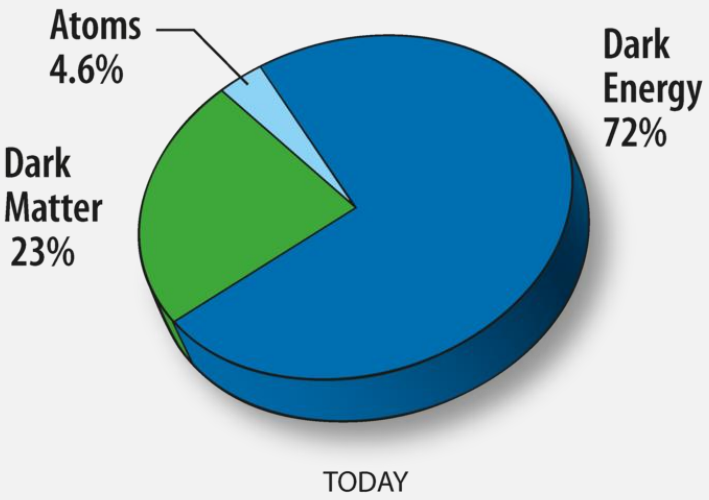


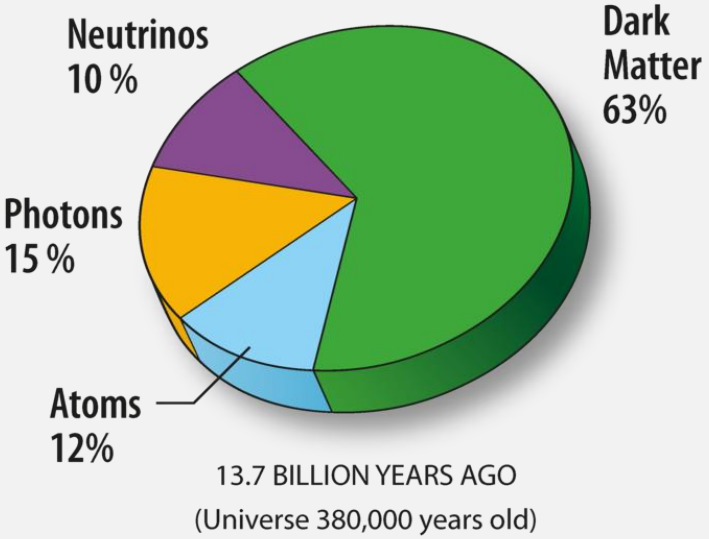




arXiv:astro-ph/0409280

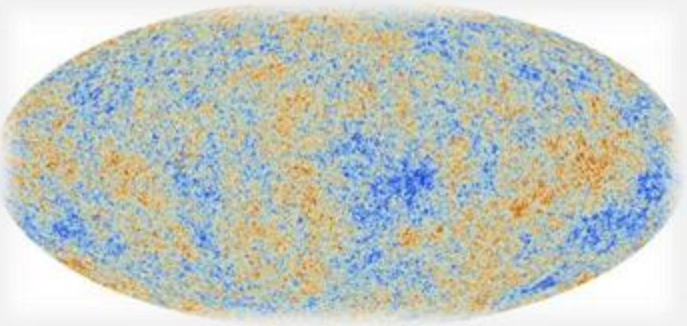
Modern Measurements

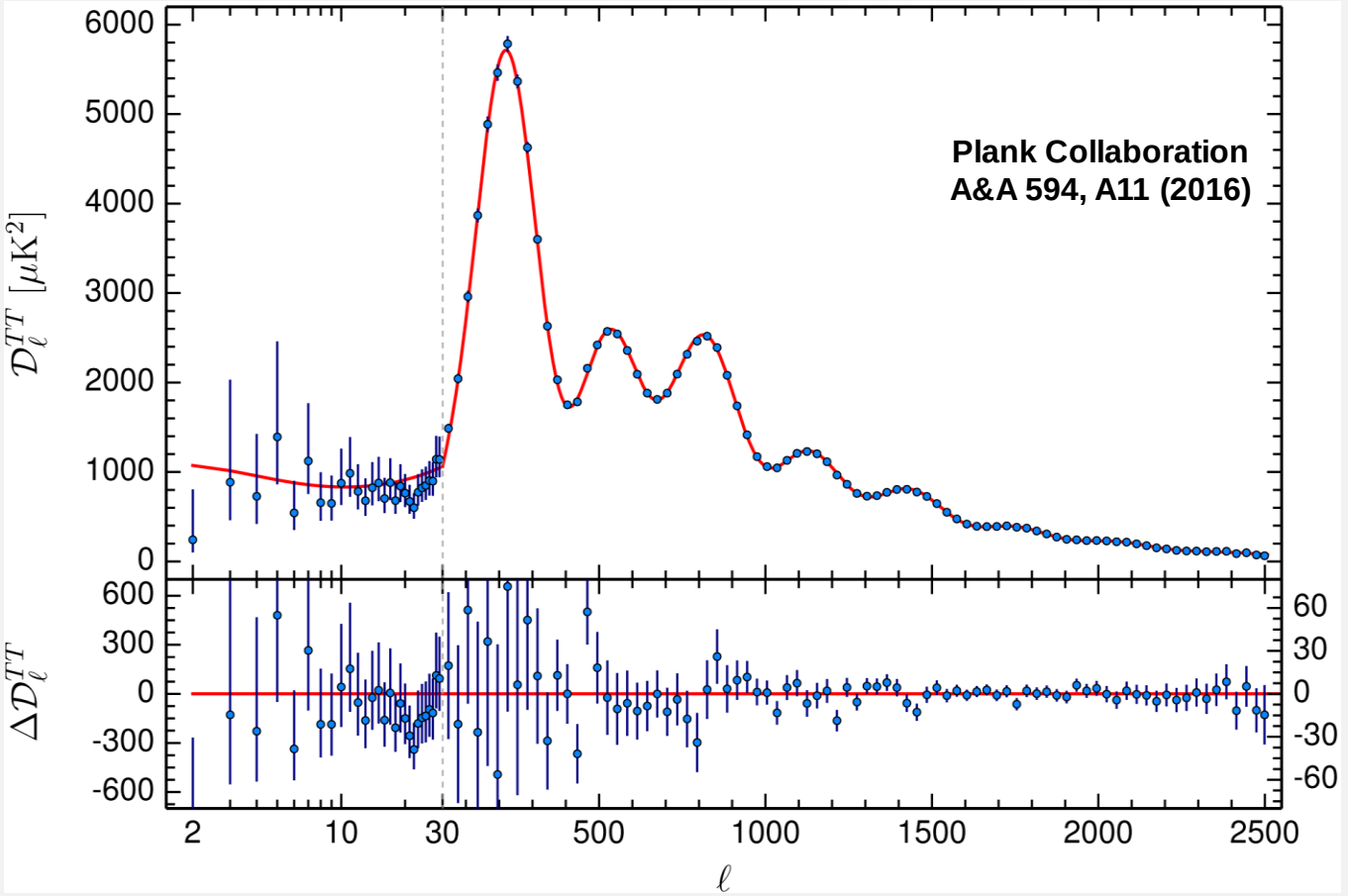




Measurement of CMB implies existence of cold dark matter

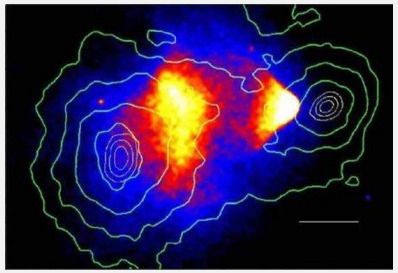
Additional evidence of changing dark matter component





Detection Strategies

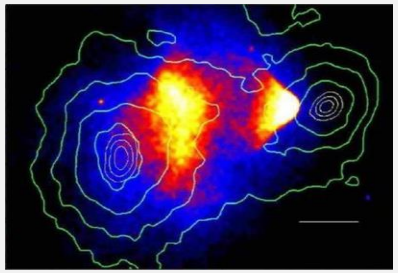
- Self Interaction



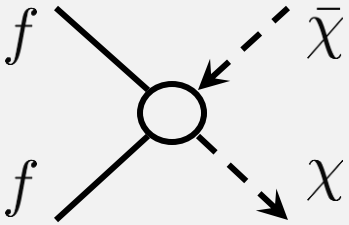
- Production
- Annihilation
- Scattering

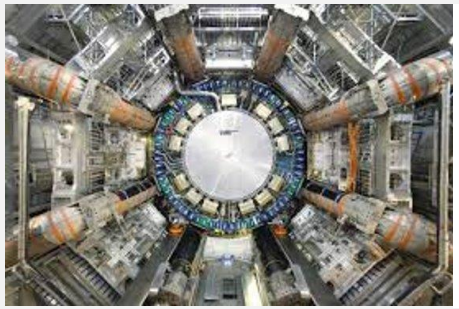
Detection Strategies

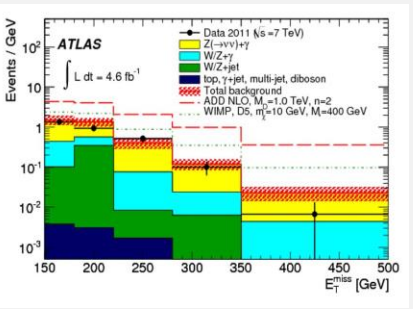
- Self Interaction



- Production





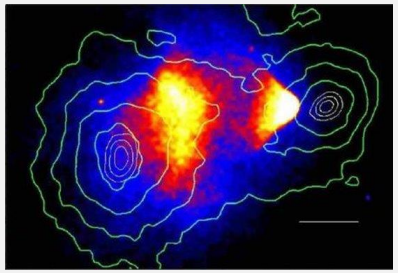


- Annihilation

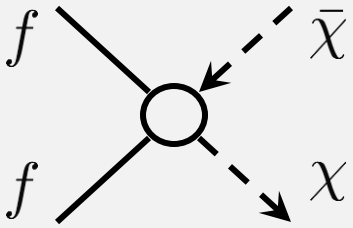
- Scattering

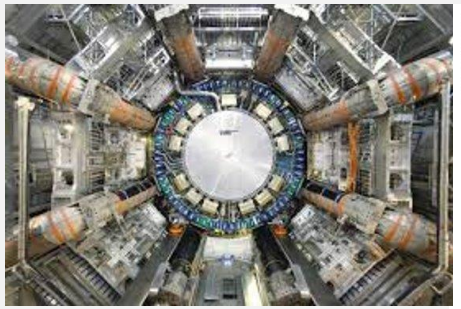
Detection Strategies

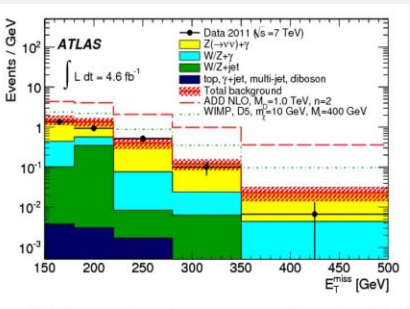
- Self Interaction



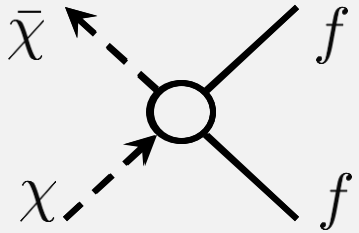
- Production

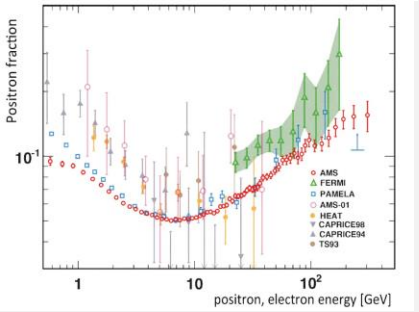






- Annihilation
  - Indirect Detection (now)
  - Thermal freeze-out (early Univ.)

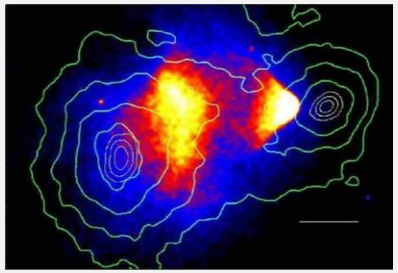




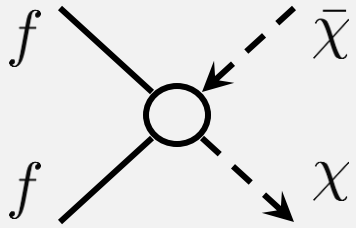
- Scattering

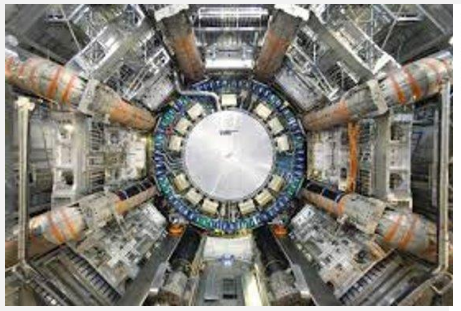
Detection Strategies

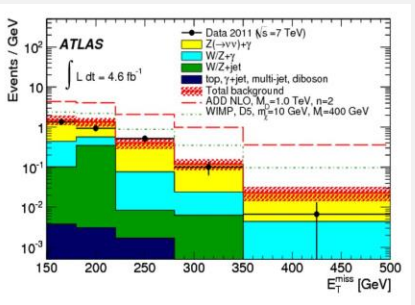
- Self Interaction



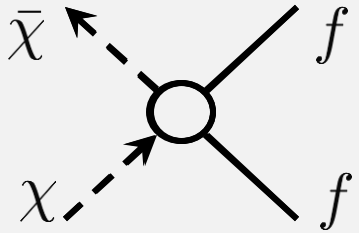
- Production

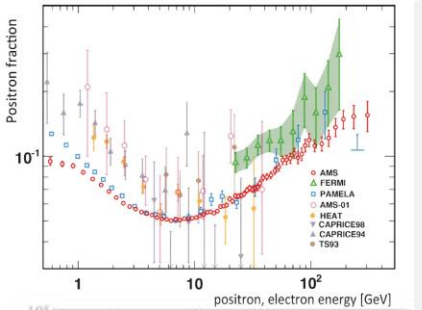




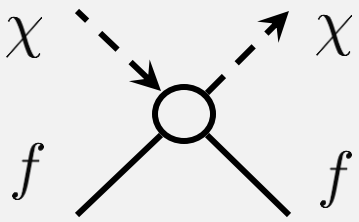


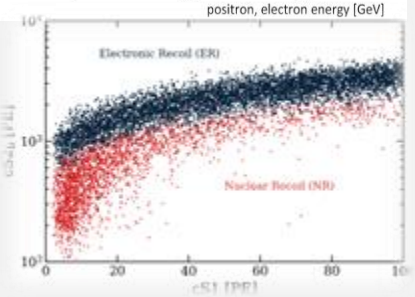
- Annihilation
  - Indirect Detection (now)
  - Thermal freeze-out (early Univ.)



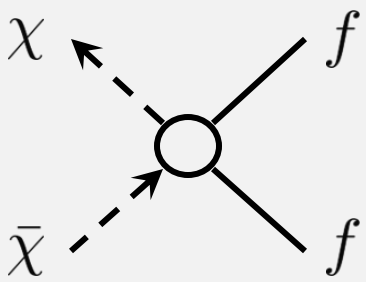


- Scattering
  - Direct Detection



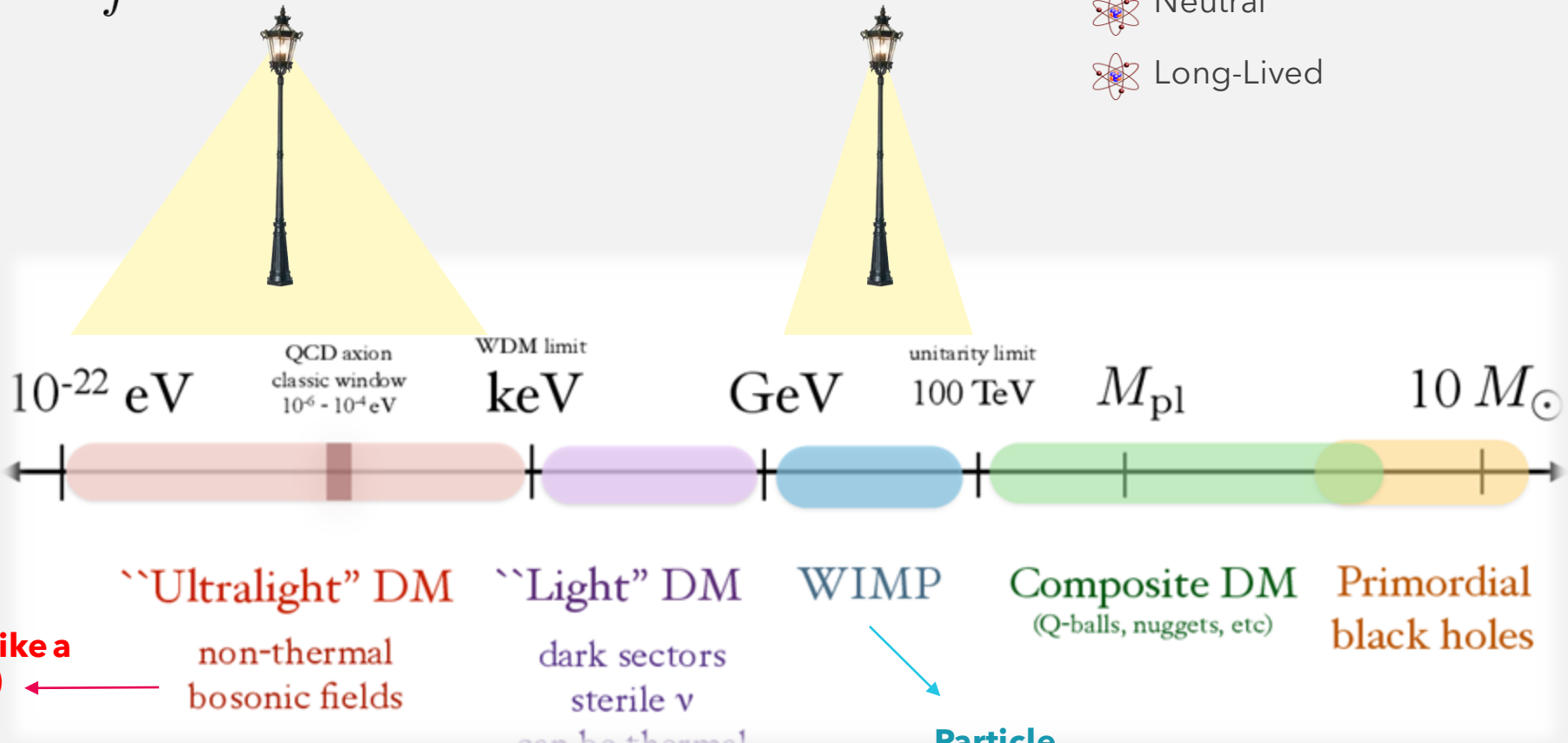


Searching Under The Lamp Post



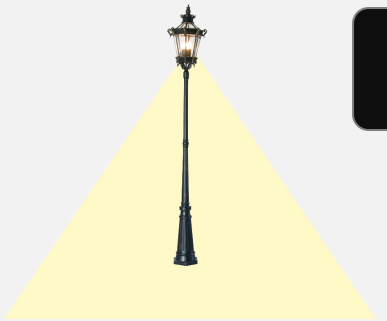
Dark Matter Candidates are

- Massive
- Non-baryonic
- Neutral
- Long-Lived



DM behaves like a wave (axions)

Particle Interactions



The Axion Lamp Post

Axions originate from strong CP Problem:

- Experimental limits on electon-dipole moment of neutrons are $<10^{-26}$ e cm
- Corresponds to a fine tuned CP-violating phase near zero, even though strong force should violate CP symmtery in QCD

Peccei-Quin Mechanism as Solution:

- Introduce a new U(1) symmetry
- When broken thiscancels the CP violating phase
- New pseudo-scalar called an axion

With right abundance this looks like dark matter!

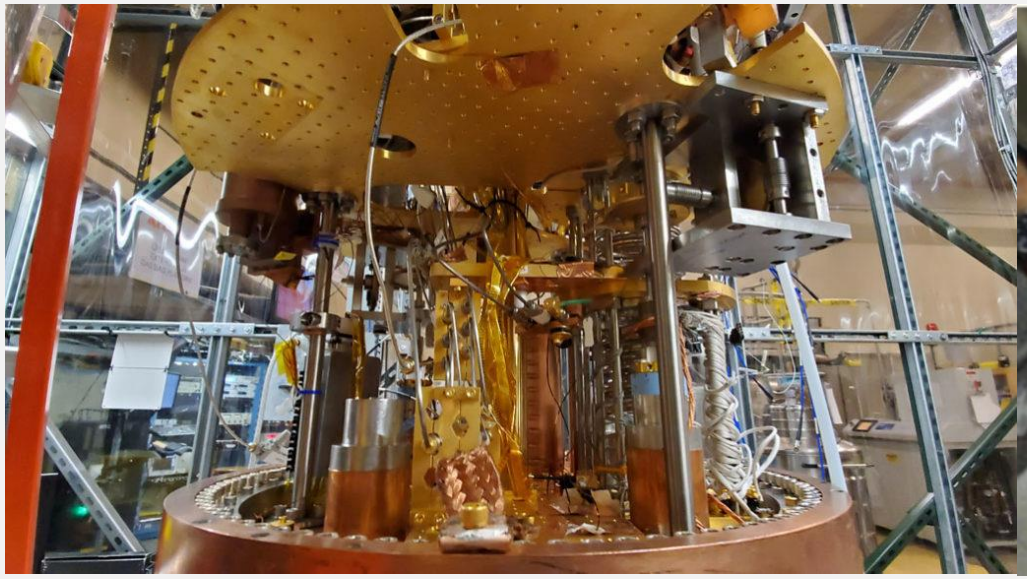
Using (EM) light to find Axions

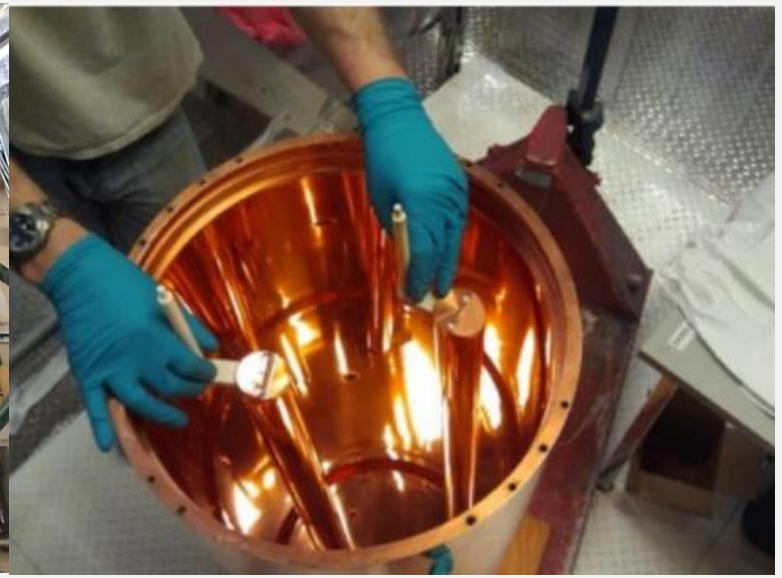
Assuming all DM corresponds to the QCD axion:

- Use Primakoff-effect (converting axions to photons and vice versa) in magnetic fields
- Observed as resonance photon production in cavities that are tuned to the axion frequency

$$\frac{df}{dt} \propto QV^2C^2B^4T^{-2}$$

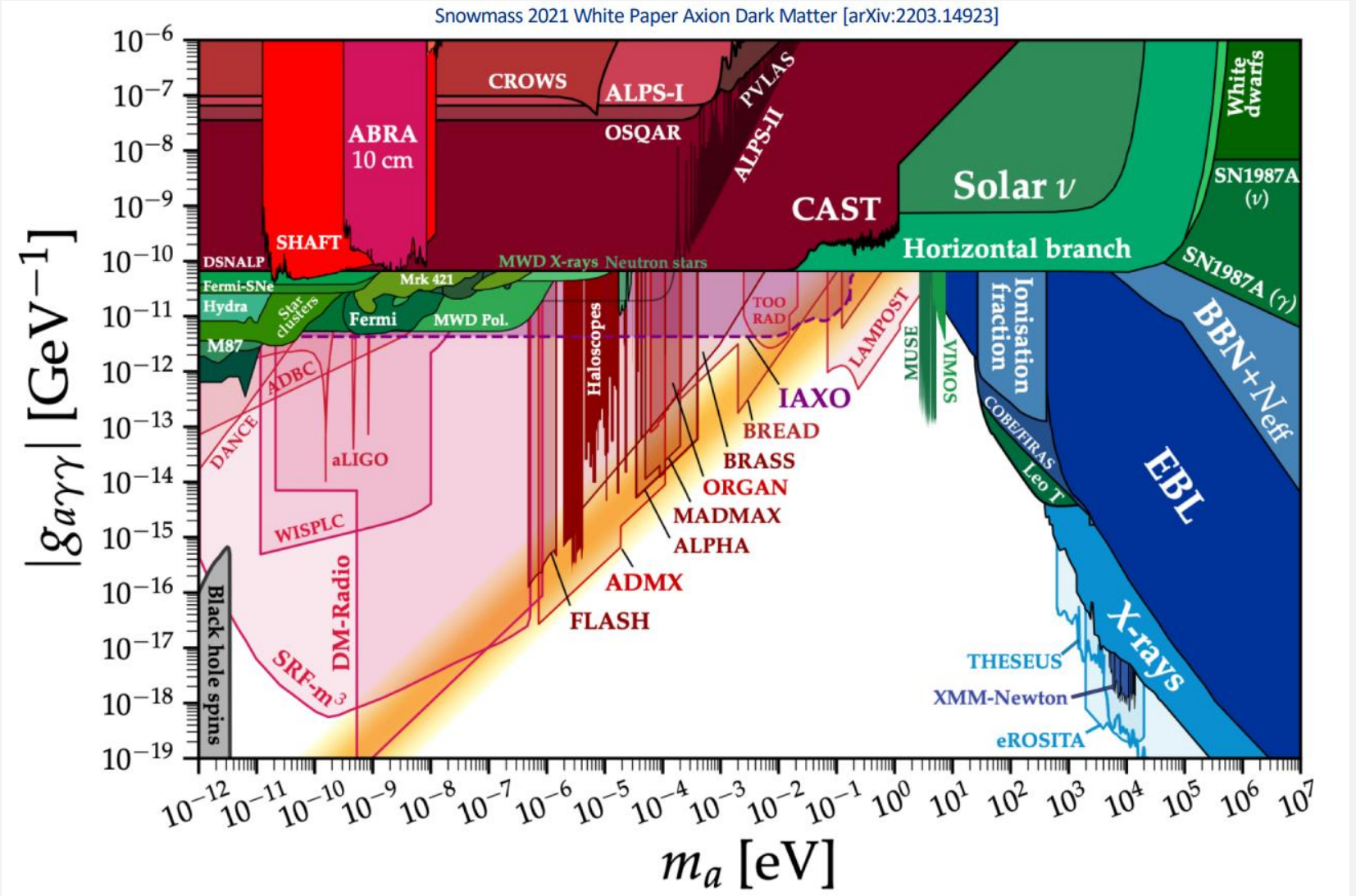
Quality factor, Cavity volume, Form factor, Magnetic Field, Noise Temperature





ADMX looking for QCD axions around 3 ueV

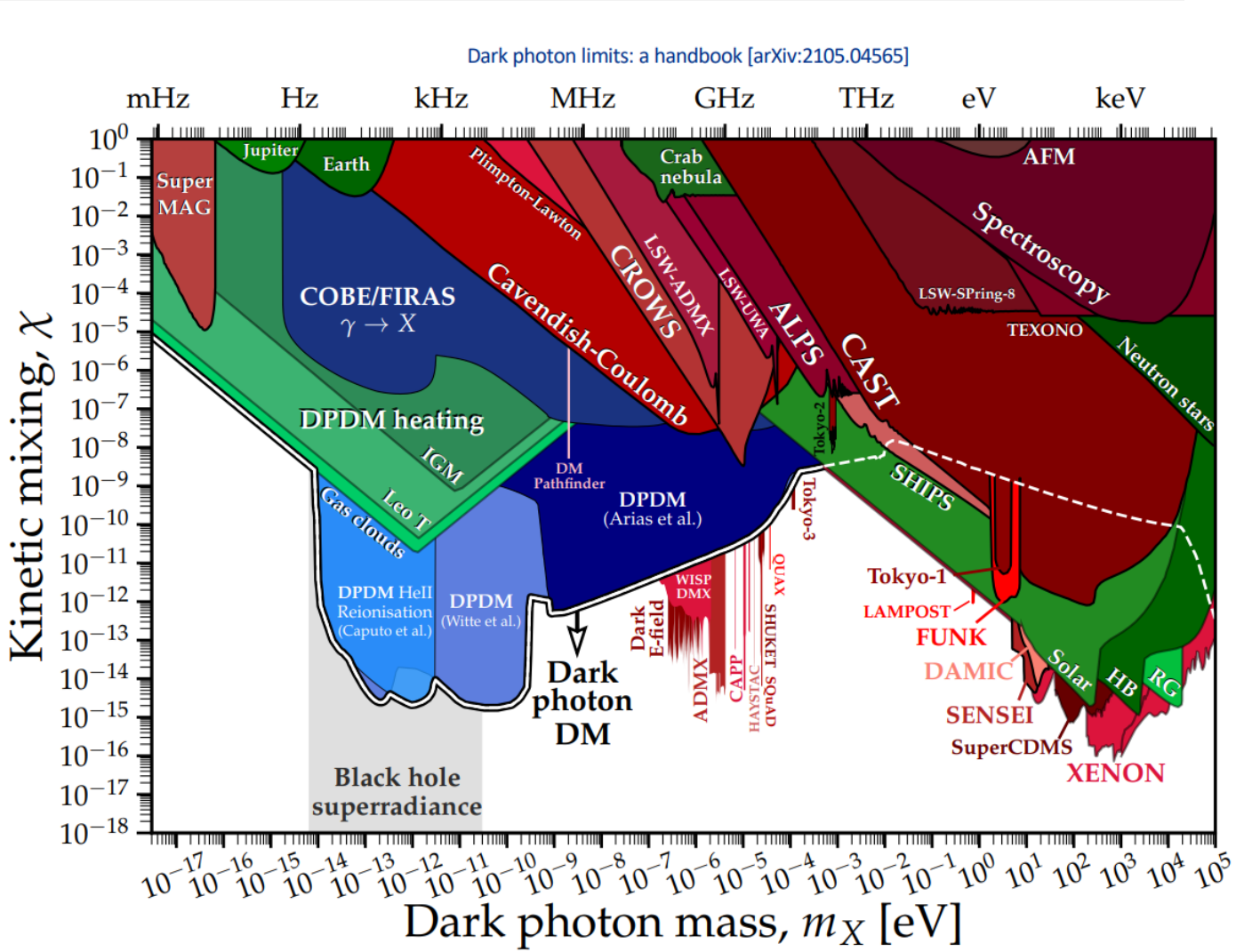
Broad axion mass range, myriad of experimental efforts



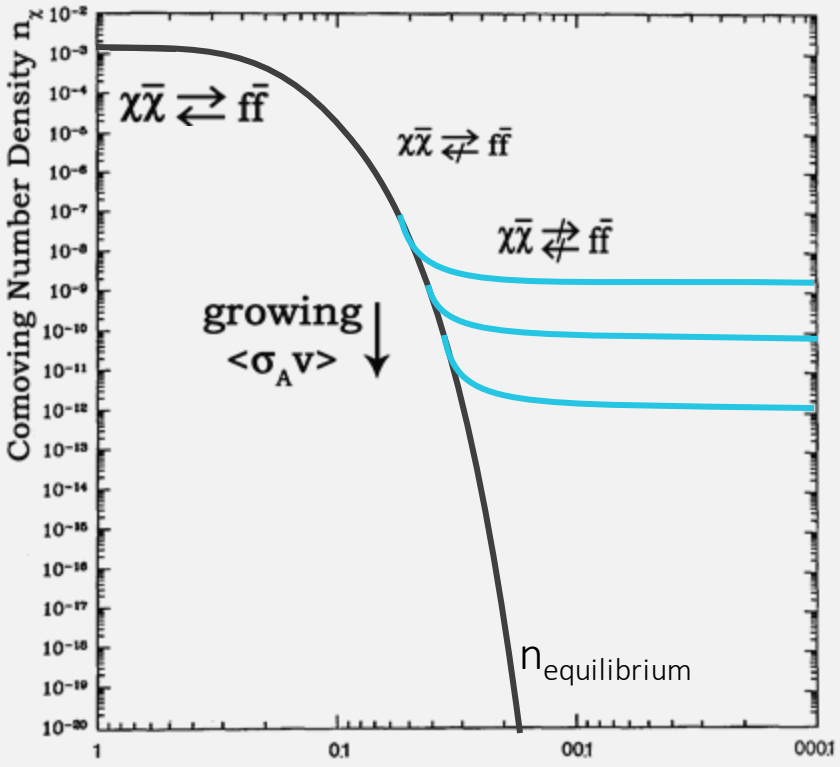
"Dark Photons"

Dark Photon (m_A) introduces a new broken U(1) symmetry

- Mixes with standard model photon
- Large degree of flexibility w.r.t. mixing angle and dark photon mass
- Many DM models with stable relic DM particle couple to SM via kinetically mixed dark photon
- With sufficently small mass ($m_A < 2\ m_e$) dark photon can only decay in SM via 3 photons, making these particles relic DM candidates themselves
- Search via:
  - Running axion cavity search without magnetic field, looking for photons from spontaneous conversion.
  - Detecting energy deposited in detector target from dark photon absorption

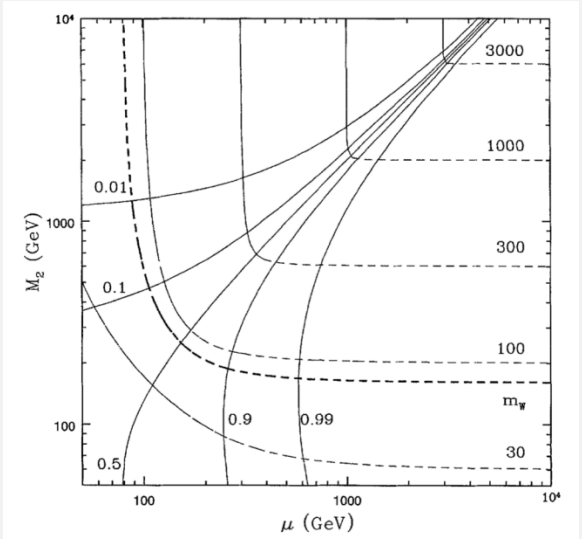


Historical Motivations for WIMPs

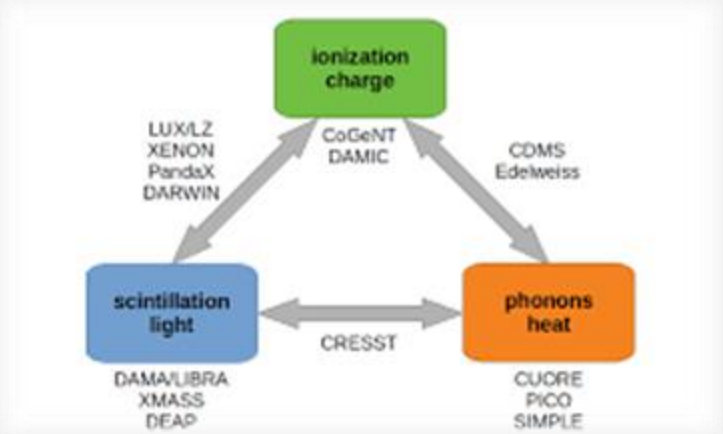


The WIMP Miracle

- As universe cools, DM production ceases
- Density drops until DM interaction become sufficiently rare
- Interaction cross section required to produce measured DM density on the order of the elctro weak scale
- Consistent with excpectation from lightest supersymmetric particles



Utilizing the WIMP Lamp



Elastic Collisions

- GeV scale WIMPS
- Recoil energy < 50 keV

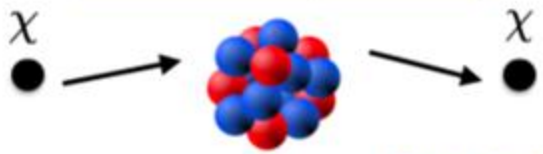
DM Detector independent

- DM density
- Galactic escape velocity
- Earth/Sun velocity

Accord in:

- **Baxter et al** *Eur. Phys. J. C* 81, 907 (2021)

Elastic two-body scattering



Rate scales linearly with DM-nucleon cross section

Spin-independent coupling enhancement by number of nucleons²

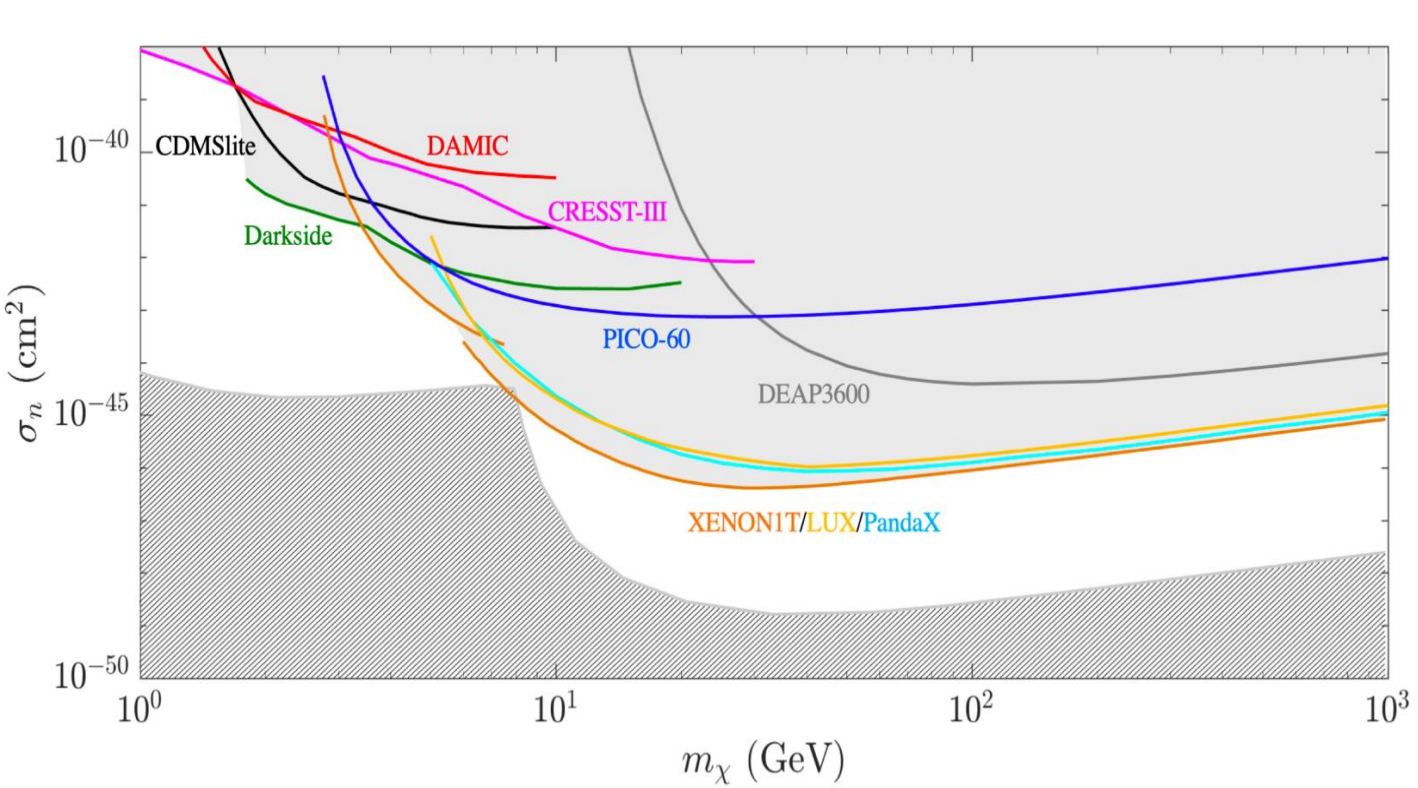
Dependence on DM velocity:
- As M_χ decreases, this integral rapidly gets smaller
- As m_A increases (heavier target), this integral gets smaller

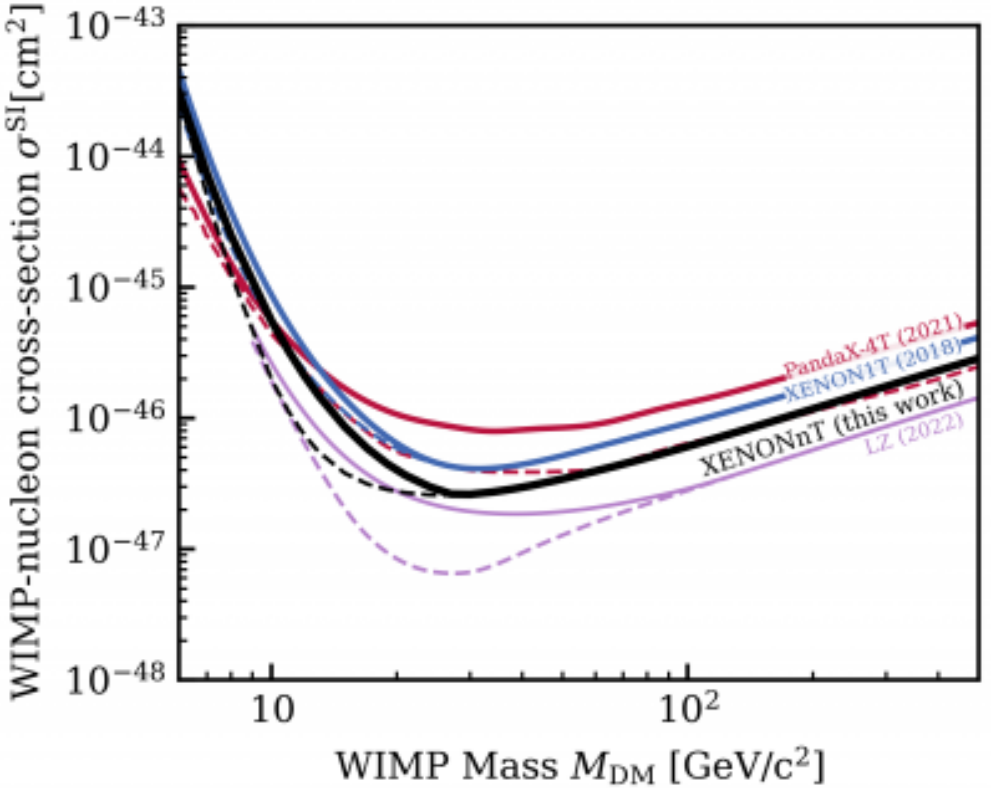
$$\frac{dR^{NR}}{dE_R} = \sigma_n \frac{\rho_\chi}{M_\chi} \frac{m_A}{2\mu_{n\chi}^2} A^2 F_A(q)^2 \int_{v_{min}(E_R)}^{v_{esc}} d^3v \frac{f(v, v_E)}{v}$$

Properties of the DM

Atomic form factor determined from nuclear physics data, $F(q=0) = 1$

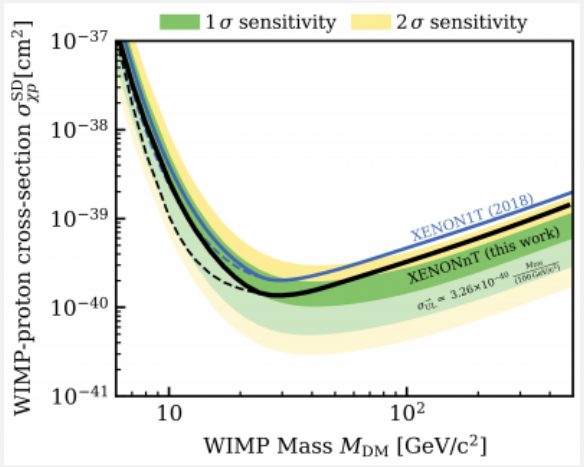
Twenty years of the WIMP lamp

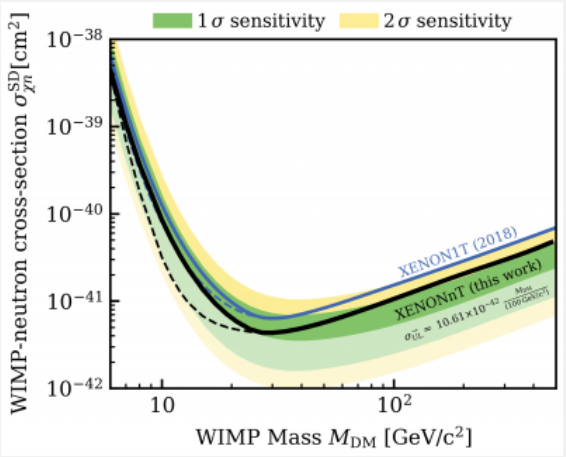


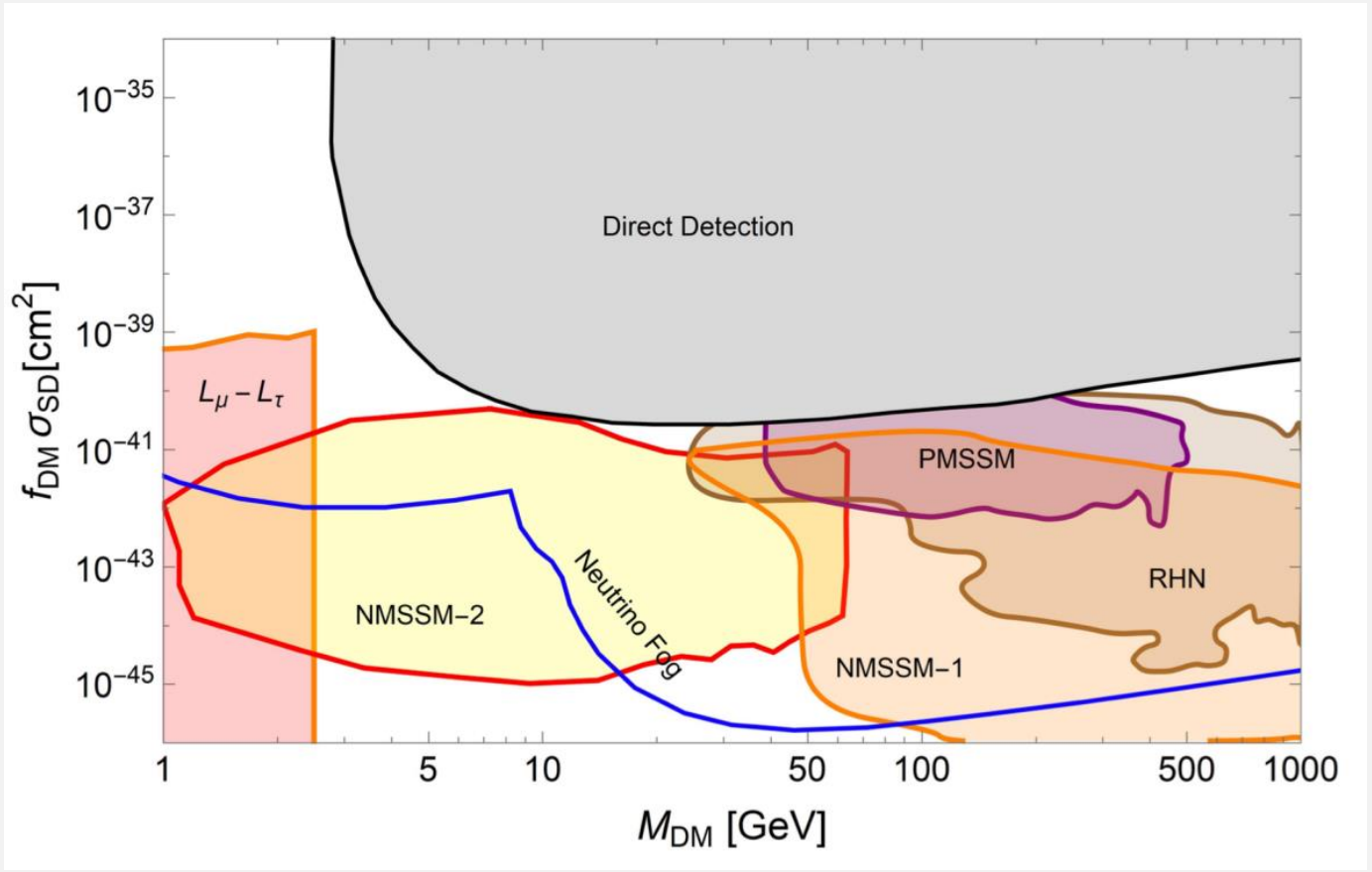


- Liquid Noble Gas Detectors pioneers above 1 GeV
- Crystal Detectors utlizing phonons have pushed sensitivity at smaller masses

Twenty years of the WIMP Lamp



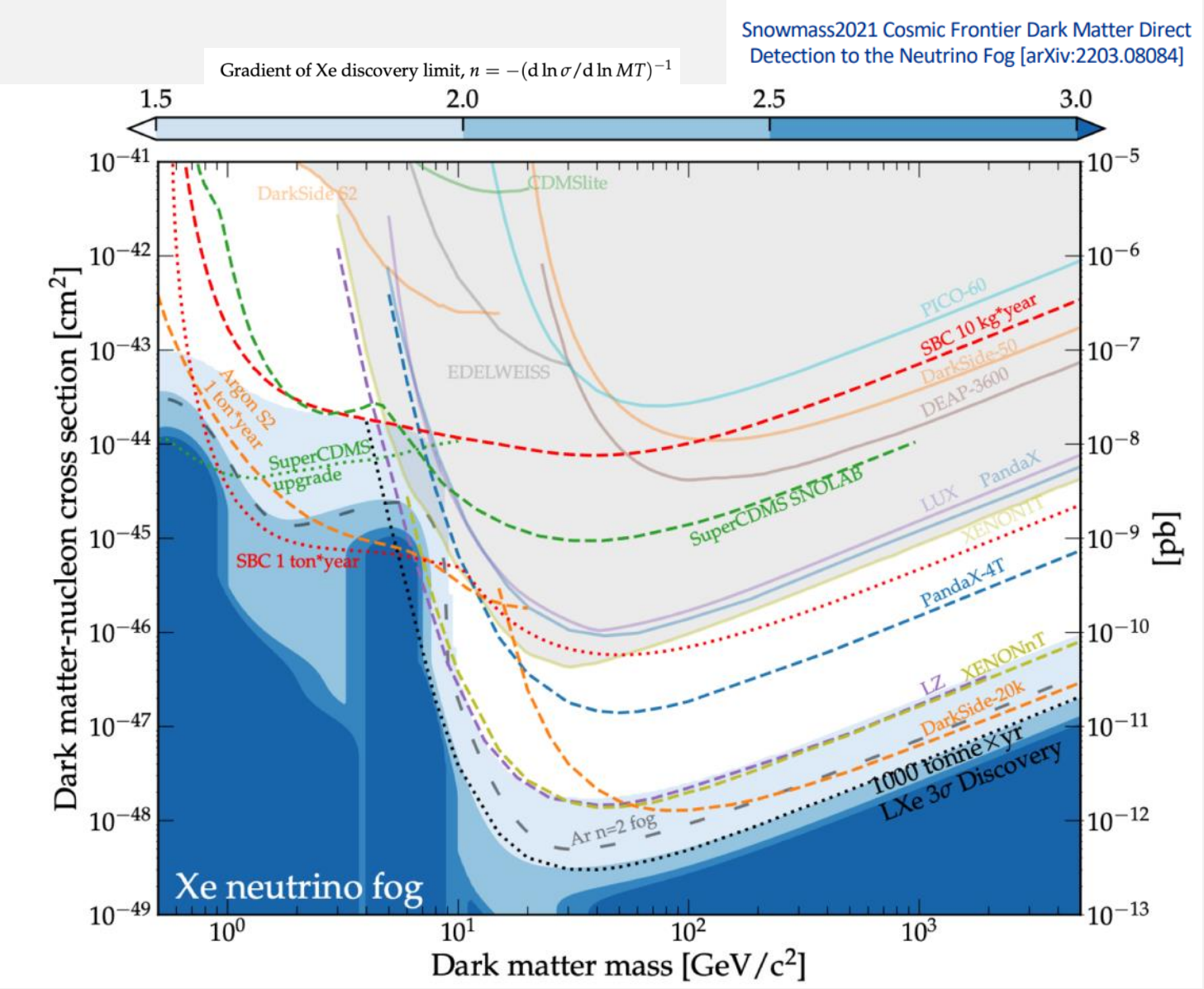




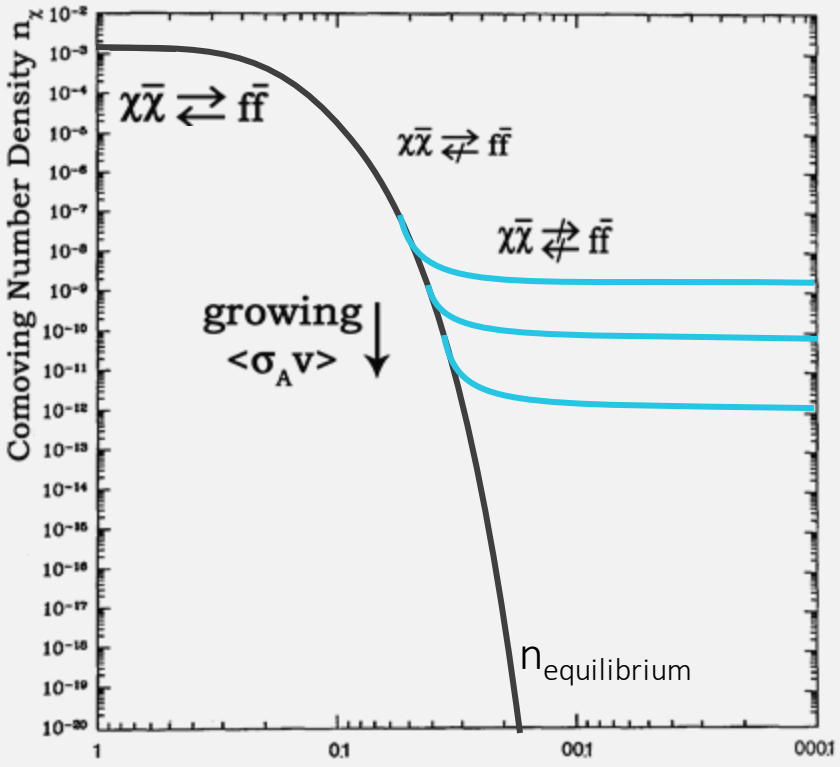
- Interactions with net nuclear spin of target atom can also be probed.

The Neutrino Fog at the Edge of the WIMP Lamp

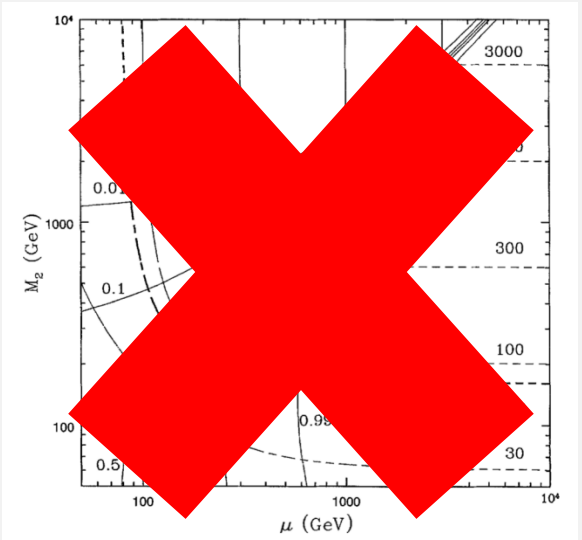
Snowmass2021 Cosmic Frontier Dark Matter Direct Detection to the Neutrino Fog [arXiv:2203.08084]



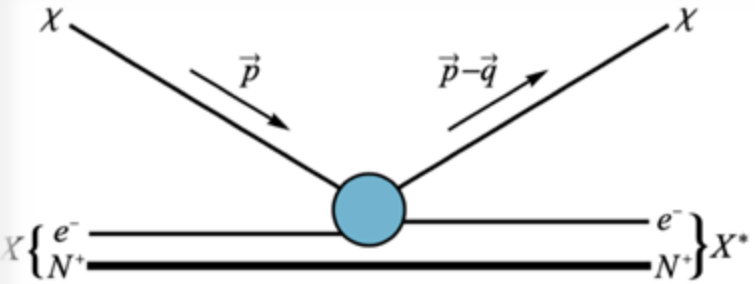
Moving beyond our Lampposts



- Disregard the SUSY motivation
- Thermal relic DM still possible with lower masses



Inelastic Scattering at Lighter DM masses



Essig et al [arXiv:1509.01598]

Inelastic two-body scattering

Integral over momentum transfer

Dependence on DM velocity

$$\frac{dR^{ER}}{dE_e} = \overline{\sigma}_e \frac{\rho_\chi}{M_\chi} \frac{1}{8\mu_{e\chi}^2} \int qdq |F_{DM}(q)|^2 |f_{n,l}^{ion}(q, E_e)|^2 \eta(v_{min})$$

$$|f_{n,l}^{ion}(q, E_e)|^2 = \frac{k'^3}{4\pi^3} \sum_{n,l} |\langle \psi_{E_e} | e^{-i \sum_\alpha \mathbf{q} \cdot \mathbf{x}^\alpha} | \psi_{n,l} \rangle|^2$$

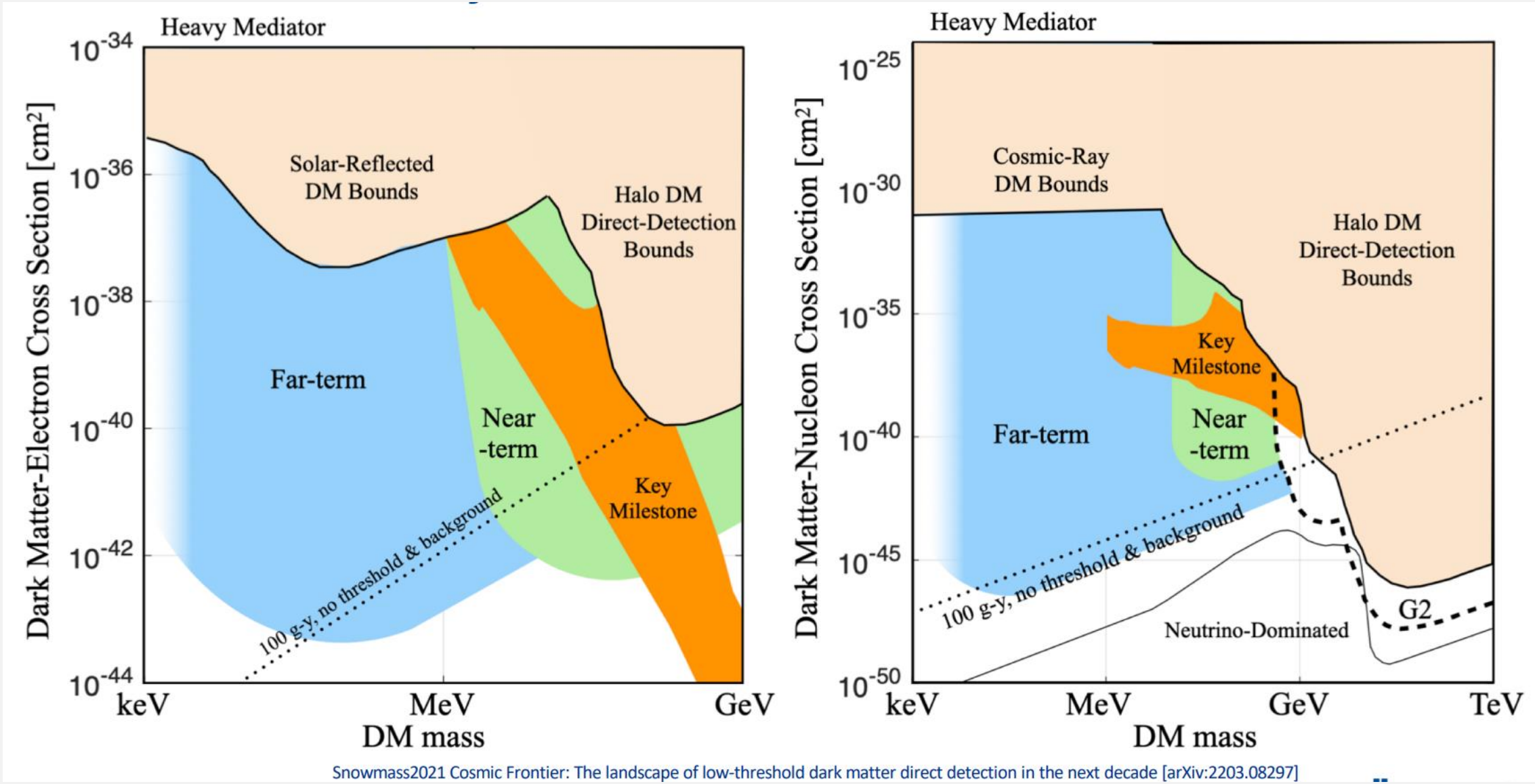
Properties of the DM

Rate scales linearly with DM-electron cross section

DM Form Factor

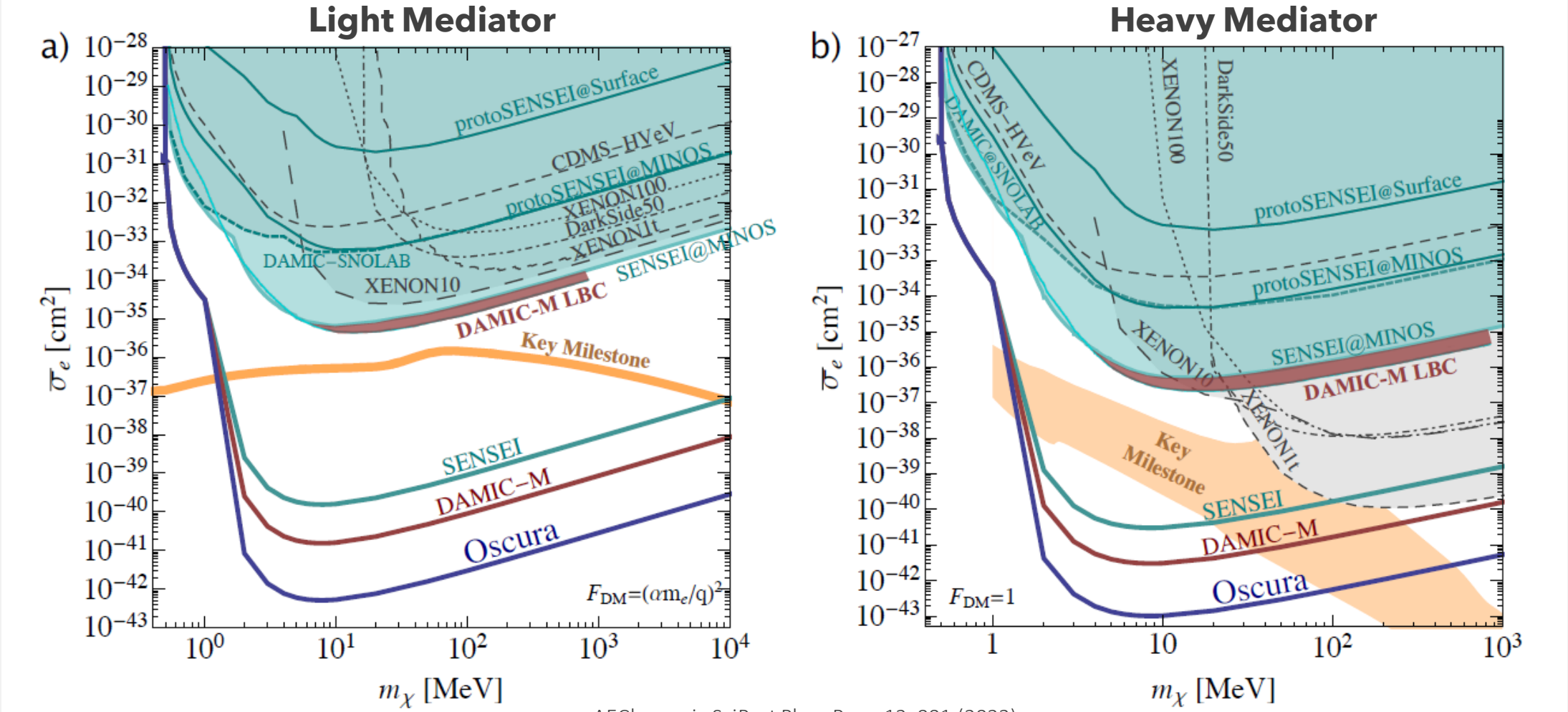
- Choice of DM interaction mediator

Thermal Relic Models are within Reach



Snowmass2021 Cosmic Frontier: The landscape of low-threshold dark matter direct detection in the next decade [arXiv:2203.08297]

New Technologies make new masses accessible

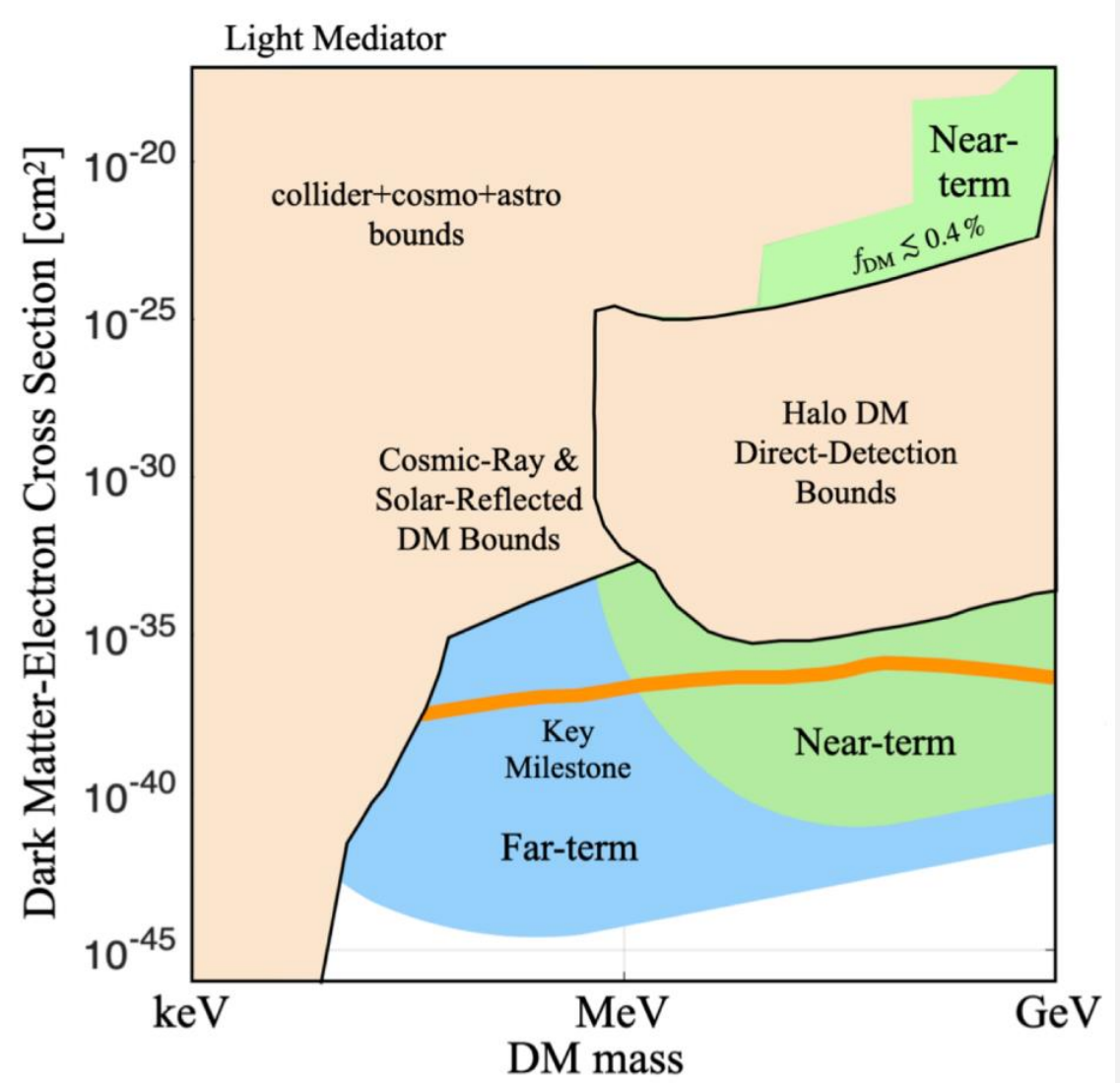


AEChavarria SciPost Phys. Proc. 12, 001 (2023)

New Motivation for Relic Density

Light Mediator:

- Cosmological DM with light mediator coupling can be produced through freeze-in to relic abundance.
- Much lower mass ranges motivated by this method, thus new materials needed to lower thresholds, novel detection techniques



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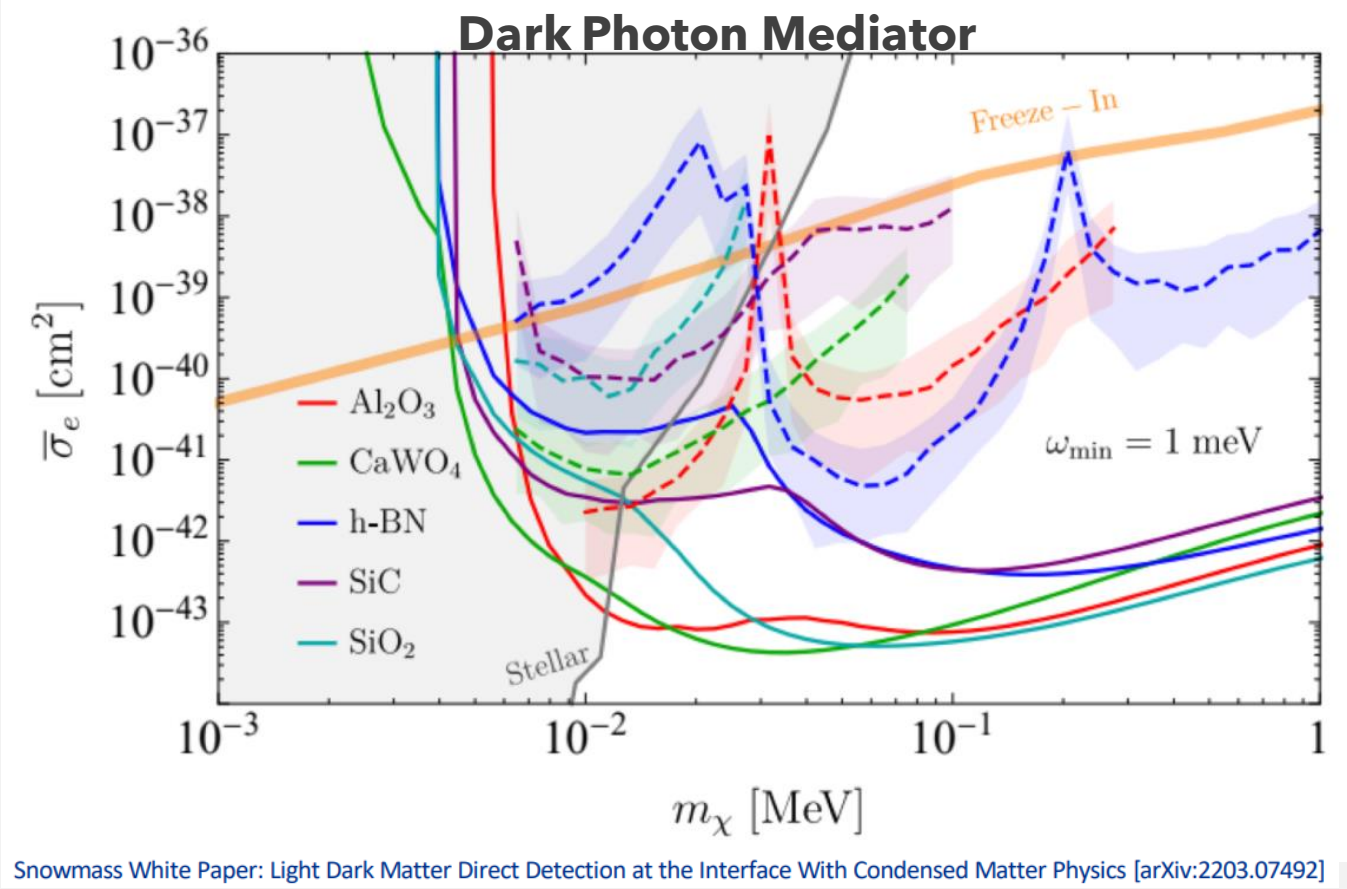
New Materials, New Sensors

- With novel materials we can probe down to eV energies
- Detectors based on crystals can exploit anistropy of crystal structure. Daily modulation of DM signal can be probed
- Sensors must be able to detect meV scale energy deposits
  - Transition Edge Sensors (Tesseract/Herald/Spice)
  - Qubits

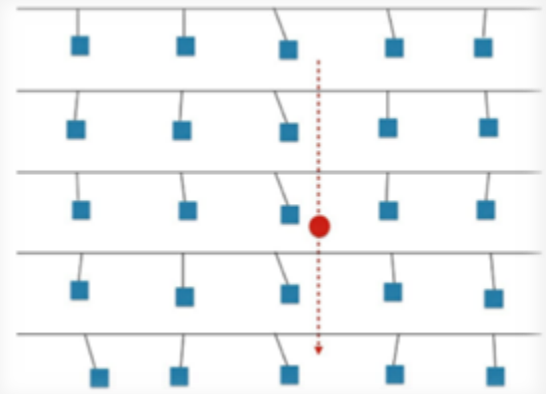


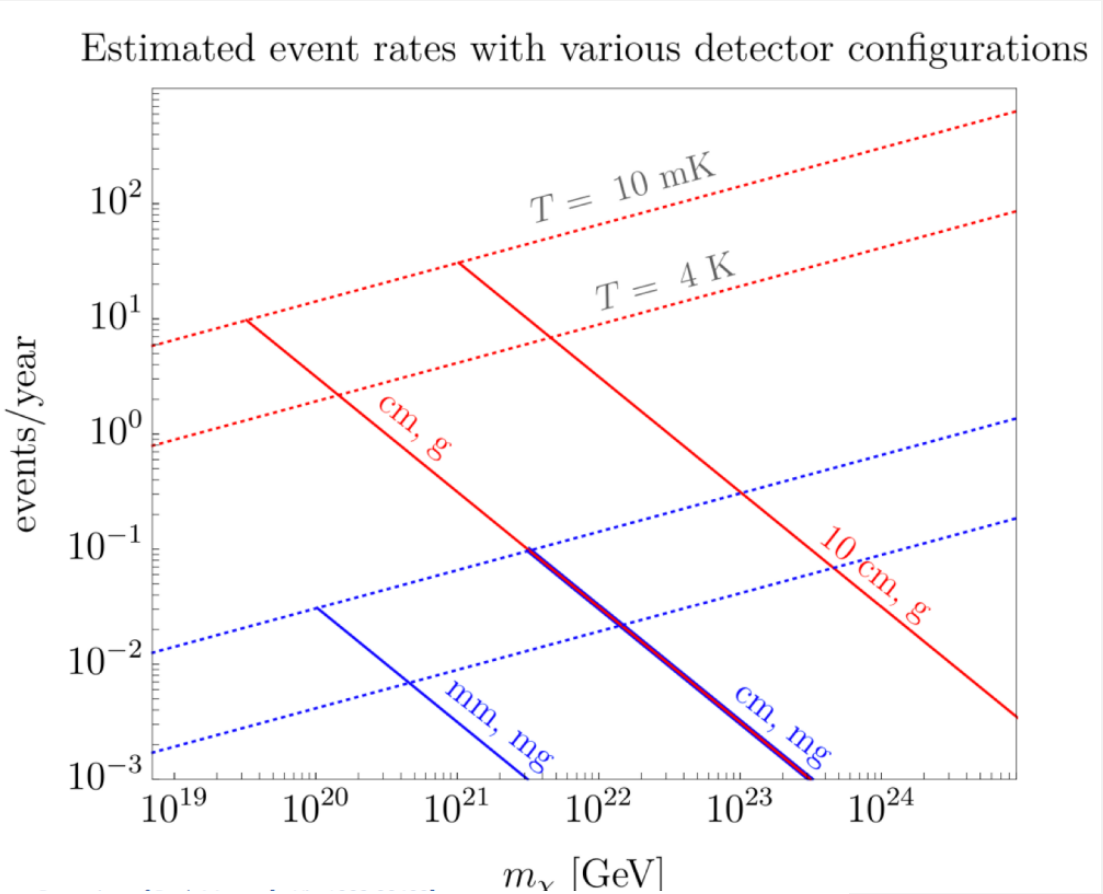
Snowmass White Paper: Light Dark Matter Direct Detection at the Interface With Condensed Matter Physics [arXiv:2203.07492]

Gravitational Probes of Particle DM

Nightmare scenarios

- DM does not couple to any SM particles through any detectable channel
- DM only interacts with gravity





Gravitational Direct Detection of Dark Matter [arXiv:1903.00492]
Snowmass 2021 White Paper: The Windchime Project [arXiv:2203.07242]

Rich Experimental Program