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Review of dark matter detection experiments

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The 20th Conference on Flavor Physics and CP Violation

26 May 2022

Outline

1. Dark Matter Overview
2. Axion Detection
3. Dark Photon Detection
4. WIMP Detection
5. LDM Detection

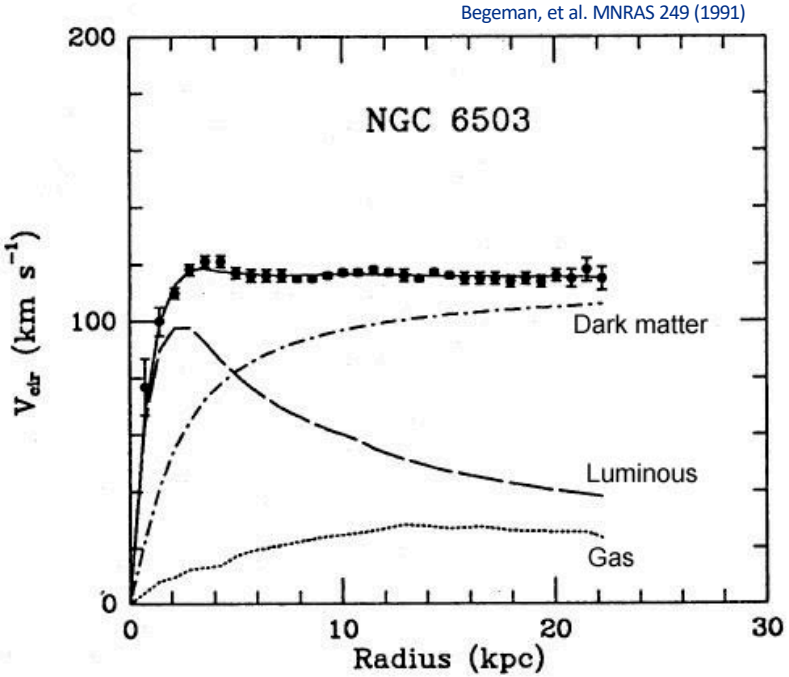
Dark Matter

- Fritz Zwicky applied the virial theorem to galaxy clusters and noted excess rotational velocity relative to the gravity of luminous matter

  → "*dunkle materie*"

- Vera Rubin observed numerous spiral galaxies to build evidence towards galactic mass being dominated by DM haloes

Dark Matter



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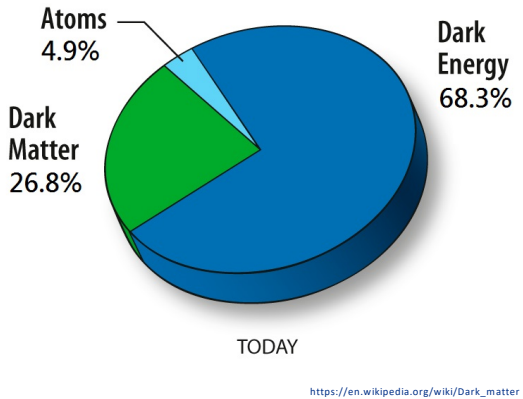
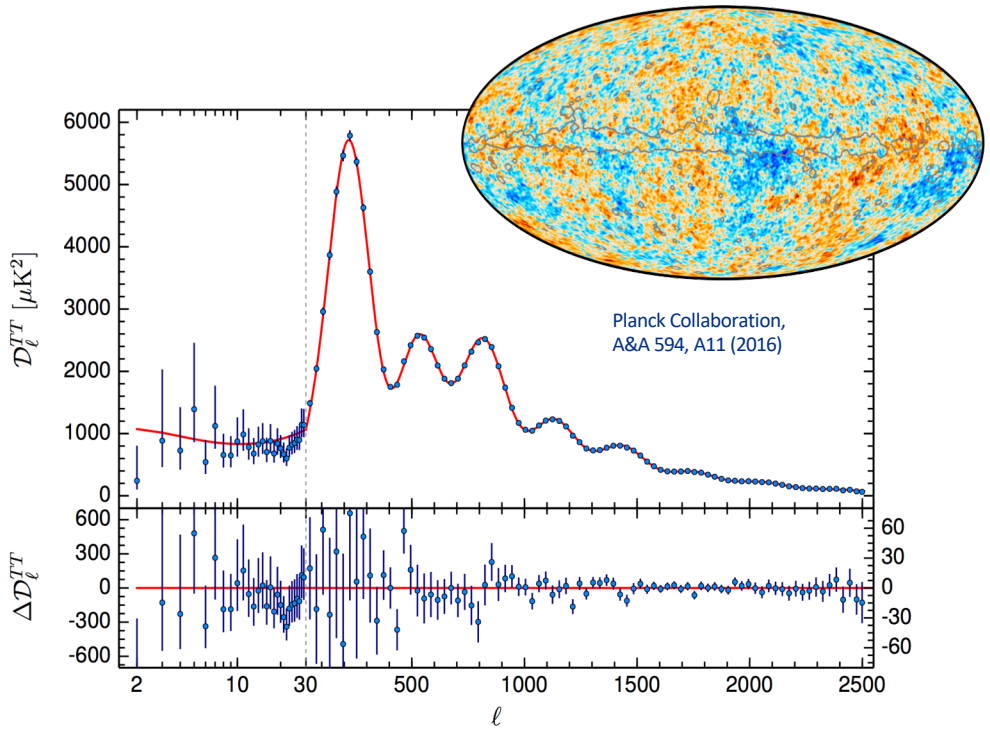
Dark Matter

Modern measurements of the CMB provide strong evidence for cosmology that includes *cold* dark matter



https://en.wikipedia.org/wiki/Dark_matter



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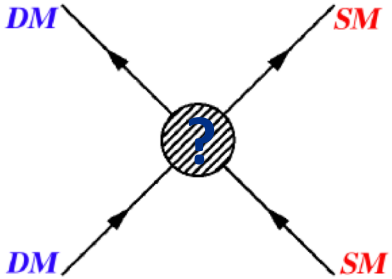
Dark Matter

Gravity – YES (*matter*)
EM – No* (*dark*)
Strong – No
Weak?



Wavelength Fits in Dwarf Galaxy
($>10^{-22}$ eV)

Elementary Particle
($<10^{28}$ eV)

← Dark Photons →

zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV $30M_{\odot}$

DM behaves like a wave (axions)

Light Dark Matter (LDM)

Traditional Models (WIMPs)

Cosmic Visions 2017 [arXiv:1707.04591]

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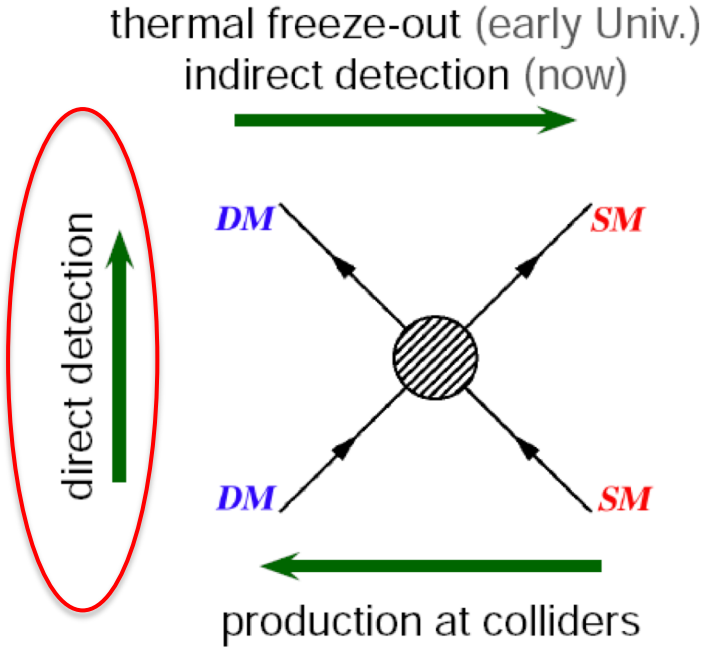
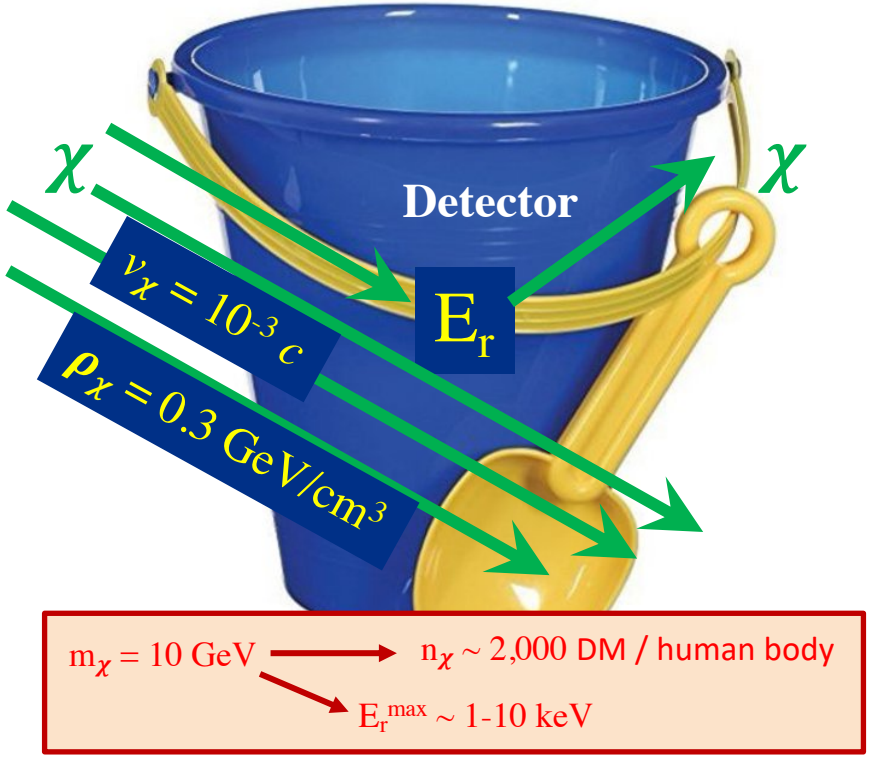
Dark Matter





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Axion Detection

- Strong CP Problem: Current experimental limits on the neutron EDM are $< 10^{-26}$ *e* cm, which corresponds to a fine-tuned, CP-violating phase near zero, even though the strong force *should* violate CP symmetry in QCD
- Peccei-Quinn Solution: Introduce a new $U(1)$ symmetry that, when broken, cancels the CP-violating phase. This leads to a new pseudo-scalar… the *axion*
- …it just so happens that this would look like DM if it carries the right abundance!

Axion Detection

- Under the assumption that the QCD axion makes up all of the DM, we can calculate a theoretical target parameter space.
- Can look for axion-photon coupling in the presence of a magnetic field, due to modification of Maxwell's equations.
- This will result in a resonance in photon production for a cavity that is tuned to the axion frequency.

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

Quality factor

Cavity volume

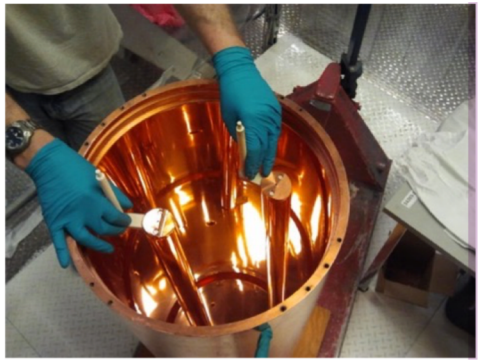
Form factor

Magnetic Field

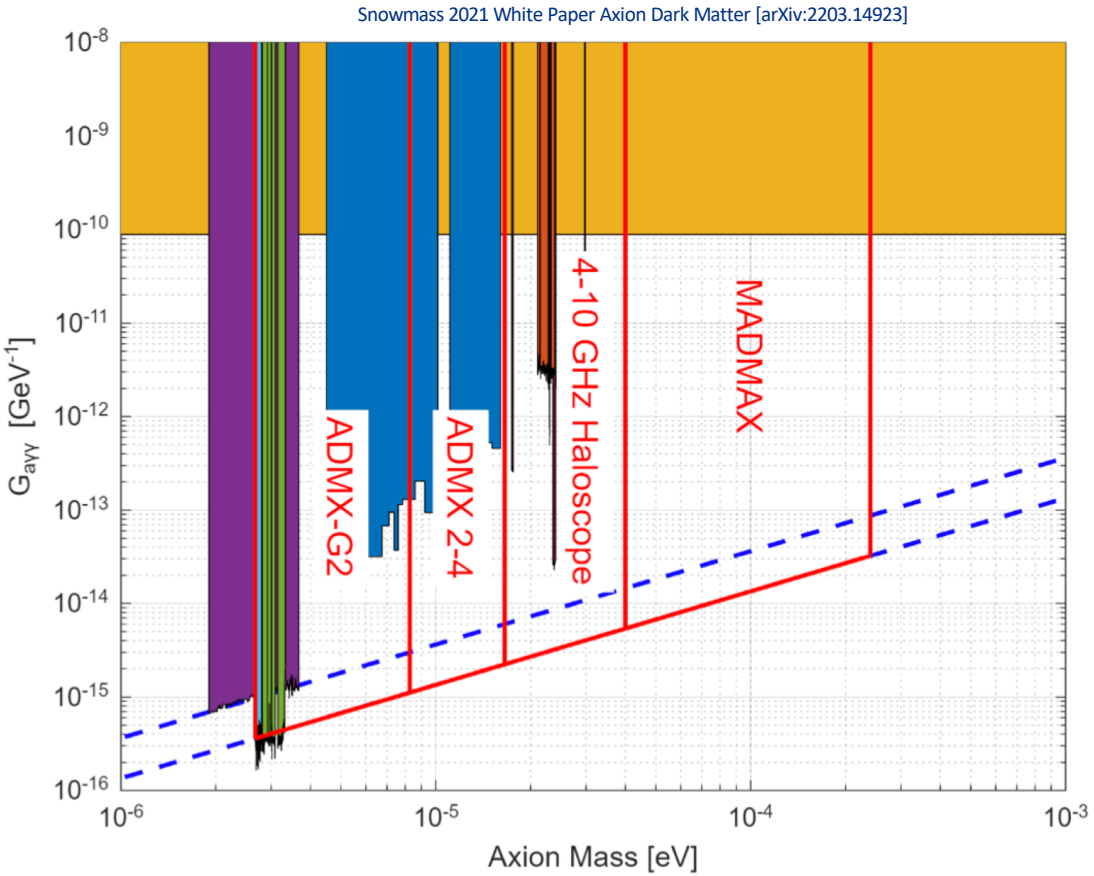
Noise Temperature

Axion Detection

- ADMX: DoE G2 experiment searching for QCD axion DM around 3 μeV



- …lots of other experiments joining in the fray



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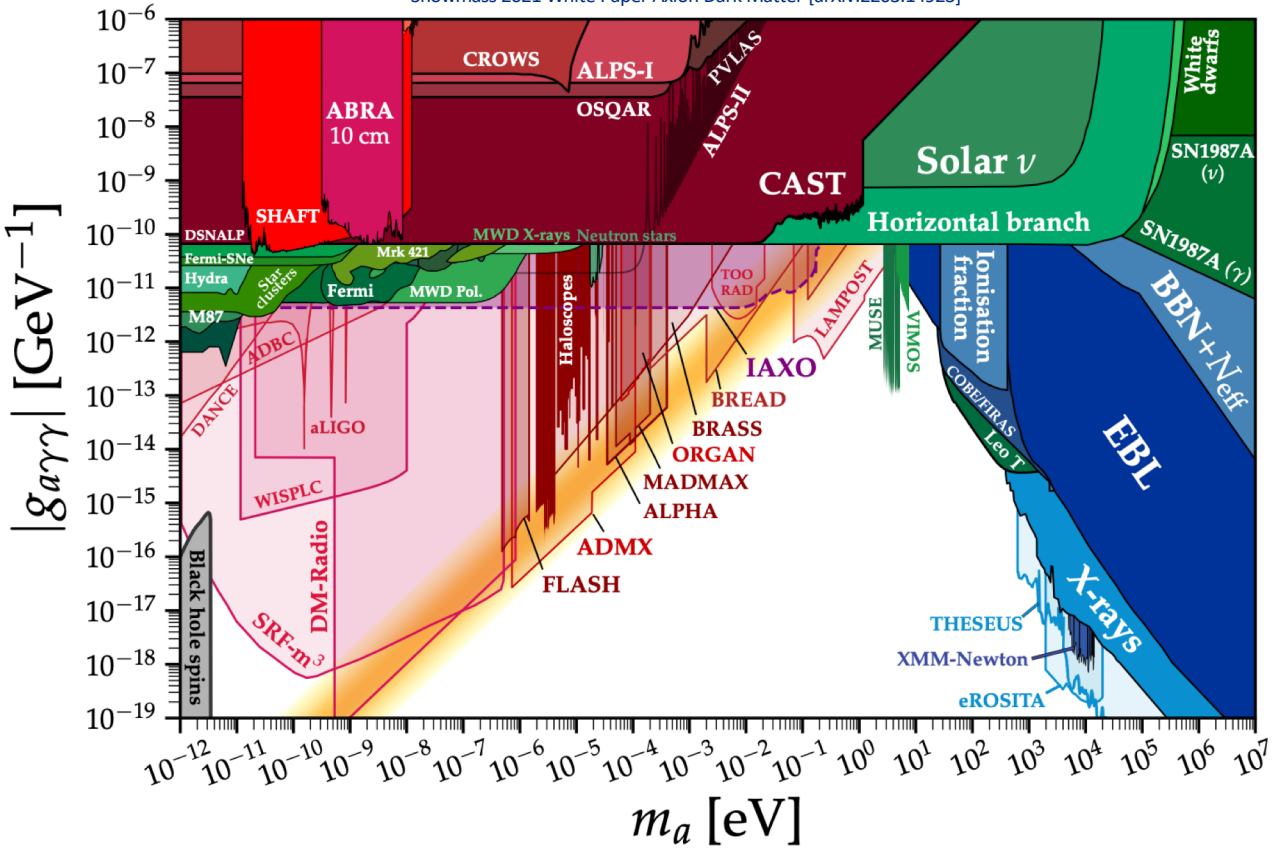
Axion Detection

Snowmass 2021 White Paper Axion Dark Matter [arXiv:2203.14923]



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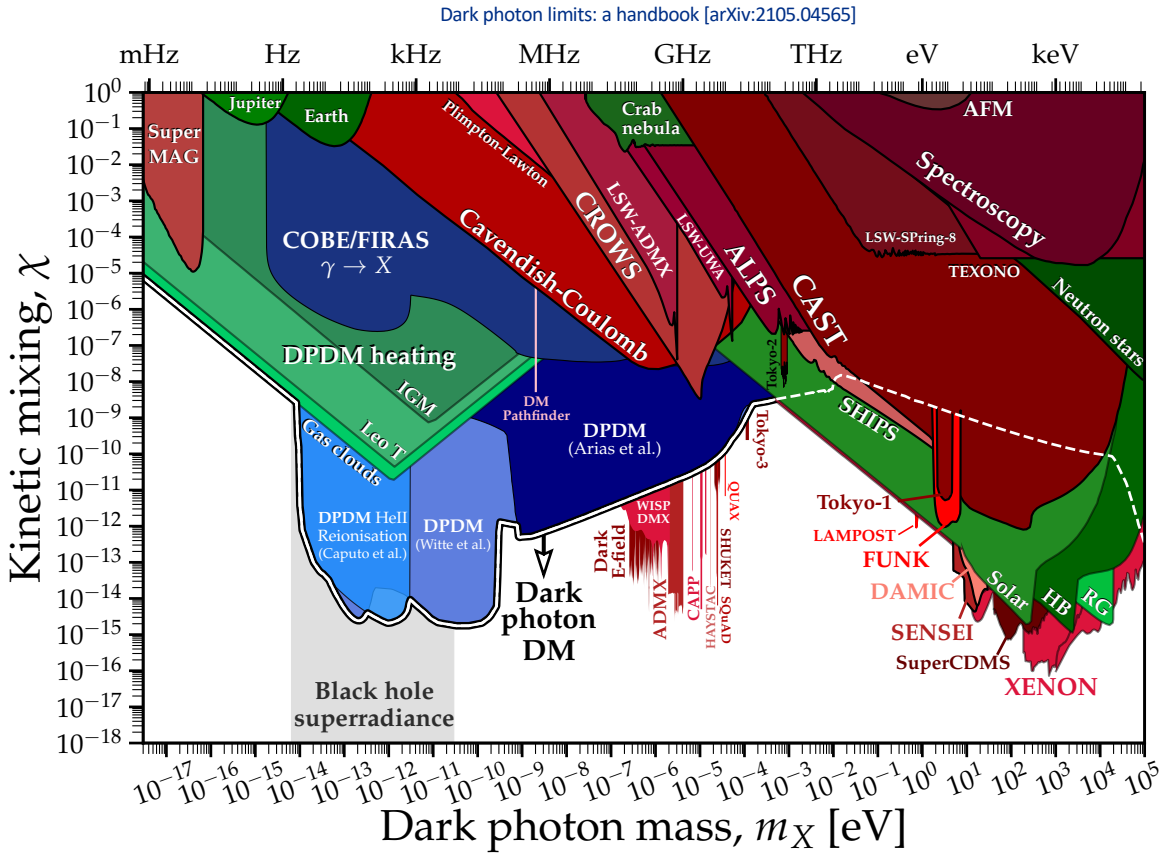
Dark Photon Detection

- A dark photon, denoted A', typically involves a new broken $U(1)$ symmetry which mixes with the standard model photon
- These models are popular in part due to the large degree of theoretical flexibility available in the mixing parameter and dark photon mass
- Many dark sector models with a stable relic DM particle χ actually couple to the SM via a kinetically-mixed dark photon

- If the dark photon has a mass $m_{A'} < 2m_e$, then the only SM decay mode is to three photons, making such particles long-lived, relic DM candidates themselves

Dark Photon Detection

- Two ways to run a dark photon search:
  1. Run axion cavity search without the magnetic field and measure photons from spontaneous conversion
  2. Look for tiny energy deposition from dark photon absorption in detector target



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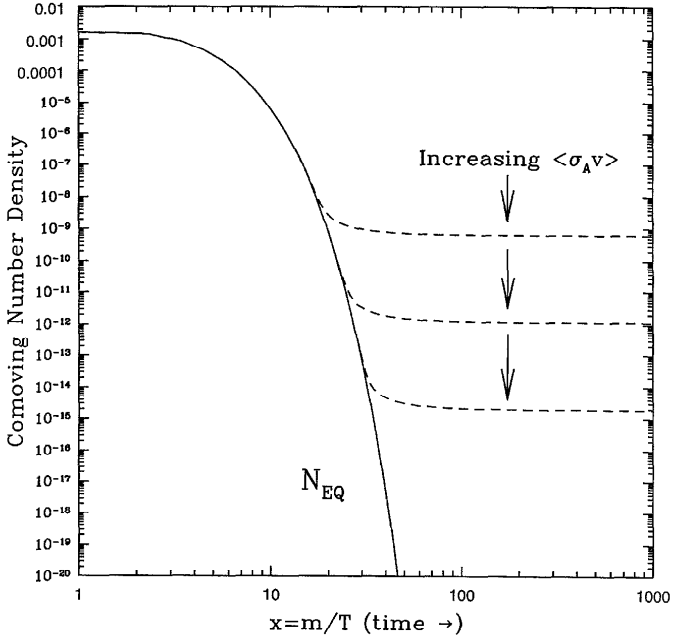
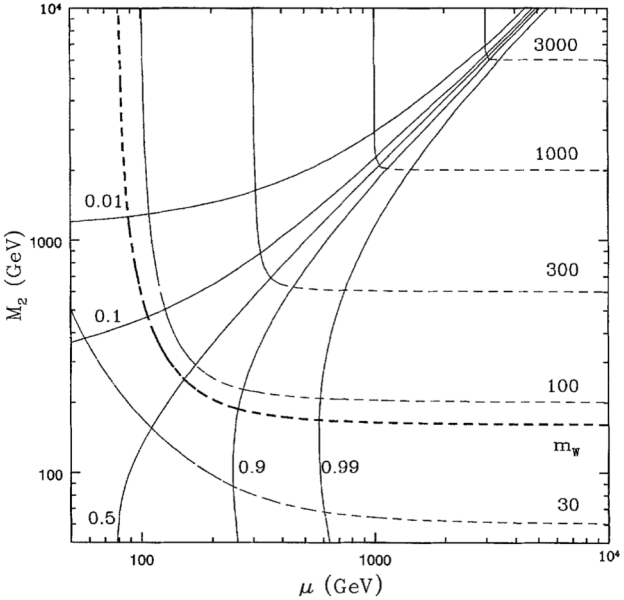
WIMP (Weakly Interacting Massive Particle) Detection

Historical Motivation

- WIMP "Miracle"



- Supersymmetry – lightest supersymmetric particle (LSP)



Jungman, et al. Physics Reports 267 (1996)

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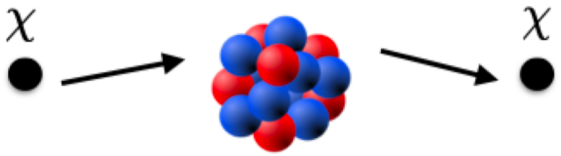
WIMP Detection

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, $F(q=0) = 1$

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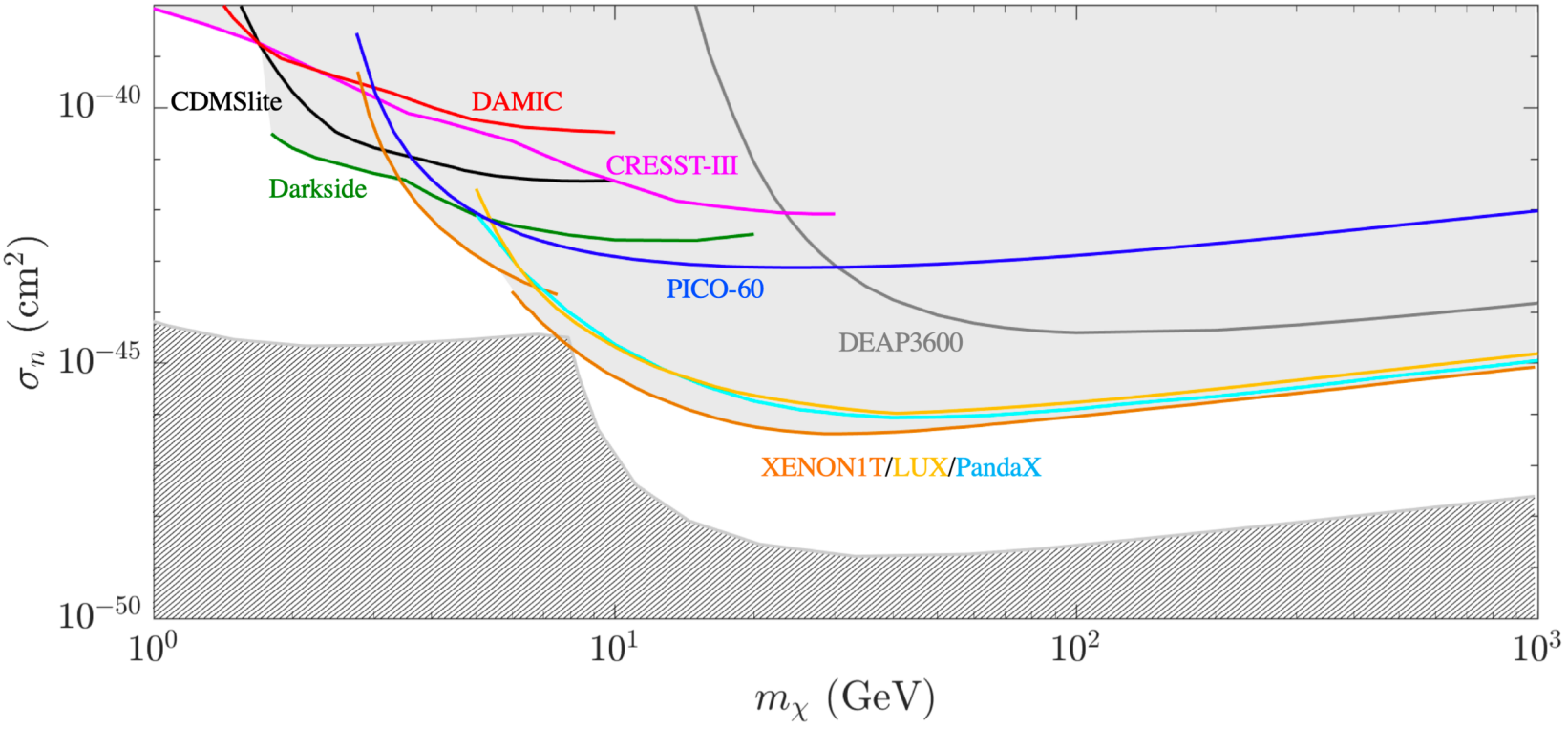
WIMP Detection – Current Limits



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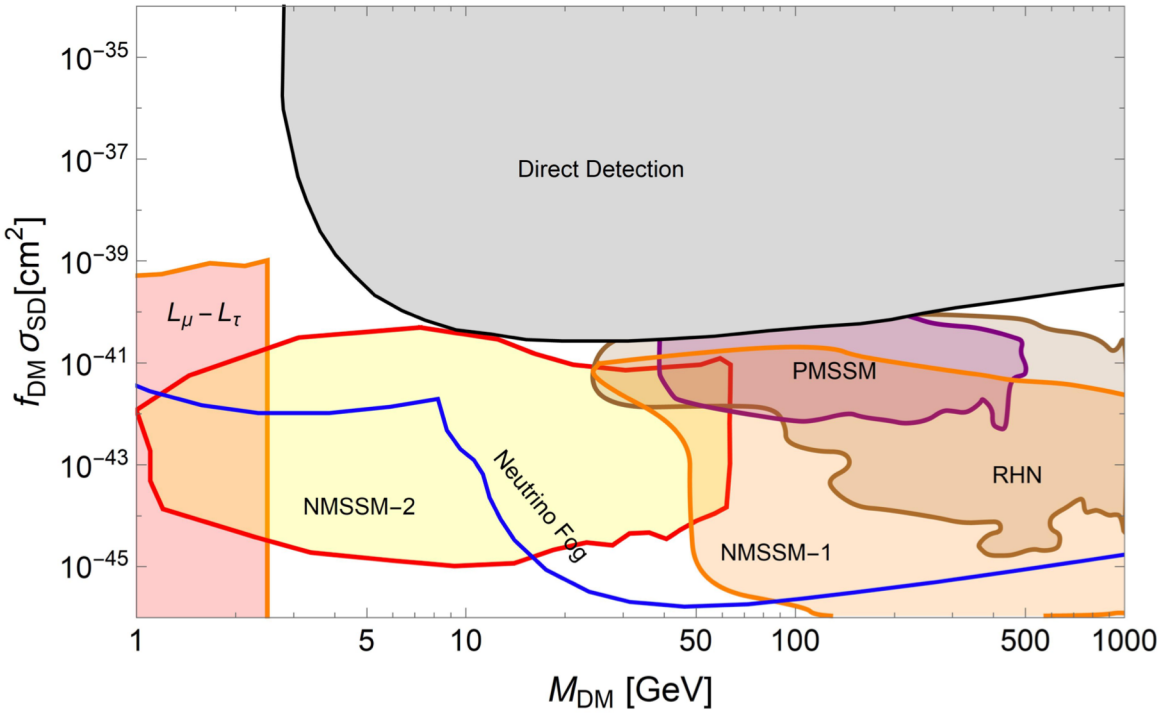
WIMP Detection – Spin-dependent Coupling

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

- Can also have more complicated interactions, for example via the net nuclear spin of the target atom
- If net spin comes from unpaired proton, H or F is your best target



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WIMP Detection

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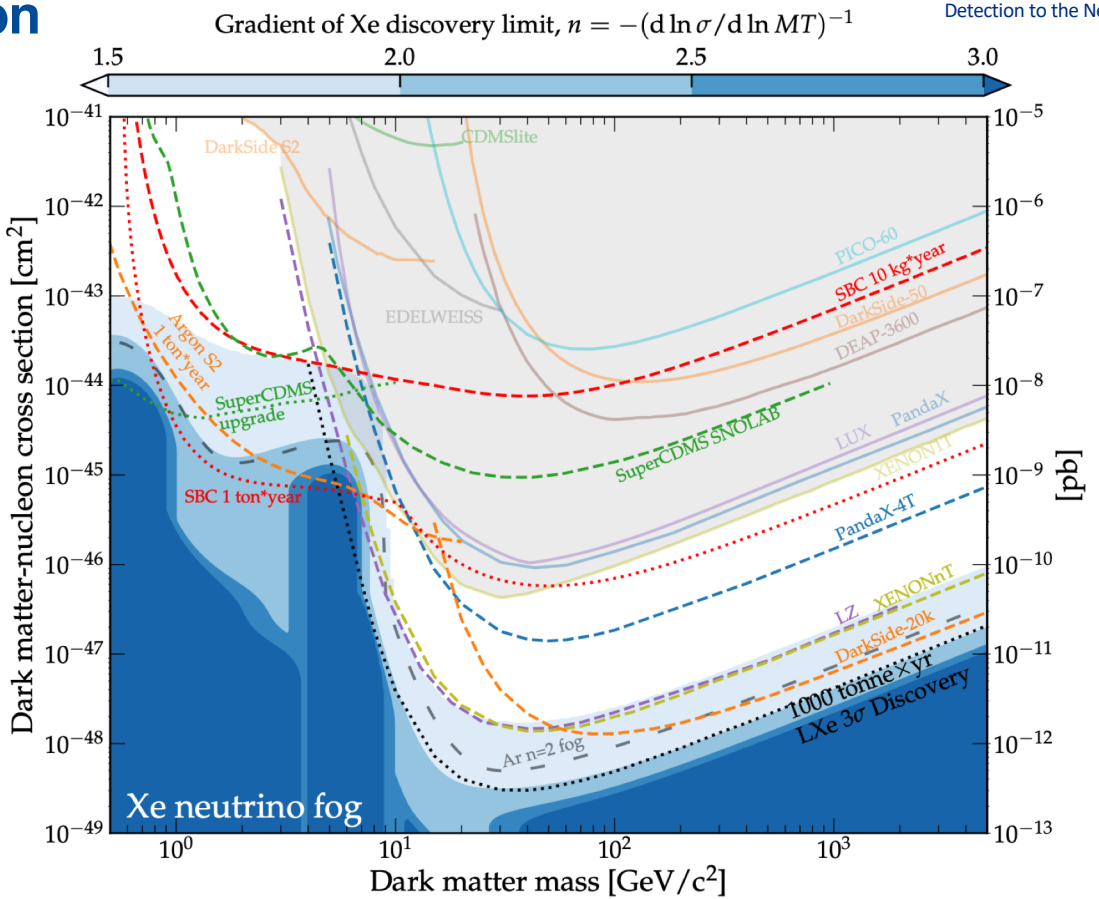

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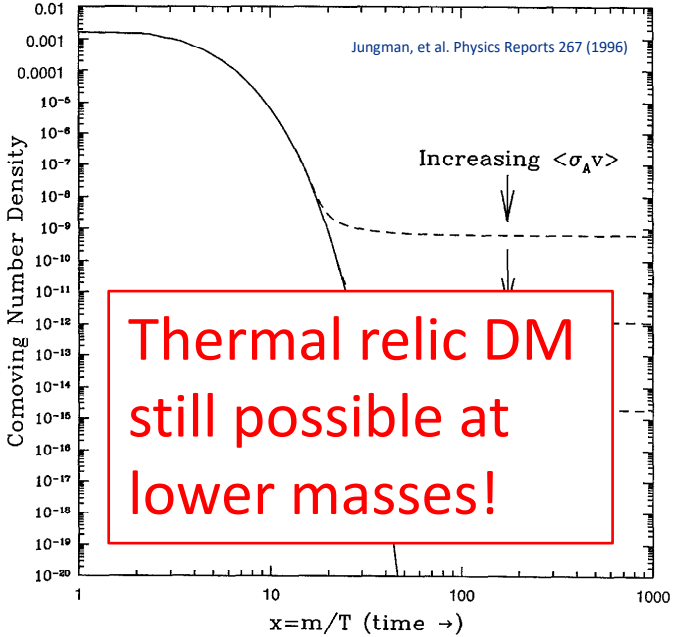
LDM (Light Dark Matter) Detection

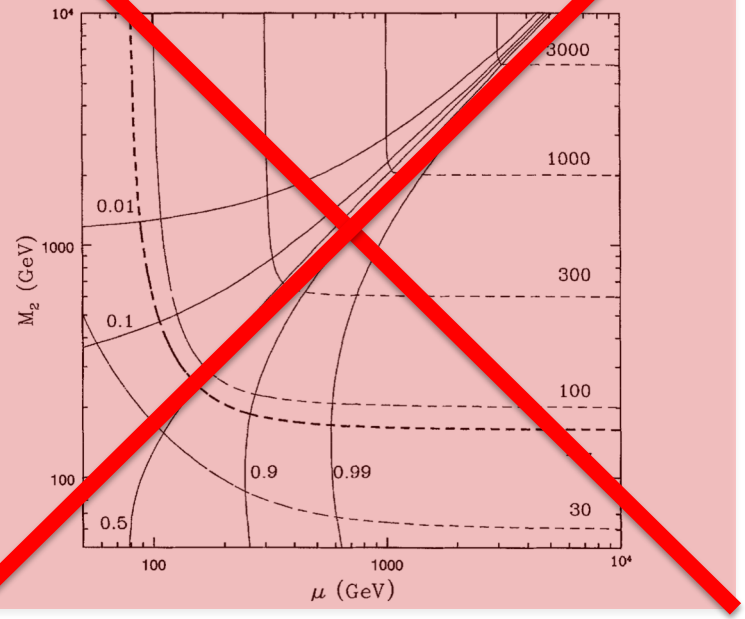
- WIMP "Miracle"



Thermal relic DM still possible at lower masses!

Relax the SUSY motivation

- Supersymmetry – lightest supersymmetric particle (LSP)



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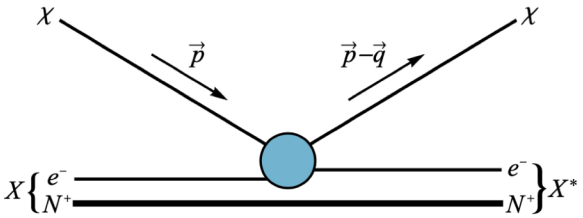
LDM Detection



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

Ionization form factor calculated using Quantum Espresso - QEDark

http://ddldm.physics.sunysb.edu/ddlDM/

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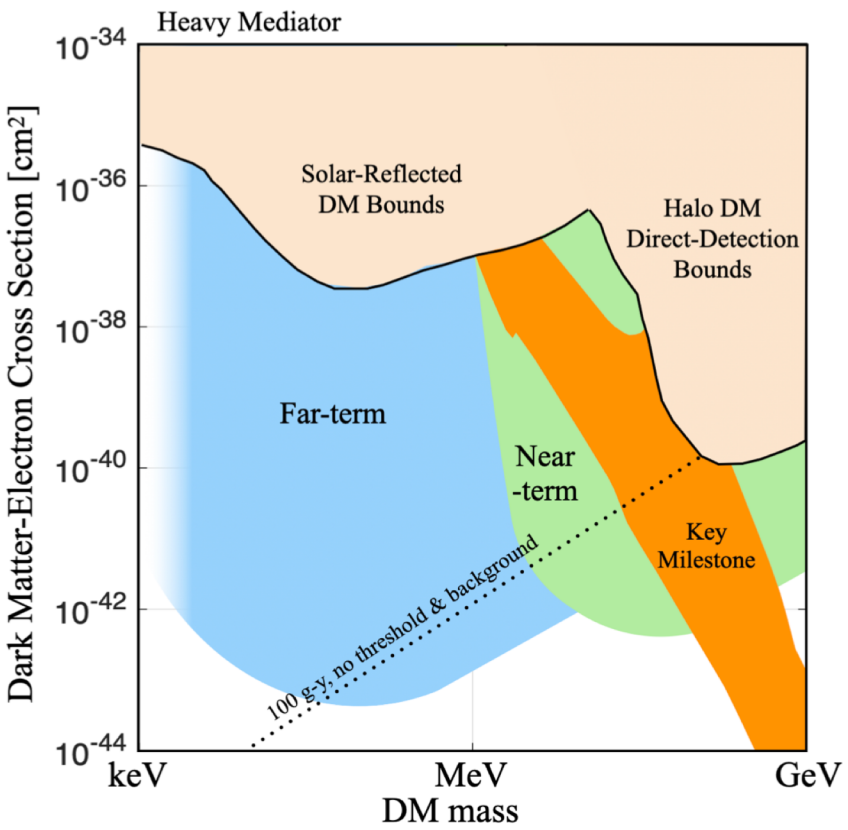
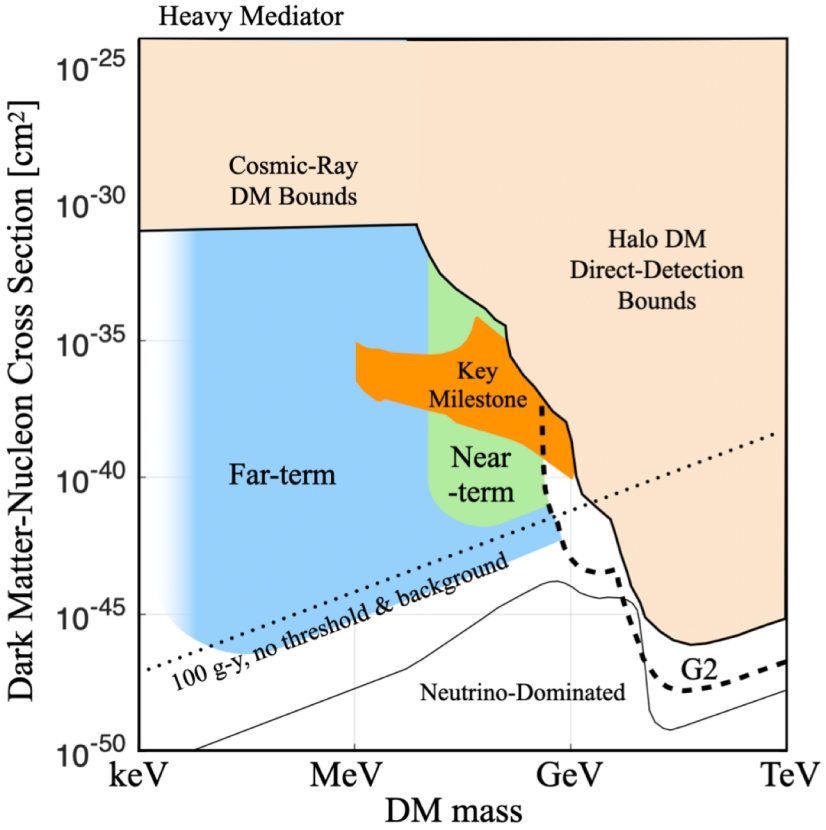
LDM Detection – Heavy Mediator





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

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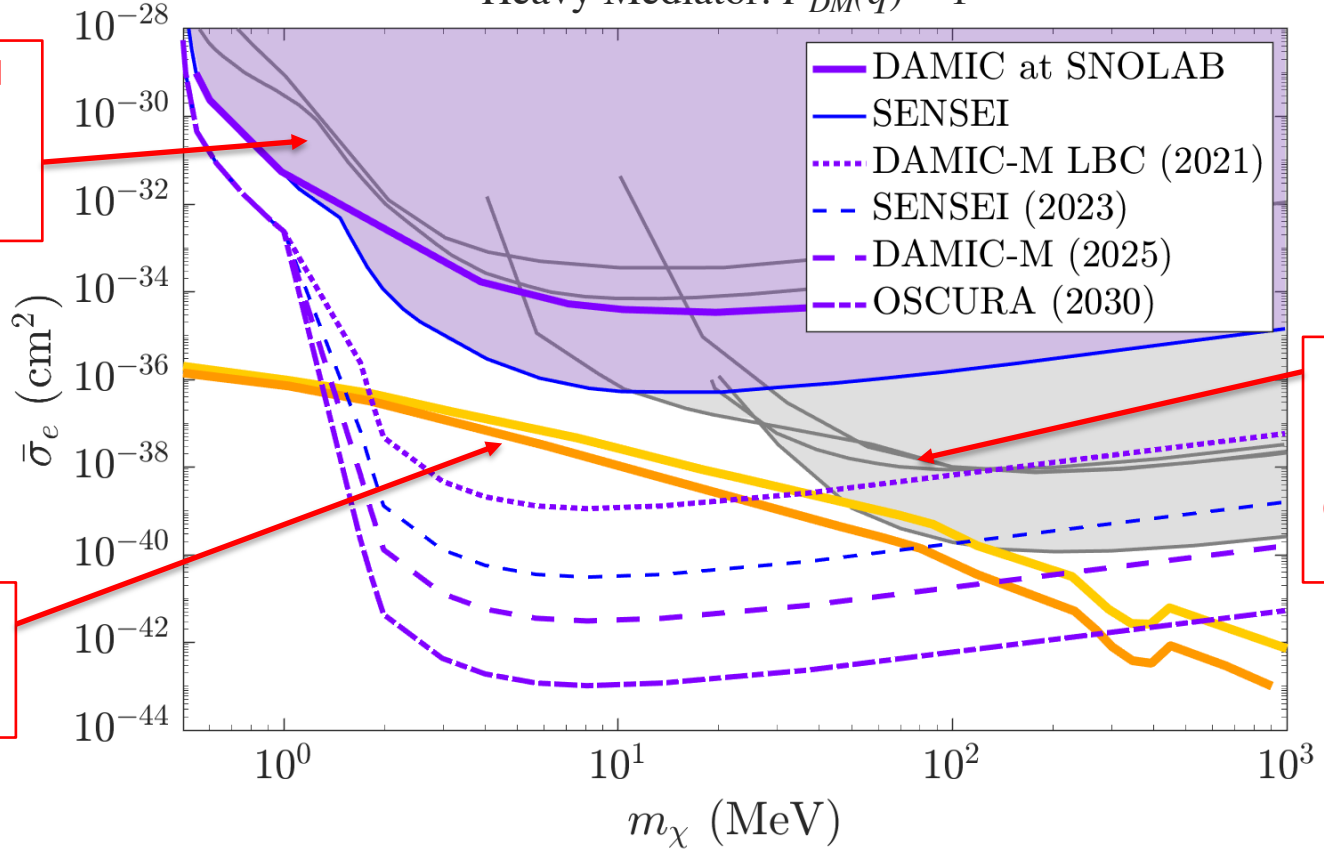
LDM Detection - CCDs

Could be a GeV-scale dark photon!

CDMS HVeV and EDELWEISS also competitive at low mass



Large mass of liquid noble TPCs makes them competitive at high DM mass

Clear thermal relic targets for freeze-out

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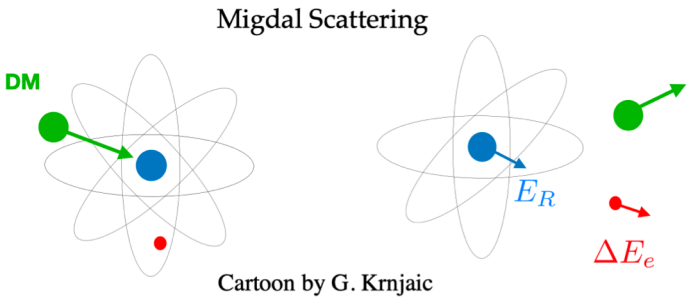
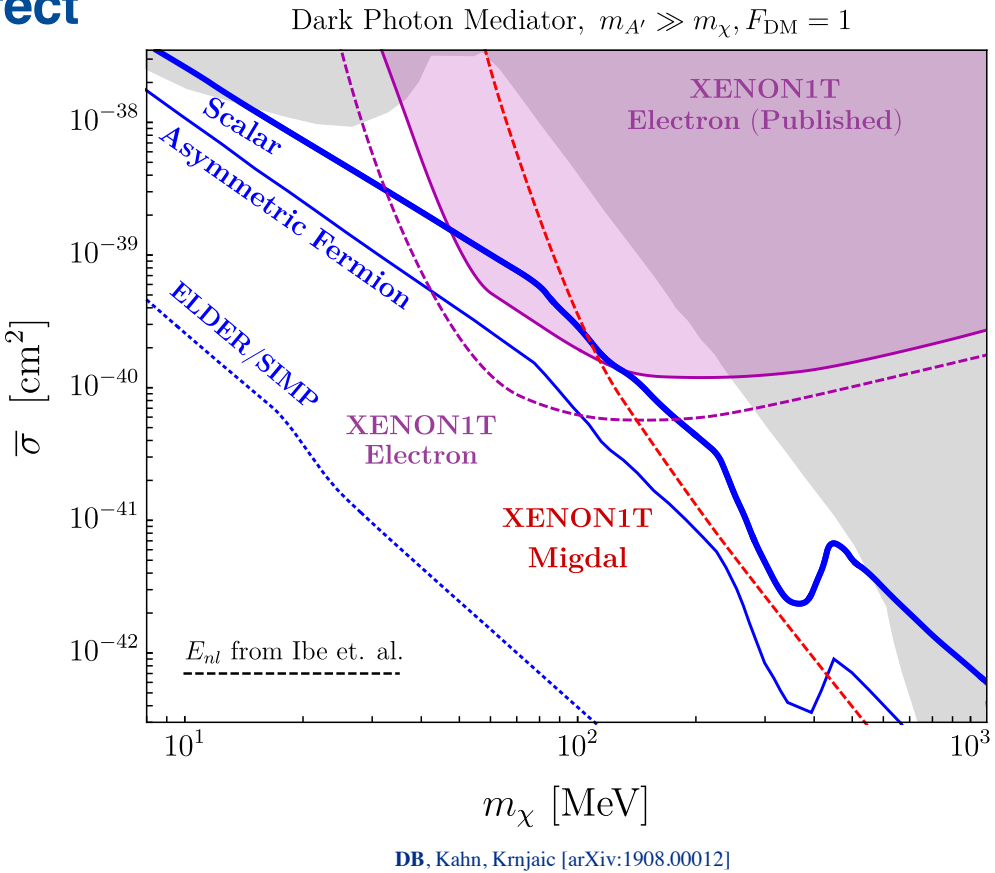
LDM Detection – the Migdal Effect



- Can also have inelastic three-body scattering off the nucleus!
- Ionization produced is actually above threshold for many experiments



DB, Kahn, Krnjaic [arXiv:1908.00012]

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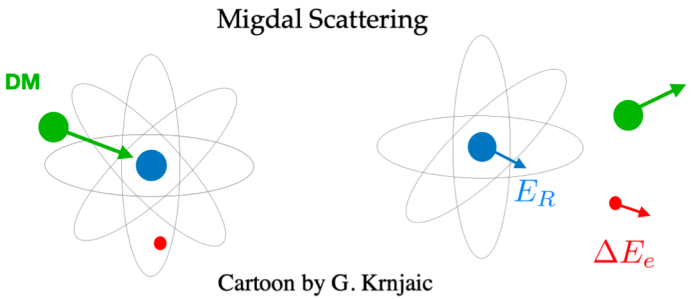

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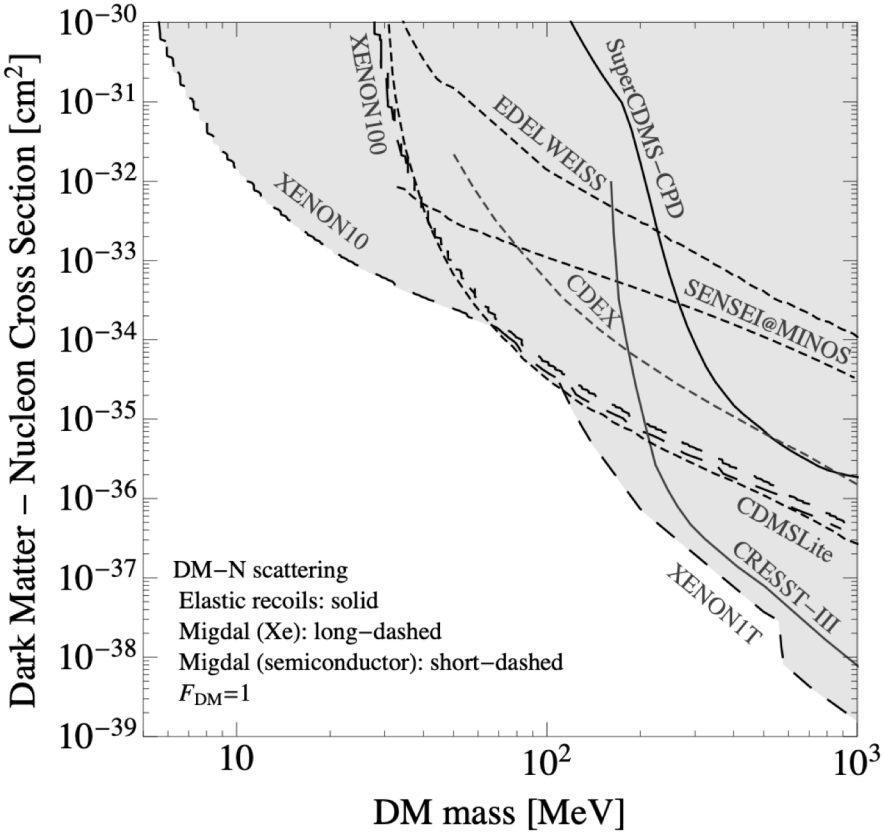

Snowmass2021 Cosmic Frontier: The landscape of low-threshold dark matter direct detection in the next decade [arXiv:2203.08297]

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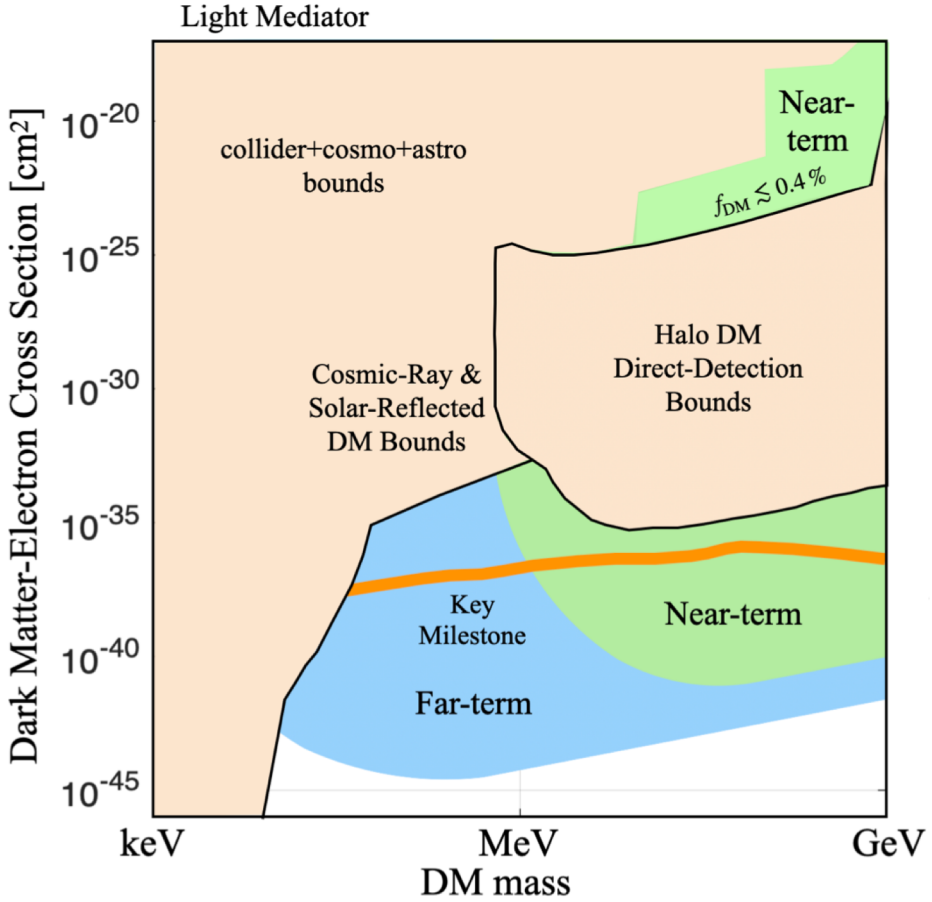
LDM Detection – Light Mediator

- Cosmologically produced DM coupling through a light mediator can "freeze-in" to the relic abundance (orange, right)
- Detecting such DM requires much lower thresholds (down to meV) and novel detection techniques



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

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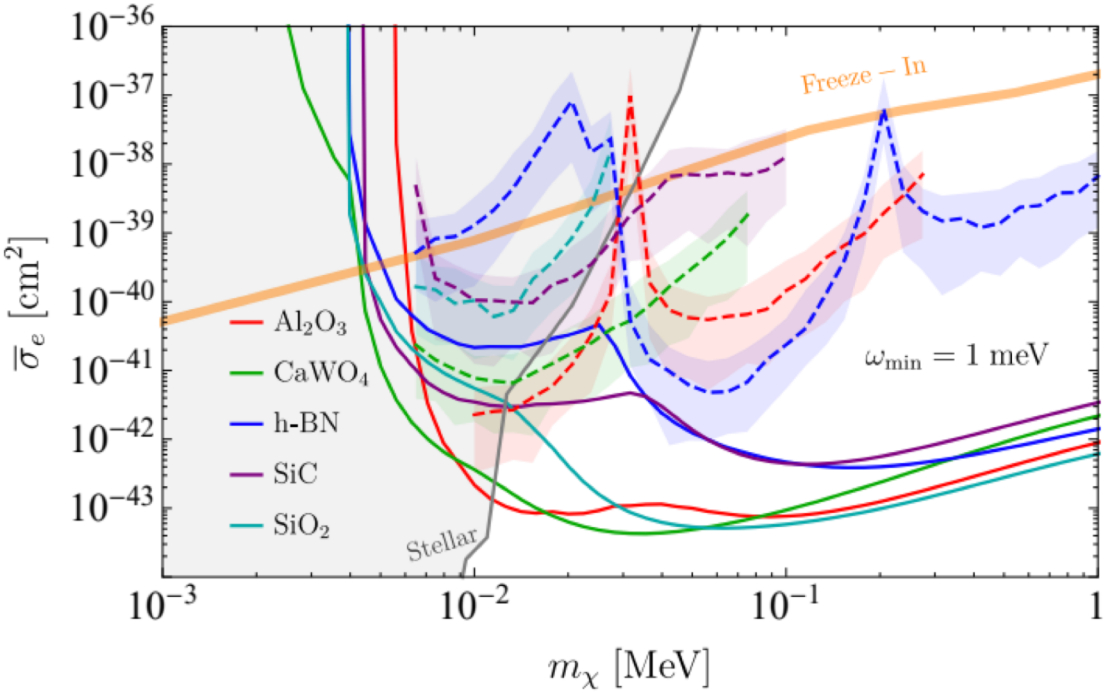
LDM Detection – Light Mediator

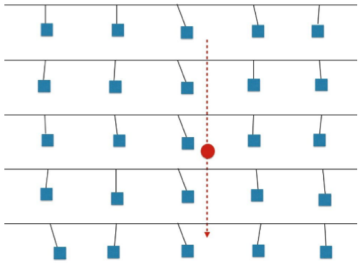
- Novel material targets produce signals down to a meV energies
- Anisotropy of crystal structures allows for measurable daily modulation in DM signal
- Need sensors that can measure meV energy deposits:
  - **qubits (QSC)**
  - TES's (TESSERACT/HeRALD/ SPICE)
  - KIDs

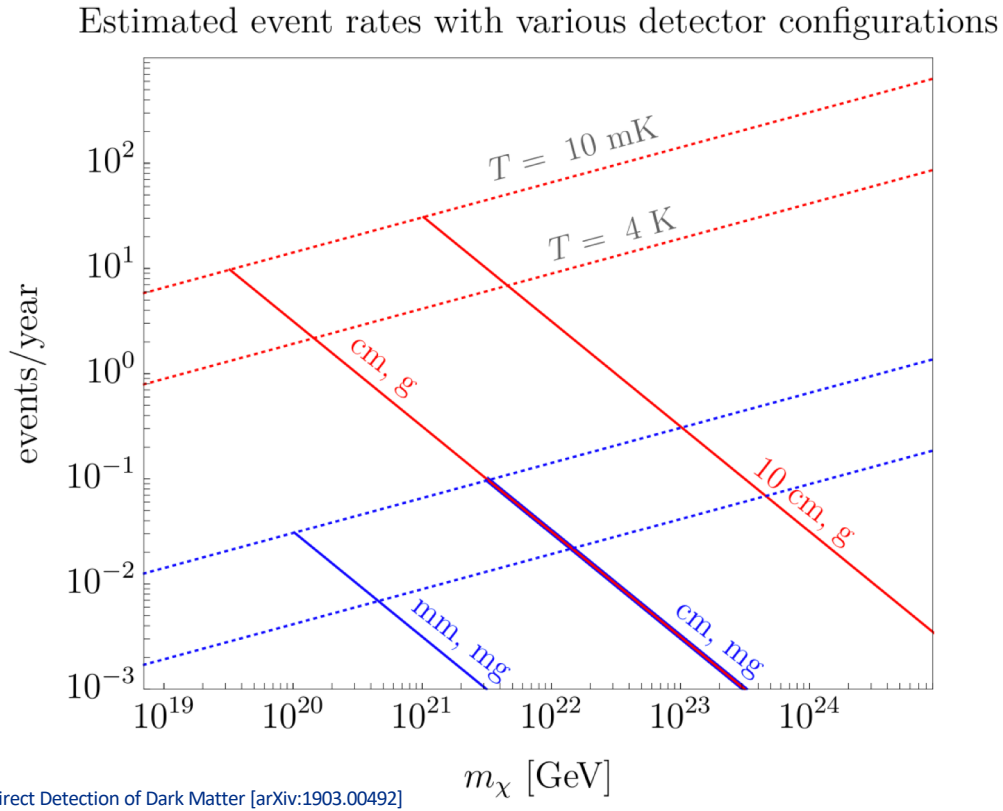


Snowmass White Paper: Light Dark Matter Direct Detection at the Interface With Condensed Matter Physics [arXiv:2203.07492]

Gravitational Detection – WINDCHIME

- What about the "nightmare scenario" for direct detection?
- DM doesn't couple to the SM through a detectable cross-section in any way other than gravitationally





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

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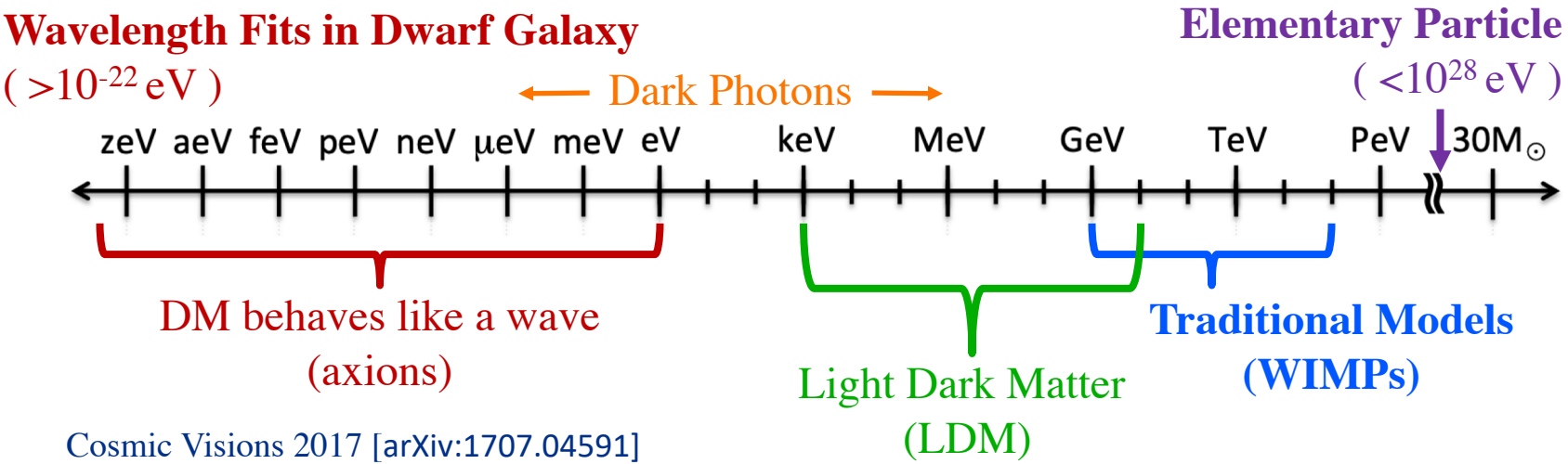
Conclusions

- Direct detection of dark matter continues to leverage the cutting-edge in detector technology to search for DM over a wide range in mass
- Detection could be on the horizon…



Cosmic Visions 2017 [arXiv:1707.04591]

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Thank you