UNIVERSITY OF OREGON

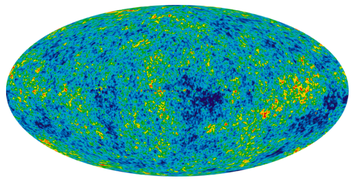
New Approaches on Dark Matter Detection

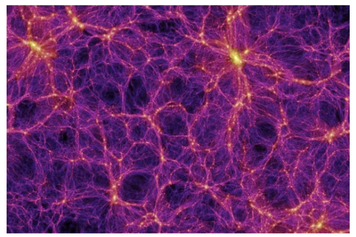
Tien-Tien Yu (University of Oregon)

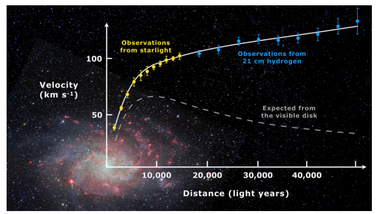
3rd African Conference on Fundamental and Applied Physics
Sept 26, 2023

Dark Matter Exists

Size







COSMIC MICROWAVE BACKGROUND

LARGE SCALE STRUCTURE

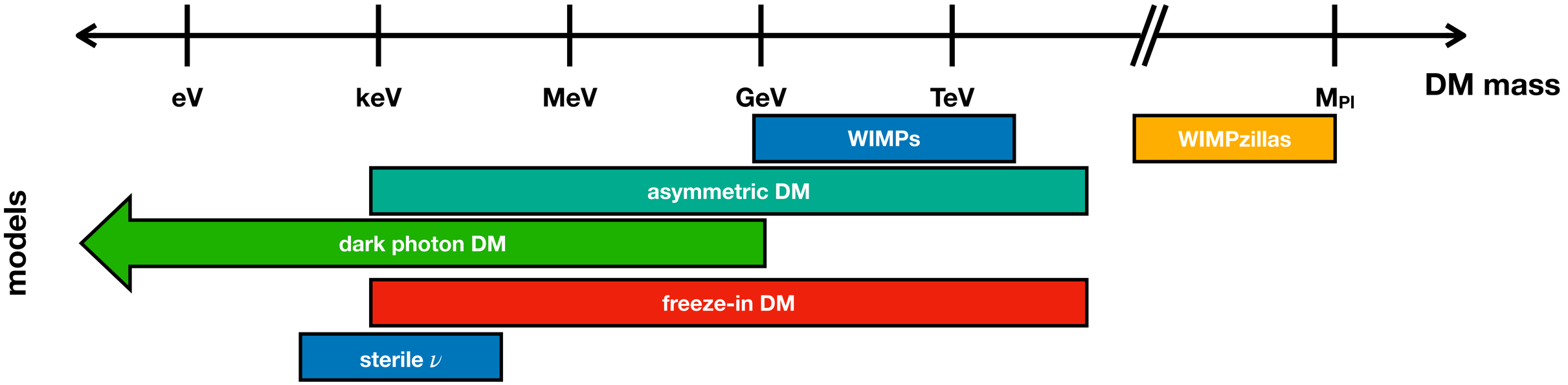
GALAXY CLUSTER MERGERS

GALACTIC ROTATION CURVES

Gravitational interactions

Dark Matter Candidates

Gravitational interactions ⟶ massive (particle)

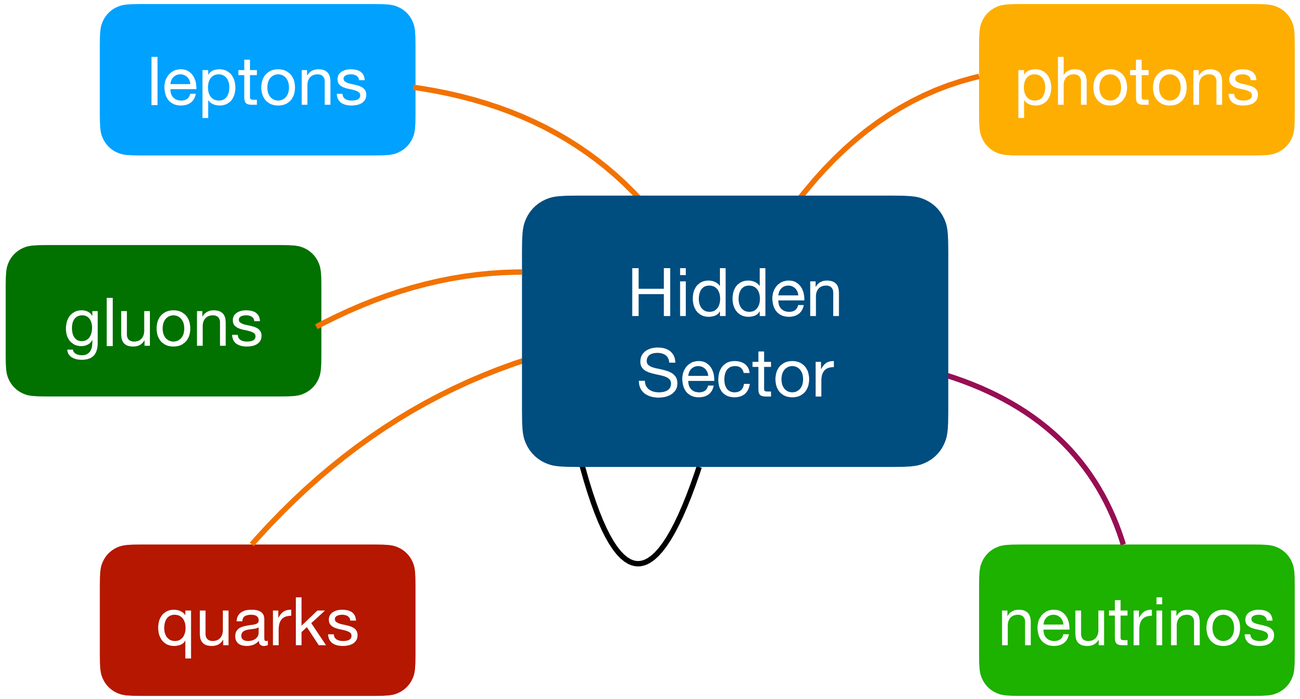


Many theoretically-motivated models!

Non-gravitational interactions of DM

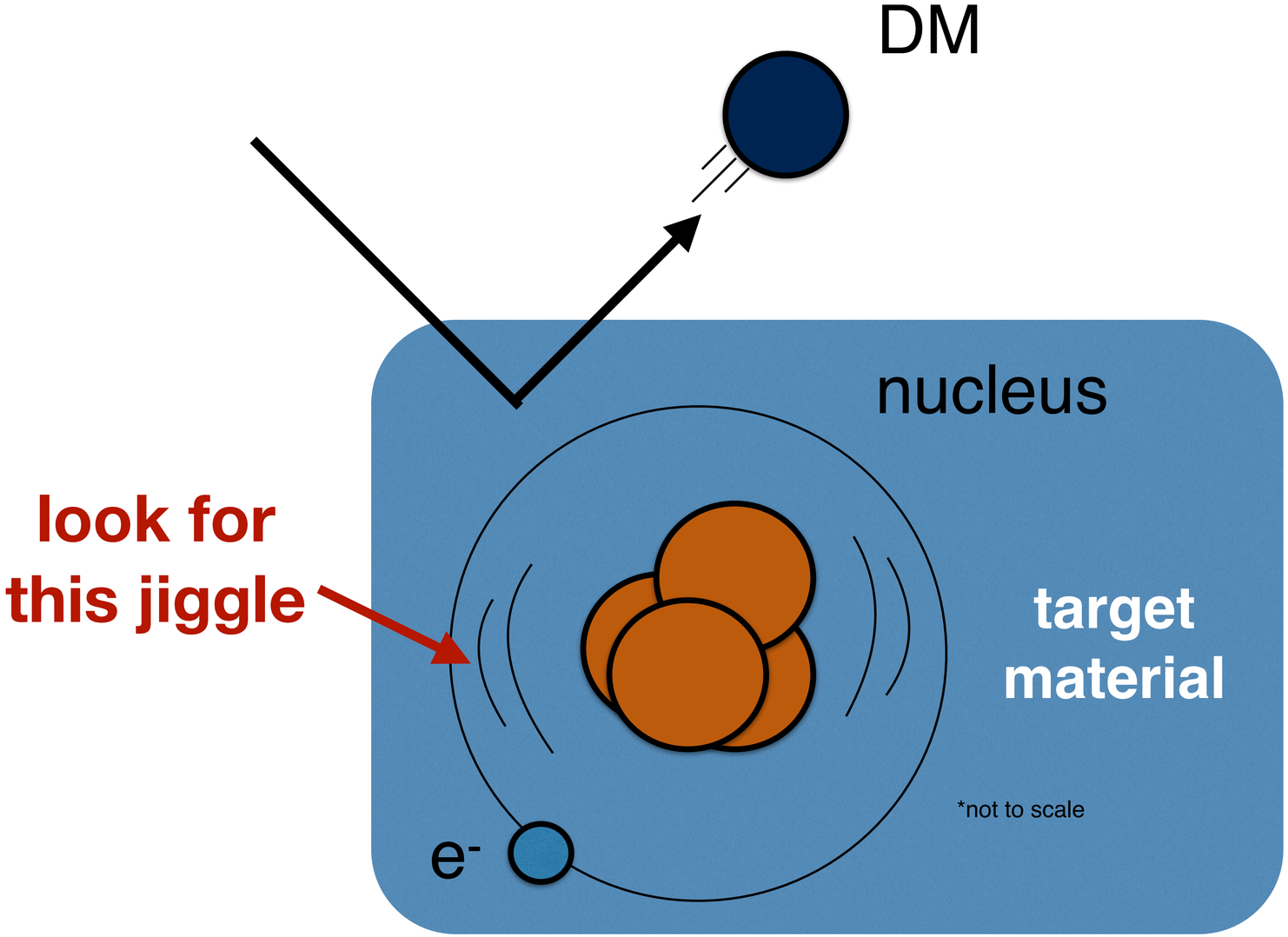
Probing all of these interactions is crucial for understanding the particle nature of DM

Direct detection can probe these

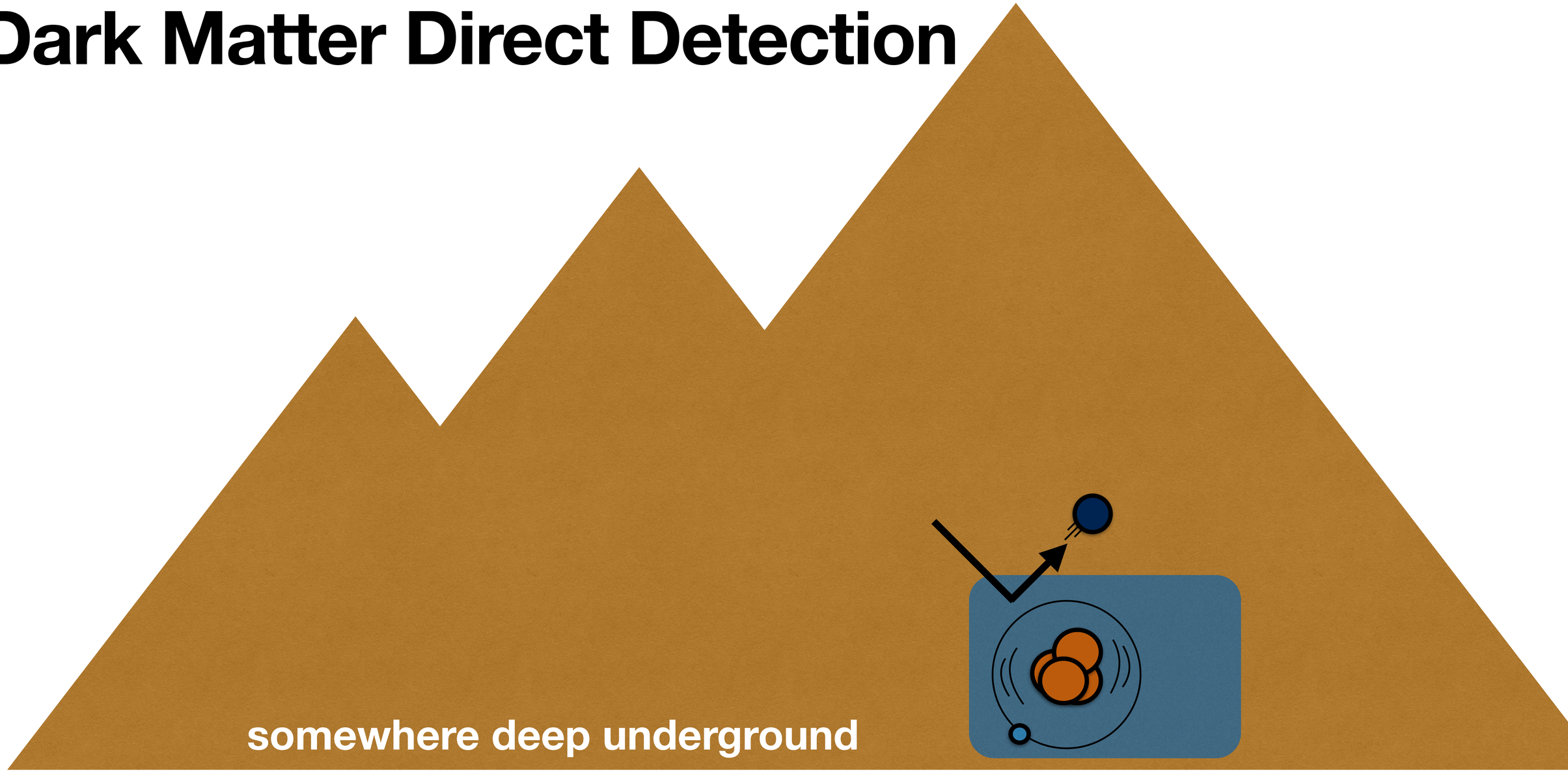


Direct detection probes our galactic dark matter halo

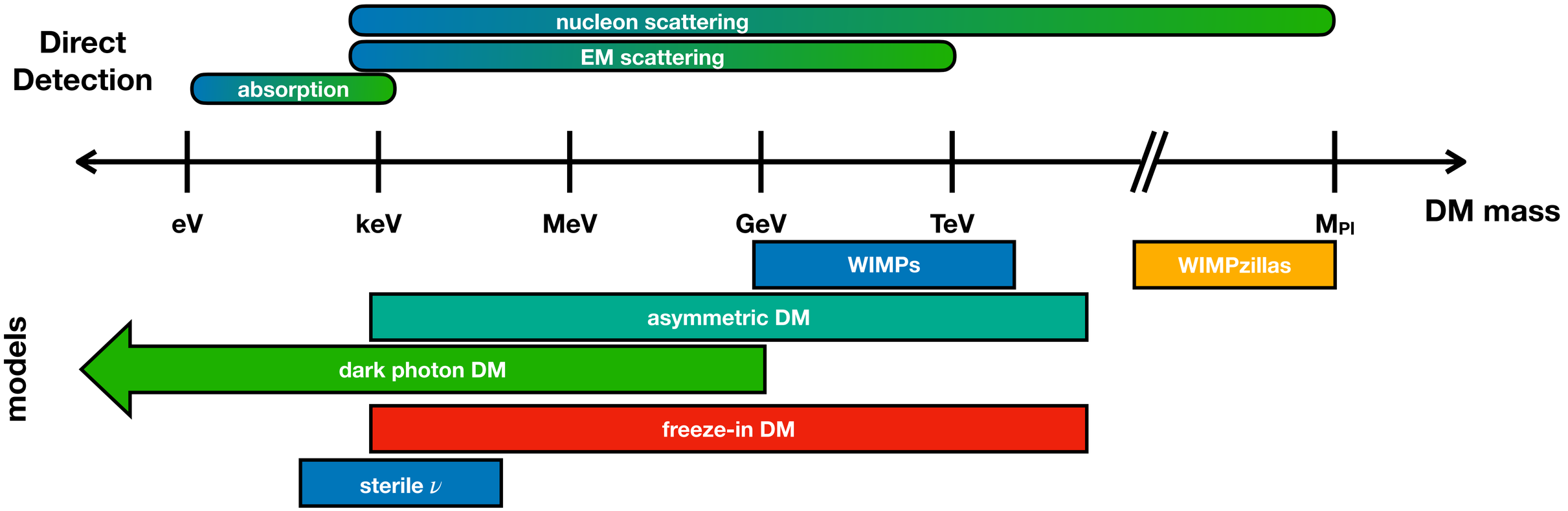
Dark Matter Direct Detection



Dark Matter Direct Detection

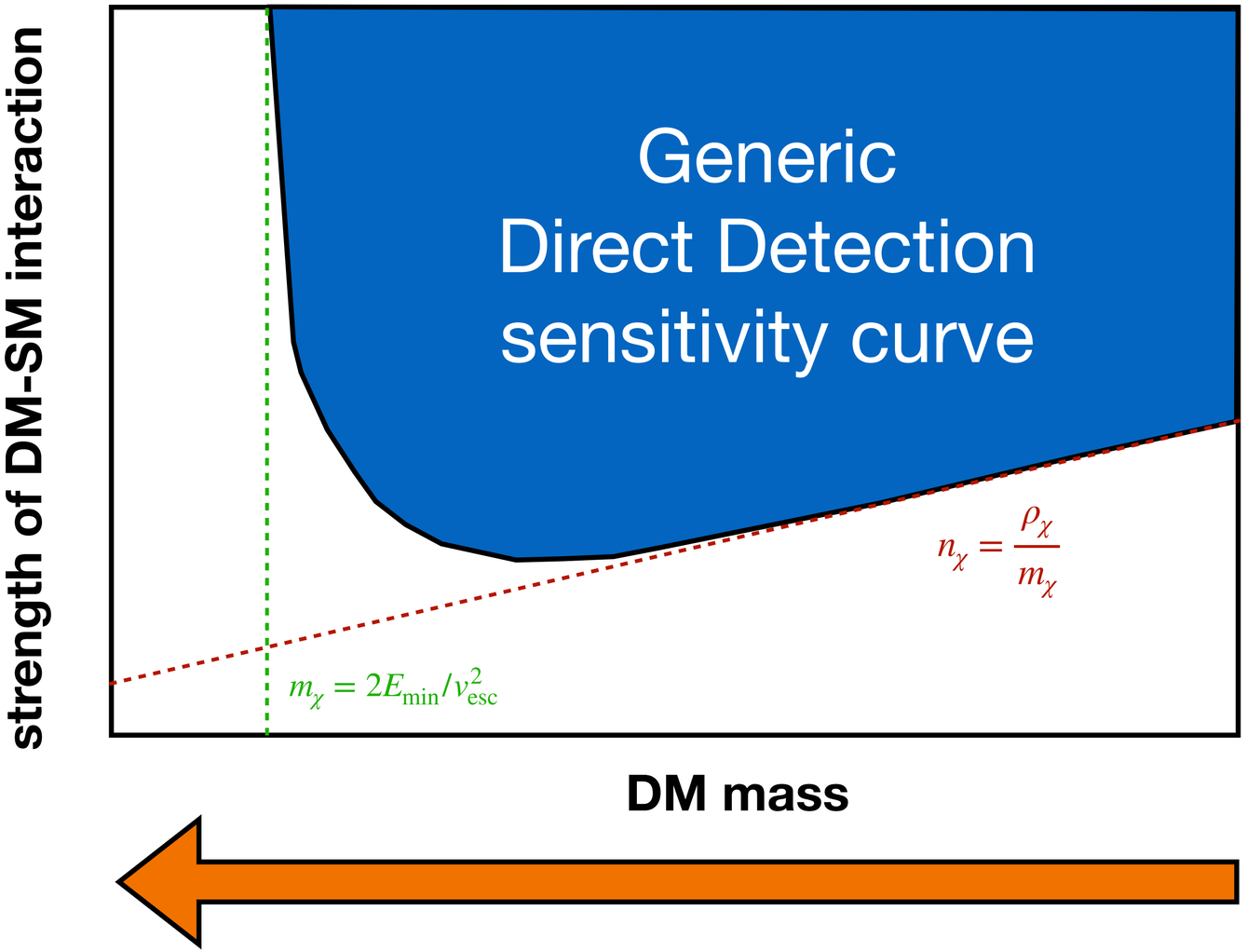


Dark Matter Candidates



Landscape of Particle Dark Matter

- consider ensemble of interactions



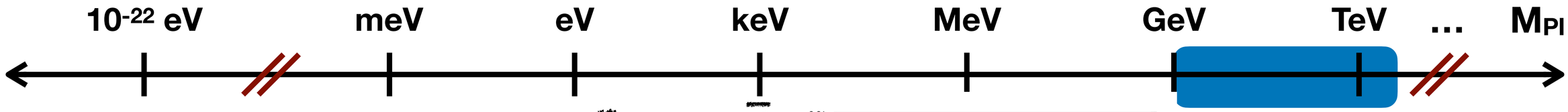
GOAL:
explore
this space

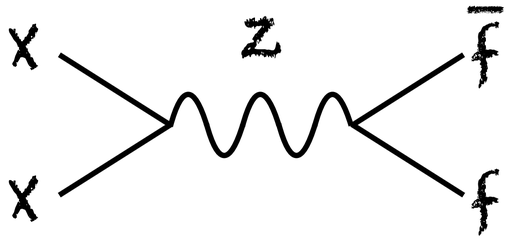
- increase target mass
- improve background discrimination

- decrease thresholds
- increase energy transfer

Dark Matter Candidates

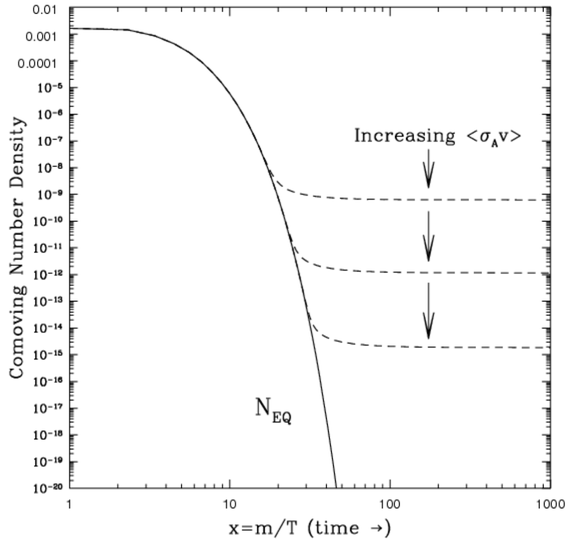
Weakly-Interacting Massive Particles (WIMPs)





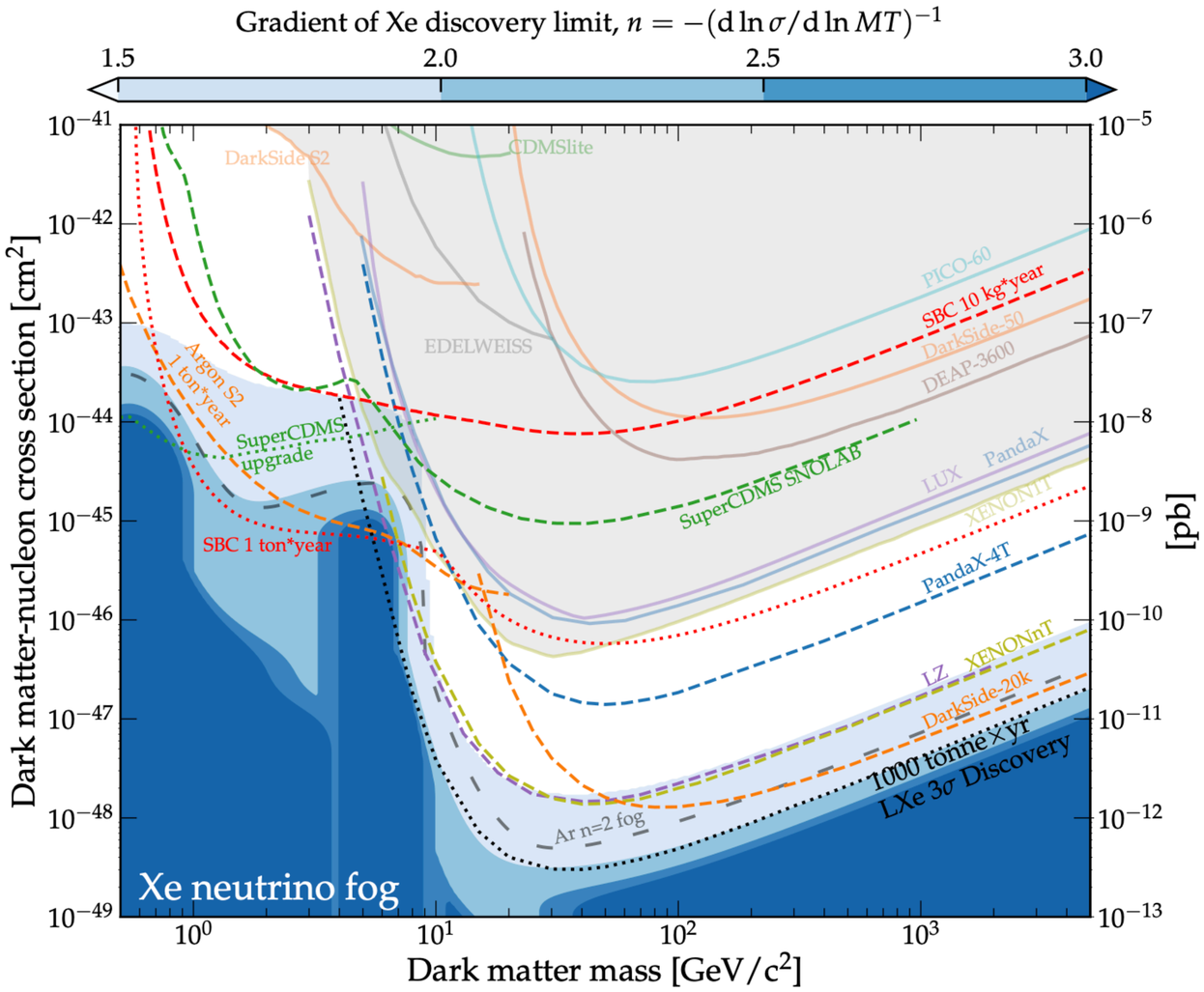
m_X~100 GeV

"WIMP miracle" → $\Omega h^2 \simeq \frac{10^{-37}\ \mathrm{cm}^2}{\langle \sigma_{\mathrm{ann}} v \rangle} \simeq 0.1$



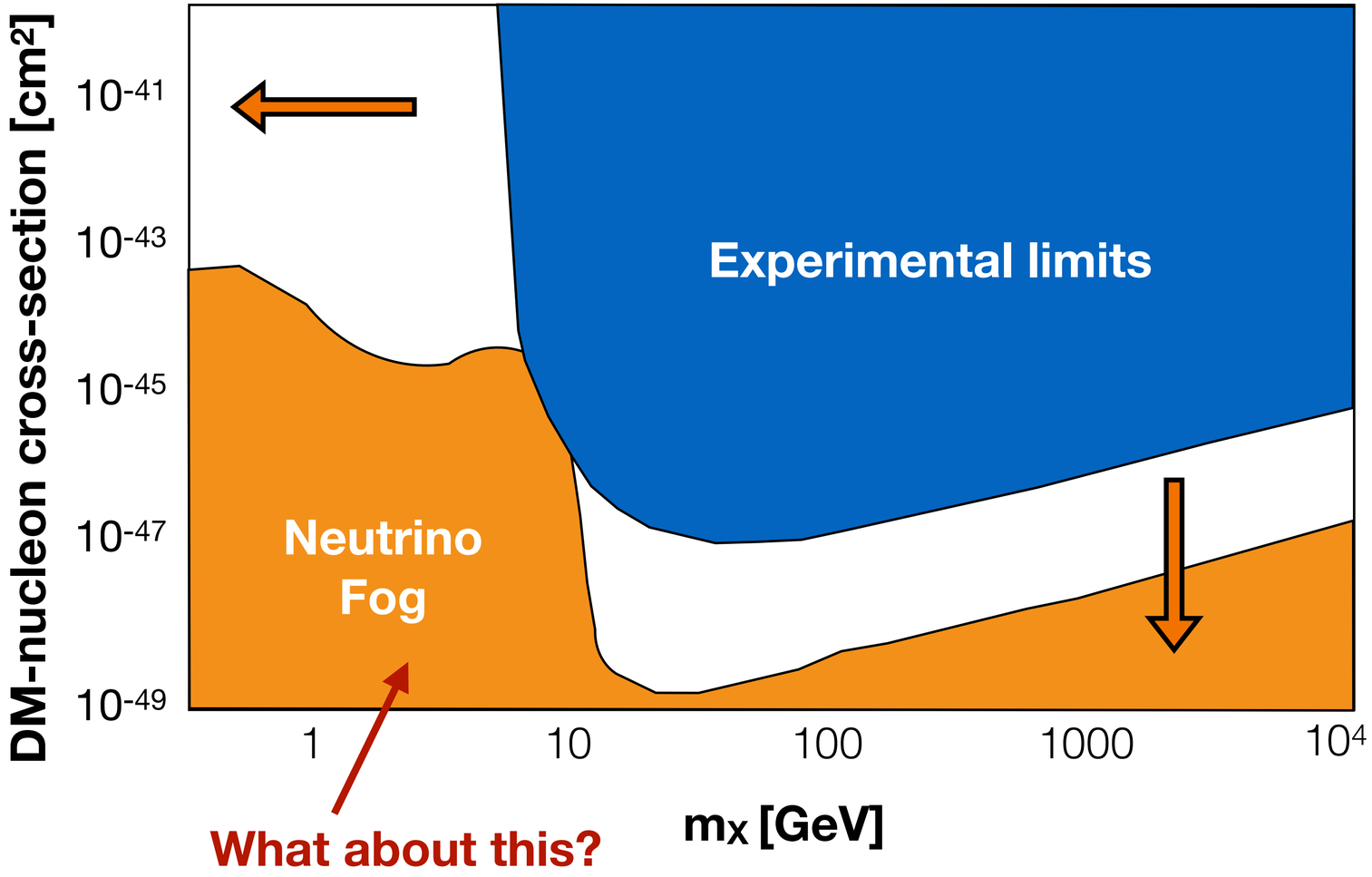
Jungman, Kamionkowski & Griest (1996)

Current Landscape: Spin-Independent



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

Path towards DM discovery



Goals:

- increase target mass
- decrease thresholds
- improve background discrimination

New technologies:

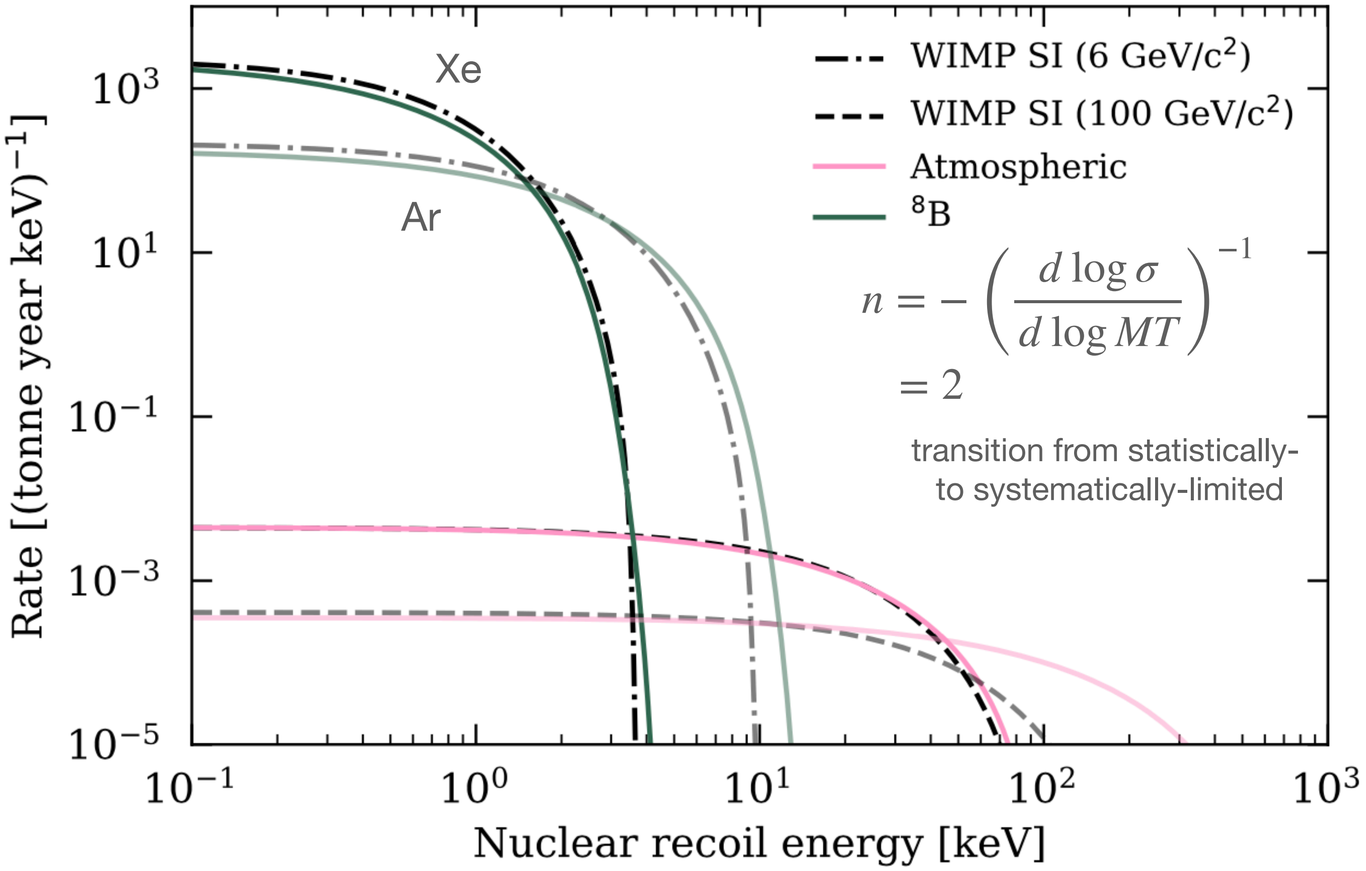
- Supercooled detectors
- Low Background DUNE-like module
- Giant gas TPCs in pressurized caverns
- …

Navigating the Neutrino Fog

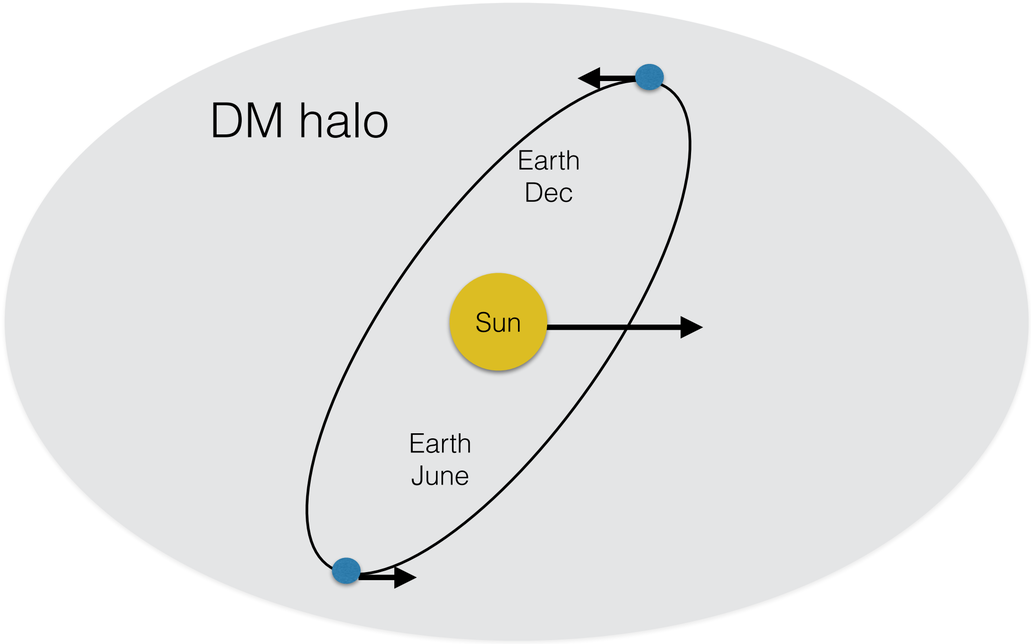
Snowmass2021 Cosmic Frontier Dark Matter

Direct Detection to the Neutrino Fog

[arXiv: 2203.08084]



Mitigation techniques:
annual modulation
directional detection



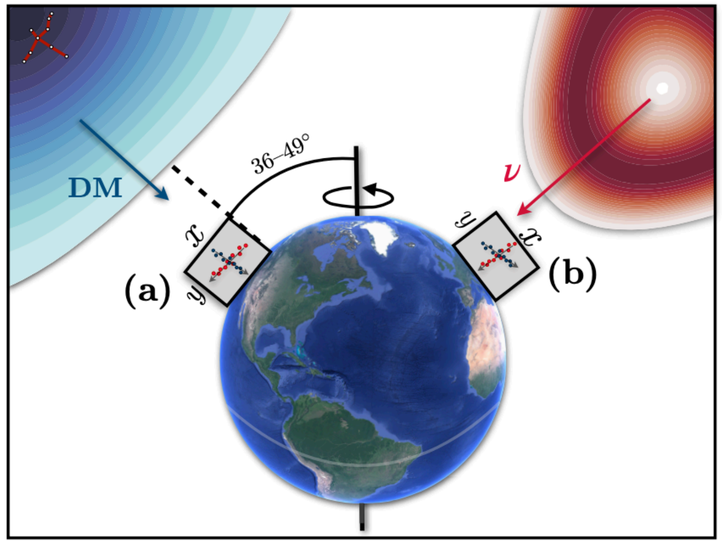
changes rate as a function of time
signature of galactic dark matter

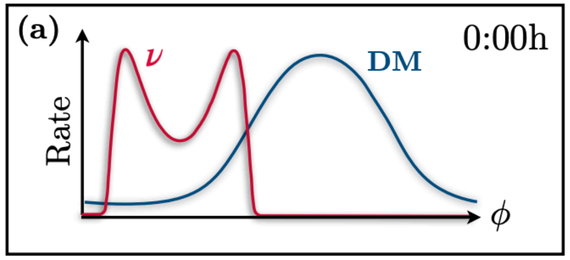
Directional Detection

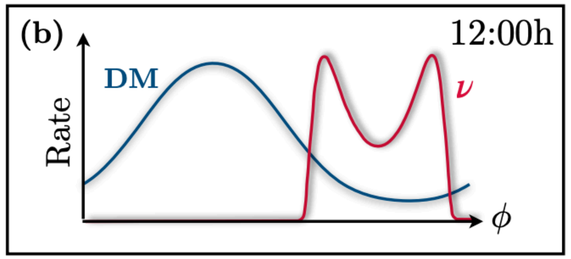
Very distinct signature!

Requires ability to reconstruct direction of nuclear recoil

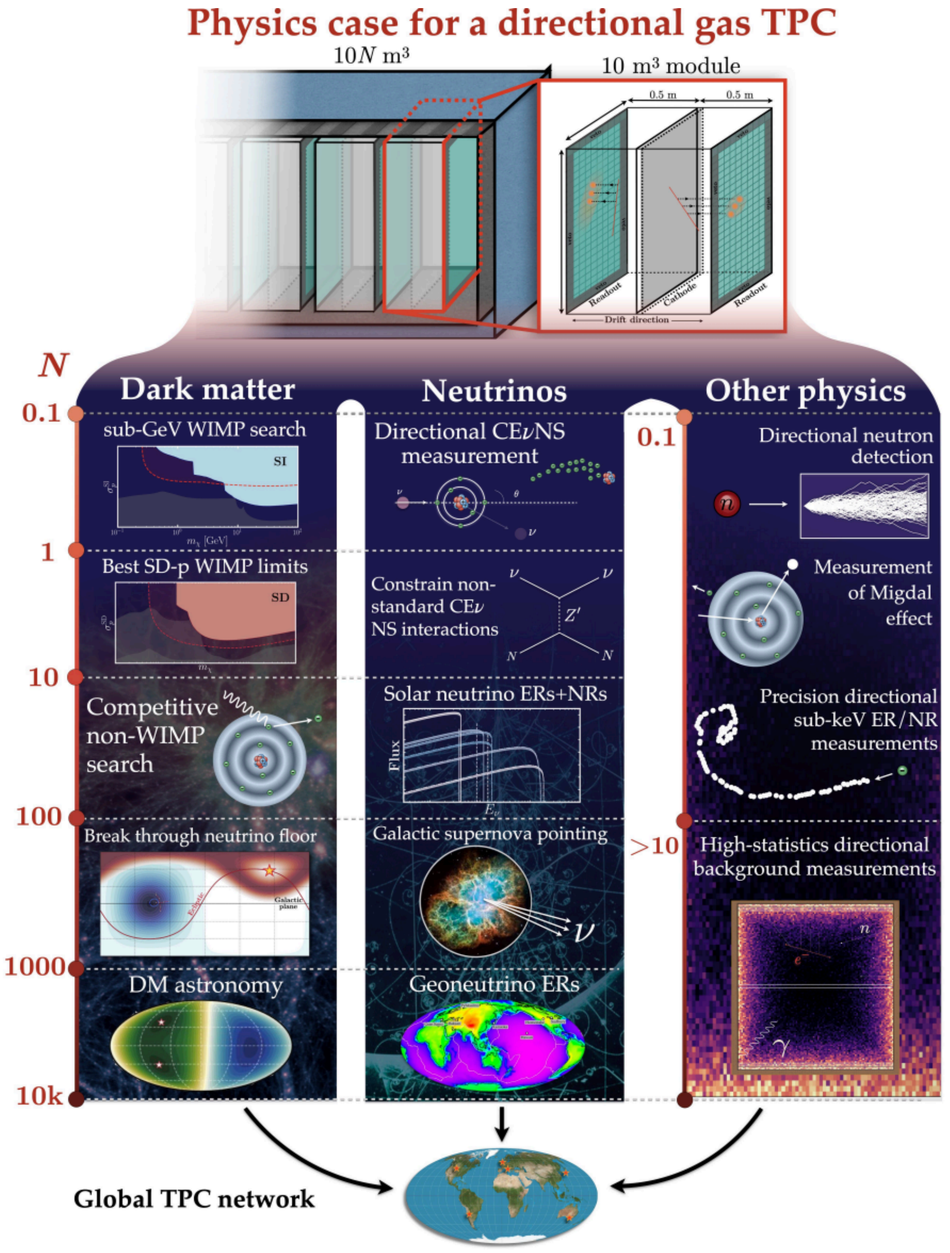
Vahsen, O'Hare, Loomba, [arXiv: 2102.04596]







Can also provide information on dark matter substructure in the galactic halo!



Landscape of Particle Dark Matter

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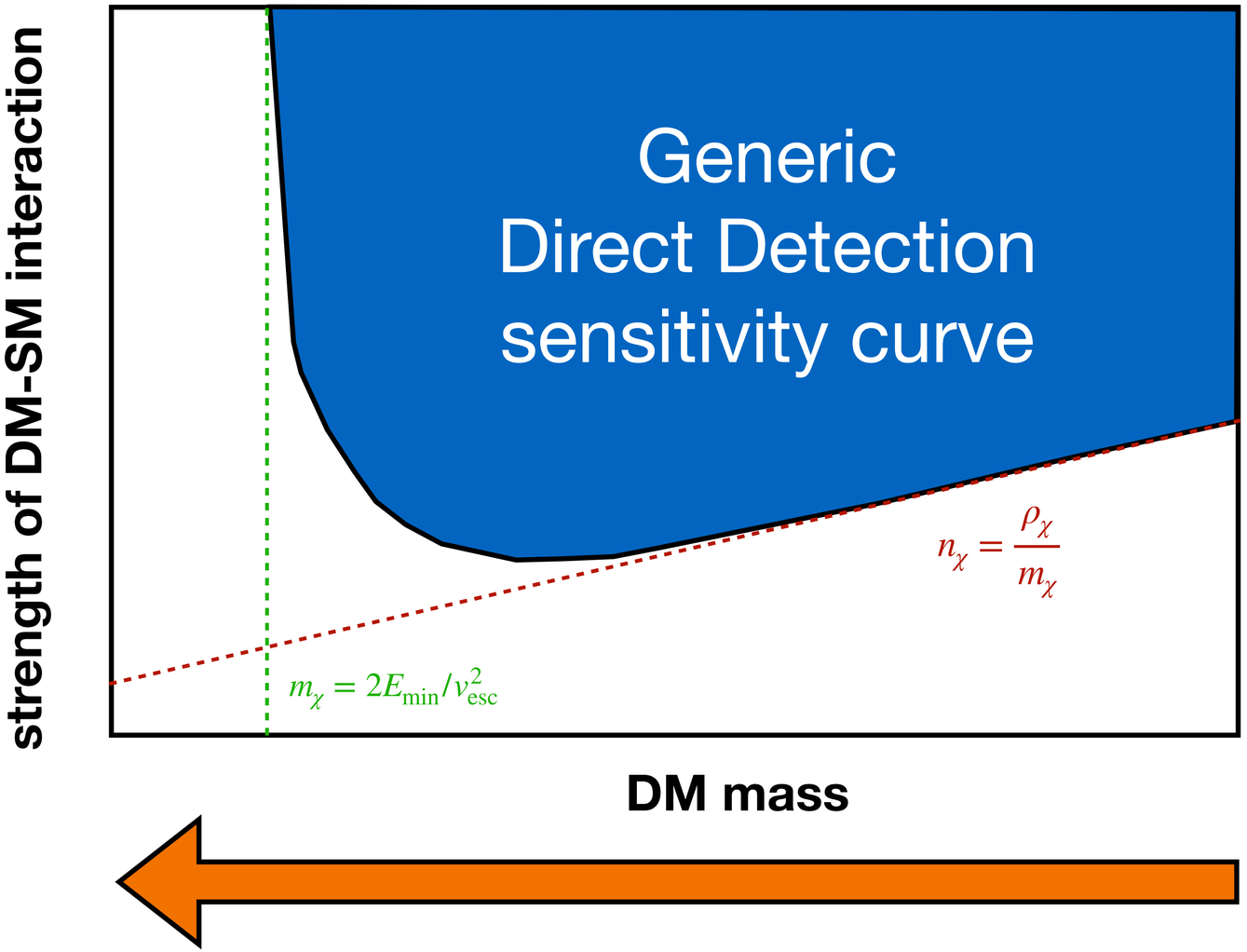

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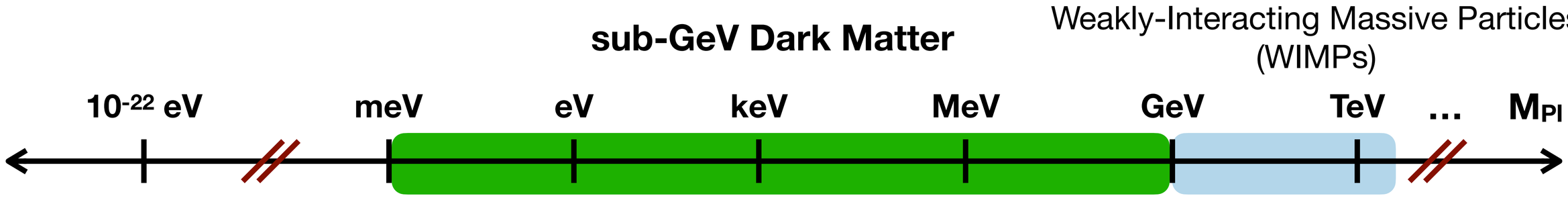
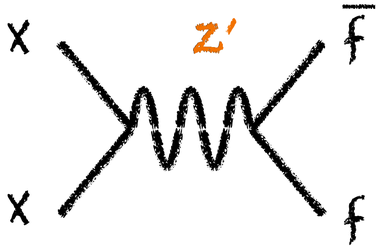
Dark Matter Candidates



Lee-Weinberg bound
Thermal DM



$$\Omega_X h^2 \lesssim 0.1 \quad \Rightarrow \quad m_X \gtrsim \text{ few GeV}$$

B. W. Lee and S. Weinberg, Phys. Rev. Lett. 39, 165 (1977)
E.W. Kolb and K. Olive, Phys.Rev. **D34** (1986) 2531

Way out: have new light boson that mediates the interaction → "hidden sector"

Boehm and Fayet [hep-ph/0305261]

Pospelov et al [0711.4866]

challenges for meV-GeV DM direct detection

fundamental challenge:

need enough **energy transfer**
from DM-target interaction
to create a detectable **signal**

depends on process
and
detector setup

detecting sub-GeV DM in 2 easy steps

1. decrease energy threshold or sensitivity

   consider a variety of materials

2. increase the energy transfer

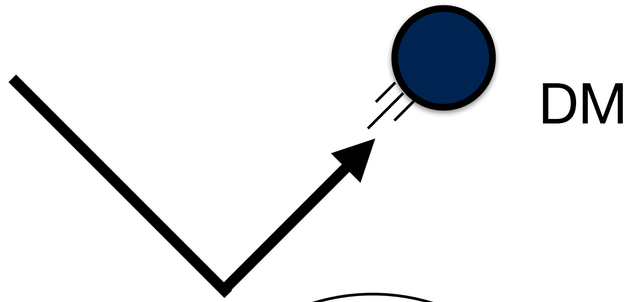
   consider different physical processes

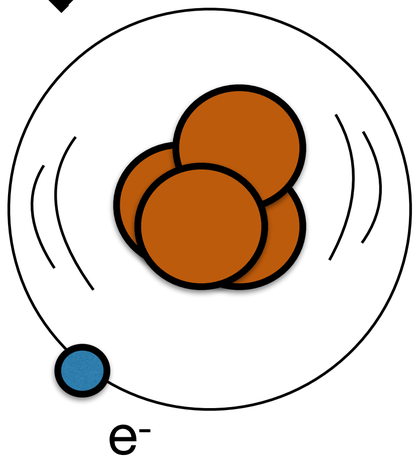
sub-GeV DM direct detection

- **Dark matter-electron scattering** in noble liquids, semiconductors, and organic molecules
- **Dark matter-nuclear scattering** through the Migdal scattering and bremsstrahlung
- **Absorption** of light dark matter, including axion-like particles and dark photons.
- **Dark matter scattering off collective modes** in molecules and in crystals (including phonons, plasmons and magnons)

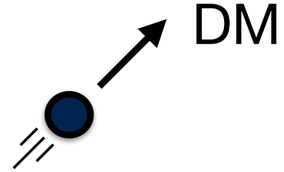
Nuclear vs. Electron Scattering

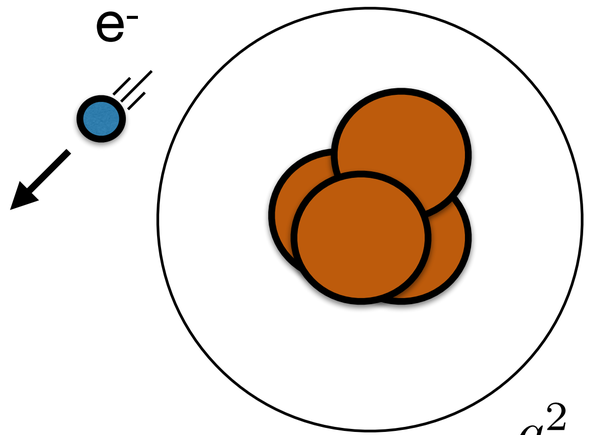
DM-nuclear scattering





DM-electron scattering





$$E_R = \frac{q^2}{2m_N} \simeq 50\ \text{keV} \left(\frac{m_\chi}{100\ \text{GeV}}\right)^2 \left(\frac{100\ \text{GeV}}{m_N}\right)$$

recoil energy

$$E_R = \vec{q}\cdot\vec{v} - \frac{q^2}{2\mu_{\chi N}} \sim \frac{1}{2}\text{eV} \times \left(\frac{m_\chi}{\text{MeV}}\right)$$

DM-electron scattering rate

particle physics

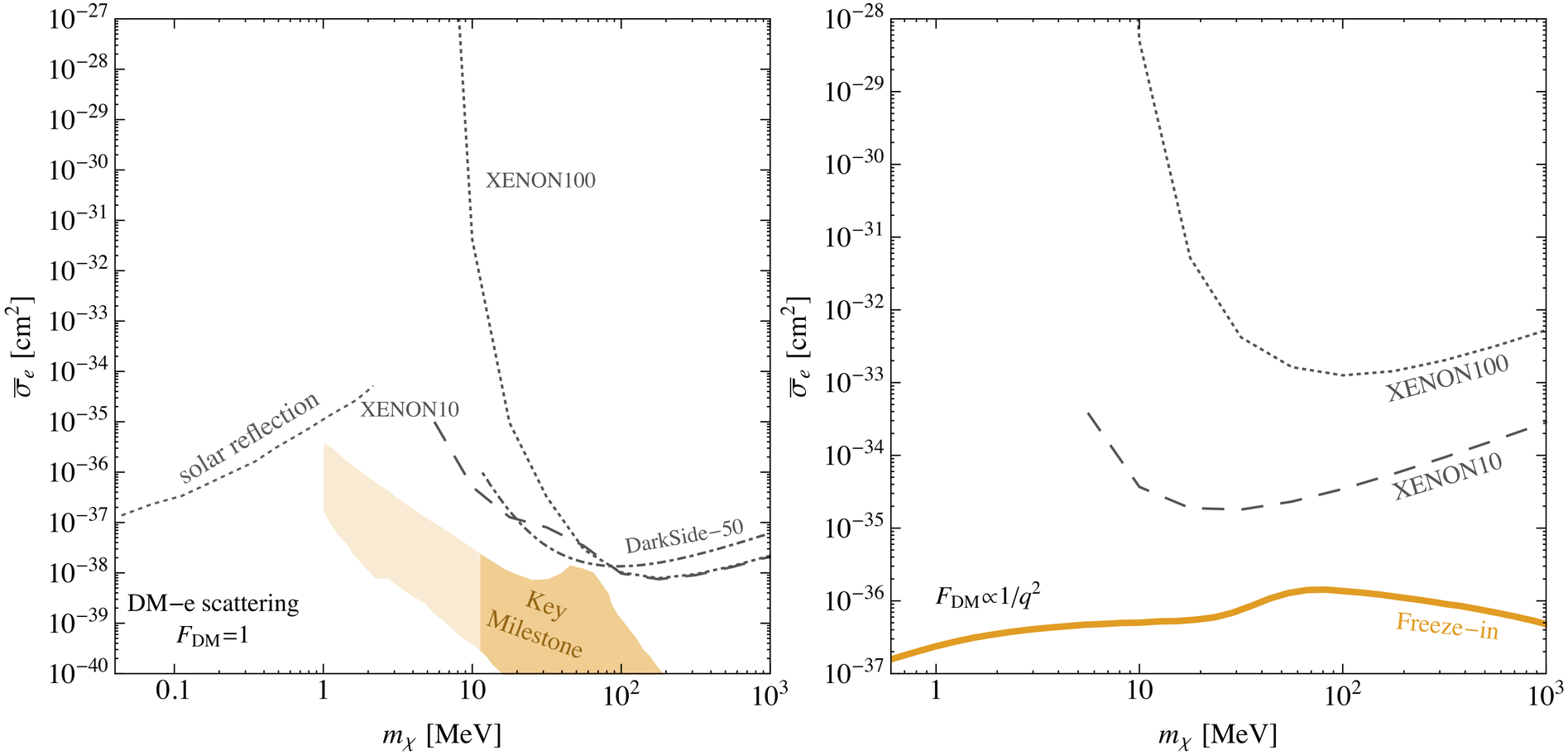
$$\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2}\int q\ \mathrm{d}q|f(k,q)|^2|F_{DM}(q)|^2\eta(v_{min})$$

$$\overline{\sigma}_e = \frac{\mu_{\chi e}^2}{16\pi m_\chi^2 m_e^2}\overline{|\mathcal{M}_{\chi e}(q)|}^2_{q^2=\alpha^2 m_e^2}$$

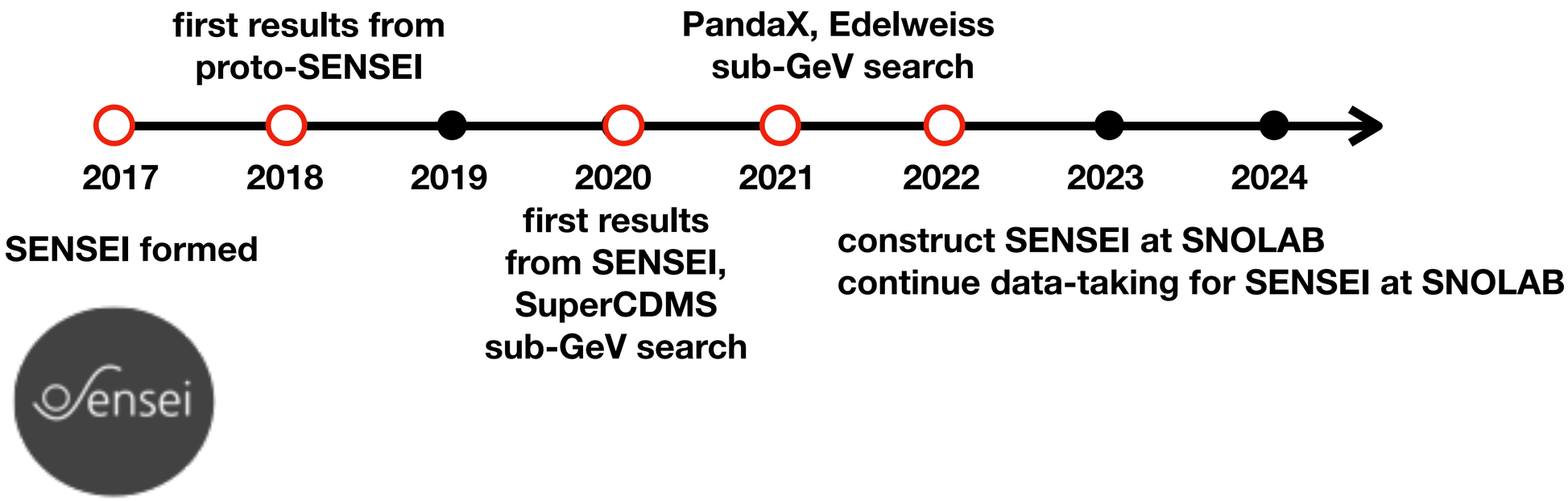
$$F_{DM}(q) \simeq \begin{cases} 1 & \textbf{\textit{heavy mediator}} \\ \frac{\alpha m_e}{q} & \textit{electric dipole moment} \\ \frac{\alpha^2 m_e^2}{q^2} & \textbf{\textit{light mediator}} \end{cases}$$

DM-electron limits in 2018

Essig, Volansky, TTY Phys.Rev.D 96 (2017) 4, 043017 [1703.00910]
DarkSide Collaboration Phys.Rev.Lett. 121 (2018) 11, 111303 [1802.06998]
An, Pospelov, Pradler, Ritz Phys.Rev.Lett. 120 (2018) 14, 141801 [1708.03642]



a brief history

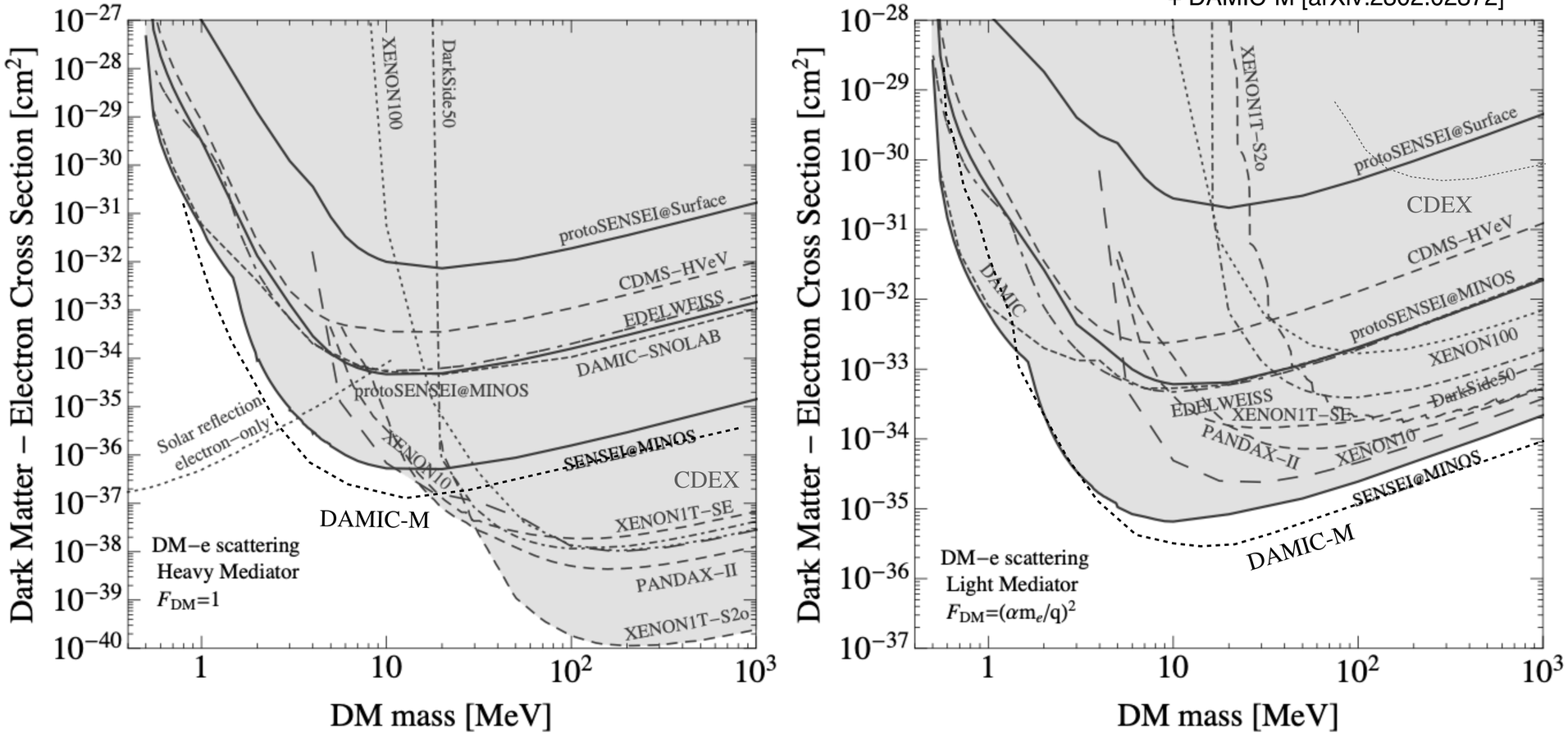


DM-electron scattering limits today*

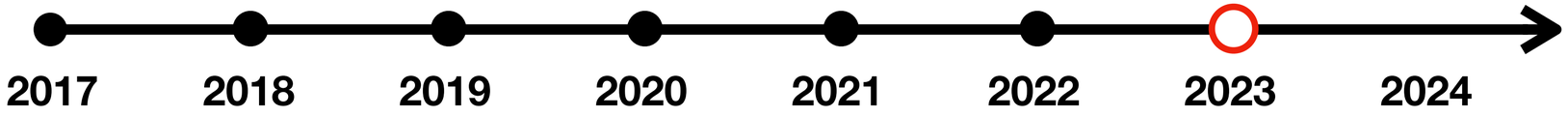
Snowmass2021 Cosmic Frontier: The landscape of low-threshold dark matter direct detection in the next decade [arXiv:2203.08297]

+CDEX [arXiv:2206.04128]

+ DAMIC-M [arXiv:2302.02372]

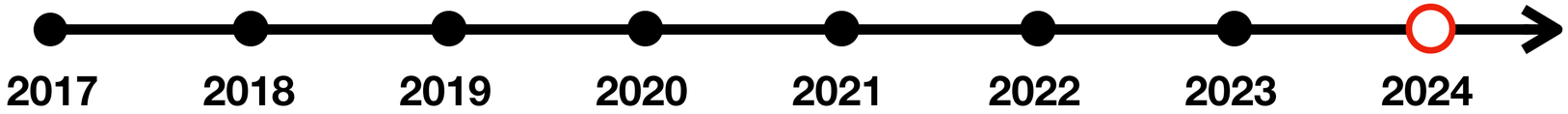


looking forward



- construct SENSEI at SNOLAB
- continue data-taking for SENSEI at SNOLAB
- **final analysis of 100-gram SENSEI data**
- **launch of 1-kg DAMIC-M at Modane**
- **complete R&D for Oscura**

looking forward



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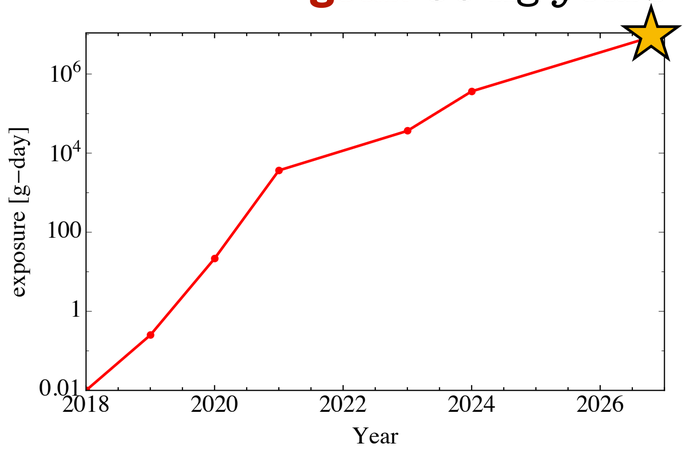
- **launch of 10-kg Oscura**

goal: 30 kg-years



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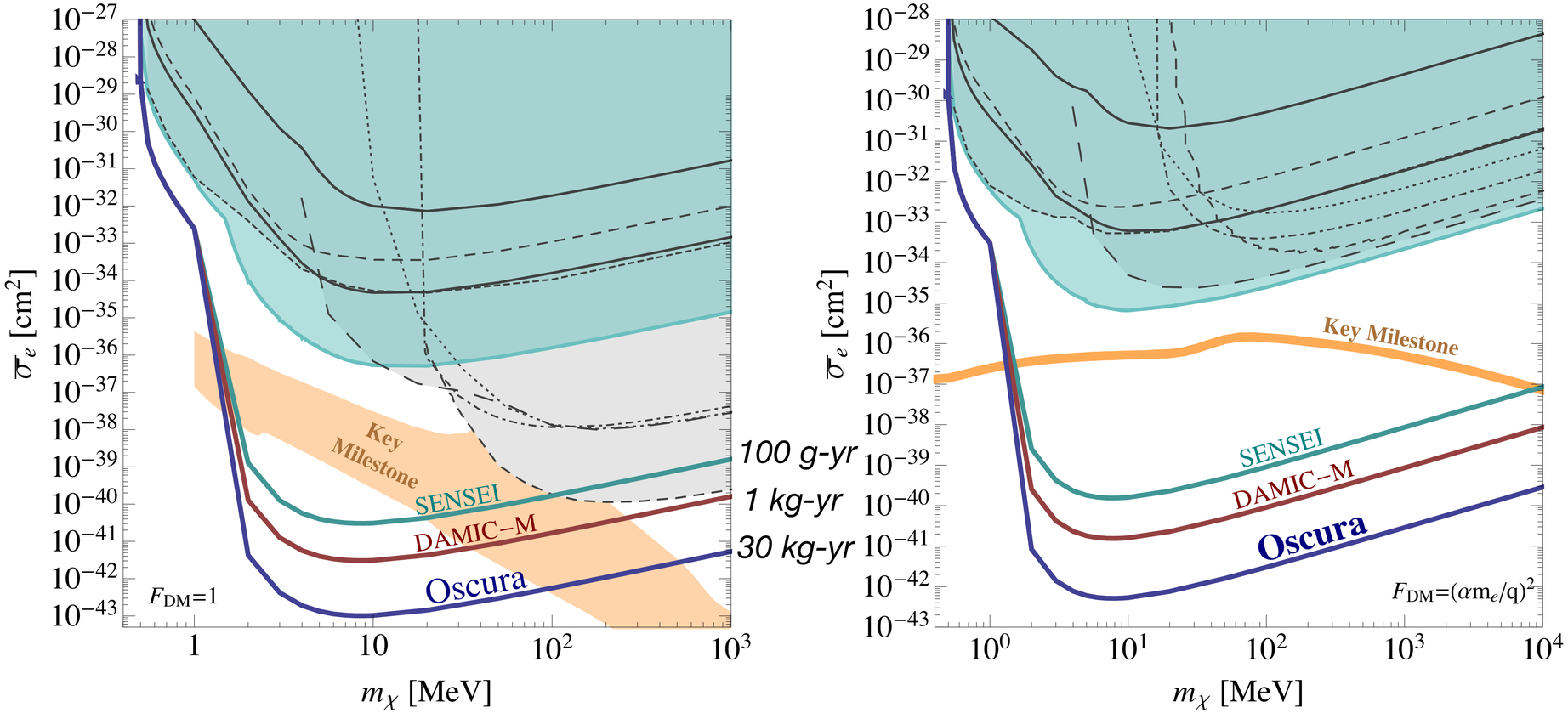
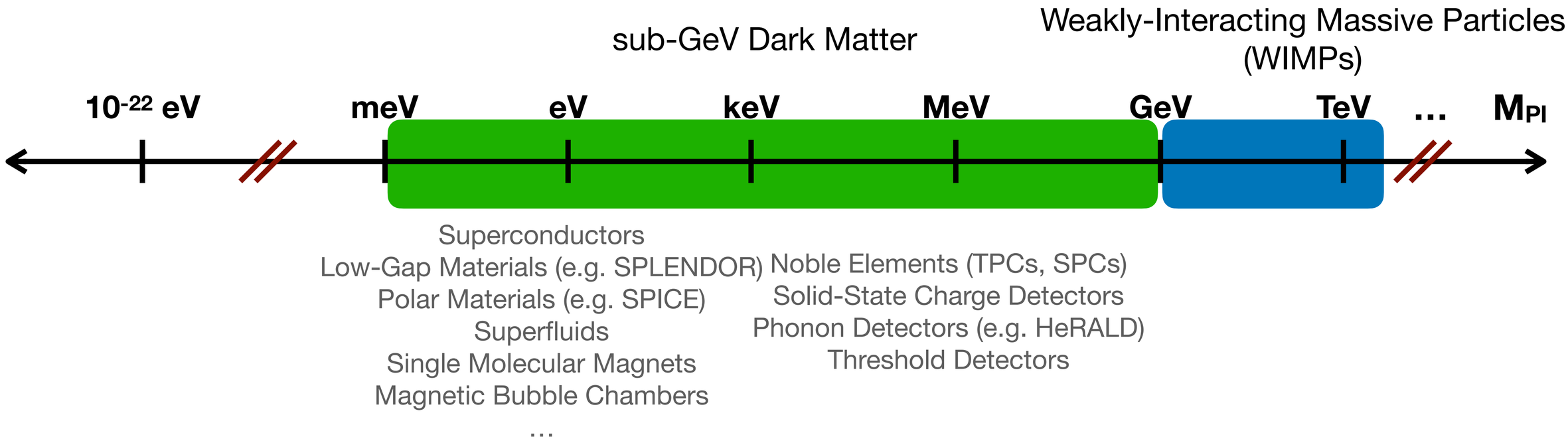
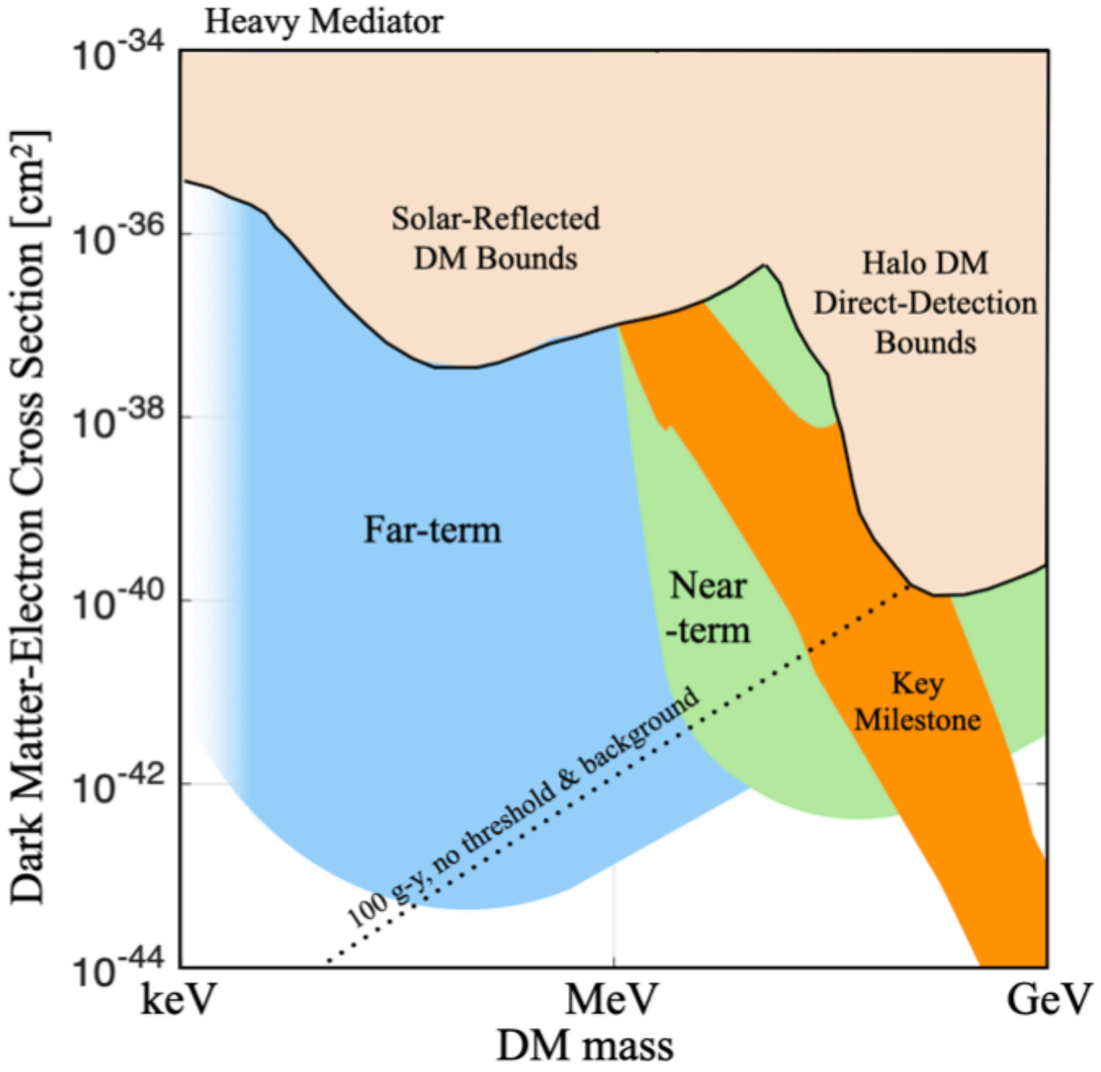


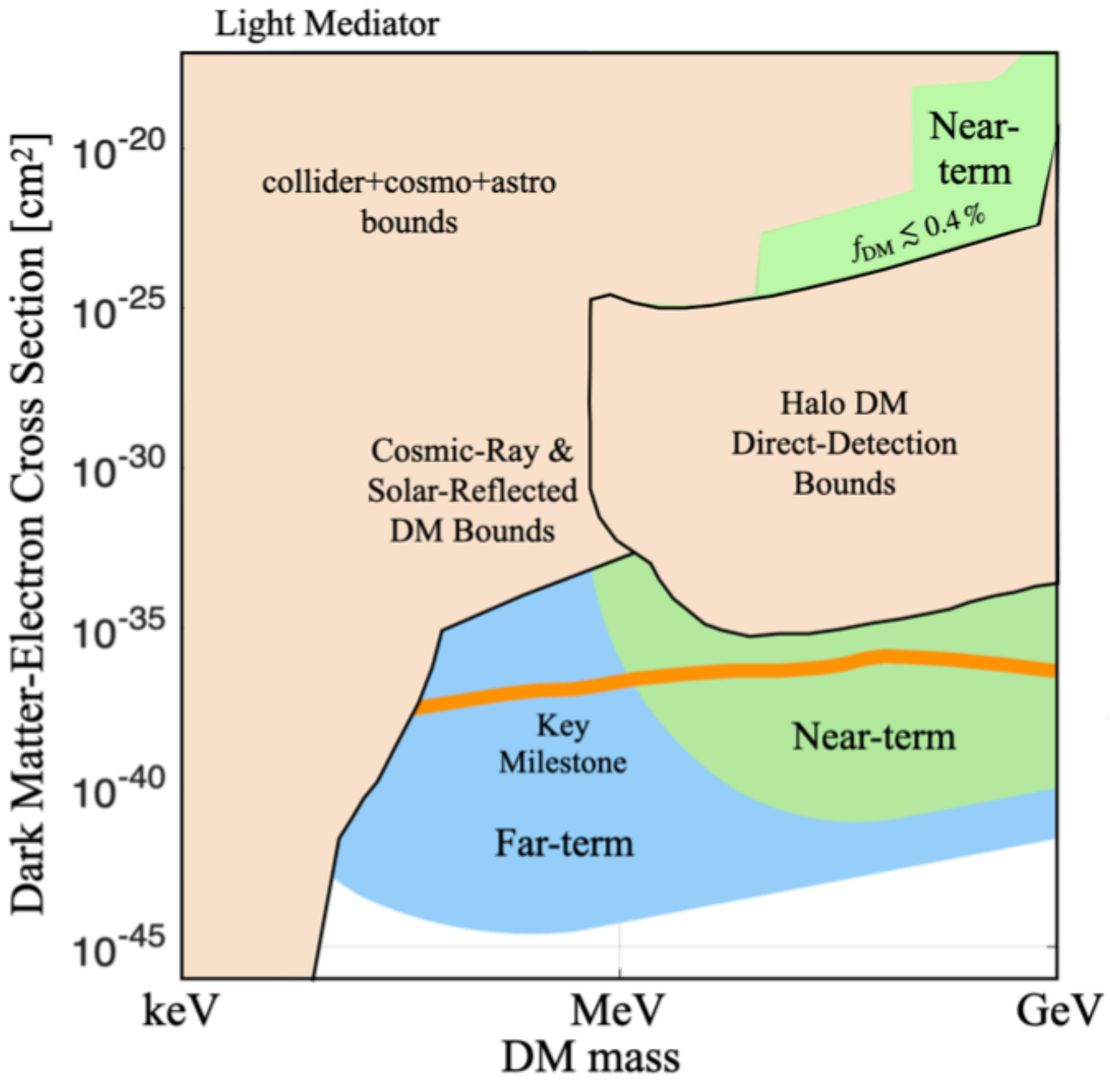
Projections for future Si Skipper-CCD experiments

Dark Matter Candidates



Outlook for sub-GeV DM direct detection





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

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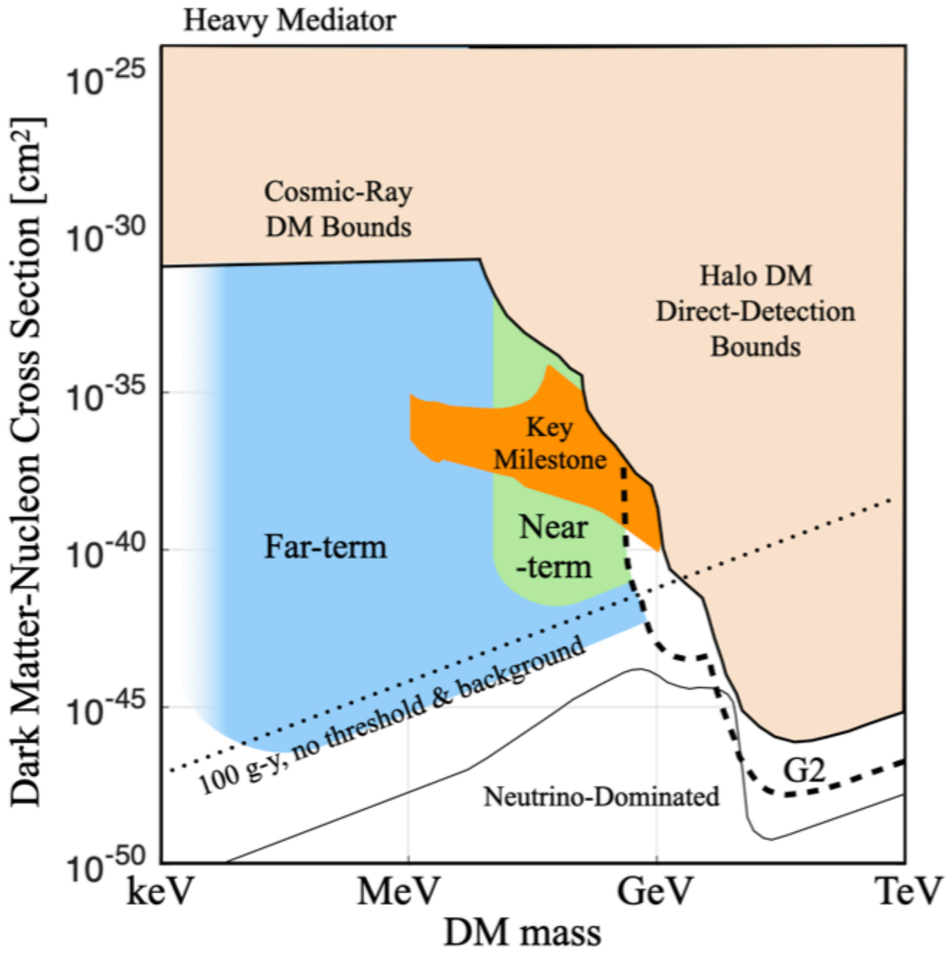
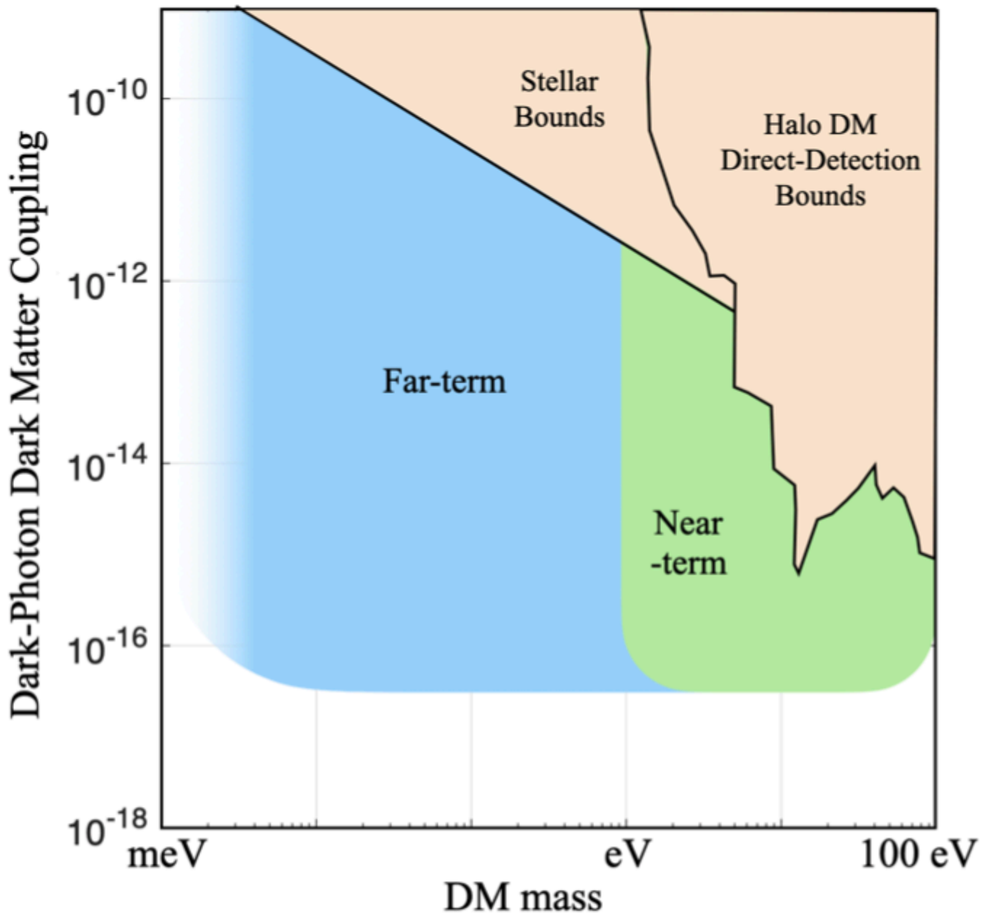
Other Models

DM-nucleon scattering



DM absorption



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Summary

- There are a wide range of motivated DM candidates spanning many orders of magnitude in mass space
- Direct detection is necessary to understand particle nature of DM as it probes cosmological abundance, stability, interactions with the SM
- Several new and upgraded experiments coming online in the next several years
- These include new technologies and techniques
- These experiments are sensitive to a wide range of DM models and more!
- complementary to accelerator experiments, cosmology, and indirect detection