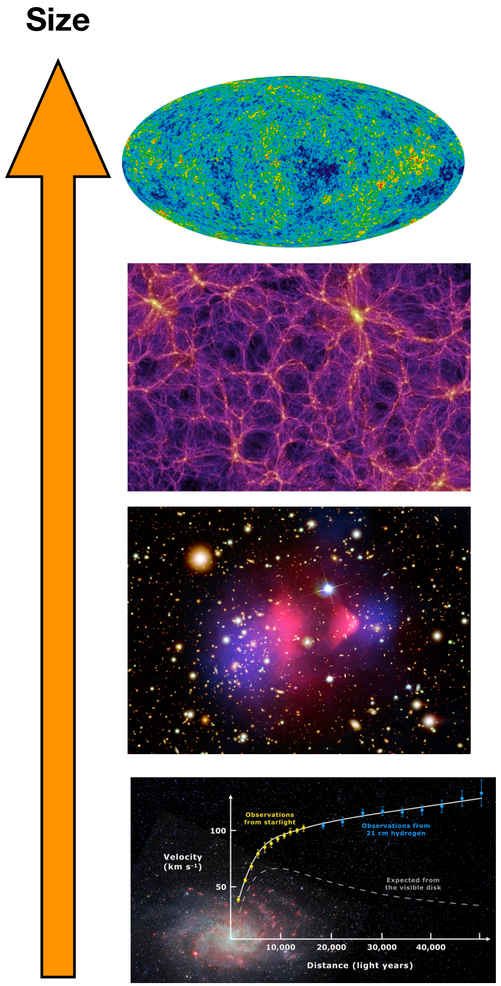
Particle Dark Matter Direct Detection

Tien-Tien Yu (University of Oregon)

Snowmass: Hot Topics on the Cosmic Frontier

June 10, 2022

Dark Matter Exists



COSMIC MICROWAVE BACKGROUND

LARGE SCALE STRUCTURE

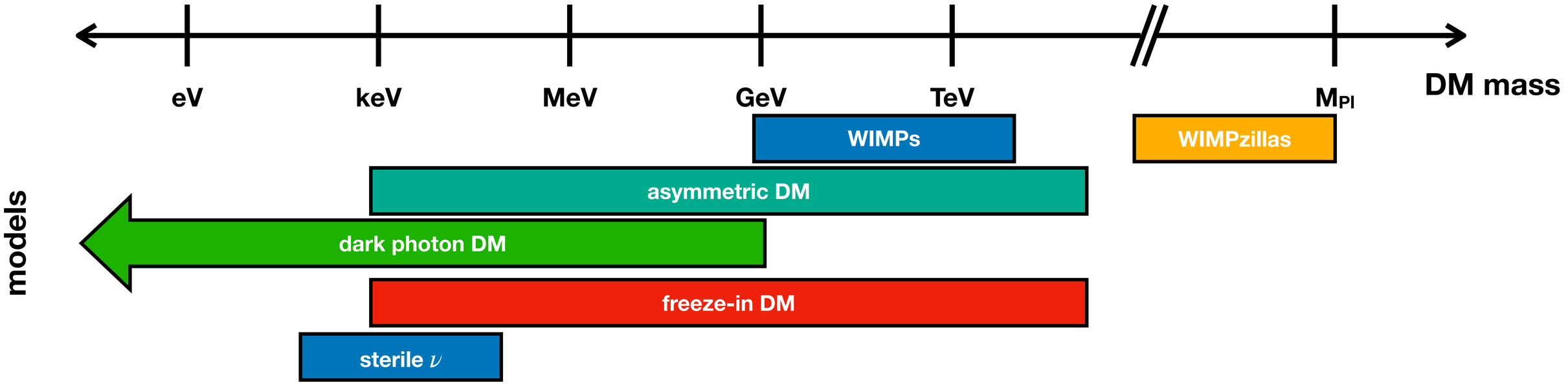
GALAXY CLUSTER MERGERS

GALACTIC ROTATION CURVES

Gravitational interactions

Dark Matter Candidates

Gravitational interactions ⟶ massive (particle)

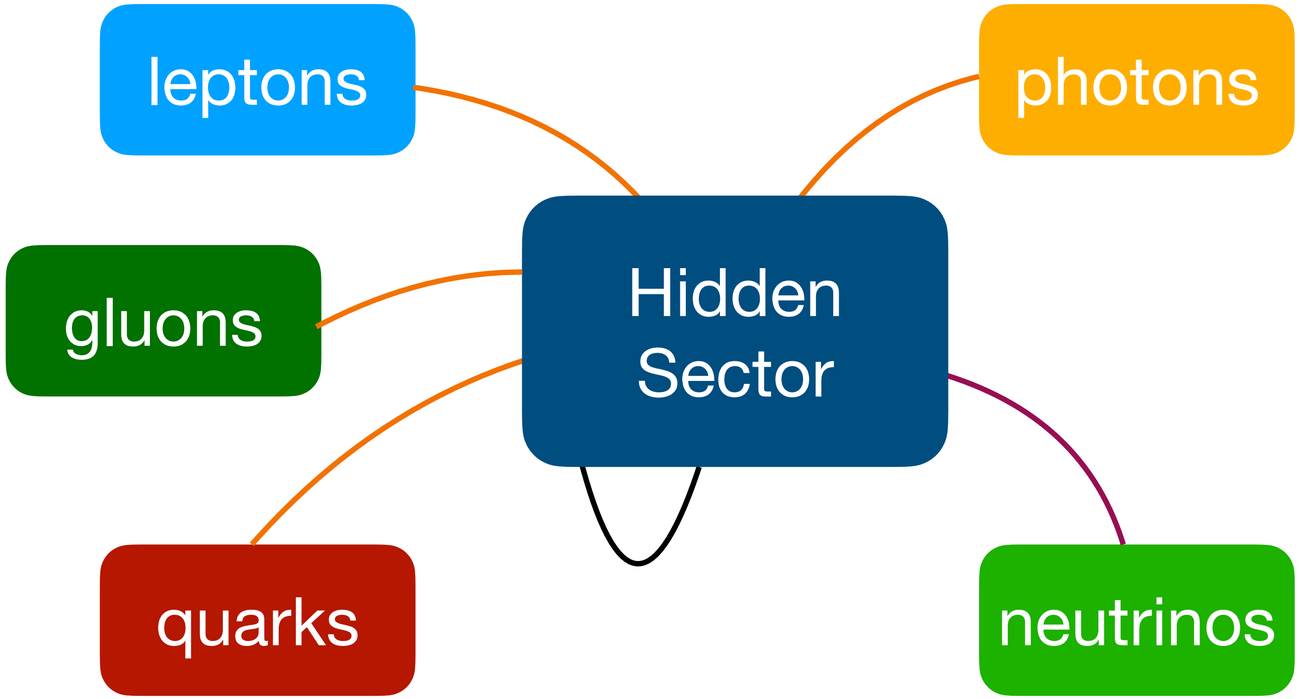


Many theoretically-motivated models!

Non-gravitational interactions of DM

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

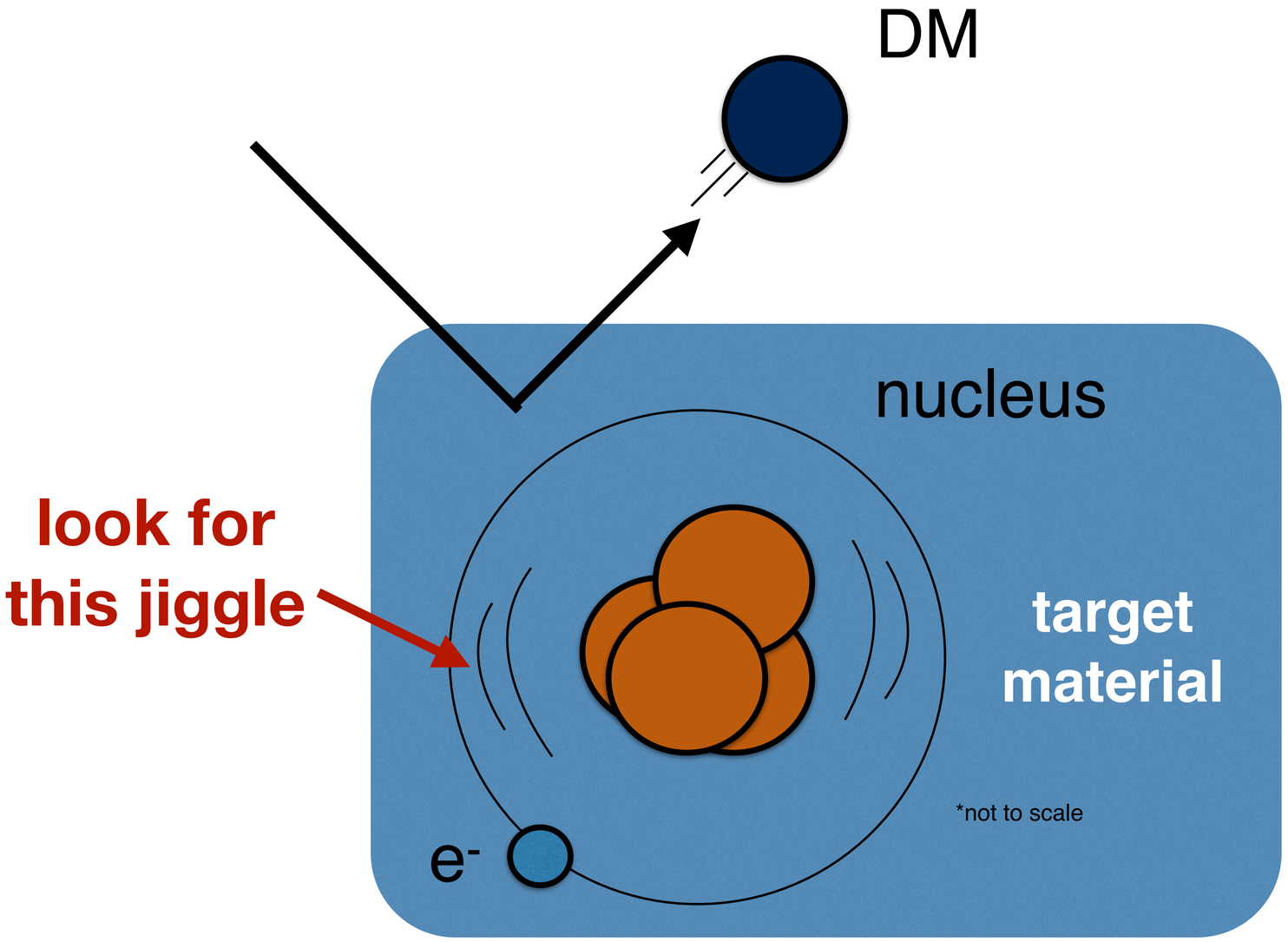
Direct detection can probe these



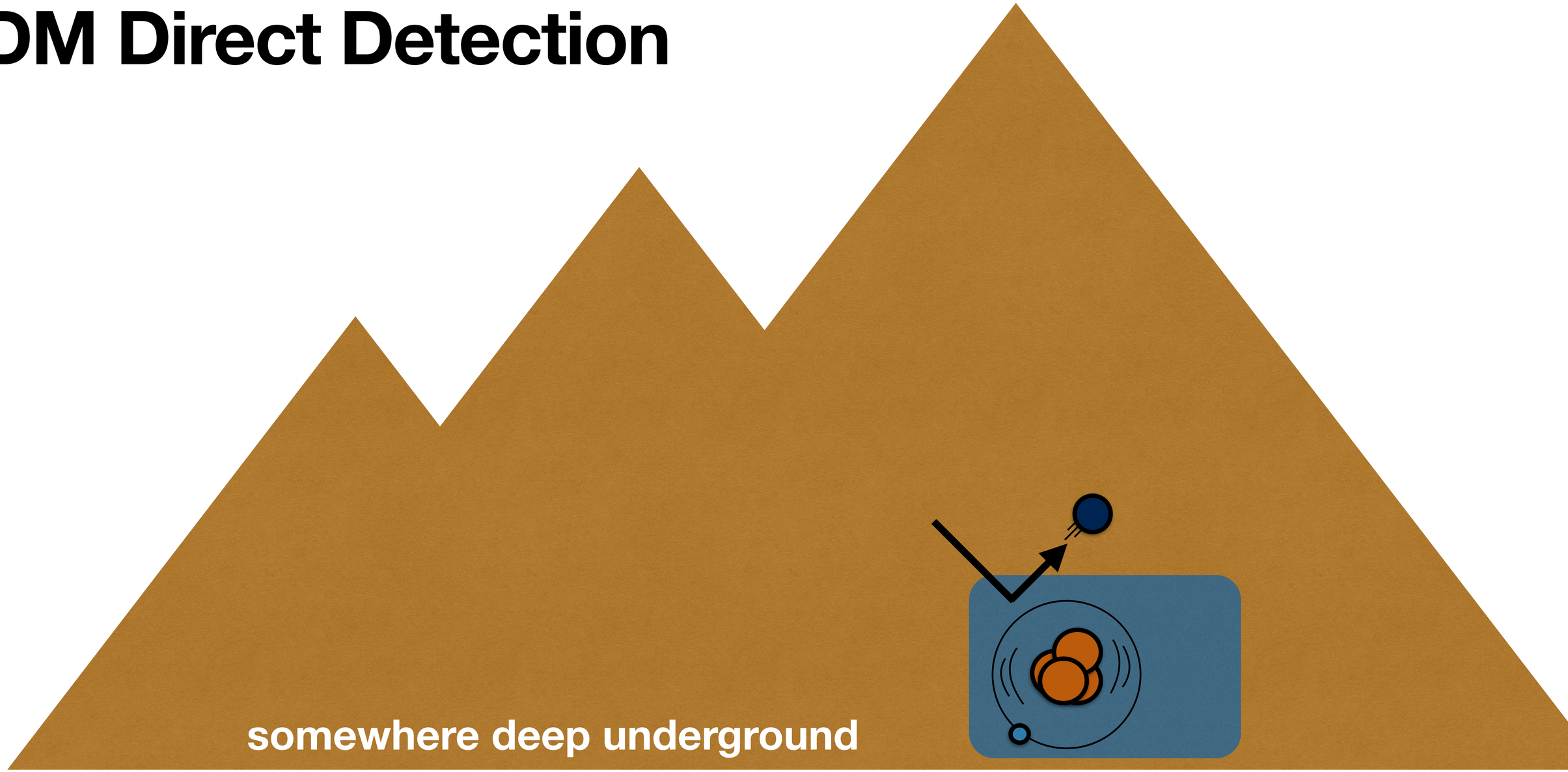
see Rebecca Leane's talk next week on indirect detection

Direct detection probes our galactic dark matter halo

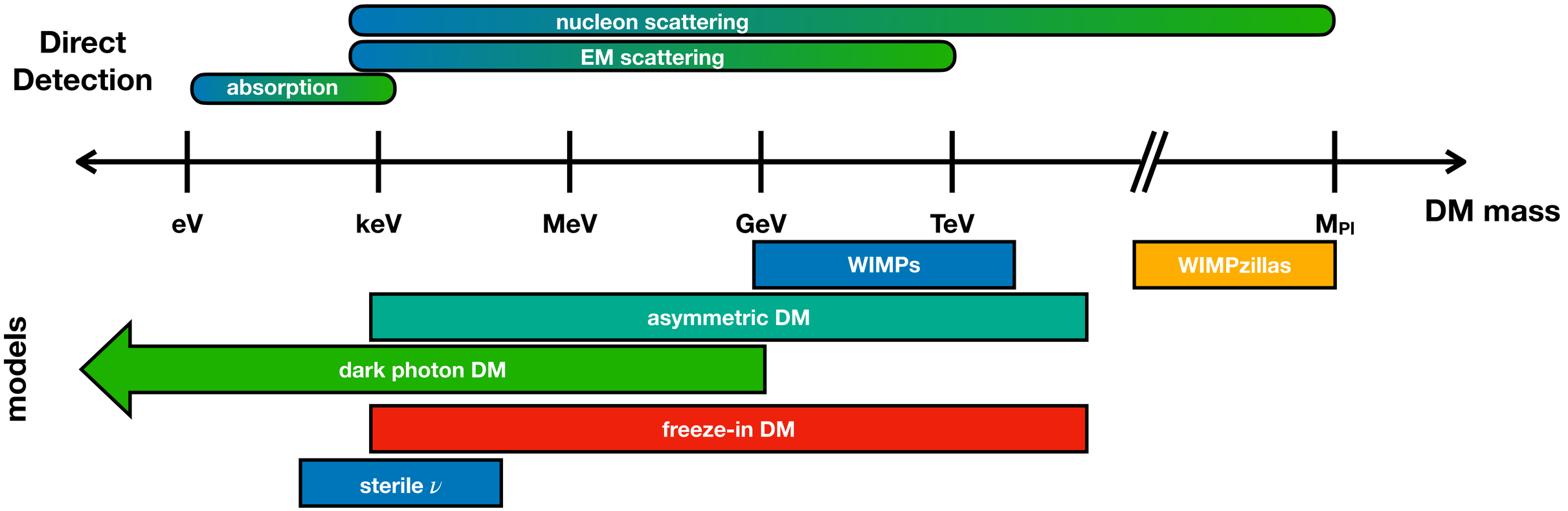
DM Direct Detection



DM Direct Detection

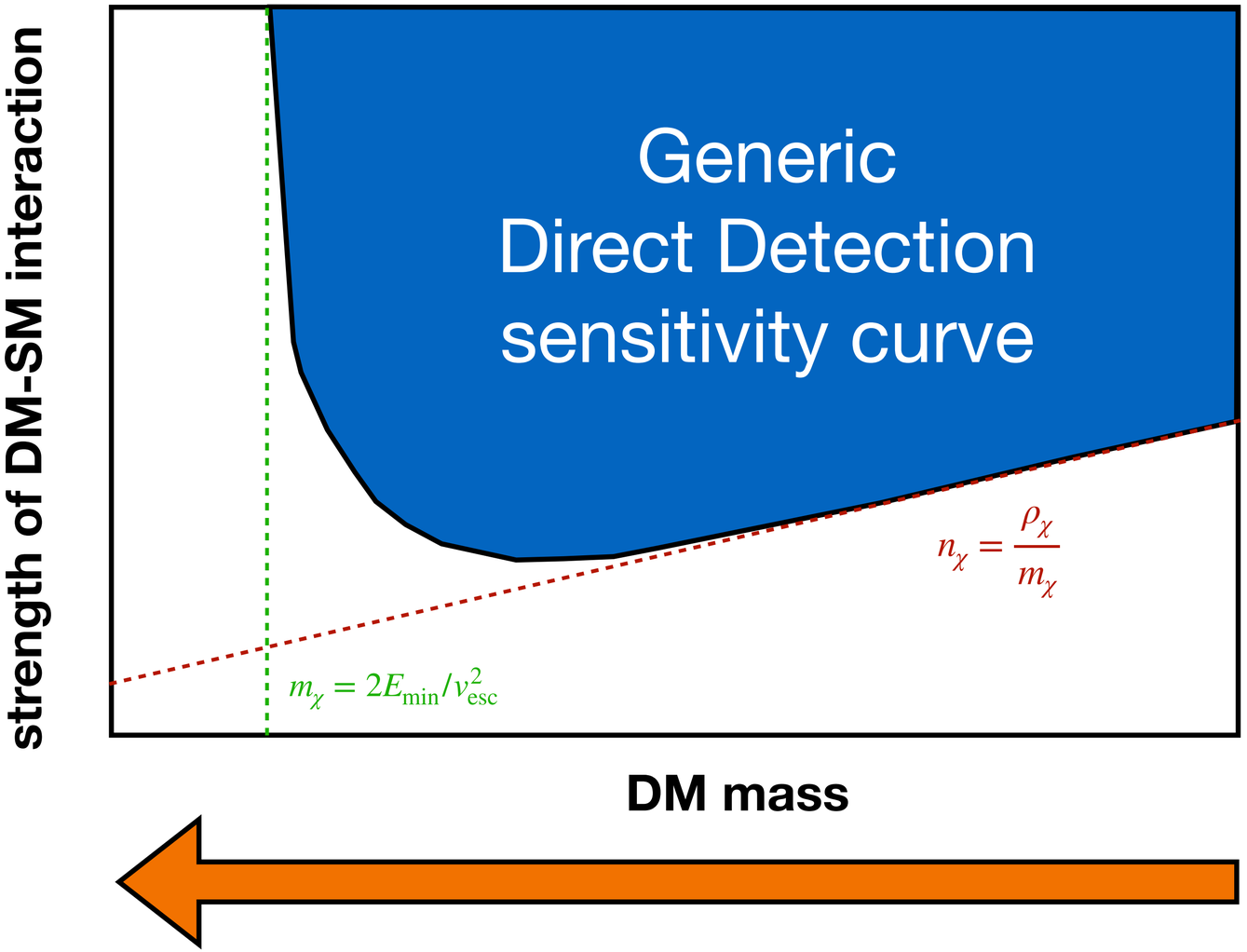


Dark Matter Candidates



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 Direct Detection

Direct detection has been a top priority for particle physics in the US

2014

"Generation 2" Experiments = currently running, improve cross-section reach by order of magnitude compared to "Generation 1"

"Generation 3" Experiments = reach neutrino fog

2018

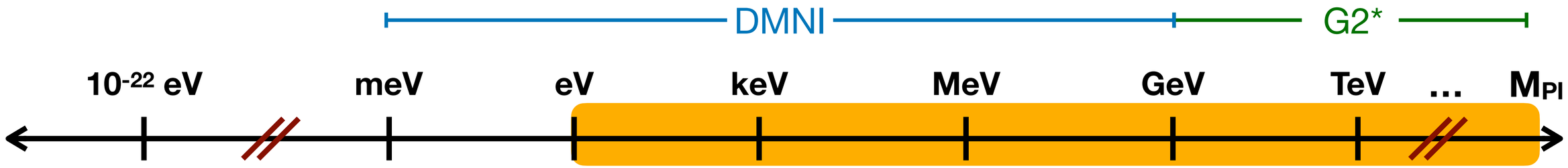
Basic Research Needs for
Dark Matter Small Projects New Initiatives

PRD 2: Detect individual galactic dark matter particles below the proton mass through interactions with advanced, ultra-sensitive detectors.

Detect Galactic Dark Matter Underground

Galactic dark matter passes through the earth undetected every second. Recent advances in particle theory highlight new compelling paradigms for the origin of dark matter and its detection. Revolutionary technological advances now allow us to discover individual dark matter particles with a mass ranging from the proton mass to twelve orders of magnitude below, through their interactions with electrons and nucleons in advanced detectors. New small projects leveraging these theoretical and technological advances are needed and can be carried out by using DOE personnel, laboratories, and infrastructure, especially the underground infrastructure already built using DOE support.

Dark Matter Candidates



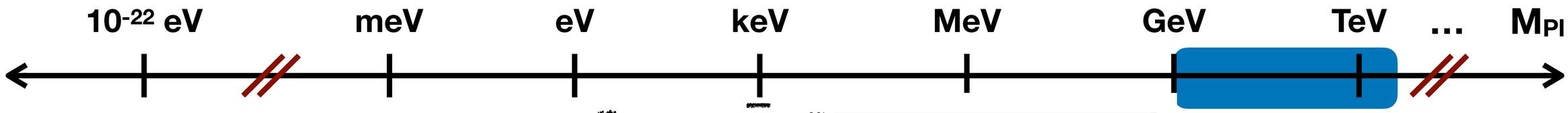
CF1: Particle Dark Matter

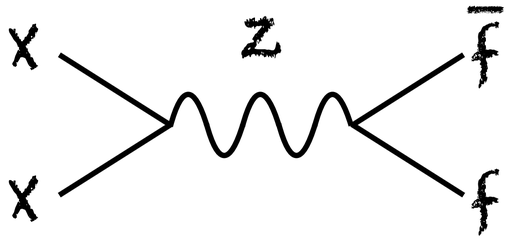
see Chelsea Bartram's talk next week on wave dark matter

*G2 defined as in previous slide

Dark Matter Candidates

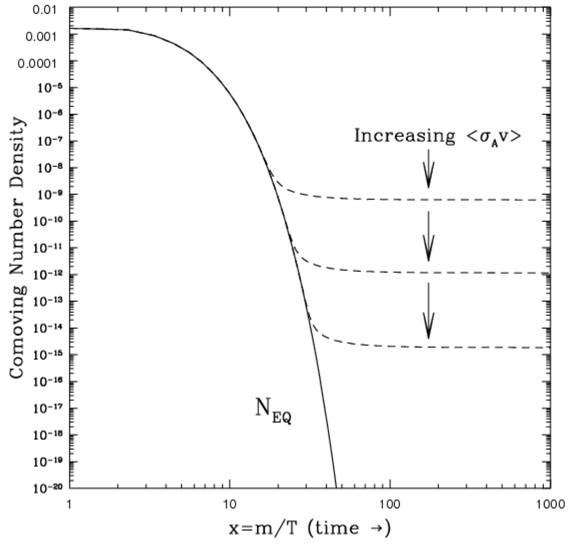
Weakly-Interacting Massive Particles (WIMPs)





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)

Dark Matter - Nucleon Scattering

$$\frac{dR}{dE_{\mathrm{NR}}} \propto \sigma_N N_T e^{-E_{\mathrm{NR}}/E_0}$$

large cross-section is better

more targets is better

Coherent
Elastic
Spin-Independent

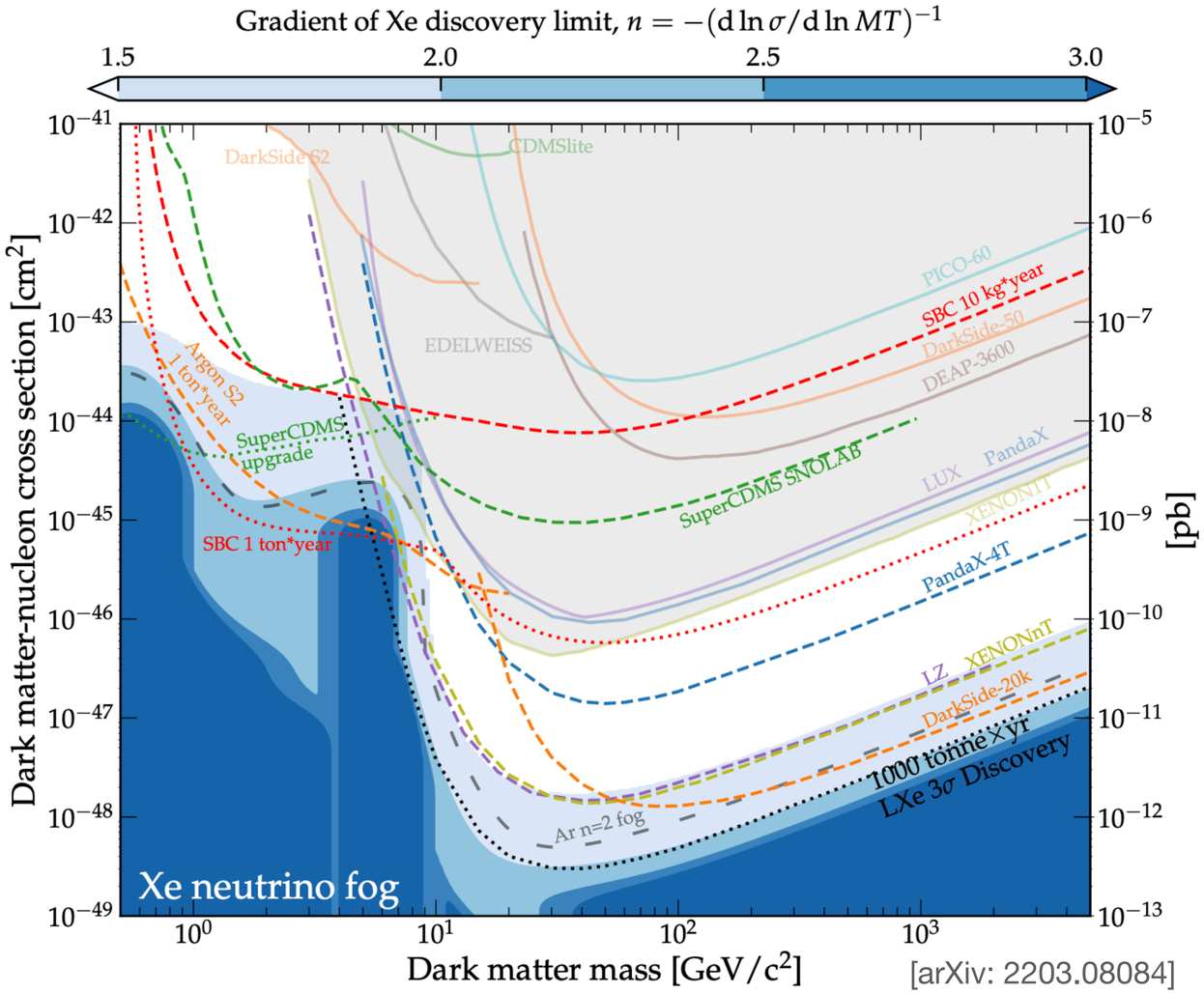
$$\sigma_{\mathrm{SI}} = \sigma_n \frac{\mu^2}{\mu_n^2} \frac{[f_p Z + f_n (A-Z)]^2}{f_n^2} \overset{f_p = f_n}{=} \sigma_n \frac{\mu^2}{\mu_n^2} A^2$$

Heavy nuclei are better

Element	A
Xenon	131
Argon	39
CsI	133 (Cs), 127 (I)
NaI	22 (Na), 127 (I)
Ge	72
Si	28

Variety of targets allow for cross-checks

Current Landscape: Spin-Independent



[arXiv: 2203.08084]

Dark Matter - Nucleon Scattering

$$\frac{dR}{dE_{\mathrm{NR}}} \propto \sigma_N N_T e^{-E_{\mathrm{NR}}/E_0}$$

large cross-section is better

more targets is better

Spin-Dependent

$$\frac{d\sigma_{\mathrm{SD}}}{d|\vec{q}|^2} = \frac{8G_F^2}{\pi v^2}\left[a_p\langle S_p\rangle + a_n\langle S_n\rangle\right]^2 \frac{J+1}{J}\frac{S(|\vec{q}|)}{S(0)}$$

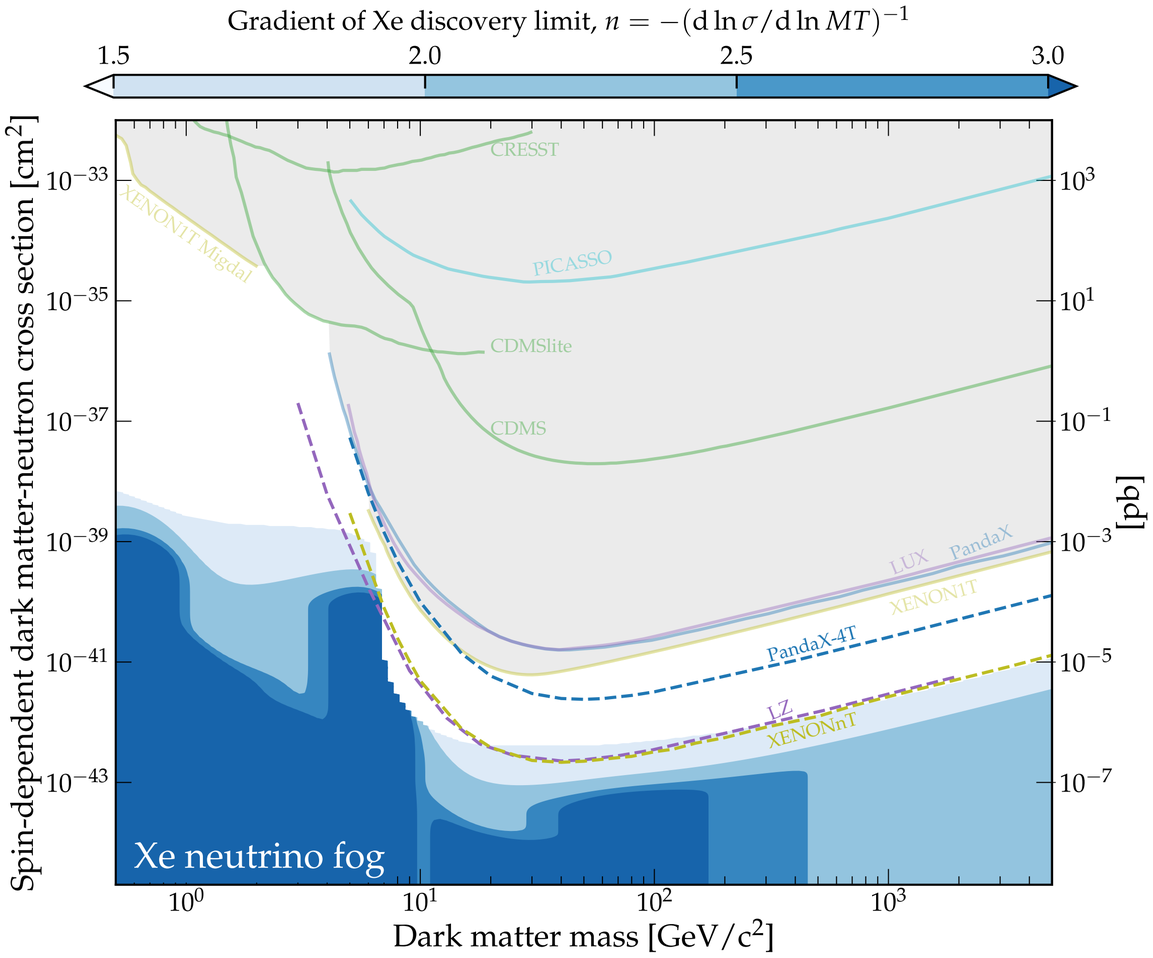
need an unpaired spin

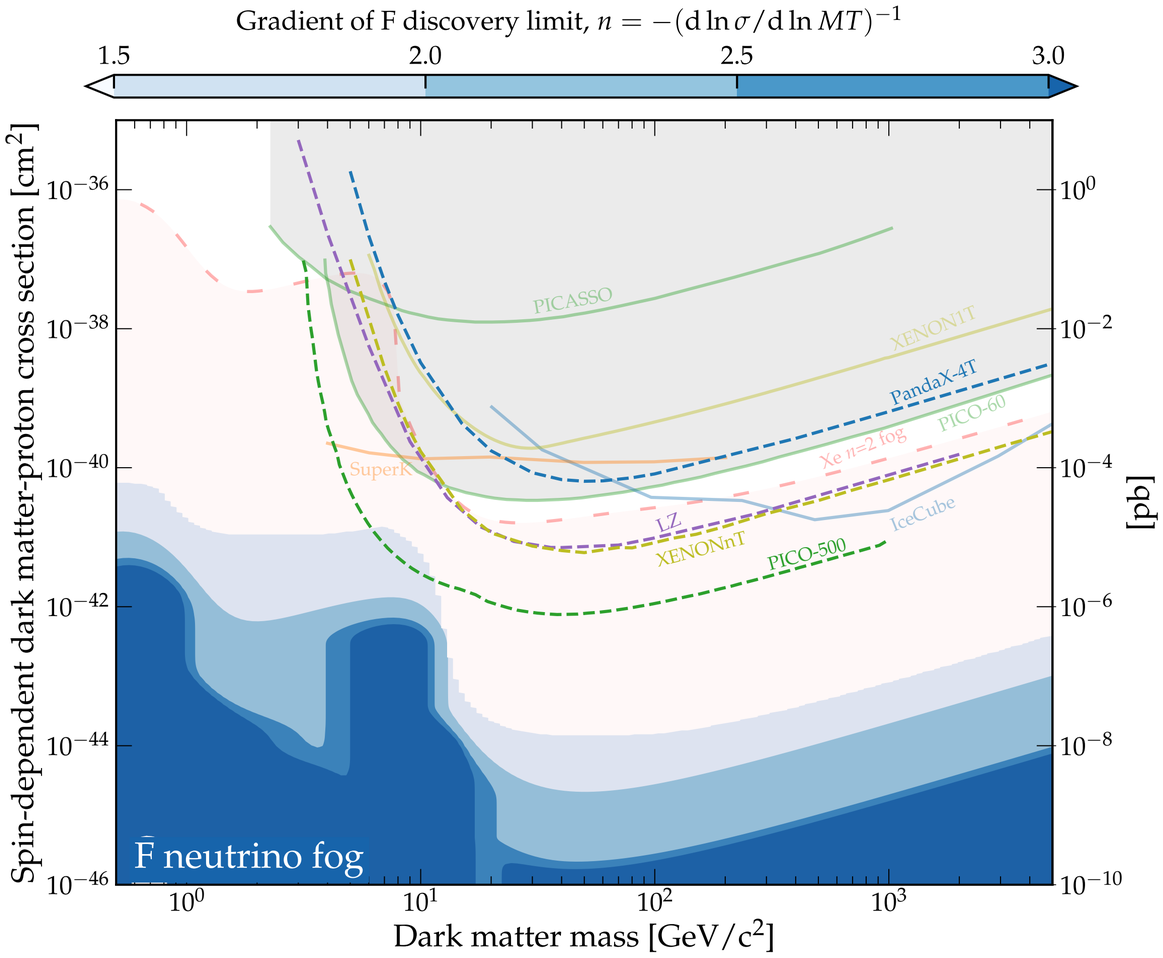
Element		J
protons	**F**	1/2
neutrons	**Ge**	9/2
neutrons	**Xe**	1/2, 3/2

← very good for spin-dependent

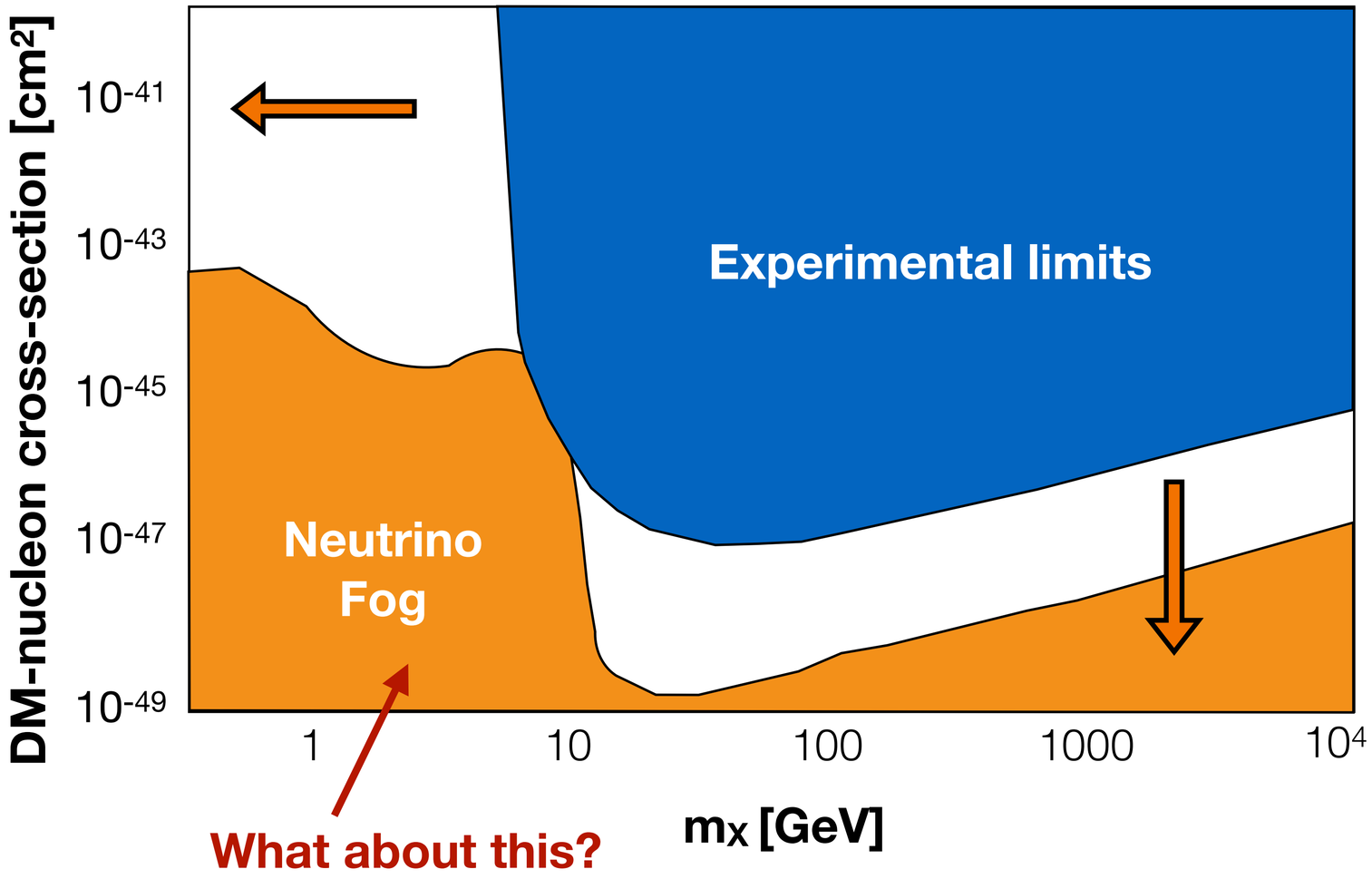
Current Landscape: Spin-Dependent

no A^2 ⟶ bounds are about 5-6 orders magnitude weaker than SI





Path towards DM discovery



Goals:

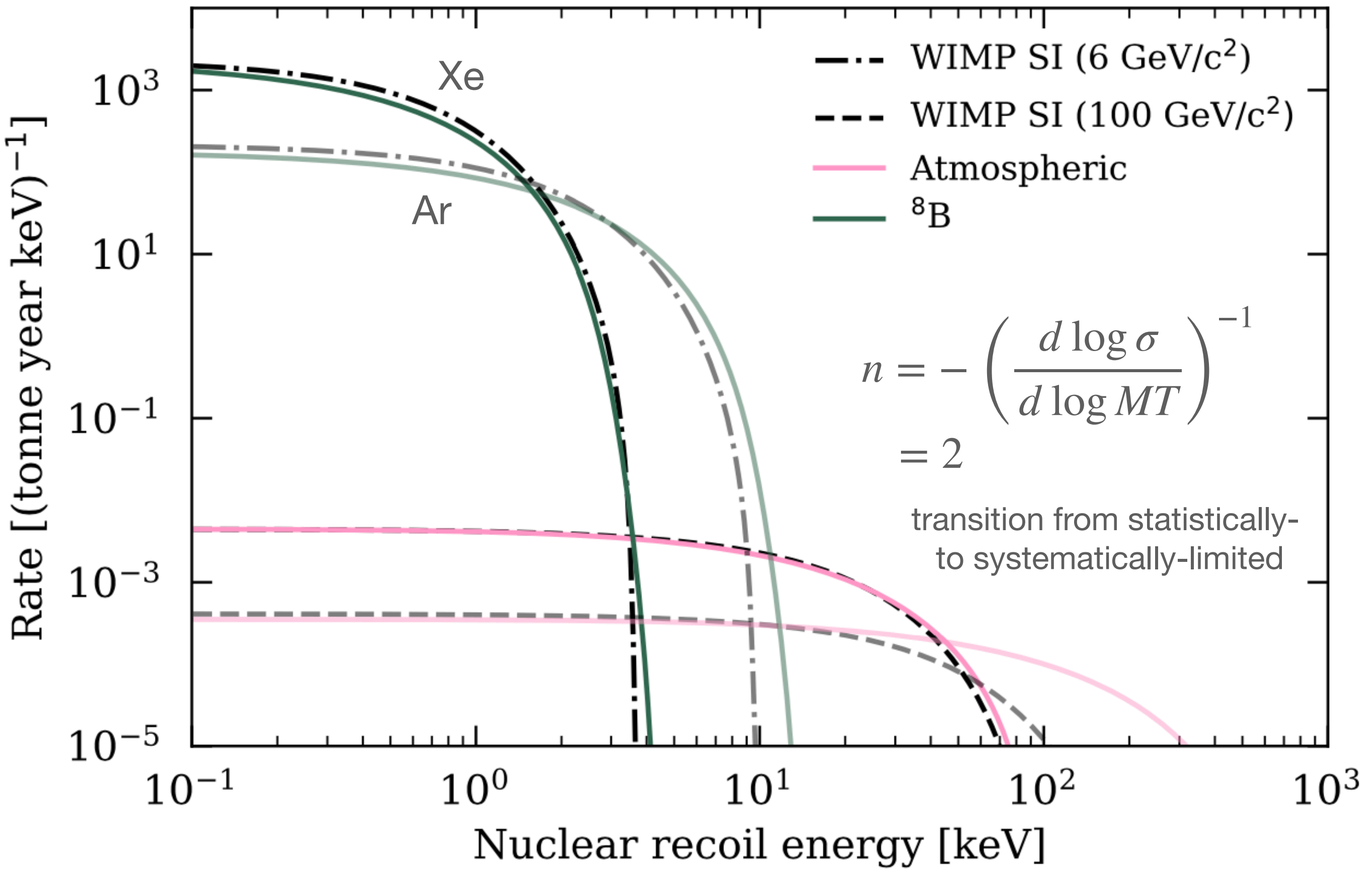
- increase target mass
- decrease thresholds
- improve background discrimination

New technologies:

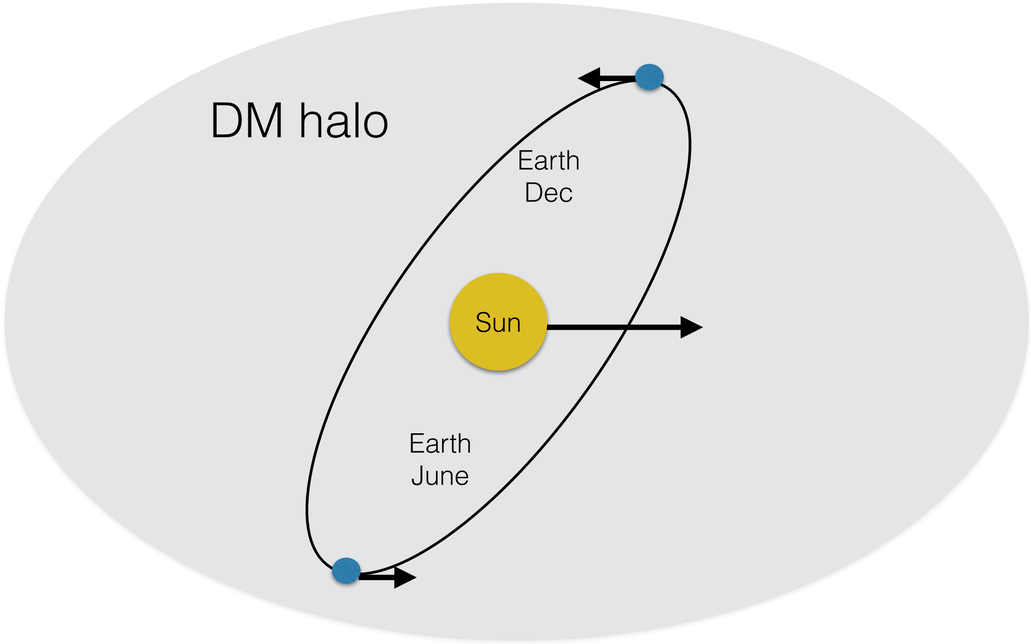
- Supercooled detectors
- Low Background DUNE-like module
- Giant gas TPCs in pressurized caverns
- …

Navigating the Neutrino Fog

[arXiv: 2203.08084]



Mitigation techniques:
annual modulation
directional detection



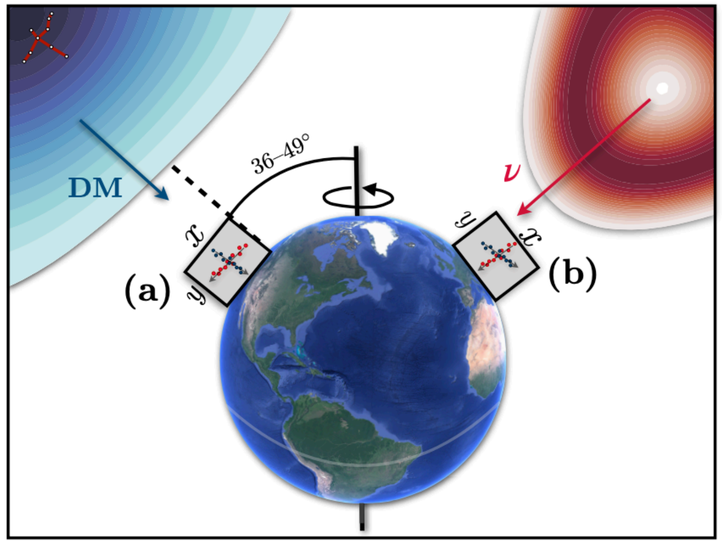
changes rate as a function of time
signature of galactic dark matter

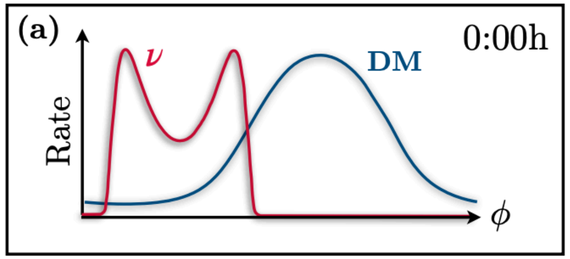
Directional Detection

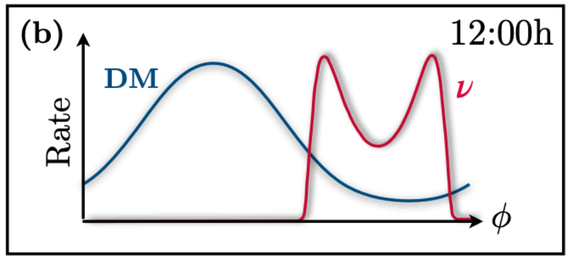
Very distinct signature!

Requires ability to reconstruct direction of nuclear recoil

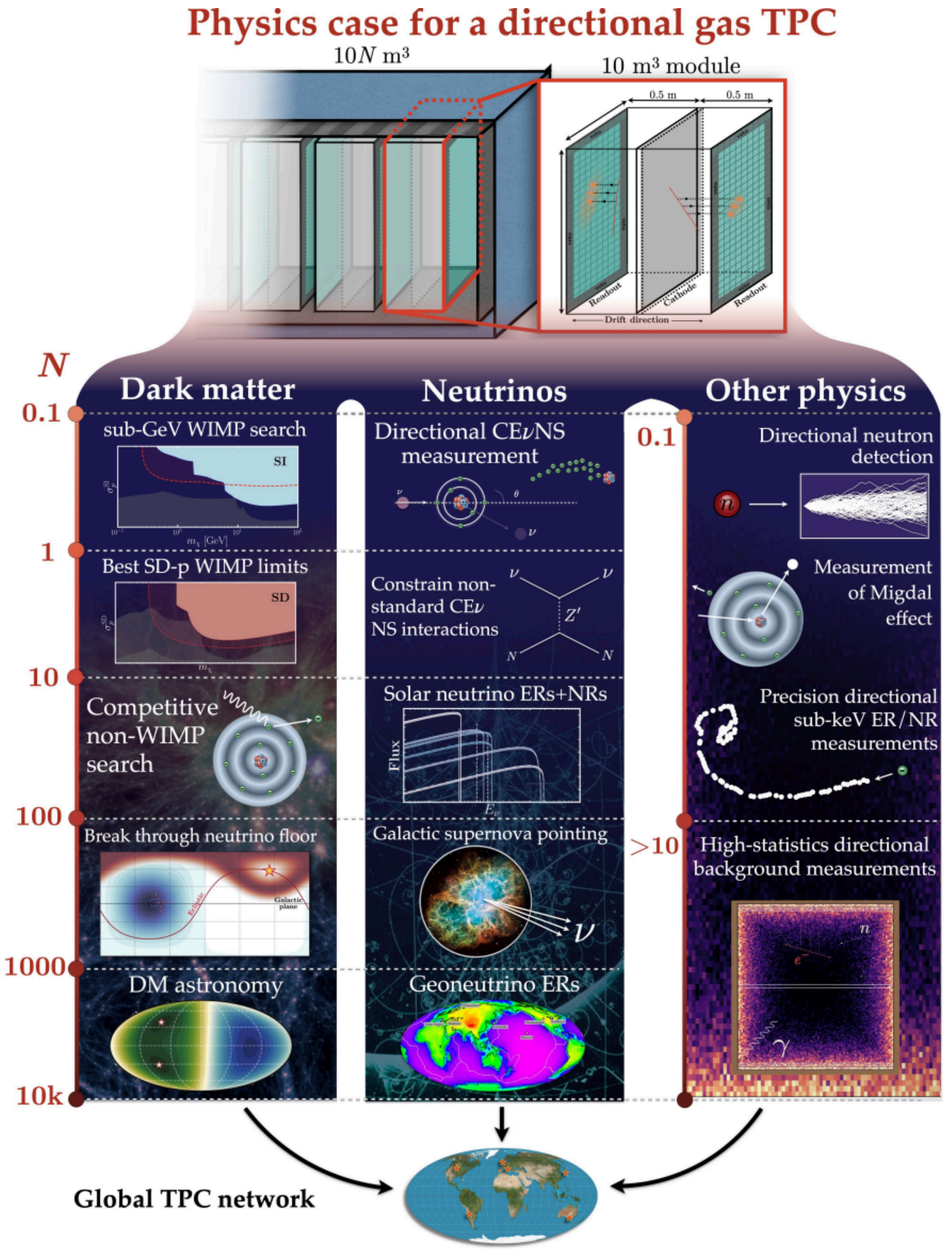
Vahsen, O'Hare, Loomba, [arXiv: 2102.04596]





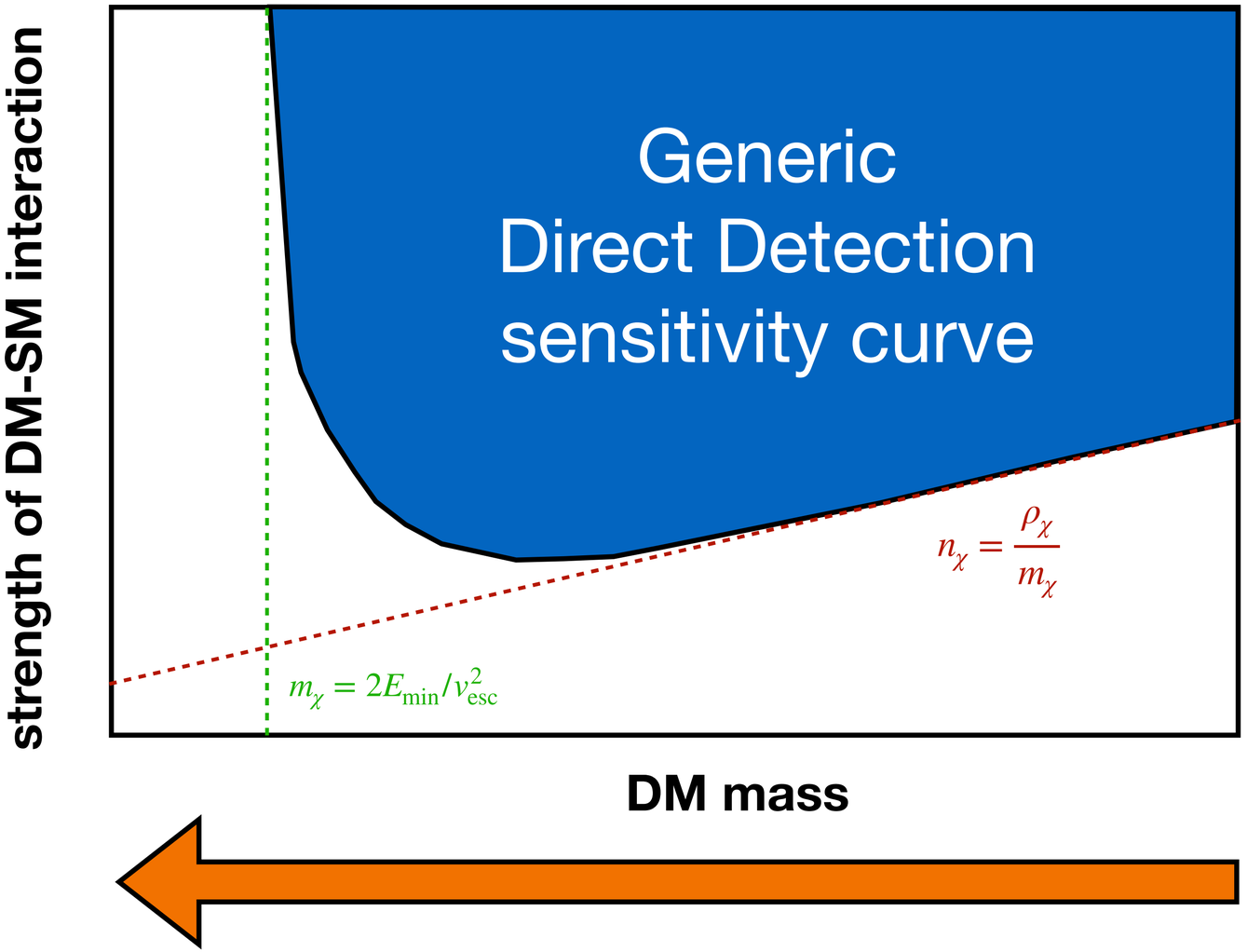


Can also provide information on dark matter substructure in the galactic halo!



Landscape of Particle Dark Matter

- consider ensemble of interactions

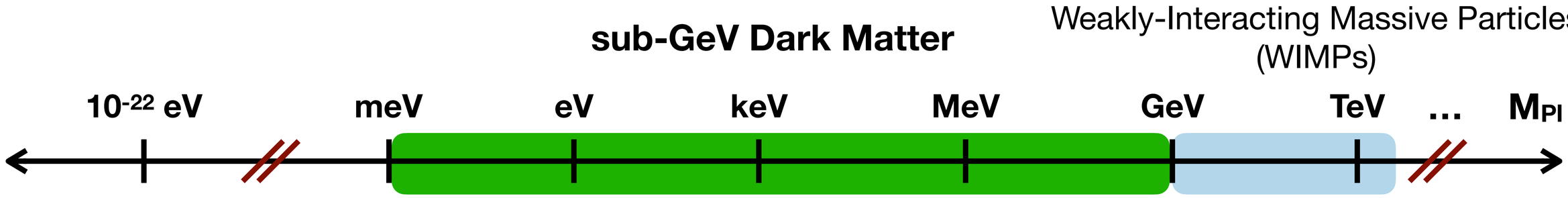


GOAL:
explore
this space

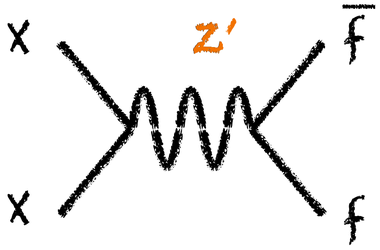
- increase target mass
- improve background discrimination

- decrease thresholds
- increase energy transfer

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

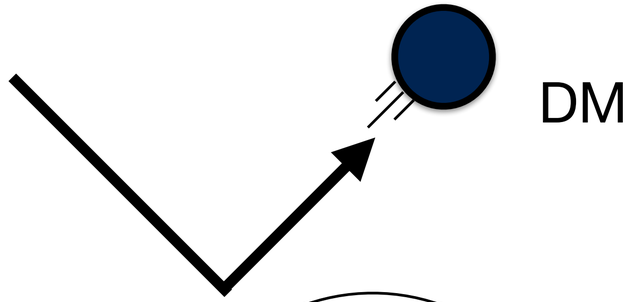
   consider a variety of materials

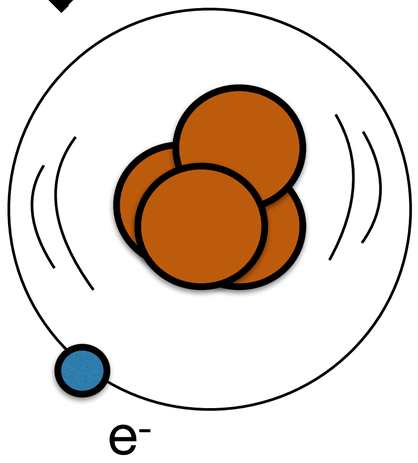
2. increase the energy transfer

   consider different physical processes

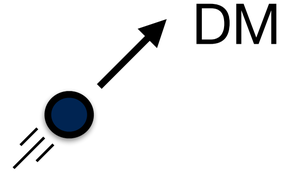
Nuclear vs. Electron Scattering

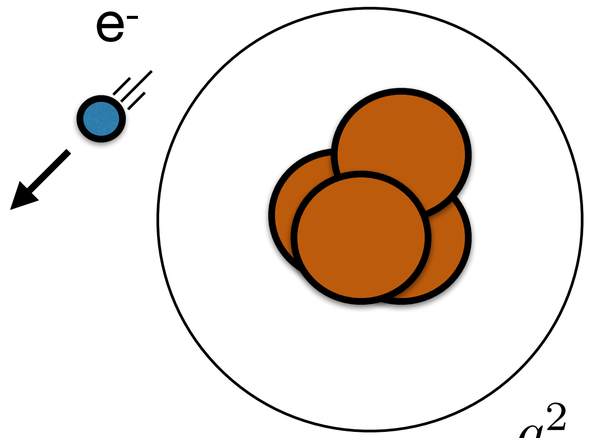
DM-nuclear scattering





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

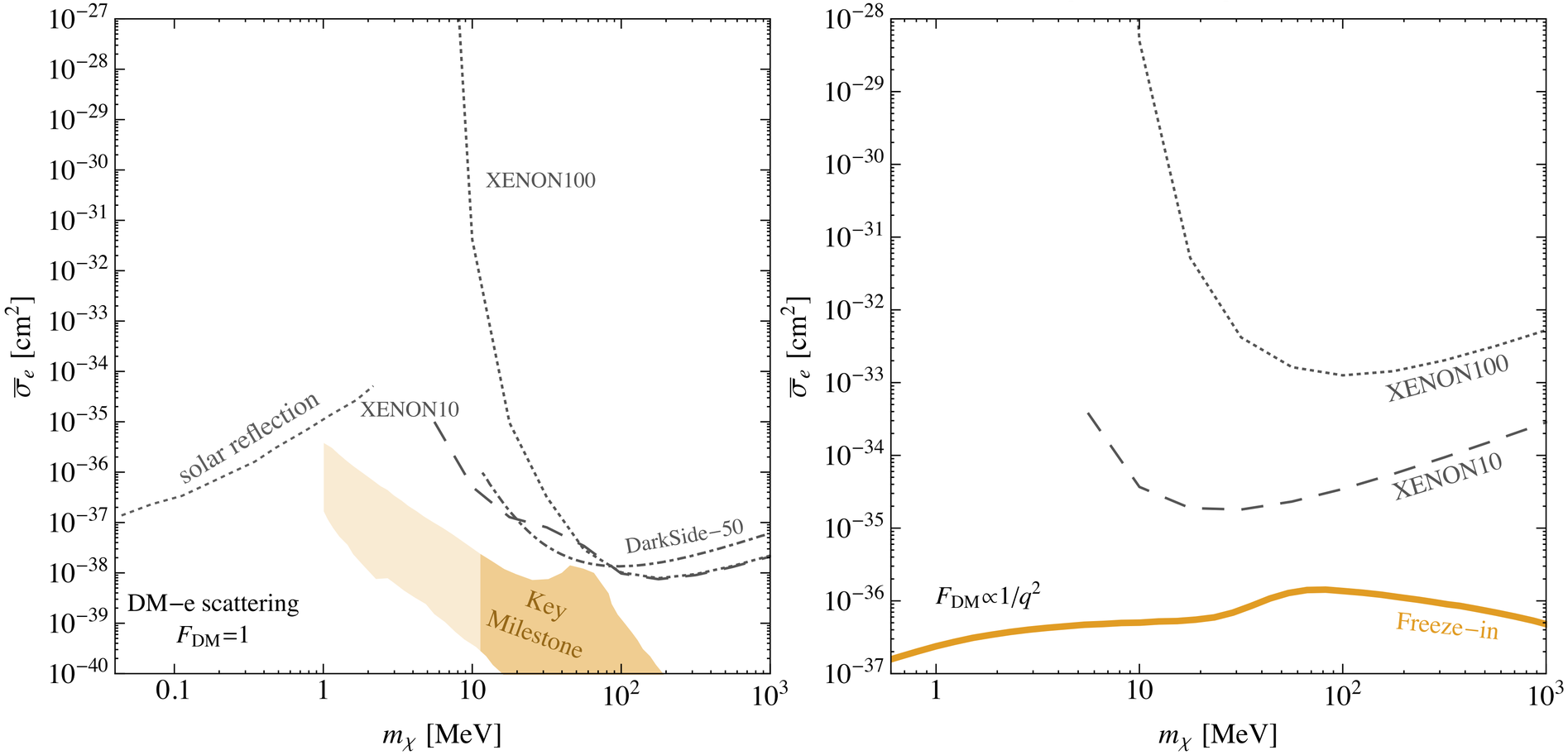
$$\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2}\int q\ \mathrm{d}q |f(k,q)|^2 |F_{DM}(q)|^2 \eta(v_{min})$$

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

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

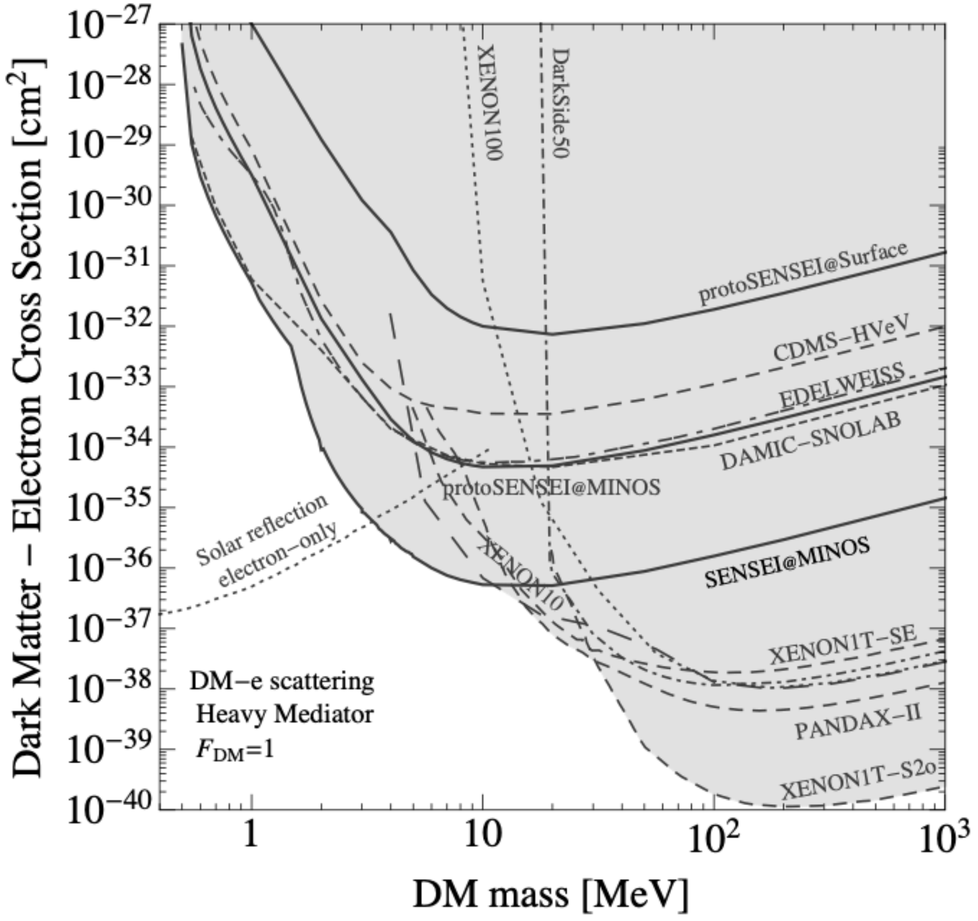
DM-electron limits in 2018

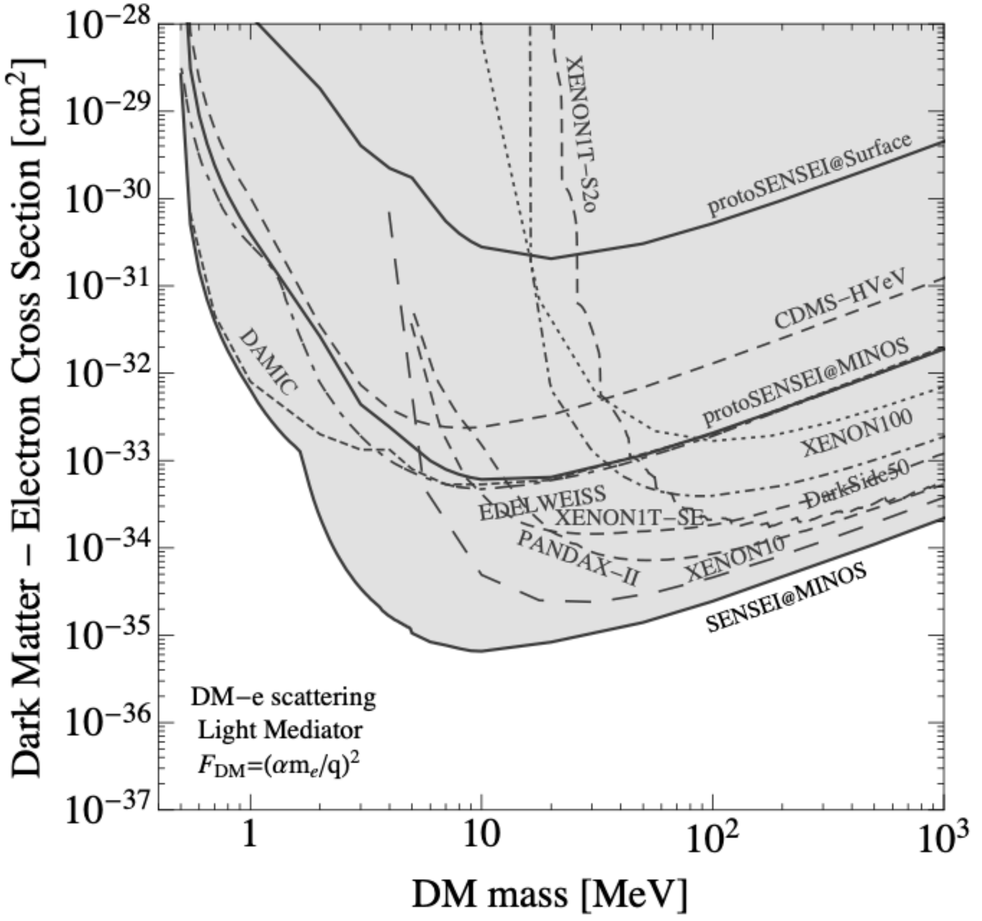
Essig, Volansky, TTY Phys.Rev.D 96 (2017) 4, 043017 [1703.00910]
DarkSide Collaboration Phys.Rev.Lett. 121 (2018) 11, 111303 [1802.06998]
An, Pospelov, Pradler, Ritz [1708.03642]



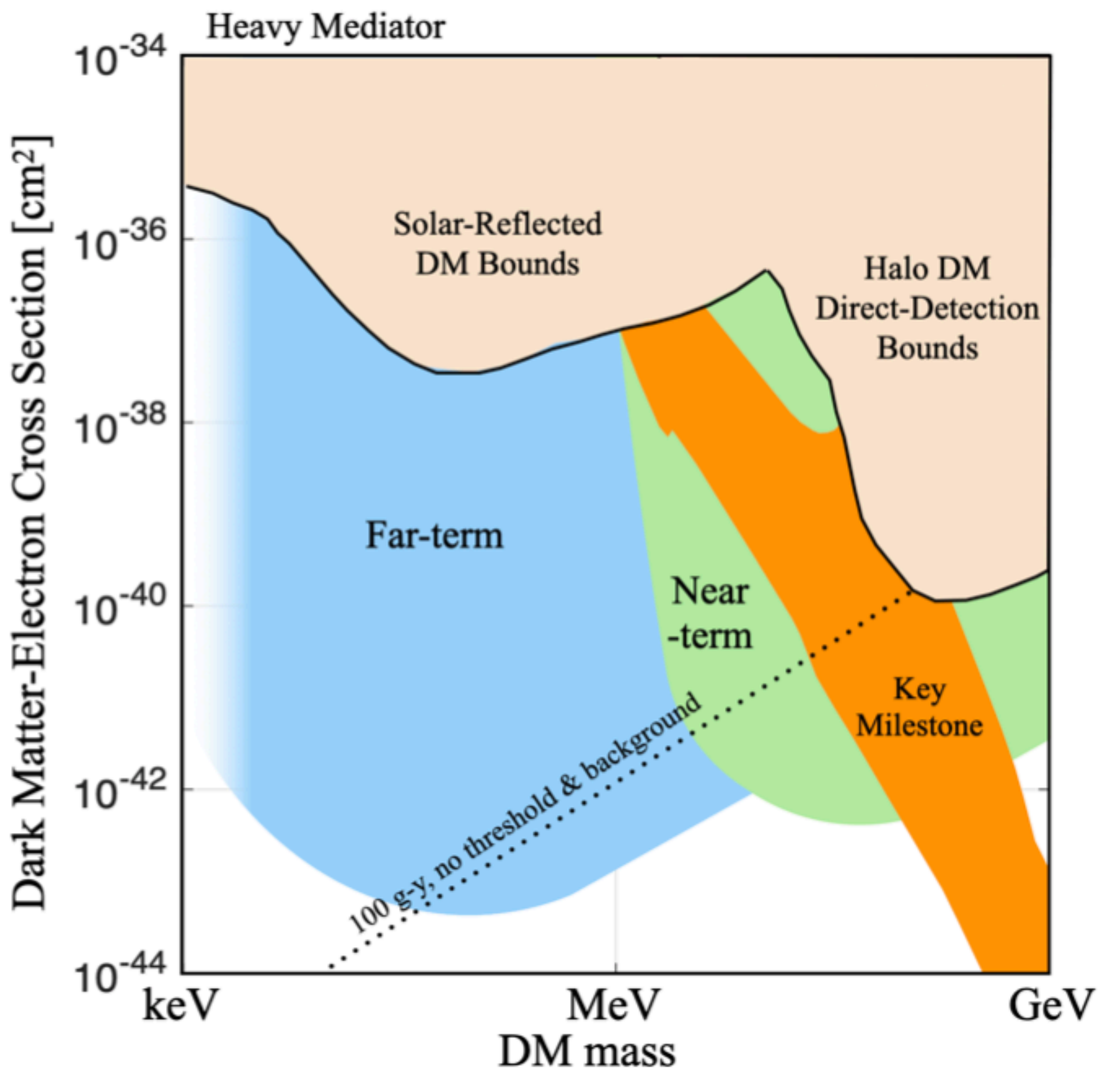
DM-electron scattering limits in 2022

[arXiv:2203.08297]

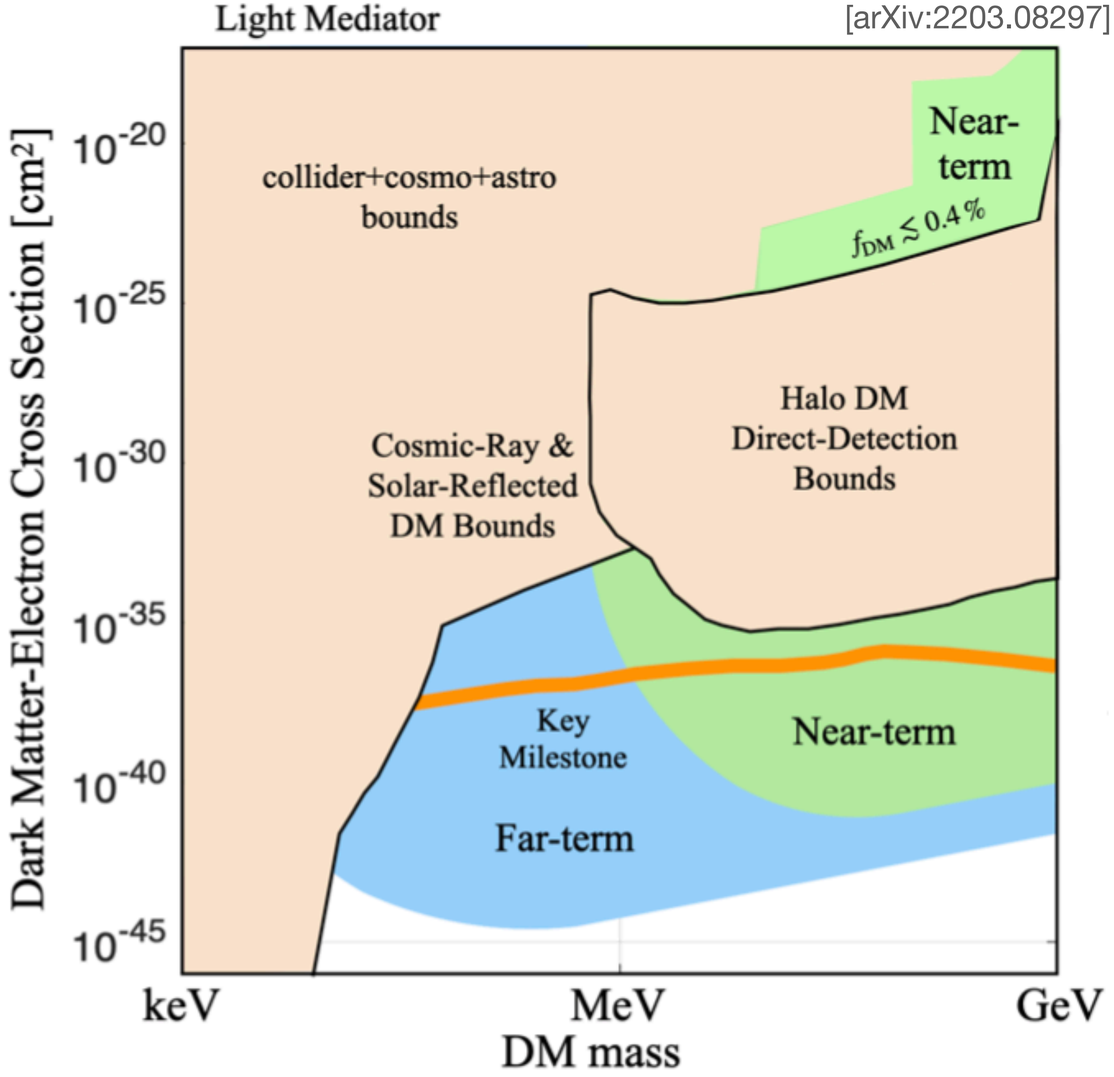




Outlook for sub-GeV DM direct detection

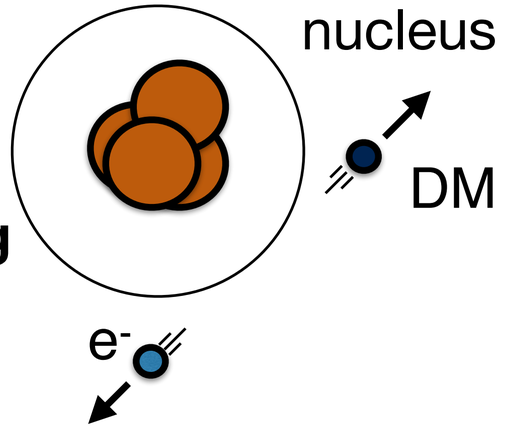


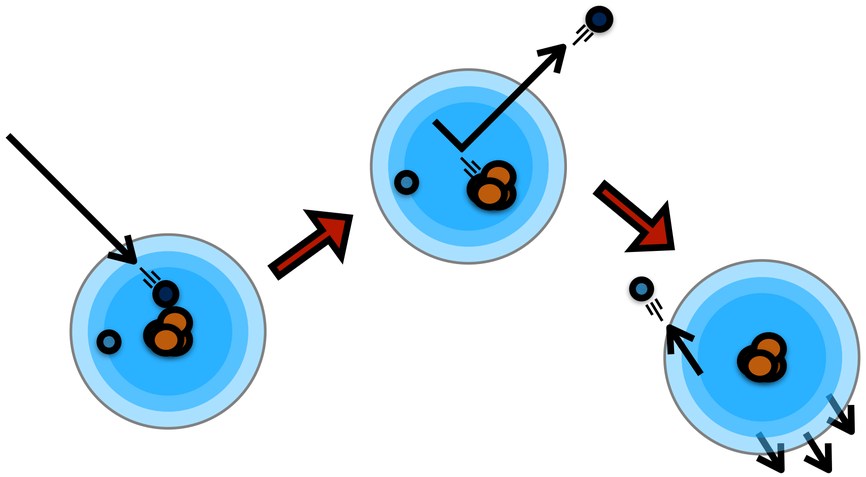
[arXiv:2203.08297]



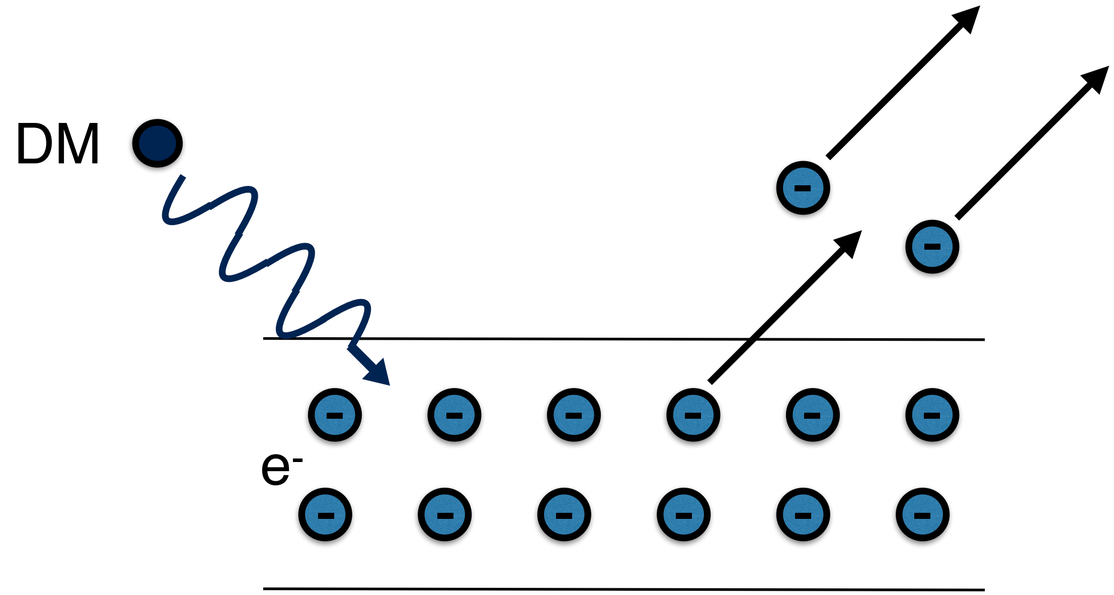
models for sub-GeV DM

dark matter-electron scattering





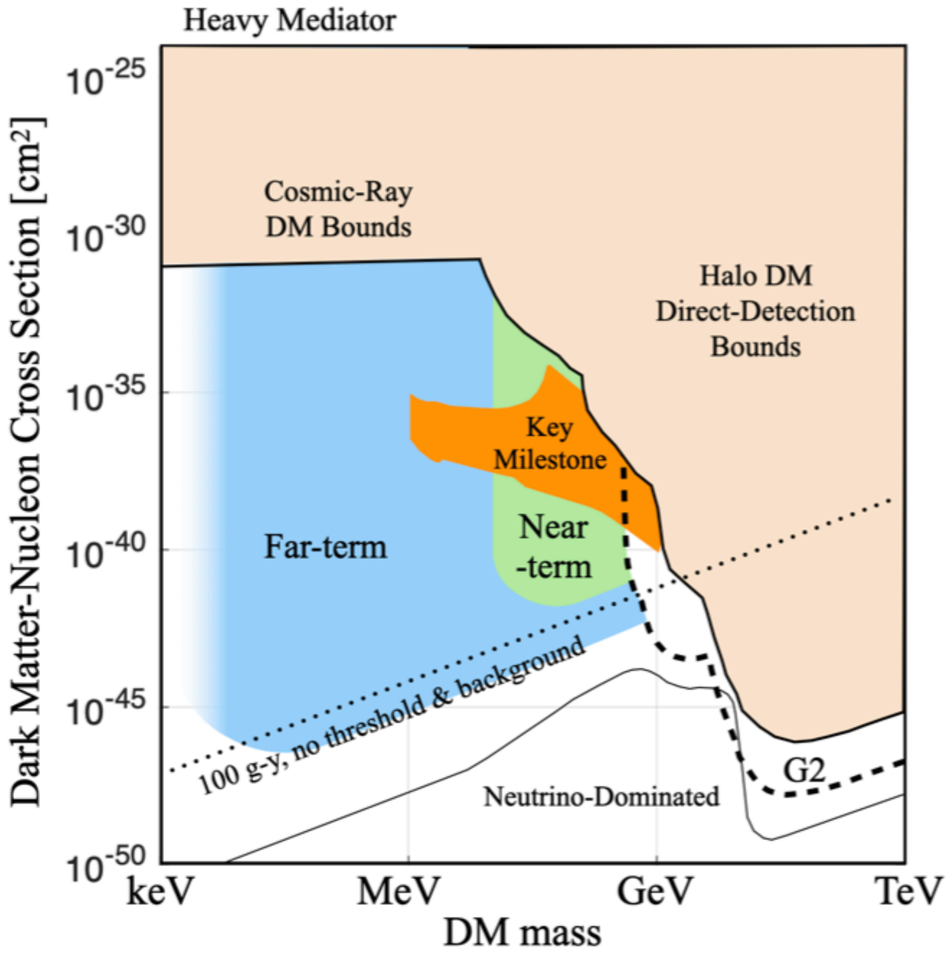
dark matter-nucleus scattering (Migdal)



dark matter absorption

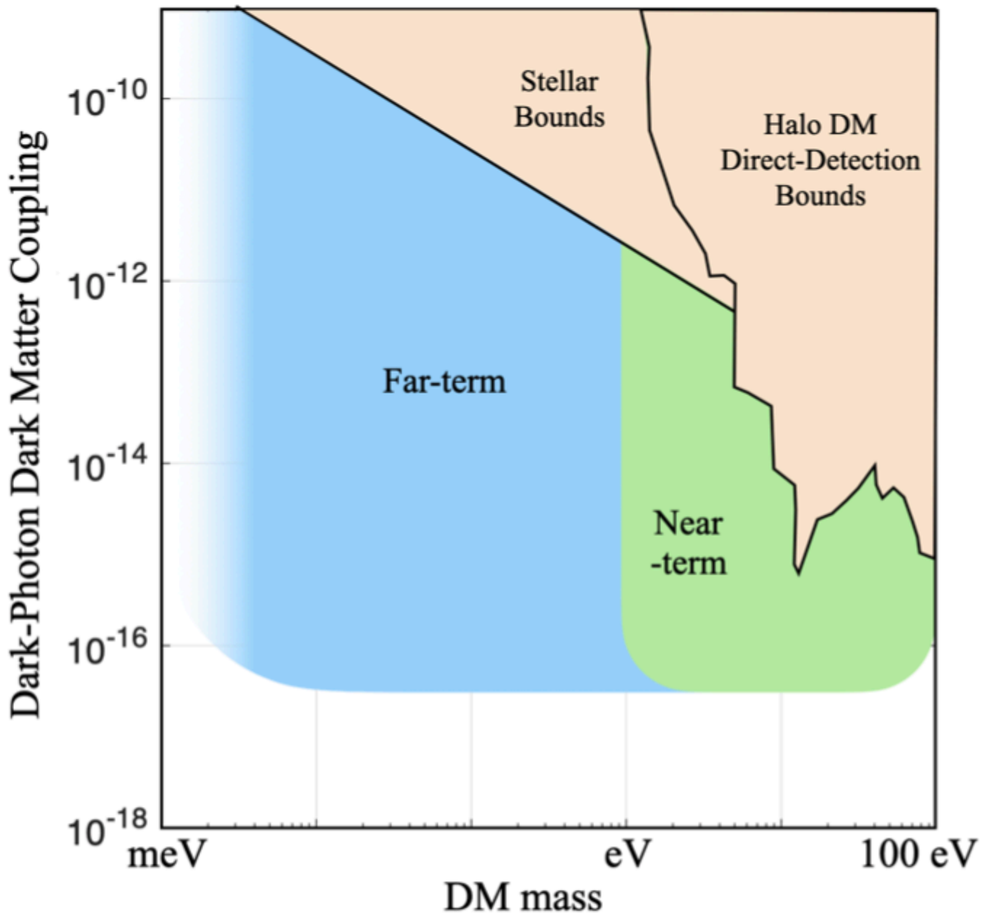
Other Models

DM-nucleon scattering

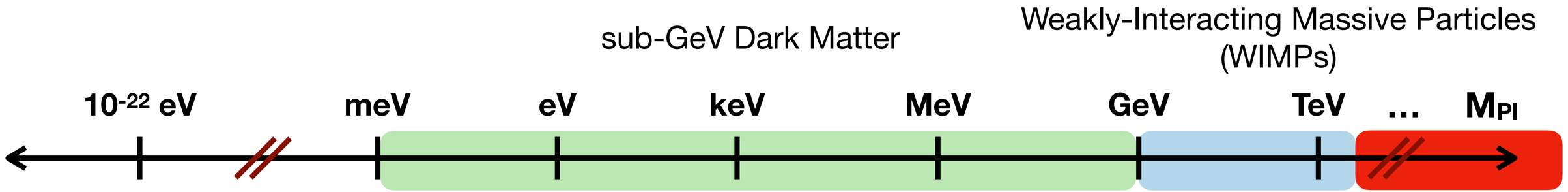


DM absorption

[arXiv:2203.08297]

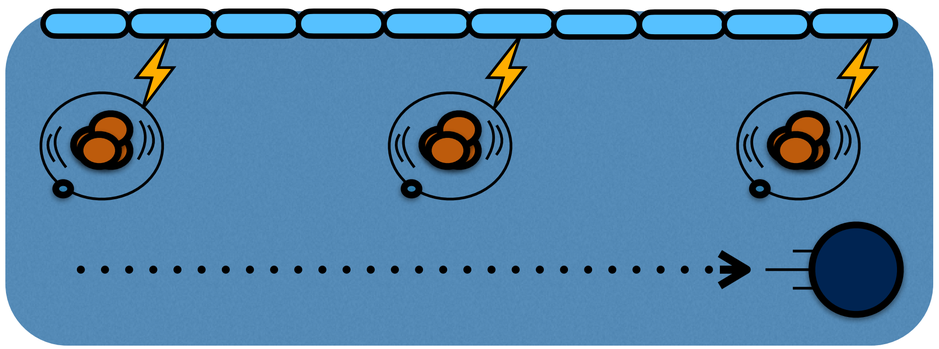


Dark Matter Candidates



Flux of DM

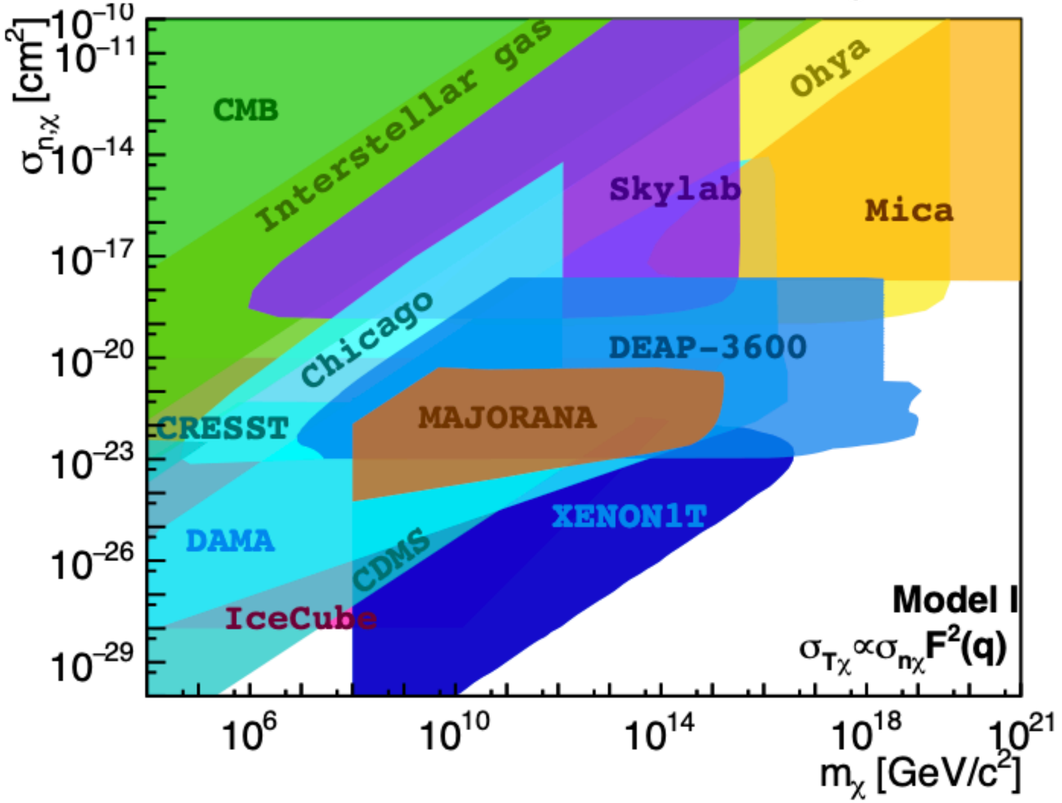
$$\Phi = n\bar{v} \simeq \frac{0.85}{\mathrm{m^2 yr}} \times \left(\frac{m_{\mathrm{pl}}}{m_\chi}\right)$$



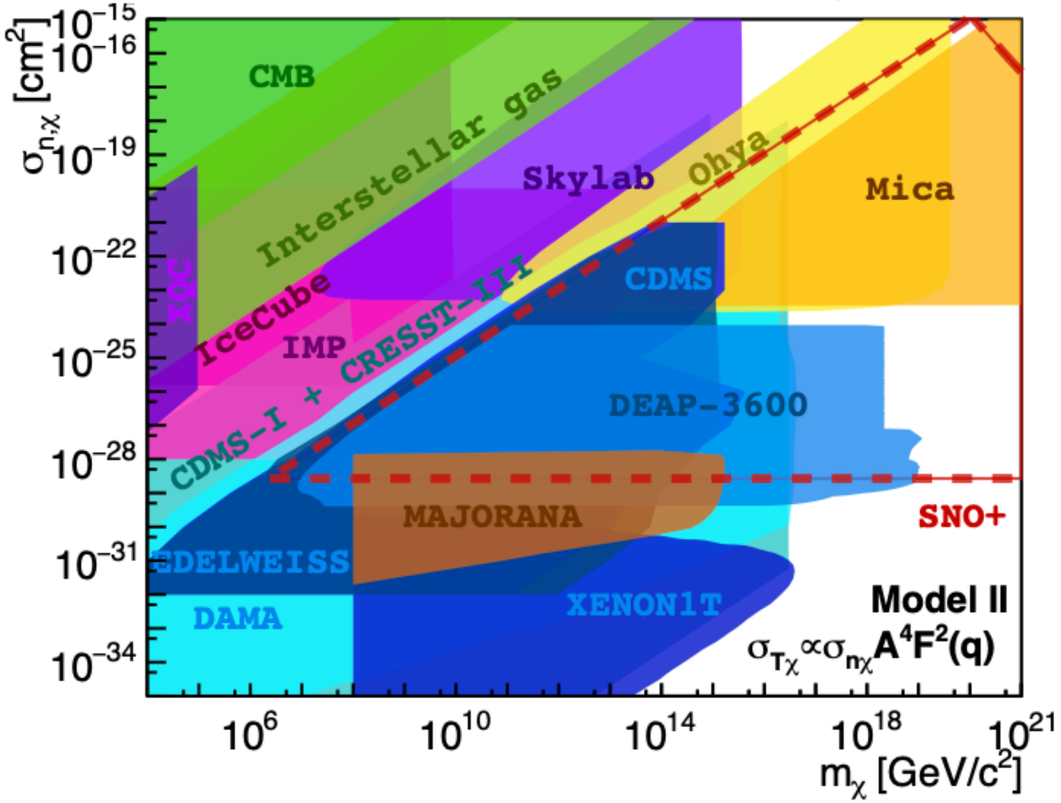
Super Heavy Dark Matter

Super-Heavy Dark Matter

DM-nucleon scattering



DM-nucleus scattering

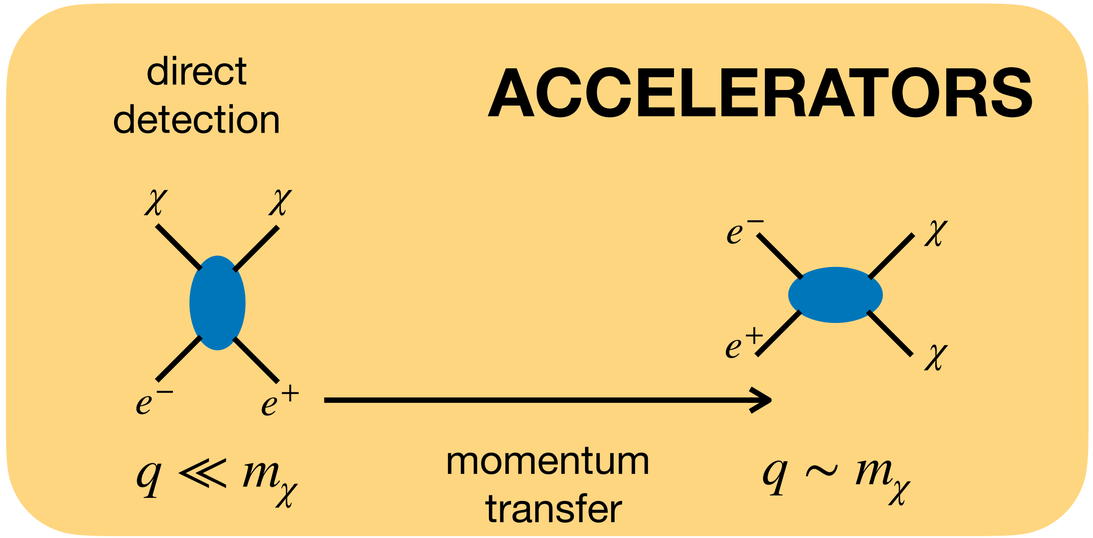


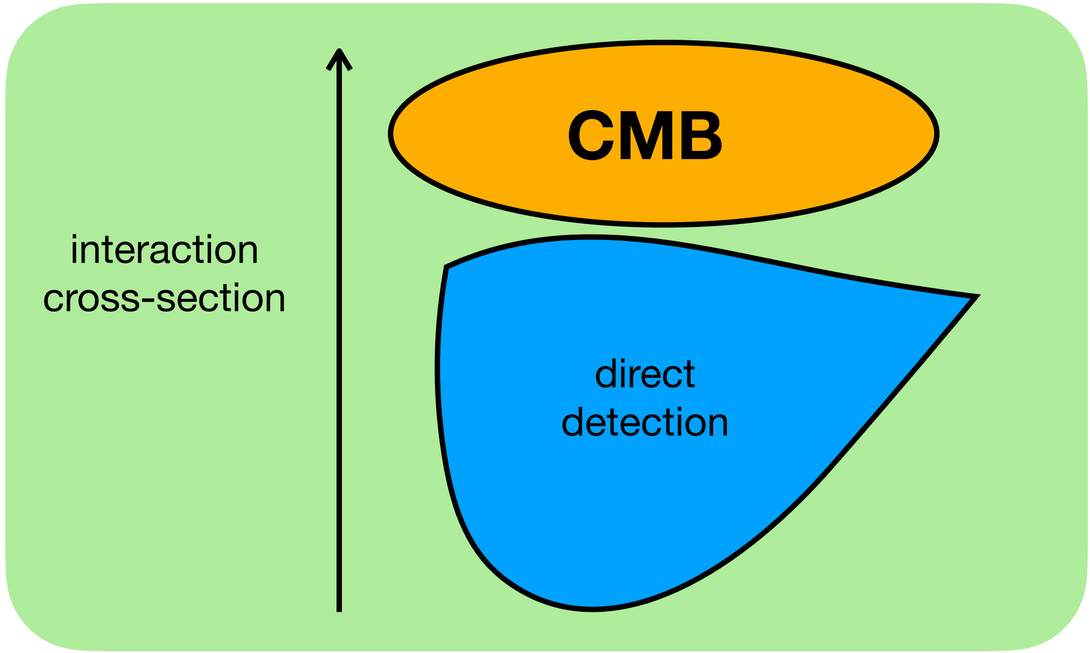
many of the same DM experiments!

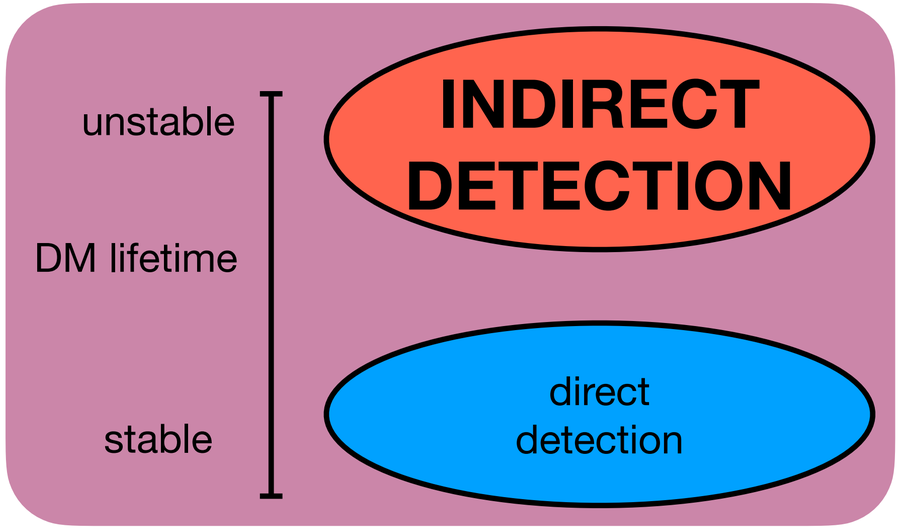
Strengths of Direct Detection

- **adaptable**: can readily respond to signals or hints
  - allows for mitigation of systematic backgrounds
  - built-in cross-checks
- **model-independent:** can search simultaneously for multiple potential signatures of DM
- **controlled**: systematic study of backgrounds, clean and configurable environment

Synergies


direct
detection
ACCELERATORS
χ χ
e^- e^+
e^- χ
e^+ χ
$q \ll m_\chi$
momentum
transfer
$q \sim m_\chi$


interaction
cross-section
CMB
direct
detection


unstable
DM lifetime
stable
INDIRECT
DETECTION
direct
detection

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