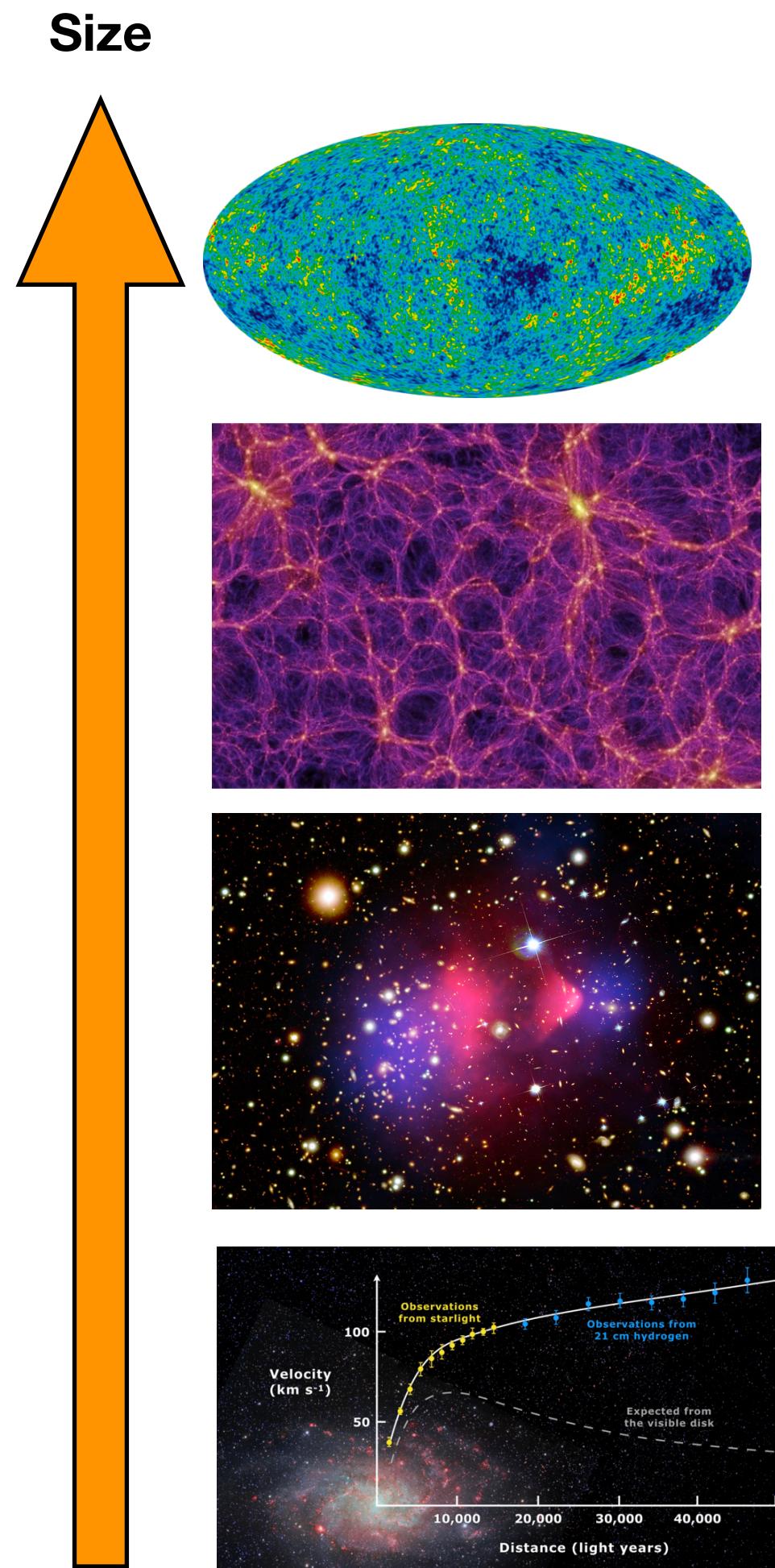


New Approaches on Dark Matter Detection

Tien-Tien Yu (University of Oregon)

Phenomenology 2023 Symposium, University of Pittsburgh
May 10, 2023

Dark Matter Exists



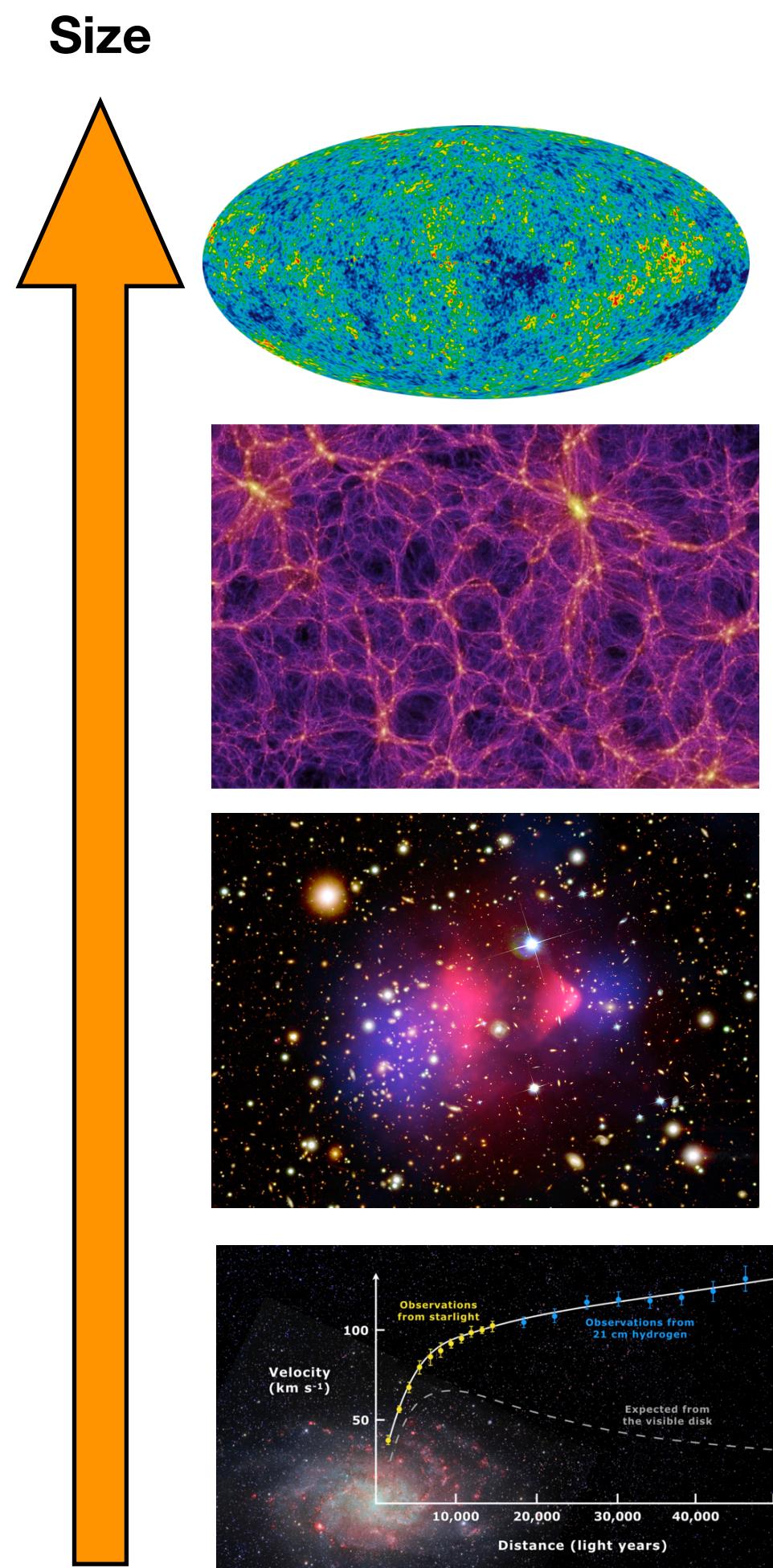
COSMIC MICROWAVE BACKGROUND

LARGE SCALE STRUCTURE

GALAXY CLUSTER MERGERS

GALACTIC ROTATION CURVES

Dark Matter Exists



COSMIC MICROWAVE BACKGROUND

LARGE SCALE STRUCTURE

GALAXY CLUSTER MERGERS

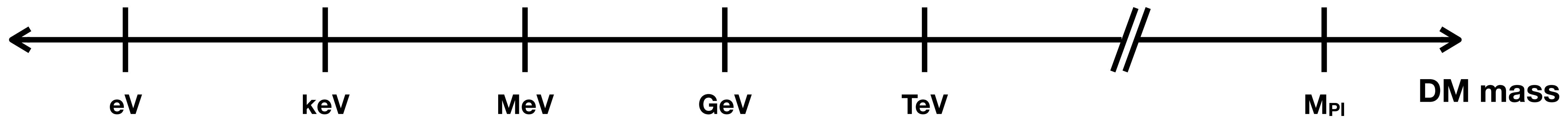
GALACTIC ROTATION CURVES



Gravitational interactions

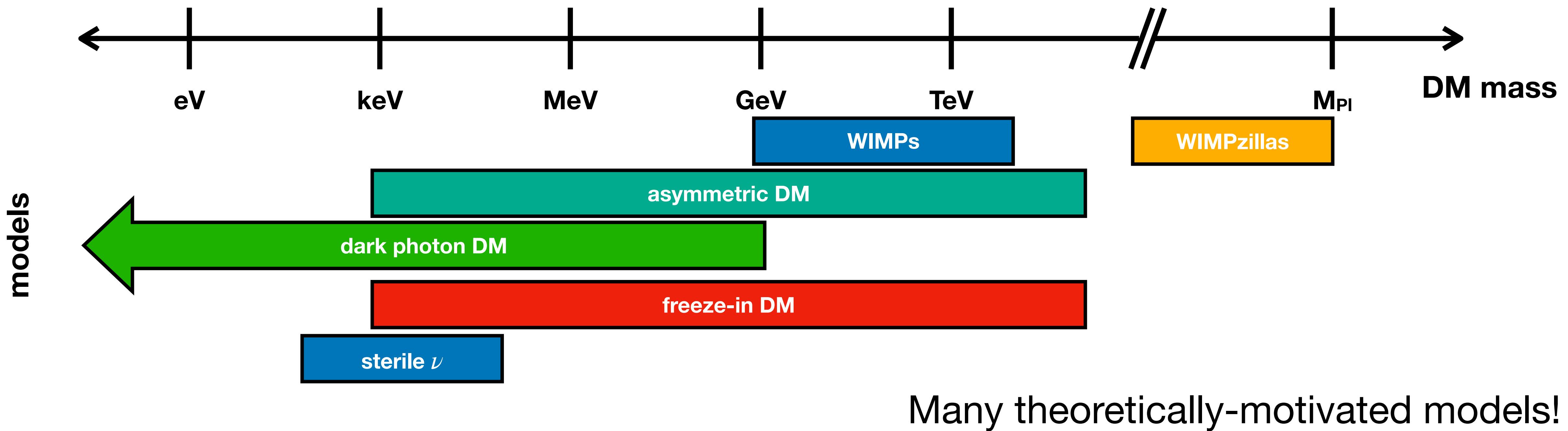
Dark Matter Candidates

Gravitational interactions → **massive** (particle)



Dark Matter Candidates

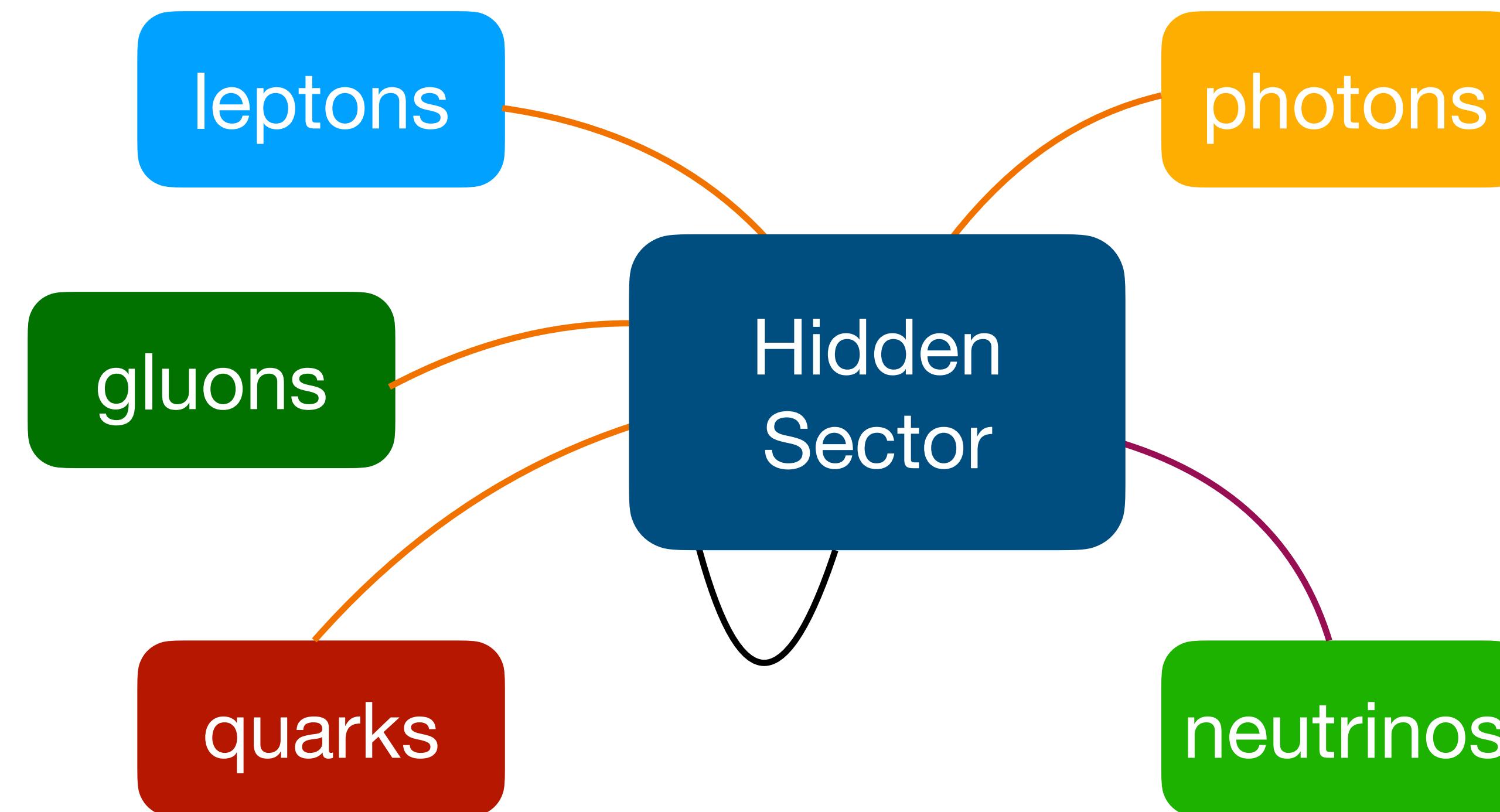
Gravitational interactions → **massive** (particle)



Non-gravitational interactions of DM

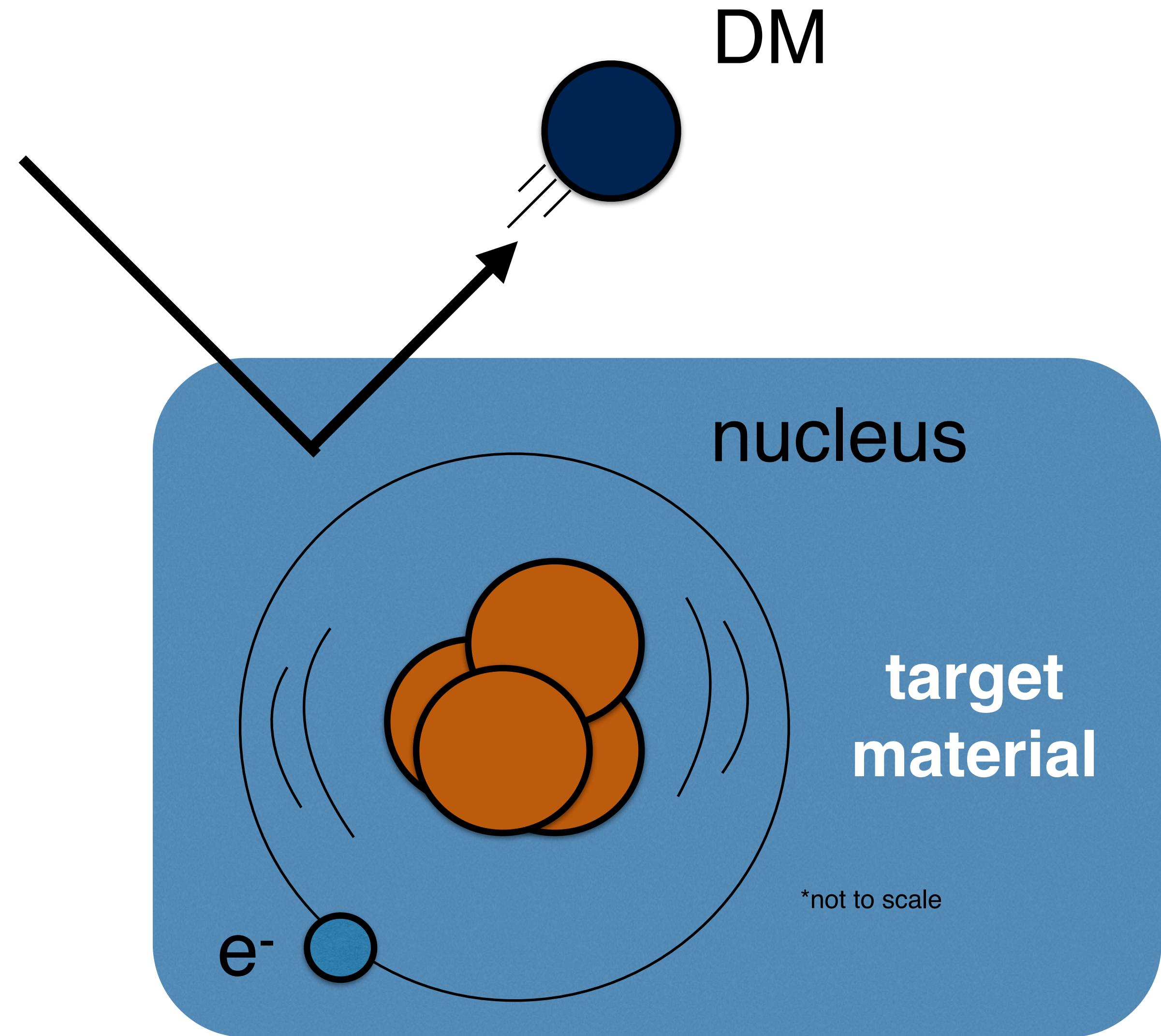
Probing all of these interactions is crucial for understanding the **particle** nature of DM

Direct detection
can probe these

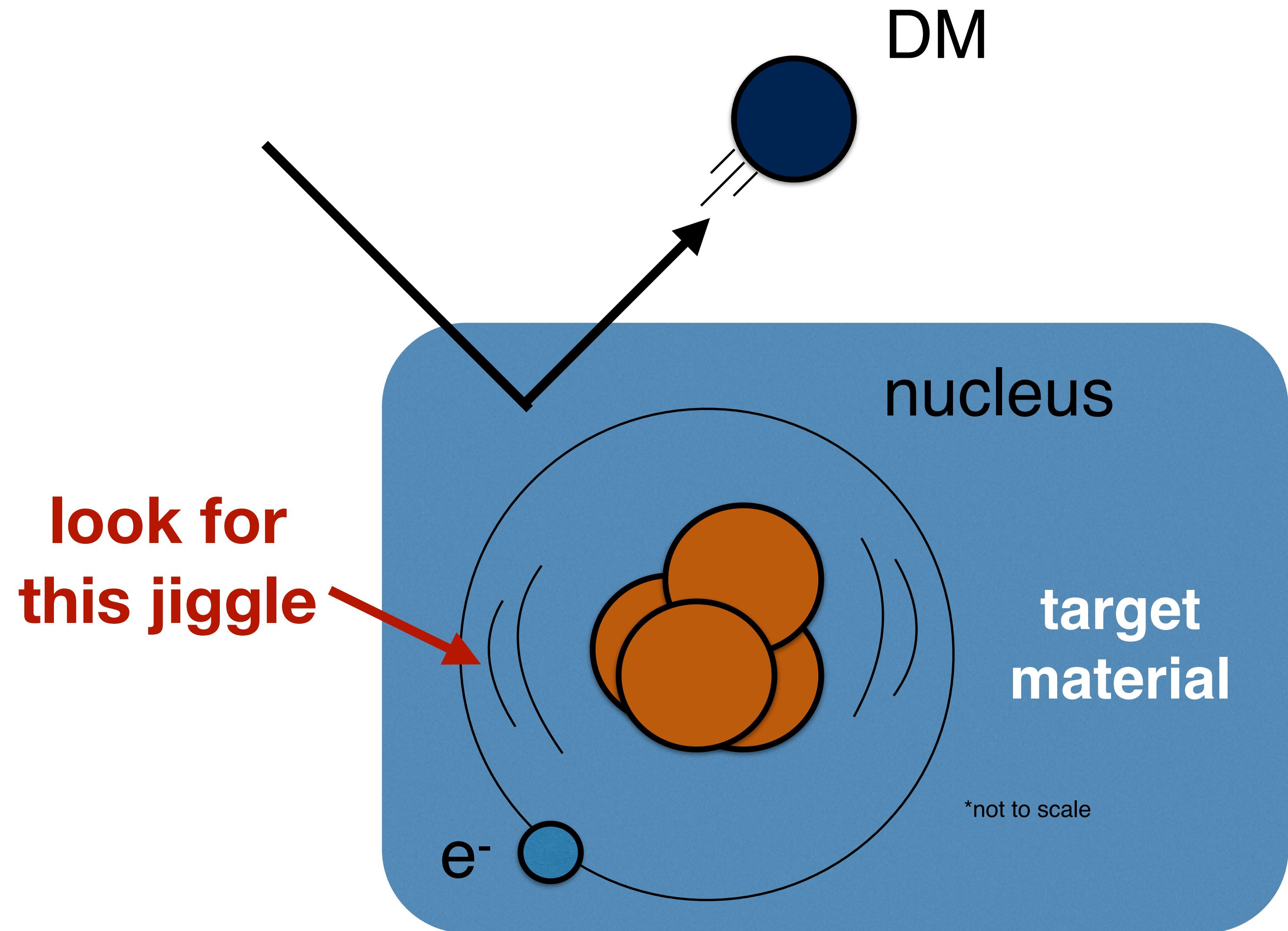


Direct detection probes our **galactic dark matter** halo

Dark Matter Direct Detection

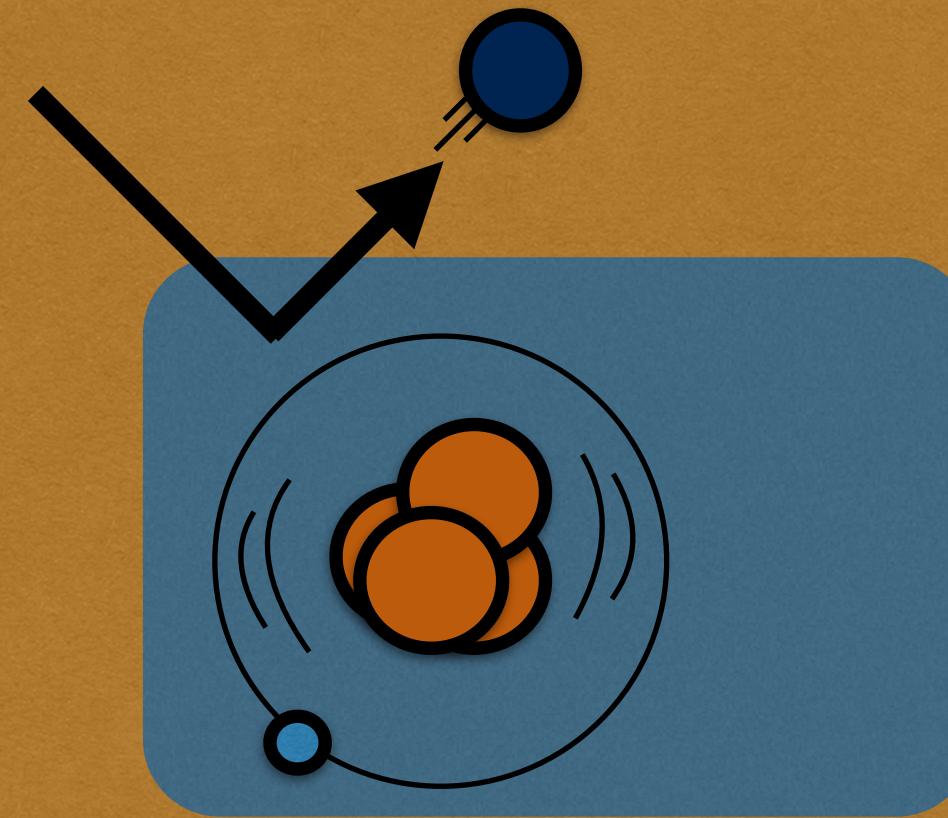


Dark Matter Direct Detection

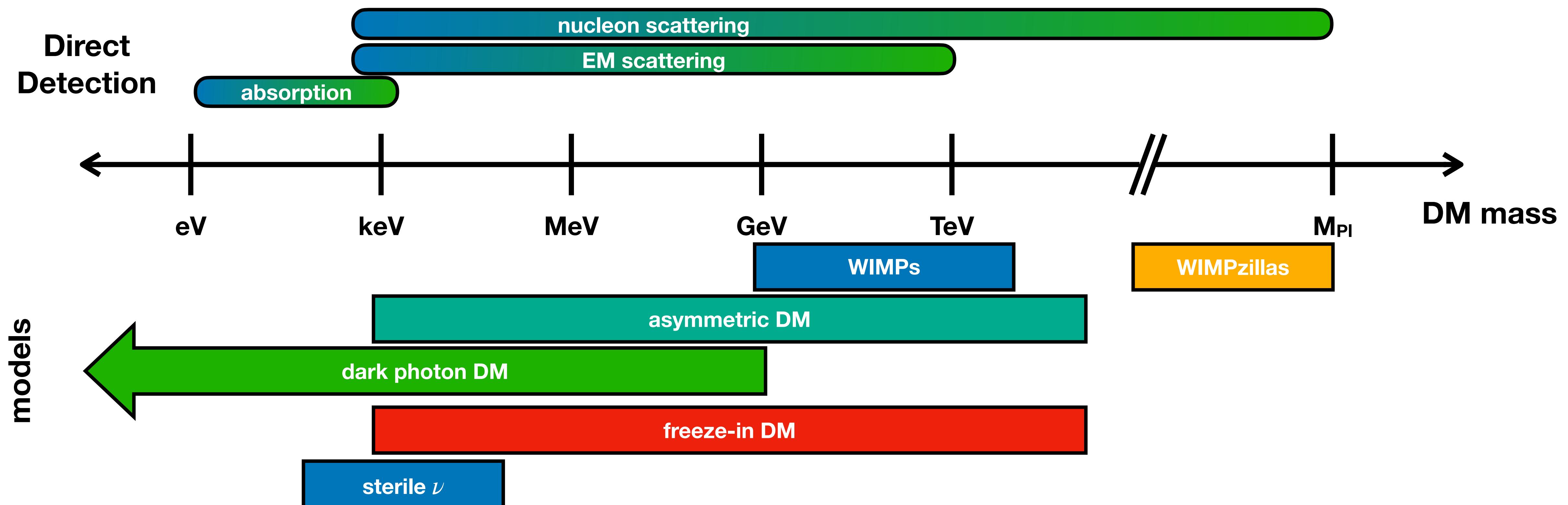


Dark Matter Direct Detection

somewhere deep underground



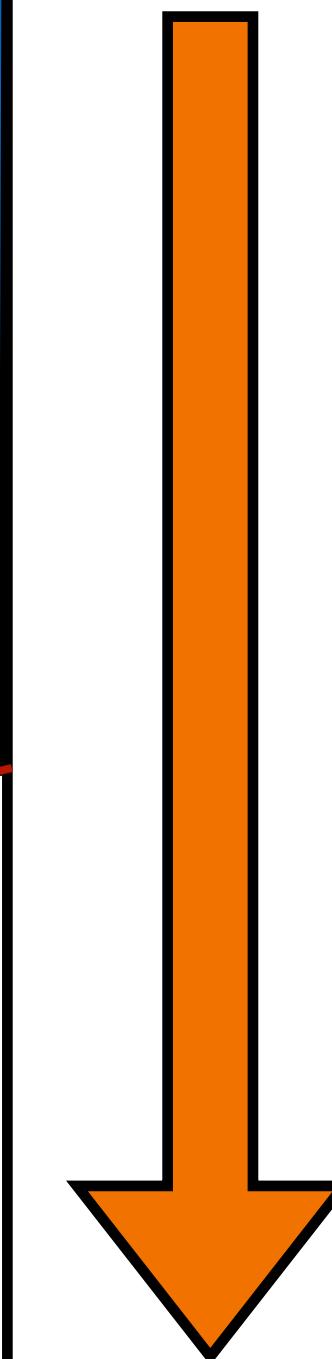
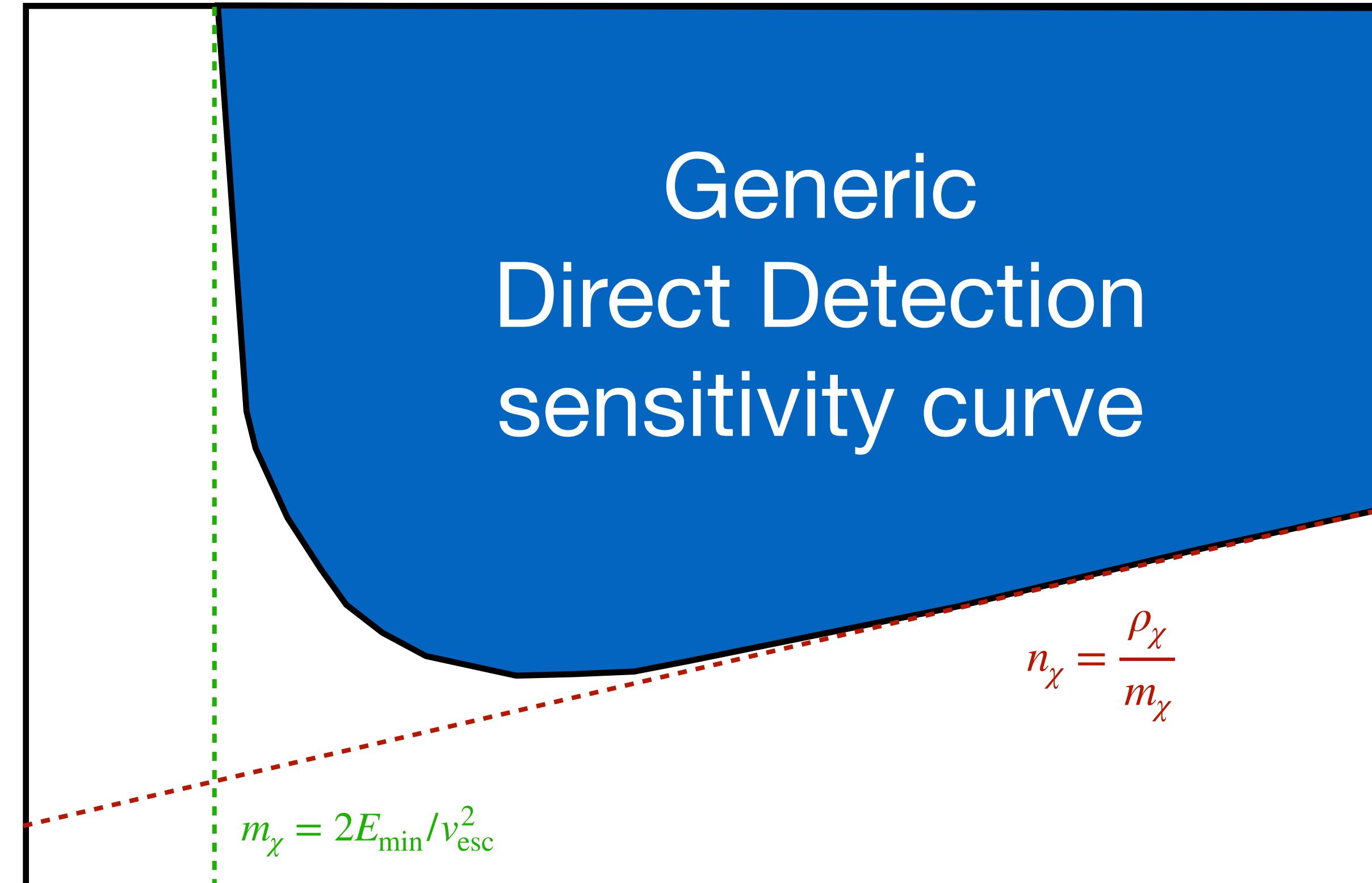
Dark Matter Candidates



Landscape of Particle Dark Matter

- consider ensemble of interactions

strength of DM-SM interaction



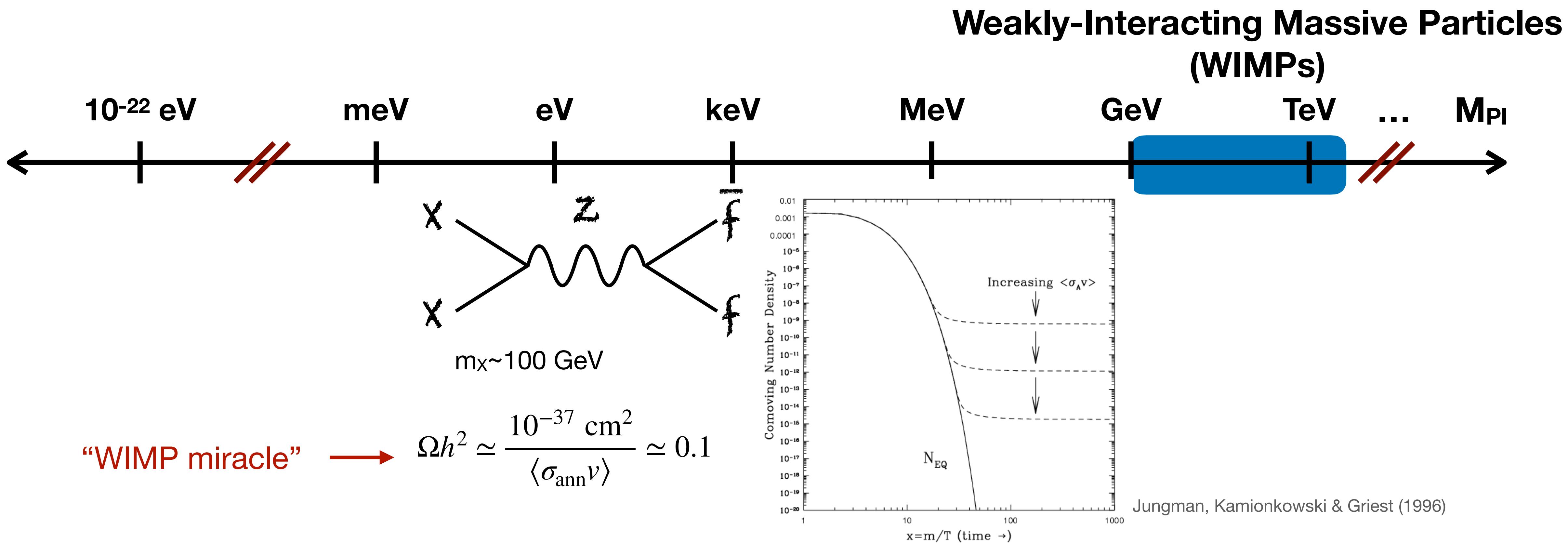
GOAL:
explore
this space

- increase target mass
- improve background discrimination

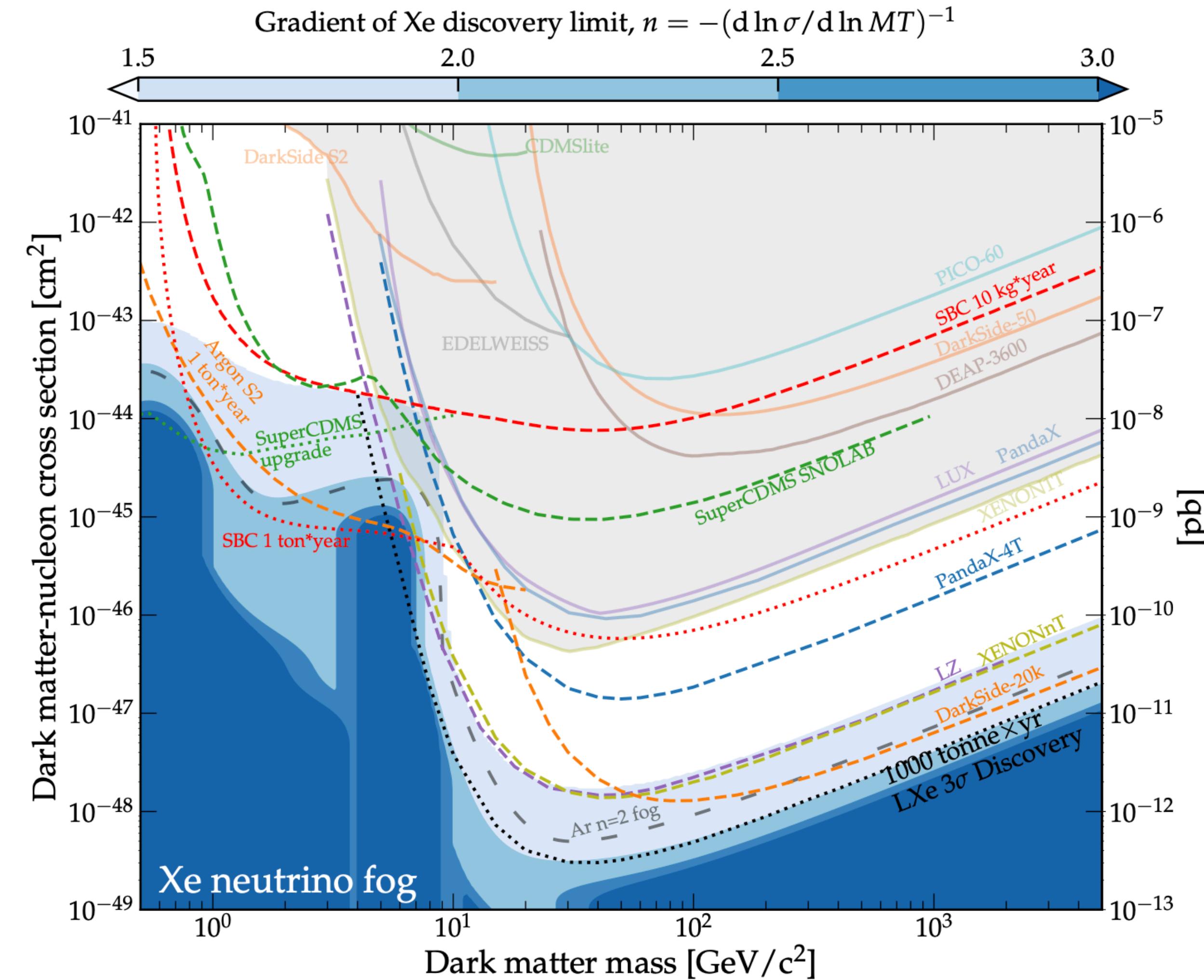
- decrease thresholds
- increase energy transfer



Dark Matter Candidates

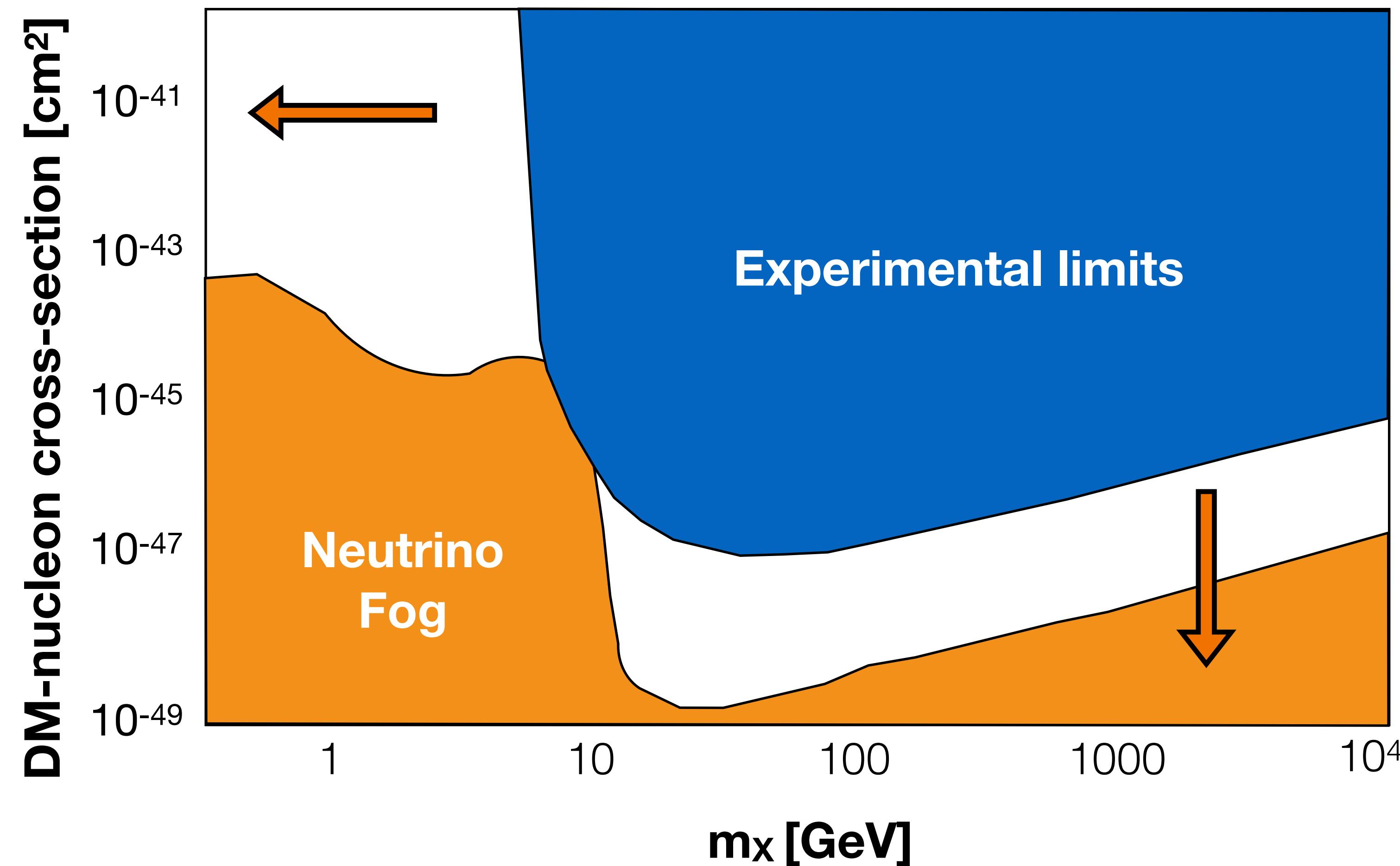


Current Landscape: Spin-Independent



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

Path towards DM discovery



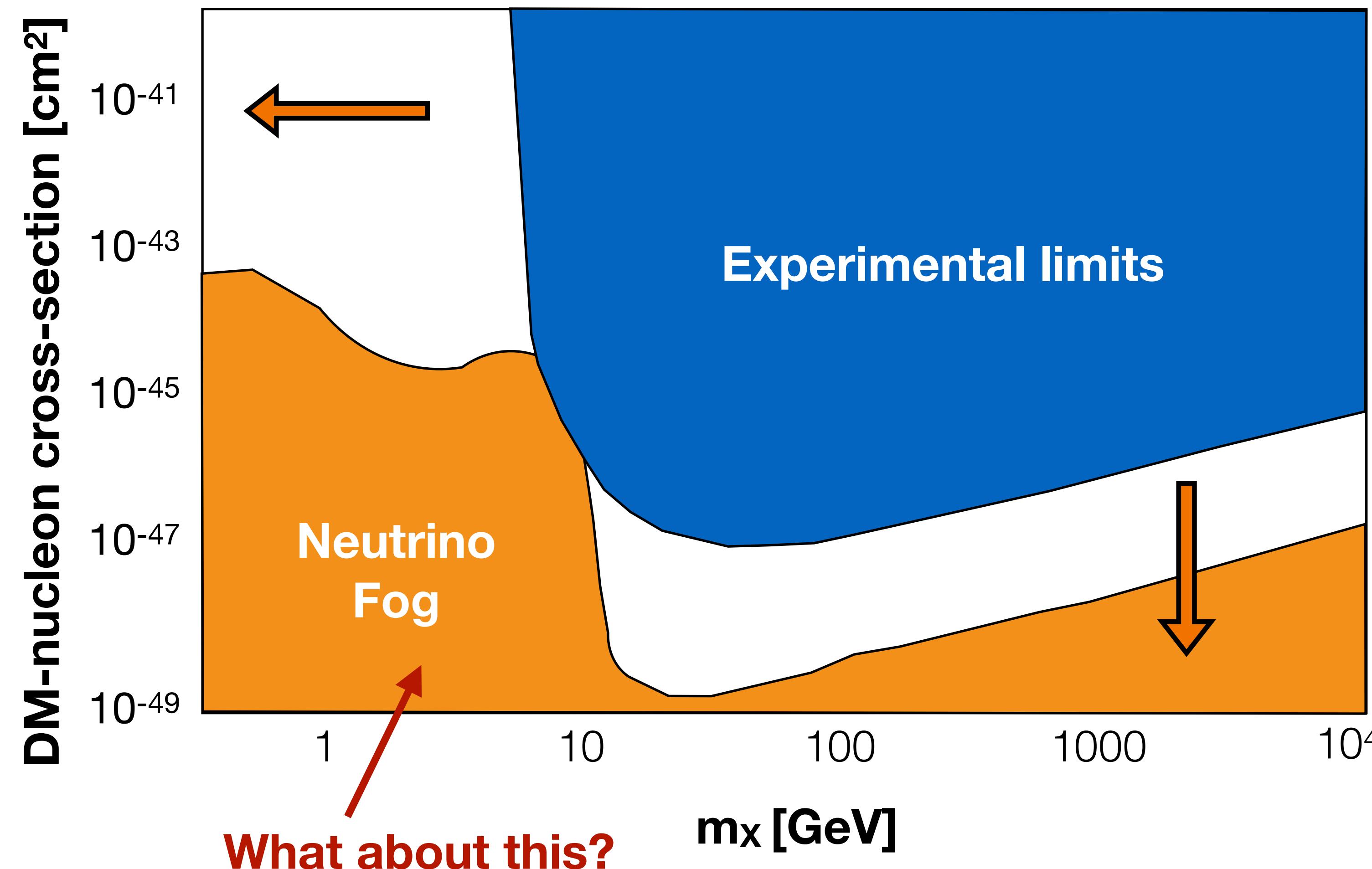
Goals:

- increase target mass
- decrease thresholds
- improve background discrimination

New technologies:

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

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
- ...

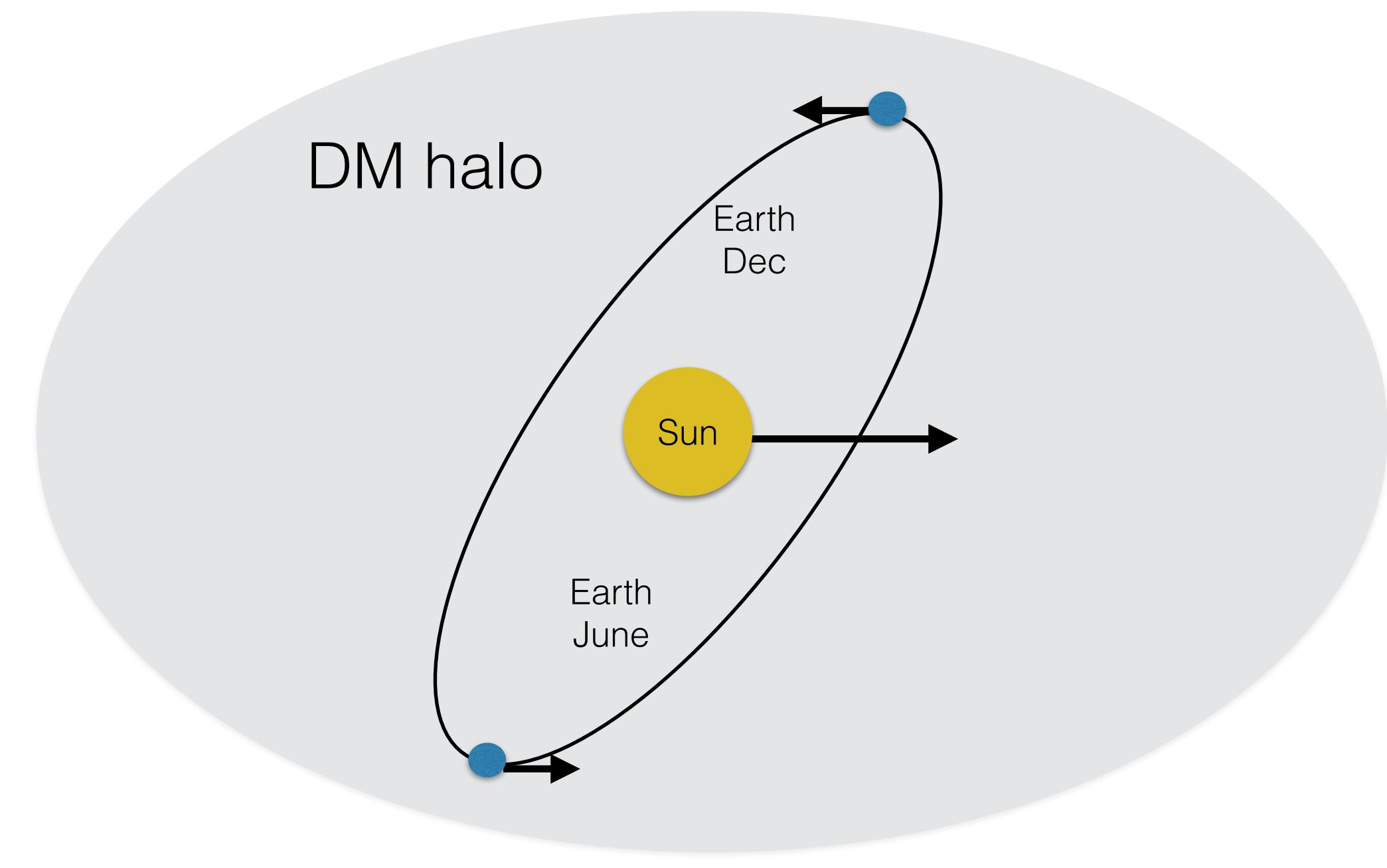
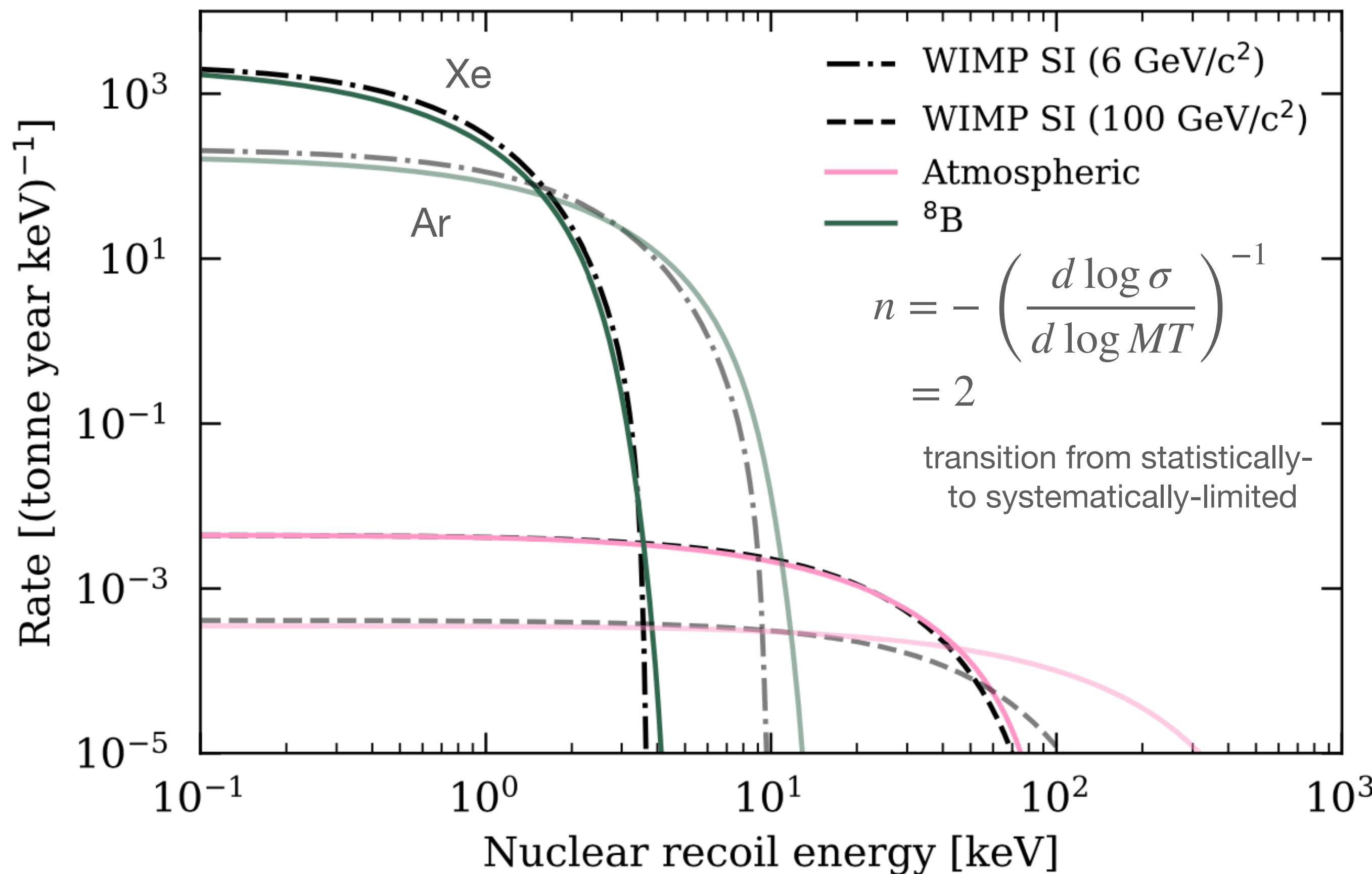
Navigating the Neutrino Fog

Snowmass2021 Cosmic Frontier Dark Matter

Direct Detection to the Neutrino Fog

[arXiv: 2203.08084]

Mitigation techniques:
annual modulation
directional detection



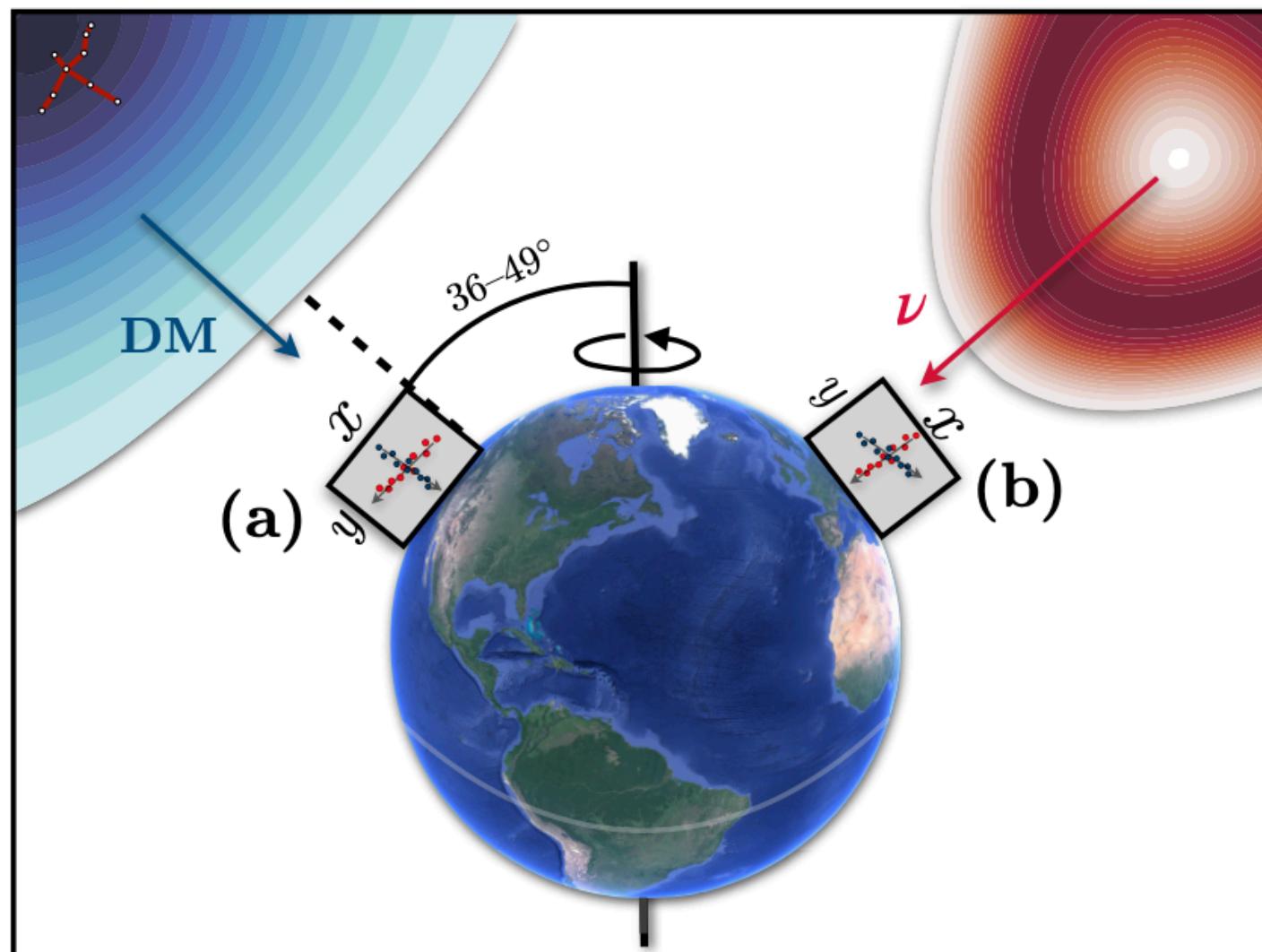
changes rate as a function of time
signature of **galactic** dark matter

Directional Detection

Very distinct signature!

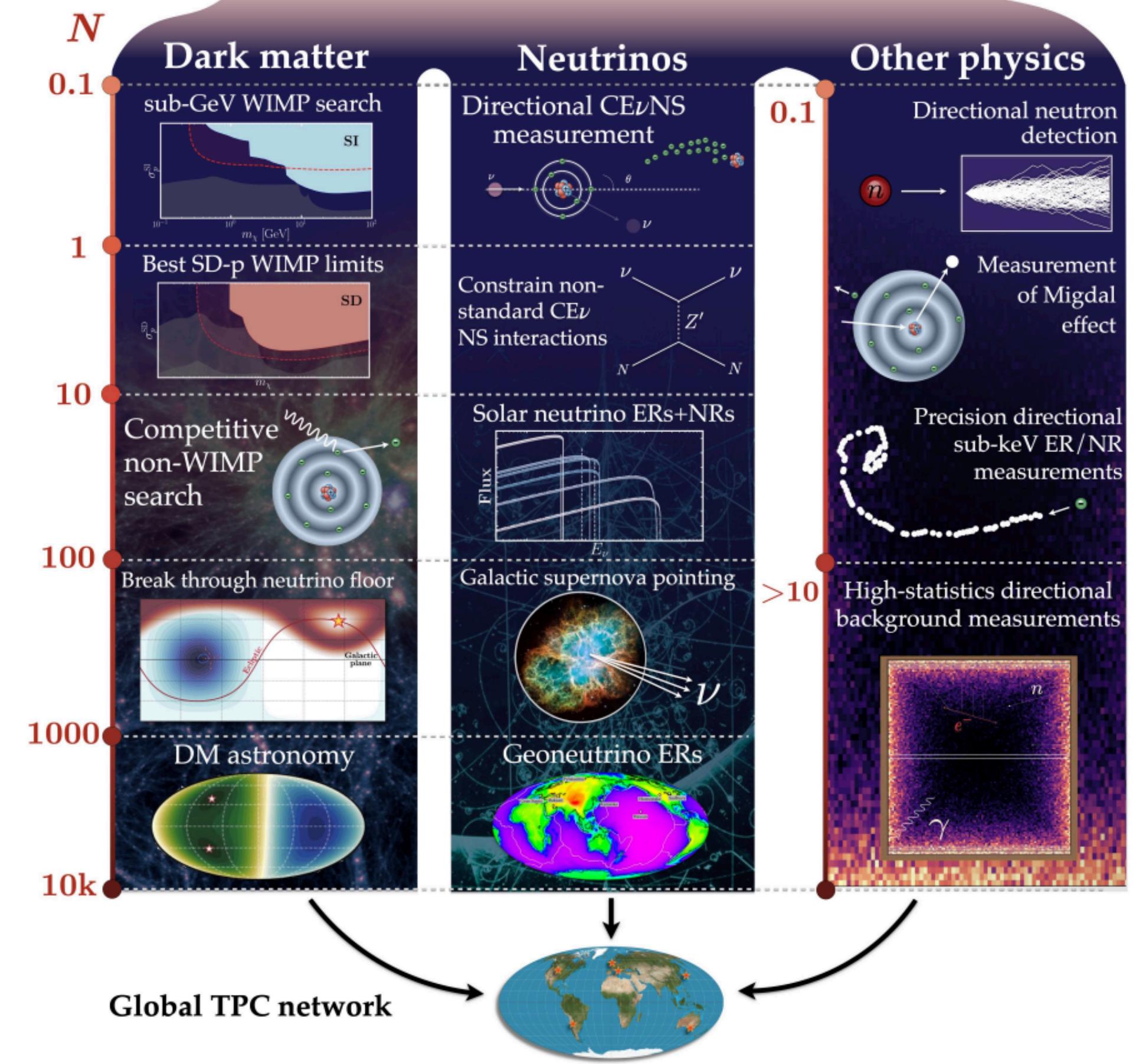
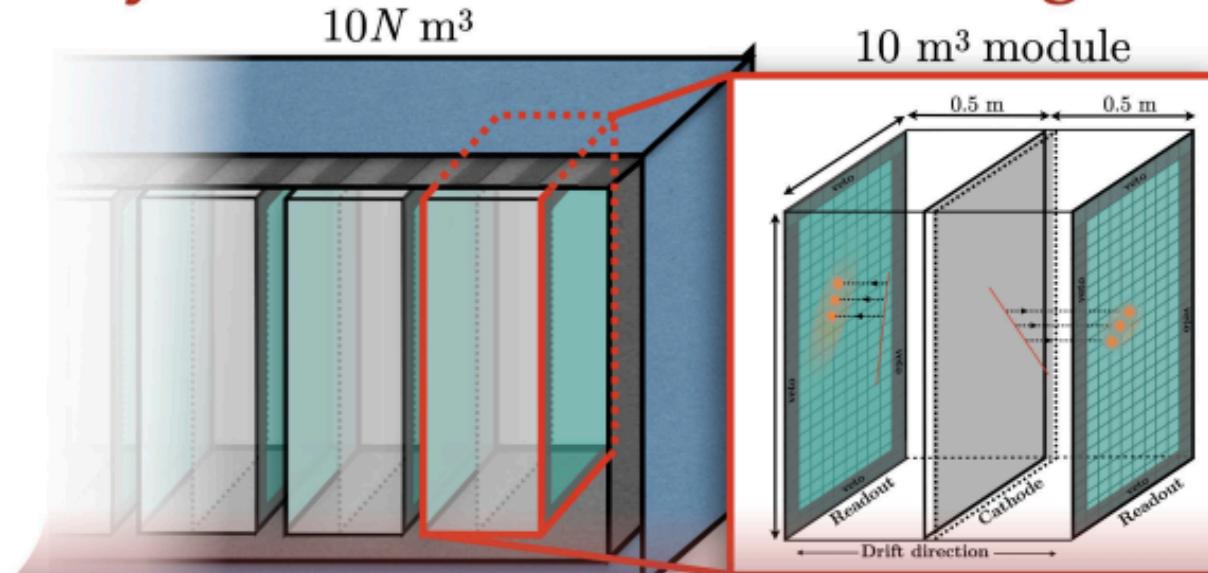
Requires ability to reconstruct
direction of nuclear recoil

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



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

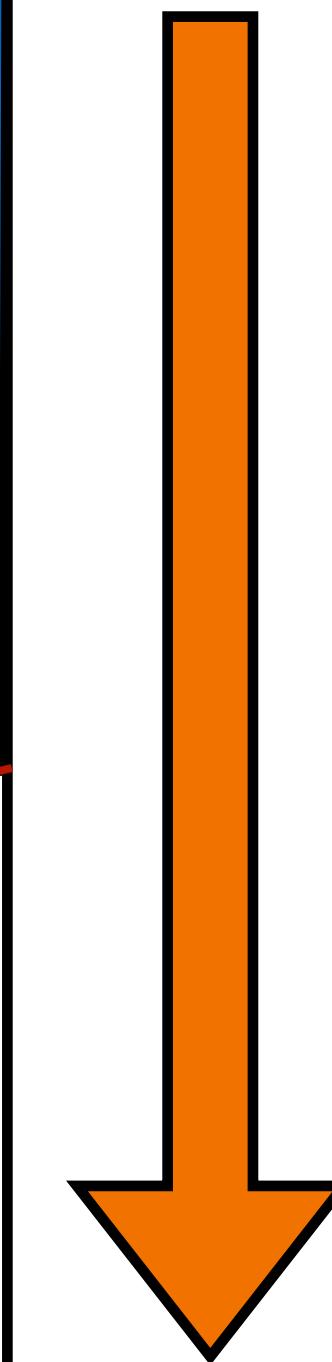
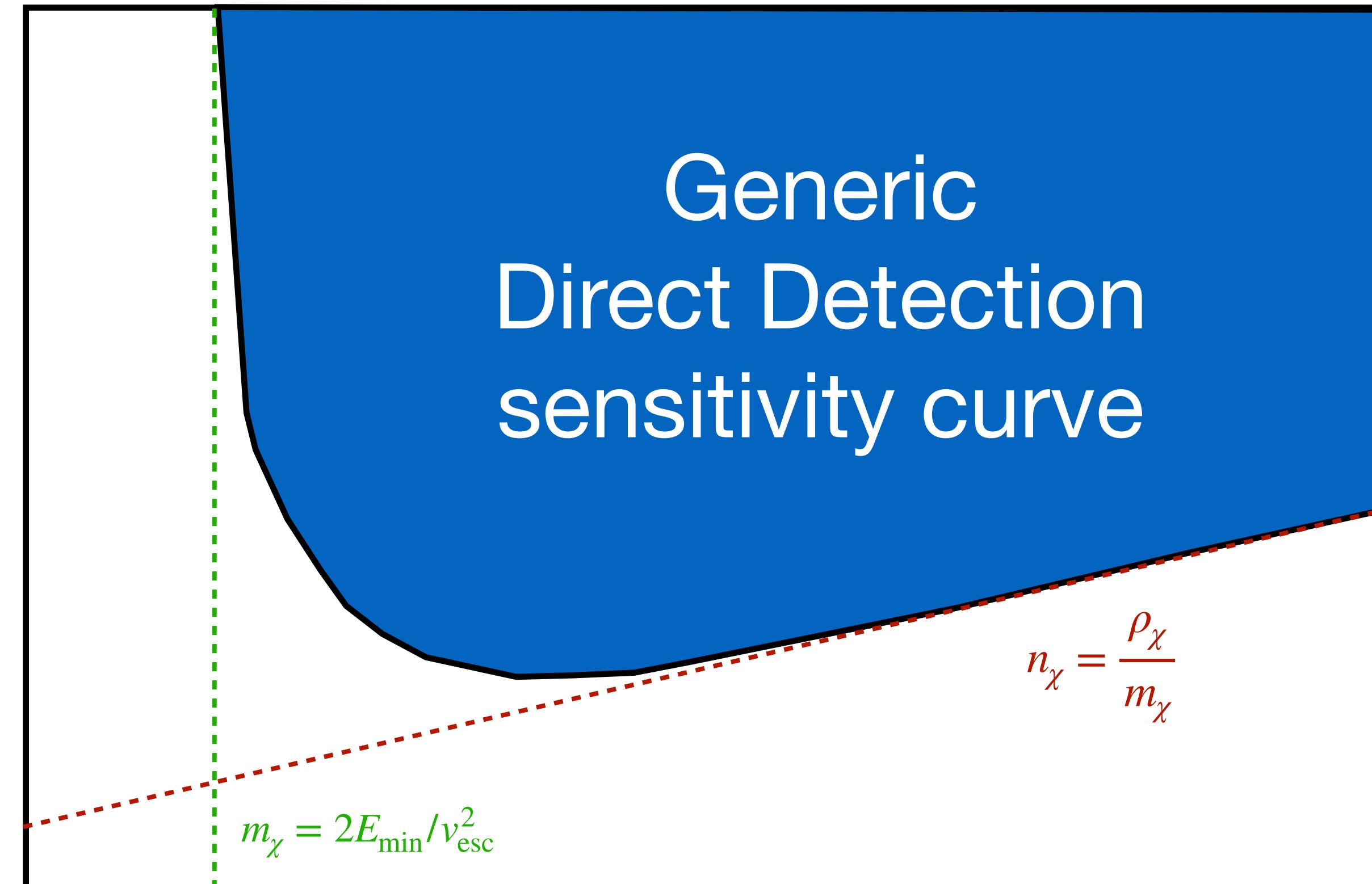
Physics case for a directional gas TPC



Landscape of Particle Dark Matter

- consider ensemble of interactions

strength of DM-SM interaction



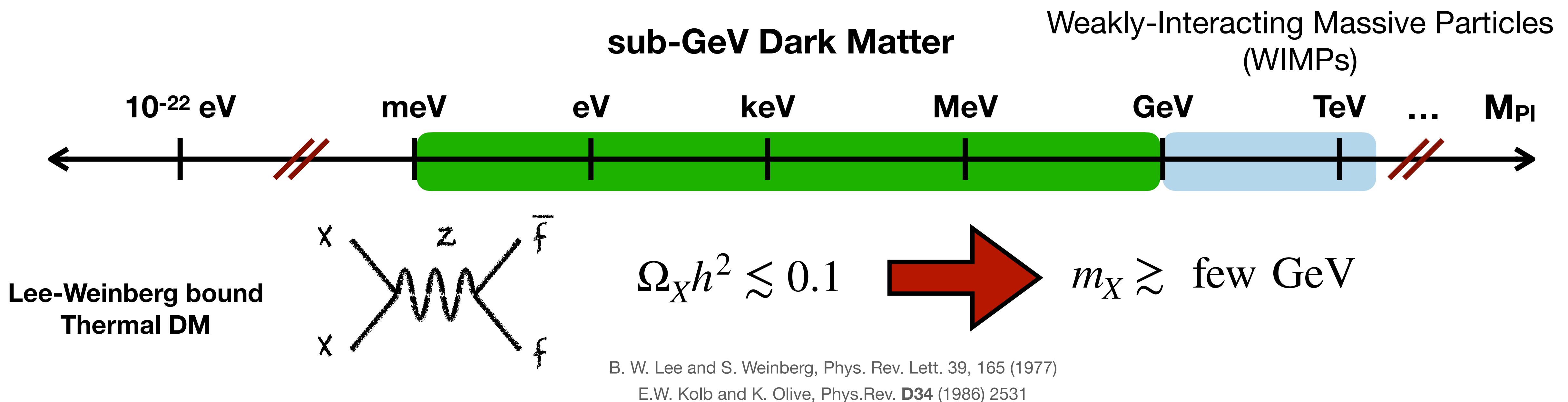
GOAL:
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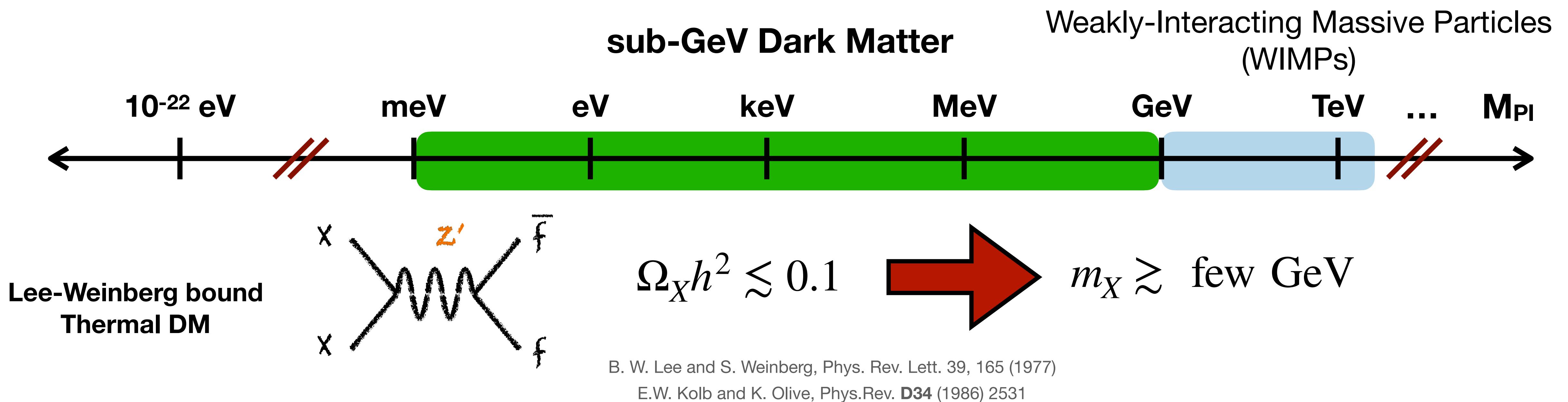
- decrease thresholds
- increase energy transfer



Dark Matter Candidates



Dark Matter Candidates



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
2. increase the energy transfer

detecting sub-GeV DM in 2 easy steps

1. decrease energy threshold or sensitivity

consider a variety of materials

2. increase the energy transfer

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

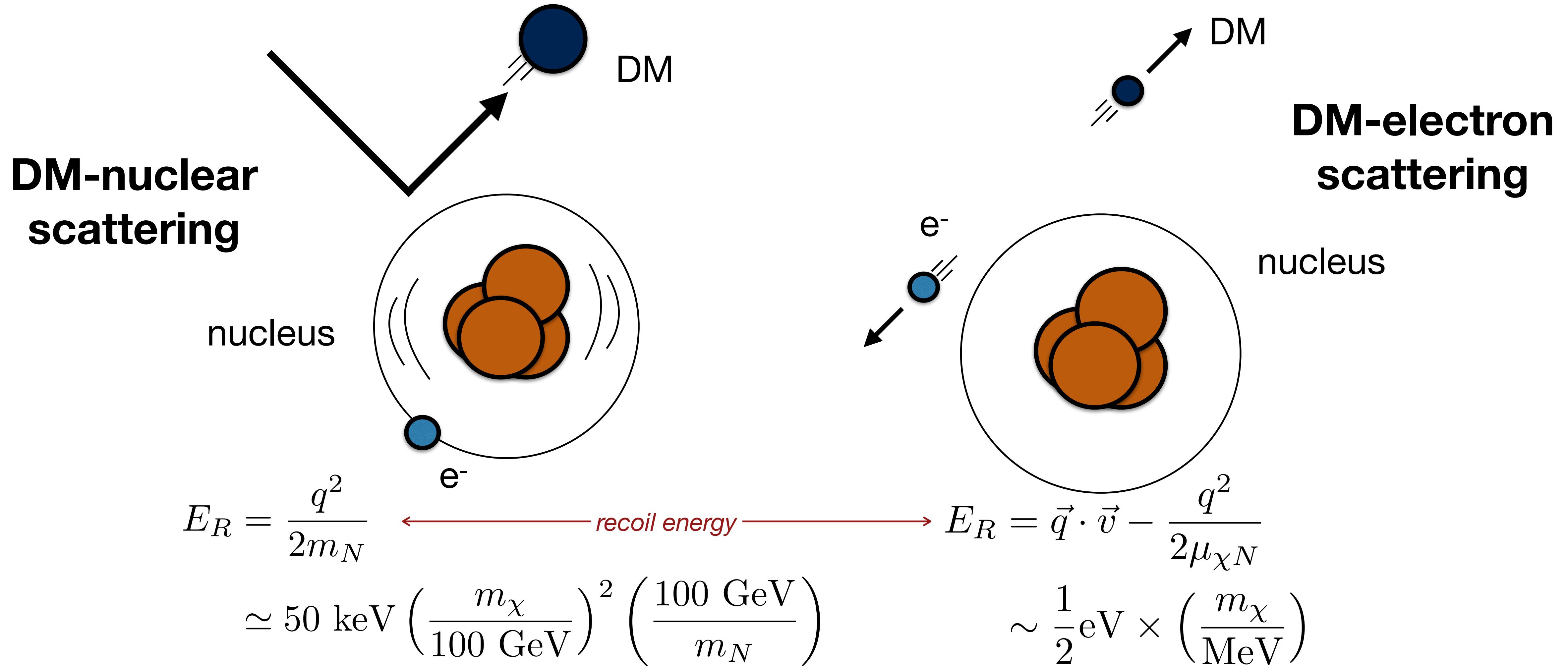
sub-GeV DM direct detection

- **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)

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Nuclear vs. Electron Scattering



DM-electron scattering rate

particle physics

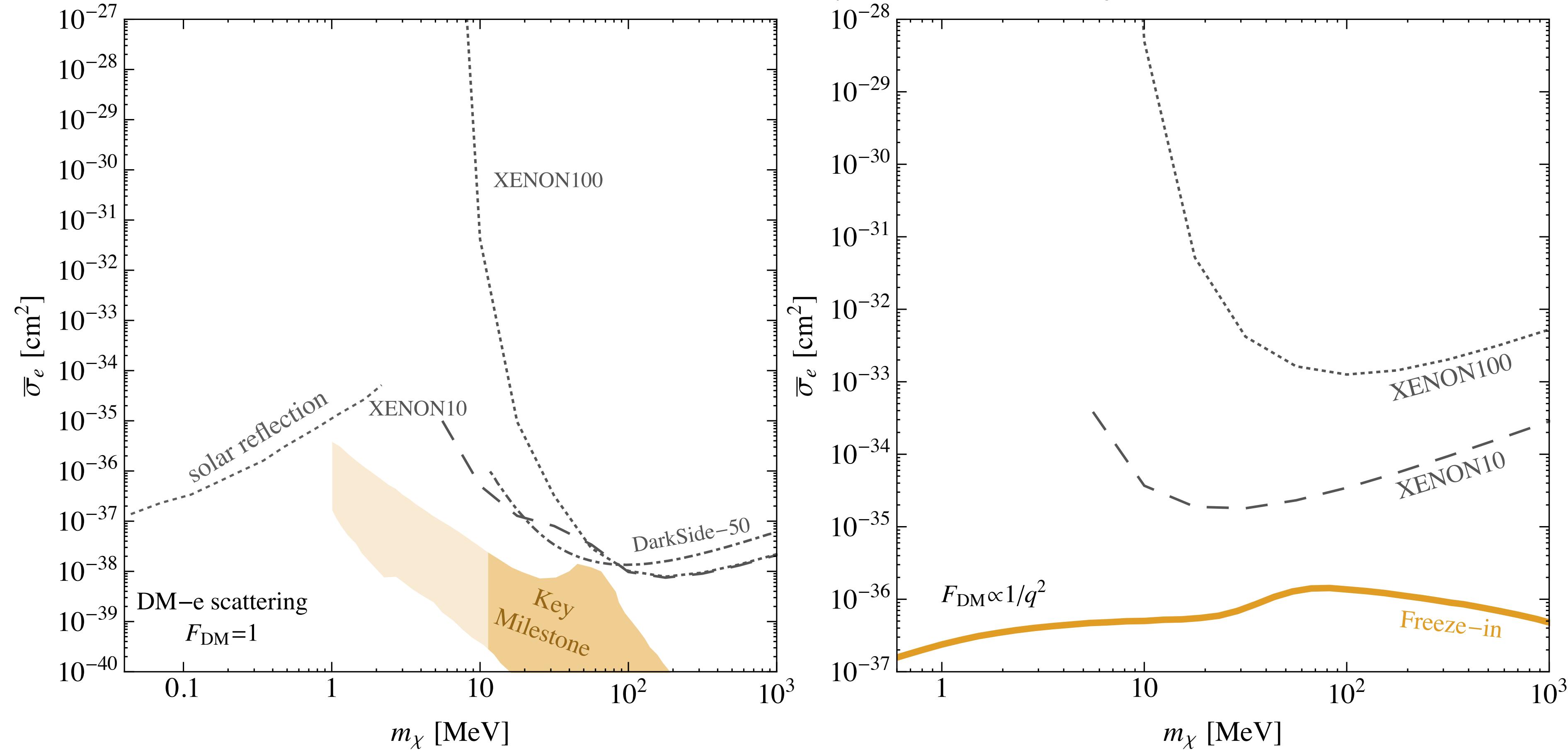
$$\frac{d\langle\sigma v\rangle}{d \ln E_R} = \frac{\bar{\sigma}_e}{8\mu_{\chi e}^2} \int q \, dq |f(k, q)|^2 |F_{DM}(q)|^2 \eta(v_{min})$$

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

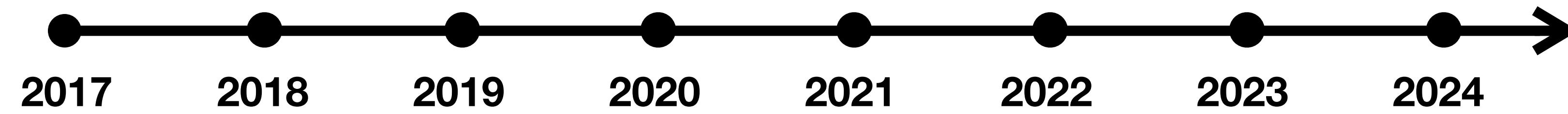
$$F_{DM}(q) \simeq \begin{cases} 1 & \textbf{heavy mediator} \\ \frac{\alpha m_e}{q} & \textit{electric dipole moment} \\ \frac{\alpha^2 m_e^2}{q^2} & \textbf{light mediator} \end{cases}$$

DM-electron limits in 2018

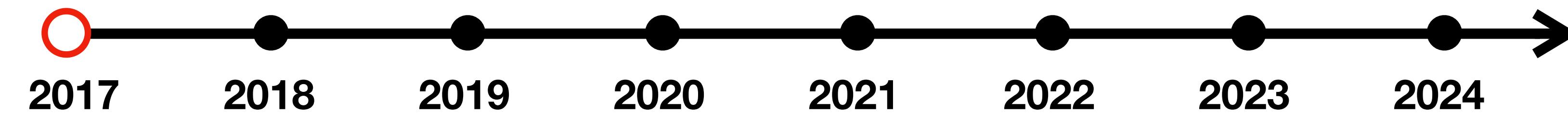
Essig, Volansky, TTY Phys.Rev.D 96 (2017) 4, 043017 [1703.00910]
DarkSide Collaboration Phys.Rev.Lett. 121 (2018) 11, 111303 [1802.06998]
An, Pospelov, Pradler, Ritz Phys.Rev.Lett. 120 (2018) 14, 141801 [1708.03642]



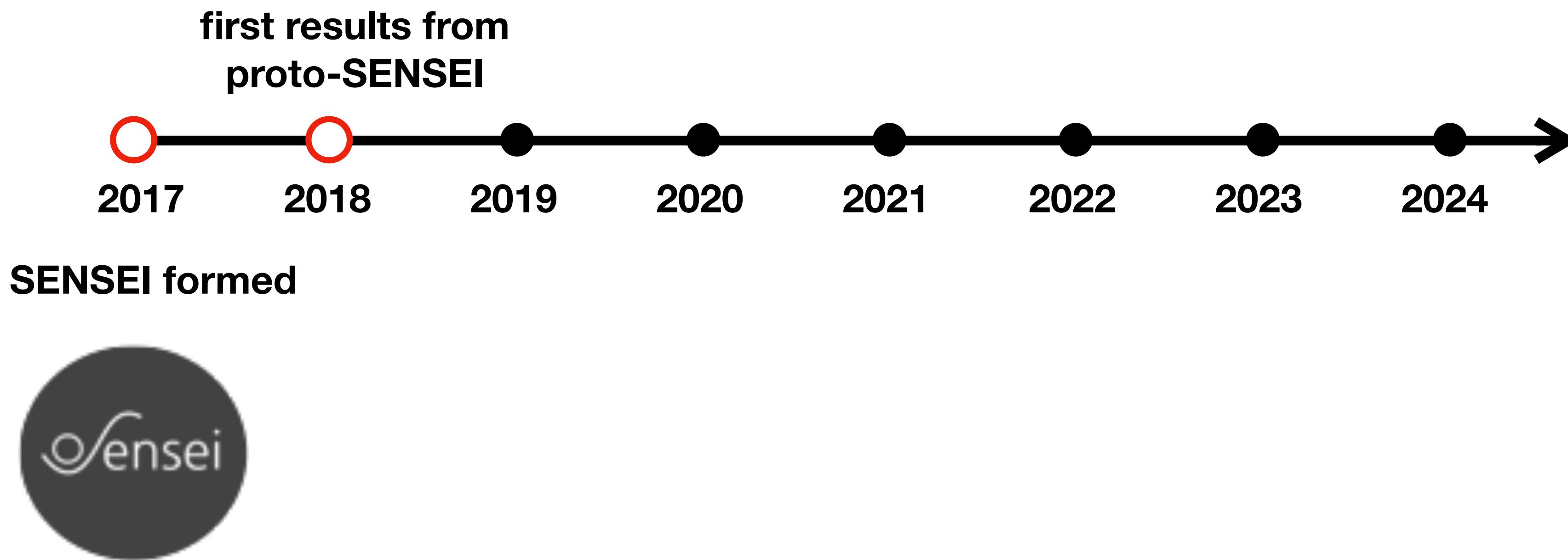
a brief history



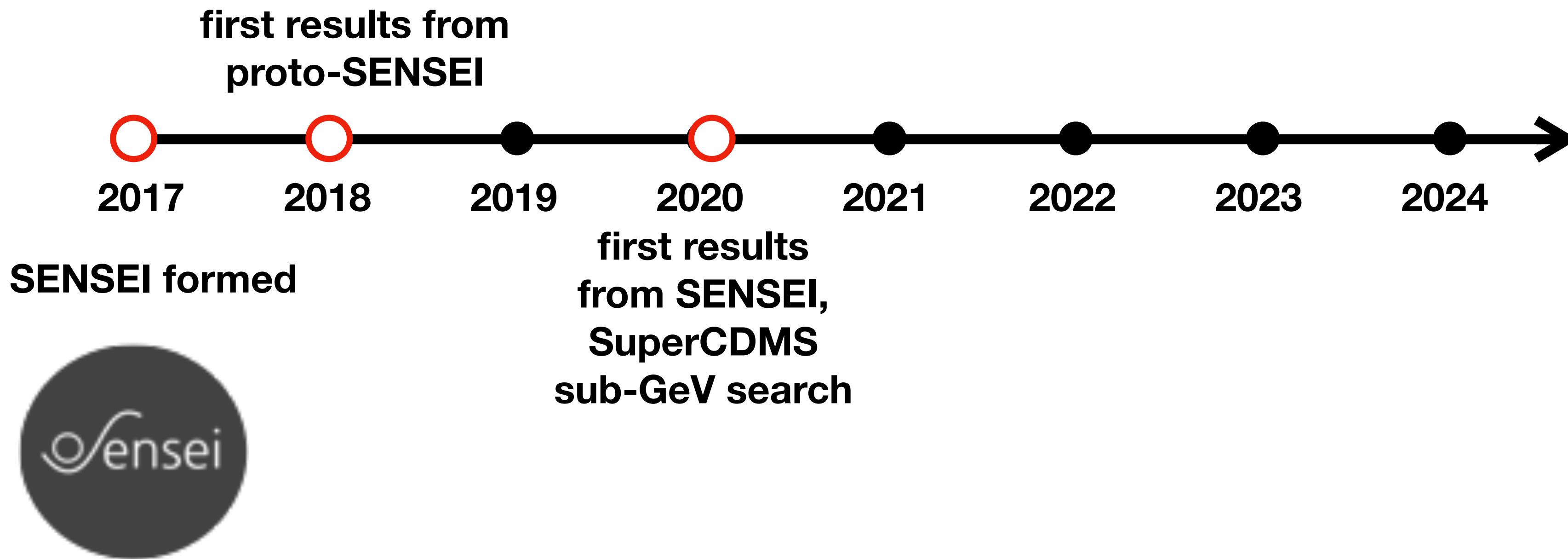
a brief history



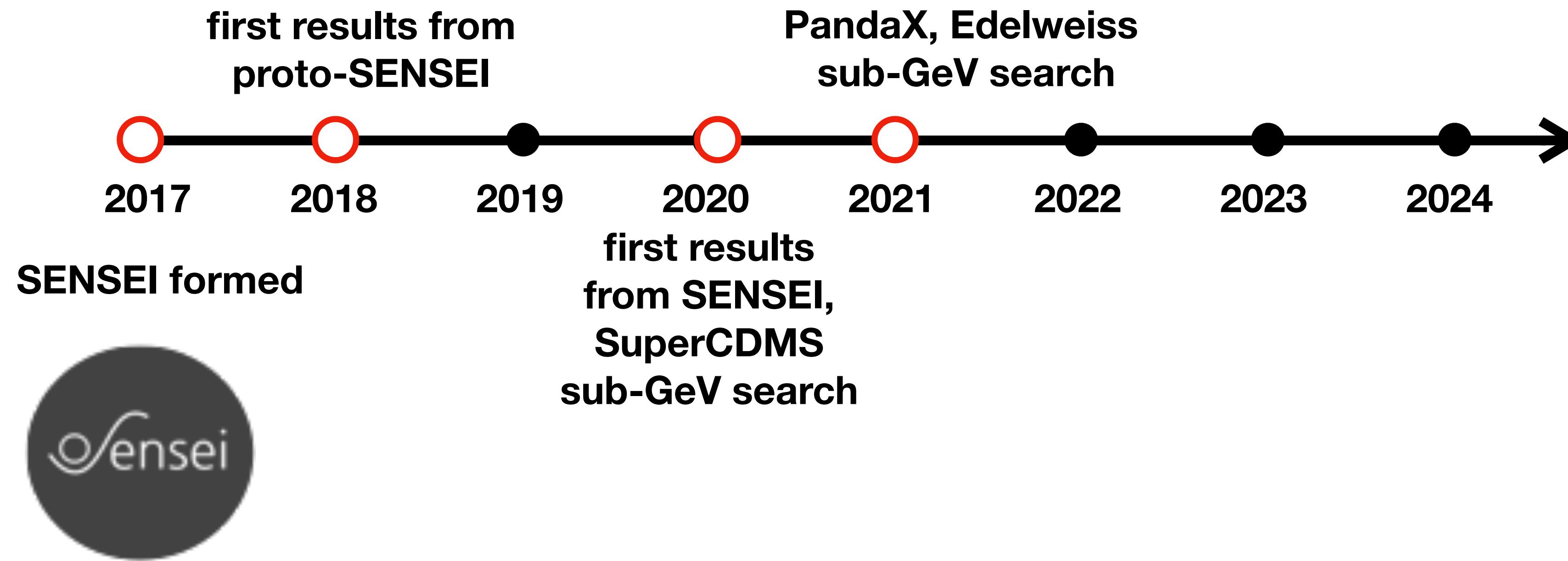
a brief history



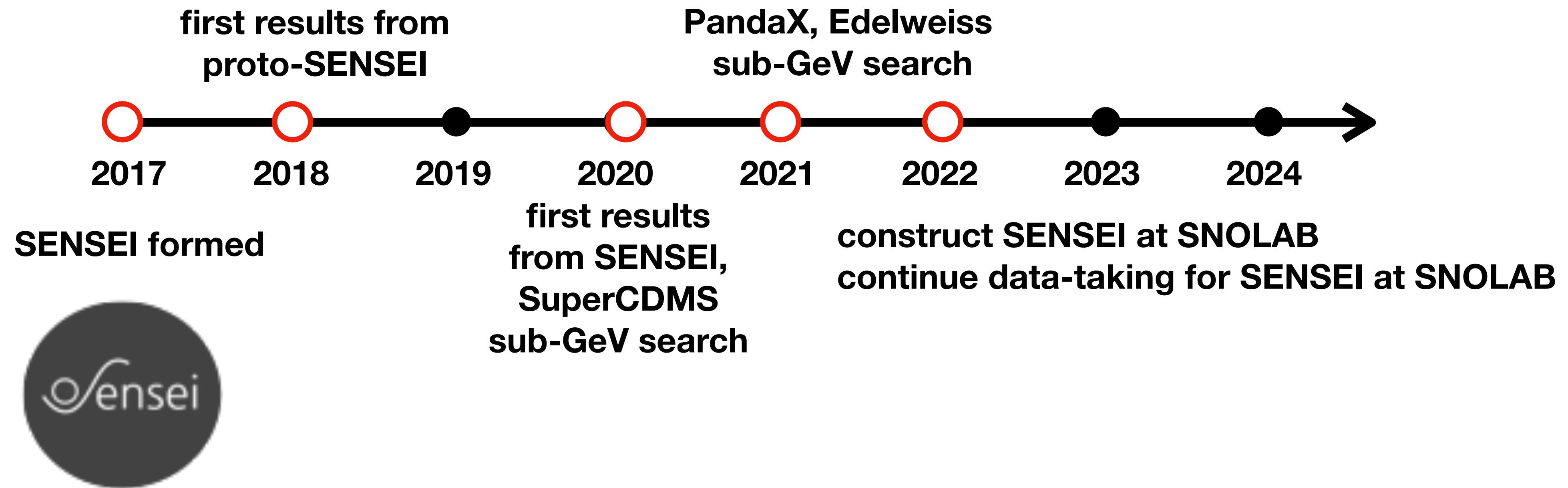
a brief history



a brief history

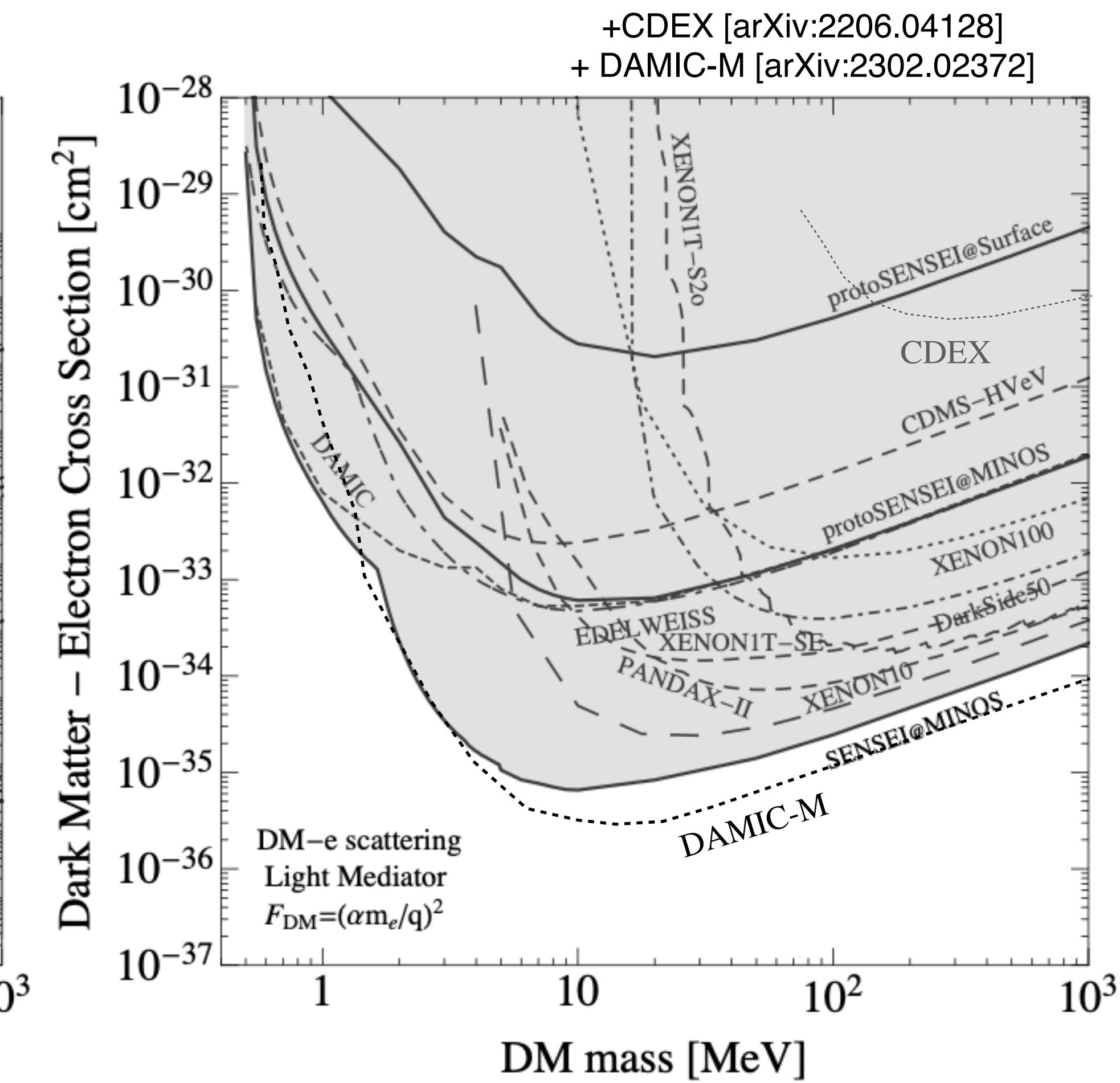
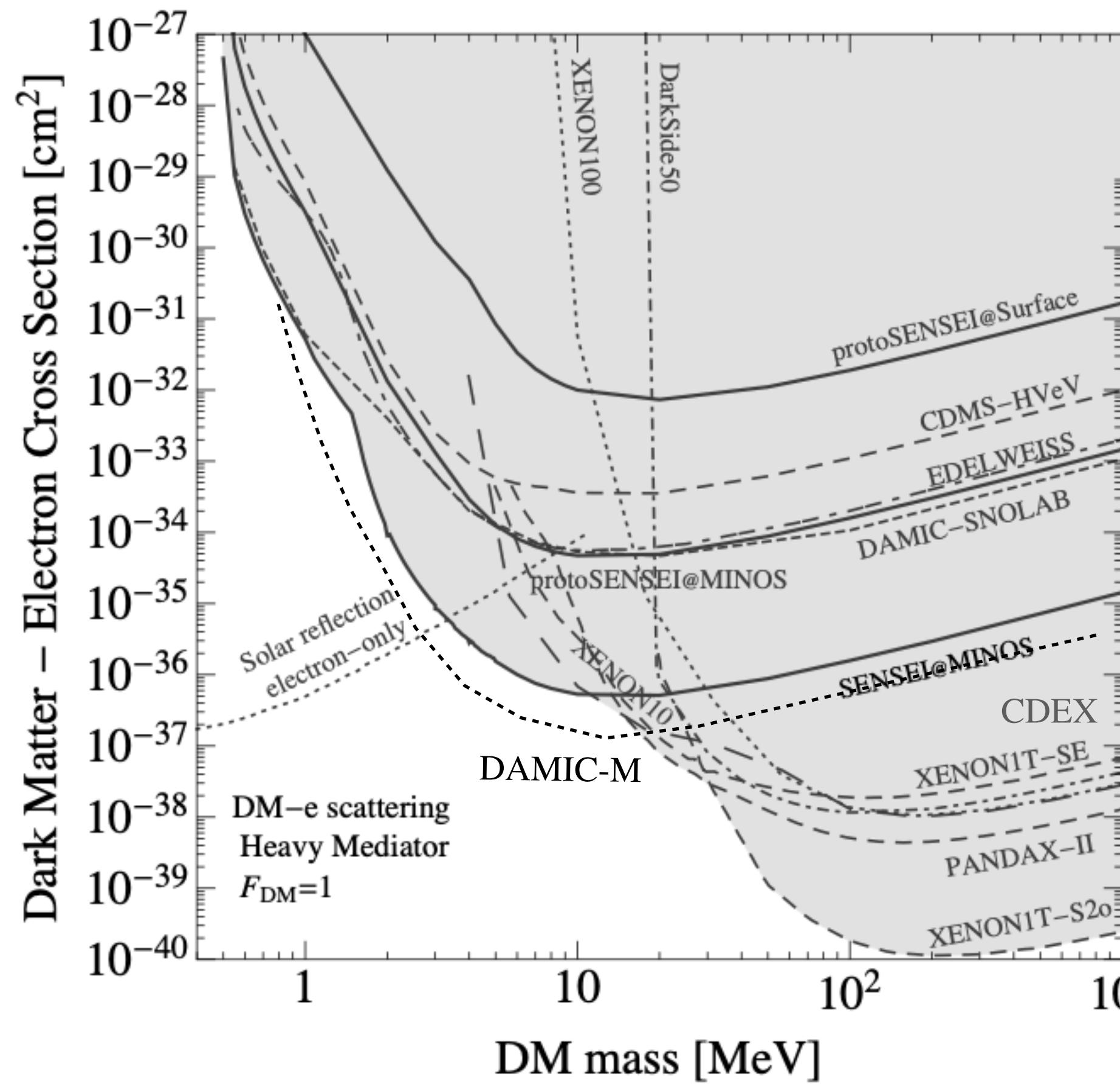


a brief history

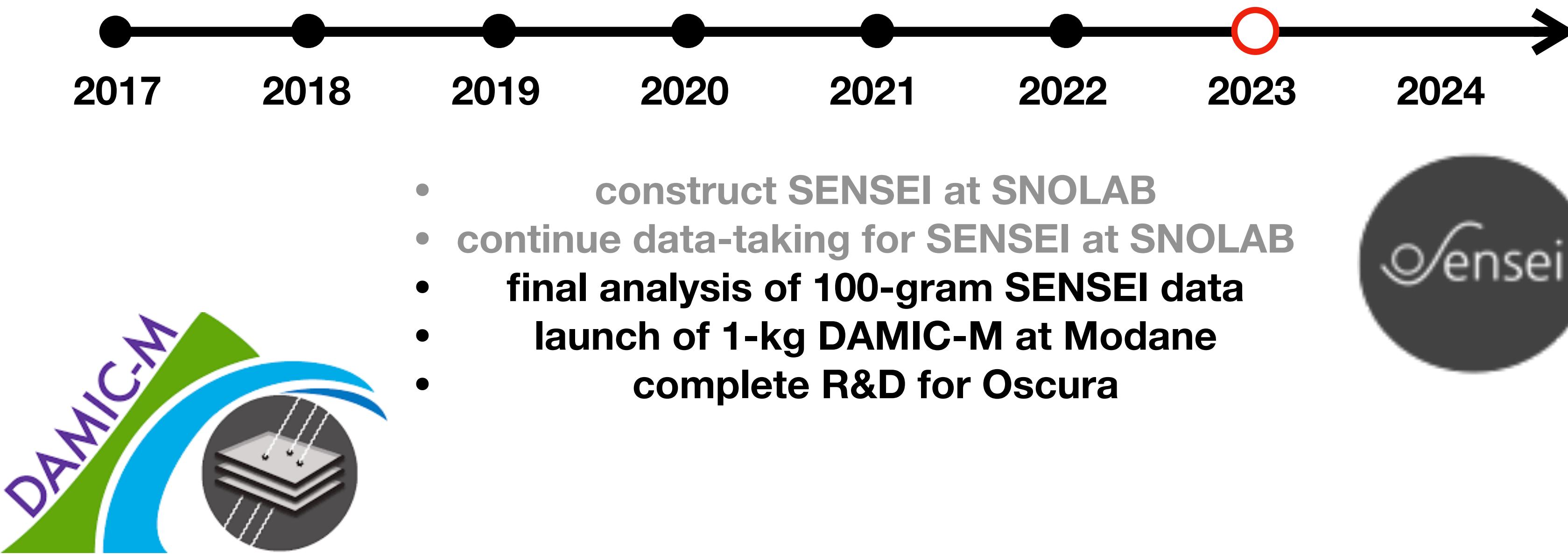


DM-electron scattering limits today*

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



looking forward



Oscura

Snowmass2021 - Letter of Interest

Status and plans for Oscura: A Multi-kilogram Skipper-CCD Array for Direct-Detection of Dark Matter.

Thematic Areas:

- (CF1) Cosmic Frontier: Dark Matter: Particle Like
- (IF2) Instrumentation Frontier: Photon Detectors

Contact Information:

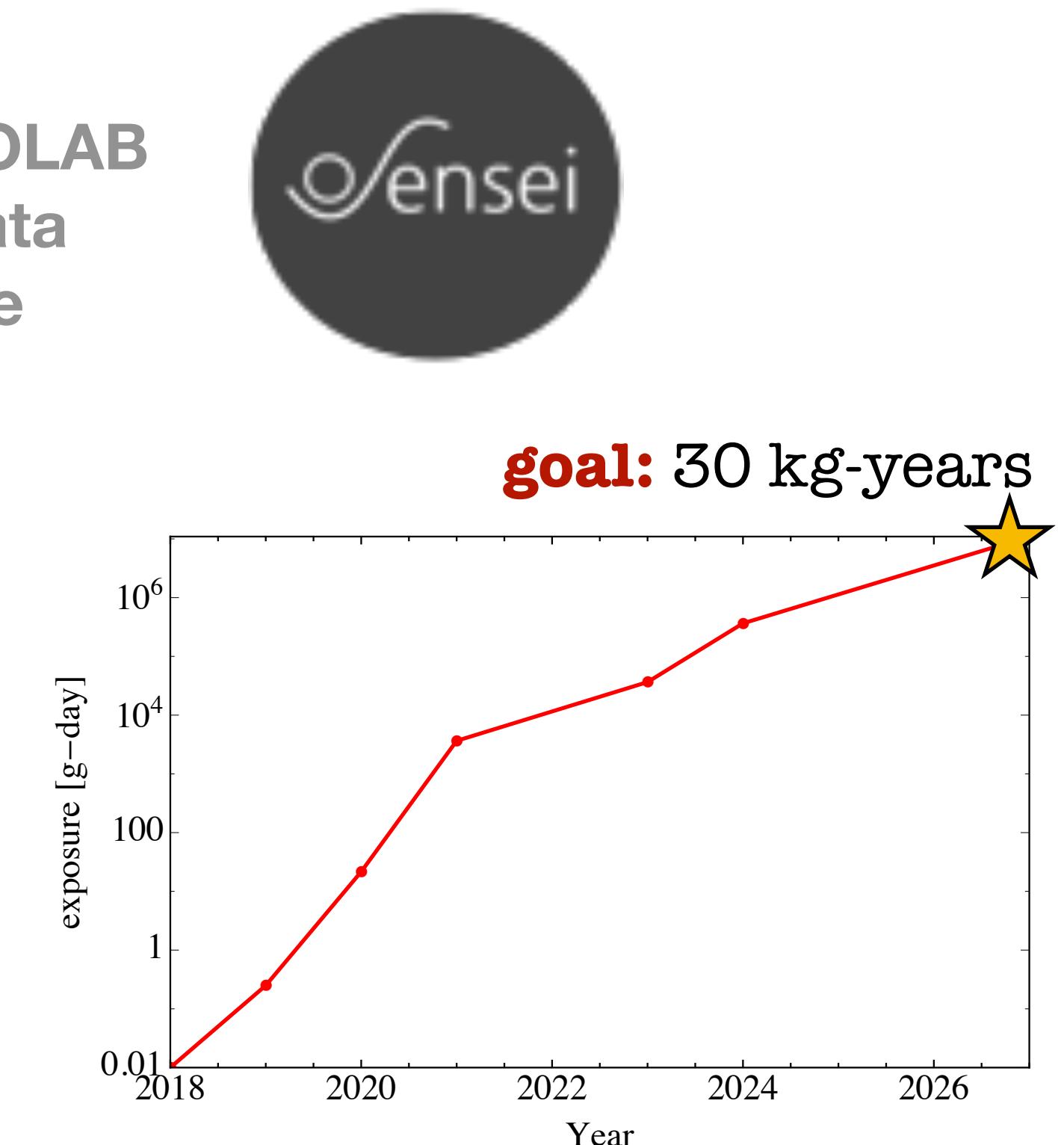
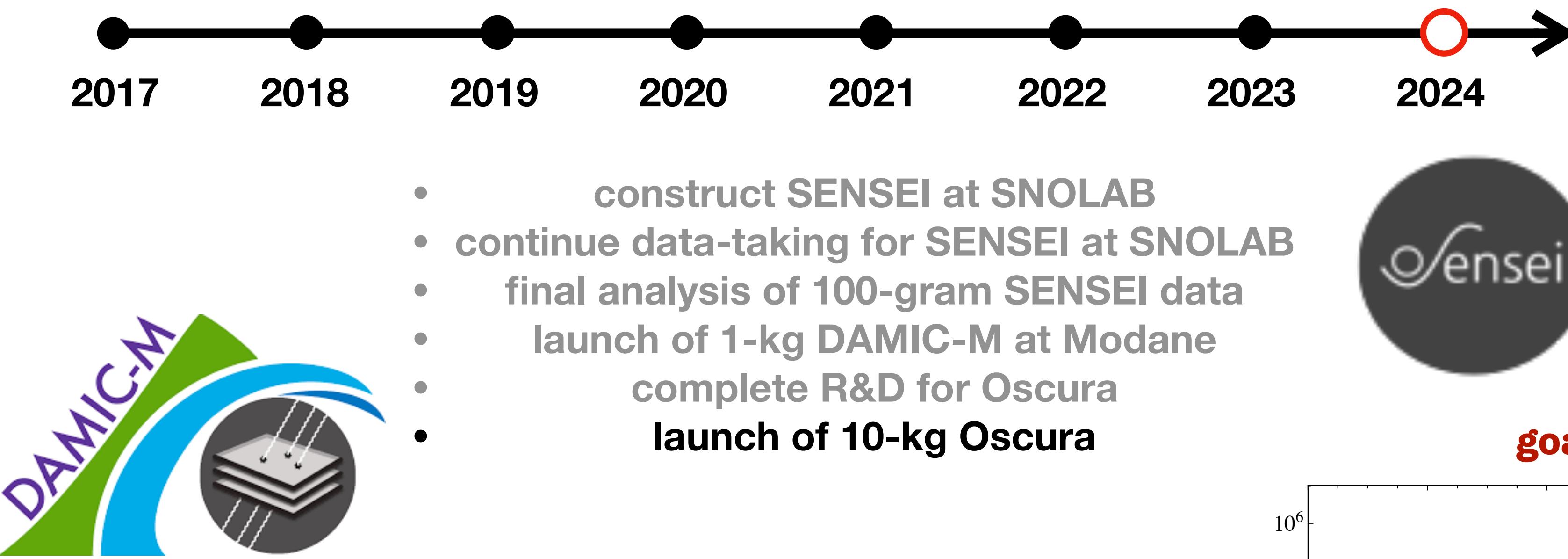
Juan Estrada (Fermilab)

Authors: Daniel Baxter (U. Chicago), Itay Bloch (Tel-Aviv), Mariano Cababie (U. Buenos Aires), Nuria Castello (Inst. de Física de Cantabria), Luke Chaplinsky (UMass Amherst), Alvaro Chavarria (U. Washington), Juan Carlos D'Olivo (UNAM), Rouven Essig (Stony Brook), Juan Estrada (FNAL), Erez Etzion (Tel-Aviv), Guillermo Fernandez-Moroni (Fermilab), Stephen Holland (LBNL), Todd W. Hossbach (PNNL), Ben Kilminster (U. Zurich), Ian Lawson (SNOLAB), Steven J. Lee (U. Zurich), Ben Loer (PNNL), Pitam Mitra (U. Washington), Jorge Molina (U. Asuncion), Danielle Norcini (U. Chicago), Paolo Privitera (U. Chicago), Karthik Ramanathan (U. Chicago), Dario Rodrigues (U. Buenos Aires), Richard Saldanha (PNNL), Radomir Smida (U. Chicago), Miguel Sofo-Haro (CNEA). Javier Tiffenberg (Fermilab), Sho Uemura (Tel-Aviv), Ivan Vila (Inst. de Física de Cantabria), Rocio Vilar (Inst. de Física de Cantabria), Tomer Volansky (Tel-Aviv), Tien-Tien Yu (Oregon),

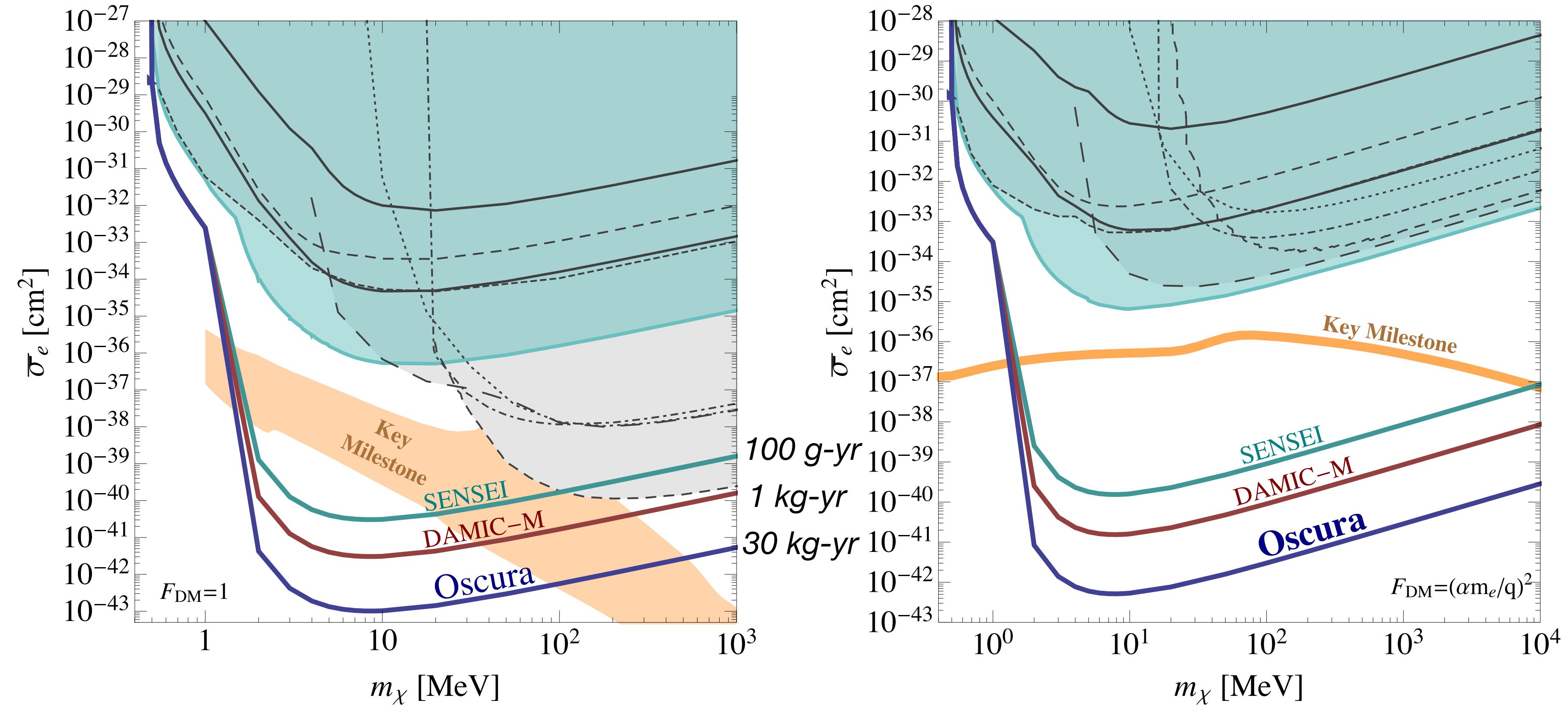
Abstract: Recent advances in silicon skipper-CCDs have demonstrated this technology as a powerful probe for sub-GeV dark matter by enabling ultra-sensitive searches for electron recoils from dark matter-electron interactions. World-leading results have already been produced by the SENSEI collaboration using a single skipper-CCD with an active mass of \sim 2 gram. Pathfinder experiments using skipper-CCDs are planned for the coming years, with SENSEI-100 (\sim 100 g detector) and DAMIC-M (\sim 1 kg detector) expected to start operations during 2020 and 2023, respectively. We are preparing a white paper describing the status and plans of the Oscura R&D effort to develop a \sim 10-kg skipper-CCD experiment for dark matter.

**Brings together
Si CCD
community**

looking forward

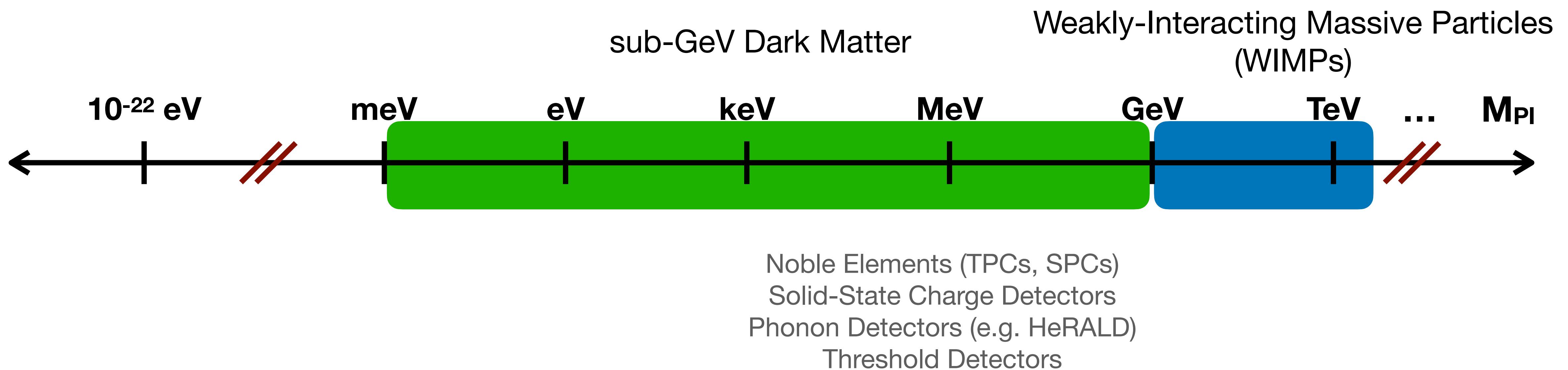


Looking forward

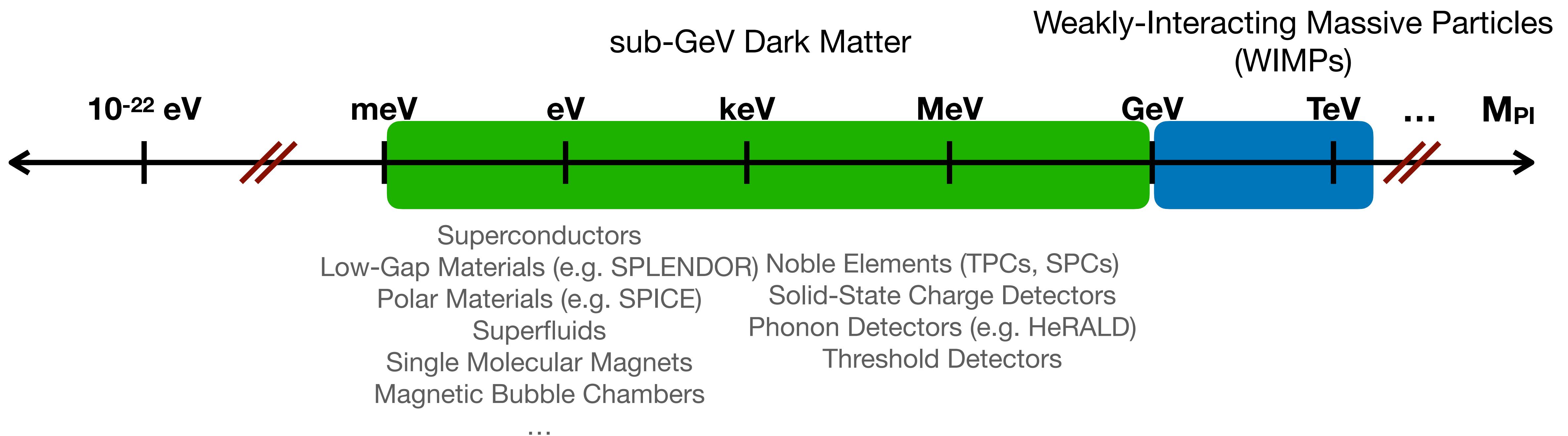


Projections for future Si Skipper-CCD experiments

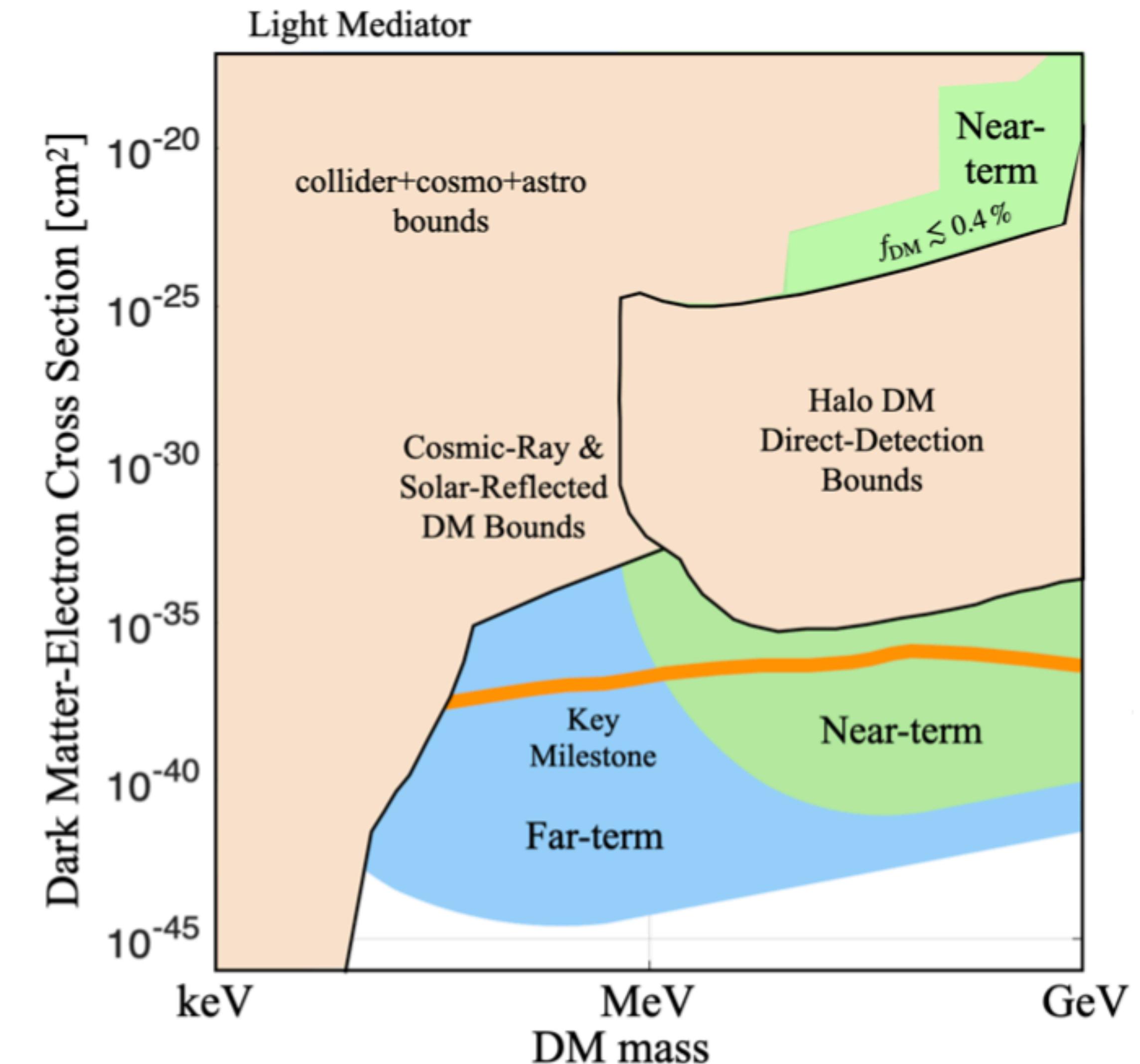
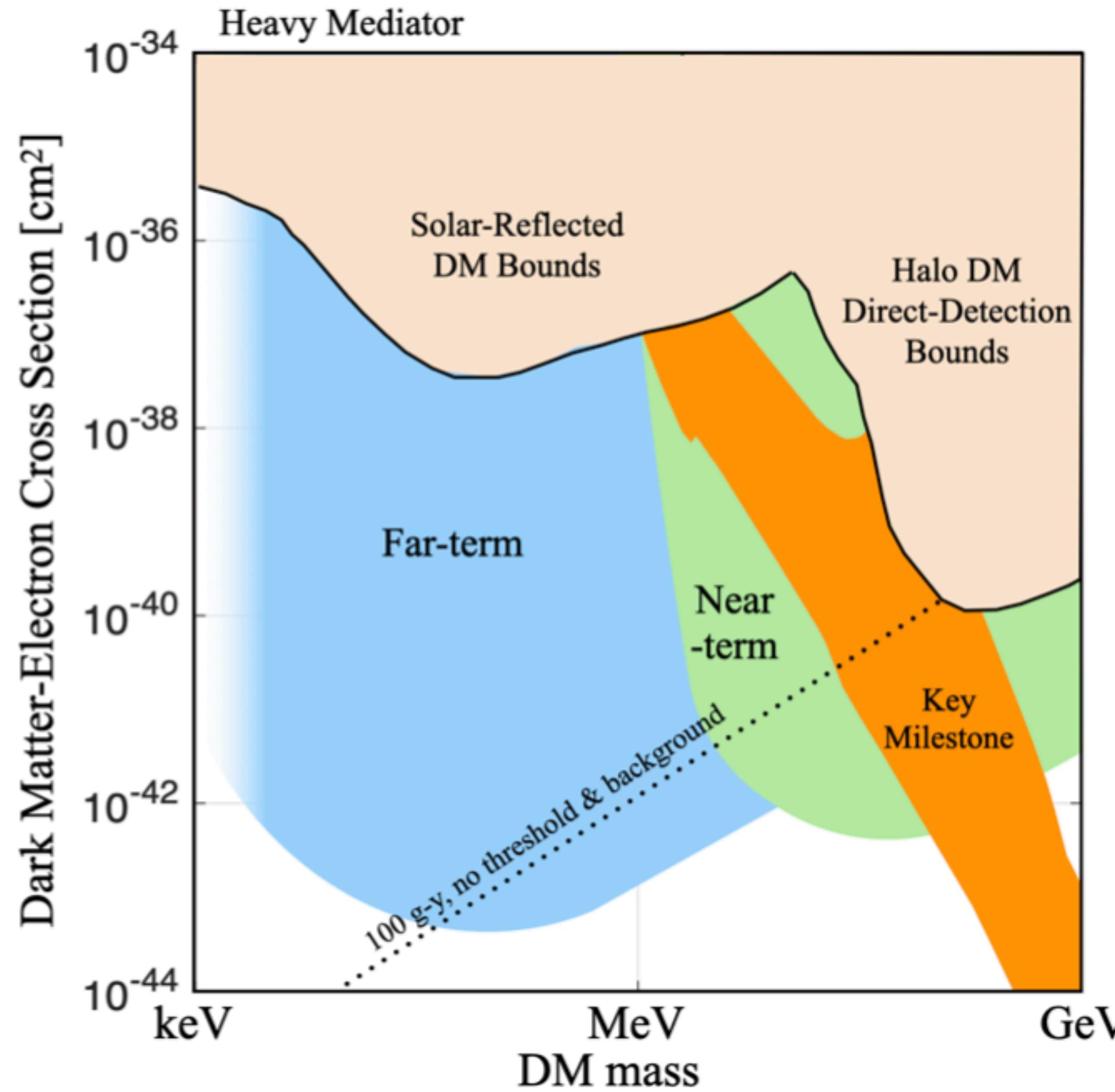
Dark Matter Candidates



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]

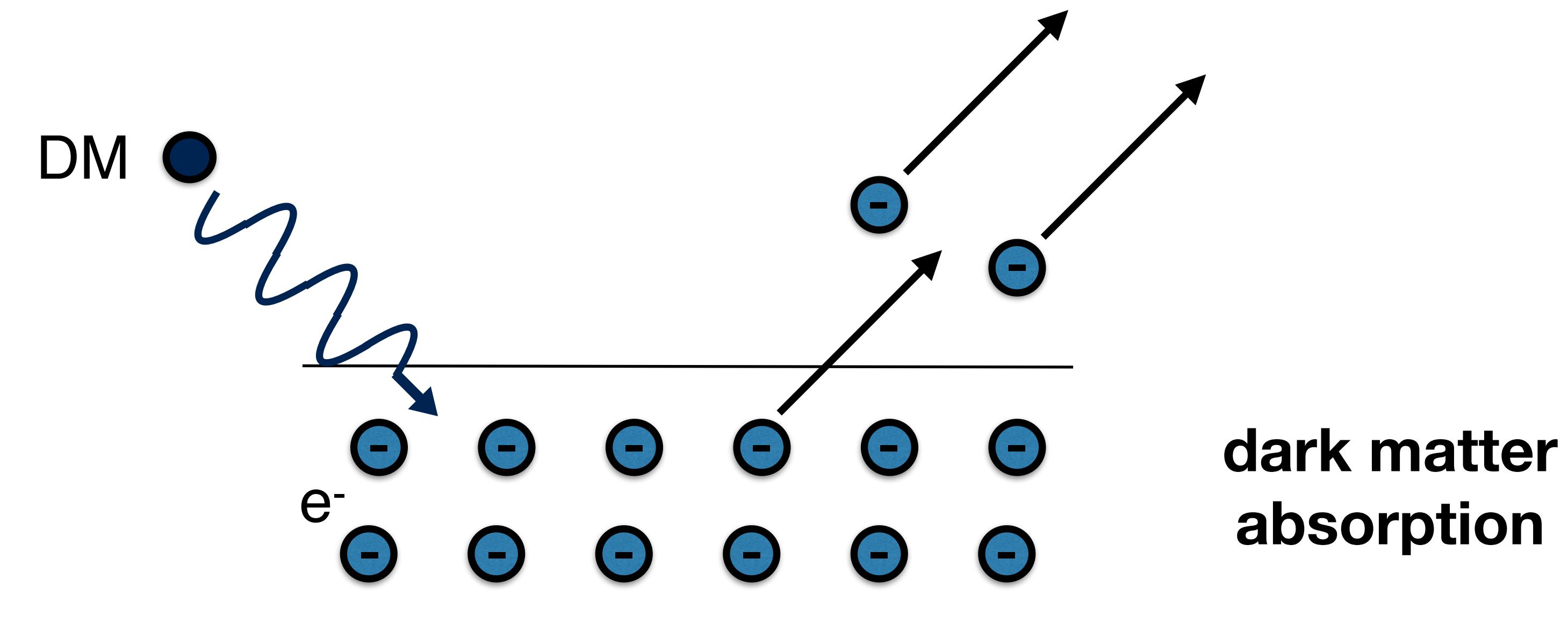
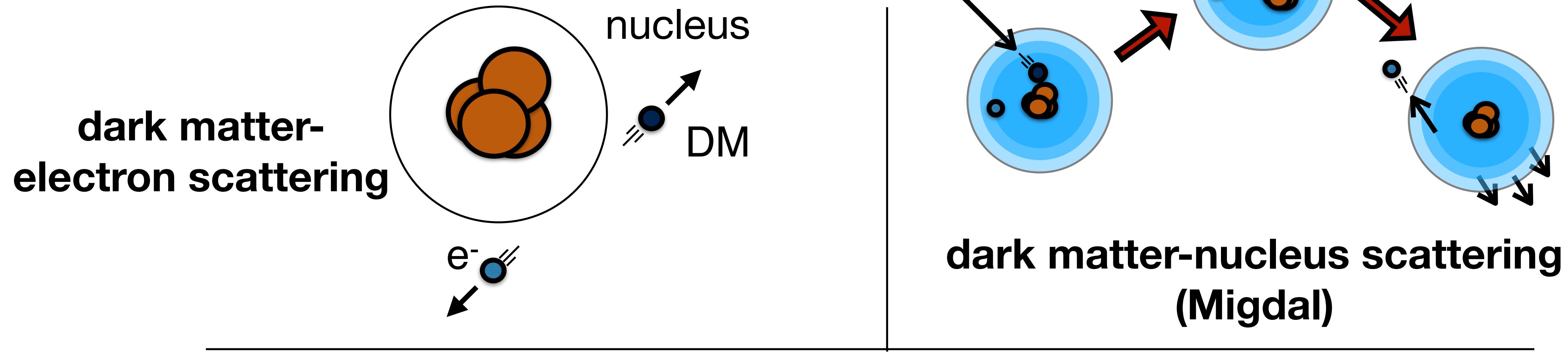
sub-GeV DM direct detection

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sub-GeV DM direct detection

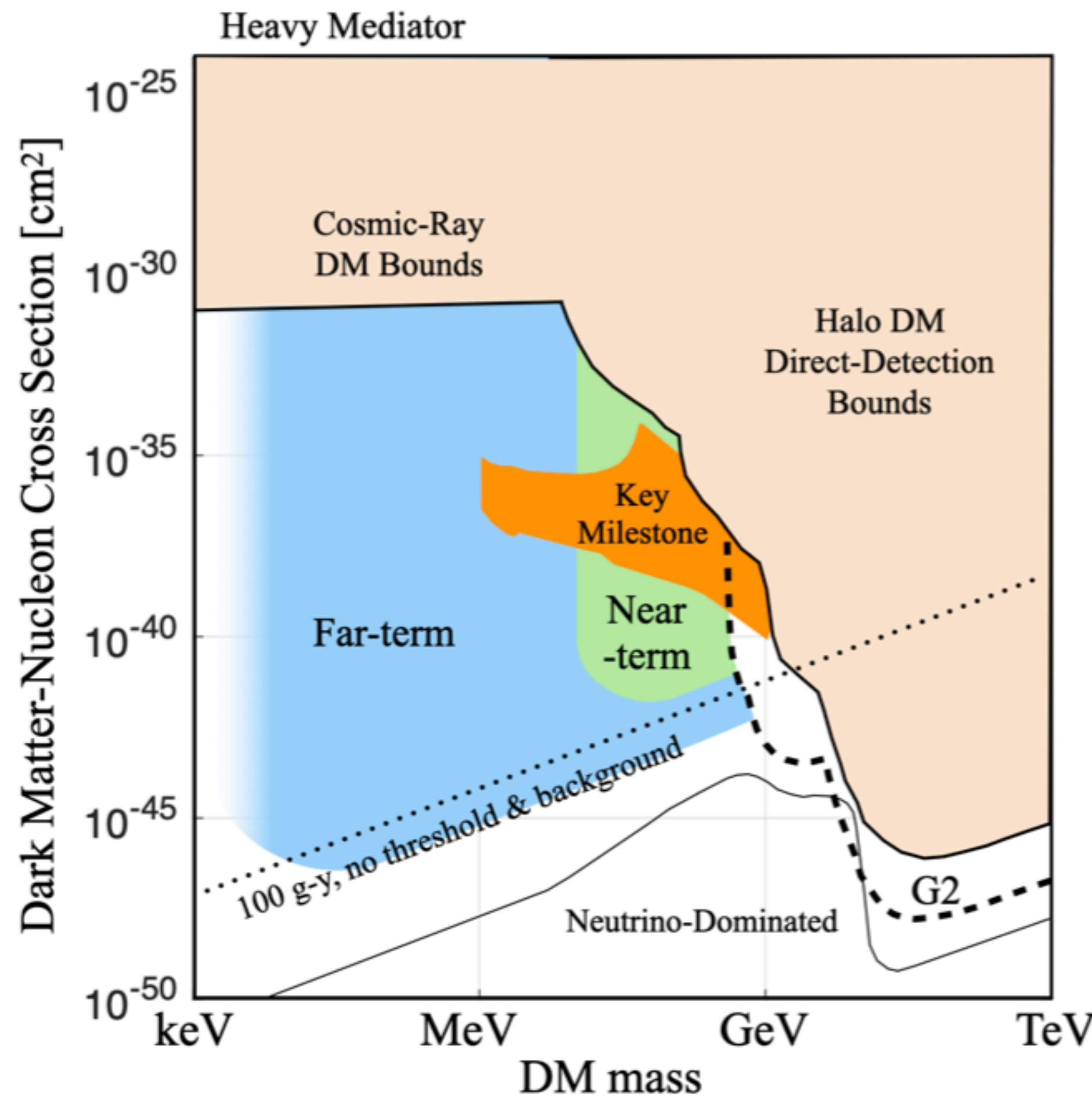
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models for sub-GeV DM

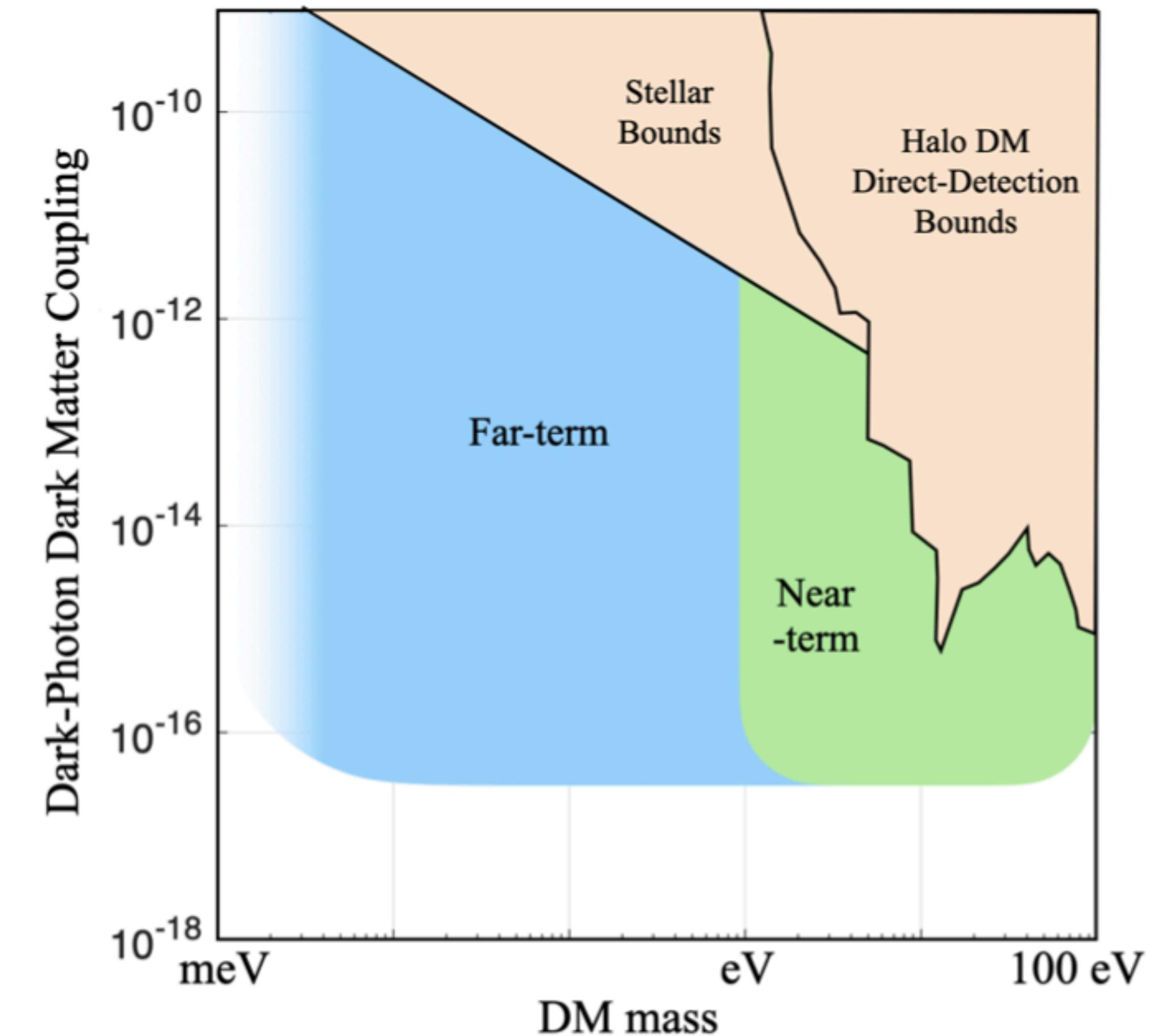


Other Models

DM-nucleon scattering



DM absorption



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

sub-GeV DM direct detection

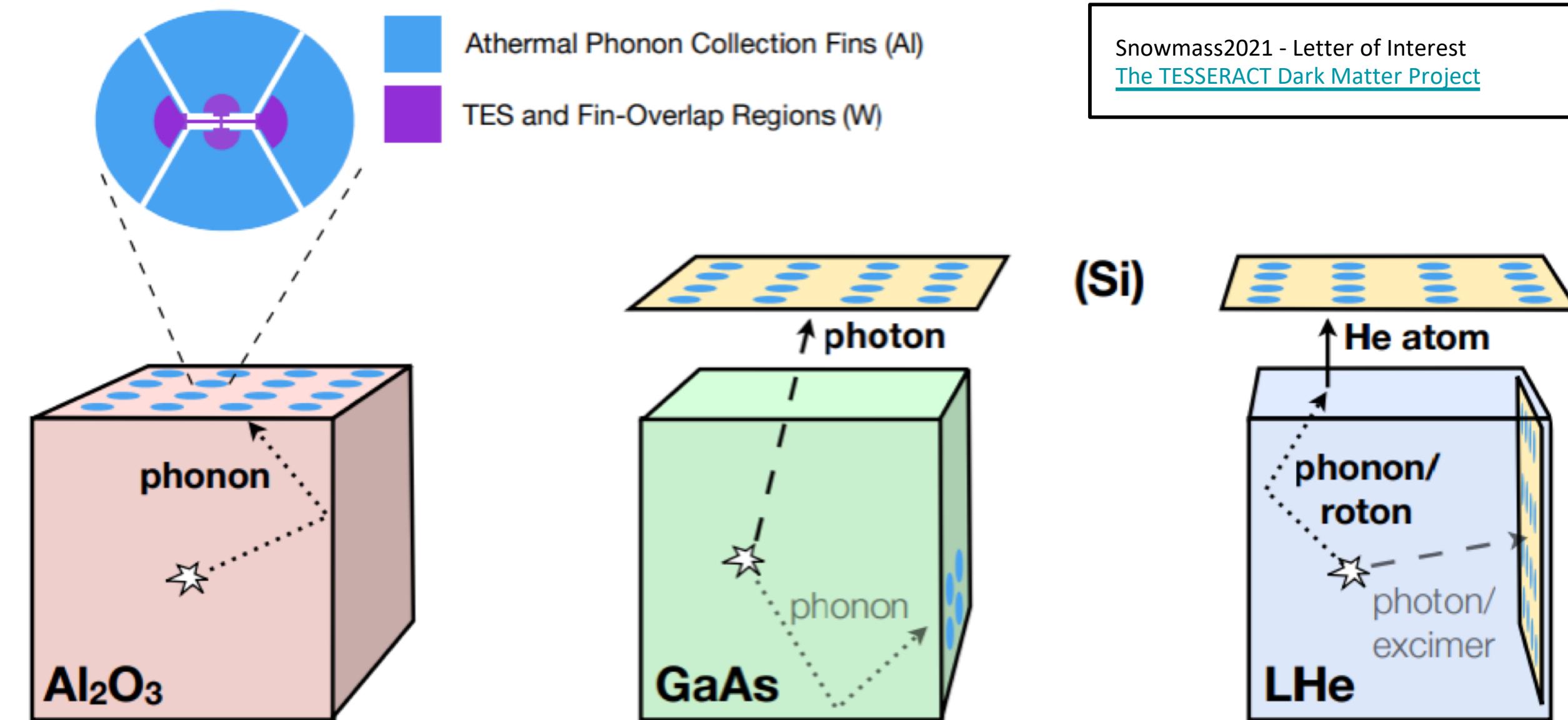
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sub-GeV DM direct detection

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TESSERACT project (part of the DMNI suite of DOE-supported efforts)

- Managed by LBNL
- Funding for R&D and project development began in June 2020.
- One experimental design, and different target materials with complementary DM sensitivity. Zero E-field.
- All using TES readout
- ~40 people from 8 institutes
- Includes SPICE (polar crystals) and HeRALD (superfluid helium). These are historical names, now shorthand for the targets.



Berkeley
UNIVERSITY OF CALIFORNIA



Caltech



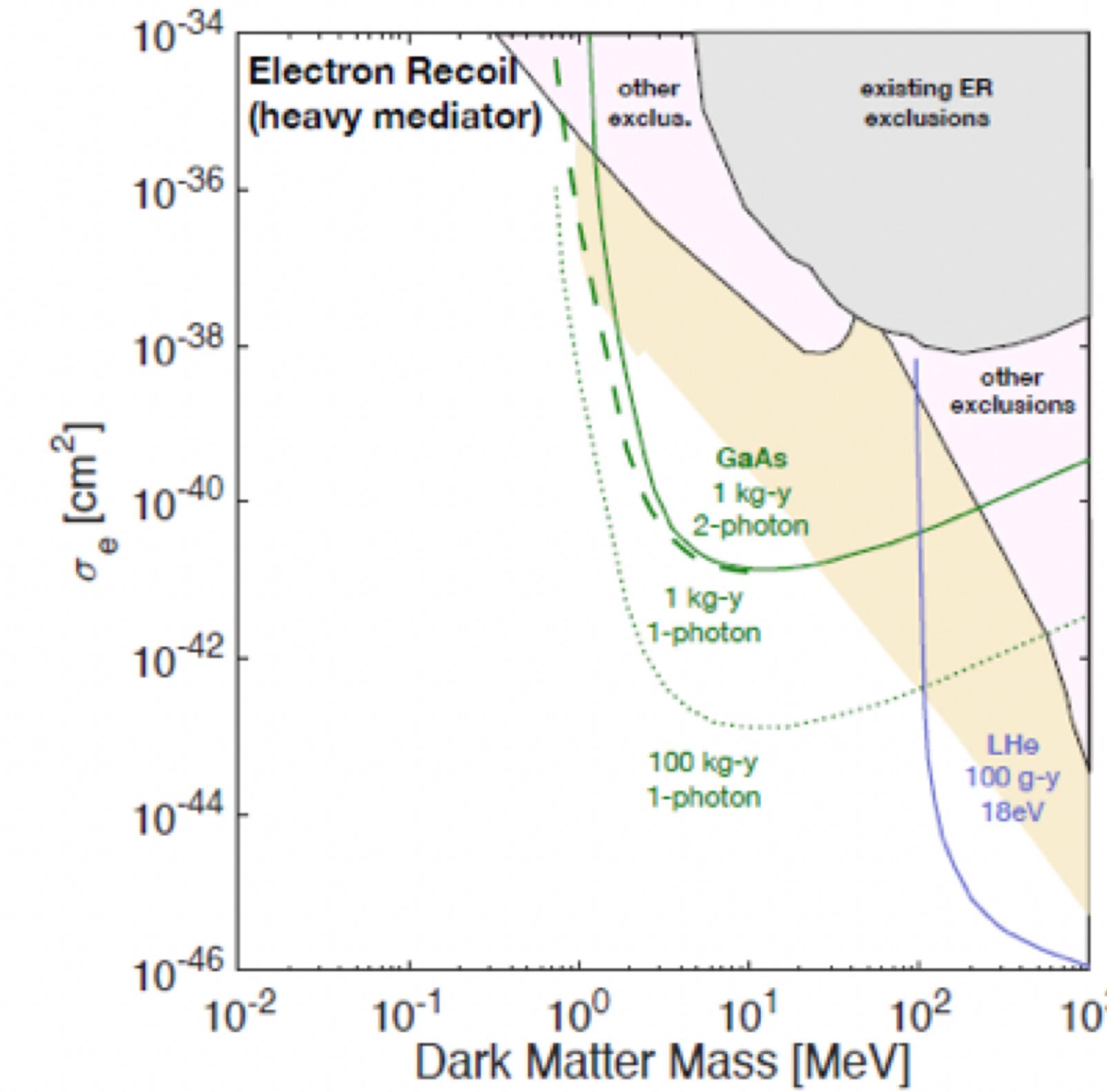
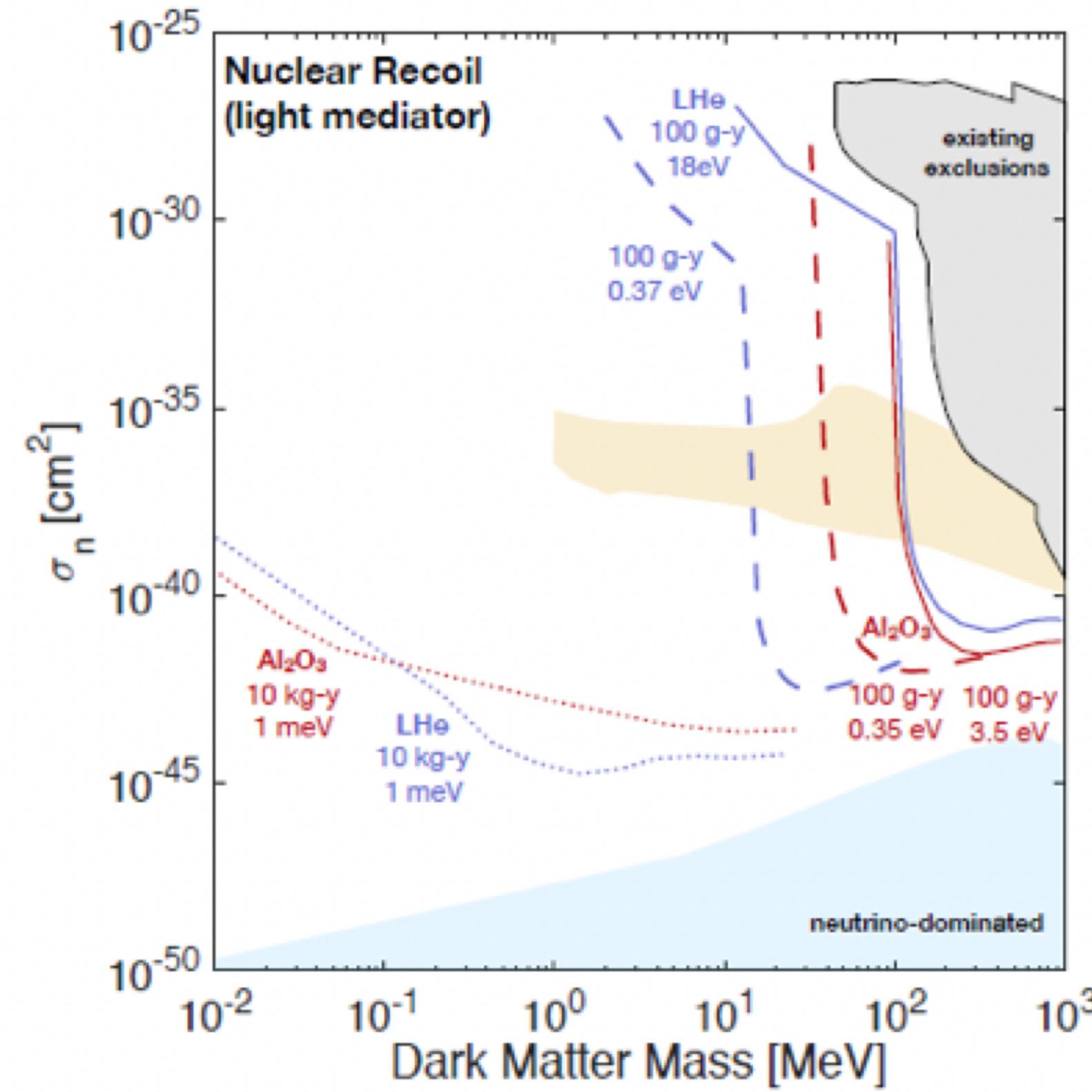
FLORIDA STATE



UMass
Amherst

SPICE and HeRALD - projected sensitivity

Snowmass2021 - Letter of Interest
[The TESSERACT Dark Matter Project](#)



11

theoretical work

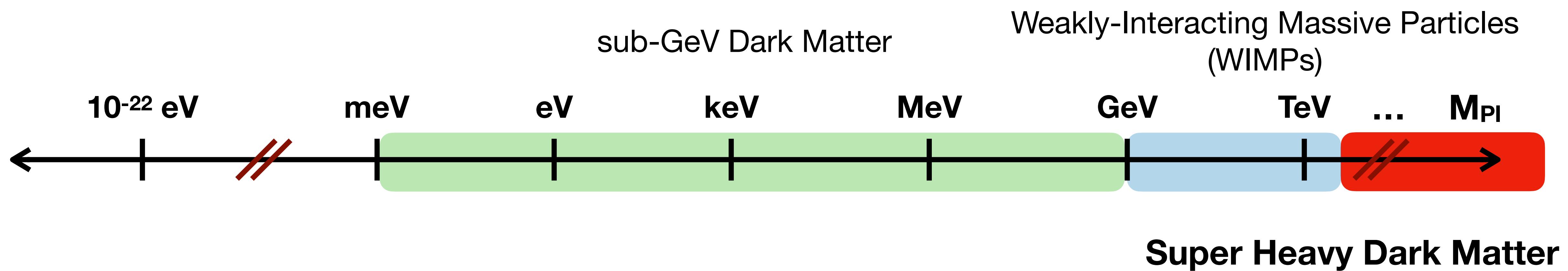
- formulation of DM-electron scattering rates using dielectric function
 - accounts for in-medium screening effects
 - data-driven form-factors

Knapen, Kozaczuk, Lin *Phys. Rev. D* 104, 015031 (2021)

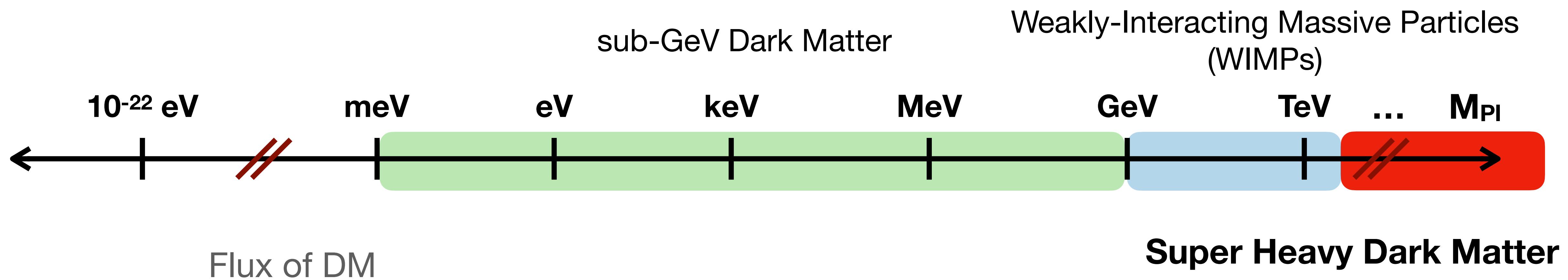
Hochberg, Kahn, Kurinsky, Lehmann, Yu, Berggren *Phys.Rev.Lett.* 127 (2021) 15, 151802

- Using semi-analytic approximations to include higher momentum components and energy states Griffin, Inzani, Trickle, Zhang, Zurek [arXiv:2105.05253]
- Analytic formalism for single-phonon to multi-phonon processes to nuclear recoil Campbell-Deem, Knapen, Lin, Villarama [arXiv:2205.02250]

Dark Matter Candidates

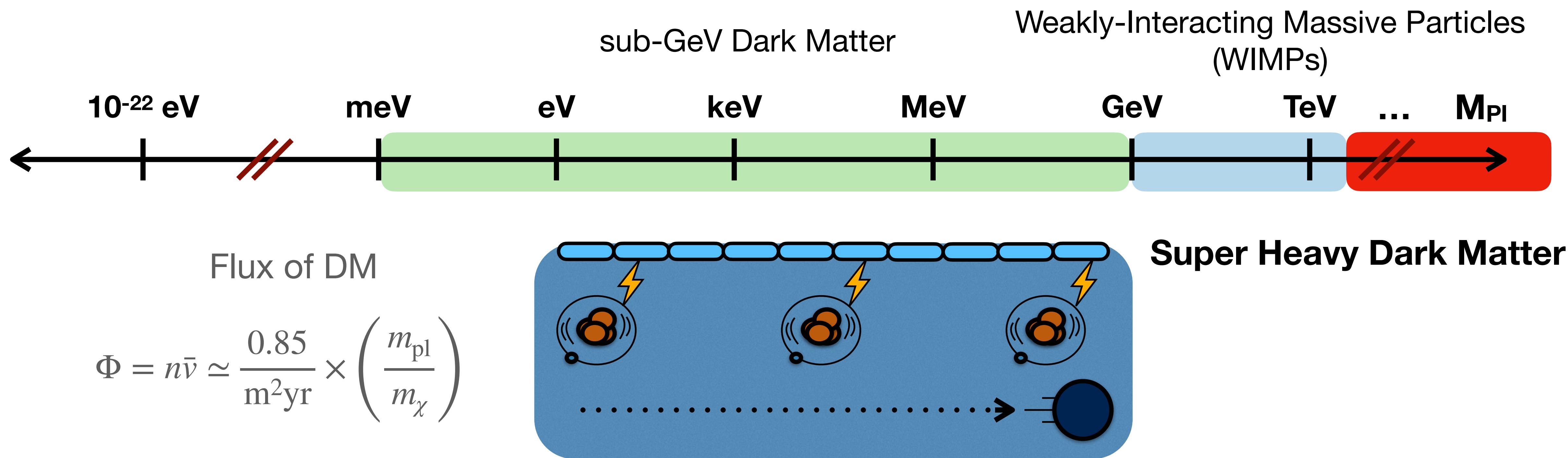


Dark Matter Candidates



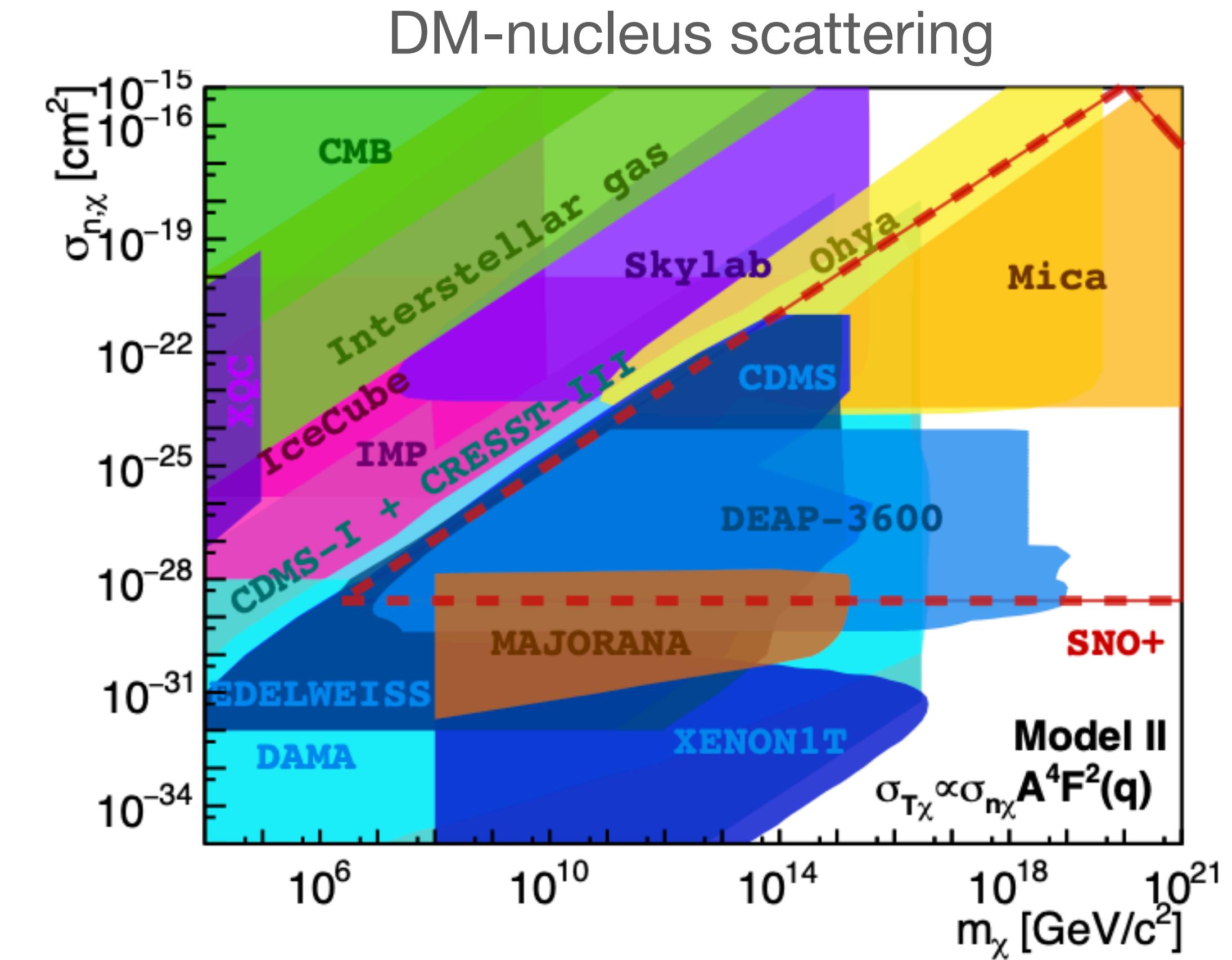
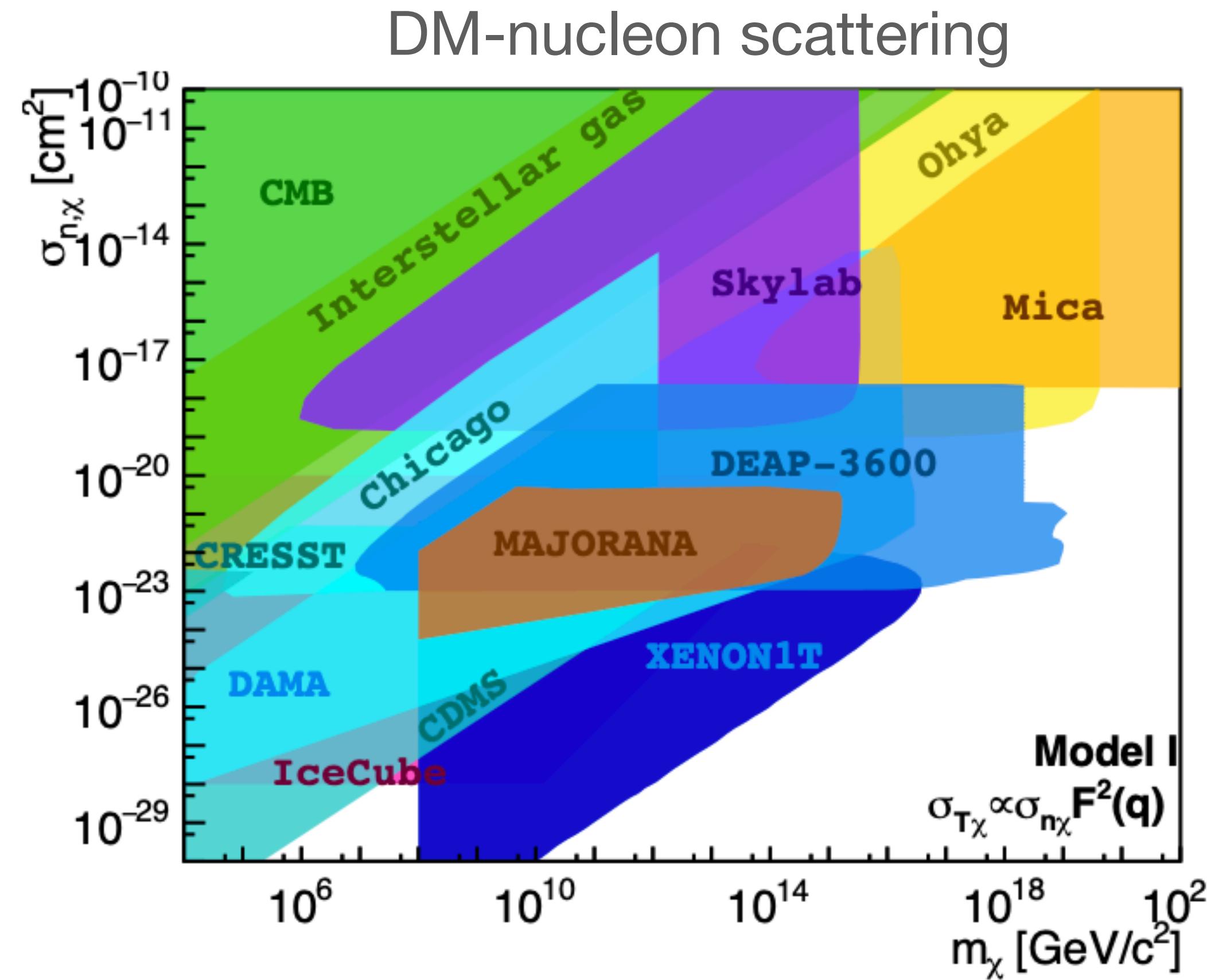
$$\Phi = n\bar{v} \simeq \frac{0.85}{\text{m}^2\text{yr}} \times \left(\frac{m_{\text{pl}}}{m_\chi} \right)$$

Dark Matter Candidates



Super-Heavy Dark Matter

[arXiv:2209.07426]



many of the **same** DM experiments!

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