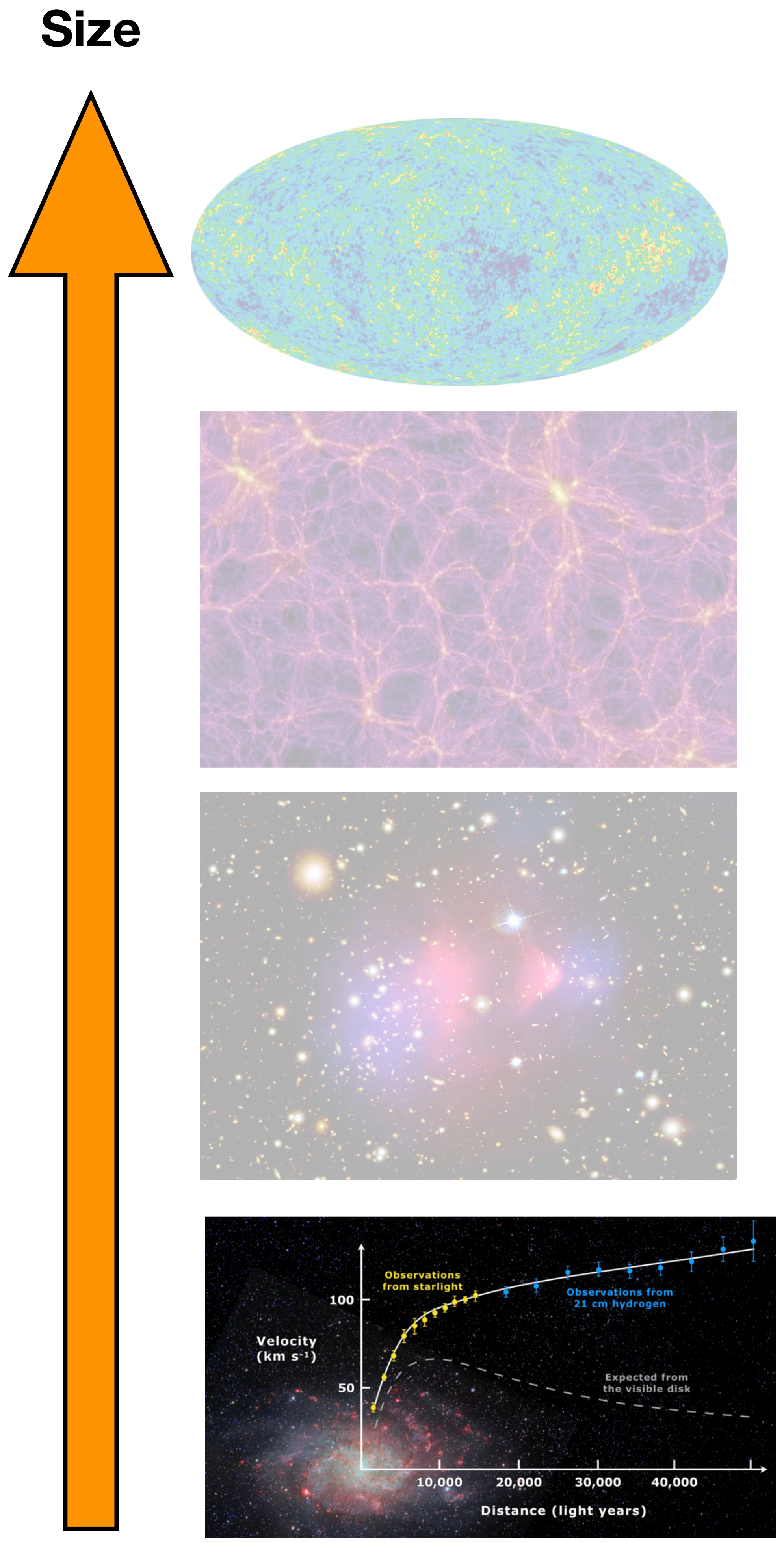
Dark Matter Direct Detection

Tien-Tien Yu (University of Oregon)

Conference on Science at the Sanford Underground Research Facility
(CoSSURF)
May 13, 2022

Why Dark Matter?

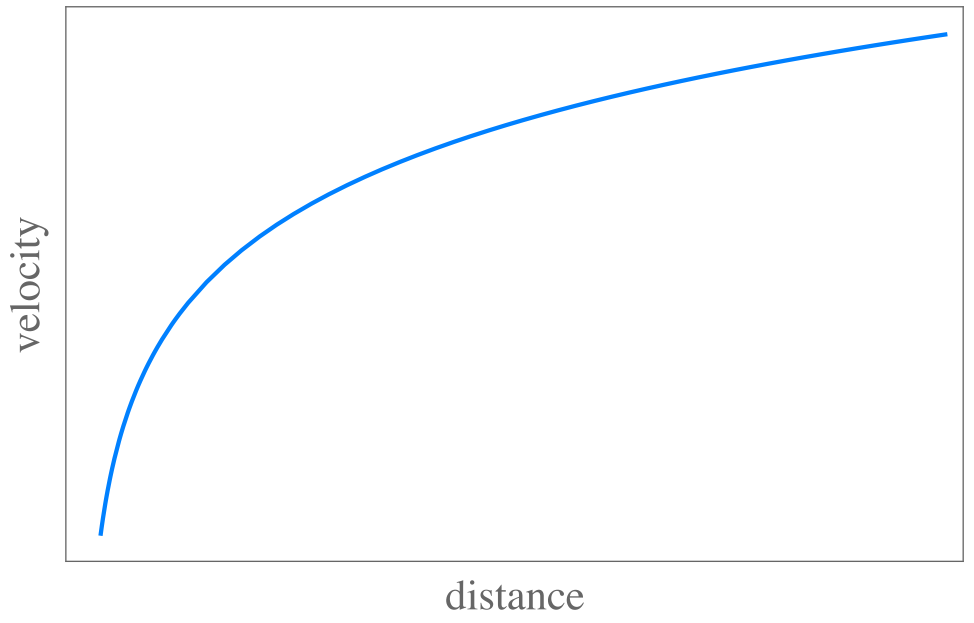


Galactic Rotation Curves

$$\frac{mv^2}{r} = \frac{GM(r)m}{r^2} \implies v = \sqrt{M(r)/r}$$ Newton's 2nd Law

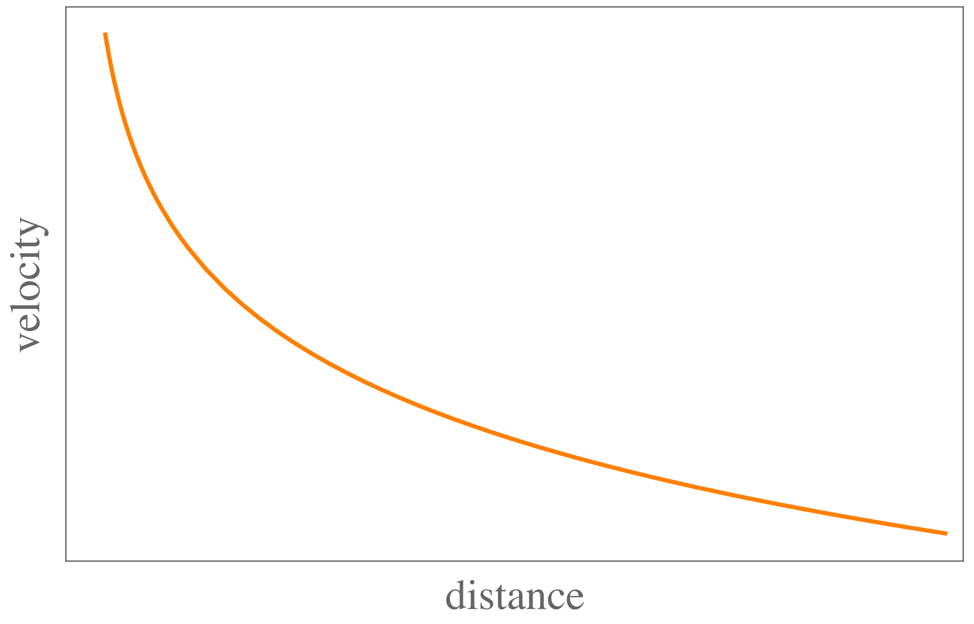
Inside galaxy:

$$M(R) = \frac{4}{3}\pi R^3 \rho \implies v \propto R$$



Far-away from galaxy:

$$M(R) = \text{constant} \implies v \propto 1/\sqrt{R}$$



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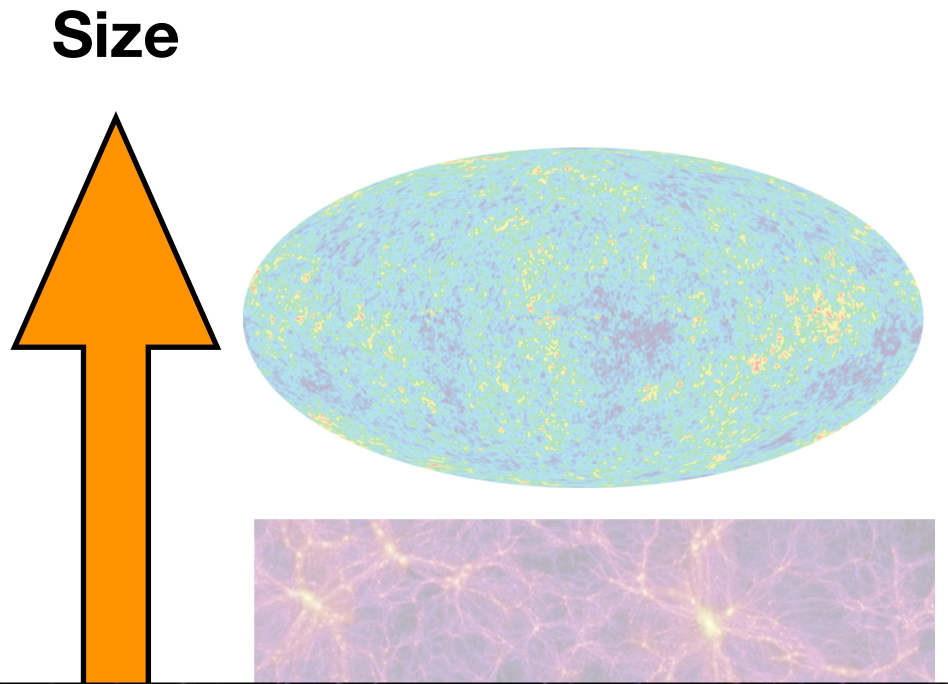

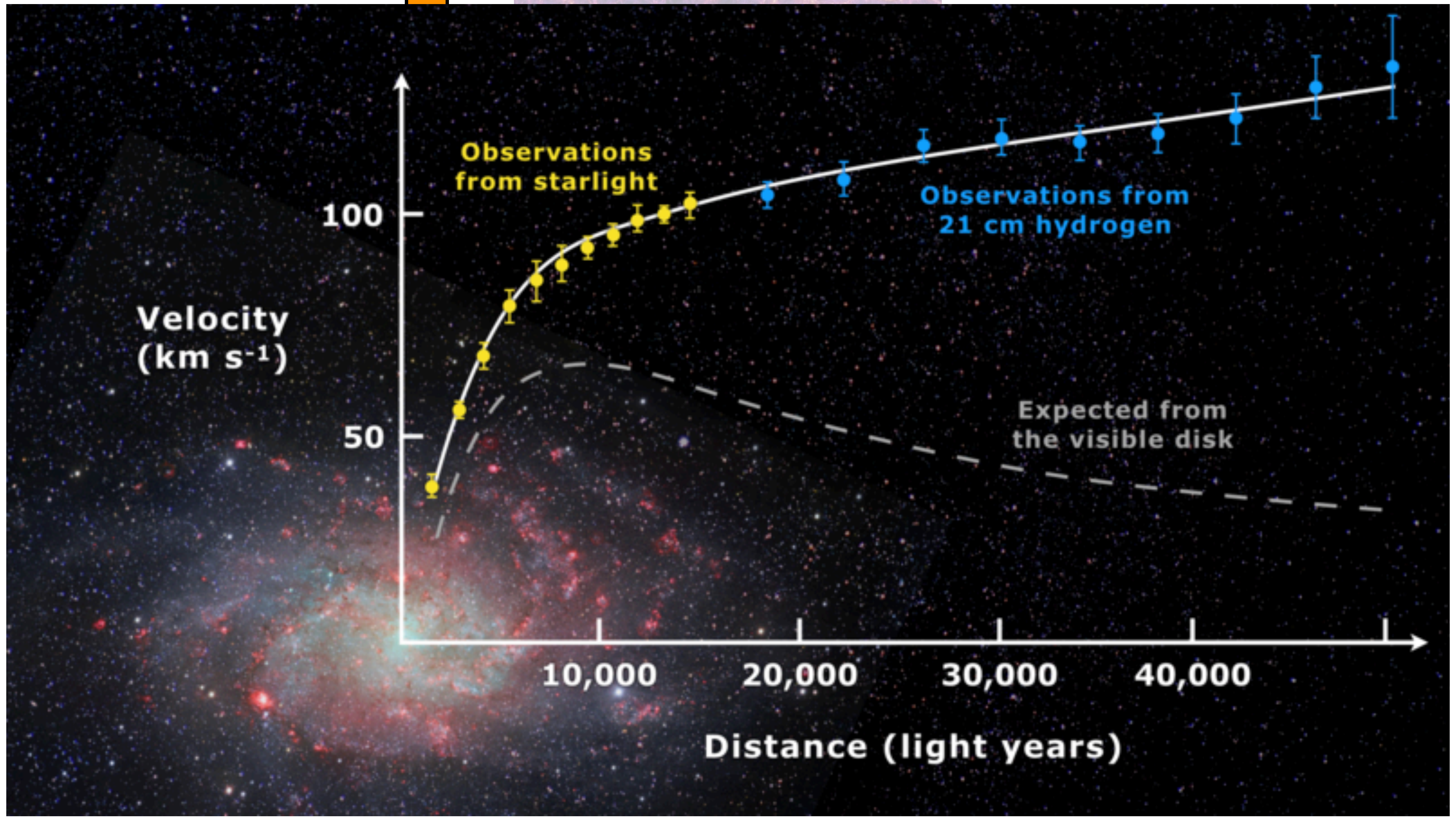

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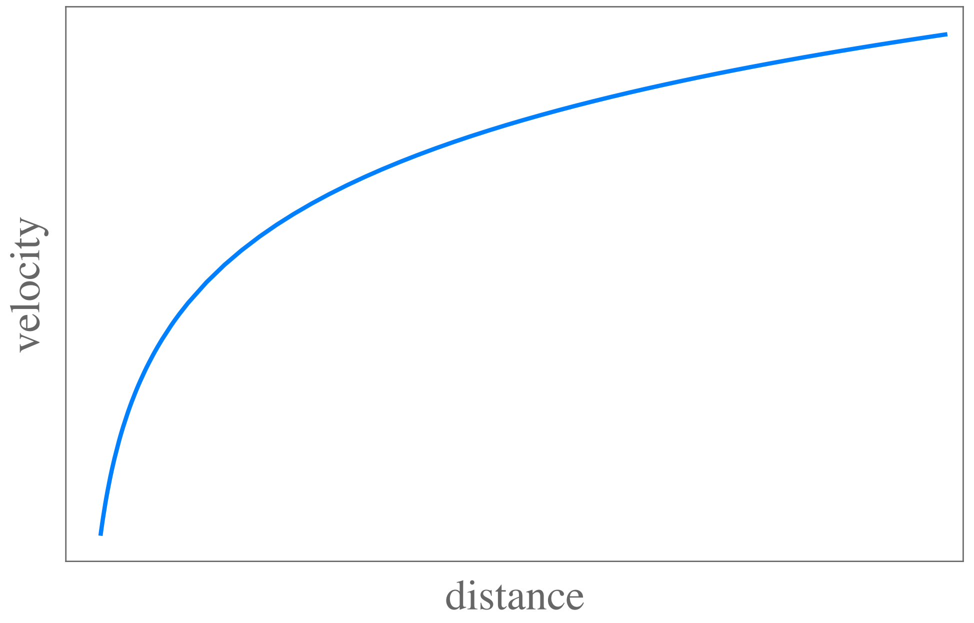

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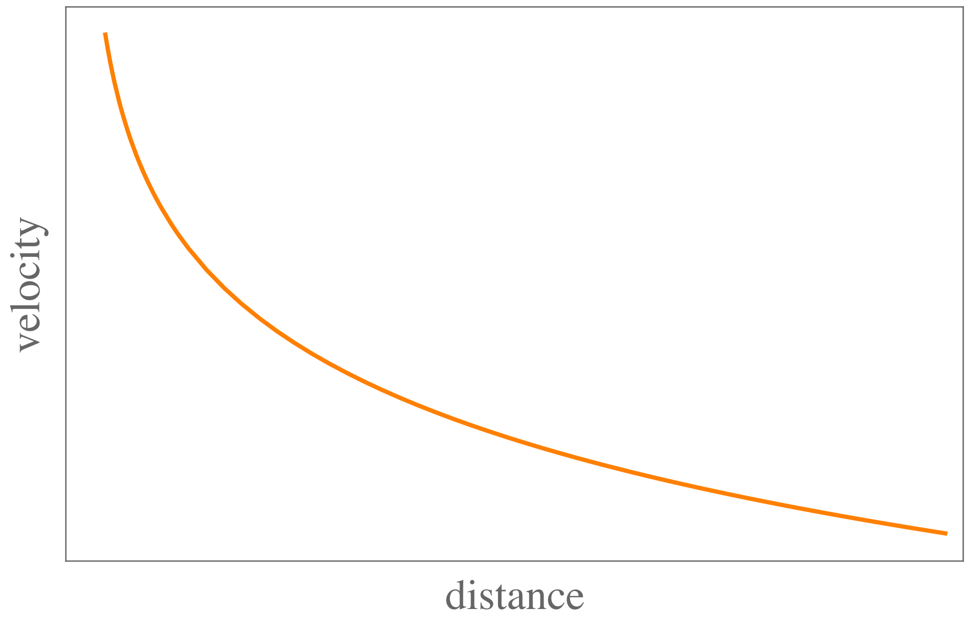

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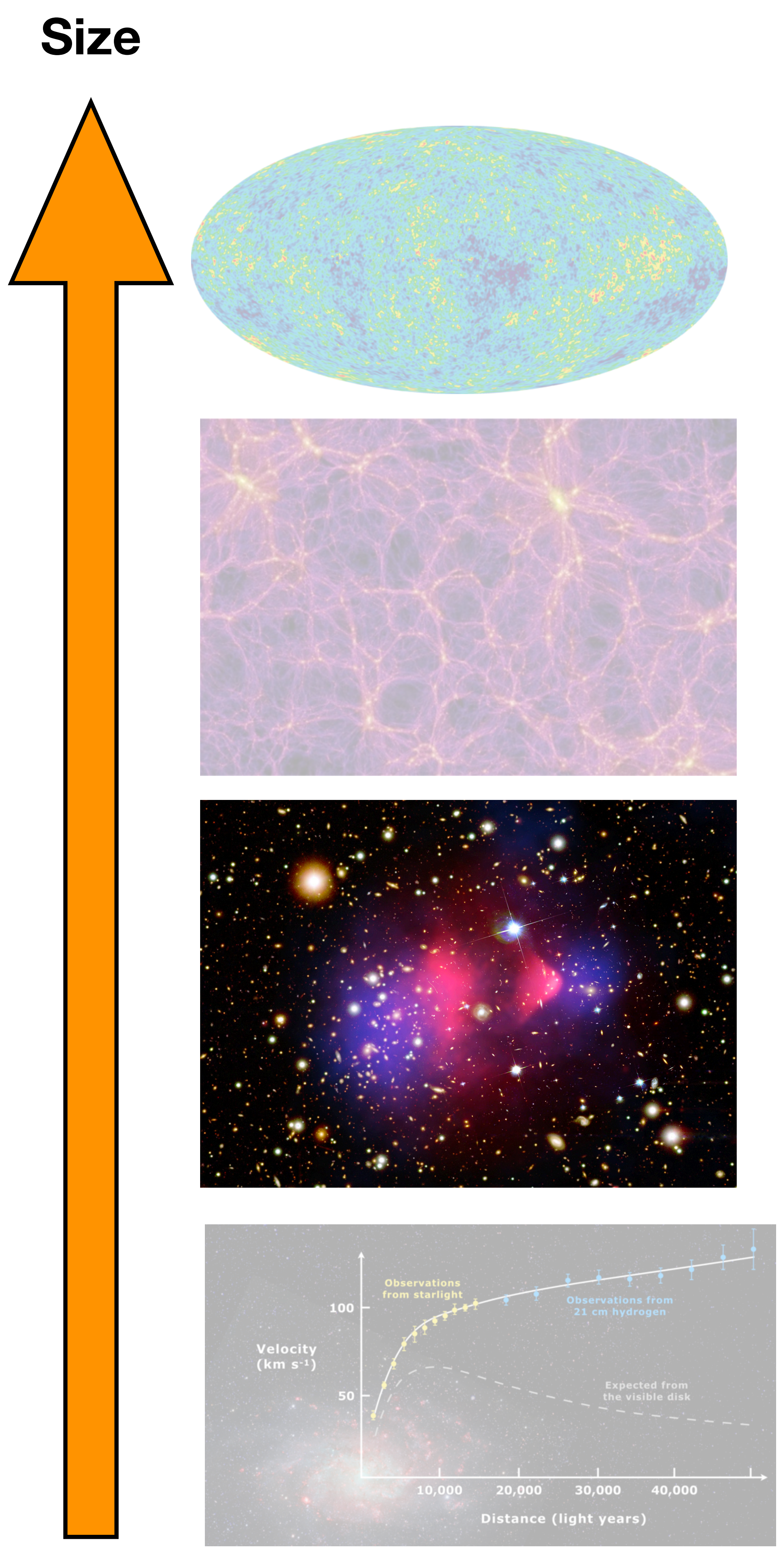
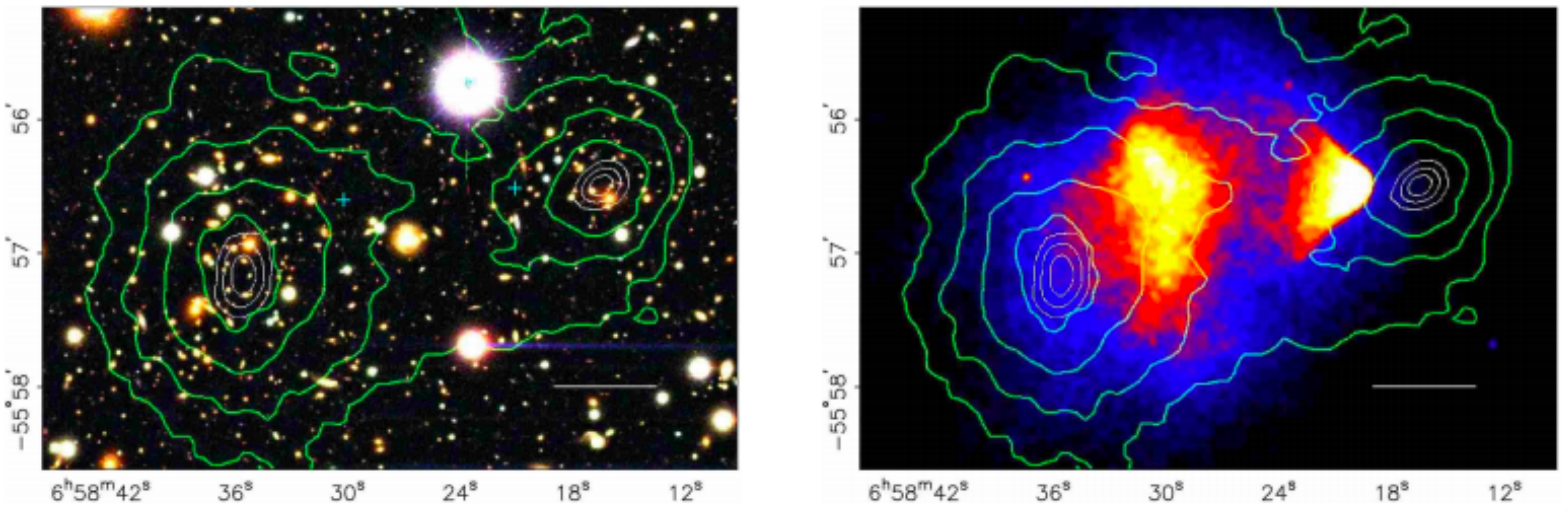
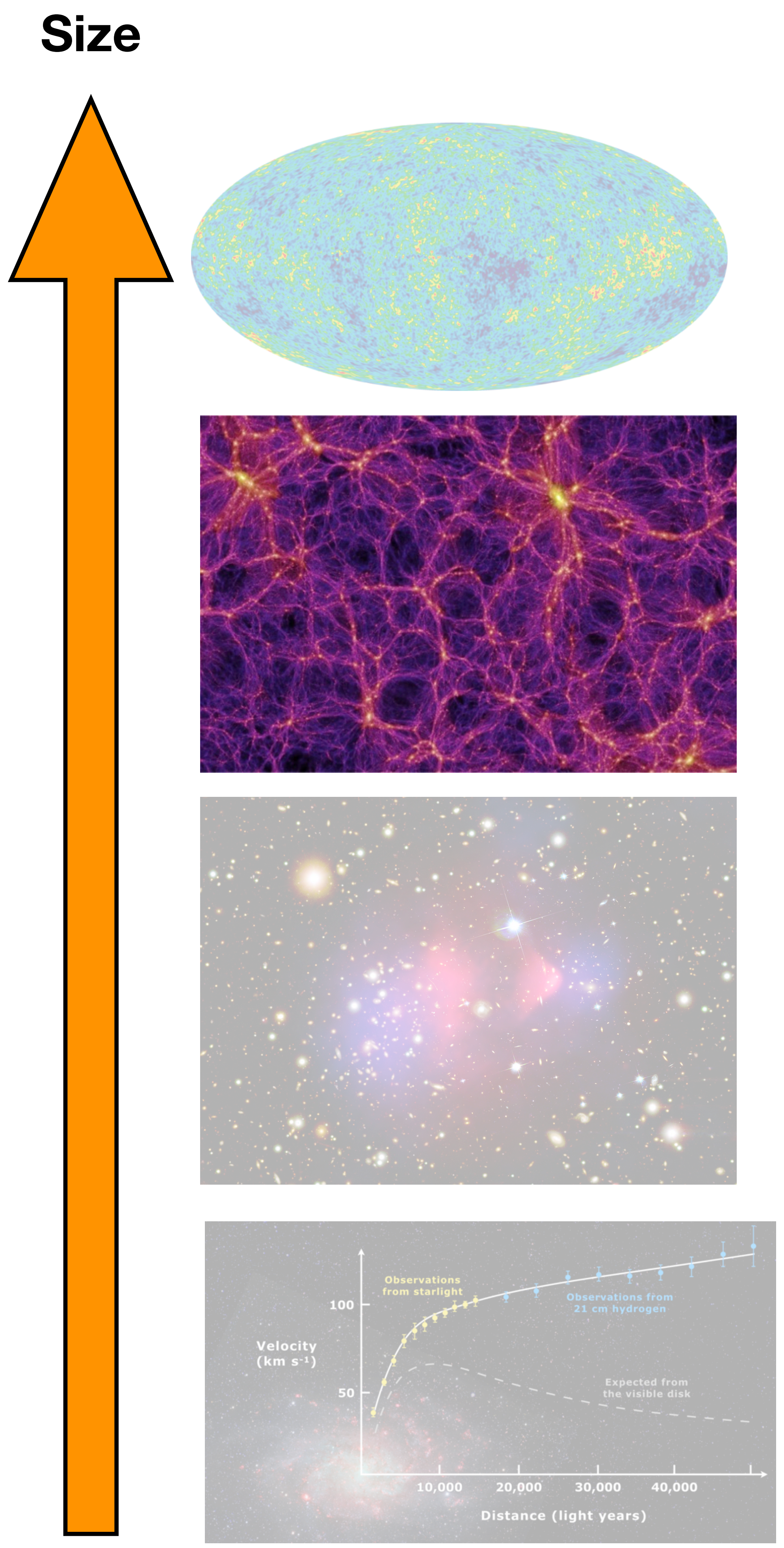


Bullet Cluster

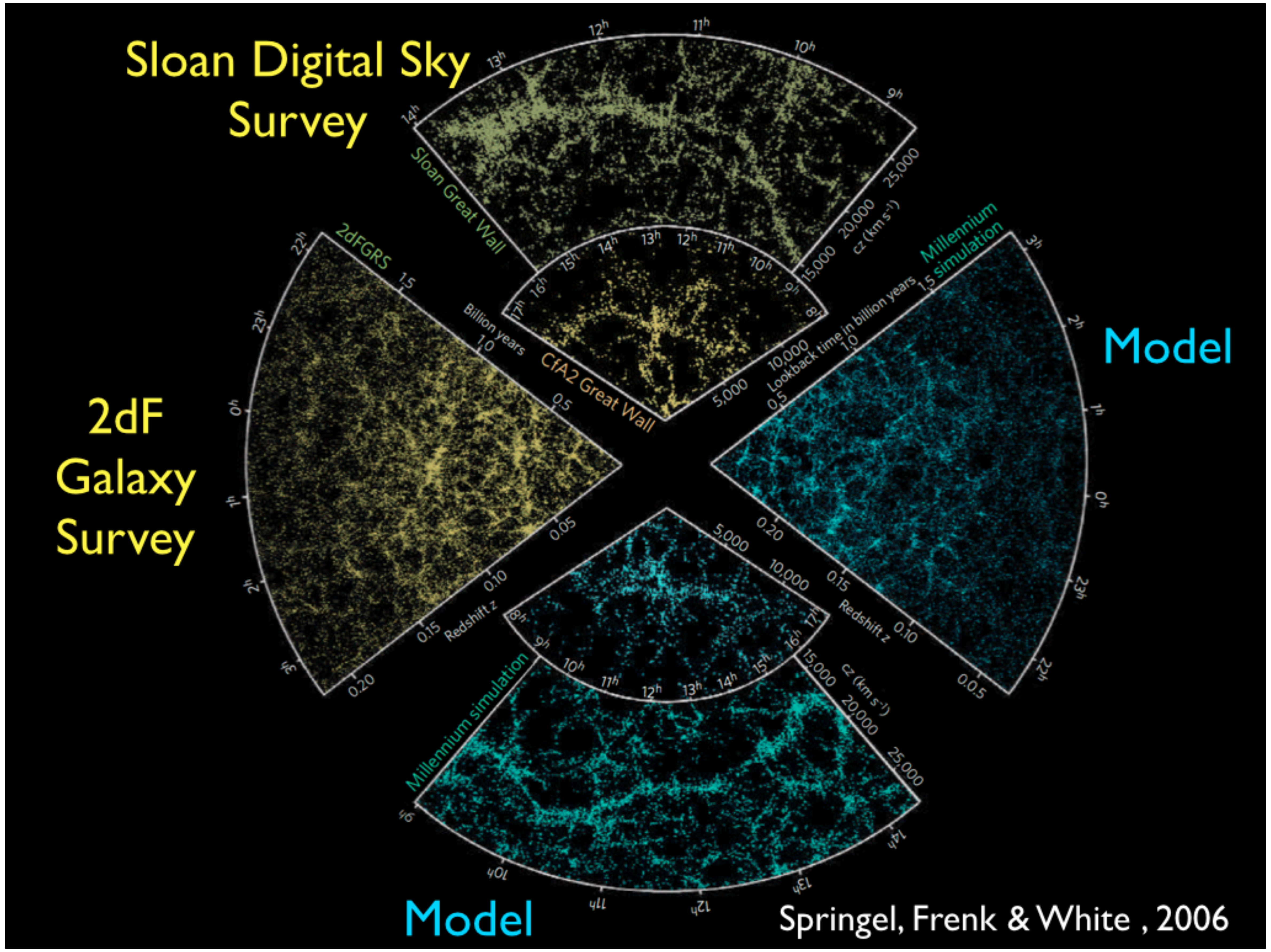


X-ray: NASA/CXC/CfA/M.Markevitch et al.;
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

Why Dark Matter?

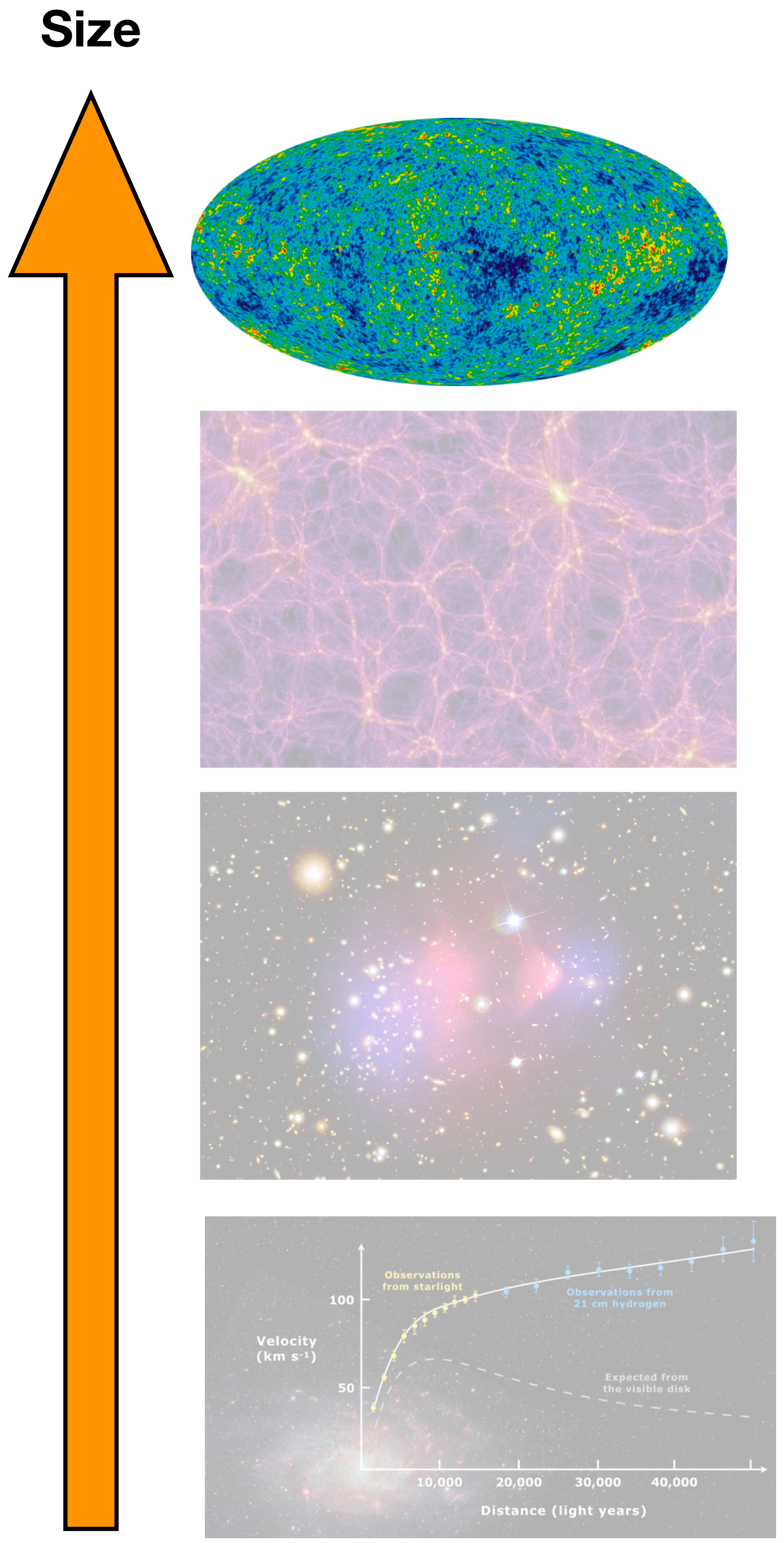


Large Scale Structure

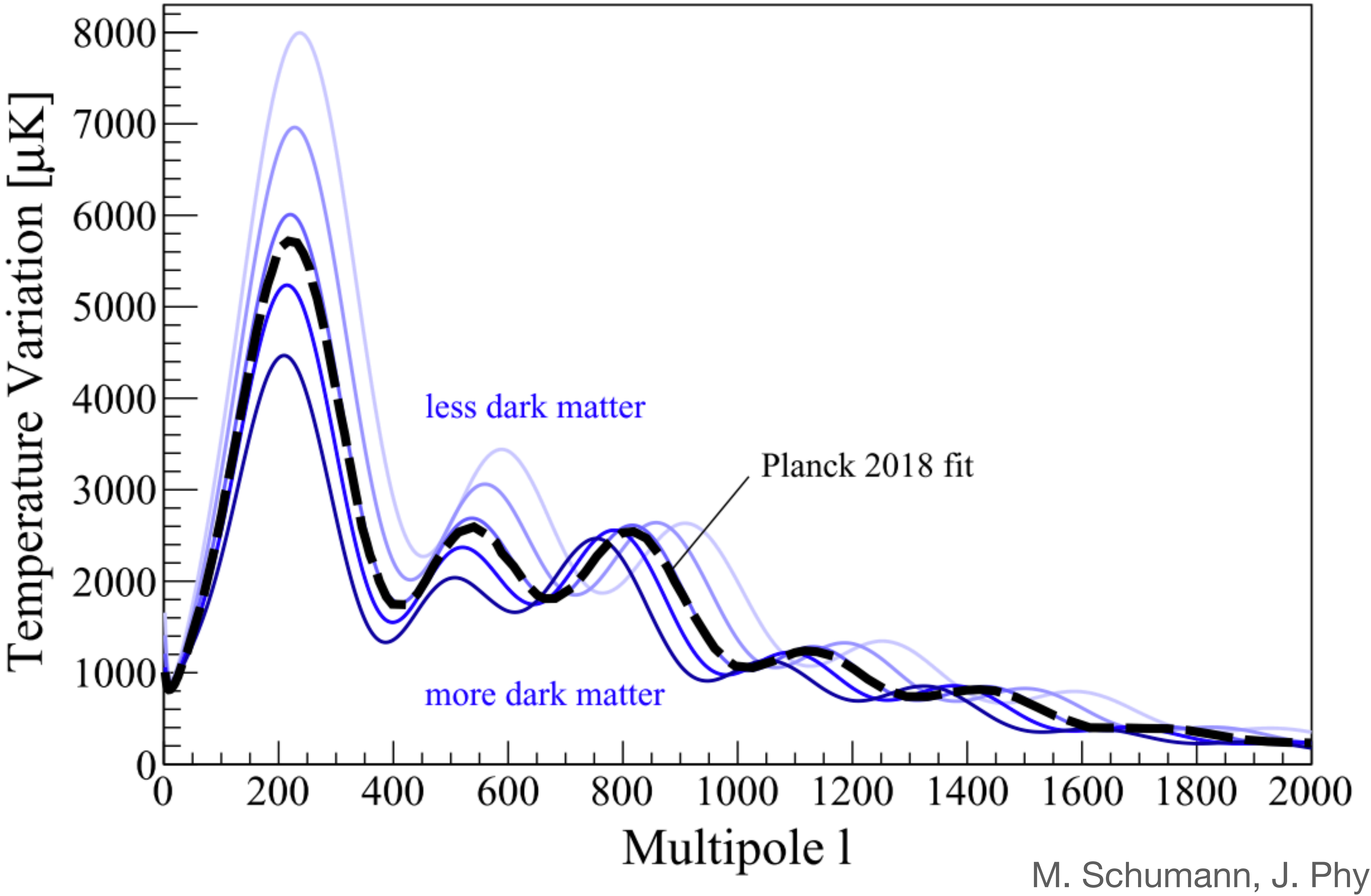


Springel, Frenk & White , 2006

Why Dark Matter?

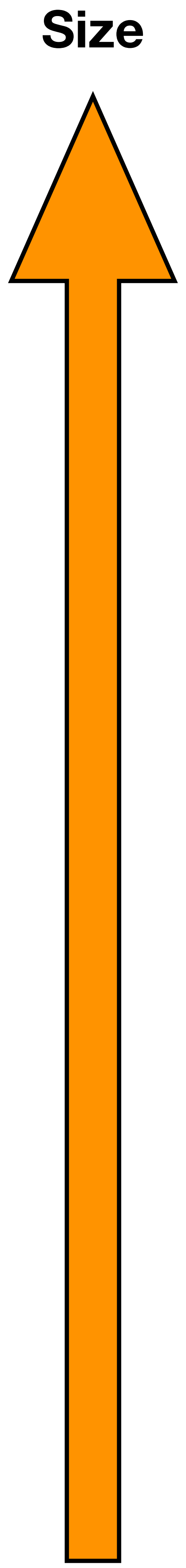


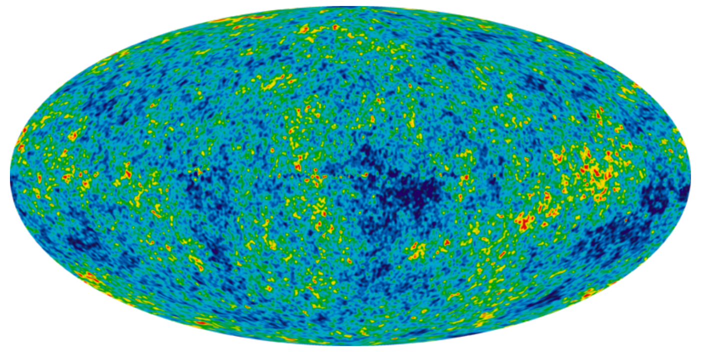
Cosmic Microwave Background



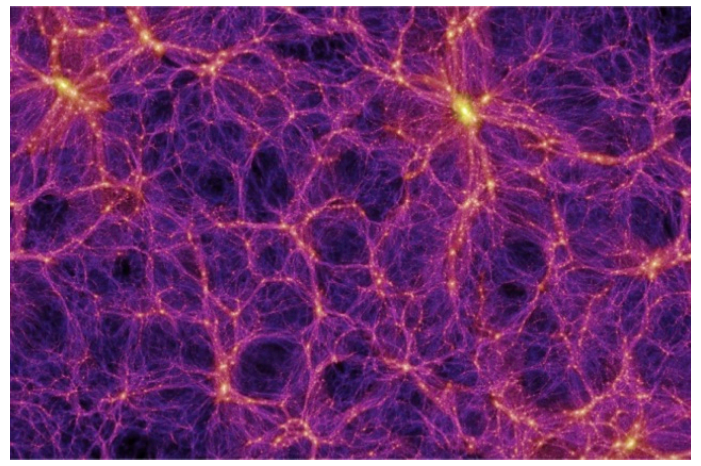
M. Schumann, J. Phys. G46 (2019) no.10, 103003
[arXiv:1903.03026]

Why Dark Matter?



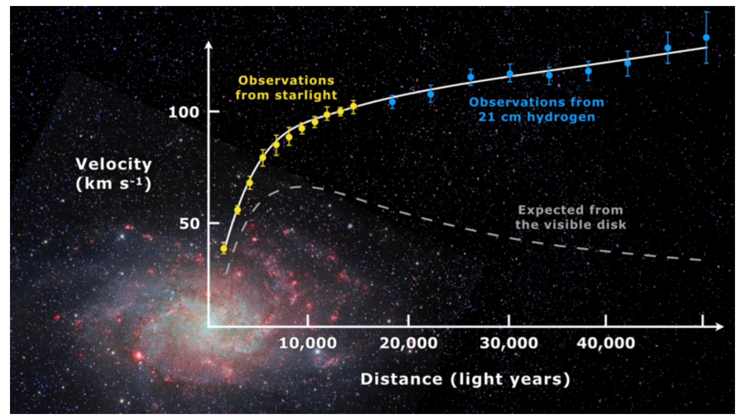


COSMIC MICROWAVE BACKGROUND



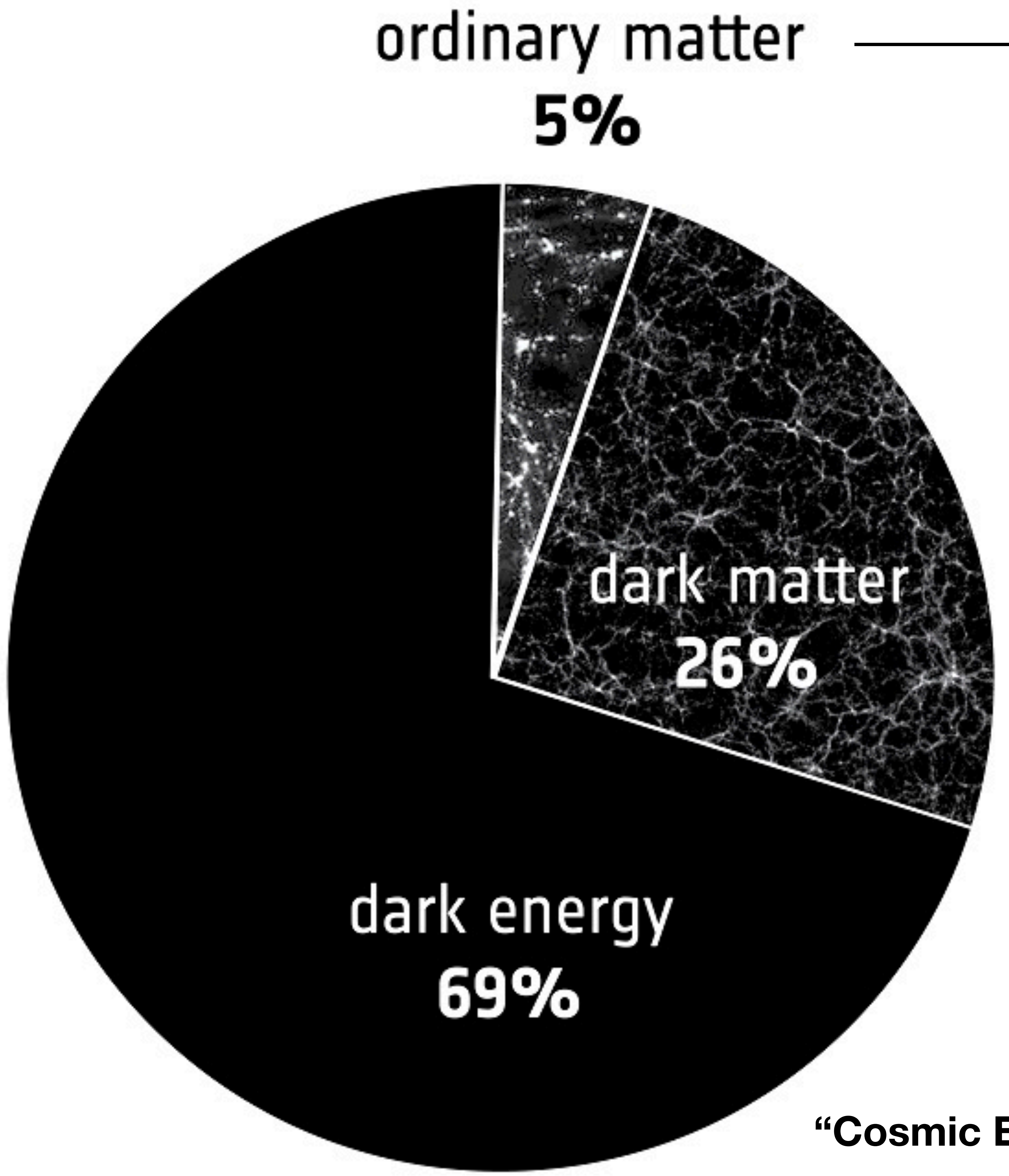
LARGE SCALE STRUCTURE

GALAXY MERGERS

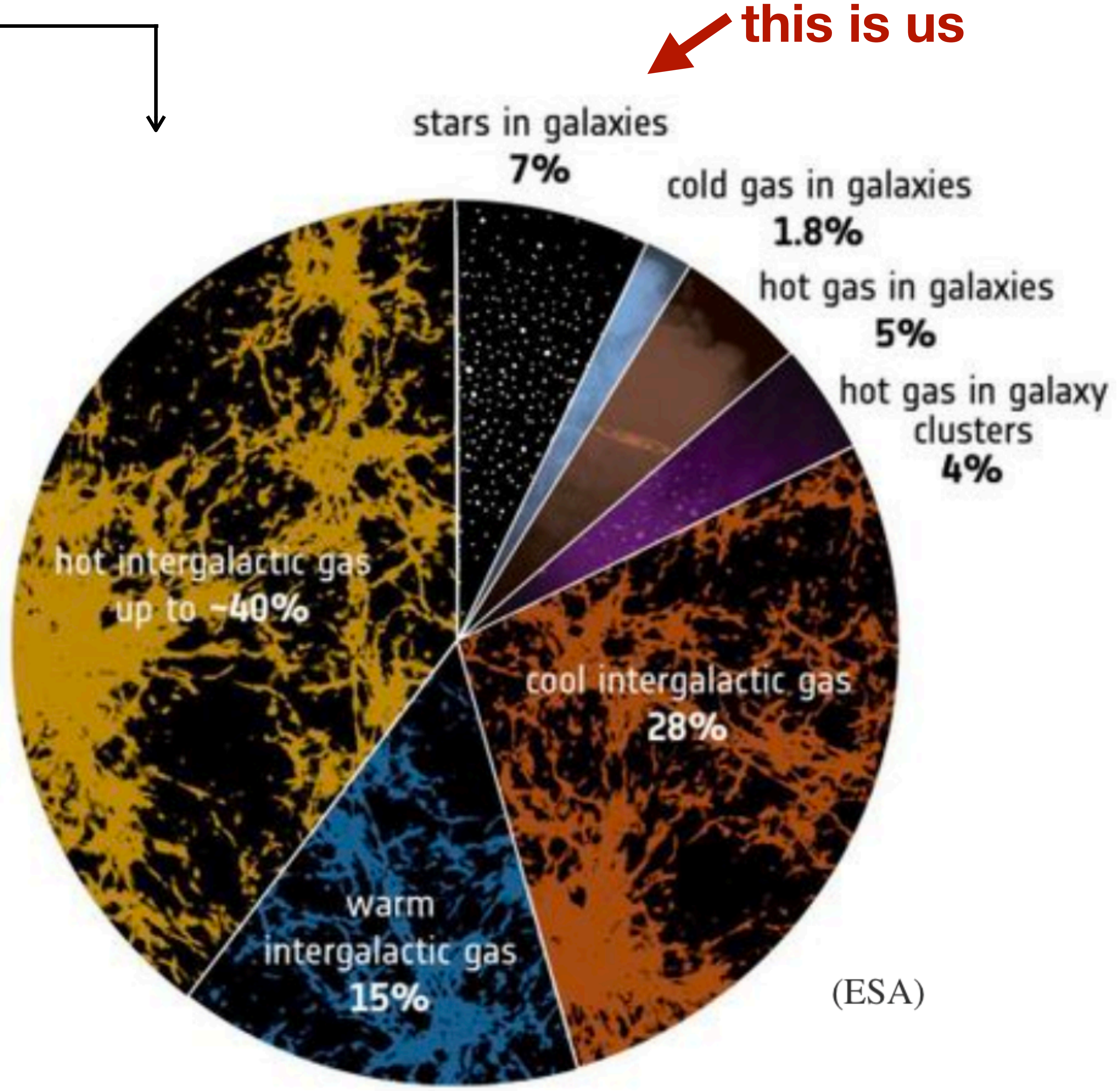


GALACTIC ROTATION CURVES

Why Dark Matter?

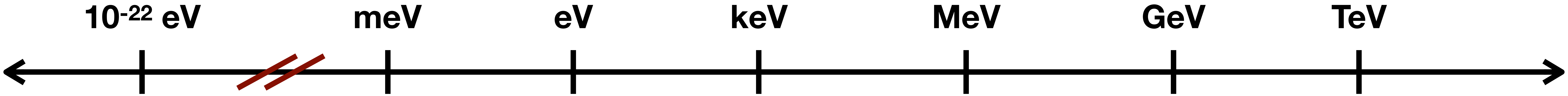


"Cosmic Energy Budget"

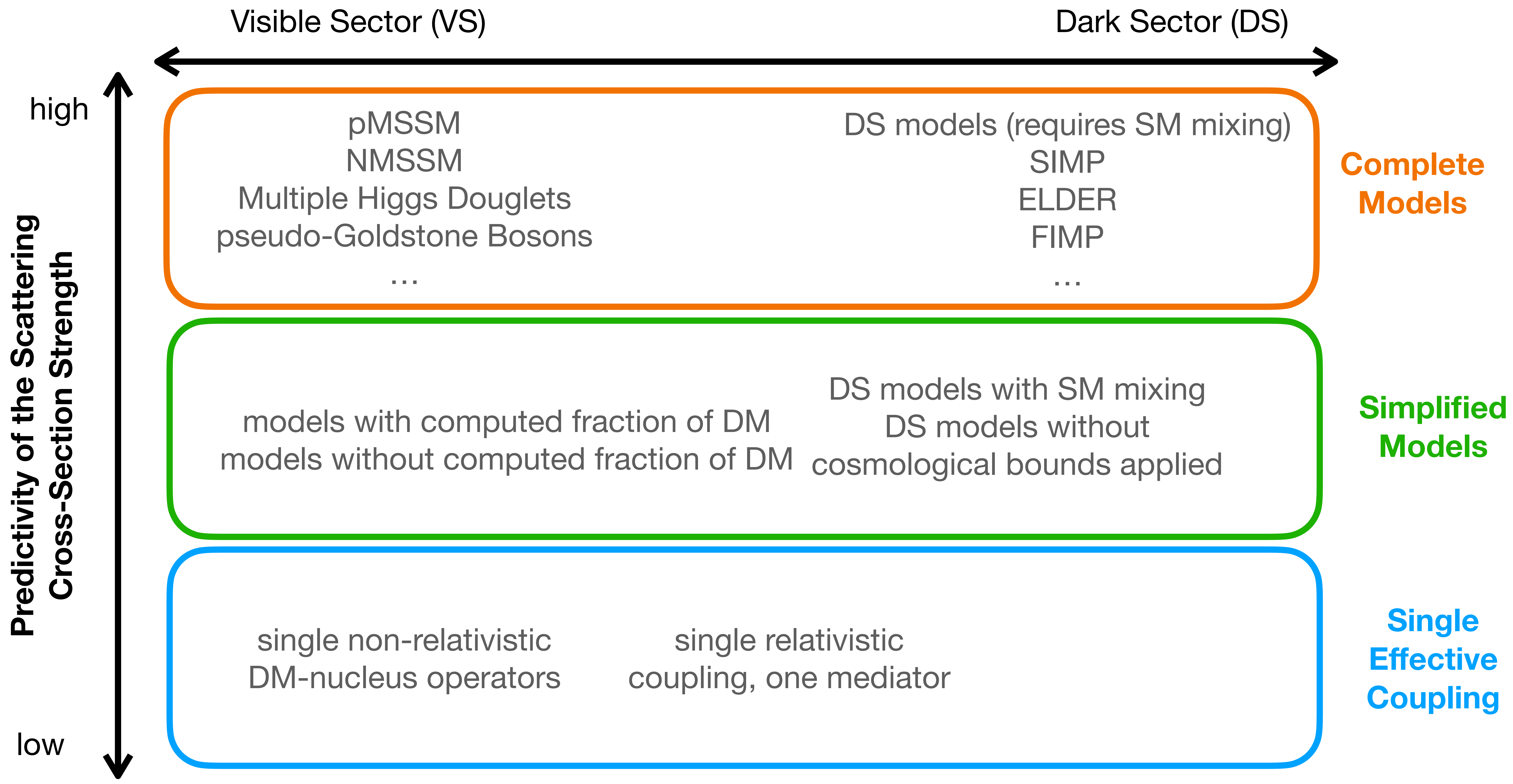


(ESA)

Dark Matter Candidates



Dark Matter Models



Visible Sector (VS)

Dark Sector (DS)

high

low

Predictivity of the Scattering Cross-Section Strength

pMSSM
NMSSM
Multiple Higgs Douglets
pseudo-Goldstone Bosons
…

DS models (requires SM mixing)
SIMP
ELDER
FIMP
…

Complete Models

models with computed fraction of DM
models without computed fraction of DM

DS models with SM mixing
DS models without cosmological bounds applied

Simplified Models

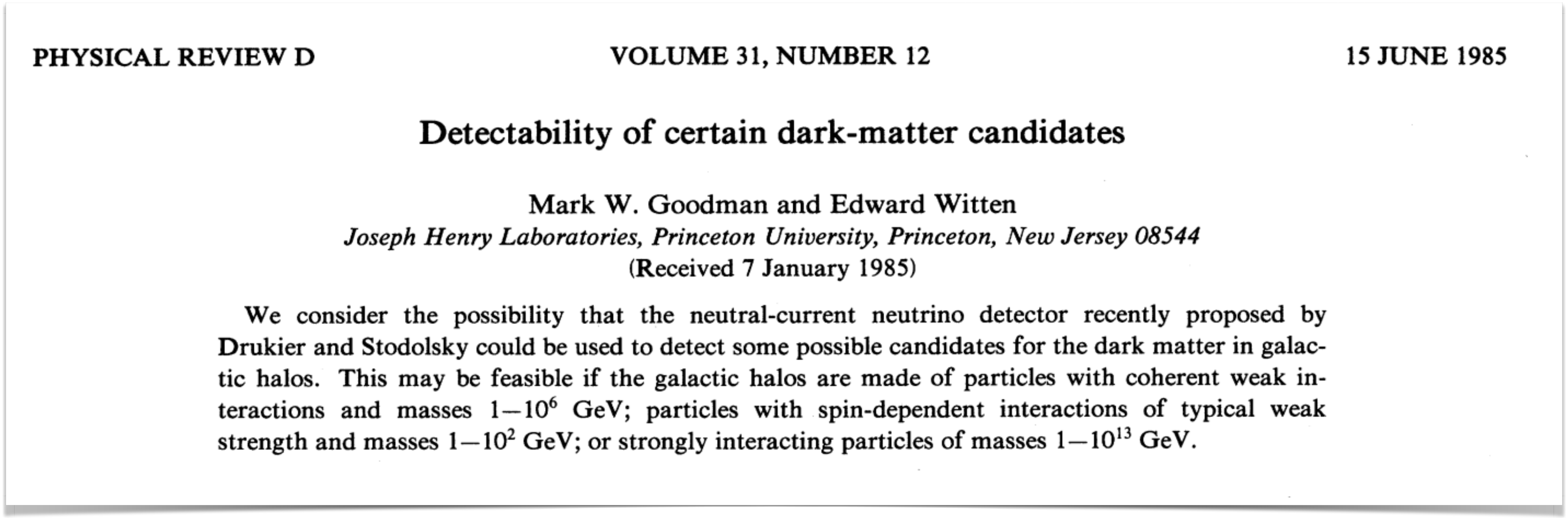
single non-relativistic DM-nucleus operators

single relativistic coupling, one mediator

Single Effective Coupling

Dark Matter Direct Detection

Goodman, Witten (1985)



PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

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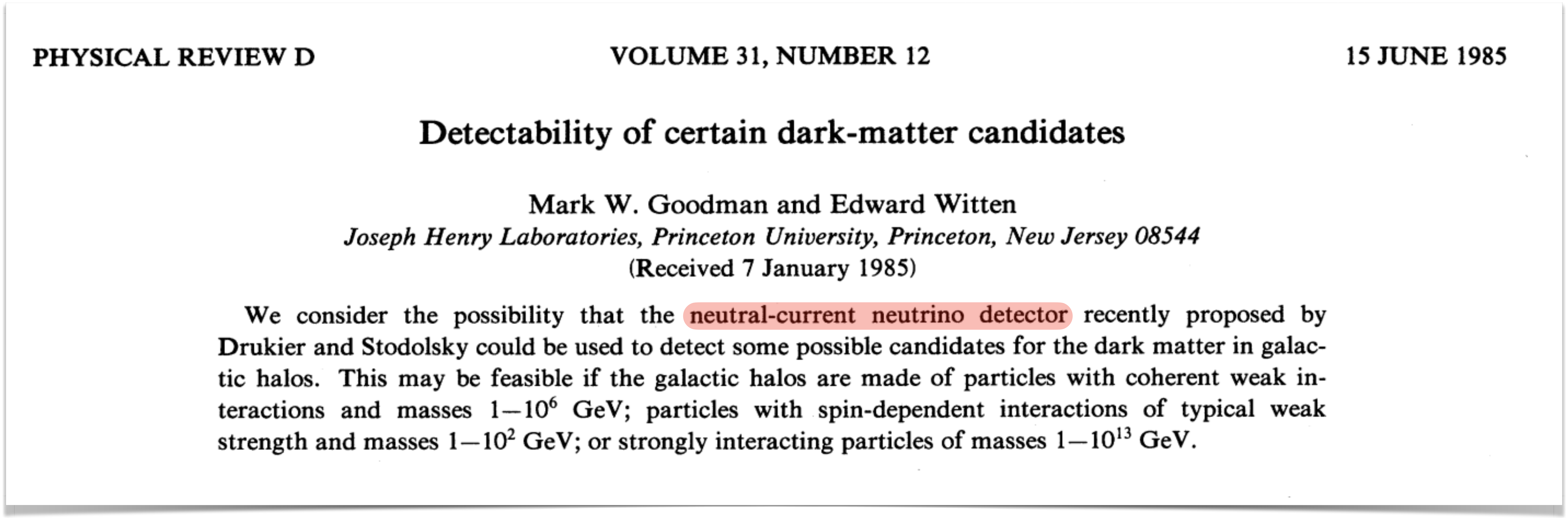

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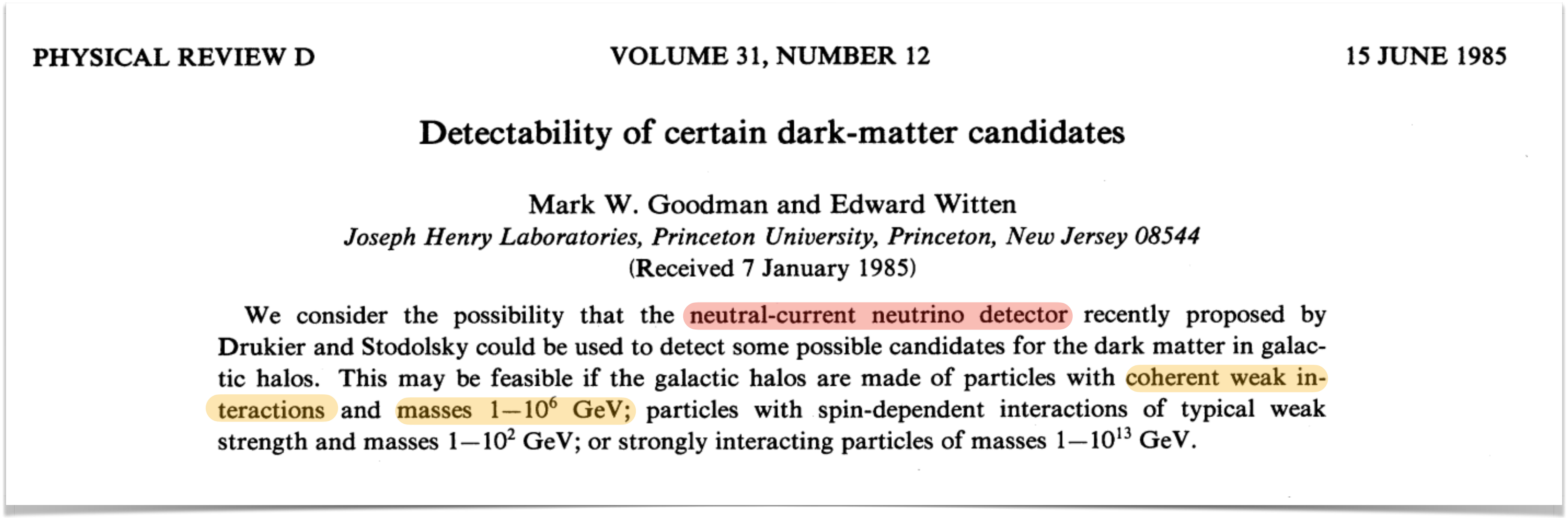

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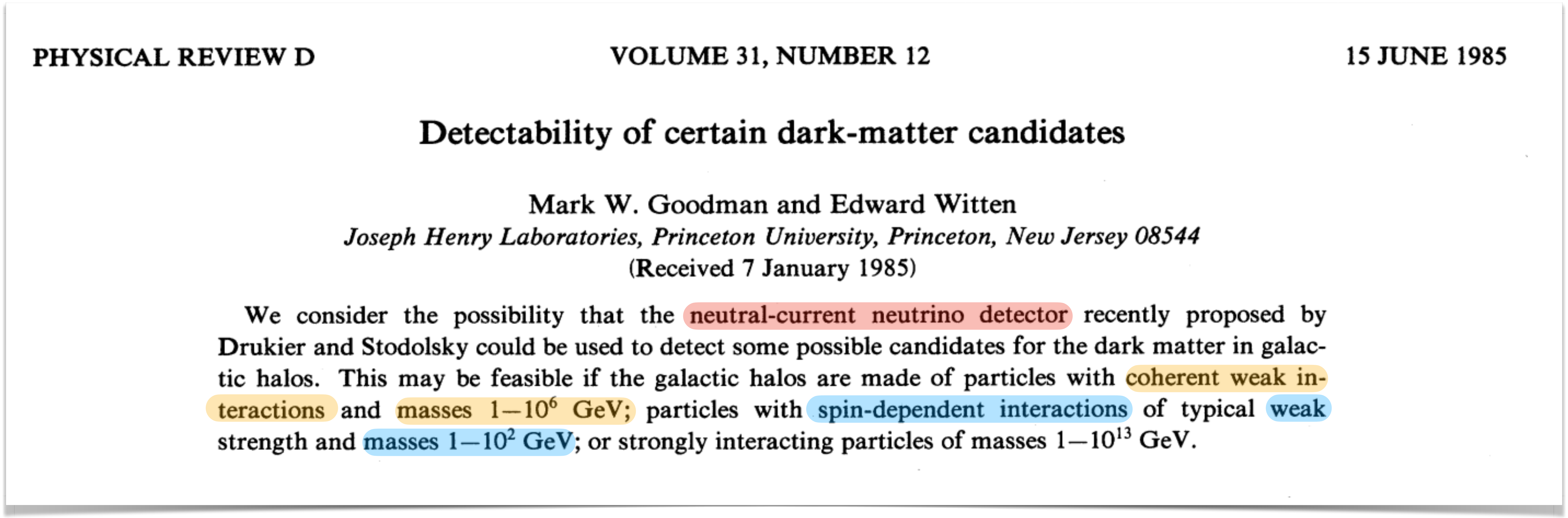

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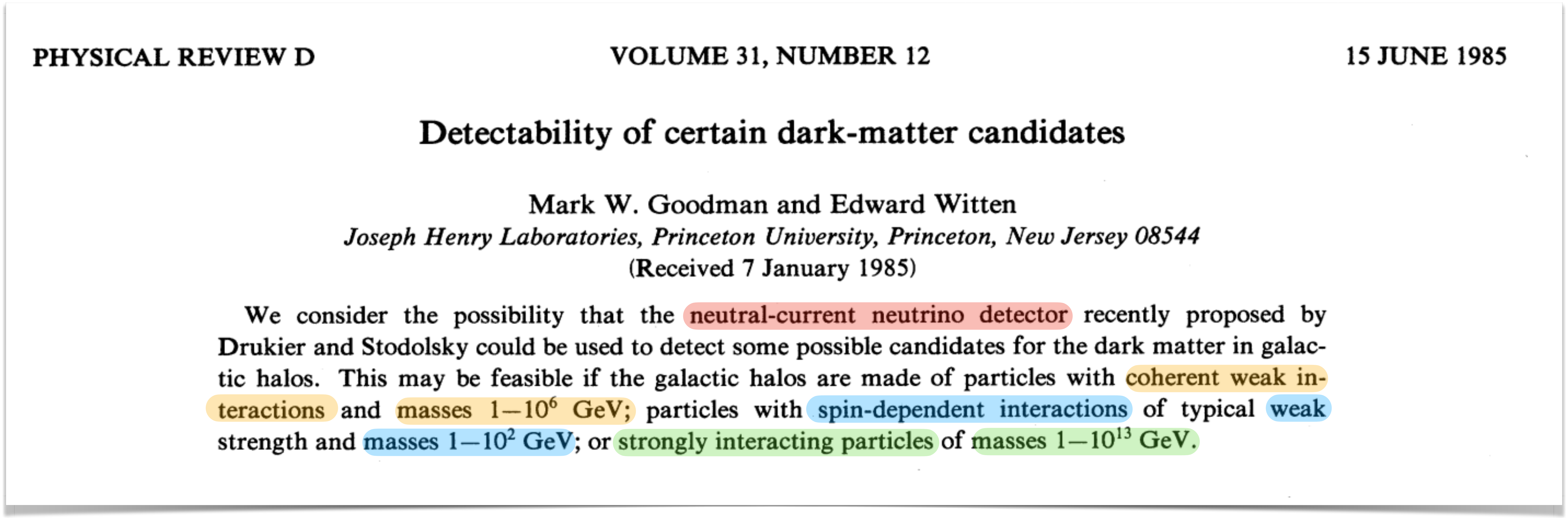

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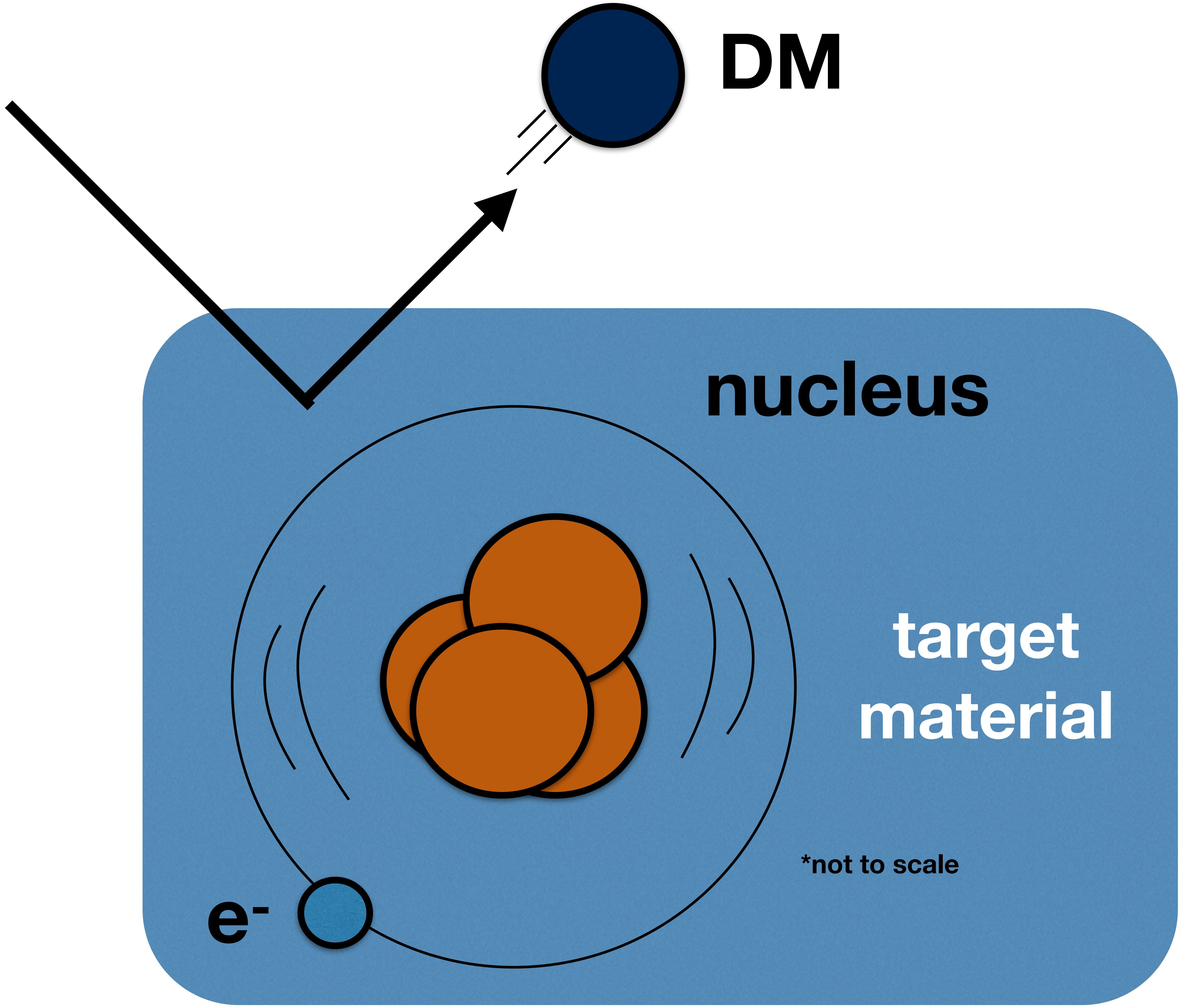
Dark Matter Nuclear Scattering



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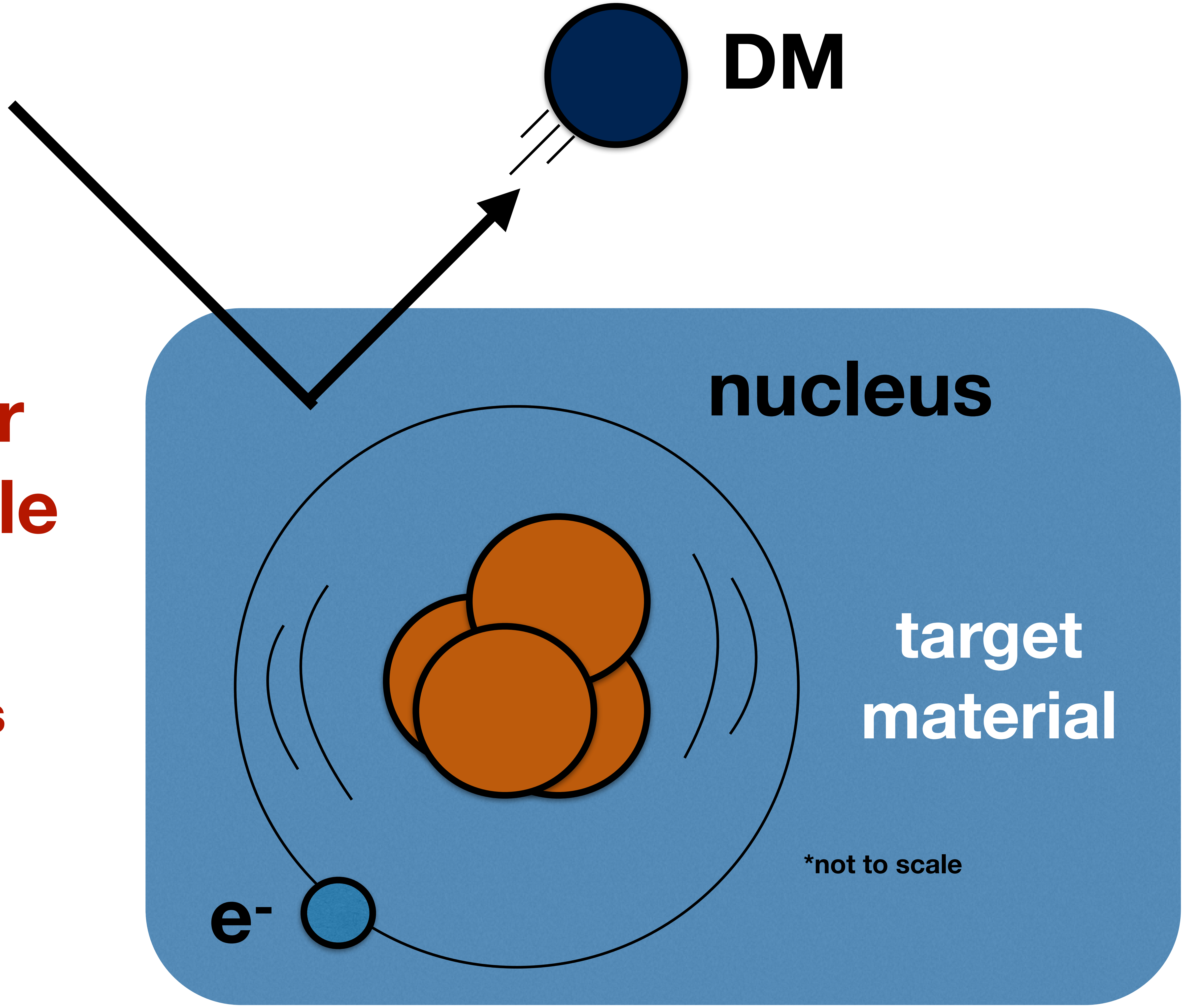
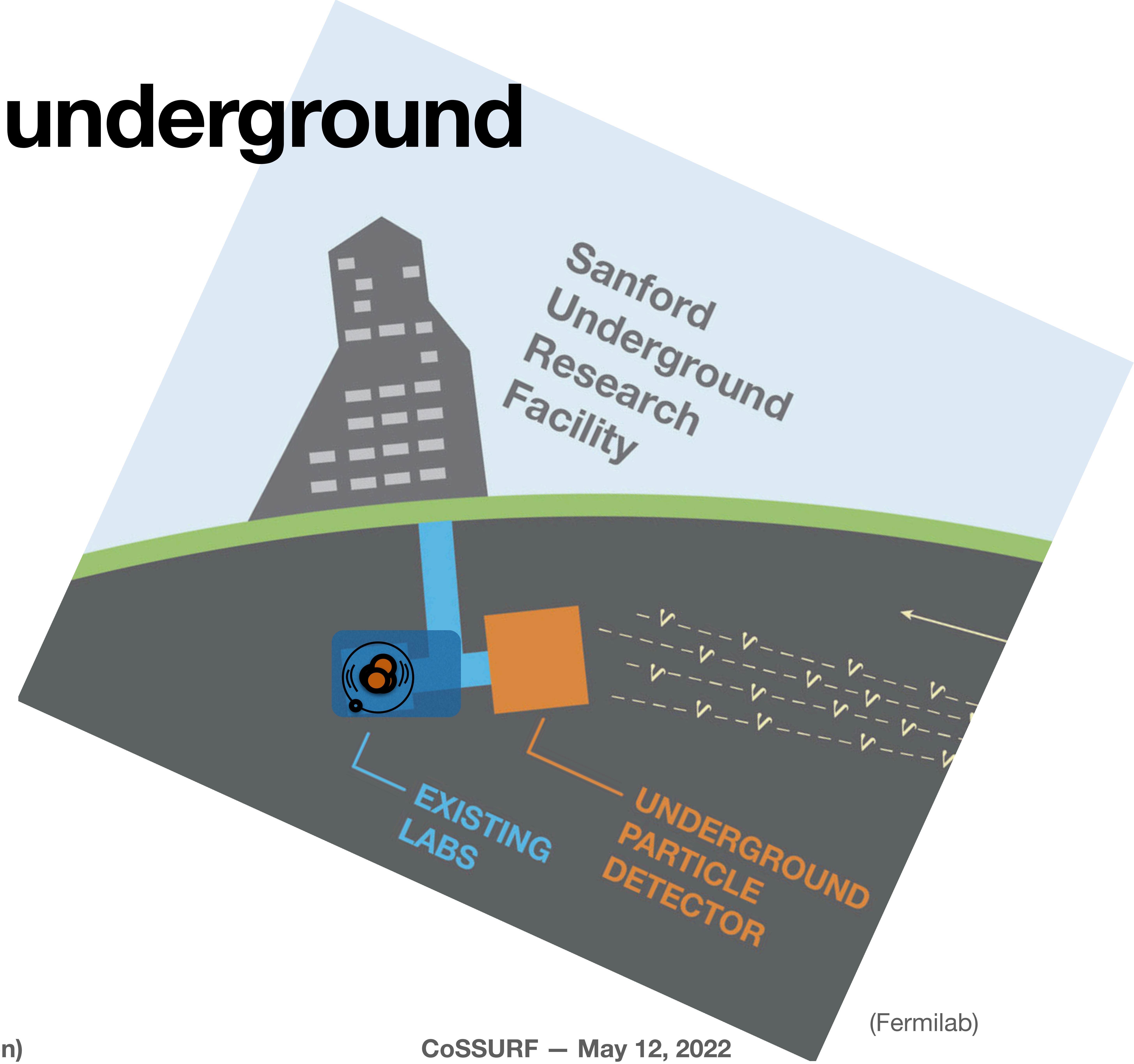


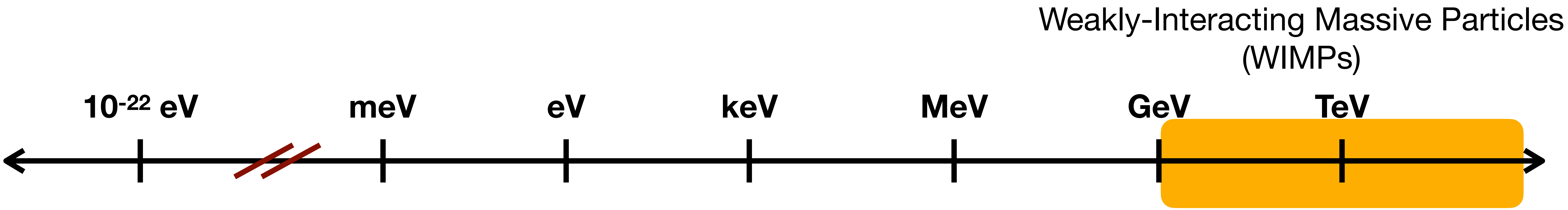
look for
this jiggle
phonons
photons
electrons

Moving underground



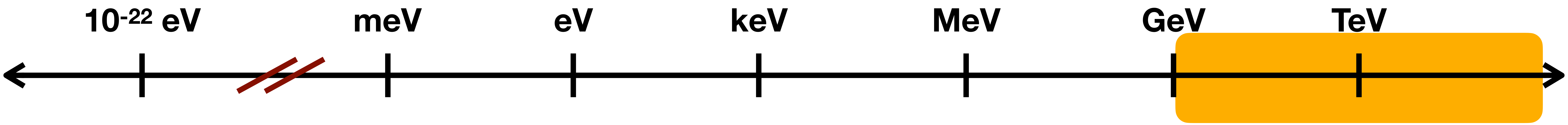
(Fermilab)

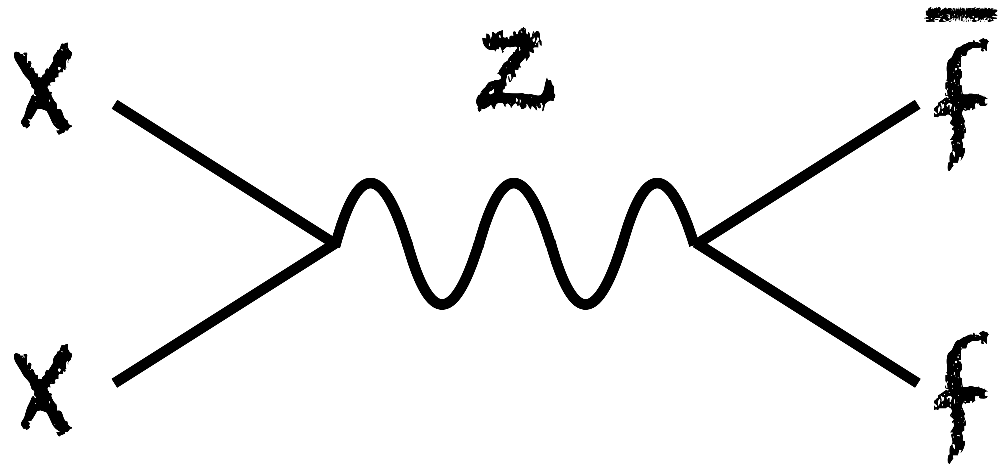
Dark Matter Candidates



Dark Matter Candidates

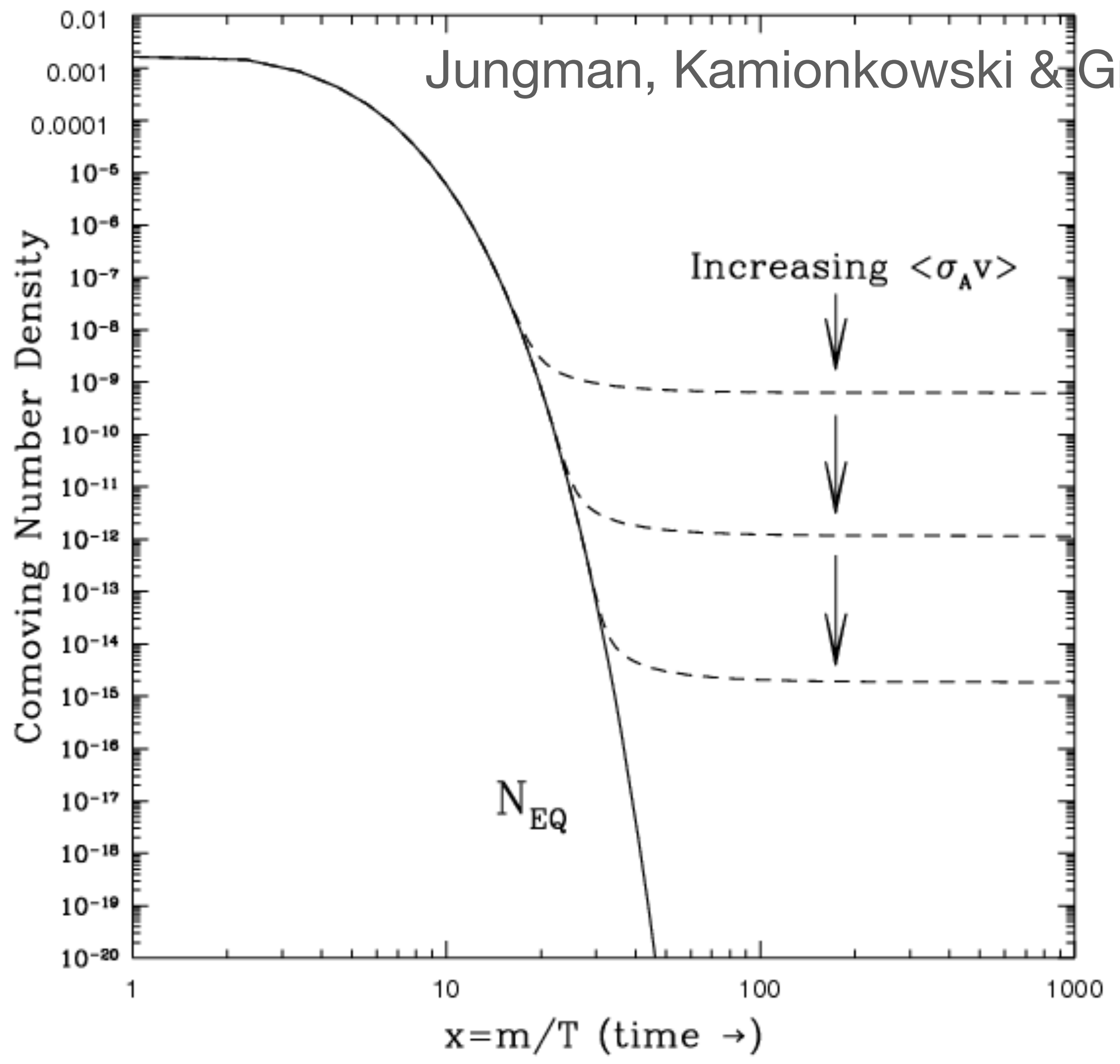
Weakly-Interacting Massive Particles
(WIMPs)





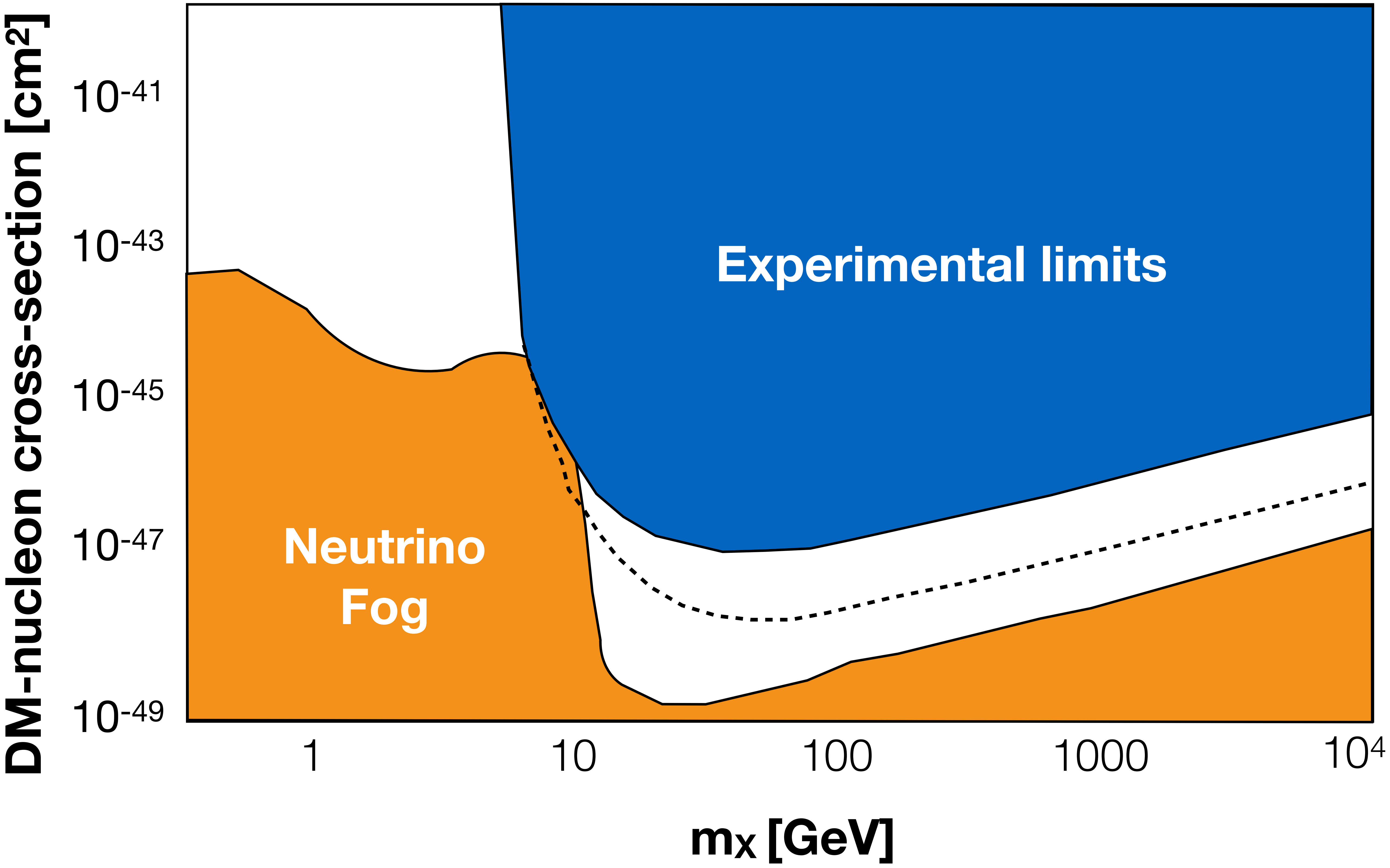
m_X~100 GeV

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



Jungman, Kamionkowski & Griest(1996)

Dark Matter Nuclear Scattering



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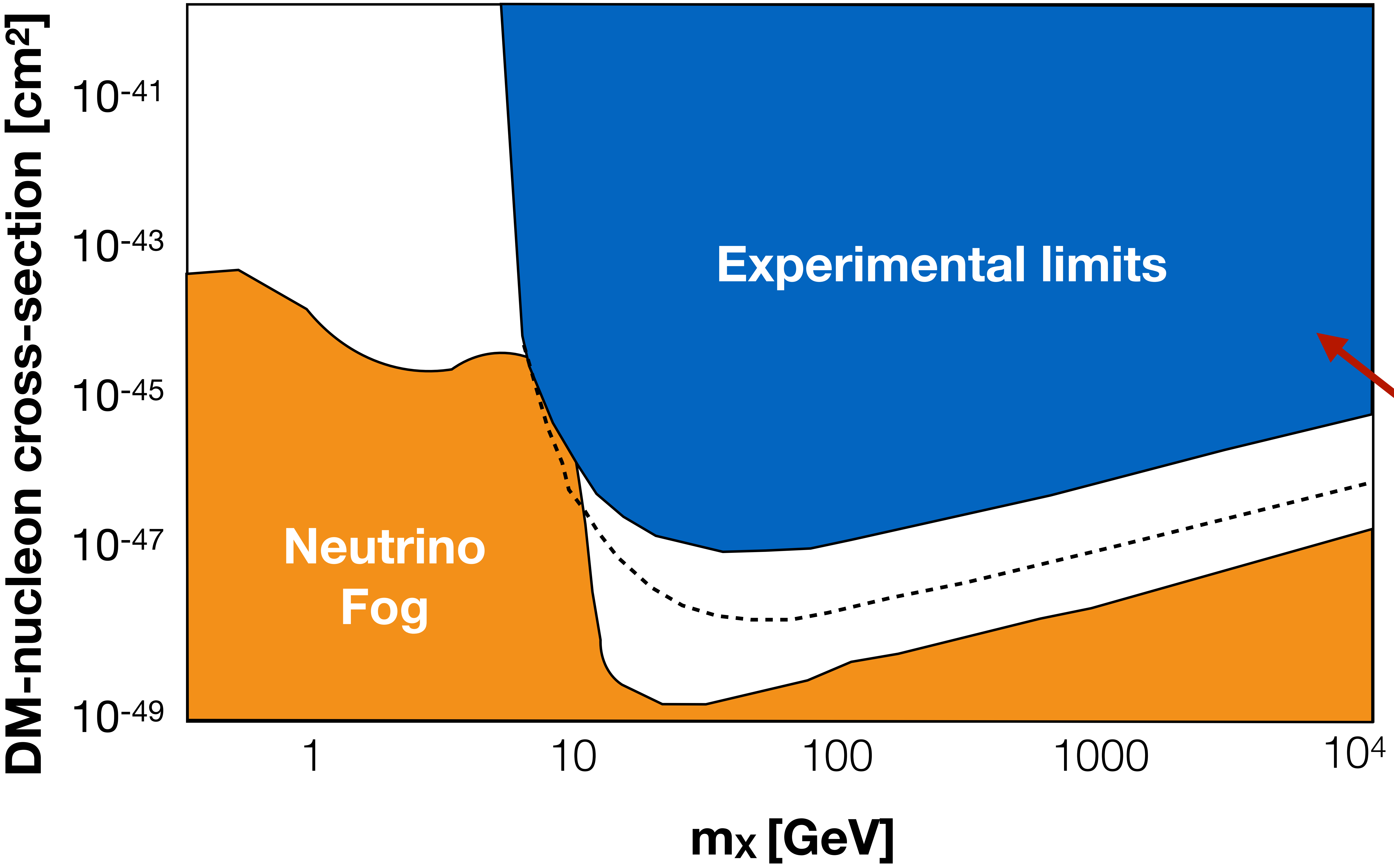

What kind of experiments?

How do we pick a target material?

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

How do we pick a target material?

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more targets is better

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large cross-section is better

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Coherent
Elastic
Spin-Independent

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

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Heavy nuclei are better

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Heavy nuclei are better

Element	A	Experiments
Xenon	131	XMASS, XENON10/100/1T, **LUX**, PandaX-II/4T
Argon	39	DEAP-1/3600, DarkSide-50/LM
CsI	133 (Cs), 127 (I)	KIMS
NaI	22 (Na), 127 (I)	DAMA/LIBRA, ANAIS-112, COSINE-100
Ge	72	CDEX, SuperCDMS, CDMSlite,
Si	28	SuperCDMS, DAMIC

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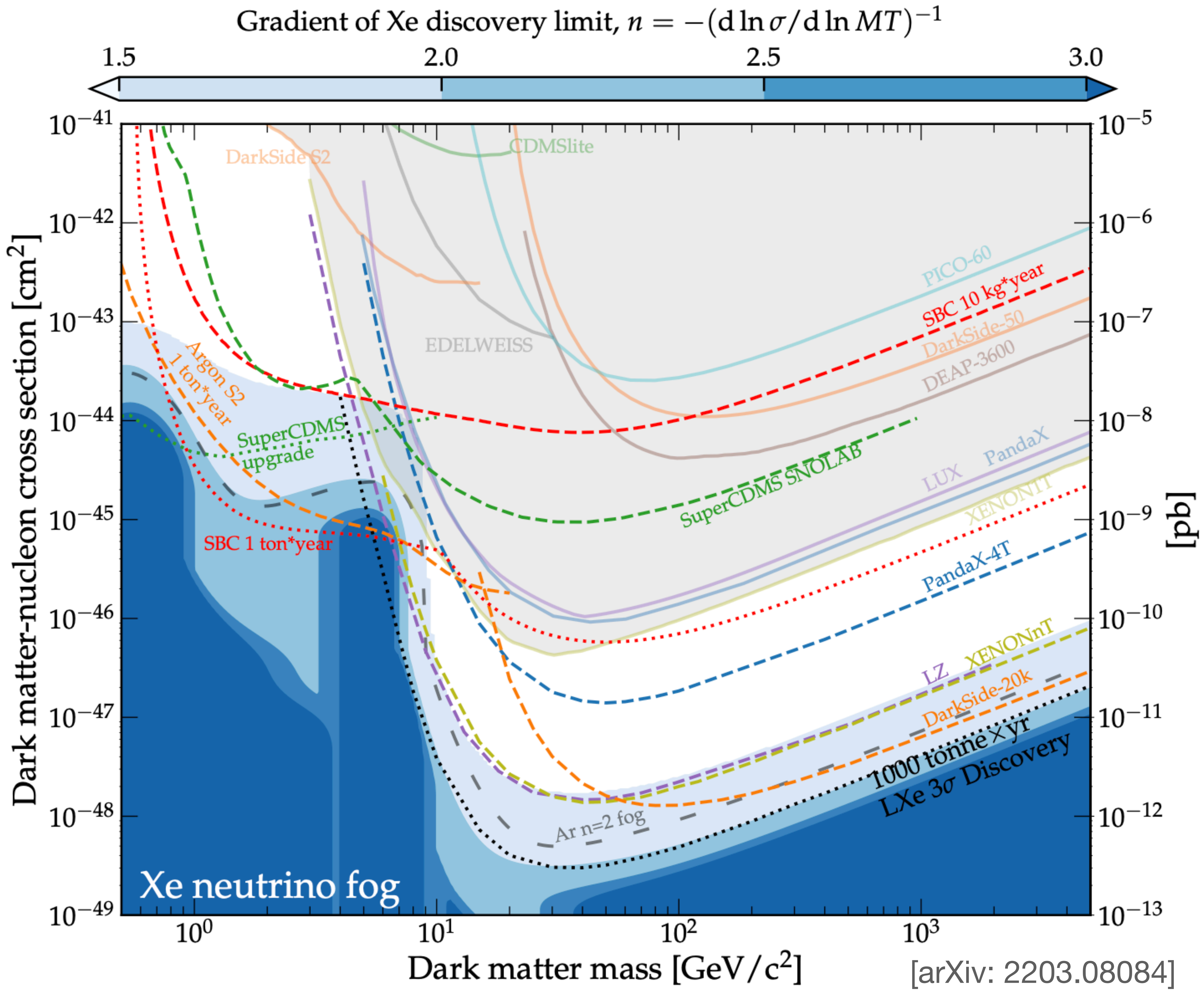
Si	28	C MIC

See talks by:
Shengchao Li (XENONnT)
Carmen Carmona-Benitez (LZ)
Rafal Wojaczsknski (DarkSide-20K)
Quihong Wang (PandaX-4T)
Govinda Adhikari (COSINE-100 + DM-Ice)
Ruslan Podviianiuk (SuperCDMS)
Stefano Di Lorenzo (CRESST)
TJ Whitis (SBC)

Current Landscape: Spin-Independent



[arXiv: 2203.08084]

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

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Spin-Dependent

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

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need an unpaired spin

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need an unpaired spin

Element	J	Experiment
F	1/2	PICO-2/40/60 (C3F8), DRIFT-II (CF4), PICASSO (C4F10), COUPP (CF3I)
Ge	9/2	SuperCDMS
Xe	1/2, 3/2	XENON10/100/1T, **LUX**, PandaX-II

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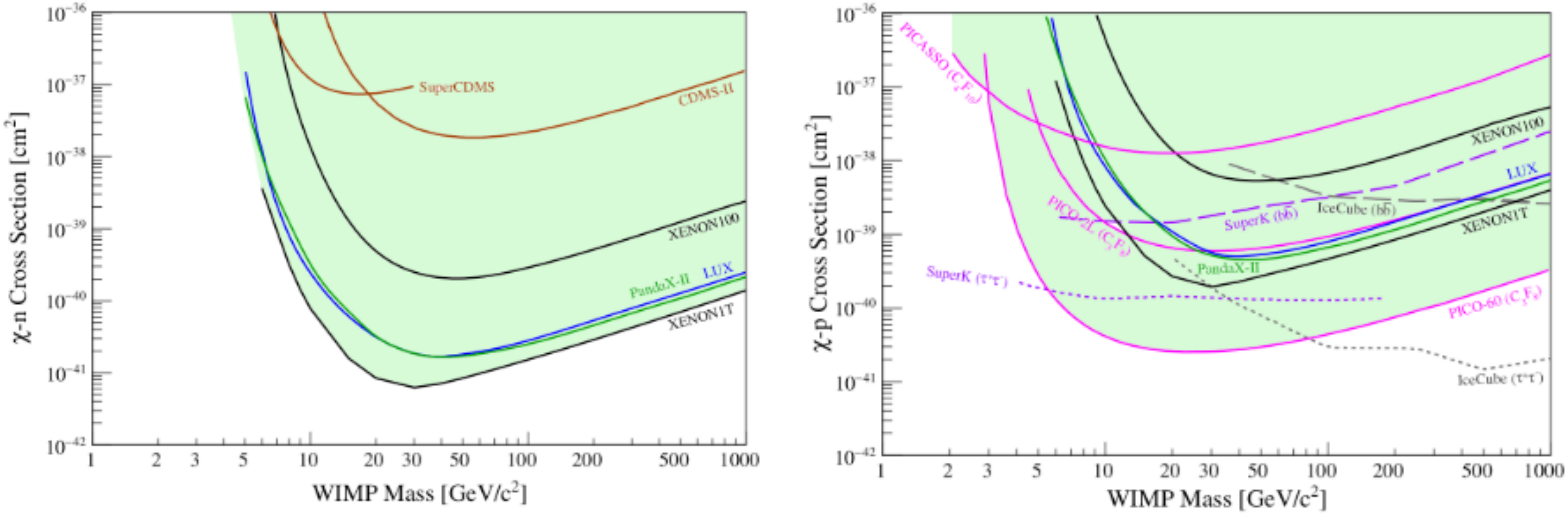
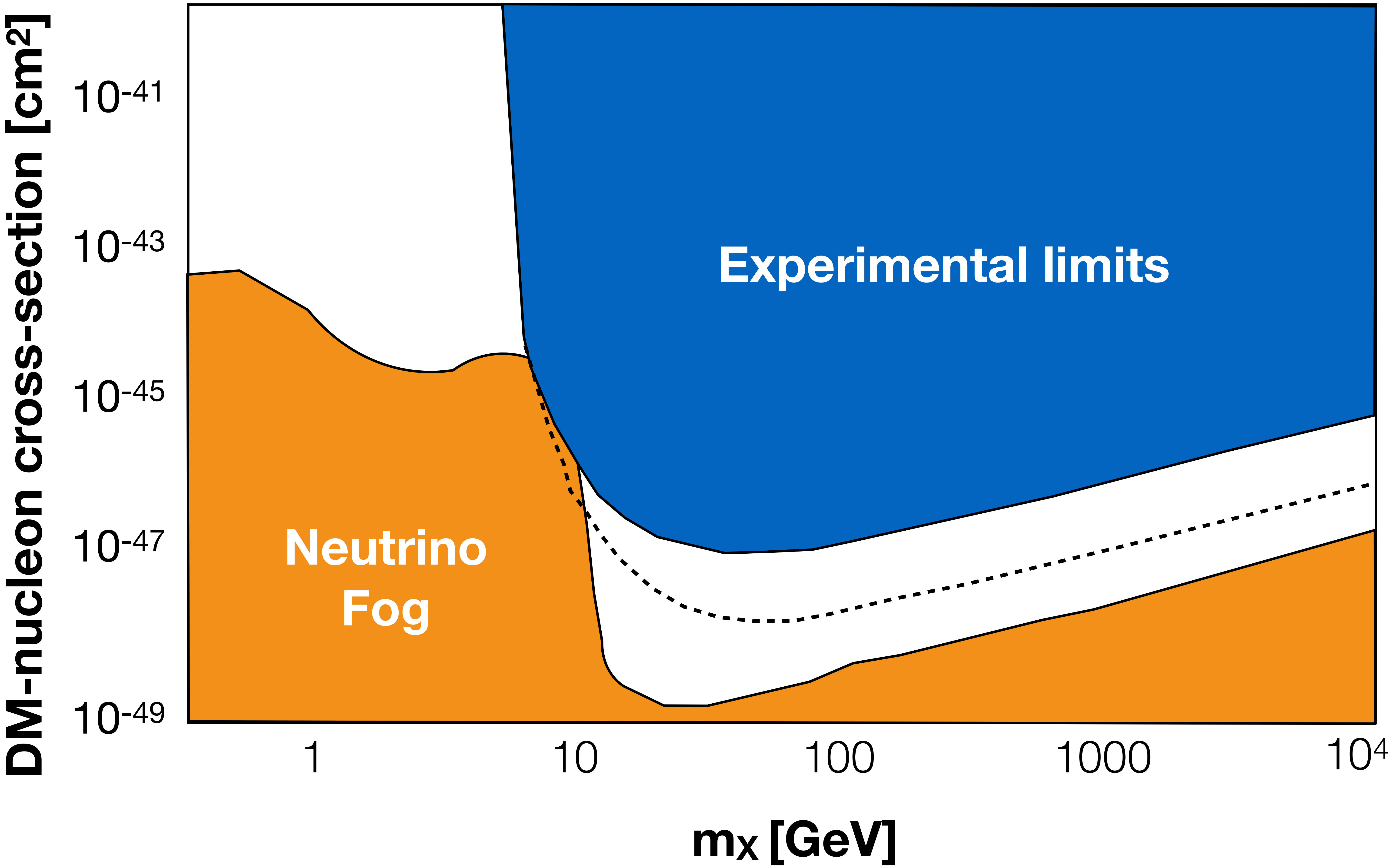
Current Landscape: Spin-Dependent

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

[arXiv:1903.03026]



Looking forward



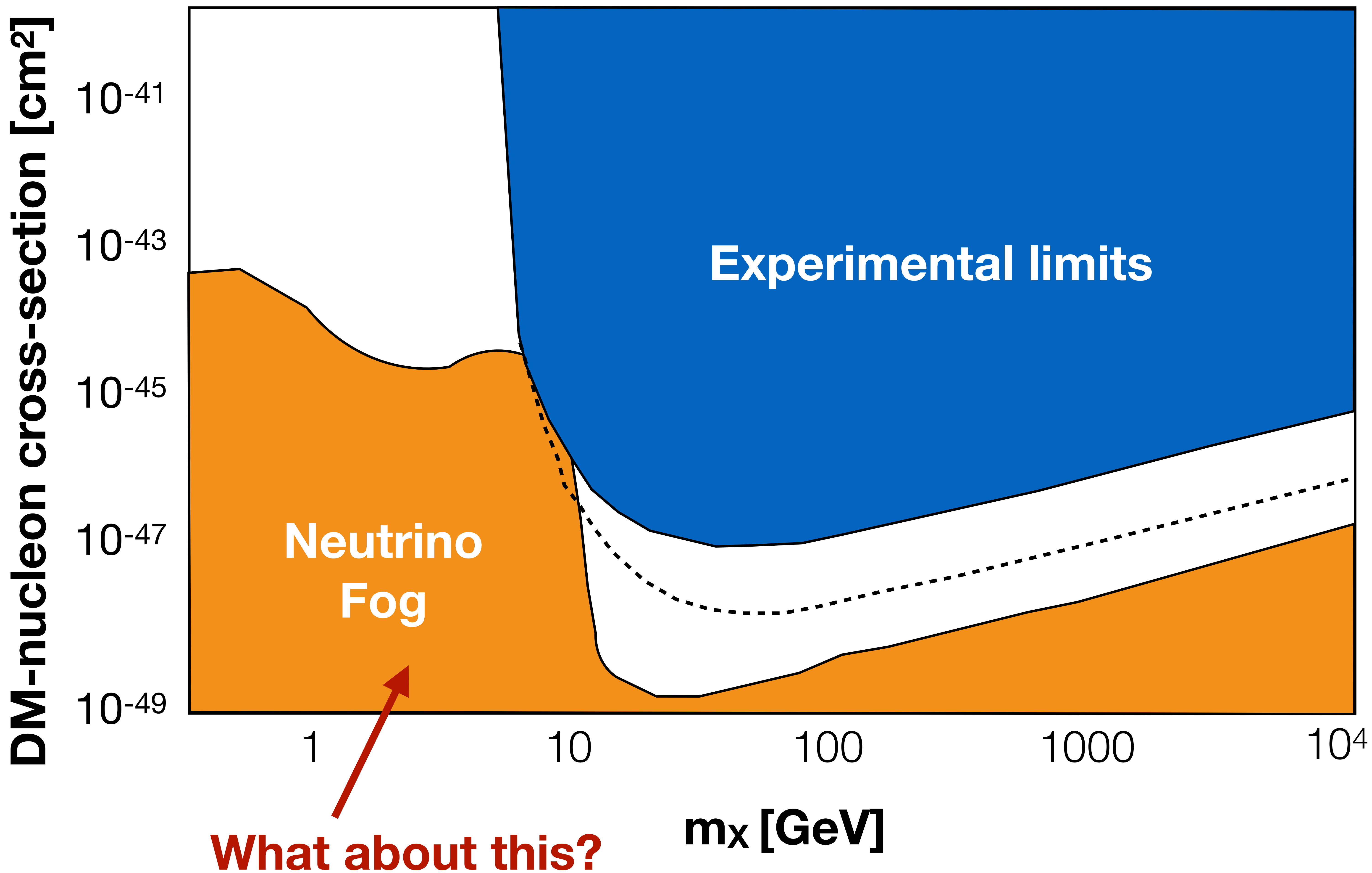
Goals:

- increase target mass
- decrease thresholds
- improve background discrimination

New technologies:

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

Looking forward



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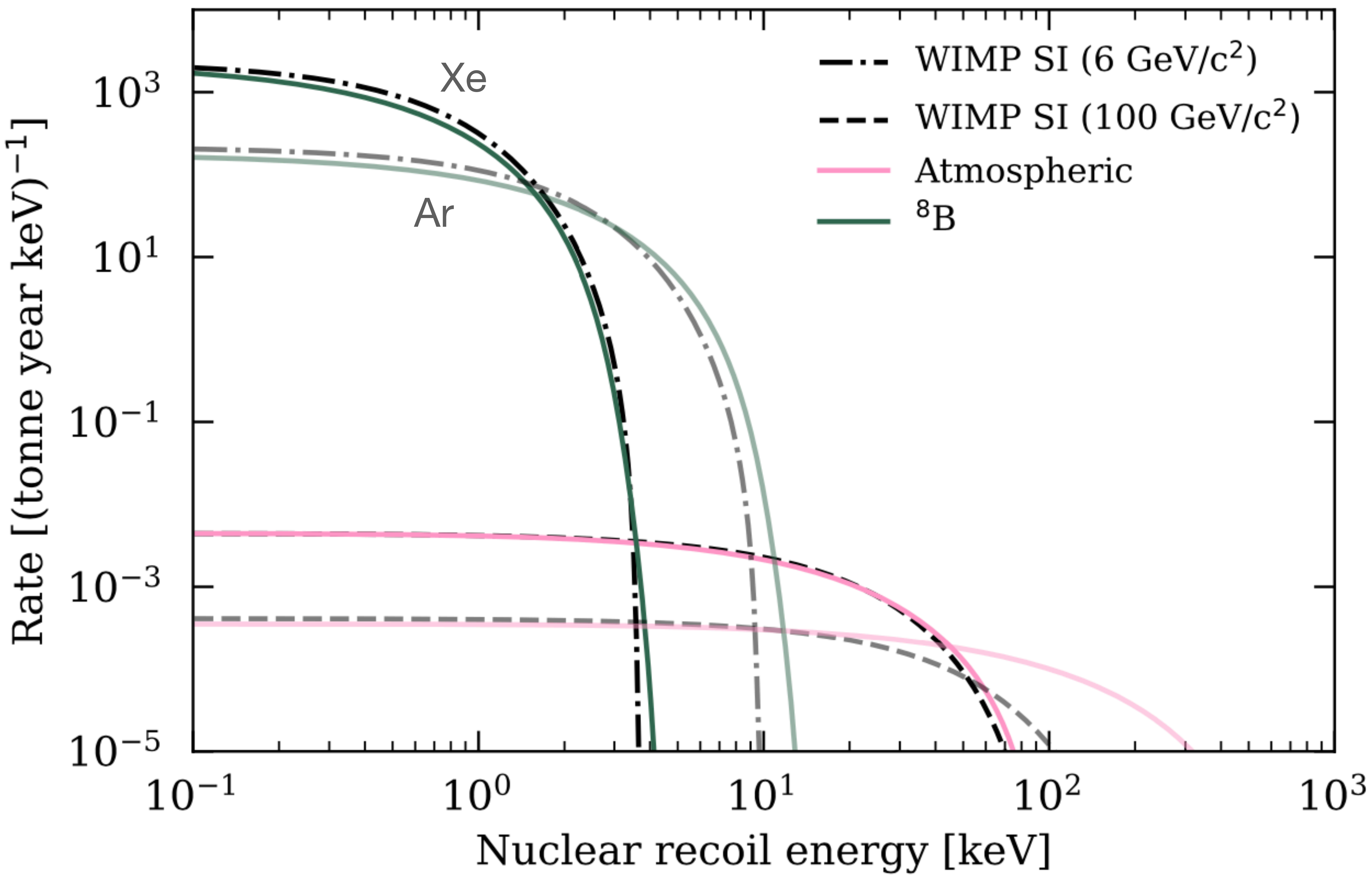
Neutrino Fog

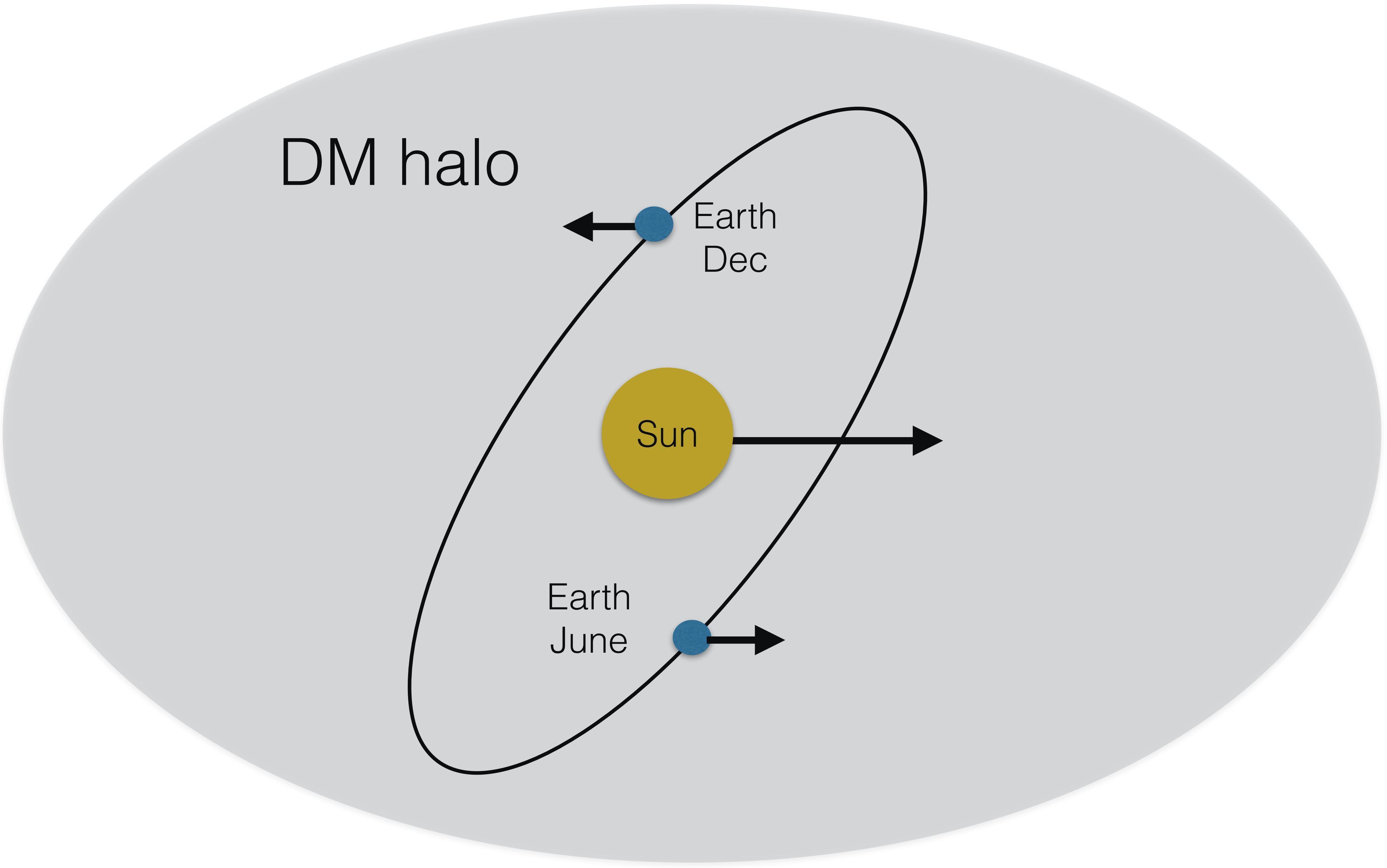
[arXiv: 2203.08084]



Mitigation techniques:

annual modulation

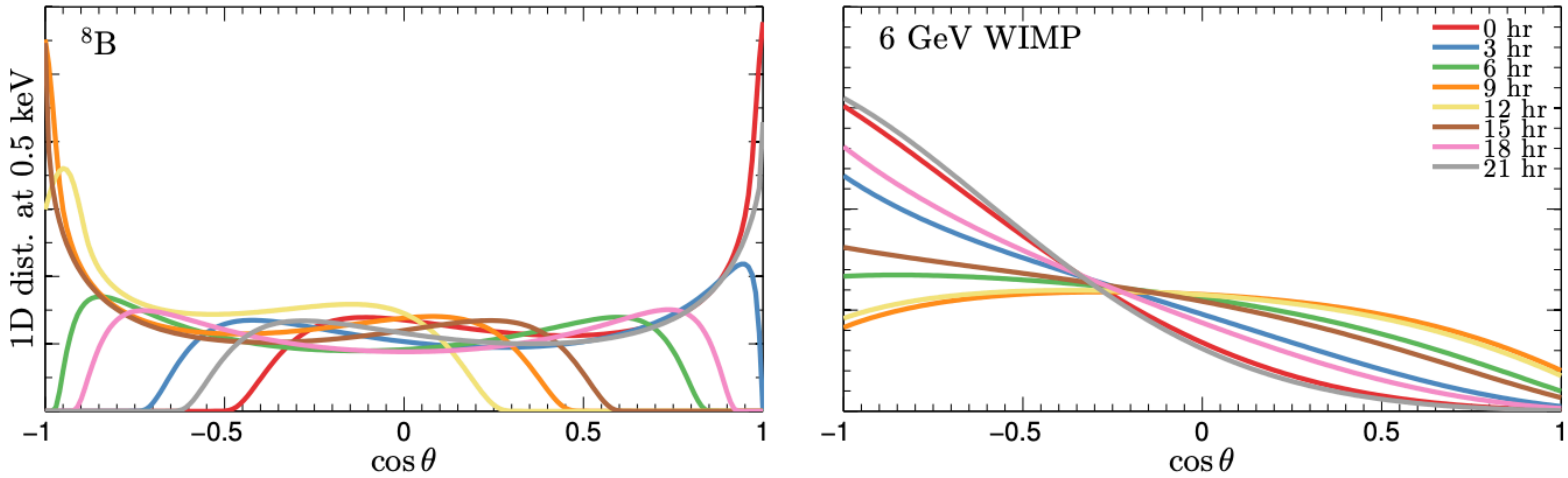
directional detection



changes rate as a function of time

Directional Detection

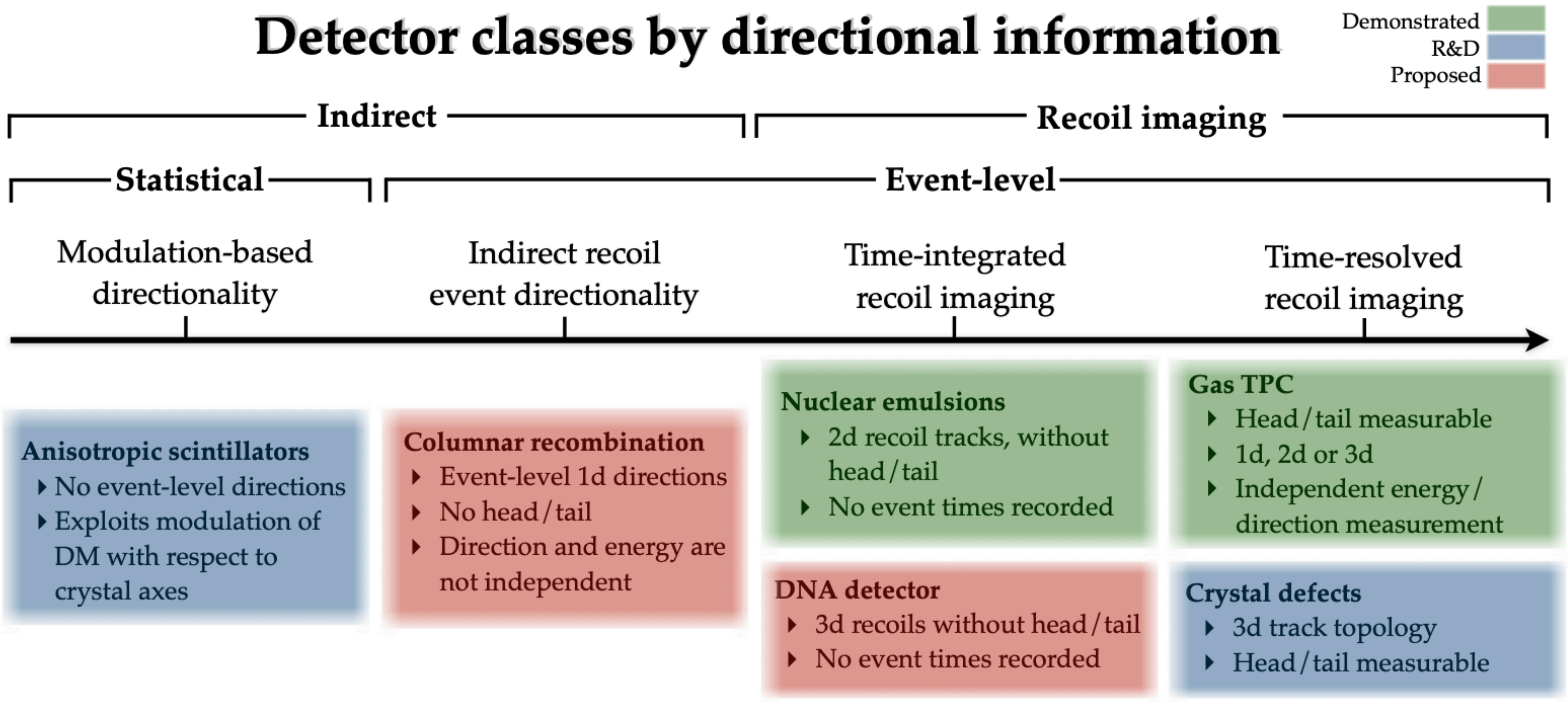
[arXiv: 1505.08061]



Very distinct signature!

Requires ability to reconstruct direction of nuclear recoil

Directional Detection



Detector classes by directional information

Demonstrated 🟩
R&D 🟦
Proposed 🟥

Indirect — **Recoil imaging**

Statistical — **Event-level**

Modulation-based directionality → Indirect recoil event directionality → Time-integrated recoil imaging → Time-resolved recoil imaging

Anisotropic scintillators
- No event-level directions
- Exploits modulation of DM with respect to crystal axes

Columnar recombination
- Event-level 1d directions
- No head / tail
- Direction and energy are not independent

Nuclear emulsions
- 2d recoil tracks, without head / tail
- No event times recorded

DNA detector
- 3d recoils without head / tail
- No event times recorded

Gas TPC
- Head / tail measurable
- 1d, 2d or 3d
- Independent energy / direction measurement

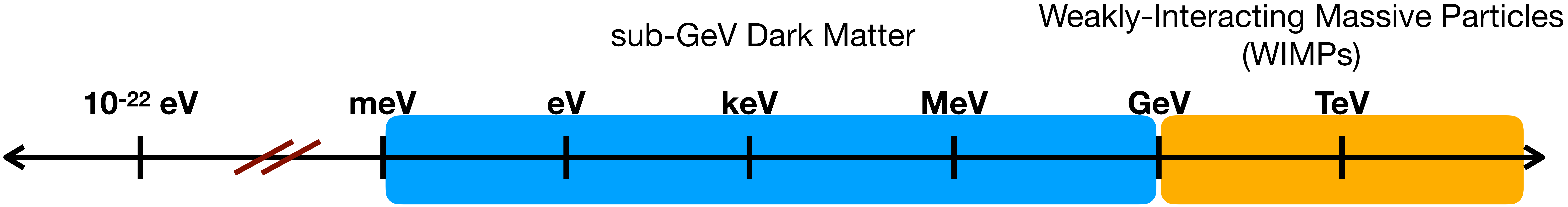
Crystal defects
- 3d track topology
- Head / tail measurable

[arXiv: 2203.08084]

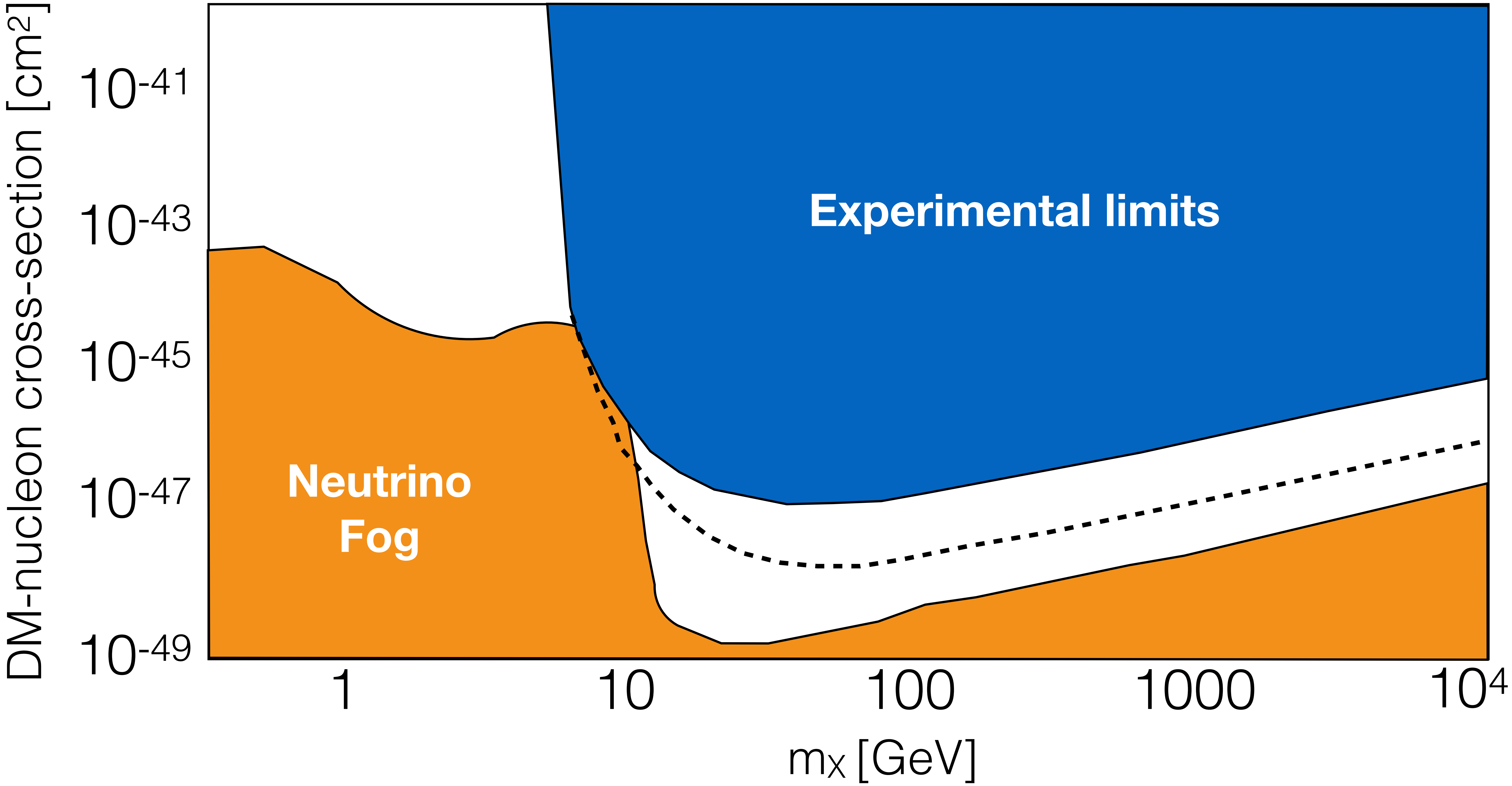
- DMTPC
- DRIFT-II
- NEWAGE-03b”
- MIMAC
- CYGNO
- CYGNUS
- NEWS

See talk by:
Sven Vahsen (CYGNUS)

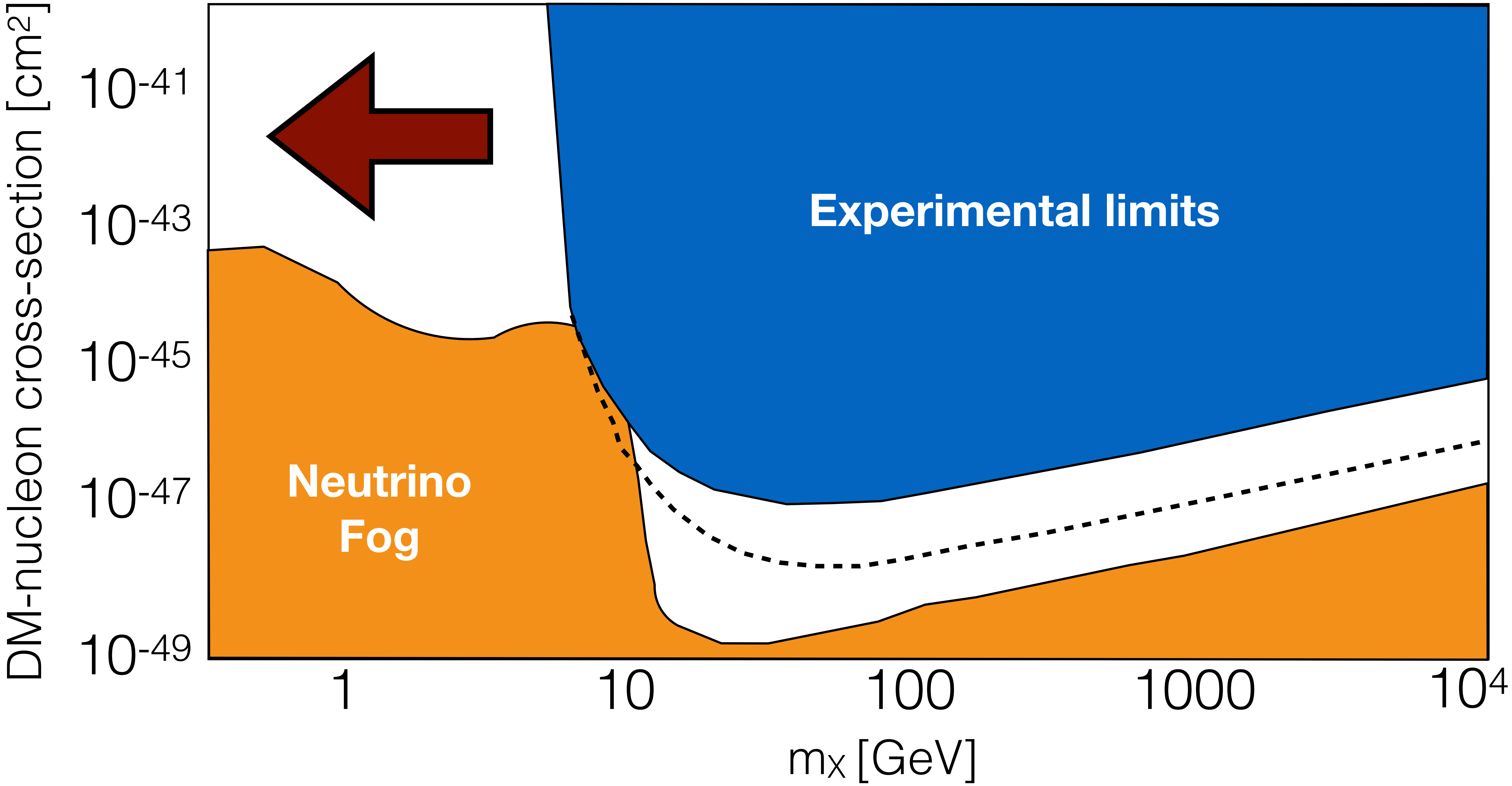
Dark Matter Candidates



sub-GeV Direct Detection



sub-GeV Direct Detection



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

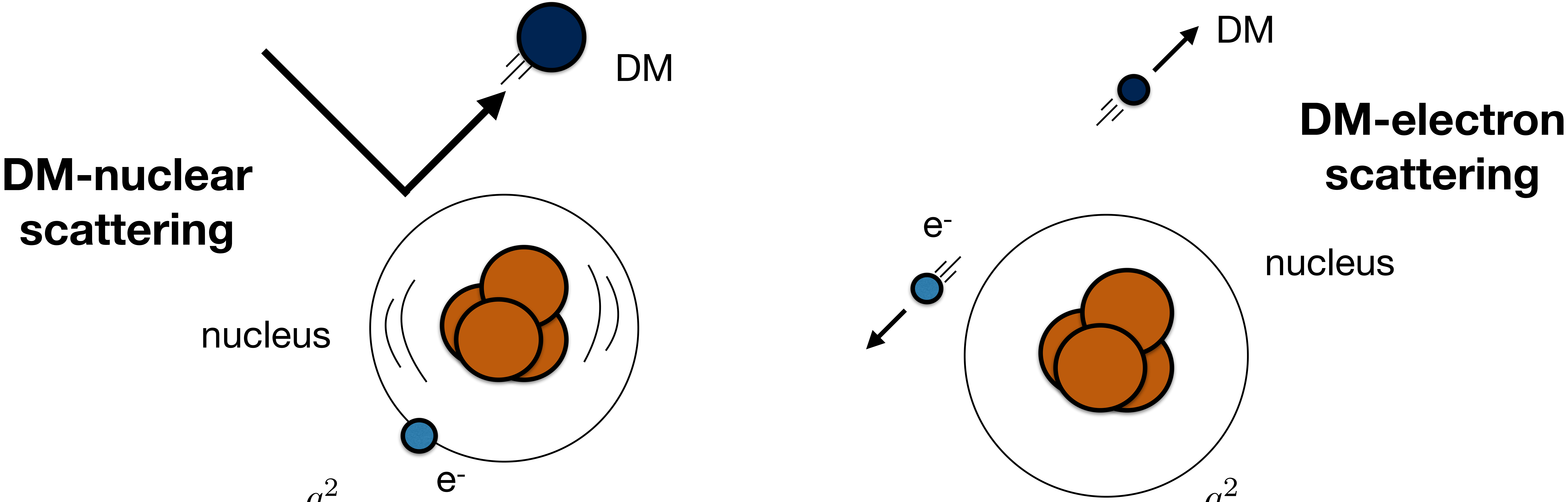
1. decrease energy threshold or sensitivity

consider a variety of materials

2. increase the energy transfer

consider different physical processes

Nuclear vs. Electron Scattering



DM-nuclear scattering

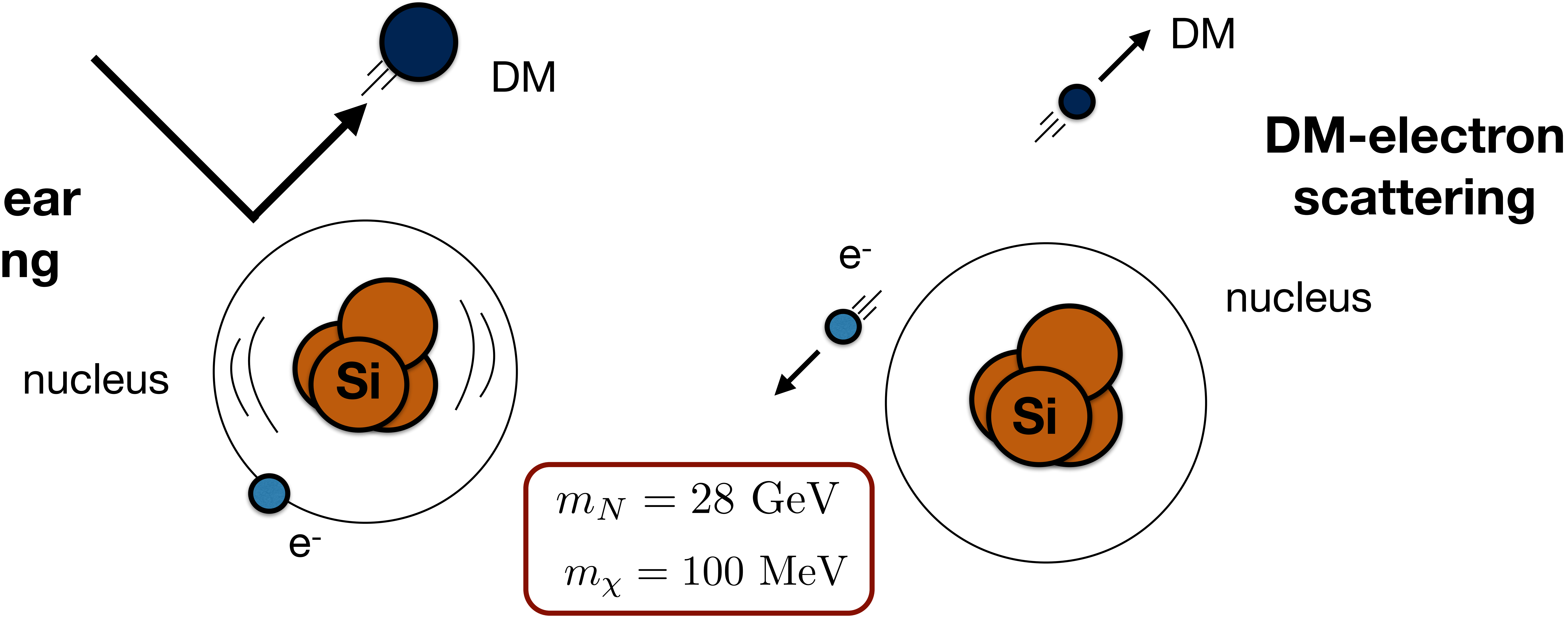
DM-electron scattering

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

recoil energy

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

Nuclear vs. Electron Scattering



DM-nuclear scattering

DM-electron scattering

$m_N = 28 \text{ GeV}$

$m_\chi = 100 \text{ MeV}$

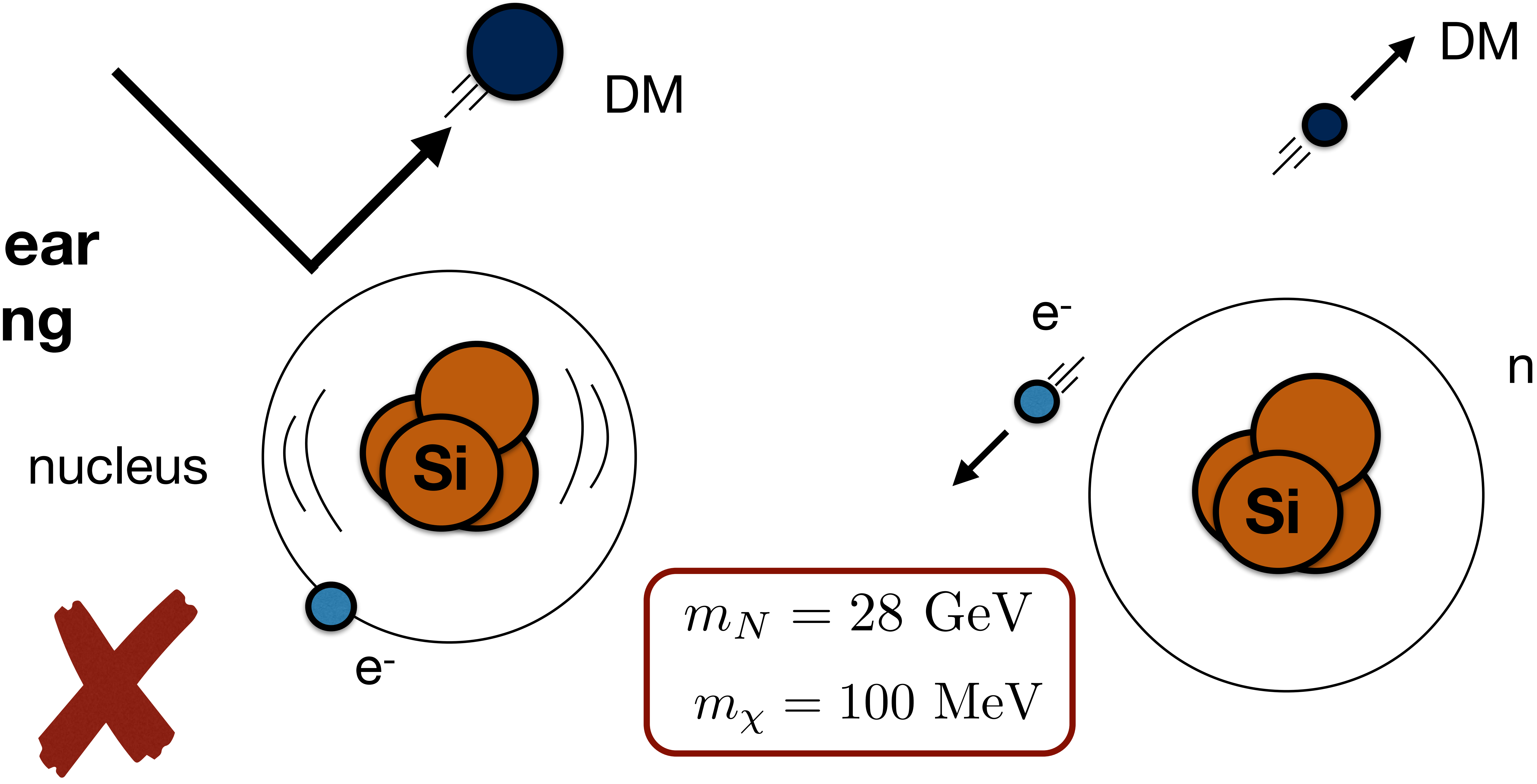
$$E_R \sim 0.1 \text{ eV}$$

$$E_R \sim 50 \text{ eV}$$

Nuclear vs. Electron Scattering

DM-nuclear scattering

DM-electron scattering



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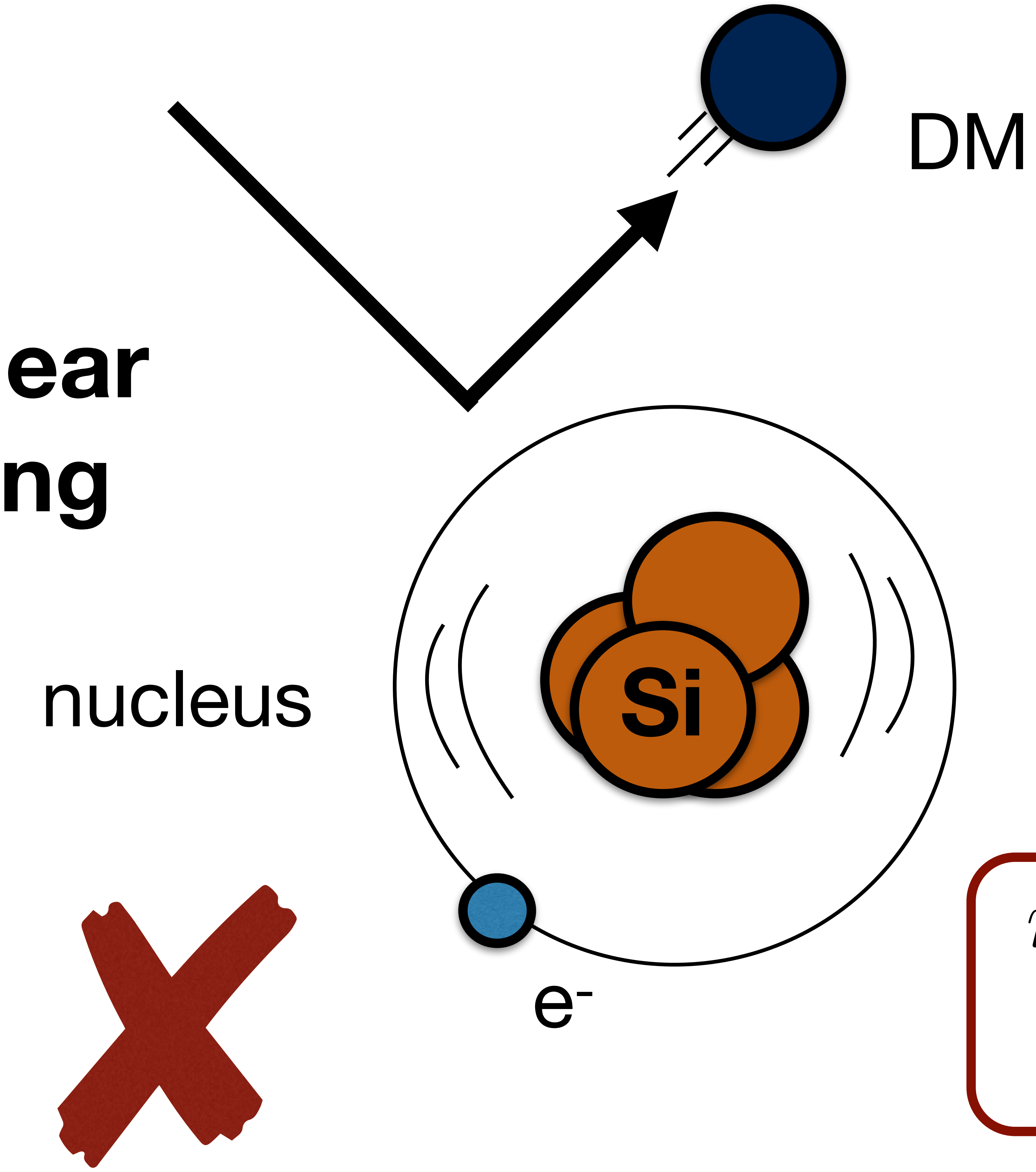

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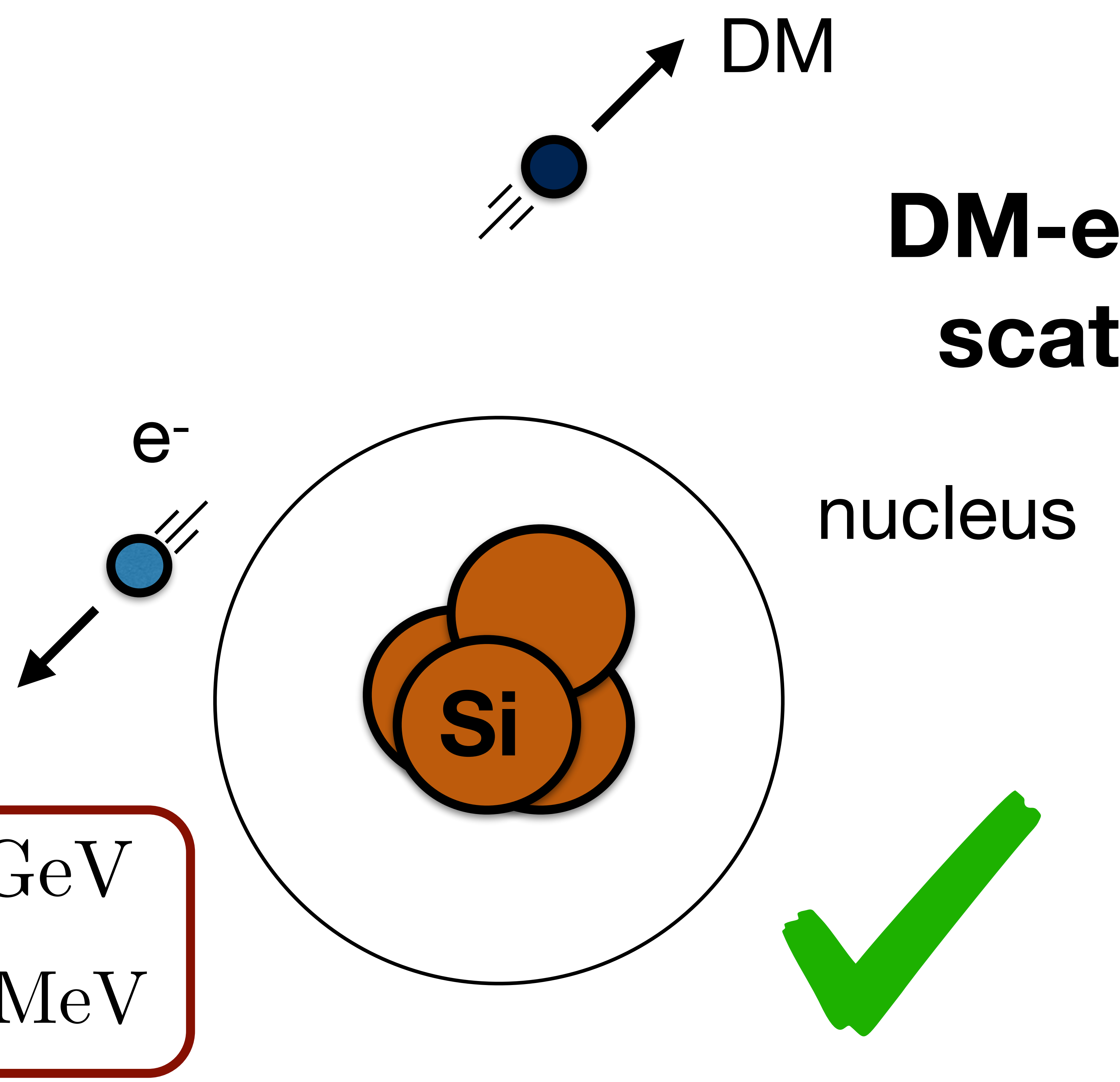

$$E_R \sim 50 \text{ eV}$$

DM-electron scattering rate

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

local DM density

$$R = N_T\frac{\rho_\chi}{m_\chi}\int_{E_{R,cut}} \mathrm{d}\ln E_R\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R}$$

number of target nuclei per unit mass

energy threshold

DM-electron scattering rate

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

particle physics

local DM density

$$R = N_T\frac{\rho_\chi}{m_\chi}\int_{E_{R,cut}} \mathrm{d}\ln E_R\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R}$$

number of target nuclei per unit mass

energy threshold

DM-electron scattering rate

astrophysics

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

particle physics

local DM density

$$R = N_T\frac{\rho_\chi}{m_\chi}\int_{E_{R,cut}}\mathrm{d}\ln E_R\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R}$$

number of target nuclei per unit mass

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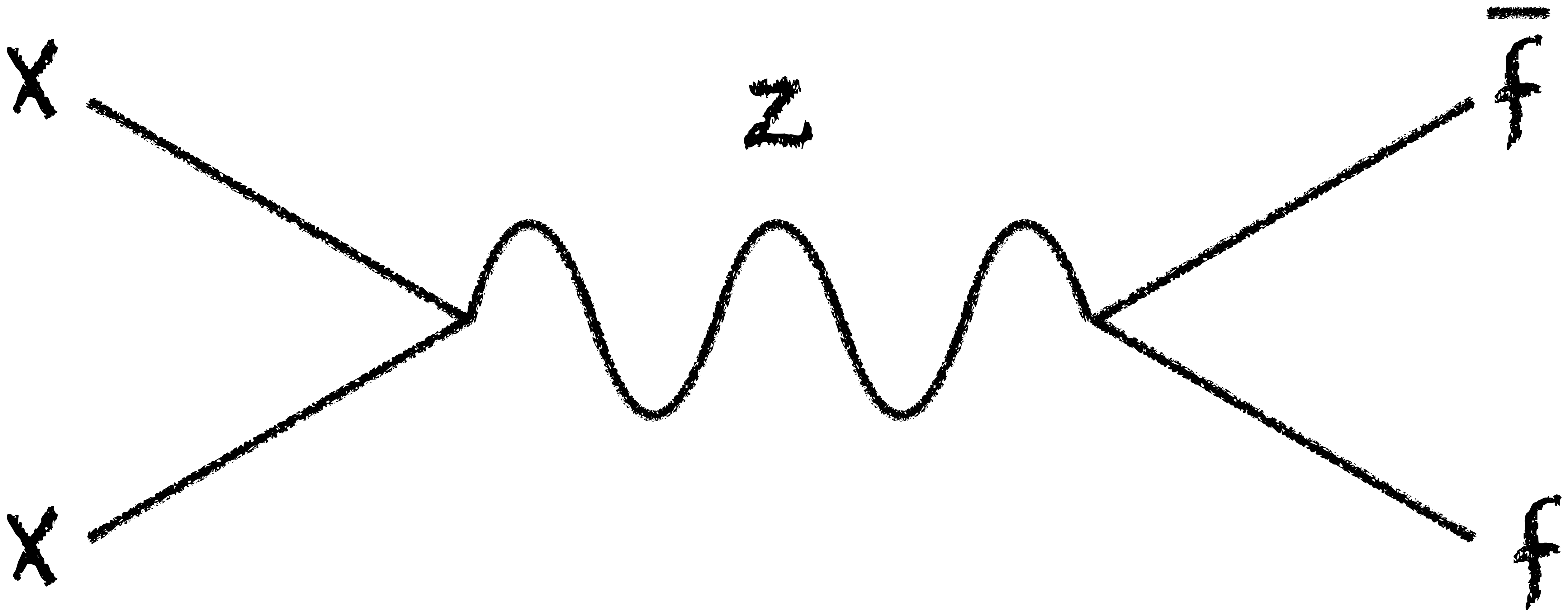
DM-electron scattering rate

$$\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R} = \frac{\boxed{\overline{\sigma}_e}}{8\mu_{\chi e}^2}\int q\,\mathrm{d}q\,\overbrace{|f(k,q)|^2}^{\text{material dependent}}\underbrace{|F_{DM}(q)|^2}_{\text{particle physics}}\overbrace{\eta(v_{min})}^{\text{astrophysics}}$$

$$R = \underset{\text{number of target nuclei per unit mass}}{N_T}\,\frac{\overset{\text{local DM density}}{\rho_\chi}}{m_\chi}\int_{\underset{\text{energy threshold}}{E_{R,cut}}} \mathrm{d}\ln E_R\,\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R}$$

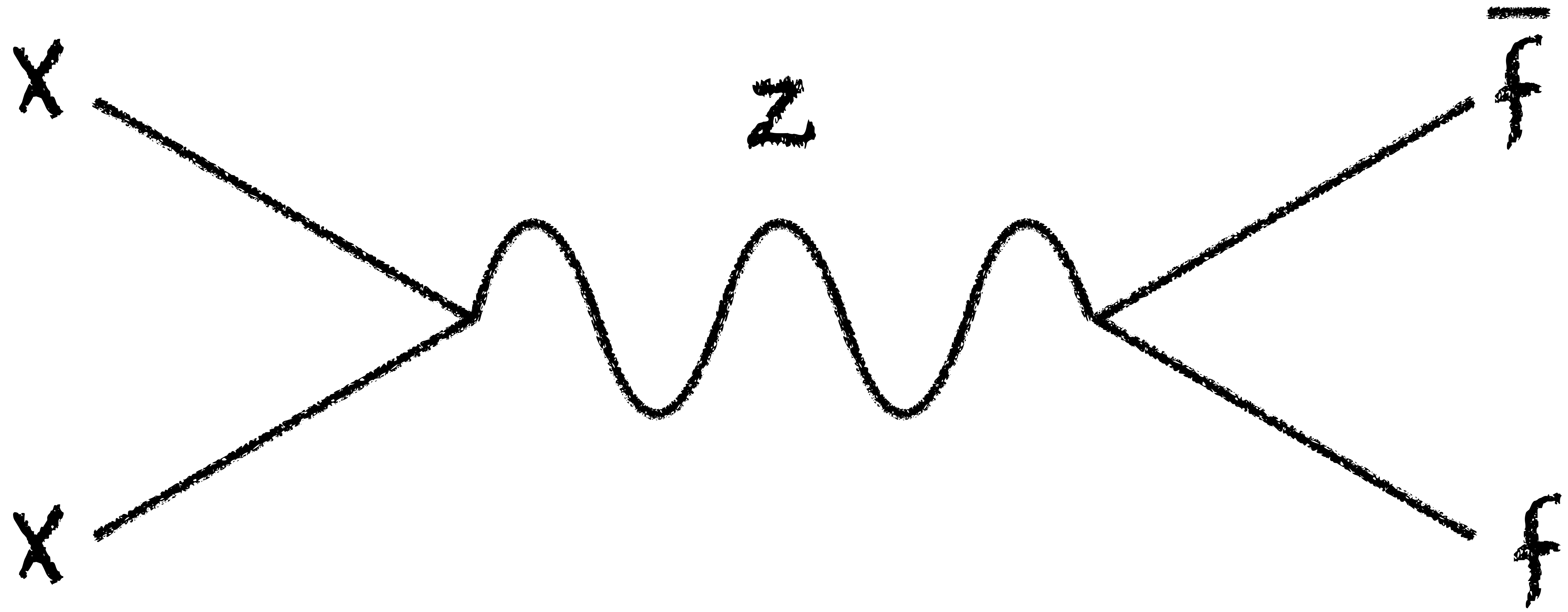
Lee-Weinberg Bound



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

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

Lee-Weinberg Bound



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

Way out: have new light boson that mediates the interaction

Boehm and Fayet [hep-ph/0305261]

Pospelov et al [0711.4866]

Dark Photon

$$SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_X$$

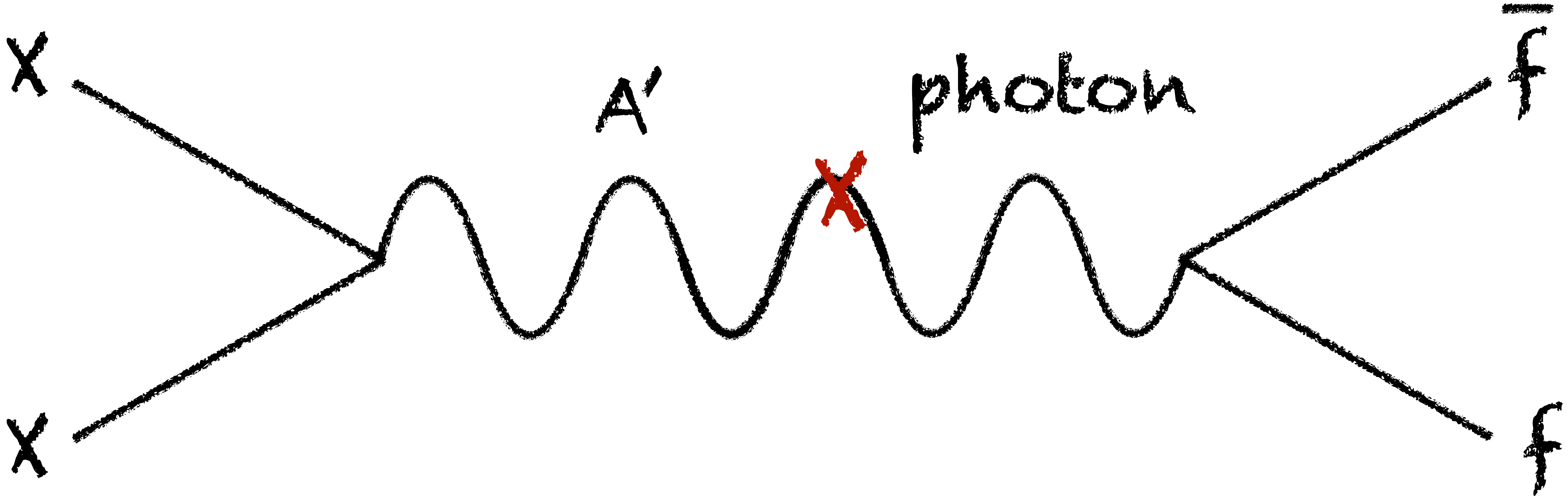
$$\mathscr{L} \supset -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}A'^{\mu}A'_{\mu}$$

kinetic mixing

Dark Photon

$$SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_X$$

$$\mathscr{L} \supset -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}A'^{\mu}A'_{\mu}$$



DM-electron scattering rate

particle physics

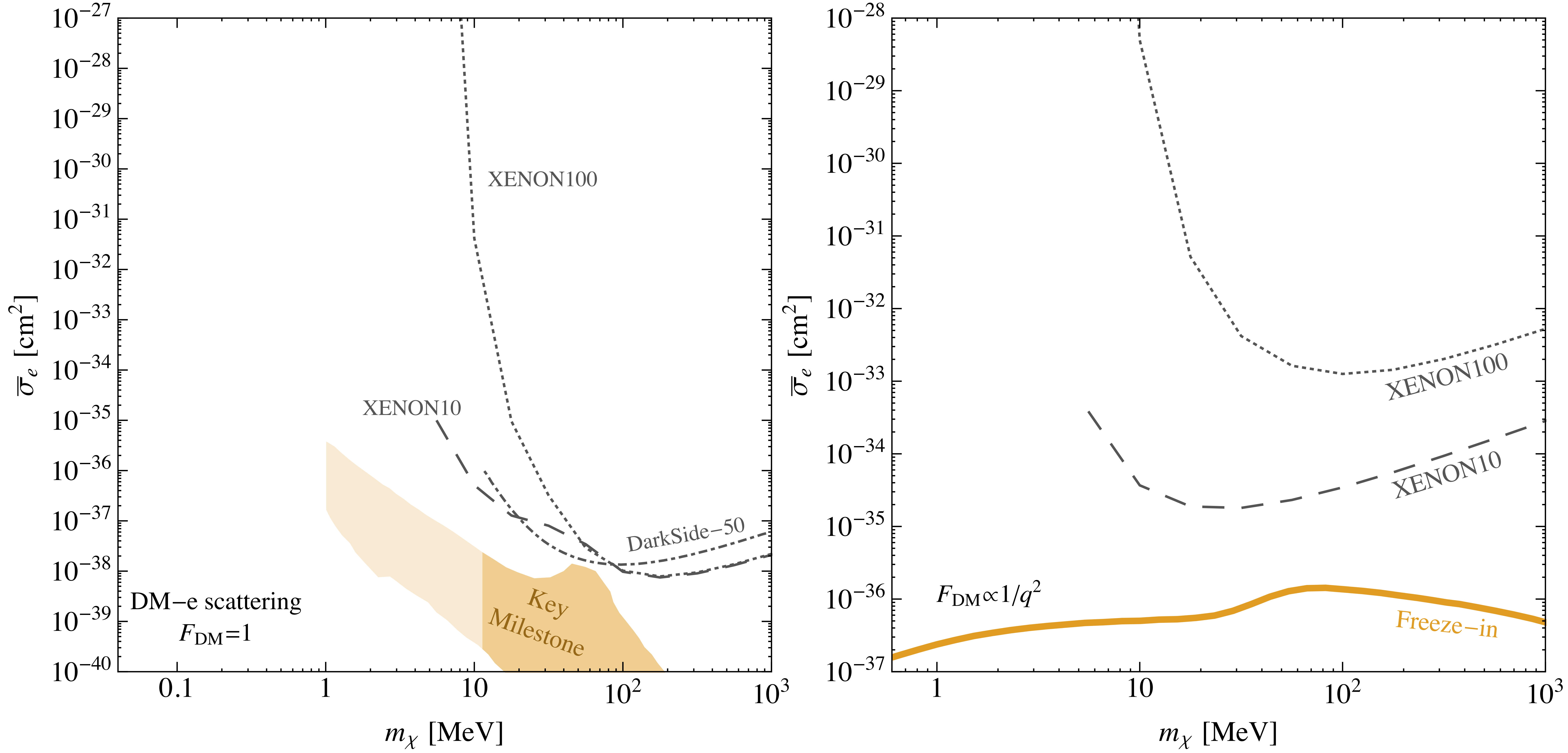
$$\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2}\int q\ \mathrm{d}q|f(k,q)|^2|F_{DM}(q)|^2\eta(v_{min})$$

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

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

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]



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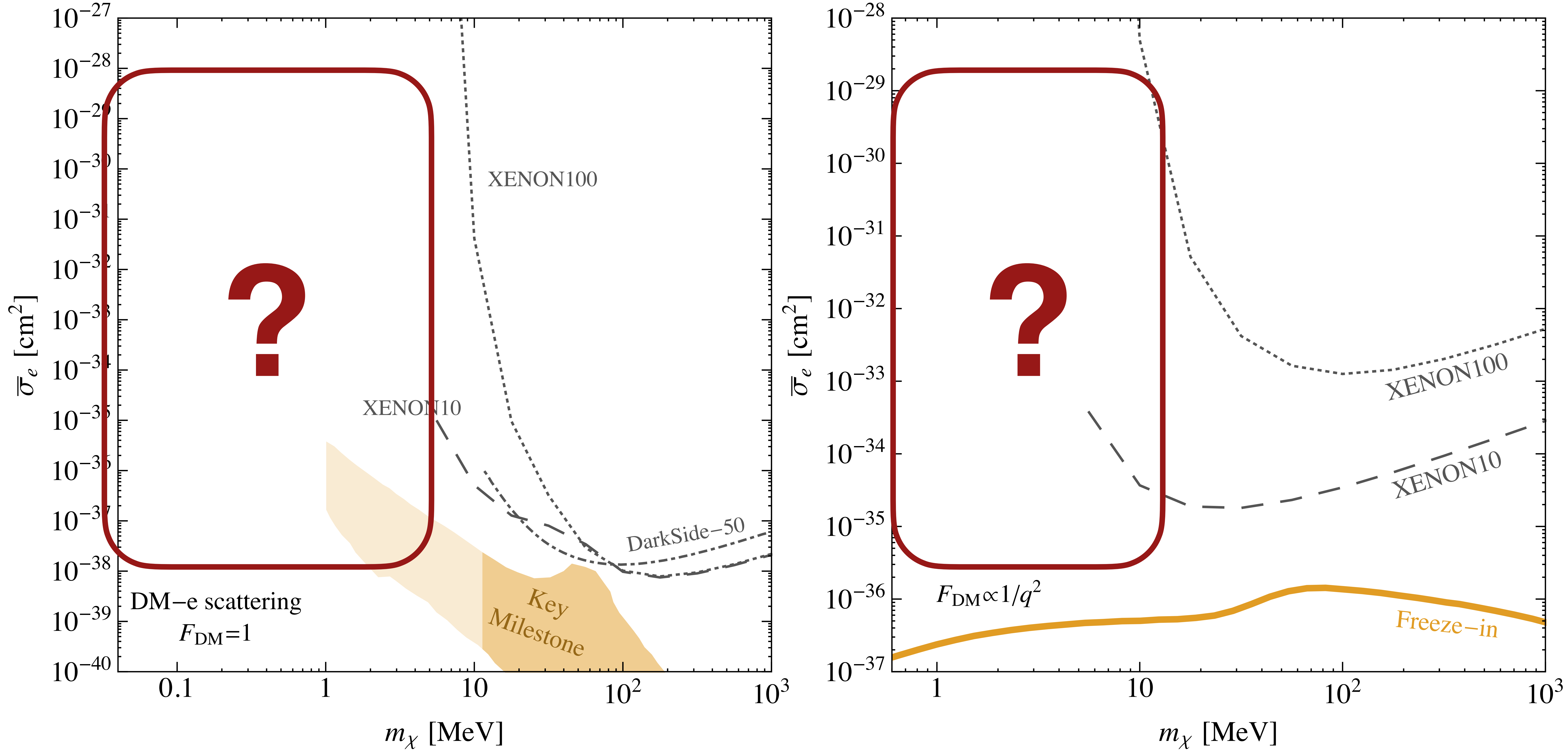

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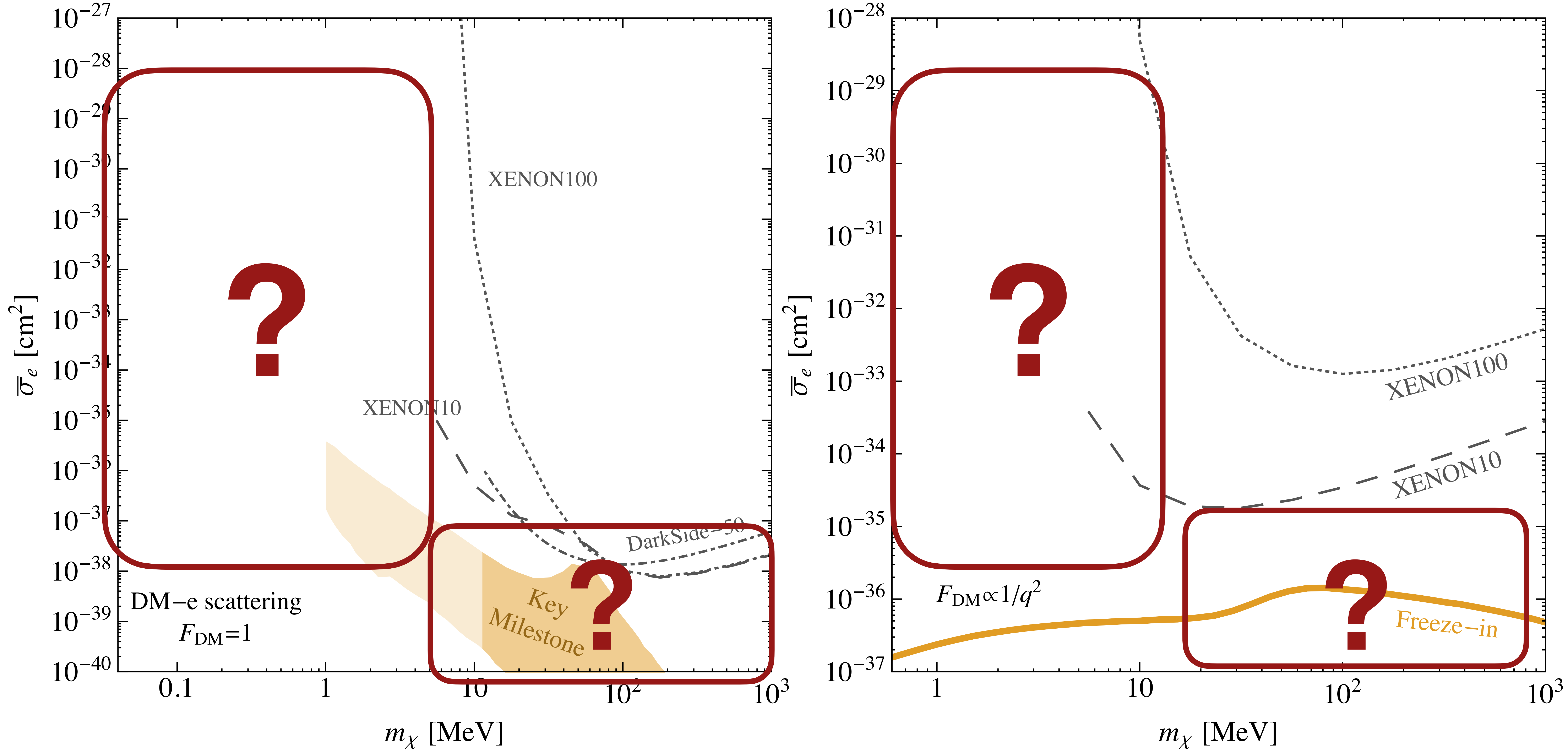
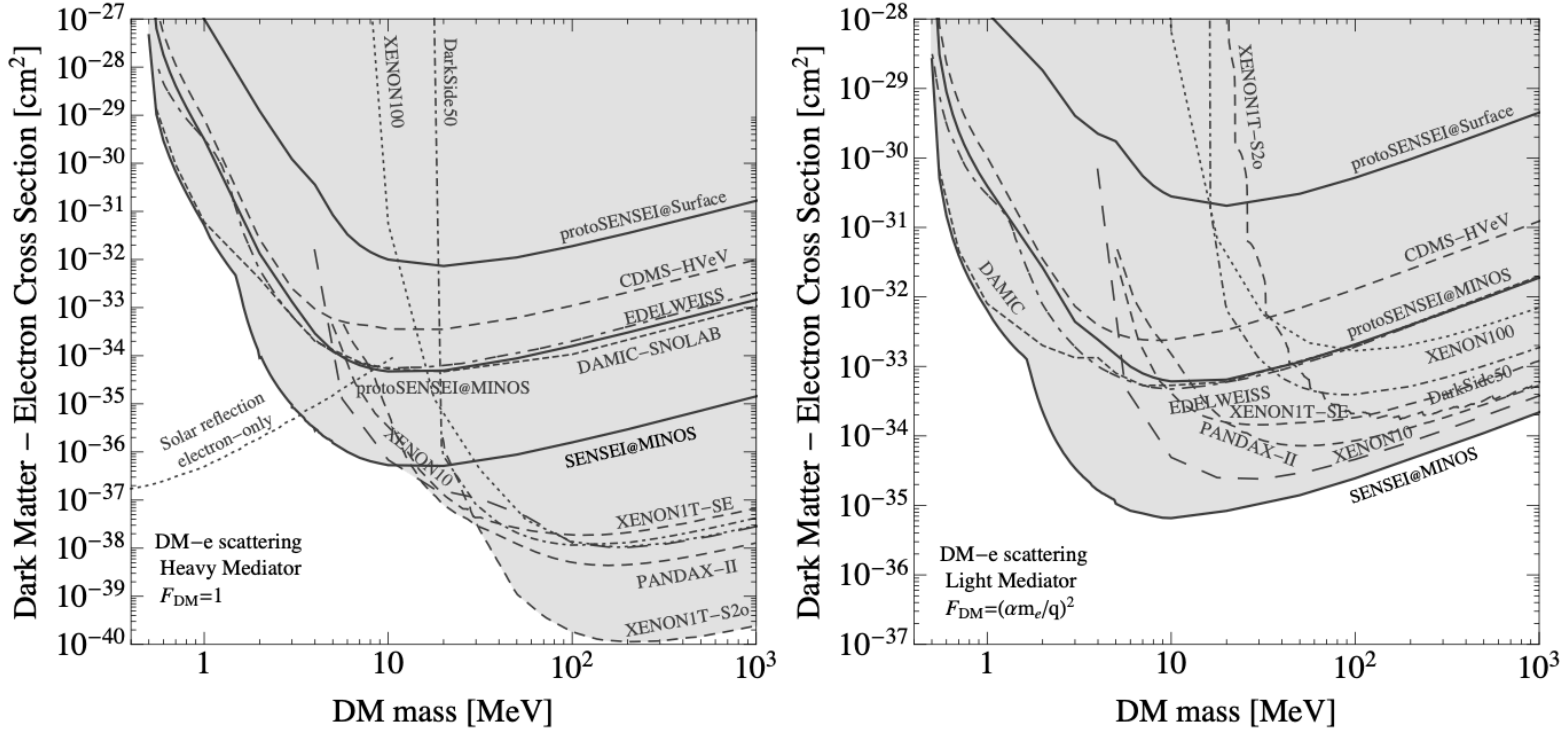


DM-electron limits in 2022

[arXiv:2203.08297]



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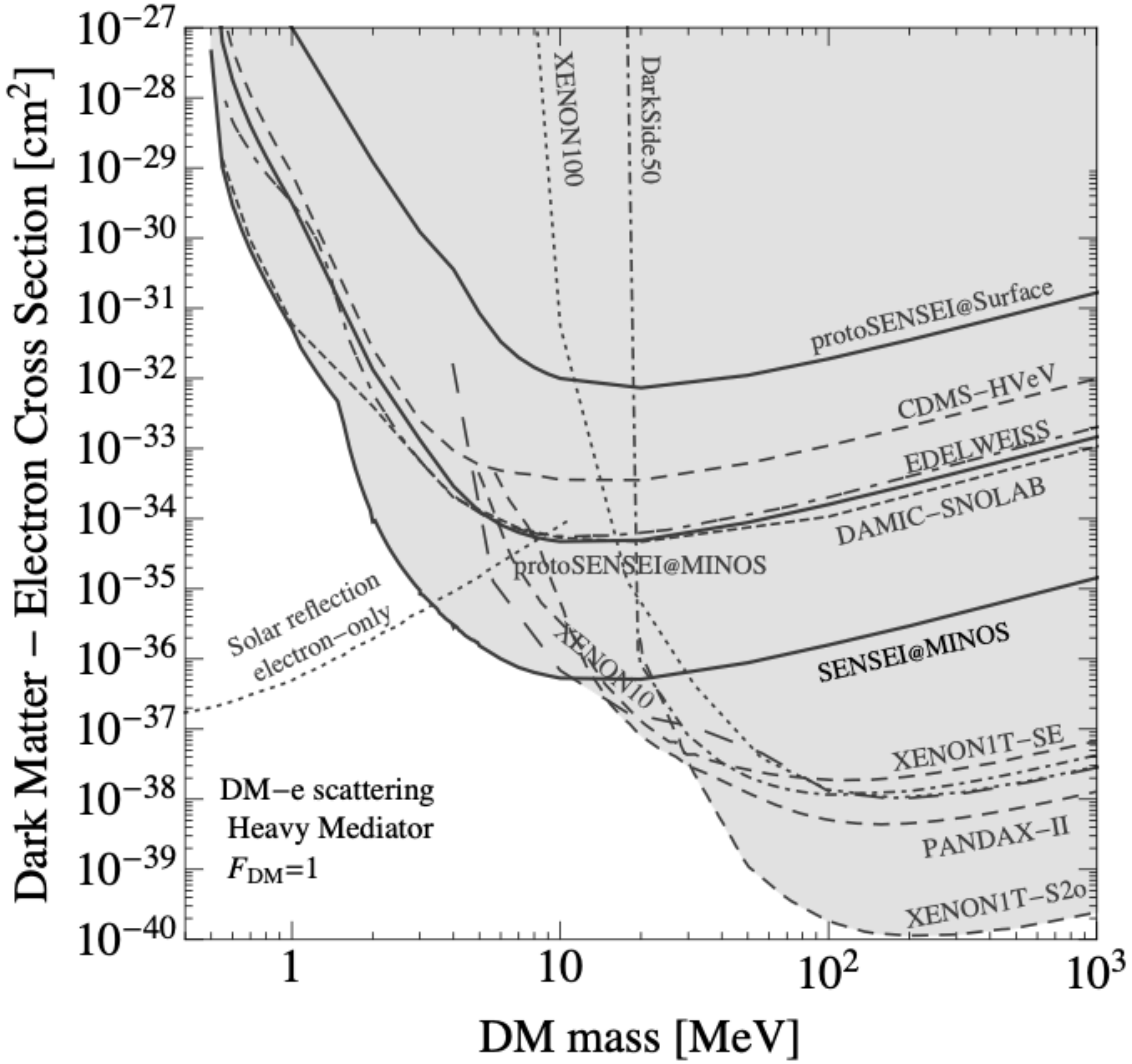
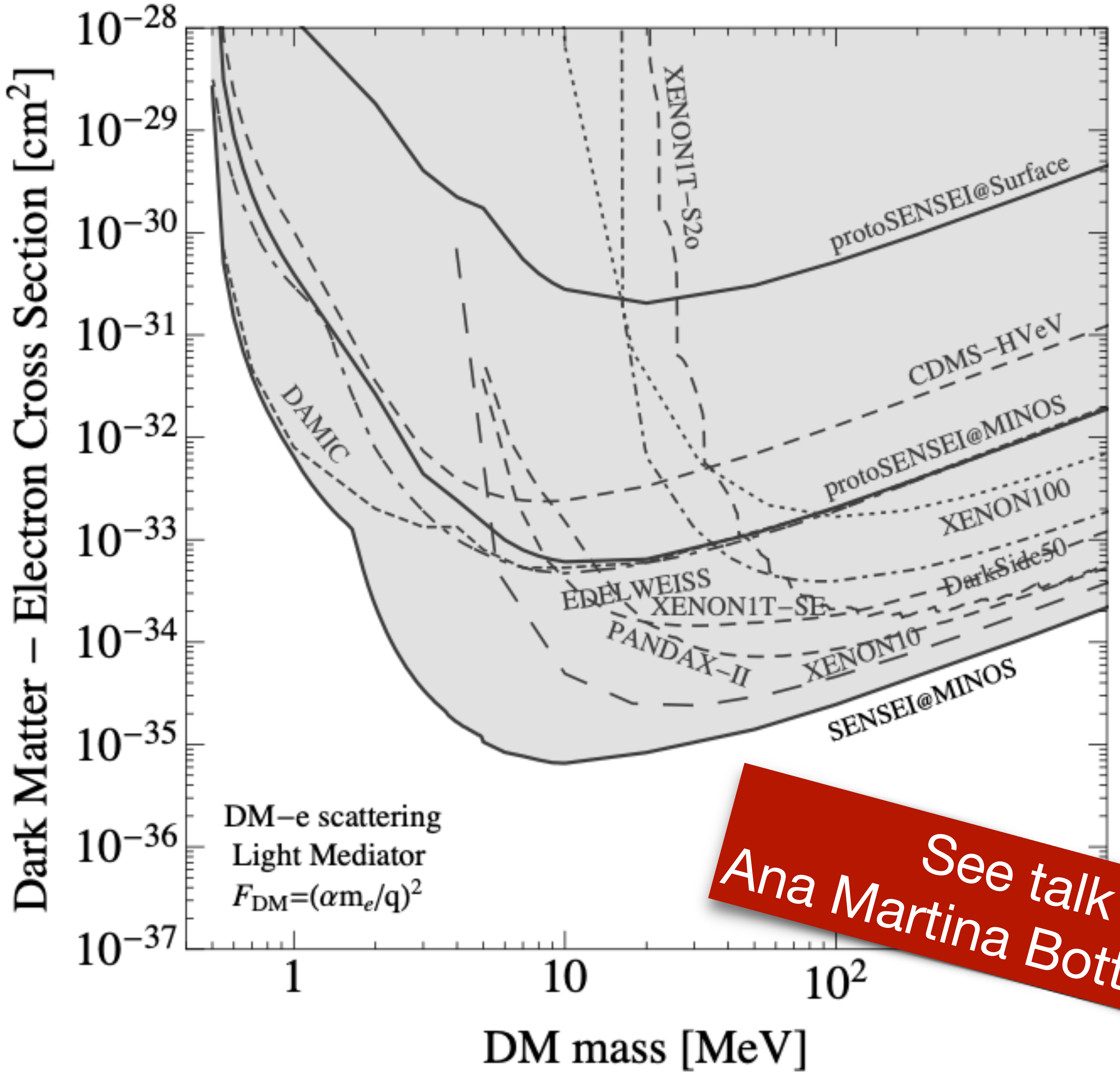
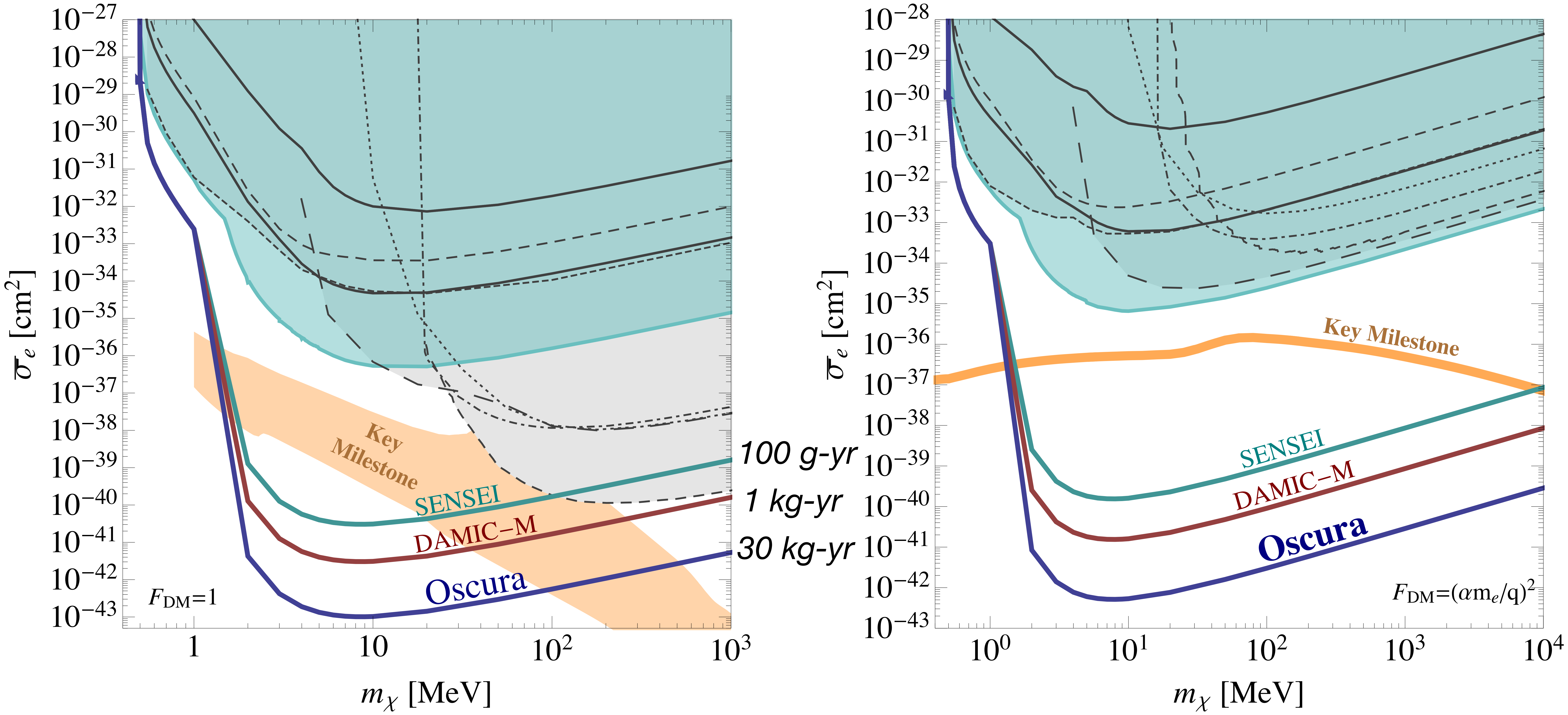
[arXiv:2203.08297]





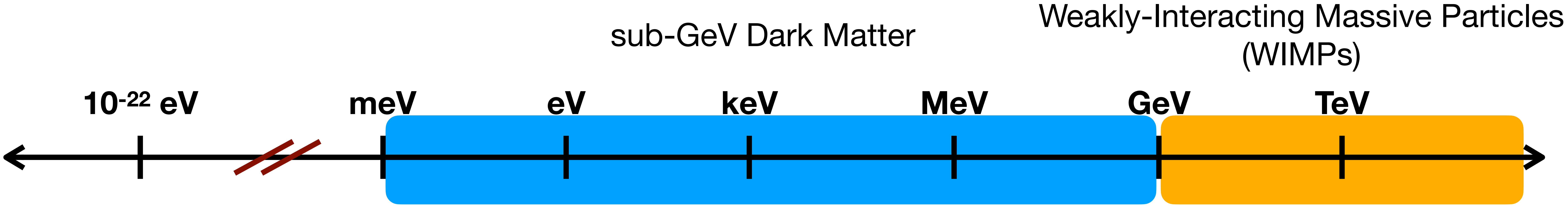
See talk by:
Ana Martina Botti (SENSEI)

Looking forward



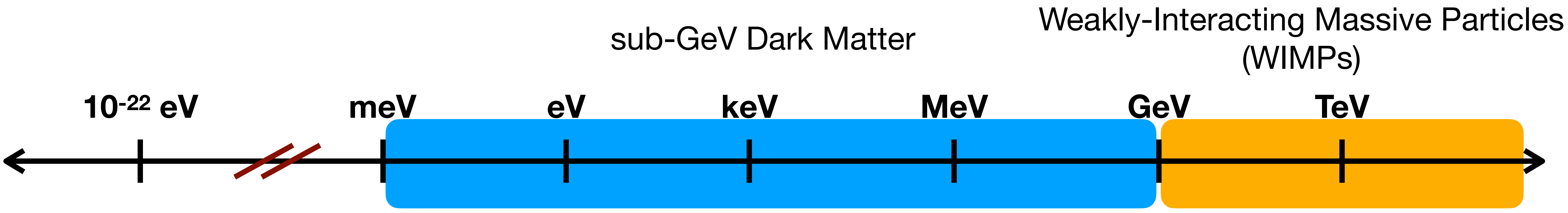
Projections for future Si Skipper-CCD experiments

Dark Matter Candidates



Noble Elements (TPCs, SPCs)
Solid-State Charge Detectors
Phonon Detectors (e.g. HeRALD)
Threshold Detectors

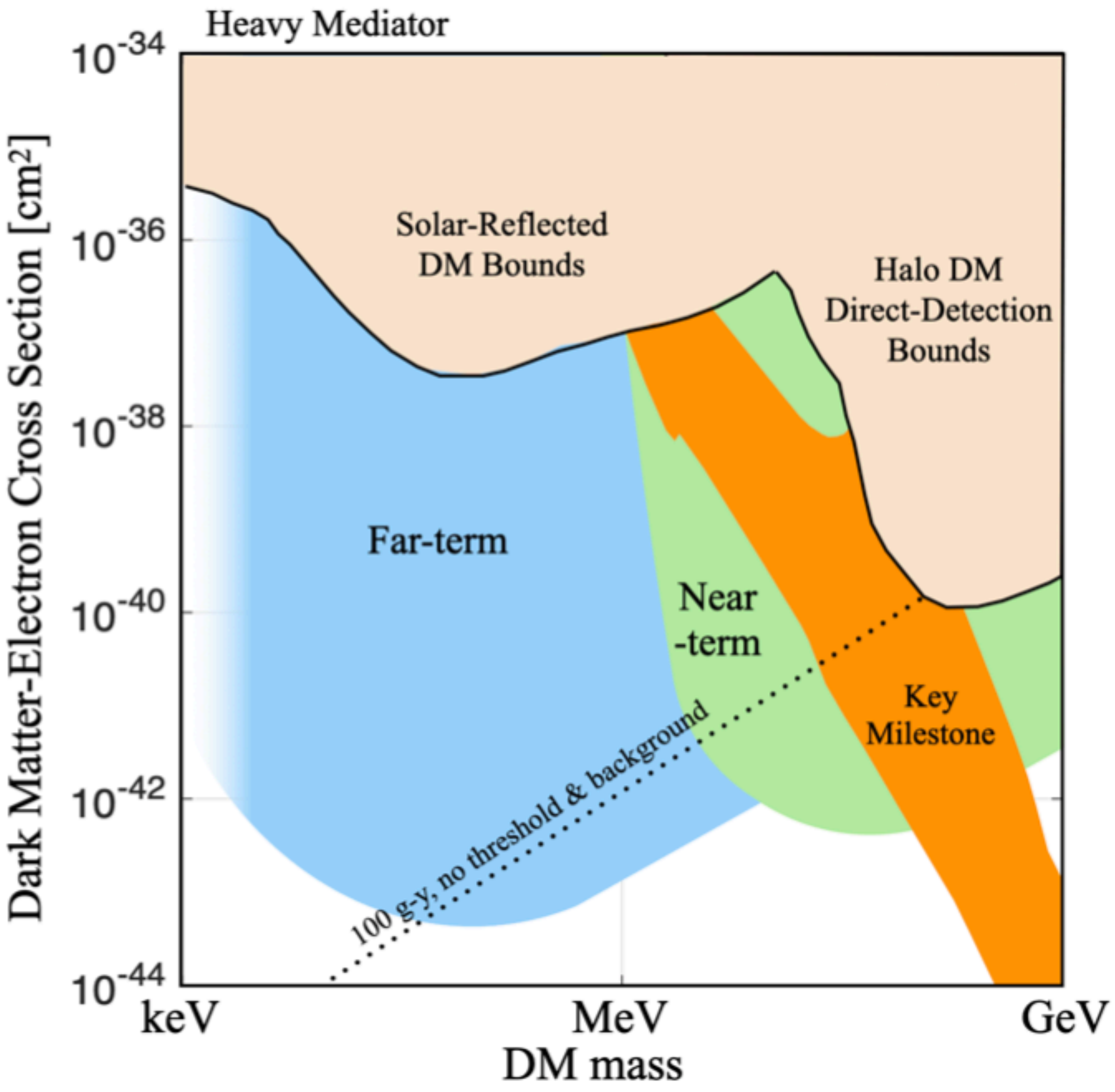
Dark Matter Candidates

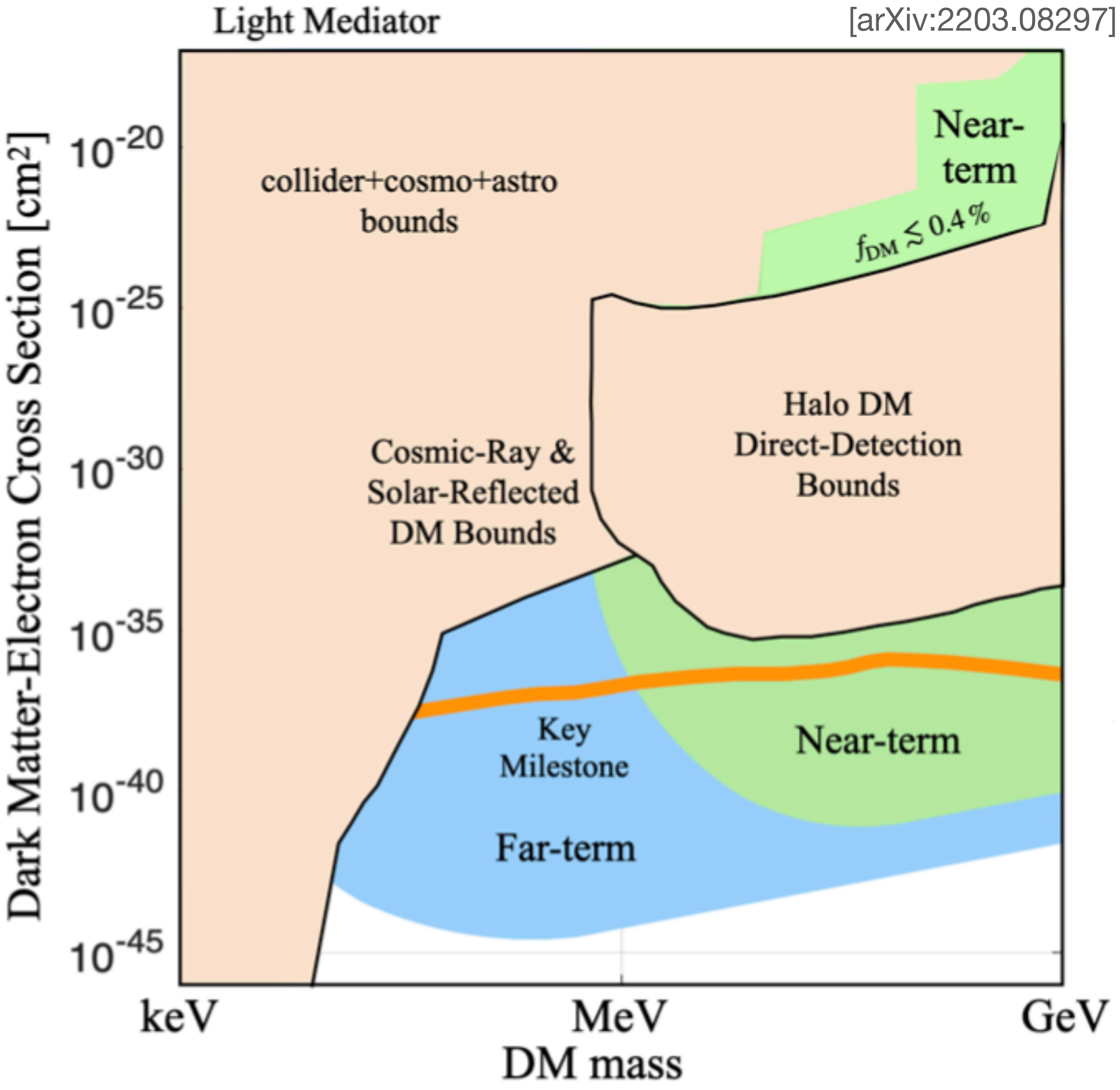


Superconductors
Low-Gap Materials (e.g. SPLENDOR)
Polar Materials (e.g. SPICE)
Superfluids
Single Molecular Magnets
Magnetic Bubble Chambers
…

Noble Elements (TPCs, SPCs)
Solid-State Charge Detectors
Phonon Detectors (e.g. HeRALD)
Threshold Detectors

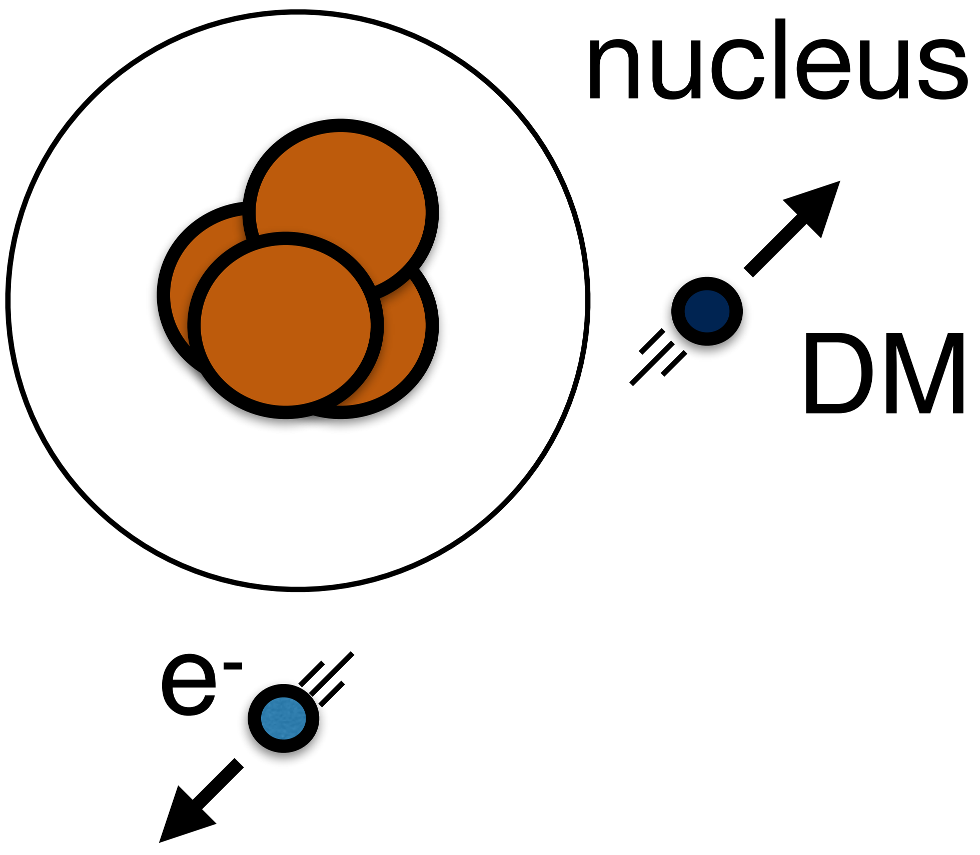
Outlook for sub-GeV DM direct detection



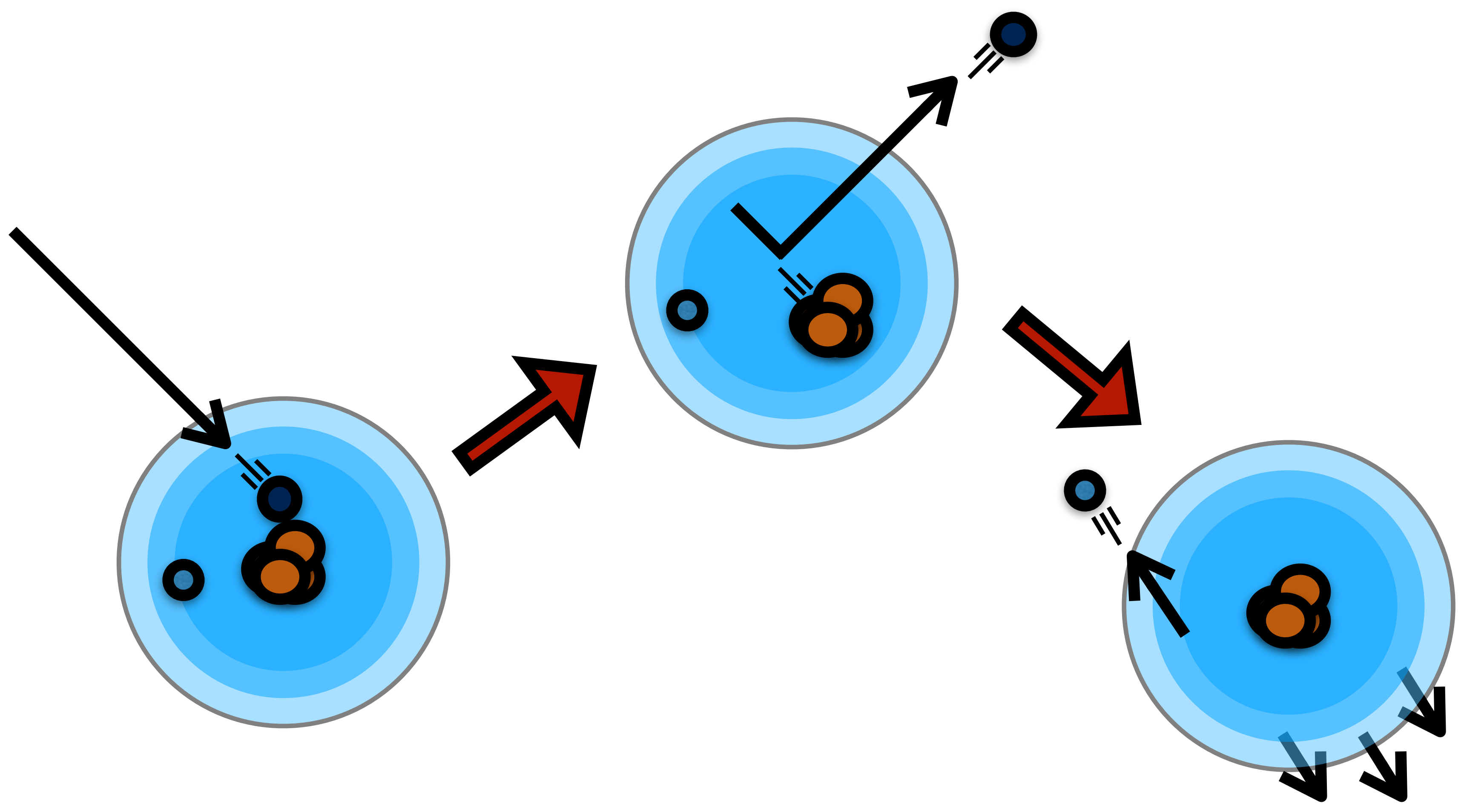


[arXiv:2203.08297]

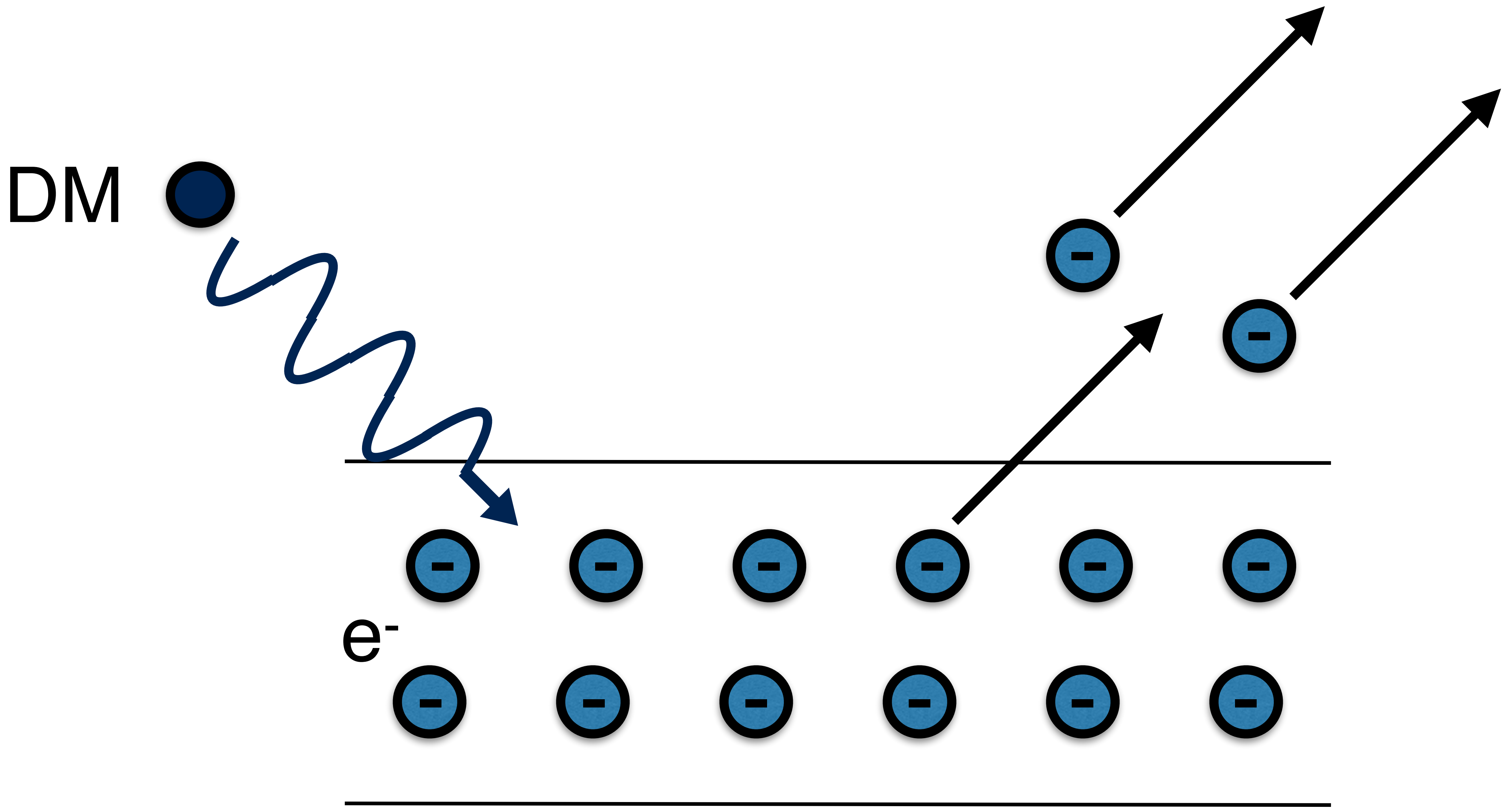
Other models



dark matter-
electron scattering



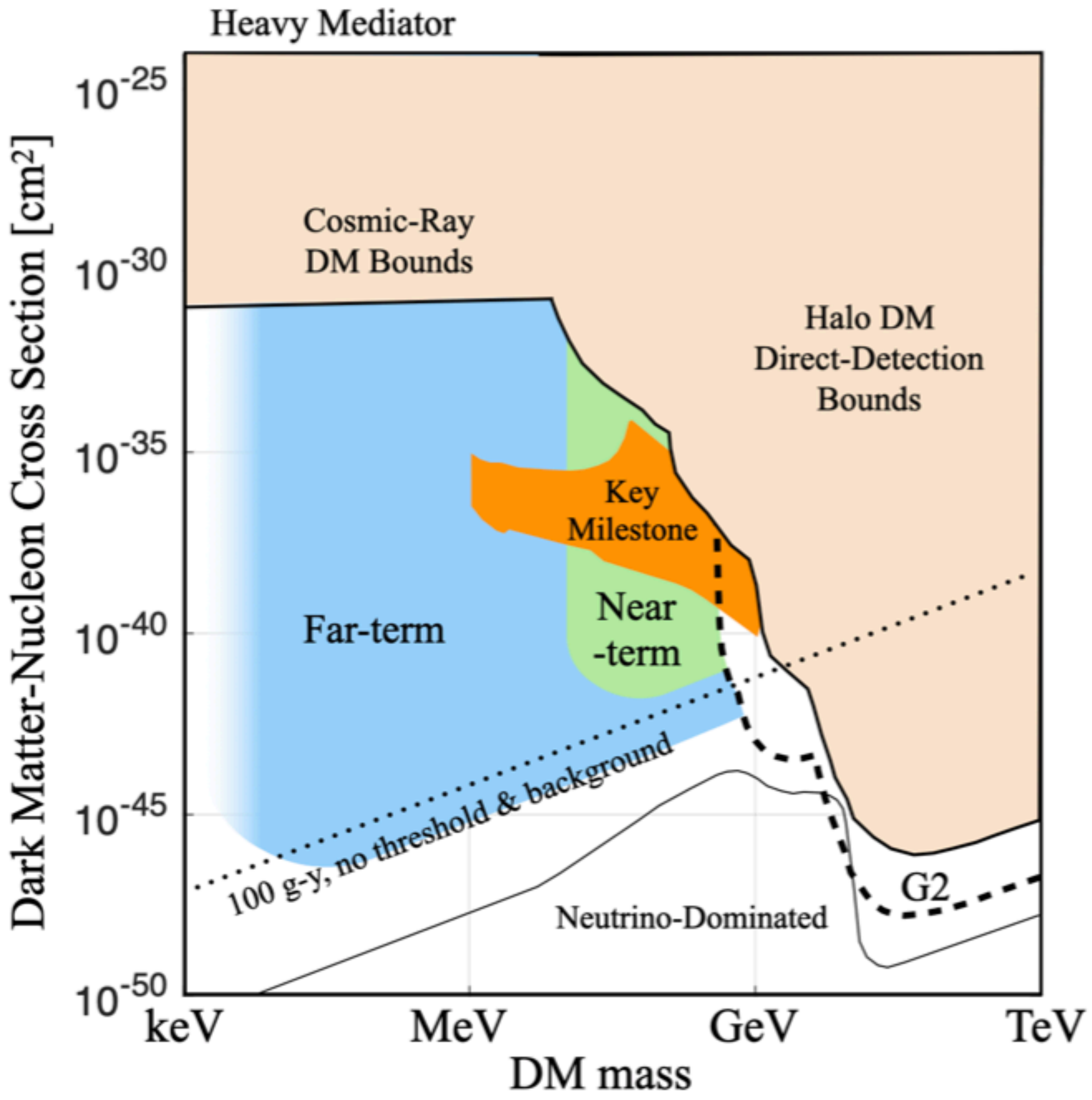
dark matter-nucleus scattering
(Migdal)



dark matter
absorption

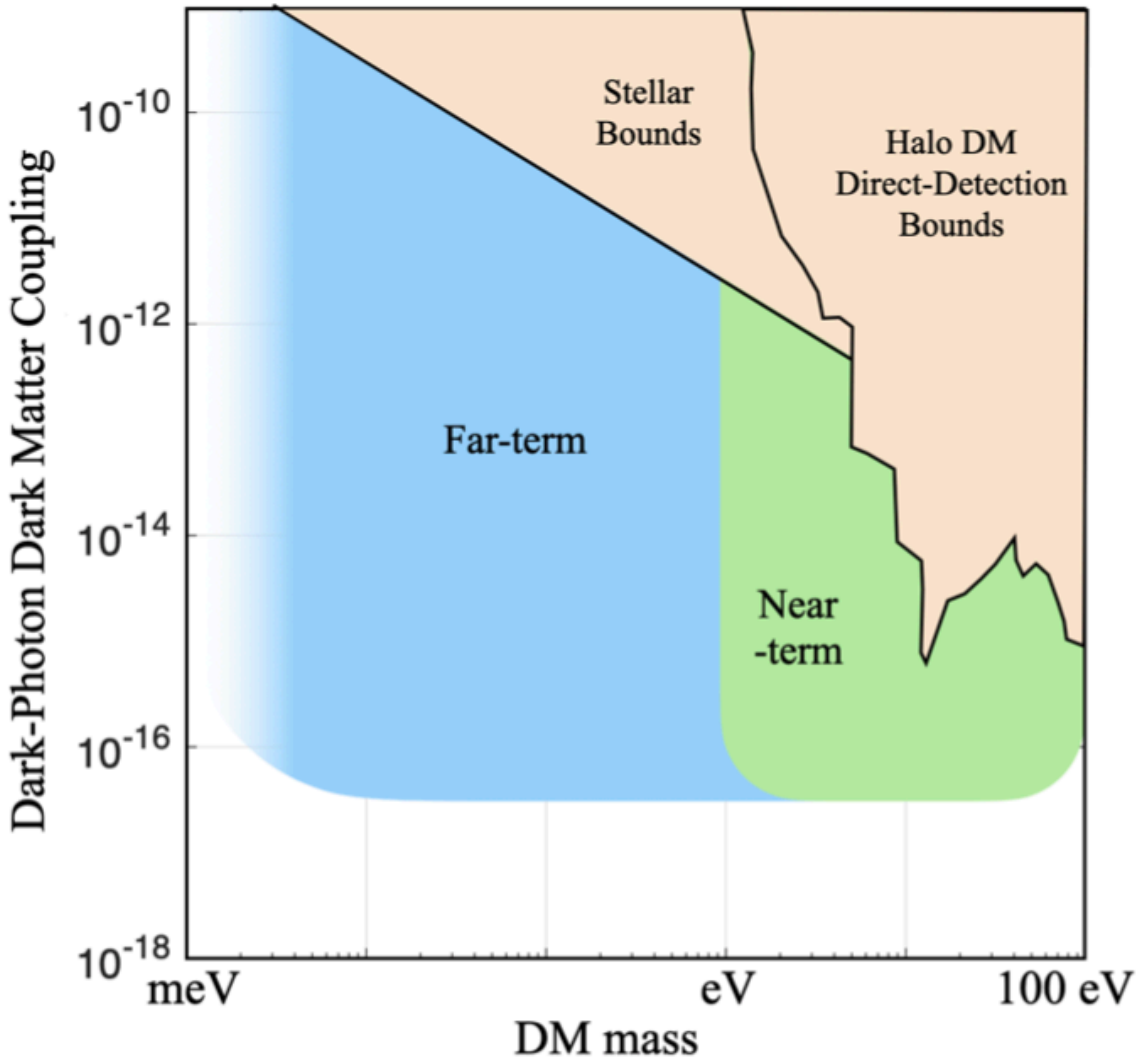
Other Models

DM-nucleon scattering

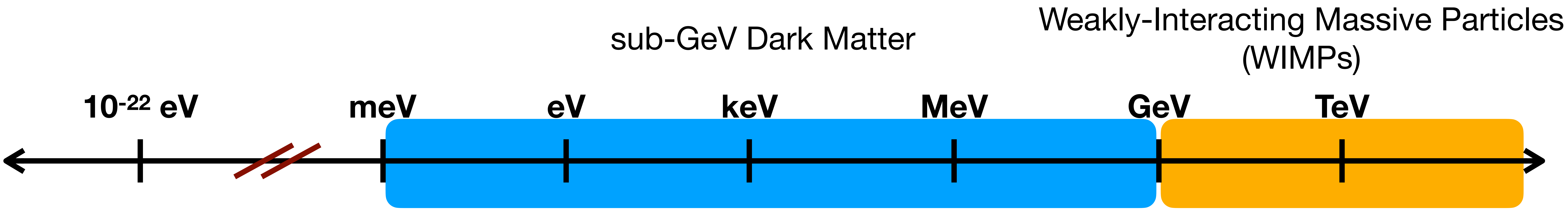


DM absorption

[arXiv:2203.08297]



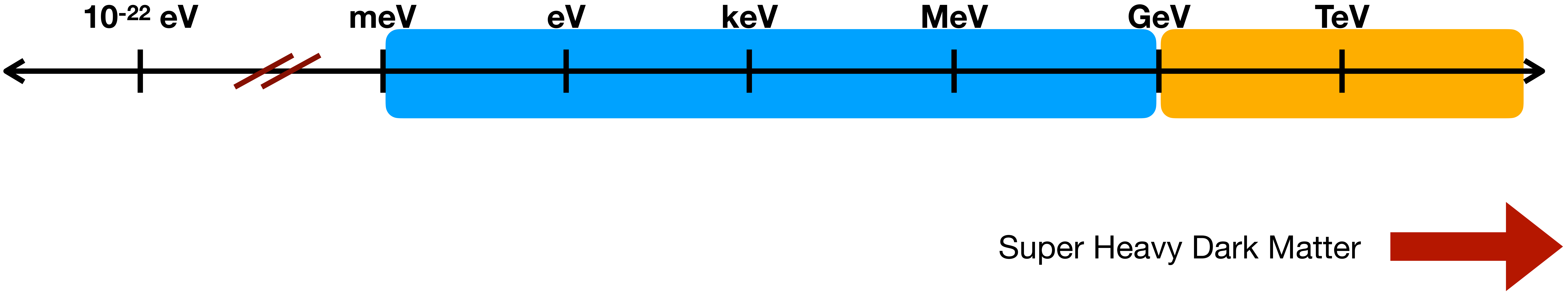
Dark Matter Candidates



sub-GeV Dark Matter

Weakly-Interacting Massive Particles
(WIMPs)

Dark Matter Candidates



sub-GeV Dark Matter

Weakly-Interacting Massive Particles
(WIMPs)

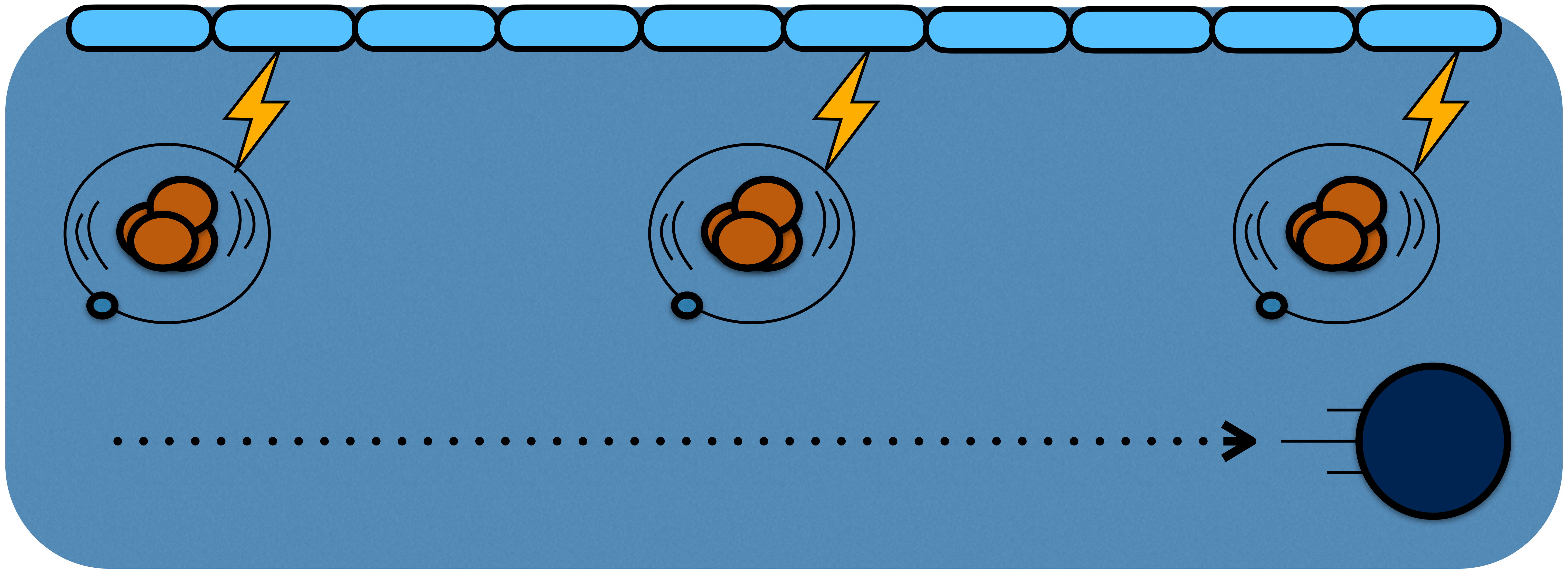
Super Heavy Dark Matter

Super-Heavy Dark Matter

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

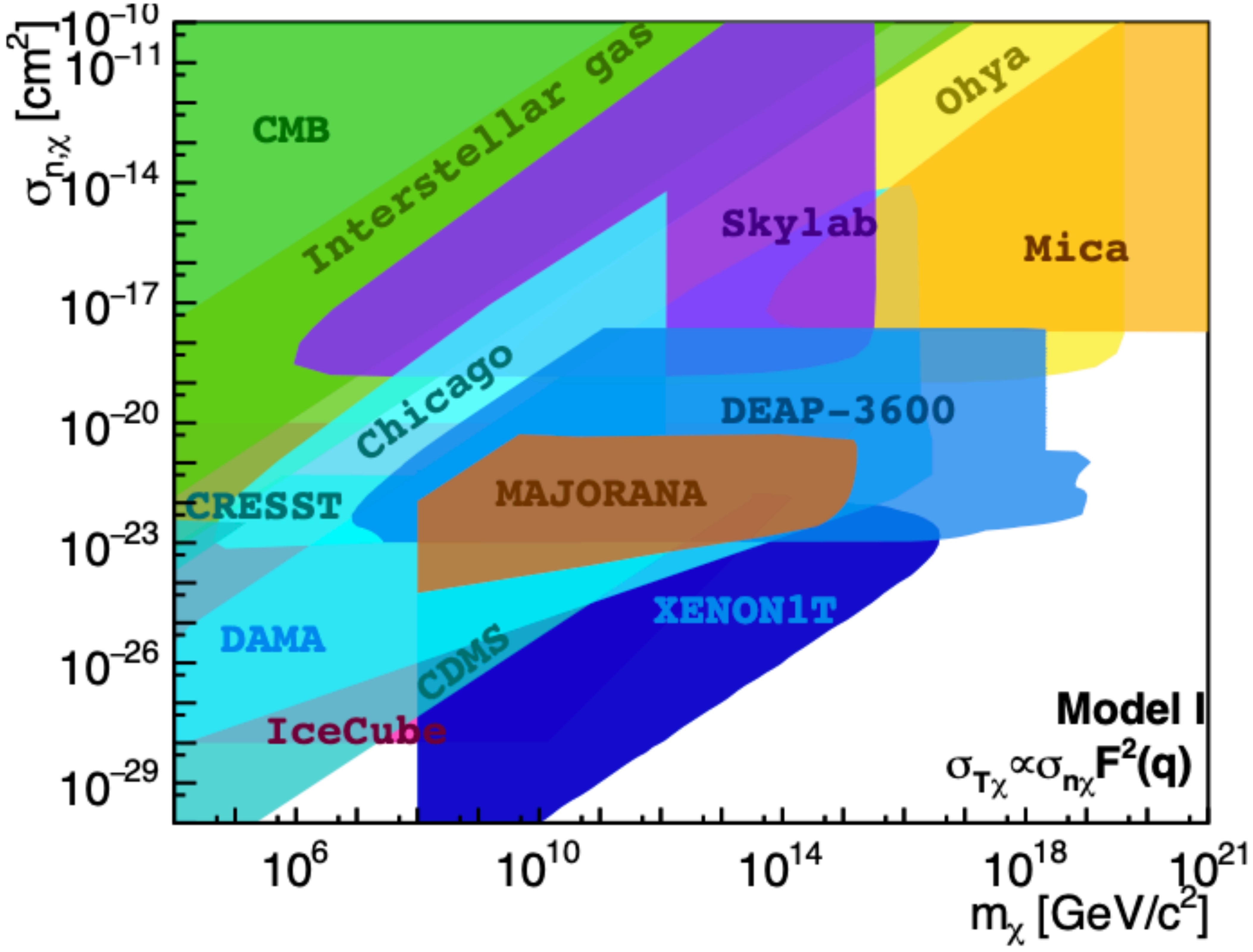
Super-Heavy Dark Matter

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

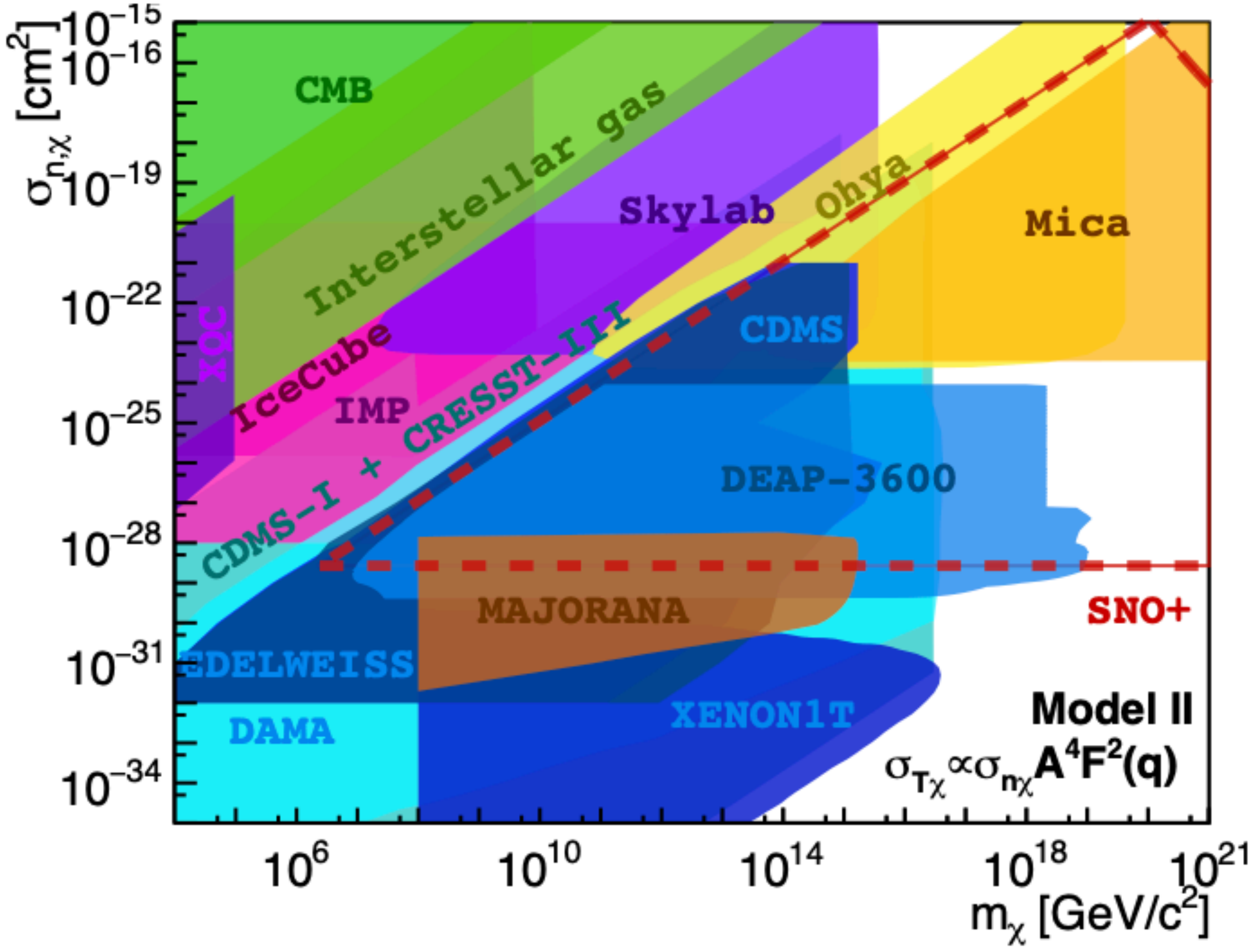


Super-Heavy Dark Matter

DM-nucleon scattering



DM-nucleus scattering



Summary

- There are a wide-range of DM candidates spanning many orders of magnitude in mass space
- Direct detection (and underground labs) can probe a large portion of parameter space
- Several new and upgraded experiments coming online in the next several years
- These include new technologies and techniques such as directional detection
- These experiments are sensitive to a wide-range of DM models and more!