

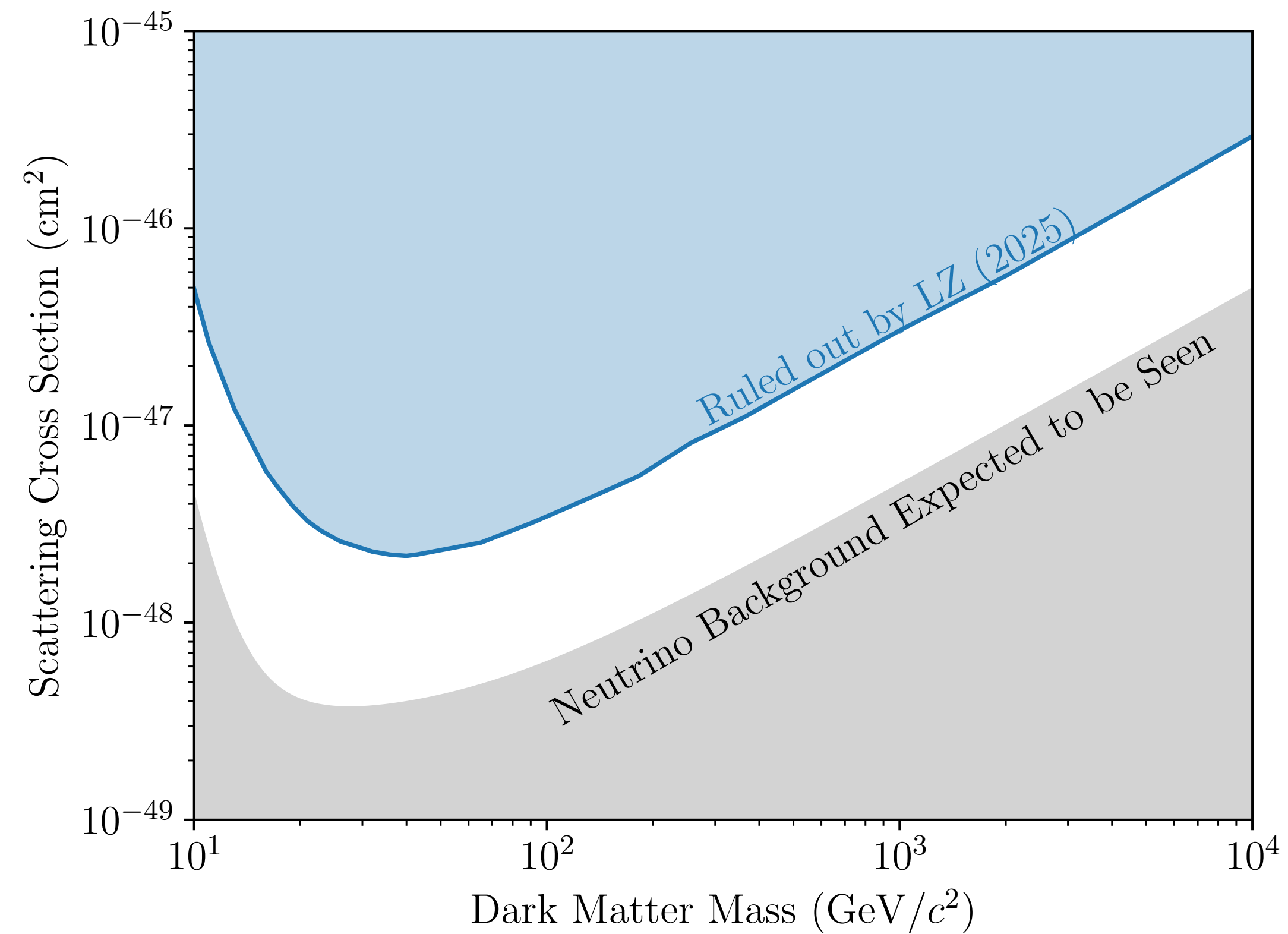


Illuminating the Dark Sector at Neutrino Experiments

JOSHUA BERGER - CETUP* 2026 - JUNE 30, 2026



Standard DM Story



Some of the many assumptions:

- Dark moving at roughly 300 km/s
- Scatters by bouncing off nucleus
- Single component of dark matter

LZ Collaboration: PRL135, 011802 (2025)

C. O'Hare: PRL 127, no.25, 251802 (2021)

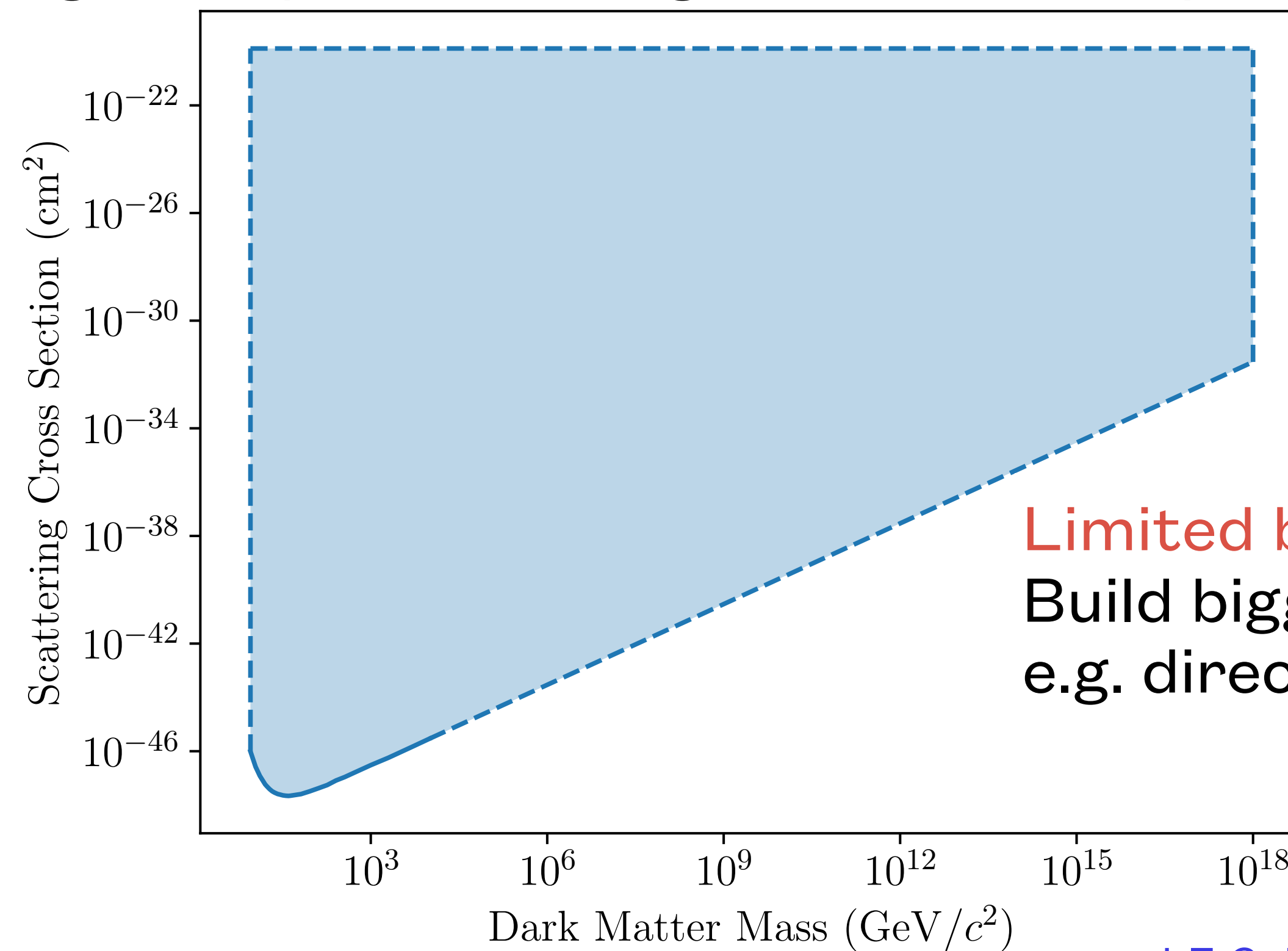
DM Direct Detection Landscape

Limited by overburden

e.g. multiple scattering / detectors in space

Limited by threshold

Build more sensitive



Limited by flux of DM

Build bigger

e.g. **DUNE**

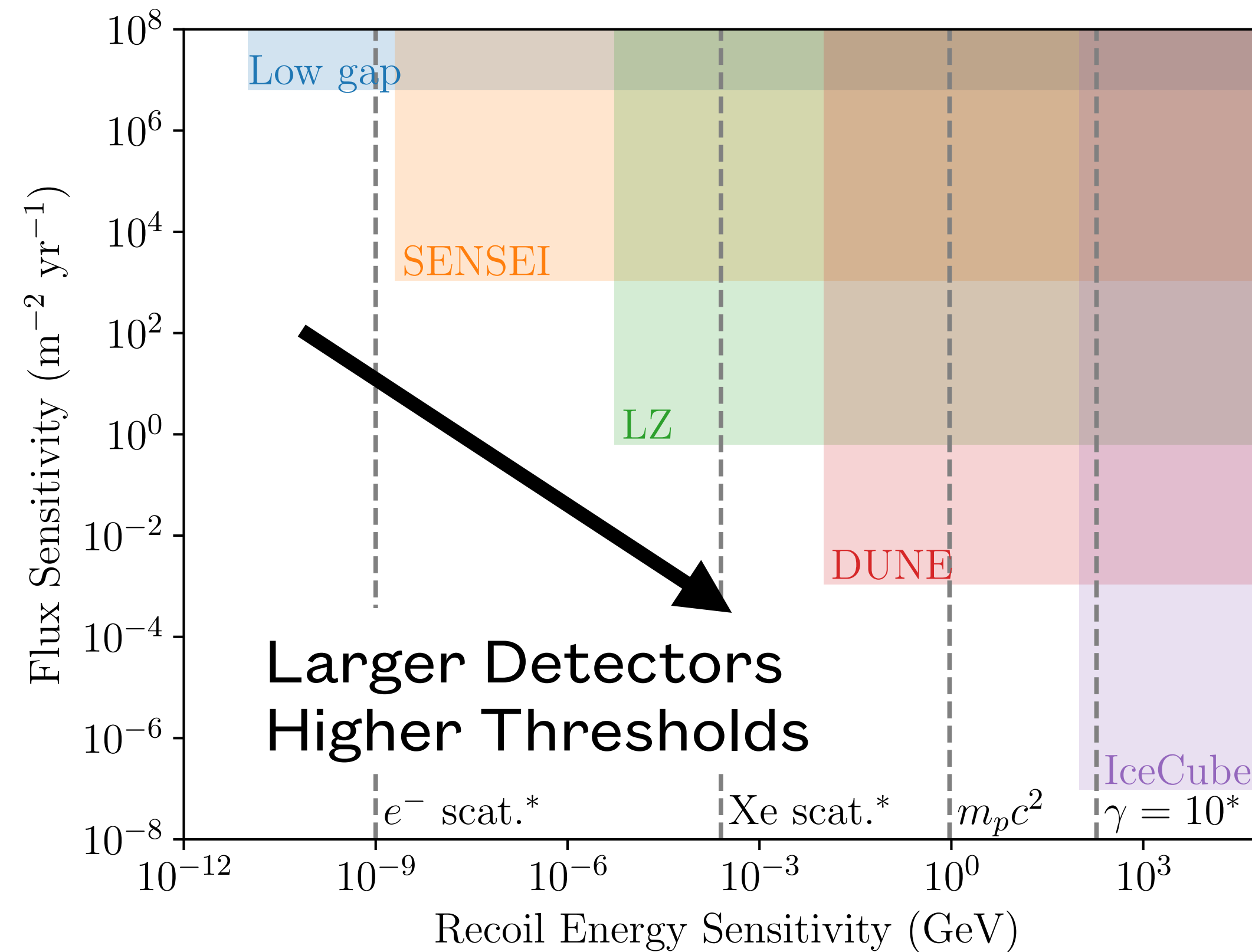
Limited by scattering rate

Build bigger, deal with ν

e.g. directional detection

LZ Collaboration: PRL135, 011802 (2025)

Another Point of View

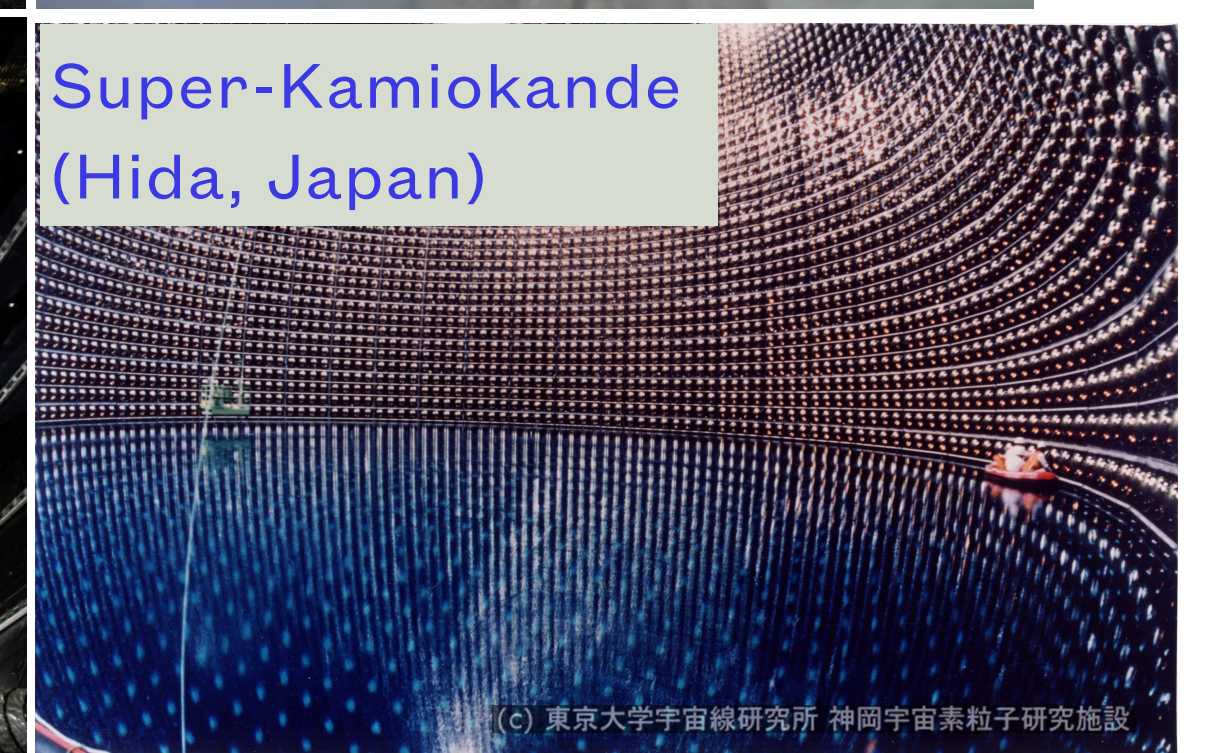
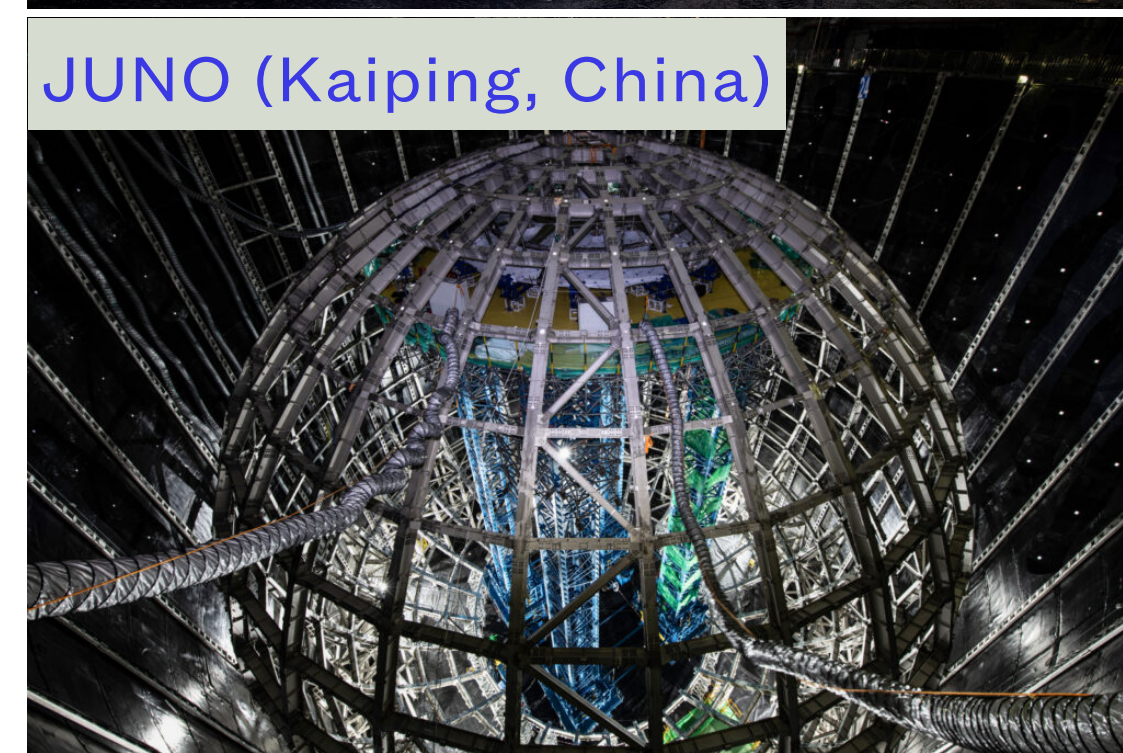
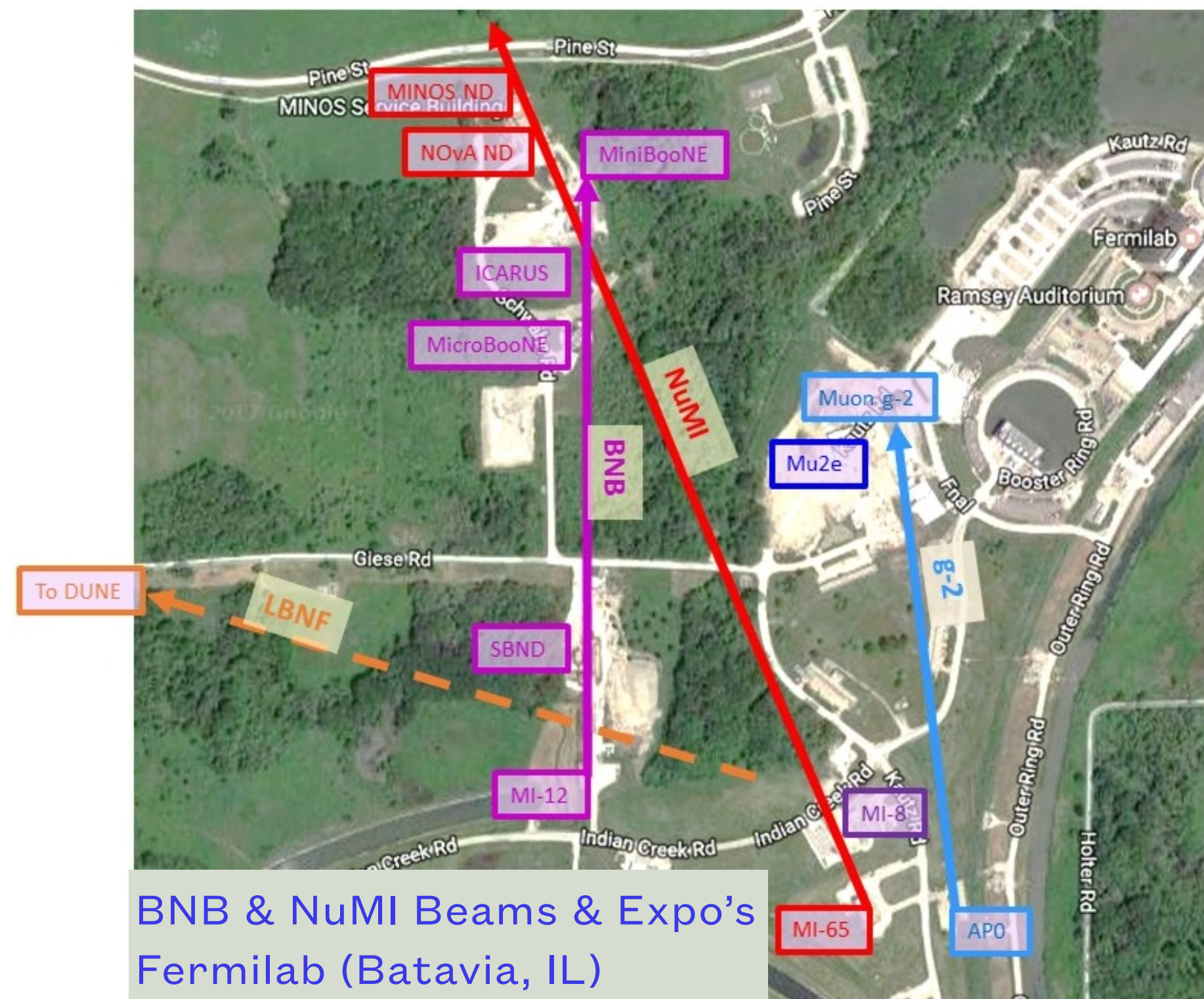


All viable possibilities for dark matter!

Roster of Neutrino Experiments

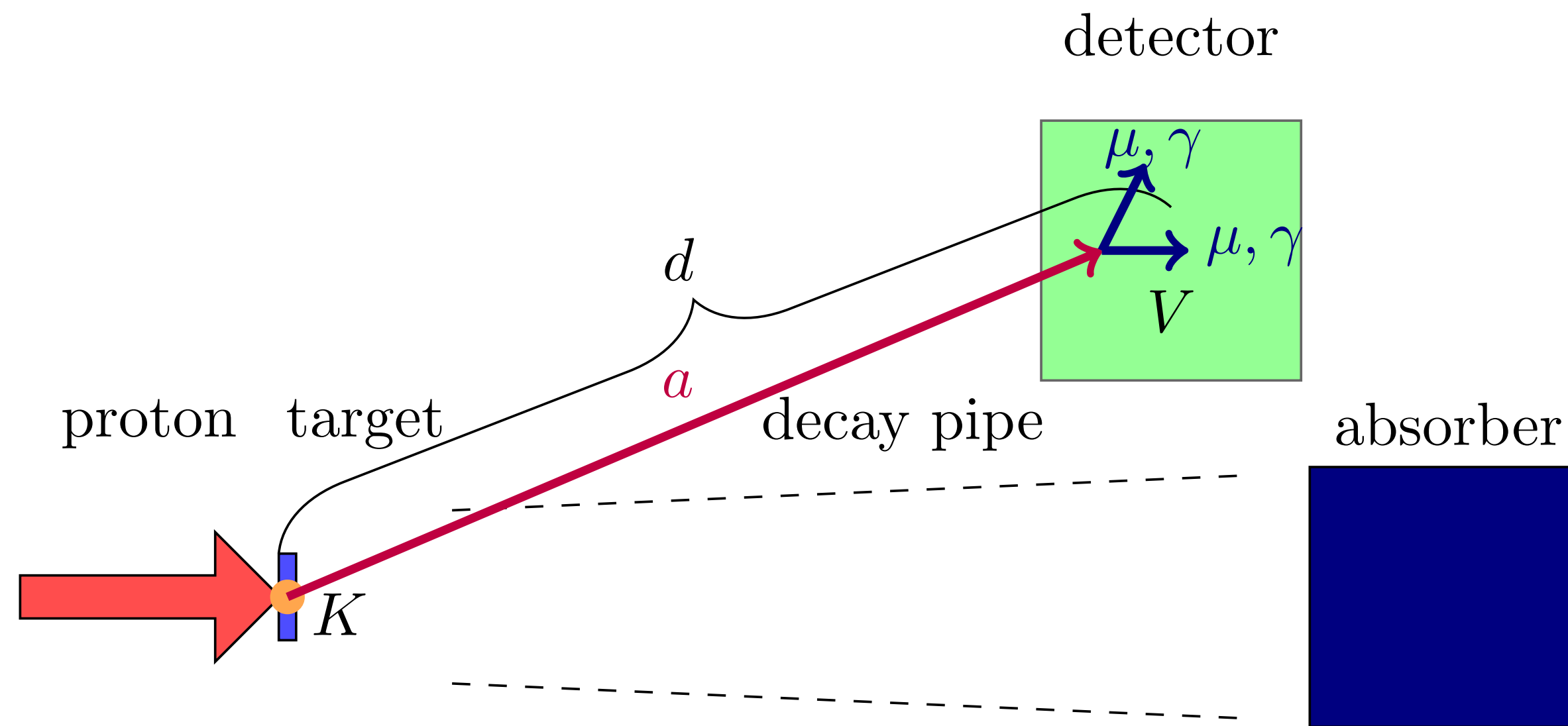
Short-Baseline Neutrino expt's:
Produce dark sector particles in beam

Large Volume Detectors:
Look for astrophysical/halo dark matter

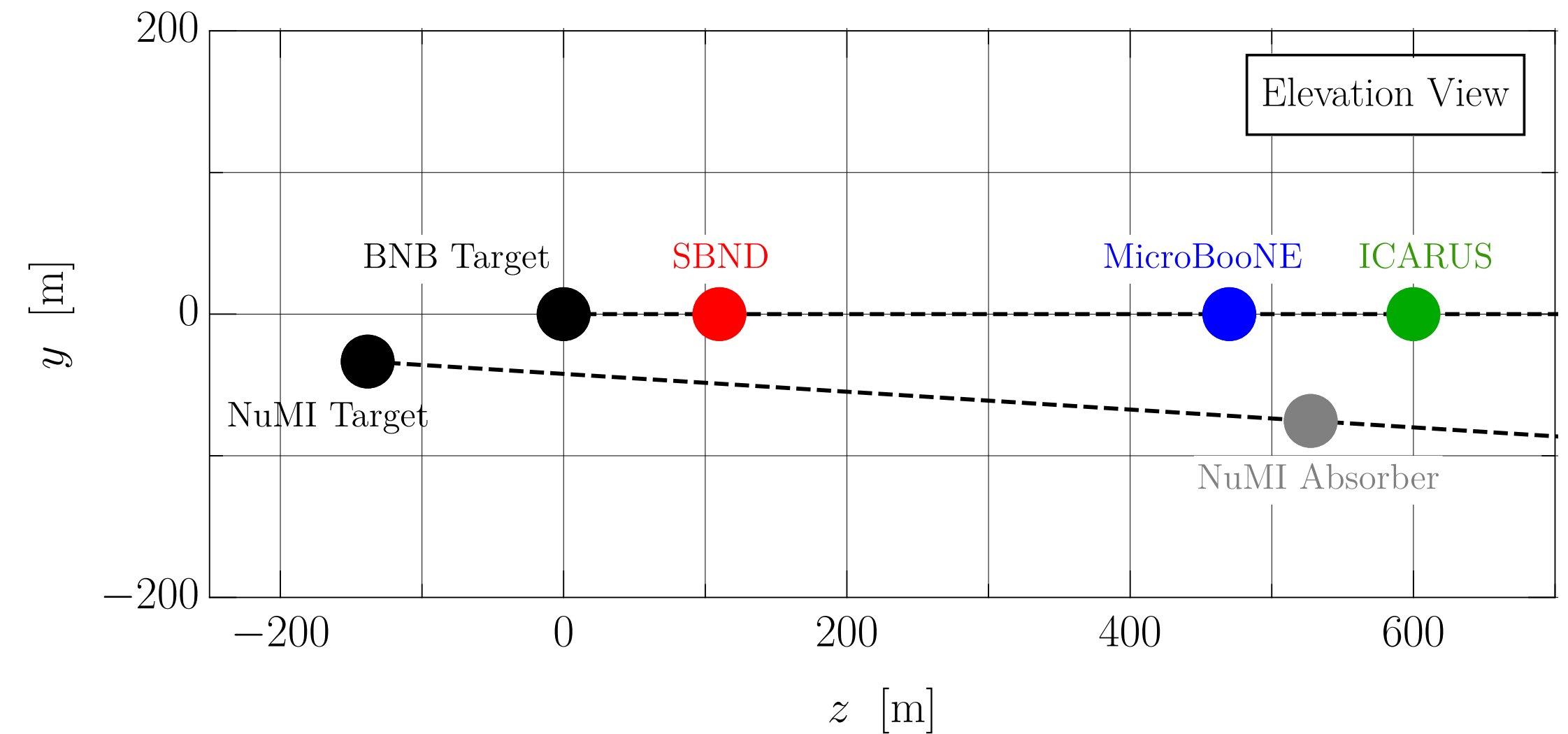


Dark Sectors in Short-Baseline Experiments

Looking for Dark Sector at ν Exp'ts



JB, Putnam: PRD 110 (2024) 5, 055035



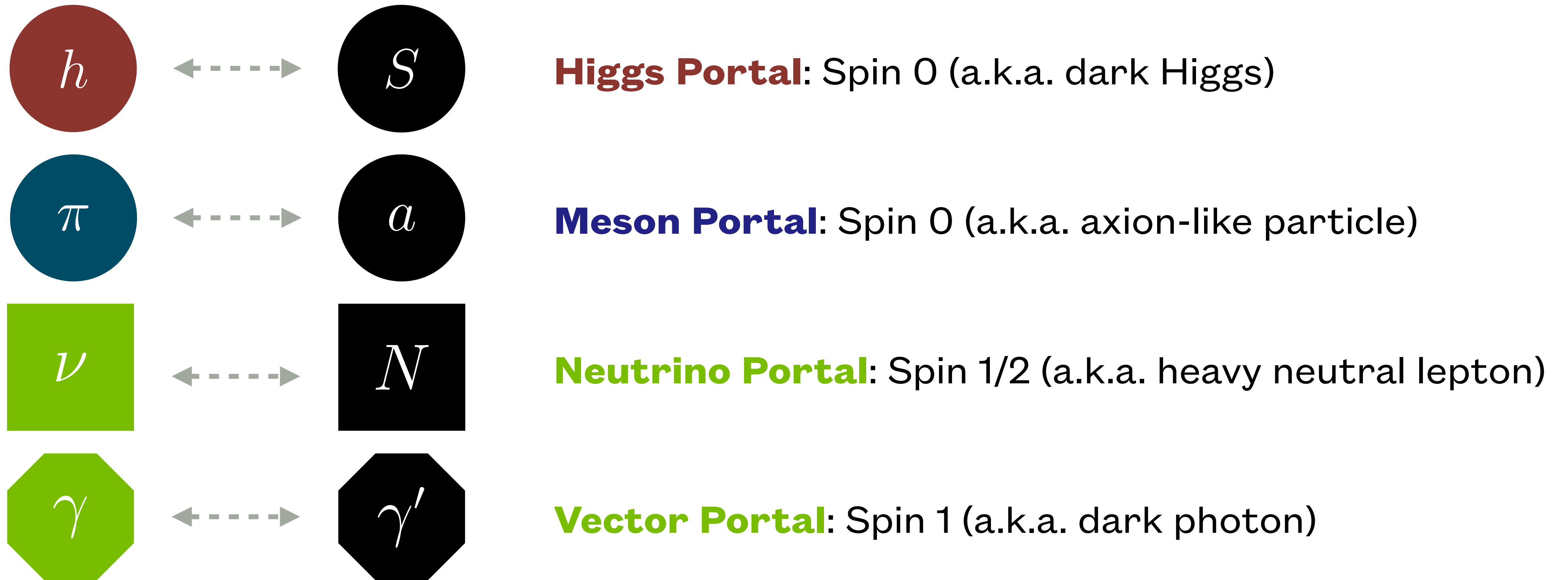
Batell, JB, Ismail: PRD 100, 115039 (2019)

SBN Experiments (but the lessons apply to other fixed target):

Two beams (8 GeV and 120 GeV)

10^{20} to $10^{21}+$ protons on target

What Kinds of Models?



Why (Heavy) Axions?

- Provides an elegant solution to the strong CP problem

$$\mathcal{L} \supset \left(c_3 \frac{\alpha_s}{8\pi f_a} a - \frac{\theta\alpha_s}{2\pi} \right) G^{a\mu\nu} \widetilde{G}_{\mu\nu}^a$$

- In this case, can't be dark matter: it's way too unstable
- But the “canonical” axion dark matter parameters with $m_a \sim 10^{-5}$ eV have a quality problem
- Planck-scale operators are expected to explicitly break PQ symmetry and spoil the dynamical mechanism whereby $\bar{\theta} < 10^{-10}$ as required by neutron EDM
- Lower f_a scale required for higher mass: heavy QCD axions can give a high quality axion

ALP Production, Carefully: Kaons

- Light quark sector has a $U(3)_V \times U(3)_A$ symmetry with anomalous $U(1)_A$
- Couplings and individual diagrams can depend on the choice of $U(3)_V \times U(3)_A$ basis
- Total amplitude should be (and is found to be) basis-independent
- Calculate within chiral perturbation theory keeping the full basis dependence that cancels at the end of the day

$$\frac{\text{Br}(K^\pm \rightarrow \pi^\pm a)}{\text{Br}(K_S^0 \rightarrow \pi^+ \pi^-)} = \frac{\tau_{K^\pm}}{\tau_{K_S}} \frac{2f_\pi^2 c_3^2}{f_a^2} \left(\frac{m_K^2 - m_a^2}{4m_K^2 - 3m_a^2 - m_\pi^2} \right)^2 \sqrt{\frac{\lambda(1, m_\pi^2/m_K^2, m_a^2/m_K^2)}{1 - 4m_\pi^2/m_K^2}}$$
$$\text{Br}(K_S^0 \rightarrow \pi^0 a) \approx \frac{\tau_{K_S}}{\tau_{K^\pm}} \text{Br}(K^+ \rightarrow \pi^+ a) \ll \text{Br}(K^+ \rightarrow \pi^+ a)$$

Bauer, Neubert, Renner, Schnubel, Thamm: PRL 127 (2021) 8, 081803
JB, Putnam: PRD 110 (2024) 5, 055035

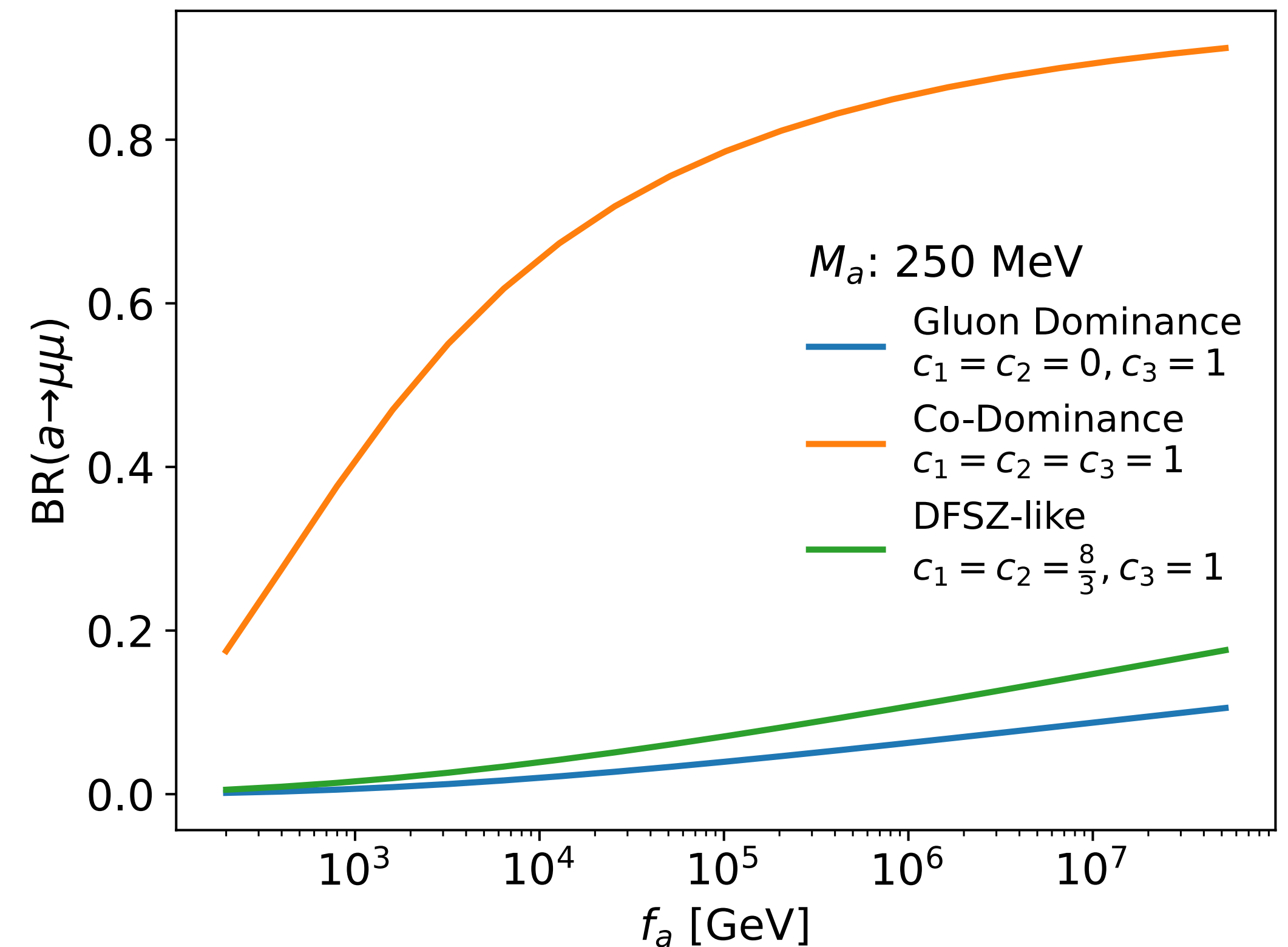
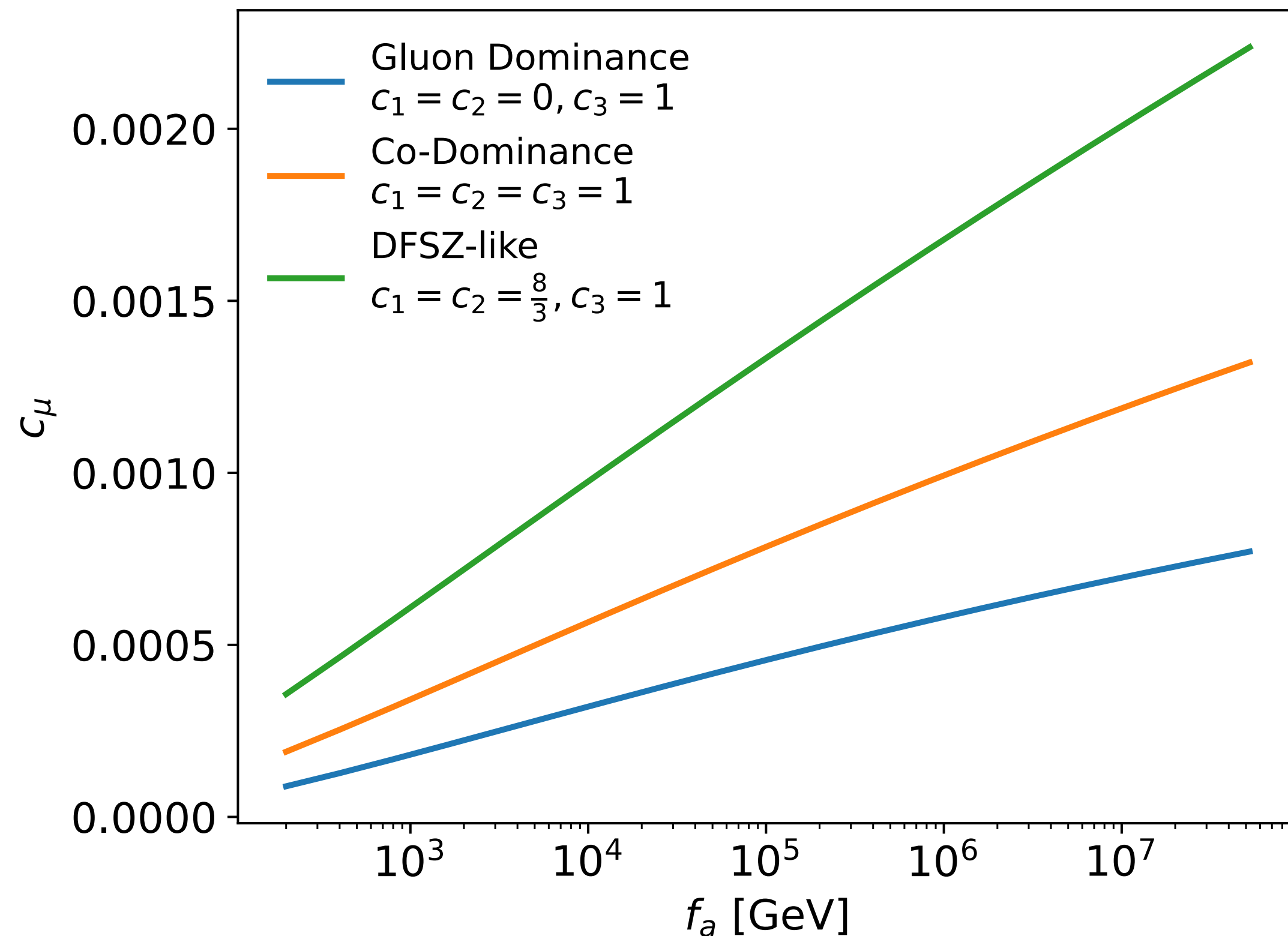
ALP Production: Neutral Mesons

- Axions, being neutral pseudo-scalars, mix with neutral pseudo-scalar mesons, i.e. π^0, η, η'
- Two issues here, one theoretical and one procedural
- Theory issue: mixing angle is quark flavor basis dependent again!
- Answer: sum over all diagrams should be baked into your production, rather than simply rescaling neutral meson production rates by θ^2

See Kyselov, Mrenna, Ouchynniov: PRD 112 (2025) 055033

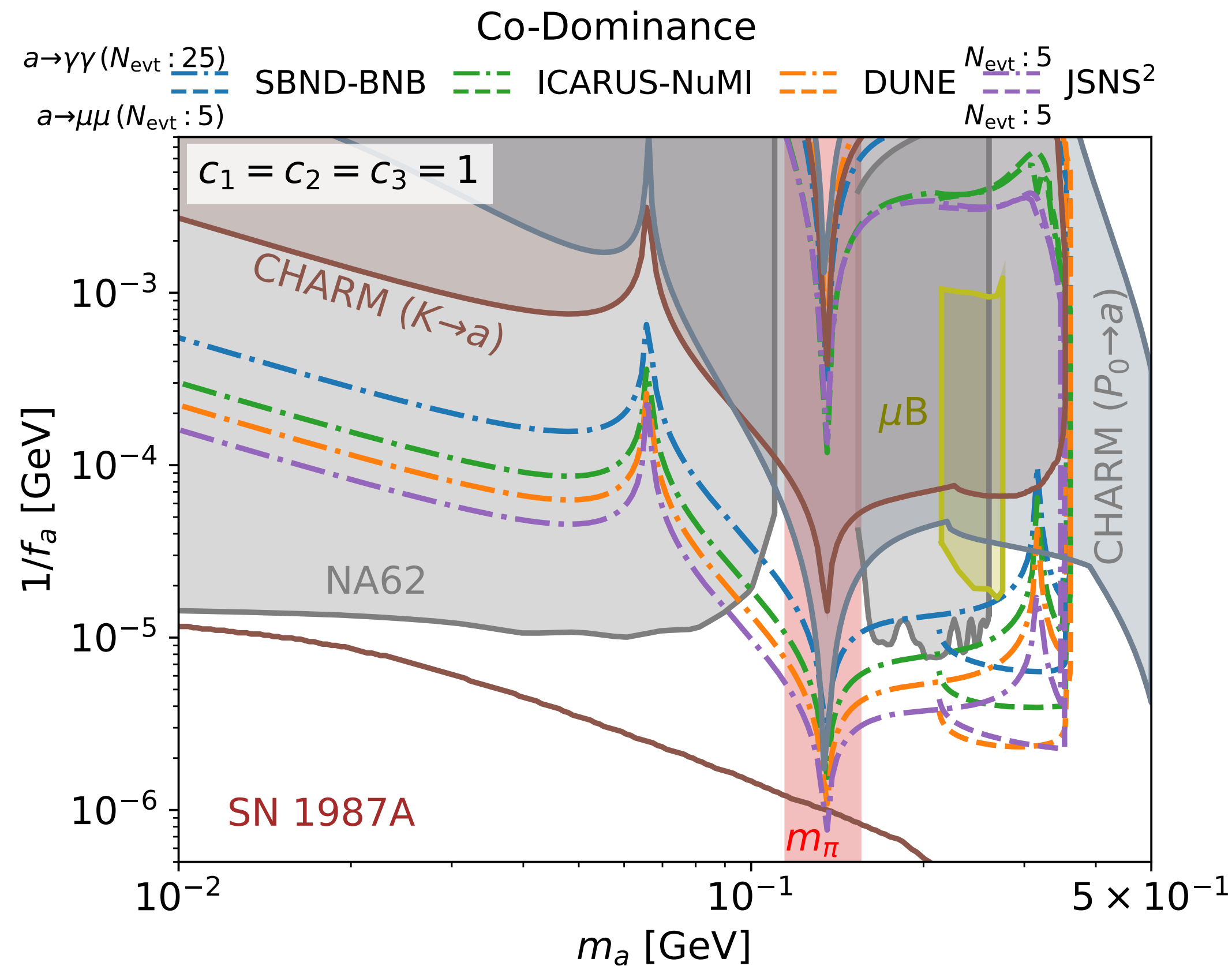
- Procedural issue: most simulations rely on Pythia, which assumes a single proton-nucleon interaction, but the targets are usually thick

ALP: Loop-induced Couplings to $\mu\mu$

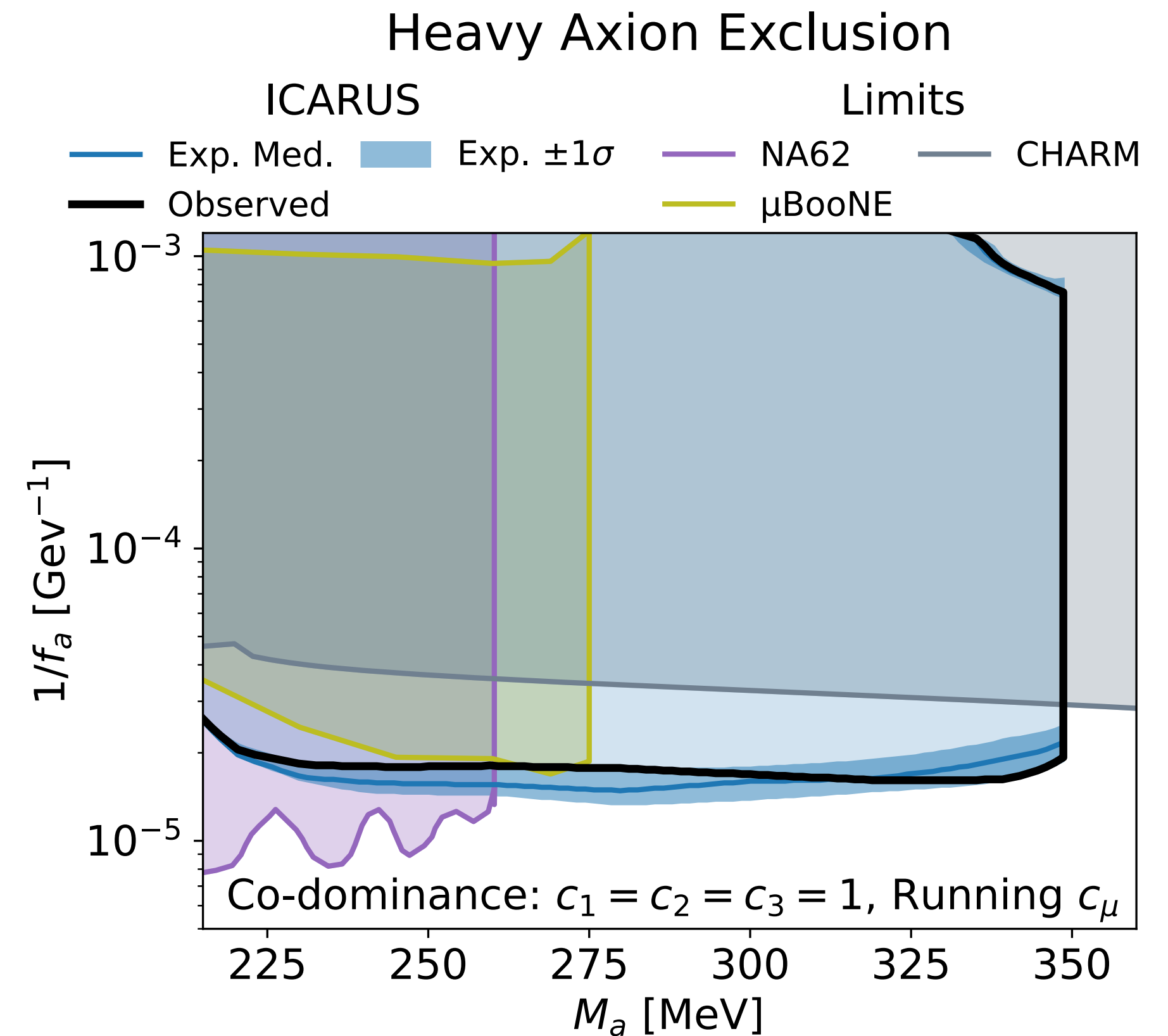


JB, Putnam: PRD110 (2024) 5, 055035
Co, Kumar, Liu: JHEP 111 (2023)

Projected/Actual Sensitivity



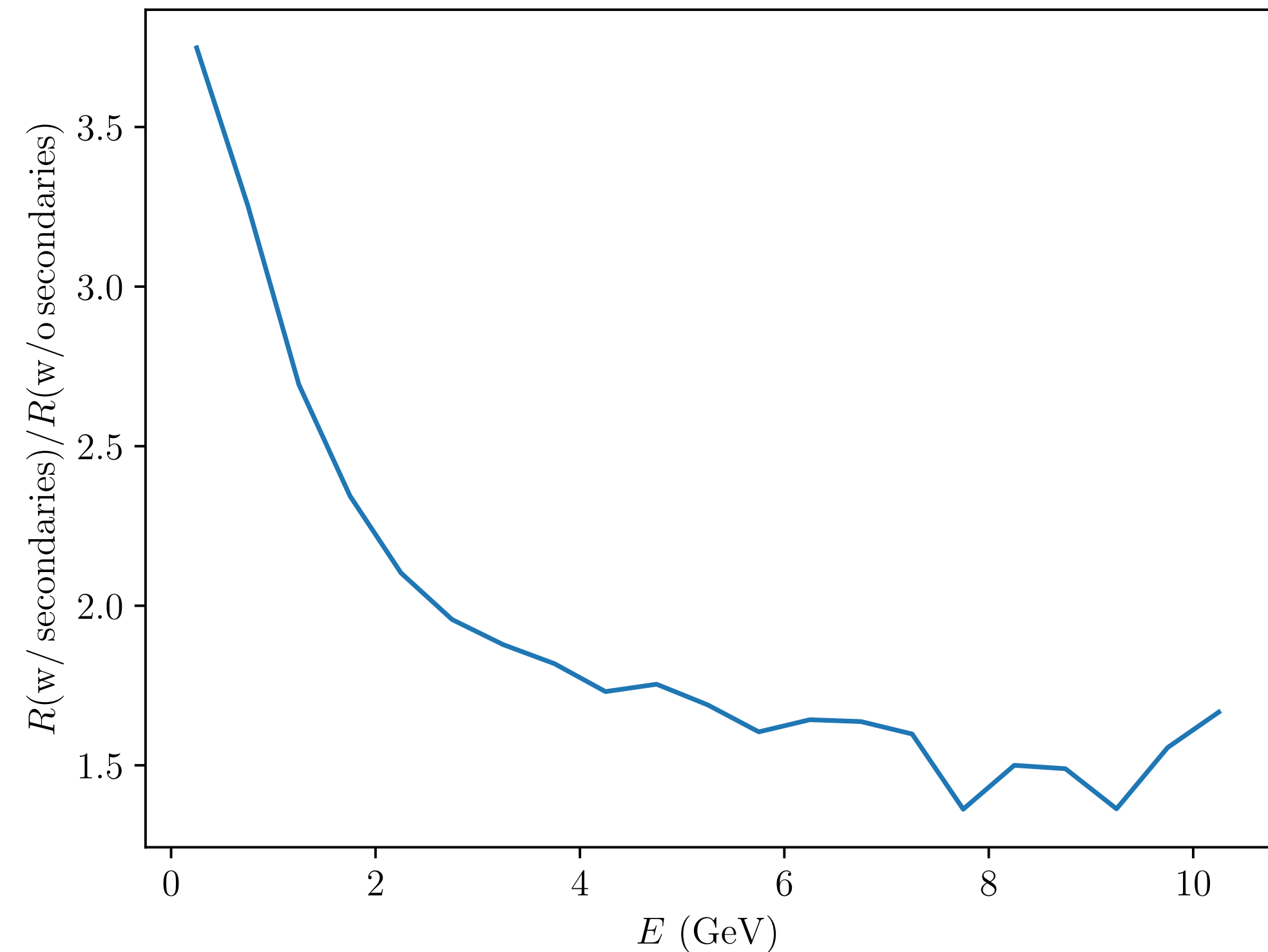
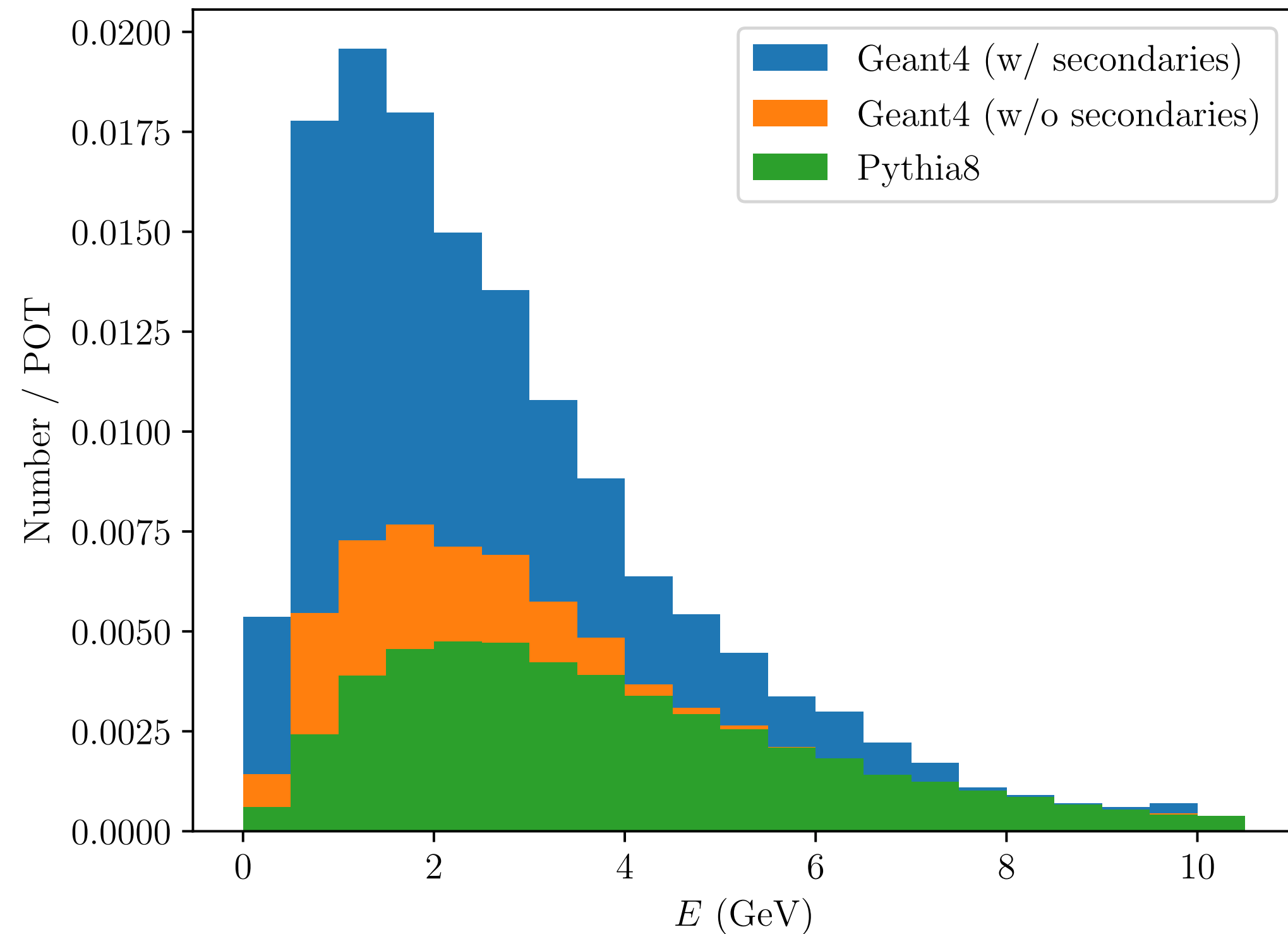
JB, Putnam: PRD 110 (2024) 5, 055035



ICARUS: PRL 134, 151801 (2025)

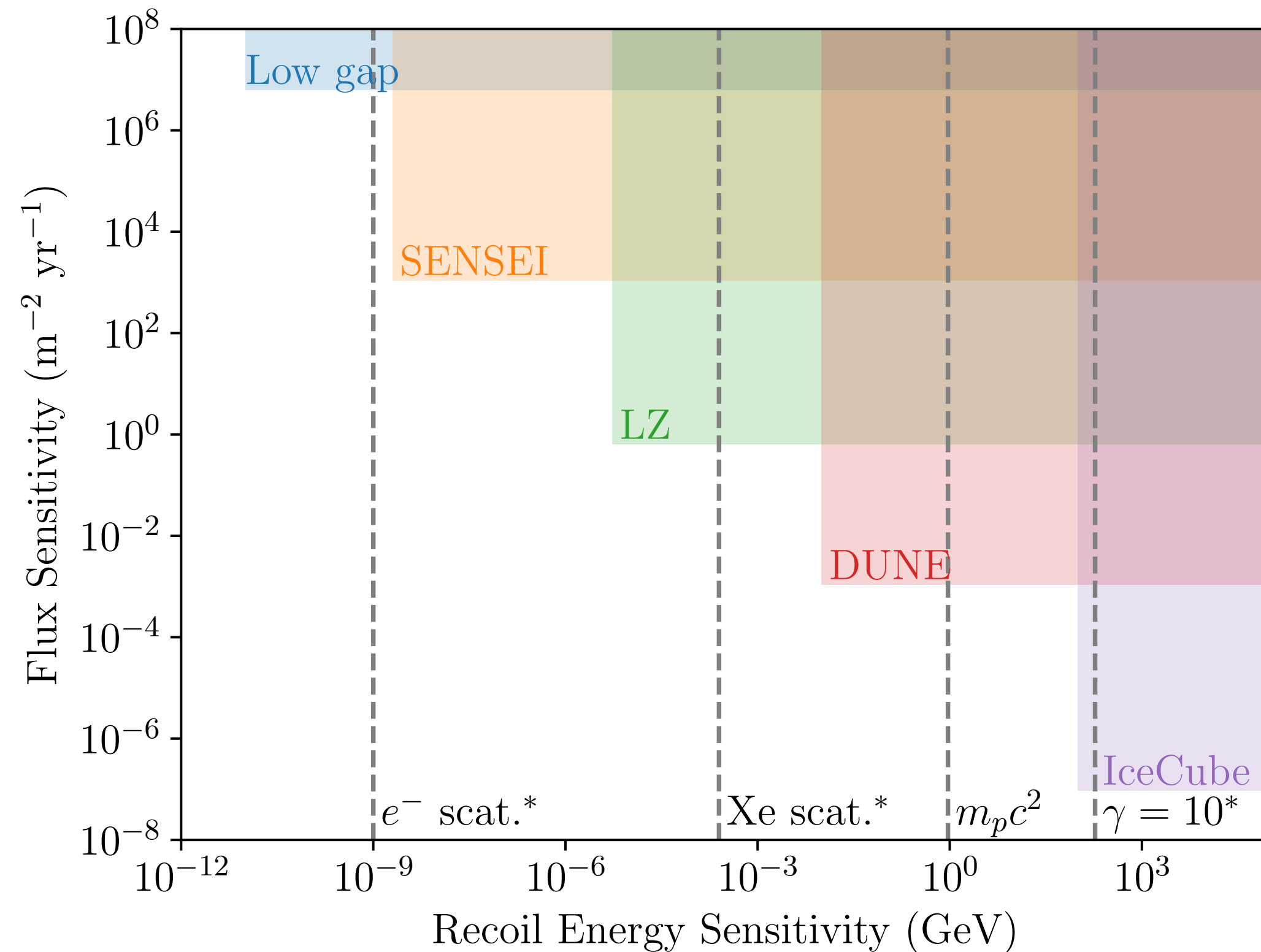
Do Secondaries Matter?

Fine Print: 120 GeV protons on NuMI-like carbon target producing π^0 heading with θ toward ICARUS



Boosted Dark Matter Signals

Why Higher Recoil Energy?



Halo kinematics are fixed by the **virial theorem**

$$\text{Local expected DM: } v^2 \sim \frac{GM}{r} \implies v \sim 10^{-3} c$$

Recoil energy is limited to few 100 keV

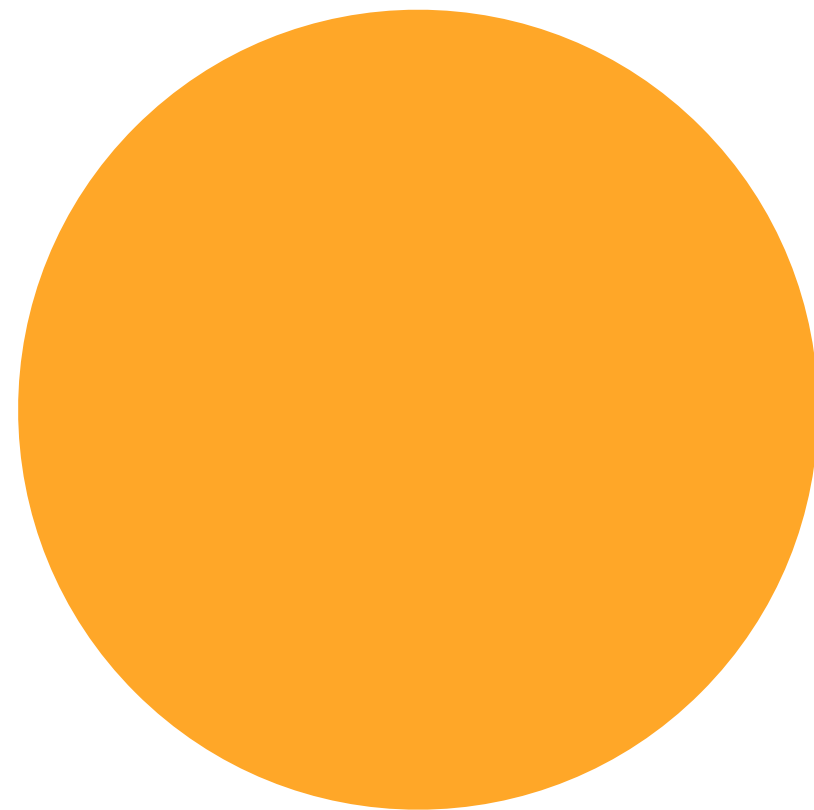
A few assumptions here:

- **No additional forces** on DM
- **No additional flux** of DM

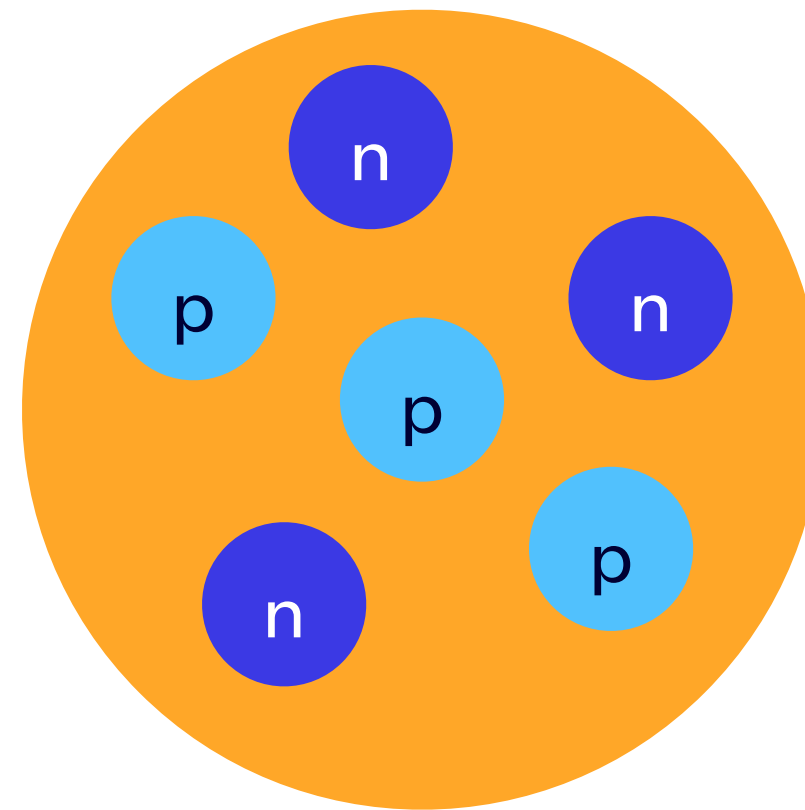
Dark matter might not play by these rules

Toward Higher Energies

Higher energies & momenta means the dark matter resolves **smaller** structure



$E_{\text{recoil}} \lesssim 10 \text{ MeV}$:
Resolve the nucleus
as a “blob”



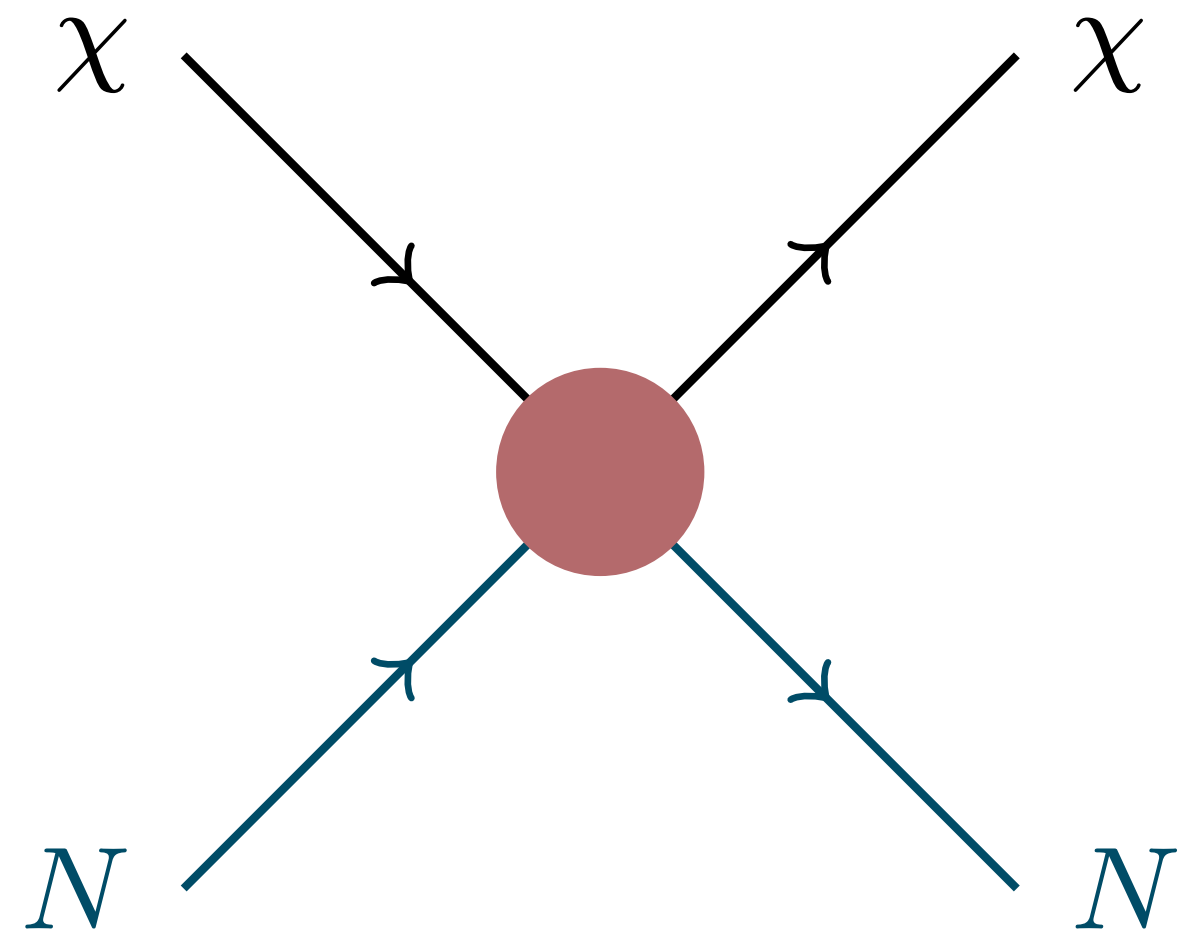
$10 \text{ MeV} \lesssim E_{\text{recoil}} \lesssim 1 \text{ GeV}$:
Resolve protons and
neutrons



$1 \text{ GeV} \lesssim E_{\text{recoil}} \lesssim 2 \text{ GeV}$:
Create excited states of the
proton and neutron

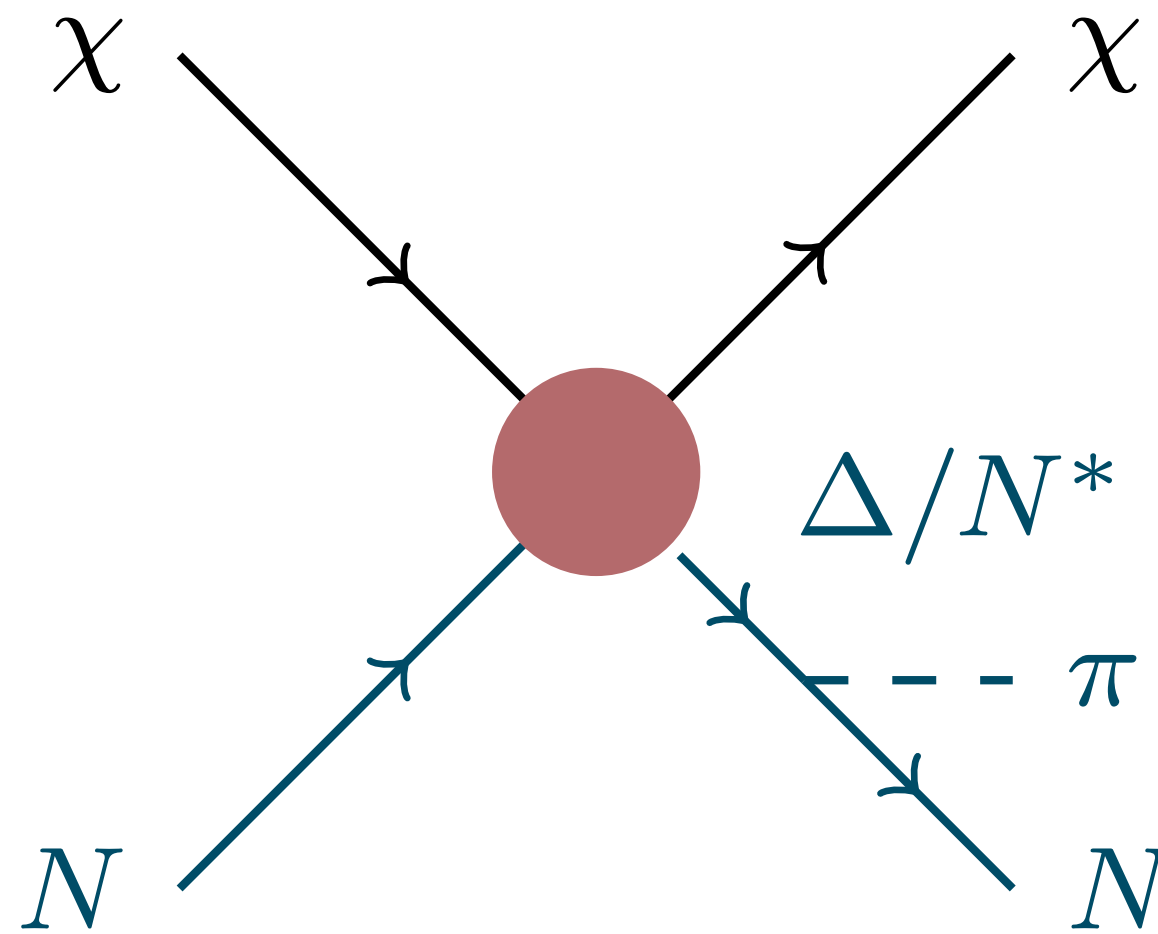
JB, Orr: JHEP 31 (2025)

Three Potentially Relevant Channels



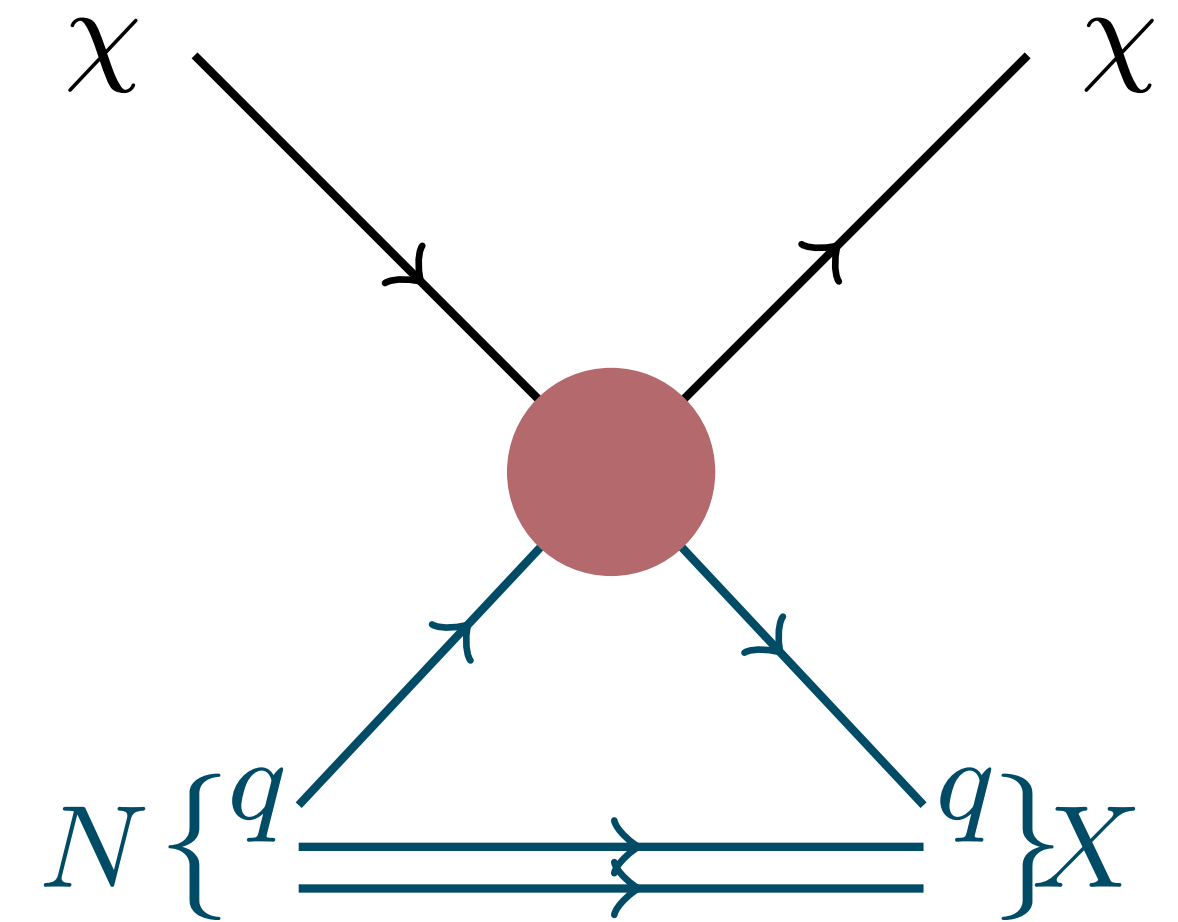
Elastic

Relevant at lower energy
 Relatively simple
 Implemented in GENIE



Resonant

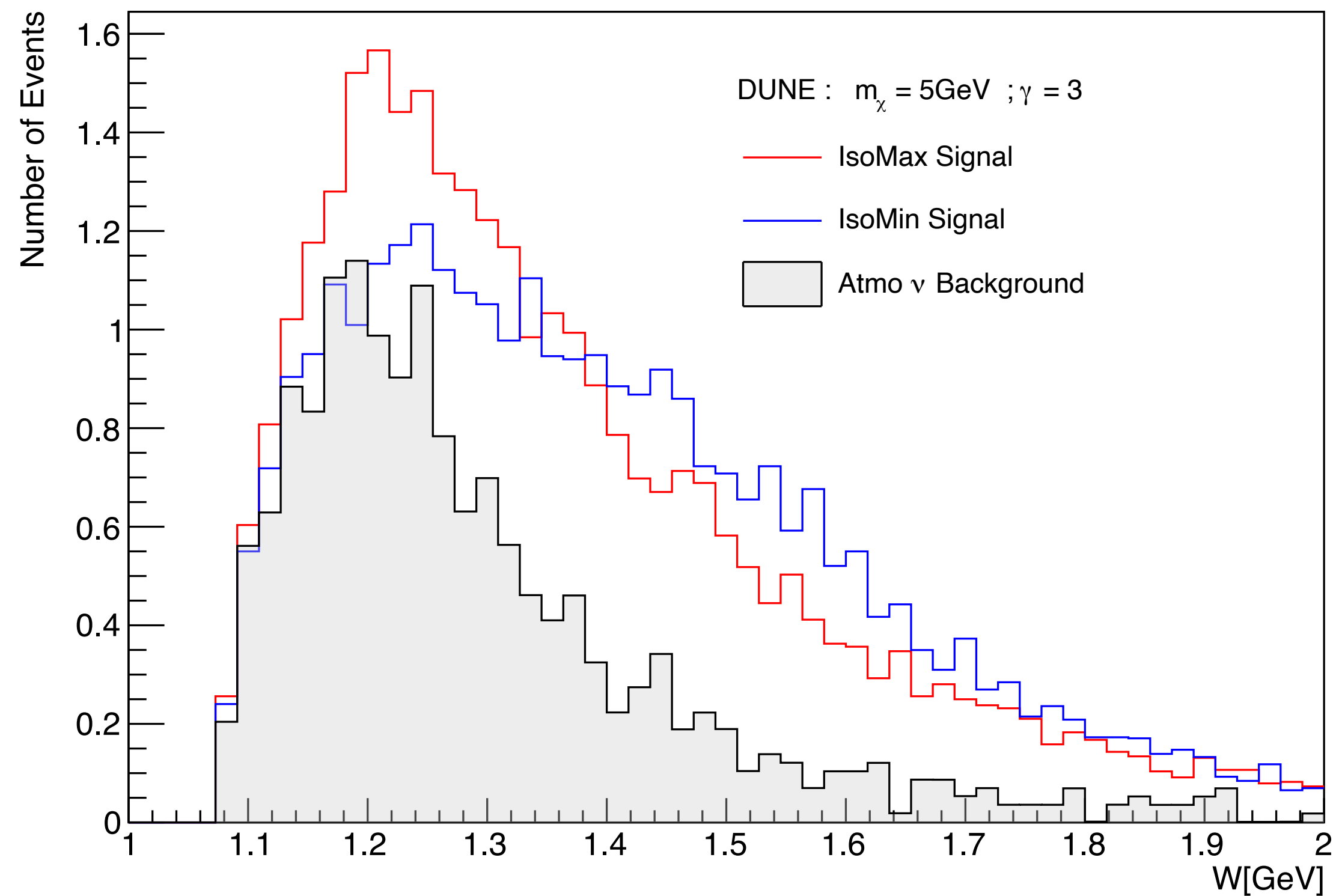
Relevant at QCD energies
 Challenging to model
New! To be merged in GENIE



Deep Inelastic (DIS)

Relevant at high energies
 Not too bad... mostly
 Implemented in GENIE

Real Searches Need Simulations



JB, Orr: arXiv:2509.02678, accepted to JHEP

Work by Z. Orr



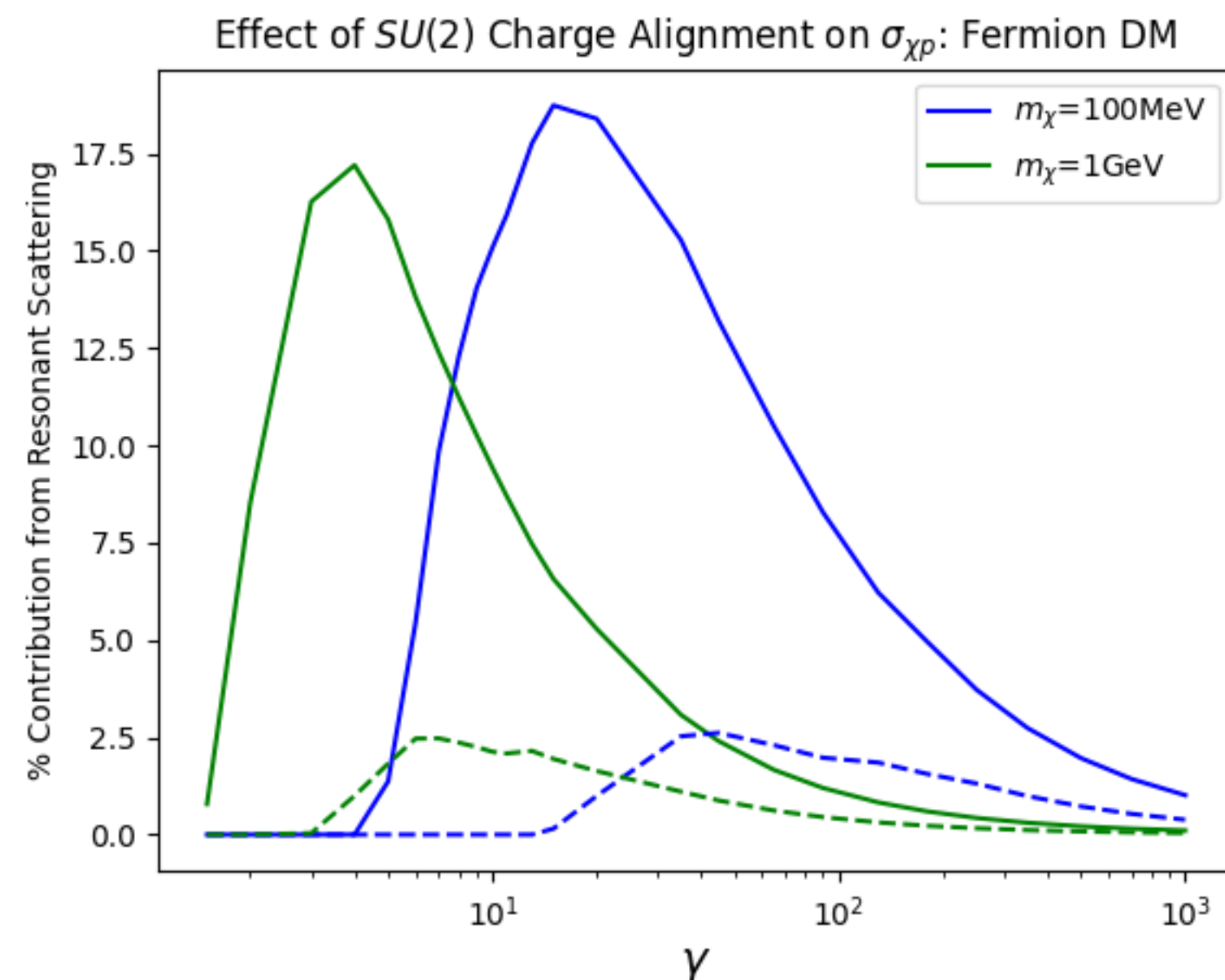
With enough data: can potentially determine **isospin structure** of dark matter interactions

Fine print:

- Projection assuming 400 kt-years exposure
- Signal normalized to estimated 5σ discovery

More on Isospin

- Resonant scattering can be an $\mathcal{O}(1)$ fraction of boosted DM scattering events
- But a big caveat: going from N to Δ requires isospin breaking
- A dramatic effect on the rate of resonant scattering!



Solid: Maximum isospin breaking
Dashed: Isospin conserving

JB, Orr: JHEP 31 (2025)

Model 1: Solar Capture & Annihilation

Heavy DM Scatters in the Sun, becomes bound

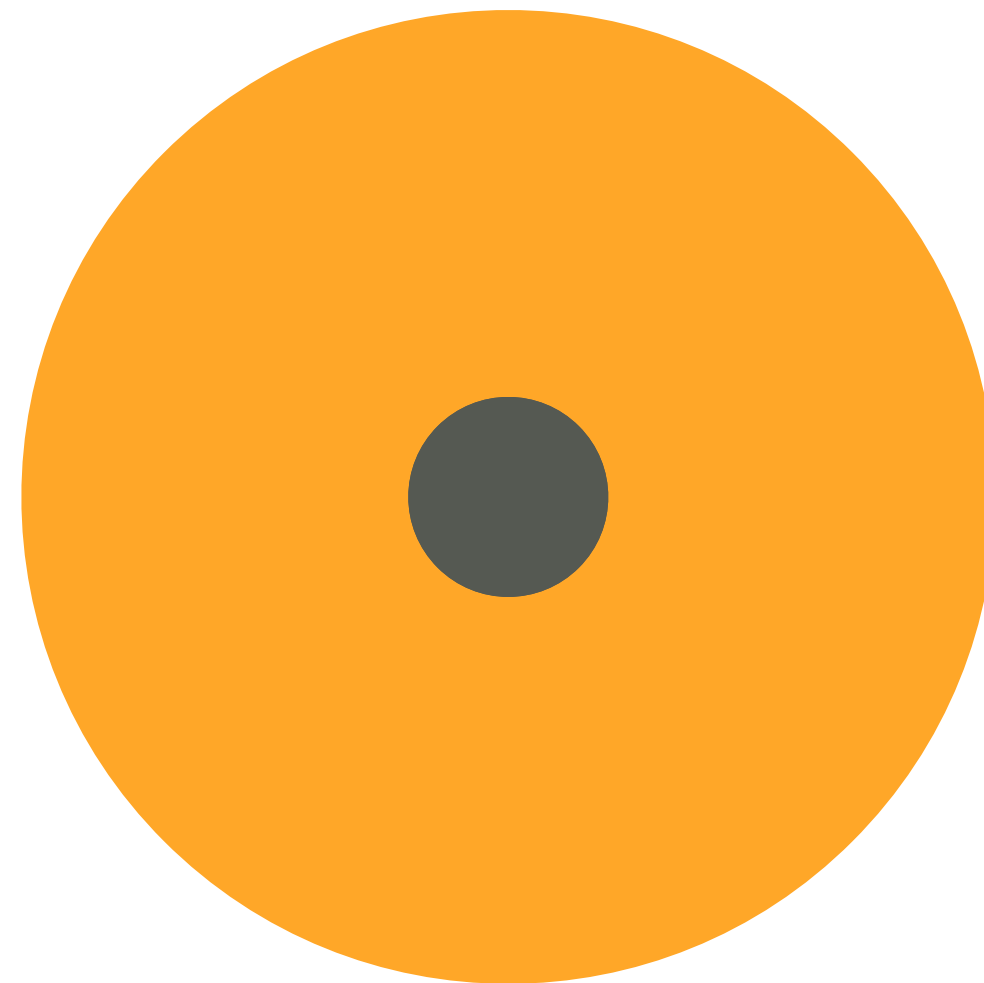


JB, Cui, Zhao: JCAP 02 (2015) 005

JB, Cui, Graham, et. al.: PRD 103 (2021) 095012

Model 1: Solar Capture & Annihilation

Heavy DM Scatters in the Sun, becomes bound



Sun



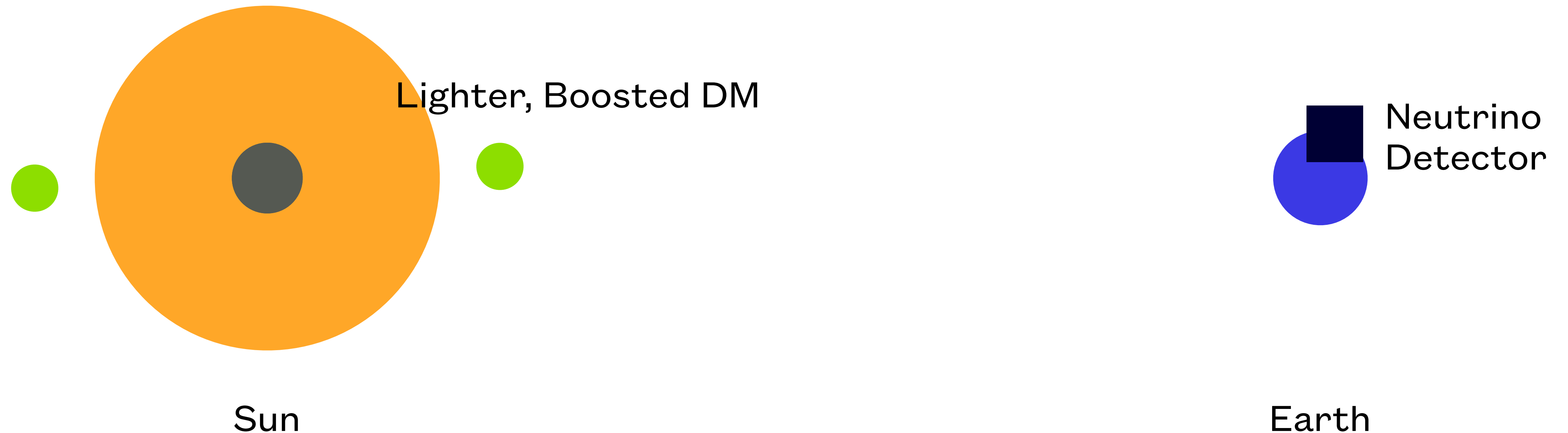
Earth

JB, Cui, Zhao: JCAP 02 (2015) 005

JB, Cui, Graham, et. al.: PRD 103 (2021) 095012

Model 1: Solar Capture & Annihilation

Heavy DM annihilates into BDM, one of which heads toward us*



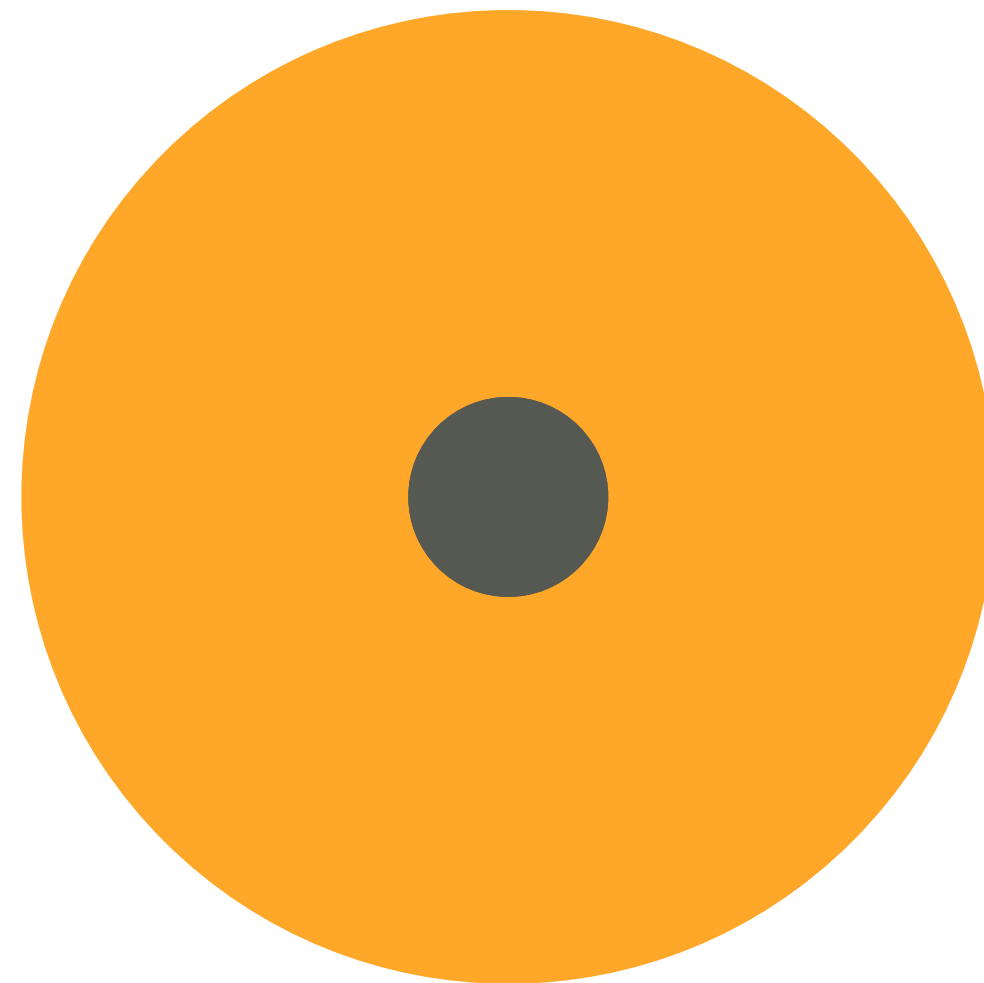
*Some of the time

JB, Cui, Zhao: JCAP 02 (2015) 005

JB, Cui, Graham, et. al.: PRD 103 (2021) 095012

Model 1: Solar Capture & Annihilation

DM sometimes scatters in detector



Sun



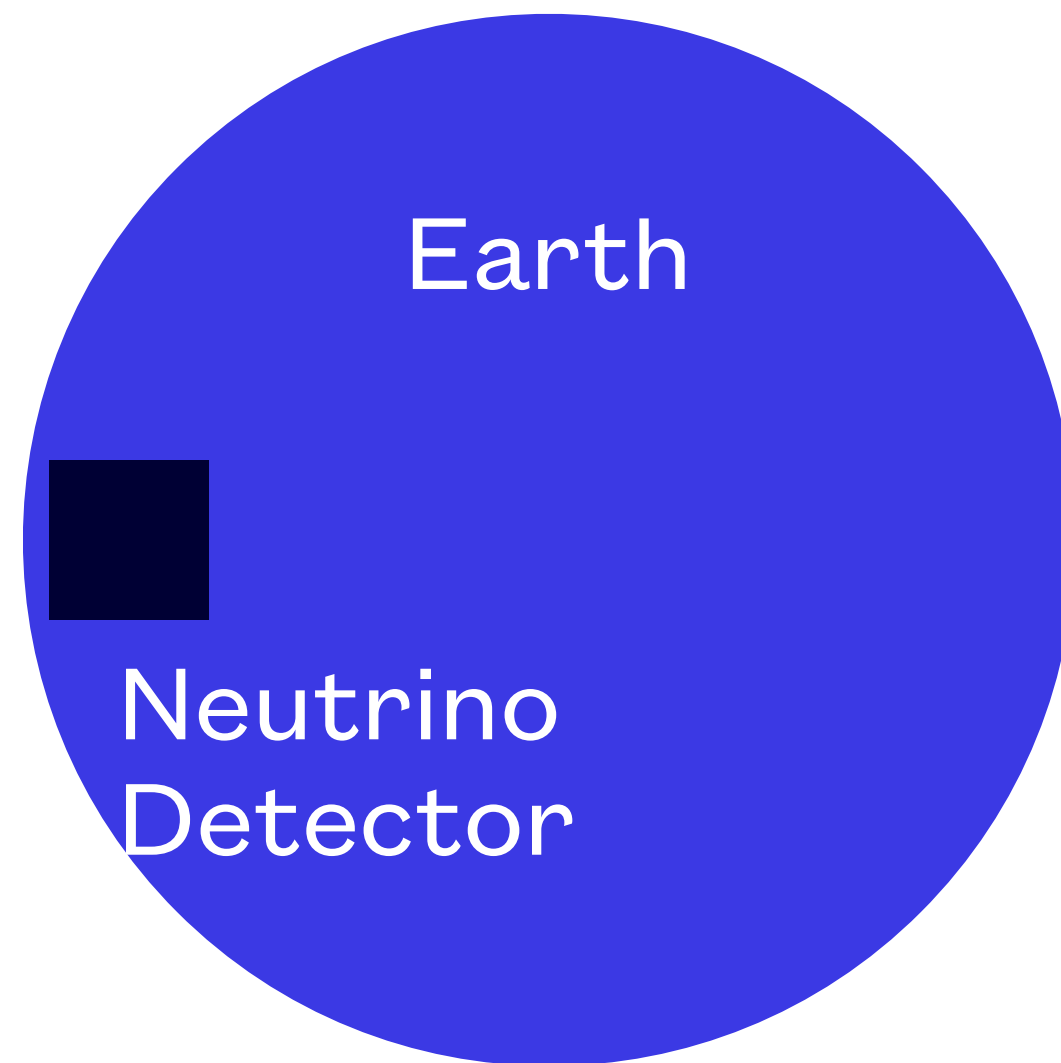
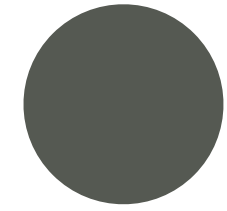
Earth

JB, Cui, Zhao: JCAP 02 (2015) 005

JB, Cui, Graham, et. al.: PRD 103 (2021) 095012

Model 2: Dark Matter Rain

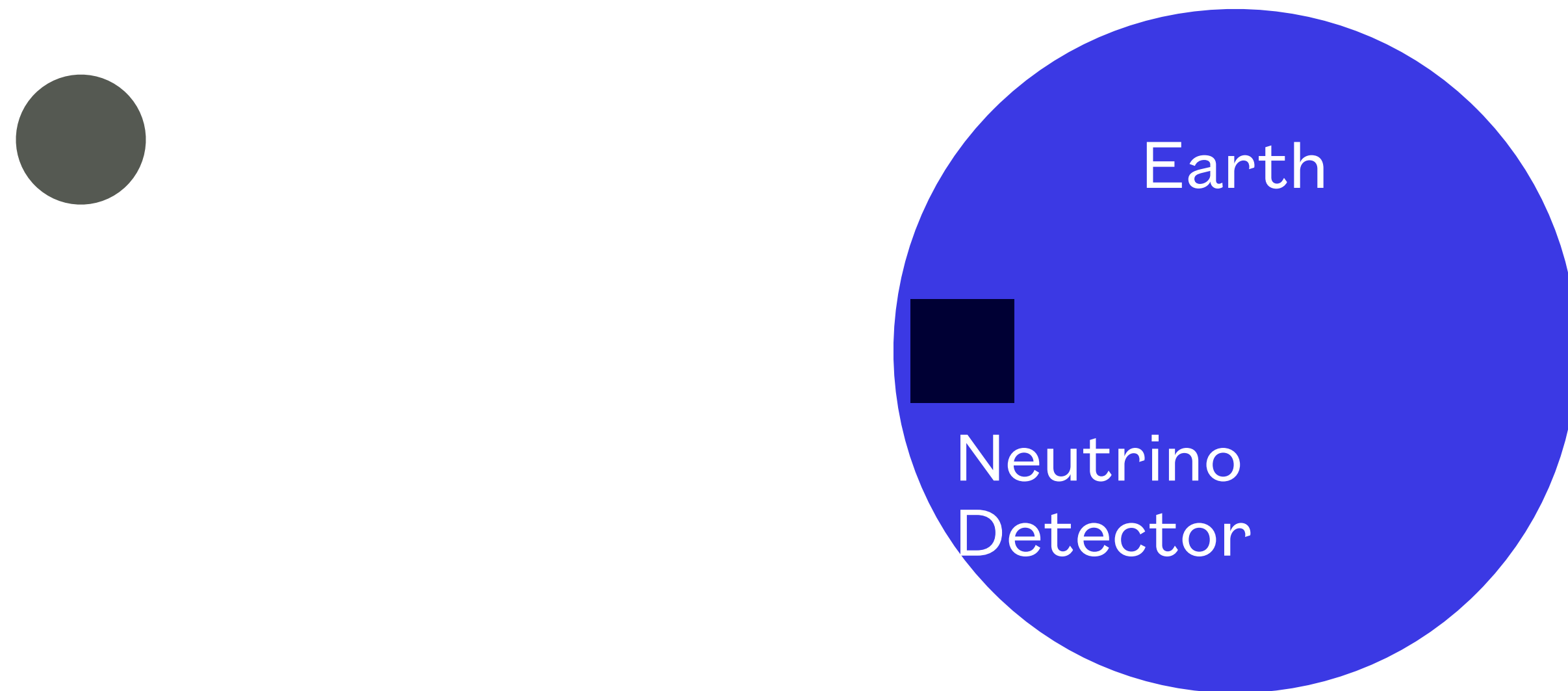
Halo DM is moving slowly and approaching the Earth



Acevedo, JB, Denton: JHEP 11 (2024) 011

Model 2: Dark Matter Rain

Halo DM is moving slowly and approaching the Earth



Acevedo, JB, Denton: JHEP 11 (2024) 011

Model 2: Dark Matter Rain

When DM gets close enough to Earth, it gets pulled toward center, “falls,” then sometimes scatters



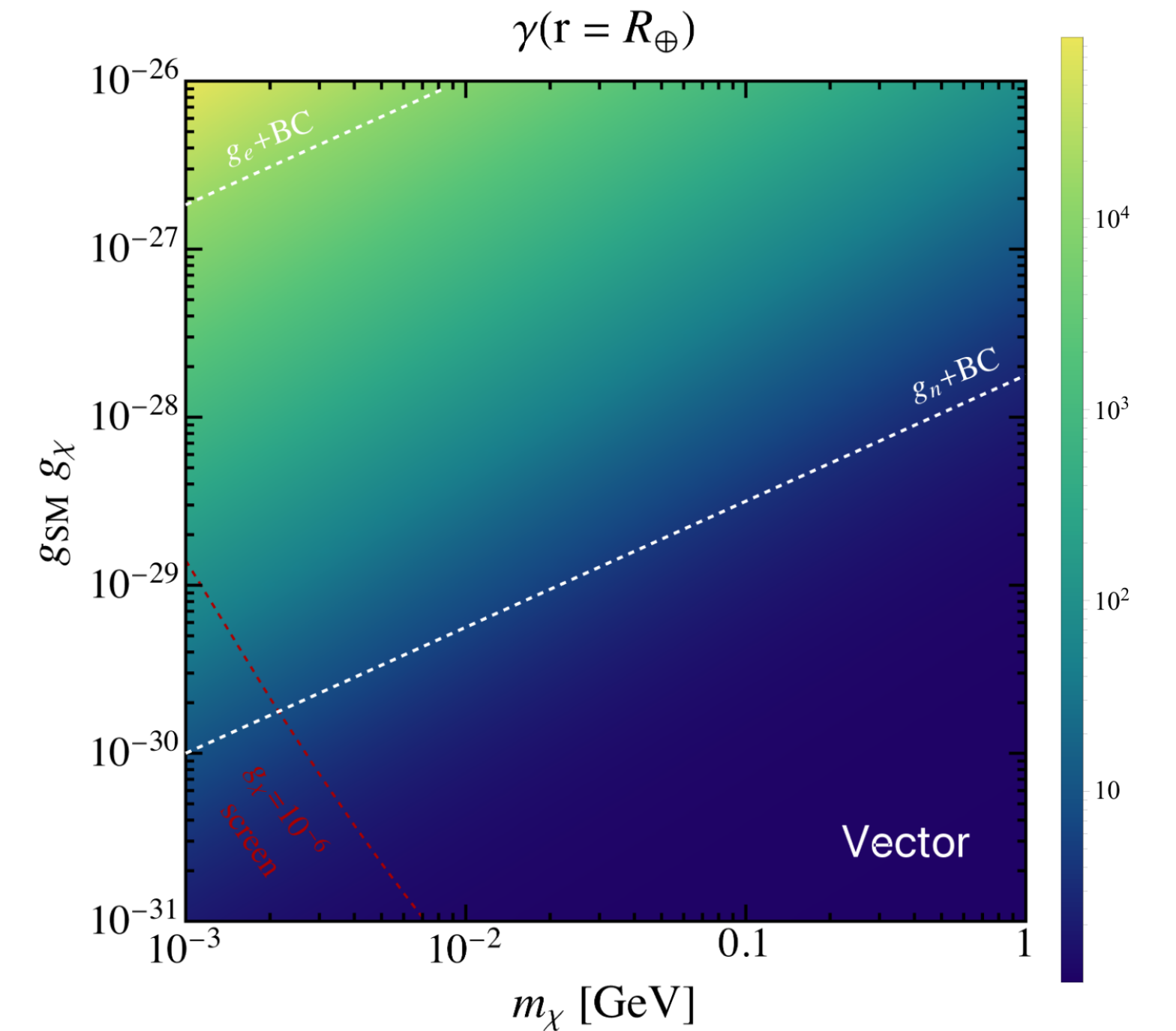
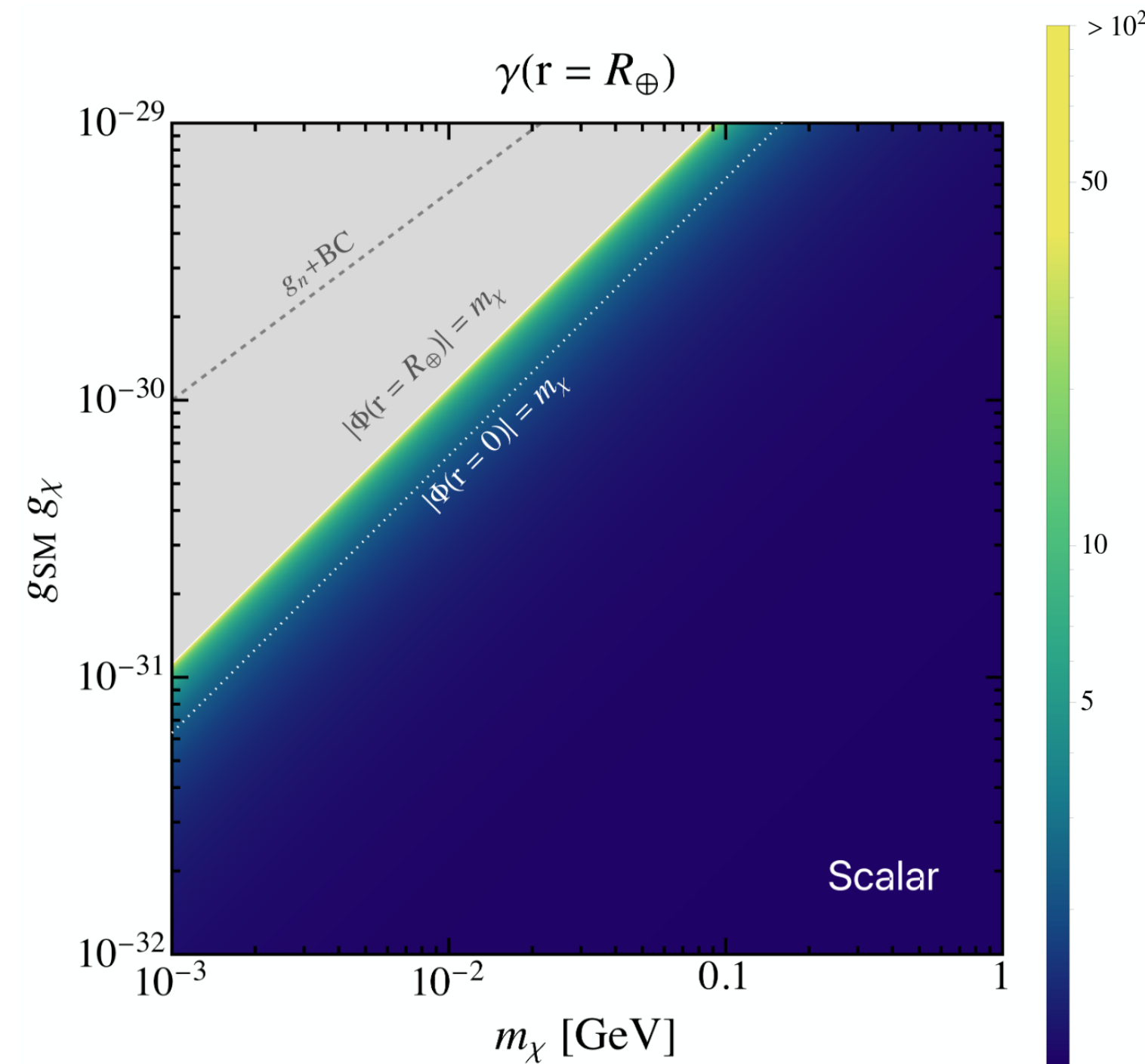
Acevedo, JB, Denton: JHEP 11 (2024) 011

Model 2: Flexibility in Boost

Is the force carrier
spin 0 (scalar) or spin 1 (vector)?

Without relativity: no difference

With relativity: quite different!



Acevedo, **JB**, Denton: JHEP 11 (2024) 011

Additional Considerations

Larmor radiation rate: $\frac{dp_{\text{rad}}^{\mu}}{d\tau} = -Q a^{\lambda} a_{\lambda} U^{\mu}$, where $Q = \frac{g_{\chi}^2}{12\pi}, \frac{g_{\chi}^2}{6\pi}$ for scalar, vector

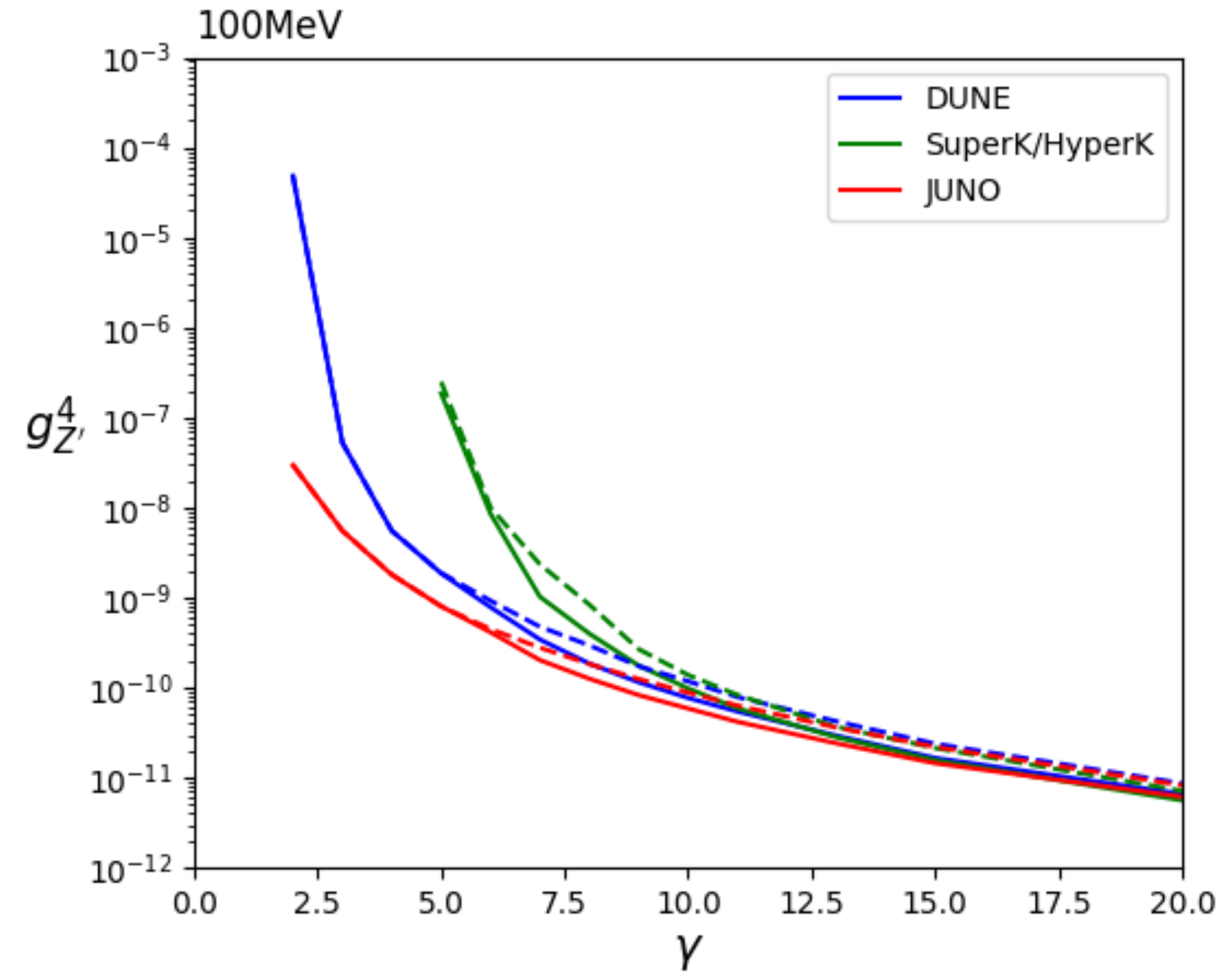
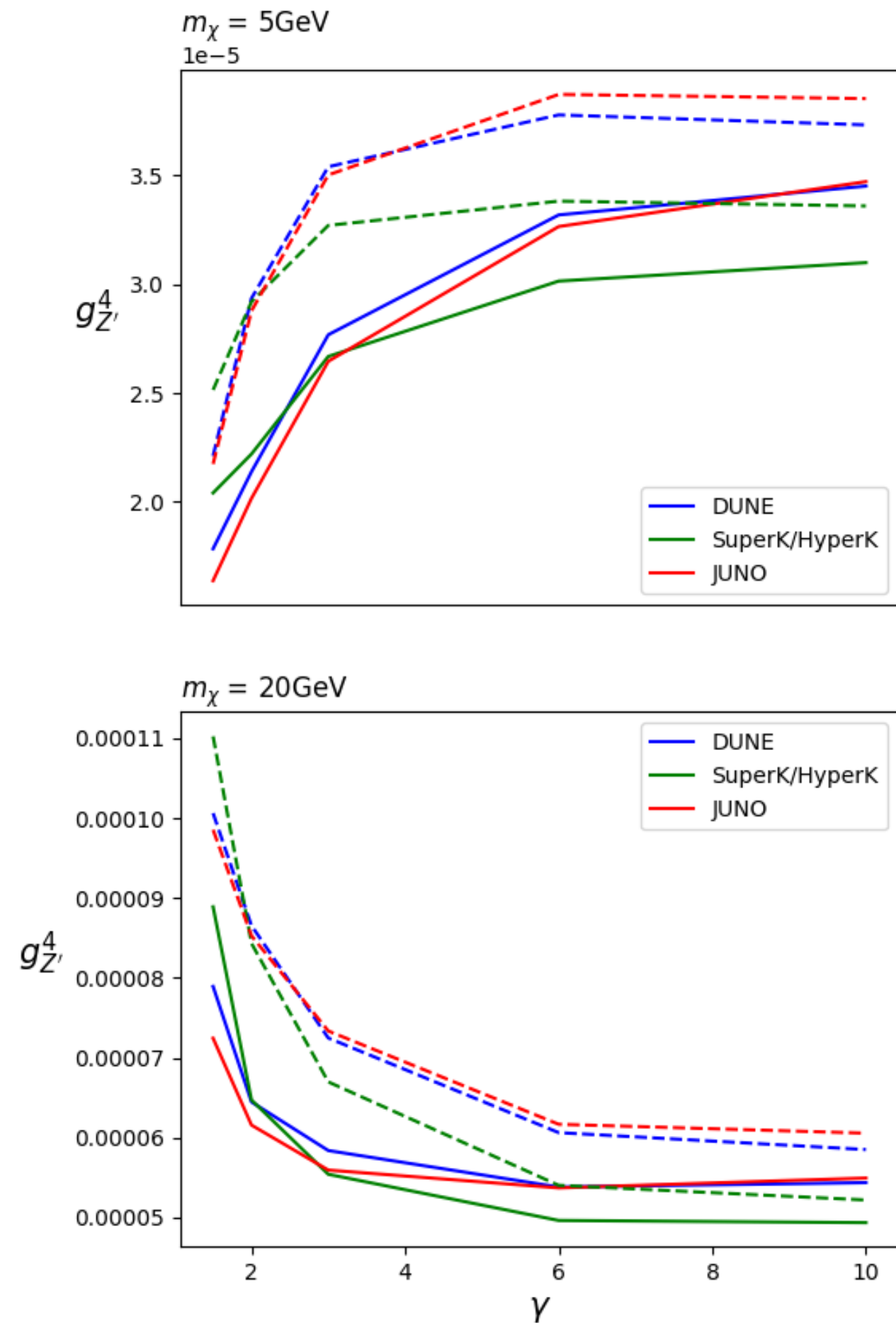
$$\Delta E_{\text{rad}} \approx Q \frac{m_{\chi}}{g_{\chi} g_n N_{\oplus}} \left\{ \frac{\gamma^3}{3}, \frac{\gamma^5}{5} \right\}$$

\implies Relevant at very high boosts, $\gamma \gtrsim 10^{10}$

Centrifugal barrier: if we limit to $R_{\oplus} \lesssim m_{\phi}^{-1} \lesssim 1 \text{ AU}$ not very relevant

Flux enhancement: extra pull enhances maximum impact parameter by $\sim \{1, \gamma^2\}/v_{\text{halo}}^2$

Updated Sensitivities



JB, Orr: JHEP 31 (2025)

Macroscopic Dark Matter Signals

Extended Macroscopic DM

Can we extend the upper end of DM searches beyond the μg mass scale?

Can consider elastic scattering and look for multi-scatter events at direct detection experiments

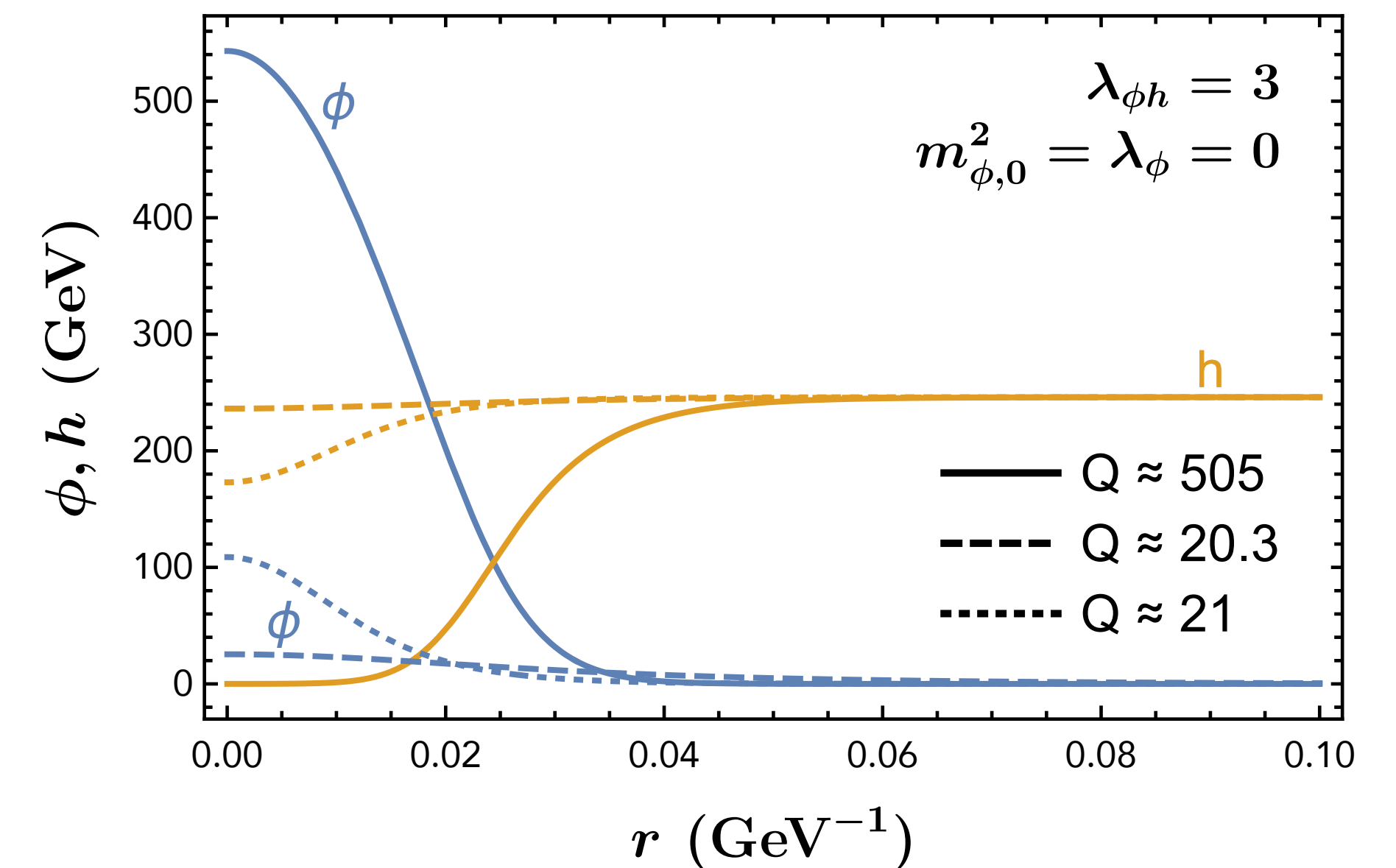
But there is room for some interesting inelastic signals

Electroweak symmetric balls:

Non-topological solitons in which Higgs VEV goes to 0

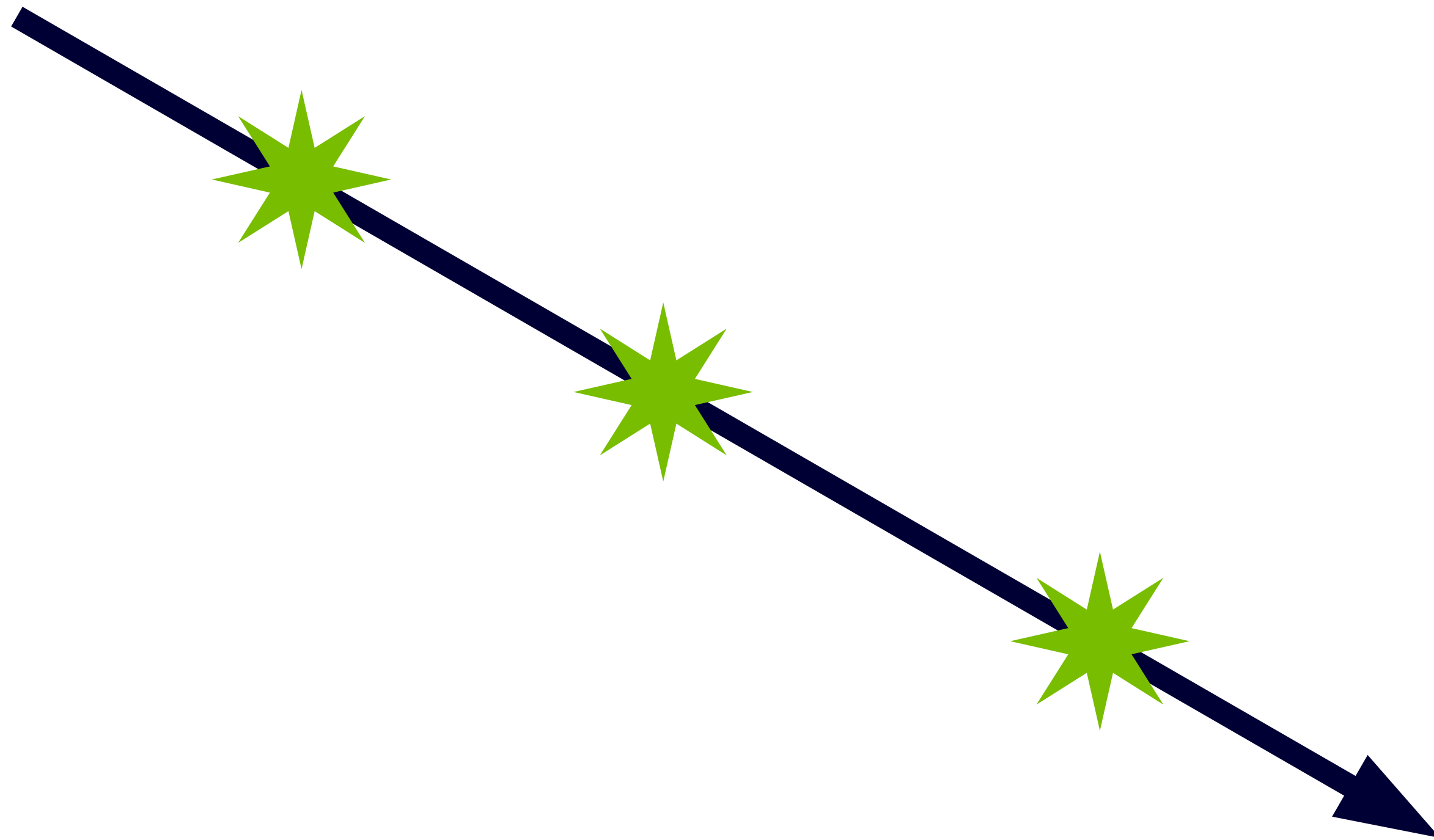
Nuclei lose a bit of their mass inside the soliton

Creates a potential into which the nuclei can fall



Pontón, Bai, Jain: JHEP 09 (2019) 011

A Striking Signal



As DM passes through the detector, can periodically capture a nucleus

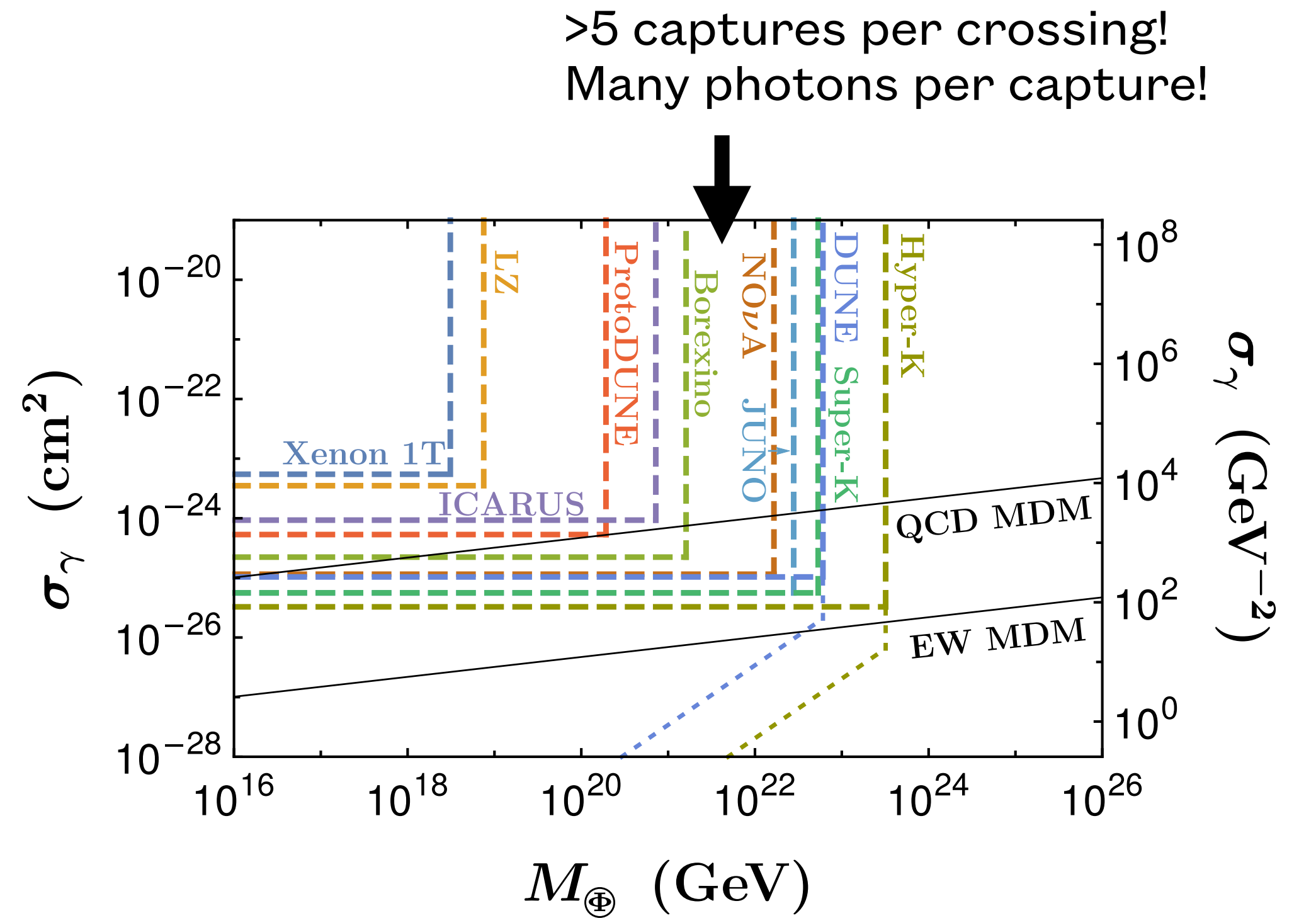
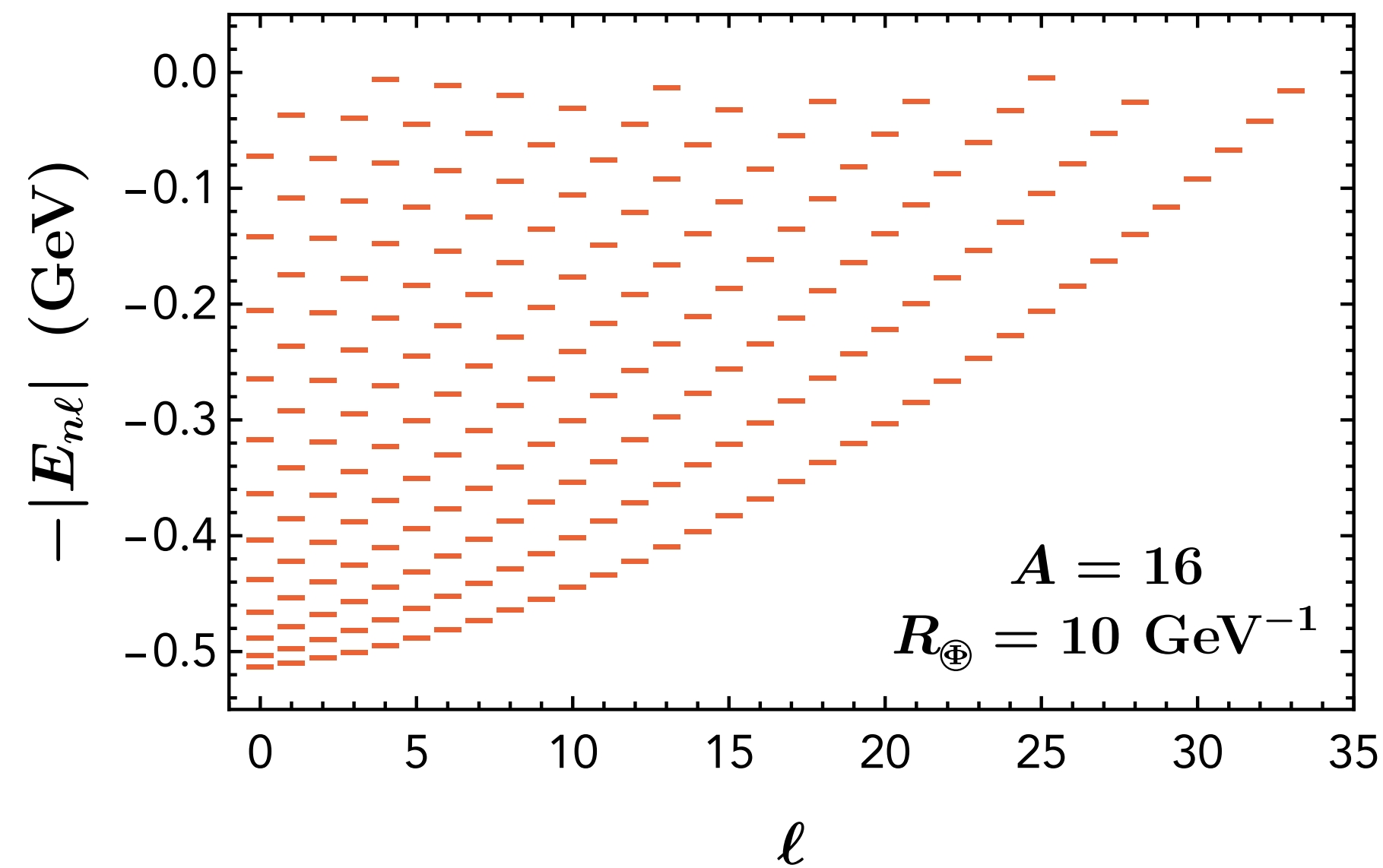
Each capture leads to emission of a spray of photons

Can be several captures per DM crossing at high masses

Can be millions of photons per capture as DM-nucleus state decays to ground state

Signals of Macroscopic DM

- Radiative capture emits a photon
- Falling to ground state emits many more photons



Bai, JB: JHEP 05 (2020) 160

Can We Understand This Better?

- At $R_{\text{EWSB}} \sim 10^6 \text{ GeV}^{-1}$ and $\Delta m \sim 100 \text{ MeV}$: $\sim 10^{12}$ bound states
- Dominated by small steps in n, ℓ toward the ground state

$$\mathcal{M} \propto \int e^{i\mathbf{q}\cdot\mathbf{x}} \boldsymbol{\epsilon}^* \cdot [\nabla \psi_f^*(\mathbf{x}) \nabla \psi_i(\mathbf{x}) - \psi_f^*(\mathbf{x}) \nabla \psi_i(\mathbf{x})] d^3x$$

- Dark matter scattering/bound states described by a spherical constant well
- Can solve for the wavefunctions, but integrating numerically for the amplitude many times over is essentially impossible

Approximating the Amplitude

- Approximation 1: bound state wavefunctions (mostly) fall off quickly outside the well, so make an infinite square well approximation (good for lower states, less good for highly excited states)
- Approximation 2: make a dipole approximation
- In the limit $|\mathbf{q}| R_{\text{EWSB}} \ll 1$, $e^{-i\mathbf{q}\cdot\mathbf{x}} \rightarrow 1$
- $|\mathbf{q}| = E_i - E_f$ by energy conservation, so this works for small jumps
- In the limit $|\mathbf{q}| R_{\text{EWSB}} \gg 1$: integrand is highly oscillatory and cancels out to be very small
- Ignore large jumps, use dipole approximation for small jumps

Result for the Dipole Amplitude

Capture scattering amplitude (for example: similar result for bound state decay)

$$\mathcal{M}_{n\ell m} = \sum_{\ell'=\ell\pm 1} Ze(|E_{n\ell}| + E_k) \int d^3r^3 R_{n\ell} R_{\mathbf{k},\ell'} \int d\Omega Y_{\ell m}^*(\hat{r}) Y_{\ell'0}(\hat{z}) Y_{\ell'0}(\hat{r}) \hat{r} \cdot \boldsymbol{\epsilon}^*$$

Radial wavefunctions are spherical Bessel functions, which can be integrated to

$$\int_0^R dr r^3 j_\ell(\kappa_1 r) j_{\ell'}(\kappa_2 r) \approx \frac{1}{2\kappa_1 \kappa_2 (\kappa_1^2 - \kappa_2^2)^2 R^2} \left[(-1)^{(\ell-\ell'+1)/2} \widehat{\Sigma\kappa}^2 (\widehat{\Delta\kappa} \cos \widehat{\Delta\kappa} - \sin \widehat{\Delta\kappa}) + (-1)^{(\ell+\ell'-1)/2} \widehat{\Delta\kappa}^2 (\widehat{\Sigma\kappa} \cos \widehat{\Sigma\kappa} - \sin \widehat{\Sigma\kappa}) \right]$$

Spherical harmonics can be integrating using standard orthogonality relations

Next Steps

- Validate the regime in which the approximations can be applied
- Dipole should always work, but infinite square well approximation breaks for excited states
- Develop a simulation of this process, likely with some additional approximations for very large radius macroscopic dark matter
- With a simulation, experiments will be able to find sensitivity to this rather exotic signal

Outlook

- Several neutrino experiments are online and/or on shell and offer opportunities to look for non-neutrino BSM, in addition to their core program
- Work is needed to develop new models, carefully determine signals, and pass simulations over to experimentalists who can then look for these signals
- At short baselines: tradeoff between higher energy vs. higher intensity or shorter baseline leads to complementarity between projects
- At large volume detectors: tradeoff between volume vs. energy threshold
- If there is no simulation of your model, no one will look for your model