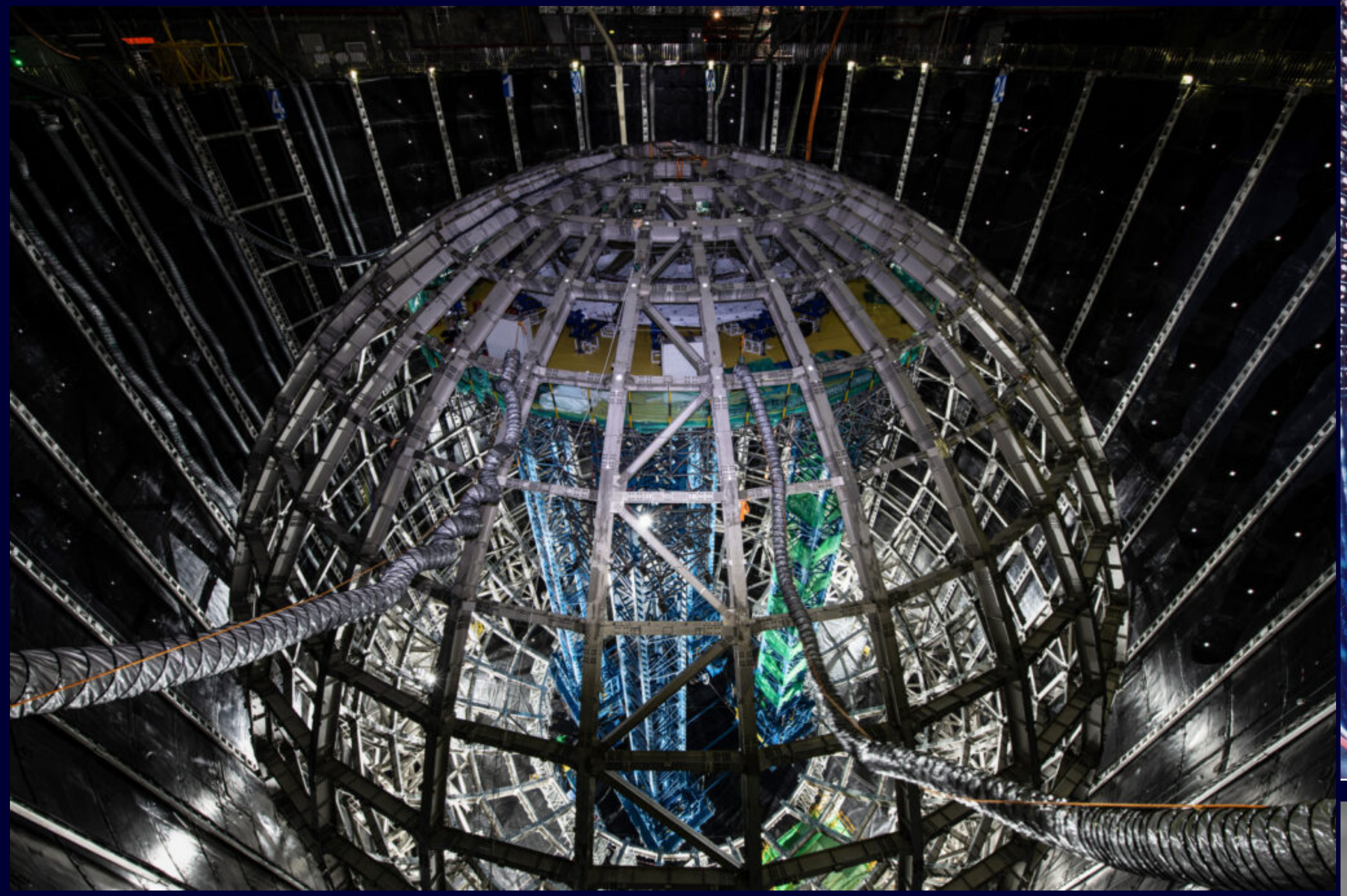
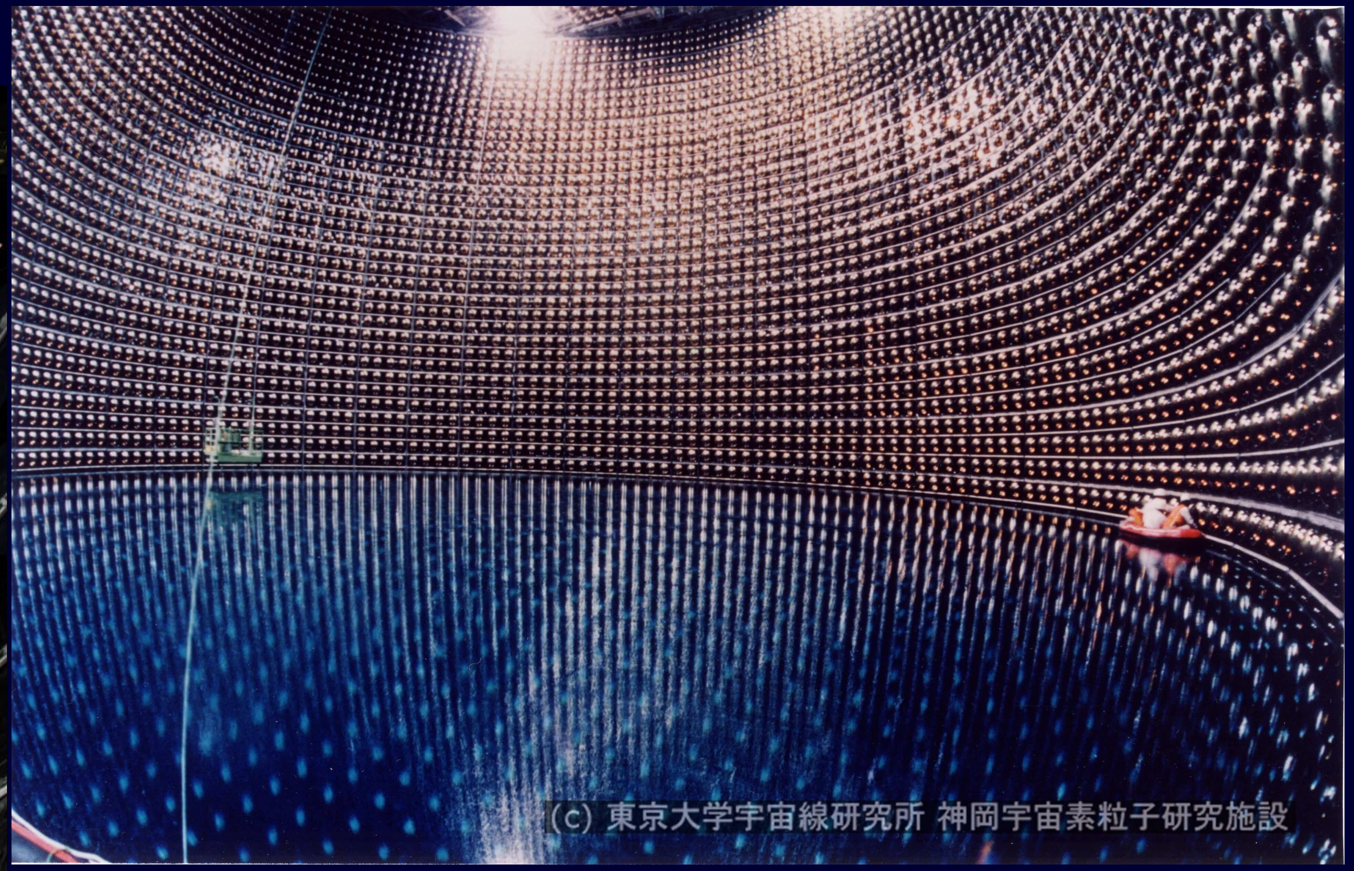
Joshua Berger
Colorado State University

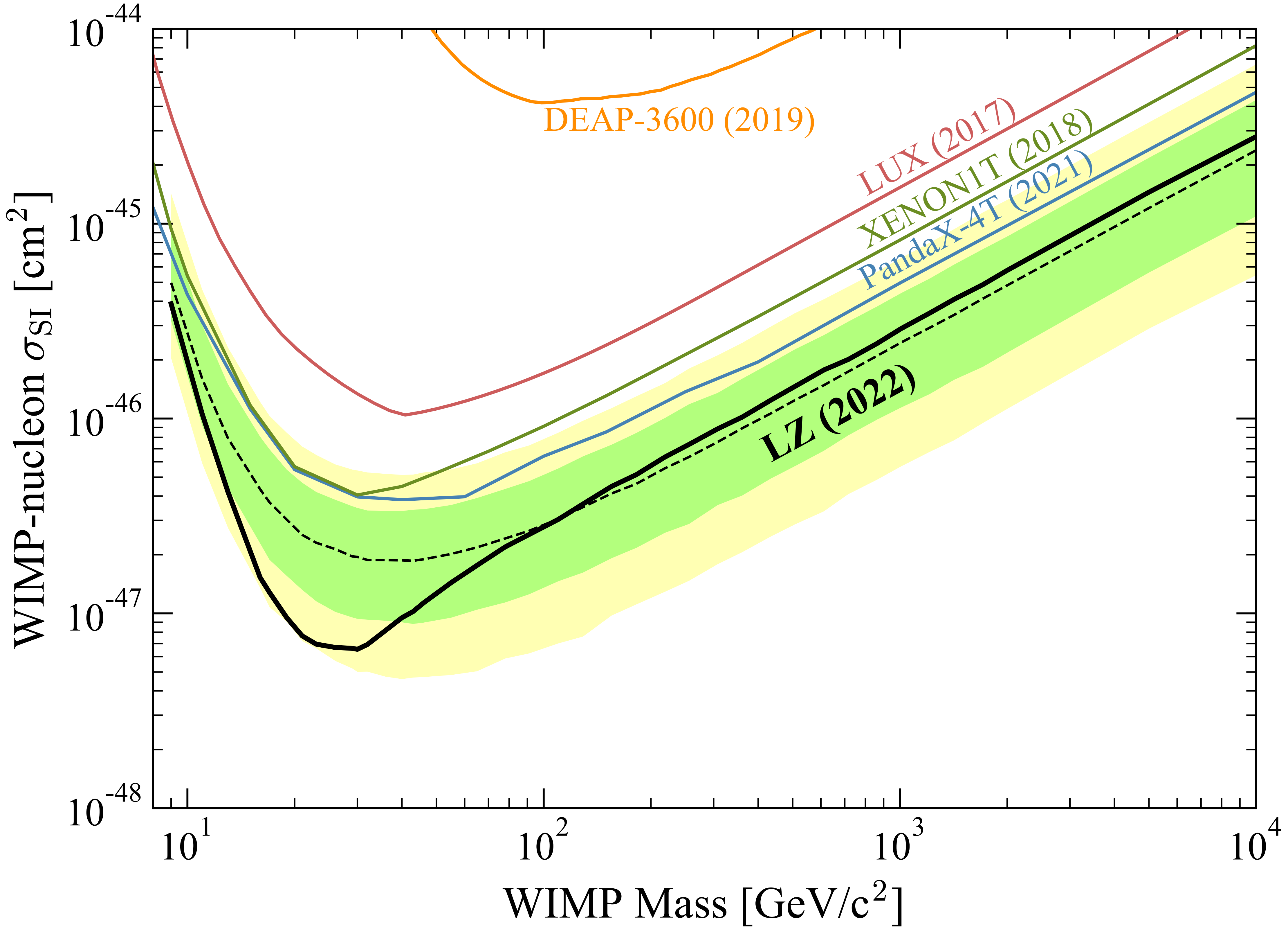




Dark Matter Stories @ ν Experiments

PHENOMENOLOGY AT FRONTIERS

The "Usual" Story: WIMPs



LZ: PRL 131, 041002 (2023)

Abridged List of Assumptions:

- Halo DM (flux and speed)
- Elastic Scattering
- GeV to 10 TeV mass
- Small Cross Section
- No Long Range Forces

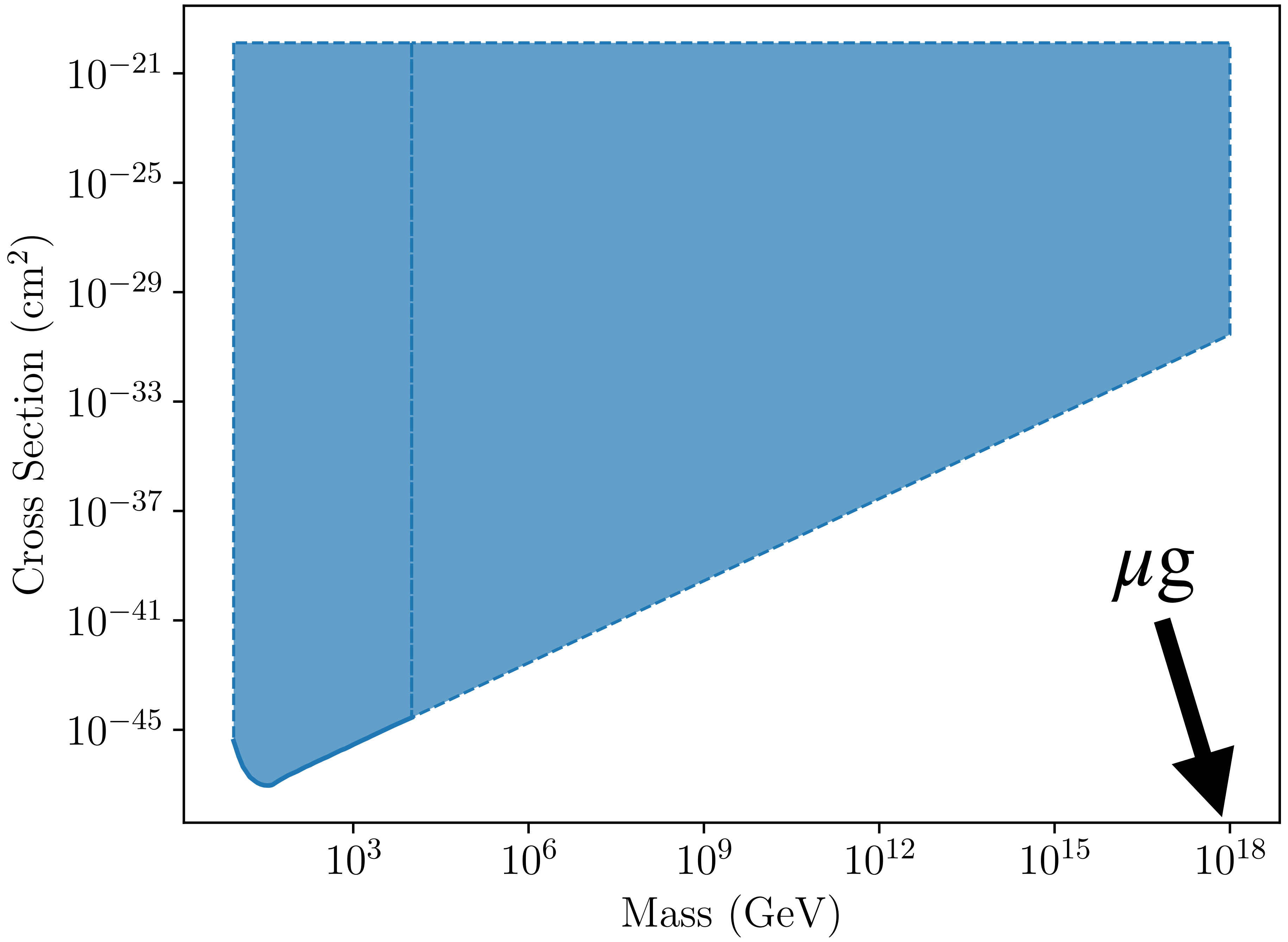
The Expanded WIMP Story

Overburden: Space/Surface

Bramante et. al., PRD 98, 083516 (2018)

Light DM

Electron scattering
Light Elements
Condensed Matter/
Semi-conductors



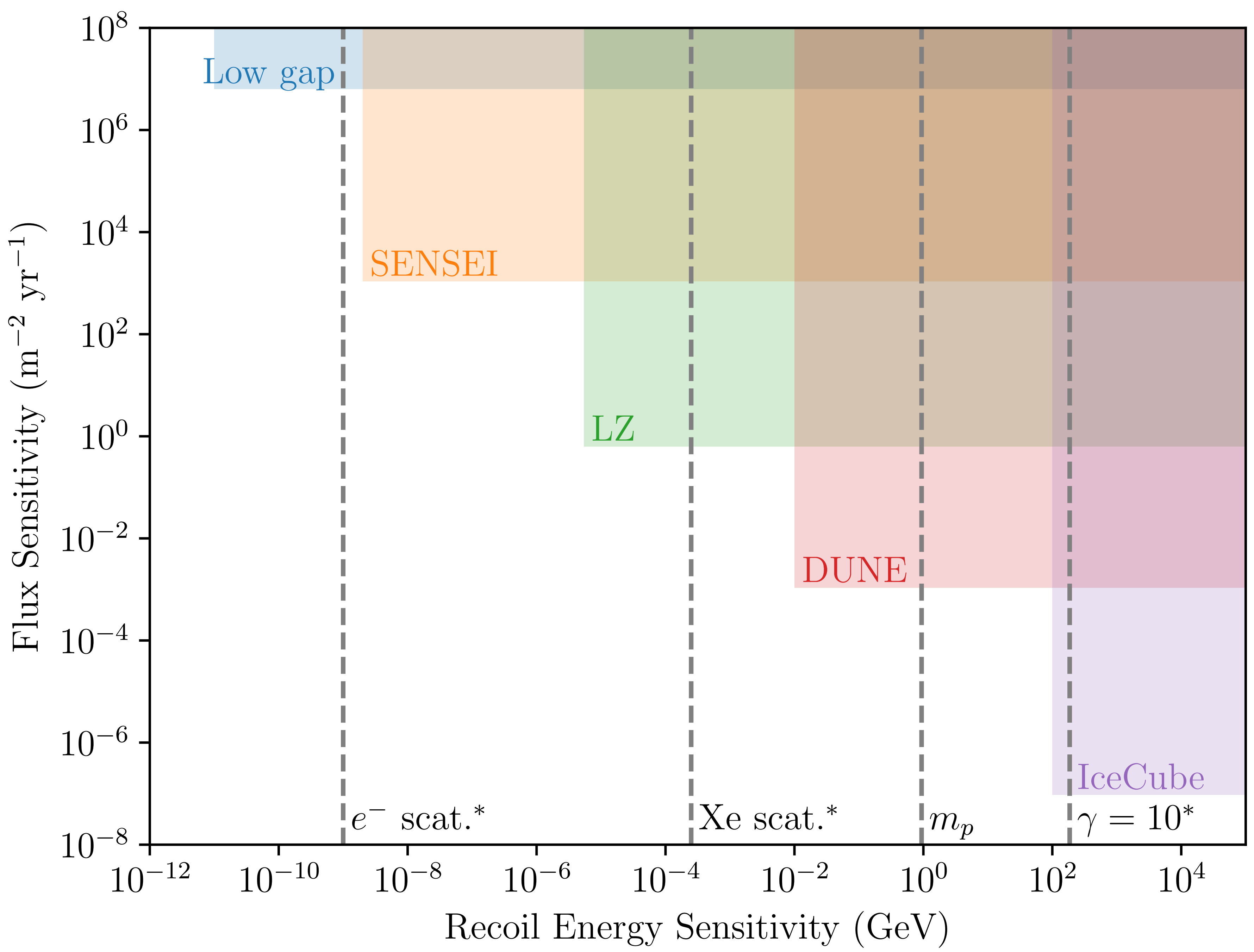
Macroscopic DM

No DM in detectors
Multiple interactions

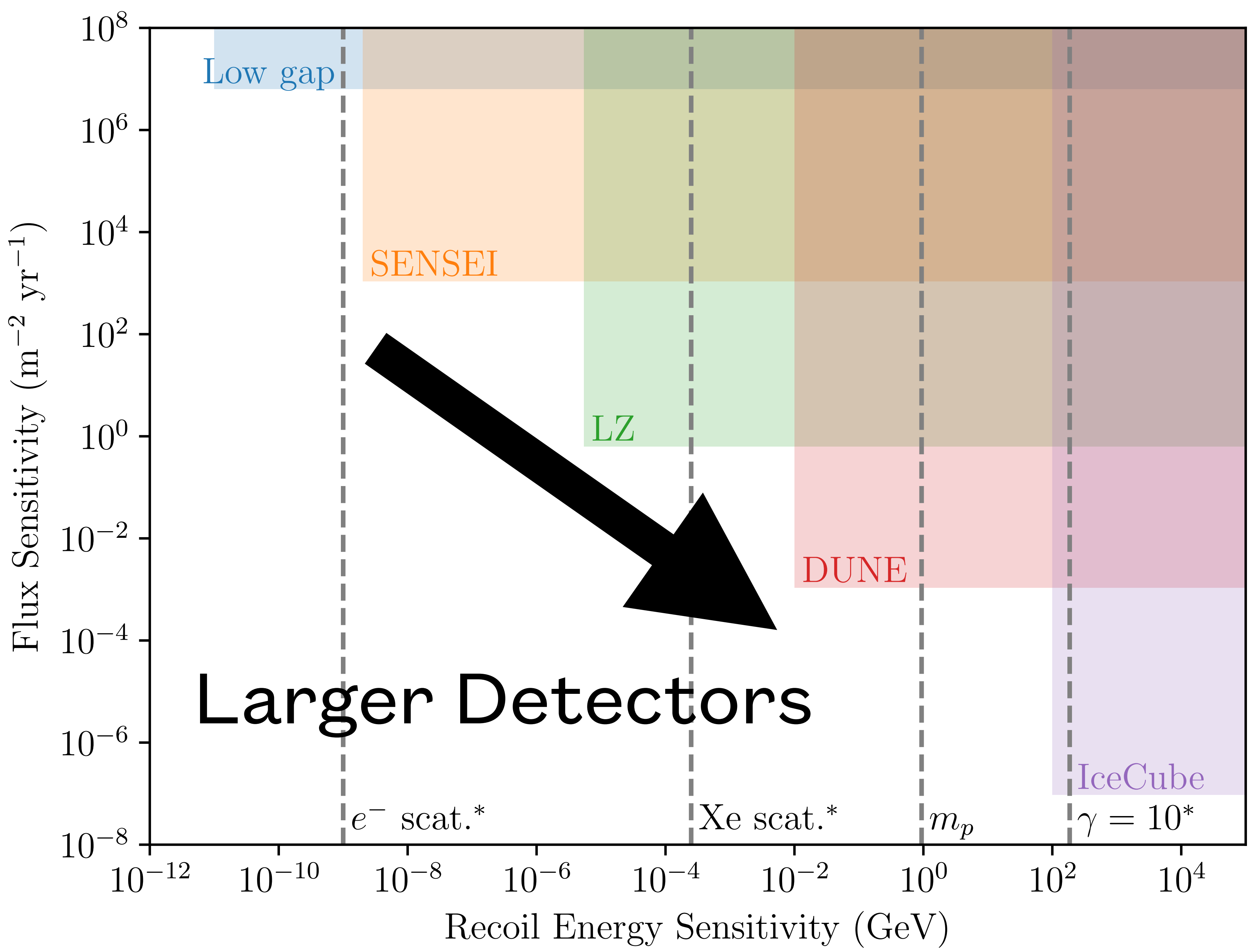
LZ: PRL 131, 041002 (2023)

Neutrino Fog Eventually: Directional Detection

Another View: Flux vs. Energy

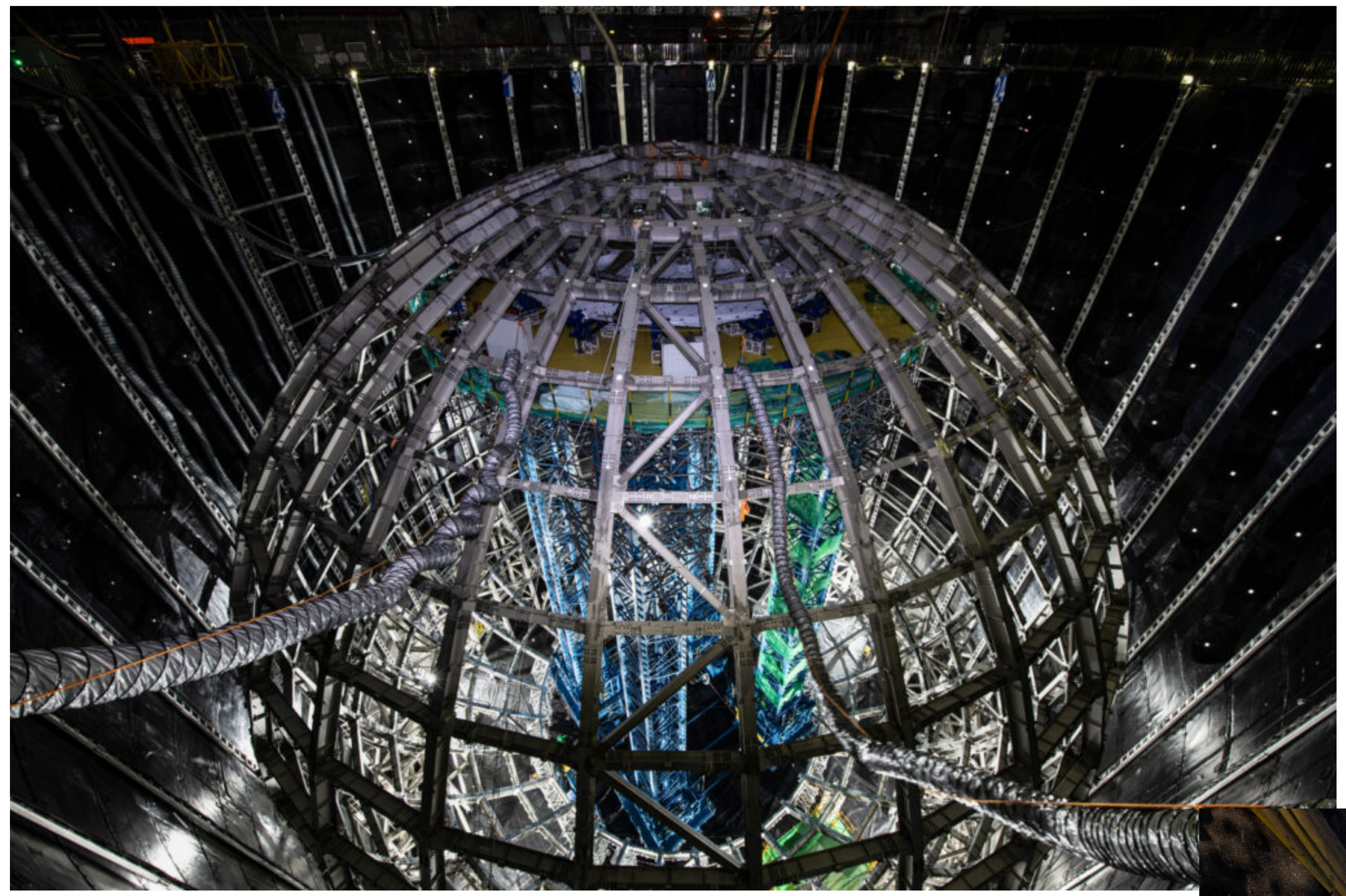


Another View: Flux vs. Energy



*Assuming heavy DM, short-range scattering

Higher Energies Means ν Detectors

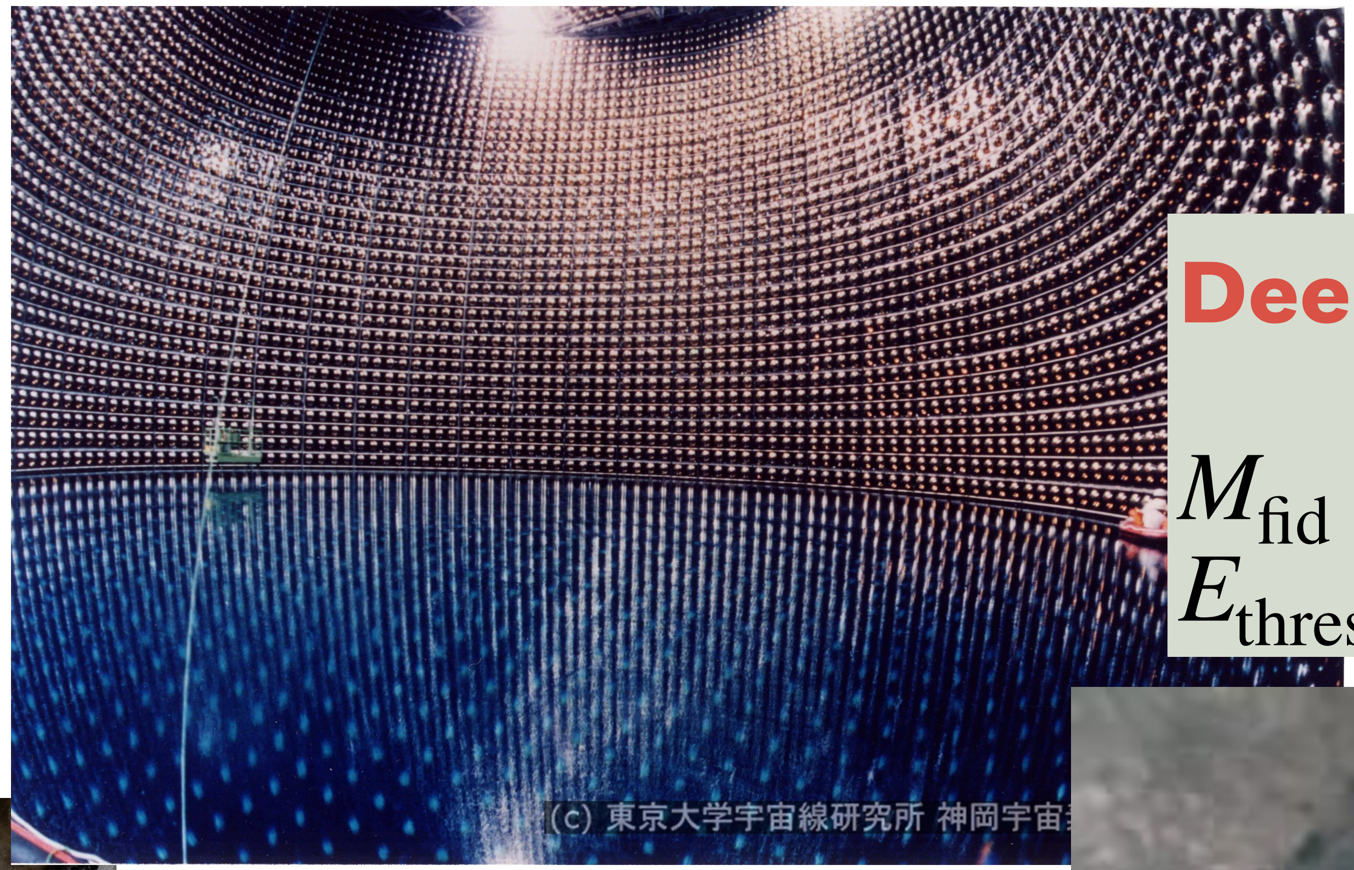


JUNO

$M_{\text{fid}} = 20$ kton
$E_{\text{thresh}} \sim 1$ MeV

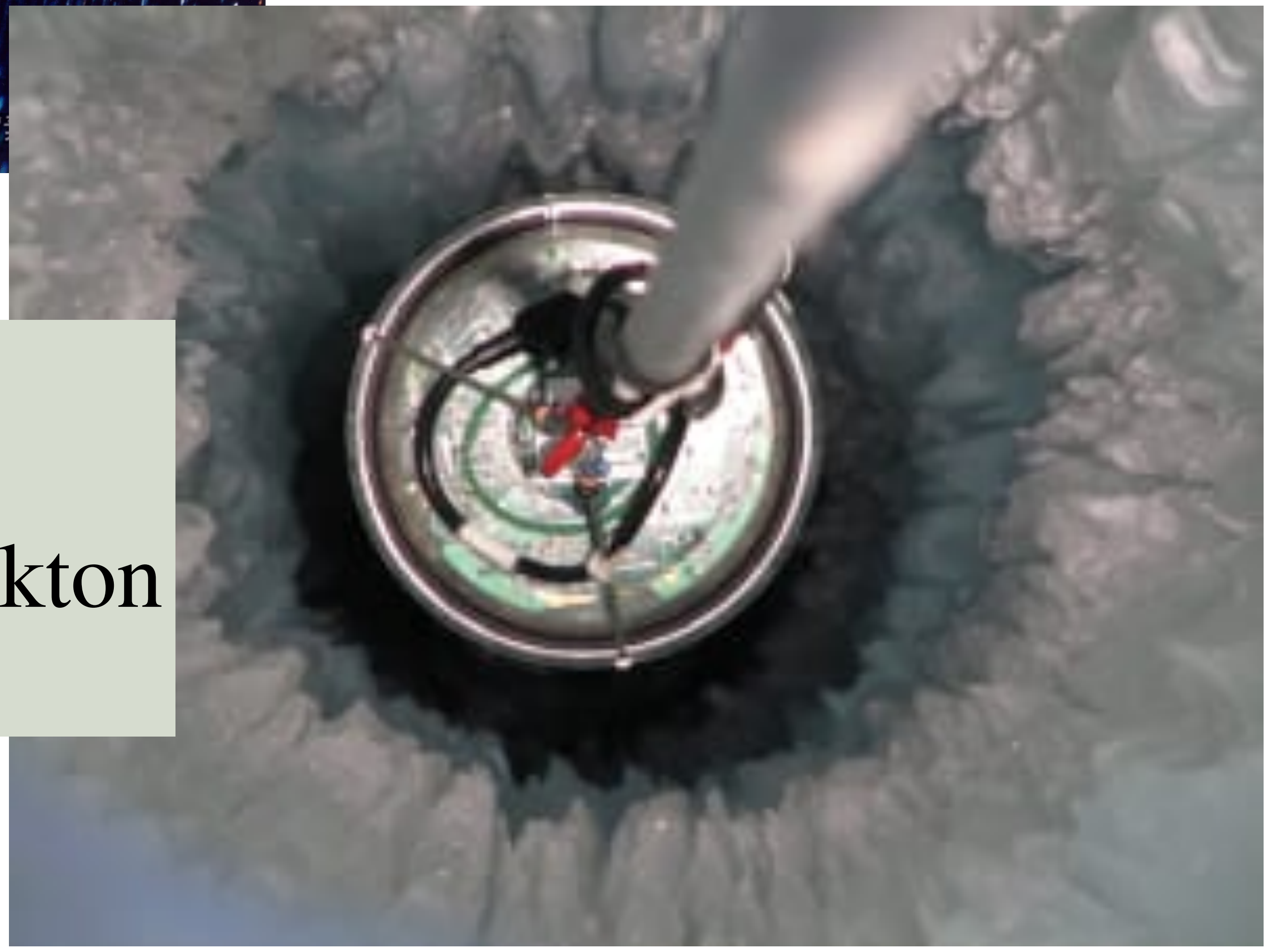
DUNE FD

$M_{\text{fid}} = 40$ kton
$E_{\text{thresh}} \sim 10 - 100$ MeV



Super-K/Hyper-K

$M_{\text{fid}} = 22.5$ kton $- 560$ kton
$E_{\text{thresh}} \sim 1 - 500$ MeV



DeepCore/IceCube

$M_{\text{fid}} \sim 30$ Mton $- 1$ Gton
$E_{\text{thresh}} \sim 10 - 100$ GeV

Boosted Dark Matter

Baseline Halo DM: $v \sim 10^{-3} \implies E_{\text{recoil}} \lesssim 200 \text{ keV}$

Can we get a flux of sped up dark matter to increase the energy deposited?

- Dark matter annihilation into other dark matter
  Agashe et. al.:, JCAP10 (2014) 062
  JB, Cui, Zhao: JCAP02 (2015) 005
  Kong, Mohlabeng, Park: PLB 743 (2015) 256-266
- Cosmic ray acceleration
  Bringmann, Pospelov: PRL 122 (2019) 171801
  Dent, Dutta, Newstead, Shoemaker: PRD 101 (2020) 11, 116007
- Dark matter rain
  Acevedo, JB, Denton: JHEP 11 (2024) 011

Solar Captured BDM

Analogy: indirect detection of neutrinos from the Sun

Some features of this model:

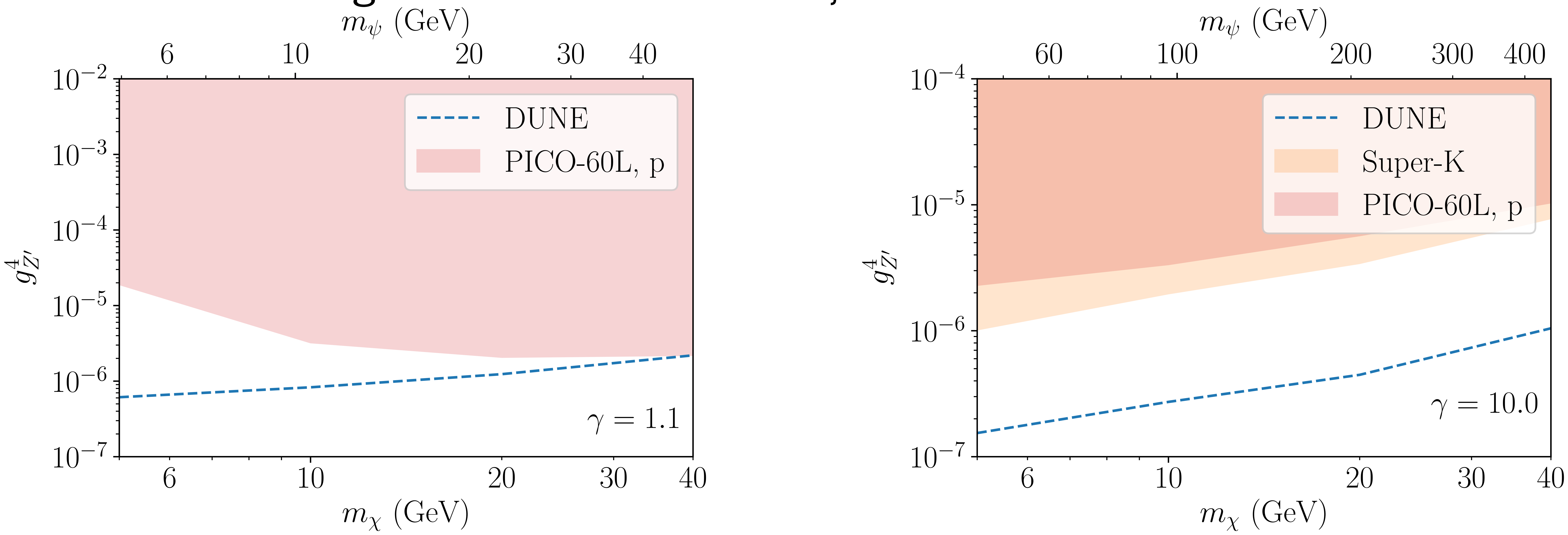
- Heavy dark matter ψ constrained by direct detection, so look at spin-dependent, scalar DM
- Light DM χ emerges from the Sun with a boost $\gamma = m_\psi / m_\chi$
- As long as cross sections are big enough, flux determined entirely by capture cross section

$$\Phi \approx \frac{C}{4\pi(1\ \mathrm{AU})^2}$$

- Mass $\gtrsim 4\ \mathrm{GeV}$ allows for negligible evaporation

Solar BDM: Projected Sensitivity

Limitations: not a full-fledged detector simulation, doesn't include resonant BDM scattering



JB et. al.: PRD 103 (2021) 9, 095012

Some Limitations of Solar BDM

- DM needs to be scalar, axially coupled to evade direct detection of heavy component
- Direct detection can/will catch up with improved spin-dependent searches
- Mass must be larger than $4\ \mathrm{GeV}$
- Need more ingredients to get observed relic abundance

Is there another way?

Dark Matter Rain

Introduce a new long-range force (longer than Earth radius) between dark matter and nuclei

$$\Phi = -\frac{g_\chi g_n N_\oplus}{r} e^{-m_\phi r}$$

Nucleus force constrained by fifth force searches: $g_n \lesssim 8 \times 10^{-25}$

MICROSCOPE, PRL 129 (2022) 121102

Dark matter force constrained less, dominantly from the bullet cluster: $g_\chi \lesssim 4 \times 10^{-6}\ (m_\chi/\mathrm{MeV})^{3/4}$

Davoudiasl, PRD 96 (2017) 095019

Acceleration of dark matter toward the Earth means it moves nearly vertically at high γ

Subject to conservation of angular momentum and total energy… or is it?

How Big a Boost?

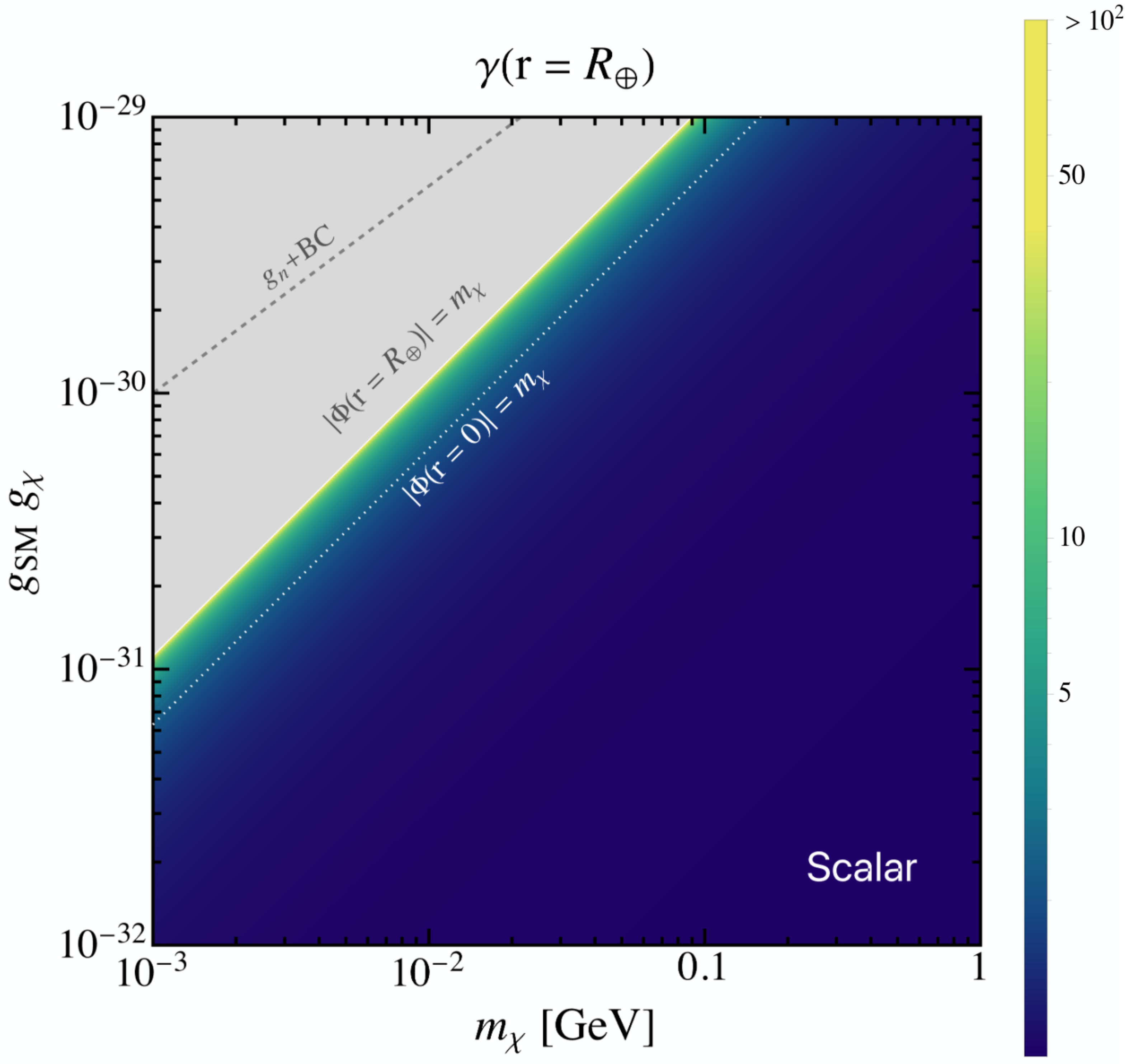
Non-relativistic:

Scalar & vector don’t differ

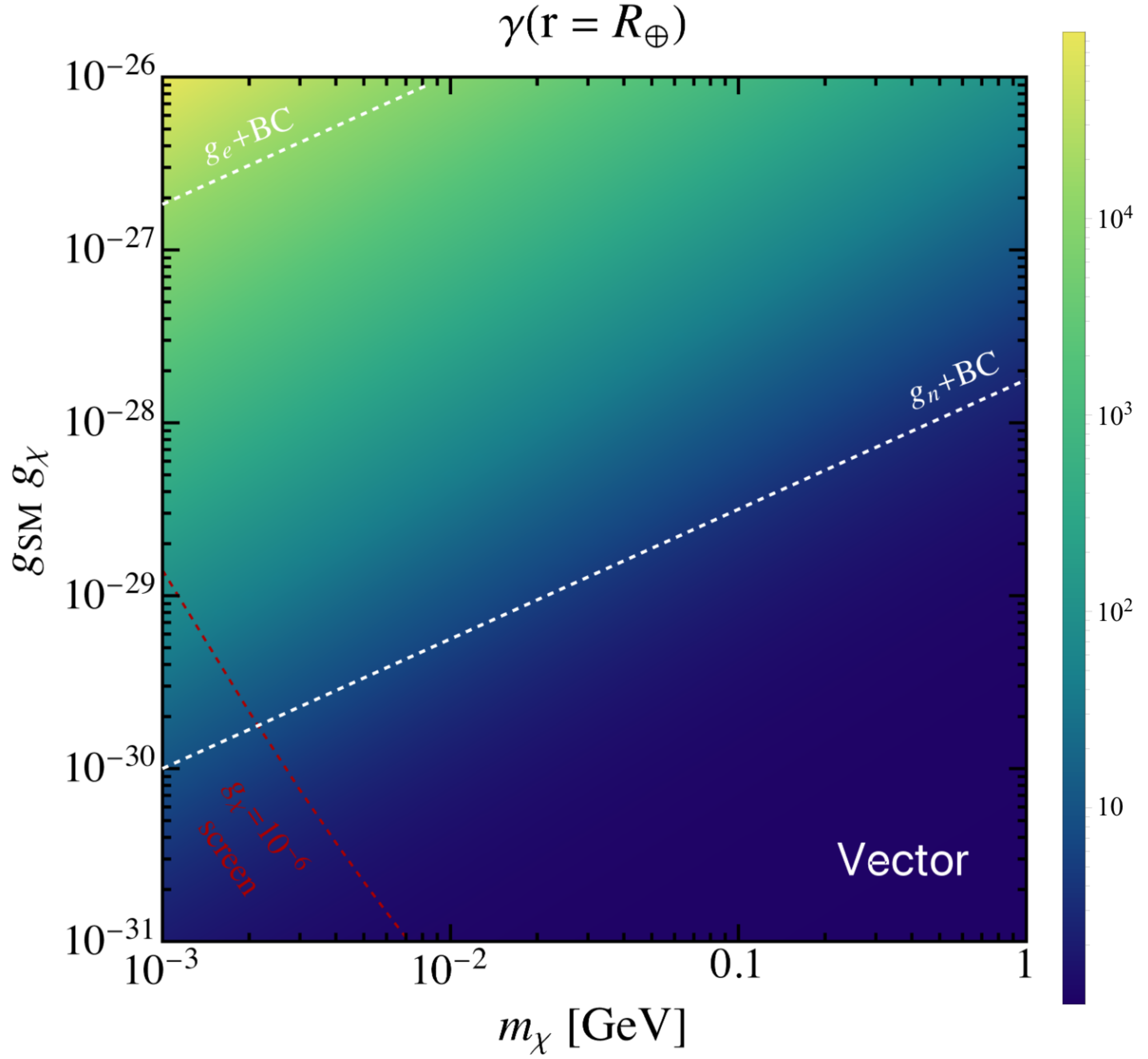
Relativistic:

Scalar & vector differ

$E = \gamma(m + \Phi)$ and $\mathbf{L} = E\mathbf{r} \times \mathbf{v}$



$E = \gamma m + \Phi$ and $\mathbf{L} = \gamma m\mathbf{r} \times \mathbf{v}$



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

Additional Considerations

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

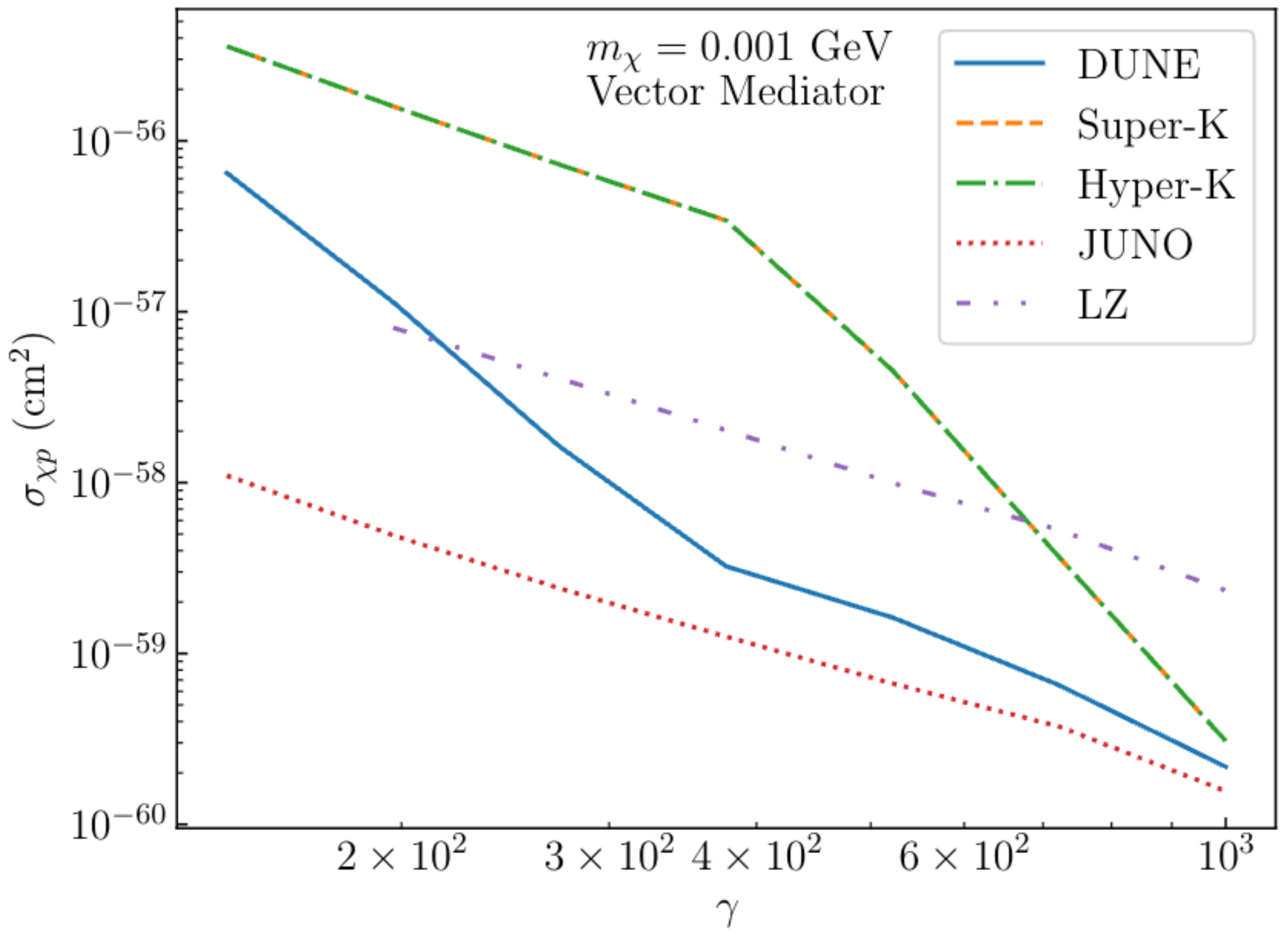
$$\Delta E_{\rm rad} \approx \mathcal{Q}\frac{m_\chi}{g_\chi g_n N_\oplus}\left\{\frac{\gamma^3}{3}, \frac{\gamma^5}{5}\right\}$$

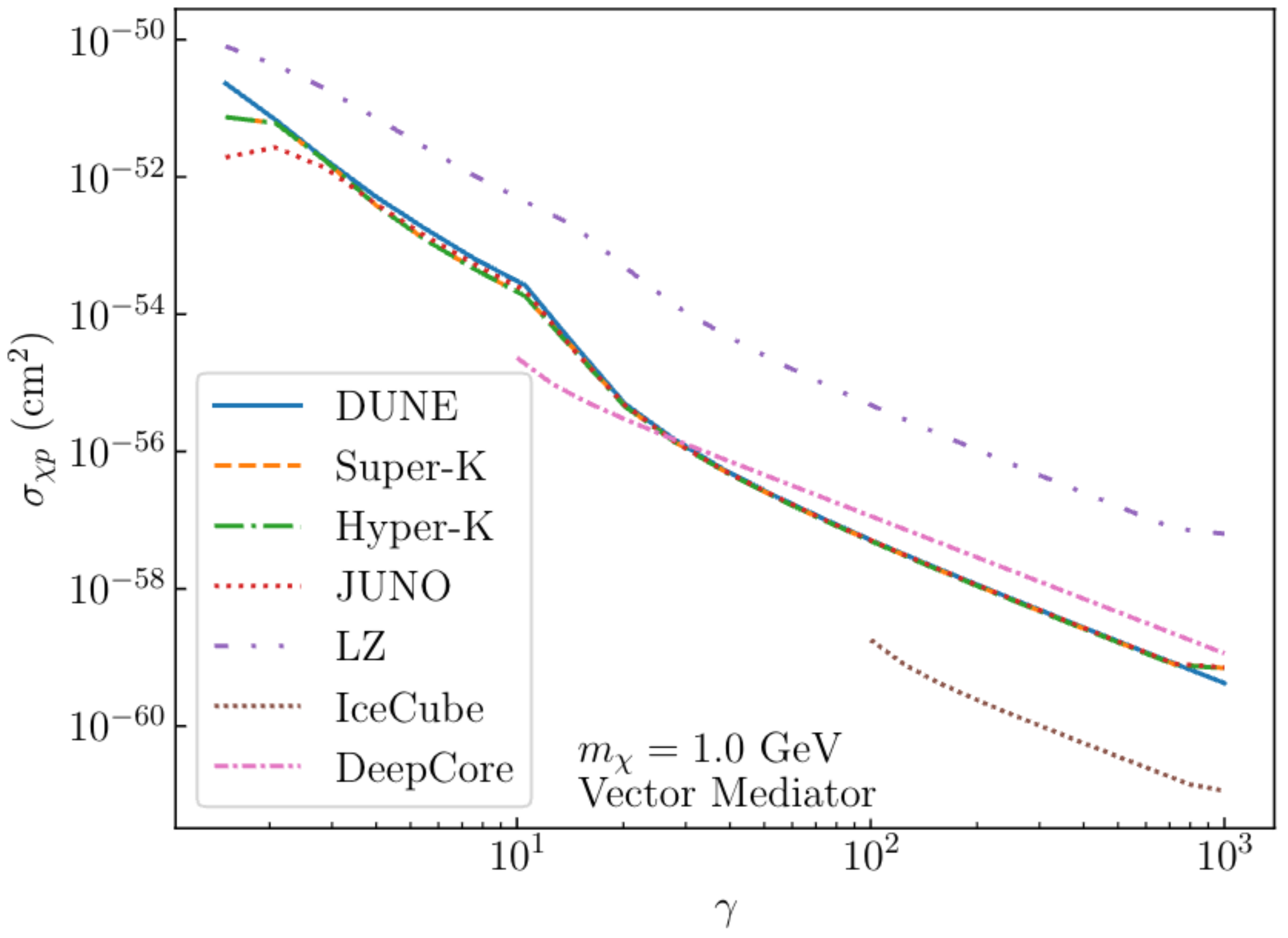
$\Longrightarrow$ Relevant at very high boosts, $\gamma \gtrsim 10^{10}$

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 $\sim \{1, \gamma^2\}/v_{\rm halo}^2$

Dark Matter Rain Results





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

Resonant Scattering

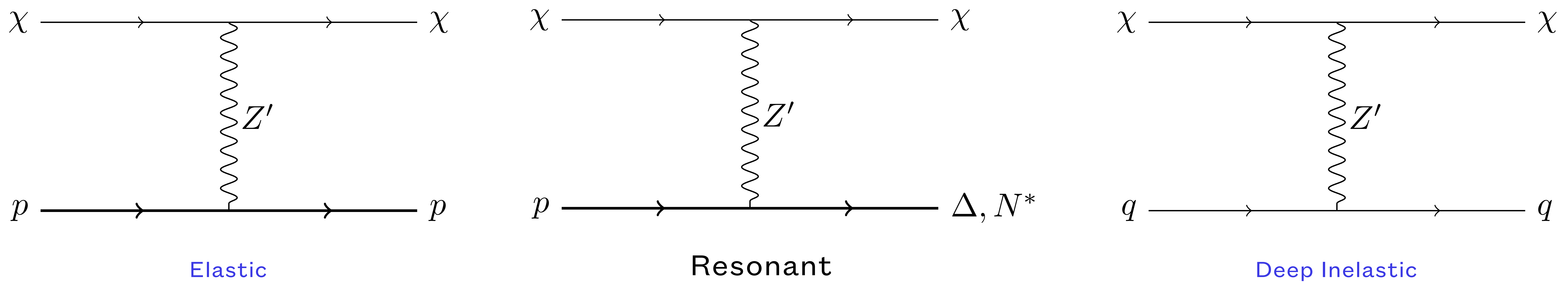
Dominant baryonic resonance is Δ: need to increase isospin by 1

If we see evidence of baryonic resonance, strong hint for isospin-violating BDM

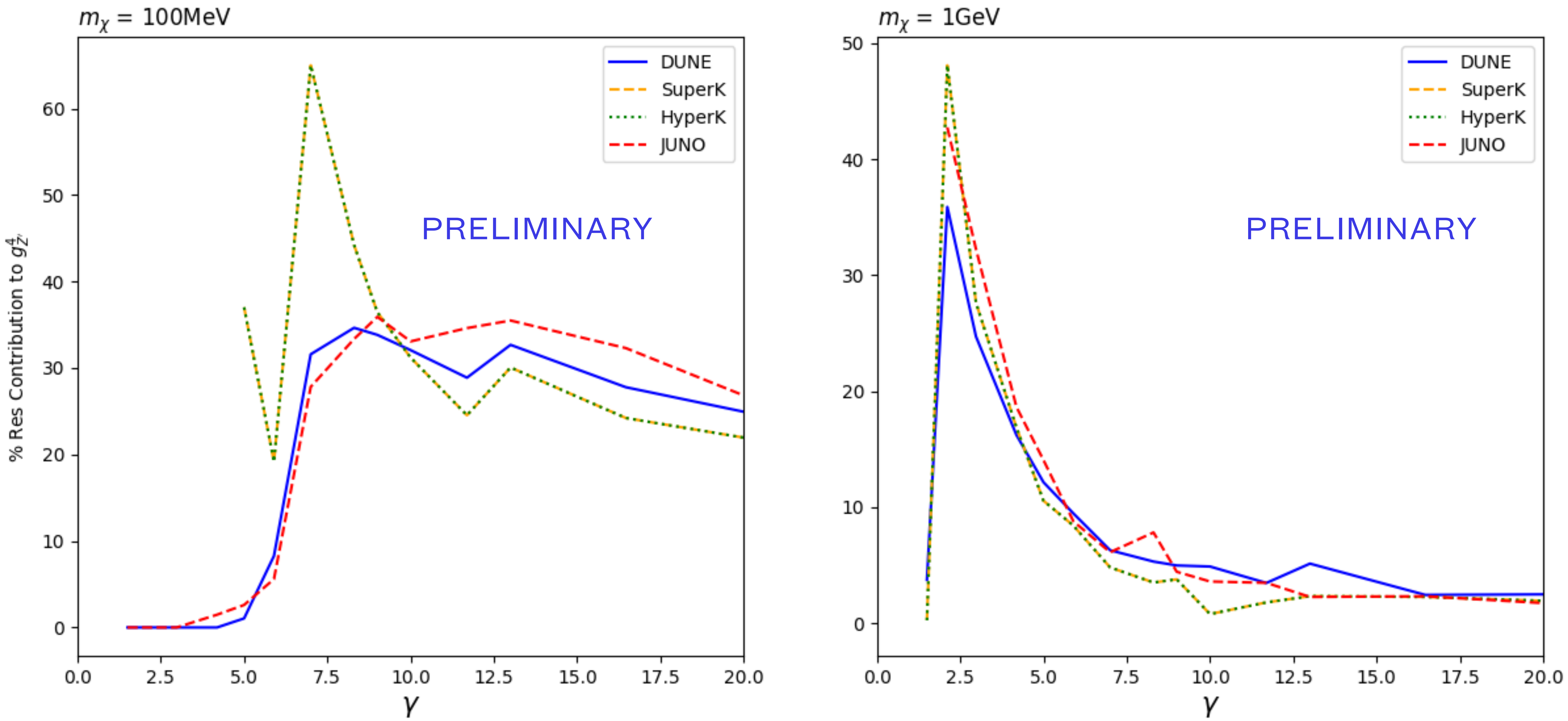
Implementation of resonant scattering in GENIE is ready to go

JB: 1812.05616
JB, Orr: 2506.xxxxx

- Based on Rein-Sehgal model, which is based on 1971 model by Feynman, Kislinger, Ravndal



Resonant Scattering's Effect

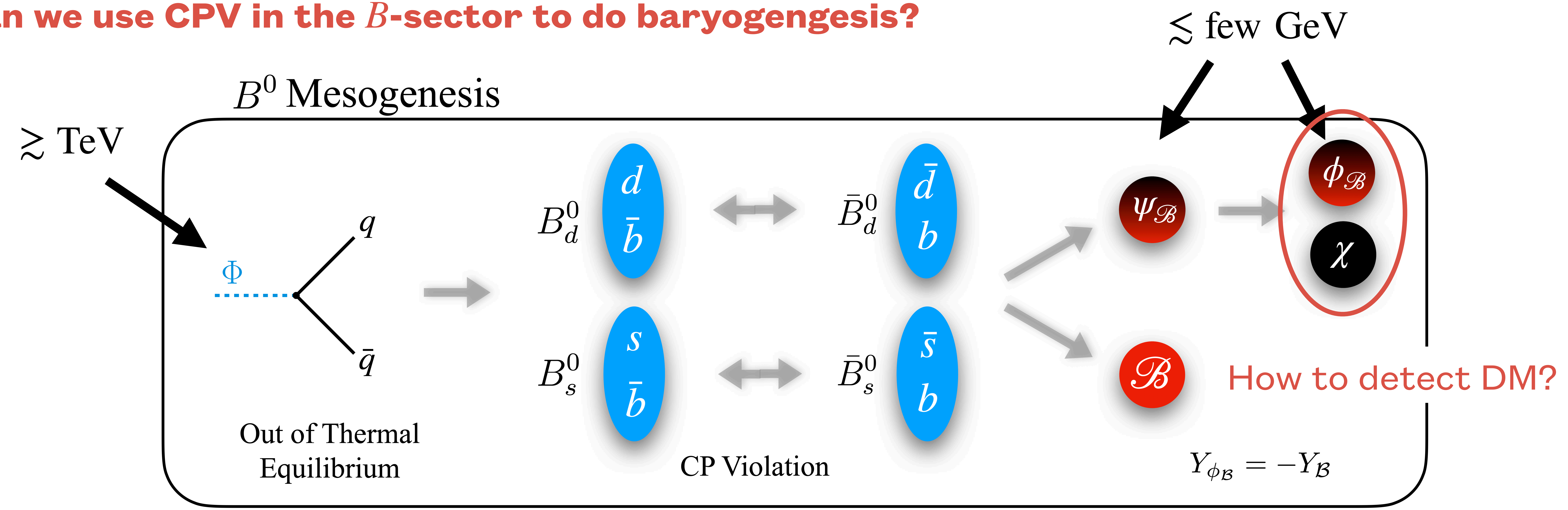


JB, Orr: 2506.xxxxx

See also Zink, Ramirez-Quezada: 2502.17573

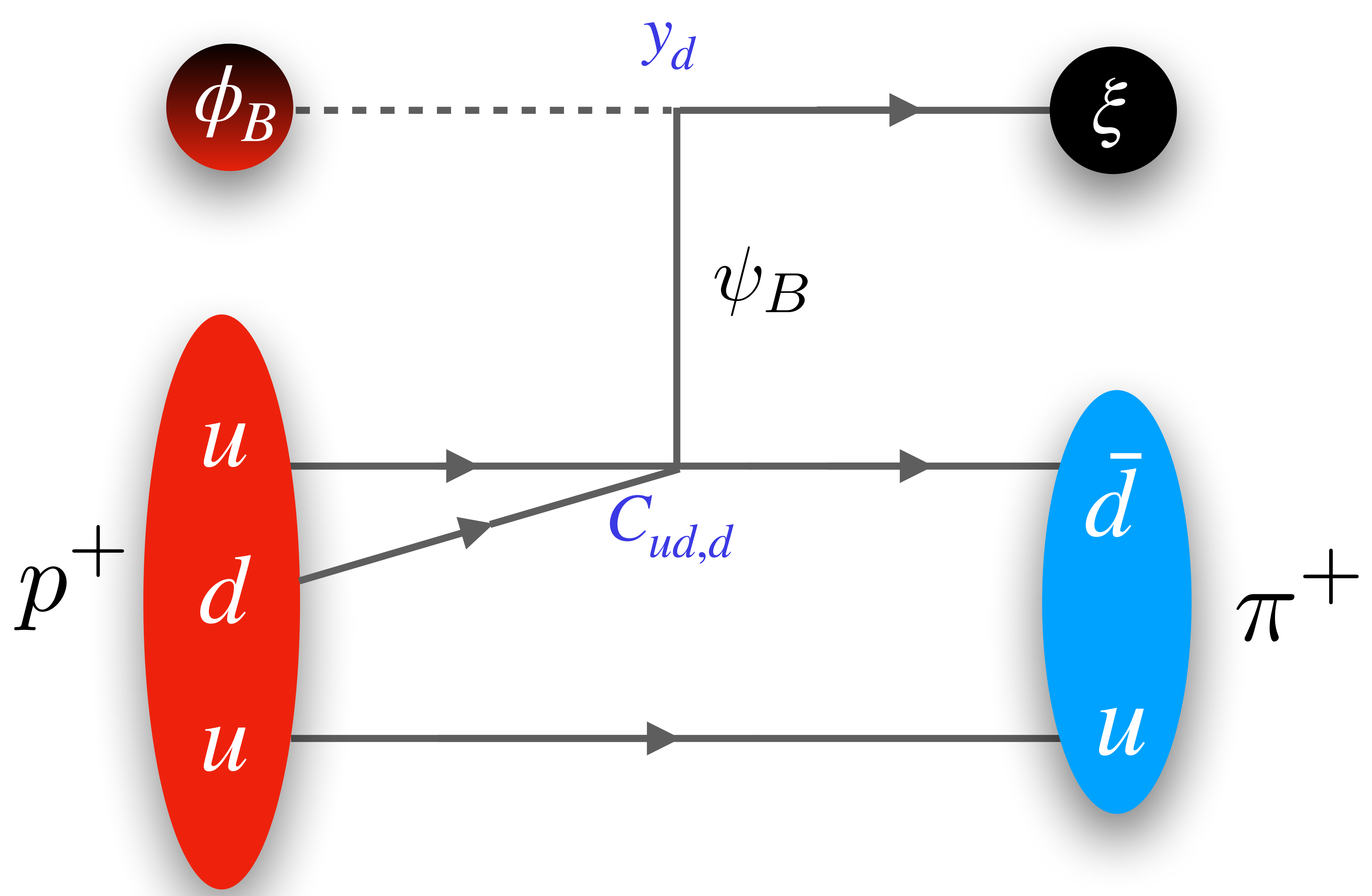
Mesogenesis and Dark Matter

Can we use CPV in the B-sector to do baryogengesis?



Elor, Escudero, Nelson: PRD 99, 035031 (2019)

Induced Nucleon Decay



JB, Elor: PRL 132 (2024) 8, 081002

See also Huang, Zhao: JHEP 77 (2014)

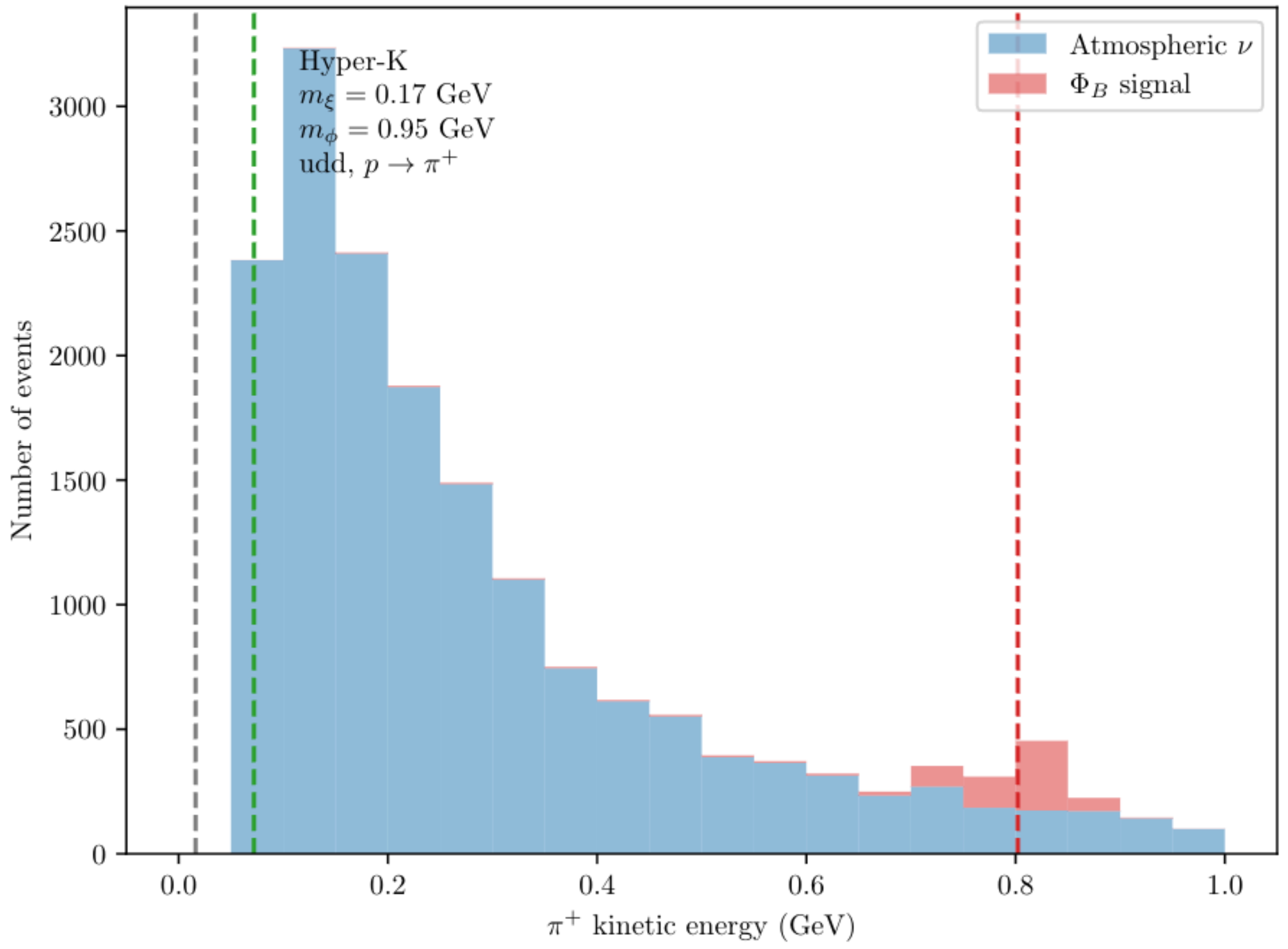
- Meson emerges with energy around GeV
- Differs from spontaneous p decay in kinematics

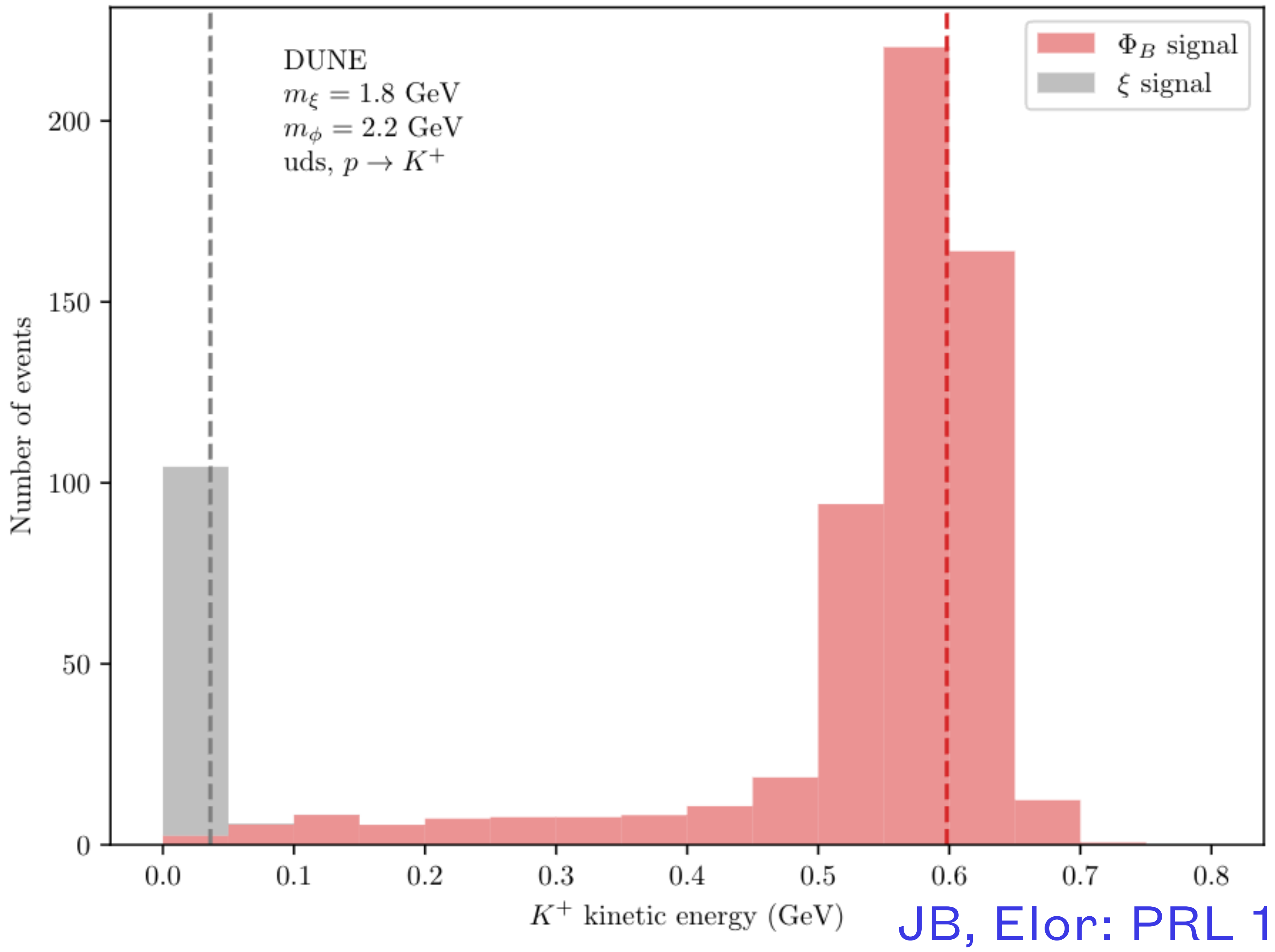
  $\Longrightarrow$ Existing Super-K searches cut away events
- Can reverse, $\xi \to \phi_B$, for different kinematics
- Up to nucleon motion, mono energetic signal

$$E^{\mathscr{M}}_{\phi_B N \to \xi \mathscr{M}} = \frac{m^2_{\mathscr{M}} + (m_N + m_{\phi_B})^2 - m_\xi^2}{2(m_N + m_{\phi_B})}$$

Mesogenesis Results

- Think about bounds on dim-6 coupling C_{ud_i,d_j} relative to max allowed by collider searches for Φ
- DUNE, JUNO, Hyper-Kamiokande: complementary bound of order $10^{-3} - 10^{-2}$





JB, Elor: PRL 132 (2024) 8, 081002

Macroscopic Dark Matter

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

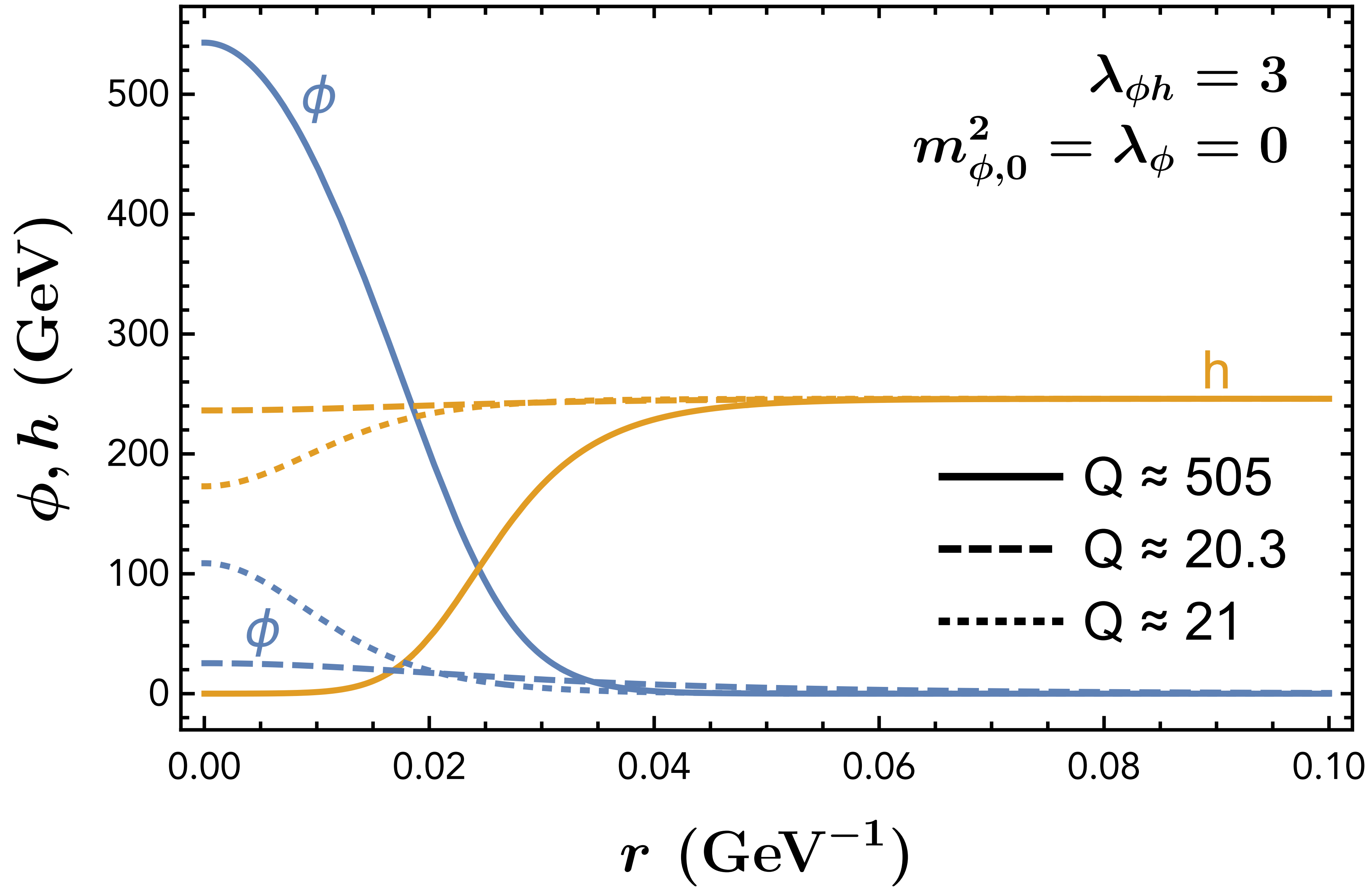
Can consider elastic scattering and look for multi-scatter events at direct detection experiments

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

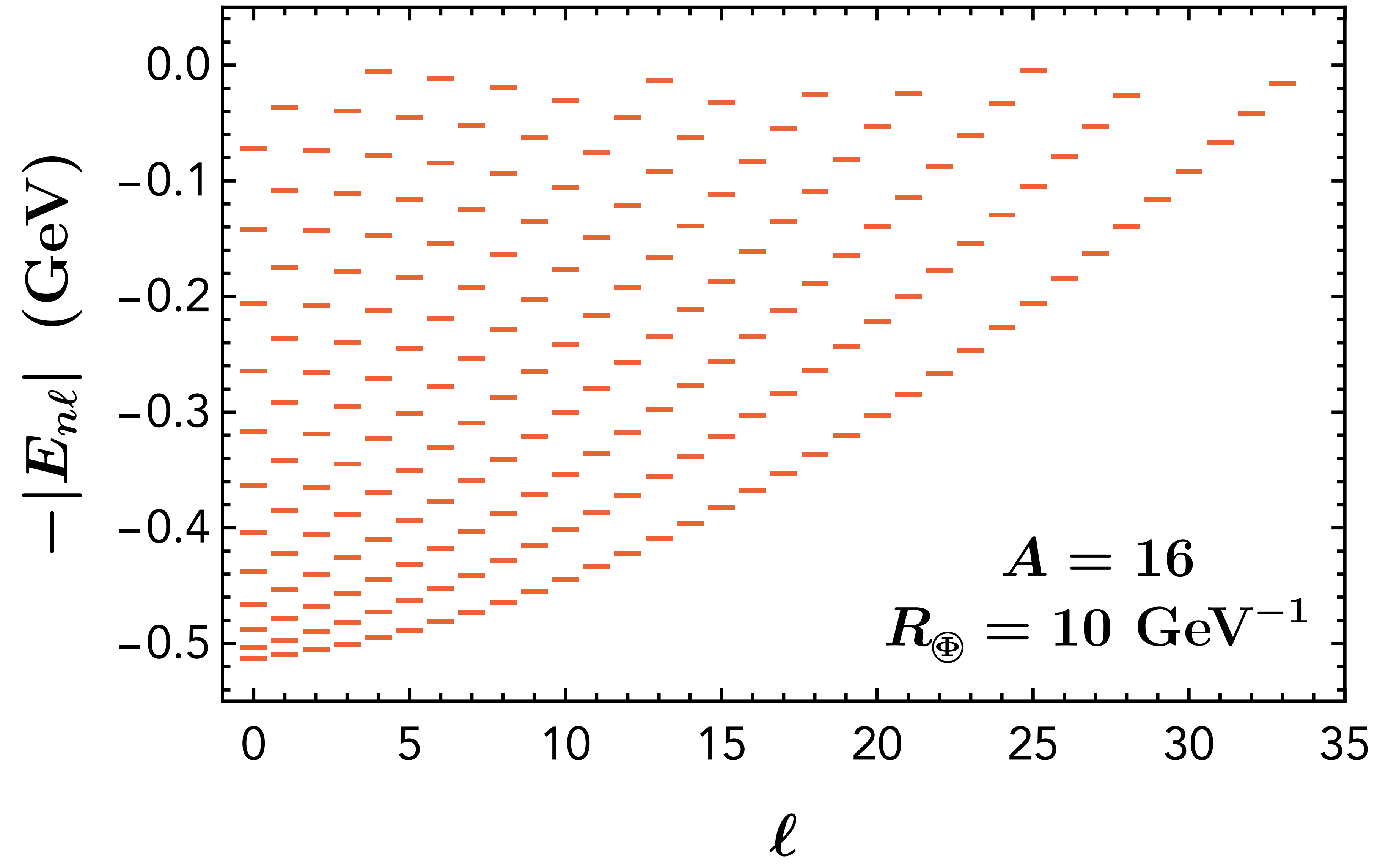
Creates a potential into which the nuclei can fall



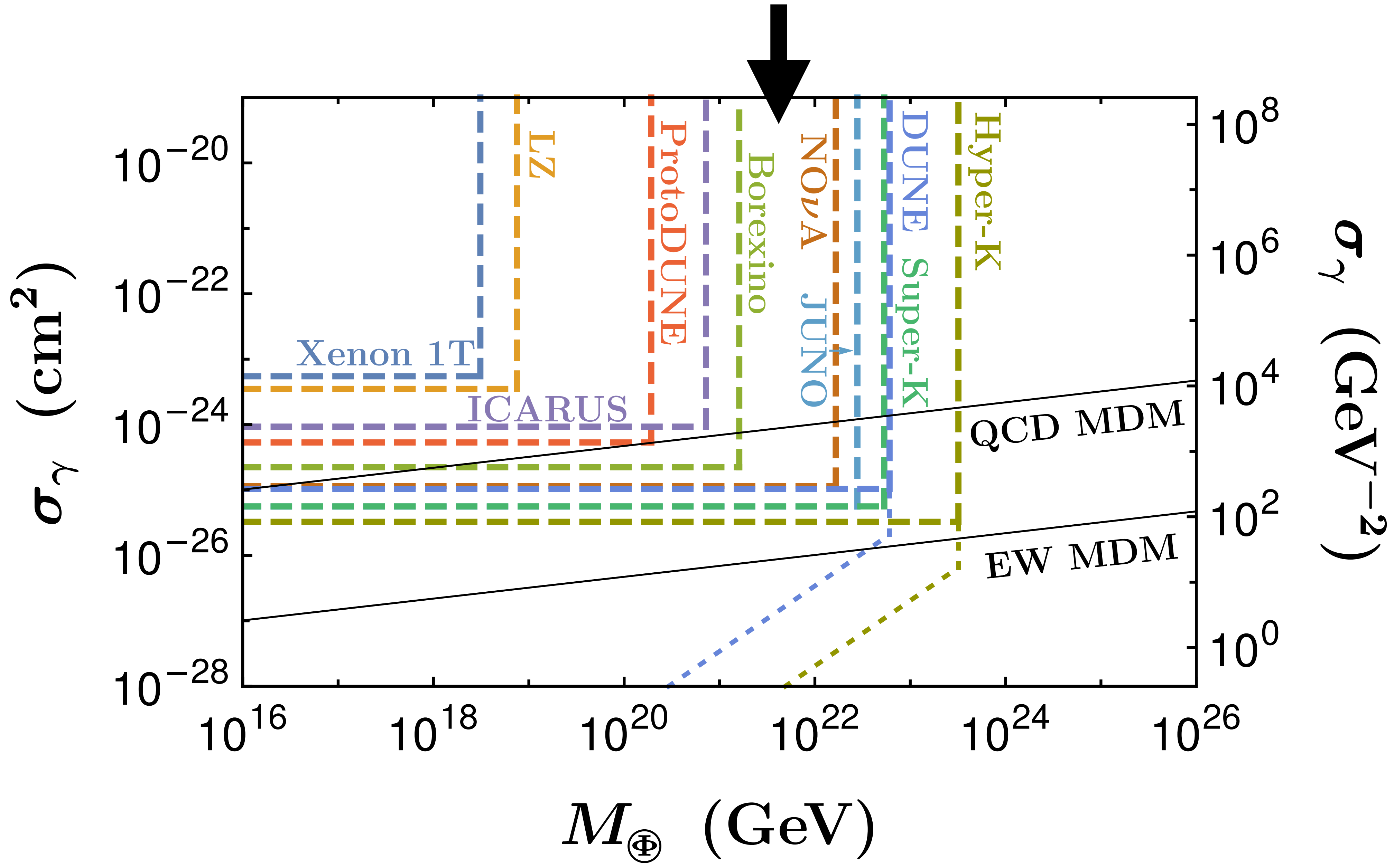
Pontón, Bai, Jain: JHEP 09 (2019) 011

Signals of Nucleus Capture

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



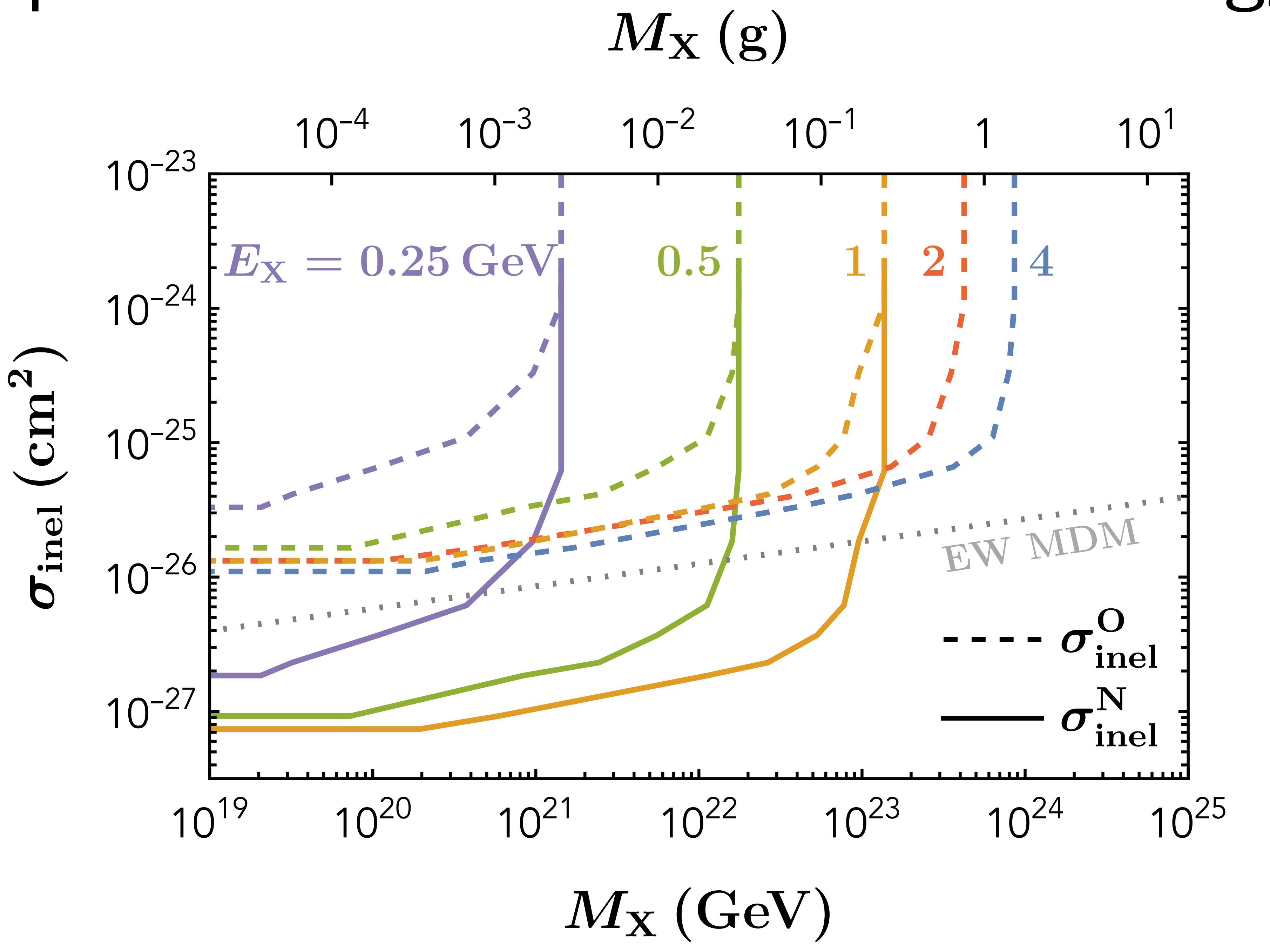
>5 captures per crossing!
Many photons per capture!

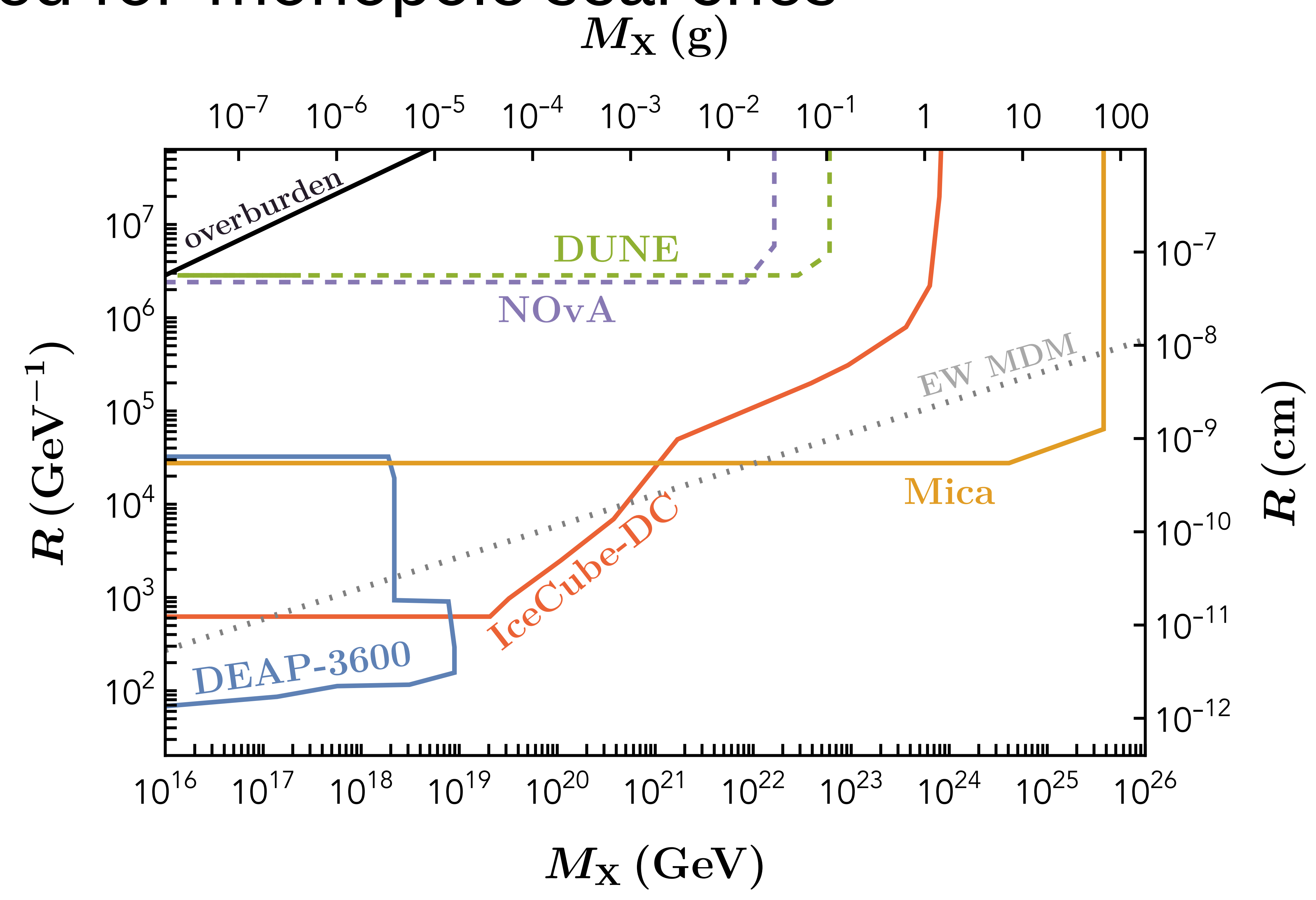


Bai, JB: JHEP 05 (2020) 160

DeepCore Signal

- Repurpose the IceCube Slow Particle Trigger used for monopole searches





Bai, JB, Korwar: JHEP 11 (2022) 079

Toward More Realism?

- 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

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

- Dipole approximation $e^{i\mathbf{q}\cdot\mathbf{x}} \approx 1$ reasonable when $|\mathbf{q}| \ll R_{\text{EWSB}}^{-1}$
- Most transitions: this doesn't work, but also rapidly oscillating $e^{i\mathbf{q}\cdot\mathbf{x}}$ makes integral small
- Can we get away with dipole approximation + analytic integral over small number of FS?
- Answer seems to be yes, but can we now simulate in a reasonable amount of time?

Outlook

- Direct detection works best in a particular region of parameter space, when framed in terms of recoil E
- At large recoil energies:
  We need to think about ν experiments
- At low recoil energies:
  Condensed matter devices
  Wavelike DM (not shown)
- Keep an open mind beyond the WIMP direct detection plot as to how we may see DM!