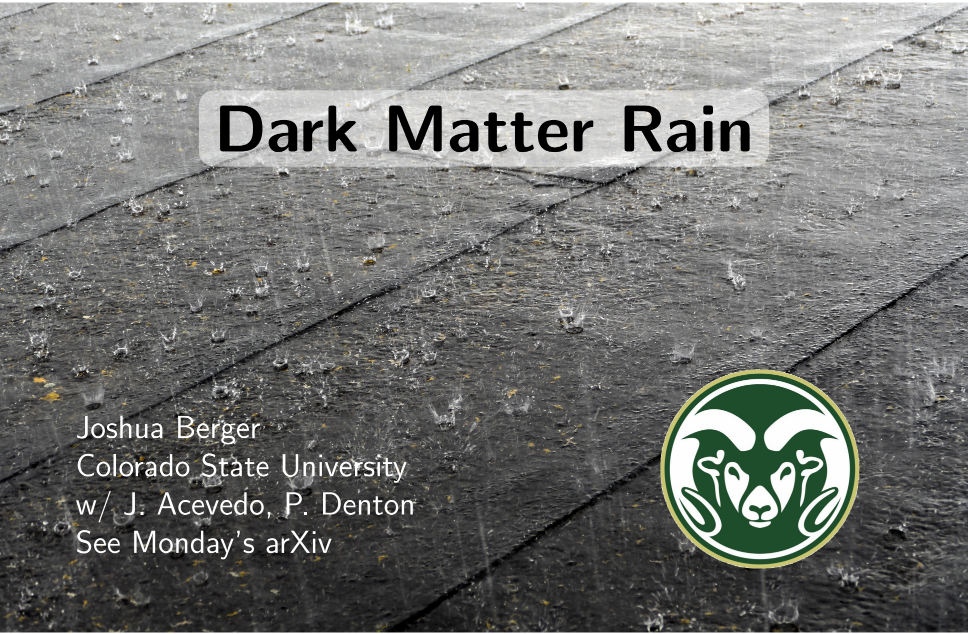


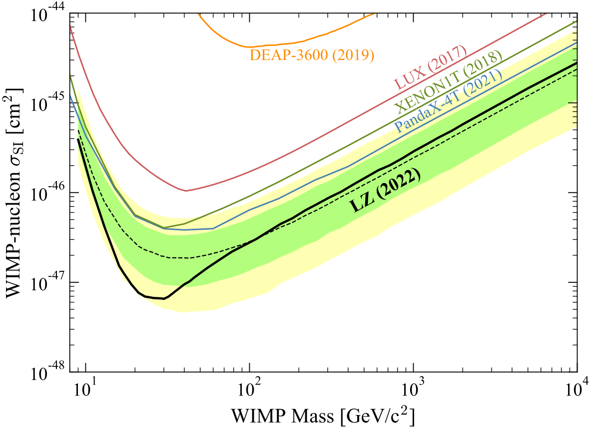
Dark Matter Rain

Joshua Berger
Colorado State University
w/ J. Acevedo, P. Denton
See Monday's arXiv

June 28, 2024

CETUP* 2024

Direct Detection & WIMP Paradigm



LZ: PRL 131, 041002 (2023)

What is DD Looking For?

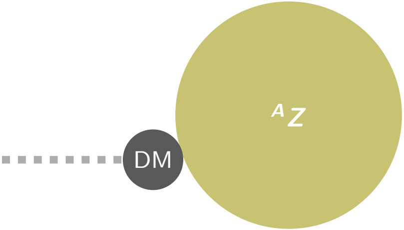
Local dark matter in Milky Way halo

$v \sim 10^{-3}\, c$

Ton-scale detector

What is DD Looking For?

Local dark matter in Milky Way halo



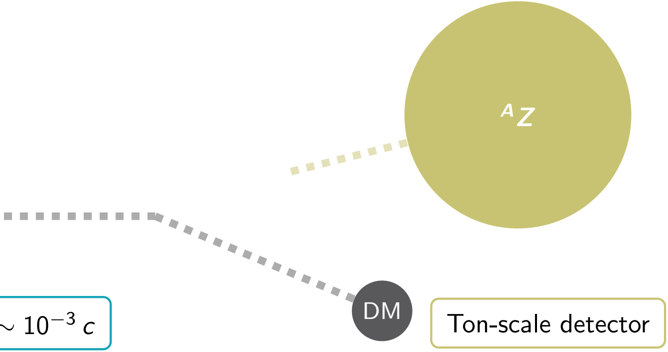
$v \sim 10^{-3}\, c$

Ton-scale detector

What is DD Looking For?

Local dark matter in Milky Way halo

Small nuclear kinetic energy 10s of keV (very non-relativistic)



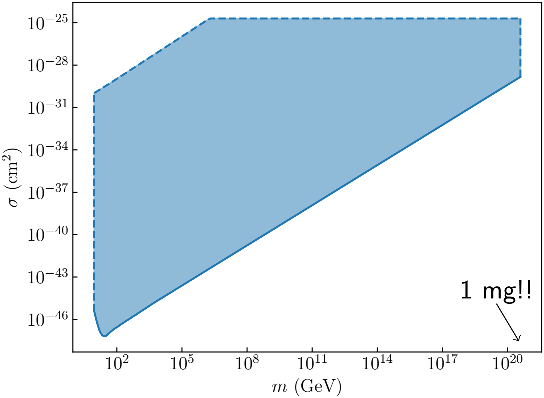
$v \sim 10^{-3}\, c$

Ton-scale detector

Joshua Berger

Beyond the WIMP?

DM stops due to Earth overburden/Multiple scattering



Nuclear recoil energy suppressed

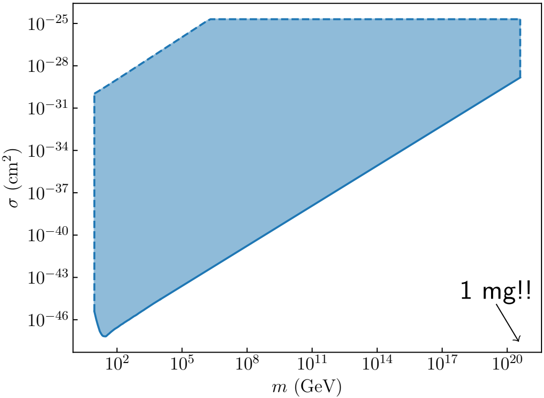
Flux through detector goes to 0

Interaction rate limited

LZ: PRL 131, 041002 (2023)

Beyond the WIMP?

Use astrophysics/rocks/Look for multiple scattering



Look in electrons/novel detectors/Migdal

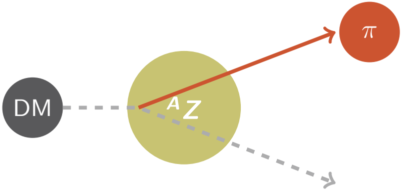
Multiple interactions in larger detectors

Keep building bigger + deal with ν fog

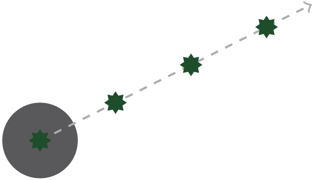
LZ: PRL 131, 041002 (2023)

Modify the Interactions Themselves?

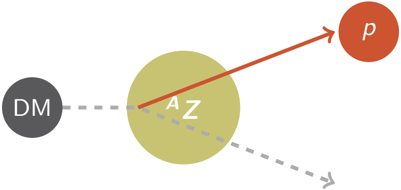
Induced nucleon decay



Nucleus capture in macro DM



Boosted dark matter scattering



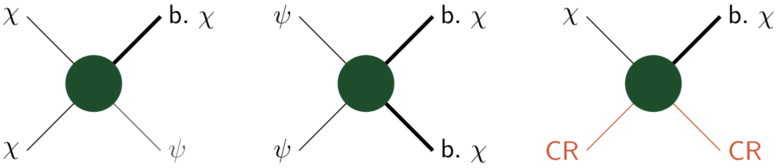
This Talk: Boosting Dark Matter

What if (some of) the dark matter flux at $v \gg 10^{-3}$?

- New detection opportunities
  - Potentially harness larger volume, higher threshold detectors
- New backgrounds
  - Learning to live in the neutrino fog prematurely
- Extended "easily" accessible mass range
  - Light, but high boost DM is visible if possible

Some Sources of DM Flux

Step 1: A boosting process



Semi-Annihilation

Two Component DM

Cosmic Ray Acceleration

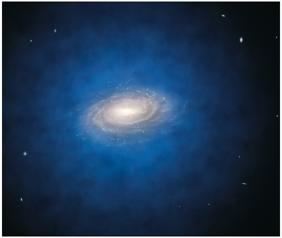
D'Eramo, Thaler
1003.5912

Agashe et. al.
1405.7370

Bringmann, Pospelov
1810.10543

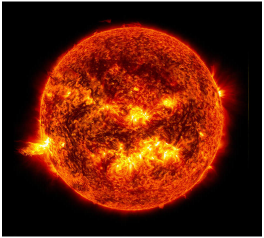
Some Sources of DM Flux

Step 2: A location



Galactic center

Agashe et. al.:
JCAP10(2014)062



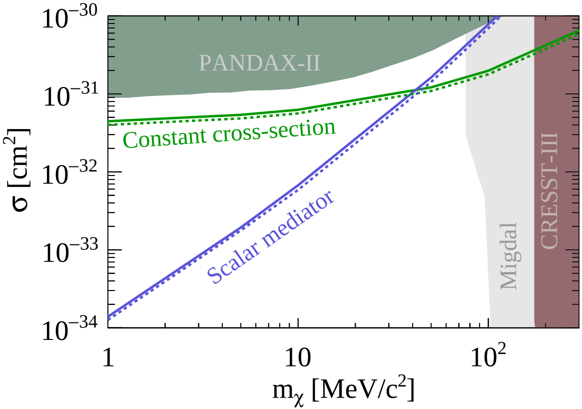
Sun

JB et. al.:
JCAP02(2015)005

Near Earth

Bringmann, Pospelov
1810.10543

Searches Ongoing!



Super-K: PRL 130 (2023) 031802

- Search for CR boosted dark matter scattering off protons

A New Mechanism for Boosting

(1) A very light boson, roughly $R_\oplus \ll m^{-1} \ll 1\ A.U.$

$$\mathcal{L} = -g_\chi \, \phi \, \overline{\chi}\chi - g_{\mathrm{SM}} \, \phi \, \overline{f} f$$

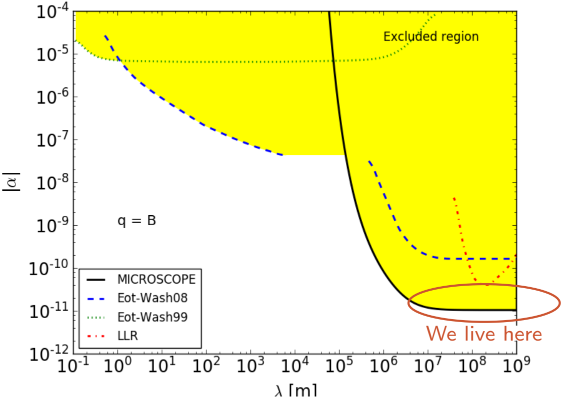
or

$$\mathcal{L} = -g_\chi \, A'_\mu \, \overline{\chi}\gamma^\mu\chi - g_{\mathrm{SM}} \, A'_\mu \, \overline{f}\gamma^\mu f$$

(2) A short range interaction

$$\mathcal{L} = \frac{1}{\Lambda^2} \, (\overline{f}\gamma^\mu f) \, (\overline{\chi}\gamma_\mu\chi)$$

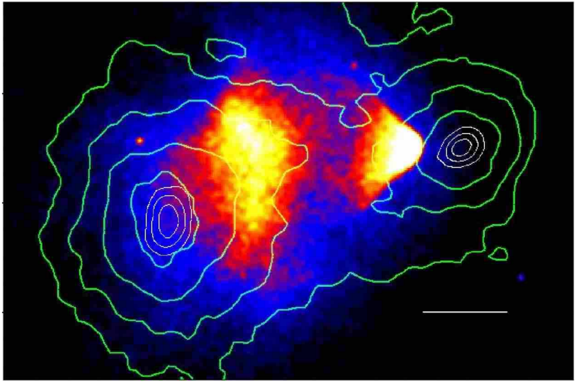
Constraints on Fifth Force



MICROSCOPE: PRL120, 141101 (2018), PRL129, 121102

In our notation: $g_{\mathrm{SM}} \lesssim 8 \times 10^{-25}$

Dark Matter Self-Interactions



Clowe et. al.: Astrophys.J.648:L109-L113,2006

- Bullet cluster self-interaction limit: $\sigma \lesssim 0.1\ \mathrm{cm}^2/\mathrm{g}$
- Implies $g_\chi \lesssim 4 \times 10^{-6}\,(m_\chi/\mathrm{MeV})^{3/4}$

Davoudiasl: PRD96, 095019 (2017)

Range of Interest

- On the low end: range longer than size of Earth
  - Avoid Yukawa suppression of interactions
- On the high end: range shorter than 1 A.U.
  - Avoid potential from Sun dominating over Earth locally
- In principle, can go longer range, but distribution distorted
- For comparison: dwarf spheroidals start at about 2×10^7 A.U.

Attractive Long Range Force

- Earth sets up a potential

$$\Phi = -\frac{g_\chi \, g_{\mathrm{SM}} \, N_\oplus}{4\pi \, r} \, e^{-m_\phi \, r} = -\frac{\alpha}{r} \, e^{-m_\phi \, r} \quad \text{or} \quad V^0 = -\frac{\alpha}{r} \, e^{-m_{A'} \, r}$$

- Particle Lagrangian:

$$L = -(m + \Phi) \sqrt{1 - v^2} \quad \text{or} \quad L = -(m + U^\mu \, V_\mu) \sqrt{1 - v^2}$$

- Energy:

$$E = \frac{m + \Phi}{\sqrt{1 - v^2}} \quad \text{or} \quad E = \frac{m}{\sqrt{1 - v^2}} + V^0$$

- Angular momentum:

$$\mathbf{L} = E \, \mathbf{r} \times \mathbf{v} \quad \text{or} \quad \mathbf{L} = \gamma \, m \, \mathbf{r} \times \mathbf{v}$$

Relativistic Infall: Vector Case

- Energy is conserved*, so $E \approx m$ far away is the total energy

$$E = \gamma(r)\, m + V^0(r) \implies \gamma(r) \approx 1 - \frac{V^0(r)}{m} \approx 1 + \frac{\alpha}{m\, r}$$

- Also want maximum impact parameter to hit the Earth:

$$b_{\text{max}} = \frac{R_\oplus}{u} \sqrt{\left(\frac{E - V_0(R_\oplus)}{m_\chi}\right)^2 - 1} = R_\oplus\, \gamma \left(\frac{v_\chi}{u}\right)$$

- From maximum impact parameter: maximum angular momentum

$$L_{\text{max}} = b_{\text{max}}\, m_\chi\, u = R_\oplus\, m_\chi\, \gamma\, v_\chi$$

Relativistic Infall: Scalar Case

- Similarly use energy conservation:

$$E = \gamma(r)\,[m + \Phi(r)] \implies \gamma(r) \approx \frac{E}{m + \Phi(r)} \approx \frac{1}{1 - \frac{\alpha}{m\,r}}$$

- Boost naively diverges at $r \approx m/\alpha$!
- Revisit divergent boost shortly
- Maximum impact parameter

$$b_{\max} = \frac{R_\oplus\,(m_\chi + \Phi(R_\oplus))}{m_\chi u}\sqrt{\left(\frac{E}{m_\chi + \Phi(R_\oplus)}\right)^2 - 1} = R_\oplus \left(\frac{v_\chi}{u}\right)$$

- Maximum angular momentum differs by a boost factor!

$$L_{\max} = b_{\max}\, m_\chi\, u = R_\oplus\, m_\chi\, v_\chi$$

Radiation Losses

- If γ becomes too large: radiation of mediators becomes important
- Particularly relevant for the scalar case
- Apply Larmor's formula:

$$\frac{dp^\mu_{\text{rad}}}{d\tau} = -\mathcal{Q}\, a^\lambda\, a_\lambda\, U^\mu, \qquad \mathcal{Q} = \frac{g_\chi^2}{6\,\pi^2} \text{ or } \frac{g_\chi^2}{12\,\pi^2}$$

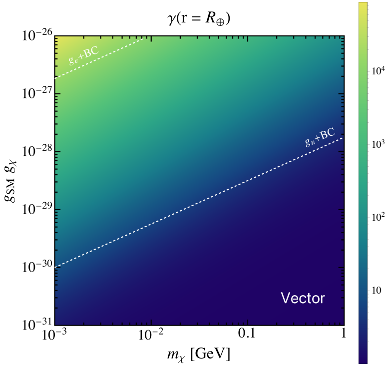
- Write energy loss as a function of (large) boost

$$\Delta E_{\text{rad}} \approx \mathcal{Q}\,\frac{m_\chi}{\alpha}\begin{cases} \frac{\gamma^5}{5}, & \text{vector} \\ \frac{\gamma^3}{3}, & \text{scalar} \end{cases}$$

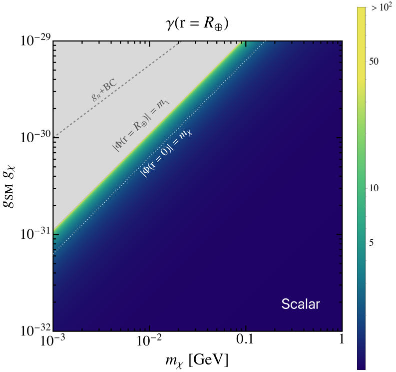
- Scalar case: can lose kinetic energy down to $m_{\text{eff}}(r) = m + \Phi(r)$
- Radiation relevant for very large boosts, above at least 10^{10}

Boost at Earth

Vector



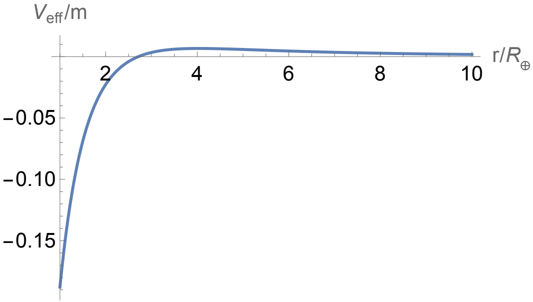
Scalar



- Scalar case: need to sit on narrow line to get large boost
- Vector case: wide open possibilities

Centrifugal Barrier?

- Potential falls off exponentially
- At some point $L^2/(2\,m\,r^2)$ dominates and a barrier forms



- Barrier height is tiny. . . but so is kinetic energy

Should We Be Worried?

- Can solve numerically for turning radius and barrier height
- But we also have an analytic approximation

$$\frac{dV_{\mathrm{eff}}}{dr} \simeq \frac{L^2}{m_\chi\, r^3} + \frac{\alpha\, m_{\phi,A'}}{r}\, e^{-m_{\phi,A'}\, r} = 0$$

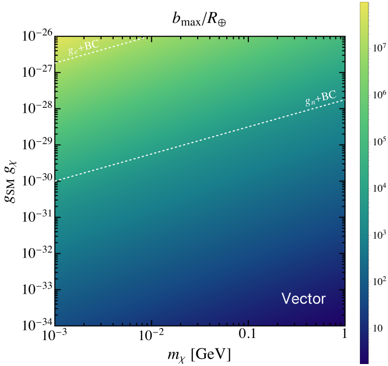
- Neglect small terms in $1/(m_{\phi,A'}\, r)$
- Naively good at the $\sim 10\%$ level
- Result:

$$\frac{b\, m_{\phi,A'}}{2} \lesssim \sqrt{\frac{W_{-1}^3(-\beta)}{W_{-1}(-\beta)+1}}, \qquad \beta = \frac{L}{2}\sqrt{\frac{m_{\phi,A'}}{\alpha\, m_\chi}}$$

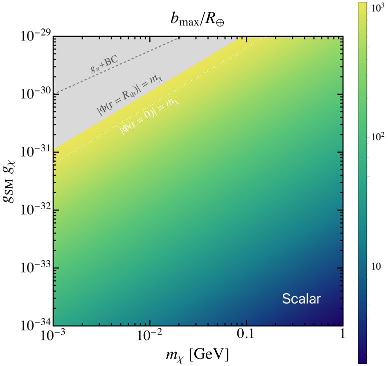
- At large $m_{\phi,A'}^{-1}$: impact parameter limited
- Below a range of 1 AU: parameter space is open

Maximum Impact Parameter

Vector



Scalar



- Larger impact parameters $\Longrightarrow$ larger flux
- Vector case again more promising

Dark Matter Flux

- Get differential flux at a radius far away then change to conserved angular momentum

$$d\mathcal{F} = \pi \, \frac{f(u)}{u} \, du \, dJ^2$$

- Flux per unit area differs for vector and scalar cases

$$\frac{d\mathcal{F}}{dA} \simeq \frac{1}{4} \, n_\chi \, v_\chi^2 \, \left\langle \frac{1}{u} \right\rangle \times \begin{cases} \gamma^2 & \text{(vector)} \\ \\ 1/2 & \text{(scalar)} \end{cases}$$

- Either way, a Sommerfeld-like enhancement, but extra γ^2

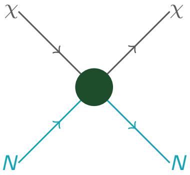
Toward Detection Prospects

- Event rate can be written in terms of nuclear interaction $\sigma_{\chi i}$:

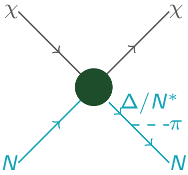
$$N_{\mathrm{event}} = T\, n_\chi \sum_i N_i\, \sigma_{\chi i}\, v_\chi^2 \left\langle \frac{1}{u} \right\rangle \times \begin{cases} \gamma^2 & \text{(vector)} \\ 1 & \text{(scalar)} \end{cases}$$

- How do we model cross section?
- Focus beyond coherent regime and use neutrino Monte Carlo code

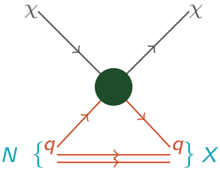
Modeling Interactions



Elastic



Resonant



Deep Inelastic

- Model using `GENIE`
- Implementation of resonant scattering forthcoming

JB: 1812.05616
JB, Orr: Forthcoming

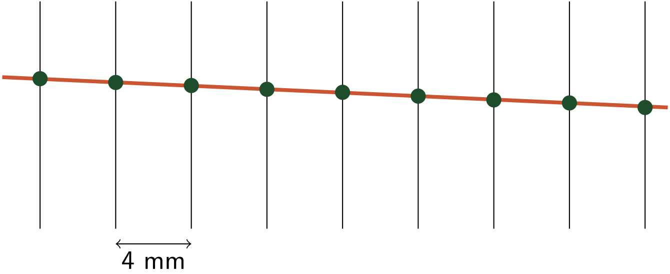
A Slate of Experiments to Look At

Lower threshold

- LZ & Other DD: few keV KE threshold, scintillation + TPC
- JUNO: ~ 0.5 MeV KE threshold, scintillation detector
- DUNE: ~ 10s MeV KE threshold, LArTPC + scintillation
- Super-K/Hyper-K: ~ 100s MeV KE hadronic, water Cherenkov
- DeepCore: ~ 10 GeV KE threshold, ice Cherenkov
- IceCube: ~ 100 GeV KE threshold, ice Cherenkov

Higher threshold

What Do Experiments See?



- DUNE: stable charged particles cross 10 wires
- Water Cherenkov: boost $\gamma > n$

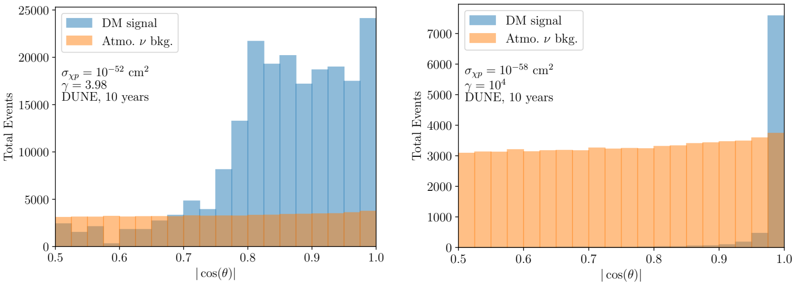
Experiment	$\mu^\pm$ (MeV)	$\pi^\pm$ (MeV)	p (MeV)	$e^\pm$ (MeV)	γ (MeV)
DUNE	35	35	80	30	30
Super-K/Hyper-K	55	75	485	3	3
JUNO	0.5	0.5	0.5	0.5	0.5

Ugh. . . Backgrounds

- Trickiest background: atmospheric ν scattering
- Split into two neutrino energy regimes, below and above 10 GeV
- Low energy: use Bartol fluxes at Soudan (DUNE/LZ) and Kamioka (Super-K/Hyper-K/JUNO)
- High energy: nearly location independent, just use high energy flux at Kamioka
- Model scattering using `GENIE`

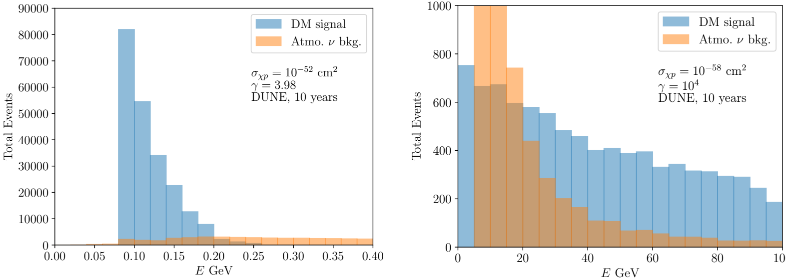
Barr et. al.: PRD70:023006,2004
Andreopoulos et. al.: NIM A614:87-104,2010, arXiv:1510.05494

Kinematic Distributions: Angular



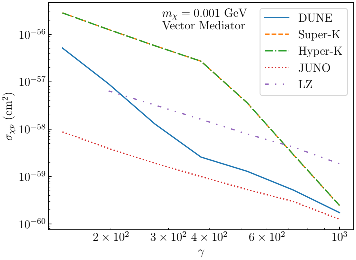
- Reconstruct total momentum of all visible particles above threshold
- θ: angle of that momentum w.r.t. vertical
- Two cut boxes: $|\cos\theta| > 0.8$, $|\cos\theta| > 0.9$

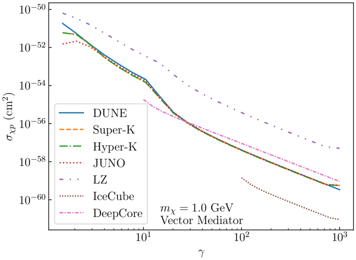
Kinematic Distributions: Energy



- Reconstruct total energy of all visible particles above threshold
- Two cut boxes: $E > 20$ MeV, $E > 10$ GeV
- DeepCore/IceCube: Just cut on DM energy above 10 GeV/100 GeV

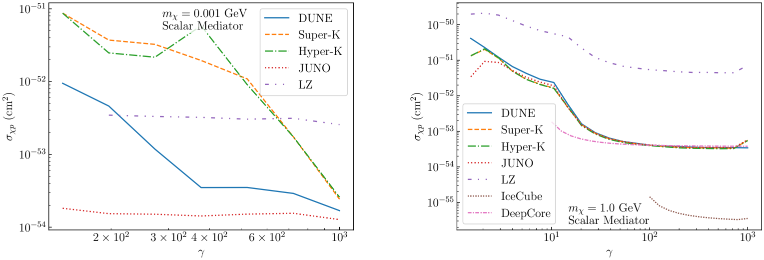
Results: Vector Mediator





- Assume 30% background normalization systematic
- Estimated 2σ sensitivities

Results: Scalar Mediator



- Assume 30% background normalization systematic
- Estimated 2σ sensitivities

The Future

- Large volume neutrino experiments can have interesting dark matter signals in addition to the flagship neutrino physics program
- Dark matter rain is a scenario in which all the dark matter is boosted and potentially visible at large experiments
- Some future directions:
  - What happens at longer range?
  - What happens in scalar case when infinite boost is approached?