Dark Sector Physics at Neutrino Experiments

Joshua Berger
Colorado State University

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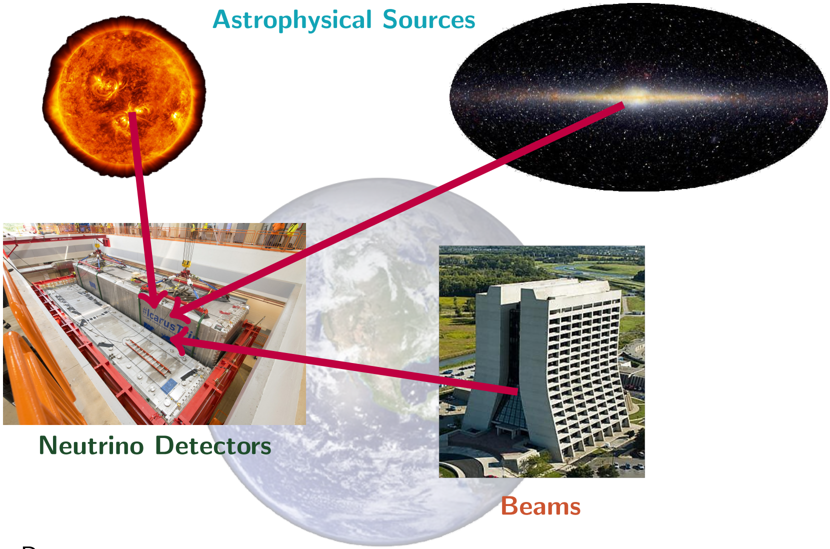
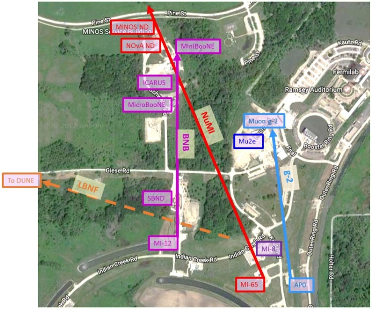
NuPhys 2023

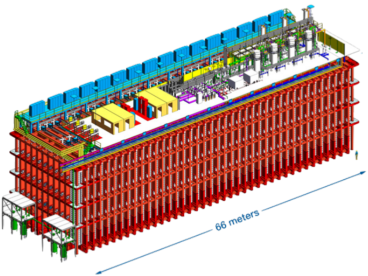
How Do We Get Dark Stuff?



Why Neutrino Experiments?

Short Baseline/Near Detectors: | **~~Long Baseline~~/Far Detectors:**





✓ Intense Proton Beam!

$\Longrightarrow$ Produce rare events

✓ 100s kton-year exposure!

$\Longrightarrow$ Largest DD experiments

Dark Sectors at Short Baseline

Short Baseline Opportunities

- Long-lived Portal Particles
  - Higgs portal: $S \leftrightarrow h$

    Batell, **JB**, Ismail: PRD100, 115039 (2019)
    MicroBooNE: PRL127, 151803 (2021)
  - Heavy neutral leptons: $N \leftrightarrow \nu$

    Ballett, Pascoli, Ross-Lonergan: JHEP 04 (2017) 102
    MicroBooNE: PRD106, 092006 (2022)
  - Heavy axions: $a \leftrightarrow \pi^0, \eta$

    Aloni, Soreq, Williams: PRL123, 031803 (2019)
    ArgoNeuT: arXiv:2207.08448
  - Dark Photons: $\gamma' \leftrightarrow \gamma$

    Berryman et. al.: JHEP 02 (2020) 174
- Light dark matter

  deNiverville, Chen, Pospelov, Ritz: PRD95, 035006 (2017)
- Inelastic dark matter

  Batell, **JB**, Darmé, Frugiuele: PRD104 (2021) 7, 075026
- Millicharged particles

  Magill, Plestid, Pospelov, Tsai: PRL122, 071801 (2019)

The SBN Experiments

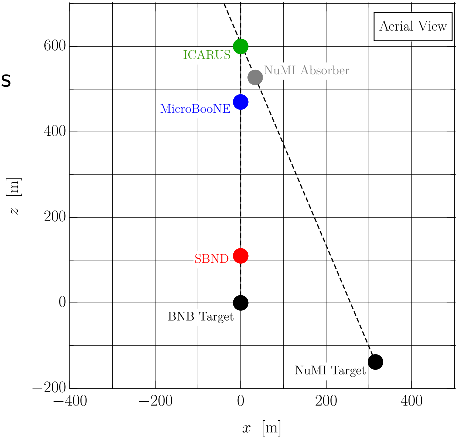
3 Liquid Argon TPC detectors:

- Can reconstruct full 3D events

Two beamlines:

- BNB: 8 GeV, on-axis
- NuMI: 120 GeV, off-axis
- Possible run using BNB absorber (not illustrated)?

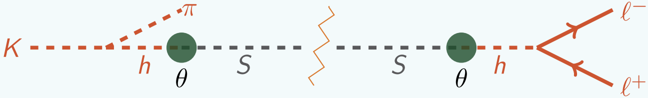
Data-taking ongoing now

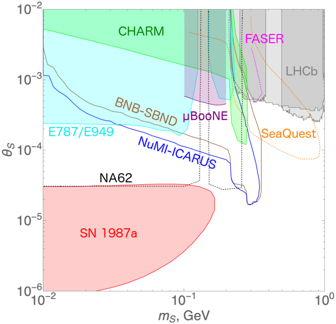


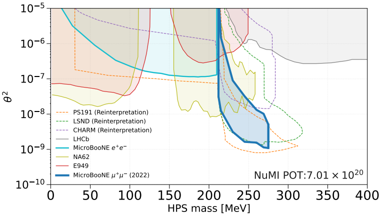
Batell, **JB**, Ismail: PRD 100 (2019) 11, 115039

Higgs Portal

Production



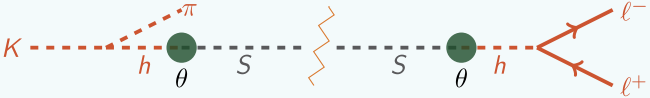


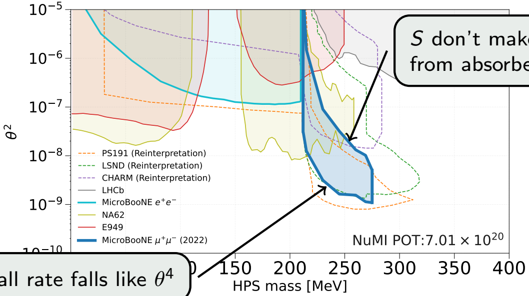


Batell, **JB**, Ismail: PRD (2019) MicroBooNE: PRD 106 (2022) 092006

Higgs Portal

Production





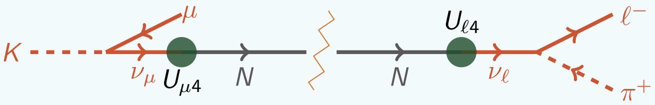
S don't make it $\sim$ 100 m from absorber to detector

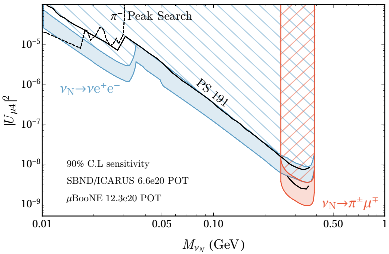
Overall rate falls like θ^4

MicroBooNE: PRD 106 (2022) 092006

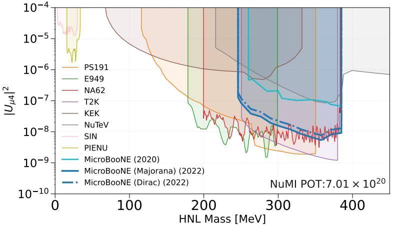
Heavy Neutral Leptons

Production





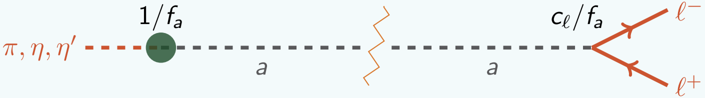
Ballett, Pascoli, Ross-Lonergan: JHEP 102 (2017)

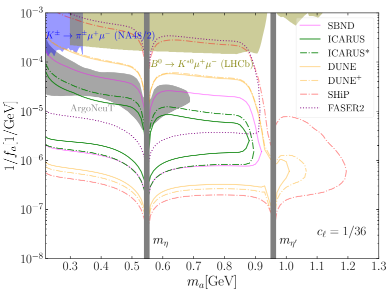


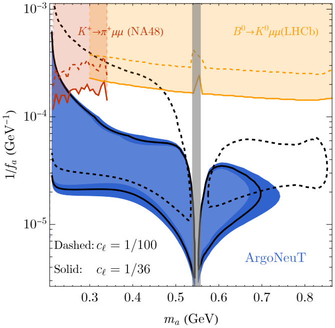
MicroBooNE: PRD 106 (2022) 092006

Heavy QCD Axions

Production



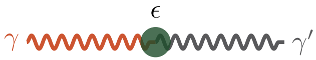


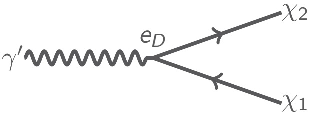


Co, Kumar, Liu: JHEP 111 (2023)   MicroBooNE: PRD 106 (2022) 092006

Inelastic Dark Matter: Many Targets

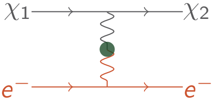
- Combine dark photon + dark matter



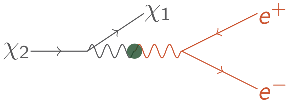


- Three possible signals in detector:

Short Lifetimes: Up-scattering



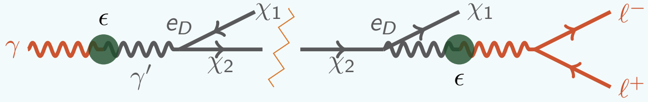
Long Lifetimes: Decay

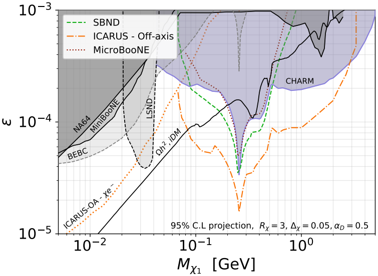


Very Long Lifetimes: Up- and down-scattering

Inelastic Dark Matter: Decay Mode

Production



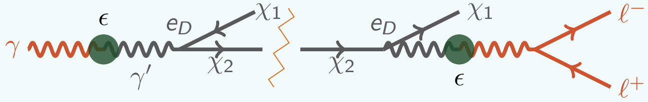


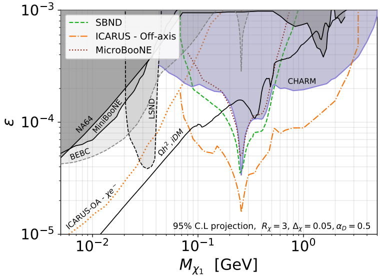
Insert Plot Here

Batell, **JB**, Darmé, Frugiuele: PRD (2021)

Inelastic Dark Matter: Decay Mode

Production





- Simulation available using modified `BdNMC` w/ `MadDump`
- Up-scattering also interesting: very distinctive signal!
- "Target-less" mode diverting to absorber would help @ SBND

de Niverville et. al.: PRD 95 (2017) 035006

Batell, **JB**, Darmé, Frugiuele: PRD (2021)

Buonocuore et. al.: JHEP 028 (2019)

Next Steps

- If you want to look for a particular signal, you need a simulation
  - All models discussed here have been simulated in some way
  - New models should follow this trend!
- Simulations can be challenging: tough range for QCD
  - Heavy QCD axions: no robust way to handle kinematics
  - Need accurate meson fluxes: need a database?
  - Not streamlined across theory groups and experiments
- Need more people to pick up analyses
  - Insert you here

Dark Matter at Far Detectors

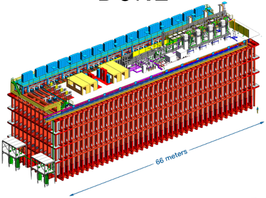
The Good, The Bad, and The Ugly

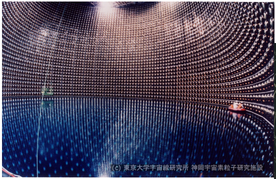
The Good: Far detectors (along with HE neutrino telescopes) are the largest detectors on Earth, typically 10s to 100s of kton

The Bad: Thresholds are higher than traditional direct detection experiments, typically MeV to GeV

The Ugly: Neutrinos become a background for searches, usually quite a large and sometimes irreducible background

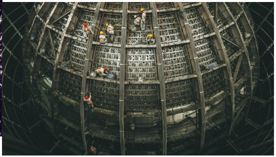
DUNE





Super-/Hyper-K

JUNO



The "Standard" WIMP Picture

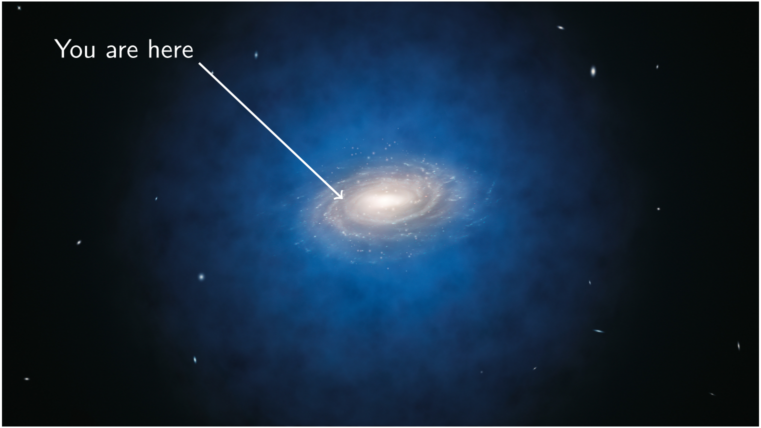
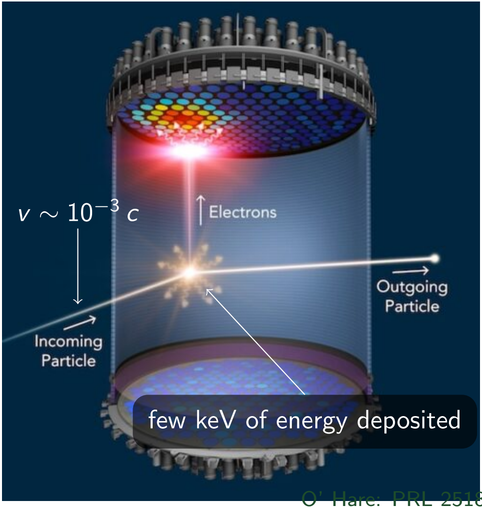
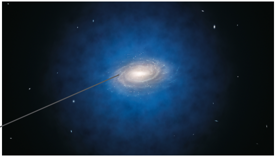


Image credit: ESO/L. Calçada

O' Hare: PRL 251802 (2021), LZ: PRL 041002 (2023)

The "Standard" WIMP Picture





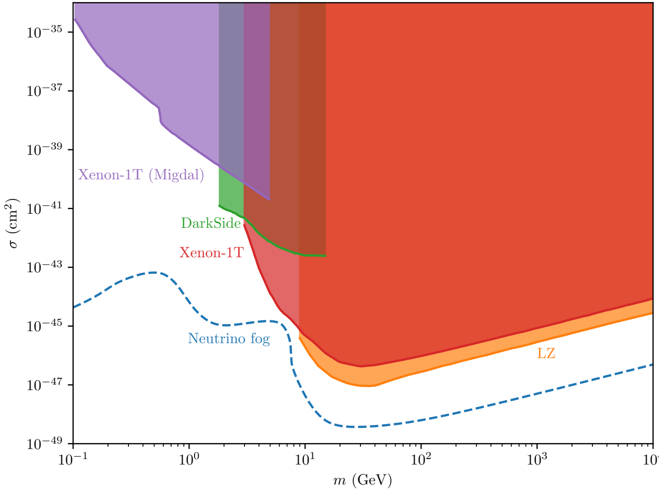
Assuming:

- Detecting halo DM
- Elastic nuclear recoils
- Single DM interaction
- One DM species

Image credit: LZ Collaboration

O' Hare: PRL 251802 (2021), LZ: PRL 041002 (2023)

The "Standard" WIMP Picture



O' Hare: PRL 251802 (2021), LZ: PRL 041002 (2023)

Boosted Dark Matter

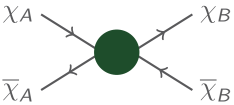
Standard WIMP Dark Matter

- Virial theorem tells us $\sqrt{\langle v^2 \rangle} \approx \sqrt{G\, M_{\mathrm{MW}}/R_{\mathrm{MW}}} \sim 10^{-3}\, c$
- Flux is fixed at $\rho_\chi\, v/m_\chi$

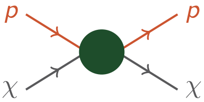
Boosted Dark Matter

- $\sqrt{\langle v^2 \rangle} \gg 10^{-3}\, c$, typically close to c
- Flux may be modified

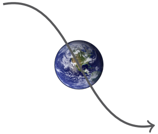
Several Mechanisms!



DM $\to$ DM



Cosmic Ray Kick

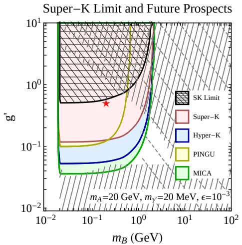


Dark Matter Rain

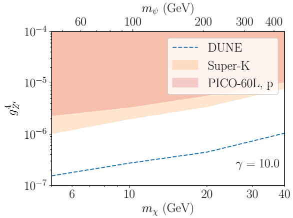
DM to DM Processes

Where?	Galactic center Sun	DM rich
How?	Heavy to Light Annihilation Semi-Annihilation Heavy to Light Decay	Gives part of rest mass
What?	Electron scattering Hadron scattering Inelastic scattering	Striking

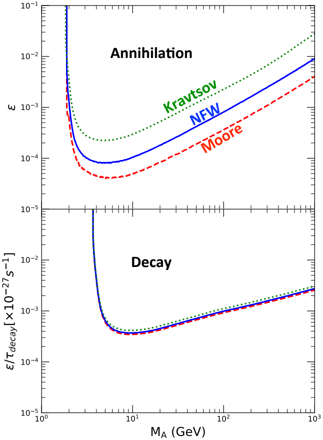
DM to DM Results



Agashe, Cui, Necib, Thaler: JCAP (2014)



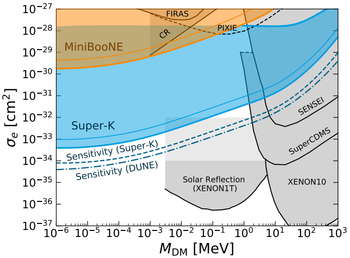
JB et. al.: PRD (2019)



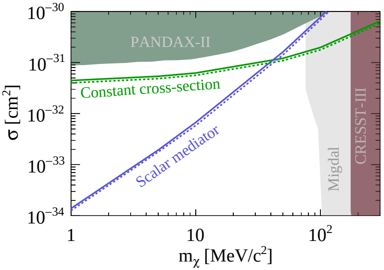
Super-K: PRL 120, 221301 (2018)

Cosmic Ray Acceleration

- For neutrino detectors: focus on $e^\pm$ cosmic rays, e^- detection
- Significant acceleration for $m \lesssim$ GeV
- Up to 10 GeV recoil electrons!



Ema, Sala, Sato: PRL (2019)



Super-K: PRL (2018)

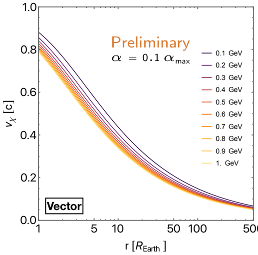
Dark Matter Rain

Could dark matter have a long range force with standard matter?

- Galactic scale: would mess up DM halo
- Earth scale: $g_n \lesssim 10^{-24}$ from 5th force, equivalence principle
  Schlamminger et. al.: PRL 041101 (2008), Fayet: PRD 055039 (2018)
- Long range $g_\chi \lesssim 4 \times 10^{-6} (m_\chi/\mathrm{GeV})^{3/4}$ from dwarf galaxies
  Davoudiasl: PRD 095019 (2017)

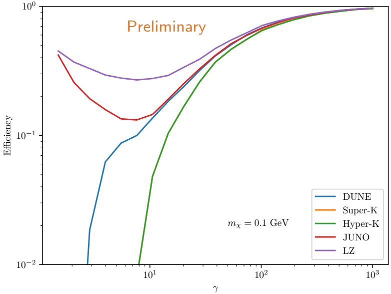
$$m \approx \begin{cases} \gamma\,(m - g_\chi \phi), & \text{scalar} \\ \gamma\, m - g_\chi\, \phi, & \text{vector} \end{cases}$$

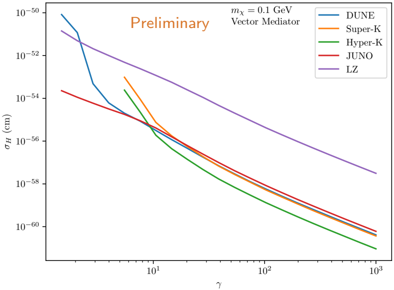
$$R = \frac{\rho_\chi}{m_\chi} \left\langle \sigma \, \frac{(1, \gamma^2)\, w^2}{u} \right\rangle N_{\text{target}}$$



Acevedo, **JB**, Denton: 2401.xxxxx

DM Rain: Projected Sensitivity





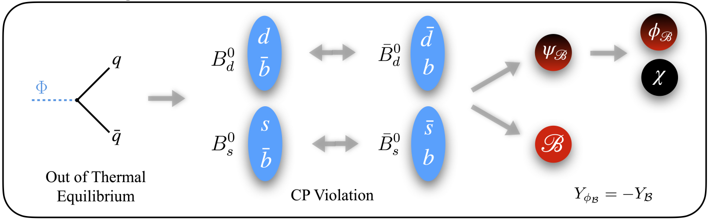
- No traditional direct detection
- Directional and energy cuts to reduce NC atmo. ν background
- Large experiments can look now

Acevedo, **JB**, Denton: 2401.xxxxx

Induced Nucleon Decay

Can dark matter carry baryon number?

B^0 Mesogenesis

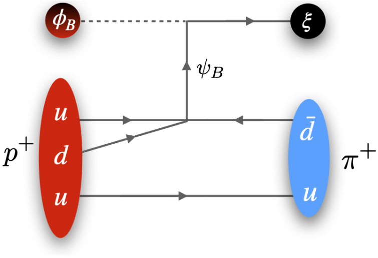


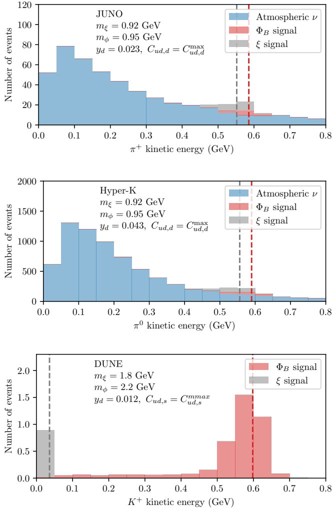
Elor, Escudero, Nelson: PRD 99, 035031 (2019)

- In models like hylogenesis and mesogenesis, yes!
- Also gives mechanism for matter–anti-matter asymmetry
- Can reverse: DM induces proton decay

Davoudiasl, Morrissey, Sigurdson, Tulin: PRL 211304 (2010)

Detecting Induced Nucleon Decay



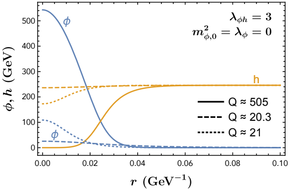


- Different energy spectrum from spontaneous proton decay
- Sensitivity to couplings 10^{-3} to 10^{-2} of collider bounds

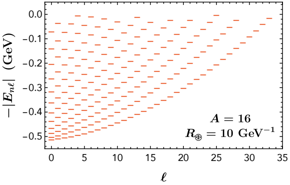
JB, Elor: 2301.04165; see also Huang, Zhao: JHEP 077 (2014)

Macroscopic Dark Matter

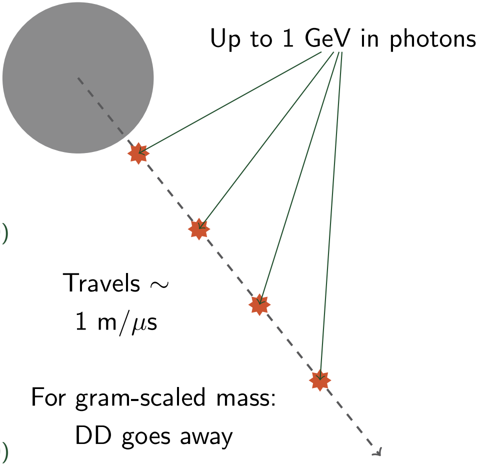
Can dark matter be large in extent?



Pontón, Bai, Jain: JHEP 11 (2019)



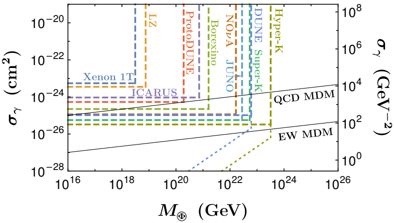
Bai, **JB**: JHEP 160 (2020)



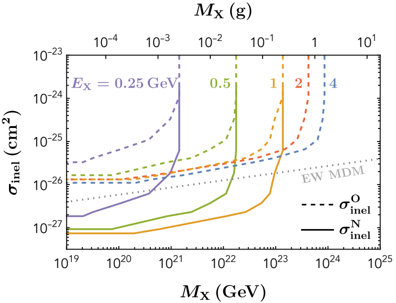
Travels ∼ 1 m/μs

For gram-scaled mass: DD goes away

Detecting MDM



Bai, **JB**: JHEP 160 (2020)



Bai, **JB**, Korwar: JHEP 79 (2022)

- Large detectors heavily favored, depending on energy spectrum
- DeepCore has sensitivity to GeV deposits using SLOP trigger
- In progress (w/ Rutledge): Monte Carlo for capture & decay chain

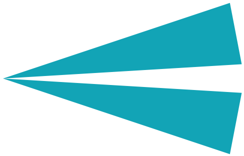
Outlook

- Dark sector searches complement ν program, but several challenges
- Simulation: flux generation, propagation, detector interaction
- Complex detection topologies possible
- Experimental pipeline is `ROOT`-based
- Nuclear modeling uncertainty propagation
- Large full simulation event size
- Some experiments are smaller: personnel?
- No general reconstruction tools or parameterized efficiency/resolution for fast simulation

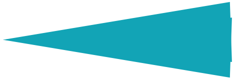
Backup

More on e^+e^- Background

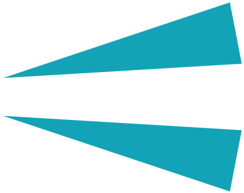
Signal:



Single γ Bkg:

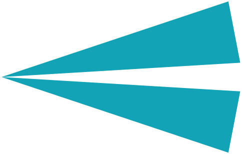


Two γ or $e + \gamma$ Bkg:



More on e^+e^- Background

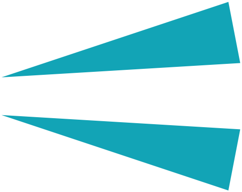
Signal:



Single γ Bkg:

Run photons through `Geant4`

Two γ or $e + \gamma$ Bkg:



Fixed kinetic energy

- In nucleon rest frame: Fixed meson K.E.

$$E^{\mathcal{M},\,\mathrm{kin}}_{\phi_{\mathcal{B}} N \to \xi \mathcal{M}} = \frac{m_{\mathcal{M}}^2 - m_{\xi}^2 + (m_N + m_{\phi_B})^2}{2(m_N + m_{\phi_B})} - m_{\mathcal{M}}$$

- Smeared by nucleon motion:

$$p_{\mathcal{M}} \lesssim p_F \approx 240 \text{ MeV} \quad \text{(Argon)}$$

- Hydrogen in water: no smearing!
- Ideally: simulate this process!

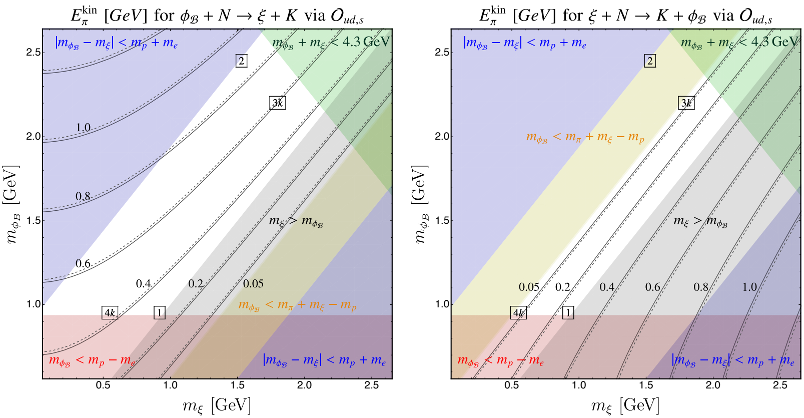
Parameter Space

✓	$B \to \mathcal{B}_{\mathrm{SM}}\, \psi_{\mathcal{B}}$:	$m_{\psi_{\mathcal{B}}} < m_B - m_p \simeq 4.34\,\mathrm{GeV}$
✓	$\psi_{\mathcal{B}} \to \xi + \phi_{\mathcal{B}}$:	$m_{\psi_{\mathcal{B}}} > m_\xi + m_{\phi_{\mathcal{B}}}$
×	$\phi_{\mathcal{B}} + \xi \to \mathcal{B}_{\mathrm{SM}}$:	$\lvert m_{\phi_{\mathcal{B}}} - m_\xi \rvert < m_p + m_e \simeq 938.8\ \mathrm{MeV}$
×	$\mathcal{B}_{\mathrm{SM}} \to \phi_{\mathcal{B}}, \xi$:	$m_{\phi_{\mathcal{B}}}, m_\xi < m_p - m_e$
✓	$\phi_{\mathcal{B}} + \overline{\phi}_{\mathcal{B}} \to \xi + \xi$:	$m_{\phi_{\mathcal{B}}} > m_\xi$

Benchmarks

Benchmark	$m_{\phi_{\mathcal{B}}}$ [GeV]	m_{ξ} [GeV]
1	0.95	0.92
2	2.45	1.53
3p	2.38	1.6
3k	2.2	1.8
4p	0.95	0.17
4k	0.95	0.55

Parameter Space: K Channel

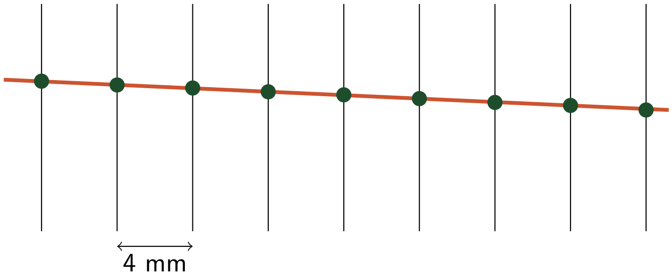


Backgrounds: Atmospheric ν

- Trickiest background: atmo ν NC with $\nu + N \to \nu + n + \pi$
- Also: CC, p FS with missed particles
- Bkg: events with only π above threshold
- K background extremely tiny
- Model ν scattering in `GENIE` using Bartol fluxes at Soudan (DUNE) and Kamioka (Super-K/Hyper-K)

Barr et. al.: PRD70:023006,2004

DUNE Thresholds



- Charged particles: cross 10 wires
- Unstable particles: energetic decay products

Water Cherenkov Thresholds

- Charged & heavy: require $\beta > 1/n$ for Cherenkov radiation
- e & γ: 3.5 MeV

Super-Kamiokande: PRD94, 052010 (2016)

- Unstable particles: energetic decay products
- $\mu^\pm$ vs. $\pi^\pm$: challenging to distinguish
  For Cherenkov: assume no distinction

A bit crude... but need experimental input for more!

Model Structure

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{\mathcal{B}}$	Z_2
Y	3	1	$-1/3$	$2/3$	1
ψ_B	1	1	0	-1	1
ϕ_B	1	1	0	-1	-1
ξ	1	1	0	0	-1

Integrate out TeV-scale Y to get EFT:

$$\mathcal{L} = \frac{y_{u_a d_b}\, y_{\psi d_c}}{M_Y^2} \epsilon_{ijk} \left(u^i_{R,a} d^j_{R,b} \right) \left(\psi_B d^k_{R,c} \right) - y_d \bar{\psi}_{\mathcal{B}} \phi_{\mathcal{B}} \xi + \text{h.c.}$$

Other Observables

Asymmetry given by:

$$Y_{\mathcal{B}} = \frac{n_{\mathcal{B}} - n_{\overline{\mathcal{B}}}}{s} = 8.7 \times 10^{-11} \frac{\text{Br}(B \to \psi_{\mathcal{B}} \mathcal{B}_{\text{SM}})}{10^{-2}} \sum_{q=s,d} \alpha_q \frac{A^q_{SL}}{10^{-4}}$$

- A^q_{SL}: CP asymmetry in $\overset{(-)}{B}_q \to \ell^{\mp} + X$
  Constrained by LHC, B factories
- Exotic B decays at B factories
- Indirect effects on B^0 oscillation/CP violation
  e.g. $\phi^{d,s}_{1,2}$, $\Delta M_{d,s}$, $\Delta\Gamma_{d,s}$
- Direct production of Y @ LHC

Modeling IND

- Amplitude written in terms of $N \to \pi, K$ form factors

$$\mathcal{A} \propto W_0(q^2) - i\,\frac{\not{q}}{m_N}\,W_1(q^2)$$

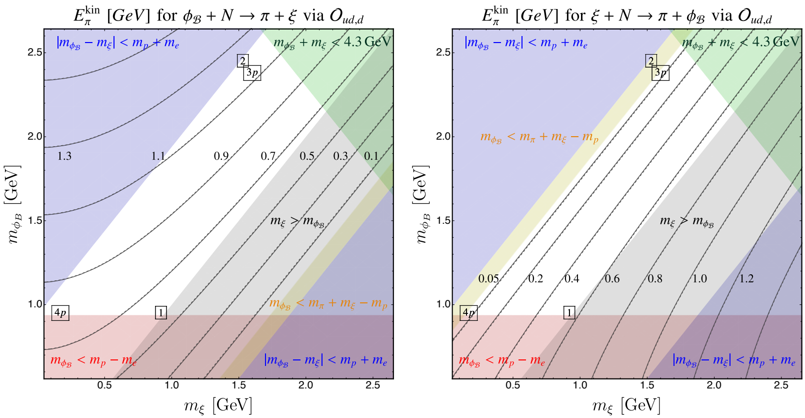
- Calculated on the lattice at $q^2 = 0,\ 1\ \text{GeV}^2$

Yoo et. al.: PRD105, 074501 (2022)

- 3 choices of *udd* operator

$$(u_R\, d_R)\, d_R, \quad (u_R\, d_R)\, s_R, \quad (u_R\, s_R)\, d_R$$

Parameter Space: π Channel



Can We Simulate?

- Hacked together simulation in GENIE v3.06
  Based on existing nucleon decay module
- Event generation of model points by request
  https://github.com/jberger7/Generator-IND
- Why GENIE?
  - Standard tool in ν experiment
  - Includes important nuclear effects
  - Get full kinetic energy distributions!
- Allowed meson FS: π, K, D^0

Current Status

Process	Production				Flux	Dark → Standard				Det.	Reco.
	Brem.	Direct	Prompt	LL	Flux	Decay	*e*	*N* El.	*N* Inel.	Det.	Reco.
`MadDump`		✓	✓		✓		✓		✓		
`BdNMC`	✓	✓	✓		✓	✓	✓	✓	✓		
`GENIE`							✓	✓	✓		
`Geant4`			✓	✓	✓	✓				✓	
`ACHILLES`						✓	✓	✓	✓		
`FORESEE`	✓	✓	✓	✓	✓	✓	✓	✓			

Batell, **JB**, et. al. (Snowmass): 2207.06898