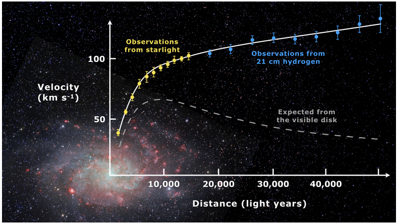
Theory of Dark Matter

Joshua Berger
Colorado State University

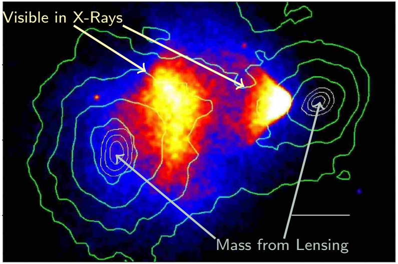
May 15, 2024

CoSSURF 2024

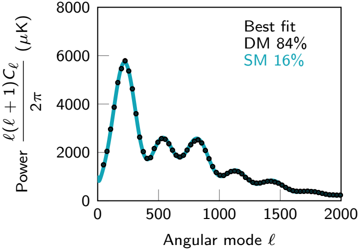
What We Know



De Leo
Corbelli, Salucci: MNRAS 311 (2000) 441-447

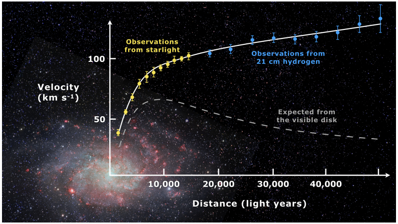


Clowe et. al.: AJL 648 (2006) L109-L113

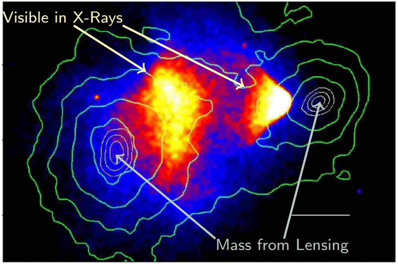


Planck: AA 641 (2020) A6
CAMB (Lewis & Challinor)

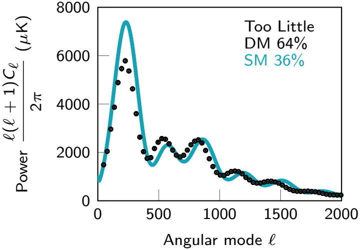
What We Know



De Leo
Corbelli, Salucci: MNRAS 311 (2000) 441-447

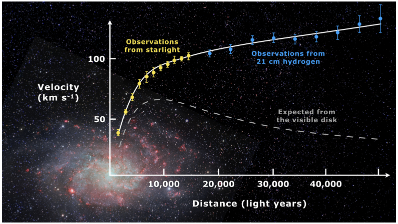


Clowe et. al.: AJL 648 (2006) L109-L113

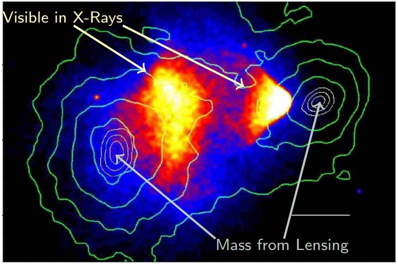


Planck: AA 641 (2020) A6
CAMB (Lewis & Challinor)

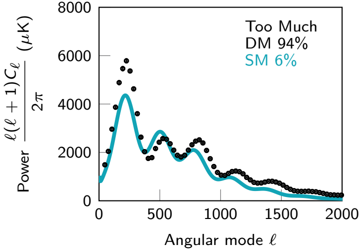
What We Know



De Leo
Corbelli, Salucci: MNRAS 311 (2000) 441-447

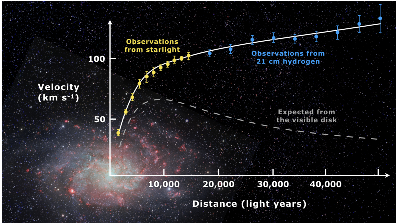


Clowe et. al.: AJL 648 (2006) L109-L113

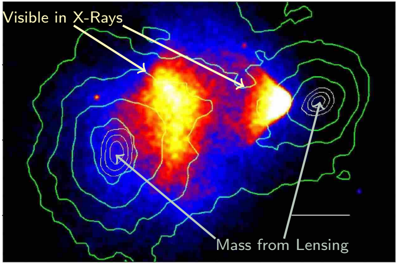


Planck: AA 641 (2020) A6
CAMB (Lewis & Challinor)

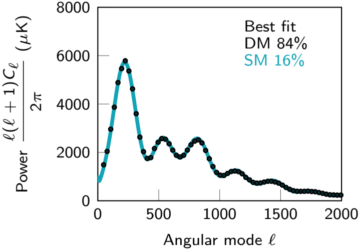
What We Know



De Leo
Corbelli, Salucci: MNRAS 311 (2000) 441-447

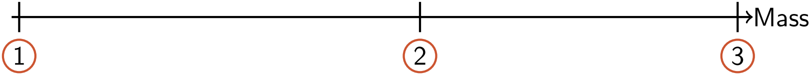


Clowe et. al.: AJL 648 (2006) L109-L113



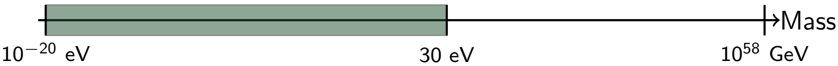
Planck: AA 641 (2020) A6
CAMB (Lewis & Challinor)

What We Don't Know: Mass



1. 10^{-20} eV $\sim 10^{-26}\ m_e$: small scale structure
2. 30 eV $\sim 10^{-4}\ m_e$: Fermi degeneracy (fermions)
3. 10^{58} GeV$/c^2 \sim M_\odot$: tidal disruption

What We Don't Know: Mass



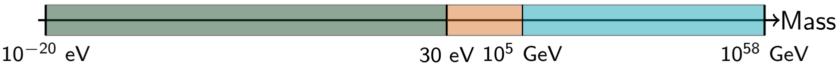
Ultralight/Wavy Dark Matter

DM has to be a boson

Wavefunctions overlap in MW: coherent, wavelike

e.g. QCD Axion

What We Don't Know: Mass

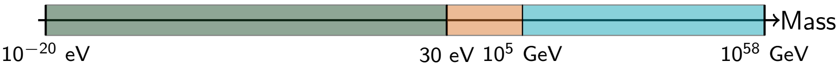


Ultraheavy Dark Matter

DM probably has to be a composite
Small lab event rate for $m \gtrsim 10^{20}$ GeV

e.g. Primordial Black Hole

What We Don't Know: Mass



The WIMP sweet spot

Particle DM could "freeze out" of SM plasma

e.g. Lightest Supersymmetric Partner

A Related Story for Interactions

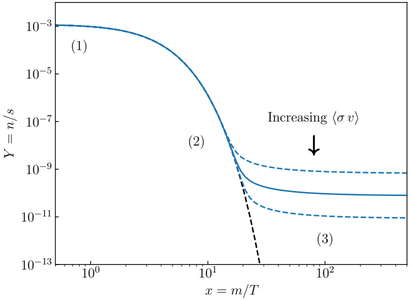
(1) Equilibrium: DM $\chi + \overline{\chi} \leftrightarrow$ SM

(2) Non-relativistic: SM not sufficiently energetic to produce DM

(3) Freeze-out: DM too sparse to continue annihilating away

CMB + freeze-out:
$\langle \sigma v \rangle \approx 2 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$

Implies few keV $< m < 10^5$ GeV
For $m \gtrsim 1$ GeV: nuclear recoils



Is This Possible?

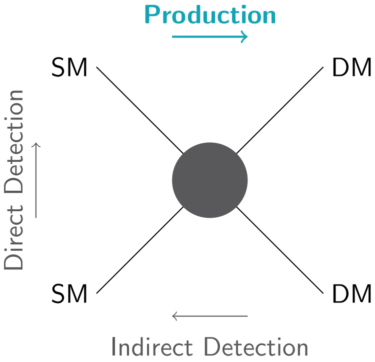
Three perspectives:

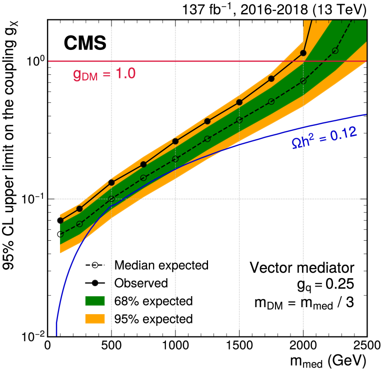
- Complete theory: solves many puzzles, but highly complex and possibly restrictive
  - supersymmetry, extra-dimensions, composite SM, ...
- Simplified model: inspired by complete theory, simpler, more flexible, but don't actually address puzzles
  - fermion portals, ...

  Bai, JB: JHEP11 (2013) 171;
  An et. al.: PRD89 (2014) 115014;
  Chang et. al.: PRD89, 015011 (2014);
  DiFranzo et. al.: JHEP11 (2013)
- Effective theory: covers almost any scenario simply, but comparisons between experiments may break

  Fitzpatrick et. al.: JCAP02 (2013) 004

Three Ways to Look

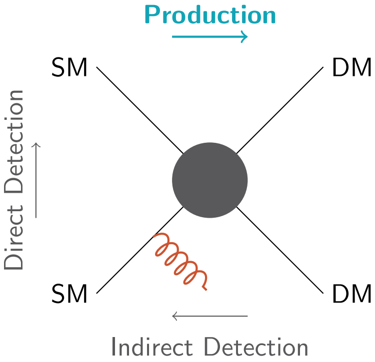


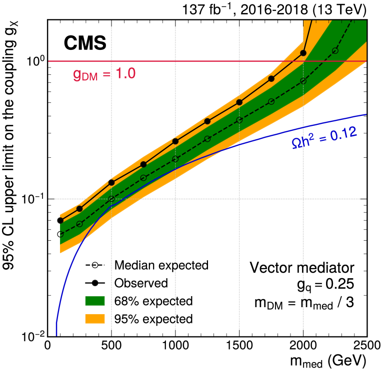


CMS: JHEP11 (2021) 153

DM produced in high energy colliders (e.g. LHC)

Three Ways to Look

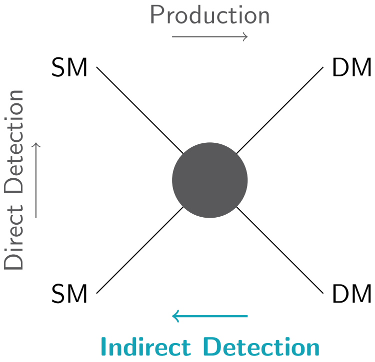


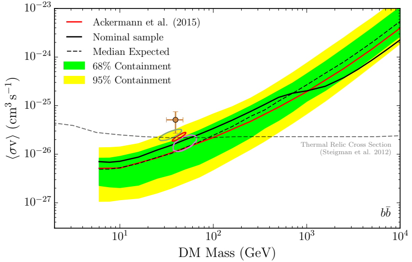


CMS: JHEP11 (2021) 153

DM + "missing" energy produced in high energy colliders (e.g. LHC)

Three Ways to Look

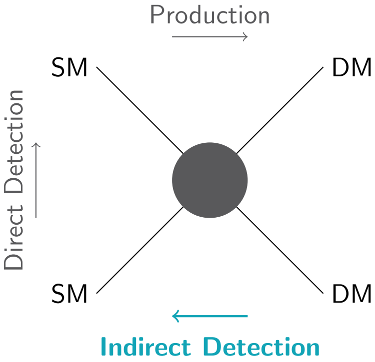


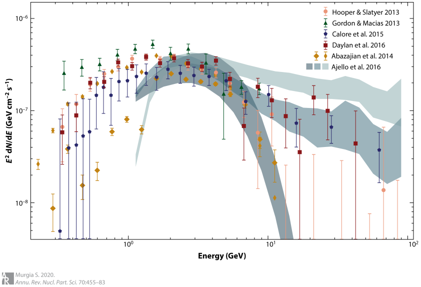


Fermi-LAT and DES: Astrophys.J. 834 (2017) 2, 110

Excess radiation from DM annihilations (e.g. in MW subhalos)

Three Ways to Look

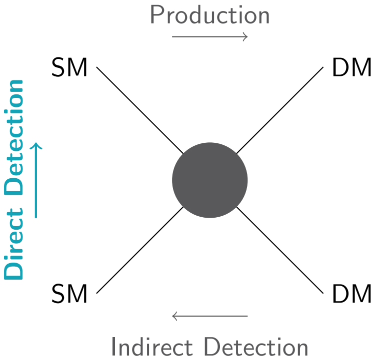


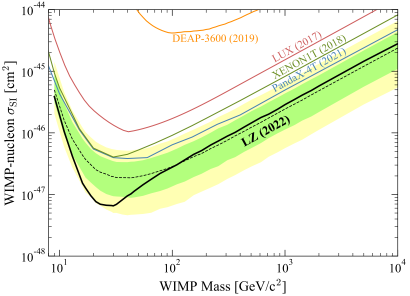


Murgia: Ann.Rev.Nucl.Part.Sci. 70 (2020) 455-483

Excess observed in galactic center photons–is it DM?

Three Ways to Look

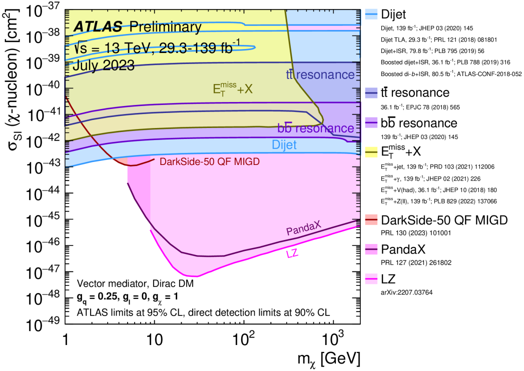




LZ: PRL 131, 041002 (2023)

Small energy deposits from DM bumping into nuclei

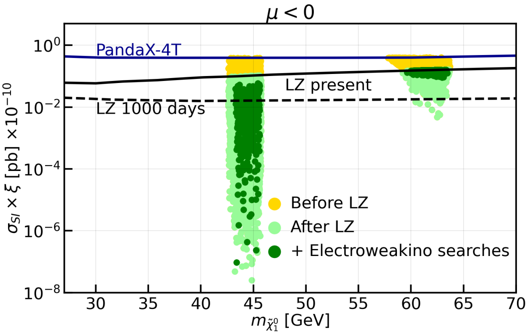
Fair Comparison w/ Simplified Models



ATLAS: ATL-PHYS-PUB-2023-018

- Simplified models still have many parameters
- Complementarity between DD/LHC at high/low masses

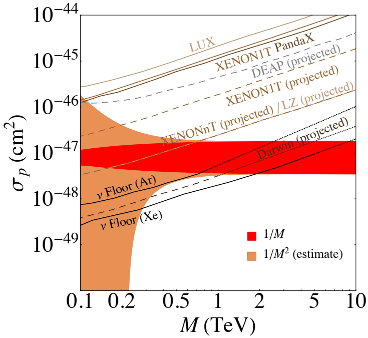
Complete SUSY Models Still Kicking

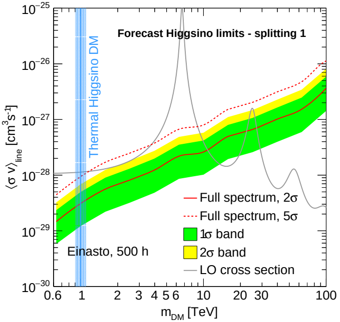


Barman et. al.: PRL 131, 011802 (2023)

- pMSSM: minimal SUSY limited to most pheno-relevant parameters
- Complete models give complex options

Another Option: Heavy SUSY

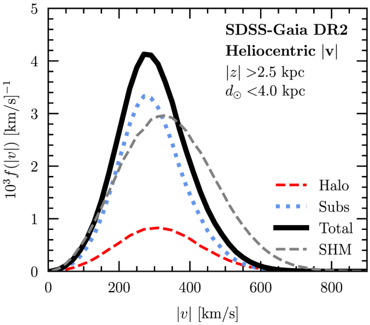


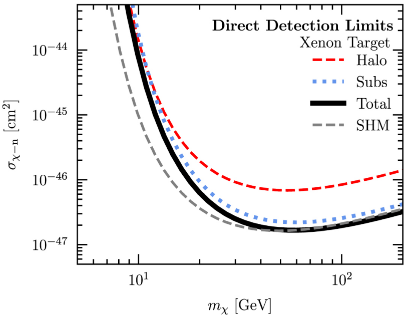


Chen et. al.: PLB781 (2018) 473-479 Richiuso et. al.: PRD103, 023011 (2021)

- Near-pure Higgsino: a generic option from split SUSY
- Challenging: low cross sections effectively for direct and indirect
- Hopeless for current colliders

Astrophysics Also Matters for DD

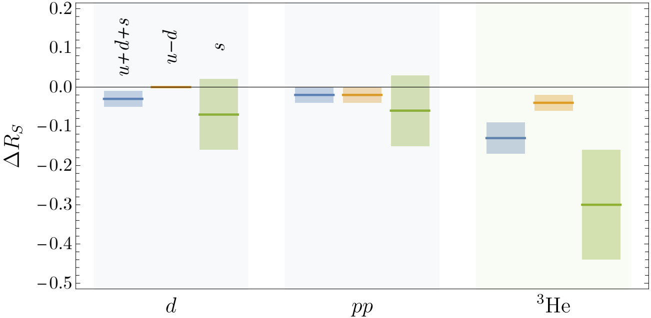




Necib et. al.: ApJ 874 (2019) 3

- SDSS + Gaia constraining local properties of DM
- Even more dramatic for inelastic dark matter

From Theory to Experiment



Davoudi et. al.: Phys.Rept. 900 (2021) 1-74

- Experiments: sensitive to non-relativistic scattering off nuclei
- Theory: interactions of DM with quarks and gluons
- Mapping requires QCD + nuclear physics

What Are We Missing?

Slow moving:	$v \sim 10^{-3}\,c$ locally
Scatters elastically:	tiny energy deposits @ low energy
Single component:	fewer constraints on subdominant component
Point-like:	no extended structure as in e.g. nuclei
Scatters off nuclei:	electron scattering important at low masses

$\Longrightarrow$ Continue to look for WIMPs, while thinking about new probes

Boosted Dark Matter

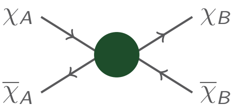
Standard WIMP Dark Matter

- 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 $\rho_\chi\, v/m_\chi$

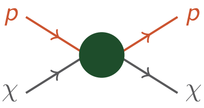
Boosted Dark Matter

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

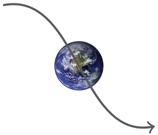
Several Mechanisms!



DM $\to$ DM



Cosmic Ray Kick


Dark Matter Rain

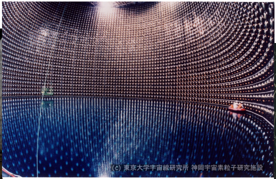
Can We Use ν (Far) Detectors?

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

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

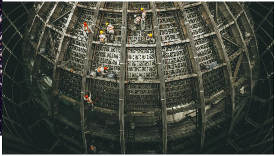
The Ugly: Neutrinos become a background for searches, usually quite a large and sometimes irreducible background

DUNE



Super-/Hyper-K

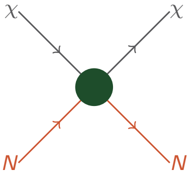
JUNO



DM to DM Signals

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

Simulating Boosted DM Interactions

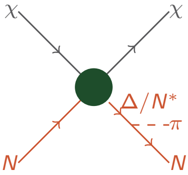


Elastic

Below 1 GeV

Need to simulate nuclear effects

Implemented in `GENIE`!

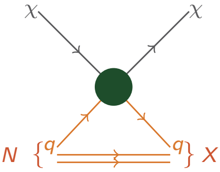


Resonant

1-2 GeV

Need a model

Work in progress w/ Z. Orr



Deep Inelastic

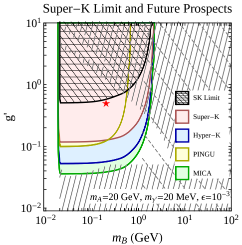
Above 2 GeV

Need to handle low E

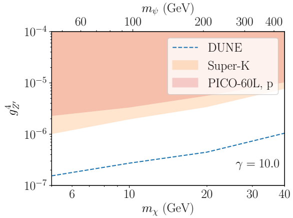
Implemented in `GENIE`!

JB: 1812.05616

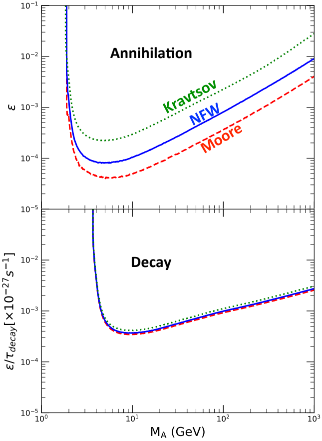
DM to DM Results



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



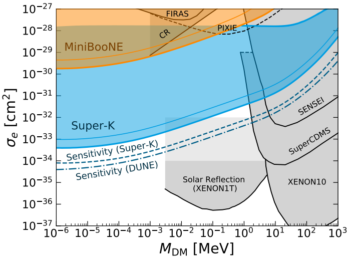
JB et. al.: PRD (2019)



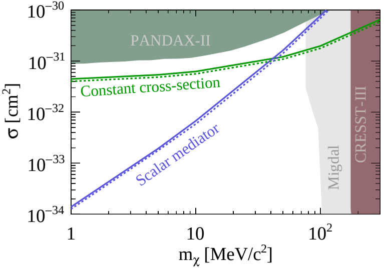
Super-K: PRL 120, 221301 (2018)

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)

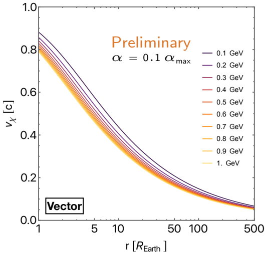
Dark Matter Rain

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)

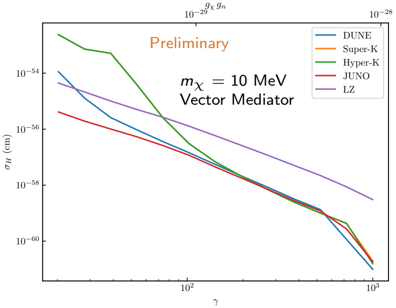
$$m \approx \begin{cases} \gamma\,(m - g_\chi \phi), & \text{scalar} \\ \gamma\, m - g_\chi\, \phi, & \text{vector} \end{cases}$$

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



Acevedo, **JB**, Denton: 2406.xxxxx

DM Rain: Projected Sensitivity



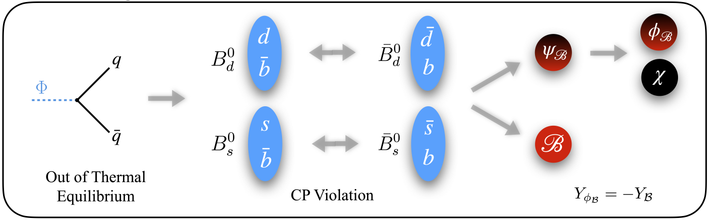
- No traditional direct detection
- Directional and energy cuts to reduce NC atmo. ν background
- Large experiments can look now

Acevedo, **JB**, Denton: 2406.xxxxx

Induced Nucleon Decay

Can dark matter carry baryon number?

B^0 Mesogenesis

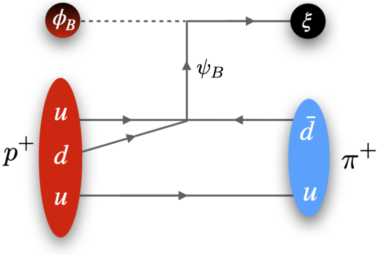


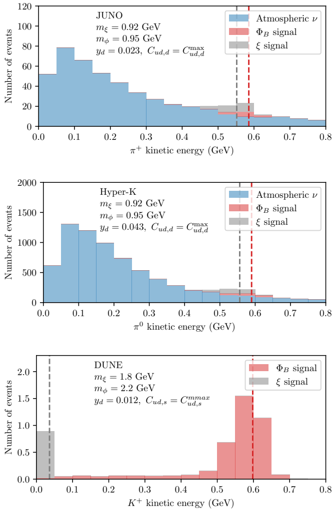
Elor, Escudero, Nelson: PRD 99, 035031 (2019)

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

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

Detecting Induced Nucleon Decay





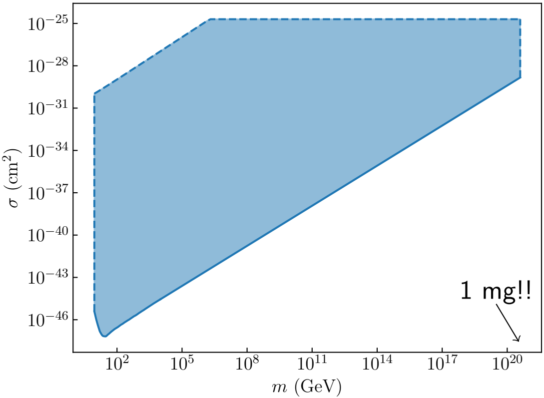
- Different energy spectrum from spontaneous proton decay
- Sensitivity to couplings 10^{-3} to 10^{-2} of collider bounds

JB, Elor: PRL 132, 081002; see also Huang, Zhao: JHEP 077 (2014)

Zooming Out on DD

DM stops due to Earth overburden/Multiple scattering

Nuclear recoil energy suppressed



Flux through detector goes to 0

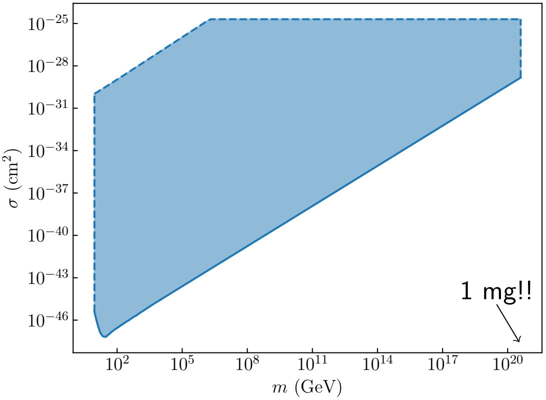
Interaction rate limited

LZ: PRL 131, 041002 (2023)

Zooming Out on DD

Use astrophysics/rocks/Look for multiple scattering

Look in electrons/novel device detectors

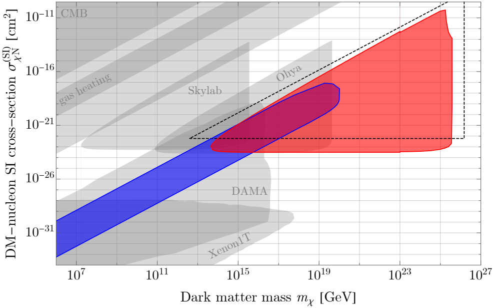


Multiple interactions in larger detectors

Keep building bigger + deal with ν fog

LZ: PRL 131, 041002 (2023)

Dark Matter (in) Rocks

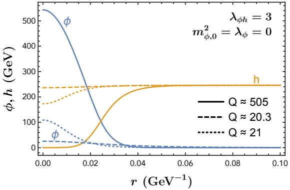


- High mass DM can leave tracks in excavated minerals
- Interpretation of two difference searches in excavated mica
- Other bounds: large plastic detectors, detectors in space, heating of gas clouds and CMB

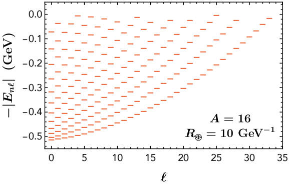
Acevedo et. al.: JCAP 11 (2023) 085

Macroscopic Dark Matter

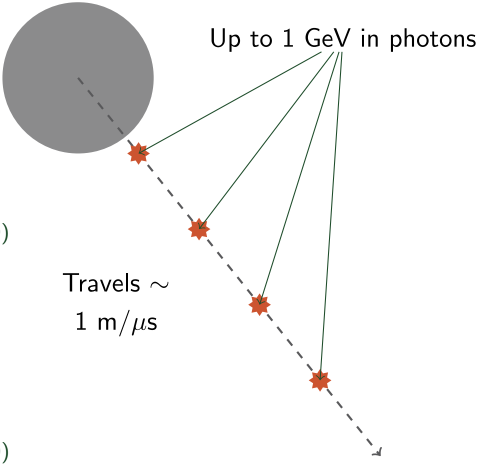
Can dark matter be large in extent?



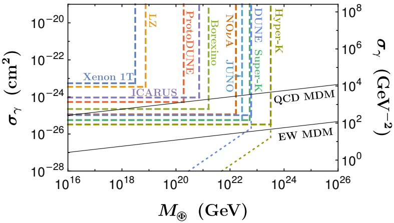
Pontón, Bai, Jain: JHEP 11 (2019)



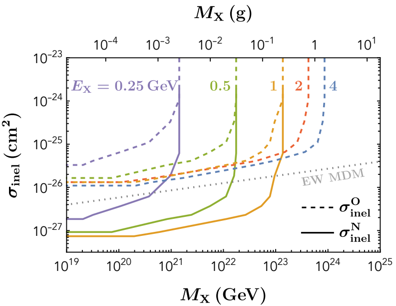
Bai, JB: JHEP 160 (2020)



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: Monte Carlo for capture & decay chain

Outlook

- Continue to improve WIMP searches and calculations of rates
- But also: think about models beyond the WIMP
- Neutrino far detectors can play a key role
- Need new simulations and pipelines to develop searches for exotic DM signals

Backup

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!

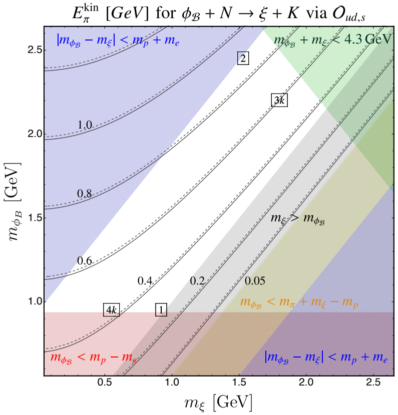
Parameter Space

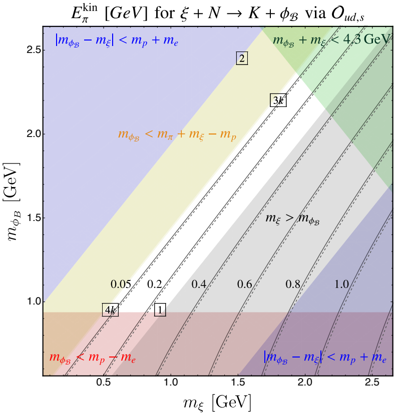
✓ $B \to \mathcal{B}_{\text{SM}}\, \psi_{\mathcal{B}}$:	$m_{\psi_{\mathcal{B}}} < m_B - m_p \simeq 4.34\,\text{GeV}$
✓ $\psi_{\mathcal{B}} \to \xi + \phi_{\mathcal{B}}$:	$m_{\psi_{\mathcal{B}}} > m_\xi + m_{\phi_{\mathcal{B}}}$
× $\phi_{\mathcal{B}} + \xi \to \mathcal{B}_{\text{SM}}$:	$\lvert m_{\phi_{\mathcal{B}}}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

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



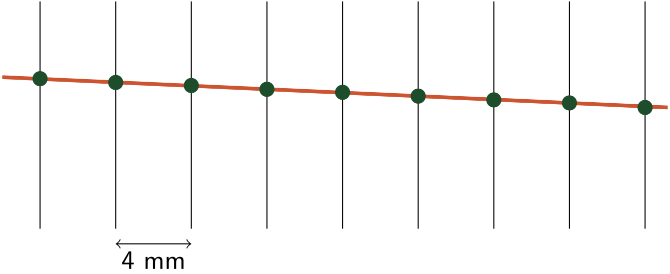


Backgrounds: Atmospheric ν

- 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:

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

- A_{SL}^q: 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. $\phi_{1,2}^{d,s}$, $\Delta M_{d,s}$, $\Delta\Gamma_{d,s}$
- Direct production of Y @ LHC

Modeling IND

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

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

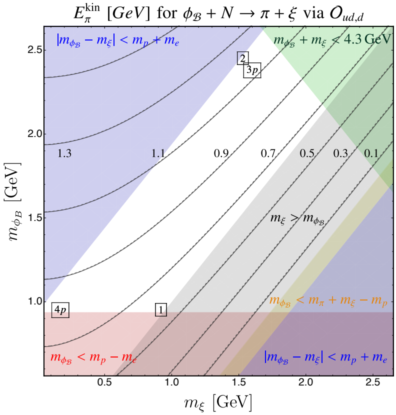
- Calculated on the lattice at $q^2 = 0,\ 1\ \mathrm{GeV}^2$

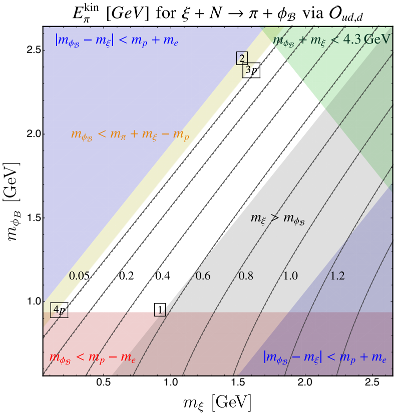
Yoo et. al.: PRD105, 074501 (2022)

- 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