Boosted Dark Matter at Large Volume Neutrino Detectors

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Cui, JB, Zhao: JCAP 1502 (2015) no.02, 005
JB: In progress
JB, **Tsai**, Petrillo, Stocks, Graham, Convery, Cui, Necib, Zhao, Assadi: In progress

Nu Theories Workshop, University of Pittsburgh November 5, 2018

Parks of Pittsburgh!

As seen in Frick Park!

Outline

Motivation

BDM Benchmark Models

BDM Flux

BDM Monte Carlo

Conclusions

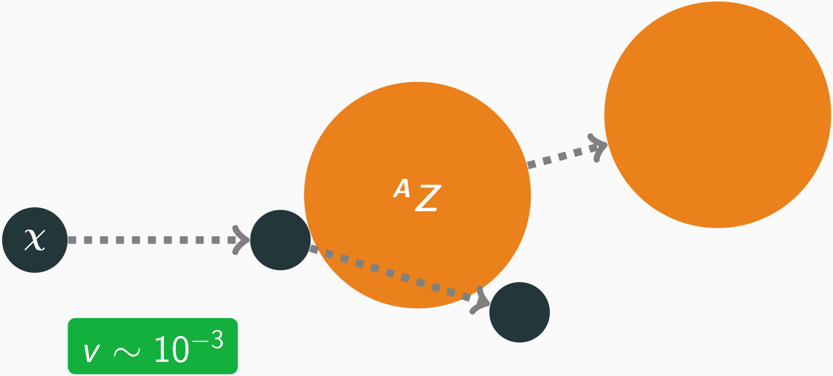
Motivation

Beyond a minimal WIMP

- Spin dependent interactions only
- Velocity suppression at low v
- Non-SM annihilation modes
- Non-minimal stabilization symmetry
- Multi-component DM sector
- High(er) velocity flux (i.e. boosted)

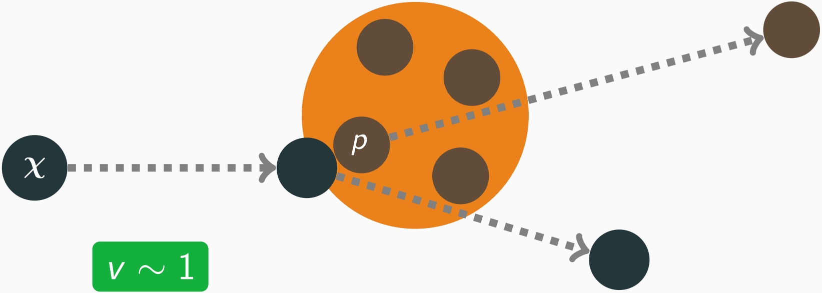
Thermal relic dark matter is slow

Nucleus Kinetic Energy $\mathcal{O}$**(10 KeV)**



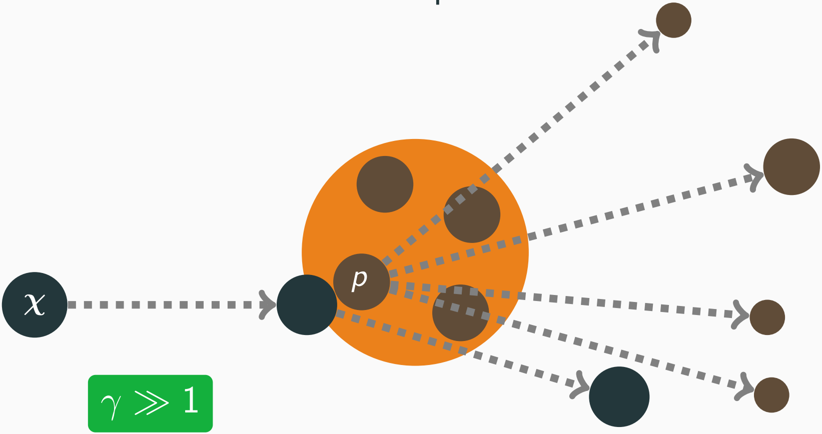
Boosted DM: “Elastic” scattering

Nucleon Kinetic Energy $\mathcal{O}$**(100 MeV)**



Boosted DM: Inelastic scattering

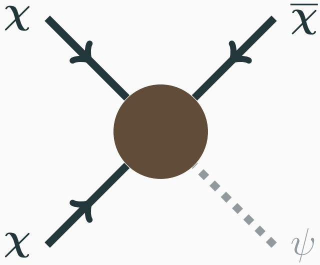
Multihadron production



BDM Benchmark Models

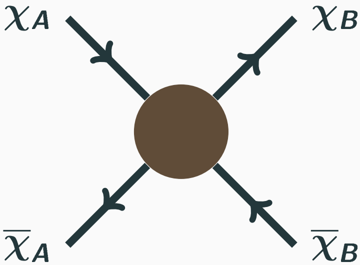
Simple BDM models exist

Z_3 Dark Matter with semi-annihilation



$v \approx 0.6$

Two component Dark Matter



$v = \sqrt{1 - m_B^2/m_A^2}$

First benchmark: Axial Z'

- In addition to annihilation, there is a scattering process that allows for detection

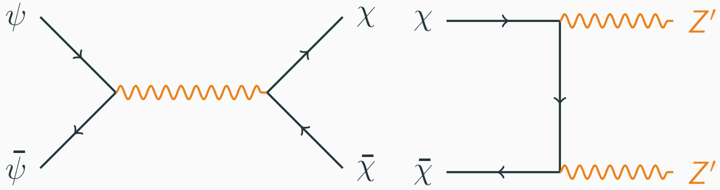
$$\begin{aligned} \mathcal{L} \supset & -Q_\chi^{V,(A)}\, g_{Z'}\, Z'_\mu\, \bar{\chi}\gamma^\mu(\gamma^5)\chi \\ & -\sum_f Q_f^{V,(A)}\, g_{Z'}\, Z'_\mu\, \bar{q}_f\gamma^\mu(\gamma^5)q_f \end{aligned}$$

- As a first benchmark, take

$$Q_i^V = 0$$

Note on two component case

- Two component: annihilation with Z' with $Q_\psi \ll Q_\chi$

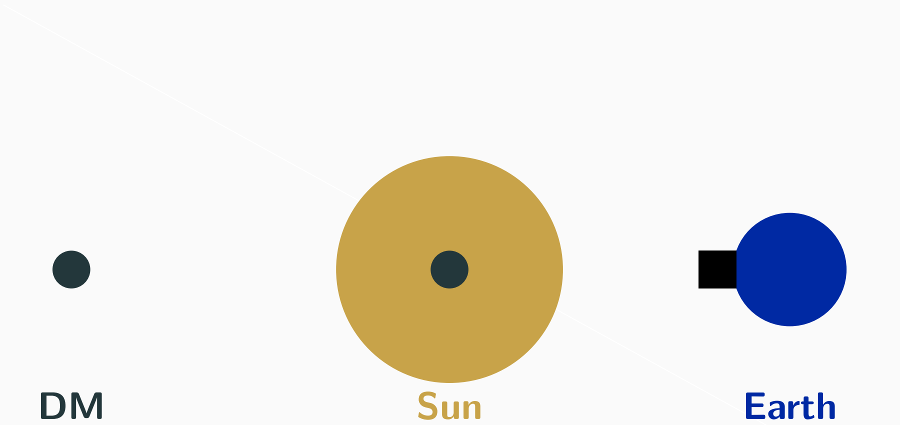


- Abundance of χ much less than ψ

- Charge of ψ floats the thermal relic abundance

BDM Flux

Solar capture & detection



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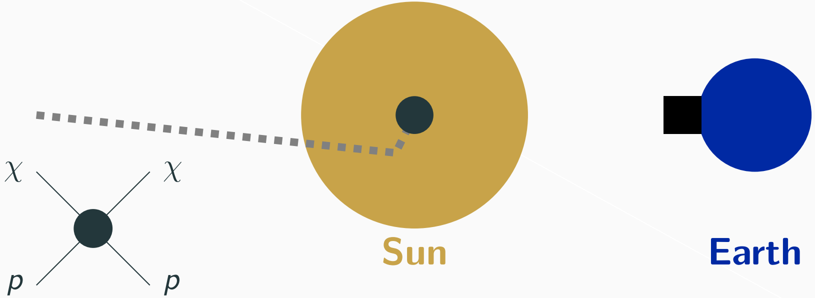
Solar capture & detection

Capture

Hadron scattering



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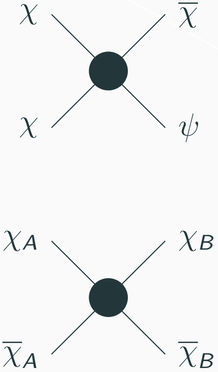
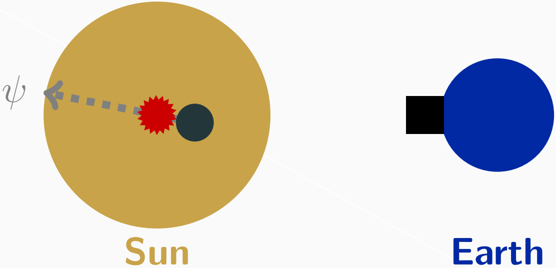
Solar capture & detection

Annihilation





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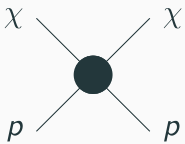
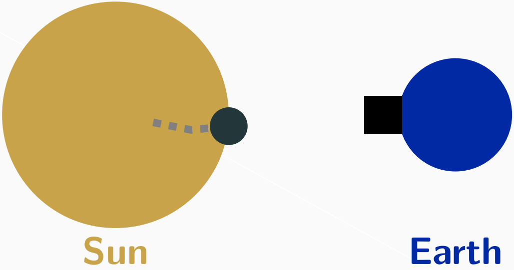
Solar capture & detection

Rescattering

Hadron scattering





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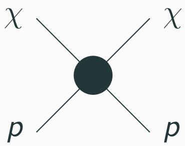
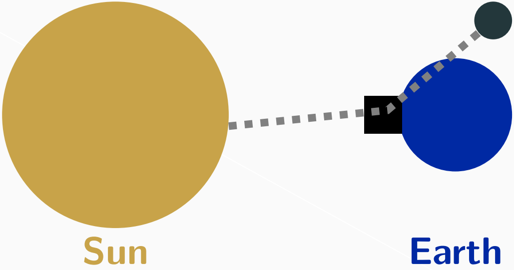
Solar capture & detection

Detection

Hadron scattering





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DM capture: Framework

$$C = \int dV\, du\, \underline{\sigma_{\chi,p}(w \to v)|_{v<v_{\rm esc}}}\, \underline{\frac{w^2}{u}}\, \underline{n_\chi}\, \underline{n_H}\, \underline{f(u)}$$

- $\sigma_{\chi,p} \sim \sigma_{\rm DD}$
- w/u: Velocity enhancement
- n_χ: Halo DM density
- n_H: Solor hydrogen density (from model AGSS-09)
- $f(u)$: DM (Boltzmann) velocity distribution at $r = \infty$

DM annihilation

- DM annihilation determined by equilibrium

$$A\,N^2 = C - E\,N$$

- Assuming annilation $\sigma \sim \mathrm{pb}$, $t_\odot \gg \tau_{\mathrm{eq}}$

- DM evaporation: DM upscattering by tail of H thermal distribution

- Evaporation negligible for $m_\chi > 5\ \mathrm{Gev}$

DM detection rate

- Flux at Earth is given by

$$\Phi = \frac{C}{4\,\pi\,\mathrm{AU}^2}$$

- Combining to determine the detection rate

$$R = \Phi \times \sigma_{\chi,p} \times \epsilon \times N_p$$

- Detection rates accessible to kton detectors

$$R \sim 1\ \mathrm{yr}^{-1}\mathrm{kton}^{-1}$$

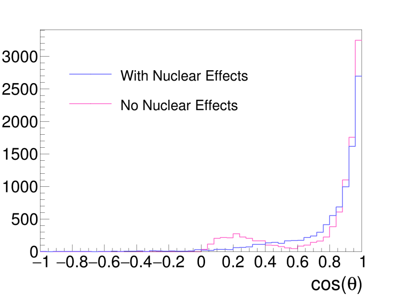
for accessible allowed parameter space

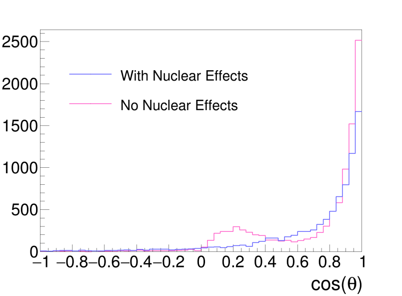
BDM Monte Carlo

A New Tool

- Elastic scattering off free nucleons can be calculated analytically
- Nuclear physics at scale 250 MeV
- DIS above scale 2 GeV
- New Monte Carlo tool as part of GENIE

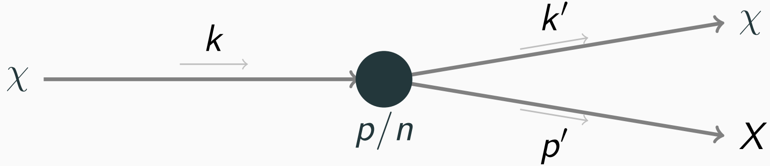
Nuclear Effects Matter





Courtesy of Yun-Tse Tsai!

Fixed target kinematics primer



$$p = (M_N, 0, 0, 0)$$

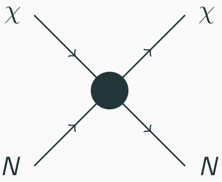
X: p/n for elastic, mess of hadrons for inelastic

$$q^2 = -Q^2 = (p' - p)^2 \quad \& \quad W^2 = k'^2$$

$$0 \leq Q^2 \leq 4p_{1,\mathrm{CM}}^2 \quad \& \quad M_N \leq W \leq \sqrt{s} - M_\chi$$

Inelastic can begin at $\gamma \gtrsim 1 + M_\pi/M_N$

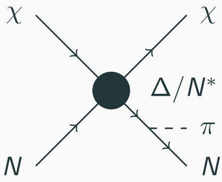
Three different processes



Elastic

Relatively easy

Needs form factor



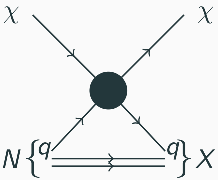
Resonant

Dominated by Δ, N^*

$W \in [1, 2]$ GeV

Needs a model

Rein & Sehgal: Ann.Phys.133, 79 (1981)

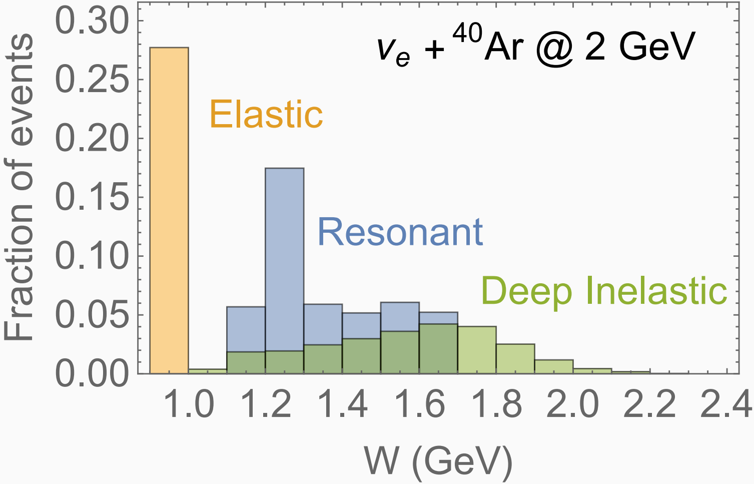


Deep Inelastic

Use standard parton model

DM beam?

All processes could be important



Elastic scattering

- Three form factors required to describe elastic

$$\Gamma^\mu = F_1(q^2)\,\gamma^\mu + \frac{1}{2\,M_N}\,F_2(q^2)\,\sigma^{\mu\nu}\,iq_\nu + F_A(q^2)\,\gamma^\mu\,\gamma^5$$

- Assume the standard dipole form

$$F \propto \frac{1}{(1+Q^2/M_{V,A}^2)^2}$$

- $F_1(0)$ constrained by charge conservation
- $F_2(0)$ given by anomalous magnetic moments
- $F_A(0)$ fit from data or lattice (spin form factors)

Deep inelastic scattering

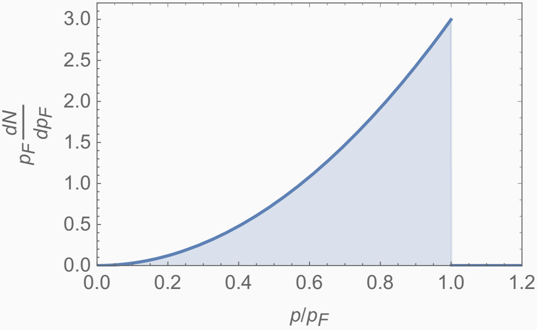
- Low W: semi-empirical Koba-Nielsen-Olesen model
  - Imported from νN data, so inaccurate

- High W: simplified Pythia model
  - Treats beam remnant as a diquark
  - Fragments and hadronizes final state quark-diquark pair
  - Radiation not be handled correctly–relevant at high W

Nuclear effects are important

Model large nucleus as Fermi gas with $p_F \sim 250\ \mathrm{MeV}$

Fermi motion



Pauli blocking

$$\frac{d\sigma}{dp'} \to \frac{d\sigma}{dp'}\theta(p' - p_F)$$

Final state interactions

Current Status of BDM in GENIE

- ✓ 2 models: fermion or scalar DM, axial Z' coupling
- ✓ Elastic and Deep Inelastic scattering implemented
- ✓ Framework mostly set for further models
- ✓ Integrated into GENIE v3

Conclusions

Conclusions

- Traditional direct detection continues to put pressure on minimal WIMP scenarios
- Boosted dark matter models are an alternative with signals at large volume neutrino detectors
- New Monte Carlo tools required to determine sensitivity to BSM at fixed target experiments