Boosted Dark Matter at Large Volume Neutrino Detectors

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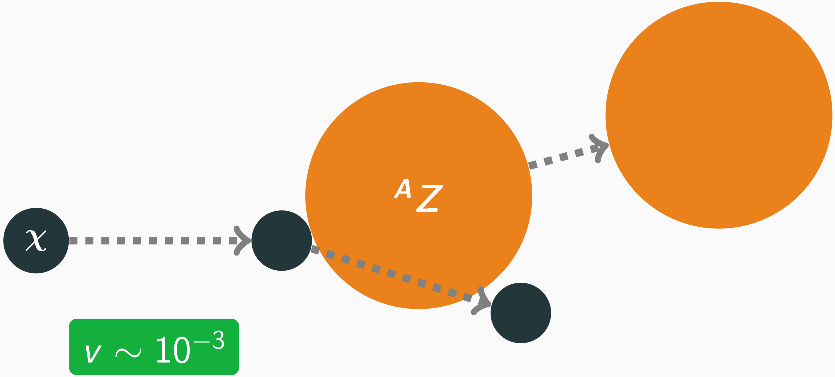
1st International High Energy Physics School and Workshop in Western China

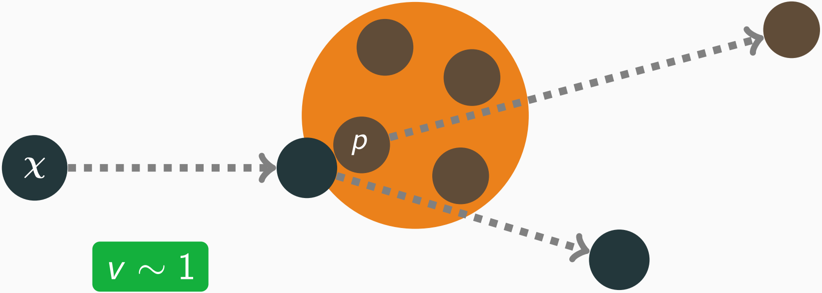
Thermal relic dark matter is slow

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



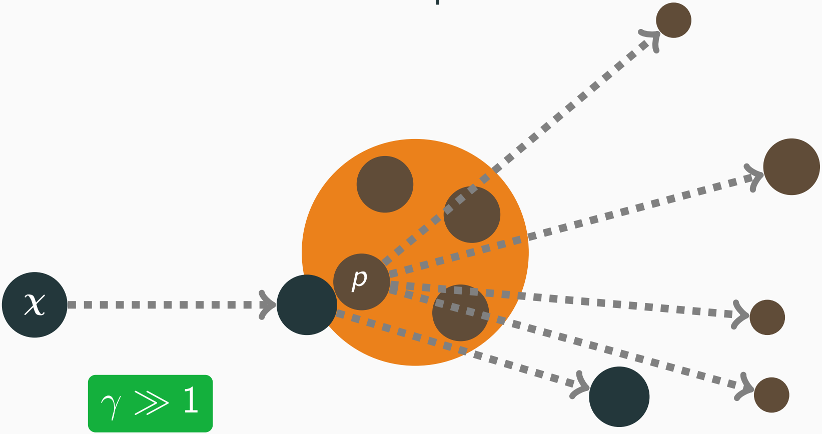
Boosted DM: “Elastic” scattering

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



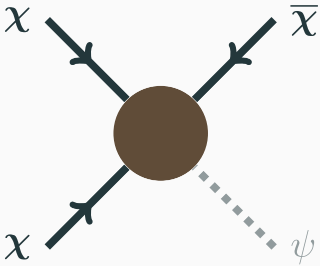
Boosted DM: Inelastic scattering

Multihadron production



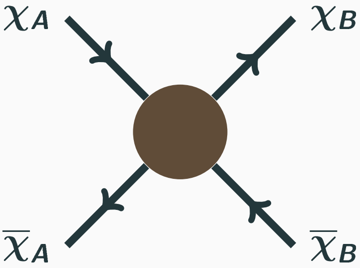
Simple BDM models exist

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

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

- As a first benchmark, take

$$Q_i^V = 0, \quad Q_\chi^A = 1, \quad Q_{p,\mathrm{eff}}^A = 1$$

Simple parametrization for elastic case

Direct detection cross-section: $\sigma_{\rm DD} \equiv \sigma_{\chi,p}^{v\to 10^{-3}}$

- Semi-annihilation has just 2 dominant parameters:

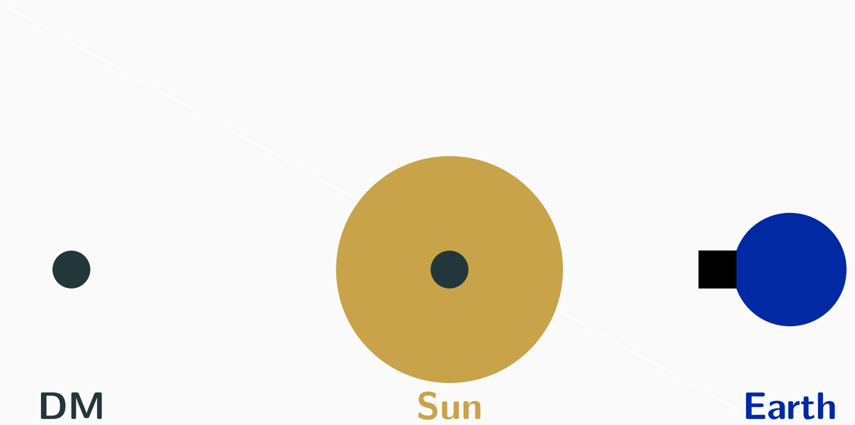
$$m_\chi, \sigma_{\rm DD}, (m_{Z'})$$

- Two component more complex, flexible:

$$m_A, m_B/m_A, \sigma_A, \sigma_B/\sigma_A, (m_{Z'}/m_A)$$

- Fermionic DM: $\sigma_{\chi,p} \propto v^0$ Scalar DM: $\sigma_{\chi,p} \propto v^2$

Solar capture & detection



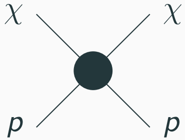
JB, Cui, Zhao, JCAP 1502 (2015) 005

Solar capture & detection

Capture

Hadron scattering

$C \sim 10^{25}\ \mathrm{sec}^{-1}$



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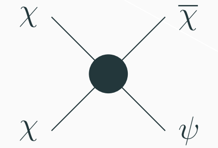
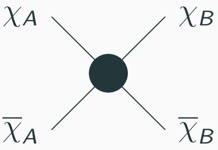
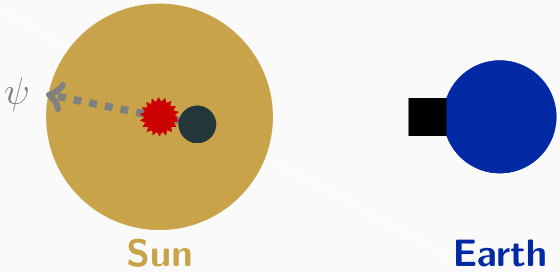
Solar capture & detection

Annihilation





$$AN^2 \approx C \sim 10^{25}\ \mathrm{sec}^{-1}$$



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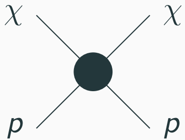
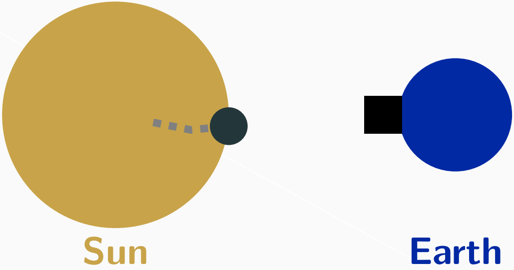
Solar capture & detection

Rescattering

Hadron scattering





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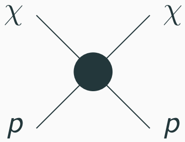
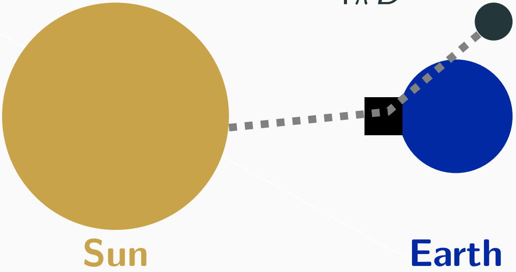
Solar capture & detection

Detection

Hadron scattering



$$R \sim \frac{C}{4\pi D^2}\sigma_{\chi p} N_p$$



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Looking with water Čerenkov

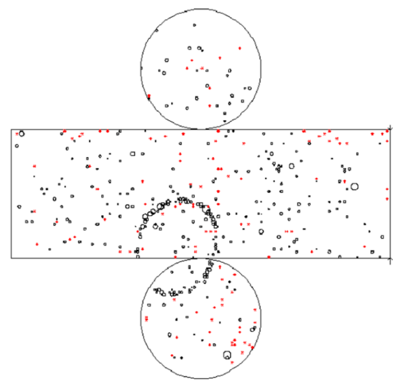
Physical energy threshold:

$$E_{\mathrm{K,recoil}} = 480\ \mathrm{MeV}$$

Hard to reconstruct inelastic

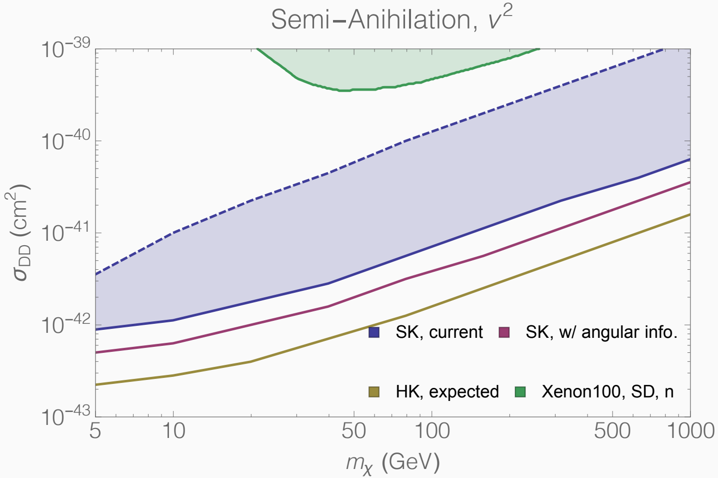
Experiments:

- Super-Kamiokande
- Hyper-Kamiokande



Super-Kamiokande: PRD79 (2009) 112010

Water Čerenkov results



JB, Cui, Zhao: JCAP 1502 (2015) 005

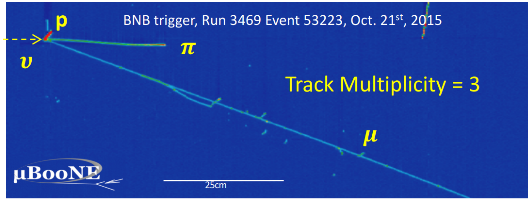
A future in liquid argon TPCs

Threshold:
$E_{\mathrm{K,recoil}} \lesssim 50\ \mathrm{MeV}$

Inelastic reconstruction possible

Experiments

- LArIAT
- ICARUS
- MicroBooNE
- DUNE



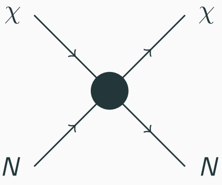
Yellow captions from talk by Luo

Checklist for DUNE

- ✓ Develop a Monte Carlo
  - Based on GENIE neutrino MC
  - Includes DIS and nuclear effects
  - Merged into GENIE v3
- ✓ Simulate dark matter flux from sun
- ✓ Integrate into LArSoft detector simulation
- Develop an analysis strategy & make projections

Theory: JB, Cui, Necib, Zhao
Experiment: Petrillo, Tsai, MicroBooNE BSM group
GENIE: Andreopoulos, Hatcher

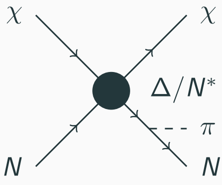
Three different processes



Elastic

Relatively easy

Needs form factor



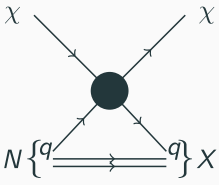
Resonant

Dominated by Δ, N^*

$M^* \in [1, 2]$ GeV

Needs a model

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



Deep Inelastic

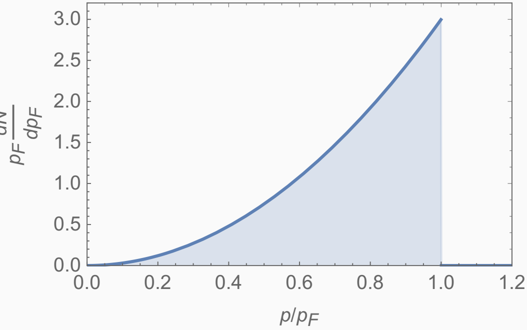
Use standard parton model

DM beam?

Nuclear effects are important

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

Fermi motion



Pauli blocking

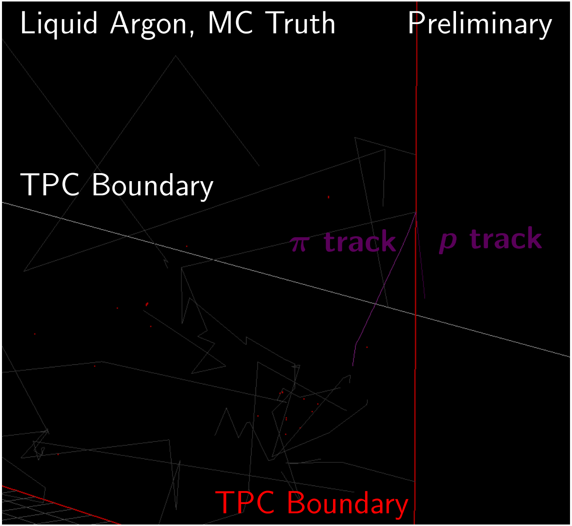
Rescattering

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

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

Next steps: Detector simulation



Courtesy of

Yun-Tse Tsai

Next steps in theory

- Include additional interaction models: more general quark charges and interaction structures
- Include resonant production of excited baryons
- Improve modeling of nuclear and hadronic physics

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