Detecting Boosted Dark Matter

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Based on: J.B., Y. Cui, Y. Zhao - 1410.2246

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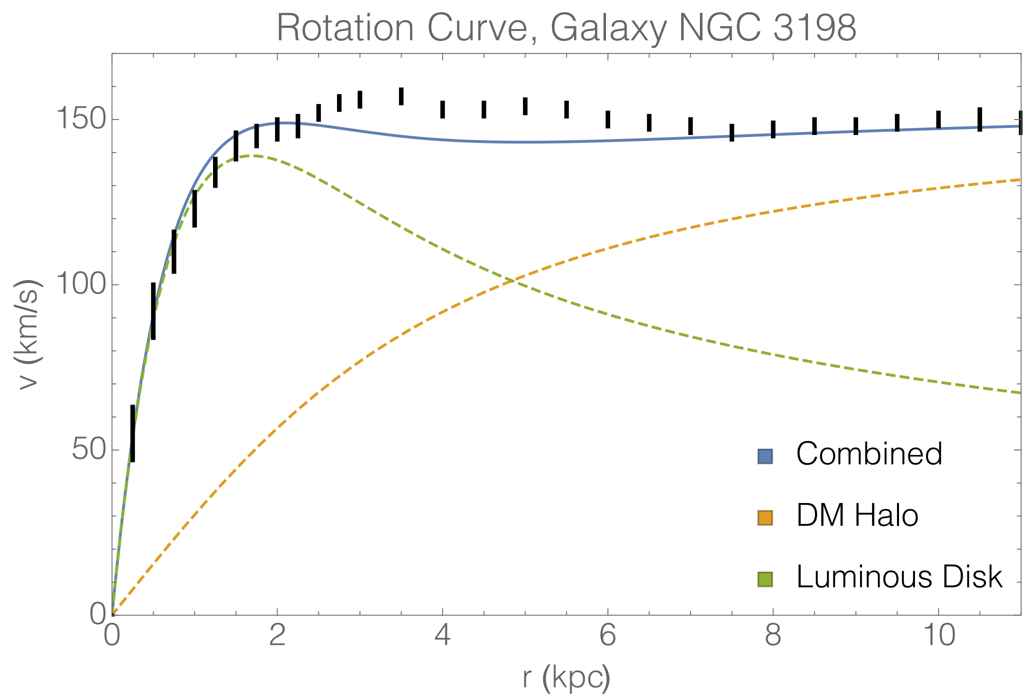
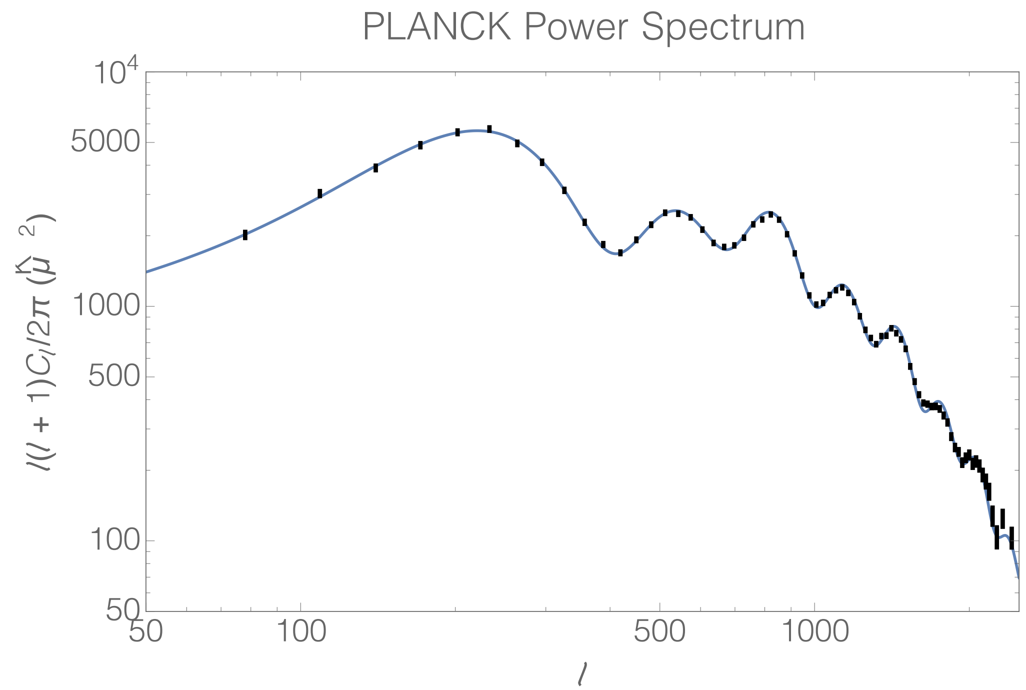
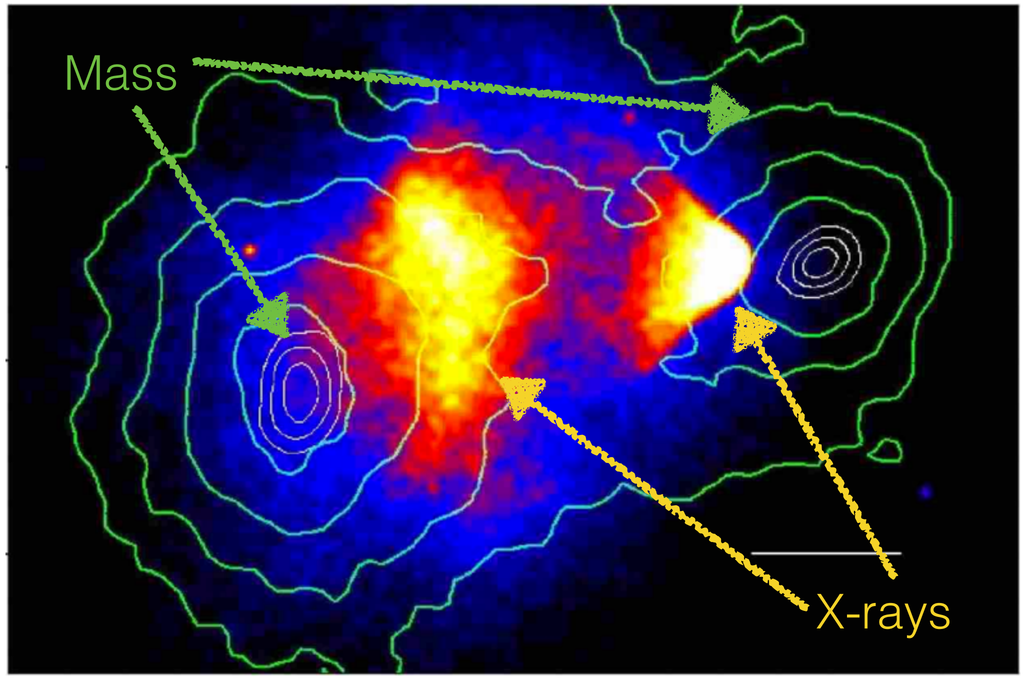
What is Dark Matter?



van Albada et. al.



PLANCK Collaboration
Lewis and Challinor



Clowe et. al.

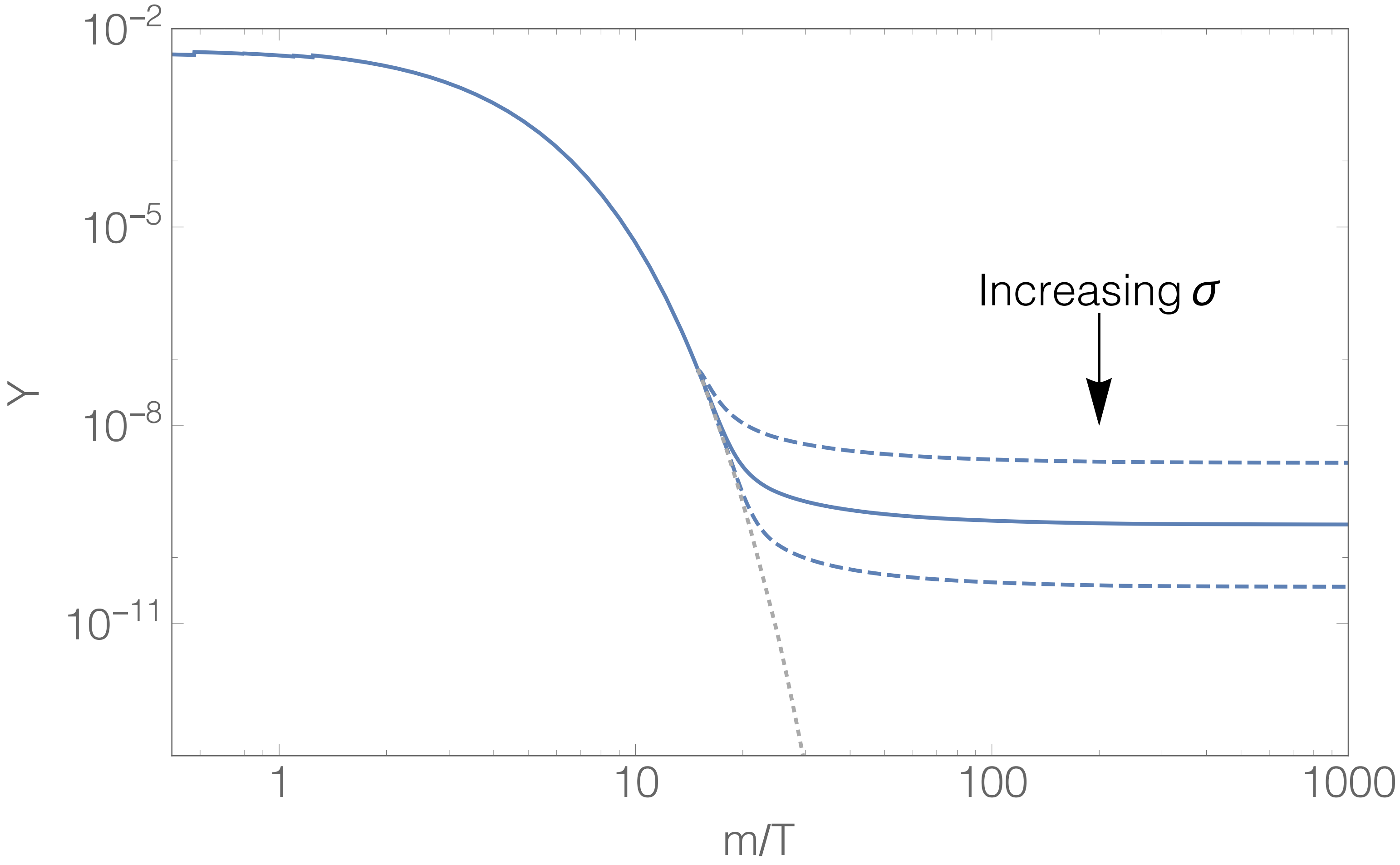
What do we know?

- Not so hot: $v \approx 10^{-3}$ in local halo
- Stable: likely protected by ~ symmetry
- Abundance: energy fraction $\Omega_c \approx 0.2$
- Many negative results on DM interactions

Non-Minimal DM

- Spin dependent interactions only
- Velocity suppression at low v
- Non-SM annihilation modes
- Non-minimal stabilization symmetry
- Multi-component DM sector

Thermal Relic DM

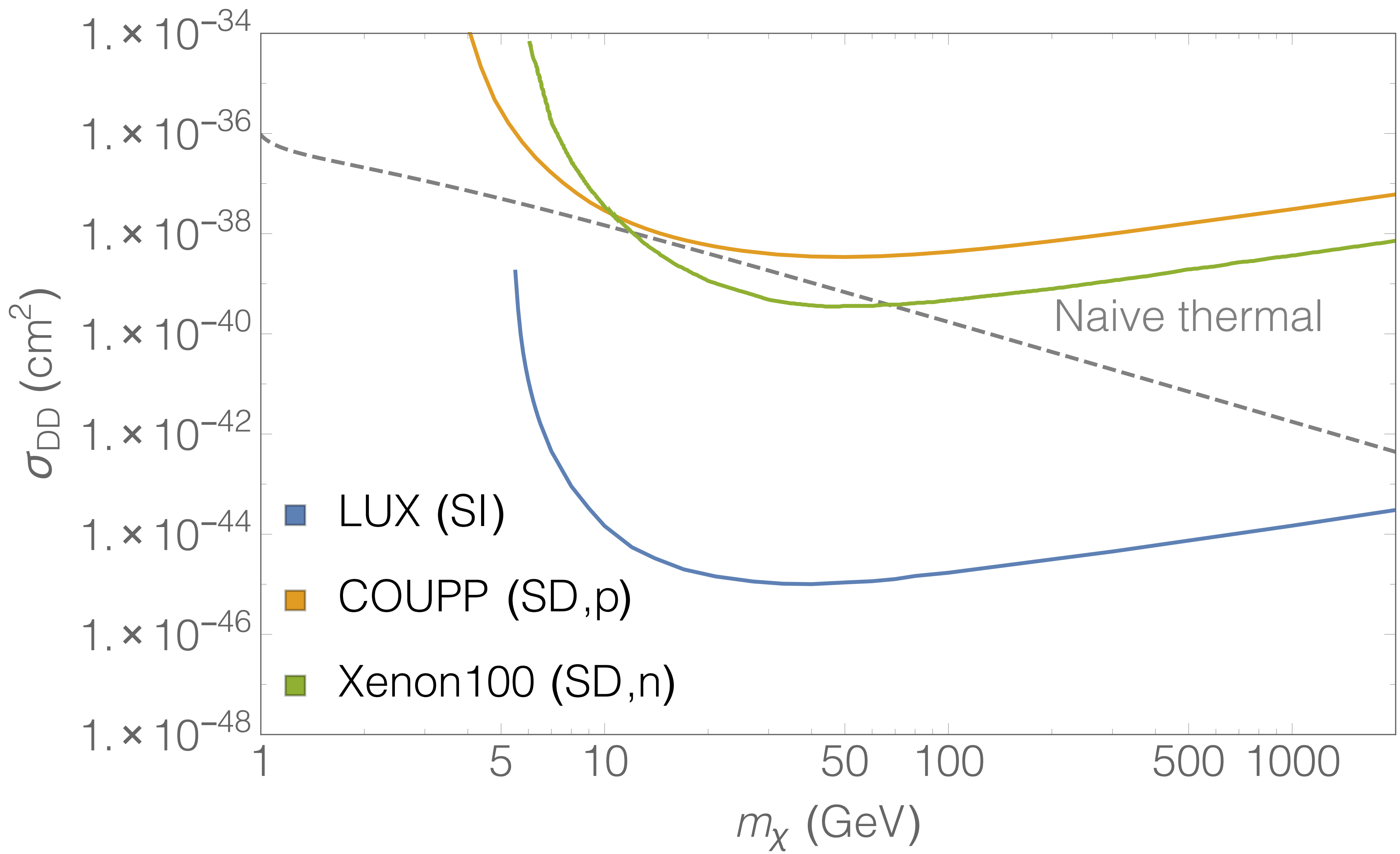


$\langle \sigma_{ann} v \rangle \sim 1$ pb

$\downarrow$

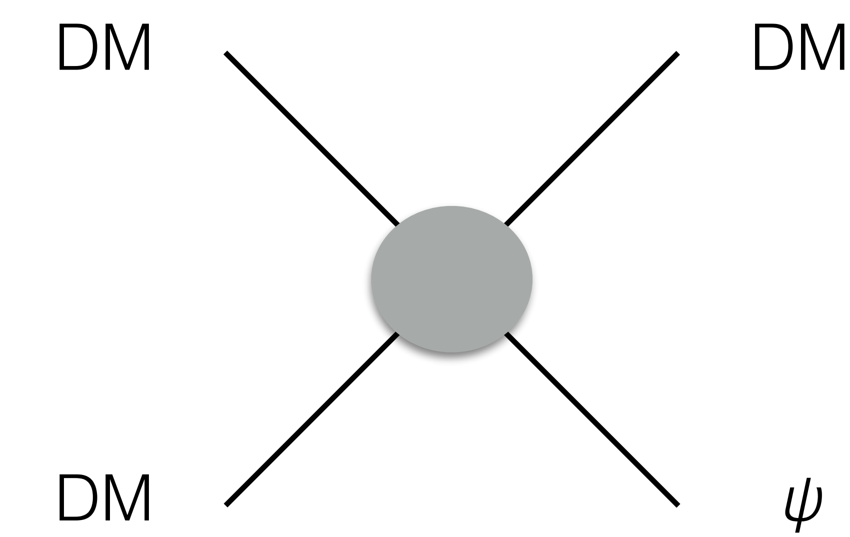
$\Omega_c \sim 0.2$

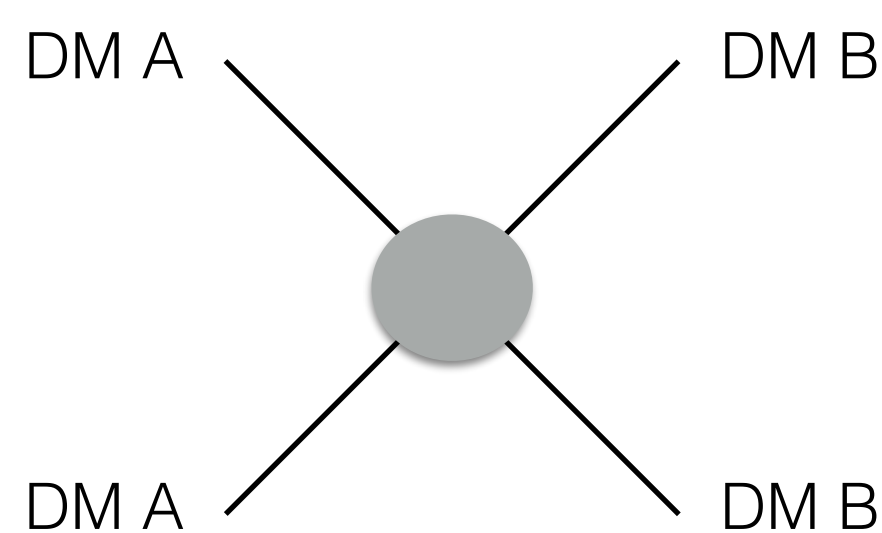
Thermal Relic Trouble?



Boosted DM from annihilation

- Two prototype scenarios:
  - Semi-annihilating DM models
  - Two component DM models





Where to Look?

- Annihilation ~ n_χ^2, so concentrated volume of DM
- Flux ~ $1/D^2$, so somewhere nearby
- Galactic center: obvious choice

$$\Phi \sim 10^{-7}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}$$

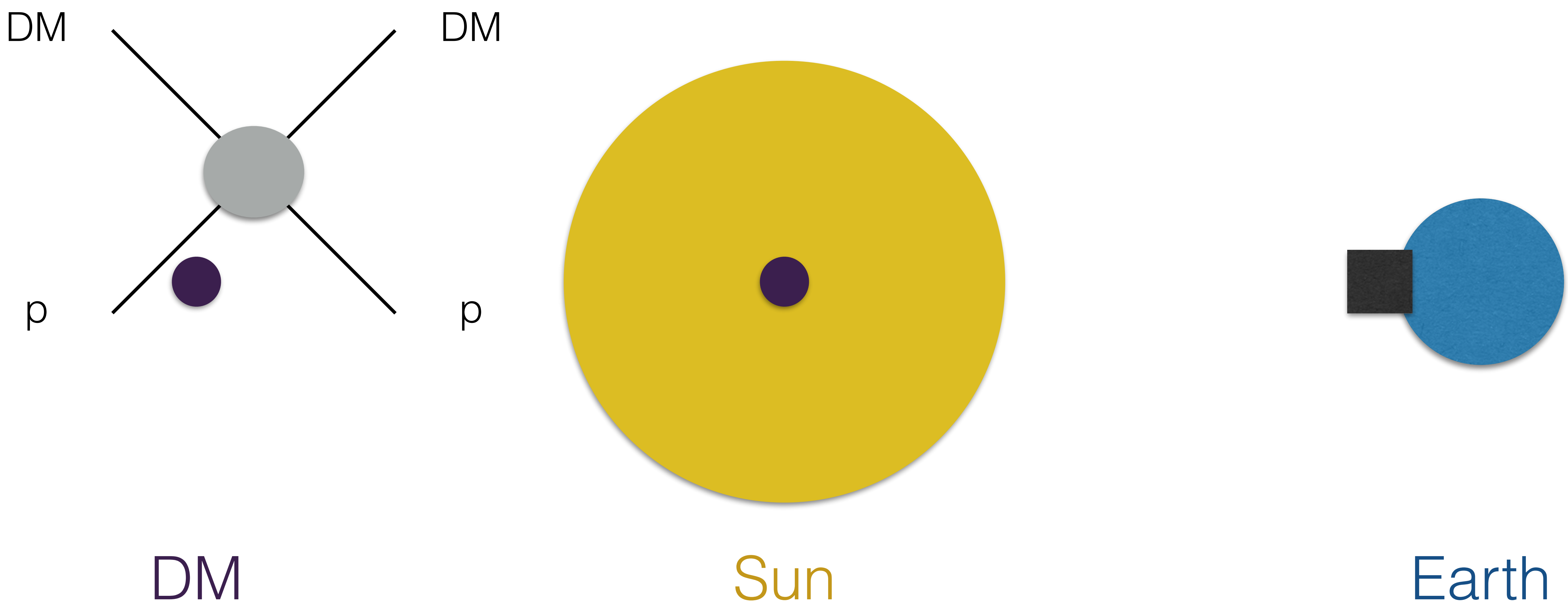
- Consider solar capture instead

$$\Phi \sim 10^{-2}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}\left(\frac{\sigma_{\mathrm{DD}}}{10^{-38}\ \mathrm{cm}^2}\right)$$

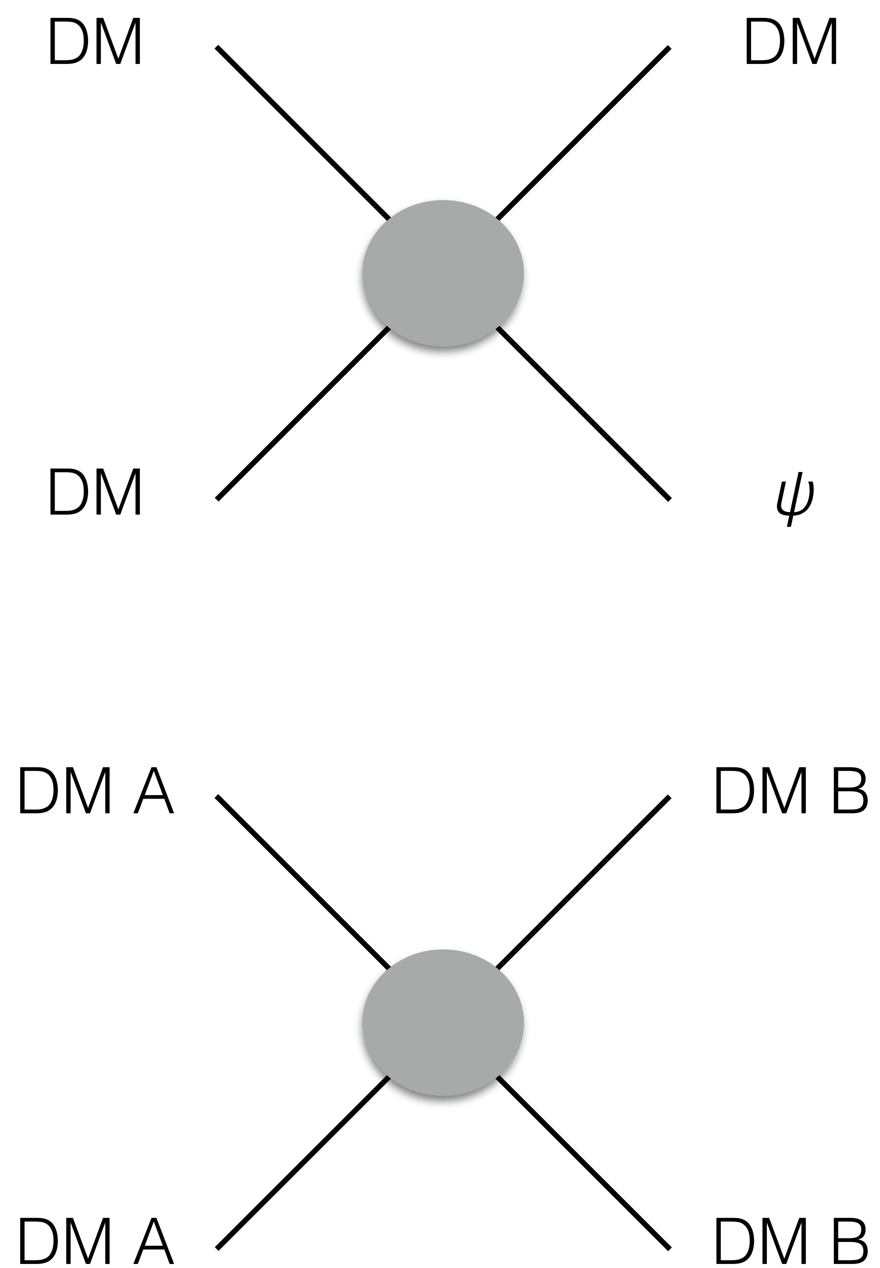
How to Look?

- Use the largest detector with low enough threshold
- Boosted DM means larger recoils
- For O(1) boost: proton recoil ~ 1 GeV
- Best strategy (for now): Proton Cherenkov light
- Recoil momentum acceptance ~ 1.07 - 2 GeV

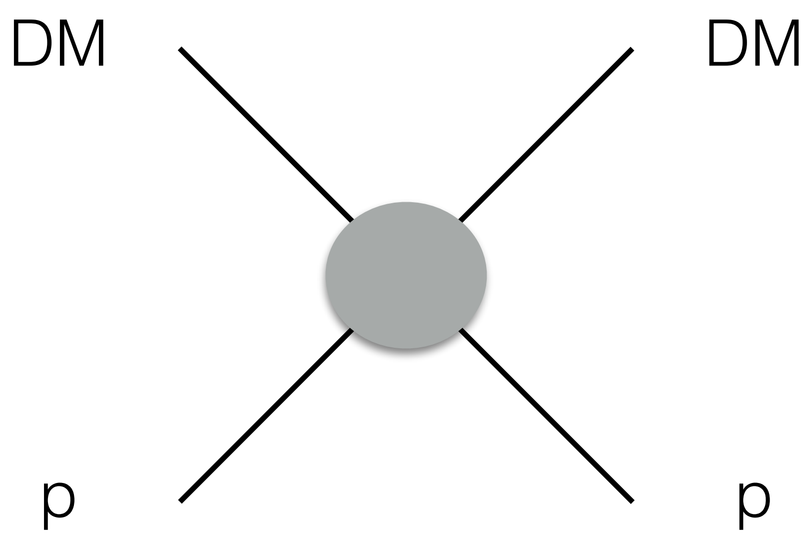
1. DM Captured by Sun

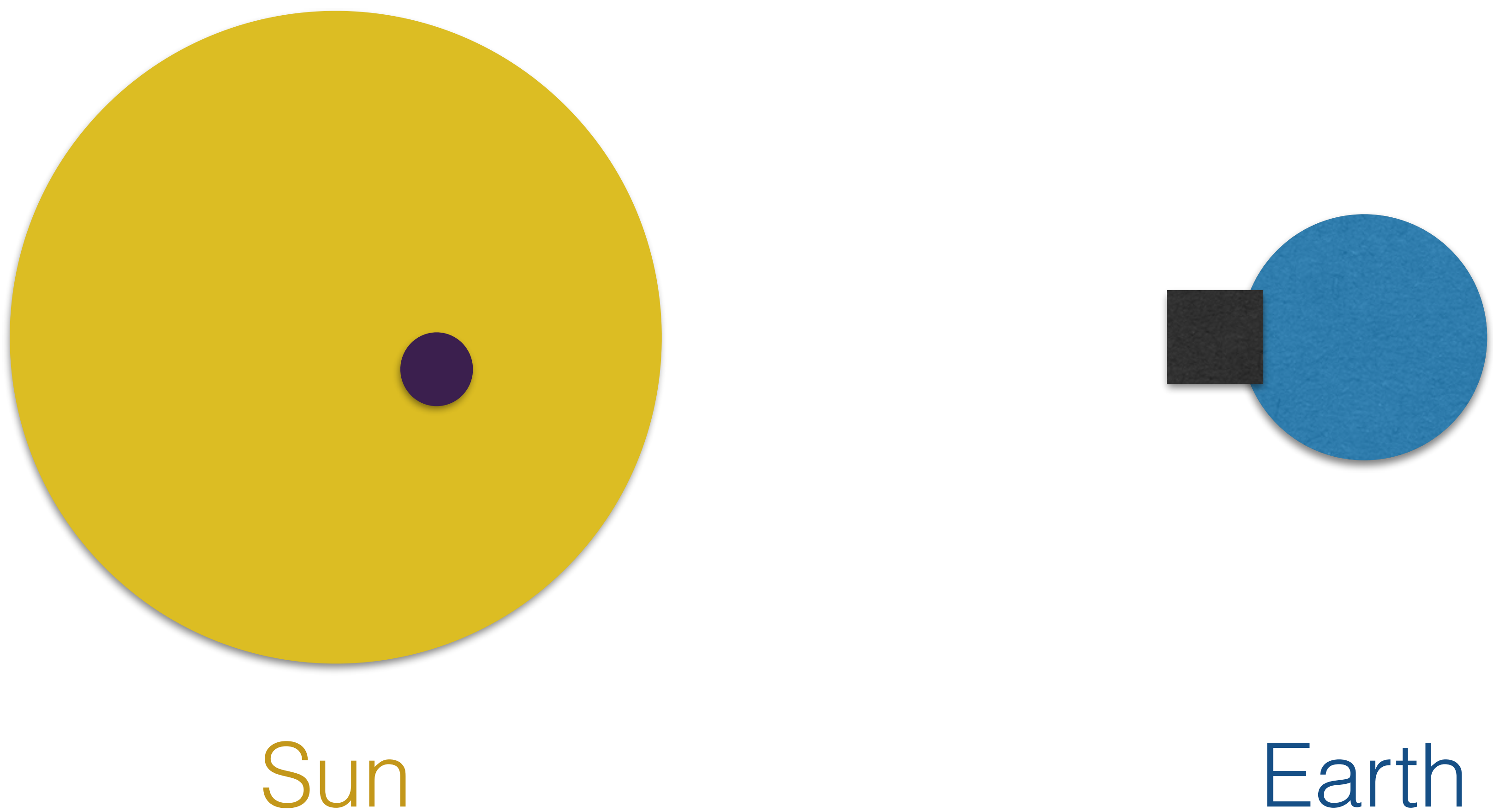


2. Annihilation

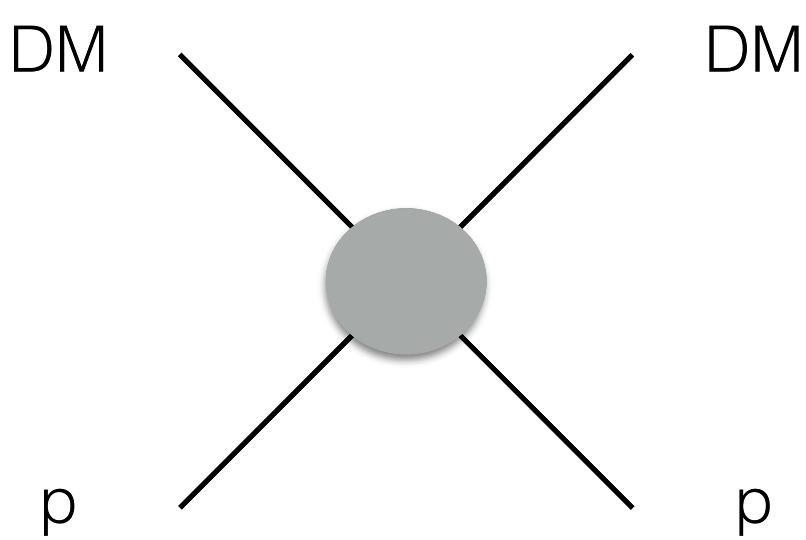


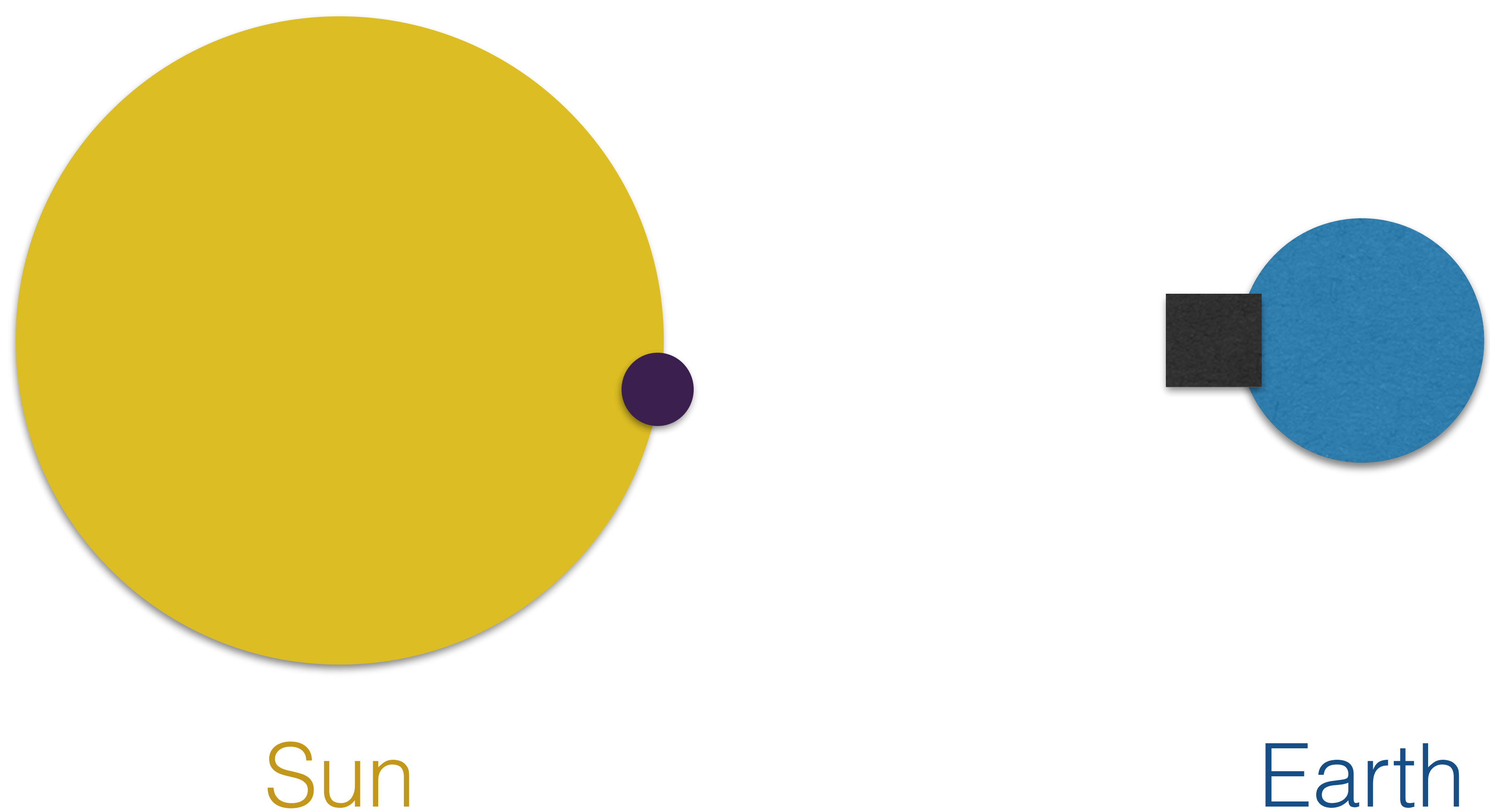
3. Re-scattering in Sun





4. Detection





Models

Overview

- Recall: 2 classes of models
  - Semi-annihilating DM: v^0 or v^2 in NR limit
  - Two component DM: v^0 only
- All cases: Assume SD interactions only

Semi-Annihilating Models

- Simplest example: Z_3 symmetric DM

- Other examples: different symmetries or near-degenerate spectrum

$$\gamma_\chi = \frac{5m_\chi^2 - m_\psi^2}{4m_\chi^2} \approx 1.25 \qquad v \approx 0.6$$

- Neglect (presumed unstable) fourth particle

v^0 couplings

- Fermionic DM χ and auxiliary particle ψ
- DM-N scattering mediated by Z' with axial coupling
- Annihilation by Z' in p-wave: SA dominates

$$\mathcal{O}_{Z'} = \frac{1}{M^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q \qquad \mathcal{O}_{\rm SA} = \frac{1}{m^2}(\chi_L\chi_L)(\chi_R^\dagger\psi_R^\dagger)$$

v^2 couplings

- **Scalar** DM χ and auxiliary particle ϕ
- DM-N scattering mediated by Z' with axial coupling
- Annihilation by Z' in p-wave: SA dominates

$$\mathcal{O}_{Z'} = \frac{1}{M^2}(\chi^\dagger \partial_\mu \chi - \partial_\mu \chi^\dagger \chi)\bar{q}\gamma^\mu \gamma^5 q \qquad \mathcal{O}_{\rm SA} = \lambda \chi^3 \phi$$

Two Component Models

- Assume $m_B < m_A$ and $\sigma_B > \sigma_A$

$$\gamma_B = \frac{m_A}{m_B} \qquad v = \sqrt{1 - \frac{m_B^2}{m_A^2}}$$

- Range of v ~ 0.5 — 0.9 for detection
- More moving parts, but more flexibility
- Can naturally realize thermal relic

Two Component Details

- Fermionic DM ψ_A and ψ_B
- ψ_B subdominant component of relic DM
- DM-N scattering mediated by Z' with axial coupling
- Annihilation of ψ_A dominantly into ψ_B

$$\mathcal{O}_{\rm DD} = \frac{1}{M^2}\bar{\psi_X}\gamma^\mu\gamma^5\psi_X\bar{q}\gamma_\mu\gamma^5 q$$
$$\mathcal{O}_{\rm ann} = \frac{1}{m^2}\bar{\psi_A}\gamma^\mu\gamma^5\psi_A\bar{\psi_B}\gamma^\mu\gamma^5\psi_B$$

Parametrizing the Models

$$\sigma_{\rm DD} = \sigma_{\chi,p}^{v\to 10^{-3}}(m_\chi, M^2)$$

- Exchange suppression scale & couplings for NR scattering cross-section
- SA parameterized by: m_χ, σ_{DD}, ($m_{Z'}$)
- 2 component by: m_A, m_B/m_A, σ_A, σ_B/σ_A, ($m_{Z'}/m_A$)

Models: They Exist

- More complex dark sector → boosted DM
- Same process for capture, re-scattering, detection
- Annihilation separate → thermal relic possible
- Convenient parametrization using DD parameters

Boosted DM Flux

DM Flux in 3 Steps

- Capture: NR elastic scattering to below escape v
- Annihilation: Yields boosted DM with rate determined by equilibrium condition
- (Evaporation: Negligible, as we will see)
- Re-scattering: Semi-relativistic scattering loss

DM Capture

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

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

DM Annihilation

- DM annihilation determined by equilibrium

$$AN^2 = C - EN$$

- Assuming annihilation ~ pb, $t_{\odot} \gg \tau_{eq}$
- DM evaporation: Elastic up-scattering by tail of hydrogen velocity distribution
- Evaporation negligible for $m_\chi > 5$ GeV

DM Re-scattering

- DM can lose energy escaping the Sun

$$\ell = \frac{1}{\sigma_{\chi,p} n_H}$$

- v^2 models: quasi-relativistic during escape
- Calculate detection rate using $\langle E_\chi \rangle$
- Conservative: fluctuations could be important

Putting the Pieces Together

- Flux of DM

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

- Large capture rate, but large distance balance out
- Next: determine effective cross-section of detector

DM Flux in Numbers

- v^0 models:

$$\Phi = 7 \times 10^{-4}\text{cm}^{-2}\text{sec}^{-1}\left(\frac{\sigma_{\text{DD}}}{10^{-38}\ \text{cm}^2}\right)\left(\frac{100\ \text{GeV}}{m_\chi}\right)^2$$

- v^2 models:

$$\Phi = 2 \times 10^{-2}\text{cm}^{-2}\text{sec}^{-1}\left(\frac{\sigma_{\text{DD}}}{10^{-38}\ \text{cm}^2}\right)\left(\frac{100\ \text{GeV}}{m_\chi}\right)^2$$

- Enhancement: DM in sun has larger v than in halo

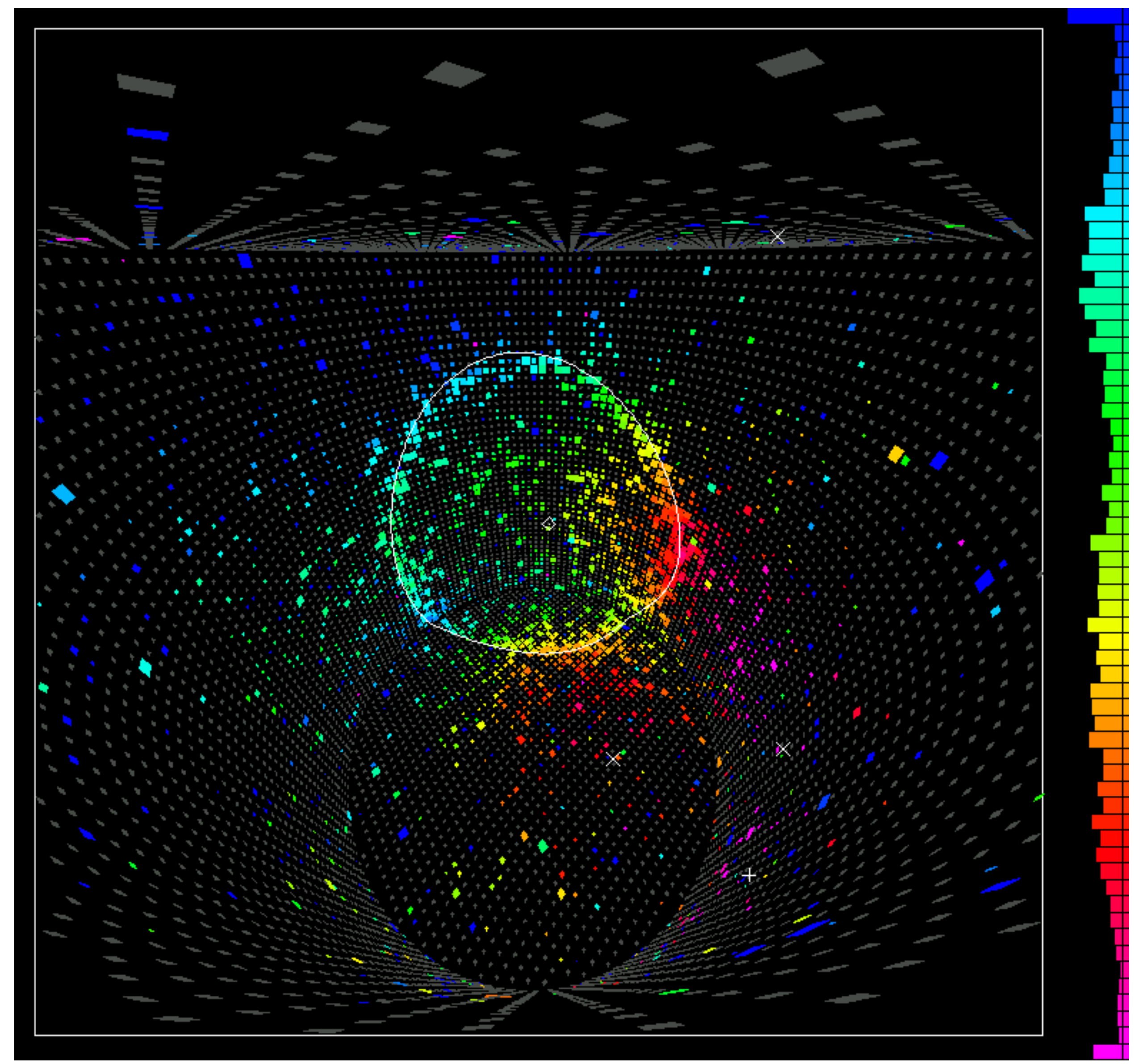
Boosted DM Detection

Strategies

- Two possibilities: scatter off *e* or *p*
  - *e* requires light mediator (see 1405.7370)
- **Not** in low recoil regime: ~ GeV threshold required
- Ideal candidate for now: Super-Kamiokande
- Future candidates: Hyper-K, L-Ar TPC

Proton Cherenkov Rings

- Proton Cherenkov momentum $p > 1.07$ GeV
- As $m_\chi \to \infty$, $v > 0.45$ required
- Single ring from elastic scattering requires $p \lesssim 2$ GeV
- For $v > 0.63$, lose some signal



Super-Kamiokande

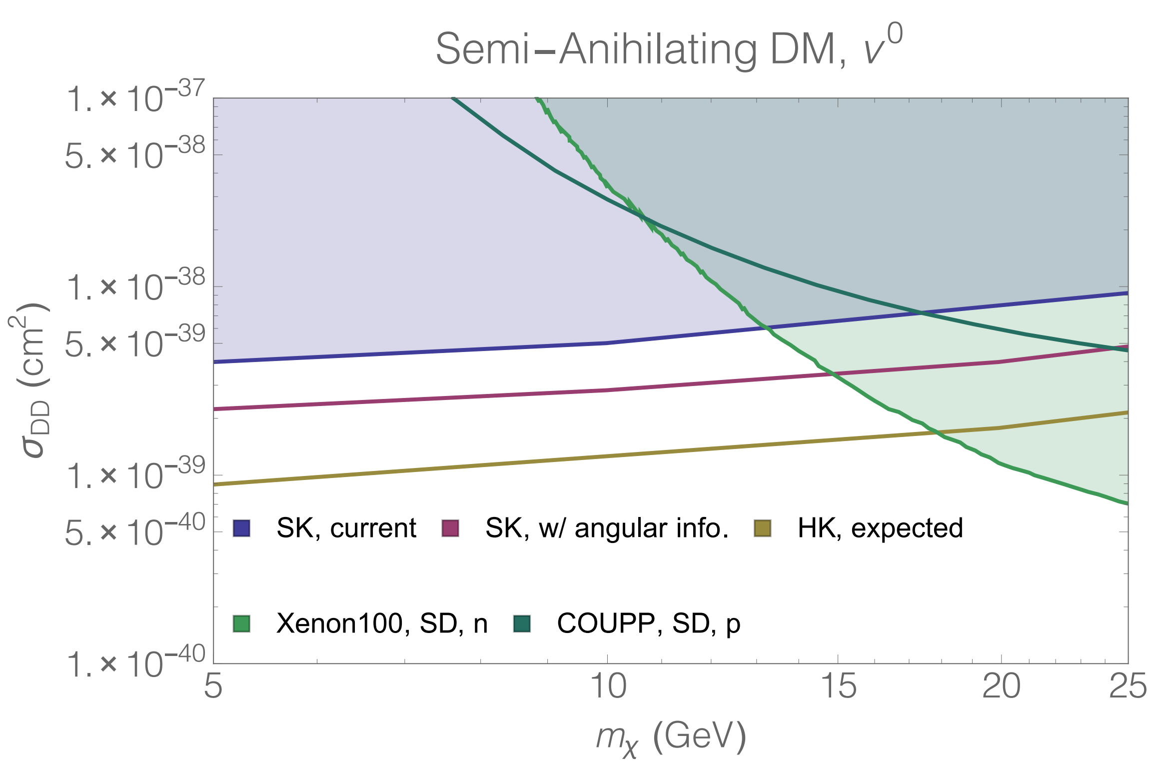
Background Reduction

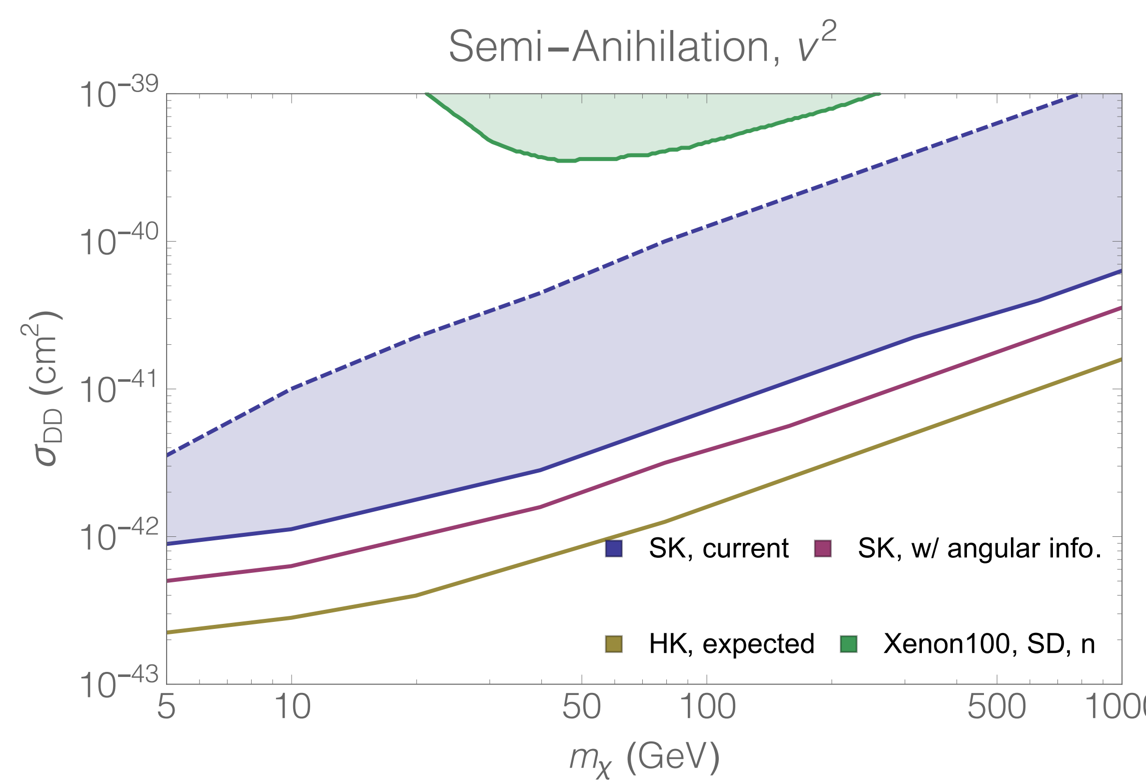
- Signal: protons recoil within $\theta \sim 40^{o}$ of the sun
- Background: nearly isotropic
- Bonus: large sideband eliminates systematics
- Also: No correlated charged-current signal

Limits & Prospects

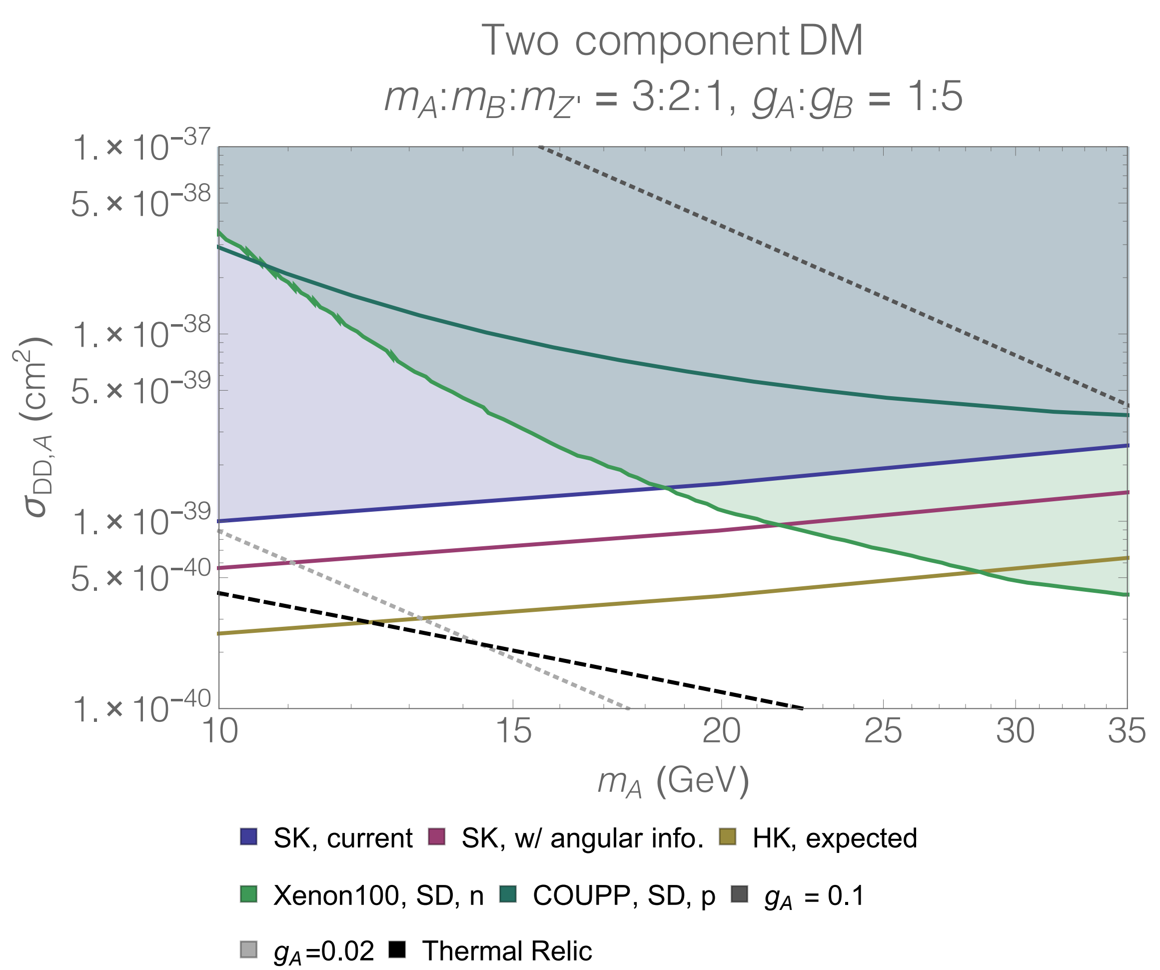
- Consider three scenarios
  - 95% limits from current SK neutral current search
  - Expected 2σ from full SK using recoil direction
  - Expected 2σ from full HK using recoil direction

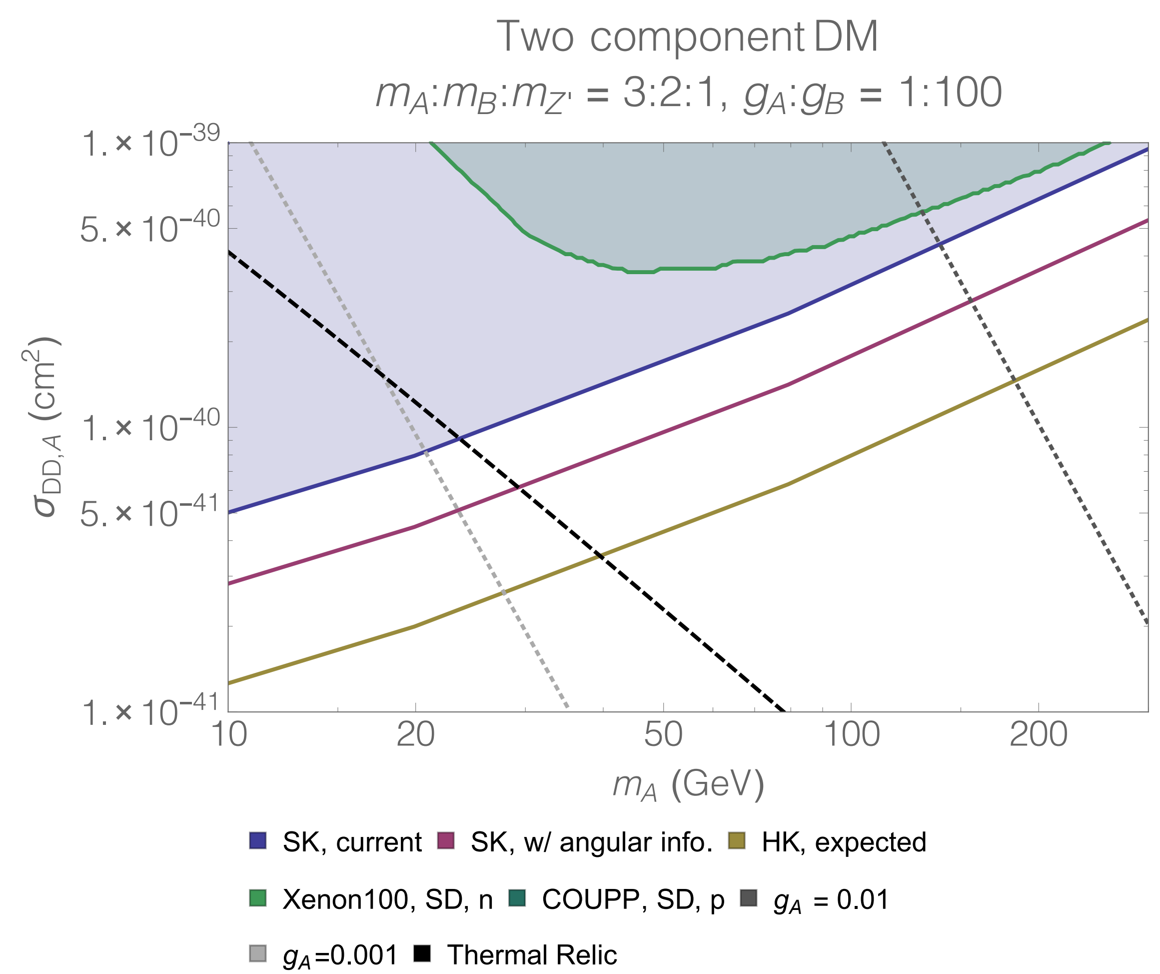
Results: SA DM





Results: 2 Component DM





Conclusions

Future Directions

- Full analysis using angular information
- Interest from LBNF group: Lower threshold
- Include inelastic and quasi-elastic events?
- Resolve the spectrum?
- Note: Need a detector with **at least** ~ kton-year

Wrap Up

- The thermal relic scenario provides a generic mechanism for DM production, but may involve a non-minimal dark sector

- Several candidate models can generate boosted DM coming from annihilations

- Large volume neutrino detectors can be repurposed for boosted DM discovery