# Searching for Boosted Dark Matter in Large Volume Neutrino Detectors

Joshua Berger
University of Wisconsin-Madison

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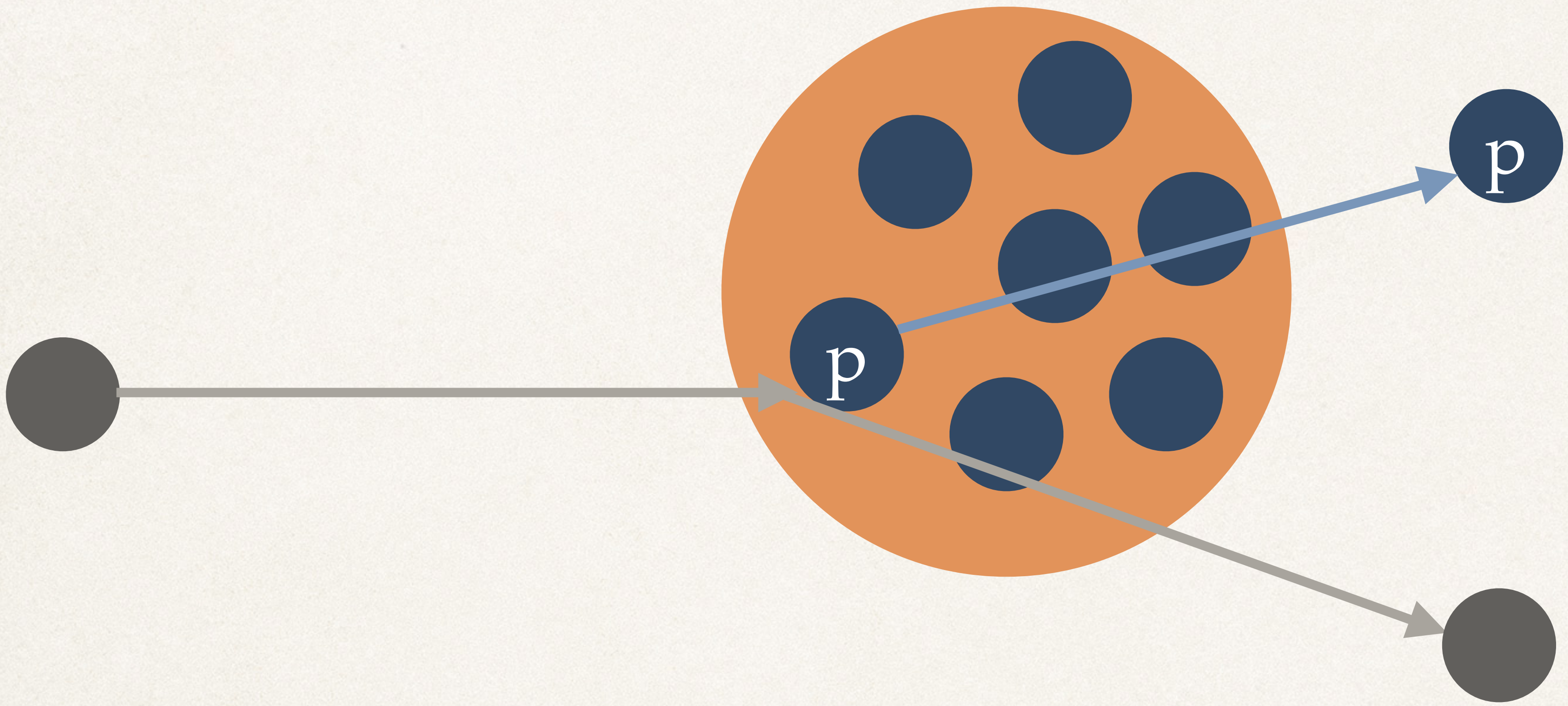
UCLA Dark Matter 2018

# The difference with boosted

**Elastic Nucleon Scattering**

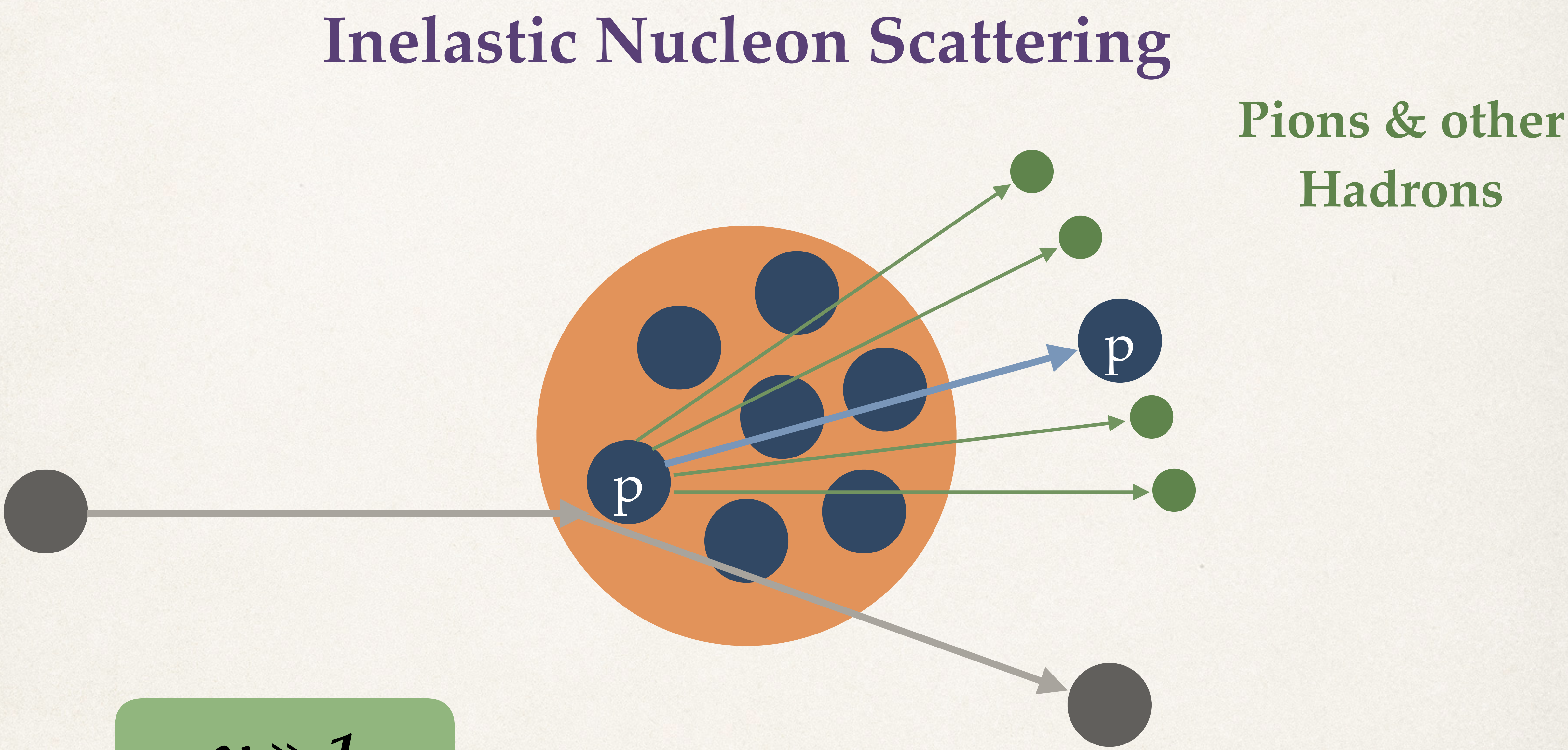



$\gamma \sim 1$

$E_K \sim$ **1 GeV**

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

# The difference with boosted

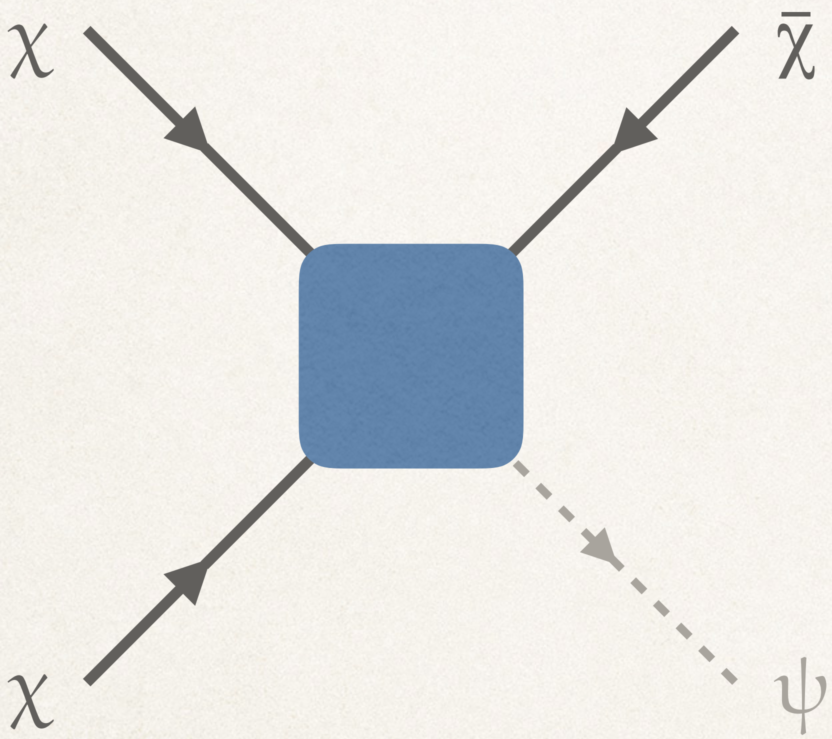



$\gamma \gg 1$

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

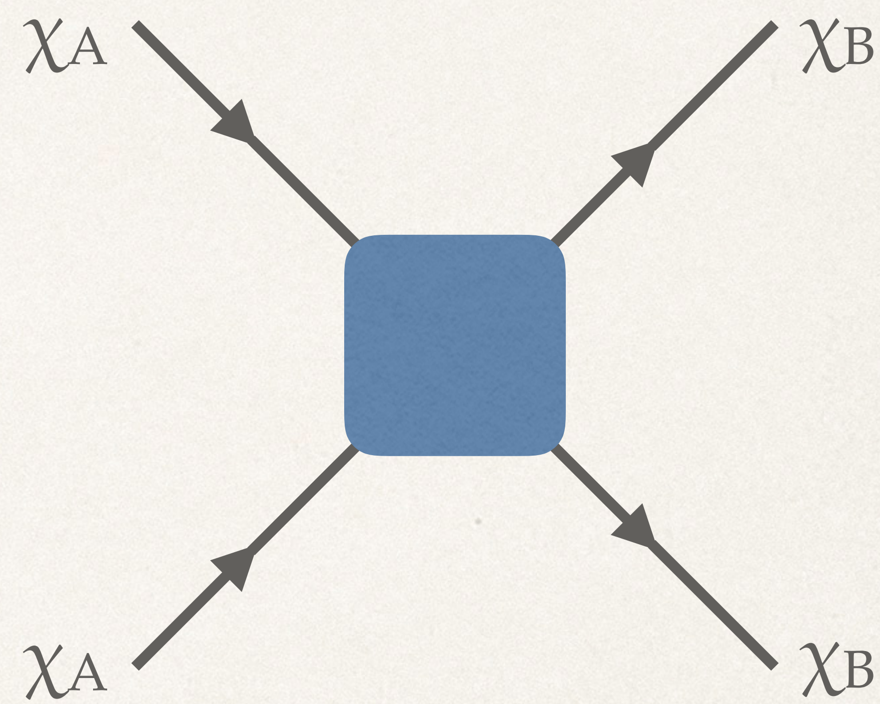
# Two models with Boosted DM

## $Z_3$ symmetry




$$v \approx 0.6$$

## Two component



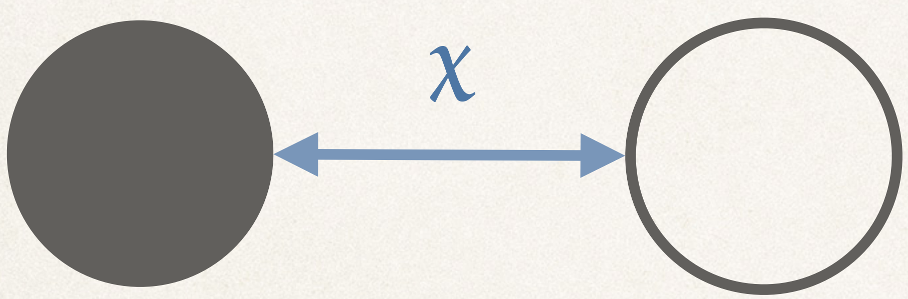

$$v = (1 - m_B^2/m_A^2)^{1/2}$$

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

# Semi-annihilation $Z_2 \rightarrow Z_3$

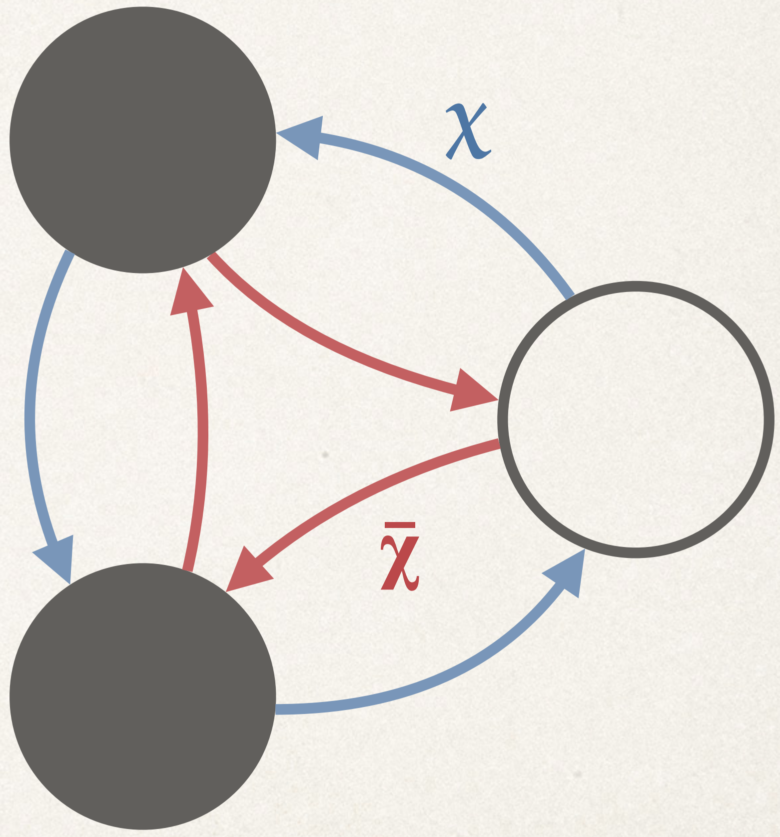
Classic Thermal Relic

$Z_2$ symmetry




Boosted Thermal Relic

$Z_3$ symmetry

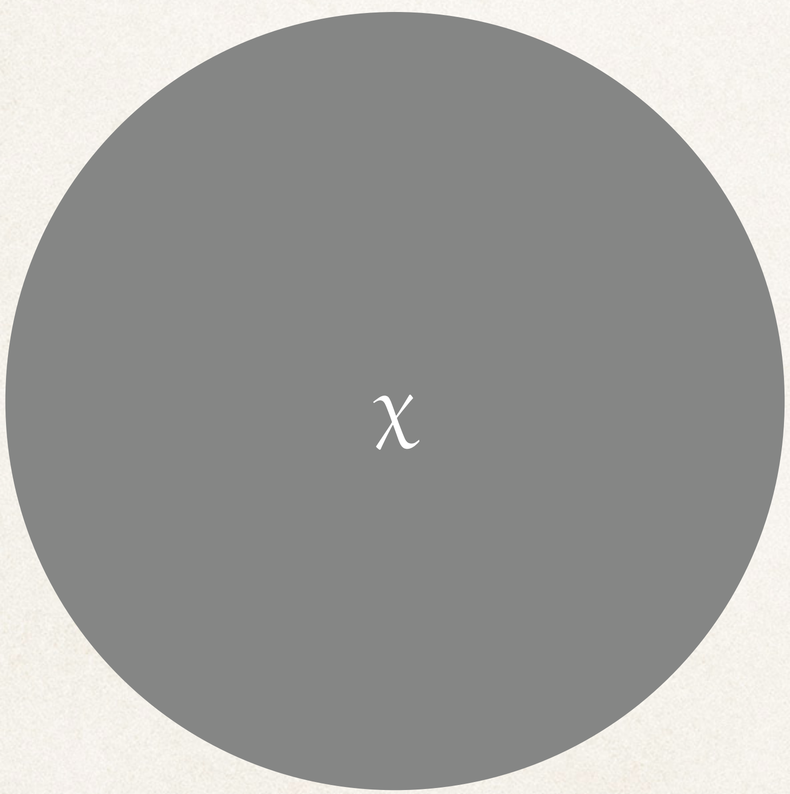



D'Eramo & Thaler: JHEP 1006 (2010) 109

# One component → Two component

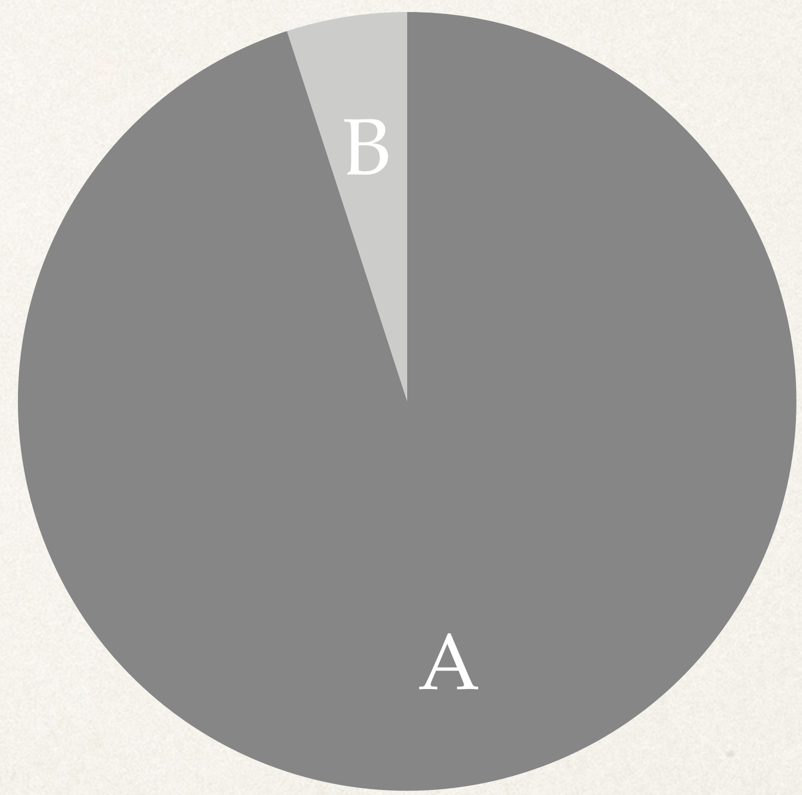
Classic Thermal Relic

**One** component




Boosted Thermal Relic

**Two** component




Agashe et. al.: JCAP 1410 (2014) no.10, 062

# Parametrizing the Models

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

- **Semi-annihilation** just 2-3 parameters:

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

- **Two component** slightly more intricate:

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

- **Fermionic DM**: $\sigma \propto v^0$ **Scalar DM**: $\sigma \propto v^2$

# Solar capture & Detection

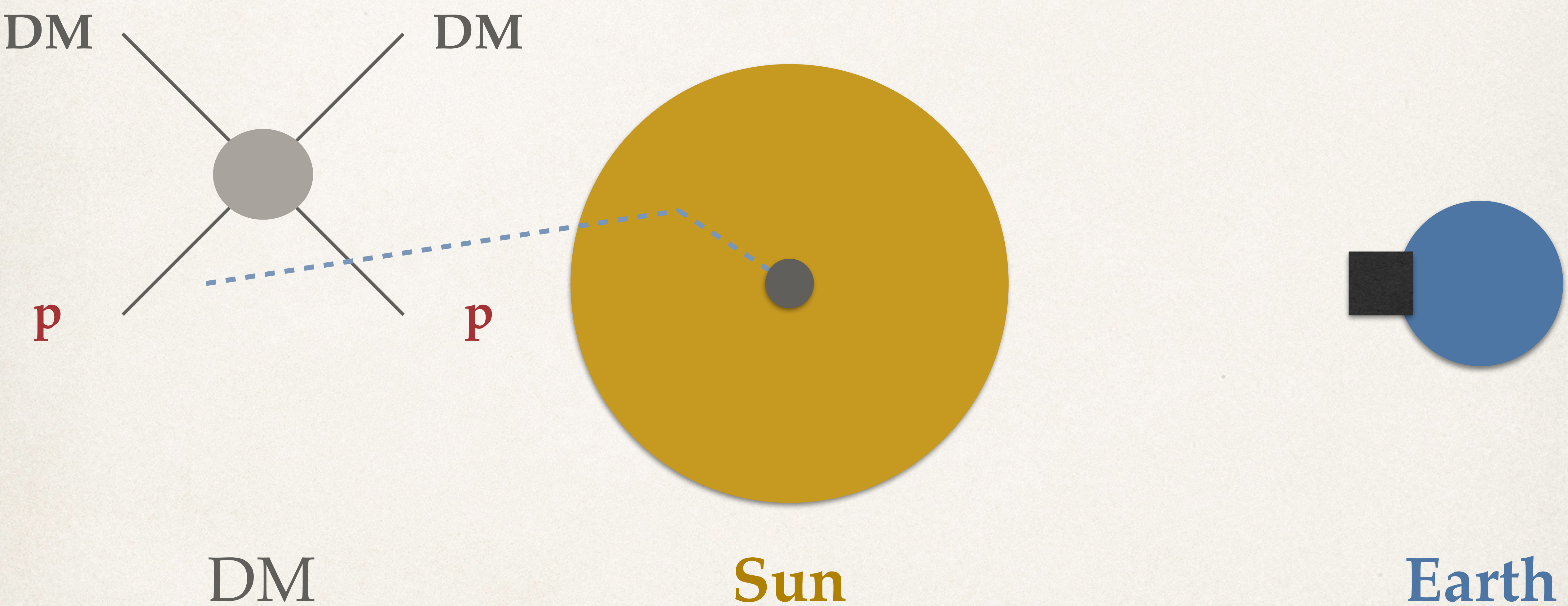
Solar Capture


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

# Solar capture & Detection

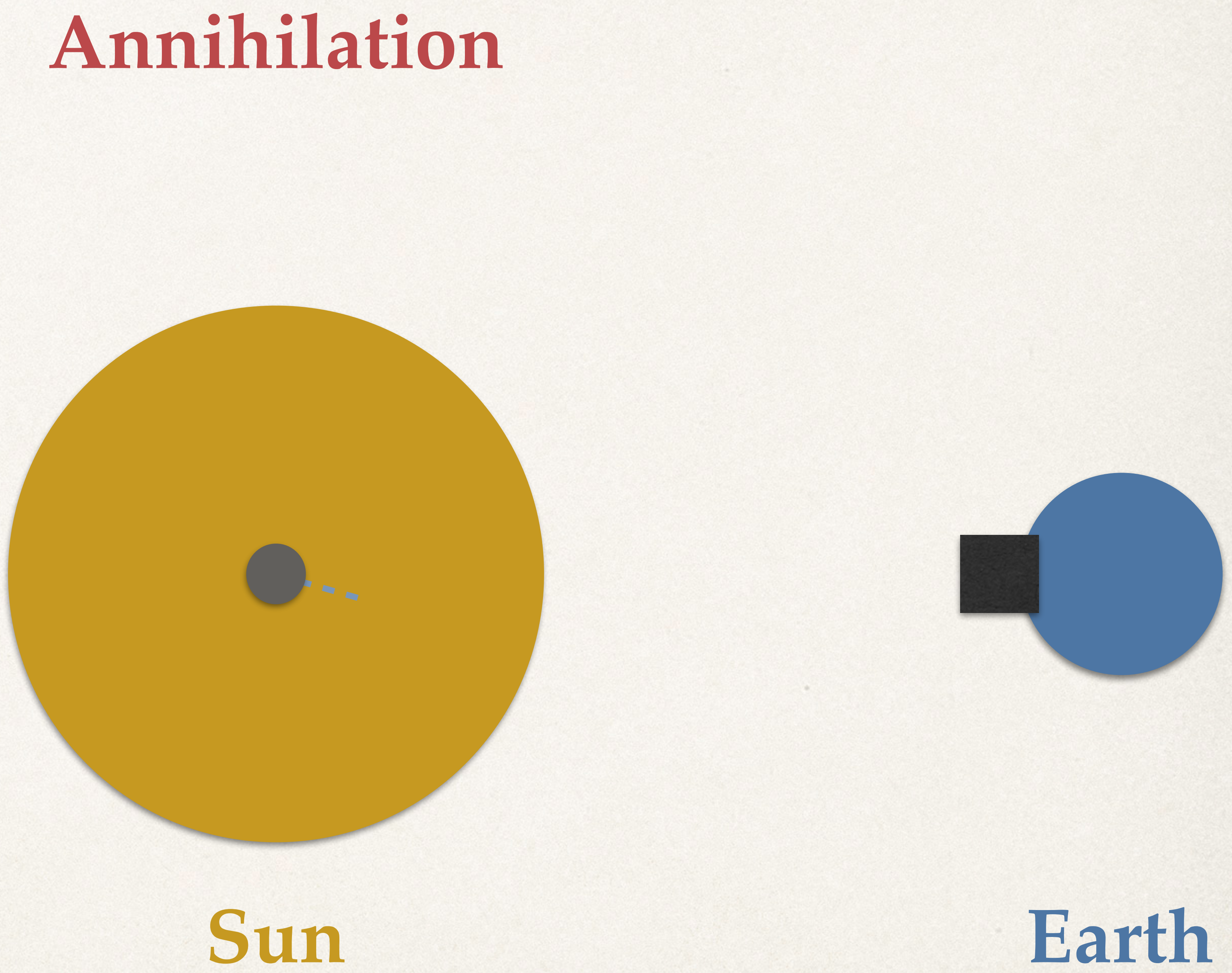
## Solar Capture

Proton scattering



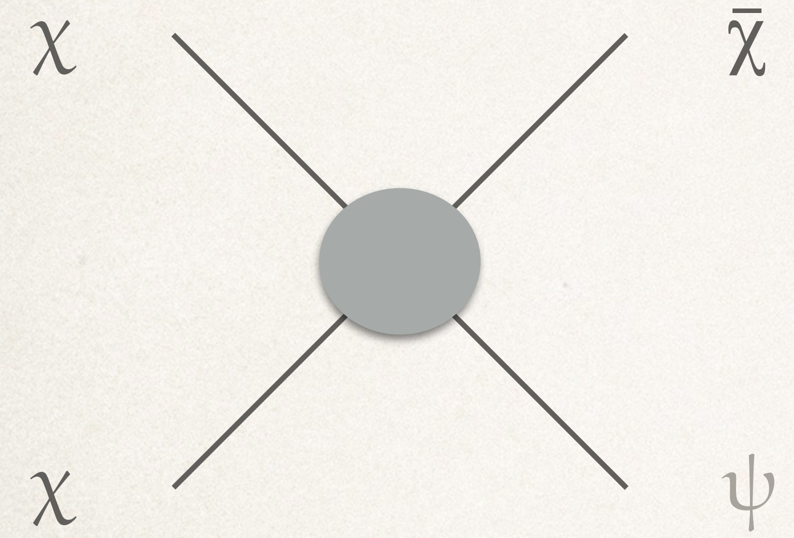

JB, Cui, Zhao: JCAP 1502 (2015) 005

# Solar capture & Detection

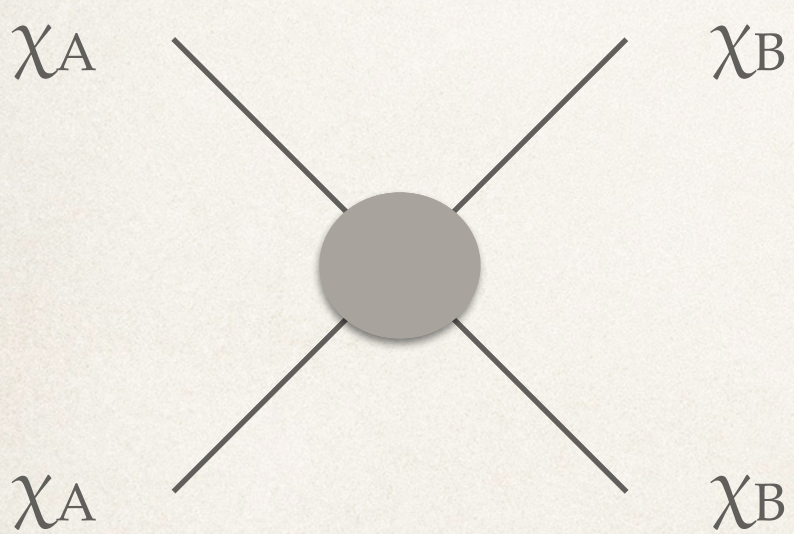


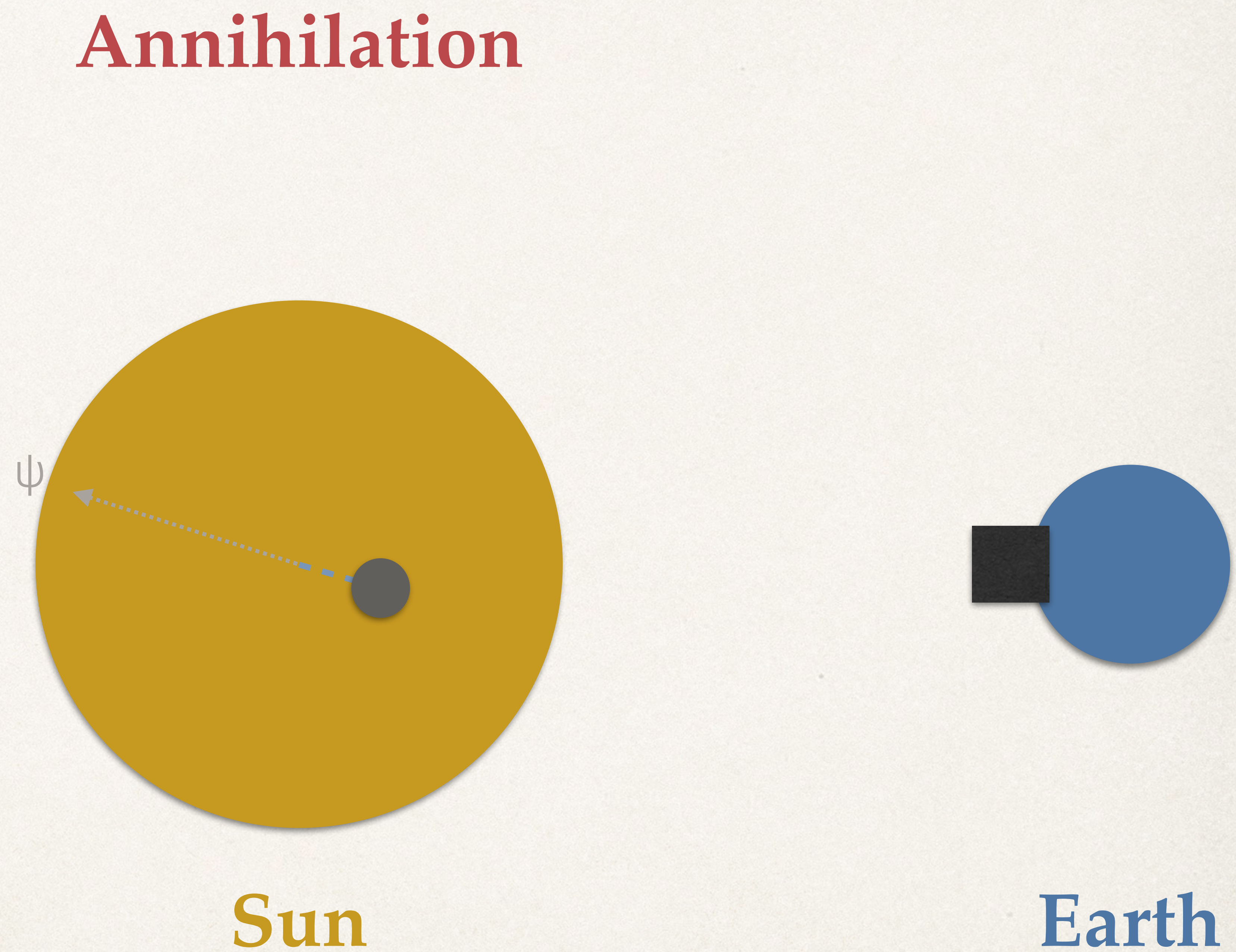

JB, Cui, Zhao: JCAP 1502 (2015) 005

# Solar capture & Detection




or

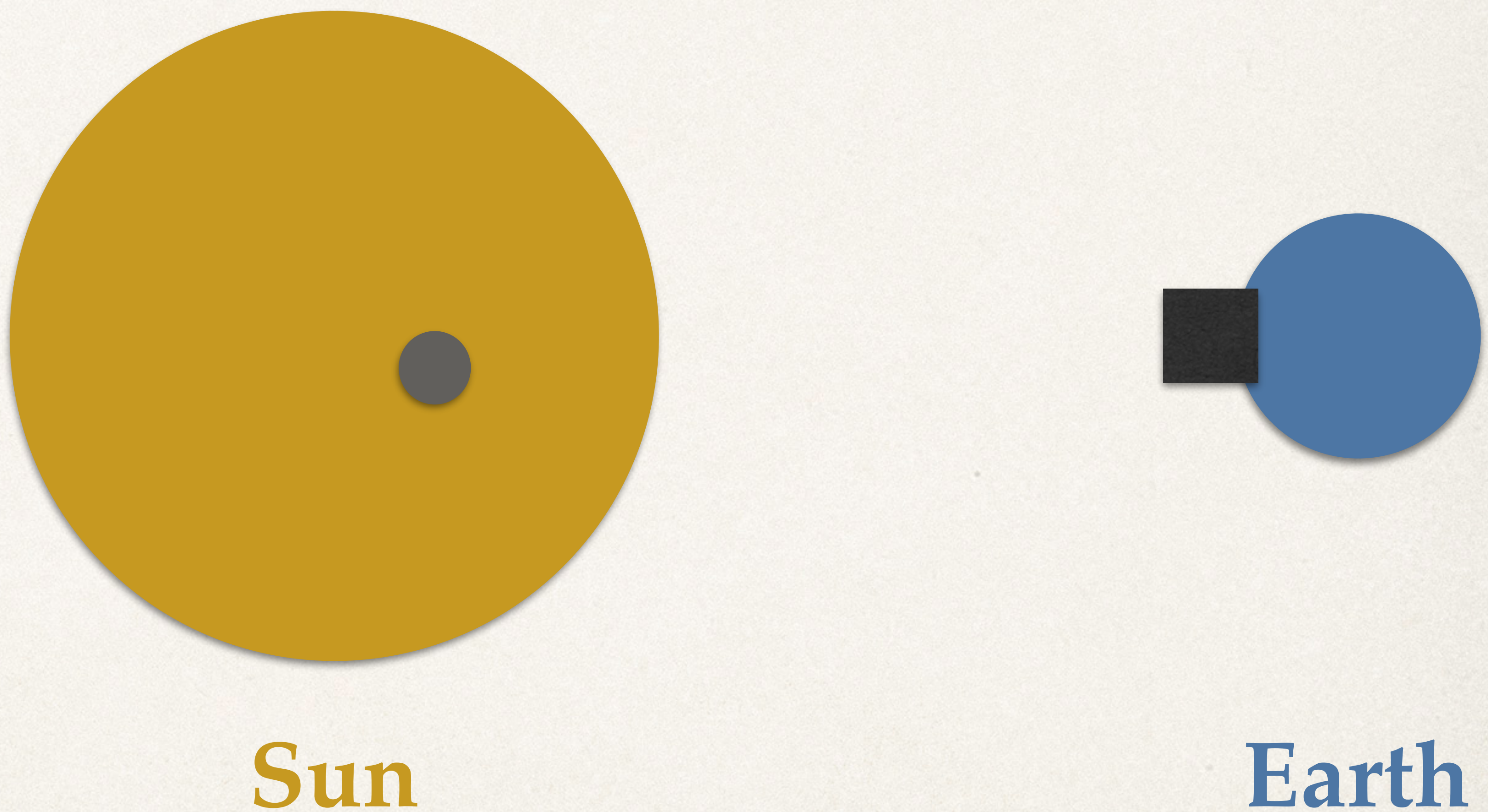



**JB**, Cui, Zhao: JCAP 1502 (2015) 005

# Solar Capture & Detection

**Re-scattering**

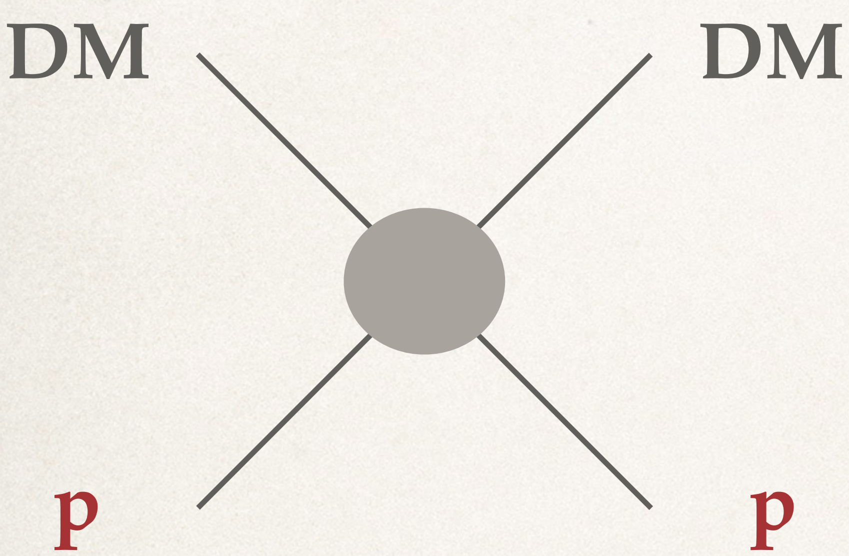


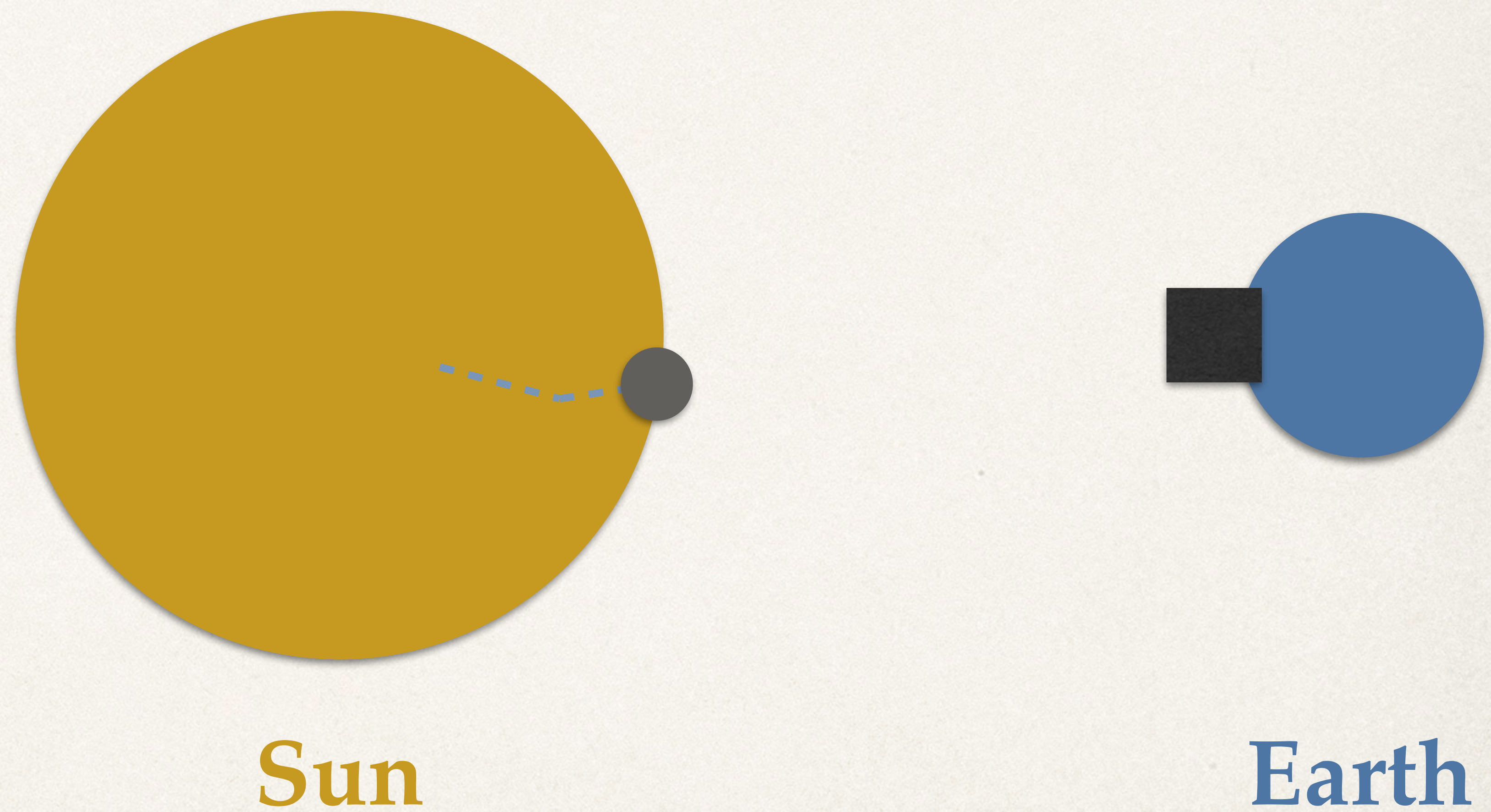

**JB**, Cui, Zhao: JCAP 1502 (2015) 005

# Solar Capture & Detection

**Re-scattering**

**Proton** scattering

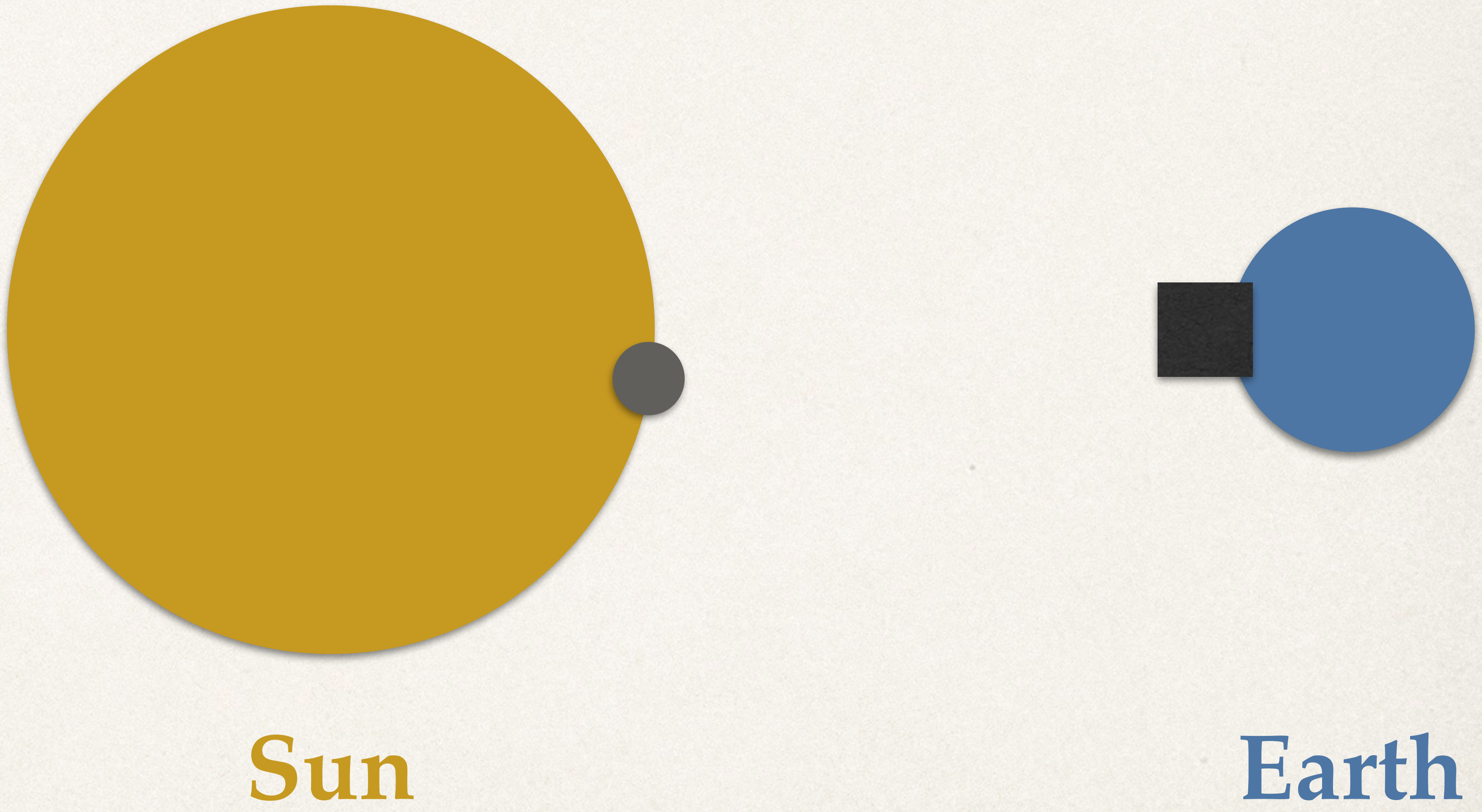



**JB**, Cui, Zhao: JCAP 1502 (2015) 005

# Solar Capture & Detection

**Detection**

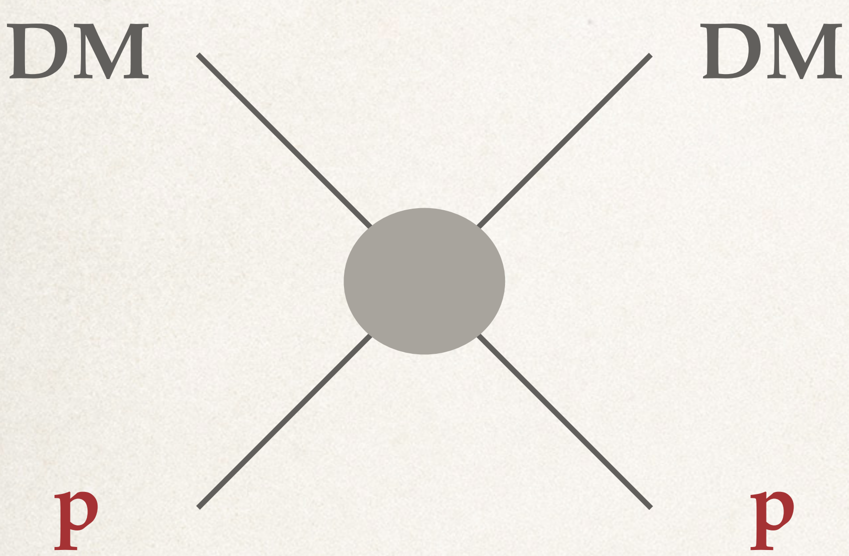


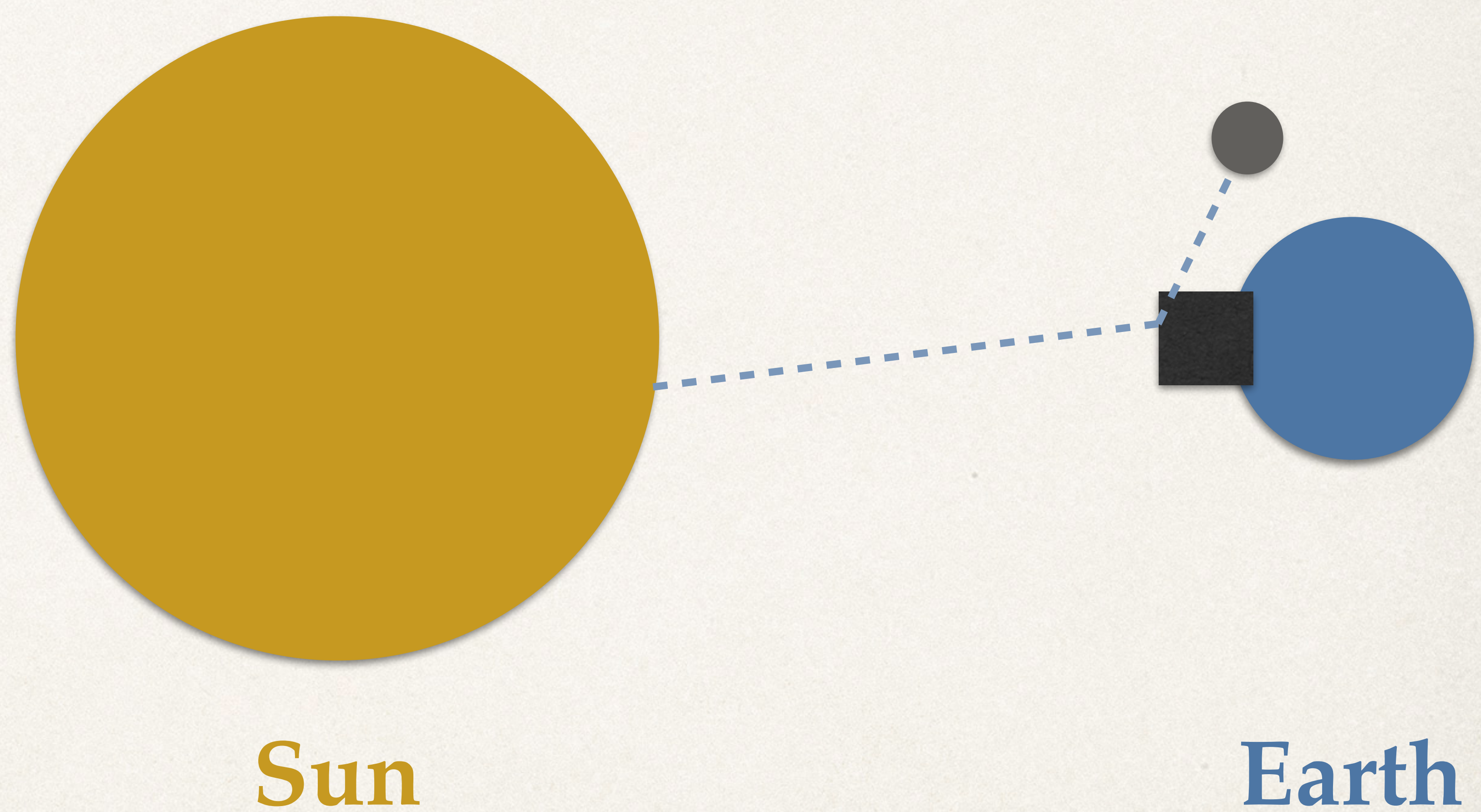

**JB**, Cui, Zhao: JCAP 1502 (2015) 005

# Solar Capture & Detection

**Detection**

**Proton** scattering




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

# Why look at the sun?

Annihilation to boosted DM $\propto n^2$

Somewhere dense in dark matter

Flux through detector $\propto 1/D^2$

Somewhere nearby

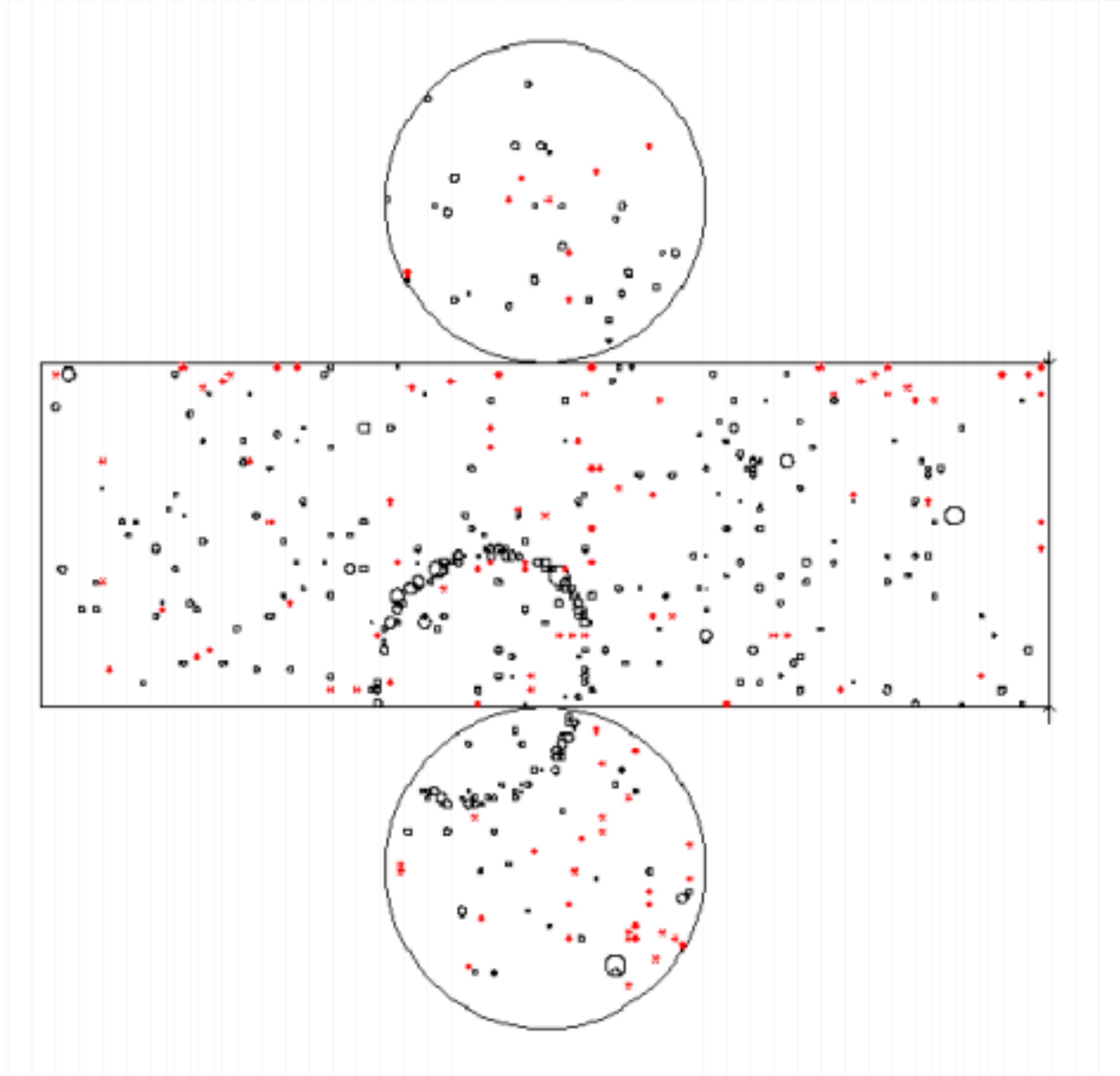
| Galactic Center | ✔Solar Capture |
| --- | --- |
| $\Phi \sim 10^{-7}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}$ | $\Phi \sim 10^{-2}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1} \left(\frac{\sigma_{\mathrm{DD}}}{10^{-38}\ \mathrm{cm}^2}\right)$ |

# Looking with Water Cherenkov

Threshold:

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

Hard to reconstruct **inelastic**



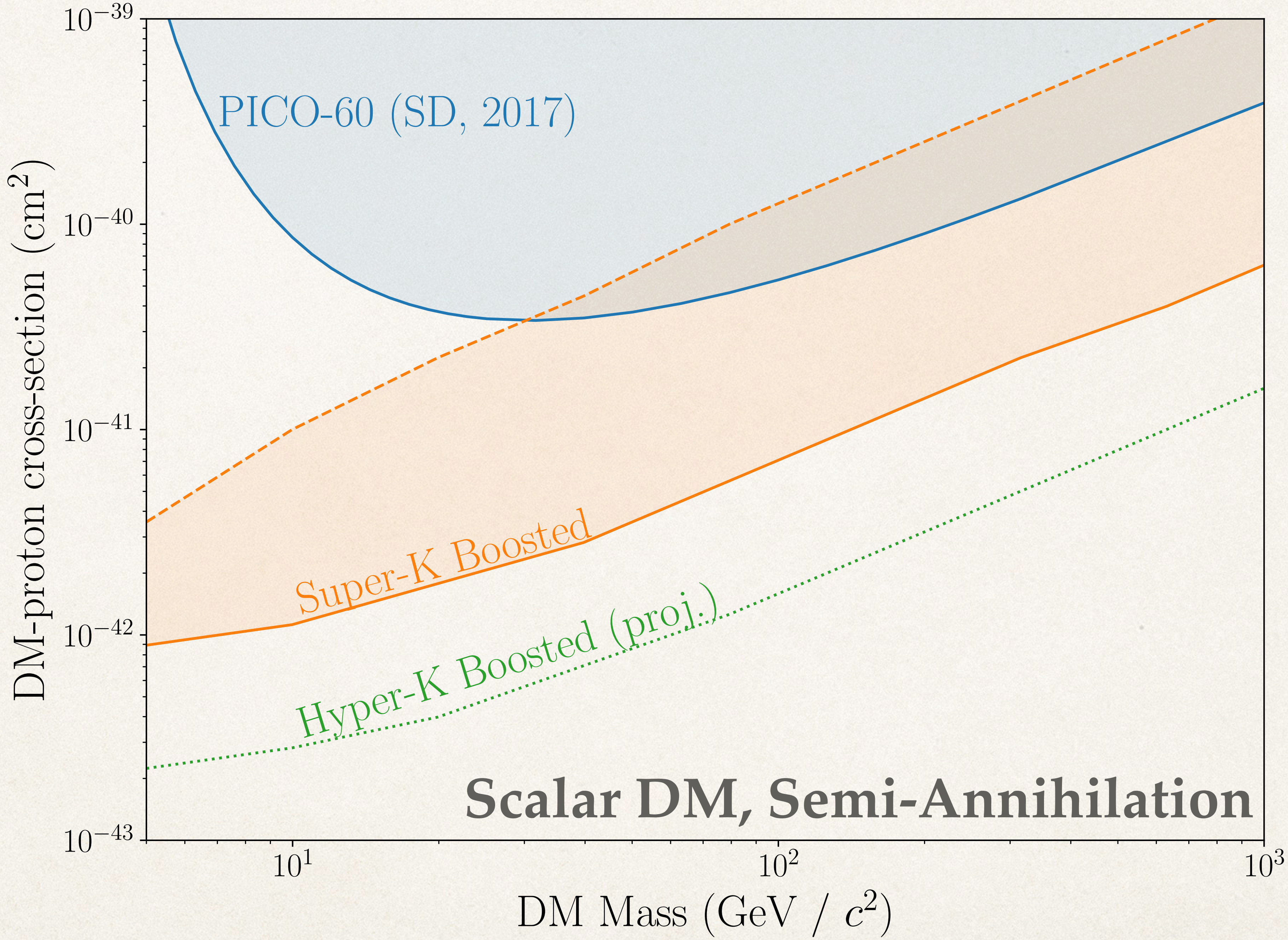
Super-Kamiokande: PRD79 (2009) 112010

Experiments:

**Super-Kamiokande**

**Hyper-Kamiokande**

# Water Cherenkov Results




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

# A Future in Liquid Argon TPC

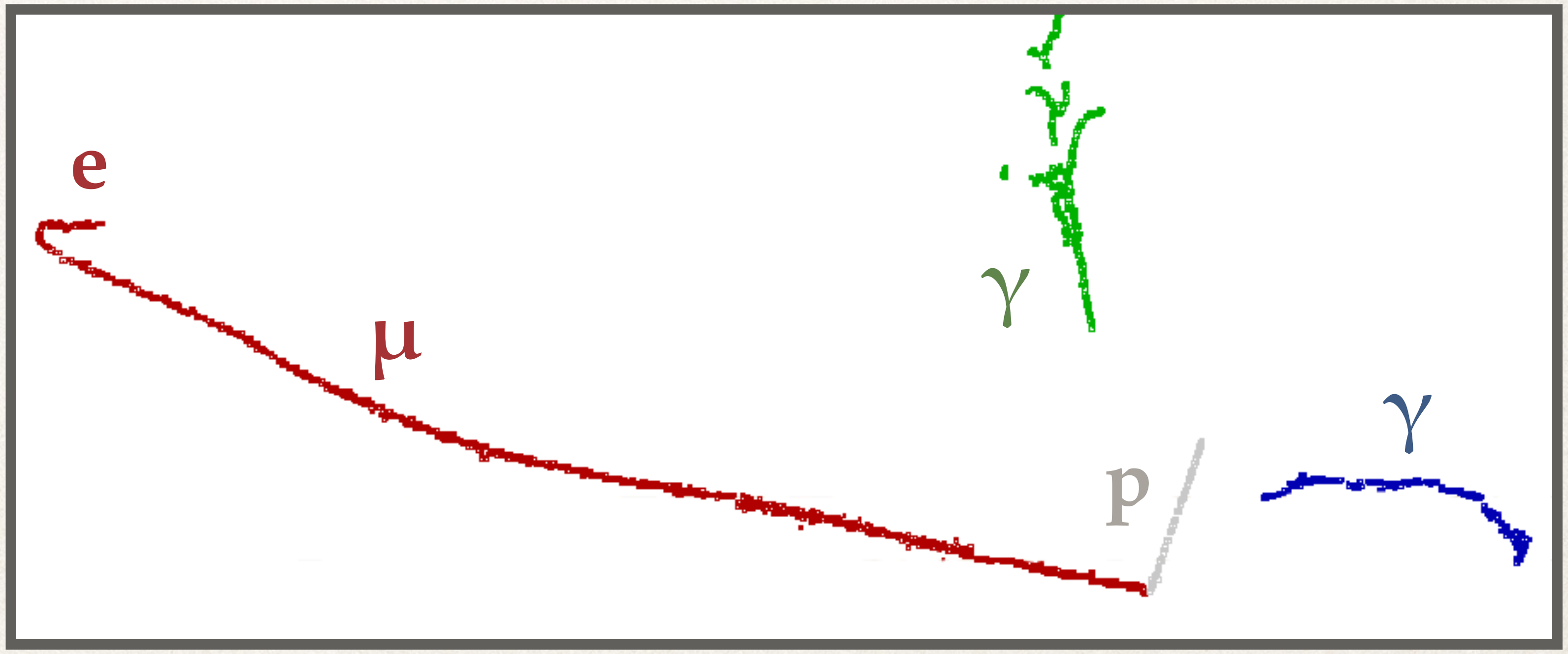
Threshold:

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

**Inelastic** reconstruction possible

Experiments:

- **LArIAT**
- **ICARUS**
- **MicroBooNE**
- **DUNE**




LArSoft

# What do we need for DUNE?

✓ Develop a **Monte Carlo**

- Based on **GENIE** neutrino MC
- Does **inelastic** and **nuclear** effects
- Merge into official version shortly

Integrate into LArSoft detector simulation

Develop analysis strategy

Projections for DUNE TDR

Theory: **JB**, Cui, Necib, Zhao
Tools & Experiment: Andreopoulos, Hatcher, Petrillo, Russell, Tsai

# Backup Slides

# Dark Matter Capture

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

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

# Capture Reaches Equilibrium

- In equilibrium: capture balances with escape

$$AN^2 = C - \underline{EN}$$

- Assuming annihilation ~ pb: equilibration by now

- **Evaporation:** hydrogen kicks DM out of sun

  Turns off exponentially at $m_\chi \gtrsim 5$ GeV

- Flux **independent** of annihilation cross-section

# 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

# Background Reduction

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