Detecting *Boosted* Dark Matter

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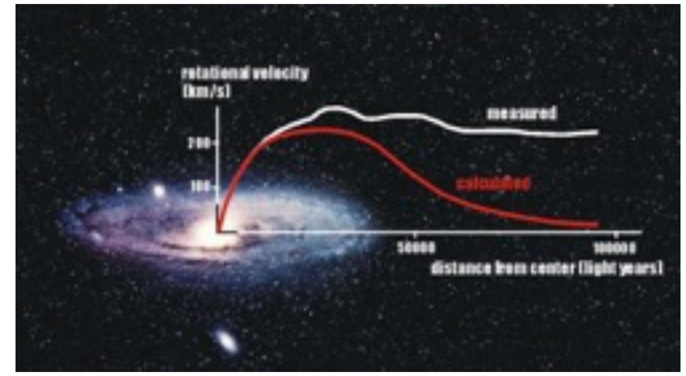
- **arxiv:1405.7370** (JCAP 1410 (2014) 062), K. Agashe, YC, L.Necib and J.Thaler
- **arxiv:1410.2246**, (JCAP 1502 (2015) 02, 005), J. Berger, YC and Y. Zhao

Conventional Concepts of DM

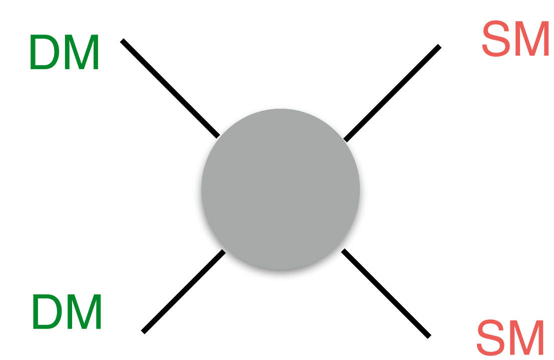


- **Dark Matter:** overwhelming gravitational evidence, $\Omega_{\rm DM} \approx 23\%$
- **Compelling paradigm:** DM is composed of massive particles

Current-day DM is highly non-relativistic, $v_{\rm DM,0} \simeq \mathcal{O}(10^{-3})$.

E.g. Simplest, best studied: One species of WIMP, Z_2 parity, direct interaction with SM states, $\Omega_{\rm DM}$ set by thermal annihilation to SM states

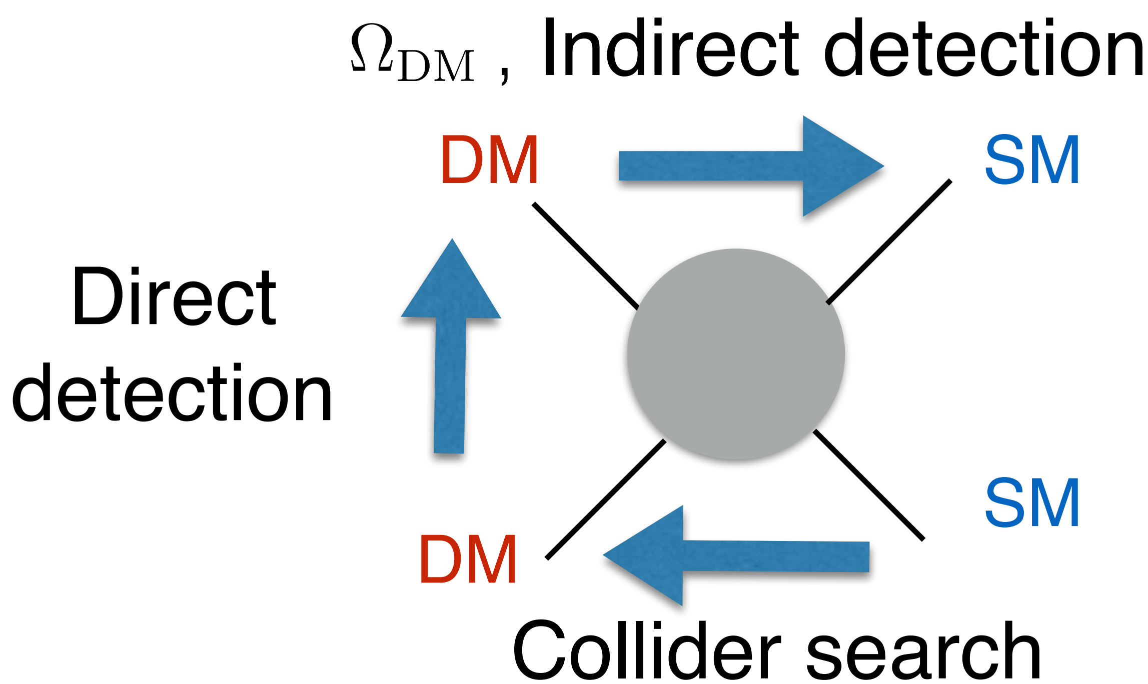
WIMP miracle: $$\Omega_\chi \propto \langle \sigma_{\rm ann} v \rangle^{-1} \sim 0.1 \left(\frac{G_{\rm Fermi}}{G_\chi}\right)^2 \left(\frac{M_{\rm weak}}{m_\chi}\right)^2$$



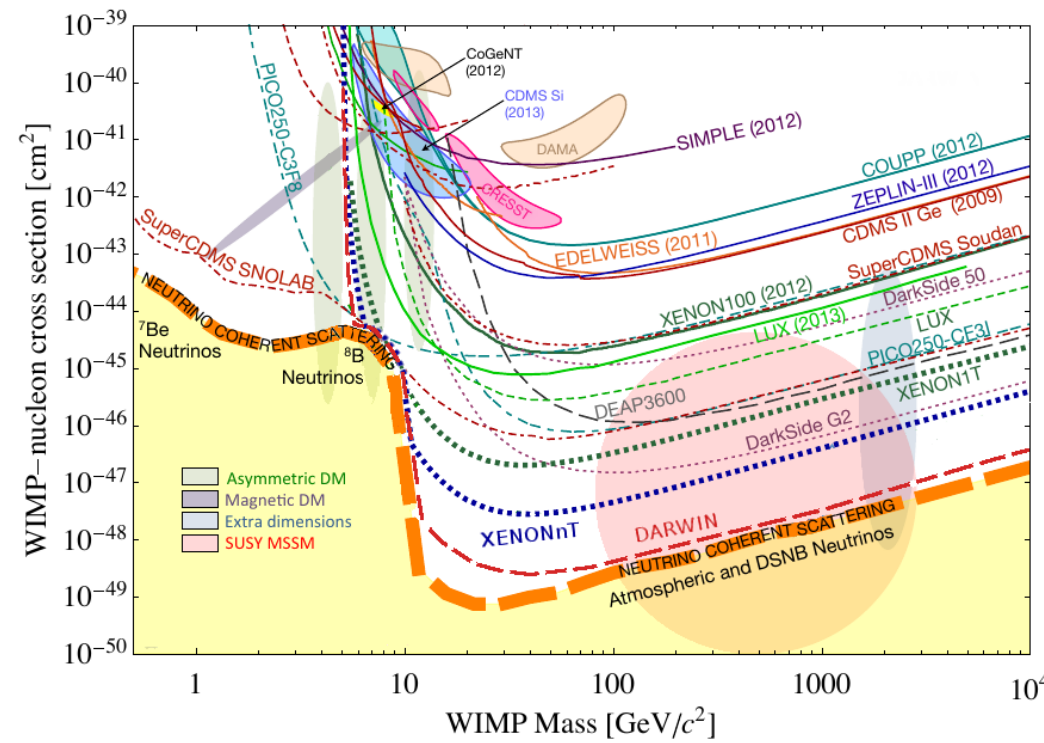
Design of DM detection experiments

Detectability, Challenges of WIMP DM

- Multi-pronged detectability (w/DM-SM interactions) 🙂

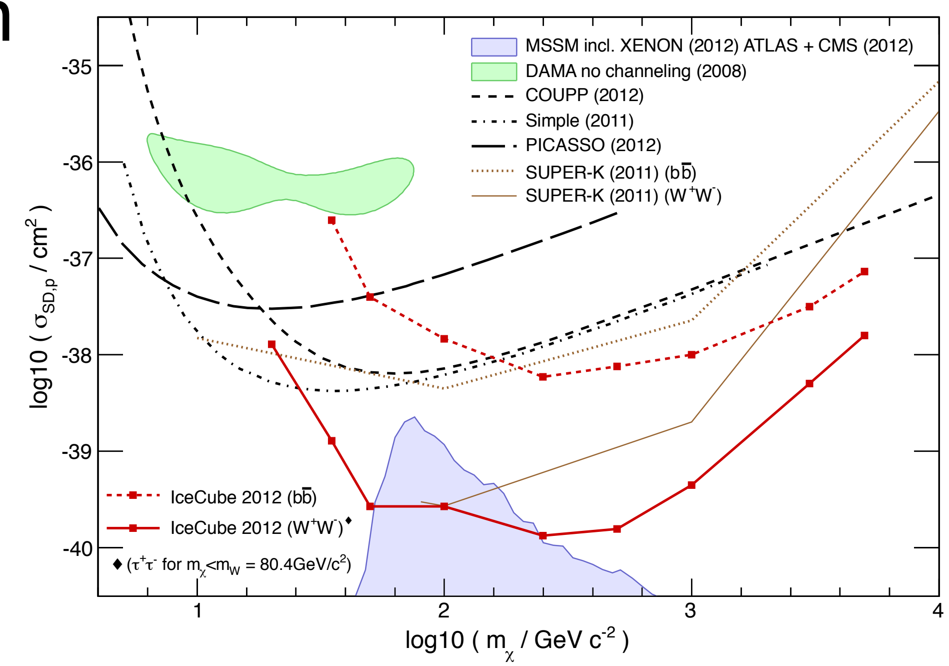


- No convincing signal so far, constraints getting strong 🙁



★ Indirect detection: nearly-at-rest annihilation

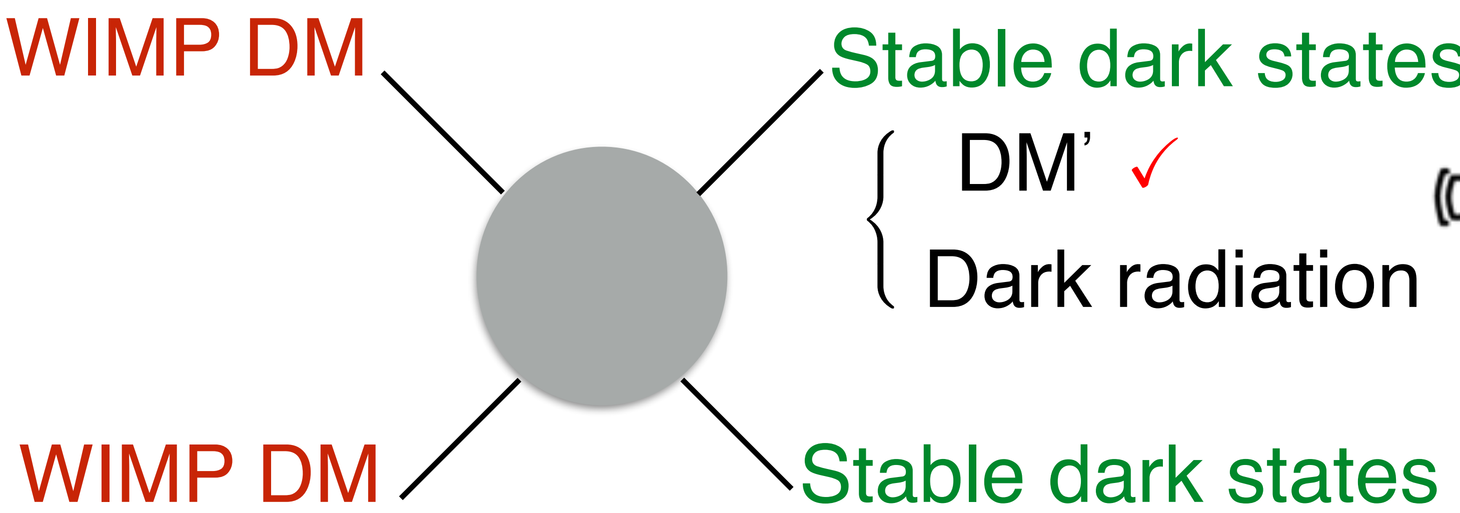
★ Direct detection: scattering w/small E_{recoil}



- Around the corner?
- Alternative? (axion…)
- Or…

Preserve WIMP DM Miracle
— New Realization?

Simple, generic variation:
(overlooked!)



Boosted DM'
(Vs. "slow" DM)
YC, w/Agashe, Necib,Thaler;
w/Berger and Zhao, 2014

- WIMP miracle intact: $\Omega_\chi \propto \langle \sigma_{\rm ann} v \rangle^{-1}$ insensitive to final states
- Conventional search signals: absent or suppressed
- DM': depleted, subdominant DM, $\Omega_{\rm DM'} < \Omega_{\rm DM}$
- Motivate non-minimal DM sector! (SM non-minimal! *p, e*⁻ …)

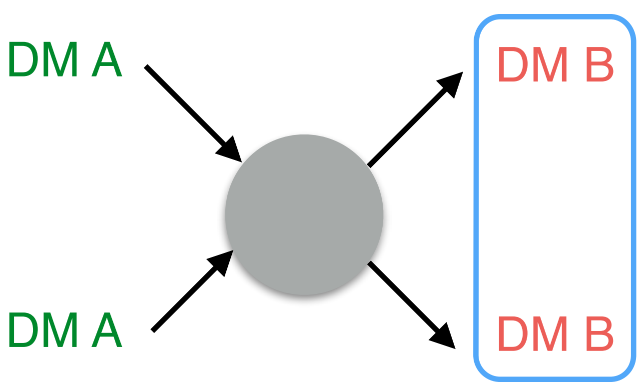
Boosted Dark Matter

- A generic phenomena in non-minimal DM sector preserving WIMP miracle

- **Novel possibility:** A small fraction of DM today is relativistic!
  (from late-time *non-thermal* processes)

  (vs. all DM today is cold)

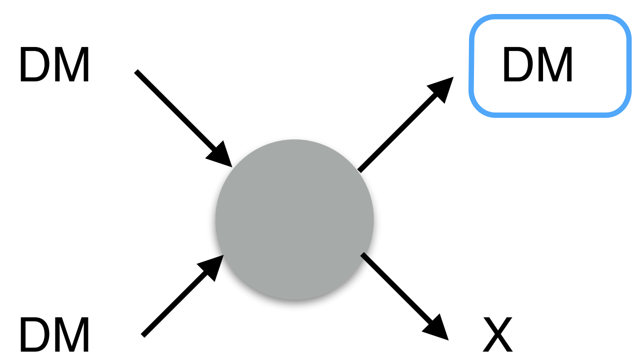
- **Motivations of Boosted DM: generic**



Two-component DM

$m_A > m_B,\ \Omega_A \approx \Omega_{\rm DM}$

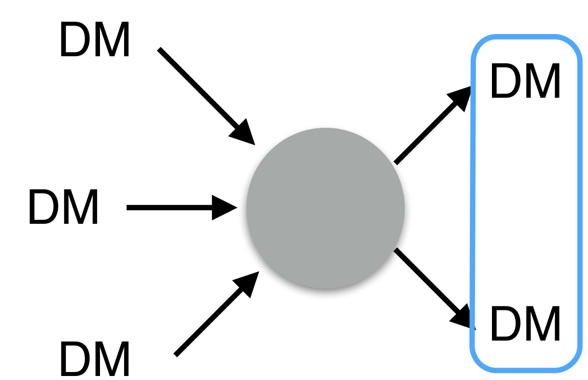
$\gamma_B = m_A/m_B$



$\mathbb{Z}_3$ Semi-annihilating DM

X can decay, $m_X < m_{\rm DM}$

$\gamma_{\rm DM} \approx 1.25$



Self-annihilating DM

$\gamma_{\rm DM} = 1.5$

- **Detection of Boosted DM:**
  - ✦ **Impact:** reveal novel/non-minimal nature of DM sector, can be the smoking-gun!
  - ✦ **Challenge:** conventional DM detections unsuitable, new strategies needed!

Detection Strategy for Boosted DM

— Some clues first

- **Where to look?** analogous to DM indirect detection…

Annihilation ~ n_χ^2 , Flux ~ $1/D^2$

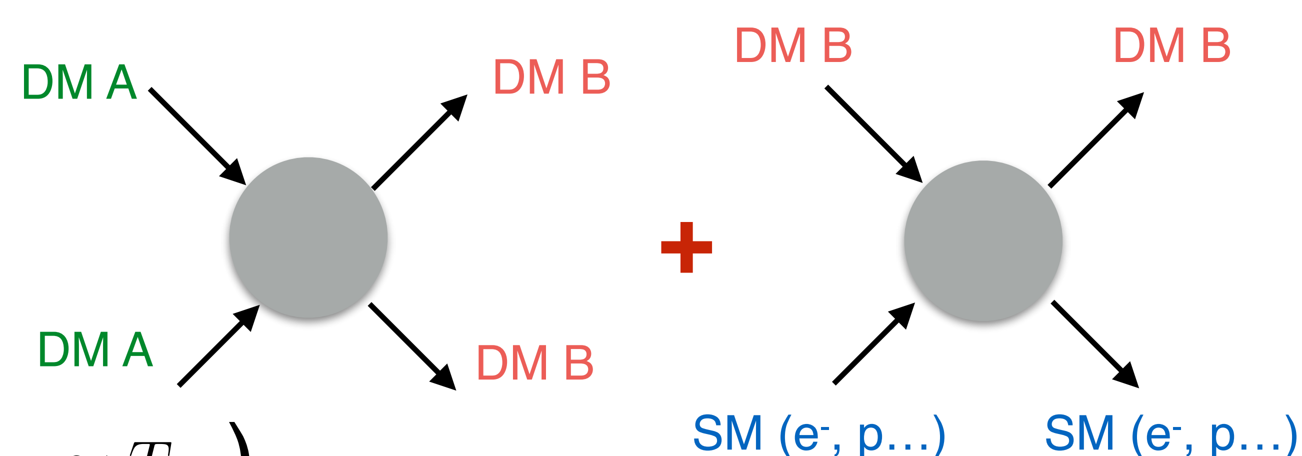
☞ DM concentrated, nearby sources

➡ From the Galactic Center, Sun (Sun: only if there is enough DM-p scattering/solar capture (accumulation))

- **Detectability?**

To preserve WIMP miracle,

☞ DM-SM kinetic equilibrium ($T_{\rm DM} \simeq T_{\rm SM}$) at DM freezeout ➡ $\sigma^{\rm scatt}_{bDM-SM} \neq 0$



➡ Detectability at terrestrial experiments today

Outline

- **Proofs of Principles:**

  Model examples, Detection prospect

  - Boosted DM from the GC (DM solar capture $\rightarrow$ 0, e^- signal)

    arxiv:1405.7370, JCAP, K.Agashe, YC, L.Necib and J.Thaler

  - Boosted DM from the Sun (DM solar capture $\neq$ 0, proton signal)

    arxiv:1410.2246, JCAP, J.Berger, YC and Y.Zhao

- **Conclusions/Outlook**

Scenario #1: Boosted DM from the GC

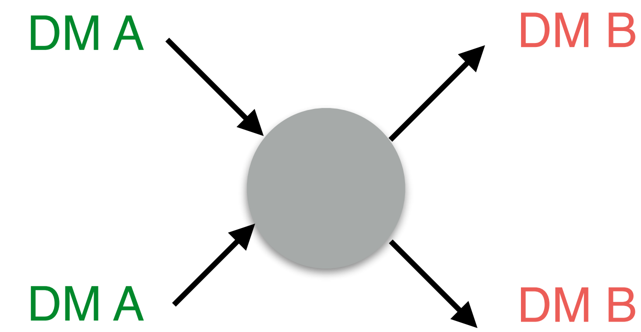
(In)direct Detection of Boosted Dark Matter

arxiv:1405.7370, JCAP, K.Agashe, YC, L.Necib and J.Thaler

Two Component DM Sector

Consider two species of DM: $\psi_A,\ \psi_B,\ m_A > m_B$

- ψ_A : dominant DM component,



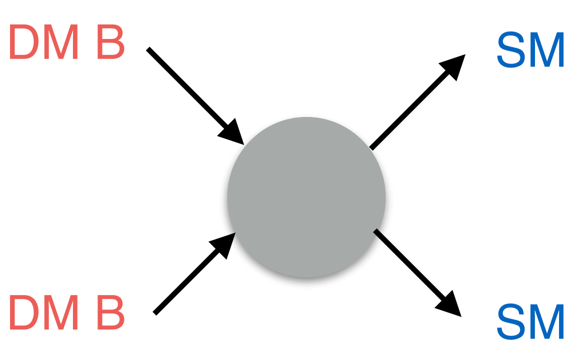
$\psi_A\overline{\psi}_A \to \psi_B\overline{\psi}_B$

Relic abundance $\Omega_{\rm DM} \approx \Omega_{\psi_{\rm A}}$

Boosted DM production today!

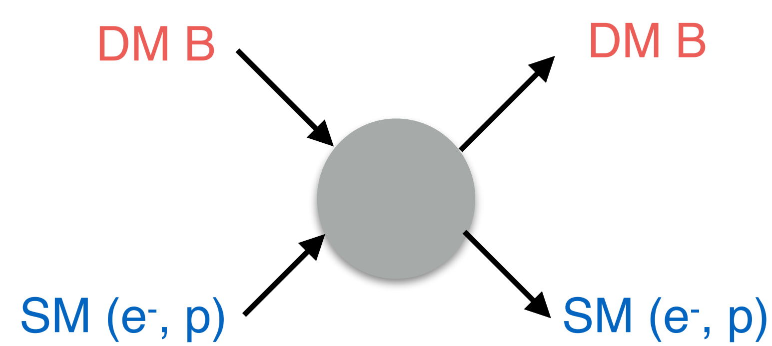
ψ_A : no direct coupling to the SM, $\sigma^{\rm scatt,ann}_{\psi_A-{\rm SM}} \to 0$ GC  , solar 

- ψ_B : subdominant DM component, $\Omega_B < \Omega_A$, $\sigma^{\rm scatt,ann}_{\psi_B-{\rm SM}}$ appreciable



Annihilation: deplete Ω_{ψ_B}

$\Omega_{\psi_B} \propto (G_{\psi_B})^{-2}$



$\sigma^{\rm scatt}_{\psi_B} \propto (G_{\psi_B})^2$

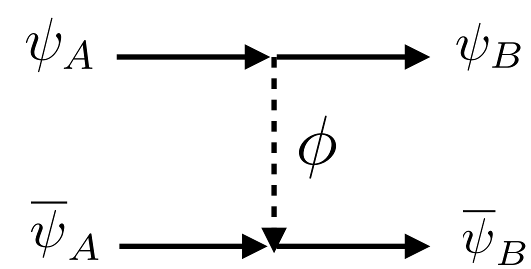
Scattering: ensure $T_{\rm DM} \simeq T_{\rm SM}$ at WIMP DM freeze out;
+ detectability of boosted DM today

A Concrete Model Example

Dirac fermion DM: $\psi_A,\ \psi_B,\ m_A > m_B$, stabilized by $\mathbb{Z}_2 \times \mathbb{Z}_2$

- Contact operator $\frac{1}{\Lambda^2}\overline{\psi}_A\psi_B\overline{\psi}_B\psi_A$

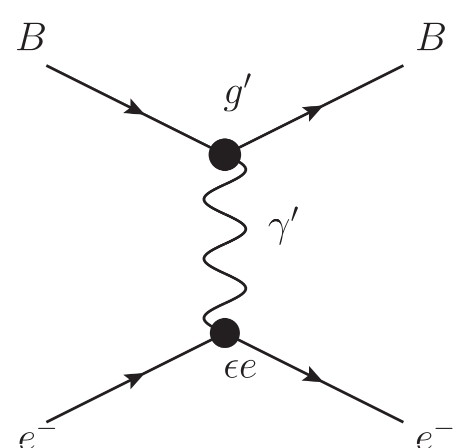
  ensure s-wave annihilation of ψ_A



- ψ_B charged under a broken dark $U(1)'$, dark photon γ'

  kinetic mixing with SM photon: $\mathcal{L} \supset -\frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$ New force!

➡ Neutral-current-type scattering off SM target X: $\psi_B X \to \psi_B X^{(\prime)}$



Model Parametrization

Model parameter space: $\{m_A, m_B, m_{\gamma'}, \Lambda, g', \epsilon\}$.

- Λ : adjusted to yield $\Omega_A \approx \Omega_{\rm DM}$
- g', ϵ : $\sigma_{\psi_B X \to \psi_B X^{(\prime)}}$ scales homogeneously with g', ϵ (trivial)
- Masses $m_A, m_B, m_{\gamma'}$: dominant factors for phenomenology

Observable signal (sufficient flux, $\sigma_{\psi_B X \to \psi_B X^{(\prime)}}$) + other constraints

Focus on low mass DM, with mass hierarchy $m_A > m_B > m_{\gamma'}$.

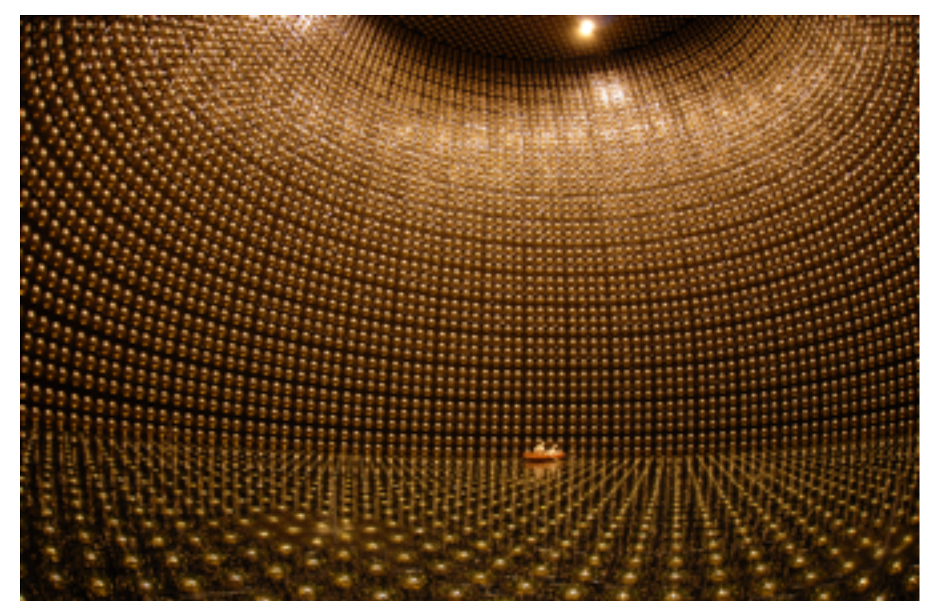
Benchmark points: $m_A \simeq \mathcal{O}(10~\text{GeV}), \quad m_B \simeq \mathcal{O}(100~\text{MeV}), \quad m_{\gamma'} \simeq \mathcal{O}(10~\text{MeV}).$

$g' \simeq O(0.1), \quad \epsilon \simeq O(10^{-3})$

General detection strategy

- A combination of conventional DM indirect and direct detections:

indirect | direct



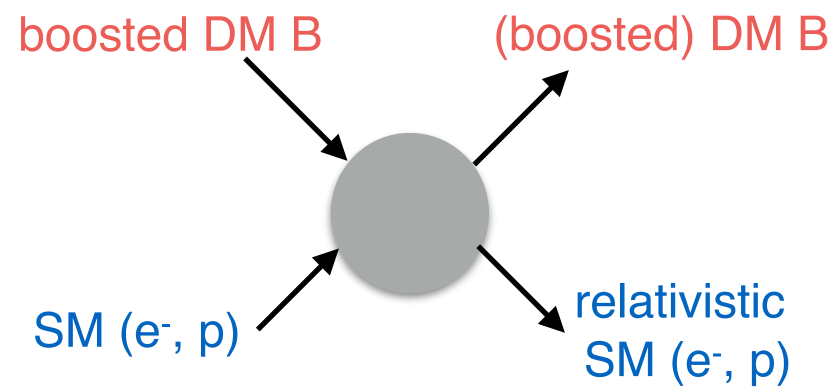
Detecting Boosted DM from the GC

- Mono-energetic flux ($E_B = m_A$) of boosted ψ_B from GC: very small!

$$\Phi_{\rm GC}^{10^\circ} = 1.6\times 10^{-8}\ {\rm cm^{-2}s^{-1}} \left(\frac{\langle \sigma_{A\bar{A}\to B\bar{B}} v\rangle}{5\times 10^{-26}\ {\rm cm^3/s}}\right)\left(\frac{20\ {\rm GeV}}{m_A}\right)^2 \ll \Phi_{\rm local}^{\rm therm} = 4.5\times 10^{5}\ {\rm cm^{-2}s^{-1}} \left(\frac{20\ {\rm GeV}}{m_{\rm DM}}\right)^2$$

- Boosted incoming ψ_B

→ relativistic outgoing e⁻, p



What experiment(s)?

Large volume detector + sensitive to energetic outgoing e⁻, p

(Conventional dark matter direct detection)

Existing experiments for neutrinos or proton decay!

✓ • Based on Cherenkov-radiation:

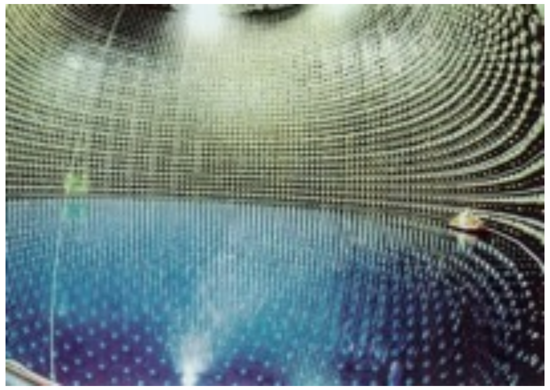
SuperK/HyperK, IceCube/PINGU(MICA)…

- **Based on ionization:** (future, planned)

LBNE, GLACIER… (liquid Argon/LArTpc)

IceCube

SuperK

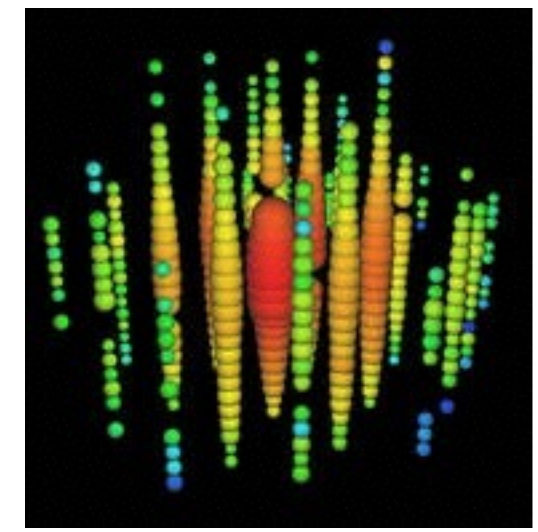


Detection Strategy at Neutrino Detectors

- Cherenkov threshold for charged particles:

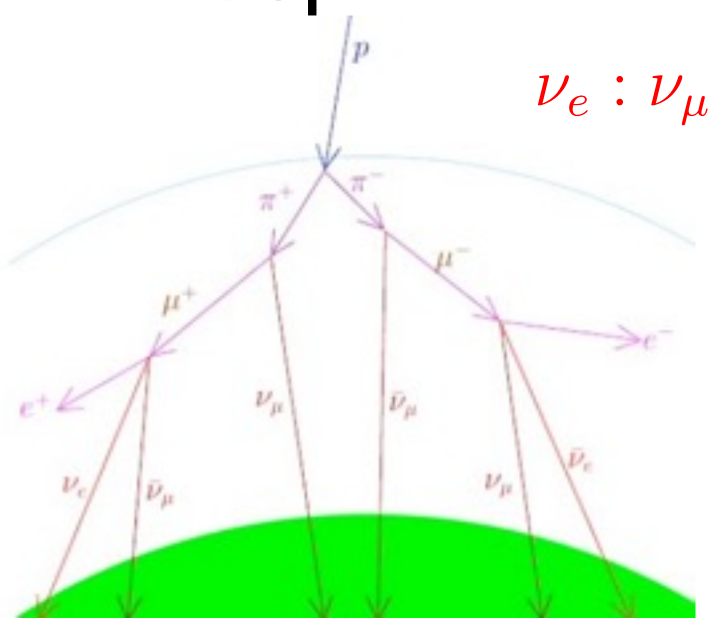
$$\text{Water: } \gamma_{\text{Cherenkov}} = 1.51, \qquad \text{Ice: } \gamma_{\text{Cherenkov}} = 1.55,$$

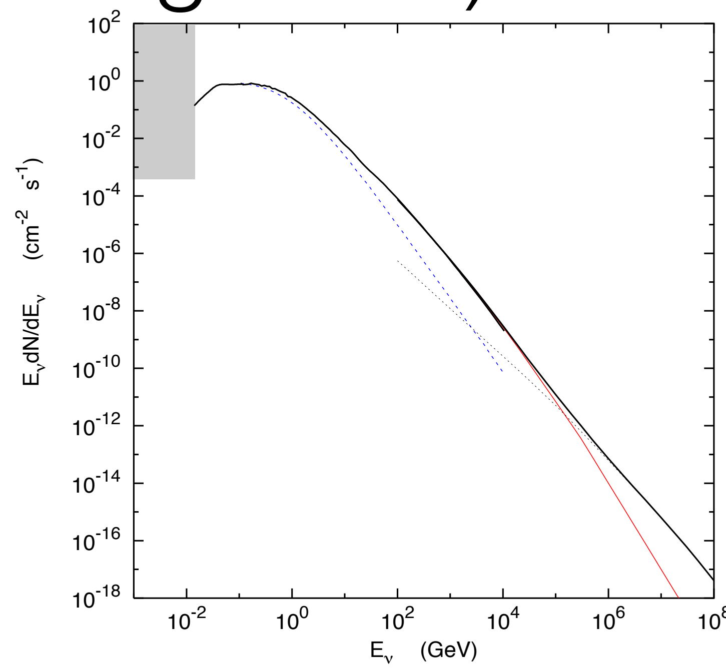
Cherenkov light at Icecube:



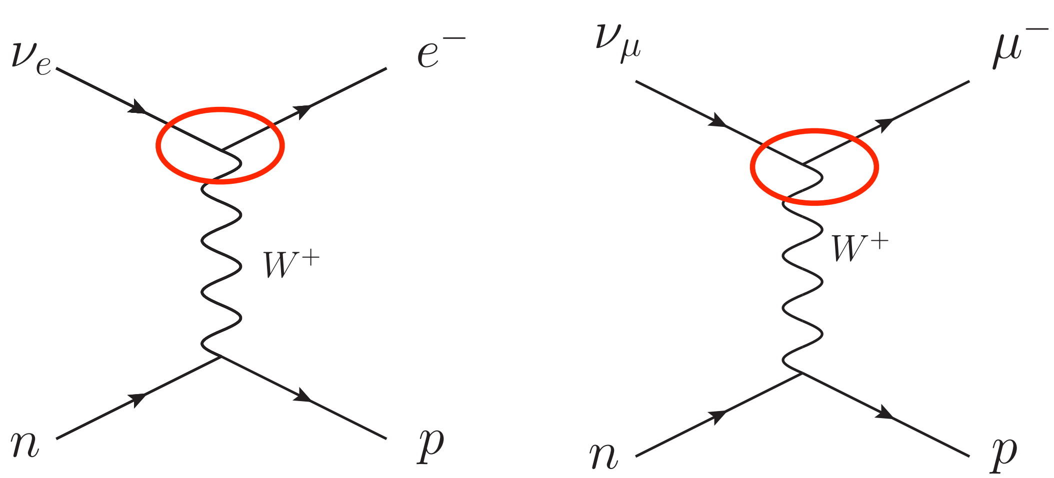
- Atmospheric neutrinos (background)

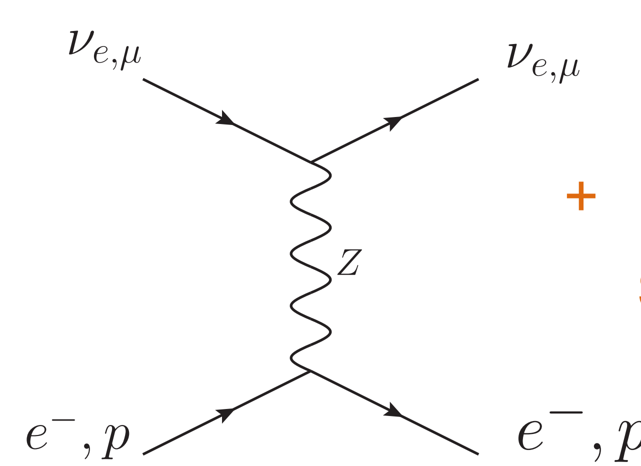
$\nu_e : \nu_\mu \sim 1 : 2$





- Detection of neutrinos:





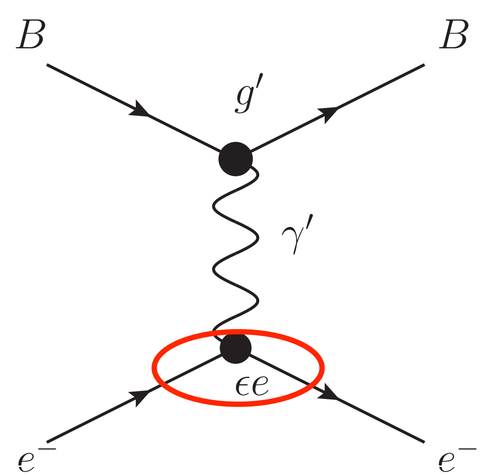
+ hadronic inelastic scattering

charged-current scattering

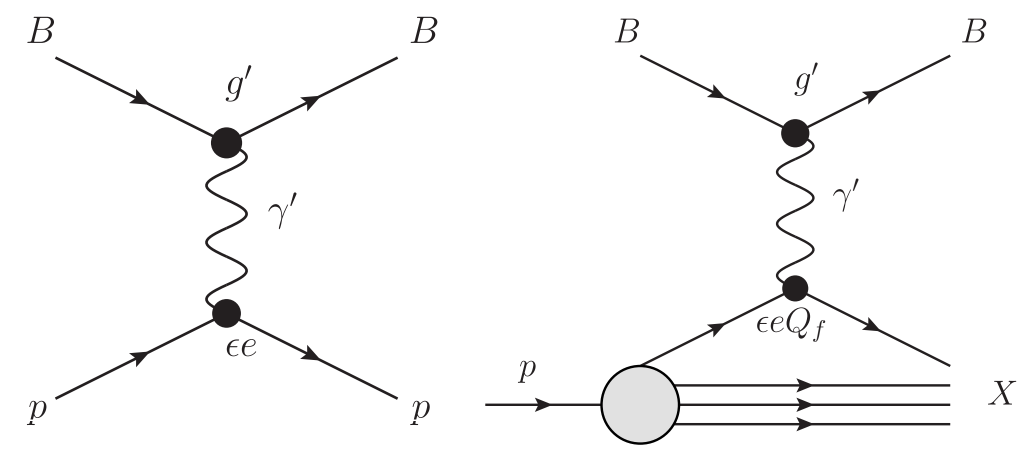
neutral-current scattering

Scattering Signal of Boosted DM

- Detection channels for boosted DM: neutral-current scattering only, no correlated μ^-



Leading channel : single e^-



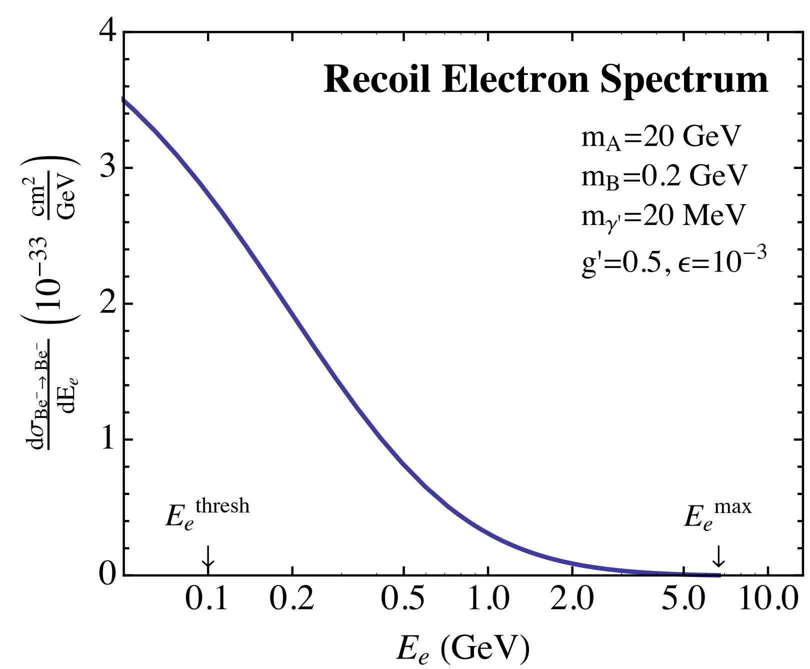
Subleading: hadronic channels

$m_p \gg m_e$, $E_p < E_{\rm Cherenkov}$ in light t-channel γ' models

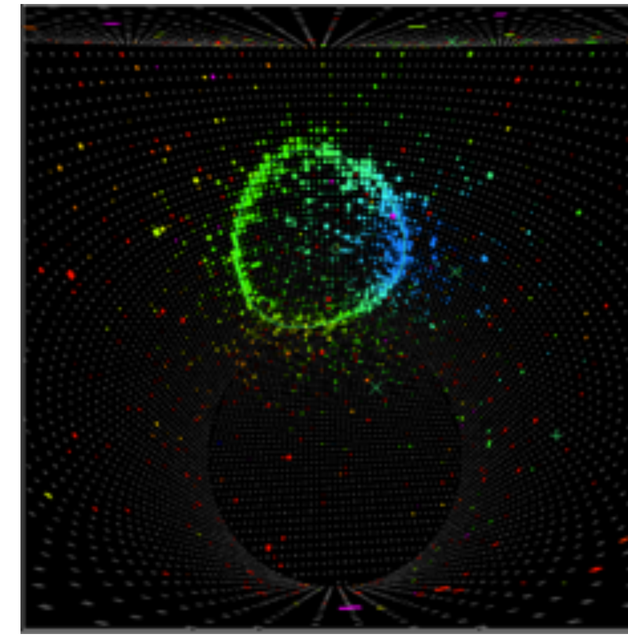
- Energy spectrum of e$^-$:

  peaks at low energy

  (t-channel light mediator γ')



Strategy for Background Rejection



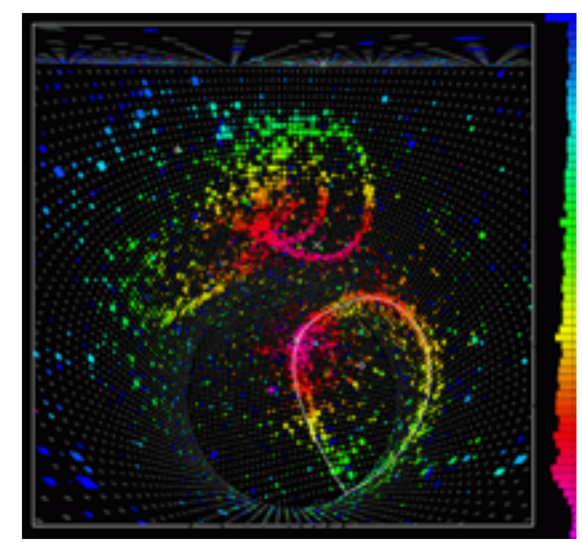
- Signal: single e[-] ;

  Background: $\nu_e n \rightarrow e^- p$, p undetected

Discriminate boosted DM signal Vs. neutrino bkg?

- Directional info.: boosted DM from GC vs. isotropic $\nu_{\rm atm}$
- Absence of correlated muon excess
- Multi-ring veto: $\nu_{\rm atm}$ (in)elastic scattering →

  e^-+other charged ($p,\pi^{\pm}$): multi-ring events



- Solar neutrino veto: $\nu_{\rm solar}$ dominates bkg at $\lesssim 20~{\rm MeV}$, impose energy cut

Candidate Experiments

- Parameters of candidate experiments:

	Experiment	Volume (MTon)	E_e^{thresh} (GeV)	θ_e^{res} (degree)
	Super-K	2.24×10^{-2}	0.01	3°
	Hyper-K	0.56	0.01	3°
	IceCube	10^3	100	30°
	PINGU	0.5	1	23°(at GeV scale)
(?)	MICA	5	0.01	30°(at 10 MeV scale)

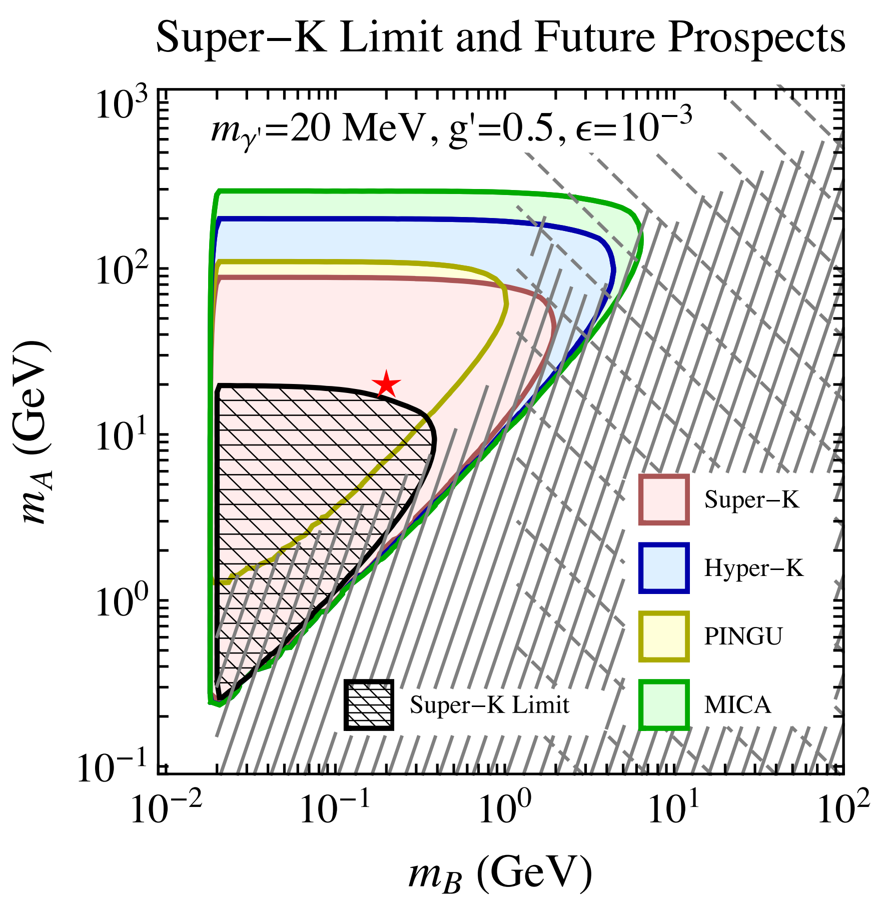
Signal favors: large volume, low $E_e^{\text{thresh}} \lesssim 1$ GeV, small θ_e^{res}

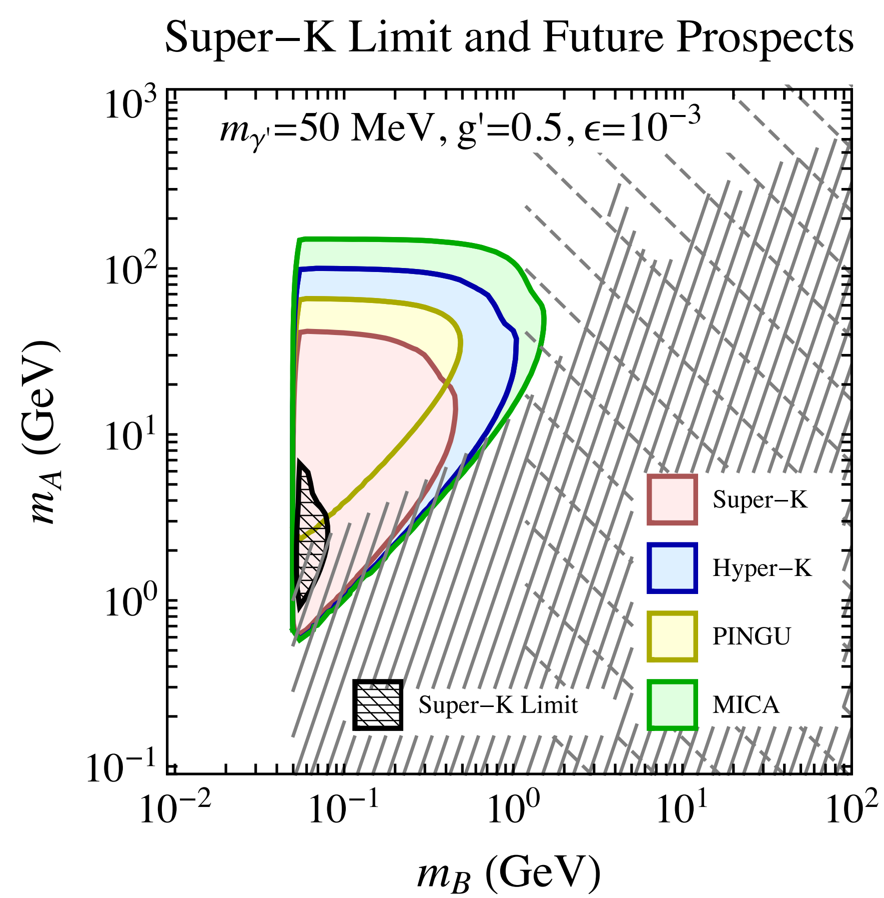
- Super-Kamiokande: 10.7 yrs data exist!

Can be used for estimating background, signal reach.

Results

- Model independent exclusion from Super-K all-sky data
- Signal sensitivity projections for various experiments





Model-dependent constraints (light grey lines✓):

- Dark photon search
- Direct detection of DM A, B ✓
- CMB heating/BBN from thermal B annihilation✓
- DM search at colliders

…

Re-purposed neutrino detectors sensitive to Boosted Dark Matter!

Scenario #2: Boosted DM from the Sun

Detecting Boosted Dark Matter from the Sun with Large Volume Neutrino Detectors

arxiv: 1410.2246, J.Berger, YC and Y.Zhao

Overview

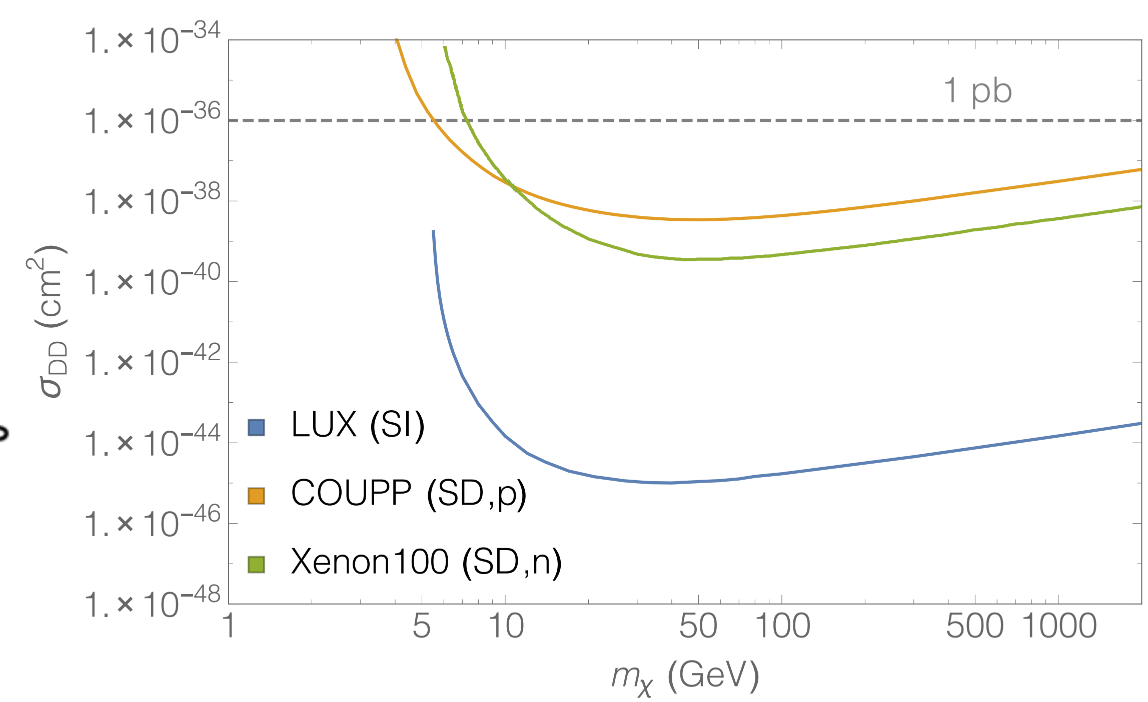
- **Motivation:** flux ~ 1/D², much larger from the Sun

➡ no need for very light mediator, $\sigma_{\rm weak}^{\rm scatt}$ enough (?)

➡ proton track: primary channel (Energy transfer efficient)

- **Challenges:** (vs. from the GC)
  - Dominant, annihilating DM needs appreciable $\sigma_{\chi,N}$ to be captured in the Sun…

Direct detection constraint? ☞



Spin-dependent (SD) bound much looser!

  - More processes involved:

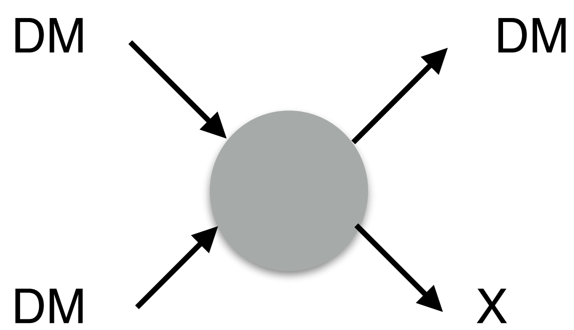
capture, re-scatter, annihilation, detection…

Models

- Consider 2 classes of models

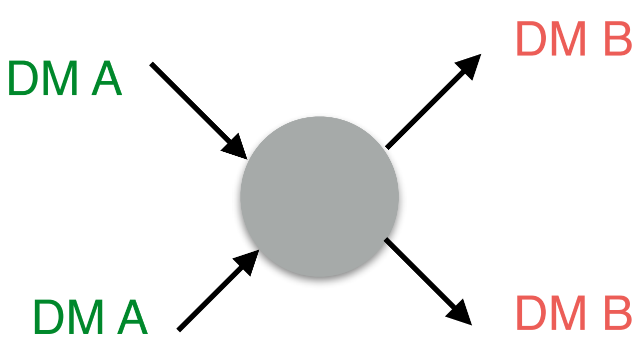
✦ Semi-annihilating DM:

$\sigma^{\rm scatt}_{\rm DM,N} \propto$ v^0 or v^2 in NR limit



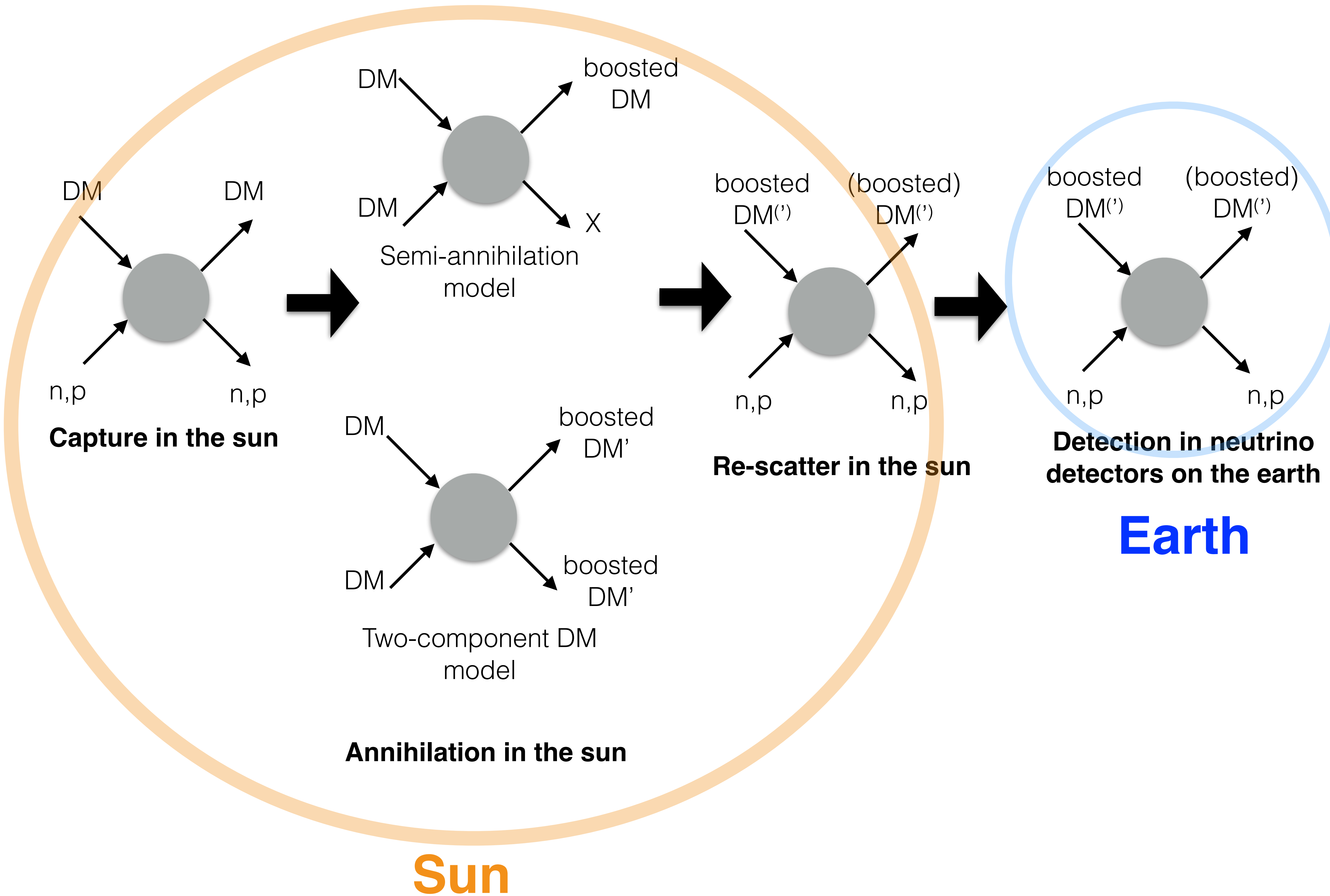
✦ Two component DM:

$\sigma^{\rm scatt}_{\rm DM,N} \propto$ v^0 only



- All cases: Assume SD interactions only

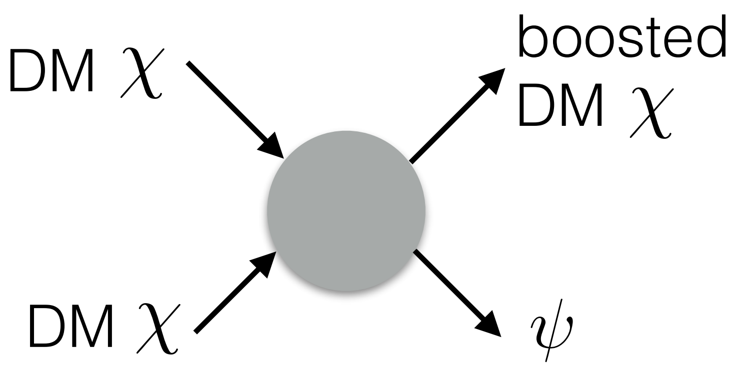
Processes involved



Semi-annihilation Models

- Simplest Example: Z_3 symmetric DM χ

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



naturally within preferred range of proton-channel detection (v ~ 0.5 -0.9)

- Focus on DM, neglect details of fourth particle ψ (assumed to be unstable)

Semi-annihilation Models #1

v^0 couplings

- Fermionic DM χ and lighter, auxiliary fermion ψ
- DM-N scattering mediated by Z' with axial coupling
- Annihilation to SM by Z' in p-wave: SA dominates

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

Semi-annihilation Models #2
v^2 couplings

- **Scalar** DM χ and auxiliary scalar ϕ
- DM-N scattering mediated by Z’ with axial coupling
- Annihilation to the SM by Z’ in p-wave: SA dominates

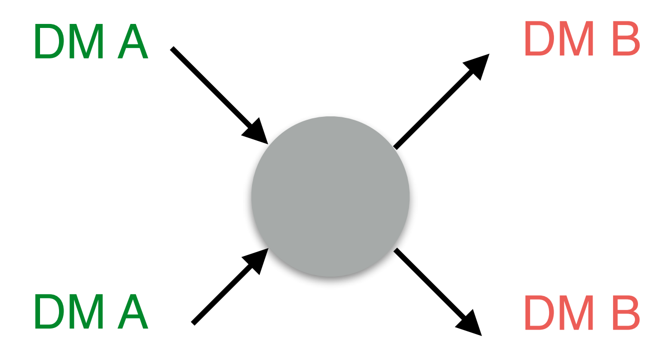
$$\mathcal{O}_{Z'} = \frac{1}{M^2}(\chi^\dagger \partial_\mu \chi - \partial_\mu \chi^\dagger \chi)\bar{q}\gamma^\mu \gamma^5 q \qquad \mathcal{O}_{\mathrm{SA}} = \lambda \chi^3 \phi$$

Two Component Models

Similar concepts as in the GC scenario:

Two species of DM: $\psi_A,\ \psi_B,\ m_A > m_B$, $\Omega_B < \Omega_A$

- ψ_A : $\psi_A \overline{\psi}_A \to \psi_B \overline{\psi}_B$
  - $\Omega_{\rm DM} \approx \Omega_{\psi_{\rm A}}$
  - Boosted DM production today



ψ_A : appreciable coupling to the SM now!

- ψ_B : subdominant DM component, $\sigma_{B,N} > \sigma_{A,N}$

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

preferred range for detection in proton-channel: $m_A/m_B \sim 1.1\text{-}2.2$

- **More moving parts** (vs. SA models), **but more flexibility**

Two Component Details

- Fermionic Majorana DM ψ_A and ψ_B
- 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

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

NR scattering cross-section: Exchange suppression (mediator) scale & couplings

— Relate to capture, re-scattering, detection

- SA model parameterized by: m_χ, σ_{DD}, ($m_{Z'}$)
- Two-component model by: m_A, m_B/m_A, σ_A, σ_B/σ_A, ($m_{Z'}/m_A$)

Flux of Boosted DM from the Sun

(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 Annihilation

DM annihilation determined by equilibrium

$$AN^2 = C - EN$$

- Assuming annihilation (AN^2) ~ pb, $t_{\odot} \gg \tau_{eq}$
- DM evaporation (E): Elastic up-scattering by tail of hydrogen velocity distribution, negligible for $m_\chi > 5$ GeV

➡ $AN^2 = C$

DM Re-scattering

- DM can lose energy escaping from the Sun

  mean free path: $\ell = \dfrac{1}{\sigma_{\chi,p} n_H}$

- Calculate detection rate using the mean energy at the exit of the Sun, $\langle E_\chi \rangle$

Towards Signal Rates

- Putting things together

➡ Flux of boosted DM from the Sun:

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

- Signal rate at detectors:

$$N_{\mathrm{sig}} = \Phi \cdot \Sigma(\langle E_\chi \rangle) \cdot \Delta t$$

$\Sigma(\langle E_\chi \rangle)$: effective detection cross-section

Detection Strategies

- Primary channel: proton track (e⁻: very light mediator)
- Ideal candidate for now: Super-Kamiokande

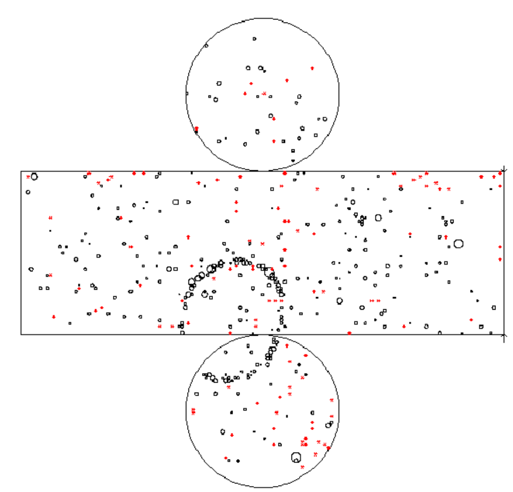
  Future candidates: Hyper-K, LAr-TPC(LBNE) (ionization)

✦ Proton Cherenkov momentum $p > 1.07$ GeV

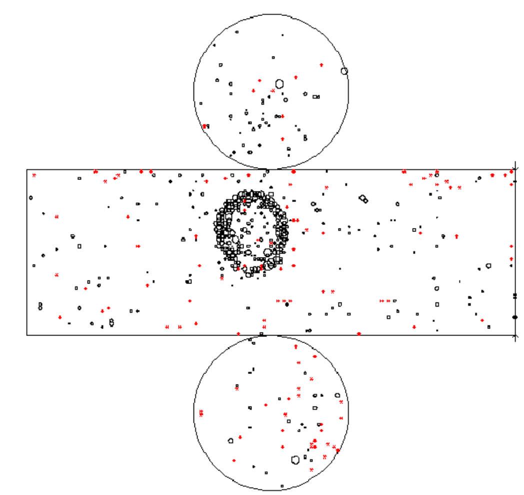
As $m_\chi \to \infty$, $v > 0.45$ required

✦ Single ring elastic scattering ⟶ $p \lesssim 2$ GeV

For $v > 0.63$, lose some signal



proton event at Super-K

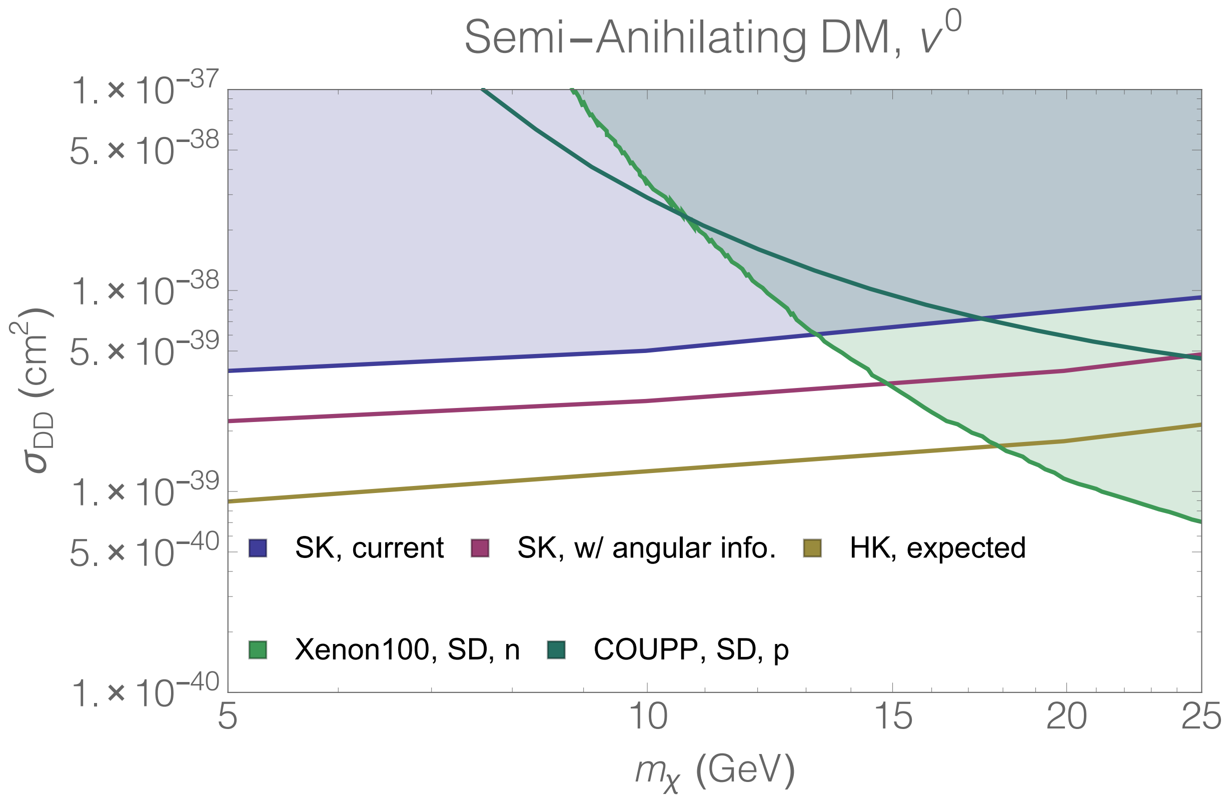


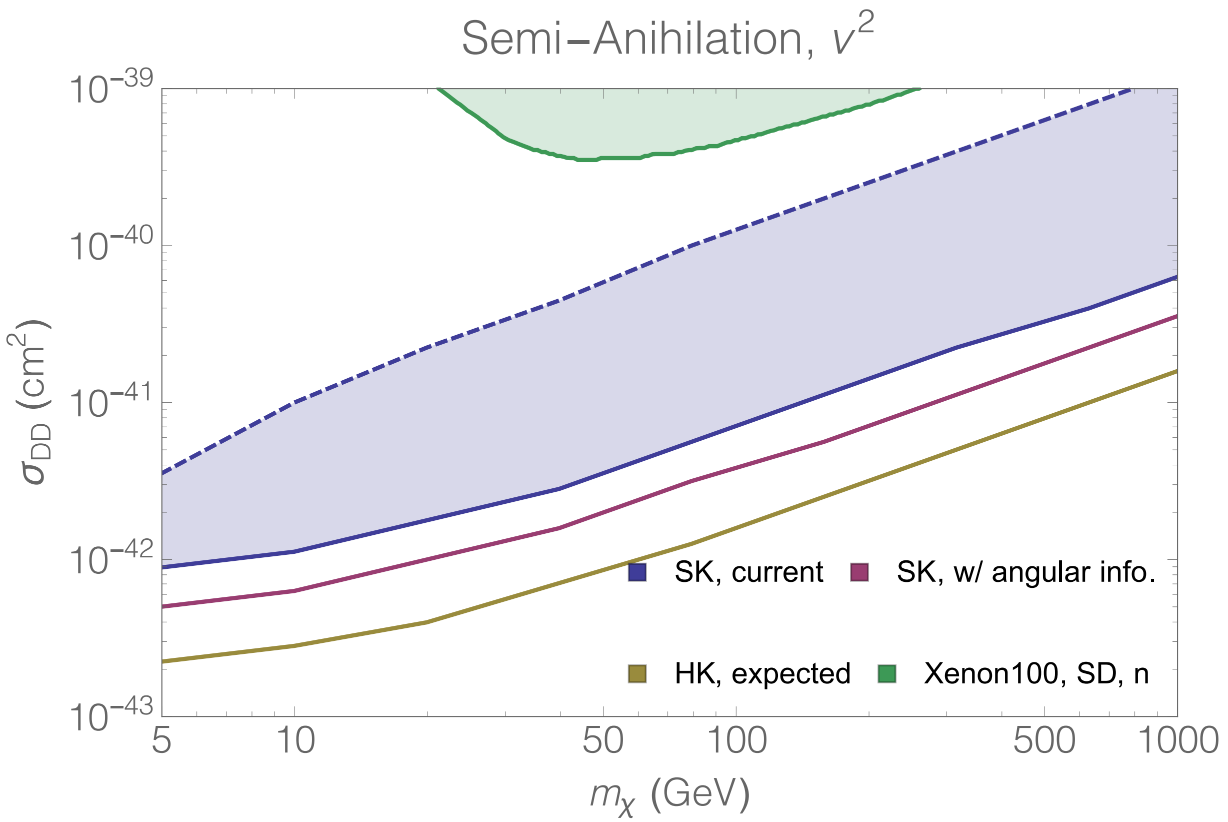
muon event at Super-K

Background Reduction

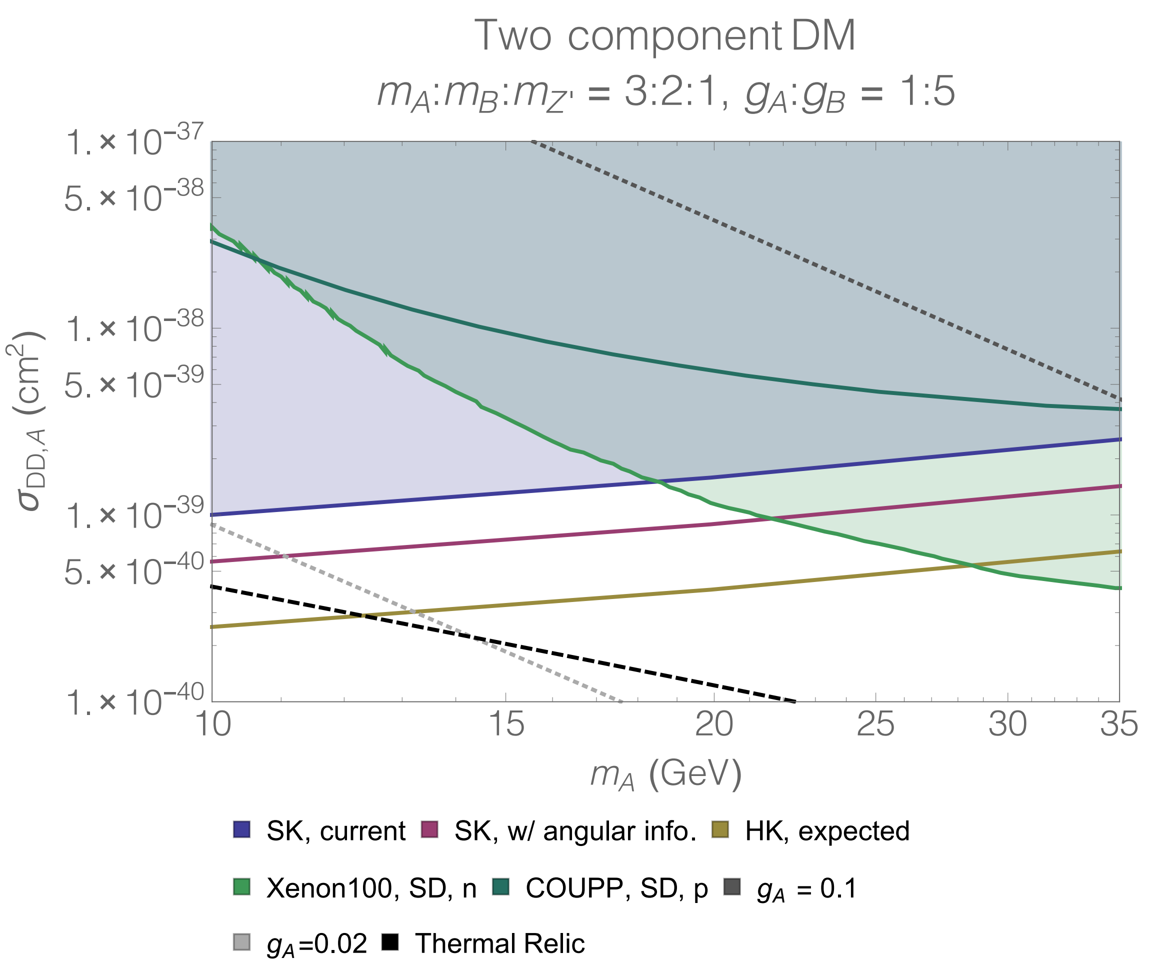
- Directional information:
  - Signal: protons recoil within $\theta \sim 40^\circ$ of the sun
  - Background: nearly isotropic ν_{atm}
- Signal: No correlated charged-current signal
  - Muon veto

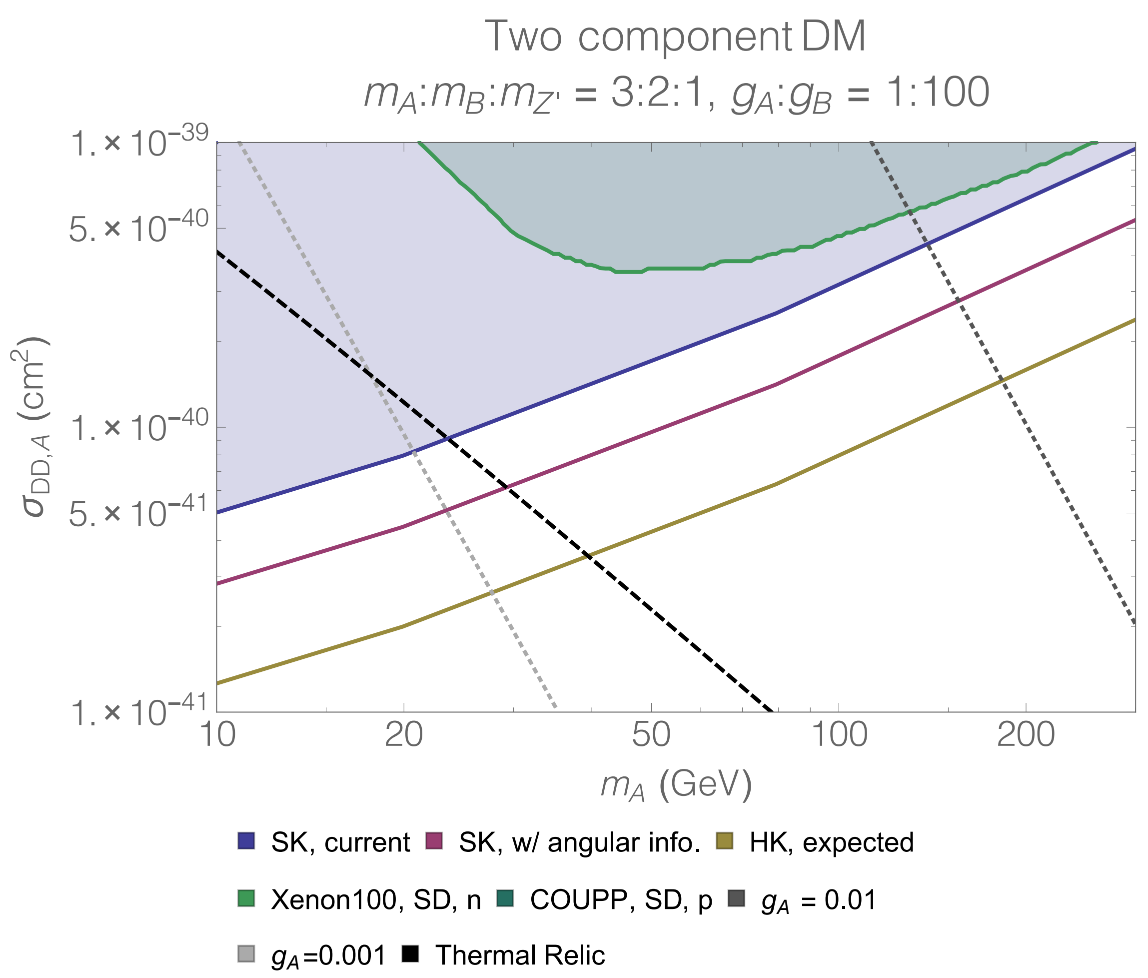
Results: SA DM Model





Results: Two Component DM





Conclusions/Outlook

- **New realization of WIMP DM paradigm**:
  - ✦ Naturally evade existing tight constraints ✓
  - ✦ Preserve thermal relic abundance " WIMP miracle" ✓

☞ Non-minimal DM sector → new pheno/search strategies

- **Boosted DM**: generically motivated, novel signals; large V neutrino detectors re-purposed

- **Other possibilities to explore:**
  - Boosted DM at future ionization-based neutrino detectors
  - Effects of subdominant self-interacting DM on halo structure (partially-interacting DM…)
  - WIMP DM annihilate to dark radiation: cosmological signals at CMB (Chacko, YC, Hong, Okui, *to appear soon*)

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