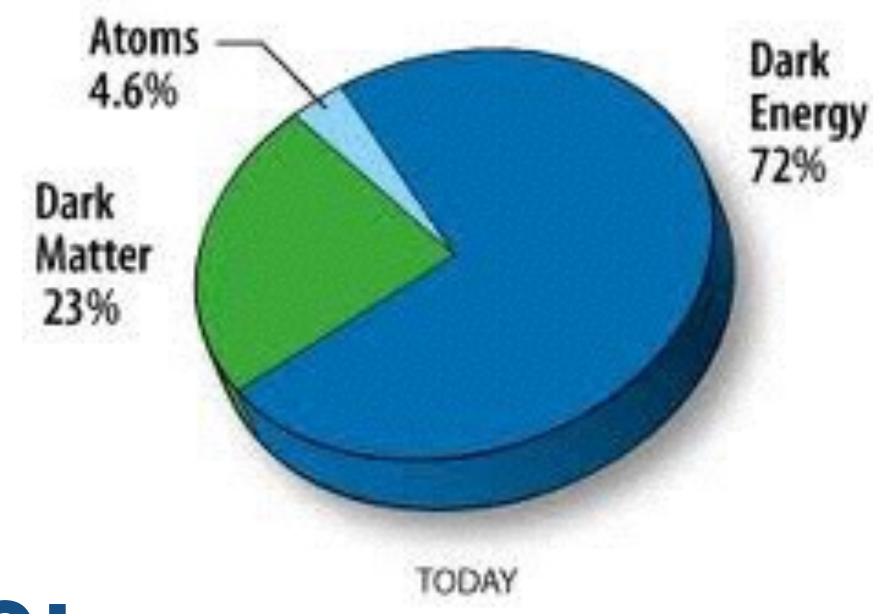
Status of Dark Matter Theories

Yanou Cui

Perimeter Institute for Theoretical Physics

CAP congress
Jun 15, 2015

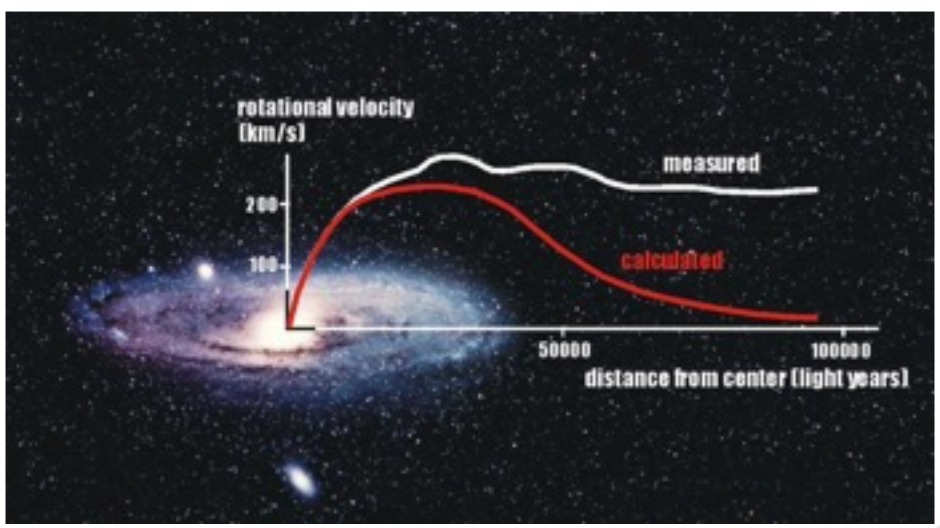
Dark Matter $\Omega_{\mathrm{DM}} \approx 23\%$
—The Known Unknown

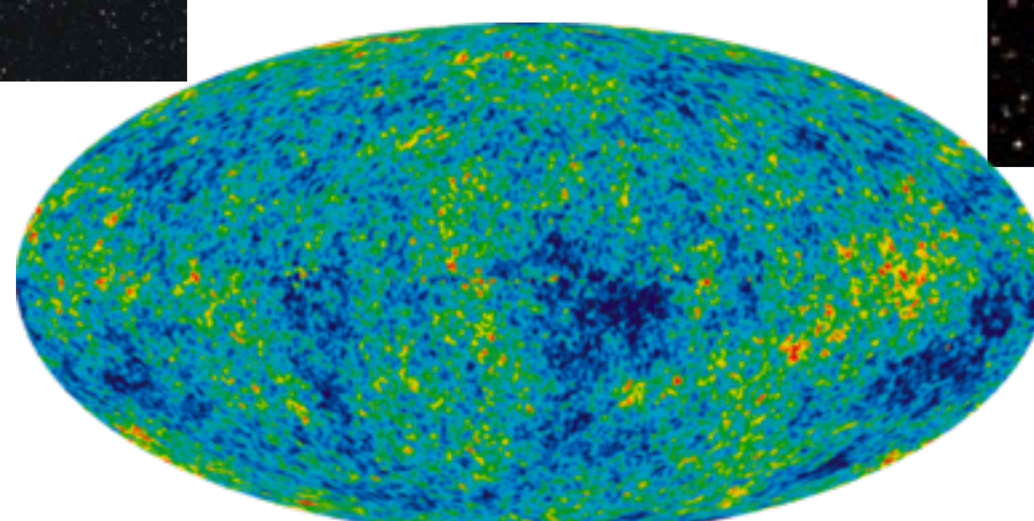


- **Dark Matter:**

  85% of cosmic matter abundance!

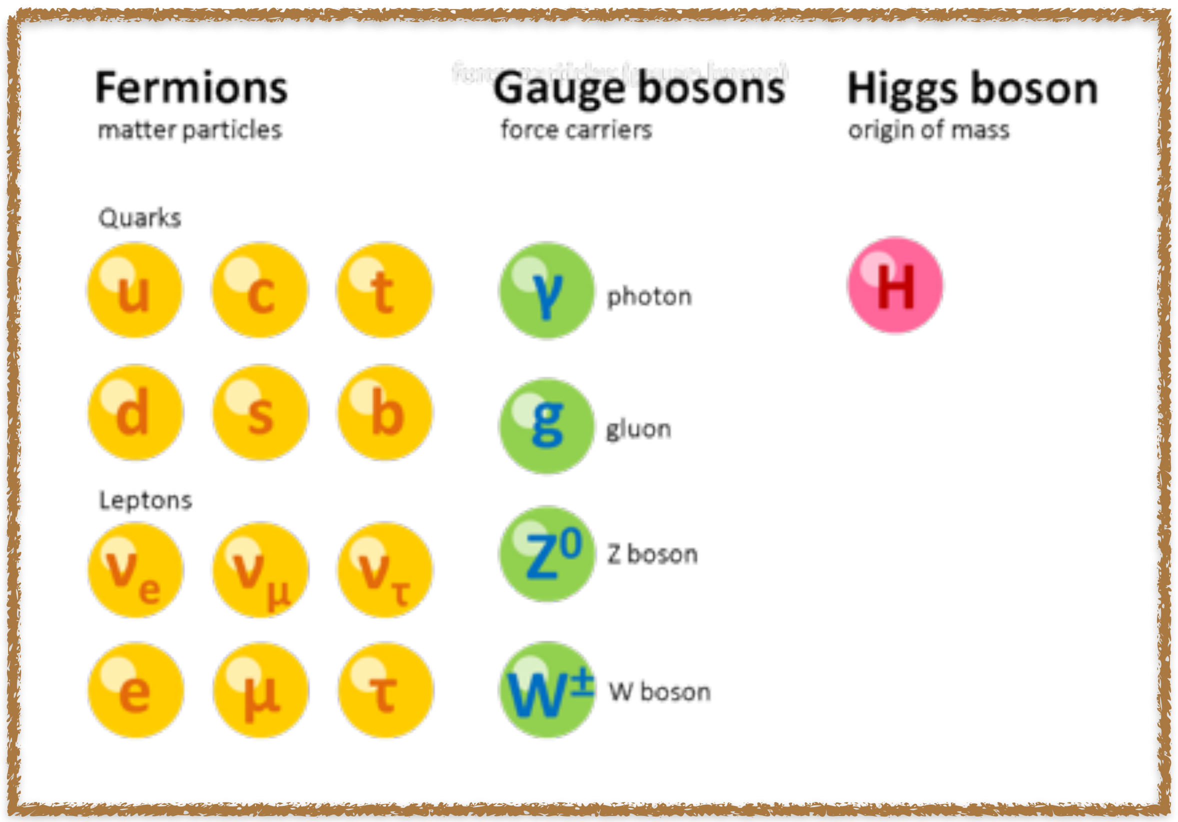
Compelling evidence:





Dark Matter $\Omega_{\rm DM} \approx 23\%$
—The Known Unknown

- **What is it? Where does Ω_{DM} come from?**



The Standard Model (SM)

Dark Matter

- Beyond the Standard Model of Particle Physics!

  ➡ New Physics !?

Towards Resolving the Mystery
— What is dark matter?

- Clues about dark matter properties: very limited
  - Must be stable ($\tau \gtrsim \tau_{universe}$)
  - Must be produced in the early universe
  - Must form cosmological structures consistent with astronomical observations: favors cold, collisionless DM, weakly interacting with the visible matter
  - Must render observed relic abundance: $\Omega_{DM} \approx 23\%$

Mass? Non-gravitational interactions?

Minimal, single particle specie or as complex as our visible matter sector?…?

Deductive approach insufficient for resolving this big mystery!

Towards Resolving the Mystery
— What can dark matter be?

- Need additional inspiration/motivation as guideline, to nail down concrete theoretical models for investigations:
  - **Theoretical:** DM candidates connect to/solve other theoretical problems, philosophical appeals

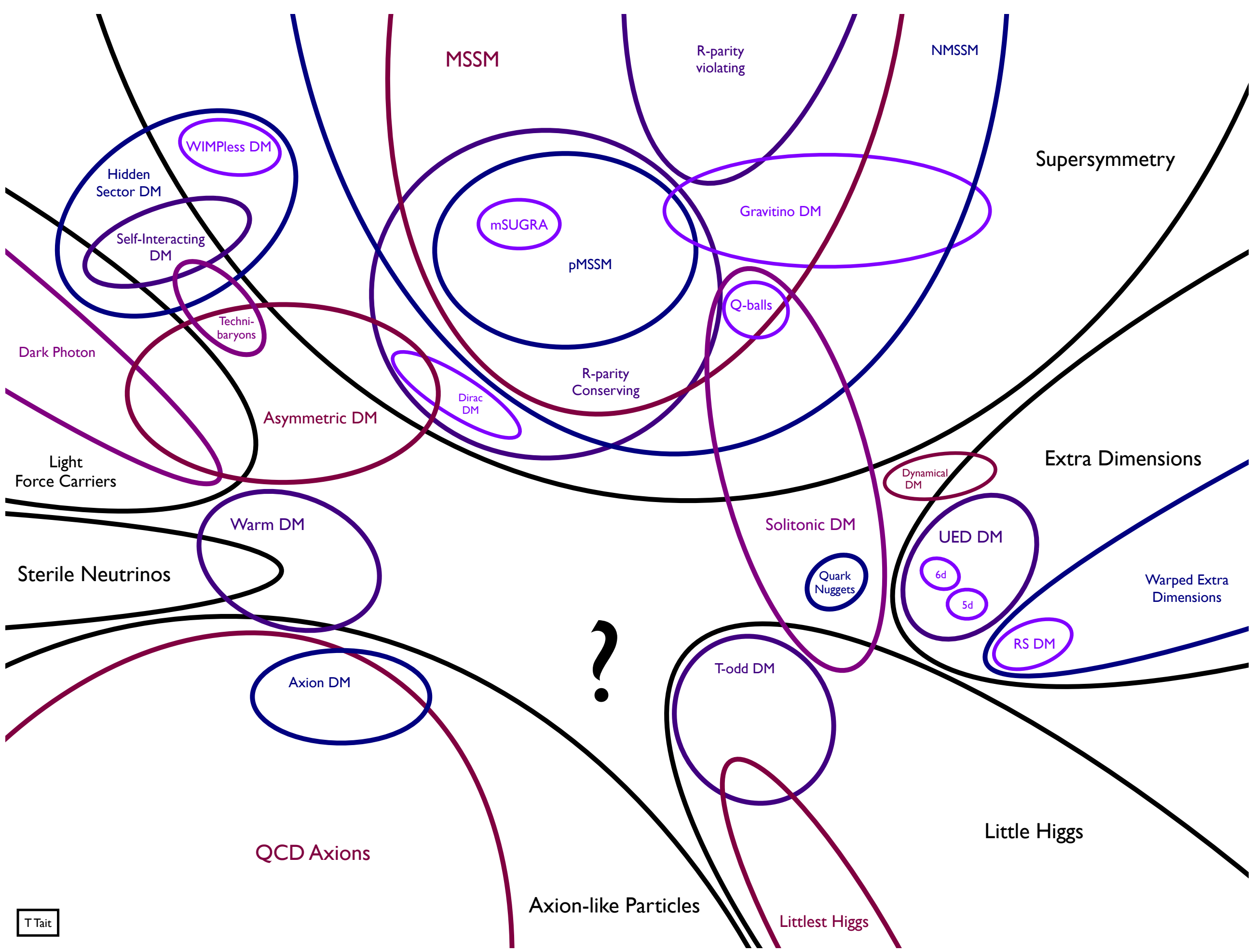
    E.g. electroweak hierarchy problem (WIMP DM); strong CP problem (axion DM), WIMP miracle for Ω_{DM}
  - **Observational:** experimental data that may be explained by certain type of DM

    E.g. cosmic ray excess unexplained by astrophysical sources (annihilating or decaying DM), $\Omega_{DM} \sim \Omega_{Baryon}$ (asymmetric DM)
- Educated guesses/hypothesis ⟶ testable predictions

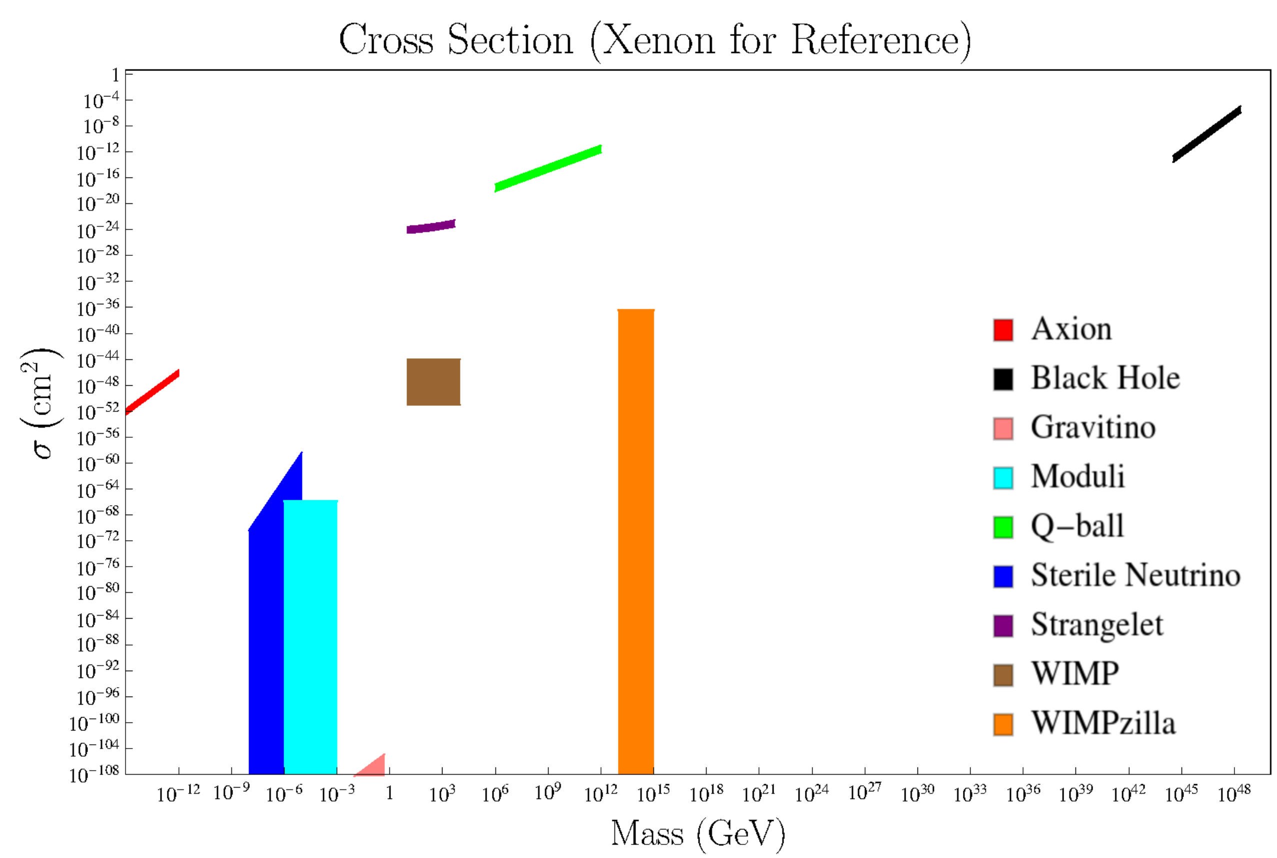
  ⟶ experimental test/search ⟶ resolve the mystery

Vast Landscape of Theoretical Candidates for Dark Matter

Proposed DM models:



Ranges of mass, interaction strength with visible matter



Classification of Dark Matter Candidates

- **Thermal dark matter:** once in thermal equilibrium in the early universe (with visible matter OR own sector)

☞ Appreciable non-gravitational interaction(s)

  - Symmetric WIMP-type DM: Ω_{DM} set by thermal freezeout

    Conventional WIMP, variations

  - Asymmetric DM: Ω_{DM} set by initial matter-antimatter asymmetry, analogous to Ω_{baryon}

- **Non-thermal dark matter:** never in a thermal bath *(lone wolf!)*

☞ Super-weak or gravitational interactions

  - Axion DM
  - Sterile neutrino, SuperWIMP (produced from late decay) …

★ **Complex DM sector:** multiple-component? self-interactions?…

Classification of Dark Matter Candidates

- **Thermal dark matter:** once in thermal equilibrium in the early universe (with visible matter OR own sector)

☞ Appreciable non-gravitational interaction(s)

✓ ‣ Symmetric WIMP-type DM: Ω_{DM} set by thermal freezeout

Conventional WIMP, variations

✓ ‣ Asymmetric DM: Ω_{DM} set by initial matter-antimatter asymmetry, analogous to Ω_{baryon}

- **Non-thermal dark matter:** never in a thermal bath *(lone wolf!)*

☞ Super-weak or gravitational interactions

✓ ‣ Axion DM

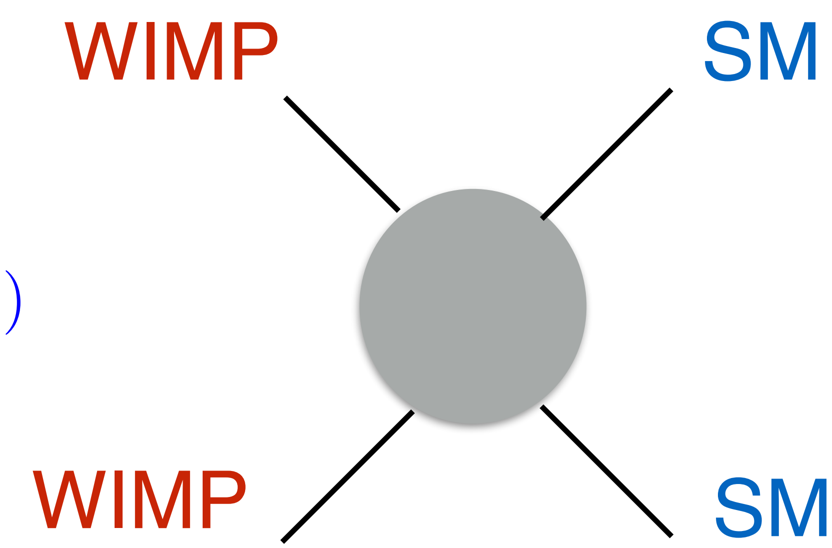
‣ Sterile neutrino, SuperWIMP (produced from late decay) …

✓★ **Complex DM sector:** multiple-component? self-interactions?…

(Conventional) WIMP Dark Matter

WIMP: Weakly Interacting Massive Particle

$m_{\rm WIMP} \sim 100~{\rm GeV}~(\sim G_{\rm Fermi}^{-1/2})$



$\sigma_{\rm WIMP} \propto G_{\rm Fermi}^2$

- Naturally expected new particle at new energy frontier of particle physics (Large Hadron Collider)!

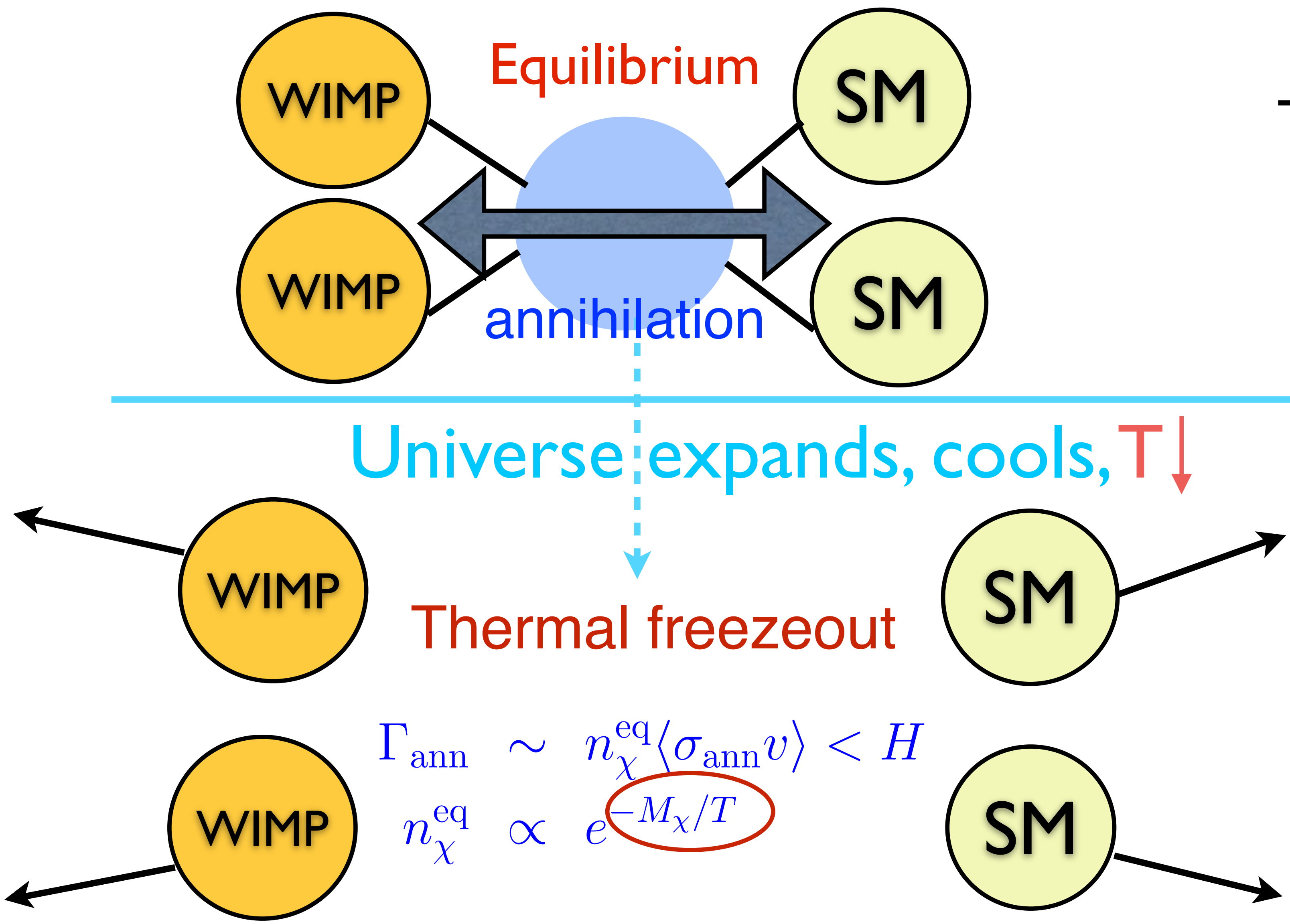
  Motivated candidates by EW naturalness/hierarchy problem

- **Could it be Dark Matter?** 

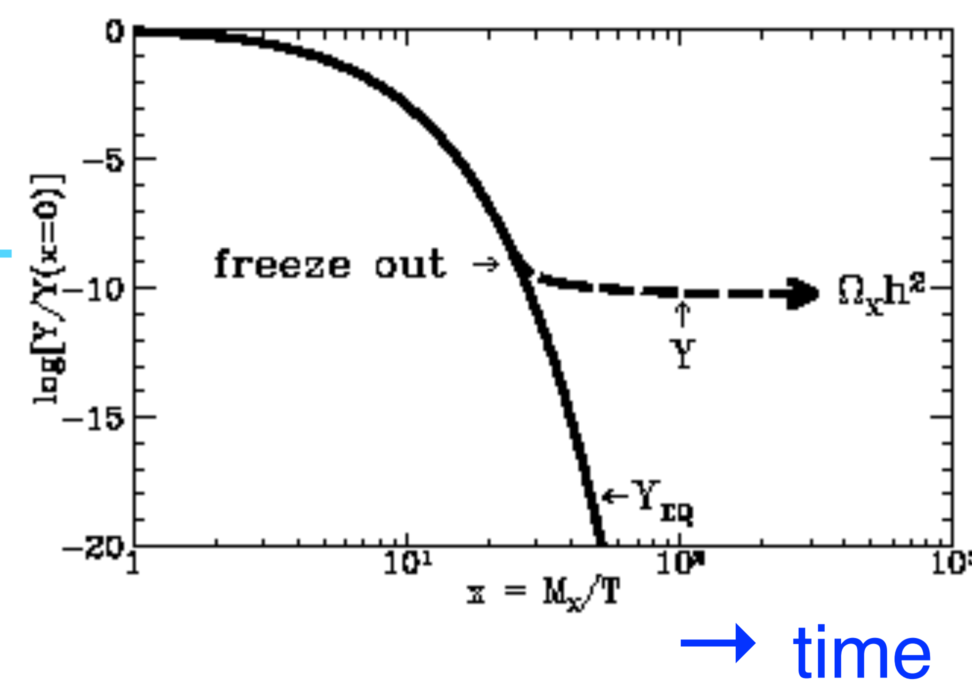
(Conventional) WIMP Miracle DM

— Ω_{DM} by weak scale new physics

- Cosmic Evolution of a stable WIMP χ :



Time evolution of χ abundance:



WIMP DM **Miracle**

- Neat prediction for the <u>absolute</u> amount of Ω_{DM} :

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

With $m_\chi \sim M_{\rm weak},\; G_\chi \sim G_{\rm Fermi}$, readily gives $\Omega_{\rm DM} \approx 23\%$!

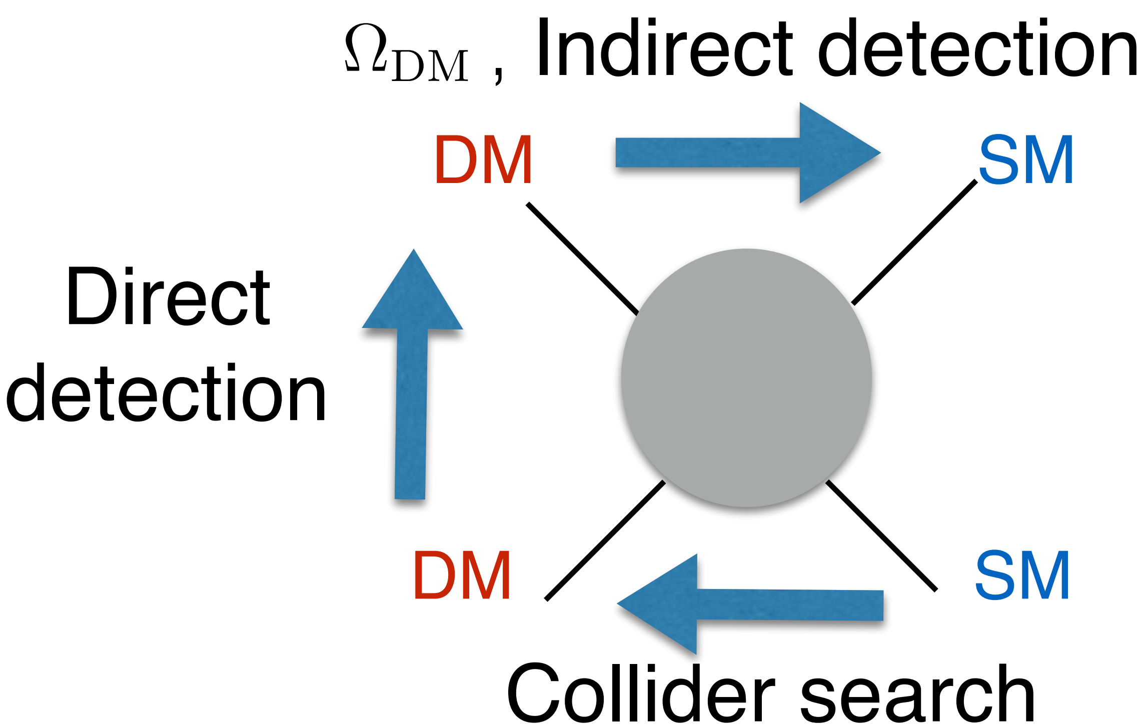
- Robust, insensitive to cosmic initial condition
- **Miracle:** Predicts the right location of <u>a needle in a haystack</u>!

Observed
$\Omega_{\rm DM} \approx 23\%$

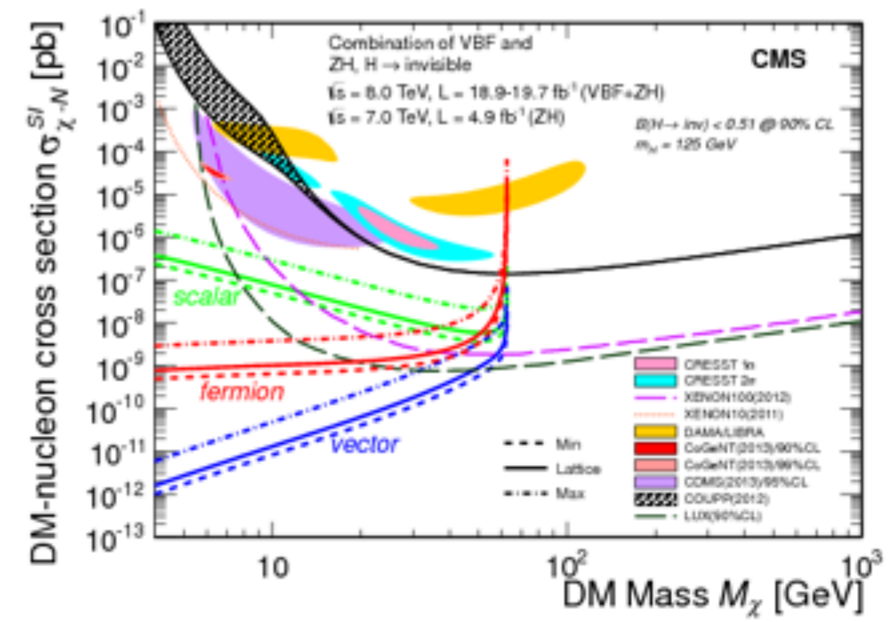
Vast possible range of a cosmological quantity: e.g. $\Omega_{\rm DM}^{\rm theory} \sim (10^{-7} - 10^{35})$

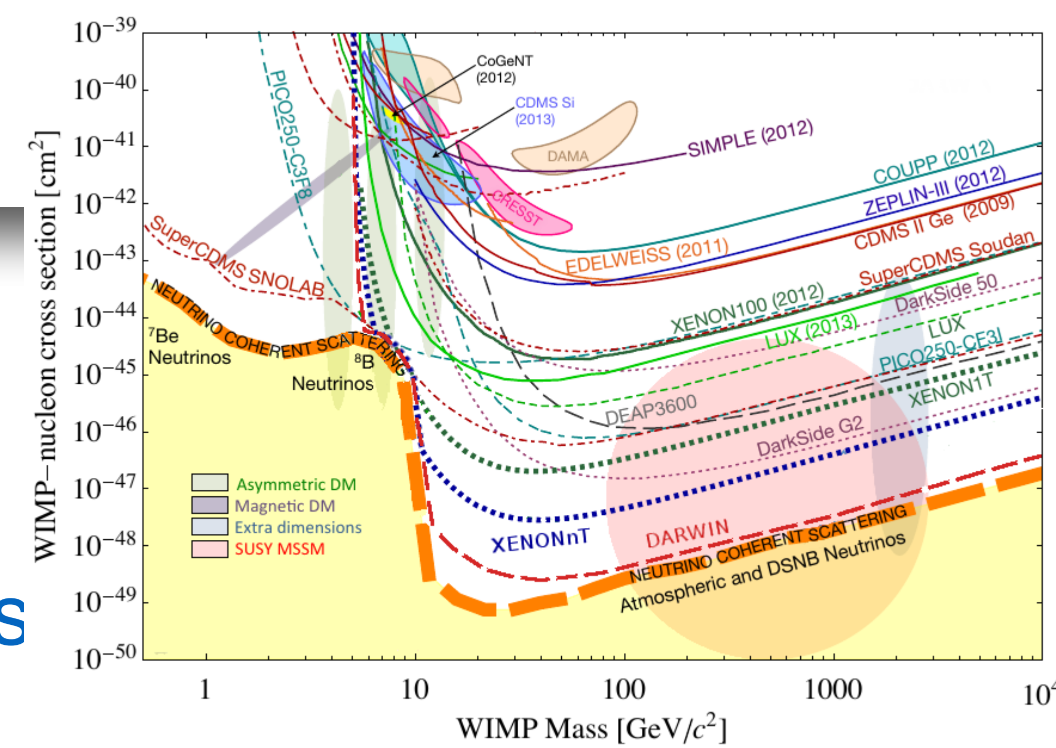
Detectability, Challenges of WIMP DM

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



- No convincing signal so far, constraints getting strong





- Could be right at the corner…
- Simple, natural variations?
  - Light thermal DM ($m_{\rm DM} \lesssim O$(GeV))
  - Thermal annihilation into dark states

Light Thermal Dark Matter

- **Motivations:**
  - Thermal DM doesn't have to be M_{weak}~100 GeV

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

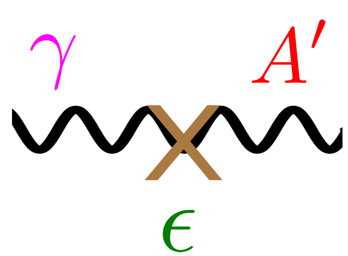
☞ weaker coupling, lighter mass ✓

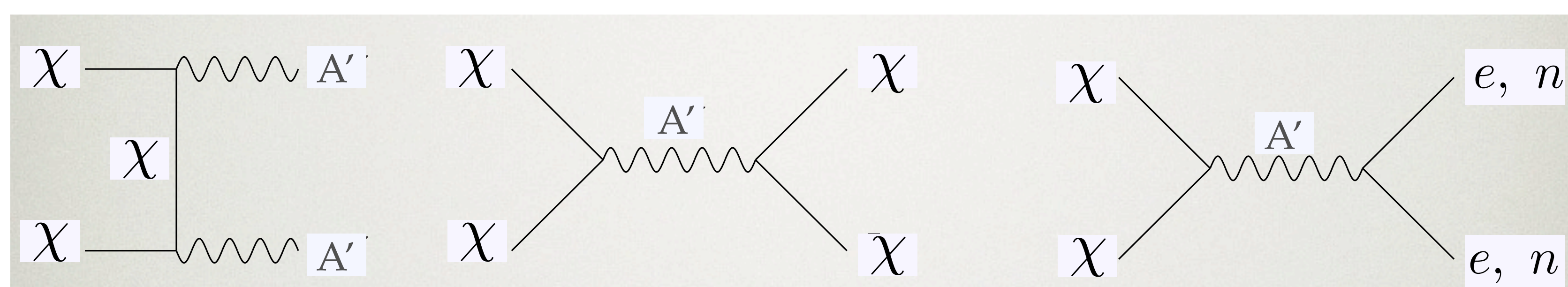
  - In part inspired by anomalies at experiments (DAMA, COGENT…)

- **Theoretical models:**

Often involve light dark photon A' ☞ New force!

kinetic mixing with SM photon



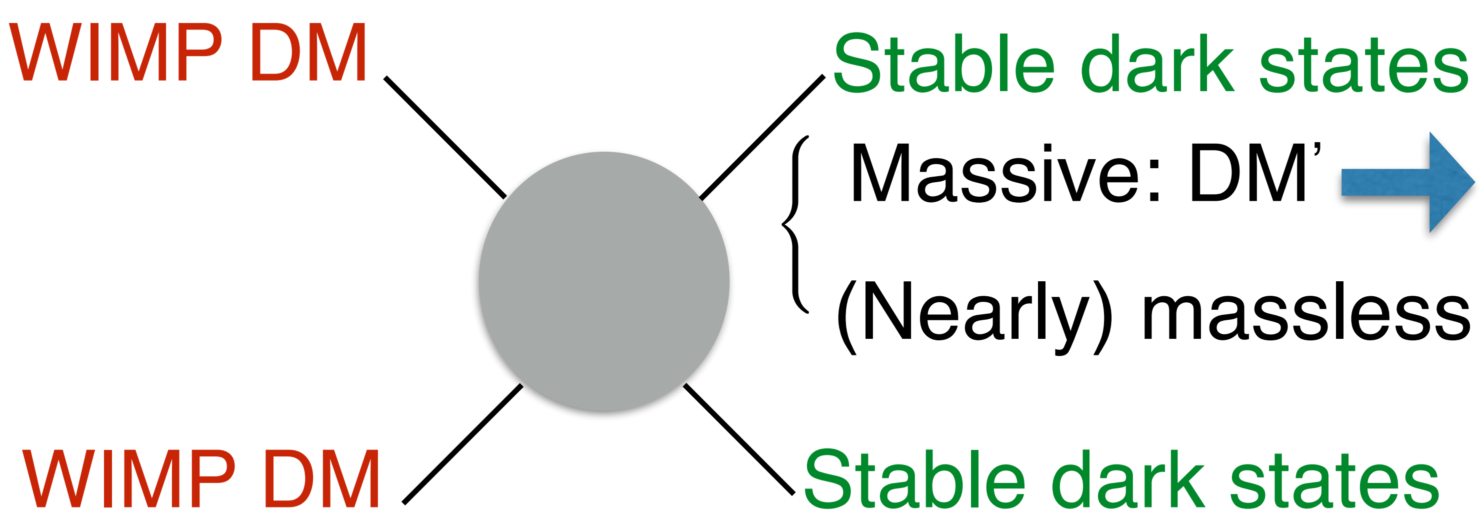


- **New detection strategies needed!** (Essig, Schuster, Toro…)

Low threshold DM experiments, dark photon search…

Thermal Annihilation into Stable Dark States
— New Realization of WIMP Miracle

Simple, generic variation: → new search strategies!

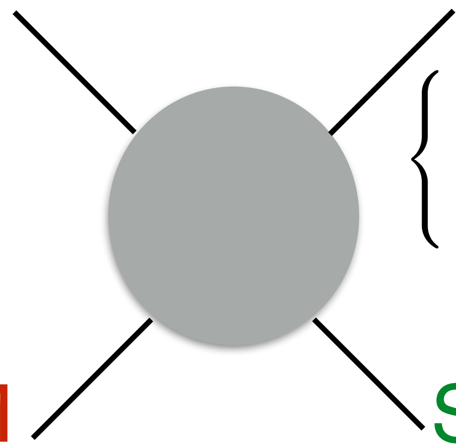


- Massive: DM' → Boosted DM! (vs. cold/slow)
- (Nearly) massless: Dark radiation → affect CMB

Thermal Annihilation into Stable Dark States
— New Realization of WIMP Miracle

Simple, generic variation: → new search strategies!

WIMP DM



WIMP DM

Stable dark states

- Massive: DM' → Boosted DM! (vs. cold/slow)
- (Nearly) massless: Dark radiation → affect CMB

Stable dark states

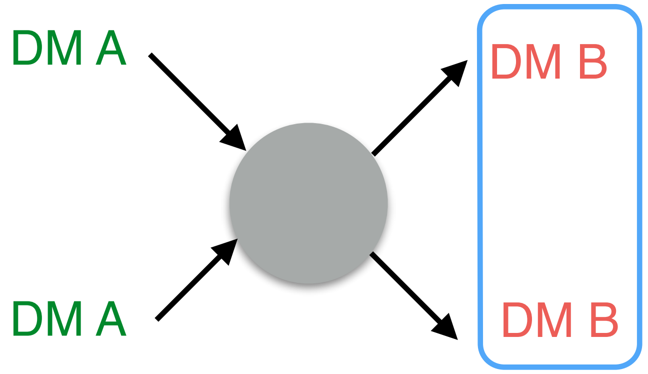
- WIMP miracle intact: $\Omega_\chi \propto \langle\sigma_{\rm ann} v\rangle^{-1}$ insensitive to final states
- Conventional search signals: absent or suppressed
- DM': depleted by annihilation, subdominant DM, $\Omega_{DM'} < \Omega_{DM}$

  Dark radiation: $\Omega_{DR} < \Omega_{DM}$, w/ $m_{DR} \lesssim O(eV)$
- Motivate non-minimal DM sector! (SM non-minimal! p, e^- …)

Scenario #1: Boosted DM

(arxiv: 1405.7370, Agashe, YC, Necib, Thaler; arxiv: 1410.2246, Berger, YC and Zhao)

E.g. Two-component DM sector



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

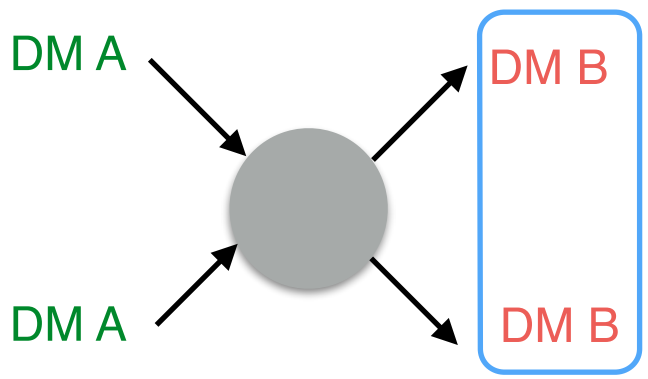
$\gamma_B = m_A/m_B$

Scenario #1: Boosted DM

(arxiv: 1405.7370, Agashe, YC, Necib, Thaler; arxiv: 1410.2246, Berger, YC and Zhao)

E.g. Two-component DM sector

- **Where to look?** Galactic Center, Sun



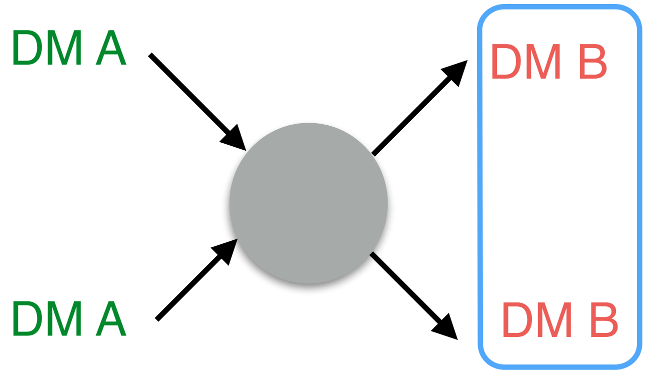
$m_A > m_B$, $\Omega_A \approx \Omega_{\rm DM}$

$\gamma_B = m_A/m_B$

Scenario #1: Boosted DM

(arxiv: 1405.7370, Agashe, YC, Necib, Thaler; arxiv: 1410.2246, Berger, YC and Zhao)

E.g. Two-component DM sector

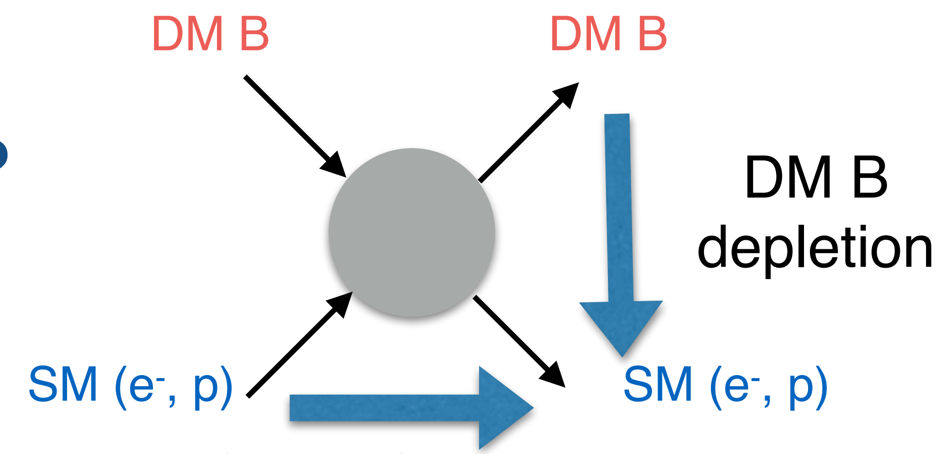


$m_A > m_B,\ \Omega_A \approx \Omega_{\rm DM}$

$\gamma_B = m_A/m_B$

- **Where to look?** Galactic Center, Sun

- **Detectable?**

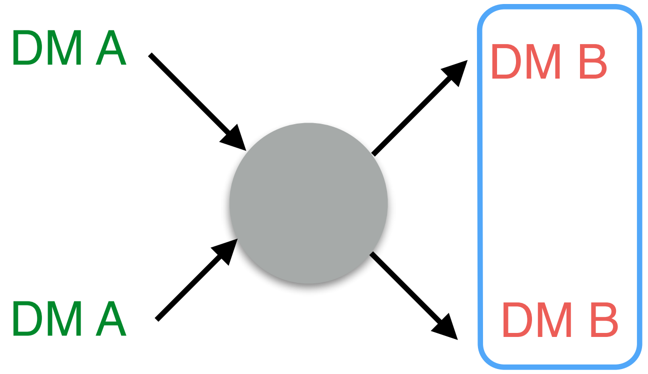


$T^{\rm f.o.}_{\rm DS} \simeq T^{\rm f.o.}_{\rm SM}$ + detectability

Scenario #1: **Boosted DM**

(arxiv: 1405.7370, Agashe, YC, Necib, Thaler; arxiv: 1410.2246, Berger, YC and Zhao)

E.g. Two-component DM sector

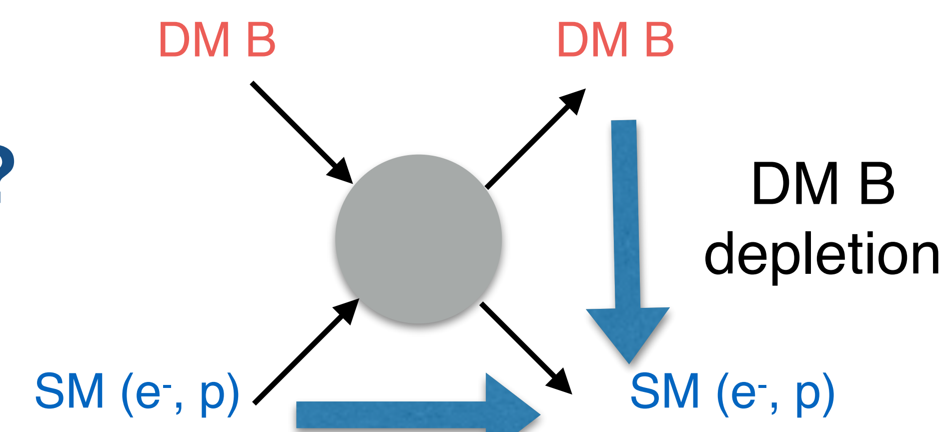


$m_A > m_B,\ \Omega_A \approx \Omega_{\rm DM}$

$\gamma_B = m_A/m_B$

- **Where to look?** Galactic Center, Sun

- **Detectable?**



$T_{\rm DS}^{\rm f.o.} \simeq T_{\rm SM}^{\rm f.o.}$ + detectability

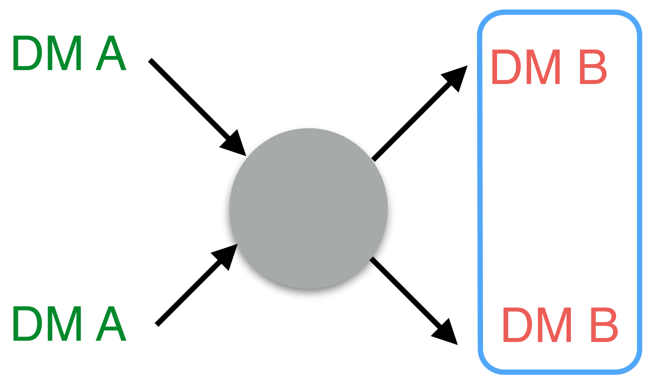
- **What experiment?** large volume, sensitive to energetic e-, p

(Conventional dark matter direct detection)

Scenario #1: Boosted DM

(arxiv: 1405.7370, Agashe, YC, Necib, Thaler; arxiv: 1410.2246, Berger, YC and Zhao)

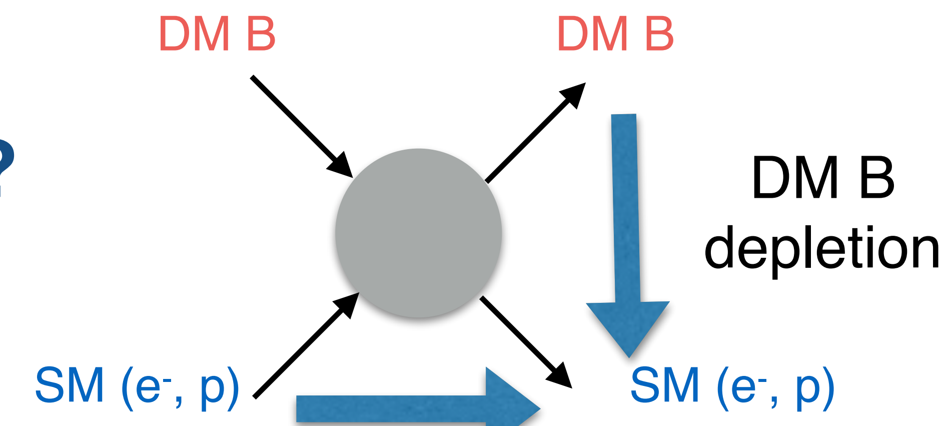
E.g. Two-component DM sector



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

$\gamma_B = m_A/m_B$

- **Where to look?** Galactic Center, Sun
- **Detectable?**



$T^{\rm f.o.}_{\rm DS} \simeq T^{\rm f.o.}_{\rm SM}$ + detectability

- **What experiment?** ☞ large volume, sensitive to energetic e⁻, p

(Conventional dark matter direct detection ☹)

Existing experiments for neutrinos, re-purposed!

✓ • Based on Cherenkov-radiation:

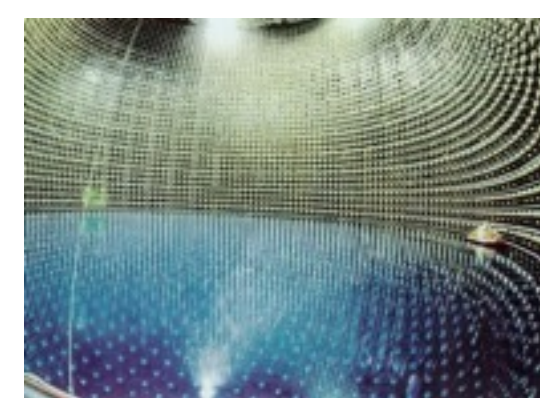
SuperK/HyperK, IceCube/PINGU(MICA)…

- Based on ionization: (future, planned)

DUNE, GLACIER… (liquid Argon/LArTpc)

IceCube

SuperK

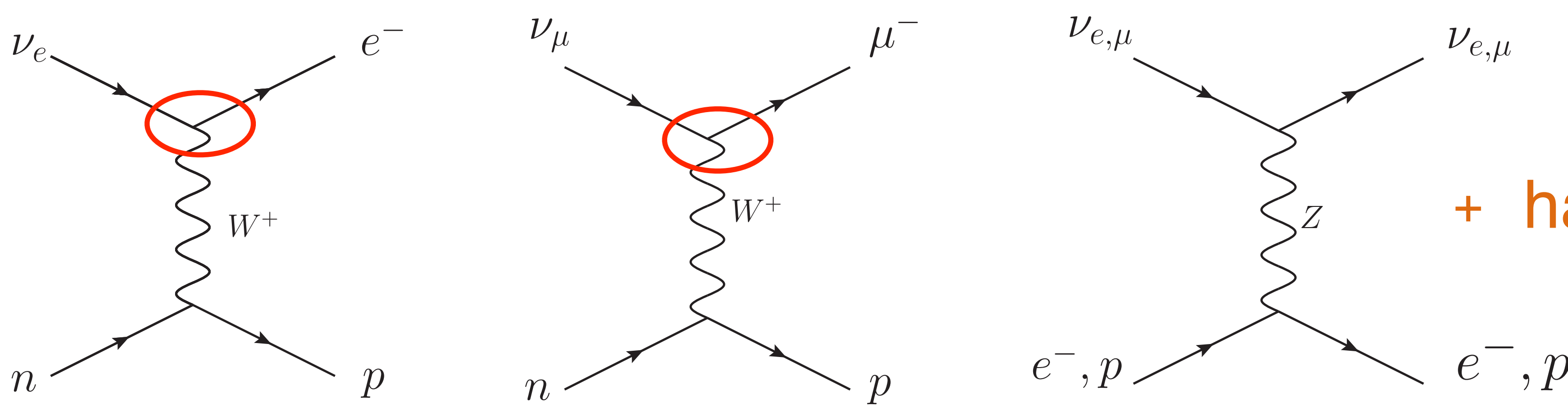


Detecting Boosted Dark Matter

"Neutrinos"? How to discriminate?

- Directional information:
  Boosted DM from GC or Sun vs. isotropic $\nu_{\rm atm}$
- Distinct interactions:

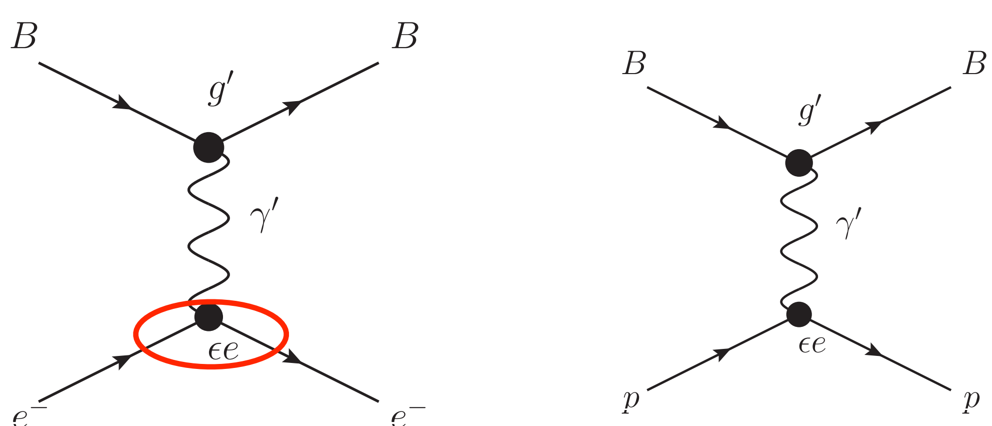
Neutrinos:



+ hadronic inelastic

Leading: charged-current scattering   neutral-current scattering

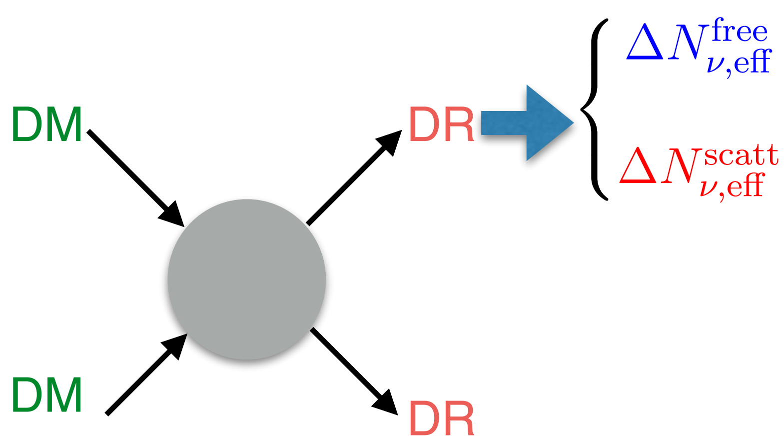
Boosted DM:



neutral-current scattering only, no correlated μ^-

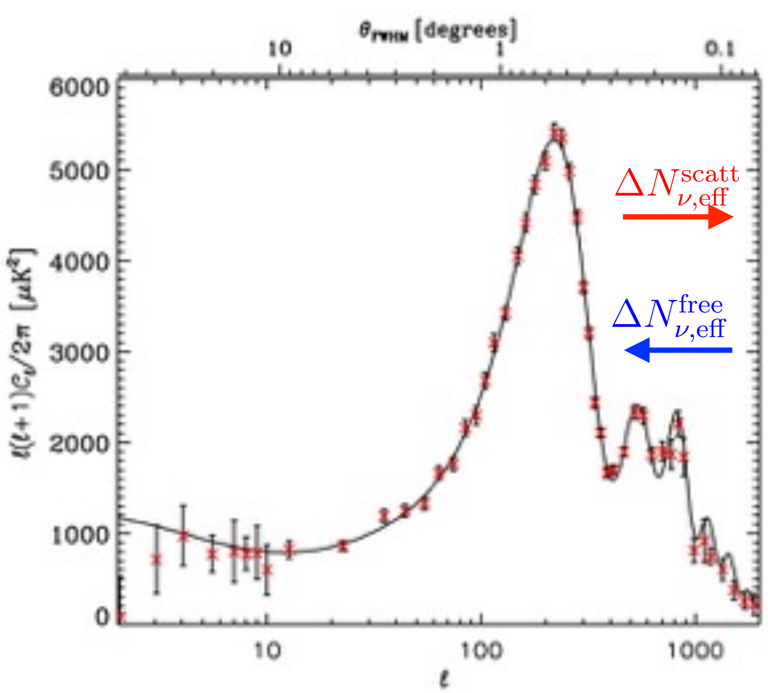
Scenario #2: CMB Signals of Dark Radiation from a Hidden DM Sector

(arXiv:1505.04192 Chacko, YC, Hong, Okui)

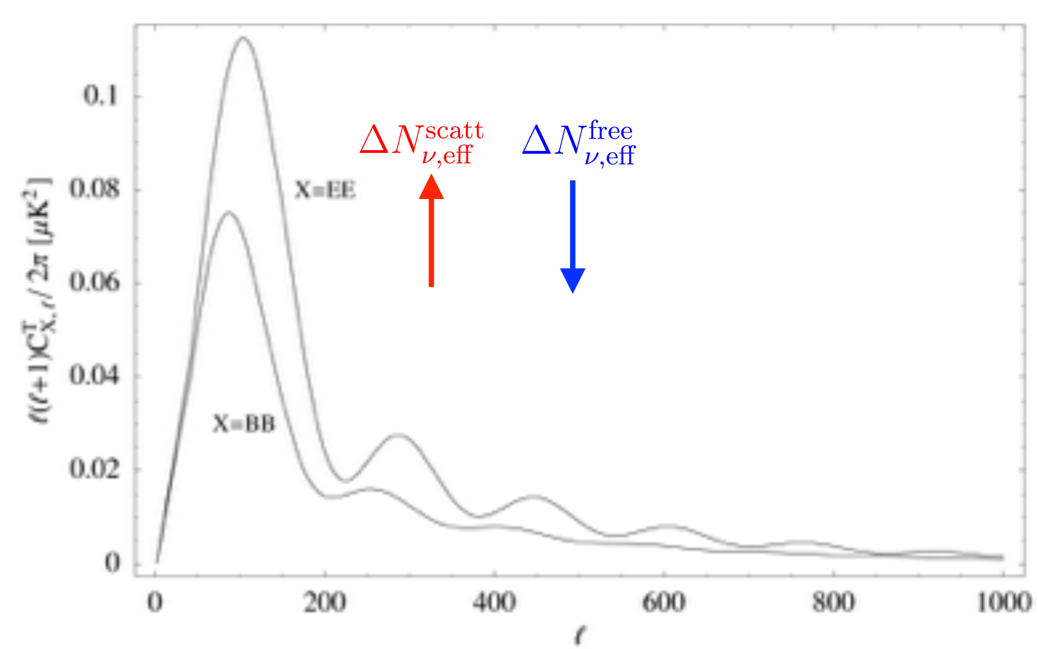


- Effect of DR on CMB: $\rho_{\mathrm{rad}}\uparrow$, Hubble expansion rate↑, Silk-damping… → $\Delta N_{\nu}^{\mathrm{eff}}$
- DR can generally be <u>interacting</u>, unlike free-streaming "neutrinos" !

CMB observables: opposite effects from $\Delta N_{\nu,\mathrm{eff}}^{\mathrm{free}}$ and $\Delta N_{\nu,\mathrm{eff}}^{\mathrm{scatt}}$



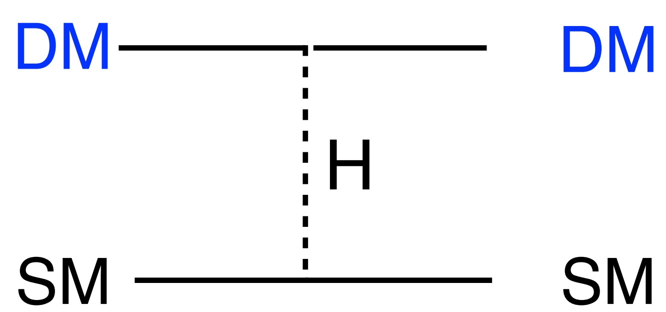
Scalar mode: universal phase shift;



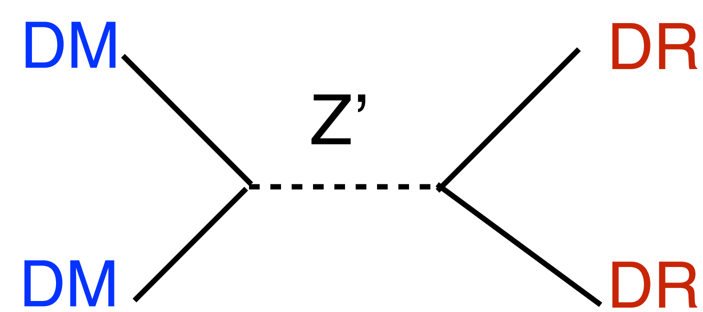
Tensor mode: amplitude change

Scenario #2: CMB Signals of Dark Radiation from a Hidden DM Sector

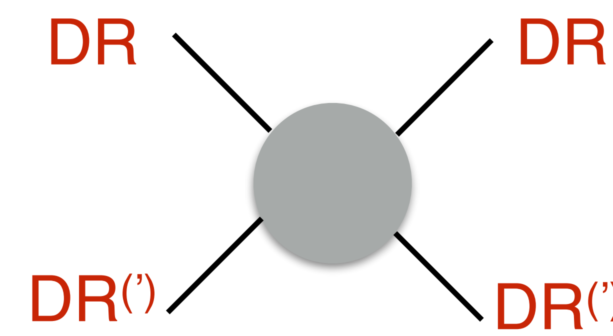
- Analyze simple example model:



Maintain $T_{DM} = T_{SM}$ at T_{EW} via Higgs-portal
(related: invisible H decay at the LHC!)

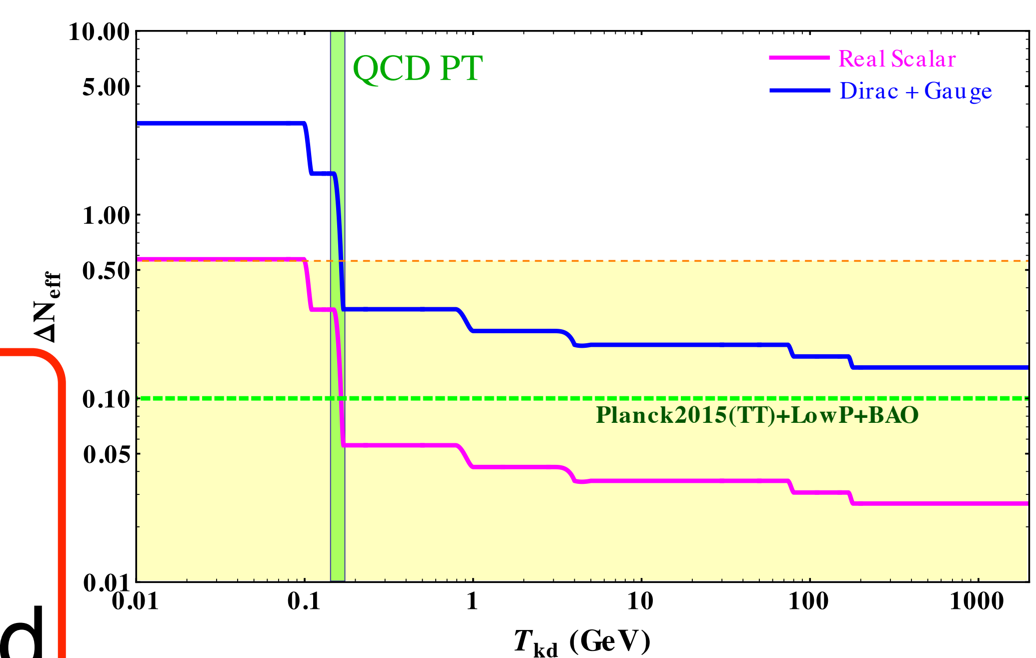


Main annihilation channel



Interacting DR

- Model prediction on $\Delta N_{\nu}^{\text{eff}}$ consistent with Planck data, better sensitivity at future CMBpol, CMB-S4!
- **Caveat:** bound from standard CMB analysis (assuming all free-streaming) may not directly apply, need dedicated study, e.g. 2-param fit: $\Delta N_{\nu,\text{eff}}^{\text{free}}$ and $\Delta N_{\nu,\text{eff}}^{\text{scatt}}$



Asymmetric Dark Matter

- **Observation**: $\Omega_{\rm DM} \sim \Omega_{\rm B}$ — coincidence or connection?
- **Paradigm**: Asymmetric dark matter

  (Nussinov 1985; Kaplan 1992; Kaplan, Luty, Zurek 2009…)

Similar origin of Ω_{DM} and Ω_B : asymmetric excess $\Omega_{\rm DM} - \Omega_{\overline{\rm DM}}$, symmetric component depleted by thermal annihilation

- Co-generation of dark & baryon asymmetry
- Asymmetry transfer by DM-baryon interactions in early universe

★ Require additional input: asymmetry generation (baryogenesis)

- **Phenomenology:**
  - DM mass range: O(GeV) motivated, but wide range possible
  - Indirect detection absent/suppressed, direct detection relevant

Axion Dark Matter

- Strong CP problem in the Standard Model:

  - Expected CP-violation in QCD: naively $\theta \sim 1$ $\quad L_{\rm QCD} = \; ... + \theta \frac{g^2}{32\pi^2} G^a{}_{\mu\nu} \tilde{G}^{a\mu\nu}$

  - But, neutron electric dipole moment measurement: $\theta \leq 10^{-10}$

Why is θ so tiny? SM can't explain…

- Solution by a small modification to the SM: (Peccei, Quinn 1977)

  spontaneously broken $U_{PQ}(1)$ → Goldstone boson $\boldsymbol{a}$ (axion)

$$L = \; ... + \frac{a}{f_a} \frac{g^2}{32\pi^2} G^a{}_{\mu\nu} \tilde{G}^{a\mu\nu} + \frac{1}{2} \partial_\mu a \, \partial^\mu a + \; ...$$

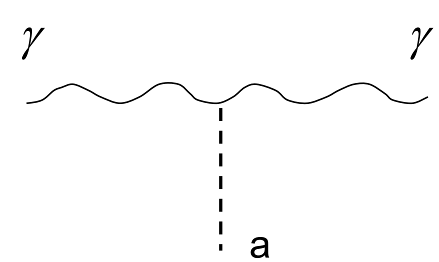
☞ $\theta = -\frac{a}{f_a}$ CPV relaxes to zero!

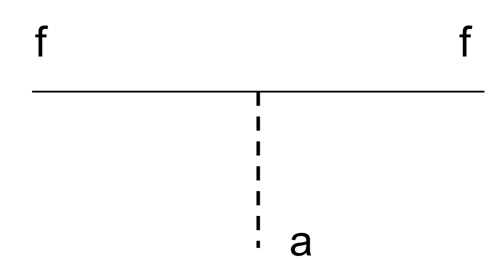
- Axion can be dark matter! Ultra-light, super-weakly interacting

$$f_{16} \equiv (f_a/\mathcal{N})/(10^{16}\ \mathrm{GeV}) \quad m_a \approx 6 \times 10^{-9}\ \mathrm{eV} \times f_{16}^{-1} \quad \Omega_a \simeq \Omega_c (\mathcal{N}\theta_i)^2 \times \begin{cases} 5 \times 10^5 f_{16}^{7/6}, & f_{16} < 1/10 \\ 3 \times 10^4 f_{16}^{3/2}, & f_{16} > 10 \end{cases}$$

- Axion interactions, detections

  Use axion-photon conversion in magnetic field (e.g. ADMX…)

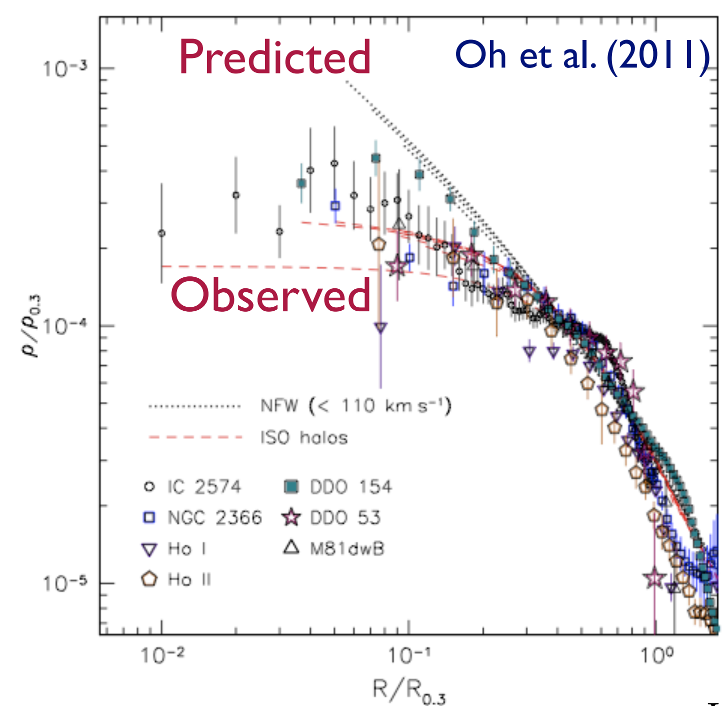




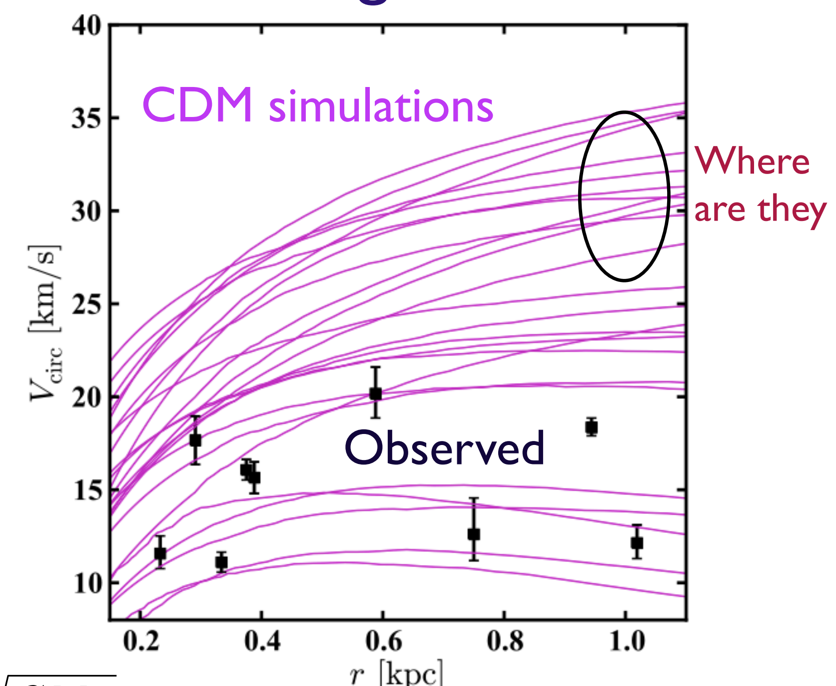
Self-interacting Dark Matter

- Collisionless cold DM: fit large scale structure very well
- “Anomalies” at small scales: dwarf galaxies, sub-halos…

Core VS. Cusp



“Too big to fail”

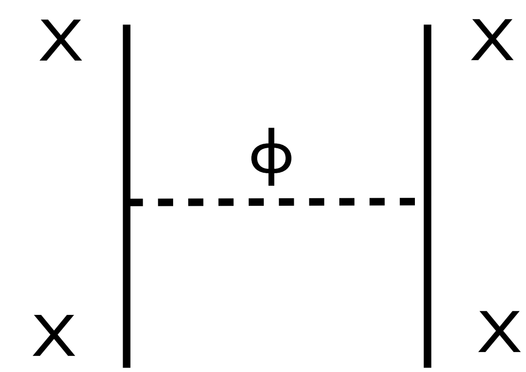


$V \sim \sqrt{\frac{GM_<}{r}}$ Boylan-Kolchin, Bullock, Kaplinghat (2011)

- Strong DM self-interaction helps! (reduce central density)

$\sigma/m_X \sim 0.1\text{-}10\ \text{cm}^2/\text{g}$

(Spergel, Steinhardt, 1999)



- Constraints: bullet cluster, halo ellipticity
- Viable model: velocity-dependent scattering via light mediator

$$\sigma \approx 5 \times 10^{-23}\,\text{cm}^2 \left(\frac{\alpha_X}{0.01}\right)^2 \left(\frac{m_X}{10\,\text{GeV}}\right)^2 \left(\frac{10\,\text{MeV}}{m_\phi}\right)^4$$

(Kaplinghat, Tulin, Yu, Zurek,…)

Conclusion/Outlook

- What is dark matter?
  - a greatest puzzle for particle physics and cosmology
  - limited observational clues, many theoretical candidates
- Conventional focus: WIMP+ direct interaction w/SM states
  - increasing constraints from data, or right at corner…
- Recent trends: theoretical scope expanded
  - Non-minimal DM sector: rich particle contents/interactions
  - More weakly/indirect interaction with the visible sector (SM)
  - Wide mass range: (in particular) light mass
- Expanded experimental search programs on the way:
  - Existing experiments re-purposed: CMB, neutrino detectors
  - Proposals for new experiments (axion, light DM, dark force…)