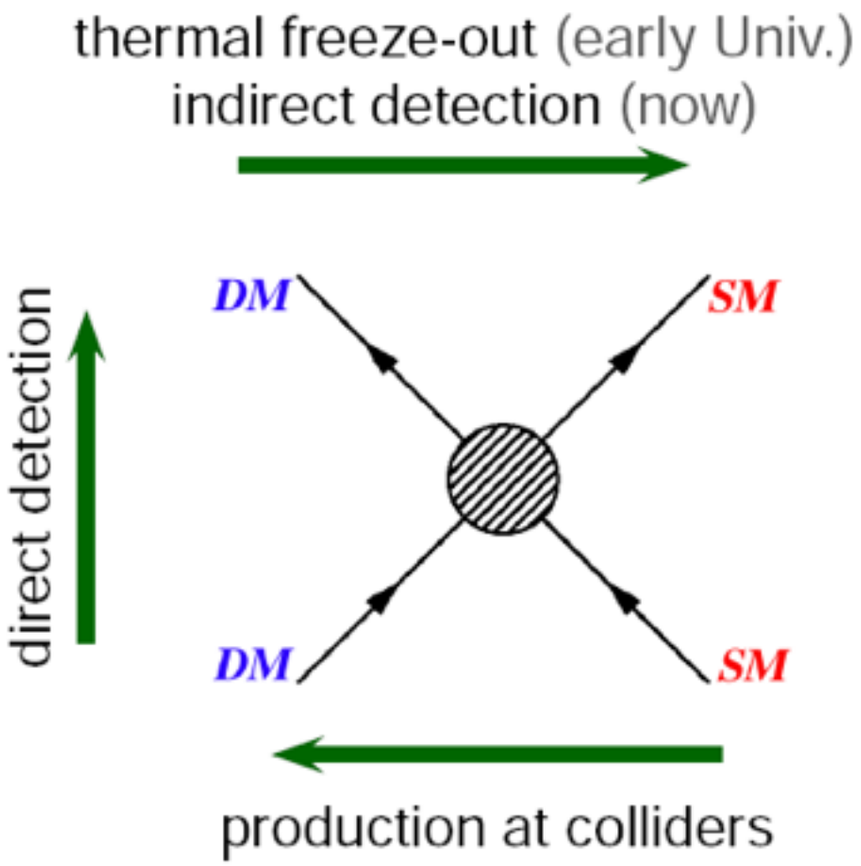
New Observational Windows for Probing Dark Sectors

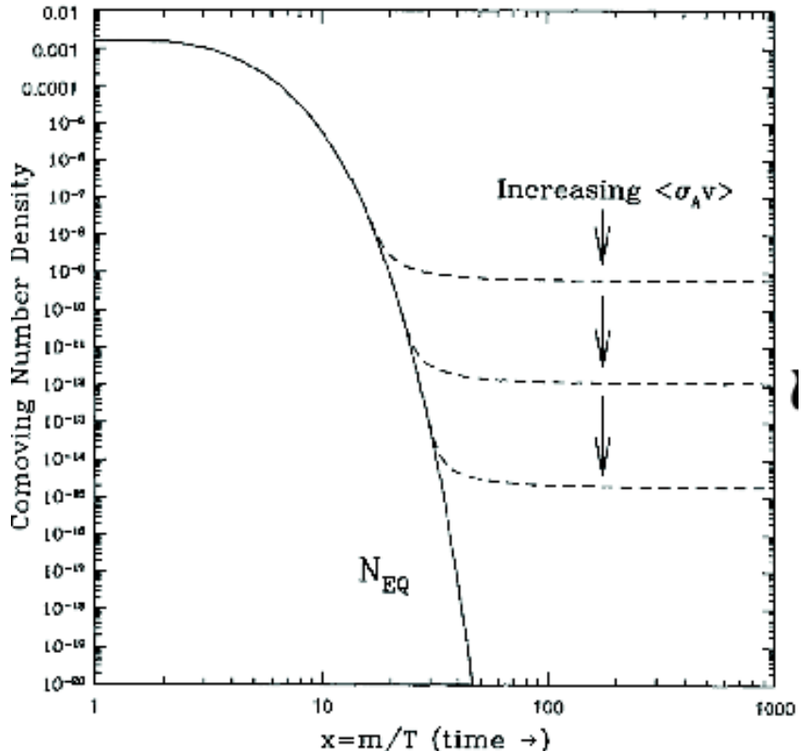
Yanou Cui

UC Riverside

DaMaSc IV: Beyond WIMP DM
Aug 30, 2017

The Challenges with the WIMP DM Paradigm

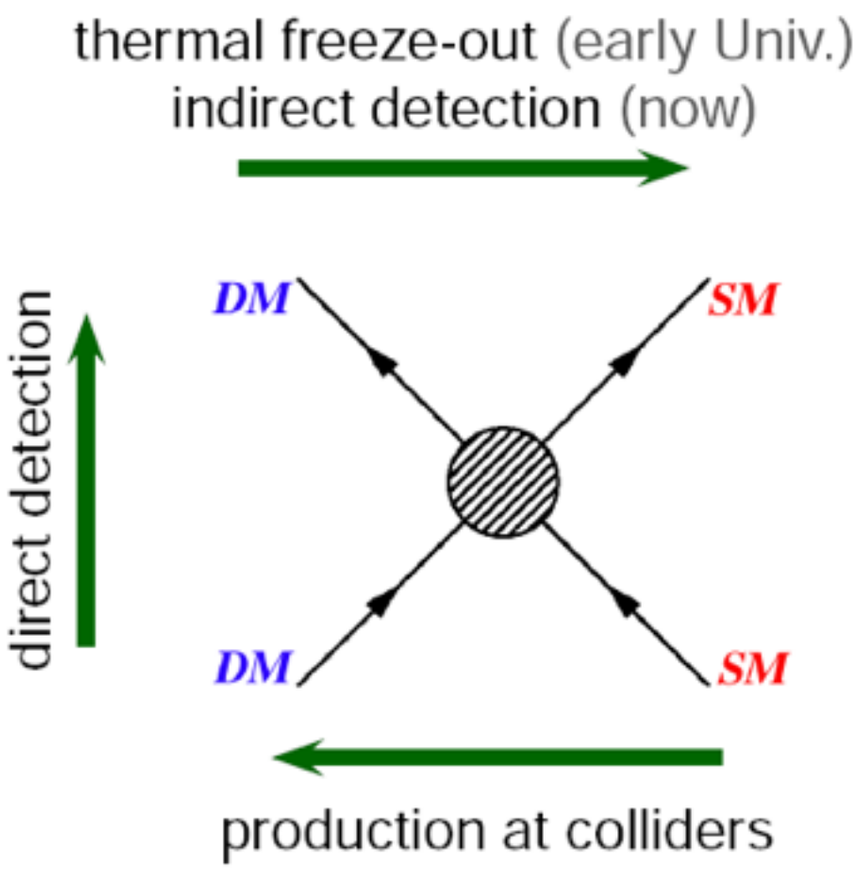




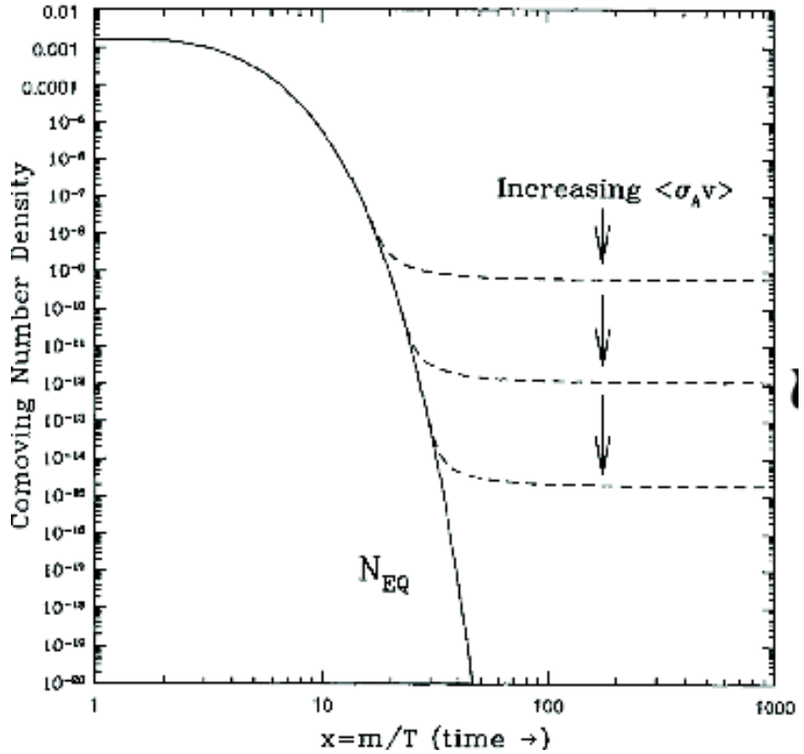
$$\Omega_\chi \propto \langle \sigma_{\rm ann} v \rangle^{-1}$$
$$\sim 0.1 \left(\frac{G_{\rm Fermi}}{G_\chi} \right)^2 \left(\frac{M_{\rm weak}}{m_\chi} \right)^2$$

WIMP Miracle!

The Challenges with the WIMP DM Paradigm



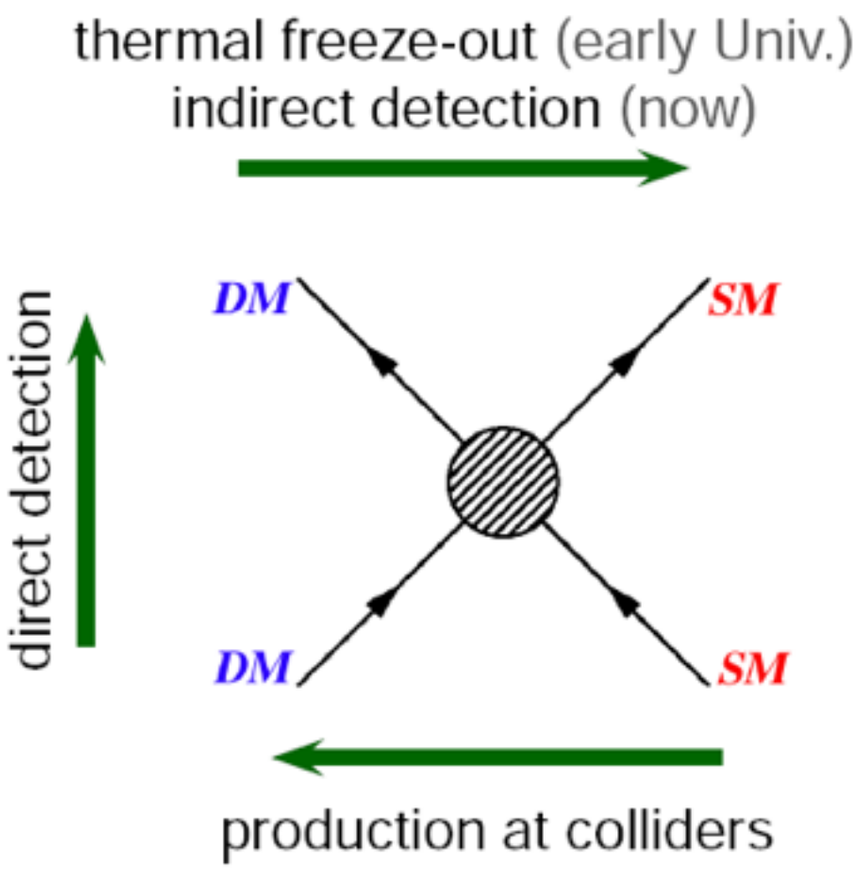
- But no convincing signal yet: many years, many experiments…

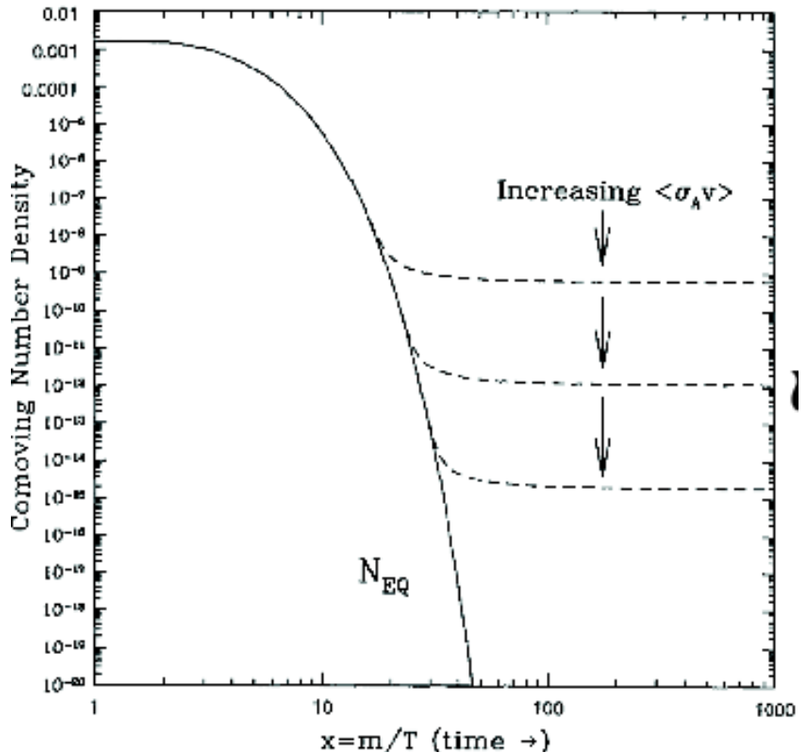


$$\Omega_\chi \propto \langle \sigma_{\rm ann} v \rangle^{-1} \sim 0.1 \left(\frac{G_{\rm Fermi}}{G_\chi} \right)^2 \left(\frac{M_{\rm weak}}{m_\chi} \right)^2$$

WIMP Miracle!

The Challenges with the WIMP DM Paradigm





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

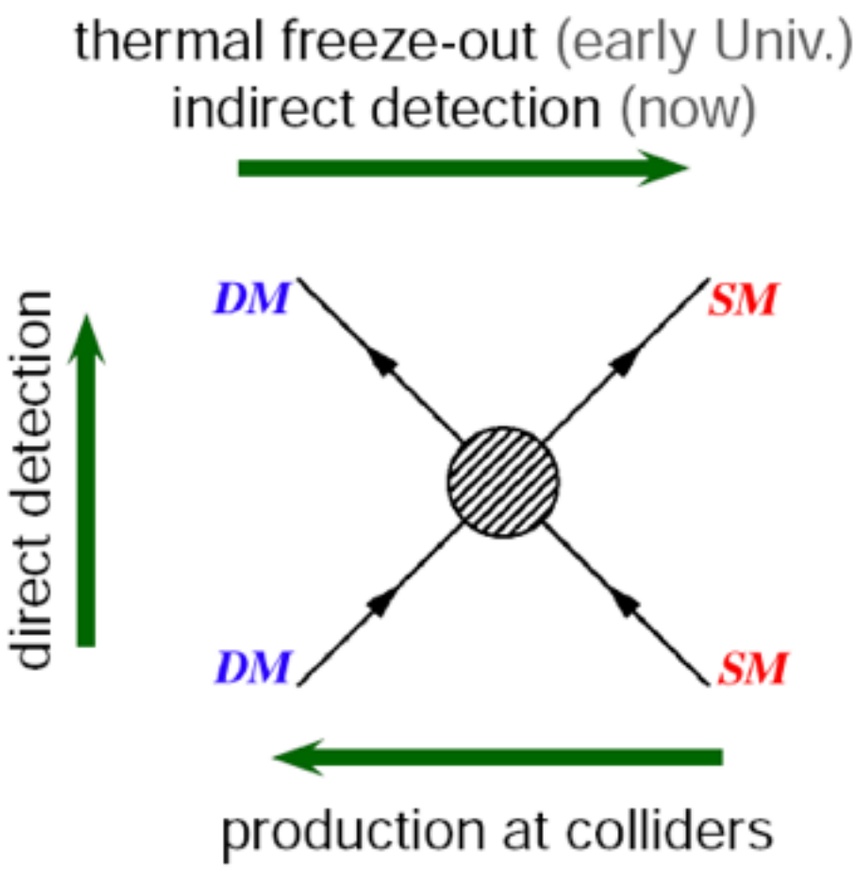
WIMP Miracle!

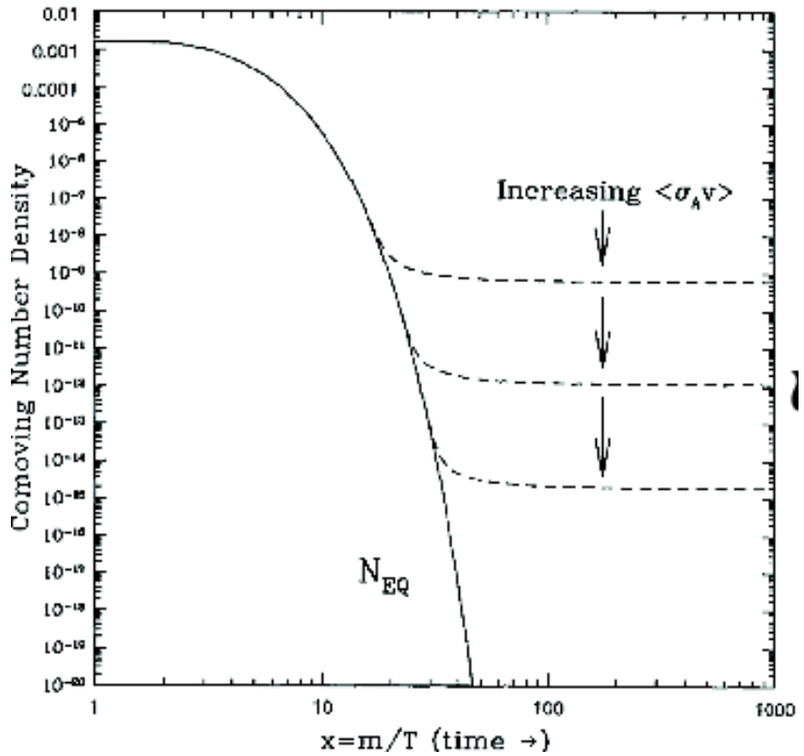
- But no convincing signal yet: many years, many experiments…

- Expand the theoretical vision: beyond a single WIMP

  light DM, axion, sterile ν, non-minimal thermal dark sector …

The Challenges with the WIMP DM Paradigm





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

WIMP Miracle!

- But no convincing signal yet: many years, many experiments…

- Expand the theoretical vision: beyond a single WIMP

  light DM, axion, sterile ν, non-minimal thermal dark sector★

  …

Simple Variations of WIMP Miracle

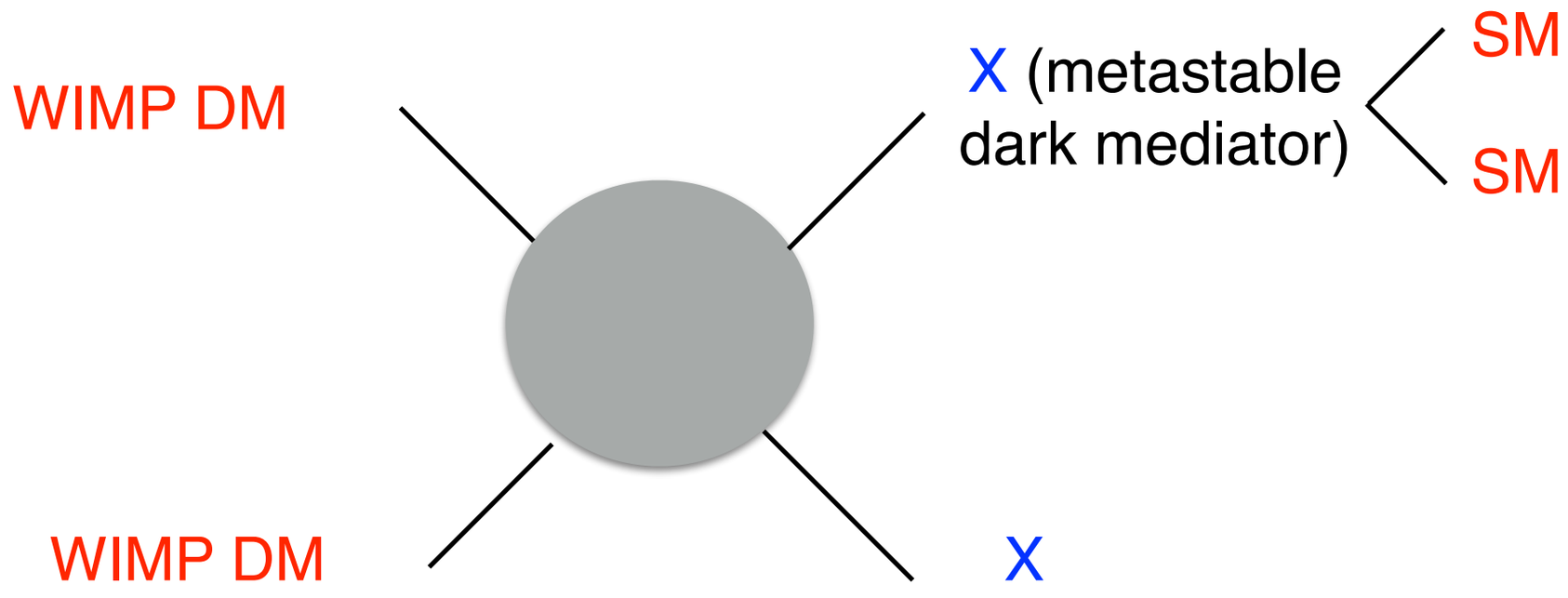
- **Decouple DM thermal relic abundance from coupling to the SM**

Simple Variations of WIMP Miracle

- **Decouple DM thermal relic abundance from coupling to the SM**

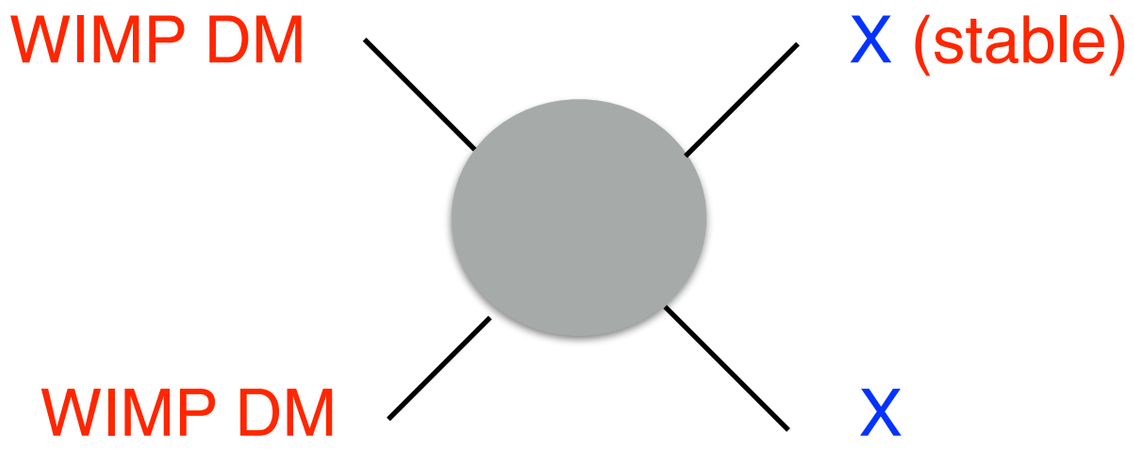
e.g. *Secluded Dark Matter*

(Pospelov, Ritz, Voloshin 2007)



Safely evades direct detection, subject to indirect detection

A New Realization of WIMP DM Miracle



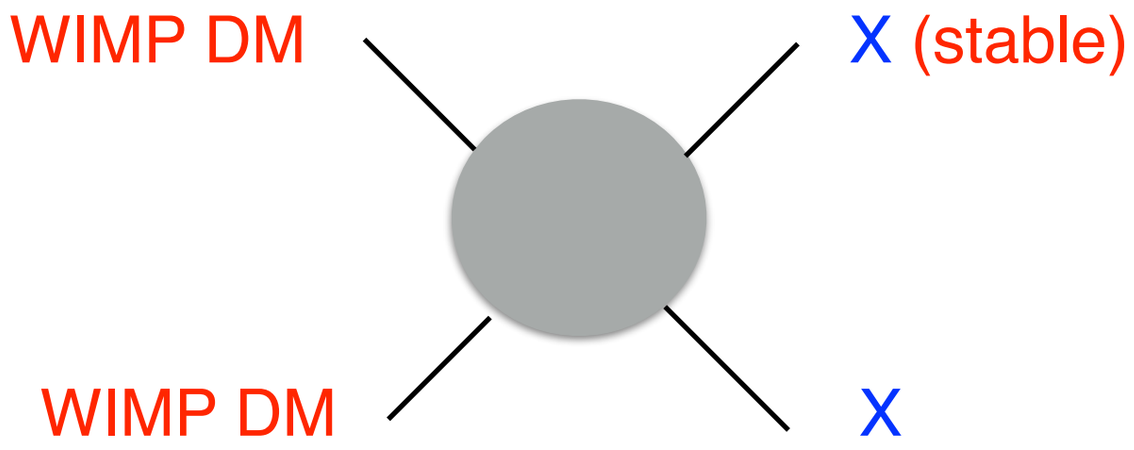
- **Determines Ω_{DM}!**

WIMP miracle intact!

$$\Omega_\chi \propto \langle \sigma_{\rm ann} v \rangle^{-1}$$

- *All* conventional searches absent/suppressed

A New Realization of WIMP DM Miracle



Not just "WIMP", applies to thermal freeze-out of DM with general masses!

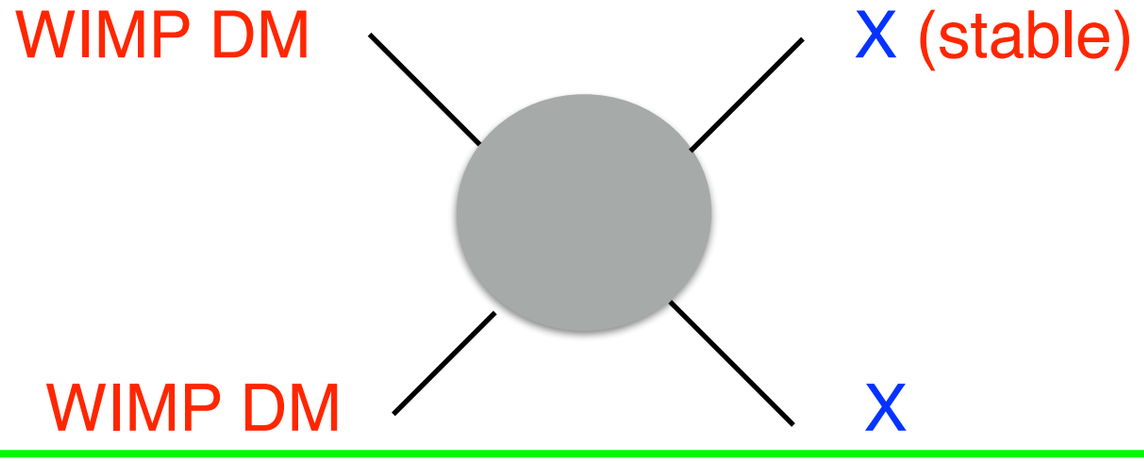
- **Determines Ω_{DM}!**

  WIMP miracle intact!

  $$\Omega_\chi \propto \langle \sigma_{\rm ann} v \rangle^{-1}$$

- *All* conventional searches absent/suppressed

A New Realization of WIMP DM Miracle



Not just "WIMP", applies to thermal freeze-out of DM with general masses!

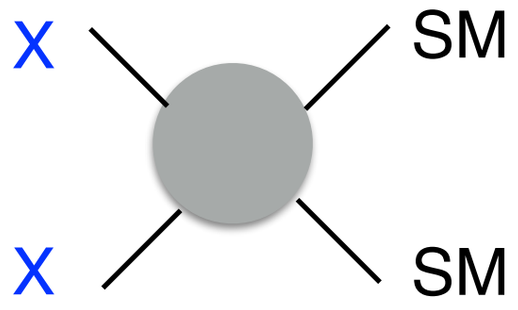
- **Determines Ω_{DM}!**

  WIMP miracle intact!

  $$\Omega_\chi \propto \langle \sigma_{\rm ann} v \rangle^{-1}$$

- *All* conventional searches absent/suppressed

- *What is X?*



  - $m_X \gtrsim$ eV: $\Omega_X > 1$ ☞ deplete X via annihilation→SM

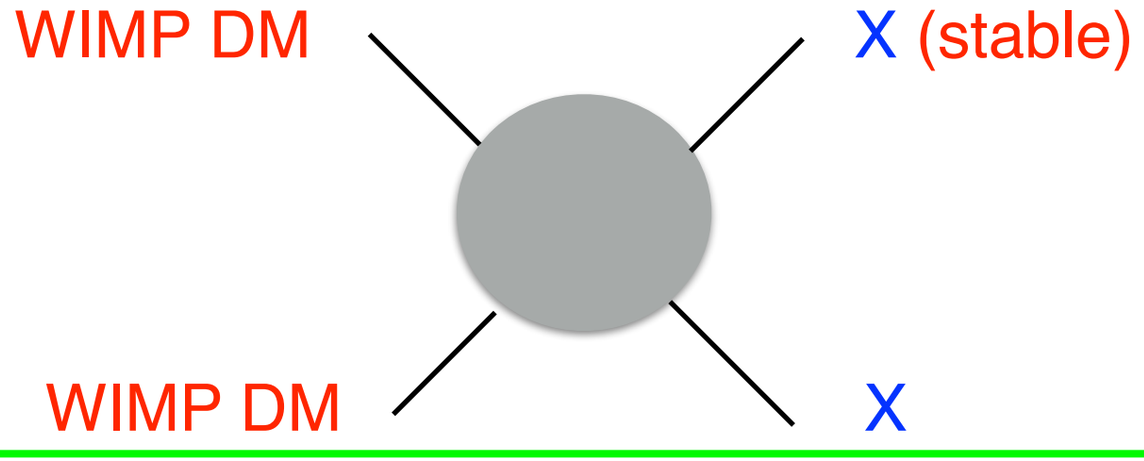
    Novel signal: **Boosted DM (X)!** (Vs. "slow" DM)

    at neutrino experiments *(**YC** w/Agashe, Necib,Thaler; **YC** w/Berger, Zhao)*

  - $m_X \lesssim$ eV: Ω_X ✓ ☞ relativistic, **dark radiation** in the **CMB**

    X-SM interaction not necessary *(**YC** w/Chacko, Hong, Okui)*

A New Realization of WIMP DM Miracle



Not just "WIMP", applies to thermal freeze-out of DM with general masses!

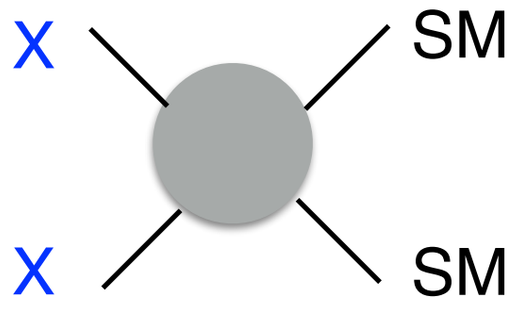
- **Determines Ω_{DM}!**

  WIMP miracle intact!

  $$\Omega_\chi \propto \langle \sigma_{\rm ann} v \rangle^{-1}$$

- *All* conventional searches absent/suppressed

- *What is X?*



  - $m_X \gtrsim$ eV: $\Omega_X > 1$ ☞ deplete X via annihilation→SM

    Novel signal: **Boosted DM (X)!** (Vs. "slow" DM)

    at neutrino experiments *(**YC** w/Agashe, Necib,Thaler; **YC** w/Berger, Zhao)*

  - $m_X \lesssim$ eV: Ω_X ✓ ☞ relativistic, **dark radiation** in the **CMB**

    X-SM interaction not necessary *(**YC** w/Chacko, Hong, Okui)*

Dark matter lives in a non-minimal hidden sector!

(a **thermal** bath of DM, X, +…)

A Hidden Dark Sector?

Rising interest, covers a great variety of DM models:

atomic DM, multi-component DM, dynamical DM, SIDM, twin Higgs DM, DDDM…

What can possibly live in the mysterious ~25% of our universe?

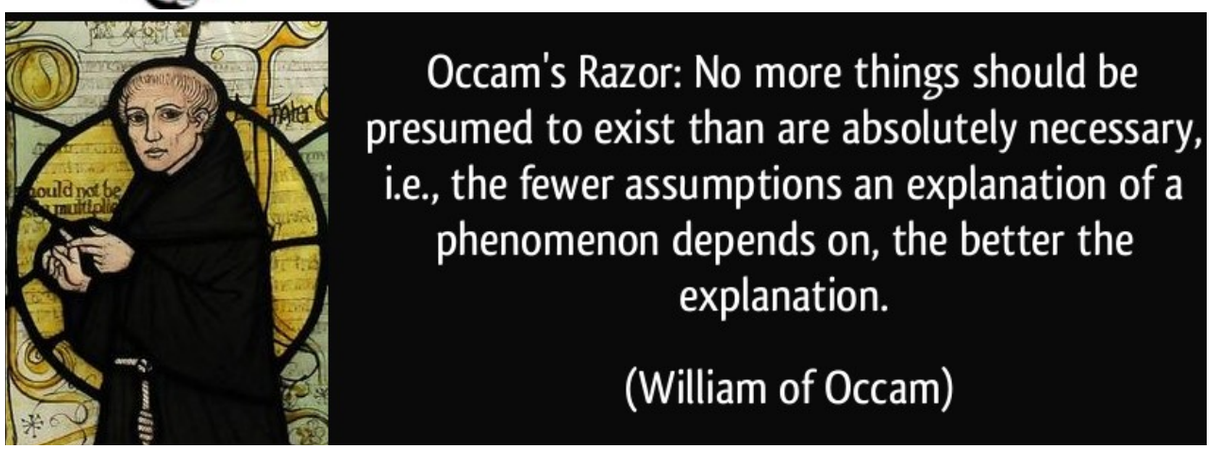
A Hidden Dark Sector?

Rising interest, covers a great variety of DM models:

atomic DM, multi-component DM, dynamical DM, SIDM, twin Higgs DM, DDDM…

What can possibly live in the mysterious ~25% of our universe?

- *Too "complicated"? Occam's razor?*



A Hidden Dark Sector?

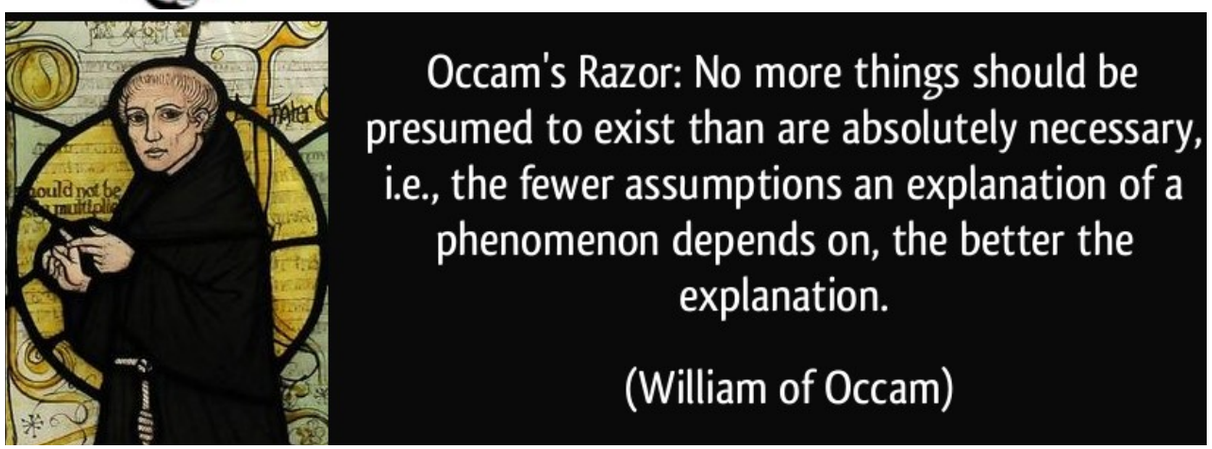
Rising interest, covers a great variety of DM models:

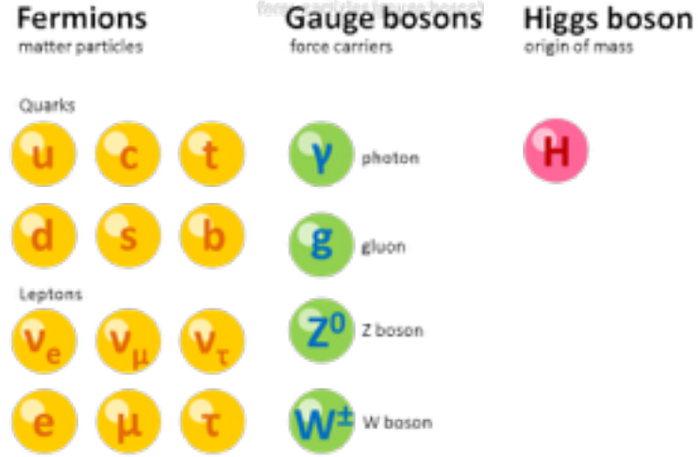
atomic DM, multi-component DM, dynamical DM, SIDM, twin Higgs DM, DDDM…

What can possibly live in the mysterious ~25% of our universe?

- *Too "complicated"? Occam's razor?*

Shave our SM??





A Hidden Dark Sector?

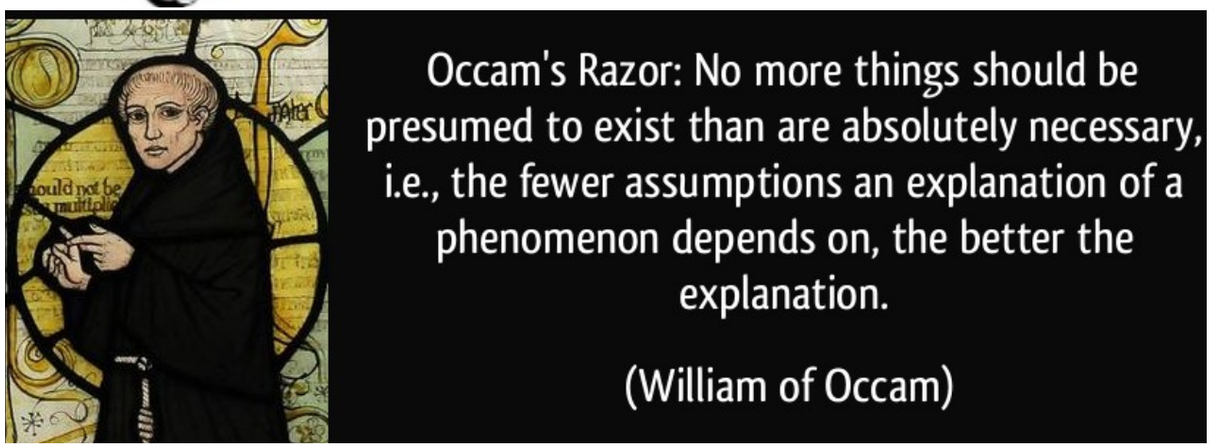
Rising interest, covers a great variety of DM models:

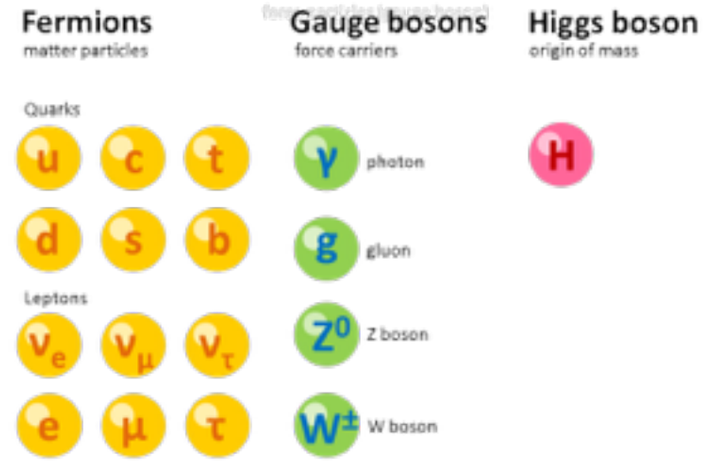
atomic DM, multi-component DM, dynamical DM, SIDM, twin Higgs DM, DDDM…

What can possibly live in the mysterious ~25% of our universe?

- *Too "complicated"? Occam's razor?*

Shave our SM??





- *No clue? "Nightmare" for discovery?*

A Hidden Dark Sector?

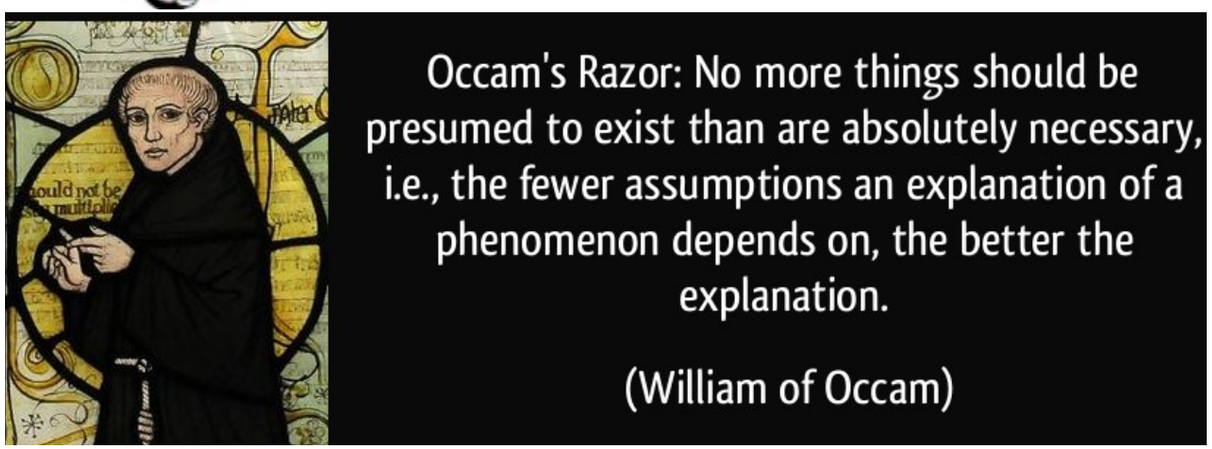
Rising interest, covers a great variety of DM models:

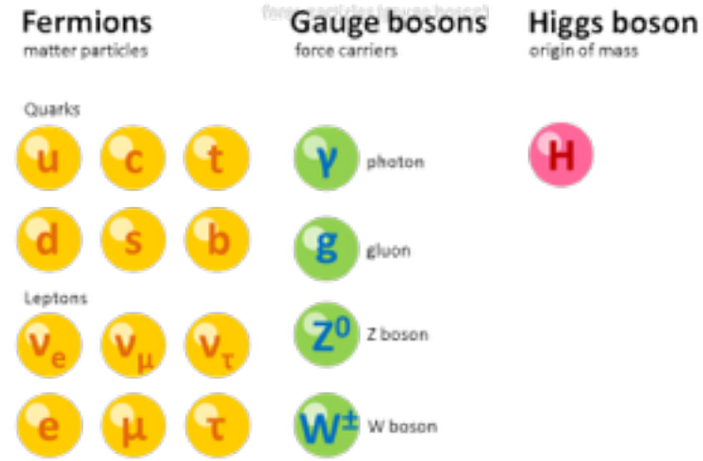
atomic DM, multi-component DM, dynamical DM, SIDM, twin Higgs DM, DDDM…

What can possibly live in the mysterious ~25% of our universe?

- *Too "complicated"? Occam's razor?*

Shave our SM??





- *No clue? "Nightmare" for discovery?*

✓ **Universal guidelines**

✓ **New observational windows!**

(this talk…)

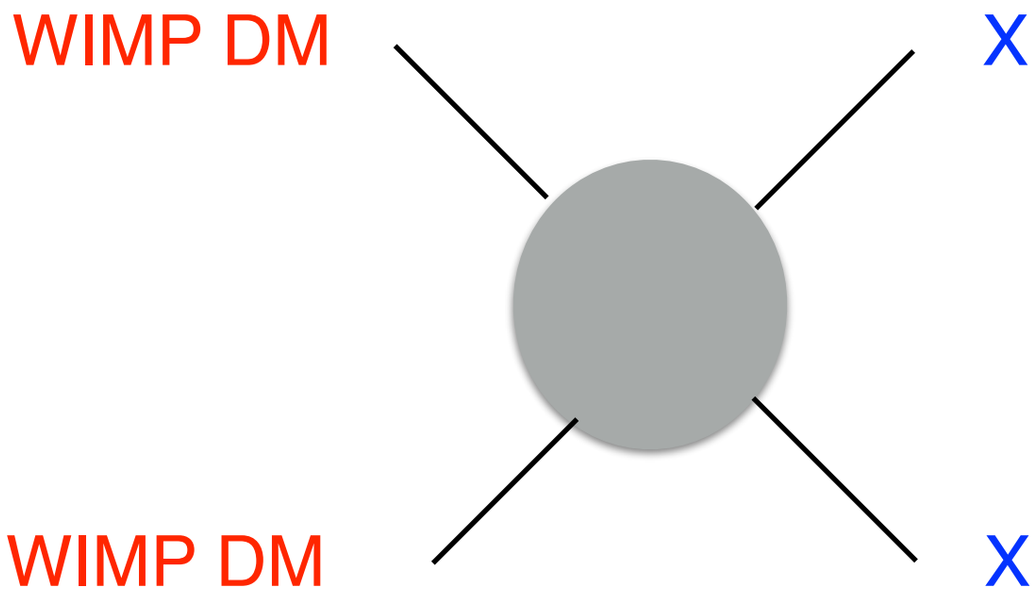
Episode- #1

Boosted Dark Matter

JCAP 1410 (2014) 062, **YC** w/Agashe, Necib, Thaler;

JCAP 1502 (2015) , **YC** w/Berger, Zhao;

YC *et.al* w/Mircoboone/DUNE collaboration *(in progress)*



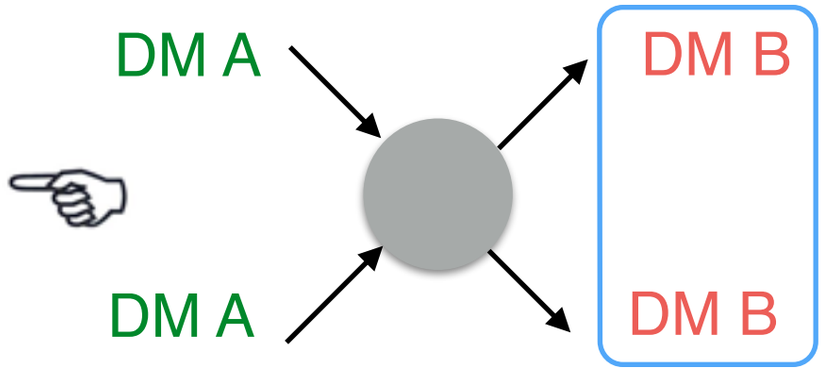
- Massive X

(DM→ DM A, X→ DM B)

Boosted Dark Matter

- **Key Processes**

- Ω_A
- Current-day annihilation



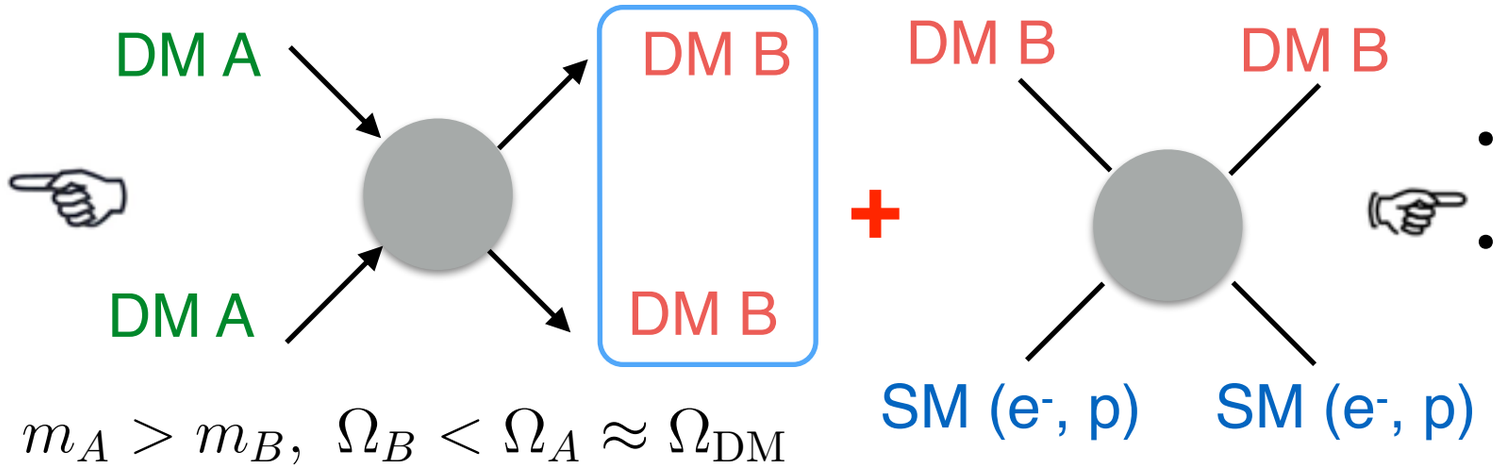
$$m_A > m_B,\ \Omega_B < \Omega_A \approx \Omega_{\rm DM}$$

Boosted DM B! $\gamma_B = m_A/m_B$

Boosted Dark Matter

- **Key Processes**

- Ω_A
- Current-day annihilation



- Deplete Ω_B
- B-SM scattering - detectability!

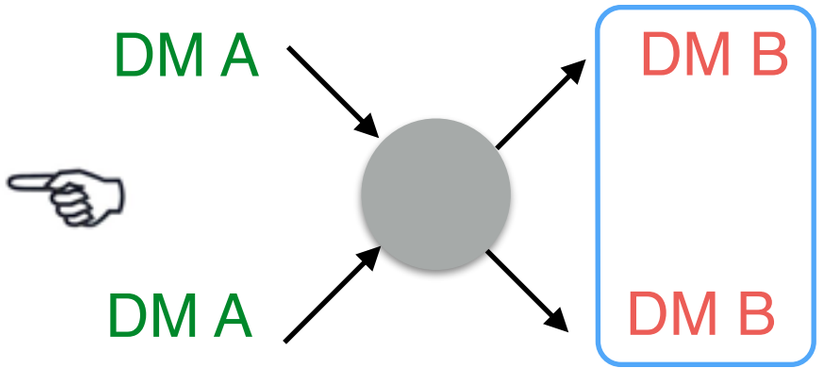
$$m_A > m_B,\ \Omega_B < \Omega_A \approx \Omega_{\rm DM}$$

Boosted DM B! $\gamma_B = m_A/m_B$

Boosted Dark Matter

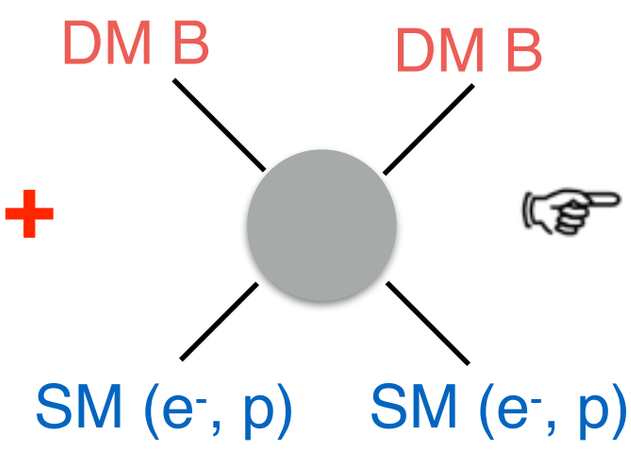
- **Key Processes**

- Ω_A
- Current-day annihilation



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

+



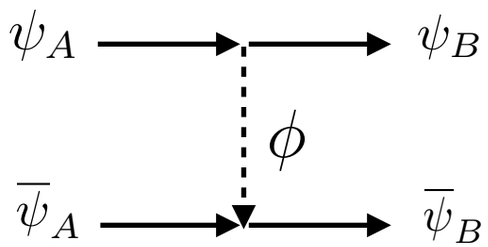
- Deplete Ω_B
- B-SM scattering - detectability!

Boosted DM B! $\gamma_B = m_A/m_B$

- **Model Example**

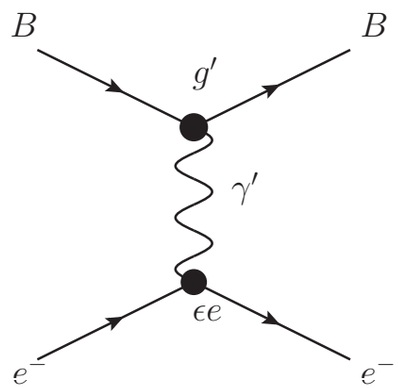
- Dirac fermion $\psi_A,\ \psi_B,\ m_A > m_B$, stabilized by $\mathbb{Z}_2 \times \mathbb{Z}_2$

$$\mathcal{L} \supset \frac{1}{\Lambda^2}\overline{\psi}_A\psi_B\overline{\psi}_B\psi_A$$



+

$$\mathcal{L} \supset -\frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$$



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

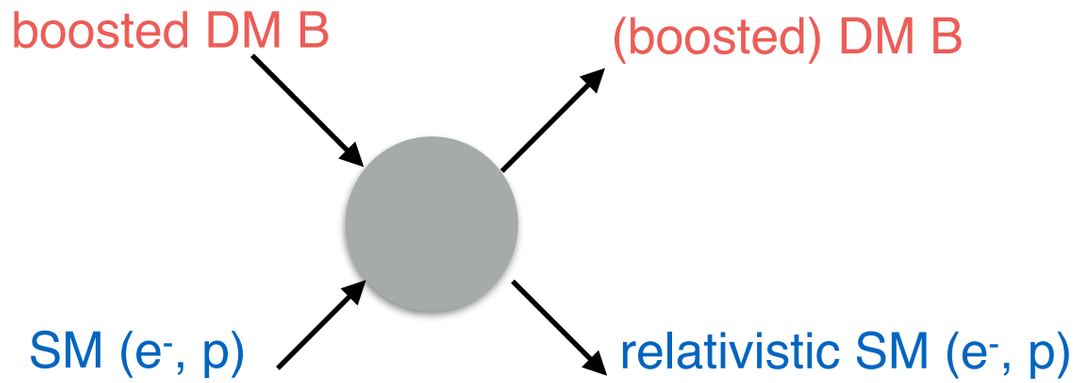
$g' \simeq O(0.1),\quad \epsilon \simeq O(10^{-3})$

How to Search for Boosted DM?

- Mono-energetic (E_B=m_A), small flux $\propto n^2_{\mathrm{DM-A}}$

- Boosted incoming B

  ⇒ Relativistic outgoing e^-, p

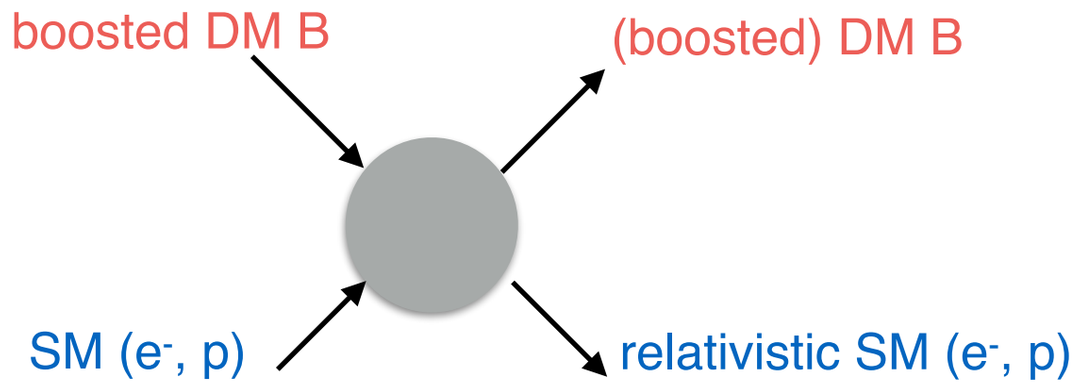


How to Search for Boosted DM?

- Mono-energetic (E_B=m_A), small flux $\propto n^2_{\mathrm{DM-A}}$

- Boosted incoming B

  ⇒ Relativistic outgoing e^-, p



What experiments?

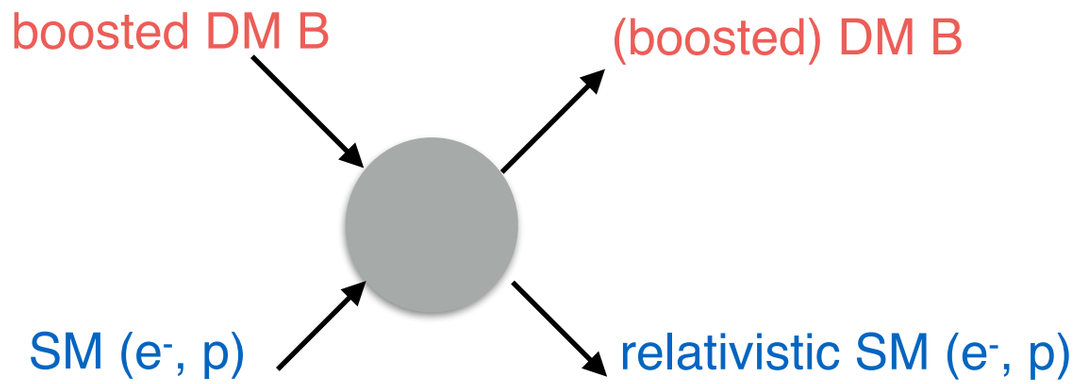
☞ Large volume detector + sensitive to energetic e^-, p

How to Search for Boosted DM?

- Mono-energetic (E_B=m_A), small flux $\propto n^2_{\mathrm{DM-A}}$

- Boosted incoming B

  ⇒ Relativistic outgoing e^-, p



What experiments?

Large volume detector + sensitive to energetic e^-, p

Experiments for neutrinos or proton decay!

- Based on Cherenkov-radiation:

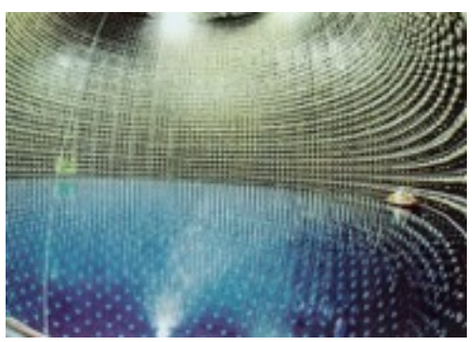
  SuperK/HyperK, IceCube/PINGU…

- Based on ionization: (next generation!)

  DUNE/LBNF… (liquid Argon)

IceCube

SuperK



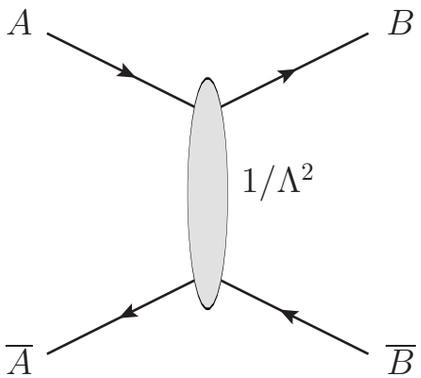
Search Strategy for Boosted DM

- A combination of conventional DM indirect and direct detections; e.g. Boosted DM from the GC:

Search Strategy for Boosted DM

- A combination of conventional DM indirect and direct detections; e.g. Boosted DM from the GC:

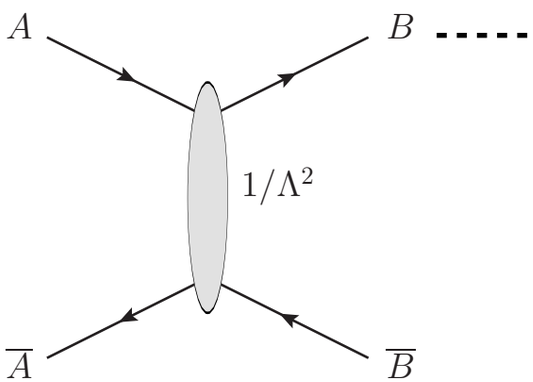
indirect



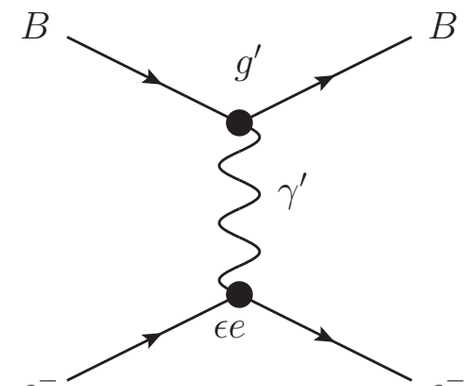
Search Strategy for Boosted DM

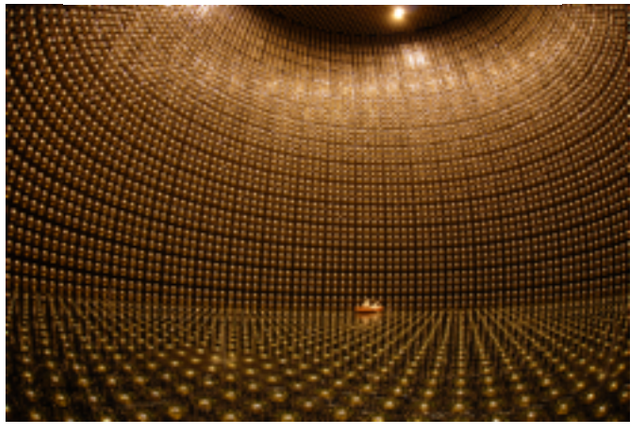
- A combination of conventional DM indirect and direct detections; e.g. Boosted DM from the GC:

indirect



direct

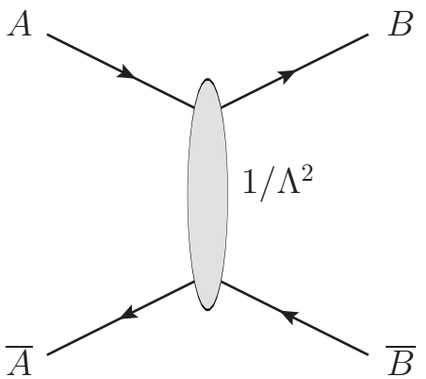




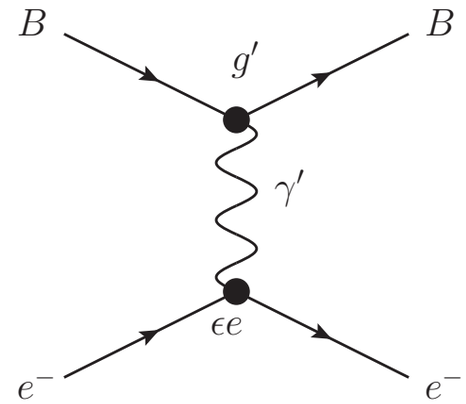
Search Strategy for Boosted DM

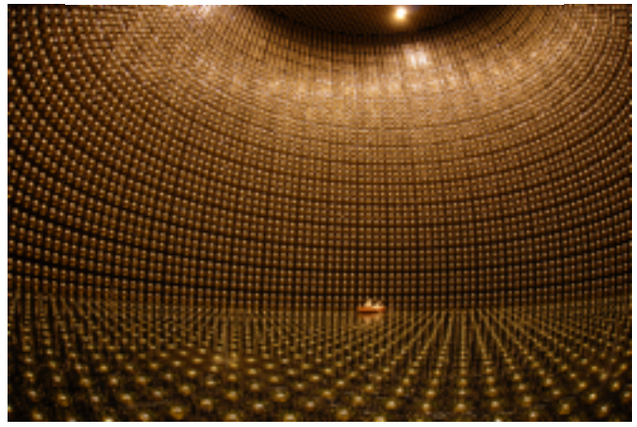
- A combination of conventional DM indirect and direct detections; e.g. Boosted DM from the GC:

indirect



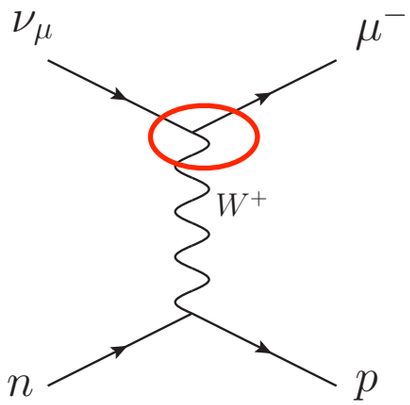
direct





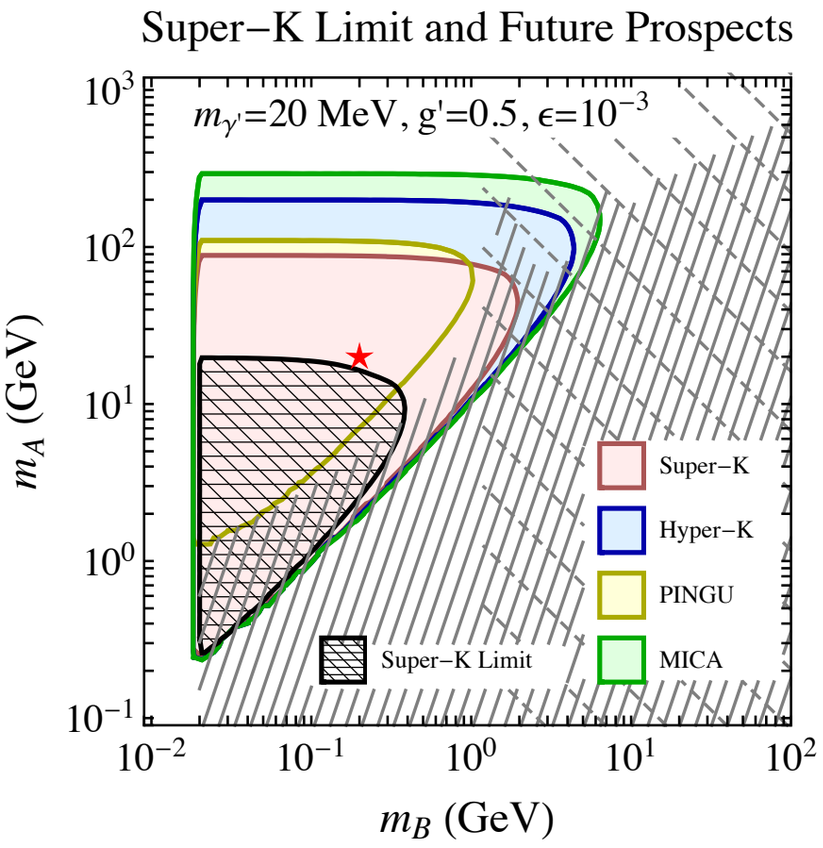
Distinguishable from ν !

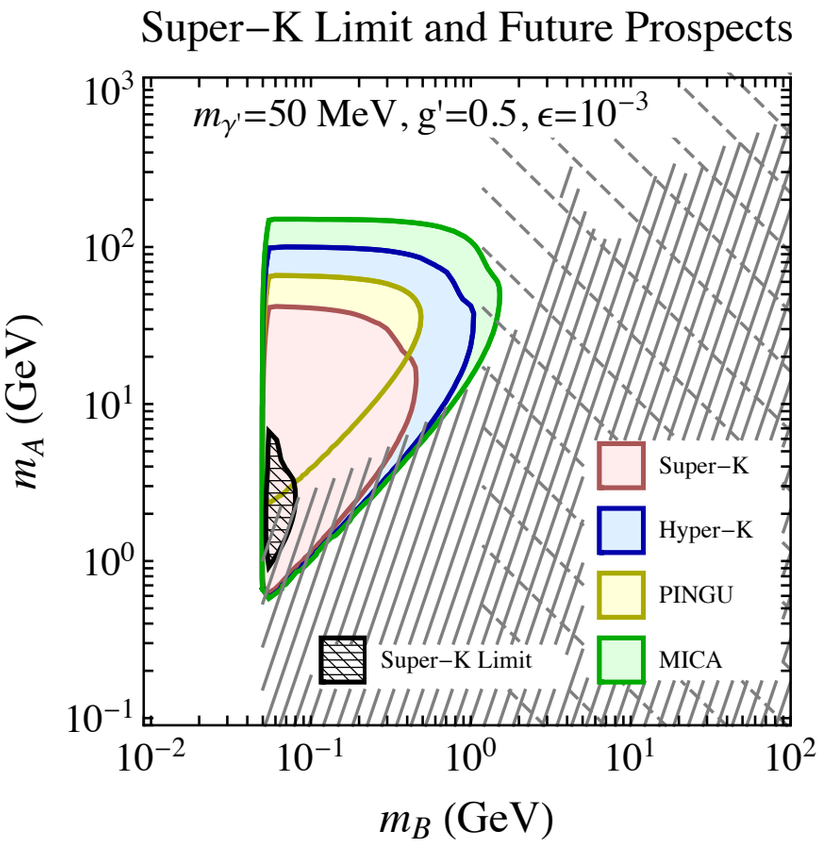
- Directionality
- No charge current interaction (e.g. muon veto)



Analysis, Prospect

- Exclusion from Super-K all-sky data
- Sensitivity projections for various experiments





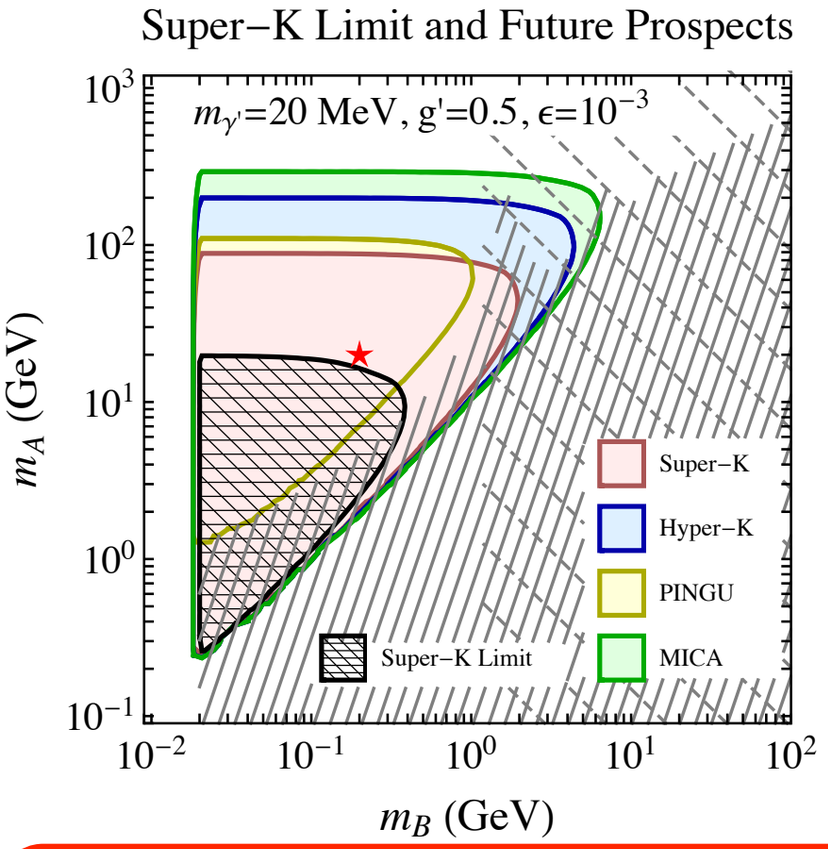
Model-dependent constraints (light grey lines ✓):

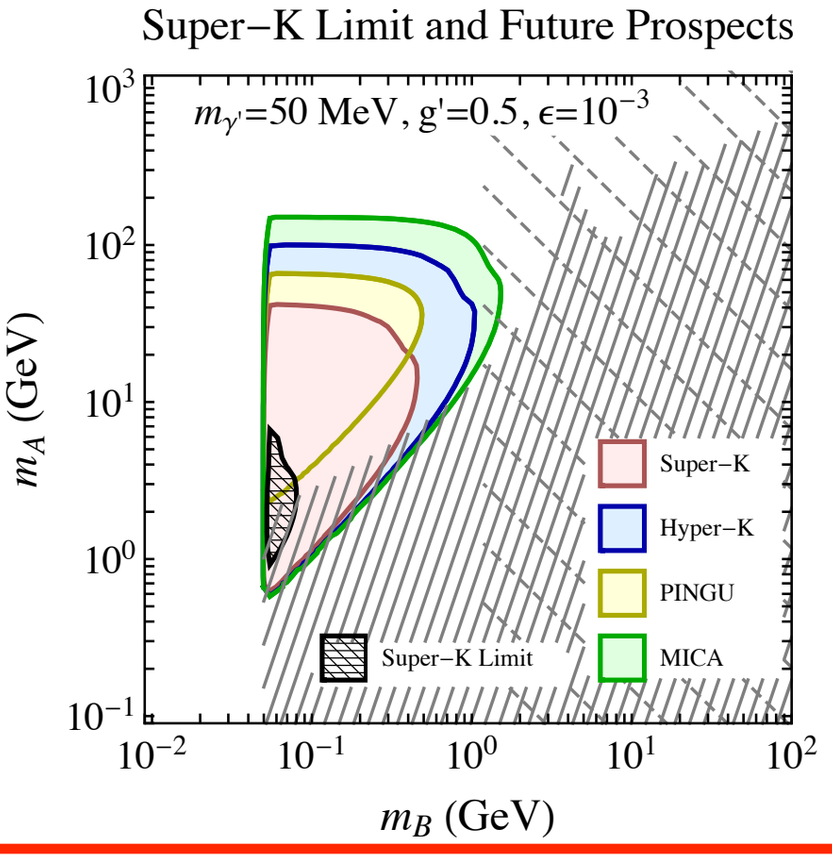
- Dark photon search
- Direct detection of DM A, B ✓
- CMB heating/BBN from thermal B annihilation ✓
- DM search at colliders

…

Analysis, Prospect

- Exclusion from Super-K all-sky data
- 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

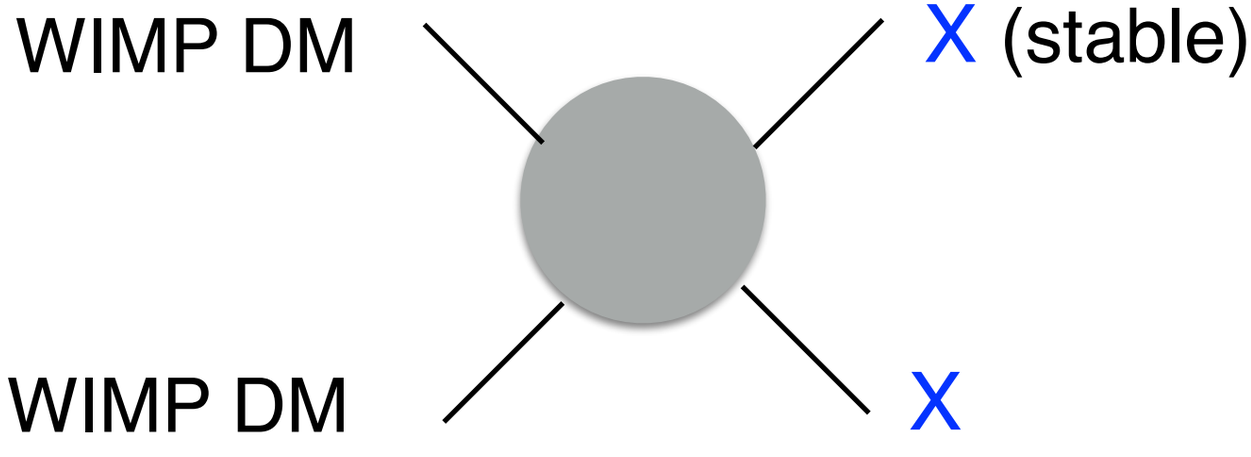
...

- **Boosted DM**: New scientific goal for neutrino experiments
  - direct detection of DM sector!
- Substantial interest from neutrino physicists, collaborations

(Super-K/Hyper-K, Microboone/DUNE)

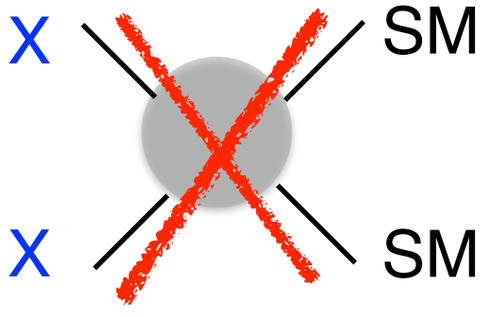
A New Realization of WIMP DM Miracle

- Episode #2



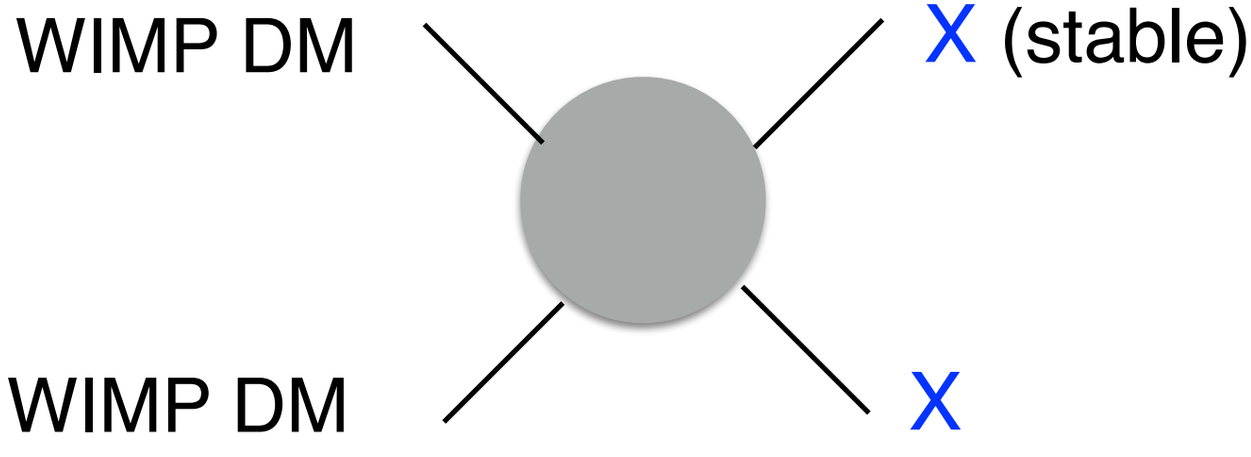
Case-2 :
(nearly) Massless X

- $m_X \lesssim$ eV: Ω_X ✓, do not need further depletion/interaction w/SM!



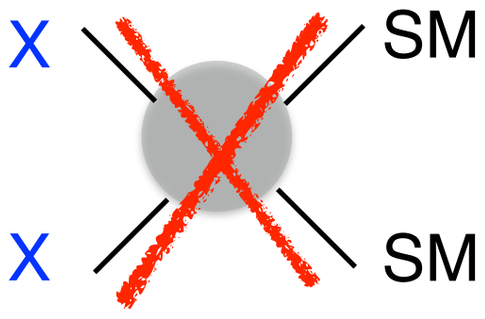
A New Realization of WIMP DM Miracle

- Episode #2



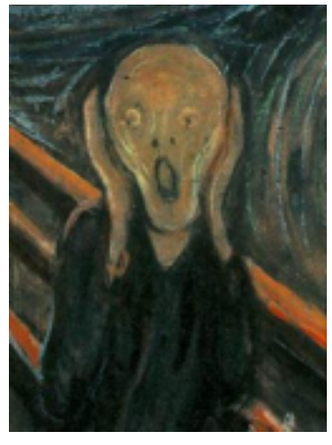
Case-2 :
(nearly) Massless X

- $m_X \lesssim$ eV: Ω_X ✓, do not need further depletion/interaction w/SM!



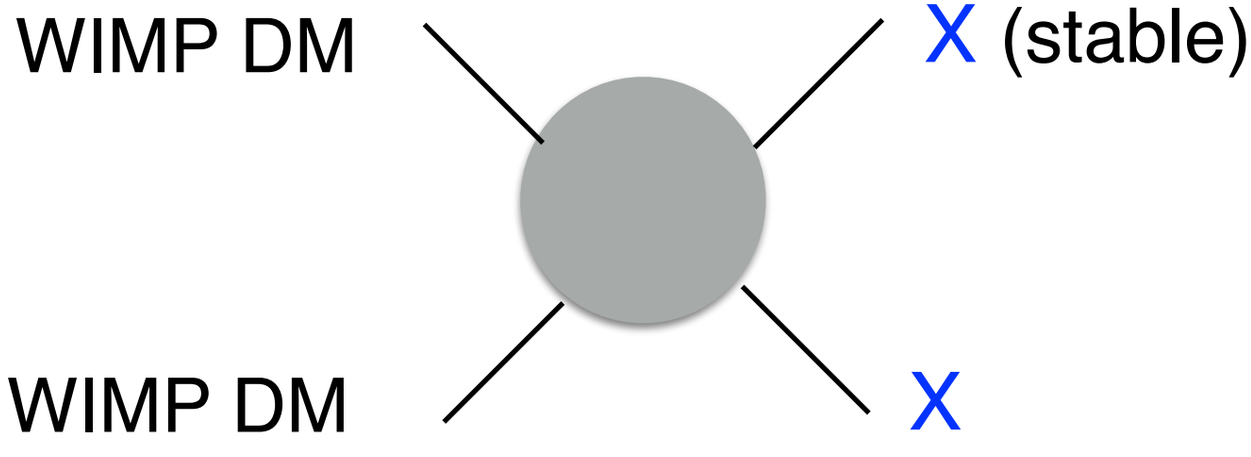
Nightmare for discovery?

(gravity…)



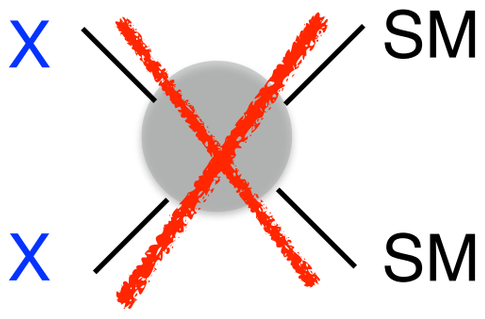
A New Realization of WIMP DM Miracle

- Episode #2



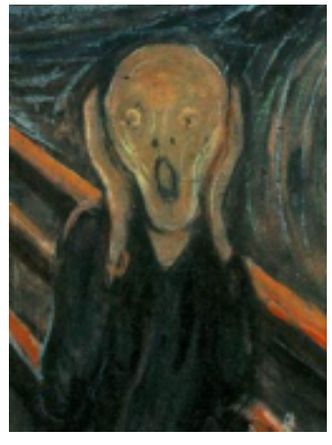
Case-2 :
(nearly) Massless X

- $m_X \lesssim$ eV: Ω_X ✓, do not need further depletion/interaction w/SM!

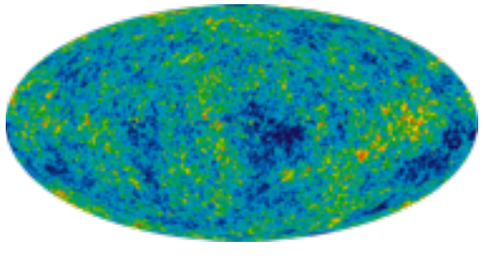


Nightmare for discovery?

(gravity…)



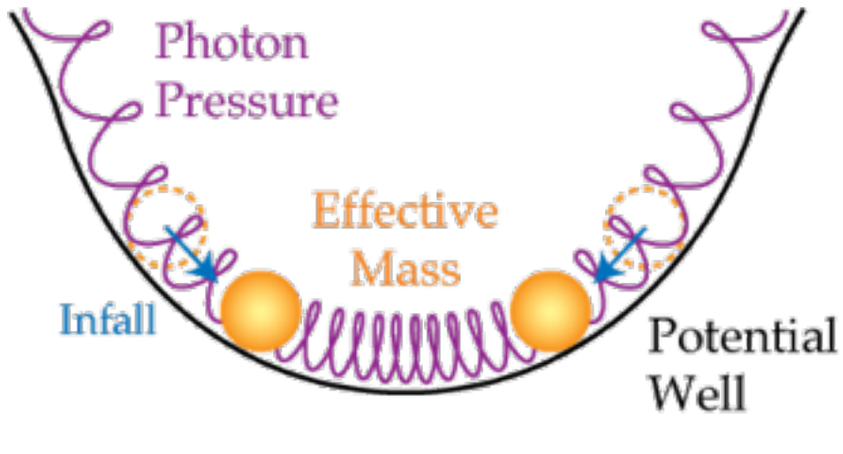
☞ *X* is relativistic, **dark radiation** in the **Cosmic Microwave Background (CMB) !**



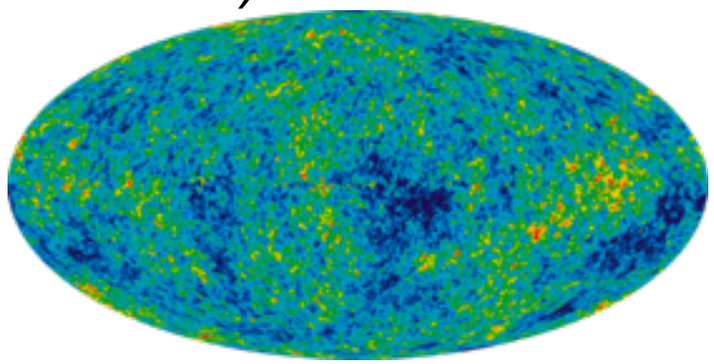
*(**YC** w/Chacko,Hong, Okui; Adshead, Shelton; Brust, Sigurdson)*

Dark Radiation in the CMB

Until~3.8×10^5 yrs after big bang:
photon-baryon fluid,
acoustic oscillation



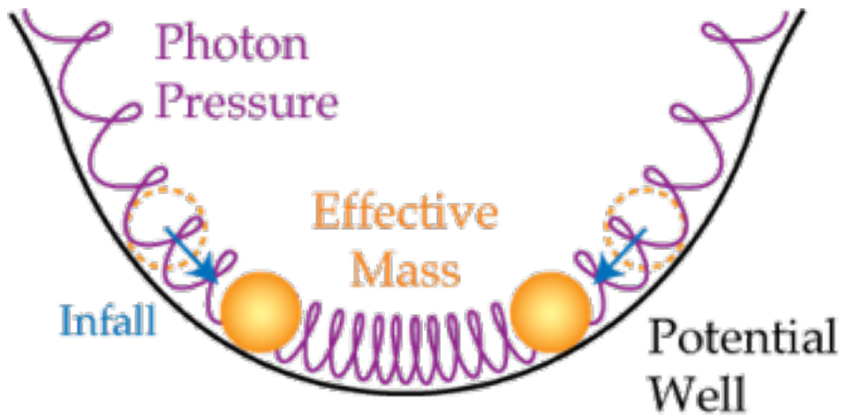
CMB: photon decouples from
baryon-γ fluid at $T\sim eV$
(2.7255 K)



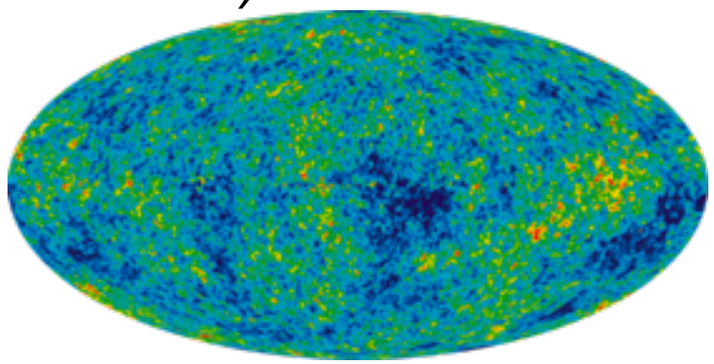
Cosmic fossil: cosmic sound waves!

Dark Radiation in the CMB

Until~3.8×10^5 yrs after big bang:
photon-baryon fluid,
acoustic oscillation

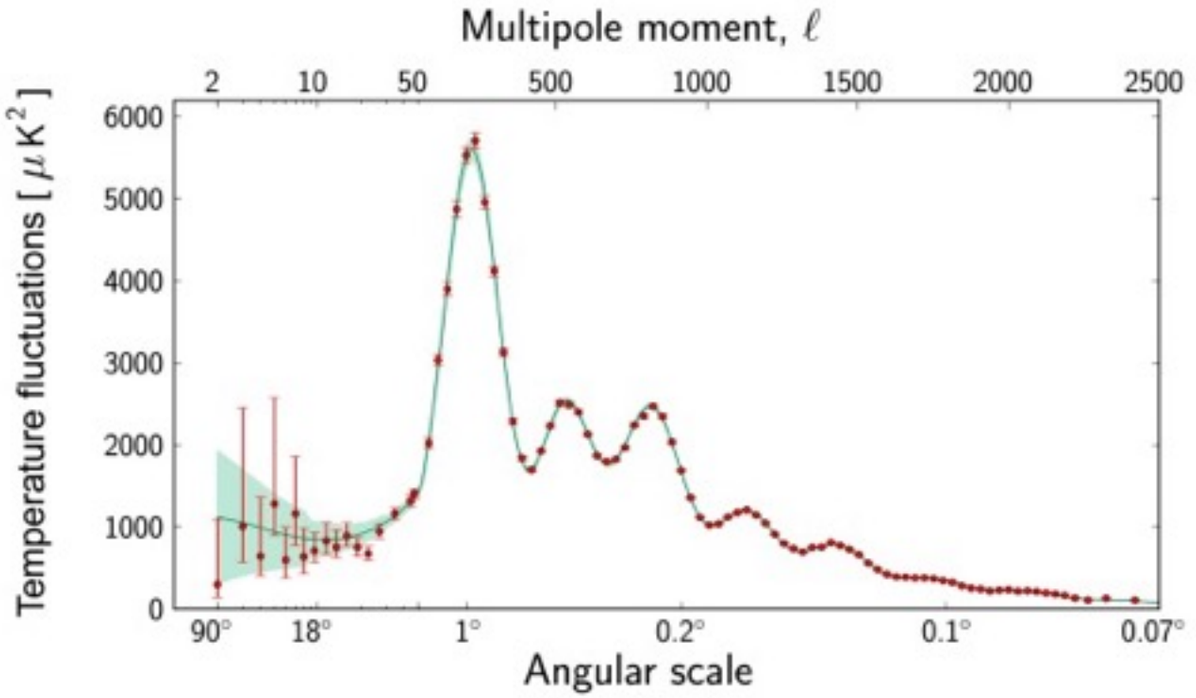


CMB: photon decouples from baryon-γ fluid at $T\sim eV$
(2.7255 K)



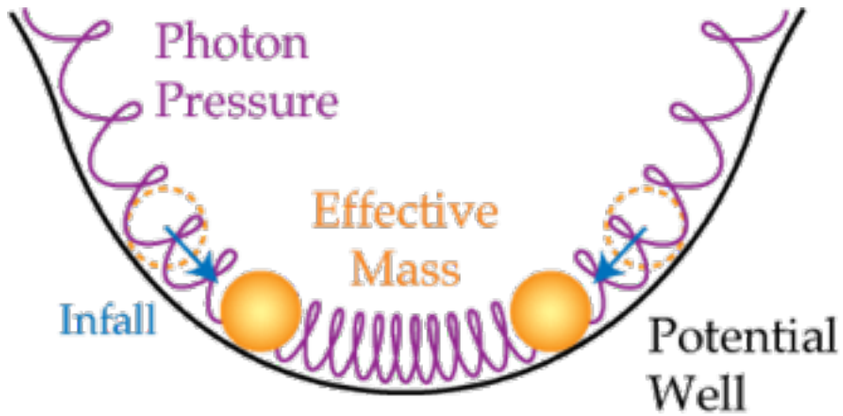
Cosmic fossil: cosmic sound waves!

CMB sky map → Fourier transform → CMB anisotropy spectrum

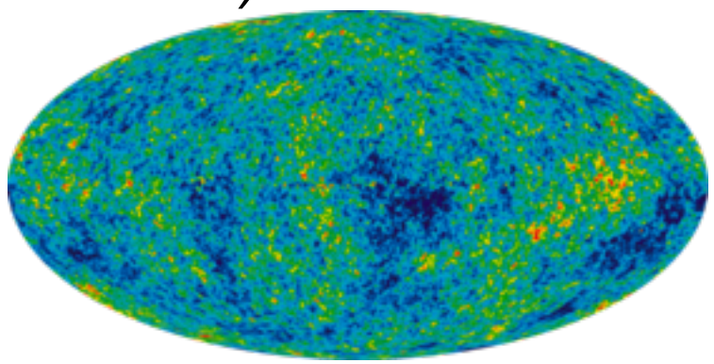


Dark Radiation in the CMB

Until~3.8×10^5 yrs after big bang:
photon-baryon fluid,
acoustic oscillation

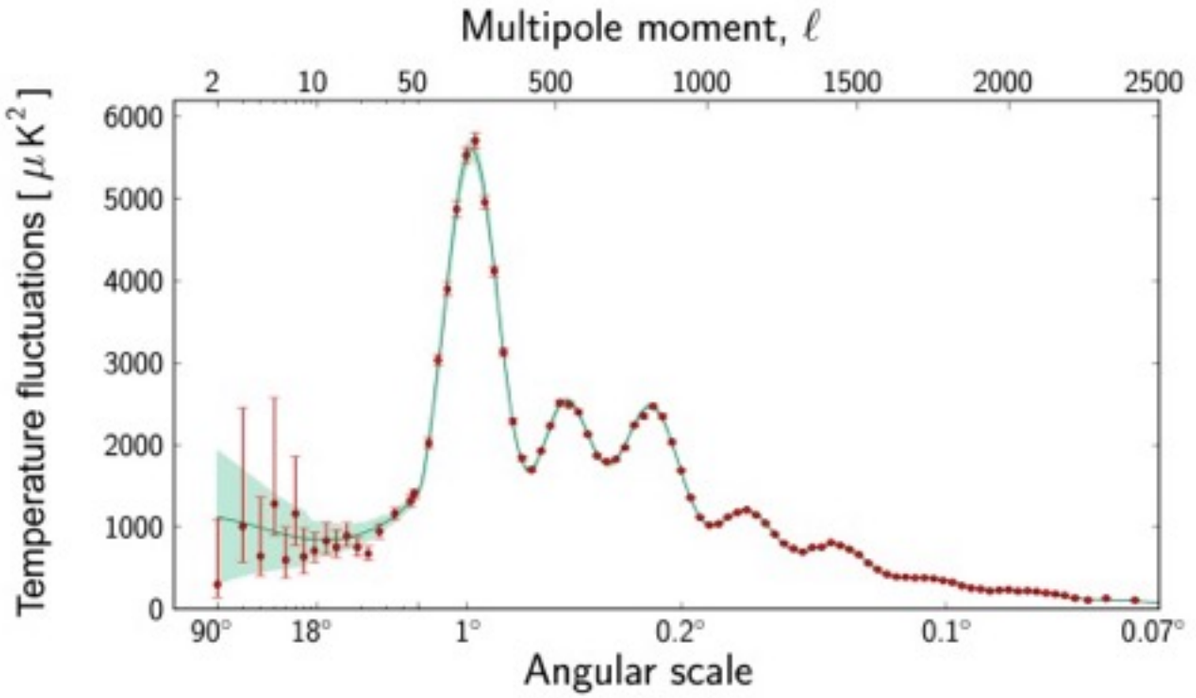


CMB: photon decouples from baryon-γ fluid at $T\sim eV$
(2.7255 K)



Cosmic fossil: cosmic sound waves!

CMB sky map —Fourier transform→ CMB anisotropy spectrum



Beyond the SM particle w/m≲T_{CMB}~eV

- Relativistic at CMB, $\rho_{rad}\uparrow$, $H_{CMB}\uparrow$
- Affect CMB spectrum by increasing effective neutrino number, ΔN_{eff}
  (N_{eff}=3.046 in SM)
  e.g. suppress high ℓ peak amplitude

Dark Radiation in the CMB

$$\Delta N_{\rm eff} = \rho_{\rm DR} : \rho_{1\nu}, \;\; \rho_{\rm DR} \propto g_{*\rm DR} T_{\rm DR}^4$$

- $g_{*\rm DR}$: Number of degrees of freedom in DR
- $T_{\rm DR}$: when dark sector and SM kinetically decouple

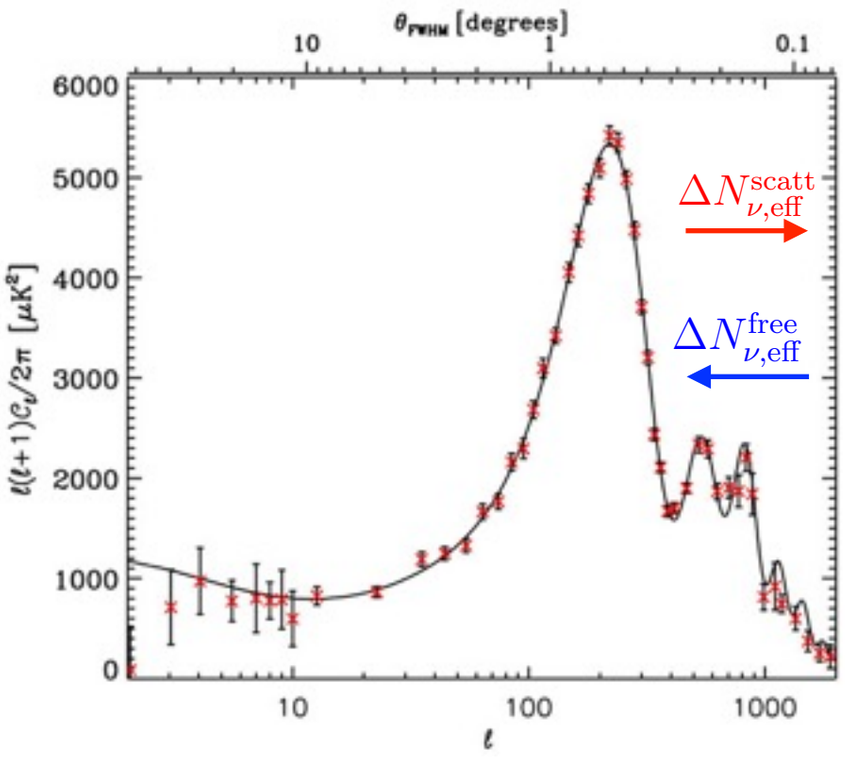
- **Does dark radiation interact at the CMB time?**
  - Free-streaming DR: $L_{mean\text{-}free} > H^{-1}$, e.g. SM neutrinos
    - Implicitly assumed in official expt. analysis (e.g. Planck)
  - Scattering (fluid-like) DR: $L_{mean\text{-}free} < H^{-1}$, generic in a dark sector
    - Not included! But…

Observable Difference Between the Two Types of DR

- Free streaming species: $v_{FS} > v_{sound}$ ⟶ σ: anisotropy in $T^{\mu\nu}$
- Observable effects increase with FS energy fraction: $f_\nu \equiv \dfrac{\rho_{\text{all free rad}}}{\rho_{\text{all rad}}}$

photon perturbation ← $\ddot{d}_\gamma - c_\gamma^2 \nabla^2 d_\gamma = \nabla^2 \Phi_+$ → Gravitational forcing; w/anisotropy, e.g. d_γ out of phase w.r.t free oscillating

✦ **Universal phase shift** of high ℓ peaks (SM **ν**: Bashinsky, Seljak 2003)



$$\Delta\ell \equiv \delta\ell - \delta\ell\big|_{\rm SM}$$

$$= -57\left(f_\nu - f_\nu\big|_{\rm SM}\right)\frac{\ell_{\rm A}}{300}$$

Opposite sign!

$$\simeq -7.8\left(0.59\Delta N_{\rm eff}^{\rm free} - 0.41\Delta N_{\rm eff}^{\rm scatt}\right)\frac{\ell_{\rm A}}{300}$$

(**YC**, w/Chacko, Hong, Okui 2015)

Add free-streaming DR ⟶ f_ν ↑

Add scattering DR ⟶ f_ν ↓

Cosmological Constraints on Interacting Light Particles

(**YC** with Brust and Sigurdson, JCAP, arXiv: 1703.10732)

- Two param fit: N_{fld}, N_{eff}
- More robust/physical param: f_{fs}, N_{tot}

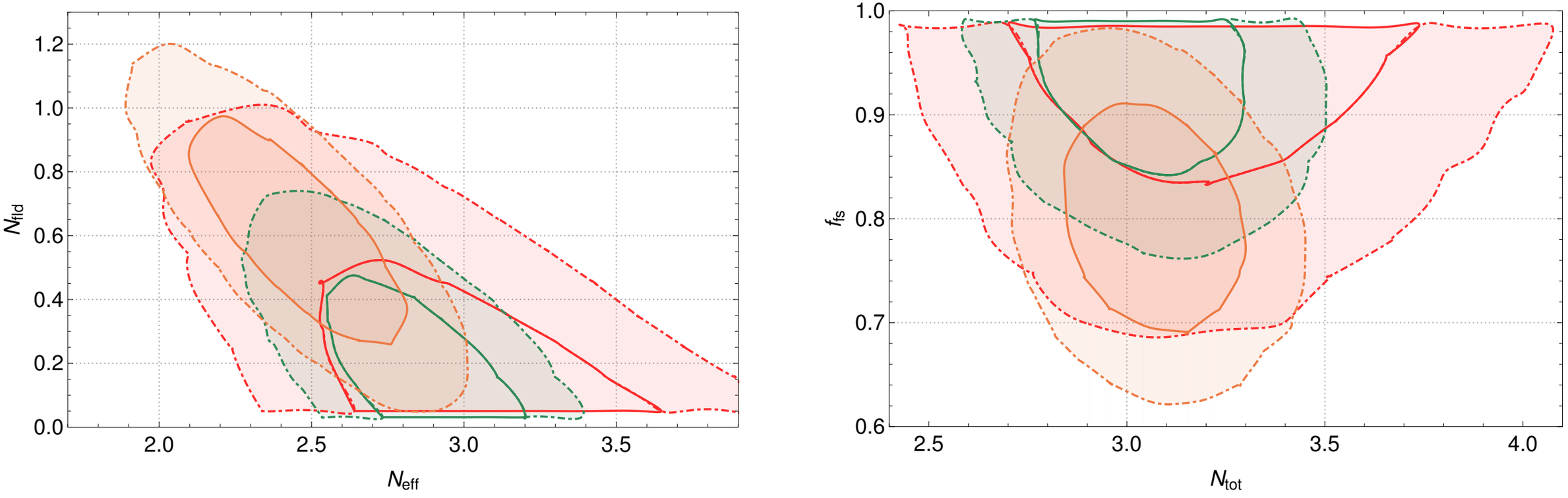


Figure 2. Here we show two different 2d posteriors for three of the five scans (Planck T, Planck P+BAO, and Planck P+BAO+H_0+LSS). The solid lines are 1σ contours, and the dot-dashed lines are 2σ contours. The posteriors in the top figure exhibit degeneracy between $N_{\rm eff}$ and $N_{\rm fld}$, motivating the parametrization in terms of $N_{\rm tot}$ and $f_{\rm fs}$ in the bottom figure, and demonstrating that the strongest constraints arise on the sum $N_{\rm tot}$.

(also see: Baumann, Green, Meyers, Wallisch *v2*)

$$\Delta N_{\rm tot} \; < \; 0.39 \;\; \text{at} \;\; 2\sigma$$

A Theoretical Benchmark for Dark Radiation Search with CMB

(**YC** w/Adshead, Shelton, 2016)

- If a dark sector is ever **in thermal equilibrium** with SM
  ⇒**A lower limit on ΔN_{eff}** ! *(insensitive to dark sector details!)*

$$\Delta N_{\rm eff} = \frac{\hat{g}_* \hat{T}^4}{\frac{7}{4} T_\nu^4} = 2.2 \hat{g}_* \left(\frac{\hat{g}_*}{g_*} \frac{g_{*\rm kd}}{\hat{g}_{*\rm kd}} \right)^{-4/3}$$

$T_{\rm SM} = T_{\rm HS}$ ever

$$\Delta N_{\rm eff} \geq 0.027$$

$\Delta N_{\rm eff}$

$\frac{g_{*\rm kd}}{\hat{g}_{*\rm kd}}$

SM: $g_{*\rm kd} \leq 106.75$

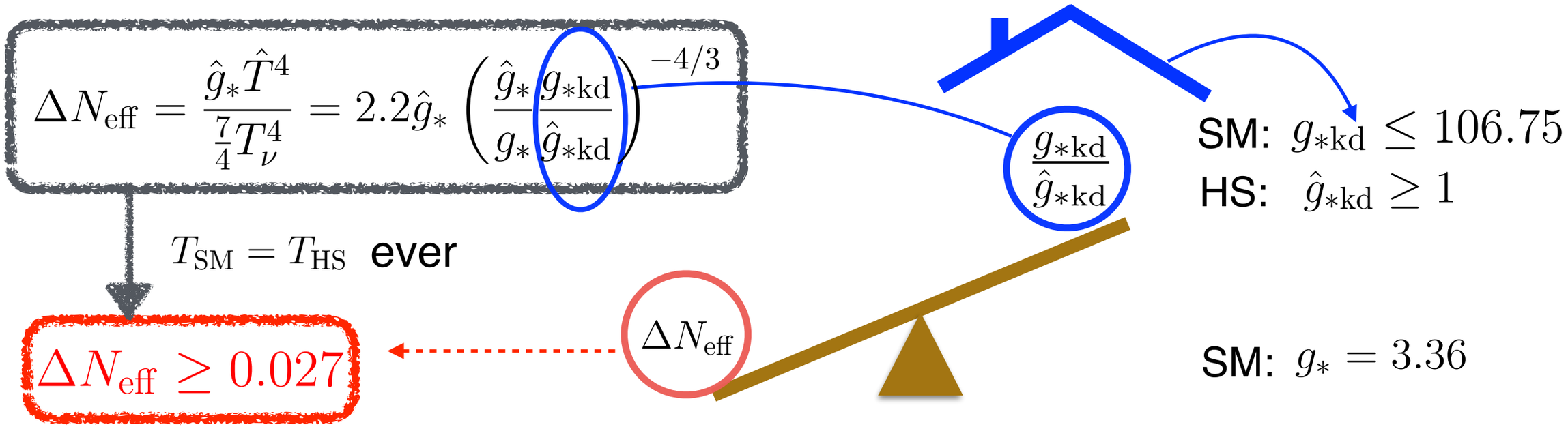
HS: $\hat{g}_{*\rm kd} \geq 1$

SM: $g_* = 3.36$

A Theoretical Benchmark for Dark Radiation Search with CMB

(**YC** w/Adshead, Shelton, 2016)

- If a dark sector is ever **in thermal equilibrium** with SM
  ⇒**A lower limit on ΔN_{eff}** ! *(insensitive to dark sector details!)*

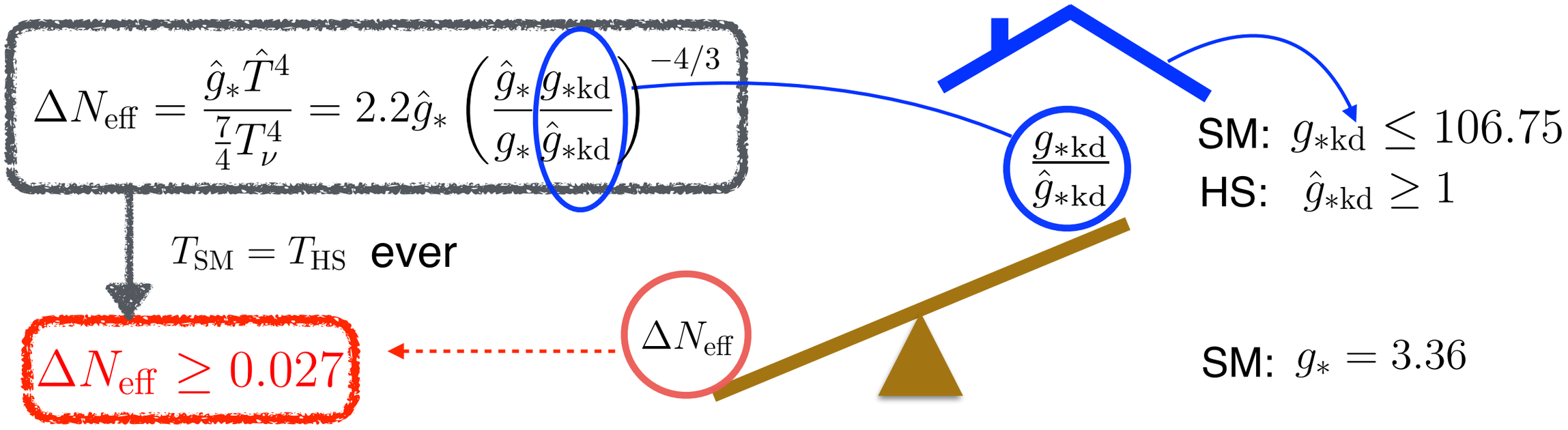


- *(preliminary) Forecast for future CMB-S4?* $\sigma(N_{\rm eff}) \approx 0.015 - 0.03$

A Theoretical Benchmark for Dark Radiation Search with CMB

(**YC** w/Adshead, Shelton, 2016)

- If a dark sector is ever **in thermal equilibrium** with SM
  ⇒**A lower limit on ΔN_{eff}** ! *(insensitive to dark sector details!)*

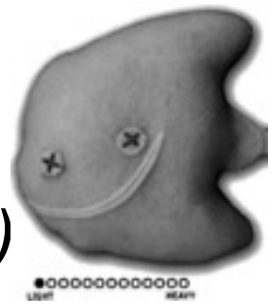


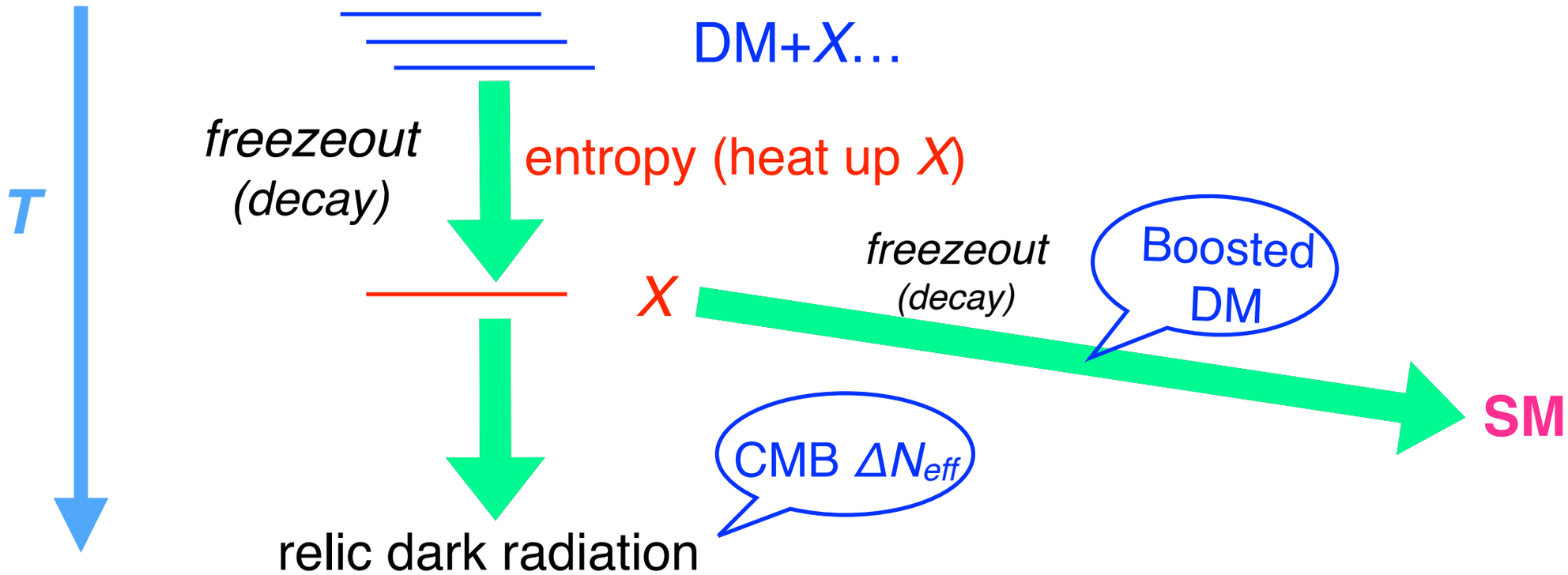
- *(preliminary) Forecast for future CMB-S4?* $\sigma(N_{\rm eff}) \approx 0.015 - 0.03$
  - Likely able to discover or exclude ***any*** hidden dark sector once in equilibrium with SM!
  - Timely theoretical motivation/benchmark for setting performance goal of CMB-S4

A Unified Picture of Thermal DM

- **A universal guideline:**

  Last carrier of the dark sector entropy, e.g. the ***X***,
  analogous to SM γ, ν! *(generalized concept of dark radiation)*

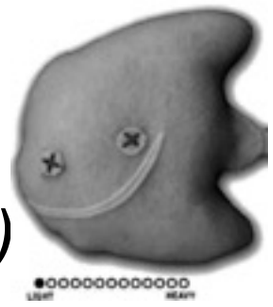


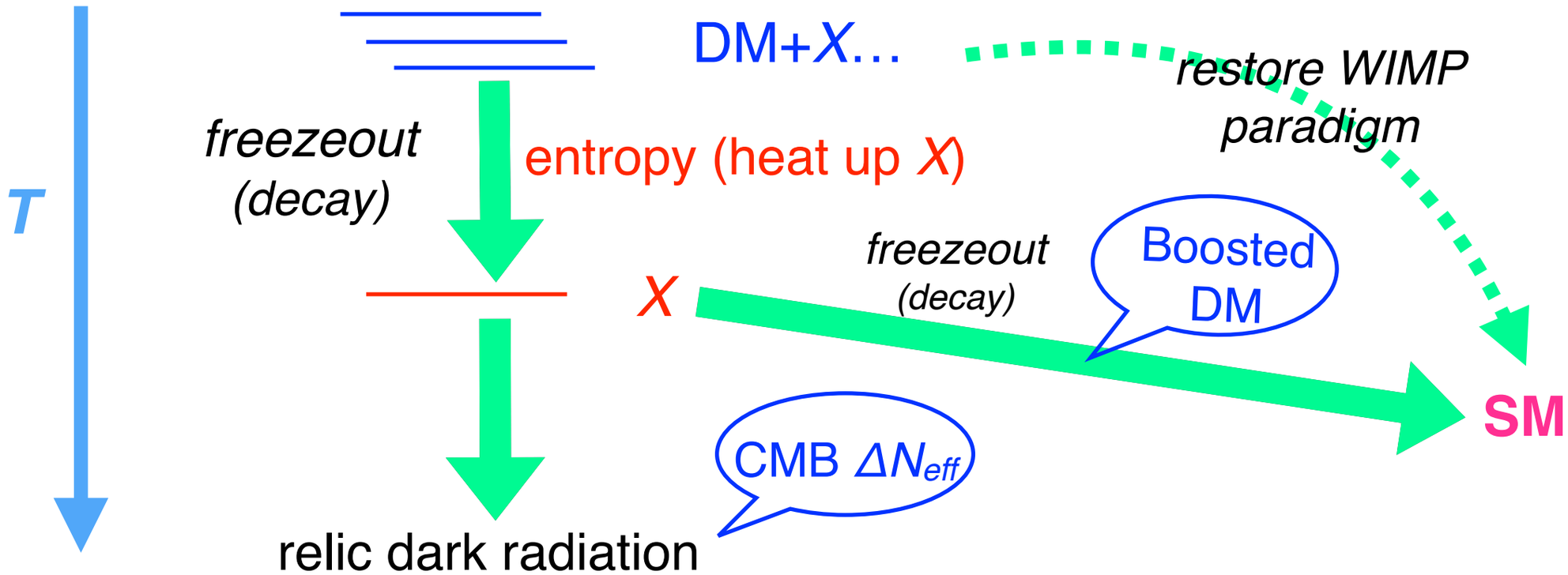


A Unified Picture of Thermal DM

- **A universal guideline:**

  Last carrier of the dark sector entropy, e.g. the ***X***,
  analogous to SM γ, ν! *(generalized concept of dark radiation)*

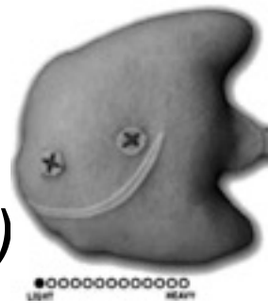


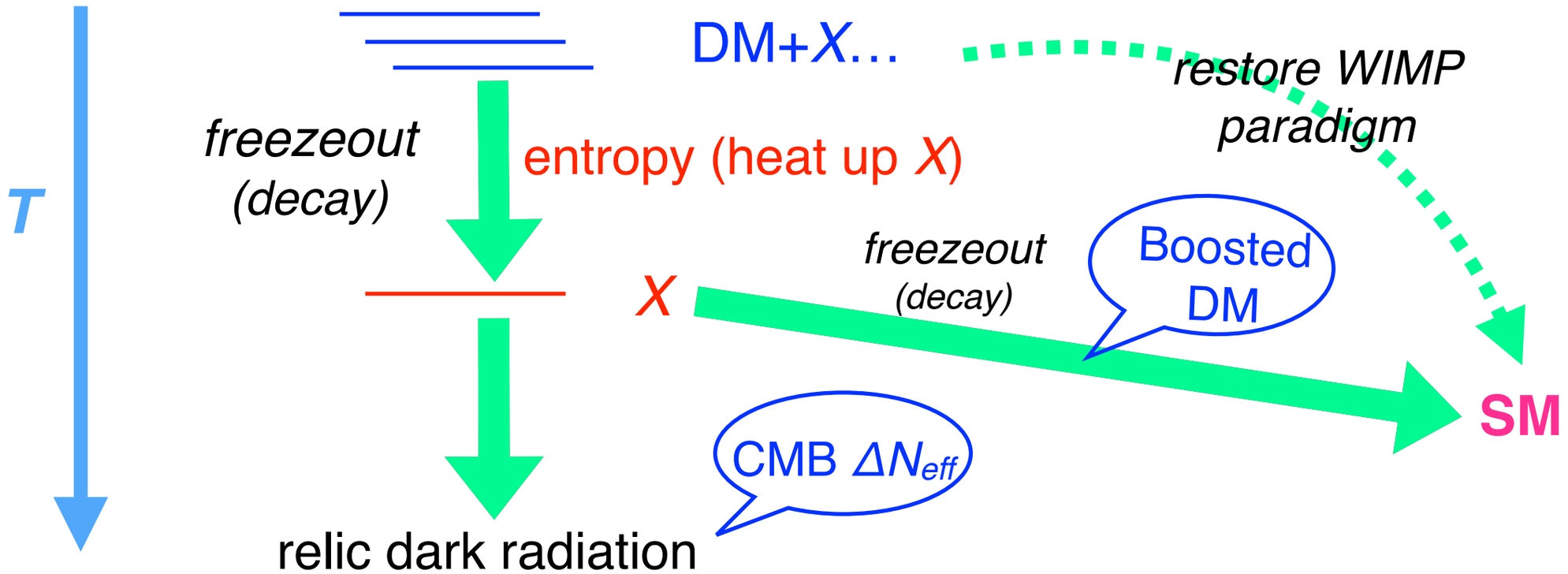


A Unified Picture of Thermal DM

- **A universal guideline:**

  Last carrier of the dark sector entropy, e.g. the ***X***,
  analogous to SM γ, ν! *(generalized concept of dark radiation)*





- ***X*** : subdominant abundance, $\Omega_X < \Omega_{DM}$
  yet plays an important cosmological role!
- ***X***: may be the **smoking-gun** for the whole dark sector!
  New observational directions!

Conclusion/Outlook

- **Thermal Dark Sectors:** motivated scenario
  - Systematic studies feasible, despite complexity
  - New directions for DM searches: neutrino experiments, CMB, (structure formation)…
- **Further directions:**
  - General studies on non-gravitational signatures of dark radiation (e.g. with DM direct detection, work in prep)
  - Effects of DM-DR interaction on CMB, LSS:
    - Partially Acoustic Dark Matter (PAcDM) (YC with Chacko, Hong, Okui and Tsai, arxiv: 1609.03569, JHEP): H_0, σ_8
    - Non-thermal injection of DR from DM annihilation (work in progress)

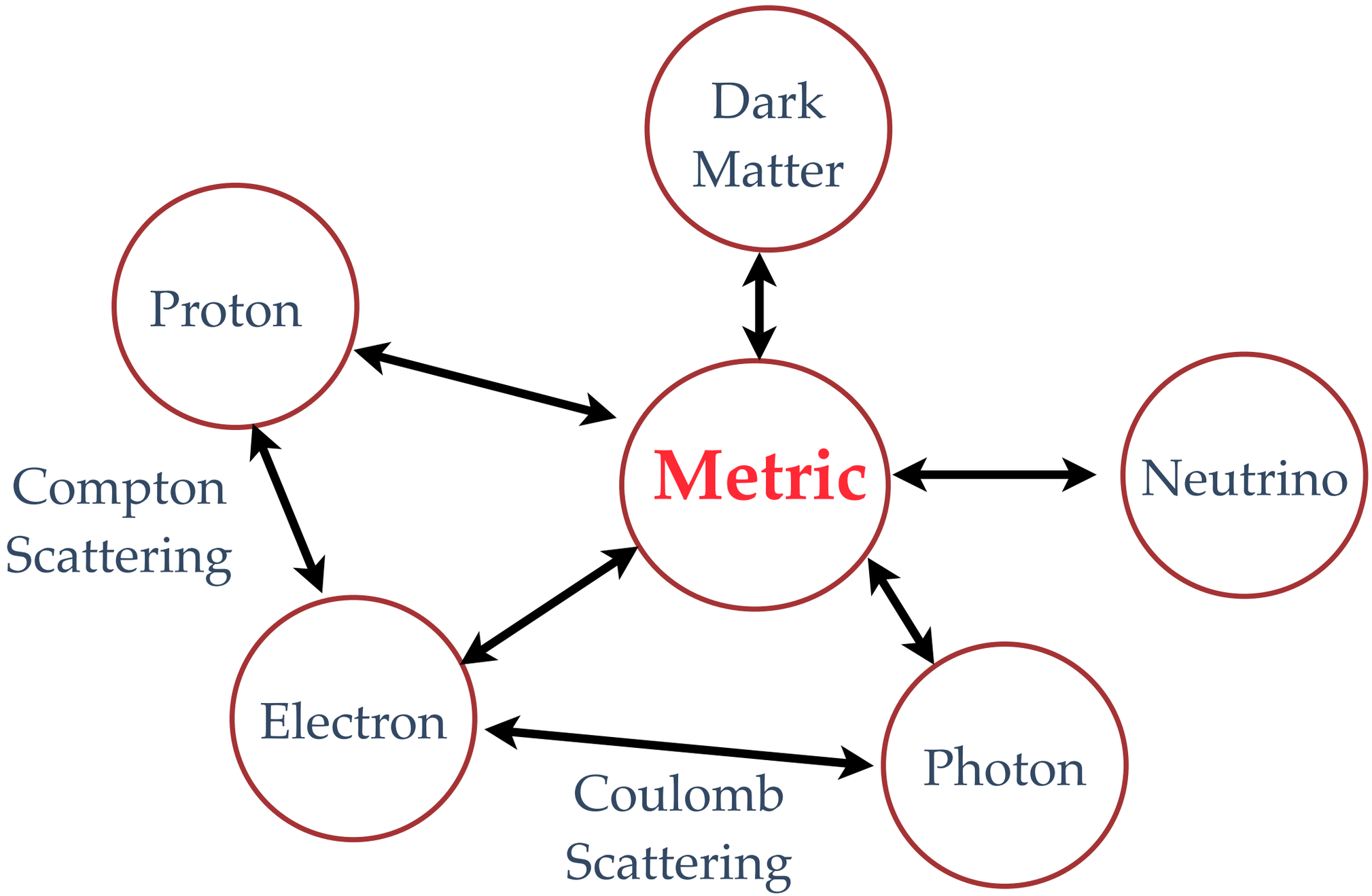
Backup Slides

Nightmare scenario (?):
What if DM/DS does not couple to SM?

Nightmare scenario (?):

What if DM/DS does not couple to SM?

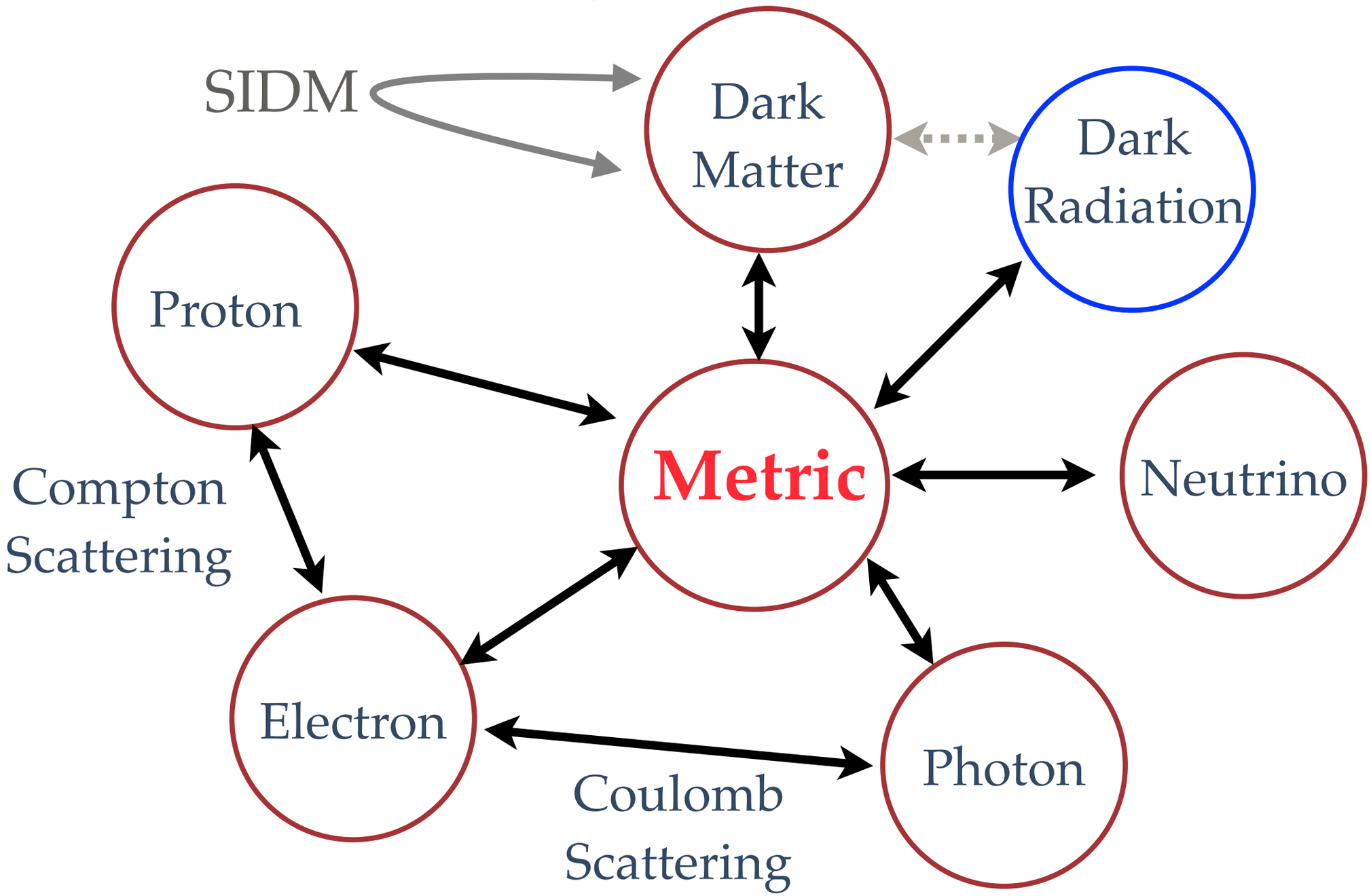
No, everything couples to gravity!



Nightmare scenario (?):

What if DM/DS does not couple to SM?

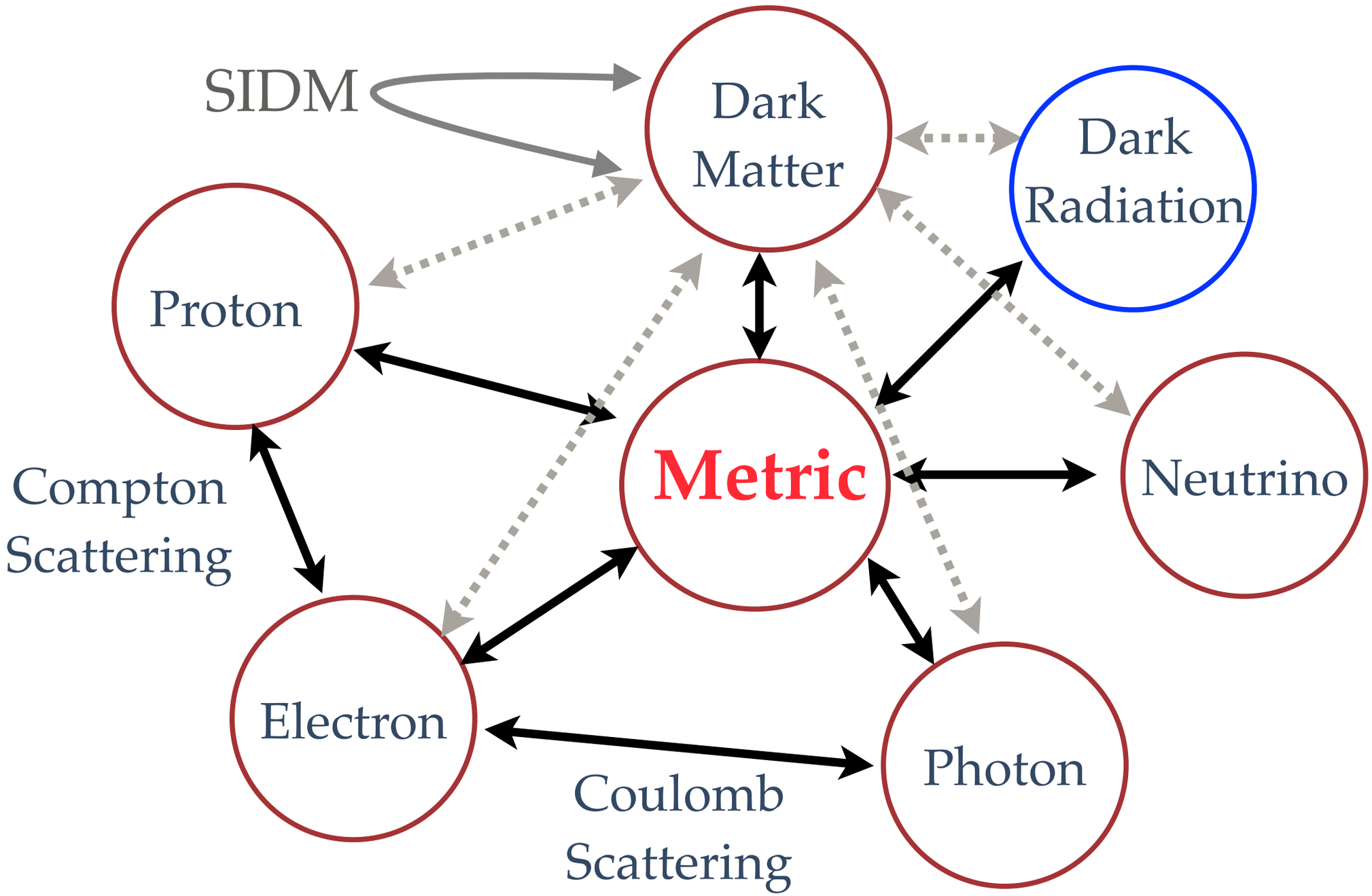
No, everything couples to gravity!



Nightmare scenario (?):

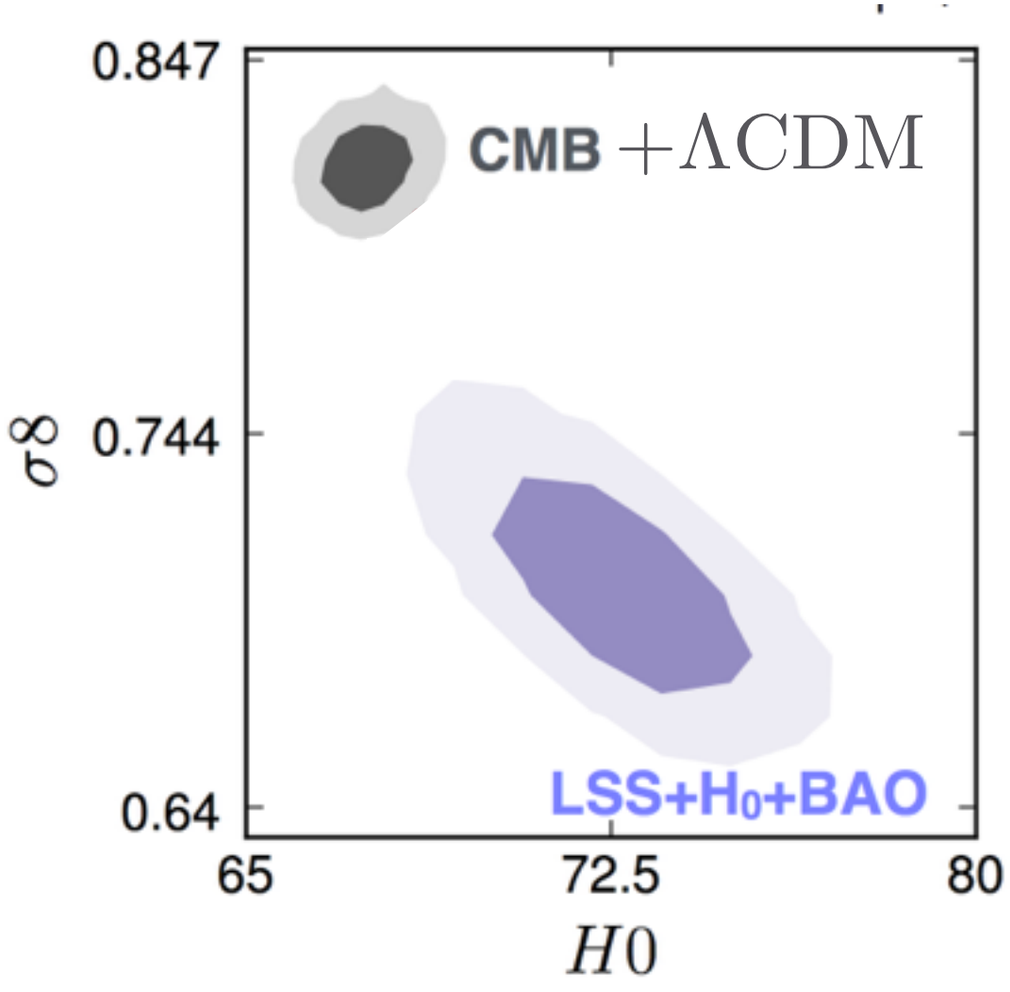
What if DM/DS does not couple to SM?

No, everything couples to gravity!



Puzzles from Large Scale Structure

Poulin et. al. 1606.02073



Comparing to ΛCDM model,
we want to obtain a

- Smaller density perturbation
- Larger Hubble expansion rate

at the late time universe