

Title: New Observational Windows for Probing Dark Sectors

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Abstract:

New Observational Windows for Probing Dark Sectors



Yanou Cui

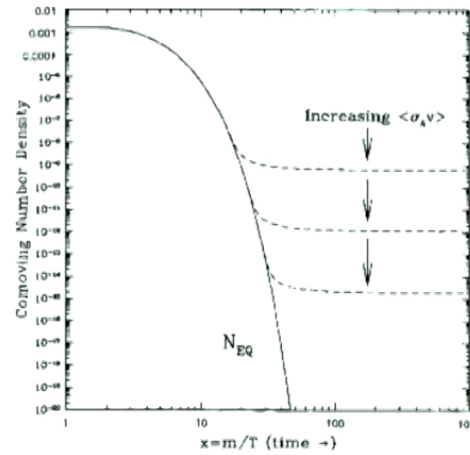
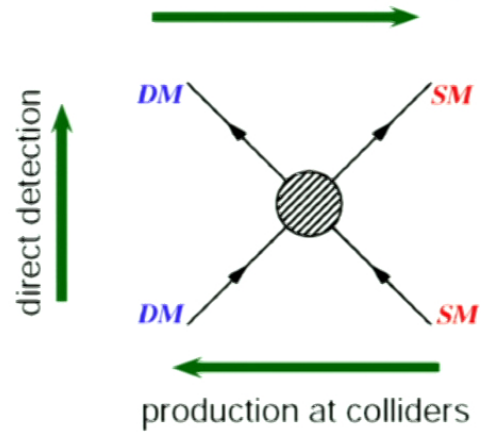
UC Riverside



*PI Dark Matter workshop
July 20, 2017*

The Challenges with the WIMP DM Paradigm

☞ thermal freeze-out (early Univ.)
indirect detection (now)



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

$$\sim 0.1 \left(\frac{G_{\text{Fermi}}}{G_{\chi}}\right)^2 \left(\frac{M_{\text{weak}}}{m_{\chi}}\right)^2$$

WIMP Miracle!

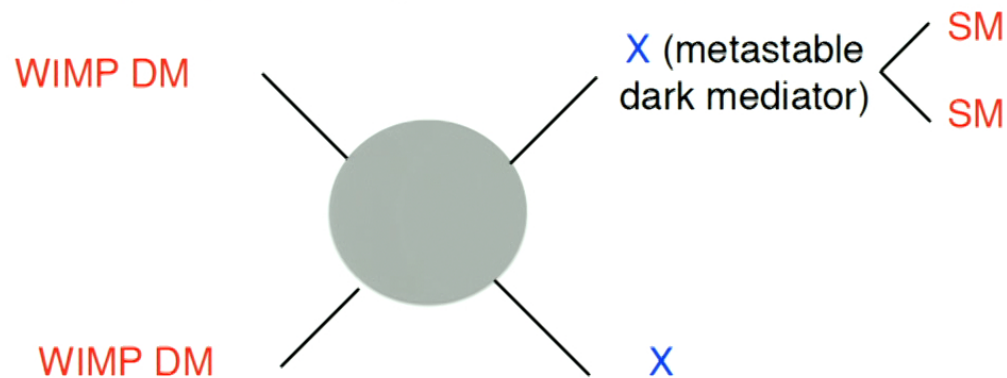
Simple Variations of WIMP Miracle

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

Simple Variations of WIMP Miracle

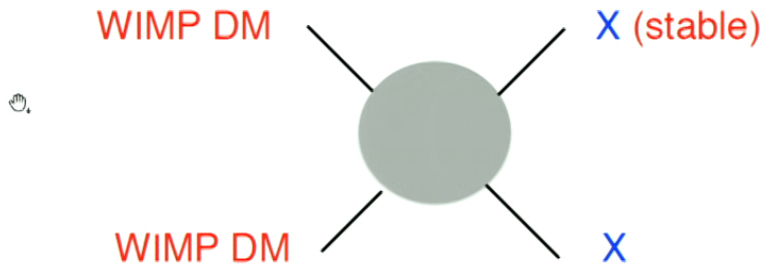
- **Decouple DM thermal relic abundance from coupling to the SM**

e.g. *Secluded Dark Matter*
(Pospelov, Ritz, Voloshin 2007)



Safely evade direct detection, subject to indirect detection

A New Realization of WIMP DM Miracle



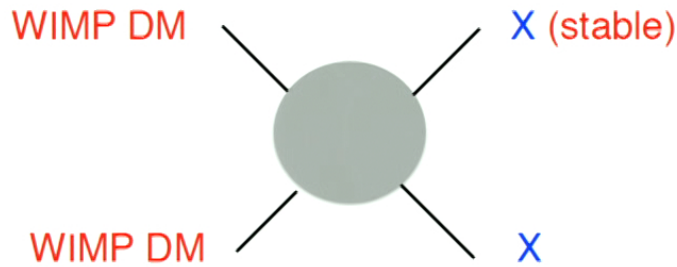
- **Determines Ω_{DM} !**

WIMP miracle intact!

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

- *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!

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- *What is X?*

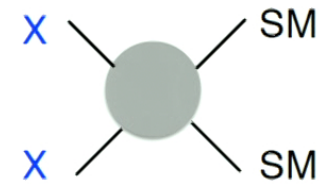
▶ $m_X \gtrsim eV$: $\Omega_X > 1$ → deplete X via annihilation → SM

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

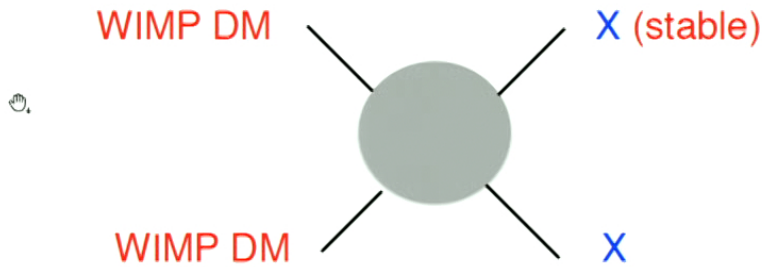
at neutrino experiments (YC w/Agashe, Necib, Thaler; YC w/Berger, Zhao)

▶ $m_X \lesssim eV$: $\Omega_X \checkmark$ → relativistic, **dark radiation** in the **CMB**

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



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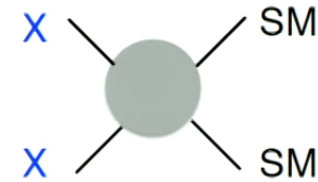
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Dark matter lives in a non-minimal hidden sector!

(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 $\sim 25\%$ of our universe?

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Too “complicated”? Occam’s razor?



Occam’s Razor: No more things should be presumed to exist than are absolutely necessary, i.e., the fewer assumptions an explanation of a phenomenon depends on, the better the explanation.

(William of Occam)



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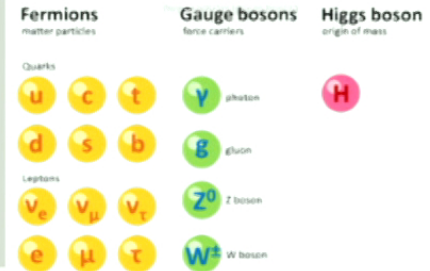


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Shave our SM??



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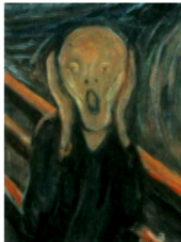


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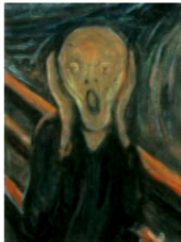
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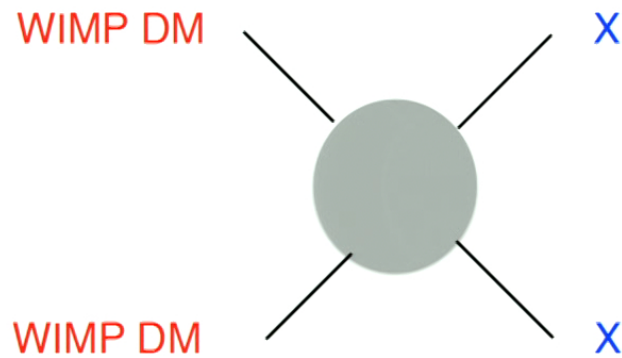
- ✓ Universal guidelines
- ✓ New observational windows!
(this talk...)



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

$(DM \rightarrow DM A, X \rightarrow DM B)$

6

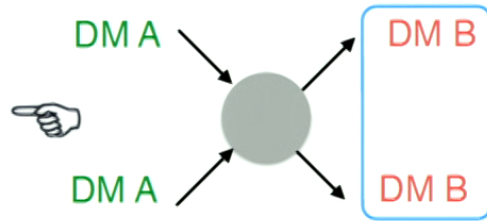
Boosted Dark Matter



• Key Processes



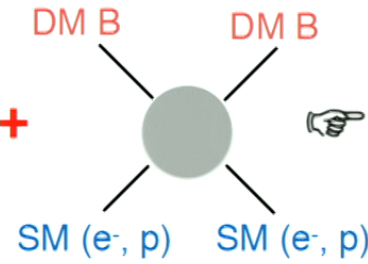
- Ω_A
- Current-day annihilation



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

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

+



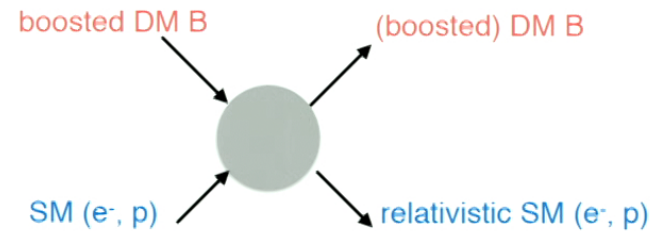
- Deplete Ω_B
- B-SM scattering - detectability!

How to Search for Boosted DM?

- Mono-energetic ($E_B=m_A$), **small flux** $\propto n_{\text{DM}-A}^2$

☞

- Boosted incoming B
⇒ **Relativistic outgoing e^- , p**



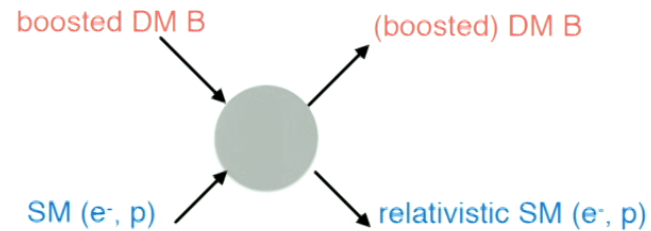
(e.g. Cherry, Brandson, Shoemaker 2015)

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What experiments?



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

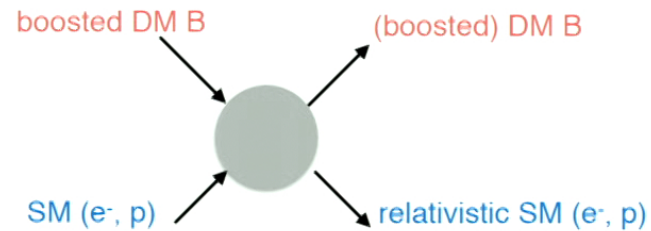
(Conventional DM direct detection 😞, BUT good for light (sub-)GeV DM!)
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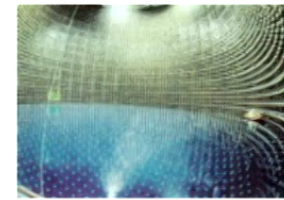
Experiments for neutrinos or proton decay!

- Based on Cherenkov-radiation:
 SuperK/HyperK, IceCube/PINGU...
- Based on ionization: (next generation!)
 DUNE/LBNF... (liquid Argon)

IceCube



SuperK

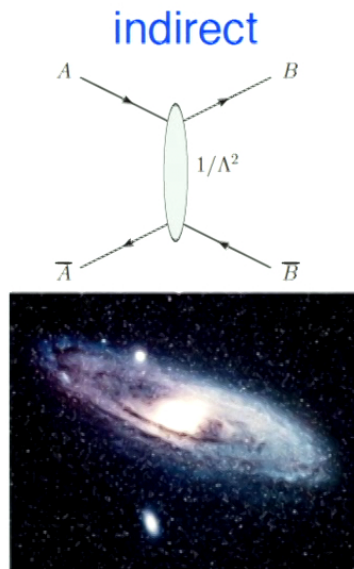


Search Strategy for Boosted DM

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

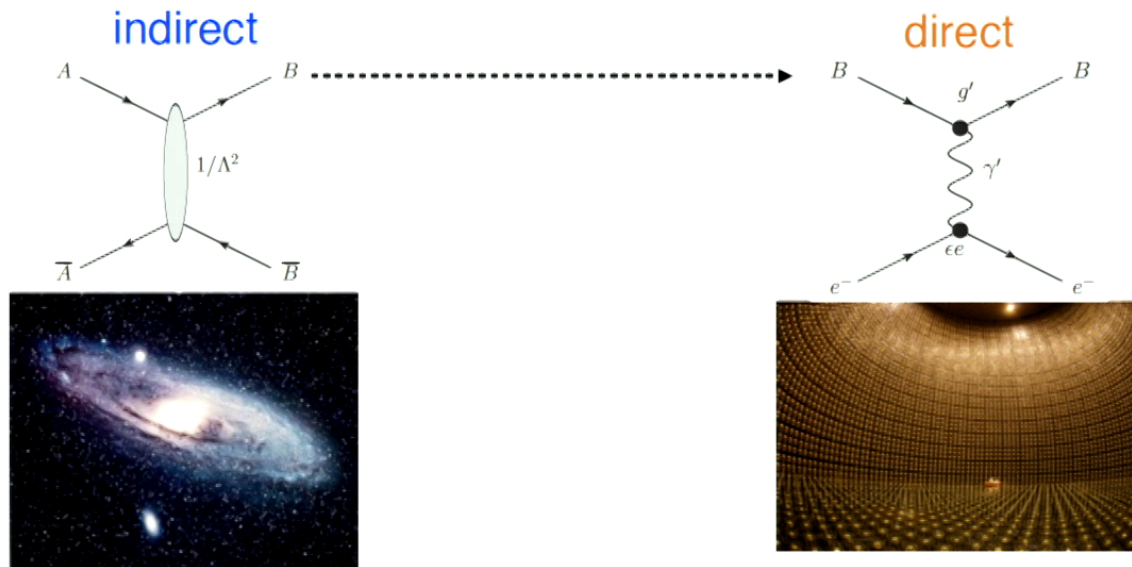
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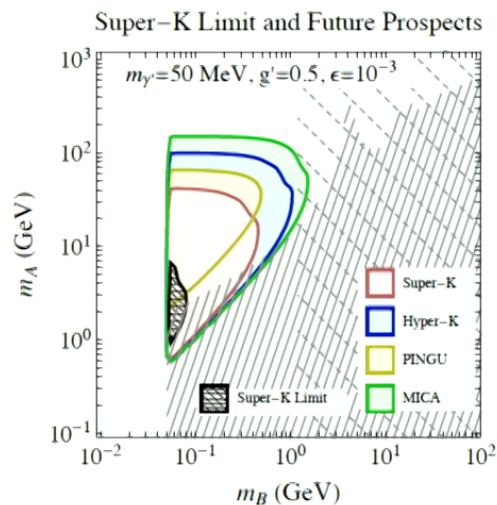
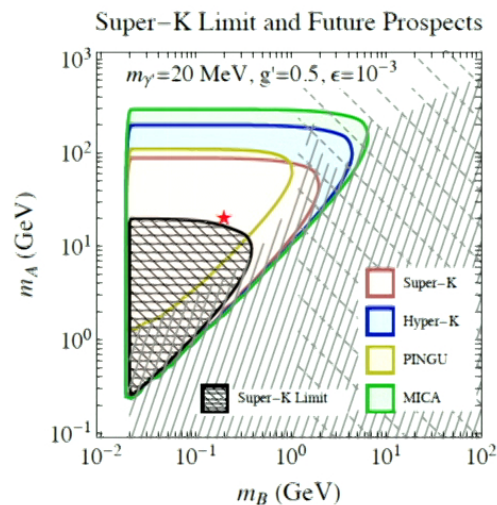
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Analysis, Prospect

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



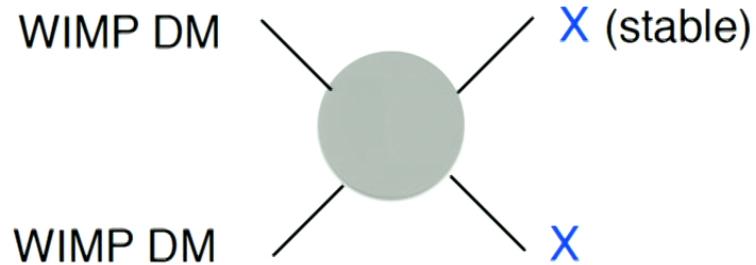
Model-dependent constraints (light grey lines ✓):

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

...

A New Realization of WIMP DM Miracle

- Episode #2



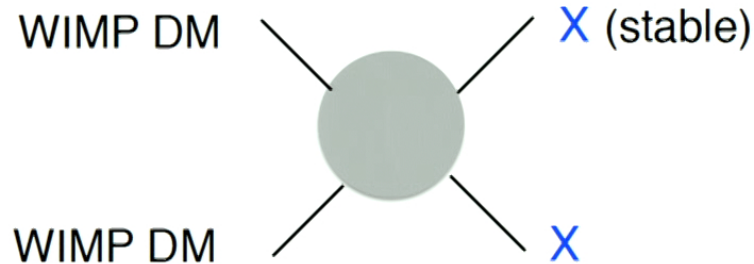
Case-2 :
(nearly) Massless X

- ▶ $m_X \lesssim eV$: $\Omega_X \checkmark$, do not need further depletion/interaction w/SM!



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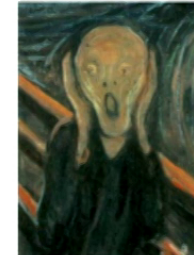


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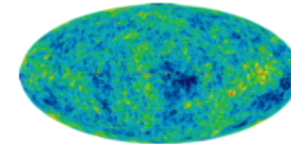


Nightmare for discovery?
(gravity...)



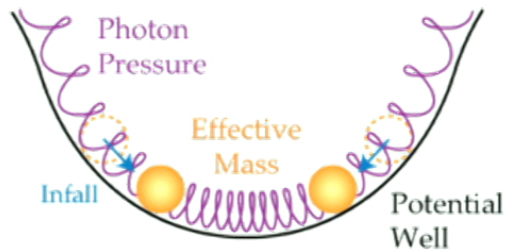
- ▶ X is relativistic, **dark radiation** in the **Cosmic Microwave Background (CMB) !**

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

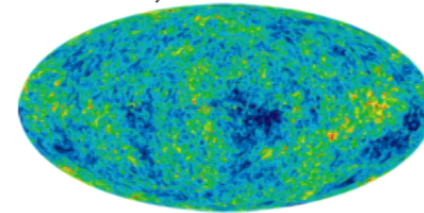


Dark Radiation in the CMB

Until $\sim 3.8 \times 10^5$ yrs after big bang:
☞ photon-baryon fluid,
acoustic oscillation



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



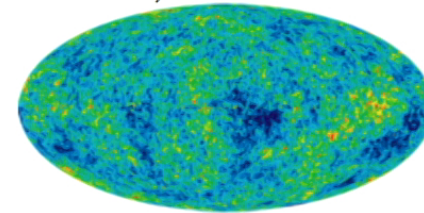
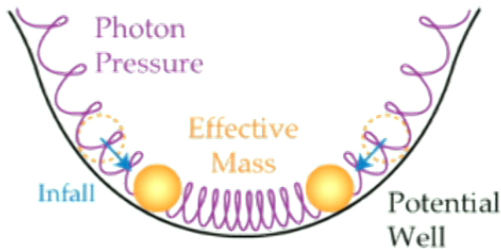
Cosmic fossil: cosmic sound waves!

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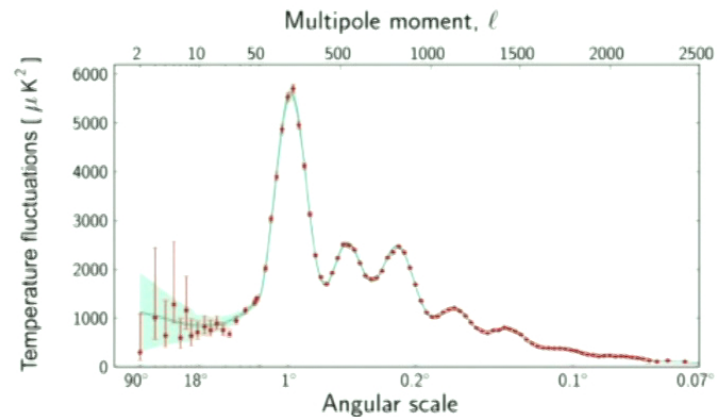


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CMB sky map $\xrightarrow{\text{Fourier transform}}$ CMB anisotropy spectrum

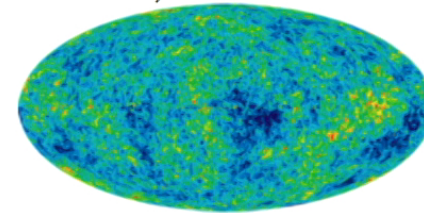
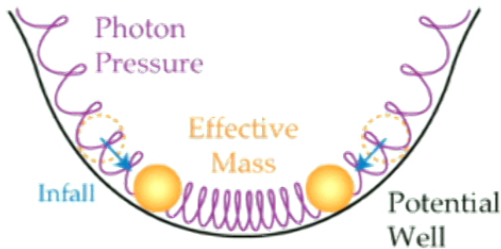


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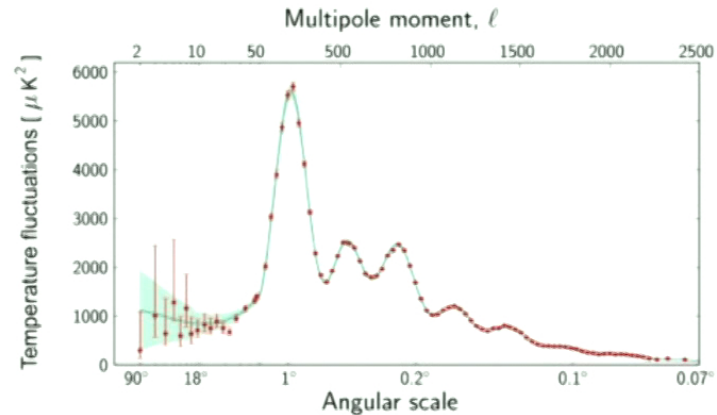


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CMB sky map $\xrightarrow{\text{Fourier transform}}$ CMB anisotropy spectrum

Beyond the SM particle $w/m \lesssim T_{\text{CMB}} \sim eV$

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



Dark Radiation in the CMB



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

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

Observable Difference between the Two Types of DR

Free streaming species: $v_{FS} > v_{sound} \rightarrow \sigma$: anisotropy in $T^{\mu\nu}$

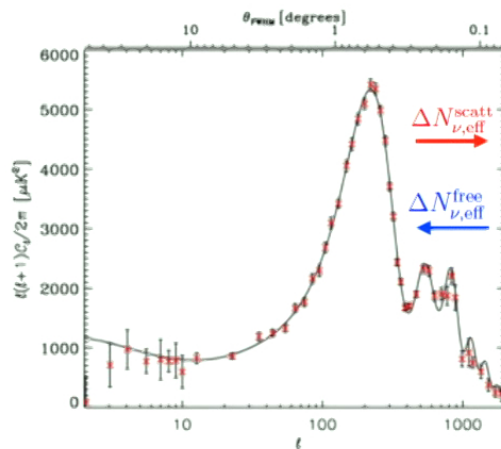
Observable effects increase with FS energy fraction: $f_\nu \equiv \frac{\rho_{\text{all free rad}}}{\rho_{\text{all rad}}}$

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 v: Bashinsky, Seljak 2003)



$$\begin{aligned} \Delta\ell &\equiv \delta\ell - \delta\ell|_{\text{SM}} \\ &= -57(f_\nu - f_\nu|_{\text{SM}}) \frac{\ell_A}{300} \\ &\simeq -7.8 (0.59\Delta N_{\text{eff}}^{\text{free}} - 0.41\Delta N_{\text{eff}}^{\text{scatt}}) \frac{\ell_A}{300} \end{aligned}$$

Opposite sign!

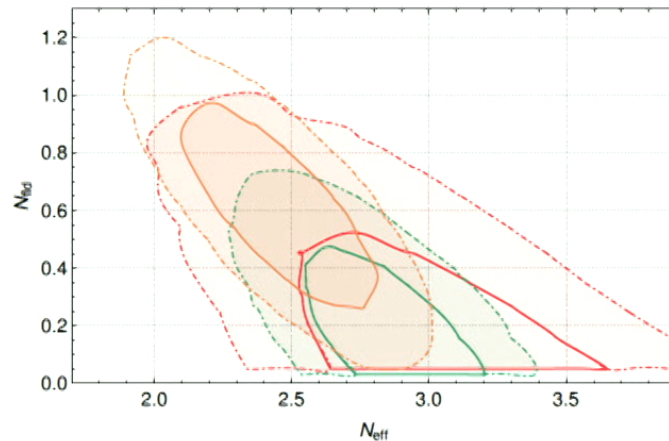
(YC, w/Chacko, Hong, Okui 2015)

Add free-streaming DR $\rightarrow f_\nu \uparrow$
Add scattering DR $\rightarrow f_\nu \downarrow$

Cosmological Constraints on Interacting Light Particles

(YC with Brust and Sigurdson, arXiv: 1703.10732)

- Two param fit: N_{fld}, N_{eff}



- More robust/physical param: f_{fs}, N_{tot}

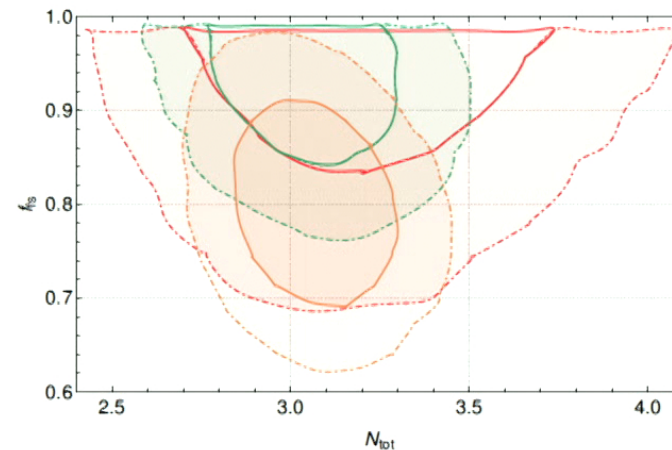


Figure 2. Here we show two different 2d posteriors for three of the five scans (Planck T, Planck P+BAO, and Planck P+BAO+ H_0 +LSS). The solid lines are 1 σ contours, and the dot-dashed lines are 2 σ contours. The posteriors in the top figure exhibit degeneracy between N_{eff} and N_{fld} , motivating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

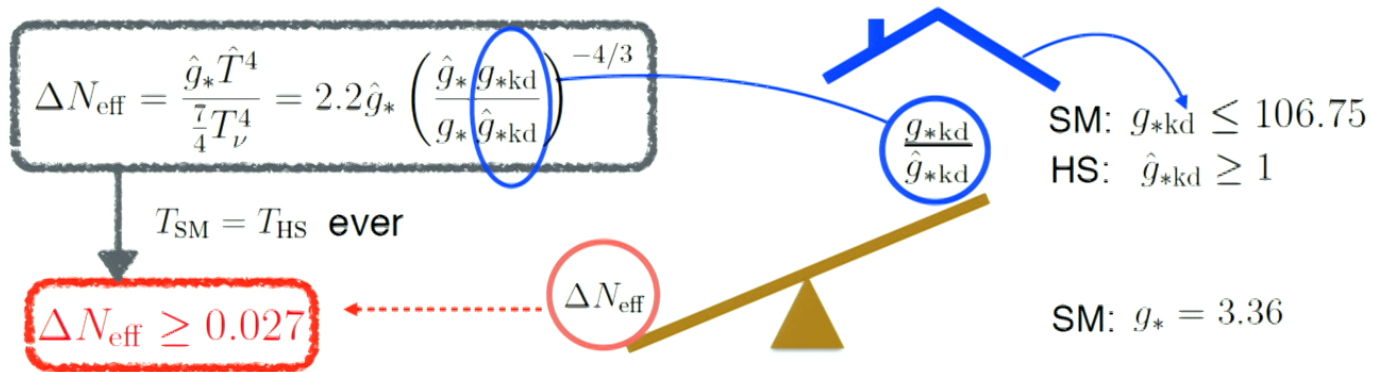
(also see: Baumann, Green, Meyers, Wallisch v2)

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

A Theoretical Benchmark for Dark Radiation Search with CMB

(YC w/Adshead, Shelton, 2016)

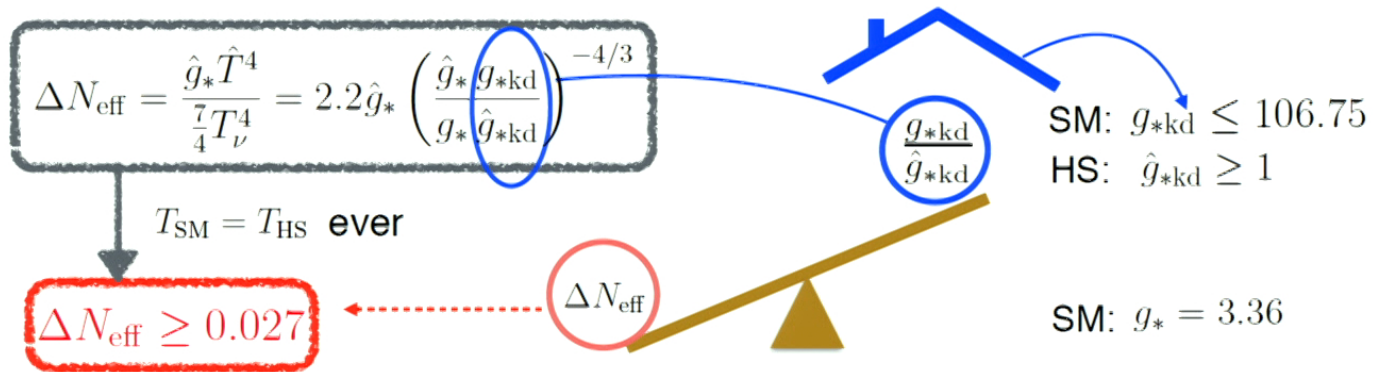
- If a dark sector is ever in thermal equilibrium with SM \Rightarrow **A lower limit on ΔN_{eff} !** (insensitive to dark sector details!)



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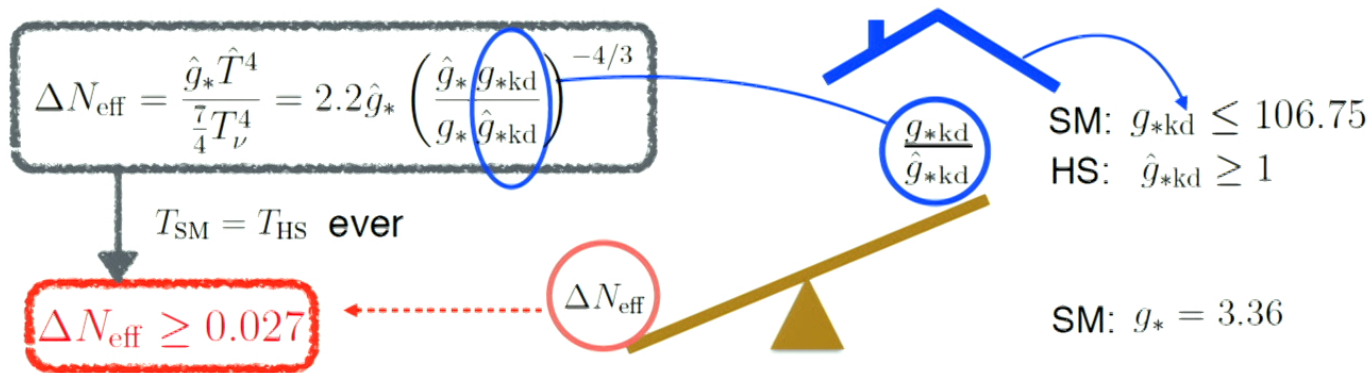


- (preliminary) Forecast for future CMB-S4? $\sigma(N_{\text{eff}}) \approx 0.015 - 0.03$

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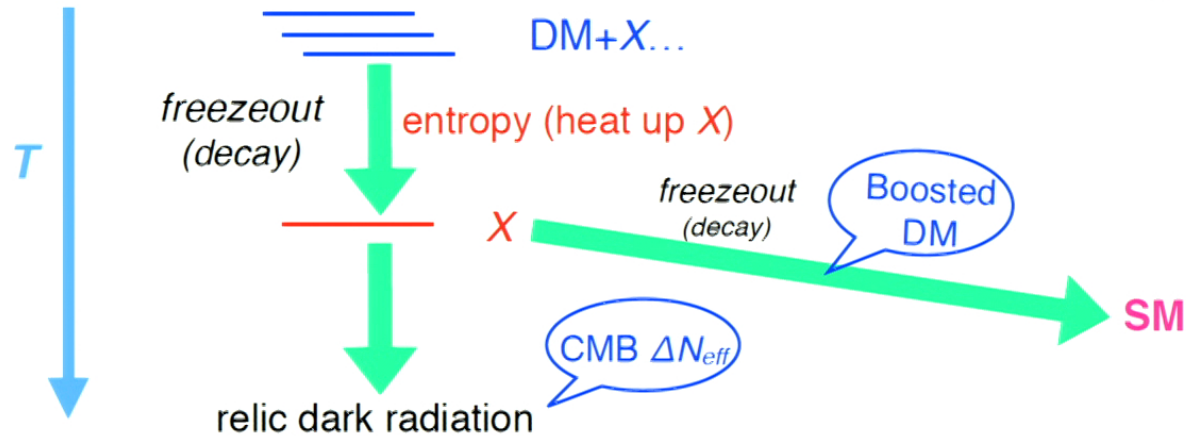


- (preliminary) Forecast for future CMB-S4? $\sigma(N_{\text{eff}}) \approx 0.015 - 0.03$
 - ▶ Likely able to **discover or exclude any** hidden dark sector once in equilibrium with SM!
 - ▶ Timely theoretical motivation/benchmark for setting performance goal of CMB-S4!

A Unified Picture of Thermal DM

- A universal guideline:

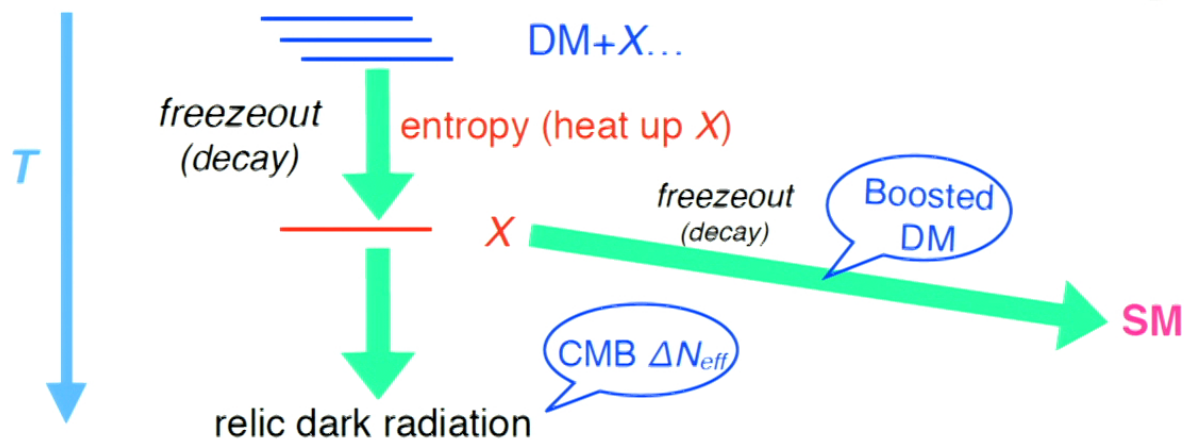
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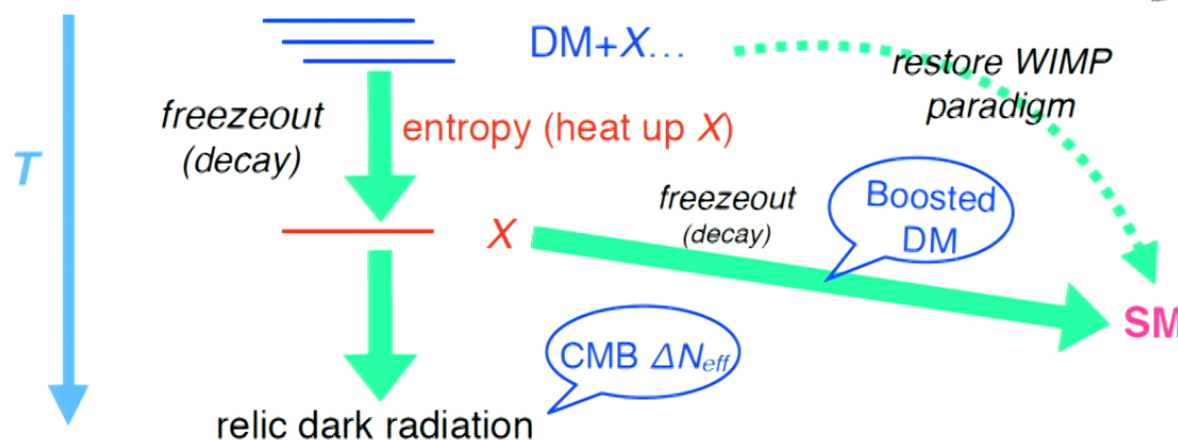
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- **X**: **subdominant** abundance, $\Omega_X < \Omega_{DM}$ yet plays an **important cosmological role!**
- **X**: may be the **smoking-gun** for the whole dark sector!
New observational directions!

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. light DM decaying to DR, with **DM direct detection** experiments, ν floor, work in prep w/Maxim, Josef)
 - 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 prep)