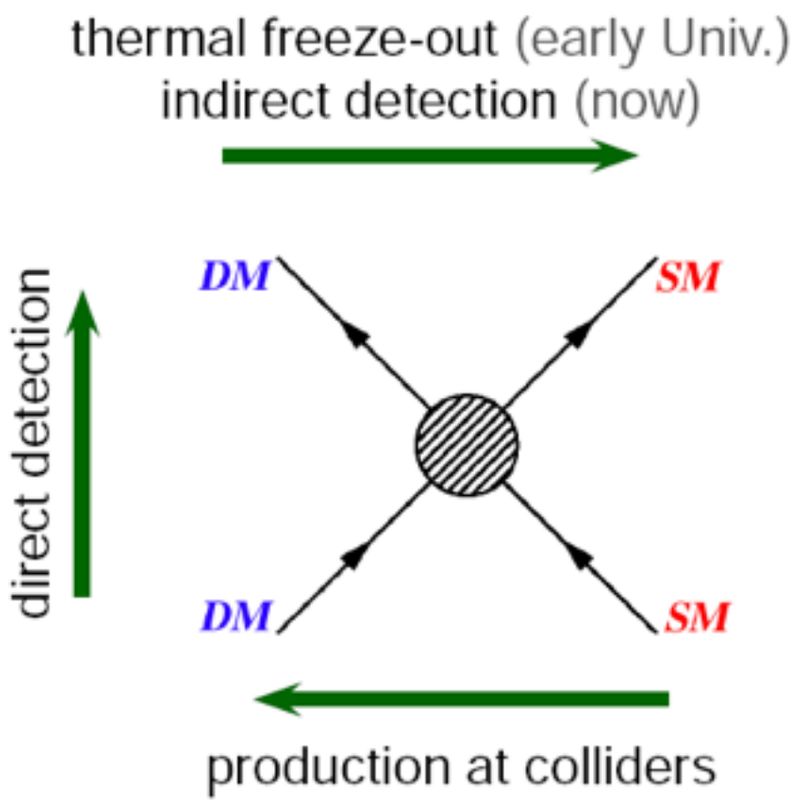
New Observational Windows for Probing Hidden Dark Sectors

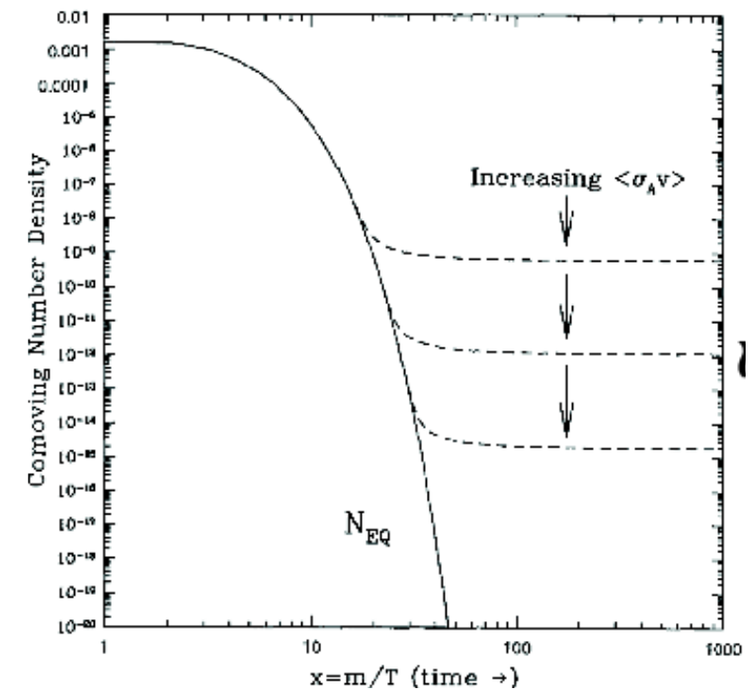
Yanou Cui

UC Riverside

"Towards Dark Matter Discovery"
KICP workshop Apr 12, 2018

The Challenges with the WIMP DM Paradigm





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

WIMP Miracle!

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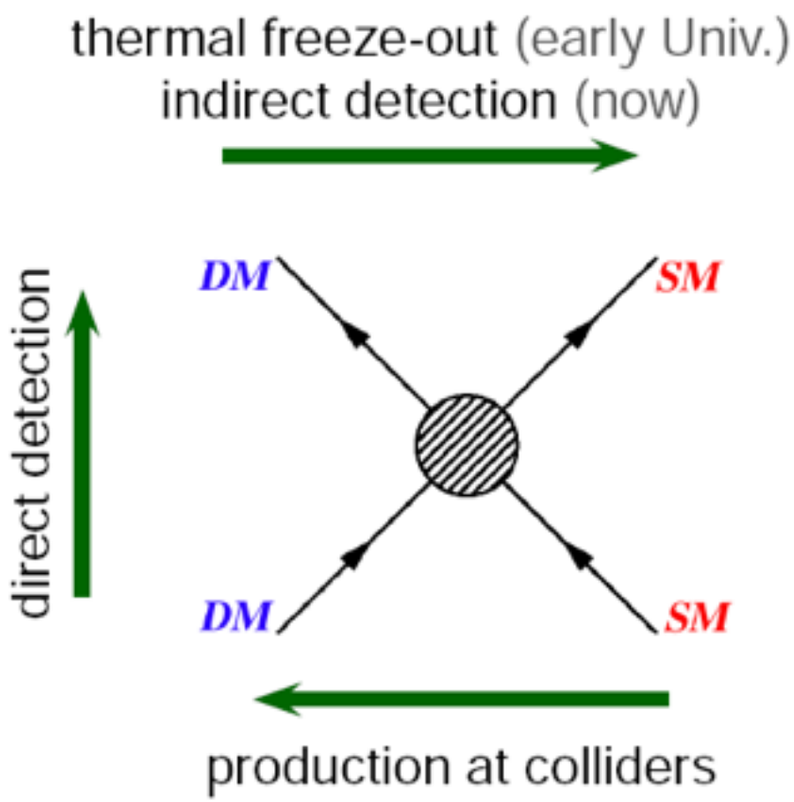

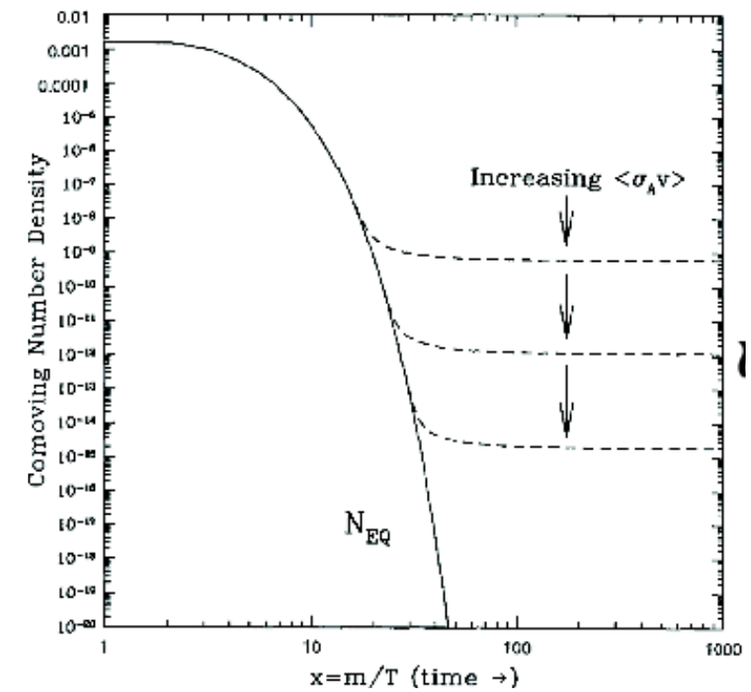

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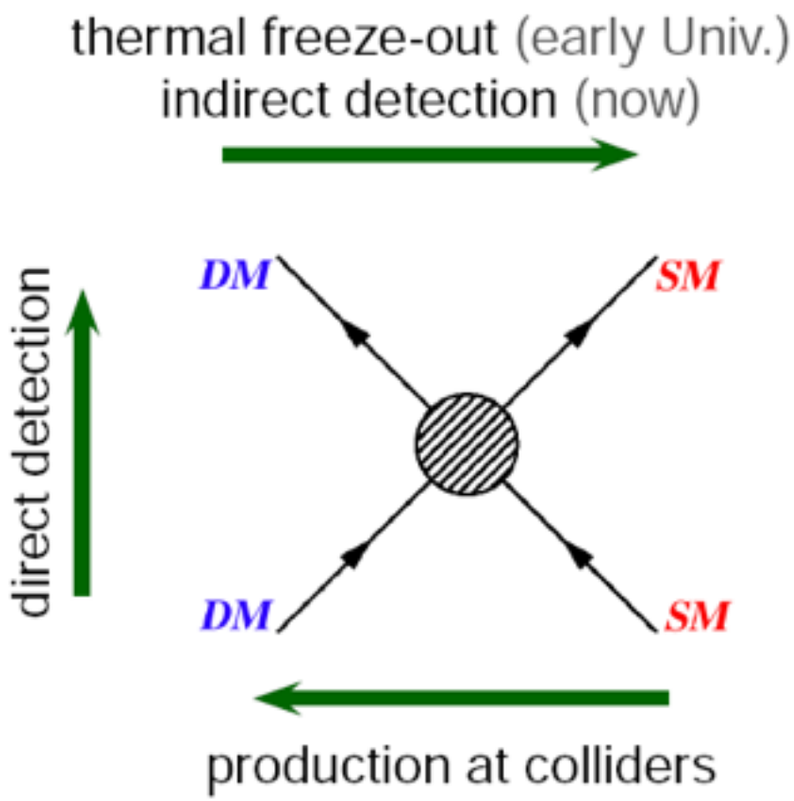

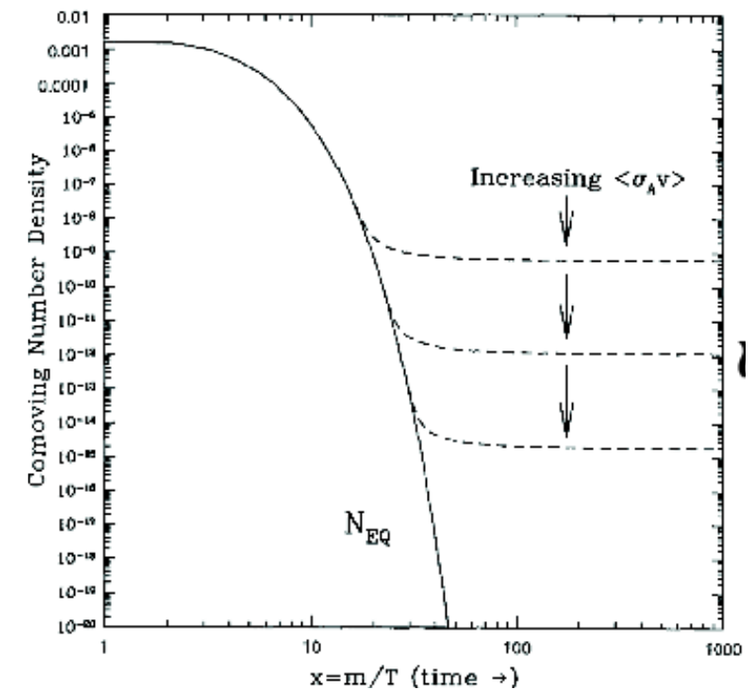

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WIMP Miracle!

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

- Expand the theoretical vision: beyond the WIMP paradigm

  light DM, axion, PBH, <u>non-minimal thermal dark sector</u> ★…
- Exciting new pheno: DUNE, CMB-S4, structure formation…

Simple Variations of WIMP Miracle

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

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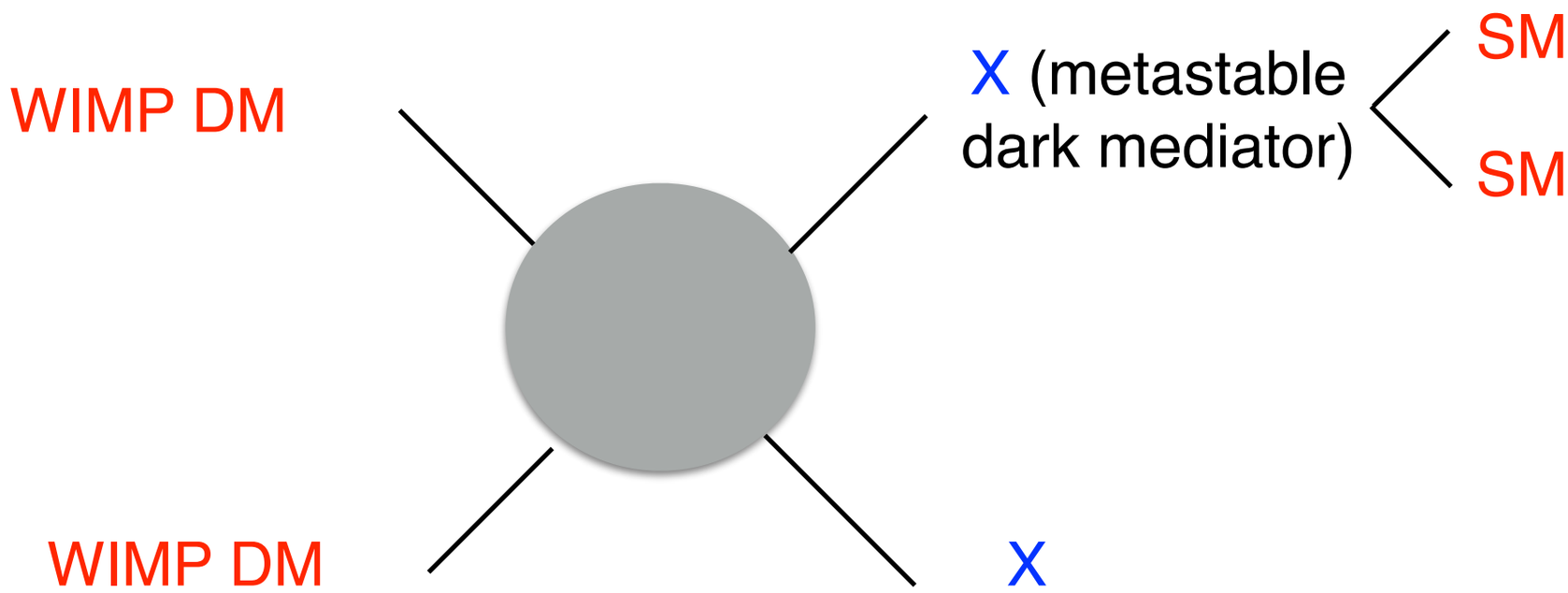
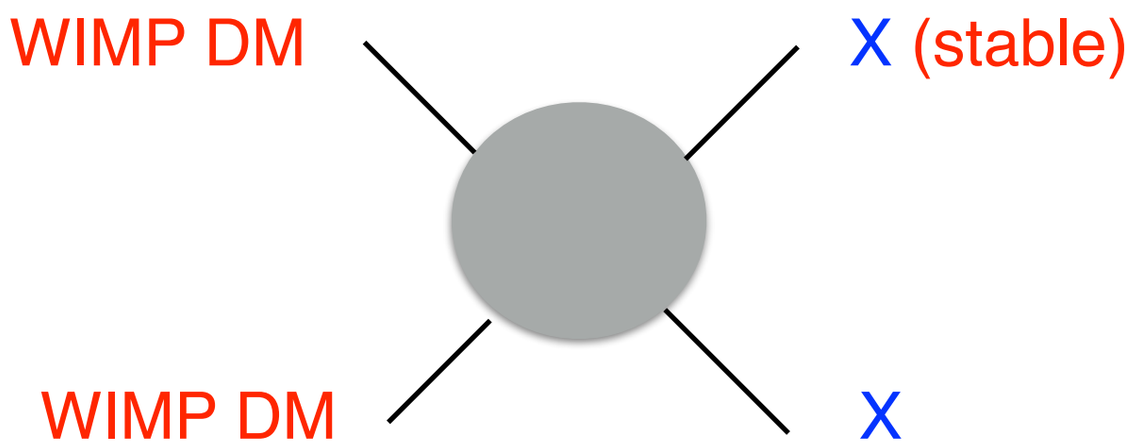
e.g. *Secluded Dark Matter*

(Pospelov, Ritz, Voloshin 2007)



Safely evades direct detection, subject to indirect detection

A New Realization of WIMP DM Miracle



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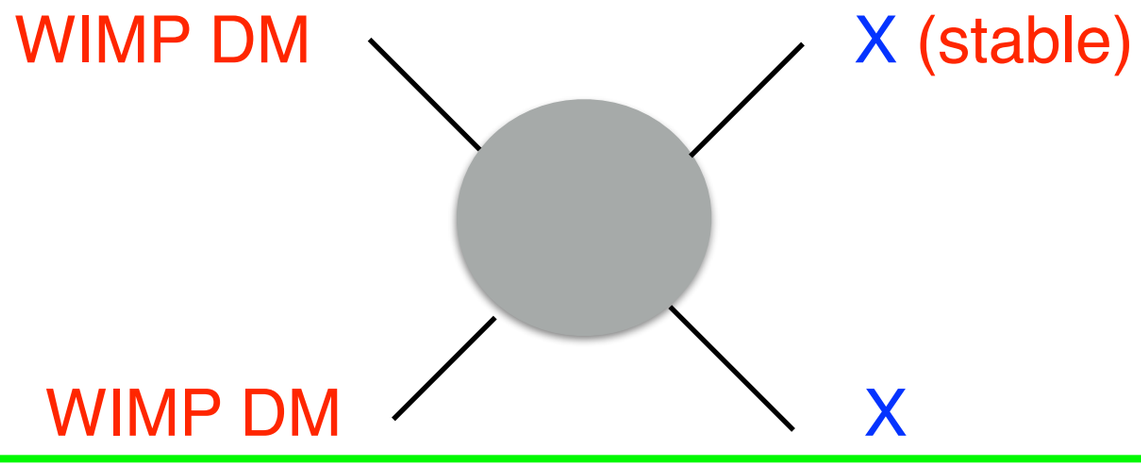

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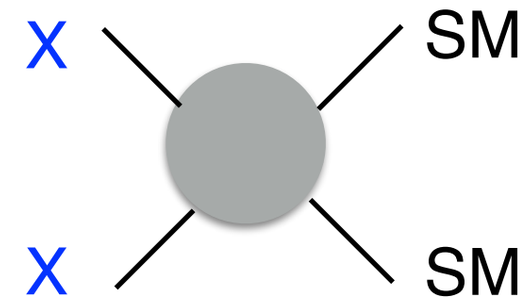

- $m_X \gtrsim$eV: Ω_X>1 ☞ deplete X via annihilation→SM

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

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

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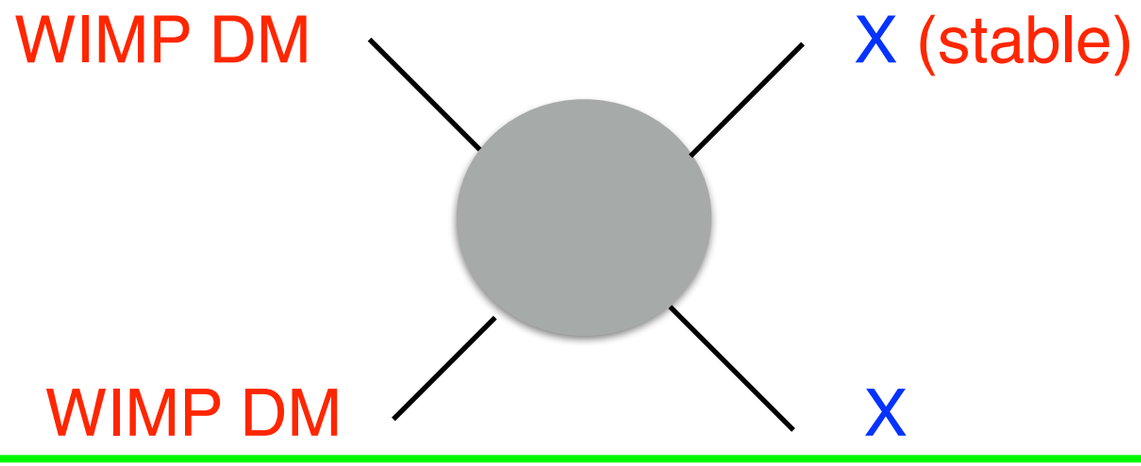

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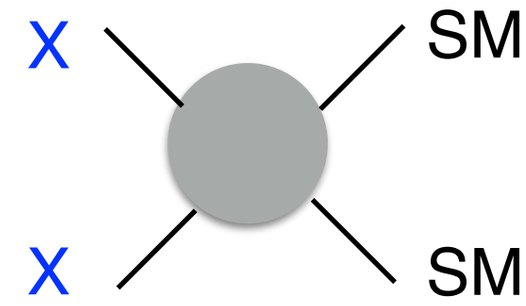

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Dark matter lives in a non-minimal hidden sector!

(a **thermal** bath of DM, X, +…) Hidden dark sector freezeout

A Hidden Dark Sector?

Rising interest, covers a great variety of DM models:

atomic DM, mirror world DM, SIDM, twin Higgs DM, DDDM…

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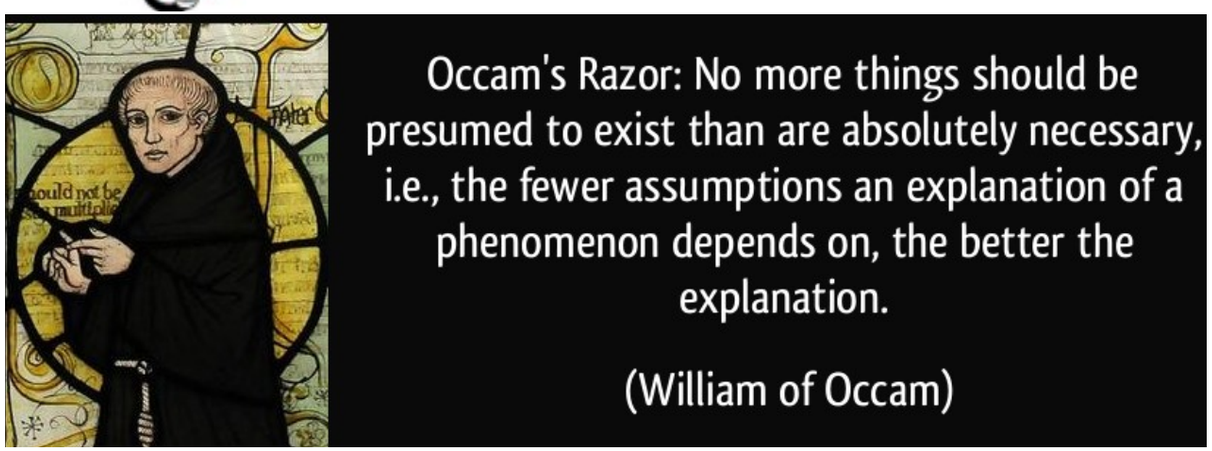

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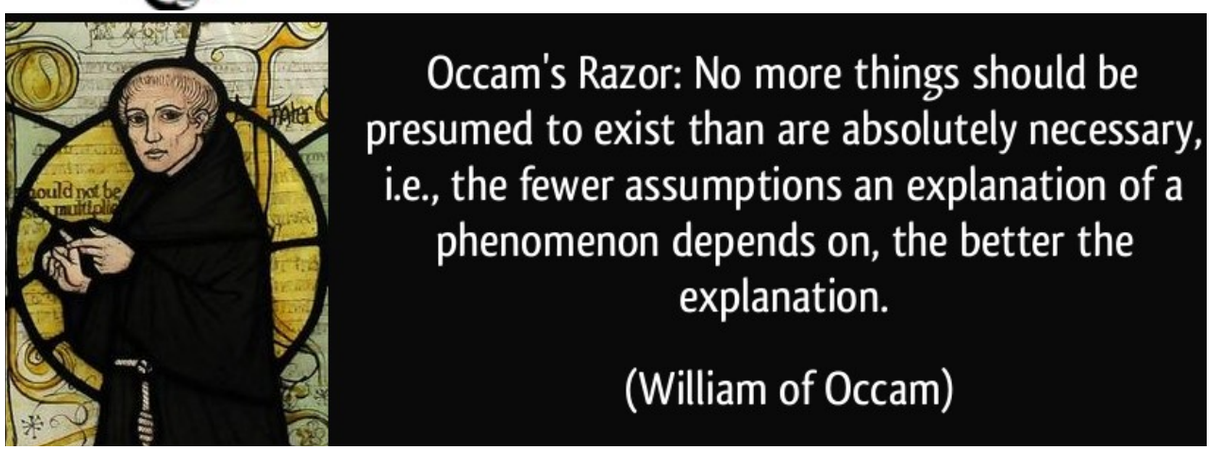

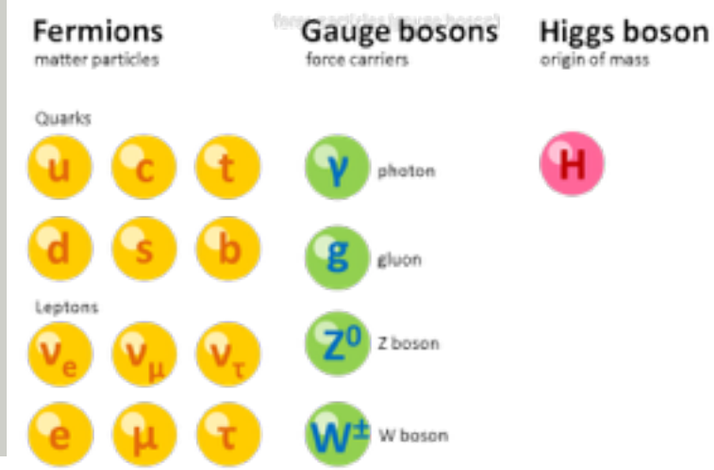

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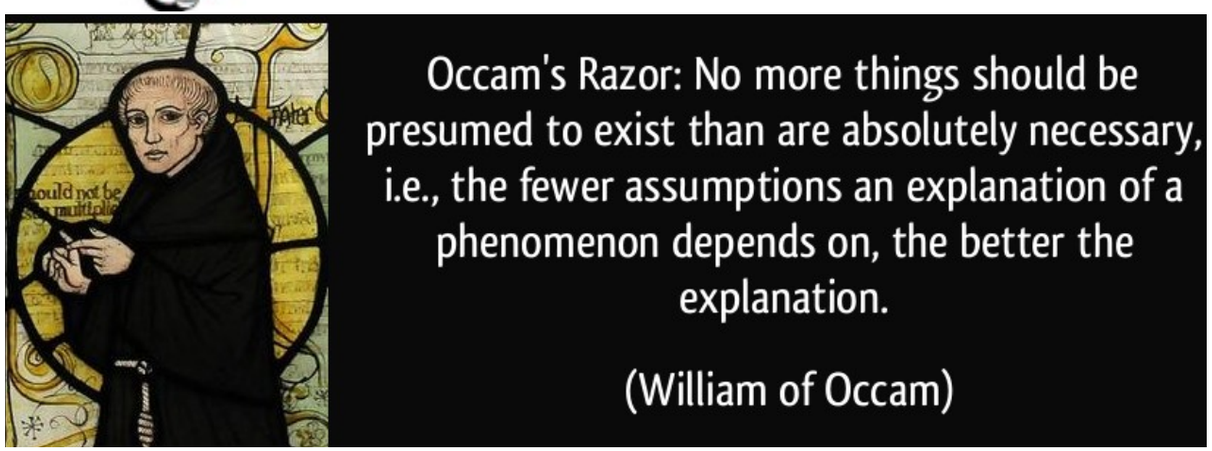

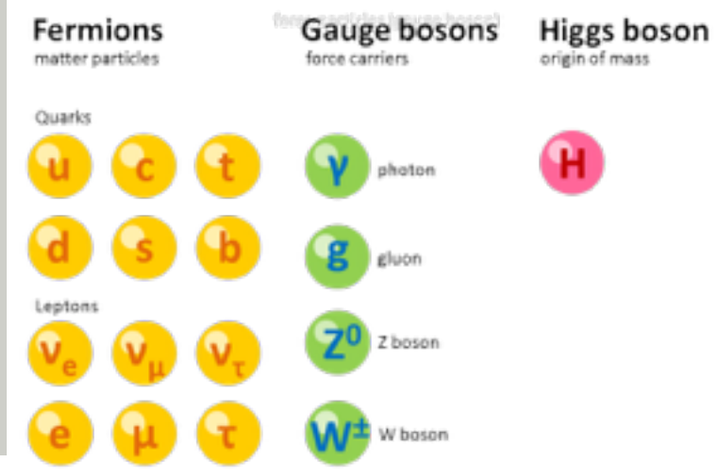

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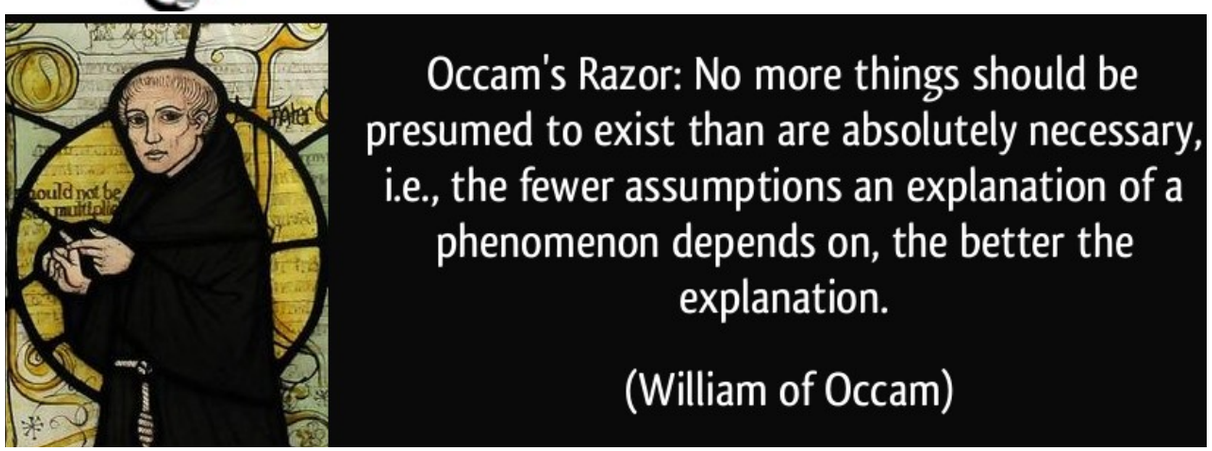

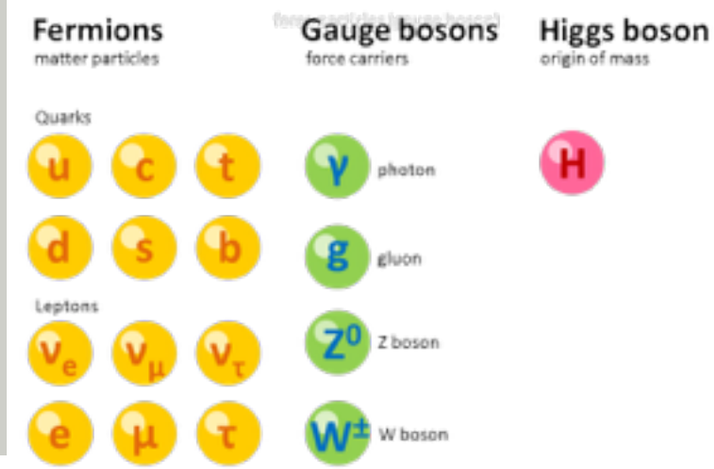

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✓ **Universal guidelines**

✓ **New observational windows!**

(this talk…)

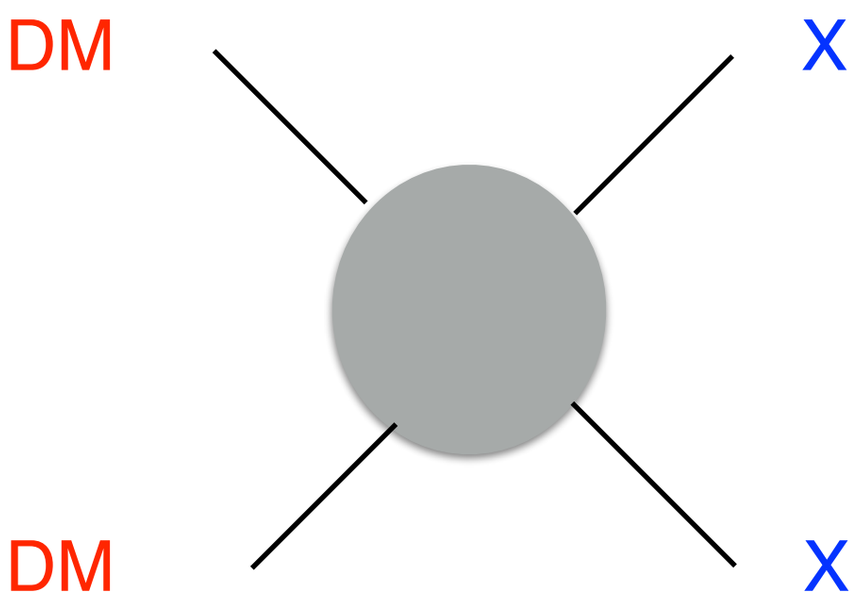
Episode- #1

Boosted Dark Matter

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

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

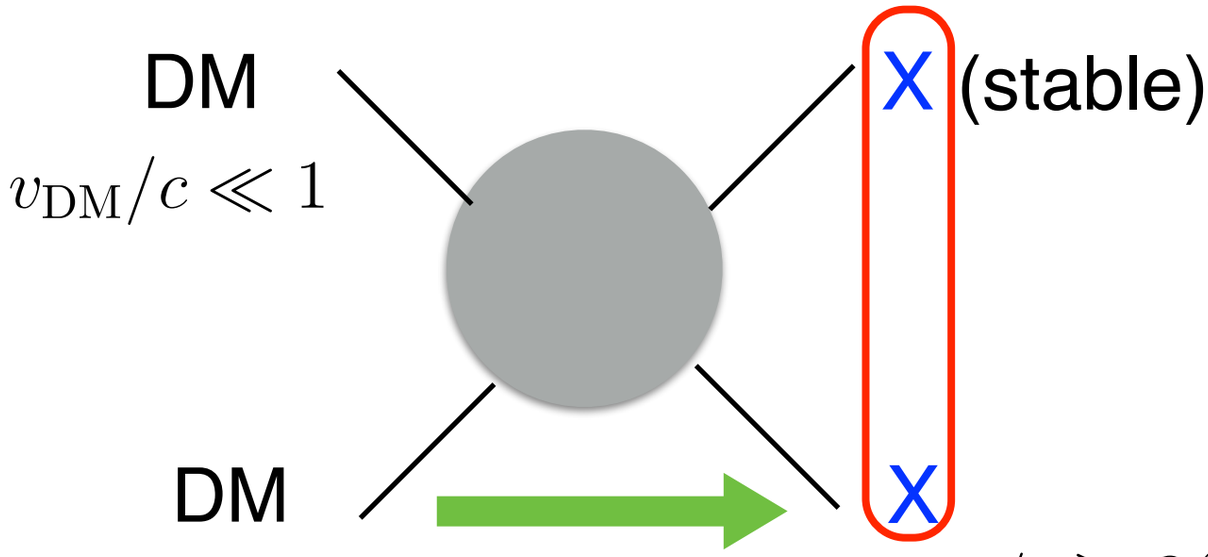
YC *et al.* w/Mircoboone/DUNE collaboration*(in progress)*



- Massive X

(DM→ DM A, X→DM B)

Boosted Dark Matter



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- Conventional signals absent/suppressed

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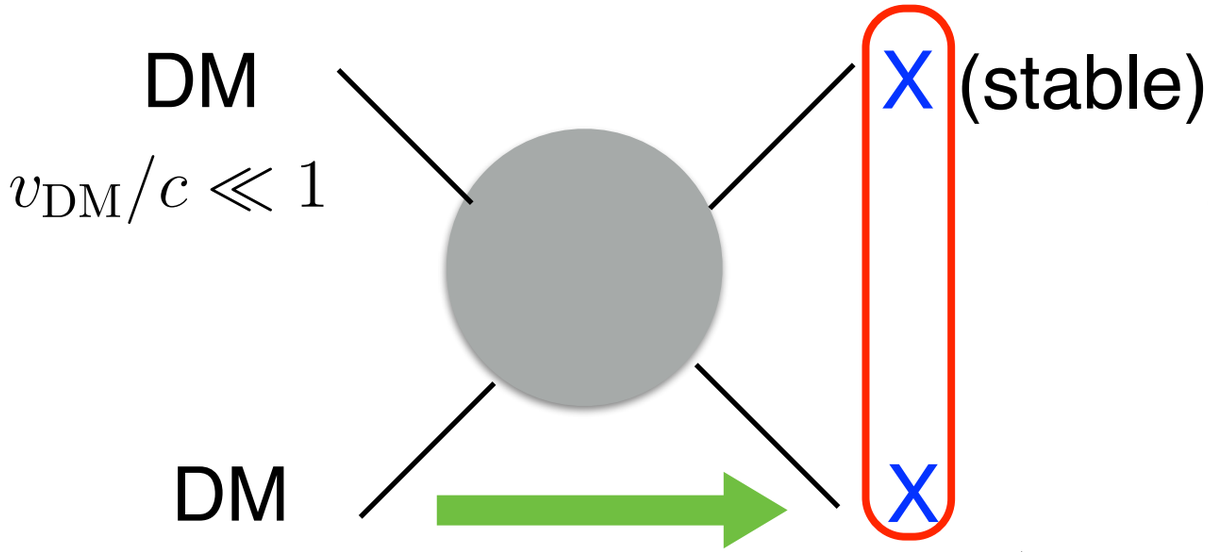

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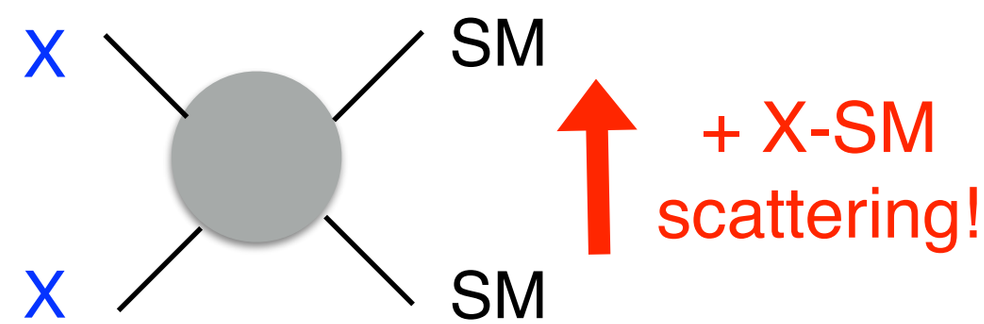

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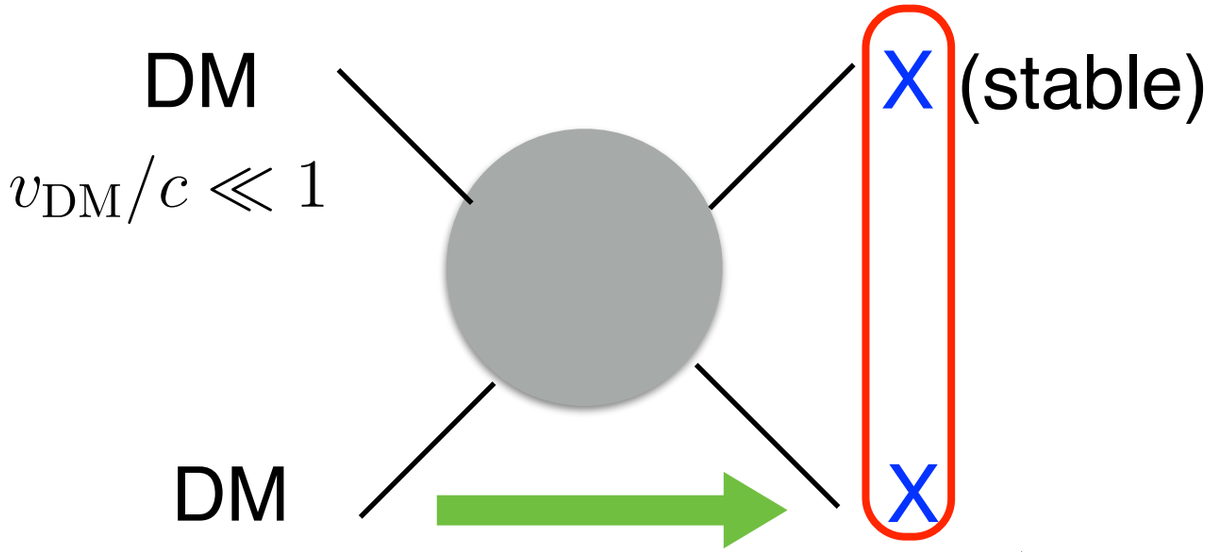

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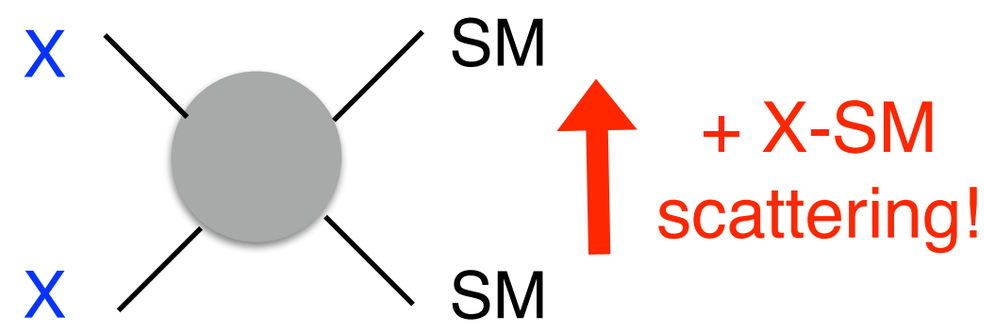
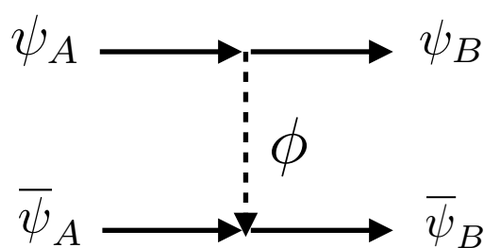


Model Example

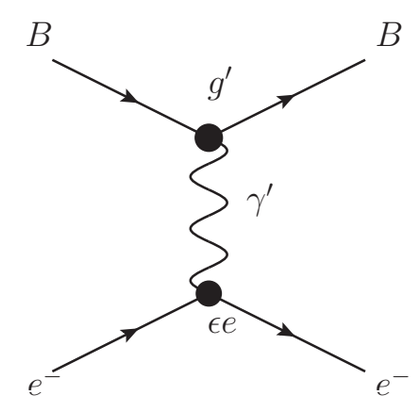
- Dirac fermion $\psi_A,\ \psi_B,\ m_A > m_B$, stabilized by $\mathbb{Z}_2 \times \mathbb{Z}_2$

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



+

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



Search Strategy for Boosted DM

- A combination of DM indirect and direct detections

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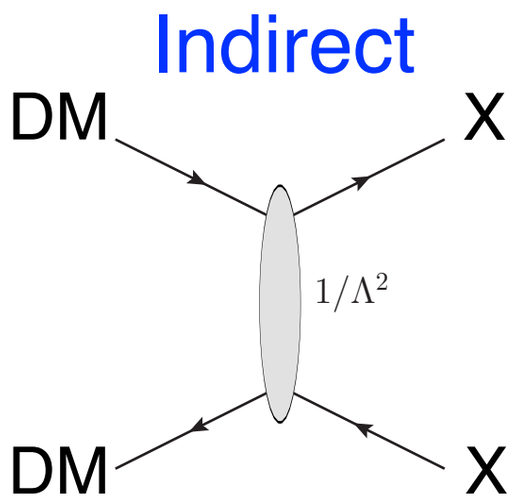

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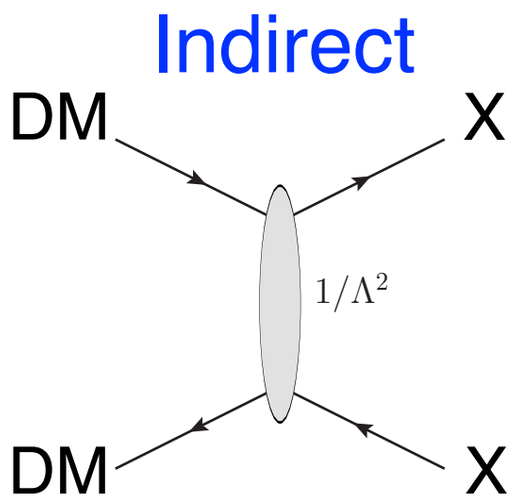

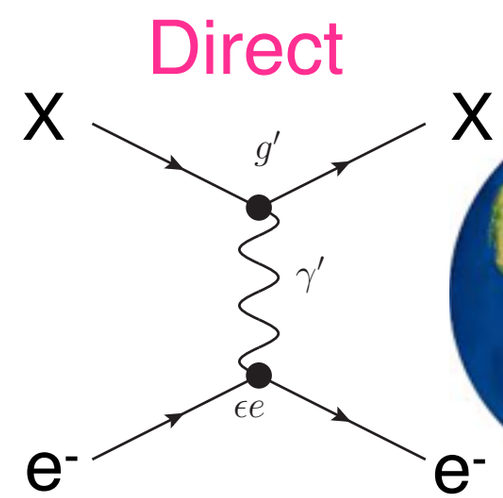

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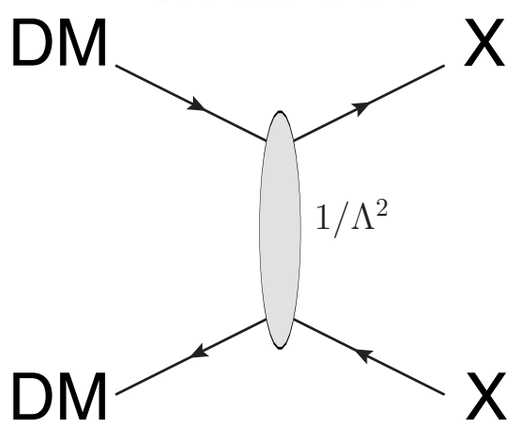

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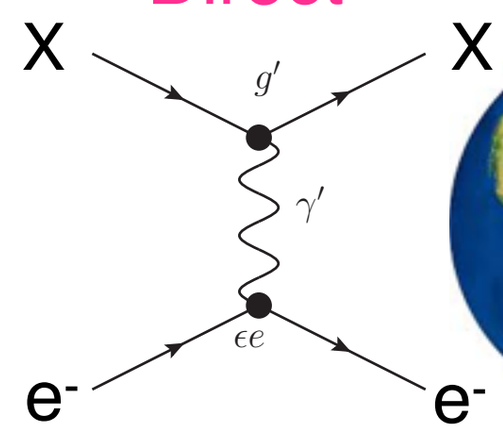

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★ Boosted X ➜ relativistic outgoing e-, p

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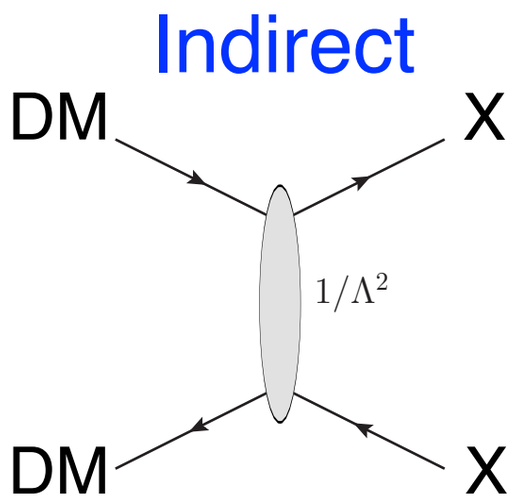

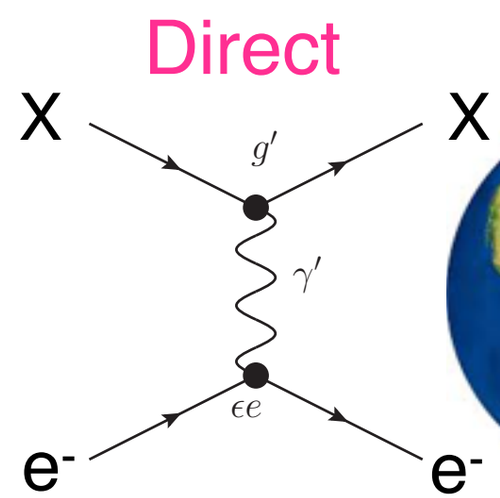

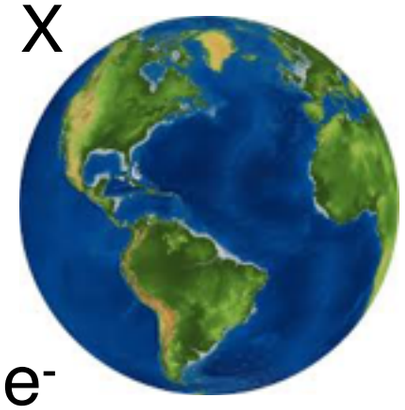

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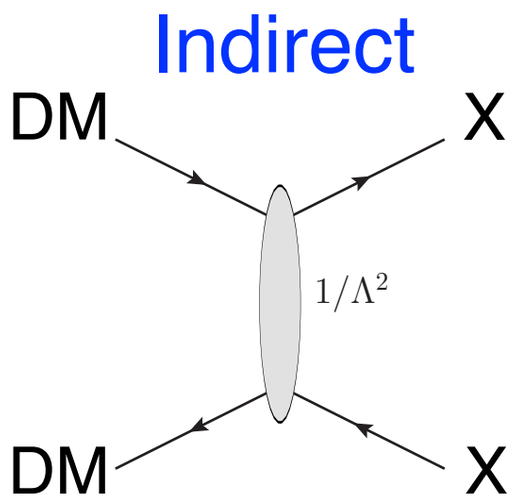

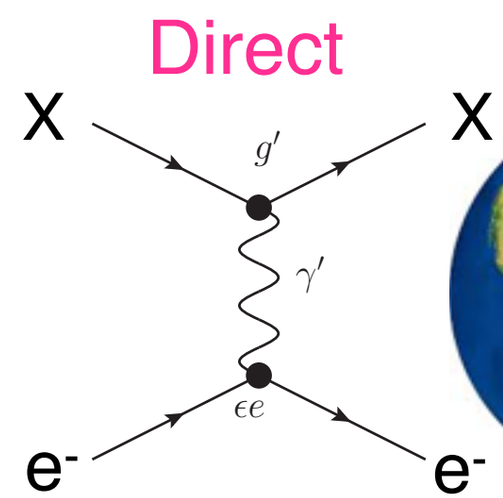

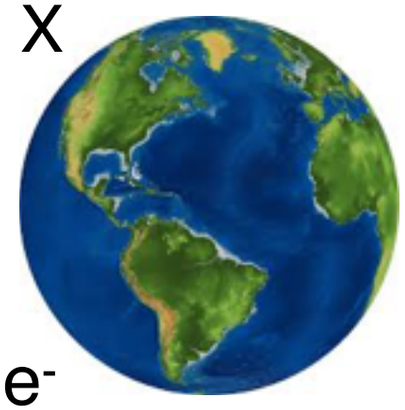

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DM direct detection 😟 ; Opportunity:

low energy boosted DM ($E \lesssim O(GeV)$)

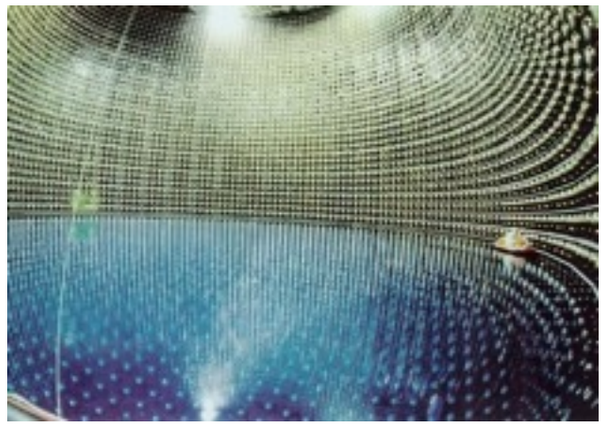
(Cherry et.al 2015, **YC** w/Pospelov, Pradler arXiv:1711.04531)

Boosted DM@Neutrino Experiments

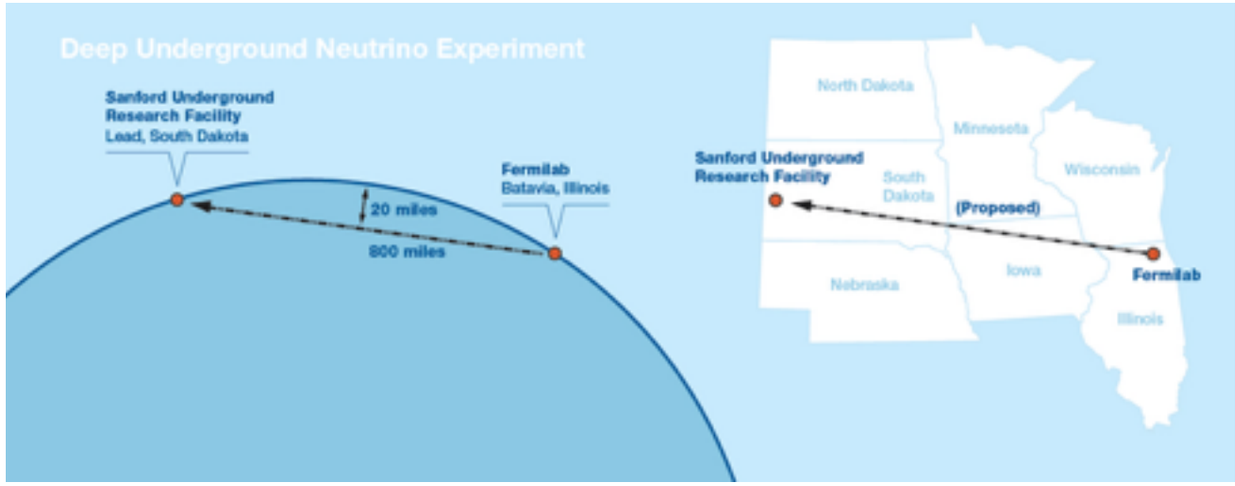
- Conventional: Cherenkov detectors; New: LArTpc

IceCube

SuperK



DUNE/LBNF (major future project)



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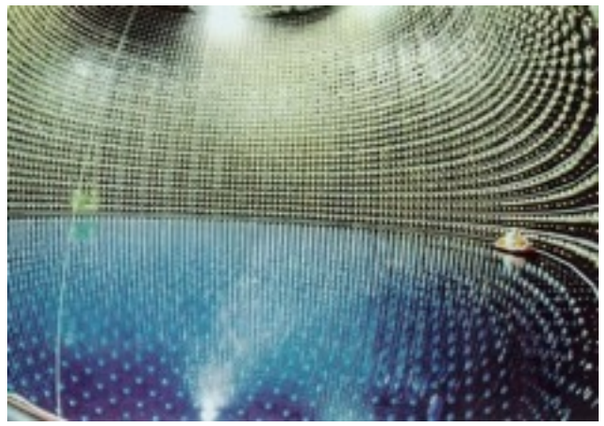

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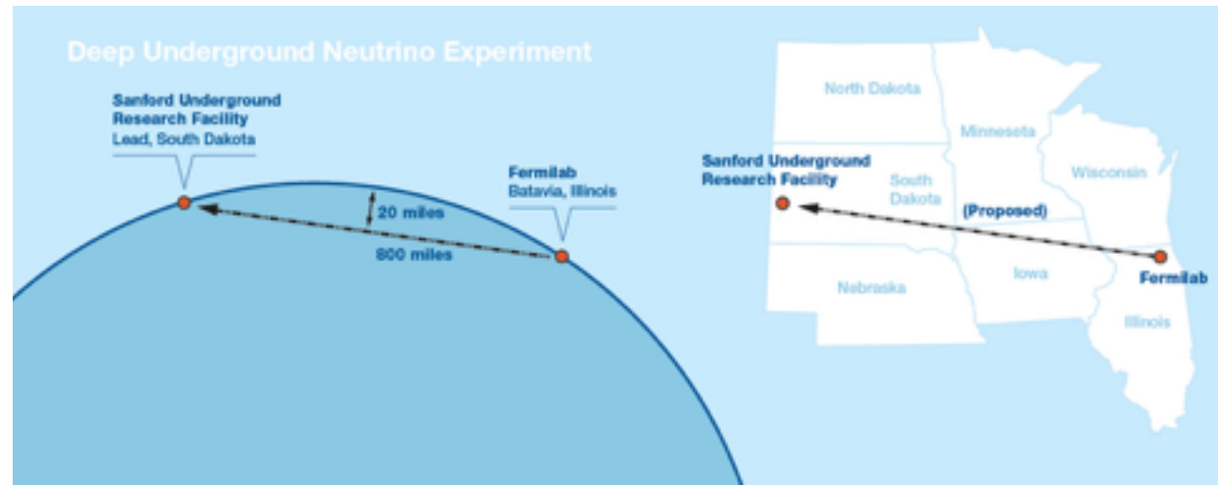
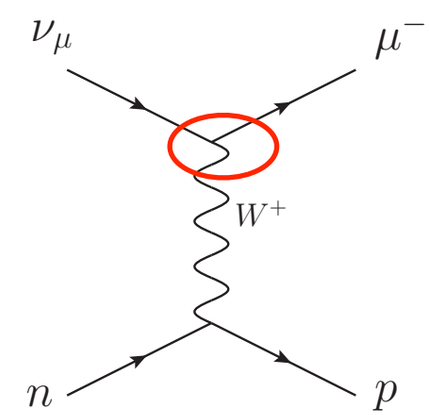


- Boosted DM distinguishable from ν !
  - Directionality
  - No charge current interaction (e.g. muon veto)



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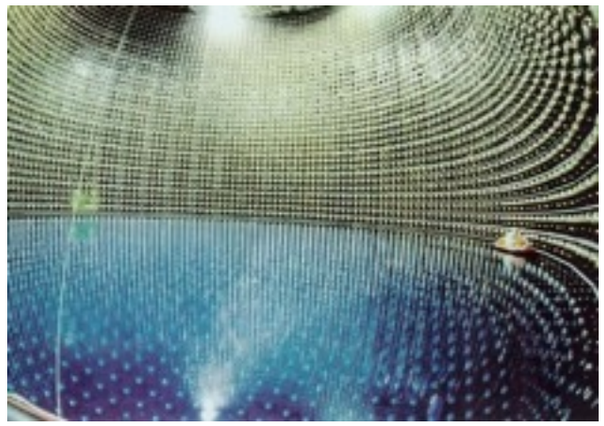
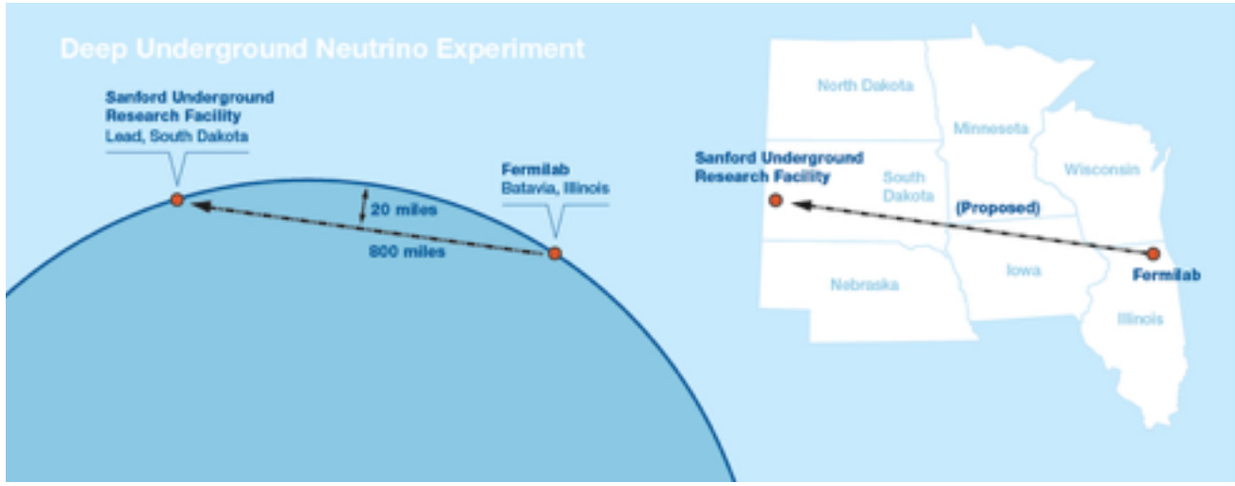
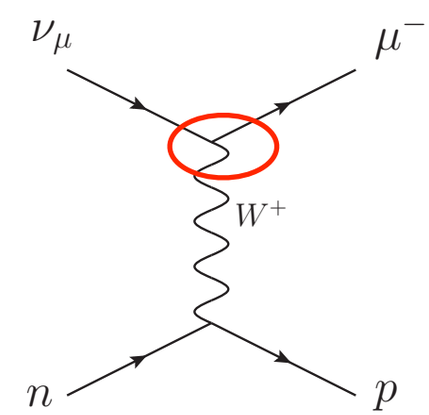


DUNE/LBNF (major future project)



- Boosted DM distinguishable from ν !
  - Directionality
  - No charge current interaction (e.g. muon veto)



Boosted DM:
New scientific programs for neutrino experiments

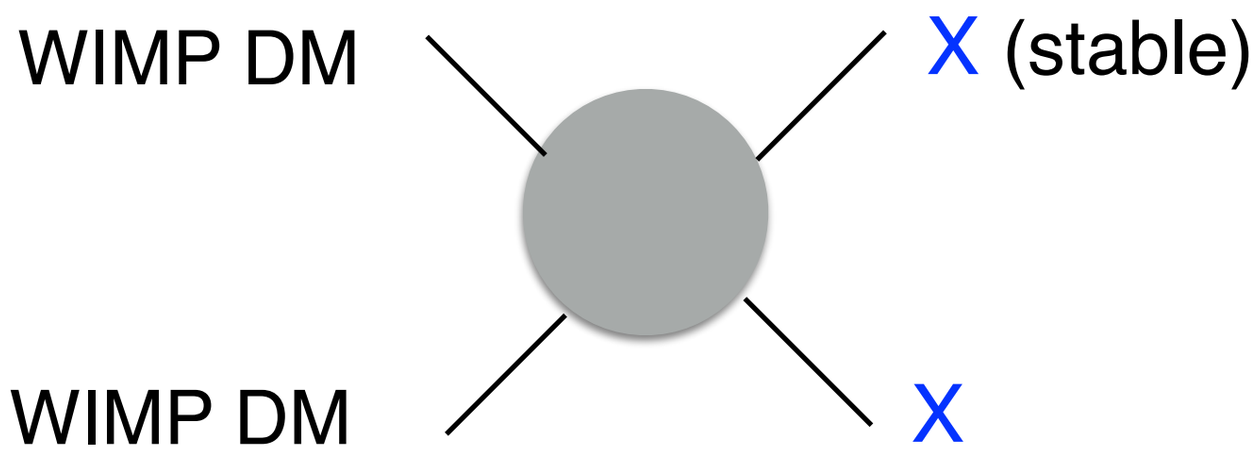
Recent Development of Boosted DM

- **Substantial recognition + action from major neutrino experimental collaborations**
  - SuperK: official analysis on boosted DM (arxiv: 1711.05278)
  - DUNE/Microboone: a working group (theorists + experimentalists) developed since 2016, recently became a subgroup of DUNE BSM group; will contribute to DUNE TDR — We are focusing on high priority benchmarks now, but in the long term open to other related exotic DM signals observable (e.g. self-destructing DM, Grossman et al. arXiv:1712.00455)
- **Theoretical development**
  - Several groups involved: signals with DM direct detection, IceCube… (e.g. Jia, Seodong, Xiaoping here)
  - Inelastic Boosted DM (e.g. Giudice et al. arXiv:1712.07126)

Episode #2

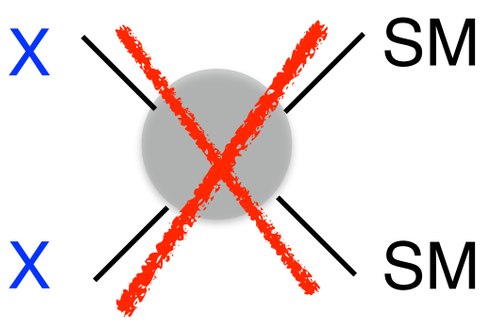
Dark Radiation in the CMB

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



Case-2 :
(nearly) Massless X

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



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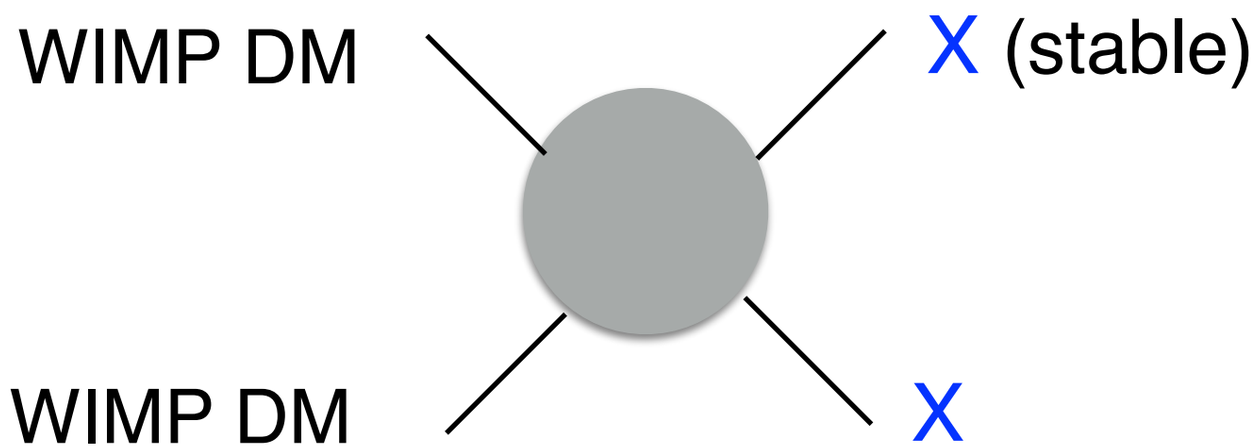

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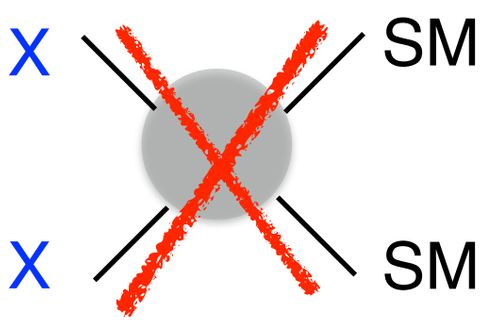

Nightmare for discovery?

(gravity…)

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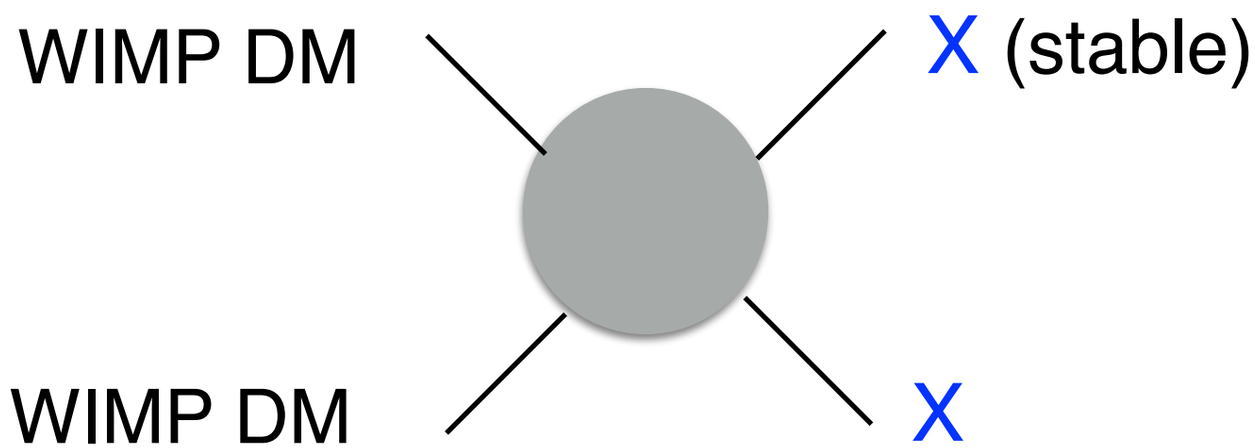

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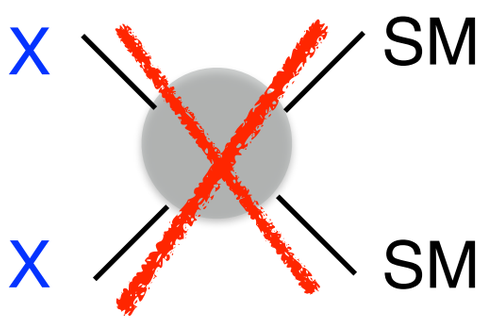
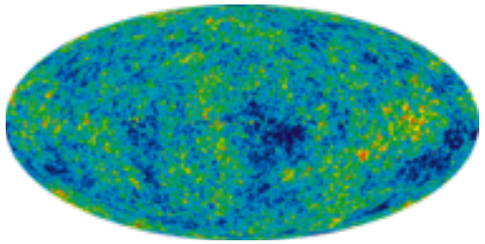


Nightmare for discovery?

(gravity…)

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



Dark Radiation in the CMB

Beyond the SM particle w/m$\lesssim T_{CMB}\sim$eV (DR):

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

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- Affect CMB spectrum by increasing effective neutrino number, ΔN_{eff} (N_{eff}=3.046 in SM)
  e.g. suppress high ℓ peak amplitude

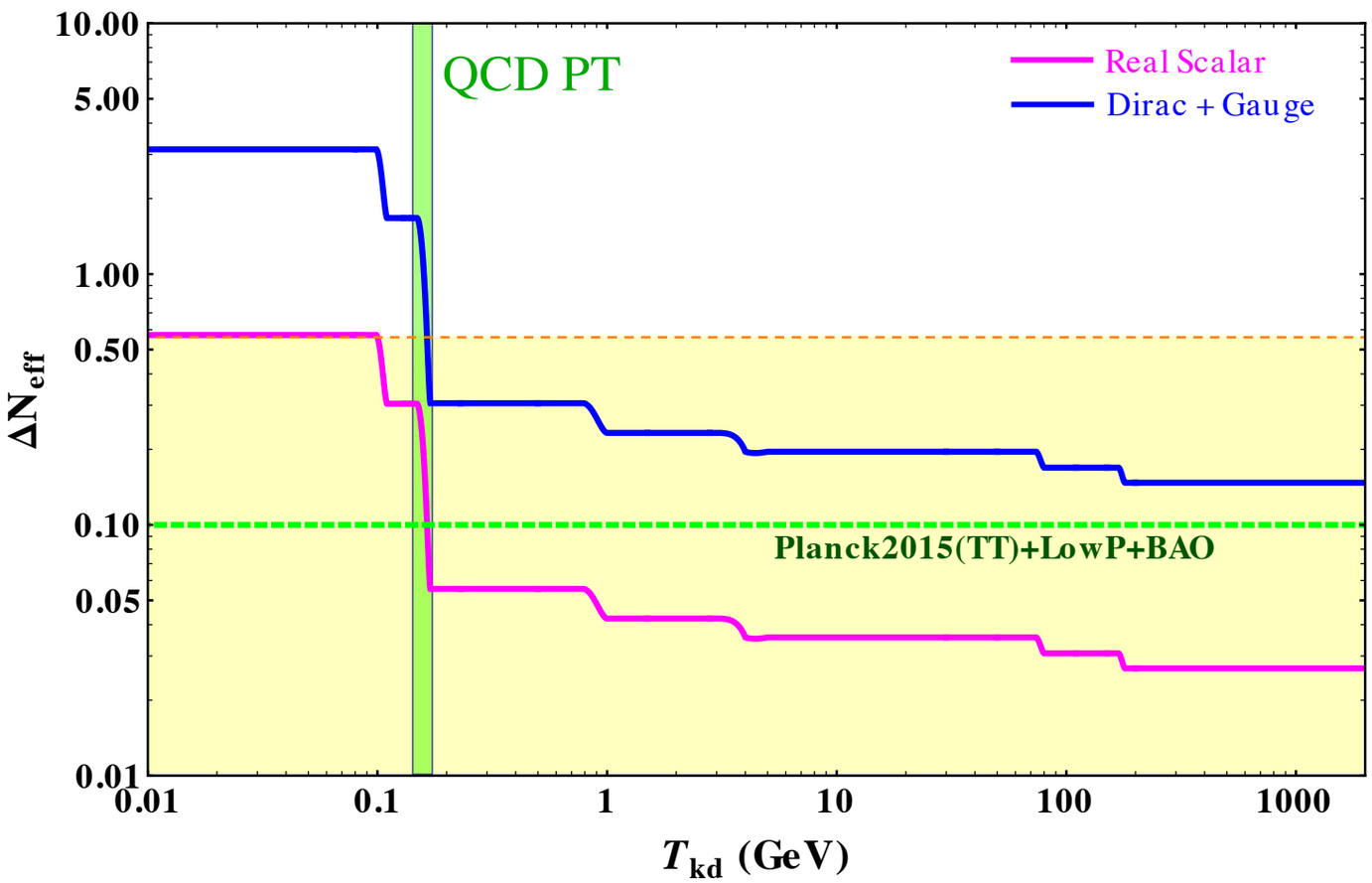
Calculation of <u>thermal</u> dark radiation: *(c.f. non-thermal later)*

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

- $g_{*\rm DR}$: Number of degrees of freedom in DR
- $T_{\rm DR}$: determined by when DS and SM <u>kinetically decouple</u>

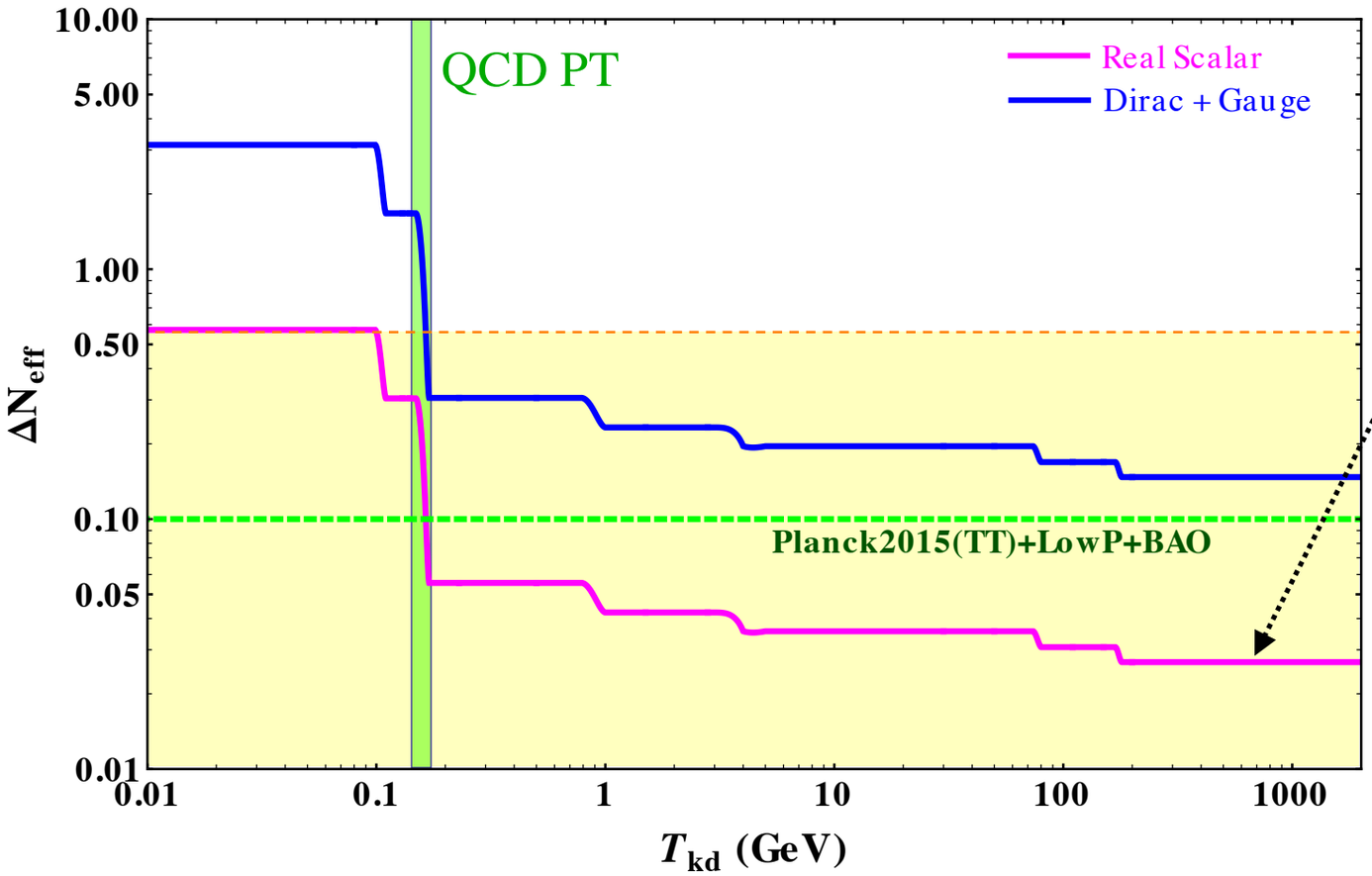
Initial thermal (kinetic) equilibrium ☞ effective portal interaction between DS and SM (e.g. higgs portal)

Dark Radiation in the CMB



Phys.Rev. D92 (2015) 055033, **YC** w/Chacko, Hong, Okui

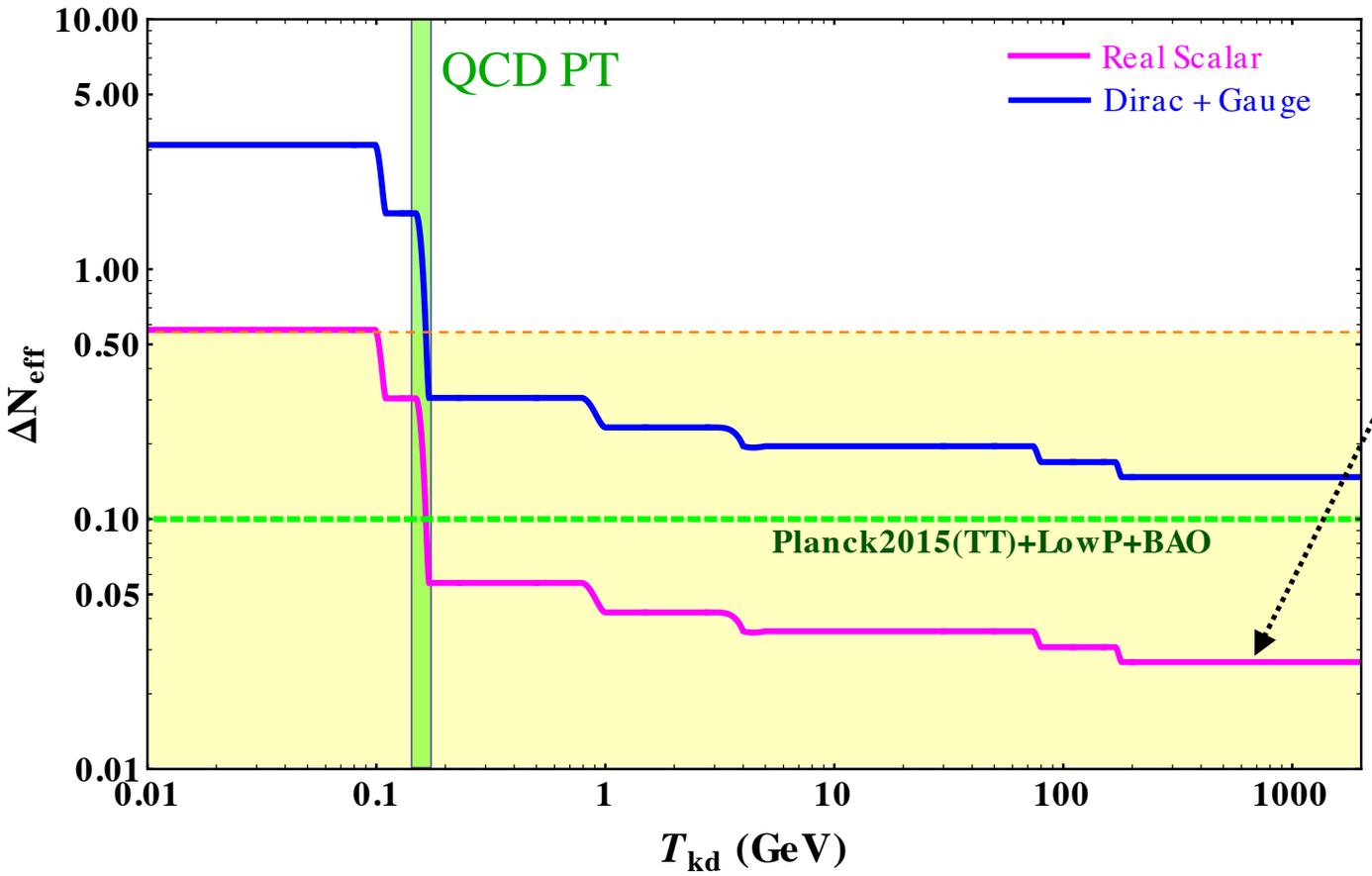
Dark Radiation in the CMB



A lower limit $\Delta N_{\rm eff} \geq 0.027$

Phys.Rev. D92 (2015) 055033, **YC** w/Chacko, Hong, Okui

Dark Radiation in the CMB



A lower limit $\Delta N_{\rm eff} \geq 0.027$

Forecast for CMB-S4 sensitivity:

$\sigma(N_{\rm eff}) \approx 0.015 - 0.03$

Phys.Rev. D92 (2015) 055033, **YC** w/Chacko, Hong, Okui

- Likely able to discover or exclude <u>any</u> hidden dark sector once in equilibrium with SM (CMB-S4)!

JHEP 1606 (2016) 016, **YC** w/Adshead, Shelton

Dark Radiation in the CMB

-Simply extra neutrinos?

- **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 (e.g. dark gluons, dark photon+dark electrons)
    — Not included in expt. analysis! But…

Observable Difference Between the Two Types of DR

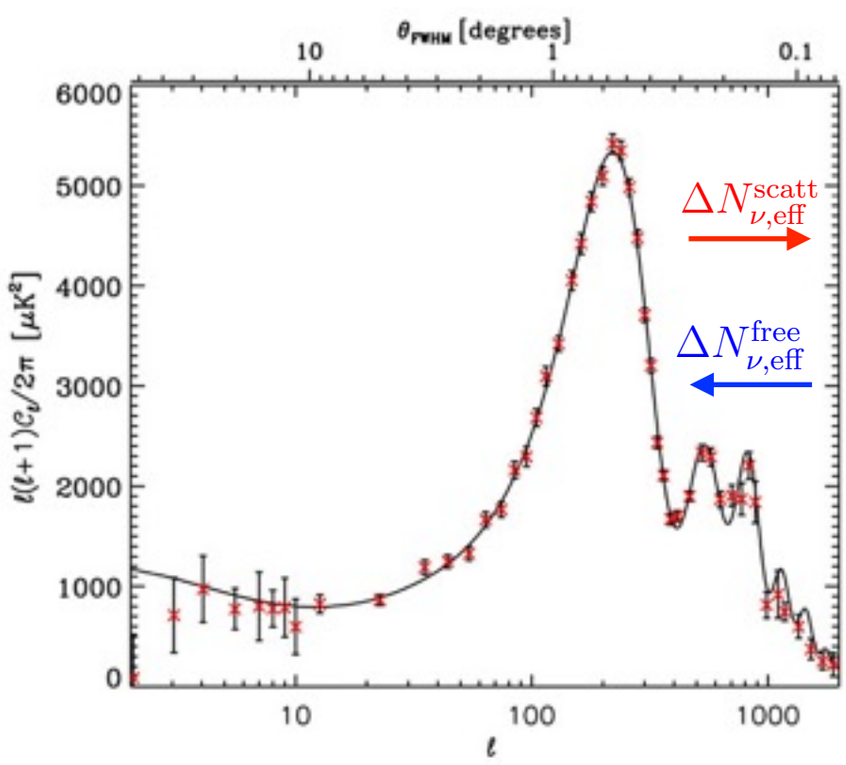
- Free streaming species: $v_{FS} > v_{sound}$ ⟶ σ: anisotropy in $T^{\mu\nu}$
- Observable effects increase with FS energy fraction: $f_\nu \equiv \frac{\rho_{\text{all free rad}}}{\rho_{\text{all rad}}}$

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 ν: Bashinsky, Seljak 2003)



$$\Delta\ell \equiv \delta\ell - \delta\ell\big|_{\text{SM}}$$
$$= -57\left(f_\nu - f_\nu\big|_{\text{SM}}\right)\frac{\ell_{\text{A}}}{300}$$
$$\simeq -7.8\left(0.59\Delta N_{\text{eff}}^{\text{free}} - 0.41\Delta N_{\text{eff}}^{\text{scatt}}\right)\frac{\ell_{\text{A}}}{300}$$

Opposite sign!

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

Add free-streaming DR ⟶ $f_\nu \uparrow$

Add scattering DR ⟶ $f_\nu \downarrow$

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}

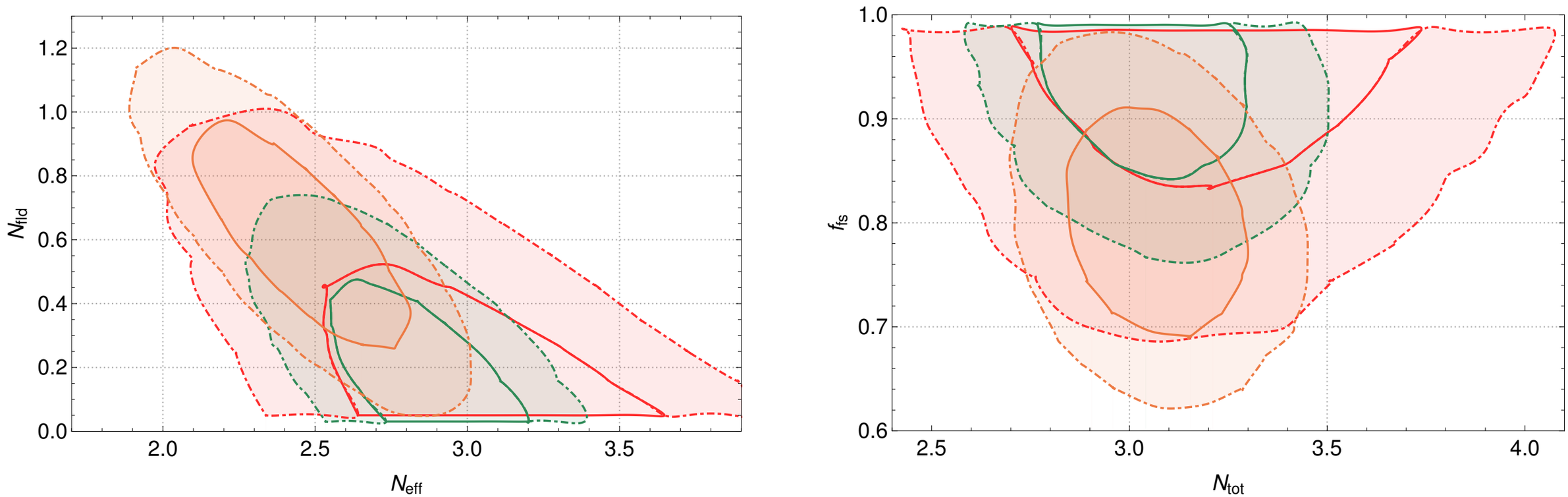


Figure 2. Here we show two different 2d posteriors for three of the five scans (Planck T, Planck P+BAO, and Planck P+BAO+H_0+LSS). The solid lines are 1σ contours, and the dot-dashed lines are 2σ contours. The posteriors in the top figure exhibit degeneracy between $N_{\rm eff}$ and $N_{\rm fld}$, motivating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

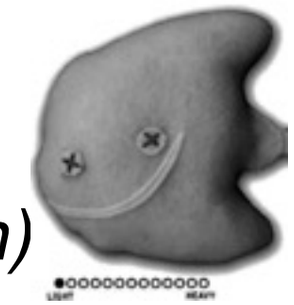
(also see: Baumann, Green, Meyers, Wallisch *v2*)

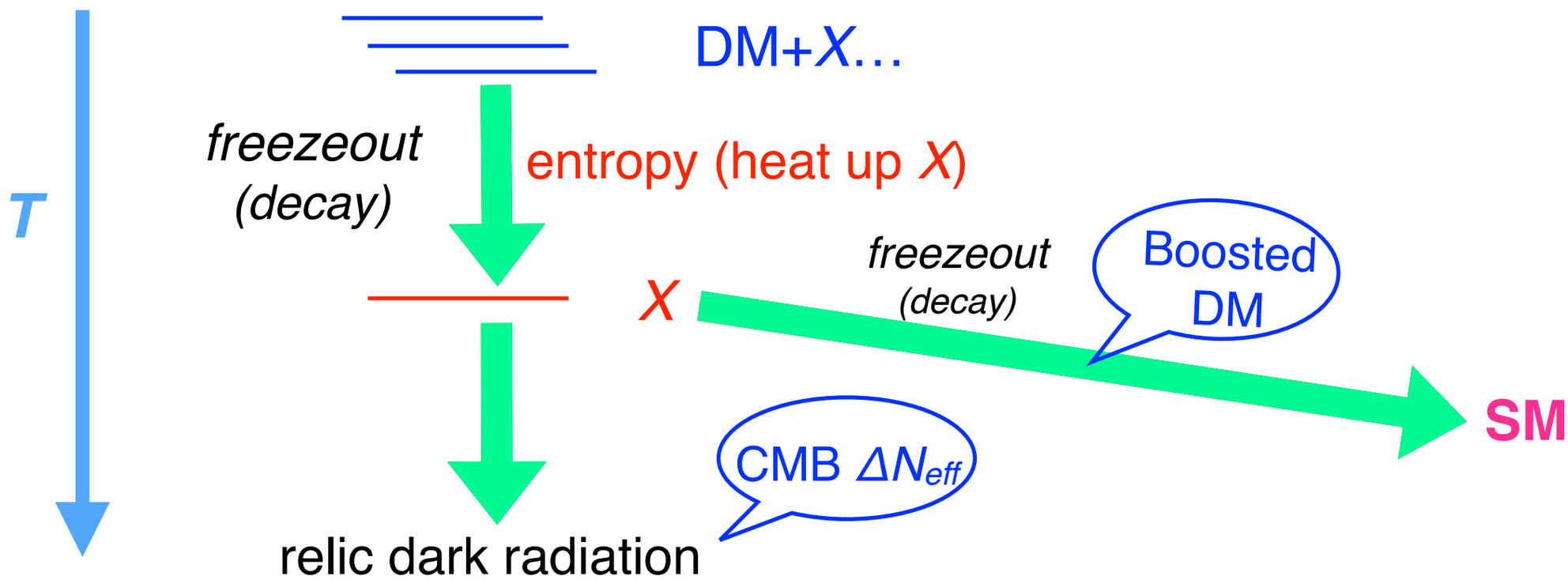
$$\Delta N_{\rm tot} < 0.39 \text{ at } 2\sigma$$

A 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)*





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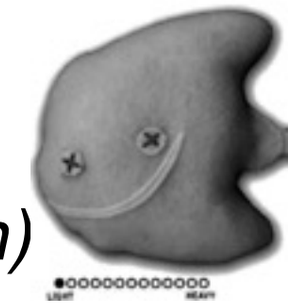

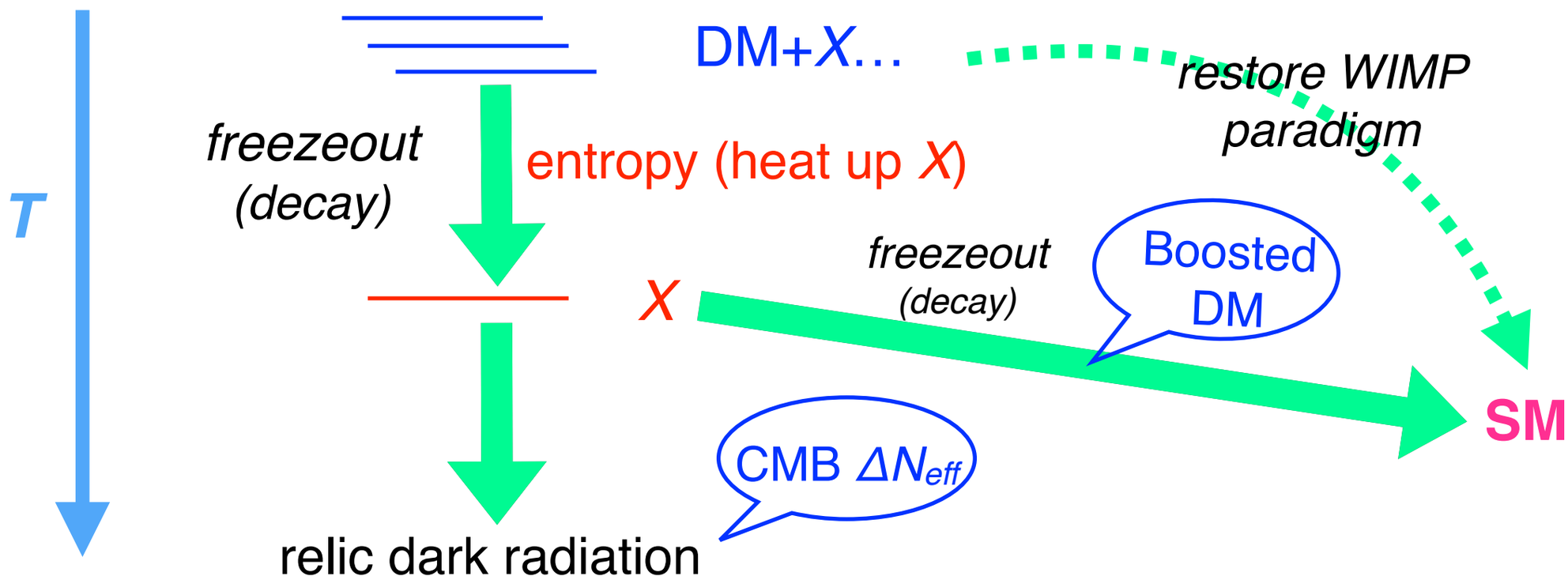

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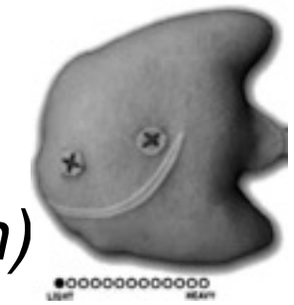
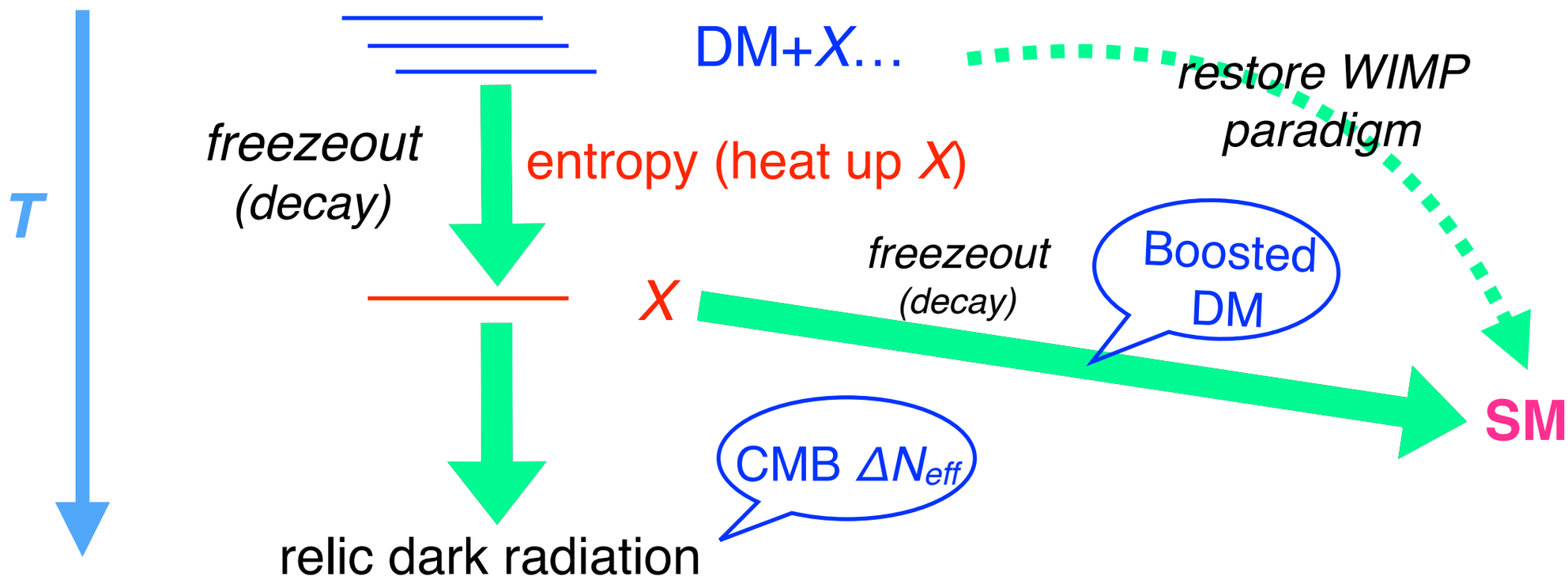




- ***X*** : subdominant abundance, $\Omega_X < \Omega_{DM}$
  yet plays an important cosmological role!
- ***X***: may be the **smoking-gun** for the whole dark sector!
  New observational directions!

Episode #3

Cosmological Signatures of DM-DR Interactions

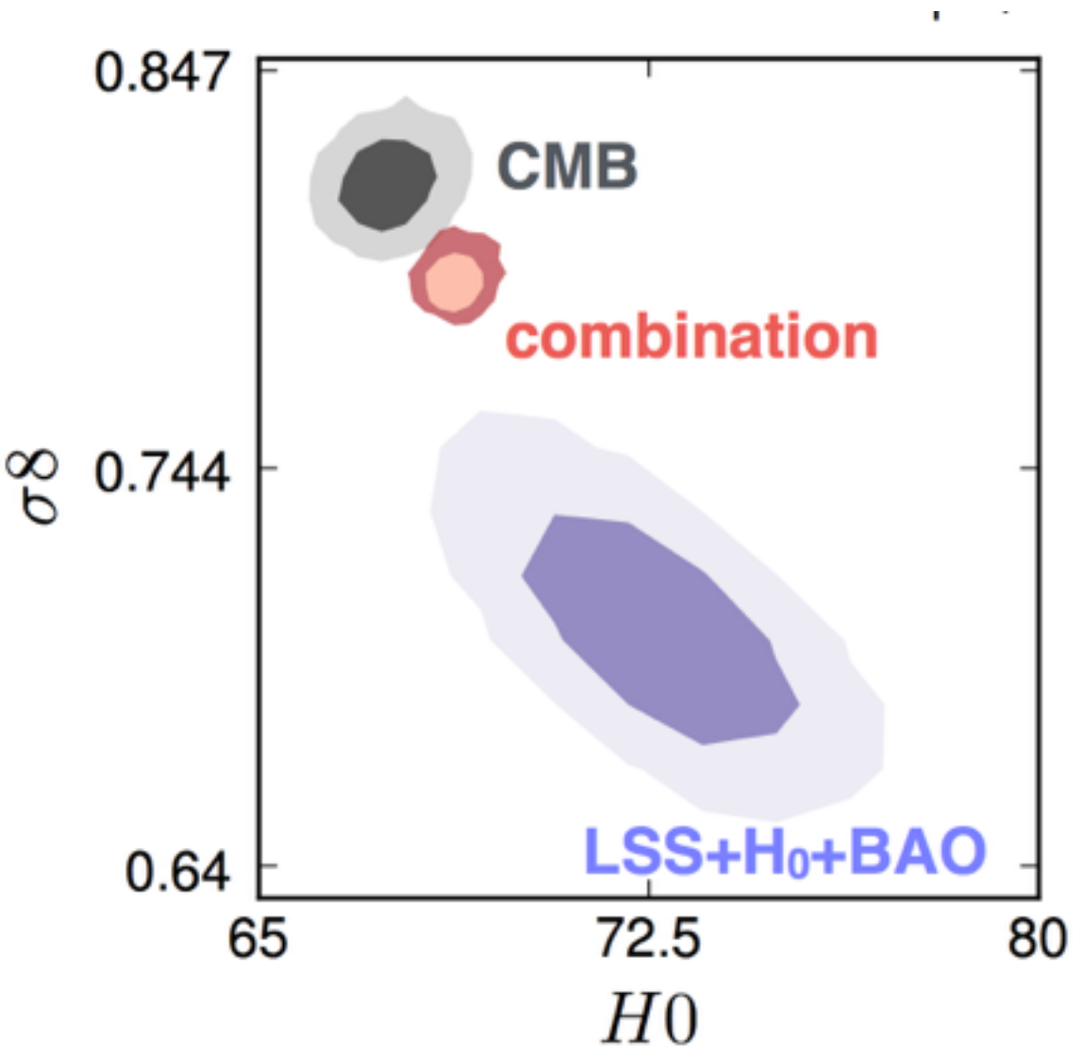
(CMB, structure formation)

- YC w/Chacko, Hong, Okui and Tsai JHEP 1612 (2016) 108
- YC and Ran Huo, work in prep

Partially Acoustic DM (PAcDM)

YC with Chacko, Hong, Okui and Tsai, JHEP 1612 (2016)

Puzzles from Large Scale Structure



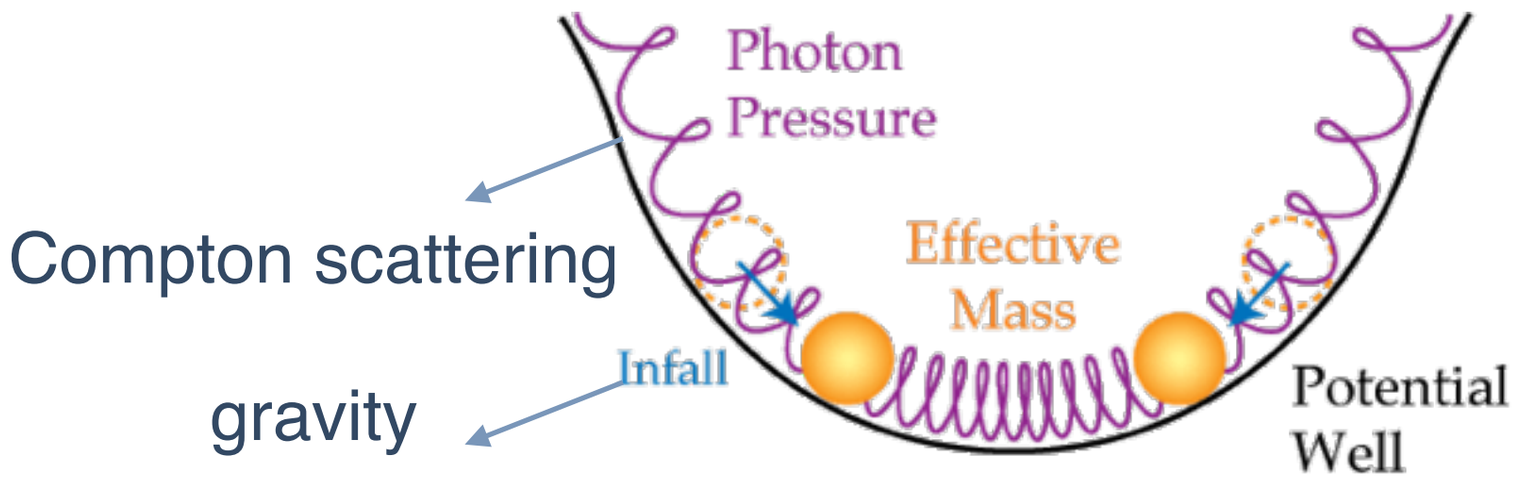
Poulin et. al. JCAP 1608 (2016)

Comparing to ΛCDM model, we want to obtain a

- Smaller density perturbation
- Larger Hubble expansion rate at the late time universe

A Dark Sector Offers a Solution?

- Additional dark radiation (DR) helps increase Hubble rate at recombination time: $H_0 \propto \sqrt{\rho}$
- Dark acoustic oscillation: coupled DM + DR prohibit growth of structure, reduce σ_8



— *inspiration from the SM*

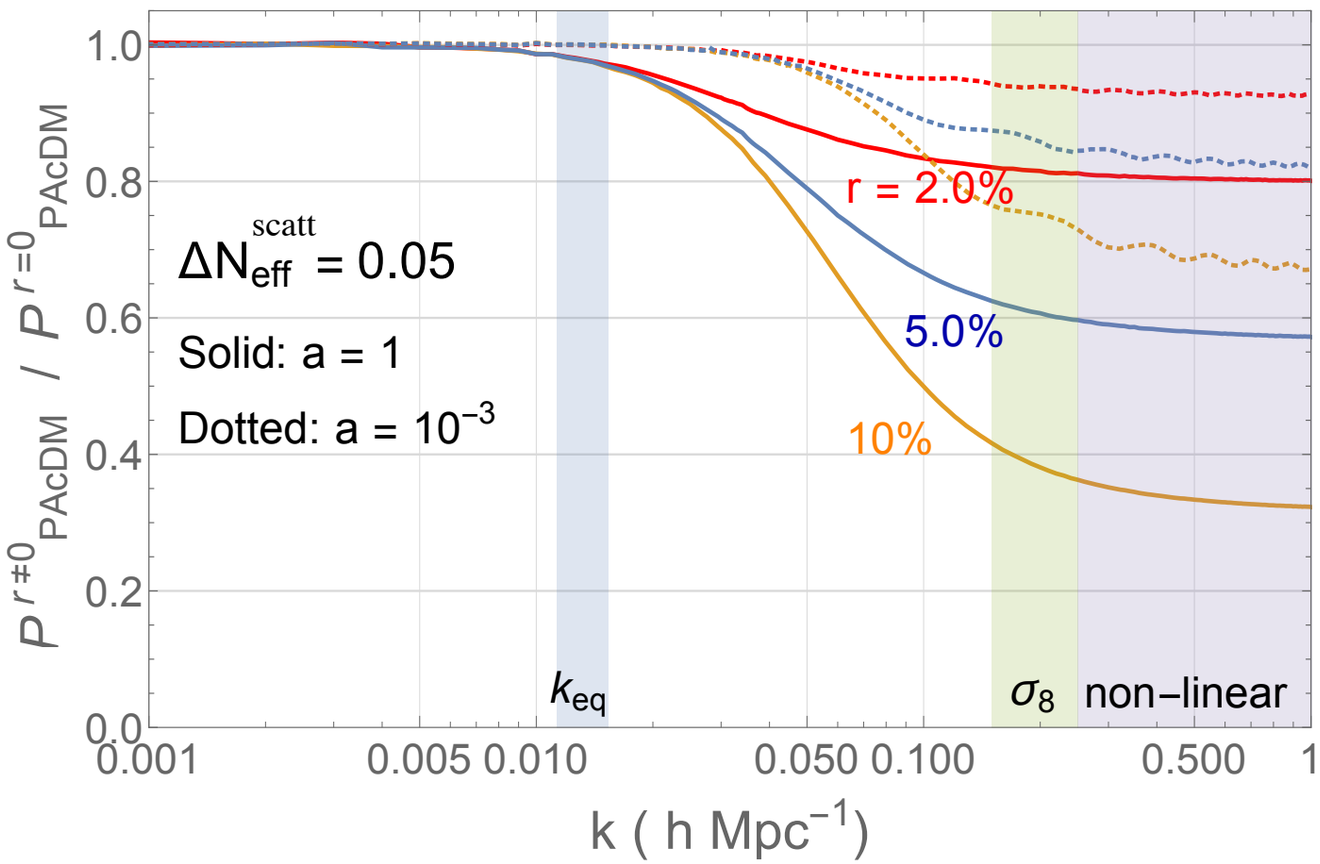
- 100% acoustic DM: too much suppression;
- Other related approach:

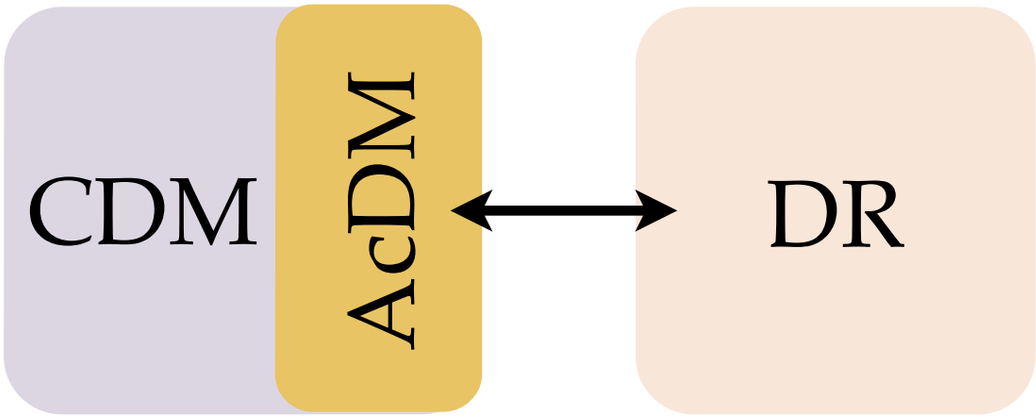
Buen-Abad, Marques-Tavares, and Schmaltz (2015)

Lesgourgues, Marques-Tavares, and Schmaltz (2015)

Partially Acoustic Dark Matter

- A small fraction (r) of DM having acoustic oscillation





$$\frac{P(r)}{P(0)} \simeq (1-2r)\left(\frac{a}{a_{\rm eq}}\right)^{-1.2r}$$

-analytic solution

- Structure grows slower comparing to CDM
- Redshift dependent suppression (a modified power law!)

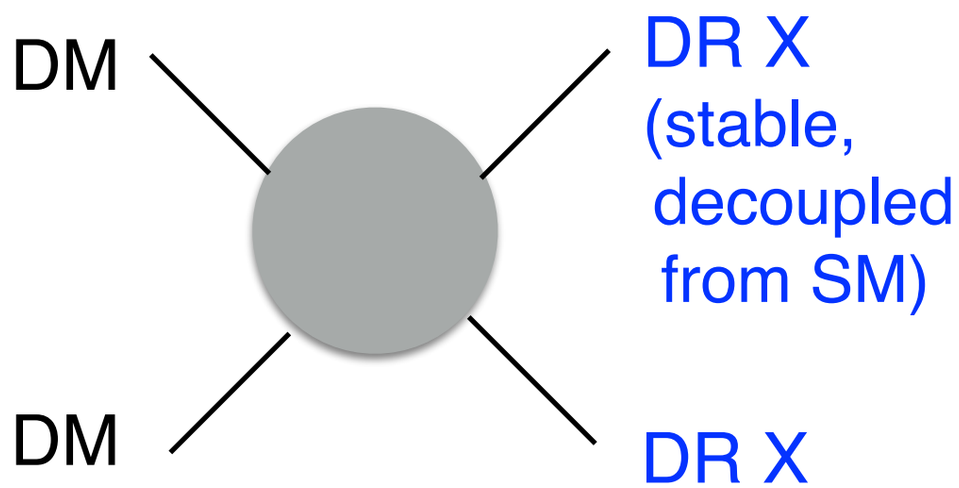
Smaller correction to the CMB spectrum vs. 100% AcDM

Recent: may not fully address both σ_8 and H_0, *Raveri et al. 2017*

Visualizing Invisibly Annihilating DM (IAnDM)

YC with Ran Huo, work in prep

The theoretically minimal, observationally challenging dark sector scenario (IAnDM):



—no effective portal interaction

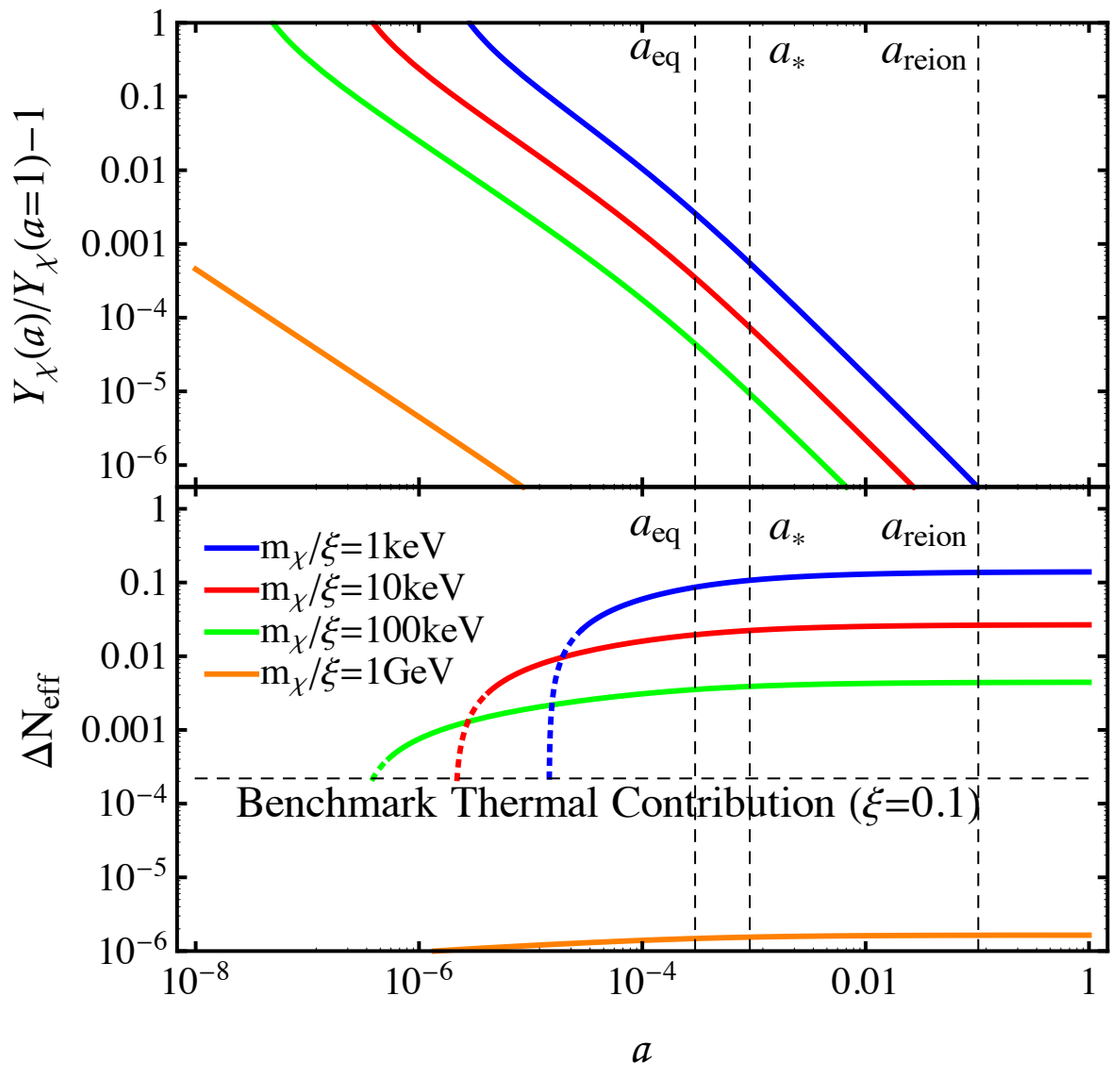
- <u>Thermal relic</u> of DR X (N_{fld}, N_{eff} or f_{fs}, N_{tot}) can be very suppressed for very decoupled, colder dark sector
- <u>Direct</u> smoking-gun signature from the DM invisible annihilation itself? *(analogy to DM indirect detection)*

  - the <u>non-thermal</u> injection of DR X ($E_x = m_{DM}$)

Visualizing Invisibly Annihilating DM (IAnDM)

YC with Ran Huo, work in prep

- Scale-dependent ΔN_{eff} : accumulation of DR from DM annihilation over time



- Effects on matter power spectrum (WDM-like but distinguishable)

Conclusion

- **Hidden Thermal Dark Sectors:**
  - Well motivated: resembles SM, solutions to naturalness problem…
  - A simple variation to WIMP paradigm:
    DM →stable X annihilation, dramatically different/ challenging phenomenology!
  - Systematic studies possible, despite complexity!
- **New Observational Windows for Dark Sectors:**
  - Secondary stable dark state X as the smoking gun: Boosted DM (neutrino expts., DM direct detection); interacting dark radiation (CMB, DM direct detection)
  - Imprints of DM-X interaction: structure formation, CMB (e.g. PAcDM, IAnDM)

Thank you!