

Title: Probing the Invisible Cosmos: from the Early Universe to the Near Field - VIRTUAL

Speakers: Rui An

Series: Cosmology & Gravitation

Date: January 23, 2024 - 11:00 AM

URL: <https://pirsa.org/24010090>

Abstract: The fundamental nature of dark matter and dark energy remains unknown and requires new physics to explain. This talk will present a cosmological quest to understand the properties of these two dominant but invisible components of our universe. I will present my work on early and late-universe searches for the identity of dark matter, and discuss cosmological limits on its mass, interactions with Standard Model, and production mechanisms, using the measurements of Big Bang Nucleosynthesis, Cosmic Microwave Background, 21-cm, and cosmic structure. Within the next decade, upcoming surveys will dramatically improve our measurements of these probes, enabling new insights into the invisible universe. If time permits, I will briefly introduce my work on cosmological searches for dark energy, as well as modified gravity.

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Zoom link

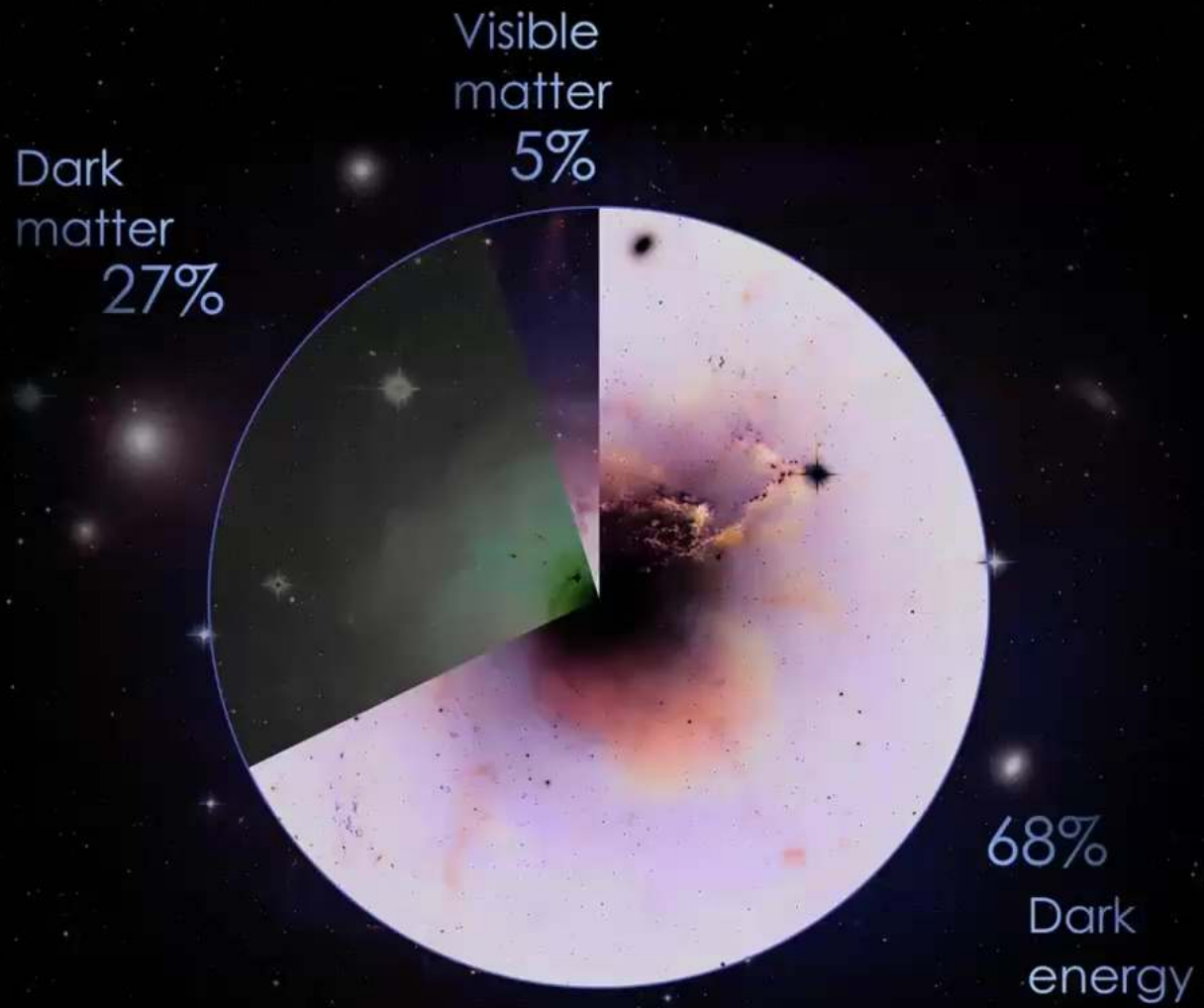


# Probing the Invisible Cosmos: from the Early Universe to the Near Field

Rui An

University of Southern California, Los Angeles, U.S.

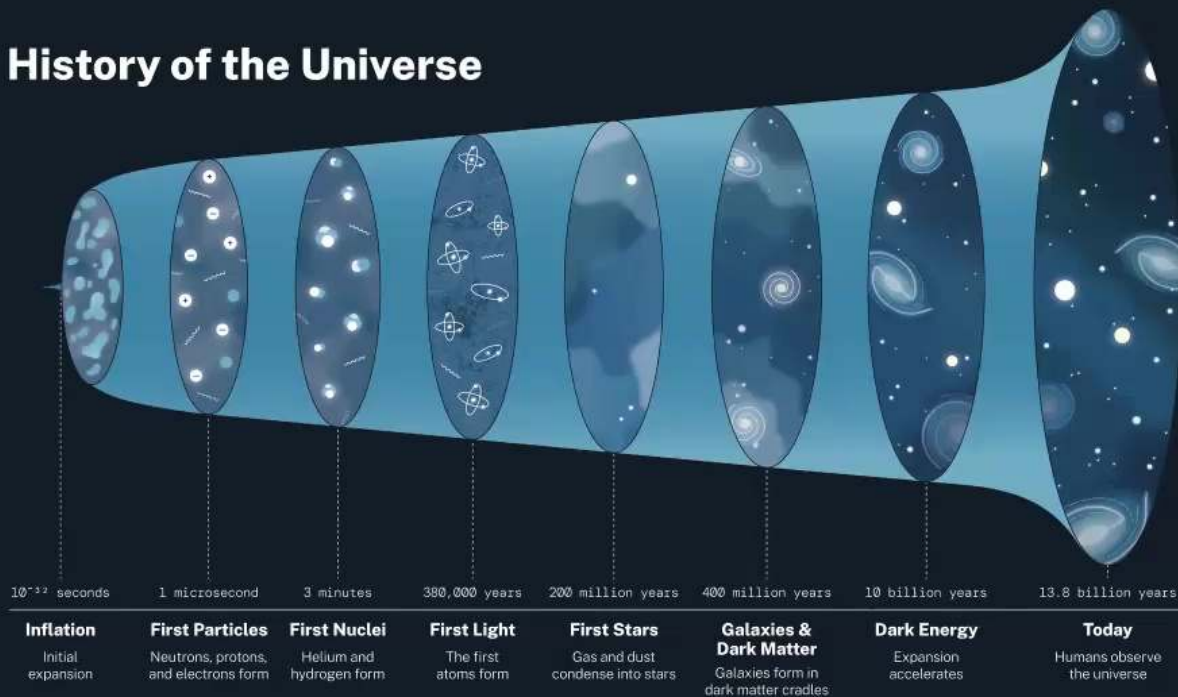




Plot Credit: NASA

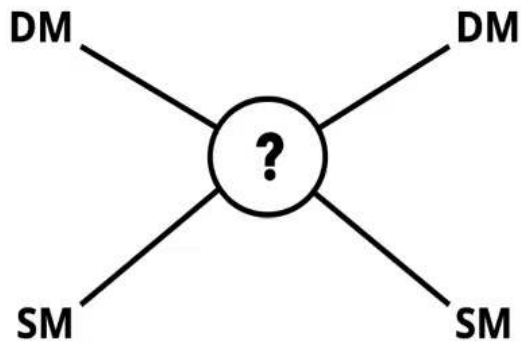
# Cosmological probes from the early to late Universe

## History of the Universe



- Big Bang Nucleosynthesis
- Cosmic Microwave Background
- 21-cm signal
- Large Scale Structure
- Near Field Cosmology

# The Fundamental Nature of Dark Matter



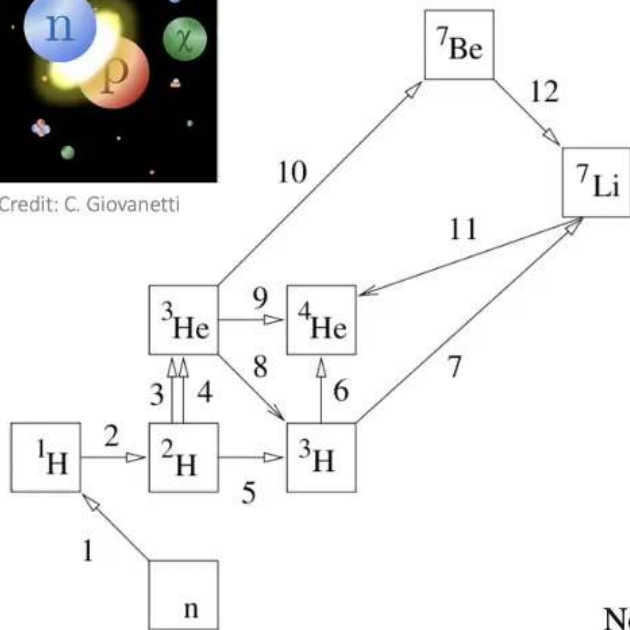
- Mass?
- Interactions with Standard Model?
- Production Mechanisms?

# What can we learn from the early Universe? -- BBN and CMB

# Big Bang Nucleosynthesis



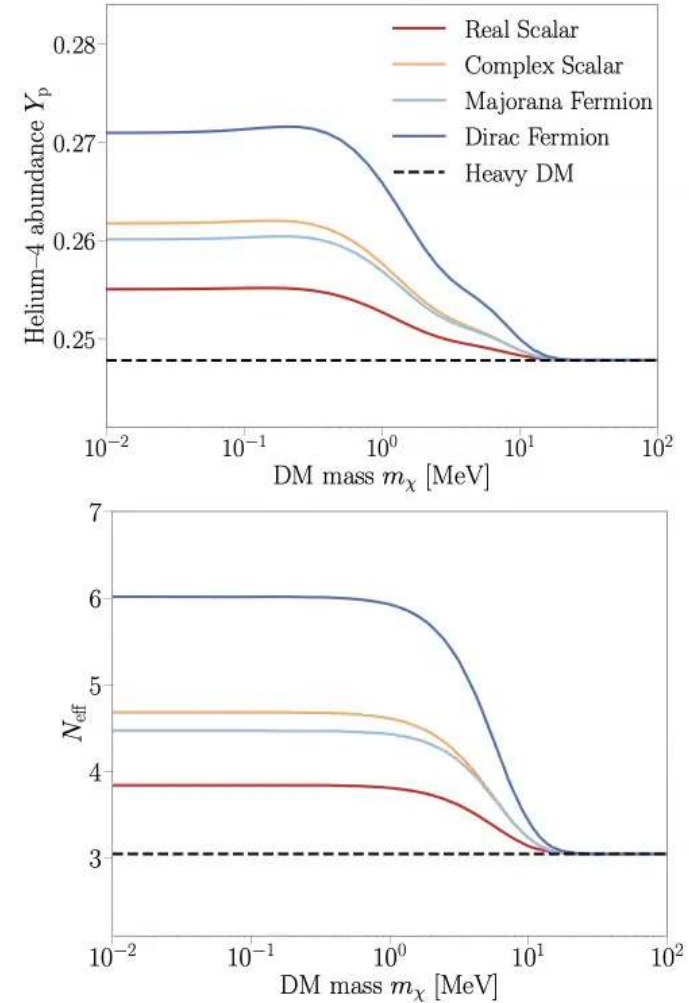
Plot Credit: C. Giovanetti



1.  $p \leftrightarrow n$
2.  $p(n, \gamma)d$
3.  $d(p, \gamma)^3\text{He}$
4.  $d(d, n)^3\text{He}$
5.  $d(d, p)t$
6.  $t(d, n)^4\text{He}$
7.  $t(\alpha, \gamma)^7\text{Li}$
8.  $^3\text{He}(n, p)t$
9.  $^3\text{He}(d, p)^4\text{He}$
10.  $^3\text{He}(\alpha, \gamma)^7\text{Be}$
11.  $^7\text{Li}(p, \alpha)^4\text{He}$
12.  $^7\text{Be}(n, p)^7\text{Li}$

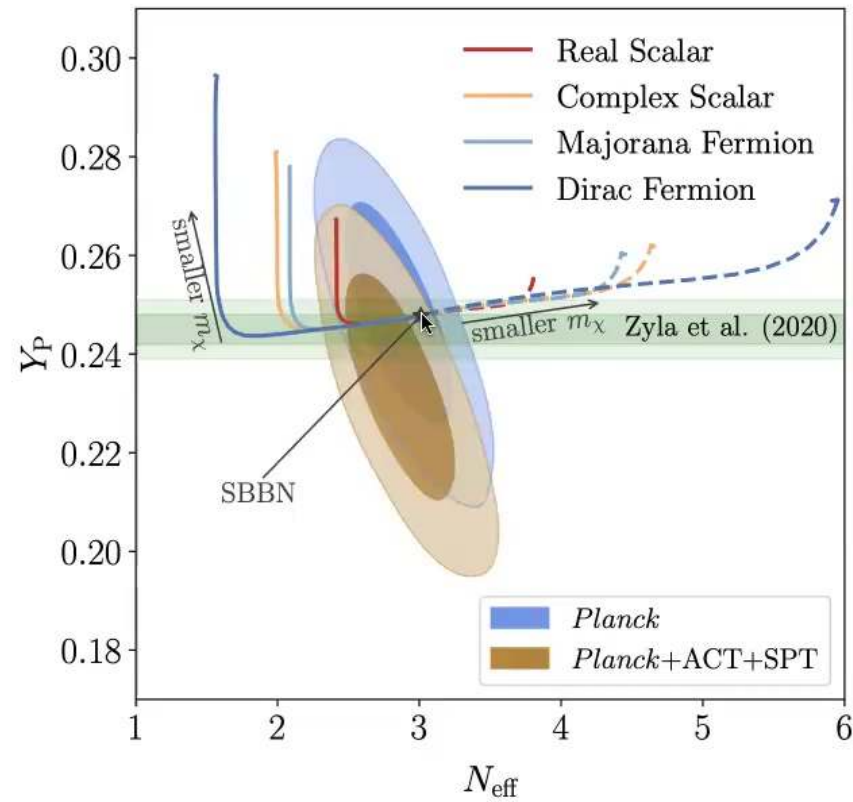
Nollet, Burles, 2000

## Neutrino coupled DM



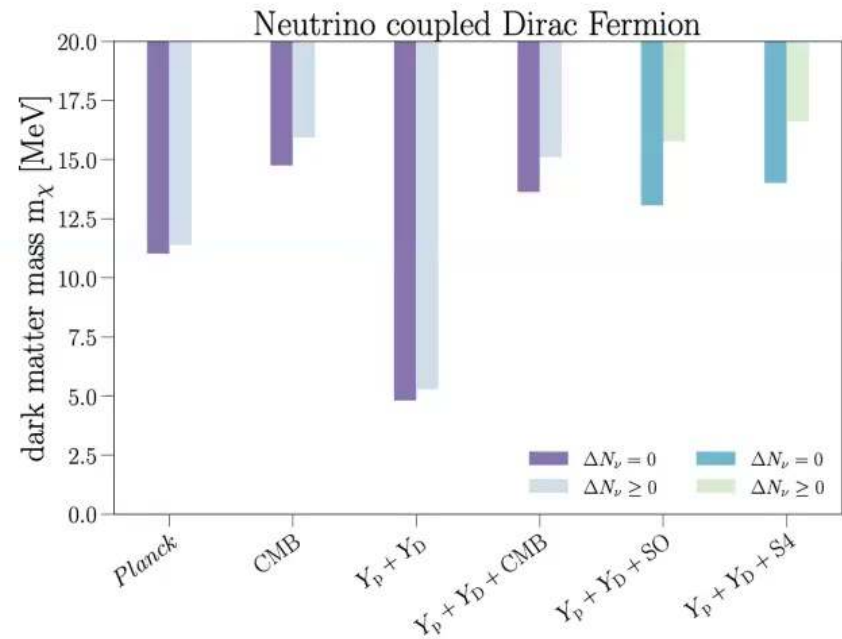
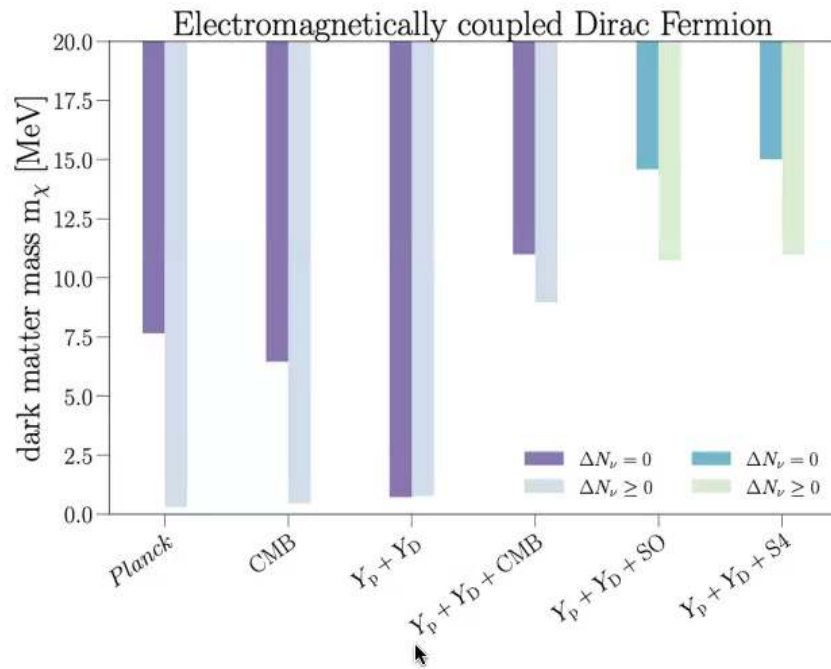
RA, Gluscevic, Calabrese, Hill, JCAP 2022 [arXiv: 2202.03515]

# Cosmic Microwave Background Measurements

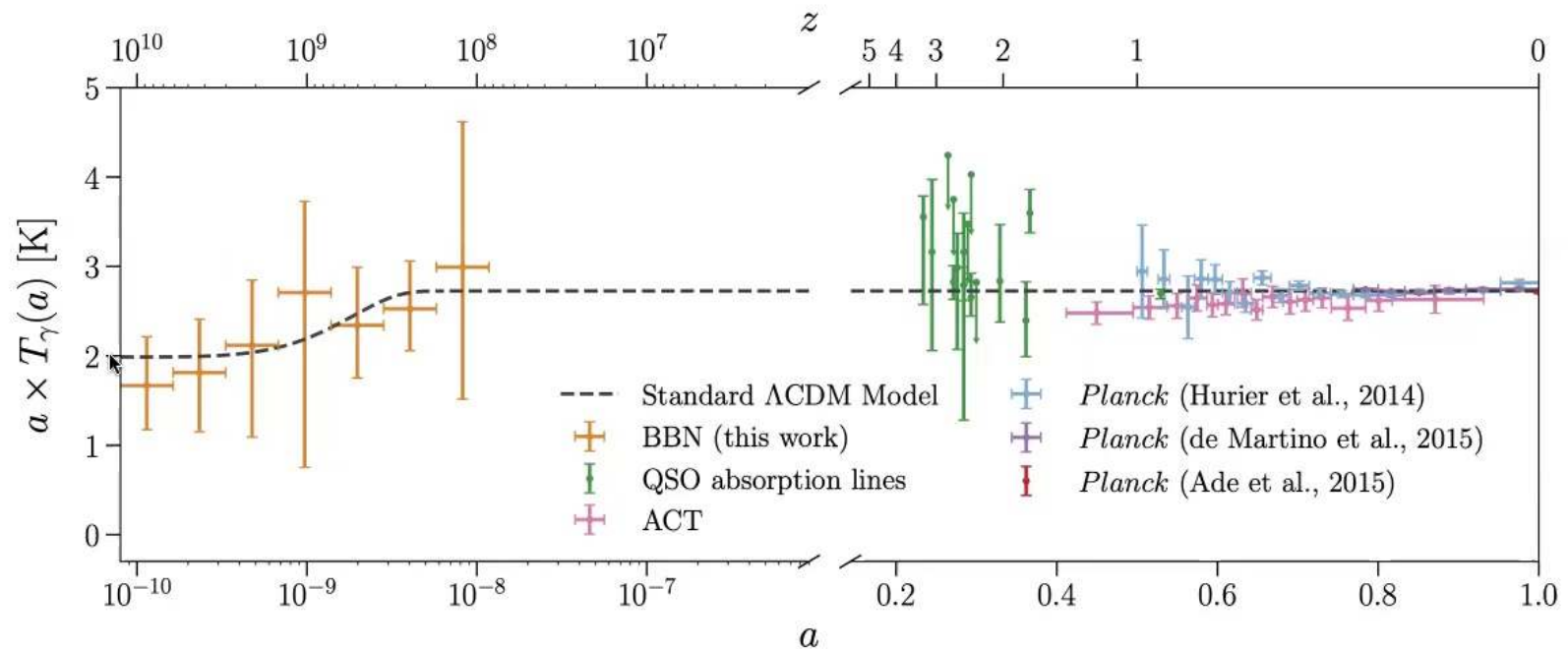


RA, Gluscevic, Calabrese, Hill, JCAP 2022 [arXiv: 2202.03515]

## Lower bounds on light thermal-relic DM mass

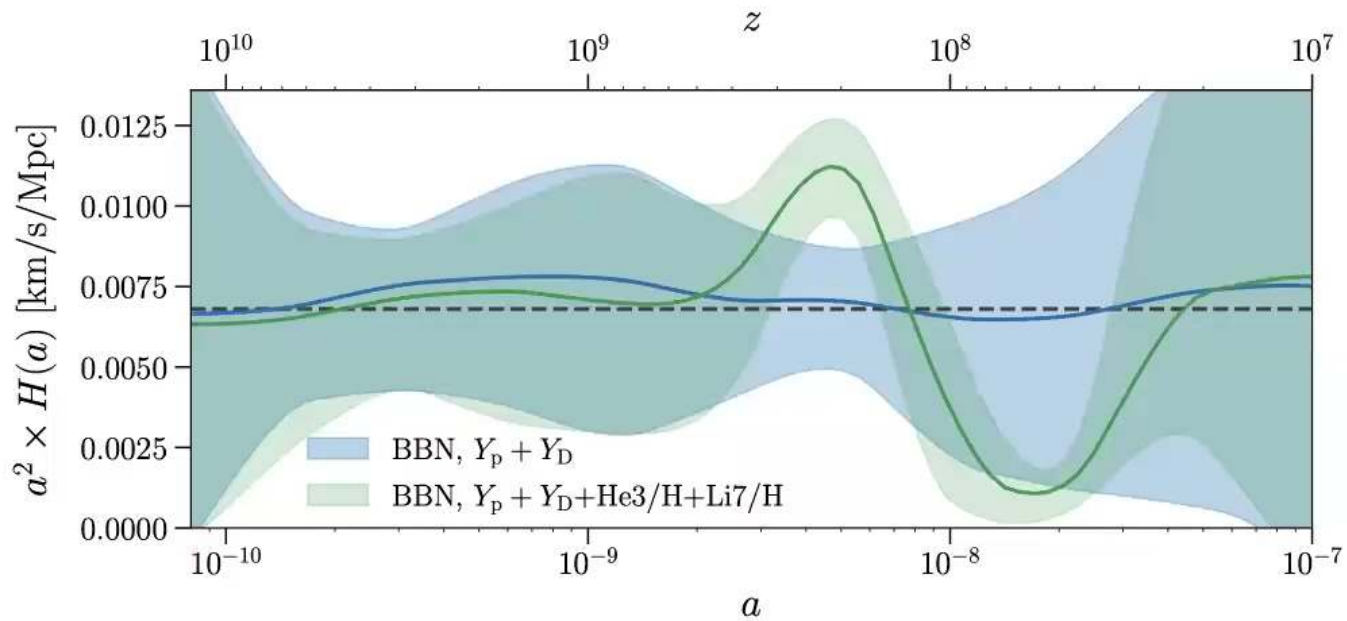


# Reconstruction of the radiation temperature from BBN yield measurements



RA, Gluscevic, PRD 2024 [arXiv: 2310.17195]

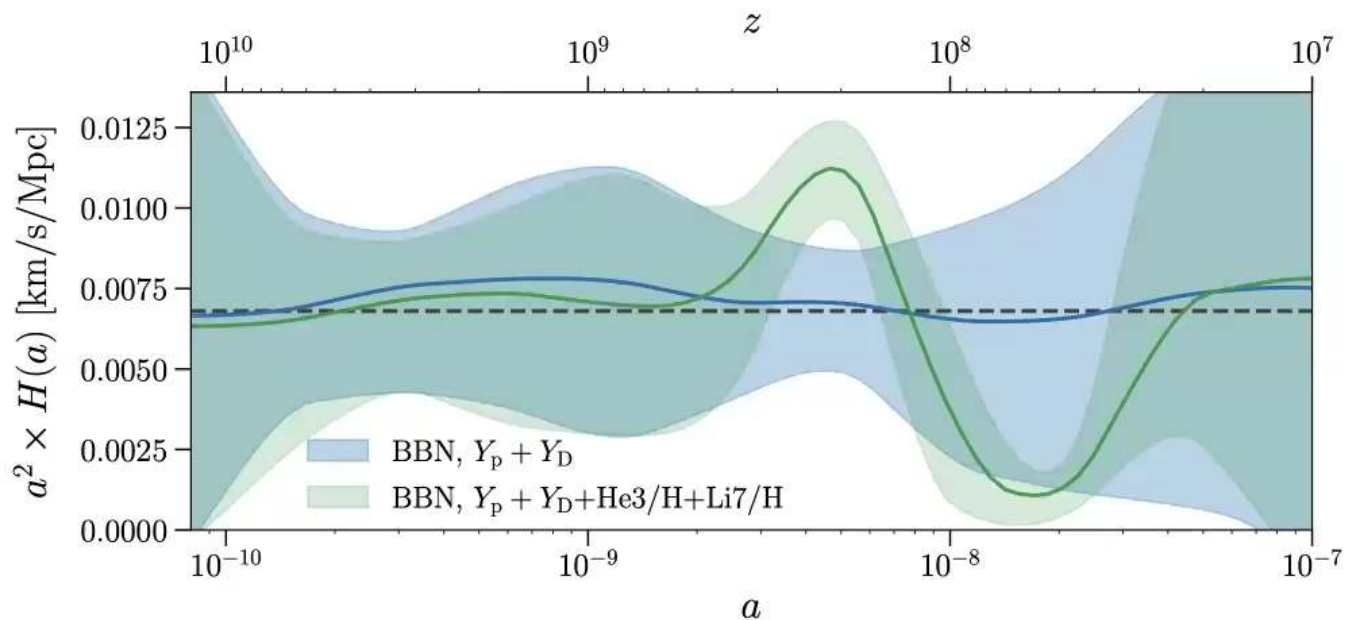
# Reconstruction of the expansion rate from BBN yield measurements



RA, Gluscevic, PRD 2024 [arXiv: 2310.17195]



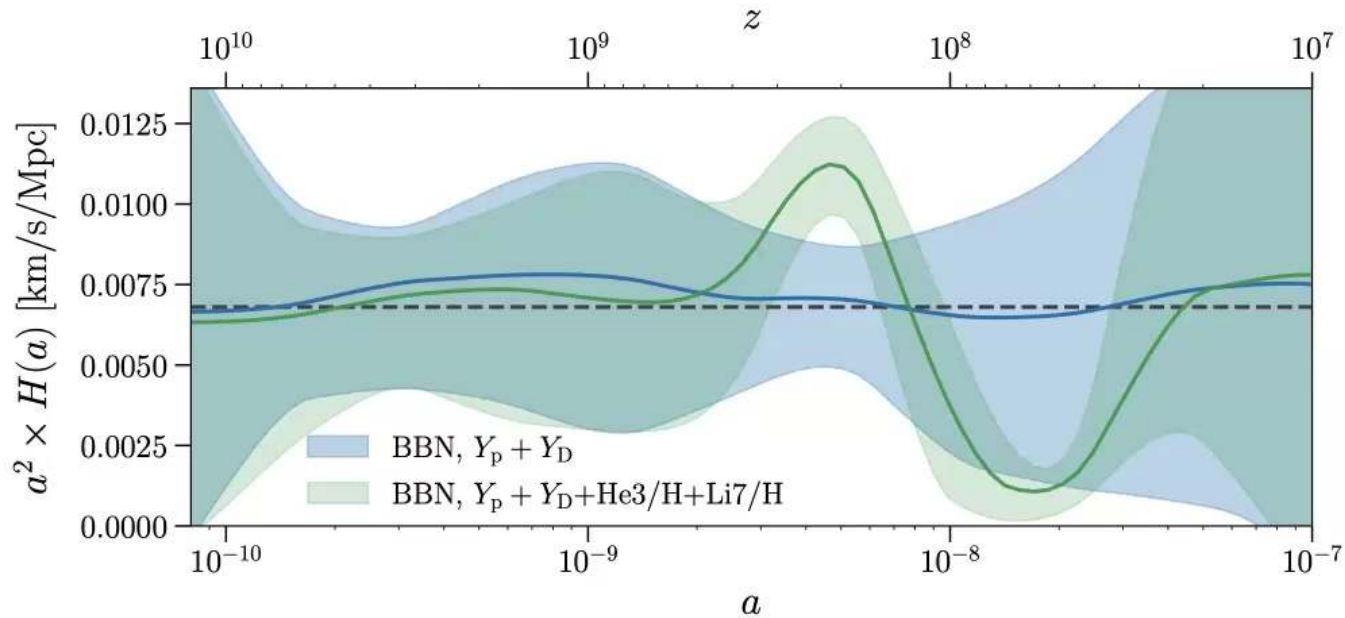
# Reconstruction of the expansion rate from BBN yield measurements



**Lithium Problem:** The SBBN-predicted abundance of Lithium-7 is a factor of 3-4 higher than its observed value

RA, Gluscevic, PRD 2024 [arXiv: 2310.17195]

# Reconstruction of the expansion rate from BBN yield measurements

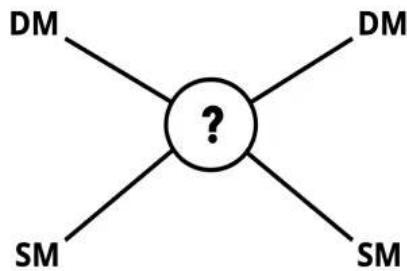


**Lithium Problem:** The SBBN-predicted abundance of Lithium-7 is a factor of 3-4 higher than its observed value

**One possible solution:** Large deviations to the SBBN evolution around and soon after the on-set of nuclear interactions

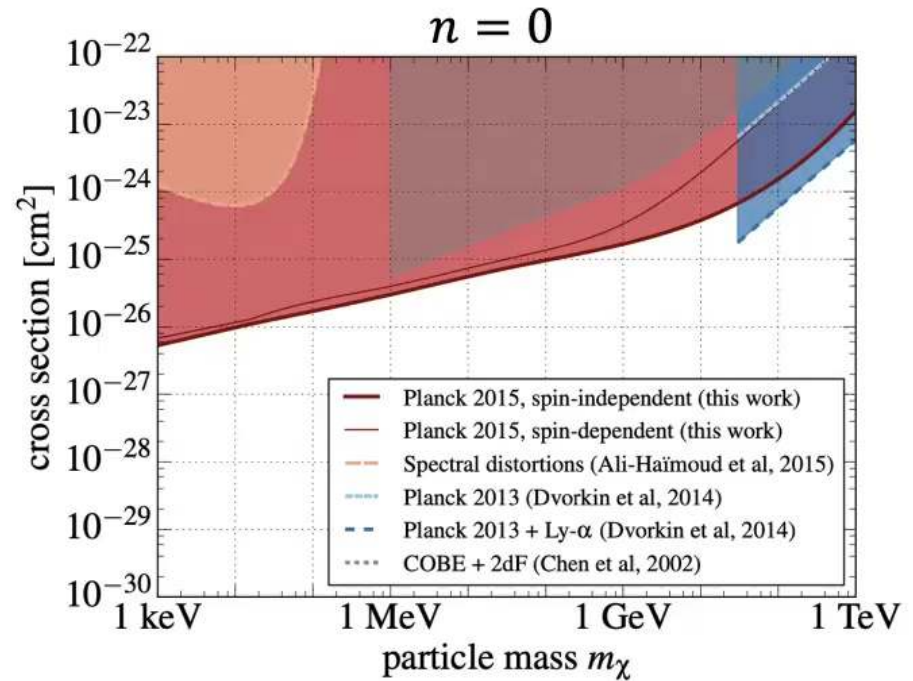
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# Interactions with Standard Model (Baryons)



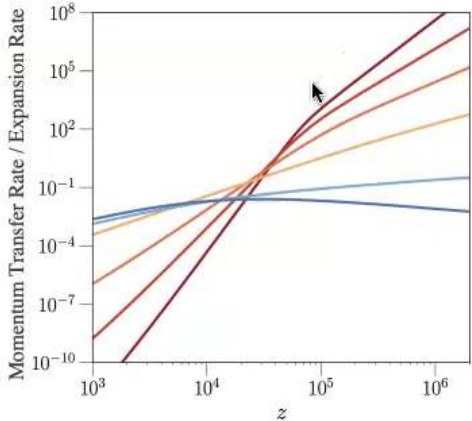
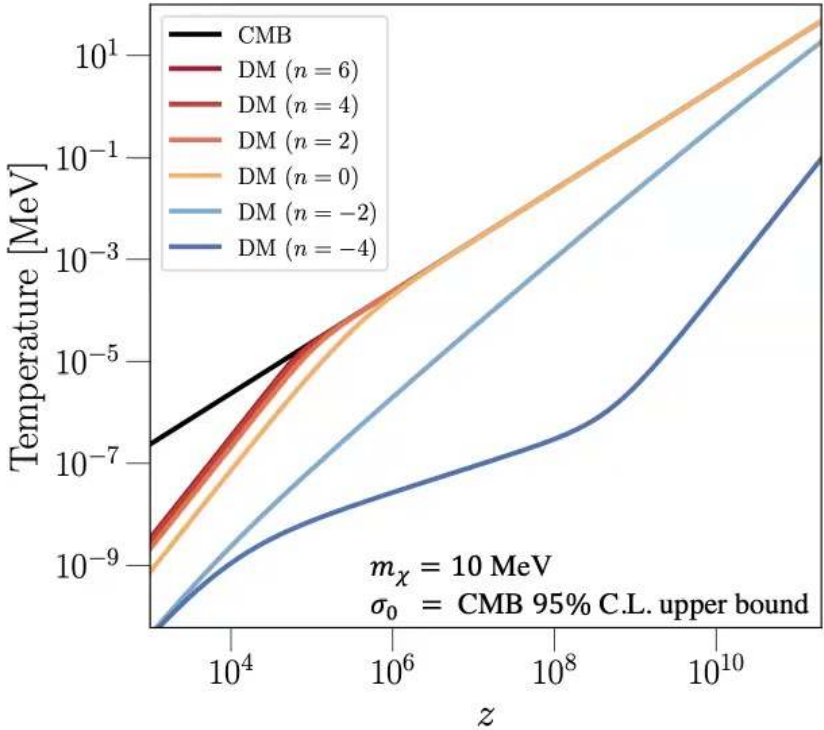
$$\sigma_{\text{MT}} = \sigma_0 v^n$$

Momentum-transfer cross section



Boddy, Gluscevic, 2017

# Evolution of the DM temperature for different DM-baryon scattering models

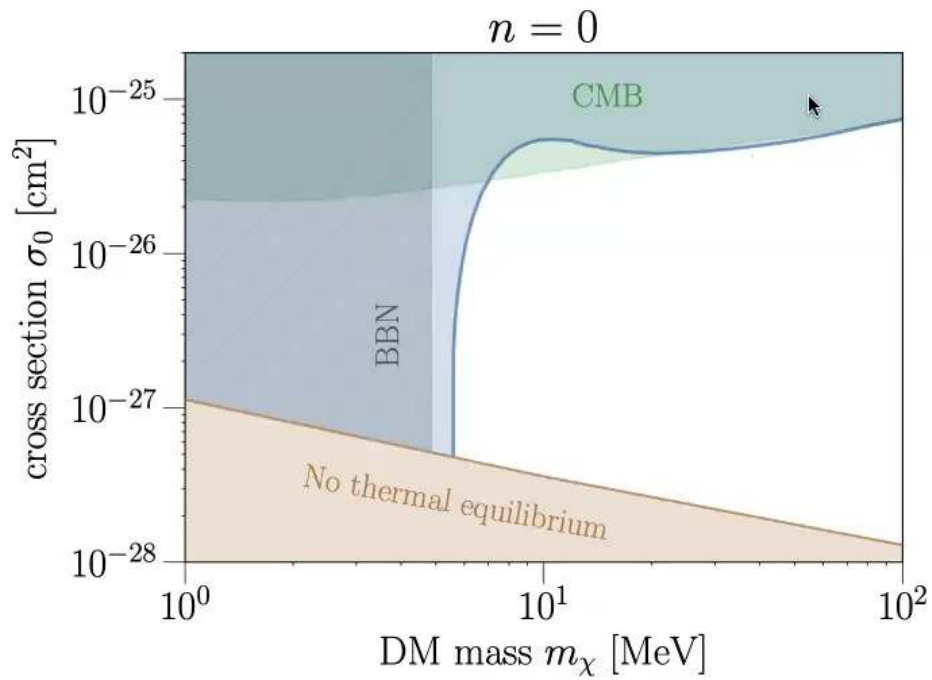


RA, Boddy, Gluscevic, in prep

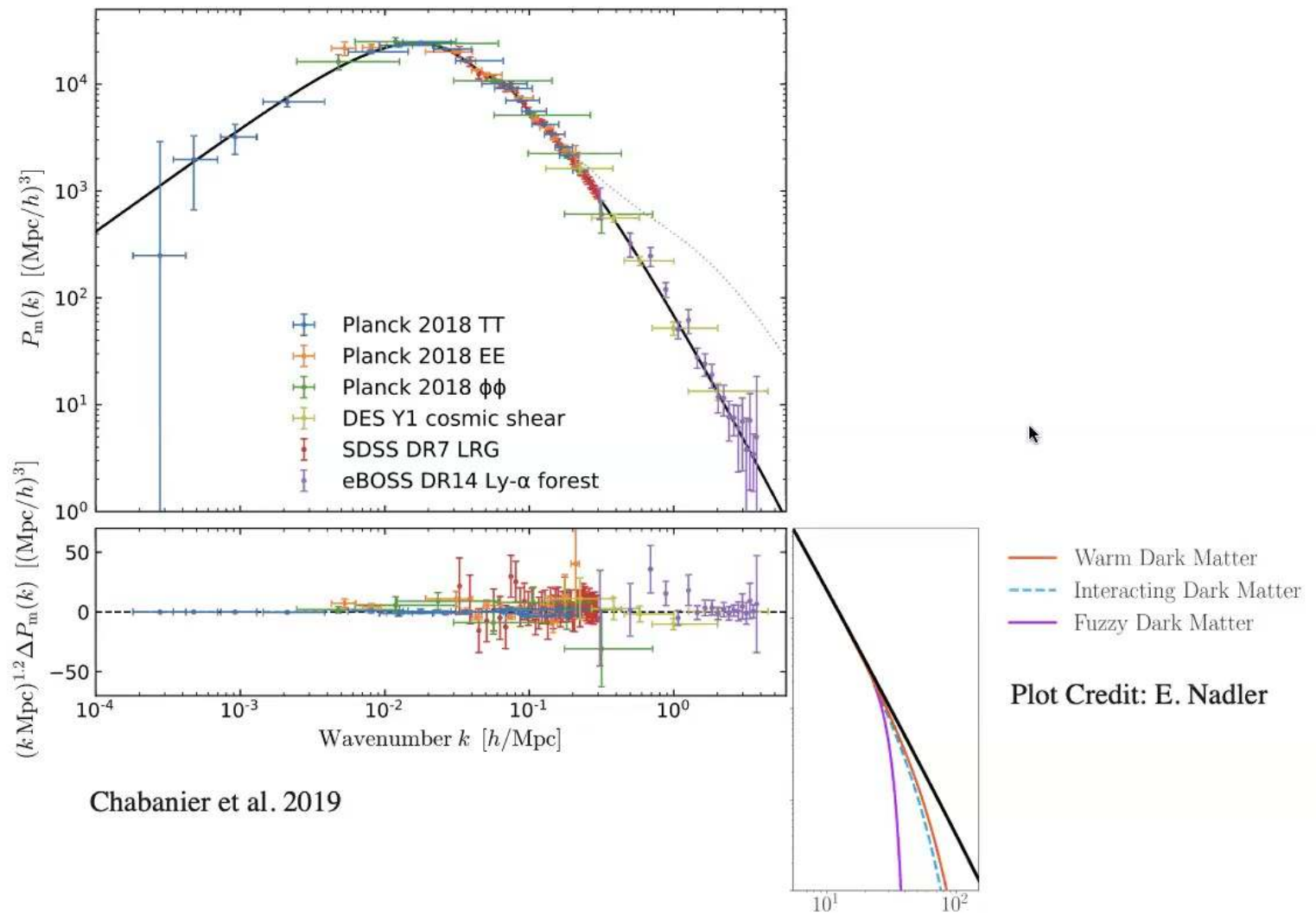


# Self-consistent CMB bounds on interacting thermal-relic dark matter

## Light thermal relic DM mass + DM and baryon scattering



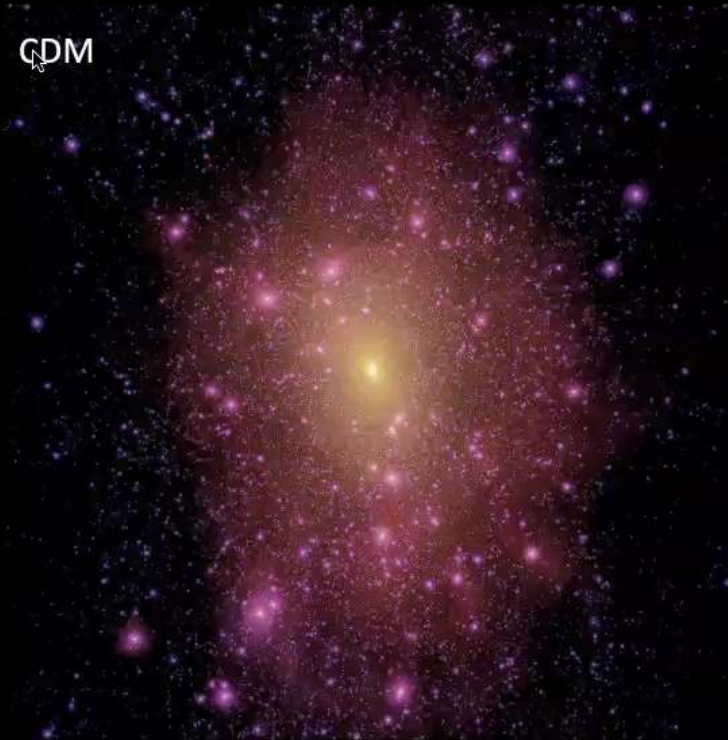
RA, Boddy, Gluscevic, in prep



Chabanier et al. 2019

# Small Halos as Dark Matter Probes

CDM



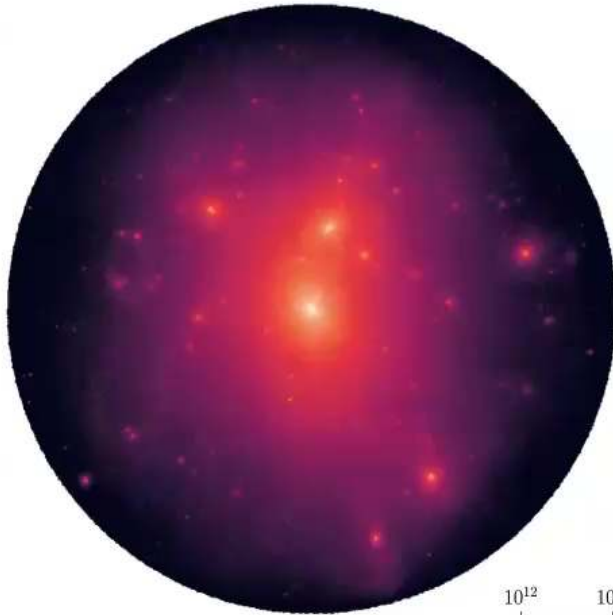
WDM



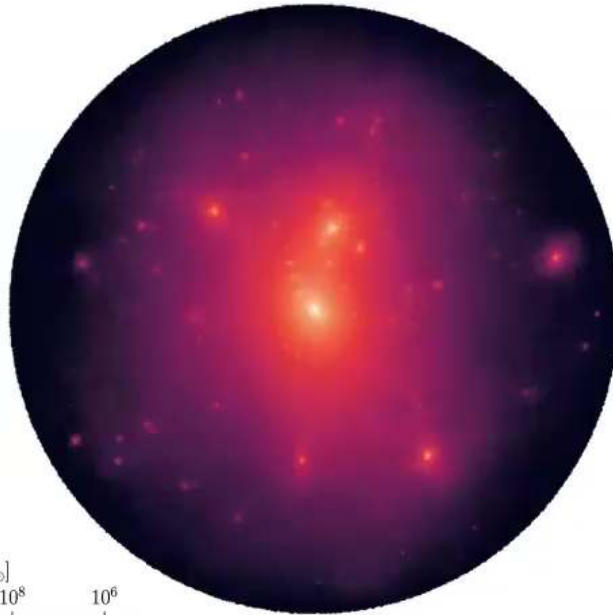
Lovell et al. 2011



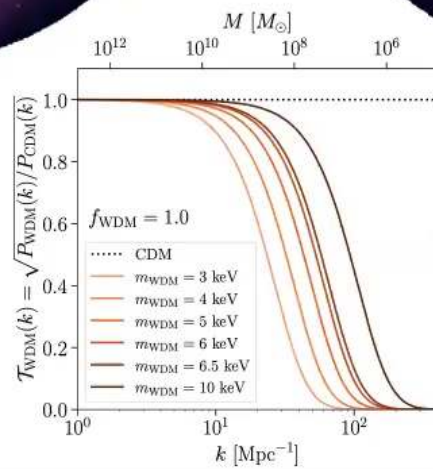
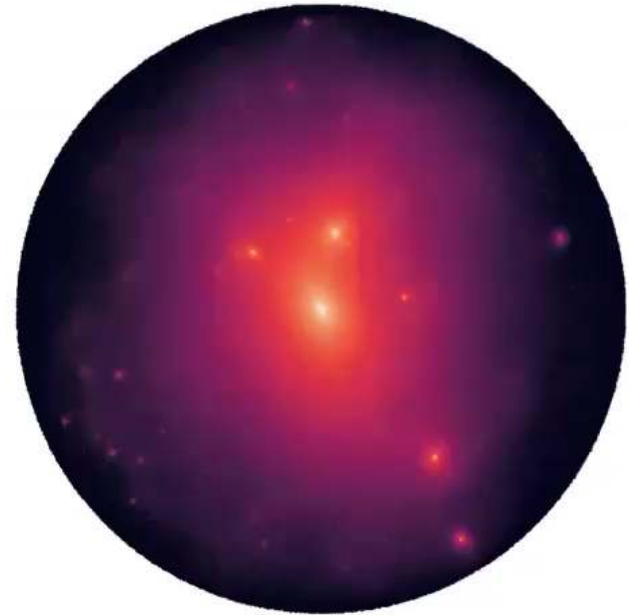
10keV WDM



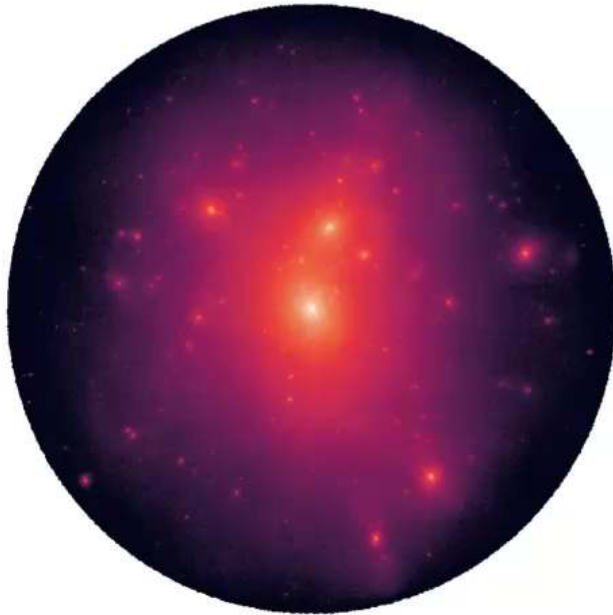
6.5keV WDM



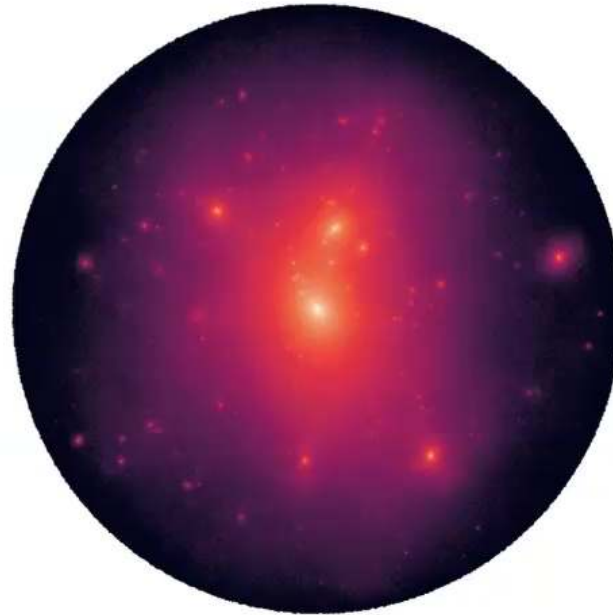
3keV WDM



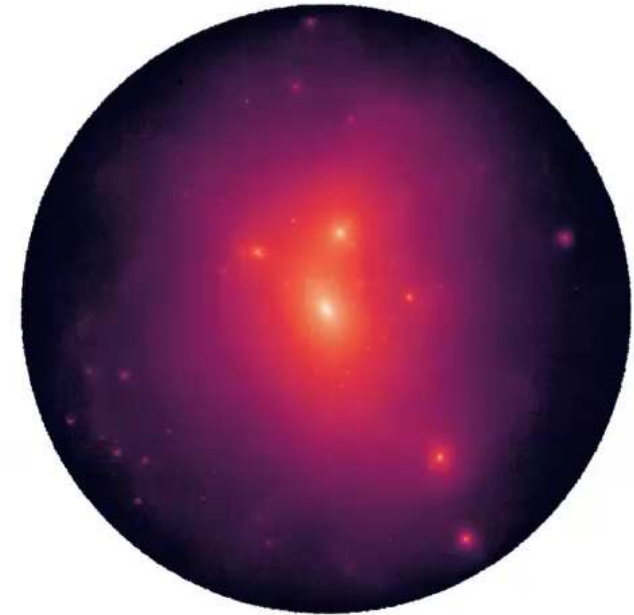
10keV WDM



6.5keV WDM



3keV WDM



+ Galaxy-halo connection model + Observations of Milky Way Satellite populations from DES and Pan-STARRS1



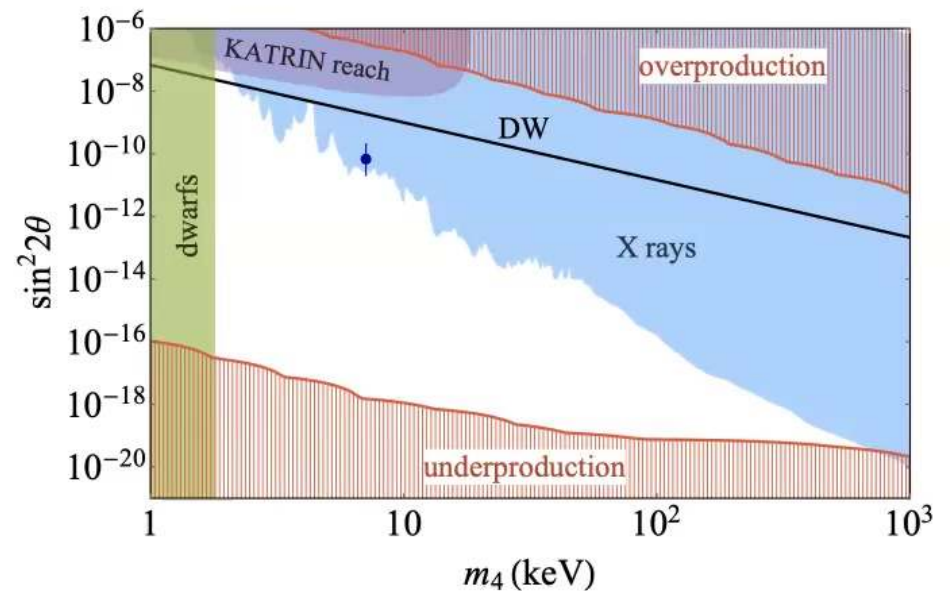
$m_{\text{WDM}} > 6.5 \text{ keV}$  at 95% C. L.

Nadler et al. 2020

# Sterile Neutrino Dark Matter

**Problem:** Dodelson and Widrow (DW) showed that  $\nu_4$  can be produced non-thermally with the correct relic abundance to constitute all of DM. However, this mechanism is in tension with X-rays limits.

$$|\nu_4\rangle = \cos\theta|\nu_s\rangle + \sin\theta|\nu_a\rangle$$



A. de Gouvea et al. 2019

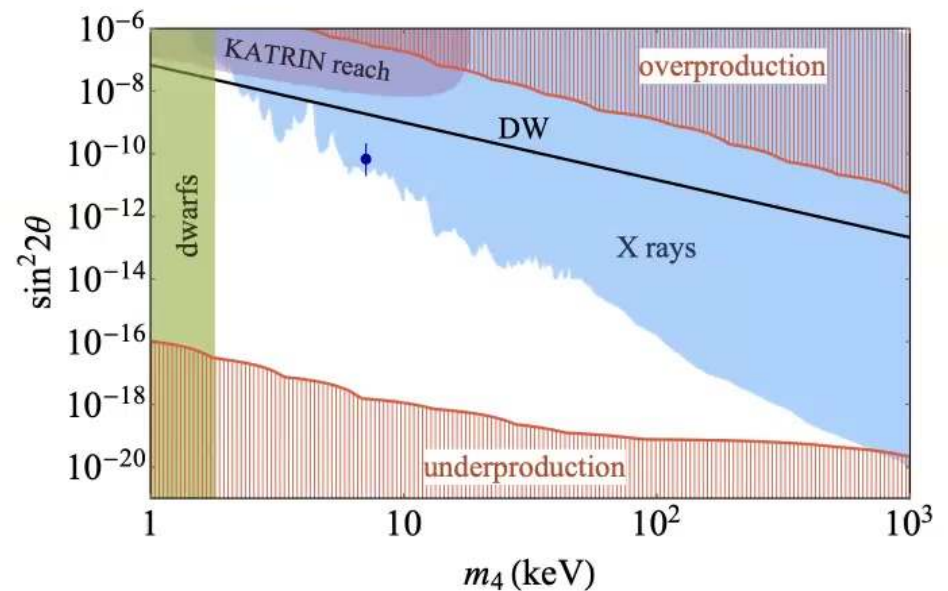
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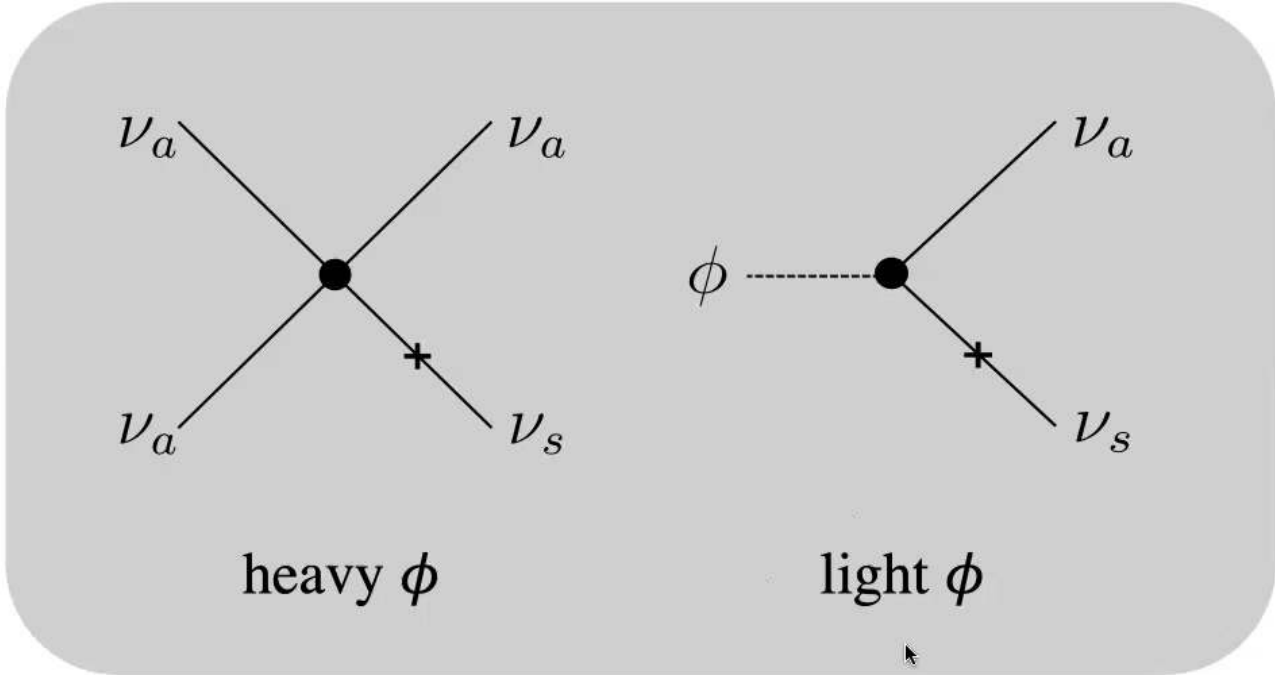
$$|\nu_4\rangle = \cos\theta|\nu_s\rangle + \sin\theta|\nu_a\rangle$$

**Solution:** Introducing a self-interaction among the active neutrinos. The new force enables more frequent active neutrino scattering than normal weak interactions, thereby, DM can be produced with a smaller mixing angle than required by DW

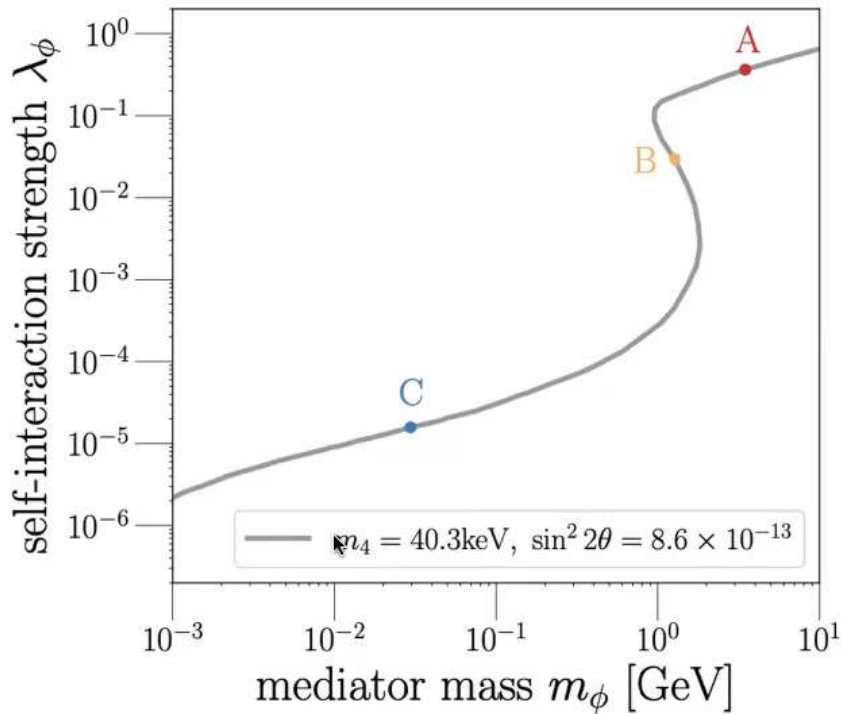
Interaction Term:  $\mathcal{L} \supset \frac{\lambda_\phi}{2} \nu_a \nu_a \phi + \text{h.c.}$



A. de Gouvea et al. 2019



Diagrams for sterile-neutrino production in the presence of neutrino self-interactions

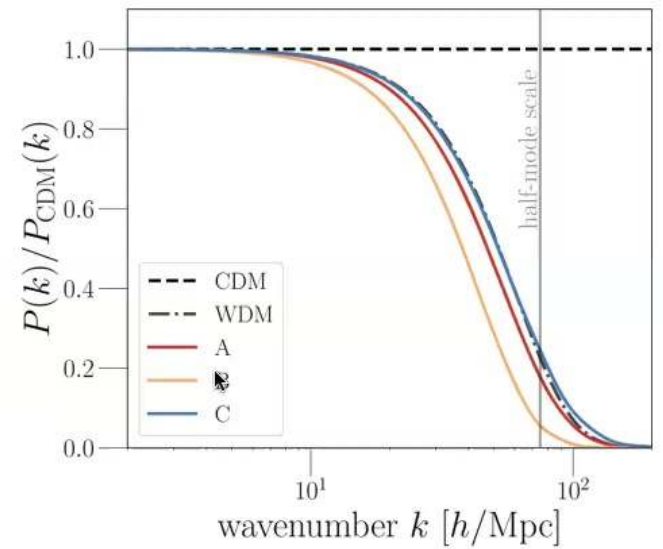
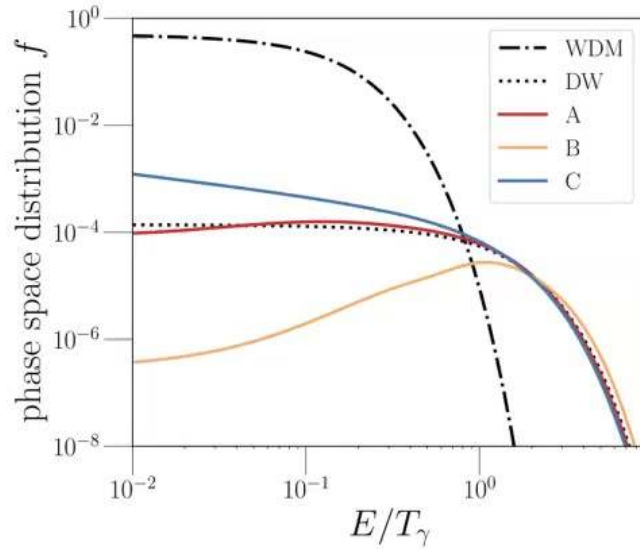
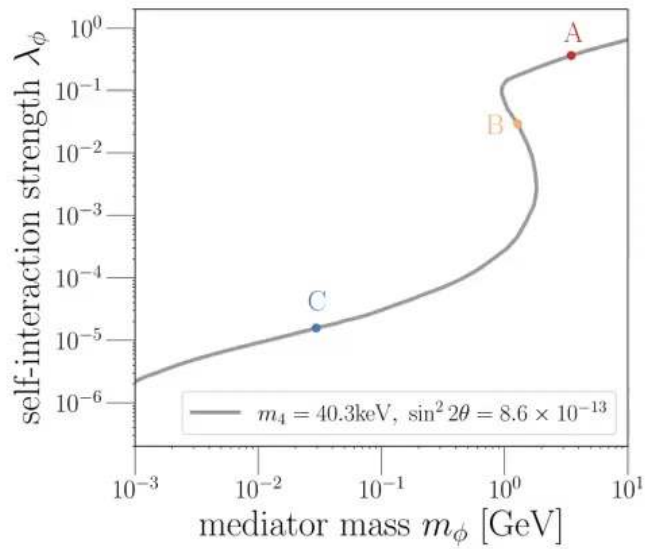


**Case A:** DM production through a heavy mediator, and a strong self-interaction

**Case B:** DM production through a light mediator, with a suppressed in-medium mixing angle

**Case C:** DM production through a light mediator, with the effective active-sterile mixing angle close to the vacuum mixing angle

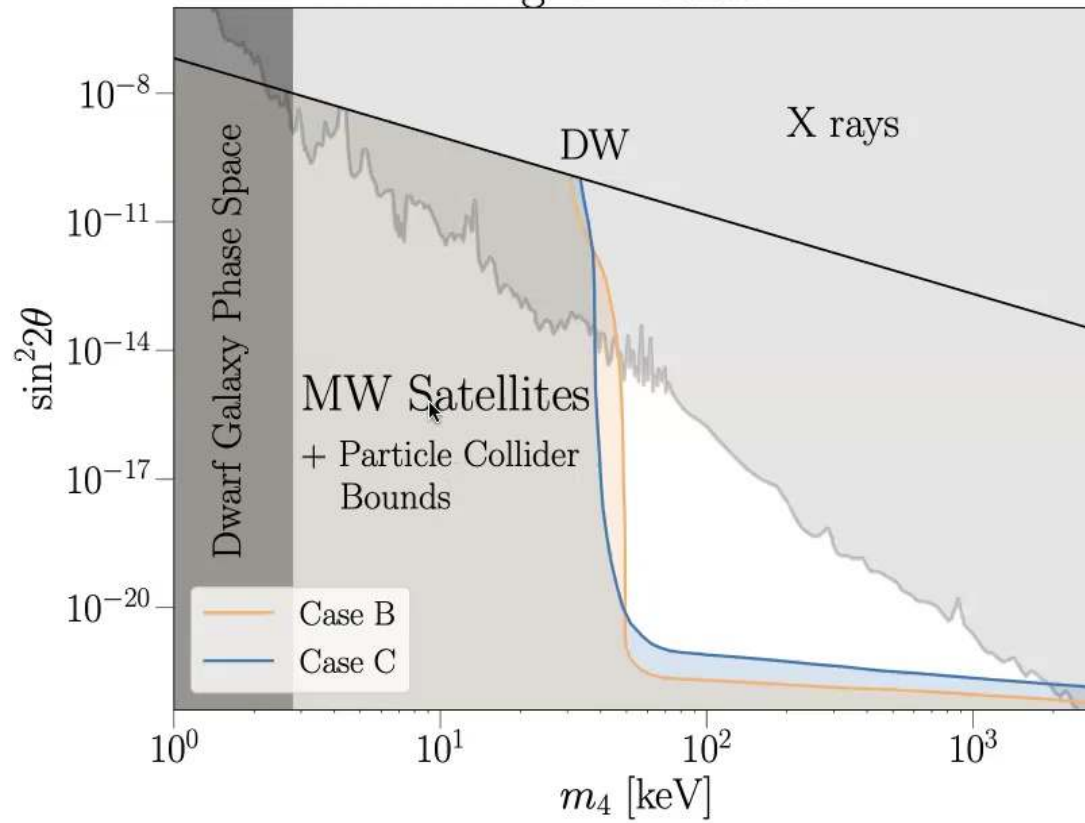
RA, Gluscevic, Nadler, Zhang, ApJL 2023 [arXiv: 2301.08299]



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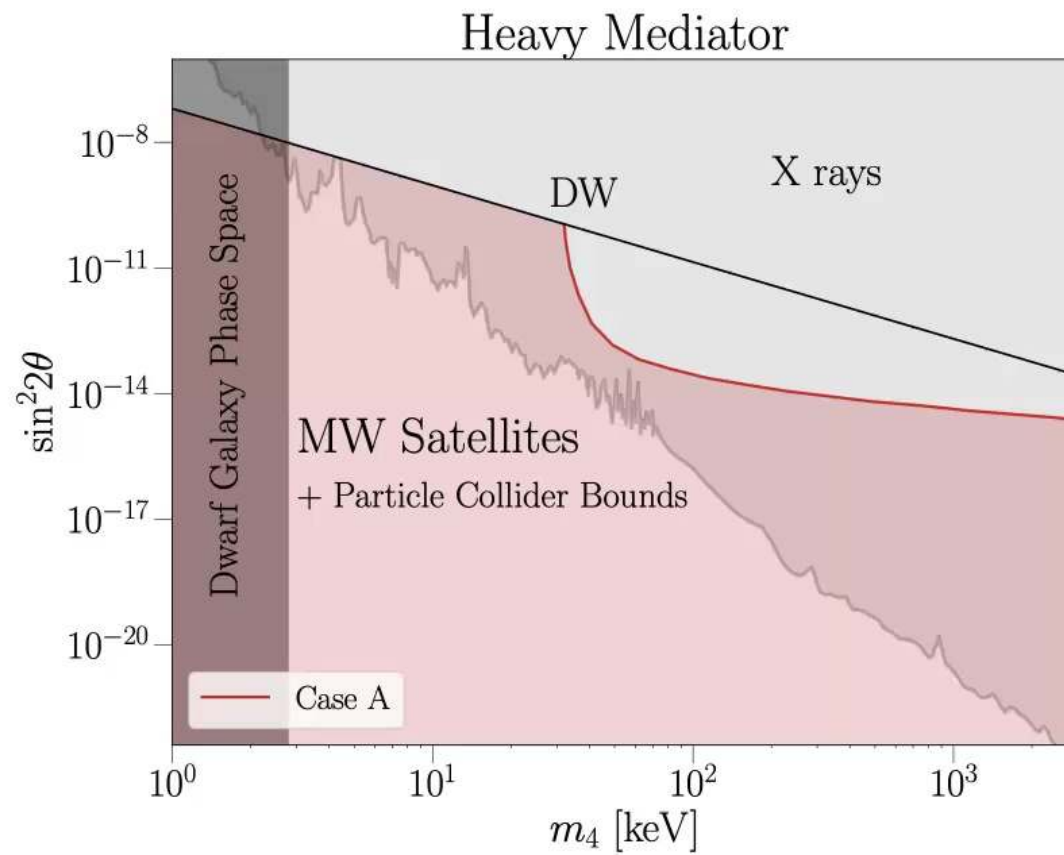


# Light Mediator



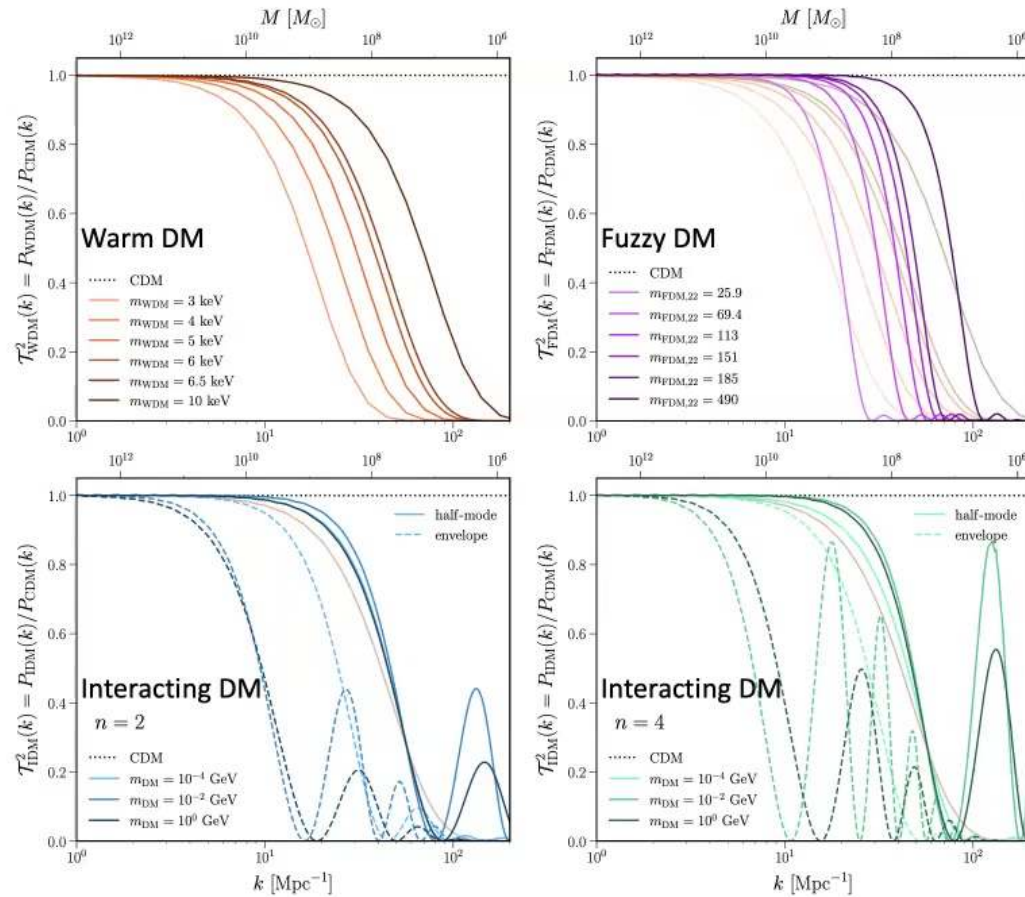
RA, Gluscevic, Nadler, Zhang, ApJL 2023 [arXiv: 2301.08299]



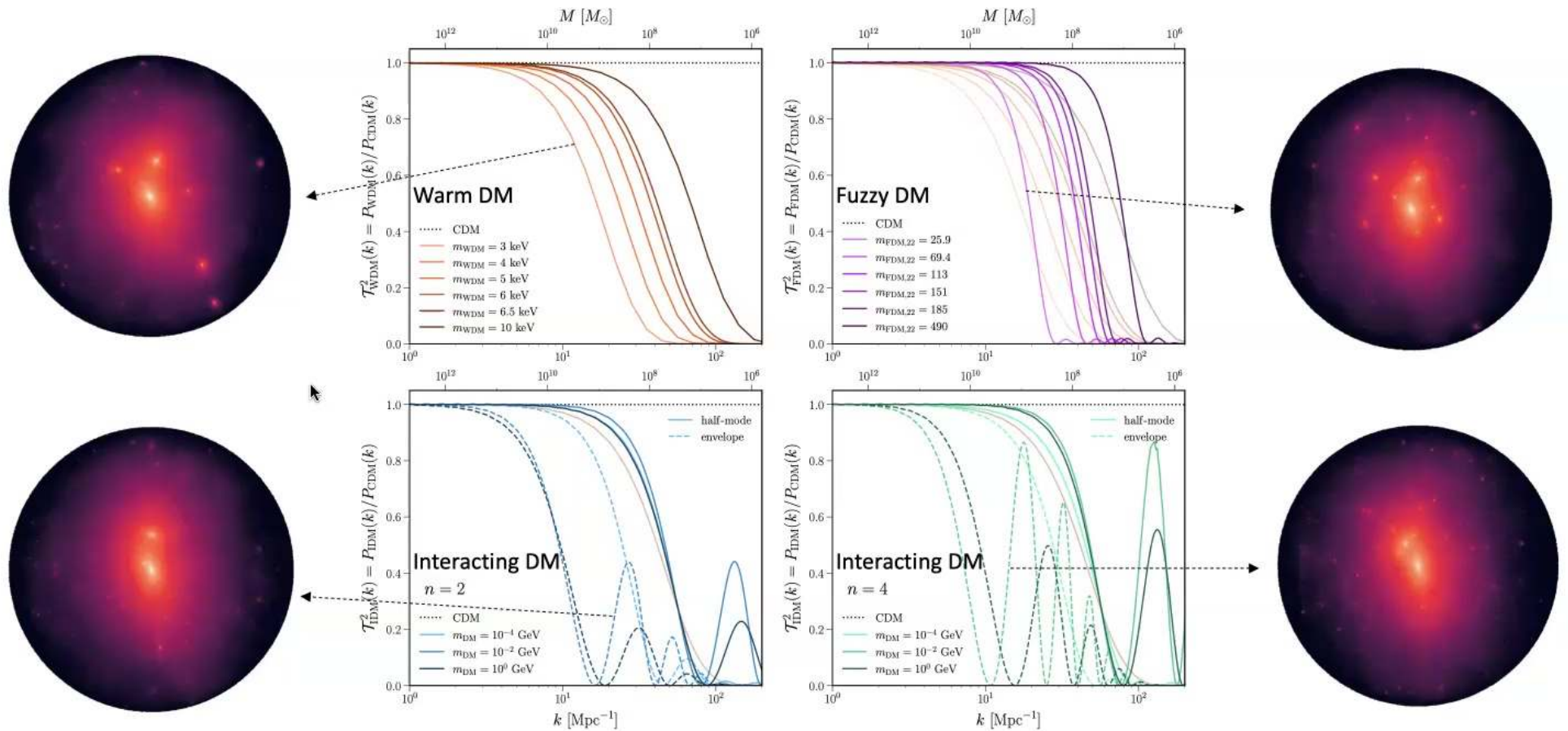


RA, Gluscevic, Nadler, Zhang, ApJL 2023 [arXiv: 2301.08299]

# Cosmological simulations of Milky Way-like systems within various DM models



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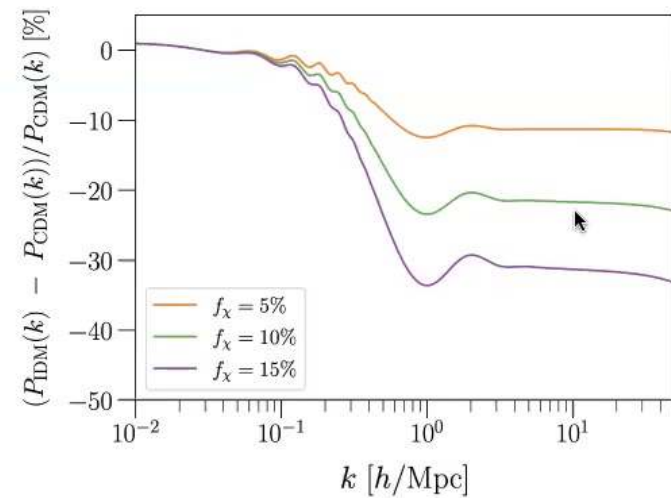
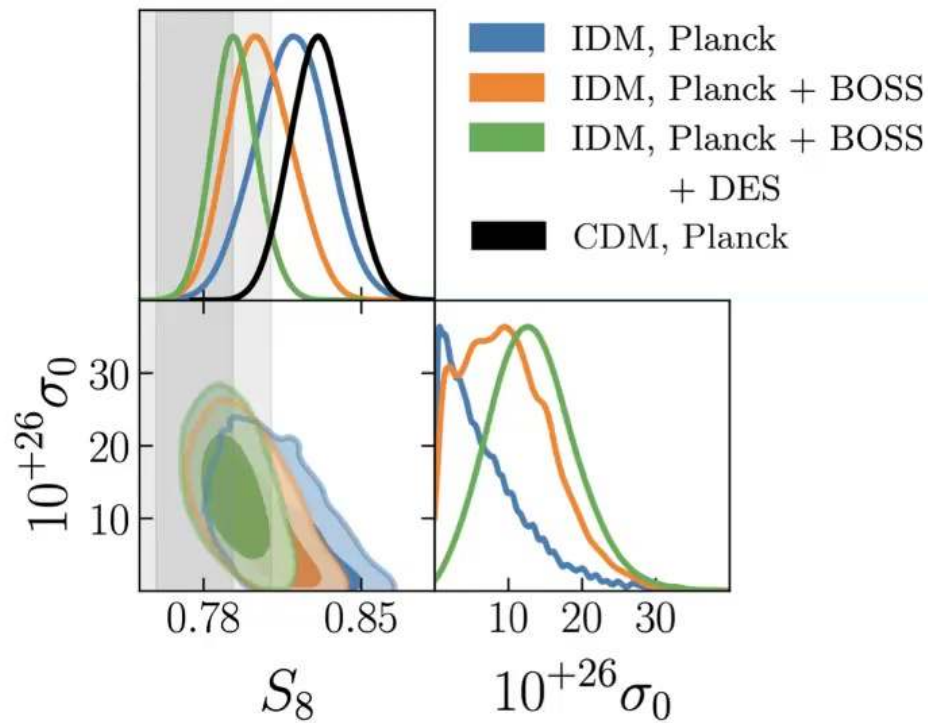


# What can we learn from Large-Scale Structure?

# $S_8$ Tension in the Context of DM-Baryon Scattering ( $n=0$ )

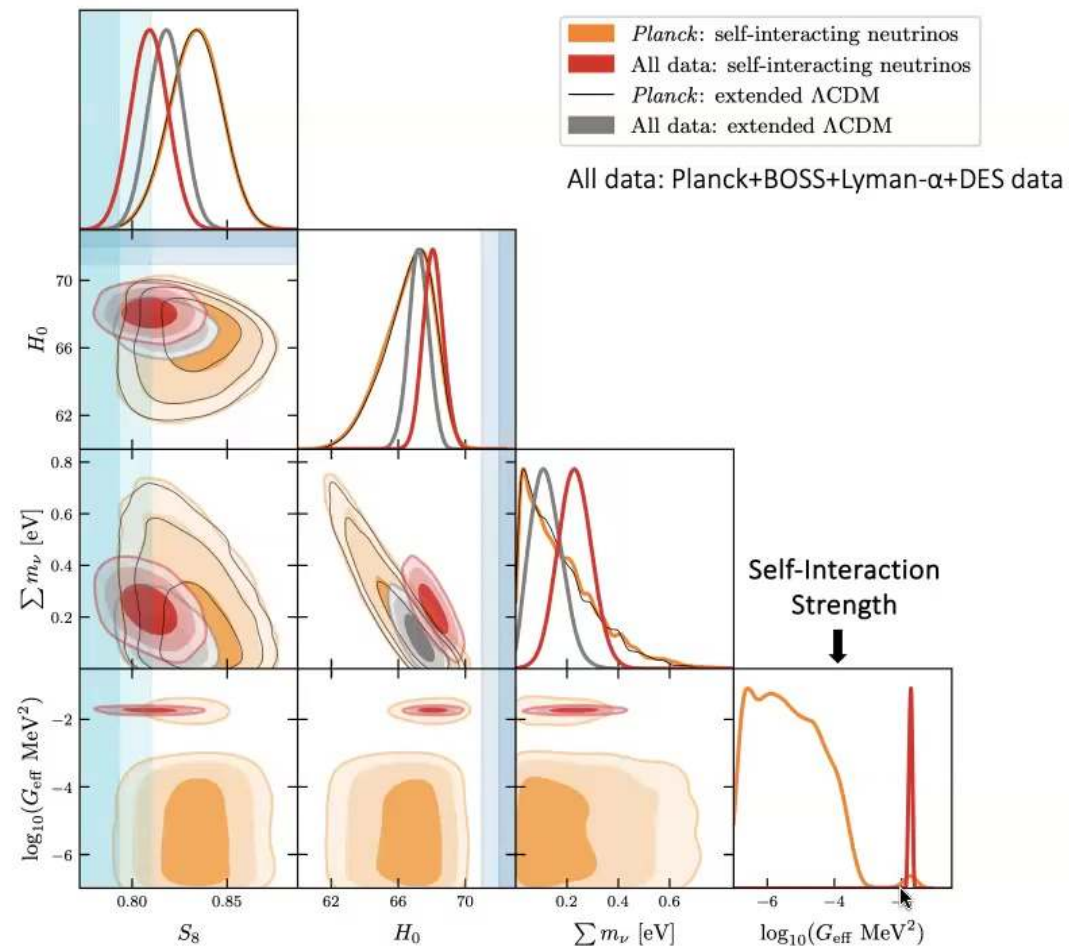


Adam He



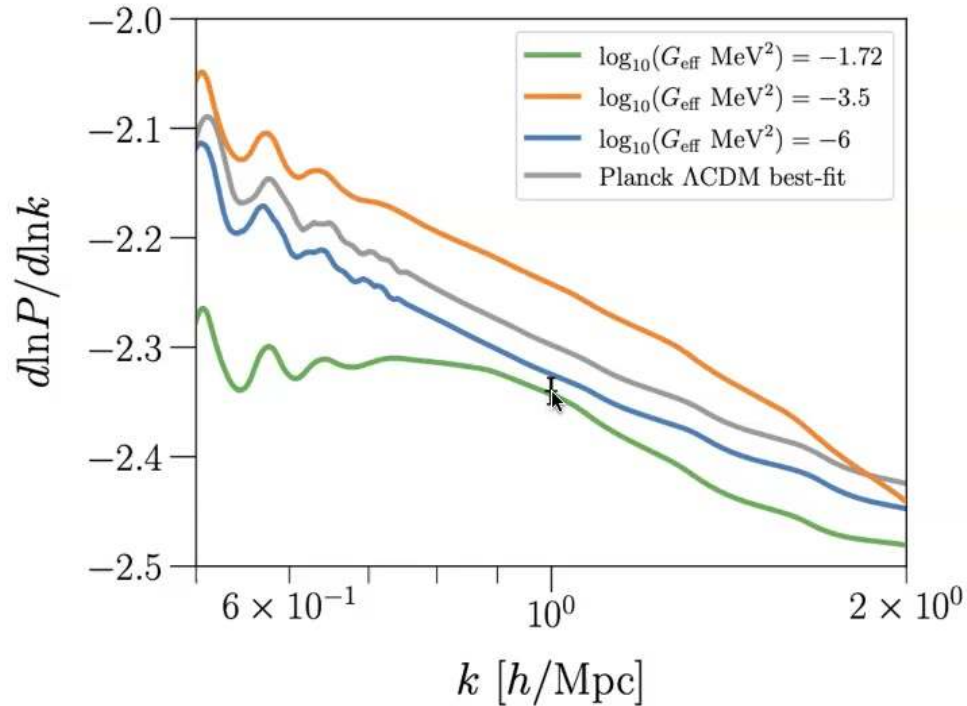
He, Ivanov, **RA**, and Gluscevic, ApJL 2023 [arXiv: 2301.08260]

# Neutrino Self-Interactions in Light of Large-Scale Structure Data



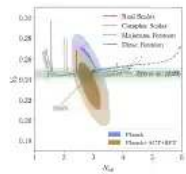
Adam He

He, RA, Ivanov, Gluscevic, arXiv: 2309.03956

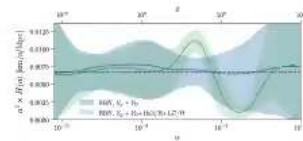


**Figure 2.** The slope  $d \ln P / d \ln k$  of the linear matter power spectrum for a self-interacting neutrino cosmology and  $\Lambda$ CDM, where the latter is generated with best-fit parameter values from a *Planck*-only analysis. The parameters for the self-interacting cases are chosen in the same way as in Fig. 1. The data point indicates the slope of the linear power spectrum measured by the Lyman- $\alpha$  data, with  $\pm 2\sigma$  error bars.

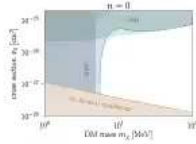
# Key Points



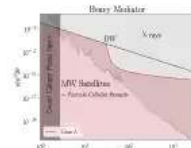
**Lower bounds on thermal-relic DM mass from the measurements of BBN and CMB**



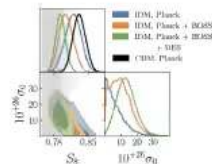
**Reconstruction of early-universe evolution from BBN measurements**



**Self-consistent CMB bounds on interacting thermal-relic dark matter**



**Sterile neutrino DM is heavily constrained by the small-scale structure data**



**DM-baryon scattering alleviates S8 tension, through scale-dependent power suppression**

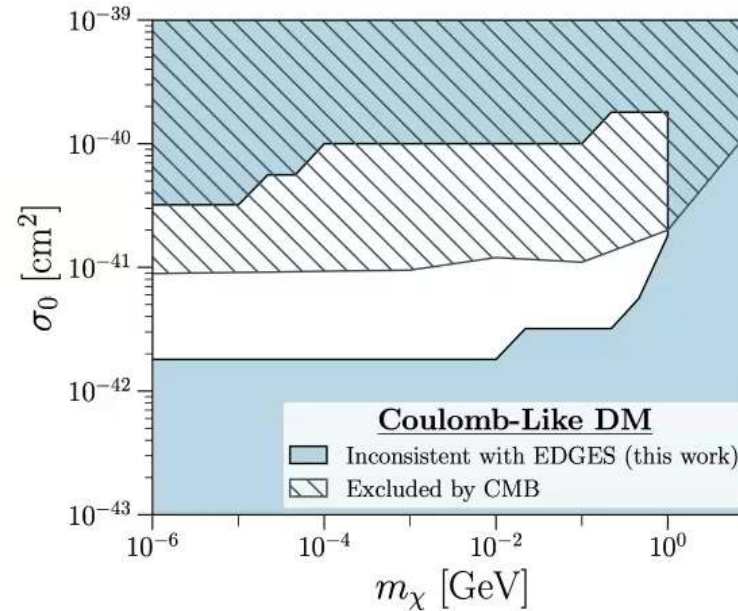
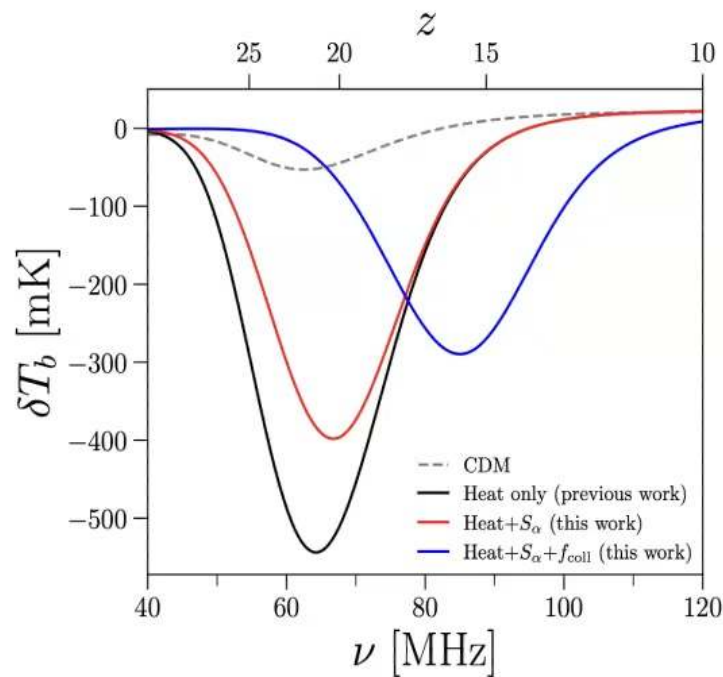
What can we learn from 21cm cosmology?

# 21cm signal in the Context of DM-Baryon Scattering ( $n=-4$ )

**Comprehensive study:** In addition to the known effects on the thermal history of hydrogen, we include the effects of the scattering on structure formation.

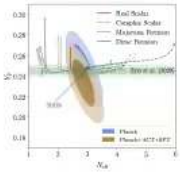


Trey Driskell

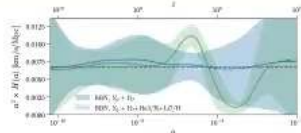


Driskell et al.(incl RA), PRD 2022 [arXiv: 2209.04499]

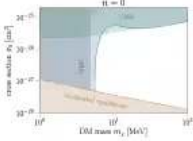
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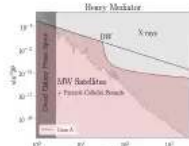
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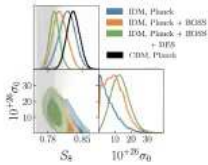
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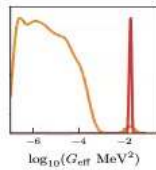
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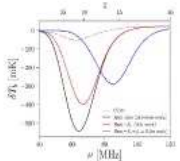
**Sterile neutrino DM is heavily constrained by the small-scale structure data**



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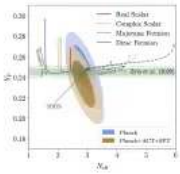


**Neutrino self-interaction is strongly favored by the large-scale structure data**

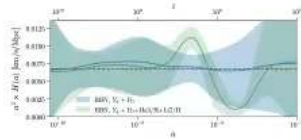


**21cm signal requires accurate modeling of structure formation and thermal history**

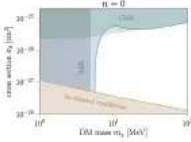
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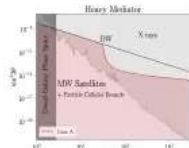
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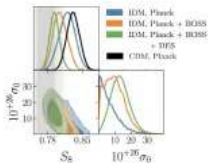
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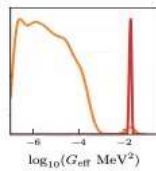
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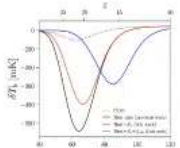
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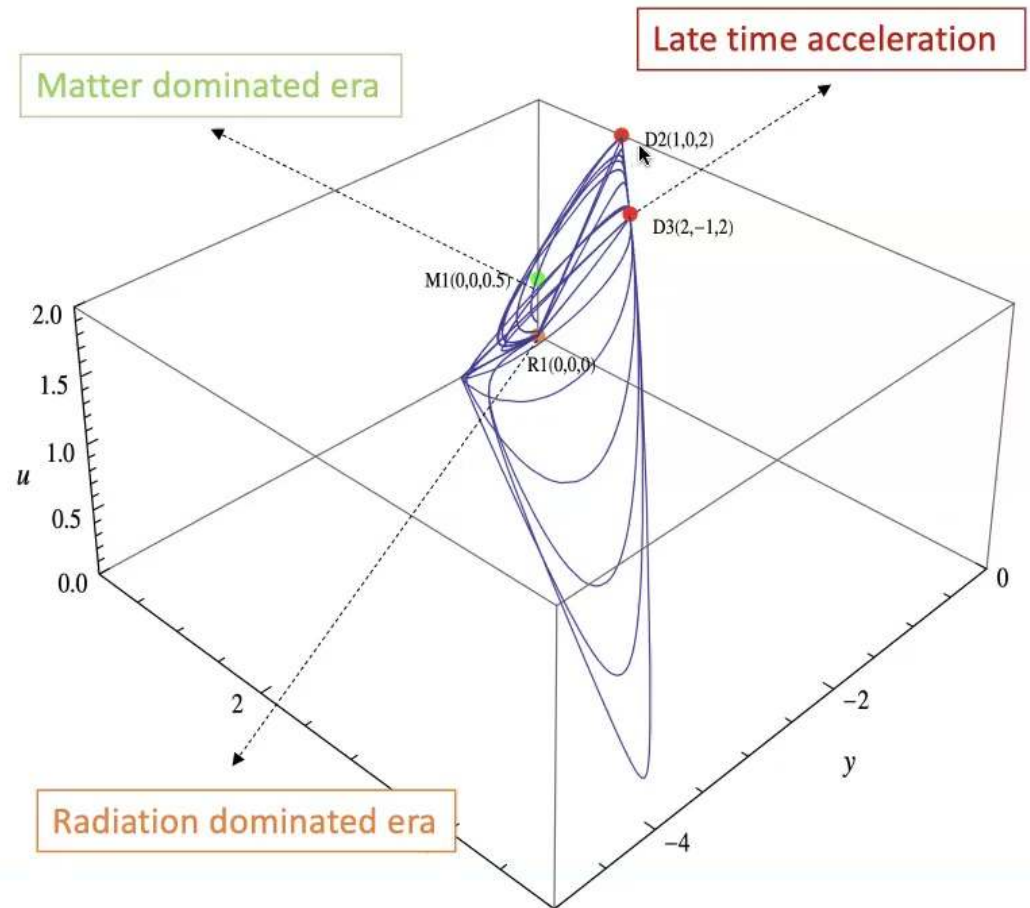
# Modified Gravity

$f(R)$  gravity with nonminimal coupling between matter and geometry:

$$S = \int d^4x \sqrt{-g} \{ \kappa f_1(R) + [1 + \lambda f_2(R)] \mathcal{L} \}$$

$$f_1(R) = R, \quad f_2(R) = (R/R_0)^n$$

- The power-law form of the curvature scalar is able to describe the late time acceleration
- This model is consistent with observations



RA, Xu, Wang, Gong, PRD 2017 [arXiv: 1512.09281]

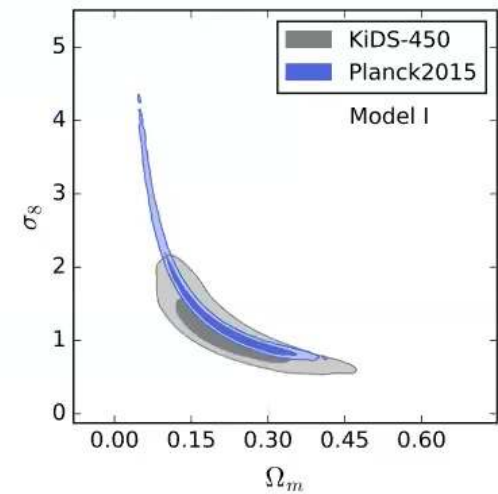
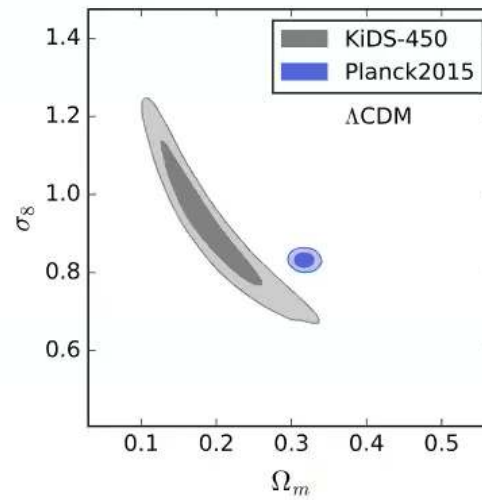
# Dark Energy



Interaction?

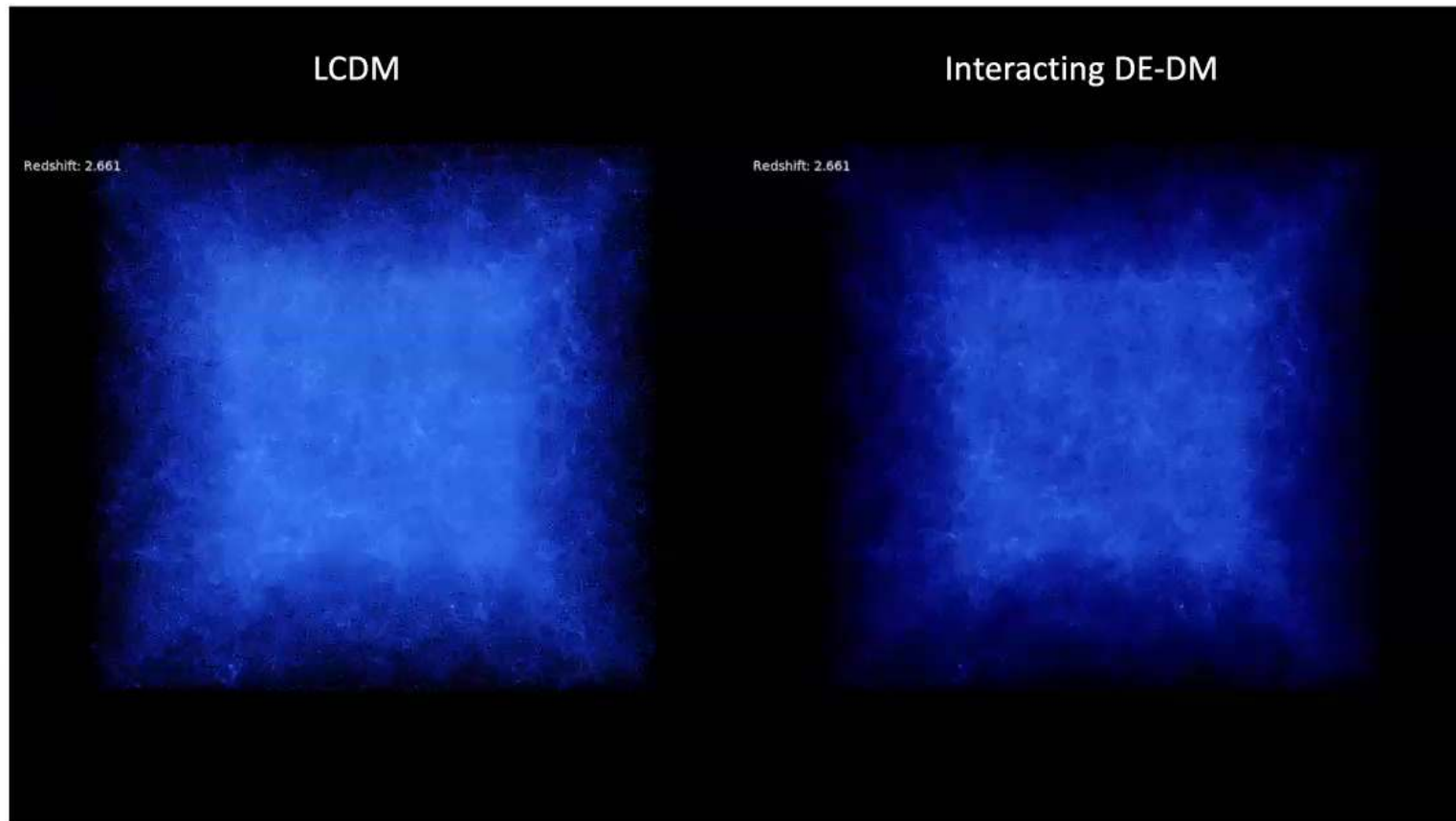


Alleviate  $S_8$  tension between weak lensing and Planck data

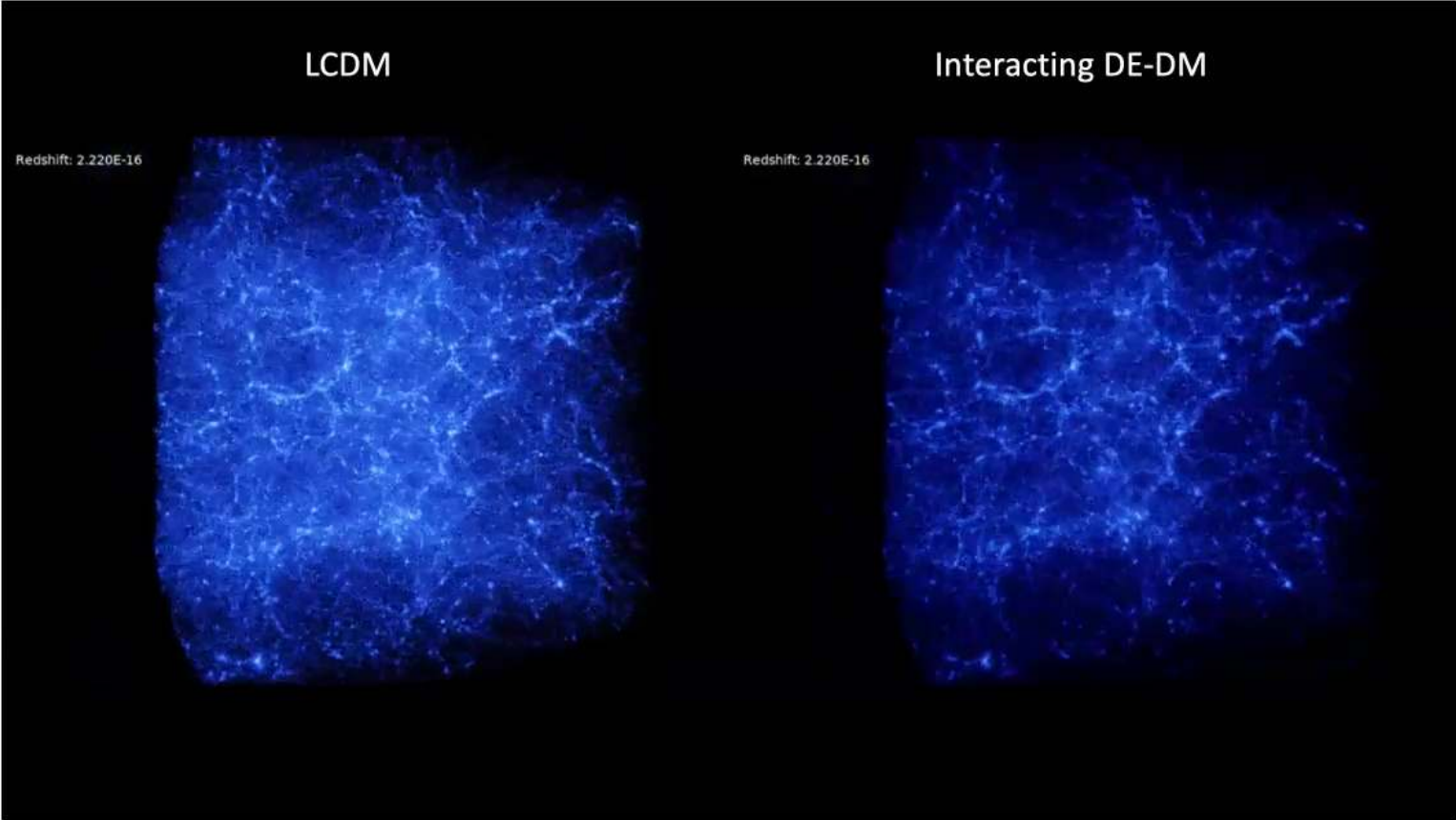


RA, Chang, Wang, JCAP 2018, [arXiv: 1711.06799]

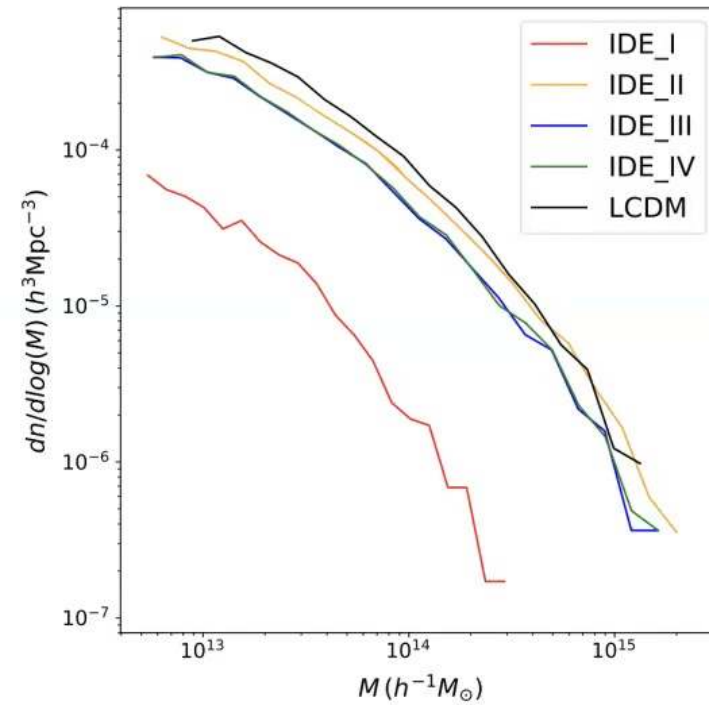
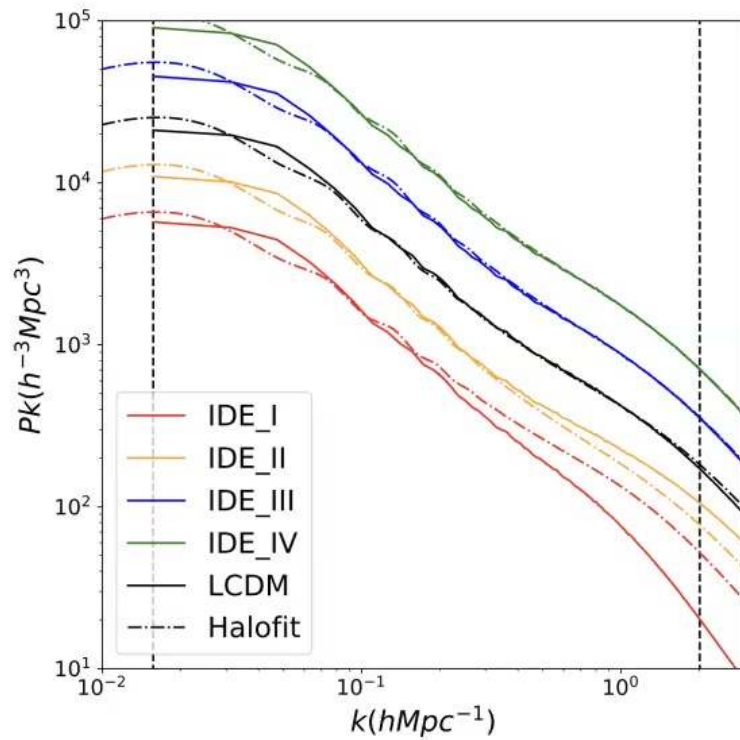
## Cosmological simulations with DE-DM interacting models



# Cosmological simulations with DE-DM interacting models



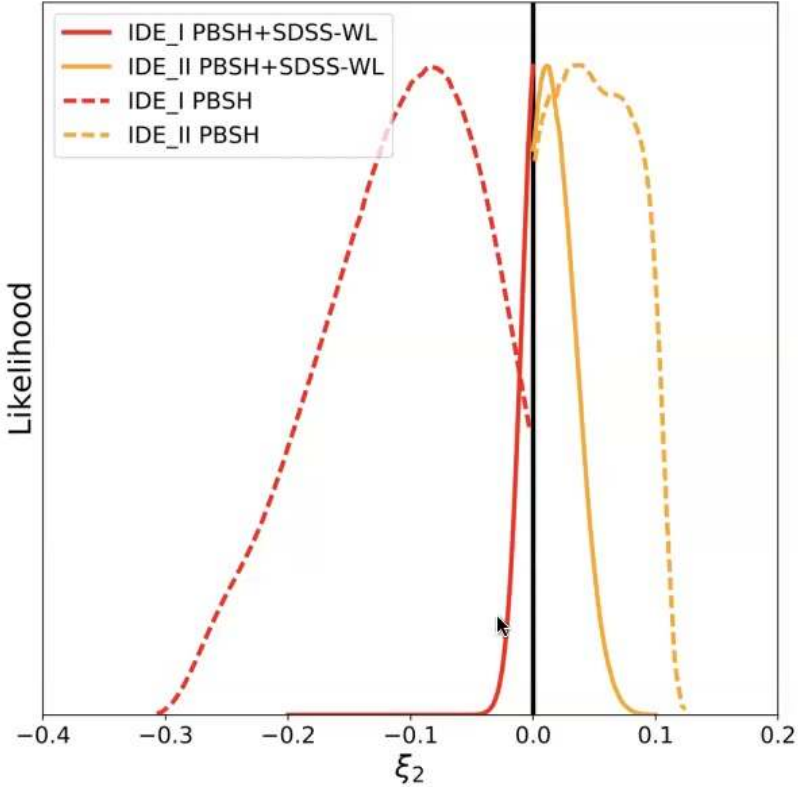
## The resulting matter power spectra and halo mass functions for four different models



\* Note that Pks are rescaled for better illustration

Zhang, RA, Liao, Luo, Li, Wang, PRD 2018 [arXiv: 1811.01519]

Constraints on interactions were vastly improved using small-scale probes + simulations



Zhang, RA, Liao, Luo, Li, Wang, ApJL 2018 [arXiv: 1807.05522]



Thank you