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

Speakers: Rui An

Series: Cosmology & Gravitation

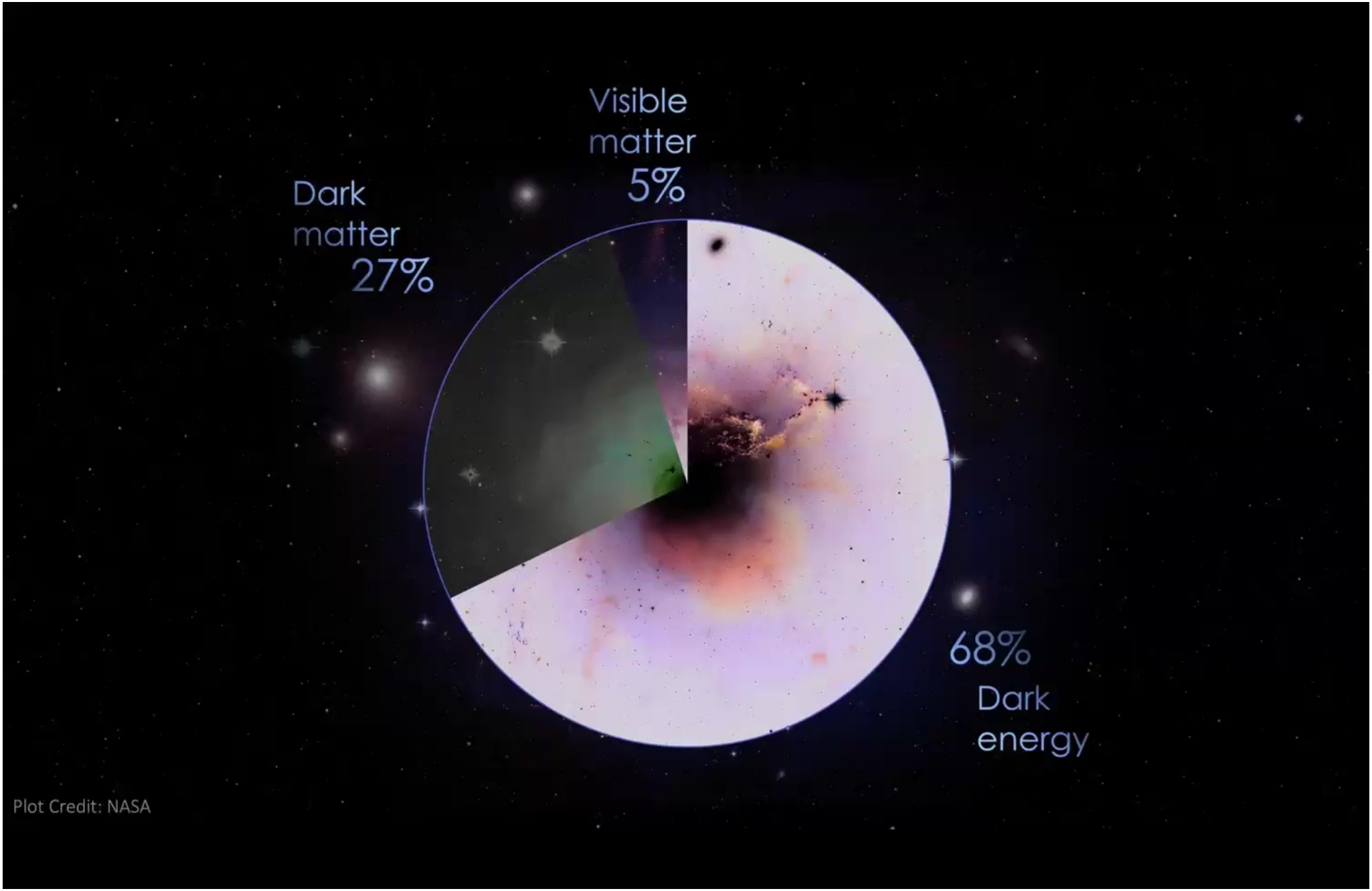
Date: January 23, 2024 - 11:00 AM

URL: https://pirsa.org/24010090

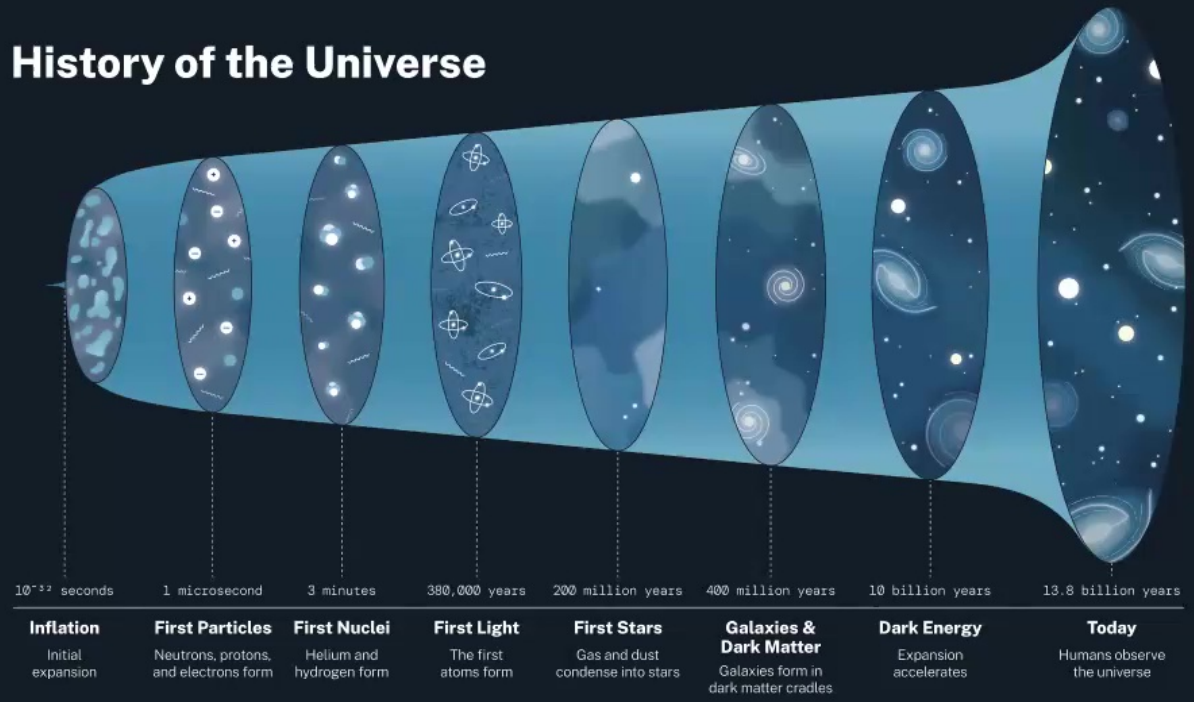
Abstract: The fundamental nature of dark matter and dark energy remains unknown and requires new physics to explain. This talk will present a cosmological quest to understand the properties of these two dominant but invisible components of our universe. I will present my work on early and late-universe 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.

Zoom link


Probing the Invisible Cosmos:
from the Early Universe to the Near Field
Rui An
University of Southern California, Los Angeles, U.S.


Visible
matter
5%
Dark
matter
27%
68%
Dark
energy
Plot Credit: NASA

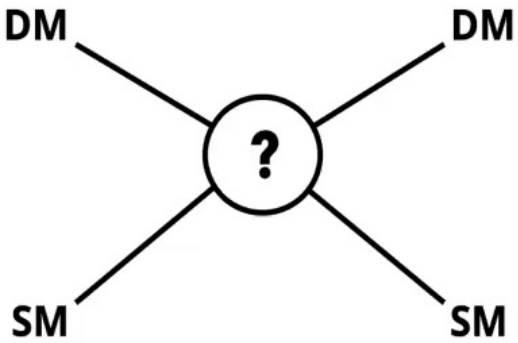
Cosmological probes from the early to late Universe



Plot Credit: NASA

- 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

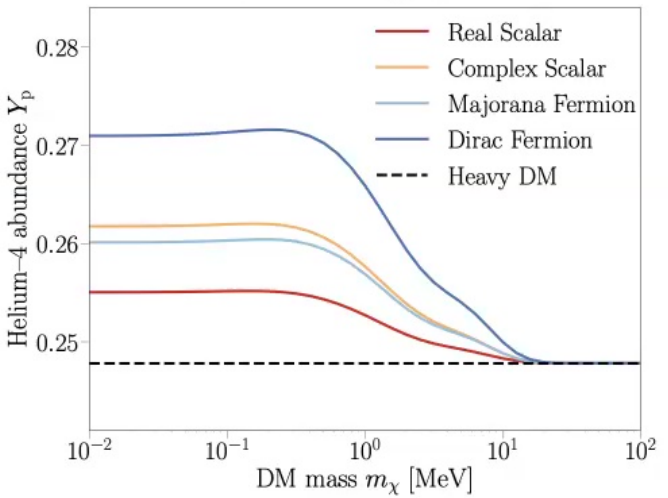
Big Bang Nucleosynthesis

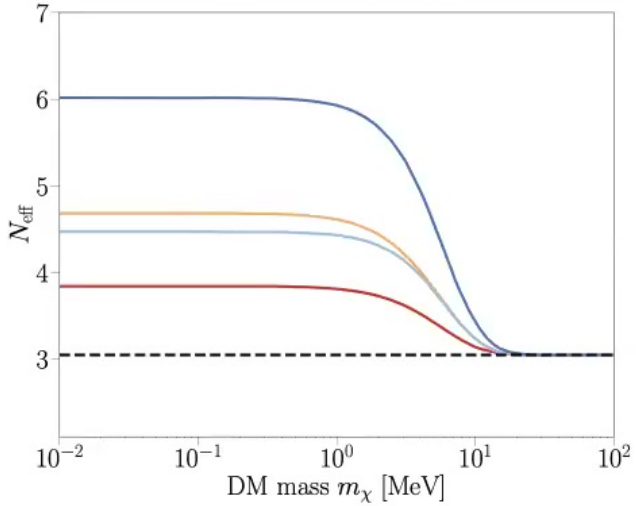
Plot Credit: C. Giovanetti

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

Nollet, Burles, 2000

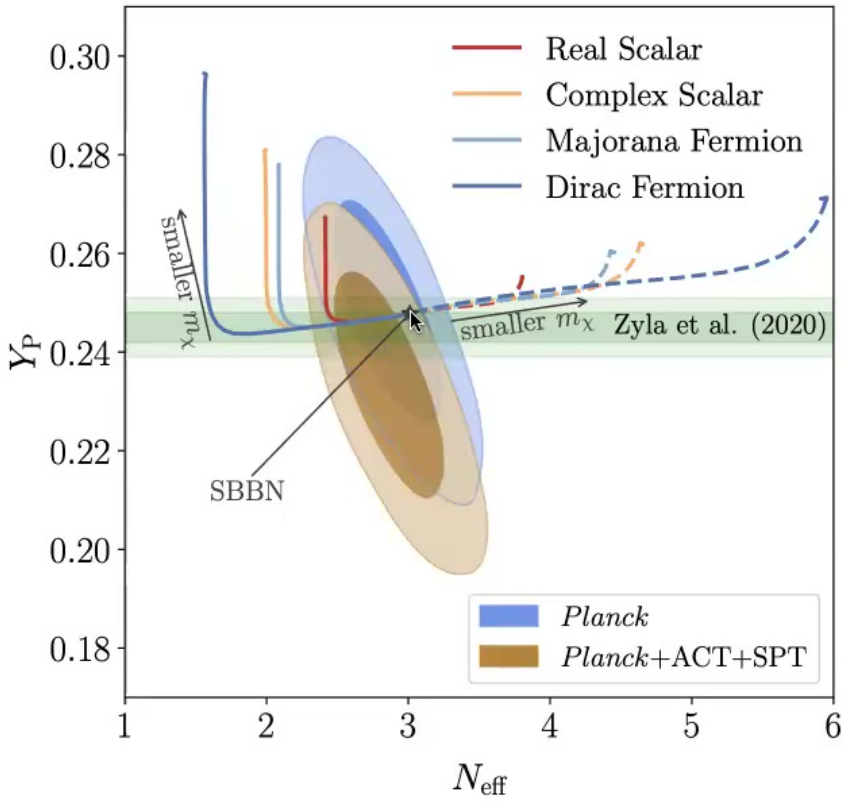
Neutrino coupled DM





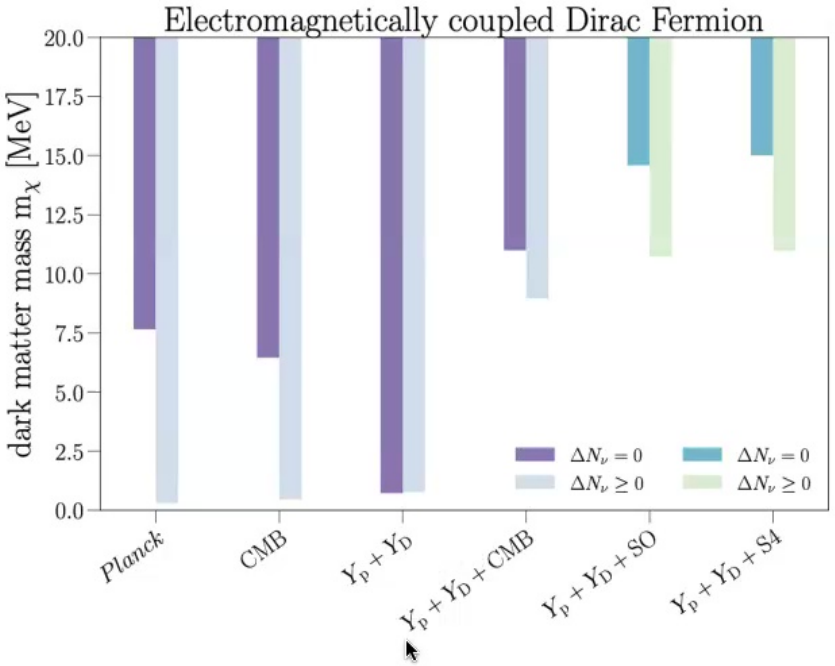
RA, Gluscevic, Calabrese, Hill, JCAP 2022 [arXiv: 2202.03515]

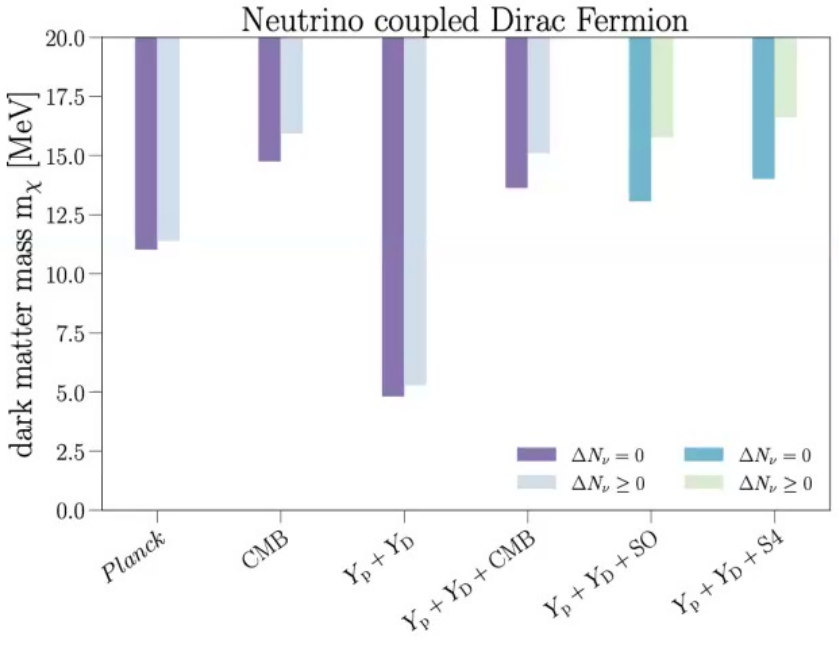
Cosmic Microwave Background Measurements



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

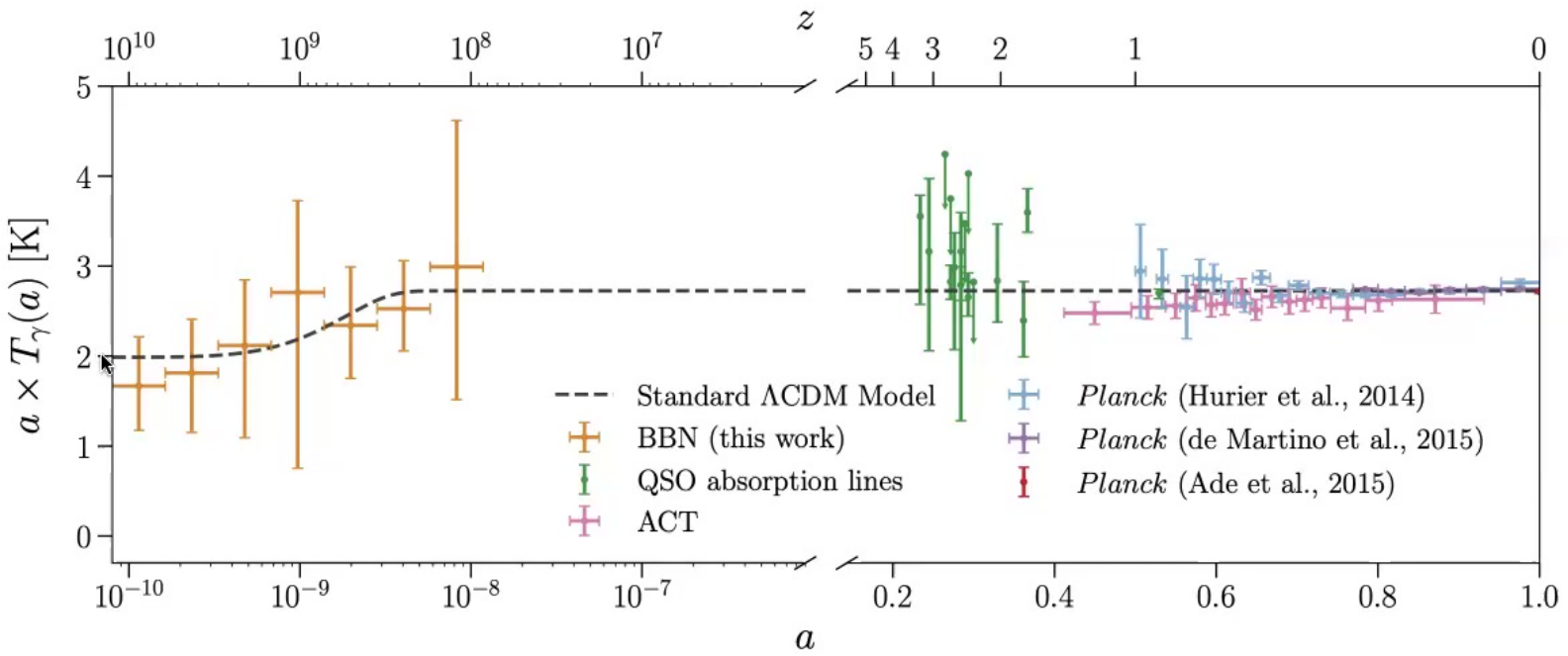
Lower bounds on light thermal-relic DM mass





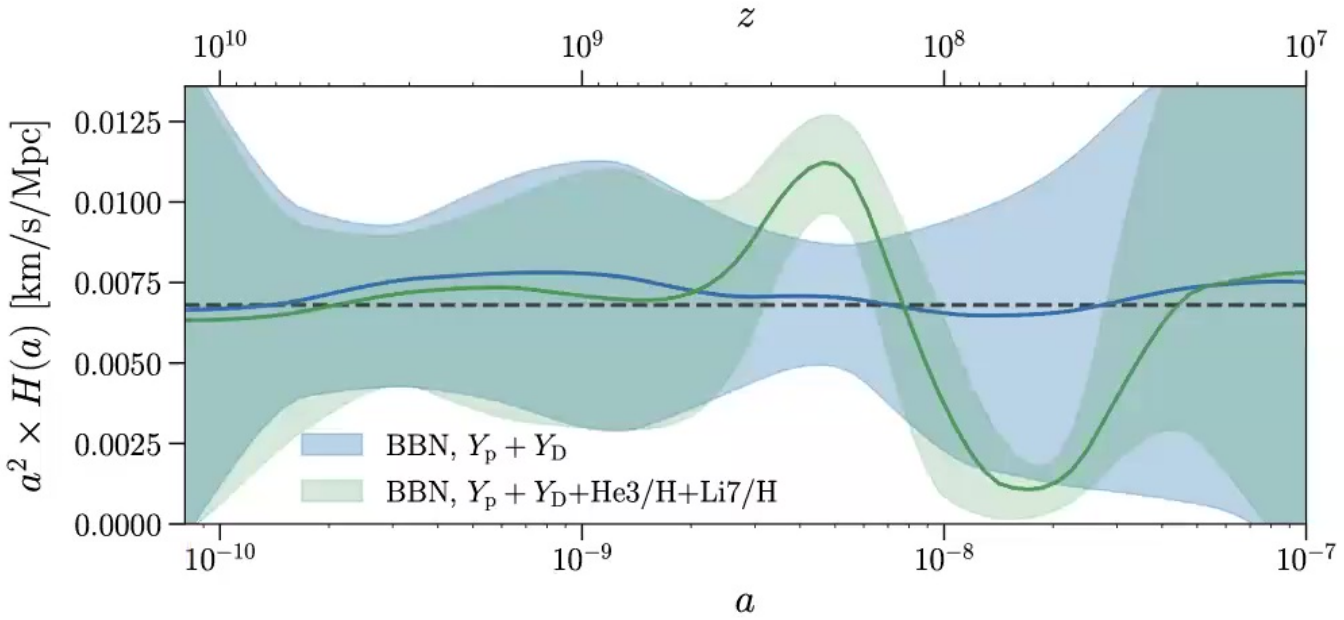
RA, Gluscevic, Calabrese, Hill, JCAP 2022 [arXiv: 2202.03515]

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



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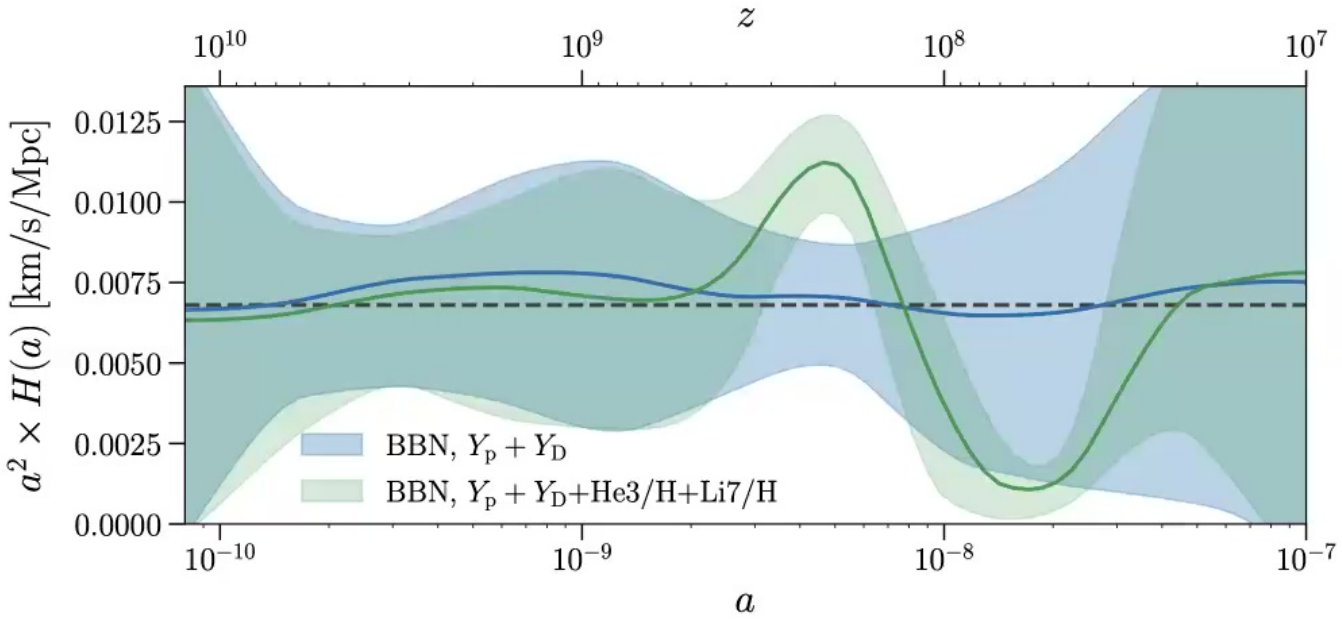
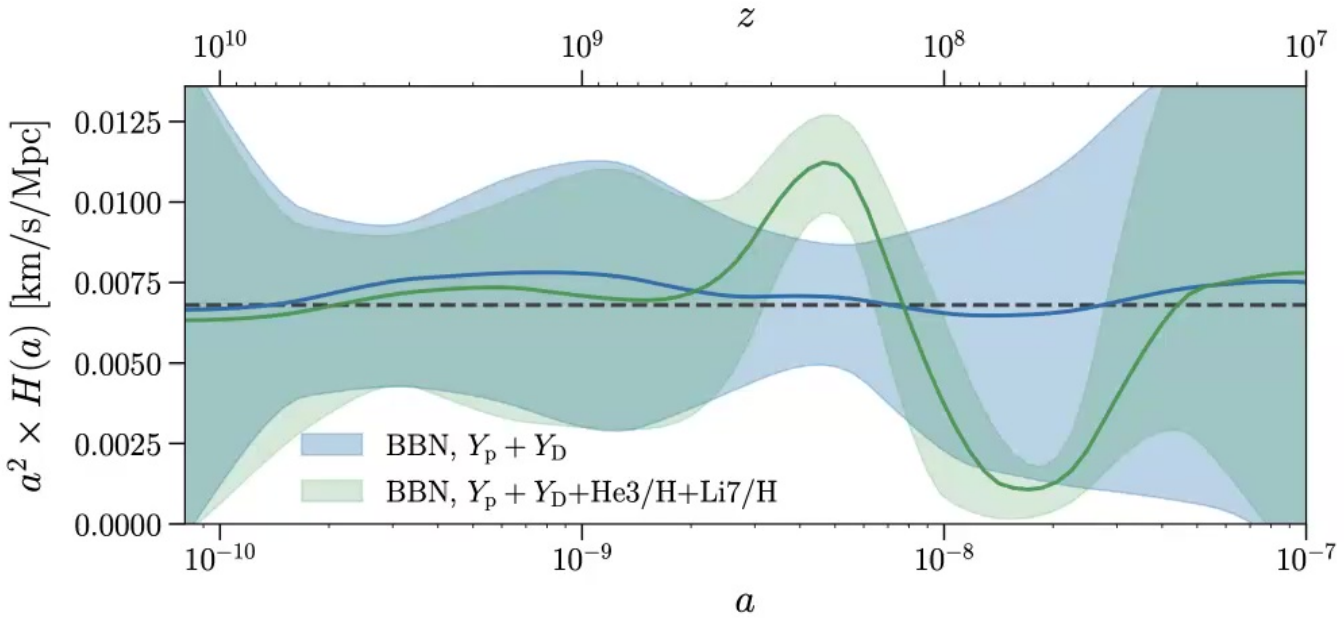


Lithium Problem: The SBBN-predicted abundance of Lithium-7 is a factor of 3-4 higher than its observed value

RA, Gluscevic, PRD 2024 [arXiv: 2310.17195]

Reconstruction of the expansion rate from BBN yield measurements

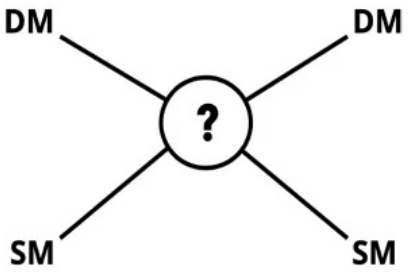


Lithium Problem: The SBBN-predicted abundance of Lithium-7 is a factor of 3-4 higher than its observed value

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

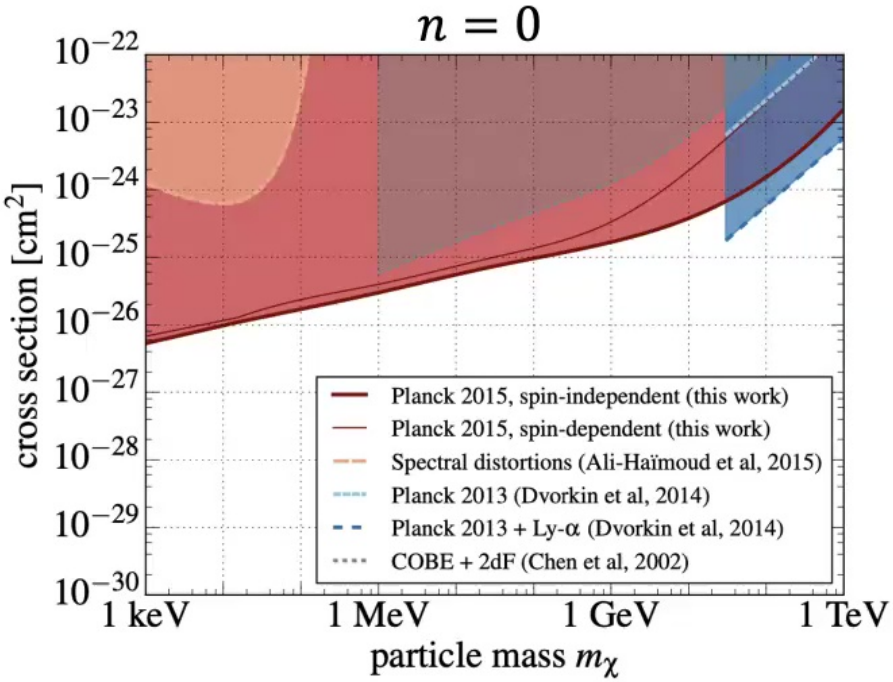
RA, Gluscevic, PRD 2024 [arXiv: 2310.17195]

Interactions with Standard Model (Baryons)



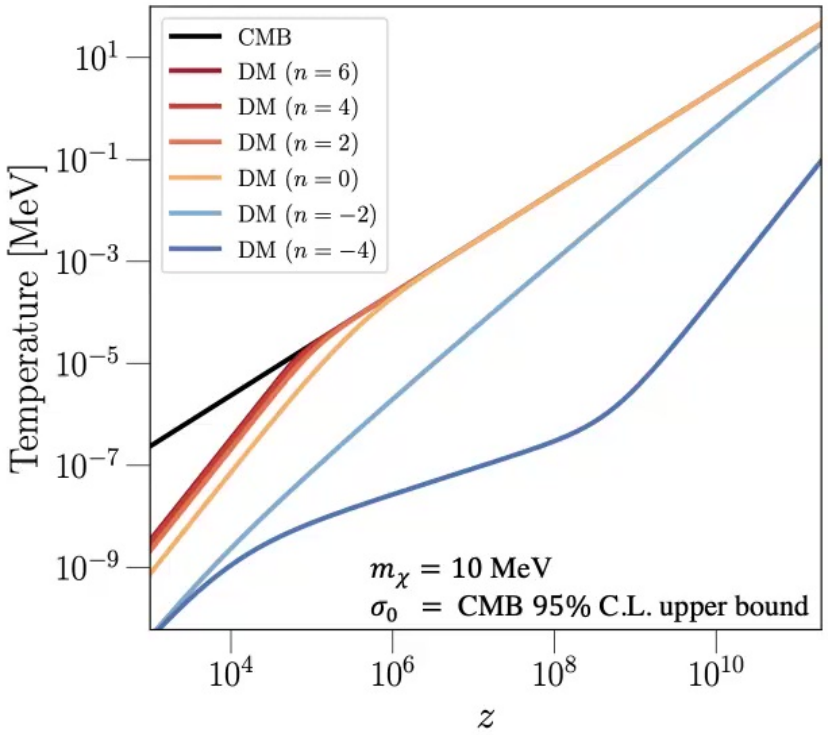
$$\sigma_{\mathrm{MT}} = \sigma_0 v^n$$

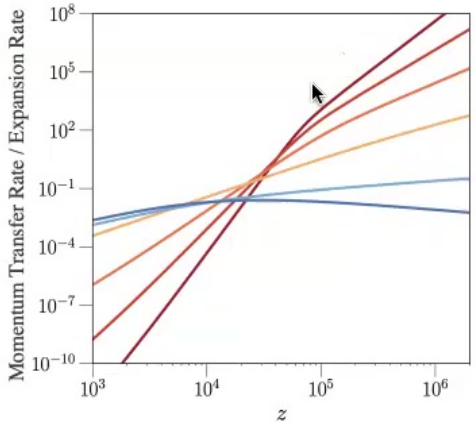
Momentum-transfer cross section



Boddy, Gluscevic, 2017

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

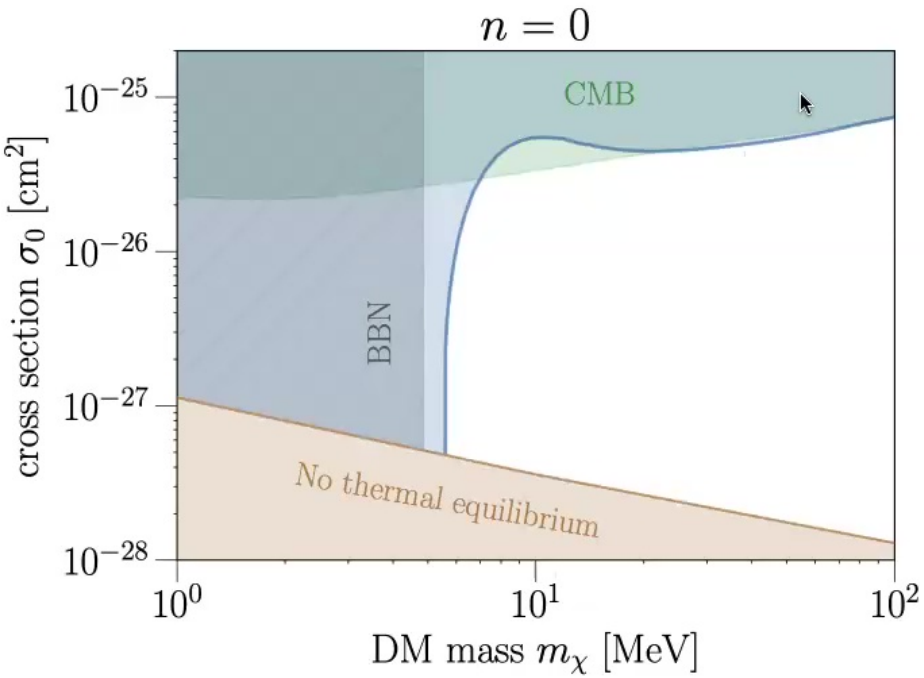




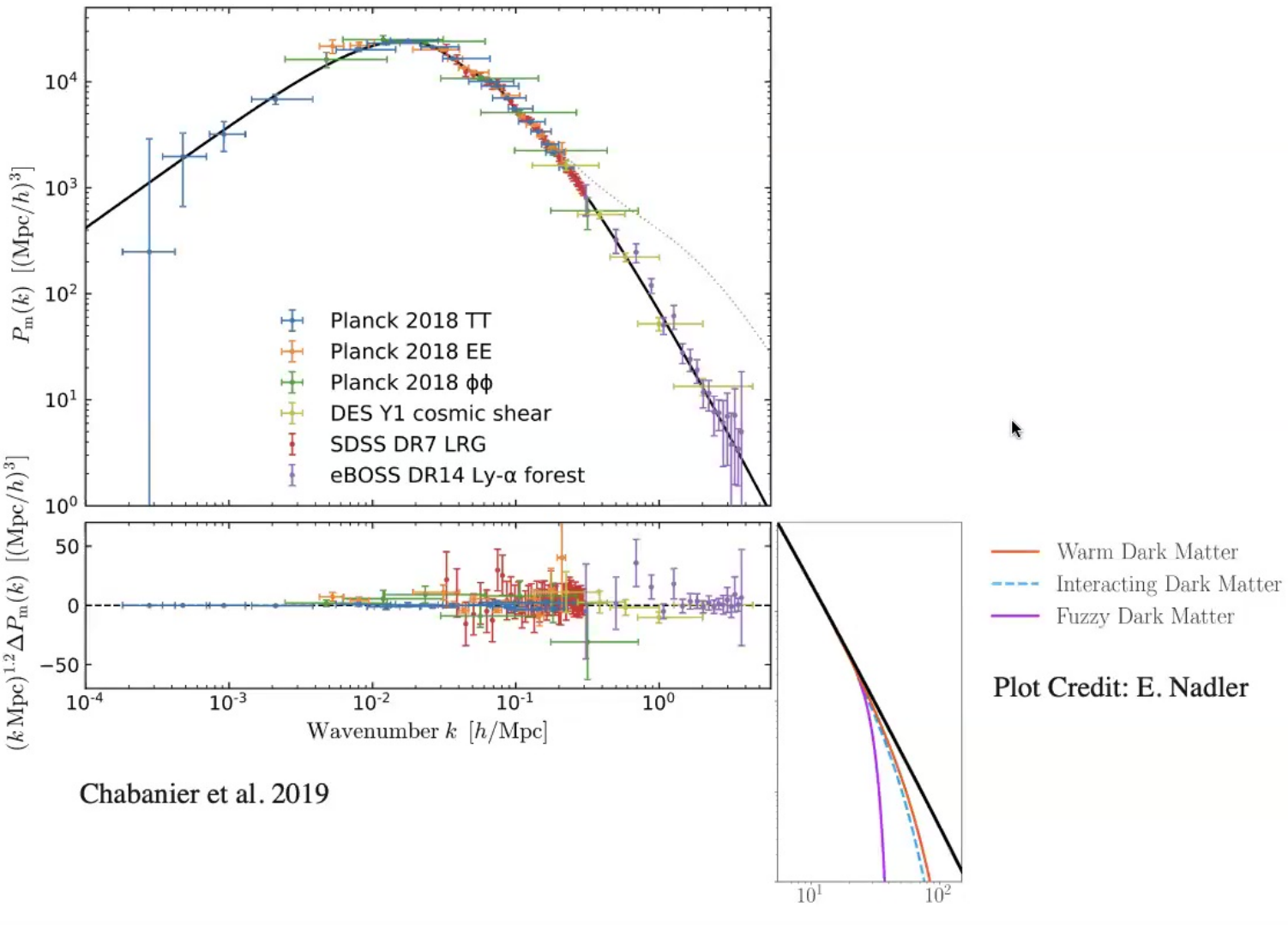
RA, Boddy, Gluscevic, in prep

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

Light thermal relic DM mass + DM and baryon scattering



RA, Boddy, Gluscevic, in prep



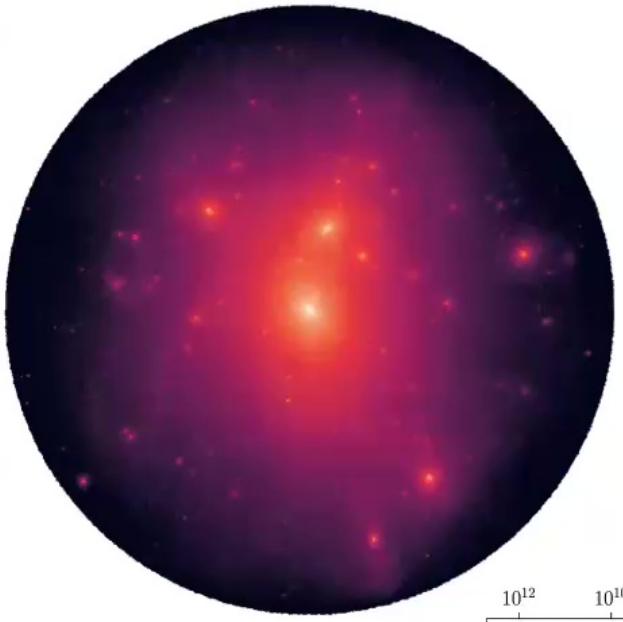
Chabanier et al. 2019

Plot Credit: E. Nadler

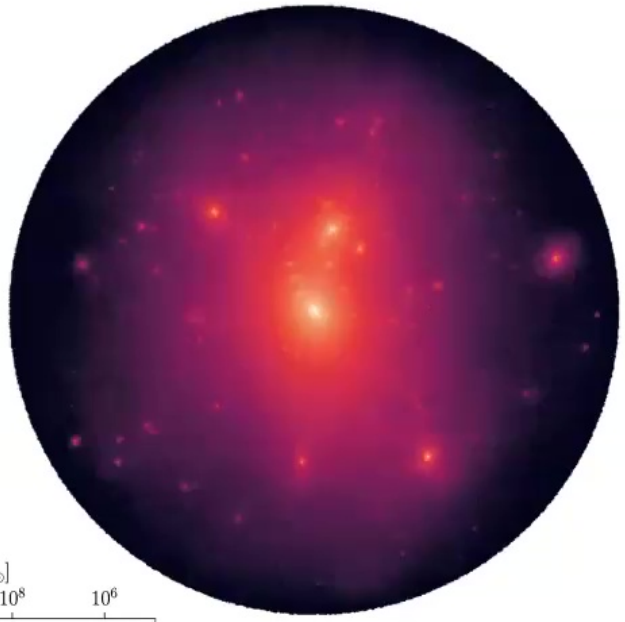
Small Halos as Dark Matter Probes

Lovell et al. 2011

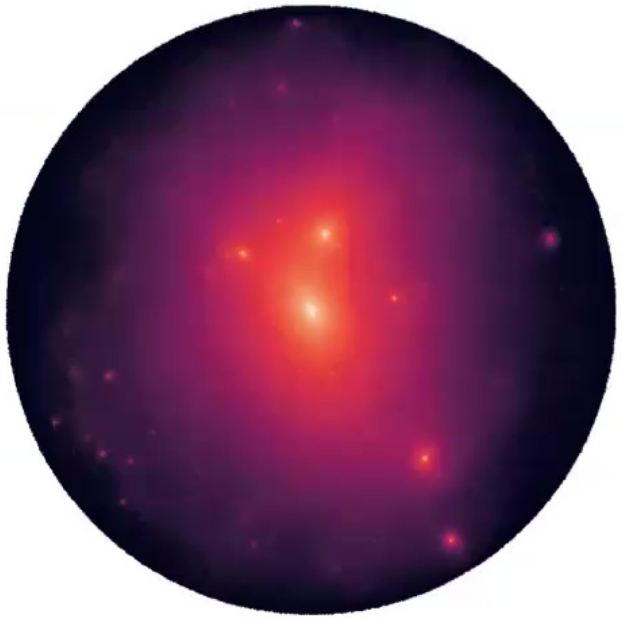
10keV WDM

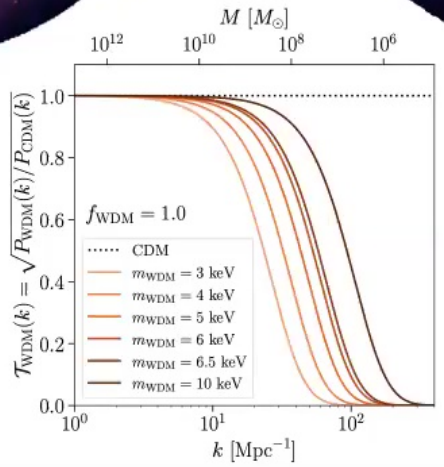


6.5keV WDM



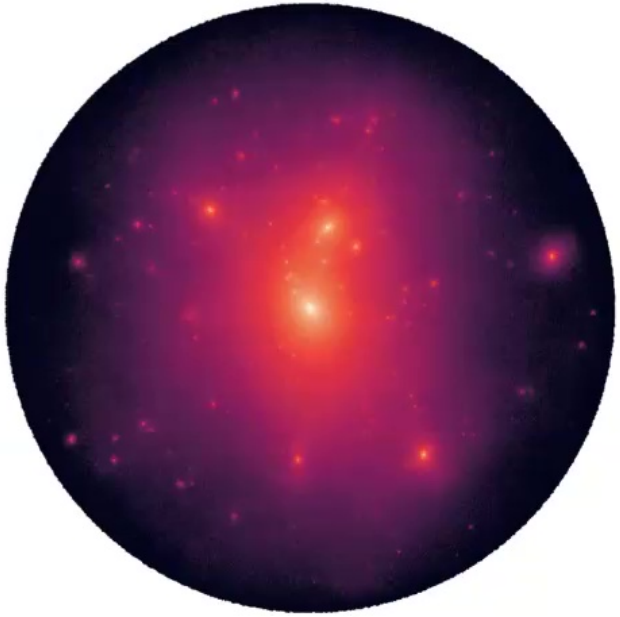
3keV WDM



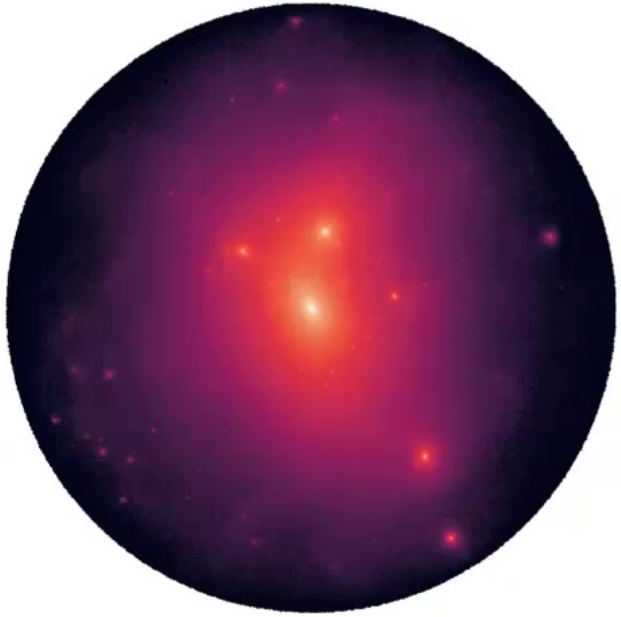


10keV WDM

6.5keV WDM



3keV WDM



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

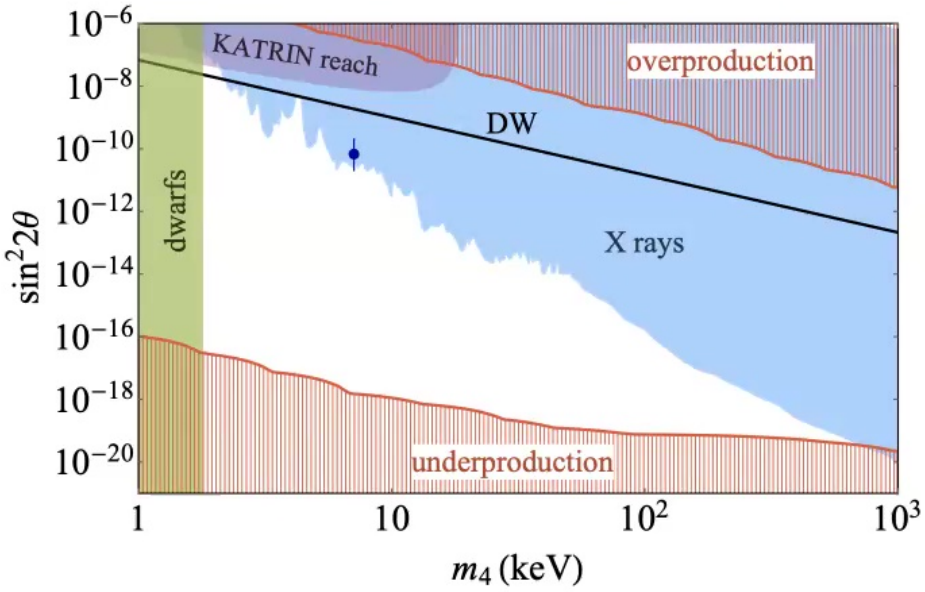
$m_{\mathrm{WDM}} > 6.5$ keV at 95% C. L.

Nadler et al. 2020

Sterile Neutrino Dark Matter

Problem: Dodelson and Widrow (DW) showed that ν_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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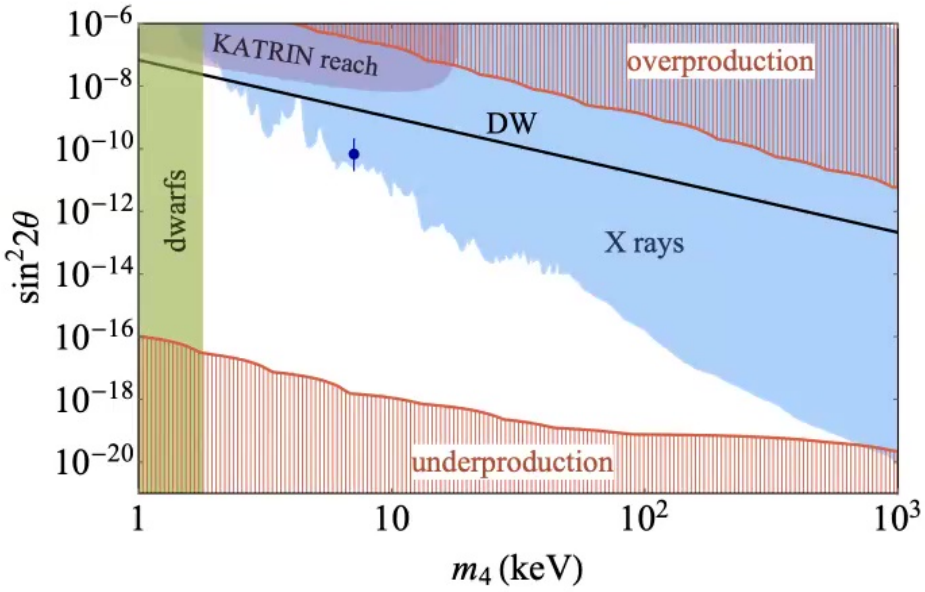
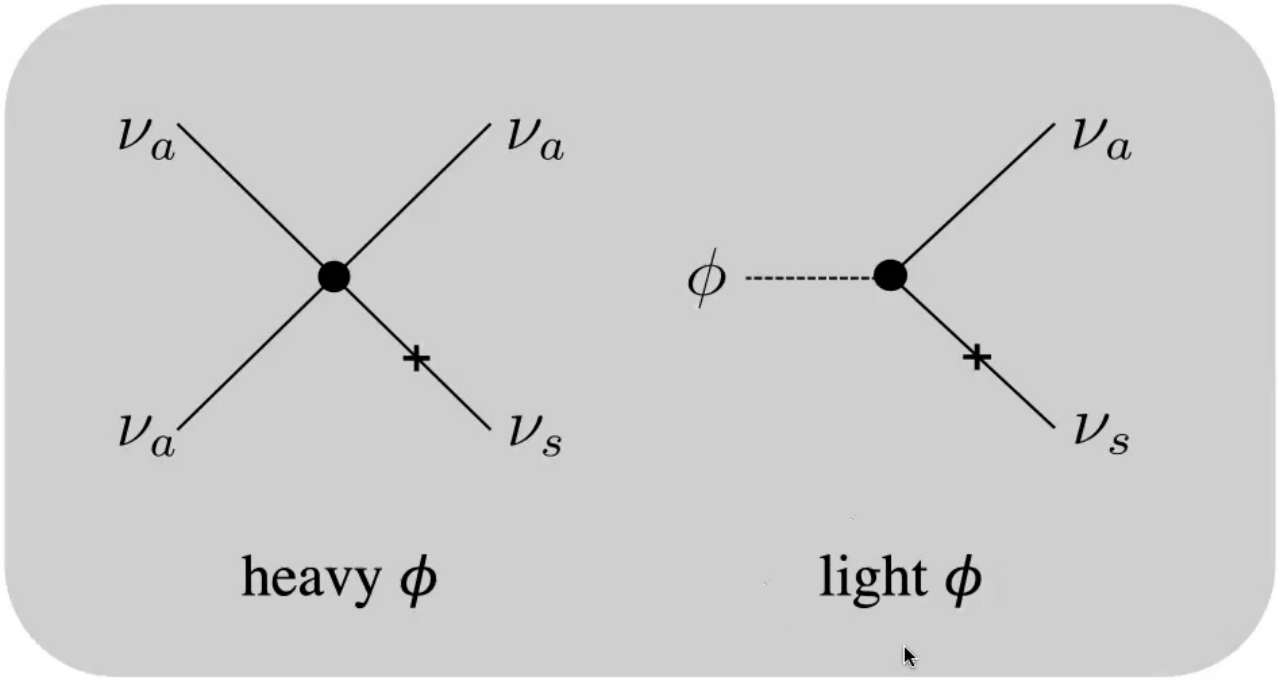
$$|\nu_4\rangle = \cos\theta|\nu_s\rangle + \sin\theta|\nu_a\rangle$$

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

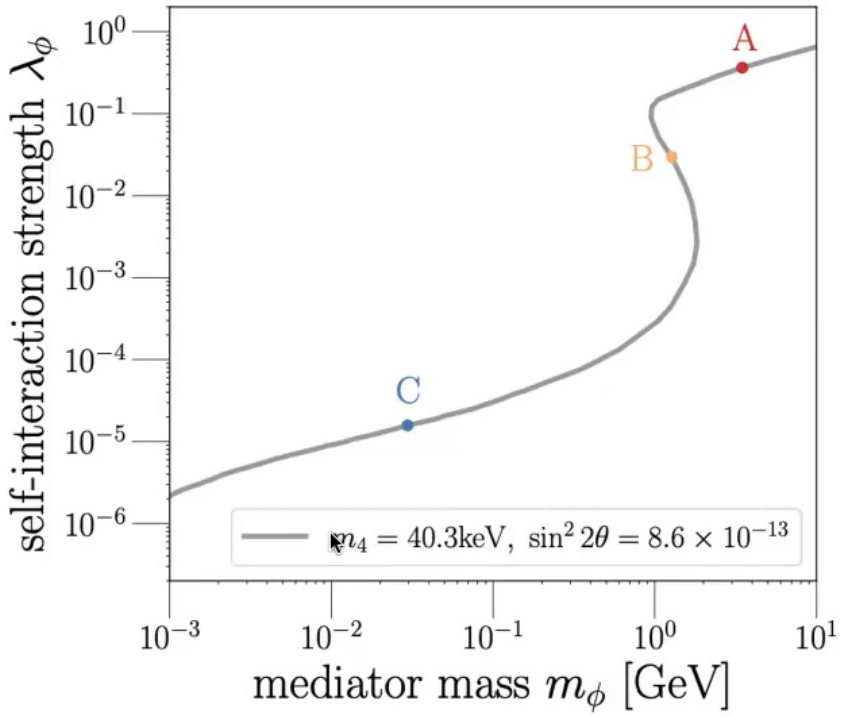
Interaction Term: $\mathcal{L} \supset \frac{\lambda_\phi}{2}\nu_a\nu_a\phi + \text{h.c.}$



A. de Gouvea et al. 2019



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

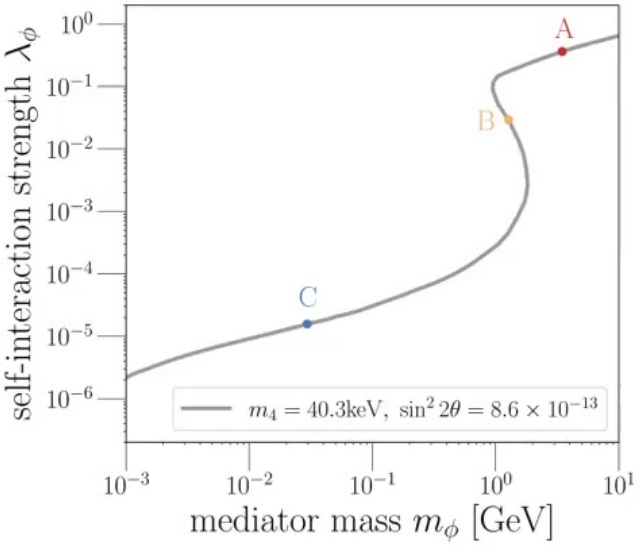


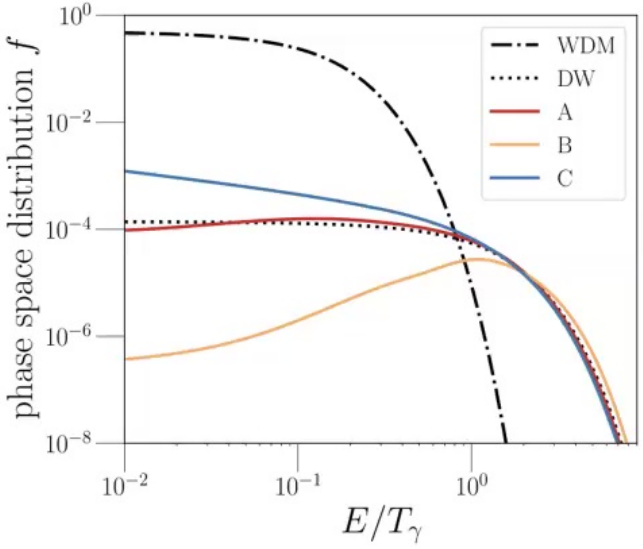
Case A: DM production through a heavy mediator, and a strong self-interaction

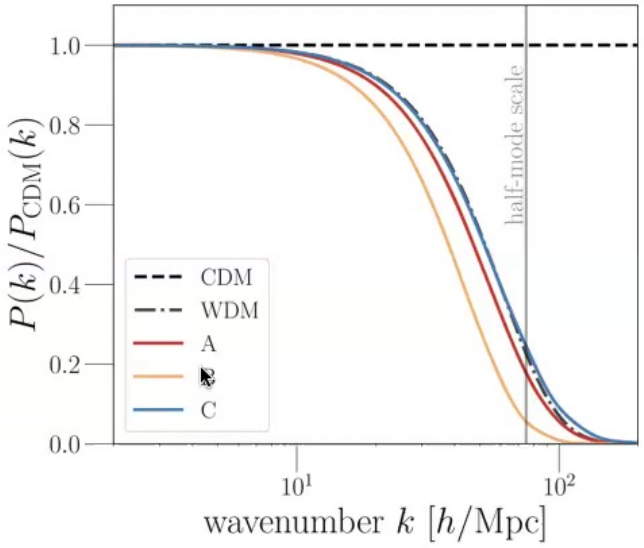
Case B: DM production through a light mediator, with a suppressed in-medium mixing angle

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

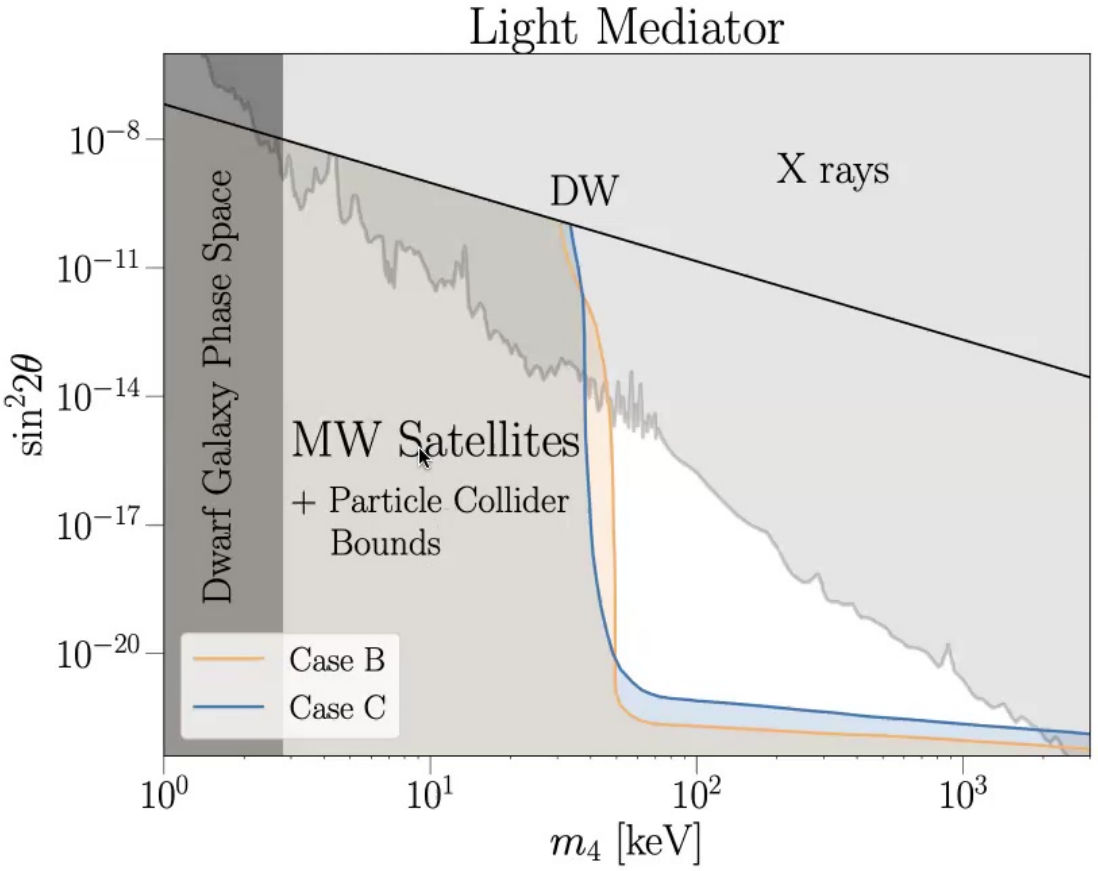
RA, Gluscevic, Nadler, Zhang, ApJL 2023 [arXiv: 2301.08299]







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



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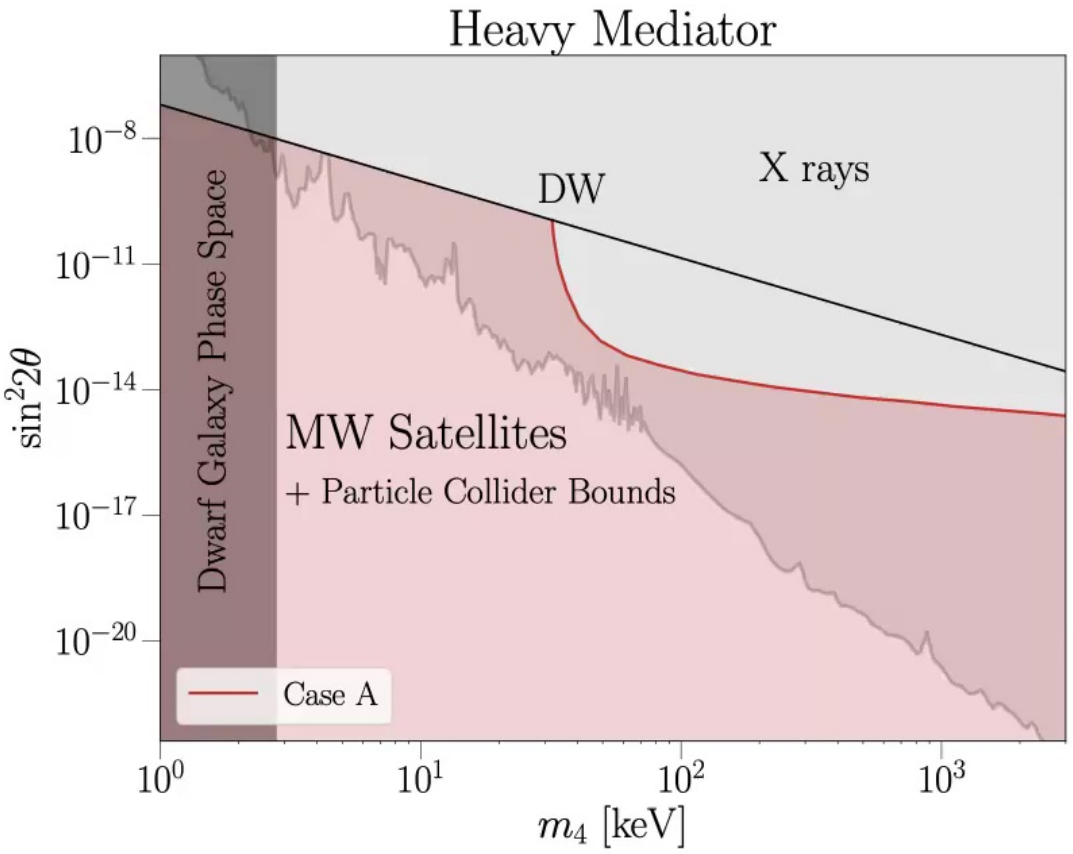
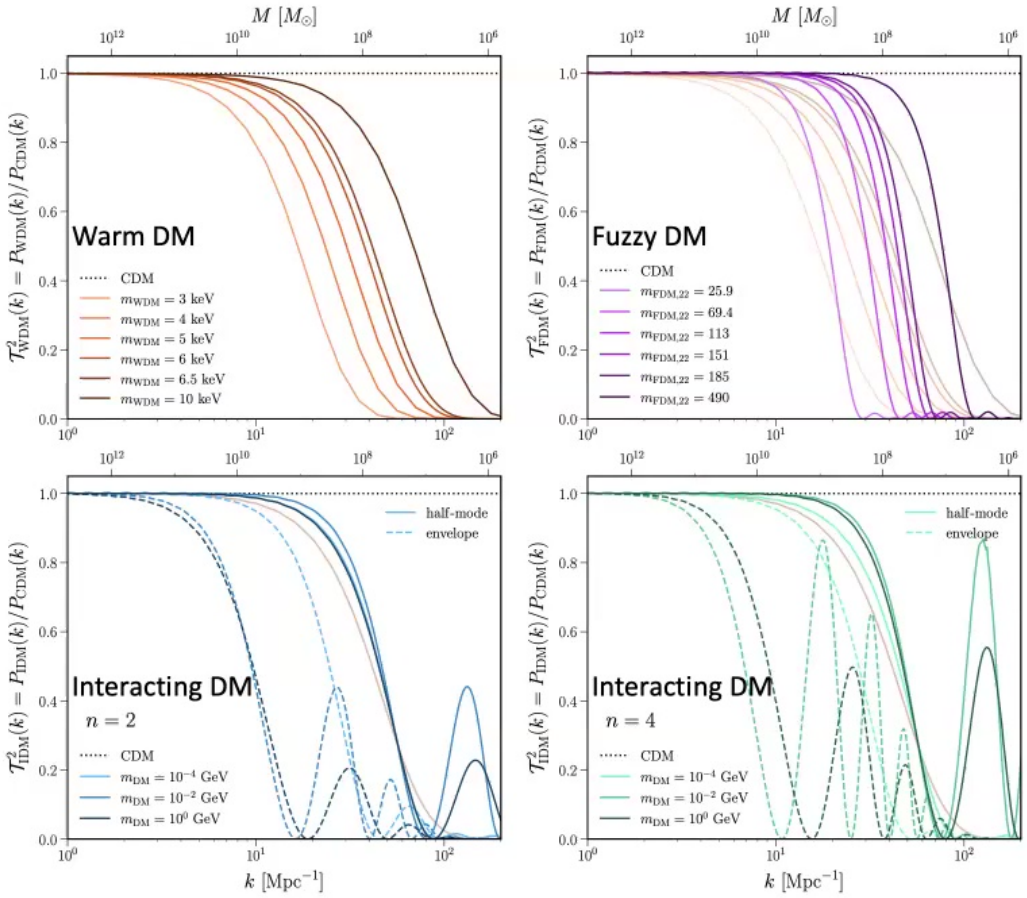
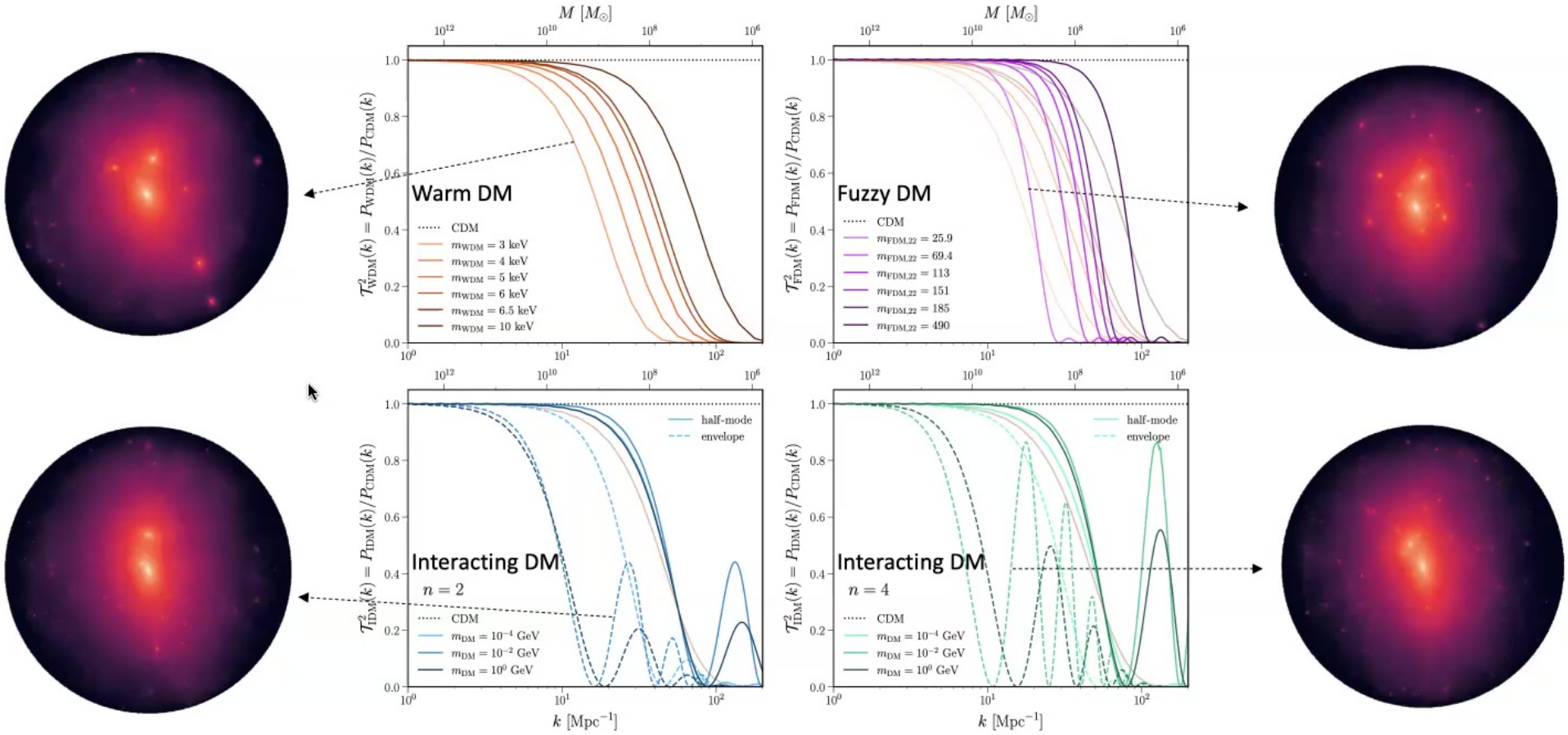


RA, Gluscevic, Nadler, Zhang, ApJL 2023 [arXiv: 2301.08299]

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

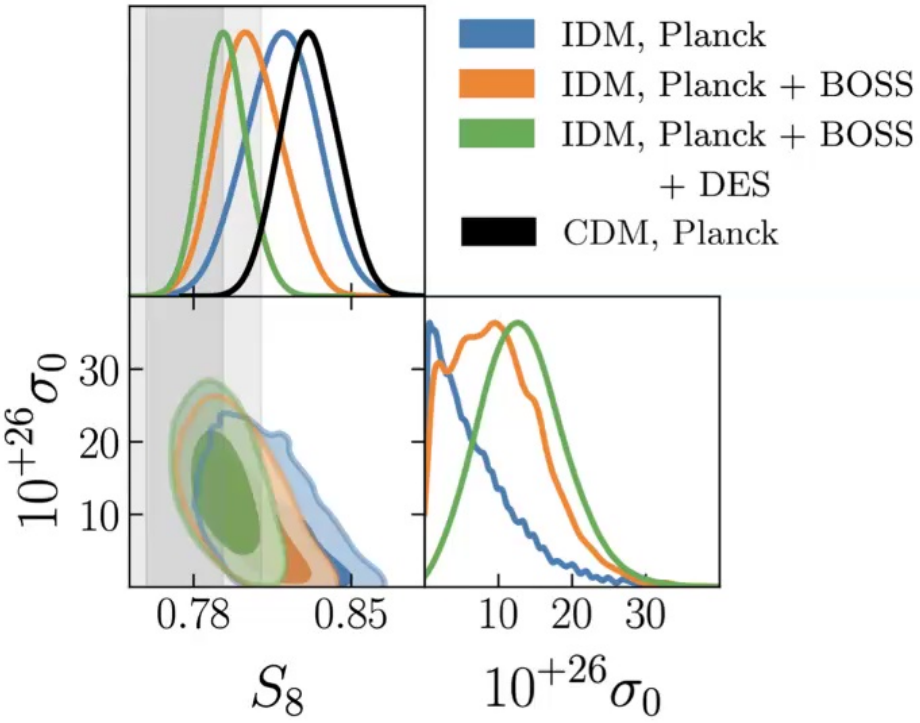


Cosmological simulations of Milky Way-like systems within various DM models

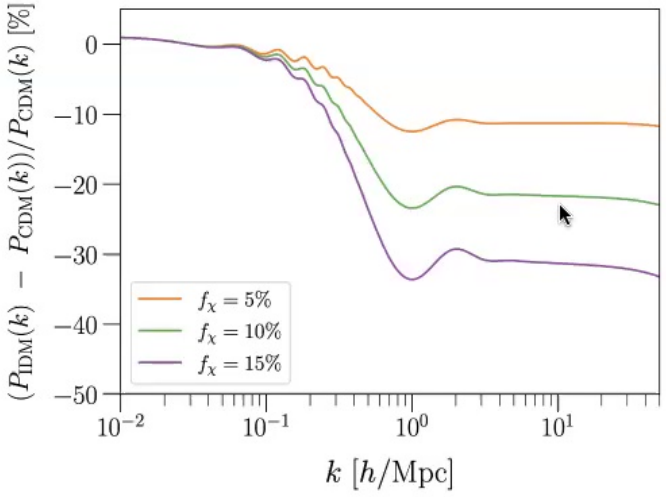


What can we learn from Large-Scale Structure?

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

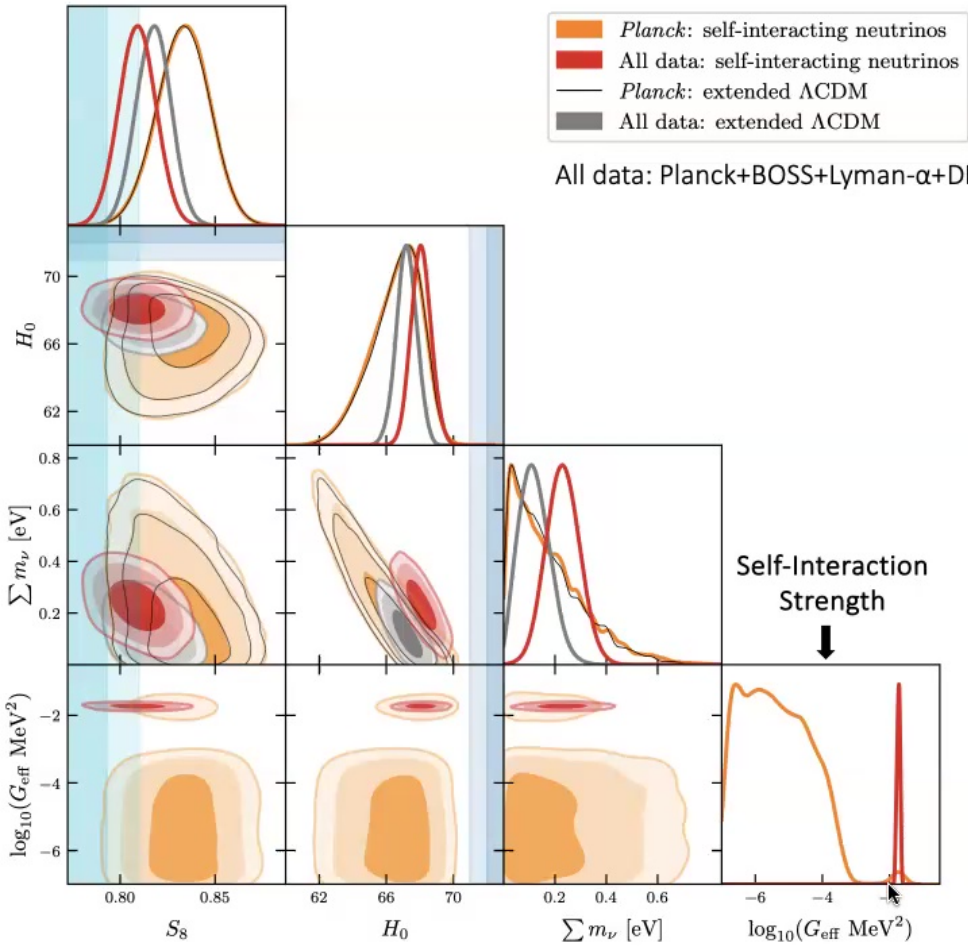


Adam He



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

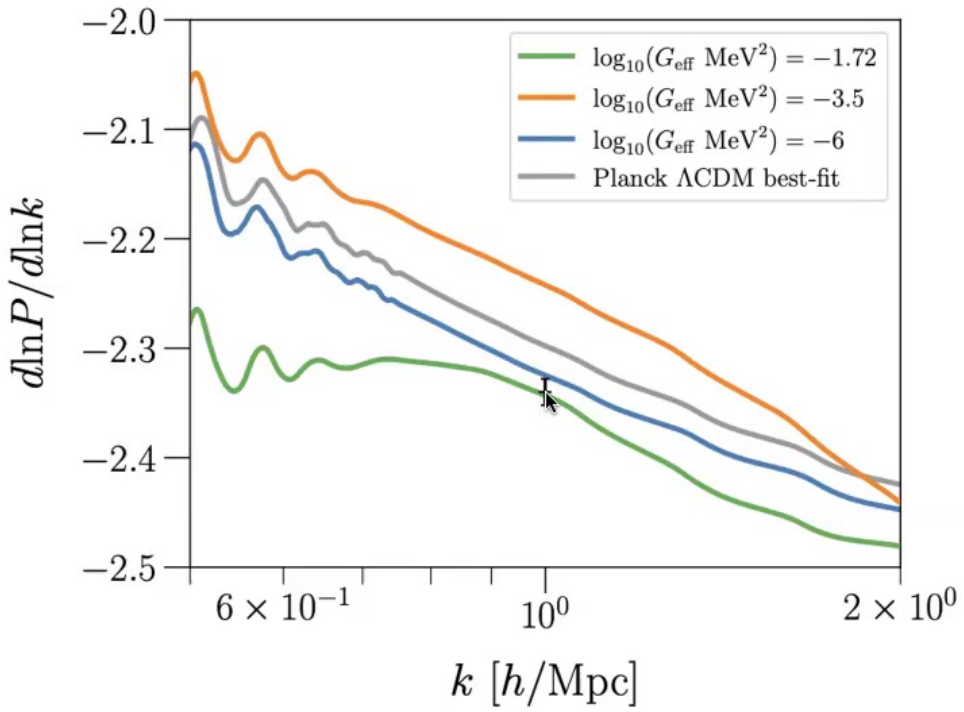
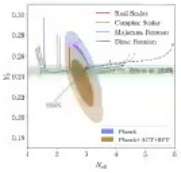
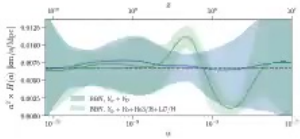


Figure 2. The slope $d\ln P/d\ln k$ of the linear matter power spectrum for a self-interacting neutrino cosmology and ΛCDM, where the latter is generated with best-fit parameter values from a *Planck*-only analysis. The parameters for the self-interacting cases are chosen in the same way as in Fig. 1.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

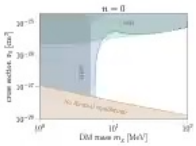
Key Points



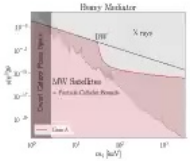
Lower bounds on thermal-relic DM mass from the measurements of BBN and CMB



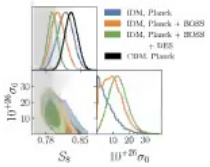
Reconstruction of early-universe evolution from BBN measurements



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



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

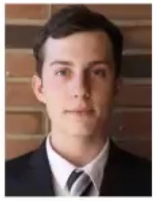


DM-baryon scattering alleviates S8 tension, through scale-dependent power suppression

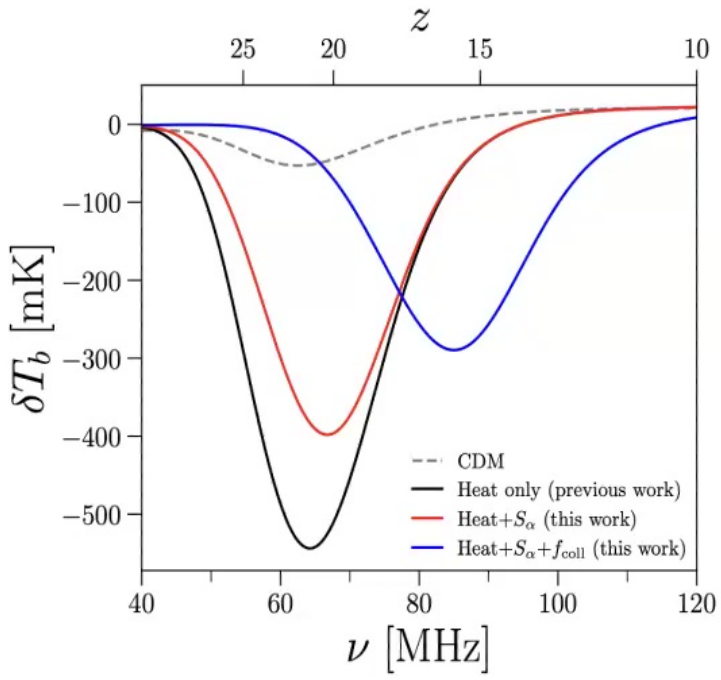
What can we learn from 21cm cosmology?

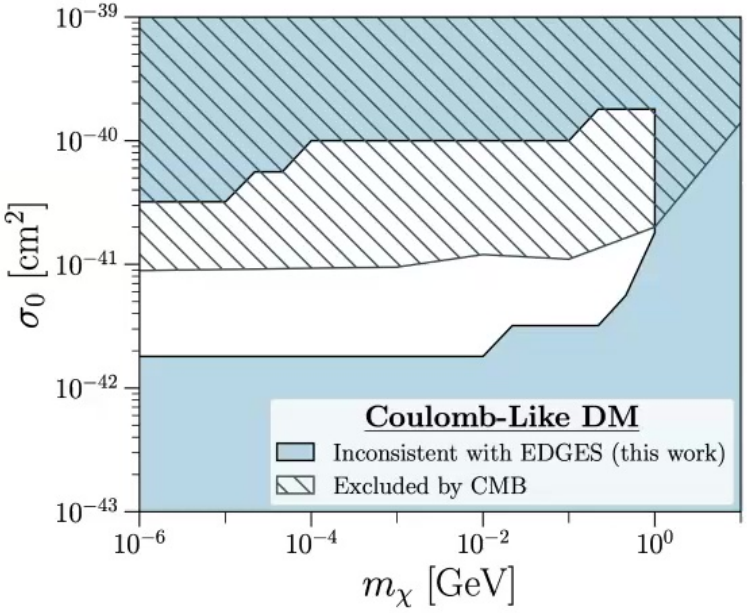
21cm signal in the Context of DM-Baryon Scattering (n=-4)

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



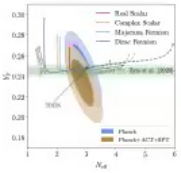
Trey Driskell



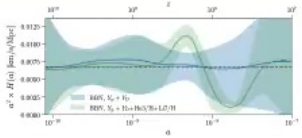


Driskell et al.(incl **RA**), PRD 2022 [arXiv: 2209.04499]

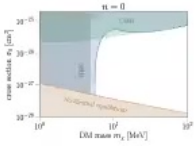
Key Points



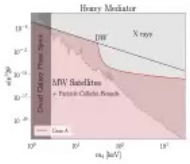
Lower bounds on thermal-relic DM mass from the measurements of BBN and CMB



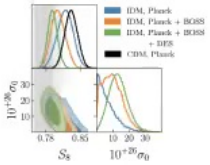
Reconstruction of early-universe evolution from BBN measurements



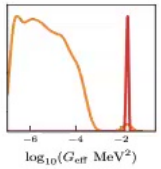
Self-consistent CMB bounds on interacting thermal-relic dark matter



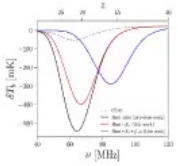
Sterile neutrino DM is heavily constrained by the small-scale structure data



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

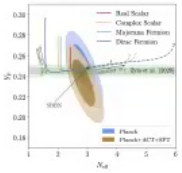


Neutrino self-interaction is strongly favored by the large-scale structure data



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

Key Points



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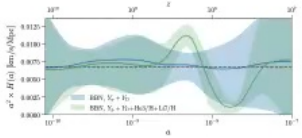

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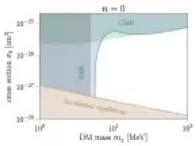
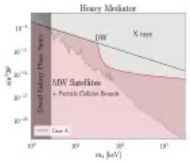


Self-consistent CMB bounds on interacting thermal-relic dark matter



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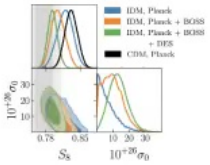

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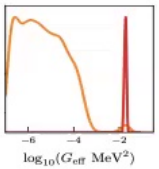

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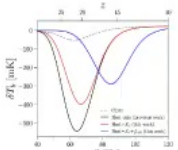


21cm signal requires accurate modeling of structure formation and thermal history

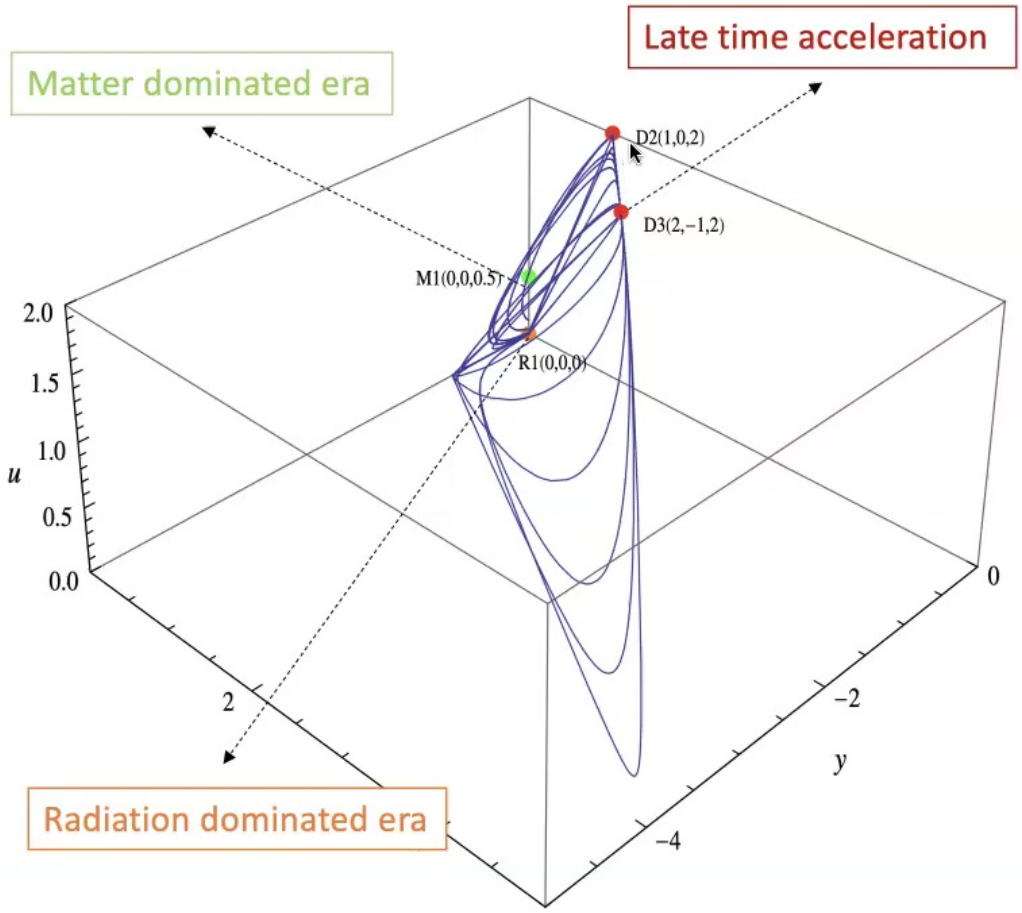
Modified Gravity

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

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

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

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

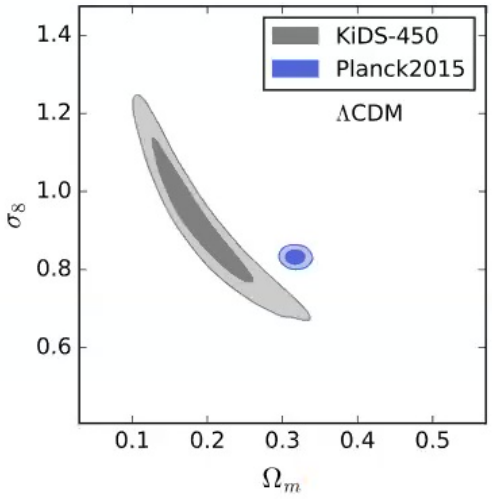


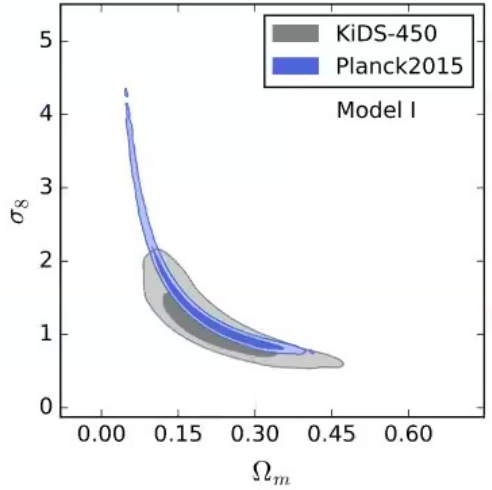
RA, Xu, Wang, Gong, PRD 2017 [arXiv: 1512.09281]

Dark Energy

Interaction?

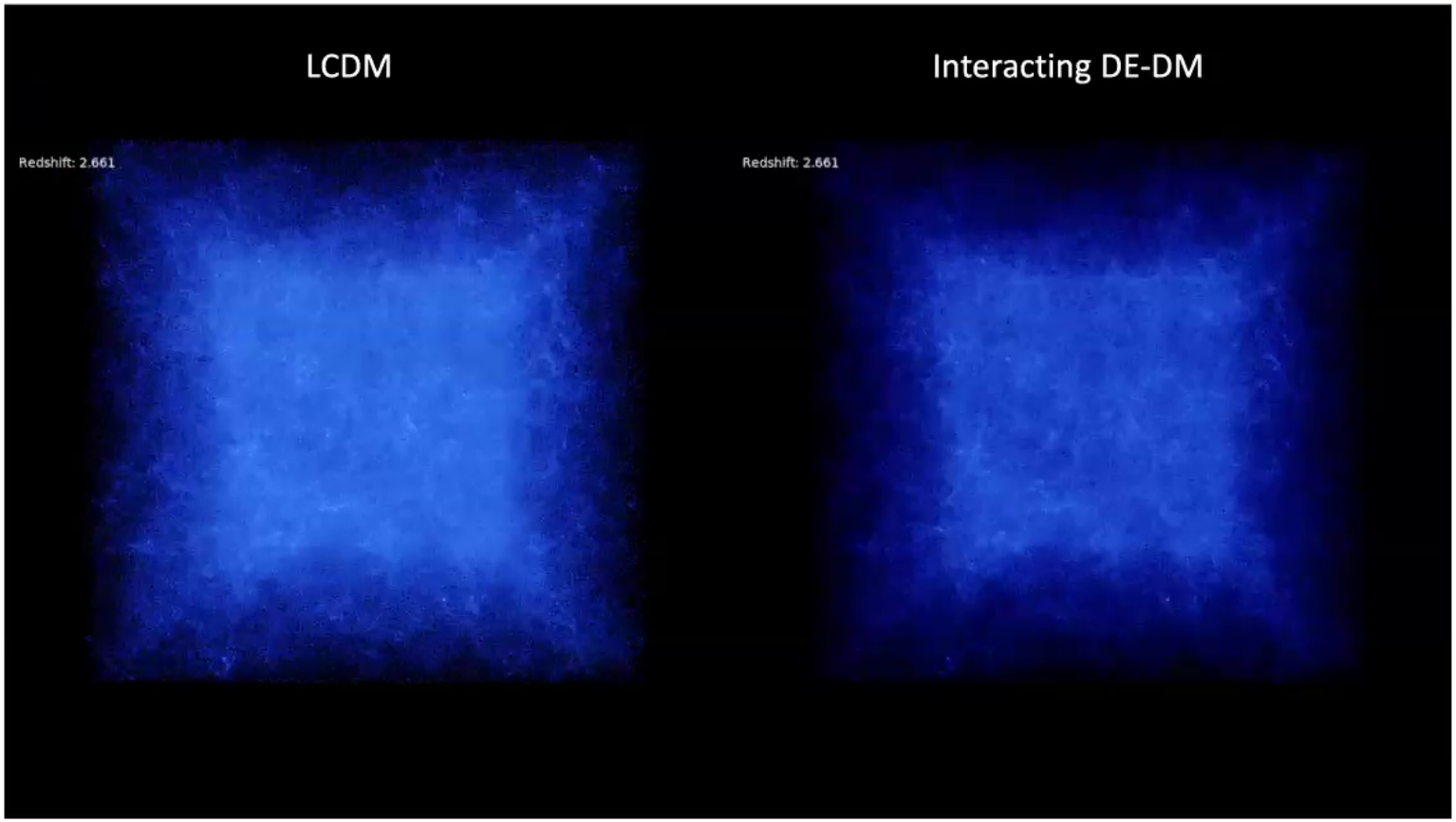
Alleviate S_8 tension between weak lensing and Planck data





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

Cosmological simulations with DE-DM interacting models



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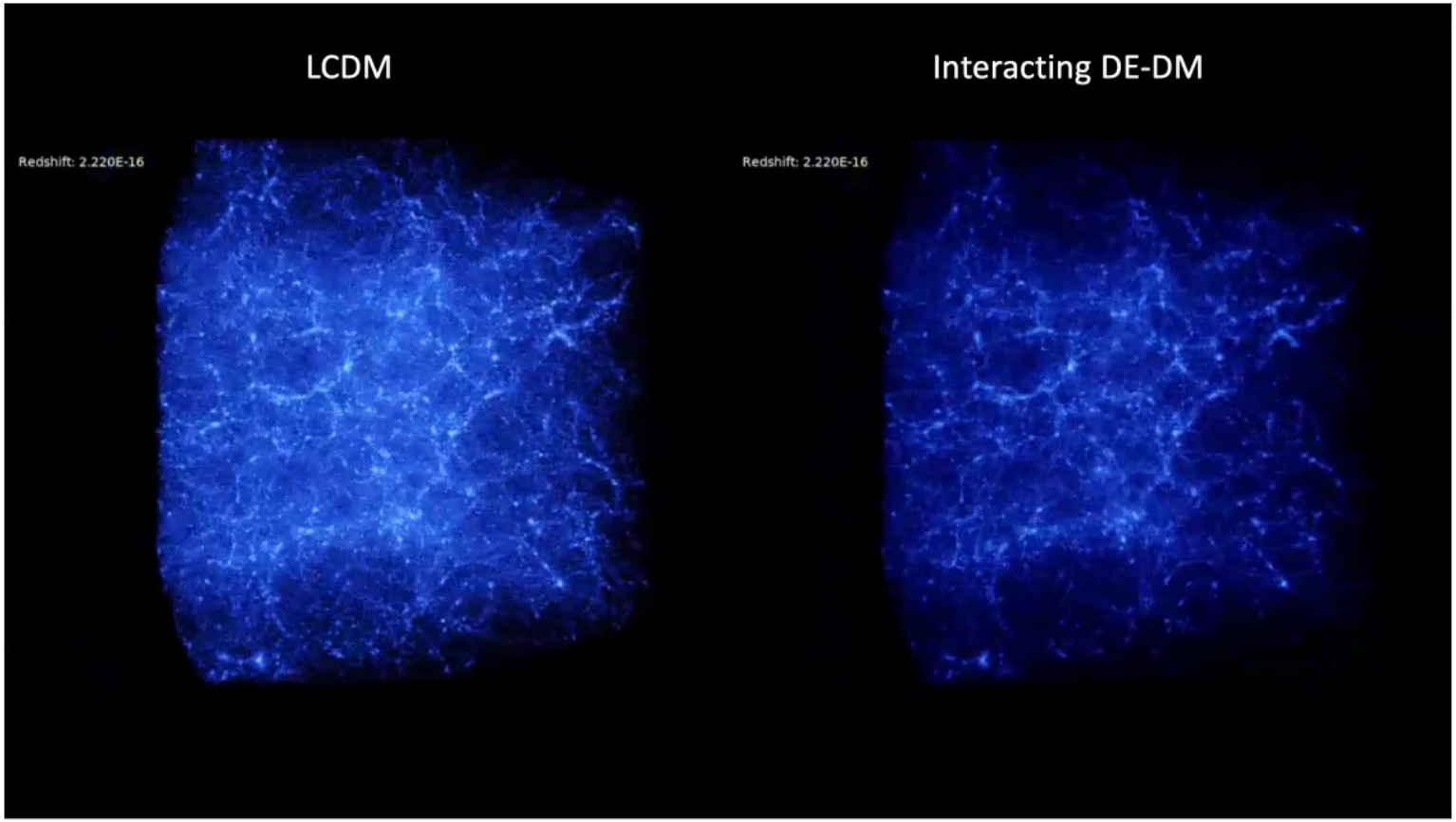
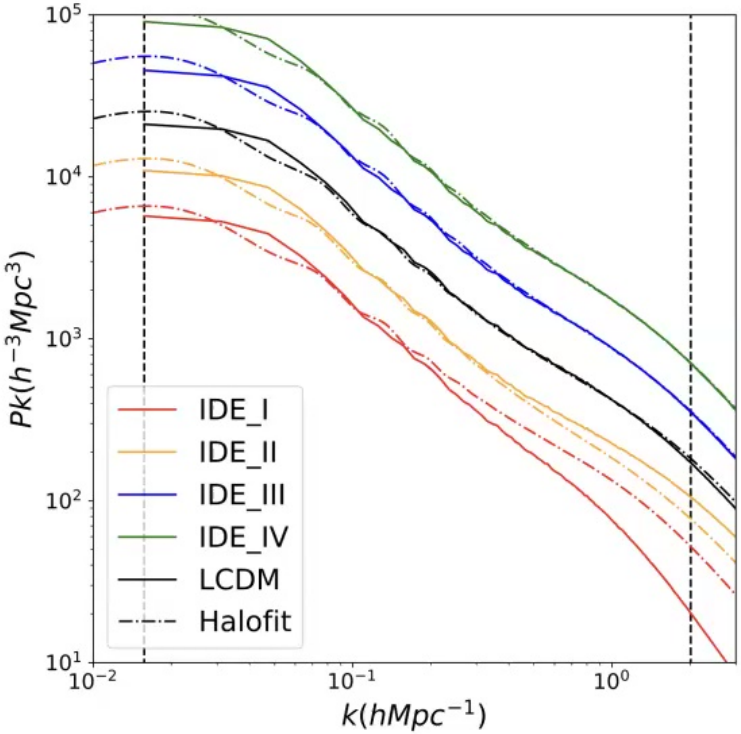
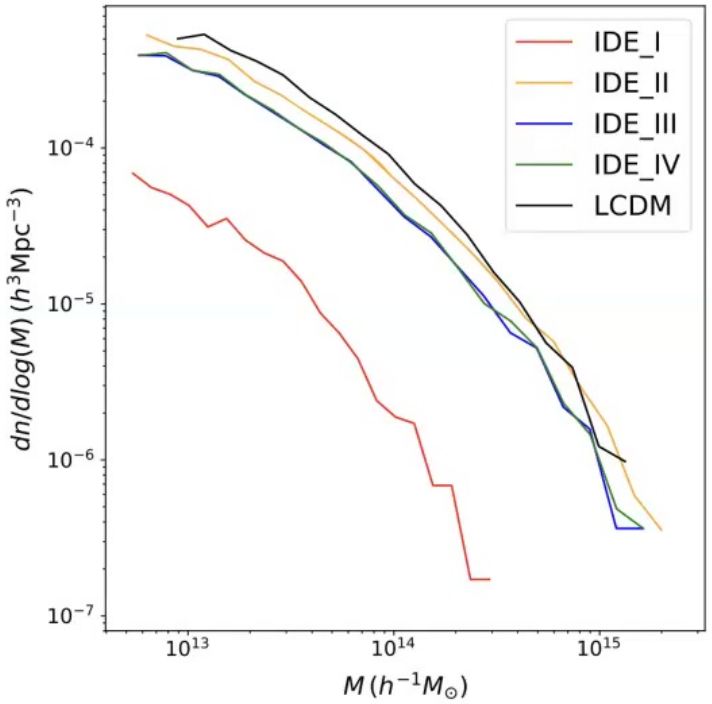


The resulting matter power spectra and halo mass functions for four different models

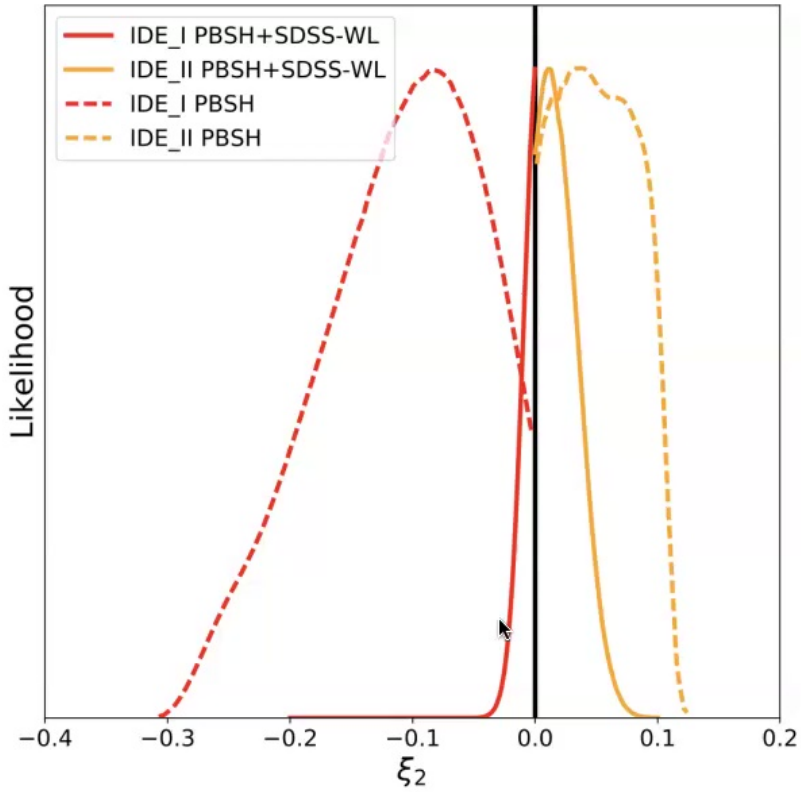




* Note that Pks are rescaled for better illustration

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