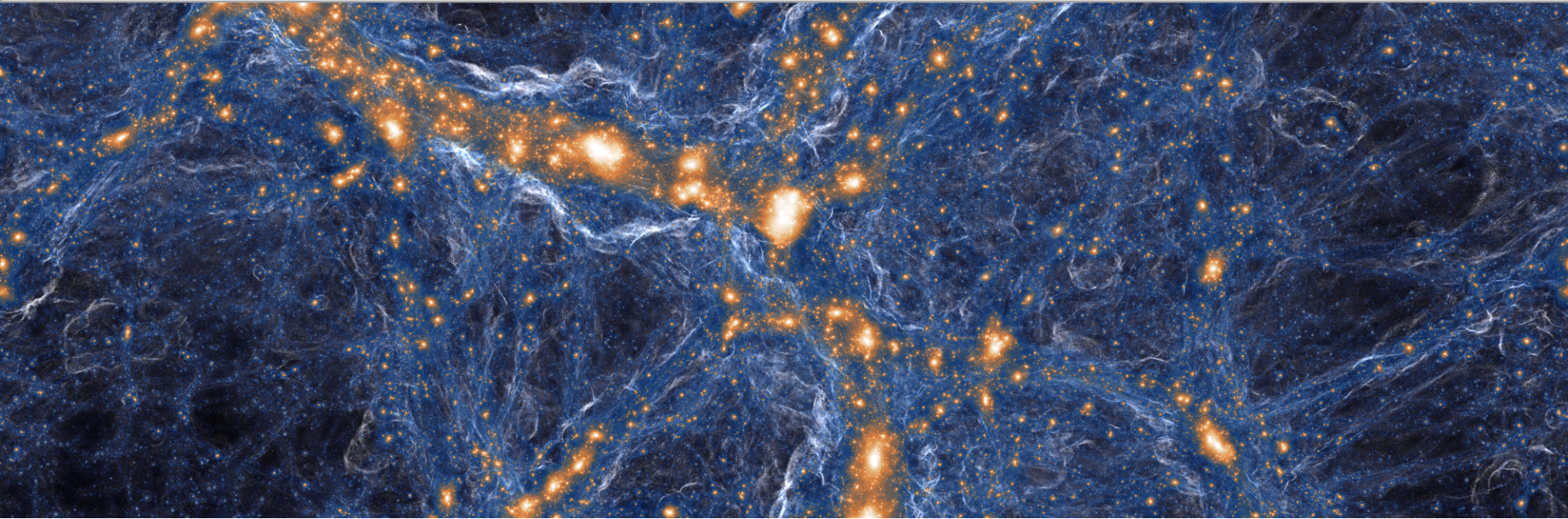


Constraining Interacting Dark Radiation with Lyman- α



Hengameh Bagherian

[IllustrisTNG - Media]

Harvard University Department of Physics

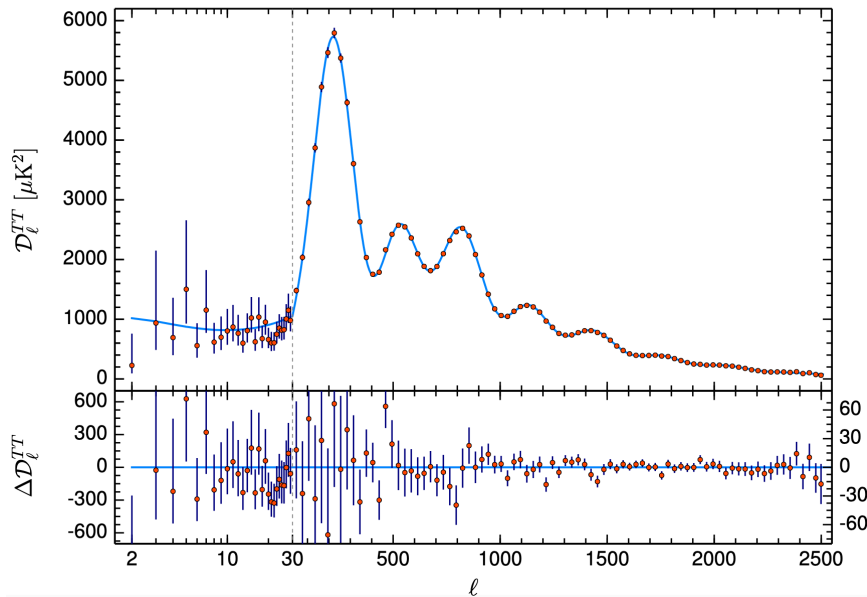
Fundamental Physics from Future Spectroscopic Surveys | May, 2024

[Bagherian, Joseph, Schmalz, and Sivarajan, [arXiv: 2404.XXXXX](#)]

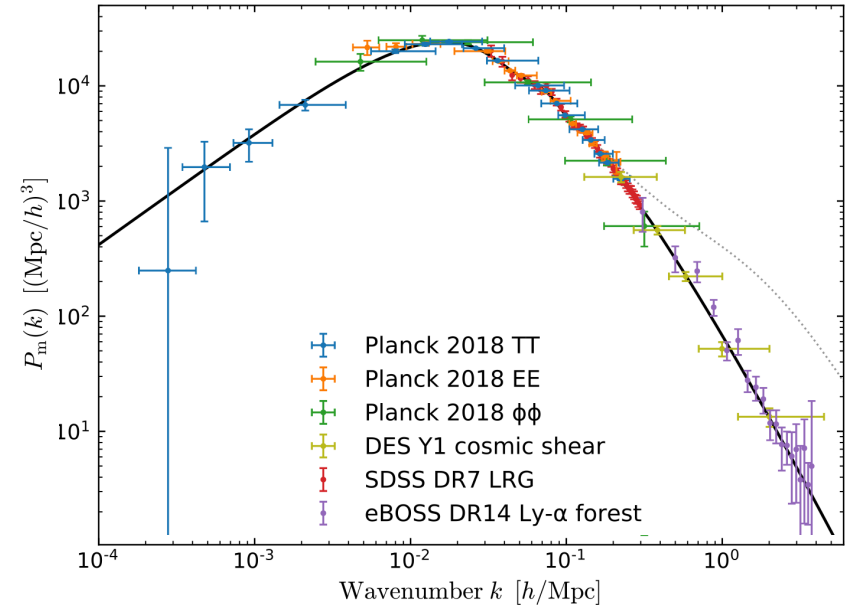
Λ CDM: SM of cosmology

Λ CDM describes our universe with 6 parameters:

ω_b	ω_{CDM}	ω_Λ	A_s	n_s	τ
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© [Planck 2018 Collab., [arXiv: 1807.06209v4](#)]

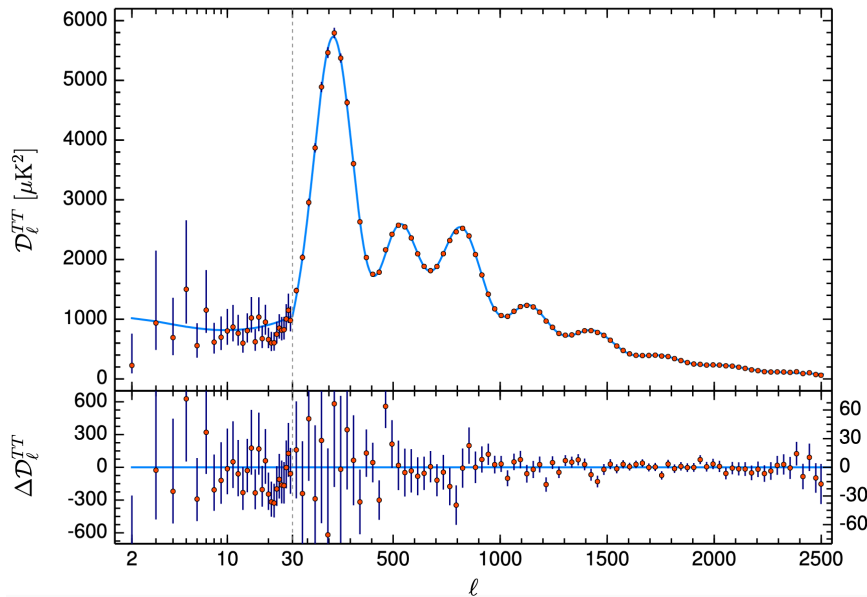


© [S. Chabanier, et al., [arXiv: 1905.08103v2](#)]

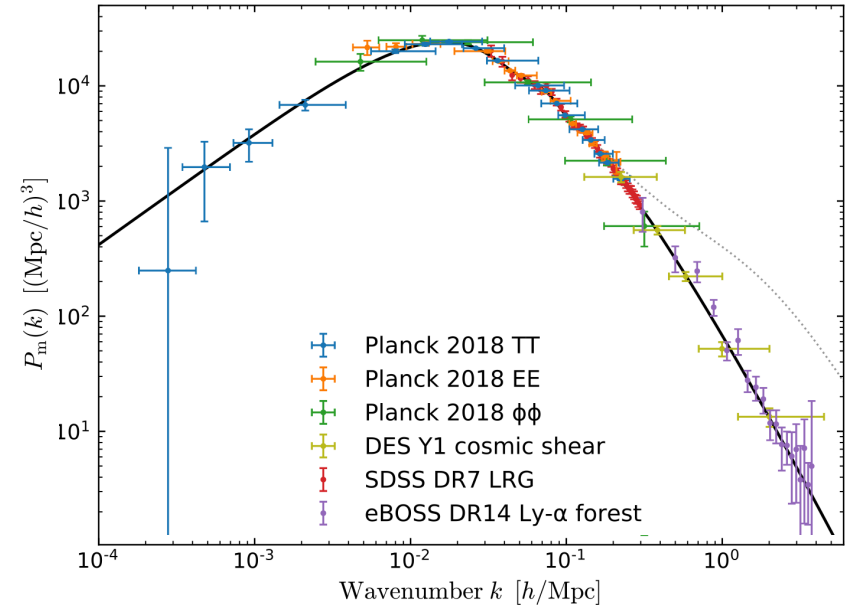
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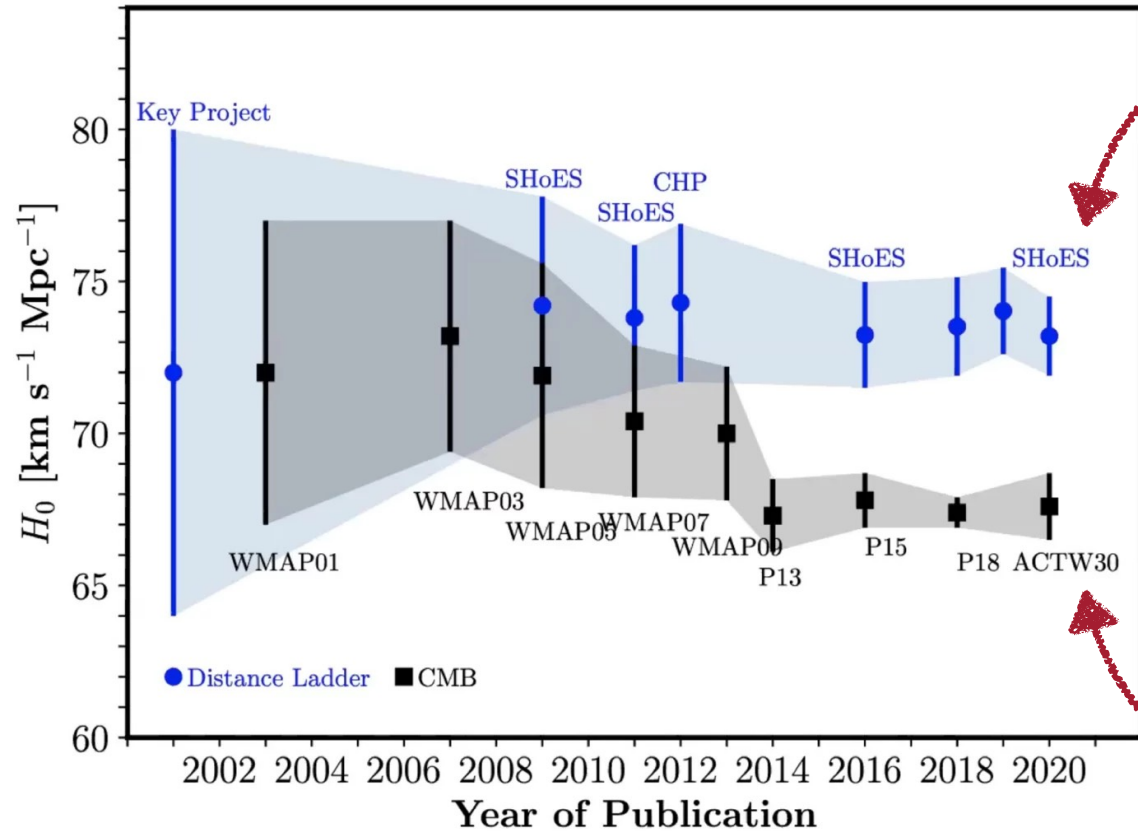
© [Planck 2018 Collab., [arXiv: 1807.06209v4](#)]



© [S. Chabanier, et al., [arXiv: 1905.08103v2](#)]

Λ CDM is **great**, but **not perfect**!

The H_0 tension

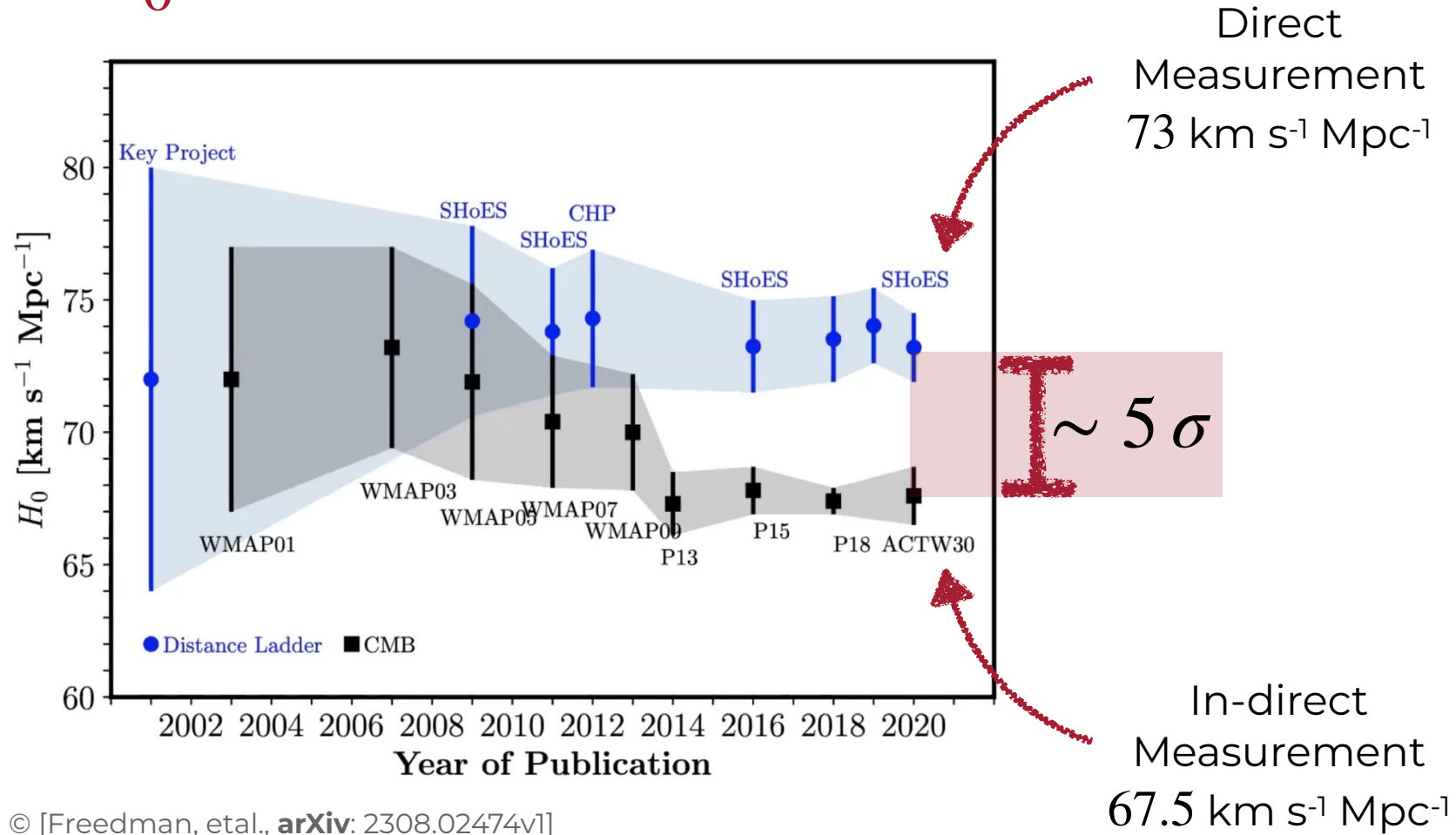


Direct
Measurement
 $73 \text{ km s}^{-1} \text{ Mpc}^{-1}$

In-direct
Measurement
 $67.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$

© [Freedman, et al., [arXiv: 2308.02474v1](https://arxiv.org/abs/2308.02474)]

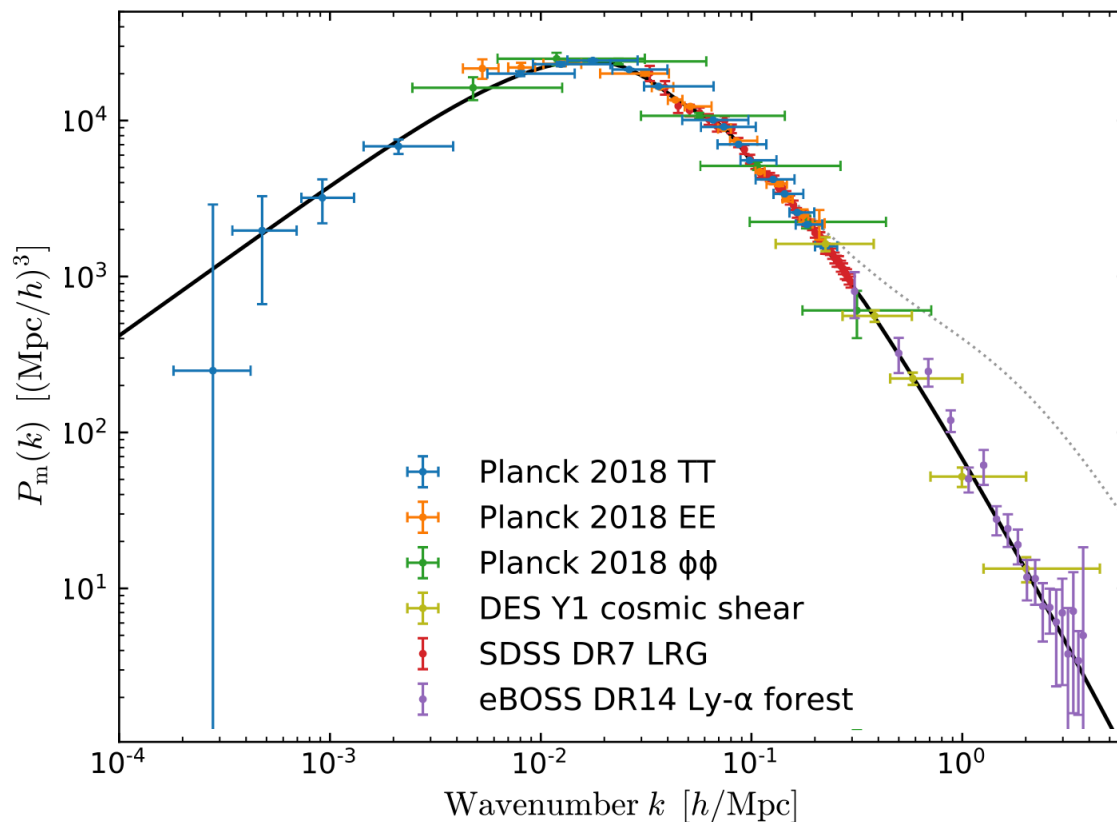
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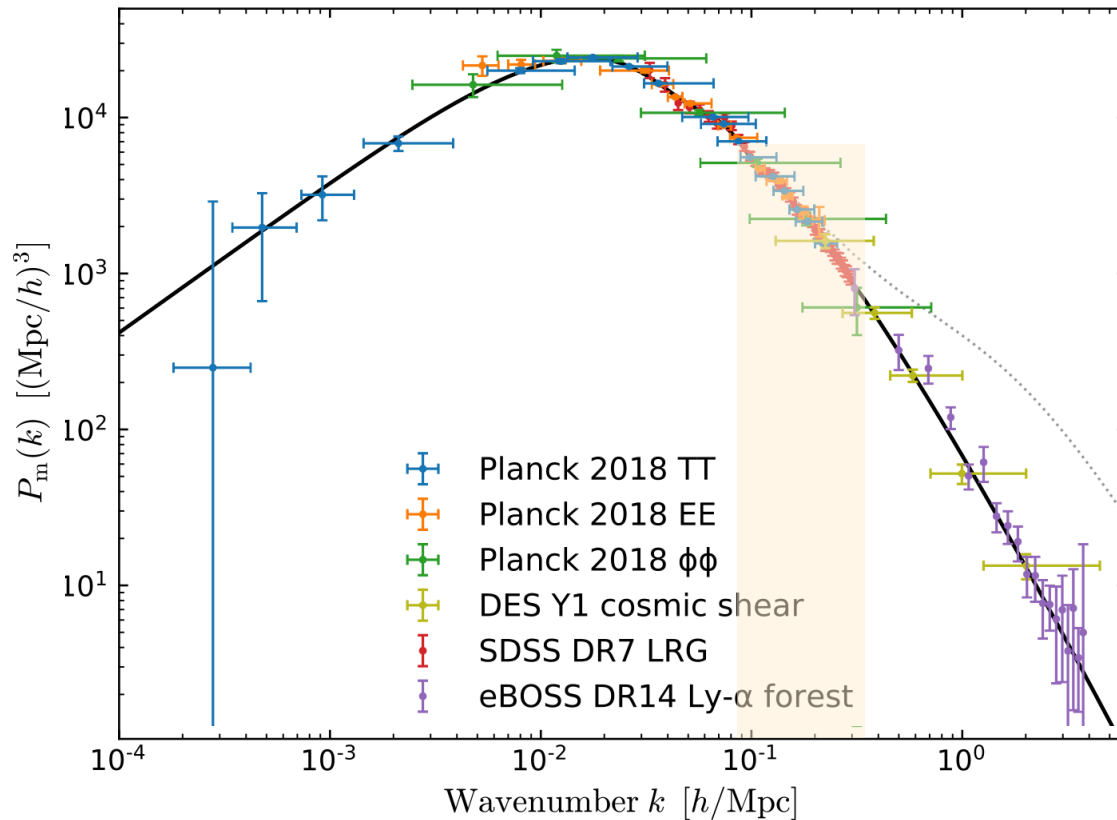
S_8 & $\text{Ly}\alpha$: LSS tensions

© [S. Chabanier, et al., [arXiv: 1905.08103v2](https://arxiv.org/abs/1905.08103v2)]



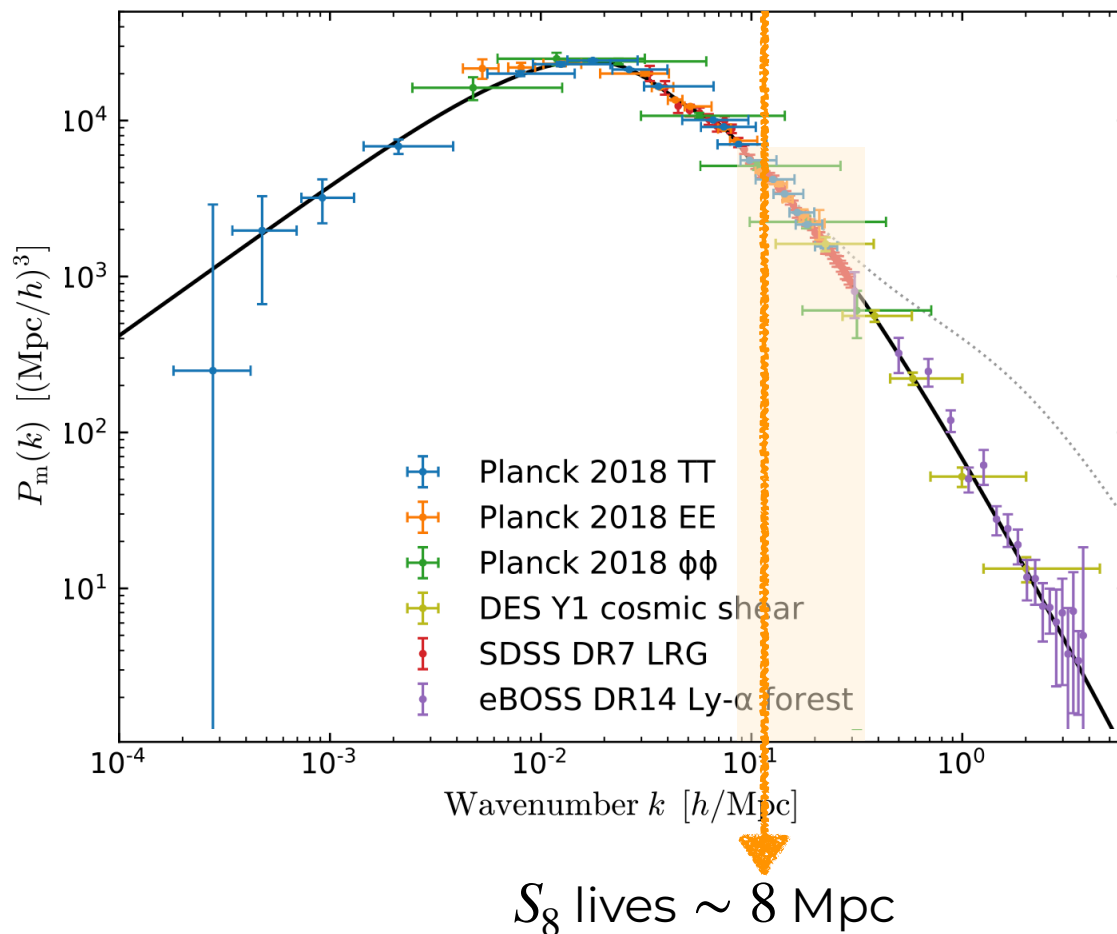
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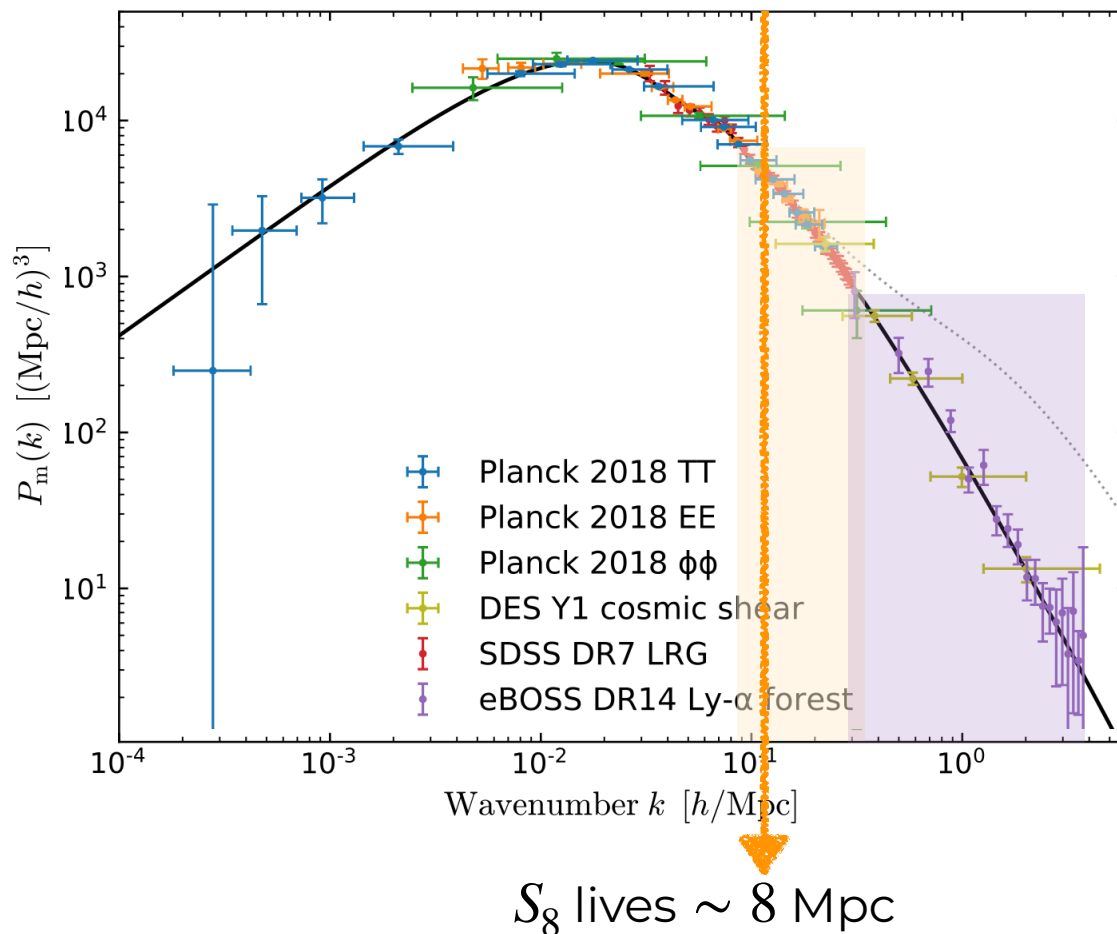
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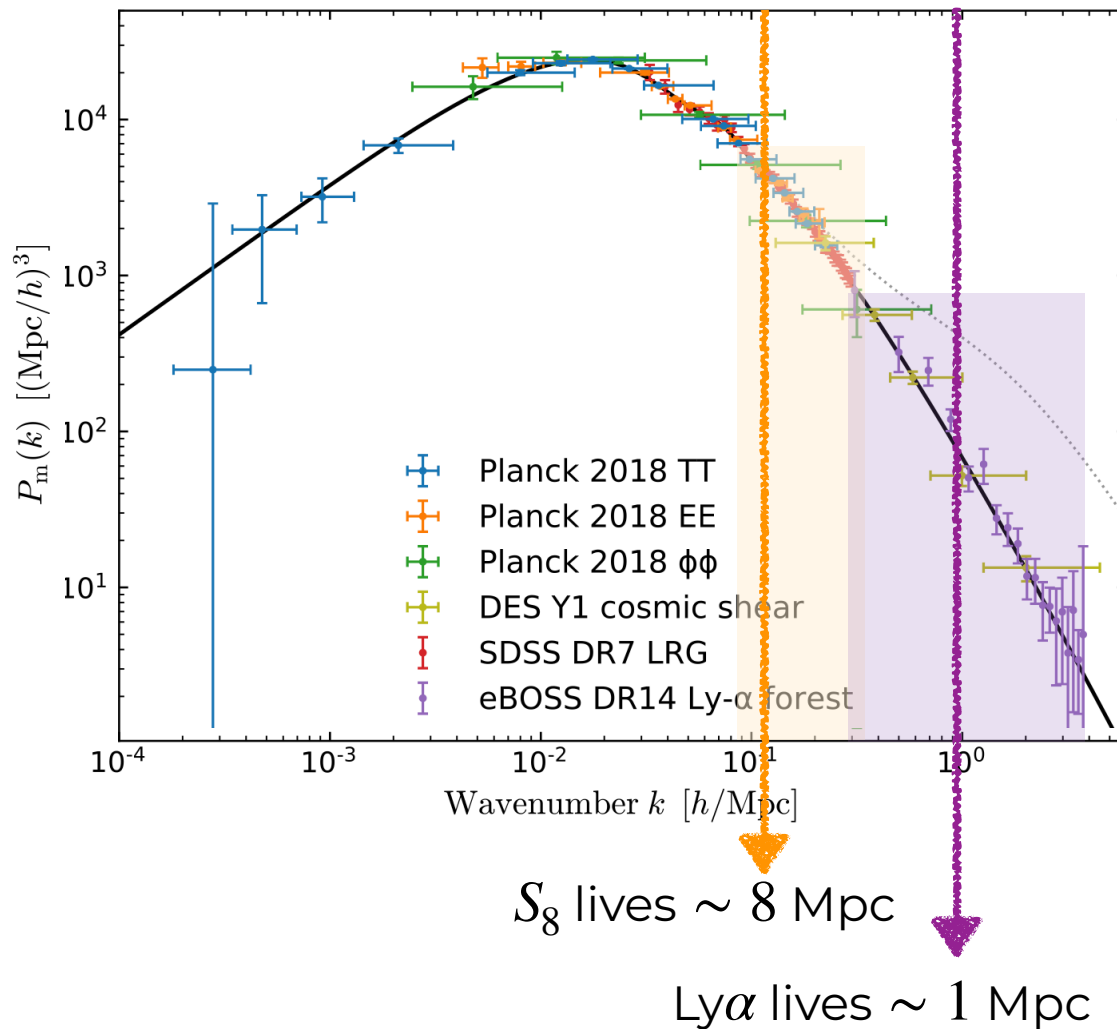
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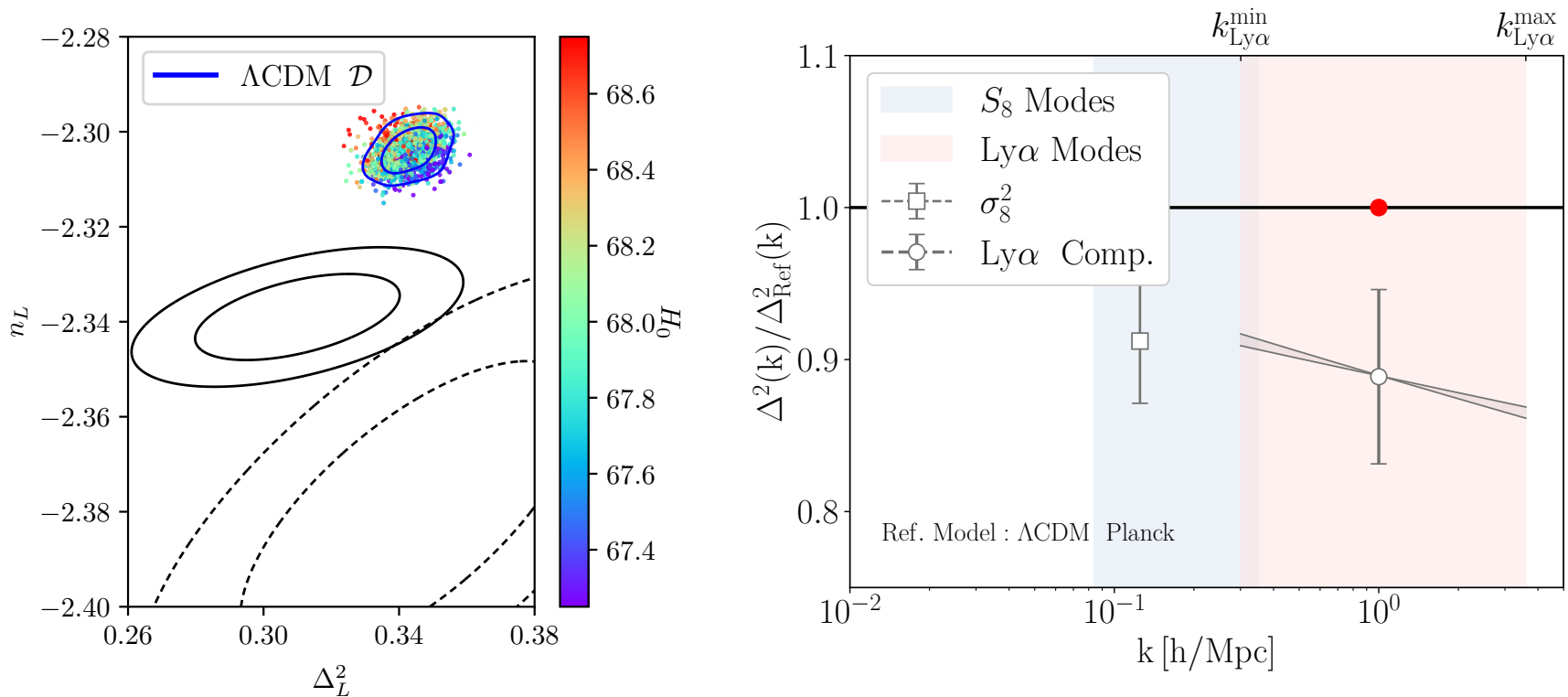


Compressed Ly- α likelihood

- Compressed Ly α [C. Pedersen, et al., [arXiv: 2209.09895](#); DR14 Collab., [arXiv: 1812.03554v3](#)]:

$$\Delta_L^2 = 0.31 \pm 0.02, \quad n_L = -2.339 \pm 0.006$$

- Λ CDM is not steep enough/ over predicts LSS at high k : $\sim 5\sigma$ tension

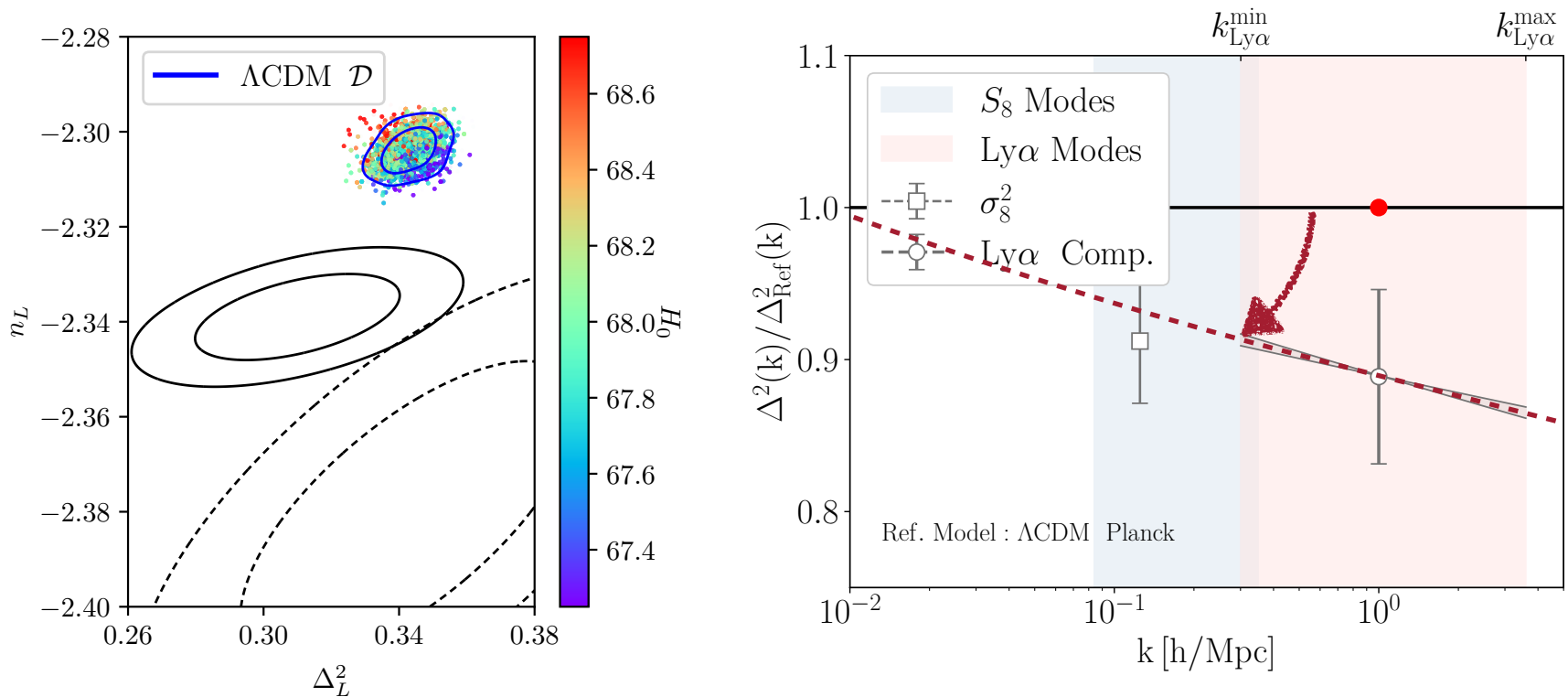


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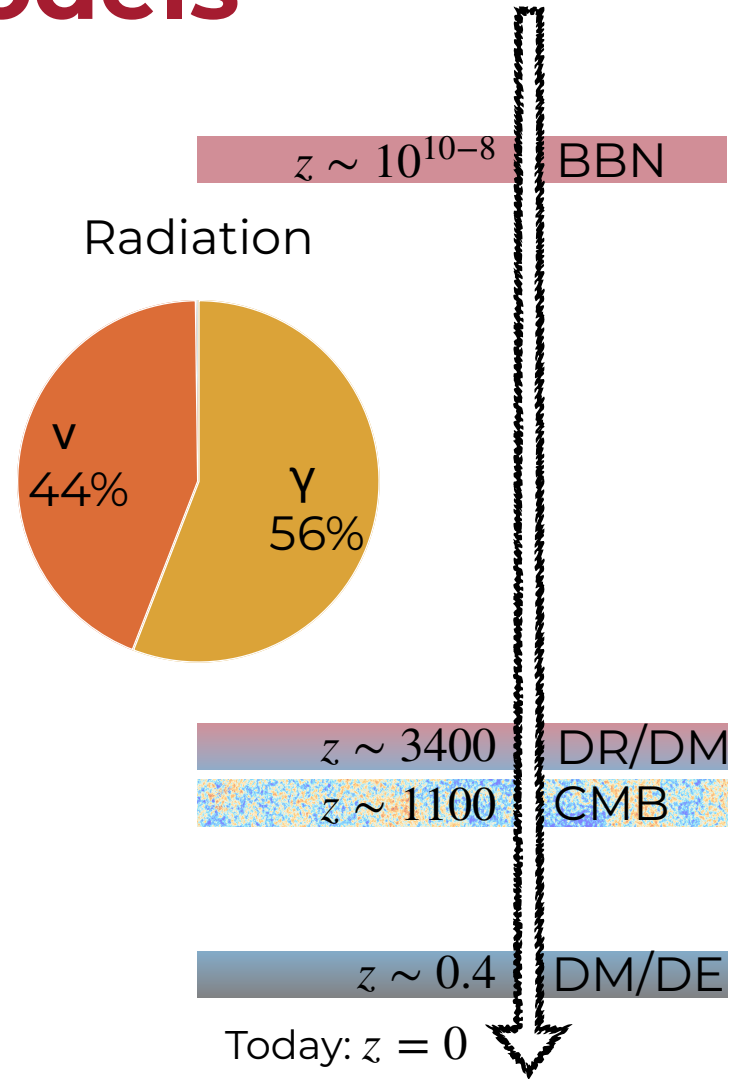
New physics: **suppress MPS** at high $k \sim 0.125$ h/Mpc, **fix H_0 correlation**

The appeal of DR models

- Modify physics of CMB to resolve H_0 :
 - **Late time** → Too many obs. (i.e. Pantheon)
 - **Early time** → **Natural** to add **DR**
- Hubble - Sound Horizon relation:

$$\theta_s \sim r_s \times H_0$$

- DR \Rightarrow DM **suppresses** LSS at large k

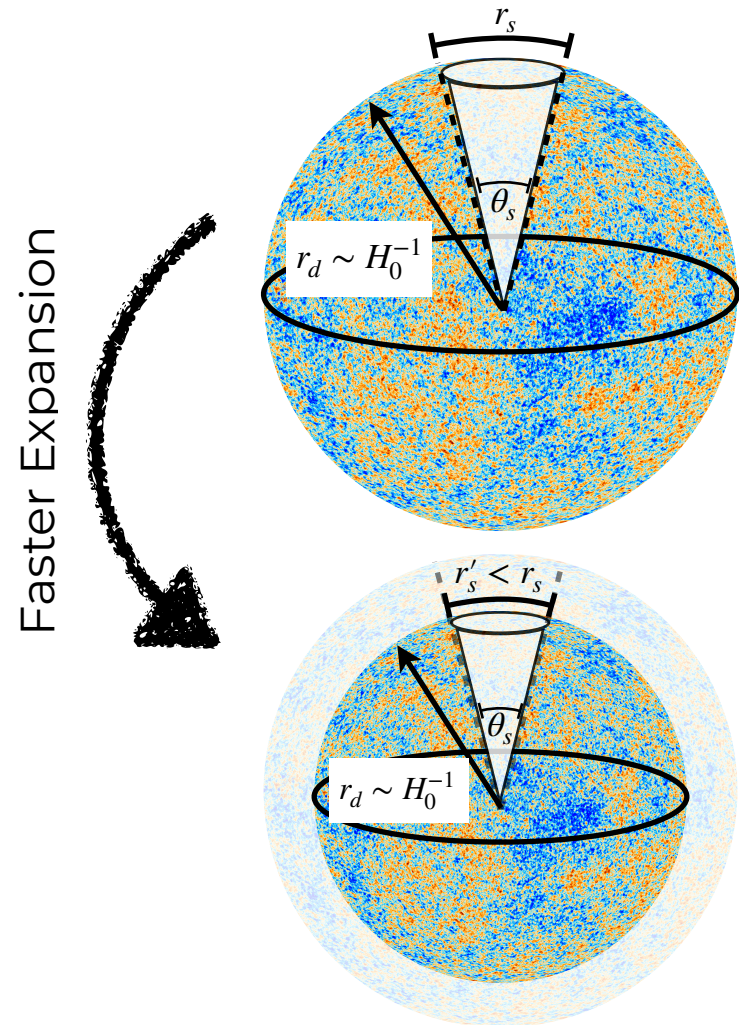


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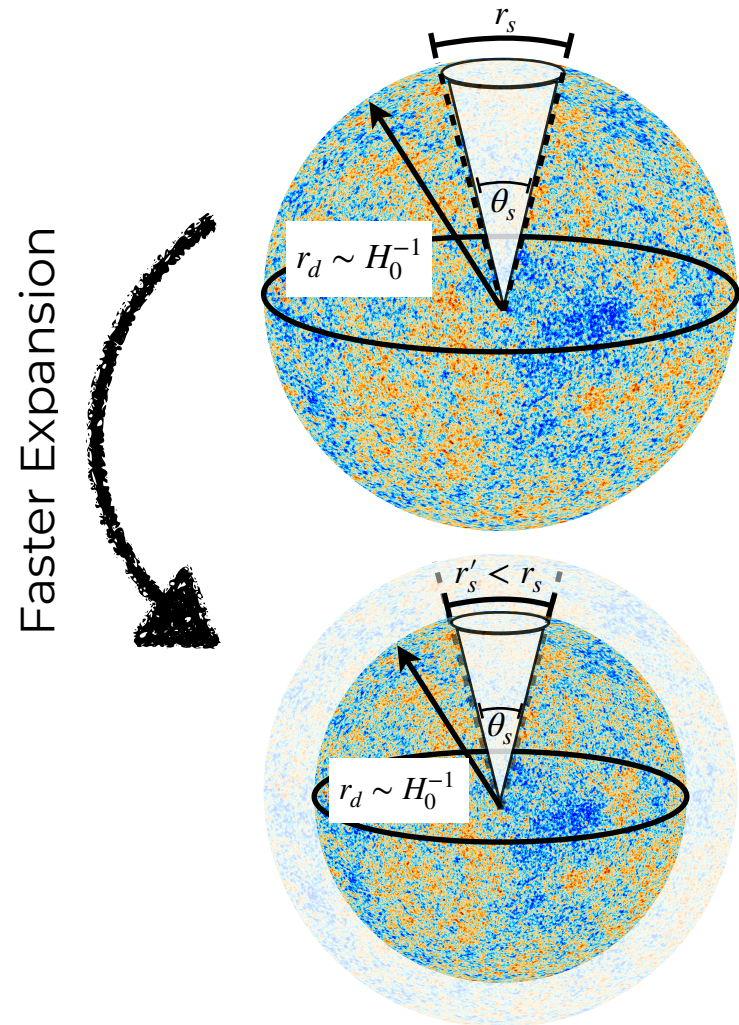
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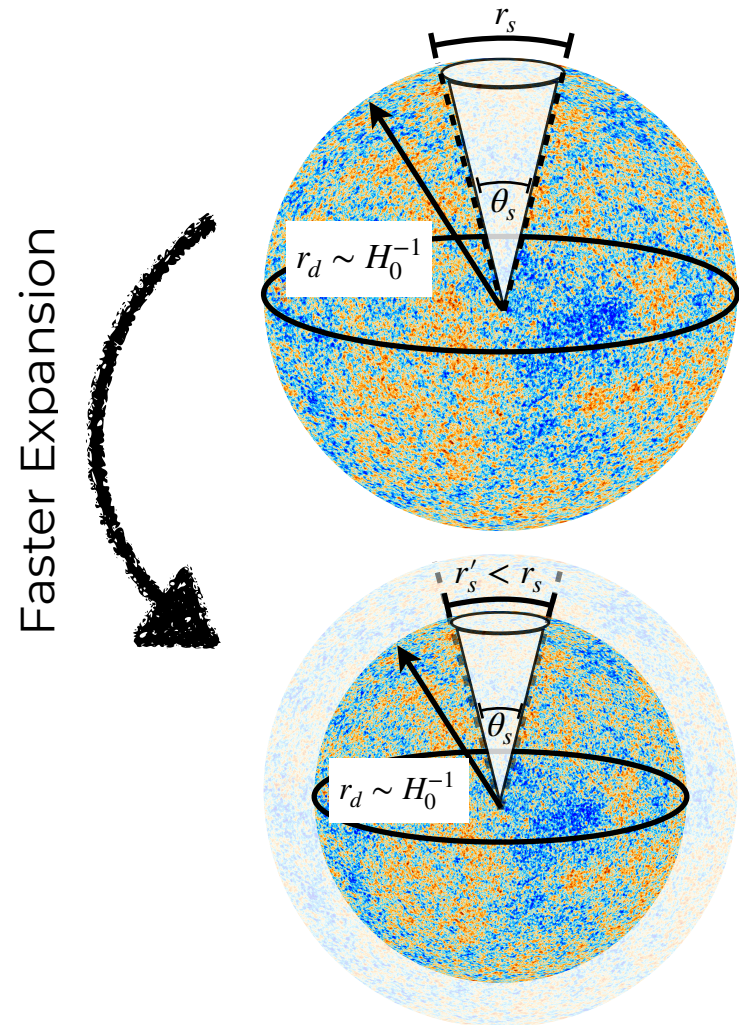
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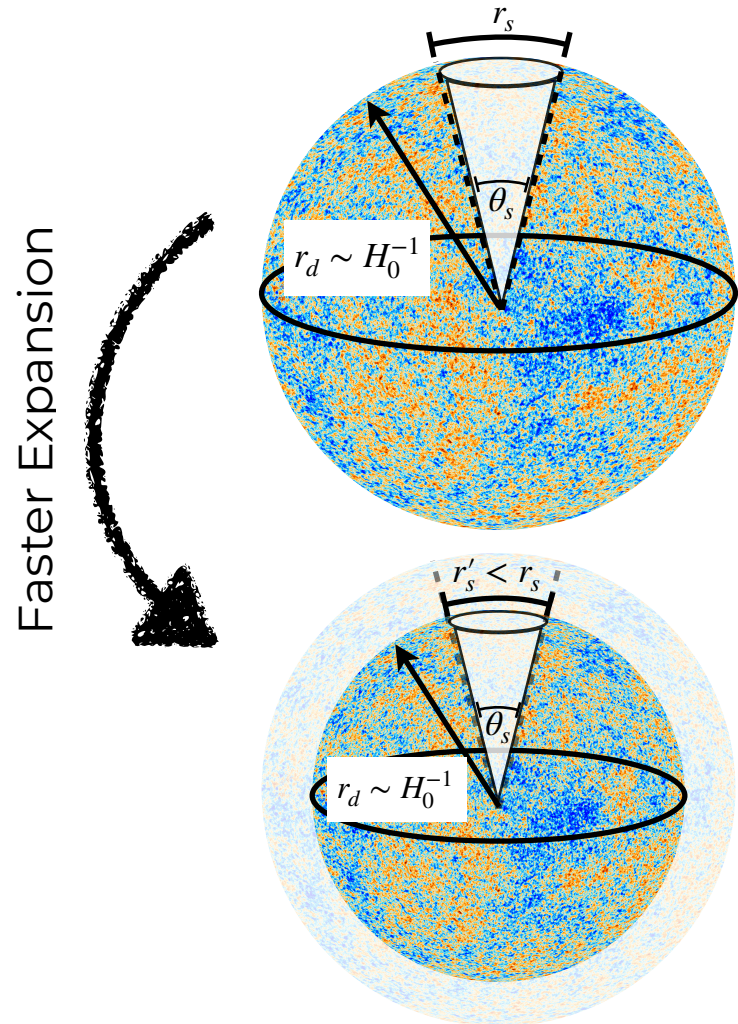
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Fixed \downarrow \downarrow \uparrow

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$67.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$

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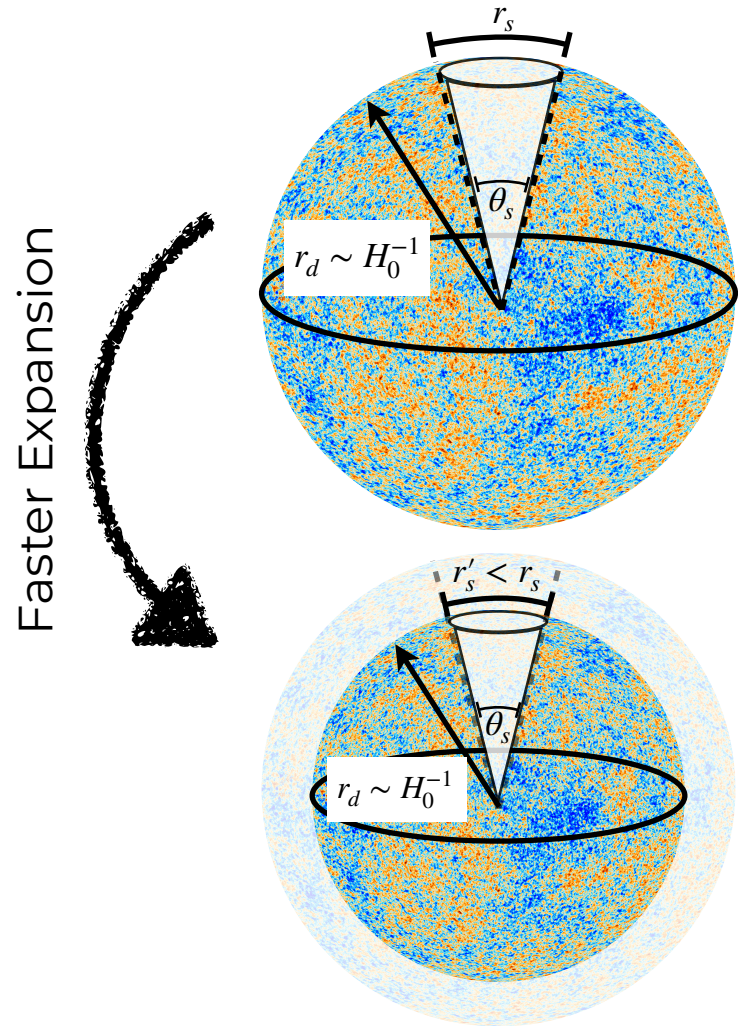
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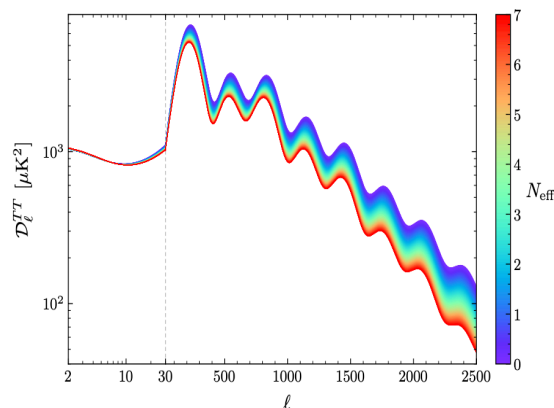
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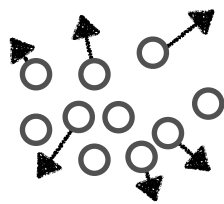


We can add **different types of DR**: What are their pros and cons?

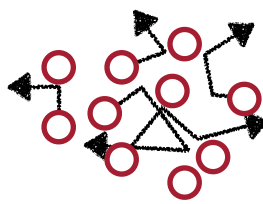
Different DR fluids: Pros & Cons



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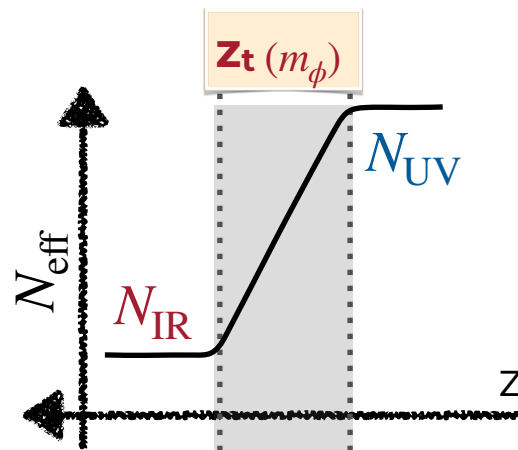


$c = 1$
Free-stream



$c = 1/3$
Self-interacting

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Self-interacting DR/ Perfect fluid (*SIDR*):

Stepped-fluid (*WZDR*):

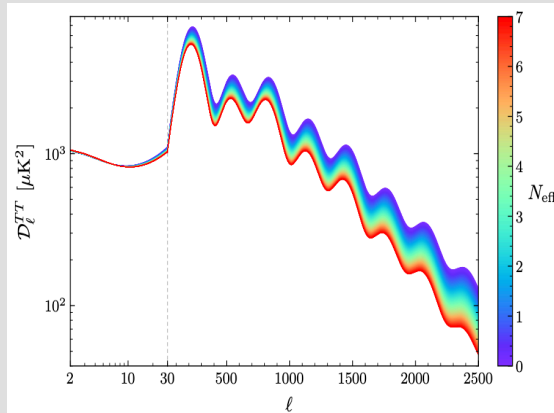
Free-stream (N_{eff}):

- Silk damping
- Phase shift

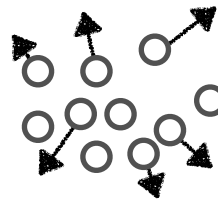
- Lower sound speed (perfect fluid dyn.)
- Less phase shift

- Perfect-fluid with massive component
- Control over z_t

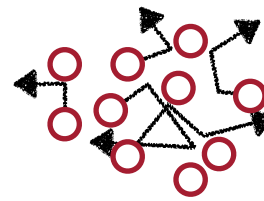
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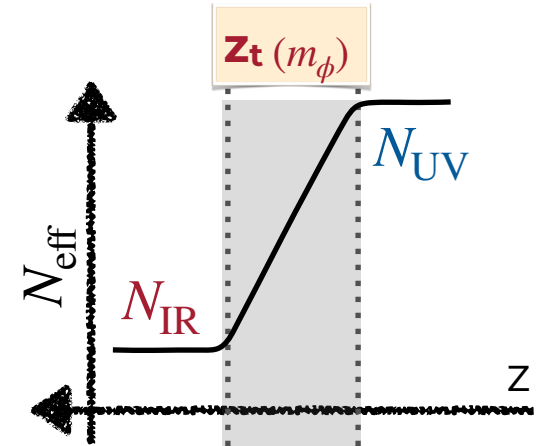
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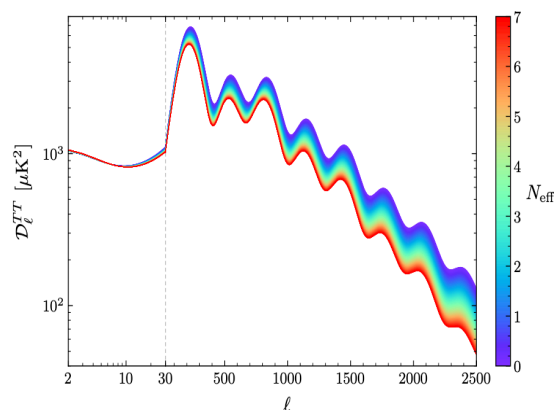
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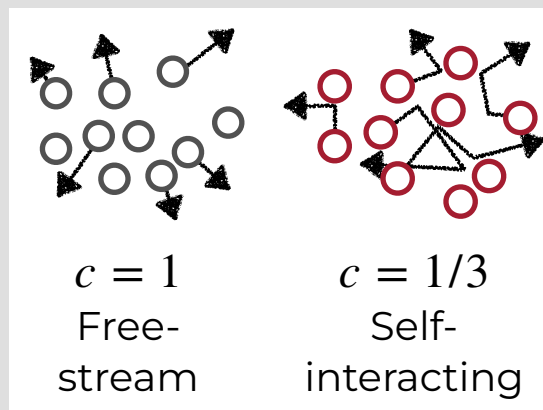
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© [M. Joseph, University of Utah]

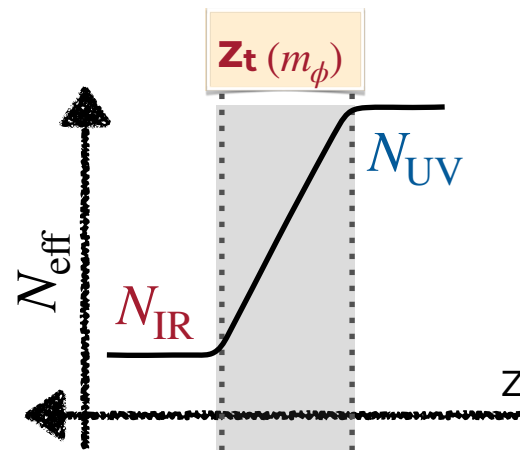
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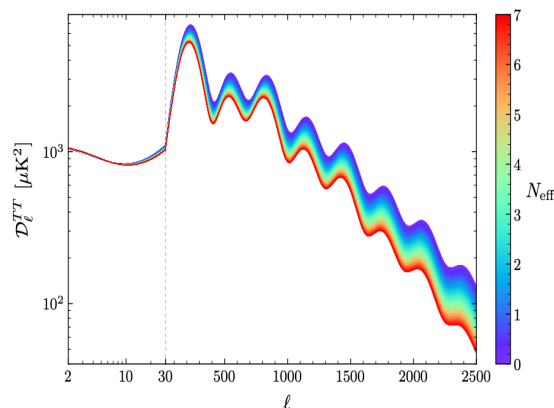
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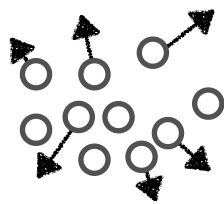
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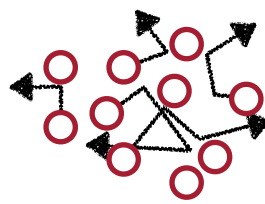
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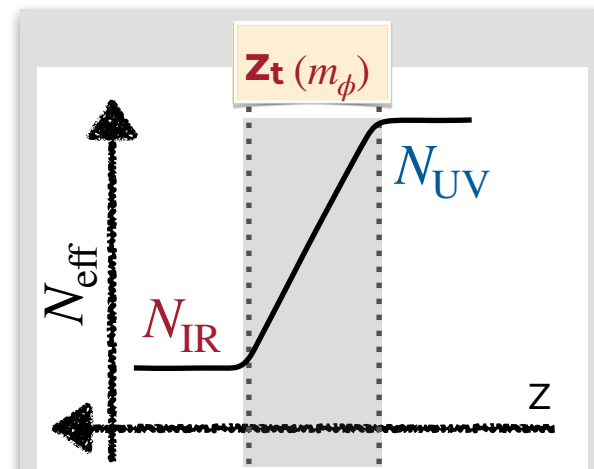


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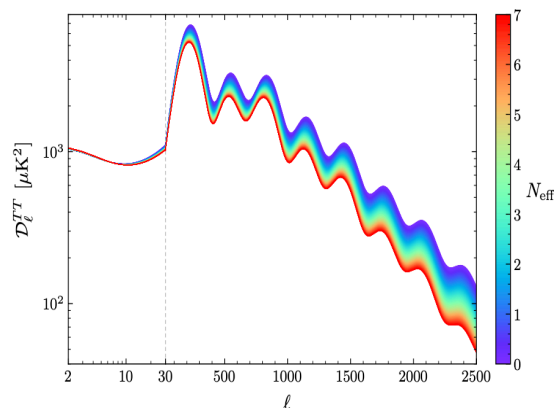
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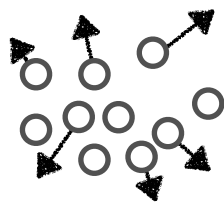
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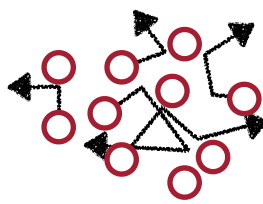
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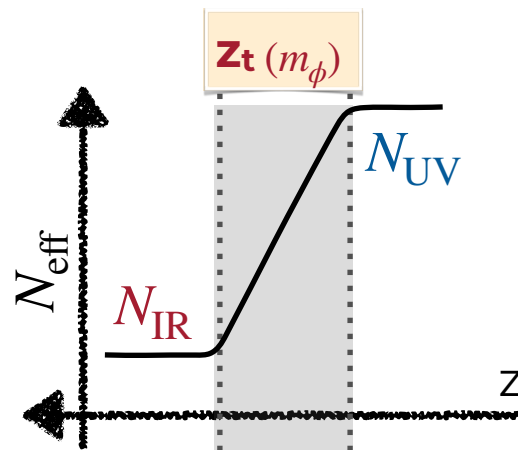


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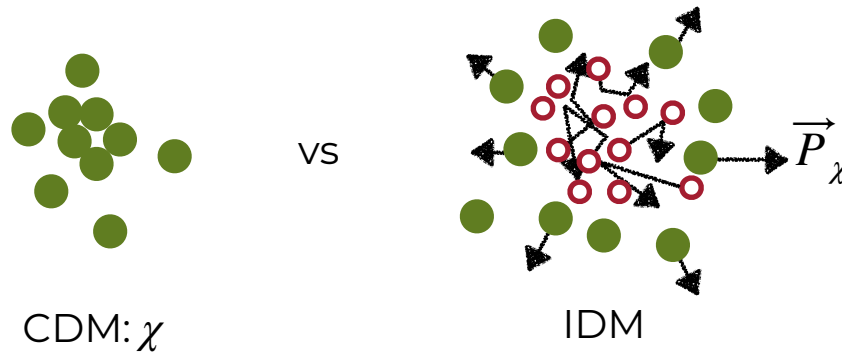
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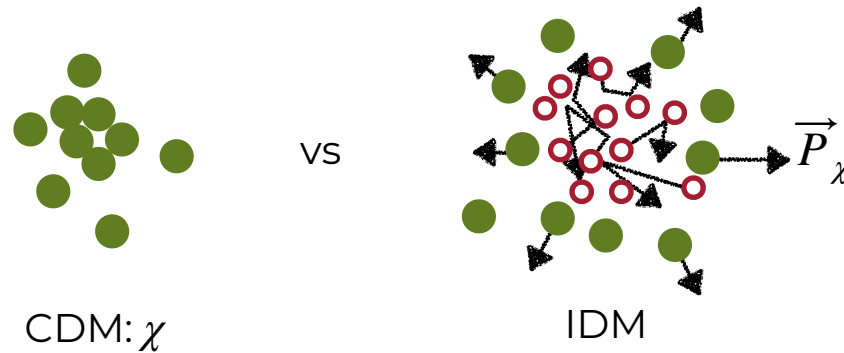
Coupled DR-DM: Fix for LSS tension

- Interaction with **DR** → **Transfers momentum** to **CDM** and gives additional **pressure**: $\dot{\vec{P}}_\chi = -a\Gamma\vec{P}_\chi$
- Additional pressure → **Suppress structure formation**



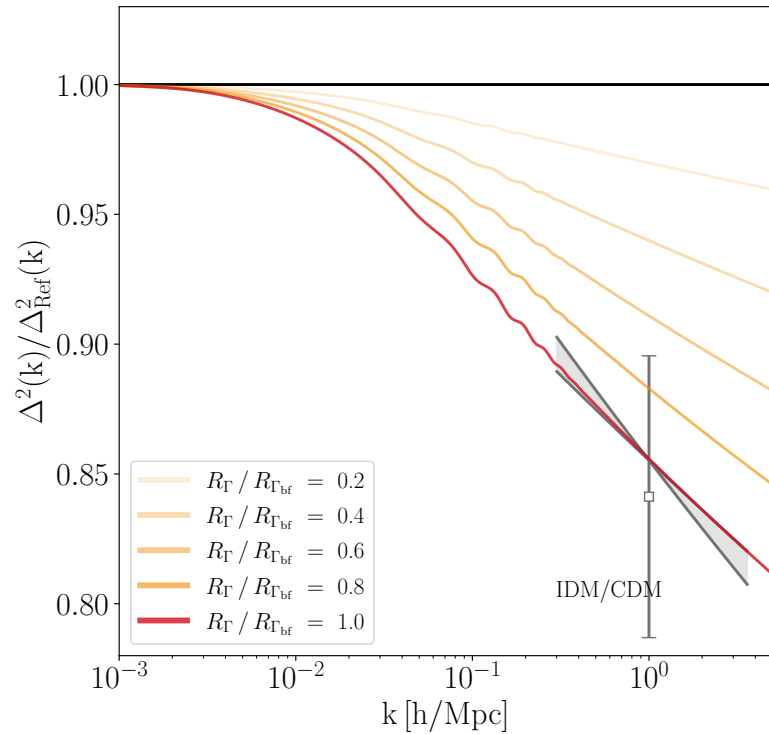
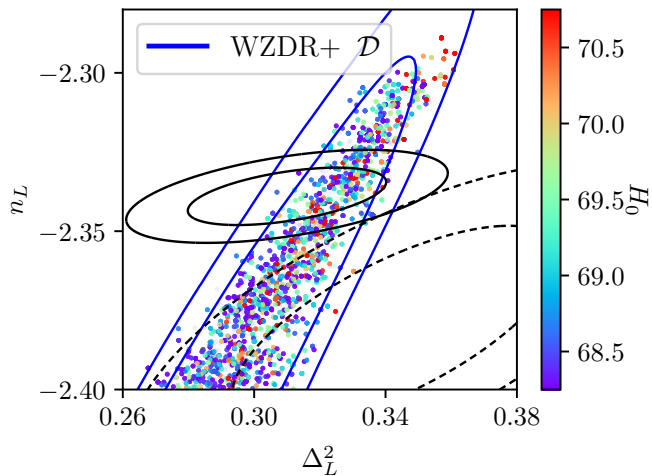
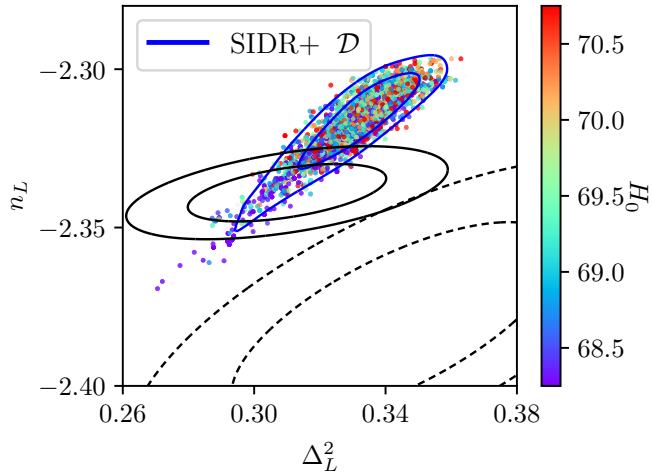
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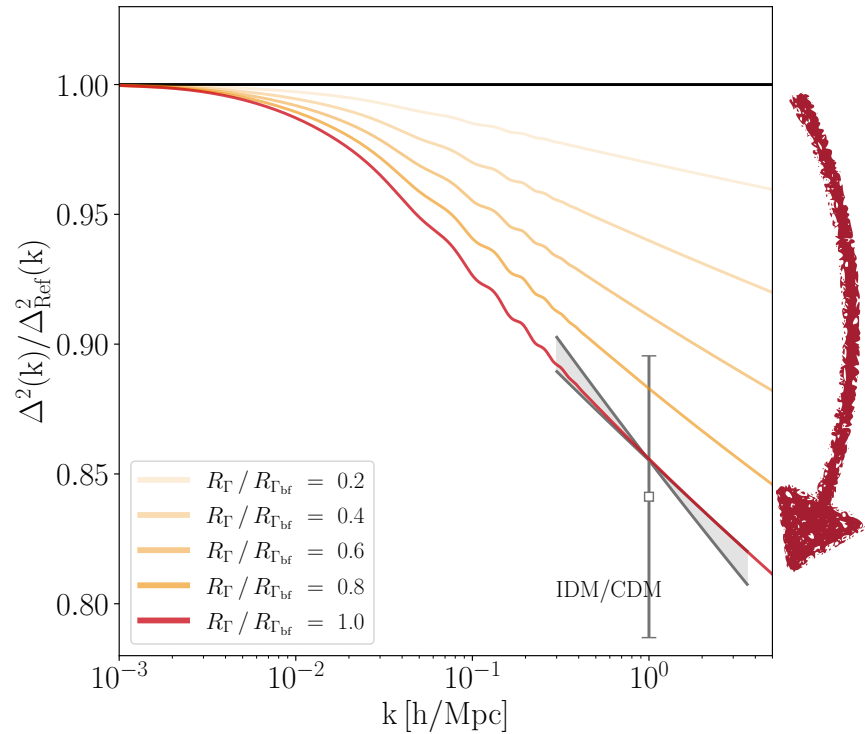
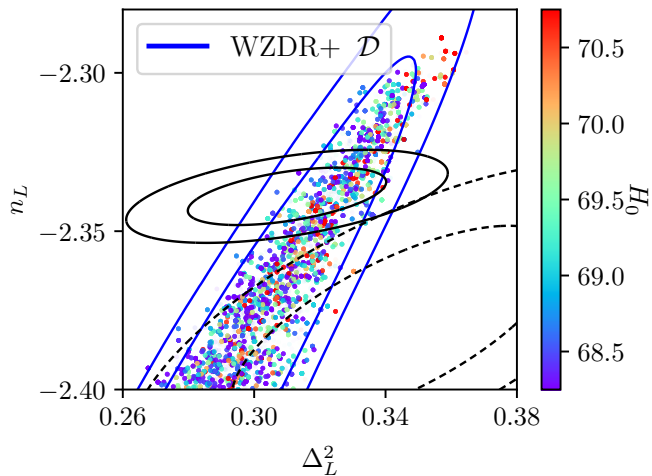
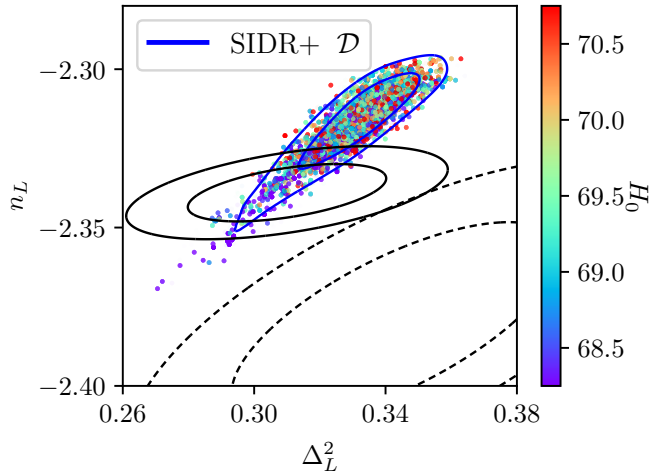
What will the **MPS** look like now?

DR interacting w DM: A drop in MPS



$$\frac{P_{\Gamma \neq 0}}{P_{\Gamma = 0}} \simeq \begin{cases} 1 & k \ll k_{\text{eq.}} \\ 1 - \frac{\Gamma}{H} \log\left(\frac{k}{k_{\text{eq.}}}\right) & k \gg k_{\text{eq.}} \end{cases}$$

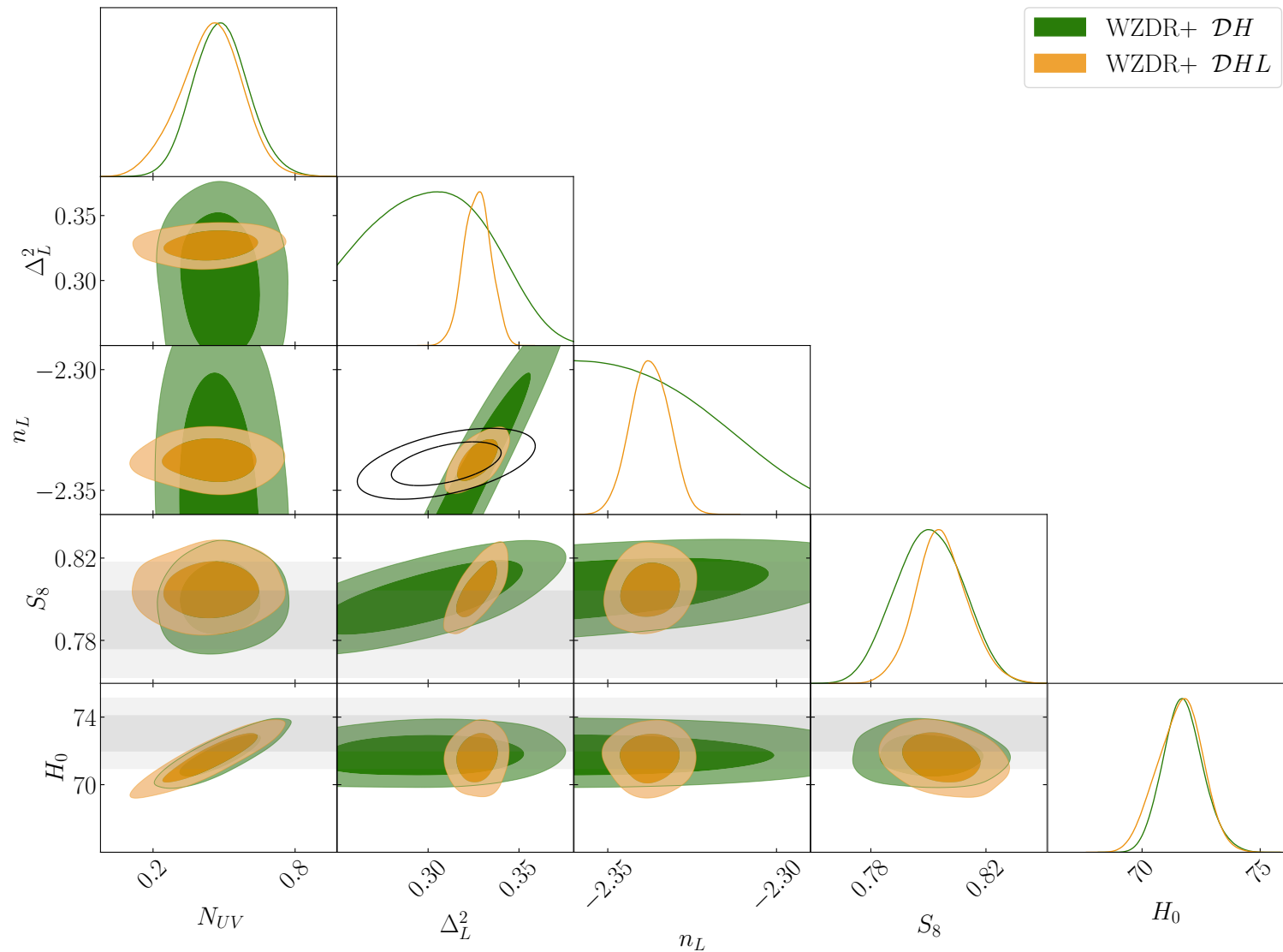
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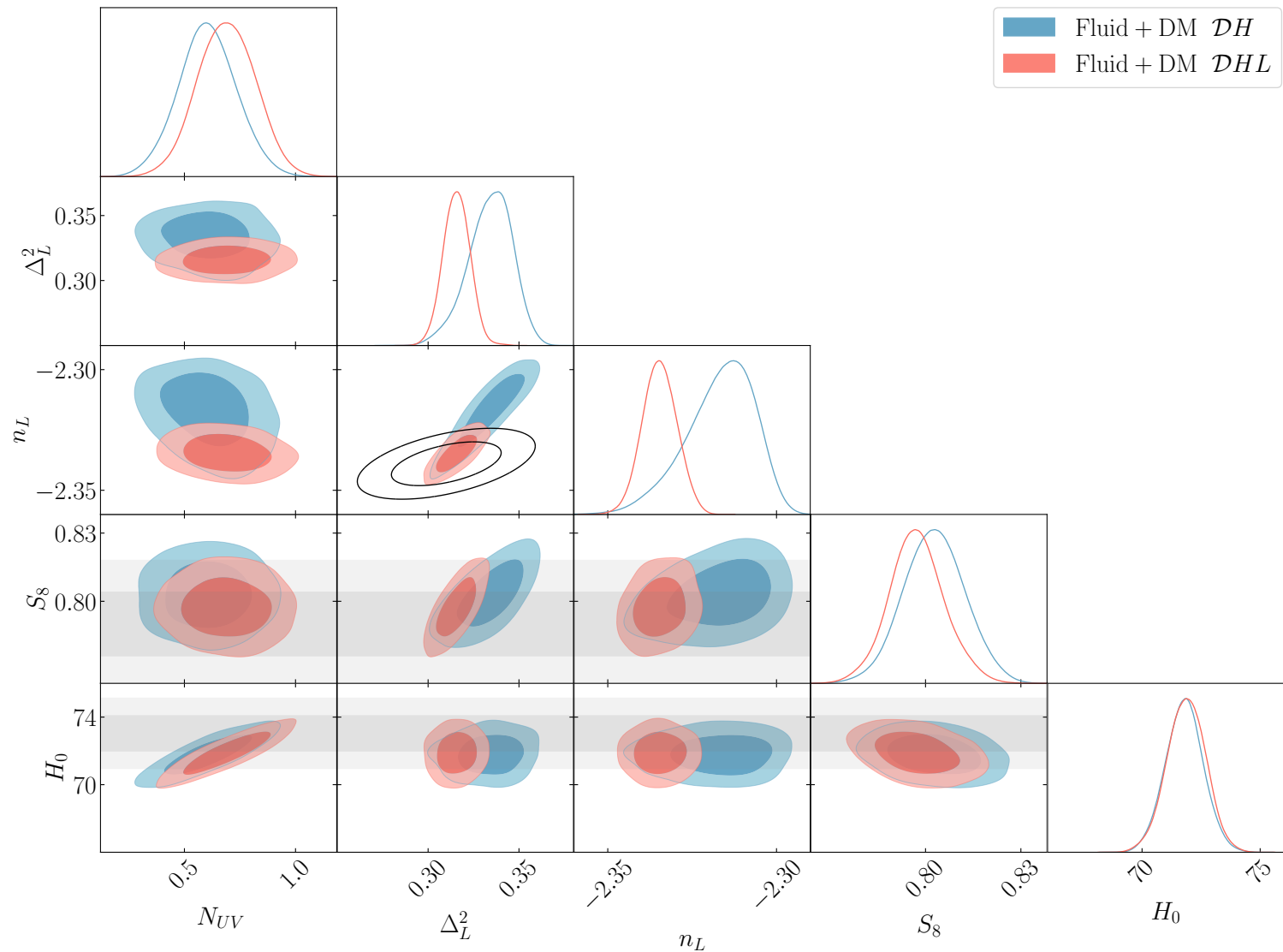
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Interaction controls the slope

WZDR + DM interactions: Full runs



SIDR + DM interactions: Full runs



DR fluid + DM interactions: Tensions

Model	H_0 Gaussian Tension	Ly- α Gaussian Tension
Λ CDM	$\sim 5.5 \sigma$	$\sim 4.9 \sigma$
SIDR + DM	$\sim 2.7 \sigma$	$\sim 1.3 \sigma$
Stepped Fluid + DM (WZDR+)	$\sim 2.6 \sigma$	0.6σ

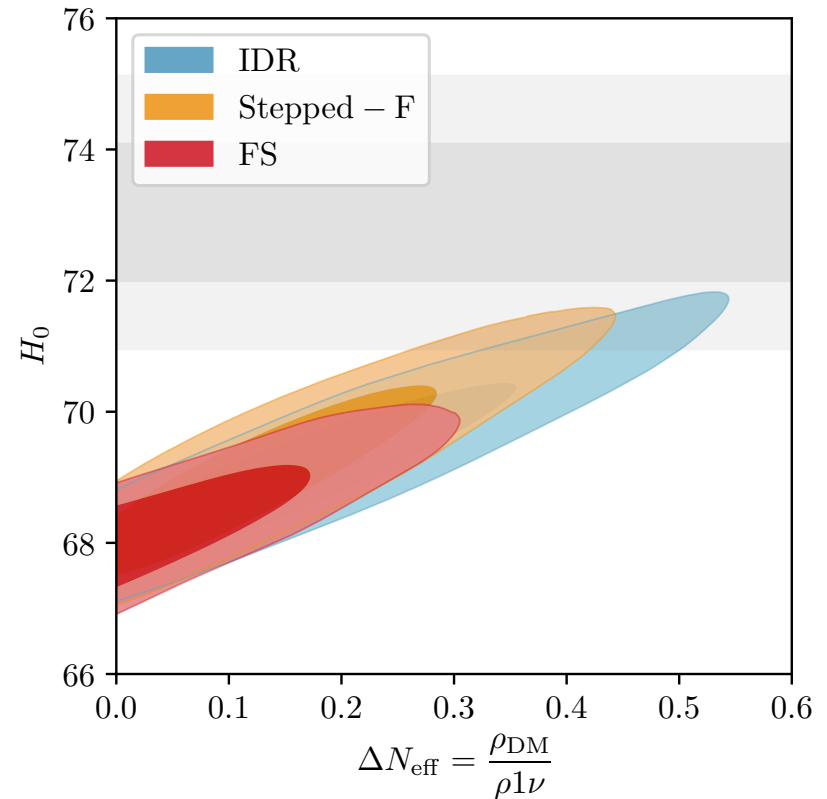
Summary

- Λ CDM is a **good model** of cosmology, but it **faces tensions** that might be pointing to **new physics**:
 - H_0 tension
 - LSS tensions (S_8 , $\text{Ly}\alpha$, etc.)
- **Interacting DR** with **massive** components provide a natural solution to both tensions.
- **Future data** will be able to **further constrain** these models.

Thank you!

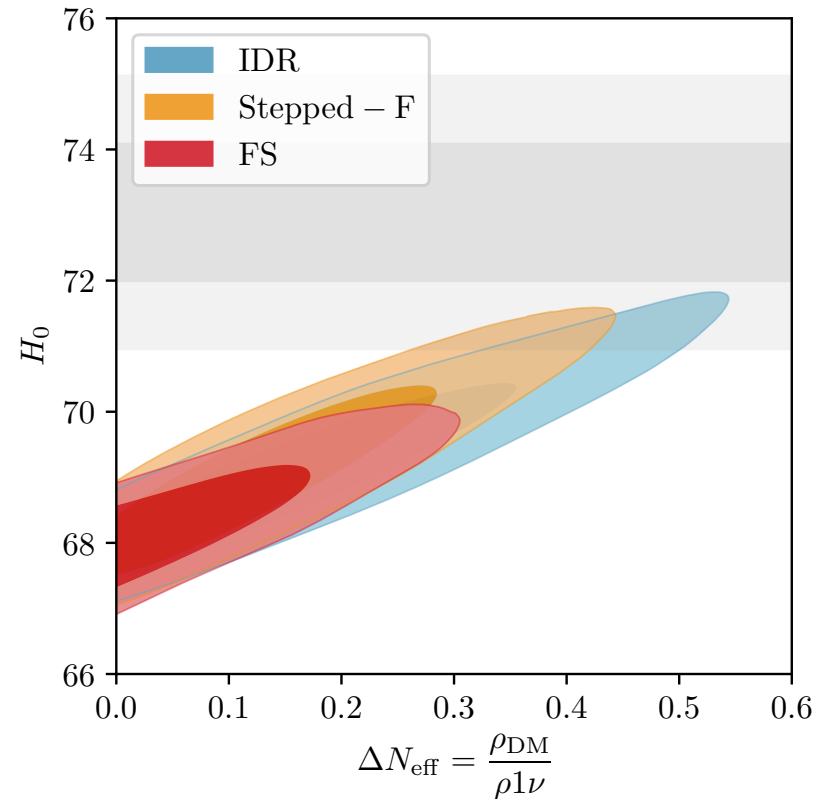
DR models: CMB/ SH0ES results

Model	Gaussian Tension (H_0)
Λ CDM	$\sim 5.0 \sigma$
N_{eff}	$\sim 3.7 \sigma$
SIDR	$\sim 3.1 \sigma$
WZDR	$\sim 2.7 \sigma$



DR models: CMB/ SH0ES results

Model	Gaussian Tension (H_0)
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WZDR	$\sim 2.7 \sigma$



H_0 Olympics **gold medal** winner! [N. Schöneberg, et al., [arXiv: 2107.10291](https://arxiv.org/abs/2107.10291)]

Free-streaming DR fails to fix H_0

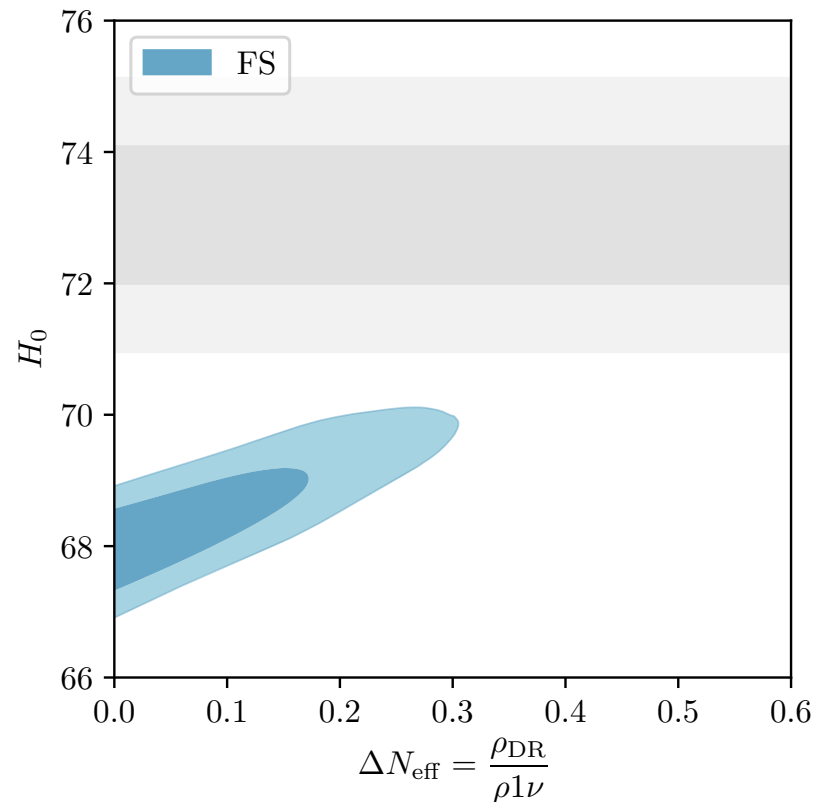
- **Simplest** implementation:

Λ CDM + ΔN_{eff} (free streaming)

- Free streaming (FS) **doesn't make it:**

- Drop in CMB tail (silk damping)
- Phase shift in CMB high ℓ (neutrino drag)

- **CMB is unhappy** →
FS too constrained



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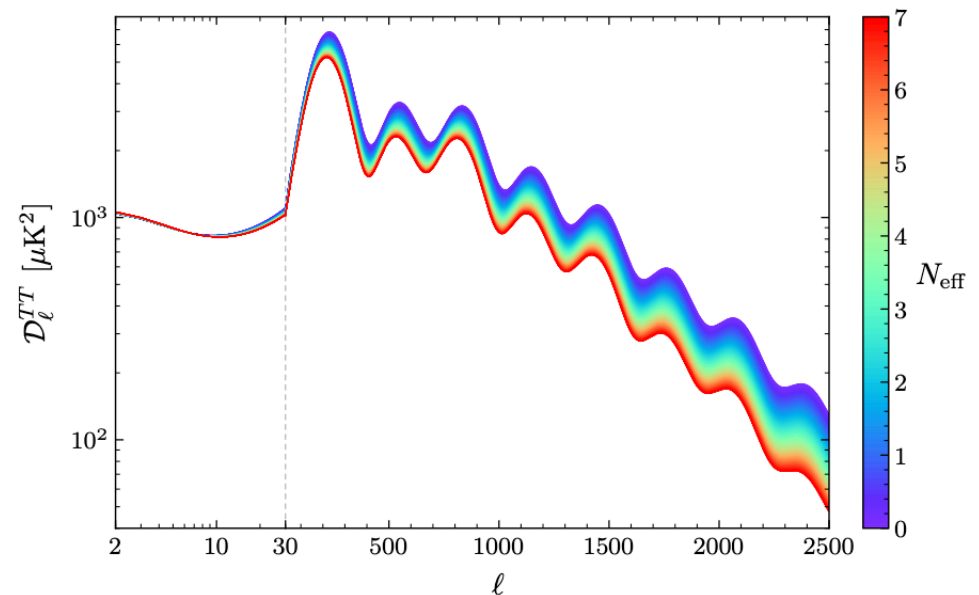
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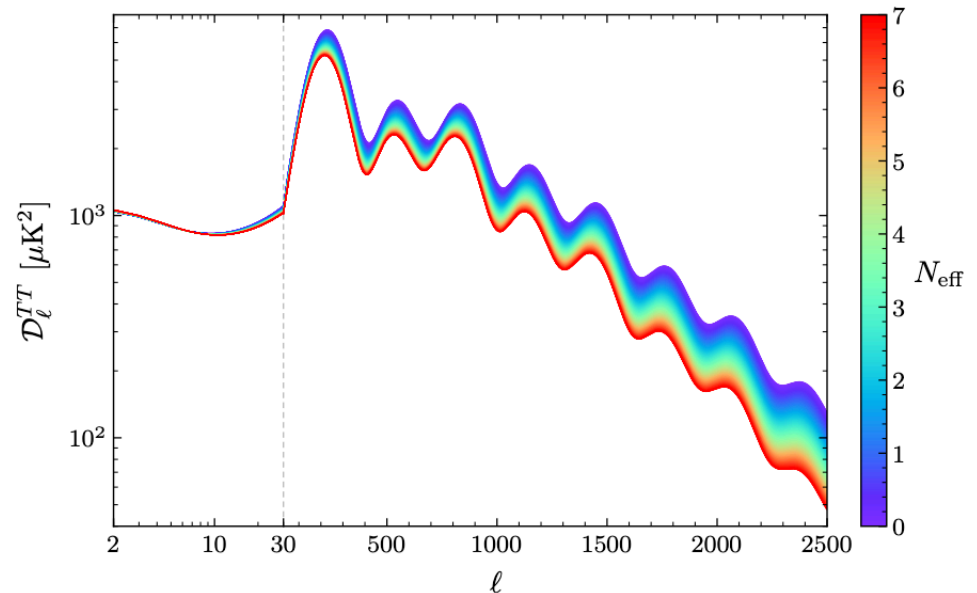
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- **CMB is unhappy** →
FS too constrained



© [B. Wallisch, [arXiv: 1810.02800](https://arxiv.org/abs/1810.02800)]

It's the **right direction**, but how can we **minimize the effect** of **FS** on **CMB**?
Maybe use **interacting DR**!

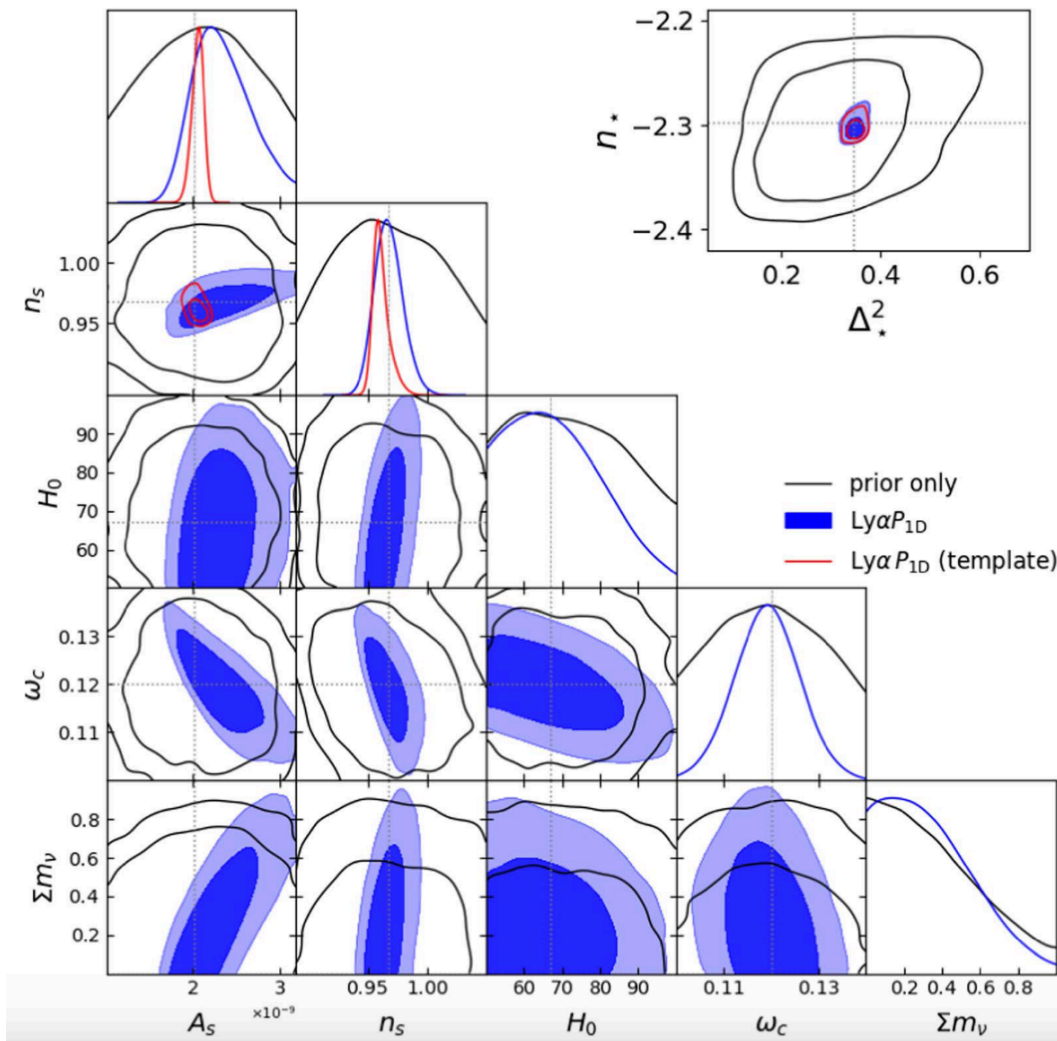
Model Summary

- Summary of model parameters:

SIDR + DM		WZDR + DM		
ΔN_{eff} or N_{UV}	Γ/H	ΔN_{eff} or N_{UV}	Γ/H	$z_t(m_\phi)$

- \mathcal{D} : **CMB** (Planck 2018 TT, EE, TTEE & Lensing),
Pantheon, BAO, Full-shape data from BOSS DR12,
 S_8 (combined DES-Y3 & KiDS-1000)
- H : **SHOES** measurement of H_0
- L : compressed likelihood on **slope** and **amplitude**
of MPS at $z = 3$ and $k = 0.009$ s/km

Ly- α likelihood: Model dep. I

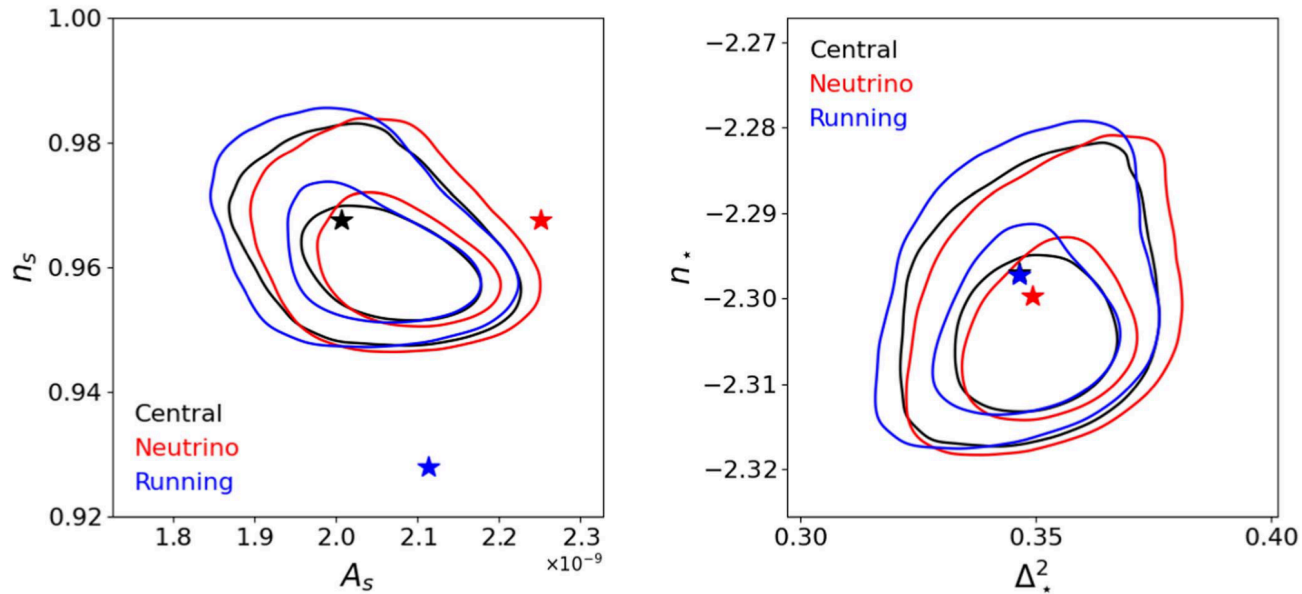


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Ly- α likelihood: Model dep. II

	Training Set	Central (Λ CDM)	Neutrino	Running
$A_s(\times 10^{-9})$	[1.35 - 2.71]	2.006	2.251	2.114
n_s	[0.92 - 1.02]	0.9676	0.9676	0.9280
α_s	0.0	0.0	0.0	0.015
Σm_ν	0.0	0.0	0.3	0.0

Template fits for different simulations (default fiducial cosmology)

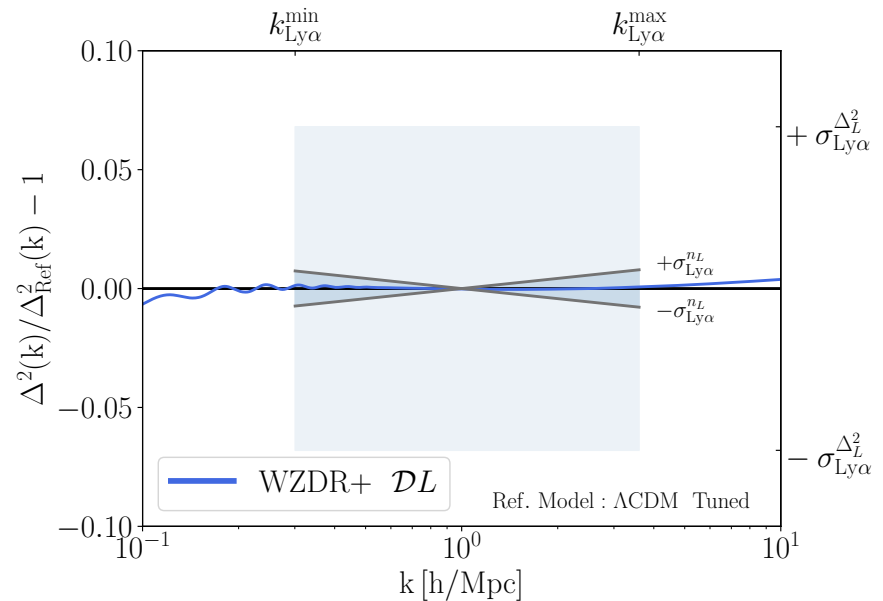
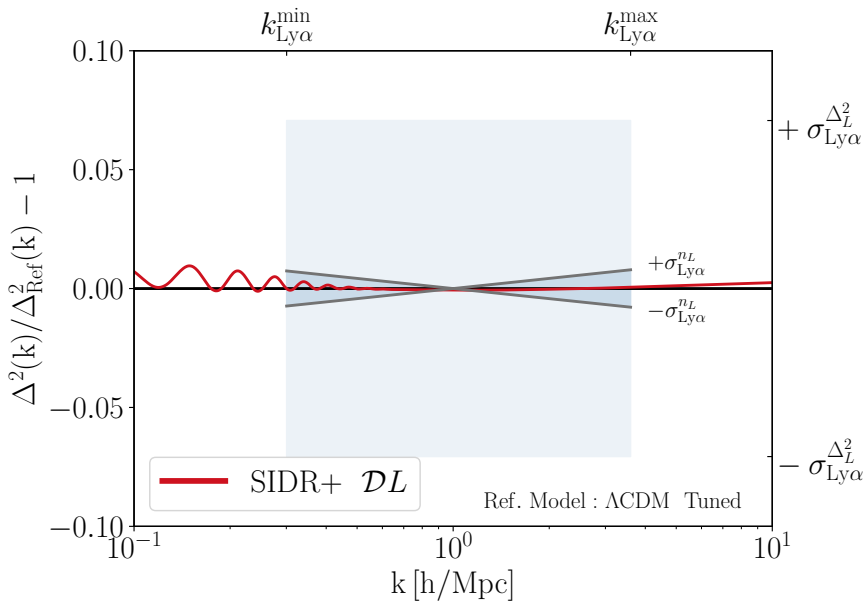


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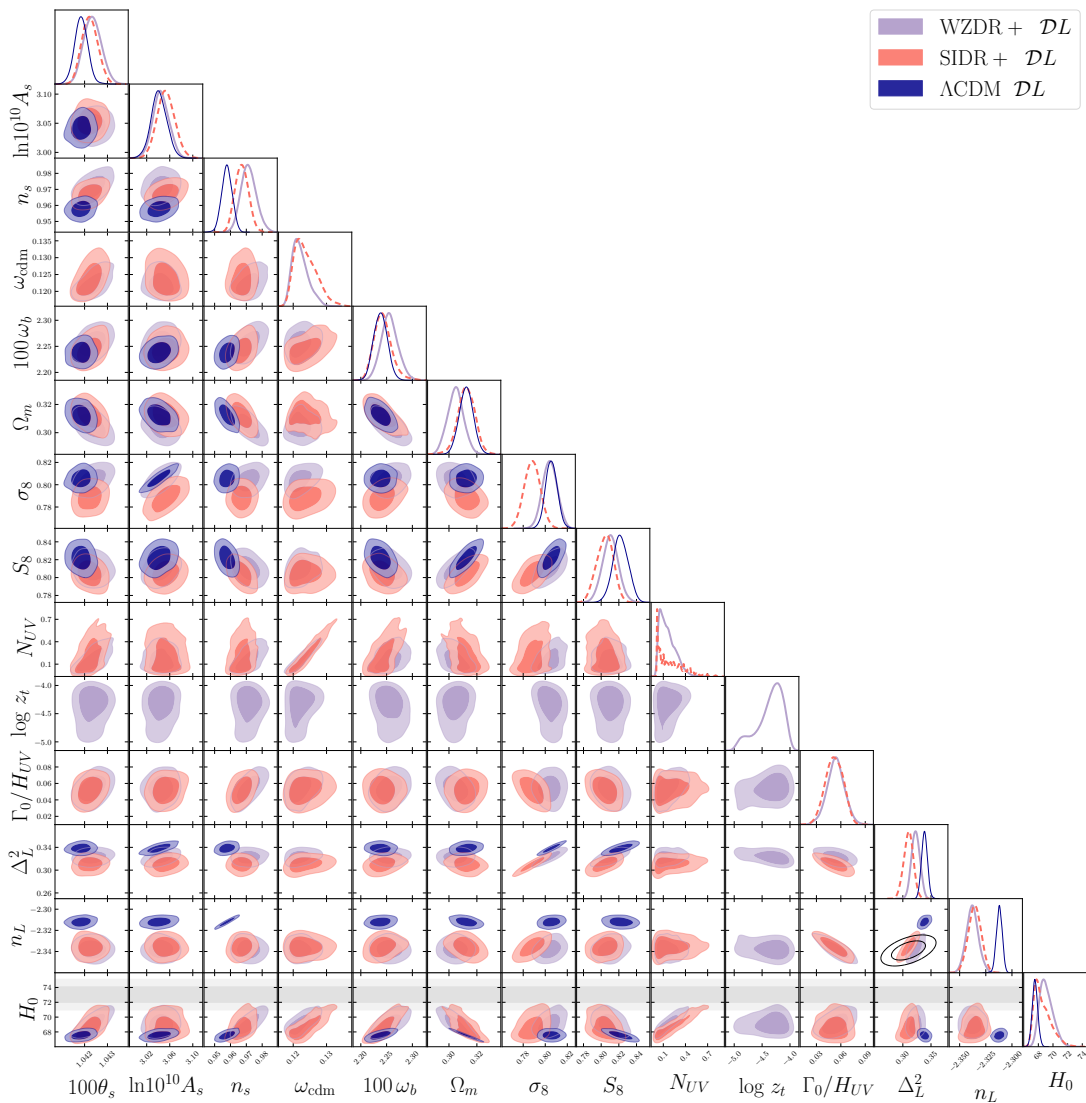
DR \Rightarrow DM: Linear variations of Λ CDM

Within the error bars of Ly- α , WZDR+/Fluid+ is degenerate with Λ CDM

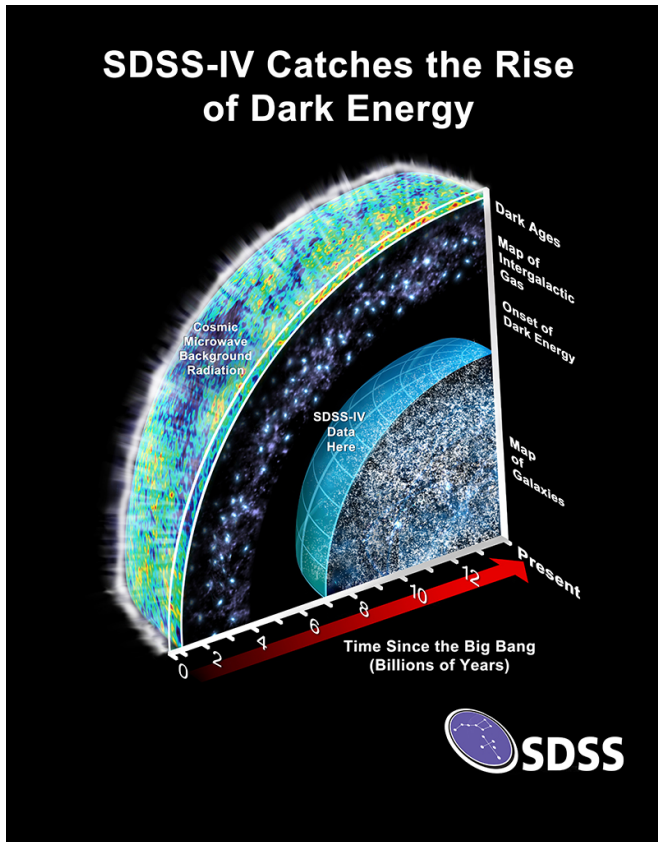
	$A_s (\times 10^{-9})$	n_s
Λ CDM start	2.103	0.968
Adjust to Fluid+ (SDR+)	2.041	0.935
Adjust to WZDR+	2.131	0.933



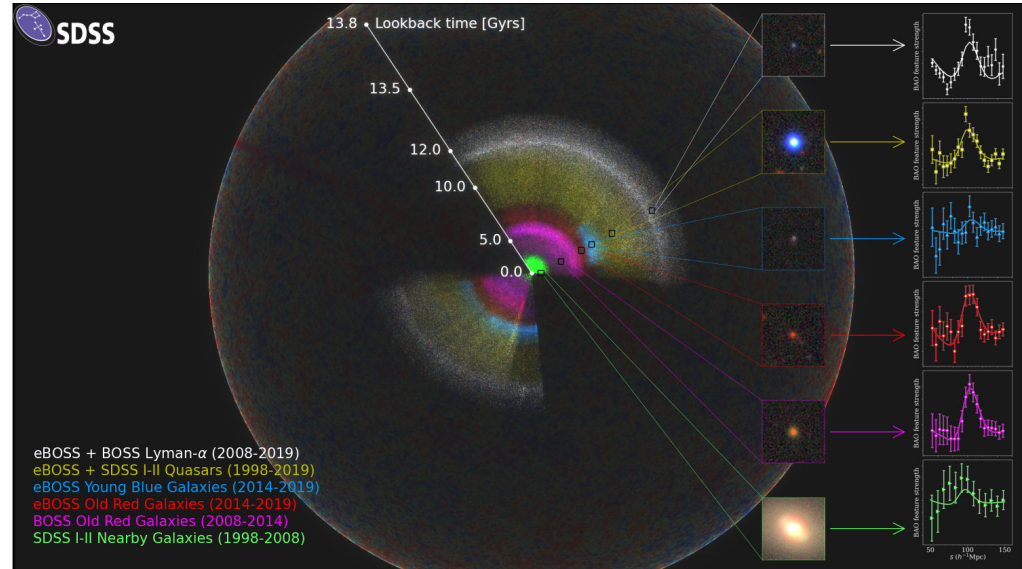
Stepped fluid \rightleftharpoons DM: Full runs



LSS data III: BOSS/ eBOSS

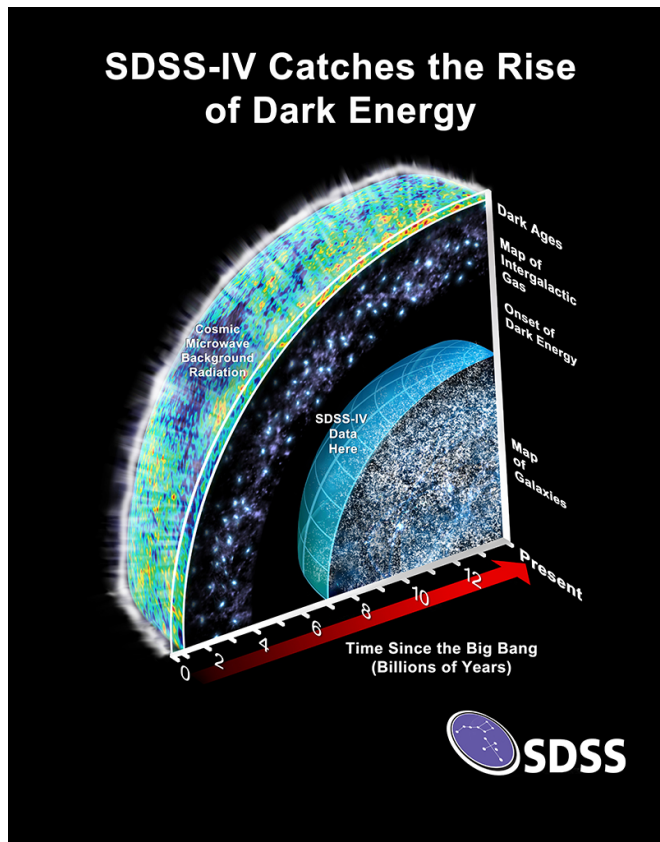


[Dana Berry, and the SDSS collaboration]

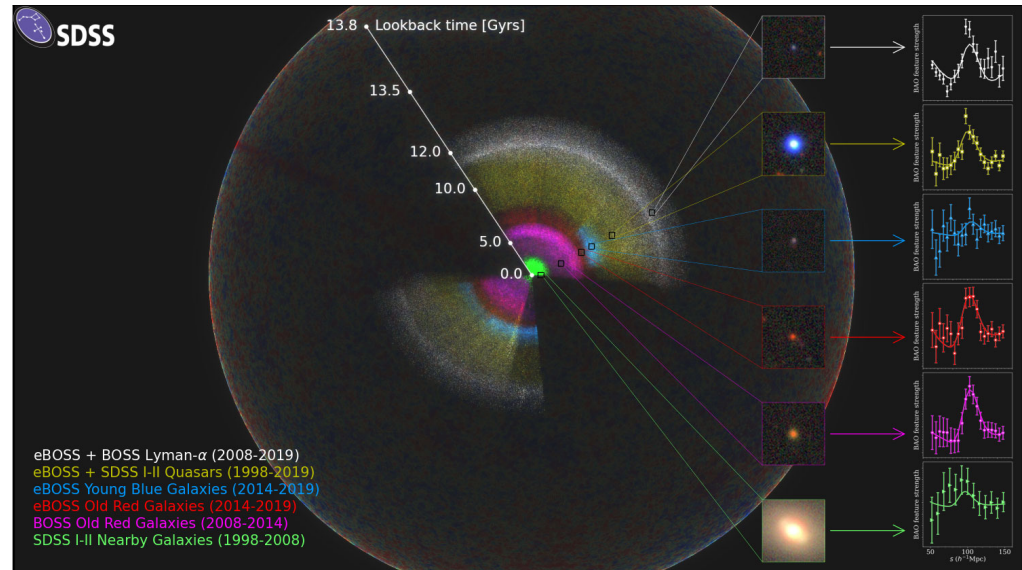


[Anand Raichoor, Ashley Ross, and the SDSS Collaboration]

LSS data III: BOSS/ eBOSS



[Dana Berry, and the SDSS collaboration]



[Anand Raichoor, Ashley Ross, and the SDSS Collaboration]

Caveat: At small scales, non-linear corrections need to be made.

Res 1: Use simulations, **Res2:** EFT of LSS