

Title: Cosmological Signatures of Interacting Dark Sectors

Speakers: Melissa Joseph

Series: Particle Physics

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Abstract: Models of dark sectors with a mass threshold can have important cosmological signatures. If, in the era prior to recombination, a relativistic species becomes non-relativistic and is then depopulated in equilibrium, there can be measurable impacts on the CMB as the entropy is transferred to lighter relativistic particles. In particular, if this "step" occurs near  $z = 20,000$ , the model can naturally accommodate larger values of  $H_0$ . If this stepped radiation is additionally coupled to dark matter, there can be a meaningful impact on the matter power spectrum as dark matter can be coupled via a species that becomes non-relativistic and depleted. This can naturally lead to suppressed power at scales inside the sound horizon before the step, while leaving conventional CDM signatures for power outside the sound horizon. We study these effects and show such models can naturally provide lower values of  $S_8$  than scenarios without a step. This suggests these models may provide an interesting framework to address the  $S_8$  tension, both in concert with the  $H_0$  tension and without.

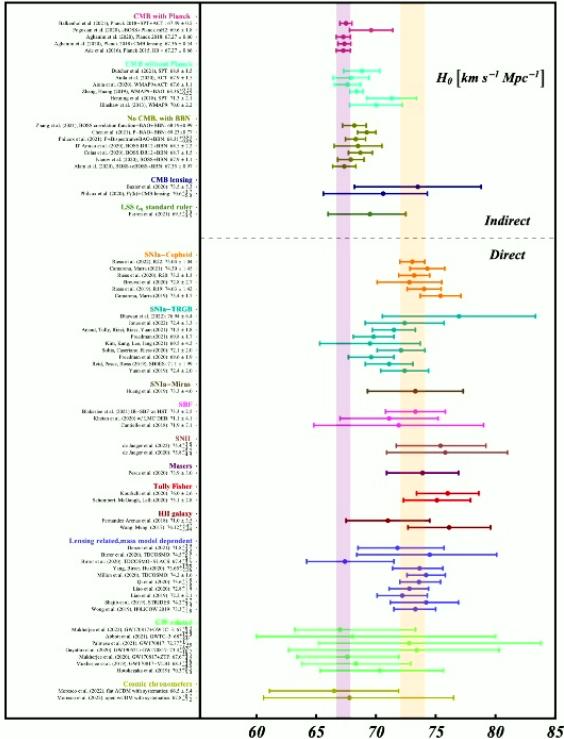
Zoom Link: <https://pitp.zoom.us/j/96399847158?pwd=RkNHMkJHeEo5Q1Q2MkhHSHZ6c1BoQT09>

# **Cosmological Signatures of Interacting Dark Sectors**

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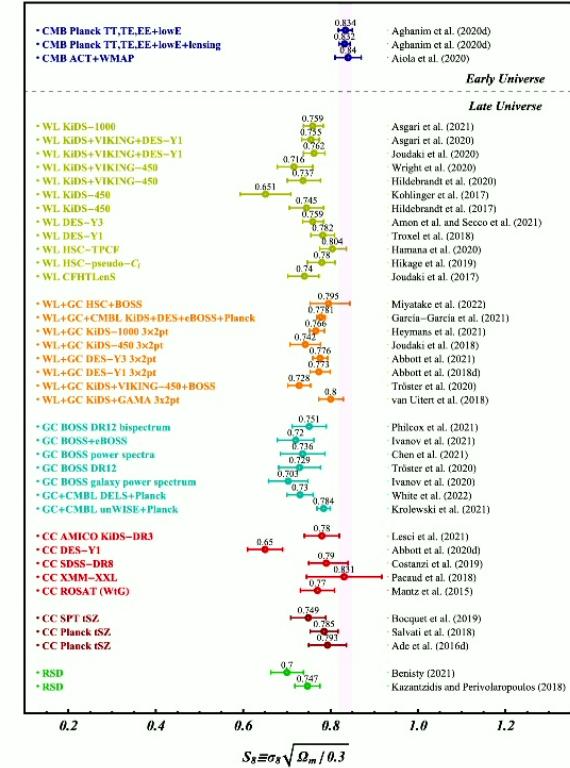
w/ **Daniel Aloni, Asher Berlin, Martin Schmaltz, Eashwar N. Sivarajan,  
Neal Weiner**  
**arXiv: 2111.00014, 2207.03500**

## $H_0$ Tension



# New Physics??

## **S<sub>8</sub> Tension**



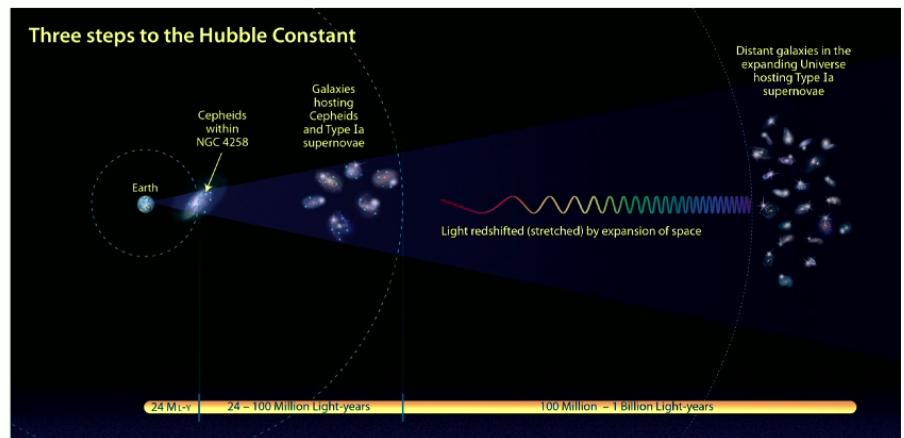
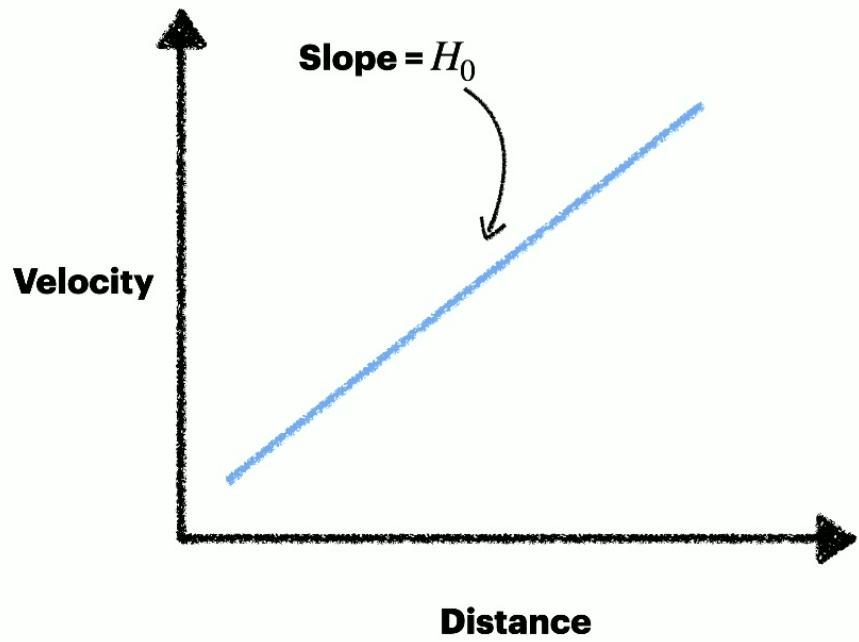
Snowmass 2021, arXiv:  
2203.06142

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# $H_0$ Tension

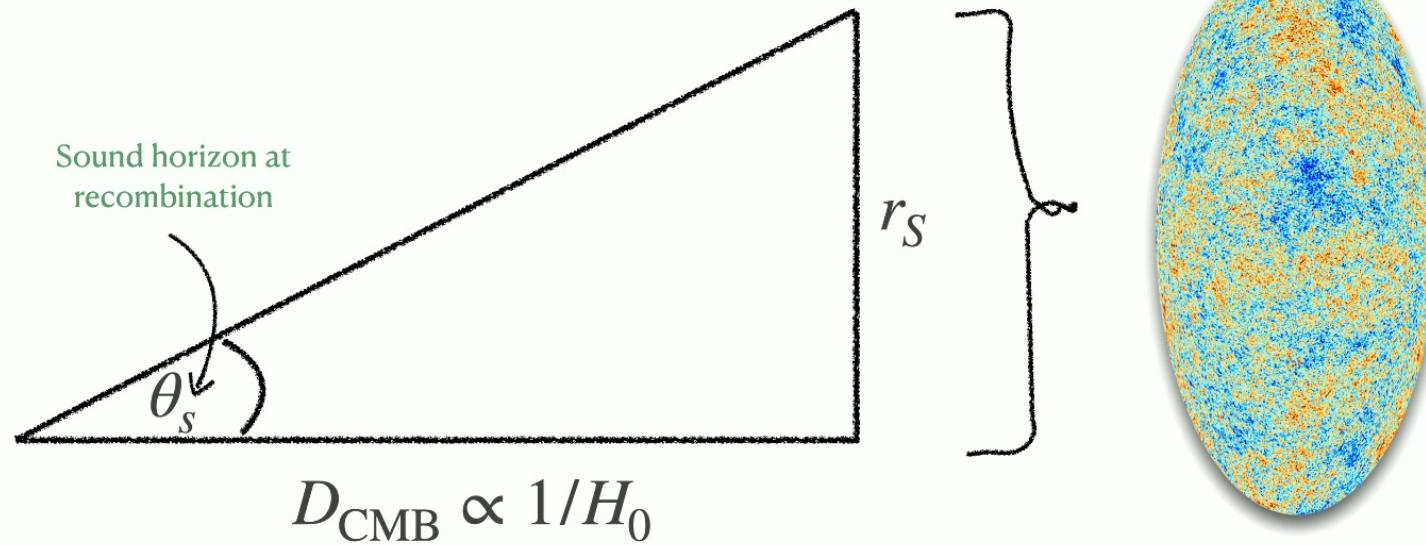
- Direct measurement:  $73.04 \pm 1.04$  km/s/Mpc (Riess et al 2022)
  - Distance ladder w/ Type 1a SN & Cepheids
- Value from  $\Lambda$ CDM (fit to CMB):  $67.4 \pm 0.5$  km/s/Mpc (Planck 2018)
  - $\sim 5\sigma$  tension

# Direct Measurement



NASA/ESA

# CMB Measurement



$$r_s = \int_{z_{rec}}^{\infty} dz \frac{c_s^2}{H(z)}$$

$$H(z) \propto \sqrt{\rho}$$

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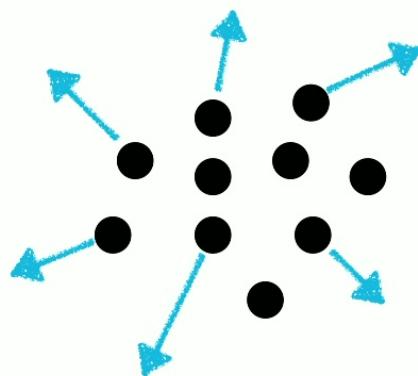
Simplest extension of  $\Lambda$ CDM - add extra radiation

$$\Delta N_{\text{eff}} = \frac{\rho_{DR}}{\rho_{1\nu}}$$

$\Lambda$ CDM :  $N_{\text{eff}} = 3.044$

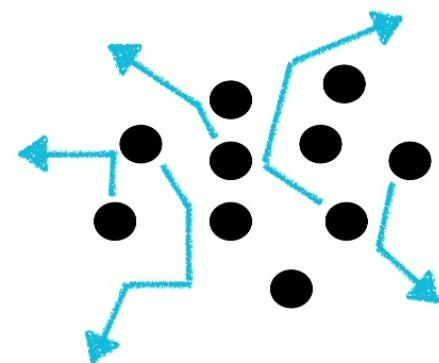
Radiation is **dark**

Free-streaming (no interactions)  
radiation

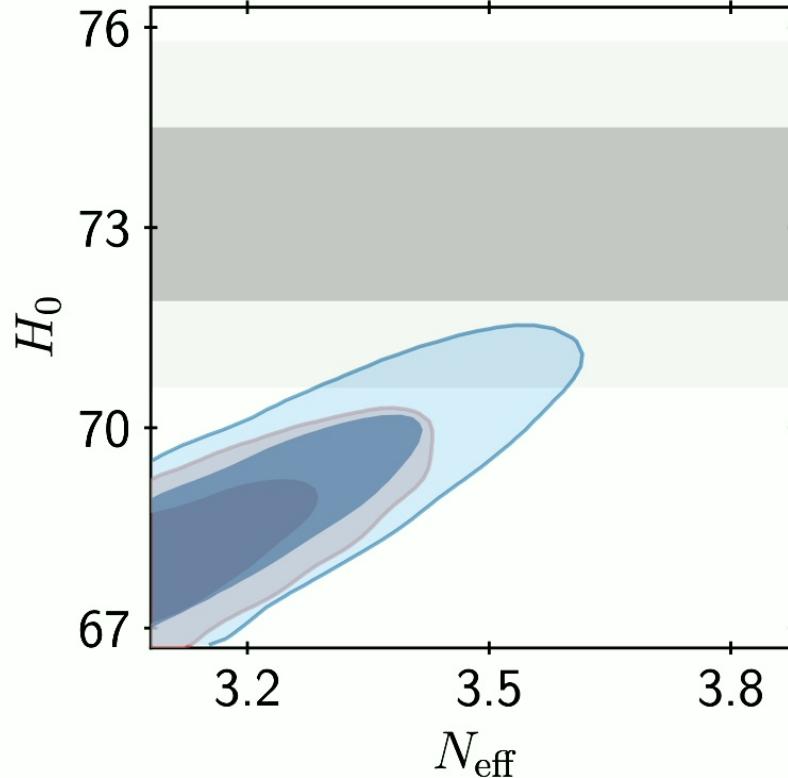


$$'c_s^2 = 1'$$

Strongly interacting radiation

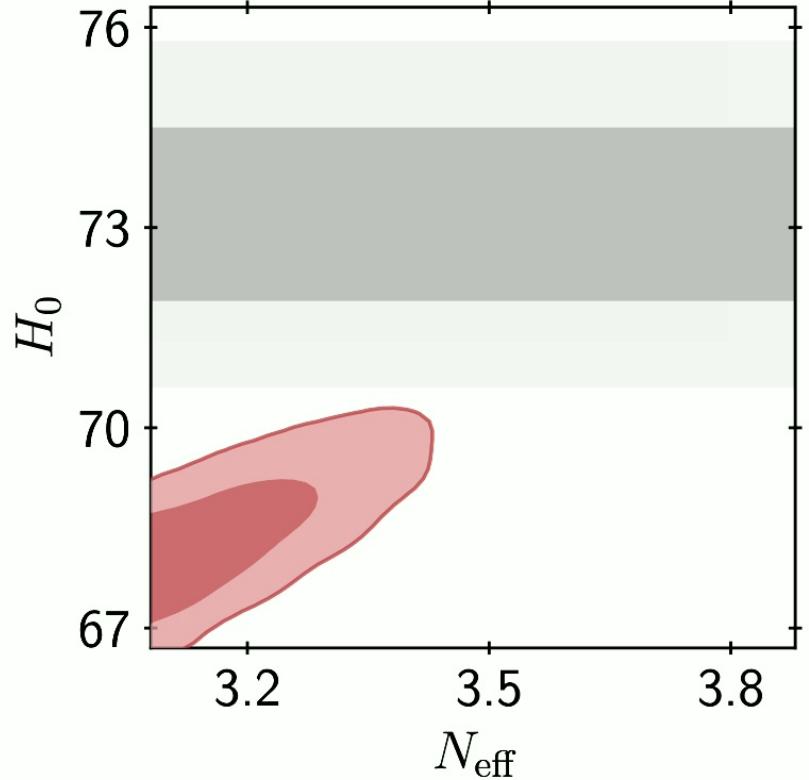


$$c_s^2 = 1/3$$



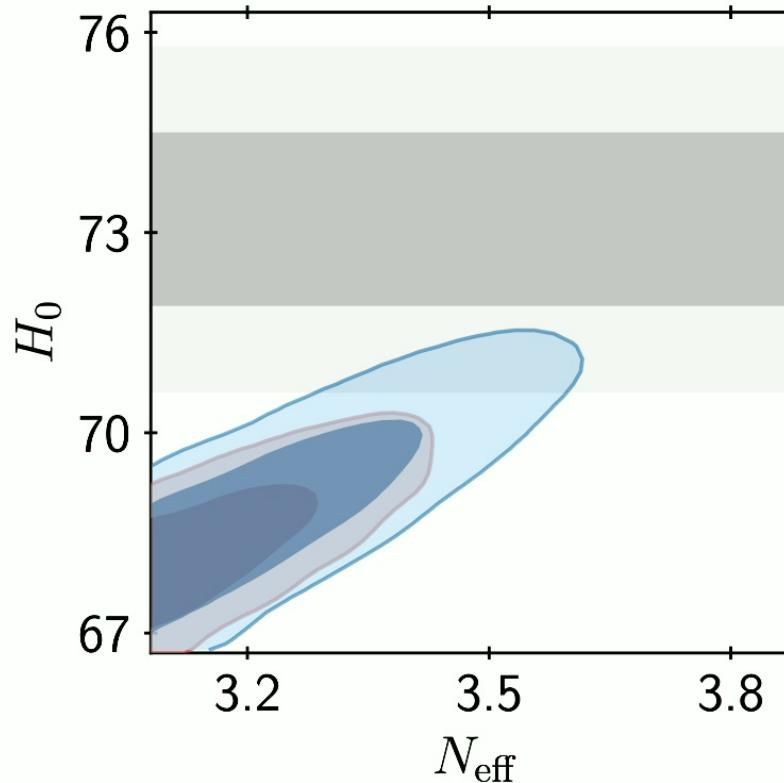
Interacting radiation (SIDR) is better  
but still  $> 3\sigma$

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Free-streaming radiation model is too constrained

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Interacting radiation (SIDR) is better  
but still  $> 3\sigma$

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If we want dark radiation as a solution we need  
to look at **interacting** radiation

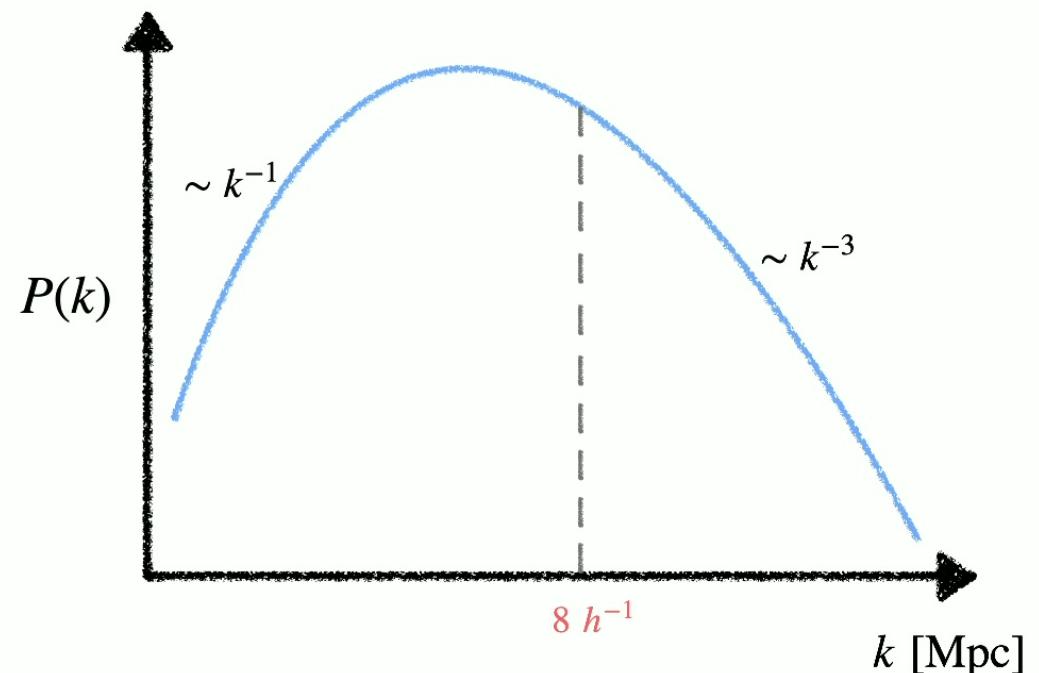
# $S_8$ Tension

- Direct measurement:  $0.769 \pm 0.016$  (KiDS-1000, DES-Y3)
- Value from  $\Lambda$ CDM (fit to CMB):  $0.834 \pm 0.016$  (Planck TT & Pol 2018)  
 $\sim 3\sigma$  tension

# Matter Power Spectrum

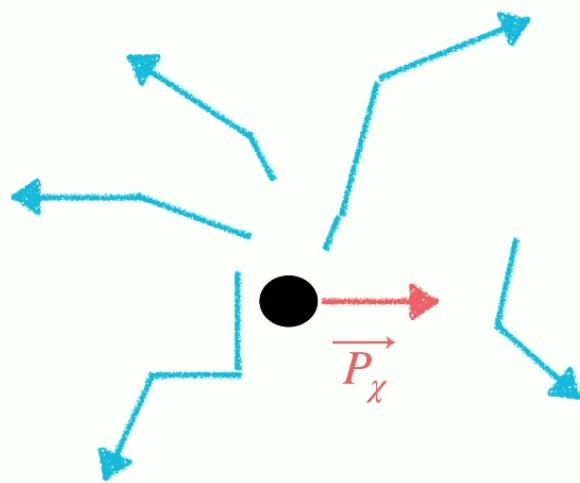
$$\delta = \frac{\delta\rho_{dm}}{\rho_{dm}}$$

$$P(k) = \langle \delta_{dm} \rangle$$



$$S_8 = \sqrt{\Omega_m/0.3}$$

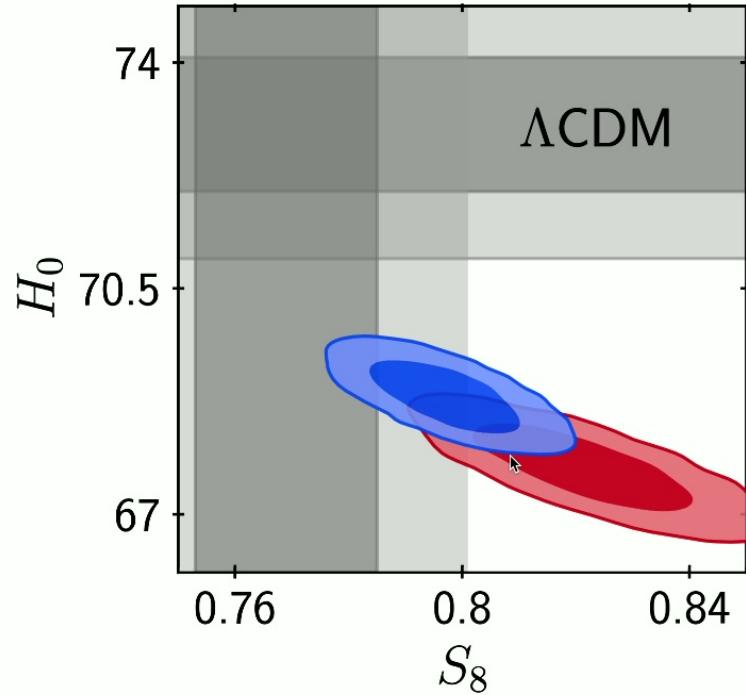
12



DM interactions with radiation gives the DM additional pressure

This can suppress the growth of perturbations at scales relevant for

$$S_8$$



### Direct Measurements

$H_0 : 73.04 \pm 1.04$  km/s/Mpc (SHOES)

$S_8 : 0.769 \pm 0.016$  (KiDS-1000, DES-Y3)

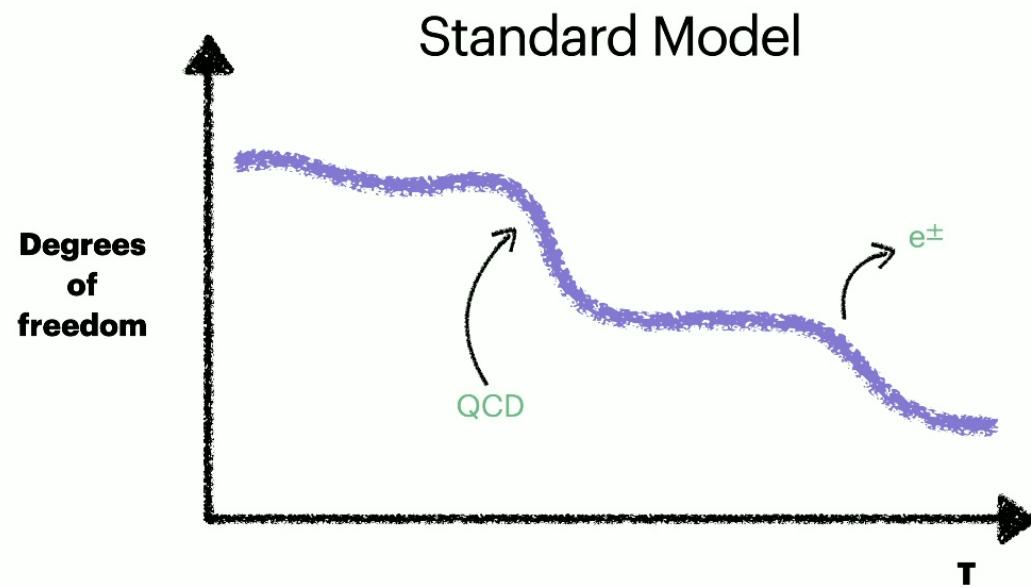
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## Anomalies suggest existence of interacting dark sector

Hubble Tension  $\rightarrow$  Interacting radiation

$S_8 \rightarrow$  Interacting dark matter and radiation

# Mass Thresholds



11 mass thresholds  
between TeV and MEV

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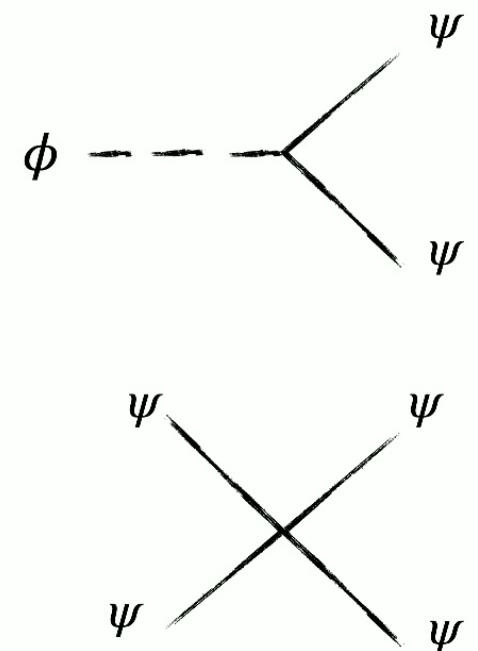
16

An interacting dark sector with two particle species

Wess-Zumino Dark Radiation (WZDR)

$$\mathcal{L}_{WZDR} \propto m_\phi^2 \phi^* \phi + \lambda \phi \psi^2 + \lambda^2 (\phi^* \phi)^2 + h.c.$$

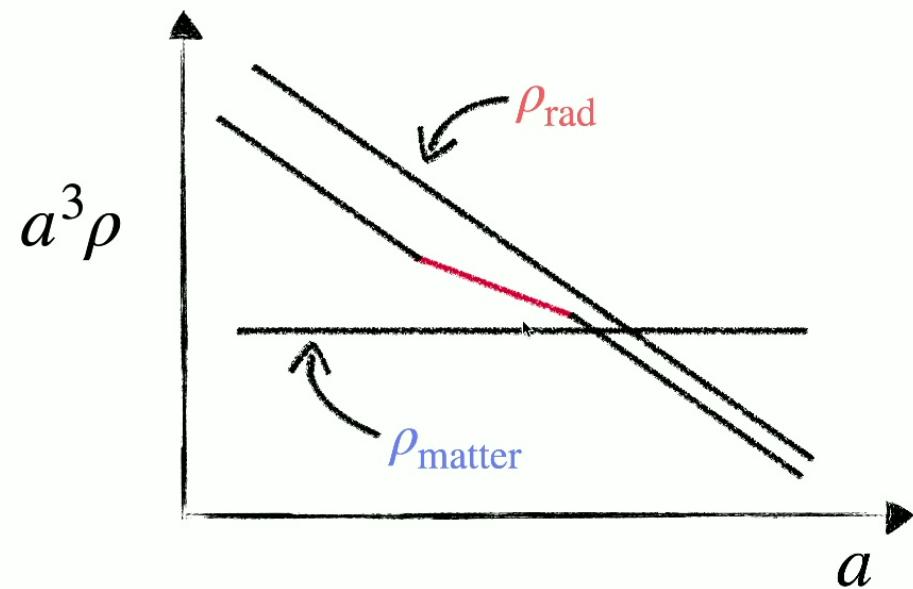
$$m_\phi \sim \text{eV}$$



What happens at the **mass** threshold?

Massive particles  
become **non-**  
**relativistic** and decay

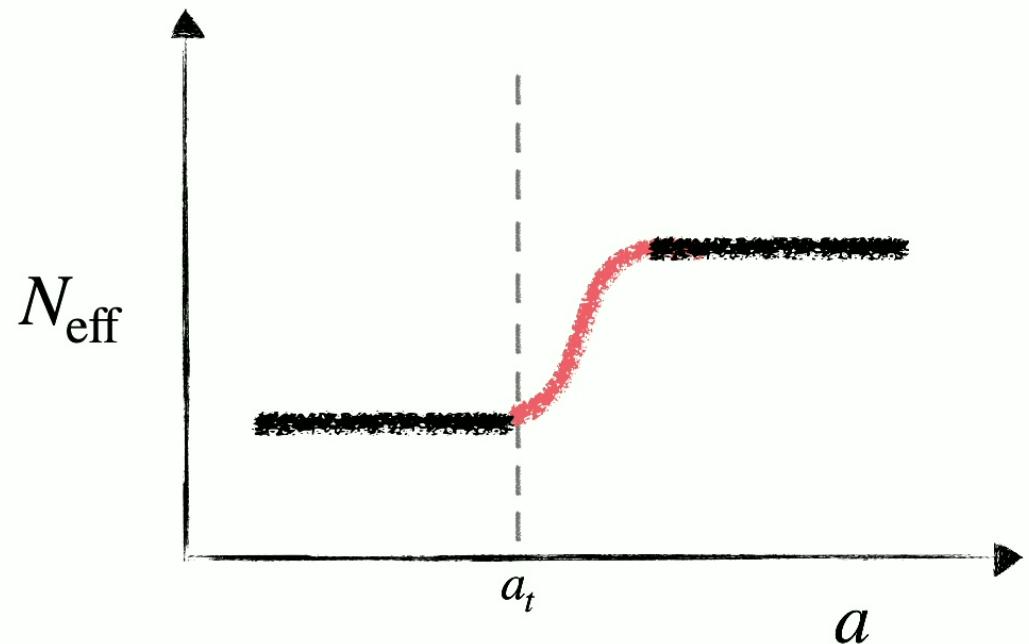
A mix of **relativistic**  $\sim a^{-4}$   
and **non-relativistic**  $\sim a^{-3}$   
particles



What happens at the **mass** threshold?

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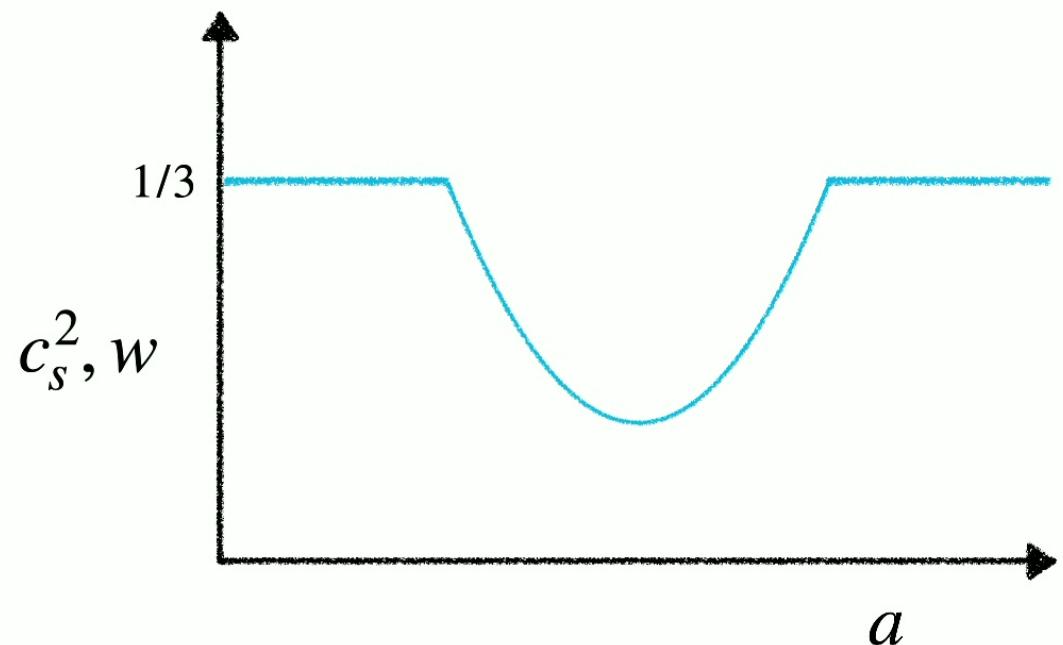
A mix of **relativistic**  $\sim a^{-4}$   
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A mix of **relativistic**  $\sim a^{-4}$   
and **non-relativistic**  $\sim a^{-3}$   
particles



## What about phase shifts?

Compare to a model with no step (SIDR) - same IR cosmology

- Before the step - different universe/cosmology for modes that enter here  $k \gg k_t$
- After the step - same universe/cosmology for modes that enter here  $k \ll k_t$

## Photon perturbation equations

$$\dot{d}_\gamma + k^2 c_s^2 d_\gamma \simeq 0$$

$$d_\gamma \simeq C_1 \cos(kc_s\tau) + C_2 \sin(kc_s\tau)$$

## Superhorizon equations

$$d_\gamma = -3\zeta \quad \dot{d}_\gamma \propto \textcolor{red}{H}^{-1}$$

$$\mathcal{H}^{-1}(z) = \begin{cases} \tau(z) & z \ll z_t \\ \tau(z) + \Delta\tau & z \gg z_t \end{cases}$$


  
 Modes which enter  
 before the step see a shift

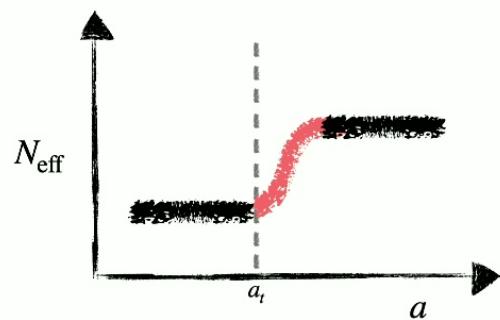
$$\Delta\tau \simeq \int_{z_t}^{\infty} dz \left( \frac{1}{H_{\text{WZDR}}(z)} - \frac{1}{H_{\text{SIDR}}(z)} \right)$$

**High- $k$**  modes have a phase shift at recombination

$$d_\gamma(z) \propto \begin{cases} \cos[c_\gamma k \tau(z)] & (k \ll k_t) \\ \cos[c_\gamma k(\tau(z) + \Delta\tau)] & (k \gg k_t) \end{cases}$$

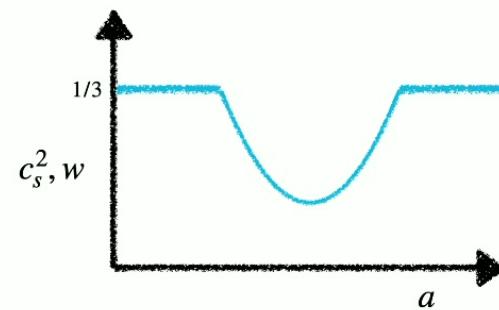
Extra interacting radiation with a “**step**” (WZDR) gives:

A step in  $N_{\text{eff}}$  during CMB



+

Change in  $c_s^2, w$

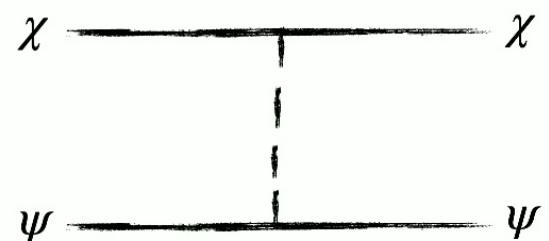


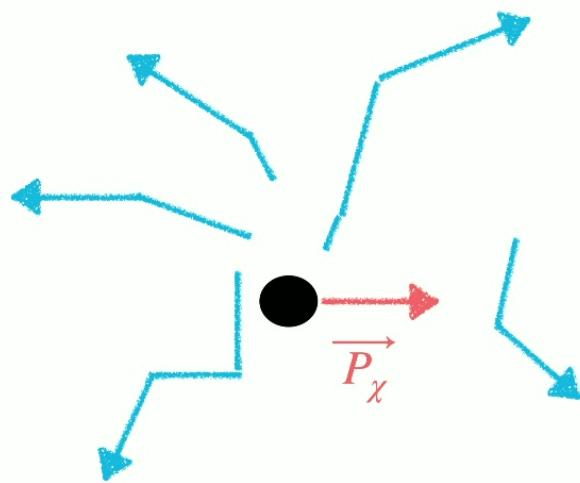
+

Phase shift  
for high-l  
modes

Add a coupling to DM...

$$\mathcal{L}_{DS} \propto \lambda \phi \psi^2 + \lambda^2 (\phi^* \phi)^2 + m_\phi^2 \phi^* \phi + \lambda_{DM} \phi \chi^2$$





momentum transfer rate

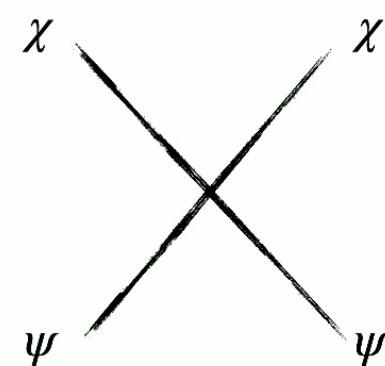
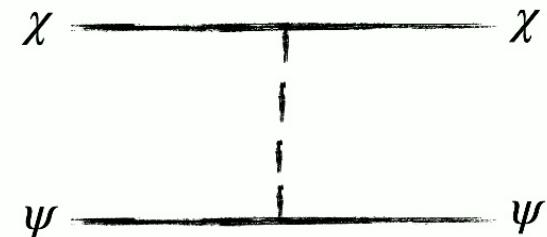
$$\dot{\overrightarrow{P}_\chi} = -a\Gamma \overrightarrow{P}_\chi$$

DM momentum

$$\dot{\vec{P}} = \frac{a}{2E_P} \int \frac{d^3k}{(2\pi)^3 2E_k} f(k; T) \int \frac{d^3k'}{(2\pi)^3 2E'_k} \frac{d^3P'}{(2\pi)^3 2E'_P} (2\pi)^4 \delta^{(4)}(P + k - P' - k') |\mathcal{M}|^2 (\vec{P}' - \vec{P})$$



$$\Gamma \propto \begin{cases} \frac{T_d^2}{M_\chi} & T_d \gg m_\phi \\ \frac{T_d^2}{M_\chi} \left( \frac{T_d}{m_\phi} \right)^4 & T_d \ll m_\phi \end{cases}$$



momentum transfer rate


$$\Gamma \propto \begin{cases} \frac{T_d^2}{M_\chi} & T_d \gg m_\phi \\ \frac{T_d^2}{M_\chi} \left( \frac{T_d}{m_\phi} \right)^4 & T_d \ll m_\phi \end{cases}$$

vs

$$H \sim \frac{T^2}{M_{pl}} \quad (\text{Radiation dominated})$$

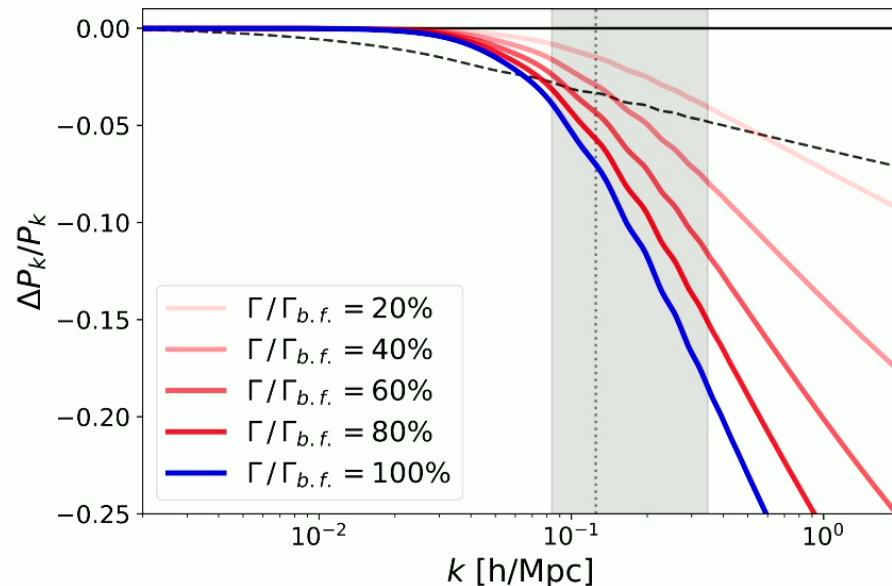
## Growth of DM Perturbations

$$\ddot{\delta} + aH \left( 1 + \frac{\Gamma}{H} \right) \dot{\delta} = \mathcal{S} \quad \frac{\Gamma}{H} = \epsilon \ll 1$$

$$\ddot{\delta} + \frac{1 + \epsilon}{\tau} \dot{\delta} \sim 0$$

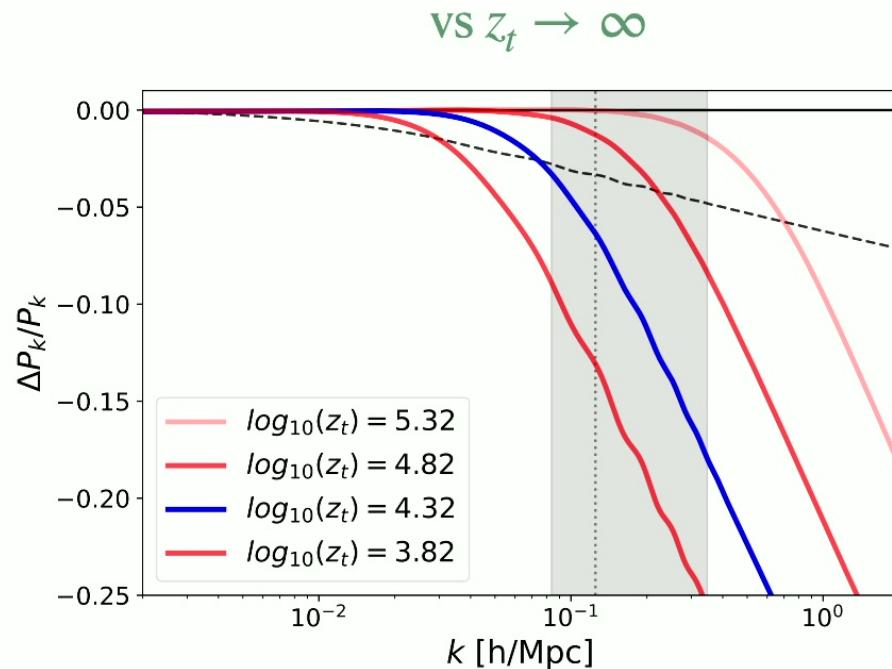
$$\dot{\delta} = \tau^{-(1+\epsilon)} \quad \delta = \log \tau (1 - \epsilon/2 \log \tau)$$

## vs no DM-DR interaction



$$\frac{P_{\text{interacting}}}{P_{\text{not-interacting}}} \simeq \begin{cases} 1 & k \ll k_{s.o.} \\ 1 - \sqrt{2} \frac{\Gamma}{H} \times \log k / k_{s.o.} & k \gg k_{s.o.} \end{cases}$$

Smooth suppression in  $\log k$



$$\frac{P_{\text{interacting}}}{P_{\text{not-interacting}}} \simeq \begin{cases} 1 & k \ll k_{s.o.} \\ 1 - \sqrt{2} \frac{\Gamma}{H} \times \log k/k_{s.o.} & k \gg k_{s.o.} \end{cases} .$$

Shut-off when  $T_d \sim m_\phi$

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# Model Summary

$$\begin{aligned}\mathcal{L}_{DS} \propto & \lambda \phi \psi^2 + \lambda^2 (\phi^* \phi)^2 \\ & + m_\phi^2 \phi^* \phi + \lambda_{DM} \phi \chi^2\end{aligned}$$

Parameters:

- Interaction strength ( $\lambda_{DM}$ )
- $z_t$
- $N_{IR}$

# Data

$\mathcal{D}$  : Planck 2018 TT, EE, TE, BAO (6dF, MGS, BOSS DR12), Pantheon

$\mathcal{H}$  : SHOES

$\mathcal{S}$  : Planck Lensing, KiDS-1000, DES-Y3 ( $S_8$  values)

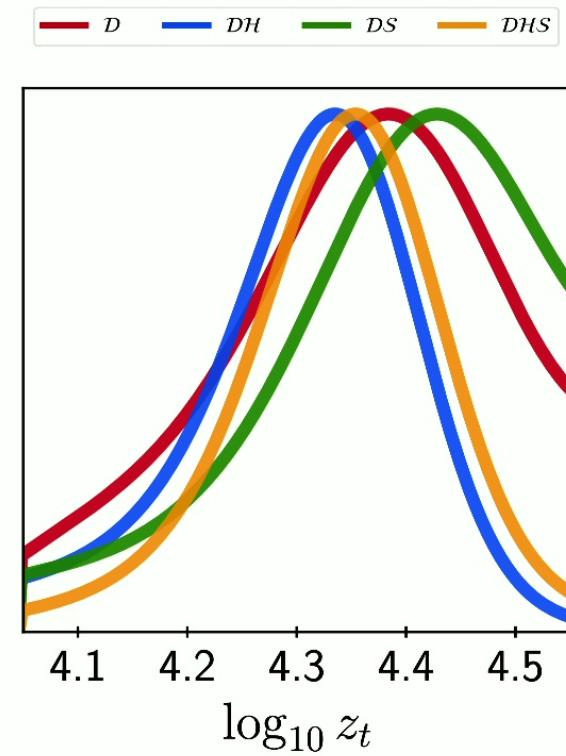
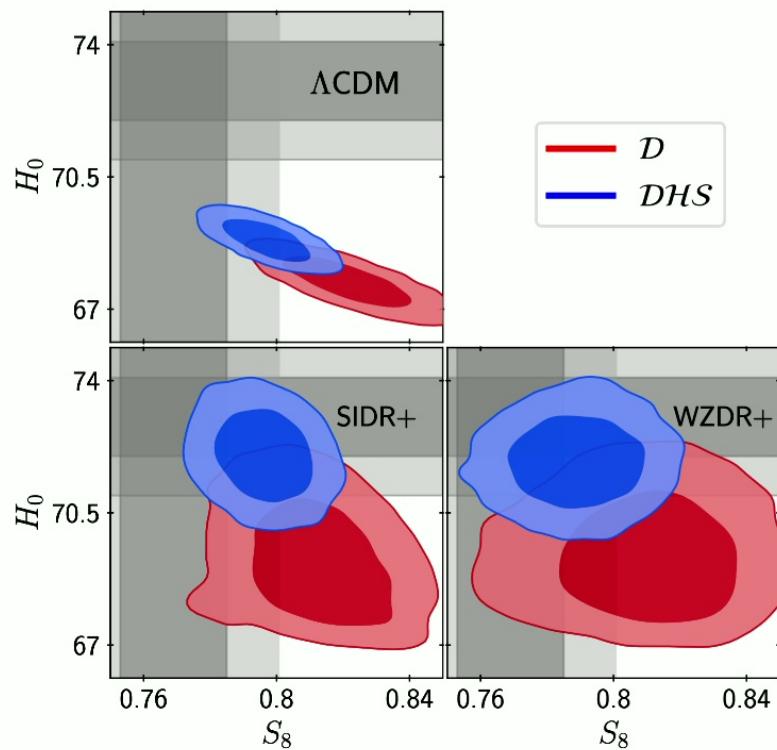
# Models

$\Lambda$ CDM

SIDR+ : interacting radiation - dark matter, no step

WZDR+

# Results



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<b>Model</b>	<b>Tension</b>	$\Delta\chi^2$	$\Delta\text{AIC}$
LCDM	<b><math>5.80\sigma</math></b>		
SIDR+	<b><math>3.62\sigma</math></b>	<b>-19.99</b>	<b>-15.99</b>
WZDR+	<b><math>3.20\sigma</math></b>	<b>-25.78</b>	<b>-19.78</b>

$$\Delta\text{AIC} = \chi_{\text{Model}}^2 - \chi_{\Lambda\text{CDM}}^2 + 2(\# \text{ of New parameters})$$

# Summary

- Interacting dark sectors present the most natural solutions to simultaneously solving the  $H_0$  and  $S_8$  tensions
- If the radiation is interacting: a simple model includes a massive particle which decays during the CMB times (WZDR)
- If we also include a coupling to the DM, this can alleviate the  $S_8$  tension