Dark Acoustic Oscillations Faces the Cosmological Tensions

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Cornell U, LEPP

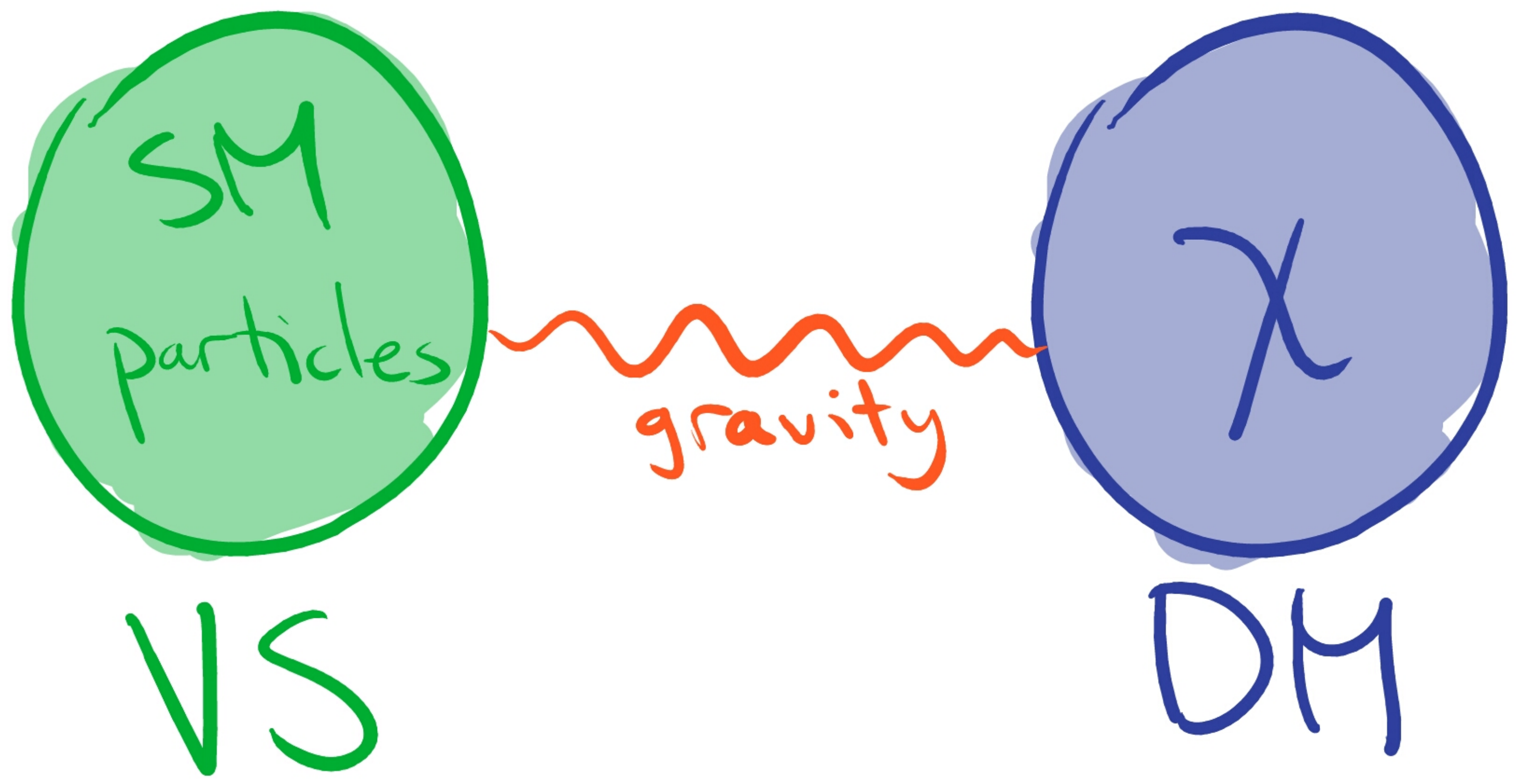
May 14th 2024

Based on [240X.XXXXX] in collaboration with I. Flood, M. A. Buen-Abad, Z. Chacko, C. Kilic, G. Marques-Tavares

Dark Matter

Dark Sector

DM could be just one particle, only interacting with SM via gravitation



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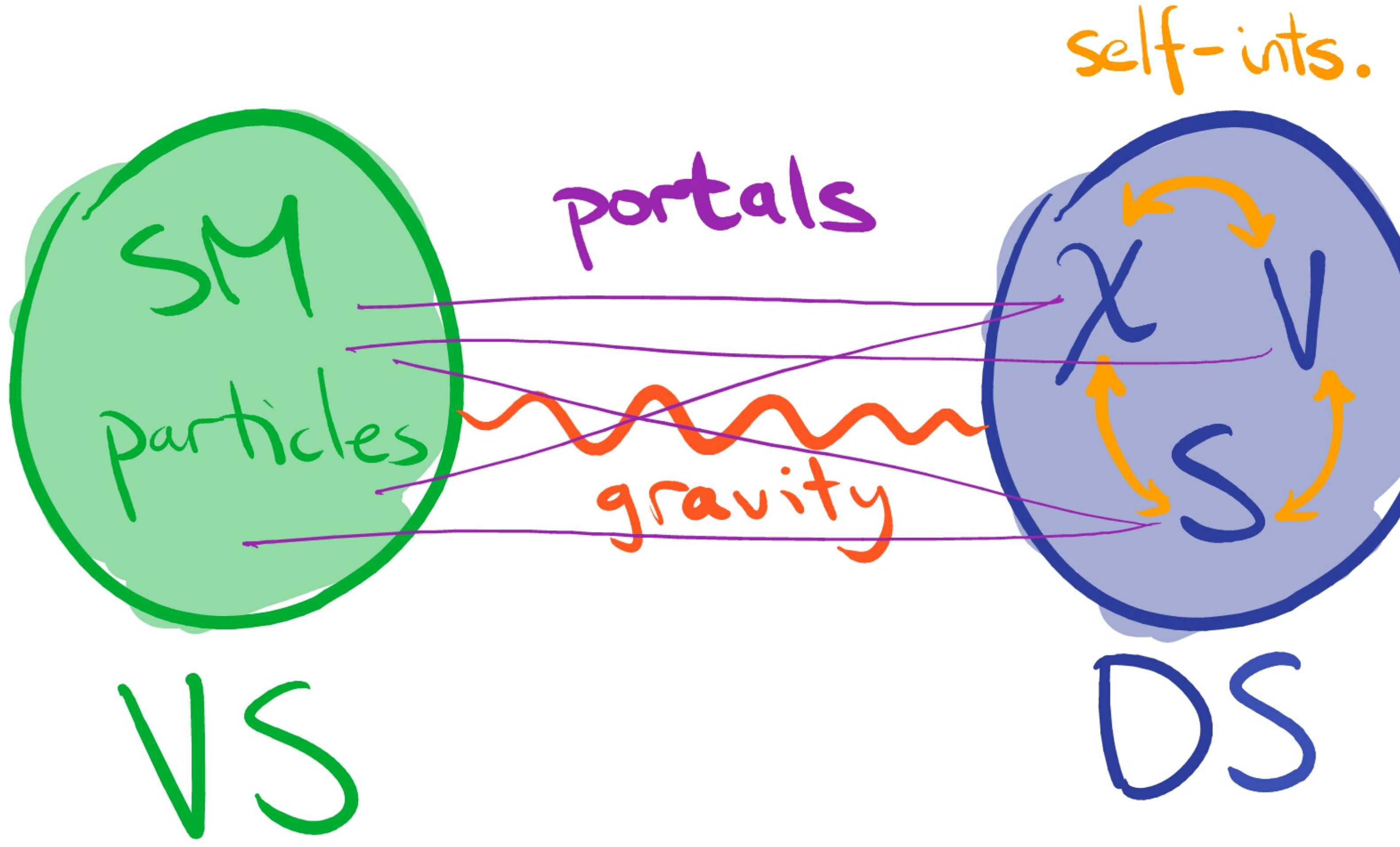
DM could be just one particle, only interacting with SM via gravitation

Not necessarily!

- Multiple States (eg. dark proton, dark photon, dark neutrino, etc.)
- Various interactions within DS (self-interactions) and/or btw SM and DS (portals)



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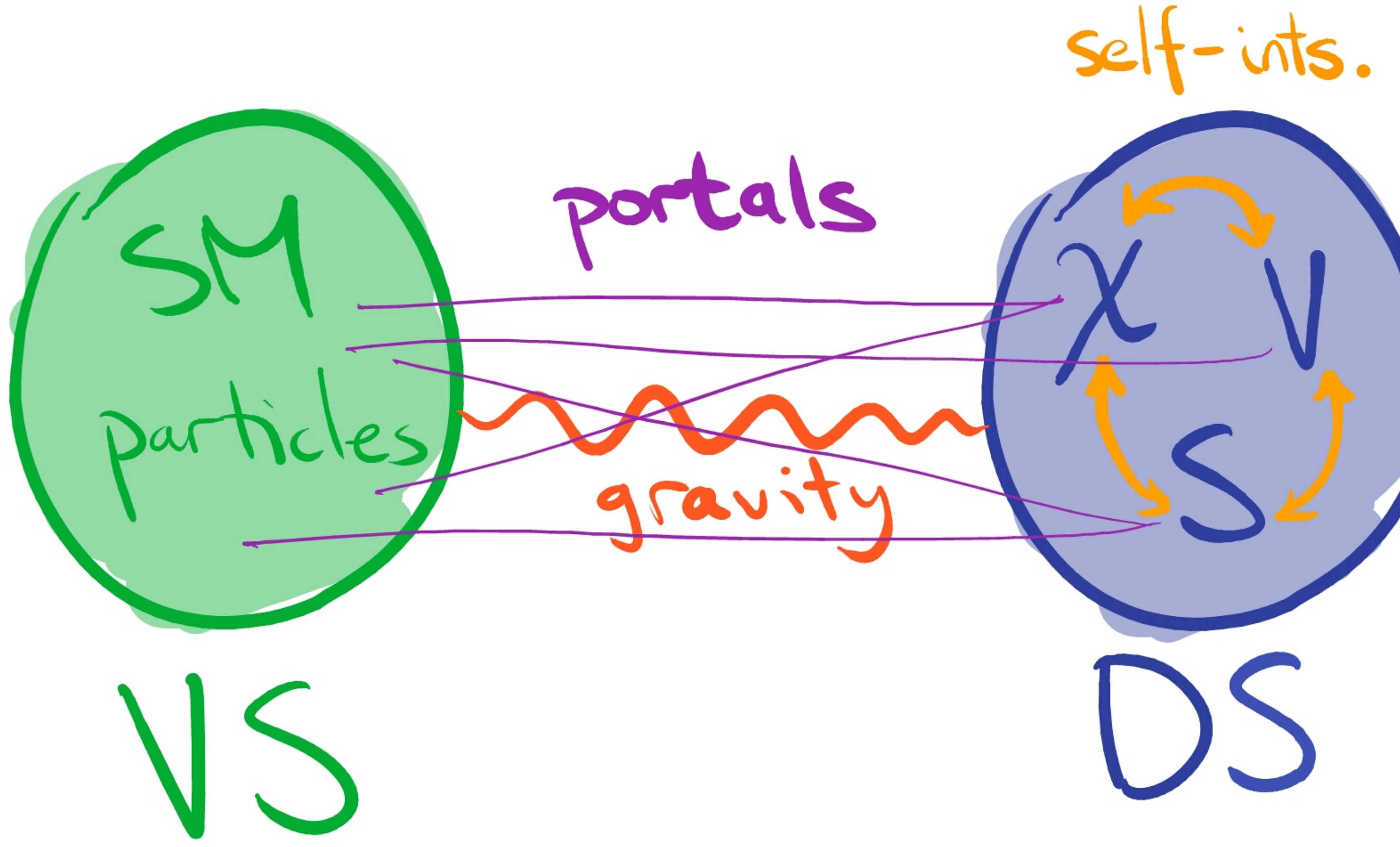
Imprint on Cosmological Observations



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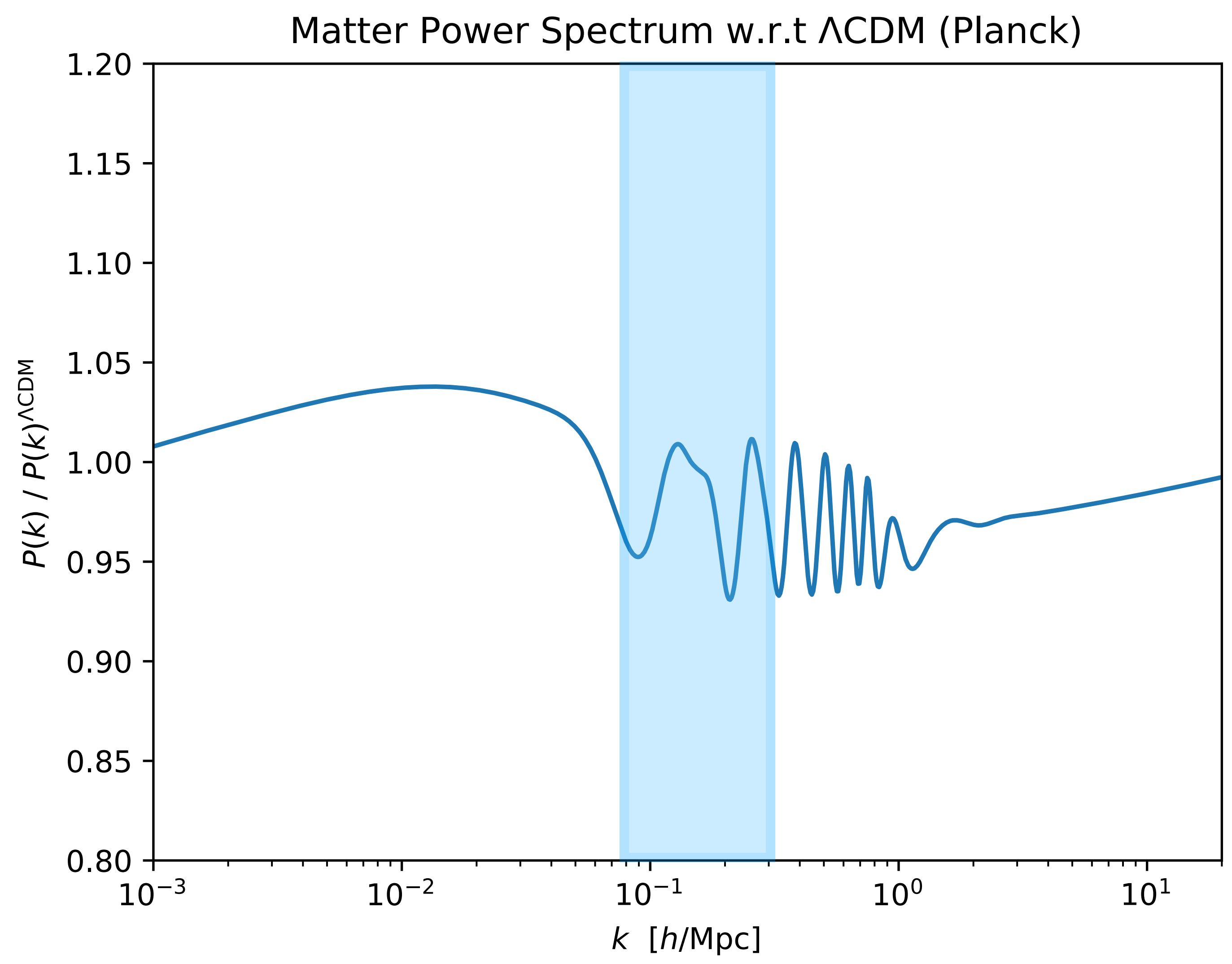
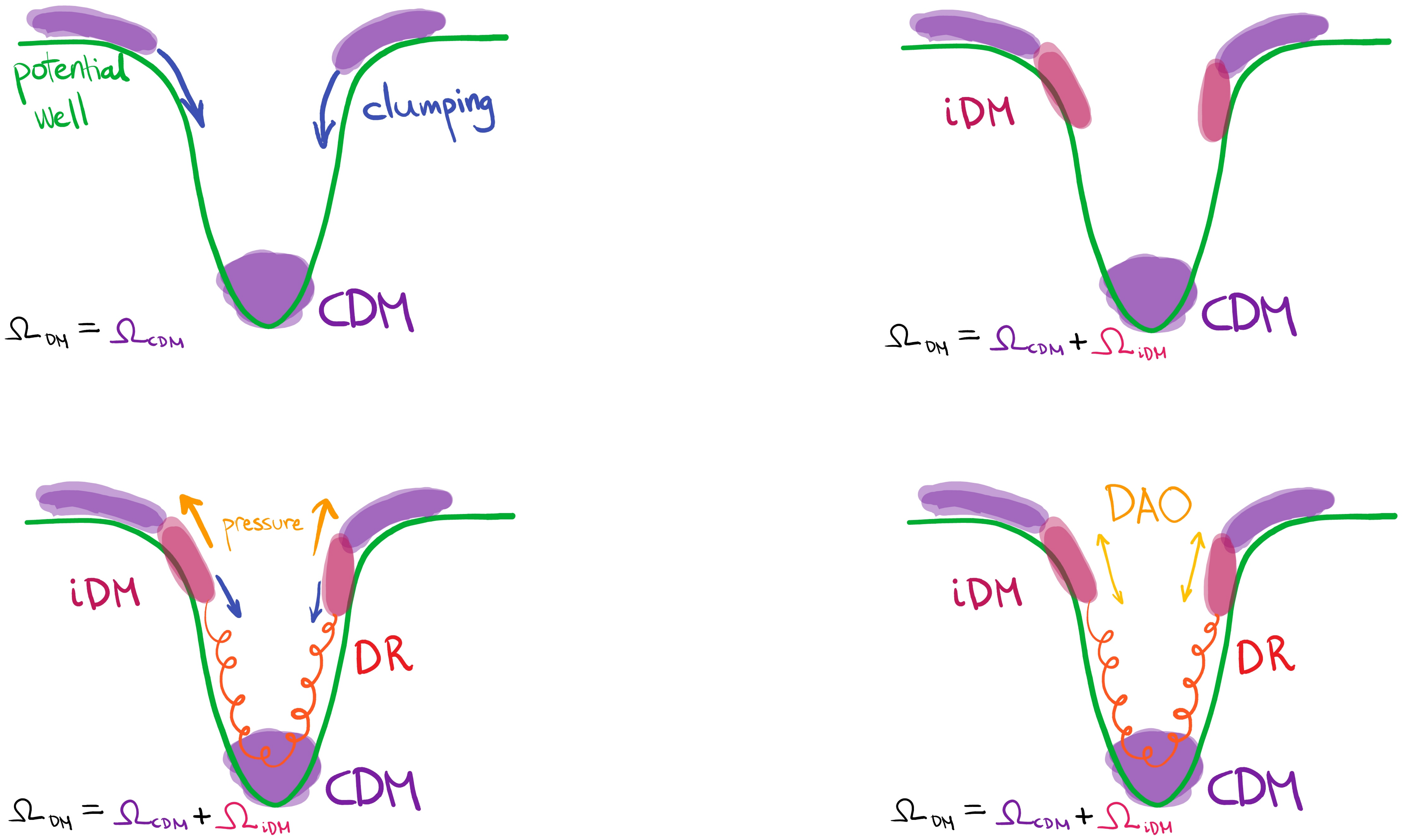
Imprint on Cosmological Observations

When some components are tightly coupled,
Dark Acoustic Oscillation (DAO) emerges



Dark Matter

Dark Acoustic Oscillation



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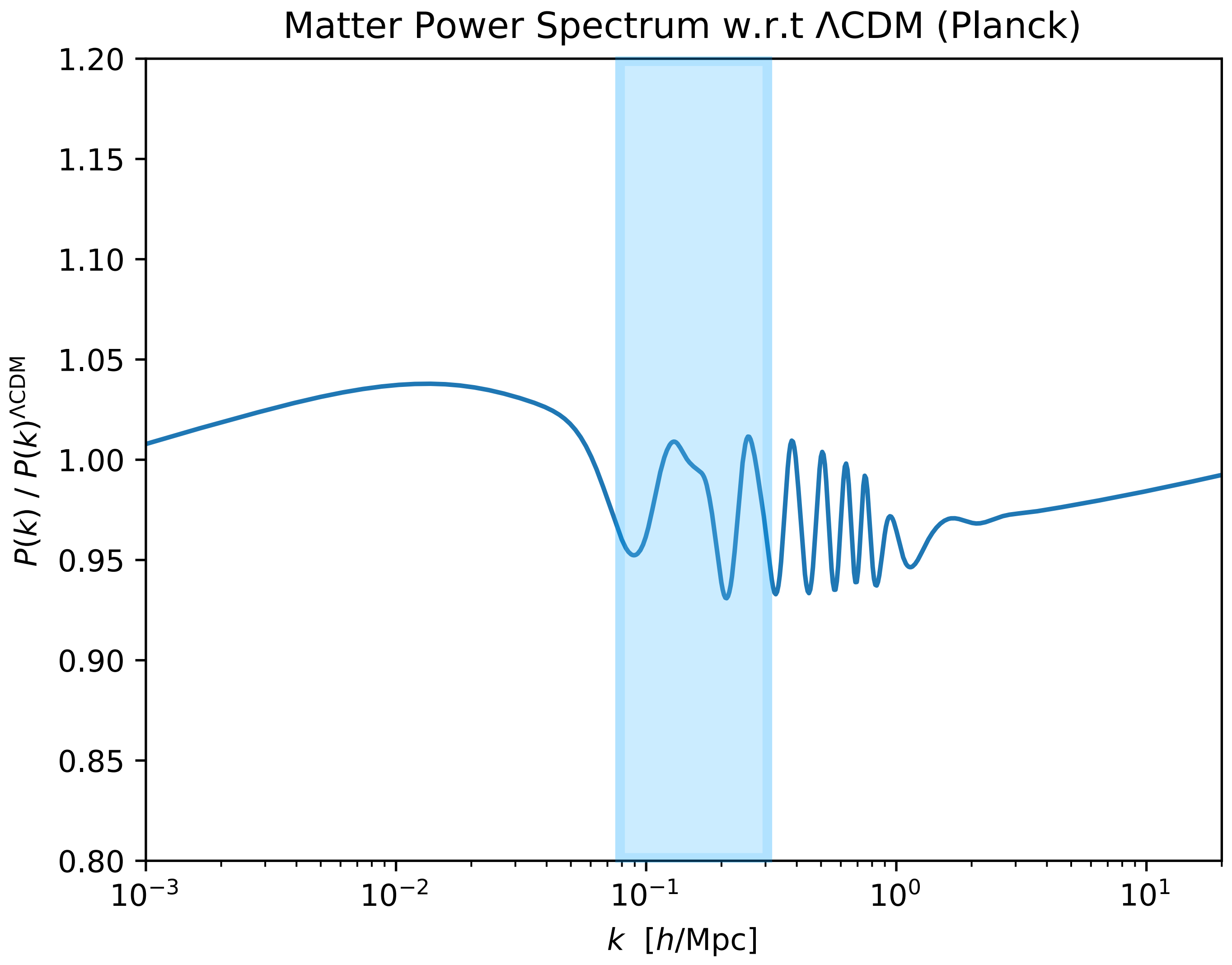
Imprint on Cosmological Observations

- **Dark Acoustic Oscillation** (DAO)
- **Possibly in H_0 and S_8 tensions**
- Even though gone, worth investigating



Cosmological Tensions

Snowmass [arXiv:2203.06142]

Hubble tension (~4-6 σ)

Early Universe

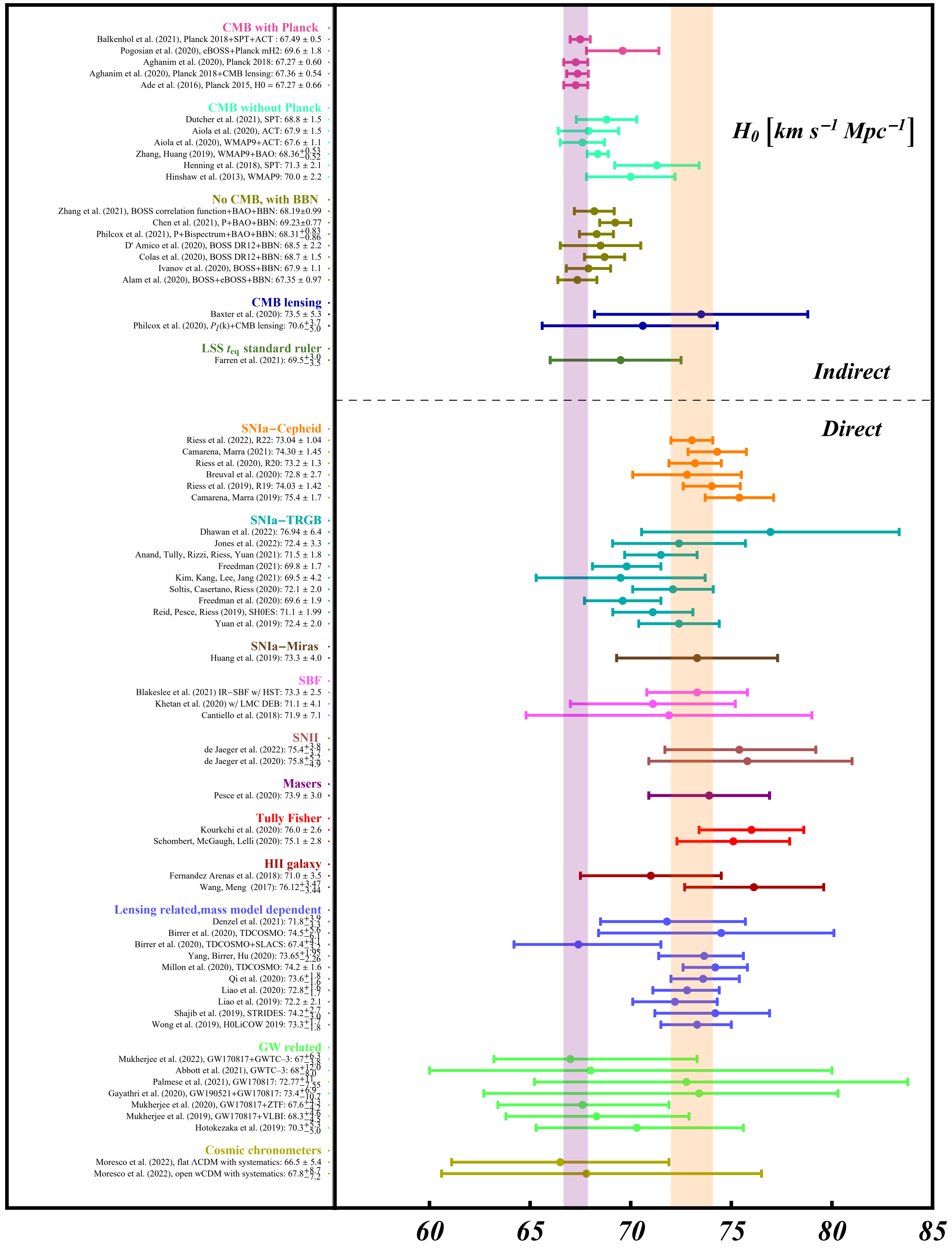
CMB fit to ΛCDM

~68 km/s/Mpc **Planck ’18 [arXiv:1807.06209]**

Late Universe

Cosmic Distance Ladder

~73 km/s/Mpc **A. G. Riess et al. [arXiv:2112.04510]**



Cosmological Tensions

Hubble tension (~4-6 σ)

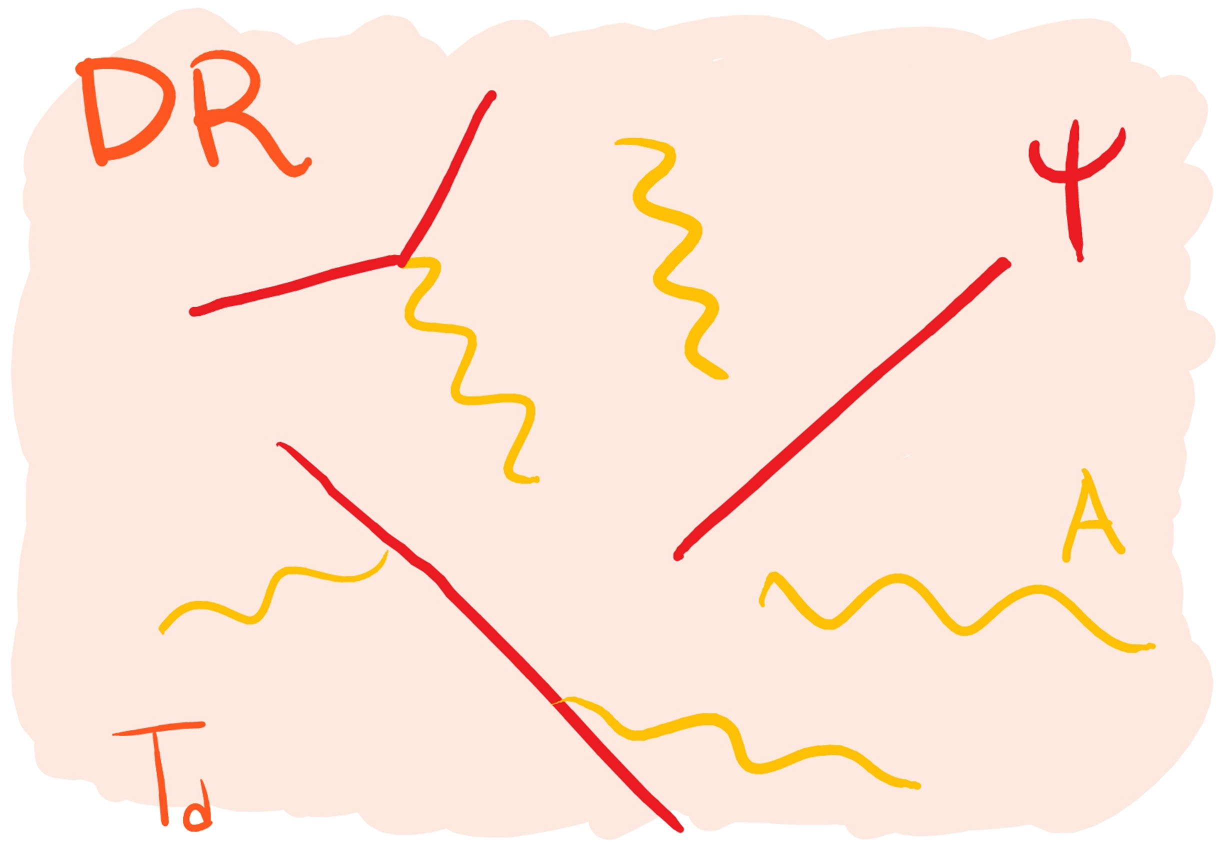
$$H_0 \sim H_{\rm rec}\theta_s \frac{c/(\rho_{\rm late}/\rho_{\rm today})^{1/2}}{c_s/(\boxed{\rho_{\rm early}}/\rho_{\rm rec})^{1/2}}$$

To increase H_0,

Increase energy density at early times (early-time solutions)

Early Dark Energy

Dark Radiation → Massless states in Dark Sector



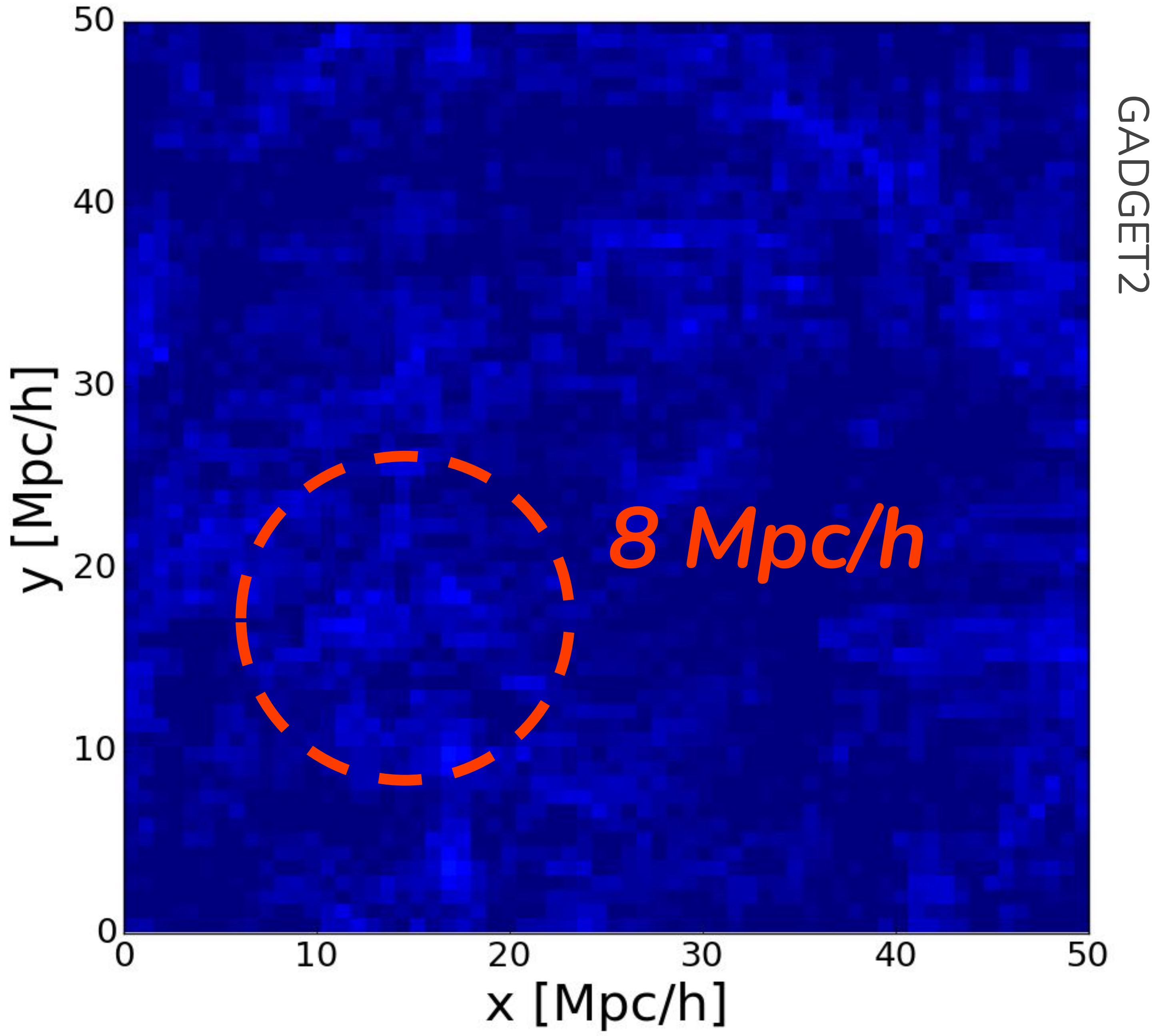
Cosmological Tensions

Snowmass [arXiv:2203.06142]

S_8 tension (~2-3 σ)

σ_8: amplitude of matter density fluctuations on the scale of 8 Mpc/h
(~ galaxy cluster scale)

$S_8 \equiv \sigma_8(\Omega_m/0.3)^{1/2}$:



Cosmological Tensions

Snowmass [arXiv:2203.06142]

S_8 tension (~2-3 σ)

Early Universe

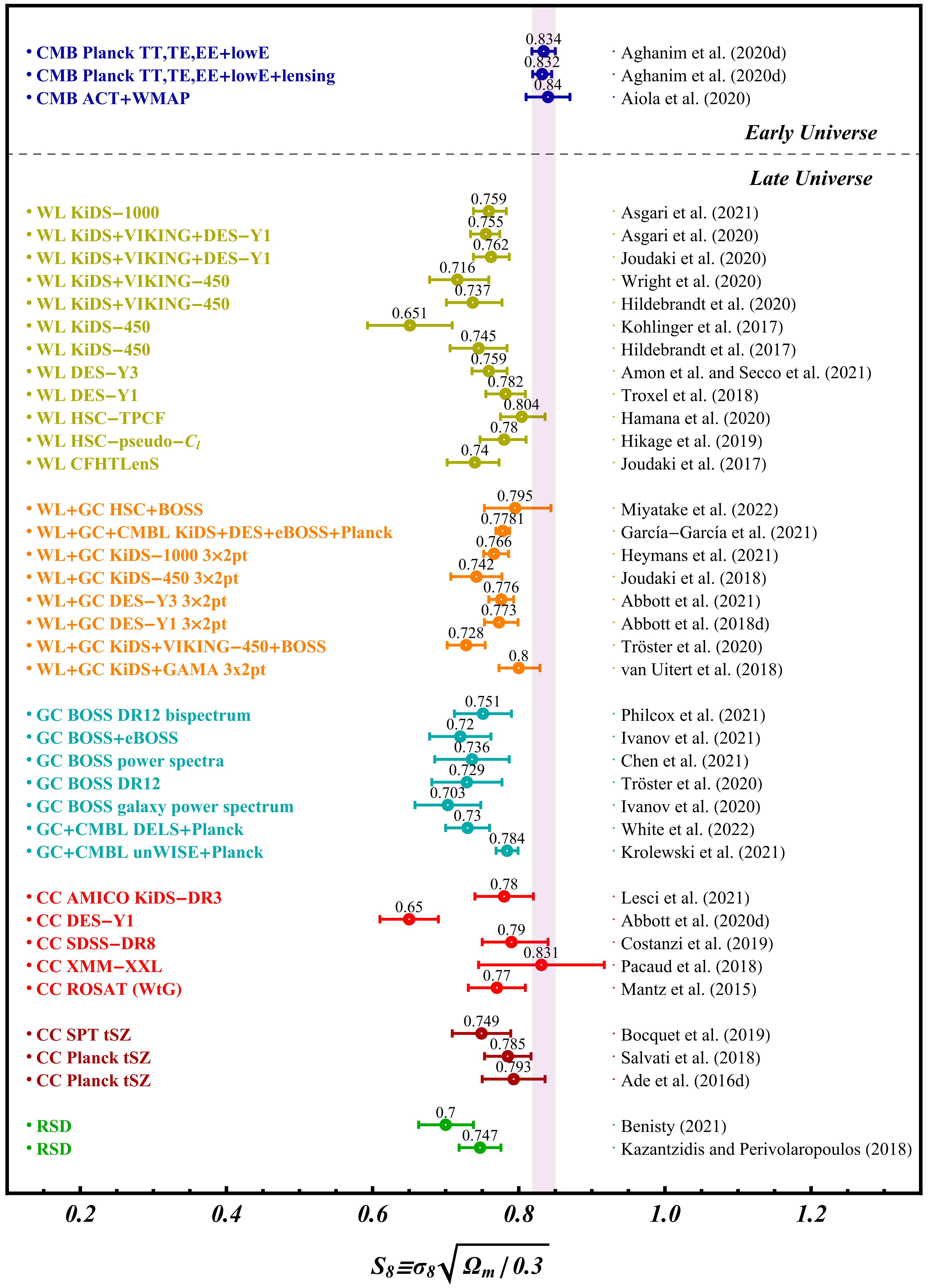
CMB fit to ΛCDM

~0.83 **Planck '18 [arXiv:1807.06209]**

Late Universe

Local measurements

~0.76 **DES '21 [arXiv:2105.13544, 2105.13543]**



Cosmological Tensions

Snowmass [arXiv:2203.06142]

S_8 tension (~2-3 σ)

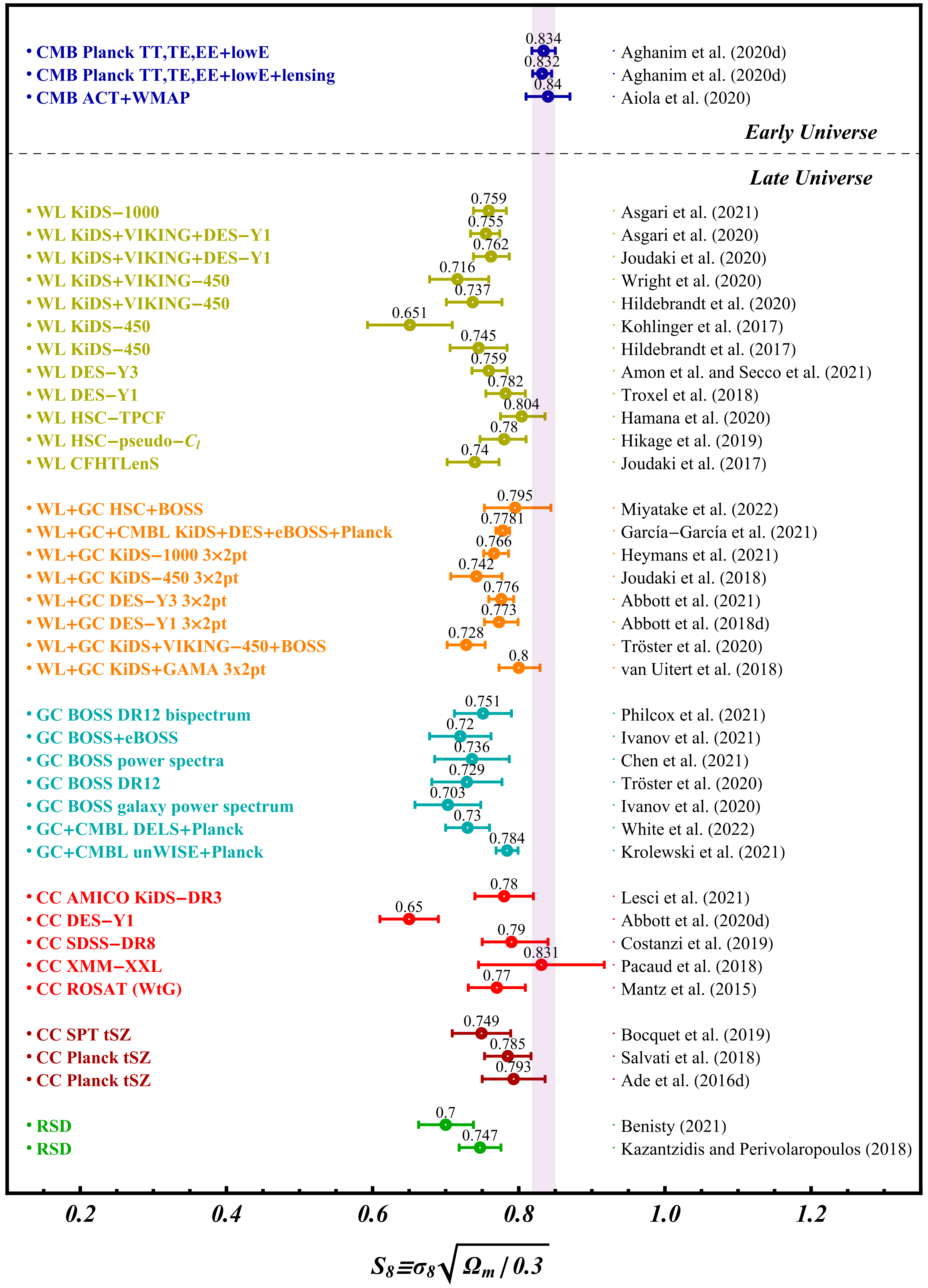
More likely systematic errors

H. G. Escudero et al. [arXiv:2208.14435]
M. Tristram et al. [arXiv:2309.10034]

Early universe solutions worsen S_8 tension

with fixed z_{eq}, $\Omega_r \uparrow \rightarrow \Omega_m \uparrow$

Early-time solutions keep in mind S_8

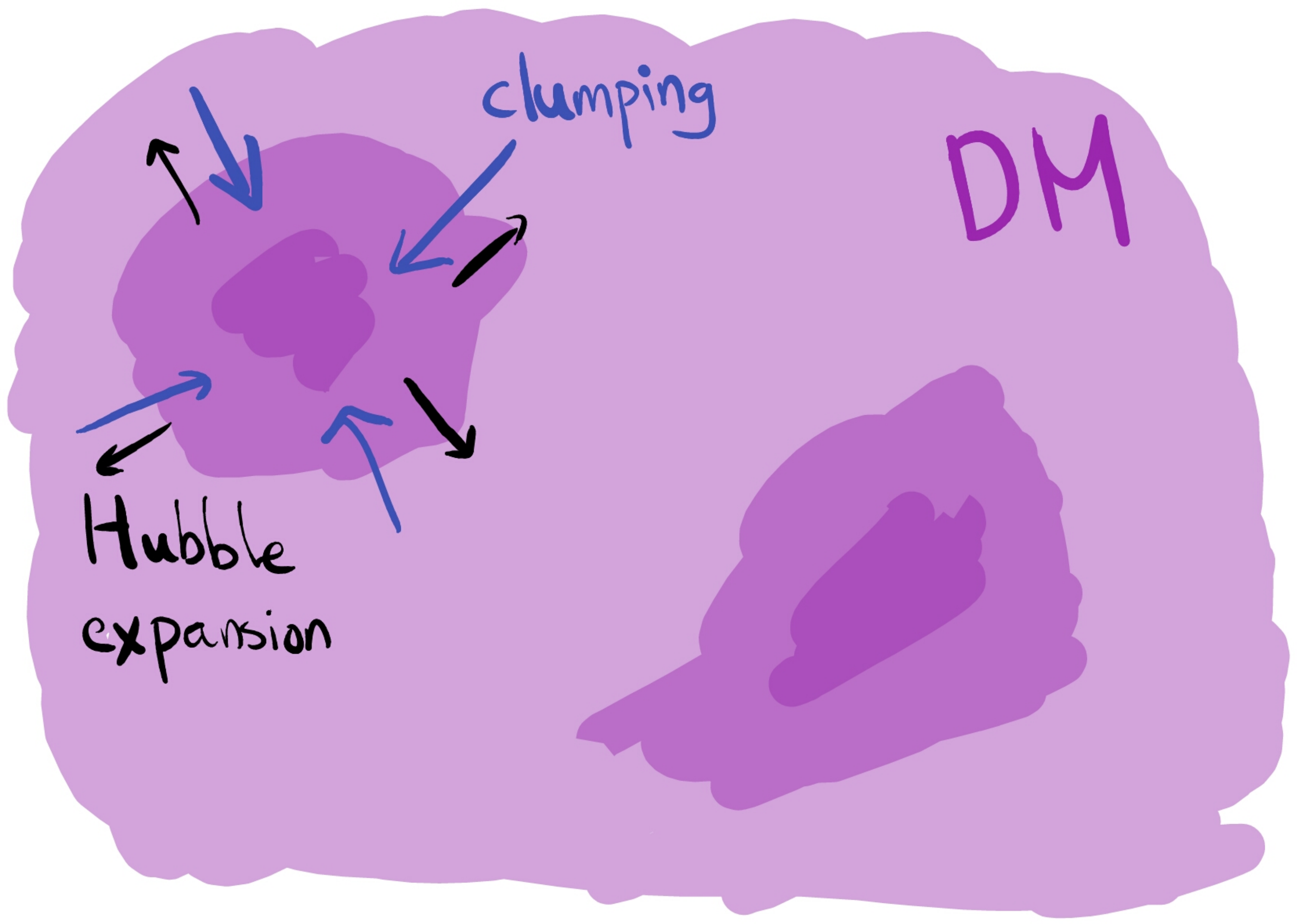


Dark Matter interaction with DR

A Class of Solutions to S_8 tension

Dark Radiation worsens S_8 tension

with fixed z_{eq}, $\Omega_r \uparrow \rightarrow \Omega_m \uparrow$



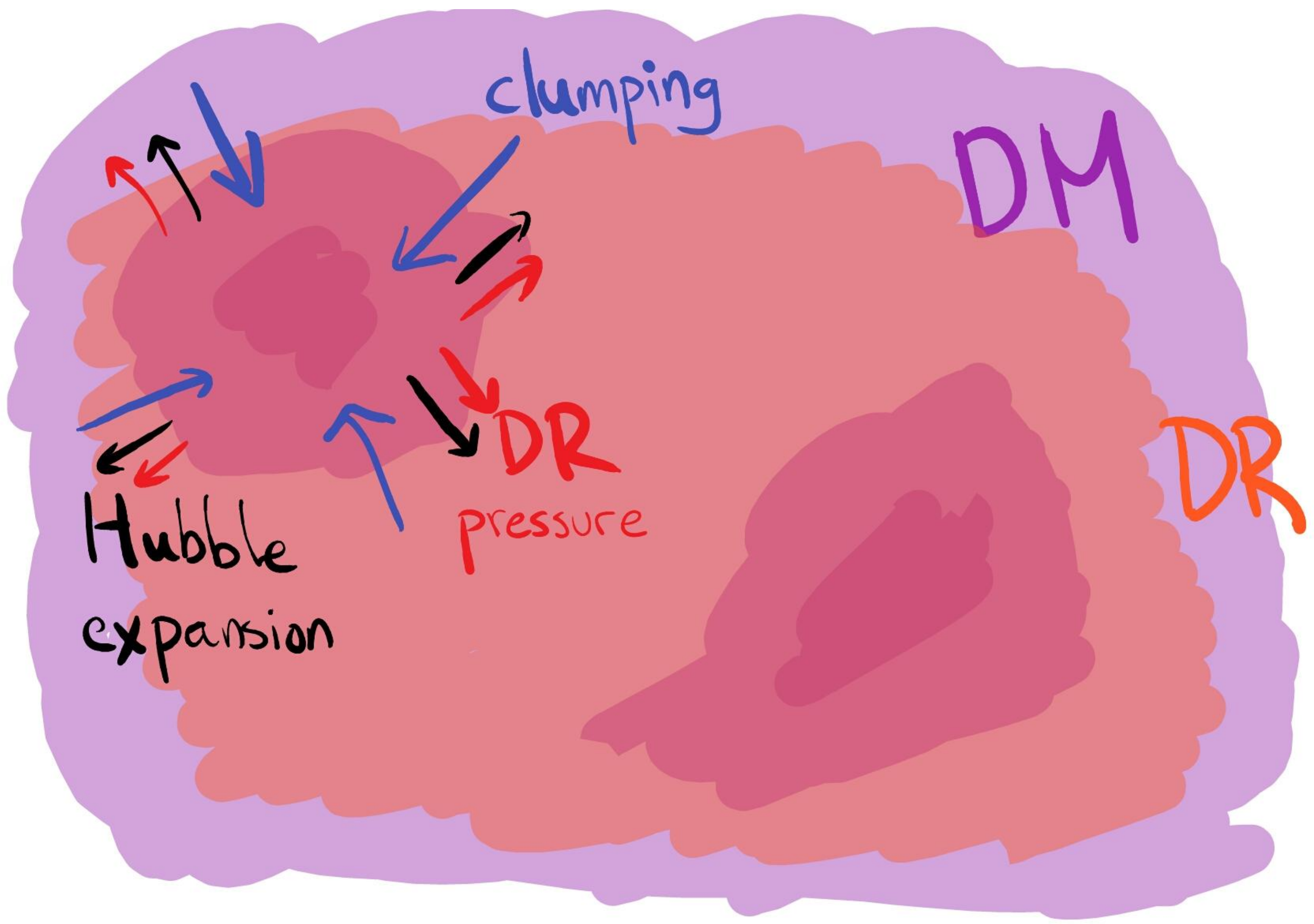
Dark Matter interaction with DR

A Class of Solutions to S_8 tension

Dark Radiation worsens S_8 tension

with fixed $z_{\rm eq}$, $\Omega_r \uparrow \rightarrow \Omega_m \uparrow$

Solution: Dark Matter interaction with Dark Radiation



Atomic DM + Dark ν

A toy model

Standard CDM

Atomic DM: χ

Dark Proton p, Dark Electron e

$f_{\text{CDM}} + f_\chi = 1$

Self-interacting Dark Radiation

Dark Photon A, Dark Neutrino ν, $U(1)_\nu$ gauge boson Z

	$U(1)_A$	$U(1)_\nu$
χ	1	0
ν	0	1

$$\mathscr{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{\epsilon}{2}F_{\mu\nu}Z^{\mu\nu} + \bar{p}(i\partial\!\!\!/ - m_p)p + \bar{e}(i\partial\!\!\!/ - m_e)e + \bar{\nu}i\partial\!\!\!/\nu + \bar{e}A_\mu(\bar{p}\gamma^\mu p - \bar{e}\gamma^\mu e) + \bar{g}Z_\mu\bar{\nu}\gamma^\mu\nu$$

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Atomic DM + Dark ν

Recombination

In νADM

Radiative recombination to the ground state, and its inverse photoionization

$$\boxed{p + e \leftrightarrow H(1s) + \gamma}$$

Free photon falls into thermal bath quickly thanks to the self-interaction

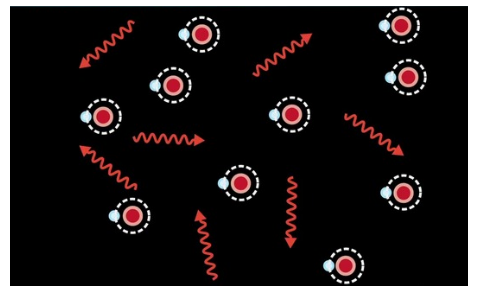
Direct recombination to the ground state is included (Case A recombination)

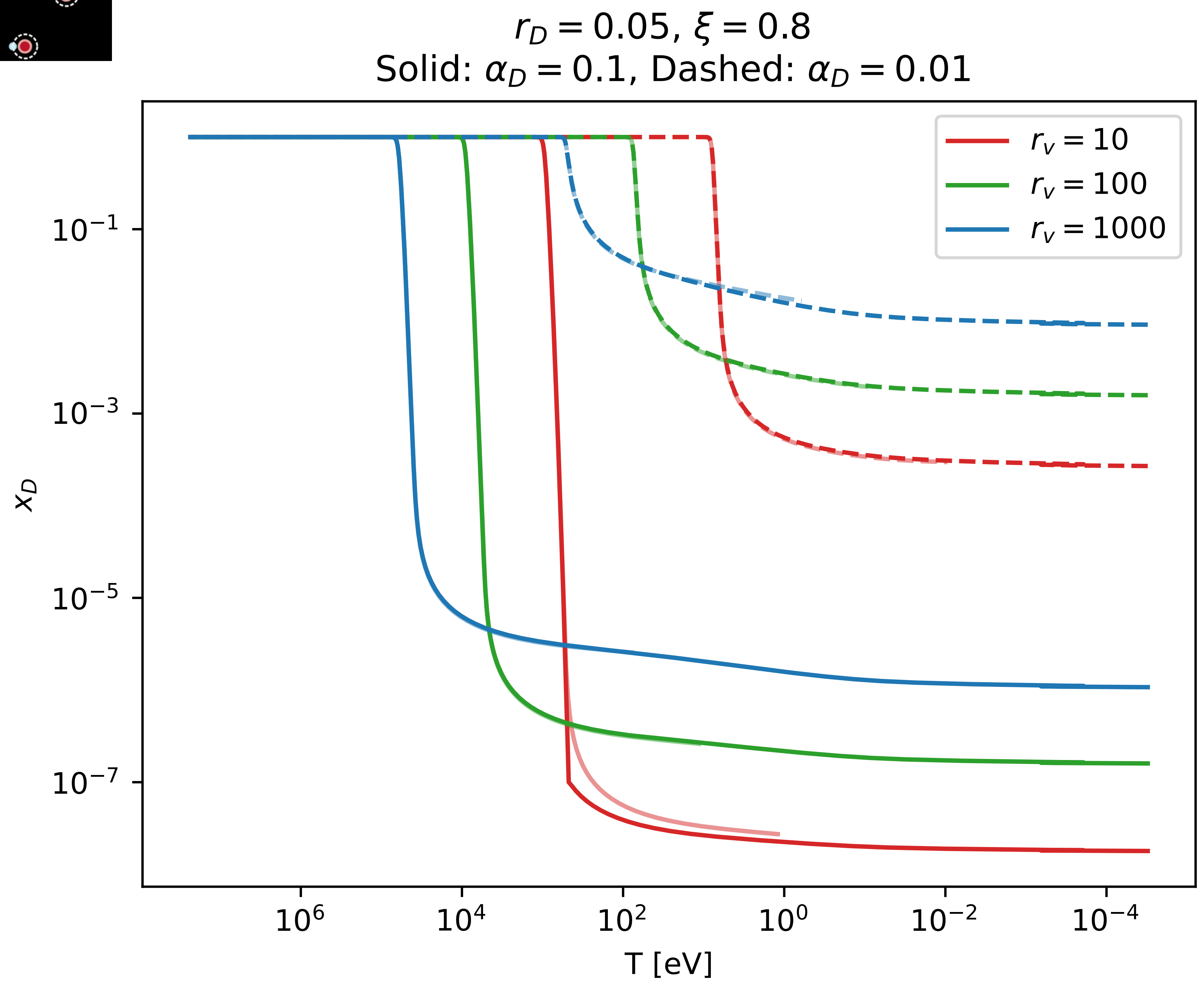
$$a_A = \sum_{n=1}^{\infty} \sum_{l=0}^{n-1} \langle \sigma[p + e \to H(nl) + \gamma \rangle$$

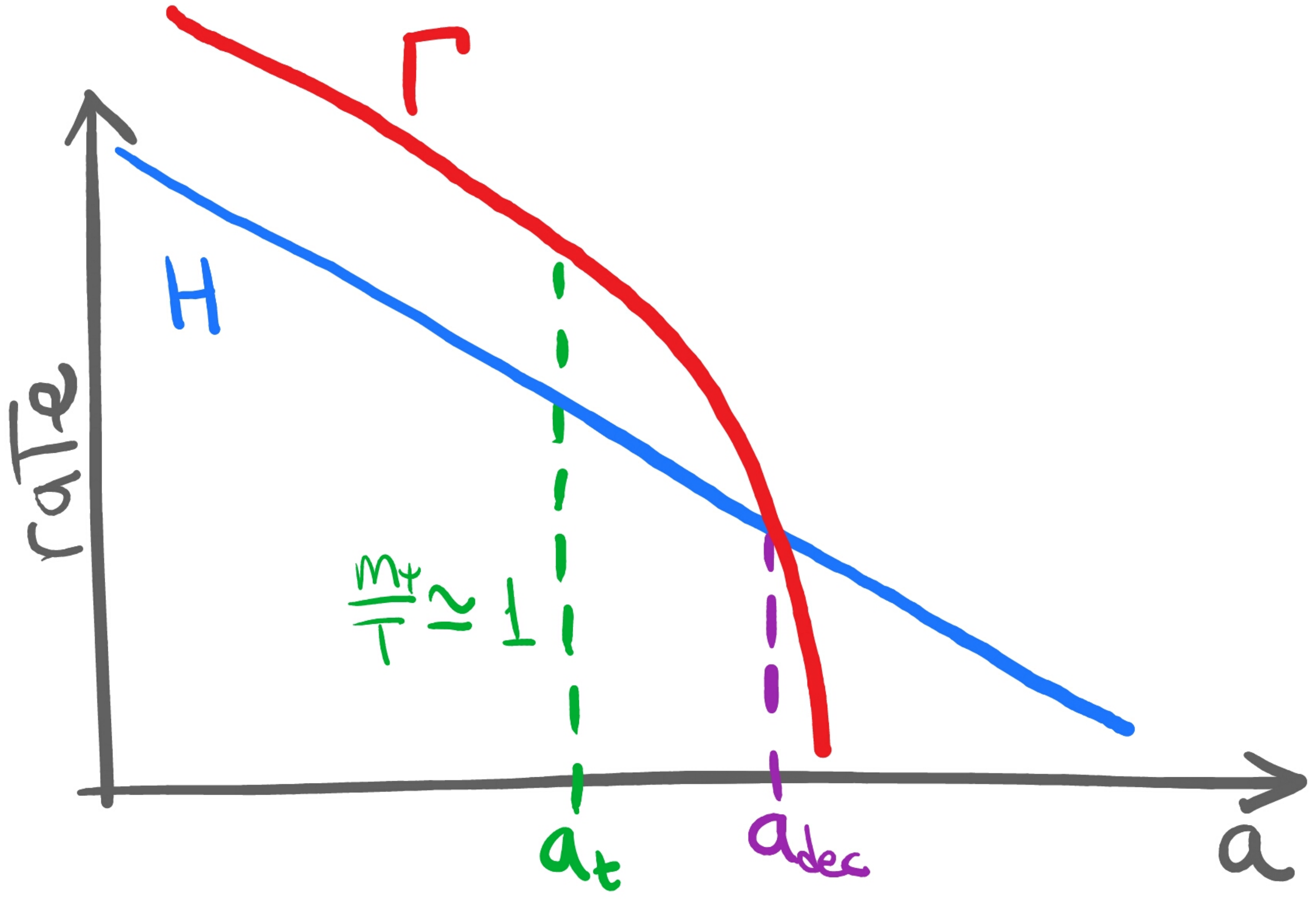
$$-\frac{d}{dt}\left(\frac{n_e}{n}\right) = \alpha_A \left[\frac{n_e^2}{n} - \left(1 - \frac{n_e}{n}\right)\left(\frac{m_e T}{2\pi}\right)^{3/2} e^{-B_1/T}\right]$$

Atomic DM + Dark ν

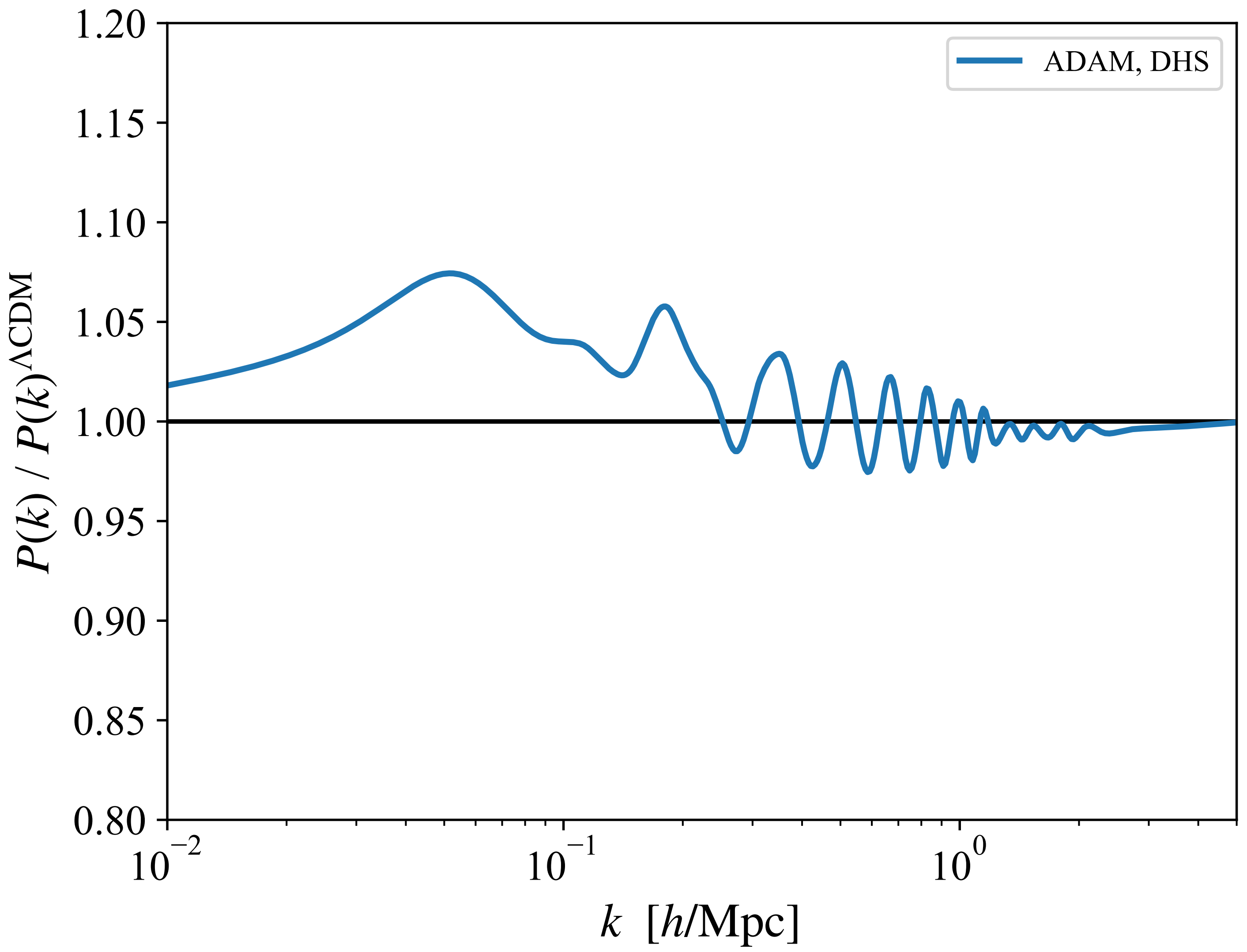
Recombination





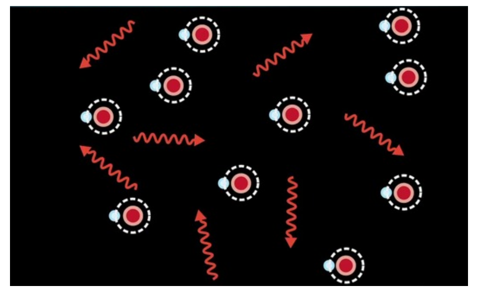


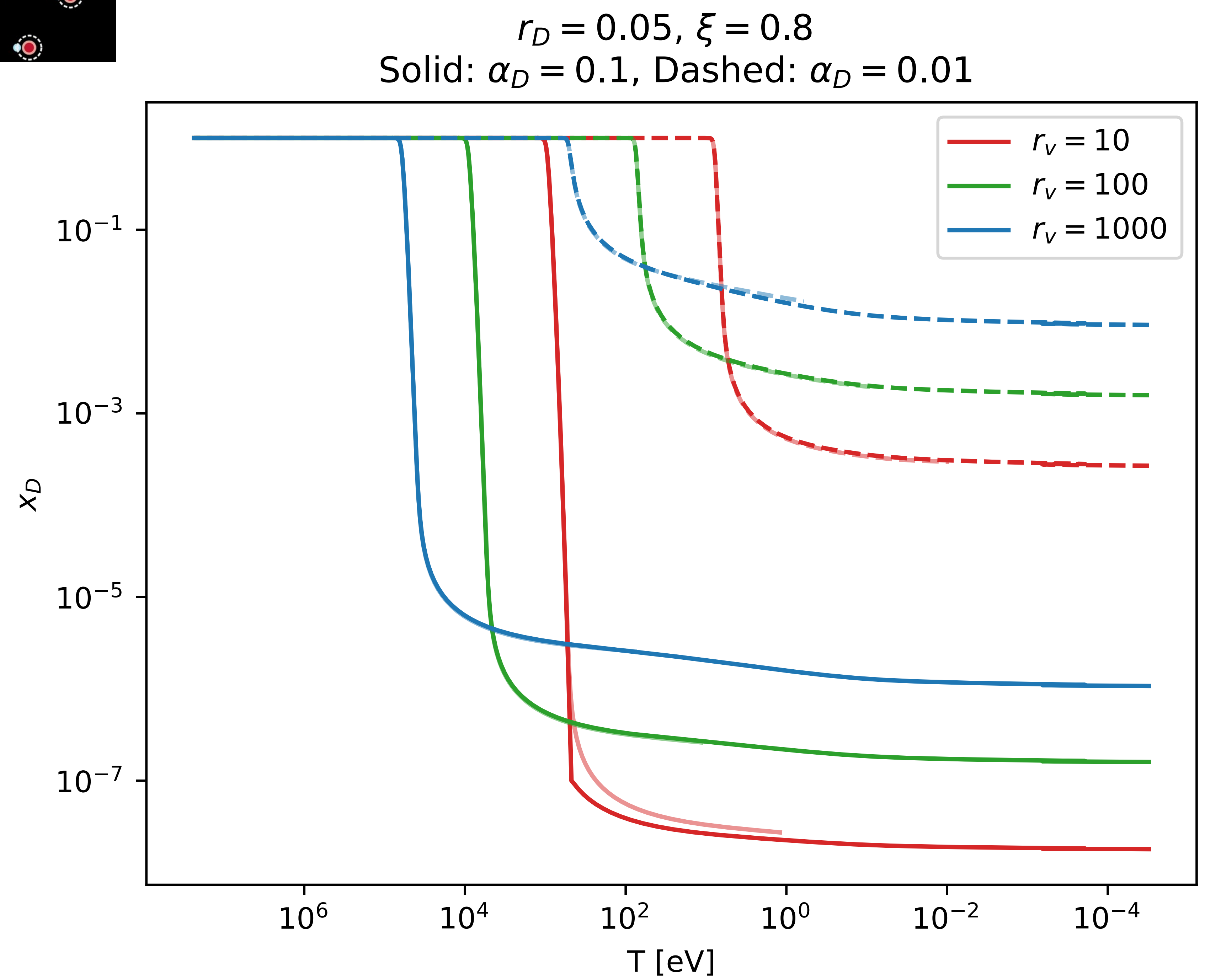
Prevent too low S_8

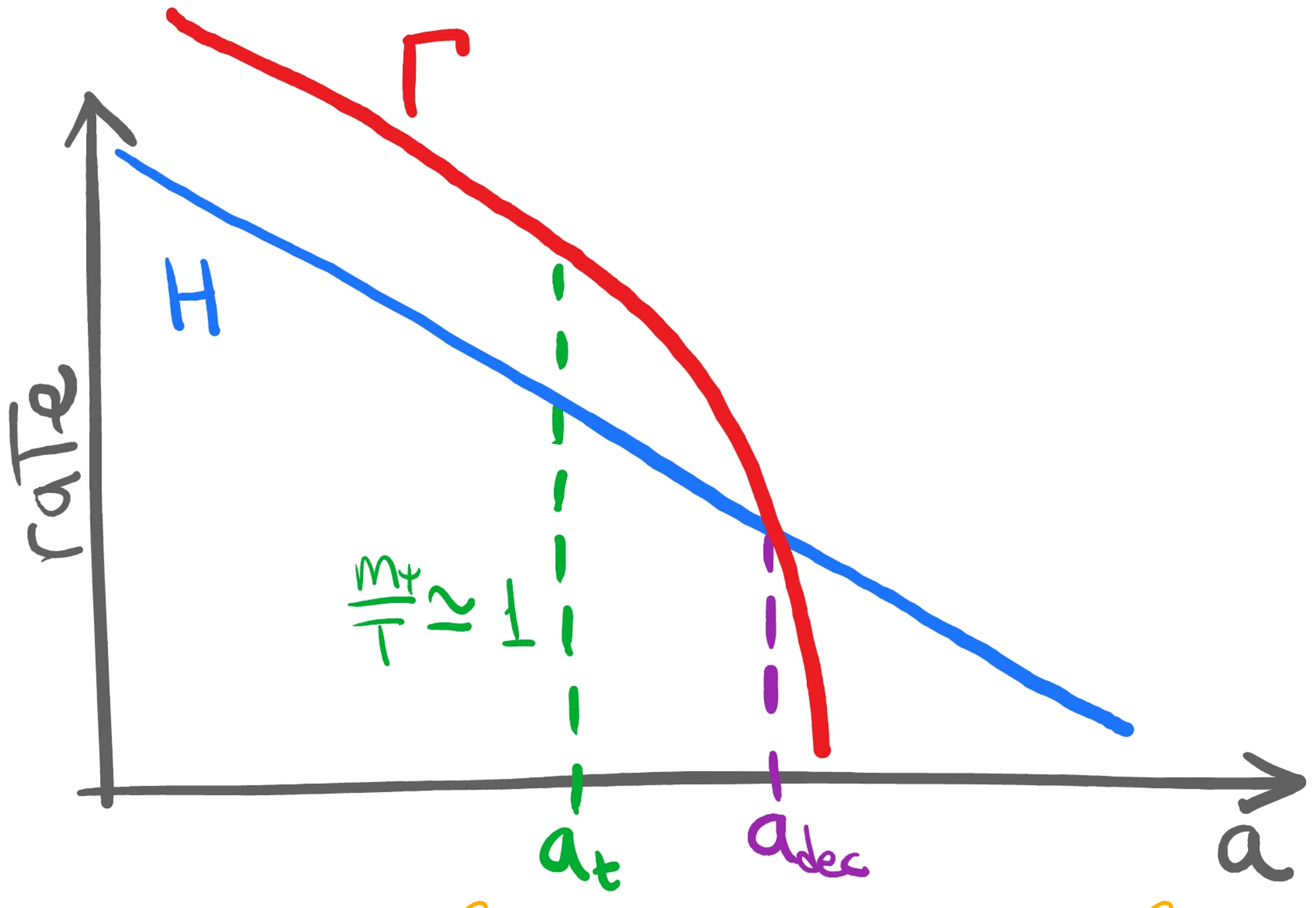


Atomic DM + Dark ν

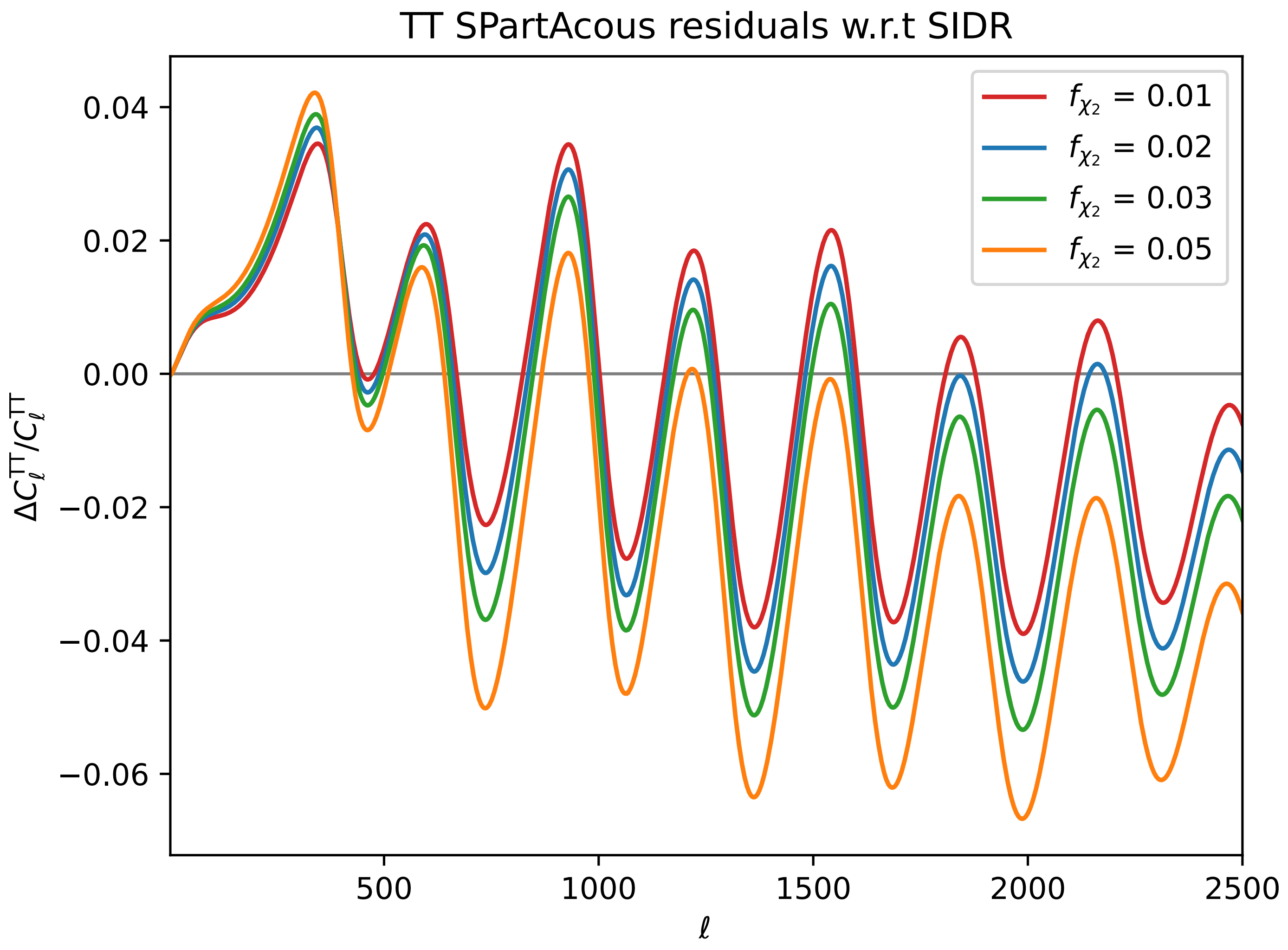
Recombination







high-ℓ **low-ℓ**



Large redshift in high-ℓ

Atomic DM + Dark ν

Solution to H_0 and S_8 tensions?

Self-interacting DR:

A, ν, Z

Increase early measurement of H_0

Less Silk Damping

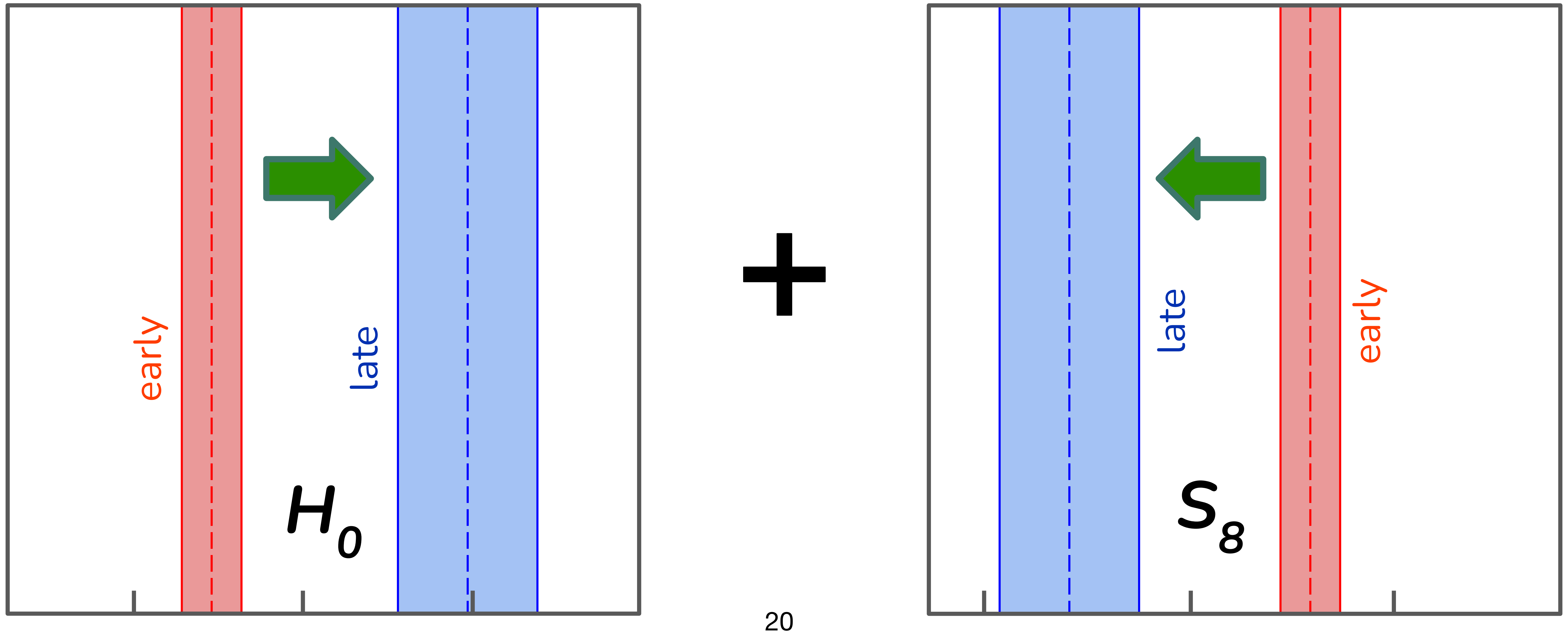
Dark Acoustic Oscillation:

χ-SIDR interaction

Decrease early measurement of S_8

Prevent too low S8

Recombination



Markov Chain Monte Carlo (MCMC)

Results

Data:

Baseline $\mathscr{D}$: Plank high ℓ TTTEEE, Planck low ℓ EE, Planck low ℓ TT, Plank lensing, BAO eBOSS DR16, BAO small z, PANTHEON+

Hubble tension $\mathscr{H}$: SH0ES; EFTofLSS $\mathscr{F}$: EFTofBOSS, EFTofeBOSS (PyBird)

S_8 tension $\mathscr{S}$: KiDS-1000x & DES-Y3 Combined

Model:

$m_p = 1$ GeV, iDM-DR interaction coupling $\alpha_e = 10^{-2}$, 3 ν flavors

Free Parameters: f_χ, $\Delta N_{\rm eff}$, m_e/m_p

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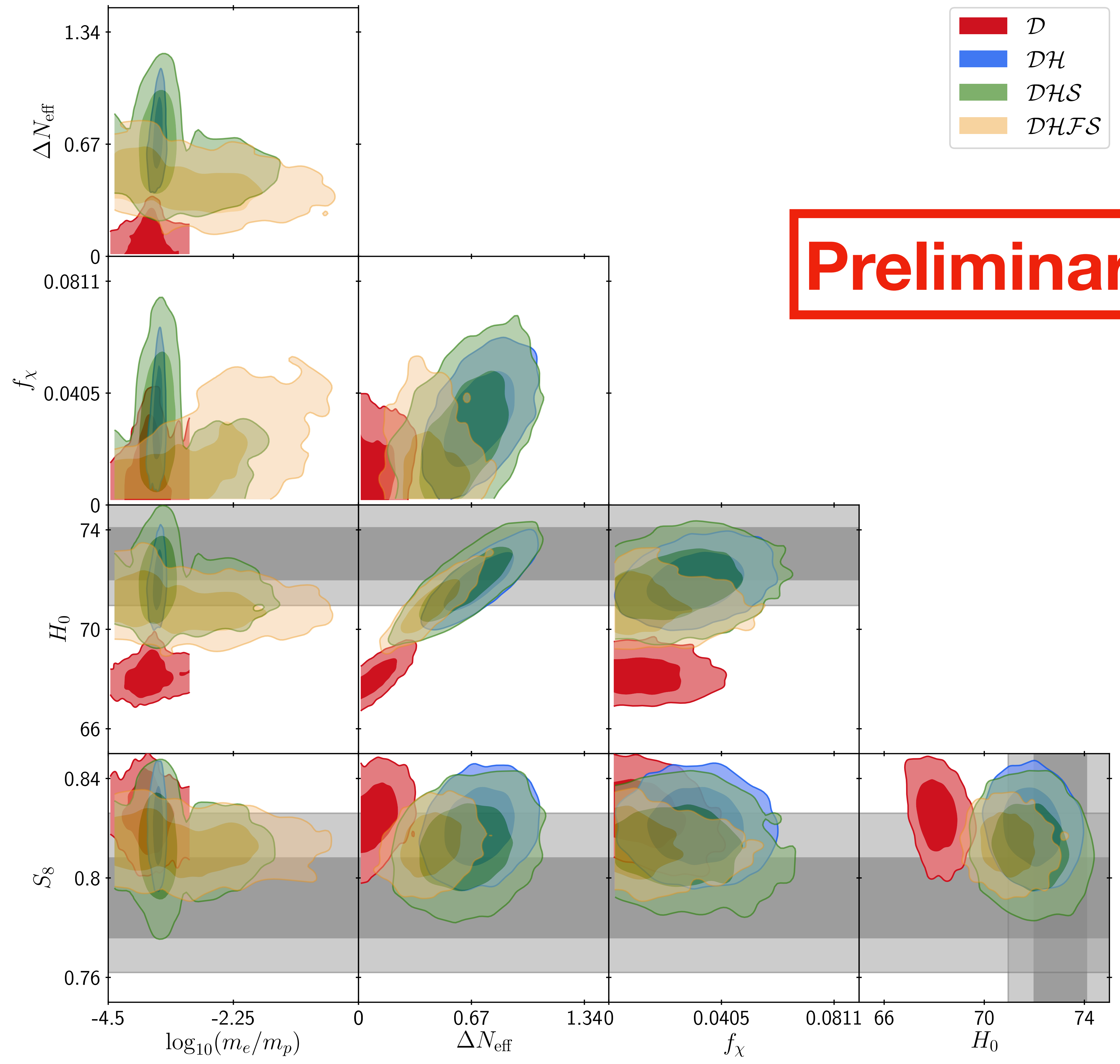

Preliminary

Best fit

Model	D	DH	DHS	DHFS
$\Delta\chi^2$	-1.14	-29.4	-28.0	-24.5
ΔAIC	4.86	-23.4	-22.0	-18.5

Model	ΔN_{eff}	f_χ	H_0	S_8
DH	0.74	3.3%	71.99	0.82
DHS	0.70	3.2%	72.01	0.81
DHFS	0.59	1.2%	71.73	0.81

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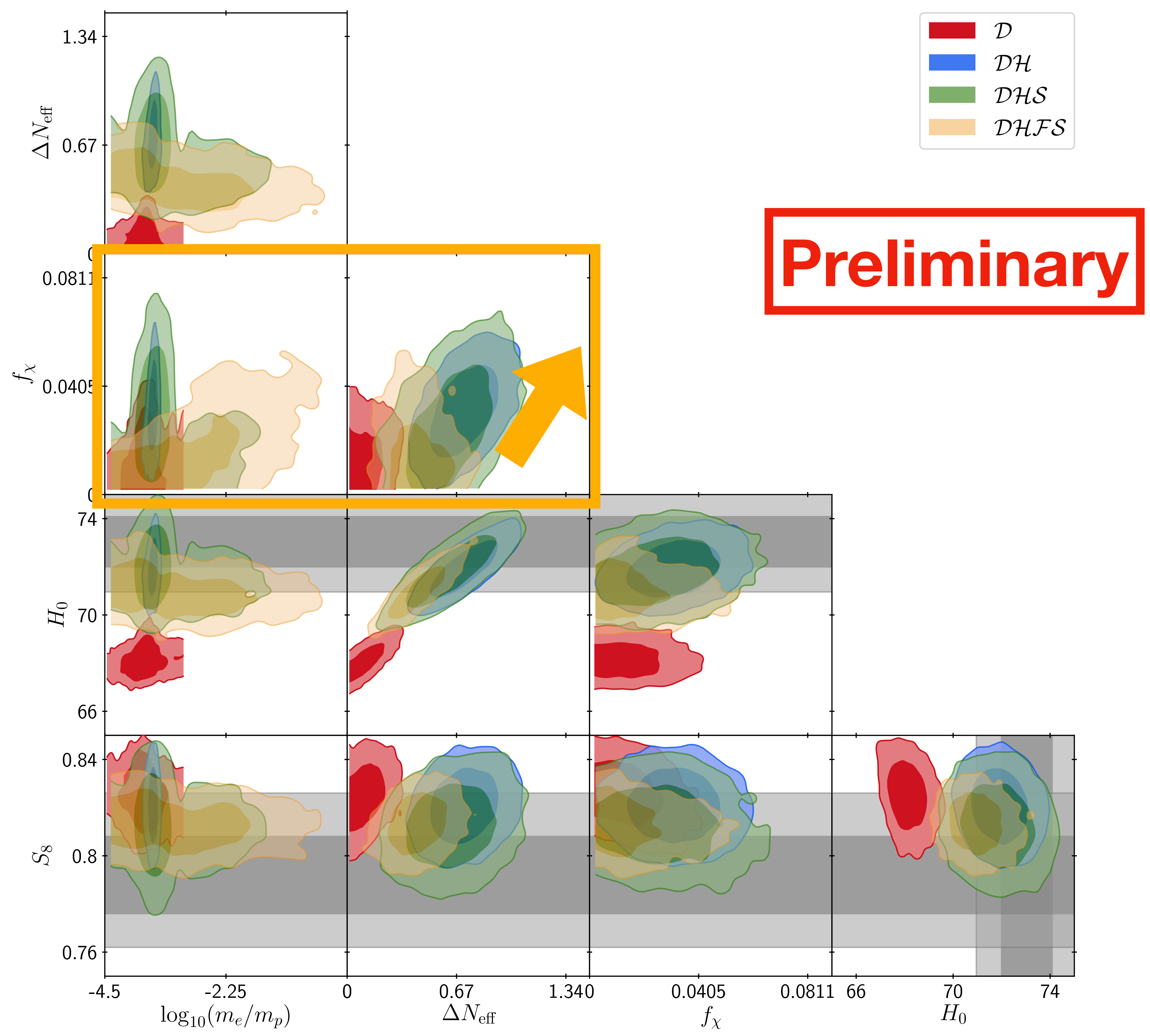

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Conclusions

Summary and Outlook

Non-trivial Dark Sector is highly motivated

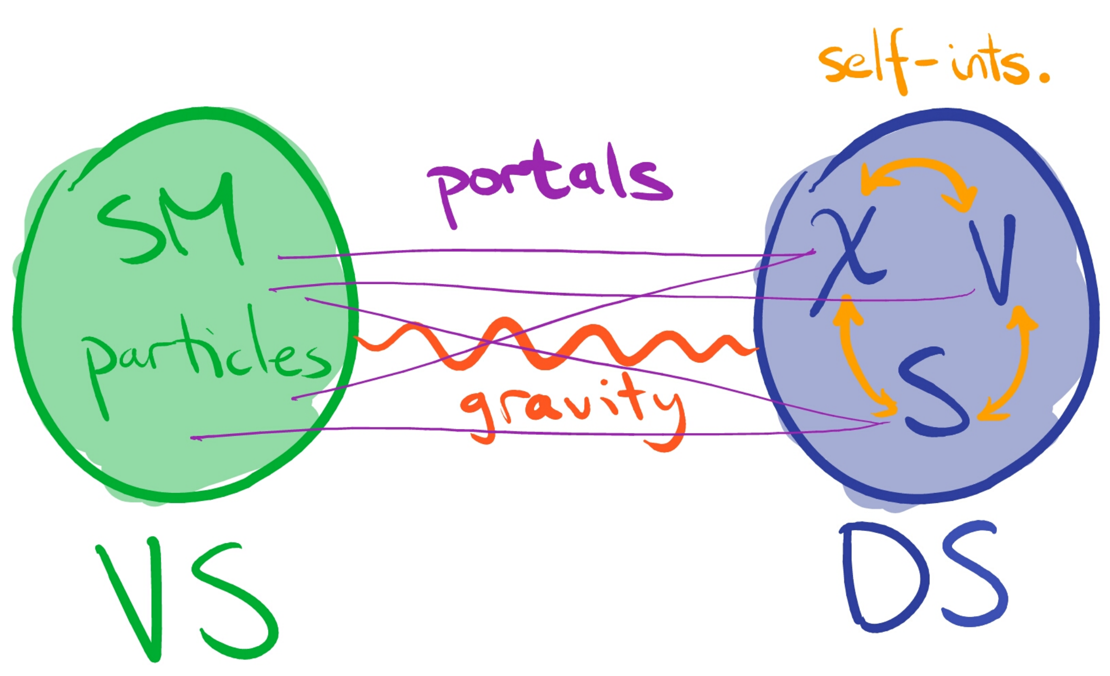
Dark Acoustic Oscillation leave unique signatures on cosmological observables

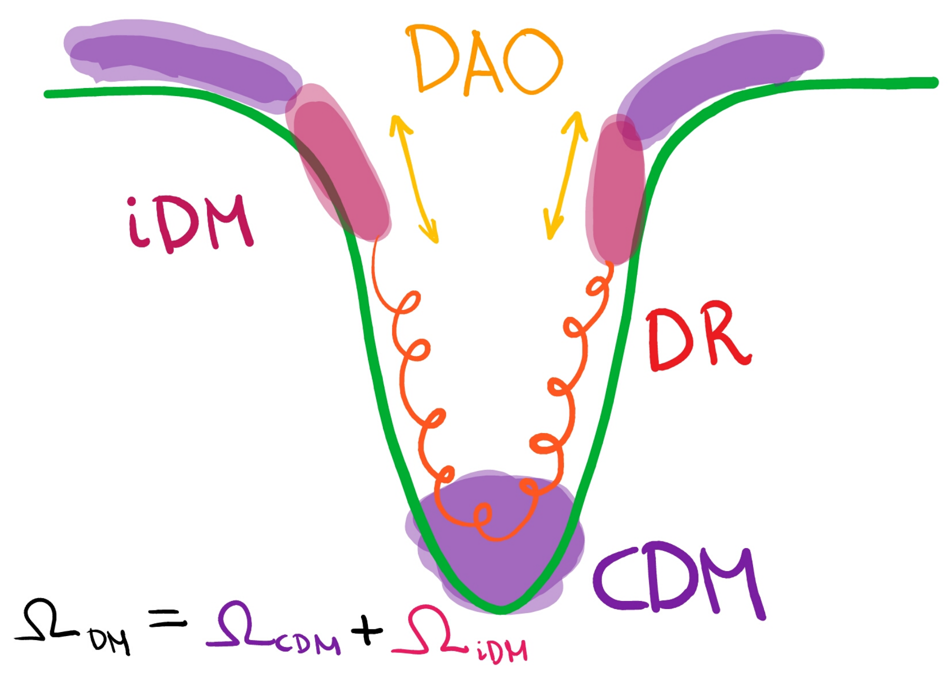
Possible solutions to Hubble / S_8 tensions in ΛCDM

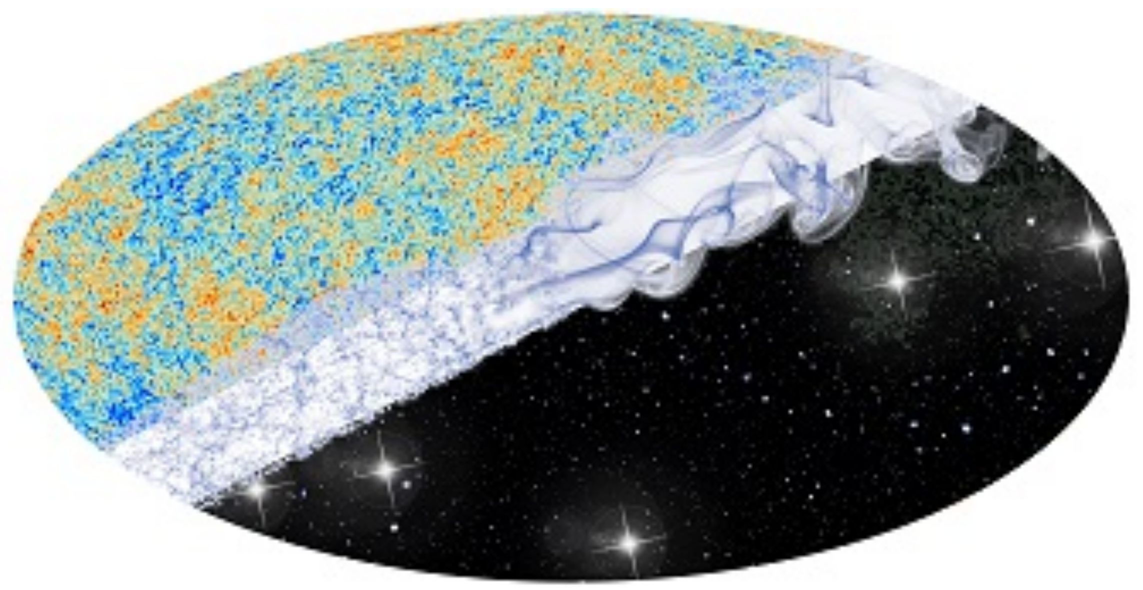
νADM

Interaction within DS is all you need

Will be probed in the future experiments!







Good ν's for Atomic Dark Matter

Thank You for Listening!

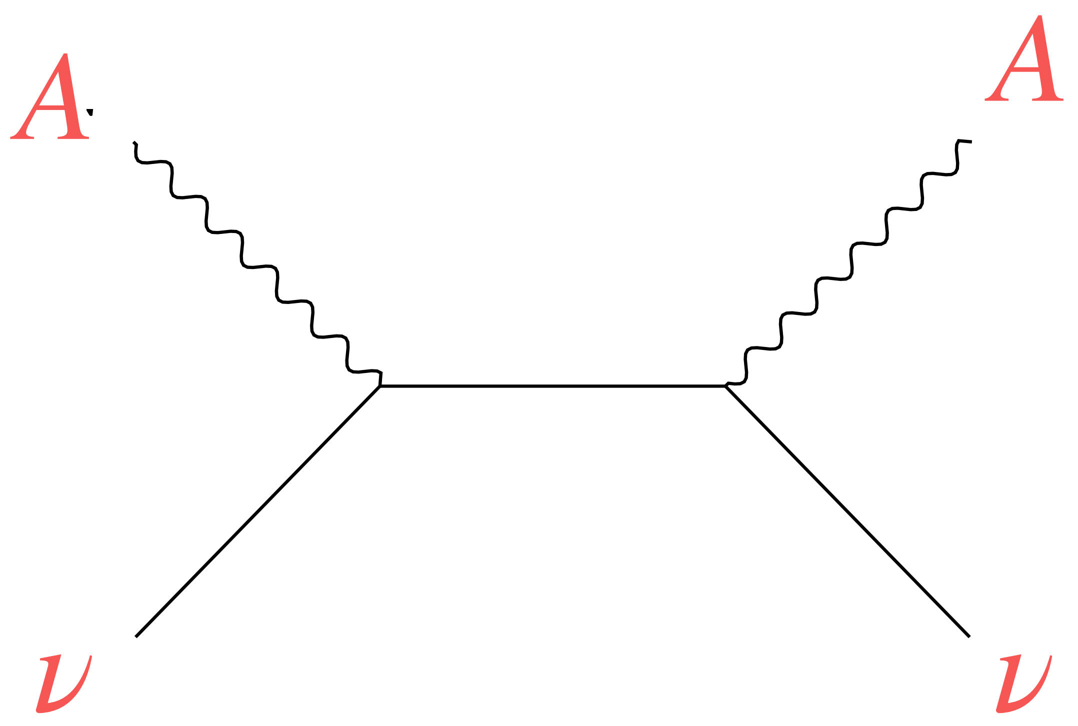
Supplements

Atomic DM + Dark ν

Requirements

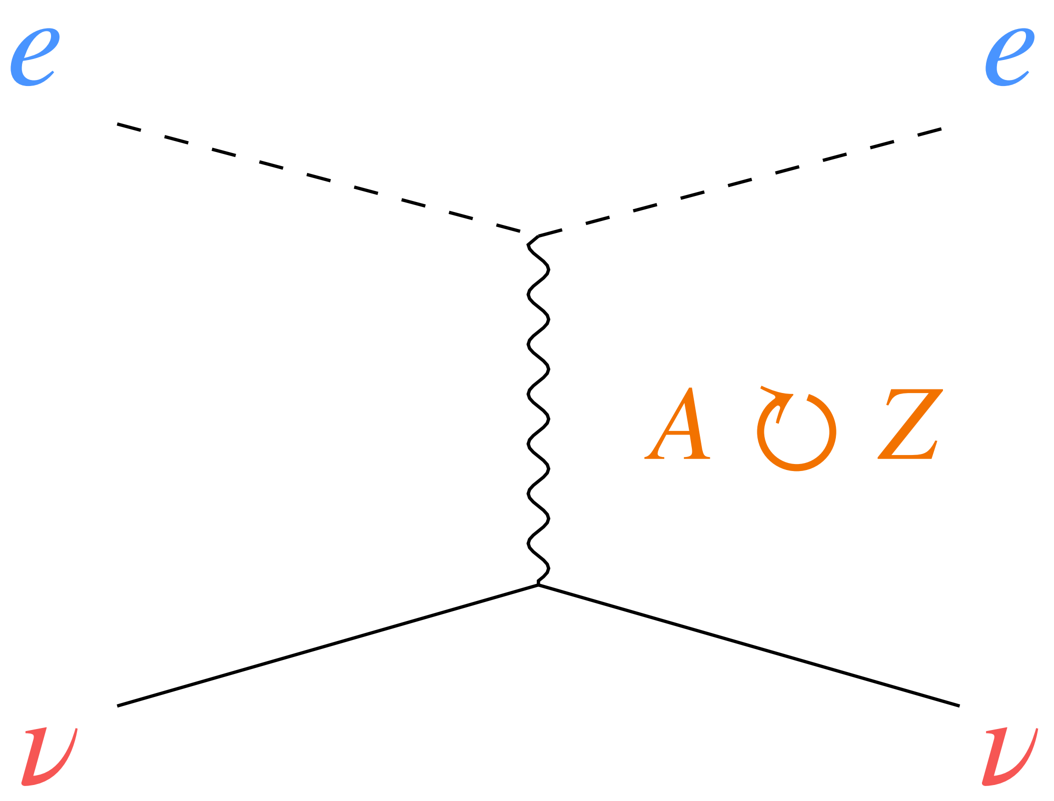
A in equilibrium with ν (DR is self-interacting)

$$\Gamma_{A-\nu} \sim \epsilon^2 \alpha_g^2 T > H \sim \frac{T^2}{M_{pl}} \Rightarrow \epsilon \alpha_g \gtrsim \sqrt{\frac{T}{M_{pl}}} \sim 10^{-13}$$



e - ν not efficient (DM-DR stops after recombination)

$$\Gamma_{e-\nu} \sim \epsilon^2 \alpha_e \alpha_g \frac{T^2}{m_p} < H \sim \frac{T^2}{M_{pl}} \Rightarrow \epsilon^2 \alpha_e \alpha_g < \frac{m_p}{M_{pl}} \sim 10^{-16}$$



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Atomic DM + SIDR

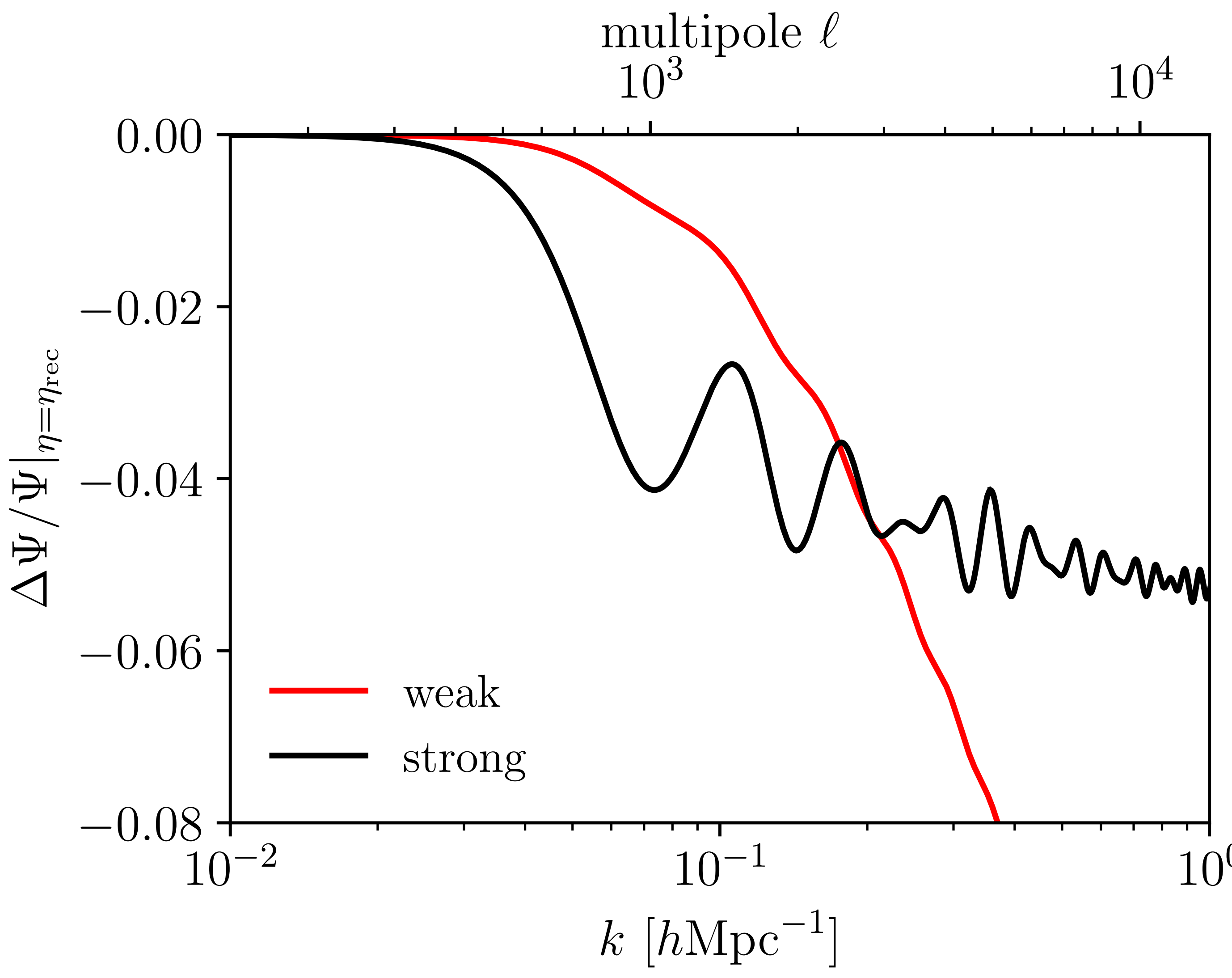
Impact on the CMB

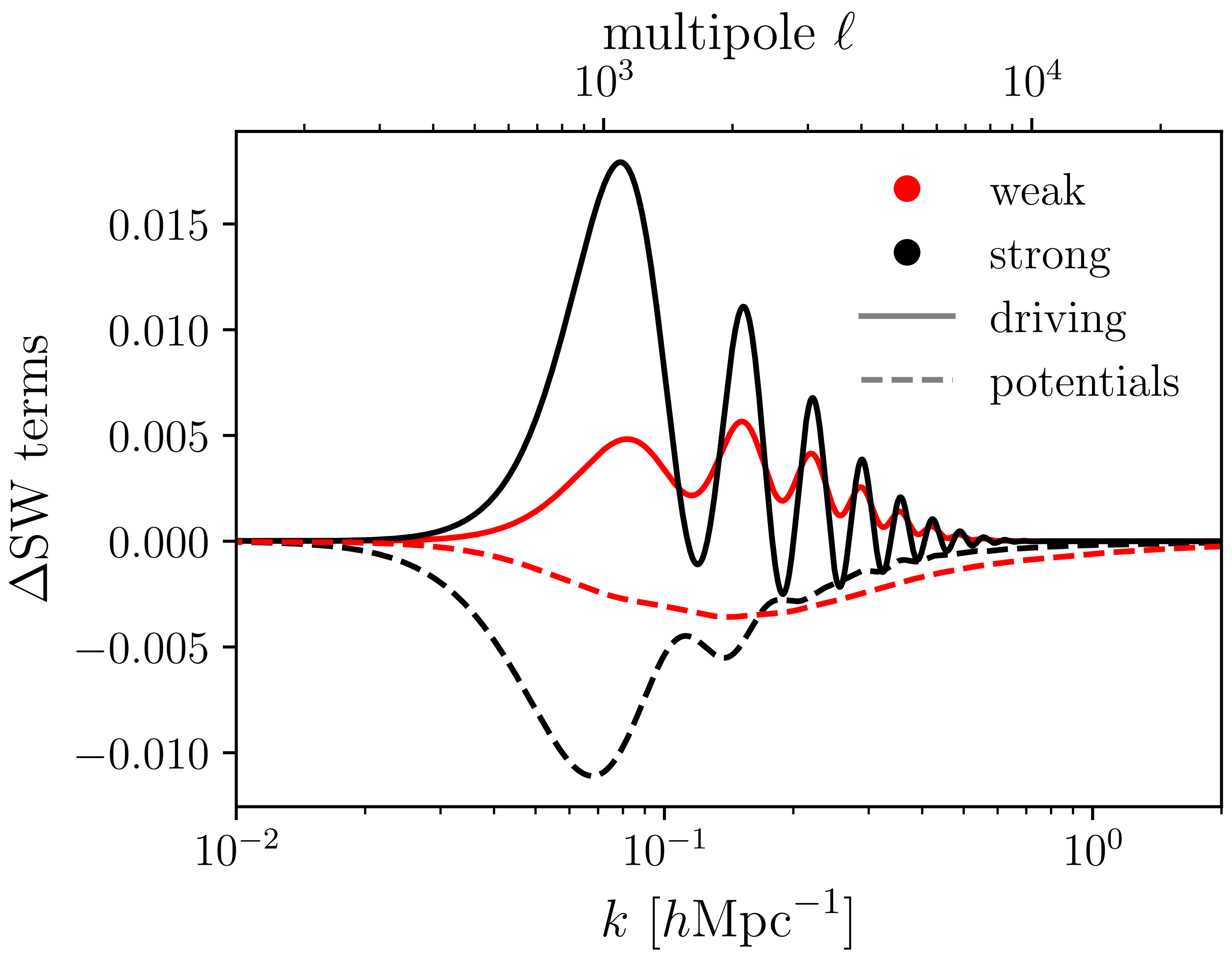
$$\Psi = (\phi + \psi)/2$$
$$r_s(\eta) \simeq \eta/\sqrt{3}$$

free oscillations **driving** **potential**

$$\left(\frac{\Delta T(\mathbf{k},\eta)}{T_{\mathrm{CMB}}}\right)_{\mathrm{SW}} \simeq \zeta(\mathbf{k})\left[e^{-k^2/k_D^2}\left\{-\cos\left(\frac{k\eta}{\sqrt{3}}\right) - \frac{2k}{\sqrt{3}}\int_0^\eta d\eta' \Psi(k,\eta')\sin\left(\frac{k[\eta-\eta']}{\sqrt{3}}\right) + \phi(k,\eta)\right\} + \psi(k,\eta)\right]$$

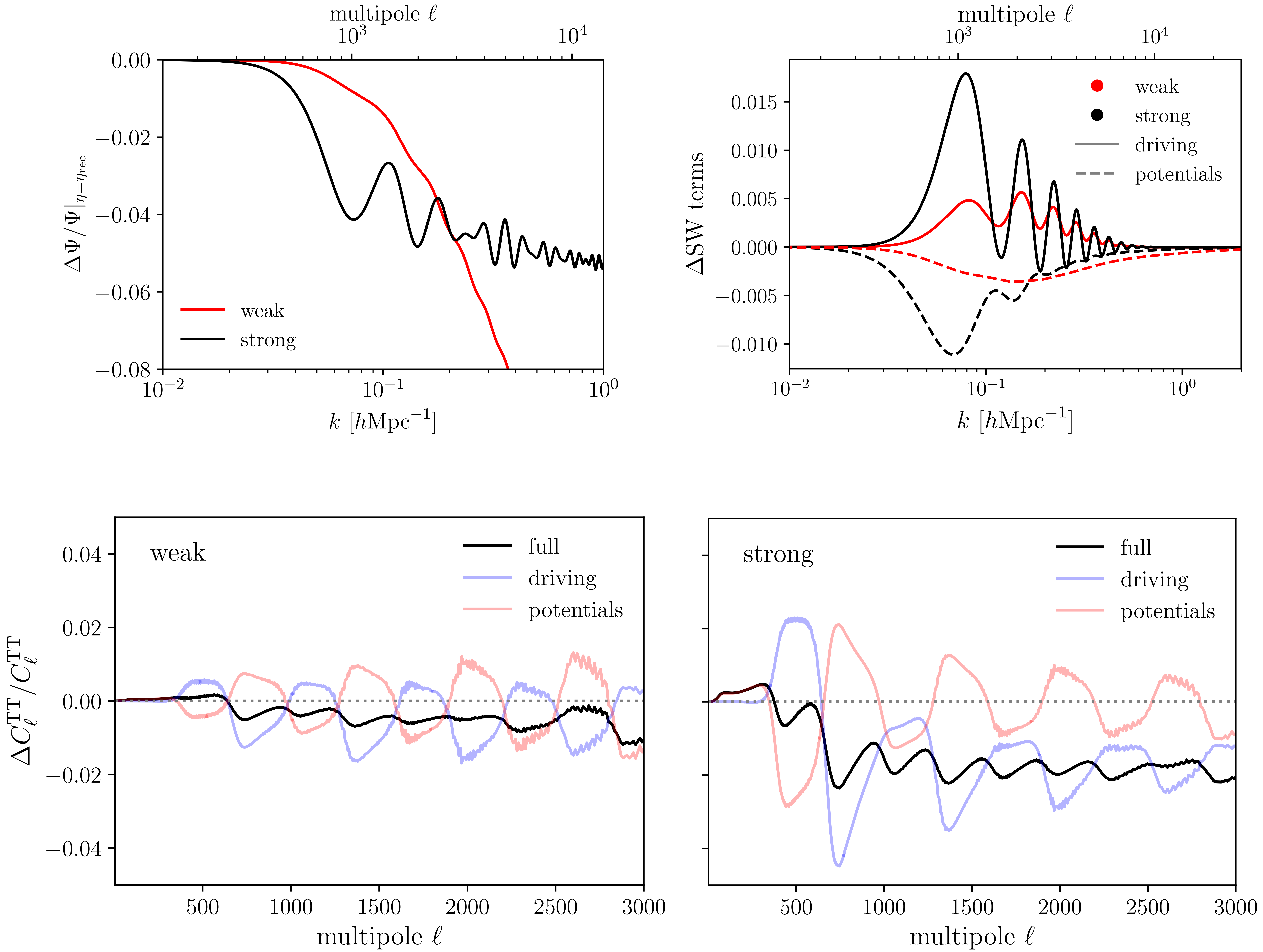
gravitational redshift





$$\ell \simeq k\eta_0$$

N. Schöneberg et al. [arXiv:2306.12469]



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