

Stepped Partially Acoustic Dark Matter

M. A. Buen-Abad, Z. Chacko, C. Kilic, G. Marques-Tavares, & TY

arXiv: 2208.05984

arXiv: 2305.xxxxx



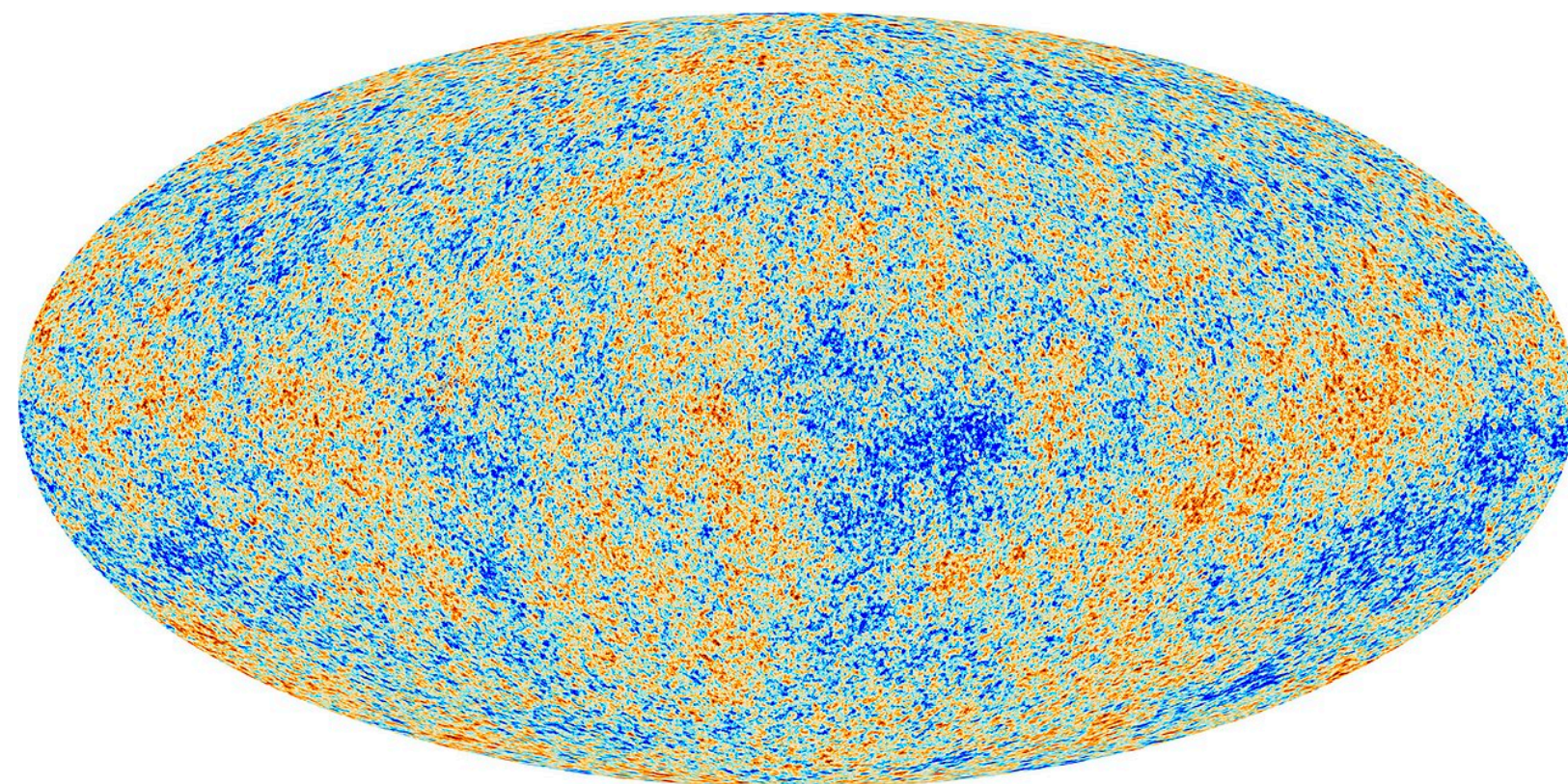
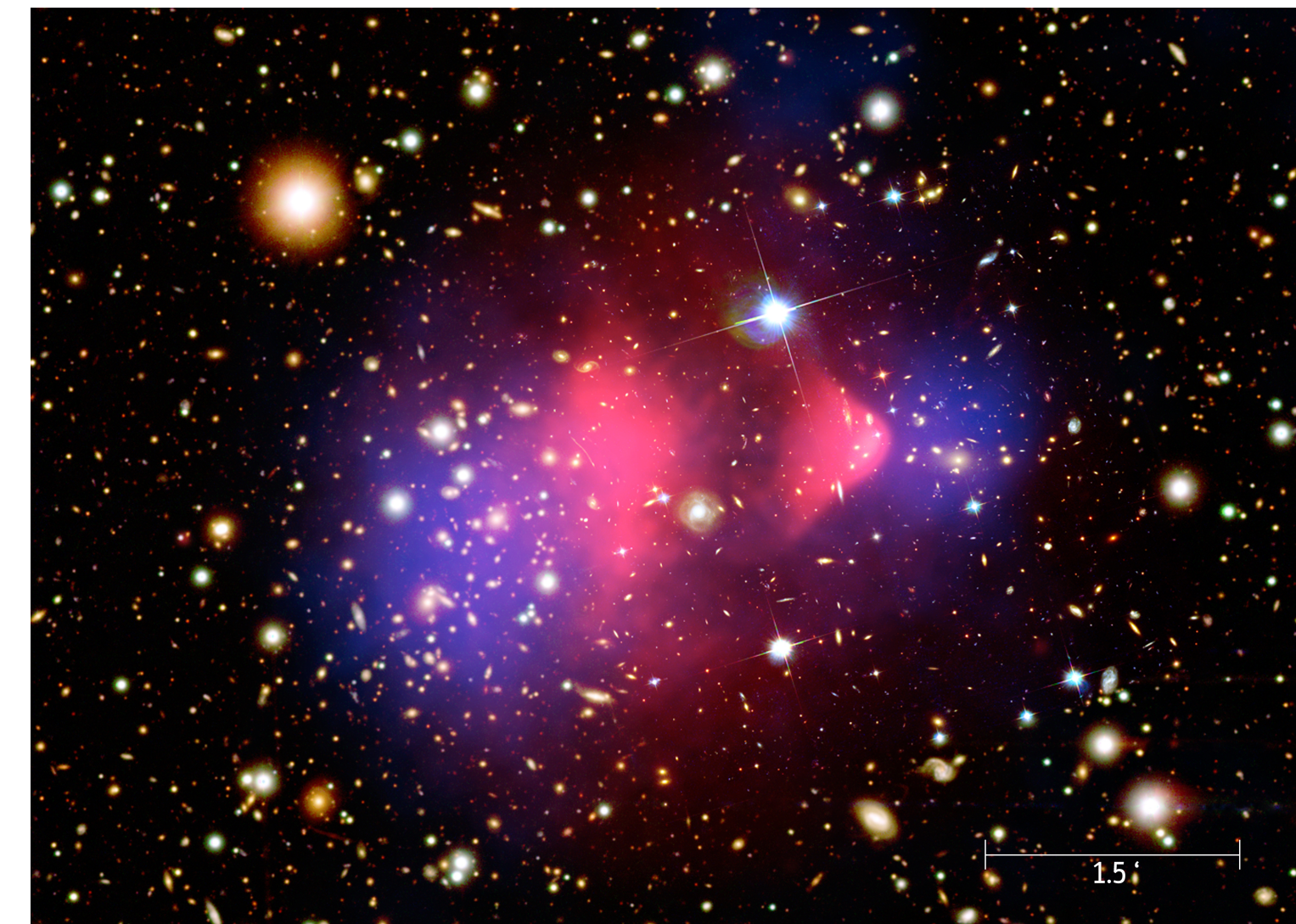
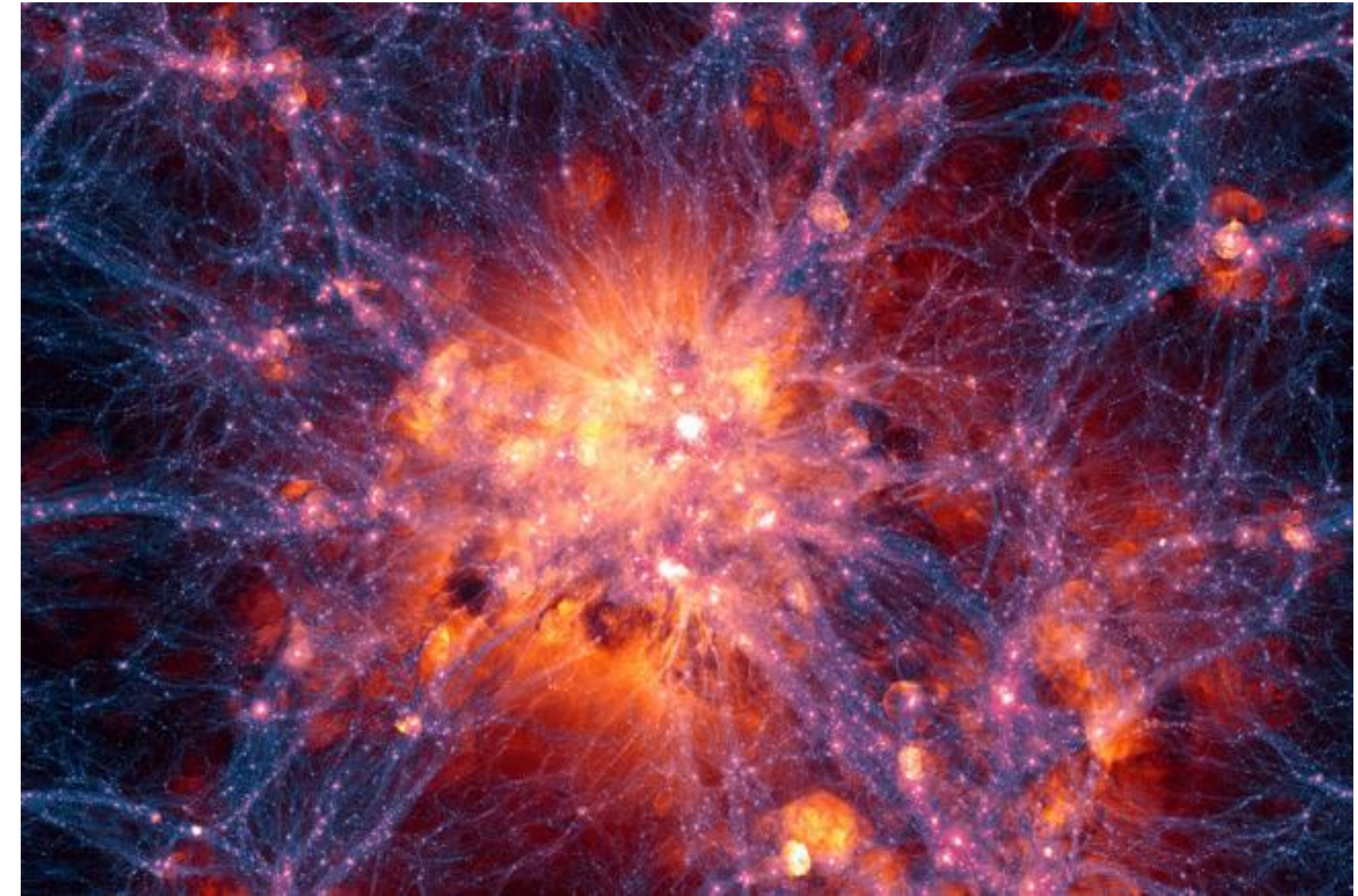
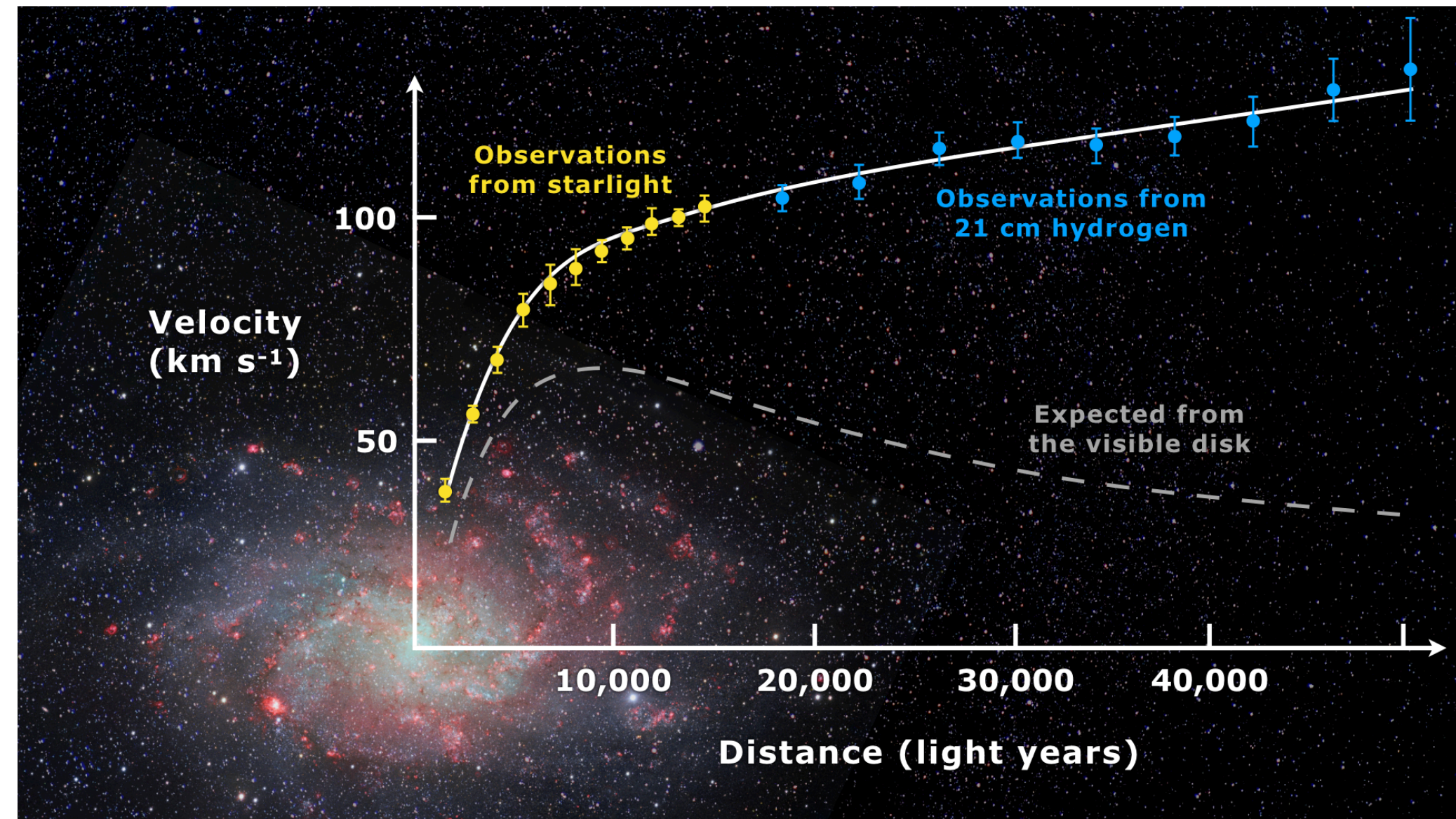
Taewook Youn
The University of Texas at Austin

Mitchell Conference 2023
MAY 16th 2023



Dark Matter

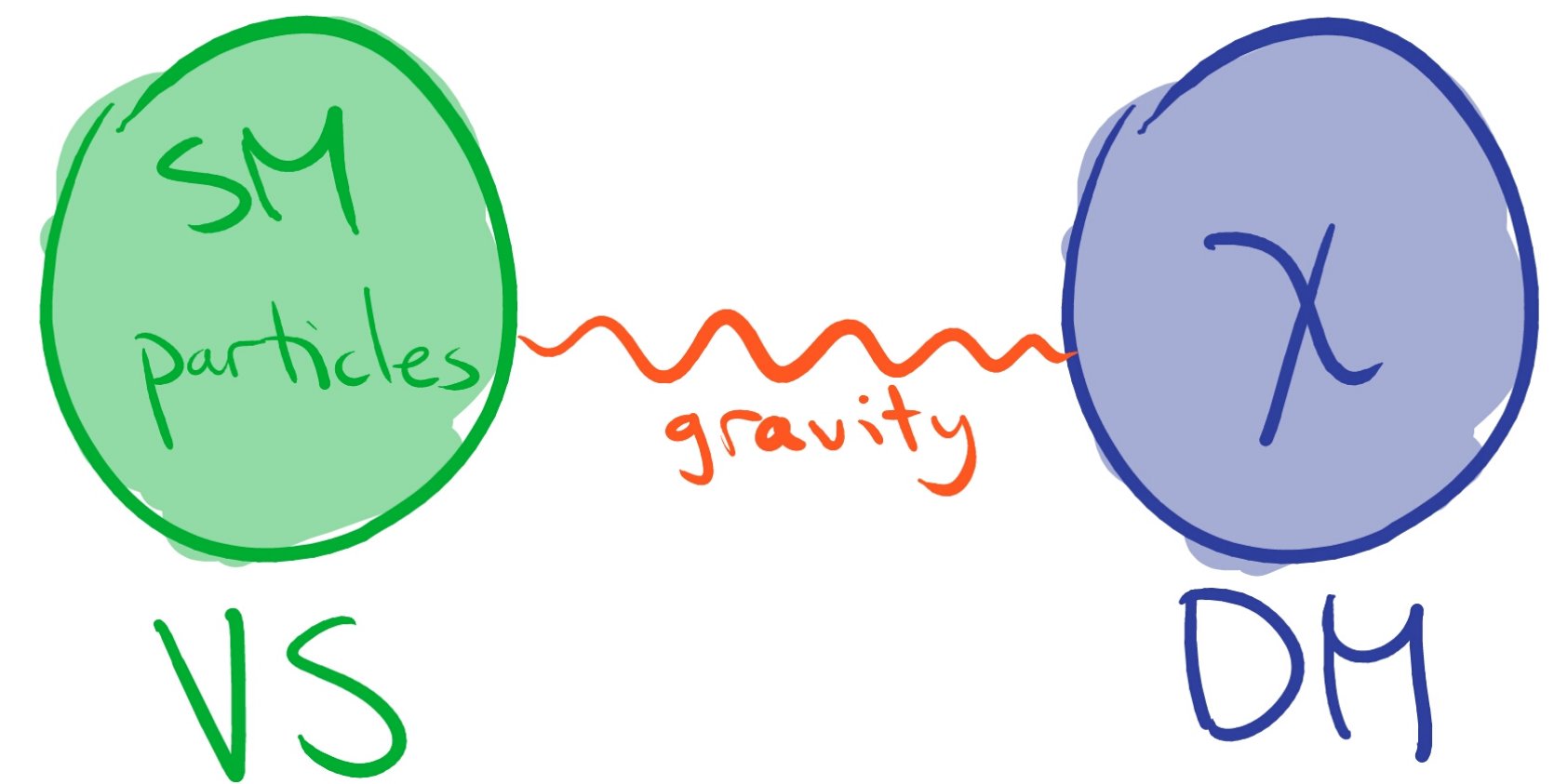
Evidence



Dark Matter

Dark Sector

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



Dark Matter

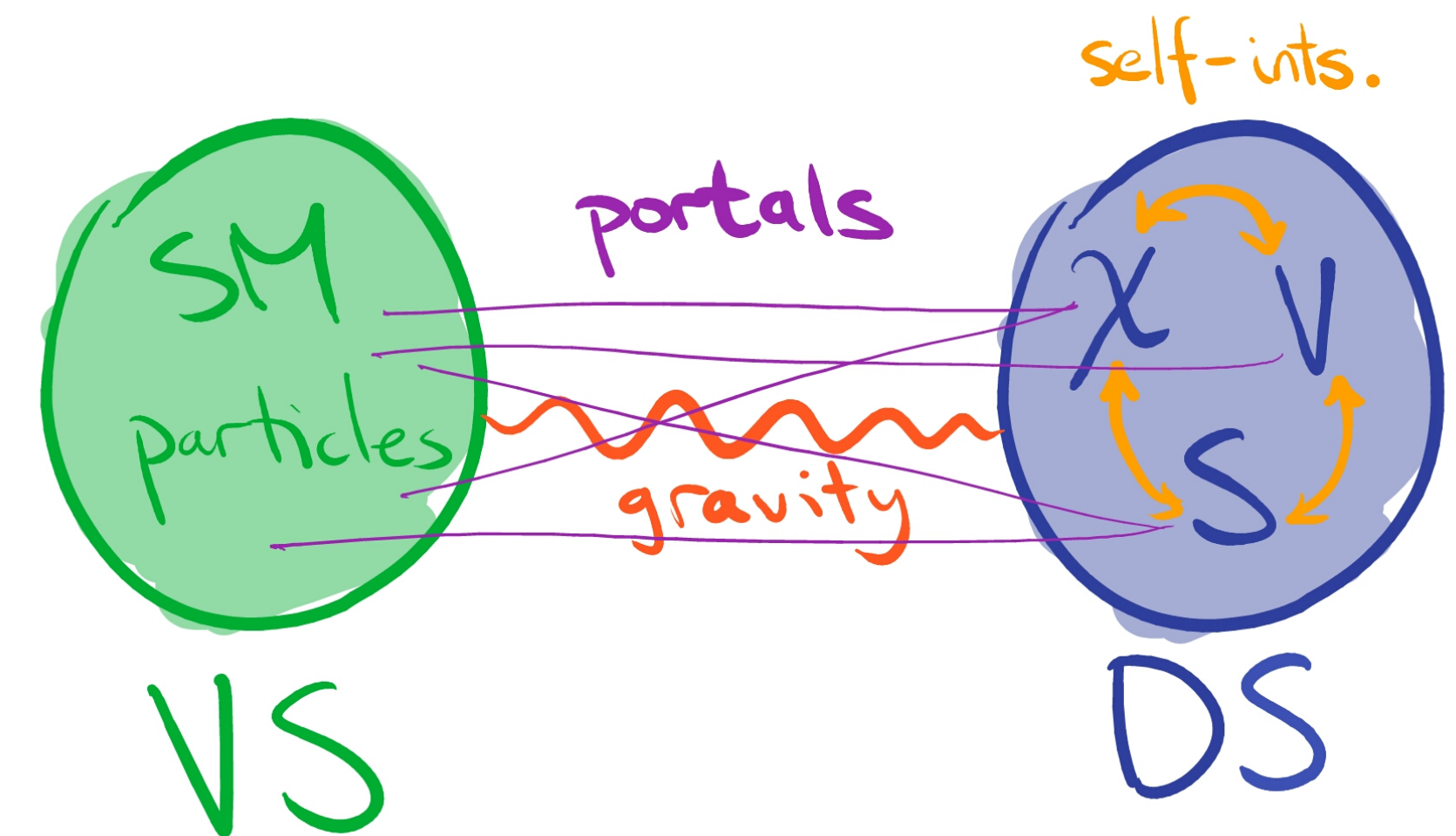
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DM could be just one particle, only interacting with SM via gravitation

Not necessarily!

Multiples States

Various interaction btw SM and DS (portals) or themselves (self-interactions)



Dark Matter

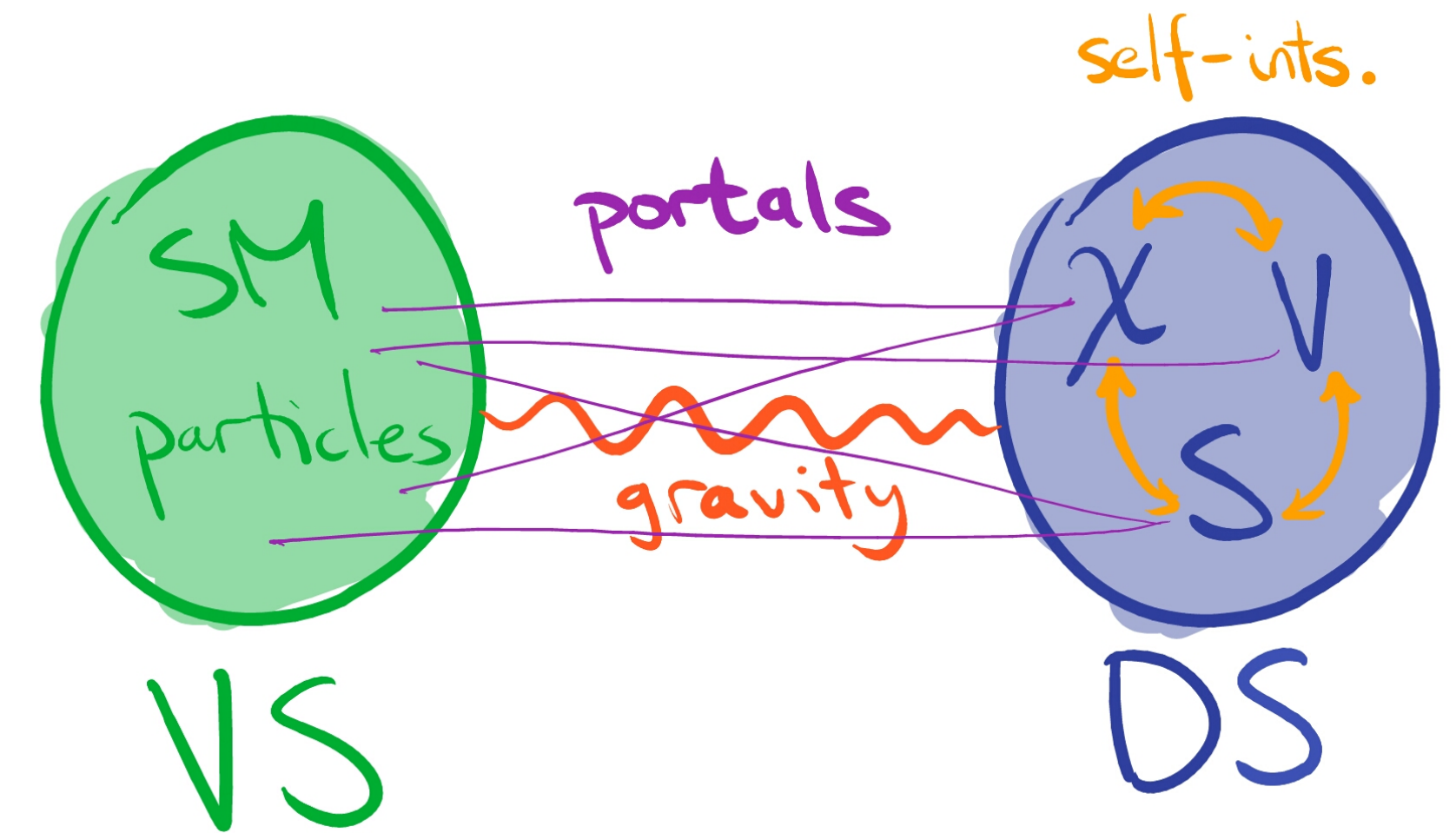
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Various interaction btw SM and DS (portals) or themselves (**self-interactions**)



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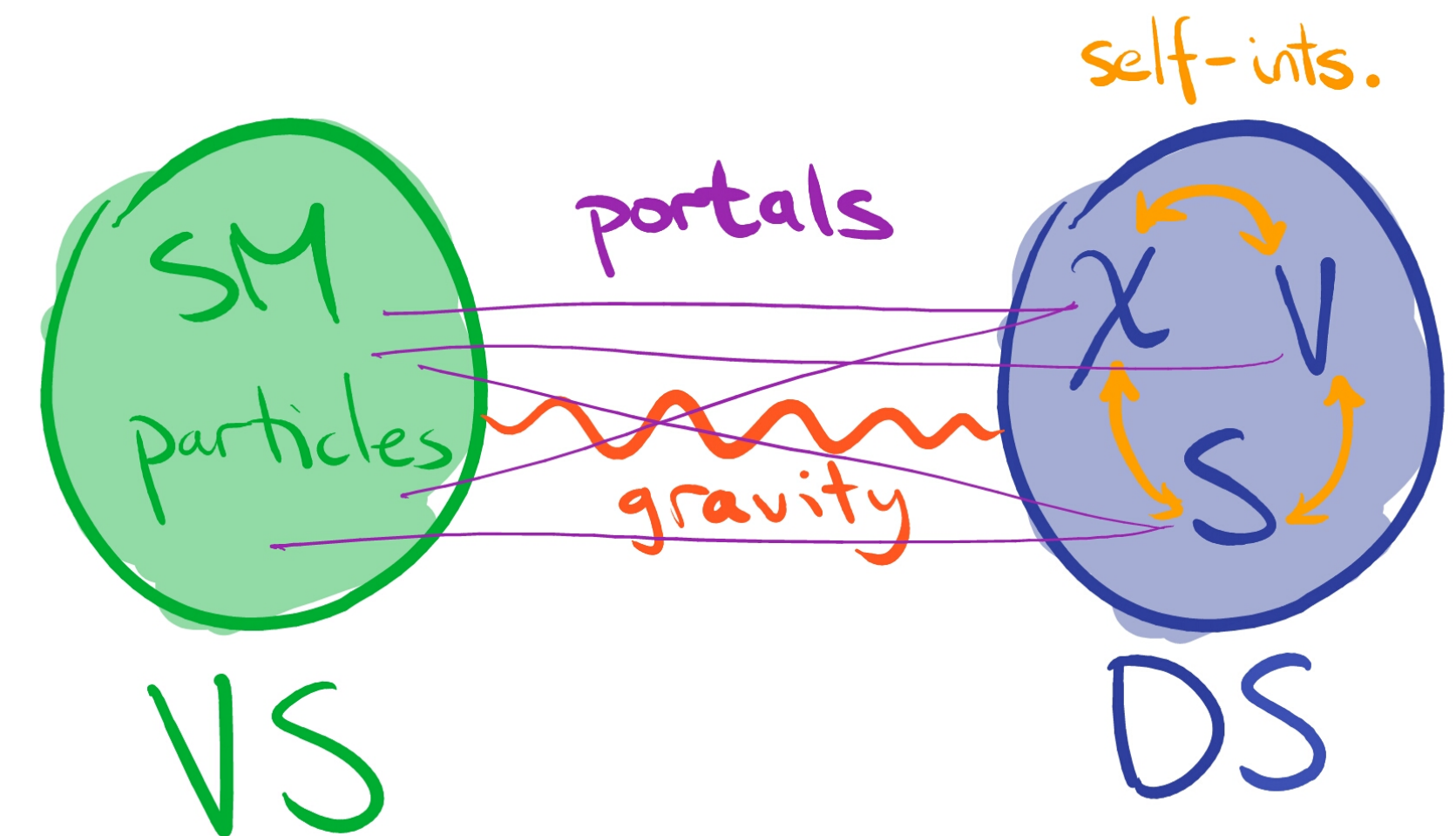
Possible signatures?

Colliders

(In)Direct Detection

Astrophysics

Cosmology



Dark Matter

Dark Sector

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Multiples States

Various interaction btw SM and DS (portals) or themselves (**self-interactions**)

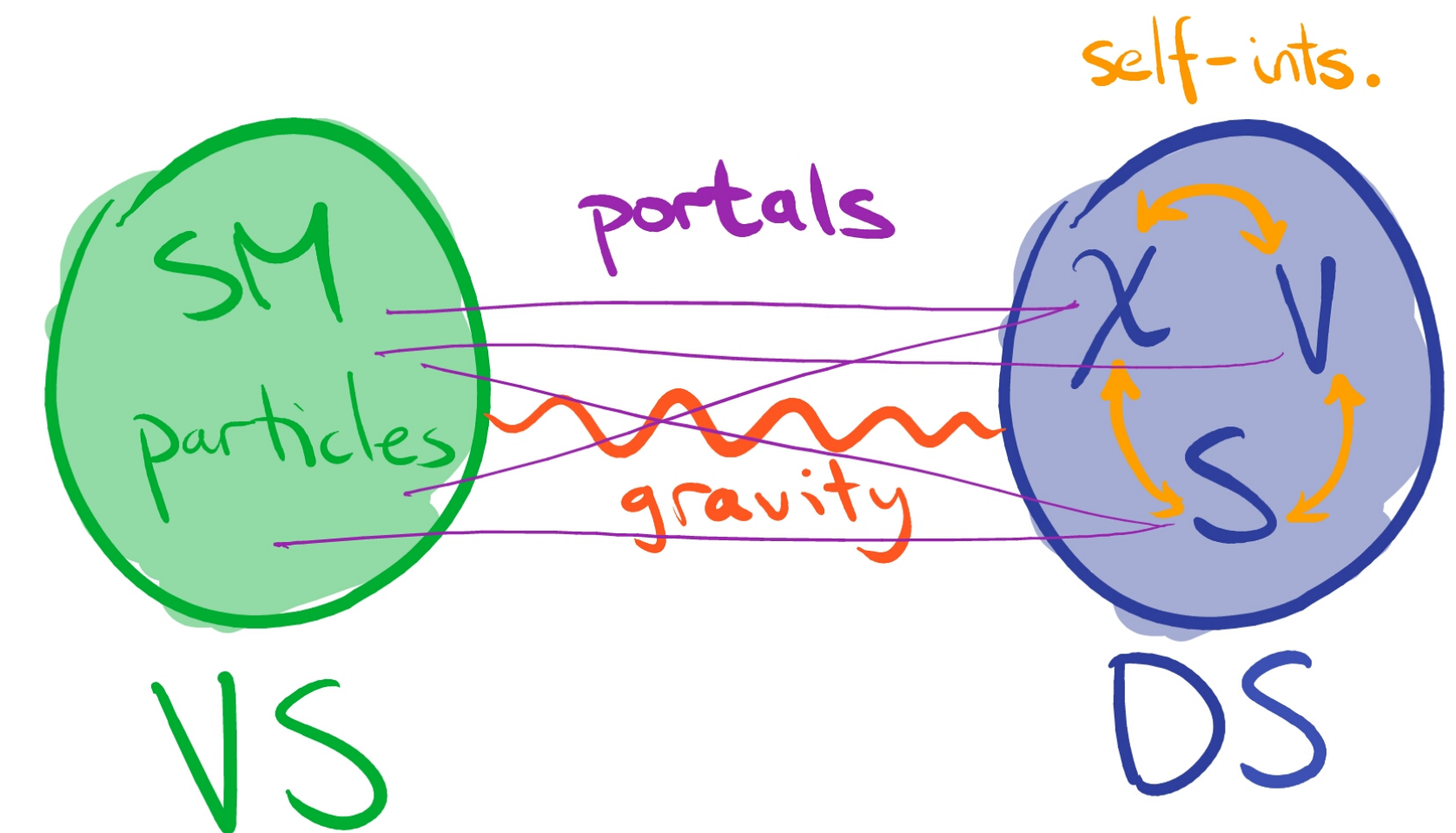
Possible signatures?

Colliders

(In)Direct Detection

Astrophysics

Cosmology: H_0 and S_8 tensions



Cosmological Tensions

Hubble tension ($\sim 4\text{--}6\ \sigma$)

Early Universe

CMB fit to Λ CDM

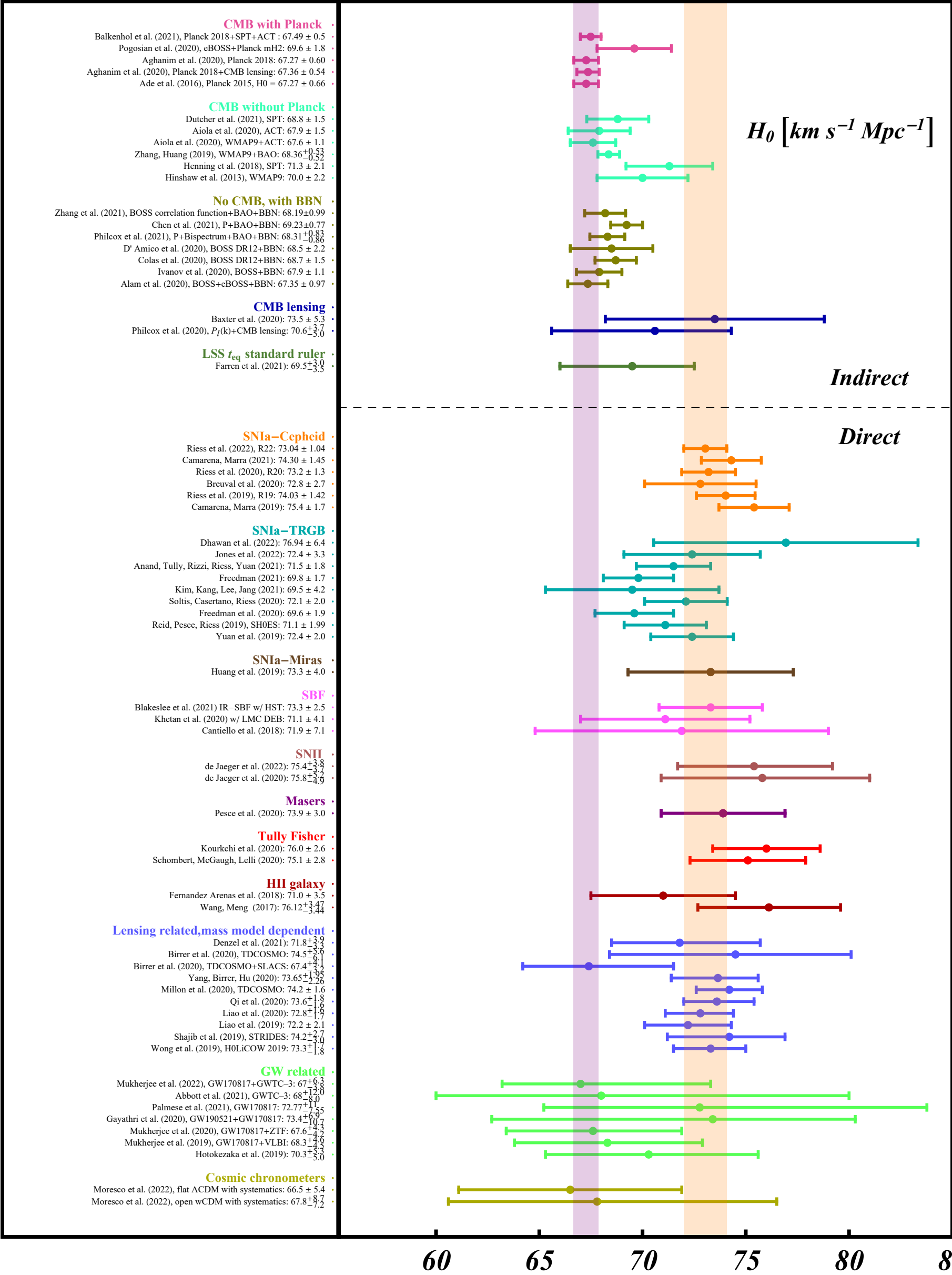
$\sim 68\text{ km/s/Mpc}$ Planck '18 [arXiv:1807.06209]

Late Universe

Local measurements

$\sim 73\text{ km/s/Mpc}$ Riess et al. [arXiv:2112.04510]

$5\ \sigma$ level is one-in-a-million chance that the findings are just a result of random variations



Dark Radiation

A Class of Solutions to Hubble tension

To increase H_0 ,

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

A Solution: Free-streaming Dark Radiation (DR)

Silk damping (diffusion) + Drag effect (supersonic propagation)

Dark Radiation

A Class of Solutions to Hubble tension

To increase H_0 ,

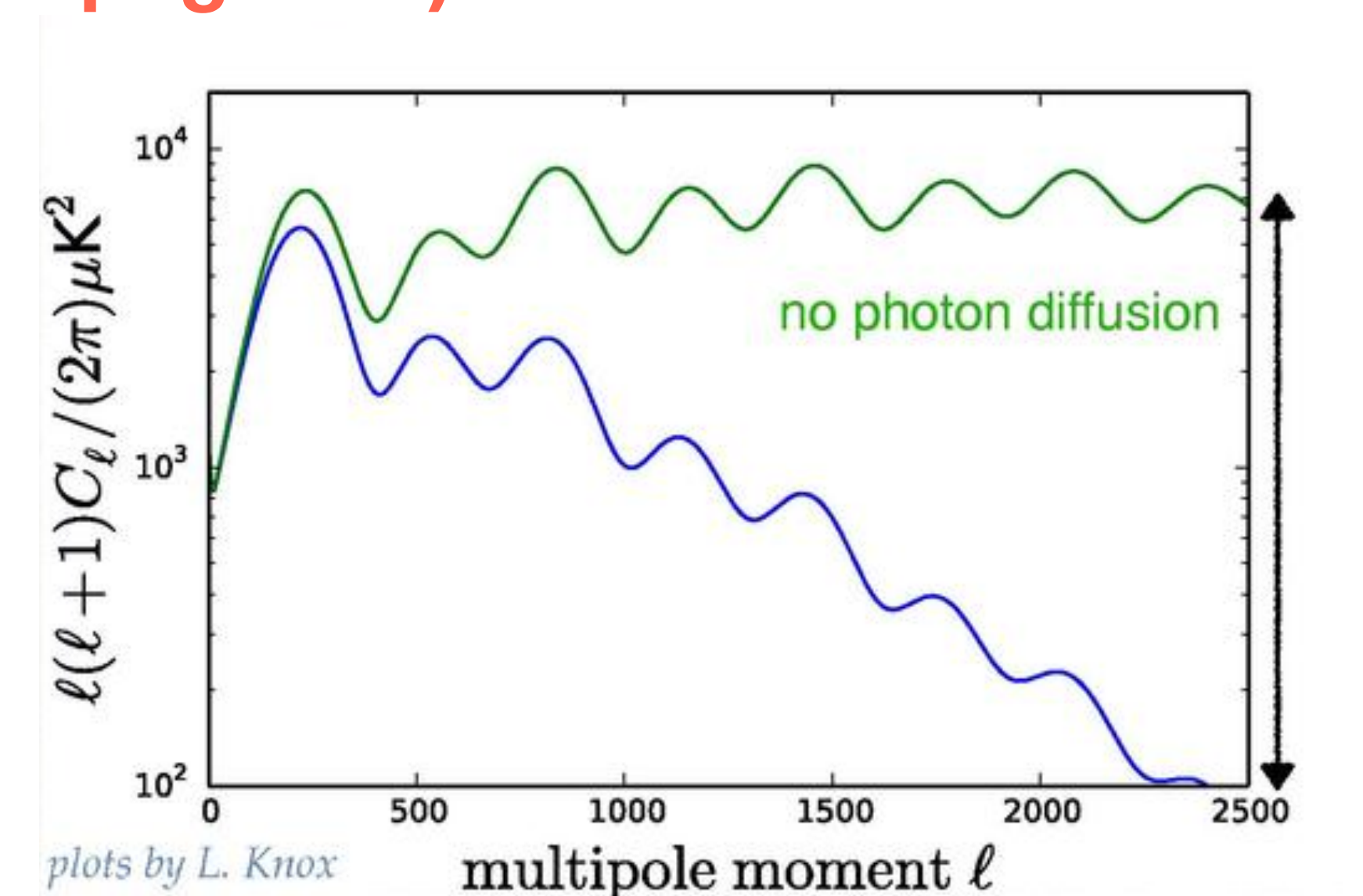
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Better: Self-interacting DR Blinov et al. [arXiv:2003.08387]

Silk damping (diffusion)



Dark Radiation

A Class of Solutions to Hubble tension

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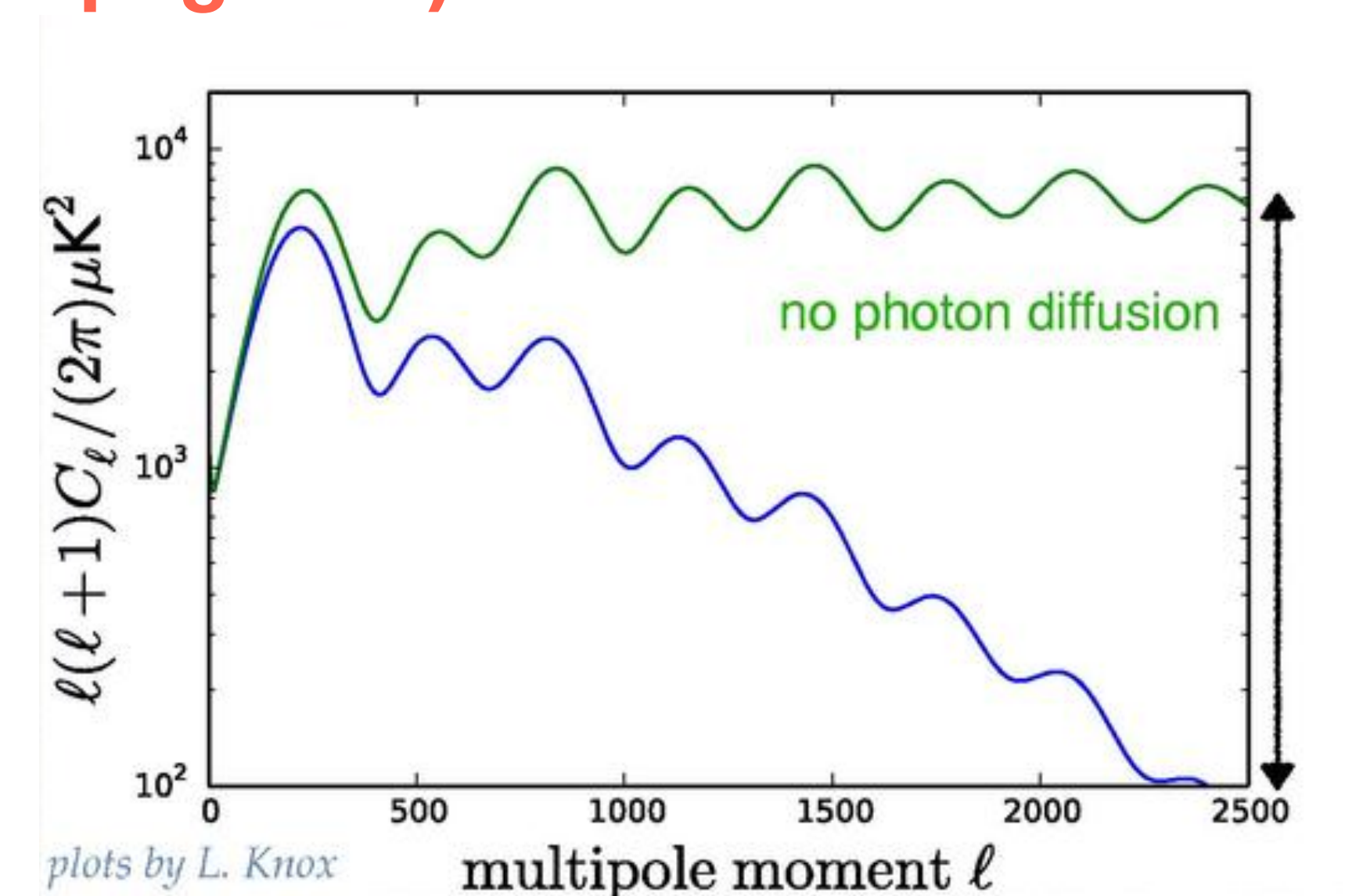
A Solution: Free-streaming Dark Radiation (DR)

Silk damping (diffusion) + Drag effect (supersonic propagation)

Better: Self-interacting DR Blinov et al. [arXiv:2003.08387]

Silk damping (diffusion)

Even Better: Add something to self-interacting DR



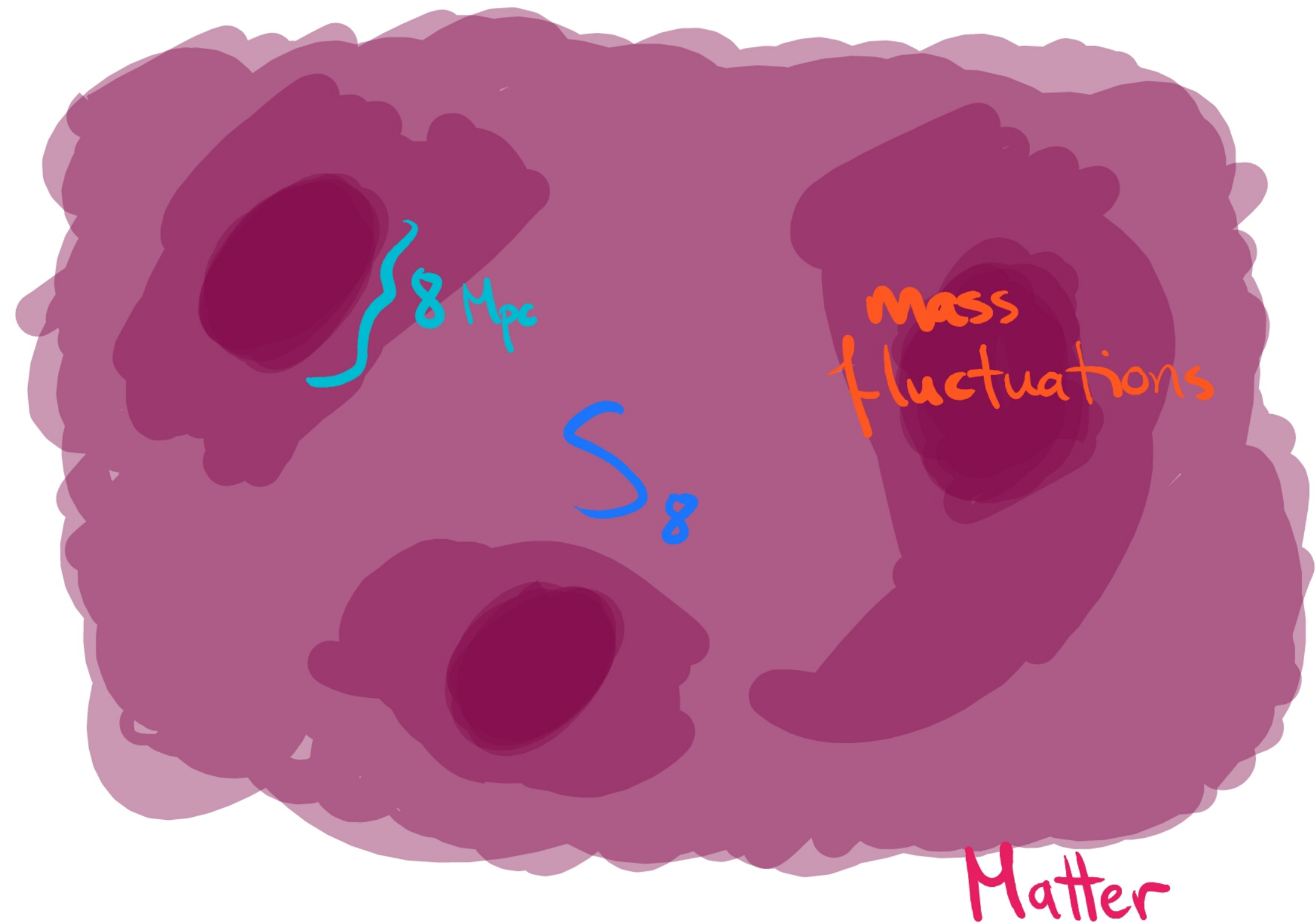
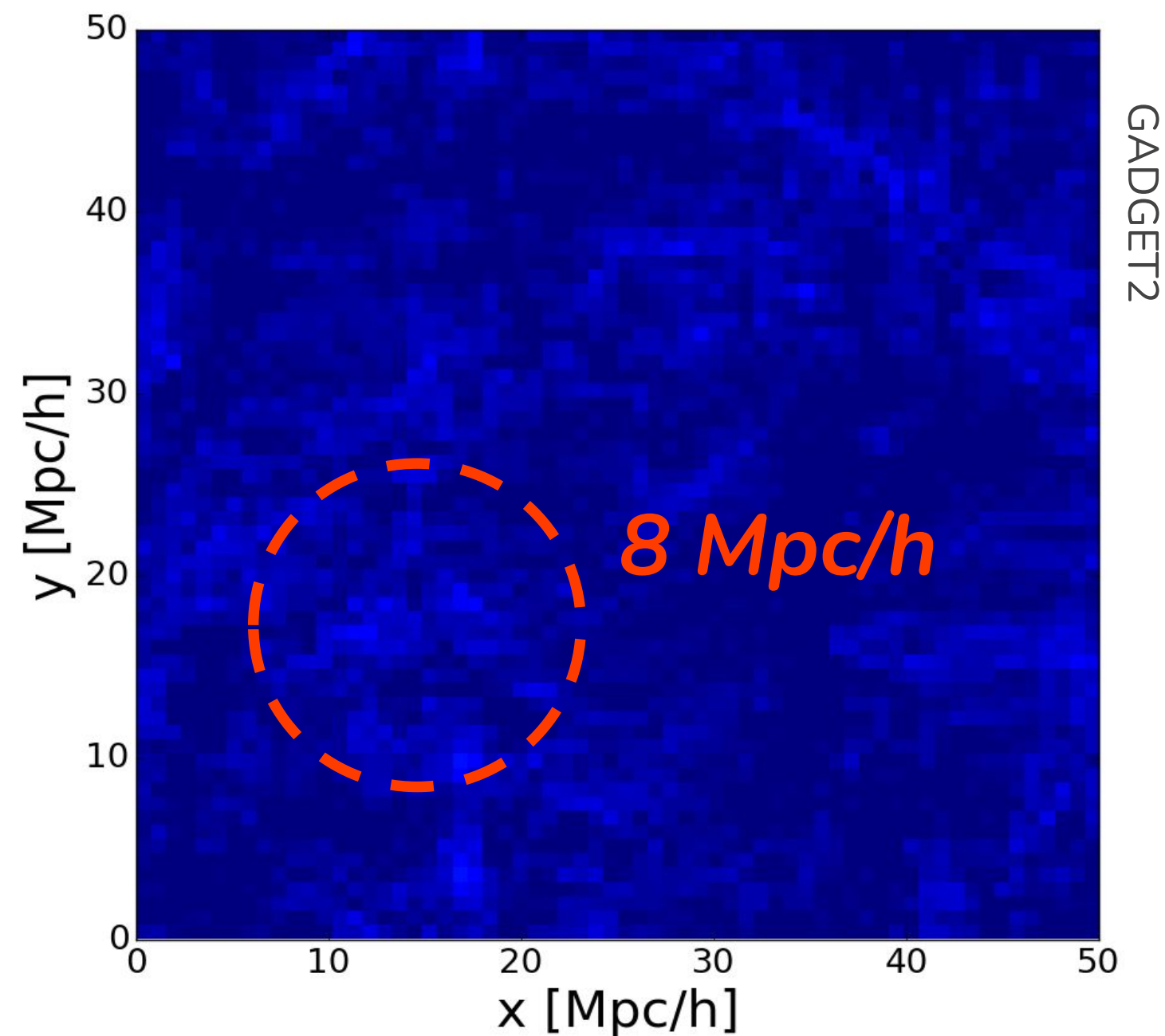
Cosmological Tensions

Snowmass [arXiv:2203.06142]

S_8 tension ($\sim 2-3 \sigma$)

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

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



Cosmological Tensions

S_8 tension ($\sim 2\text{--}3\sigma$)

Early Universe

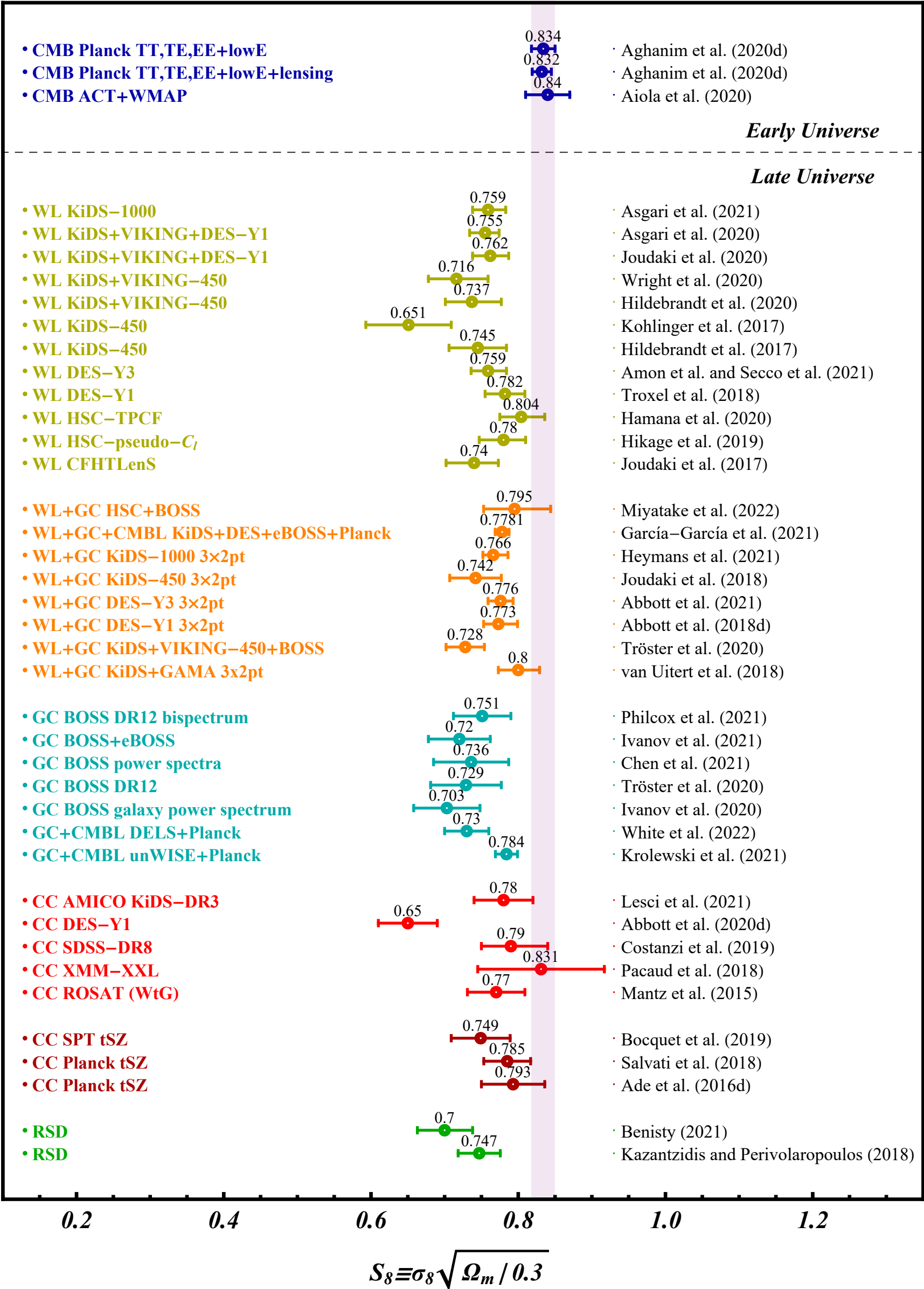
CMB fit to Λ CDM

~ 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 ($\sim 2-3 \sigma$)

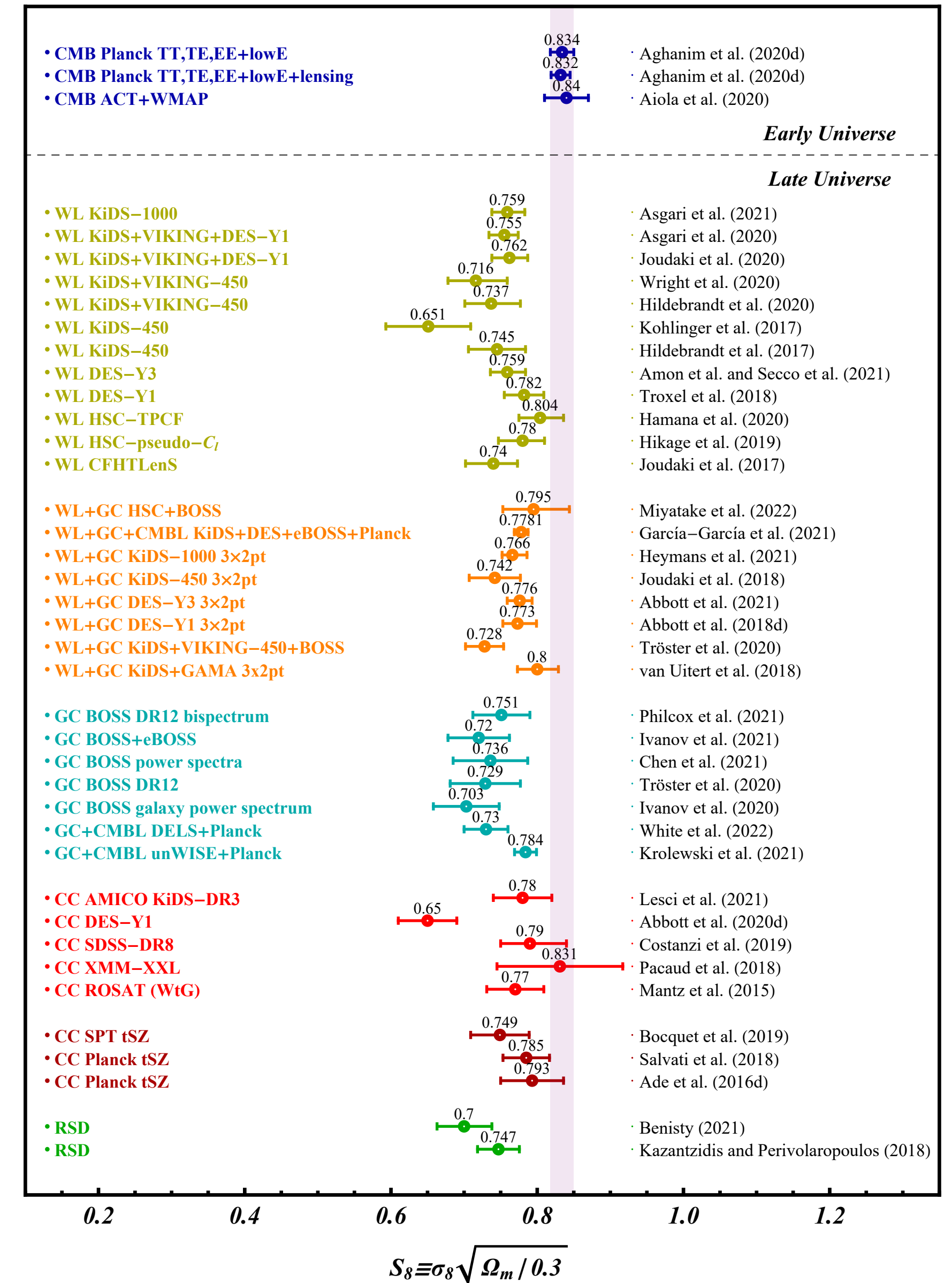
More likely unknown systematic errors

Escudero et al. [arXiv:2208.14435]

DR worsens S_8 tension

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

Another Dark Sector signal?

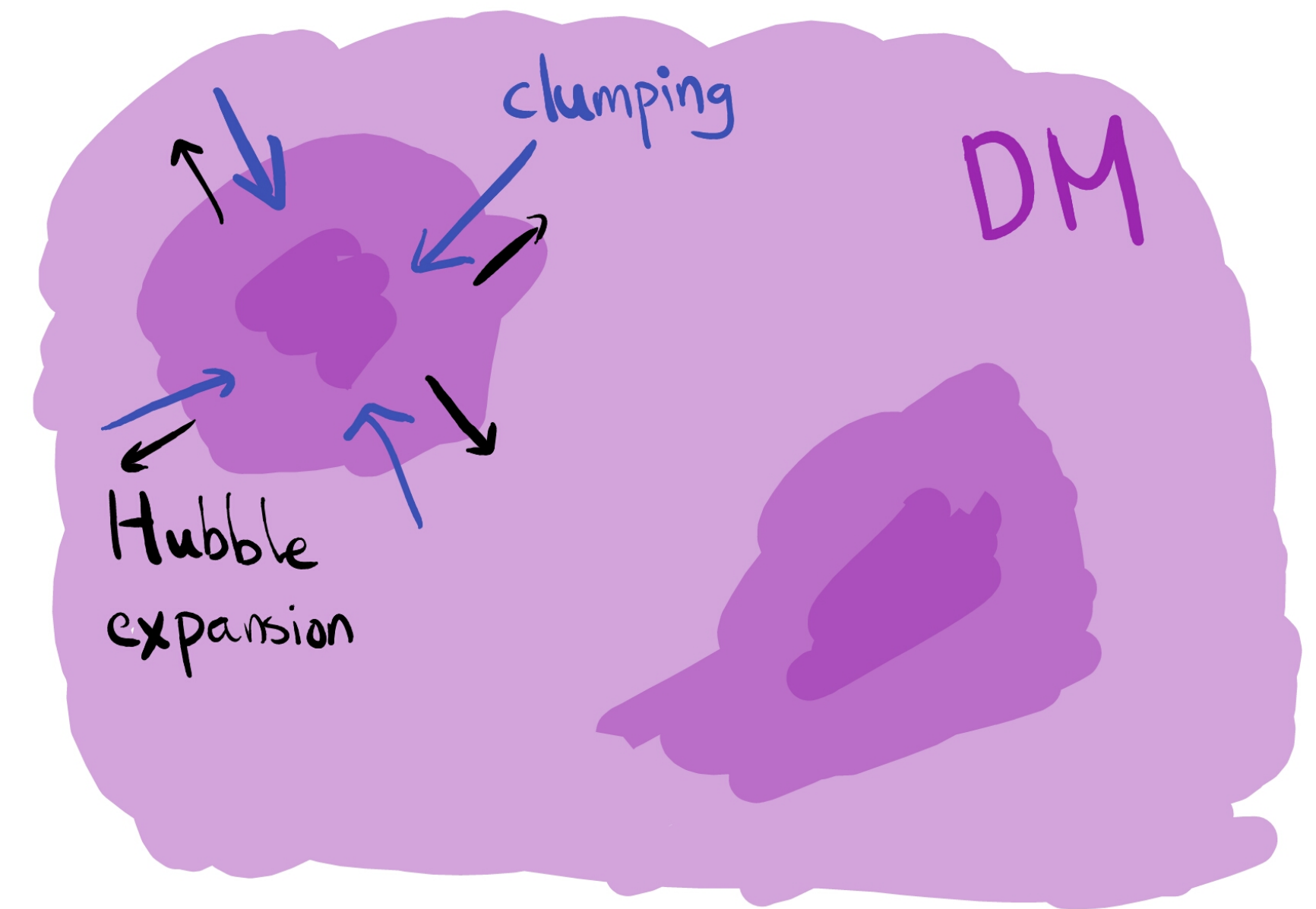


Dark Matter interaction with DR

A Class of Solutions to S_8 tension

Dark Radiation worsens S_8 tension

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



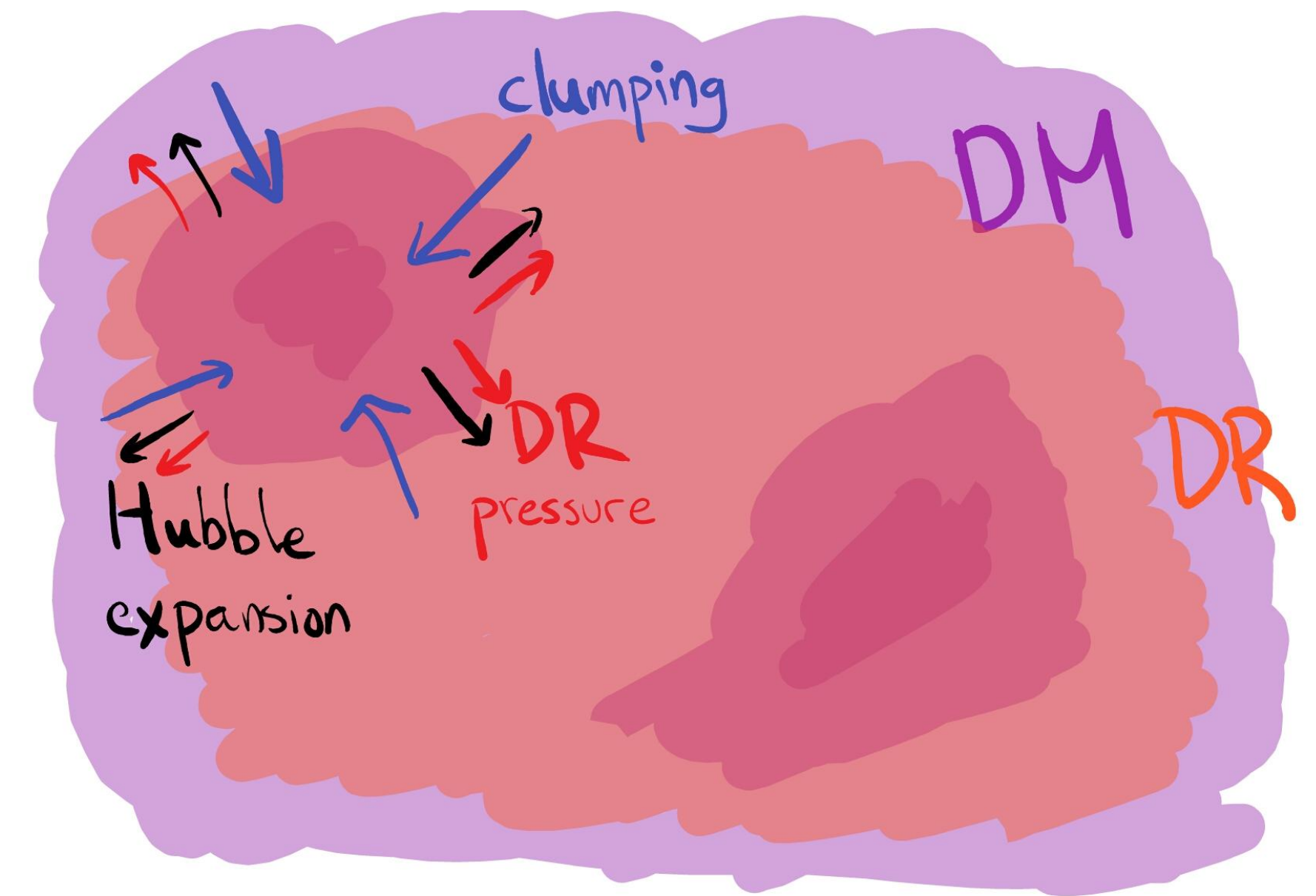
Dark Matter interaction with DR

A Class of Solutions to S_8 tension

Dark Radiation worsens S_8 tension

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

Solution: Dark Matter interaction with Dark Radiation

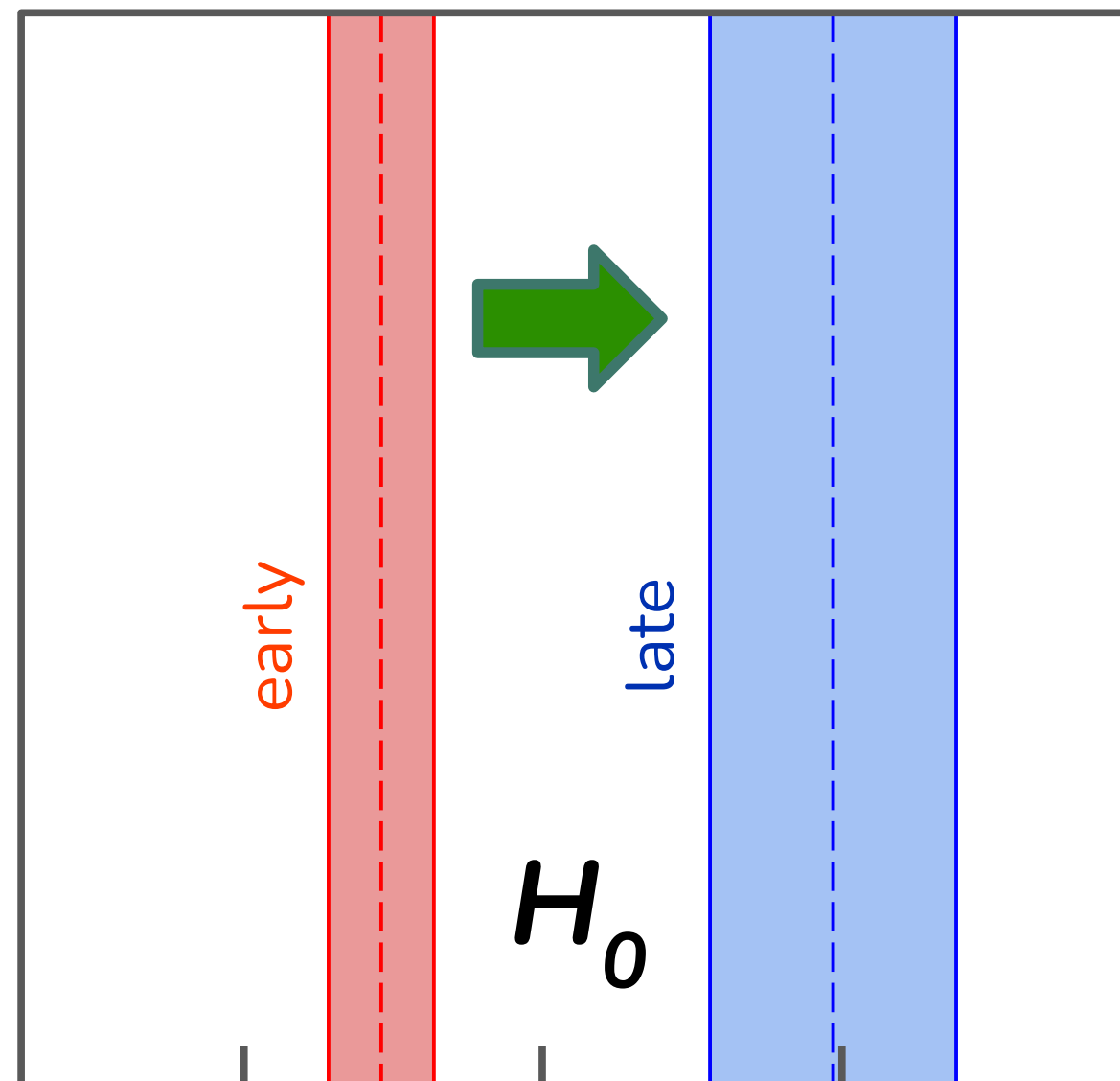


PAcDM

Solution to H_0 and S_8 tensions?

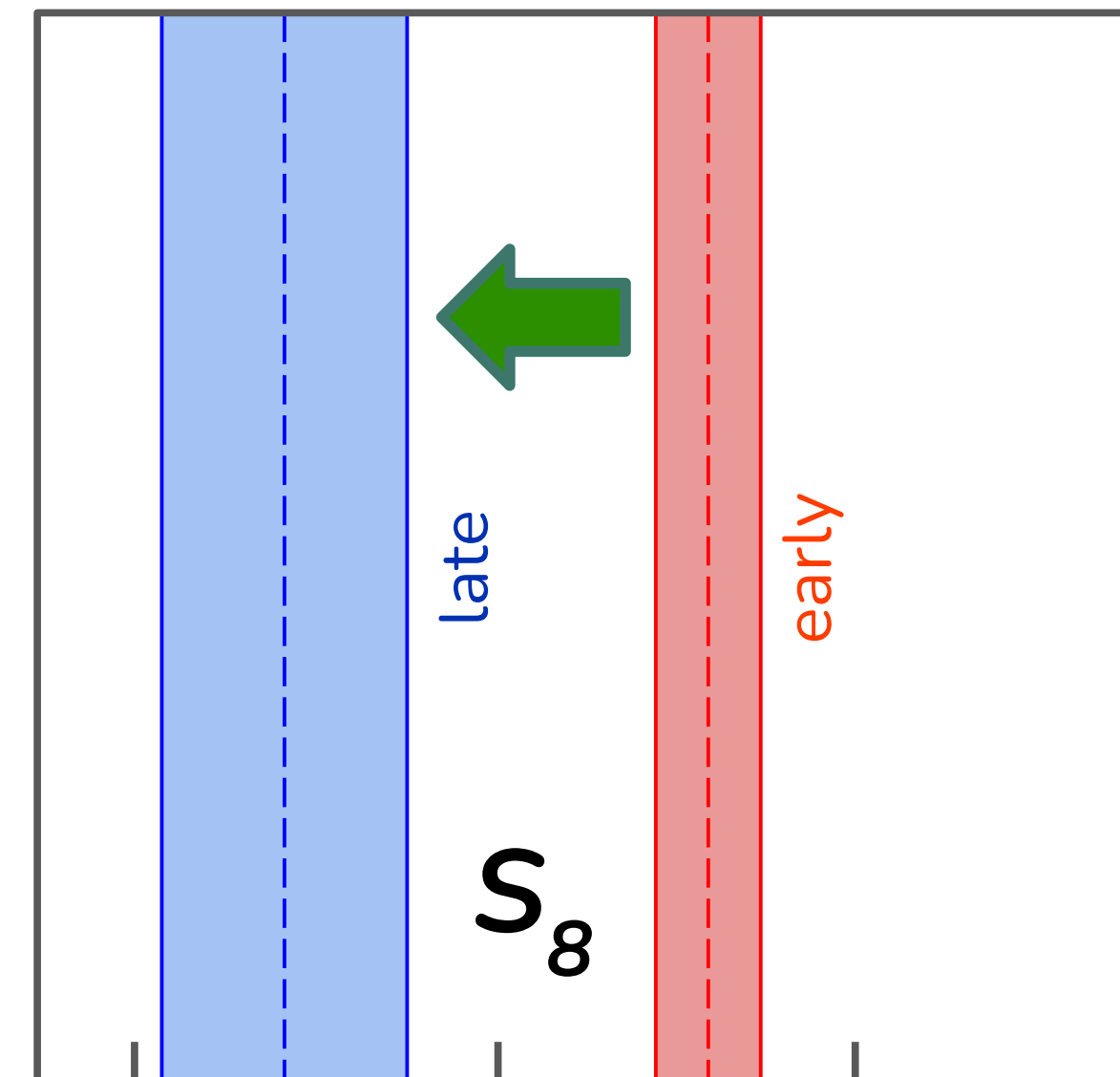
Self-interacting DR:

Increase early measurement of H_0



DM-DR interaction:

Decrease early measurement of S_8



PAcDM

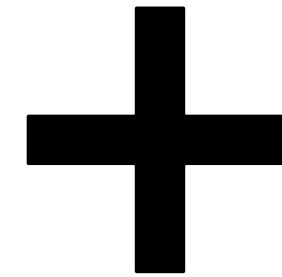
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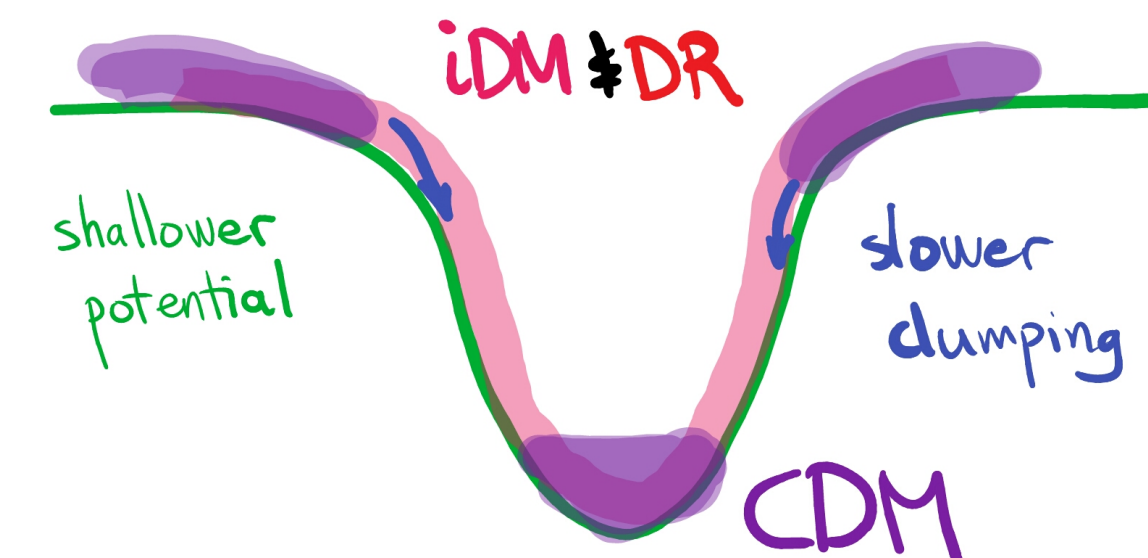
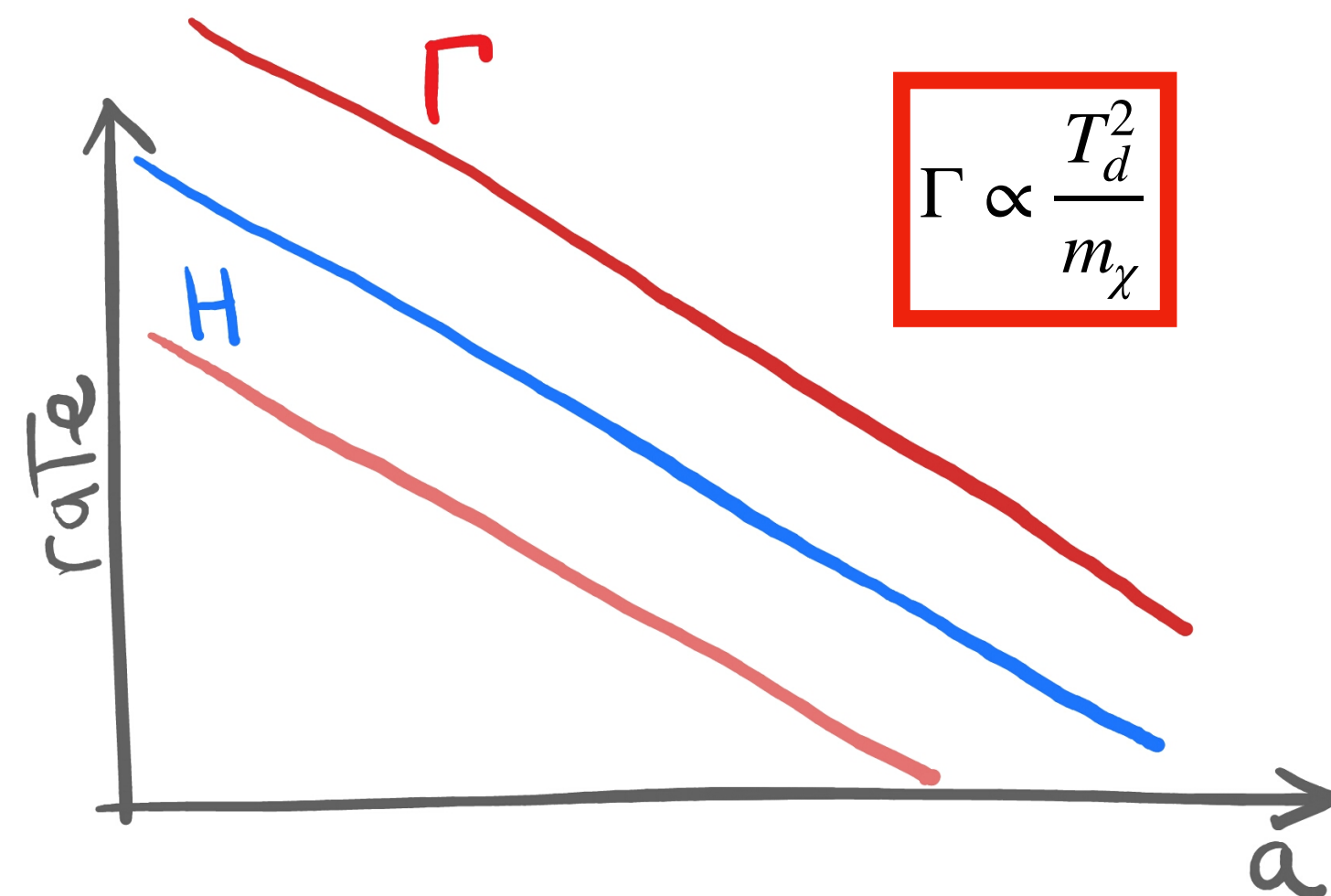
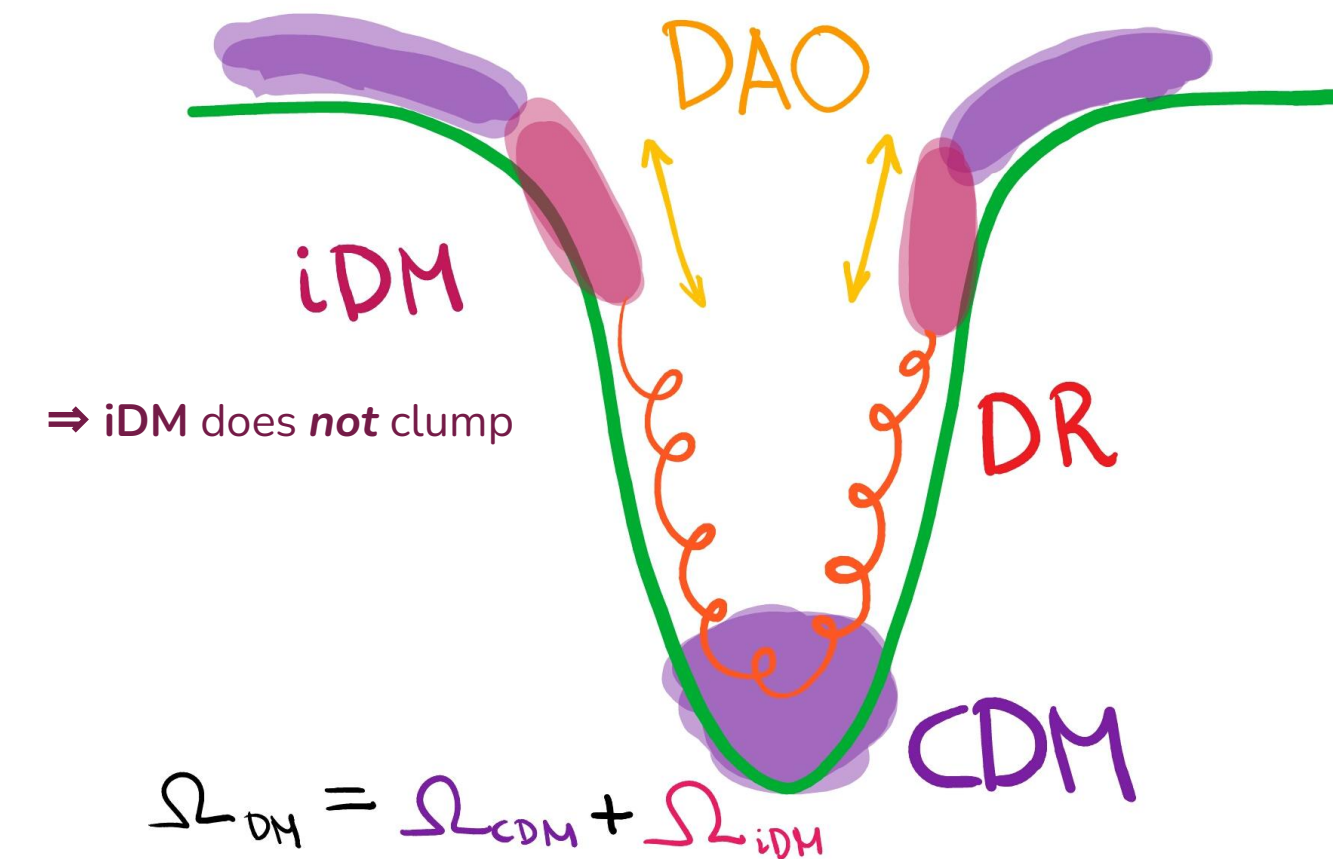
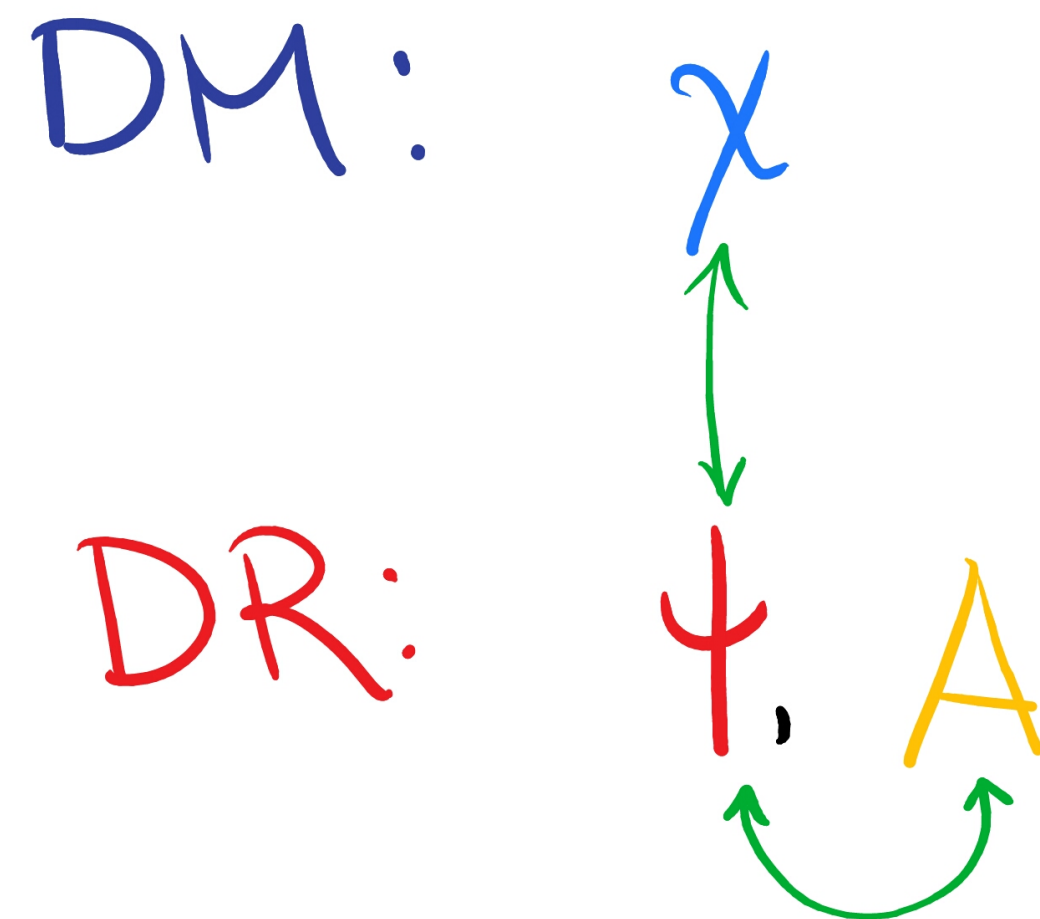


Partially **A**coustic **D**ark **M**atter

Chacko et al. [arXiv:1609.03569]

Dark Matter interaction with DR

Partially Acoustic Dark Matter (PAcDM) Chacko et al. [arXiv:1609.03569]



SPartAcous

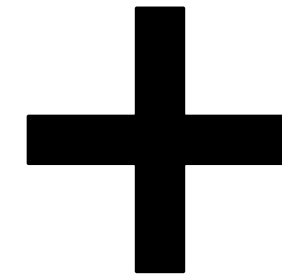
Solution to H_0 and S_8 tensions!

Self-interacting DR:

Increase early measurement of H_0

DM-DR interaction:

Decrease early measurement of S_8



Partially **A**coustic **D**ark **M**atter

Chacko et al. [arXiv:1609.03569]

MCMC fit to actual data is terrible

Decrease early measurement of S_8 too low

SPartAcous

Solution to H_0 and S_8 tensions!

Self-interacting DR:

Increase early measurement of H_0

DM-DR interaction:

Decrease early measurement of S_8

+ cut-off

Stepped Partially Acoustic Dark Matter

M. A. Buen-Abad, Z. Chacko, C. Kilic, G. Marques-Tavares & TY [arXiv:2208.05984]

SPartAcous

A New Step in Dark Sector Cosmologies for
the Hubble Tension and Large Scale Structure

Spartan

Solution

Self-inter

Increa



of S_8

arXiv:2208.05984]

A New Step in Dark Sector Cosmologies for the Hubble Tension and Large Scale Structure



Details of Model

Standard CDM

Interacting Dark Matter (iDM): χ

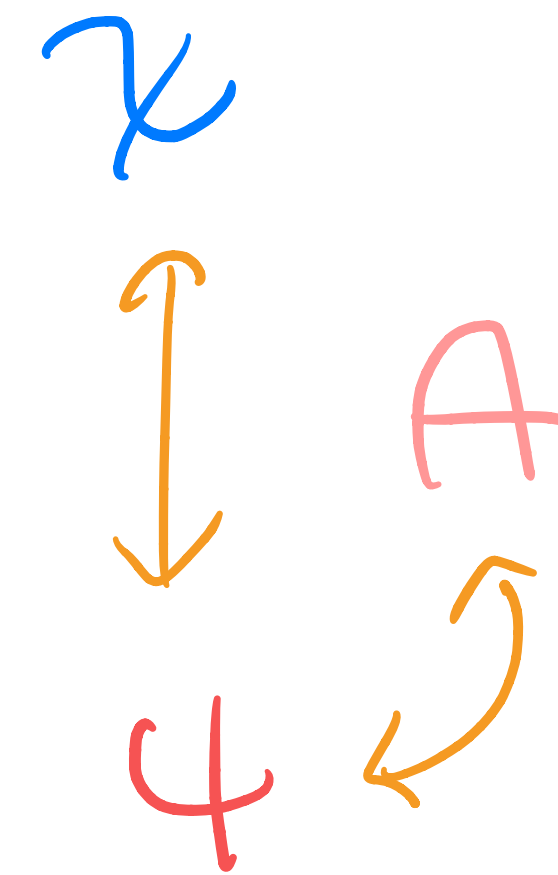
$$f_{\text{CDM}} + f_{\chi} = 1$$

Self-interacting Dark Radiation:

ψ , A

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

	$U(1)_A$
χ	1
ψ	1





Details of Model

Standard CDM

Interacting Dark Matter (iDM): χ

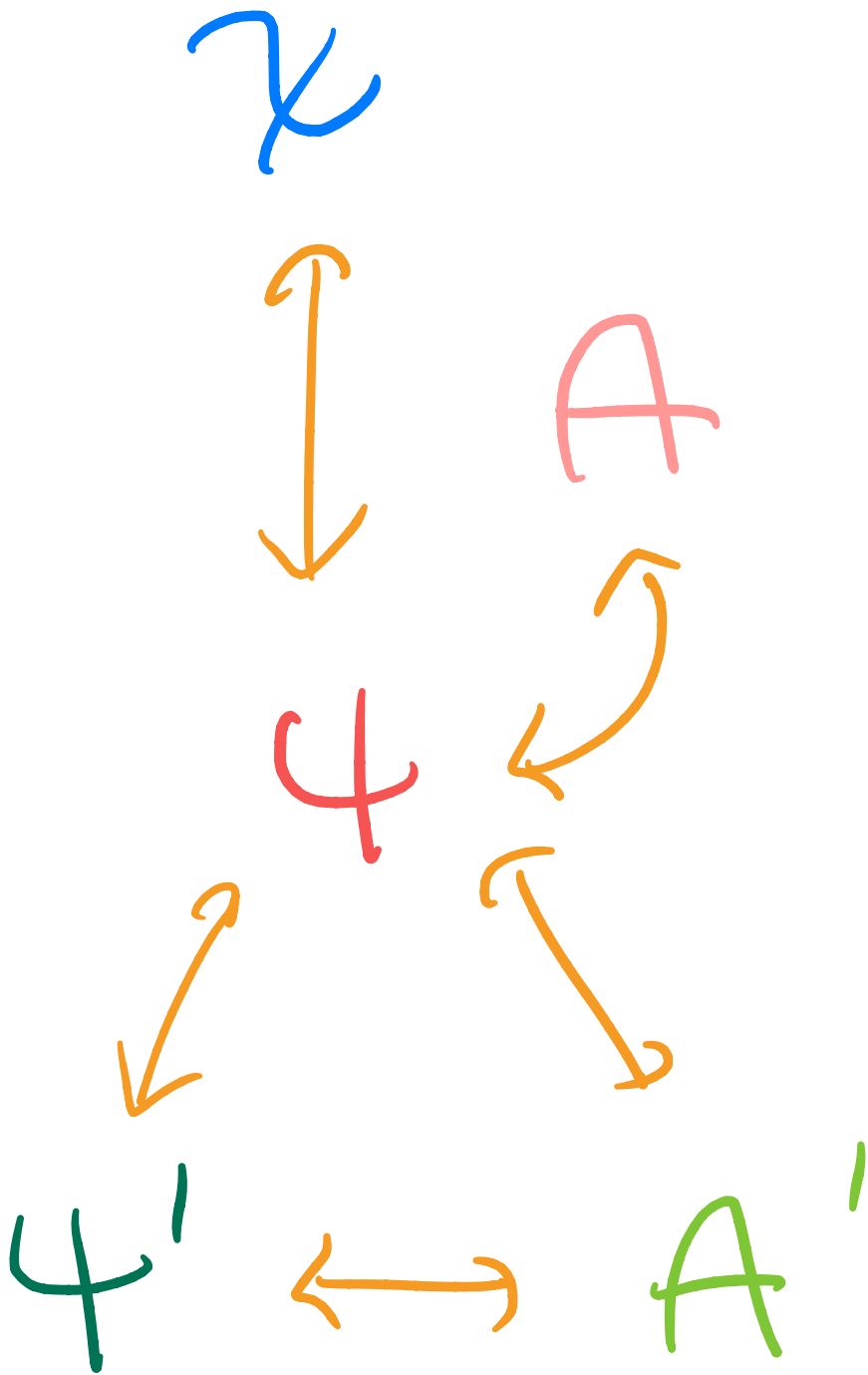
$$f_{\text{CDM}} + f_{\chi} = 1$$

Self-interacting Dark Radiation

ψ, A

ψ', A'

	$U(1)_A$	$U(1)_{A'}$
χ	1	0
ψ	1	1
ψ'	0	1



SPartAcous

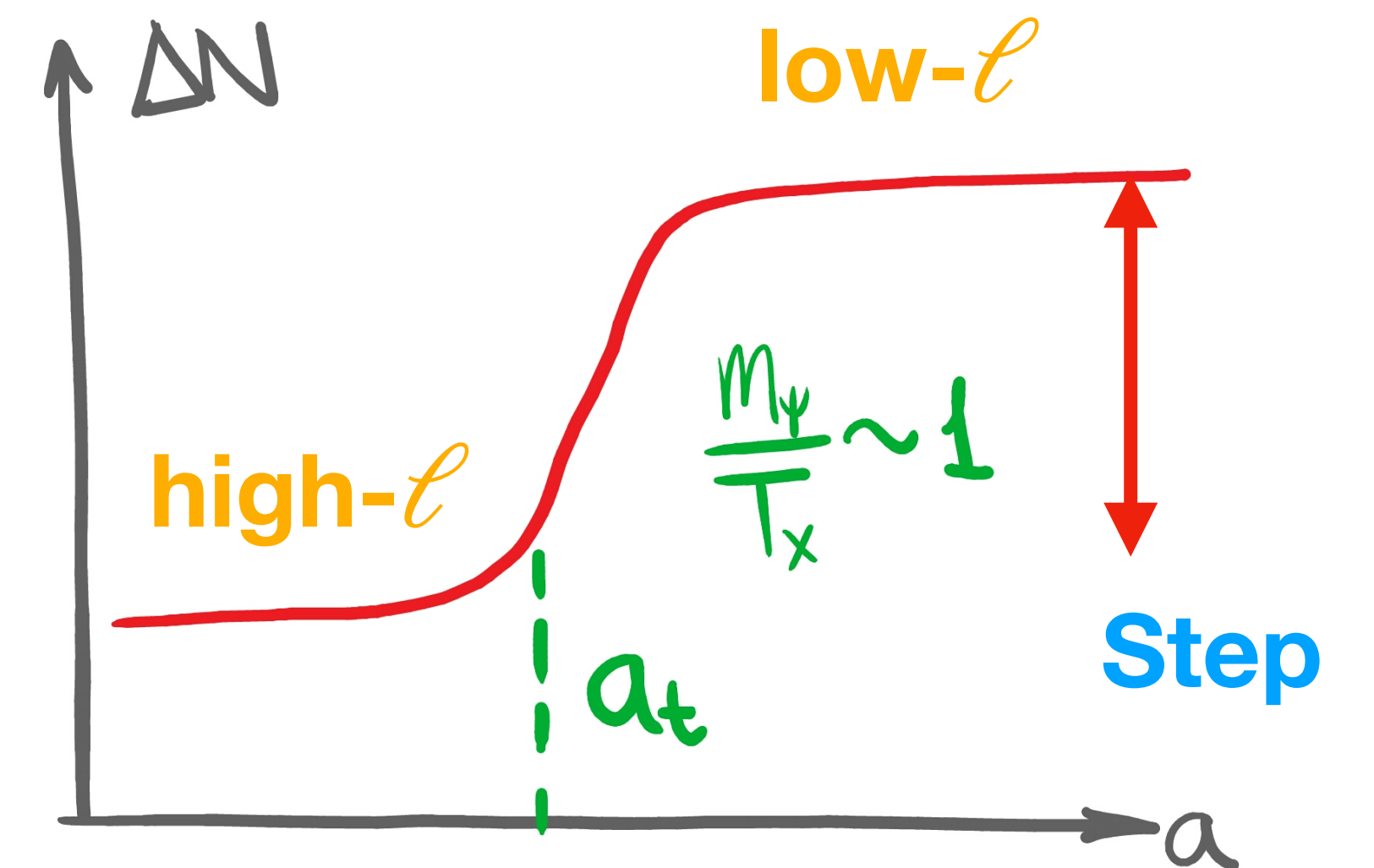
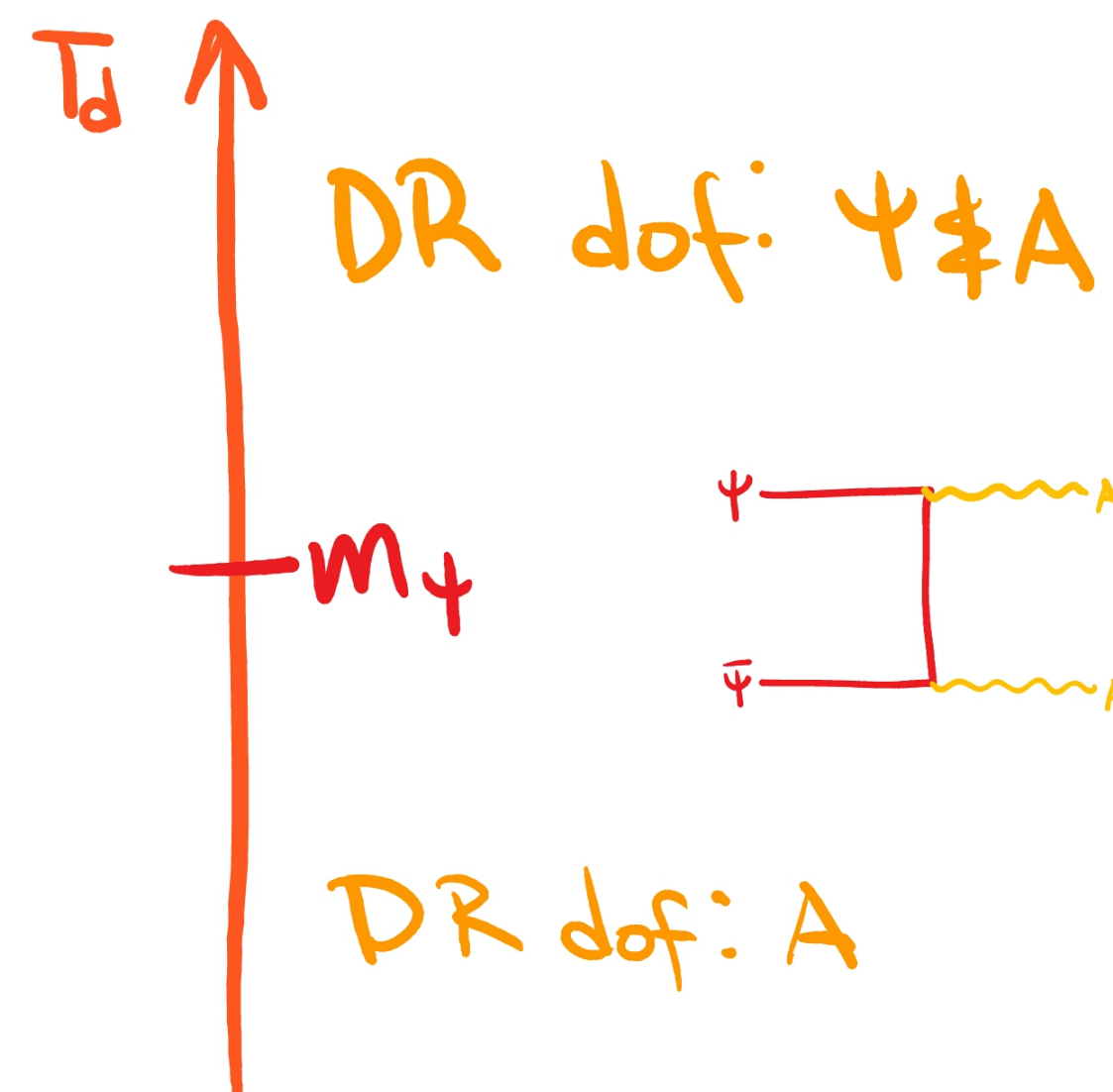
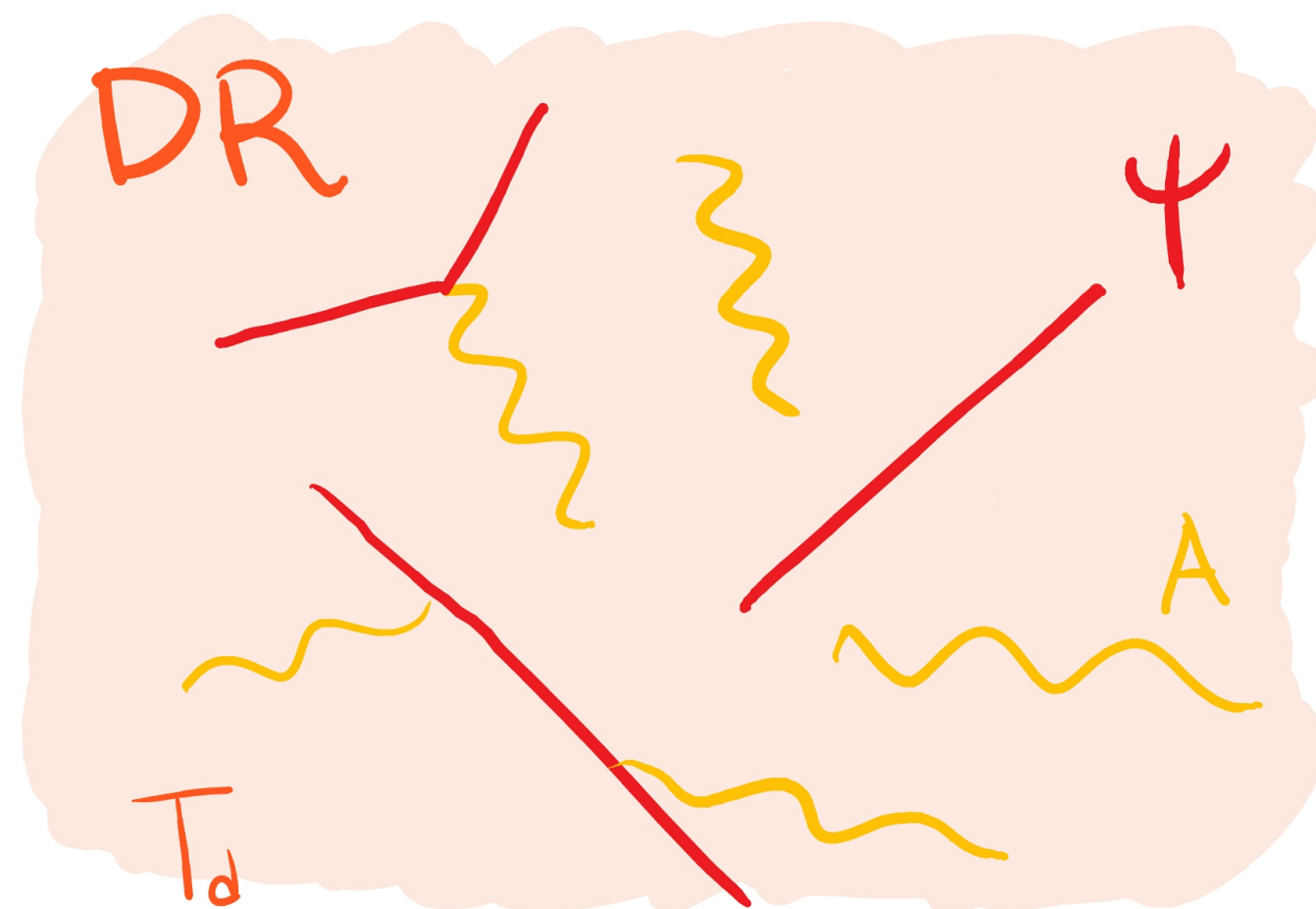
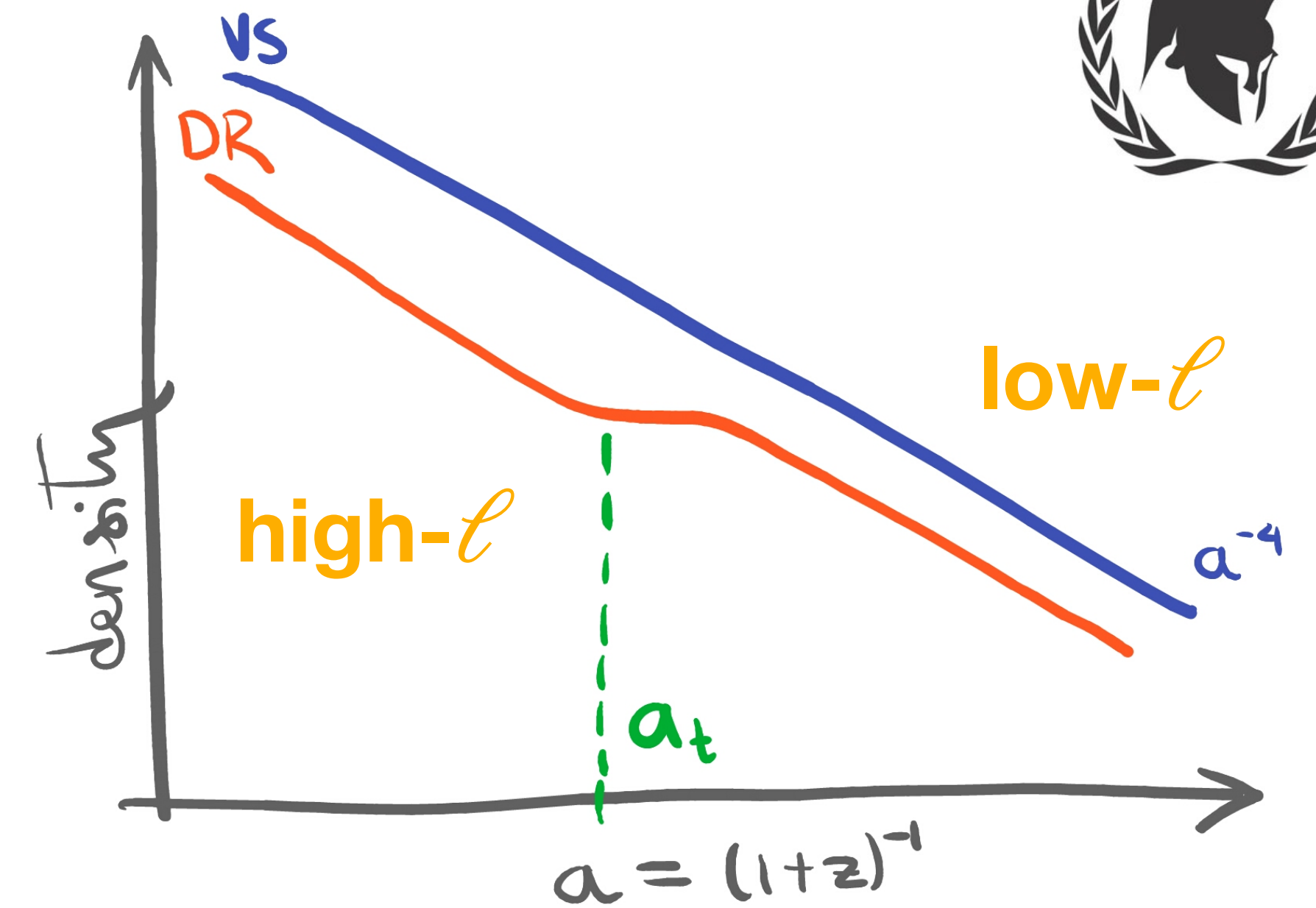
Stepped DR

Below mass threshold around $m_\psi \sim \text{eV}$

Entropy dump in DR

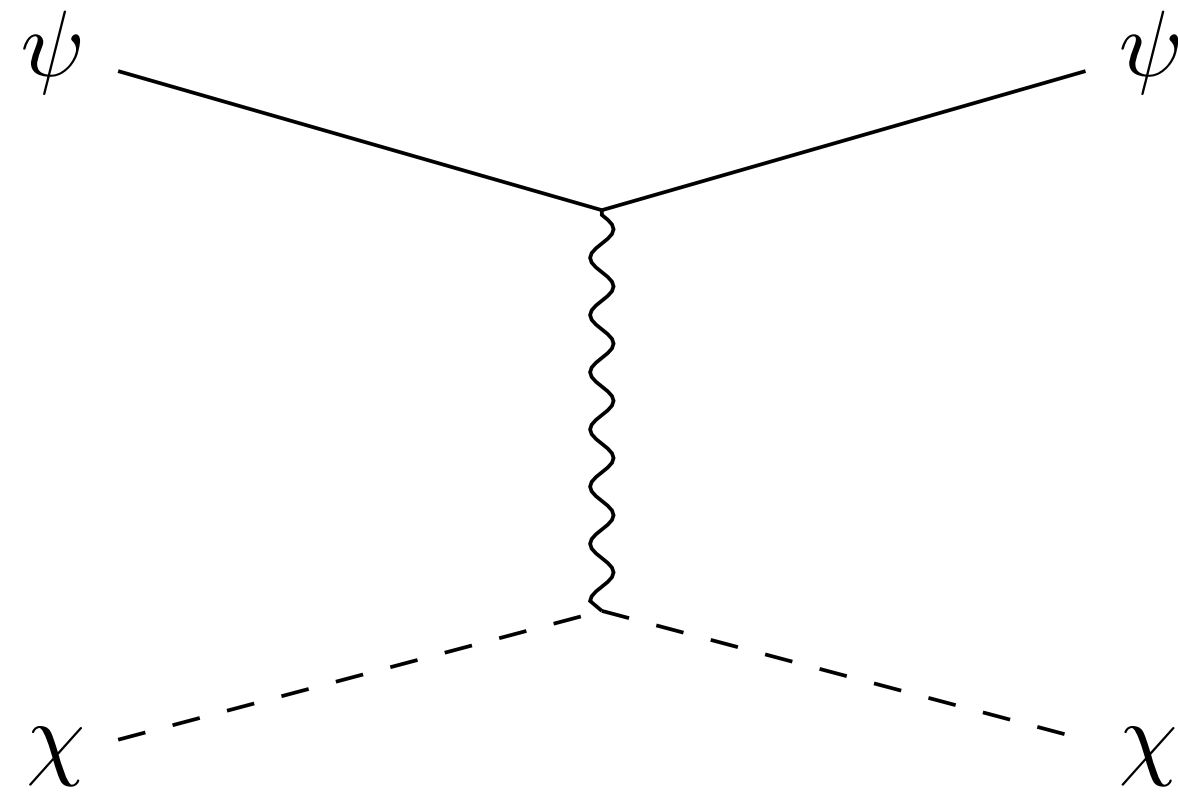
Aloni et al. [arXiv:2111.00014]

Stepped increase in ΔN_{eff}

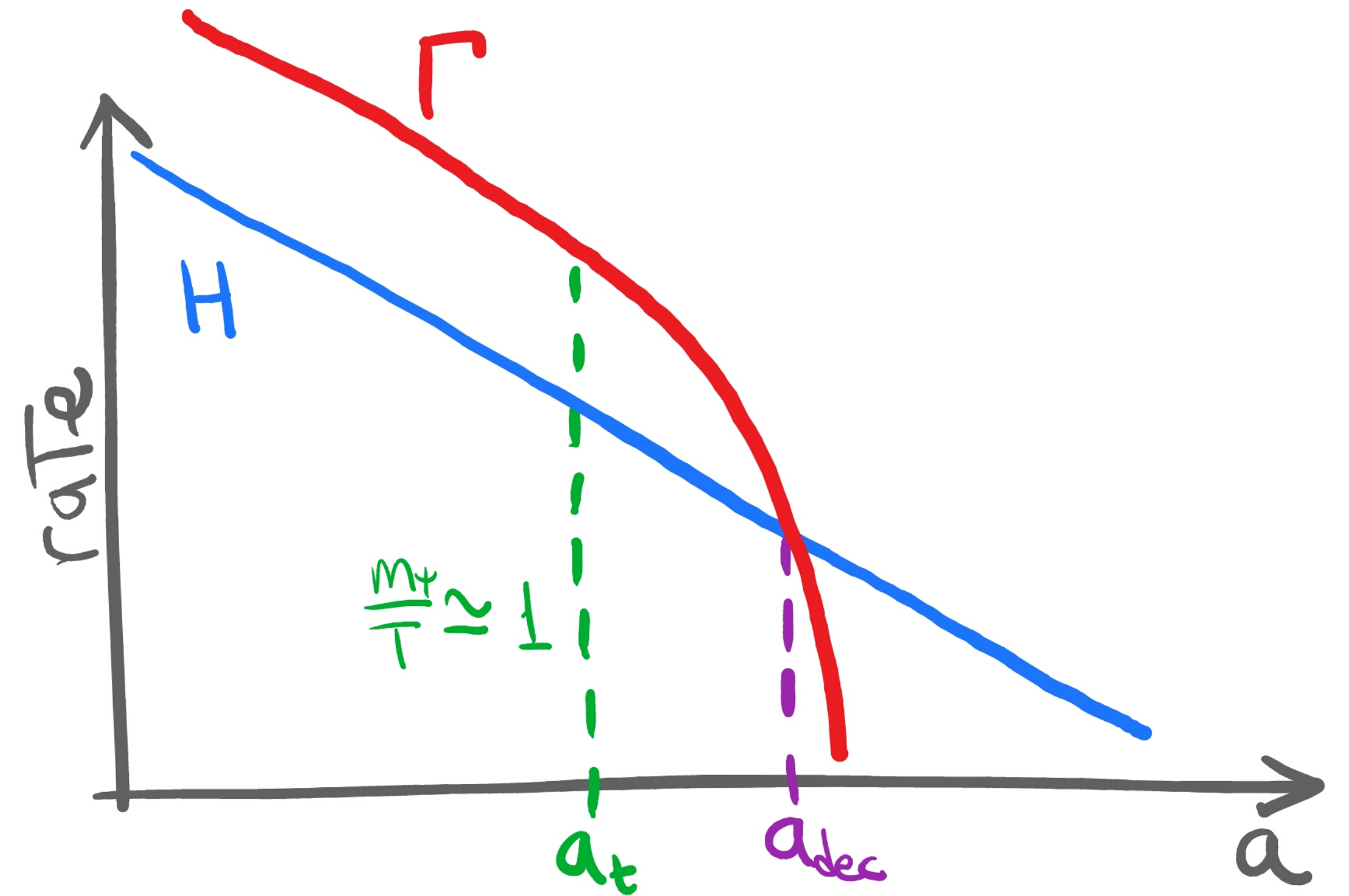


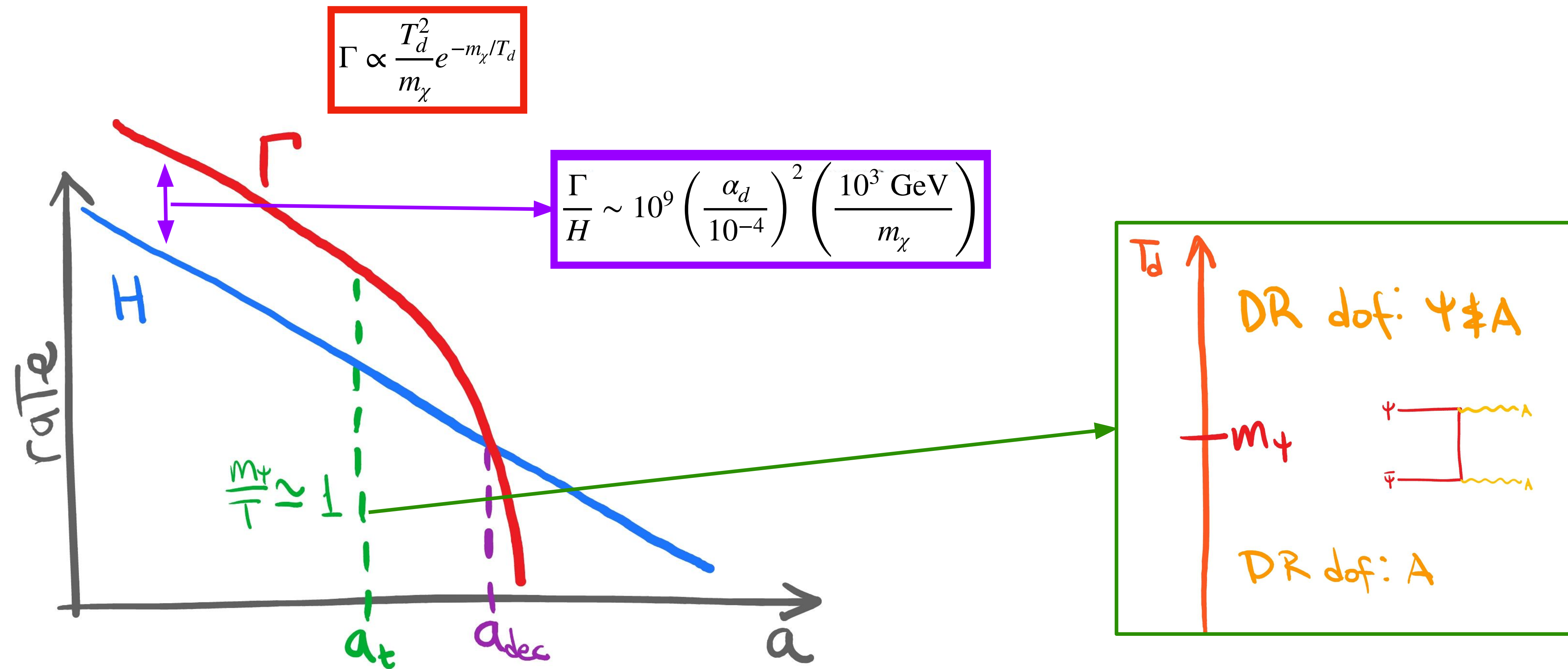
SPartAcous

iDM-DR interactions

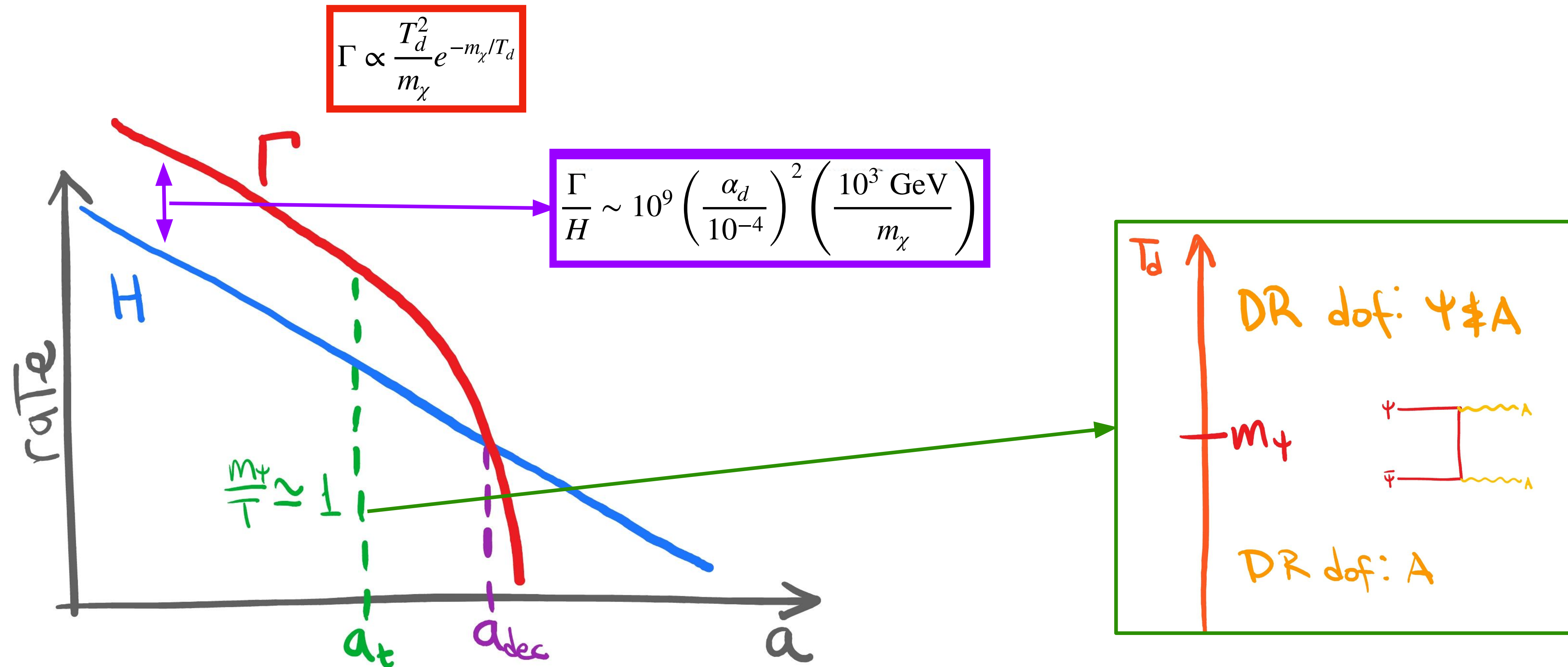


$$\Gamma \propto \frac{T_d^2}{m_\chi} e^{-m_\chi/T_d}$$





Prevents too low S_8

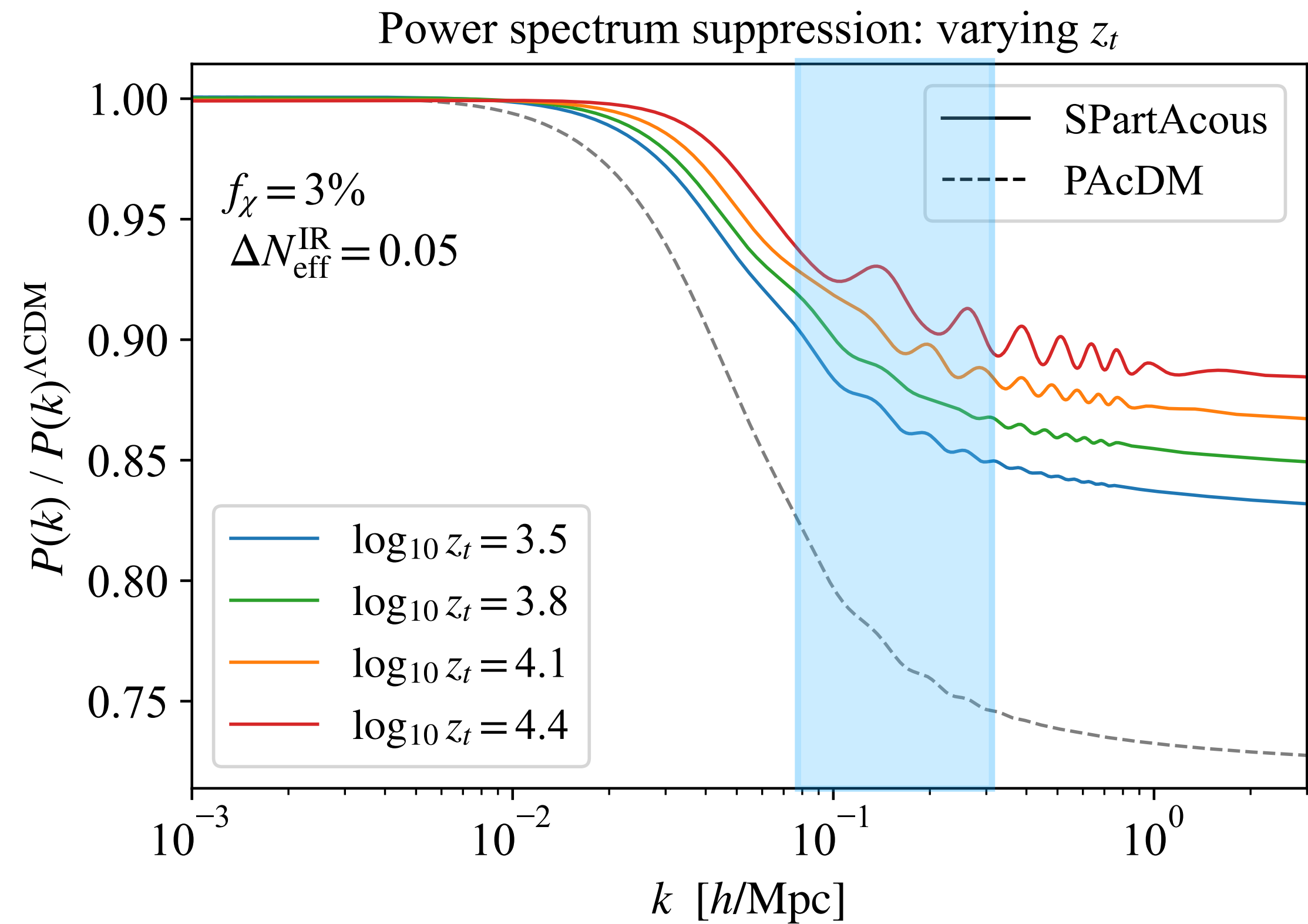
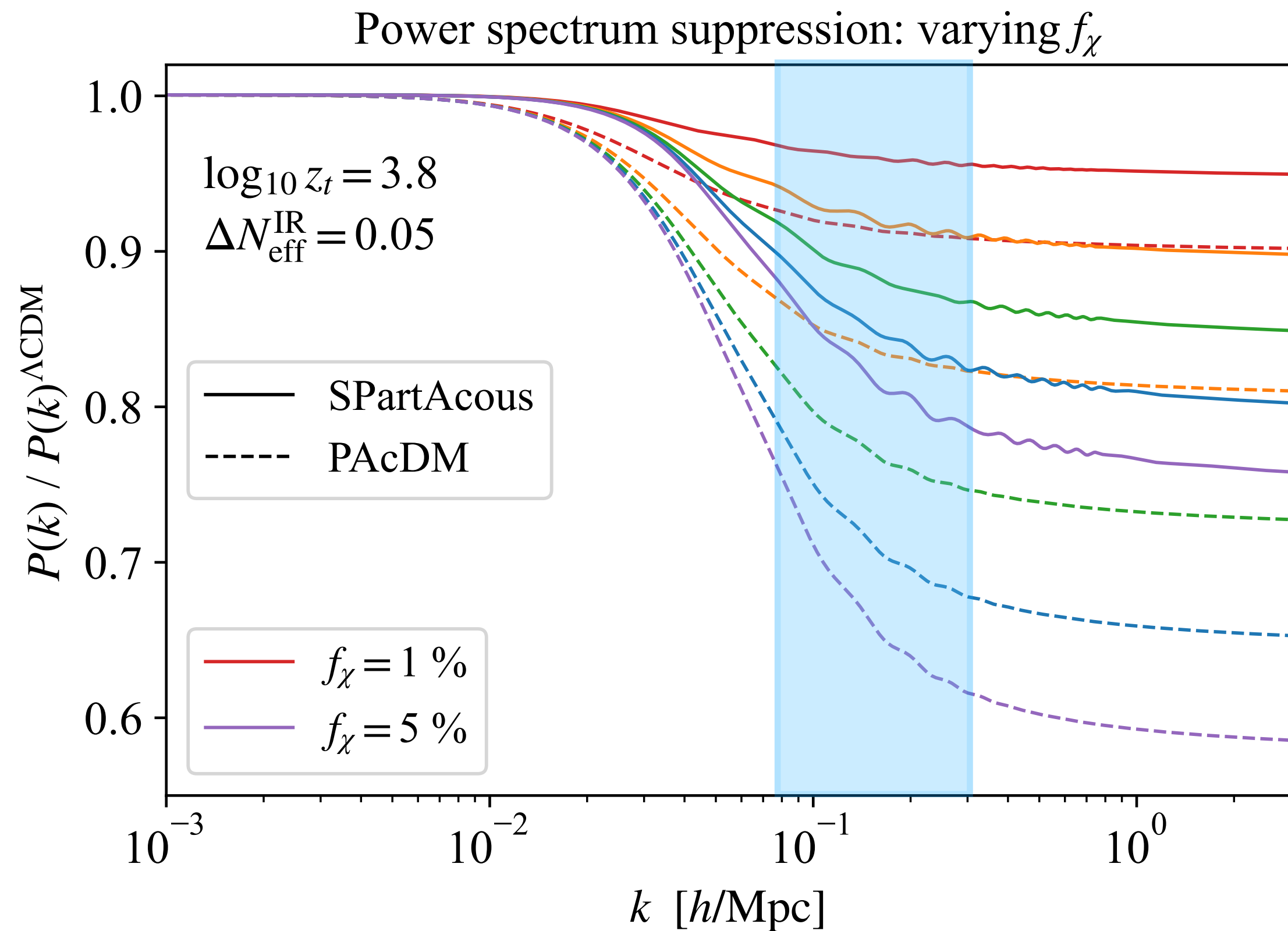


Different CMB damping to low and high ℓ modes

51

SPartAcous

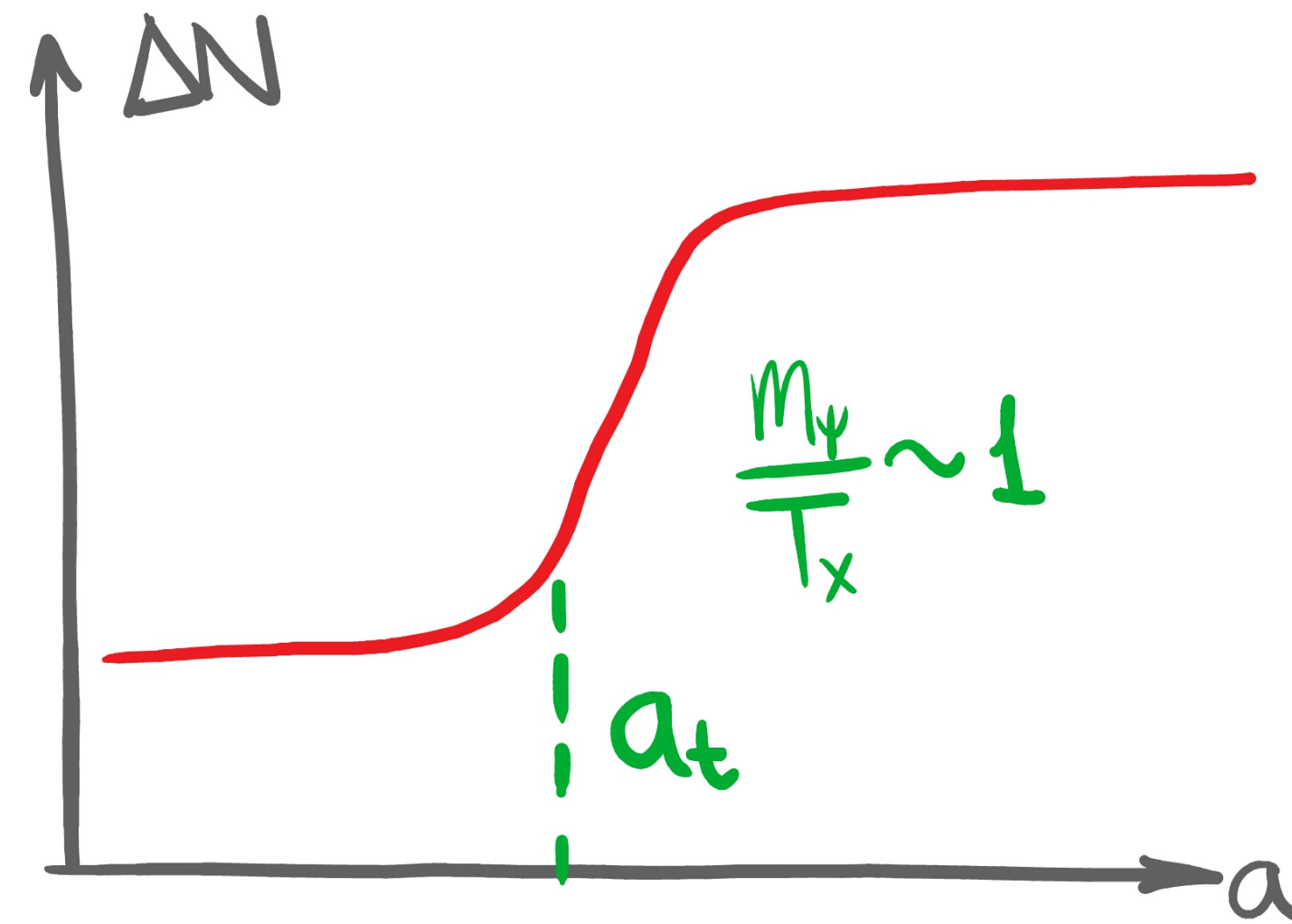
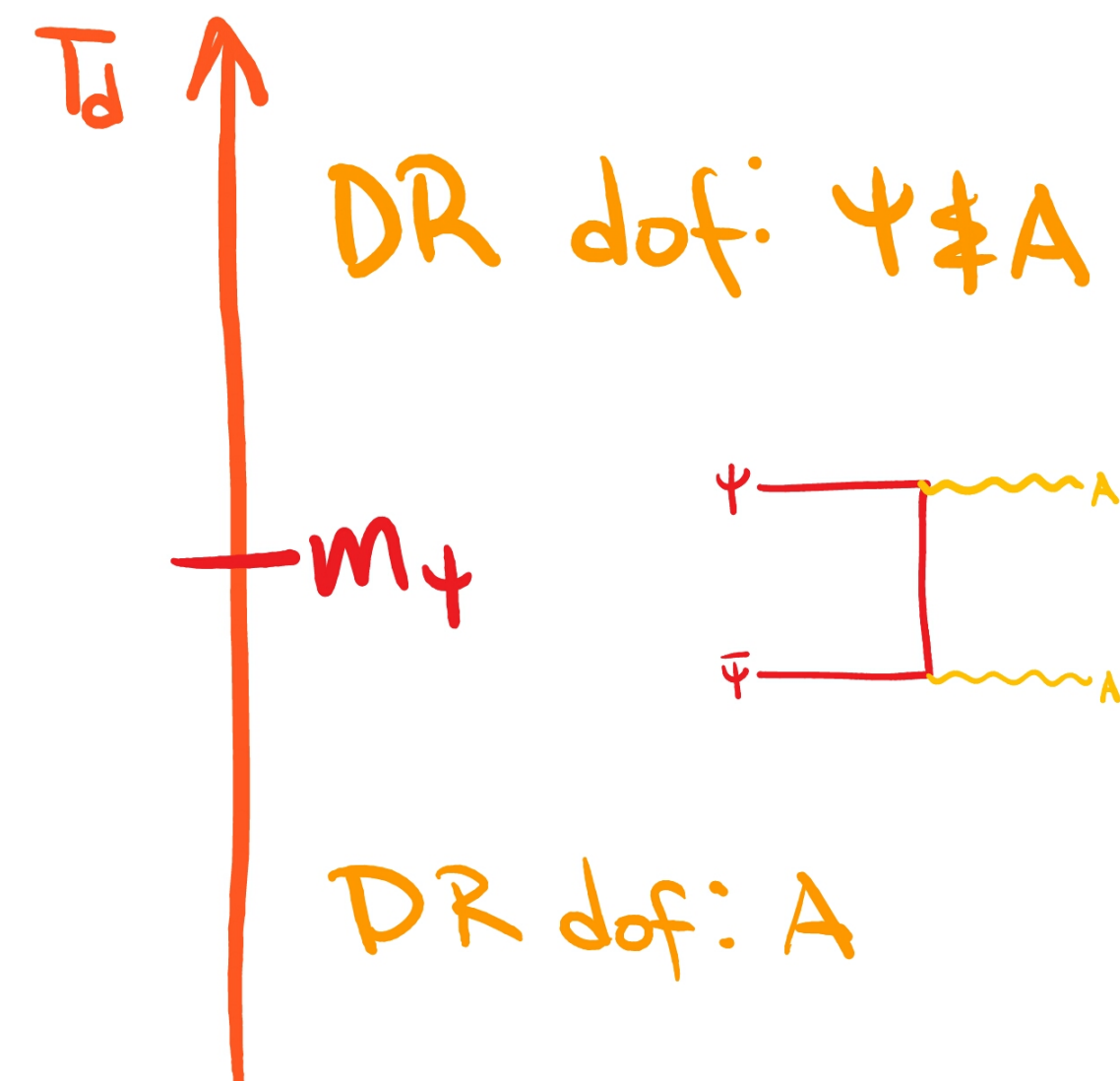
Dark Acoustic Oscillations



$$z_t = \frac{m_\chi}{T_{d0}} - 1$$

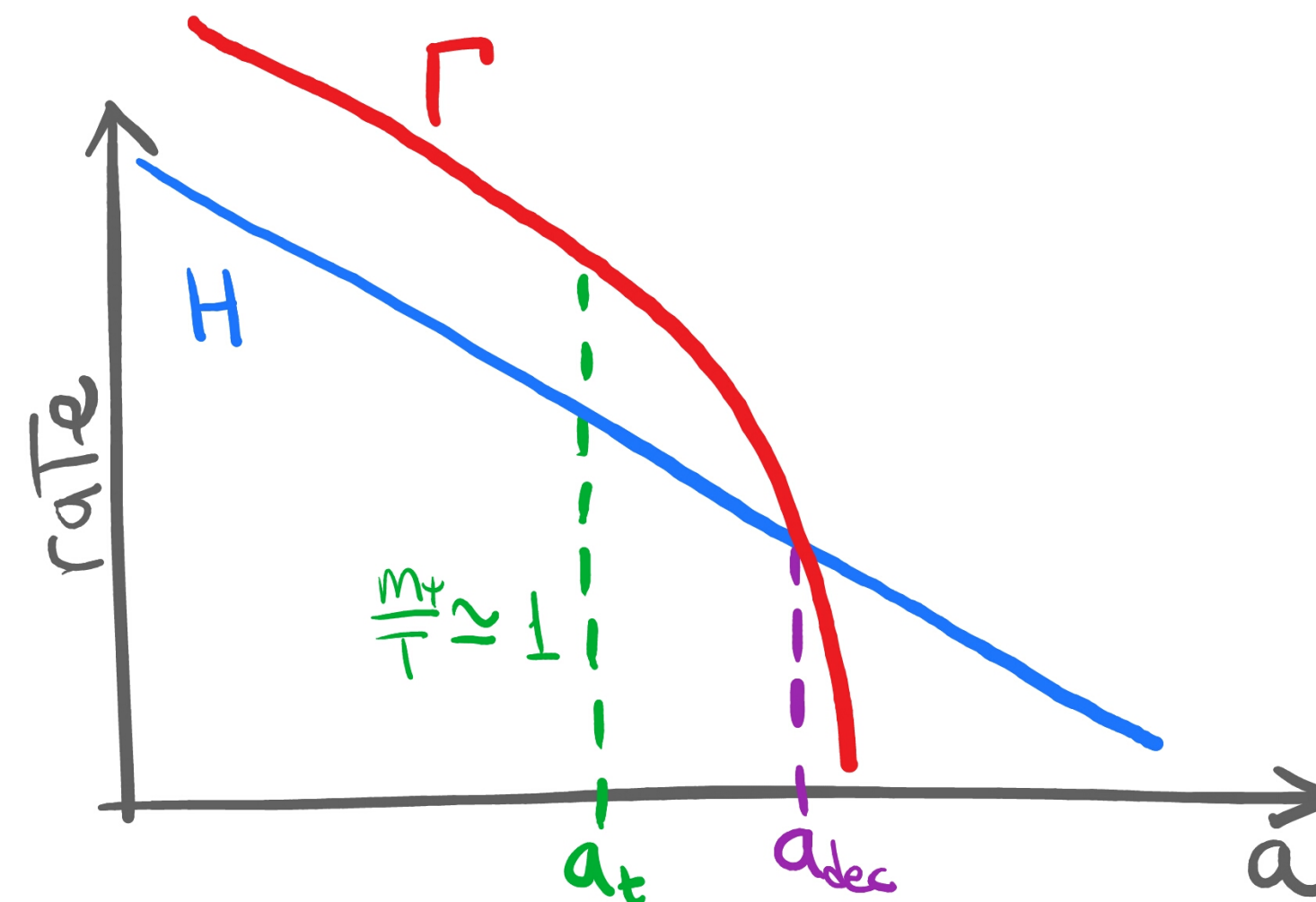
SPartAcous

Below mass threshold



high- ℓ

low- ℓ



Alleviate
the Silk Damping
and too low S_8





$$\dot{\delta}_{\text{idm}} = -\theta_{\text{idm}} + 3\dot{\phi}$$

$$r_g = \frac{g_*^{\text{UV}} - g_*^{\text{IR}}}{g_*^{\text{IR}}} = \left(\frac{\Delta N_{\text{eff}}^{\text{IR}}}{\Delta N_{\text{eff}}^{\text{UV}}} \right)^3 - 1$$

$$\dot{\theta}_{\text{idm}} = -\mathcal{H}\theta_{\text{idm}} + k^2\psi + a\Gamma(\theta_{\text{dr}} - \theta_{\text{idm}})$$

$$\dot{\delta}_{\text{dr}} = -(1+w)(\theta_{\text{dr}} - 3\dot{\phi}) - 3\mathcal{H}(c_s^2 - w)\delta_{\text{dr}}$$

$$\dot{\theta}_{\text{dr}} = - \left[(1-3w)\mathcal{H} + \frac{\dot{w}}{1+w} \right] \theta_{\text{dr}} + k^2 \left(\frac{c_s^2}{1+w} \delta_{\text{dr}} + \psi \right) + \frac{\rho_{\text{idm}}}{\rho_{\text{dr}}(1+w)} a\Gamma(\theta_{\text{idm}} - \theta_{\text{dr}})$$

$$\Gamma = \frac{4}{3\pi} \alpha_d^2 \log(\star) \frac{T_d^2}{m_\chi} e^{-m_\psi/T_d} \left[2 + \frac{m_\psi}{T_d} \left(2 + \frac{m_\psi}{T_d} \right) \right]$$

Markov Chain Monte Carlo (MCMC)



Setup

Data:

Baseline \mathcal{D} : Planck high ℓ TTTEEE, Planck low ℓ EE, Planck low ℓ TT, Planck lensing, BAO BOSS DR12, BAO small z , PANTHEON

Hubble tension \mathcal{H} : SH0ES

S_8 tension \mathcal{S} : KiDS-1000x, DES-Y3

\mathcal{D} , $\mathcal{D}\mathcal{H}$ and $\mathcal{D}\mathcal{H}\mathcal{S}$ performed

Markov Chain Monte Carlo (MCMC)



Setup

Model:

Λ CDM

SPartAcous: no $\psi' \rightarrow r_g = 1.75$ (40 % \uparrow)

SPartAcous+3: 3 $\psi' \rightarrow r_g = 0.24$ (7 % \uparrow)

iDM-DR interaction coupling $\alpha_d = 10^{-3}$

Free Parameters: f_χ , ΔN_{IR} , $z_t = \frac{m_\psi}{T_{d0}} - 1$

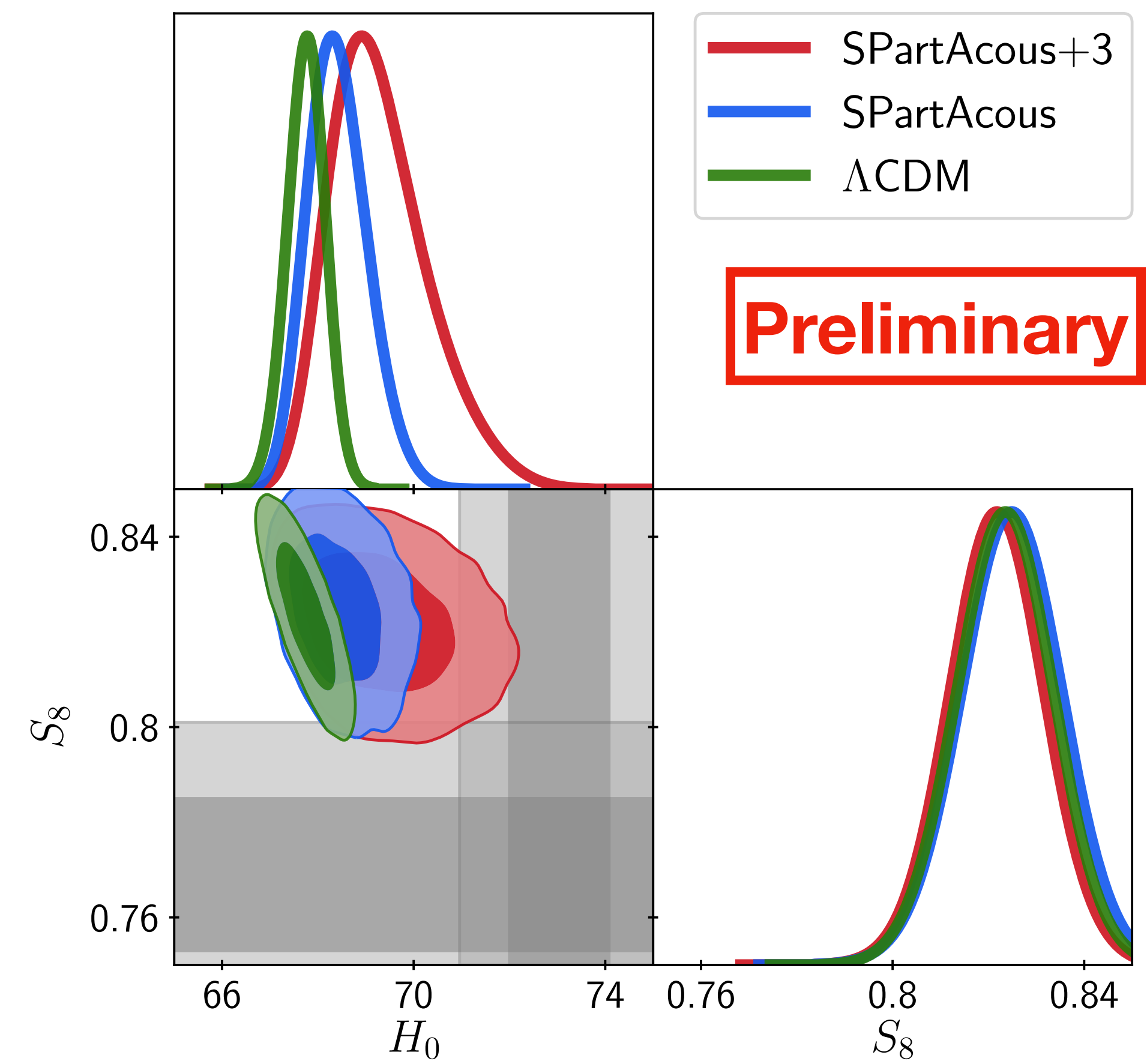
$$r_g = \frac{g_*^{\text{UV}} - g_*^{\text{IR}}}{g_*^{\text{IR}}} = \left(\frac{\Delta N_{\text{eff}}^{\text{IR}}}{\Delta N_{\text{eff}}^{\text{UV}}} \right)^3 - 1$$

Markov Chain Monte Carlo (MCMC)



Results

Dataset \mathcal{D}



Best fit

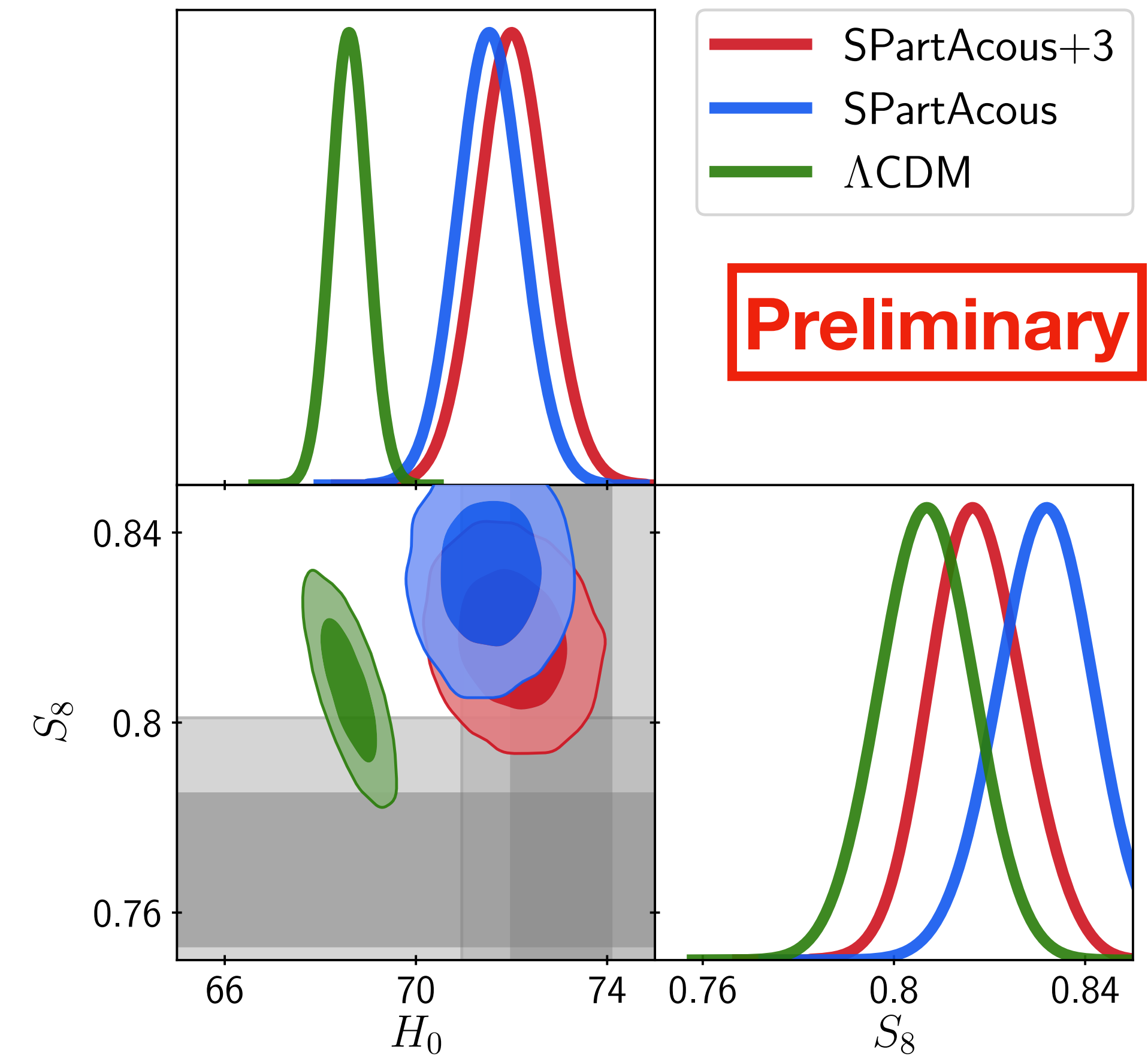
Model	$\Delta\chi^2$	ΔN_{IR}	H_0	S_8
Λ CDM	0	0	67.79	0.8227
SPartAcous	-0.59	0.12	68.46	0.8266
SPartAcous+3	-1.08	0.25	69.07	0.8224

Markov Chain Monte Carlo (MCMC)



Results

Dataset \mathcal{DH}



Best fit

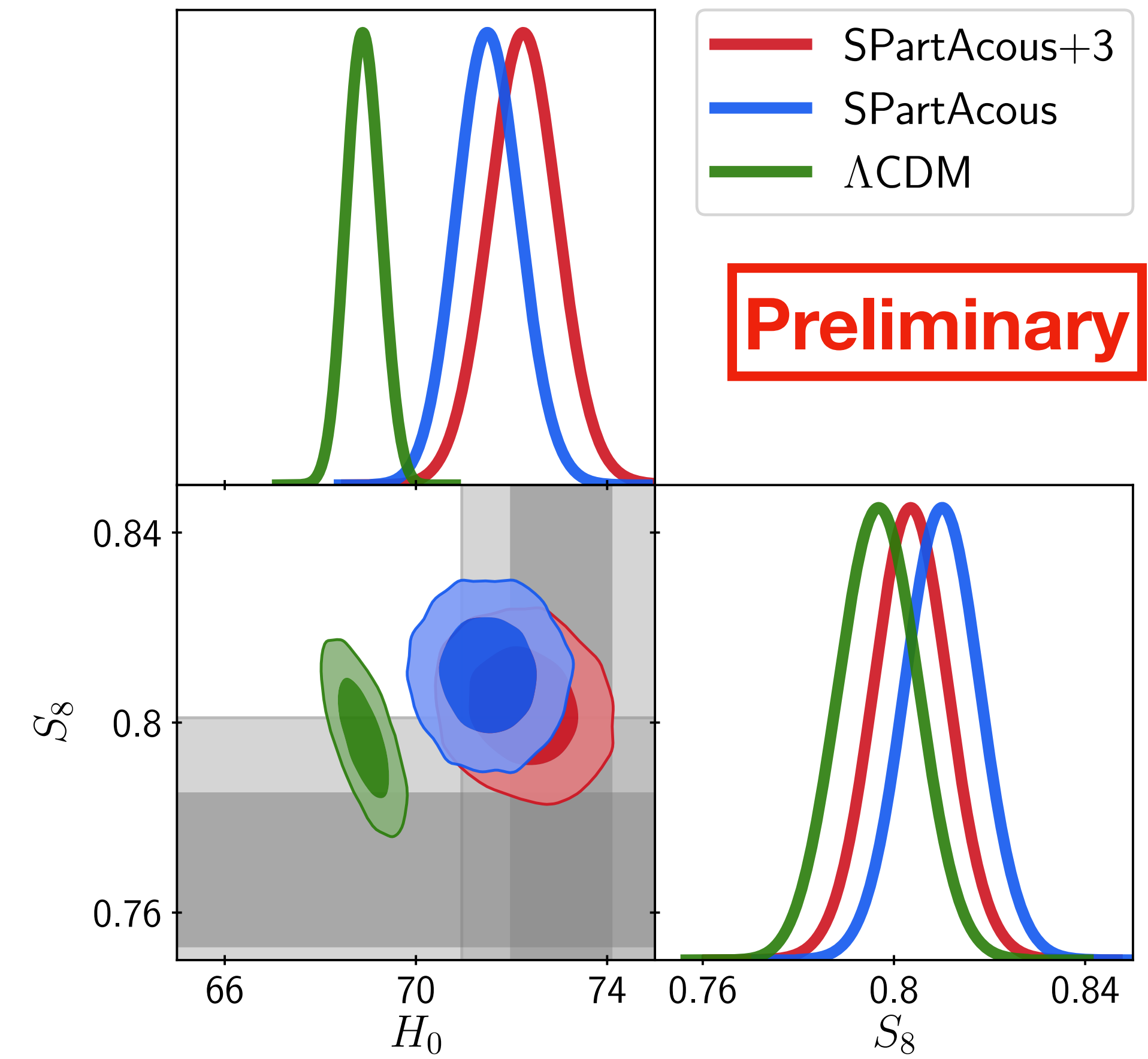
Model	$\Delta\chi^2$	ΔN_{IR}	H_0	S_8
LCDM	0	0	68.64	0.8072
SPartAcous	-23.23	0.64	71.66	0.8314
SPartAcous+3	-26.88	0.72	71.98	0.8172

Markov Chain Monte Carlo (MCMC)



Results

Dataset \mathcal{DHS}

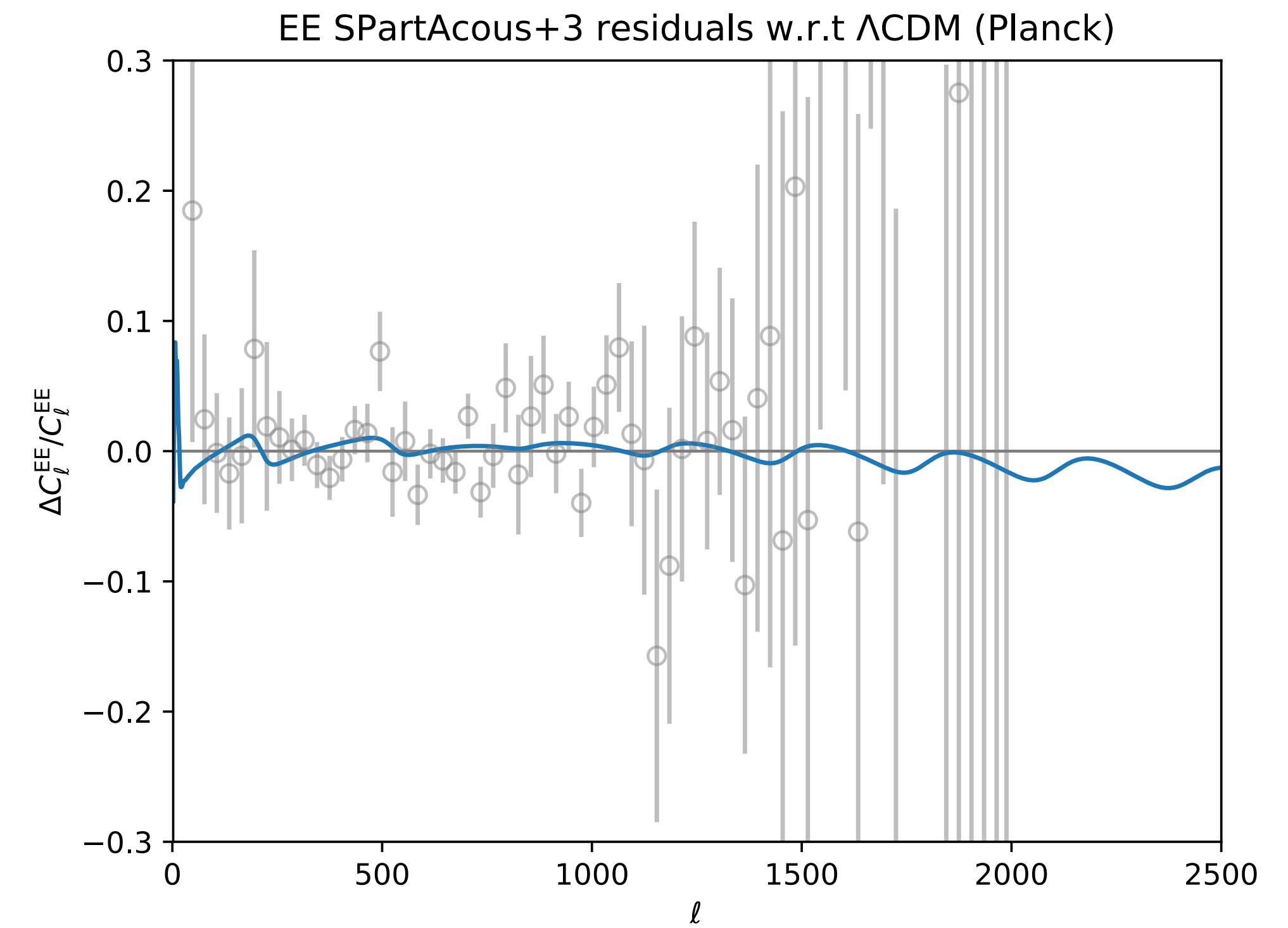
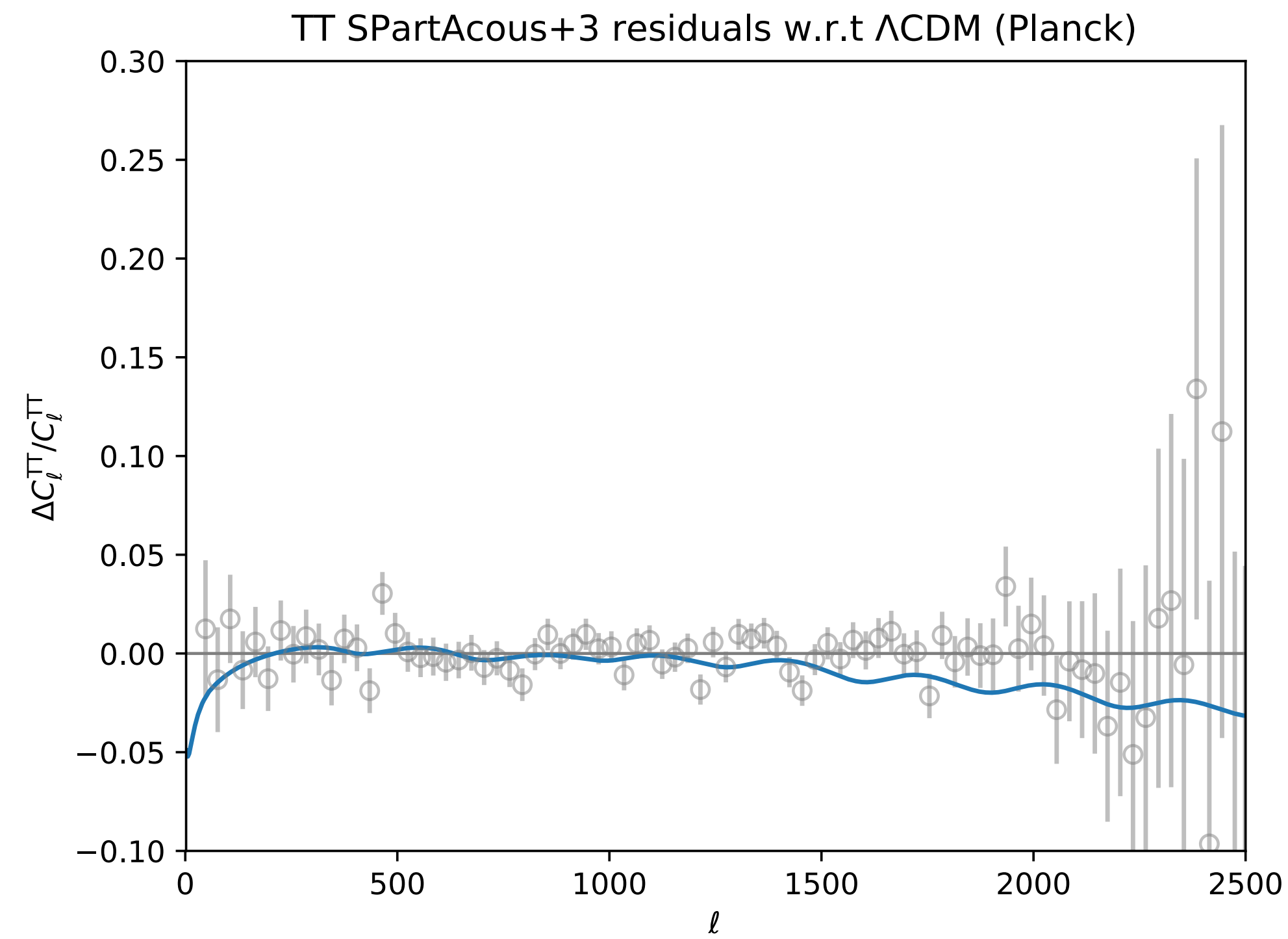


Best fit

Model	$\Delta\chi^2$	ΔN_{IR}	H_0	S_8
LCDM	0	0	68.94	0.7972
SPartAcous	-17.2	0.51	71.55	0.8103
SPartAcous+3	-24.6	0.69	72.26	0.8036

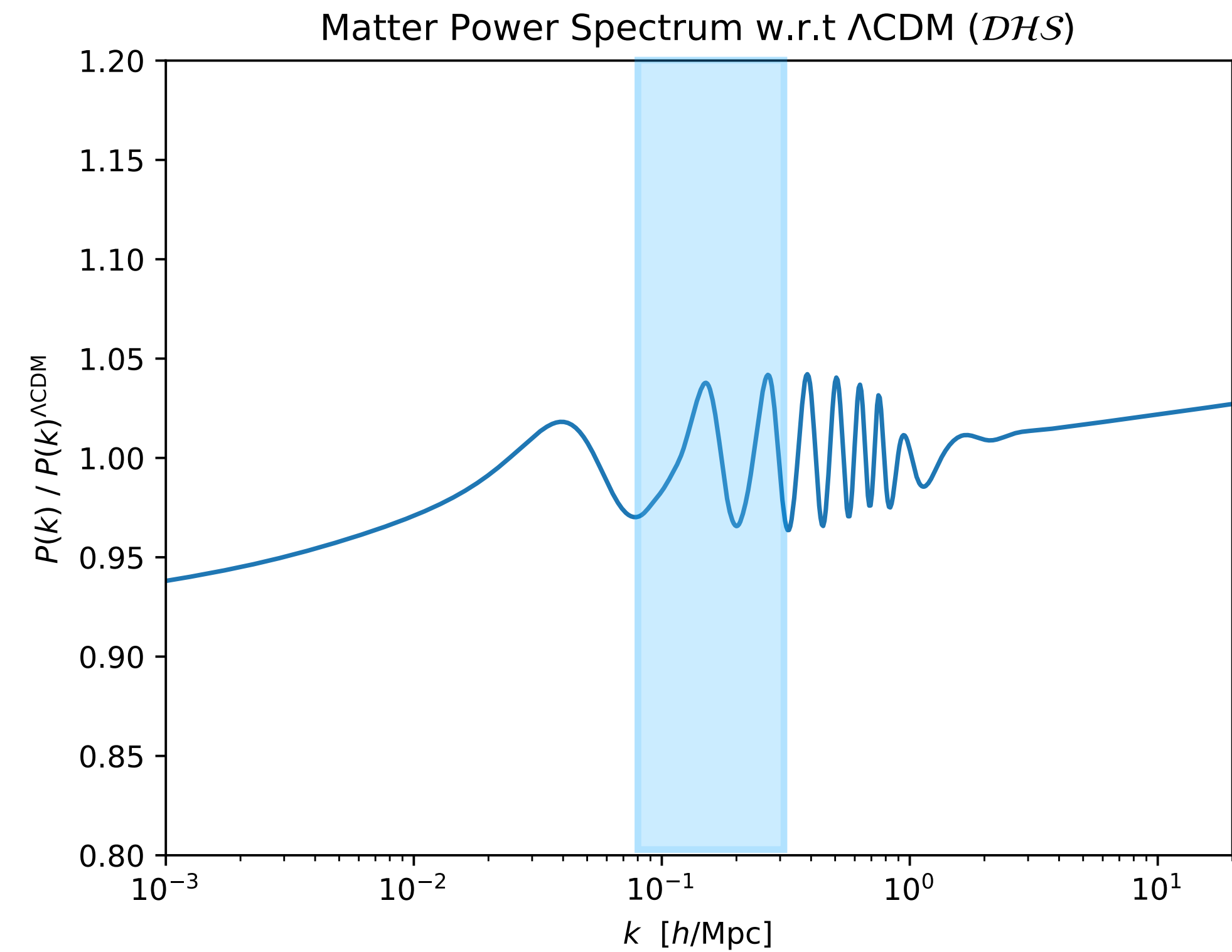
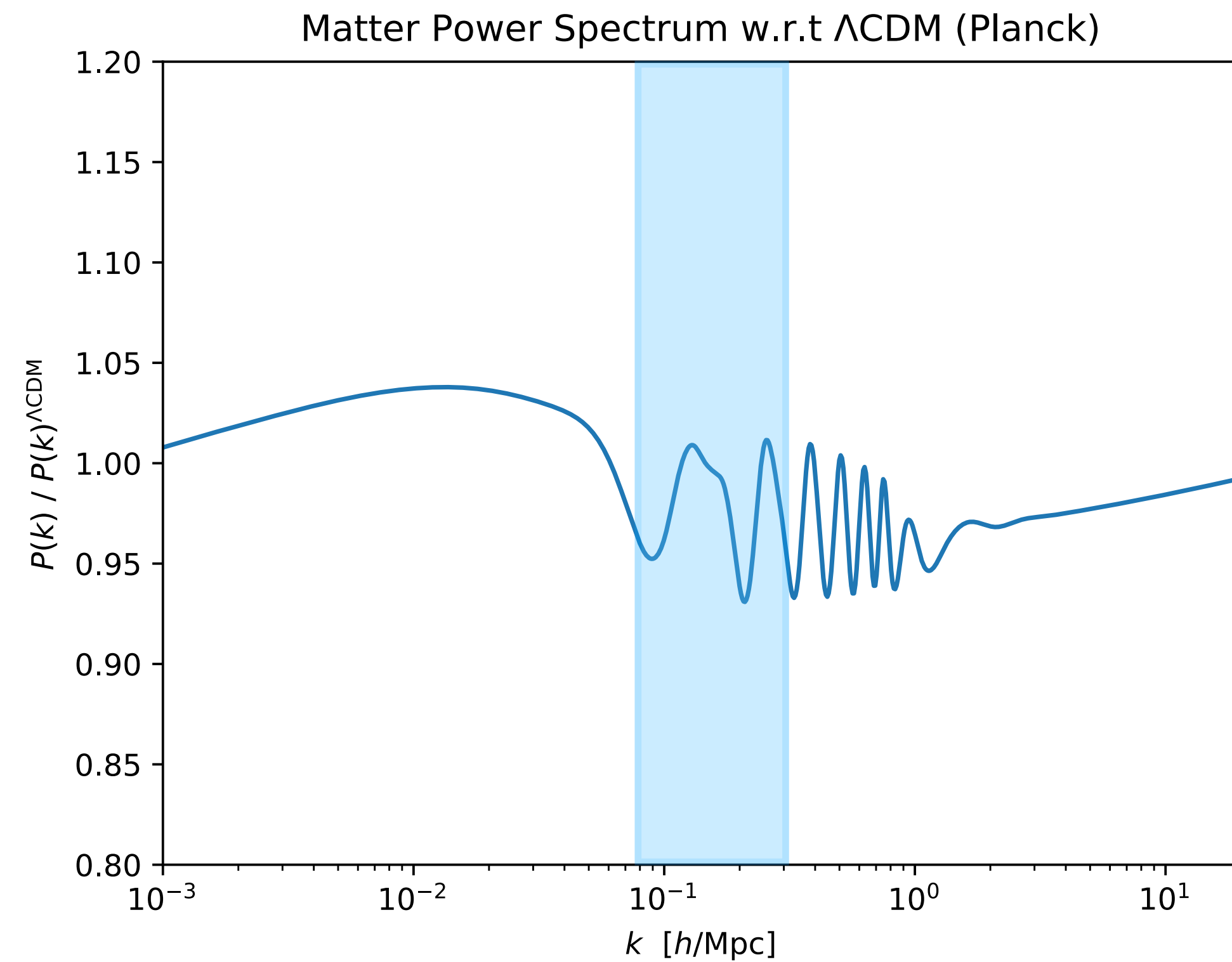
SPartAcous+3

Best-fit



SPartAcous+3

Best-fit



Conclusions

Summary and Outlook

Non-trivial Dark Sectors are well motivated

DS can be probed via Cosmology

H_0 (too small) and S_8 (too large) tensions

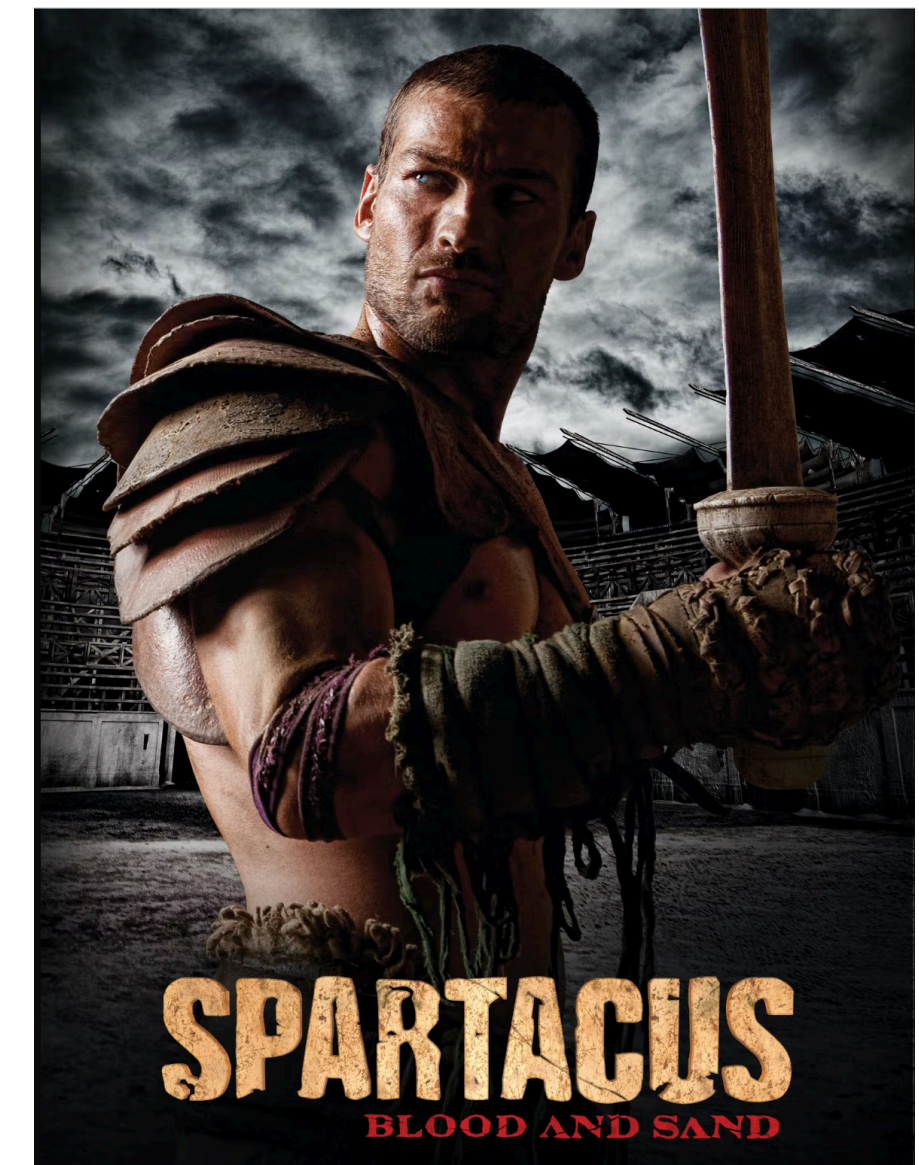
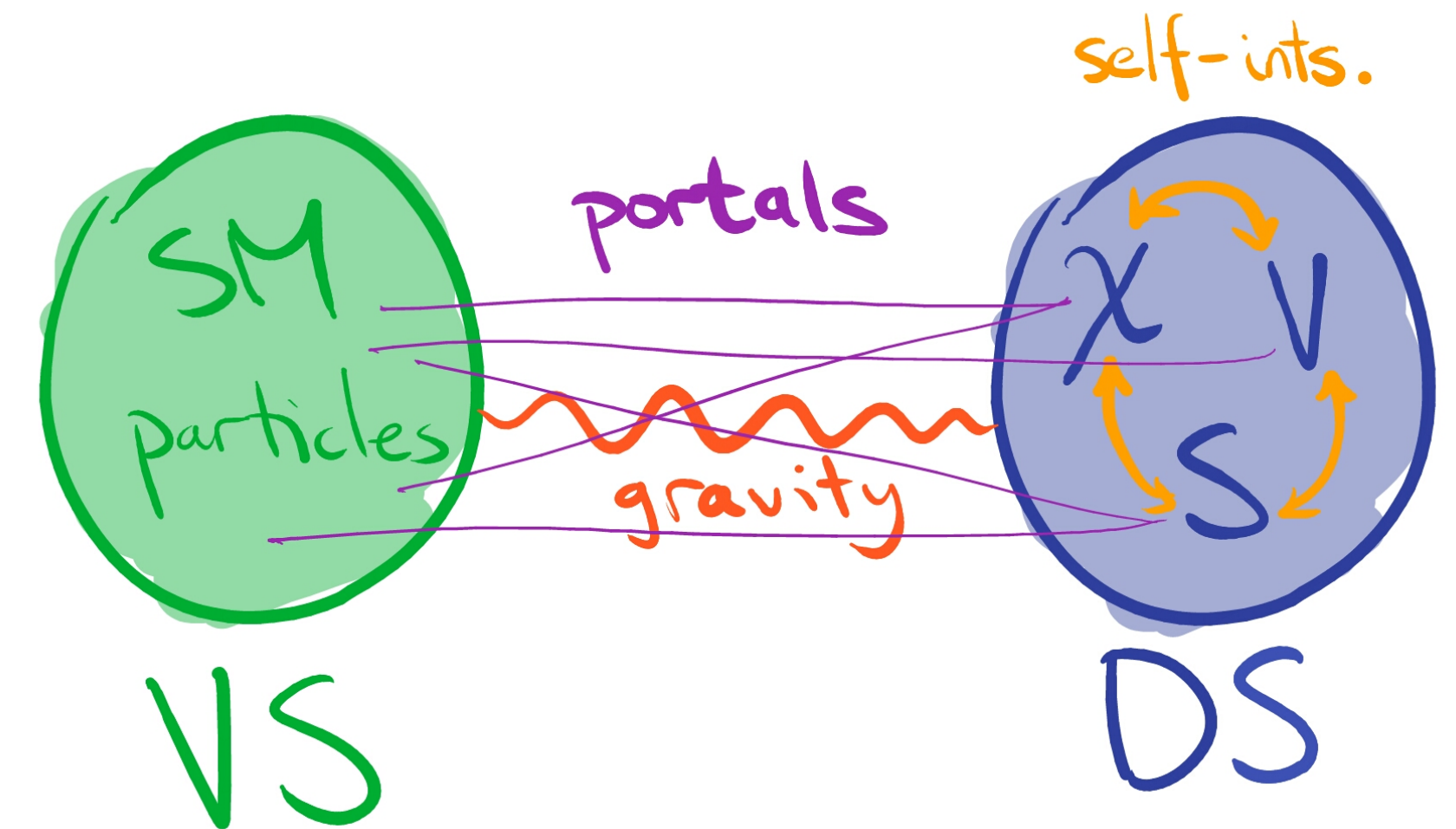
SPartAcous addresses both tensions

Stepped self-interacting DR

Stepped DM-DR interactions

Dark Acoustic Oscillations

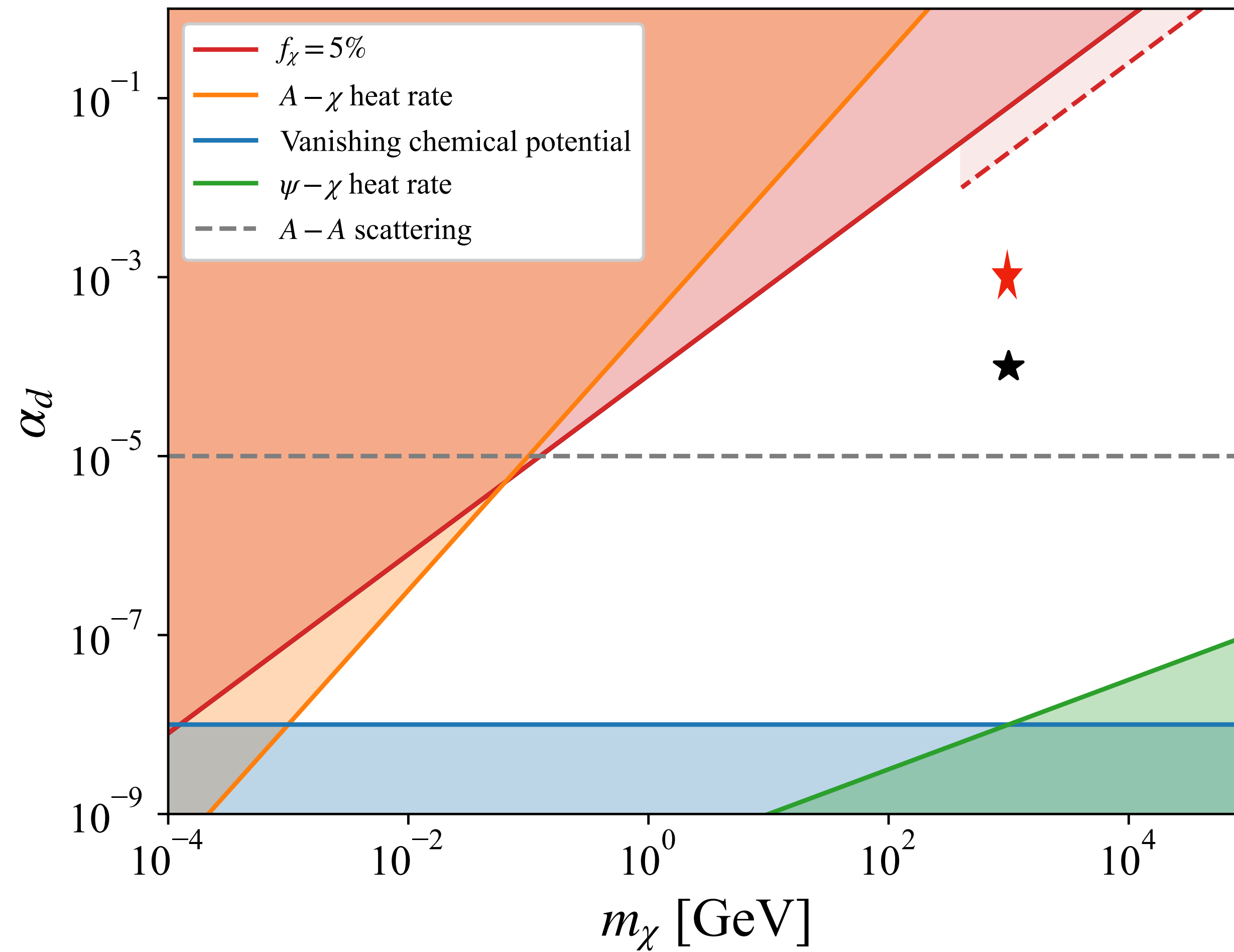
Stay tuned for **SPartAcous Part II: MCMC** coming up soon!



Supplements

SPartAcous

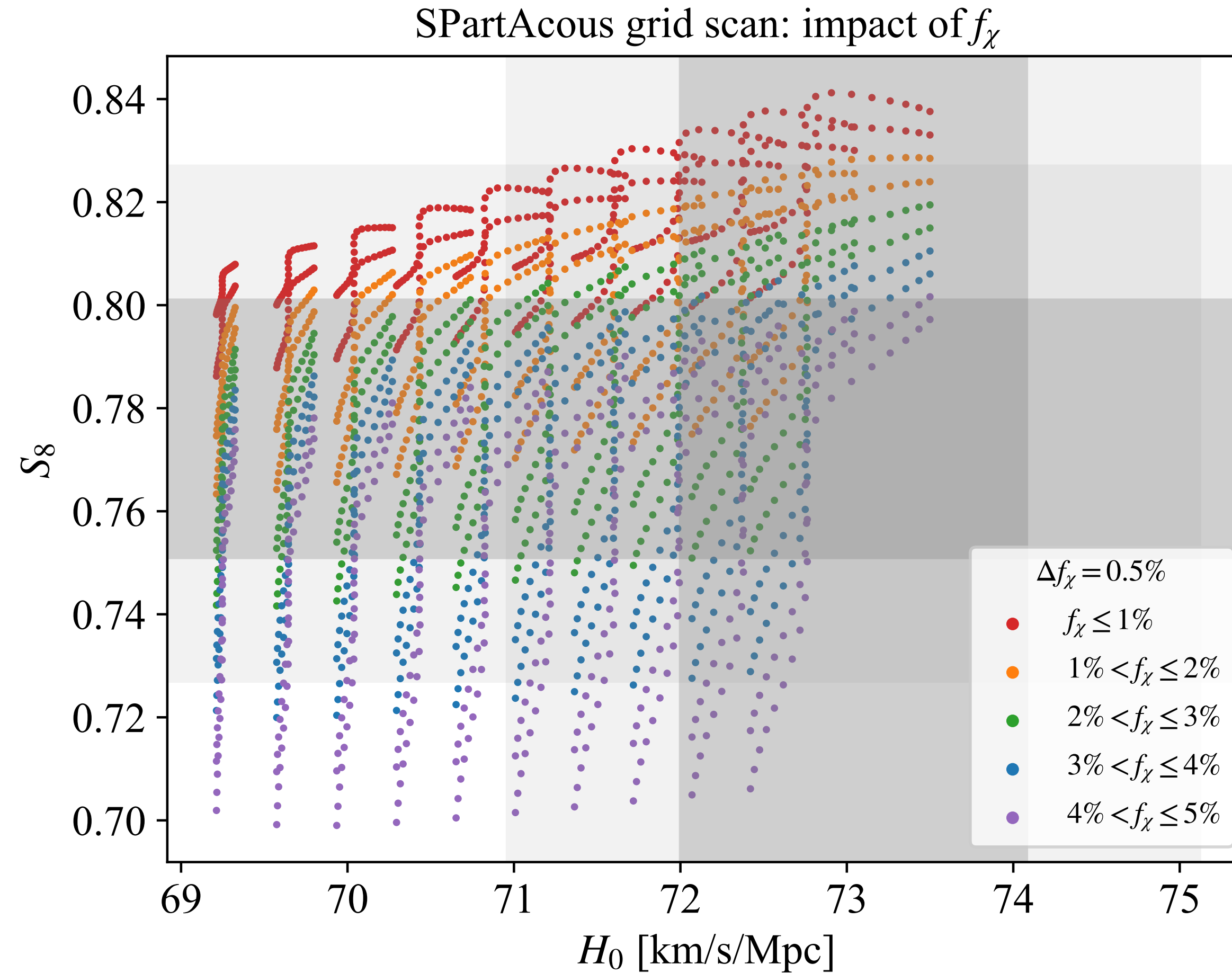
Parameter Space



H_0 and S_8 values

Using WZDR model best-fit parameters

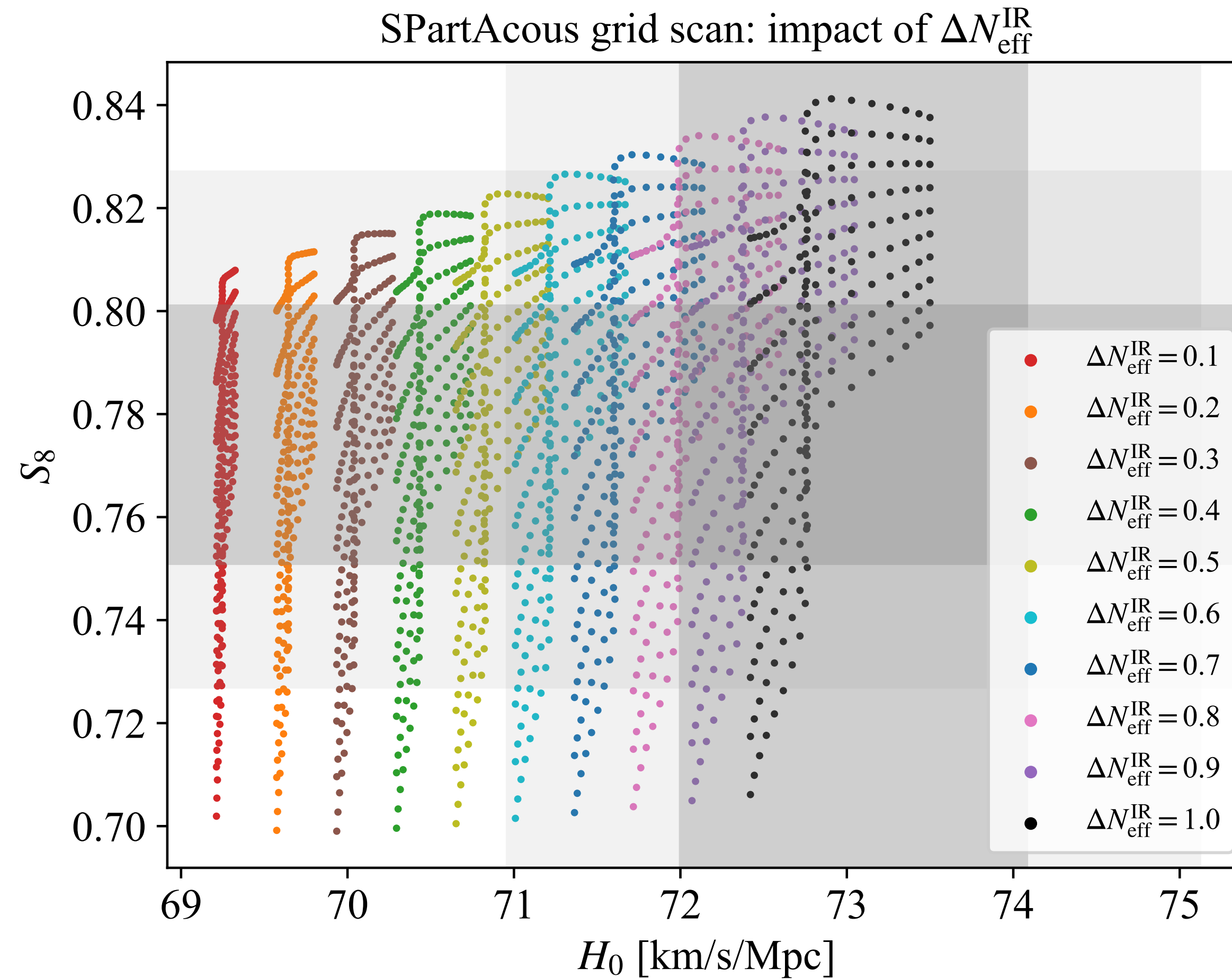
Aloni et al. [arXiv:2111.00014]



H_0 and S_8 values

Using WZDR model best-fit parameters

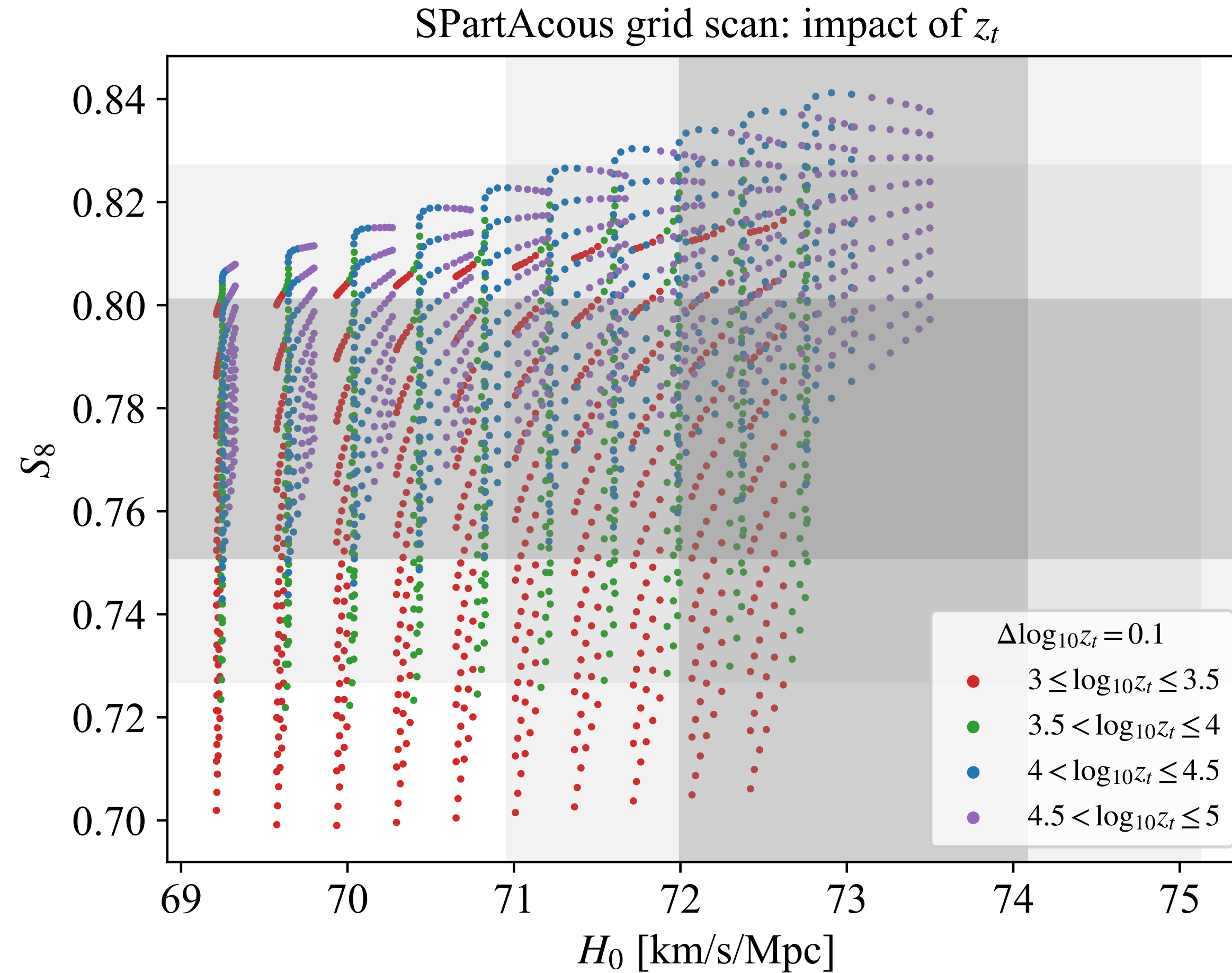
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H_0 and S_8 values

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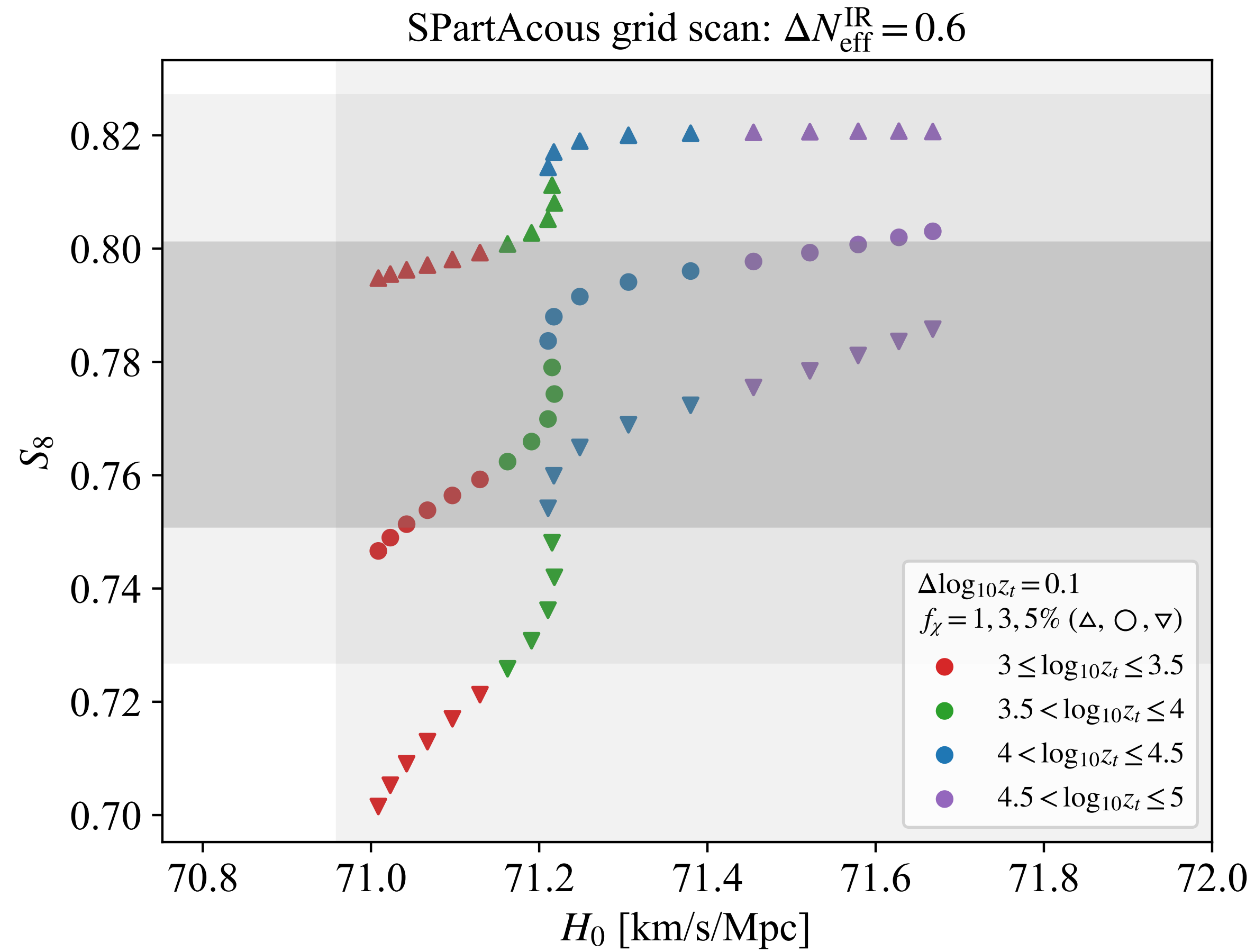
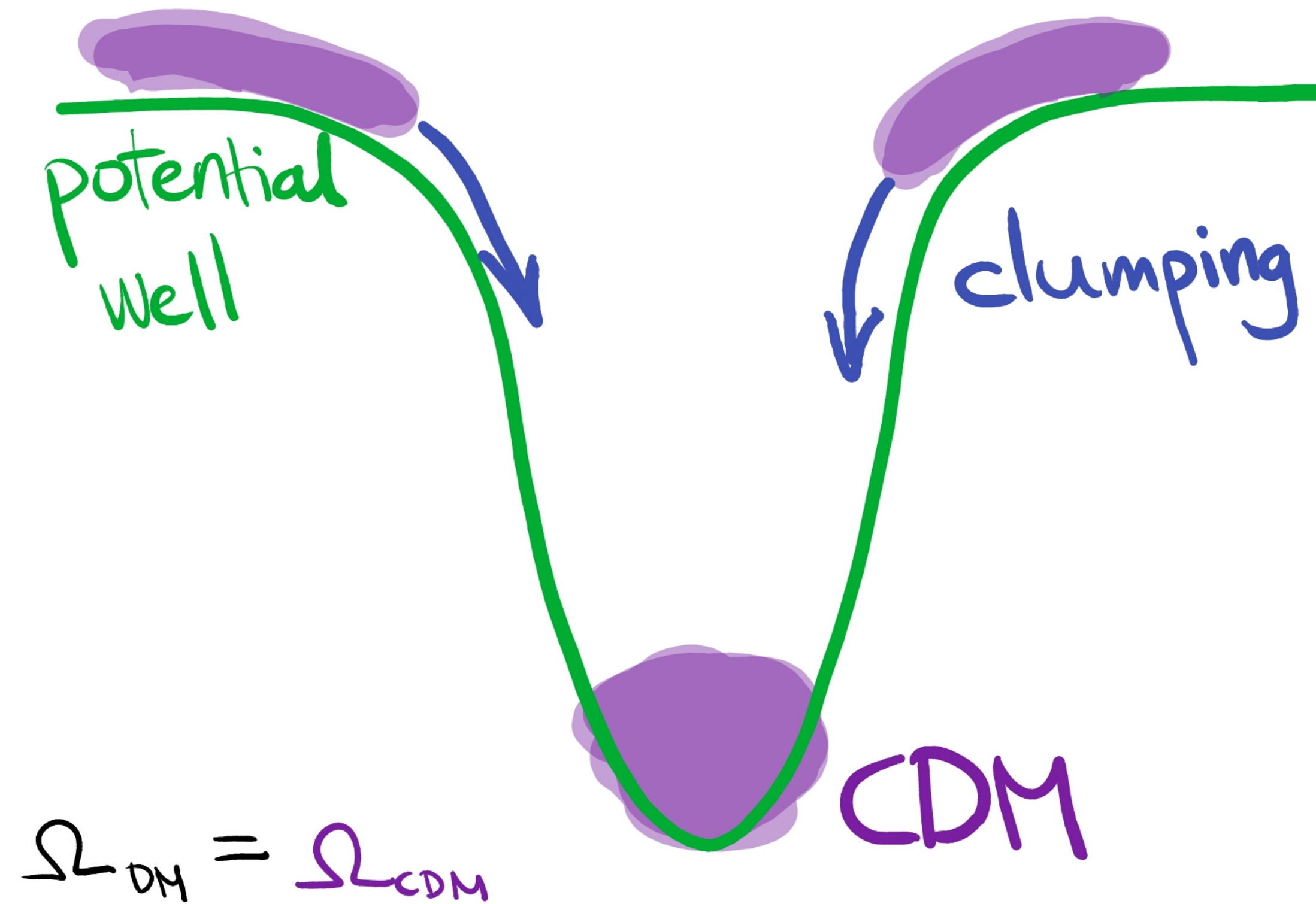


Table 1. Independent leading effects controlling the shape of the CMB temperature power spectrum C_l in the minimal Λ CDM model.

Effect		Relevant quantity	Parameter
(C1)	Peak scale	$\theta_{\text{peak}} = \frac{\pi}{l_{\text{peak}}} \sim \frac{d_{\text{s}} _{\text{dec}}}{d_{\text{a}} _{\text{dec}}}$	$\leftarrow \omega_{\text{m}}, \omega_{\text{b}}$ $\leftarrow \Omega_{\Lambda}, \omega_{\text{m}}$
(C2)	Odd/even peak amplitude ratio	$R _{\text{dec}}$	ω_{b}
(C3)	Overall peak amplitude	$\frac{a_{\text{dec}}}{a_0}$	ω_{m}
(C4)	Damping envelope	$\theta_{\text{d}} = \frac{\pi}{l_{\text{d}}} = \frac{a_{\text{dec}} r_{\text{d}} _{\text{dec}}}{d_{\text{a}} _{\text{dec}}}$	$\leftarrow \omega_{\text{m}}, \omega_{\text{b}}$ $\leftarrow \Omega_{\Lambda}, \omega_{\text{m}}$
(C5)	Global amplitude	$\mathcal{P}_{\mathcal{R}}(k_*)$	A_{s}
(C6)	Global tilt	$\frac{d \log \mathcal{P}_{\mathcal{R}}}{d \log k}$	n_{s}
(C7)	Additional plateau tilting (LISW)	$\frac{a_{\Lambda}}{a_0}$	Ω_{Λ}
(C8)	Amplitude for $l \geq 40$ only	τ_{reio}	τ_{reio}

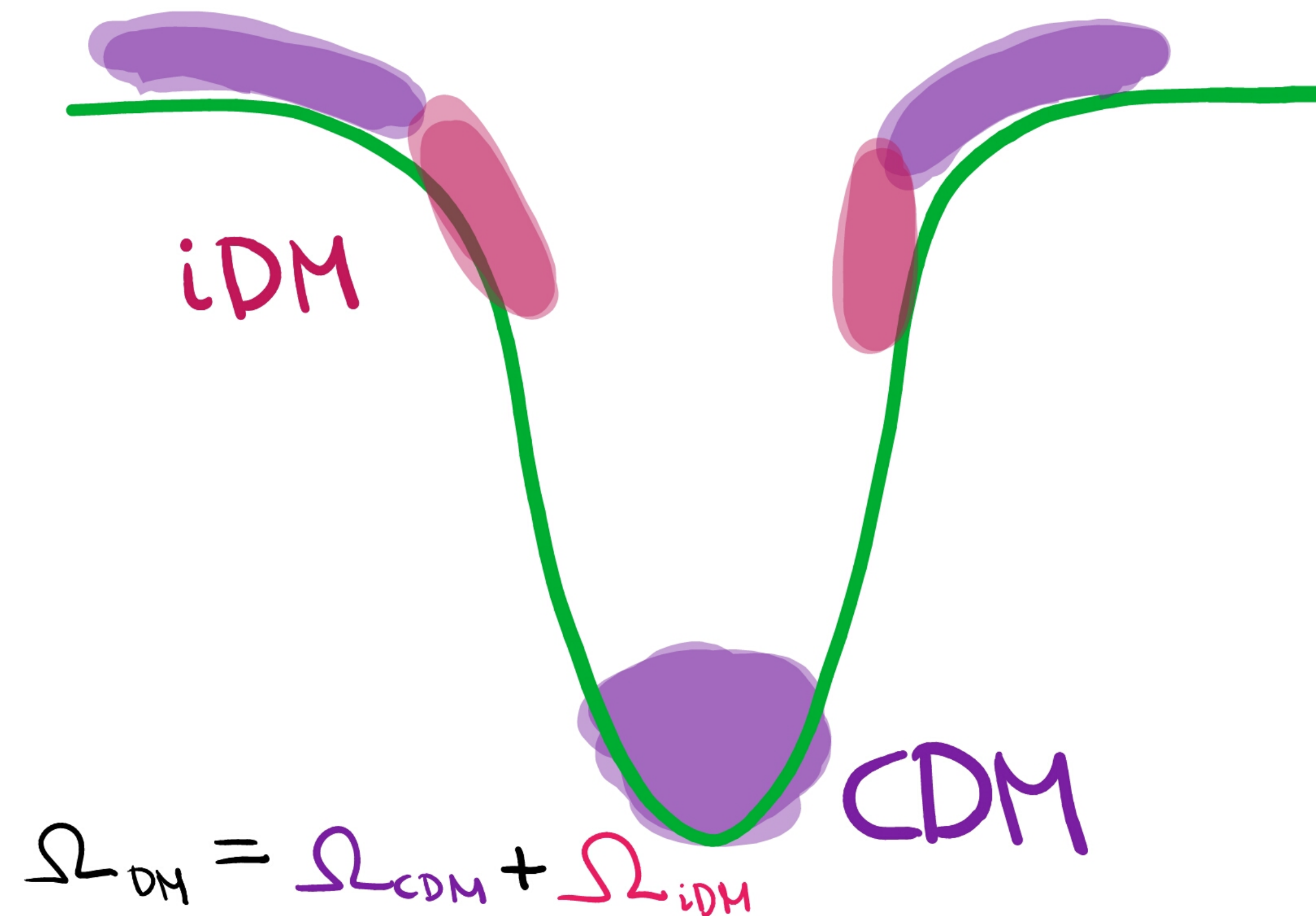
Dark Matter interaction with DR

Tightly-coupled DM-DR



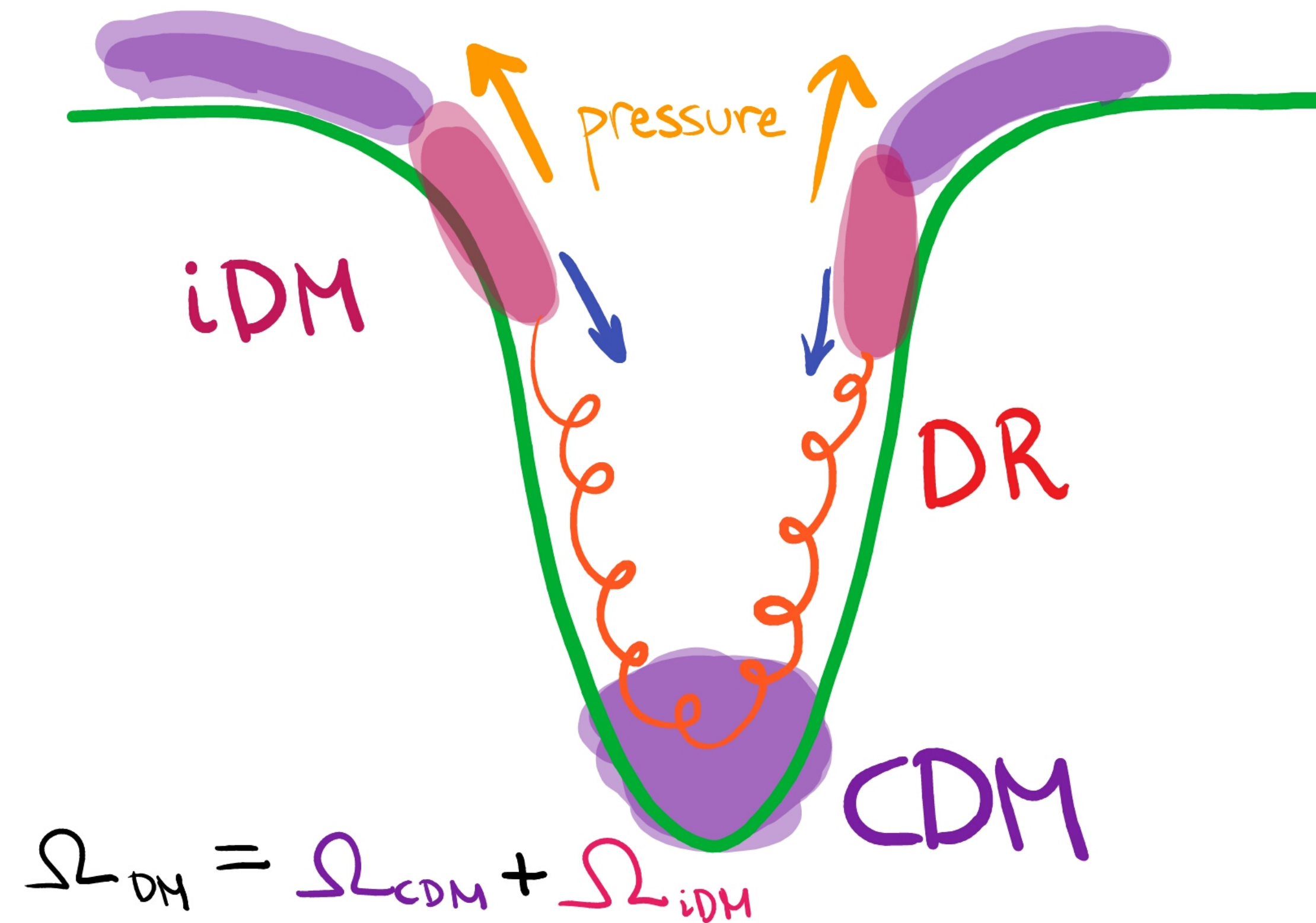
Dark Matter interaction with DR

Tightly-coupled DM-DR



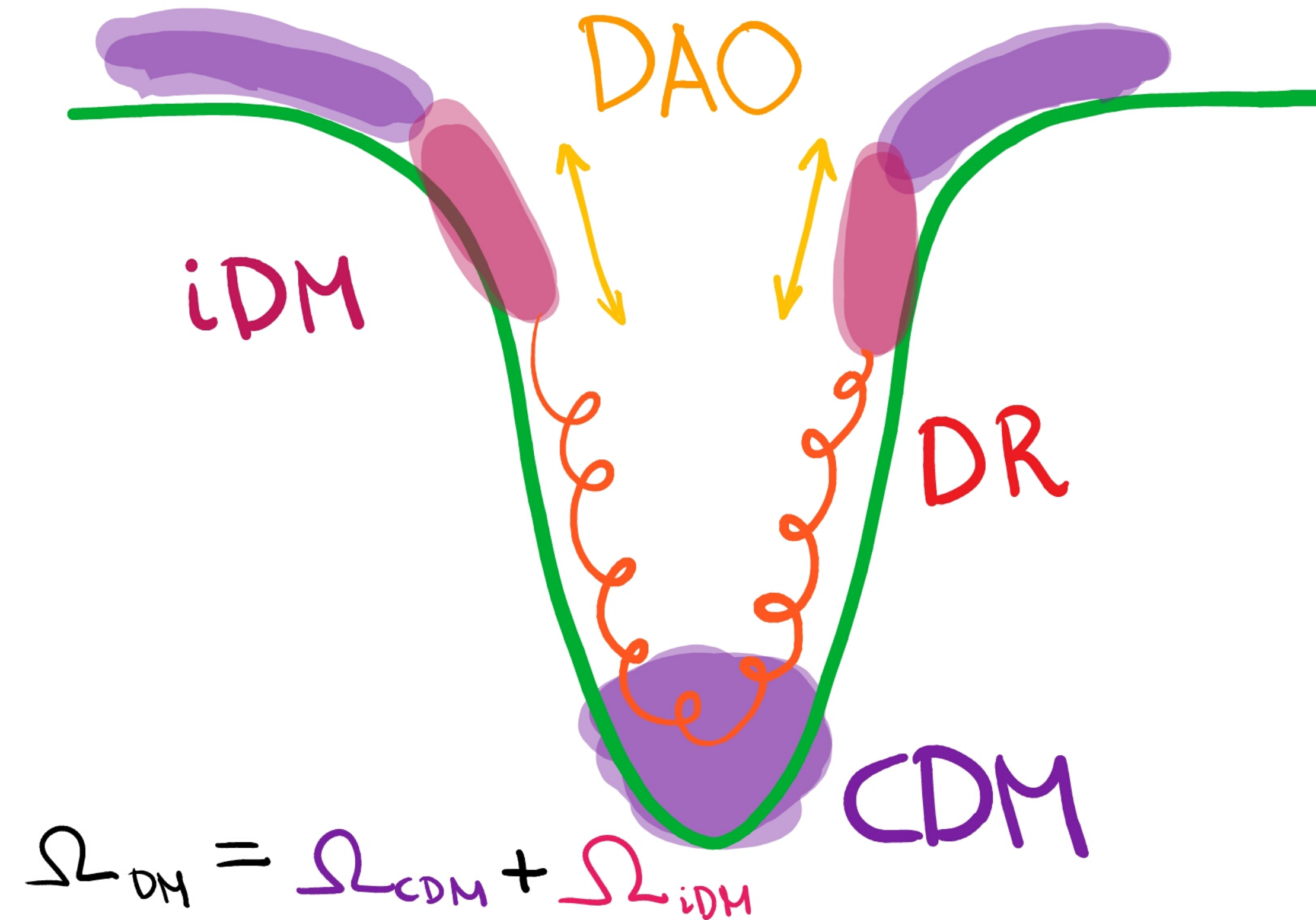
Dark Matter interaction with DR

Tightly-coupled DM-DR



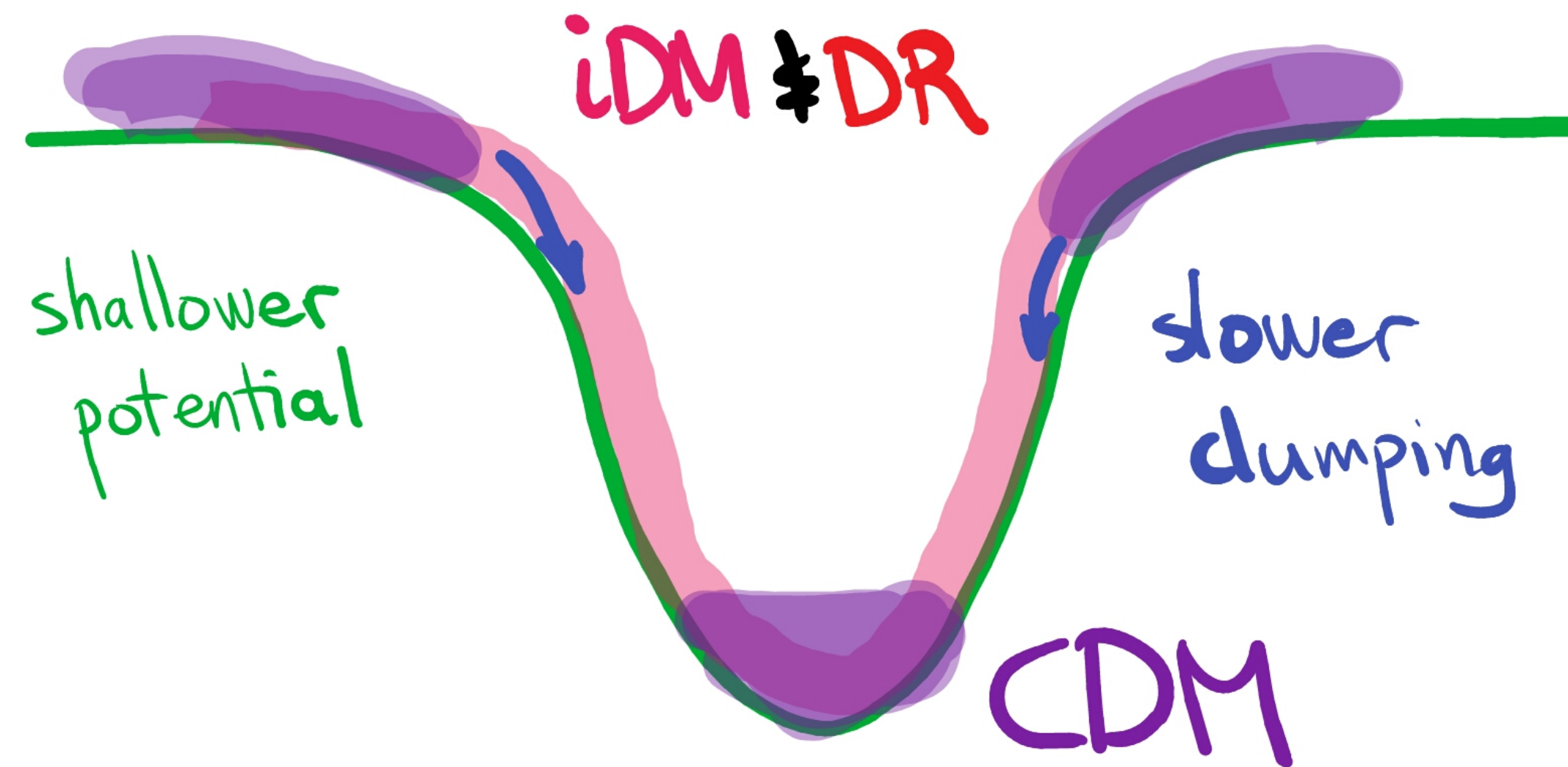
Dark Matter interaction with DR

Dark Acoustic Oscillations



Dark Matter interaction with DR

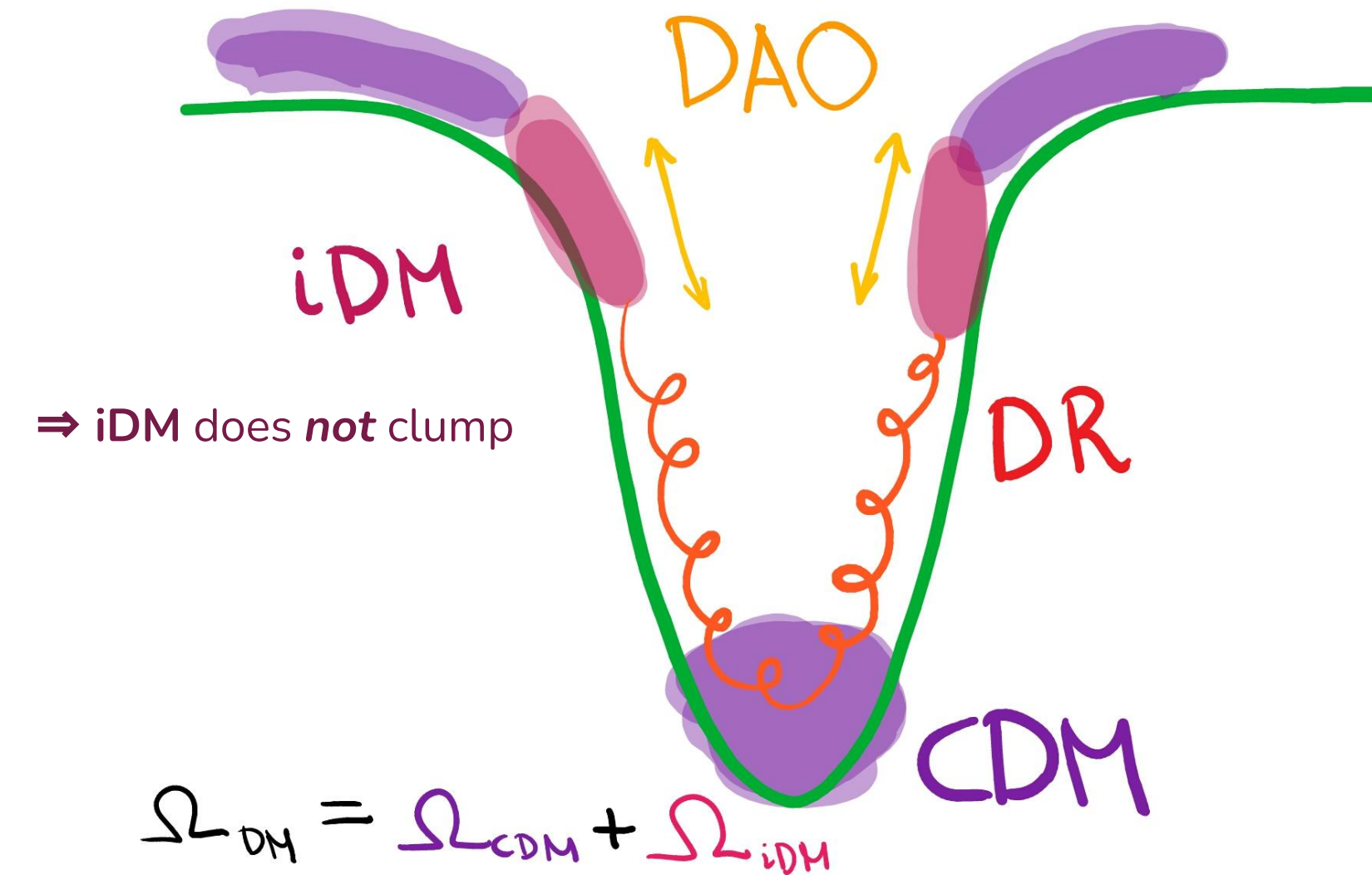
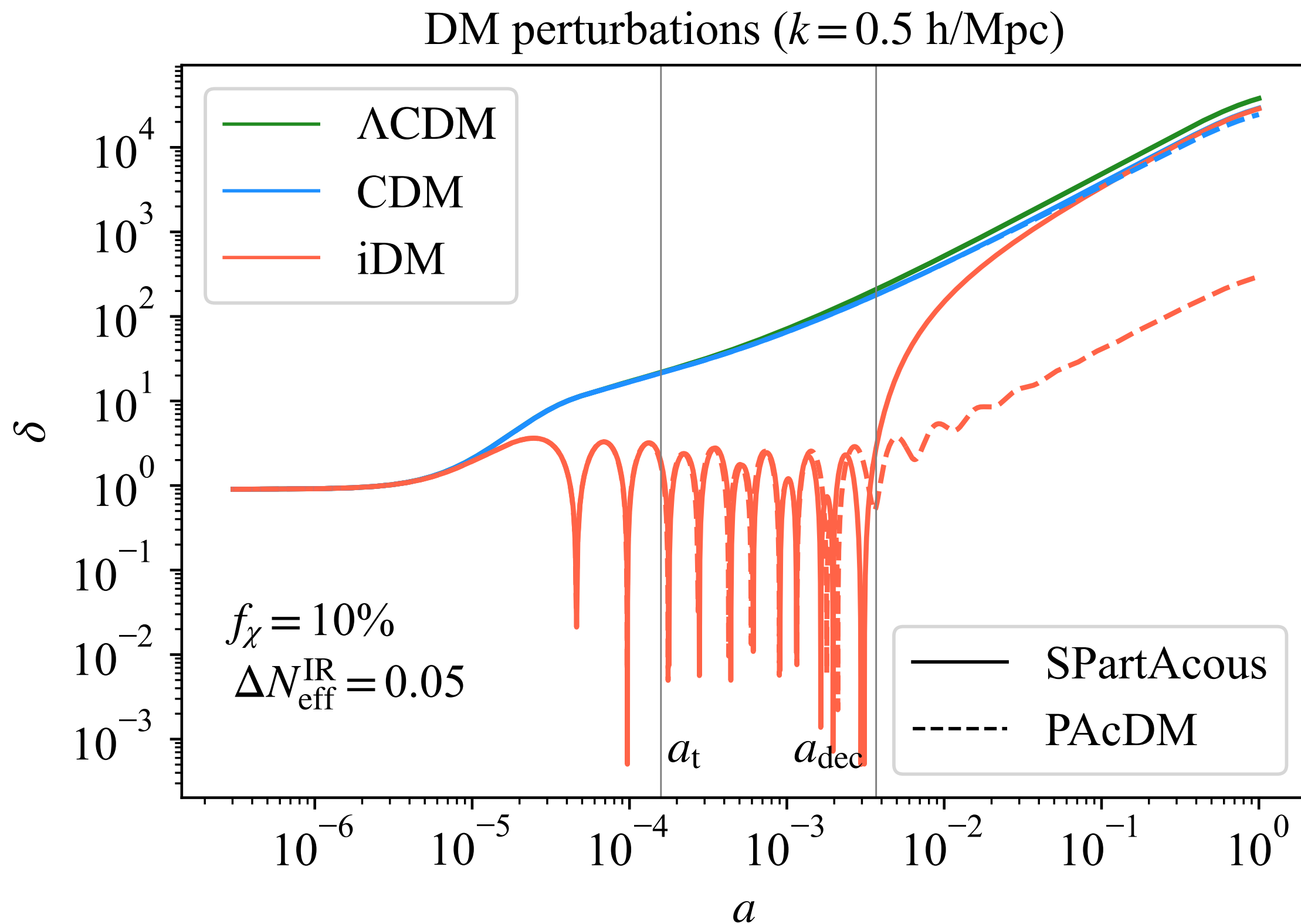
Structure Suppression



$$\Omega_{DM} = \Omega_{CDM} + \Omega_{iDM}$$

SPartAcous

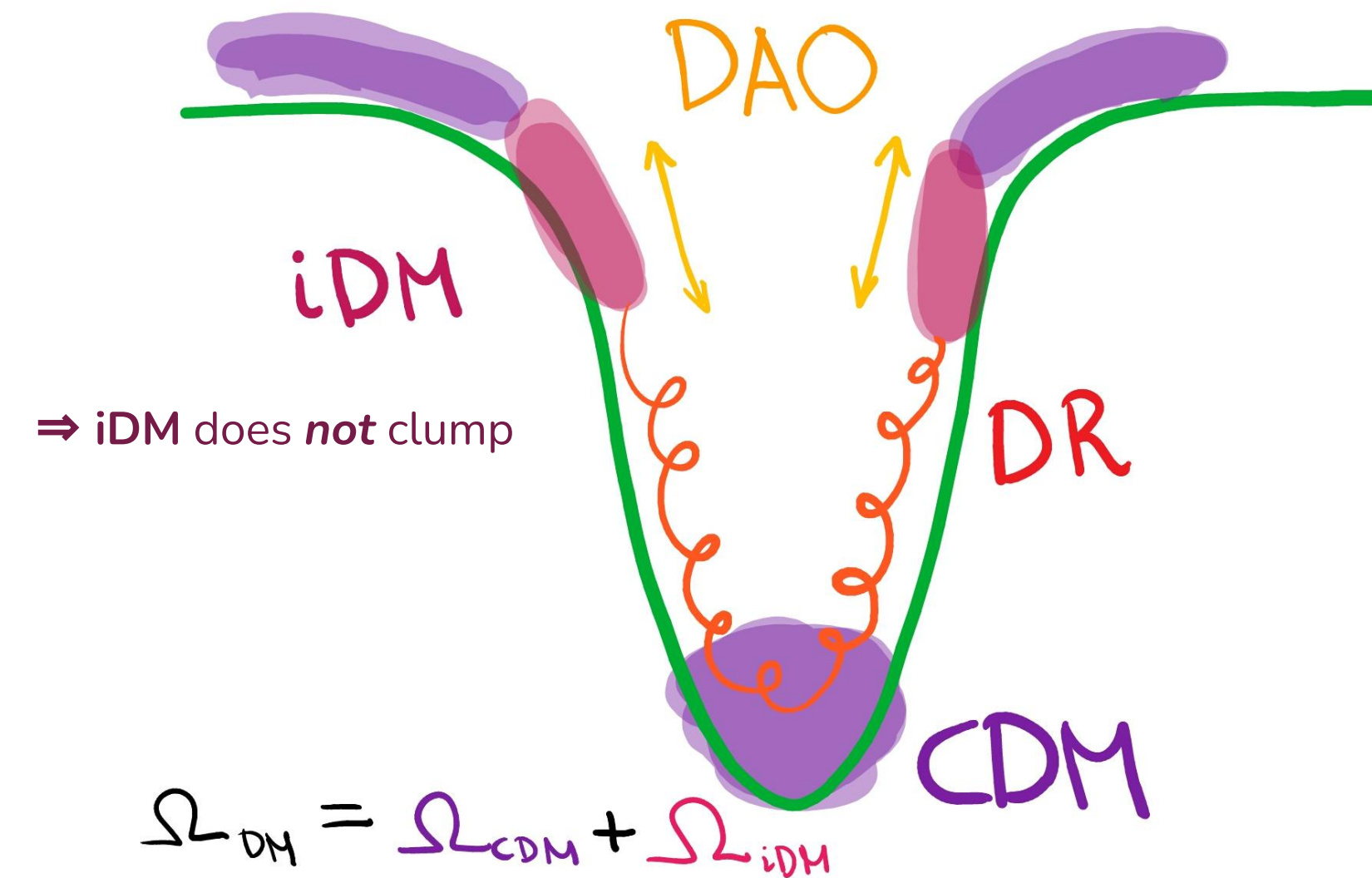
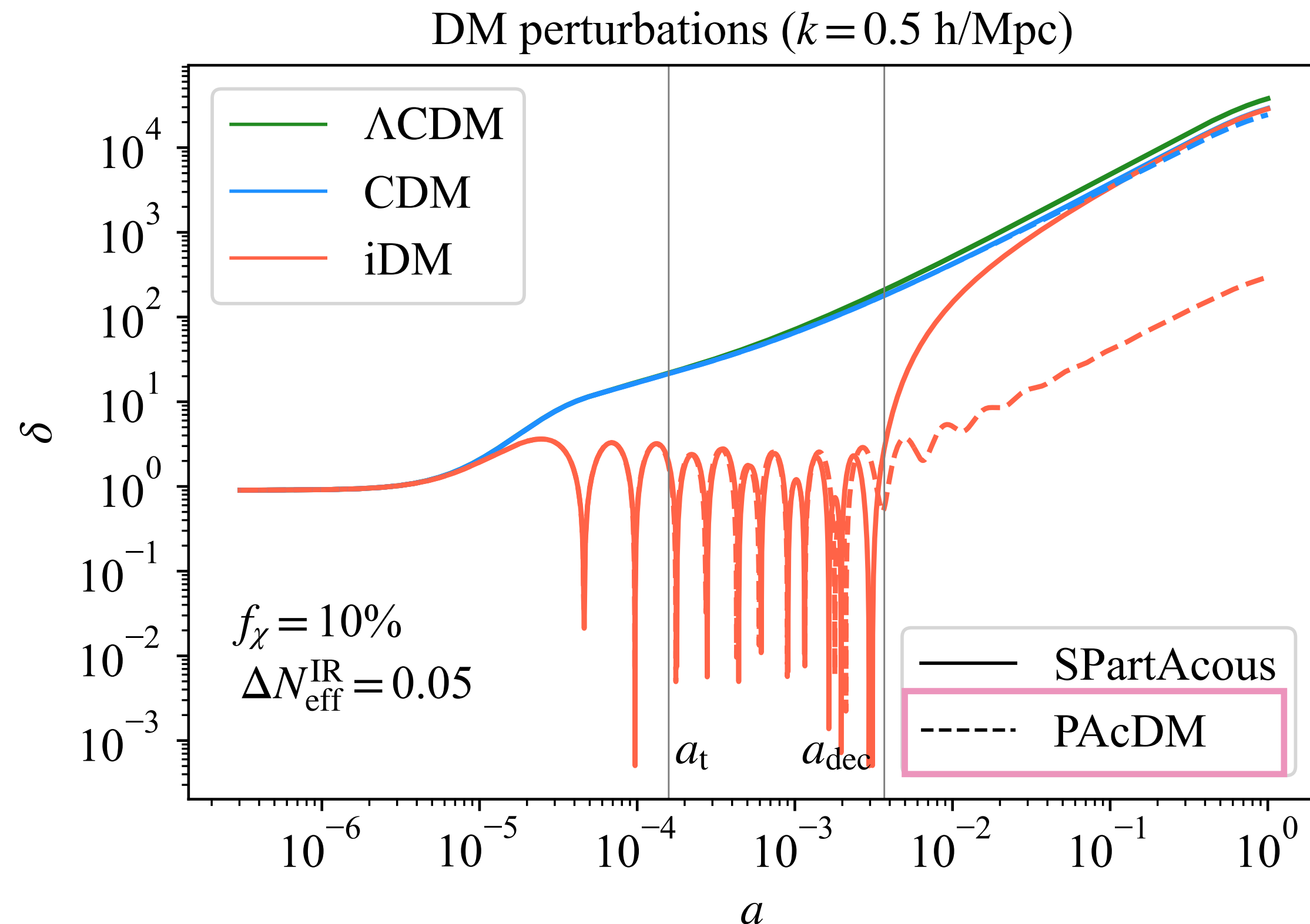
Dark Acoustic Oscillations



$$\delta \mathcal{L}_{\text{dark}} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \bar{\psi}(i\not{D} - m_\psi)\psi + |D\chi|^2 - m_\chi^2 |\chi|^2$$

SPartAcous

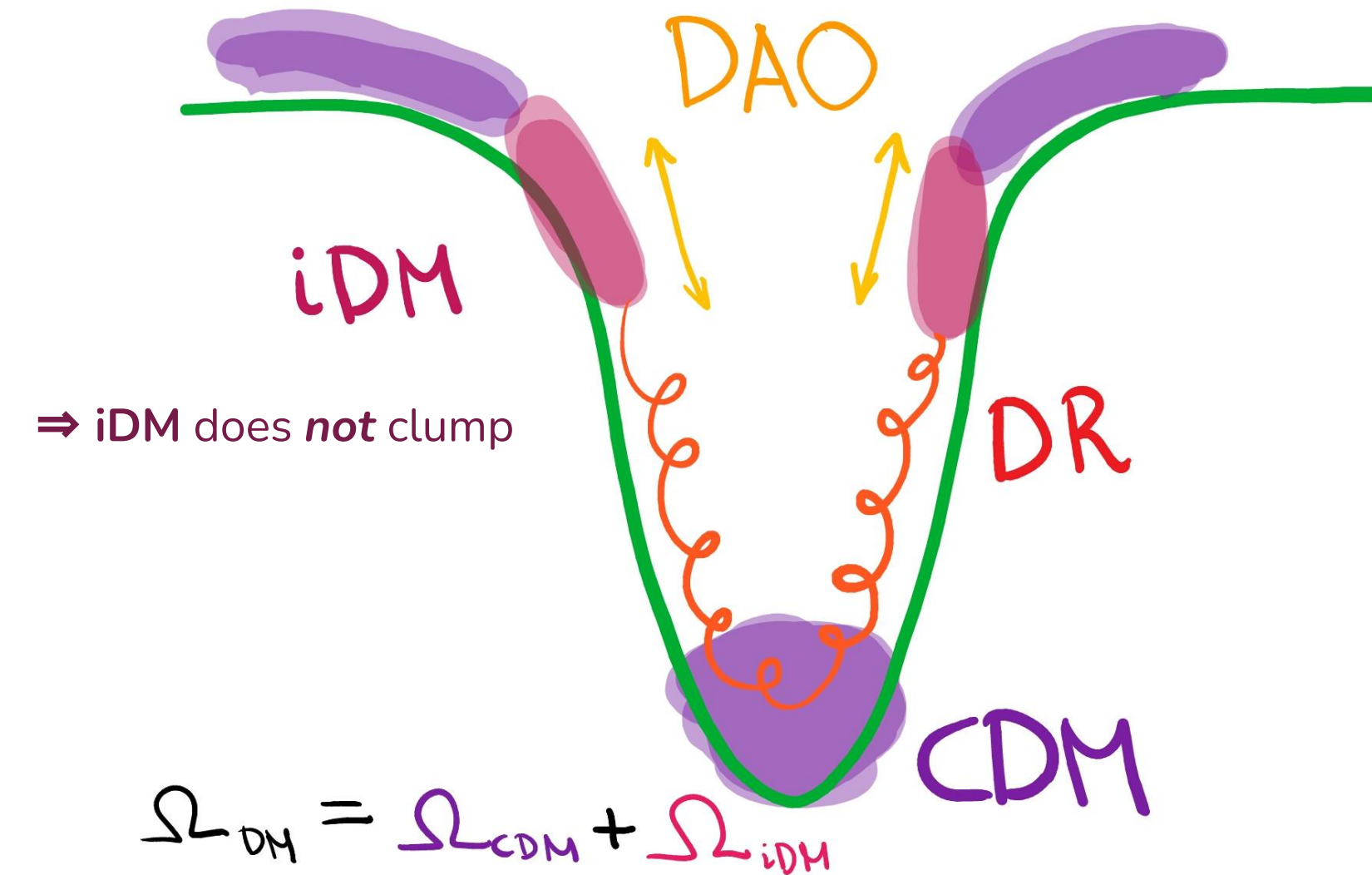
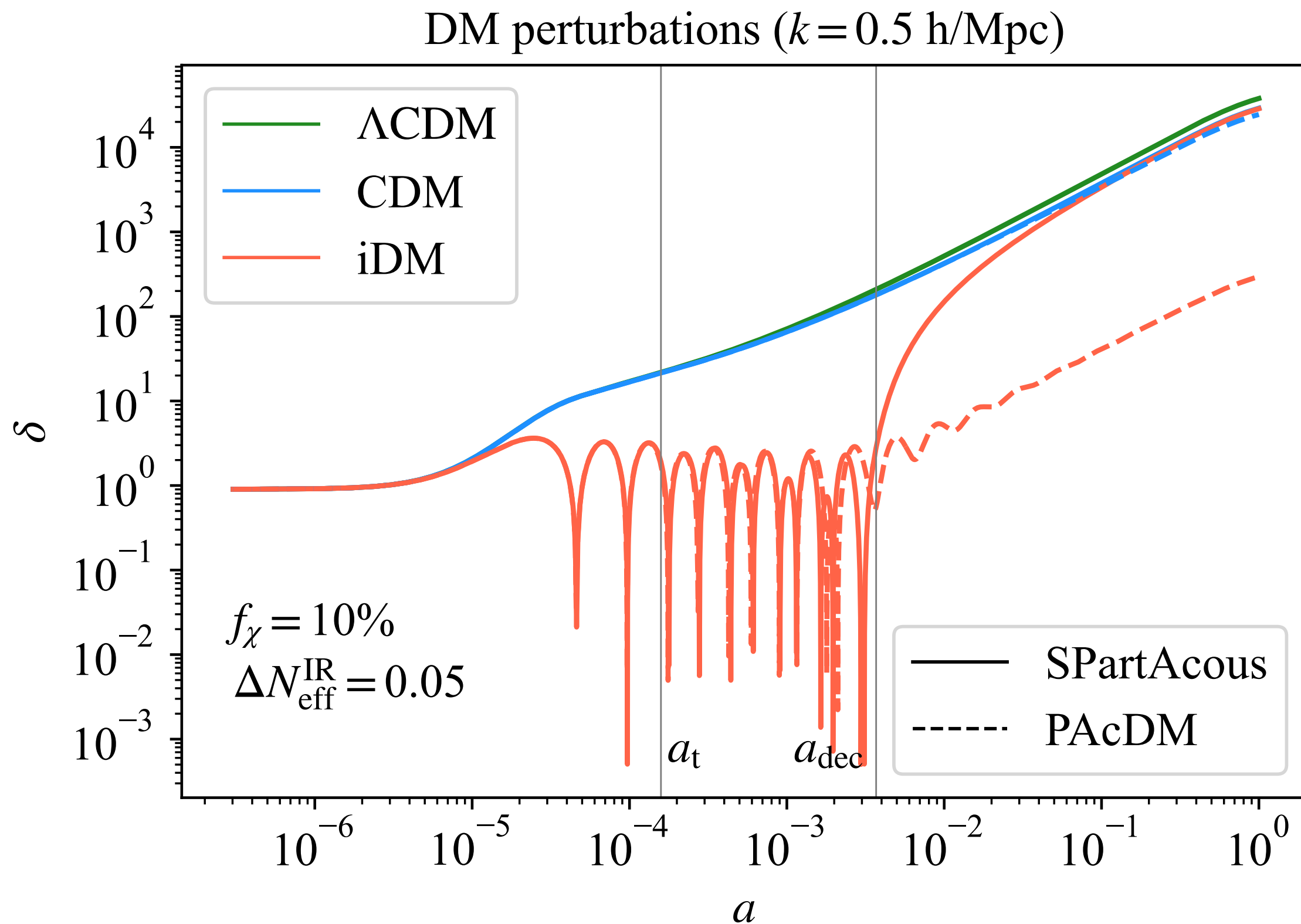
Dark Acoustic Oscillations



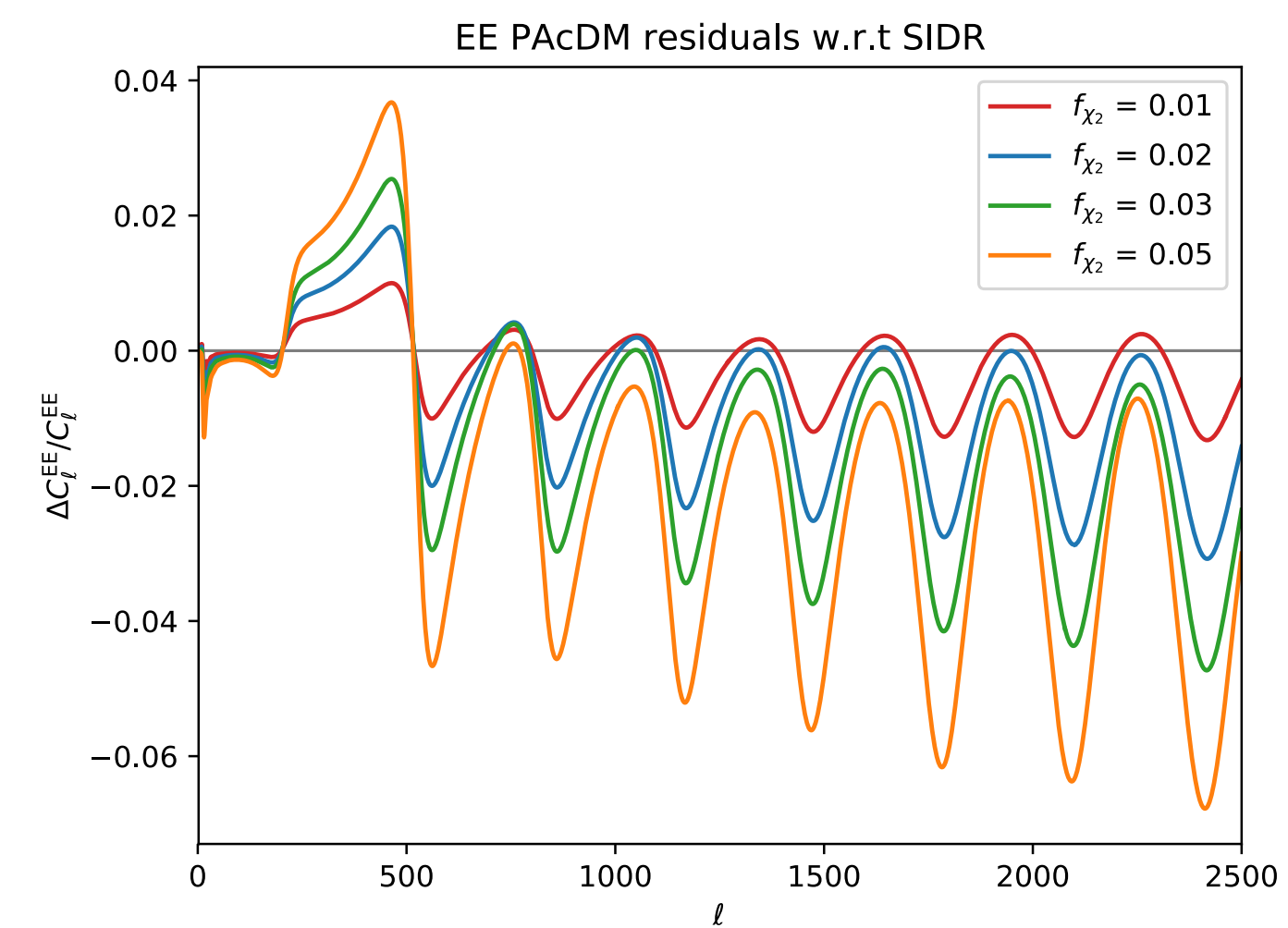
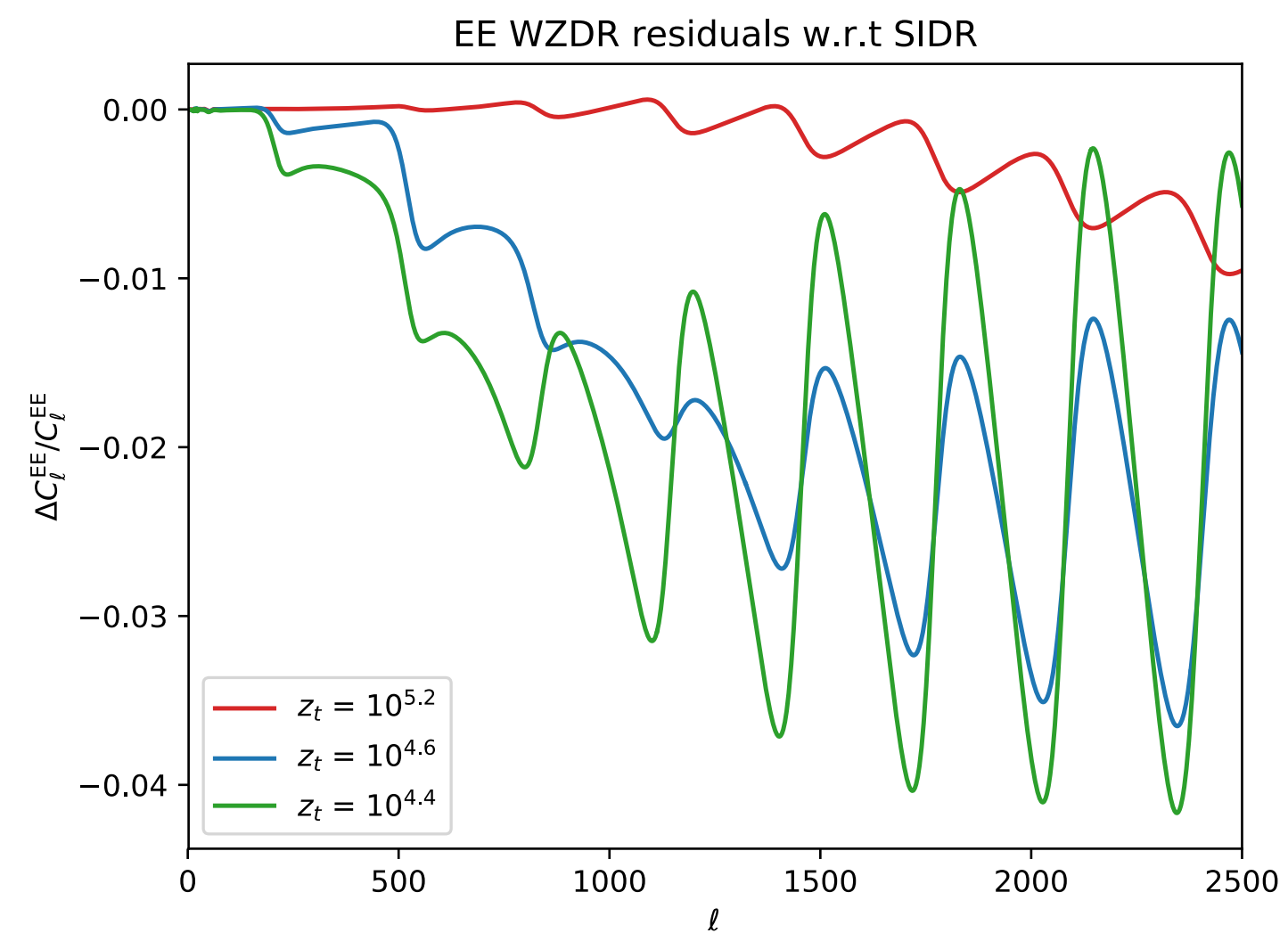
$$\delta\mathcal{L}_{\text{dark}} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \bar{\psi}(i\mathcal{D} - \cancel{m_\psi})\psi + |D\chi|^2 - m_\chi^2|\chi|^2$$

SPartAcous

Dark Acoustic Oscillations

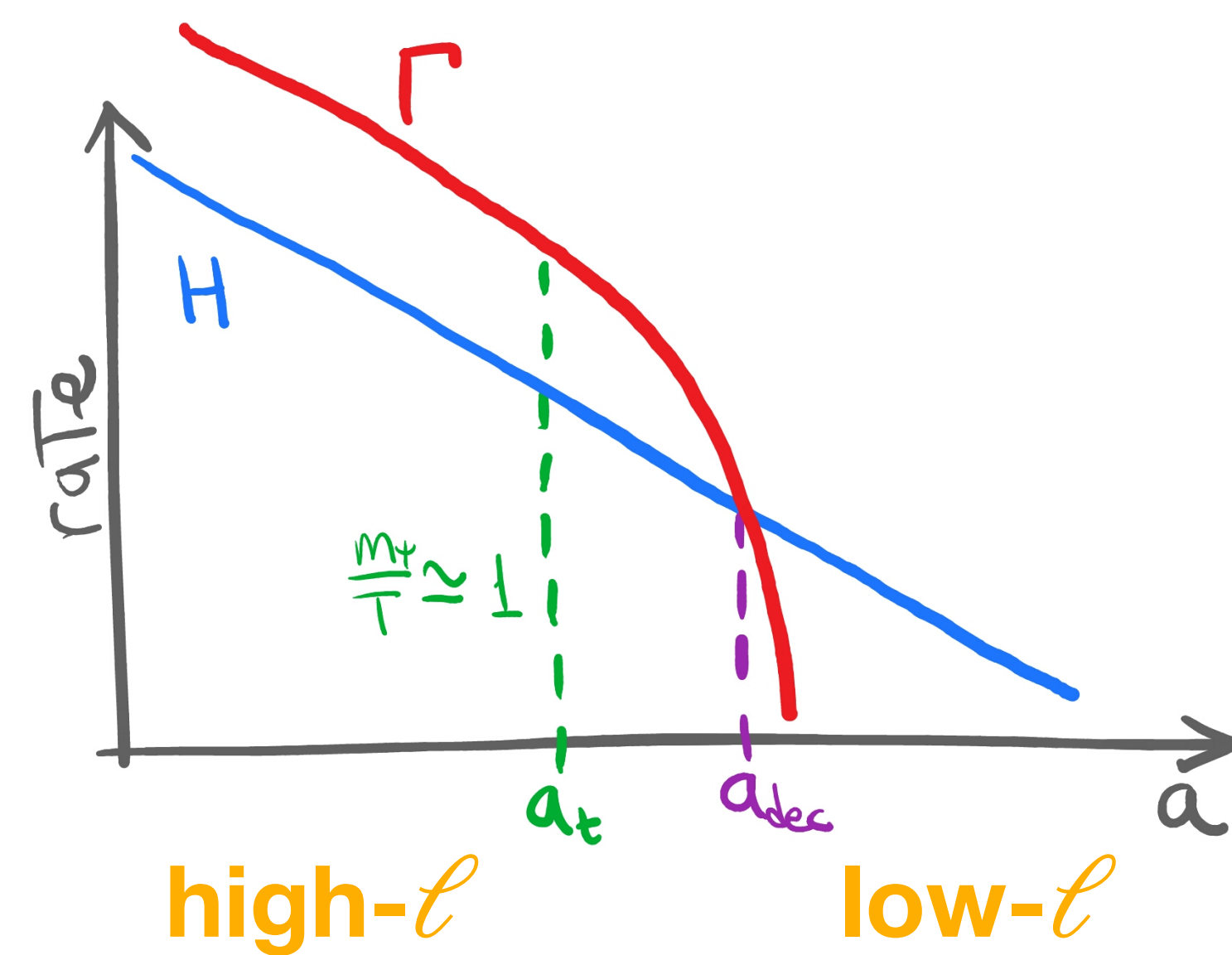
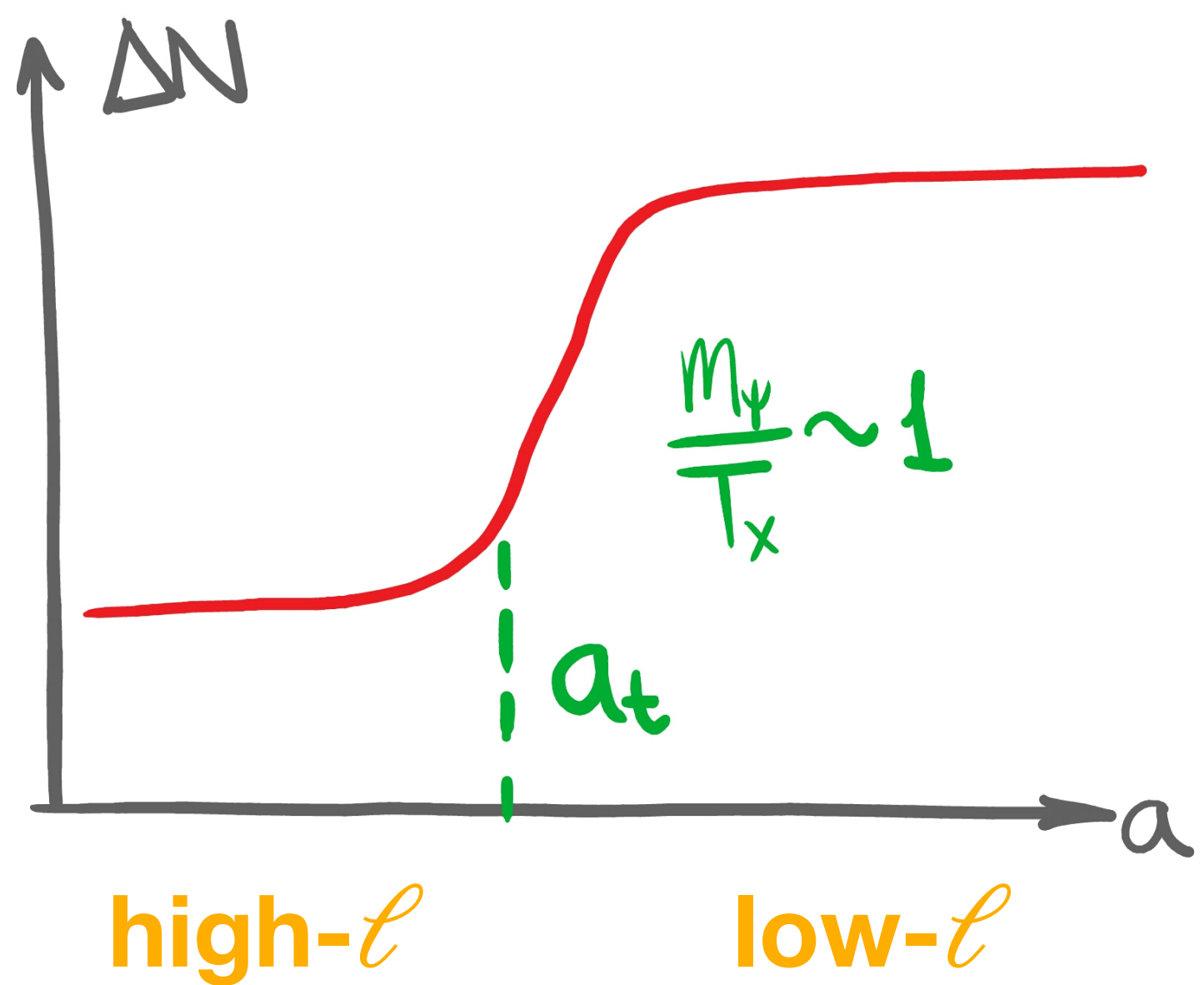


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?

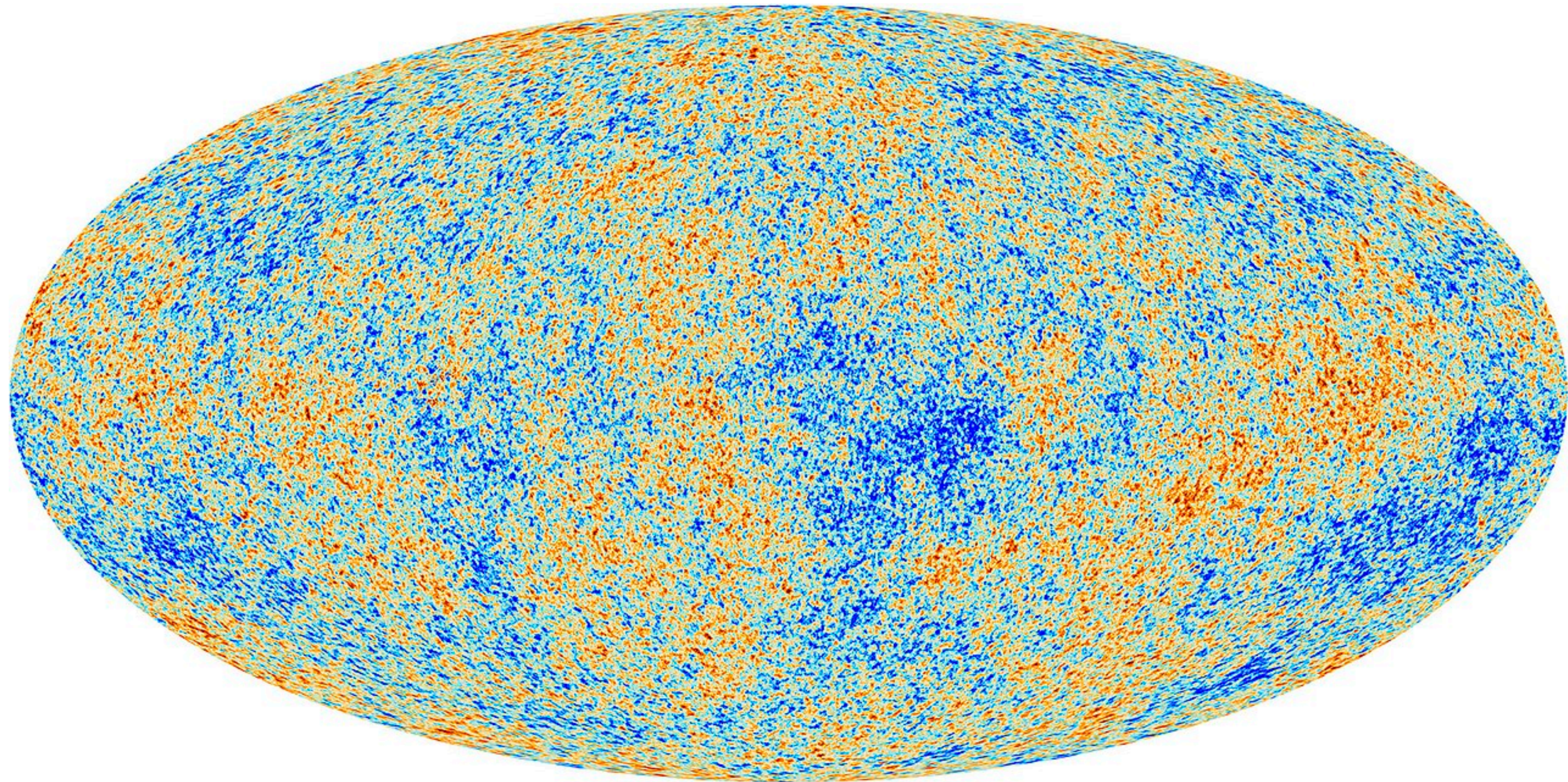
?



Cosmological Tensions

Hubble tension ($\sim 4\text{-}6\ \sigma$)

CMB measures H_0 tightly by sound horizon angle

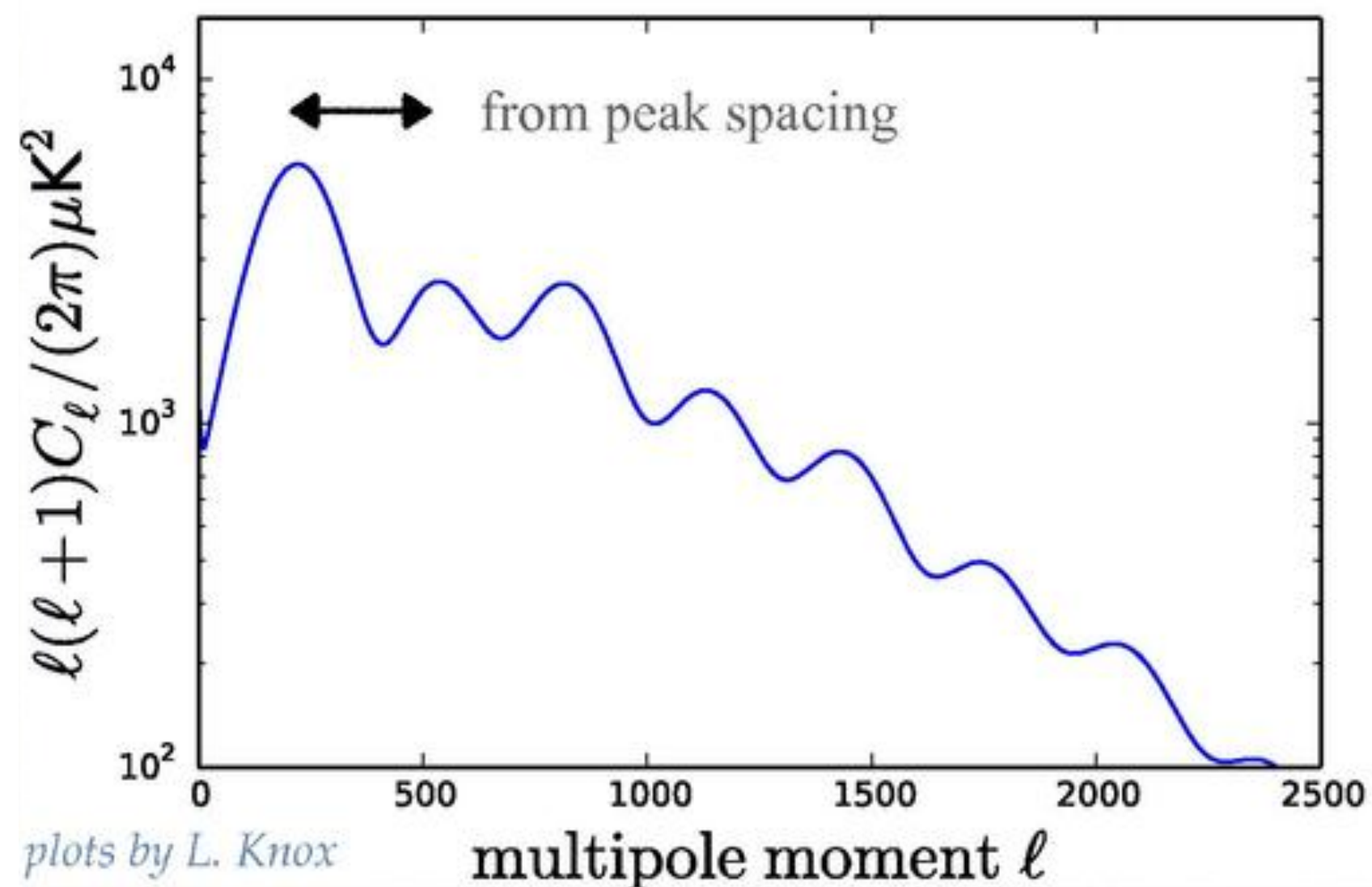
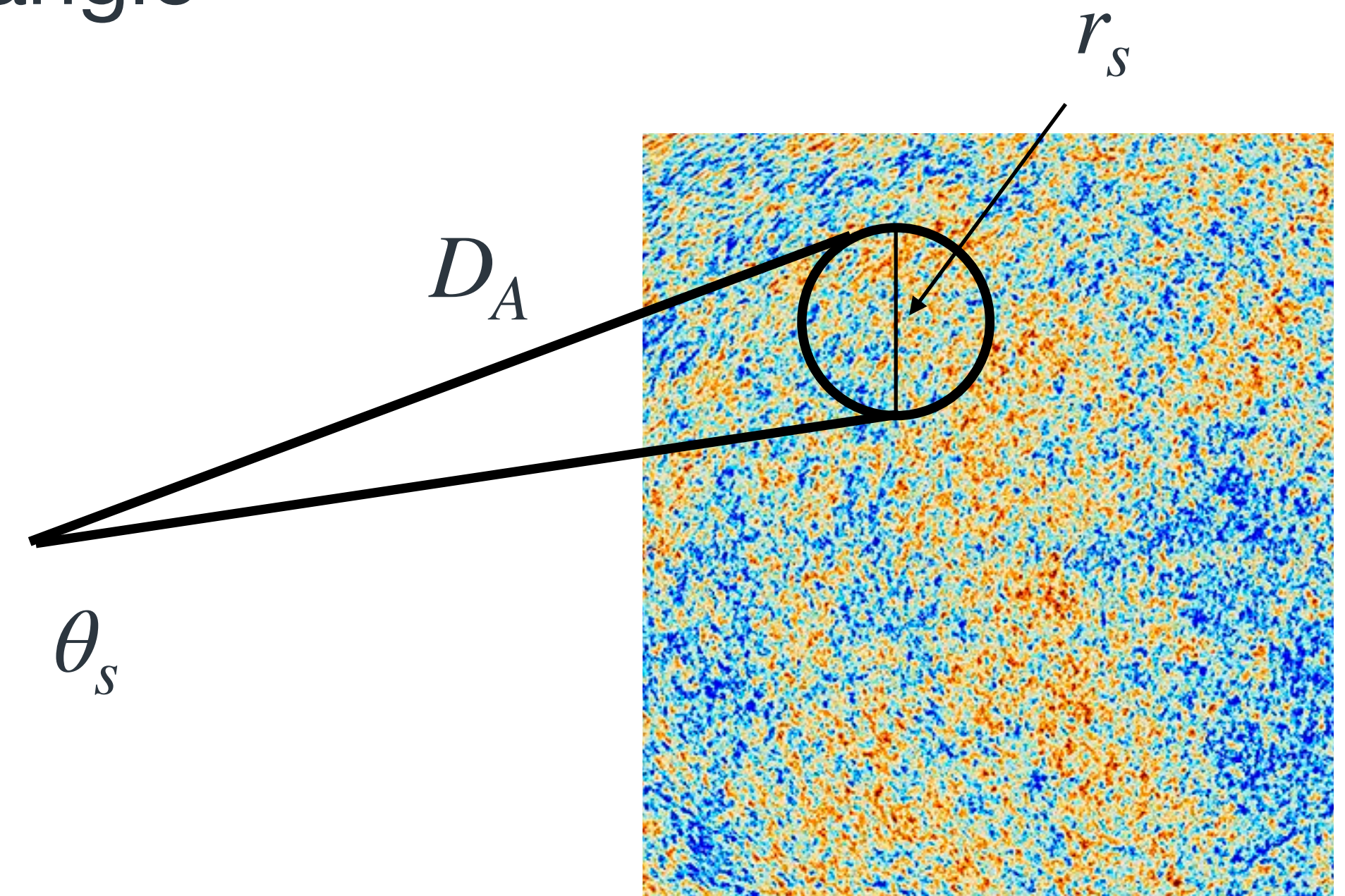


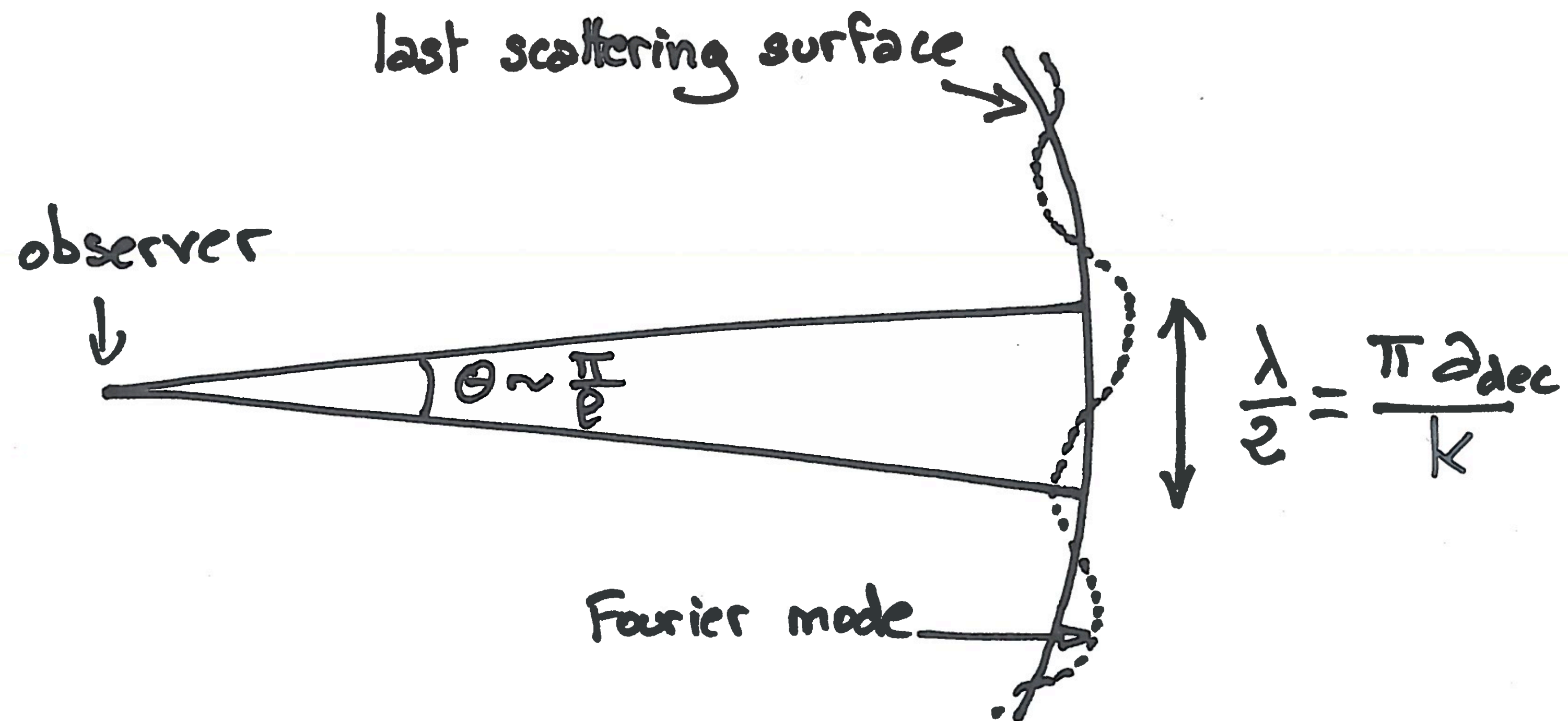
Cosmological Tensions

Hubble tension ($\sim 4\text{-}6\ \sigma$)

CMB measures H_0 tightly by sound horizon angle

$$\theta_s = \frac{r_s}{D_A}$$





Cosmological Tensions

Hubble tension ($\sim 4\text{-}6\ \sigma$)

$$D_A = \frac{c}{H_0} \int_{t_{\text{rec}}}^{t_0} \frac{dt/t_0}{[\rho(t)/\rho_0]^{1/2}}$$

$$r_s = \frac{1}{H_{\text{rec}}} \int_0^{t_{\text{rec}}} \frac{c_s(t) dt/t_{\text{rec}}}{[\rho(t)/\rho(t_{\text{rec}})]^{1/2}}$$

Cosmological Tensions

Hubble tension ($\sim 4\text{-}6\ \sigma$)

$$H_0 = H_{\text{rec}} \theta_s \frac{\int_{t_{\text{rec}}}^{t_0} \frac{dt/t_0}{[\rho(t)/\rho_0]^{1/2}}}{\int_0^{t_{\text{rec}}} \frac{c_s(t) dt/t_{\text{rec}}}{[\rho(t)/\rho(t_{\text{rec}})]^{1/2}}}$$

To increase H_0 ,

Cosmological Tensions

Hubble tension ($\sim 4\text{-}6\ \sigma$)

$$H_0 = H_{\text{rec}} \theta_s \frac{\int_{t_{\text{rec}}}^{t_0} \frac{dt/t_0}{[\rho(t)/\rho_0]^{1/2}}}{\int_0^{t_{\text{rec}}} \frac{c_s(t) dt/t_{\text{rec}}}{[\rho(t)/\rho(t_{\text{rec}})]^{1/2}}}$$

To increase H_0 ,

Decrease energy density at late times (late-time solutions)

Cosmological Tensions

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Decrease energy density at late times (late-time solutions)

Decrease sound speed in early universe (sounds crazy)

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Hubble tension ($\sim 4\text{-}6\ \sigma$)

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To increase H_0 ,

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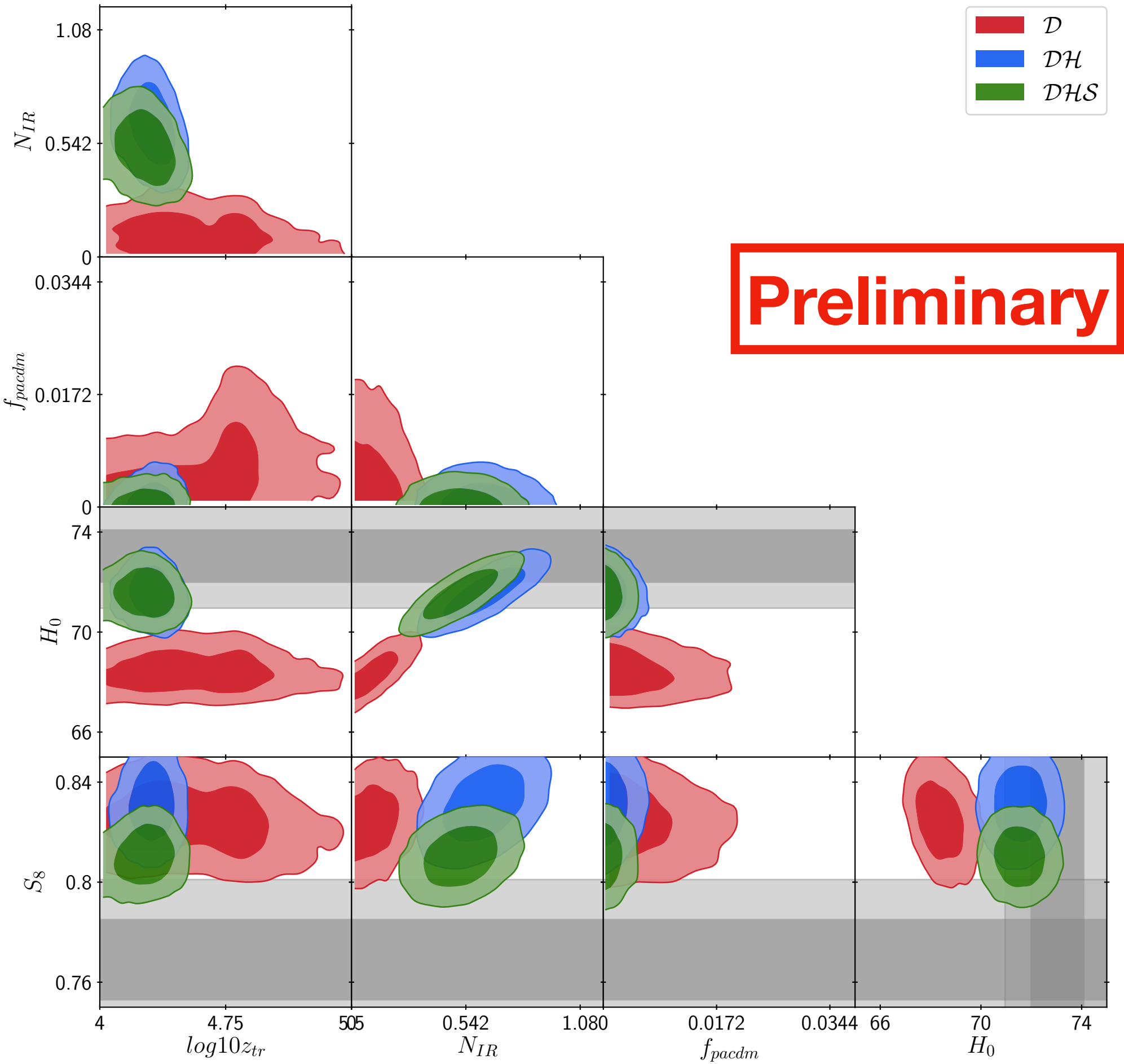
Decrease sound speed in early universe (sounds crazy)

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

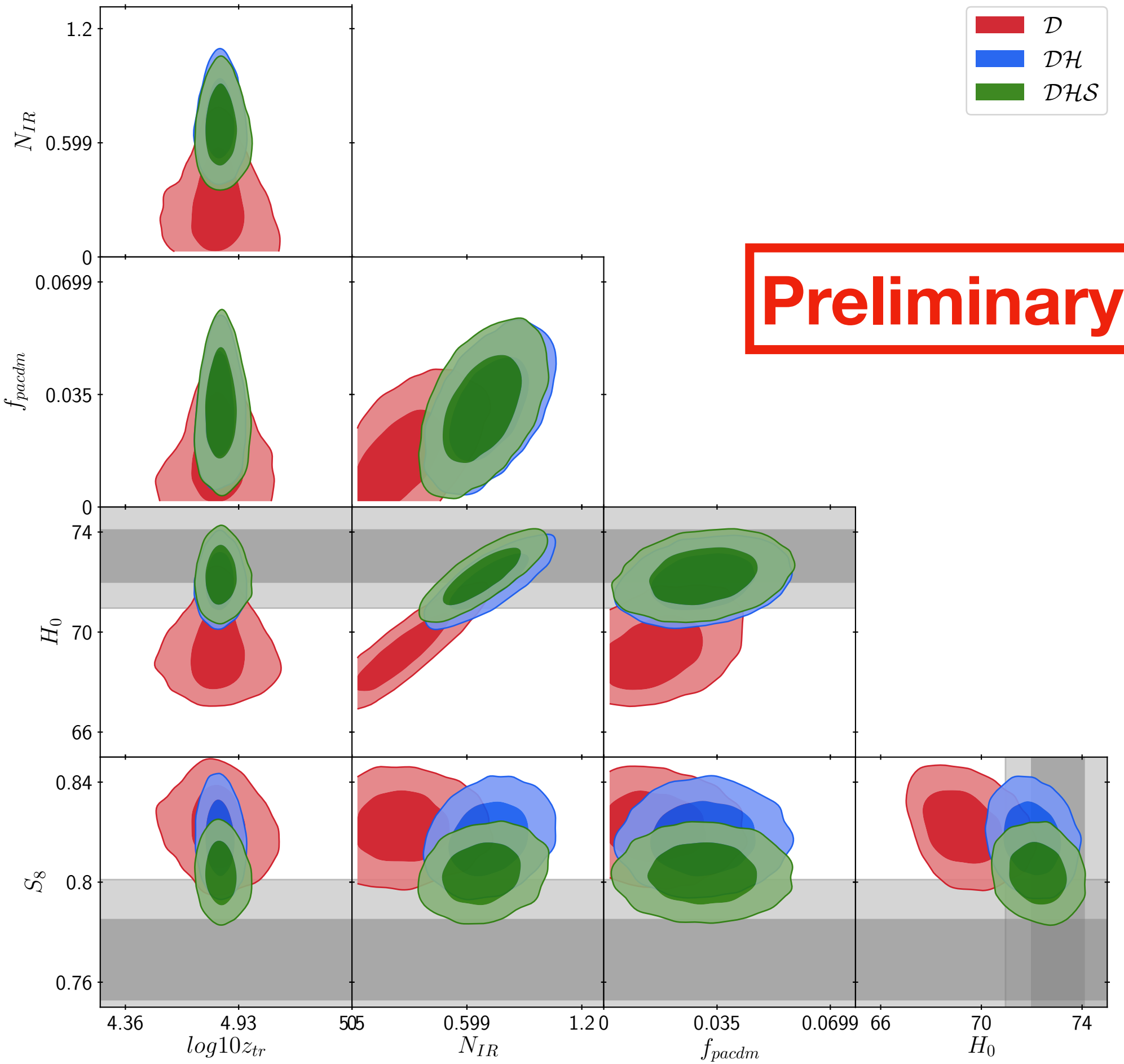
Markov Chain Monte Carlo (MCMC)



Results



SPartAcous

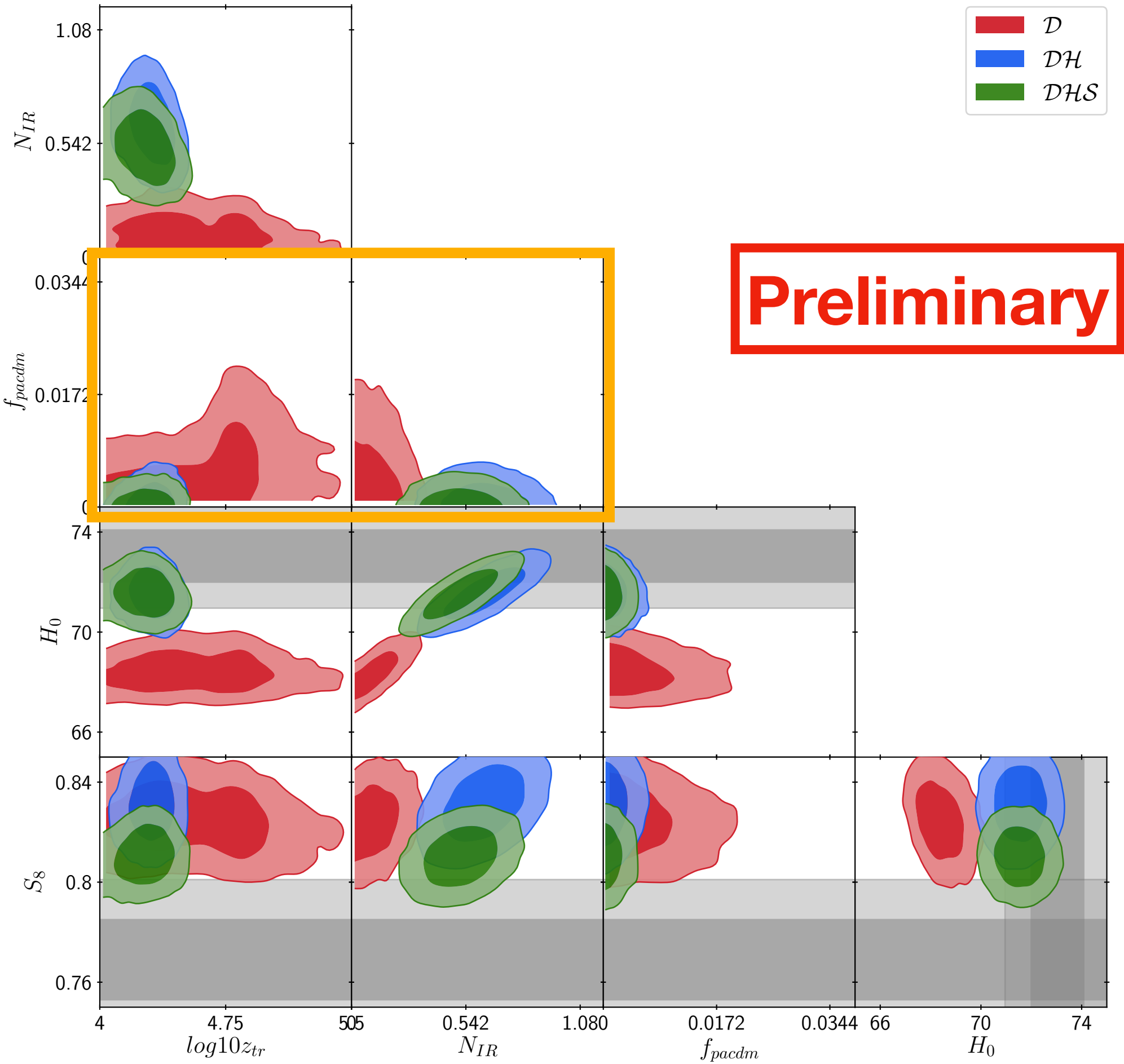


SPartAcous+3

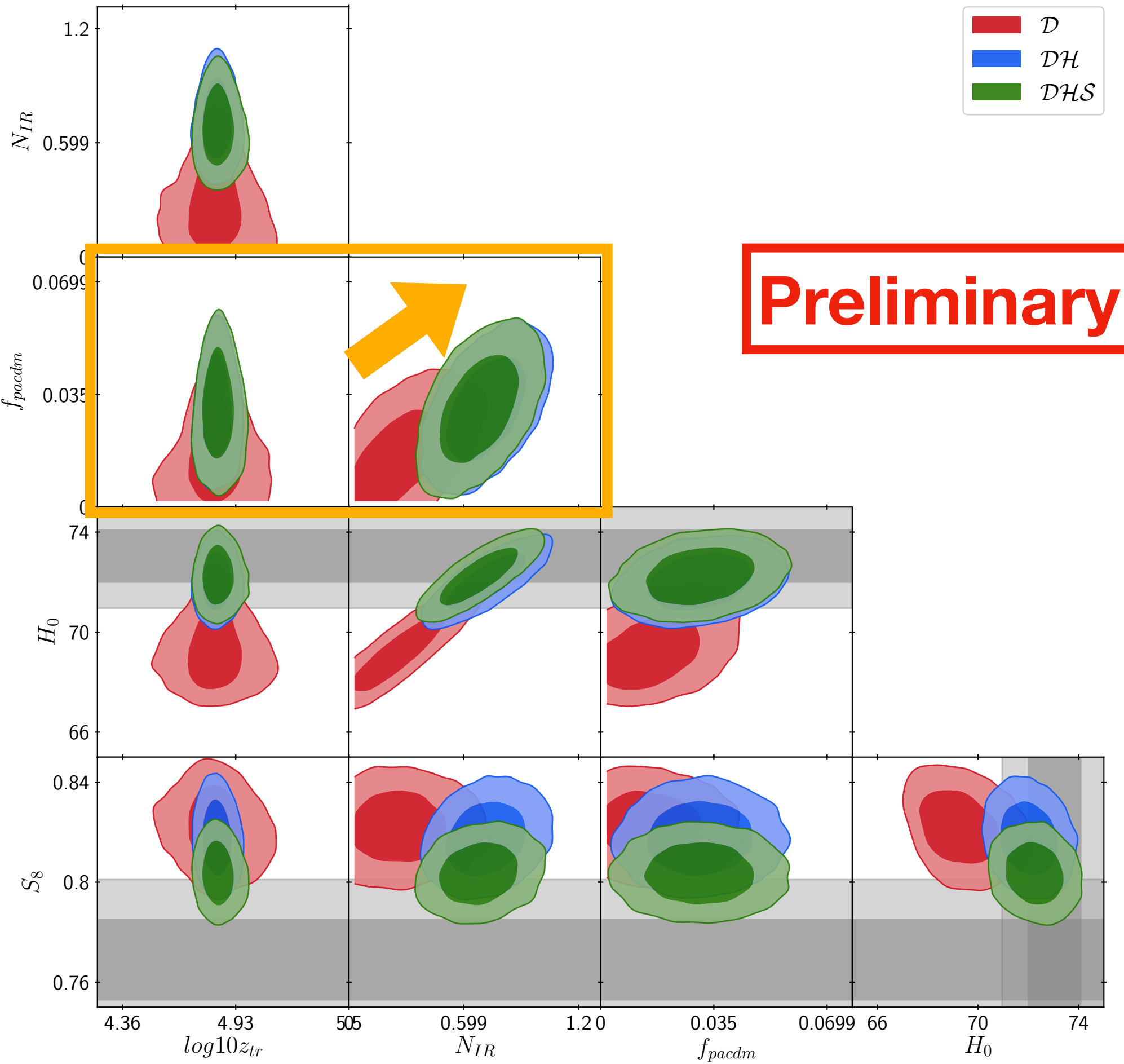
Markov Chain Monte Carlo (MCMC)



Results



SPartAcous

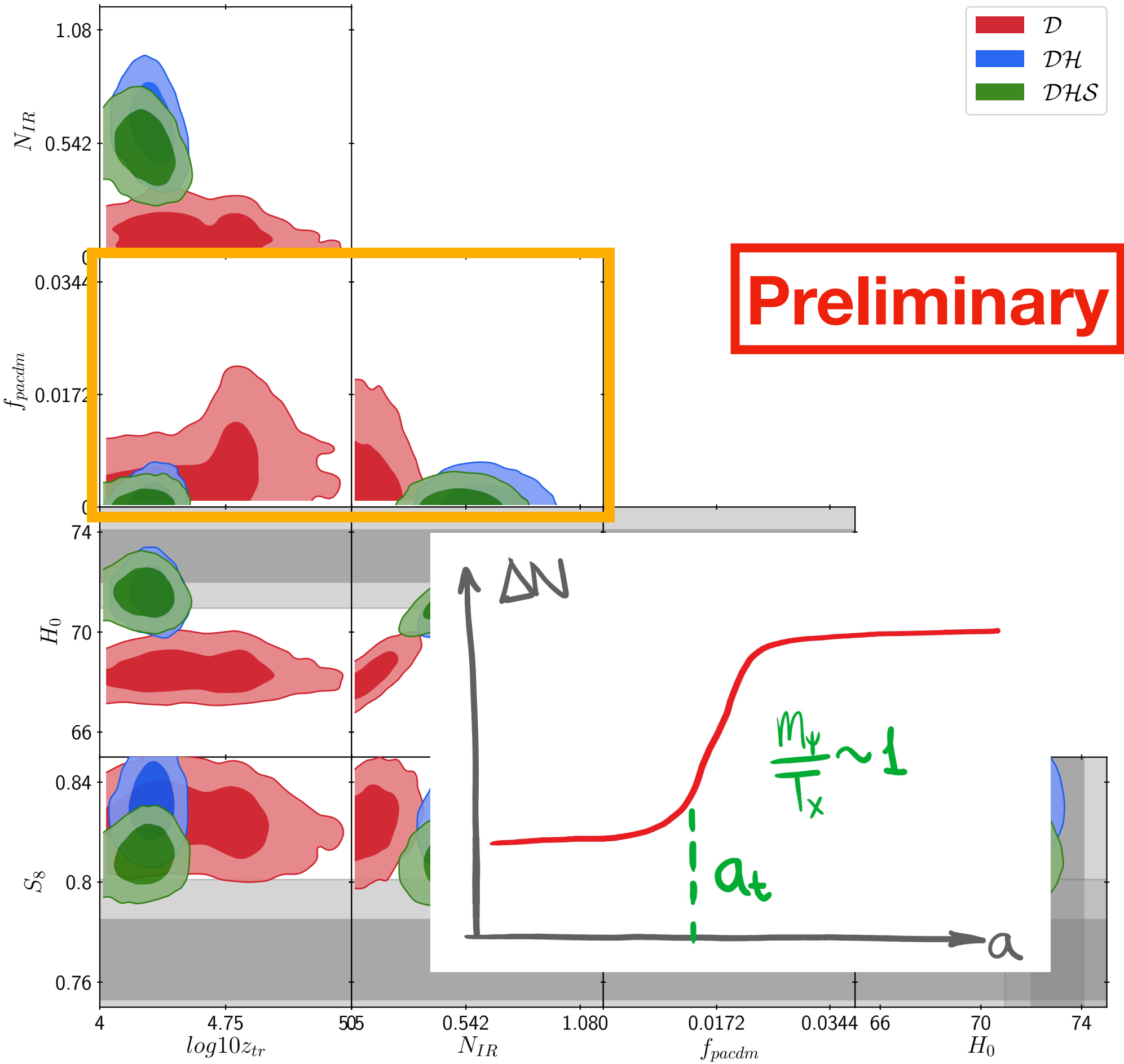


SPartAcous+3

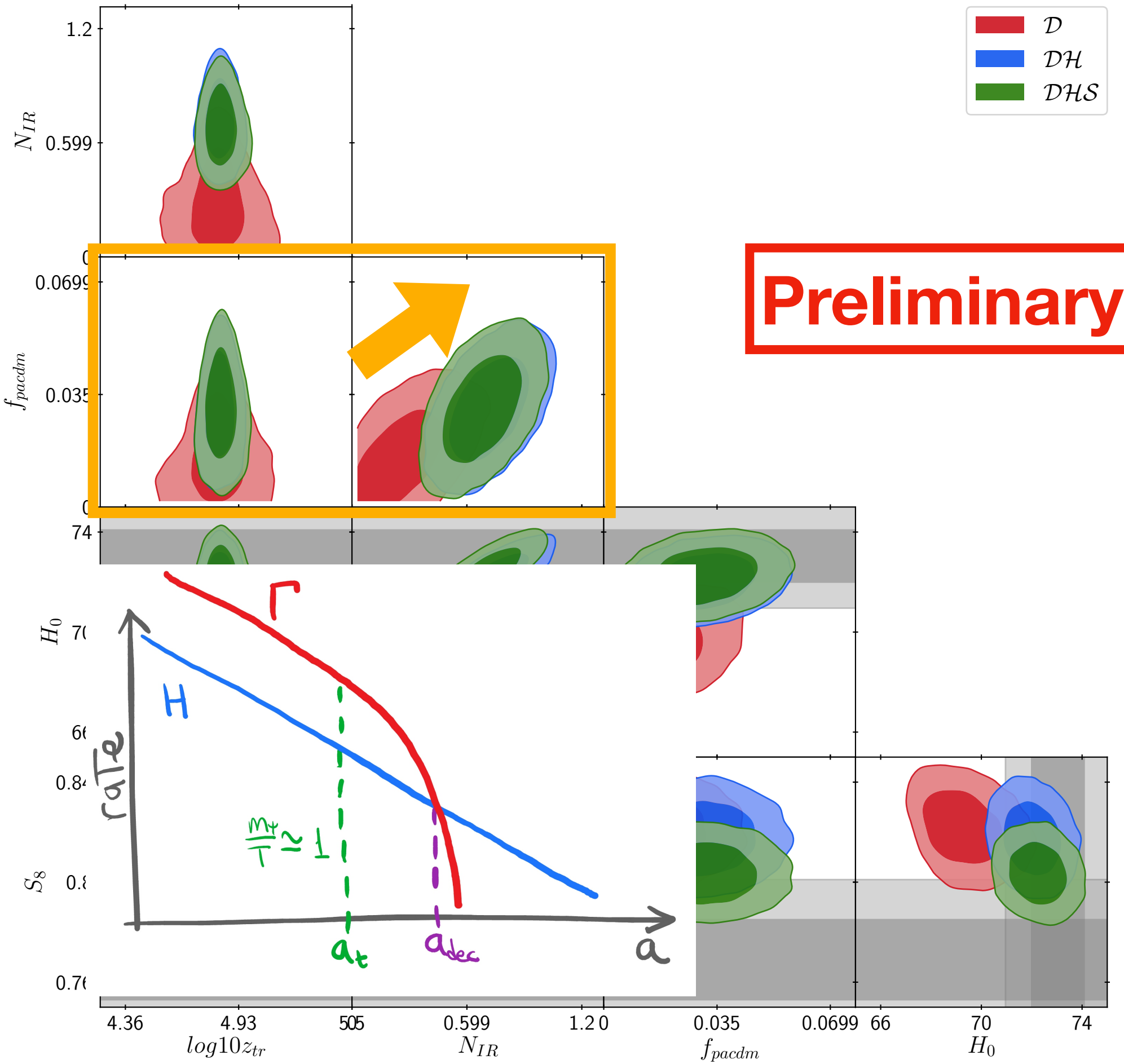
Markov Chain Monte Carlo (MCMC)



Results



SPartAcous

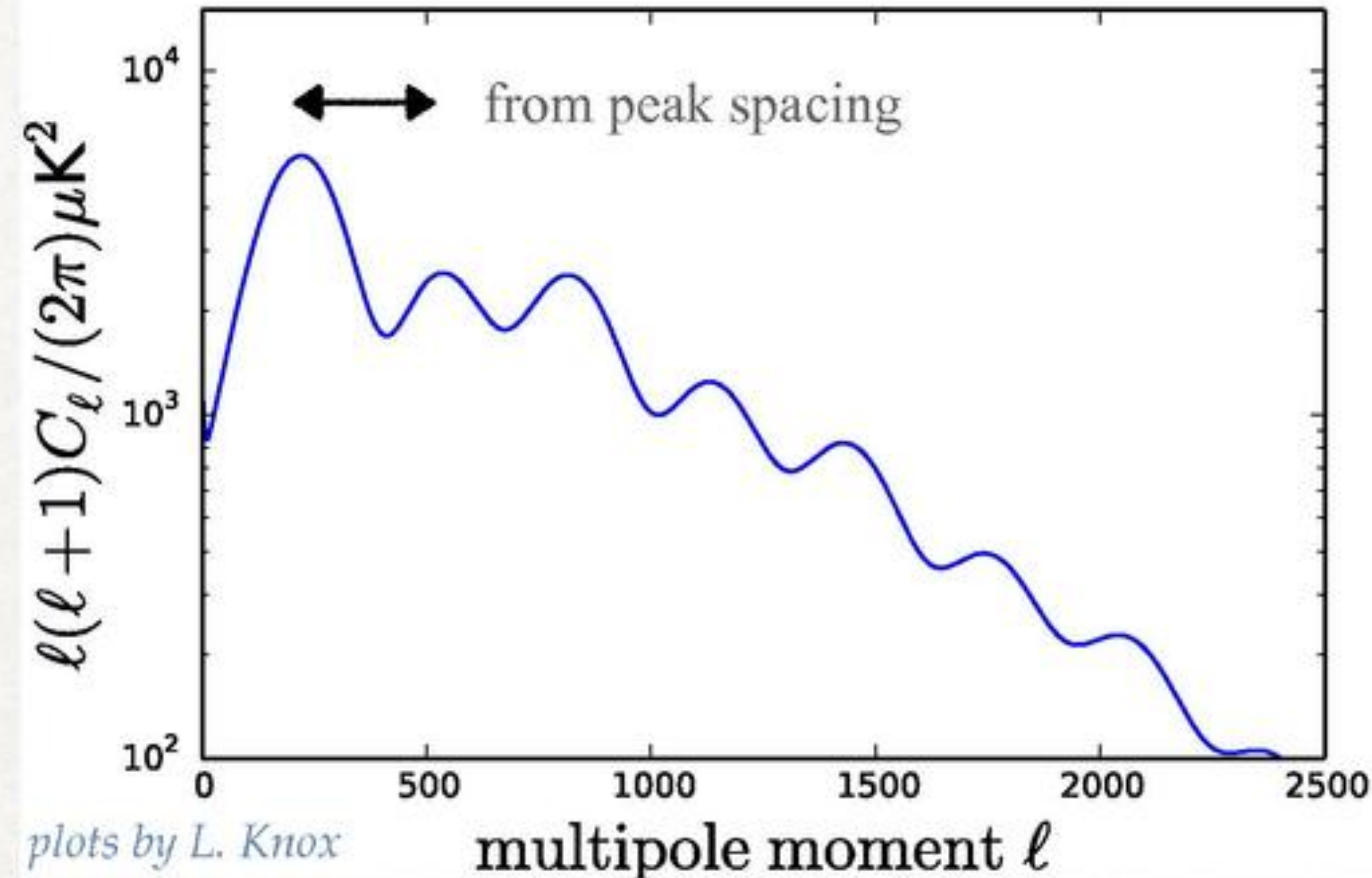


SPartAcous+3

How does CMB data measure H_0 ?

- Inference of H_0 from the CMB is model dependent.
- It comes from the measurement of **three angular scales** $\theta_s, \theta_d, \theta_{eq}$.

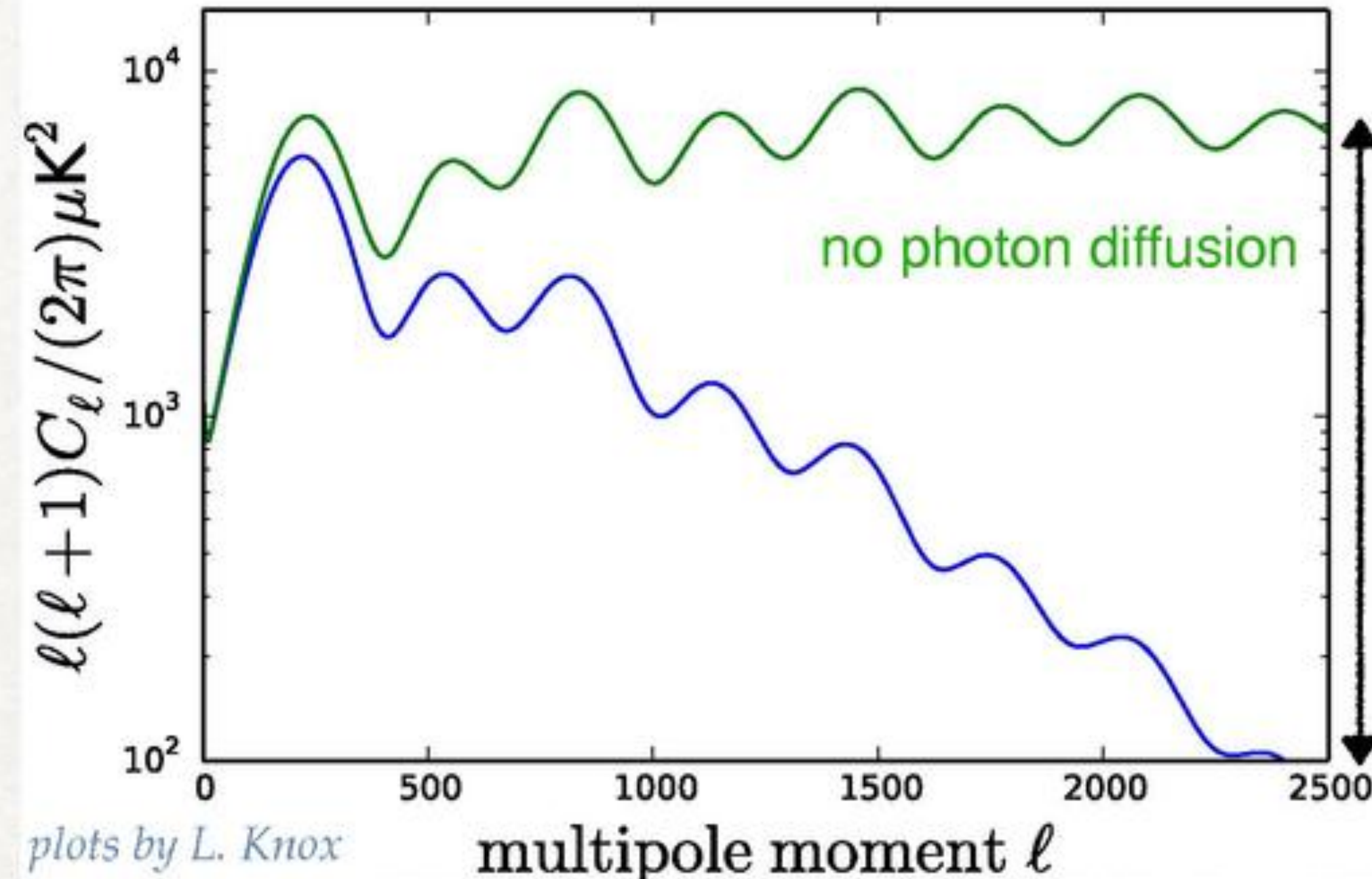
θ_s , sound horizon at last scattering ~ 1.0404



How does CMB data measure H_0 ?

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θ_d photon diffusion length at last scattering ~ 0.1609



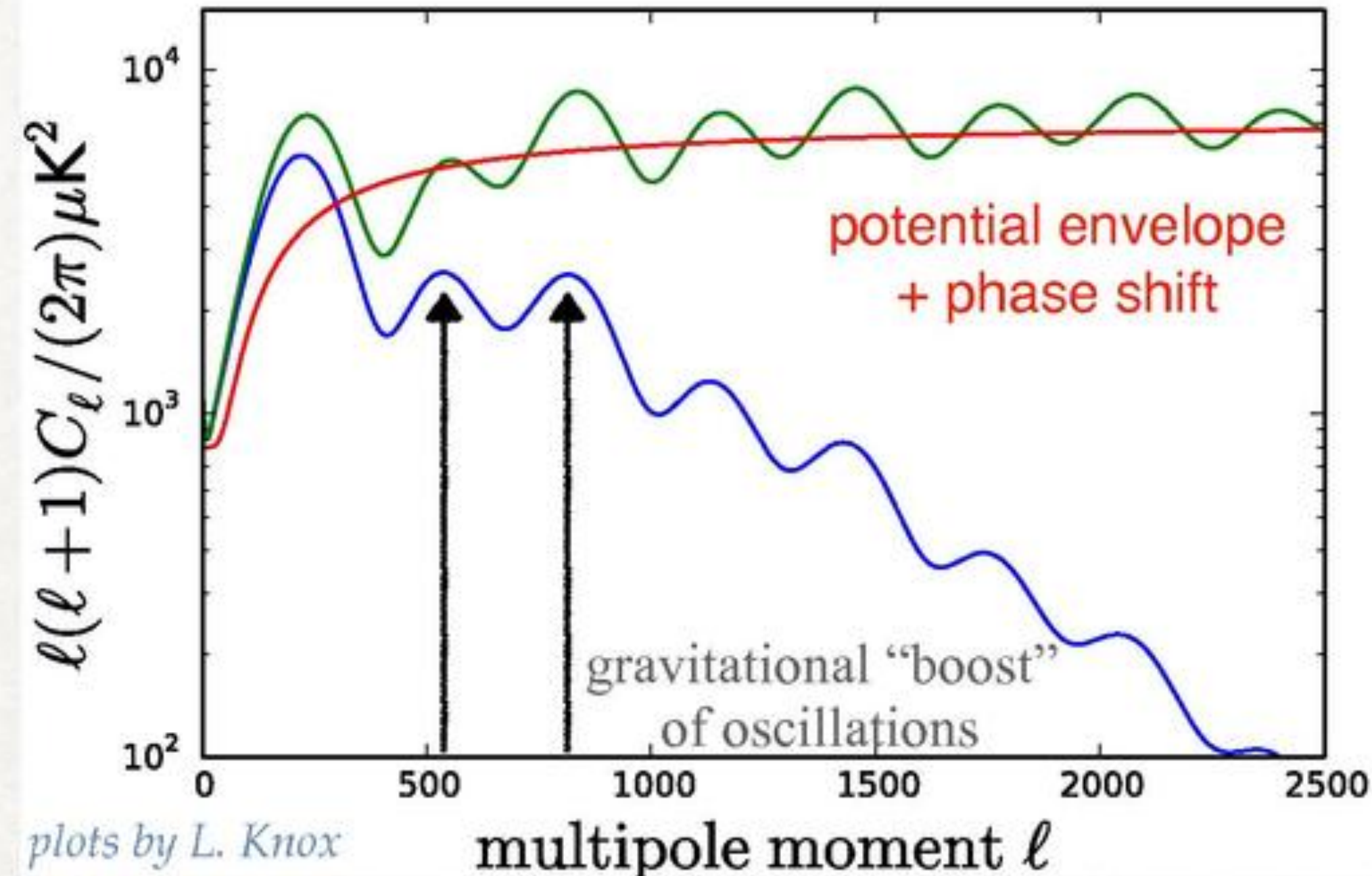
plots by L. Knox

e.g. Hu&White astro-ph/9609079, Hu++astro-ph/0006436

How does CMB data measure H_0 ?

- Inference of H_0 from the CMB is model dependent.
- It comes from the measurement of **three angular scales** $\theta_s, \theta_d, \theta_{eq}$.

θ_{eq} horizon size at matter-radiation equality ~ 0.81



e.g. Hu&White astro-ph/9609079, Hu++astro-ph/0006436