M. A. Buen-Abad, I. Flood, Z. Chacko, C. Kilic, G. Marques-Tavares, TY
[arXiv:2208.05984, 2306.01844, 2409.XXXXX]

Dark Acoustic Oscillations Faces the Cosmological Tensions

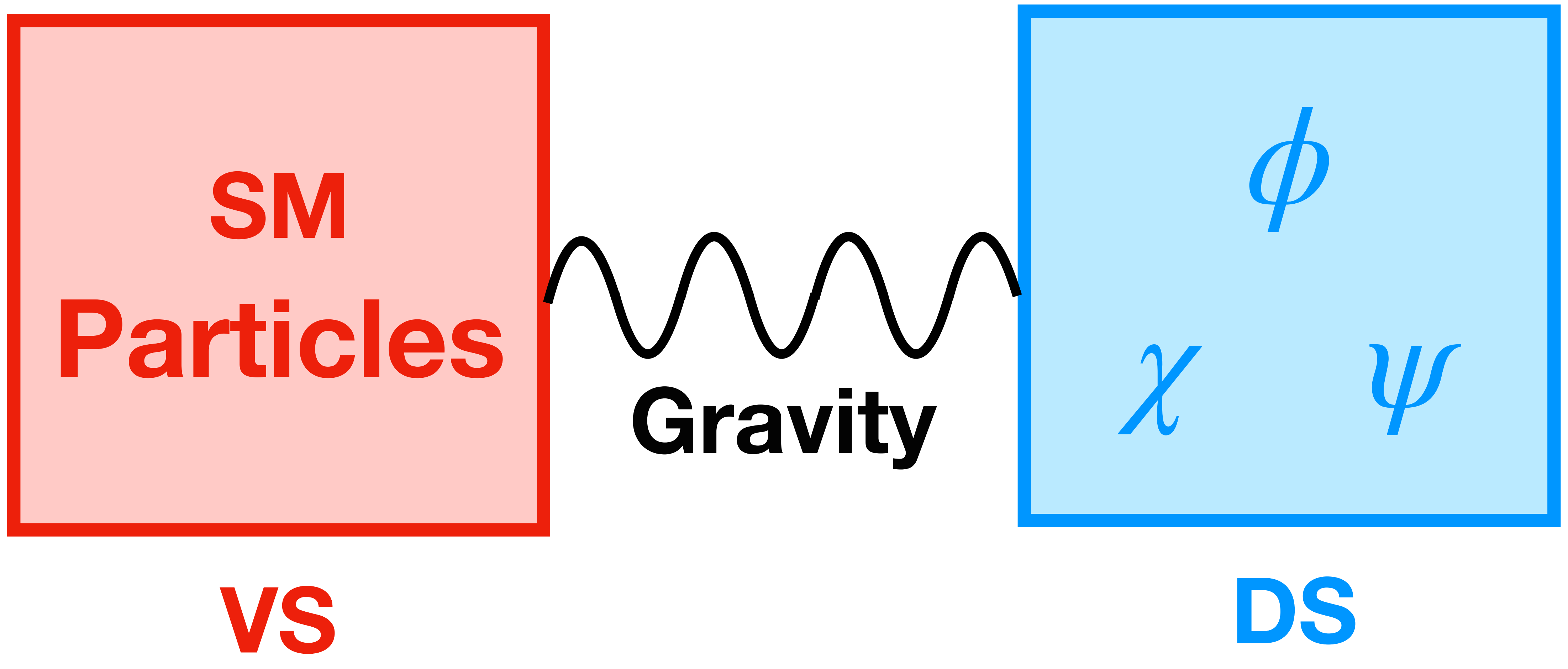
Taewook Youn
Cornell U, LEPP / Korea U

Aug 13th 2024

Light Dark World

Dark Sector

Light Dark World ~ Dark Sector (DS) with Light Degree of Freedom (LDF)



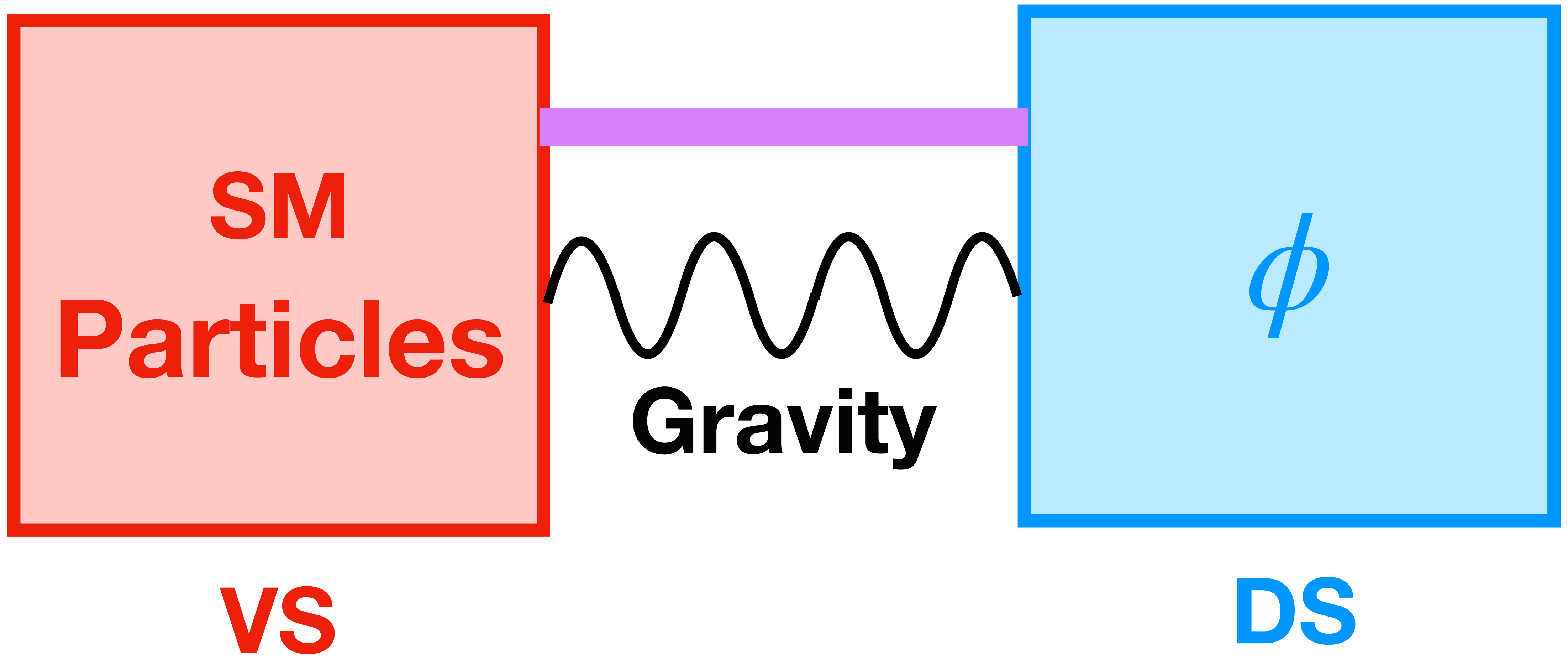
Light Dark World

Dark Sector

Light Dark World $\sim$ Dark Sector (DS) with Light Degree of Freedom (LDF)

Minimal Light Dark World

- Single Light Dark Matter (e.g. Axion)
- Might need a coupling to Visible Sector for interesting signals



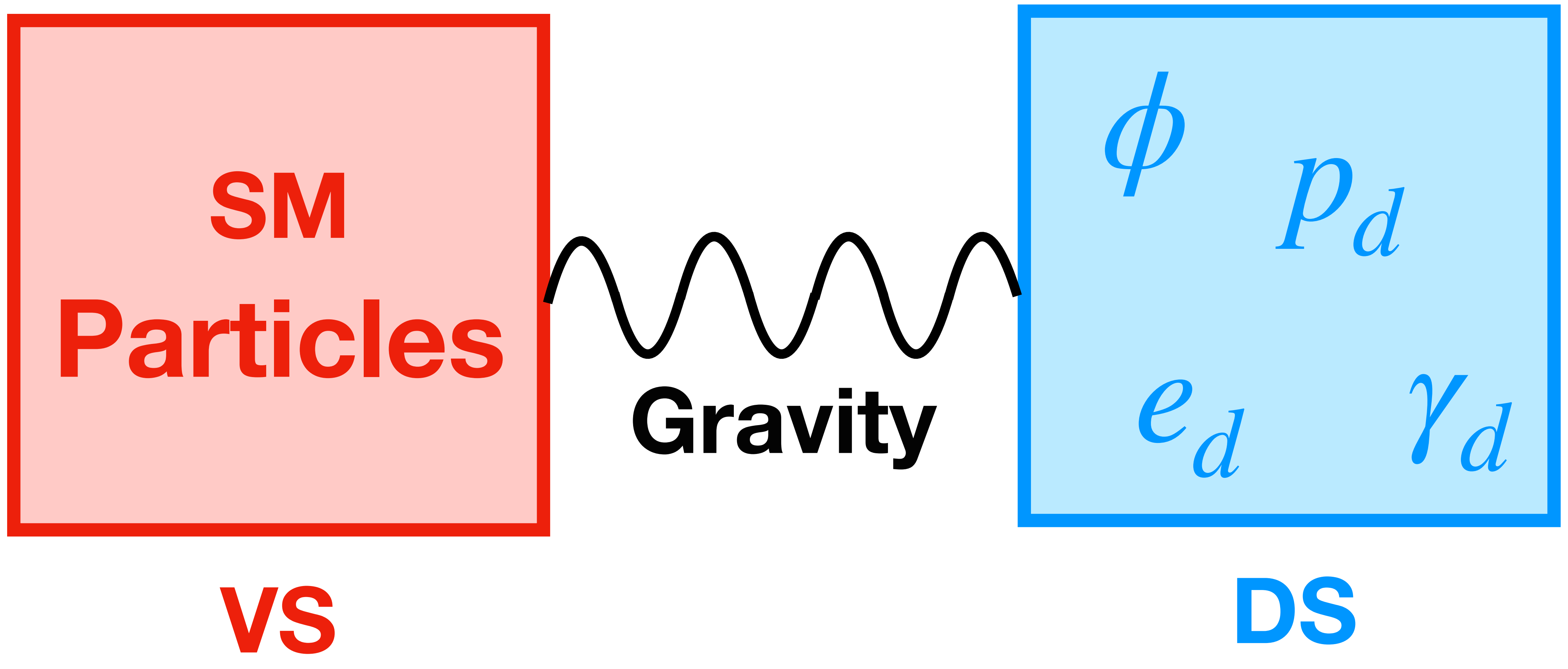
Light Dark World

Dark Sector

Light Dark World $\sim$ Dark Sector (DS) with Light Degree of Freedom (LDF)

Non-minimal but interesting Light Dark World

- Multiple DM components (e.g. axion, dark proton)
- + LDF (dark electron, dark photon)
- W/O any direct coupling to SM fields



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Non-minimal but interesting Light Dark World

Multiple DM components (e.g. axion, dark proton)

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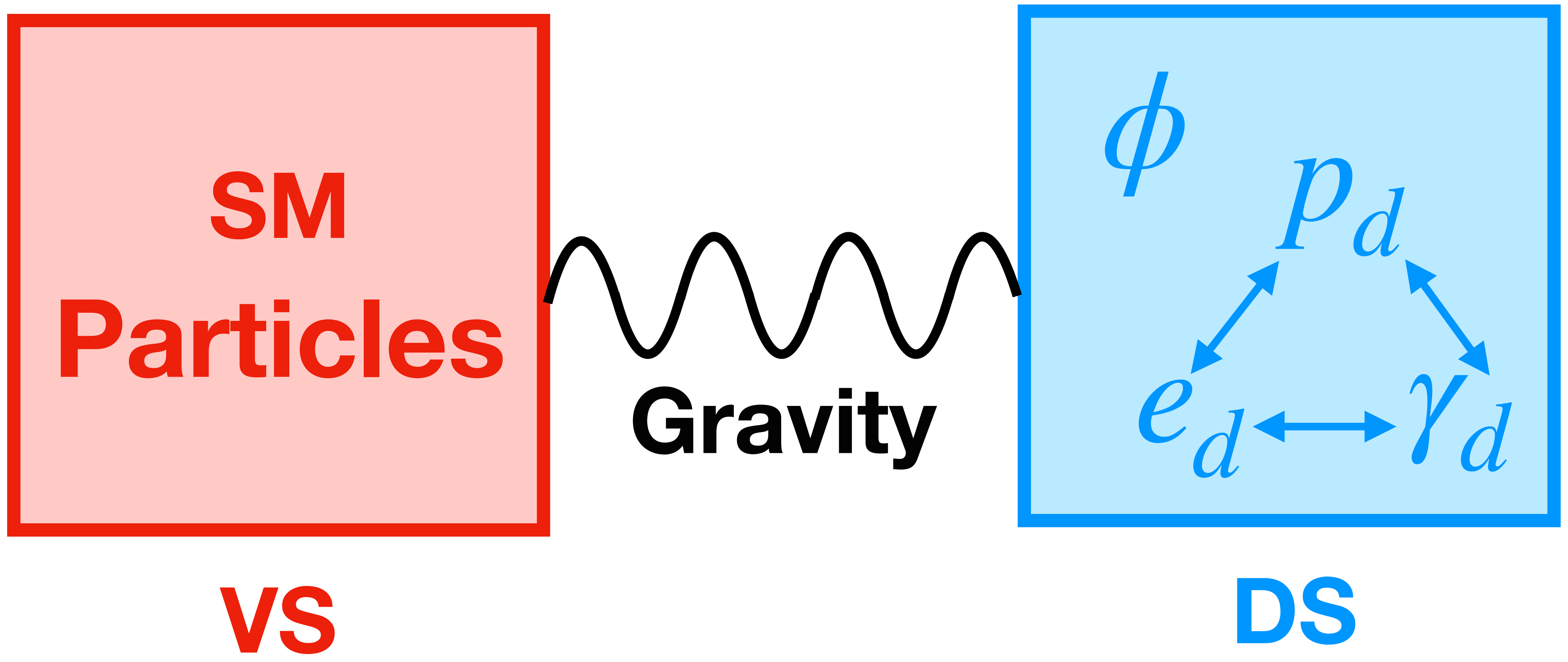
Tight coupling (e.g. p_d-γ_d) forms pressure-gravity waves that are imprinted on the clustering signal



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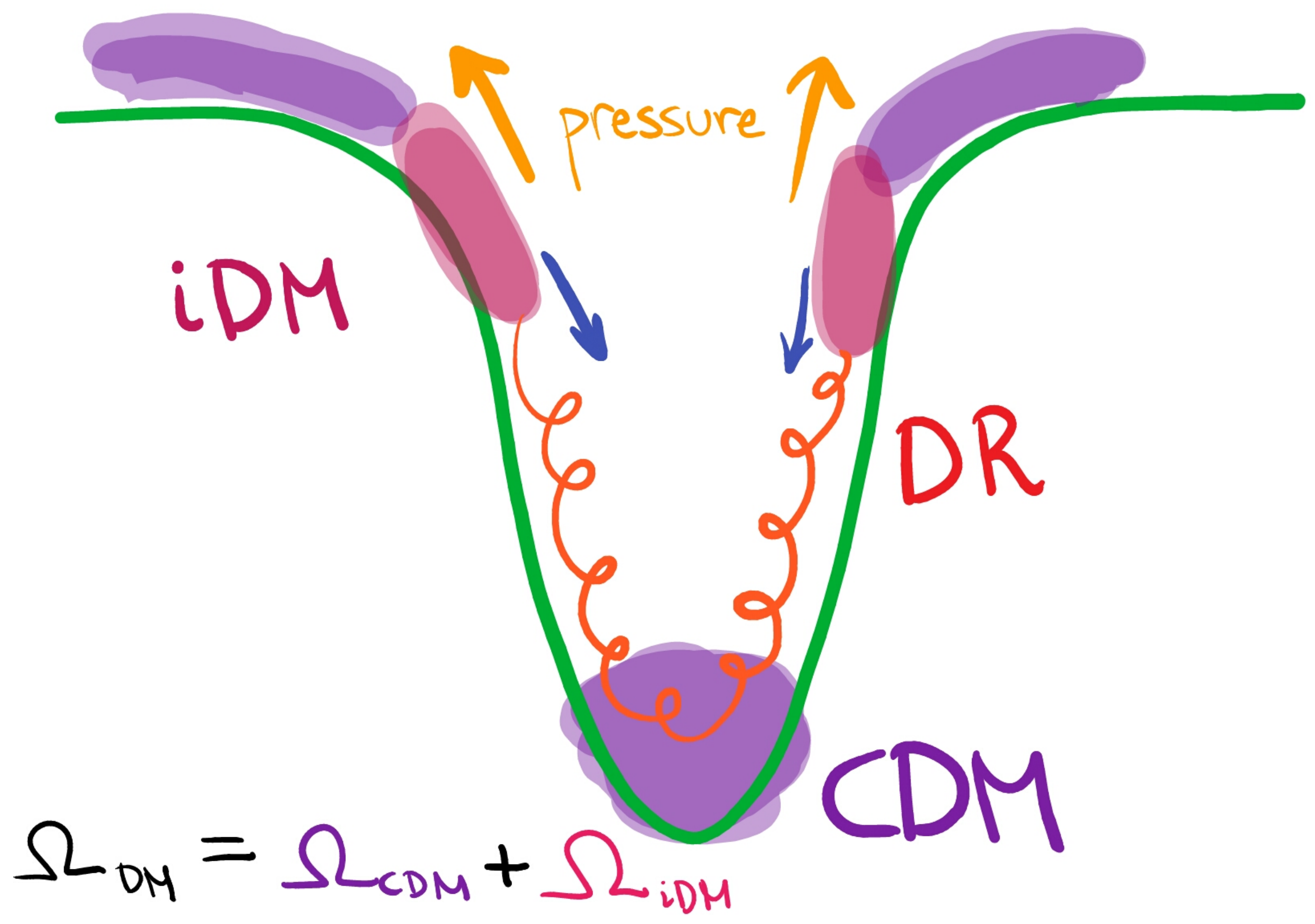

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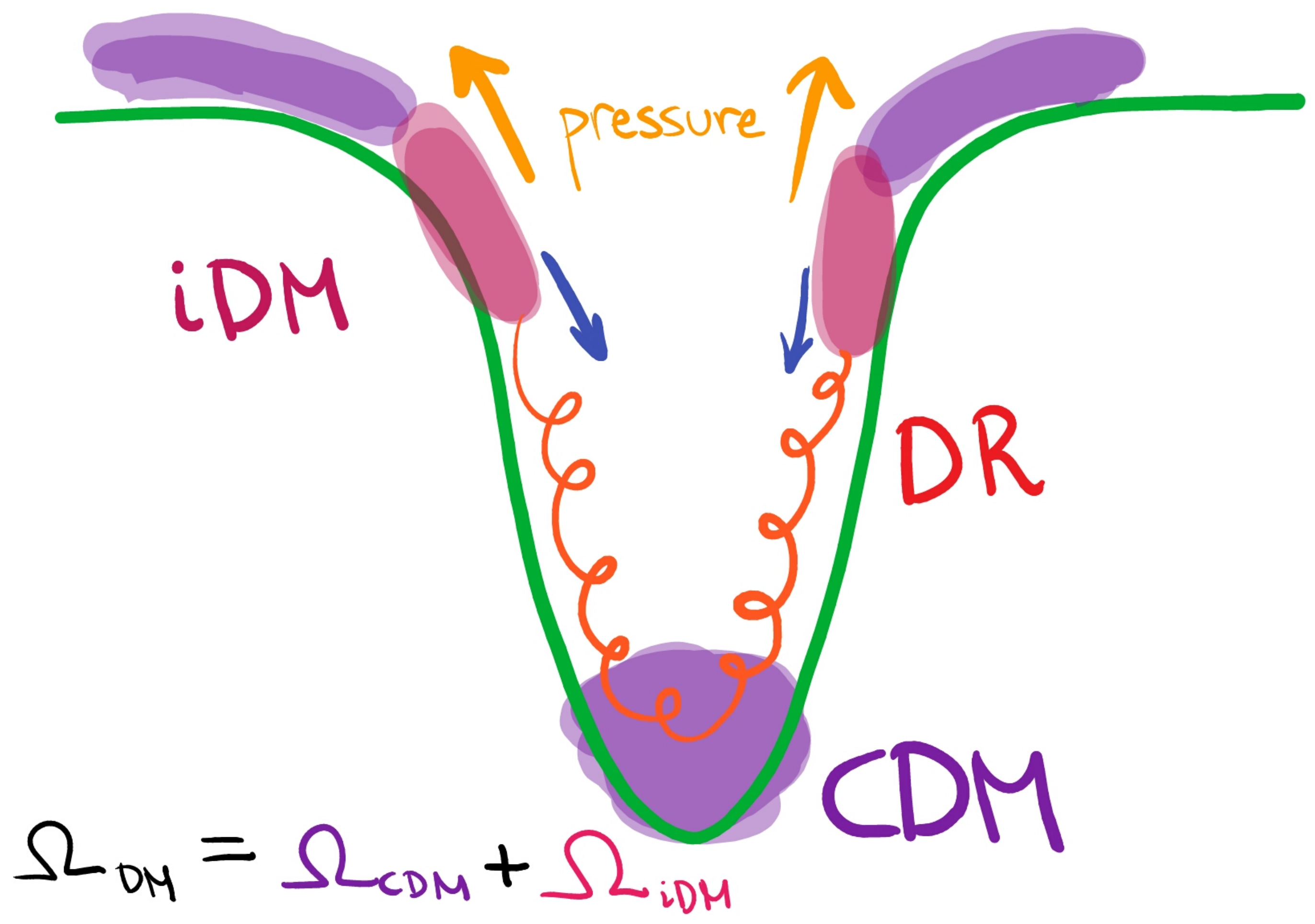
Dark Acoustic Oscillation (DAO)



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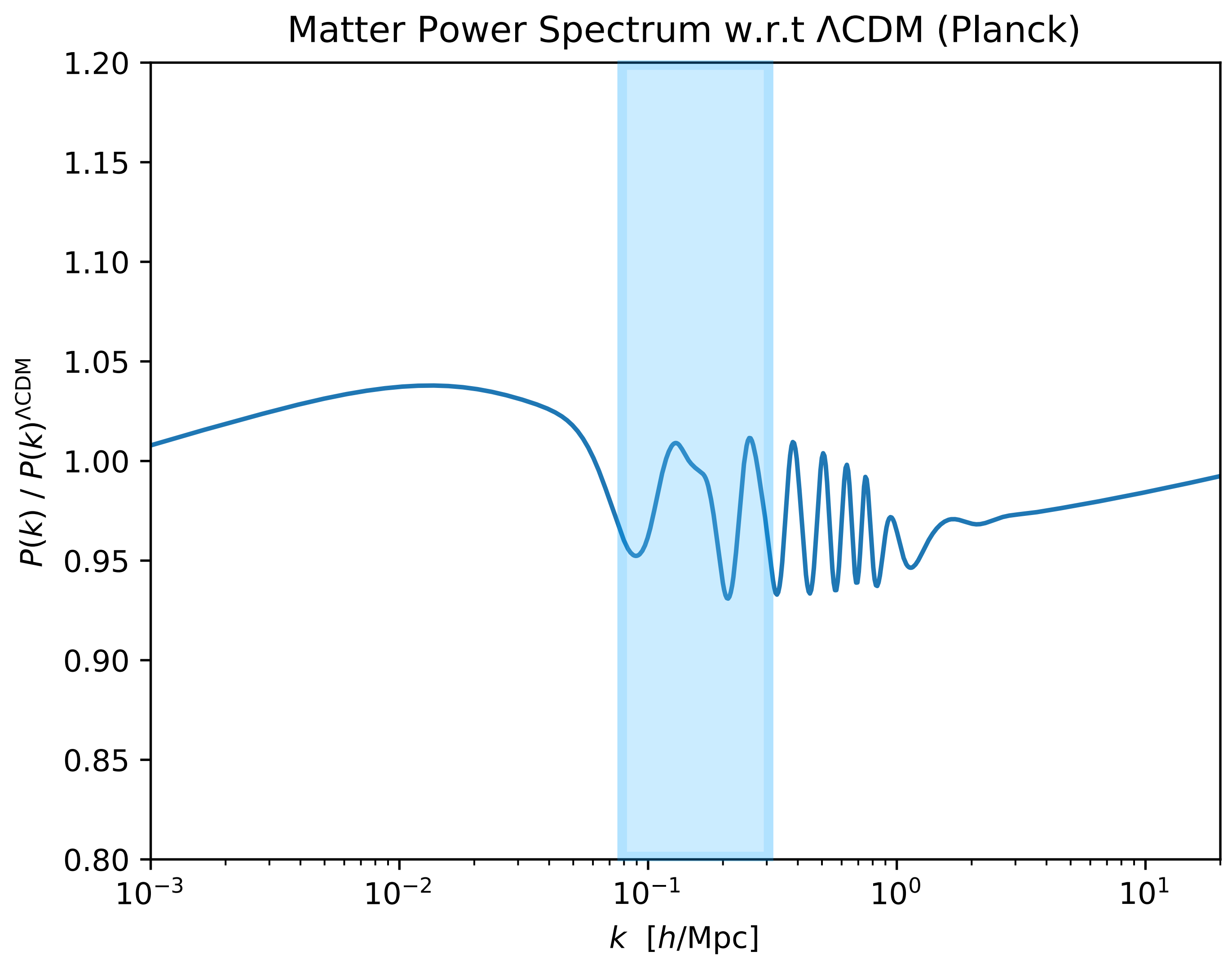

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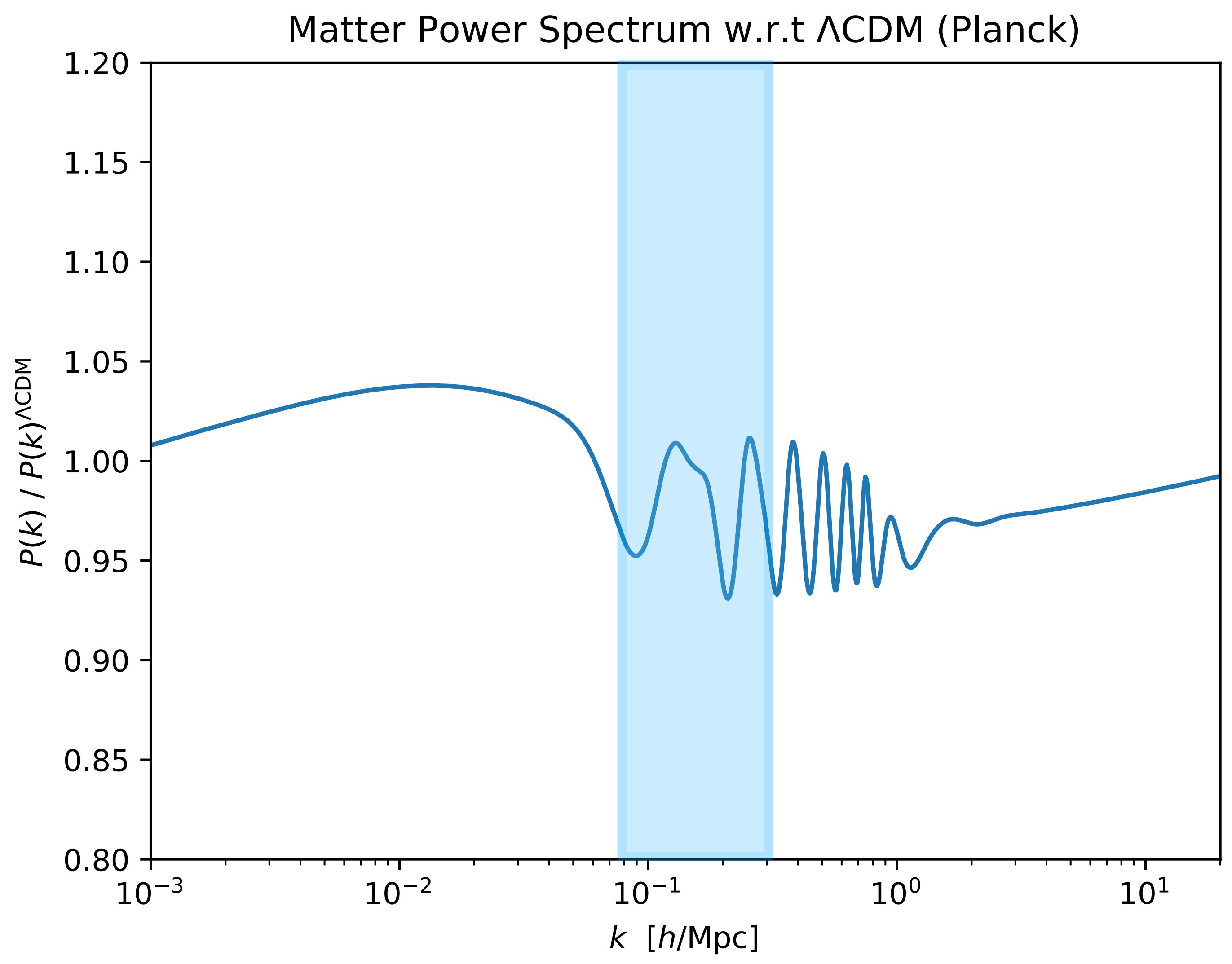
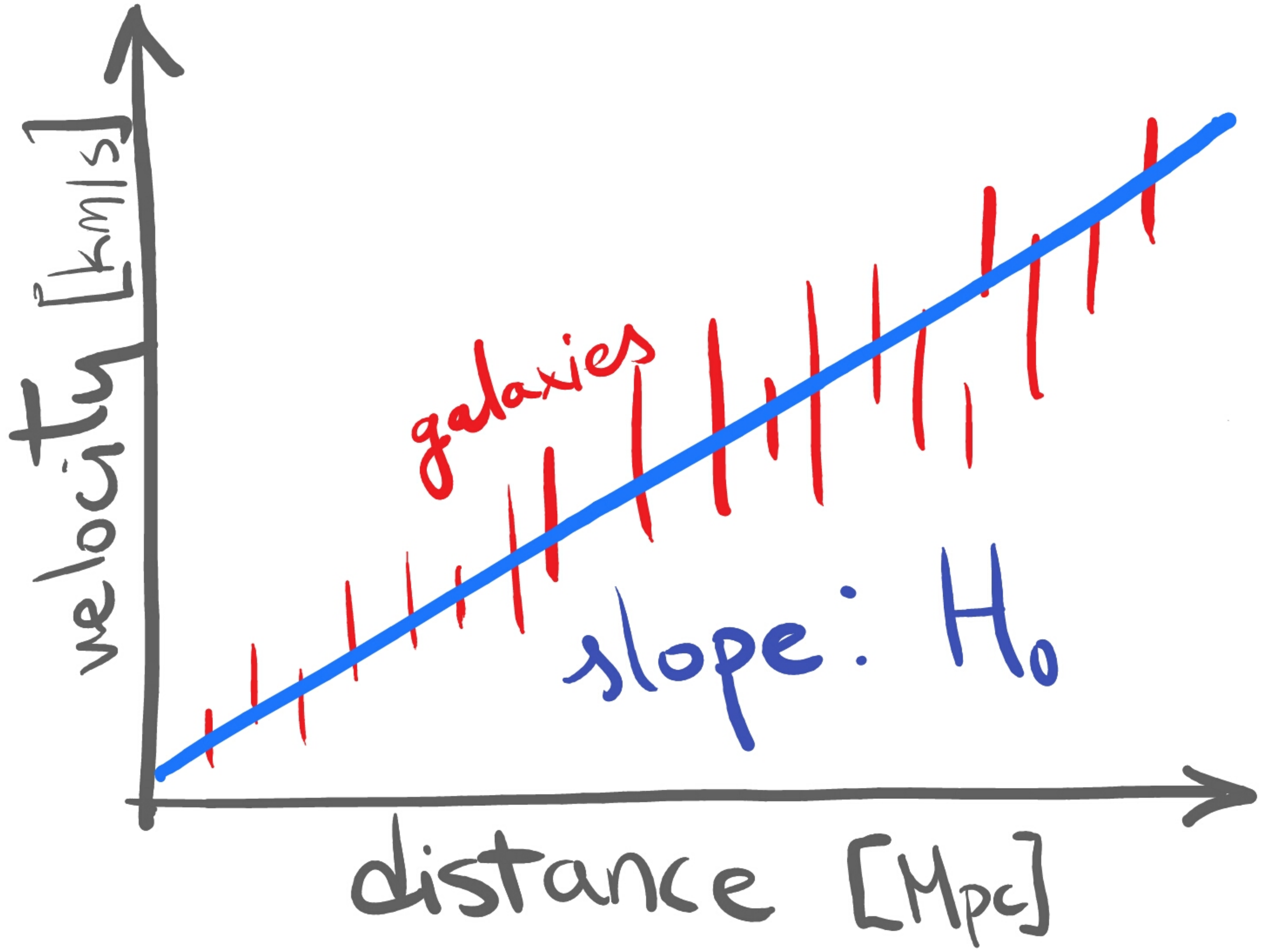
Dark Acoustic Oscillation

- Unique Imprint on Cosmological Observations
- **Possibly in H_0 and S_8 tensions**



Cosmological Tensions

Hubble tension (~4-6 σ)



$$v = H_0 D$$

Estimate the size and age of universe

Cosmological Tensions

Hubble tension (~4-6 σ)

Early Universe

CMB fit to ΛCDM

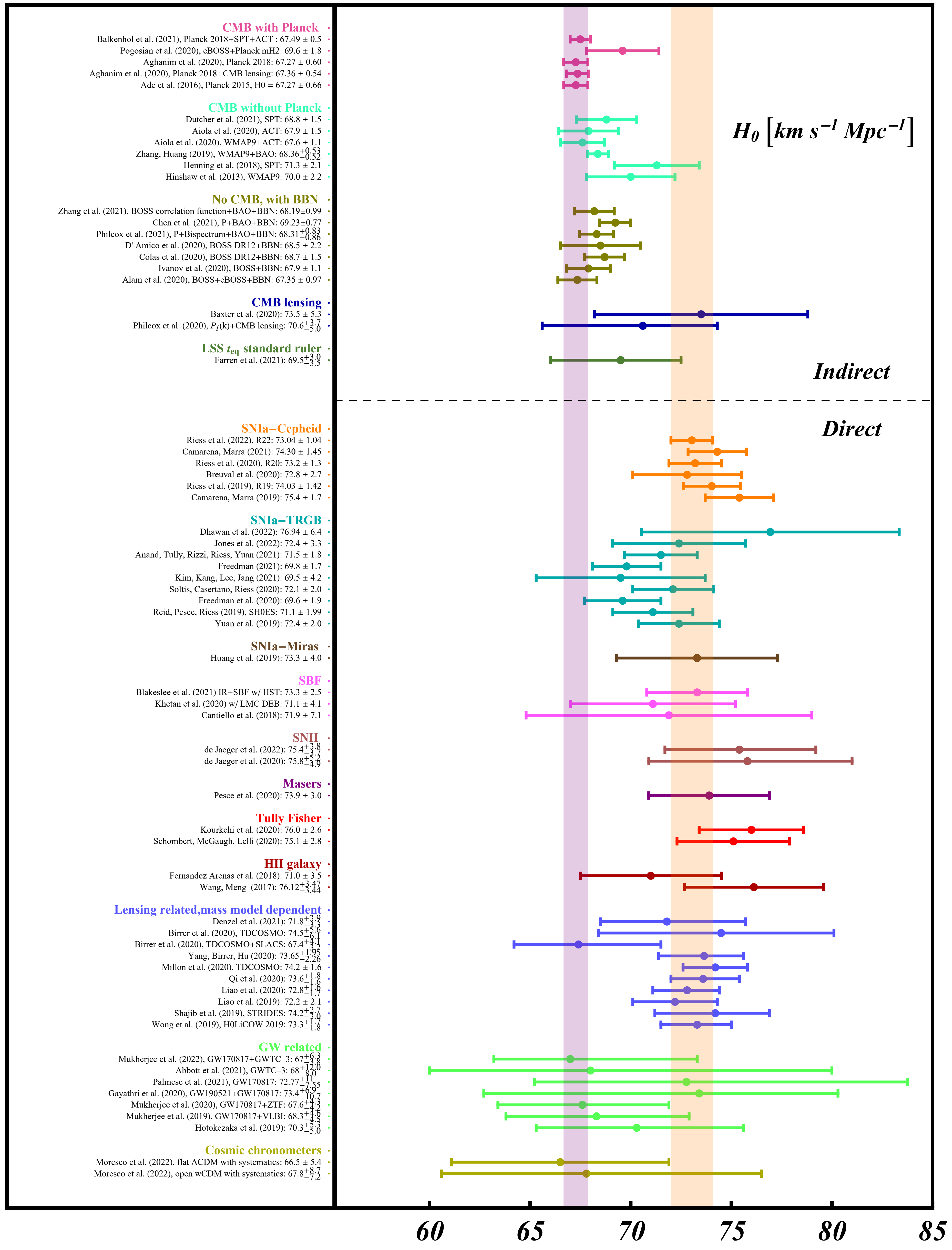
~68 km/s/Mpc **Planck ’18 [arXiv:1807.06209]**

Late Universe

Cosmic Distance Ladder

~72 km/s/Mpc **A. G. Riess et al. [arXiv:2112.04510]**

Snowmass [arXiv:2203.06142]



Cosmological Tensions

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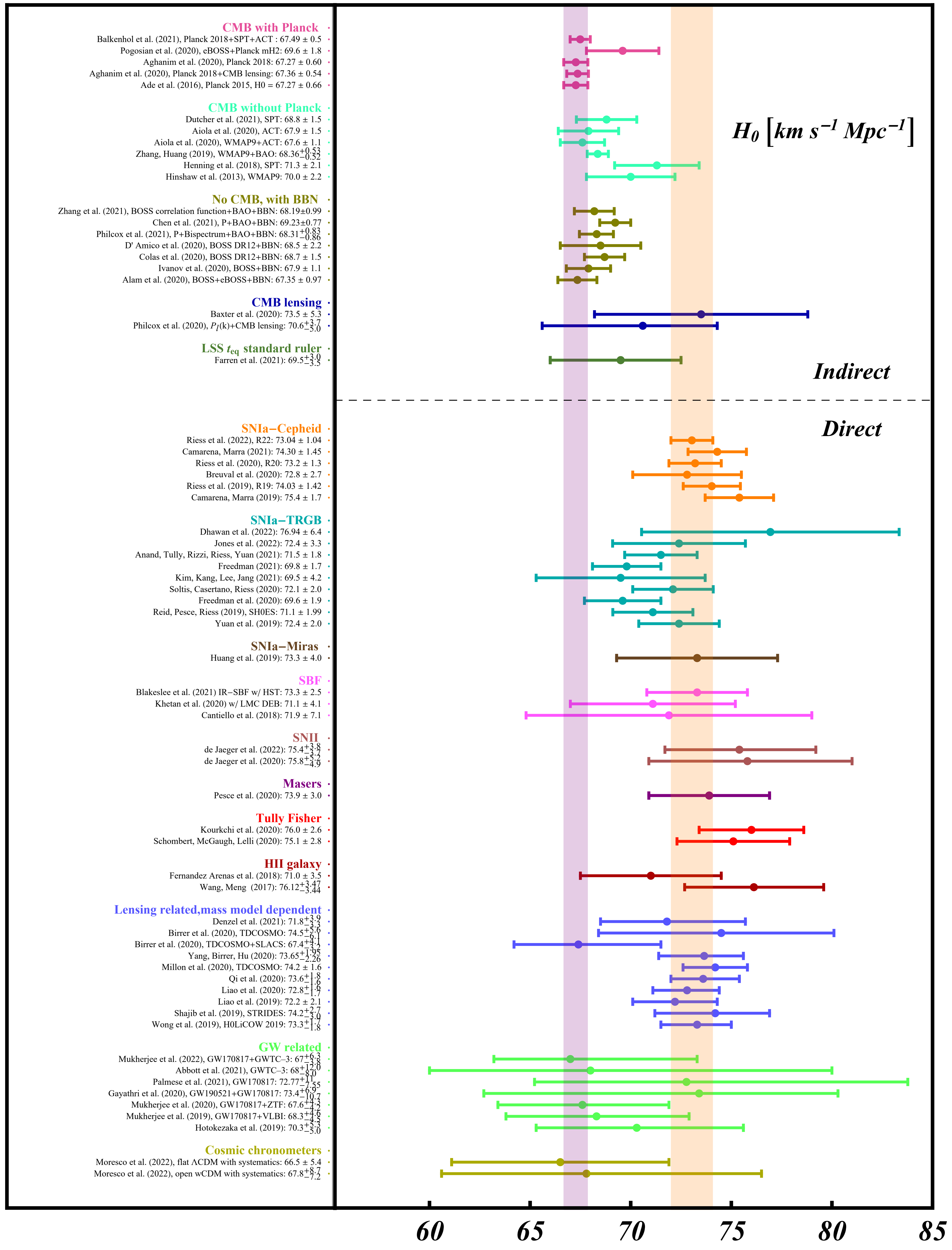

Systematic error?

JWST J-region Giant Branch

W. L. Freedman: 67.96 km/s/Mpc

A. J. Lee et al. [arXiv:2408.03474]

A. G. Riess: 74.7 km/s/Mpc

S. Li et al. [arXiv:2401.04777]

Crack in Lambda CDM?

Cosmological Tensions

Snowmass [arXiv:2203.06142]

Hubble tension (~4-6 σ)

Systematic error?

JWST J-region Gi

W. Freedman: 67.9

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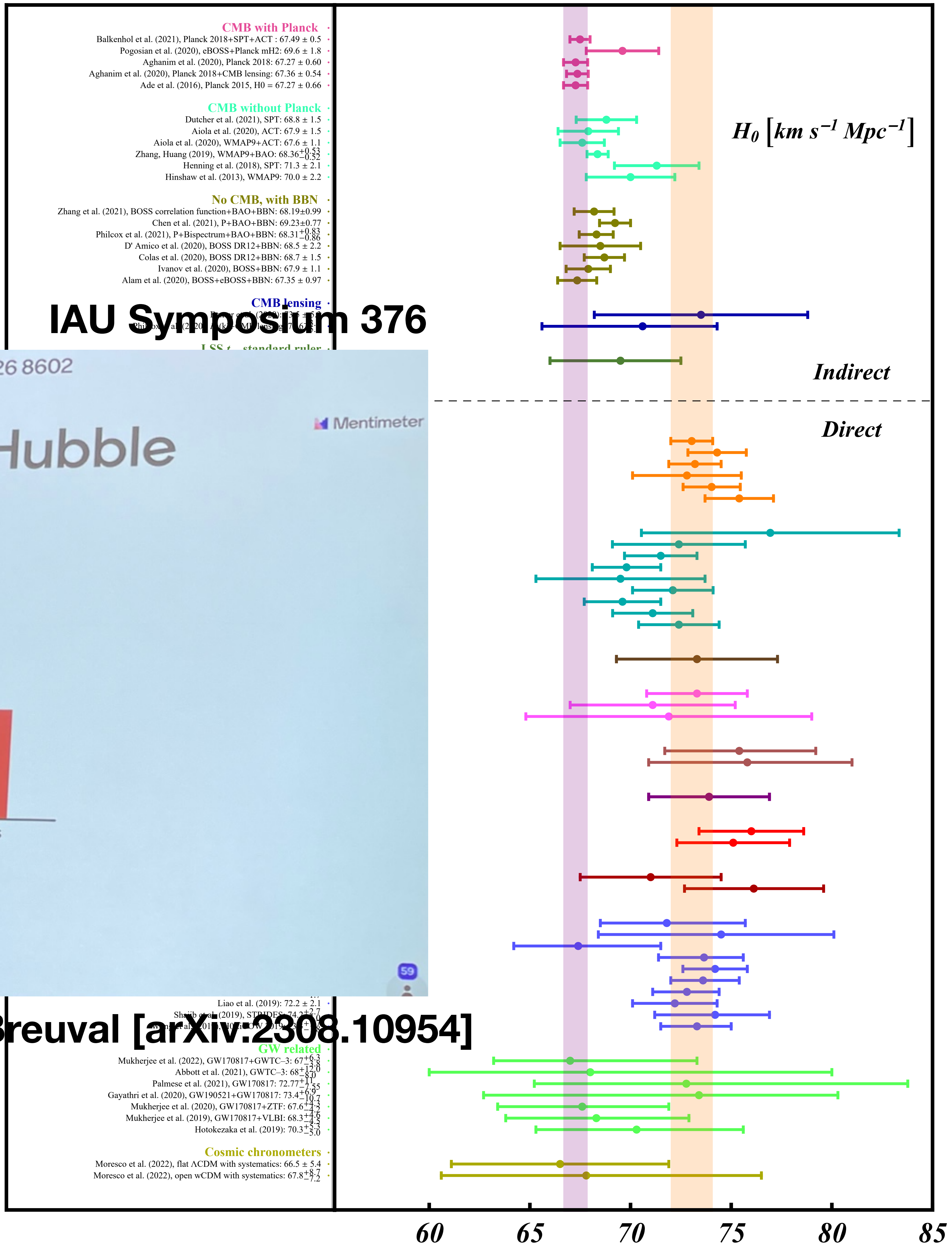
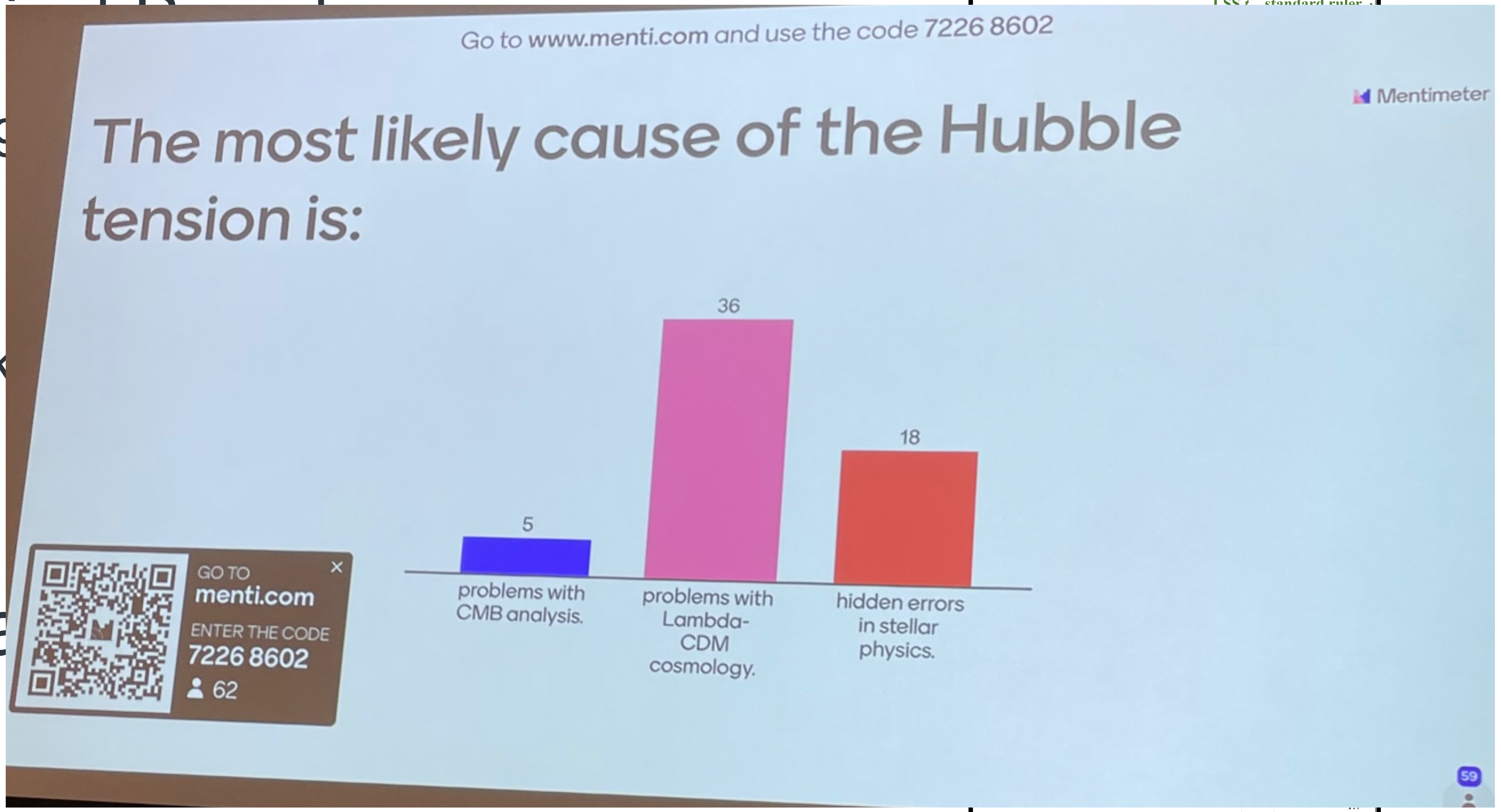
Crack in Lambda



IAU Symposium 376



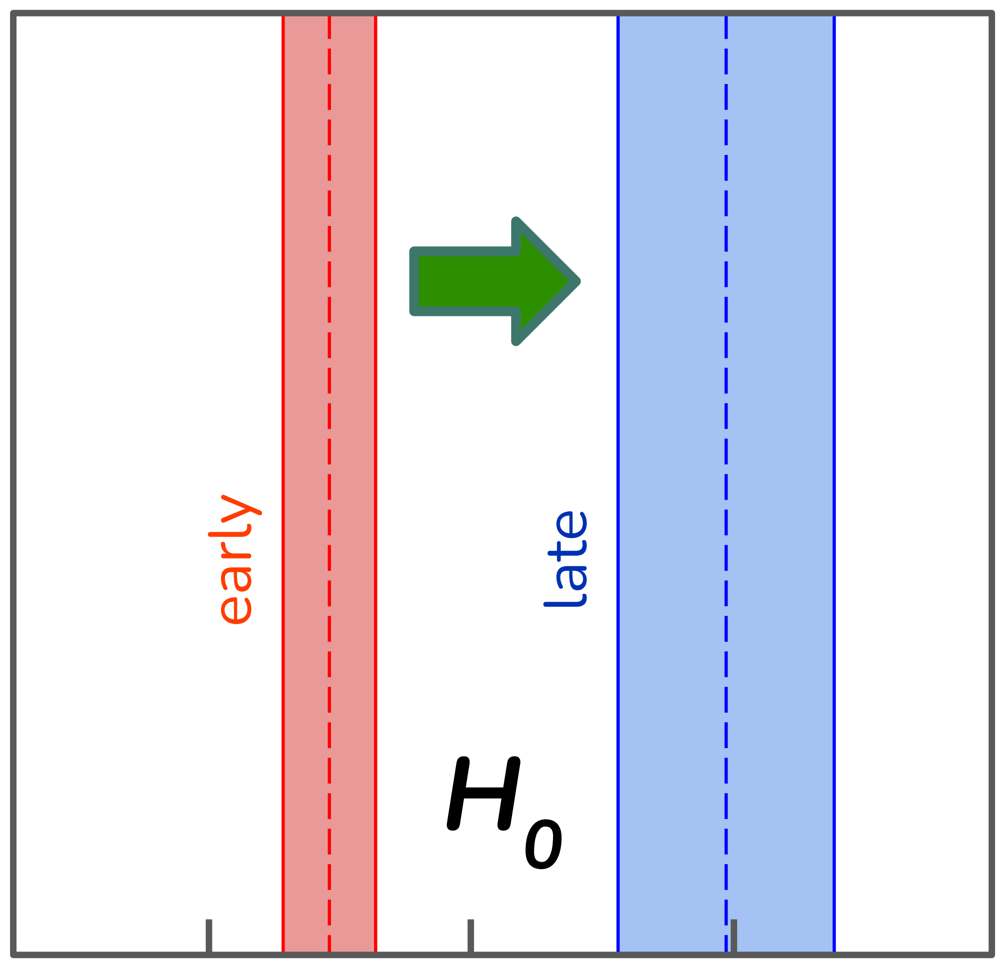
A. Riess and L. Breuval [arXiv:2308.10954]

Cosmological Tensions

Hubble tension (~4-6 σ)

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

To increase H_0,



Cosmological Tensions

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To increase H_0,

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

P. Agrawal et al. [arXiv:1904.01016]

Early Dark Energy → $V(\phi) = \Lambda_{\text{EDE}}^4 [1 - \cos(\phi/f_{\text{EDE}})]^n, \;\; V(\phi) = V_0 \left(\frac{\phi}{M_{pl}}\right)^{2n} + V_\Lambda$

V. Poulin et al. [arXiv:1806.10608]

Cosmological Tensions

Hubble tension (~4-6 σ)

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

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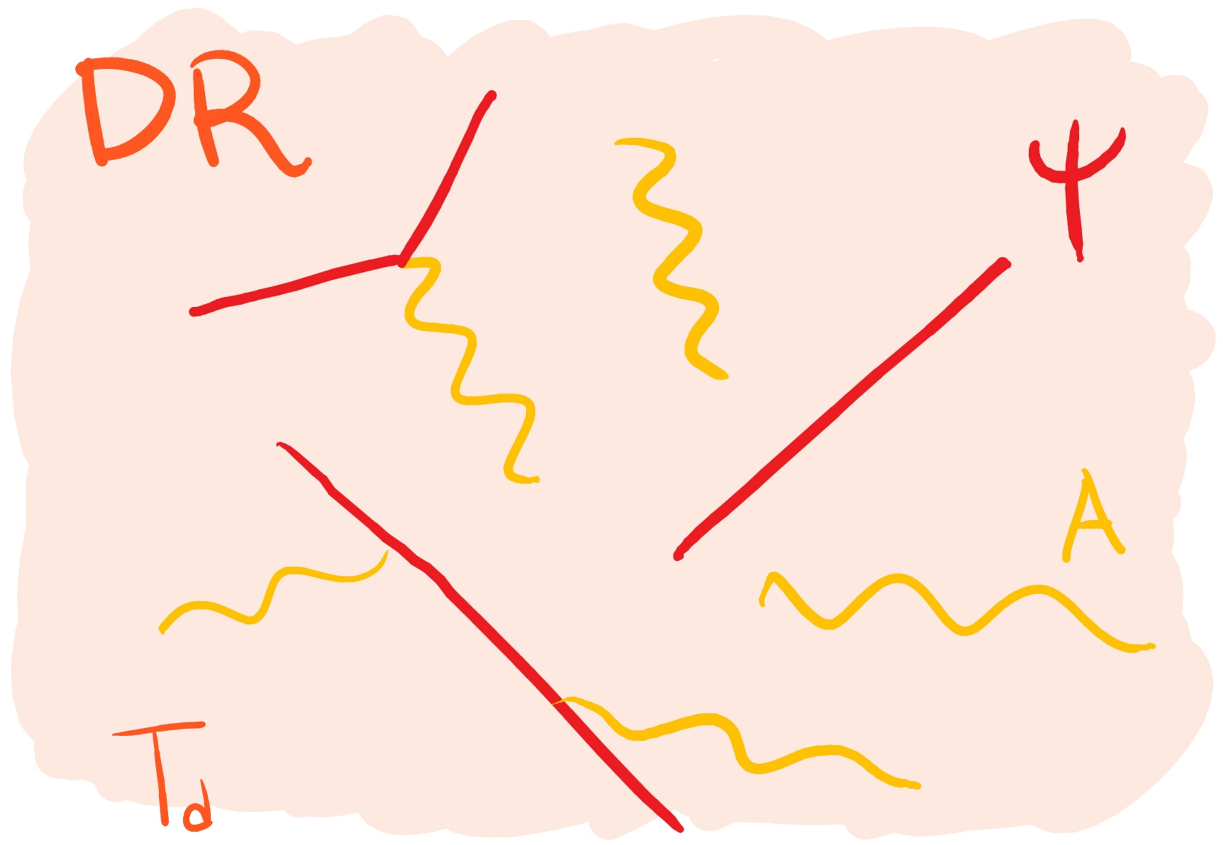
Early Dark Energy

Dark Radiation → Massless states in Dark Sector



Dark Radiation

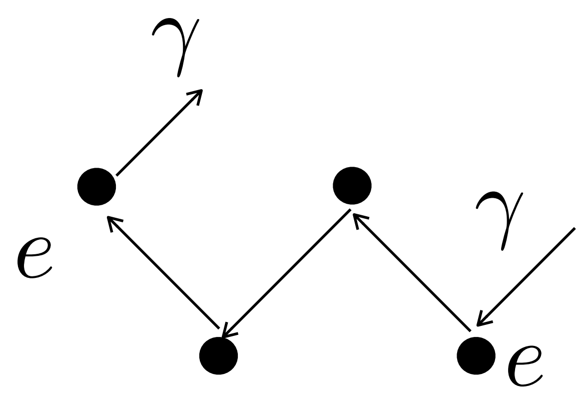
A Class of Solutions to Hubble tension

To increase H_0,

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

Free-streaming (non-interacting) Dark Radiation (DR)

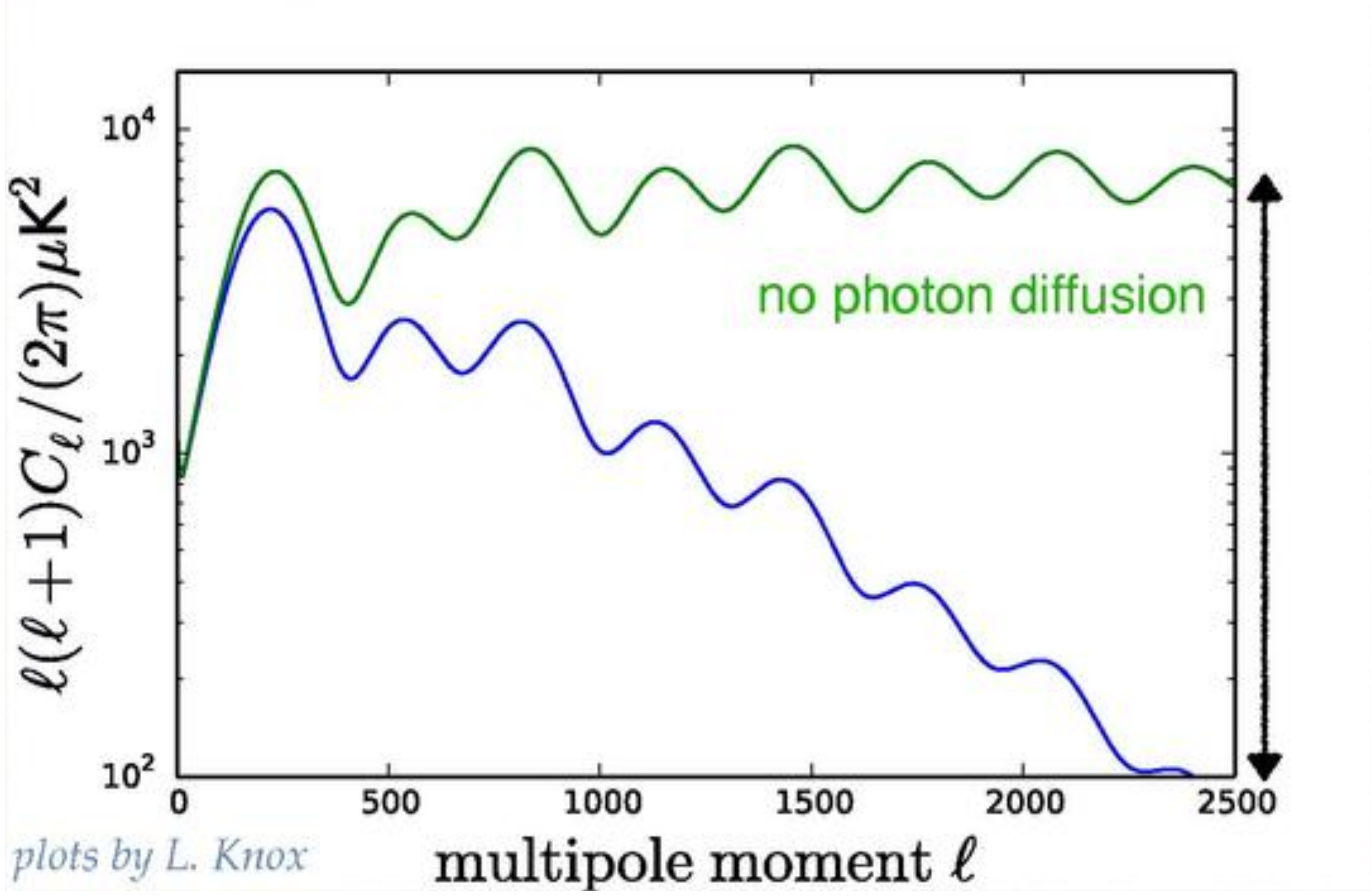
Silk damping (diffusion) + Drag effect



$$r_d \propto H_{\rm early}^{-1/2}$$

$$\theta_d = \frac{r_d}{D_A} \rightarrow \frac{\theta_d}{\theta_s} = \frac{r_d}{r_s} \propto H_{\rm early}^{1/2}$$

$$r_s \propto H_{\rm early}^{-1}$$



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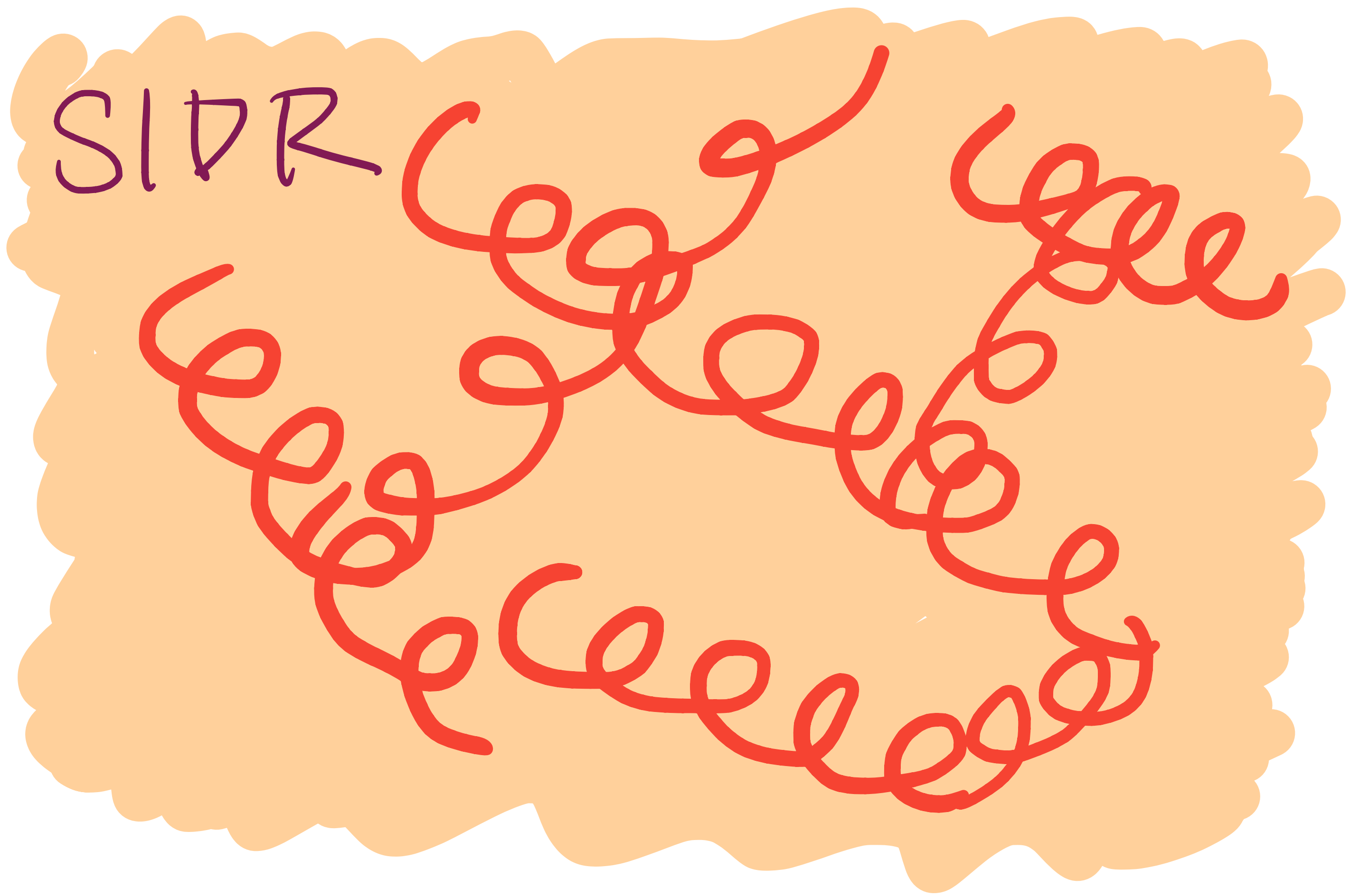
Good: Self-interacting DR **N. Blinov et al. [arXiv:2003.08387]**

Silk damping (diffusion)



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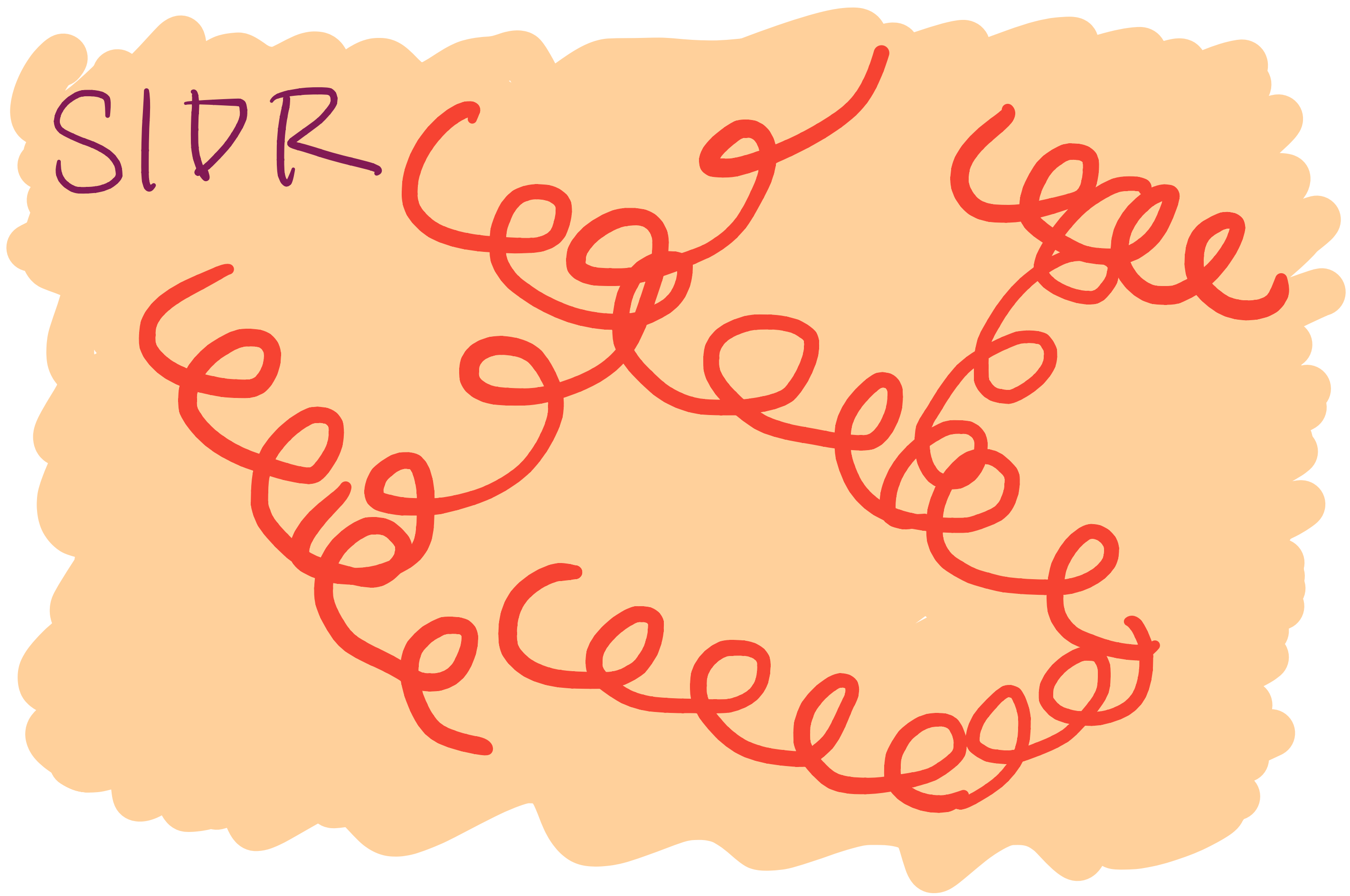
Silk damping (diffusion)

Better: need more (DAO)



Stepped Partially Acoustic Dark Matter

A Toy model for DAO + SIDR

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

Standard CDM

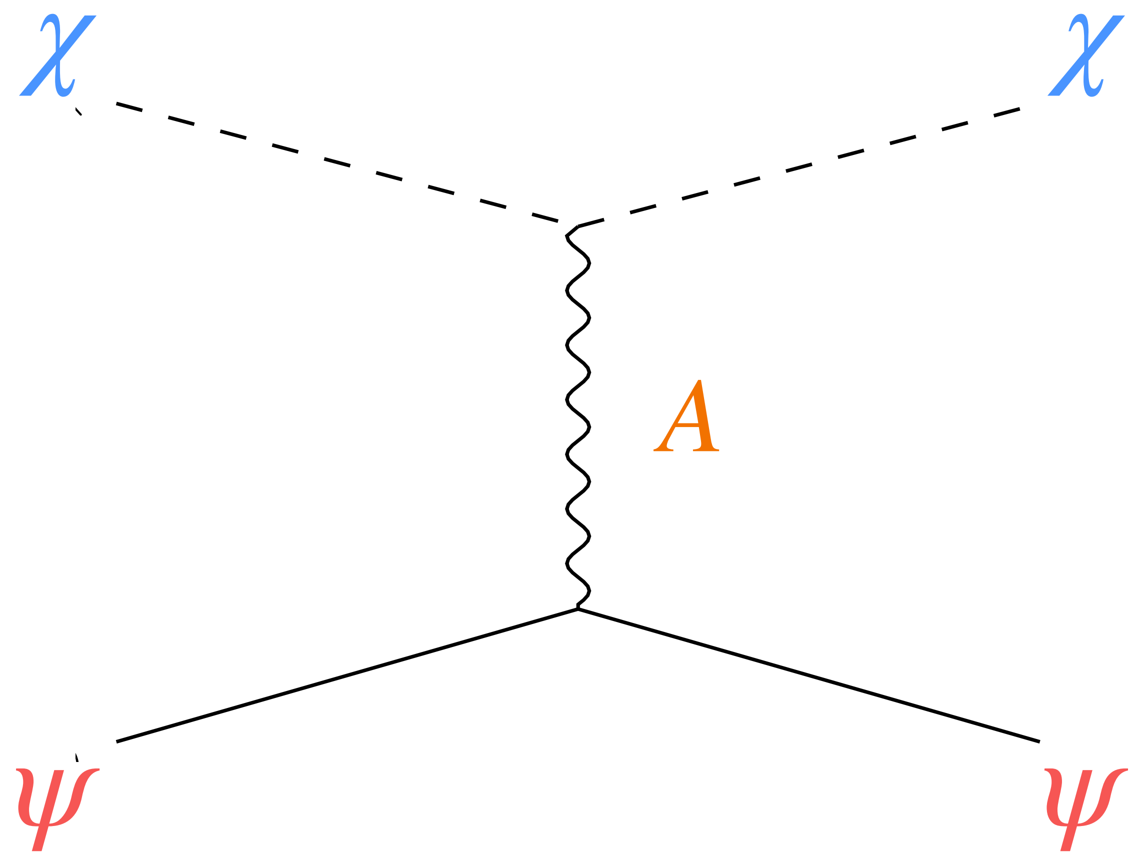
Interacting Dark Matter (iDM): χ

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

Self-interacting Dark Radiation:

ψ, A

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



	$U(1)_A$
χ	1
ψ	1

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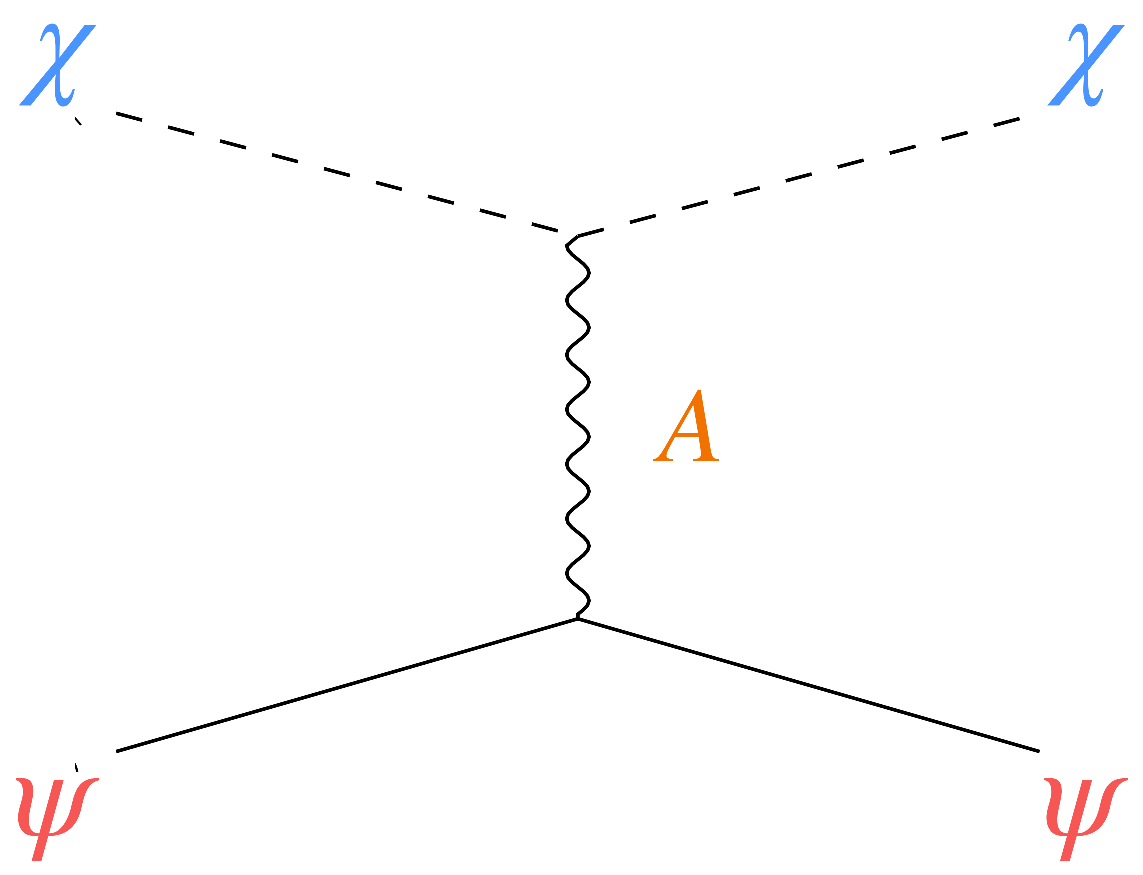
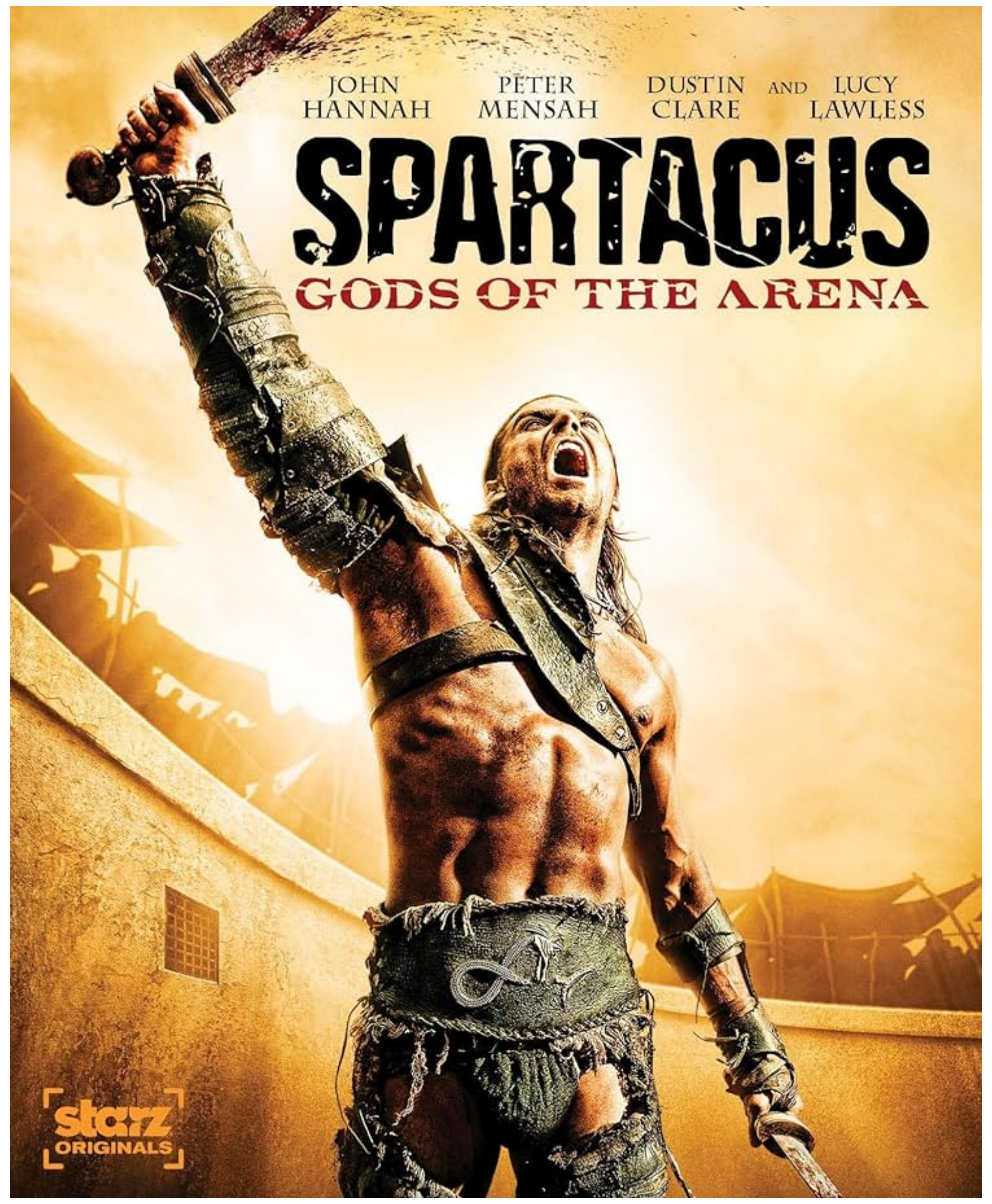




SPartAcous

Details of Model

Standard CDM

Interacting Dark Matter (iDM): χ

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

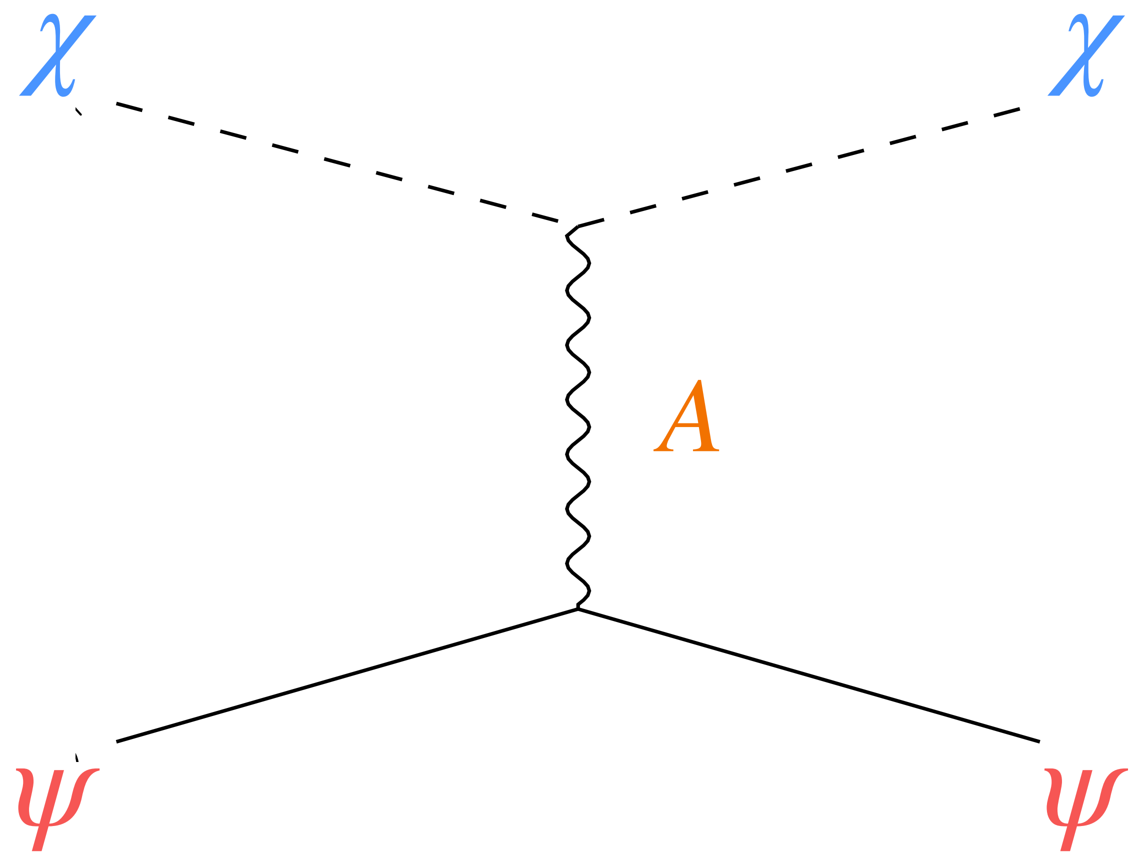
Self-interacting Dark Radiation:

ψ, A

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

Mass Threshold

Turn off iDM-DR interaction to avoid overly suppressed structure formation

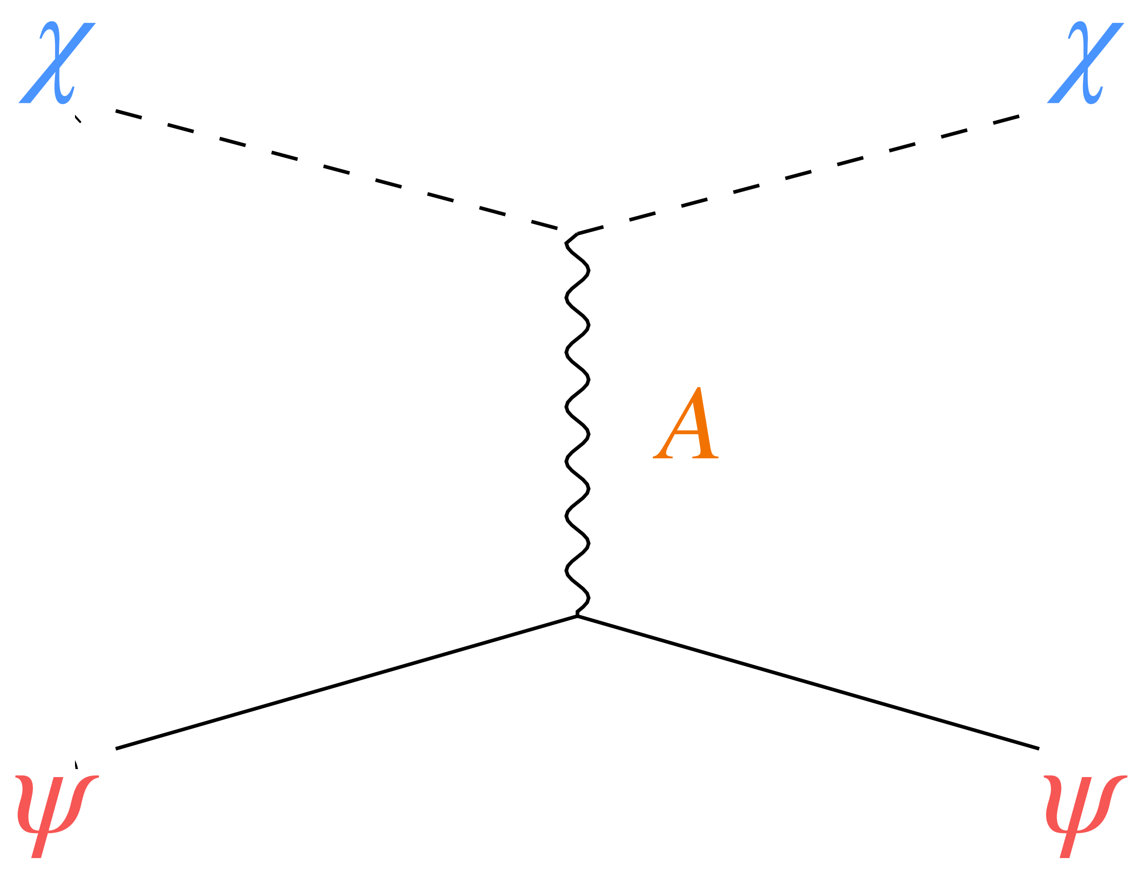


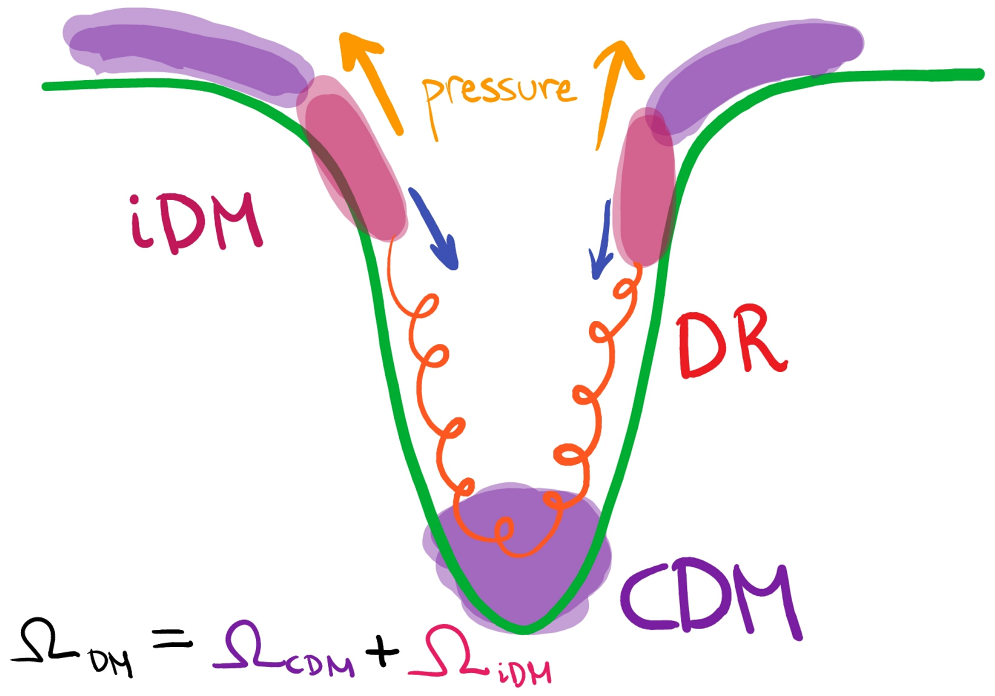
	$U(1)_A$
χ	1
ψ	1

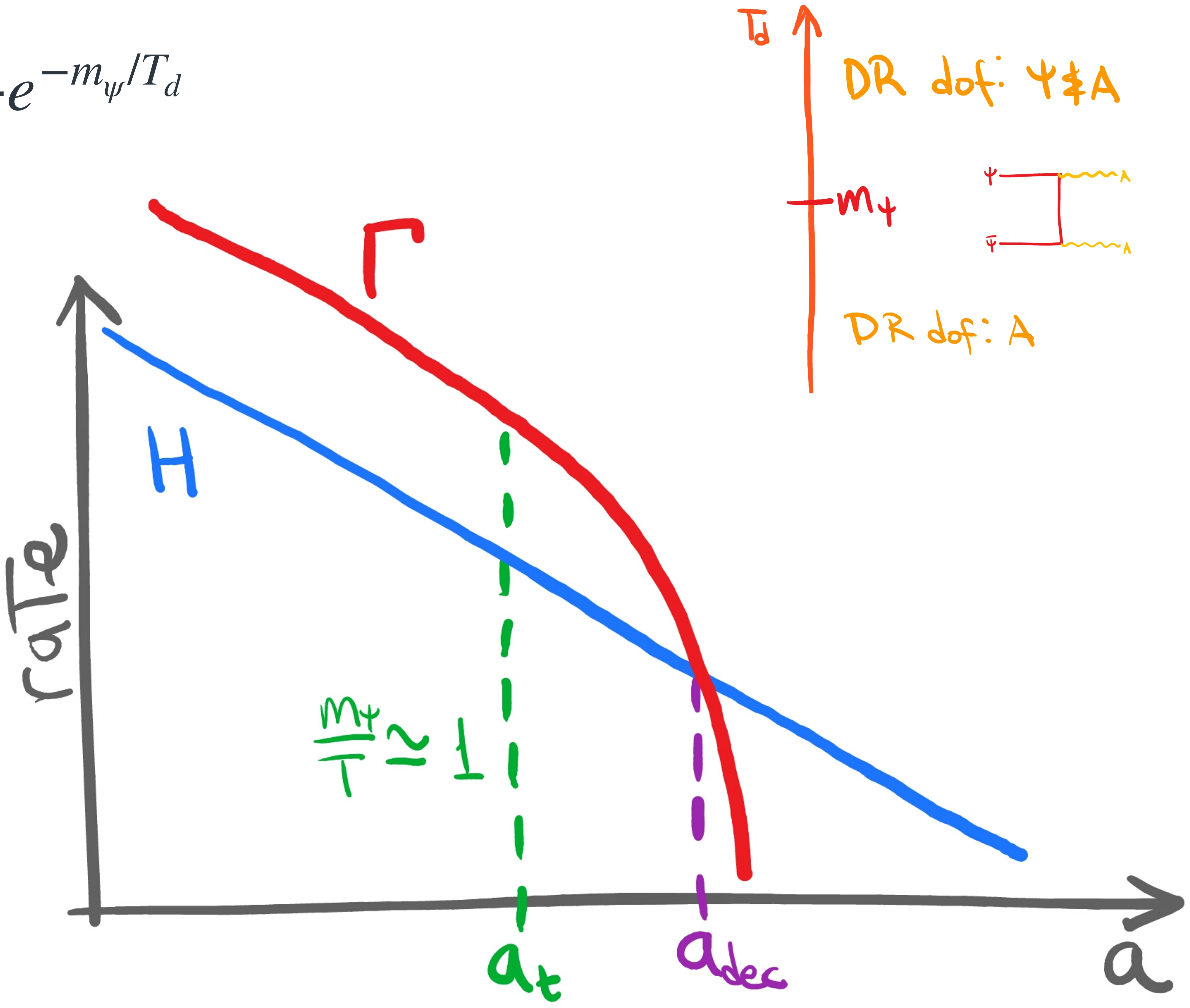
SPartAcous

iDM-DR interaction

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







Prevent too long DAO

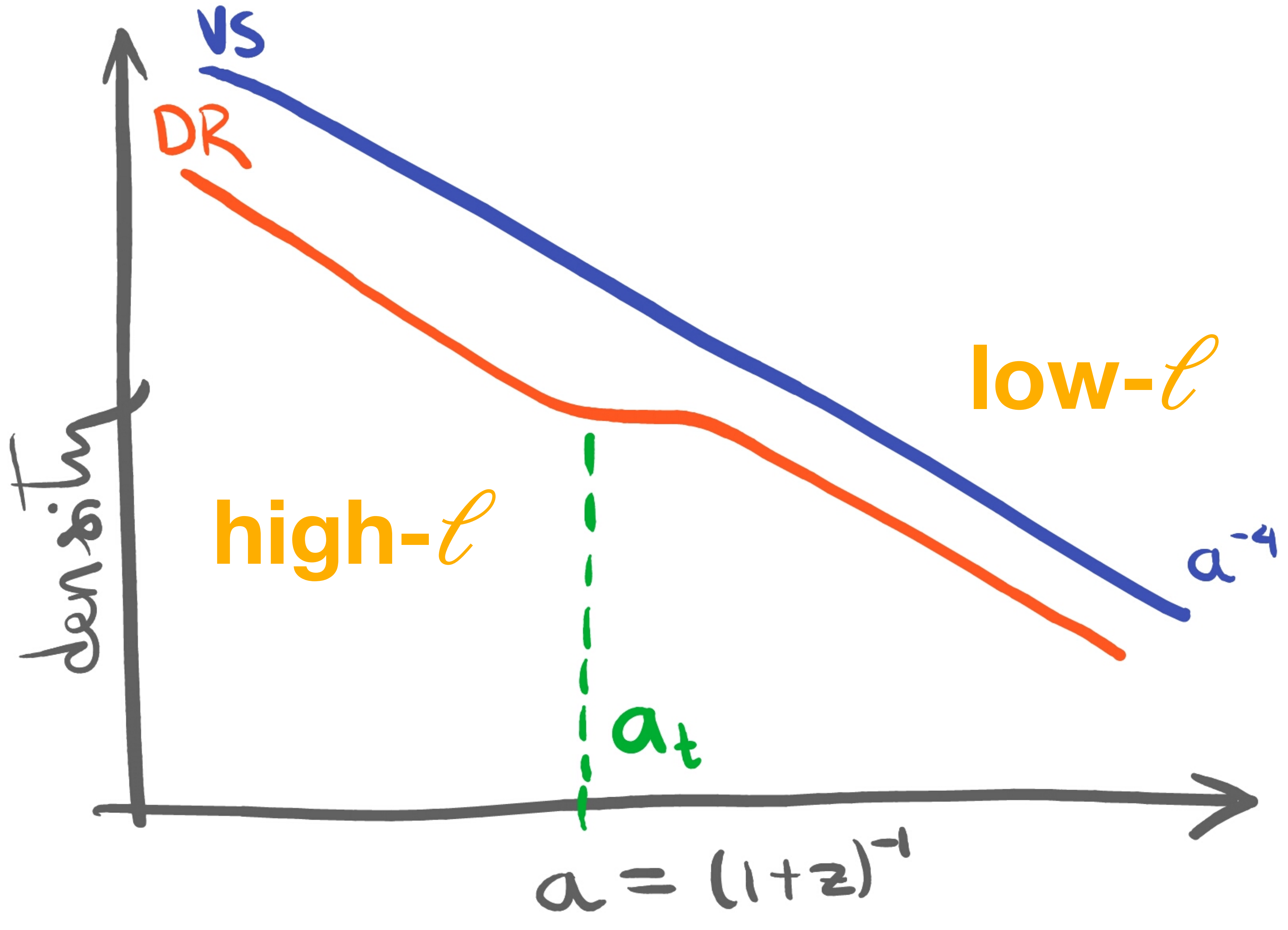
SPartAcous

Stepped Dark Radiation

Entropy dump / Reheating in DS

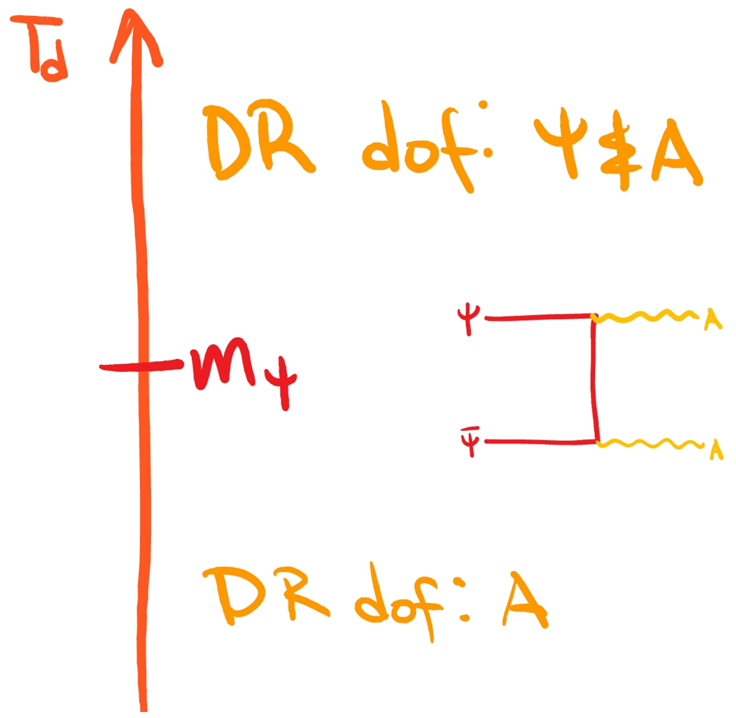
Step increase in ΔN_{eff}

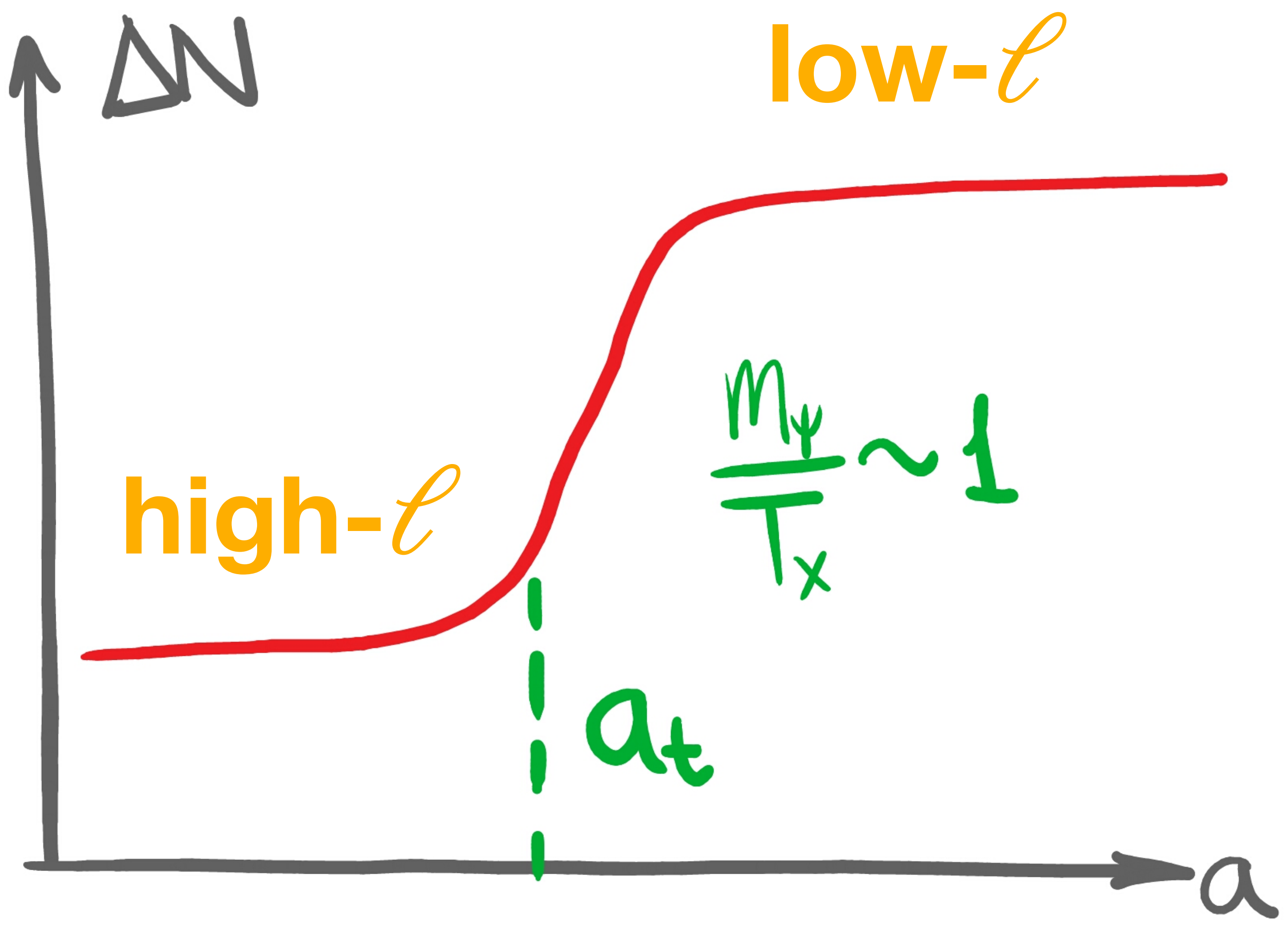
Different ℓ modes experience different Silk damping



Stepped DR **D. Aloni et al. [arXiv:2111.00014]**

A possible H_0 solution





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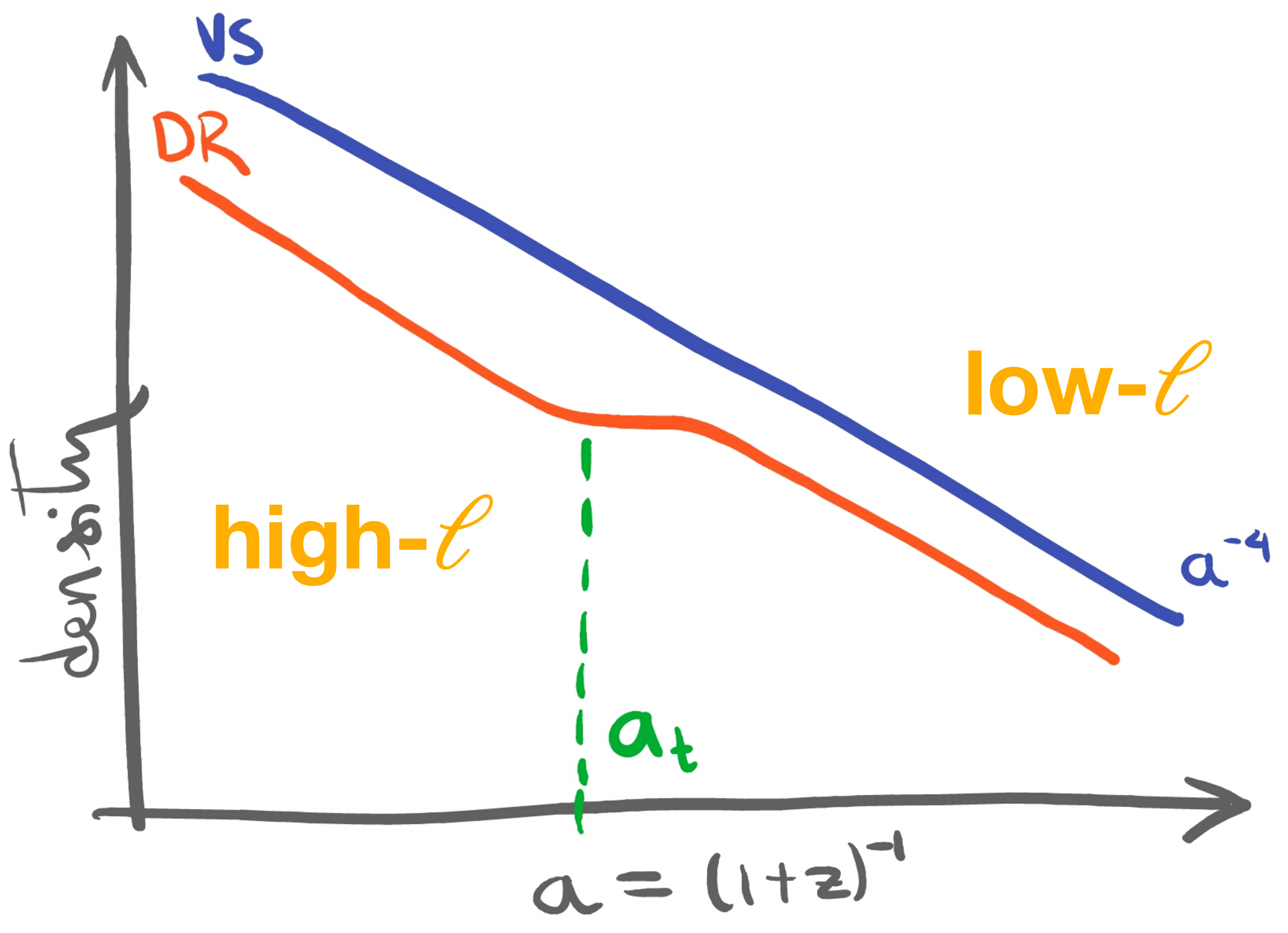
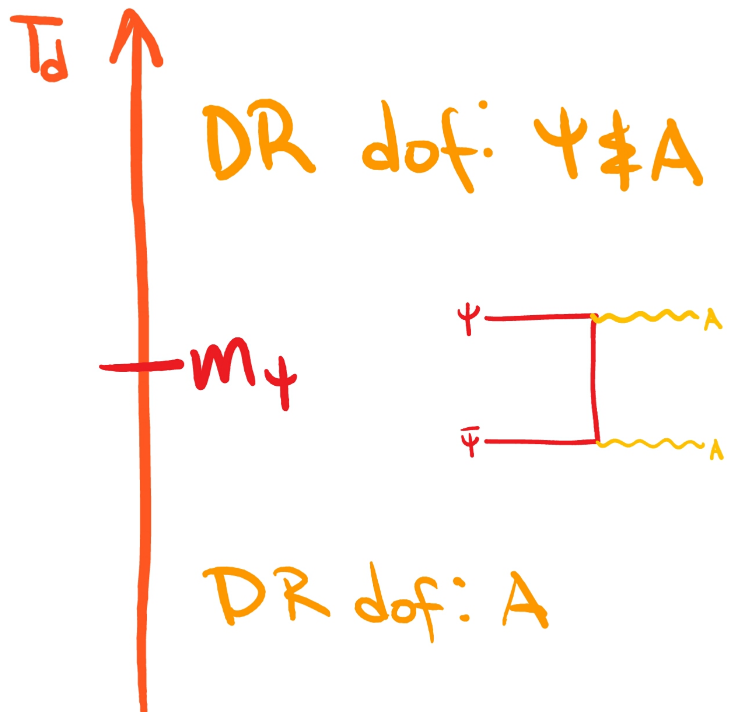
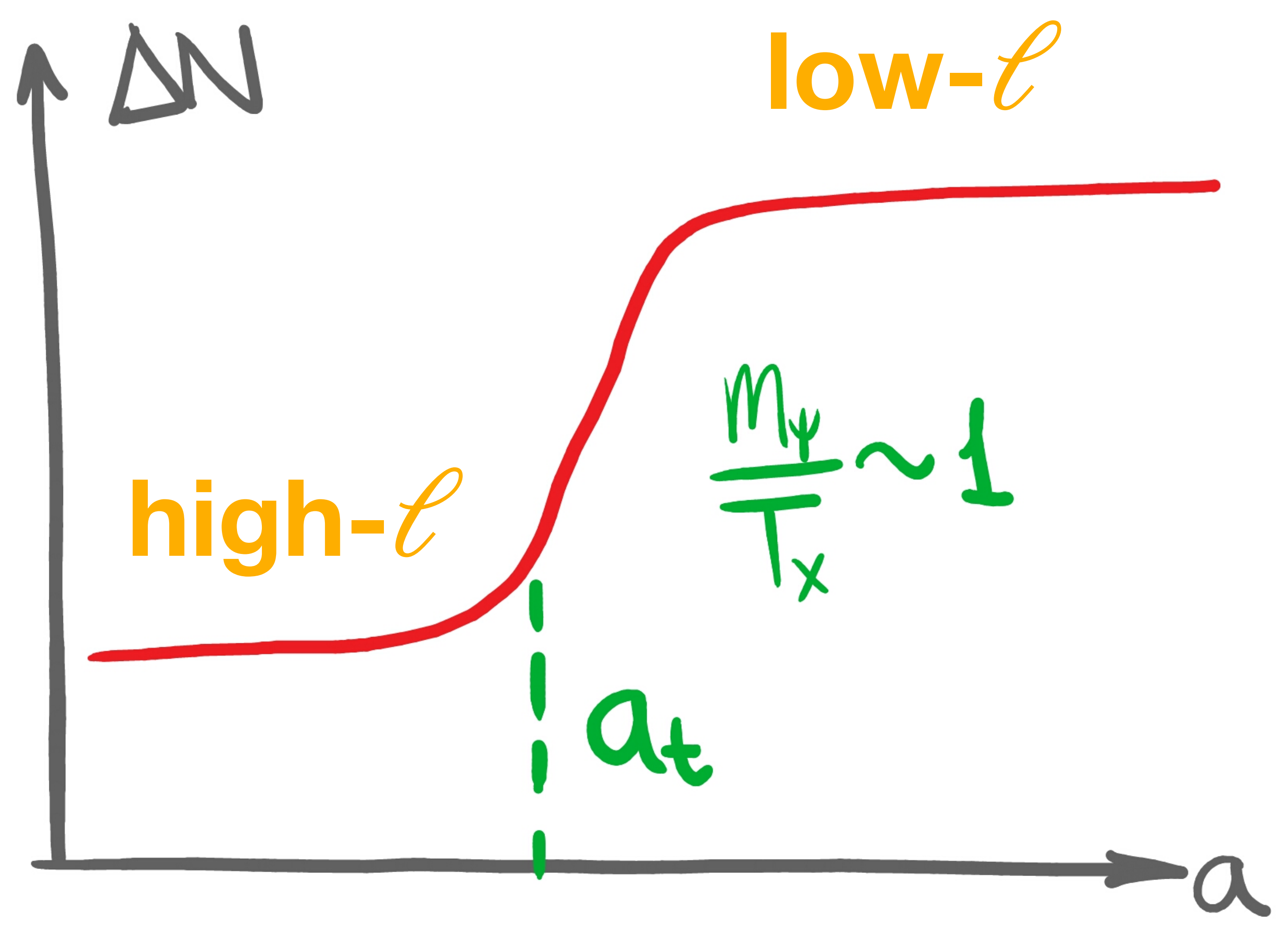
SPartAcous: DAO + SIDR w/ Step







SPartAcous

MCMC fit

Data:

Plank high ℓ TTTEEE, Planck low ℓ EE, Planck low ℓ TT, Plank lensing, BAO BOSS DR12, BAO small z, PANTHEON, SH0ES

Model:

~40% Step Size, iDM-DR interaction coupling $\alpha_d = 10^{-3}$

3 Free Parameters: f_χ, $\Delta N_{\rm IR}$, $z_{\rm t} = \frac{m_\chi}{T_{d0}} - 1$

M. A. Buen-Abad, Z. Chacko, C. Kilic, G. Marques-Tavares, TY [2306.01844]

Best fit

Model	$\Delta\chi^2$	ΔAIC	f_χ	H_0
LCDM	-	-	-	68.64
SPartAcous	-23.24	-17.24	0.1%	71.66

SPartAcous

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Only stepped DR DAO not working?

SPartAcous

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LCDM	-	-	-	68.64
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No step needed!

SPartAcous+

A Toy model for DAO + SIDR w/ small step

M. A. Buen-Abad, Z. Chacko, C. Kilic, G. Marques-Tavares, TY [2306.01844]

Standard CDM

Interacting Dark Matter (iDM): χ

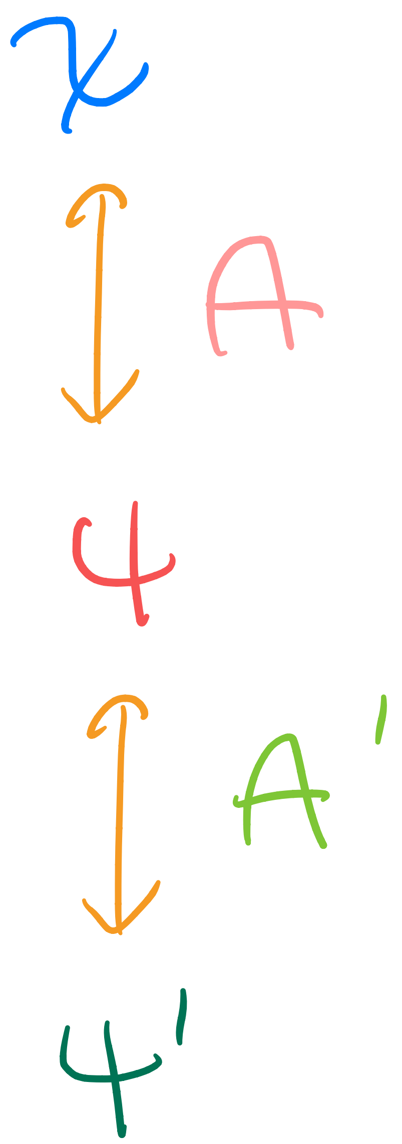
$$f_{\rm CDM} + f_\chi = 1$$

Self-interacting Dark Radiation

ψ, A

ψ', A'

0, 3 ψ' flavors: ~40, 7% jump in $\Delta N_{\rm eff}$



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

SPartAcous+

MCMC fit

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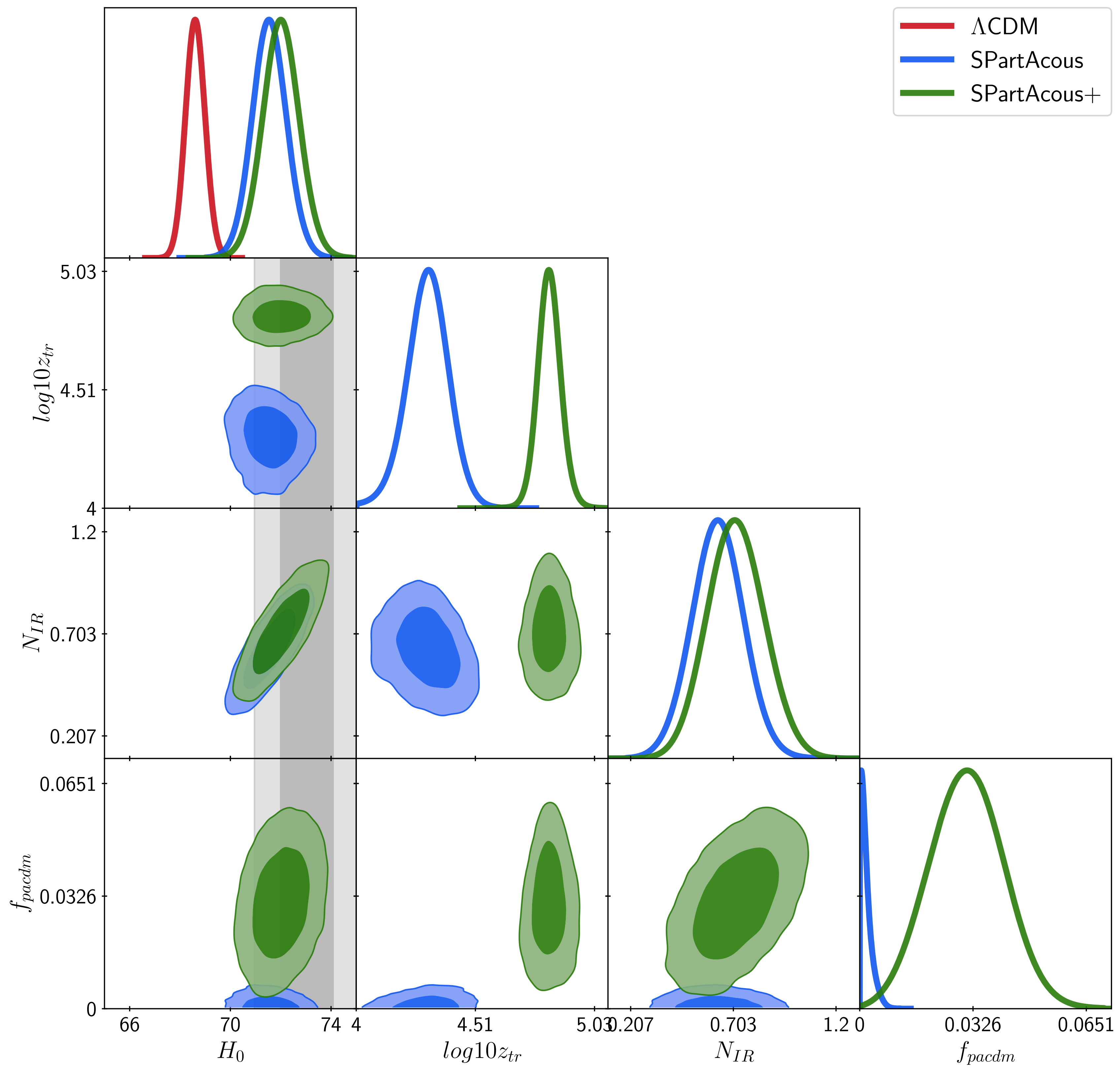

Best fit

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SPartAcous	-23.24	-17.24	0.1%	71.66
SPartAcous+	-26.89	-20.89	3.2%	71.98

M. A. Buen-Abad, Z. Chacko, C. Kilic, G. Marques-Tavares, TY [2306.01844]

SPartAcous+

MCMC fit

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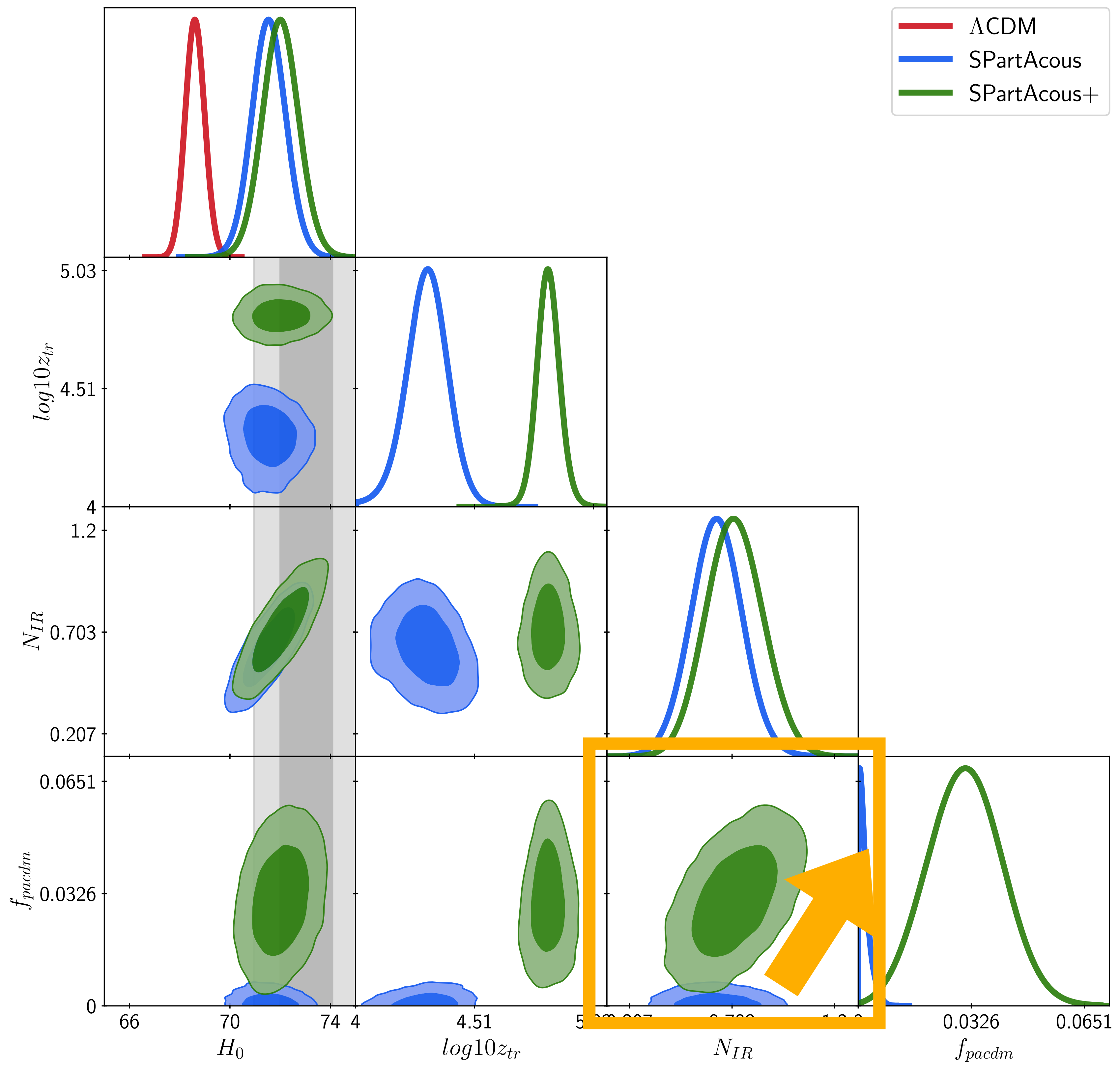

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DAO at work

M. A. Buen-Abad, Z. Chacko, C. Kilic, G. Marques-Tavares, TY [2306.01844]

νADM

M. A. Buen-Abad, Z. Chacko, I. Flood, C. Kilic, G. Marques-Tavares, TY [2409.XXXXX]

Another Toy model for DAO + SIDR w/o any step

Standard CDM

Atomic DM: χ

Dark Proton p_d, Dark Electron e_d

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

Self-interacting Dark Radiation

Dark Photon A_d, Dark Neutrino ν_d, $U(1)_\nu$ gauge boson X

	$U(1)_A$	$U(1)_\nu$
χ	1	0
ν_d	0	1

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

νADM

Atomic DM + Dark ν

Standard CDM

Atomic DM: χ

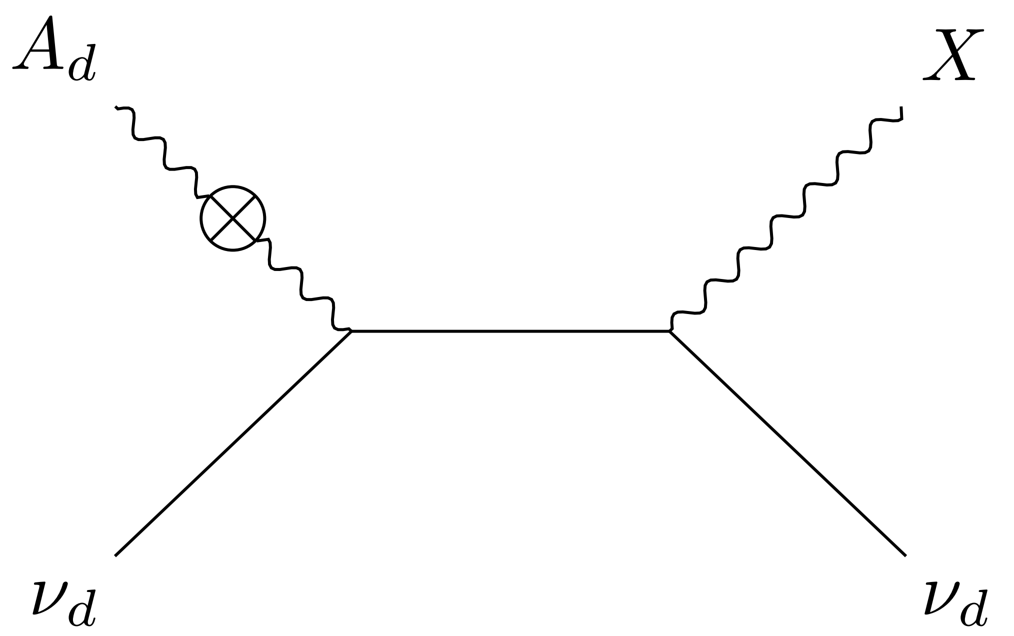
Dark Proton p_d, Dark Electron e_d

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

	$U(1)_A$	$U(1)_\nu$
χ	1	0
ν_d	0	1

Self-interacting Dark Radiation

Dark Photon A_d, Dark Neutrino ν_d, $U(1)_\nu$ gauge boson X



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

νADM

Dark Recombination

iDM-DR interaction is off by dark recombination (no step reheating in DS)

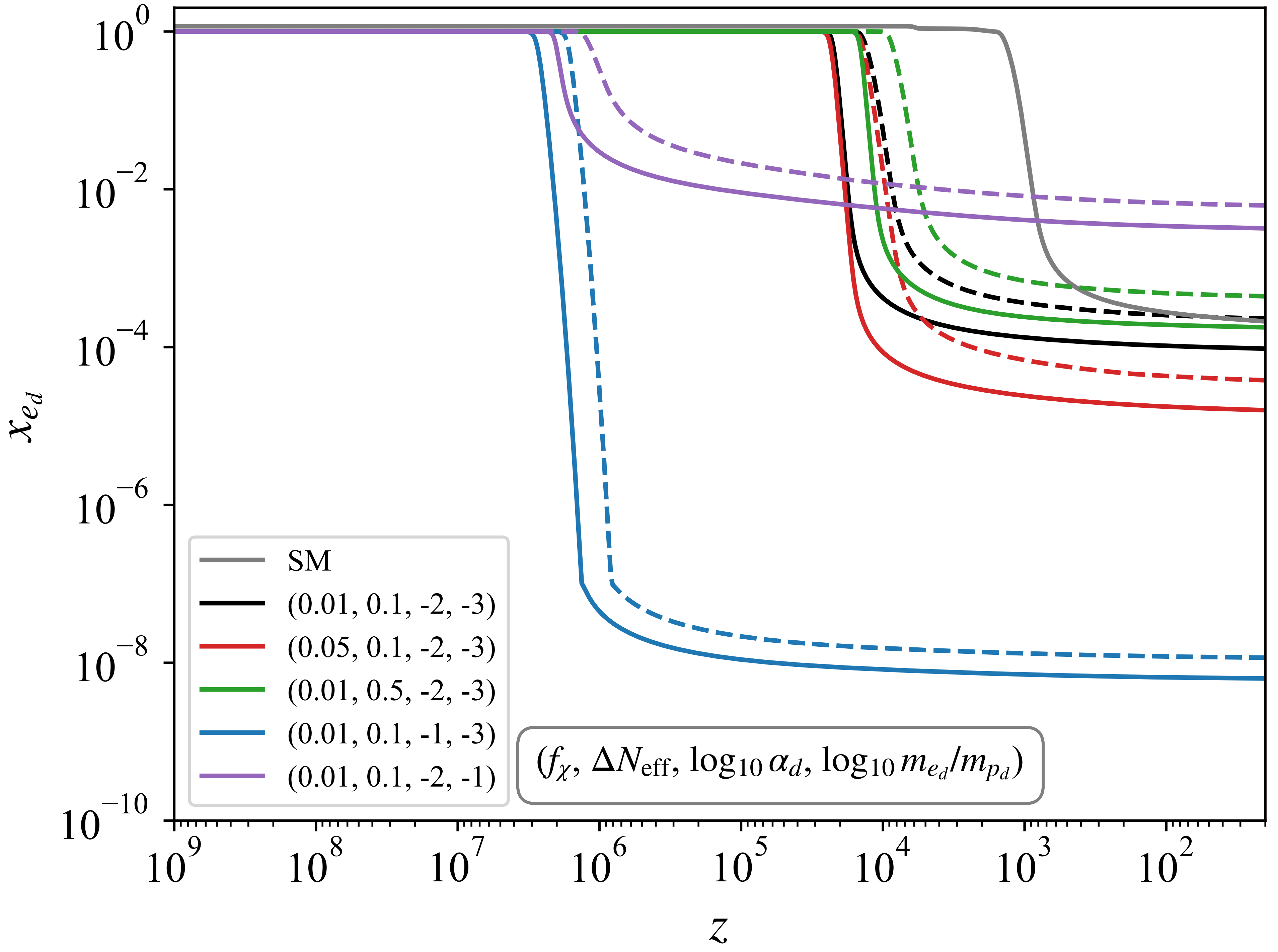
Radiative recombination to the ground state, and its inverse photoionization

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

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

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

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



νADM

MCMC fit

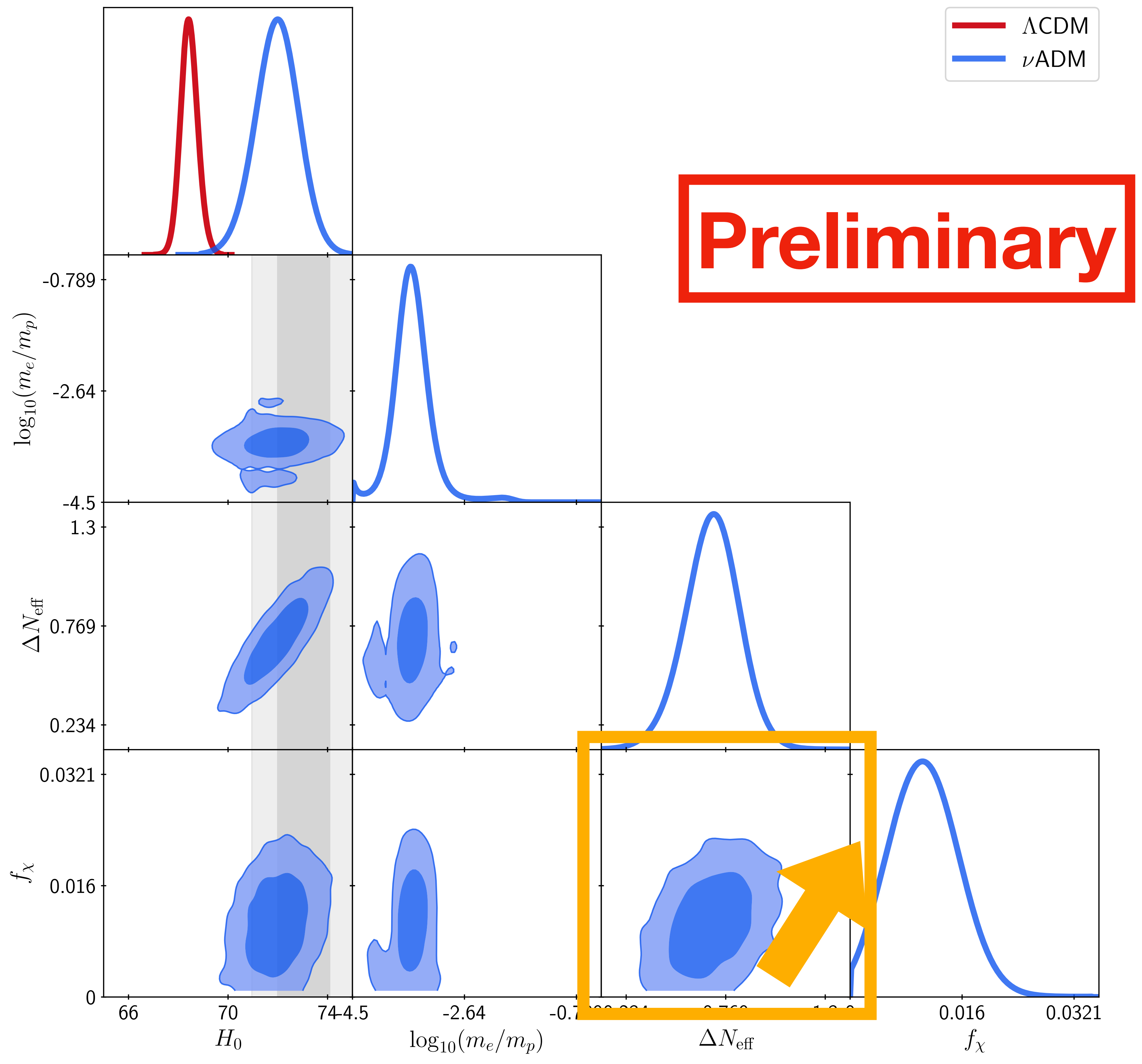
Data:

Plank high ℓ TTTEEE, Planck low ℓ EE, Planck low ℓ TT, Plank lensing, BAO eBOSS DR16, BAO small z, PANTHEON+, SH0ES

Model:

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

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



Best fit

Model	$\Delta\chi^2$	ΔAIC	f_χ	H_0
LCDM	-	-	-	68.46
νADM	-29.65	-23.65	1.2%	72.01

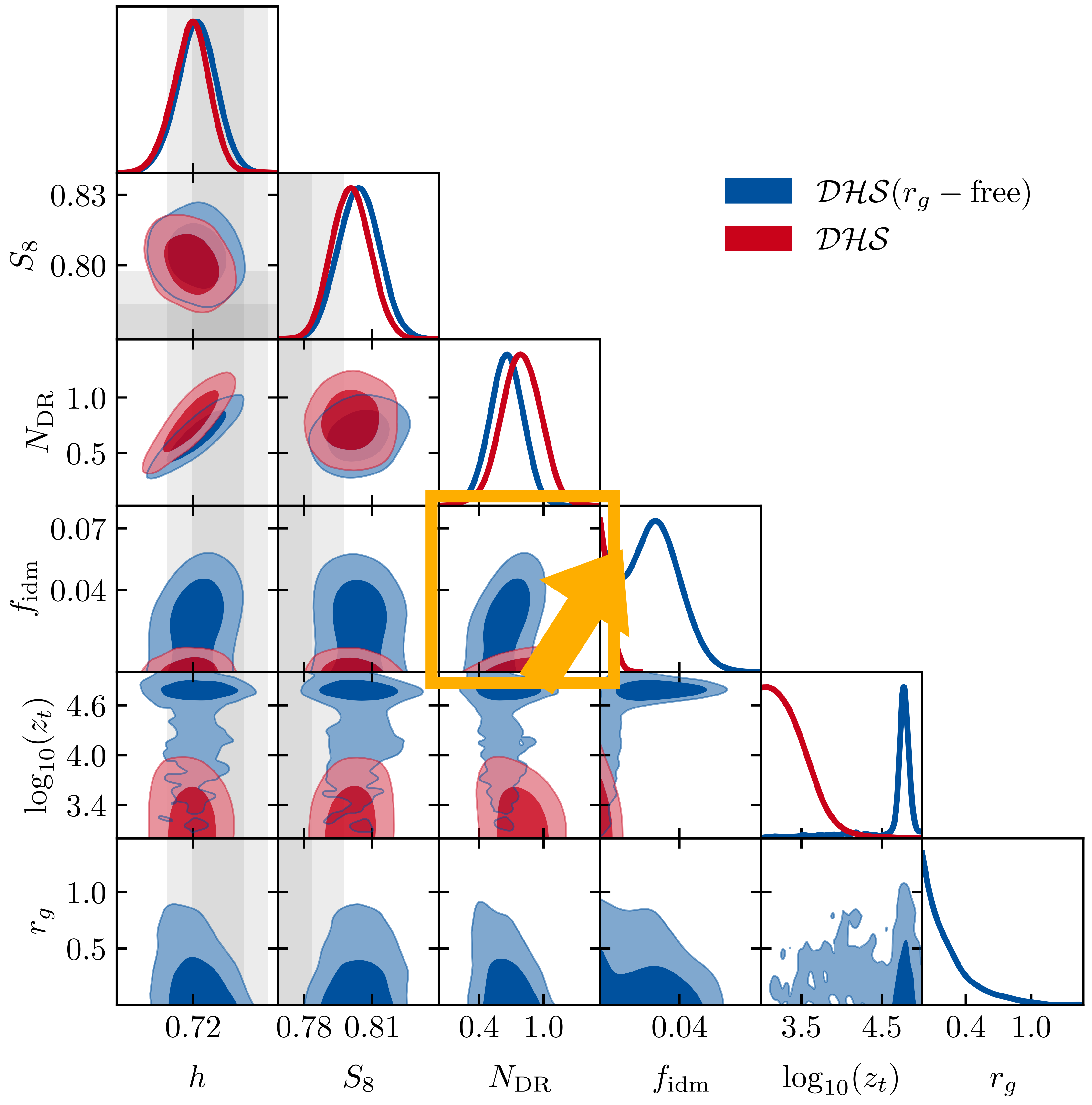
DAO at work

M. A. Buen-Abad, Z. Chacko, I. Flood, C. Kilic, G. Marques-Tavares, TY [2409.XXXXX]

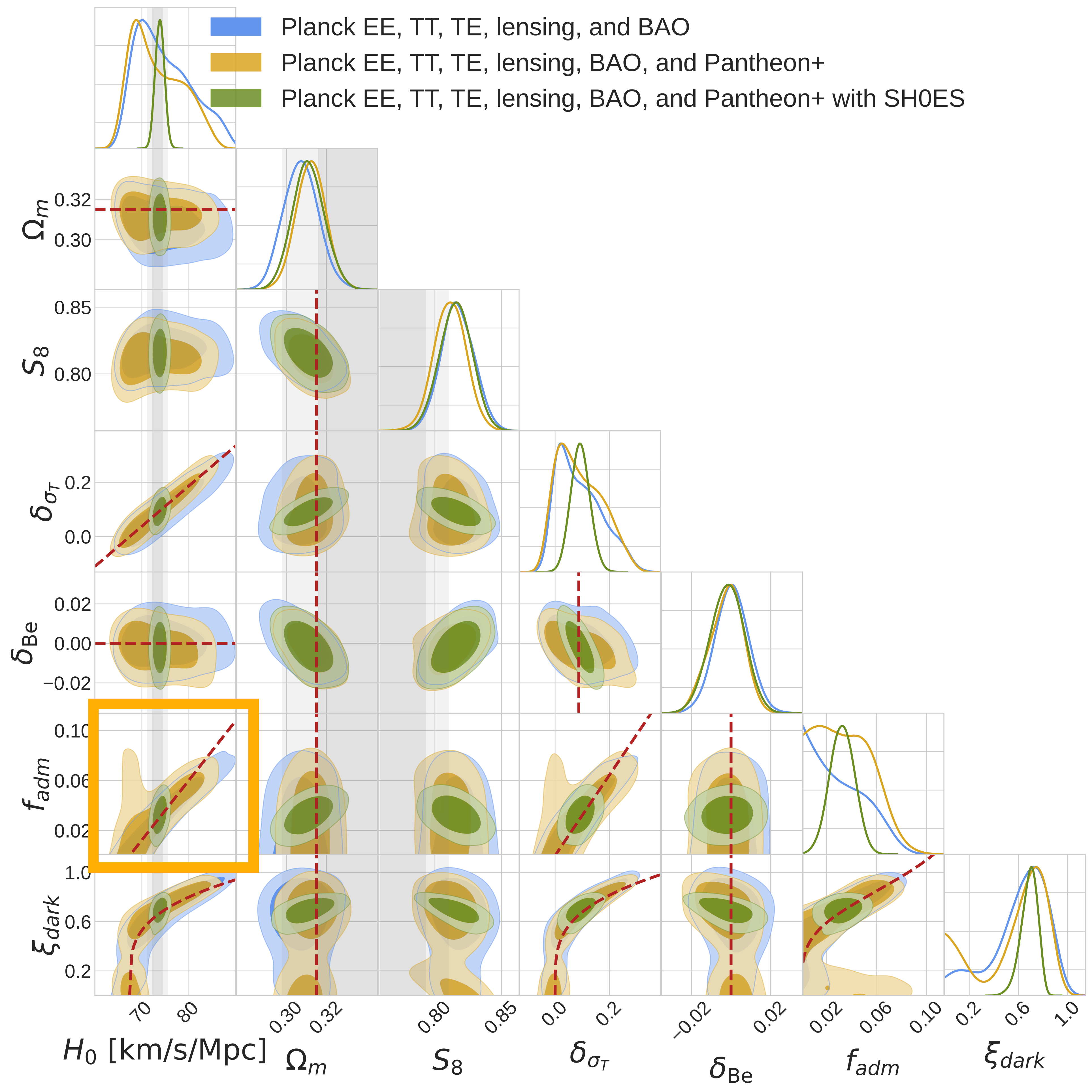
DAO at Work

S. Ghosh, D. W. R. Ho, Y. Tsai [2405.080641]

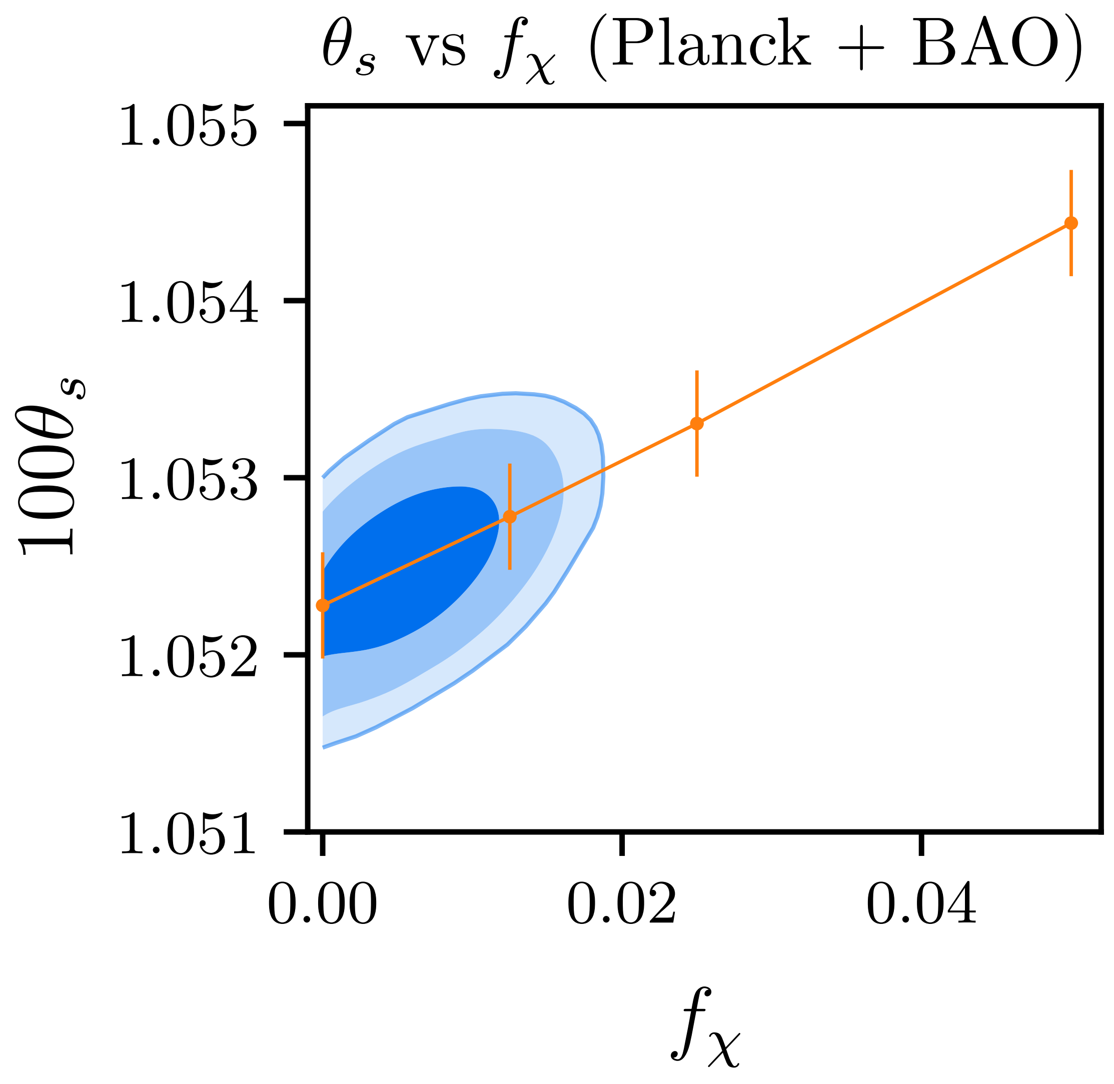
In other literature



N. Schöneberg et al. [2306.12469]



K. Greene, F.-Y. Cyr-Racine [2403.05619]



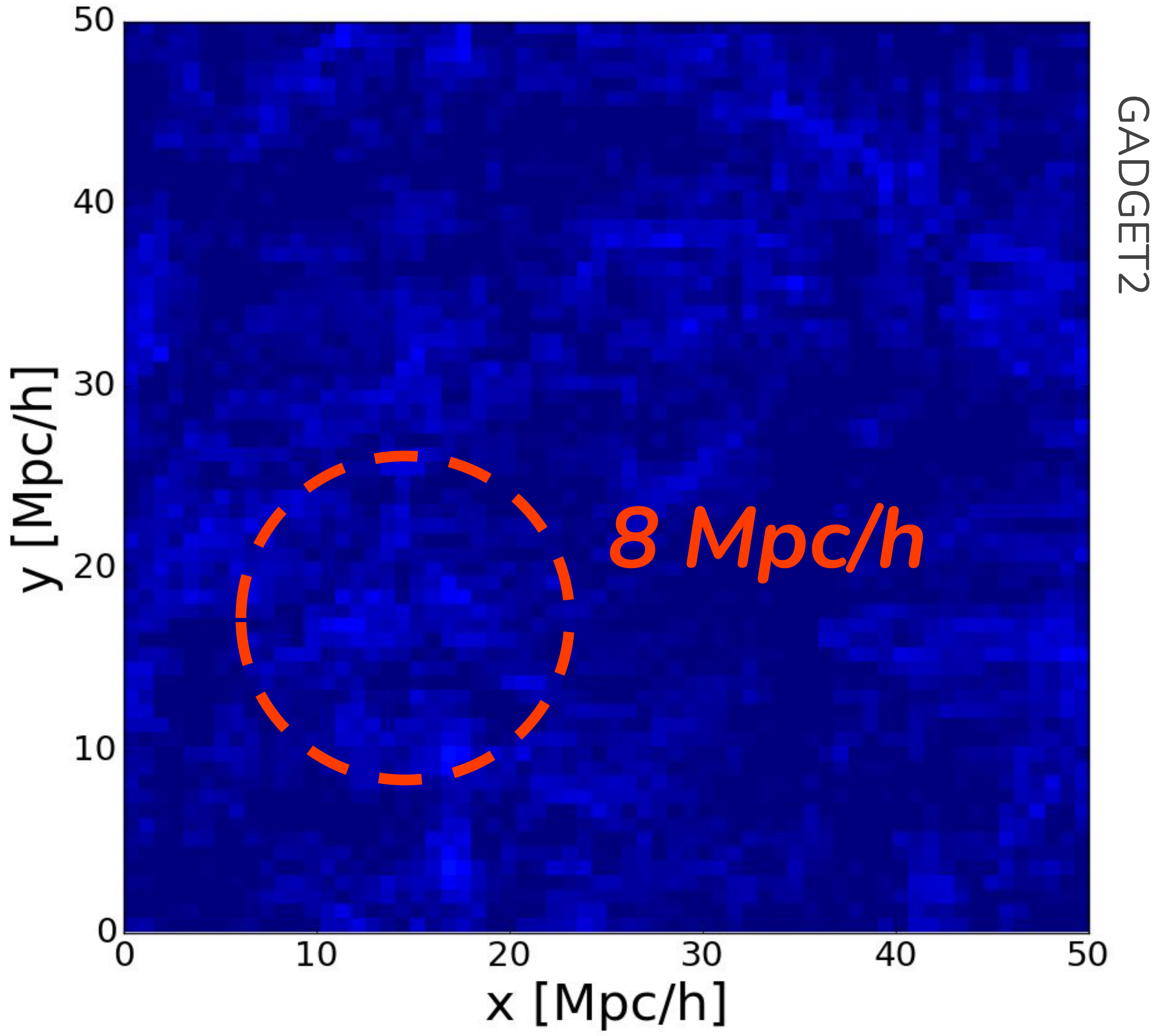
Cosmological Tensions

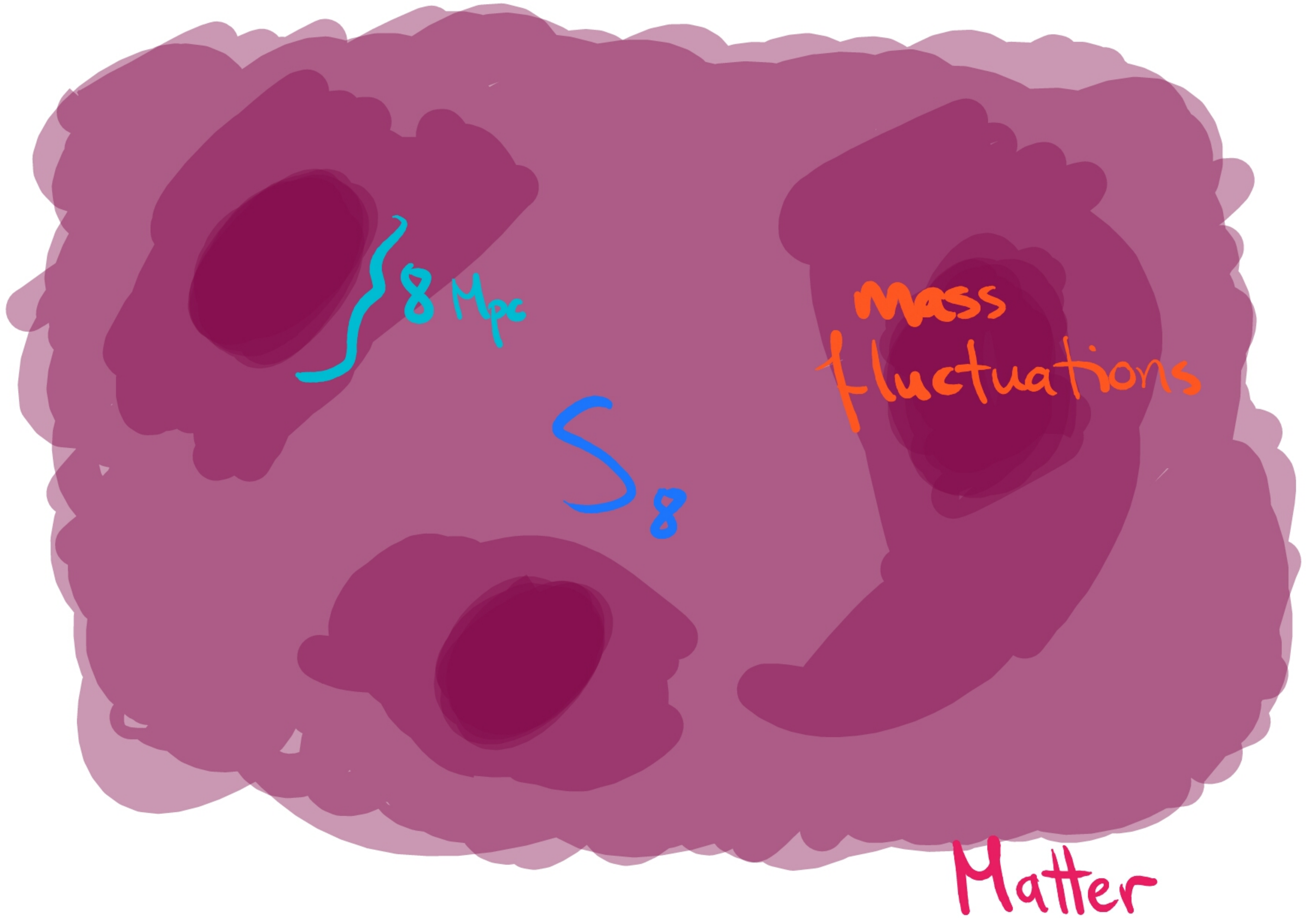
Snowmass [arXiv:2203.06142]

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

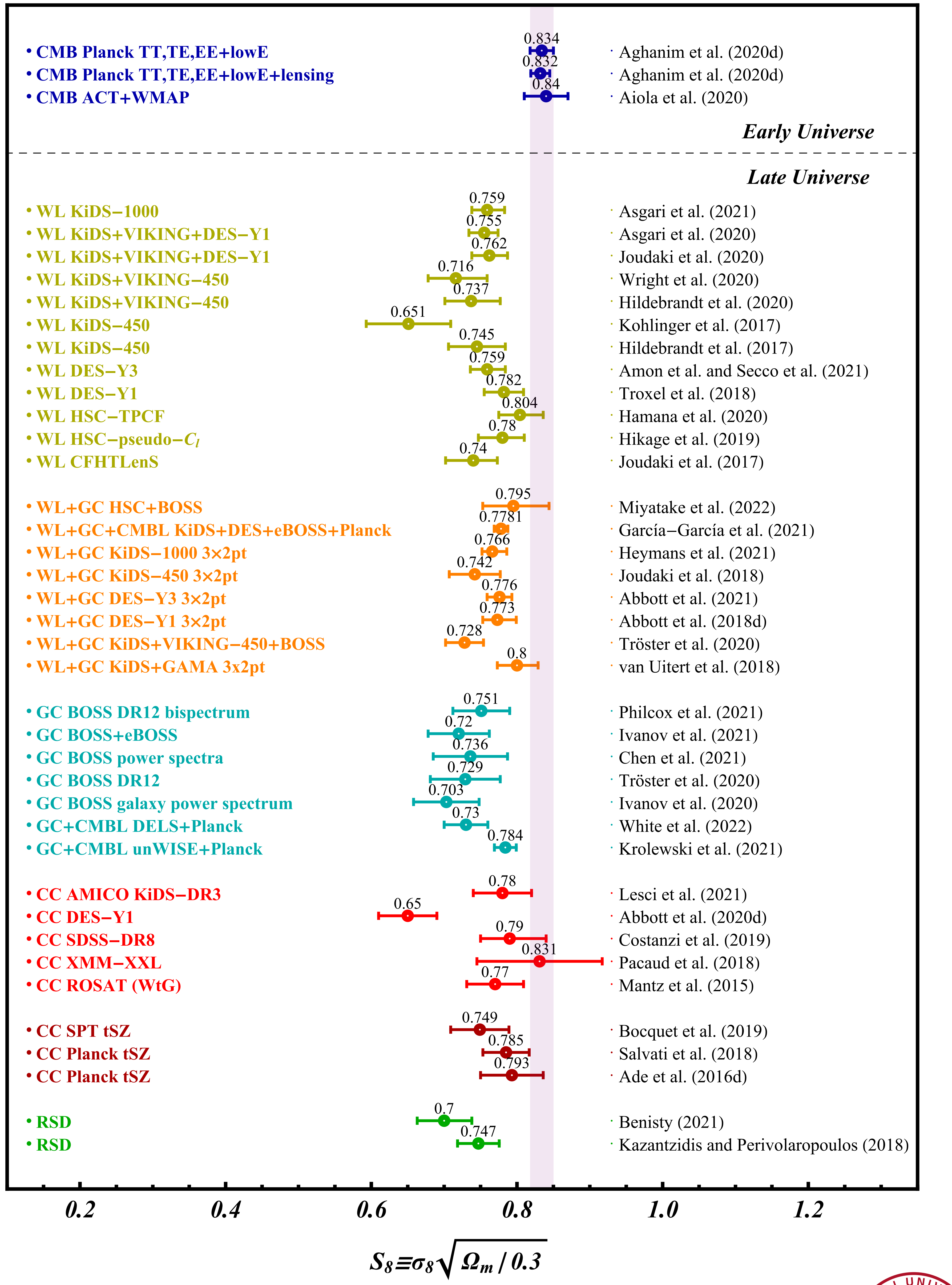
CMB fit to ΛCDM

~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)

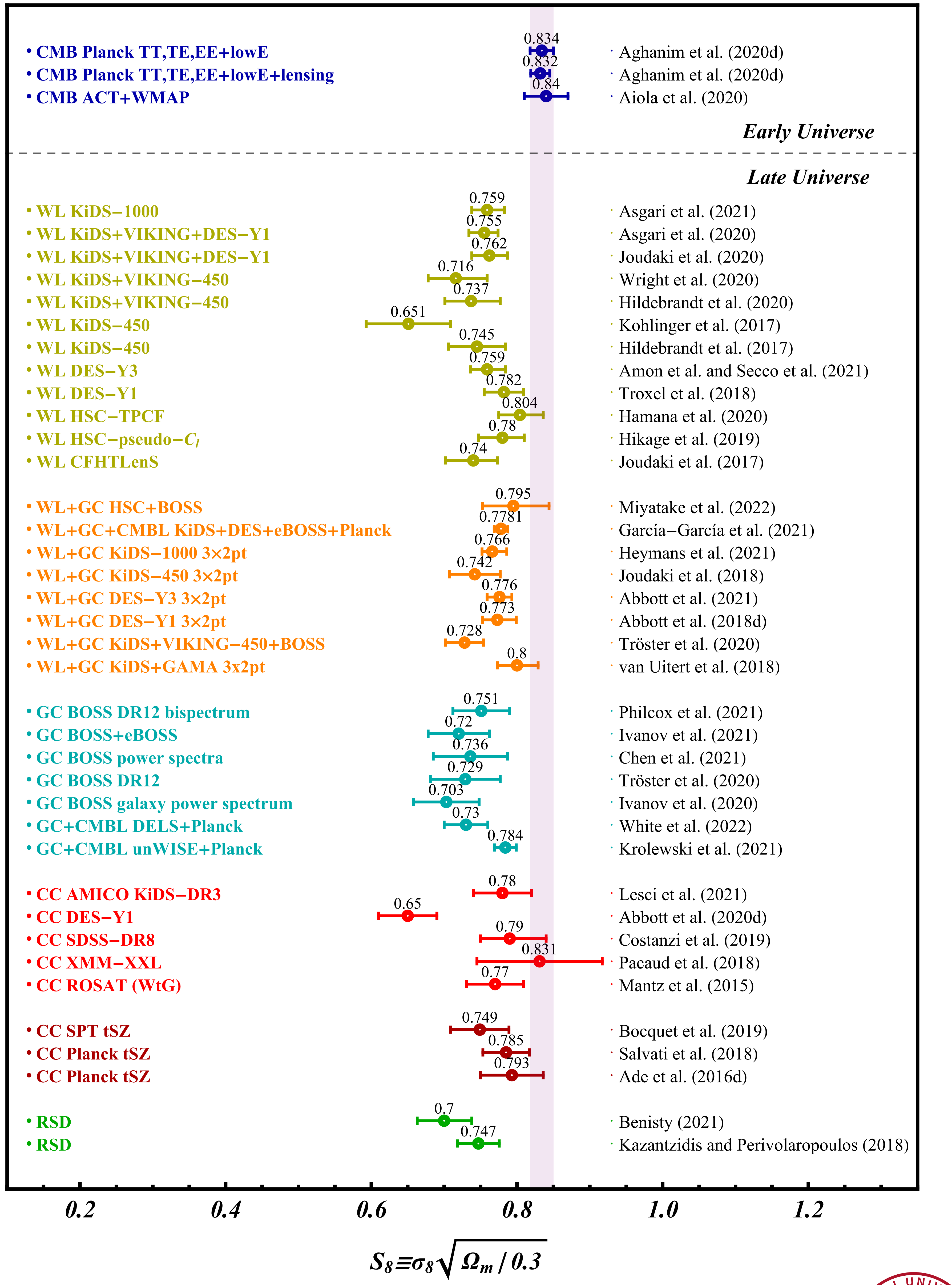
More likely systematic errors

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 need to deal with S_8

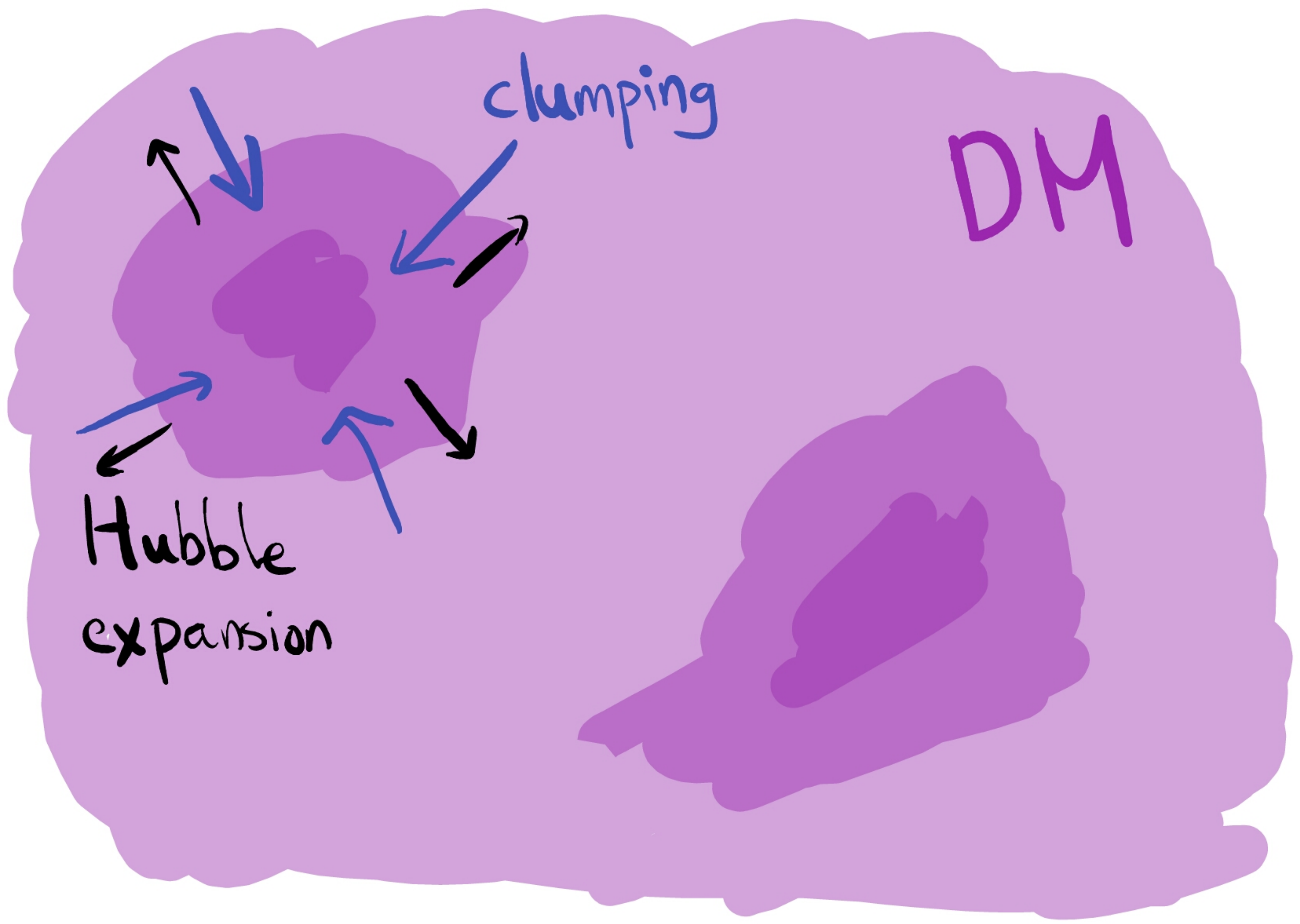


Dark Matter interaction with DR

A Class of Solutions to S_8 tension

Dark Radiation worsens S_8 tension

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



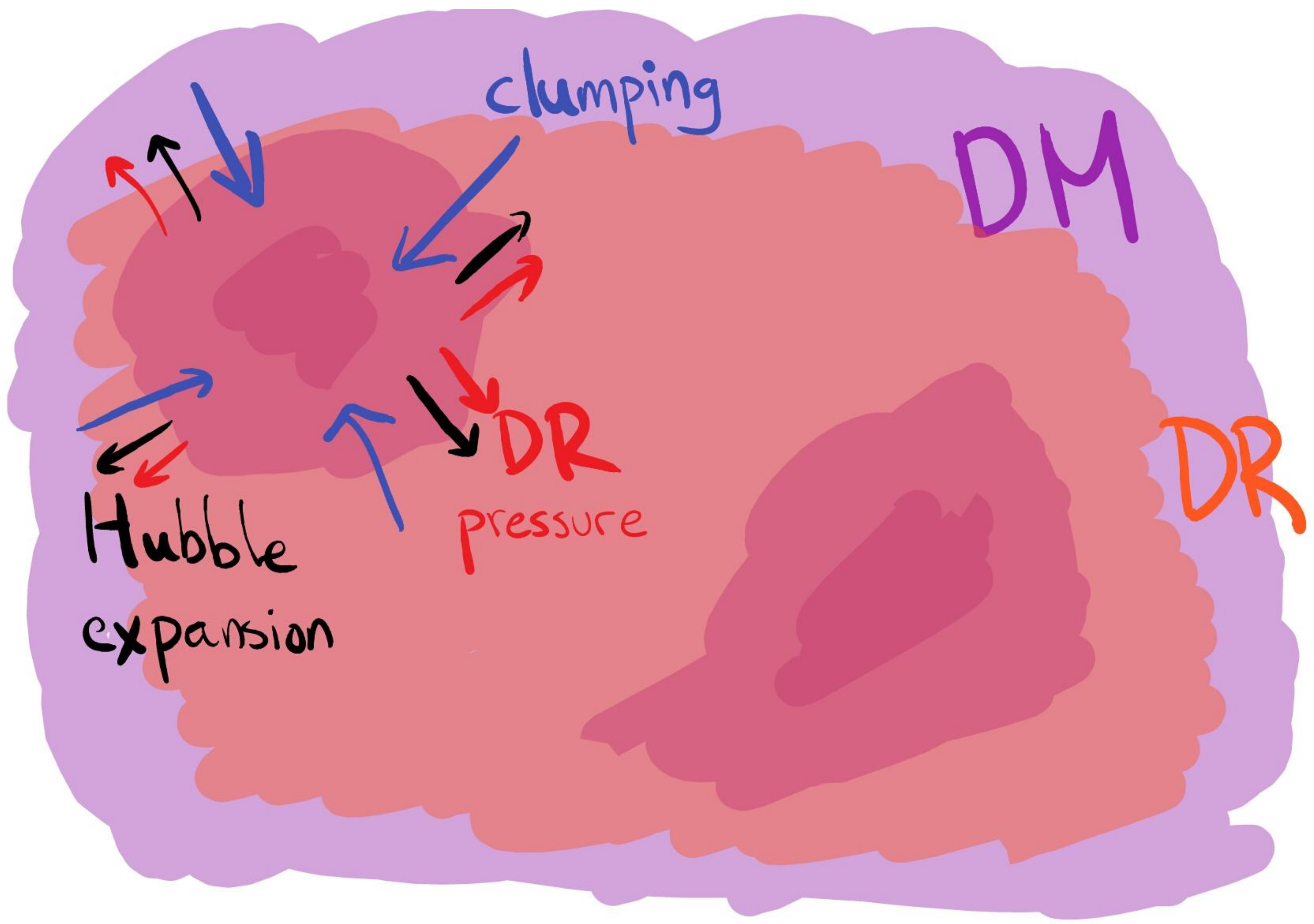
Dark Matter interaction with DR

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



Dark Matter interaction with DR

A Class of Solutions to S_8 tension

Dark Radiation worsens S_8 tension

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

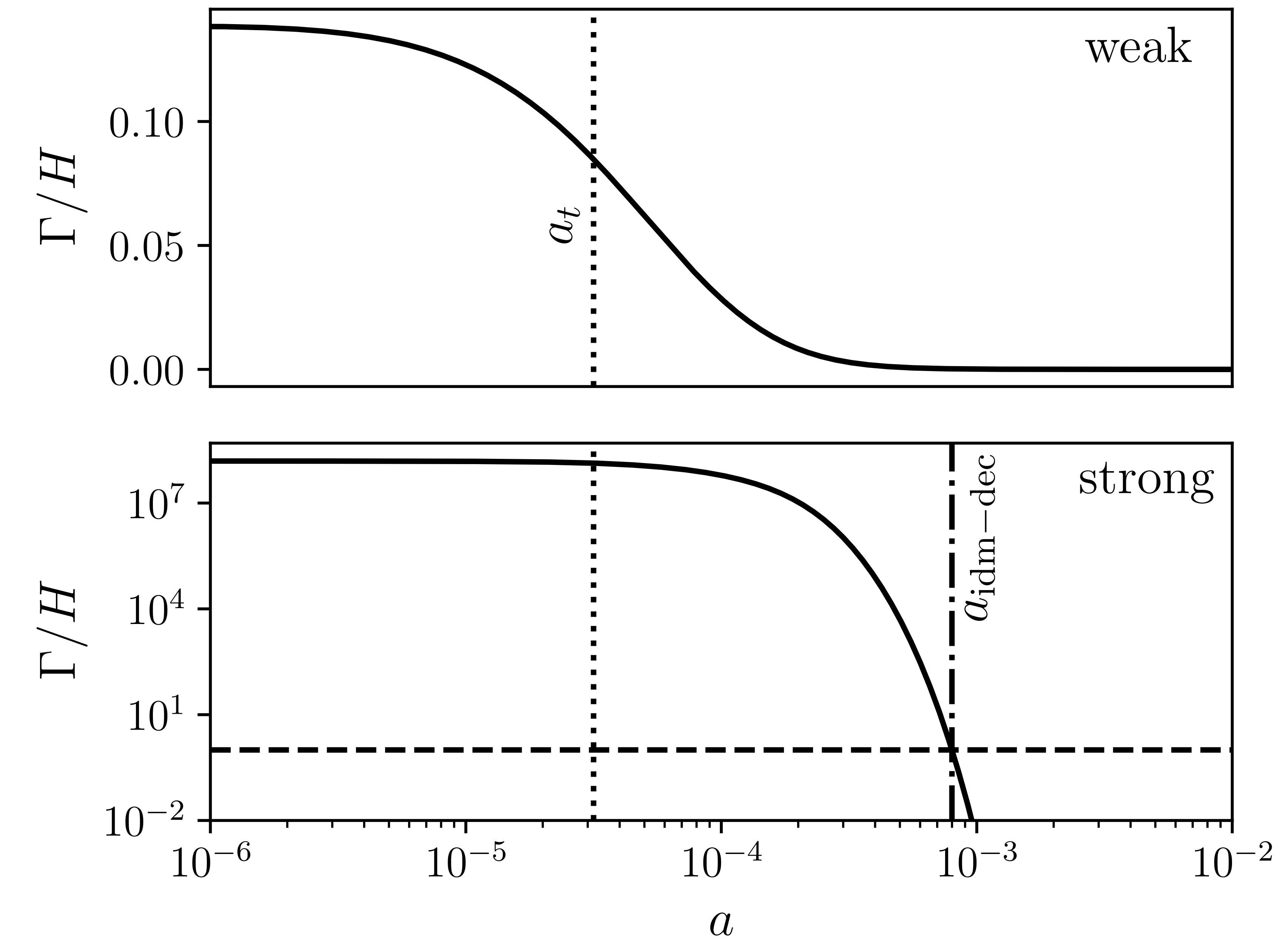
Solution: Dark Matter interaction with Dark Radiation

Weak interaction + entire dark matter interacting

M. Joseph et al. [arXiv:2207.03500]

Strong interaction + partial dark matter interacting

M. A. Buen-Abad, Z. Chacko, C. Kilic, G. Marques-Tavares, TY [arXiv:2208.05984, 2306.01844]



N. Schöneberg et al. [arXiv:2306.12469]

Dark Matter interaction with DR

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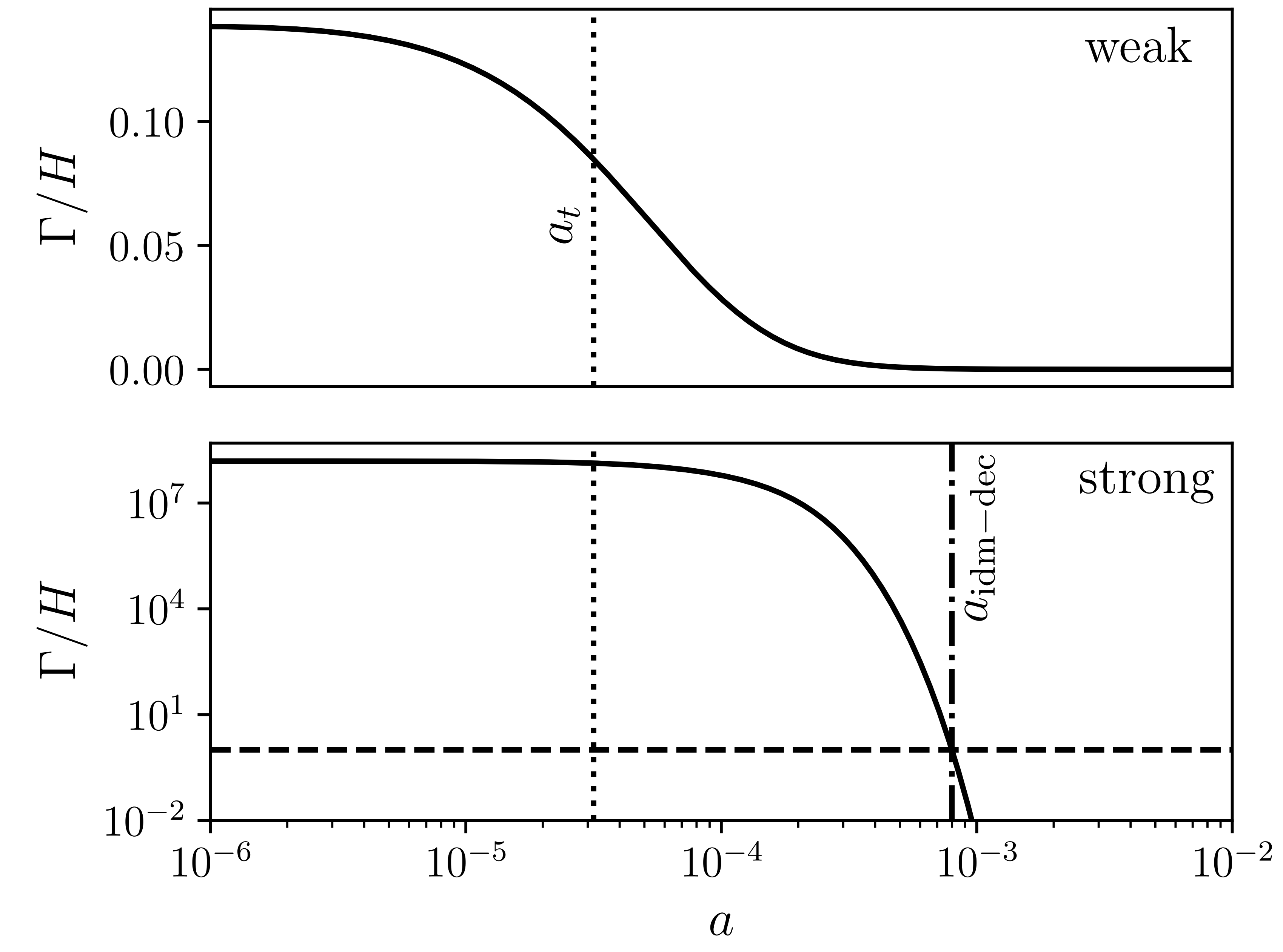
DAO models (SpartAcous, νADM)

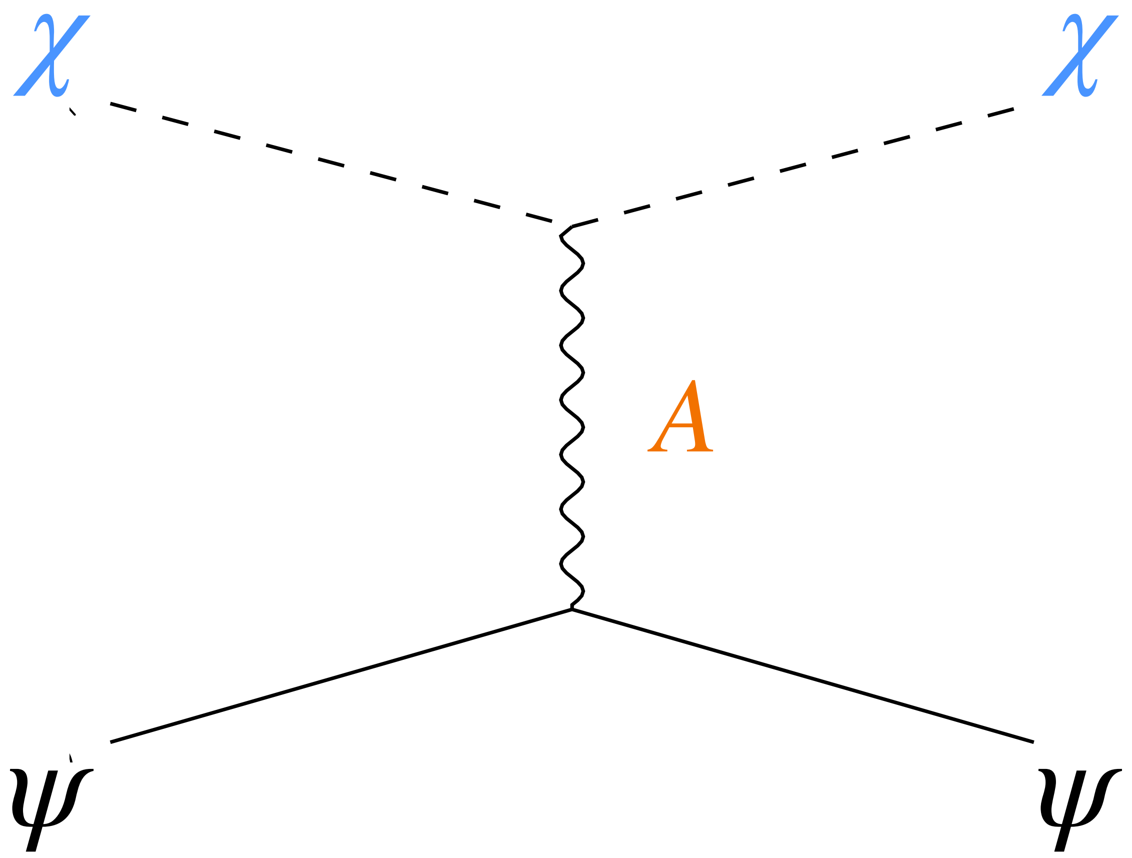


N. Schöneberg et al. [arXiv:2306.12469]

Dark Matter interaction with DR

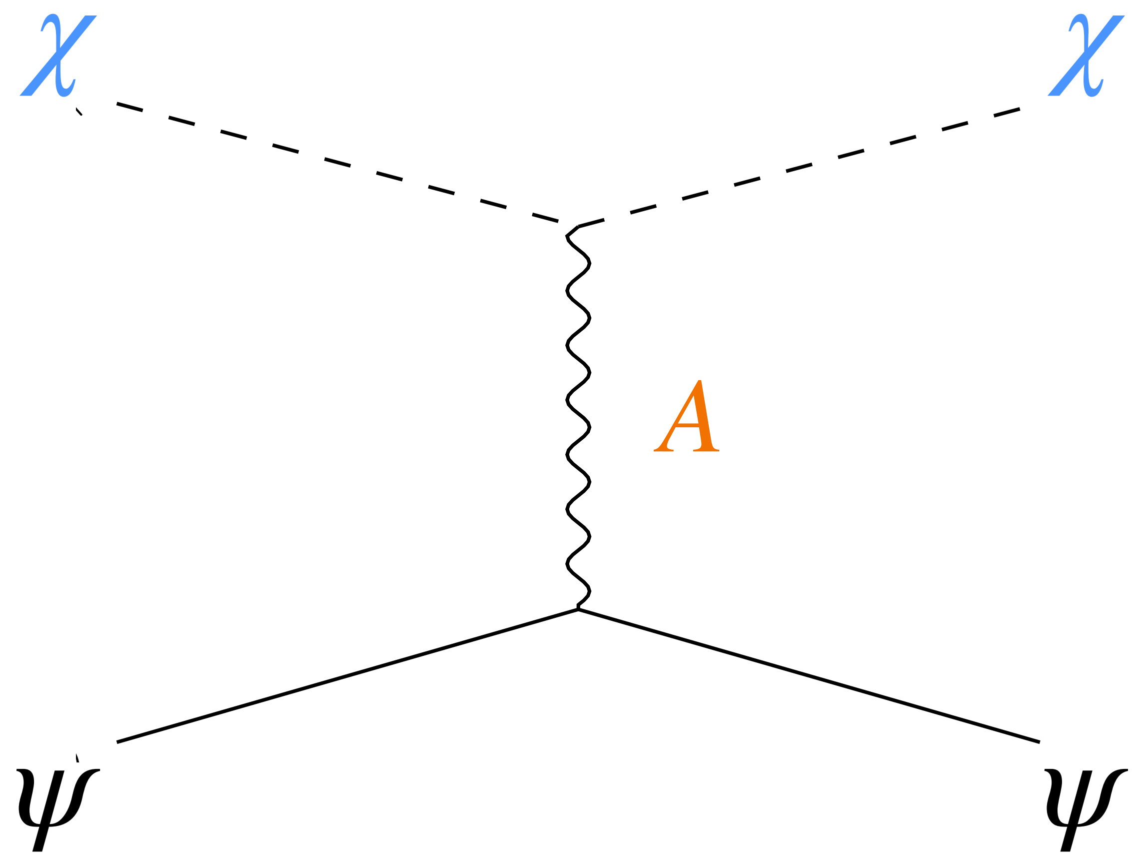
Impacts on Matter / CMB Power Spectrum

Weak

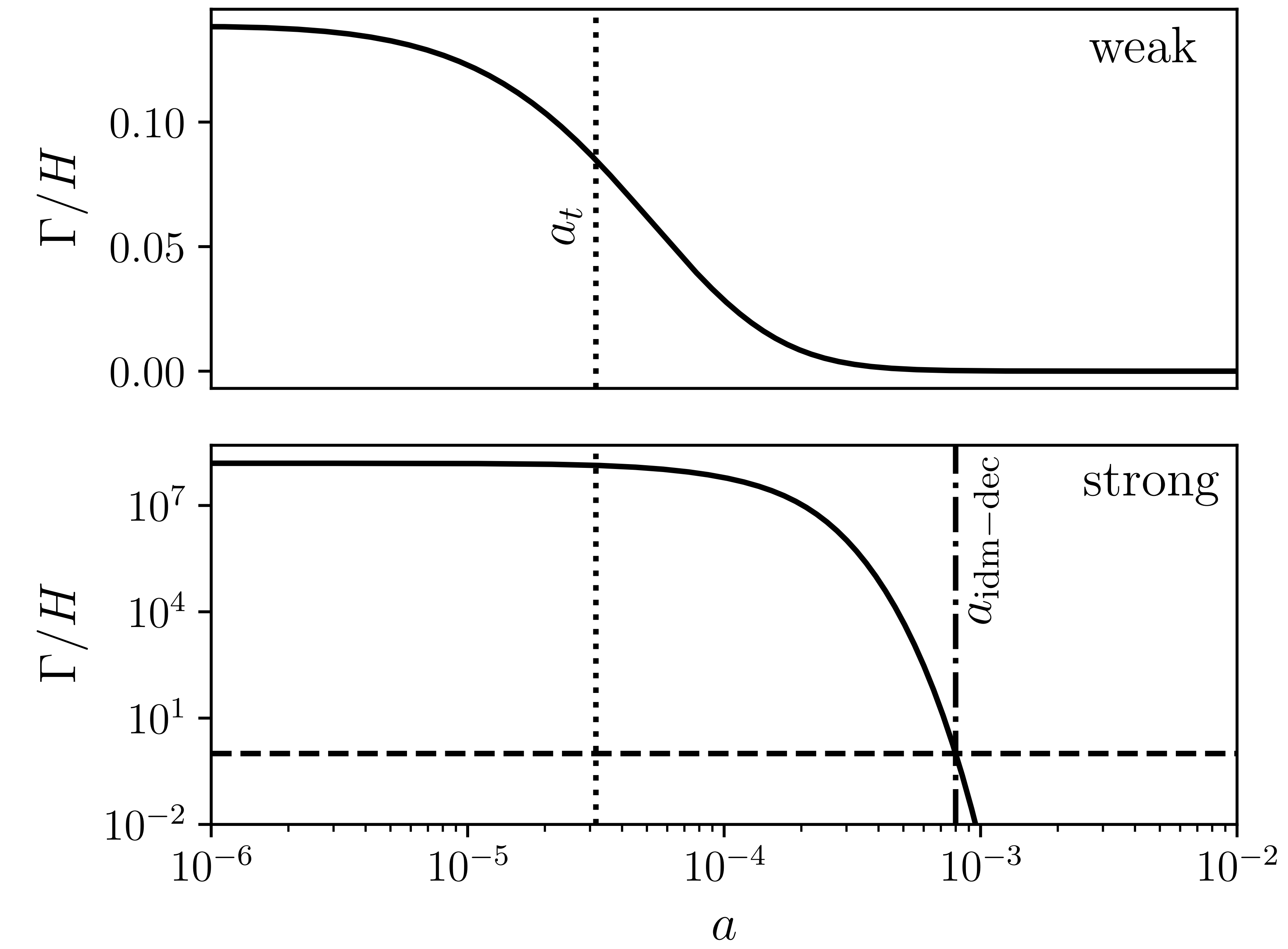


Massive A

Strong



Massive ψ

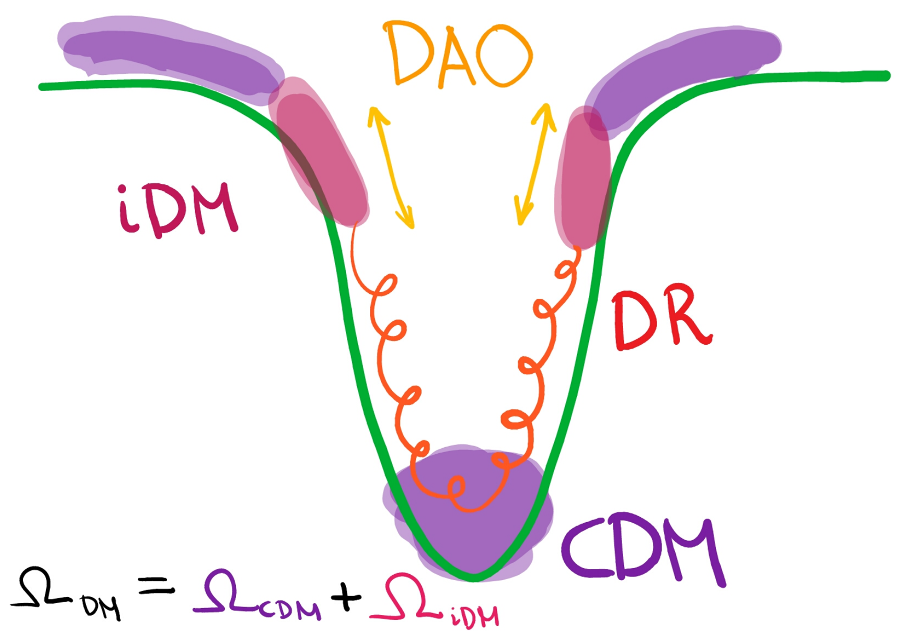


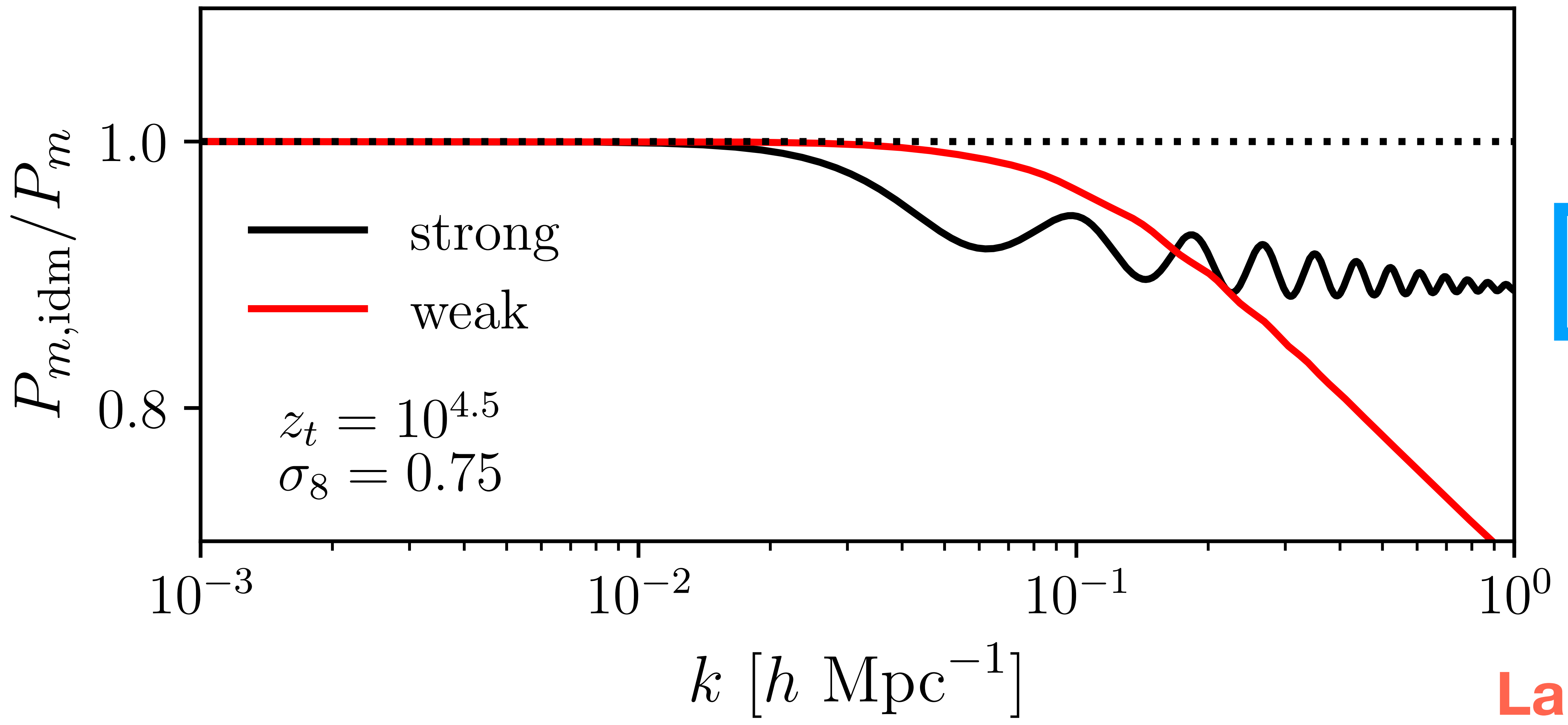
N. Schöneberg et al. [arXiv:2306.12469]

ψ, A $\in$ Self-interacting DR

Dark Matter interaction with DR

Impacts on Matter / CMB Power Spectrum





Dark Acoustic Oscillations

Large suppression at high k

Weak: Only slowing down growth → the longer inside the horizon, the larger suppression

N. Schöneberg et al. [arXiv:2306.12469]

Strong: No structure growth until decoupling, all modes grows by the same amount

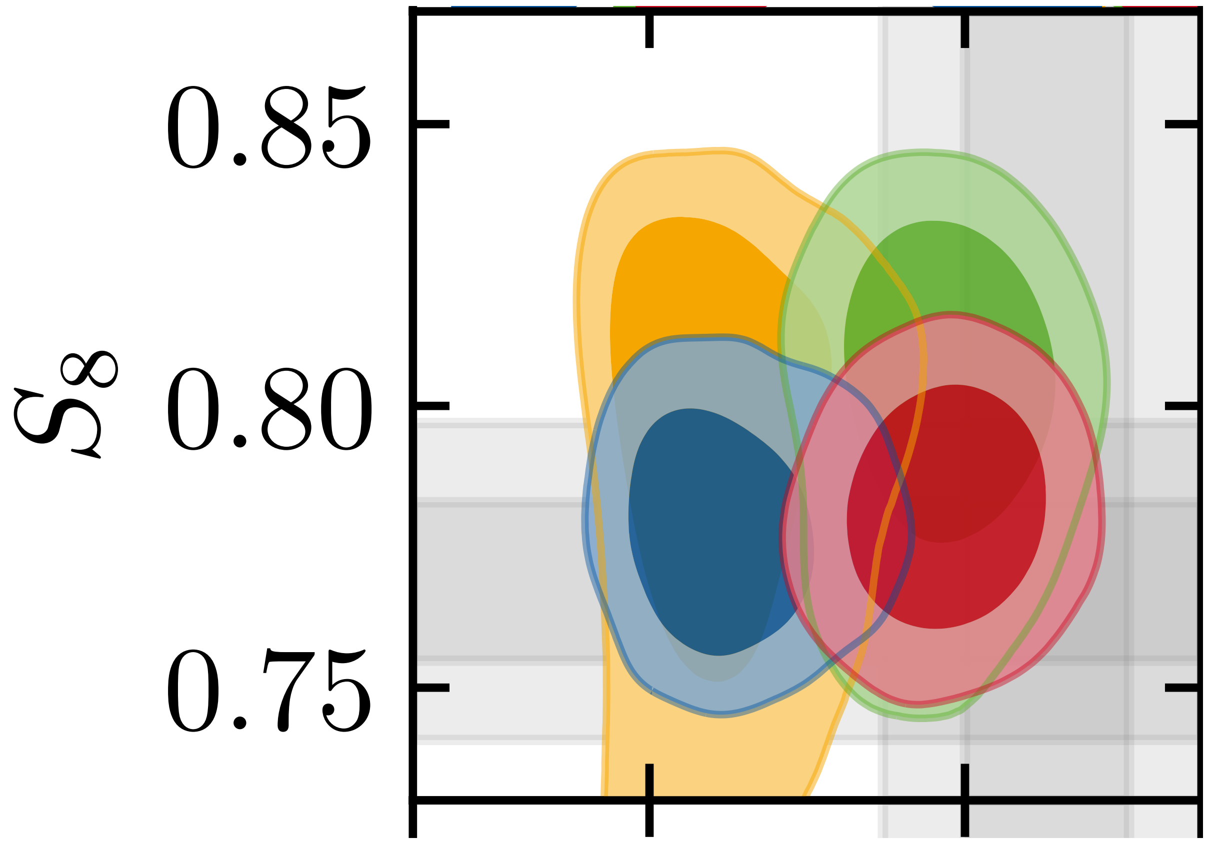
Markov Chain Monte Carlo (MCMC)

Results

Data:

Plank high ℓ TTTEEE, Planck low ℓ EE, Planck low ℓ TT, Plank lensing, BAO eBOSS DR16, BAO small z, PANTHEON+, SH0ES, KIDS-1000x, DES-Y3

Weak (with step)



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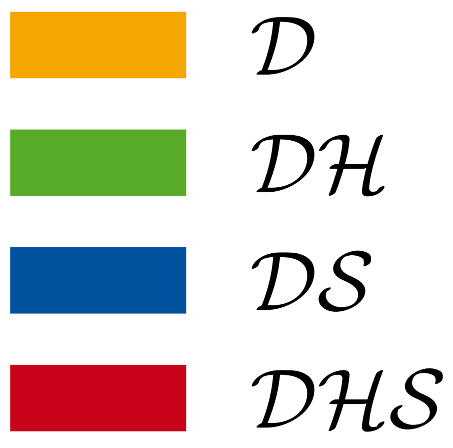
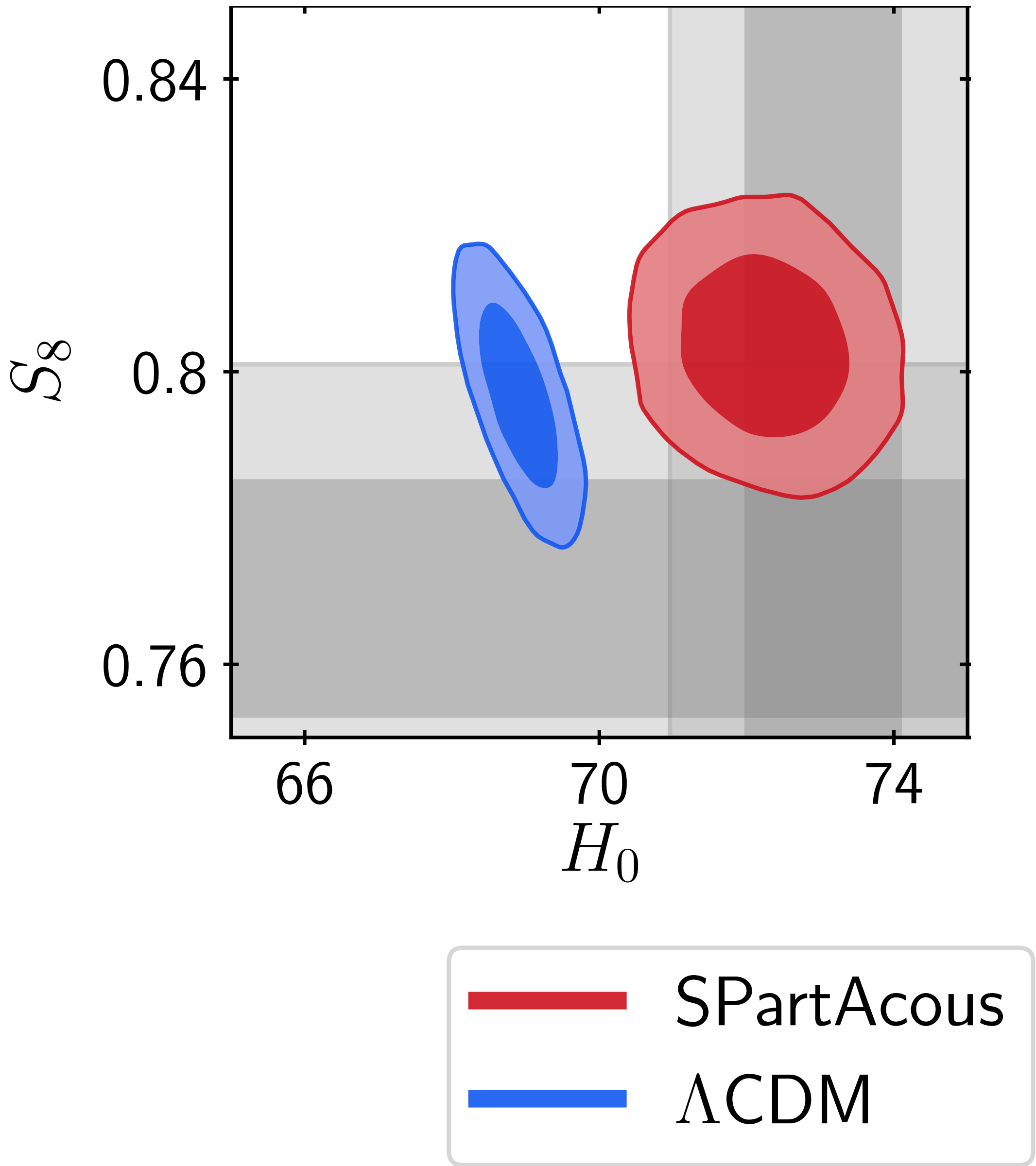


Strong (SPartAcous+)



Best fit

Model	$\Delta\chi^2$	ΔAIC	H_0	S_8
LCDM	-	-	68.94	0.7972
Weak	-25.78	-19.78	71.84	0.792
Strong	-24.56	-18.56	72.26	0.8036

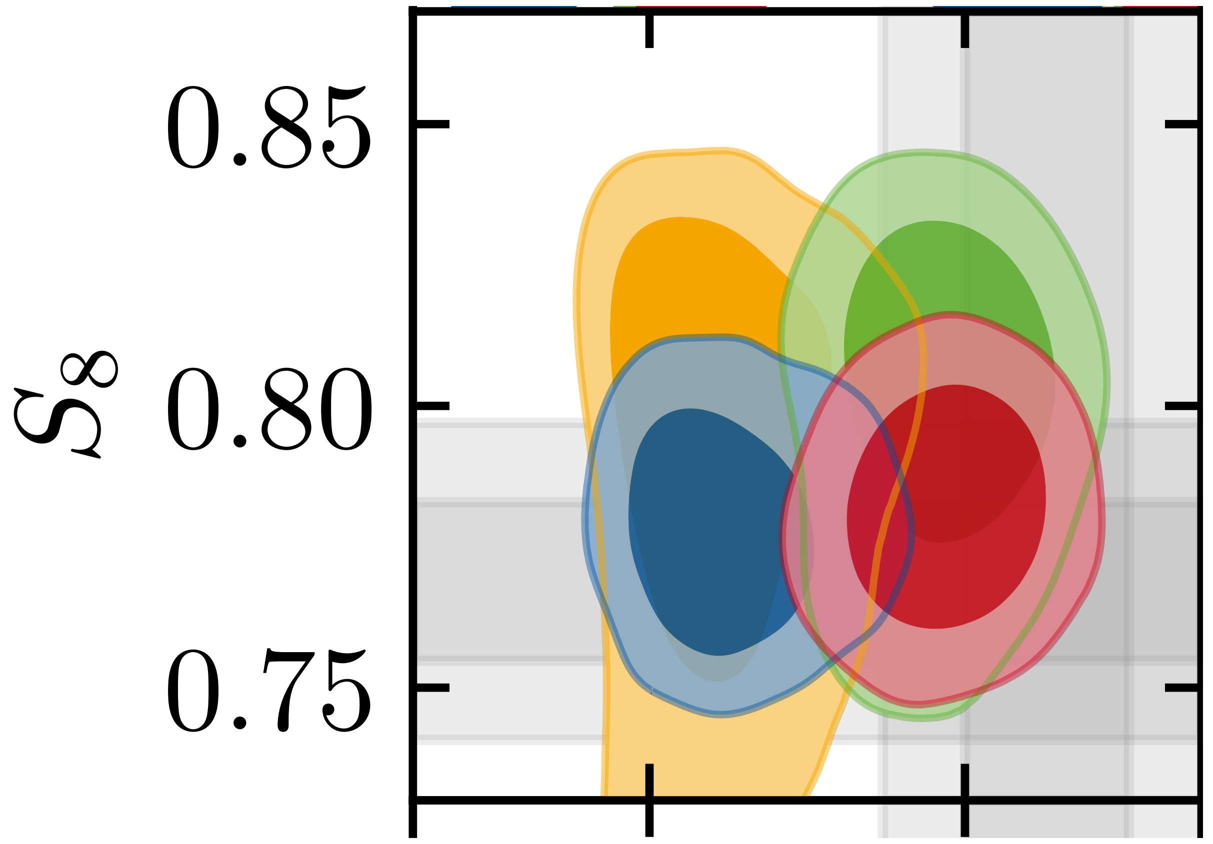
Markov Chain Monte Carlo (MCMC)

Results

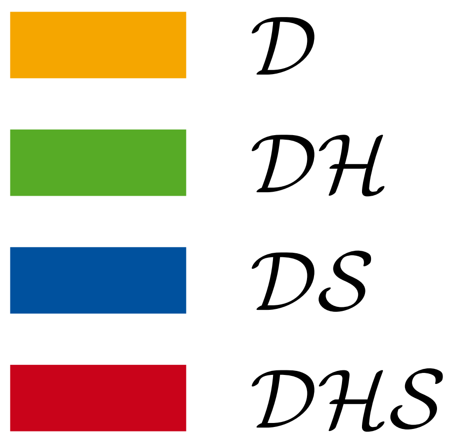
Data:

Plank high ℓ TTTEEE, Planck low ℓ EE, Planck low ℓ TT, Plank lensing, BAO eBOSS DR16, BAO small z, PANTHEON+, SH0ES, KIDS-1000x, DES-Y3

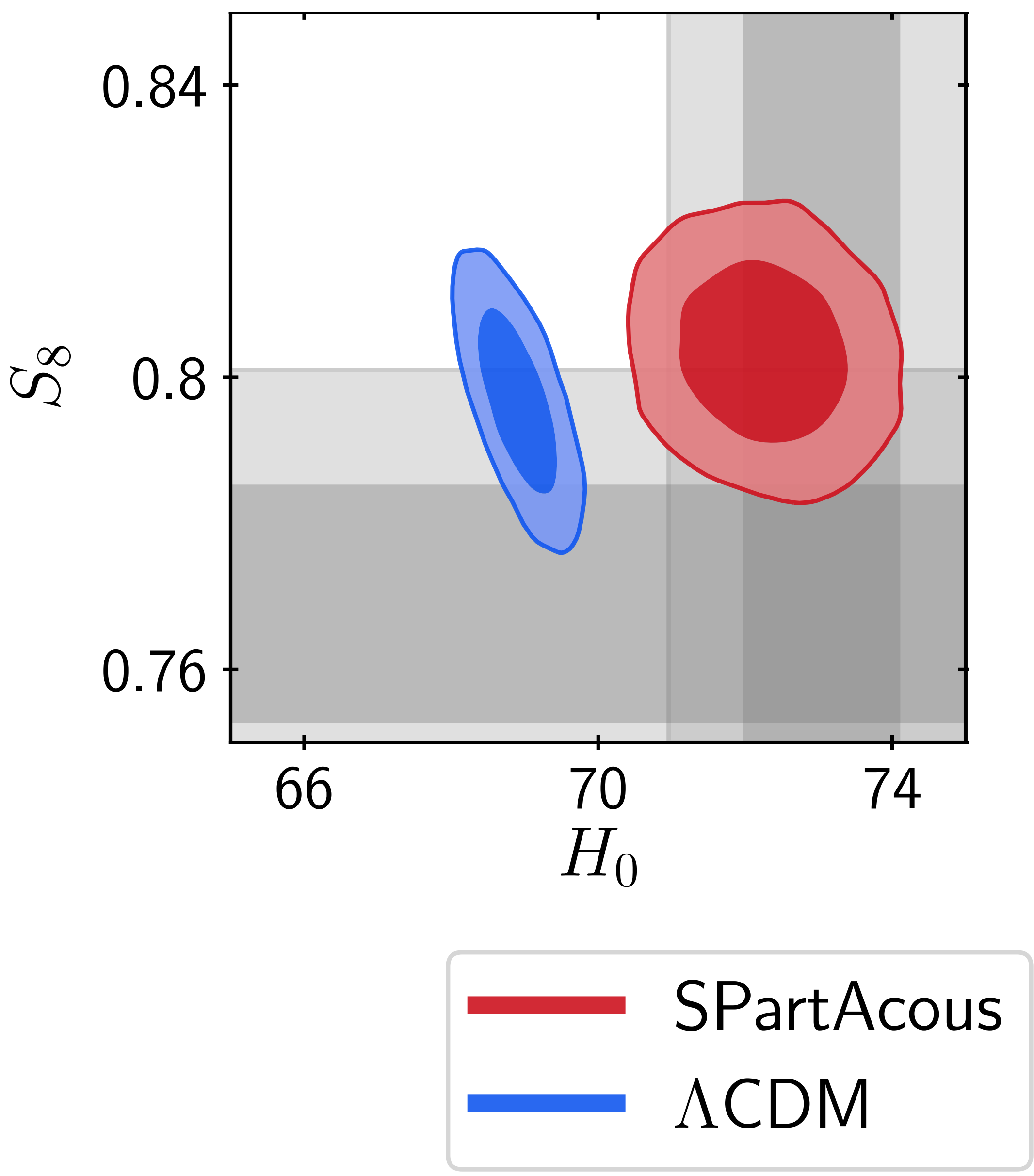
Weak (with step)



N. Schöneberg et al. [arXiv:2306.12469]



Strong (SPartAcous+)



Best fit

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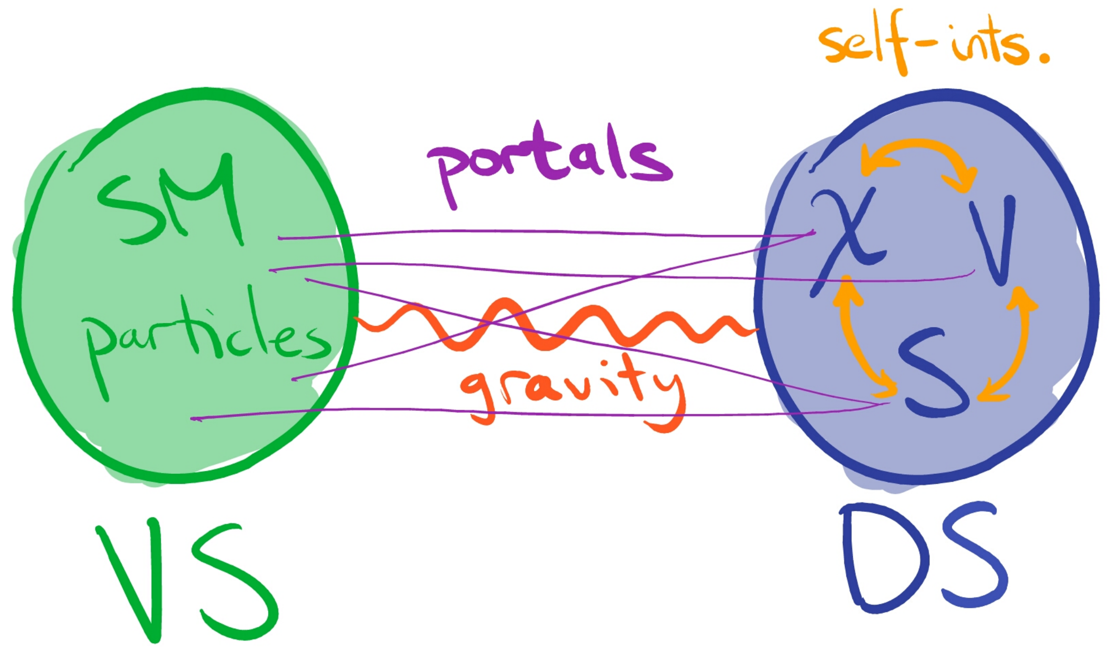
LCDM	-	-	68.94	0.7972
Weak	-25.78	-19.78	71.84	0.792
Strong	-24.56	-18.56	72.26	0.8036

DAO alone takes of both tensions

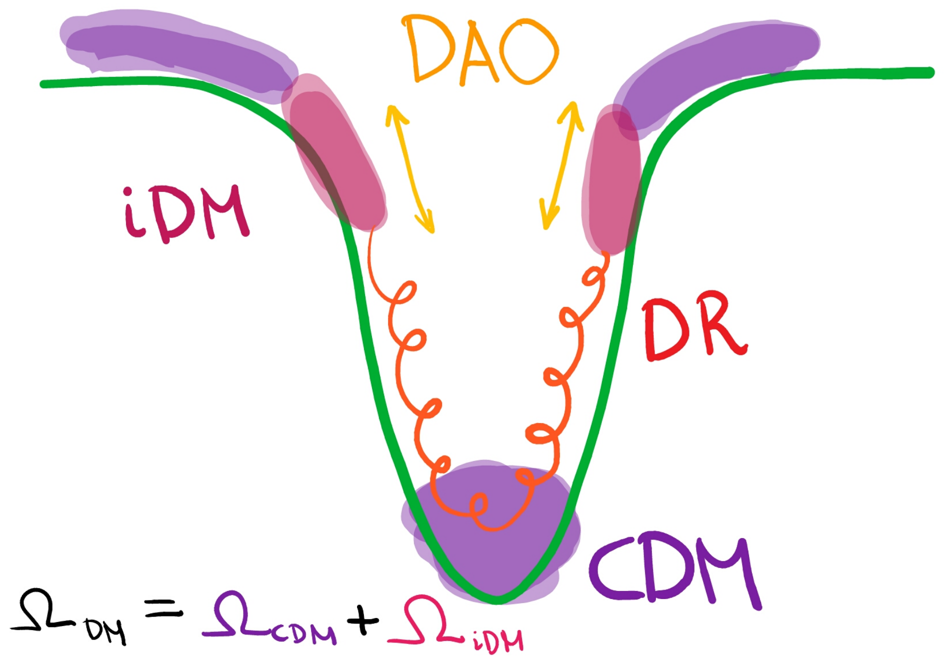
Conclusions

Summary and Outlook



Non-trivial DS with LDF is highly motivated

Dark Acoustic Oscillation leave unique signatures on cosmological observables



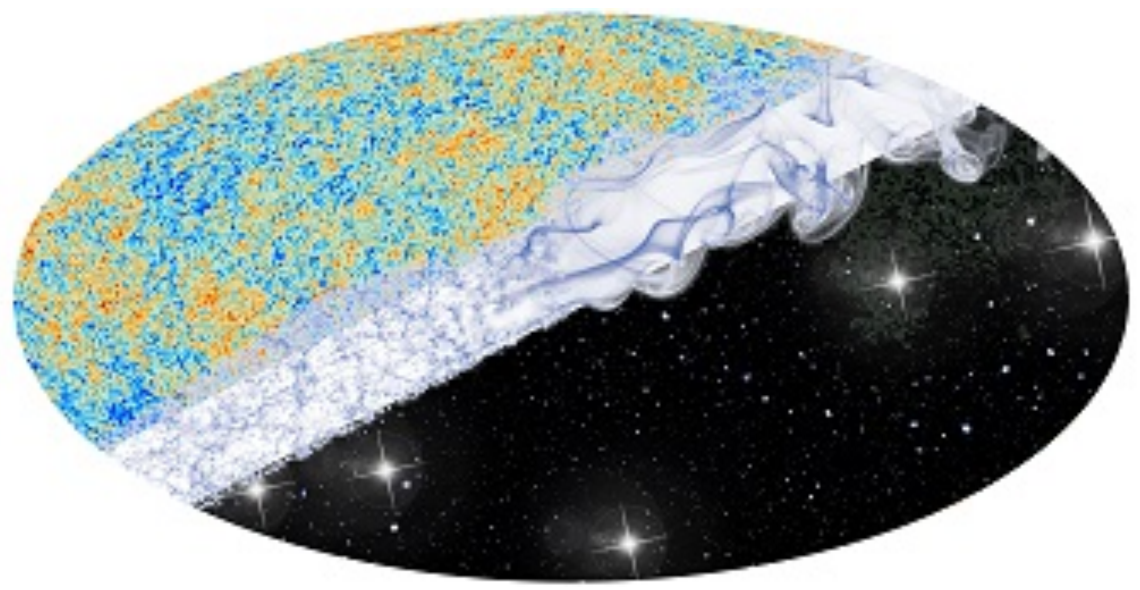
DAO toy models with different iDM-DR interaction switch

SPartAcous (Decay / Annihilation)

νADM (recombination)

DAO as Possible solutions to Hubble / S_8 tensions in ΛCDM

Now fitting EFTofLSS to νADM (entire scale of MPS)

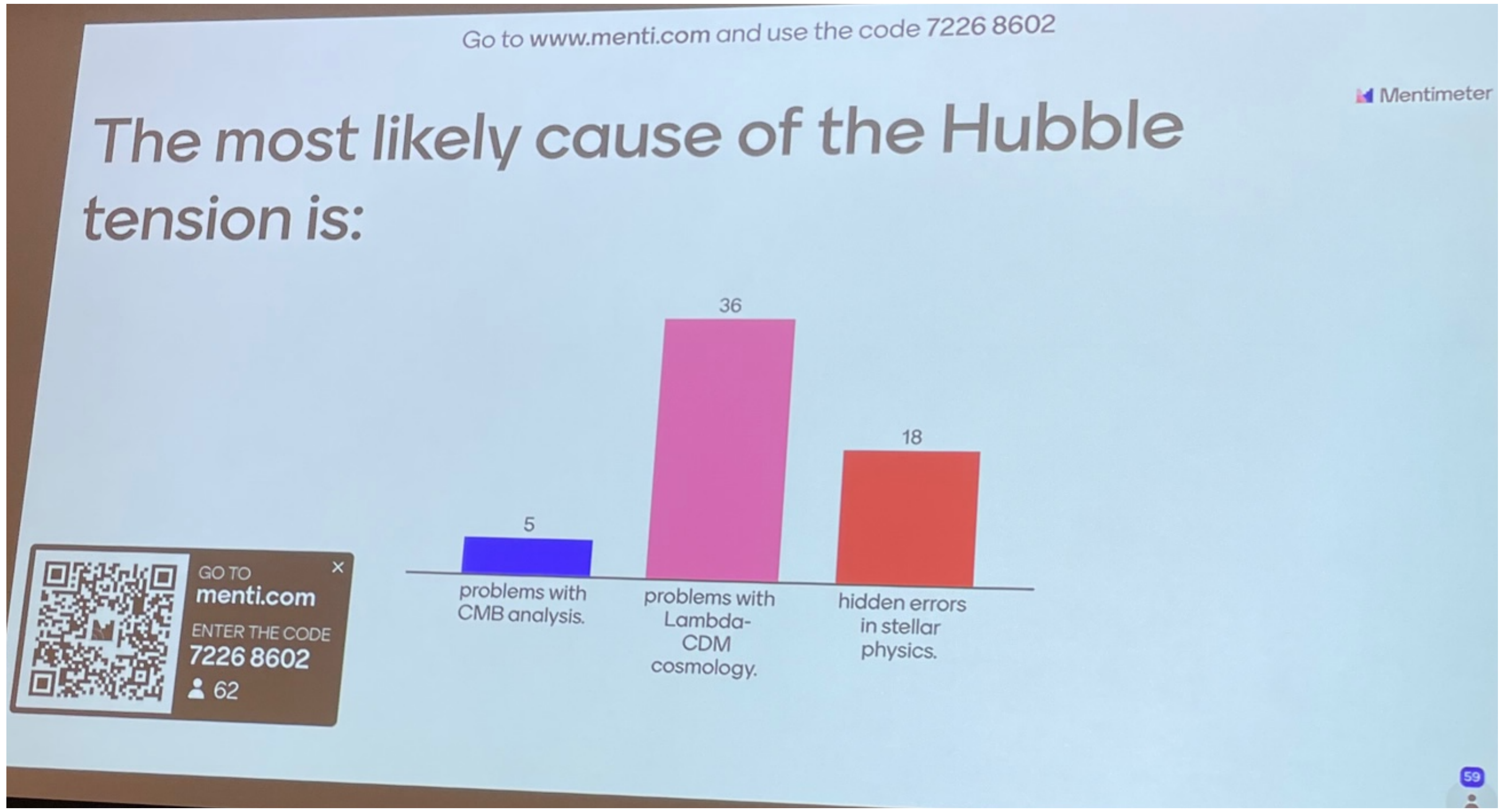


DAO will be probed in the future experiments!

Conclusions

Summary and Outlook

IAU Symposium 376



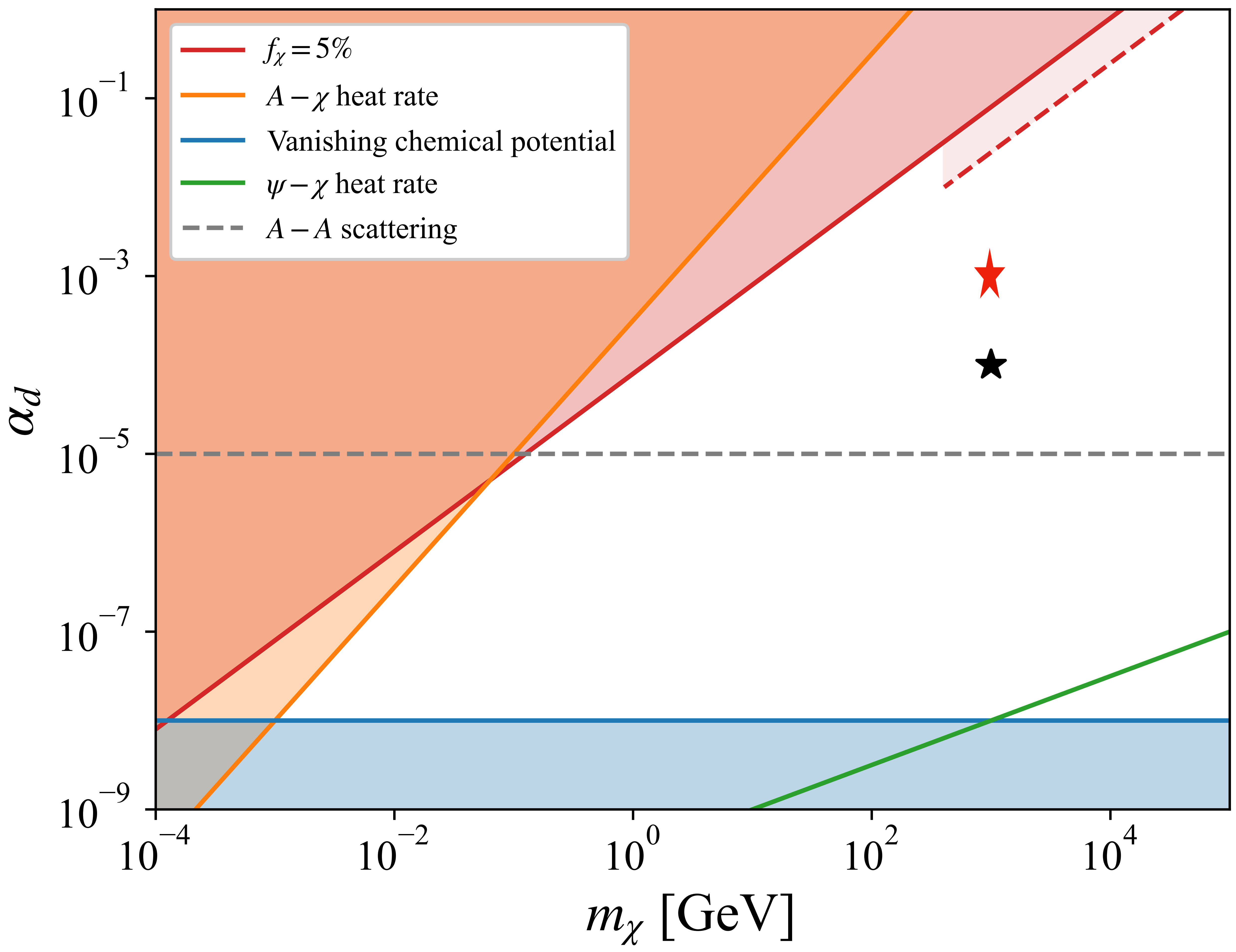
A. Riess and L. Breuval [arXiv:2308.10954]

Thank You for Listening!

Supplements

SPartAcous

Parameter Space



Atomic DM + SIDR

Impact on the CMB

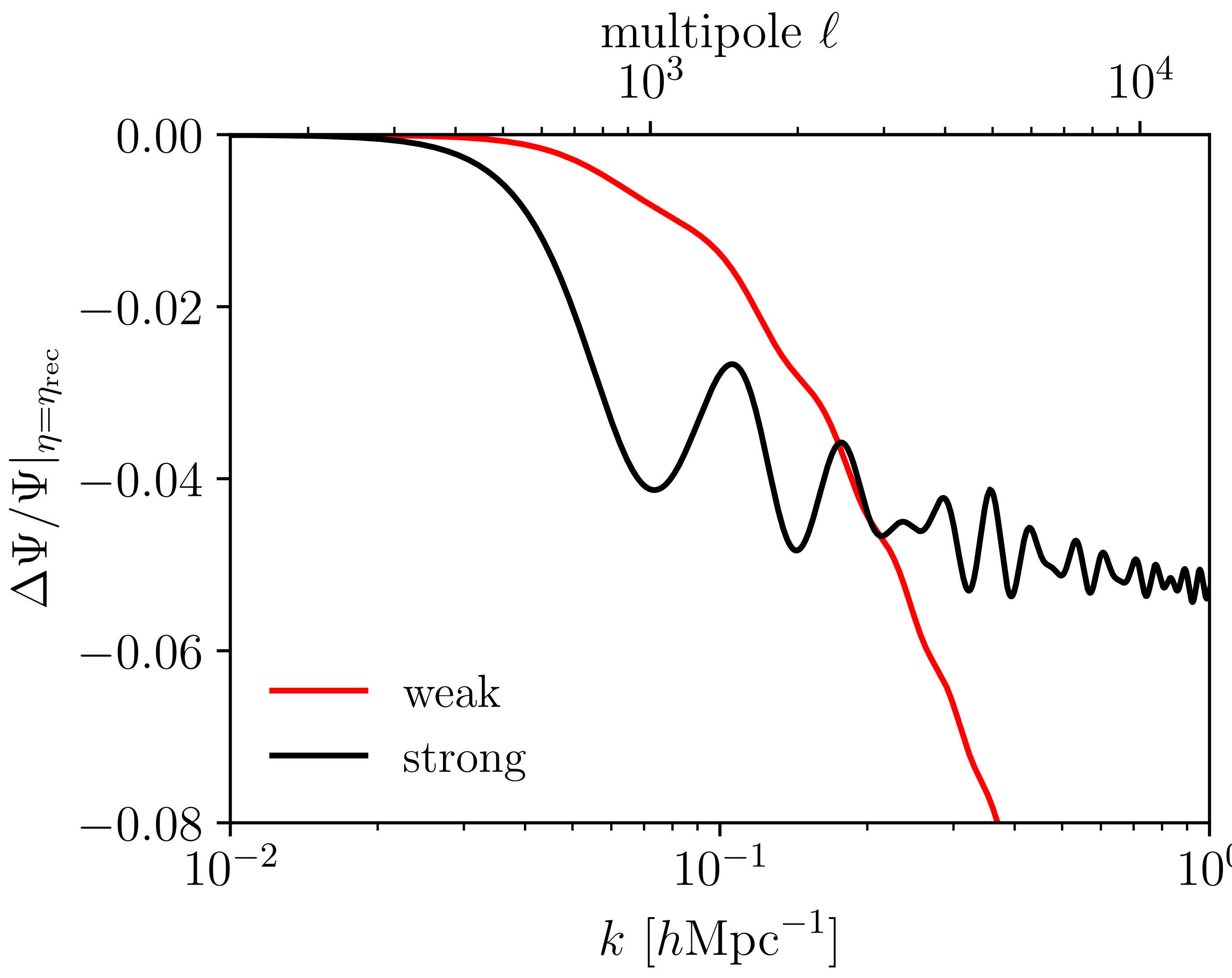
$$\Psi = (\phi + \psi)/2$$

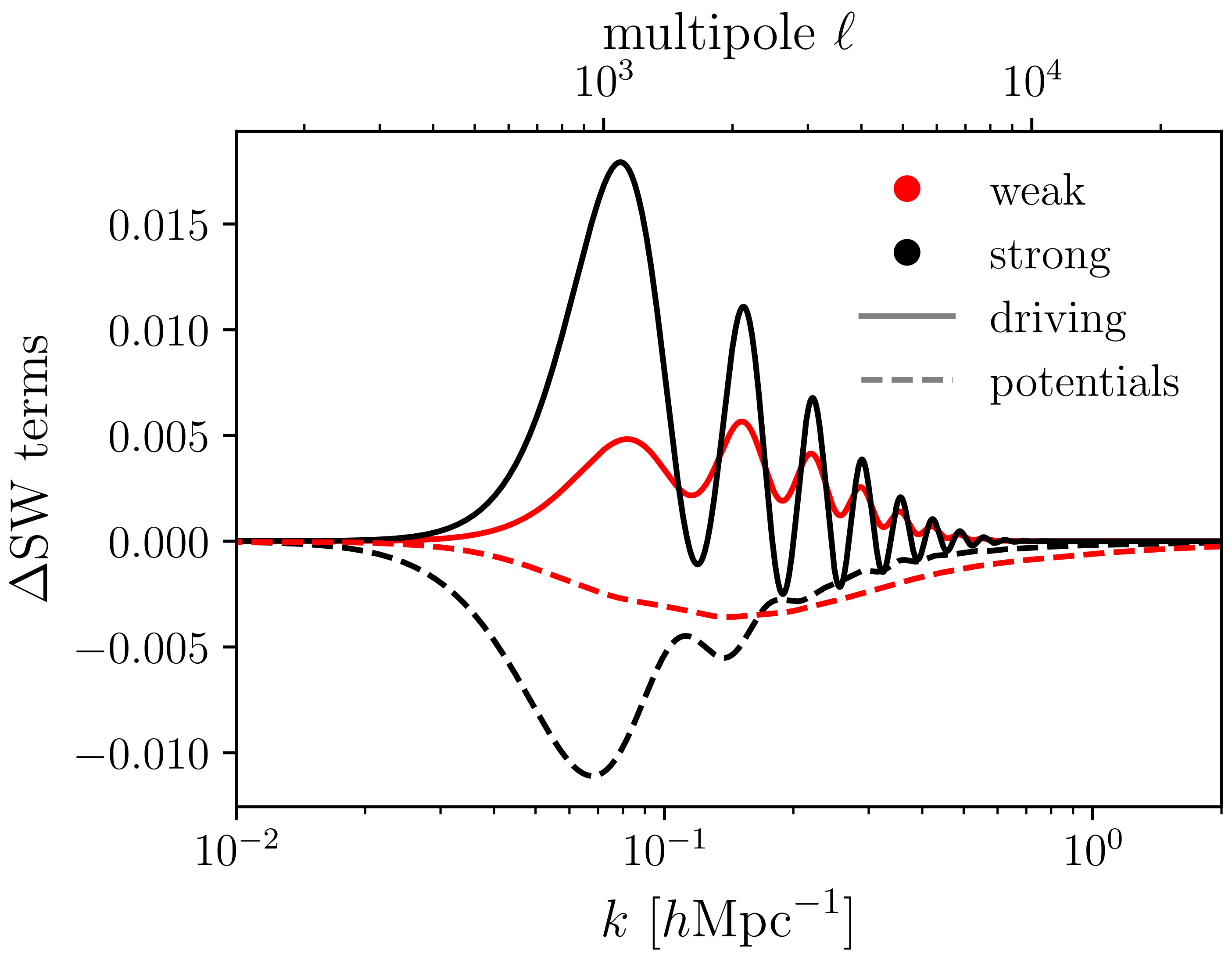
$$r_s(\eta) \simeq \eta/\sqrt{3}$$

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

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

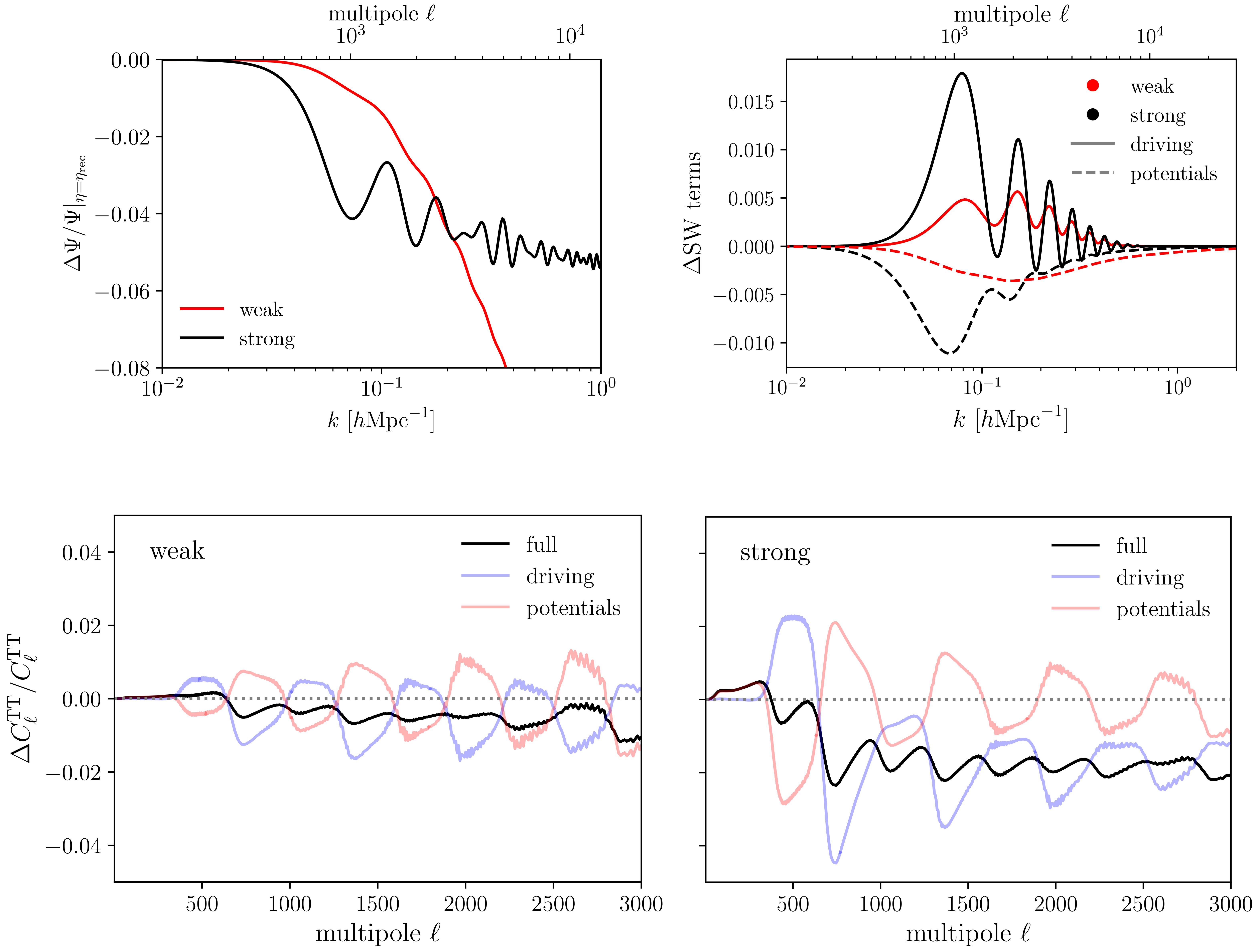
gravitational redshift





$$\ell \simeq k\eta_0$$

N. Schöneberg et al. [arXiv:2306.12469]



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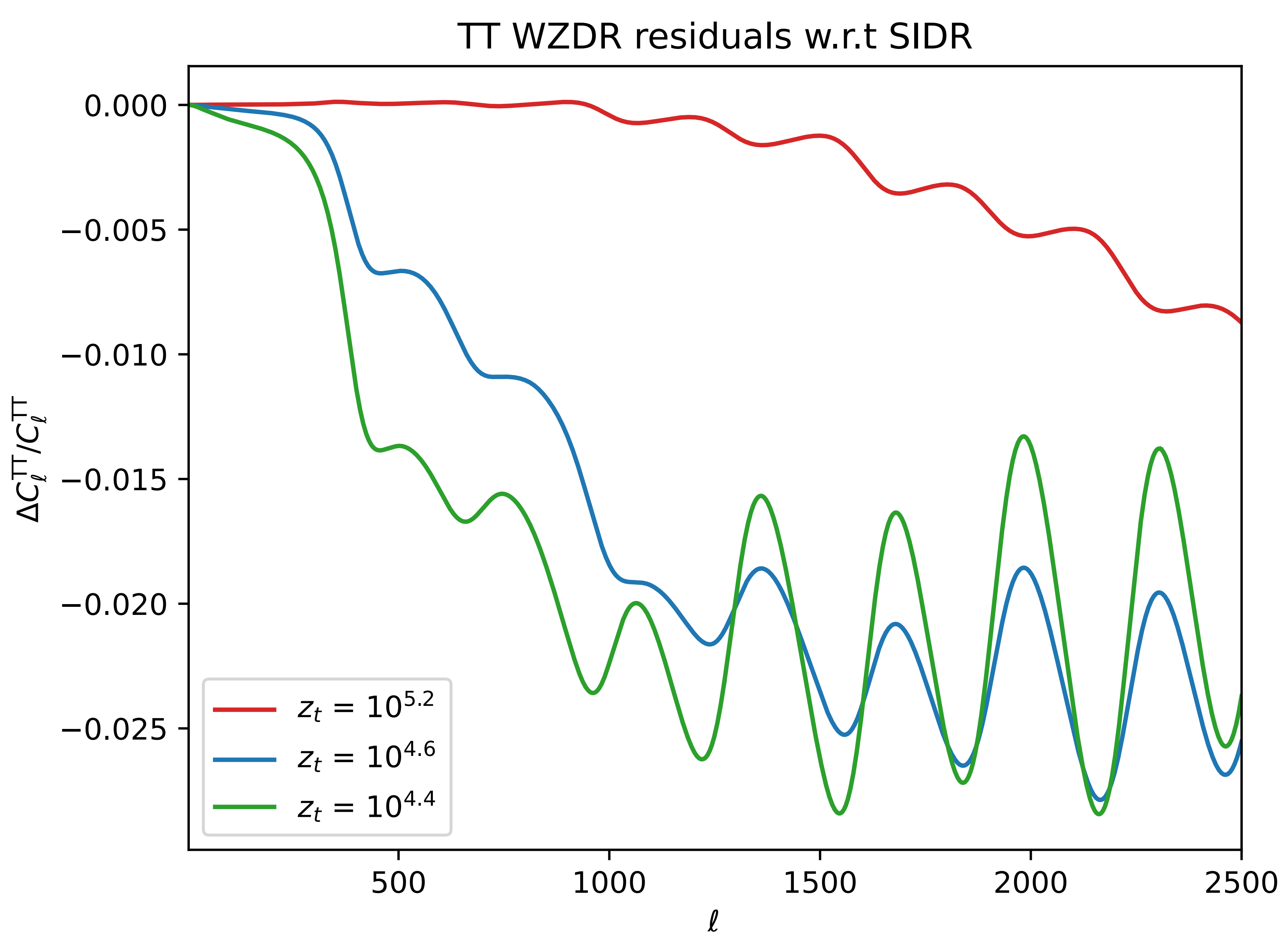
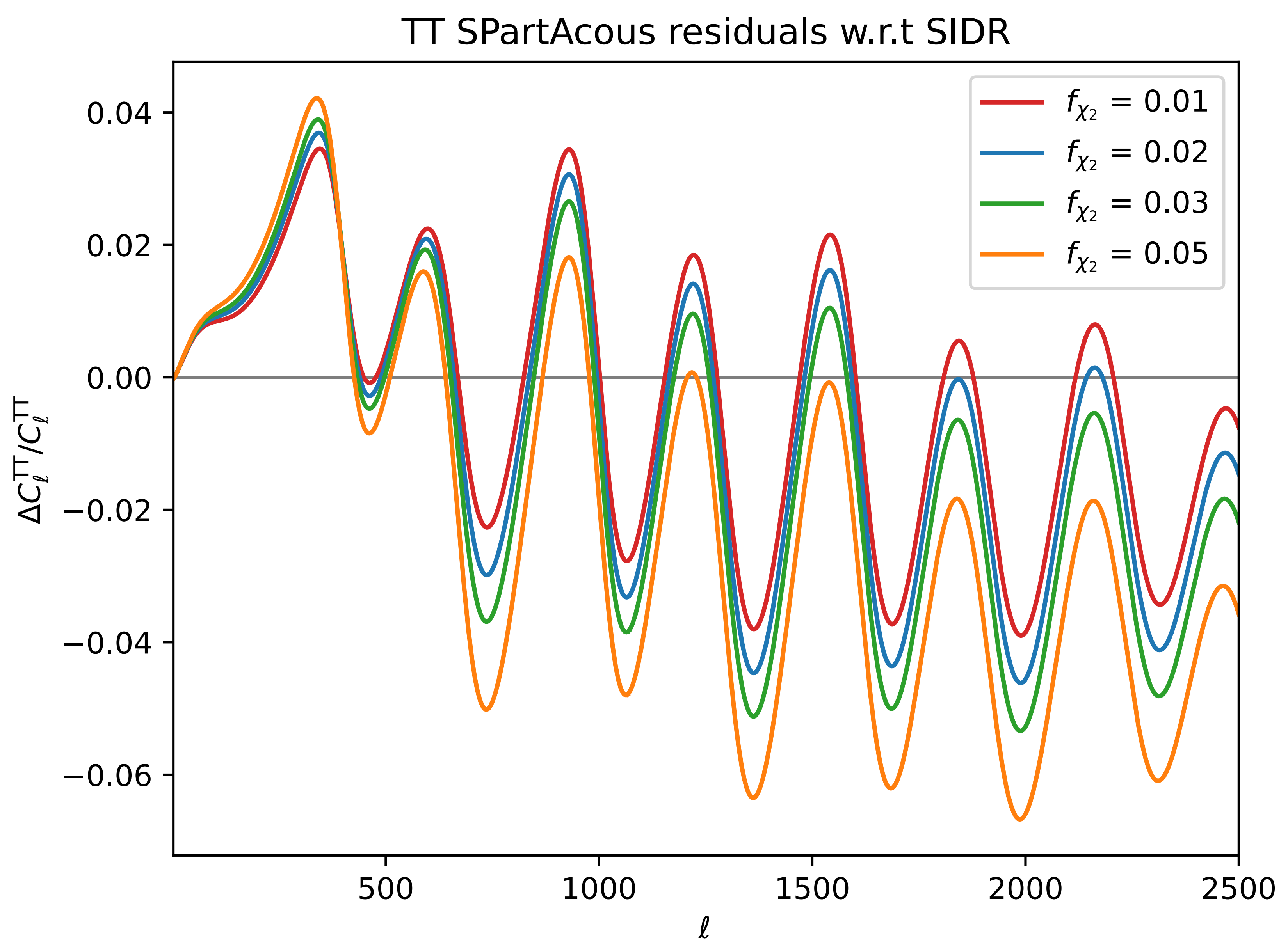
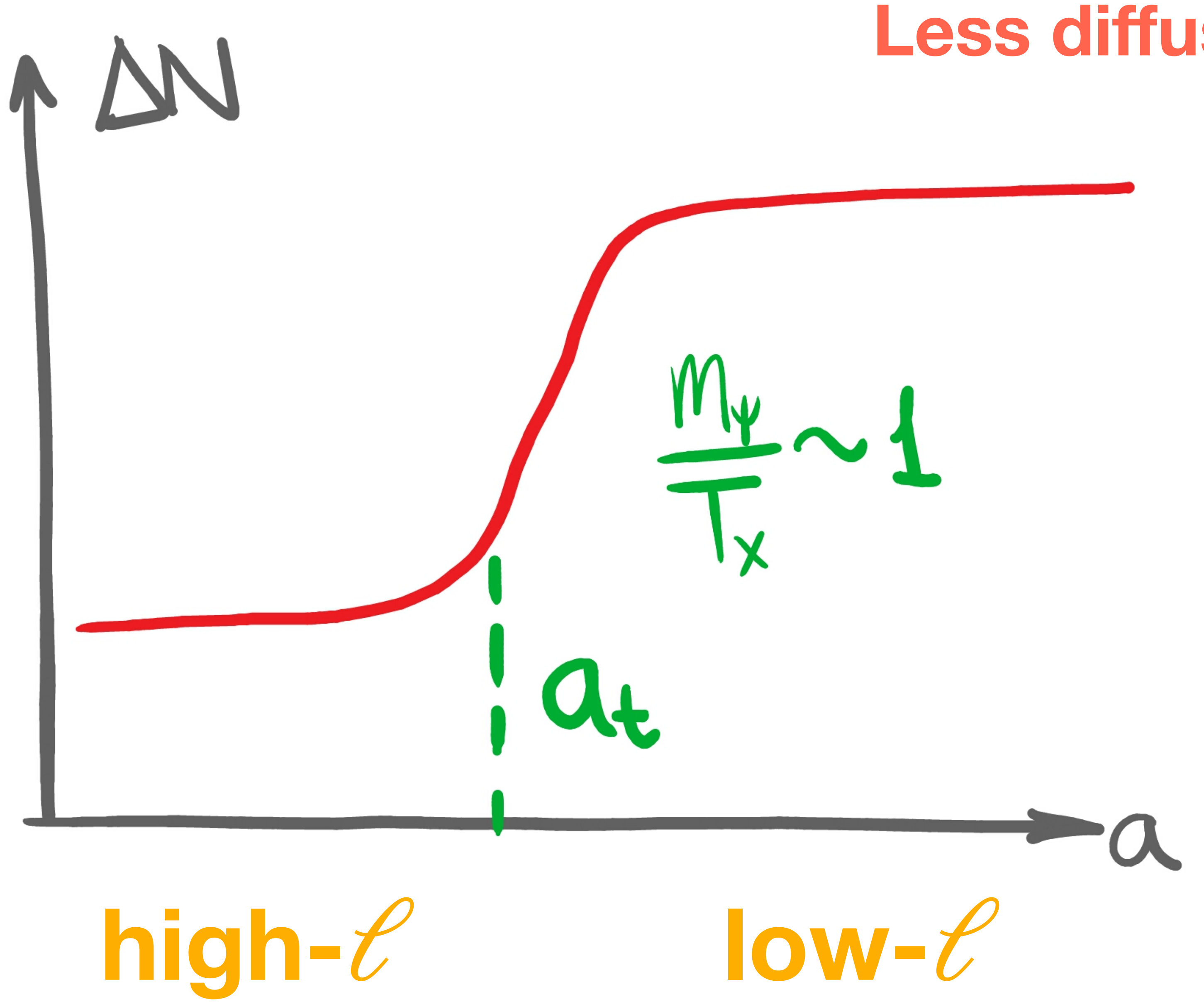
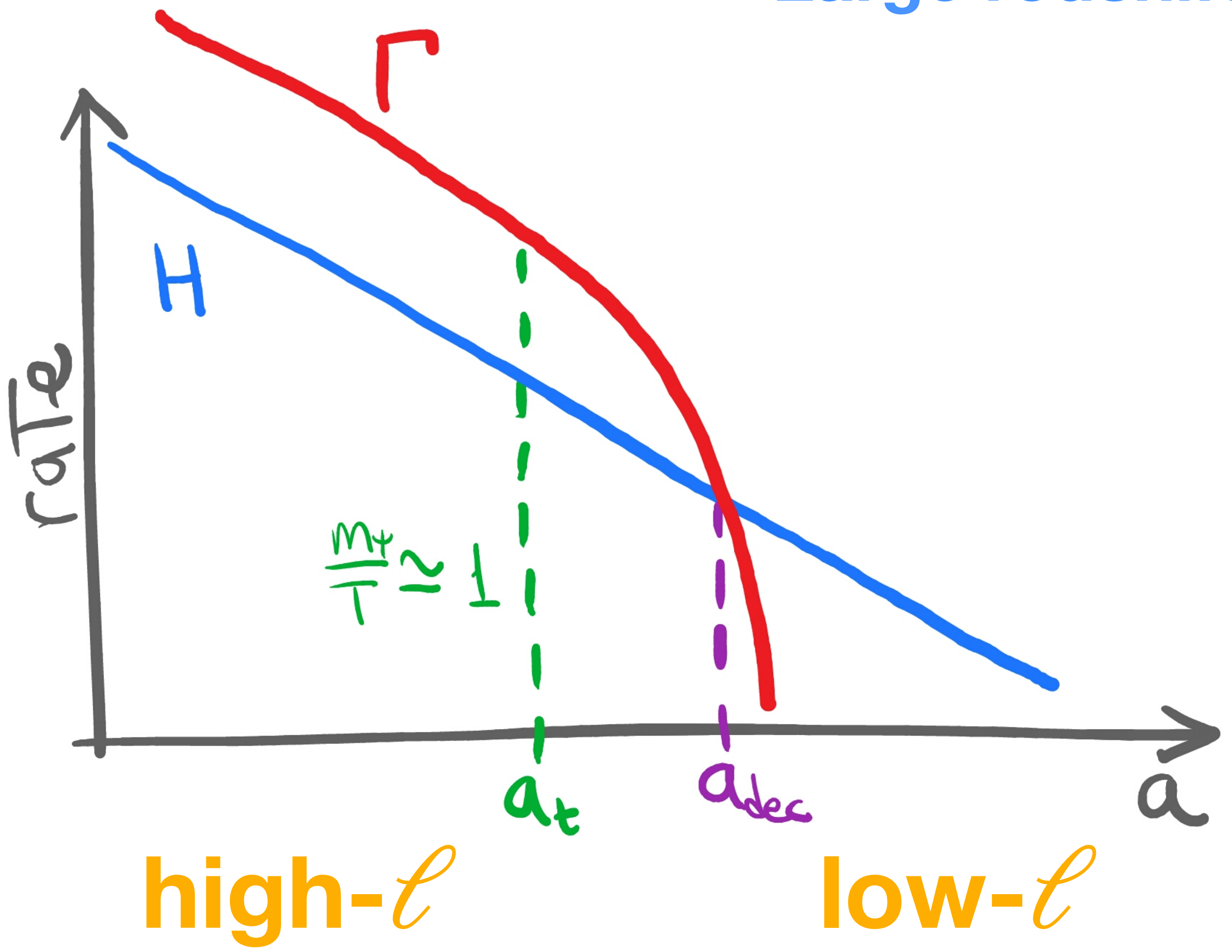




Less diffusion in high-ℓ



Large redshift in high-ℓ

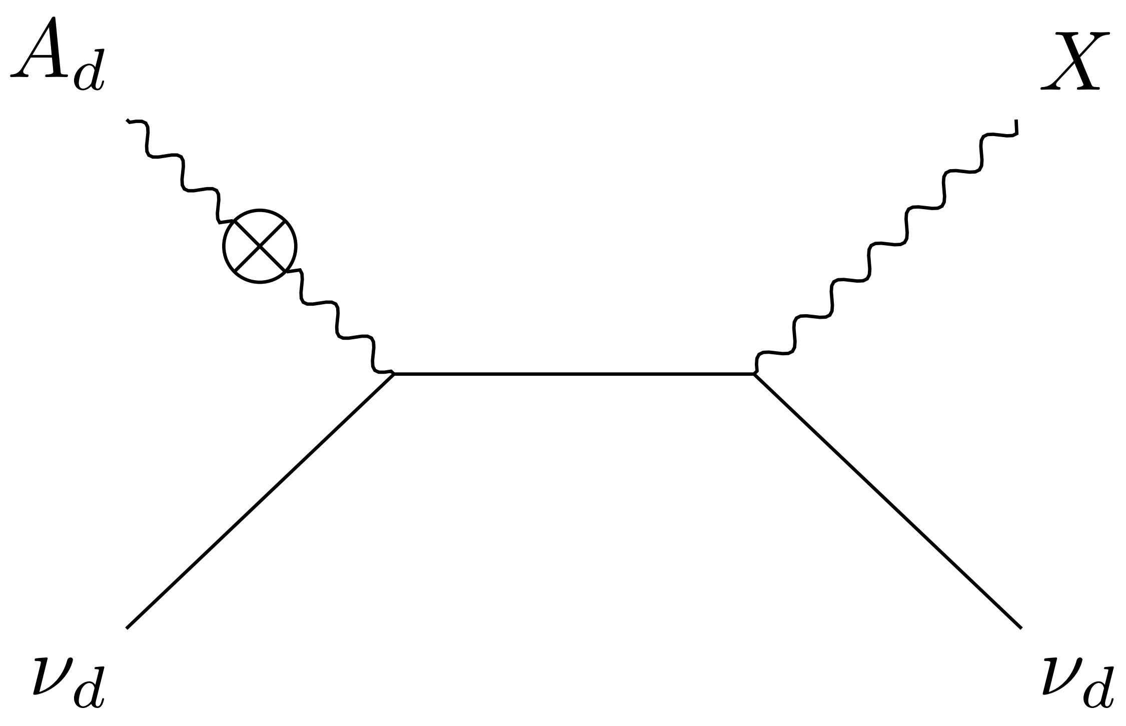


Atomic DM + Dark ν

Requirements

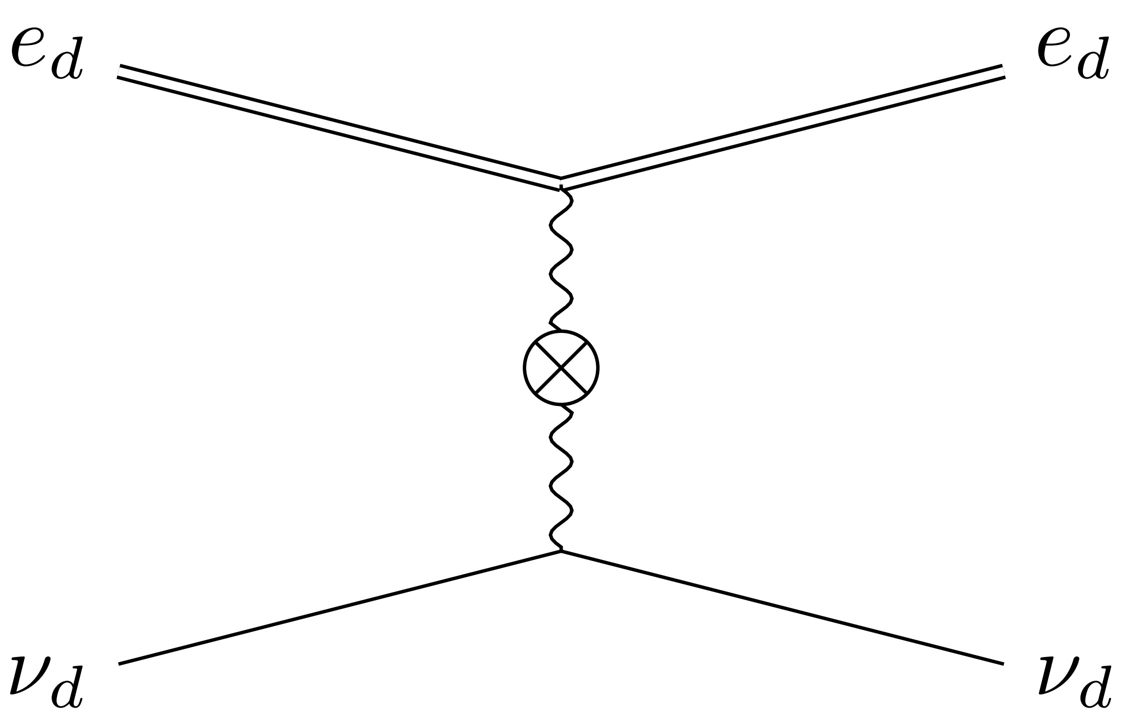
A in equilibrium with ν (DR is self-interacting)

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



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

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



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

SPartAcous

Boltzmann equations

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

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

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

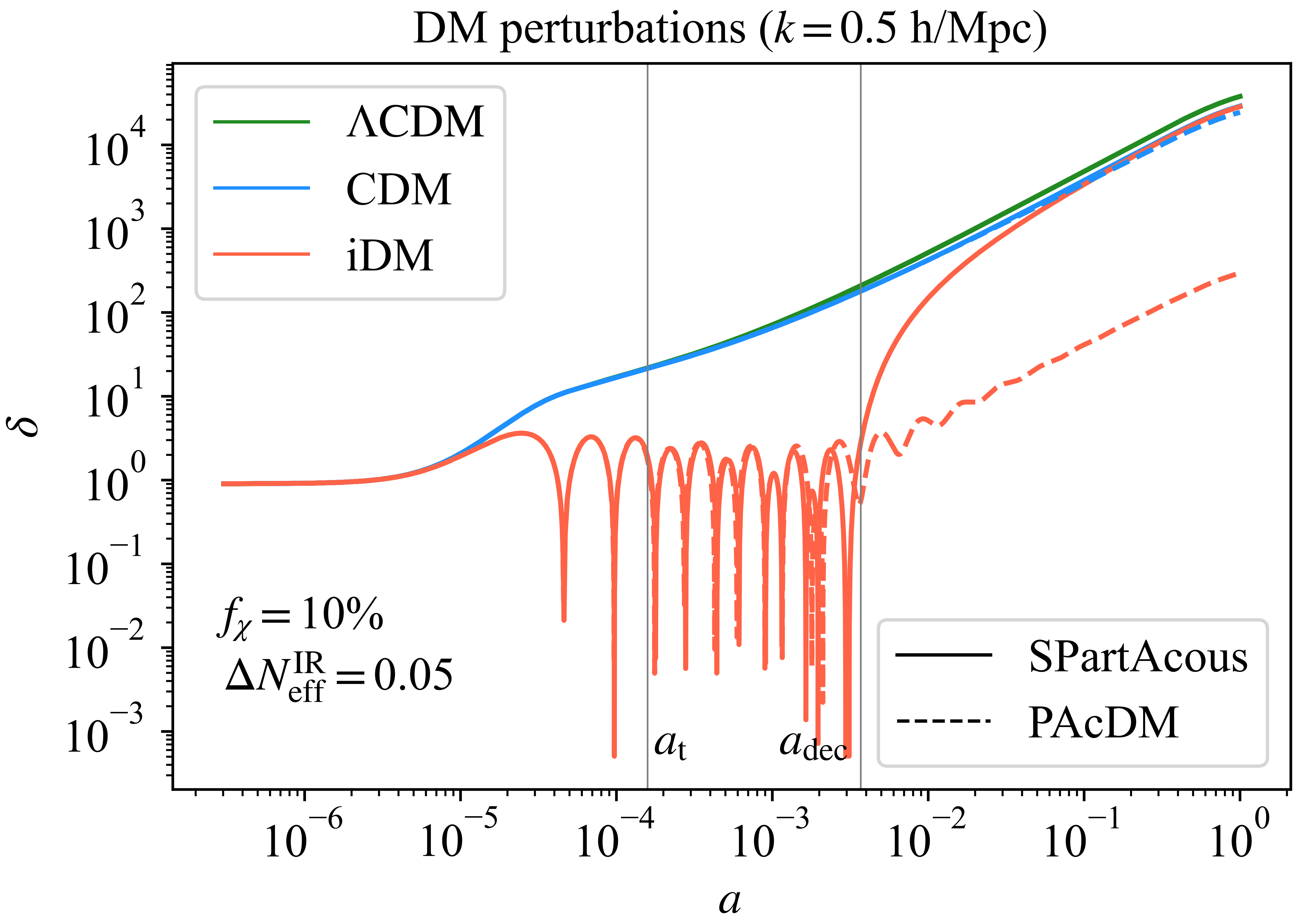
$$\dot{\delta}_{\rm dr} = -(1+w)(\theta_{\rm dr} - 3\dot{\phi}) - 3\mathscr{H}(c_s^2 - w)\delta_{\rm dr}$$

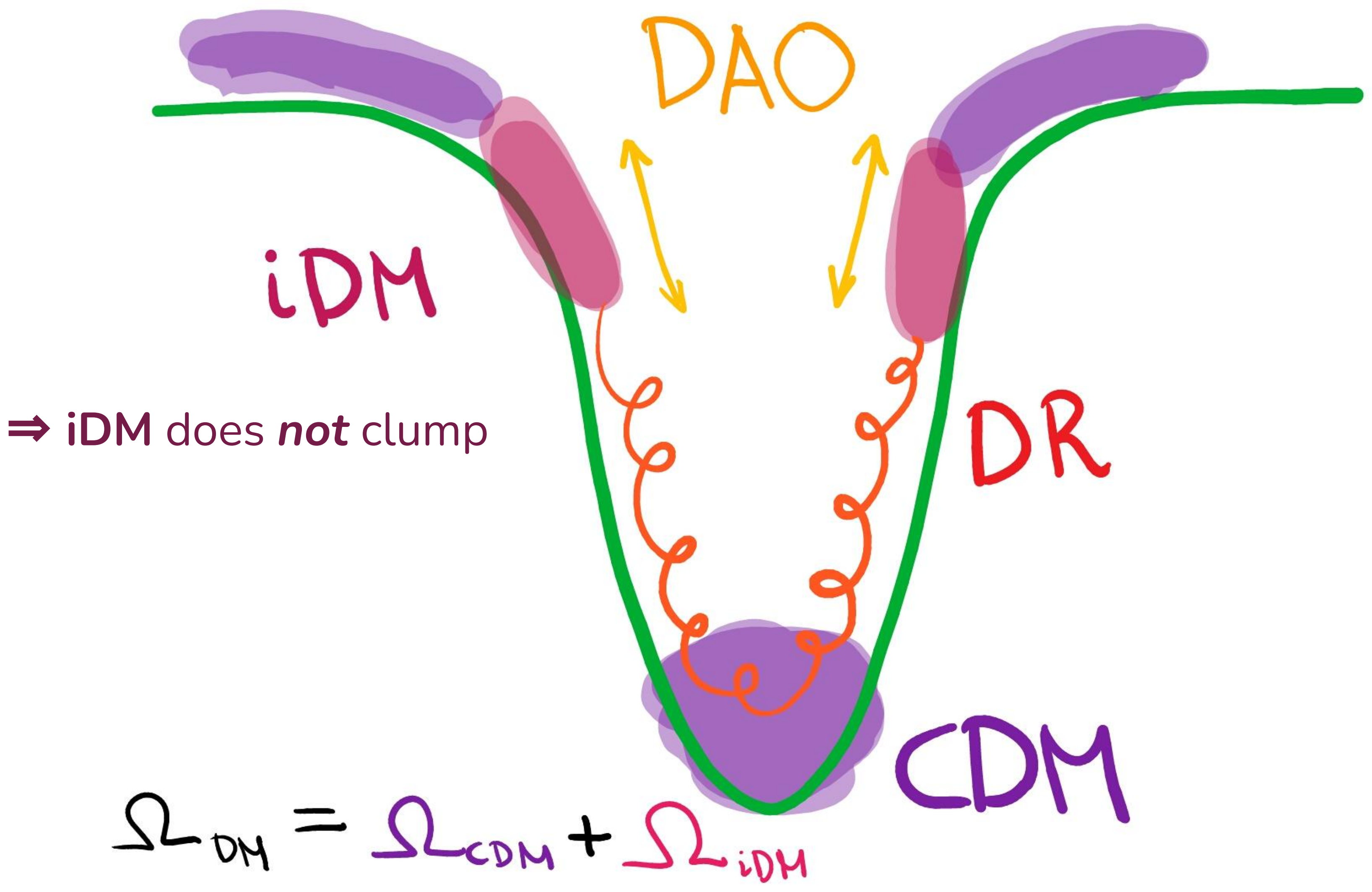
$$\dot{\theta}_{\rm dr} = -\left[(1-3w)\mathscr{H} + \frac{\dot{w}}{1+w}\right]\theta_{\rm dr} + k^2\left(\frac{c_s^2}{1+w}\delta_{\rm dr} + \psi\right) + \frac{\rho_{\rm idm}}{\rho_{\rm dr}(1+w)}a\Gamma(\theta_{\rm idm} - \theta_{\rm dr})$$

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

SPartAcous

Dark Acoustic Oscillations

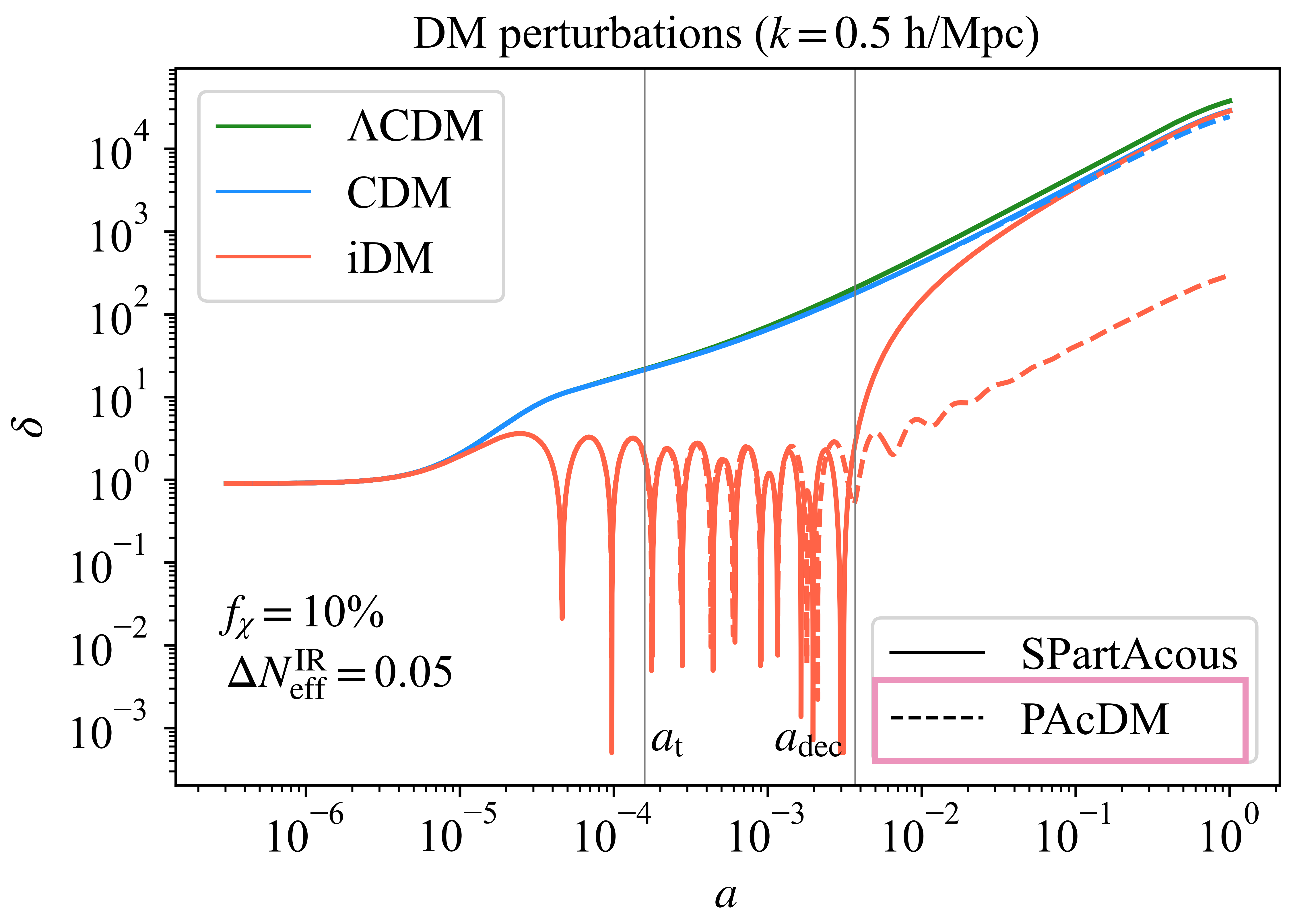


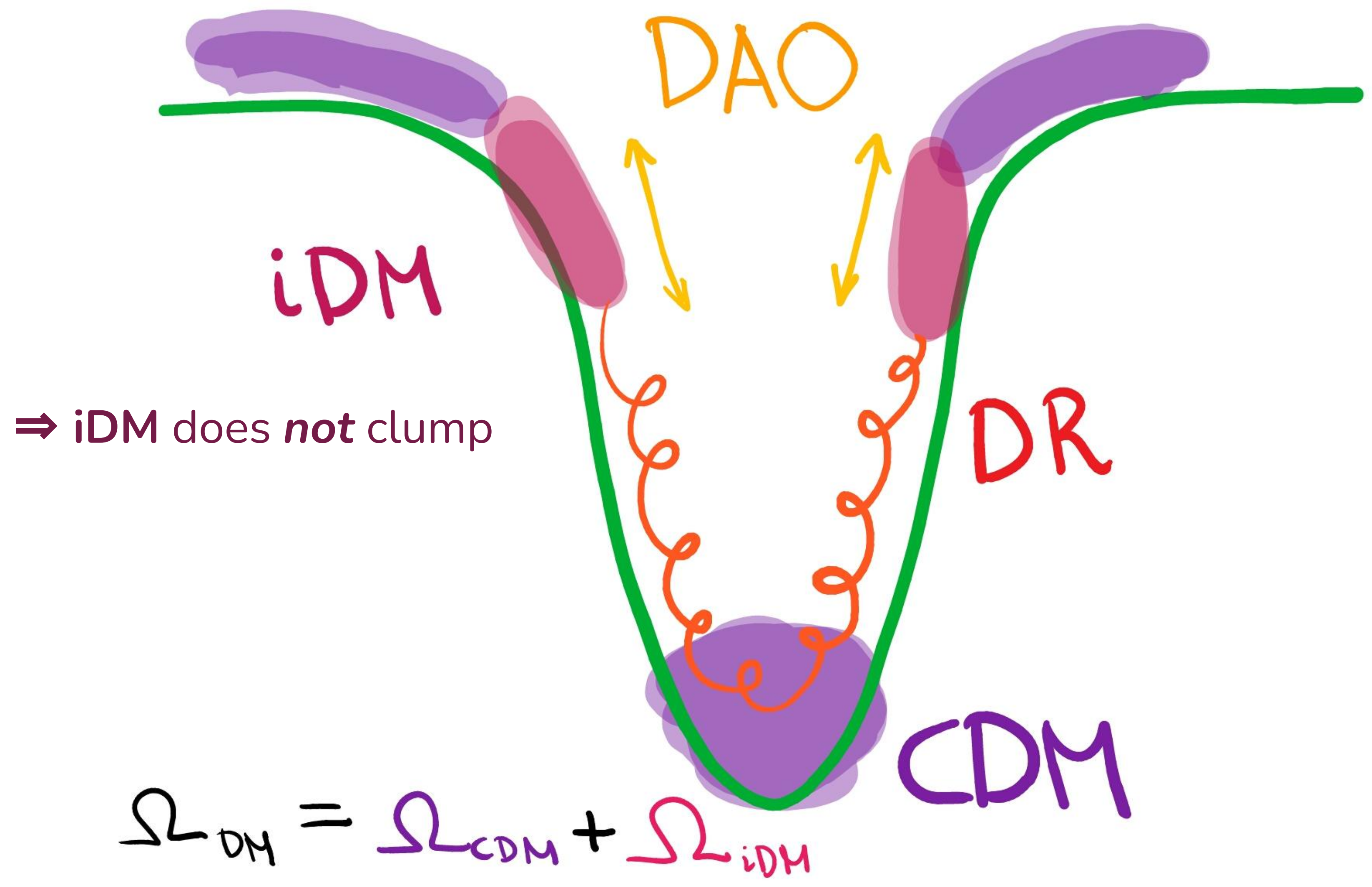


$$\delta \mathscr{L}_{\rm dark} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \bar{\psi}(i\not{D} - m_\psi)\psi + |D\chi|^2 - m_\chi^2 |\chi|^2$$

SPartAcous

Dark Acoustic Oscillations





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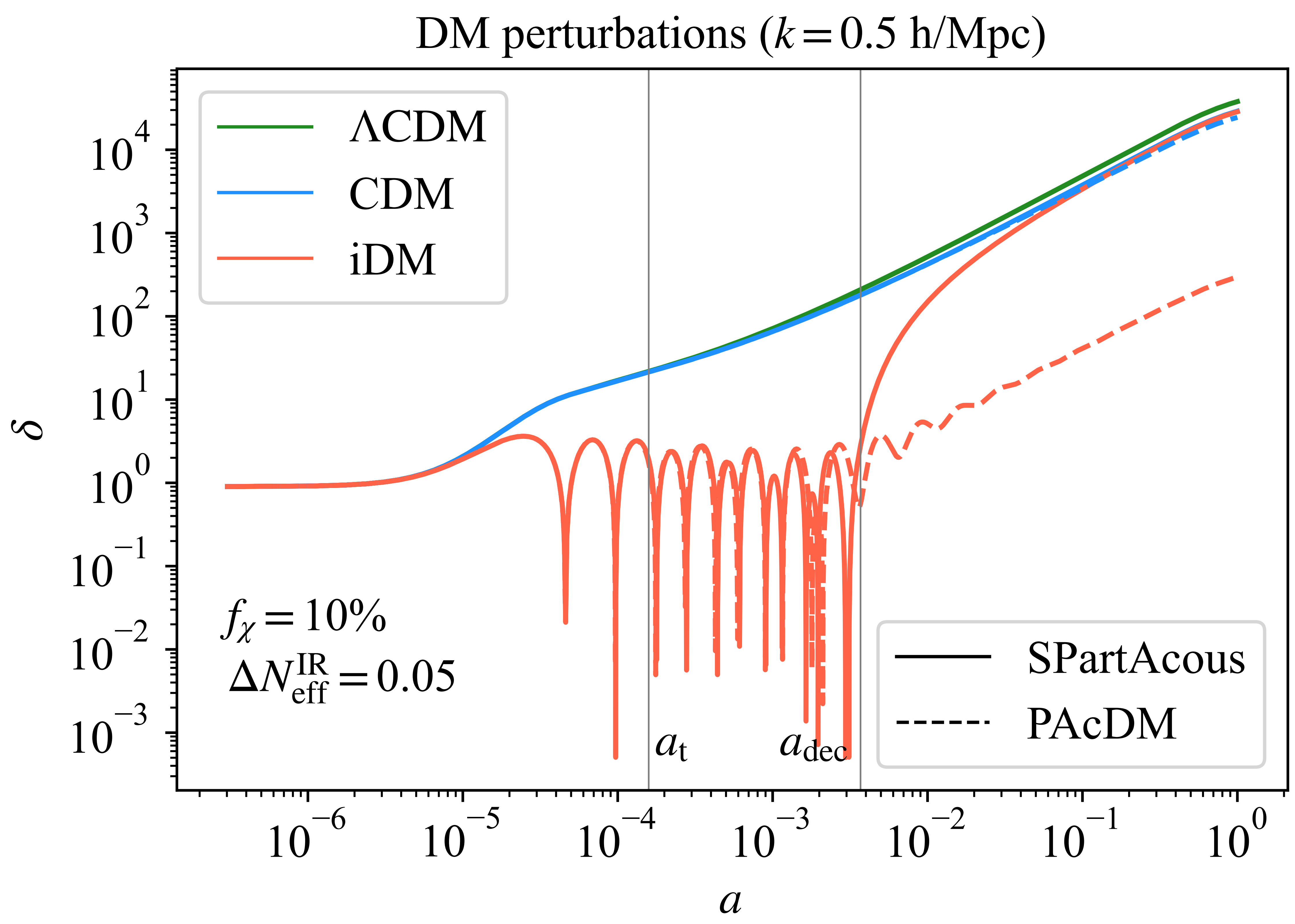
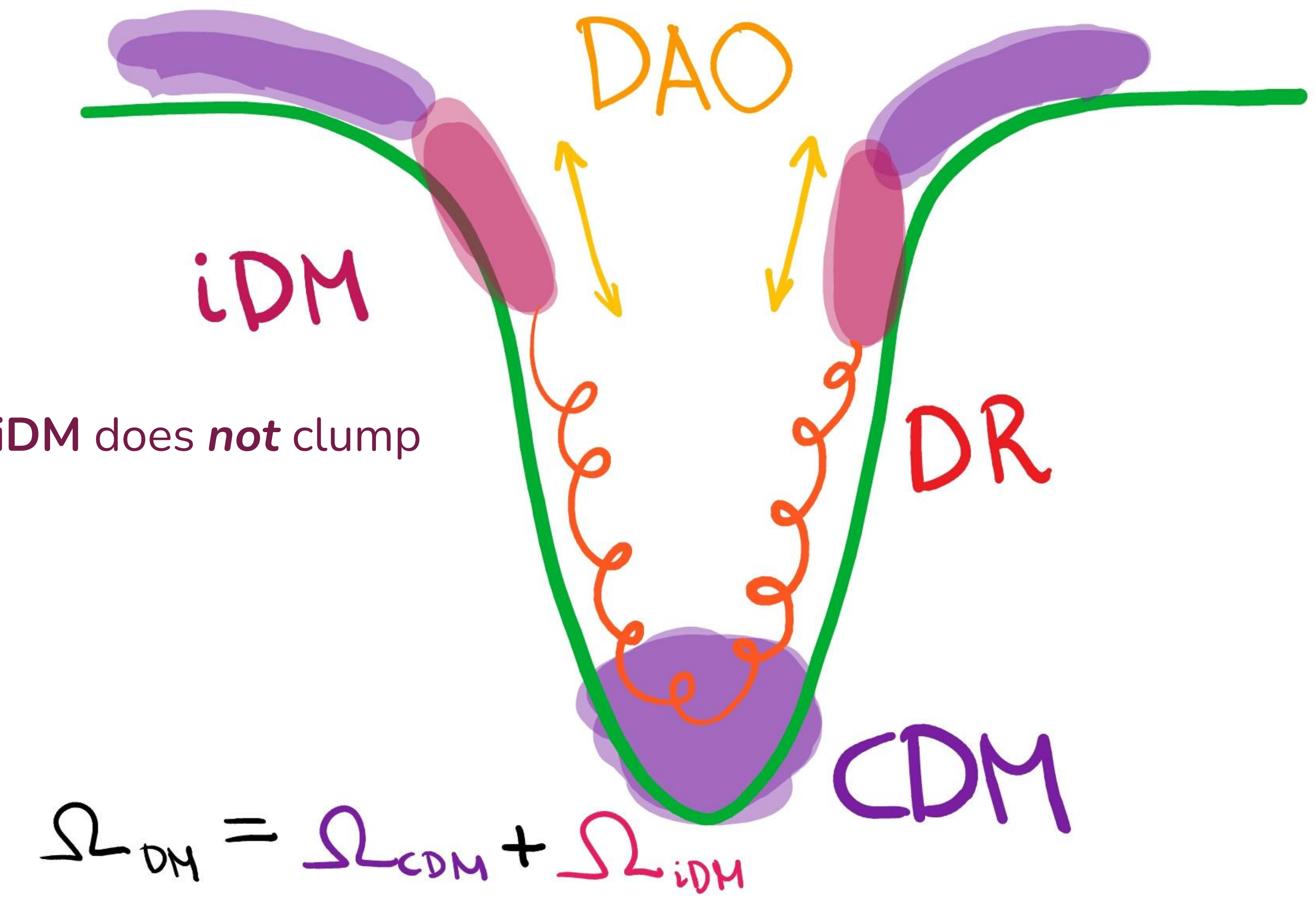
SPartAcous

Dark Acoustic Oscillations



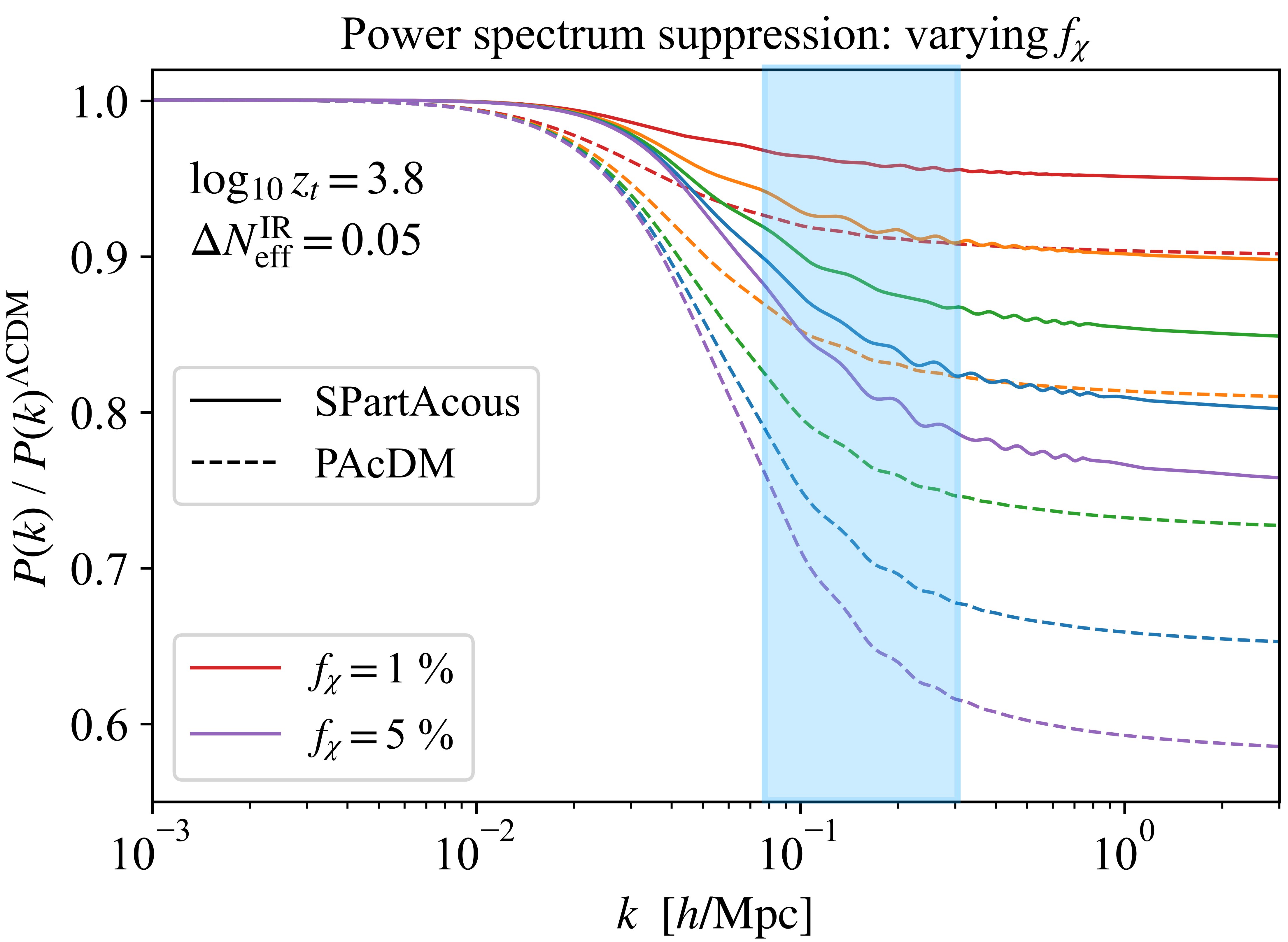
⇒ **iDM does *not* clump**

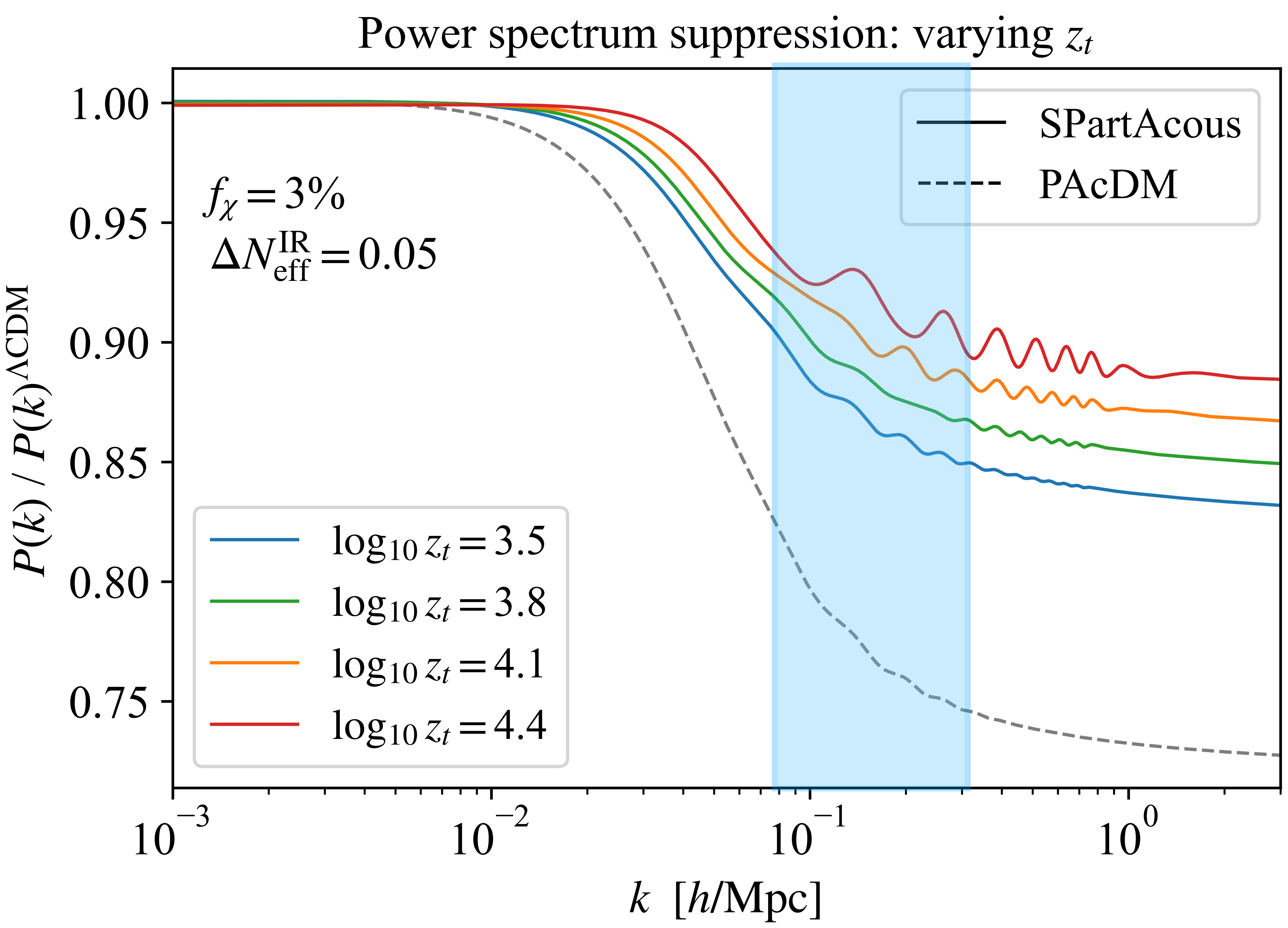


$$\delta\mathscr{L}_{\rm dark} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \bar{\psi}(i\not{D} - m_\psi)\psi + |D\chi|^2 - m_\chi^2|\chi|^2$$

SPartAcous

Dark Acoustic Oscillations

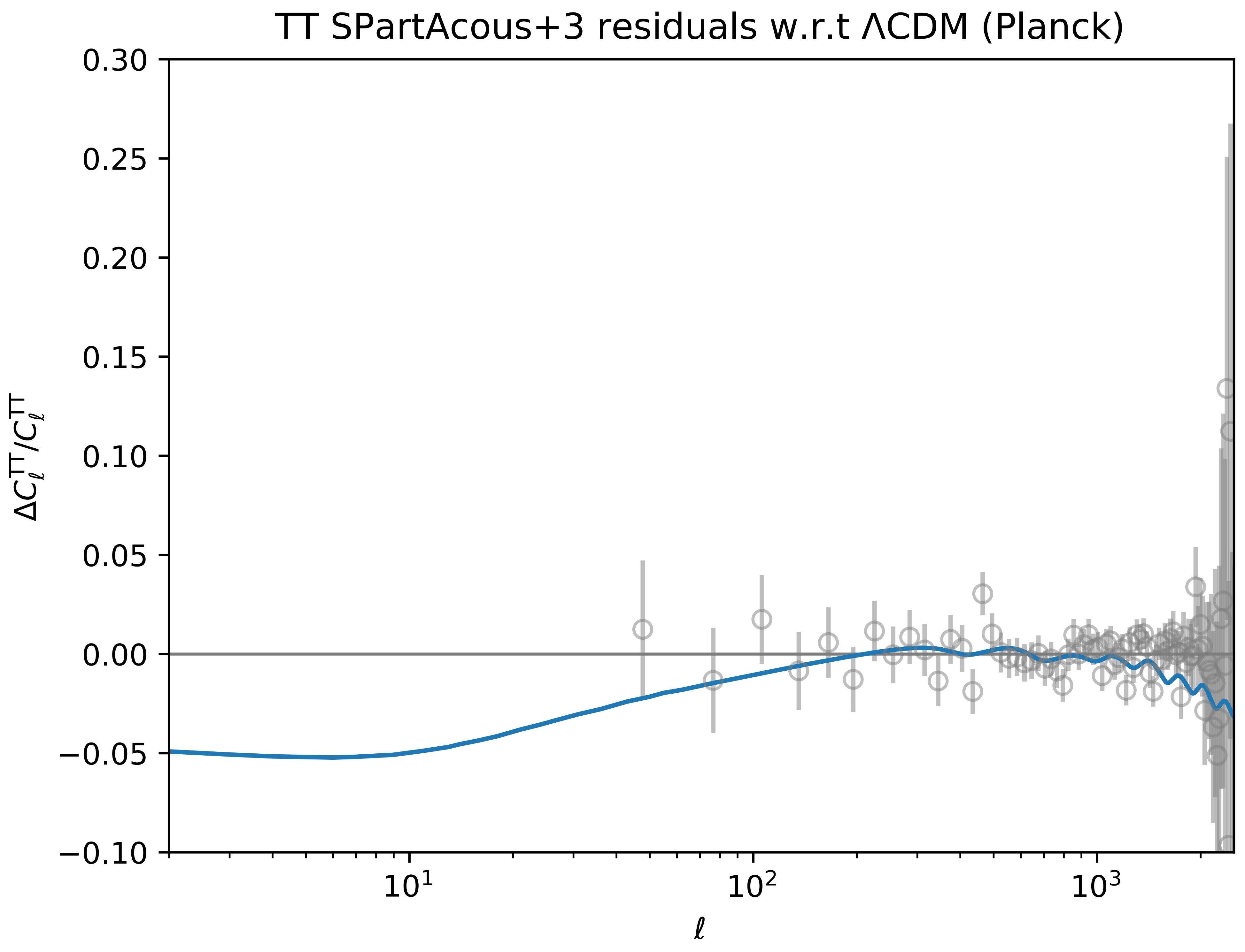


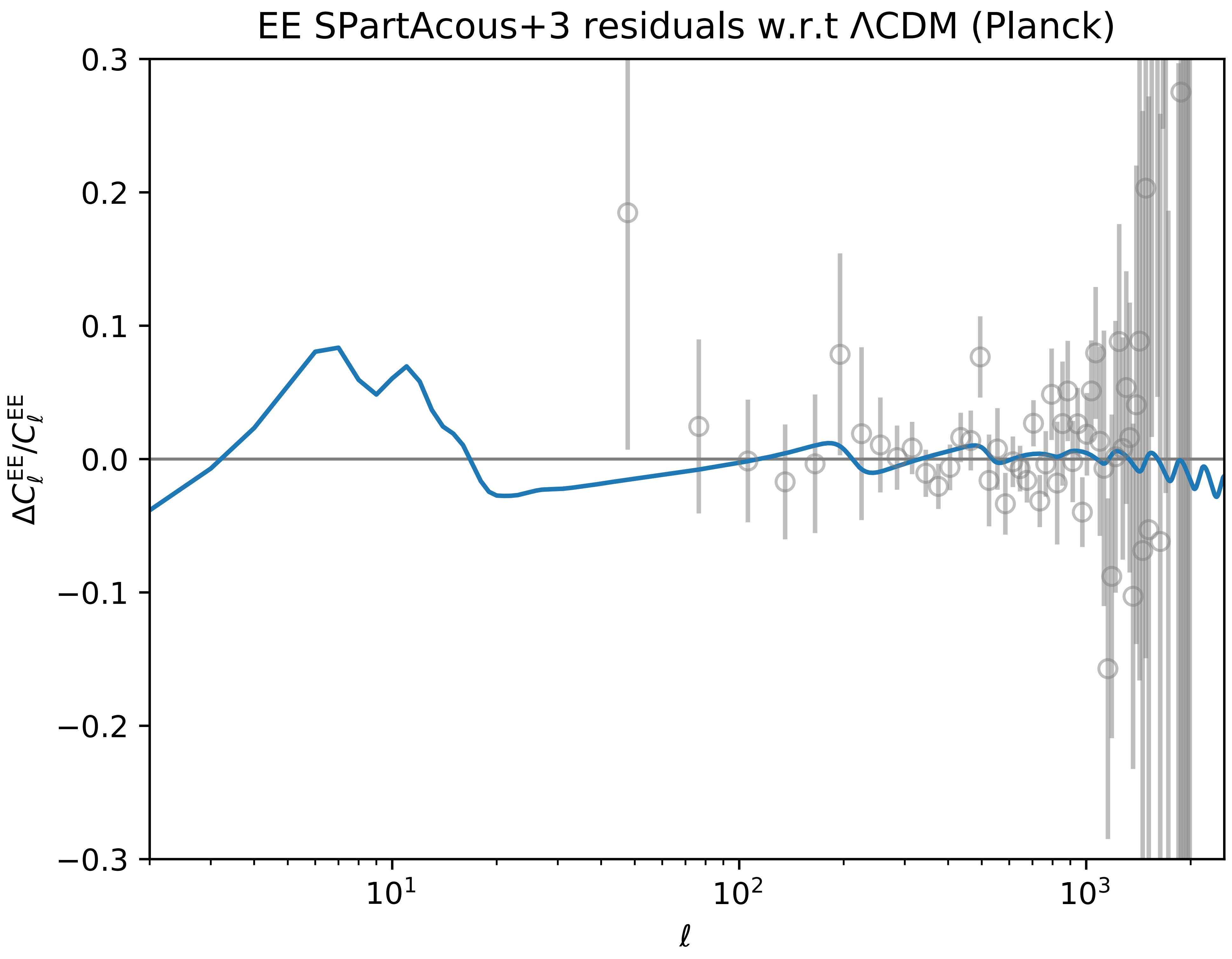


$$z_t = \frac{m_\chi}{T_{d0}} - 1$$

SPartAcous+3

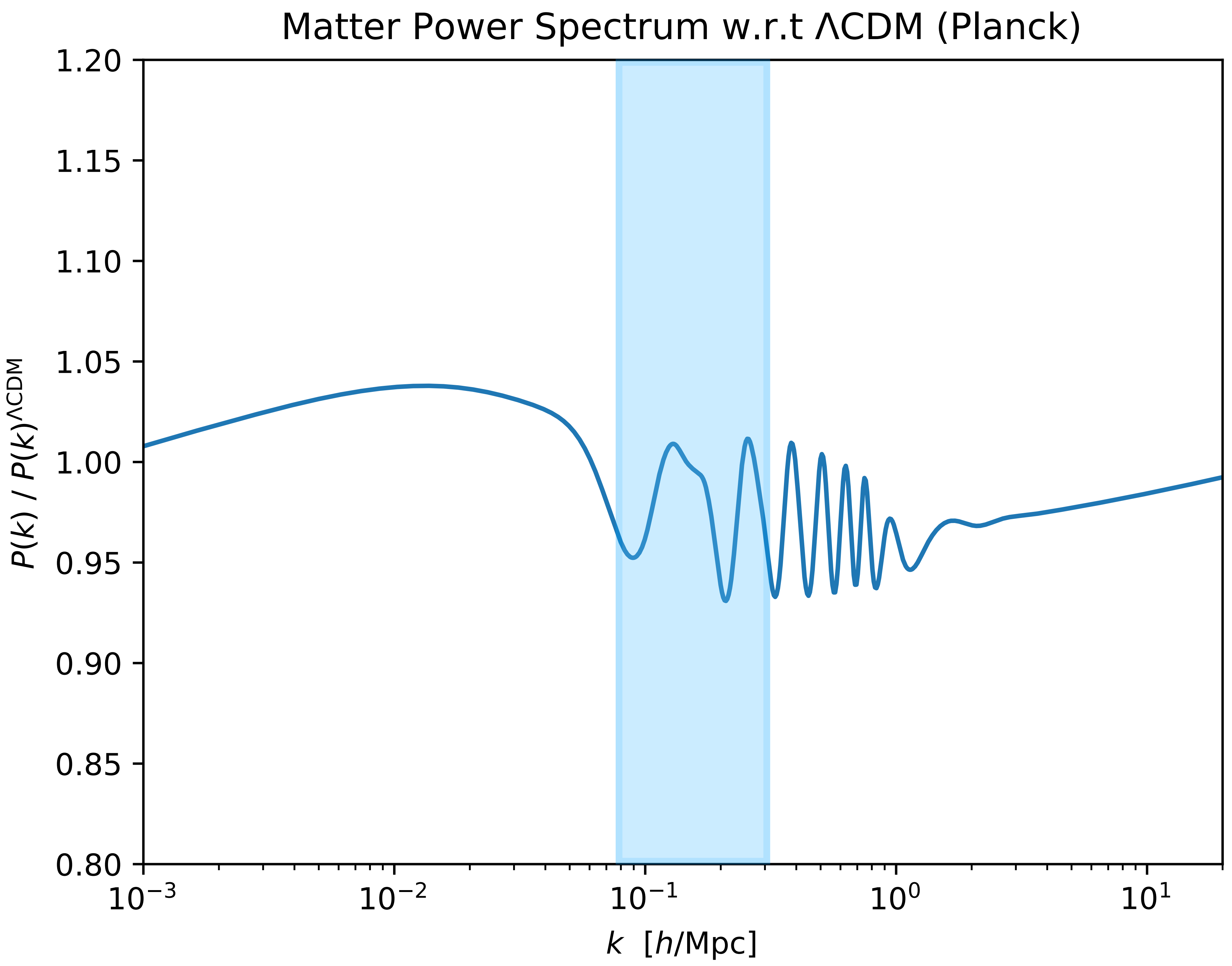
Best-fit

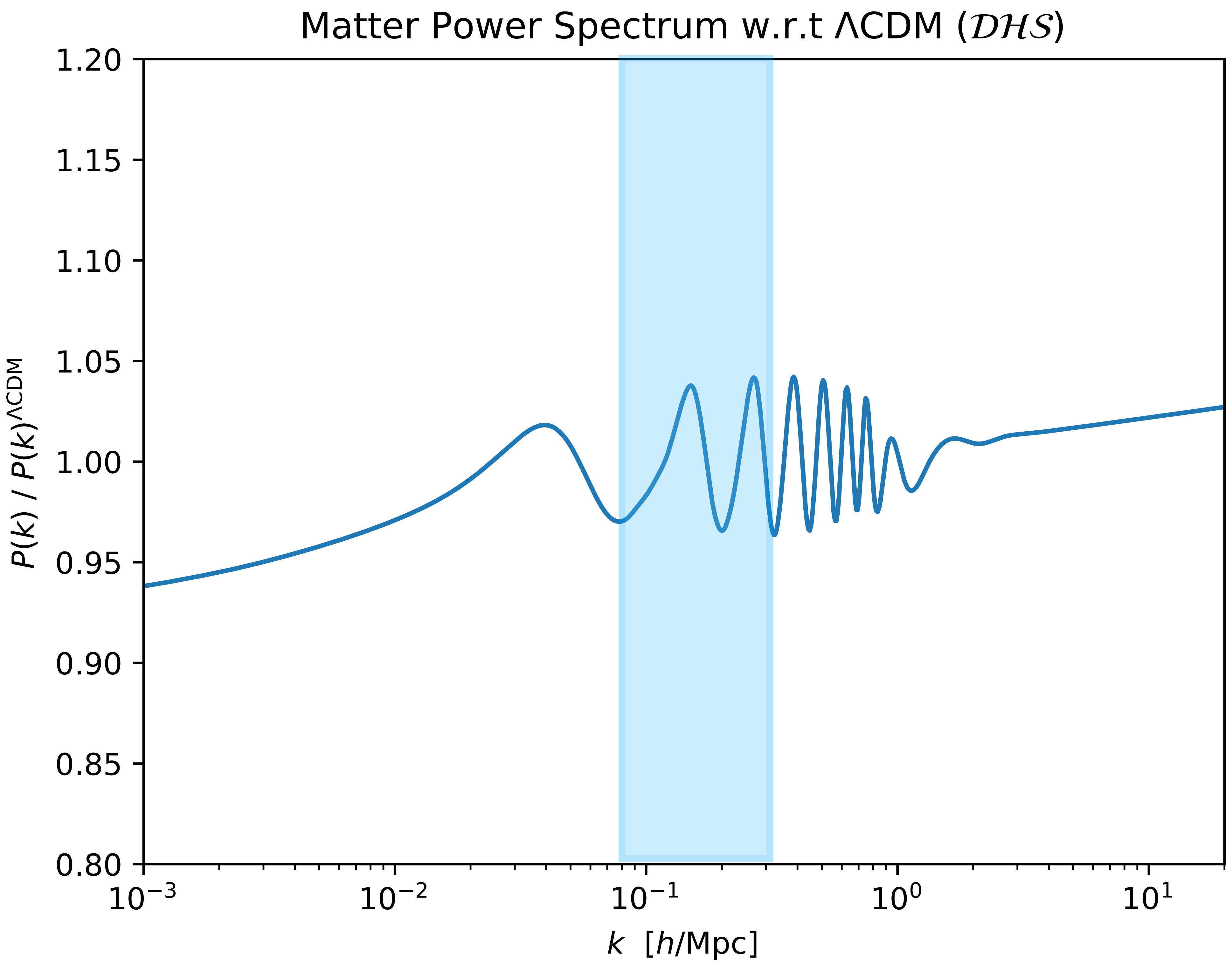




SPartAcous+3

Best-fit

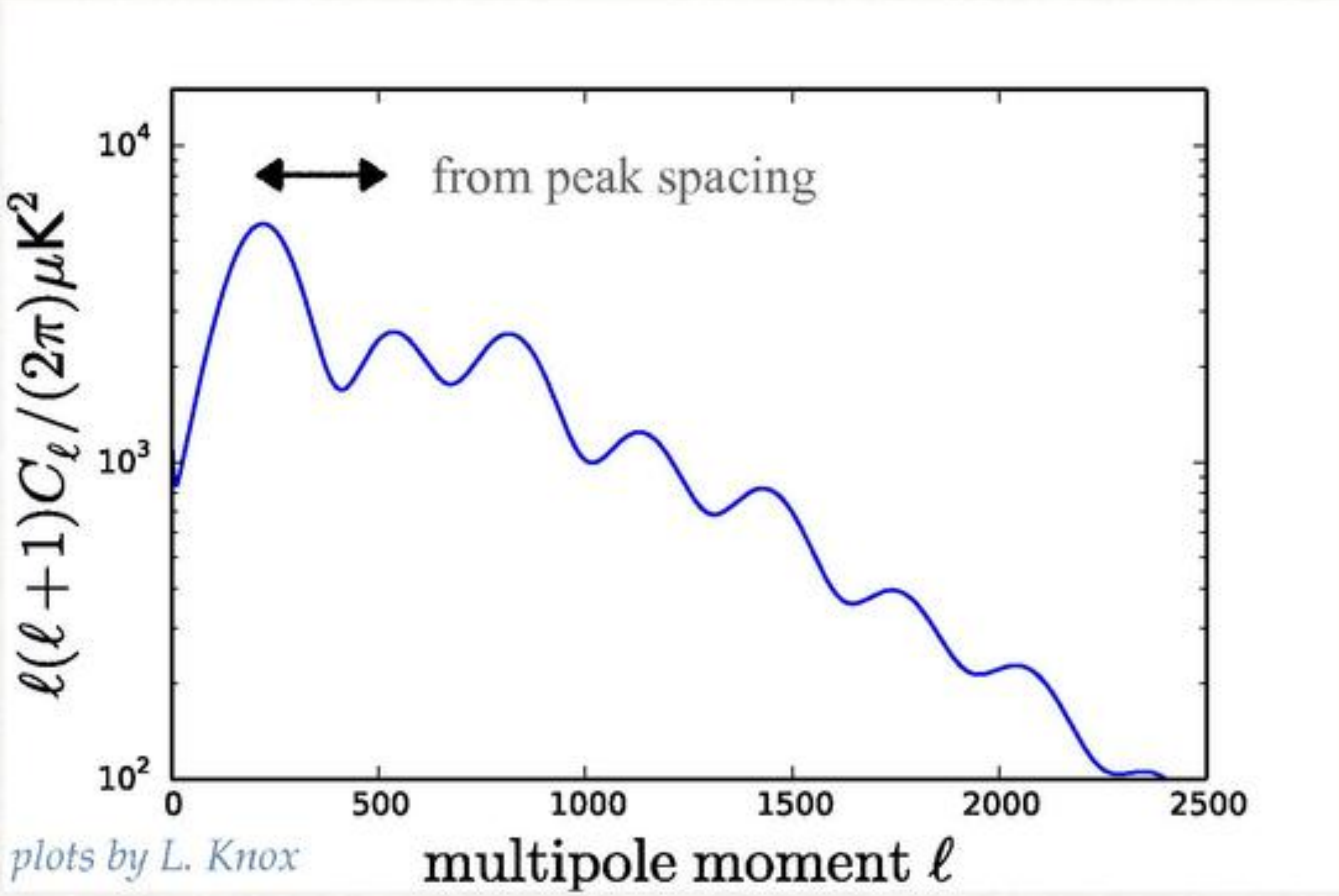




How does CMB data measure H0?

- 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



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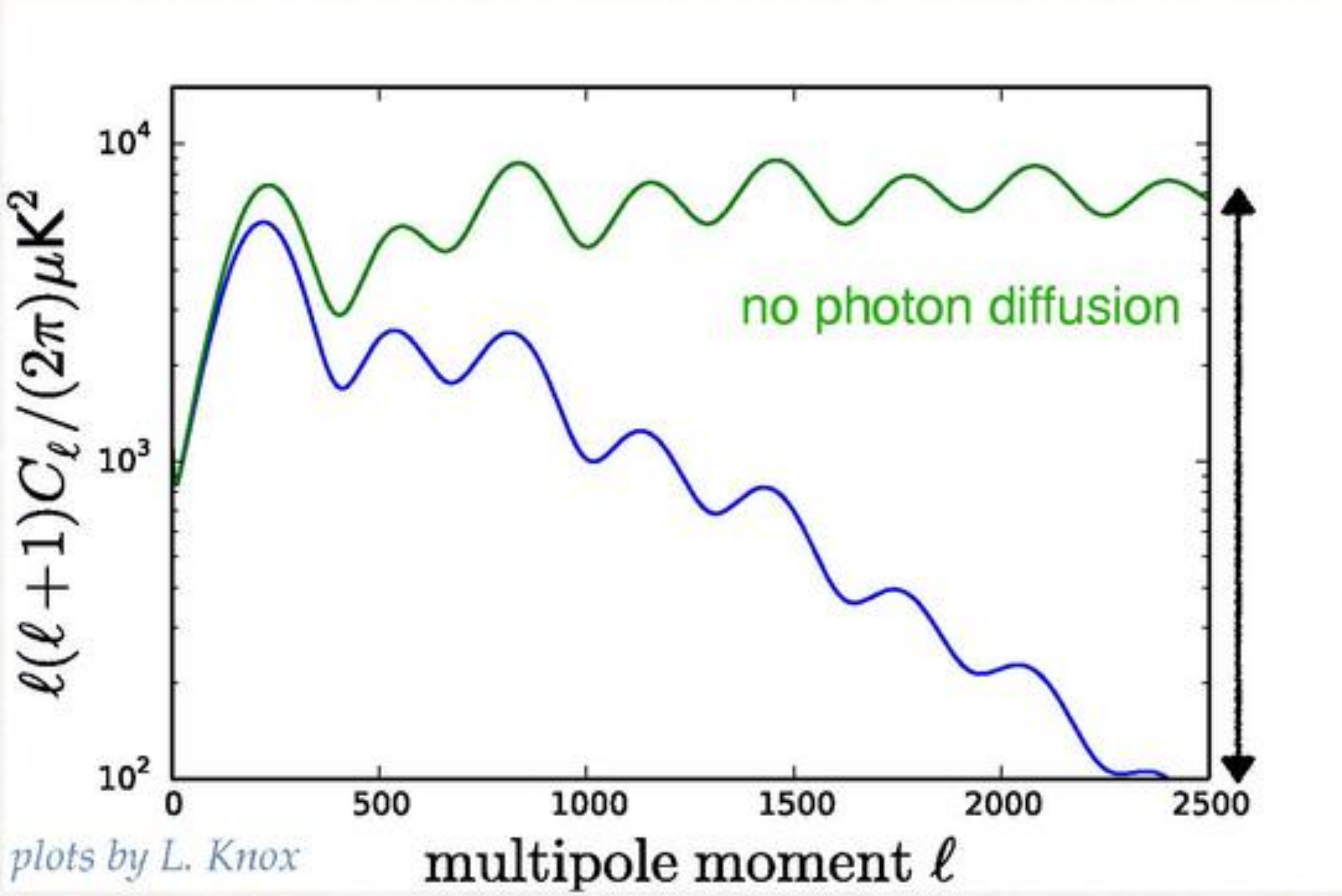
θ_d photon diffusion length at last scattering ~ 0.1609



"Silk Damping"

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

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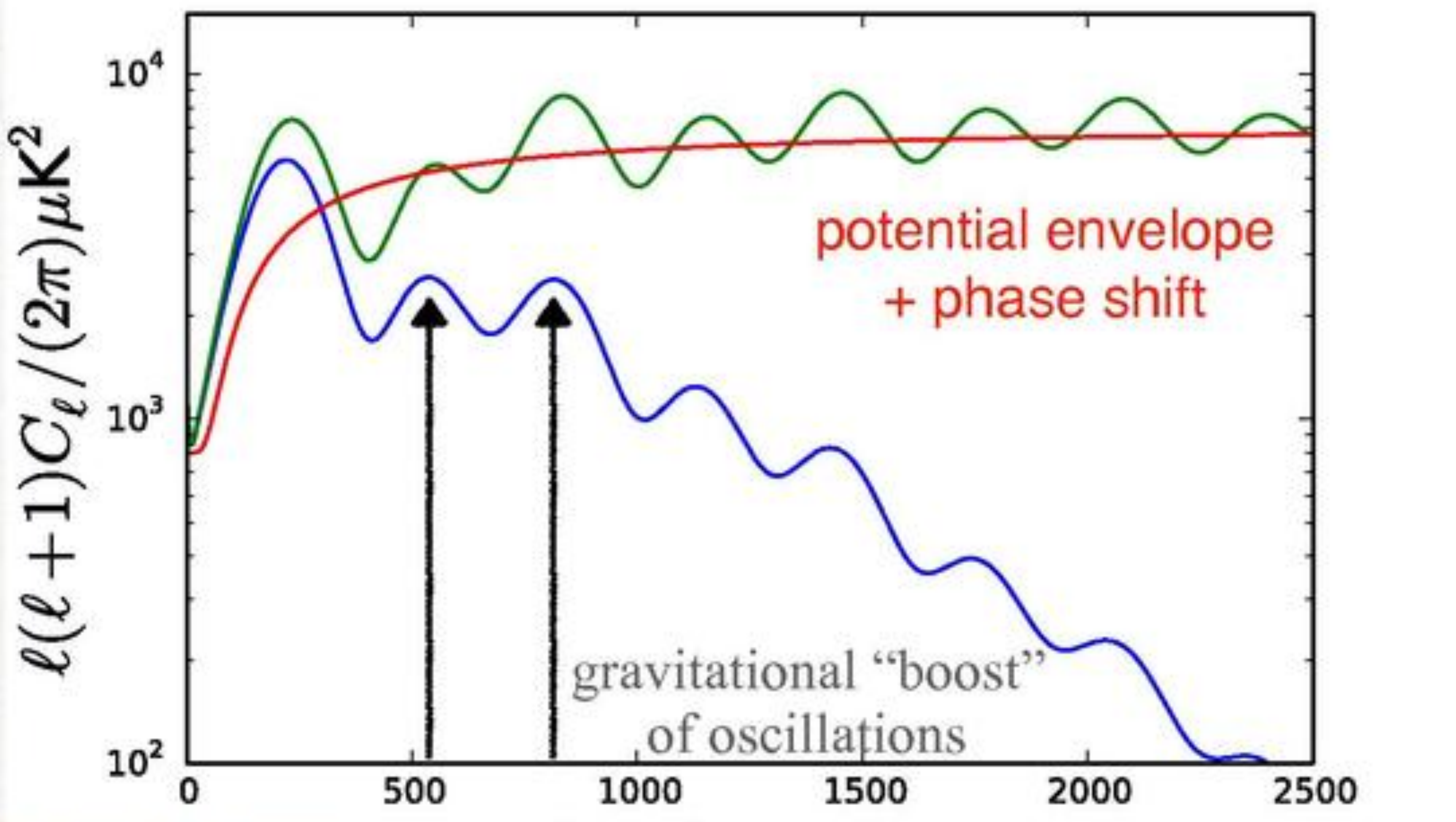
θ_{eq} horizon size at matter-radiation equality ~ 0.81



plots by L. Knox

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