Cosmological Features of Mirror Sector Models

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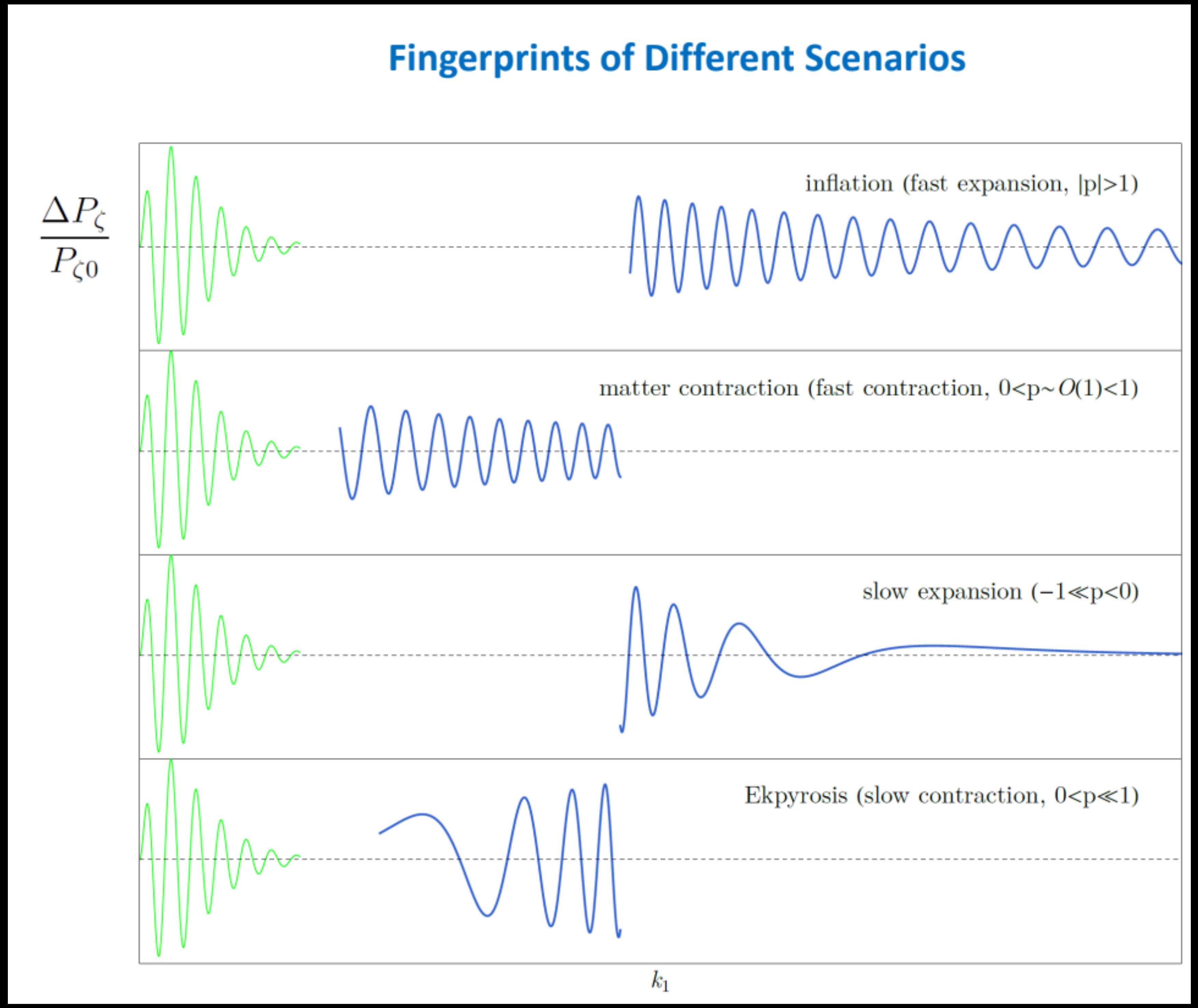
New Physics from Galaxy Clustering
IFPU, 11/08/2023

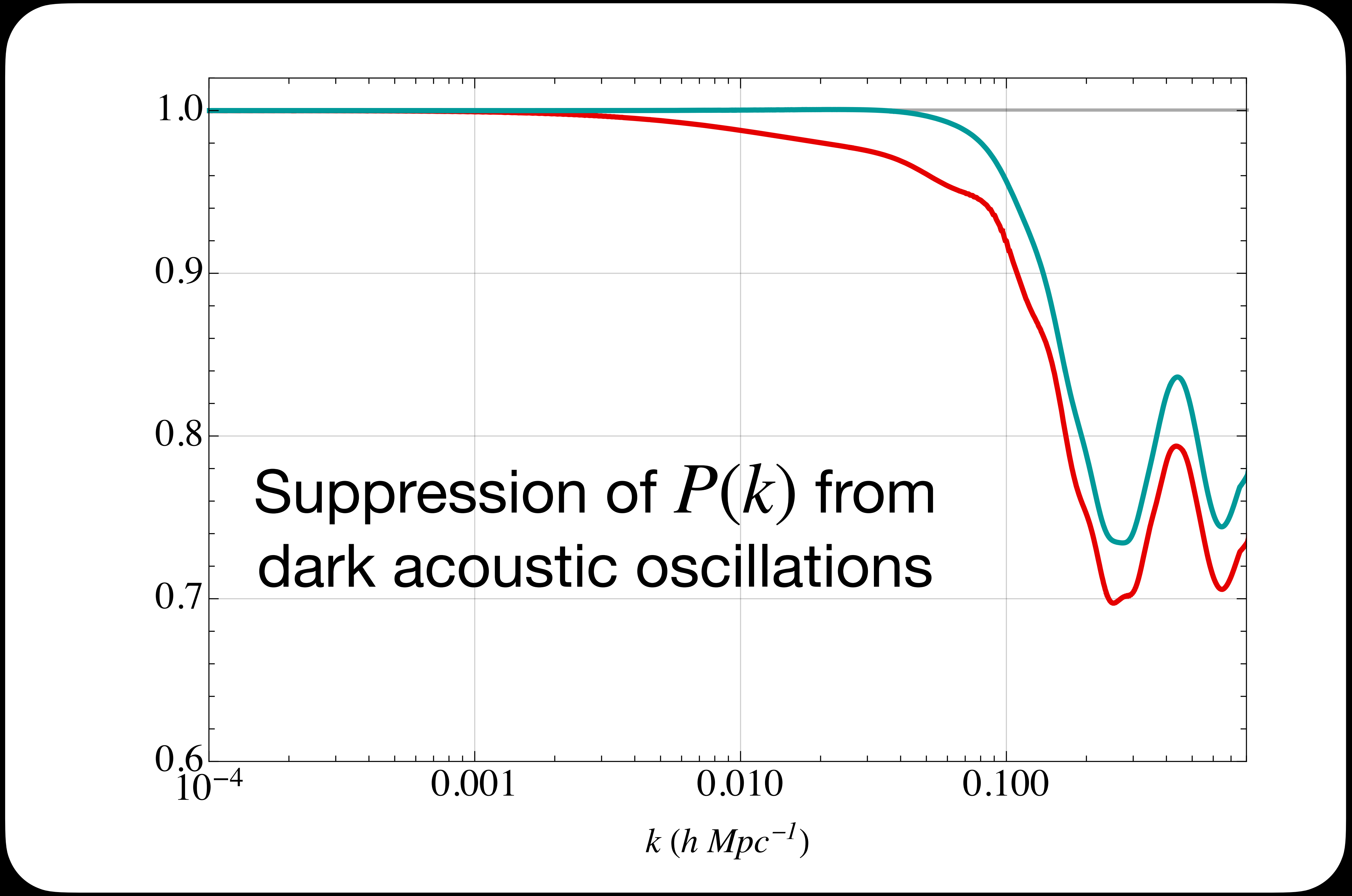
Cosmological features

Primordial "features" from inflationary models



Xingang Chen

In this talk, sub-horizon "features" from mirror sector dynamics



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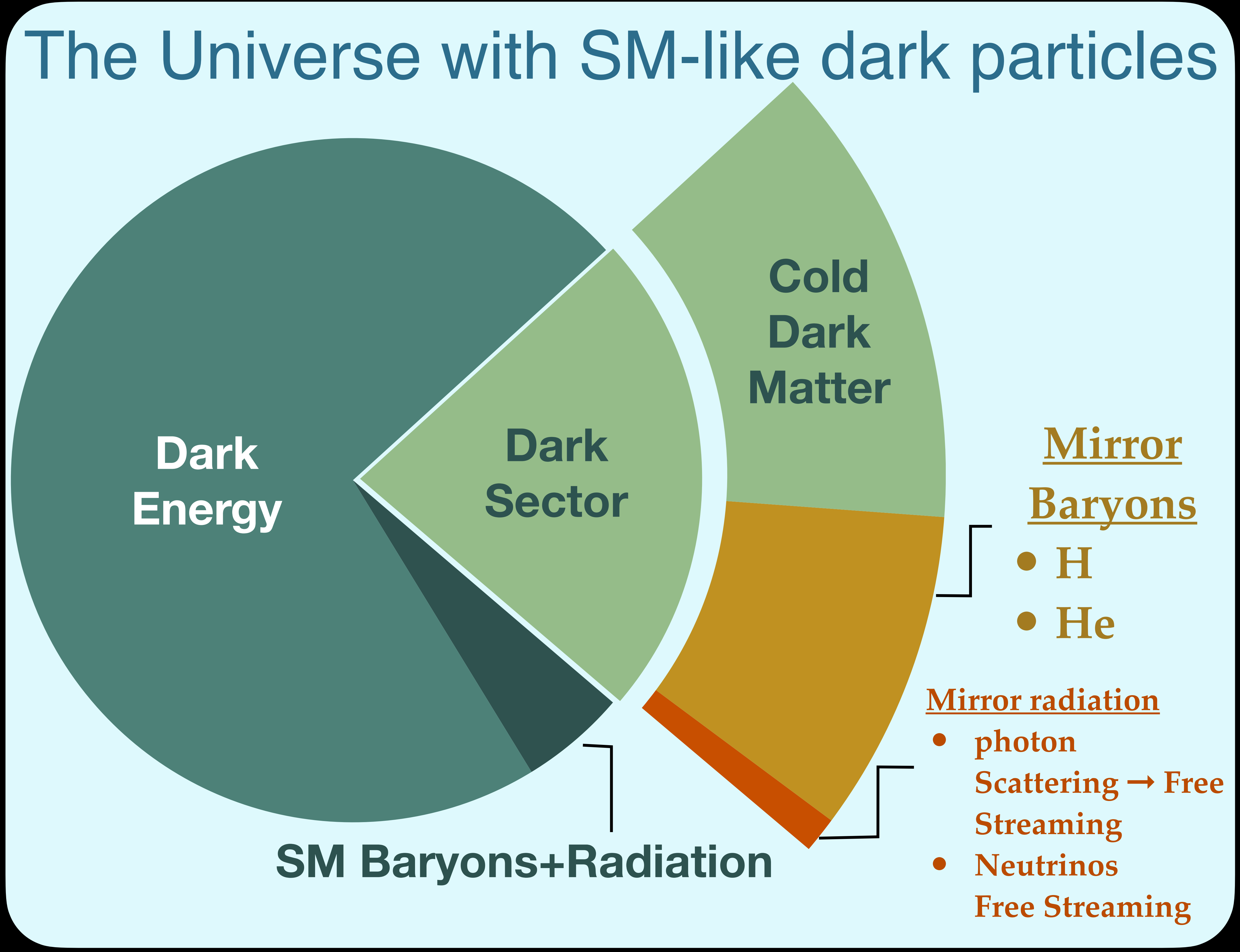
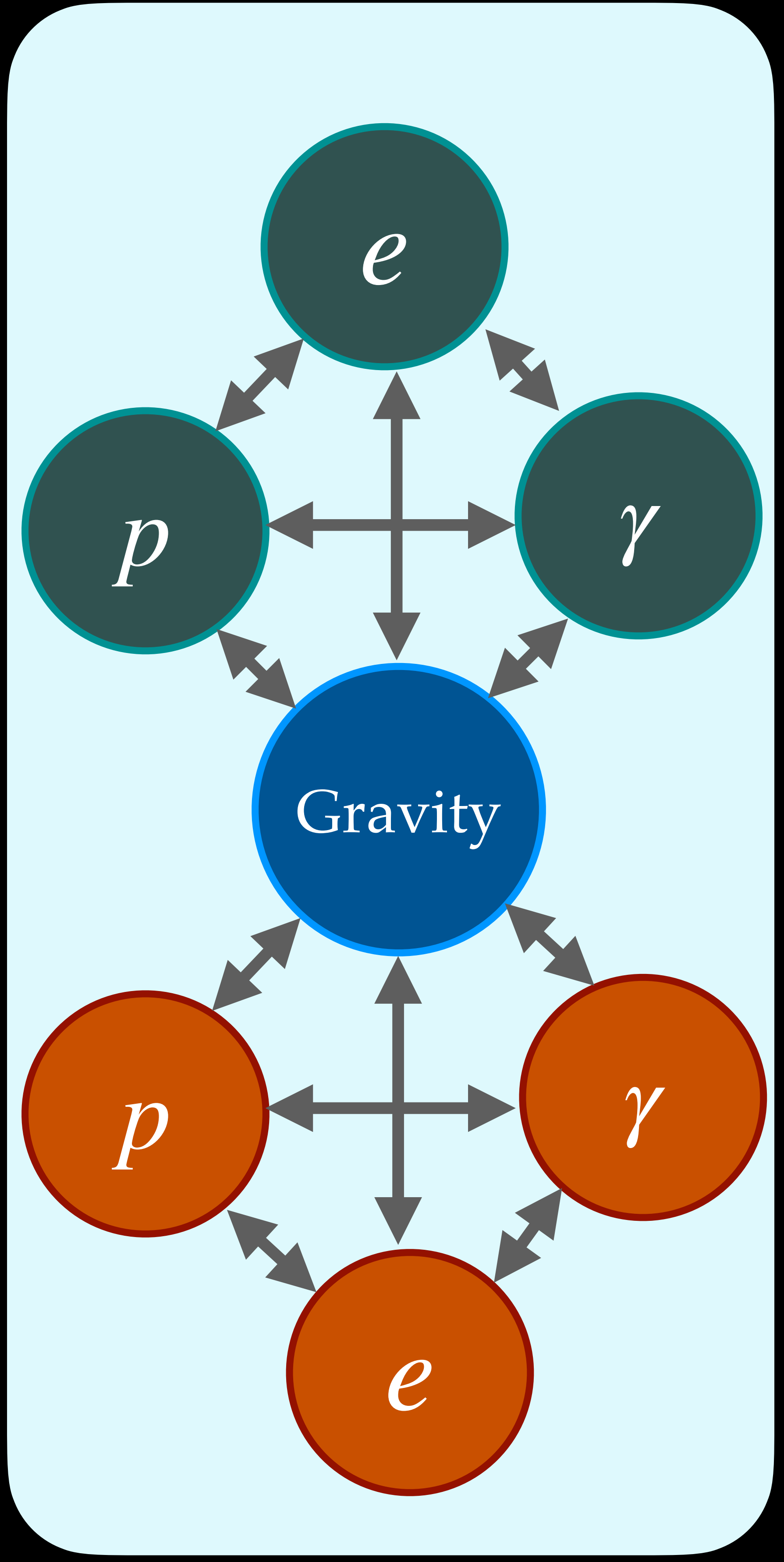
Dark sector with an approximated mirror symmetry





Some motivations:

- Dark sector can be complex
- Similarity of baryon-DM energy densities
- Solution to EW hierarchy problem: Mirror Twin Higgs

Chacko, Goh, Harnik (2005)

Will use the Mirror Twin Higgs model as an example

but the discussion is quite general

Parameters of the MTH model

$(\hat{v}/v)$	Ratio of the mirror electroweak symmetry breaking scale to the SM value $3 \lesssim (\hat{v}/v) \lesssim 5$ (LHC bound & tuning)
$\Delta\hat{N} \equiv \Delta N_{\hat{\gamma}} + \Delta N_{\hat{\nu}}$	Mirror radiation energy. From $\Delta N_{\rm eff} \lesssim 0.4$, twin particles need to be at least 50% colder than the visible photon
$\hat{r} \equiv \Omega_{\rm twin}/\Omega_{\rm DM}$	Mirror baryons vs. total DM energy density

Recombination of mirror He and H ($T \sim$ few eV w/ approx mirror symmetry)

$$\hat{\mathrm{He}}^{2+} + \hat{e}^- \rightarrow \hat{\mathrm{He}}^{+} + \hat{\gamma}$$

Approximation using Saha Equation

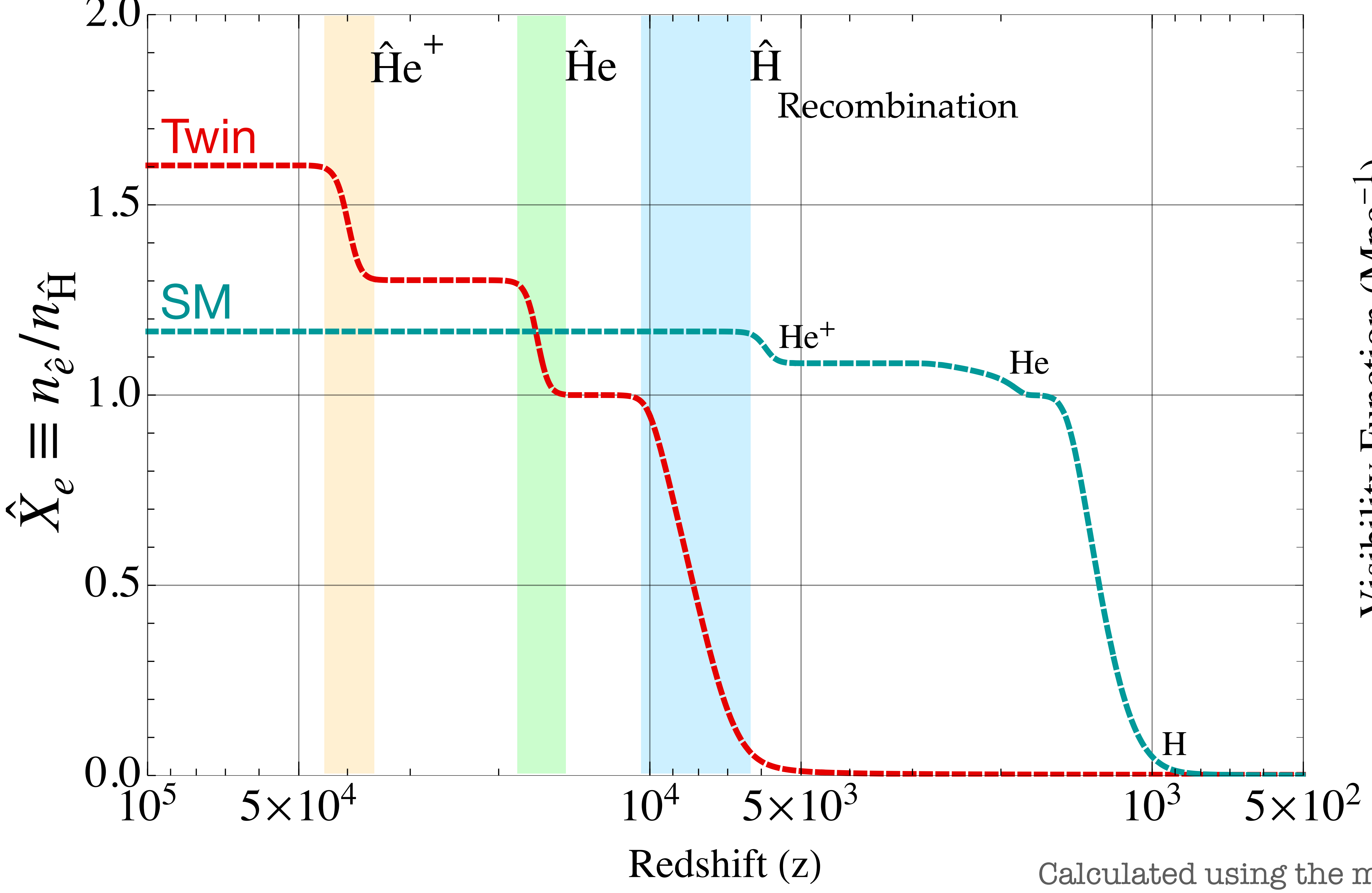
$$\hat{\mathrm{He}}^{+} + \hat{e}^- \rightarrow \hat{\mathrm{He}} + \hat{\gamma}$$

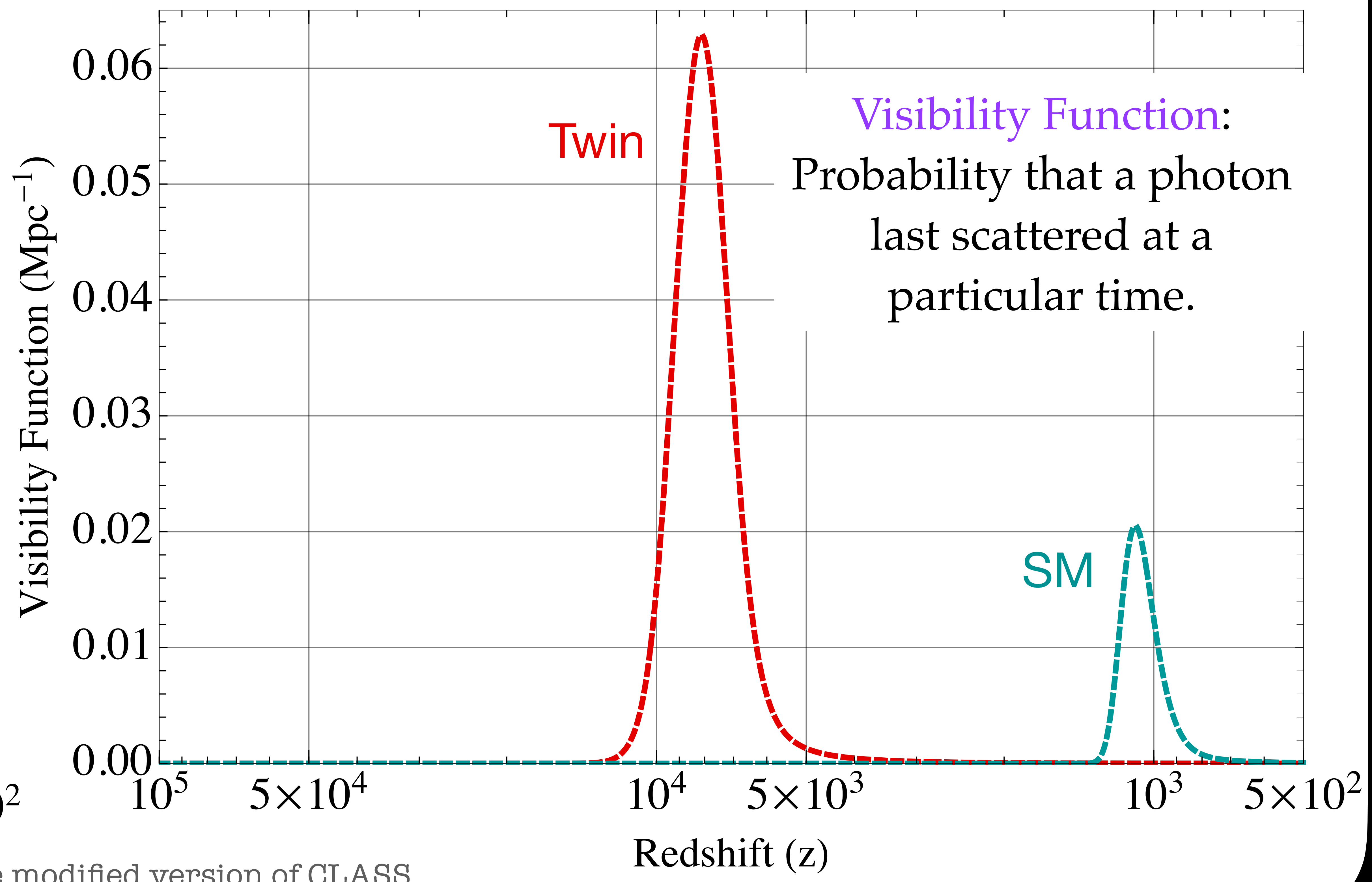
Approximation using Saha Equation

$$\hat{p} + \hat{e}^- \rightarrow \hat{\mathrm{H}} + \hat{\gamma}$$

Peebles Equation

$$\hat{r} = 0.1,\ \hat{v}/v = 3,\ \Delta\hat{N} = 0.3$$

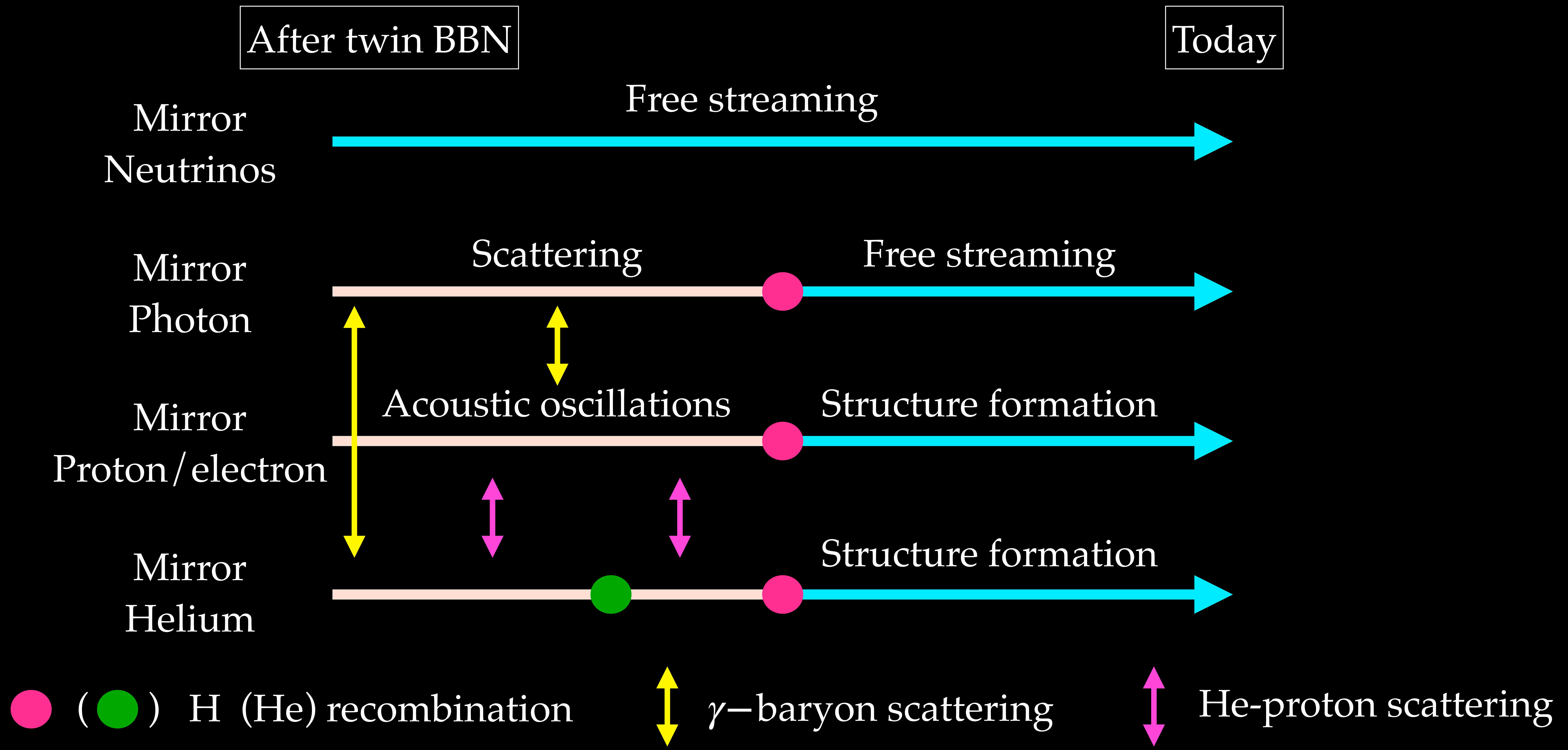




Calculated using the modified version of CLASS.

Bansal, Kim, Kolda, Low, **YT** (2022)

Scattering property of the mirror sector particles



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Suppression of matter power spectrum:
Dark Acoustic Oscillations (DAO)

Cir-Racine, Sigurdson (2012)

Cir-Racine, Putter, Raccanelli, Sigurdson (2012)

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The code for the following analysis

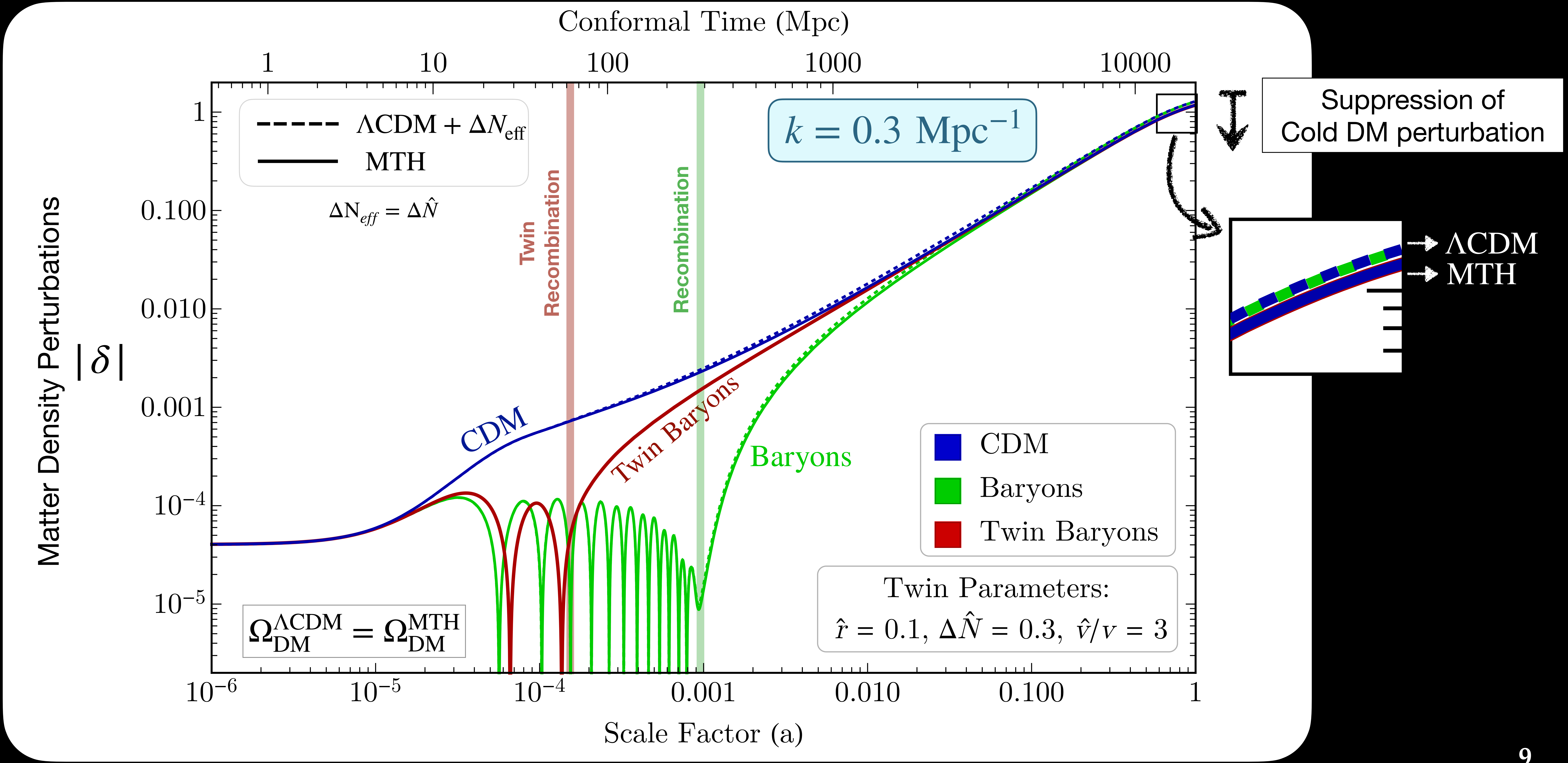
The MTH module of CLASS https://github.com/srbPhy/class_twin

Bansal, Kim, Kolda, Low, **YT** (2022)

For more general atomic DM parameters https://github.com/jp-barron/class_adm-3.1

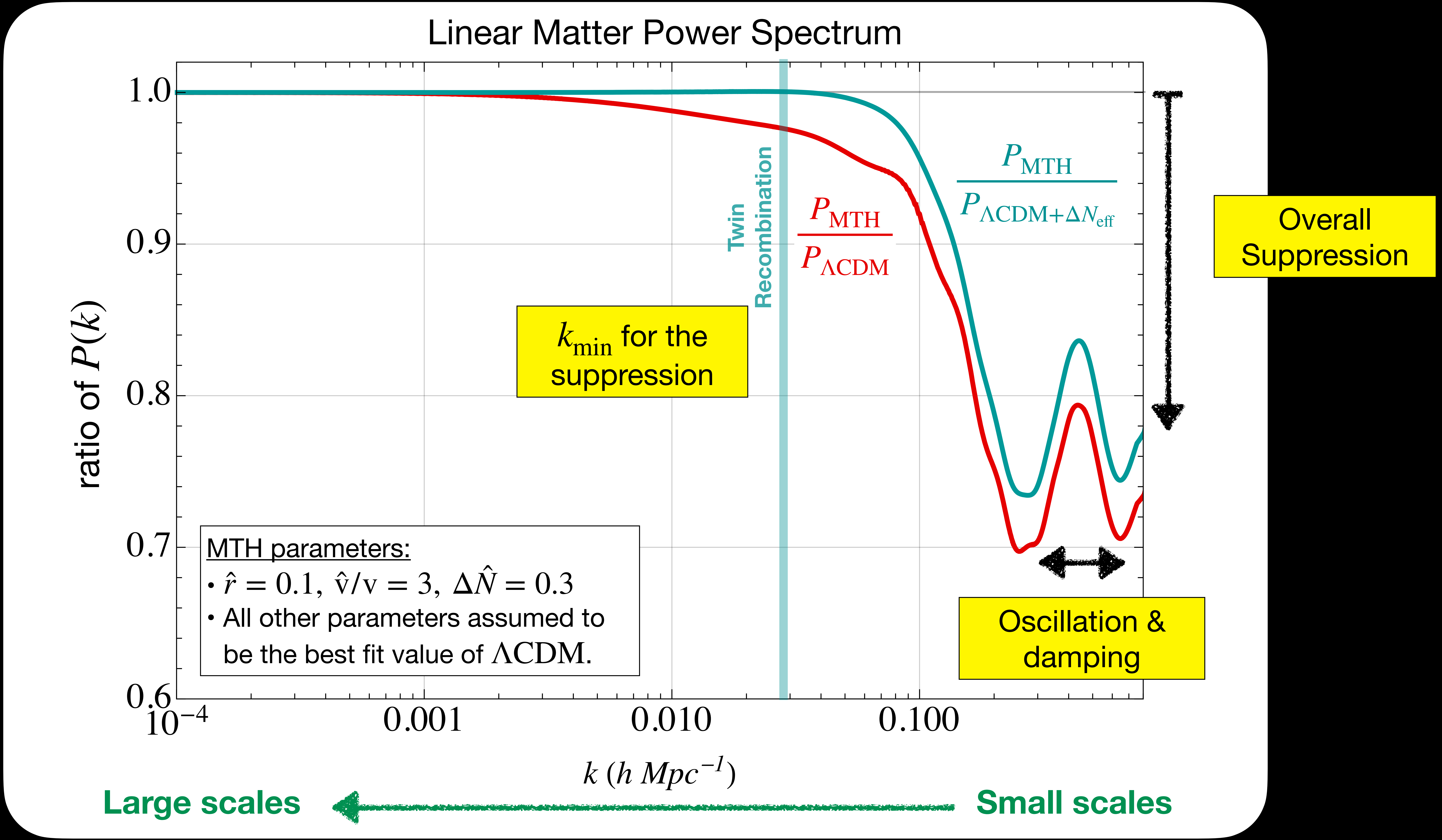
Bansal, Barron, Curtin, **YT** (2023)

Evolution of Matter perturbations $\delta_i \equiv (\rho_i - \bar{\rho}_i)/\bar{\rho}_i$



Calculated using the modified version of CLASS.

Power spectrum suppression



If we can measure the linear-power spectrum

k_{min} for the suppression	~ (Mirror recombination time)^(-1)
Overall suppression	For recombination happens before matter-radiation equality Power spectrum ratio $\approx \left(1 - \frac{\rho_{\mathrm{m-baryon}}}{\rho_{\mathrm{tot\,DM}}}\right)^2$
Oscillation frequency	$\delta_{\mathrm{p}} \sim \cos(kr_s)$ $\quad r_s \sim \tau_{\mathrm{rec}} c_s \quad c_s^2 = \frac{1}{3(1 + 3\rho_{\mathrm{m-baryon}}/4\rho_{\mathrm{m-photon}})}$
ΔN_{eff}	$\rho_{\mathrm{m-neutrino}} + \rho_{\mathrm{m-photon}}$
Damping	Mirror $\gamma - e$ scattering

Chacko, Curtin, Geller, YT, JHEP 09 (2018) 163

Non-linear correction can washout the oscillatory feature

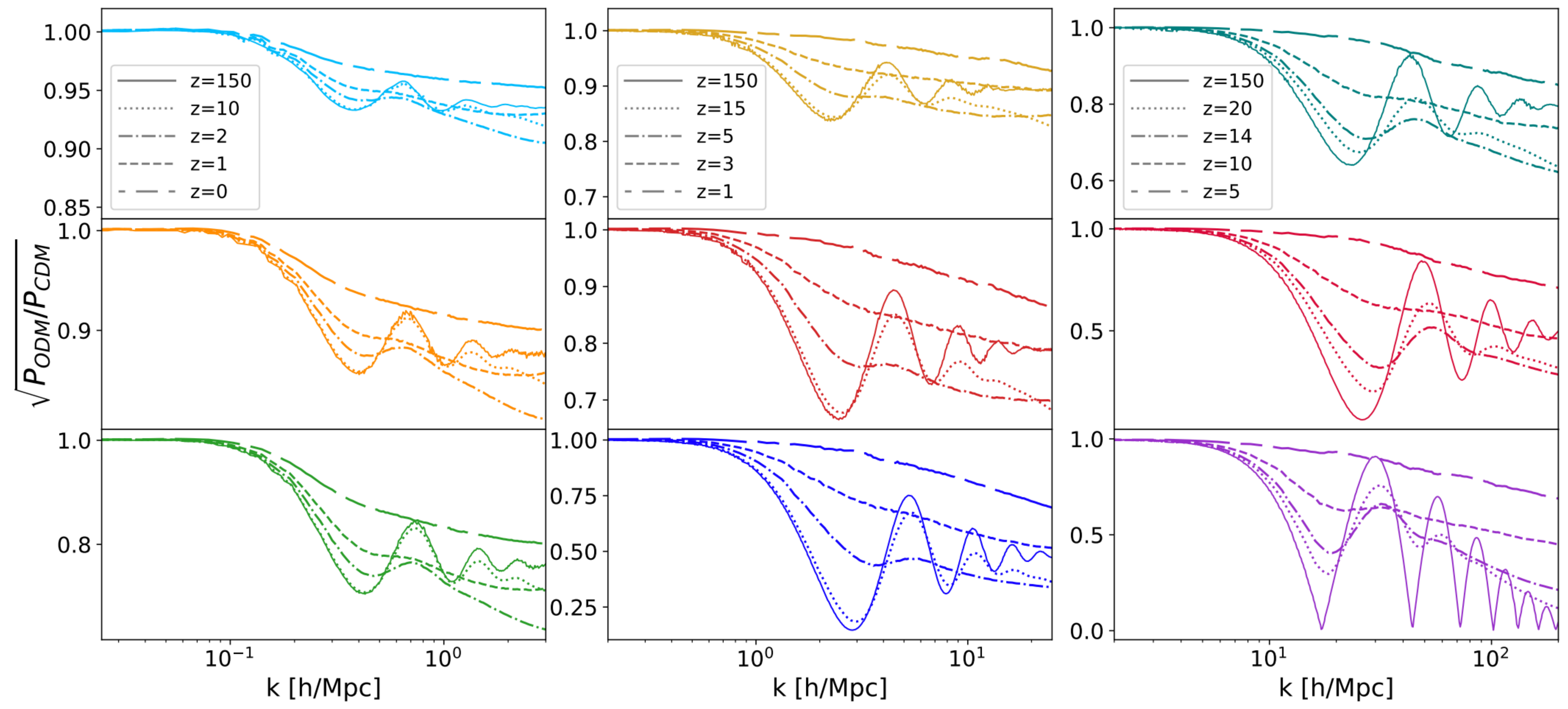


Figure 2. Square roots of the ratios between the ODM and CDM nonlinear power spectra at different redshifts. Solid lines correspond to the initial transfer functions from Fig .1. *Left panels*: ODM1 at z = 10, 2, 1, 0 (from top to bottom: f_{IDM} = 0.05, 0.1, 0.2), ODM2 at z = 15, 5, 2, 0 (f_{IDM} = 0.1, 0.2, 0.5), and ODM3 at z = 20, 14, 10, 3.5 (f_{IDM} = 0.2, 0.5, 1). All oscillations have completely disappeared at z = 1 for ODM1, z = 3 for ODM2, and z = 10 for ODM3.

Schaeffer, Schneider (2021)

Need higher-z measurements to see the DAO peaks

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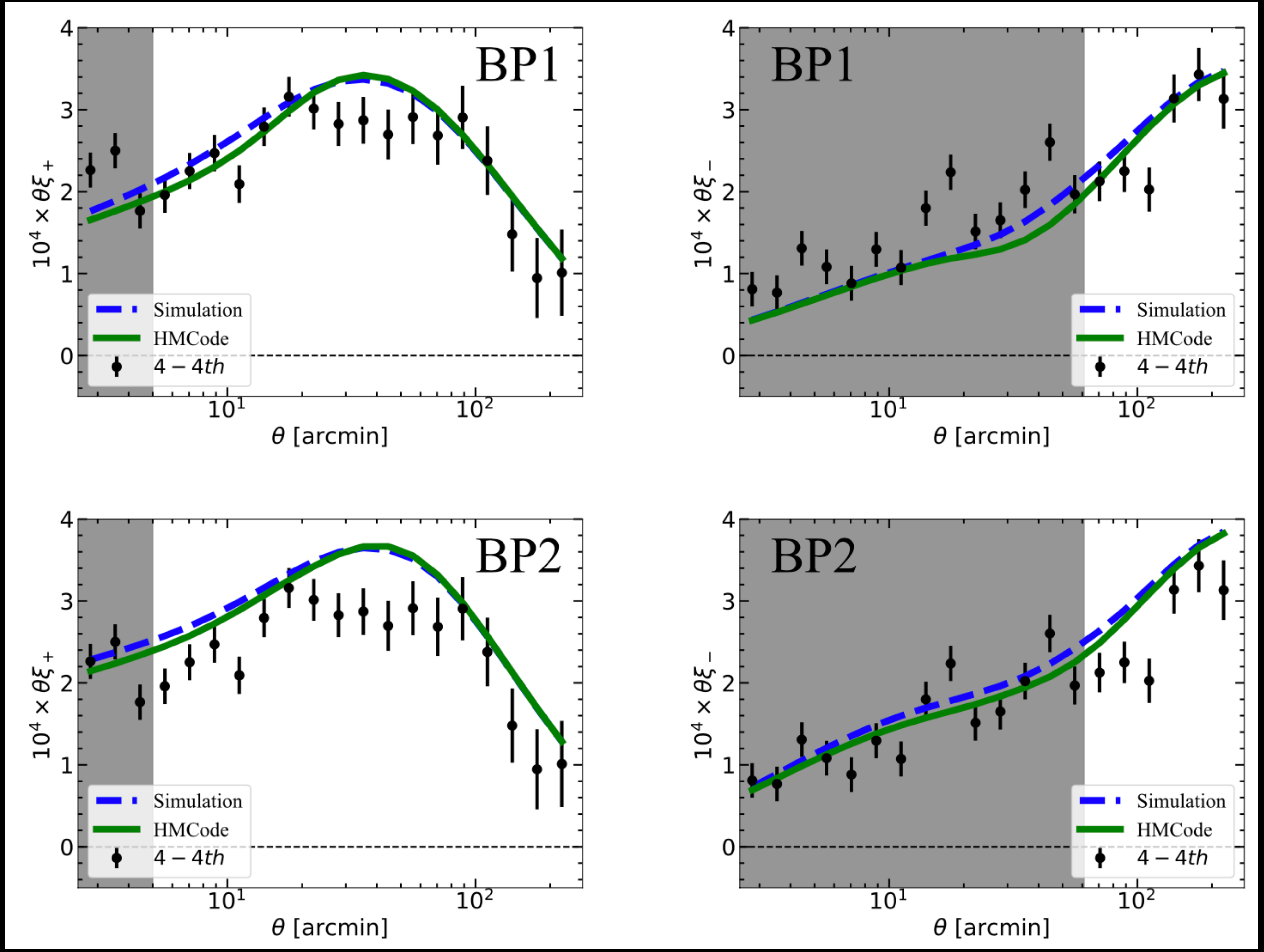
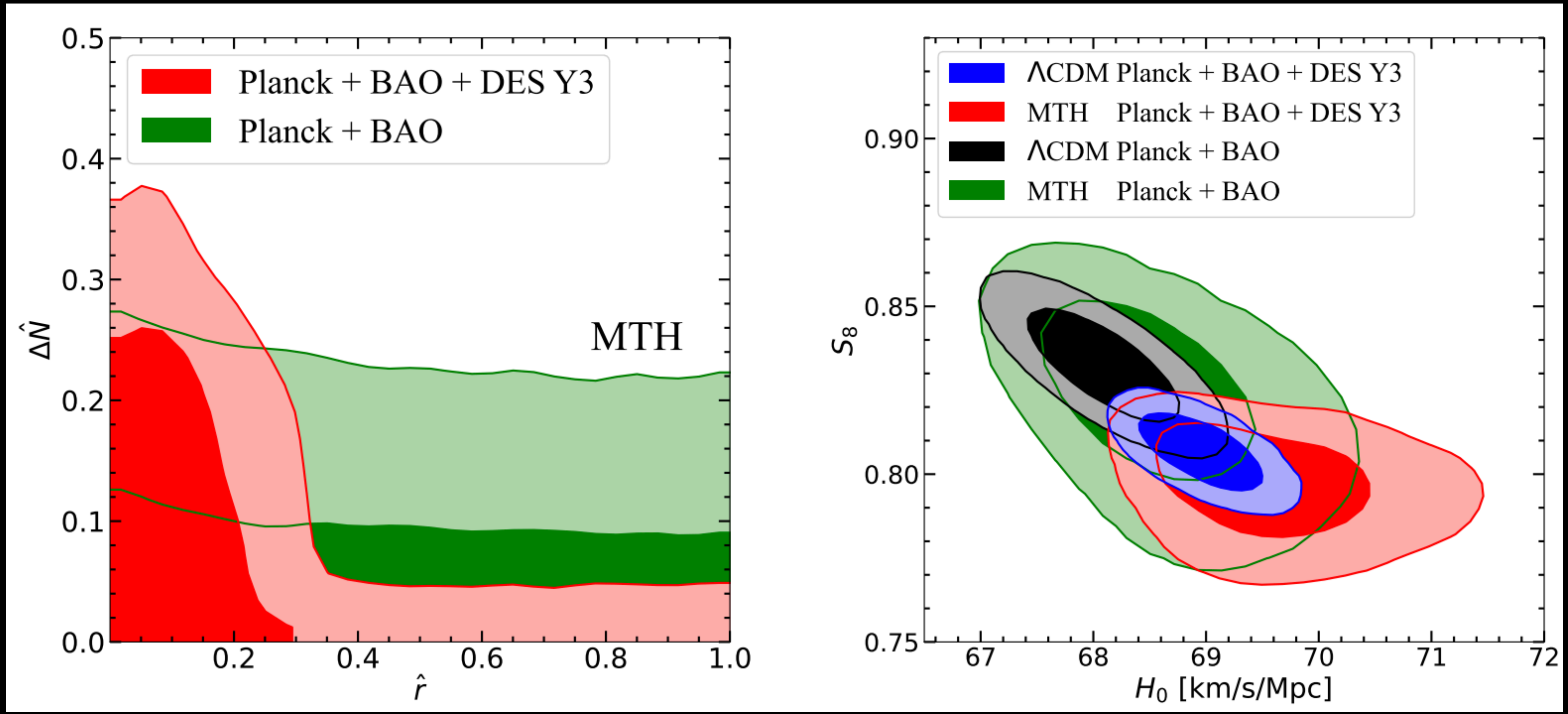
Weak lensing constraint from DES Y3

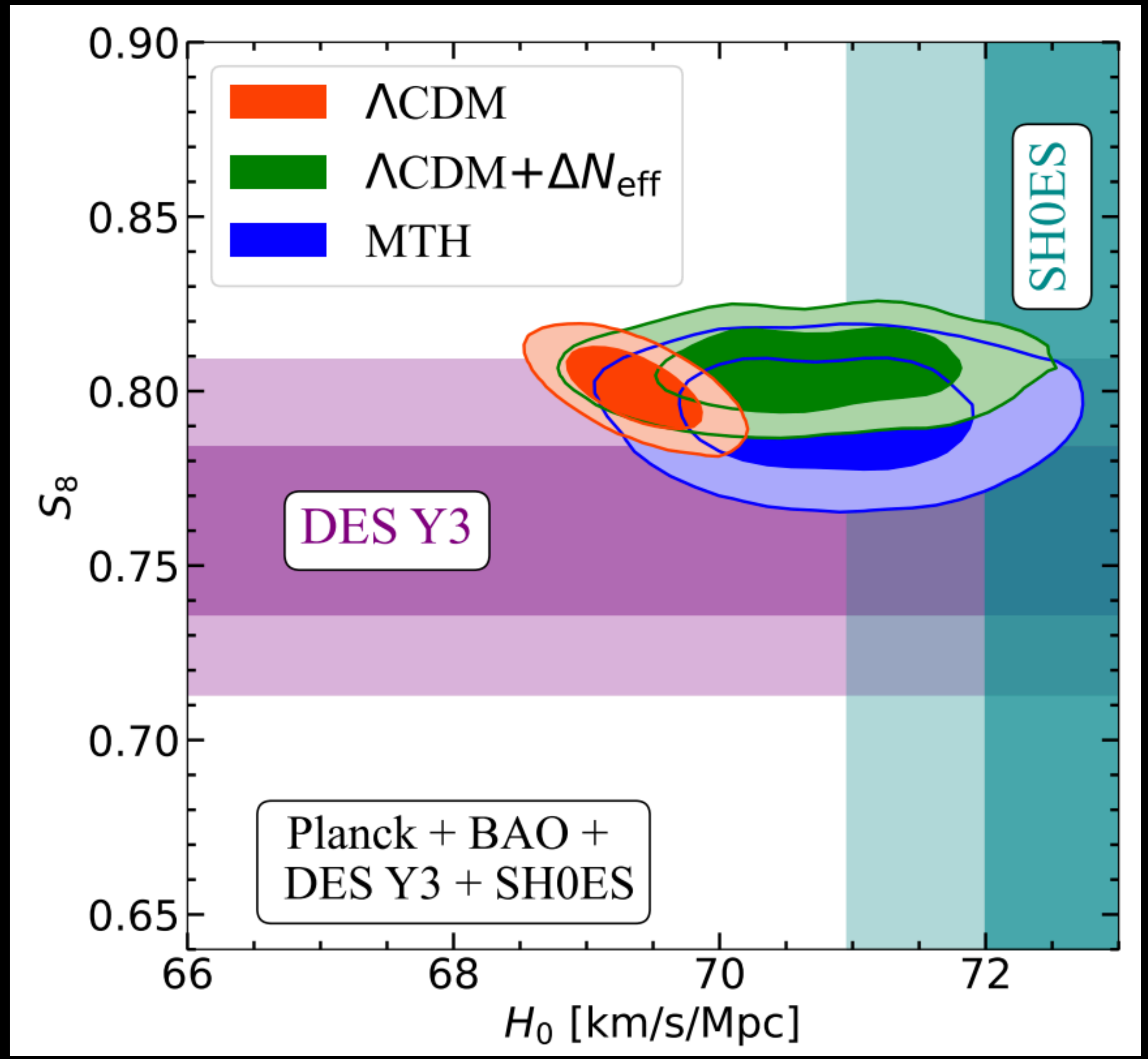


- Compare non-linear corrections w/ N-body simulation (Gadget3) vs. HMCode in CLASS
- Agree reasonably well, use HMCode for the MCMC analysis

Zu, Zhang, Chen, Wang, Tsai, **YT**, Luo, Yuan, Fan (2023)

Current constraints on the mirror twin Higgs model



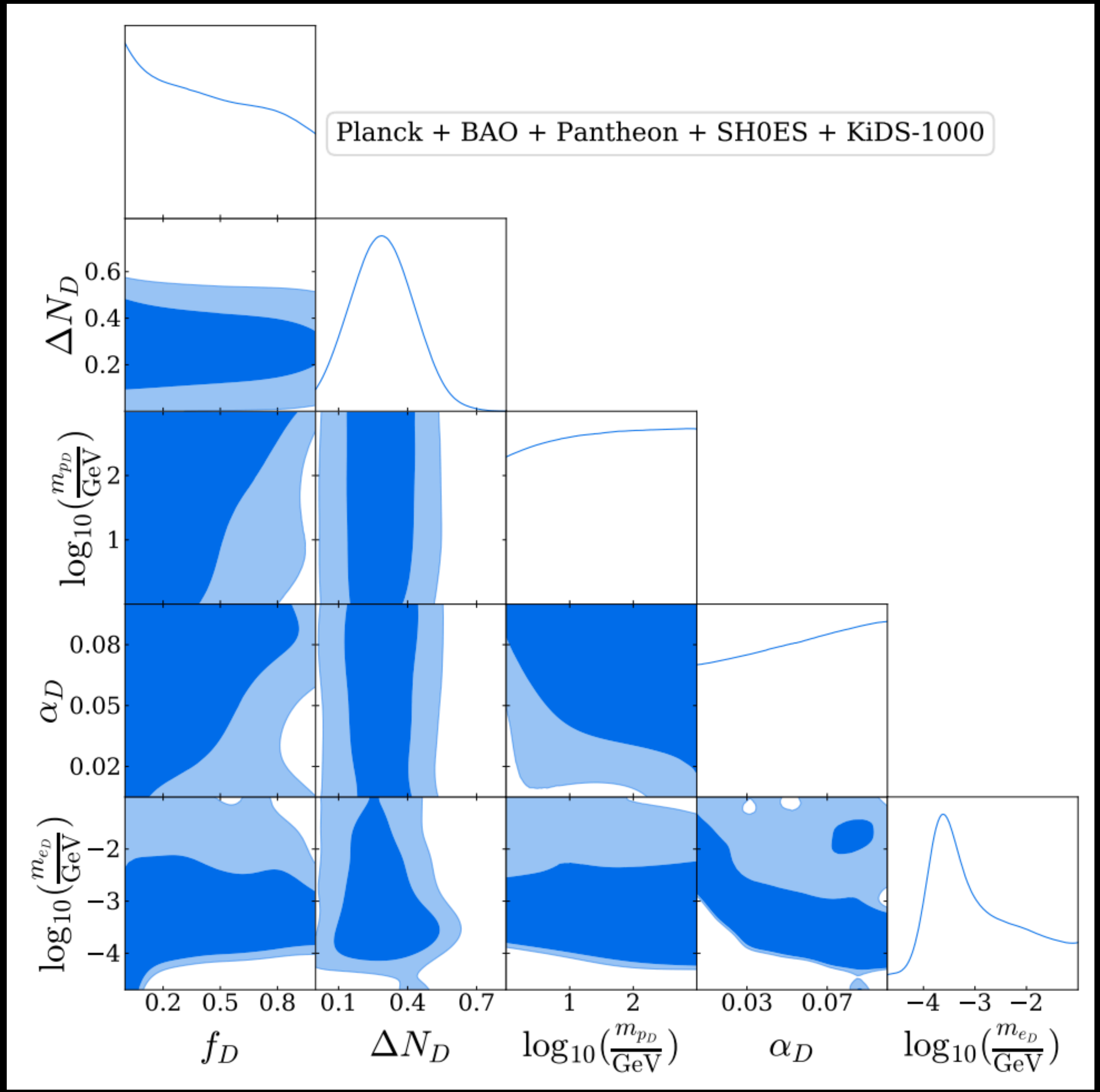


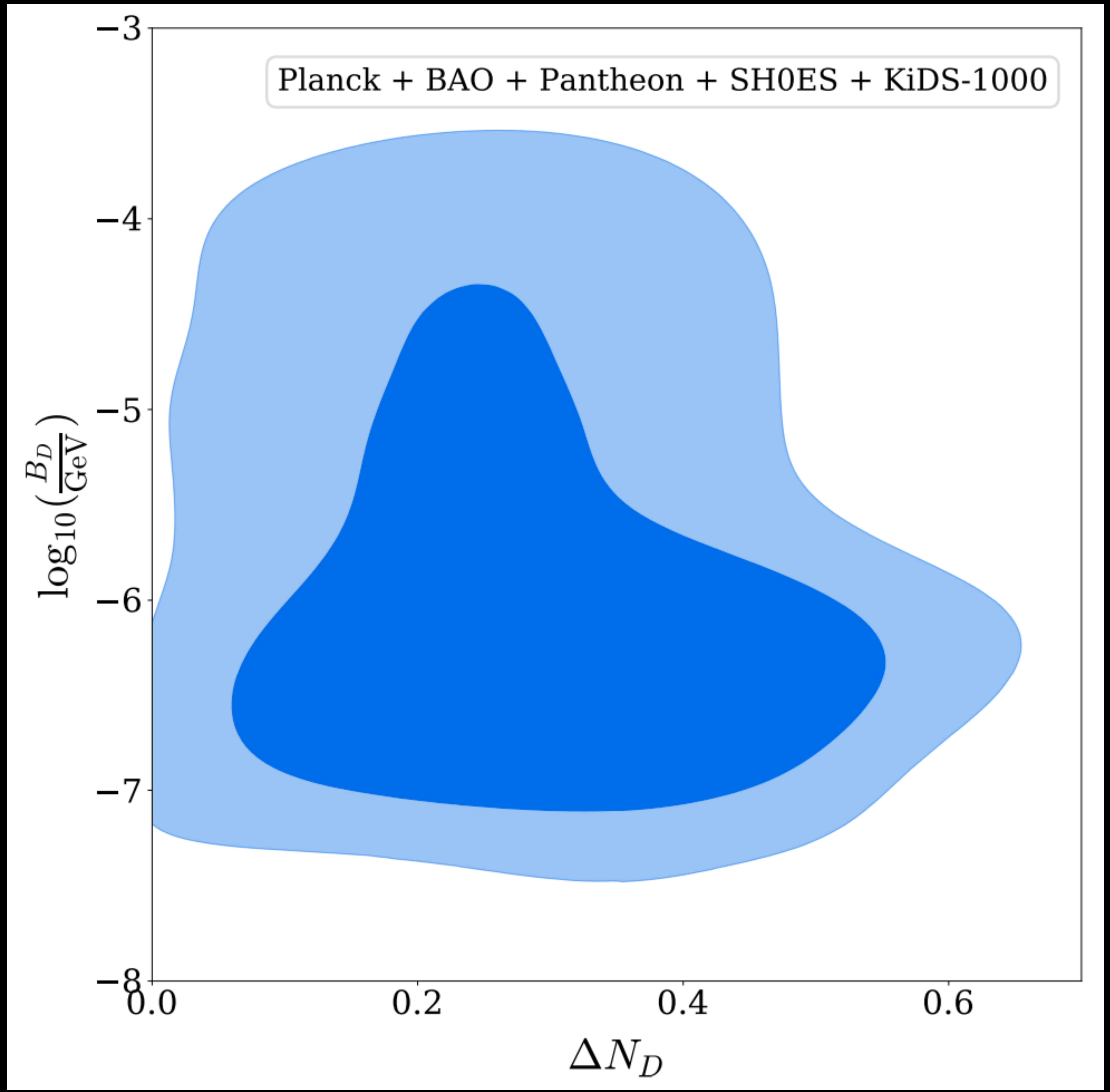
Zu, Zhang, Chen, Wang, Tsai, **YT**, Luo, Yuan, Fan (2023)

Bounds on more generic Atomic DM models

If including SH0ES & S_8 from KiDS-1000 in the fit

Bansal, Barron, Curtin, **YT** (2023)





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Phase shift on the CMB spectrum:

Scattering radiation + DM loading effect

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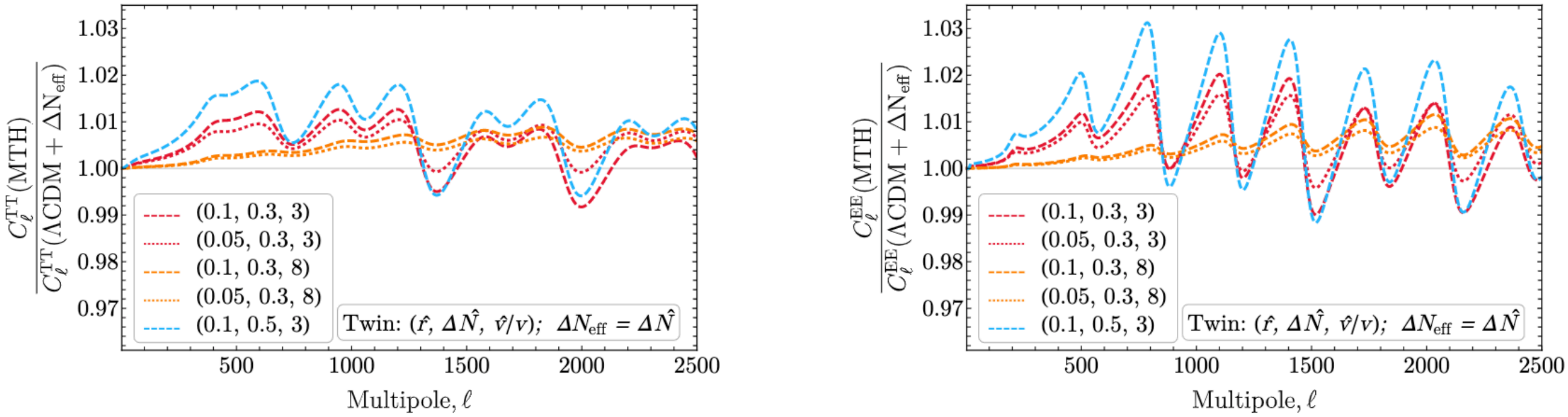
MTH particles modify the CMB spectra

Taking a ratio to the $\Lambda\mathrm{CDM} + \Delta N_{\mathrm{eff}}$ (fix θ_s)

Ratio $\gtrsim 1$, less diffusion damping than FS radiation



1~3% deviation is visible in the Planck data

Bansal, Kim, Kolda, Low, **YT** (2022)

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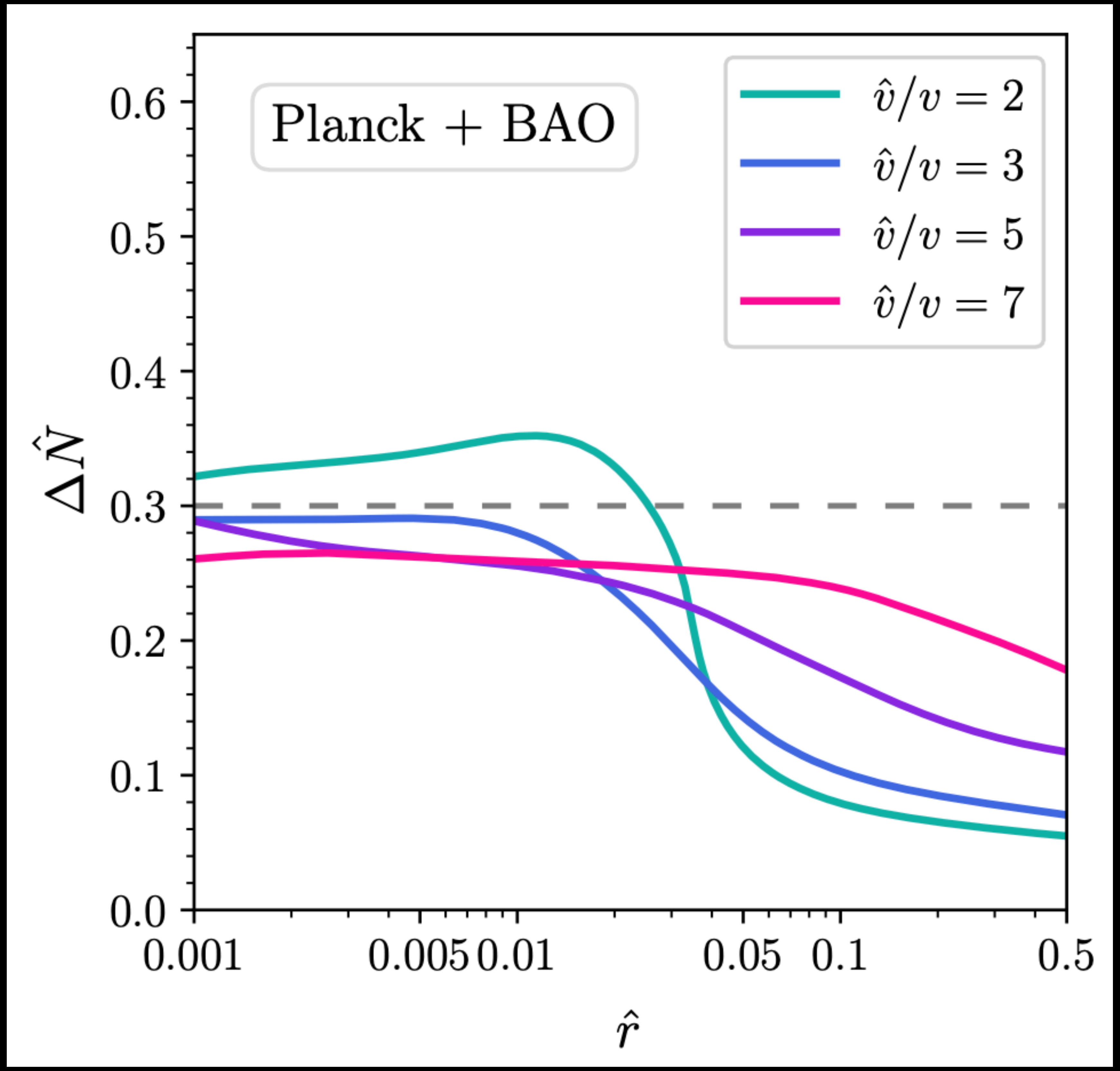
MTH particles modify the CMB spectra

Taking a ratio to the $\Lambda\text{CDM} + \Delta N_{\text{eff}}$ (~isolate changes in Silk damping)



ΔN_{eff} bound gets stronger

with larger mirror baryon abundance

Bansal, Kim, Kolda, Low, **YT** (2022)

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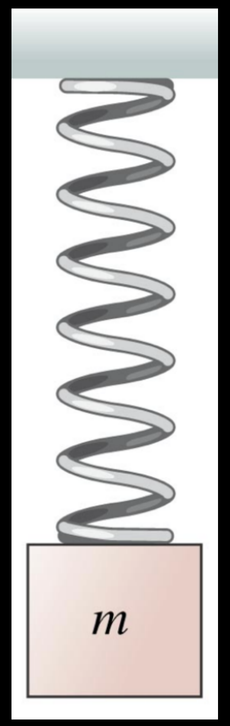
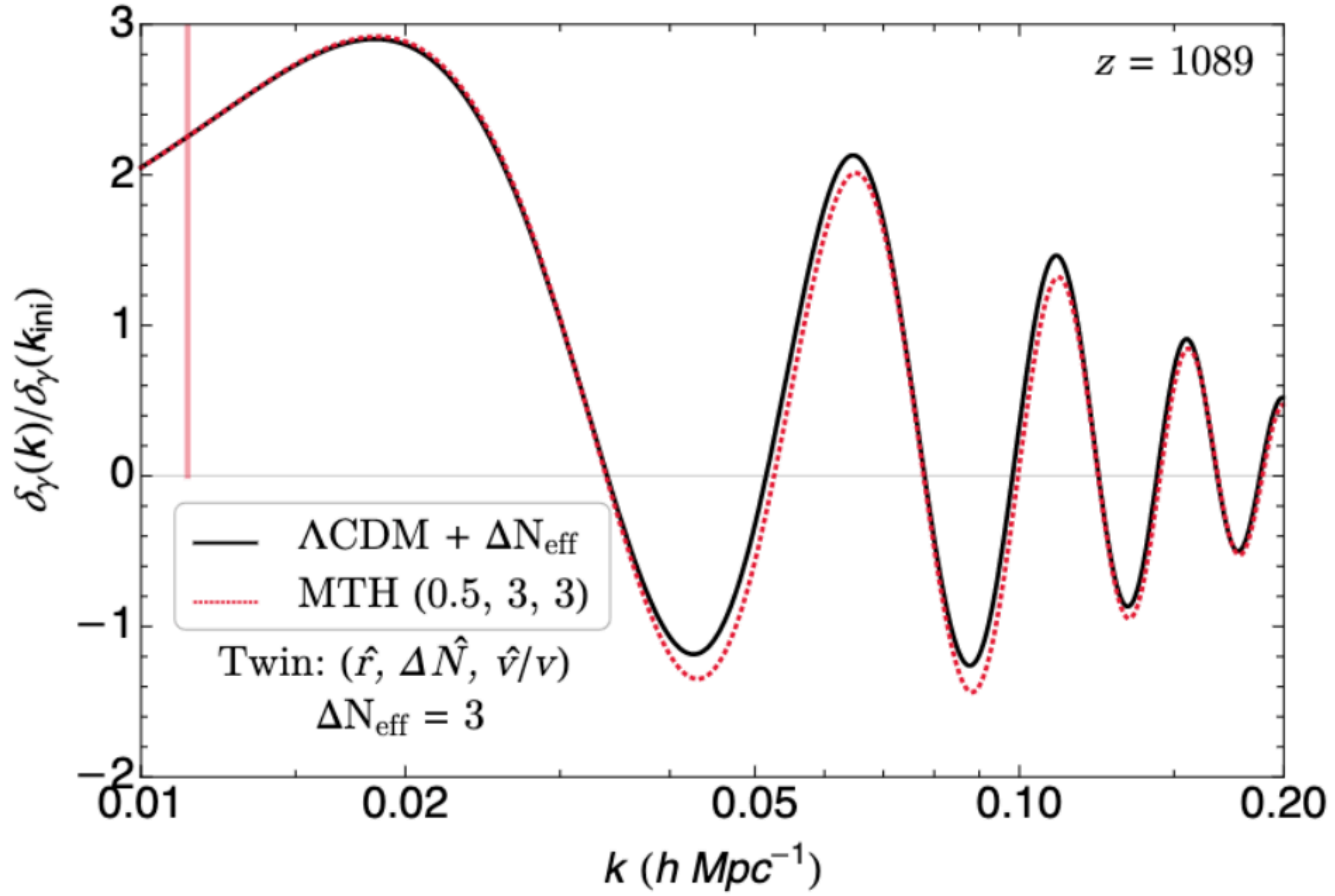
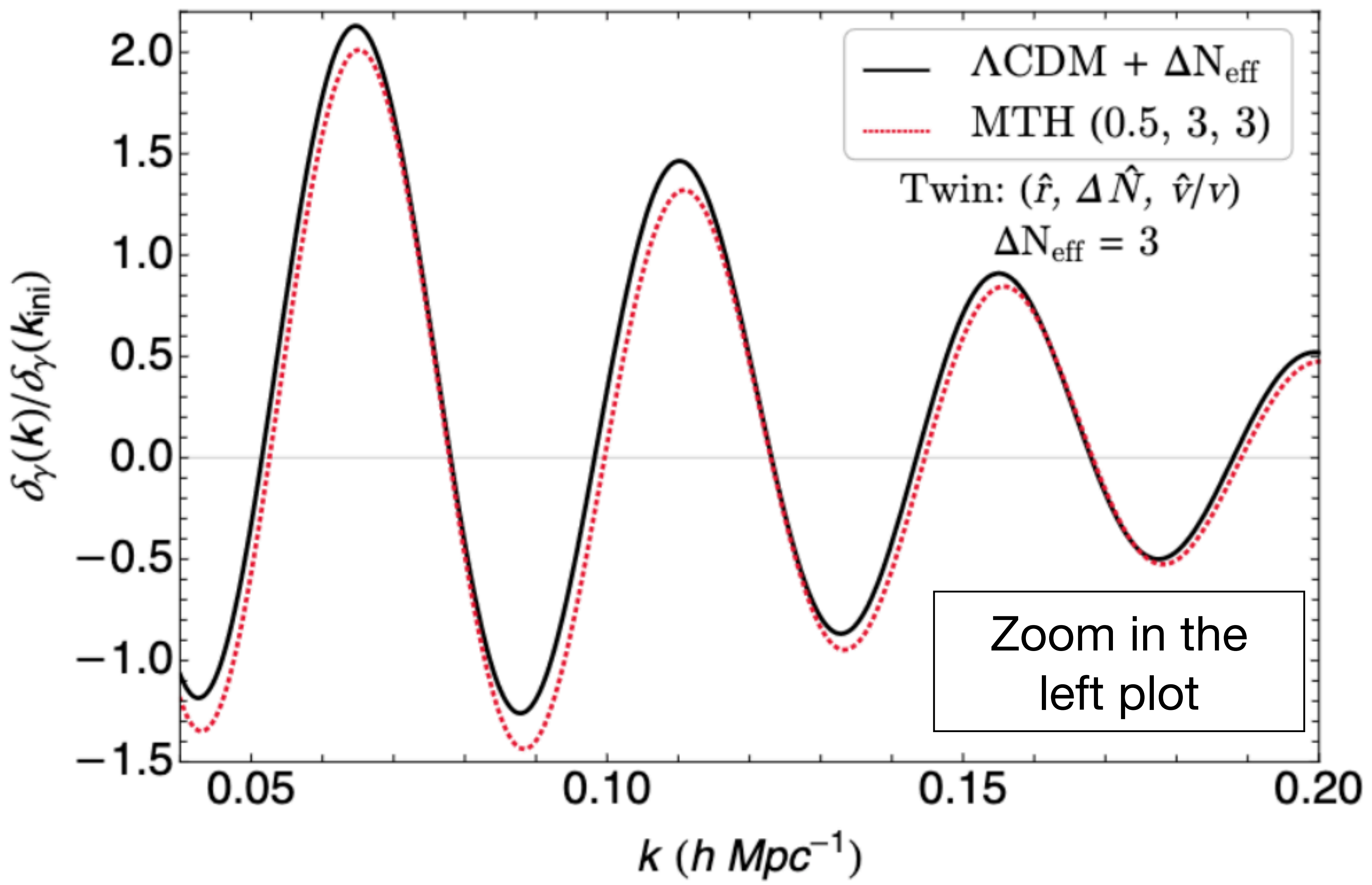
Corrections to the CMB spectrum: DAO



The dark acoustic oscillations suppress gravity perturbation

=> shifts the equilibrium point of photon oscillations

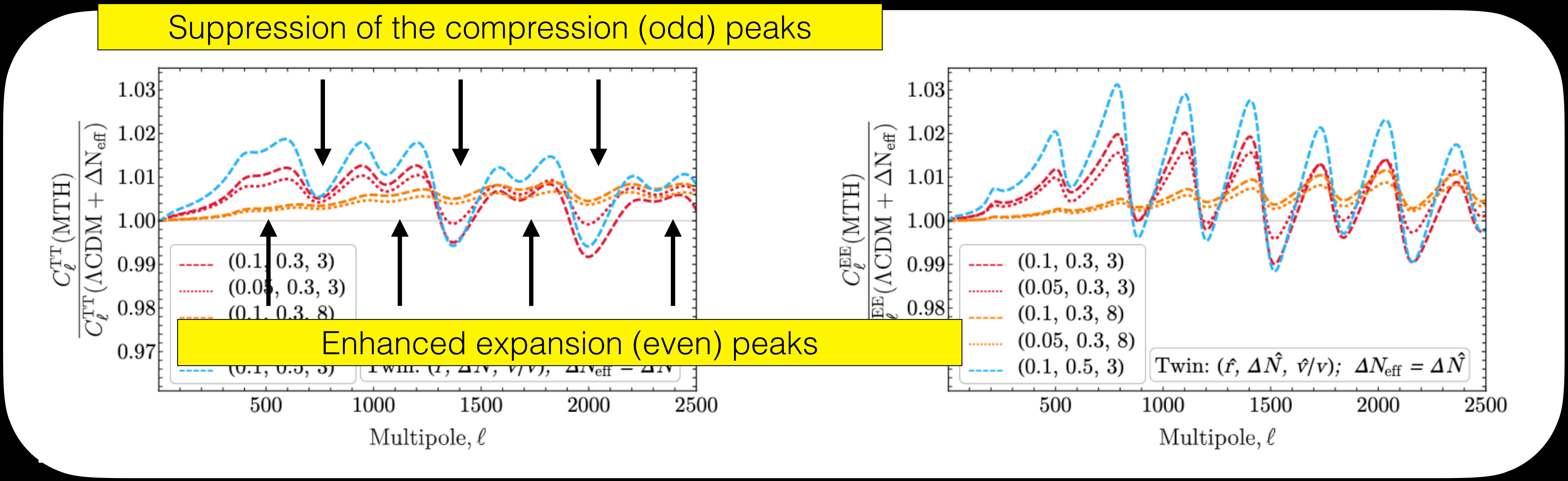




Increase the expansion modes and decrease the contraction modes

MTH particles modify the CMB spectra

Taking a ratio to the $\Lambda\text{CDM} + \Delta N_{\text{eff}}$ (fix θ_s)



Phase shift further complex the spectrum

Bansal, Kim, Kolda, Low, **YT** (2022)

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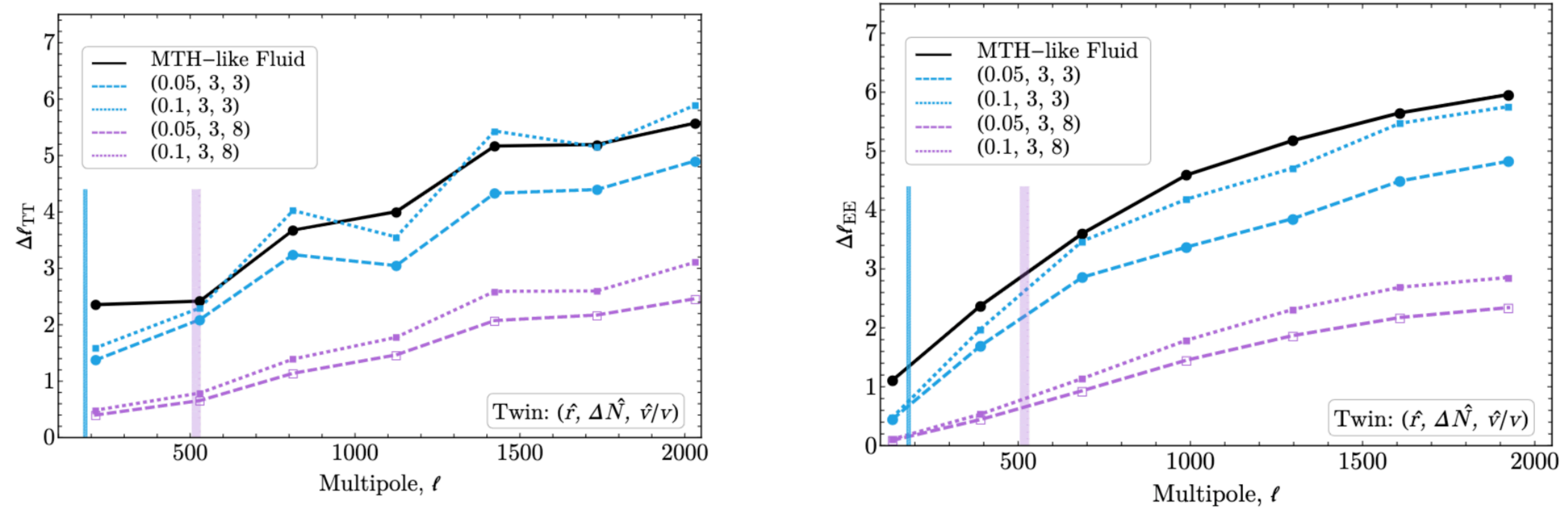
Corrections to the CMB spectrum: phase shift

Mirror photon behaves as scattering fluid,

generating a different phase shift compared to free-streaming radiation

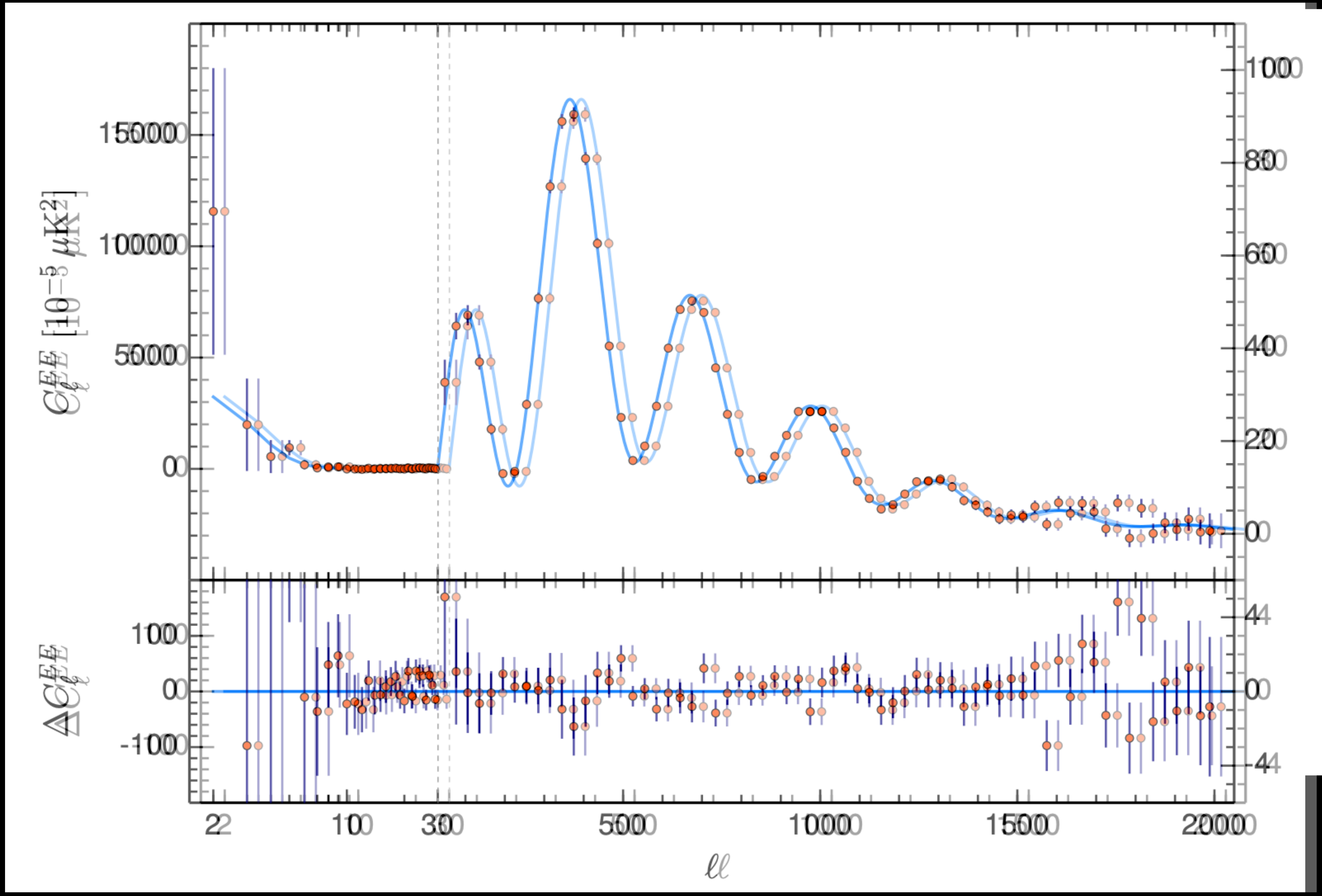
$\delta\ell_{\mathrm{peak}}$ compared to ΛCDM w/ 3 neutrinos



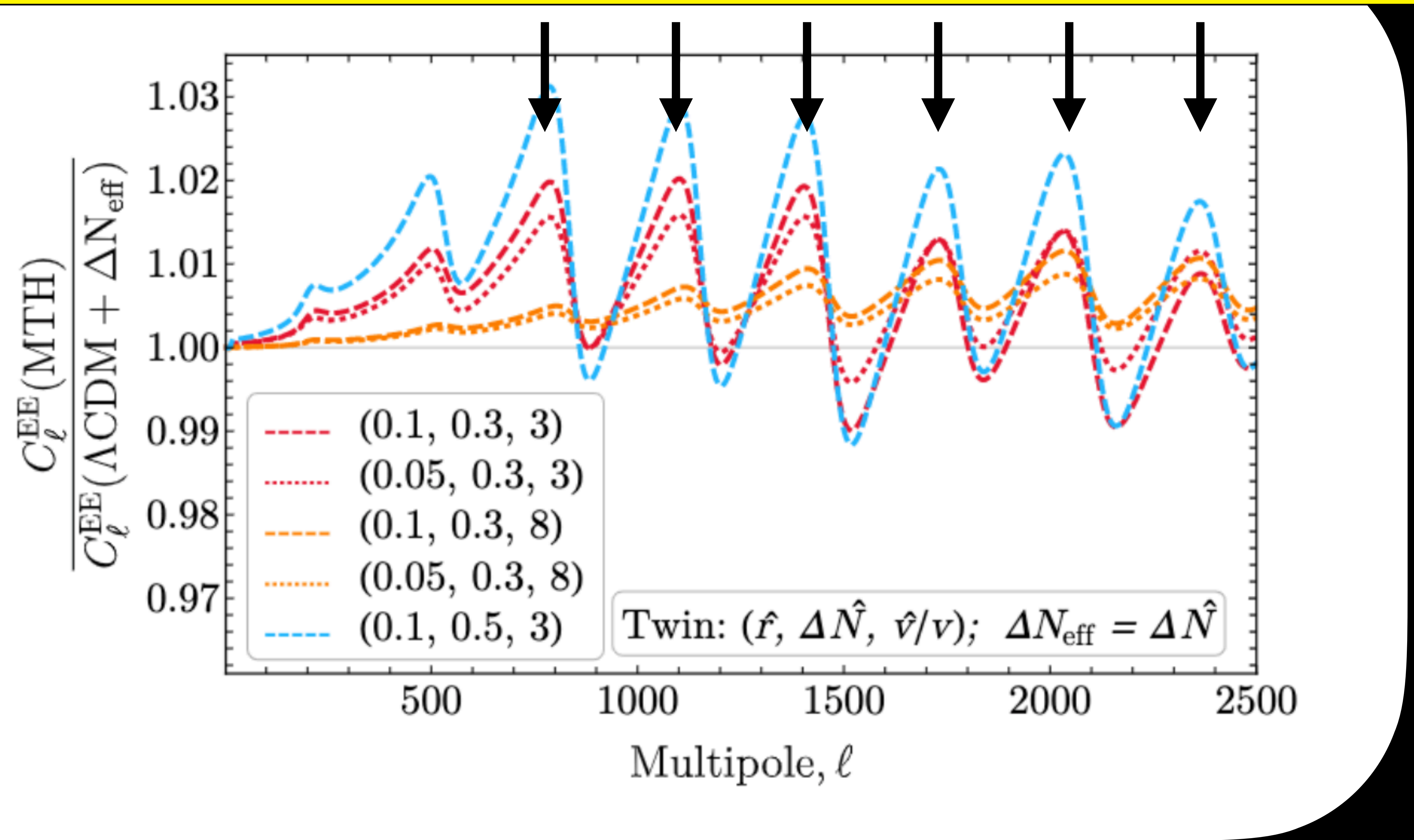
Larger phase-shift with higher mirror baryon abundance (why?)

MTH particles modify the CMB spectra

Taking a ratio to the $\Lambda\text{CDM} + \Delta N_{\text{eff}}$ (fix θ_s)



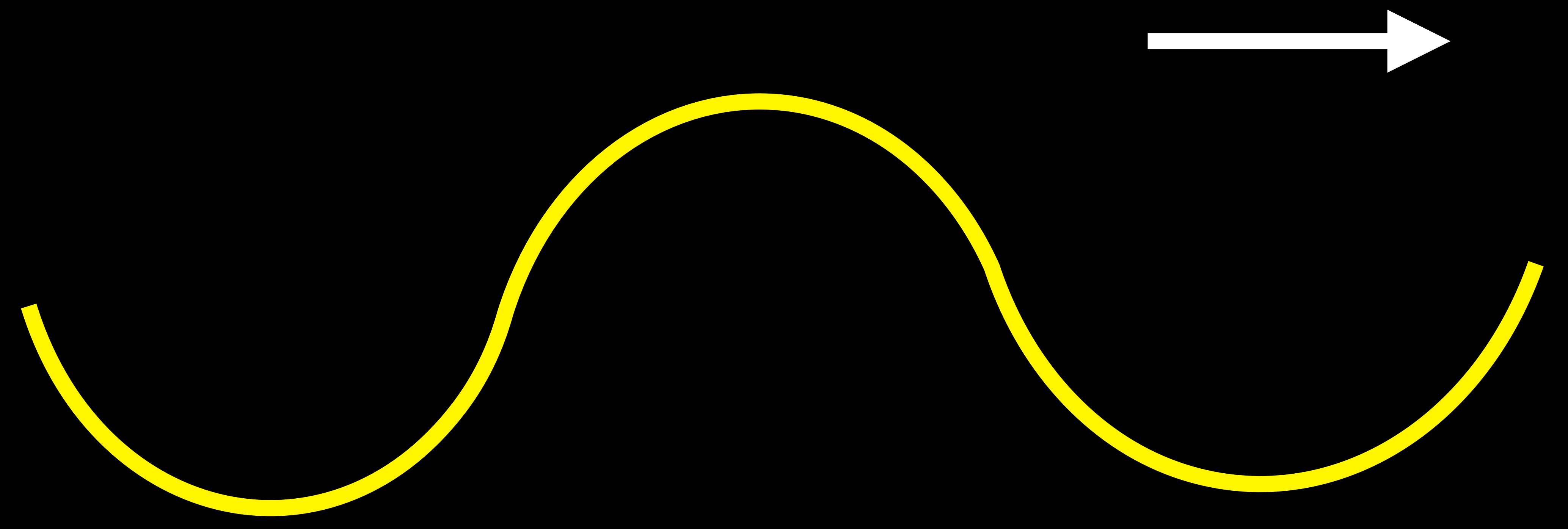
Phase shift gives enhancement to the "thrusts"



Bansal, Kim, Kolda, Low, **YT** (2022)

Corrections to the CMB spectrum: phase shift

Sound wave of the SM photon-baryon plasma



Photon wave has sound speed

$$c_s^2 \gtrsim \frac{1}{3}$$

(deep radiation dominant era)

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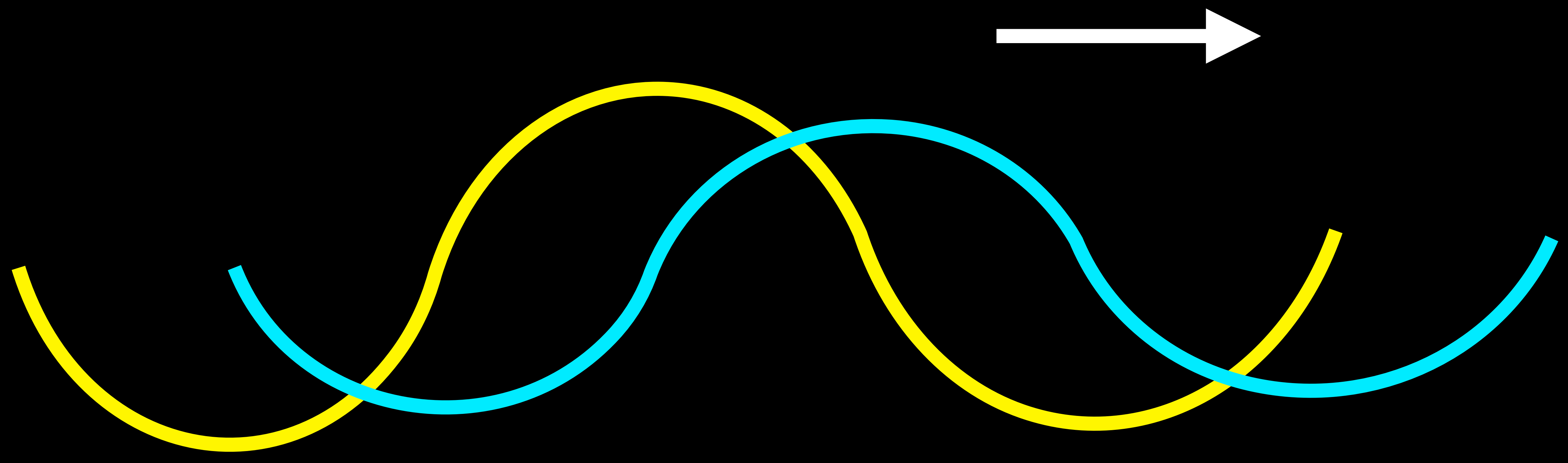
Corrections to the CMB spectrum: phase shift

When propagating alone with free-streaming radiation

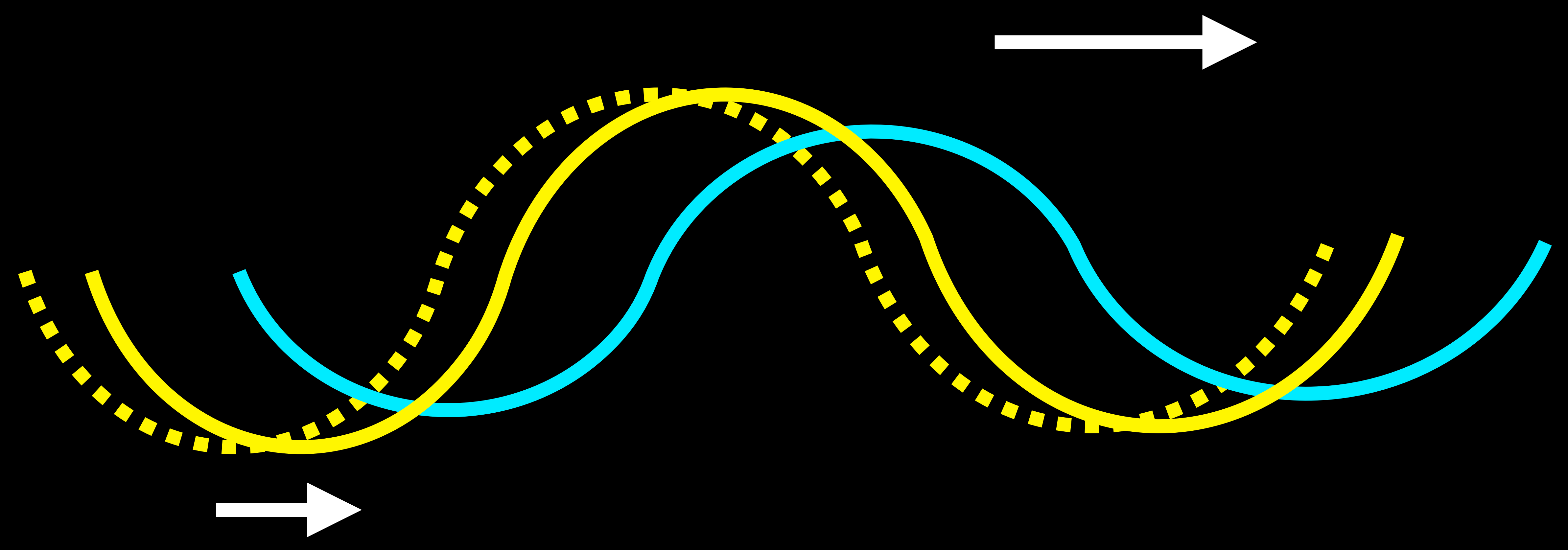


Free-streaming radiation,

$$c_s^2 = 1 > c_{s,\gamma}^2$$

Corrections to the CMB spectrum: phase shift

When propagating alone with free-streaming radiation



Phase shift

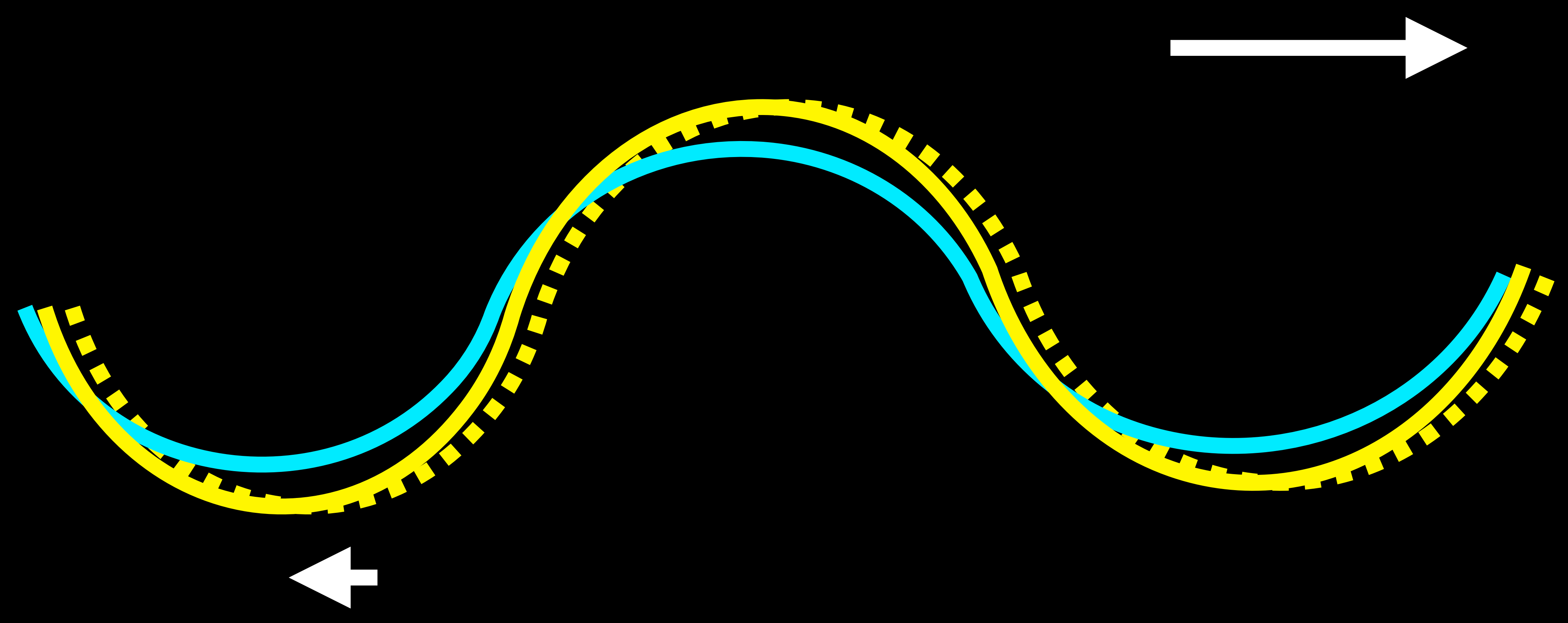
Free-streaming radiation,

$$c_s^2 = 1 \; > c_{s,\gamma}^2$$

~enlarge the sound horizon, shift CMB spectrum to lower ℓ-modes

Corrections to the CMB spectrum: phase shift

When propagating alone with perfect fluid



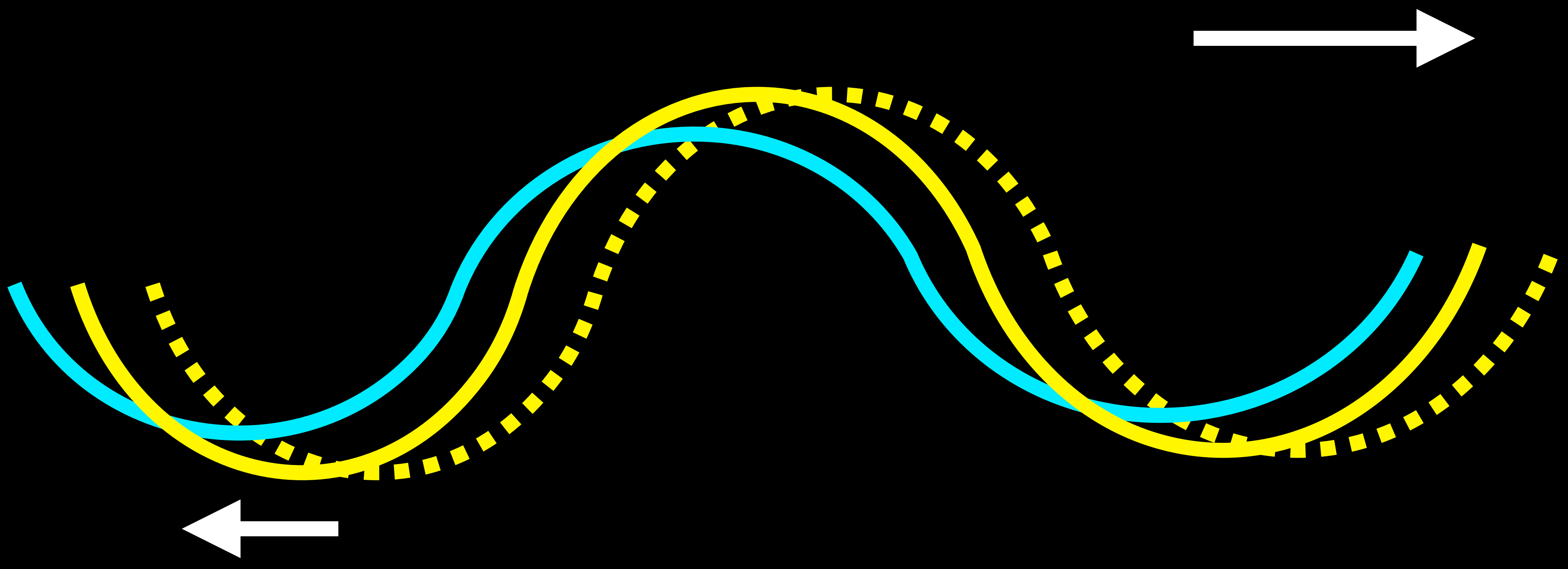
$c^2_{s,\mathrm{DR}} \lesssim c^2_{s,\gamma}$

Drag photon wave back a bit

Compared to ΛCDM with FS neutrinos, the CMB peaks shift to higher ℓ-modes

Corrections to the CMB spectrum: phase shift

When propagating alone with perfect fluid with **DM scattering**



DR propagates slower than the perfect fluid $c^2_{s,\mathrm{DR}} \ll c^2_{s,\gamma}$

Compared to ΛCDM with FS neutrinos, the CMB peaks shift to **EVEN** higher ℓ-modes

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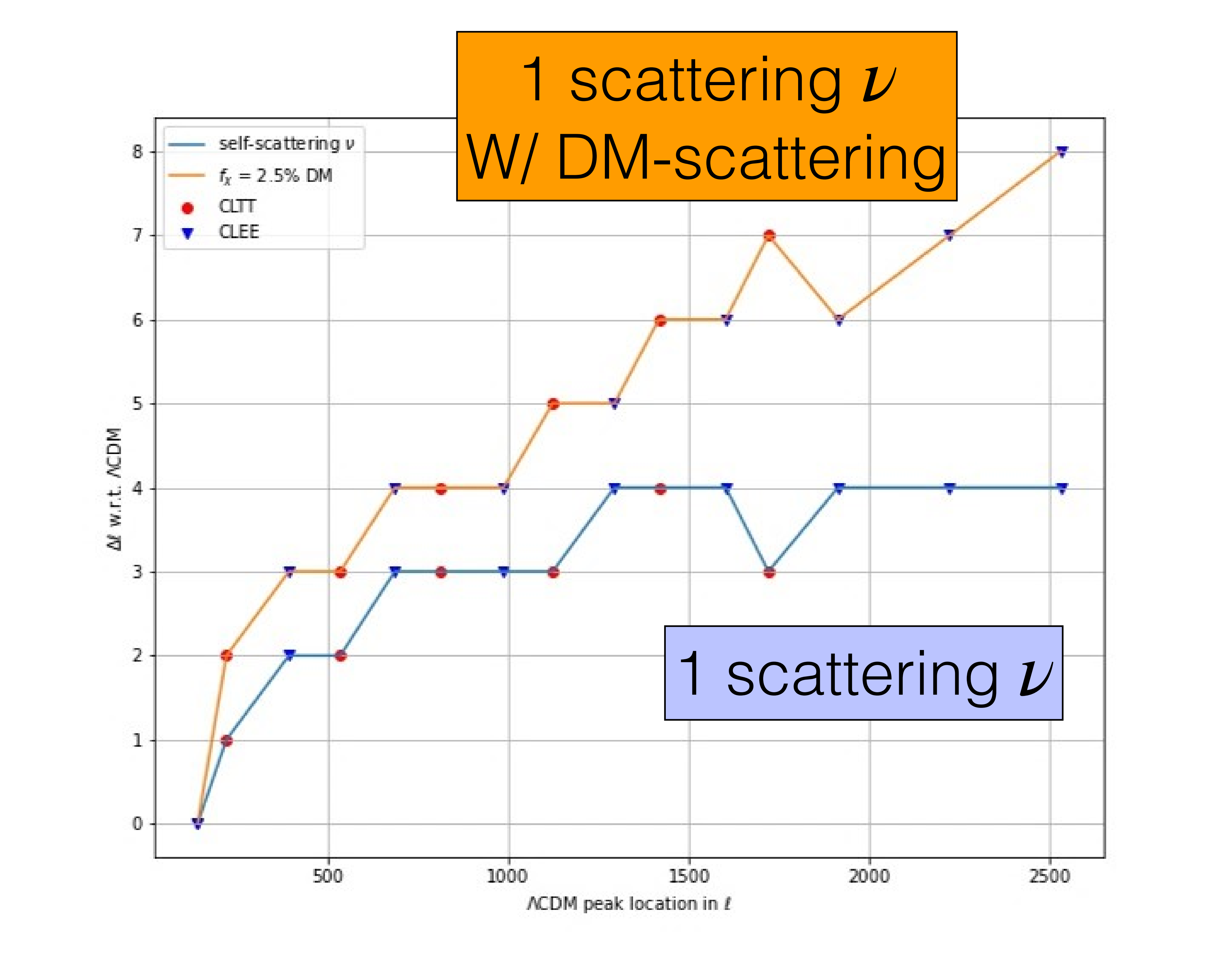
Example: neutrino or DR couples to a fraction of DM

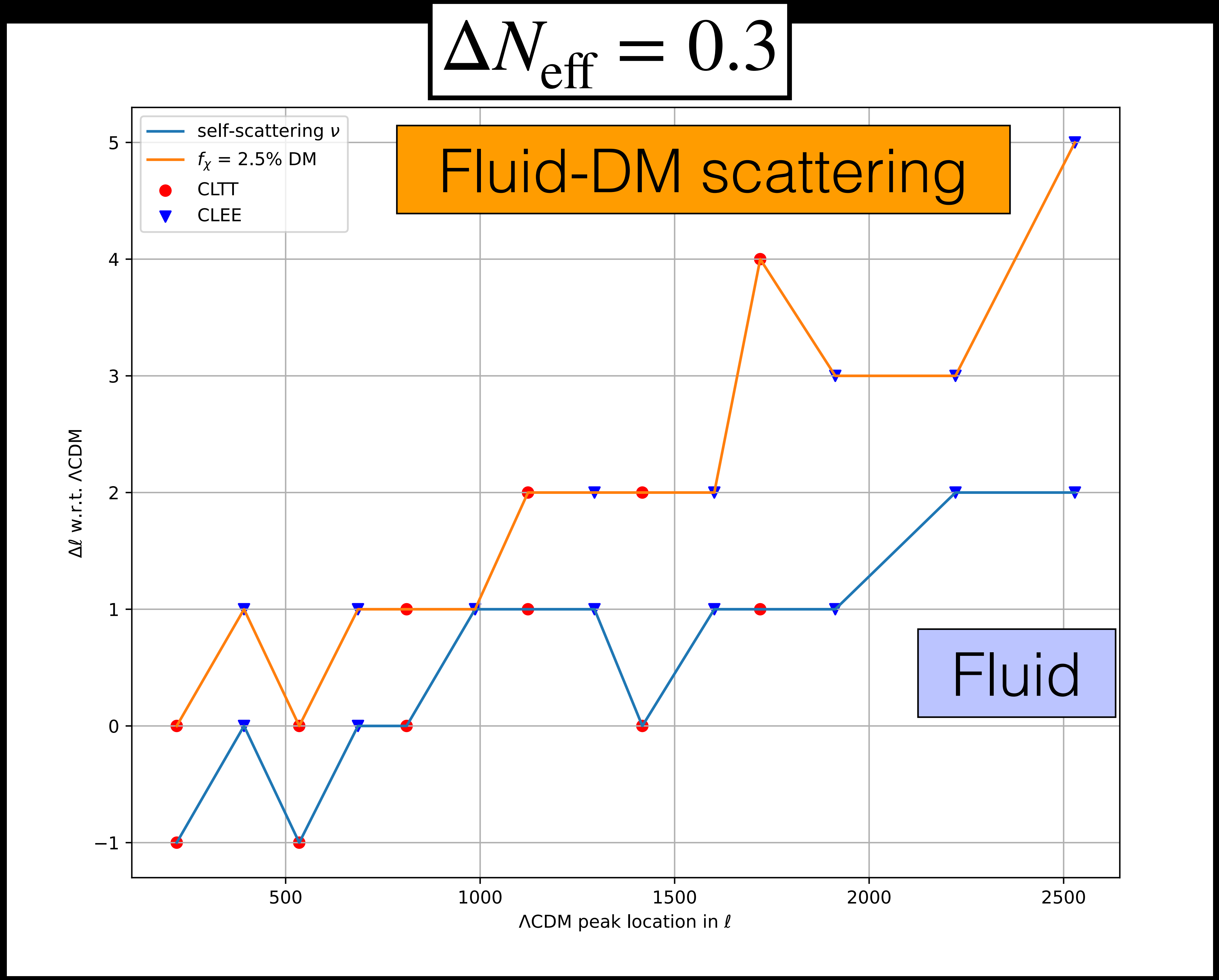
Ho, Ghosh, **YT** (in progress)

$\delta\ell_{\rm peak}$ compared to free-streaming neutrinos



TTEE power spectrum peak location

$\delta\ell_{\rm peak}$ compared to free-streaming neutrinos



TTEE power spectrum peak location

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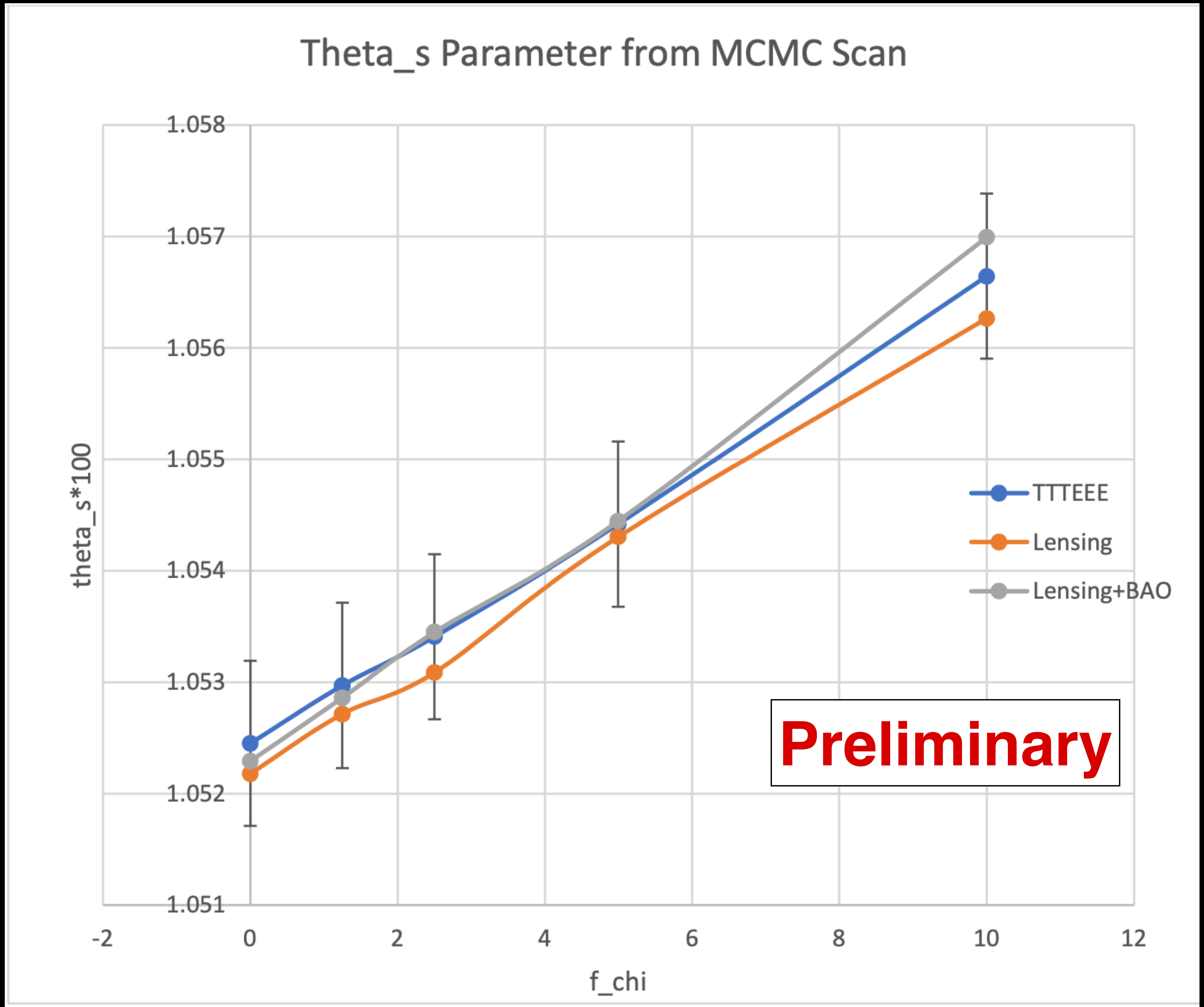
Phase shift from the MCMC study



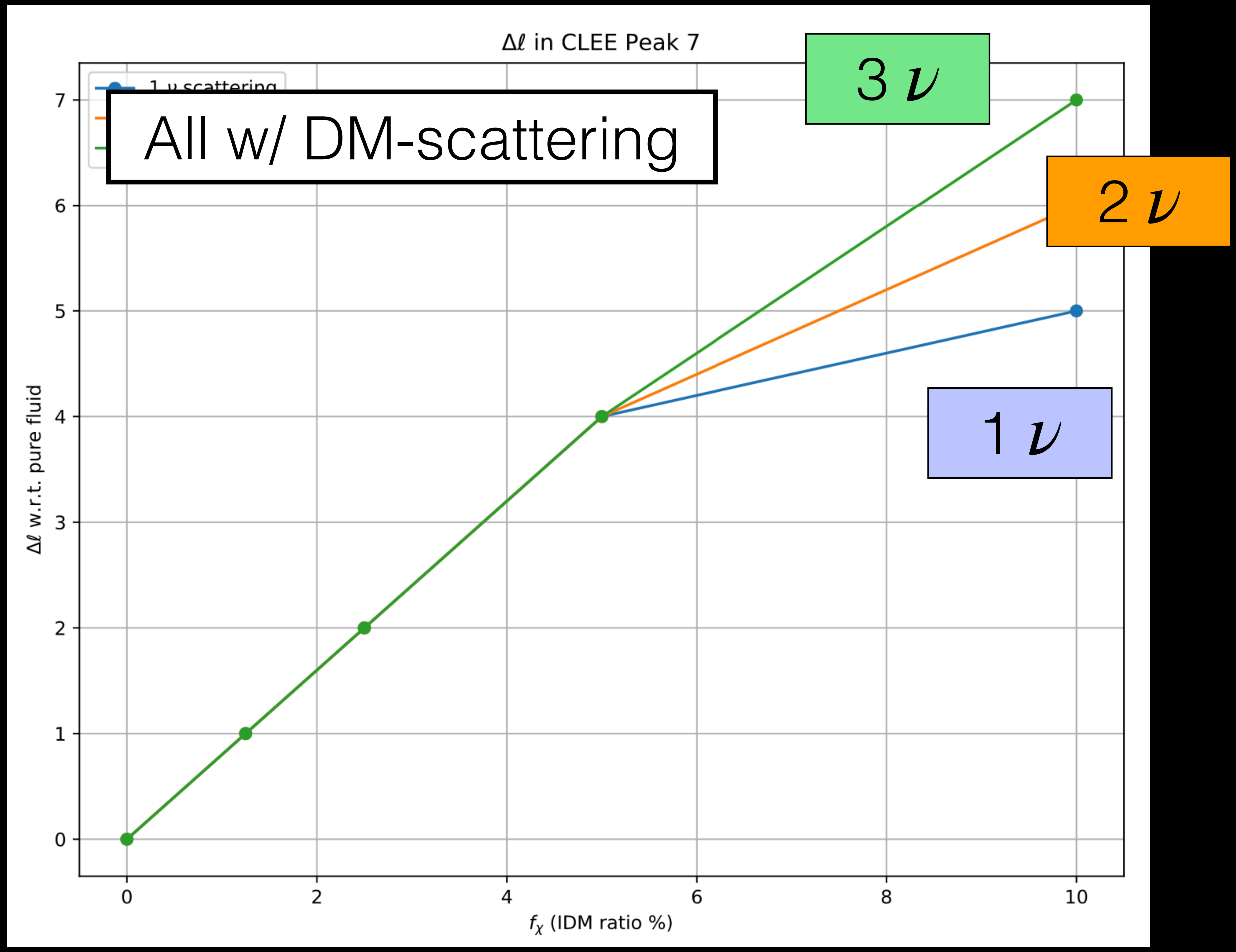
Ho, Ghosh, **YT** (in progress)

Can analytically show

If energy density of scattering DM < DR

- The extra phase shift compared to fluid (w/o DM scattering) is proportional to $\rho_{\text{scatt DM}}$
- Insensitive to DR abundance $\rho_{\text{scatt DR}}$
- If having N scattering DM-DR system, the extra phase shift is determined by the sum $\sum_i^N \rho_{i,\text{scatt DM}}$

$\delta\ell_{\text{peak}}$ compared to **fluid-like** neutrinos



Fraction of scattering DM

Summary

- Dark sector with an approximated mirror symmetry to the SM is well motivated

IDM = mirror baryons | Dark fluid = mirror photons | Free-streaming = mirror neutrinos

- Together they generate unique features on the CMB and matter power spectra
- Dark Acoustic Oscillation (DAO) process
- Scattering radiation (mirror photon) with DM-loading
- Even more copies of mirror sectors? e.g., Cosmology of Nnaturalness model

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