LSS Signals from Solutions to the Higgs & Neutrino Hierarchy Problems

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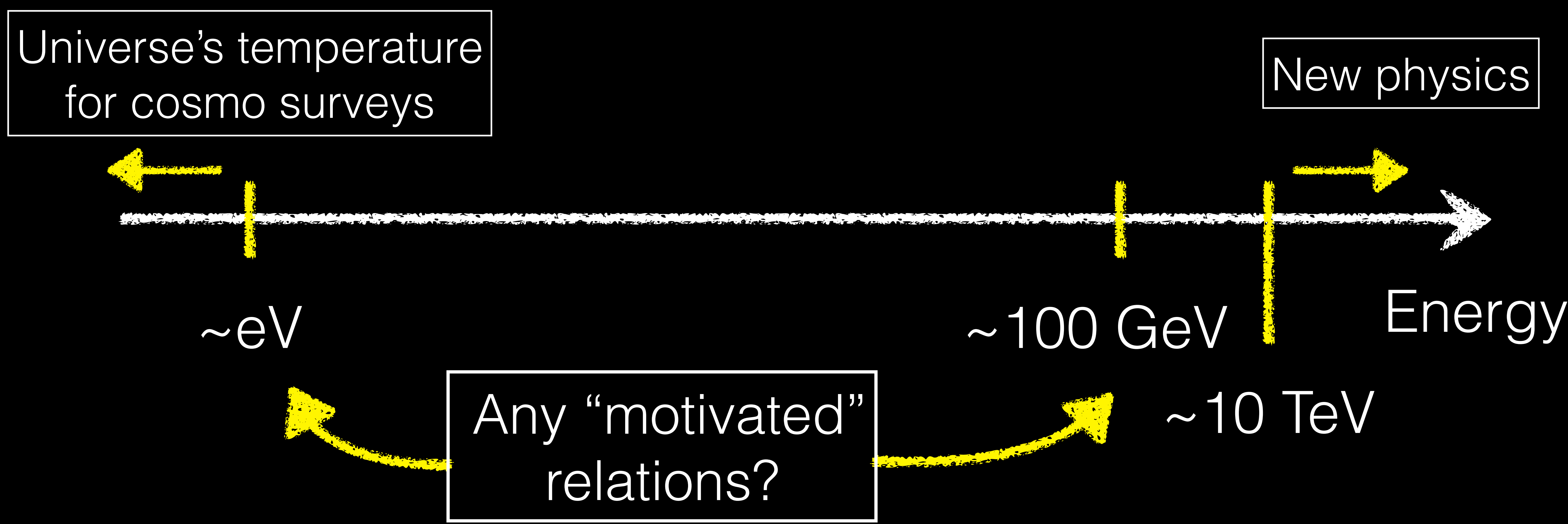
Fundamental Physics from Future Spectroscopic Surveys

LBNL 5/7/2024

Dark sector cosmology is crucial for several BSM scenarios that particle people have been thinking about



Mirror Twin Higgs

Higgs hierarchy problem

↓

Atomic DM

w/ more well-defined mass/coupling

N-naturalness

Higgs hierarchy problem

↓

Tower of WDM

w/ more well-defined Mass/temperature

Majoron

Tiny neutrino masses

↓

Neutrino decay

lifetime <-> mass generation scale

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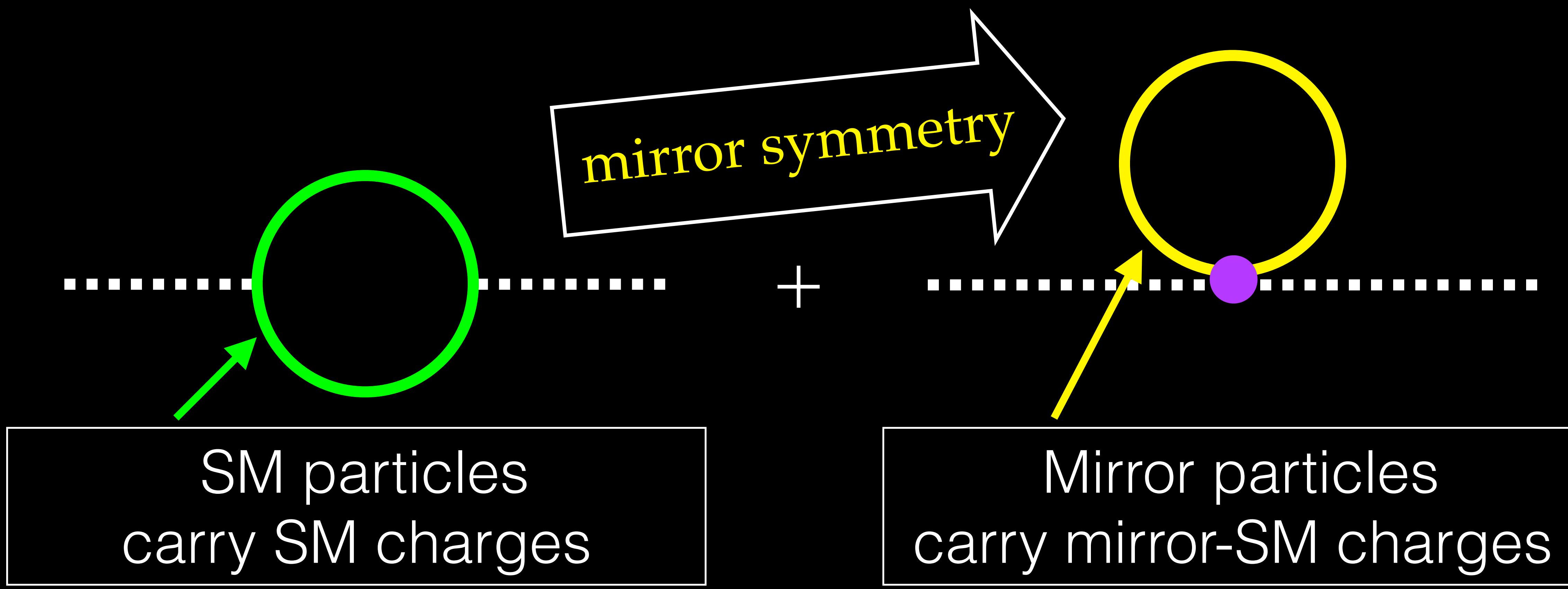
Twin Higgs Model: Chacko, Goh, Harnik (2005)

Addressing the Higgs hierarchy problem up to ~ 10 TeV scale



Mirror particles are invisible => relax LHC constraints

But… how do we examine it?

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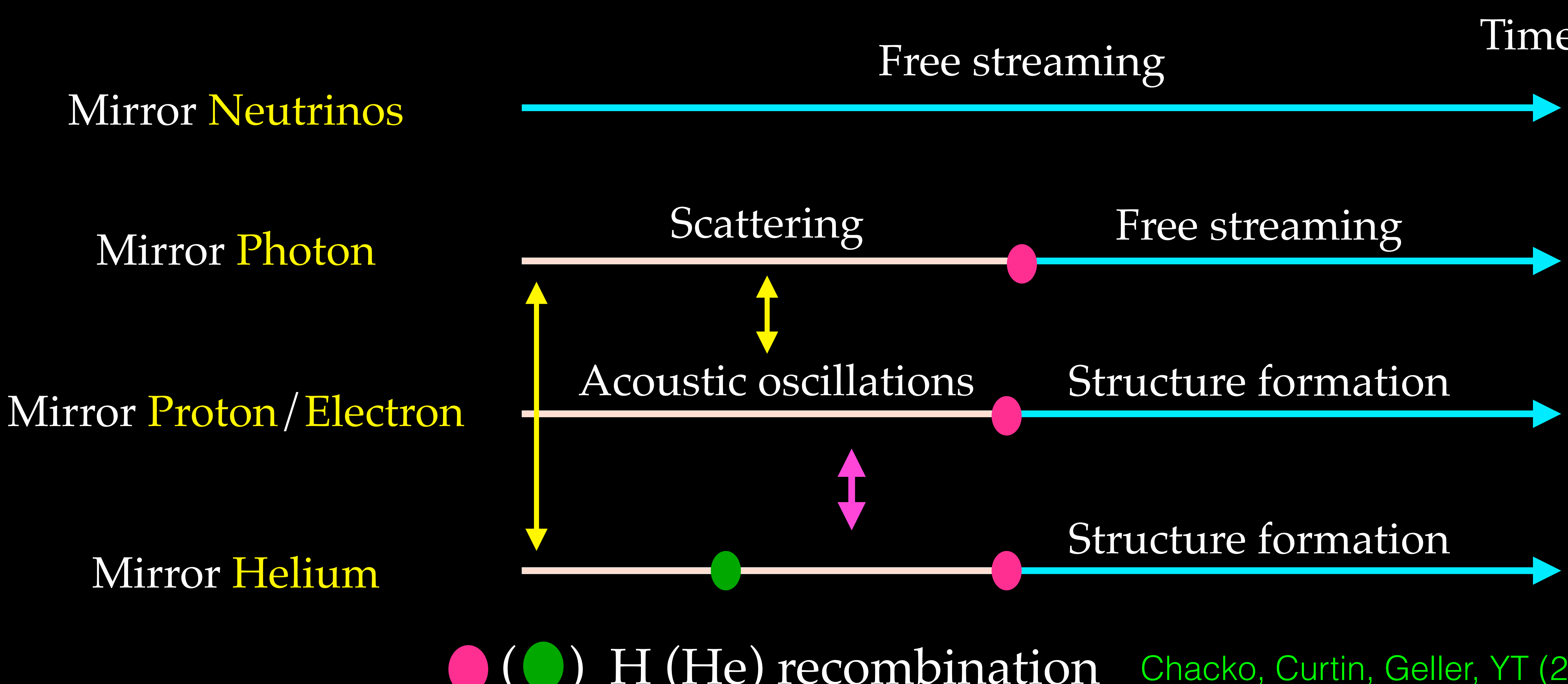
In turns of dark sector cosmology,

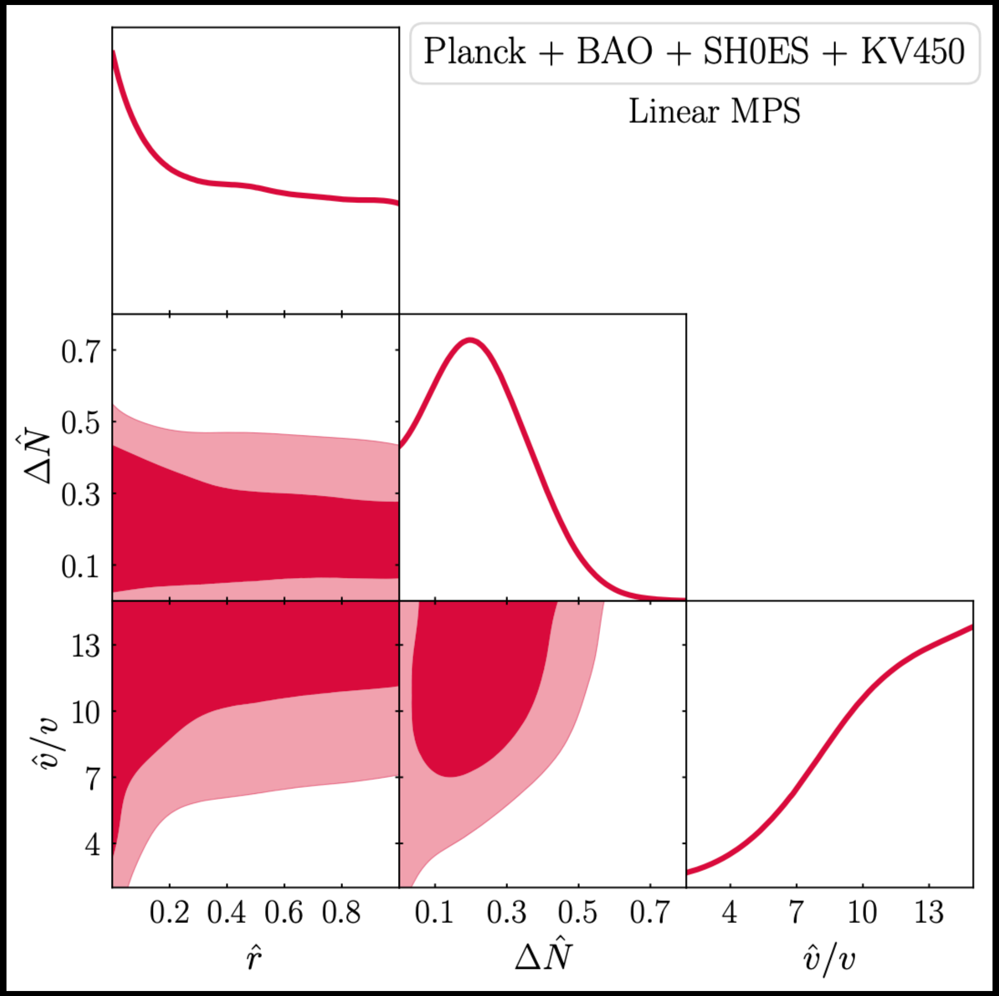
(more) well predicted dark particle masses/interactions

as a function of ($\Delta N_{\rm eff}$, $\dfrac{\hat{v}}{v} = \dfrac{\rm VEV_{mirror}}{\rm VEV_{SM}}$, $\hat{r} = \dfrac{\rho_{{\rm mirror}-b}}{\rho_{\rm total\,DM}}$)

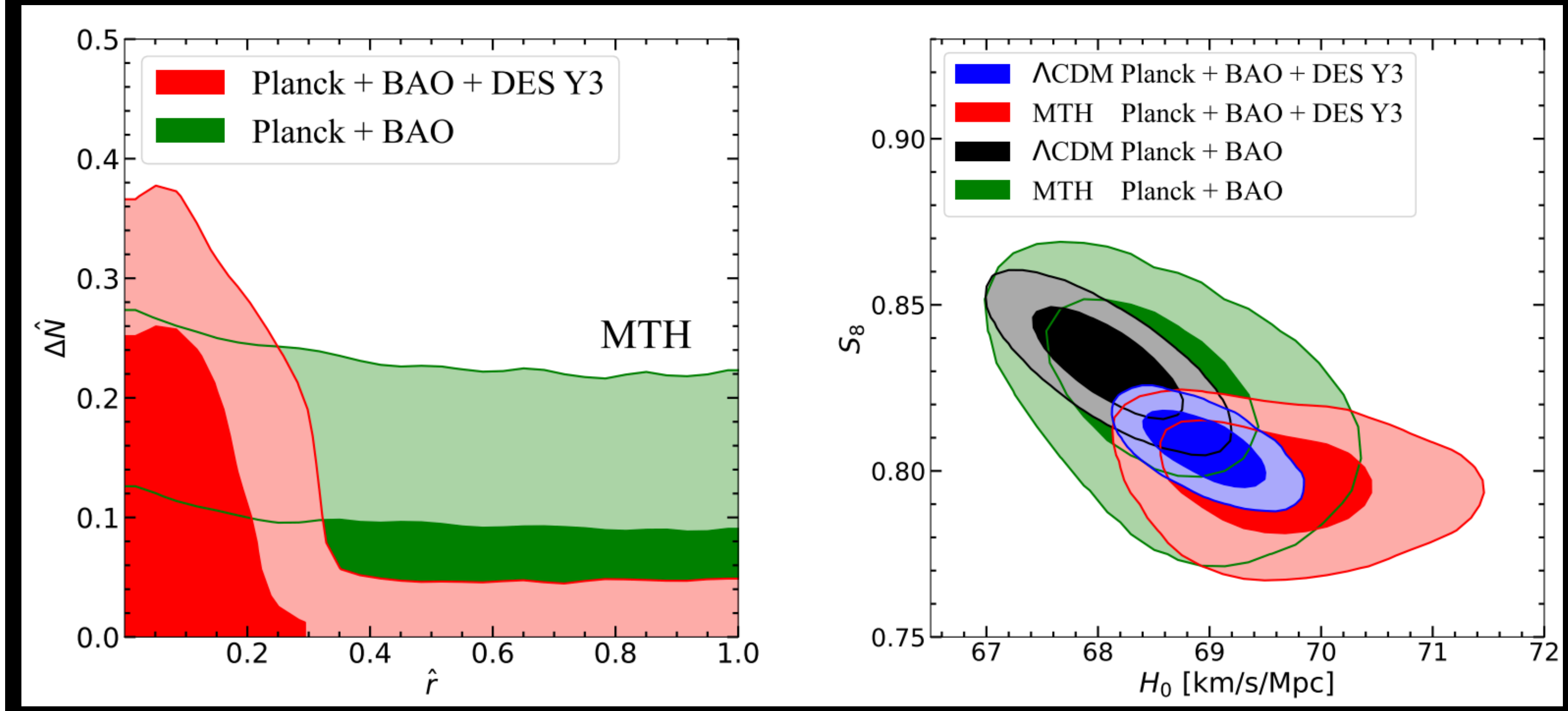


Chacko, Curtin, Geller, YT (2018)

Existing cosmo bounds

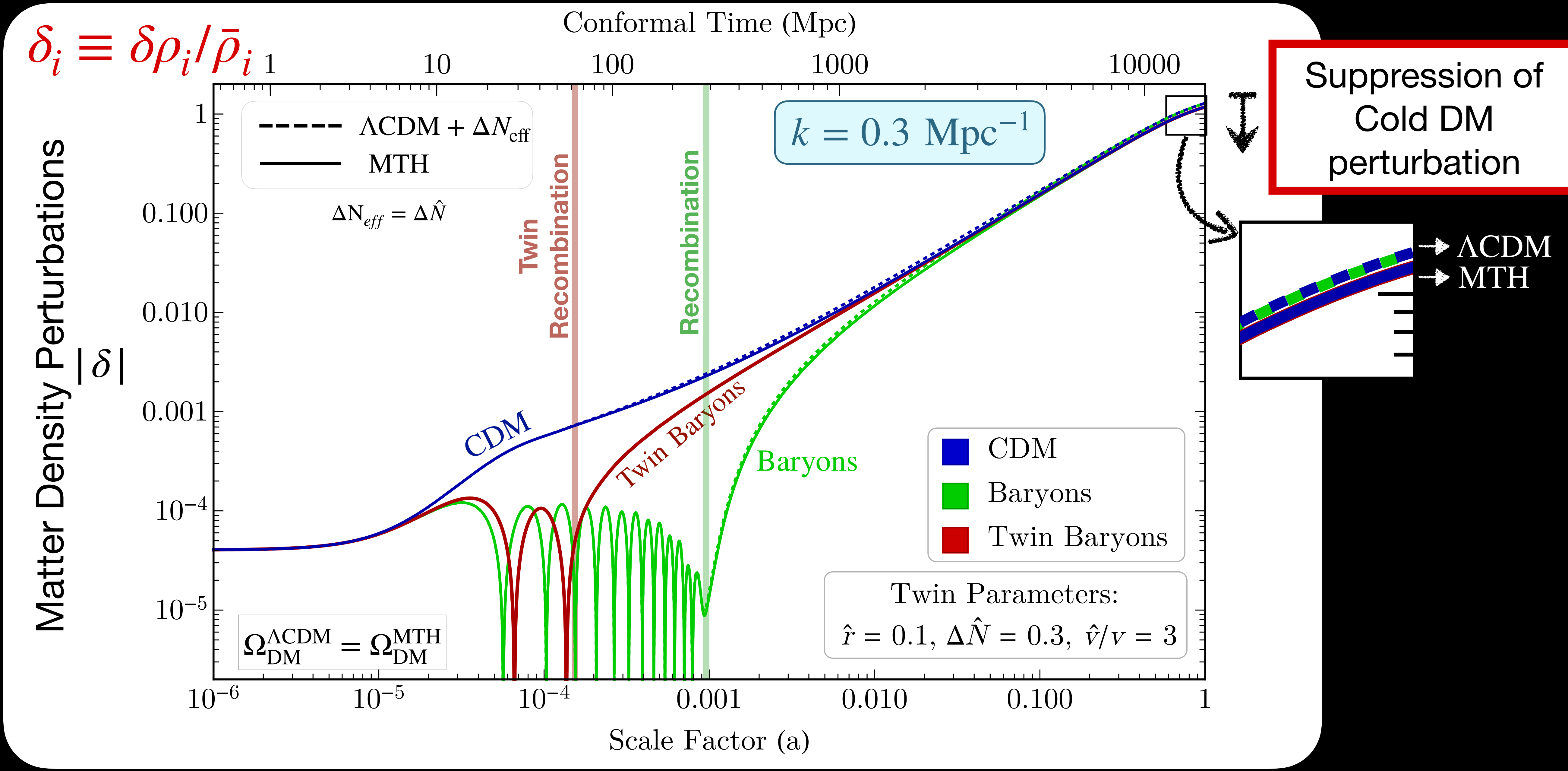


Bansal, Kim, Kolda, Low, **YT** (2021)



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

Dark Acoustic Oscillations (DAO) in DM perturbation

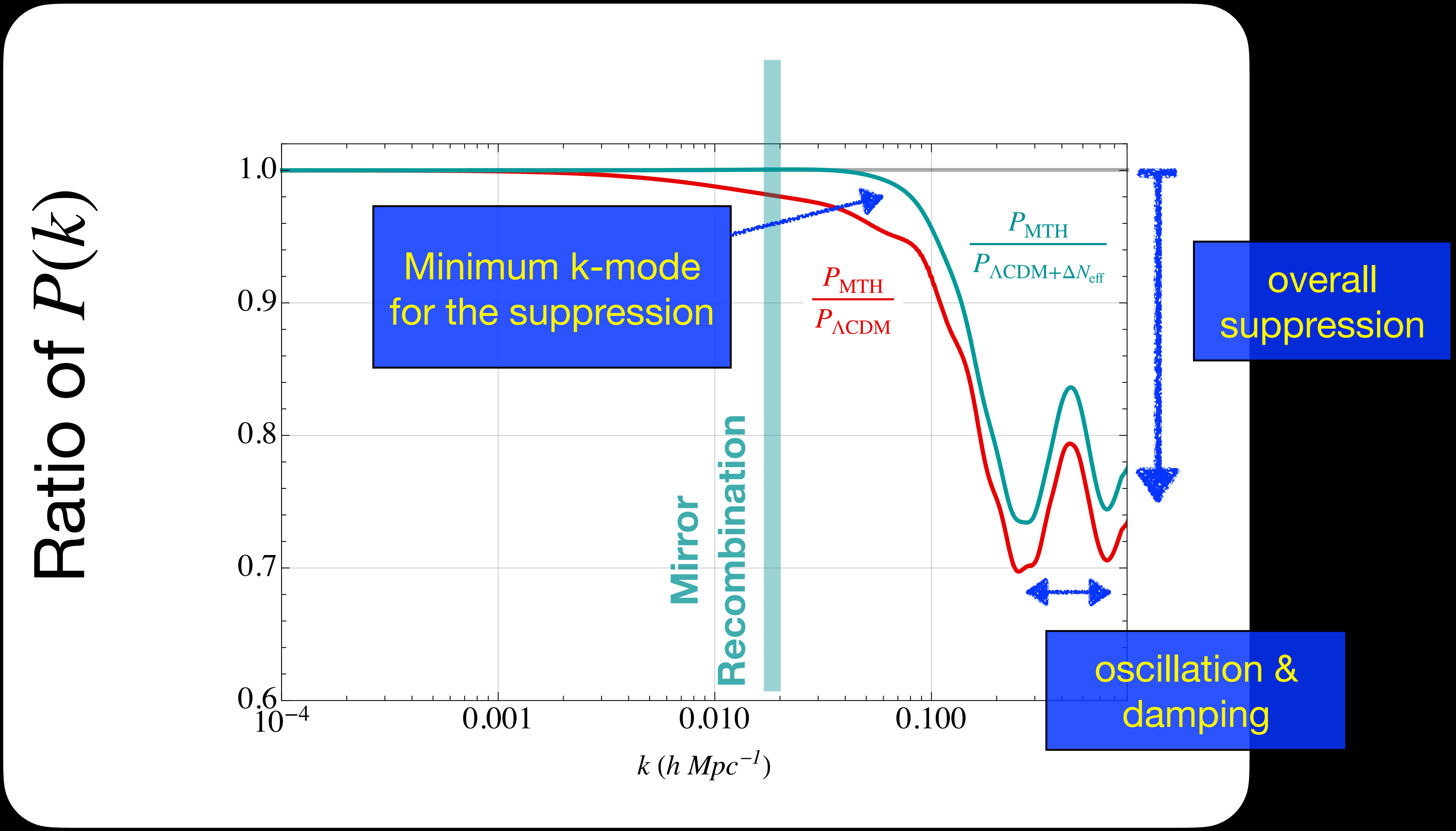


Cir-Racine, Sigurdson (2012)
Cir-Racine, Putter, Raccanelli, Sigurdson (2012)

Bansal, Kim, Kolda, Low, **YT** (2021)

Dark Acoustic Oscillations (DAO) in P(k)

Ideally, measure the various features fix all the model parameters & provide a consistency check of the Twin Higgs scenario



Mirror sector parameters: $\hat{r} = 0.1,\ \hat{\rm v}/{\rm v} = 3,\ \Delta\hat{N} = 0.3$

All other parameters assumed to be the best fit value of ΛCDM.

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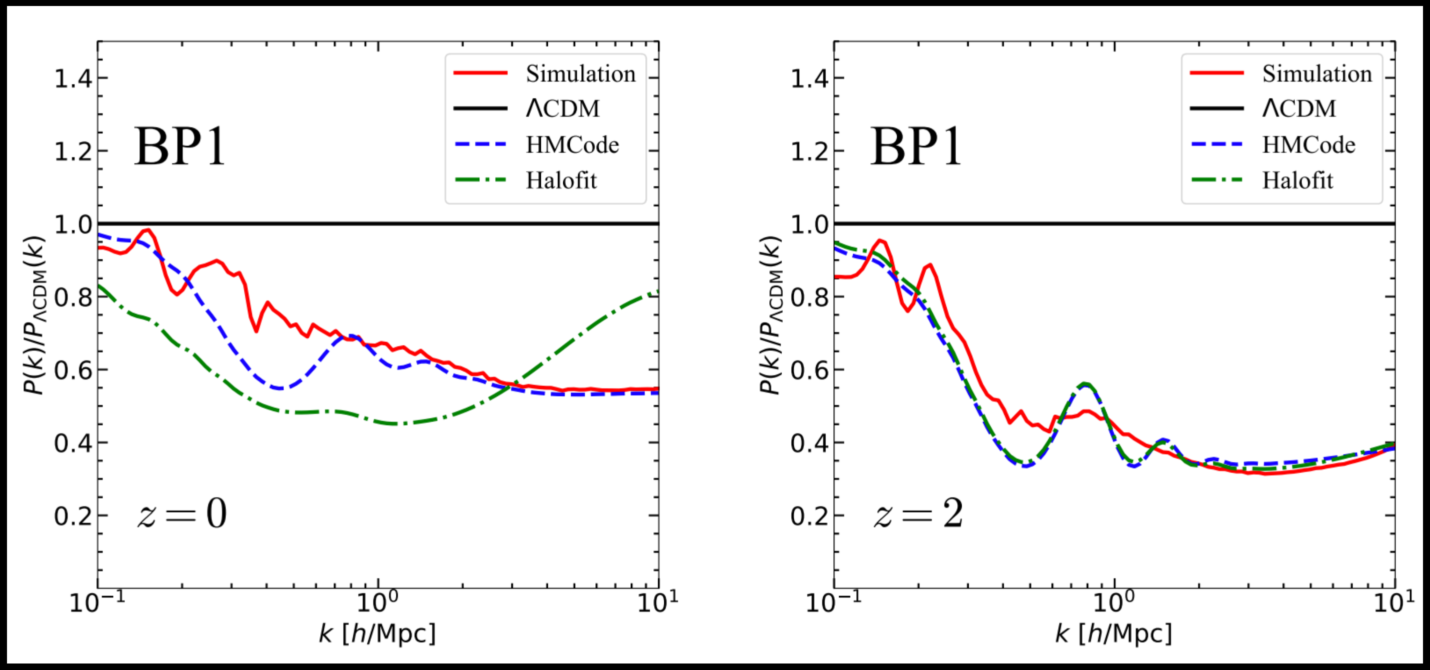
Realistically,

non-linear corrections suppress the oscillations

Matter power spectrum ratio

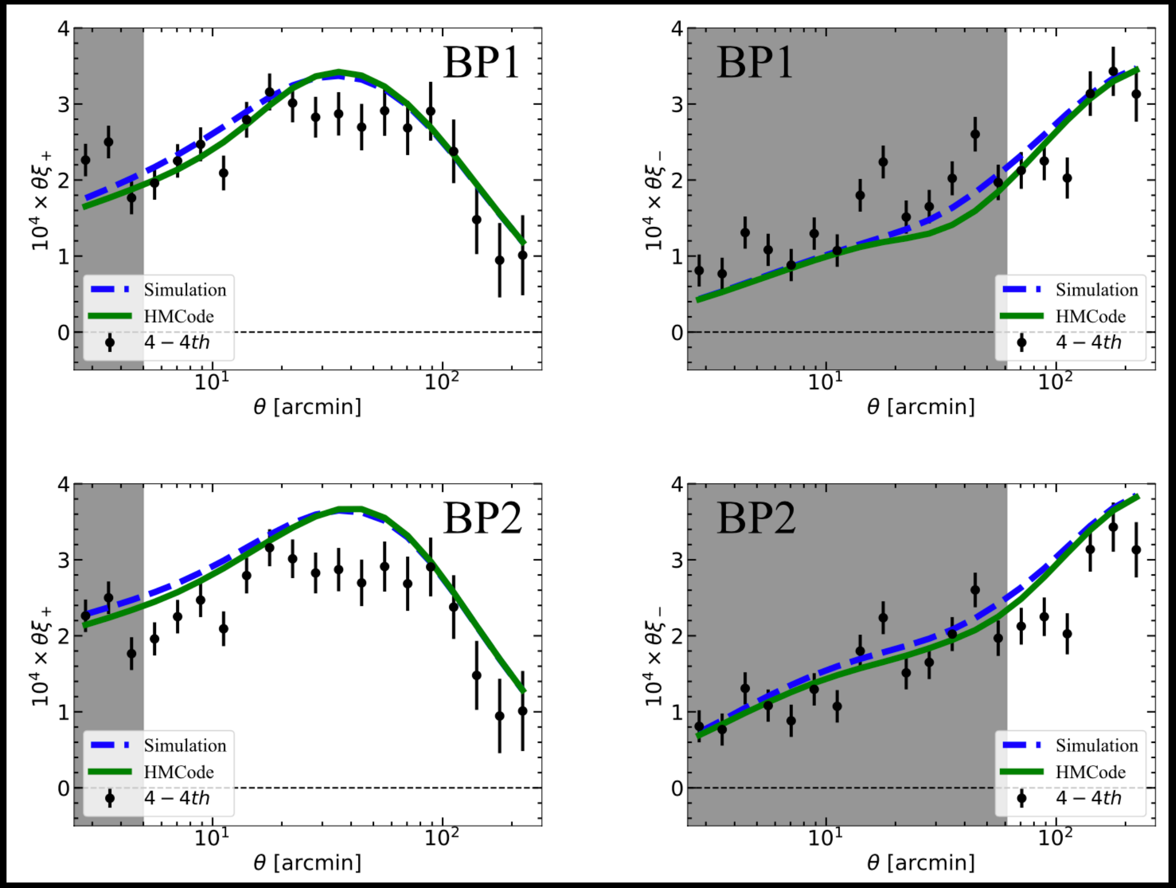
Gedget-3 DM-only vs **HMCode**



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

2-point correlation function of cosmic shear

Gedget3 DM-only vs **HMCode**



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Higher redshift measurement
may allow us to determine the features

Matter power spectrum ratio

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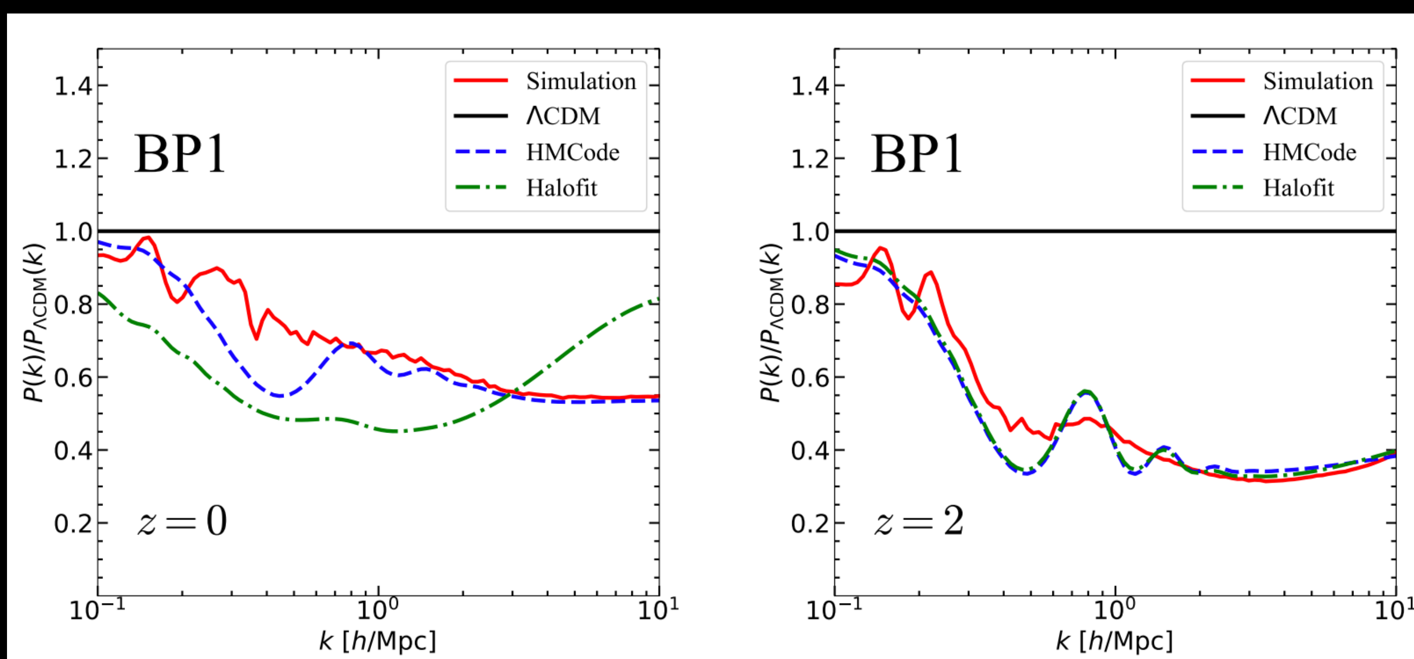

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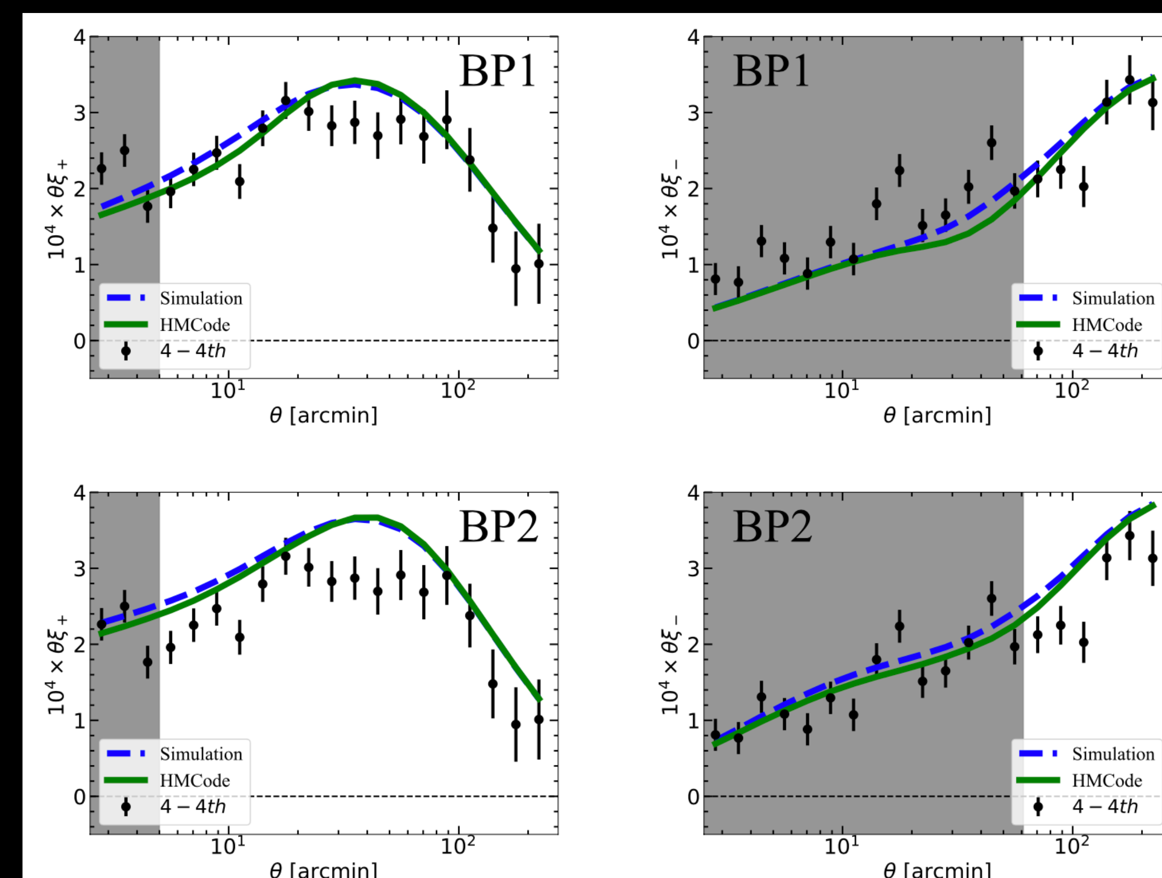

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lifetime <-> mass generation scale

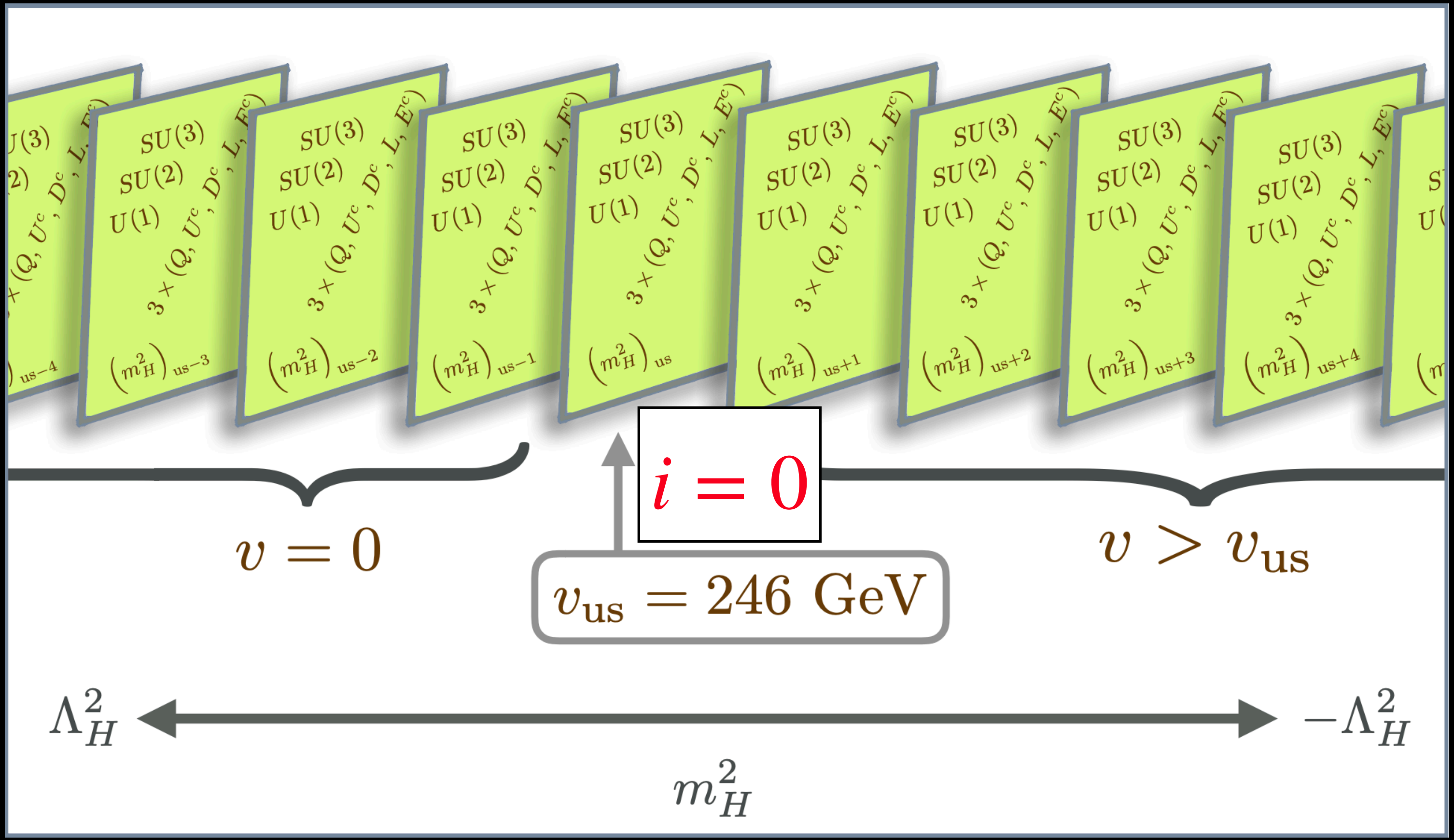
N-naturalness Model

Addressing the Higgs hierarchy problem up to ~ 10TeV

(or even the big hierarchy problem)

Arkani-Hamed, Cohen, D'Agnolo, Hook, Kim, Pinner (2016)

Consider ***N*** SM-like sectors w/ equally distributed Higgs mass parameter



$$m_{H,i}^2 = -\frac{\Lambda_H^2}{N}(2i + r)$$

$$-\frac{N}{2} \leq i \leq \frac{N}{2}$$

We are $i = 0$

For $N = 10^4$, cutoff scale

$$\Lambda_H \sim 10\,\text{TeV}$$

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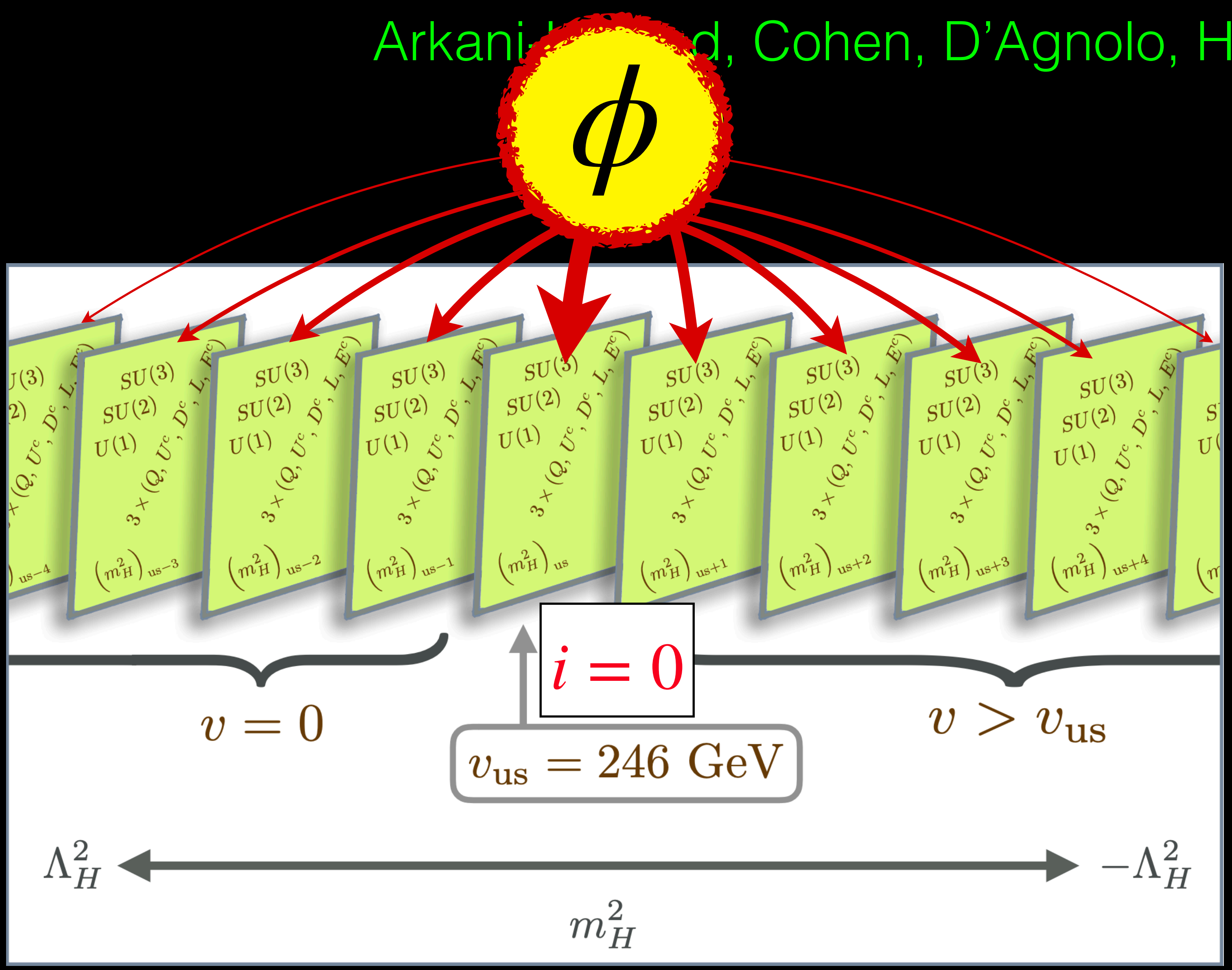

When a "reheaton" that is light (mass $< \Lambda_H/\sqrt{N}$) & couples to sectors w/ certain universal form of the couplings, it mainly reheats into the lowest scale sector (which is our SM sector)

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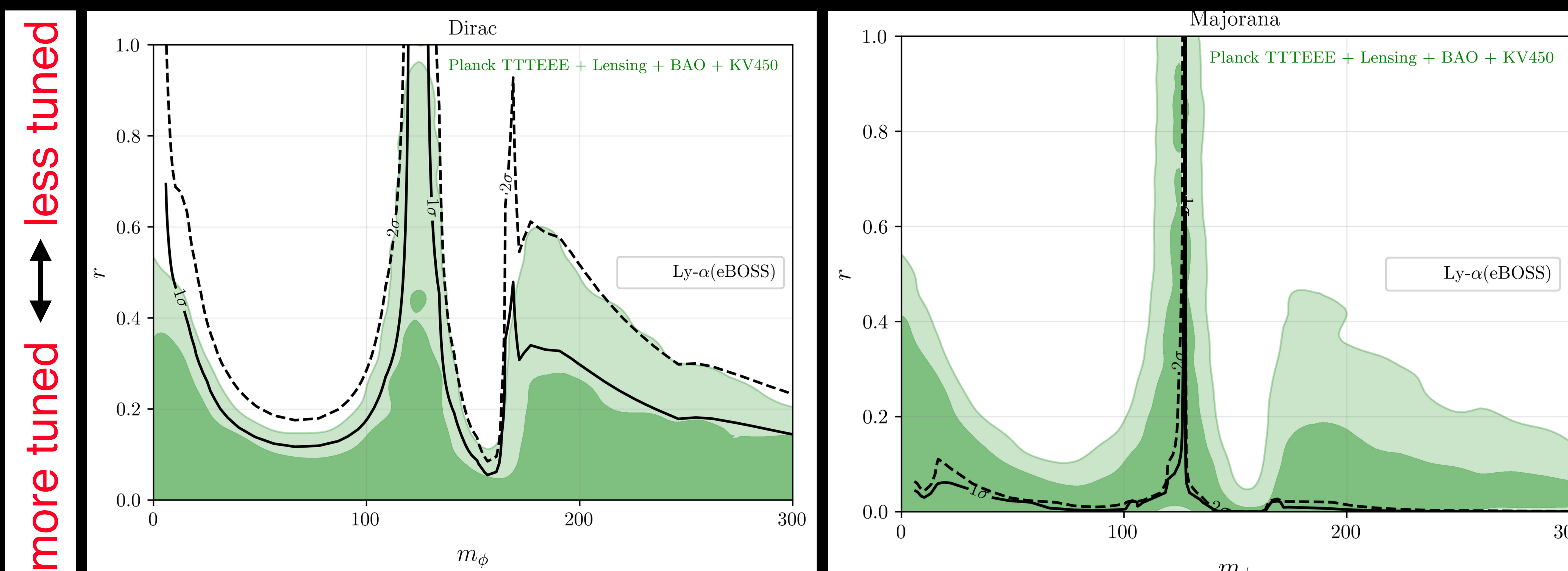
Minimum dark sector signal,

a tower of SM-like heavy neutrinos (i-sectors)

+ dark radiation (i-sectors of photons and massless particles)

WDM masses and DR energy density are determined

by 3 parameters (N, reheaton mass m_ϕ , fine-tuning parameter r)

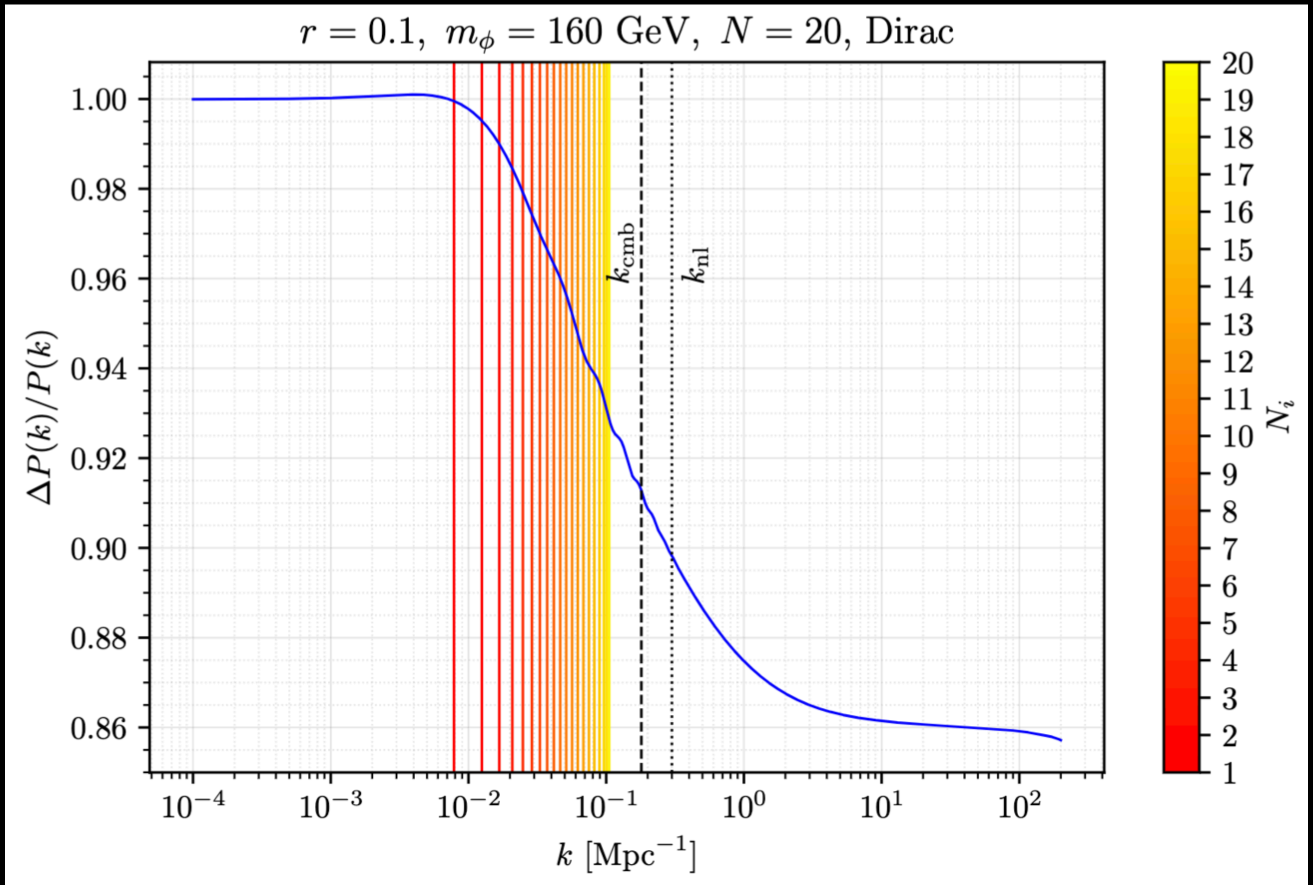


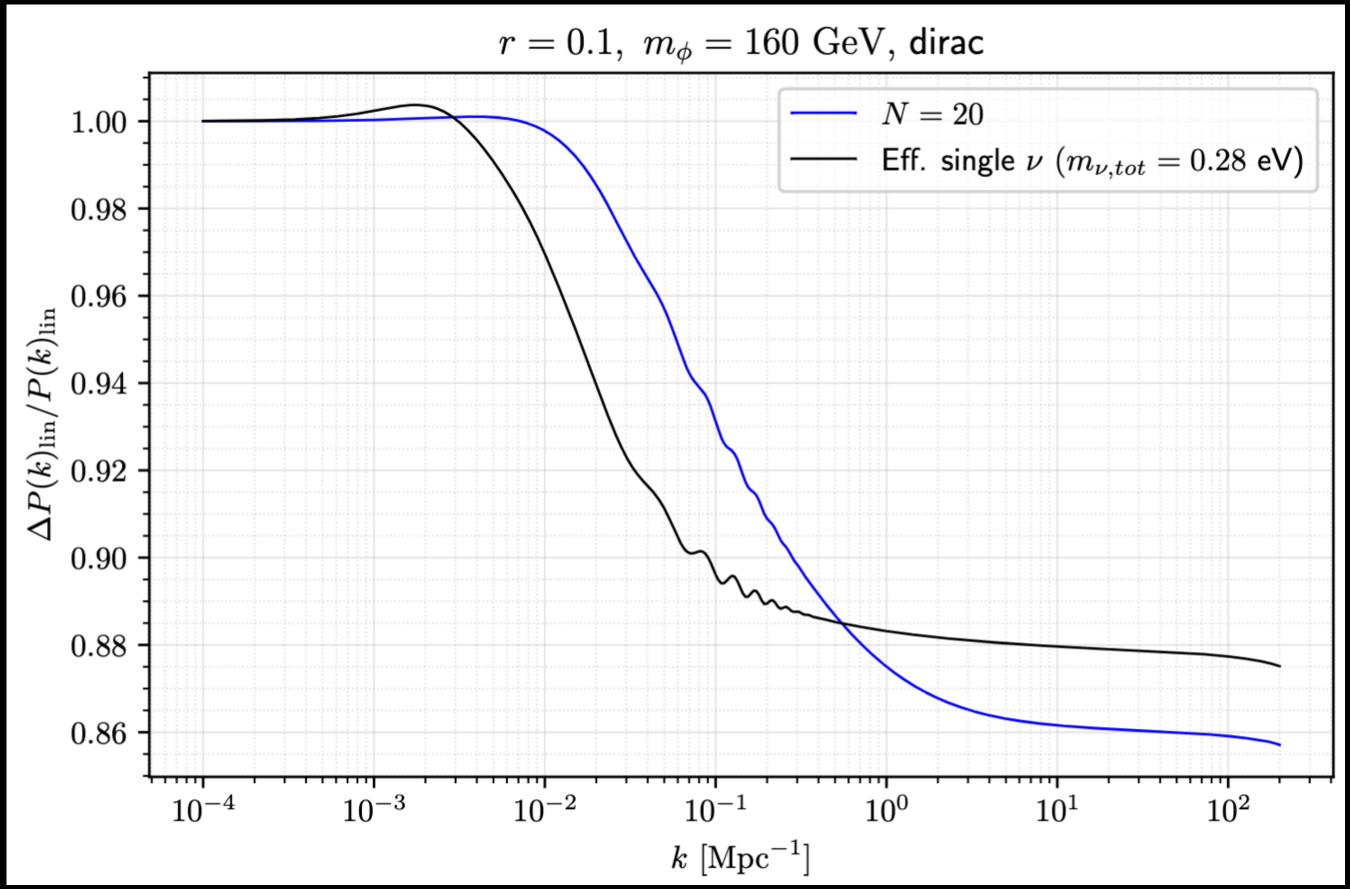
Bansal, Ghosh, Low, YT (in preparation)

See also the thermal history calculatio
in Choi, Chiang, LoVerde (2018)

P(k) suppression from a tower of warm DM

Different shape of Pk suppression from
multiple WDM becoming non-relativistic at different times



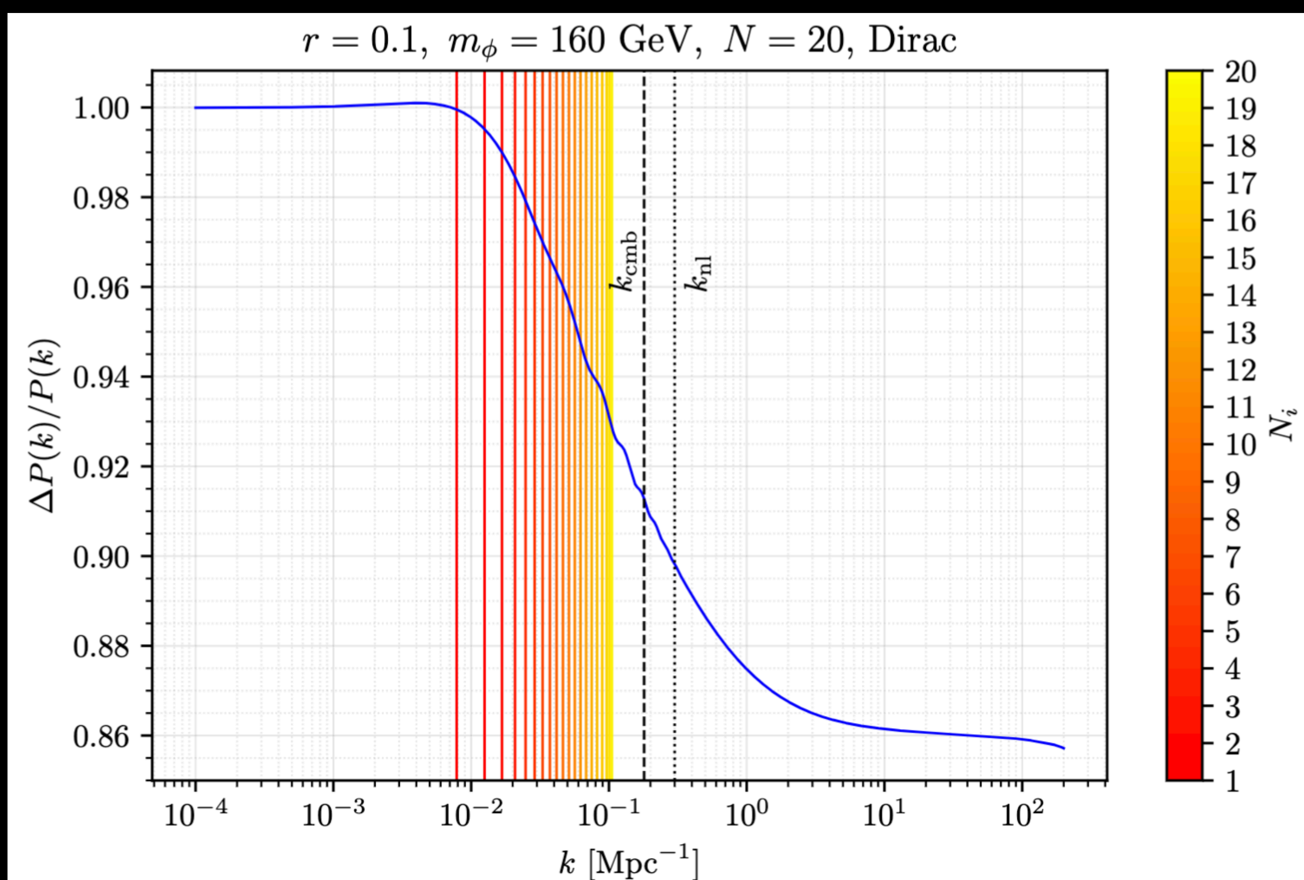


Vertical lines: inverse comoving time when each N-neutrino becomes non-relativistic

Black: "single" WDM that matches the N_{eff} and today's N-neutrino abundance

A precise Pk measurement (higher-z, larger sampling,⋯)

allow us to identify the different WDM suppression



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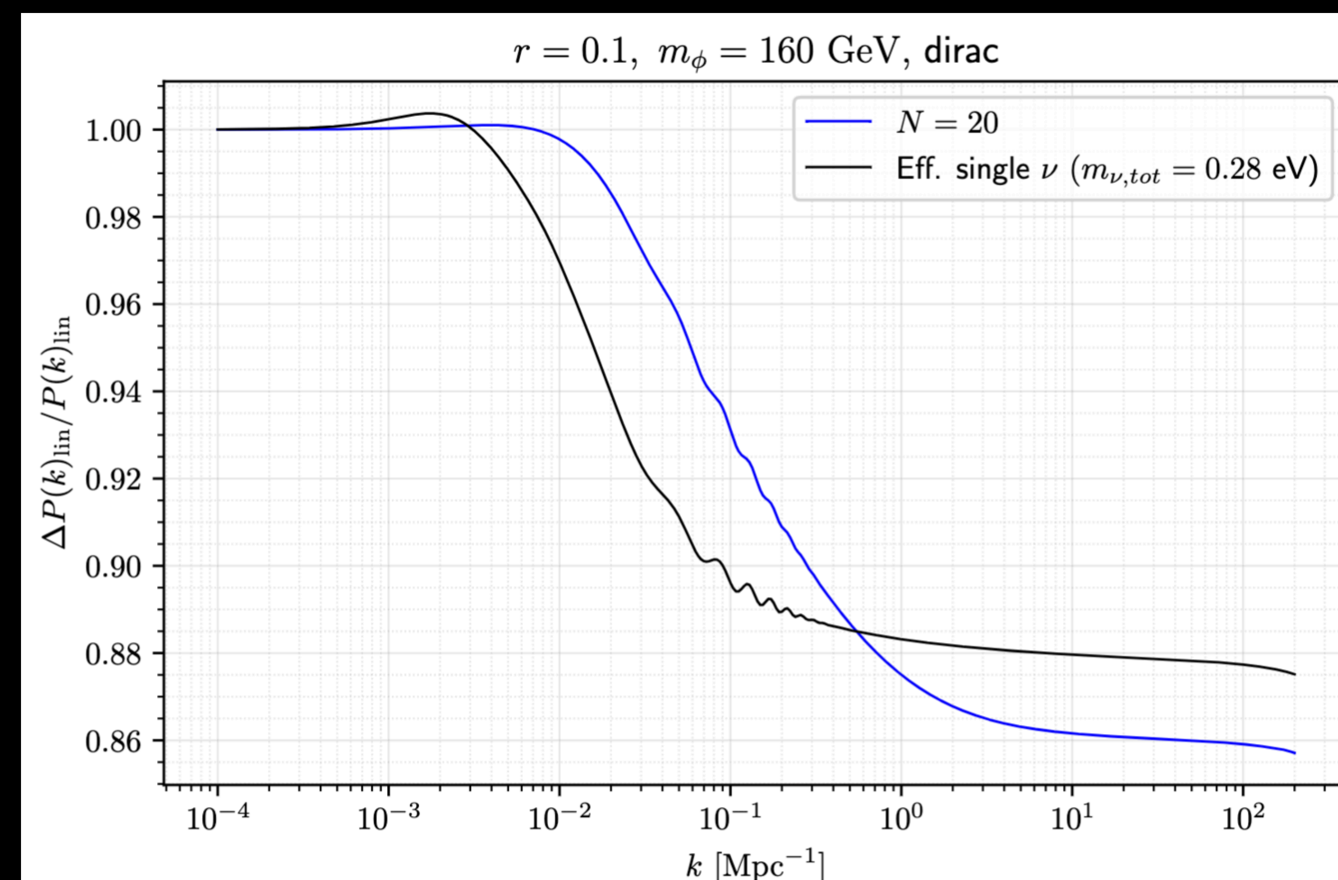

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lifetime <-> mass generation scale

Majoron and Neutrino mass generation

Neutrinos are are much lighter than other SM fermions

because their masses come from a different origin

Gelmini & Roncadelli (1981), Chikashige, Mohapatra, Peccei (1981), Georgi, Glashow, Nussinov (1981), Valle (1983), Gelmini, Valle (1984), …

For example, Majorona m_ν from a spontaneous

symmetry breaking at energy scale f

$$\frac{\Phi_\alpha \Phi_\beta}{\Lambda^3}(\bar{L}_\alpha H)(H L_\beta) \qquad \alpha, \beta = e, \mu, \tau$$

$$\Phi_\alpha = f_\alpha e^{i\frac{\phi_\alpha}{f_\alpha}} \qquad m_\nu \sim f \left(\frac{f v^2}{\Lambda^3}\right)$$

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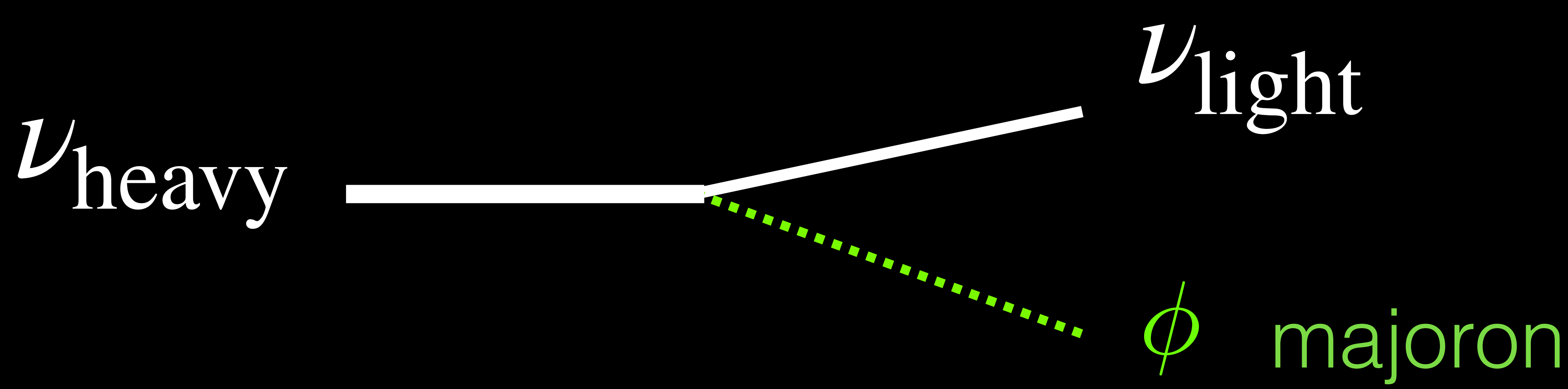
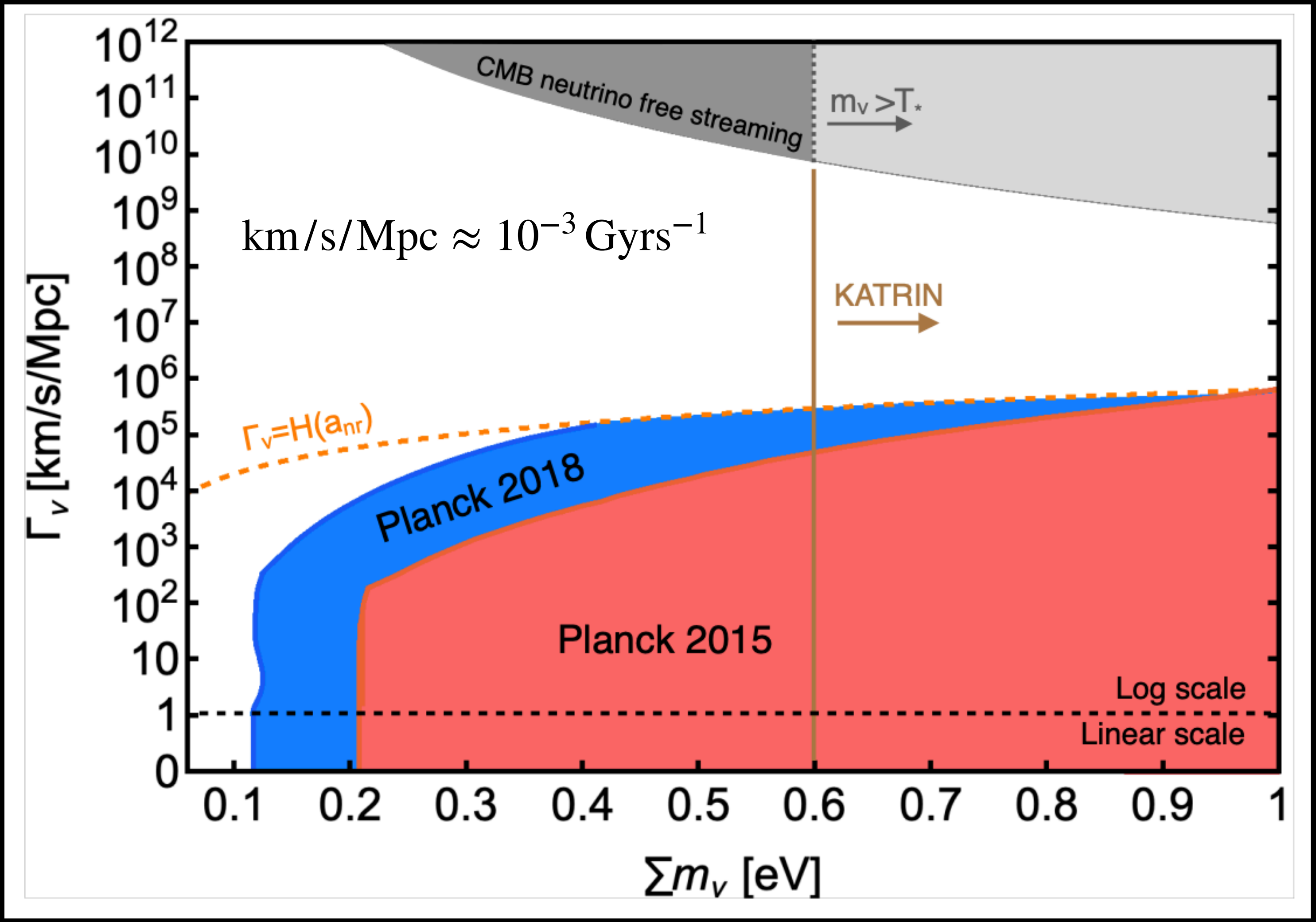
The goldstone boson of the symmetry breaking allows SM-neutrinos to decay



$$\frac{\Gamma_\nu}{H_0} \approx \frac{m_\nu^3}{8\pi f^2} \sim \left(\frac{m_\nu}{0.1\,\mathrm{eV}}\right)^3 \left(\frac{10^5\mathrm{GeV}}{f}\right)^2$$

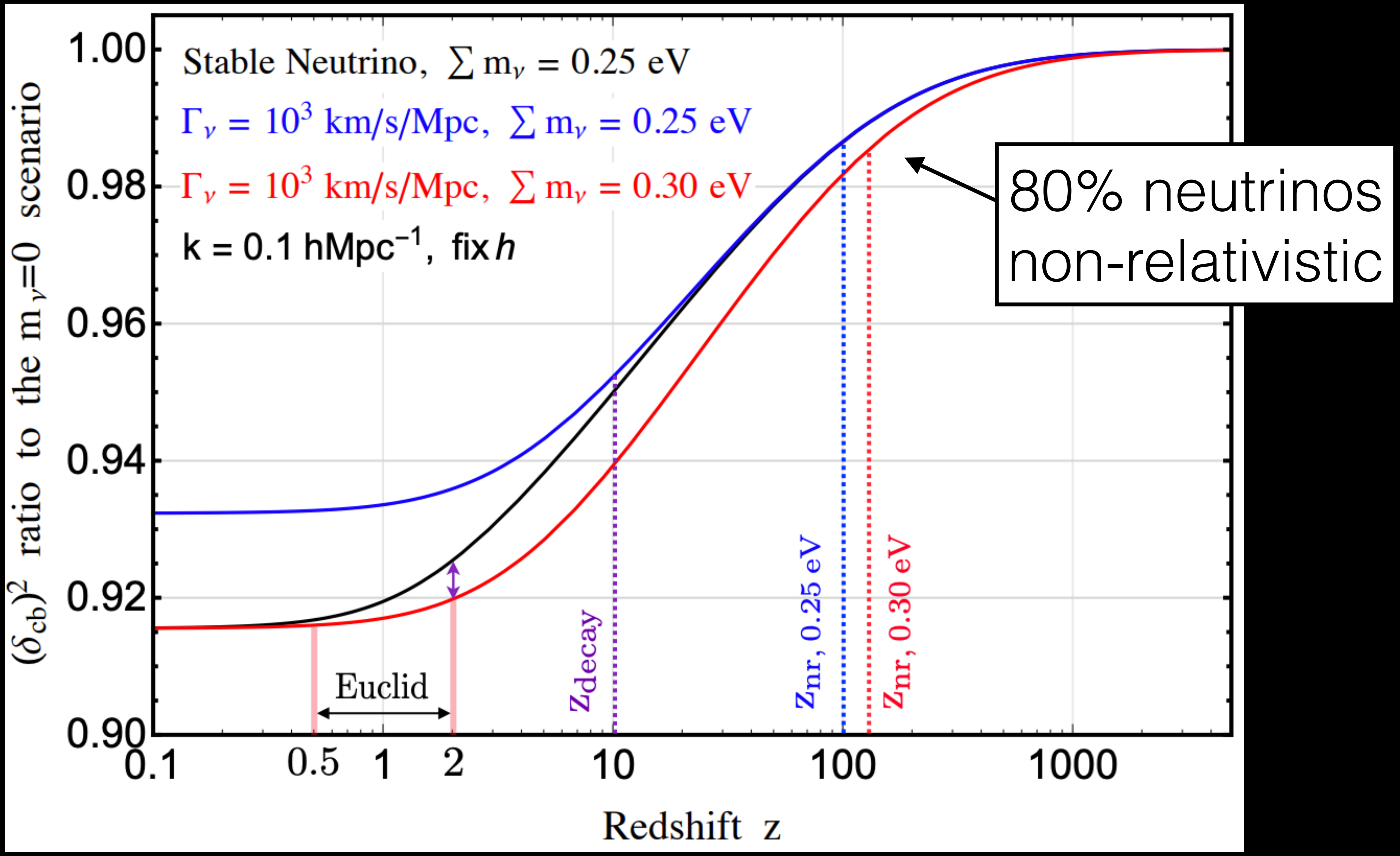
Current bound on neutrinos' mass & decay-rate

There's a degeneracy between mass-lifetime



Franco Abellan, Chacko, Dev, Du, Poulin, **YT** (2022)

Break the mass-lifetime degeneracy with higher-z data



$$\mathrm{km/s/Mpc} \approx (10^3\,\mathrm{Gyrs})^{-1}$$

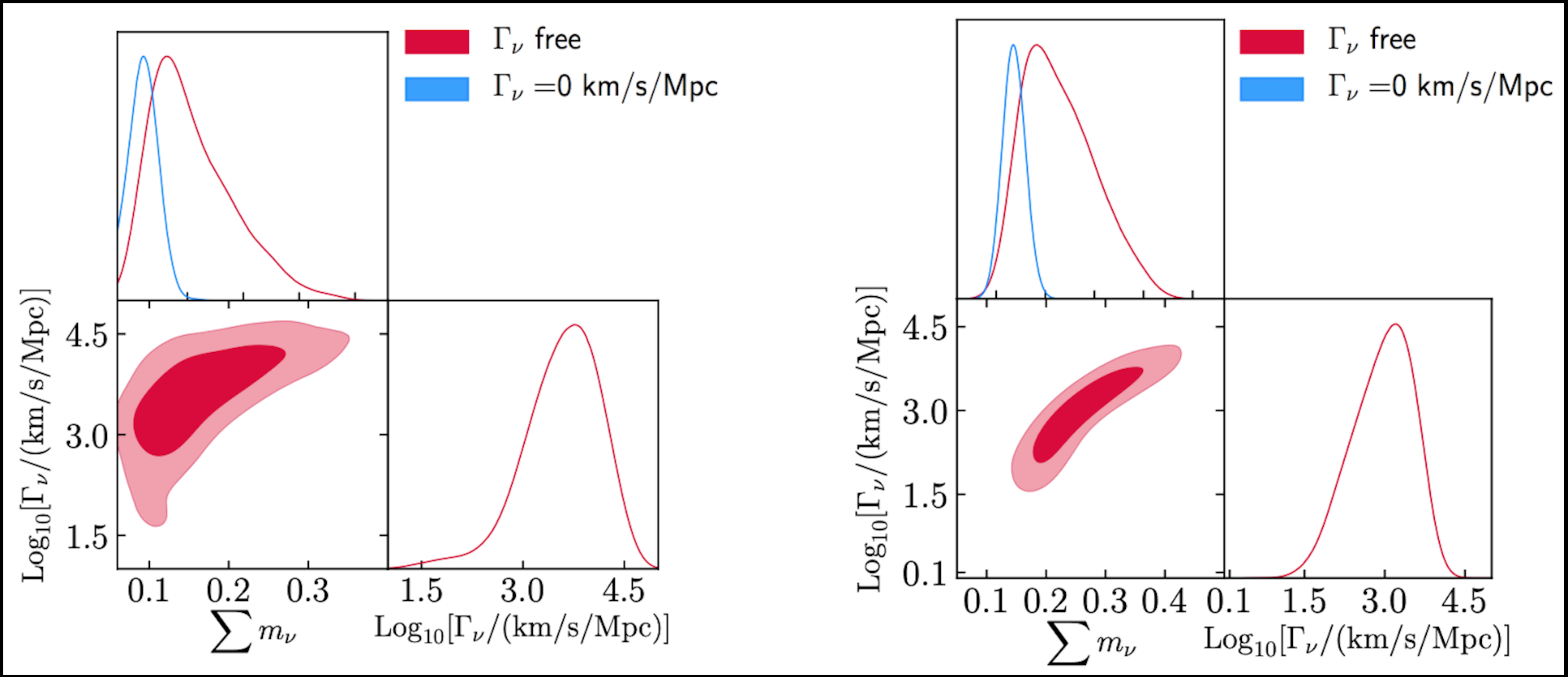
Chacko, Dev, Du, Poulin, **YT** (2020)

Serpico (2007) (2009)

Barenboim, Chen, Hannestad, Oldengott, Wong (2021)

Mass & lifetime determination

Projection with Planck+future Euclid *P(k)*+Euclid lensing



Chacko, Dev, Du, Poulin, **YT** (2020)

$$\left(\log_{10}\left(\frac{\Gamma_\nu}{\mathrm{km/s/Mpc}}\right), \sum\left(\frac{m_\nu}{\mathrm{eV}}\right)\right) = (3.7,\ 0.16)$$ (left)

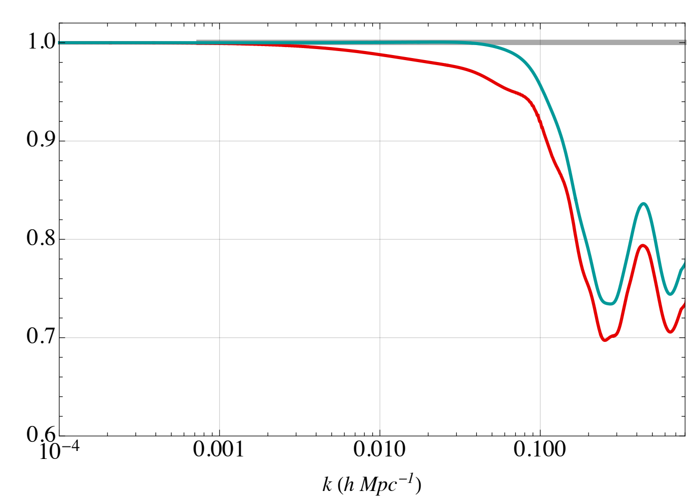
$(3.0,\ 0.25)$ (right, already disfavored by Planck18)

Precise matter power spectrum measurements allow us to probe/identify these BSM targets

Mirror Twin Higgs

Higgs hierarchy problem

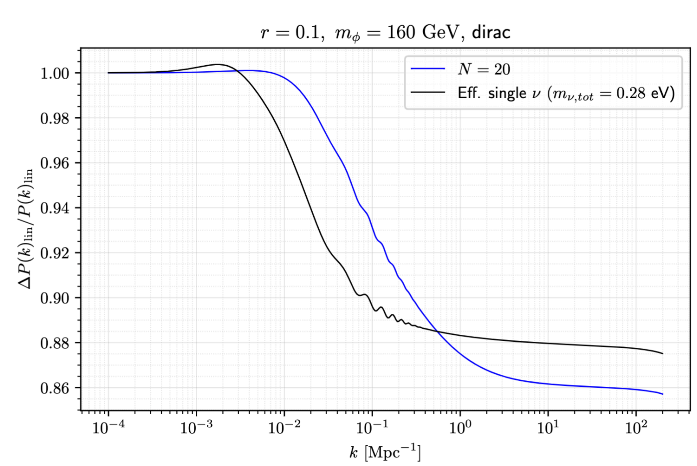
↓ DAO



N-naturalness

Higgs hierarchy problem

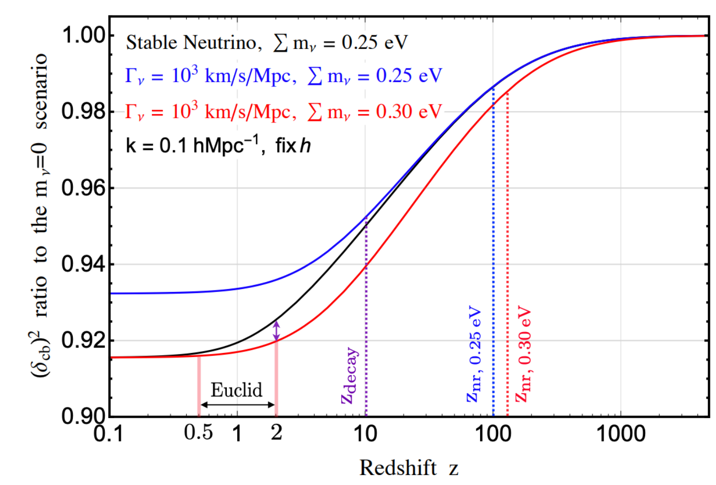
↓ Multiple WDM suppression



Majoron

Tiny neutrino masses

↓ ν-decay, modifies Pk evolution



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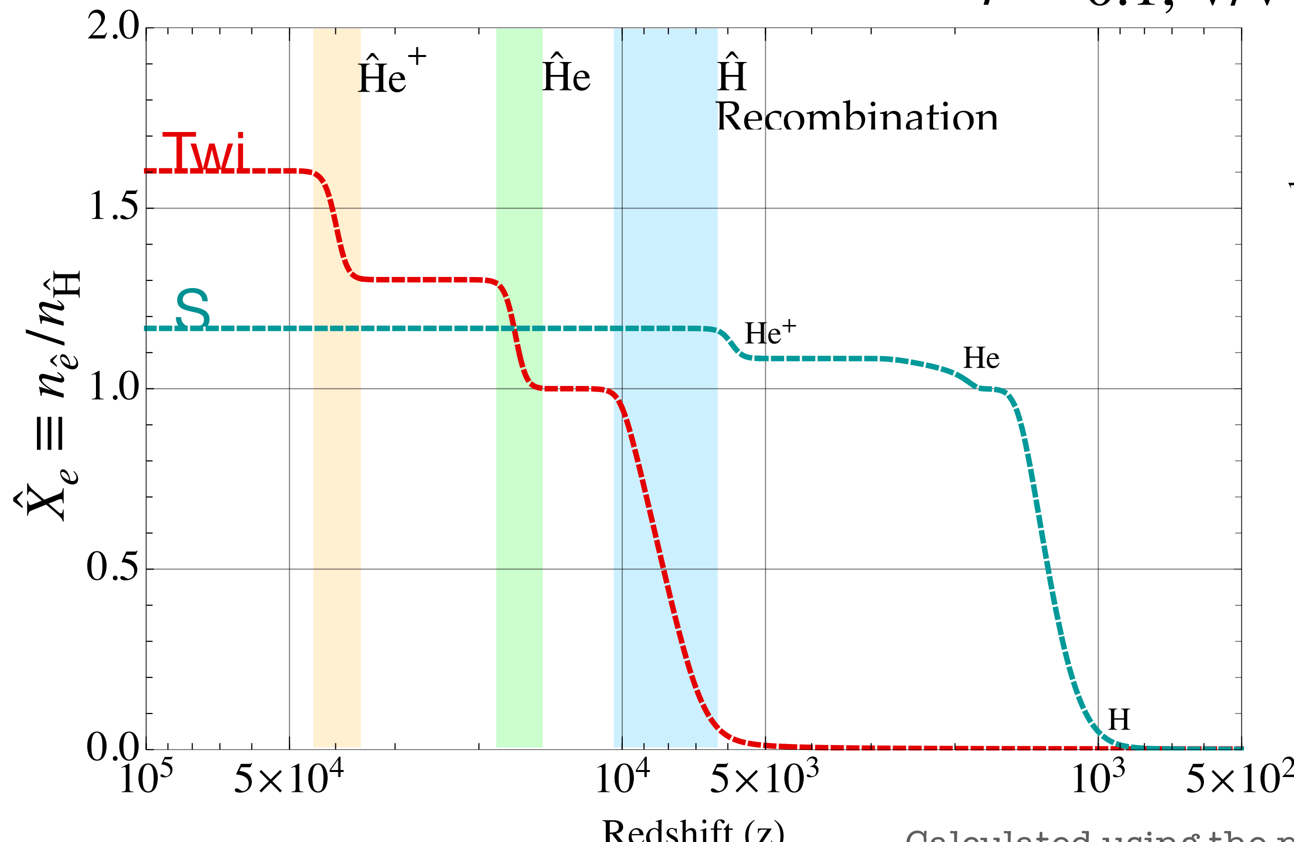
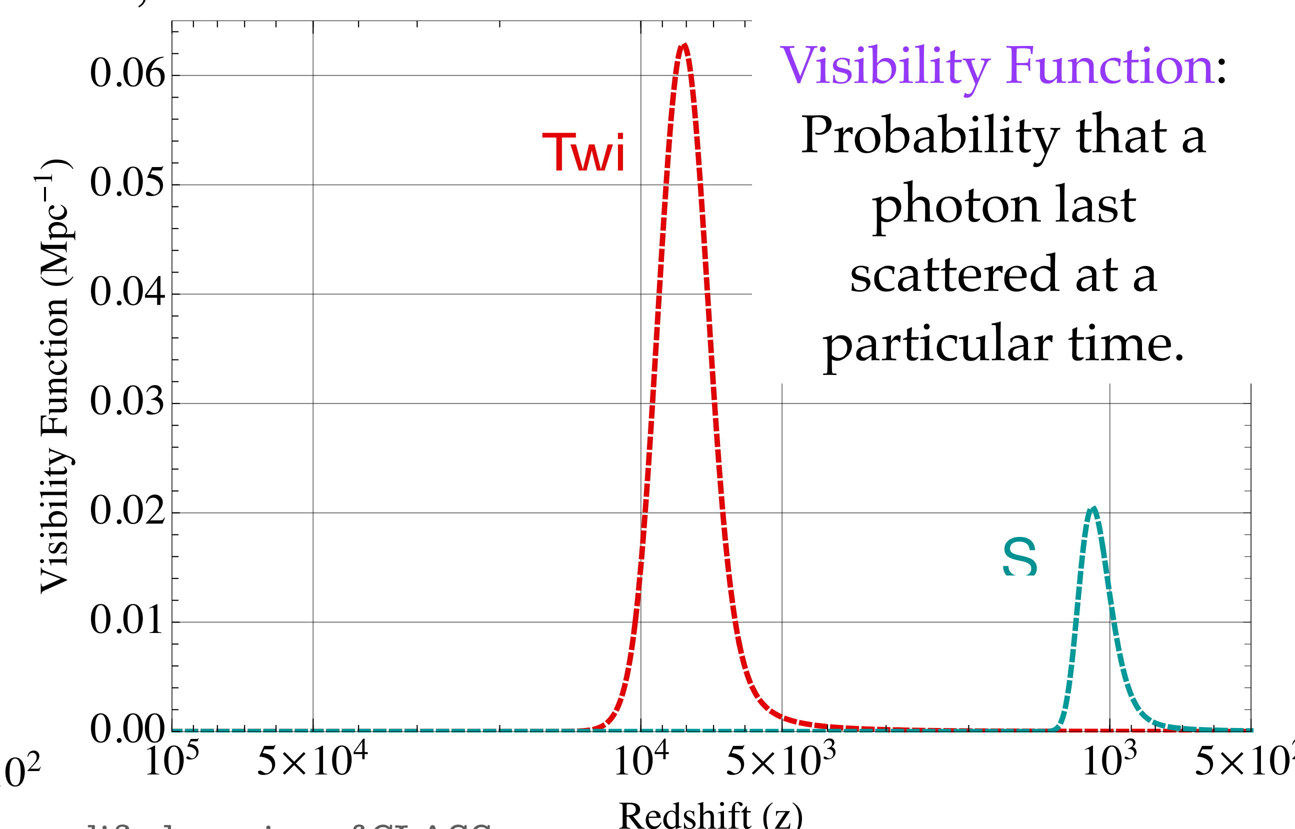
Backup Slides

Recombination of mirror He and H

$\hat{\mathrm{He}}^{2+} + \hat{e}^- \rightarrow \hat{\mathrm{He}}^+ + \hat{\gamma}$	$\hat{\mathrm{He}}^{+} + \hat{e}^- \rightarrow \hat{\mathrm{He}} + \hat{\gamma}$	$\hat{p} + \hat{e}^- \rightarrow \hat{\mathrm{H}} + \hat{\gamma}$
Approximation using Saha Equation	Approximation using Saha Equation	Peebles Equation

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





Calculated using the modified version of CLASS.

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

If we can measure the linear-power spectrum

Chacko, Curtin, Geller, YT (2018)

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

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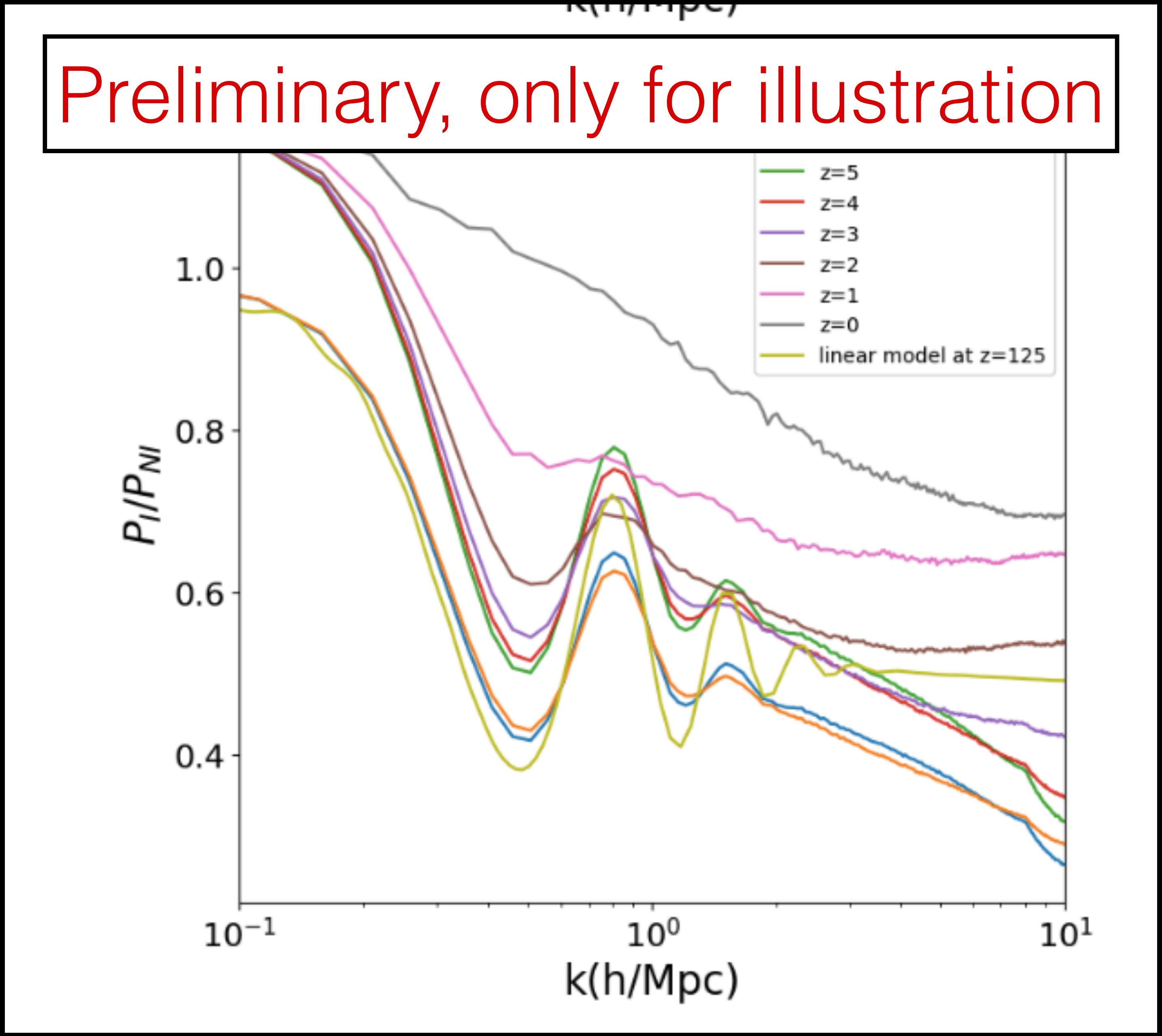
Non-linear correction to Twin Higgs DAO



Ghosh, Matthews, Tang, YT

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How stable are SM neutrinos?

Existing bounds on neutrino lifetime are very weak
(for decay into invisible particles)

ν

- long-based line experiments $\tau > 10^{-14}\,\mathrm{sec}$
- supernovae $\tau > 8\,\mathrm{hrs}$ e.g., Frieman et al (1988)
- $\tau > 13\,\mathrm{yrs}$ CMB (neutrinos need to free stream)

e.g., Archidiacono and Hannestad (2014)
Escudero and Fairbairn (2019)