Cosmology of the majoron

From leptogenesis to the Hubble tension

Samuel J. Witte

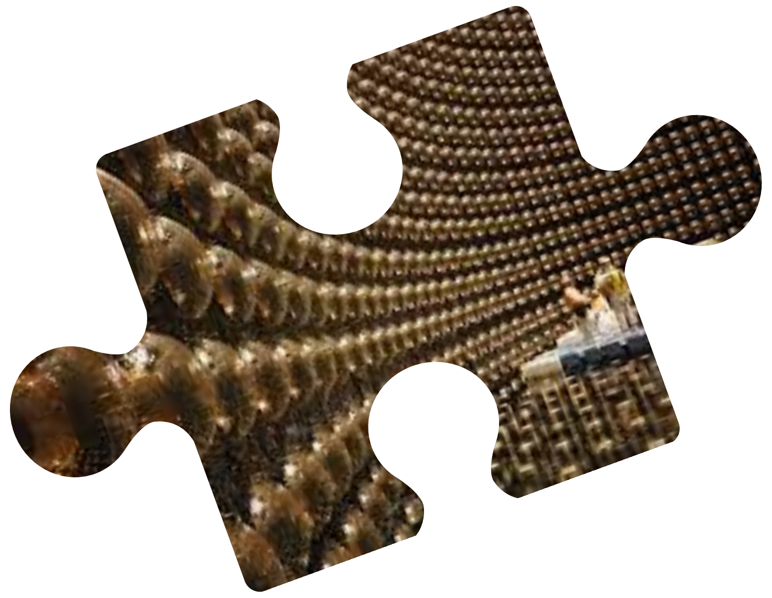
May 10, 2021

GRAPPA

GRavitation AstroParticle Physics Amsterdam

Escudero & SJW *Eur.Phys.J.C* 80 (2020) 4, 294 (arXiv:1909.04044)
Escudero & SJW arXiv: 2103.03294 (submitted to EPJC)

The Majoron



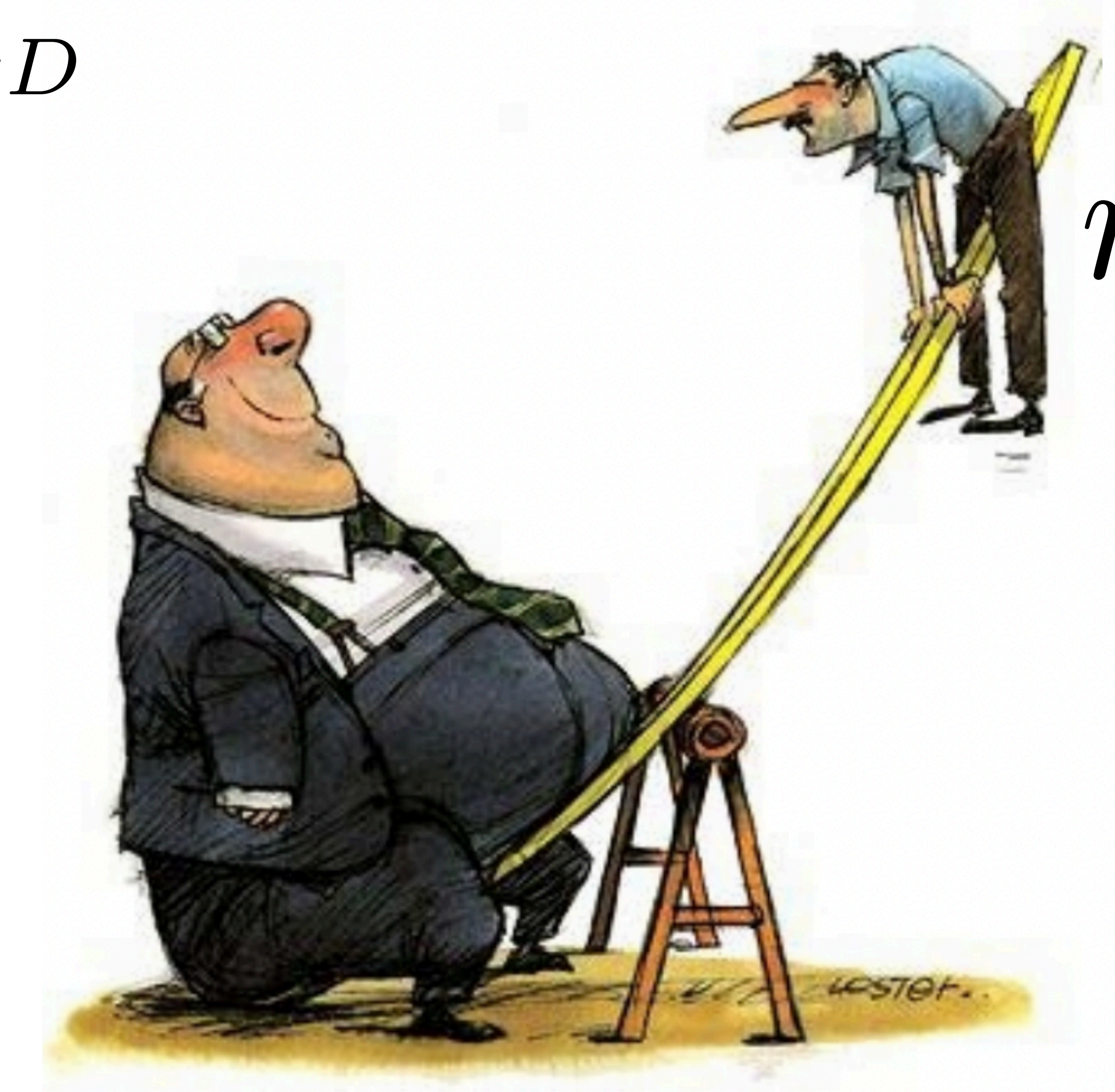
Neutrino mass problem *(i.e. how are they generated and why so small?)*

$M_R \gg m_D$

Seesaw Limit

Dirac Mass   Majorana Mass

$$\mathcal{L} \supset Y_\nu \bar{\ell}_L \tilde{\Phi}\, \nu_R + \frac{1}{2} \overline{\nu_R^c}\, M_R\, \nu_R + hc$$



m_ν

M_R

Explains origin and smallness of neutrino mass in terms of high-energy physics

The Majoron

$$\frac{1}{2}\overline{\nu_R^c}\, M_R\, \nu_R$$ Violates lepton number

Maybe it arises from broken symmetry?

If symmetry *global*, gives rise to pGB (the majoron) ϕ

Chikashige, Mohapatra, Peccei (1981)

Low Energy Phenomena — Indirect Probe → High Energy Theory

$\nu - \phi$ $\qquad$ M_R

Singlet Majoron Model

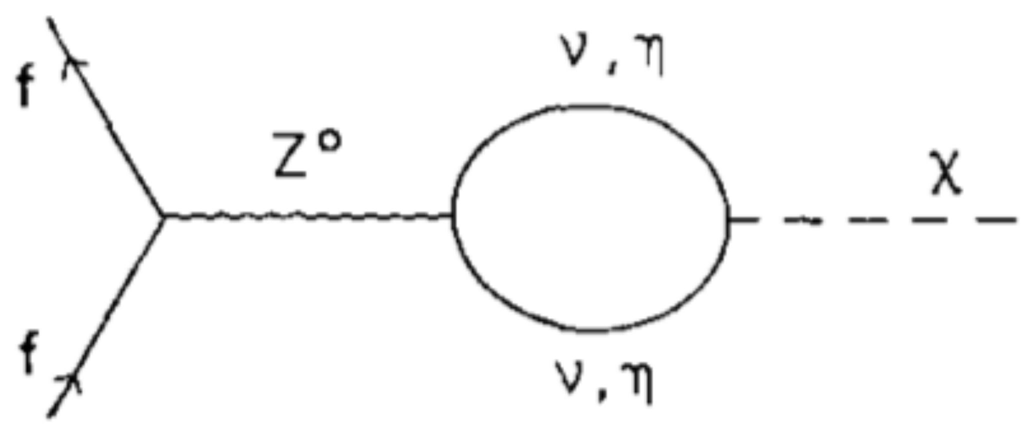
After spontaneous symmetry breaking:

$$\mathcal{L} \supset -\frac{\lambda_N}{2}\left[\rho \bar{N} N - i\phi \bar{N}\gamma_5 N\right] , \\ -\frac{\lambda_{N\nu}}{2}\left[i\rho(\bar{N}\gamma_5\nu + \bar{\nu}\gamma_5 N) - \phi(\bar{N}\nu + \bar{\nu}N)\right] \\ +\frac{\lambda_\nu}{2}\left[\rho\bar{\nu}\nu - i\phi\bar{\nu}\gamma_5\nu\right] ,$$

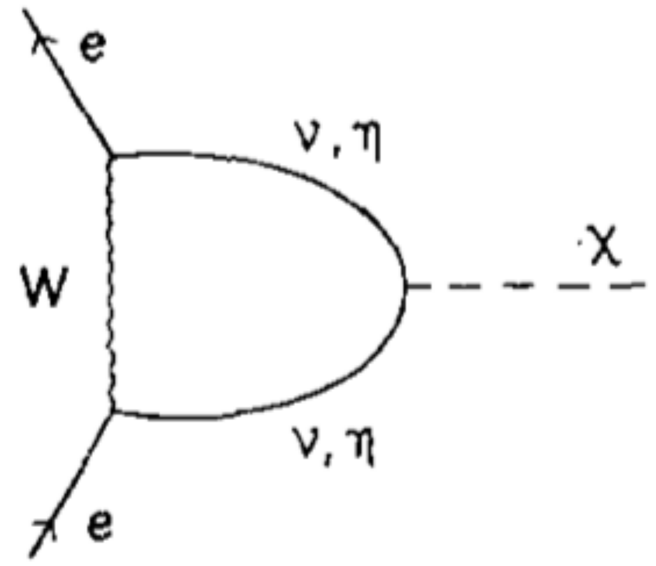
(Hierarchy between couplings)

$$\lambda_\nu \sim \sqrt{\frac{m_\nu}{m_N}}\lambda_{N\nu} \sim \frac{m_\nu}{m_N}\lambda_N$$

Loop suppressed interactions with charged fermions unavoidable…



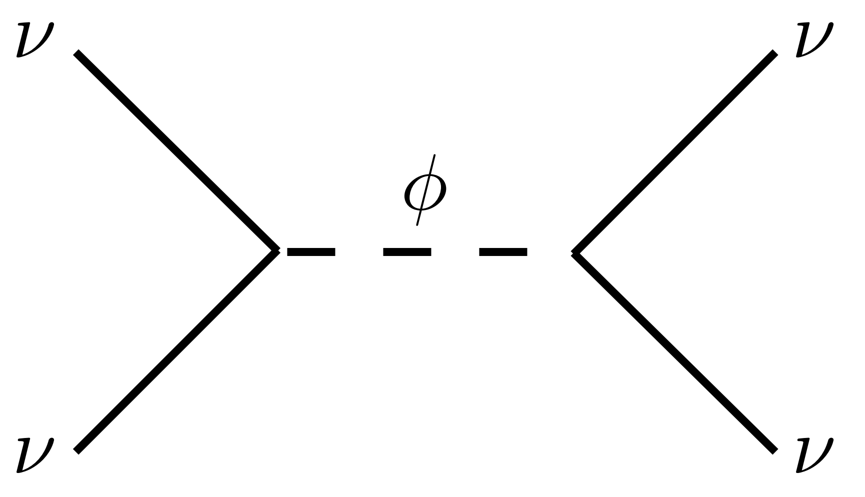
but naturally very small…



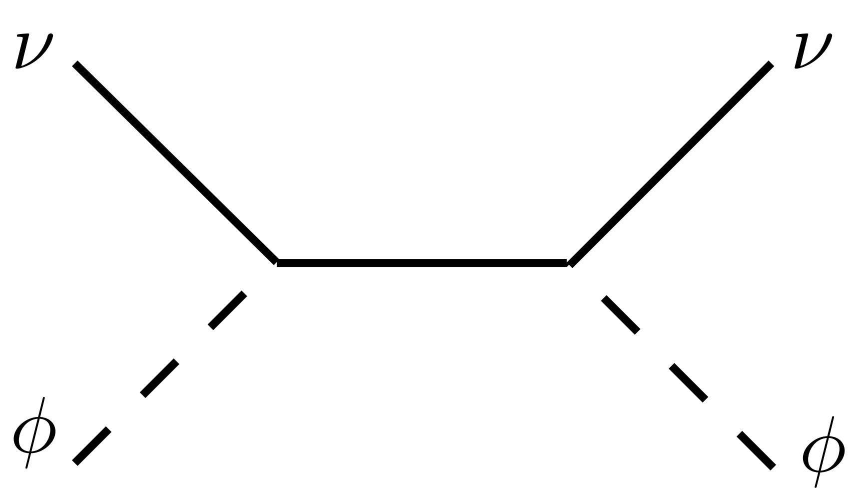
Majoron ~ neutrino-philic

Chikashige, Mohapatra, Peccei (1981)

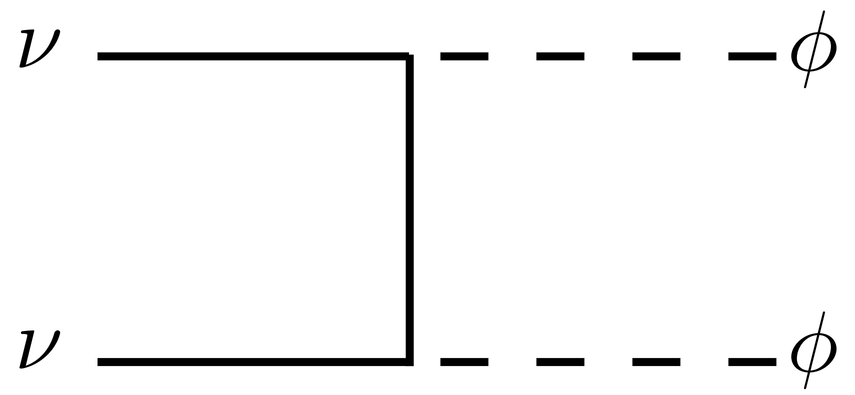
Neutrino self-interactions



2-to-2 scattering



Neutrino/majoron annihilations



Cyr-Racine et al (2013), Archidiacono et al (2014), Forastieri et al (2015), Oldengott et al (2017), Forastieri et al (2019), Kreisch et al (2019), Park et al (2019), Brinkmann et al (2020),Chacko, Hall, Okui, Oliver (2003), Escudero & **SJW** (2019), Escudero & **SJW** (2021), Archidiacono et al (2013), Escudero et al (2019), Escudero (2020), Chacko et al (2020), Barenboim et al (2021), Dolgov et al (1997), Huang et al (2018), …

Late-Time Majoron Cosmology

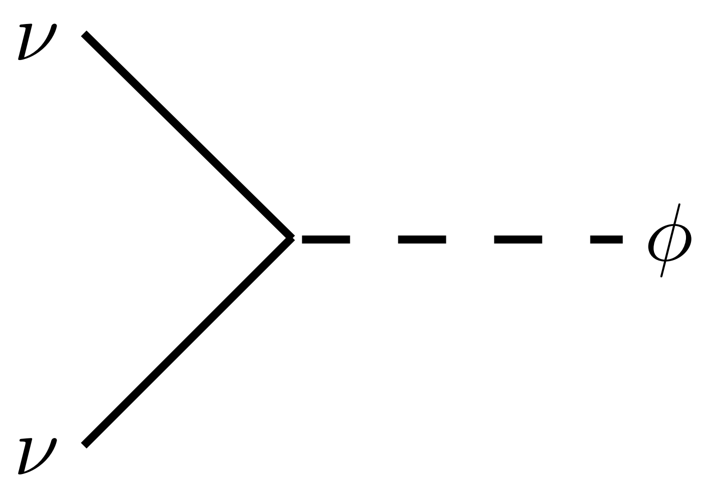
2-to-2 process typically need $g \gtrsim 10^{-7}$

Literature *largely* focused on:

- Massive 4-point contact interaction
- Massless majoron limit

Computationally *"easy"*

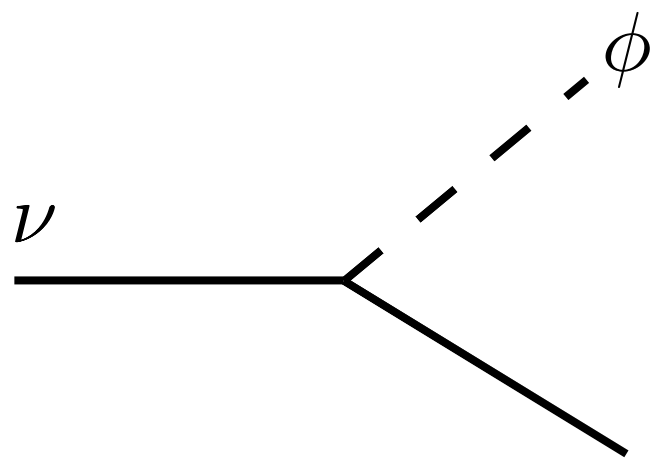
Inverse neutrino decay / Majoron decay



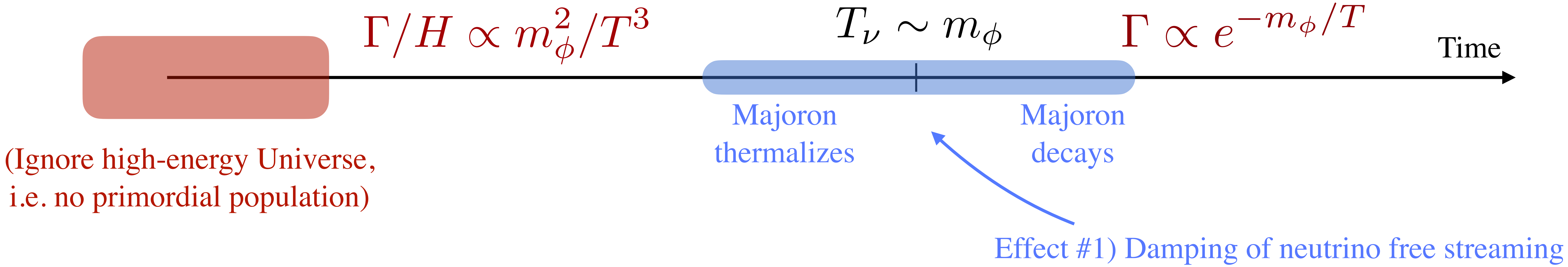
$g \lesssim 10^{-7}$

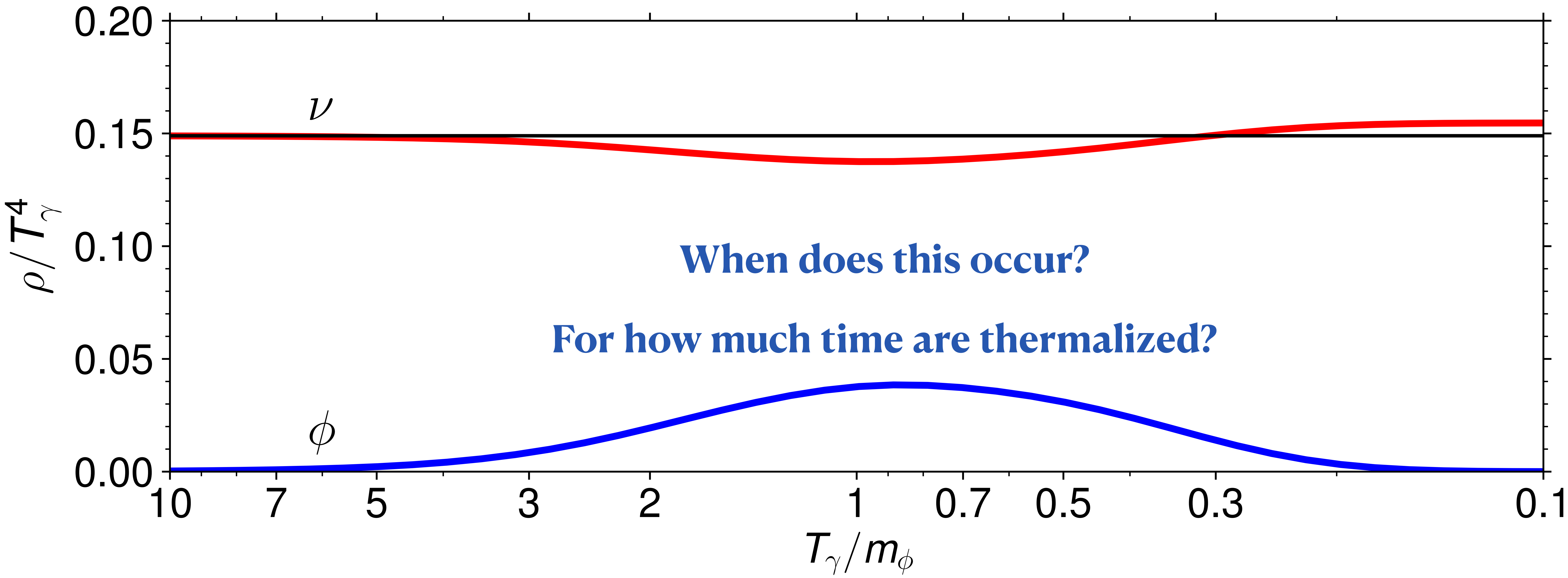
$m_\phi \in [0.1\text{eV}, \text{MeV}]$

Neutrino decay



Late-Time Neutrino-Majoron Interactions





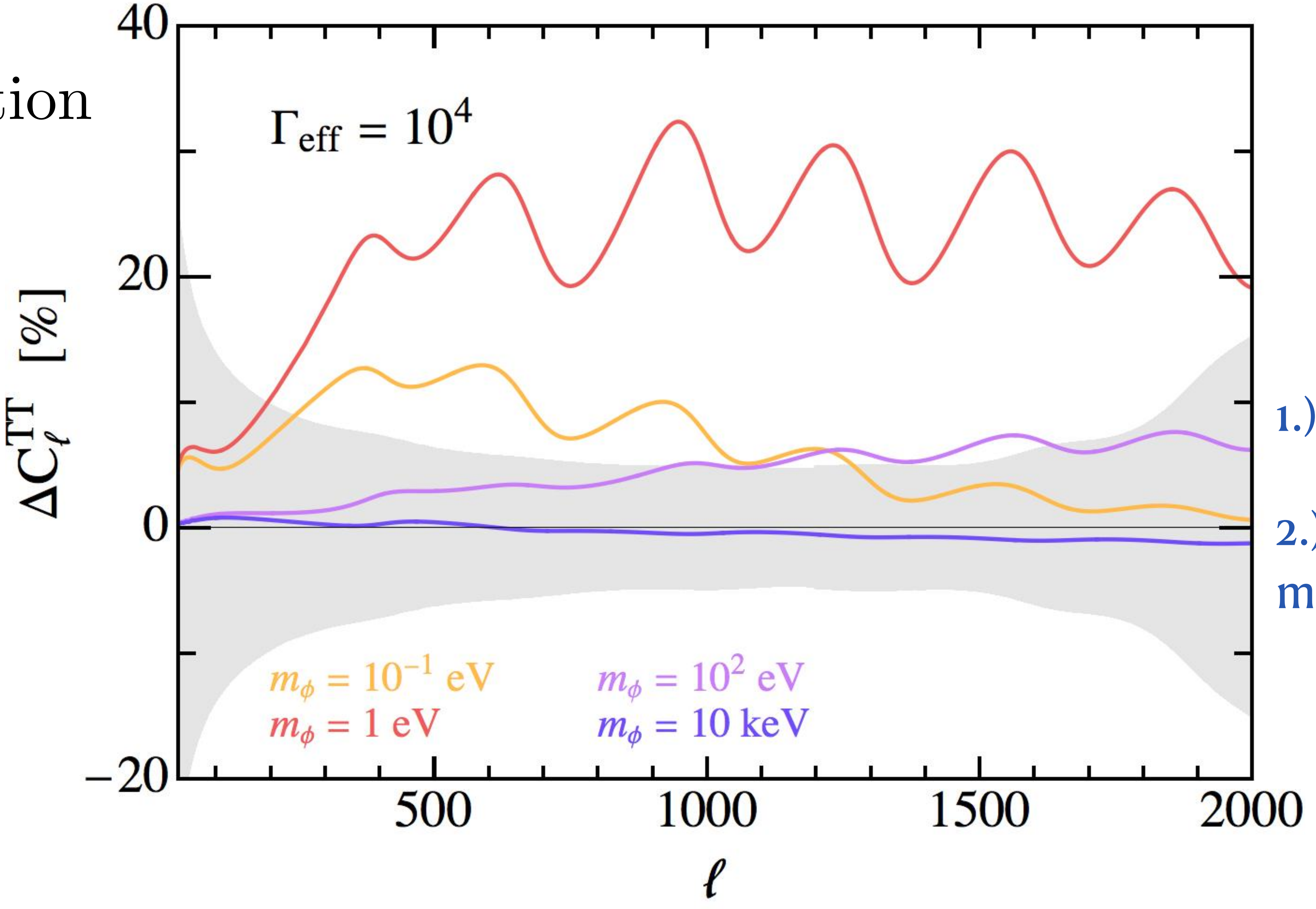
$$\Delta N_{\rm eff} \sim 0.11$$

$$N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{\rho_{rad}-\rho_\gamma}{\rho_\gamma}\right)$$

Majoron in the CMB

$\Gamma_{\rm eff} \geq 1$ thermalize

$\Gamma_{\rm eff} < 1$ No thermalization

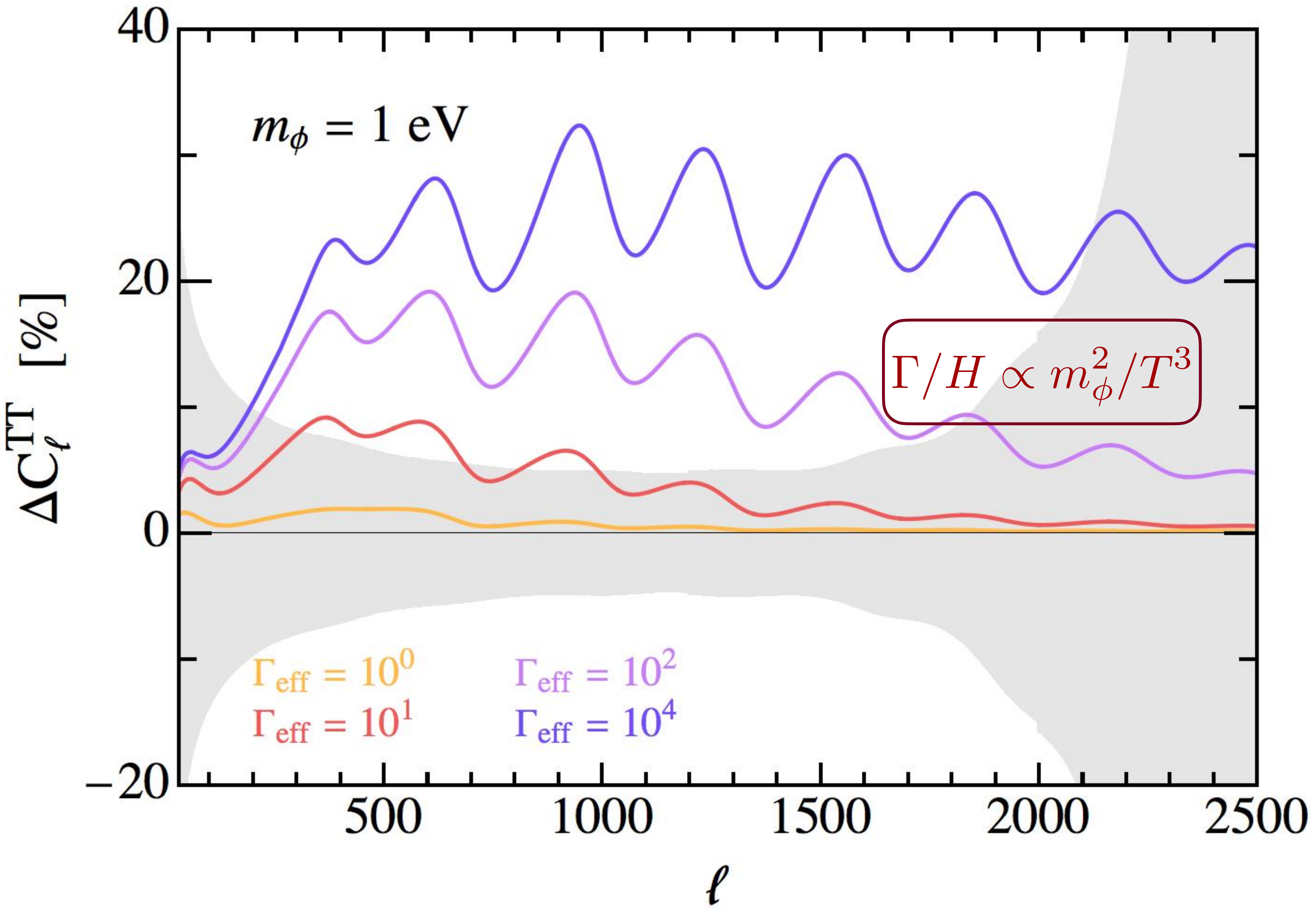


1.) Anisotropic stress is small

2.) Large masses map to large multipoles

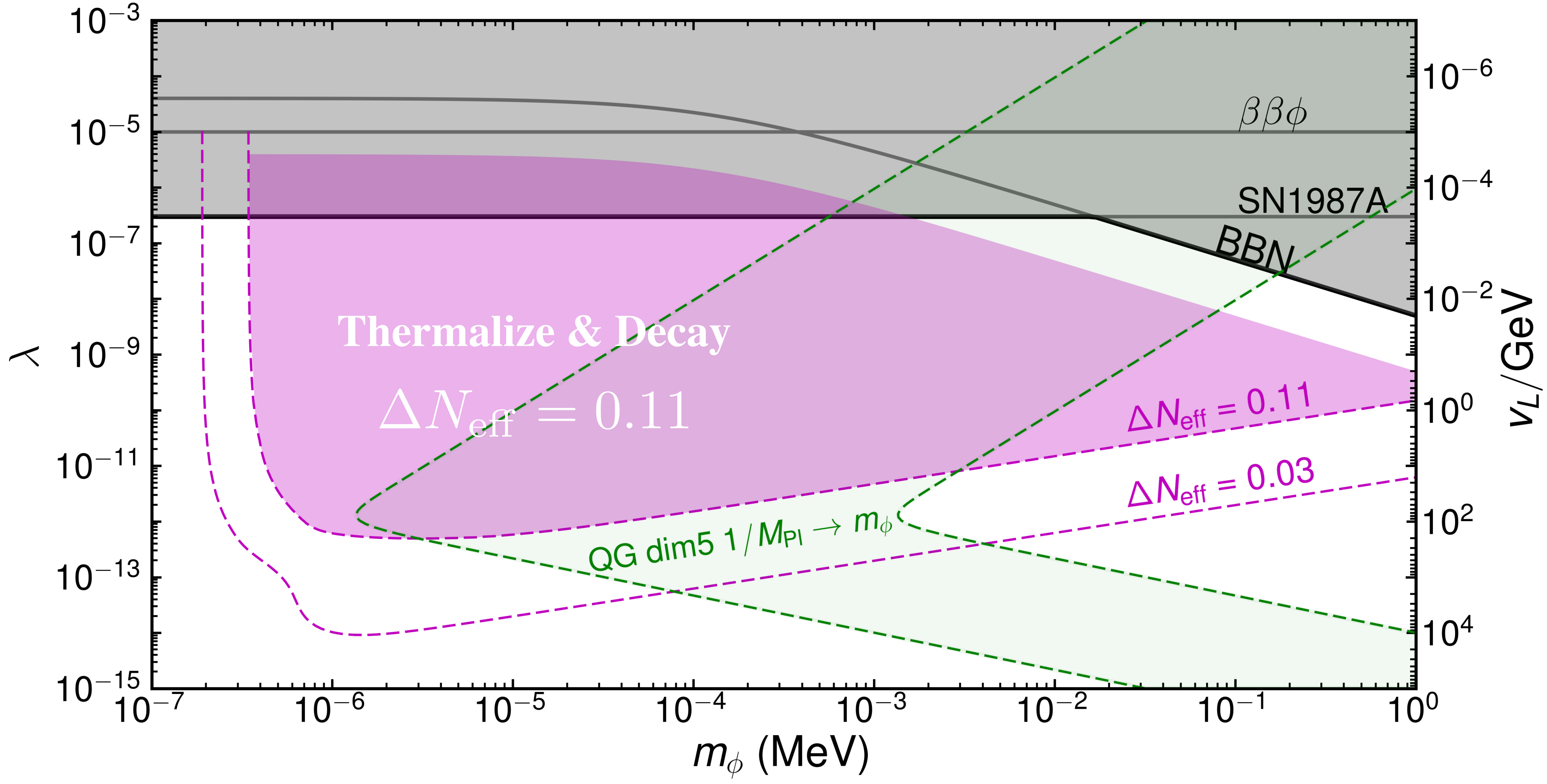
(1909.04044) Escudero, **SJW**

Majoron in the CMB



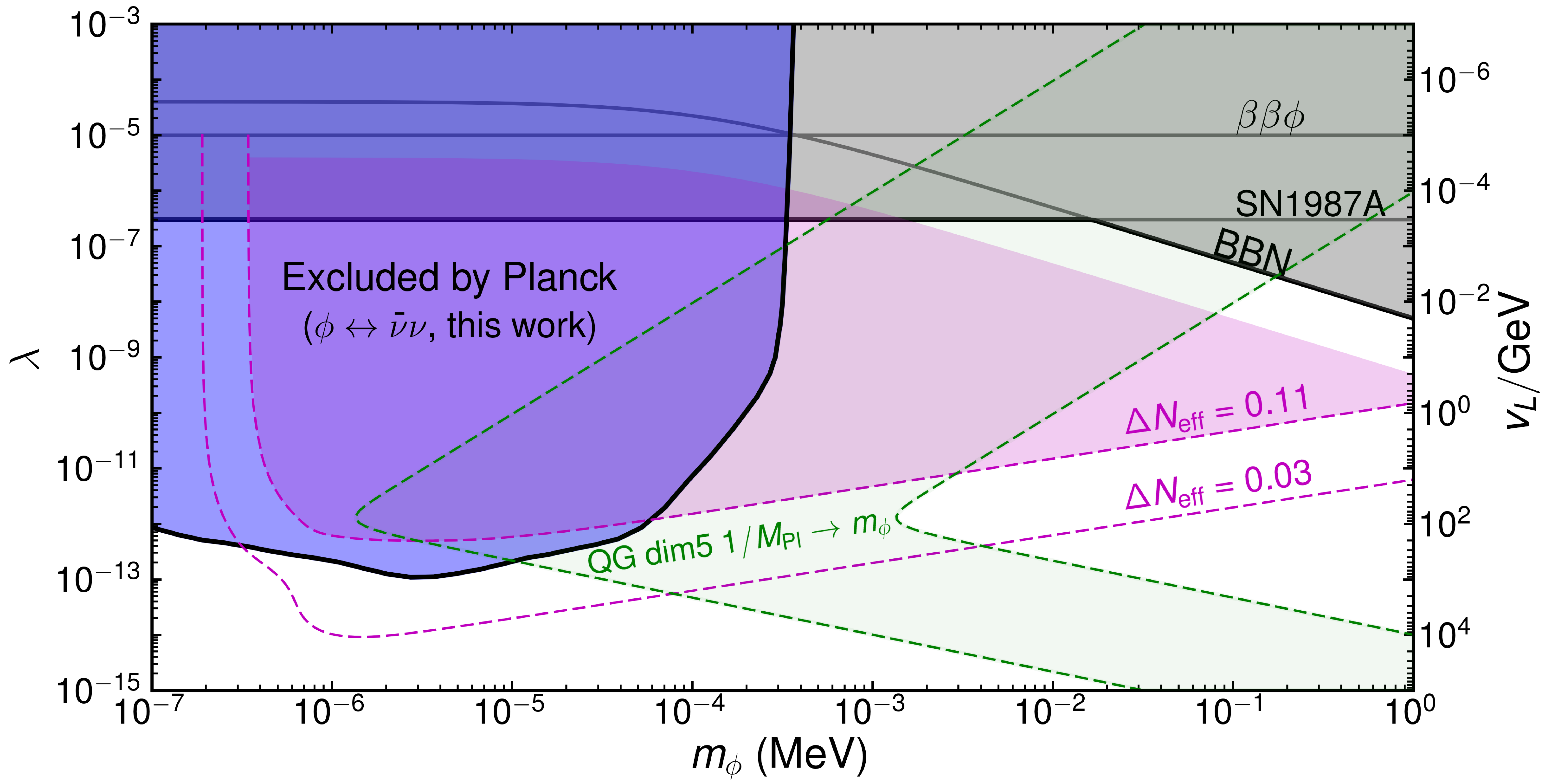
(1909.04044) Escudero, **SJW**

Majoron Parameter Space



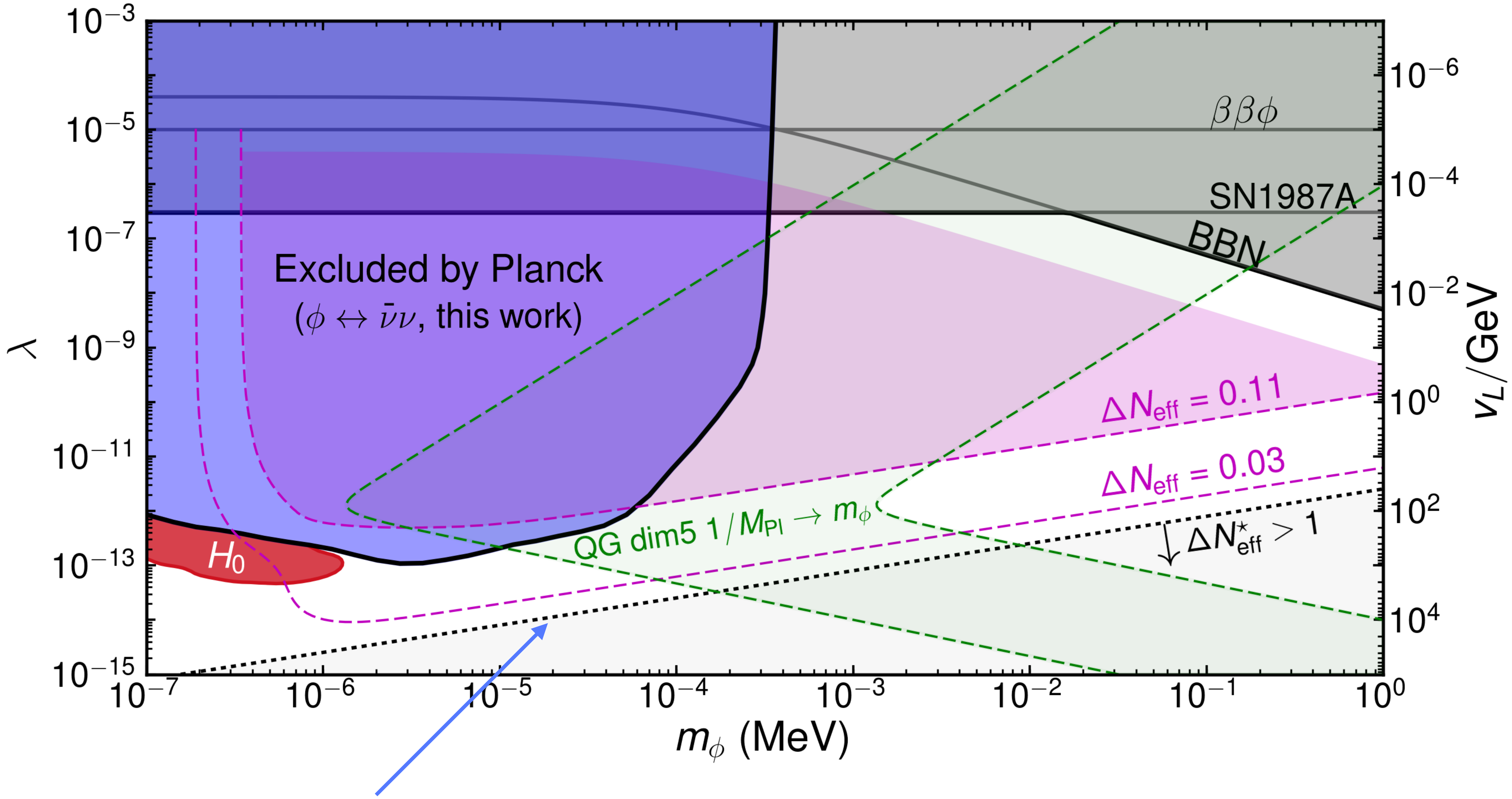
(1909.04044) Escudero, **SJW**

Majoron Parameter Space



(1909.04044) Escudero, **SJW**

Primordial Majorons



Excluded if primordial population

(1909.04044) Escudero, **SJW**

The Hubble Tension

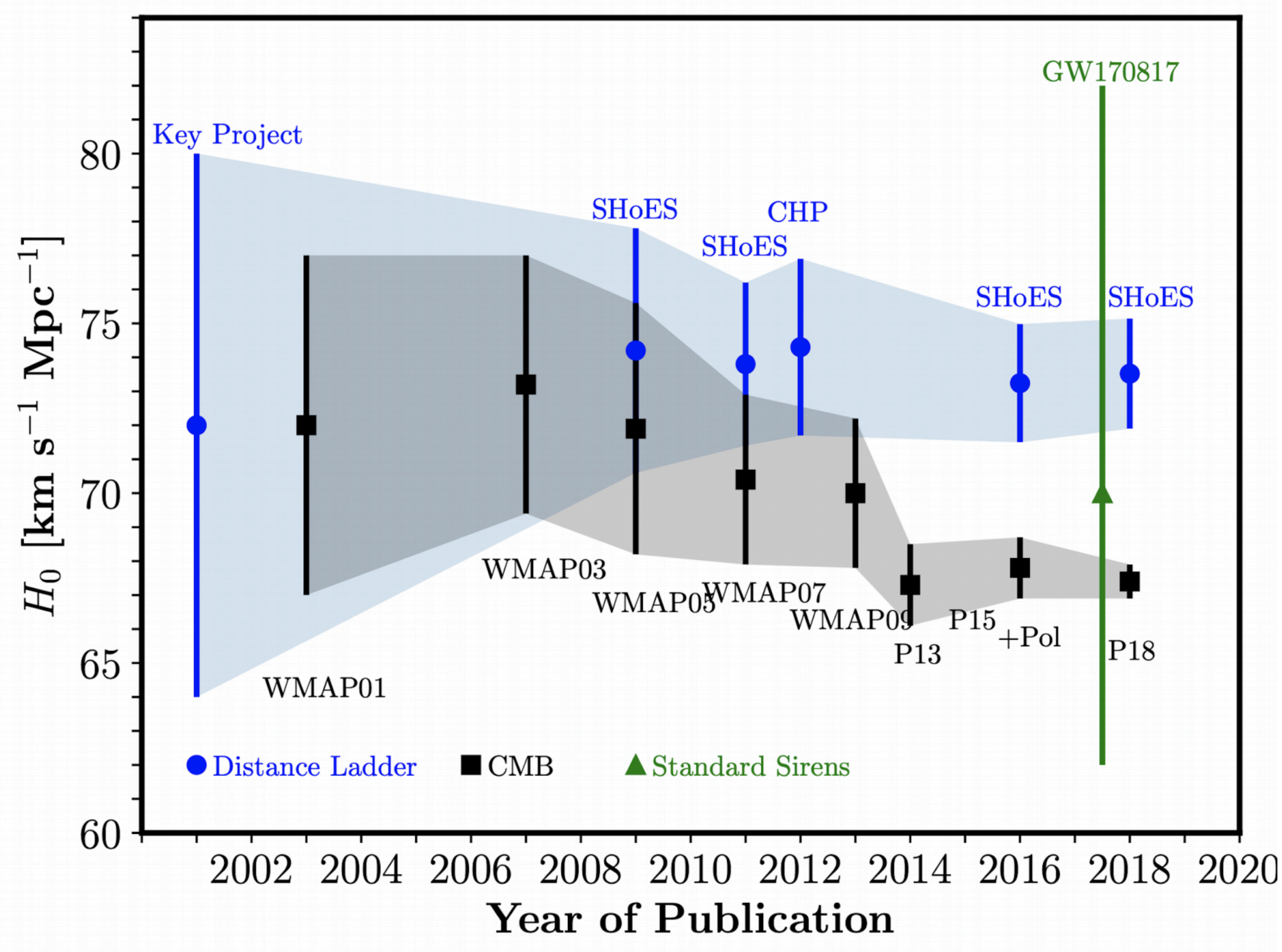
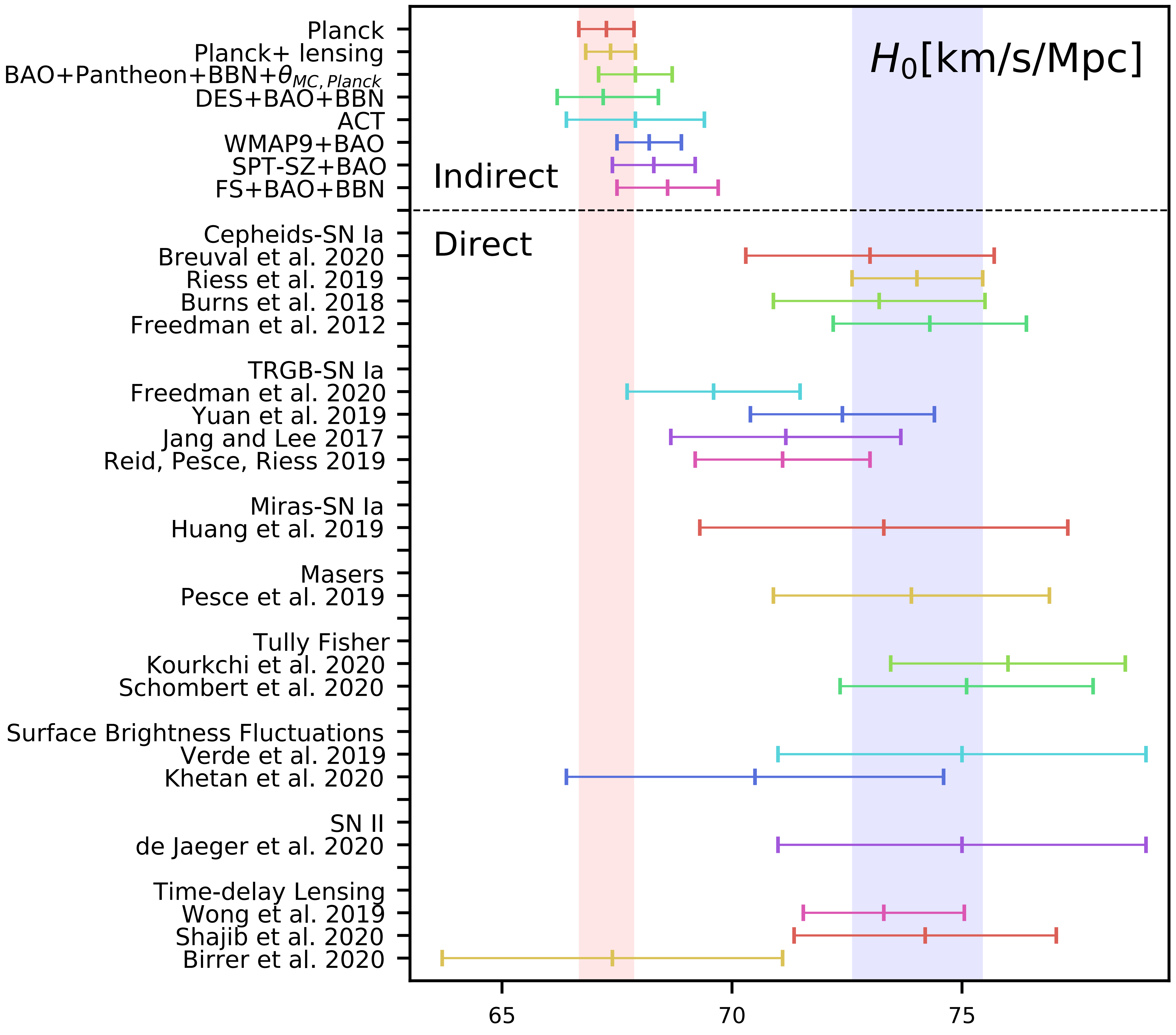


Image credit: Nandita Khetan

The Hubble Tension

Di Valentino et al 2021



How do you resolve this?

1.) Systematics in SH0ES

- Are SN1a calibrated correctly?
  - Do we have the correct local anchor distance? Is there a metallicity effect? What about dust? Bias is peculiar velocities? Local calibration systematics?
- Are we sure the SN1a populations are the same?
- Do we live in a void (would need a 5 sigma void…)

Follin & Knox (2017), Feeney et al (2017), Freedman et al (2019), Freedman et al (2020), Yuan et al (2019), Efstathiou et al (2020), Soltis et al (2020), Rigault et al (2014), Jones et al (2018), Brout&Scolnic (2020)…

2.) Systematics in Planck

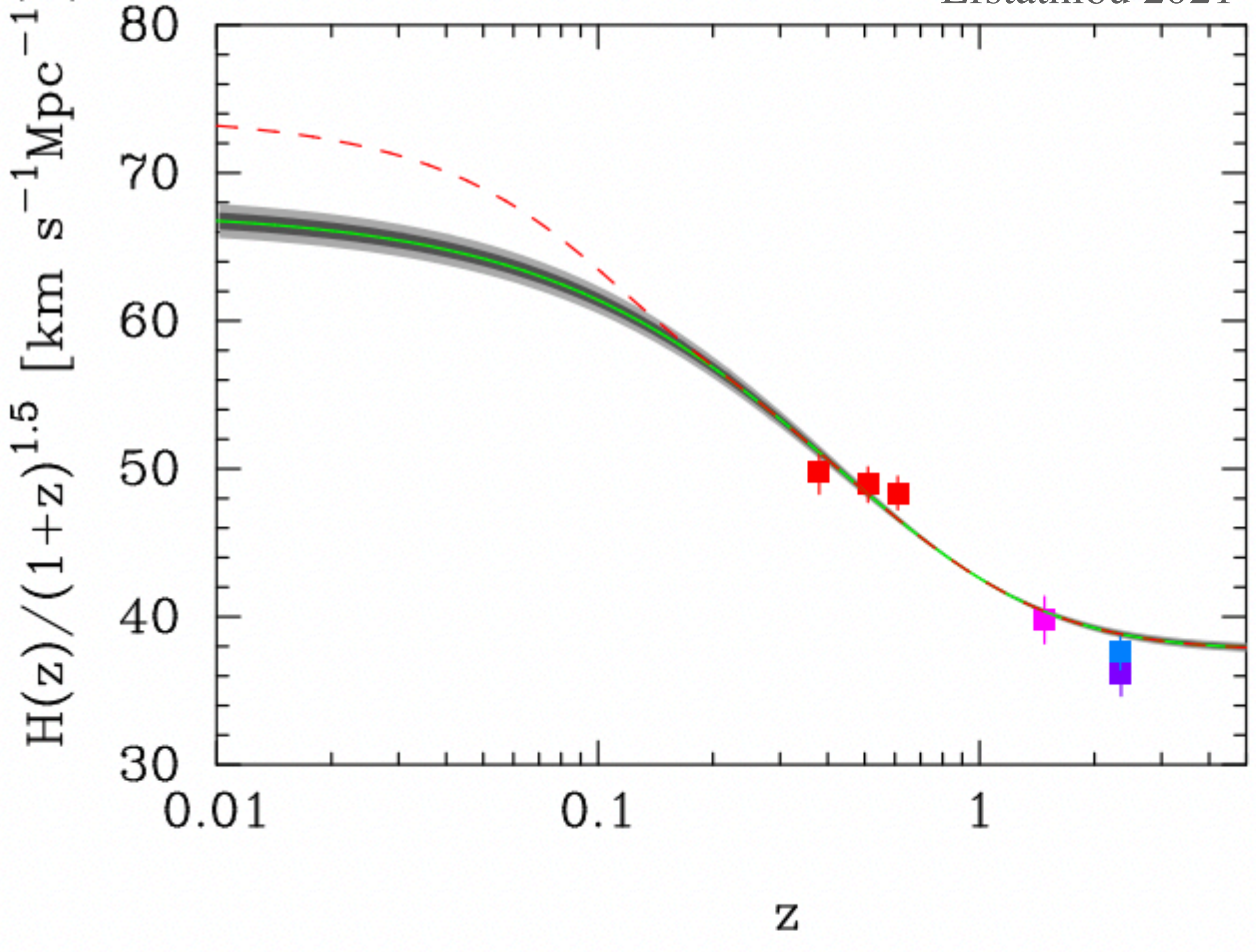
- Planck actually not needed….
- No proposed systematic known to produce this effect

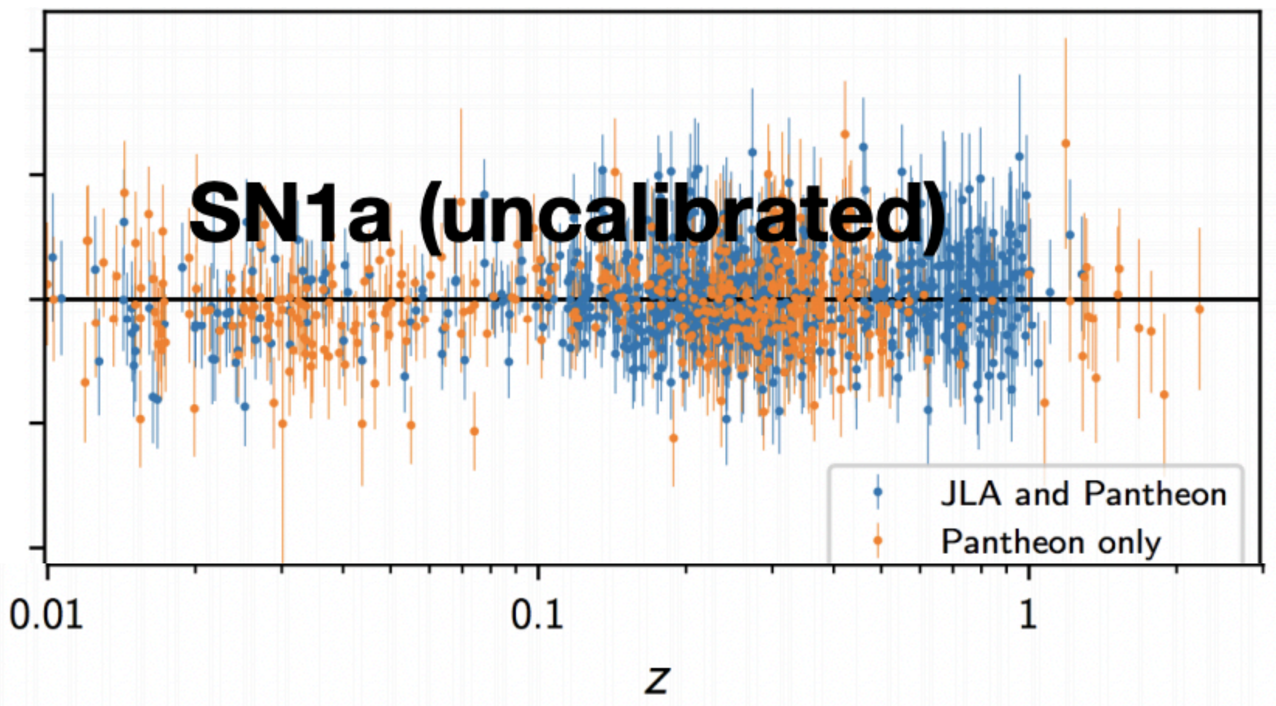
3.) Modify cosmology at late times

4.) Modify cosmology at early times

Late Time Solutions

Efstathiou 2021



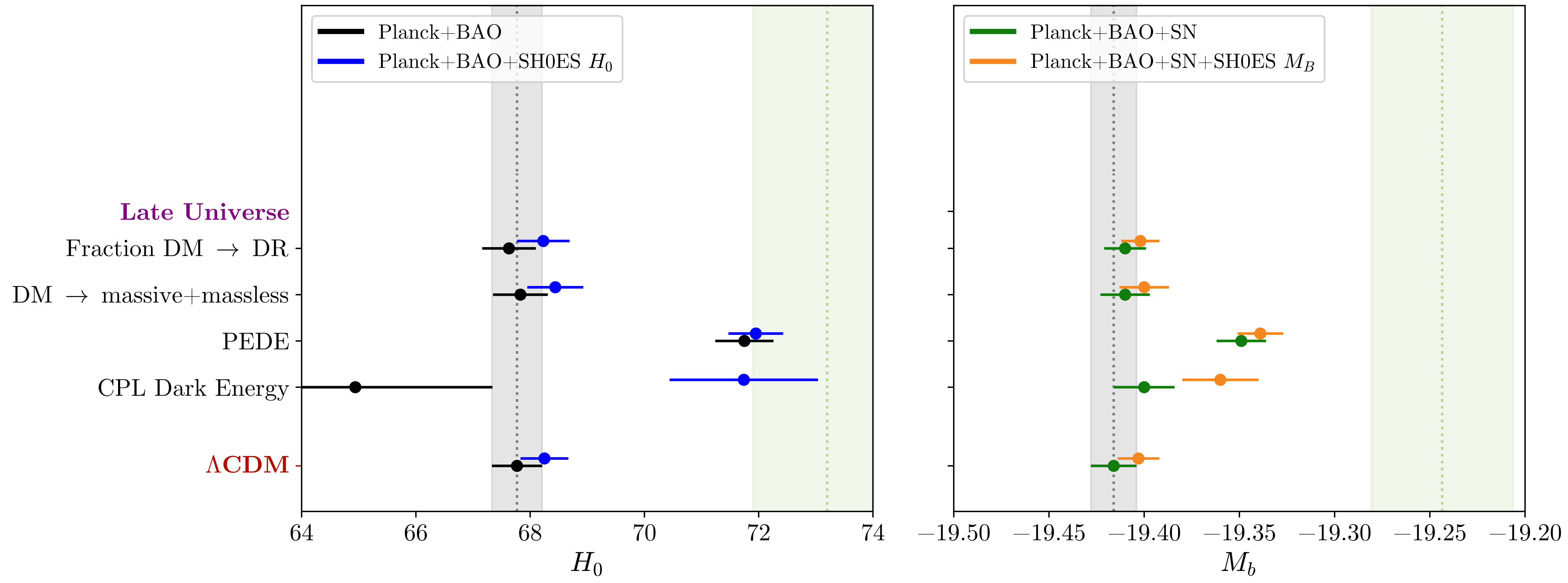


Key point: Supernova measurements do not measure H(z = 0)!

Lemos et al 2019, Benevento et al 2020, Camarena et al 2021, Efstathiou 2021

Simply doesn't work well...

(TO APPEAR SOON) Shöneberg, Franco Abellan, Pérez Sánchez, Lesgourges, Poulin, **SJW**

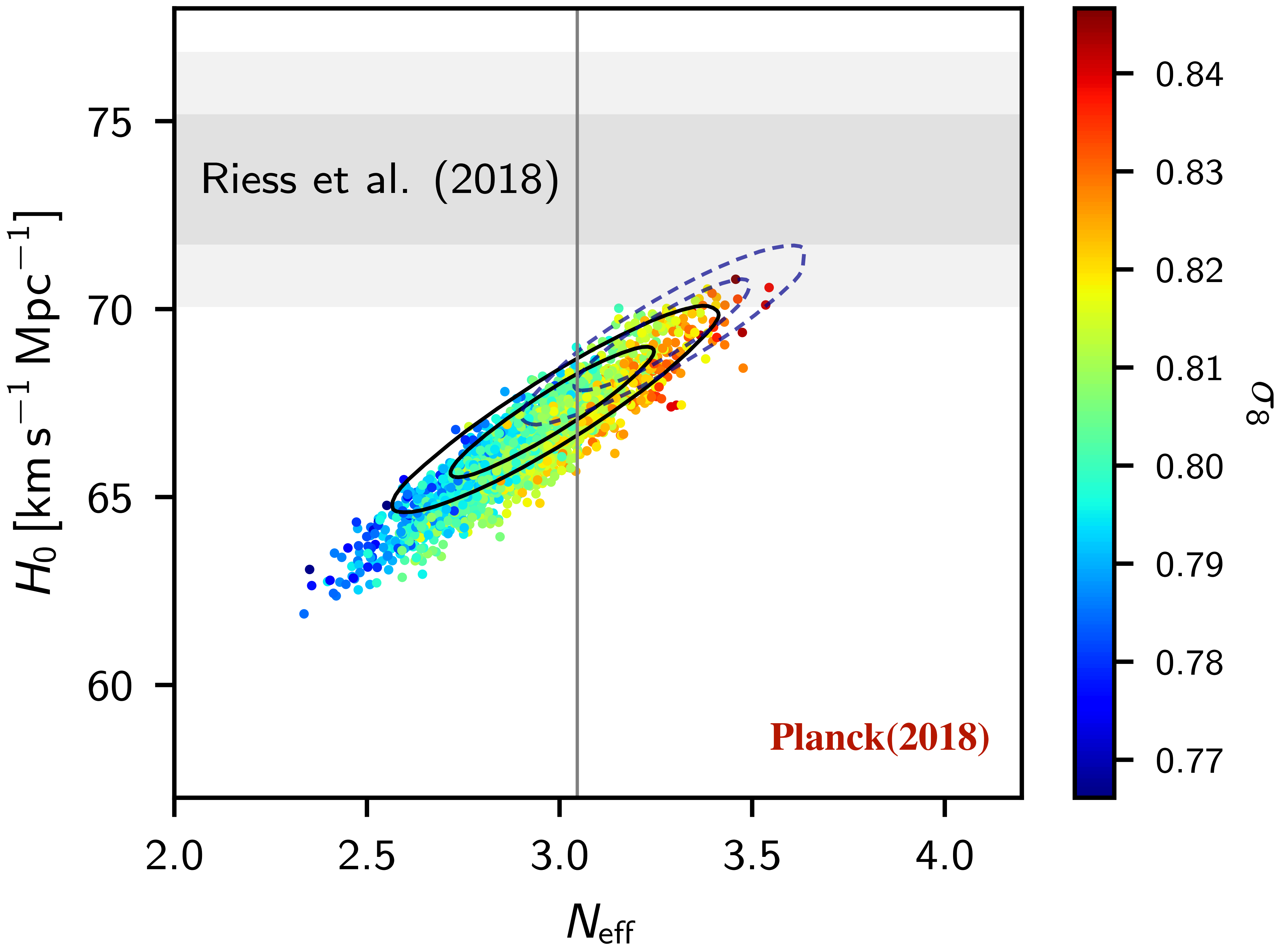


Early Time Solutions

Large number of proposals… (I can't do justice to all, or even many — see Di Valentio et al 2021 for review of proposals)

One subclass exploits degeneracy between Neff and H0

Bernal et al (2016), Morstell and Dhawan (2018)



$$H_0 \simeq \left[73.6 + 6.2(\Delta N_{\rm eff} - 1)\right] \ \mathrm{km/s/Mpc}$$

Vagnozzi (2019)

Problem: Large values disfavored by data

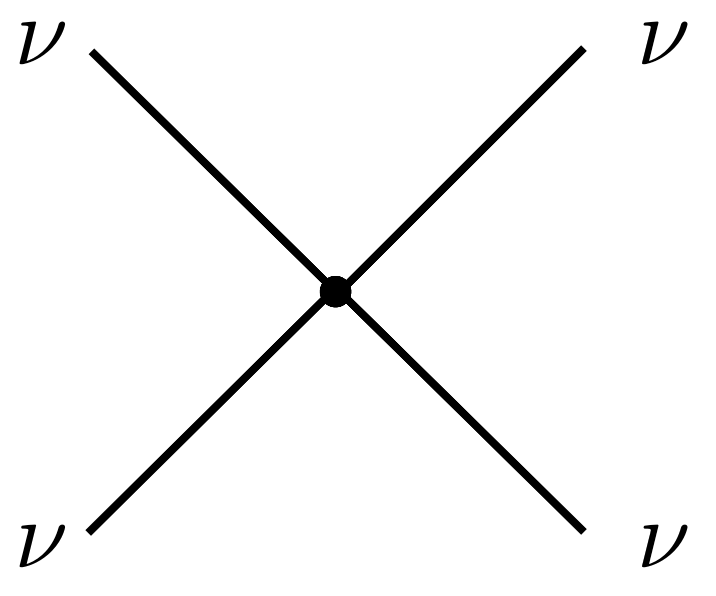
Question: What else can I add that allows me to squeeze in more Neff ?

The Role of Nu Interactions

Self-interacting neutrino solution

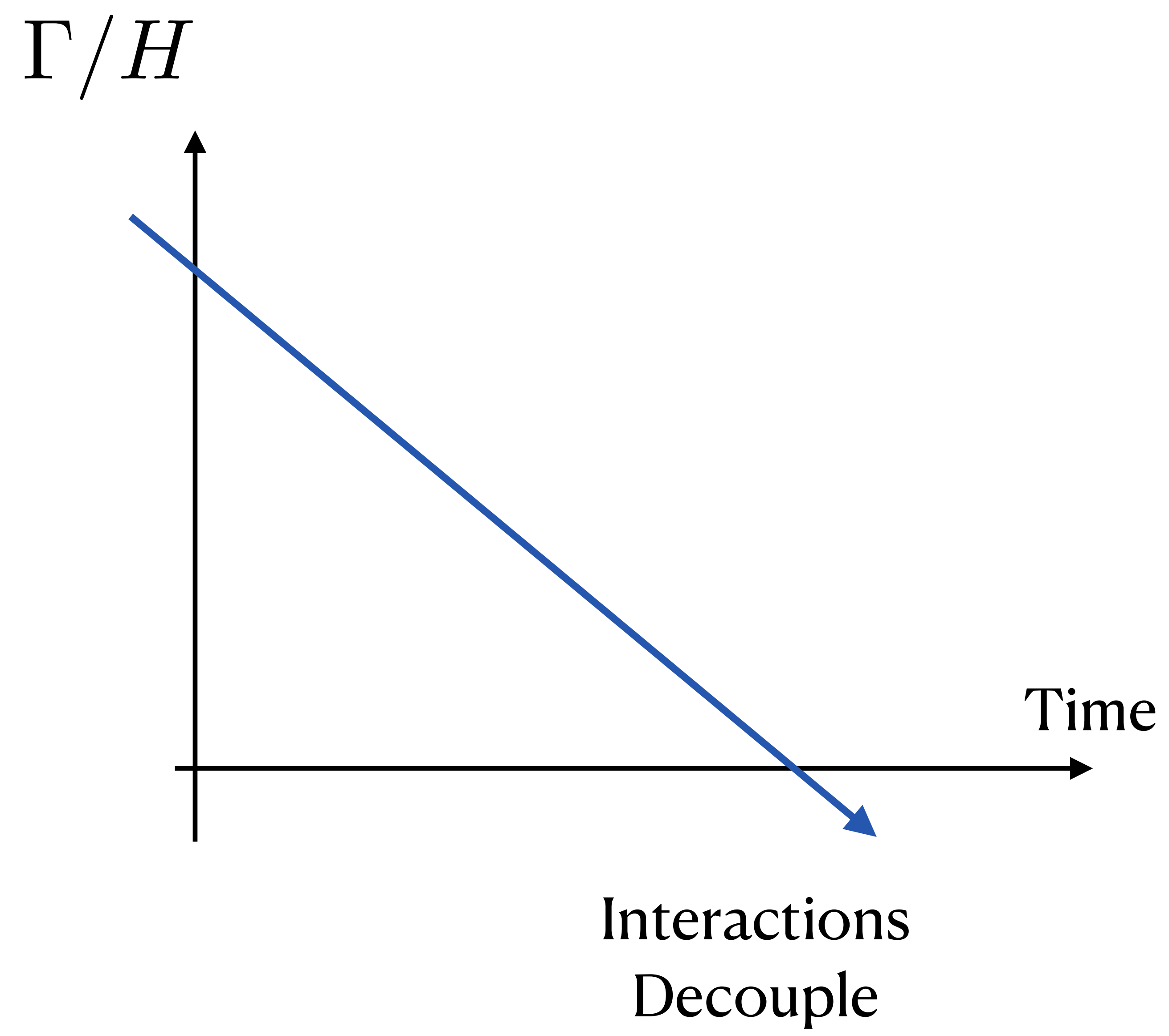
Kreisch et al (2019), Park et al (2019),
Brinckmann et al (2020), …

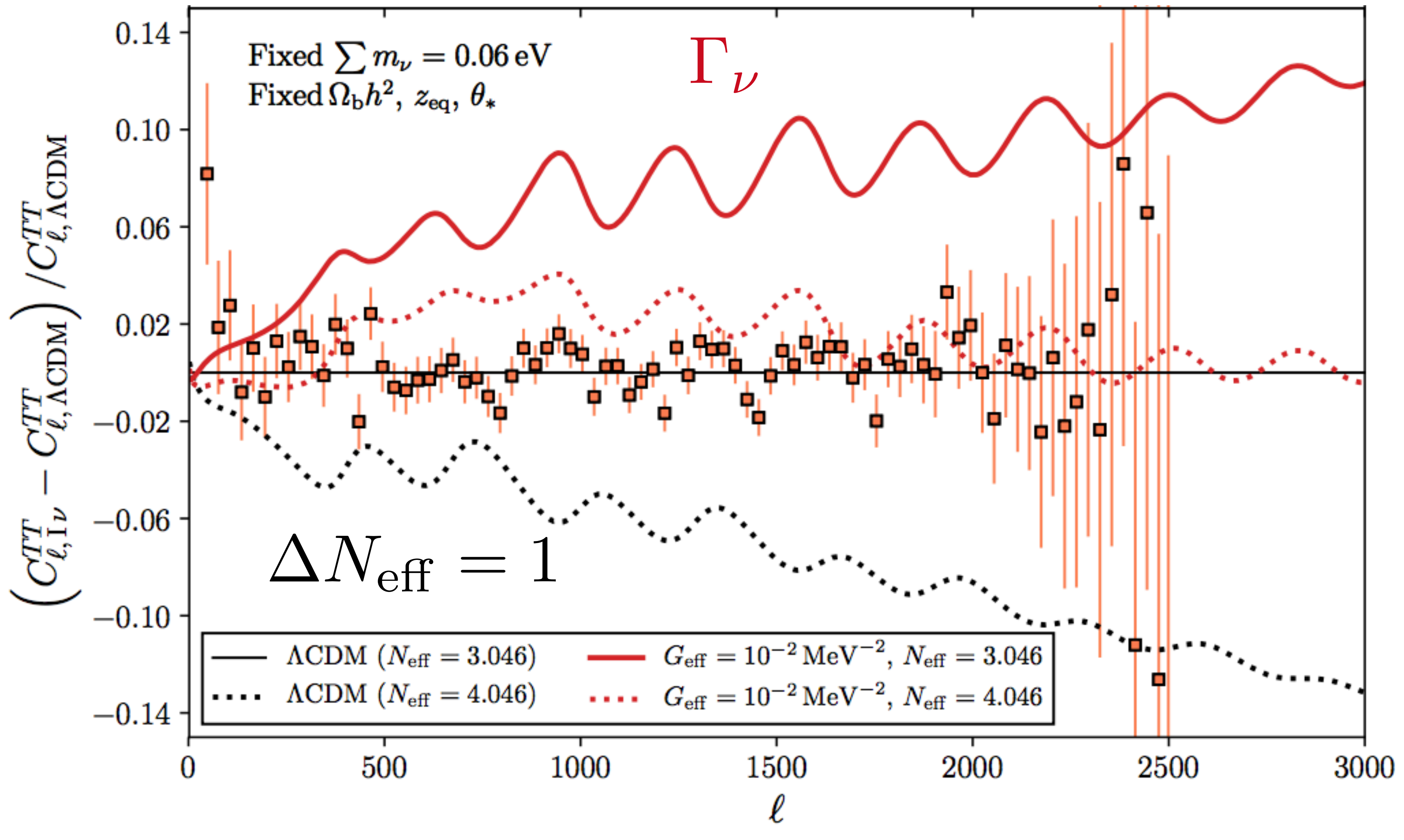
(Effective contact interaction,
Massive mediator)



$+\Delta N_{\rm eff}$

(ad hoc)

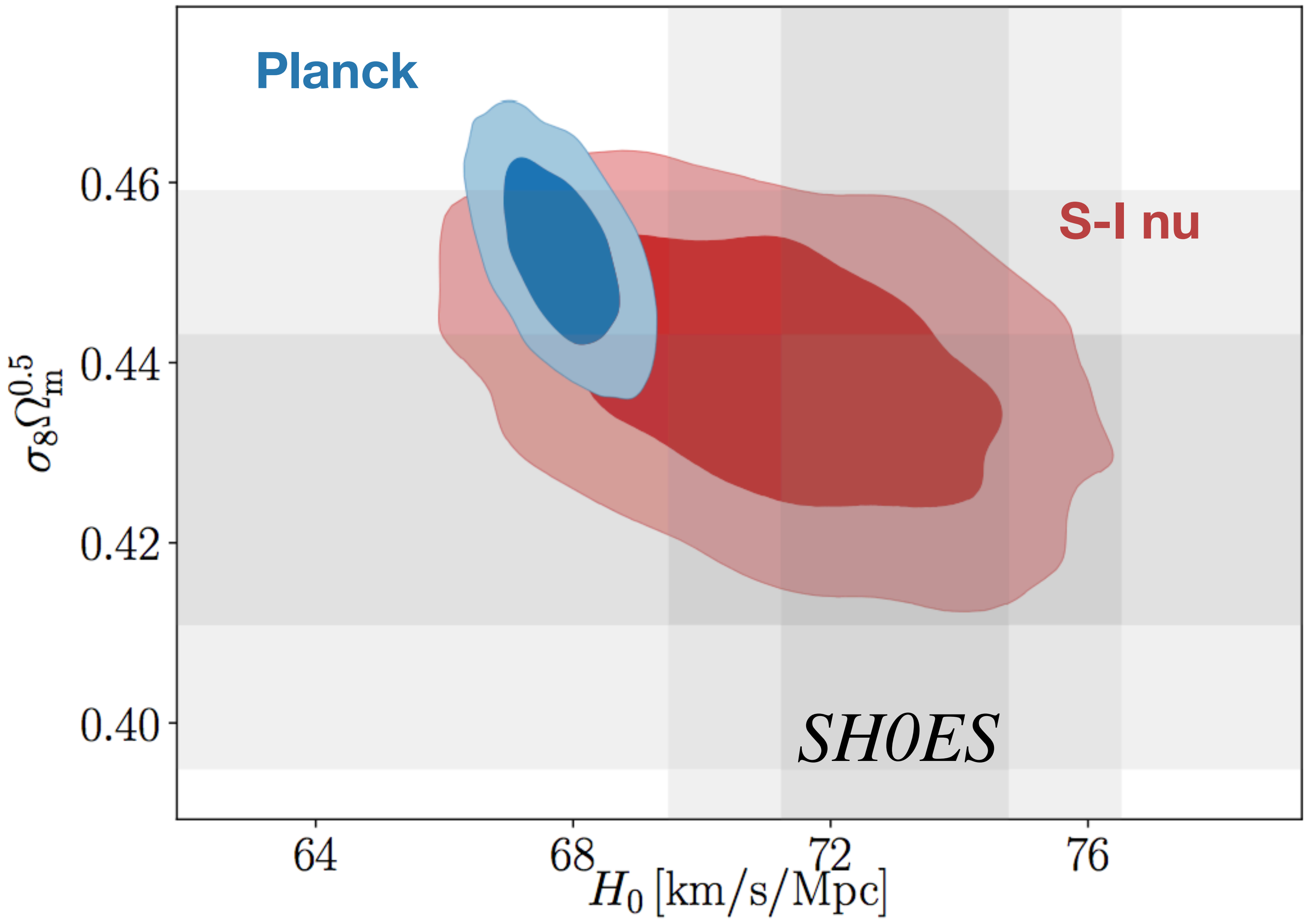




Kreisch et al (2019)

The Role of Nu Interactions

(Planck 2015 TT, Lens, BAO)



Kreisch et al (2019)

Problem 1)

Solution also requires Neff ~ 4, naively excluded by BBN…

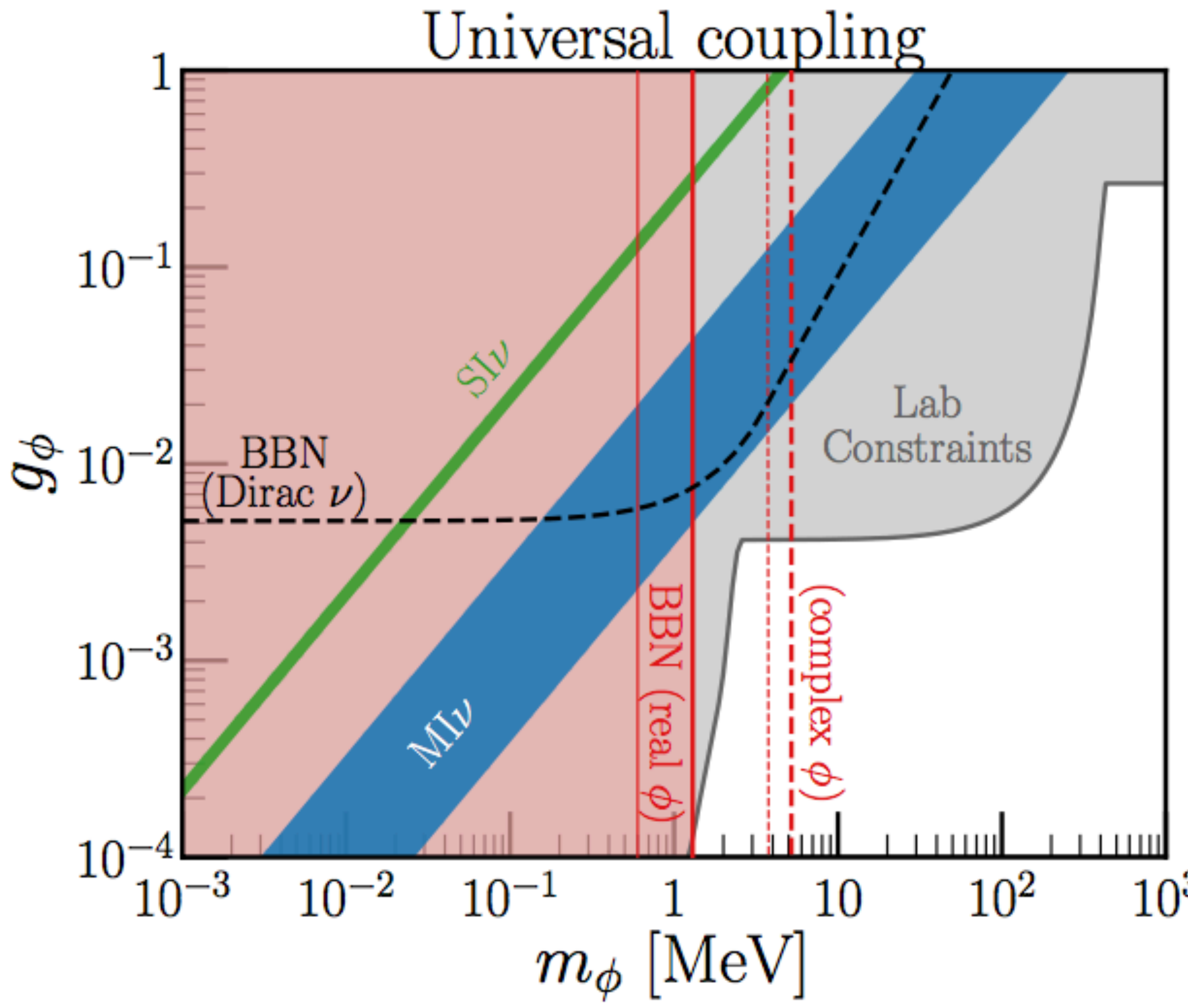
Pisanti et al. 2011.11537

Not necessarily a problem…

- Can generate Neff after BBN
- BBN bound needs to be considered in context of model
- Constraint dominated by Helium (could suffer from systematics)

See e.g. Berbig et al 2021, Huang et al 2021
Aver et al (2020), Izotov et al (2014)

Problem 2)

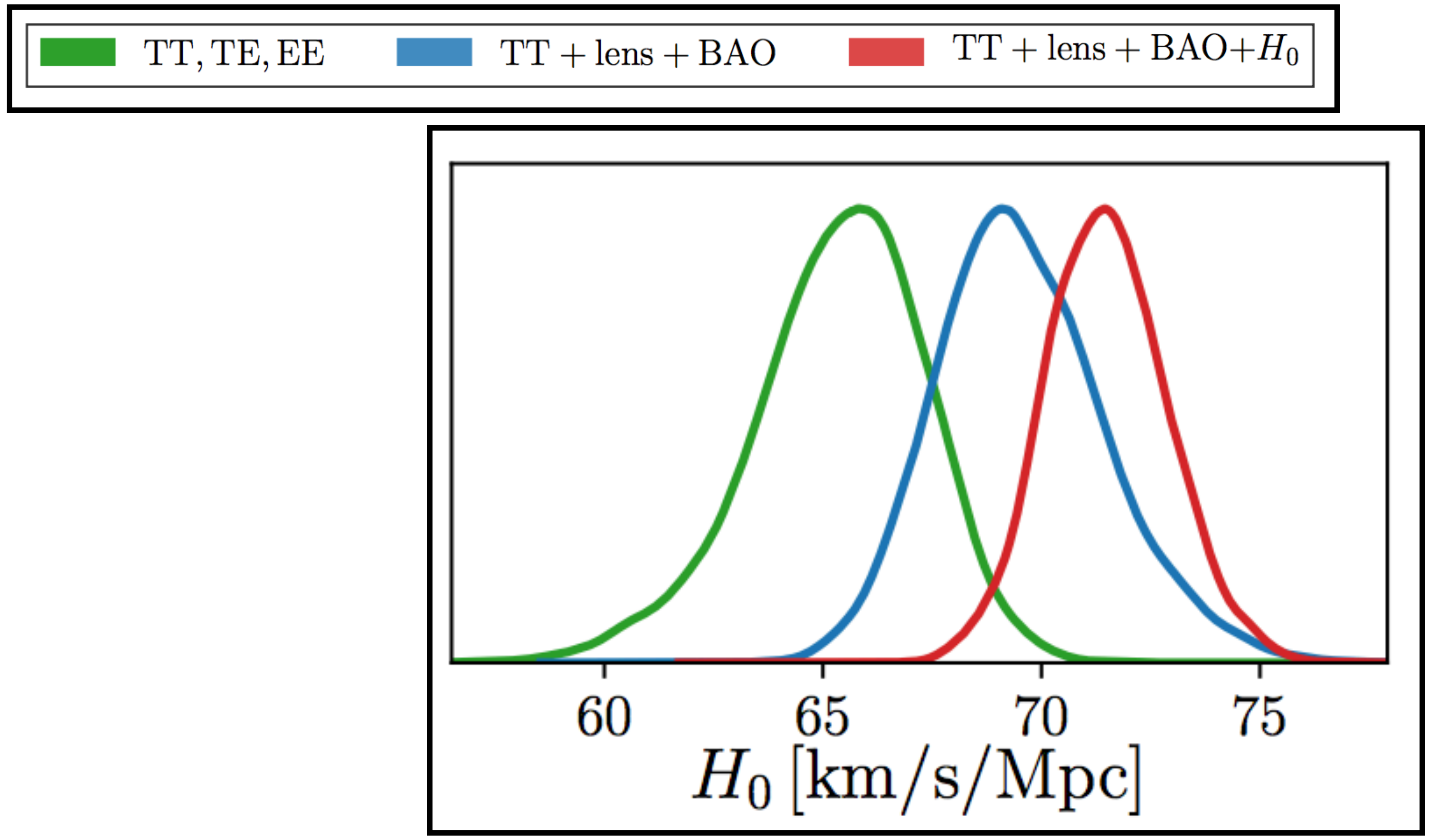


Maybe (????) viable if only coupled to taus….

Blinov, Kelley, Krnjaic, McDermott (2019)

The Role of Nu Interactions

Problem 3)



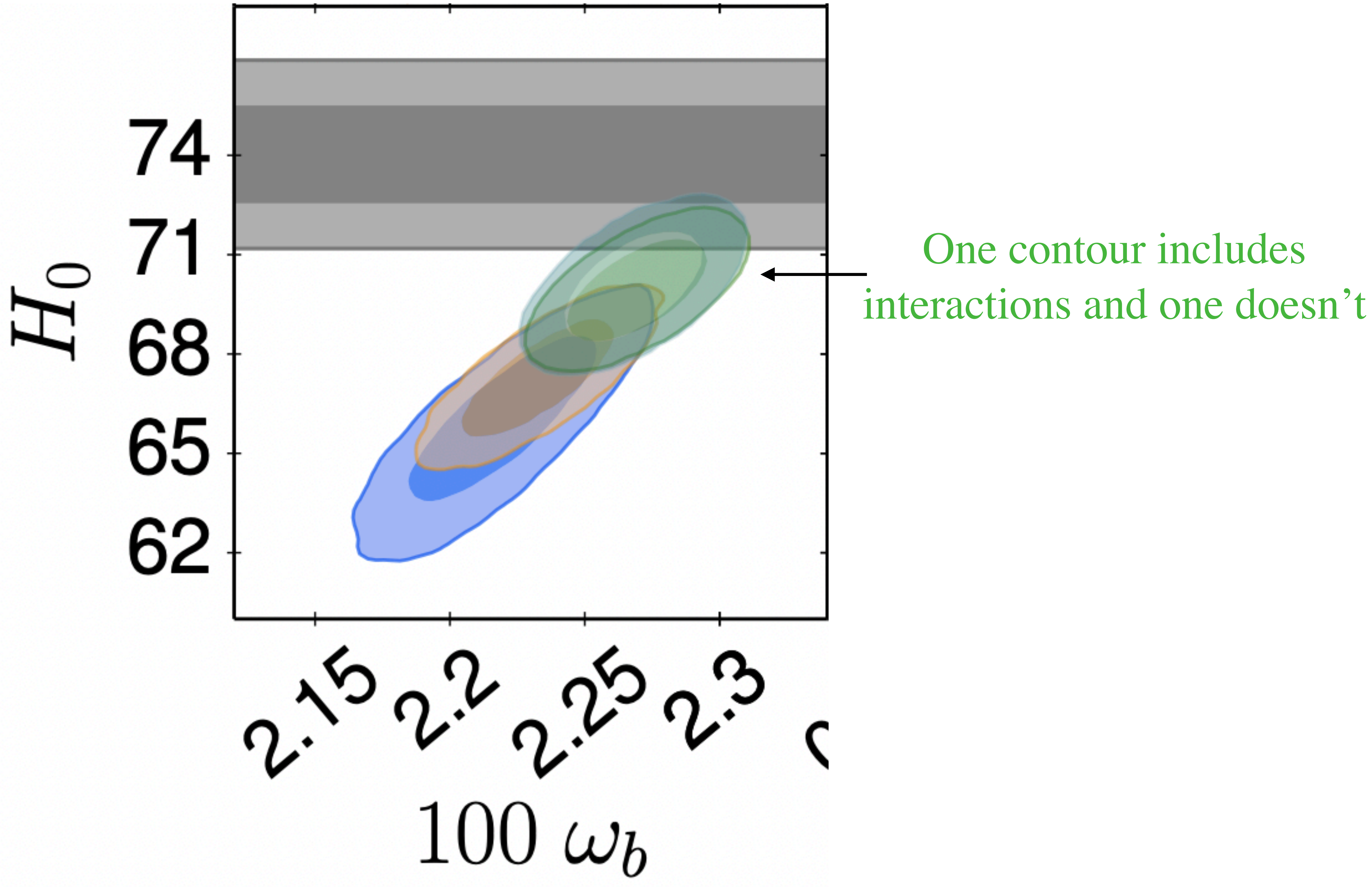
Solution killed with polarization data?

Kreisch et al (2019)

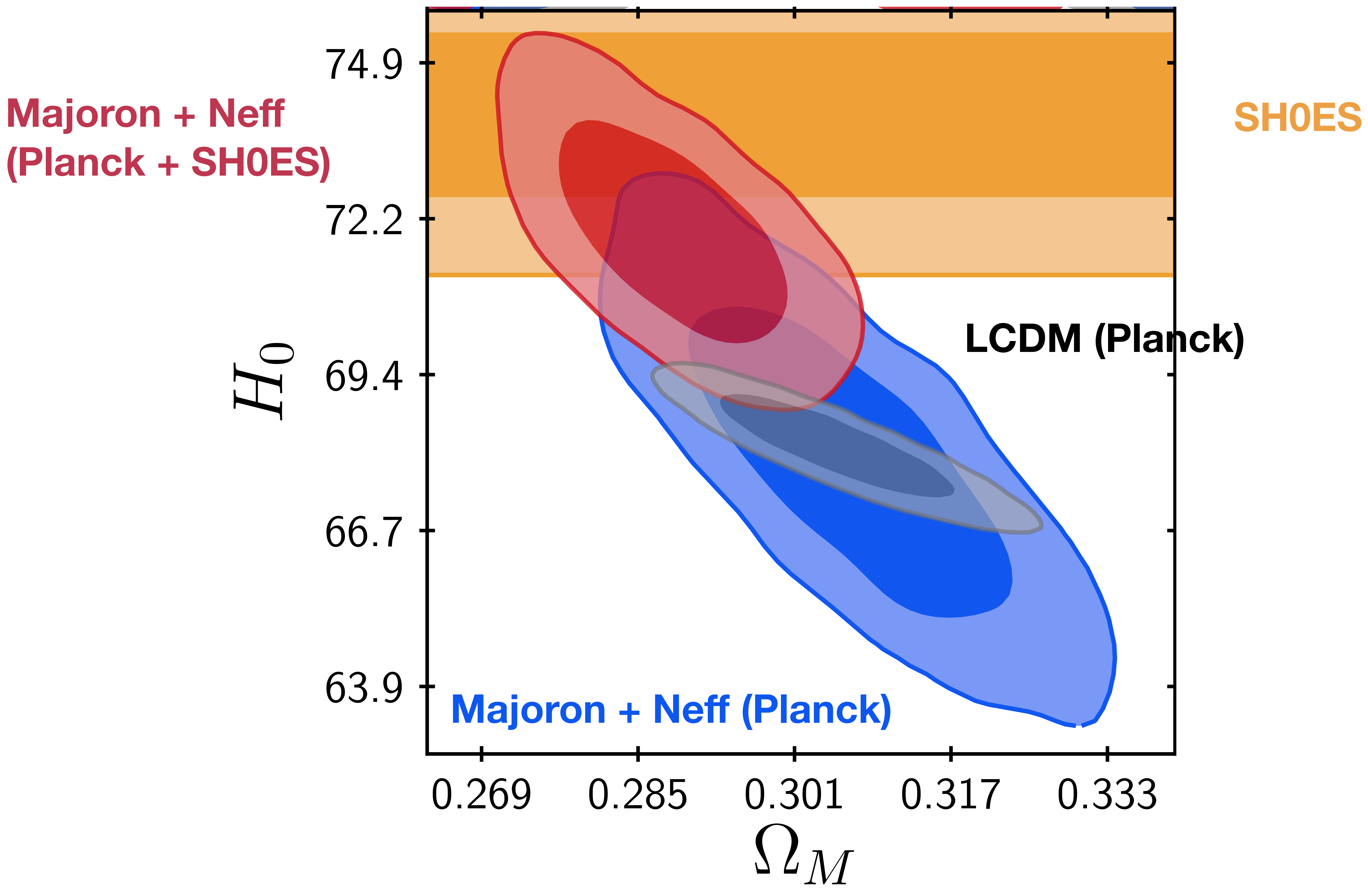
Problem 4)

Planck 2018 fit got worse

Brinkmann et al 2020



The Majoron Solution (Part 1)



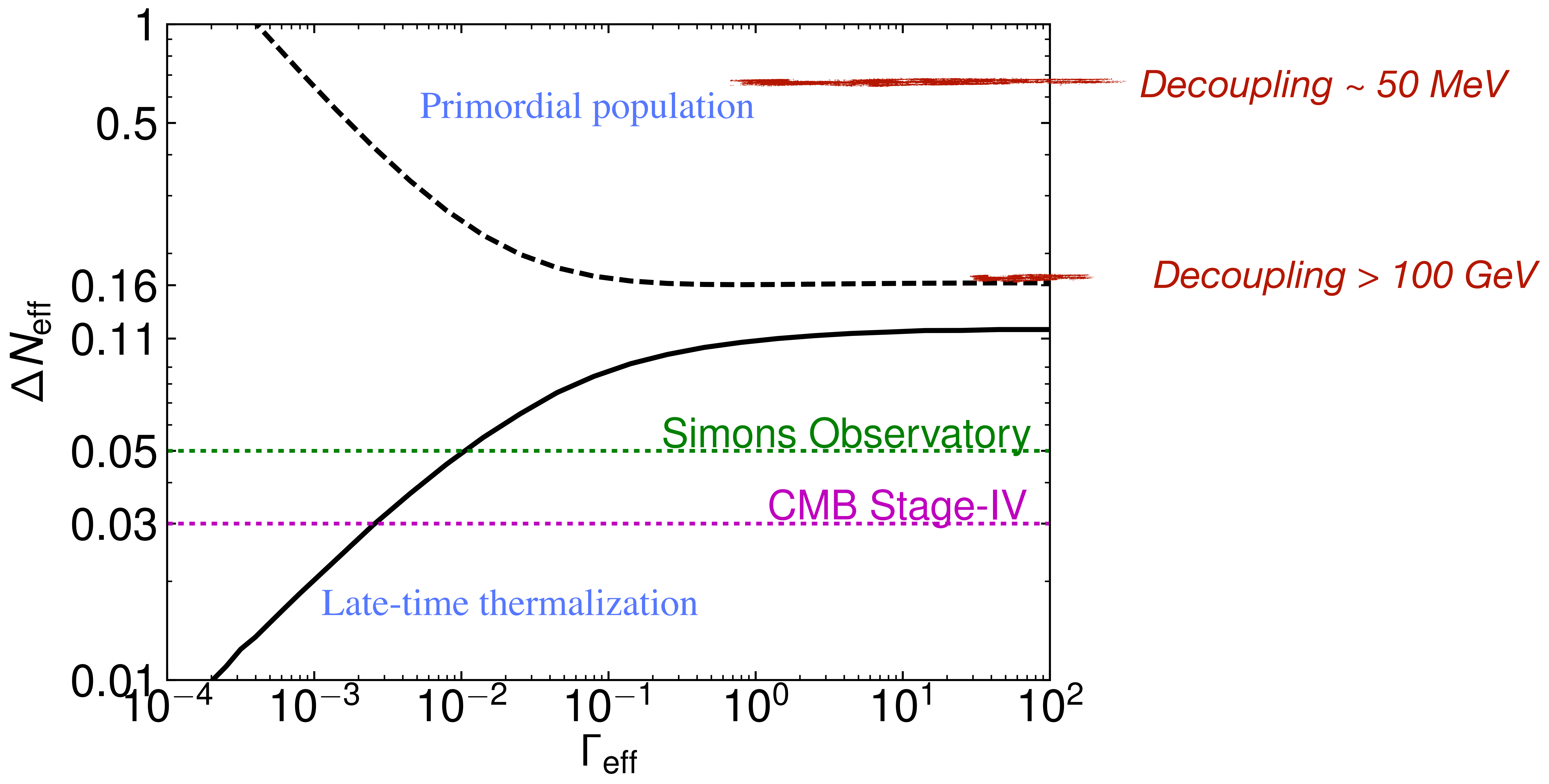
(1909.04044) Escudero, **SJW**

Tension reduced to ~2 sigma level…

Improved fit to Planck!

Still require *ad hoc* contribution to Neff

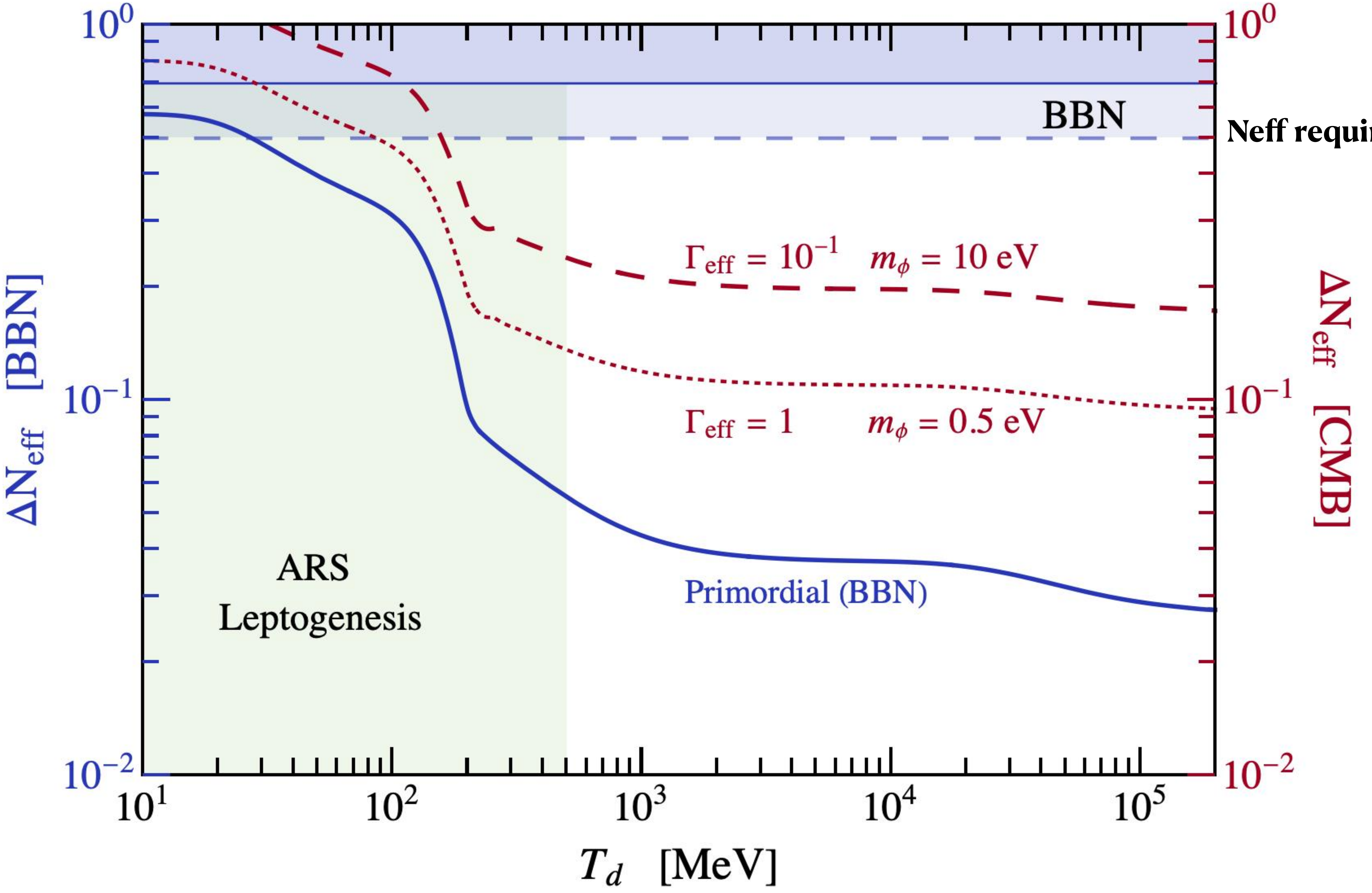
Primordial Majorons



$$\Gamma_{\rm eff} \equiv \left(\frac{\lambda}{4\times 10^{-12}}\right)^2 \left(\frac{\rm keV}{m_\phi}\right)$$

(1909.04044) Escudero, **SJW**

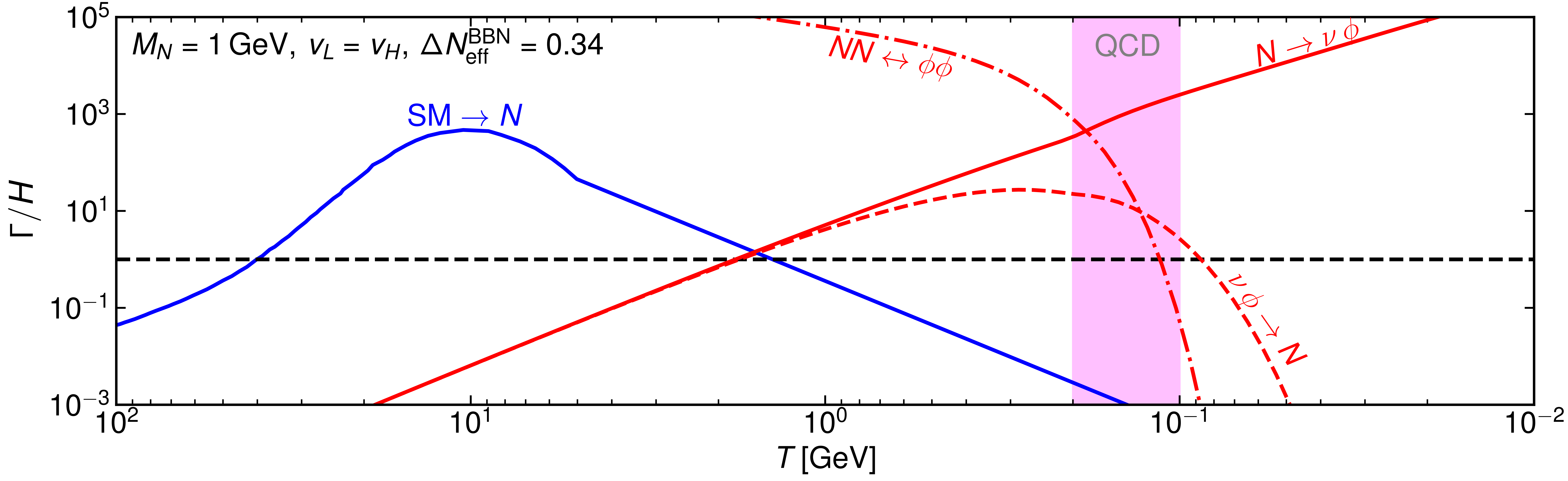
Majoron Decoupling



Neff required by Hubble Solution

Escudero & **SJW** (2021)

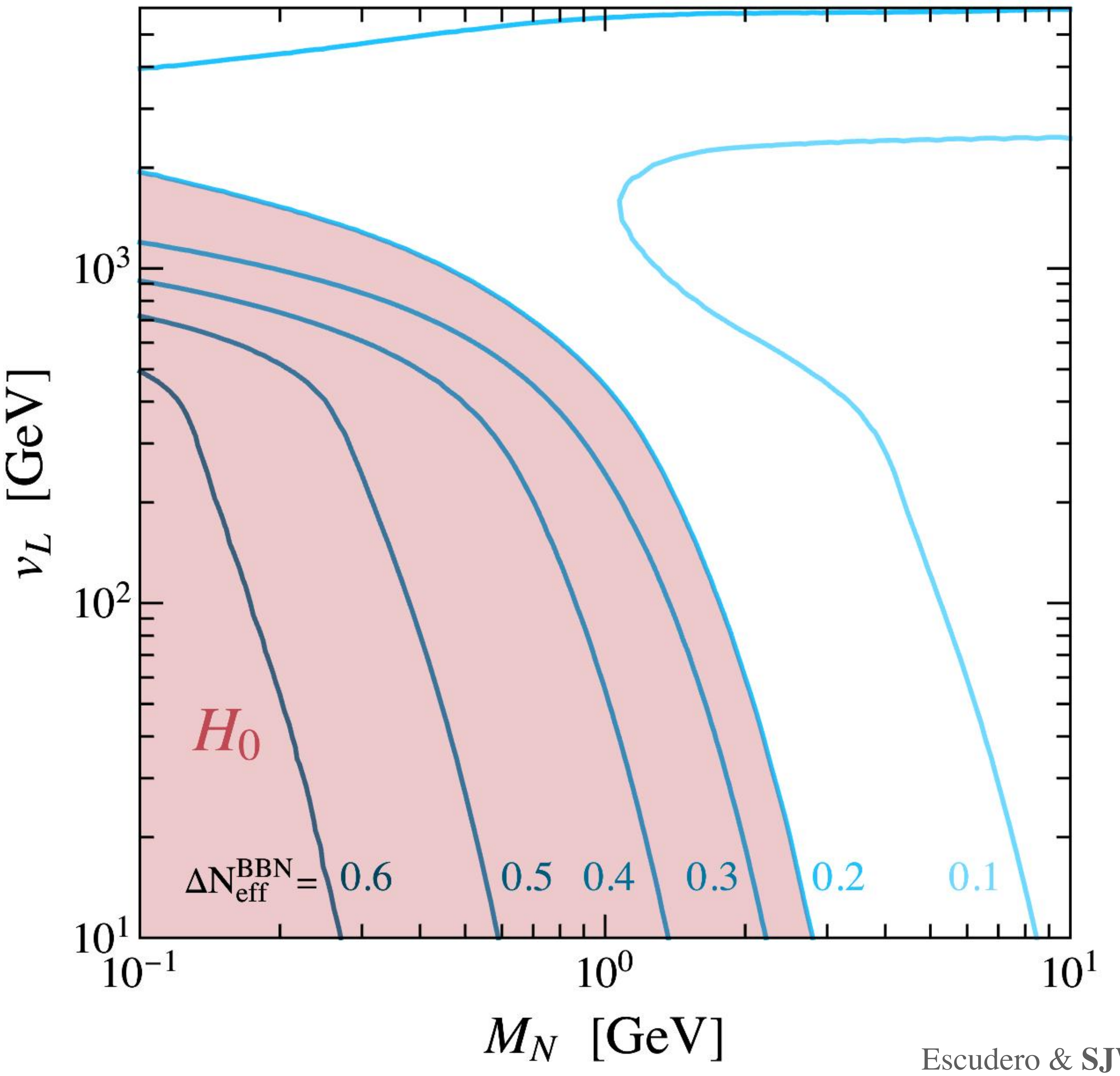
Majoron Production



Thermalization rate for N from Ghiglieri & Laine (2016)

Escudero & **SJW** (2021)

Majoron Decoupling



Escudero & **SJW** (2021)

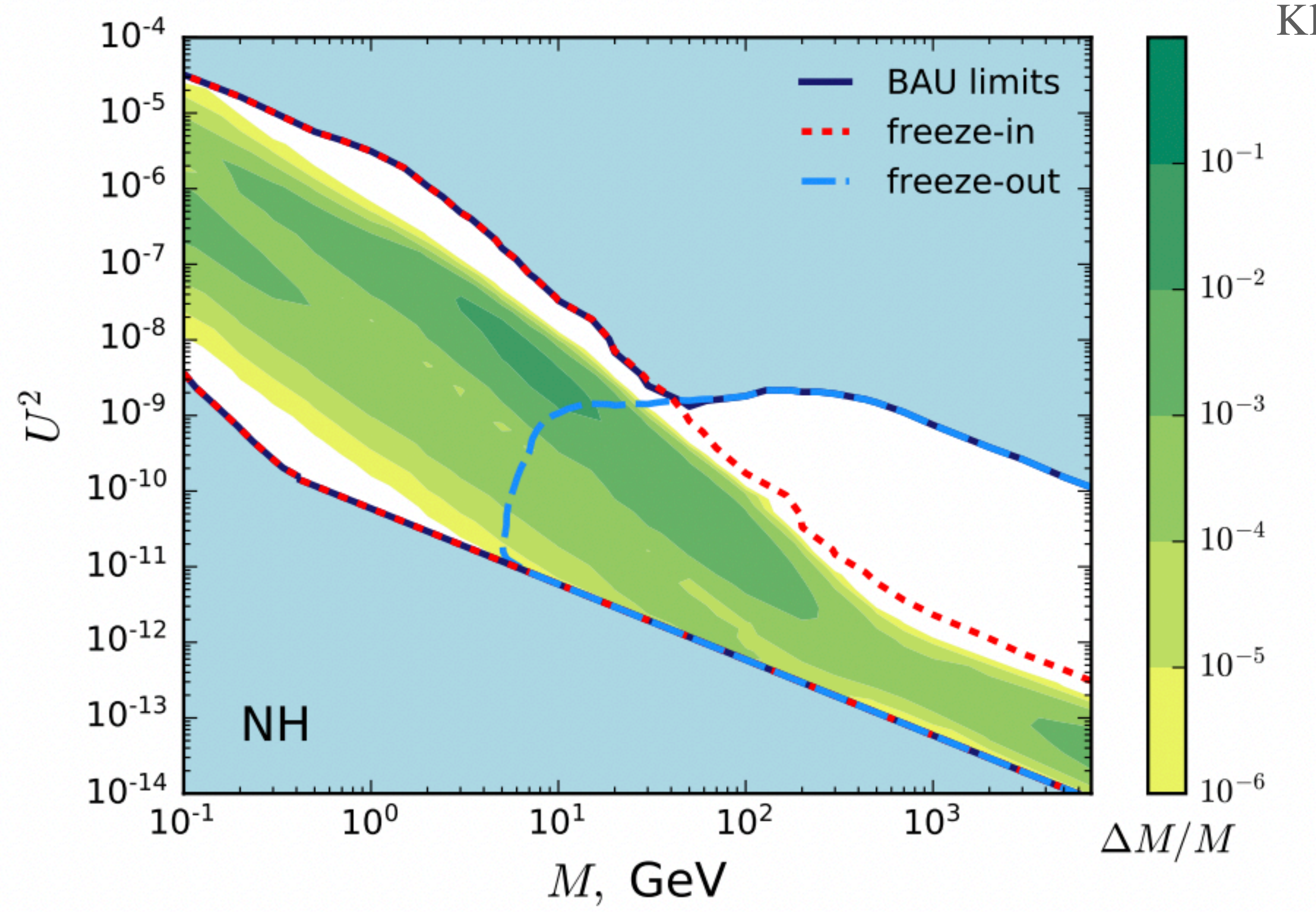
GeV Scale Sterile Neutrinos

Do we have ***motivation*** for GeV sterile neutrinos?

Baryongenesis via Sterile Neutrino Oscillations
(ARS Leptogenesis)

Akhmedov, Rubakov & Smirnov, hep-ph/9803255.
See also Asaka & Shaposhnikov, hep-ph/0505013
Nice review by Drewes et al. 1711.02862.
Recent comprehensive study: Klaric, Shaposhnikov & Timiryasov 2103.16545

Klaric et al 2021



$T \sim 10^6$ GeV | $T \sim 10^4$ GeV | $T \sim 130$ GeV

Time

Avoid production of sterile neutrinos N

Slowly produce N

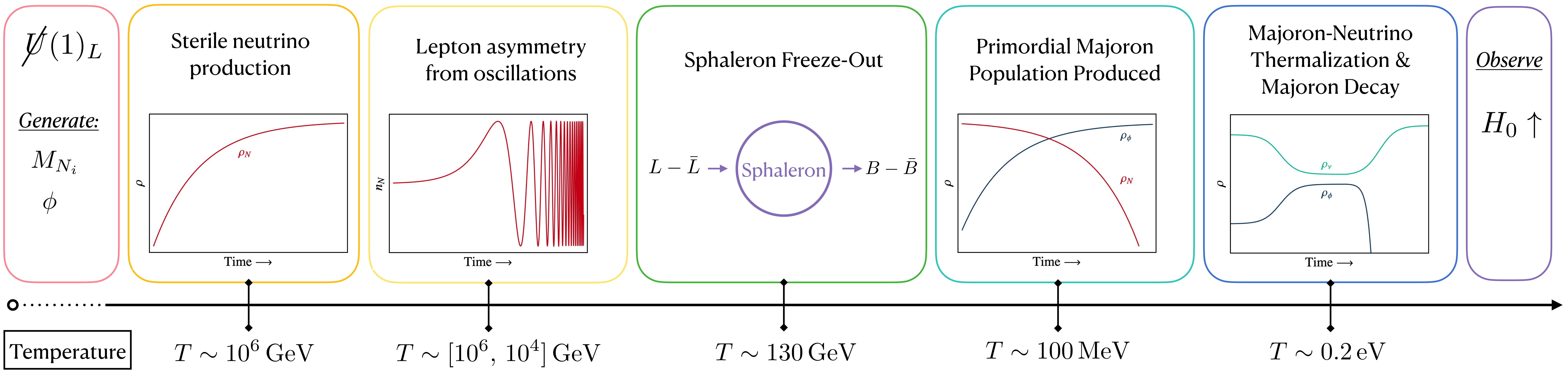
N undergo CP violating oscillations

L asymmetry transfer e.g. of one sterile

Sphalerons convert to B asymmetry

From Leptogenesis to the Hubble Tension

Escudero & **SJW** (2021)



Necessary ingredients:
~eV scale majoron
Interactions @ vL ~ TeV
Neff ~ 0.5

~GeV scale steriles

GeV scale steriles can generate baryon asymmetry in early Universe

Self-consistent?

Leptogenesis in Singlet Majoron Model

Can the presence of the majoron spoil leptogenesis?

Concerns:

1.) Sterile Neutrinos thermalize too early $\rho \to N\bar{N}$ $\rho\rho \to N\bar{N}$ $\phi\phi \to N\bar{N}$

Must avoid production!

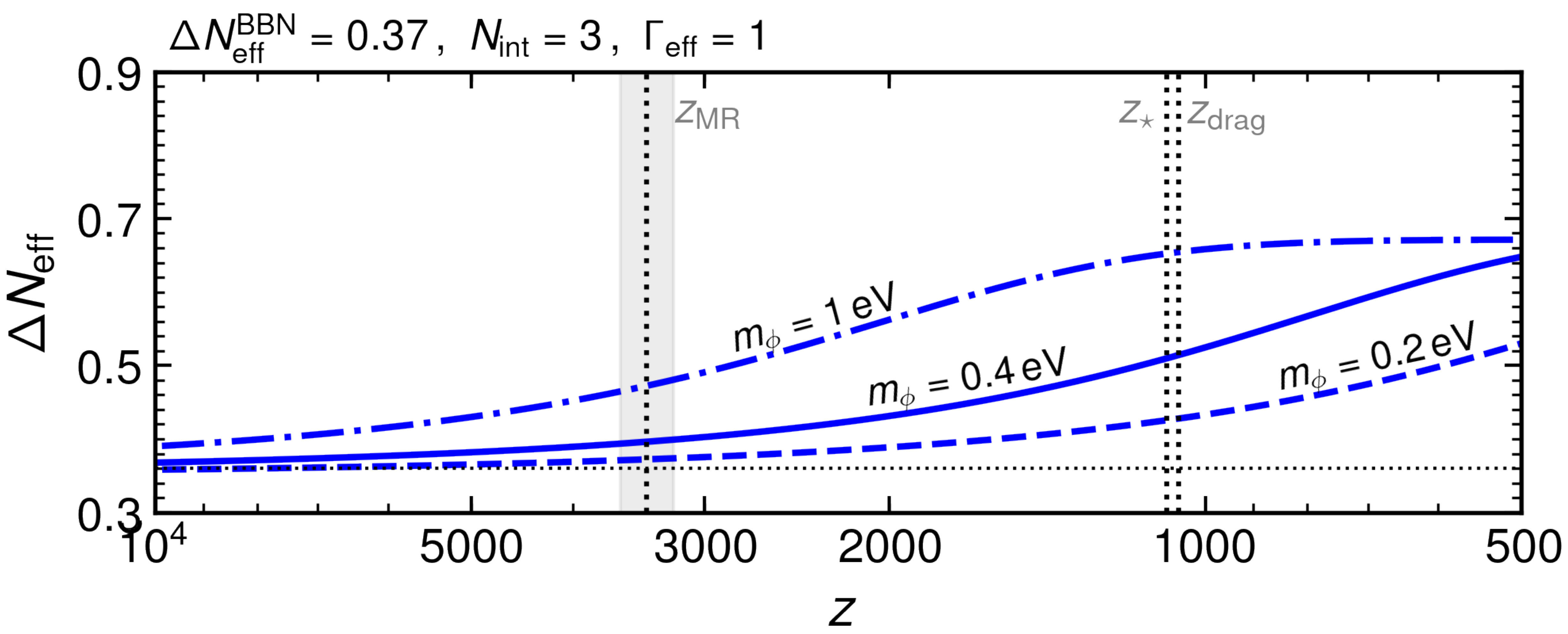
2.) Neutrinos oscillations shouldn't be altered (...could be overly restrictive, see e.g. Hambye & Teresei (2016, 2017))

Symmetry could be unbroken.... $M_N = \lambda_N \langle \Phi \rangle$ $|\lambda_{\Phi H}| < 10^{-7} \frac{v_L}{1\,\mathrm{TeV}} \sqrt{\frac{10^5\,\mathrm{GeV}}{T_c}}$

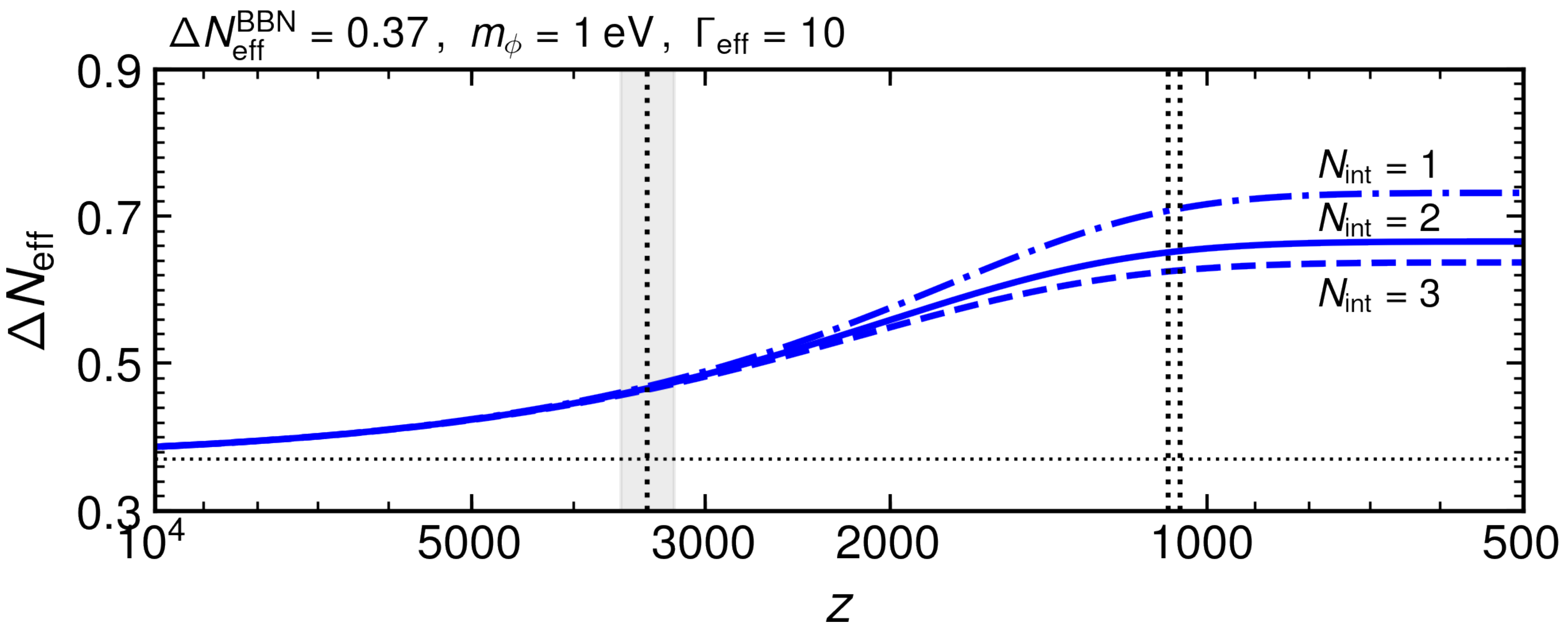
$\phi\phi \to N\bar{N}$ Could lead to decoherence $\lambda_N = \frac{M_N}{v_L} < 0.07 \sqrt{\frac{T_{\mathrm{Lepto}}}{10^5\,\mathrm{GeV}}}$

Late-Time Thermalization

Late-time thermalization altered due to primordial population



Also dependent on number of interaction neutrinos



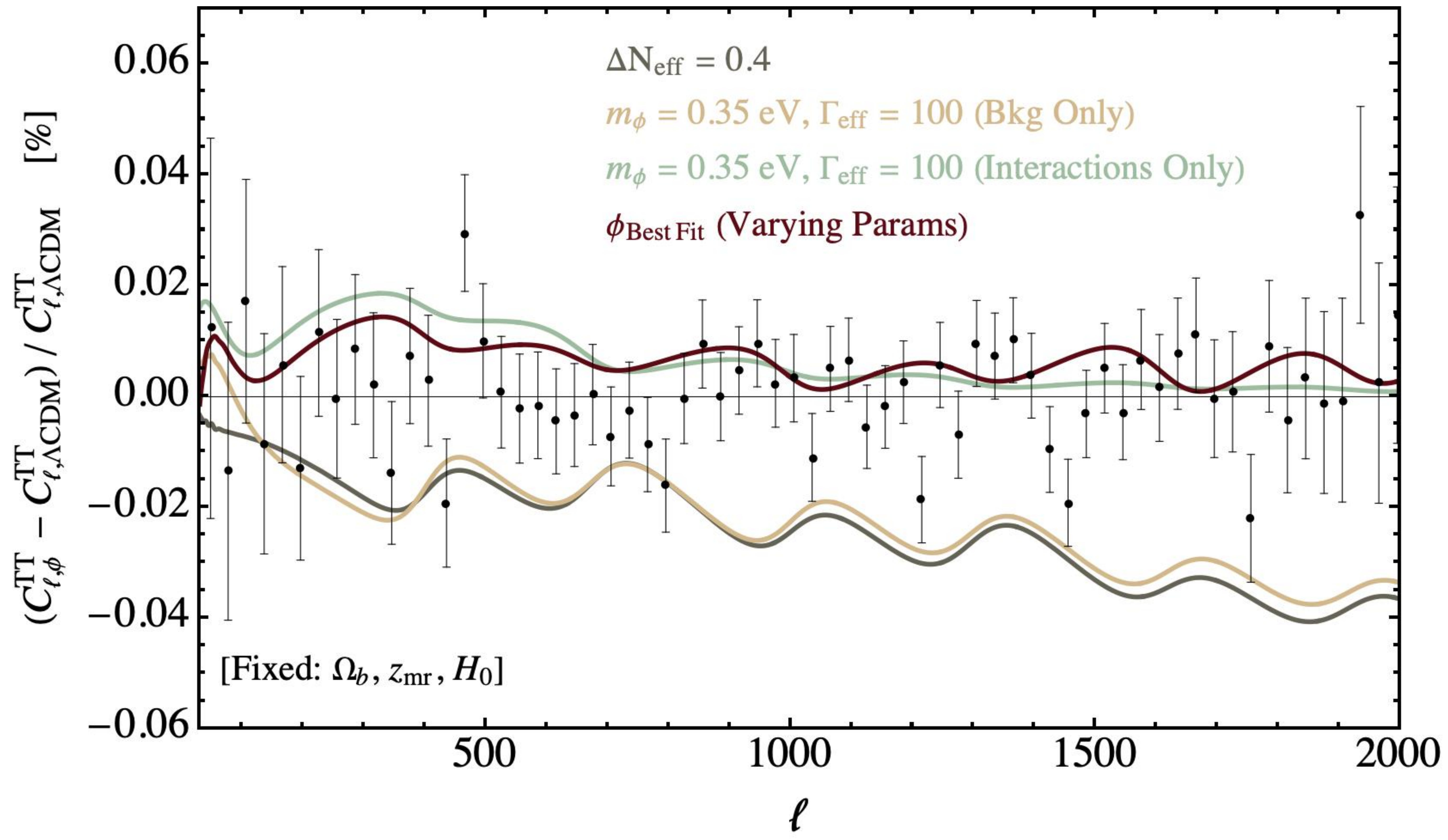
$$N_{\rm int} = 3 \longrightarrow \sum m_\nu \gtrsim 0.15$$

$$N_{\rm int} = 2 \longrightarrow m_1 \sim 0 \quad \&\text{NO}$$

$$N_{\rm int} = 1 \longrightarrow m_1 \sim 0 \quad \&\text{IO}$$

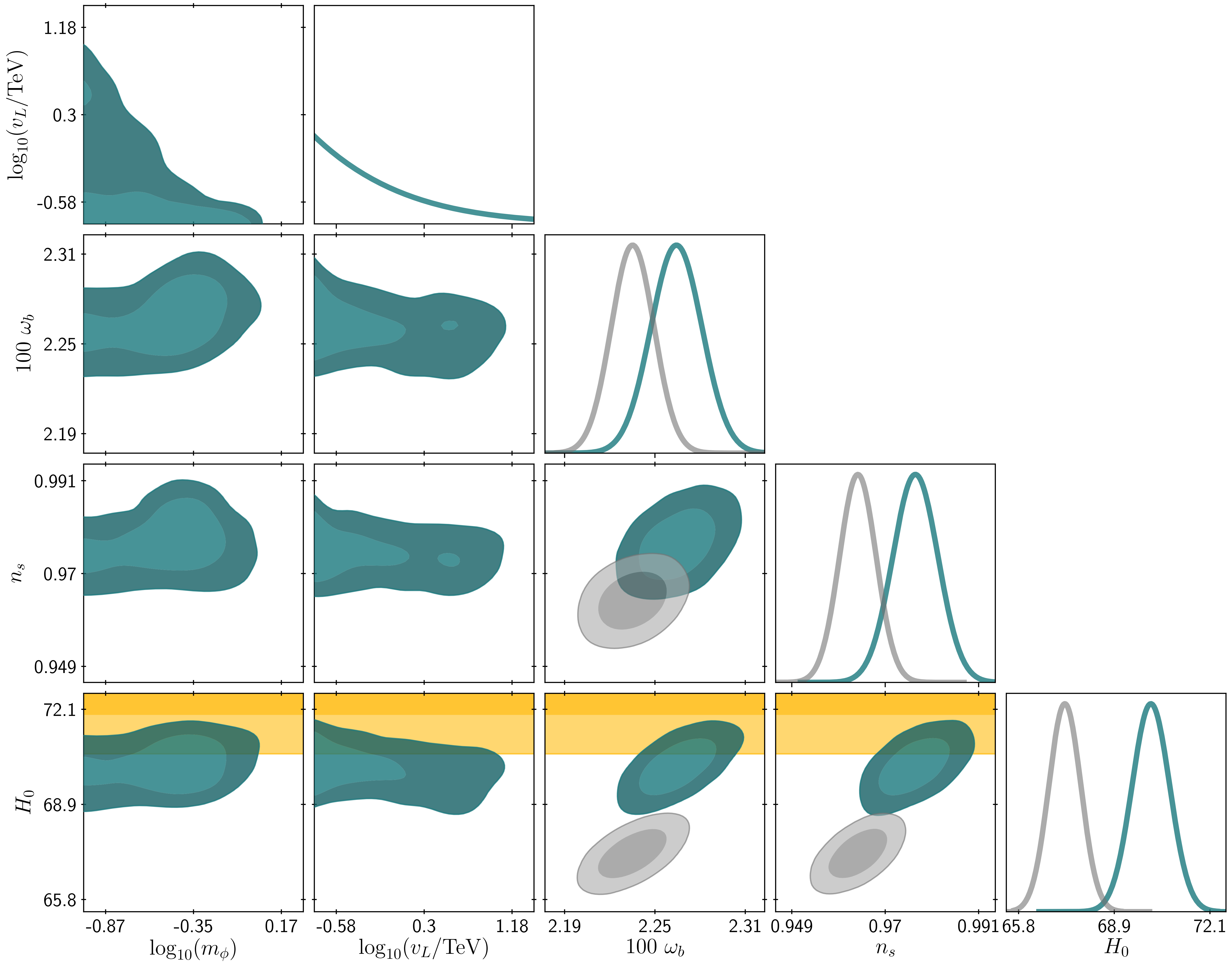
Escudero & **SJW** (2021)

TT-Power Spectrum



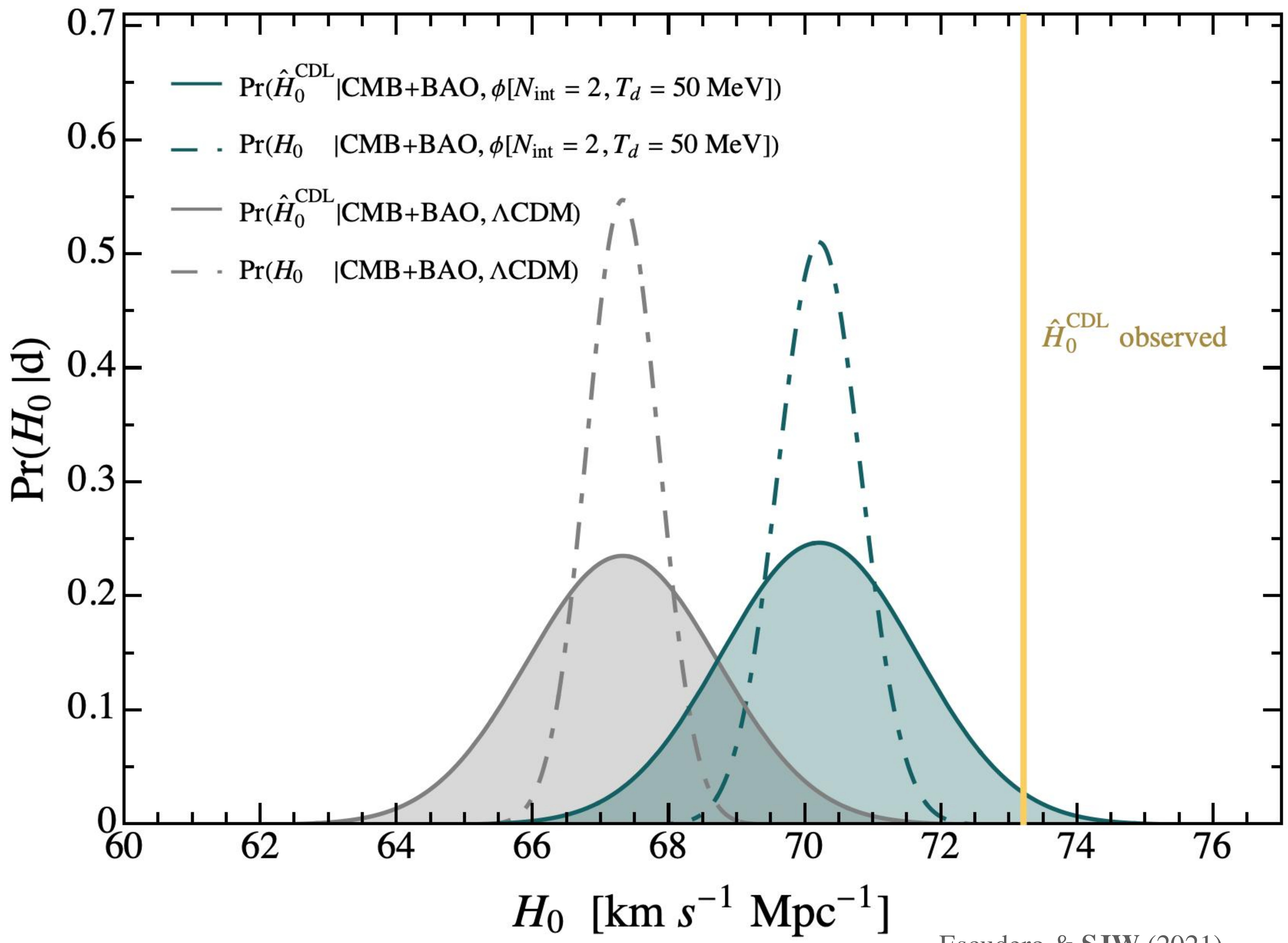
Escudero & **SJW** (2021)

Planck + BAO



Escudero & **SJW** (2021)

Posterior Predictive Distribution



Escudero & **SJW** (2021)

Conclusions

- Cosmology offers promising way to probe low-energy signatures of the neutrino mass mechanism

- The Hubble Tension has reached a point that is difficult to ignore, and the majoron solution is among the more well-motived and phenomenologically successful proposals

- Looking forward:
  - Improved cosmological treatment
    - Can non-zero neutrino masses help S8
    - Are current approximations valid
  - Could majoron actually *assist efficiency of* ARS leptogenesis
  - Additional signatures that could confirm/refute (e.g. Kaon / pion decays)

Back-up Slides

Majoron Mass

Majoron mass?

Quantum gravity expected to break all global symmetries

See e.g. Kallosh, Linde, Linde, Susskind (1995), Arkani-Hamed, Motl, Nicolis, Vafa (2016), Klawer & Geiß (2015)

D-5 Planck-scale operators (?):

Rothstein, Babu, Seckel (1993),
Akhmedov, Berezhiani, Mohapatra, Senjanovic (1992)

$$V_1(\rho) = \lambda_1 \frac{\rho^5}{M_p} + \lambda_2 \frac{\rho^* \rho^4}{M_p} + \lambda_3 \frac{\rho^{*2} \rho^3}{M_p} + h.c.$$

$$V_2(H, \rho) = \beta_1 \frac{(H^\dagger H)^2 \rho}{M_p} + \beta_2 \frac{(H^\dagger H)\rho^2 \rho^*}{M_p} + \beta_3 \frac{(H^\dagger H)\rho^3}{M_p} + h.c.$$

Assuming

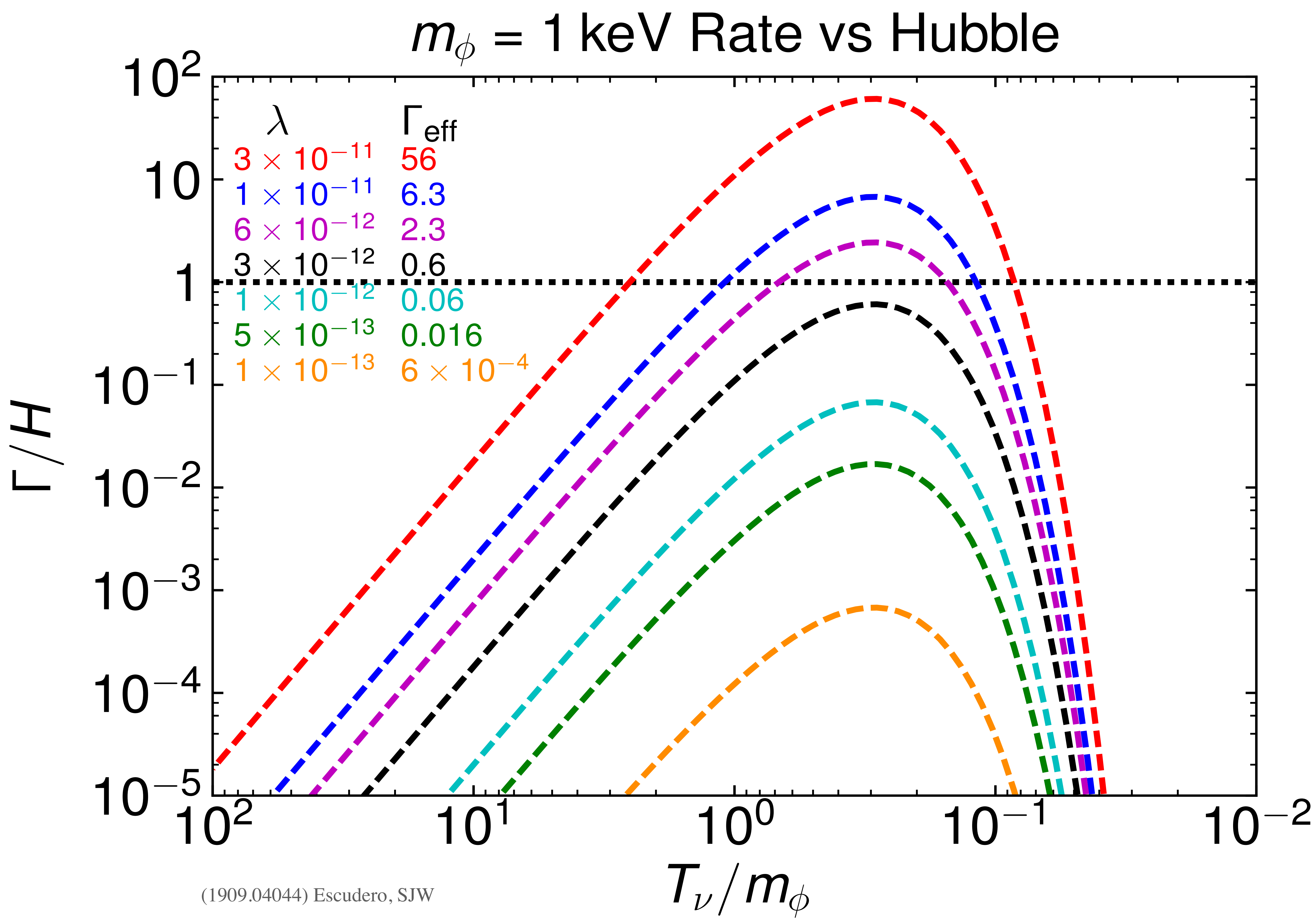
$v_L \gg v_H$

$\lambda_i \sim \beta_i$

$$m_\phi \sim \sqrt{\beta} \left(\frac{v_L}{v_H} \right)^{3/2} \text{keV}$$

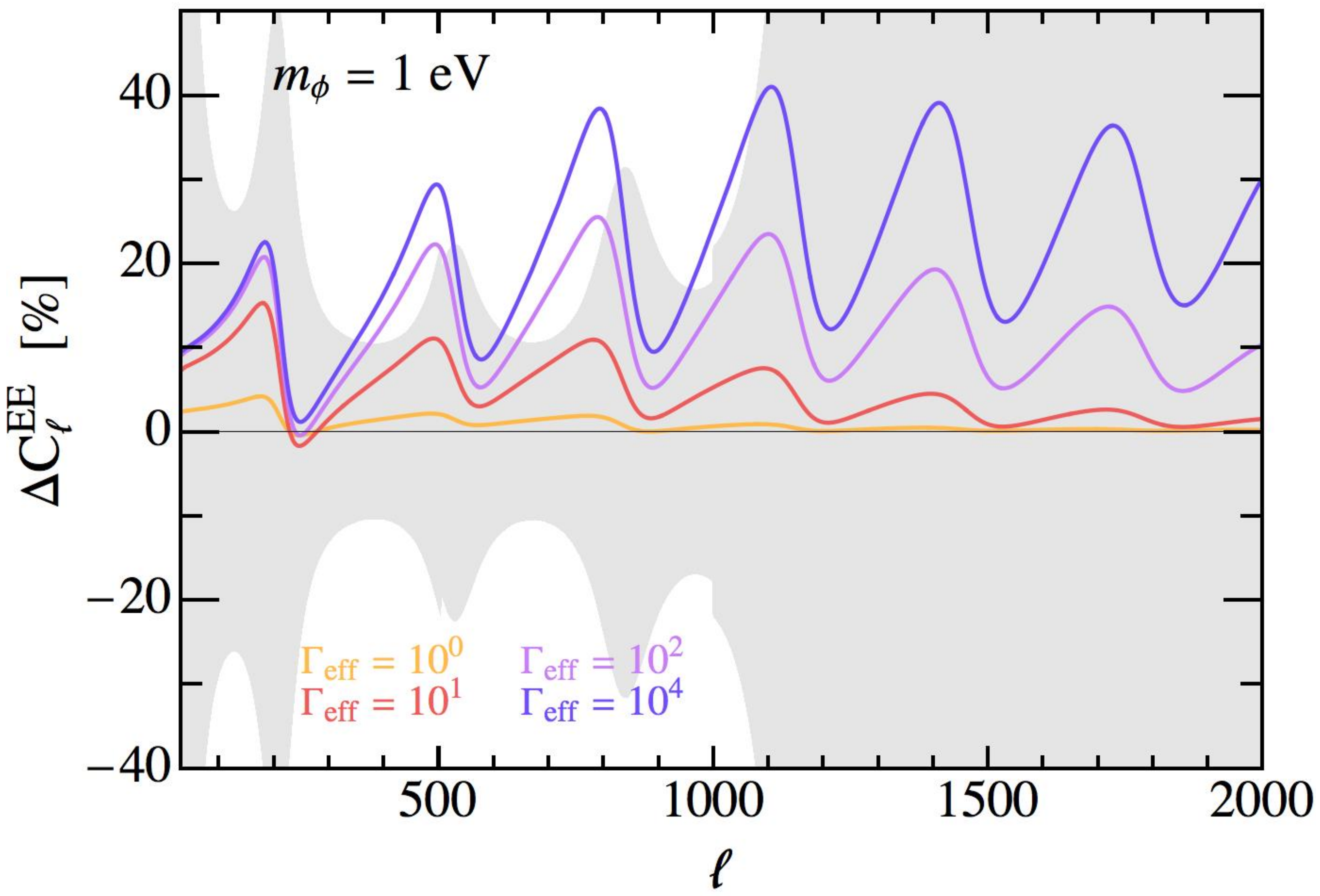
** Braking could be non-perturbative

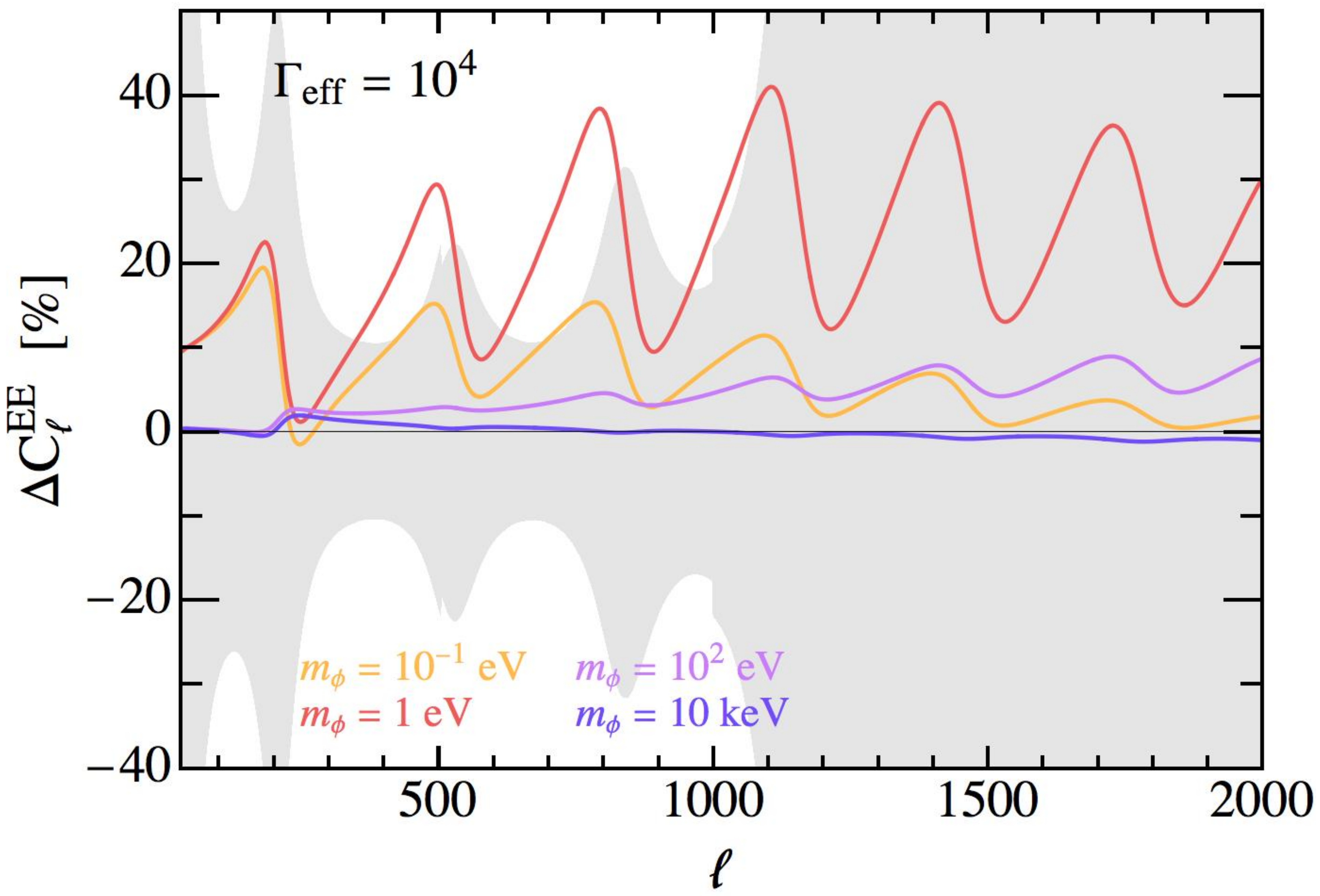
Interaction Rate



(1909.04044) Escudero, SJW

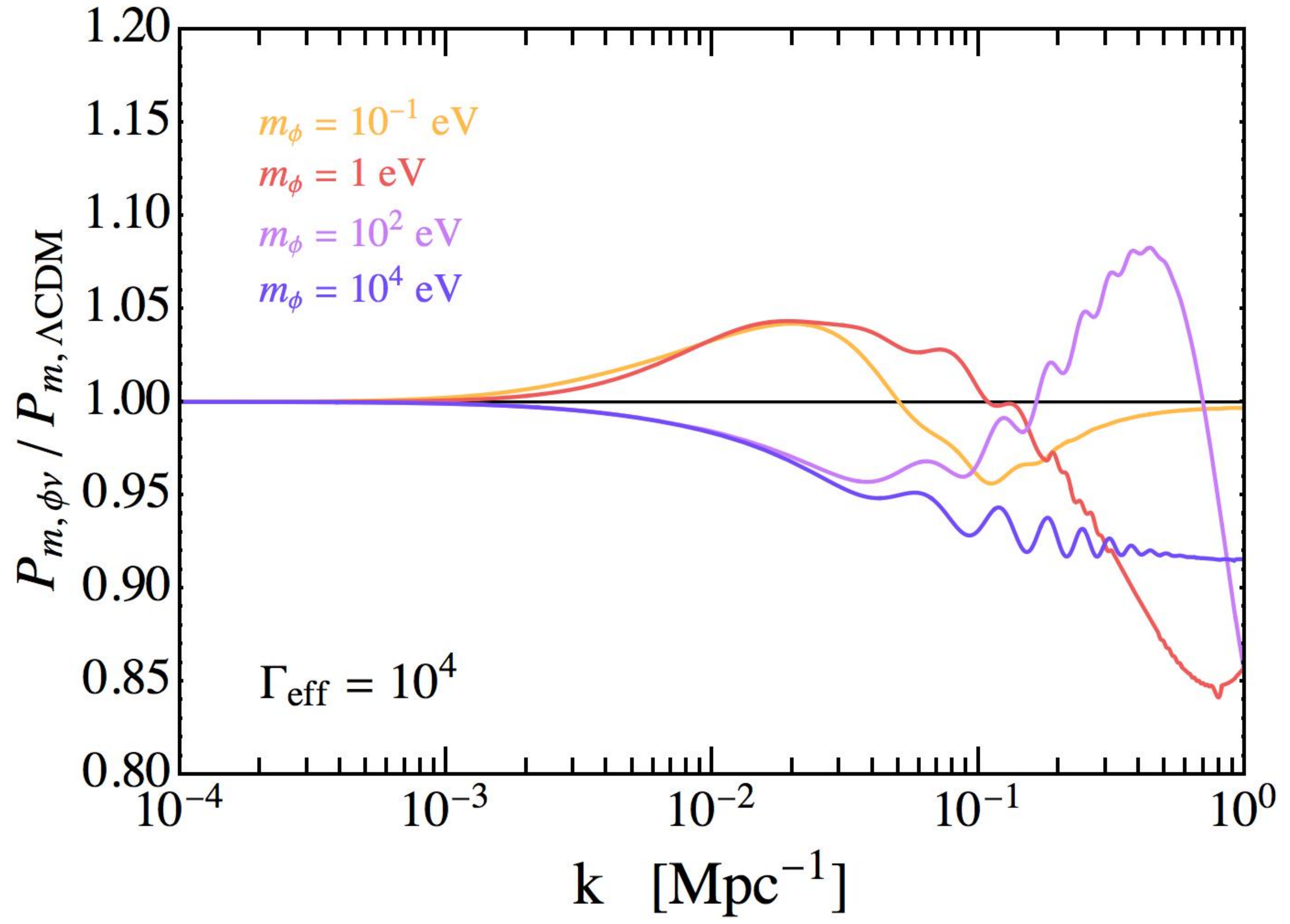
Polarization

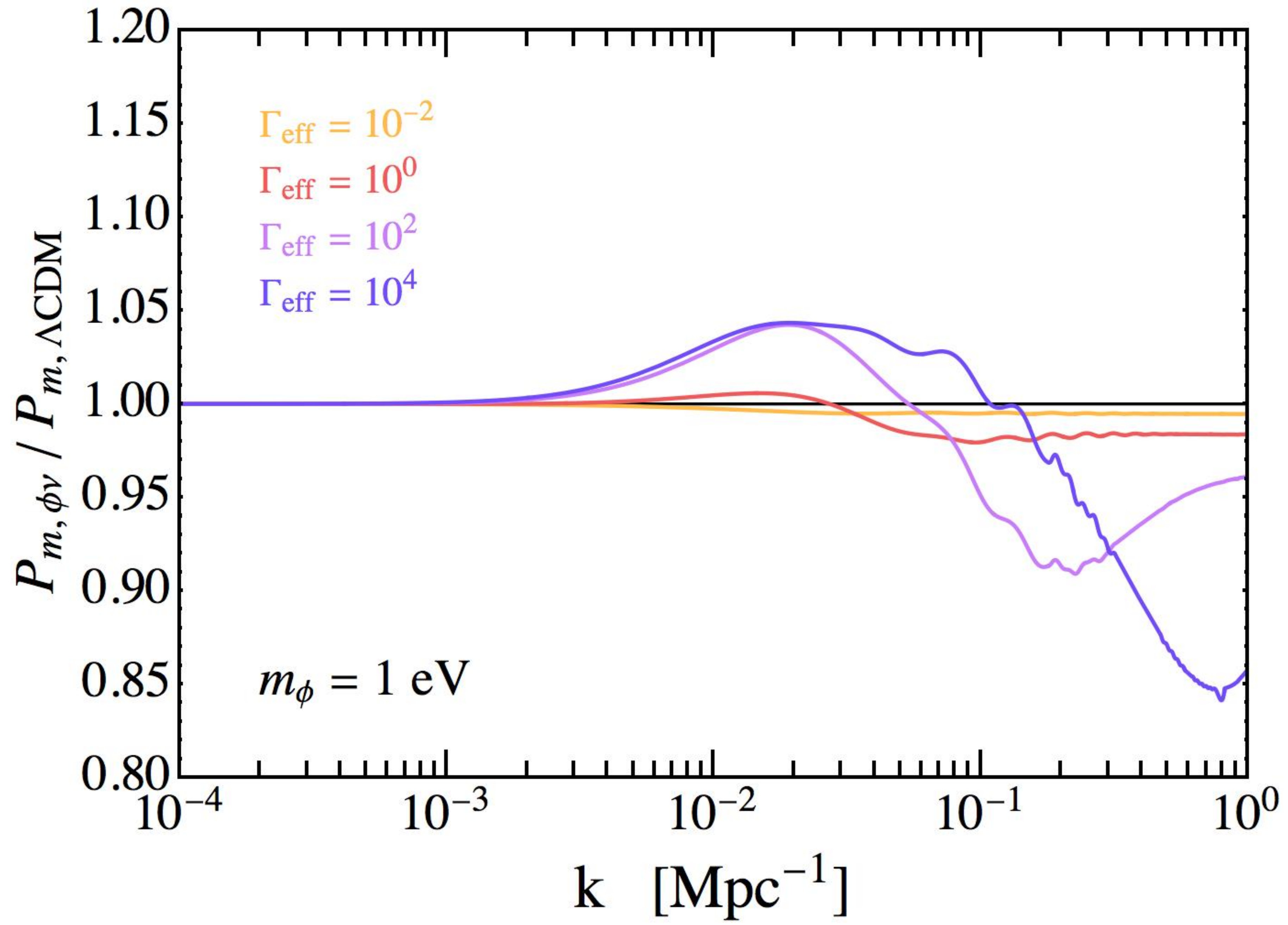




(1909.04044) Escudero, **SJW**

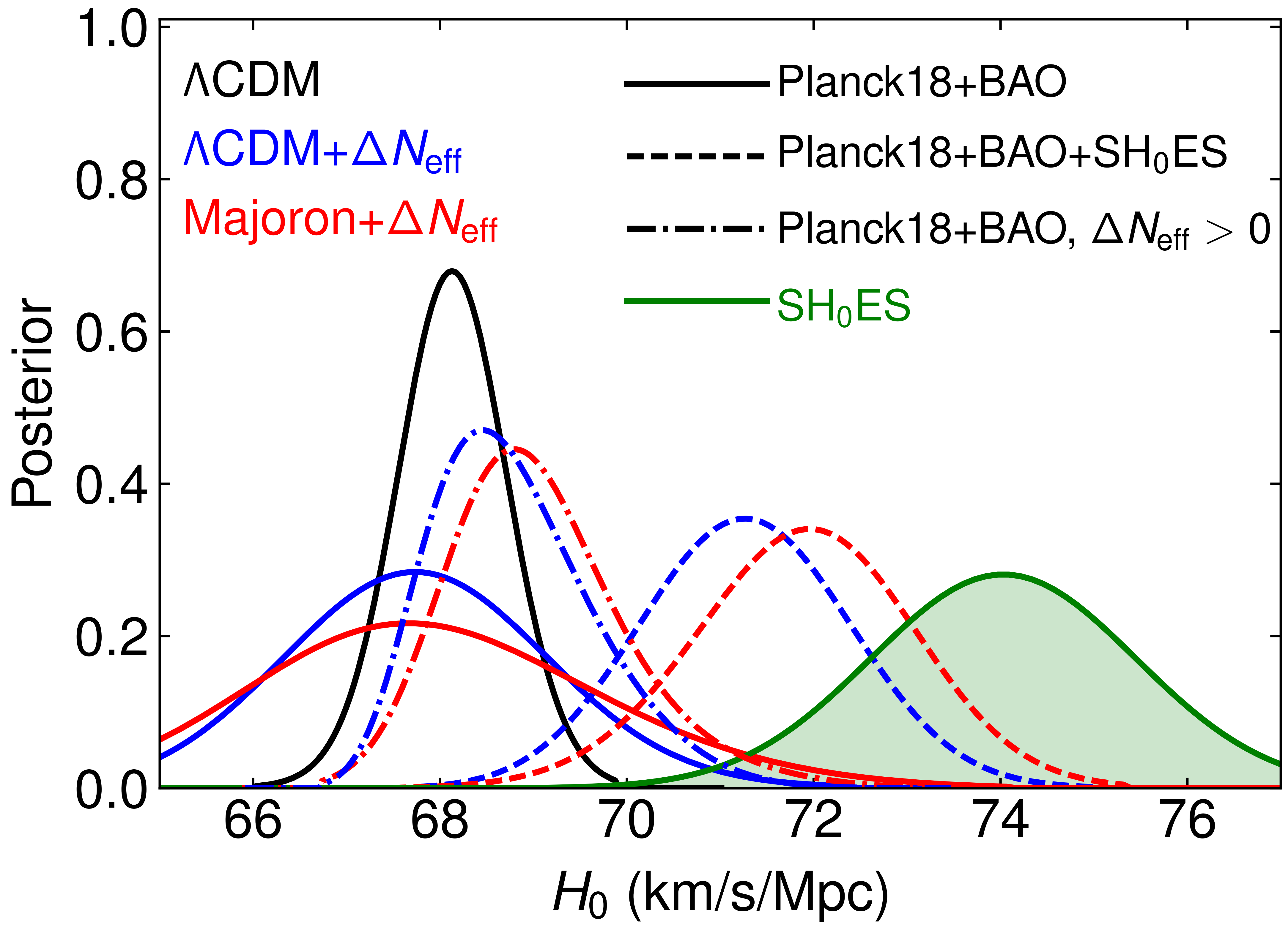
Matter Power Spectrum





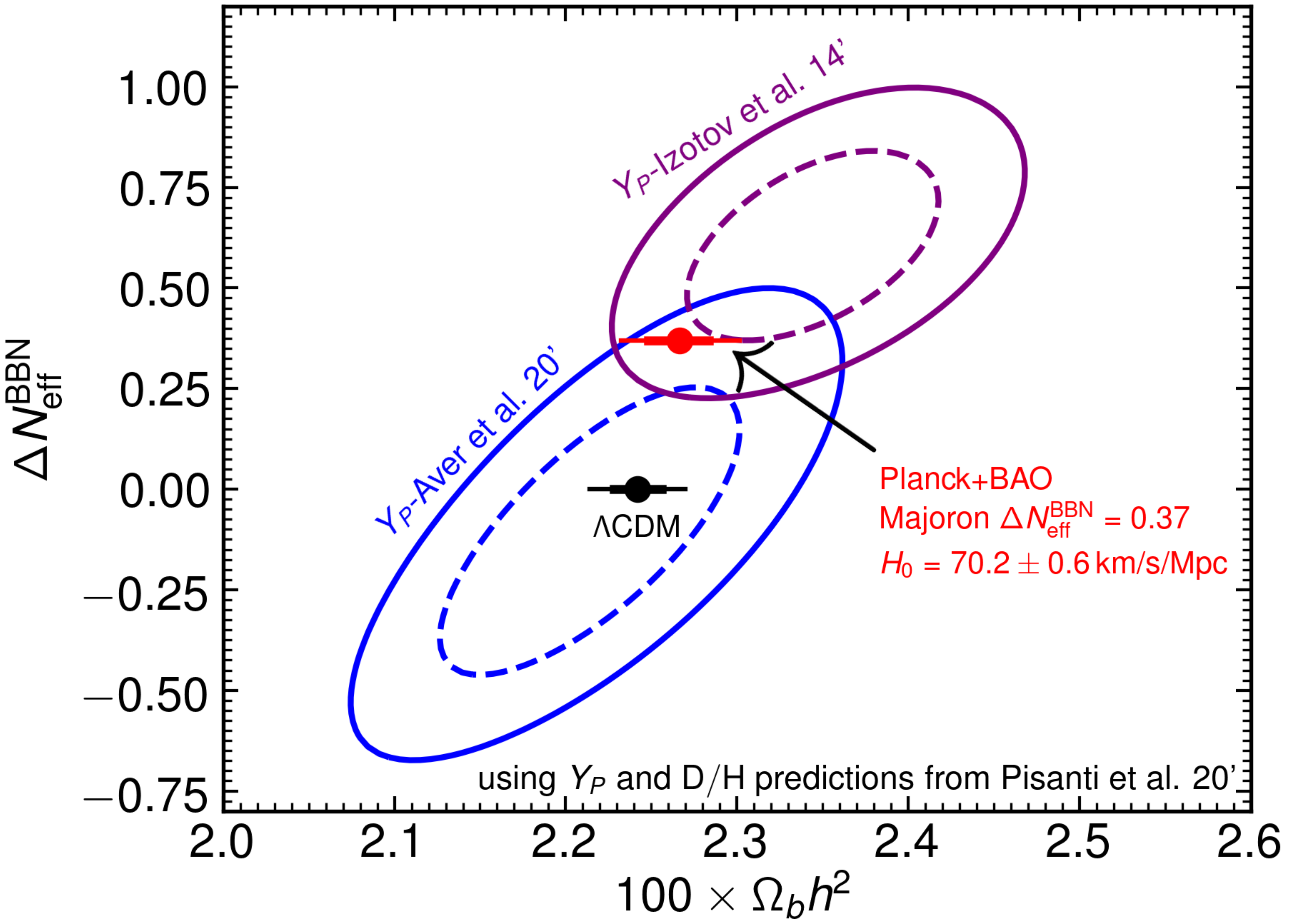
(1909.04044) Escudero, **SJW**

H0 Posterior



(1909.04044) Escudero, **SJW**

BBN



Escudero & **SJW** (2021)

Cosmic Distance Ladder

$$z = H_0\, d \; + v_{\rm pec}$$

Type Ia SN are standard candles

Supernova calibrator **Nearby supernova** **The supernova we want**

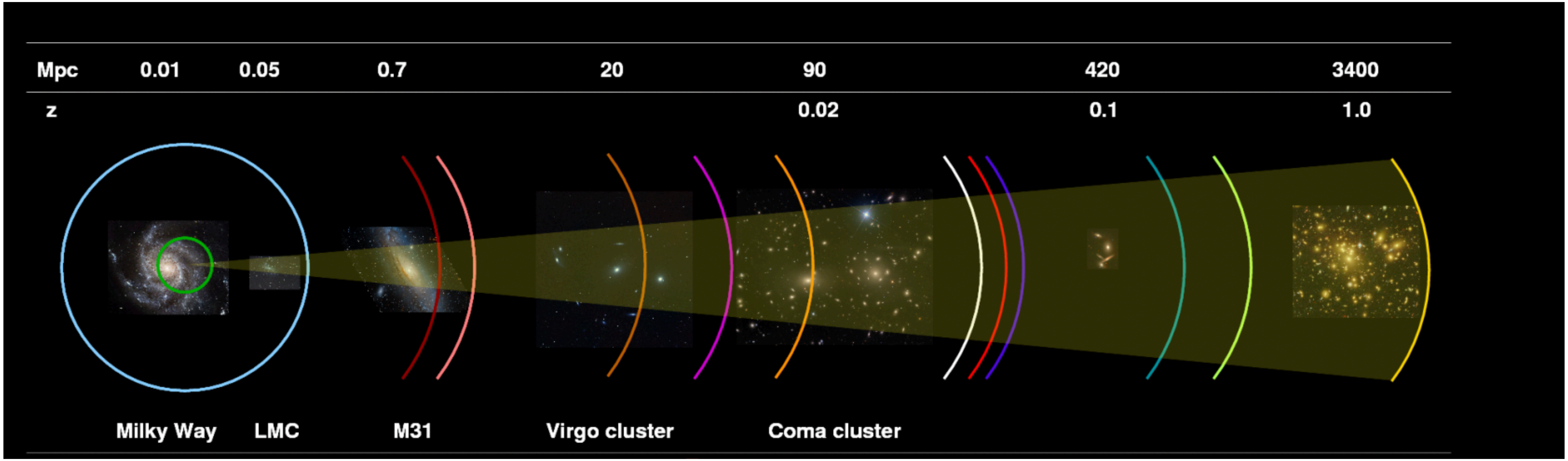
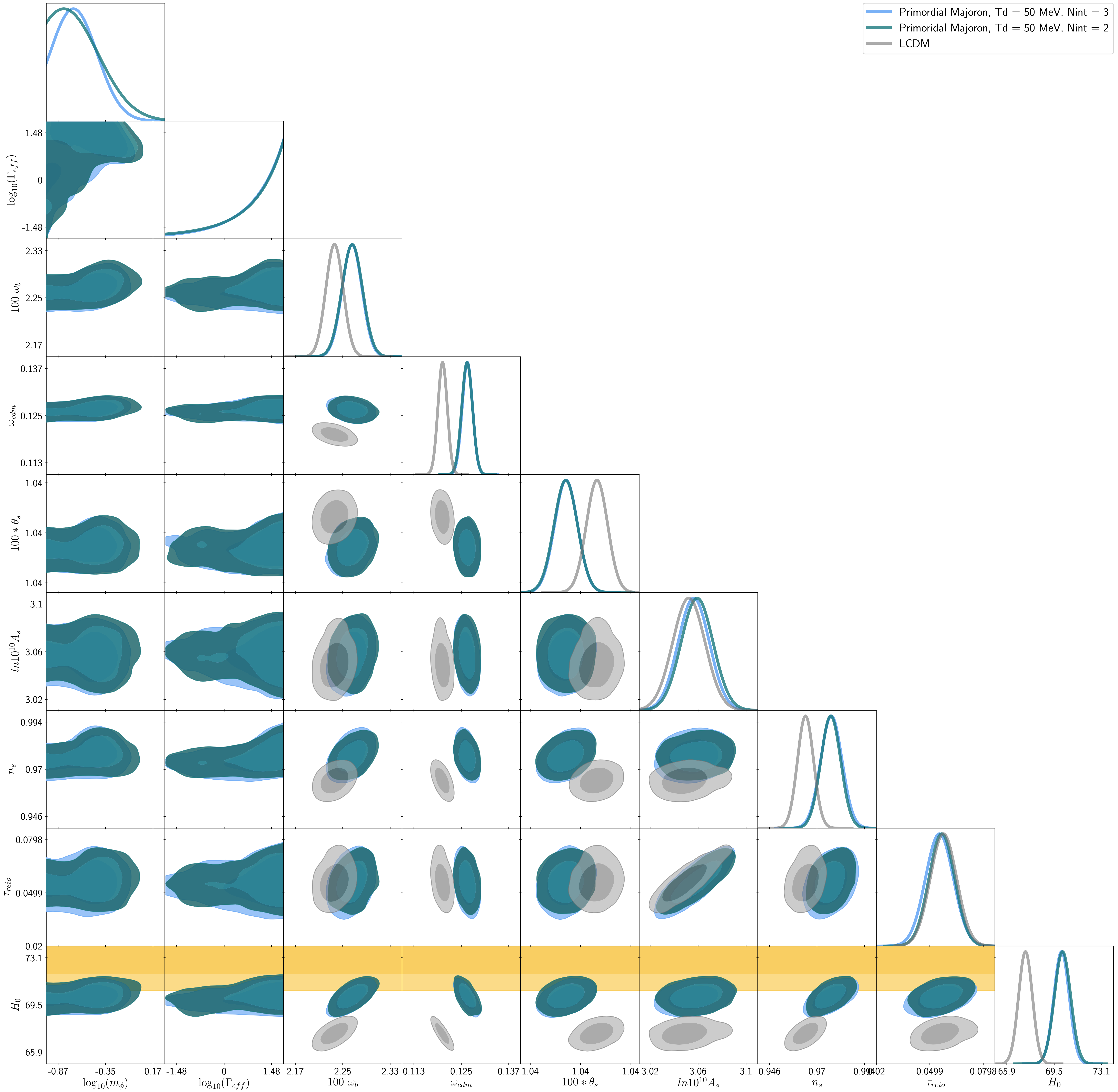
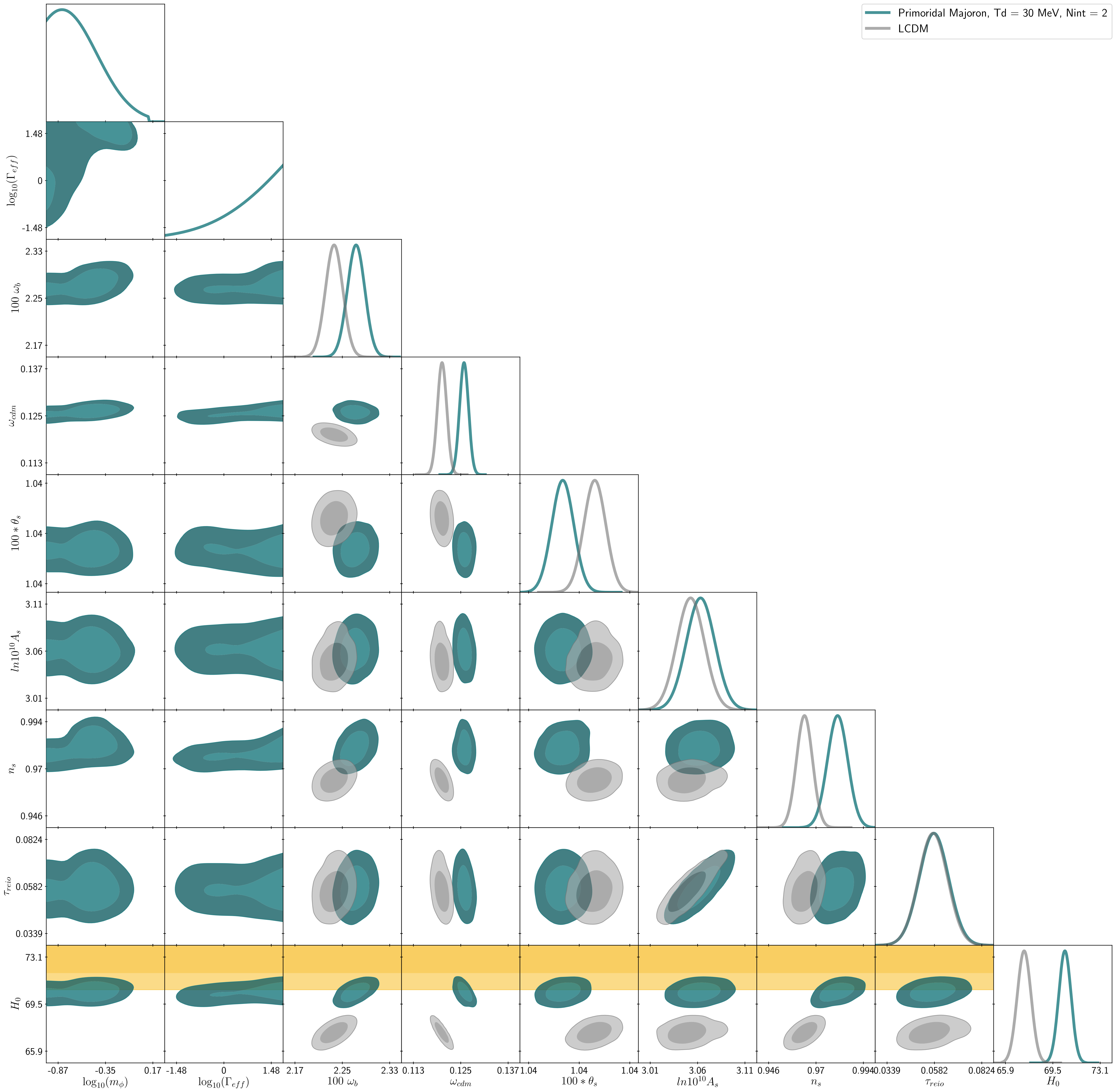


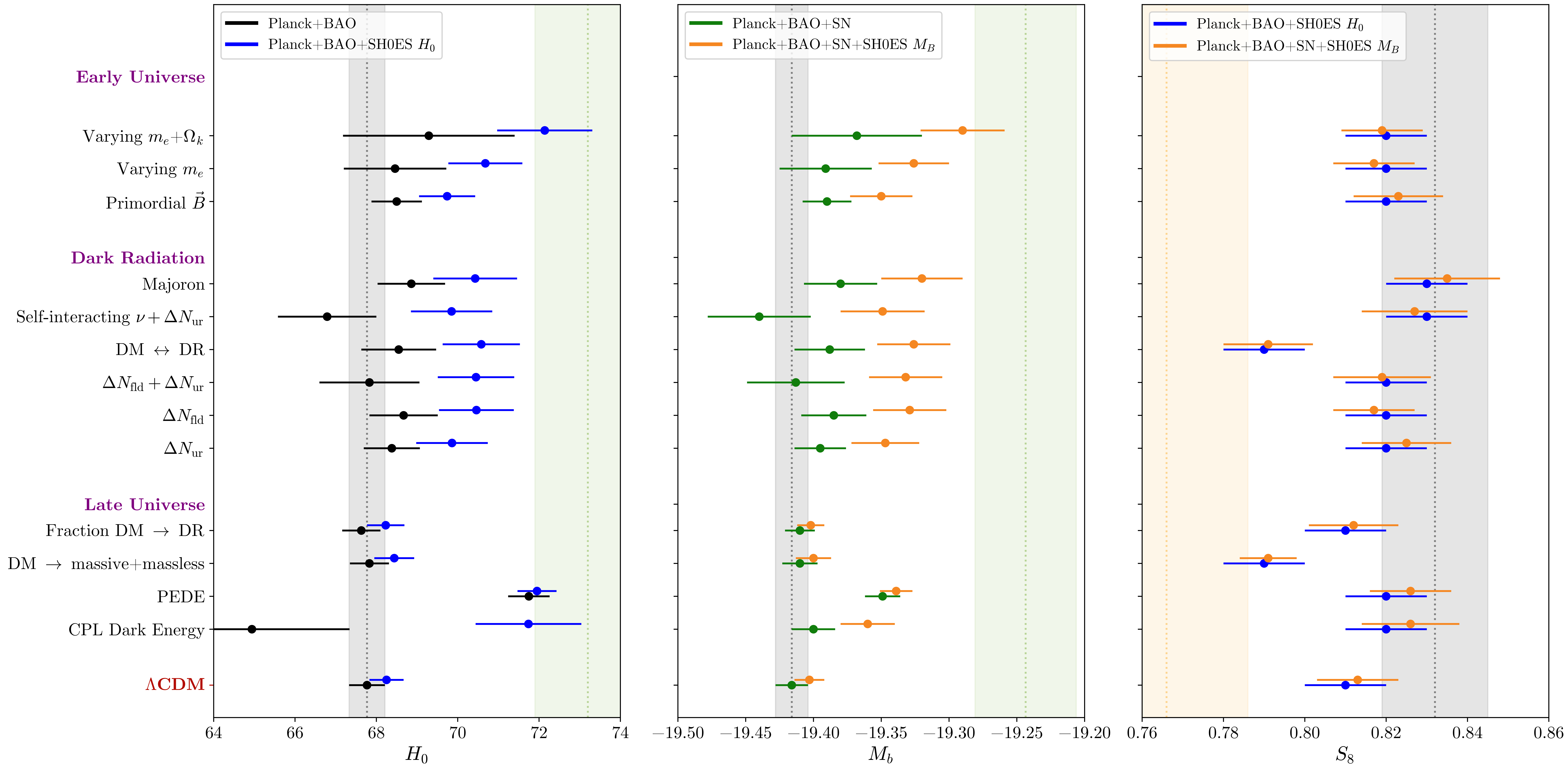
Image credit: Nandita Khetan



Escudero & **SJW** (2021)



Escudero & **SJW** (2021)



(TO APPEAR SOON) Shöneberg, Franco Abellan, Pérez Sánchez, Lesgourges, Poulin, **SJW**

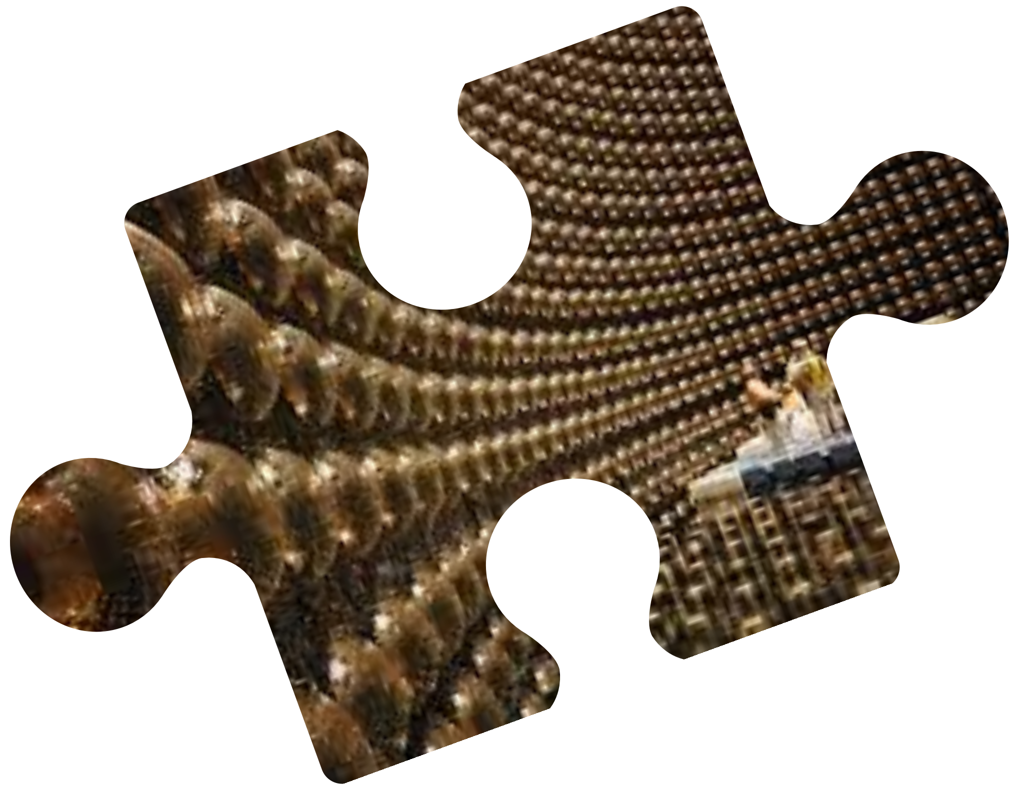
Perturbations

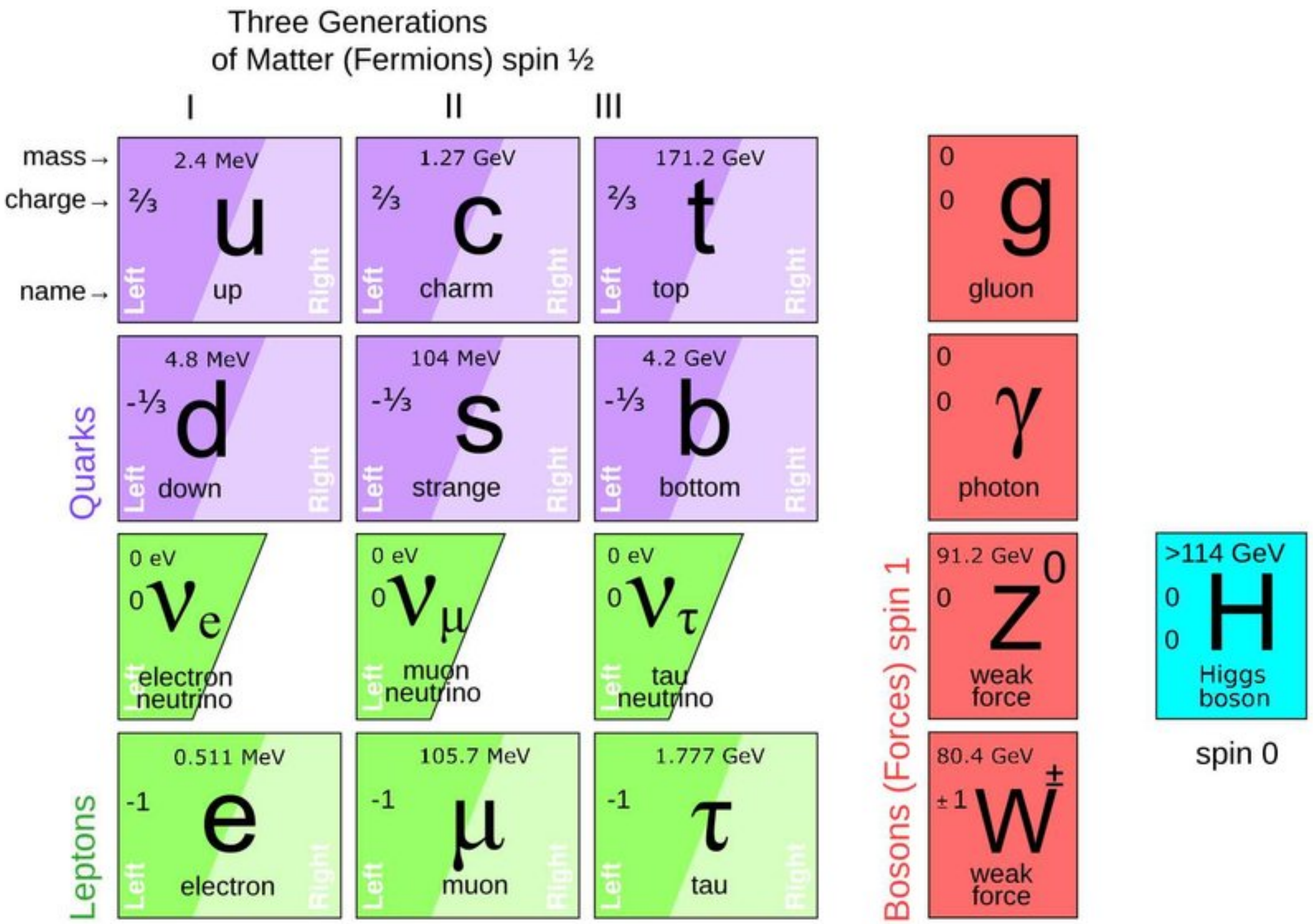
$$f(x^i, p^i, t) = f_0(p)\left[1 + \Psi(x^i, p^i, t)\right]$$
$$\Psi = \textstyle\sum_0^\infty (-i)^\ell\,(2\ell+1)\,\Psi_\ell\,P_\ell(\mu)$$

$$\dot{\delta}_{\nu\phi} = -\frac{4}{3}\theta_{\nu\phi} - \frac{2}{3}\dot{h}\,,$$
$$\dot{\theta}_{\nu\phi} = k^2\left(\frac{1}{4}\delta_{\nu\phi} - \sigma_{\nu\phi}\right)\,,$$
$$\dot{F}_{\nu\phi 2} = 2\dot{\sigma}_{\nu\phi} = \frac{8}{15}\theta_{\nu\phi} - \frac{3}{5}kF_{\nu\phi\,3} + \frac{4}{15}\dot{h} + \frac{8}{5}\dot{\eta} - 2a\Gamma\sigma_{\nu\phi}\,,$$
$$\dot{F}_{\nu\phi\,\ell} = \frac{k}{2\ell+1}\left[\ell\,F_{\nu\phi\,(\ell-1)} - (\ell+1)F_{\nu\phi\,(\ell+1)}\right] - a\Gamma F_{\nu\phi\,\ell}\,,\ \ \ell \geq 3\,.$$

$$\Gamma \equiv \frac{1}{n_\nu}\,\frac{\delta n_\nu}{\delta t}\bigg|_{\text{forward}} = \frac{\Gamma_\phi}{2}\,\frac{m_\phi^2}{T_\nu^2}\,e^{\frac{\mu_\nu}{T_\nu}}\,K_1\left(\frac{m_\phi}{T_\nu}\right)$$

Neutrino Masses





$$\Delta m^2_{12} \sim (7.50 \pm 0.2) \times 10^{-5}\,\mathrm{eV}^2$$

$$\Delta m^2_{13} \sim (2.55 \pm 0.02) \times 10^{-3}\,\mathrm{eV}^2$$

$$\sum m_\nu \lesssim 0.15\mathrm{eV}$$

de Salas et al (2021)
Planck 2018

Image credit: Drewes et al (2013)