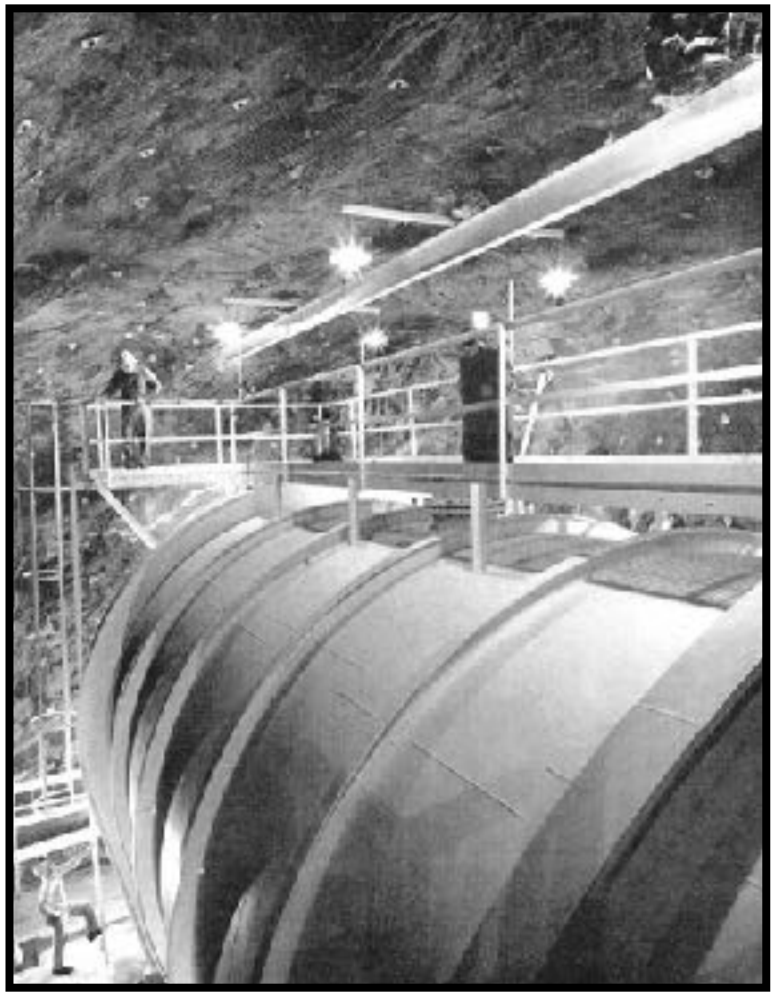
Probing the Neutrino Mass Mechanism with the CMB

Samuel J. Witte
University of Valencia (IFIC)

arXiv:1909.04044
arXiv: 20xx.xxxx
(In collaboration with Miguel Escudero)

Neutrino Oscillations

Homestake Experiment (1960s)

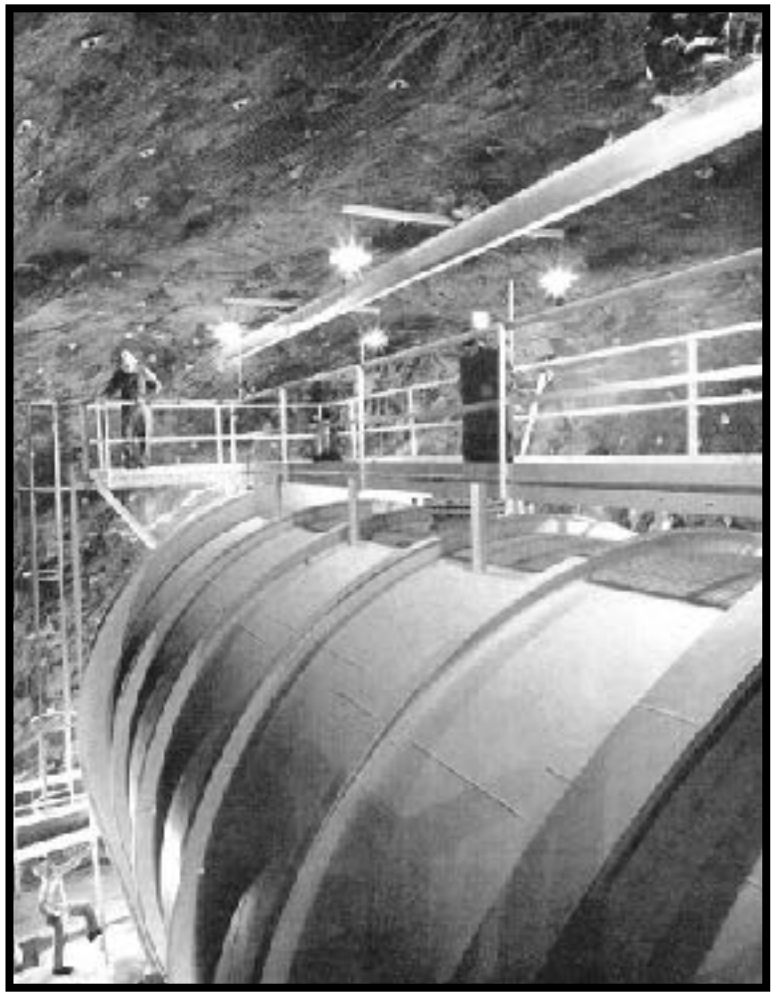


Solar neutrino problem
(deficit of neutrinos)

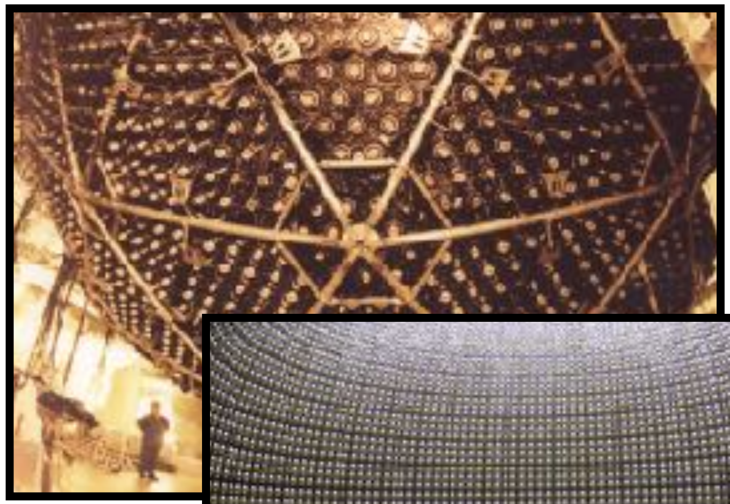
→

Neutrino Oscillations

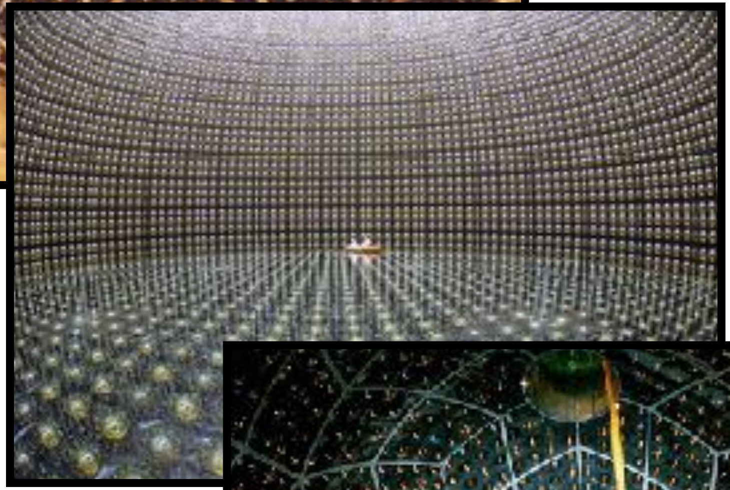
Homestake Experiment (1960s)



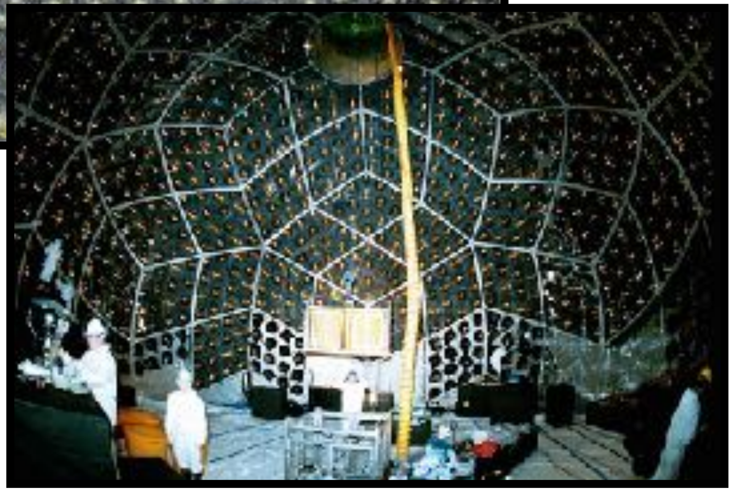
Solar neutrino problem
(deficit of neutrinos)



SNO (2001)
Solar



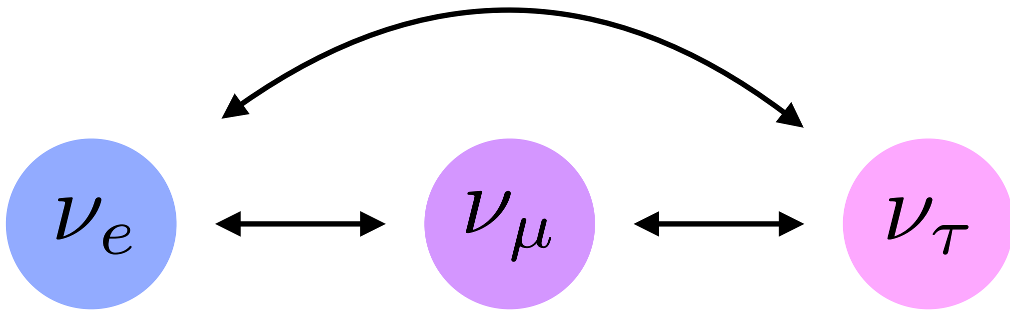
Super K (1998)
Atmospheric



Kamland (2003)
Reactor

Established conclusive evidence of neutrino oscillations

Neutrino Masses



Neutrino Oscillations

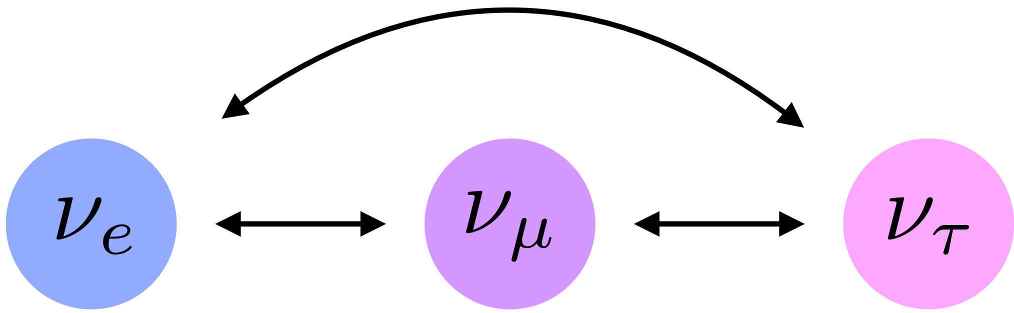
Homestake (1960s), SNO (2001), Super-K (1998), Kamland (2003) …

$$m_{\nu,i} > 0$$

$$m_{\nu,j} > 0$$

Without right-handed neutrinos, no mass in SM…

Neutrino Masses



Neutrino Oscillations

Homestake (1960s), SNO (2001), Super-K (1998), Kamland (2003) …

$$m_{\nu,i} > 0$$

$$m_{\nu,j} > 0$$

Without right-handed neutrinos, no mass in SM…

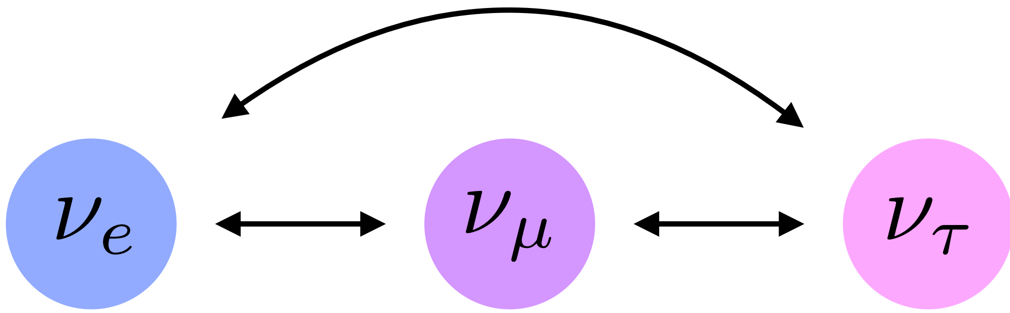
Dirac Neutrinos

$$\mathcal{L} \supset \lambda_\nu \, \bar{\ell} \, H \, \nu_R + h.c.$$

$$\lambda_\nu \lesssim 10^{-12}$$

Without more, unnatural yukawa…

Neutrino Masses



Neutrino Oscillations

Homestake (1960s), SNO (2001), Super-K (1998), Kamland (2003) …

$$m_{\nu,i} > 0$$

$$m_{\nu,j} > 0$$

Without right-handed neutrinos, no mass in SM…

Dirac Neutrinos

$$\mathcal{L} \supset \lambda_\nu \, \bar{\ell} \, H \, \nu_R + h.c.$$

$$\lambda_\nu \lesssim 10^{-12}$$

Without more, unnatural yukawa…

Majorana Neutrinos

+ Majorana mass term: $m \, \overline{\nu^c} \, \nu$

Exploit seesaw

Minkowski (1977), Yanagida (1979), Gell-Mann et al (1979), Glashow(1980), Mohapatra et al (1980)

Explain smallness of neutrino masses

The Majoron

Majorana mass $m\,\overline{\nu^c}\,\nu$ violates lepton number (or equivalently B-L)

The Majoron

Majorana mass $m\,\overline{\nu^c}\,\nu$ violates lepton number (or equivalently B-L)

1.) Broken Explicitly

The Majoron

Majorana mass $m\,\overline{\nu^c}\,\nu$ violates lepton number (or equivalently B-L)

1.) Broken Explicitly

2.) Broken Spontaneously

a.) Local symmetry

New Z' at scale ~ SSB

Less amenable to low-scale observables

b.) Global symmetry

pseudo goldstone boson ϕ

Chikashige, Mohapatra, Peccei (1981)

The Majoron

Majorana mass $m\,\overline{\nu^c}\,\nu$ violates lepton number (or equivalently B-L)

1.) Broken Explicitly

2.) Broken Spontaneously

a.) Local symmetry

New Z' at scale ~ SSB

b.) Global symmetry

pseudo goldstone boson ϕ

Chikashige, Mohapatra, Peccei (1981)

Less amenable to low-scale observables

<u>Lets consider explicit example in type-I seesaw</u>

$$\mathcal{L} \supset \lambda_\nu\,\ell\,H\,\nu_R + \mathrm{hc}$$

Conventional yukawa…

$$\mathcal{L}_N \supset h\,(\rho\,\overline{\nu_R}\,\nu_R^c + \mathrm{hc})$$

New SSB term that will violate L

The Majoron

Majorana mass $m\,\overline{\nu^c}\,\nu$ violates lepton number (or equivalently B-L)

1.) Broken Explicitly

2.) Broken Spontaneously

a.) Local symmetry → New Z' at scale ~ SSB

Less amenable to low-scale observables

b.) Global symmetry → pseudo goldstone boson ϕ

Chikashige, Mohapatra, Peccei (1981)

Lets consider explicit example in type-I seesaw

$$\mathcal{L} \supset \lambda_\nu\,\ell\,H\,\nu_R + \mathrm{hc}$$

Conventional yukawa…

$$\mathcal{L}_N \supset h\,(\rho\,\overline{\nu_R}\,\nu_R^c + \mathrm{hc})$$

New SSB term that will violate L

SSB →

$$\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}$$

$M \gg m_D$

Mass eigenstates:

$$\sim m_D^2/M$$

$$\sim M$$

The Majoron

Expected SSB of B-L (and mass scale M):

$$\lambda_\nu \sim 1 \longrightarrow v_L \sim 10^{14}\ \text{GeV}$$

Chikashige, Mohapatra, Peccei (1981)

The Majoron

Expected SSB of B-L (and mass scale M):

$$\lambda_\nu \sim 1 \longrightarrow v_L \sim 10^{14}\,\mathrm{GeV}$$

$$\lambda_\nu \sim \lambda_e \longrightarrow v_L \sim \mathcal{O}(100\,\mathrm{GeV})$$

Chikashige, Mohapatra, Peccei (1981)

The Majoron

Expected SSB of B-L (and mass scale M):

$$\lambda_\nu \sim 1 \longrightarrow v_L \sim 10^{14}\ \mathrm{GeV}$$

$$\lambda_\nu \sim \lambda_e \longrightarrow v_L \sim \mathcal{O}(100\,\mathrm{GeV})$$

Interaction between neutrinos and majoron generated

$$\mathcal{L}_N \subset h(\rho\,\overline{\nu_R^c}\,\nu_R + \mathrm{hc}) \xrightarrow[\text{SSB + Mixing}]{} \mathcal{L}_{\mathrm{int}} = i\lambda\,\phi\,\overline{\nu}\,\gamma^5\,\nu$$

Interactions extremely feeble: $\lambda \sim 10^{-13}\,\frac{m_\nu}{0.05\,\mathrm{eV}}\,\frac{246\,\mathrm{GeV}}{v_L}$

Chikashige, Mohapatra, Peccei (1981)

The Majoron

Expected SSB of B-L (and mass scale M):

$$\lambda_\nu \sim 1 \longrightarrow v_L \sim 10^{14}\,\mathrm{GeV}$$

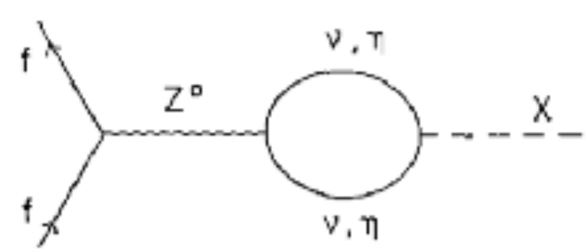
$$\lambda_\nu \sim \lambda_e \longrightarrow v_L \sim \mathcal{O}(100\,\mathrm{GeV})$$

Interaction between neutrinos and majoron generated

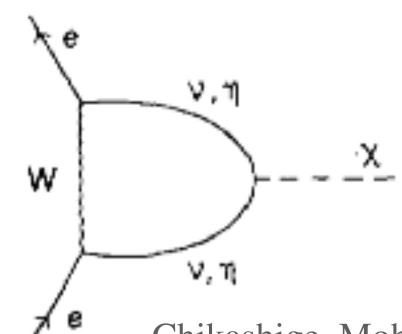
$$\mathcal{L}_N \subset h(\rho\,\overline{\nu_R^c}\,\nu_R + \mathrm{hc}) \xrightarrow[\text{SSB + Mixing}]{} \mathcal{L}_{\mathrm{int}} = i\lambda\,\phi\,\overline{\nu}\,\gamma^5\,\nu$$

Interactions extremely feeble: $\lambda \sim 10^{-13}\,\dfrac{m_\nu}{0.05\,\mathrm{eV}}\,\dfrac{246\,\mathrm{GeV}}{v_L}$

Loop suppressed interactions with charged fermions unavoidable…



but natural very small…



Chikashige, Mohapatra, Peccei (1981)

The Majoron

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)

The Majoron

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)

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

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

The Majoron

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

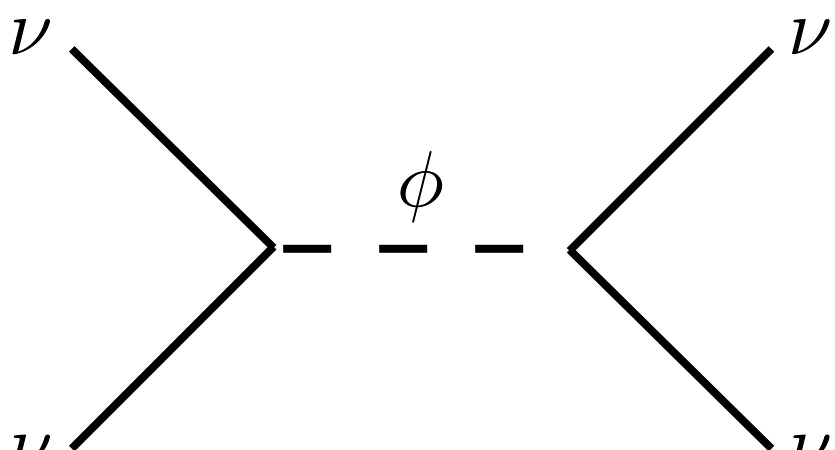
Majoron Cosmology

(**Not complete list of references)

Strong majoron interactions

Motivation from theory: limited…
Phenomenologically interesting

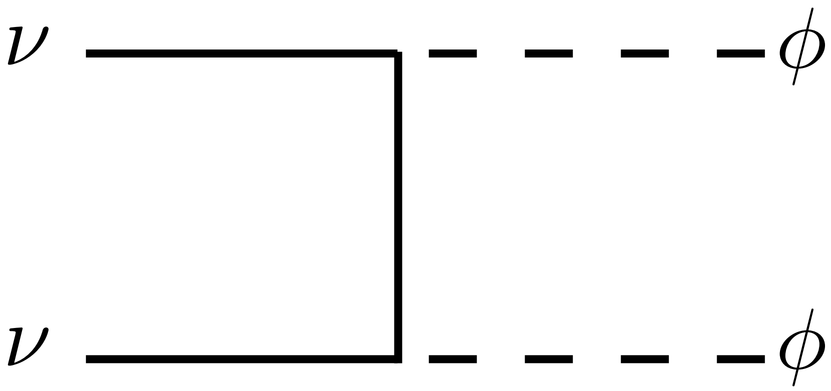
Neutrino self-interactions



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

Has been particularly interesting of late for Hubble tension

Neutrino/majoron annihilations



Dolgov et al (1997), Huang et al (2018), …

Strongly constrained….

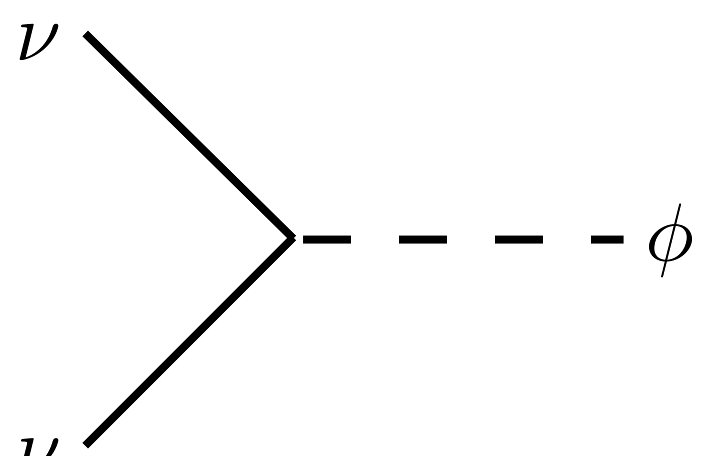
See e.g. Blinov, Kelley, Krnjaic, McDermott (2019)

Majoron Cosmology

Weak majoron interactions

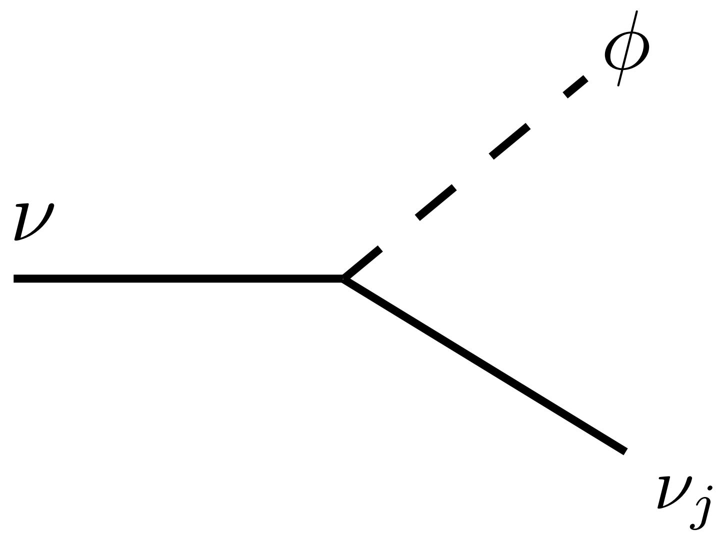
Far more motivated from theory…

Inverse neutrino decay / Majoron decay



Chacko, Hall, Okui, Oliver (2003), Escudero & SJW (2019)

Neutrino decay



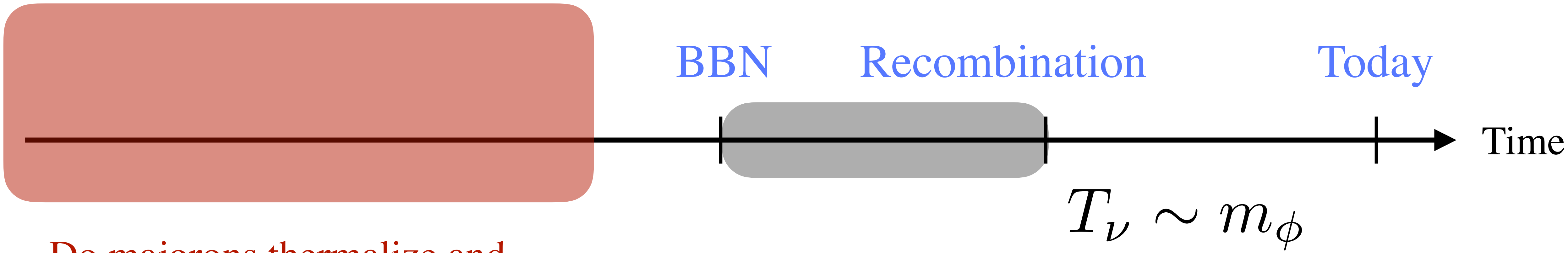
Archidiacono et al (2013), Escudero et al (2019), …

Requires: $m_\phi < m_\nu$

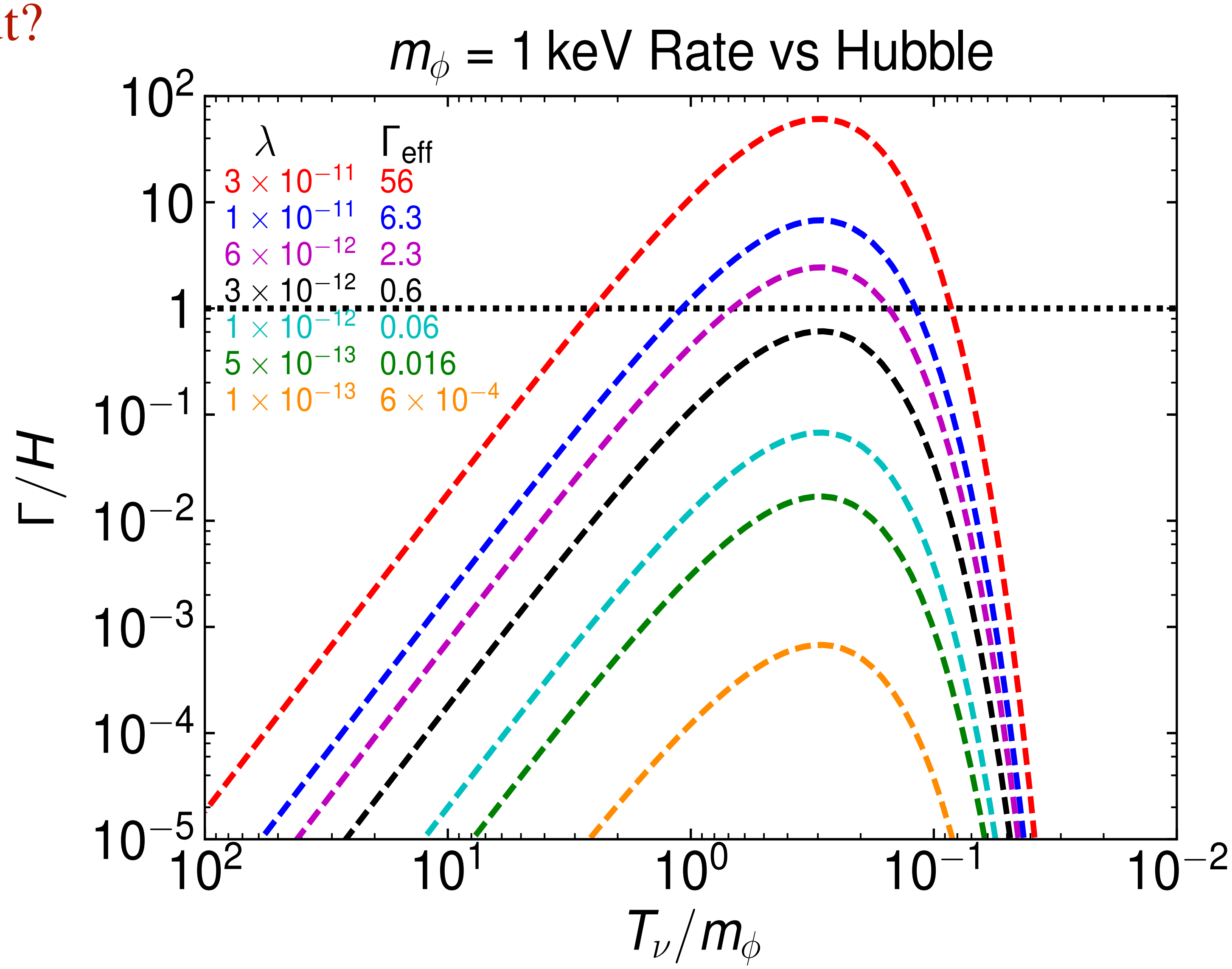
Our focus lies here….

$m_\phi \in [0.1\,\mathrm{eV},\ \mathrm{MeV}]$ $\quad \lambda \sim [10^{-15}, 10^{-6}]$

Cosmological History of Majoron

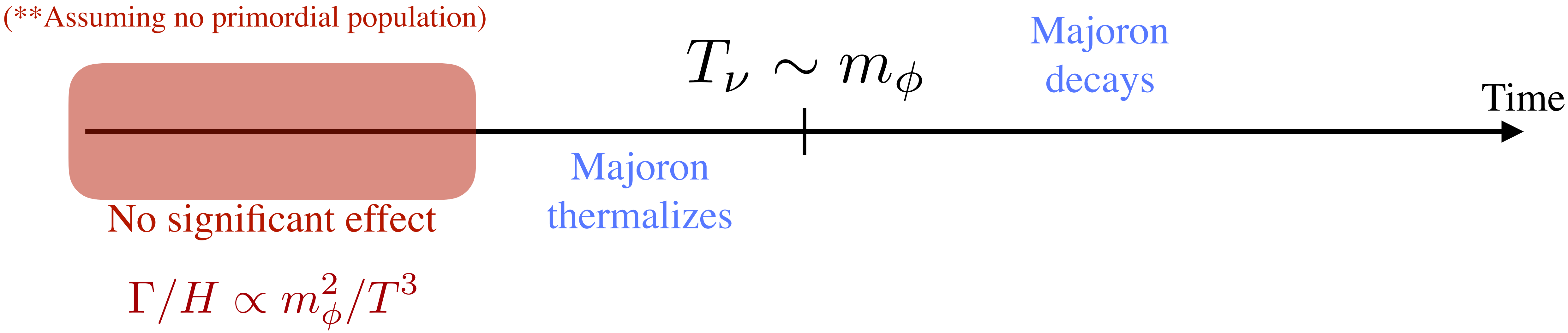


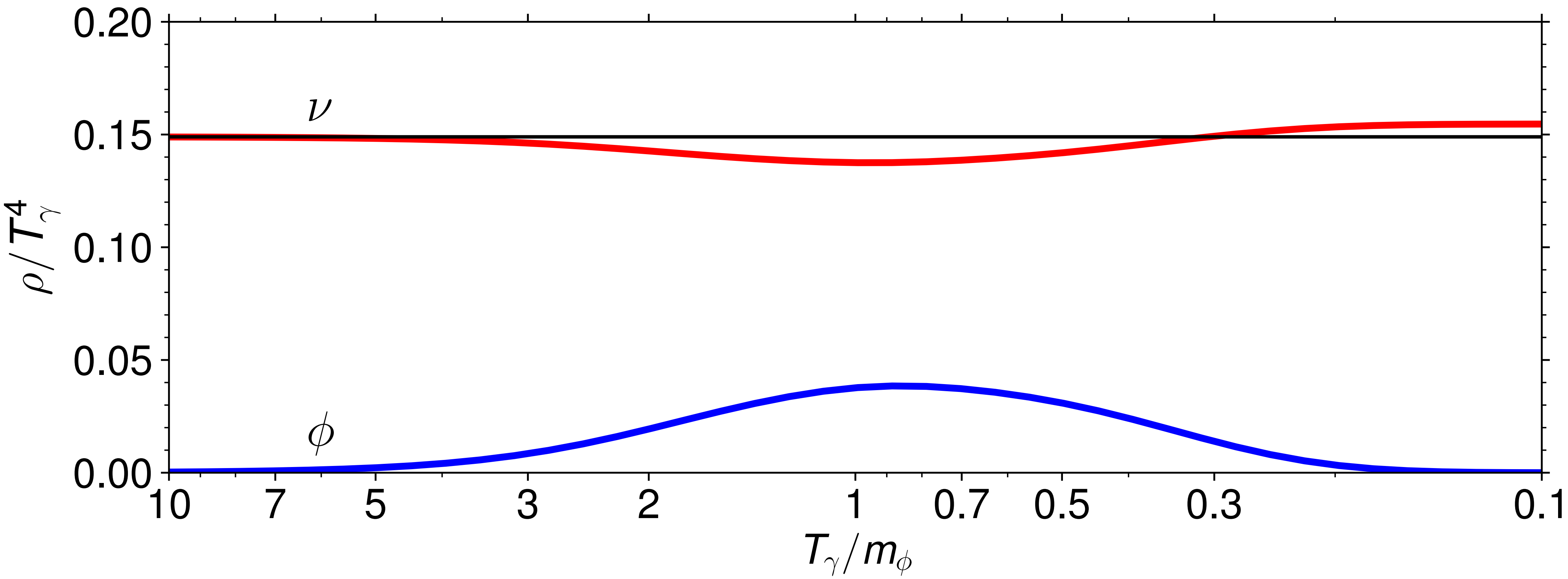
Do majorons thermalize and freeze out?



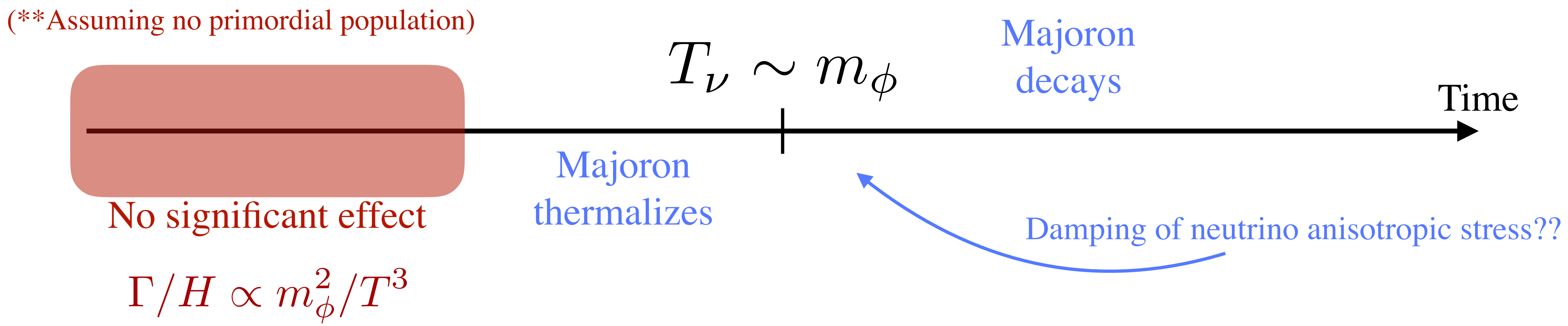
(1909.04044) Escudero, SJW

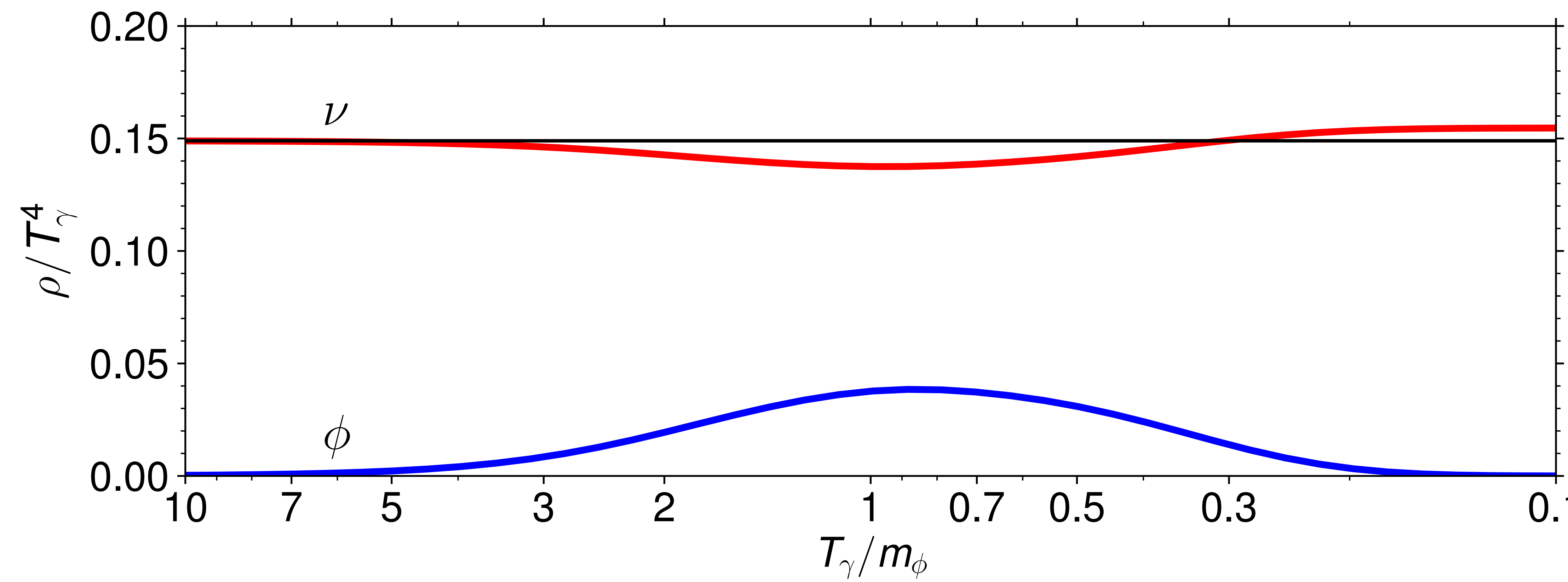
Evolution of Thermal Majoron



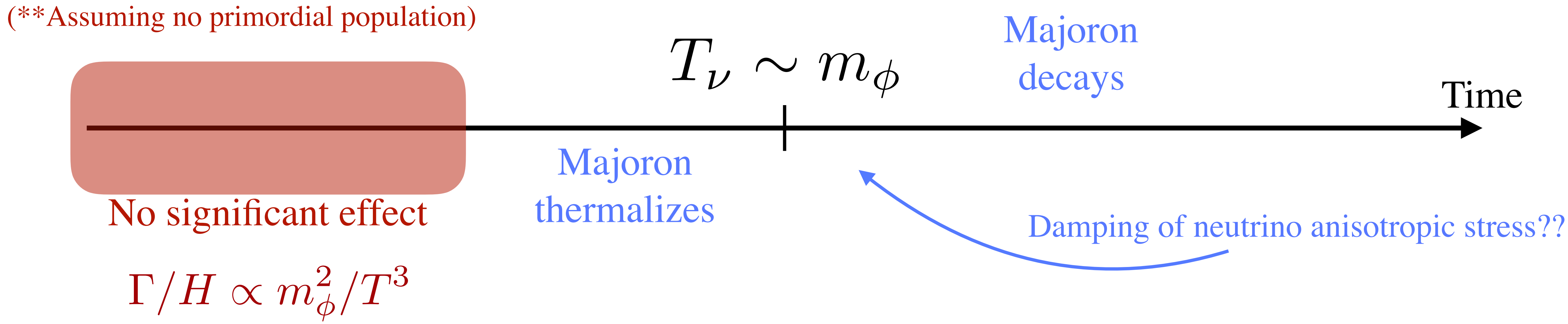


Evolution of Thermal Majoron





Evolution of Thermal Majoron



<u>Two Potential Effects:</u> Chacko et al (2003)

1.) If majoron decays long before recombination, $\Delta N_{\rm eff} \simeq 0.11$

(1909.04044) Escudero, SJW

2.) If majoron thermalizes near recombination, damping of free-streaming more important

Bashinsky and Seljak (2003)

(1909.04044) Escudero, SJW

$m_\phi \lesssim \mathcal{O}(100)\,\mathrm{eV}$

Primordial Majorons

Thus far we have assumed no primordial population…

Sterile neutrinos thermalize if $T_{RH} \gtrsim 5 \times m_N$ (**type-I seesaw, produced off yukawa)

$$\frac{\Gamma(N \to \phi\nu)}{\Gamma(N \to \text{SM})} \sim \left(\frac{v_L}{v_H}\right)^2 \qquad m_N > m_W$$

Easily generating thermal majoron population

Primordial Majorons

Thus far we have assumed no primordial population…

Sterile neutrinos thermalize if $T_{RH} \gtrsim 5 \times m_N$ (**type-I seesaw, produced off yukawa)

$$\frac{\Gamma(N \to \phi\nu)}{\Gamma(N \to \text{SM})} \sim \left(\frac{v_L}{v_H}\right)^2$$

$m_N > m_W$

Easily generating thermal majoron population

Entropy conservation: $\Delta N_{\text{eff}}\big|_{\text{BBN}} \simeq 0.027$ (if $m_\phi \lesssim \text{MeV}$)

Primordial Majorons

Thus far we have assumed no primordial population…

Sterile neutrinos thermalize if $T_{RH} \gtrsim 5 \times m_N$ (**type-I seesaw, produced off yukawa)

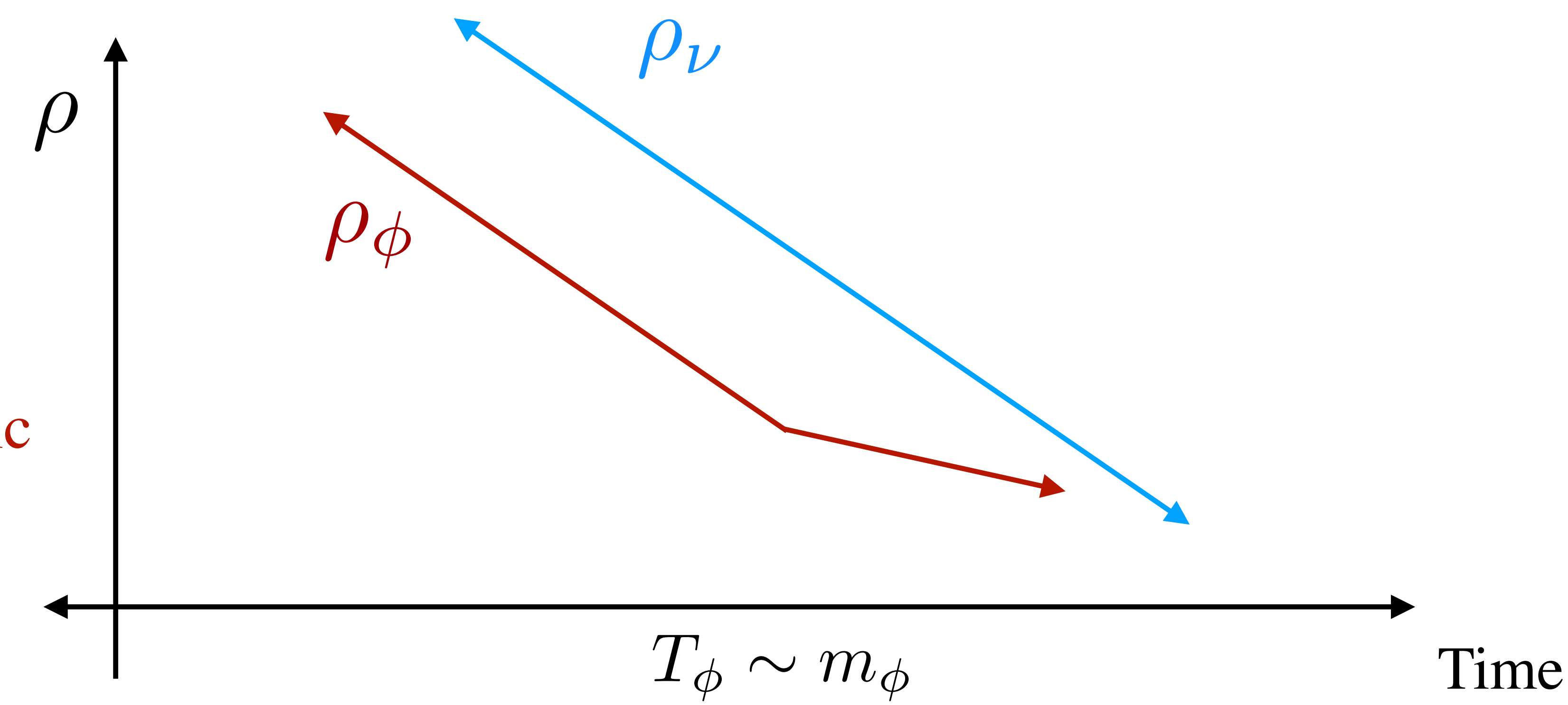
$$\frac{\Gamma(N \to \phi\nu)}{\Gamma(N \to \mathrm{SM})} \sim \left(\frac{v_L}{v_H}\right)^2 \qquad m_N > m_W$$

Easily generating thermal majoron population

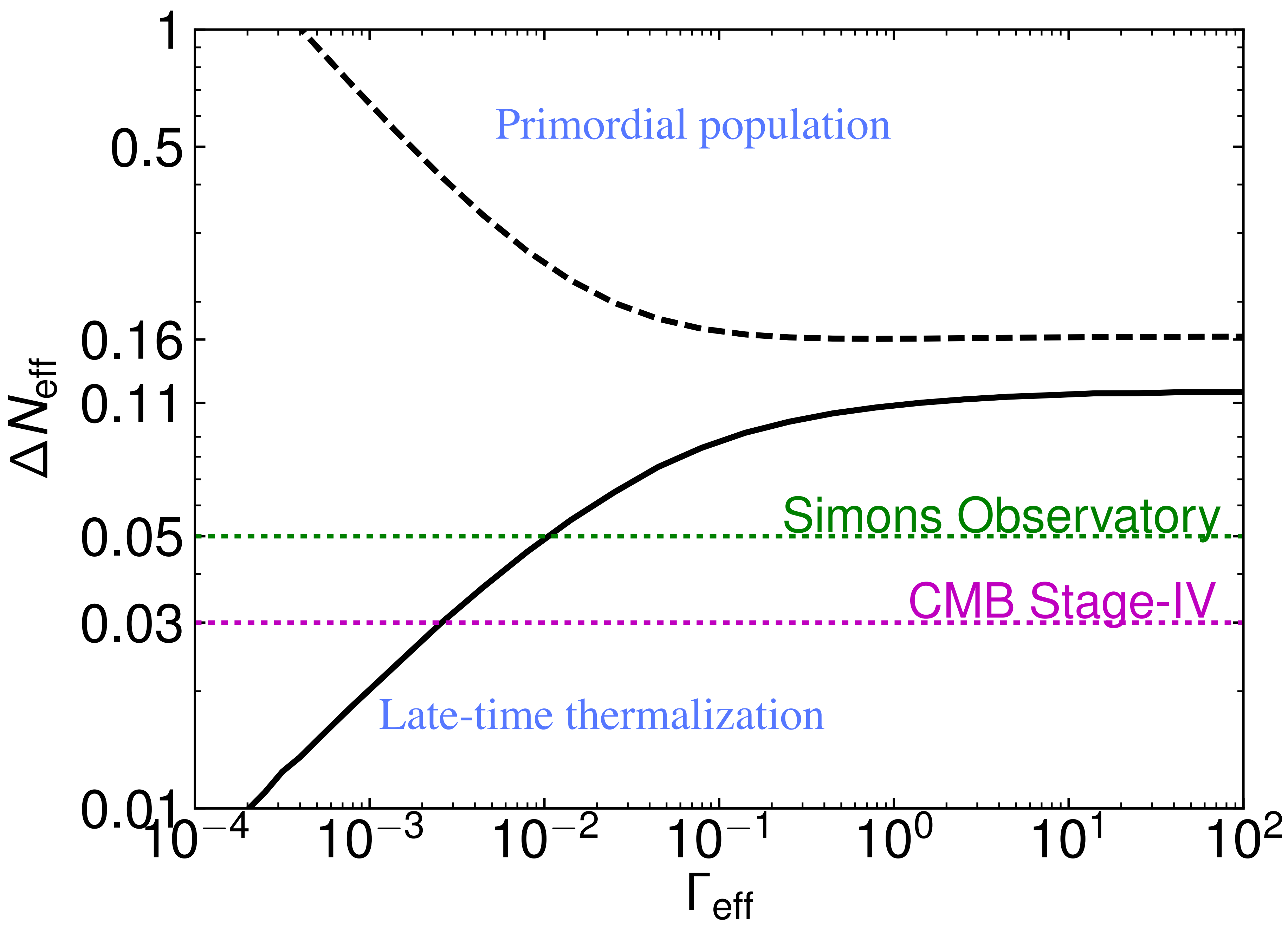
Entropy conservation: $\Delta N_{\mathrm{eff}}\big|_{\mathrm{BBN}} \simeq 0.027$ (if $m_\phi \lesssim \mathrm{MeV}$)

If coupling small enough…

Energy density continues to grow long after becoming non-relativistic



$\Delta N_{\rm eff}$



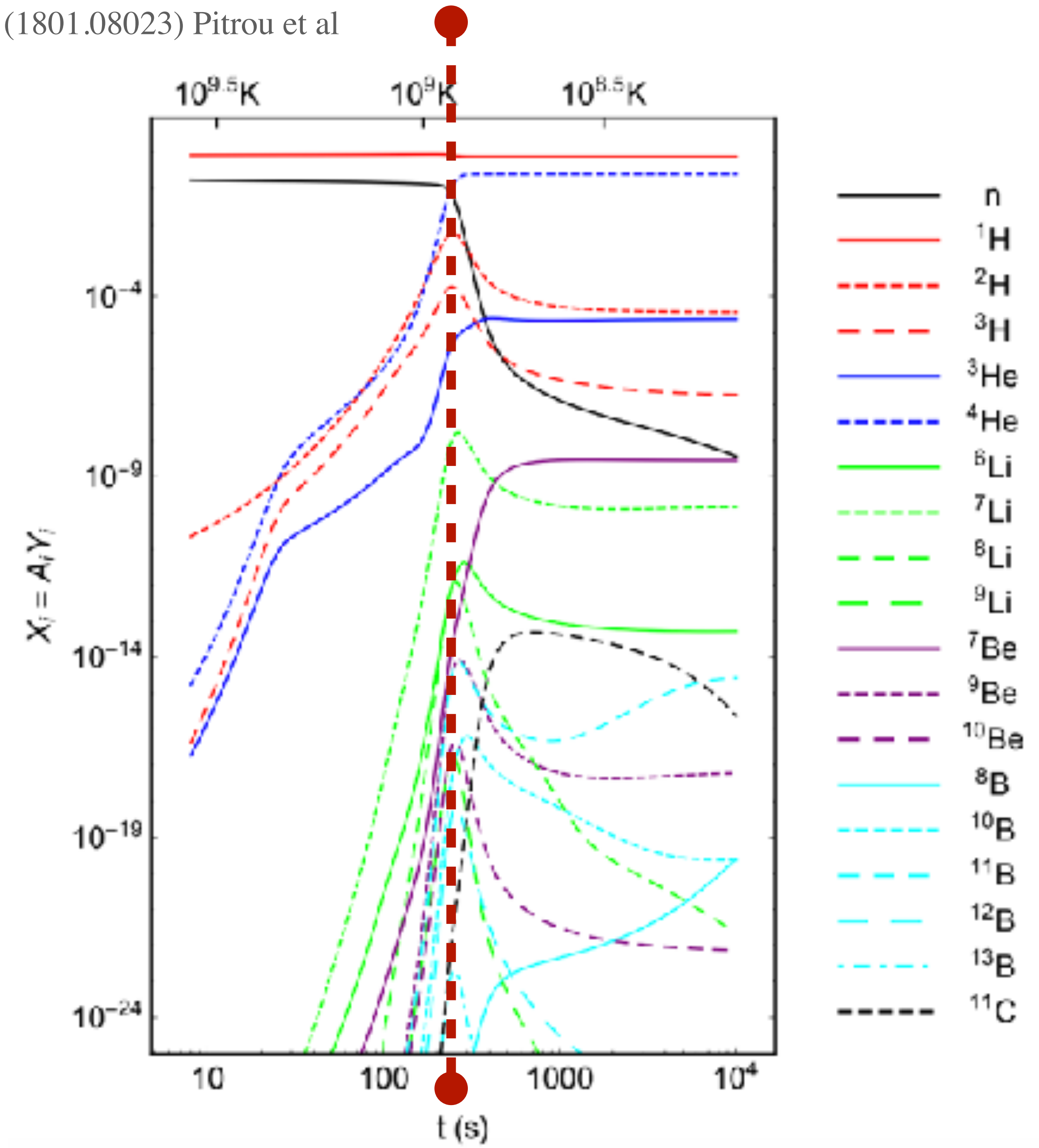
(1909.04044) Escudero, SJW

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

Current Majoron Constraints

BBN: → Don't modify D production

(1801.08023) Pitrou et al

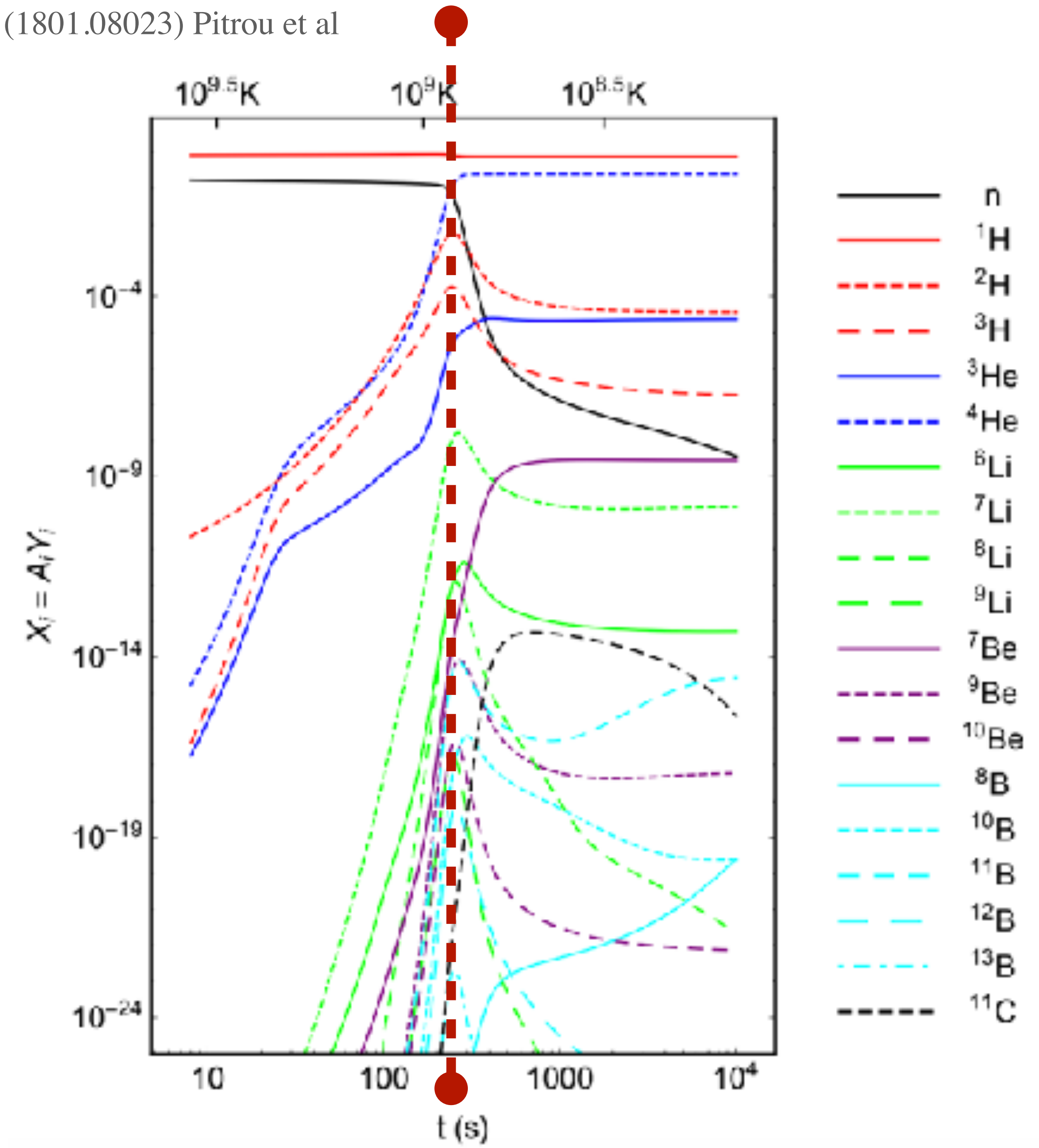


$$t_{T_\gamma = 0.7\,\mathrm{MeV}} \sim 246.6\,s$$

Current Majoron Constraints

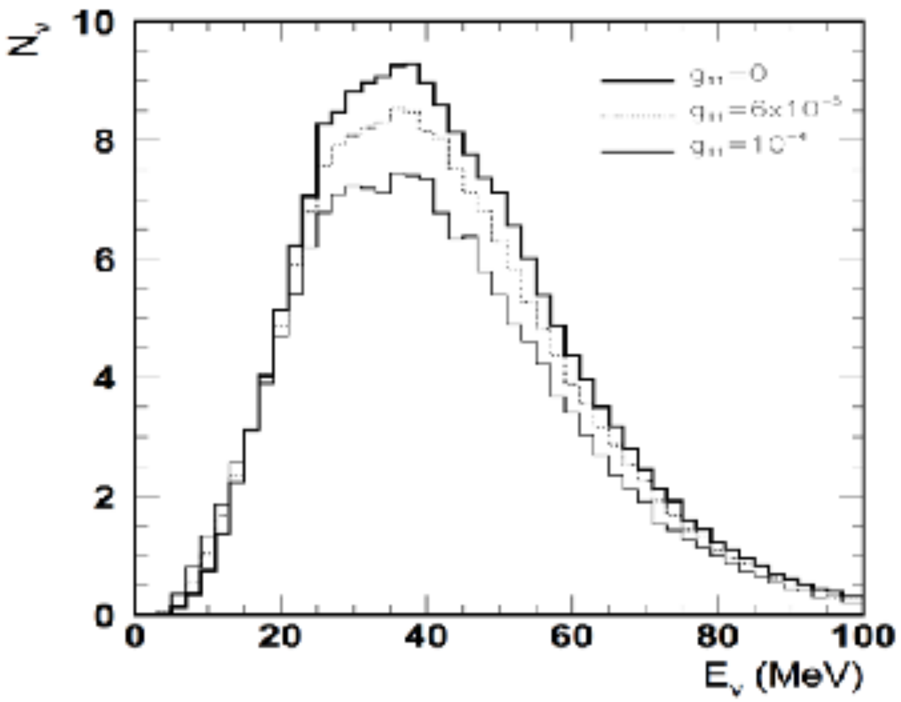
BBN: → Don't modify D production

(1801.08023) Pitrou et al



$t_{T_\gamma = 0.7\,\mathrm{MeV}} \sim 246.6\,s$

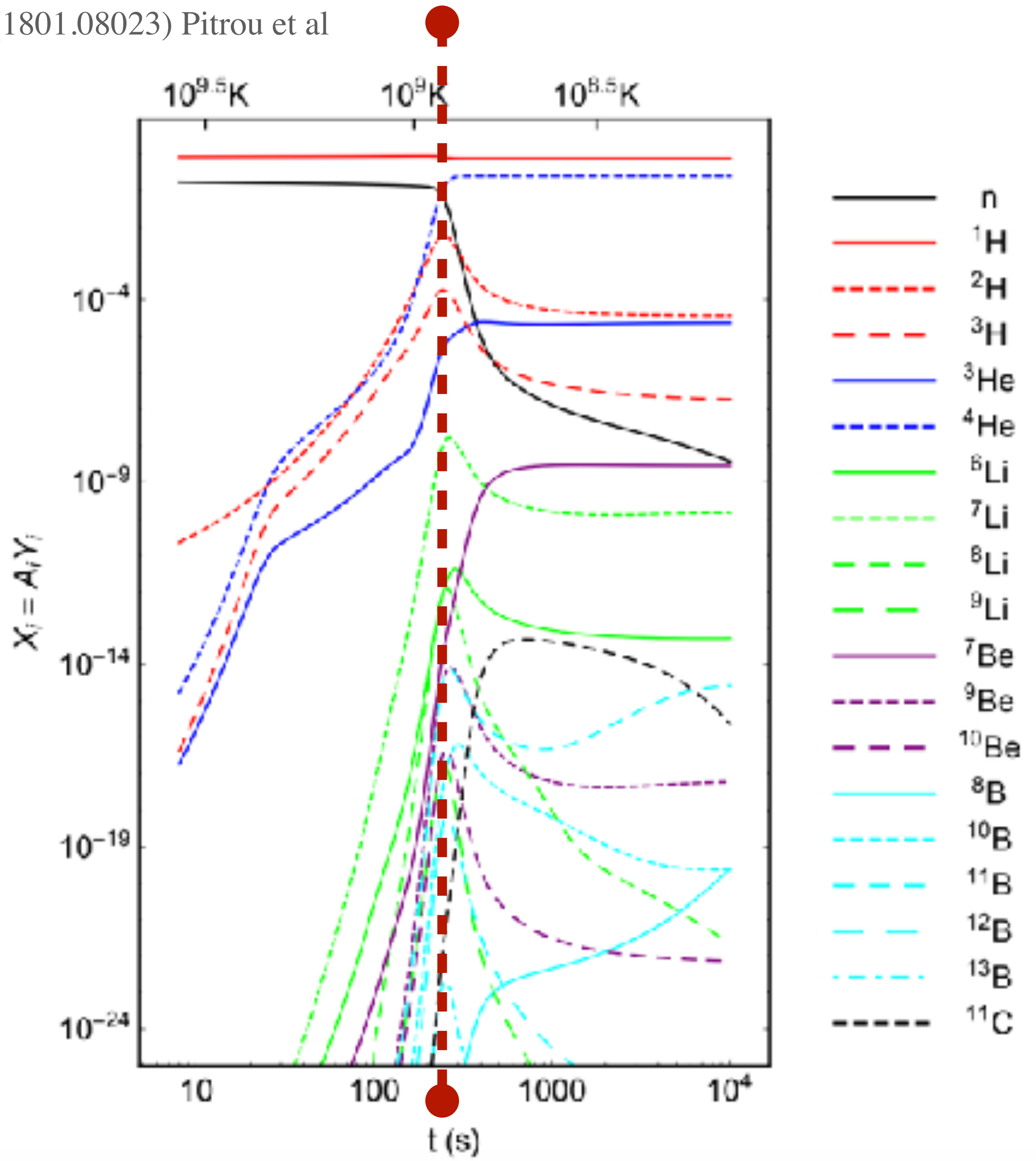
SN1987a: (0001039) Kachelrieß et al, (0211375) Farzan



Current Majoron Constraints

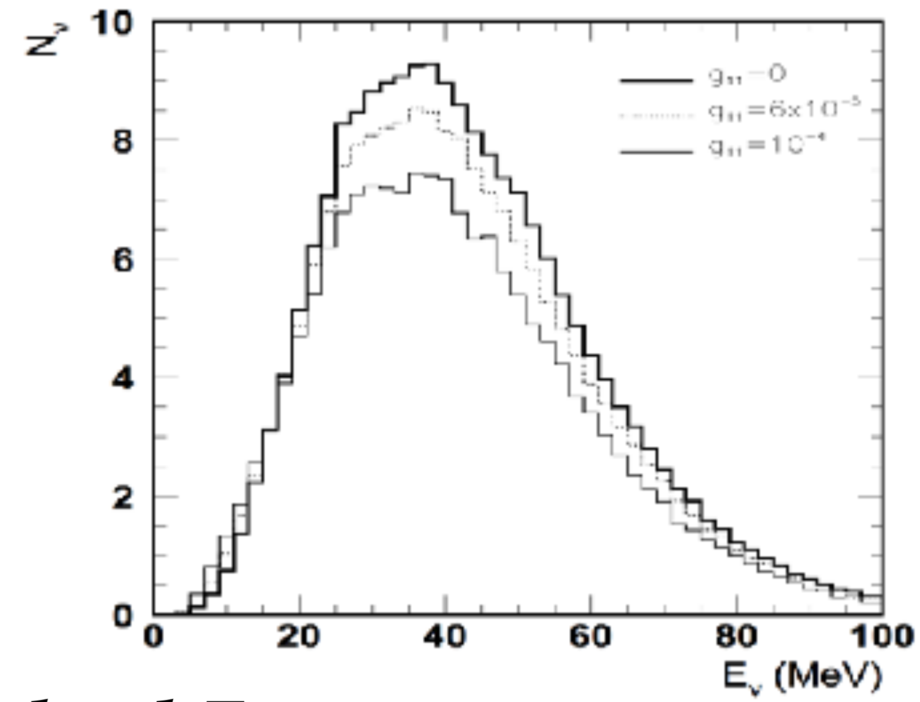
BBN: → Don't modify D production

(1801.08023) Pitrou et al



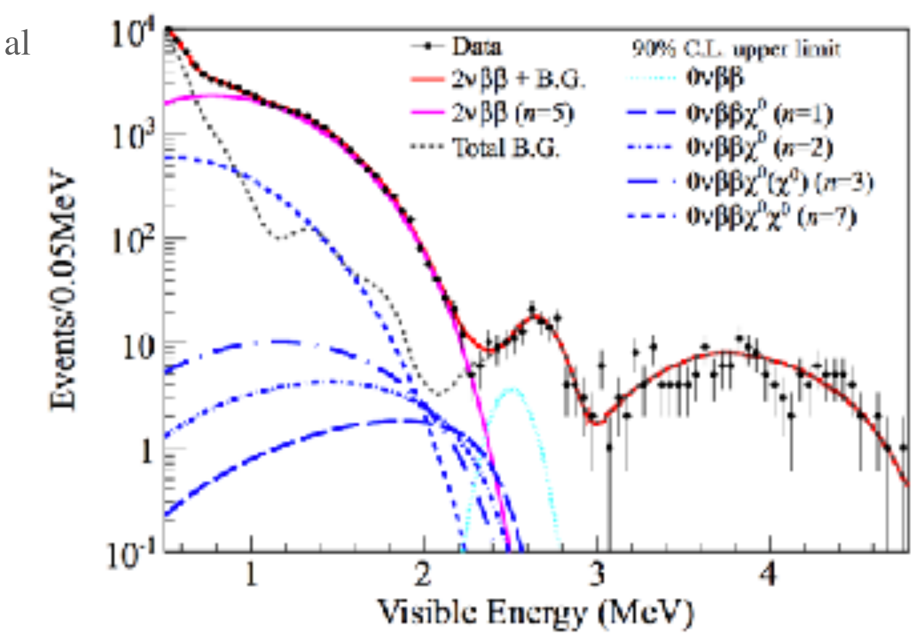
$$t_{T_\gamma=0.7\,\mathrm{MeV}} \sim 246.6\, s$$

SN1987a: (0001039) Kachelrieß et al, (0211375) Farzan

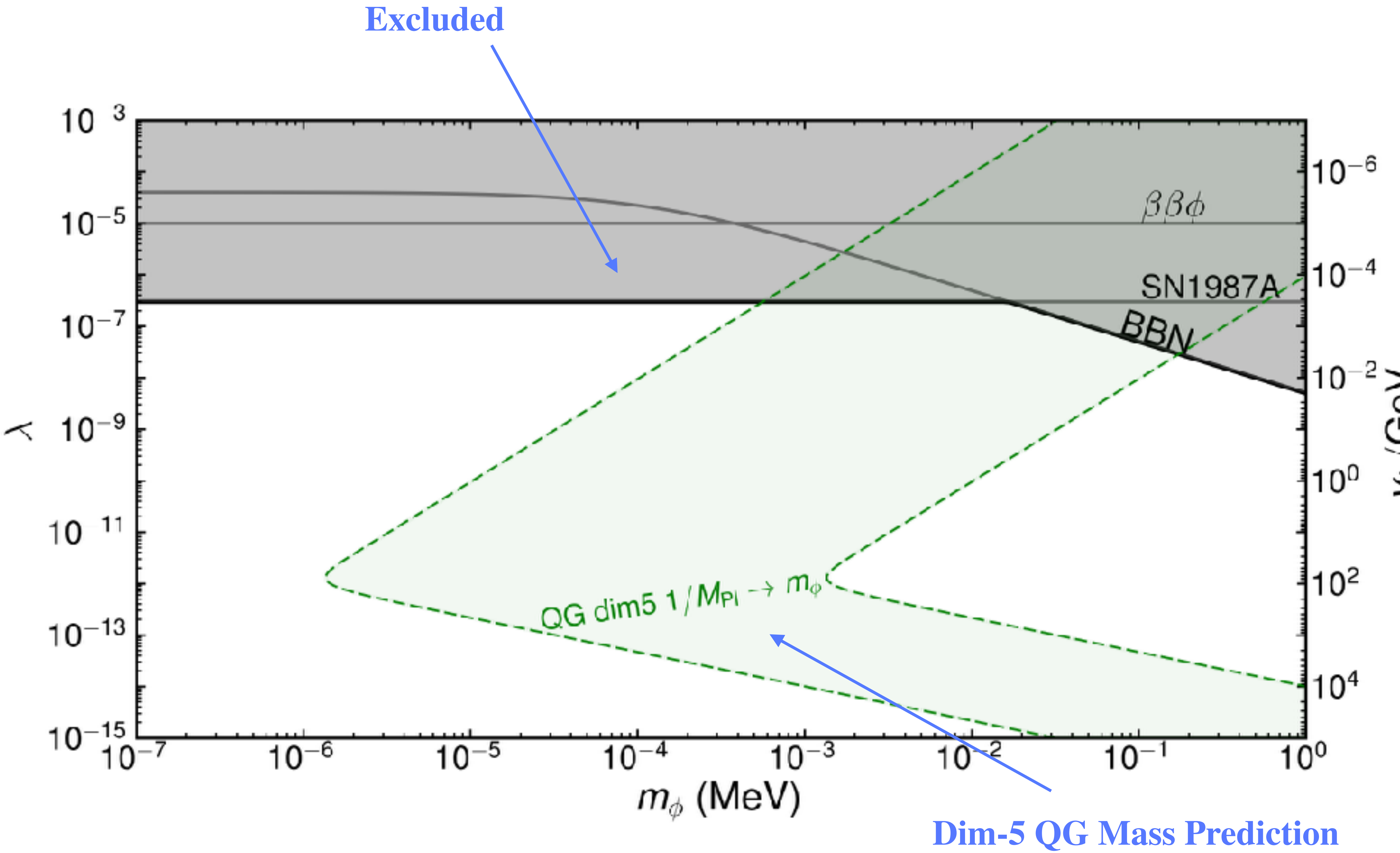


Kamland-Zen

(1205.6372) Gando et al

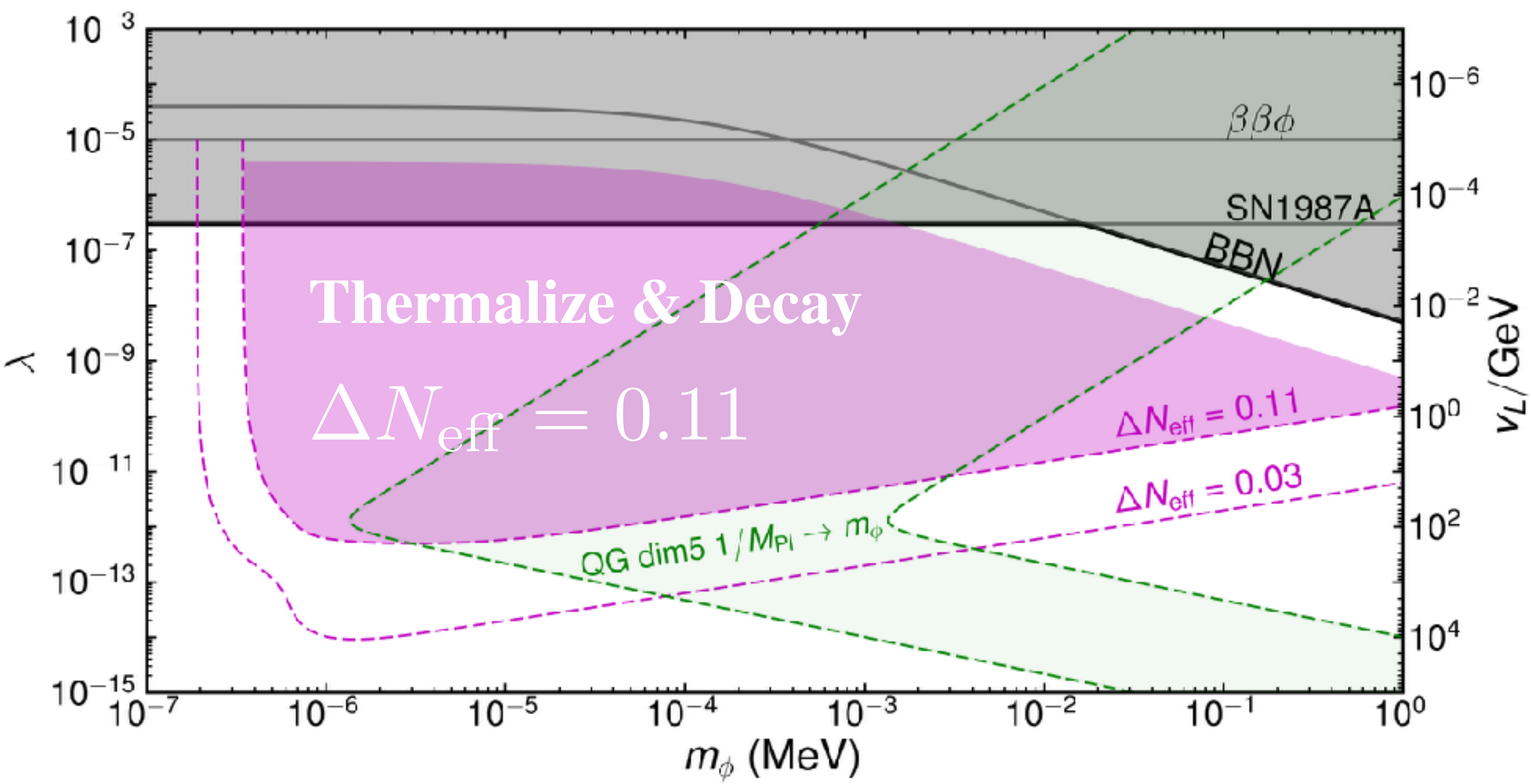


Majoron Cosmology



(1909.04044) Escudero, SJW

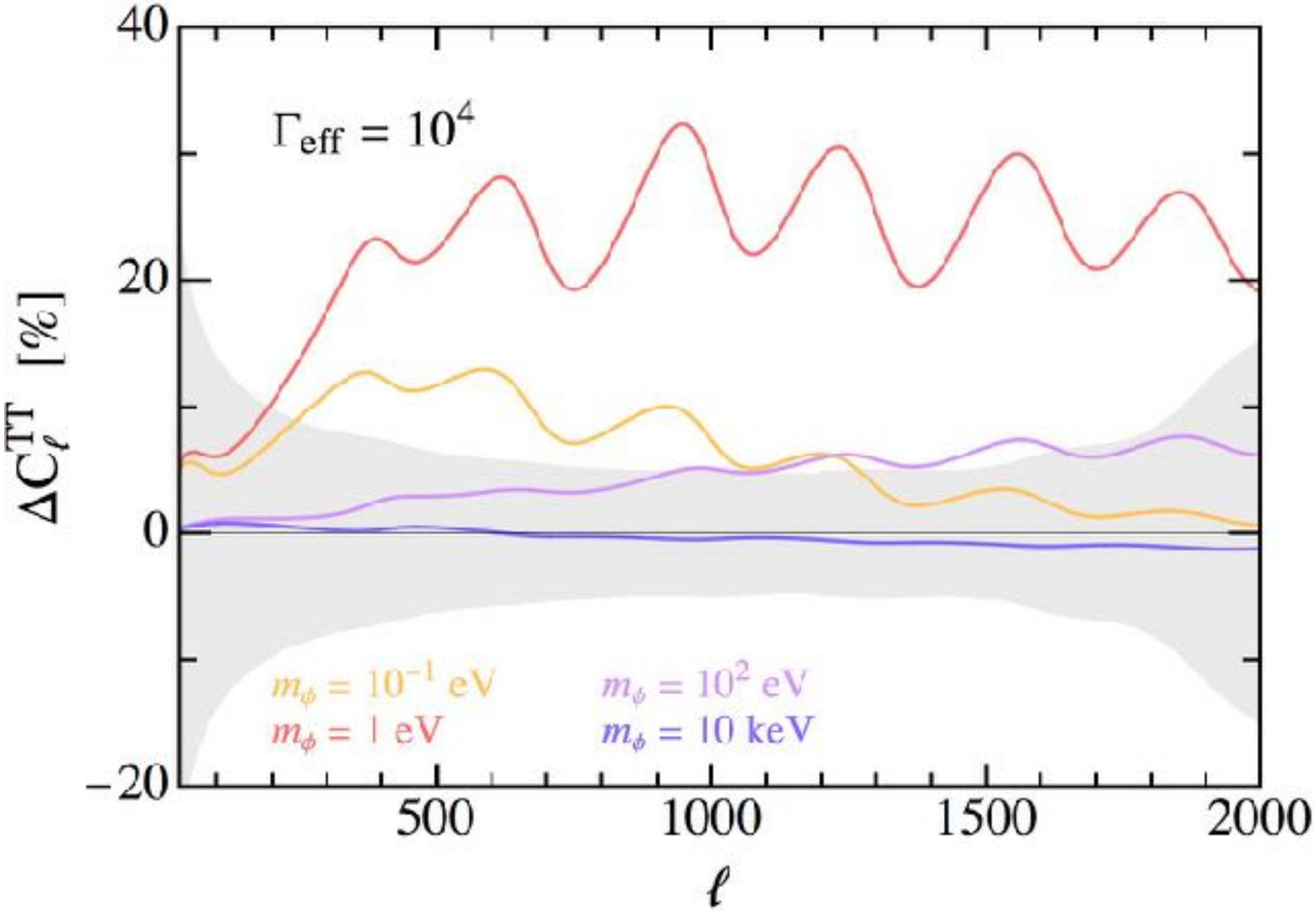
Majoron Cosmology



(1909.04044) Escudero, SJW

Temperature Cls

Effect of majoron on Cls (Planck 2108):

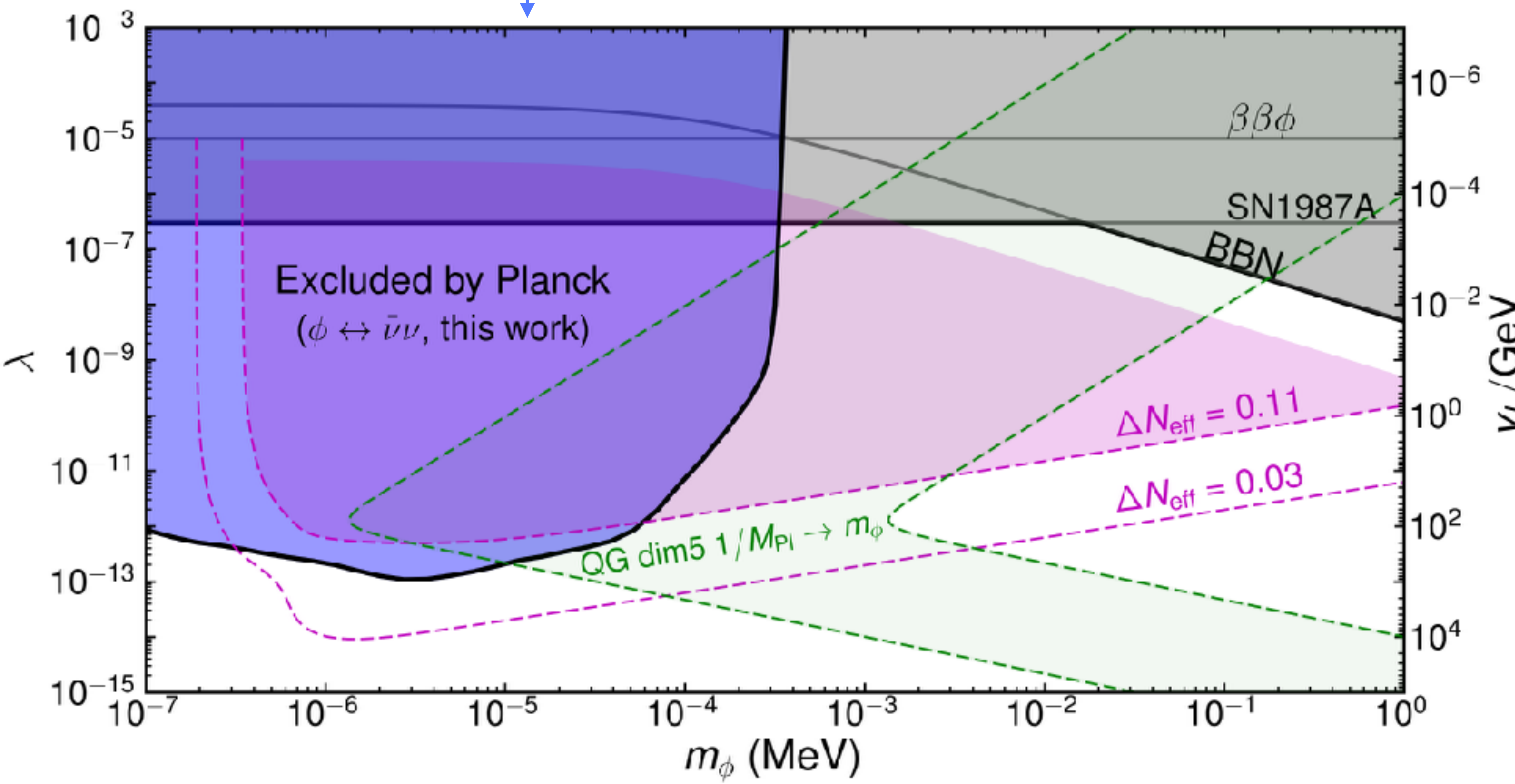


$$\Gamma_{\rm eff} \equiv \left(\frac{\lambda}{4\times10^{-12}}\right)^2 \left(\frac{\rm keV}{m_\phi}\right)$$

(1909.04044) Escudero, SJW

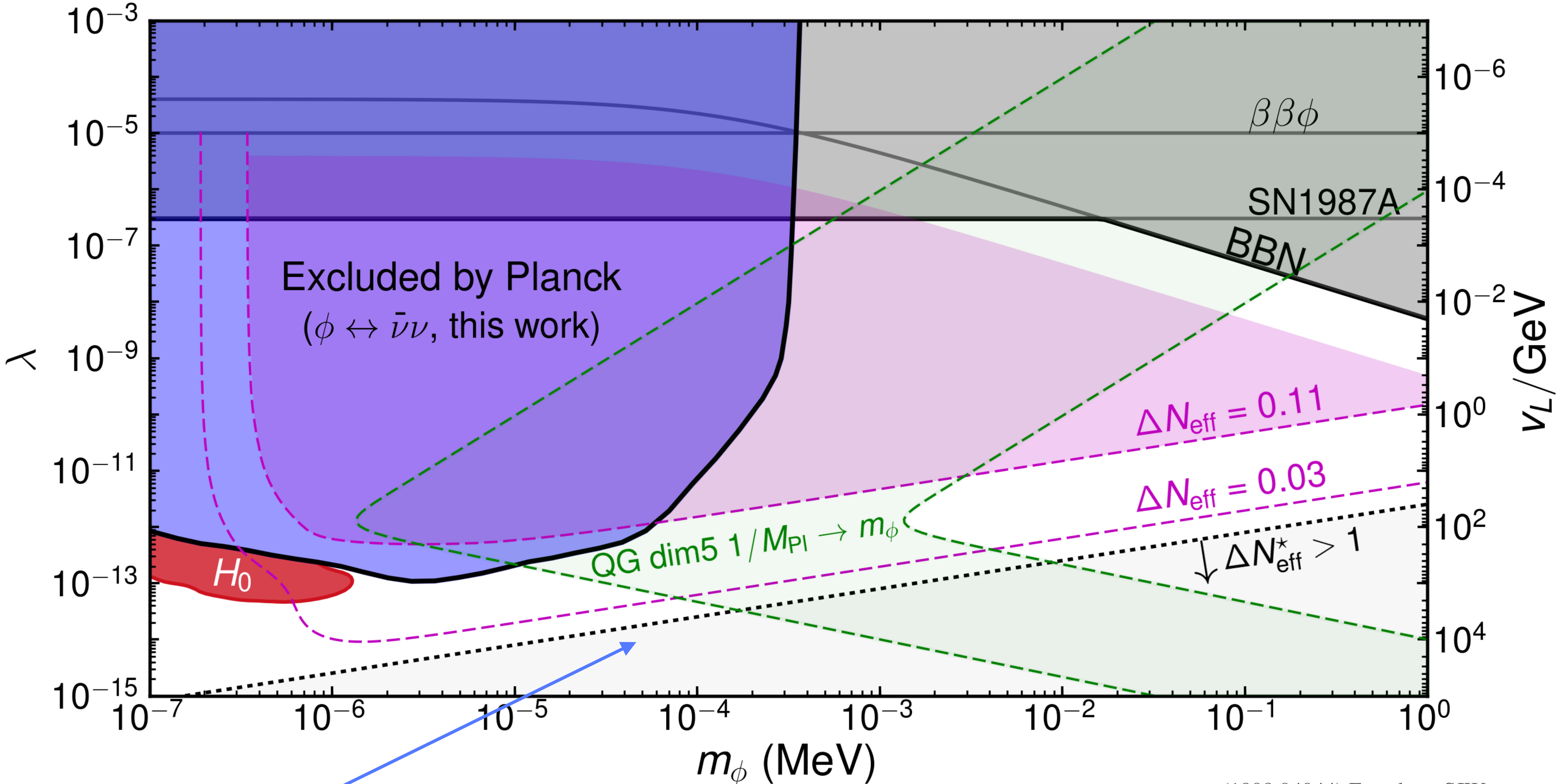
Majoron Cosmology

Excluded from damping effect



(1909.04044) Escudero, SJW

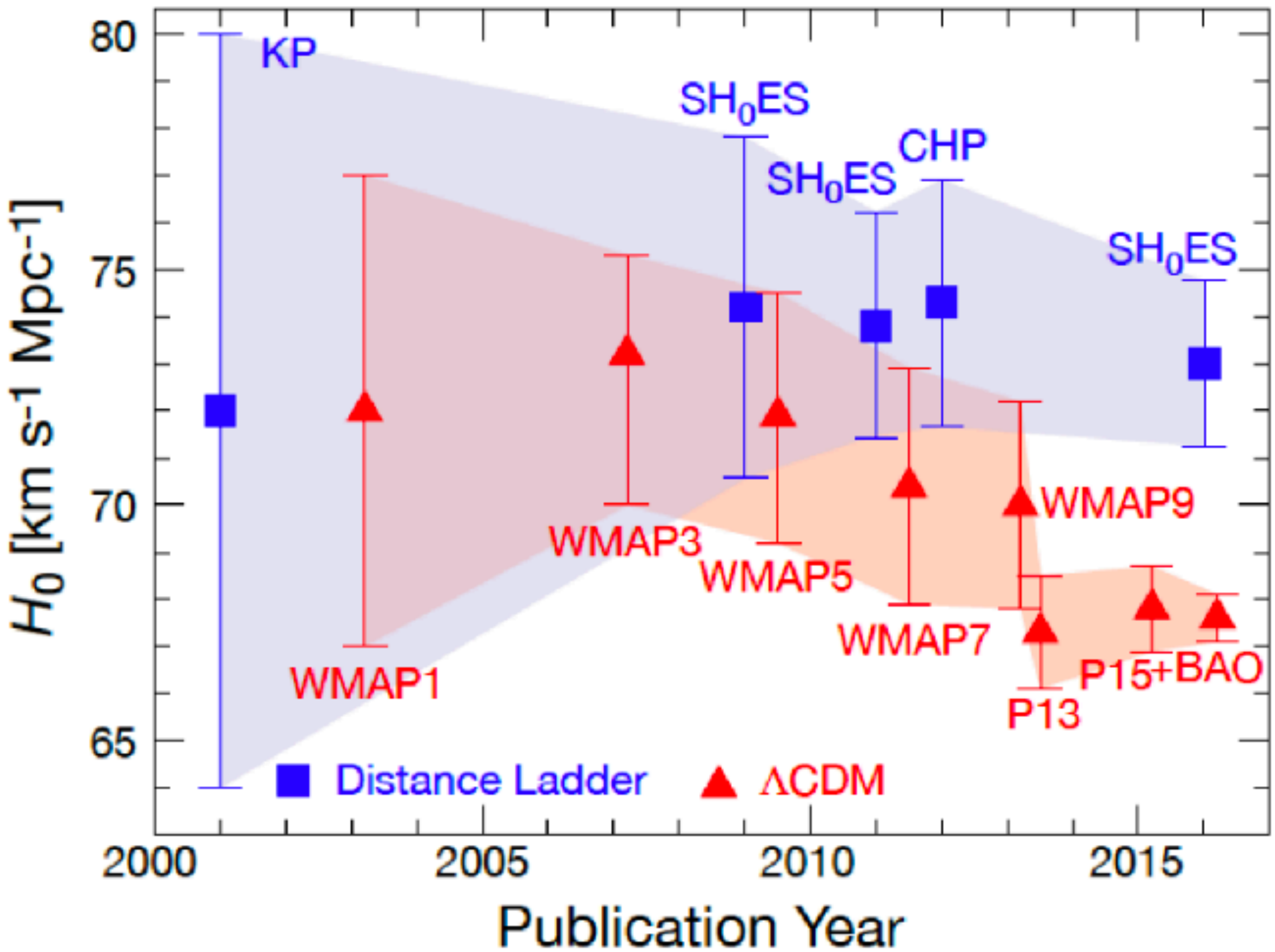
Majoron Cosmology



(1909.04044) Escudero, SJW

Excluded if primordial population

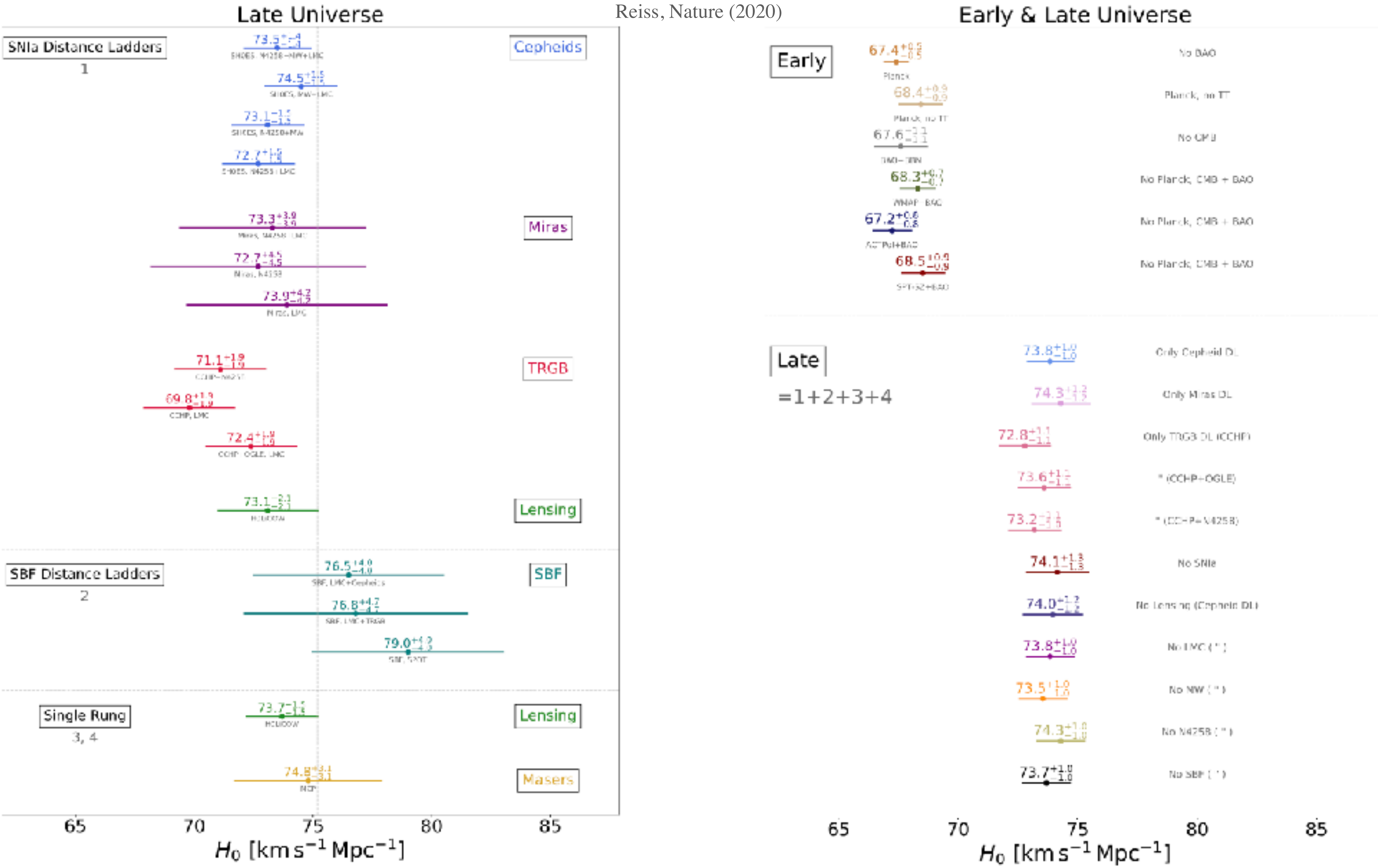
Hubble Tension



Credit: NASA/ESA/Hubble/WMAP/Planck/SHoES/BAO/Freedman et al.

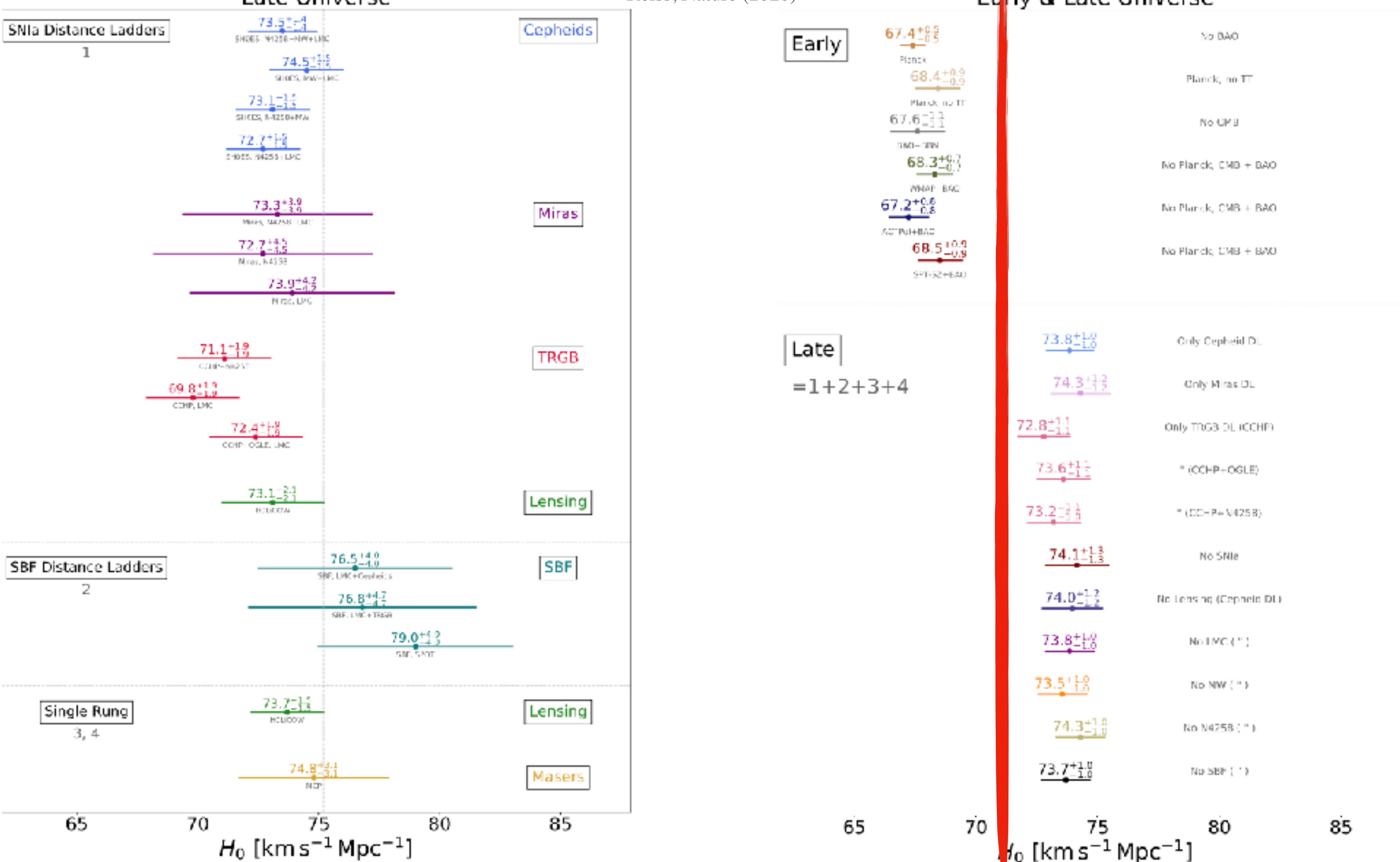
Hubble Tension

Reiss, Nature (2020)



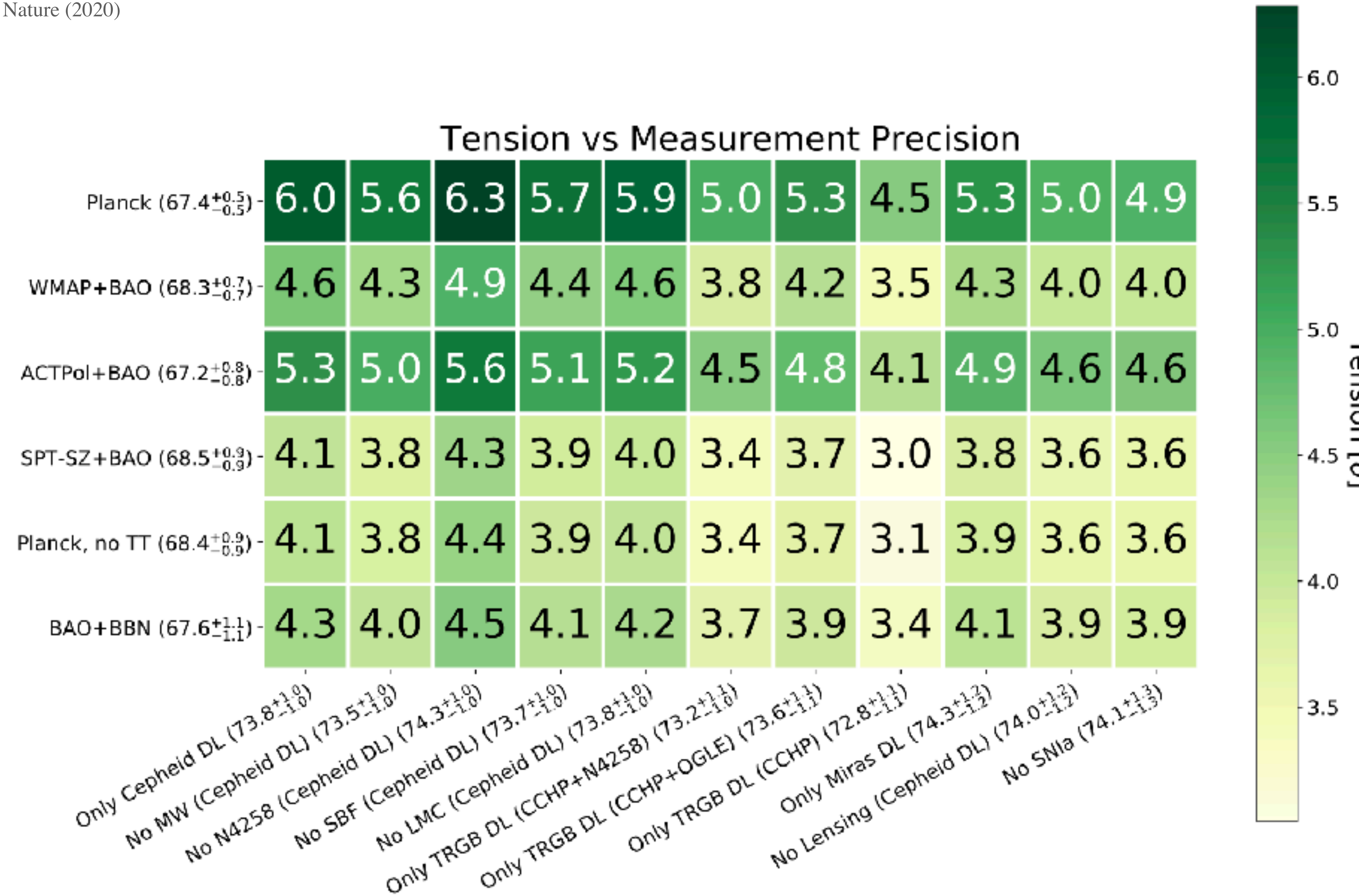
Hubble Tension

Reiss, Nature (2020)



Hubble Tension

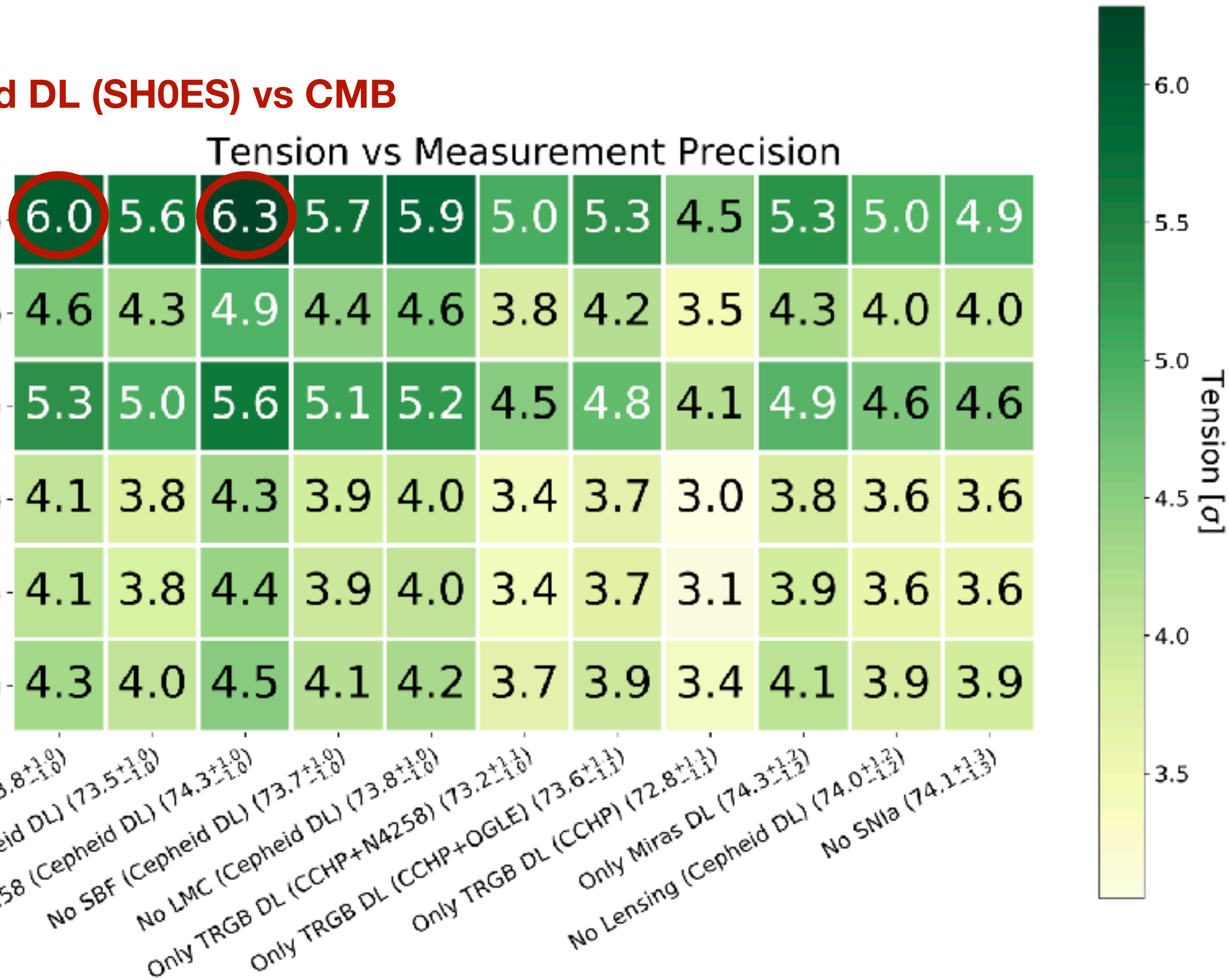
Reiss, Nature (2020)



Hubble Tension

Reiss, Nature (2020)

Cepheid DL (SH0ES) vs CMB



	Only Cepheid DL ($73.8^{+1.0}_{-1.0}$)	No MW (Cepheid DL) ($73.5^{+1.0}_{-1.0}$)	No N4258 (Cepheid DL) ($74.3^{+1.0}_{-1.0}$)	No SBF (Cepheid DL) ($73.7^{+1.0}_{-1.0}$)	No LMC (Cepheid DL) ($73.8^{+1.0}_{-1.0}$)	Only TRGB DL (CCHP+N4258) ($73.2^{+1.1}_{-1.0}$)	Only TRGB DL (CCHP+OGLE) ($73.6^{+1.1}_{-1.1}$)	Only TRGB DL (CCHP) ($72.8^{+1.1}_{-1.1}$)	Only Miras DL ($74.3^{+1.2}_{-1.2}$)	No Lensing (Cepheid DL) ($74.0^{+1.2}_{-1.2}$)	No SNIa ($74.1^{+1.3}_{-1.3}$)
Planck ($67.4^{+0.5}_{-0.5}$)	6.0	5.6	6.3	5.7	5.9	5.0	5.3	4.5	5.3	5.0	4.9
WMAP+BAO ($68.3^{+0.7}_{-0.7}$)	4.6	4.3	4.9	4.4	4.6	3.8	4.2	3.5	4.3	4.0	4.0
ACTPol+BAO ($67.2^{+0.8}_{-0.8}$)	5.3	5.0	5.6	5.1	5.2	4.5	4.8	4.1	4.9	4.6	4.6
SPT-SZ+BAO ($68.5^{+0.9}_{-0.9}$)	4.1	3.8	4.3	3.9	4.0	3.4	3.7	3.0	3.8	3.6	3.6
Planck, no TT ($68.4^{+0.9}_{-0.9}$)	4.1	3.8	4.4	3.9	4.0	3.4	3.7	3.1	3.9	3.6	3.6
BAO+BBN ($67.6^{+1.1}_{-1.1}$)	4.3	4.0	4.5	4.1	4.2	3.7	3.9	3.4	4.1	3.9	3.9

Hubble Tension

SH0ES Collaboration Goal: obtain distance measure to type-Ia SN

Riess et al (2019)

(Spectroscopy) $v_r = H_0\, d + v_{\rm pec}$ (Small if far enough away…)

Hubble Tension

SH0ES Collaboration Goal: obtain distance measure to type-Ia SN

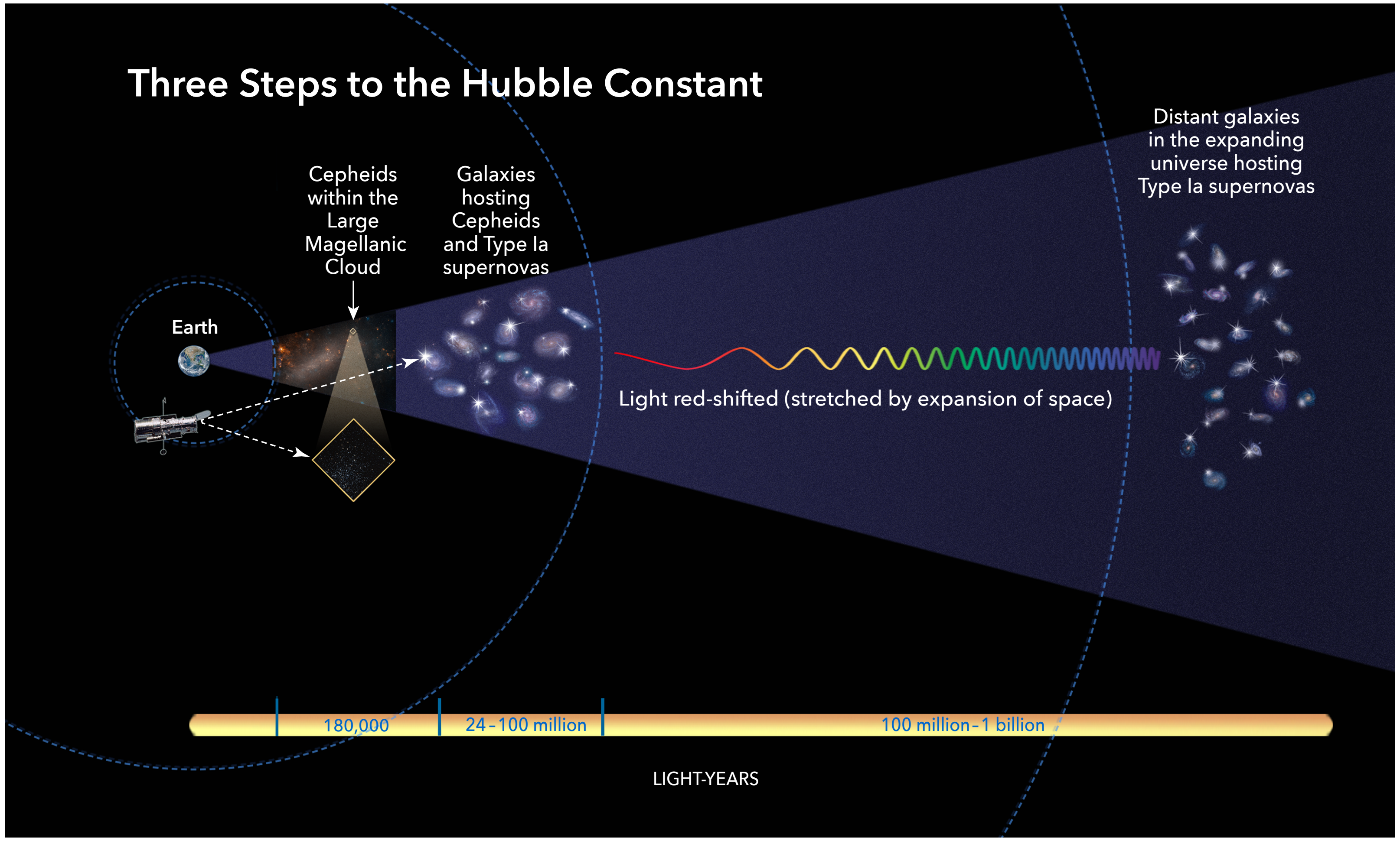
Riess et al (2019)

(Spectroscopy) $v_r = H_0\, d + v_{\rm pec}$ (Small if far enough away…)

-Use geometric ‘anchor’ to calibrate cepheid period-luminosity relation

-Use cepheids to calibrate type-Ia SN brightness (standard candle - ish)

-Use brightness of far type-Ia SN to extract H0

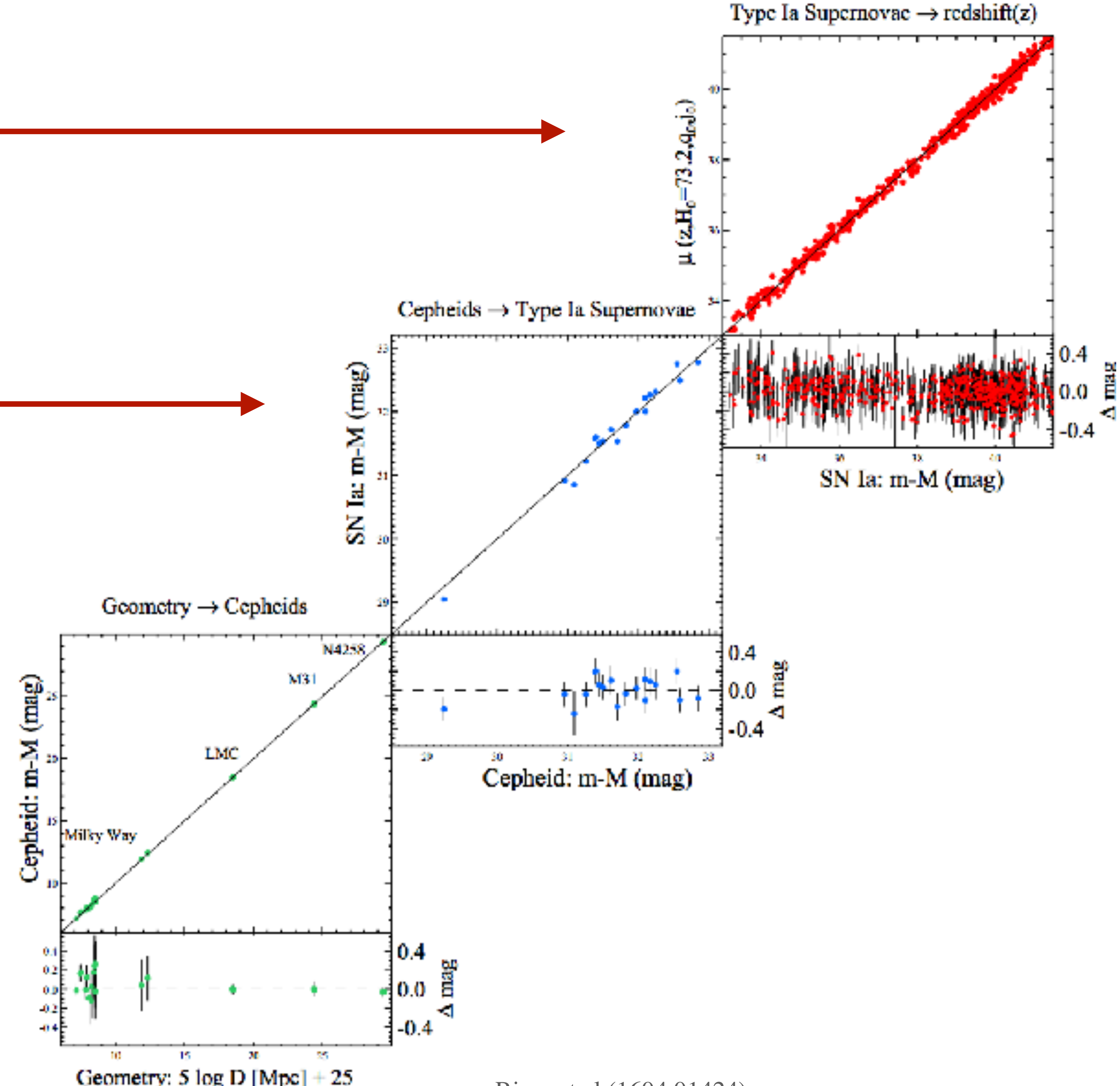


Distance Ladder

3.) Extract distance measure

2.) Calibrate type-Ia SN

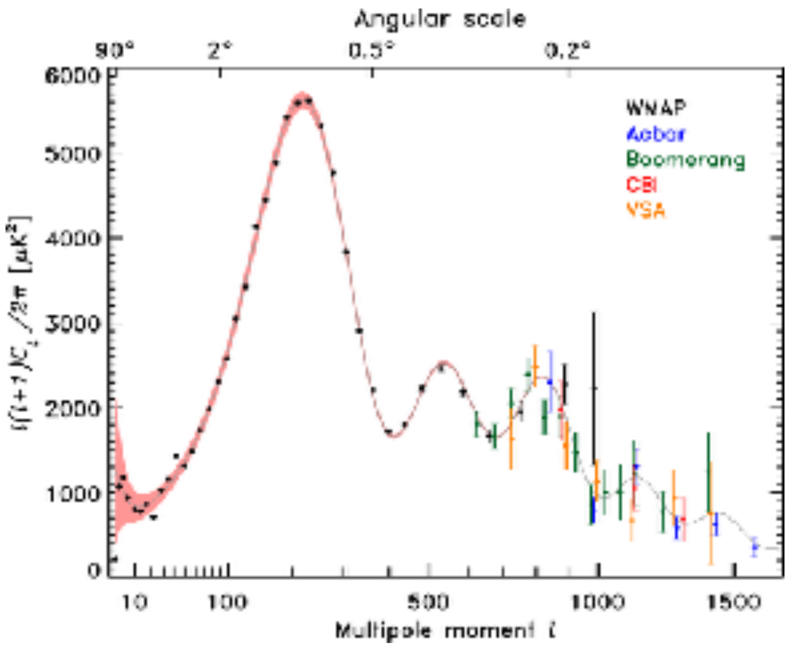
1.) Anchor cepheids



Riess et al (1604.01424)

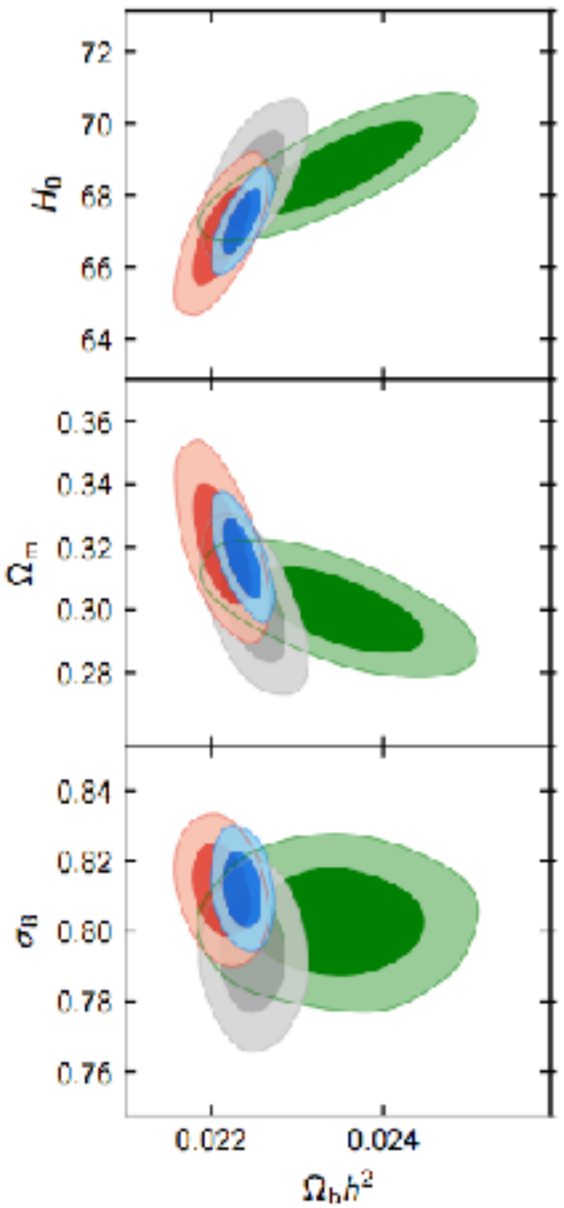
Resolving the Hubble Tension

How does the CMB determine H0? "Hubble Hunters", Knox et al (2019)
Aylor et al (2019)



Data/Likelihoods

Einstein-Boltzmann Solver + MCMC



Infer parameters

Resolving the Hubble Tension

How does the CMB determine H0?

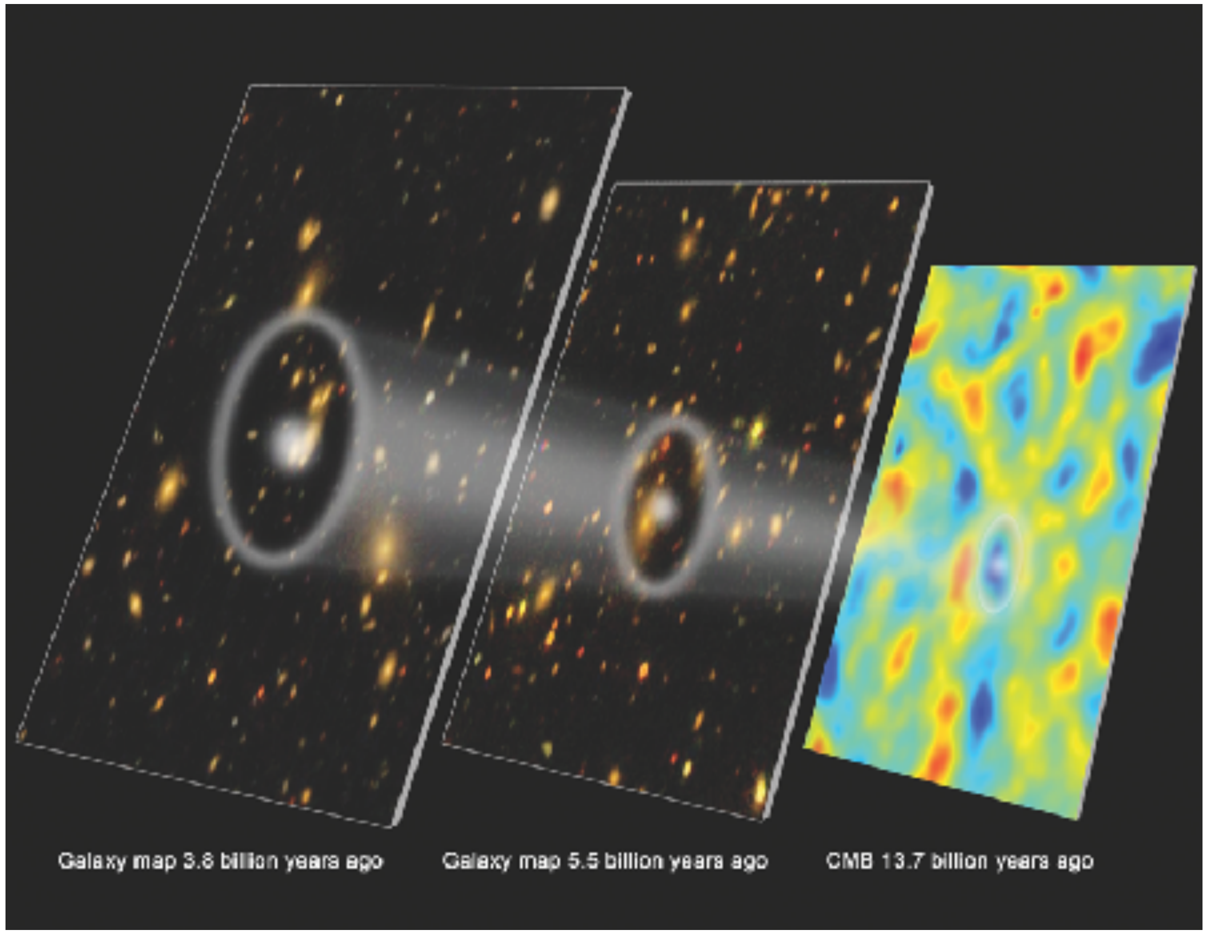
"Hubble Hunters", Knox et al (2019)
Aylor et al (2019)

1) Calibrate Standard Ruler

Sound horizon at decoupling

$$r_s = \int_0^{a_d} c_s \frac{da}{a^2 H(a)}$$

Depends on: $\rho_\gamma, \rho_\nu, \rho_m, \rho_b$



Resolving the Hubble Tension

How does the CMB determine H0? "Hubble Hunters", Knox et al (2019)
Aylor et al (2019)

1) Calibrate Standard Ruler

Sound horizon at decoupling

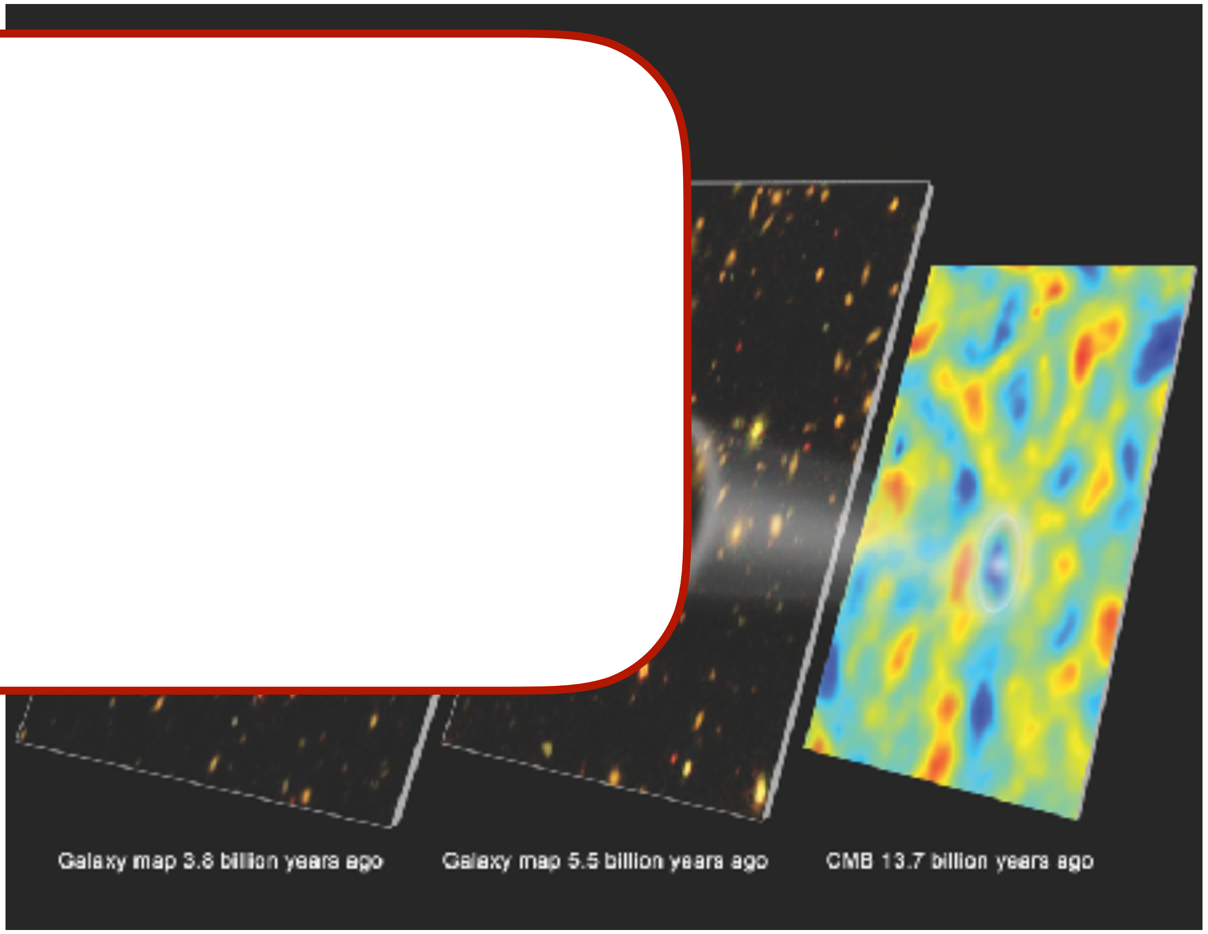
$$r_s = \int_0^{a_d} c_s \frac{da}{a^2 H(a)}$$

Depends on: $\rho_\gamma, \rho_\nu, \rho_m, \rho_b$

$$\rho_\gamma \rightarrow T_{cmb}$$

$$\rho_b \rightarrow \text{odd/even} \quad \text{peaks}$$

$$\rho_M \rightarrow \theta_s^{eq}$$



Resolving the Hubble Tension

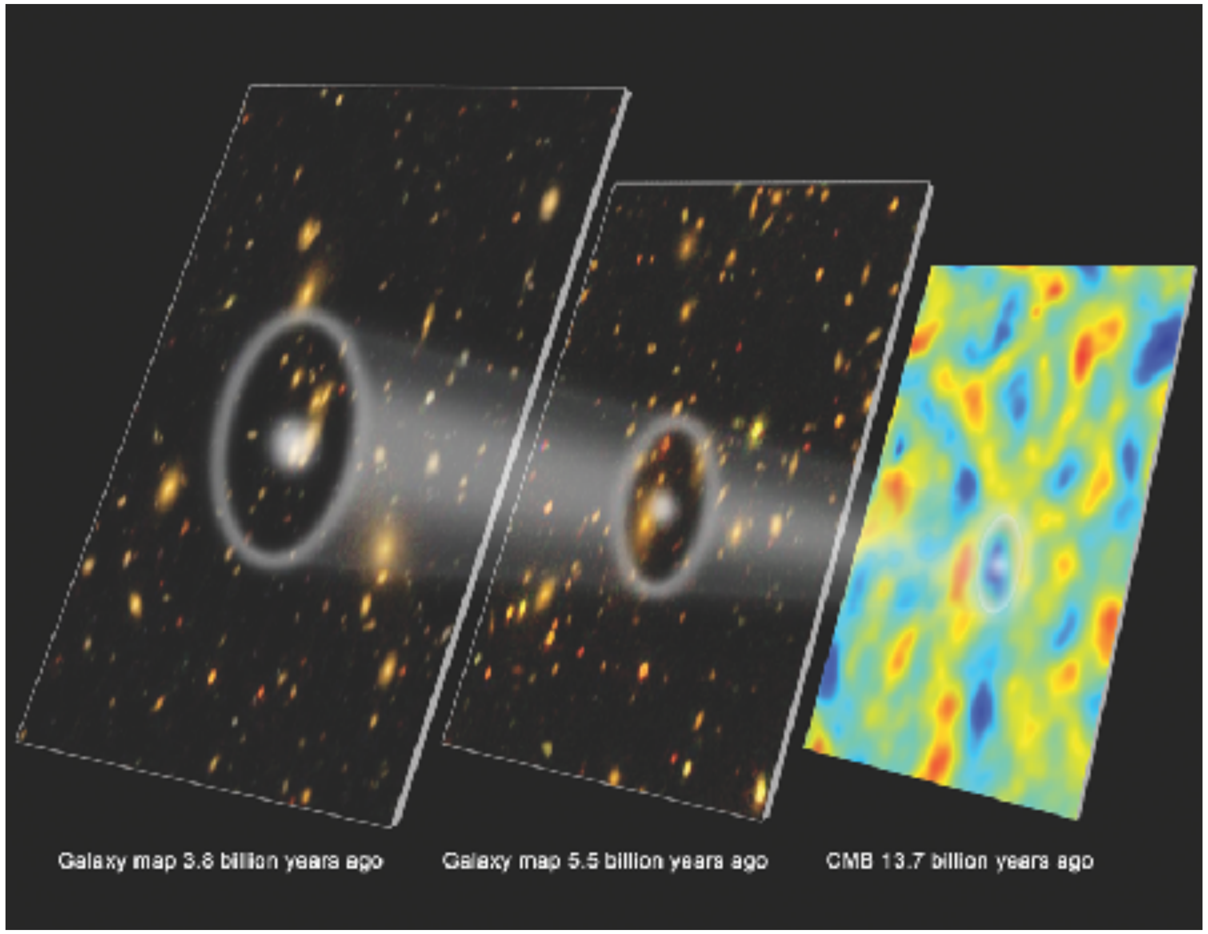
How does the CMB determine H0? "Hubble Hunters", Knox et al (2019) Aylor et al (2019)

1) Calibrate Standard Ruler

Sound horizon at decoupling

$$r_s = \int_0^{a_d} c_s \frac{da}{a^2 H(a)}$$

Depends on: $\rho_\gamma, \rho_\nu, \rho_m, \rho_b$



Resolving the Hubble Tension

How does the CMB determine H0? "Hubble Hunters", Knox et al (2019)
Aylor et al (2019)

1) Calibrate Standard Ruler

Sound horizon at decoupling

$$r_s = \int_0^{a_d} c_s \frac{da}{a^2 H(a)}$$

Depends on: $\rho_\gamma , \rho_\nu , \rho_m , \rho_b$

Resolving the Hubble Tension

How does the CMB determine H0? "Hubble Hunters", Knox et al (2019)
Aylor et al (2019)

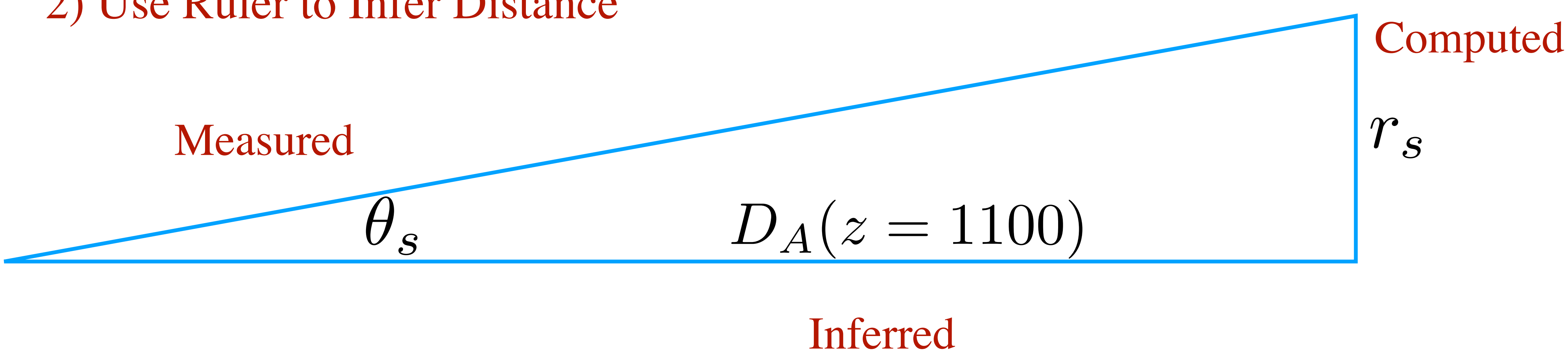
1) Calibrate Standard Ruler

Sound horizon at decoupling

$$r_s = \int_0^{a_d} c_s \frac{da}{a^2 H(a)}$$

Depends on: $\rho_\gamma, \rho_\nu, \rho_m, \rho_b$

2) Use Ruler to Infer Distance



Resolving the Hubble Tension

How does the CMB determine H0?

"Hubble Hunters", Knox et al (2019)
Aylor et al (2019)

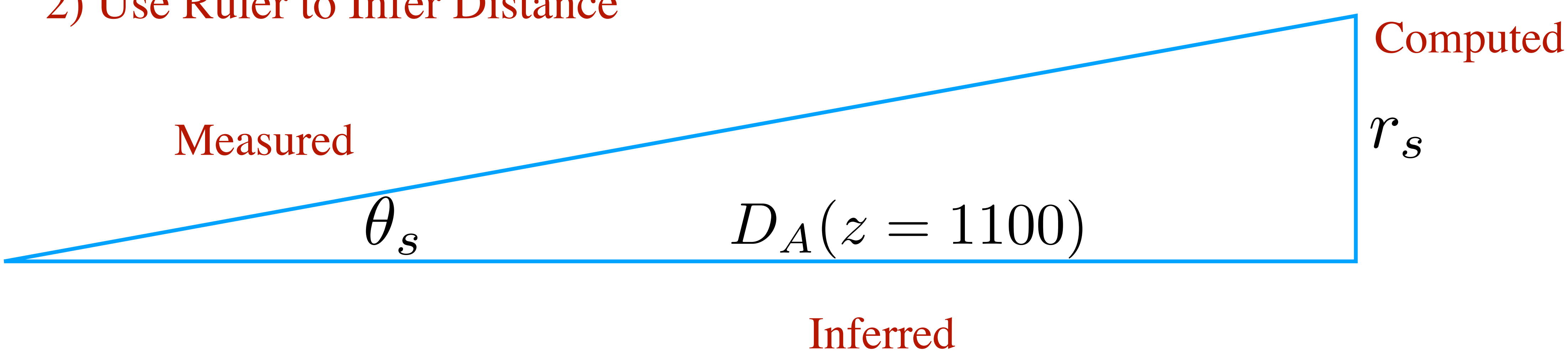
1) Calibrate Standard Ruler

Sound horizon at decoupling

$$r_s = \int_0^{a_d} c_s \frac{da}{a^2 H(a)}$$

Depends on: $\rho_\gamma, \rho_\nu, \rho_m, \rho_b$

2) Use Ruler to Infer Distance



3) Find cosmological constant to get right distance

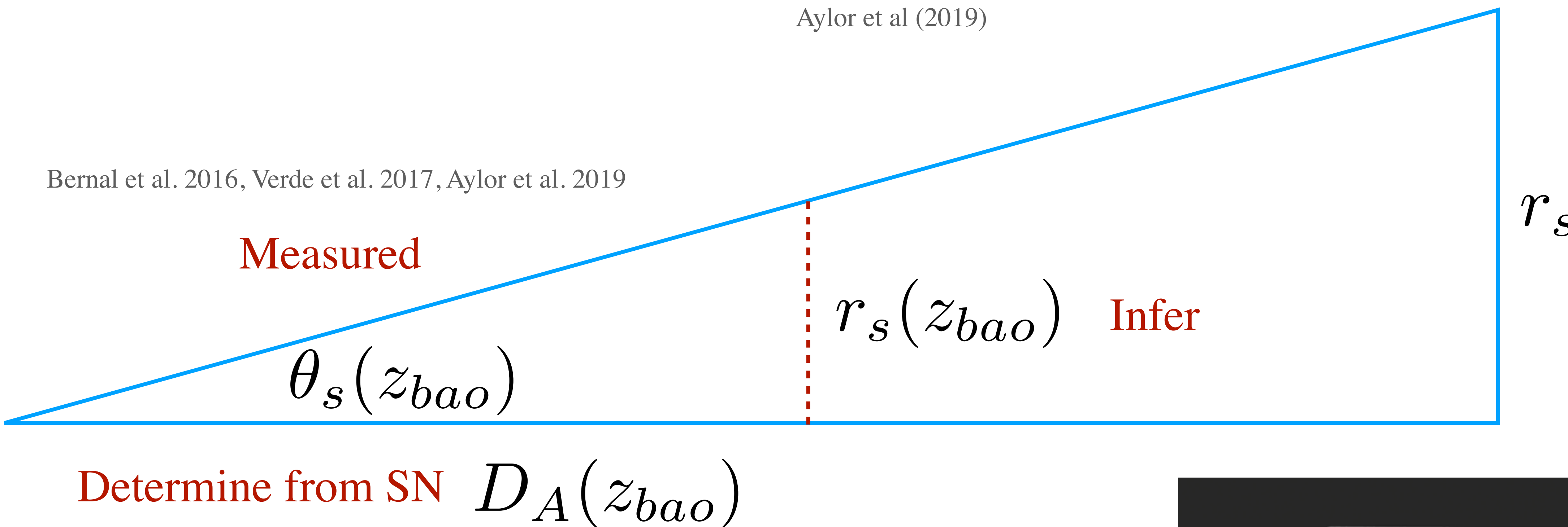
$$D_A(z) = \int_0^{z} \frac{dz'}{H(z')}$$

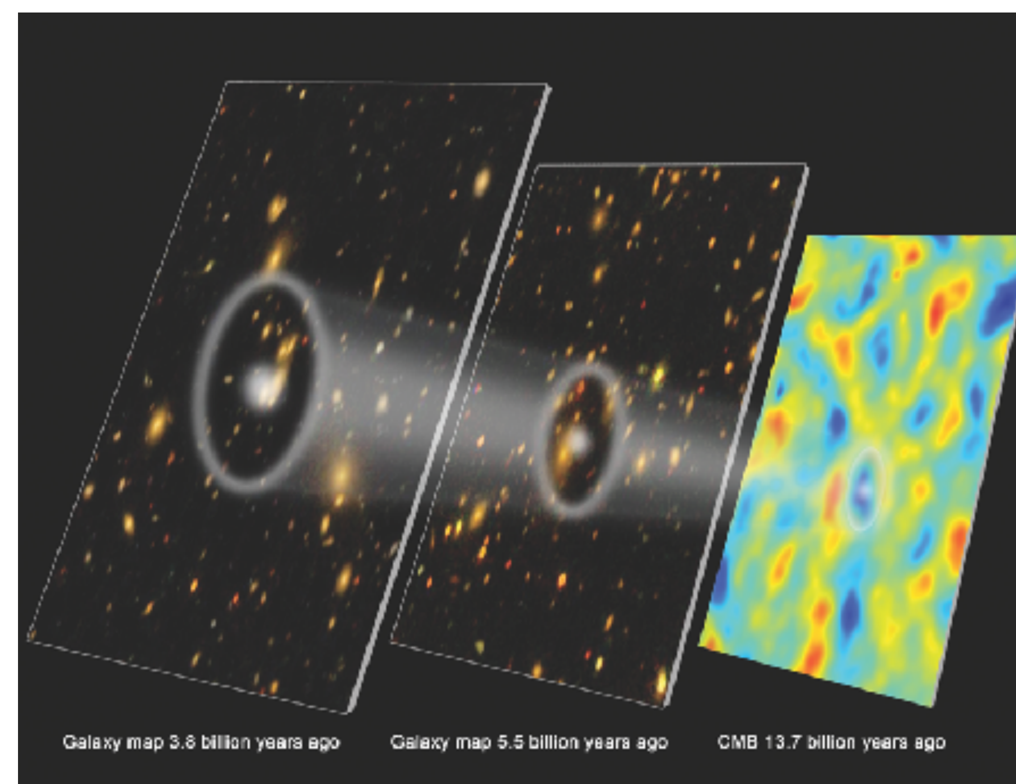
Resolving the Hubble Tension

What do BAOs have to say?

"Hubble Hunters", Knox et al (2019)

Aylor et al (2019)





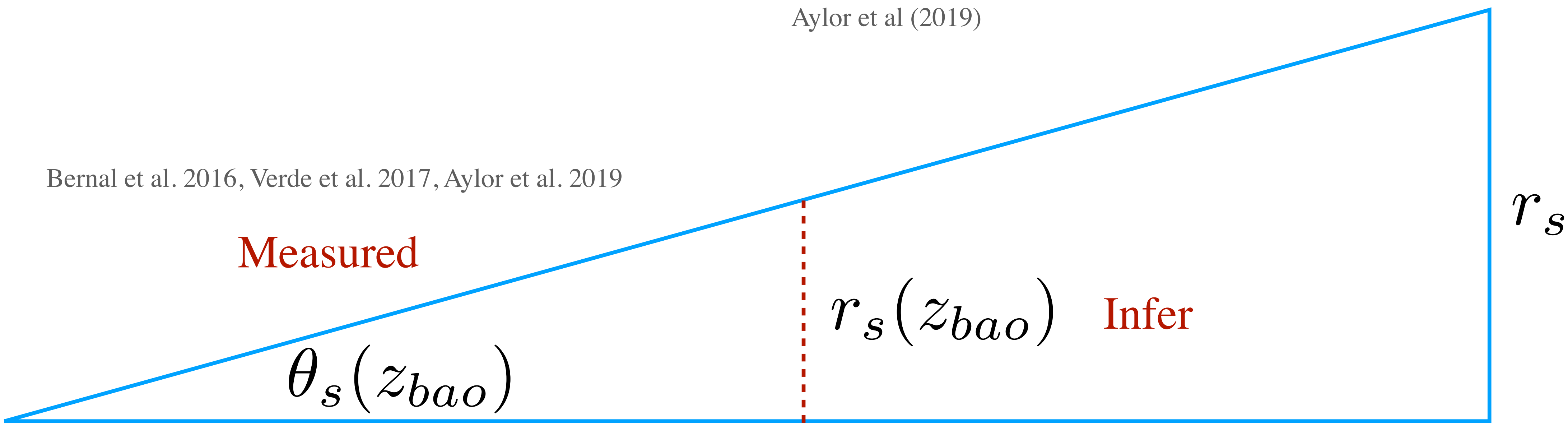
Resolving the Hubble Tension

What do BAOs have to say?

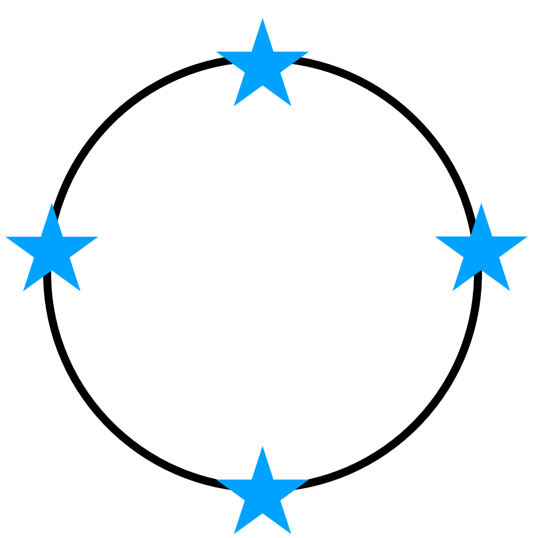
"Hubble Hunters", Knox et al (2019)

Aylor et al (2019)

Bernal et al. 2016, Verde et al. 2017, Aylor et al. 2019



Determine from SN $D_A(z_{bao})$

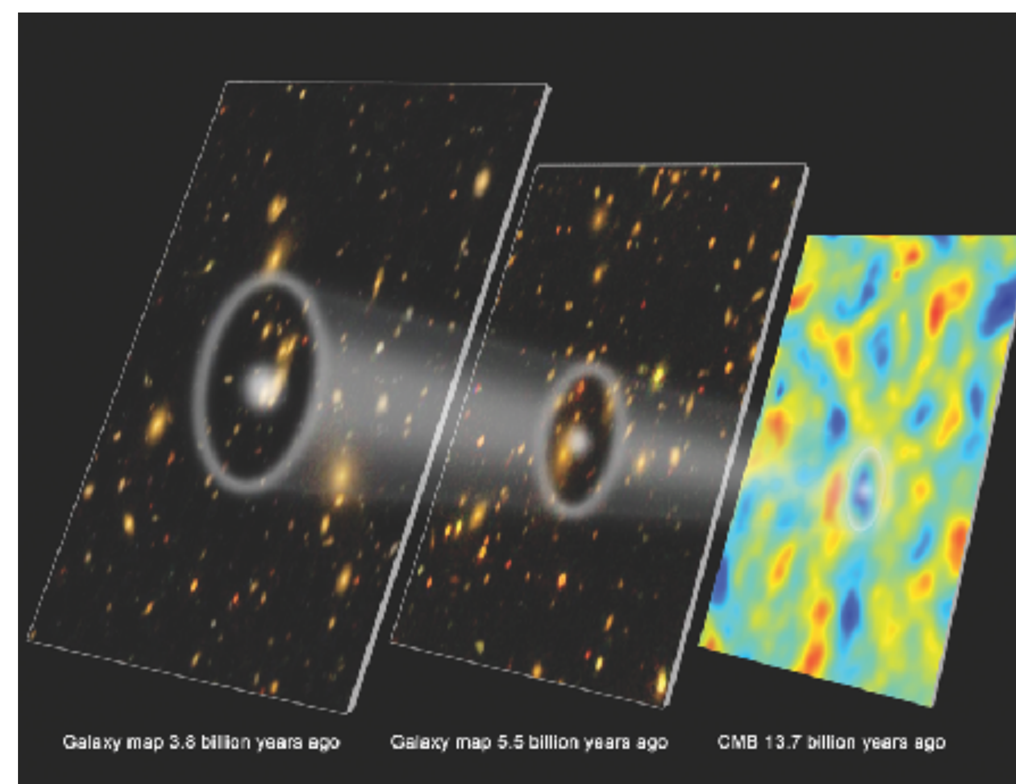


Perpendicular scale:

$$\alpha^{\perp} \propto \frac{d_M(z)}{r_s^{\mathrm{drag}}}$$

Parallel scale:

$$\alpha^{||} \propto \frac{1}{H(z)\, r_s^{\mathrm{drag}}}$$



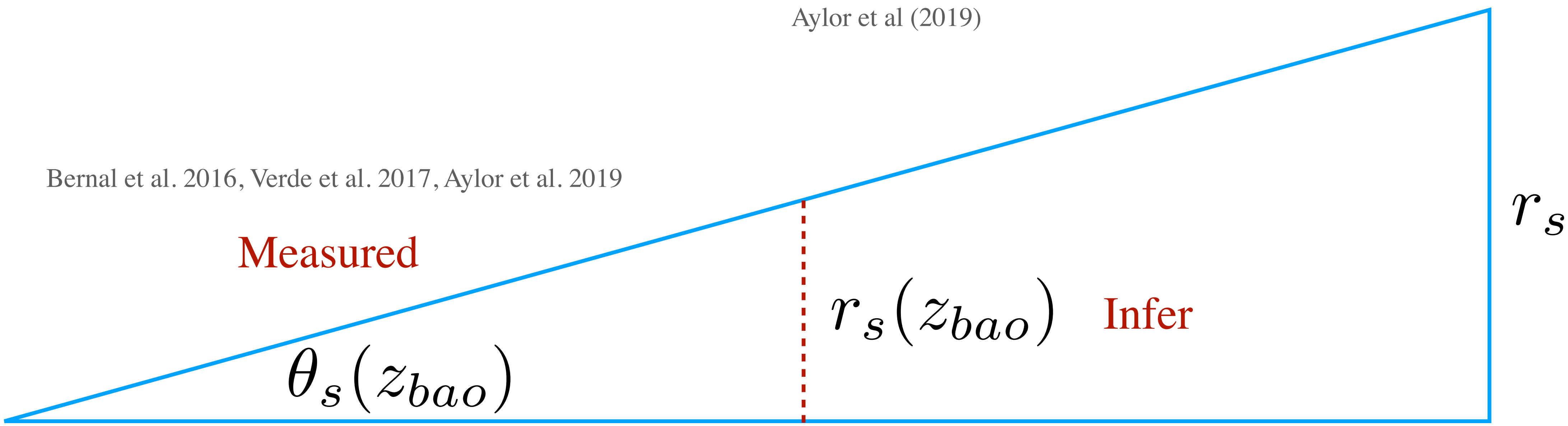
Resolving the Hubble Tension

What do BAOs have to say?

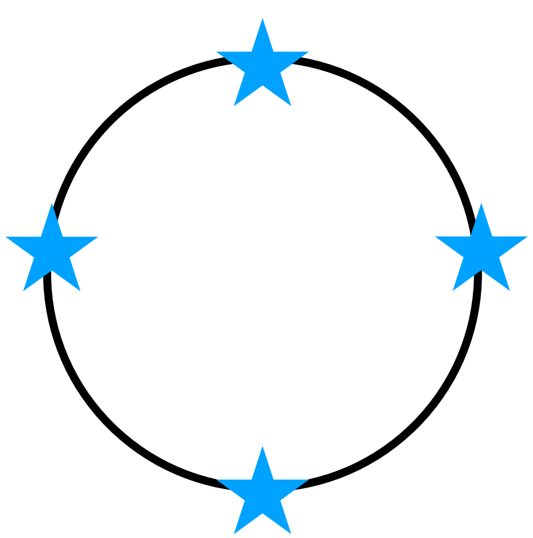
"Hubble Hunters", Knox et al (2019)

Aylor et al (2019)

Bernal et al. 2016, Verde et al. 2017, Aylor et al. 2019



Determine from SN $D_A(z_{bao})$



Perpendicular scale:

$$\alpha^{\perp} \propto \frac{d_M(z)}{r_s^{\rm drag}}$$

Parallel scale:

$$\alpha^{||} \propto \frac{1}{H(z)\, r_s^{\rm drag}}$$

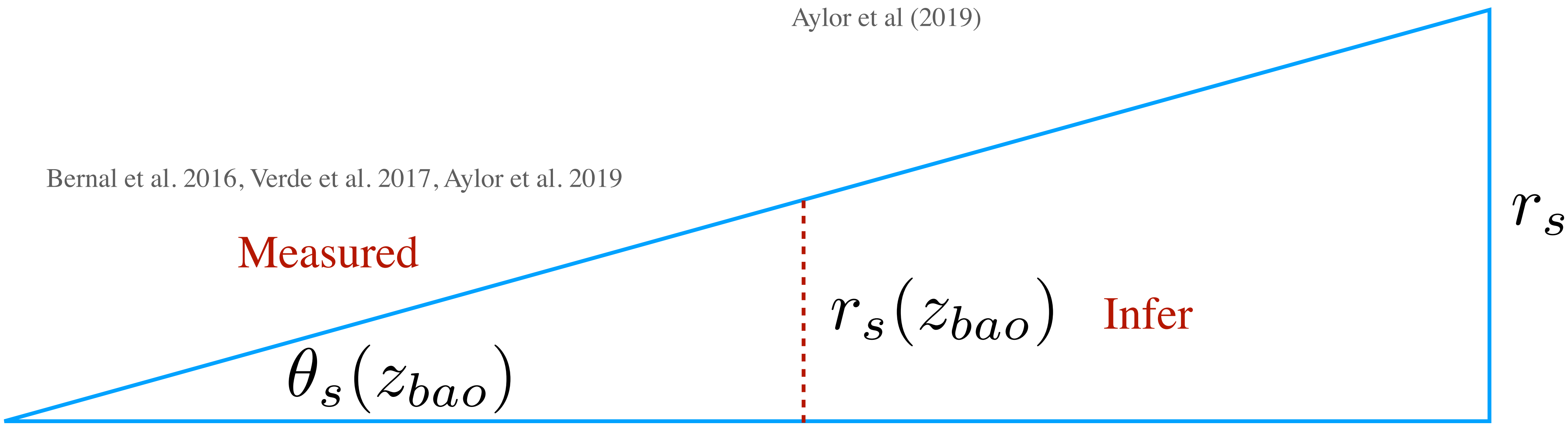
Resolving the Hubble Tension

What do BAOs have to say?

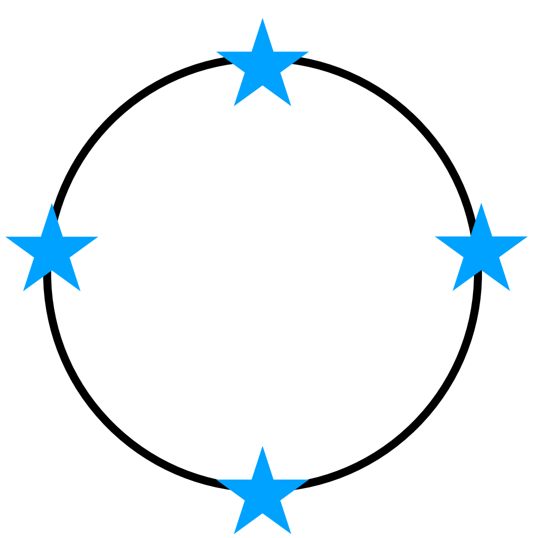
"Hubble Hunters", Knox et al (2019)

Aylor et al (2019)

Bernal et al. 2016, Verde et al. 2017, Aylor et al. 2019



Determine from SN $D_A(z_{bao})$



Perpendicular scale:

$$\alpha^{\perp} \propto \frac{d_M(z)}{r_s^{\rm drag}}$$

Parallel scale:

$$\alpha^{||} \propto \frac{1}{H(z)\, r_s^{\rm drag}}$$

Given $r_s^{\rm drag}$

Obtain $H(z_i)$ and calibrate Ia SN with d_M

Extrapolate to $z = 0$ to obtain H_0

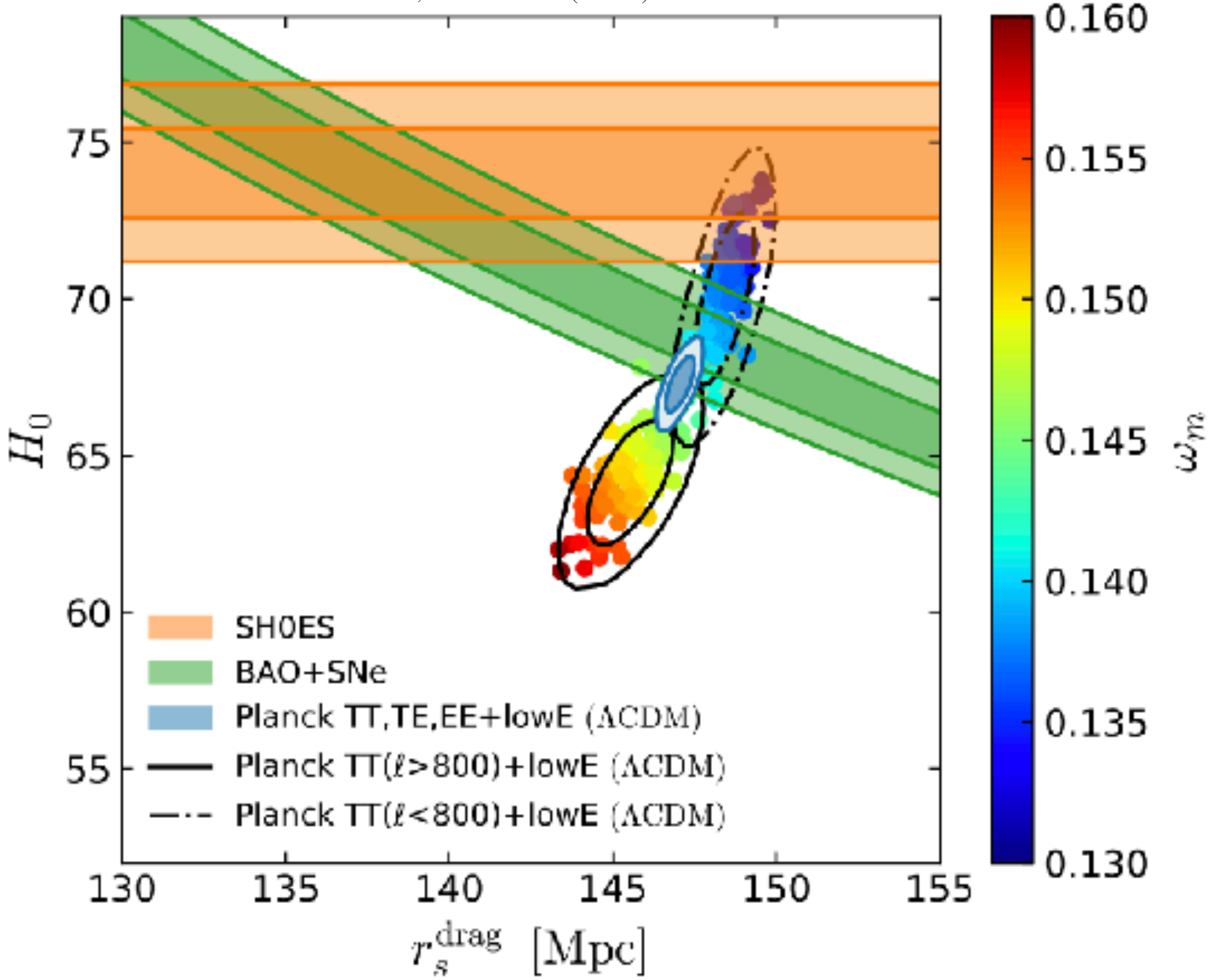
Resolving the Hubble Tension

CMB (Assume LCDM)

BAOs + SNe (No assumption)

SH0ES (No assumption)

"Hubble Hunters", Knox et al (2019)



If tension is real, seems to suggest new physics near recombination…

"We single out the set of solutions that increase the expansion rate in the decade of scale factor expansion just prior to recombination as the least unlikely." "Hubble Hunters", Knox et al (2019)

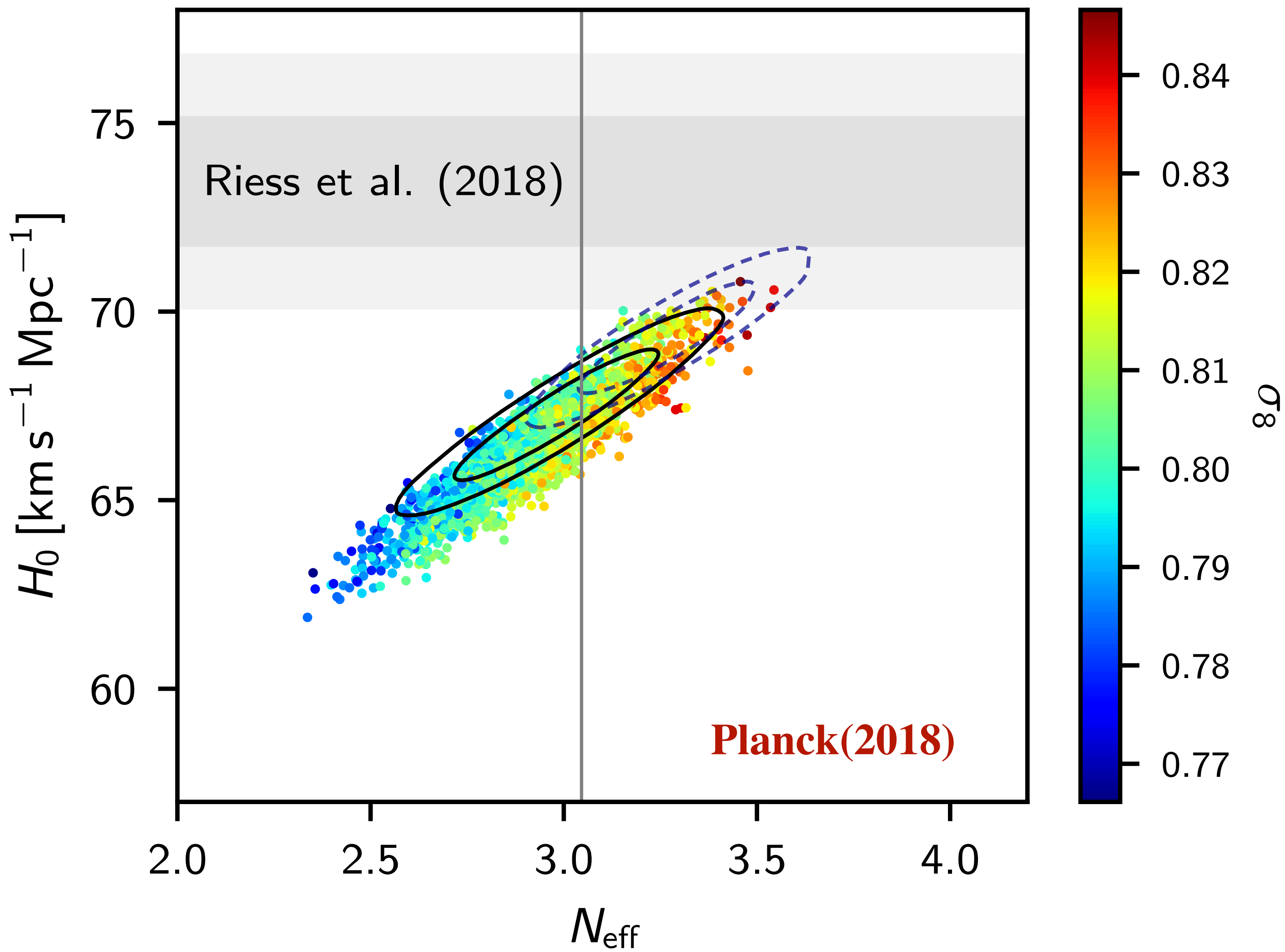
Aylor et al (2019)

Resolving the Hubble Tension

$\Delta N_{\rm eff}$

(Additional non-interacting radiation)

Degeneracy of H0 and Neff known for long time…



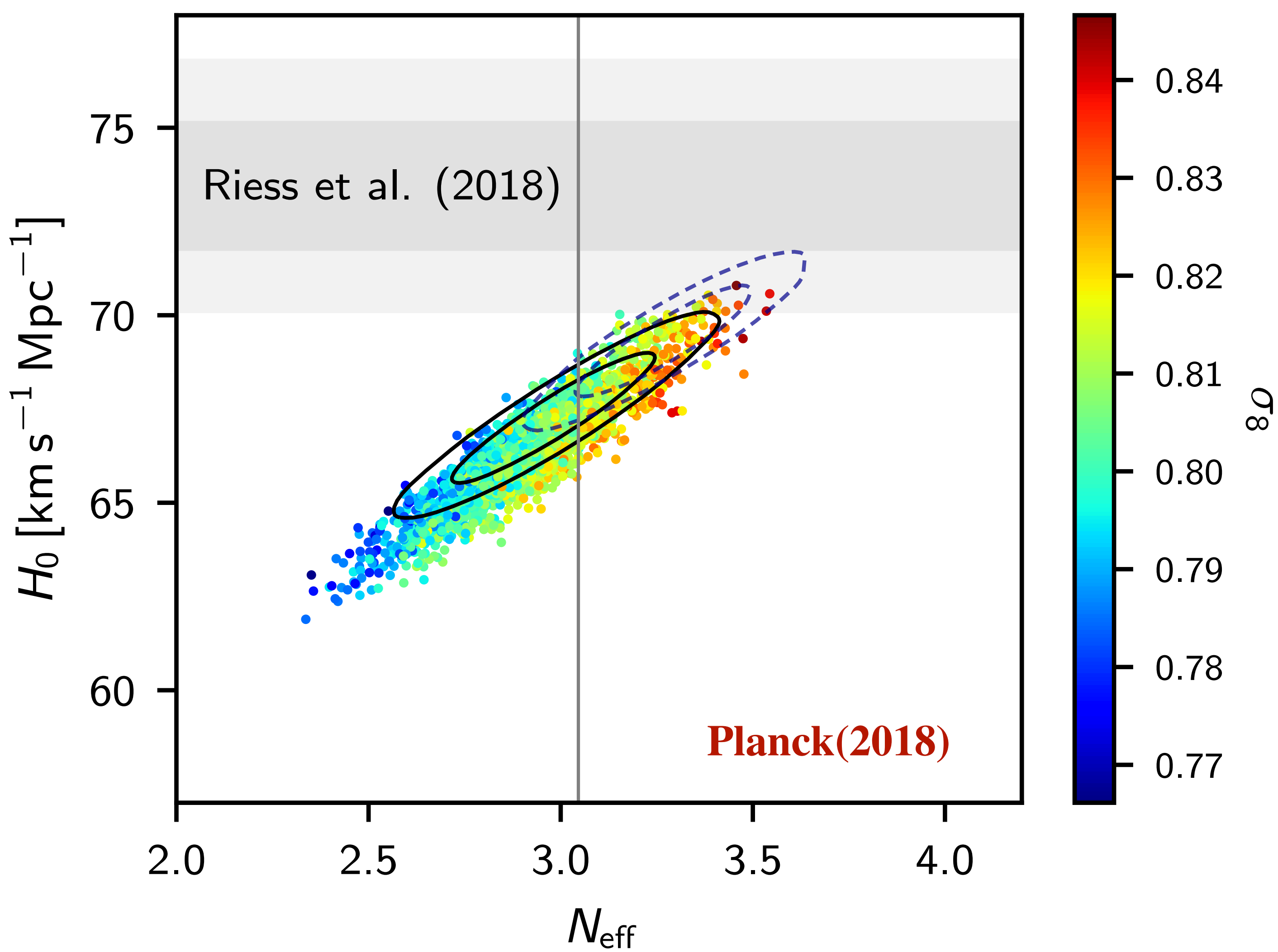
Bernal et al (2016), Morstell and Dhawan (2018)

Resolving the Hubble Tension

$\Delta N_{\rm eff}$

(Additional non-interacting radiation)

Degeneracy of H0 and Neff known for long time…



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

Undoubtedly the simplest 'solution'

But (1) doesn't improve fit, and (2) does not reduce tension significantly

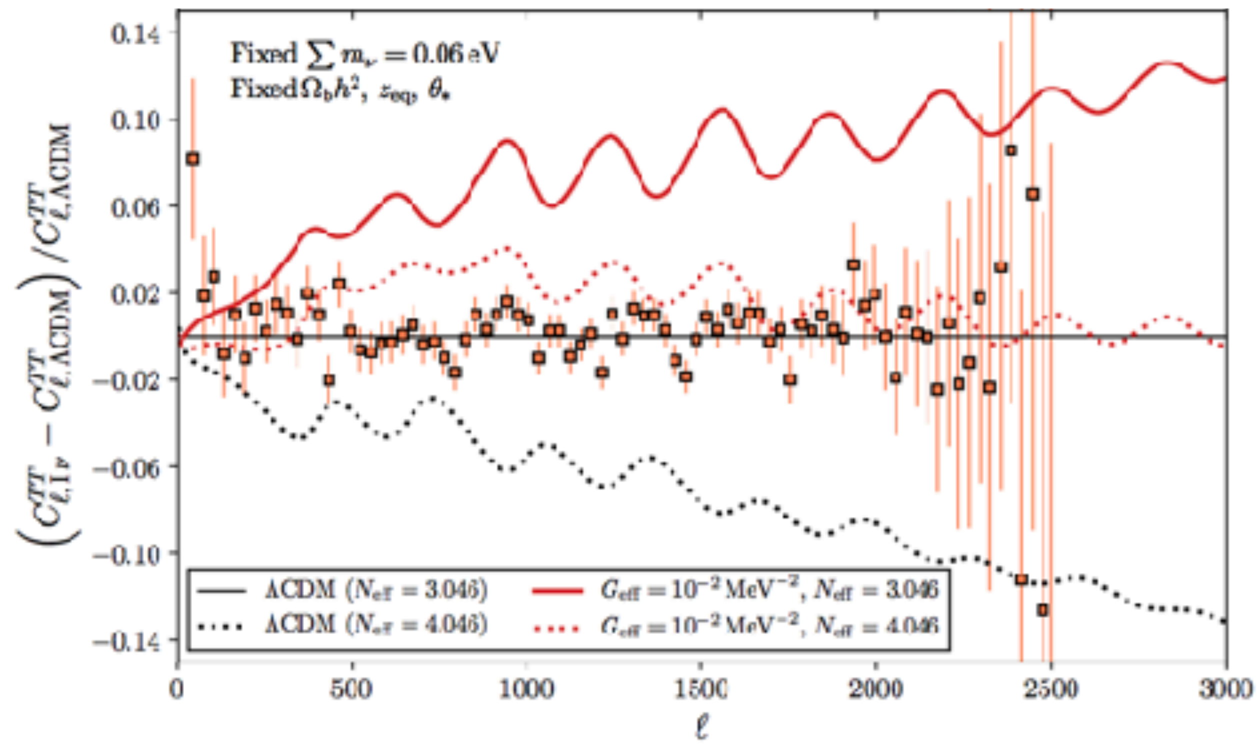
Resolution, at best $\sim 3.5\sigma$

Solutions to Hubble Tension

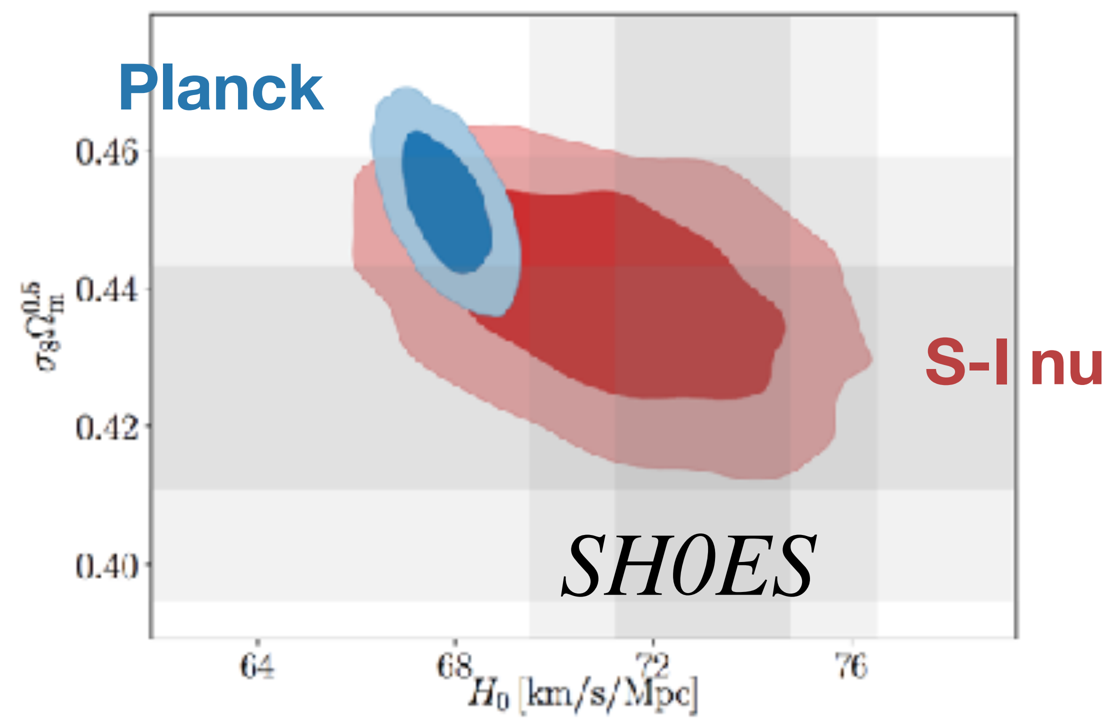
Self-interacting neutrinos

Kreisch et al (2019), Park et al (2019), Archidiacono et al (2016), Di Valentino et al (2018), …

Large Neff cancels with effect of neutrino interactions



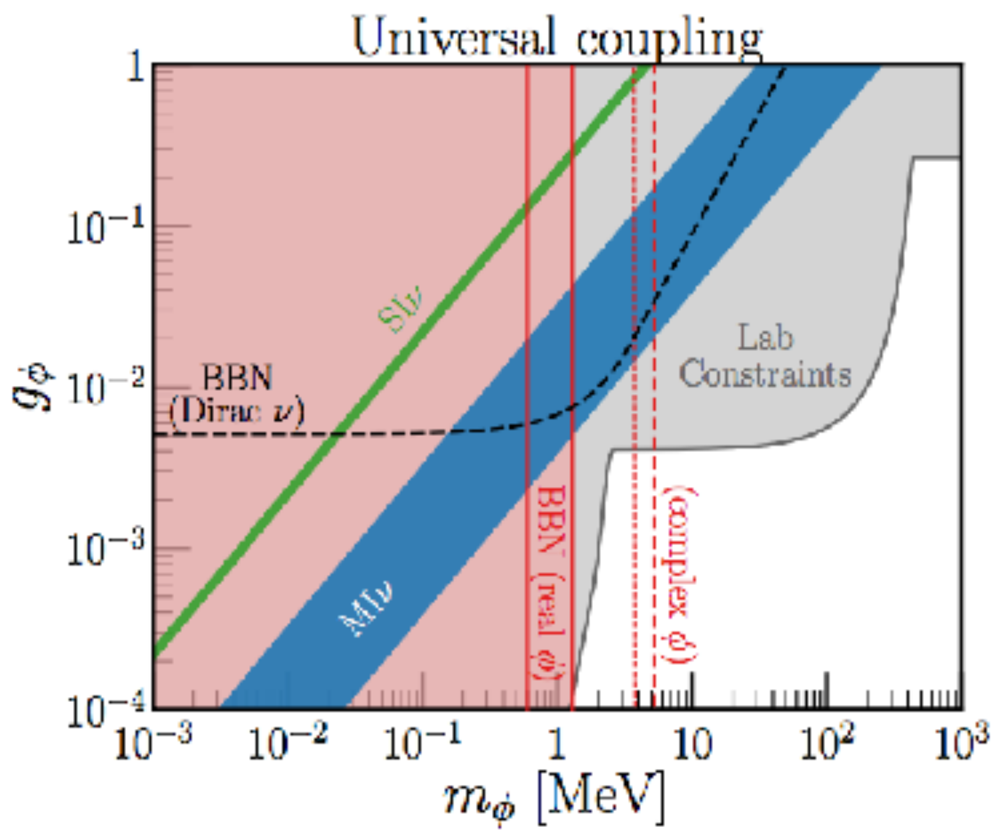
Kreisch et al (2019)



Solutions to Hubble Tension

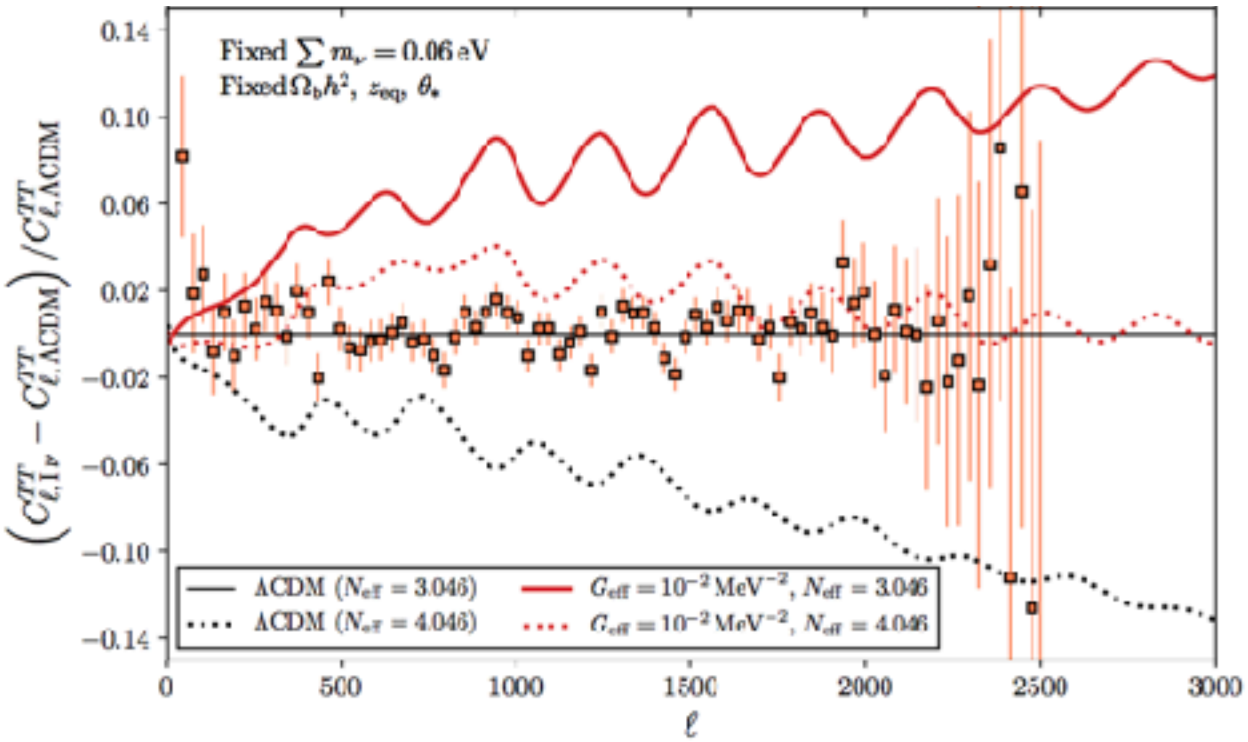
Self-interacting neutrinos

Kreisch et al (2019), Park et al (2019), Archidiacono et al (2016), Di Valentino et al (2018), …

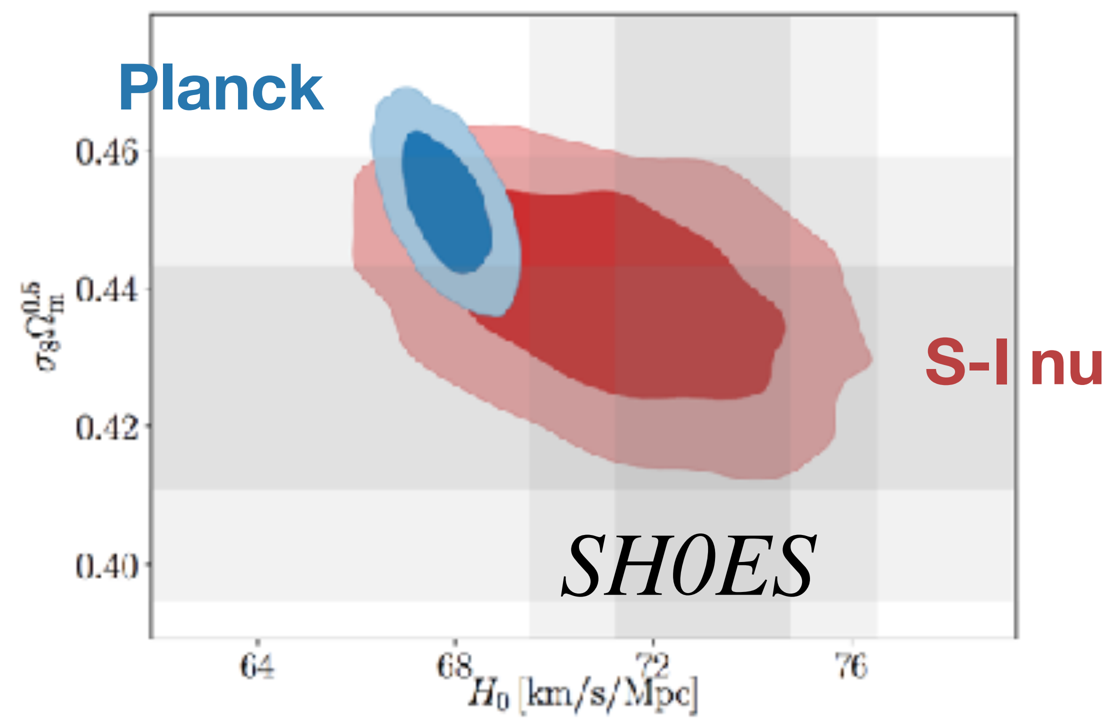


Blinov, Kelley, Krnjaic, McDermott (2019)

Large Neff cancels with effect of neutrino interactions



Kreisch et al (2019)

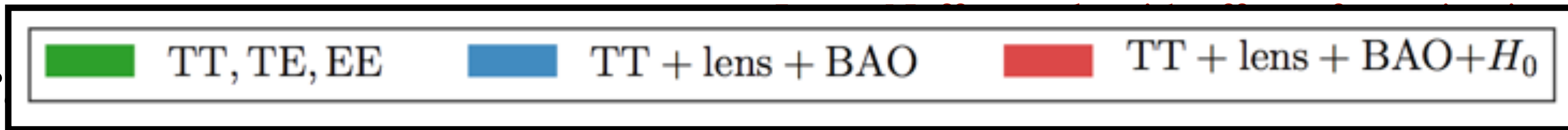


Maybe (????) viable if only coupled to taus….

Solution also requires Neff ~ 4, excluded by BBN…

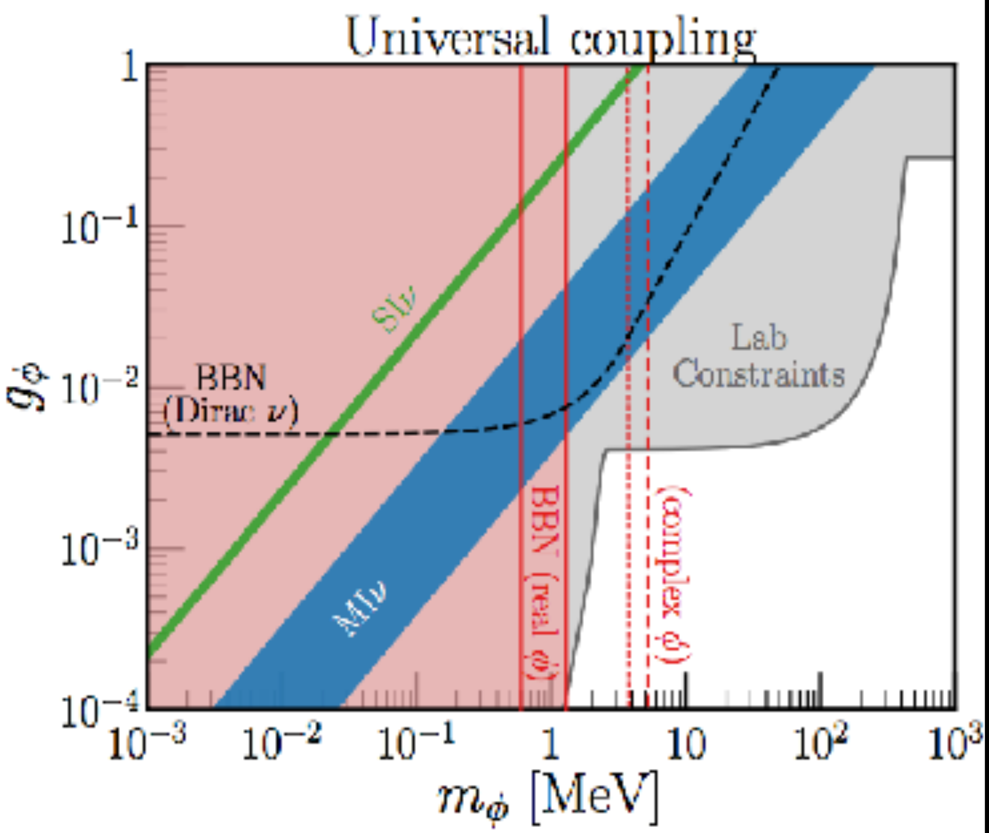
Solution killed with polarization data?

Solutions to Hubble Tension

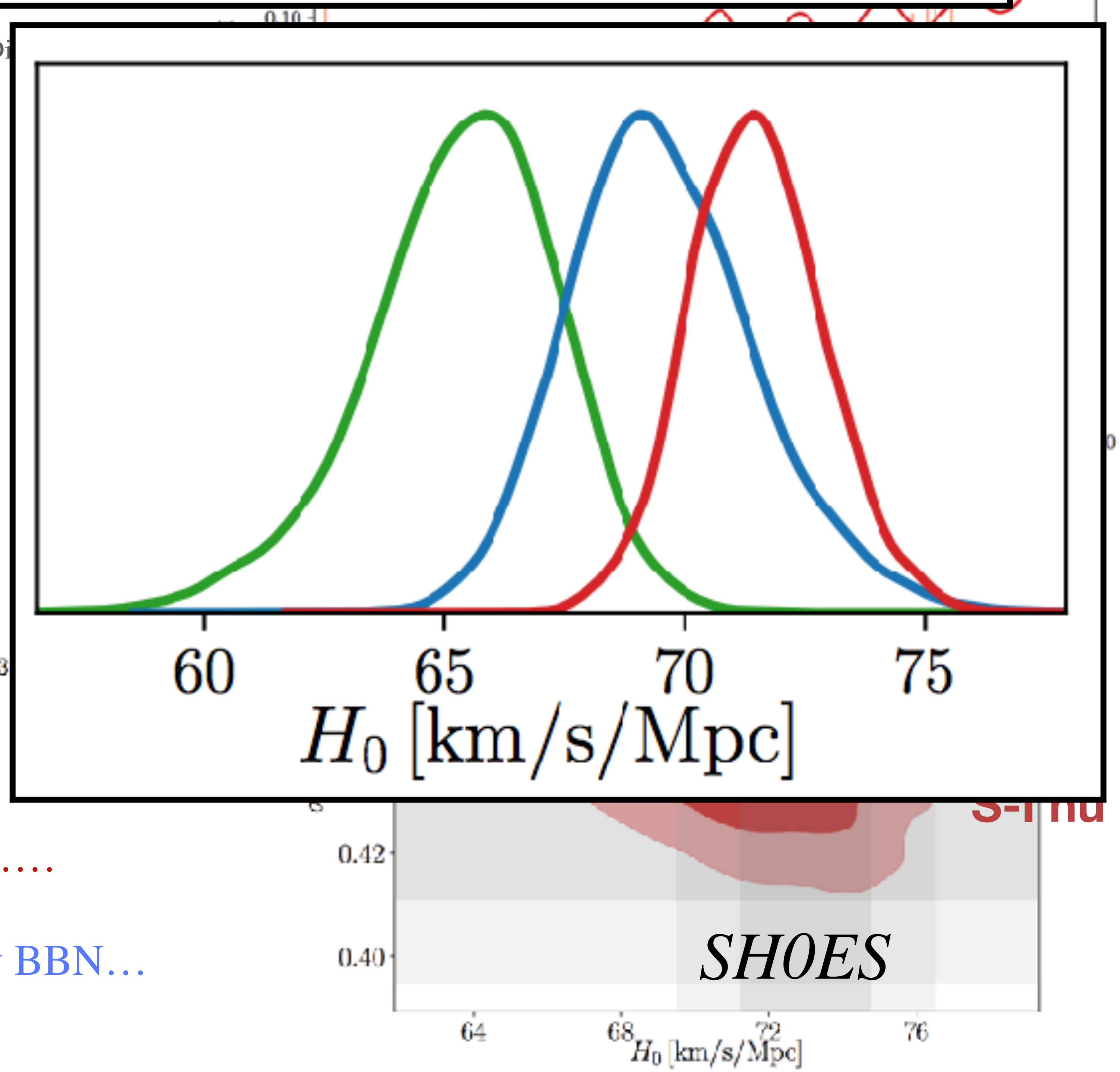


Self-interac

Kreisch et al (2019), Park et al (2019), Archidiacono et al (2016), Di
Valentino et al (2018), …



Blinov, Kelley, Krnjaic, McDermott (2019)



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

Solution also requires Neff ~ 4, excluded by BBN…

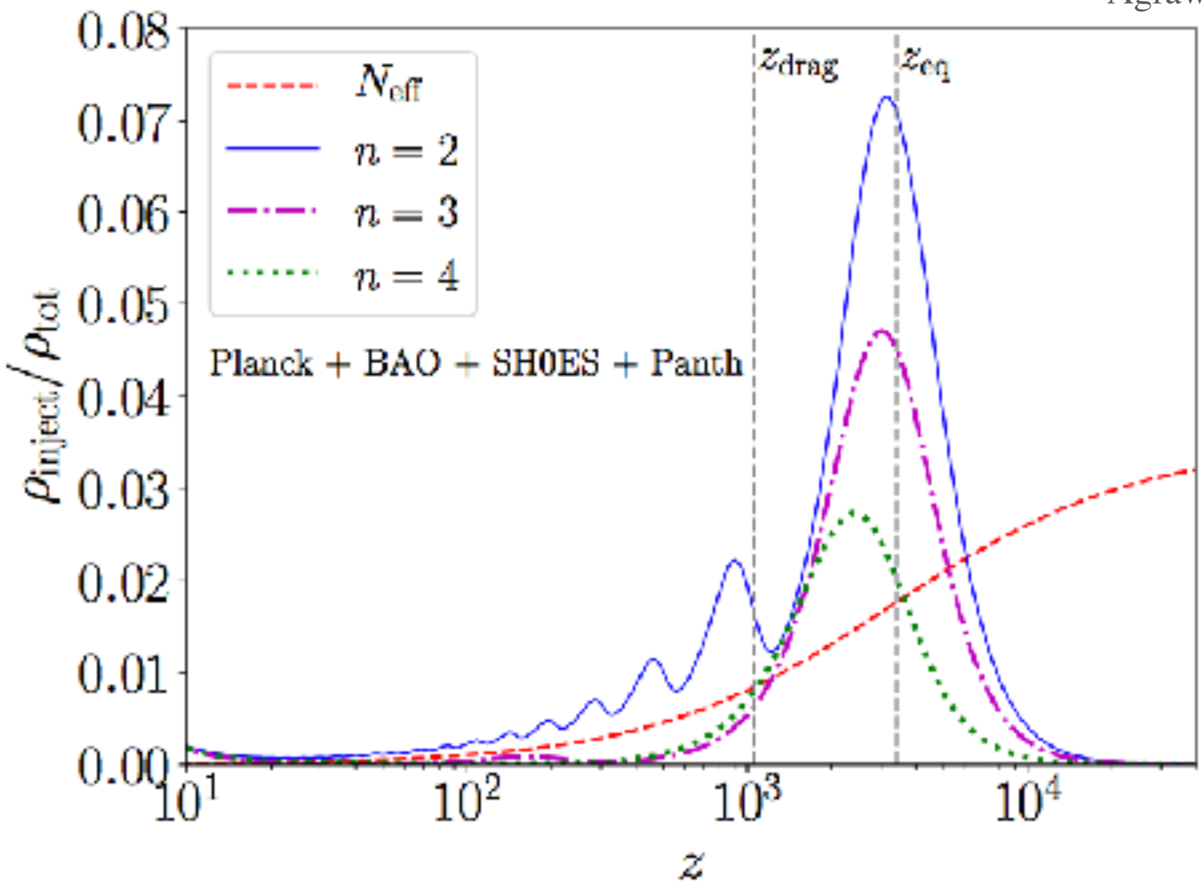
Solution killed with polarization data?

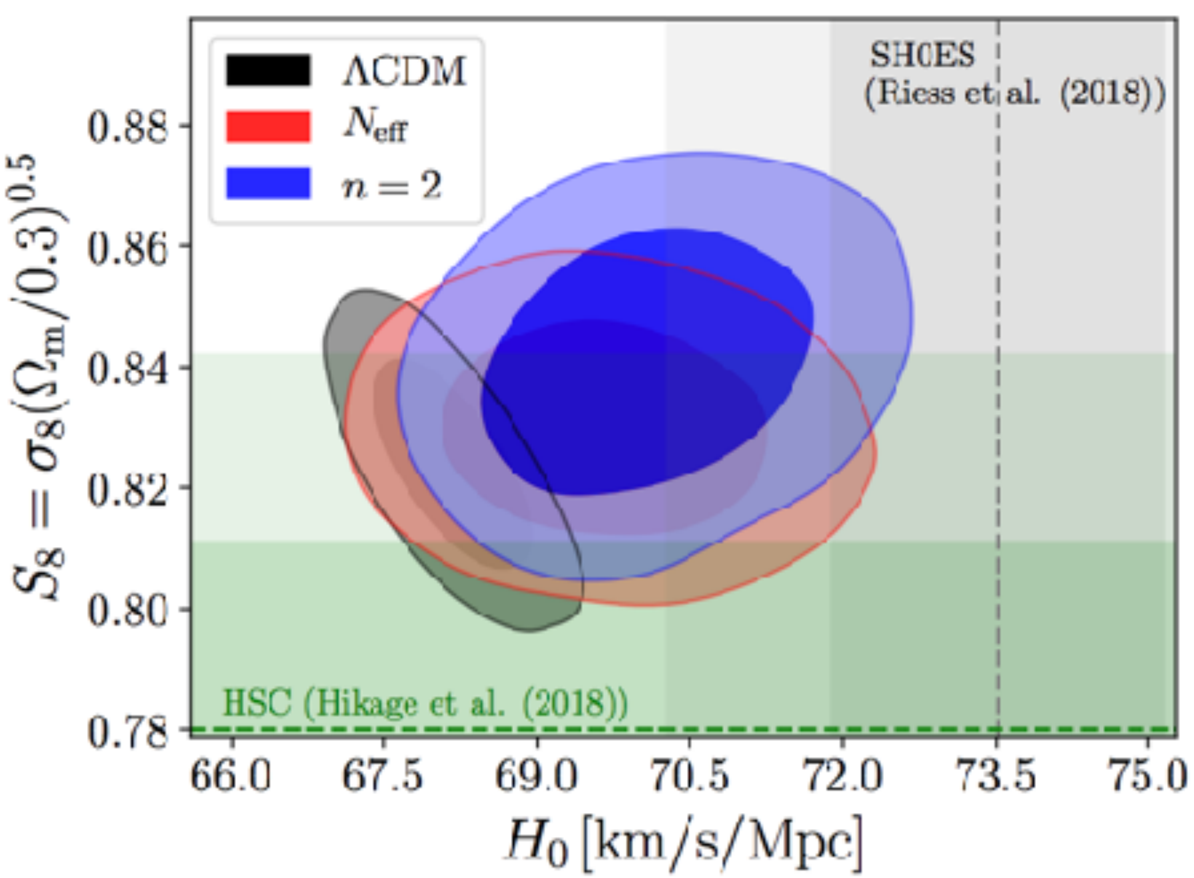
Solutions to Hubble Tension

Early Dark Energy $V(\phi) = m^2 f^2 [1 - \cos(\phi/f)]^n$

Poulin et al (2018, 2019), Agrawal et al (2019), Smith et al (2019)…

Agrawal et al (2019)



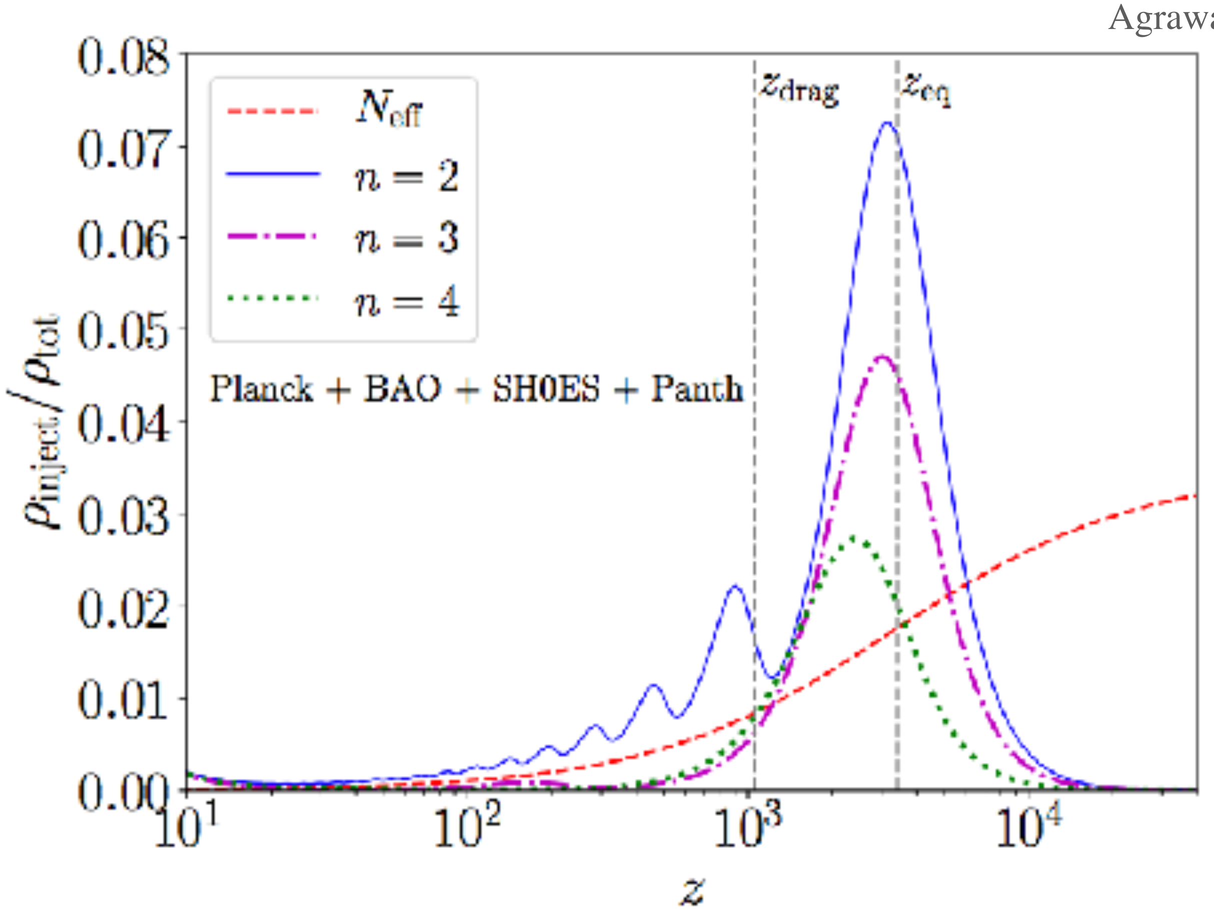


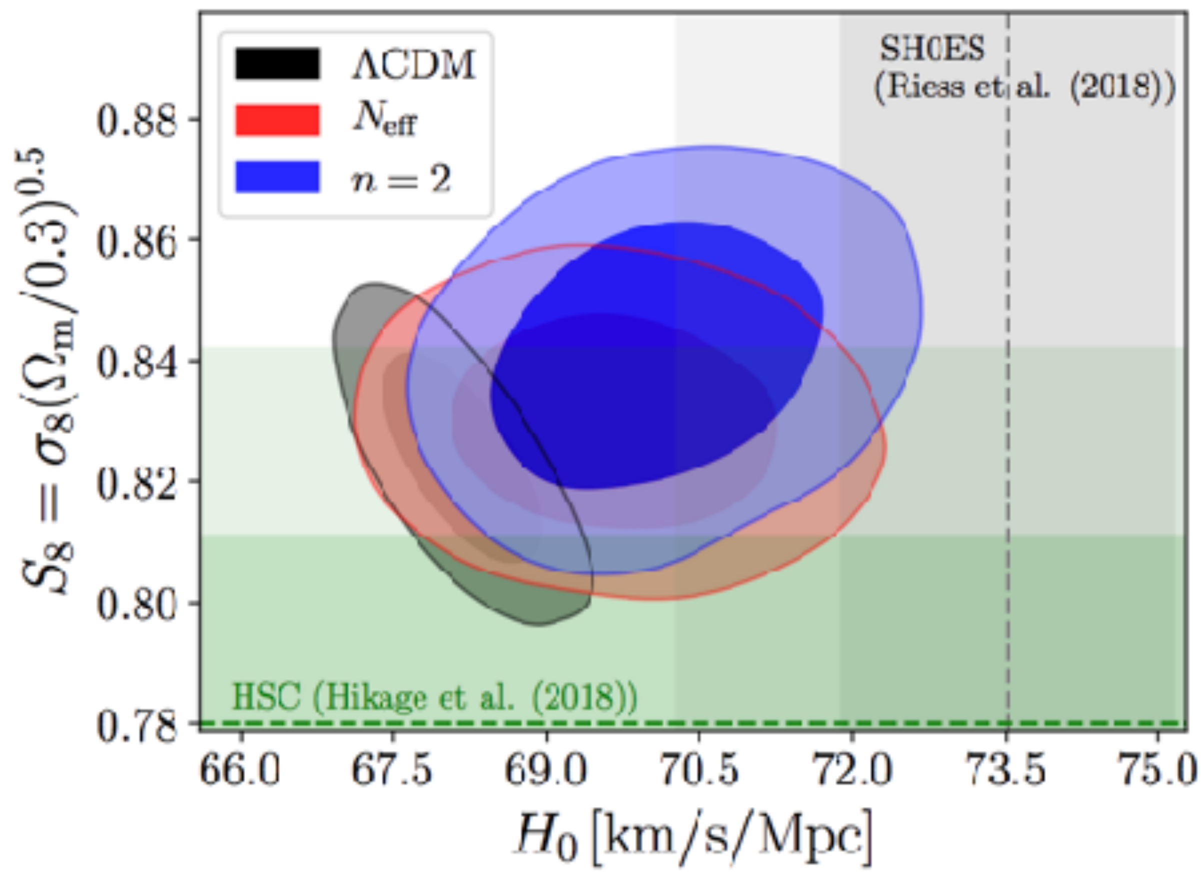
Solutions to Hubble Tension

Early Dark Energy $V(\phi) = m^2 f^2 [1 - \cos(\phi/f)]^n$

Poulin et al (2018, 2019), Agrawal et al (2019), Smith et al (2019)…

Agrawal et al (2019)





Solution only slightly better than Neff, requires higher order instanton corrections, and:

$m \sim 10^{-29}$eV (timing coincidence)

$f \sim 0.1 M_p$ (sufficient amplitude)

Resolution, at best $\sim 3\sigma$

Hubble Tension

(**Not complete list of references)

Proposed solutions:

-Systematics in CMB, SH0ES, or both

-Novel neutrino 2-to-2 interactions $+\Delta N_{\mathrm{eff}}$ Kreisch et al (2019), Park et al (2019), Archidiacono et al (2016), Di Valentino et al (2018)

-Early dark energy Poulin et al (2018), Agrawal et al (2019), Lin et al (2019)

-Dark sector interactions Bringmann et al (2018), Pandey et al (2019), Raveri et al (2019), Yang et al (2019)

-Modified gravity Renk et al (2017), Khosravi et al (2018), Lin et al (2019)

-Phantom Dark Energy Di Valentino (2016,2017,2019)

⋮

Problems:

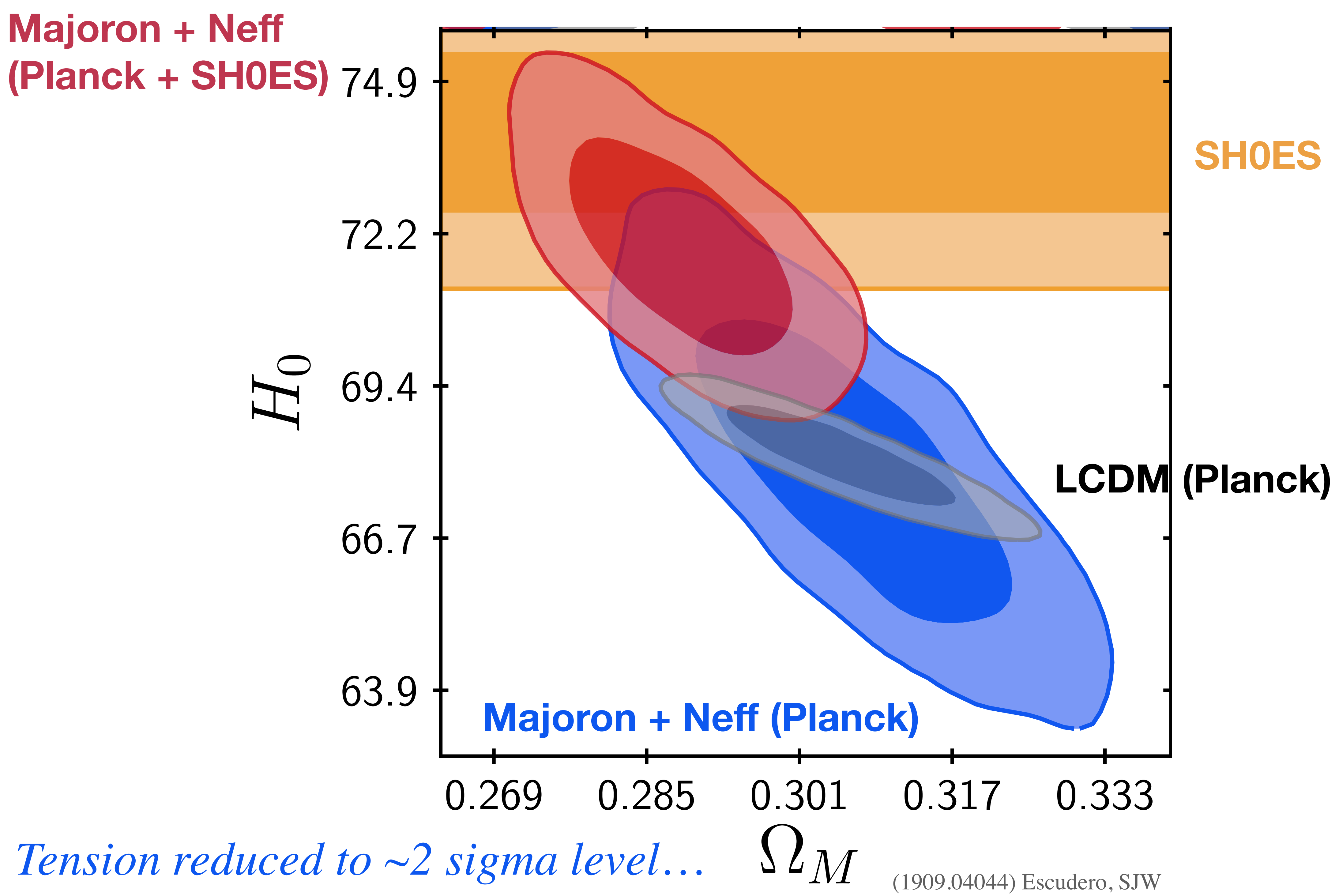
-Many proposed solutions exacerbate other tensions *(in particular low z solutions)*

-Many proposed solutions not phenomenologically viable *(e.g. 2-to-2 neutrinos…)*

-Many proposed solutions introduce enormous model complexity (or remarkably fine tuned)

Most models can't reduce tension beyond 2 sigma, many models finely tuned or poorly motivated

Hubble Tension

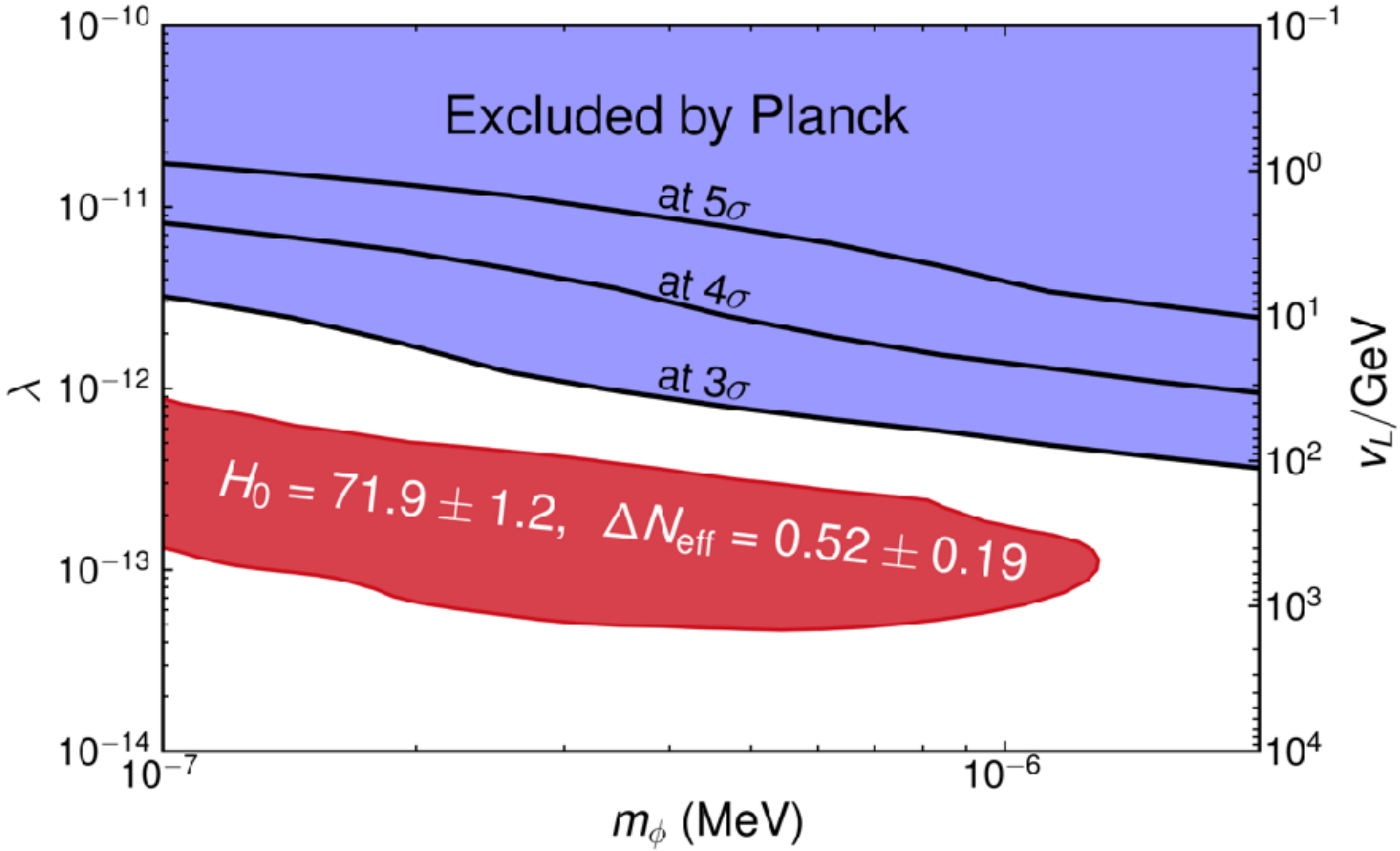


Tension reduced to ~2 sigma level…

(1909.04044) Escudero, SJW

Improved fit to Planck!

Hubble Tension



(1909.04044) Escudero, SJW

Conclusions

- CMB provides powerful probe of pGBs arising in neutrino mass models

In context of type-I seesaw, Planck currently probing SSB scales ~ TeV

Should reheating temperature be sufficiently high, future CMB experiments may be capable of probing most of parameter space (for this mass range**)

- Does the Hubble tension point to beyond ΛCDM ***?***

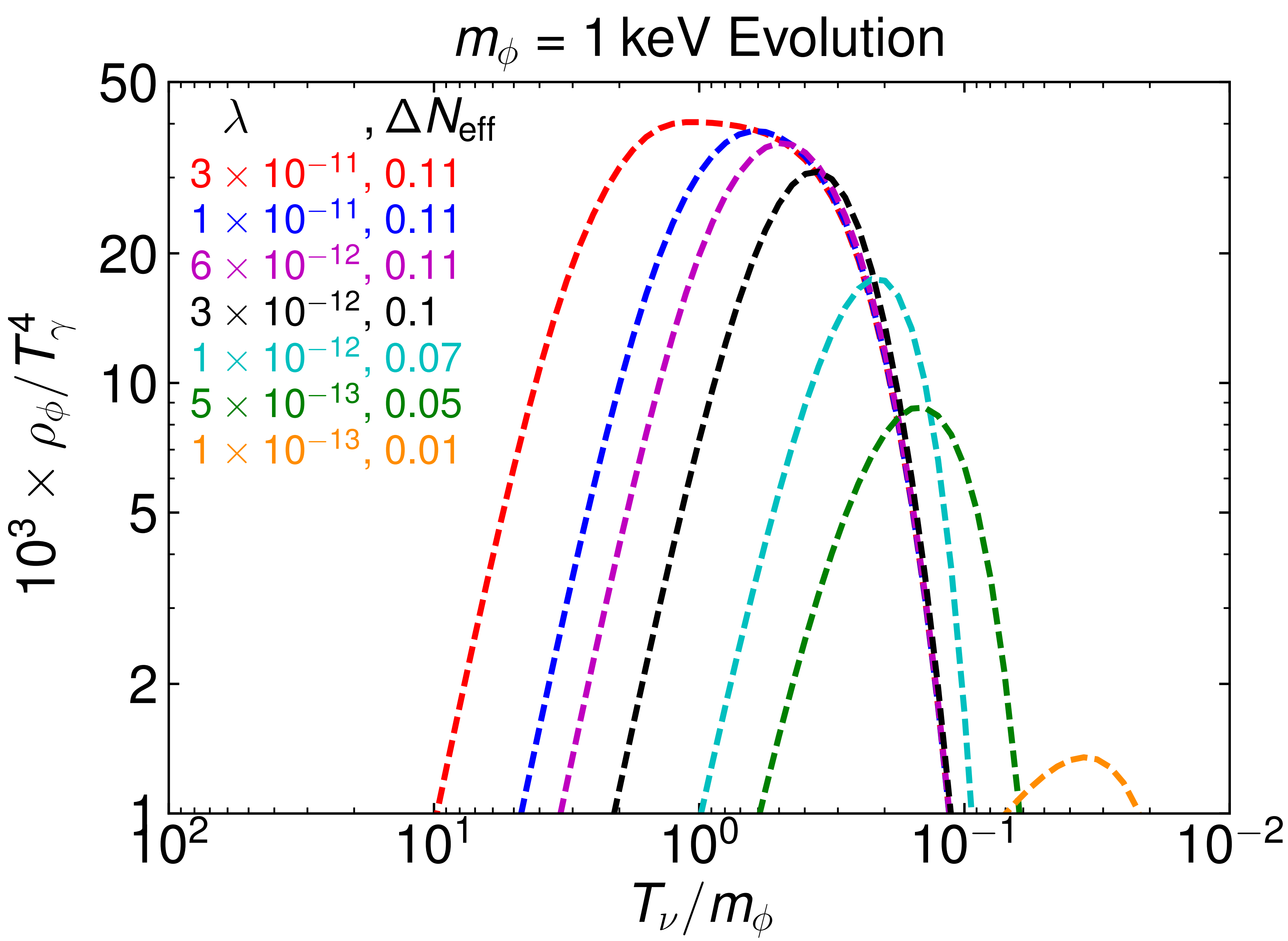
Majoron is well-motivated extension of SM that, when combined with $\Delta N_{\rm eff} \sim 0.5$ can ameliorate H0 tension

Preferred parameter space: $m_\phi \sim 0.5\,\mathrm{eV}$

$\lambda \sim 10^{-13}$ (Type-I Seesaw: $v_L \sim$ TeV)

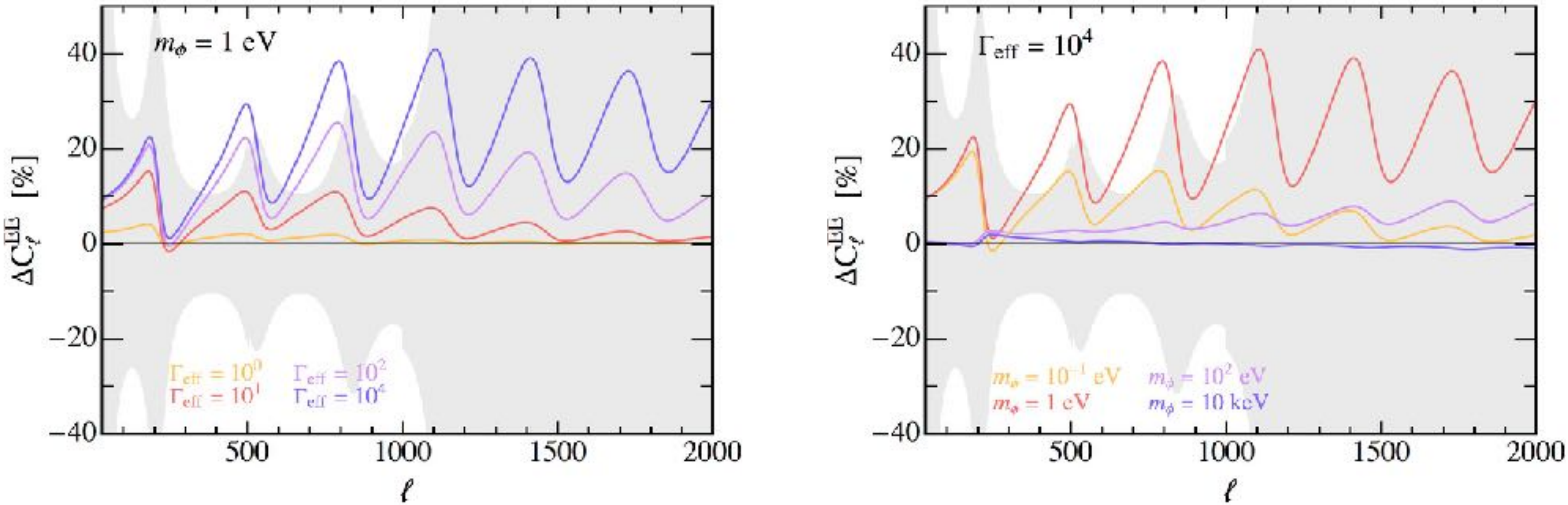
Back-Up

Majoron Thermalization



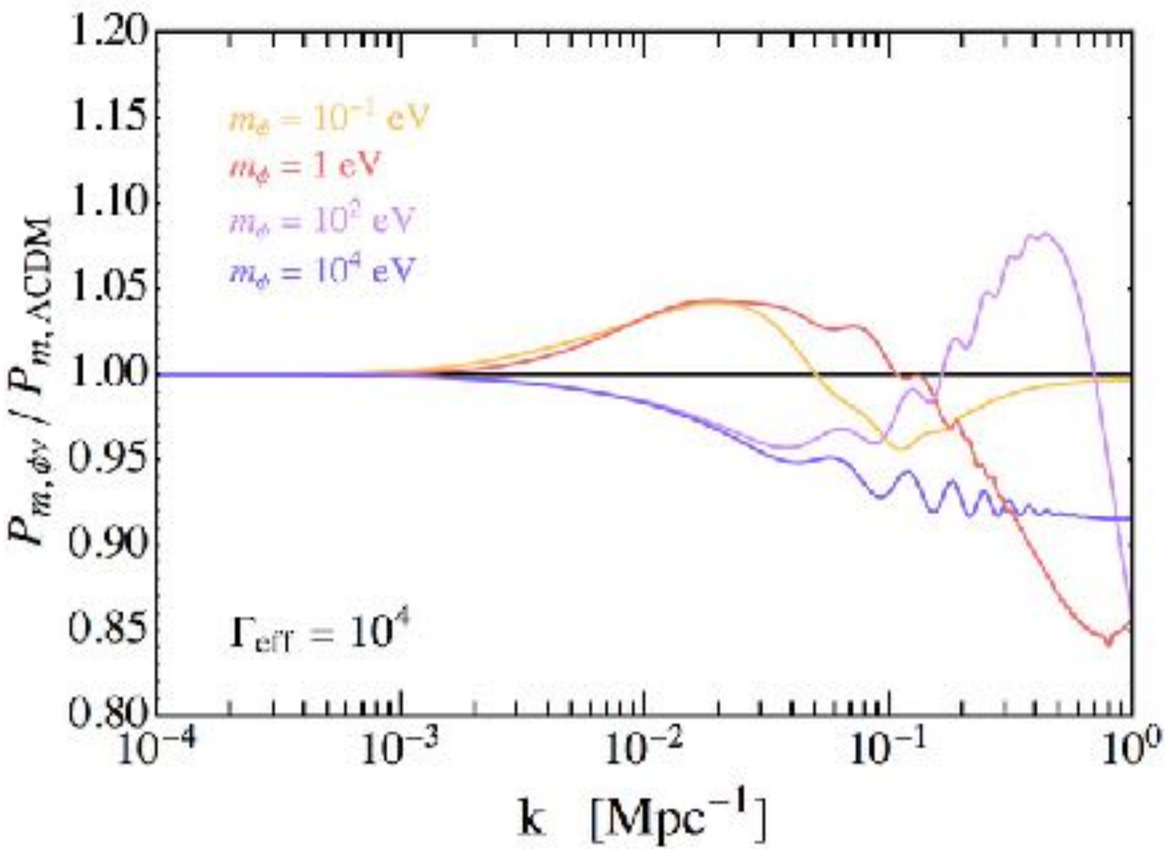
(1909.04044) Escudero, SJW

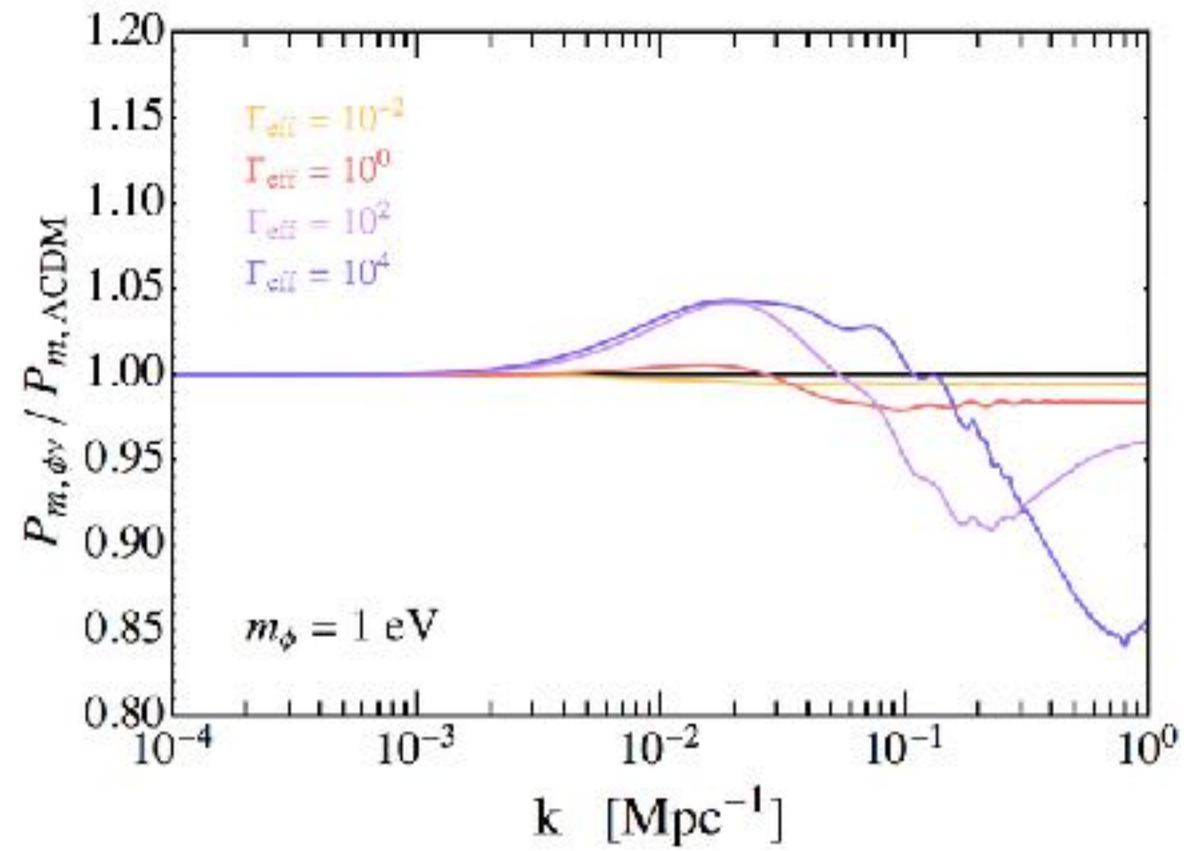
Polarization Cls



(1909.04044) Escudero, SJW

Matter Power Spectrum



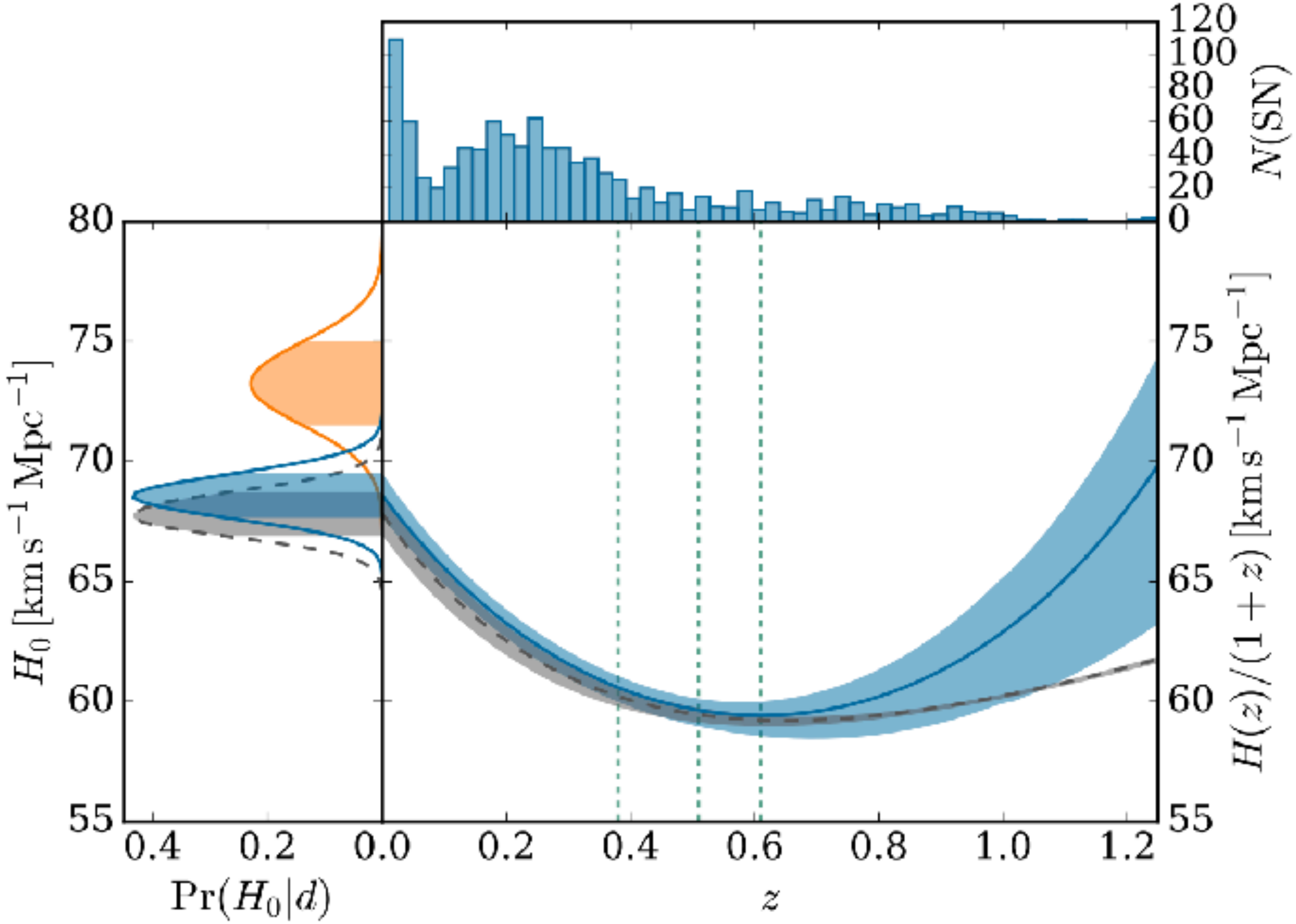


(1909.04044) Escudero, SJW

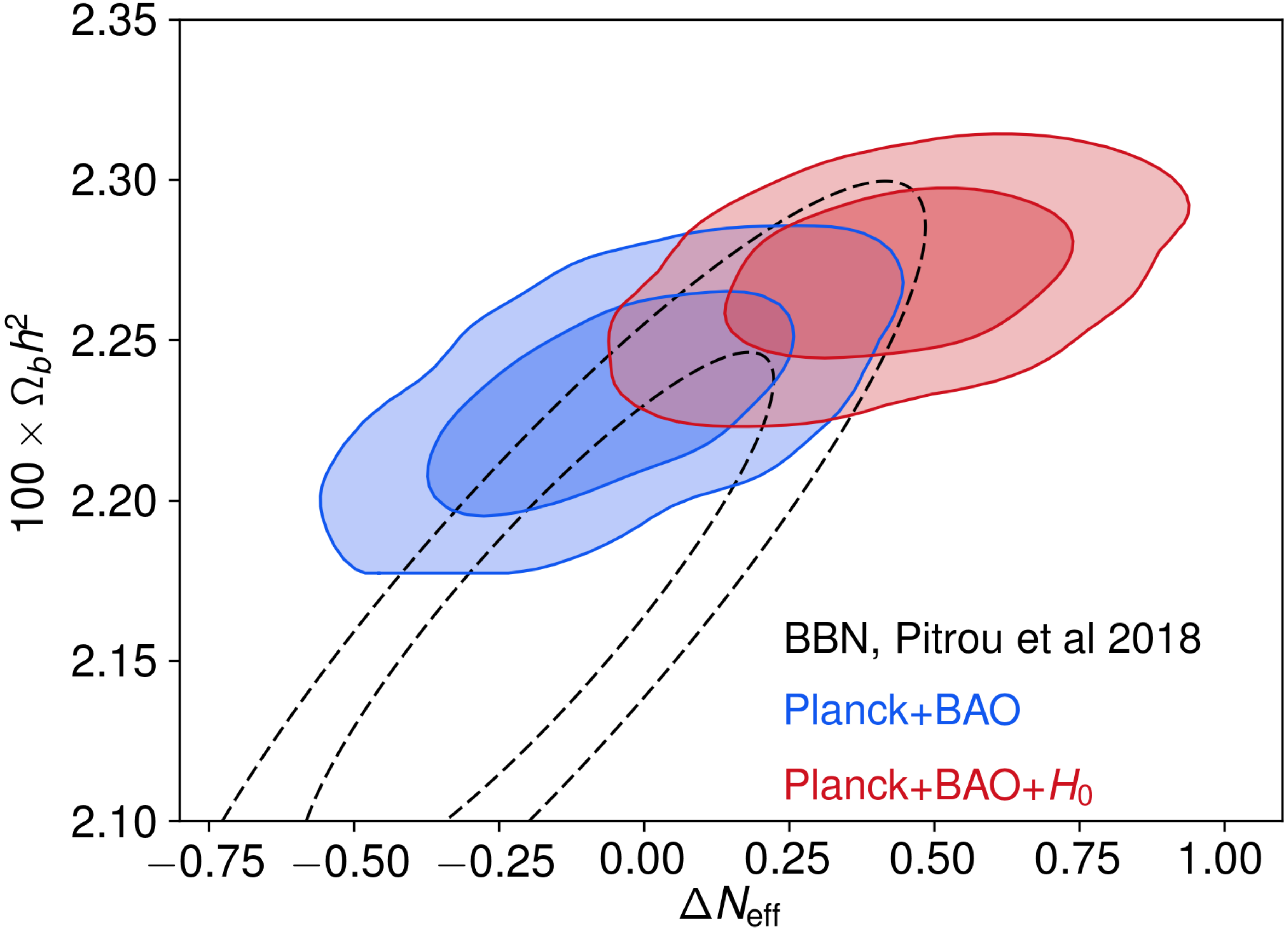
Resolving the Hubble Tension

What do BAOs have to say?

Freeny et al (2019)

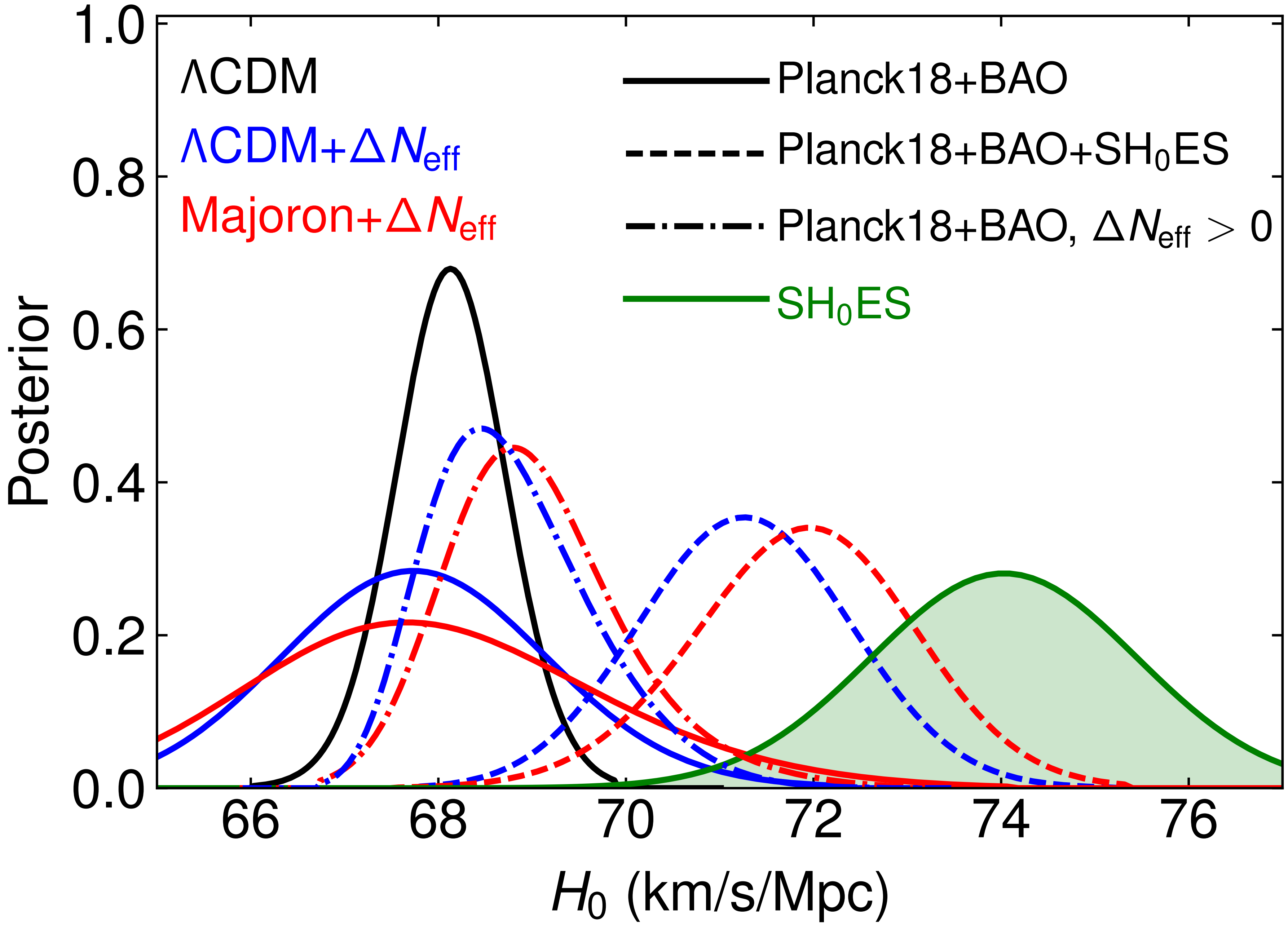


BBN



(1909.04044) Escudero, SJW

Hubble Tension



(1909.04044) Escudero, SJW