Non-standard neutrino scenarios and the cosmos

Olga Mena

IFIC-CSIC/UV Valencia (Spain)

HIDDeν

Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

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2015 Nobel Physics Prize to **Takaaki Kajita and Arthur B. McDonald**

"for the discovery of neutrino oscillations, which shows that neutrinos have mass. [...] New discoveries about the deepest neutrino secrets are expected to change our current understanding of the history, structure and future fate of the Universe"

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How Neutrinos Could Solve The Three Greatest Open Questions In Physics

Ethan Siegel Senior Contributor
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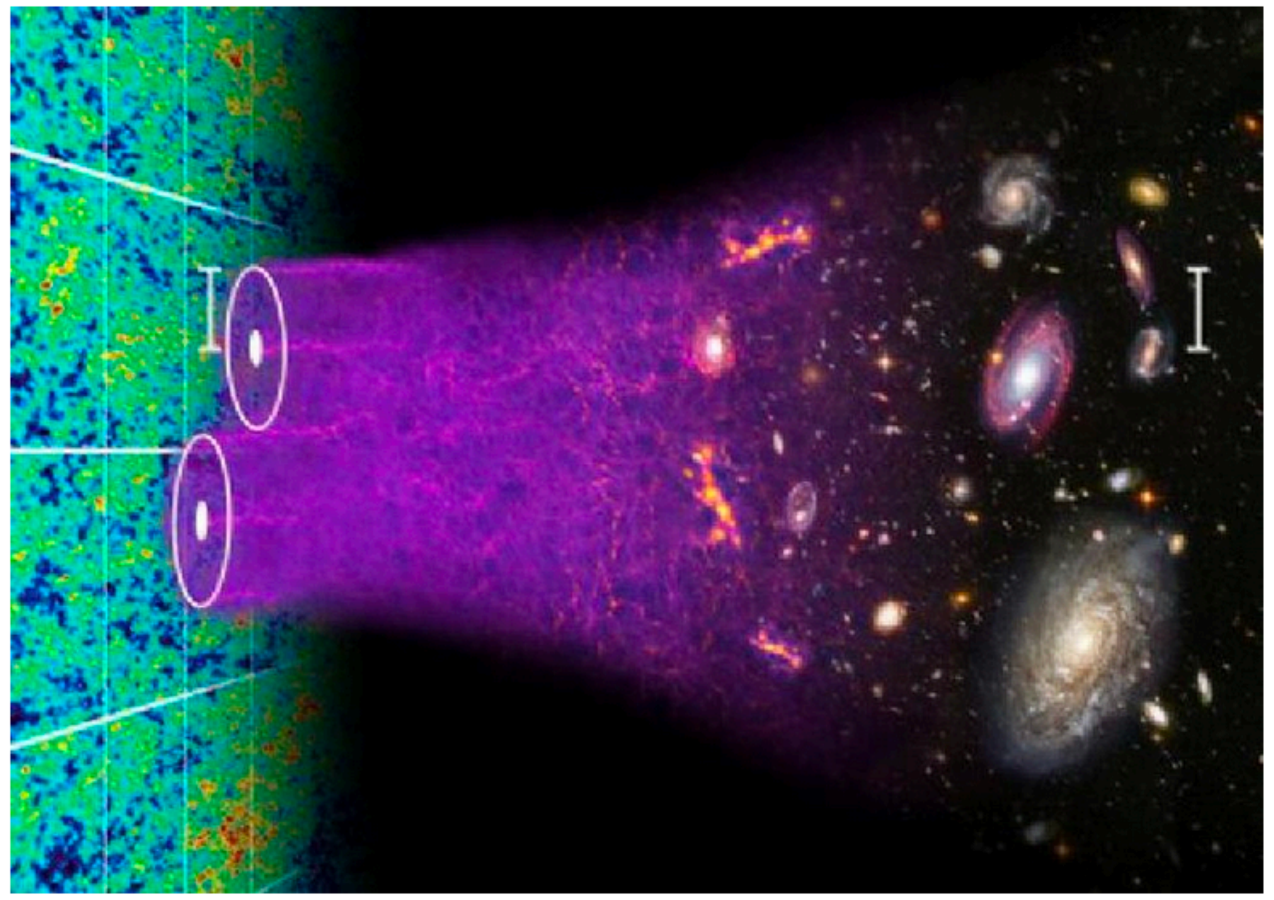
Science
The Universe is out there, waiting for you to discover it.



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This Is Why Neutrinos Are The Standard Model's Greatest Puzzle

Ethan Siegel Senior Contributor
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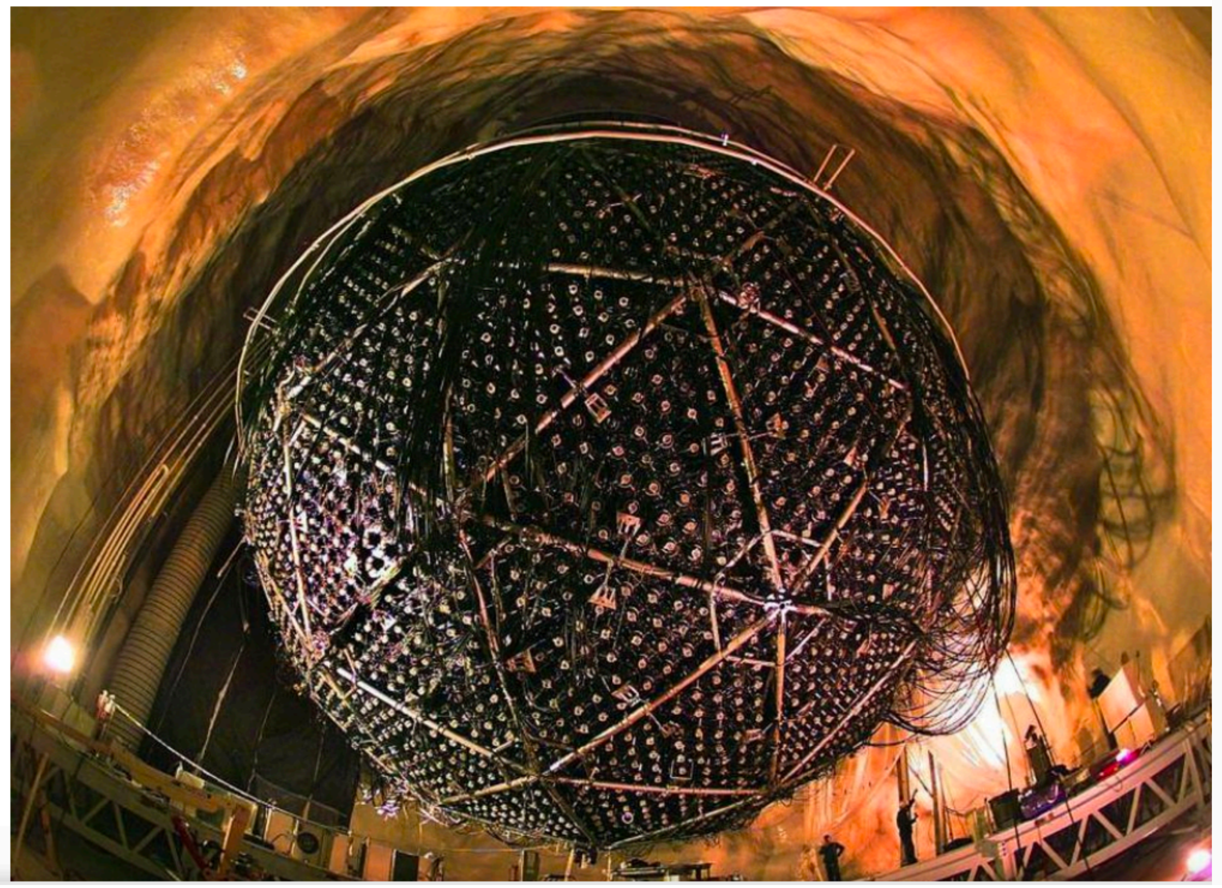

Jul 13, 2016, 11:28am EDT

Could Dark Energy Be Caused By Frozen Neutrinos?

Ethan Siegel Senior Contributor
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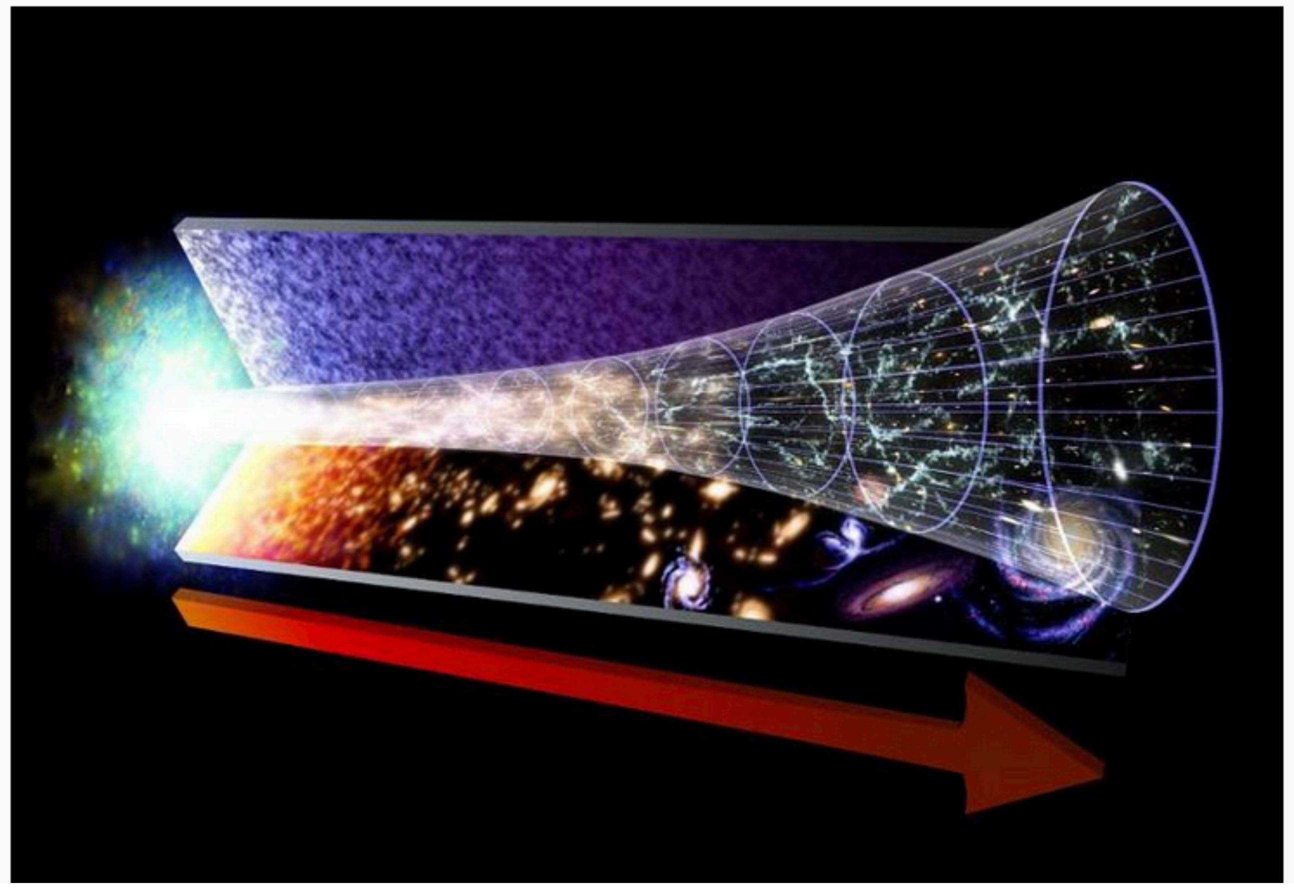

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How Much Of The Dark Matter Could Neutrinos Be?

Ethan Siegel Senior Contributor
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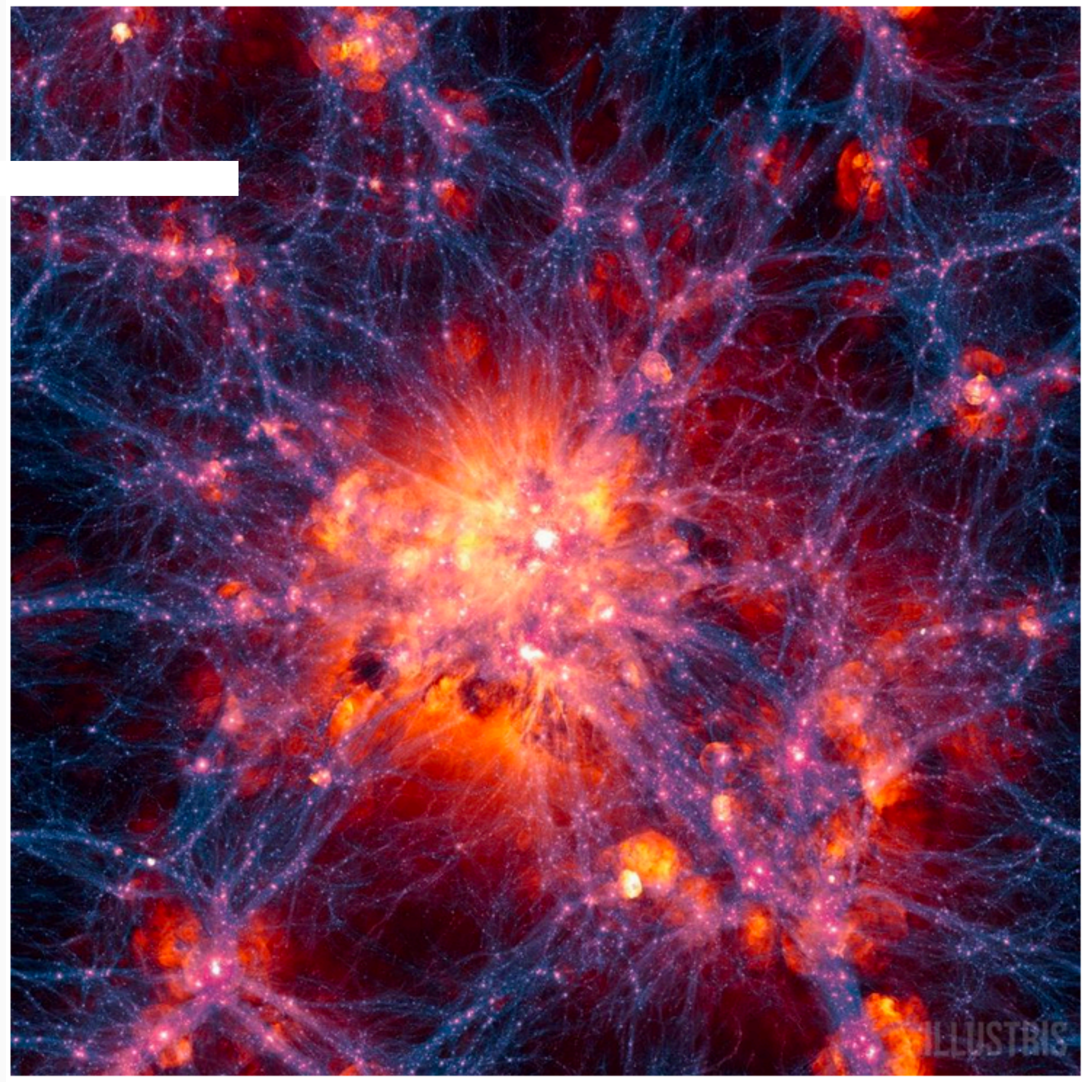


THE NEUTRINO ZARZUELA

- Overture: "Current" Cosmological Neutrino mass limits
- Aria: Neutrino mass limits in extended models
- Chorus: How and why to relax the bounds?
- "Duetto": Neutrinos, cosmology & Non-standard neutrino scenarios
- "Finale": Take home messages

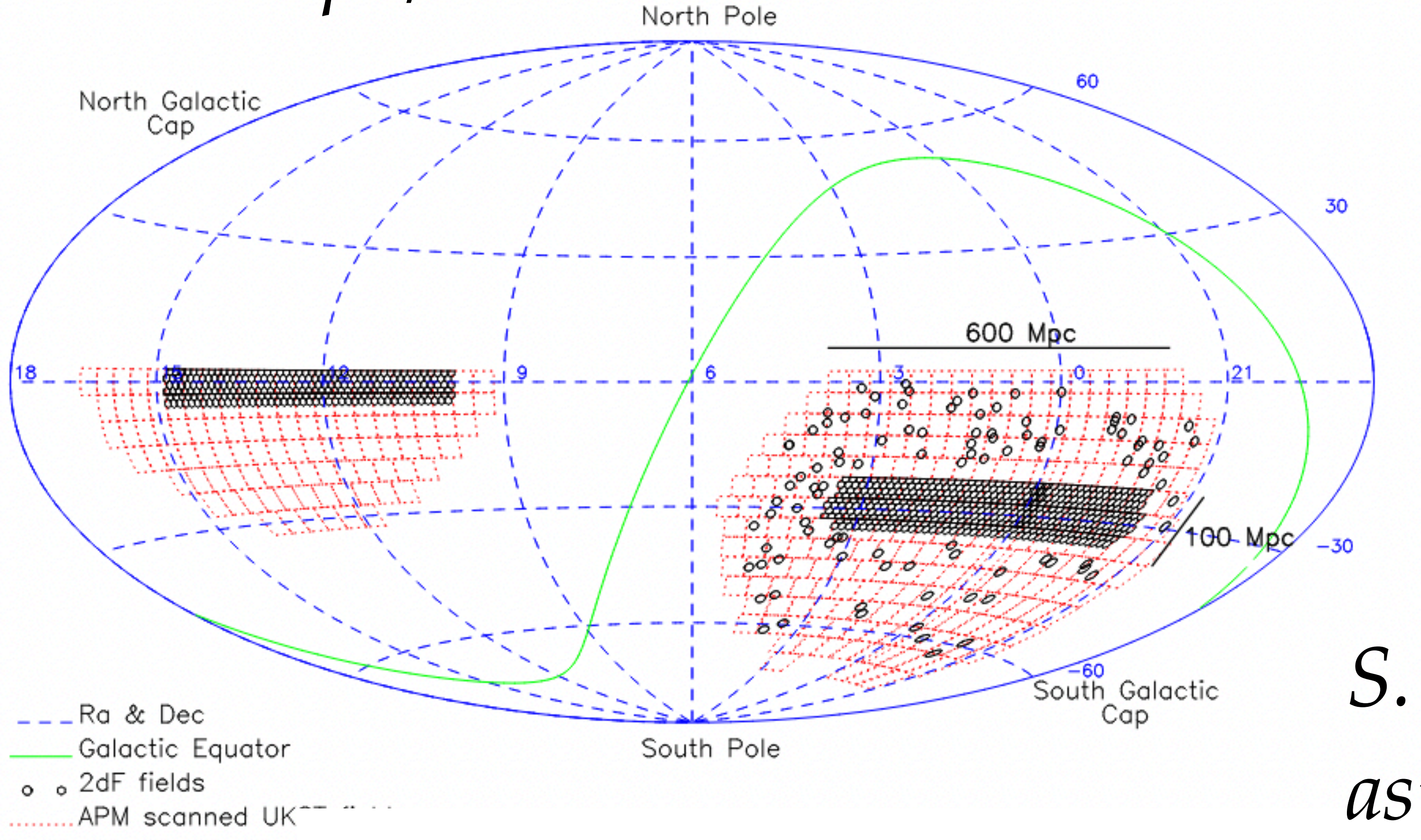
Leitmotif

“Neutrinos are very difficult to work with.
They are different than any other particles.
They are sort of pure.
It is very hard to do neutrino experiments,
but I think they may be the first ones
to show unexpected interactions."

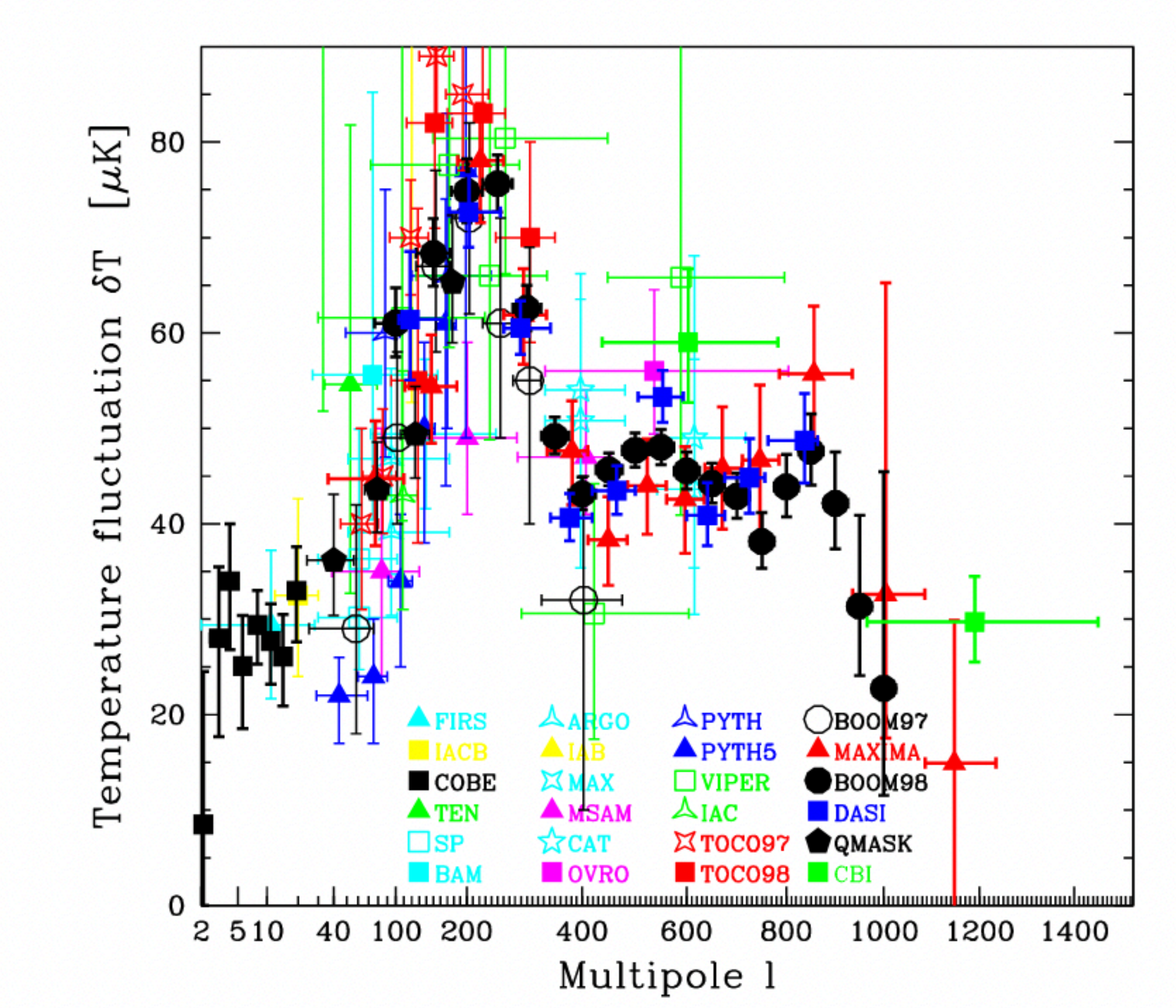
***Martin Perl**, 1995 Nobel Prize winner for the discovery of the tau lepton*

2002 Absolute neutrino mass status

astro-ph/0204239

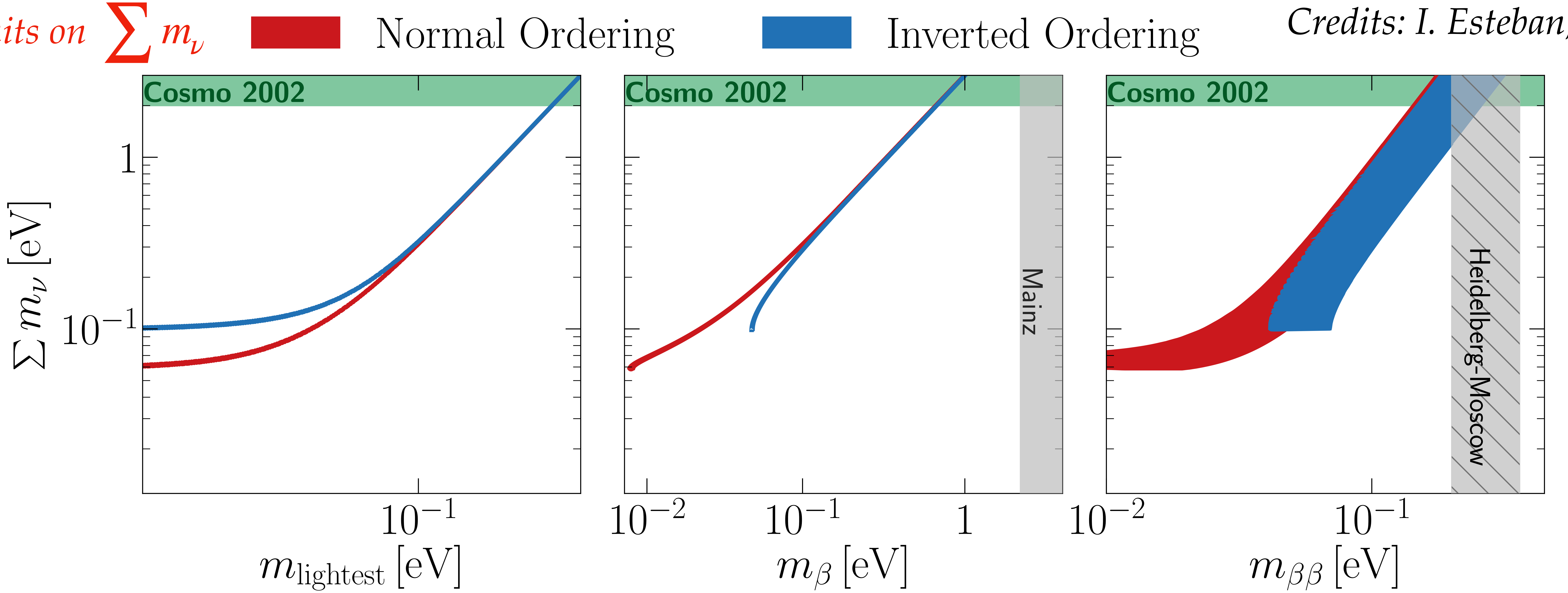


S. Hannestad, Neutrino 2002
astro-ph/0208567



Wang et al, PRD'02

95% CL limits on $\sum m_\nu$



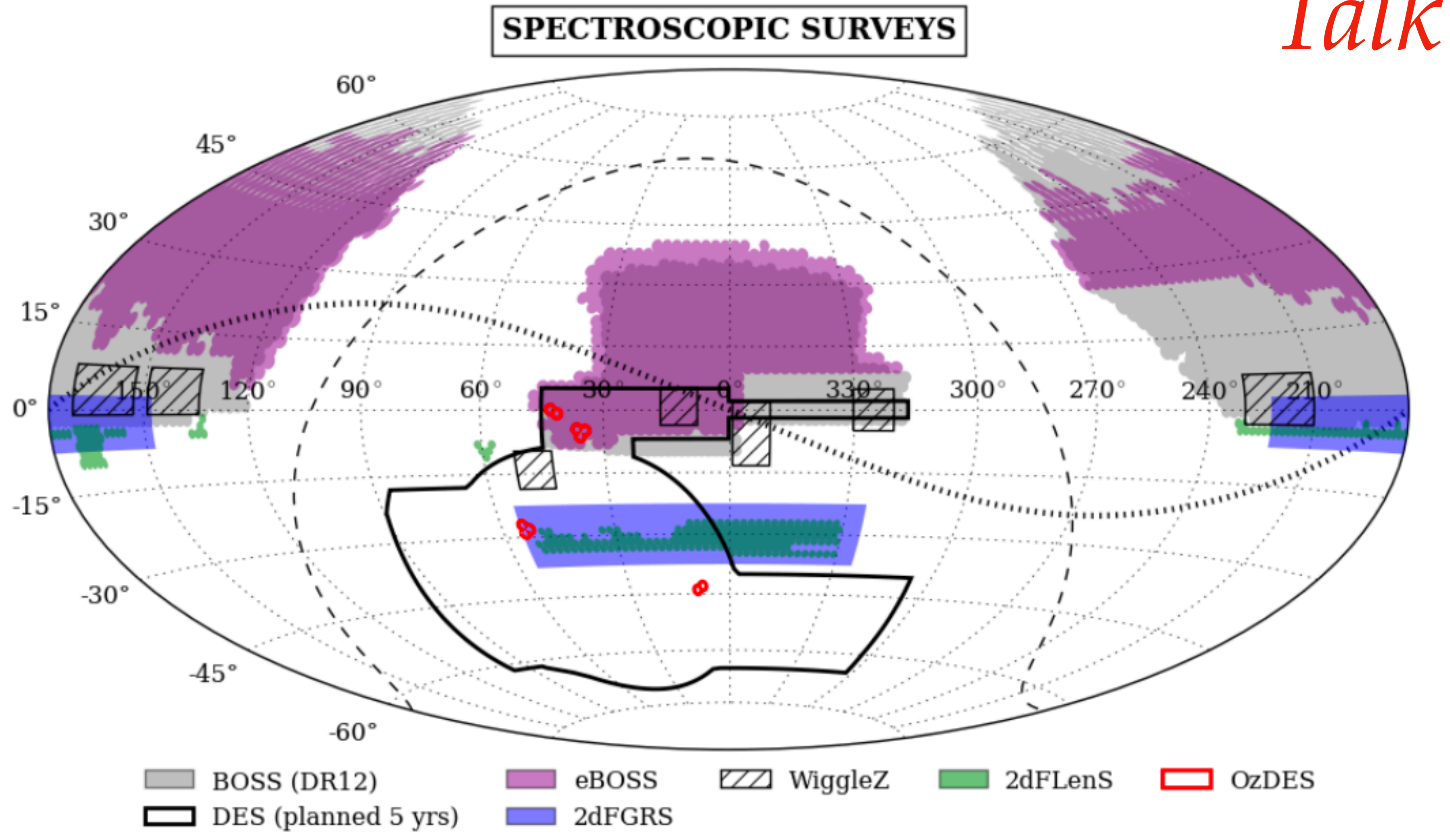
Credits: I. Esteban, S. Gariazzo

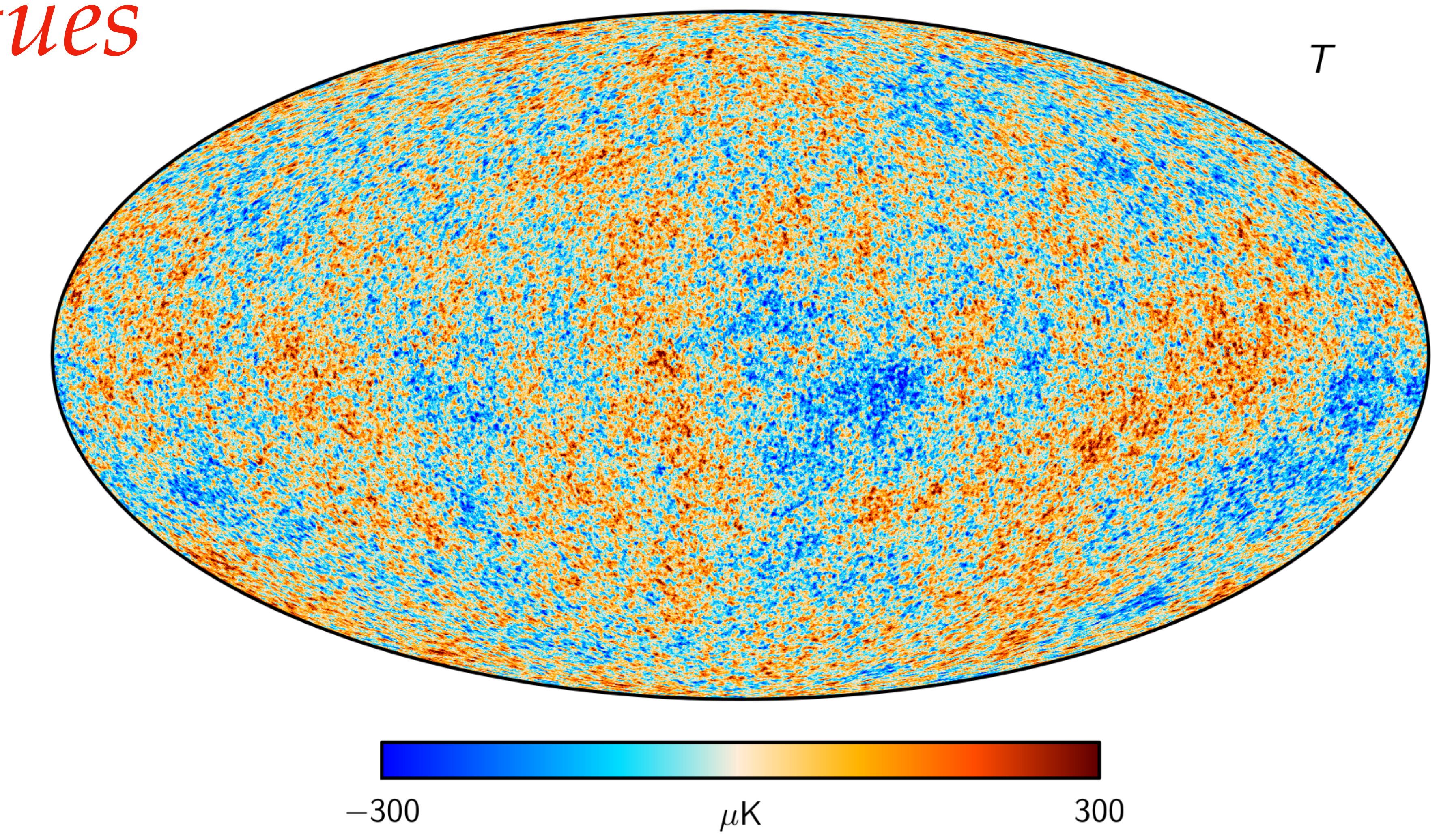
2022 absolute neutrino mass status

DES Collaboration, MNRAS'16

Talk by J. Legourgues

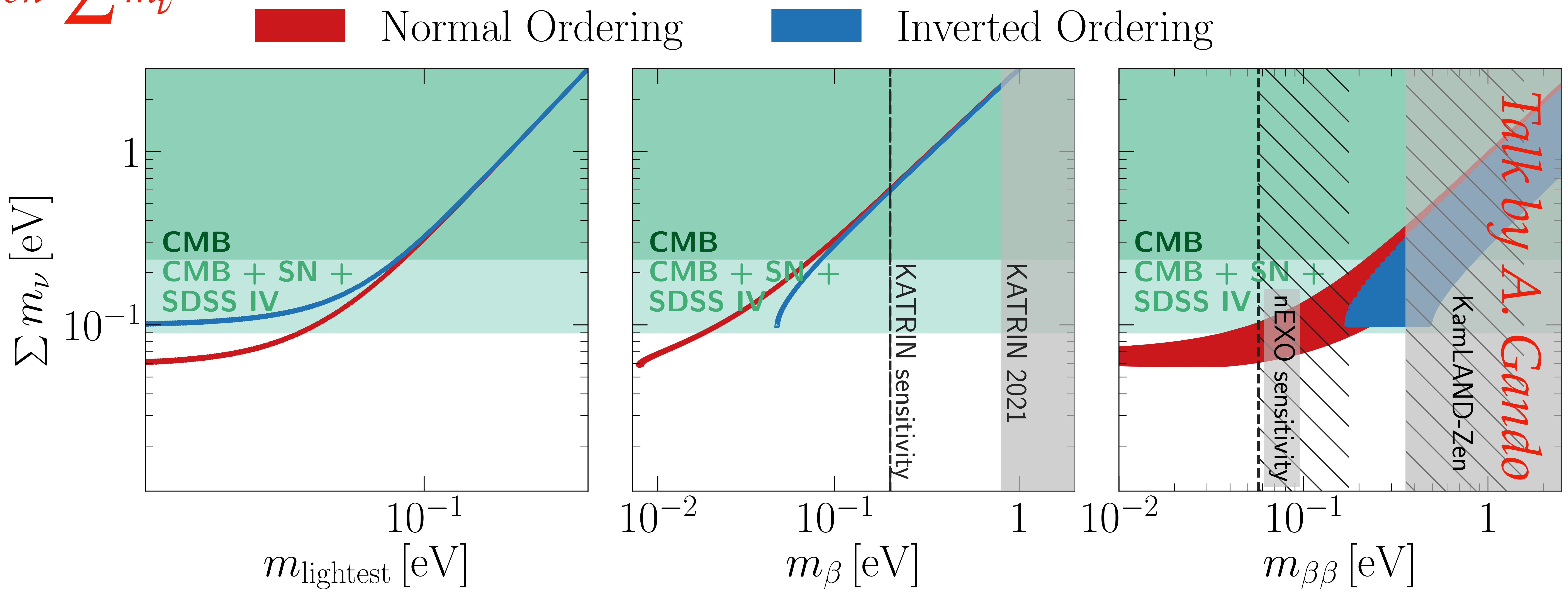
Planck coll.





95% CL limits on $\sum m_\nu$

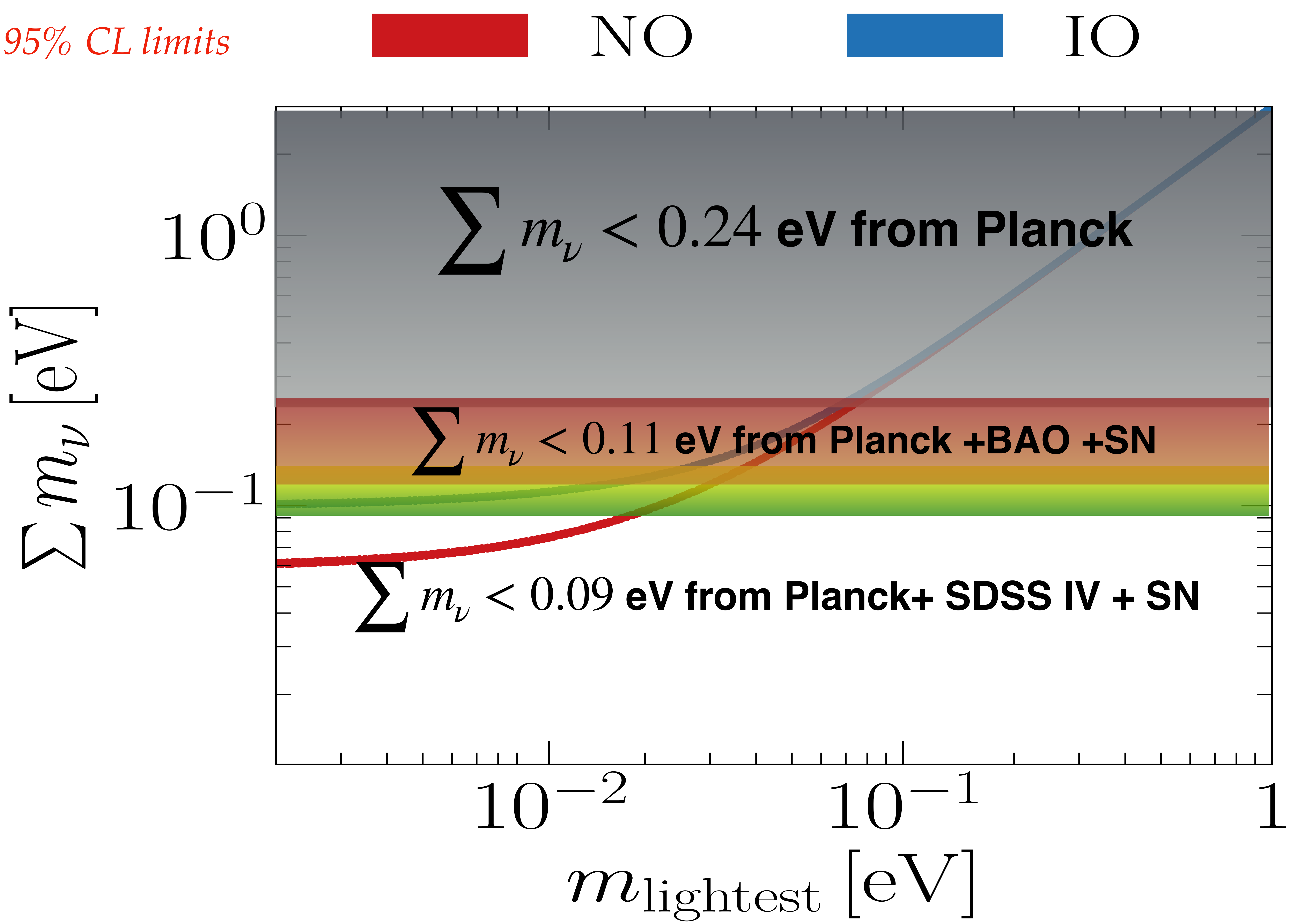
Credits: I. Esteban, S. Gariazzo



2022 Tightest bounds on $\sum m_\nu$

Talk by J. Legourgues

Planck+ SDSS-IV (DR16 + DR12) + SN $\sum m_\nu < 0.09$ eV 95% CL



Planck Coll. A&A'20

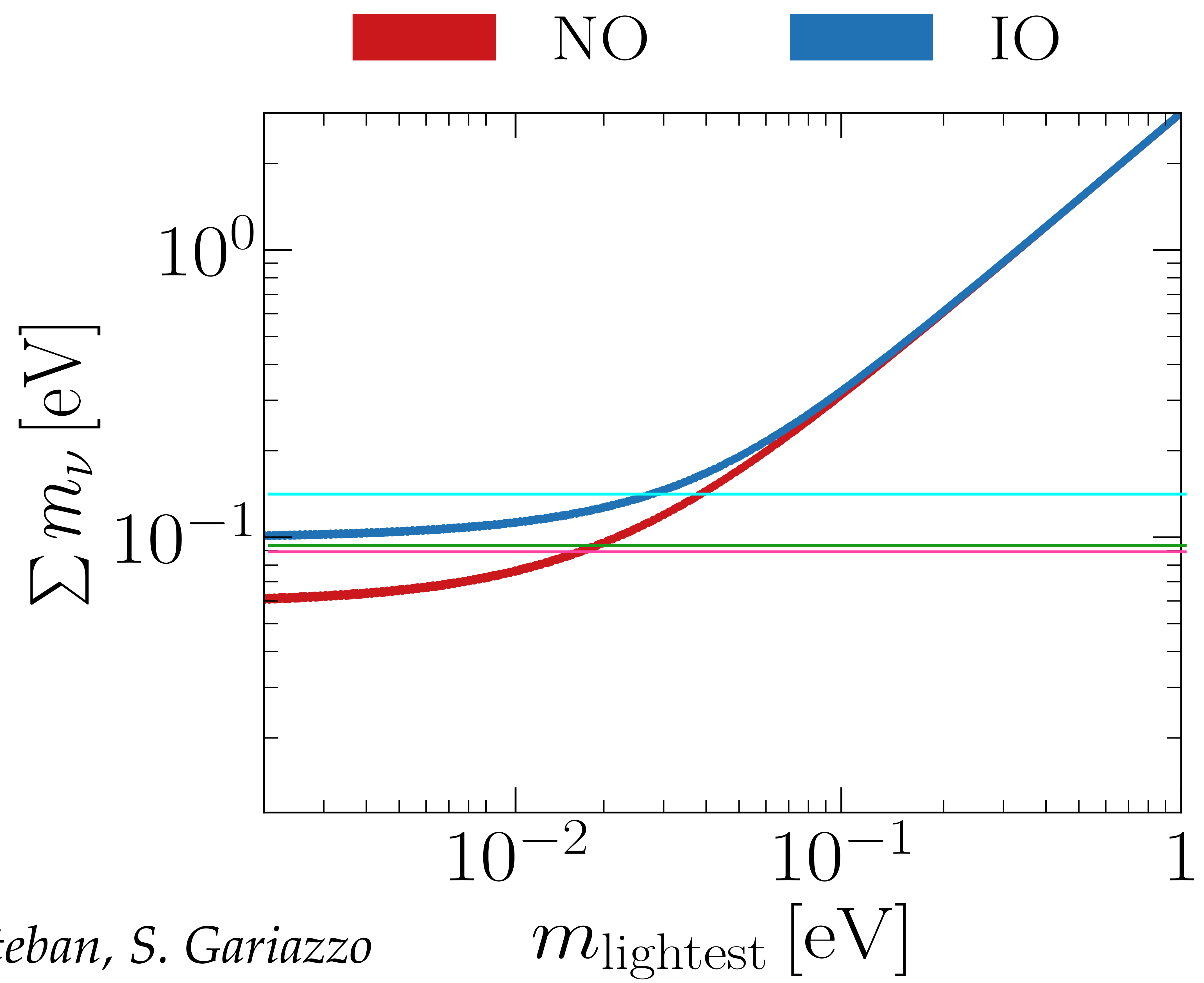
Di Valentino et al PRD'21

(see also Palanque-Delabrouille et al JCAP'20)

Credits: I. Esteban, S. Gariazzo

2022 Tightest bounds on $\sum m_\nu$

Robust: difficult to avoid in close-to-minimal models ("simple" extensions of ΛCDM)



Gariazzo & Mena PRD'19

Di Valentino et al PRD'21

$\sum m_\nu < 0.14$ **eV with Ω_k and w**

$\sum m_\nu < 0.095$ **eV with $N_{\rm eff}$**

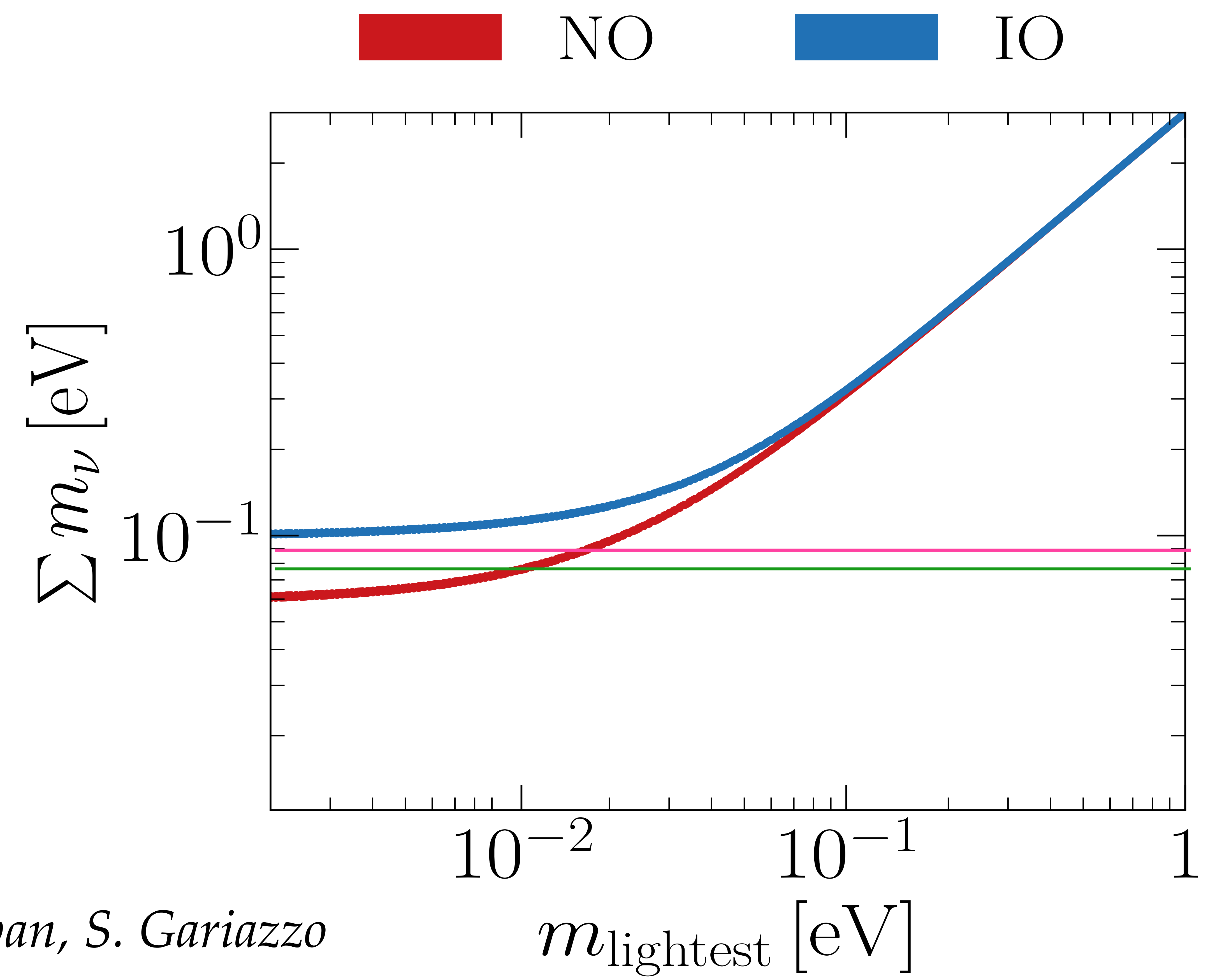
$\sum m_\nu < 0.09$ **eV**

95% CL limits

Credits: I. Esteban, S. Gariazzo

2022 Tightest bounds on $\sum m_\nu$

Robust: difficult to avoid in close-to-minimal models ("simple" extensions of ΛCDM)



Credits: I. Esteban, S. Gariazzo

95% CL limits

$\sum m_\nu < 0.09$ **eV**

$\sum m_\nu < 0.08$ **eV with w (> -1)**

Di Valentino et al PRD'21

Vagnozzi et al PRD'18

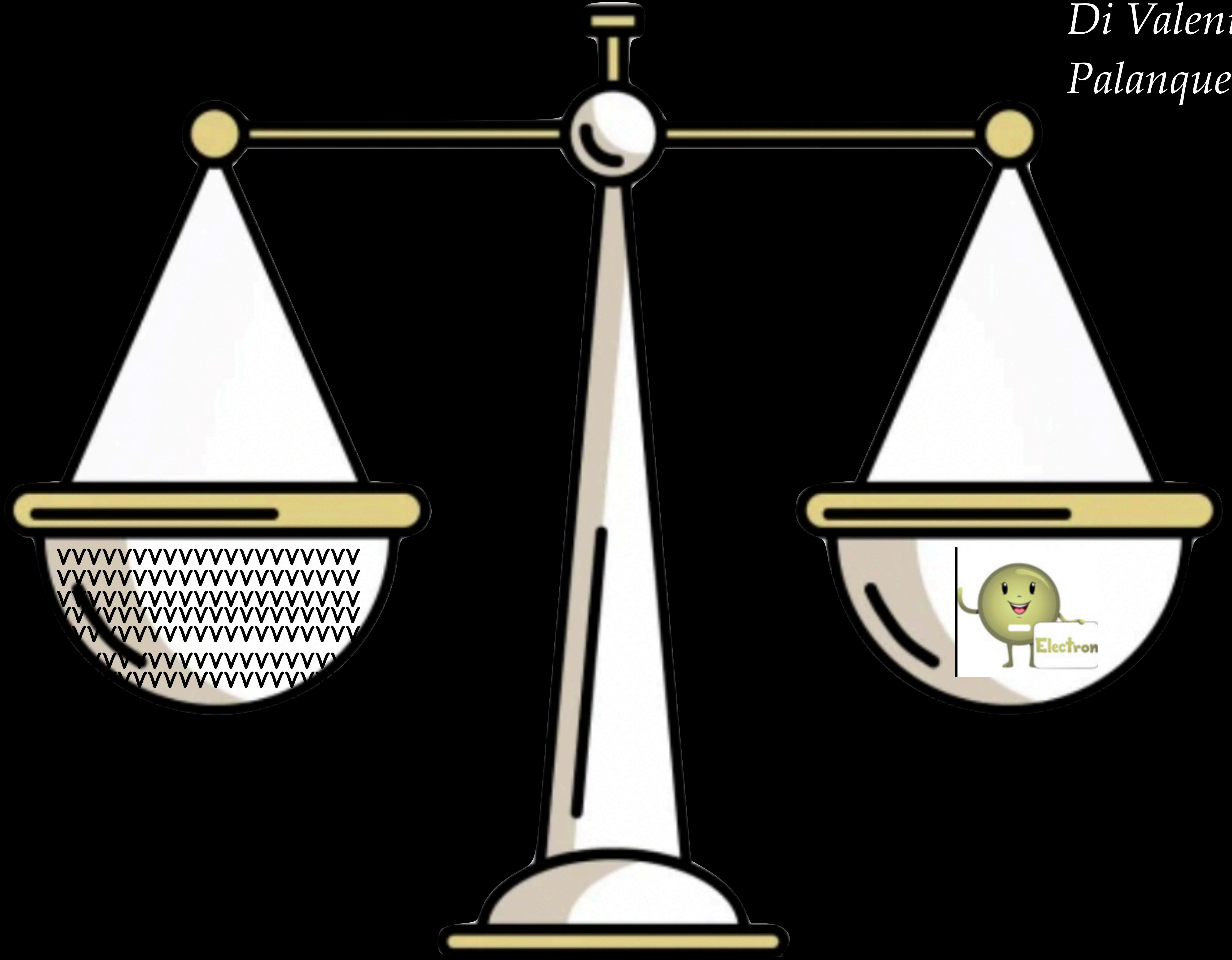
Choudhury & Choubey JCAP'18

Tightest bounds on $\sum m_\nu$

Planck+ SDSS-IV (DR16 + DR12) + SN

$$\sum m_\nu < 0.09 \text{ eV } 95\% \text{ CL}$$

Di Valentino et al PRD'21,
Palanque-Delabrouille et al JCAP'20



6 million neutrinos can't weigh more than 1 electron

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One needs to go to a non standard neutrino sector!

A THEORETICAL/Mythologycal APPROACH...

One needs to go to a non standard neutrino sector!

A THEORETICAL/Mythologycal APPROACH...

- Remember our Leitmotif

"Neutrinos are very difficult to work with.
They are different than any other particles.
They are sort of pure.
It is very hard to do neutrino experiments, but I think they may be the first ones to show unexpected interactions."

- Non standard neutrino physics can be related to the neutrino mass generation mechanism

See e.g. Forastieri et al JCAP'15 &PRD'19, Escudero & Witte EPJC'20, Escudero et al JHEP'20, Escudero & Witte EPJC'21

A PHENOMENOLOGICAL (PRACTICAL?) APPROACH…

A PHENOMENOLOGICAL (PRACTICAL?) APPROACH…

A non standard neutrino sector:

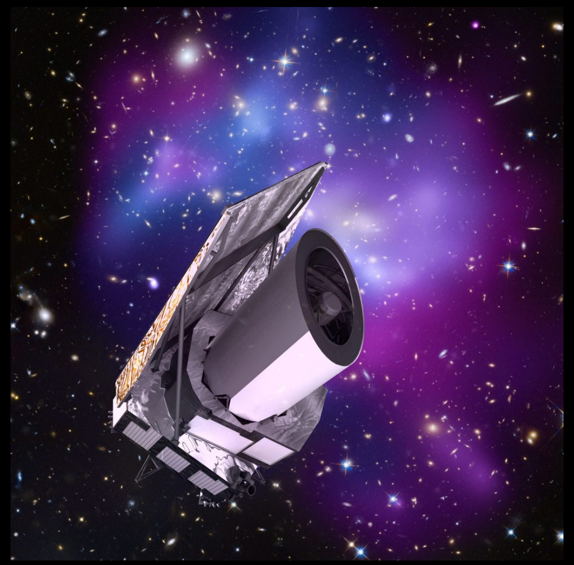
- May help in solving the so-called H_0 TENSION
- May help in solving the $A_{\rm lens}$ TENSION
- May help in solving the σ_8 TENSION *Mosbech et al, JCAP'21*
- May alleviate current sterile neutrino TENSIONS between short baseline oscillation and cosmological measurements *Talk by J. Kopp*

Dasgupta & Kopp PRL'14, Chu et al JCAP'15, Hannestad et al PRL'14, Saviano et al PRD'014, Mirizzi et al PRD'15, Archidiacono et al PRD'15 &'16 & JCAP'16, Forastieri et al JCAP'17, Chu et al JCAP'18, Archidiacono et al JCAP'20

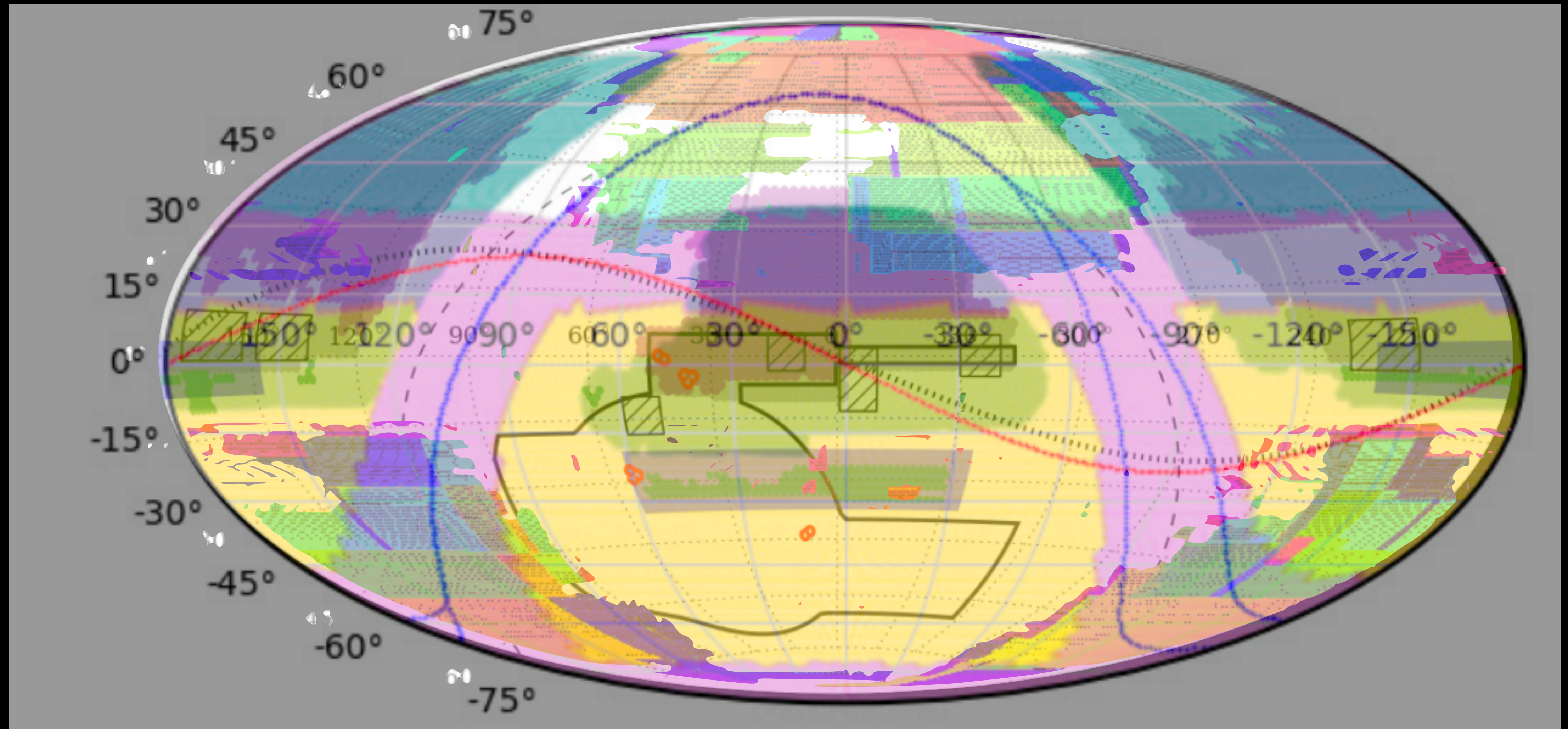
A FUTURISTIC APPROACH...

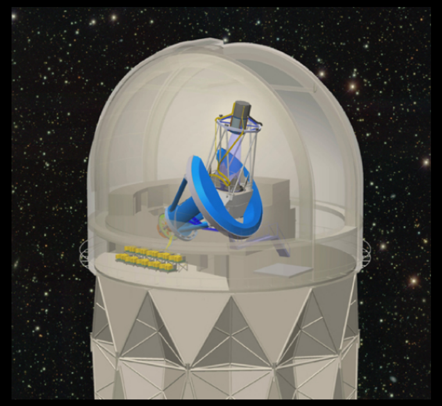
Credits: P. Jansen

Future neutrino mass bounds



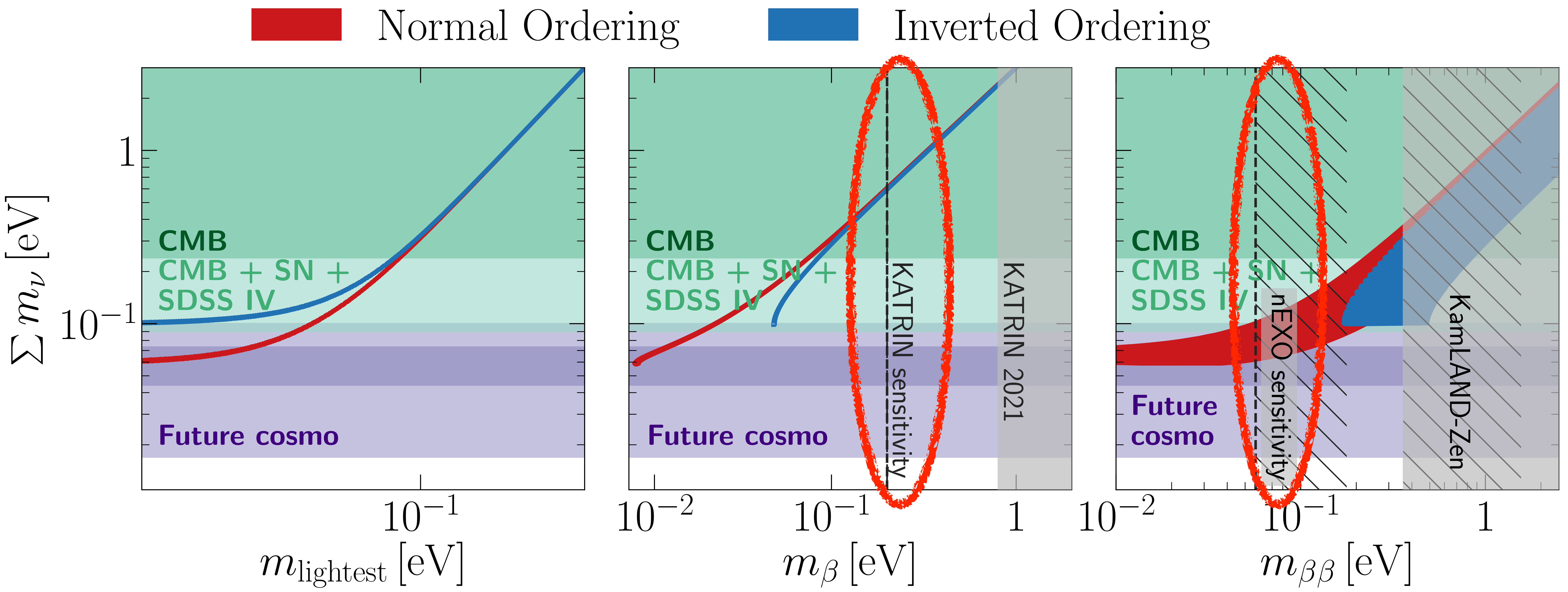
1502.00903
Euclid Coll,
IAU Symp'14





Olsen et al'18
1812.02204

95% CL limits on $\sum m_\nu$ *Credits: I. Esteban, S. Gariazzo*



A FUTURISTIC APPROACH...

- POTENTIAL TENSIONS BETWEEN future KATRIN/PTOLEMY MEASUREMENTS AND COSMOLOGY

Lorenz et al PRD'19 & PRD'21, Oldengott et al. JCAP'19,
Escudero et al JCAP'20, Esteban & Salvado JCAP'21, Abellan et al 2112.13862, Alvey et al PRD'22,
Alvey et al JCAP'22

- What if cosmological analyses see $\sum m_\nu < 0.06$ eV ?

"Synergy between cosmological and laboratory searches in neutrino physics: a white paper"
Snowmass 2203.07377

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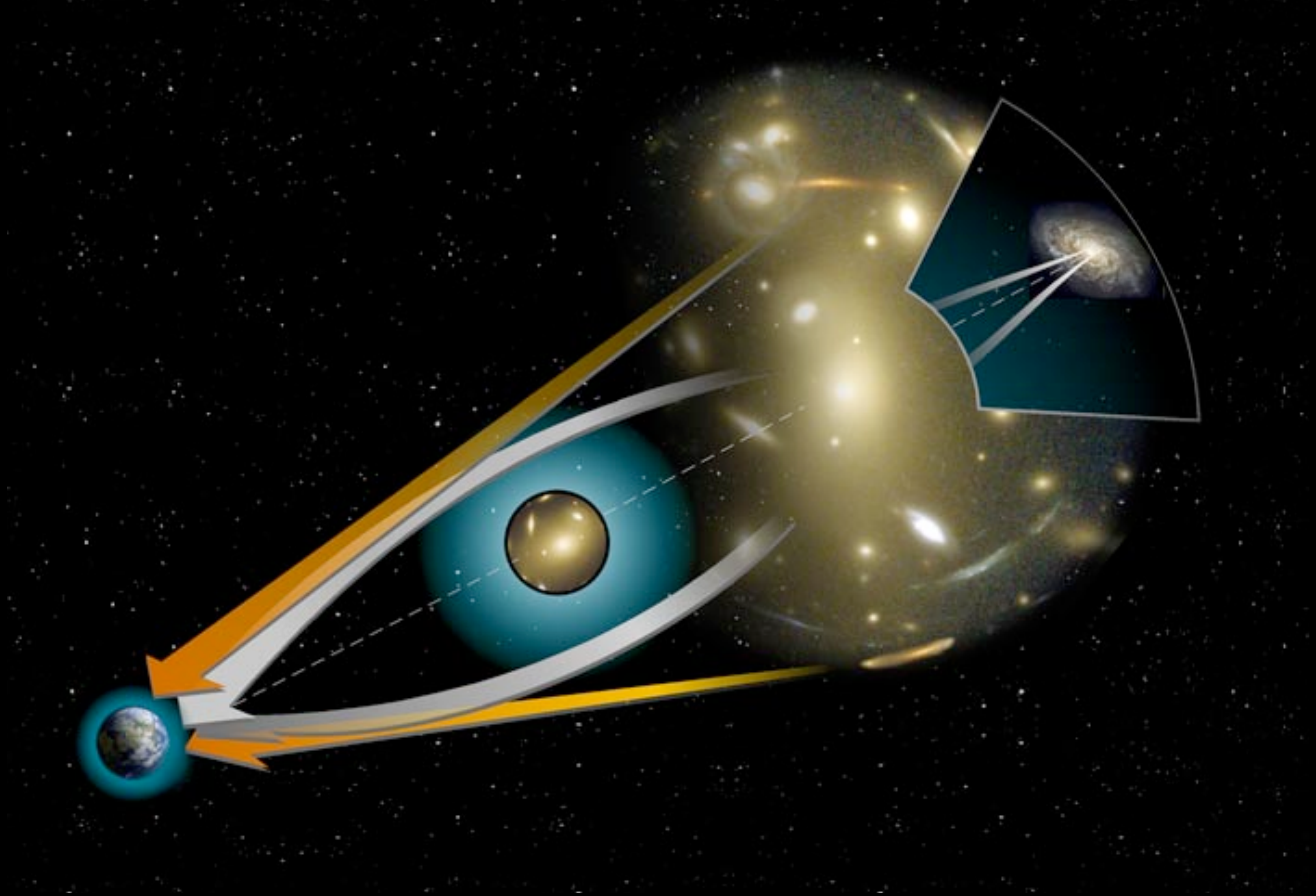
Dasgupta & Kopp PRL'14, Chu et al JCAP'15, Hannestad et al PRL'14, Saviano et al PRD'014, Mirizzi et al PRD'15, Archidiacono et al PRD'15 &'16 & JCAP'16, Forastieri et al JCAP'17, Chu et al JCAP'18, Archidiacono et al JCAP'20

Gravitational Lensing

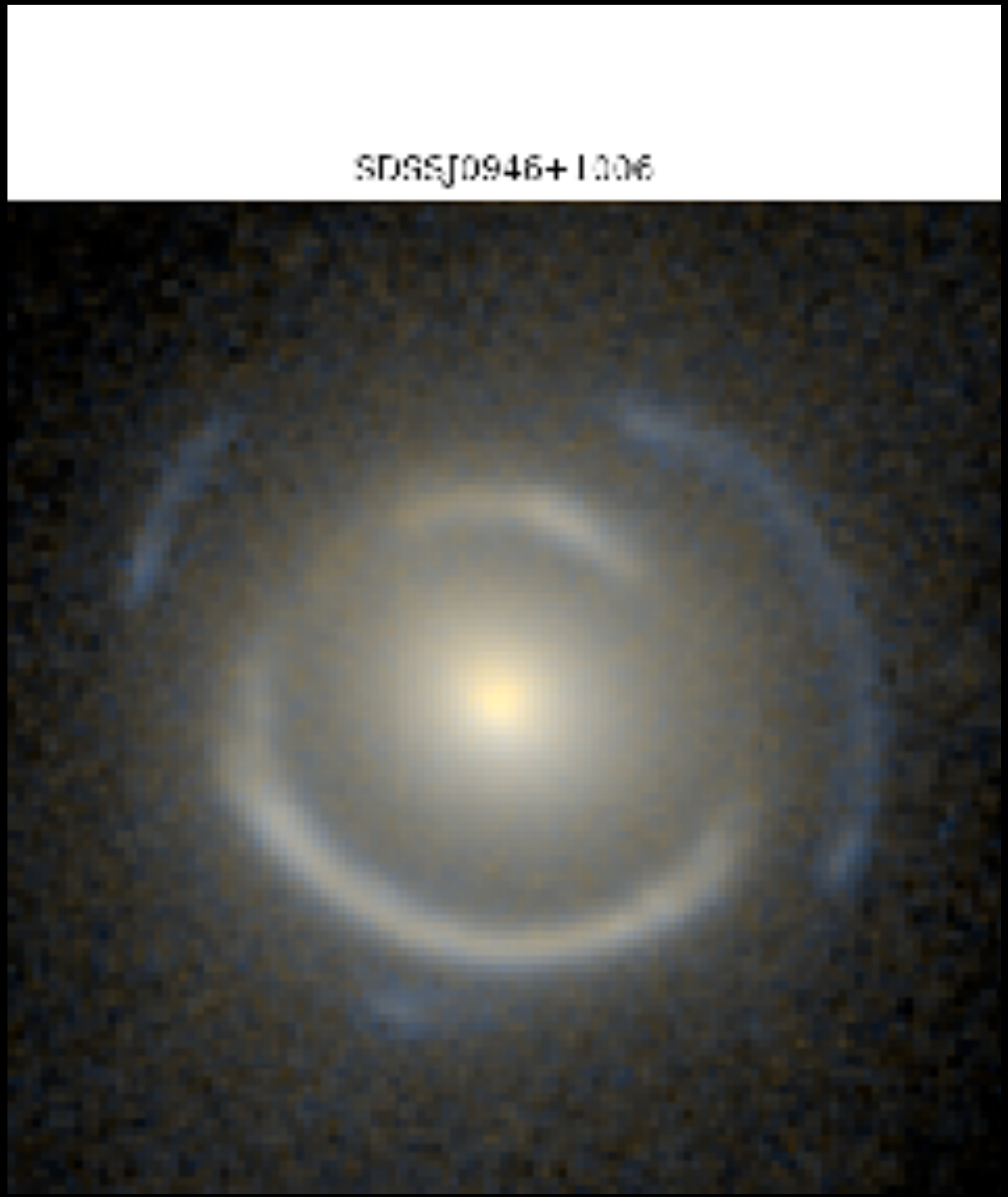


Einstein's relativity predicts that the presence of a massive body will curve space time, distorting the light trajectory. The shape of the background objects will change/multiplied by the presence of intervening galaxies.

Gravitational Lensing: Syzygy

Lensing Galaxy

Gravitational Lensing



Double Einstein ring!
3 perfectly aligned galaxies
Probably less than 100 cases in our universe, and we have seen one!

The $A_{\rm lens}$ tension

Lensing remaps the CMB fluctuations: $\Theta_{\rm lensed}(\hat{n}) = \Theta(\hat{n} + \nabla\phi(\hat{n}))$

Lensing potential ϕ: integrated mass distribution back to the last scattering surface

Geometry

$$\phi(\hat{n}) = -2\int_0^{z_{rec}} \frac{dz}{H(z)} \Psi(z, D(z)\hat{n}) \left(\frac{D(z_{rec}) - D(z)}{D(z_{rec})D(z)}\right)$$

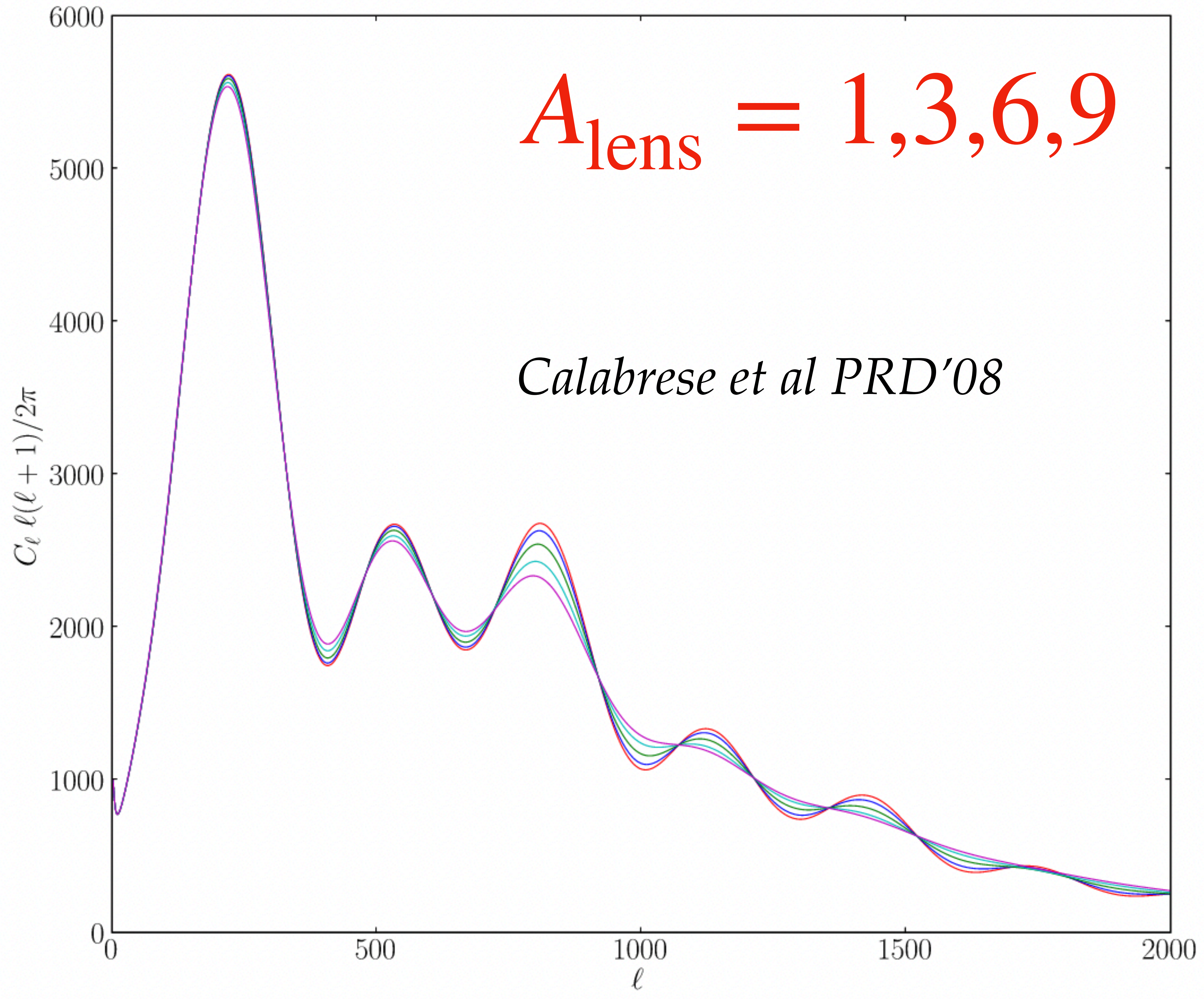
Matter distribution

$$C_L^{\phi\phi} = \frac{8\pi^2}{L^3}\int_0^{z_{rec}} \frac{dz}{H(z)} D(z) \left(\frac{D(z_{rec}) - D(z)}{D(z_{rec})D(z)}\right)^2 P_\Psi(z, k = L/D(z))$$

$$C_L^{\phi\phi} \rightarrow A_{\rm lens}\, C_L^{\phi\phi} \qquad A_{\rm lens} = 1 \rightarrow \Lambda CDM$$

Calabrese et al PRD'08

The $A_{\rm lens}$ tension



$$C_L^{\phi\phi} \rightarrow A_{\rm lens}\ C_L^{\phi\phi}$$

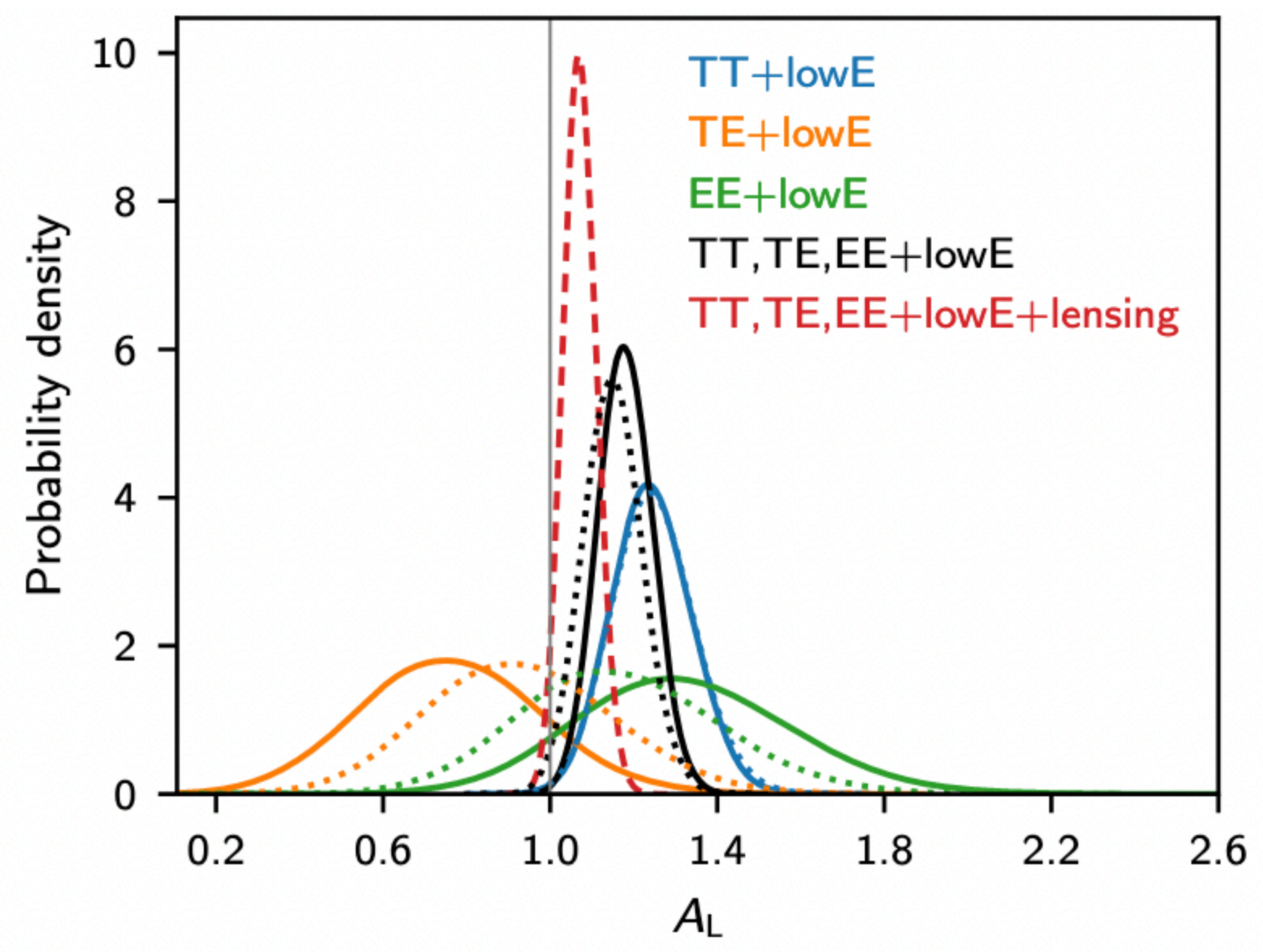
It smooths the CMB acoustic peaks: 20% change suppresses the fourth and higher peaks ~0.5%, raising troughs 1%

Consistency checks:

1) Does the smoothing effect in the CMB power spectra match $A_{\rm lens} = 1 \rightarrow \Lambda CDM$?

2) Is the amplitude of the smoothing spectra consistent with that measured by the lensing reconstruction?

The A_{lens} tension



Planck Collaboration, A&A'20

$$A_{\text{lens}} > 1 \quad 3\sigma$$

$$A_{\text{lens}} = 1 \rightarrow \Lambda CDM$$

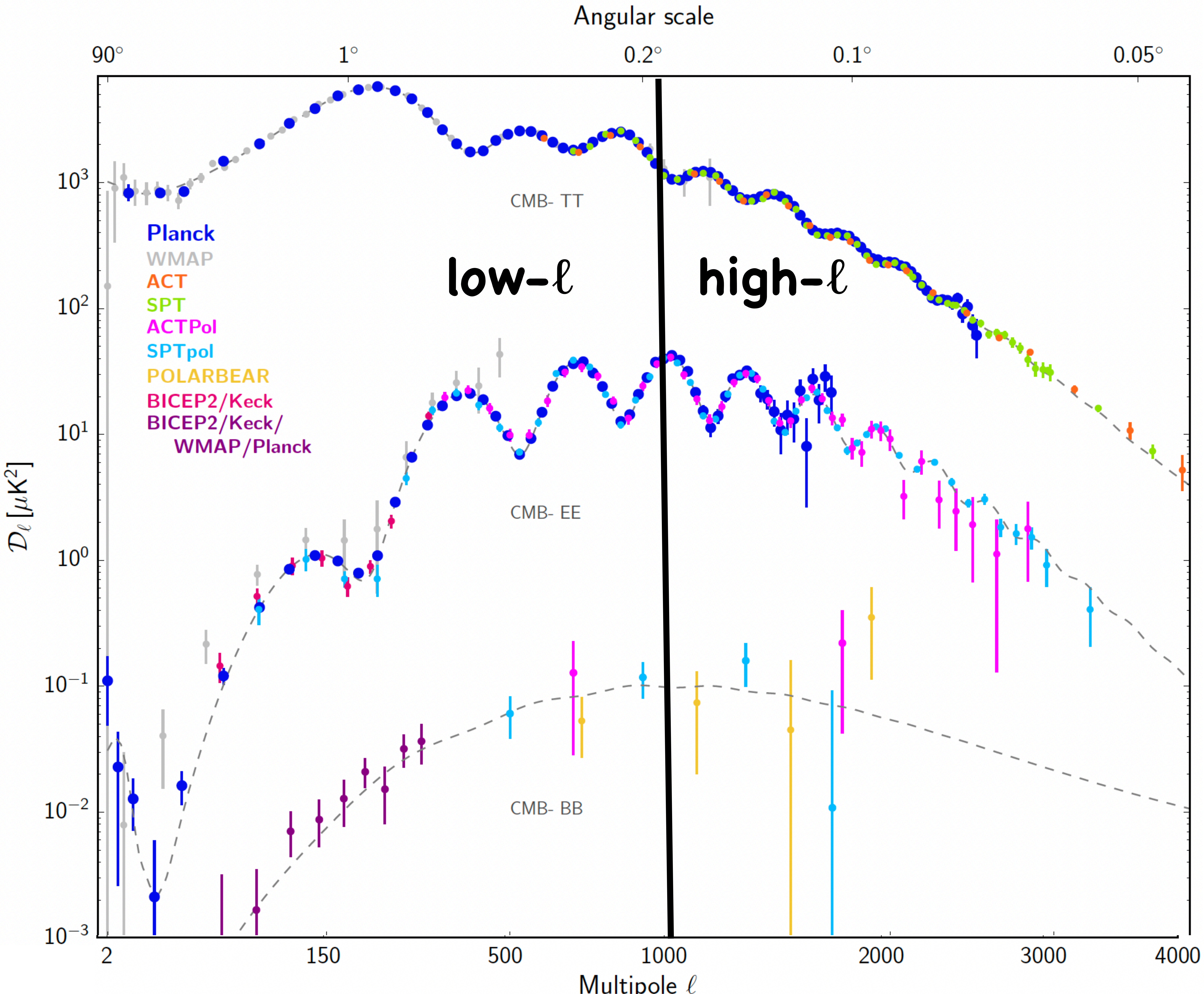
Systematics?

$$A_{\text{lens}} \neq 1 \rightarrow \Lambda CDM$$

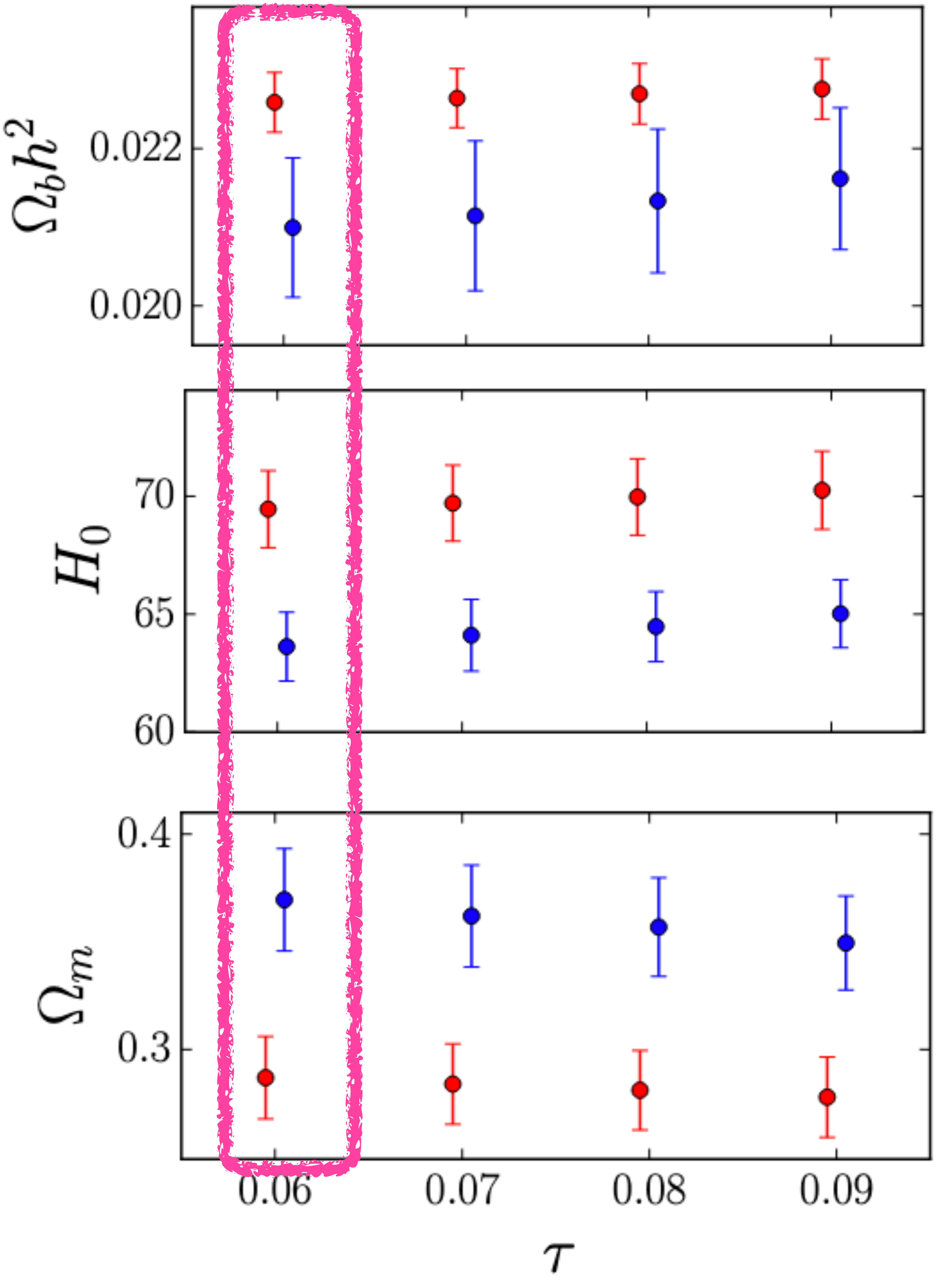
New Physics?

BEST FIT IMPROVED BY 10 UNITS WHEN ADDING A_{lens} TO THE ANALYSES

The A_{lens} tension

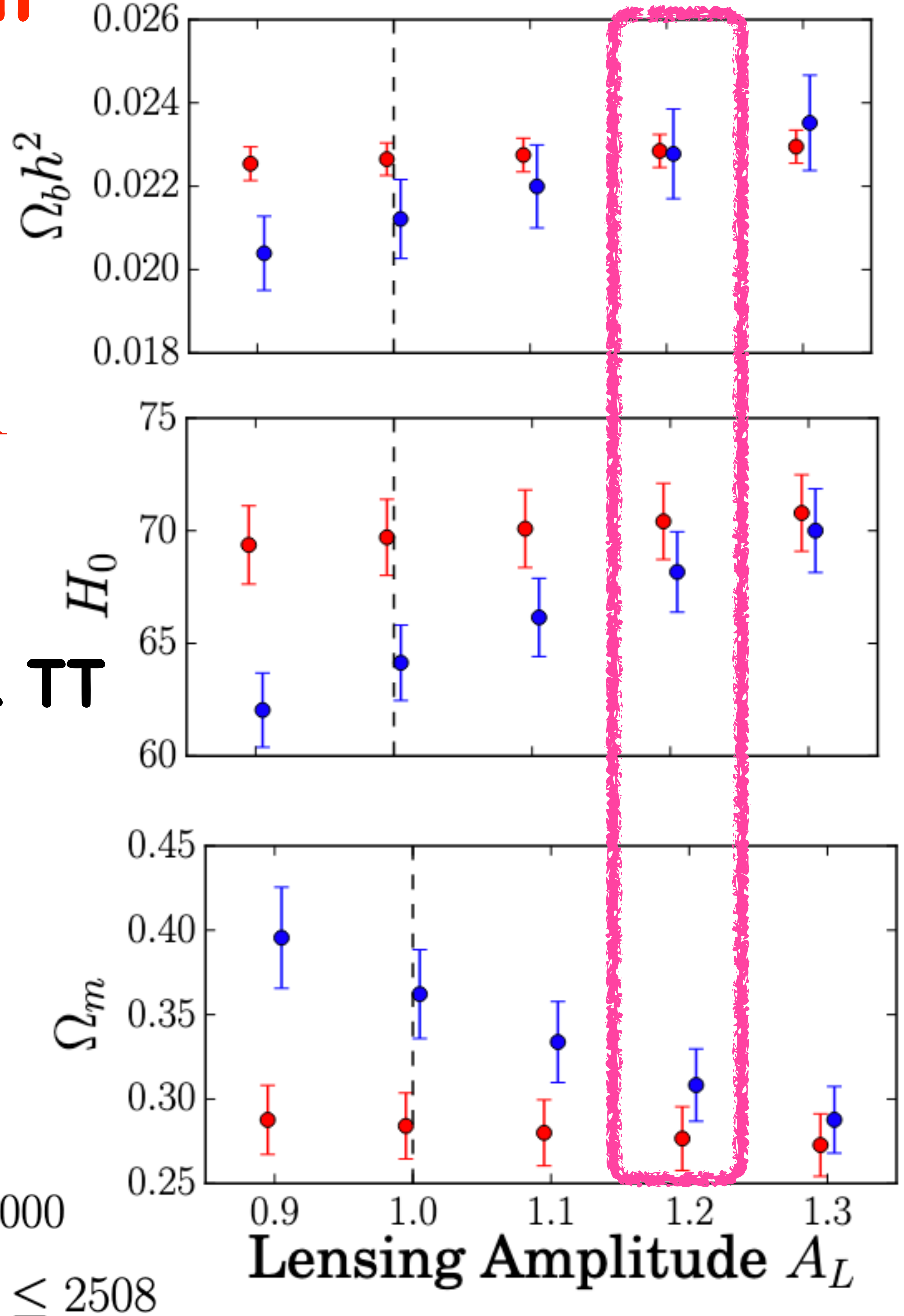


The $A_{\rm lens}$ tension



Allowing $A_{\rm lens} > 1$ relieves tensions between low-ℓ and high-ℓ Planck TT

(Addison et al, ApJ'16)

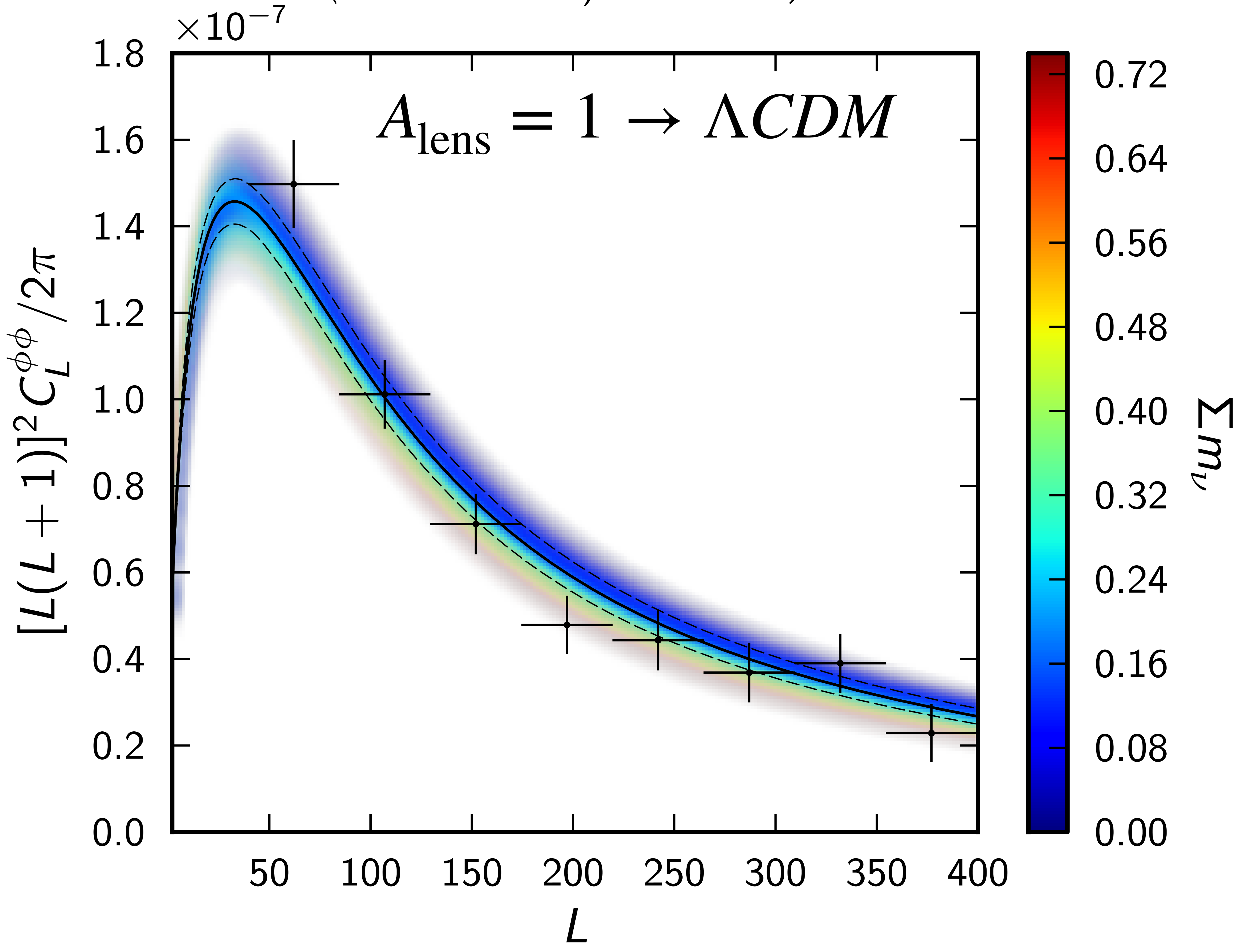


● ***Planck* TT 2015** $2 \leq \ell < 1000$

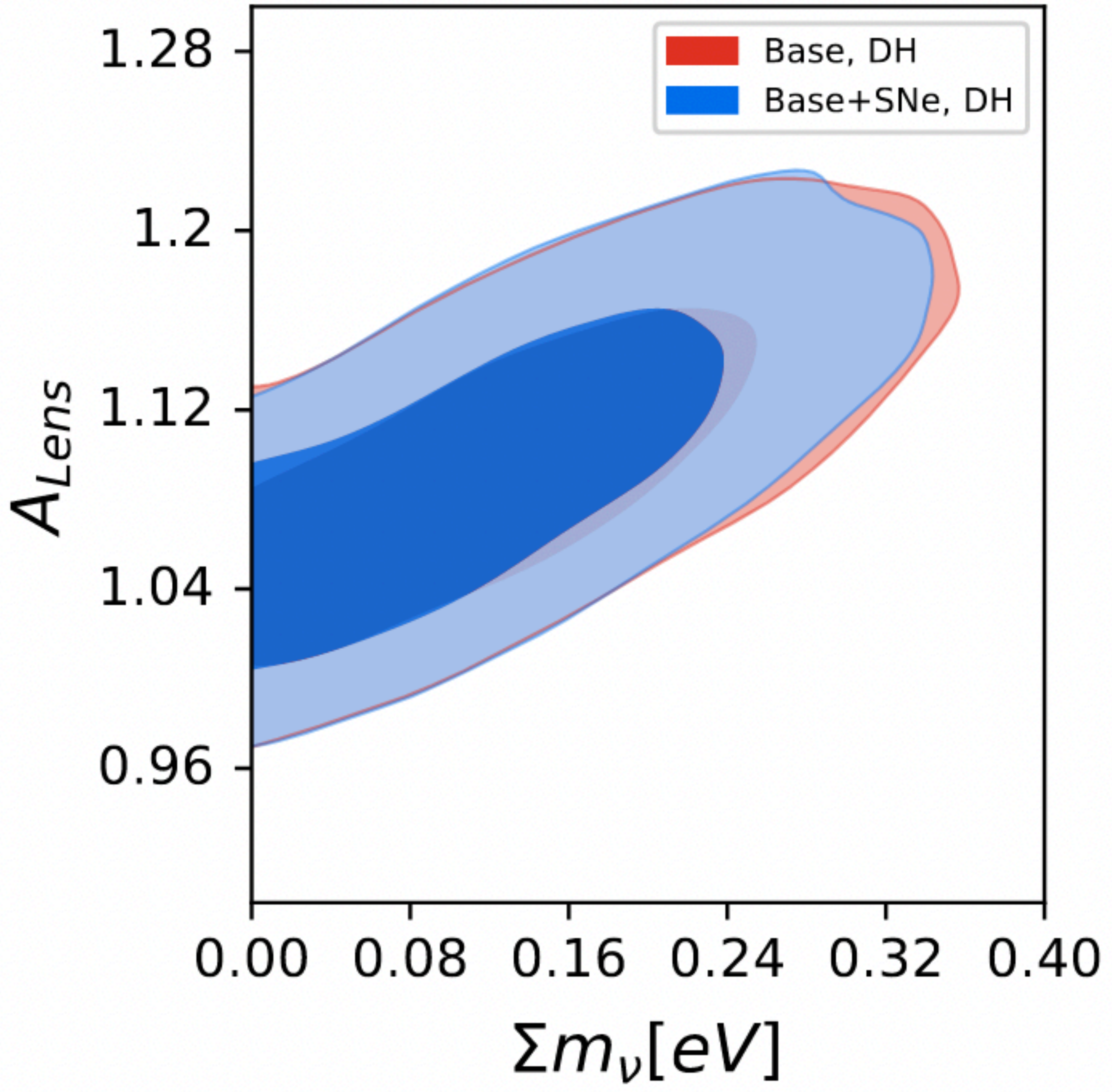
● ***Planck* TT 2015** $1000 \leq \ell \leq 2508$

Neutrinos are hot relics : less clustering on small scales, reducing CMB lensing!

(Planck coll., A&A'14)



(Choudhury & Hannestad JCAP'20)

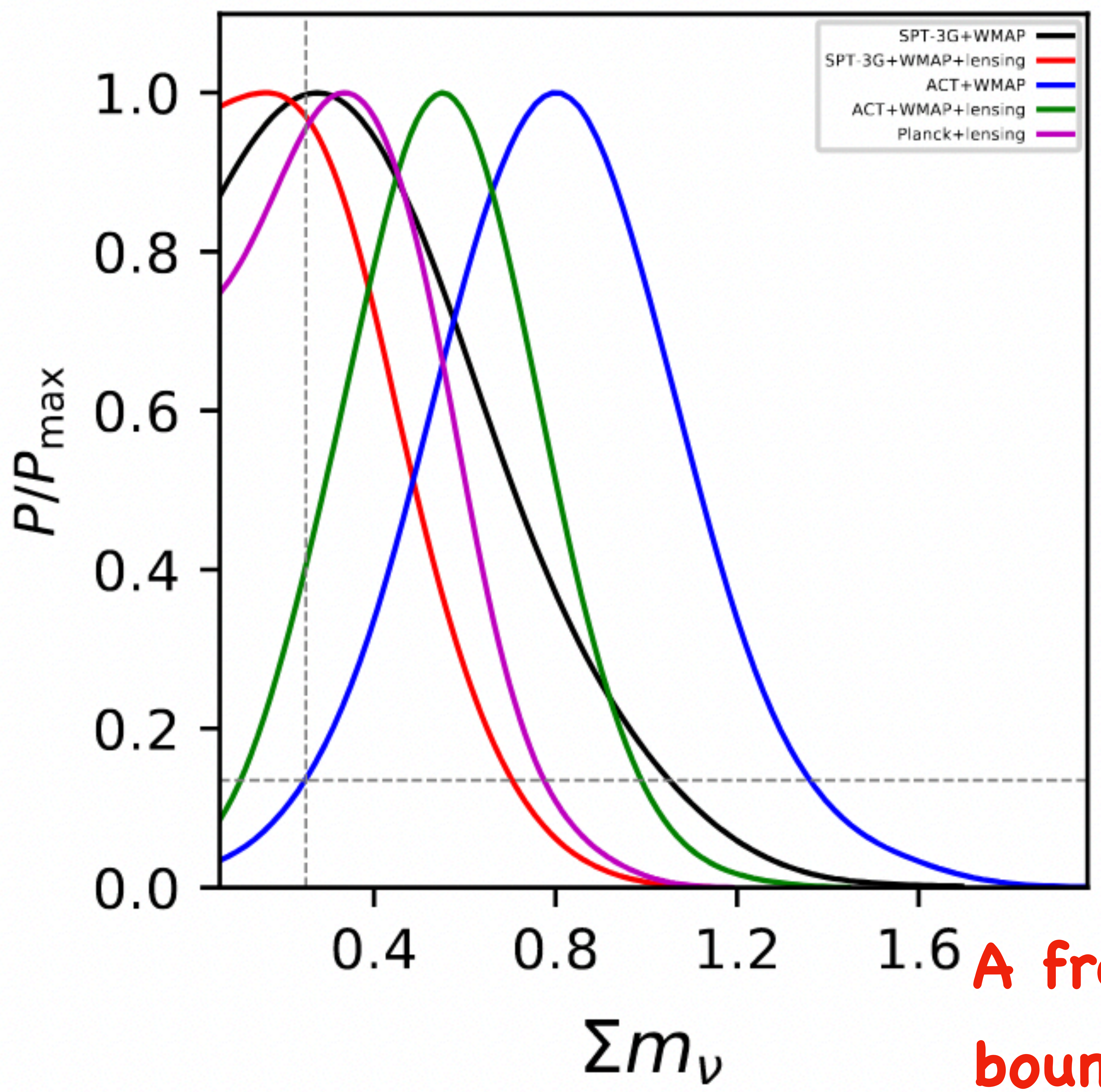


If $A_{\rm lens}$ is a free parameter the neutrino mass limits are significantly weakened

(Renzi et al PRD'18, Sgier et al 2110.03815)

If $A_{\rm lens}$ is a free parameter the neutrino mass limits are significantly weakened

(Di Valentino & Melchiorri 2112.02993)



68% CL limits

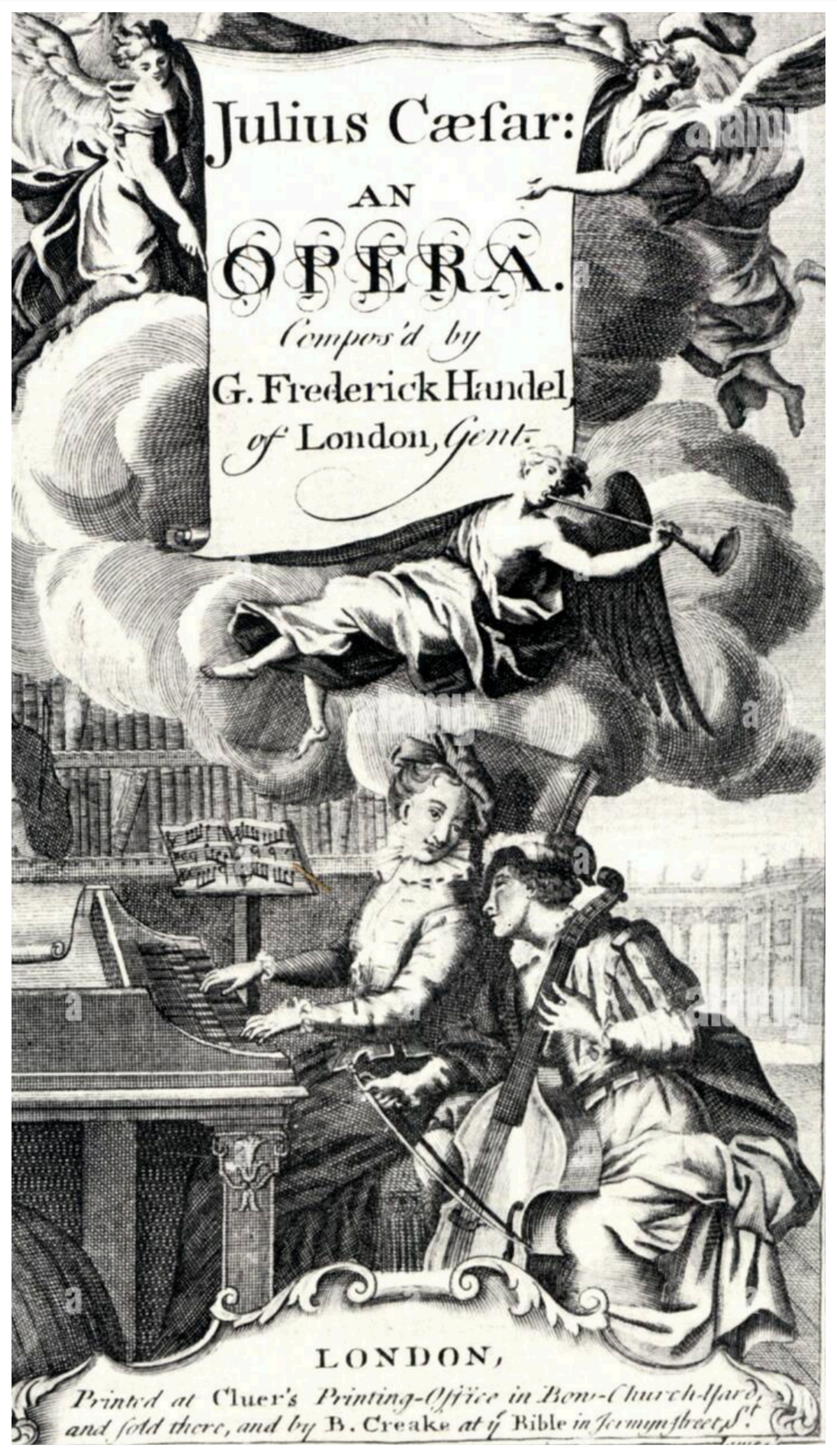
Dataset	Σm_ν [eV]
Planck ($+A_{\rm lens}$)	< 0.51
Planck+BAO ($+A_{\rm lens}$)	< 0.19
Planck+Pantheon ($+A_{\rm lens}$)	< 0.25
Planck+Lensing ($+A_{\rm lens}$)	$0.41^{+0.17}_{-0.25}$
ACT-DR4+WMAP	0.68 ± 0.31
ACT-DR4+WMAP+BAO	< 0.19
ACT-DR4+WMAP+Pantheon	< 0.25
ACT-DR4+WMAP+Lensing	0.60 ± 0.25
SPT-3G+WMAP	$0.46^{+0.14}_{-0.36}$
SPT-3G+WMAP+BAO	$0.22^{+0.056}_{-0.14}$
SPT-3G+WMAP+Pantheon	$0.25^{+0.052}_{-0.19}$
SPT-3G+WMAP+Lensing	< 0.37

A free $A_{\rm lens}$ leads to an agreement on $\sum m_\nu$ bounds between different CMB data sets

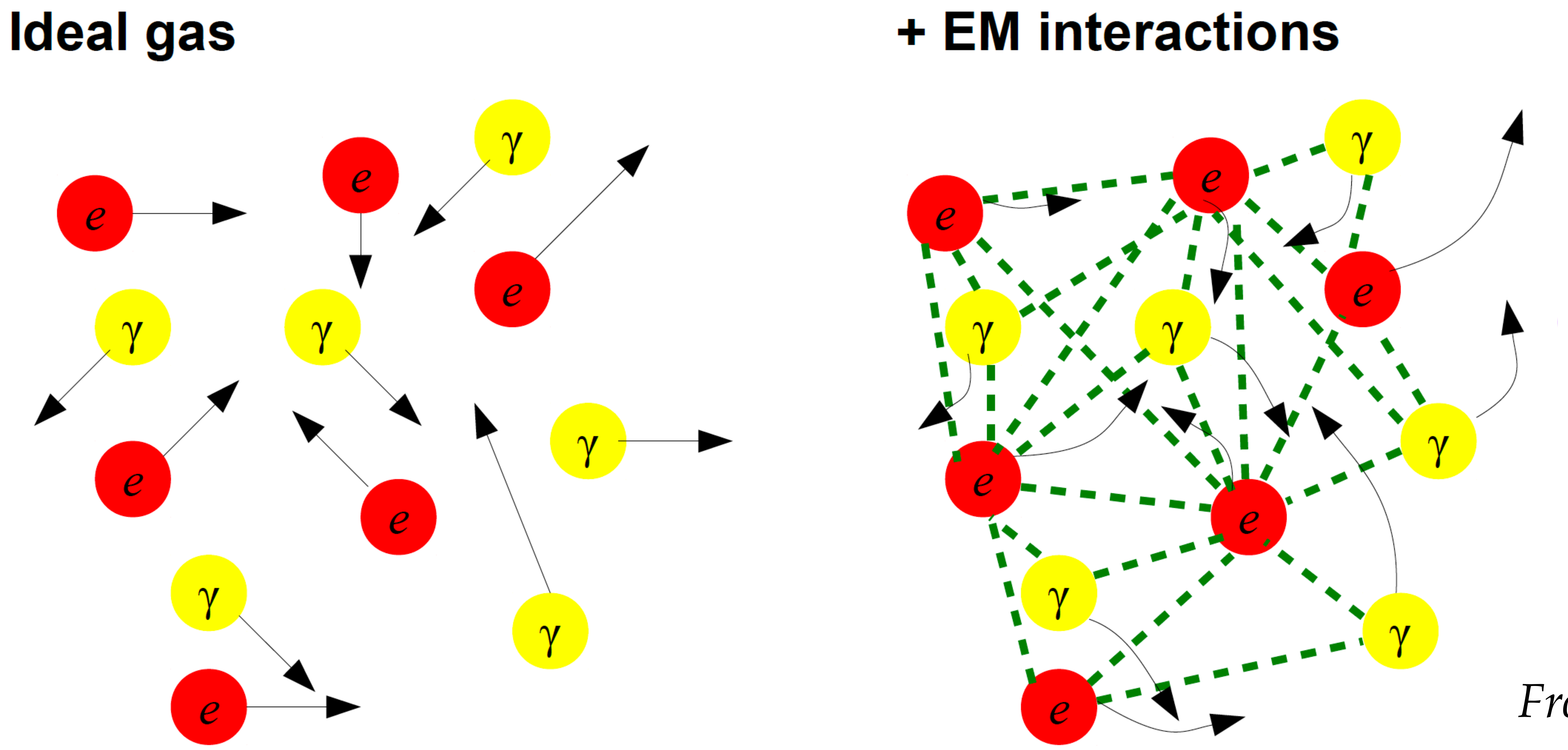
- All cosmological bounds on $\sum m_\nu$ are computed assuming that neutrinos behave as an ideal gas.

- BUT ideal gasses/perfect fluids do not exist in the physical universe.

A Historial precedent?



Dropping the ideal gas limit, the modified QED plasma equation of state leads to important corrections to $N_{\rm eff}$



From Y. Y. Y. Wong

Standard-model corrections to $N_{\rm eff}^{\rm SM}$	Leading-digit contribution
m_e/T_d correction	$+0.04$
$\mathcal{O}(e^2)$ FTQED correction to the QED EoS	$+0.01$
Non-instantaneous decoupling+spectral distortion	-0.005
$\mathcal{O}(e^3)$ FTQED correction to the QED EoS	-0.001
Flavour oscillations	$+0.0005$
Type (a) FTQED corrections to the weak rates	$\lesssim 10^{-4}$

Dicus et al PRD'82, Heckler PRD'94,
Fornengo et al PRD'97,
Lopez & Turner PRD'99,
Mangano et al PLB'02 ,
Bennett et al JCAP'20 & JCAP'21

Interacting neutrinos

Esteban & Salvado JCAP'21

See also Boehm et al PLB'01, Beacom, Bell & Dodelson PRL'04, Chacko et al PRD'04, Hannestad JCAP'05, Hannestad & Raffelt JCAP'05, Bell et al PRD'06, Mangano et al PRD'06, Friedland et al'07, Basboll et al PRD'09, Wilkinson et al JCAP'14, Cyr-Racine & Sirgurdson PRD'14, Archidiacono & Hannestad JCAP'14, Oldengott et al JCAP'15, Escudero et al JCAP'15, Oldengott et al JCAP'17, Brust et al JCAP'17, Lancaster et al JCAP'17, Di Valentino et al PRD'18, Forastieri et al JCAP'15 &PRD'19, Park et al PRD'19, Kreisch et al PRD'20, Stadler et al JCAP' 19 & JCAP'20, Blinov et al JCAP'20, Escudero & Witte EPJC'20, Gosh et al PRD'20, Mazumdar et al 2011.13685, Das & Ghosh PRD'21, Choudhury et al JCAP'21, Brinckmann et PRD'21, Mosbech et al JCAP'21

Long range neutrino interactions

- **If the mediator is light, long-range neutrino interactions**

$$S = \int \sqrt{-\mathcal{G}}\,\mathrm{d}^4x \left(-\frac{1}{2} D_\mu \hat{\phi} D^\mu \hat{\phi} - \frac{1}{2} M_\phi^2 \hat{\phi}^2 + i\bar{\psi}\not{D}\psi - m_0 \bar{\psi}\psi - g\hat{\phi}\bar{\psi}\psi \right)$$

Esteban & Salvado JCAP'21

- **Case similar to neutrino-dark energy models**

Bean PRD'01, Fardon et al JCAP'04, Kaplan, Nelson and Weiner PRL'04, Gu et al PRD'03, Peccei PRD'05, Bean and Magueijo, PLB'01

Long range neutrino interactions

Esteban & Salvado JCAP'21

$$S = \int \sqrt{-\mathscr{G}} \, \mathrm{d}^4 x \left(-\frac{1}{2} D_\mu \hat{\phi} D^\mu \hat{\phi} - \frac{1}{2} M_\phi^2 \hat{\phi}^2 + i \bar{\psi} \not{D} \psi - m_0 \bar{\psi} \psi - g \hat{\phi} \bar{\psi} \psi \right)$$

- **Long-range effects are present if** $M_\phi \gtrsim 10^{-25}$ eV
- **Laboratory, SN 1987A and CMB constraints:** $g \lesssim 10^{-7}$ **ensuring no spectral distortions and avoiding neutrino-neutrino scatterings**

Hannestad and G. Raffelt PRD' 05, Lattanzi & Valle PRL'07, Lattanzi et al PRD'13, Blinov et al PRL'19 , Agostini EPJC '15, K. Blum et al PLB'18, T. Brune and Päs PRD'19, Brdar et al PRD'20, Forastieri, Lattanzi & Natoli JCAP'15 &PRD'19

- $g \lesssim 10^{-7}$ & $\dfrac{g m_0}{M_\phi} > 1$ & $m_0 \sim 0.1$ eV & $\mathrm{M}_\phi \gg \mathrm{H}$ when $\mathrm{T} < \mathrm{m}_0$

⬇

$$10^{-8}\ \mathrm{eV} \gtrsim \mathrm{M}_\phi \gtrsim 10^{-25}\ \mathrm{eV}$$

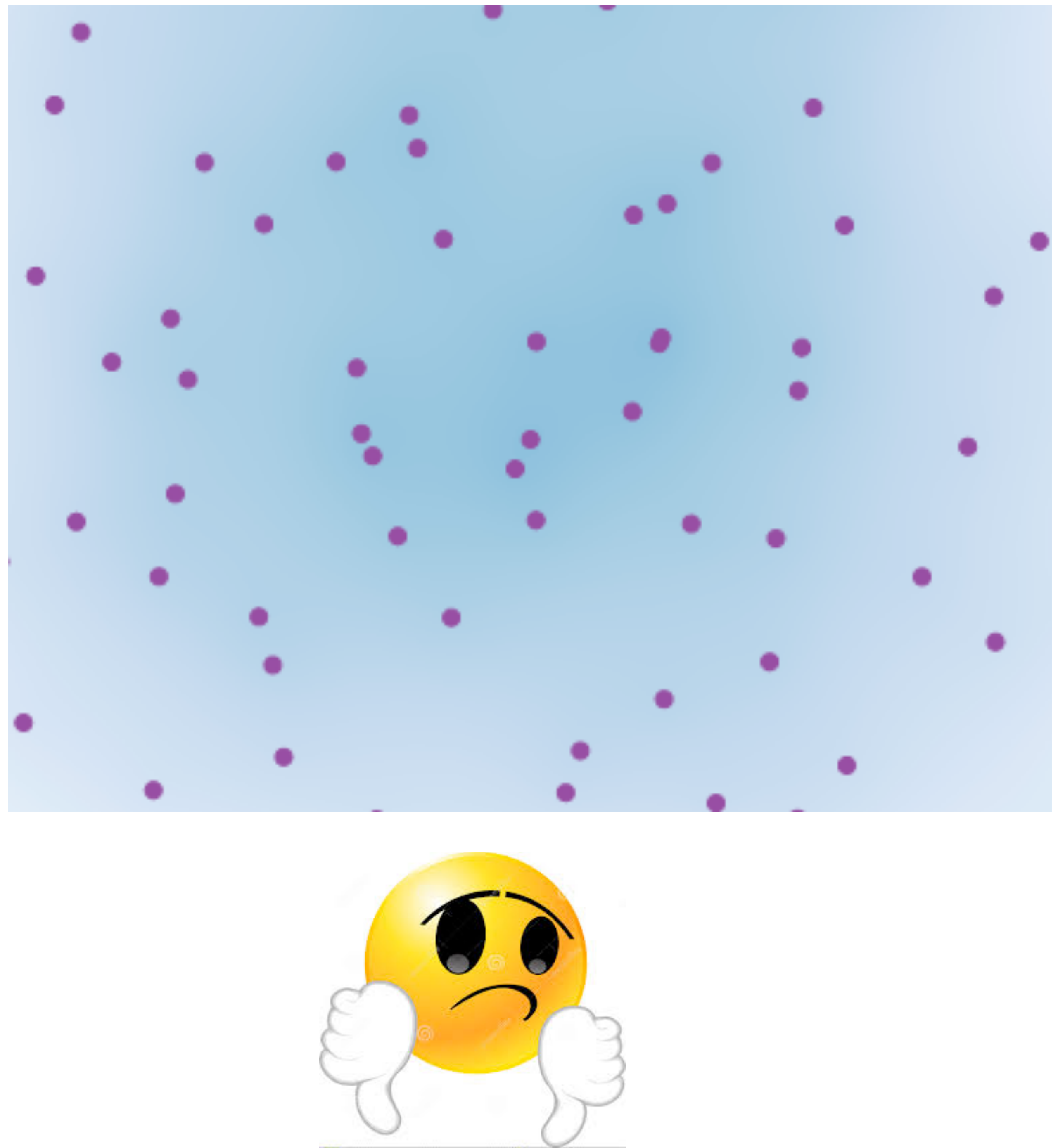
Long range neutrino interactions

$$S = \int \sqrt{-\mathcal{G}}\, \mathrm{d}^4x \left(-\frac{1}{2} D_\mu \hat{\phi} D^\mu \hat{\phi} - \frac{1}{2} M_\phi^2 \hat{\phi}^2 + i\bar{\psi}\not{D}\psi - m_0 \bar{\psi}\psi - g\hat{\phi}\bar{\psi}\psi \right)$$

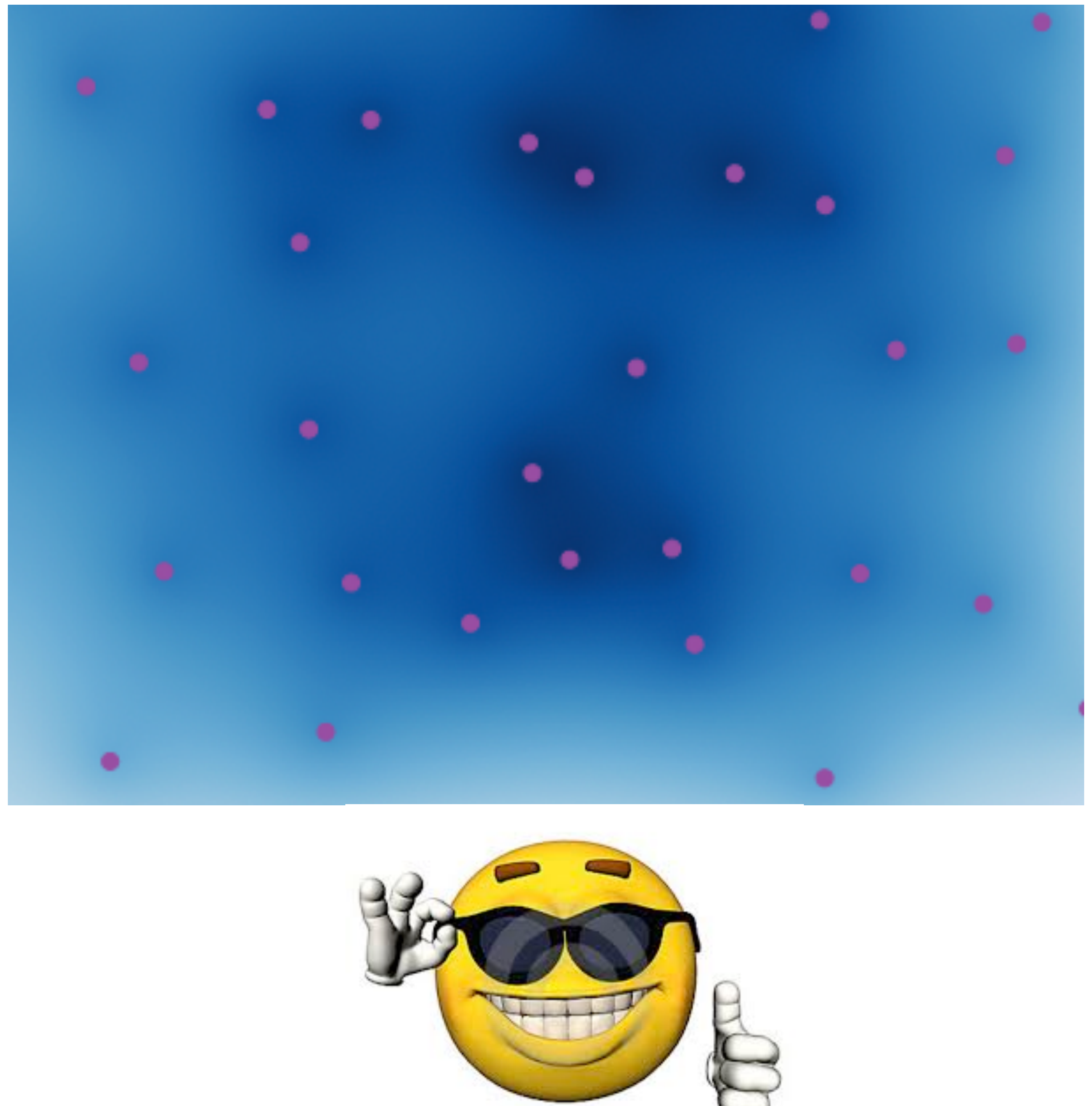
Esteban & Salvado JCAP'21

- **Effective neutrino mass** $\tilde{m} = m_0 + g\phi_0$

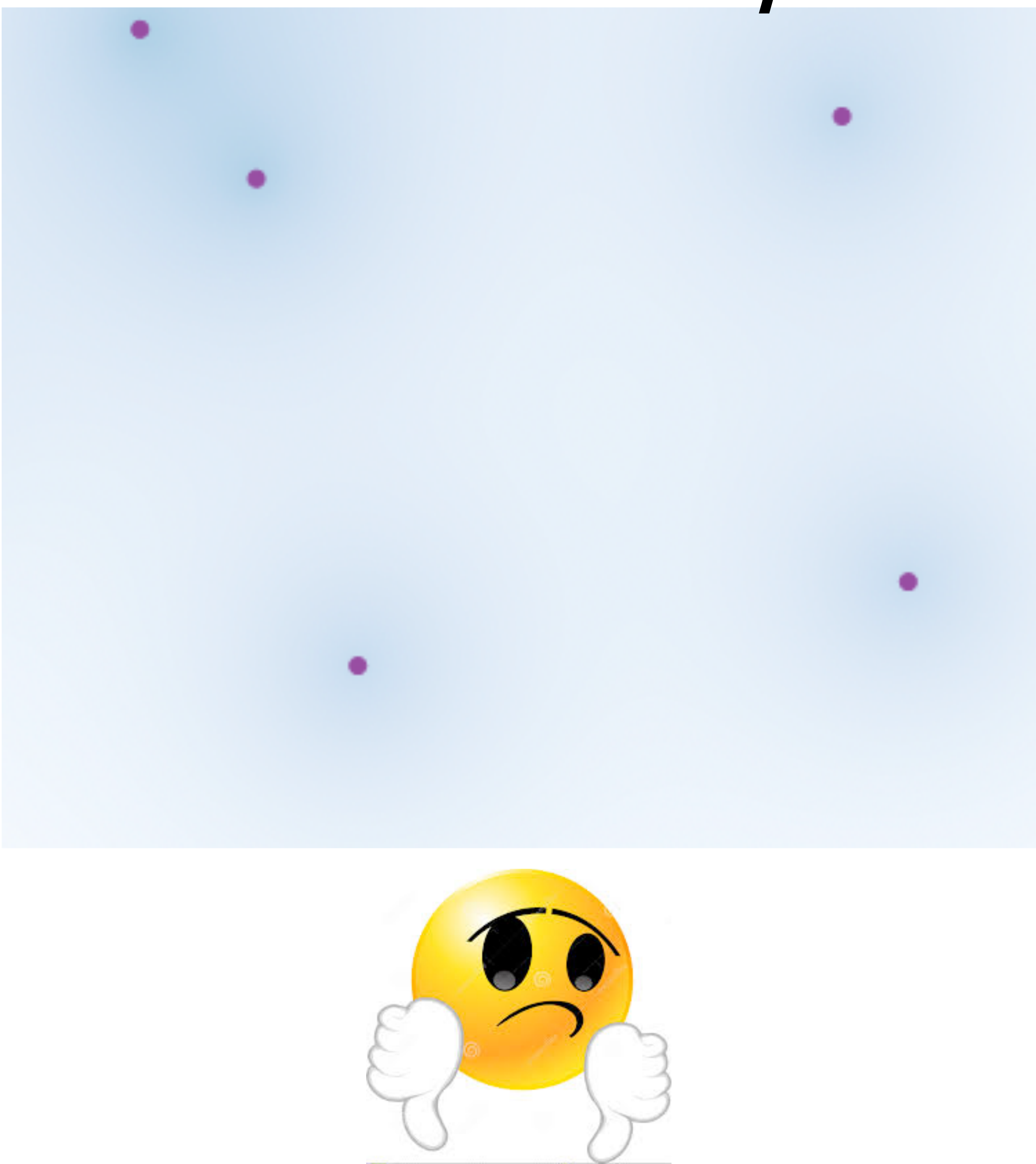
$T \gg m_0$



$T < m_0 \quad n > M_\phi^3$



$n \ll M_\phi^3$

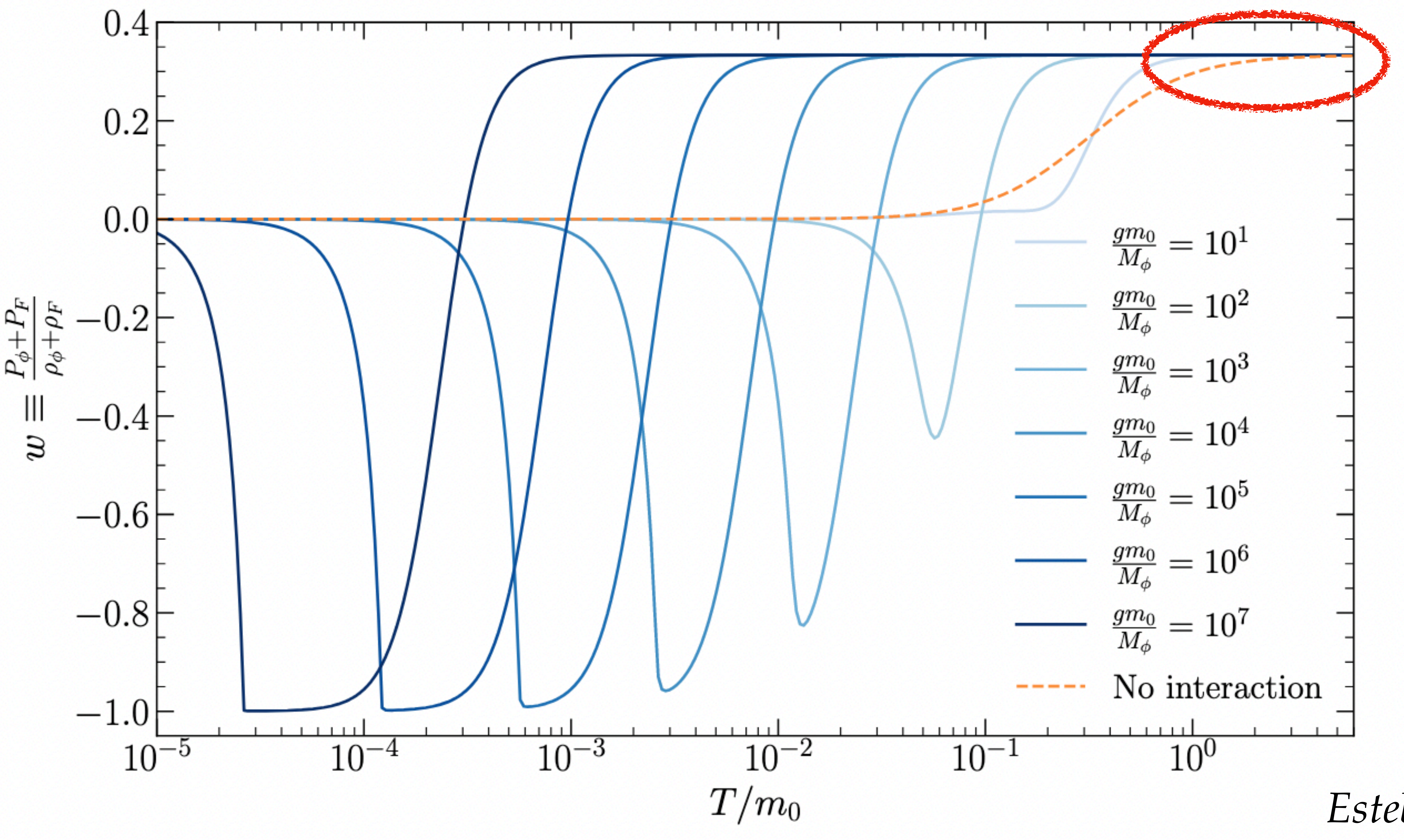


$T \gg \tilde{m}$

$$\phi_0 \simeq -\frac{\frac{\mathfrak{g}}{24} g \frac{m_0}{T} T^3}{M_\phi^2 + \frac{\mathfrak{g}}{24} g^2 T^2}$$

$$\tilde{m} \simeq m_0 \frac{1}{1 + \frac{\mathfrak{g}}{24} \frac{g^2 T^2}{M_\phi^2}}$$

$T \gg m_0$ **No interaction effects: equation of state is that of an ideal gas**



Esteban & Salvado JCAP'21

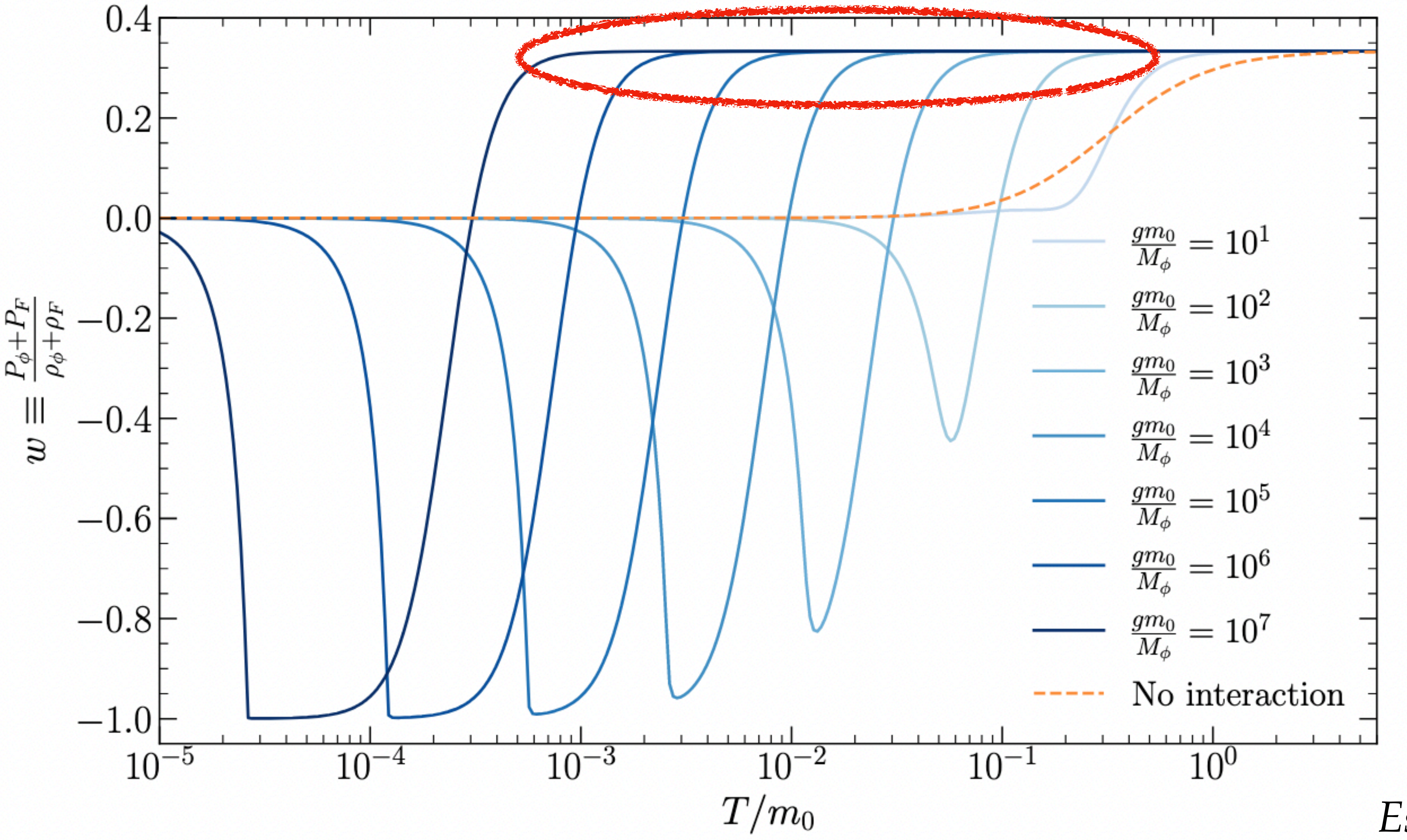
$T \gg \tilde{m}$

$$\phi_0 \simeq -\frac{\frac{\mathfrak{g}}{24} g \frac{m_0}{T} T^3}{M_\phi^2 + \frac{\mathfrak{g}}{24} g^2 T^2}$$

$$\tilde{m} \simeq m_0 \frac{1}{1 + \frac{\mathfrak{g}}{24} \frac{g^2 T^2}{M_\phi^2}}$$

$$\frac{\mathfrak{g}}{24} \frac{g^2 T^2}{M_\phi^2} \gg \frac{m_0}{T}$$

Sourced scalar field keeps neutrinos relativistic!



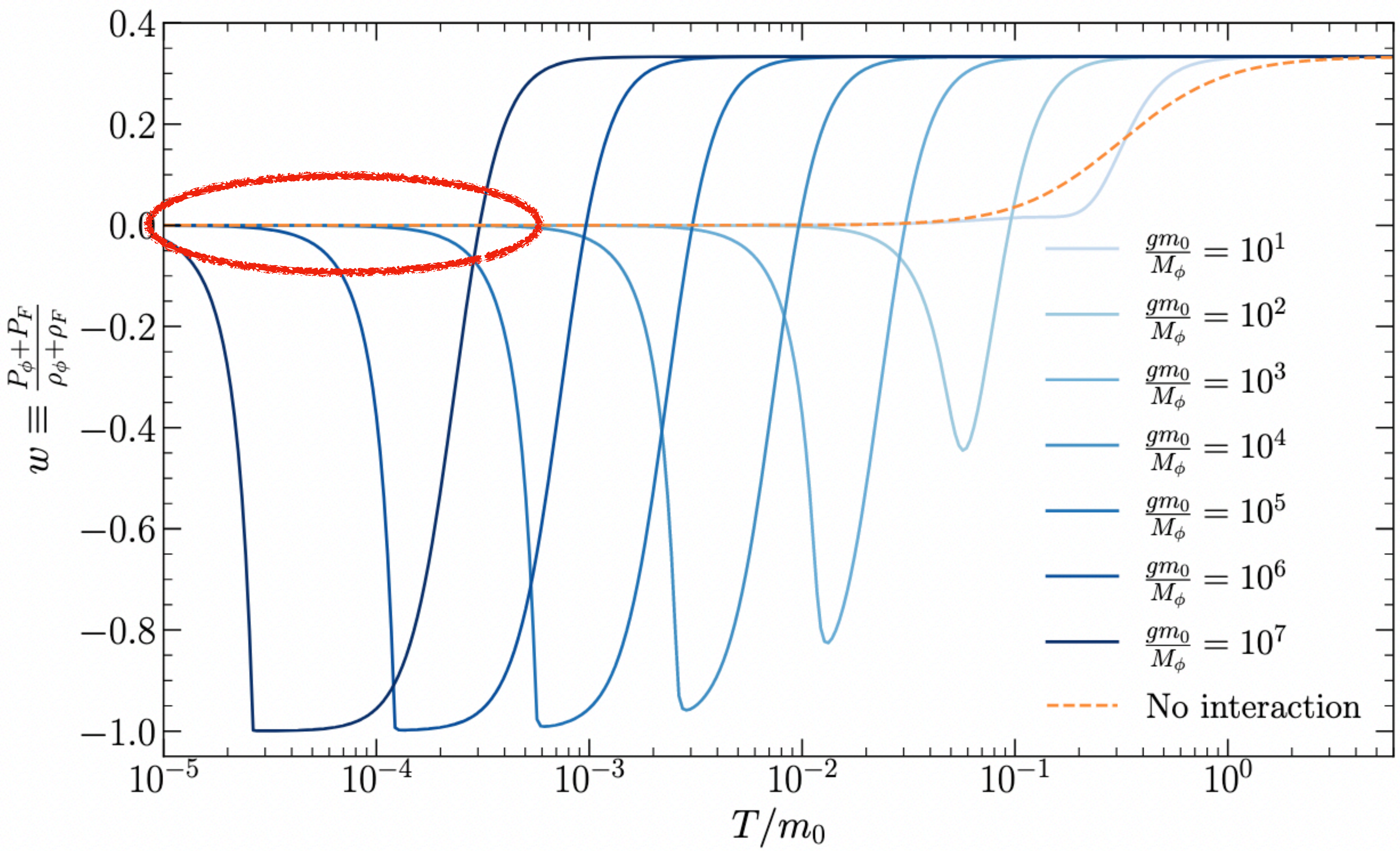
Esteban & Salvado JCAP'21

$T \ll \tilde{m}$

$$\phi_0 = \simeq -\frac{3\zeta(3)\mathfrak{g}}{4\pi^2} g \frac{T^3}{M_\phi^2} \qquad \tilde{m} \simeq m_0\left(1 - \frac{3\zeta(3)\mathfrak{g}}{4\pi^2}\frac{g^2T^2}{M^2}\frac{T}{m_0}\right)$$

$T \ll m_0$

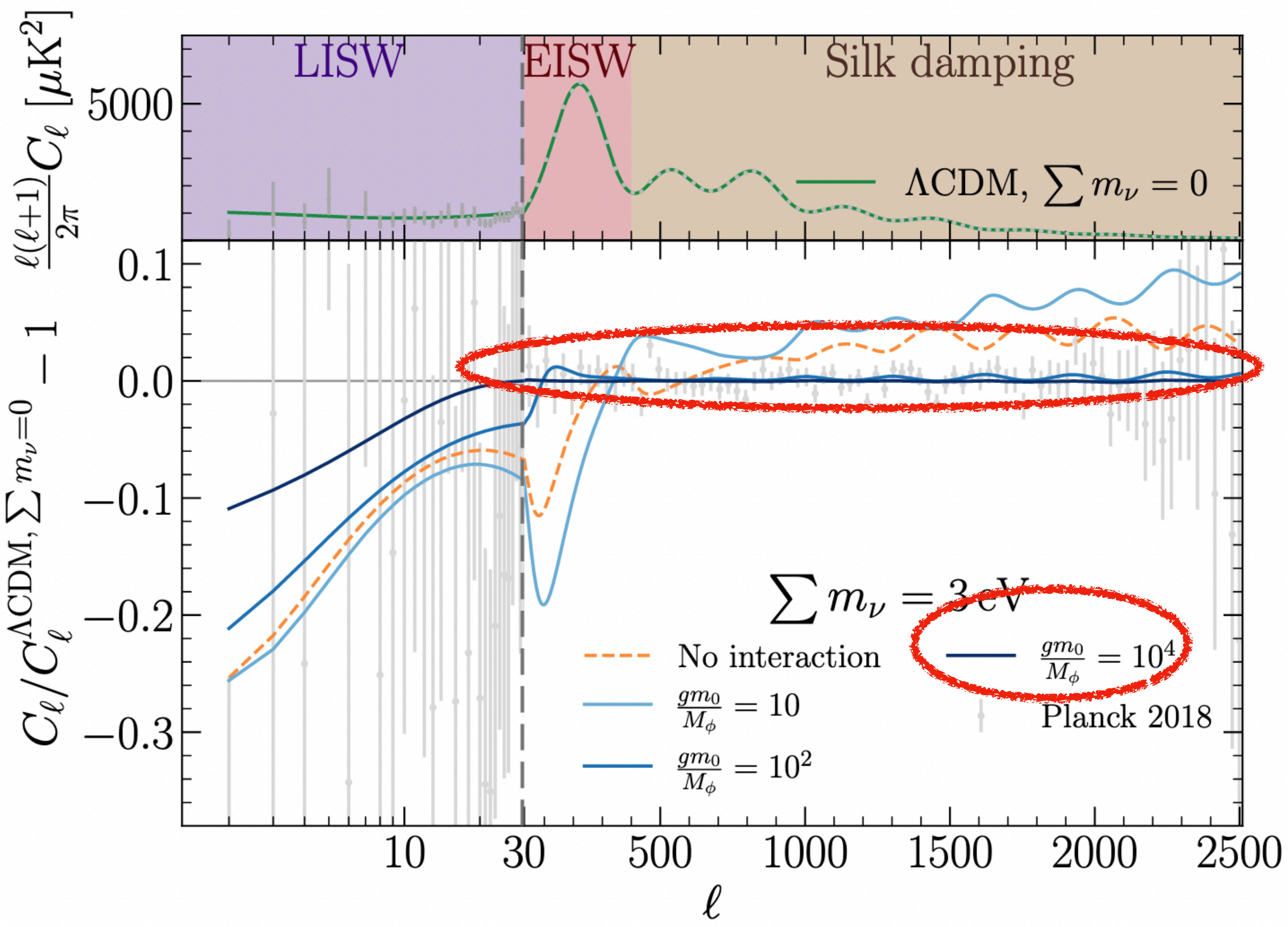
Neutrinos are non-relativistic: Inter-particle distance gets larger than the interaction range.
Long-range effects are switched off.

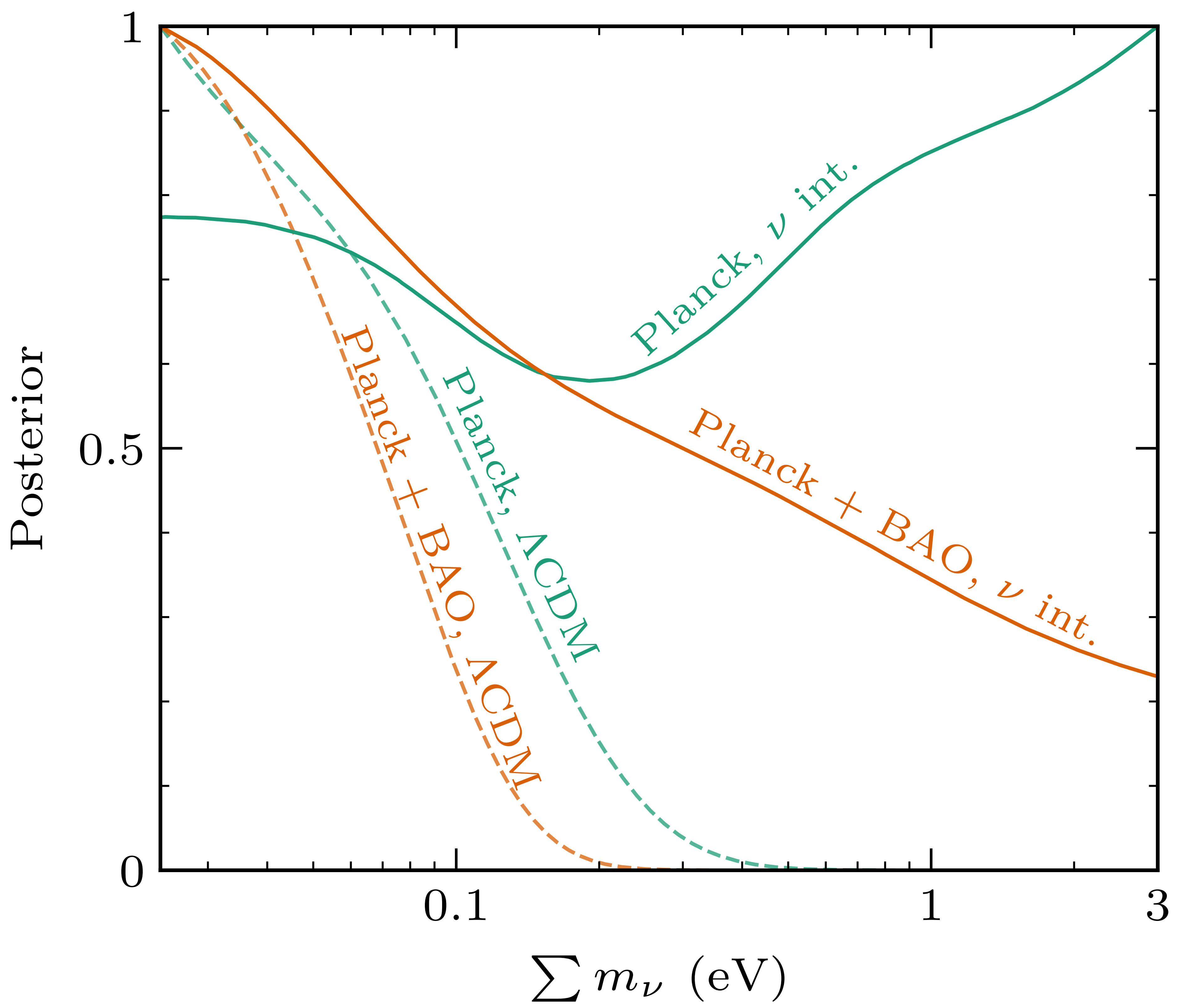


Esteban & Salvado JCAP'21

Long range neutrino interactions

- **Longe interactions modify the w = 1/3 to w = 0 neutrino transition.**
  (Cuoco, Lesgourgues et al PRD'05, OLdengott et al JCAP'19)
- **CMB neutrino mass limits could even be even avoided if the relativistic to non-relativistic transition in the neutrino sector is sufficiently delayed!**





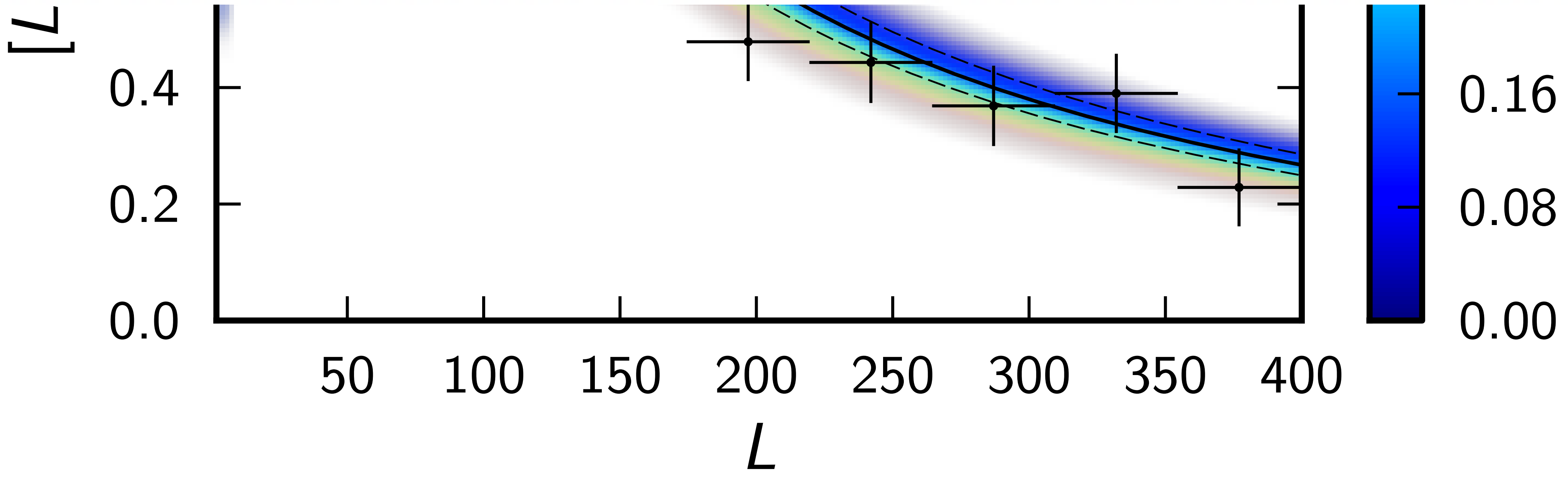
Long range neutrino interactions & the $A_{\rm lens}$ tension

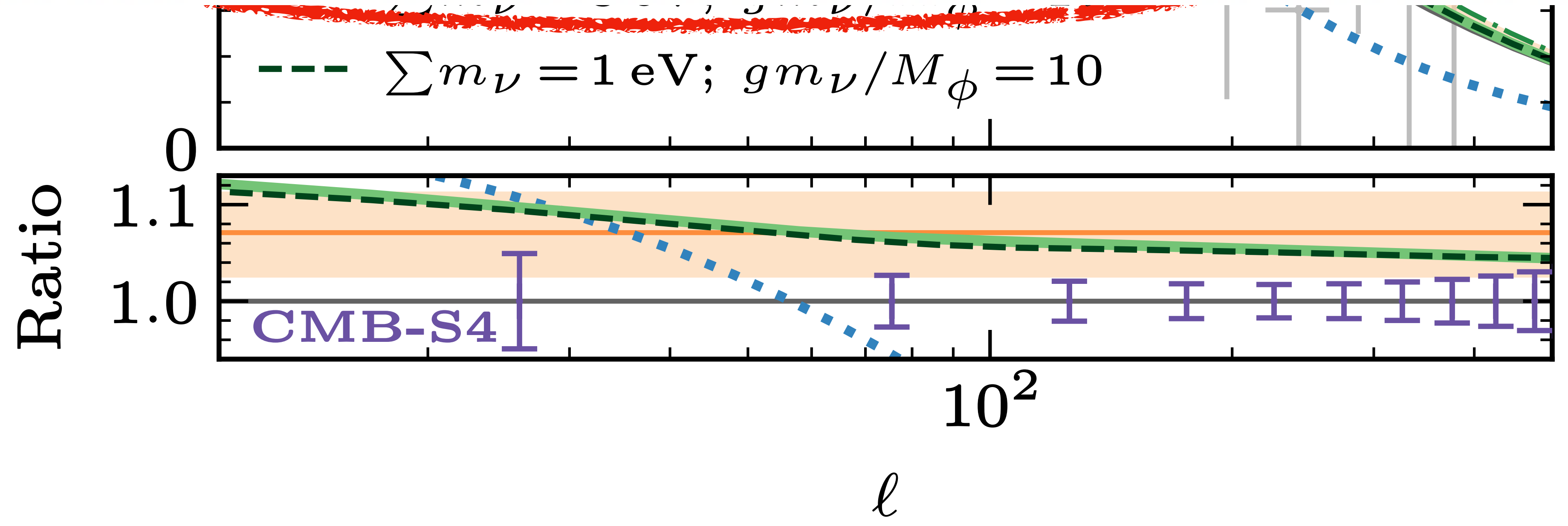
(Planck coll. A&A'14)

Esteban et al 2202.04656

$$\Delta\chi^2_{\rm eff} = \chi^2_{\rm eff}(A_{\rm lens}=1) - \chi^2_{\rm eff}(A_{\rm lens}\neq 1)$$

	TTTEEE+lowl	TTTEEE+lowl+lensing	TTTEEE+lowl+lensing+BAO
ΛCDM	9.66	3.43	4.26
Neutrino self-interactions	4.87	0.76	2.71





Neutrino long-range interactions mimic an enhanced lensing contribution, as preferred by the data!

A PHENOMENOLOGICAL (PRACTICAL?) APPROACH...

- May help in solving the so-called H_0 TENSION

- May help in solving the A_{lens} TENSION

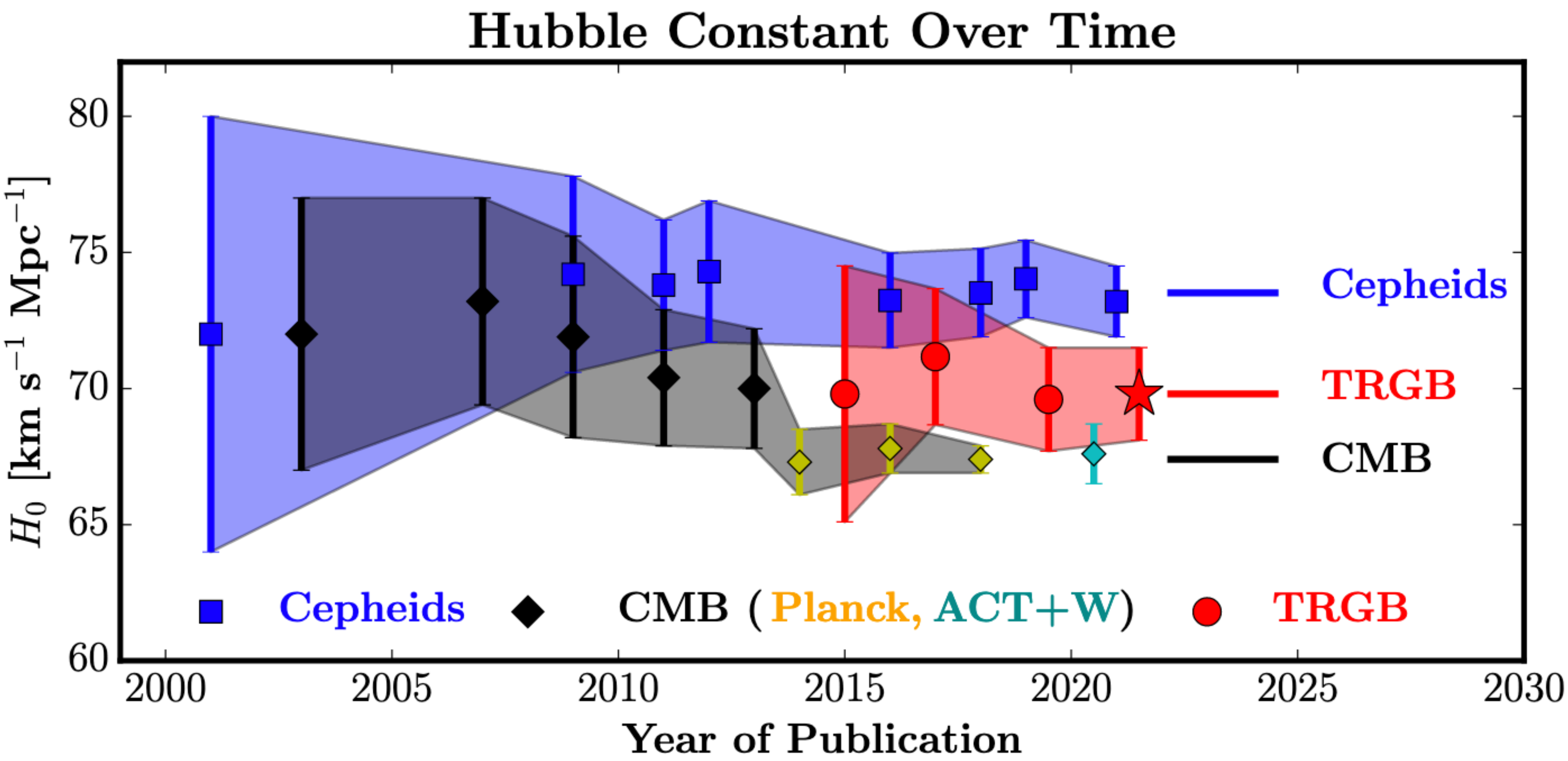
- May help in solving the σ_8 TENSION *Mosbech et al, JCAP'21*

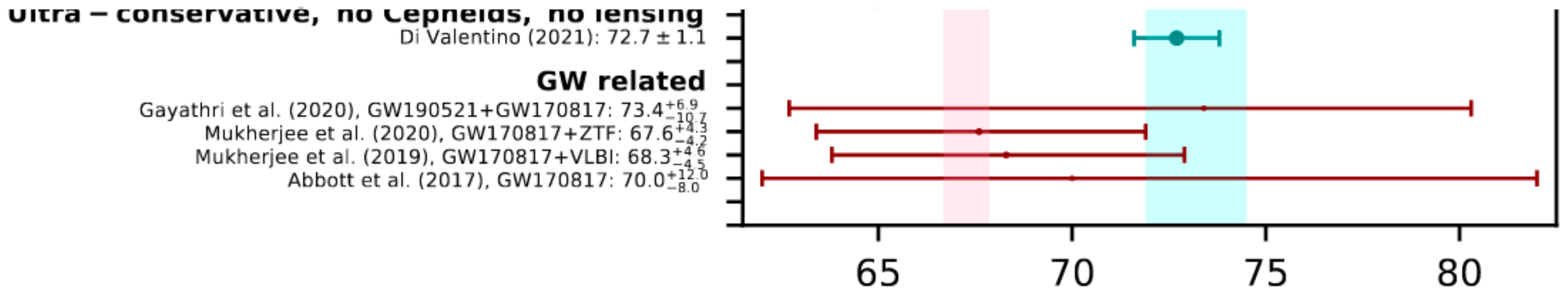
- May alleviate current sterile neutrino TENSIONS between short baseline oscillation and cosmological measurements

Dasgupta & Kopp PRL'14, Chu et al JCAP'15, Hannestad et al PRL'14, Saviano et al PRD'014, Mirizzi et al PRD'15, Archidiacono et al PRD'15 &'16 & JCAP'16, Forastieri et al JCAP'17, Chu et al JCAP'18, Archidiacono et al JCAP'20

The Hubble constant tension

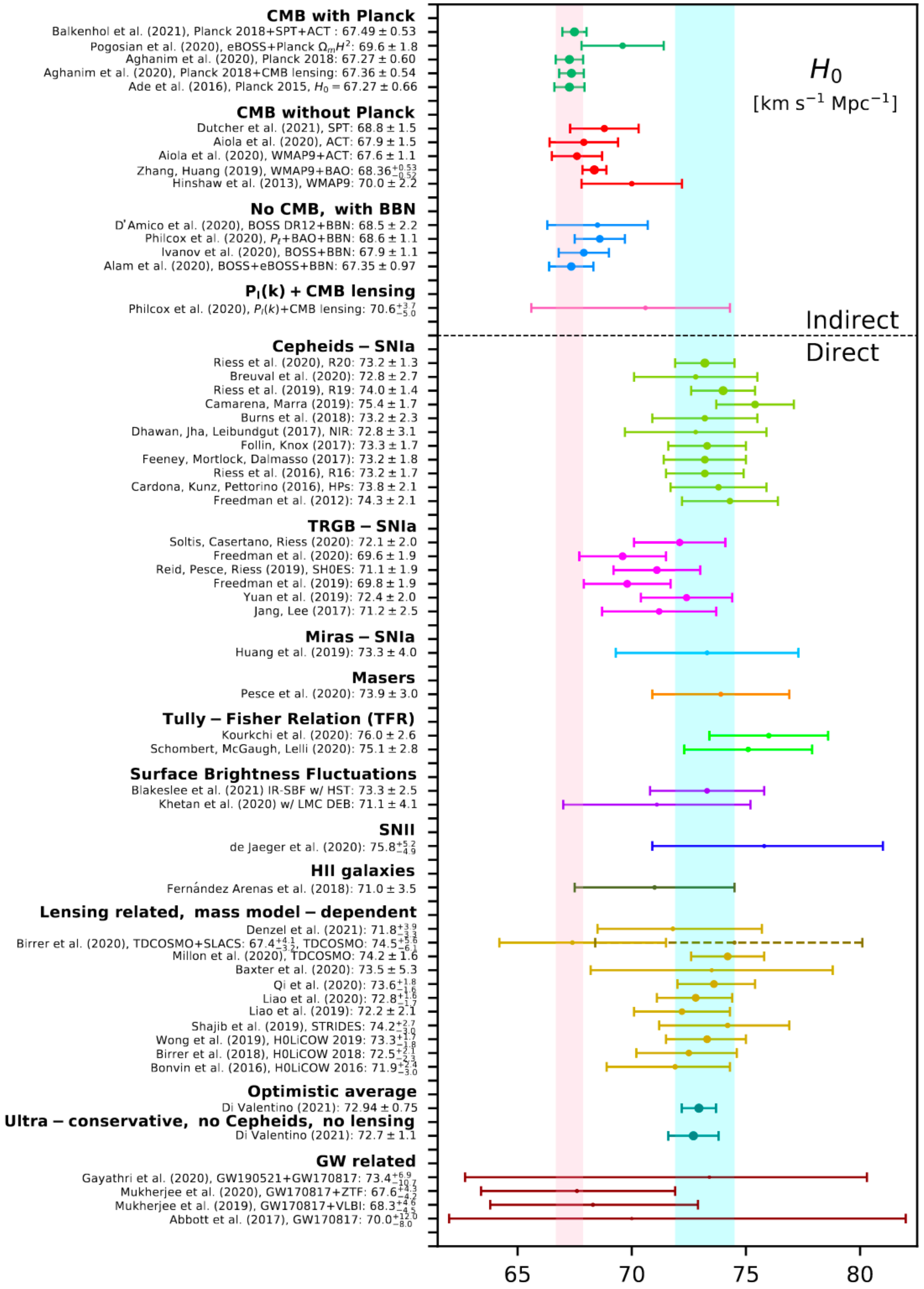
W. Freedman, APJ'21





Di Valentino et al Class.Quant.Grav'21
See also Schöneberg et al, 2107.10291

The Hubble constant tension



$$H_0 = 67.27 \pm 0.60 \text{ km/s/Mpc}$$

Planck Coll. A&A'20

$$5\sigma$$

$$H_0 = 73.04 \pm 1.04 \text{ km/s/Mpc}$$

Riess et al 2112.04510

Di Valentino et al Class.Quant.Grav'21
See also Schöneberg et al, 2107.10291

CMB and the Hubble parameter

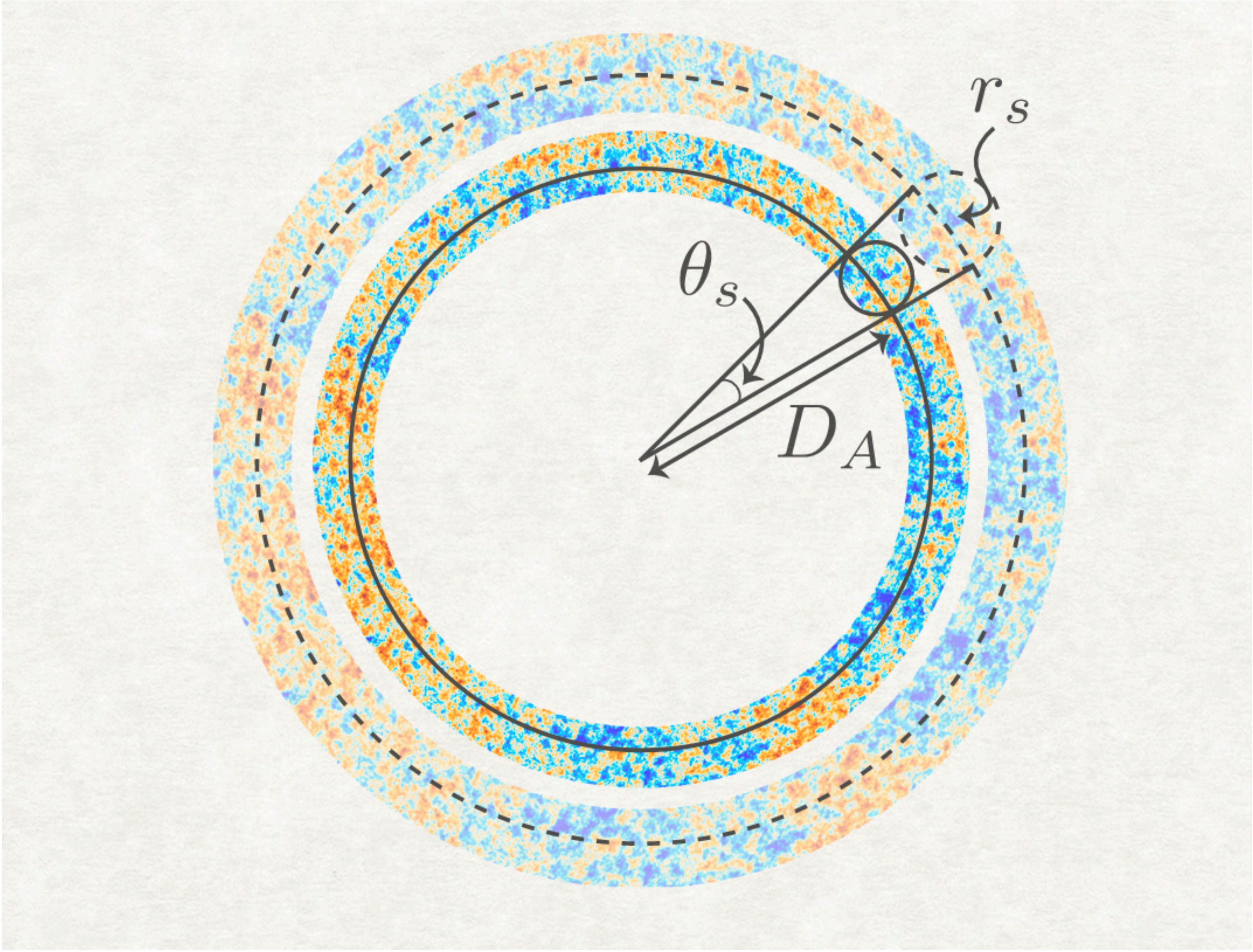
- From measurements of the matter and baryon densities given a model: derivation of r_s^* at the last scattering redshift z_s

- From the position of the CMB peaks, the comoving angular diameter distance extracted:

$$D_A^\star \equiv r_s^\star/\theta_s^\star$$

- Once we have the angular diameter distance, we can infer the value of H_0.

$$D_A^\star \propto 1/H_0$$



Could the last scattering surface be closer?
Could CMB spots be smaller?

From V. Poulin

Interacting neutrinos & the Hubble constant tension

Free-streaming neutrinos travel supersonically through the photon-baryon plasma at early times, inducing a net phase shift in the CMB power spectra towards larger scales (smaller multipoles), leading to a physical size of the photon sound horizon at last scattering that is slightly larger.

Bashinsky & Seljak PRD'04, Follin et al PRL'15; Baumann et al JCAP'16, Choi, Chiang & LoVerde JCAP'18, Baumann, Green & Zaldarriaga JCAP'17

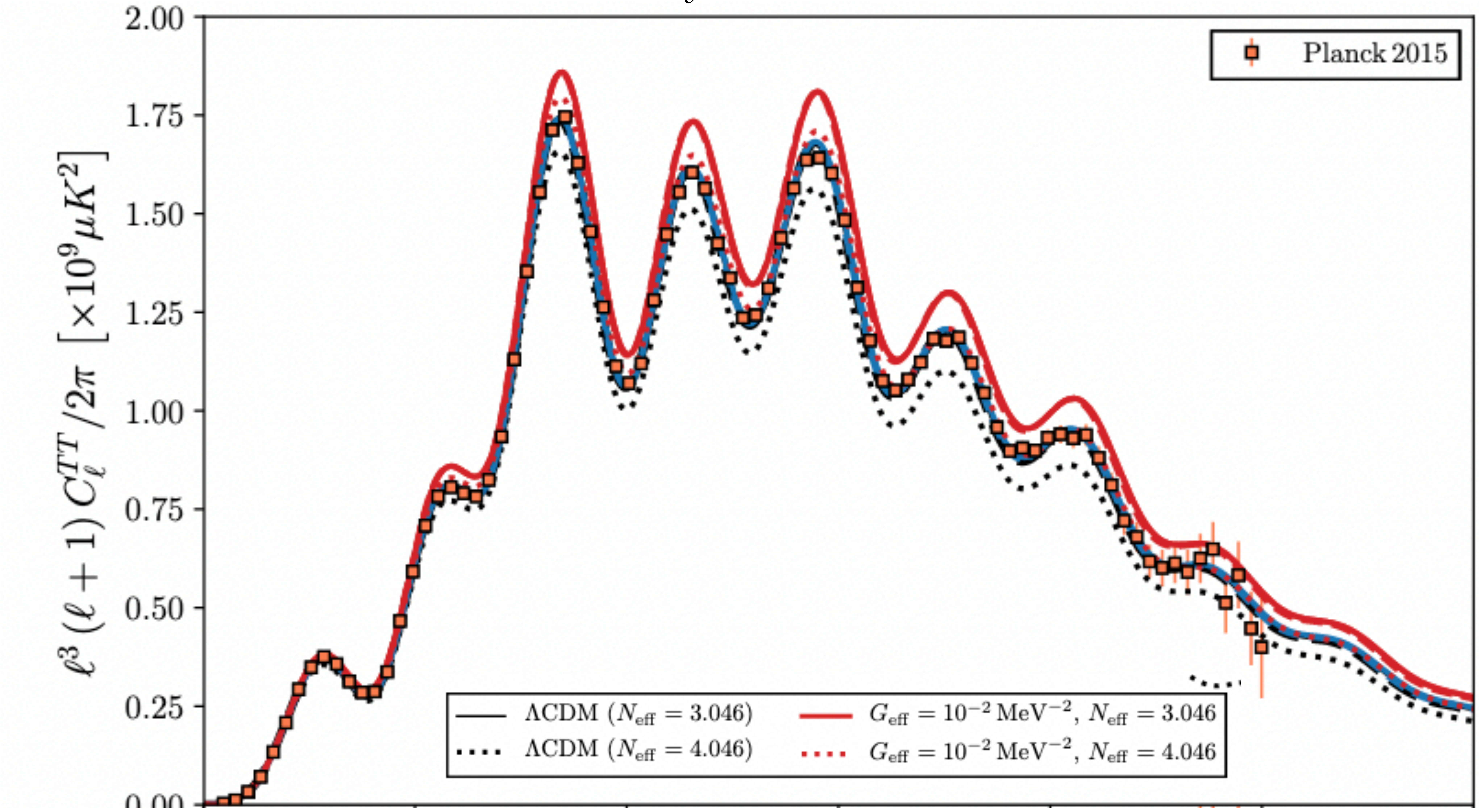
$$\delta\phi \simeq 0.1912\pi\frac{\rho_\nu}{\rho_r}$$

Interacting neutrinos shift the power spectrum towards towards smaller scales and boost their fluctuation amplitude, reducing the physical size of photon sound horizon at last scattering: a smaller value of D_A = higher value of H_0 is required!

$$\theta_s \equiv r_s/D_A \qquad D_A^\star \propto 1/H_0$$

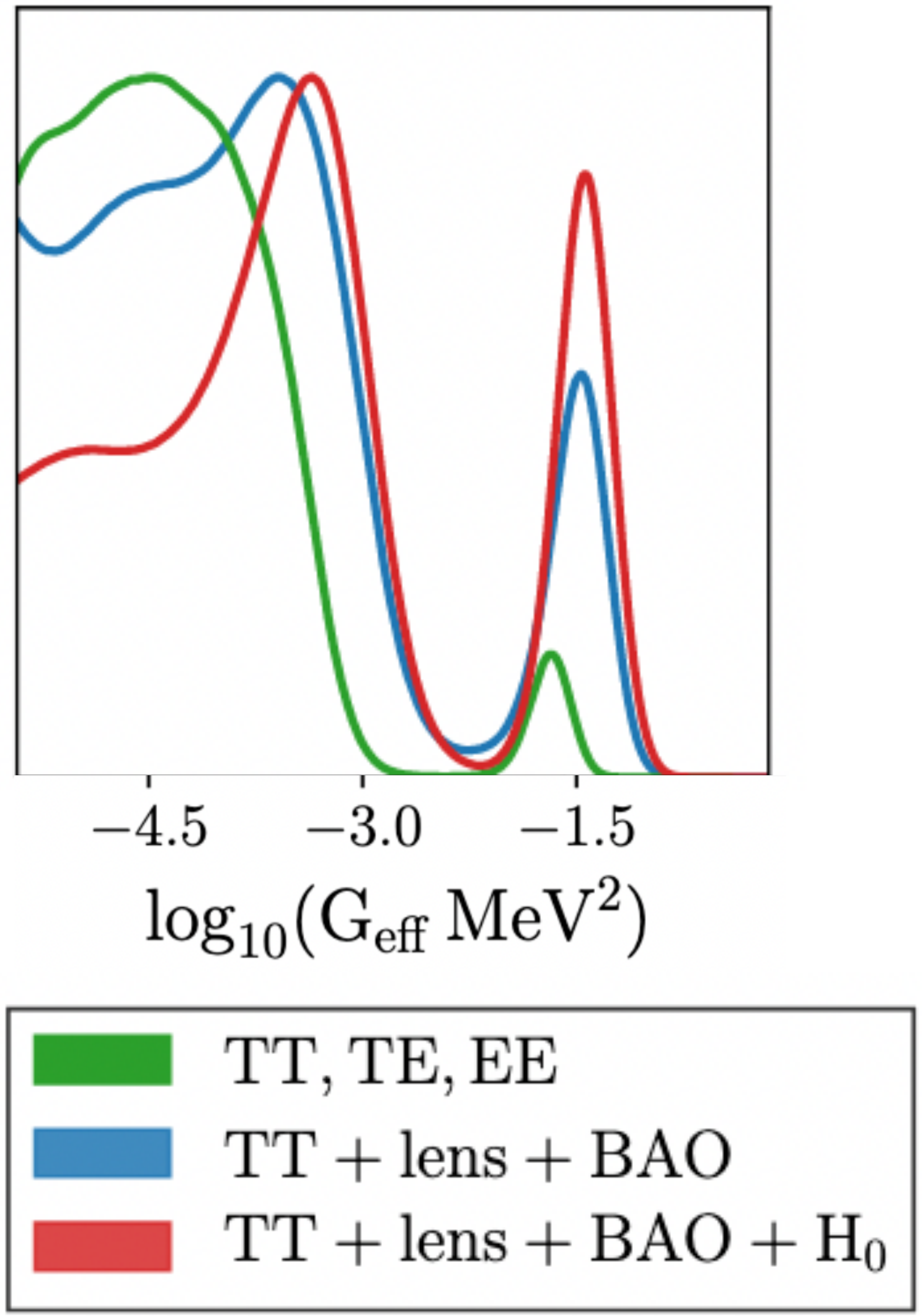
Interacting neutrinos & the Hubble constant tension

Kreisch, Cyr-Racine & Doré, PRD'20



Interacting neutrinos & the Hubble constant tension

Kreisch, Cyr-Racine & Doré, PRD'20



Heavy mediator: Effective four-fermion interaction

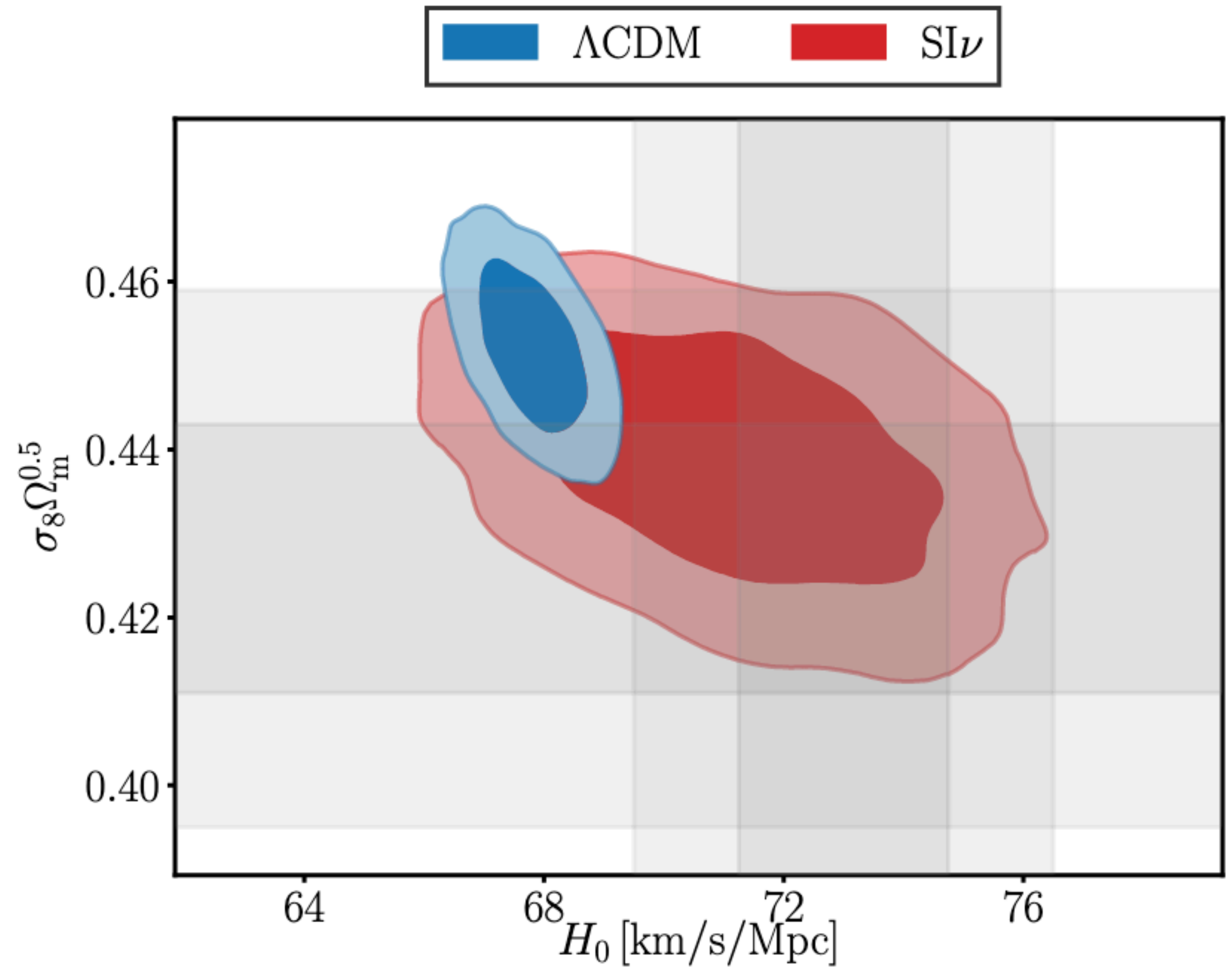
$$G_{\rm eff}\bar{\nu}\nu\bar{\nu}\nu \qquad G_{\rm eff} = \frac{g^2}{m_\phi^2} \qquad G_{\rm eff} \gg G_F$$

Neutrinos experience scattering after decoupling:
Increasing $G_{\rm eff}$ delays neutrino free-streaming

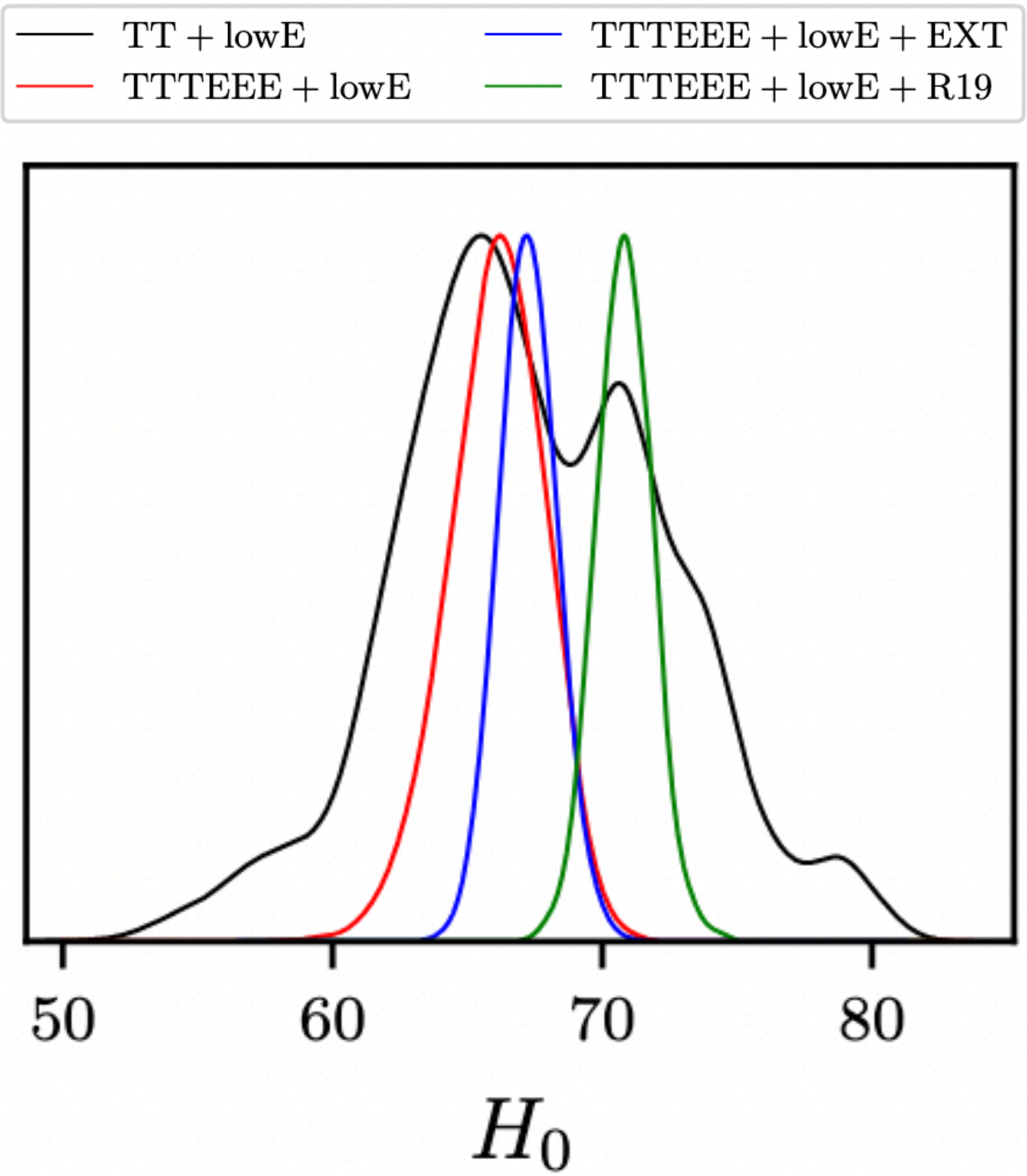
$$G_{\rm eff} < 1.4 \times 10^2\ {\rm GeV}^{-2}$$

$$G_{\rm eff} = 2.5^{+0.8}_{-0.5} \times 10^4\ {\rm GeV}^{-2}$$

Interacting neutrinos & the Hubble constant tension

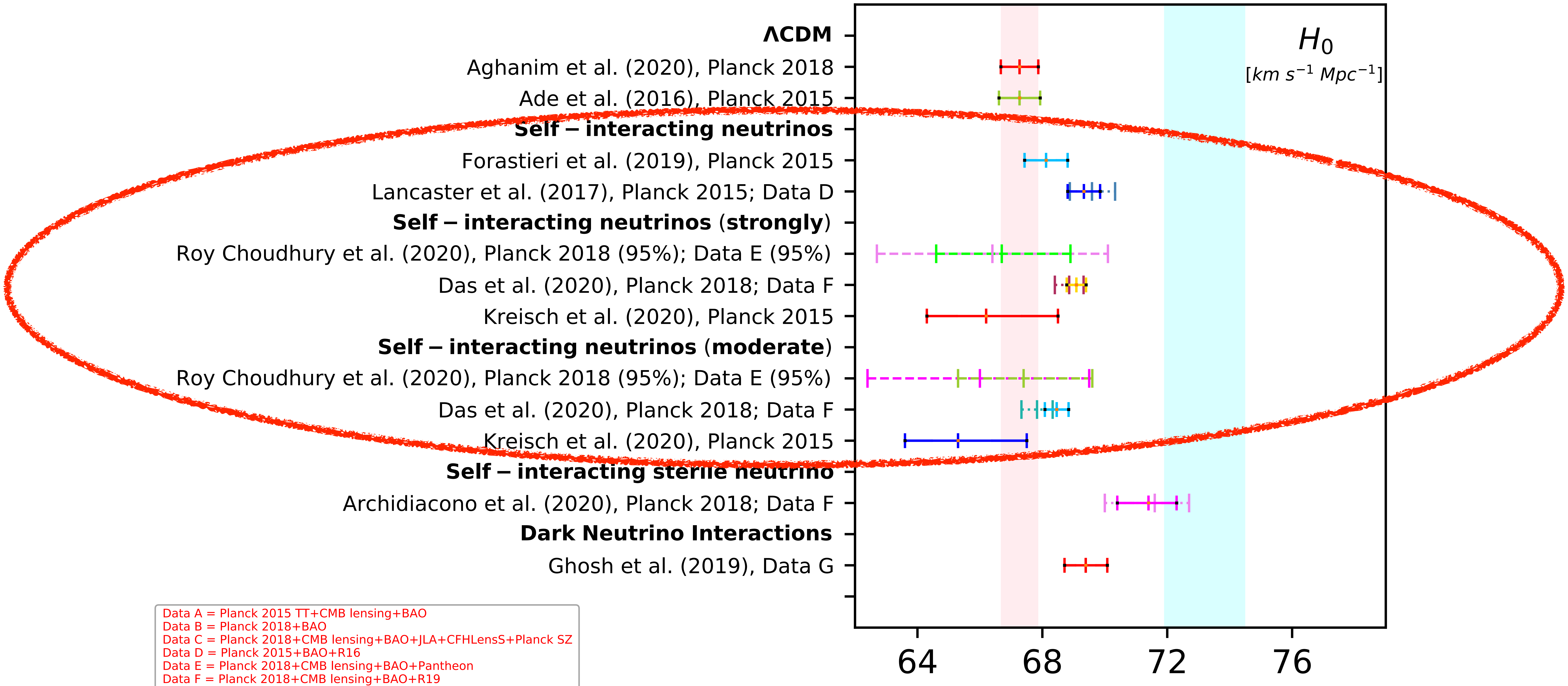


Kreisch, Cyr-Racine & Doré, PRD'20



Choudhury, Hannestad & Tram JCAP'21
See also Brinckmann, Chang and LoVerde PRD'21
Das & Ghosh JCAP'21, Blinov et al PRL'19

Non-standard neutrino scenarios & the Hubble constant tension



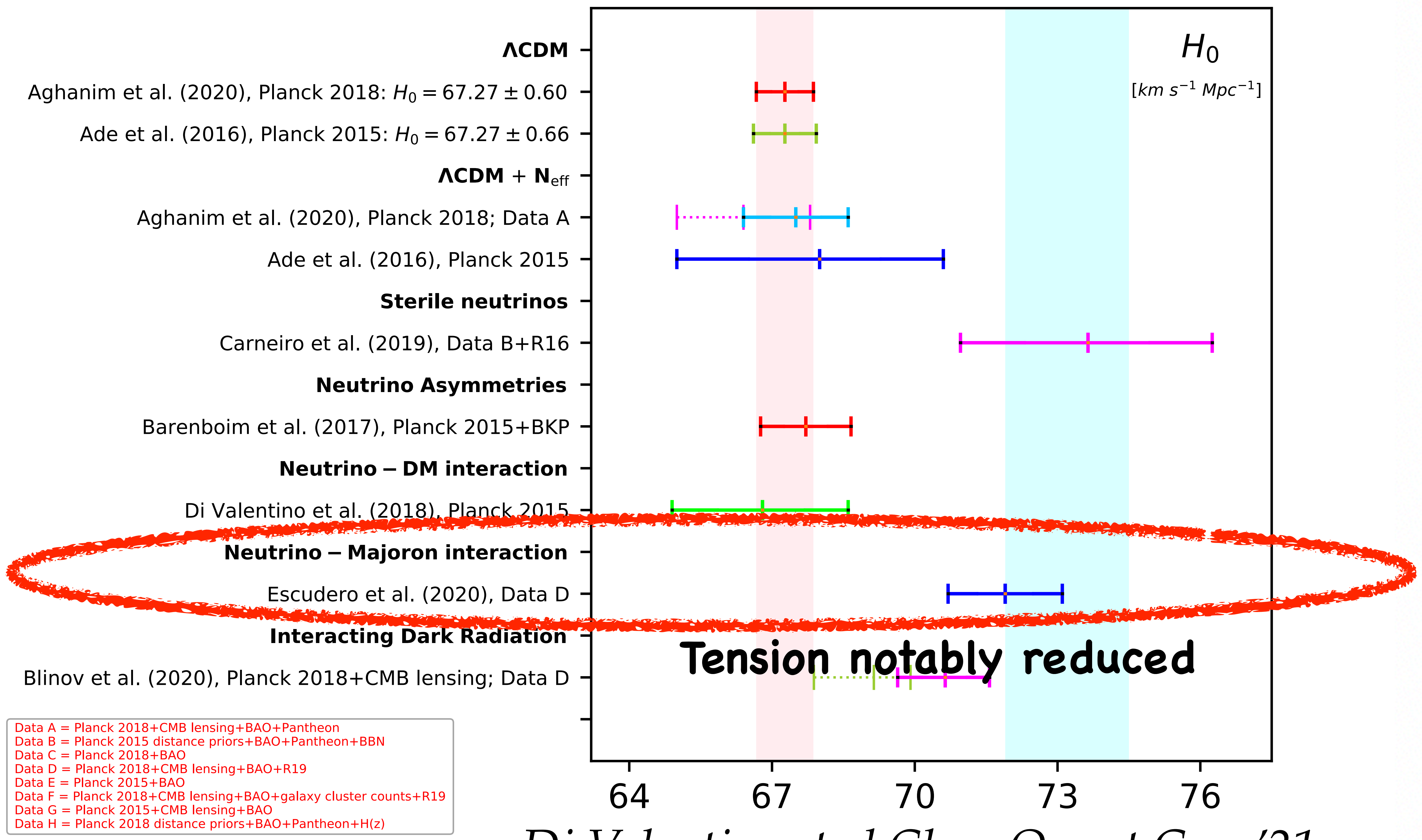
Data A = Planck 2015 TT+CMB lensing+BAO
Data B = Planck 2018+BAO
Data C = Planck 2018+CMB lensing+BAO+JLA+CFHLensS+Planck SZ
Data D = Planck 2015+BAO+R16
Data E = Planck 2018+CMB lensing+BAO+Pantheon
Data F = Planck 2018+CMB lensing+BAO+R19
Data G = Planck 2015+CMB lensing+WiggleZ

Di Valentino et al Class.Quant.Grav'21

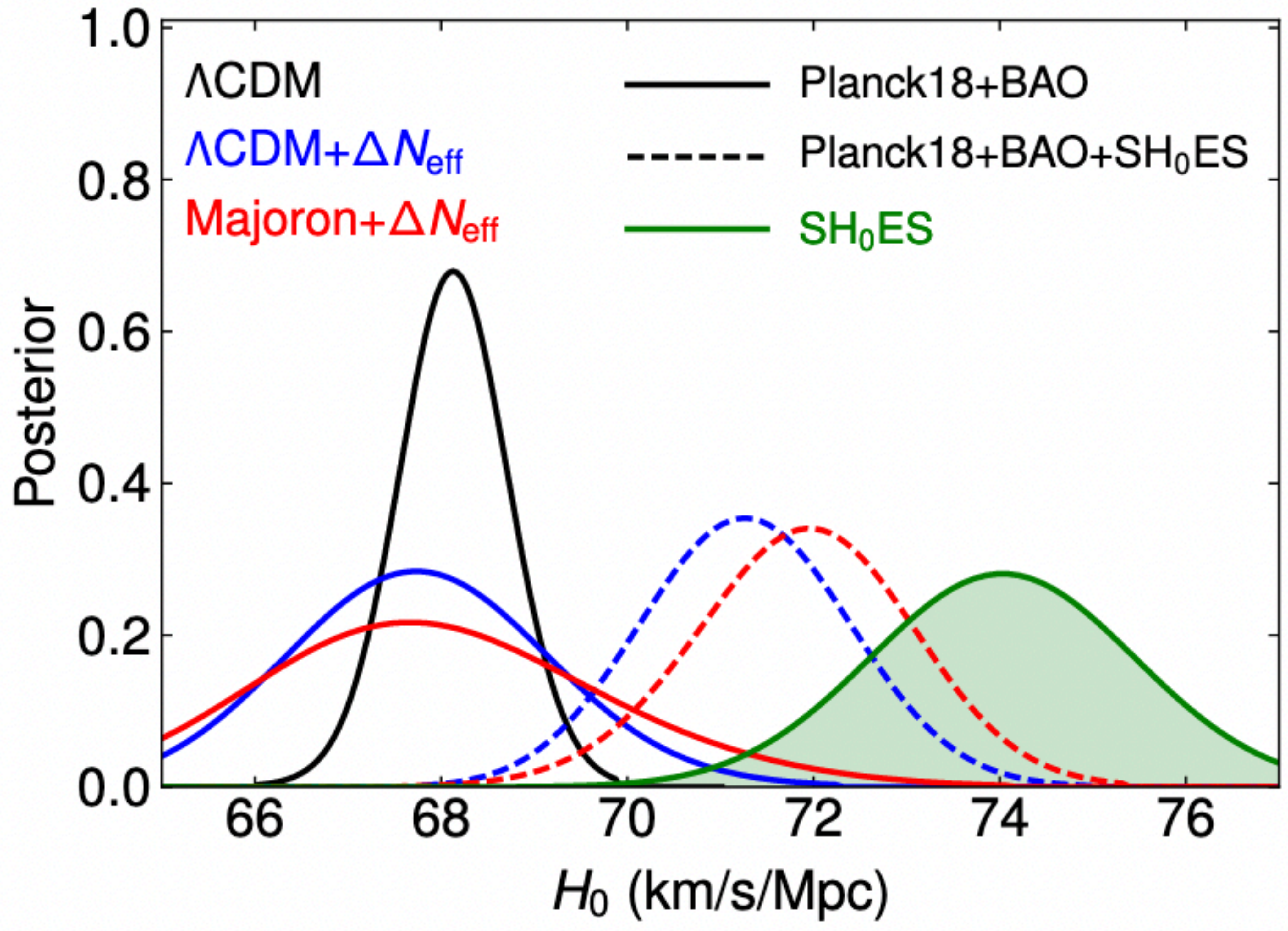
Interacting neutrinos & the Hubble constant tension

$$\mathscr{L} = i\frac{\lambda}{2}\phi\bar{\nu}\gamma_5\nu$$

Models with an eV-mass Majoron interacting with neutrinos before recombination relax the Hubble tension



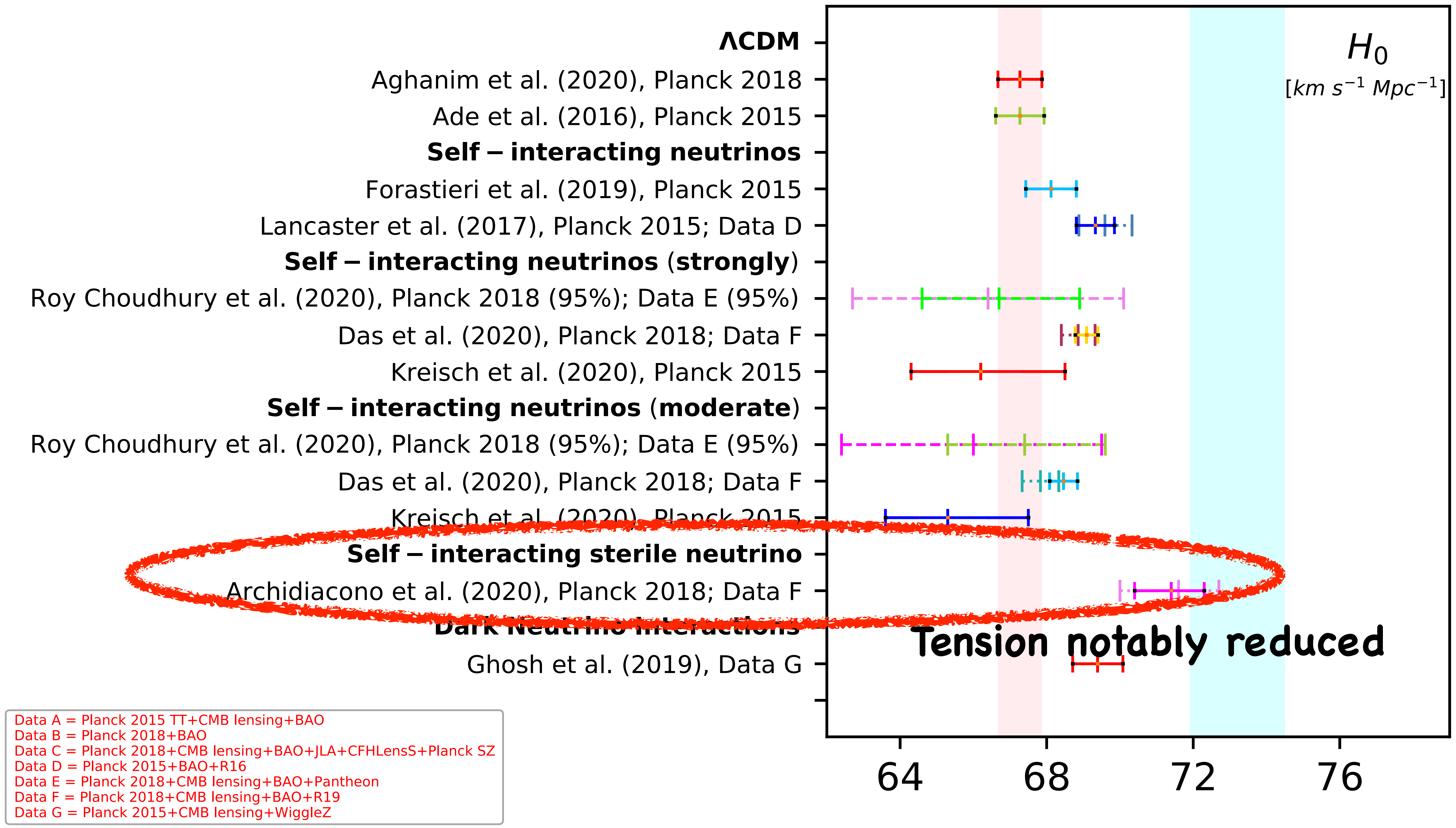
Di Valentino et al Class.Quant.Grav'21



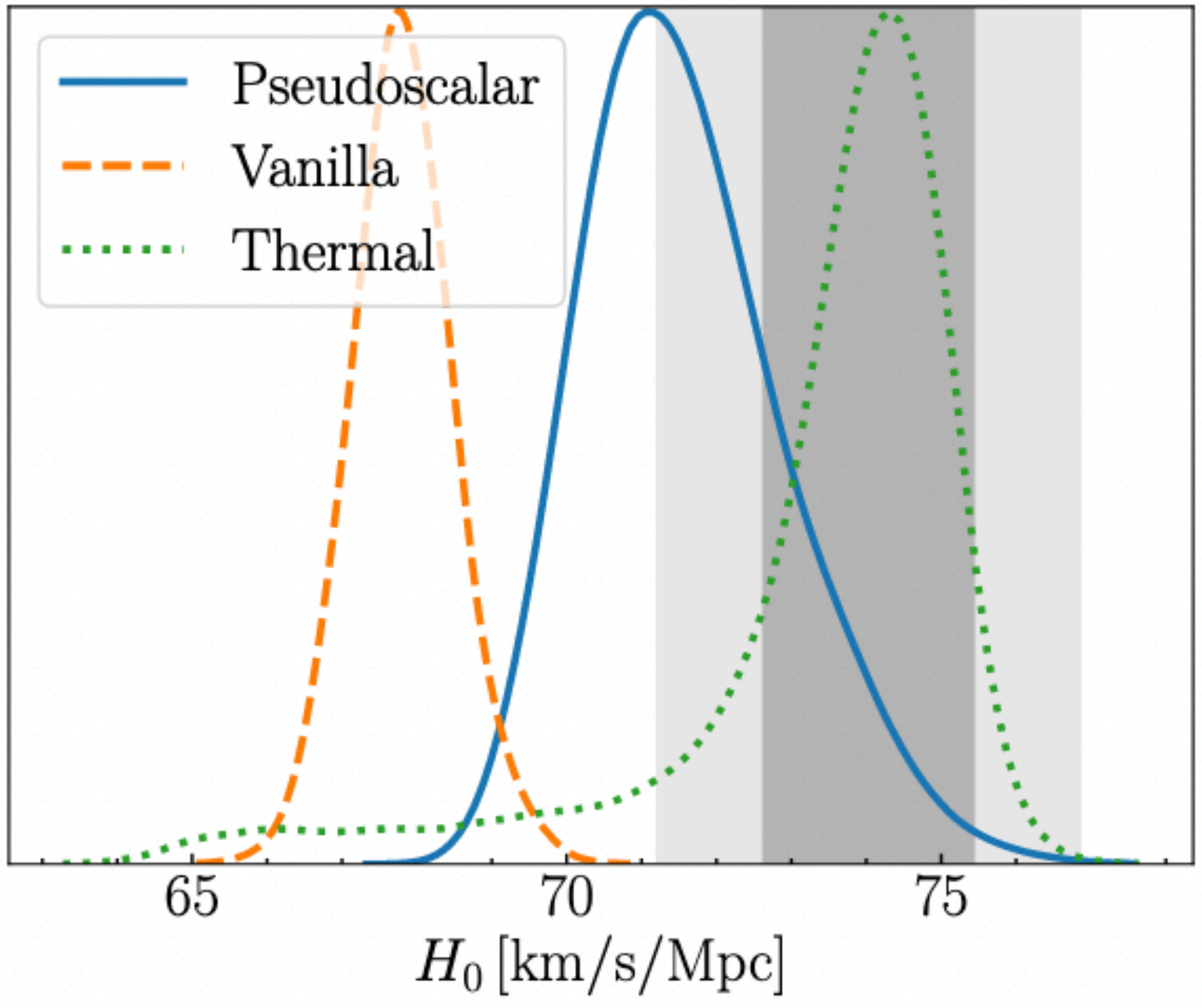
Escudero & Witte EPJC'20

Interacting neutrinos & the Hubble constant tension

$$\mathscr{L} \sim g_s \phi \bar{\nu} \gamma_5 \nu$$



Di Valentino et al Class.Quant.Grav'21



Archidiacono et al JCAP'20

Non-standard neutrino scenarios & the Hubble constant tension

tension $\leq 1\sigma$ *"Excellent models"*	tension $\leq 2\sigma$ *"Good models"*	tension $\leq 3\sigma$ *"Promising models"*
Dark energy in extended parameter spaces	Early Dark Energy	Early Dark Energy
Dynamical Dark Energy	Phantom Dark Energy	Decaying Warm DM
Metastable Dark Energy	Dynamical Dark Energy	Neutrino-DM Interaction
PEDE	GEDE	Interacting dark radiation
Elaborated Vacuum Metamorphosis	Vacuum Metamorphosis	Self-Interacting Neutrinos
IDE	IDE	IDE
Self-interacting sterile neutrinos	Critically Emergent Dark Energy	Unified Cosmologies
Generalized Chaplygin gas model	$f(\mathcal{T})$ gravity	Scalar-tensor gravity
Galileon gravity	Über-gravity	Modified recombination
Power Law Inflation	Reconstructed PPS	Super ΛCDM
$f(\mathcal{T})$		Coupled Dark Energy

Di Valentino et al Class.Quant.Grav'21

FINALE

- ν masses & abundances leave key signatures in cosmological observables.
- Cosmology provides currently the tightest bounds to neutrino masses.
- COSMOLOGICAL CONSTRAINTS ARE "ROBUST" (difficult to avoid in "simple" extensions of ΛCDM)
- $\sum m_\nu < 0.09$ eV (95%CL) from 2018 Planck +SDSS IV+SNIa data
- Non-standard ν physics can significantly relax $\sum m_\nu$ cosmological bounds
- Non-standard ν physics could alleviate present cosmological tensions and potential future ones plus provide a hint to the ν mass generation mechanism
- Non-free streaming nature of interacting neutrinos may help in tensions
- Long range neutrino interactions increase lensing $\rightarrow A_{lens}$ TENSION