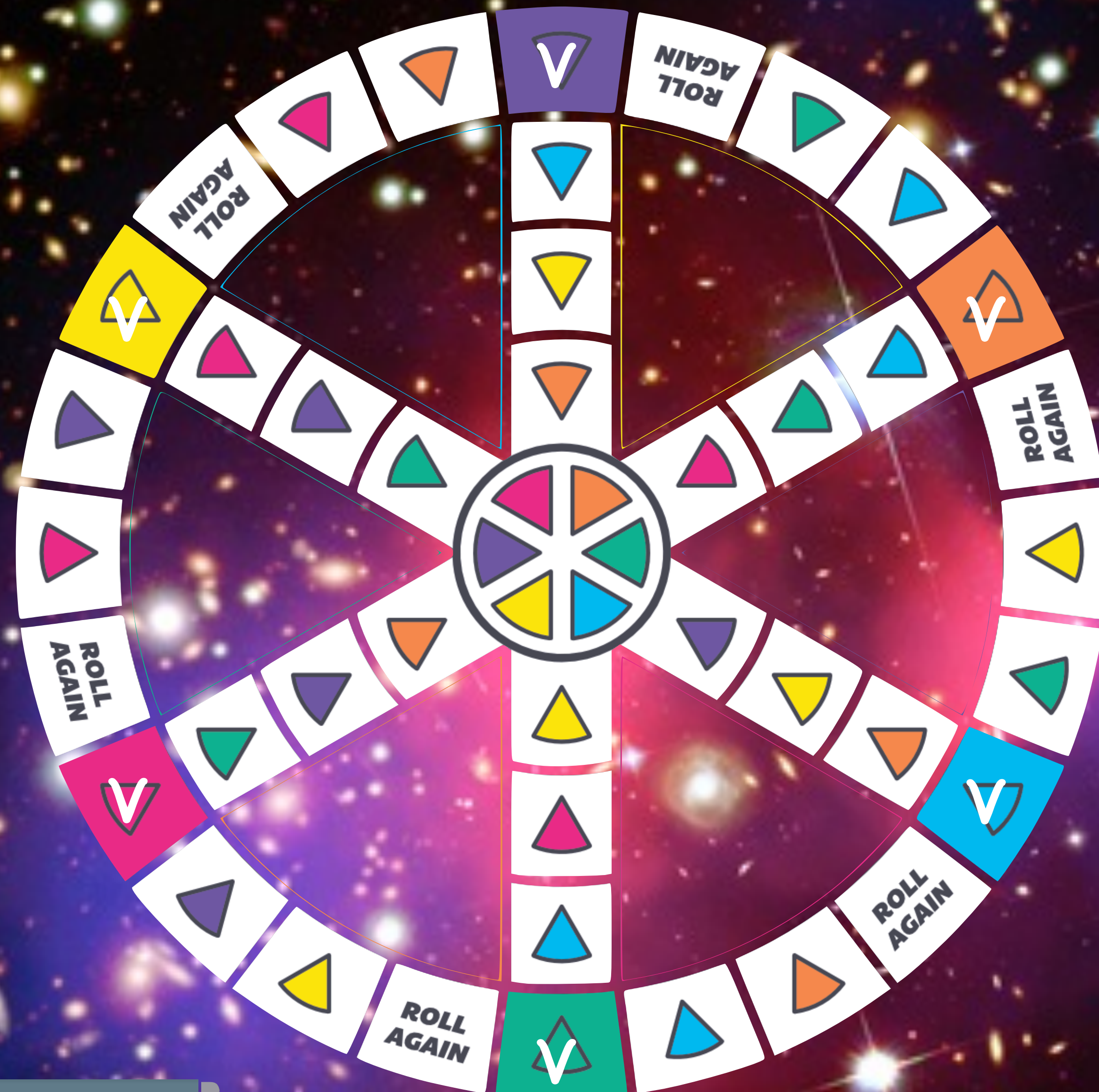
Olga Mena
IFIC-CSIC/UV Valencia (Spain)



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INSTITUT DE FÍSICA CORPUSCULAR

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VNIVERSITAT DE VALÈNCIA

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Cosmic neuTRIVIA game steps

1. Familiarize yourself with the board's layout:

- The ΛCDM **trivia: the players!**
- The neutrino pie piece: decoupling in the early universe

2. Roll the dice and get:

- Number of neutrinos and Big-Bang Nucleosynthesis
- Number of neutrinos and Cosmic Microwave Background Radiation
- Neutrino masses and Cosmic Microwave Background Radiation?
- Neutrino masses and structure formation in the universe?

3. Is anyone cheating? Neutrinos and Tensions

4. Final score:

- Take home messages

ΛCDM NeuTRIVIA: PLAYERS

$$\Omega_i \equiv \frac{\rho_i}{\rho_c}$$

Heavy elements

$\Omega_{\text{Heavy Elements}} = 0.0003$

Stars

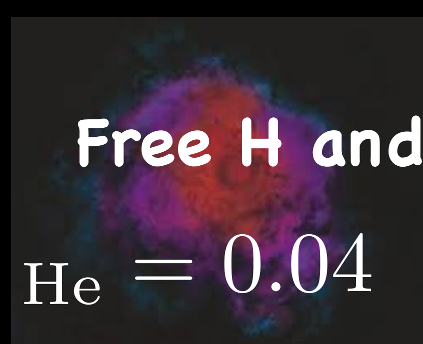
$\Omega_{\text{Stars}} = 0.005$

Dark energy

$\Omega_\Lambda = 0.7$

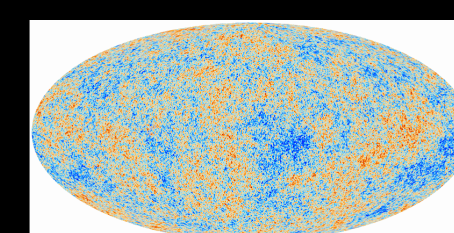
V

Neutrinos!



Free H and He

$\Omega_{\text{H, He}} = 0.04$



$\Omega_\gamma \sim 10^{-5}$

Cold Dark matter

$\Omega_{\text{CDM}} = 0.25$

How large is the MASSIVE neuTRIVIA pie piece?

Neutrinos!

ν

Cosmology tells us

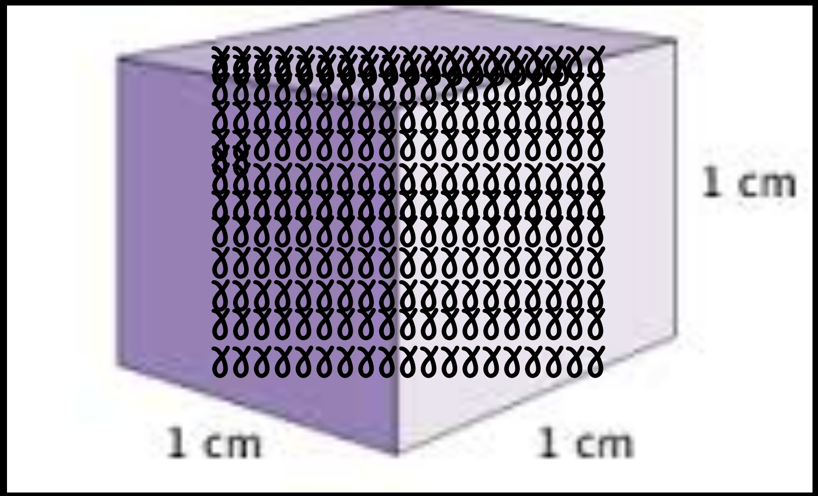
$$\Omega_\nu \lesssim 0.0024 \text{ 95\% CL}$$

Neutrino oscillations tell us

$$\Omega_\nu \gtrsim 0.0012 \text{ 95\% CL}$$

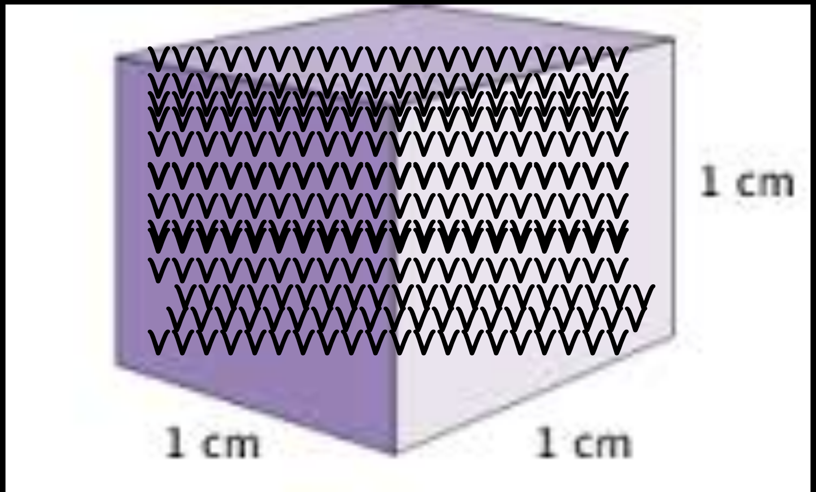
I guess all you know about dark matter/
what about dark radiation?
But radiation is visible!

410 photons/cm³



According to standard cosmology,
there is a cosmic neutrino background,
equivalent to the CMB photon background, albeit slightly colder $T \simeq 1.94$ K

340 neutrinos/cm³

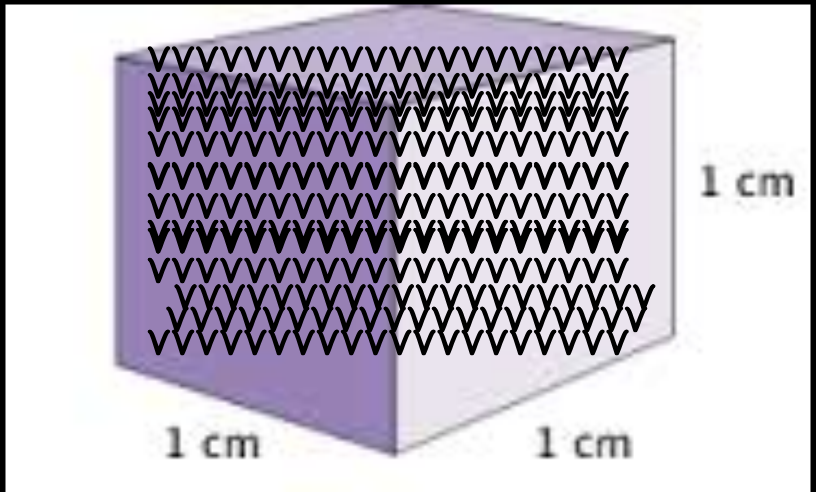


This cosmic relic neutrino background has never been detected directly.

The universe is filled with a dense flux of "relic neutrinos" created in the Big Bang.

This makes neutrinos the most abundant KNOWN form of…

340 neutrinos/cm^3



HOT dark matter!

According to standard cosmology, there are three active Dirac or Majorana neutrinos, which decouple from the thermal bath when their scattering rate is smaller than the expansion rate of the universe:

$$\Gamma_\nu \lesssim H$$

- Neutrinos only interact via weak interactions, with a rate:

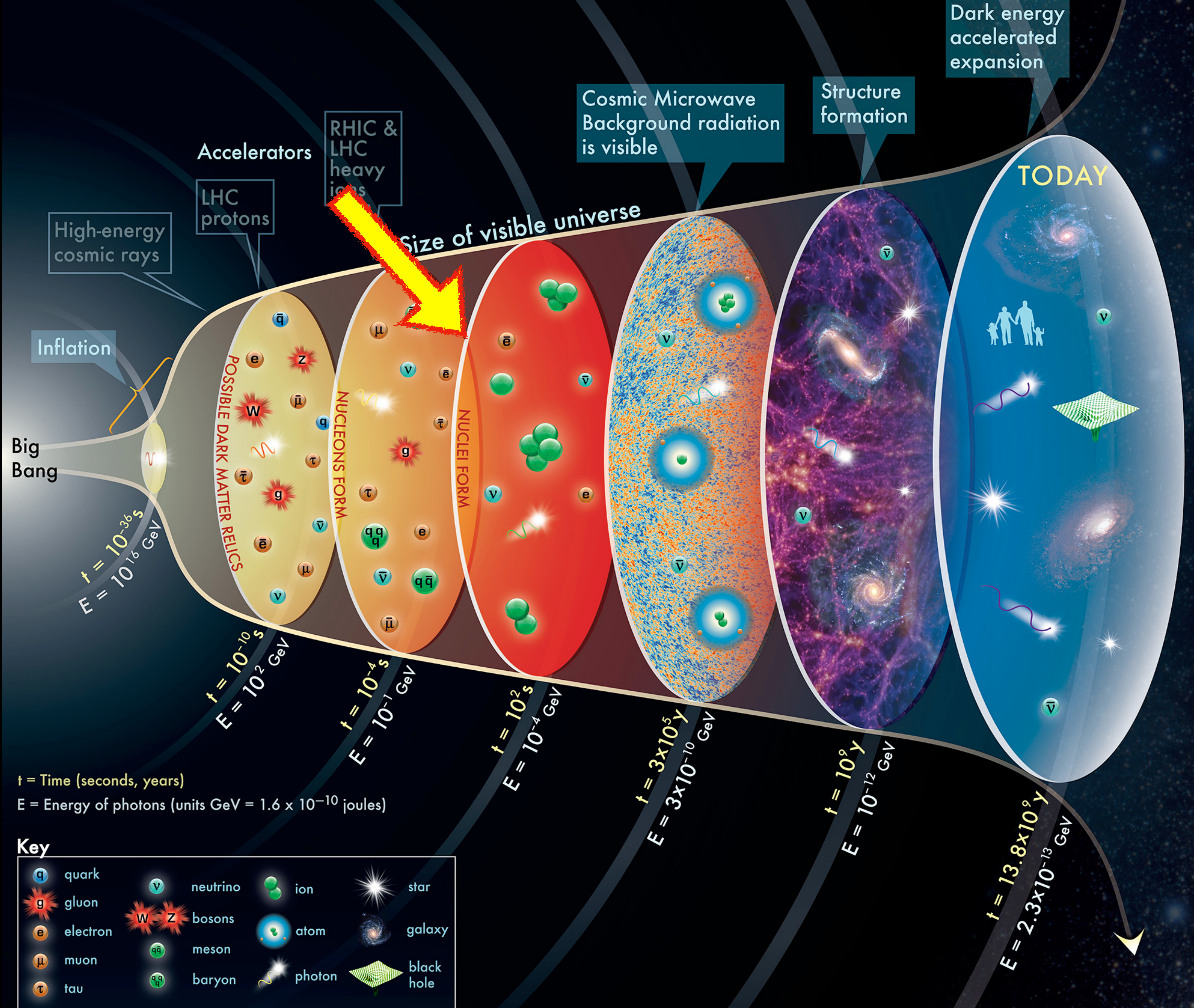
$$\Gamma_\nu = n\sigma v \simeq T^3 G_F^2 T^2 \sim G_F^2 T^5$$

- While the expansion rate of the universe is given by the Hubble factor:

$$H^2 = \frac{8\pi G}{3}\rho \sim T^4/m_{pl}^2$$

$$\Gamma_\nu/H \sim \left(\frac{T}{1\ \mathrm{MeV}}\right)^3$$

- **Therefore neutrinos decouple from the thermal bath around 1 MeV.**



The concept for the above figure originated in a 1986 paper by Michael Turner.

Particle Data Group, LBNL © 2015

Supported by DOE

Event	Time	Redshift	Temperature
Baryogenesis	?	?	?
EW phase transition	$2 \times 10^{-11} s$	10^{15}	$100 GeV$
QCD phase transition	$2 \times 10^{-5} s$	10^{12}	$150 MeV$
Neutrino decoupling	$1s$	6×10^{9}	$1 MeV$
Electron-positron annihilation	$6s$	2×10^{9}	$500 keV$
Big bang nucleosynthesis	$3min$	4×10^{8}	$100 keV$
Matter-radiation equality	$6 \times 10^{4} yrs$	3400	$.75 eV$
Recombination	$2.6 - 3.8 \times 10^{5} yrs$	1100-1400	$.26 - .33 eV$
CMB	$3.8 \times 10^{5} yrs$	1100	$.26 eV$

Relic neutrinos do not inherit any of the energy associated to $e^+ e^-$ annihilations, being colder than photons:

$$T_{\nu 0} = \left(\tfrac{4}{11}\right)^{1/3} T_0 = 1.945 \text{ K} \rightsquigarrow 1.697 \times 10^{-4} \text{ eV}$$

If these neutrinos are massive, their energy density, at T<<m is

$$\rho_\nu = m_\nu n_\nu \qquad n_{\nu_i}(T_{\nu 0}) \approx 56 \text{ cm}^{-3} \qquad \Omega_\nu h^2 = \frac{\sum m_\nu}{93 \text{ eV}}$$

Then, demanding that massive neutrinos do not over-close the universe, $\sum m_\nu \lesssim 45 \text{ eV}$

Their thermal motion is: $\langle v_{\rm thermal} \rangle \simeq 81(1+z)\left(\frac{\rm eV}{m_\nu}\right) \text{ km s}^{-1}$

For a 1 eV neutrino, thermal motion is comparable to the typical velocity dispersion of a galaxy.

For dwarf galaxies, the velocity dispersion is smaller, 10 km/s

vvvvvvvvvvvvvvvvvvvv

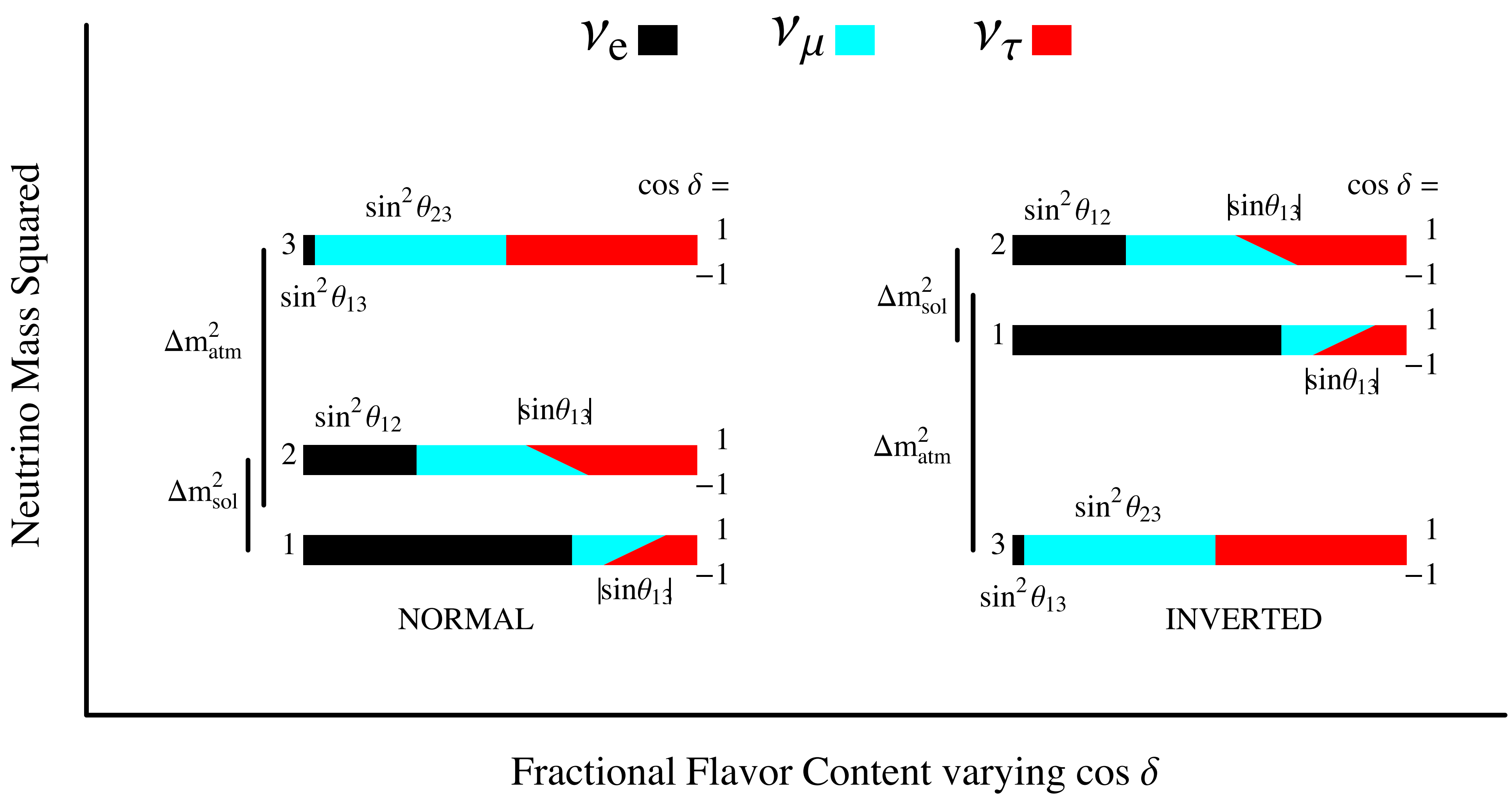
Too much thermal energy to be squeezed into small volumes to form the smaller structures we observe today! !!

According to neutrino oscillation physics, we know that there are at least two Dirac or Majorana massive neutrinos.

$$\Delta m^2_{12} = (7.05 - 8.14) \times 10^{-5}\mathrm{eV}^2$$

$$\Delta m^2_{13} = (2.41 - 2.60) \times 10^{-3}\mathrm{eV}^2$$

$$\Delta m^2_{13} = -(2.31 - 2.51) \times 10^{-3}\mathrm{eV}^2$$



(Mena,Parke, PRD'04)

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$$\Delta m^2_{13} = -(2.31 - 2.51) \times 10^{-3} \mathrm{eV}^2$$

We are sure then that two neutrinos have a mass above:

$$\sqrt{\Delta m^2_{12}} \simeq 0.008 \text{ eV}$$

and that at least one of these neutrinos has a mass larger than

$$\sqrt{|\Delta m^2_{13}|} \simeq 0.05 \text{ eV}$$

According to neutrino oscillation physics, we know that there are at least two Dirac or Majorana massive neutrinos:

$$\Delta m_{12}^2 = (7.05 - 8.14) \times 10^{-5} \mathrm{eV}^2$$

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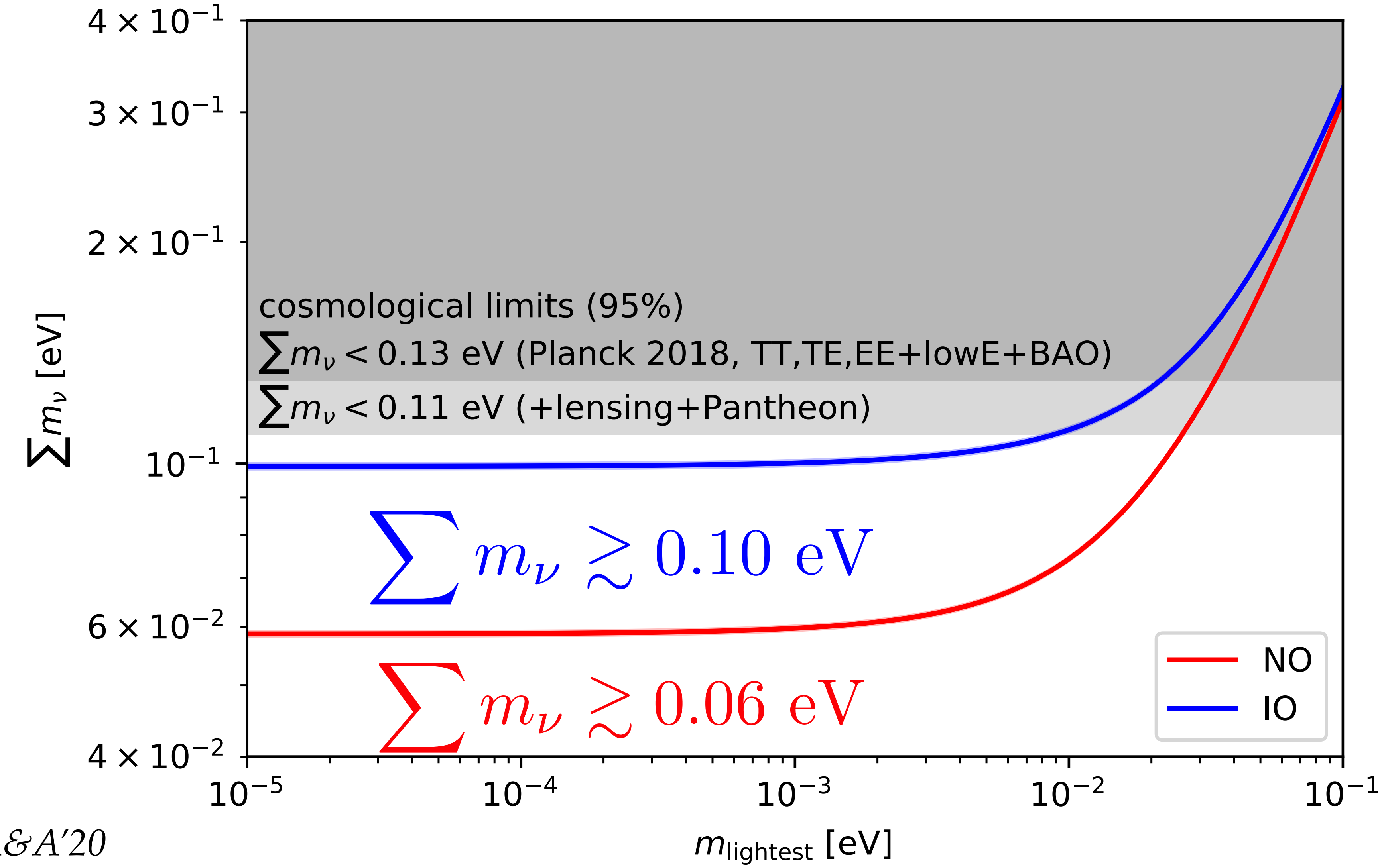
$$\Delta m_{13}^2 = -(2.31 - 2.51) \times 10^{-3} \mathrm{eV}^2$$

which translates into a lower bound on the total neutrino mass, depending on the ordering:



Planck Coll. A&A'20

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Number of neutrinos: N_{eff}

The total radiation in the universe can be written as:

$$\Omega_r h^2 = \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right)\Omega_\gamma h^2$$

Bennett et al, 2012.02726

N_{eff} = 3.0440 ± 0.0002 standard scenario: electron, muon and tau neutrinos

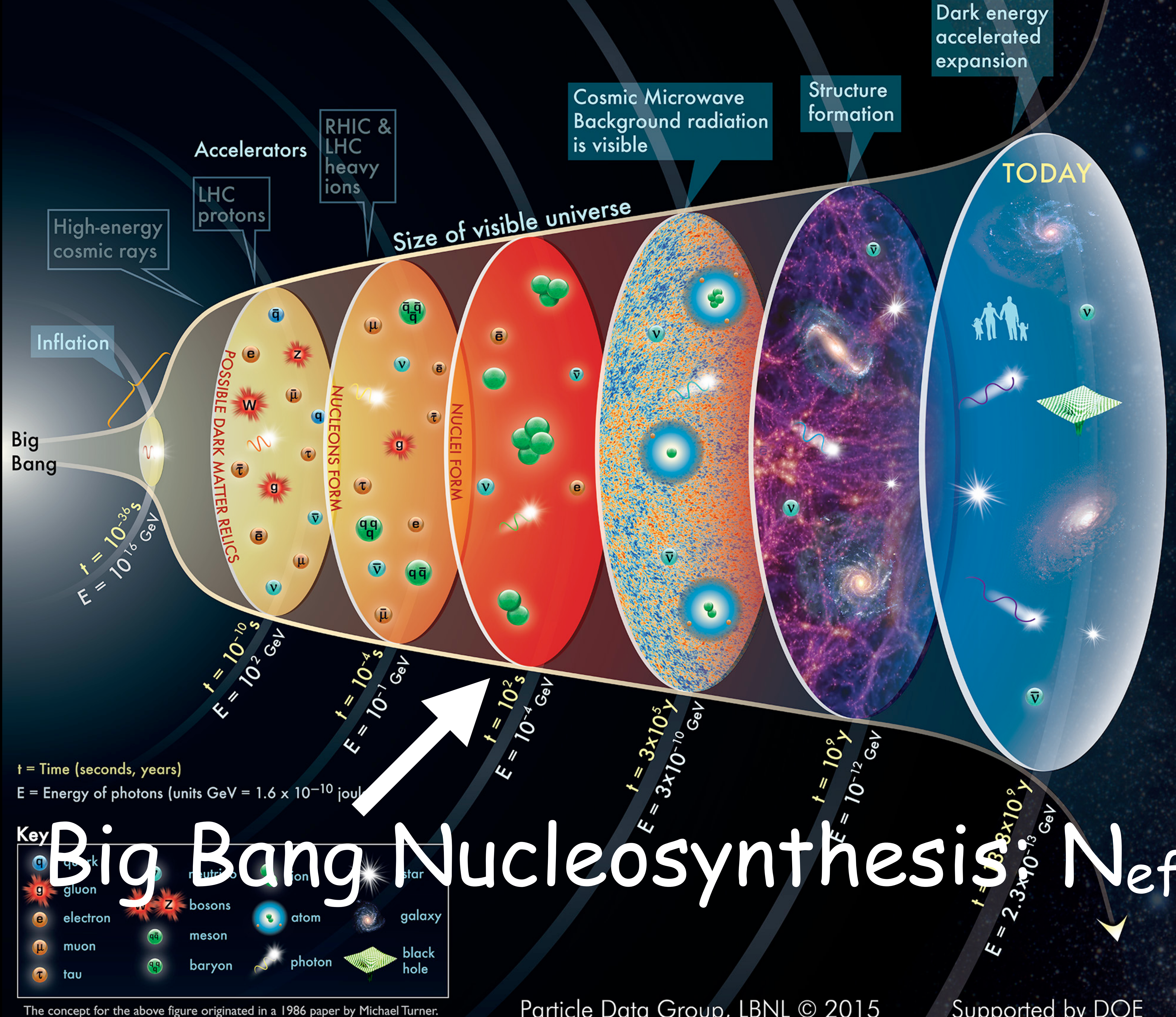
N_{eff} < 3.044 (less neutrinos): Neutrino decays ?

N_{eff} > 3.044 (more neutrinos): Sterile neutrino species ?

But….if they are sterile, and do not interact with other particles, how cosmologists measure them?

That's the dark side of the GRAVITATIONAL FORCE…

Big Bang Nucleosynthesis: N_{eff}



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Big Bang Nucleosynthesis: N_{eff}

BBN theory predicts the abundances of D, ^3He, ^4He and ^7Li which are fixed by t≃180 s.
They are observed at late times: low metallicity sites with little evolution are "ideal".

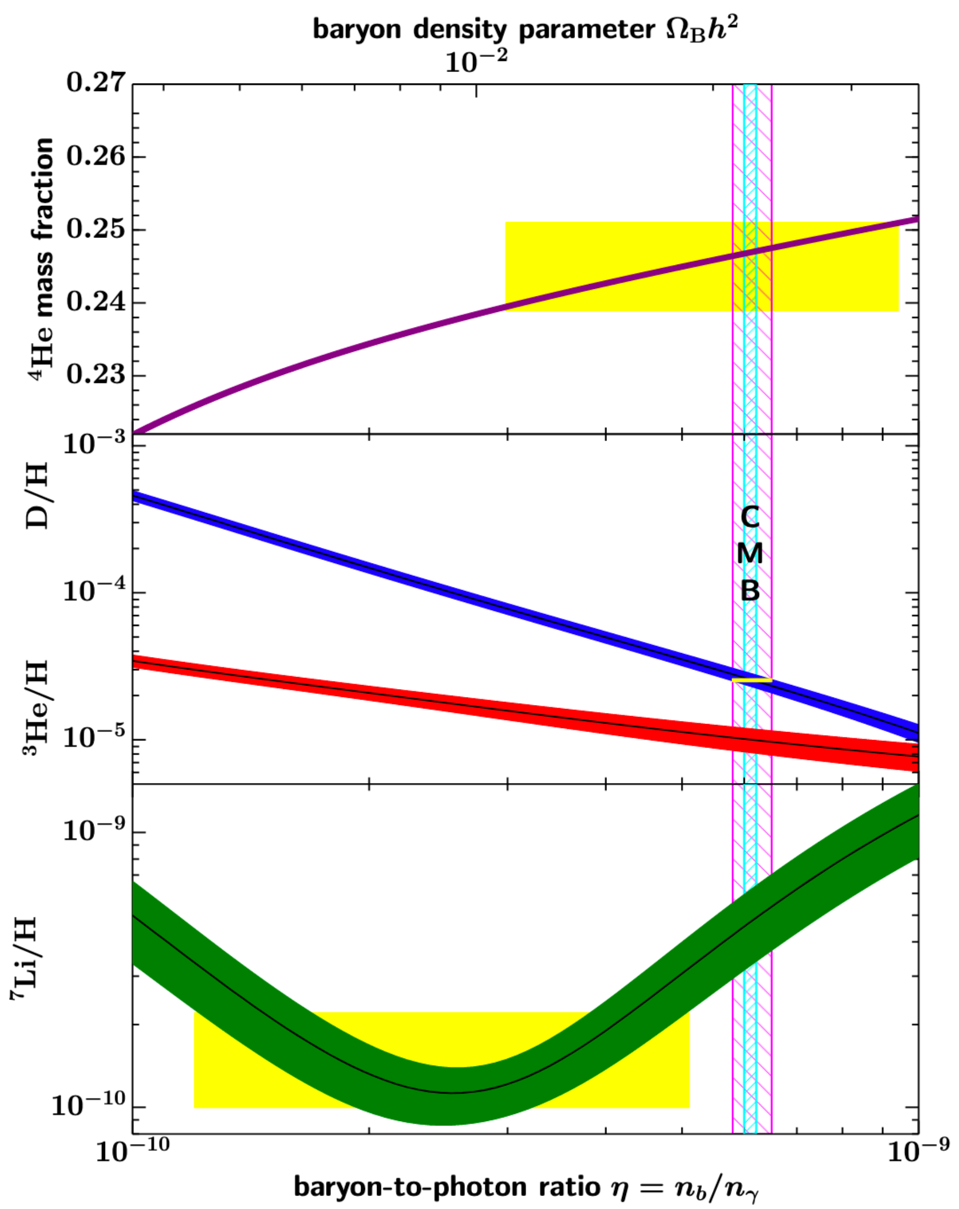


Figure 24.1: The primordial abundances of ^{4}He, D, ^{3}He, and ^{7}Li as predicted by the standard model of Big-Bang nucleosynthesis — the bands show the 95% CL range [47]. Boxes indicate the observed light element abundances. The narrow vertical band indicates the CMB measure of the cosmic baryon density, while the wider band indicates the BBN D+^{4}He concordance range (both at 95% CL).

P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. ***2020****, 083C01 (2020).*

Low metallicity extragalactic HII regions.
Produced in stars.

High z QSO absorption lines.
Destroyed in stars.

Solar system and high metallicity HII galactic regions.
^{3}He not used for cosmological constraints.

Metal poor stars in our galaxy.
Destroyed in stars and produced by galactic cosmic ray interactions.

Big Bang Nucleosynthesis: N_{eff}

N_{eff} changes the freeze out temperature of weak interactions:

$$\Gamma_{n\leftrightarrow p} \sim H$$

MORE NEUTRINOS:

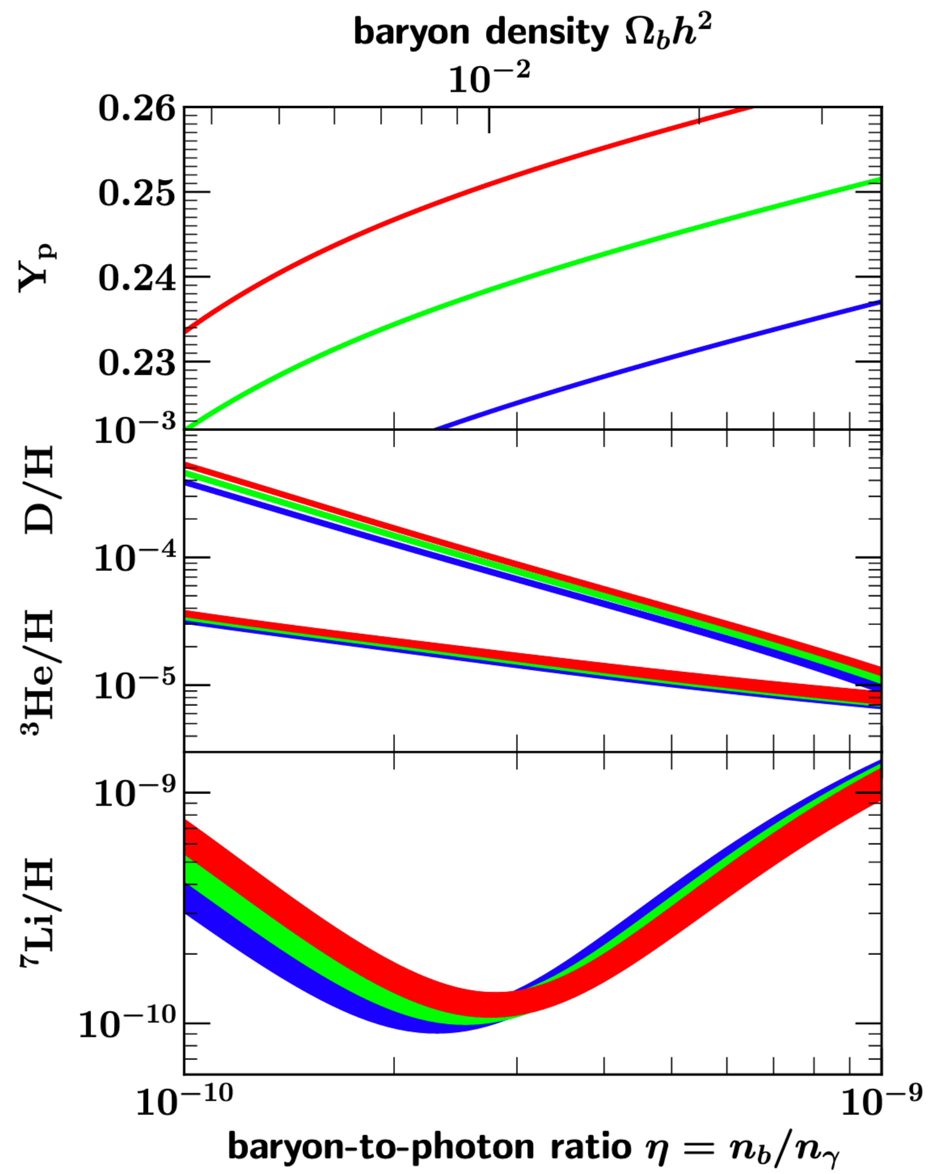
Higher N_{eff}: larger expansion rate & freeze out temperature, MORE HELIUM 4

$$n/p \simeq e^{-\frac{m_n - m_p}{T_{freeze}}} \qquad Y_p = \frac{2(n/p)}{1+n/p}$$

$N_{\rm eff} = 2$

$N_{\rm eff} = 3$

$N_{\rm eff} = 4$



Fields, Olive, Yeh & Young JCAP '20

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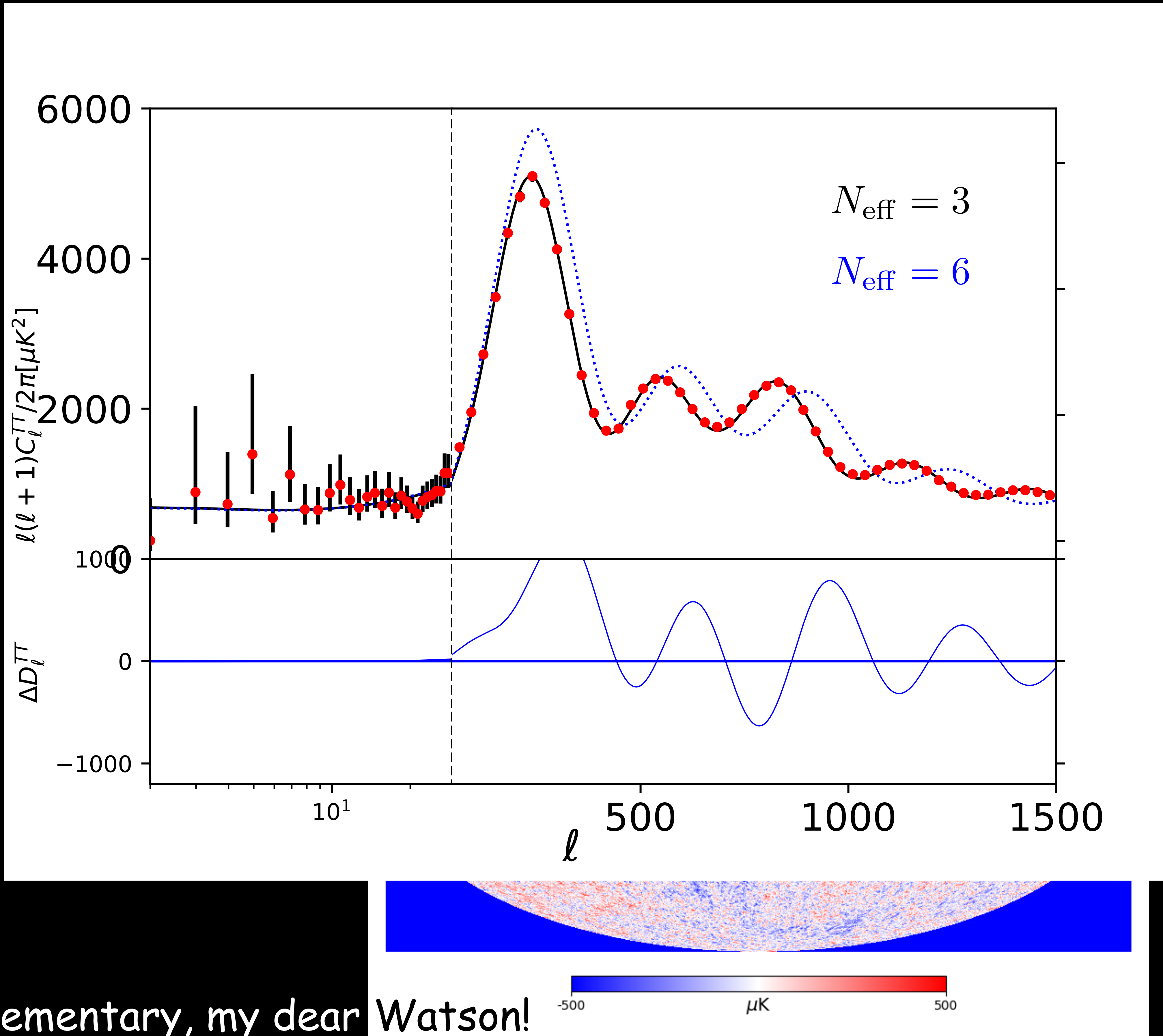
Also known as "photon decoupling", as photons started freely travel through the universe without interacting with matter and the CMB is "frozen"

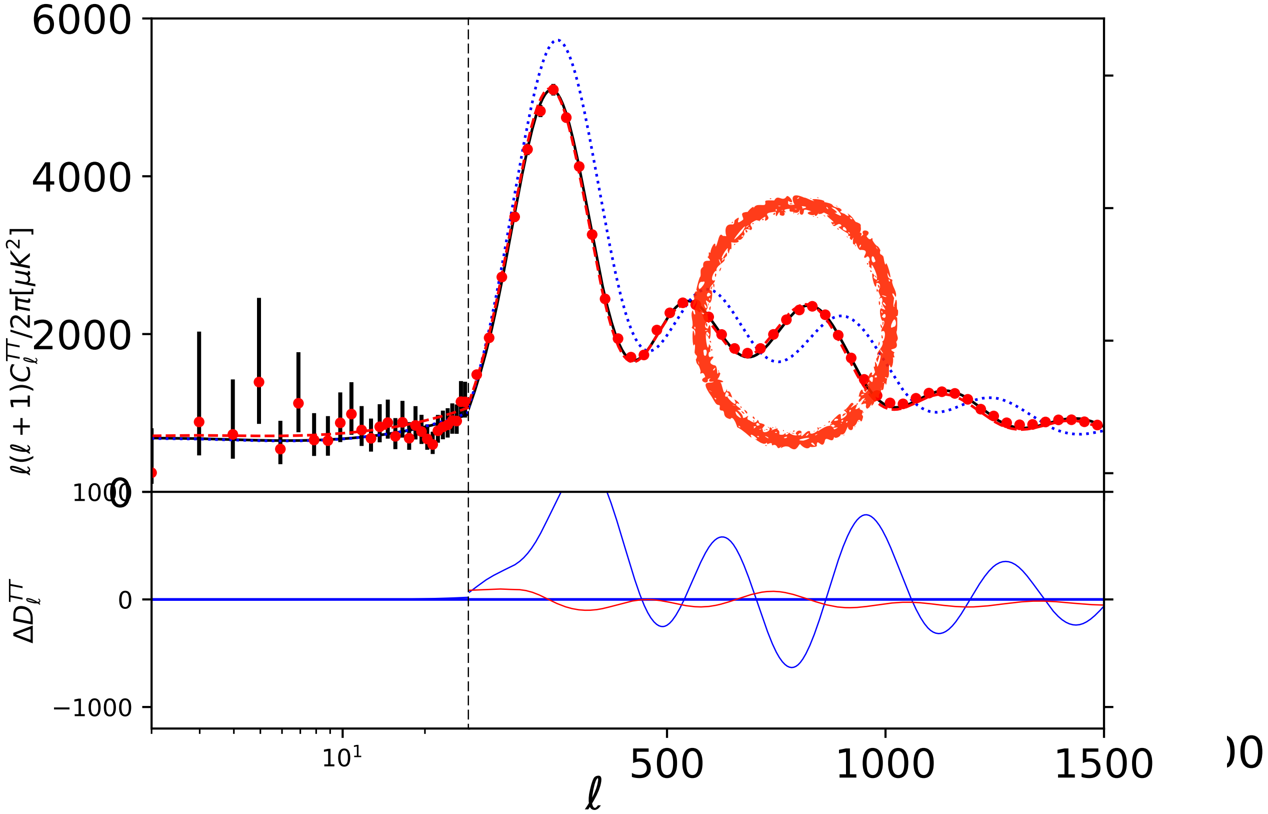
CMB: N_{eff}



Elementary, my dear Watson!

CMB: $N_{\rm eff}$

$N_{\rm eff} = 6$ $N_{\rm eff} = 3$ $N_{\rm eff} = 6$

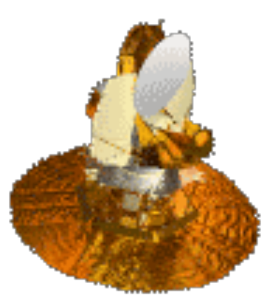


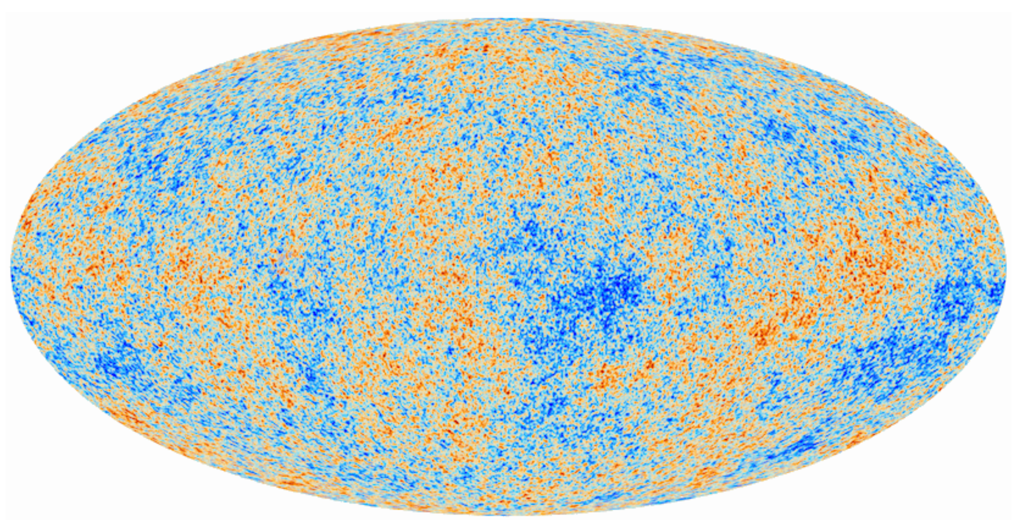
$$(\omega_b, \omega_m, h, A_s, n_s, \tau, N_{\rm eff})$$

Warning!

It is ~~elementary~~, Sherlock Holmes!

Only effect at l<1000 that can not be mimicked by others: anisotropic stress, around 3rd peak



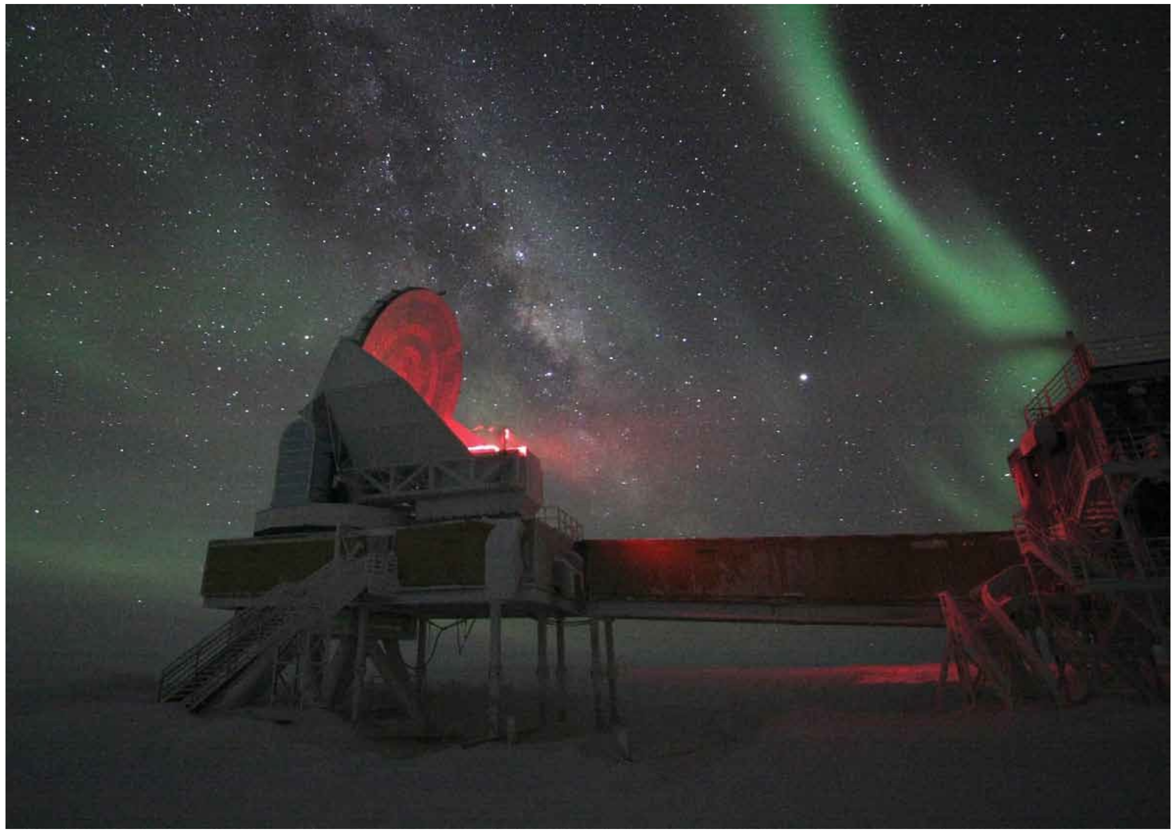


Neutrinos are free-streaming particles propagating at the speed of light, faster than the sound speed in the photon fluid, suppressing the oscillation amplitude of CMB modes that entered the horizon in the radiation epoch.

CMB: N_{eff}

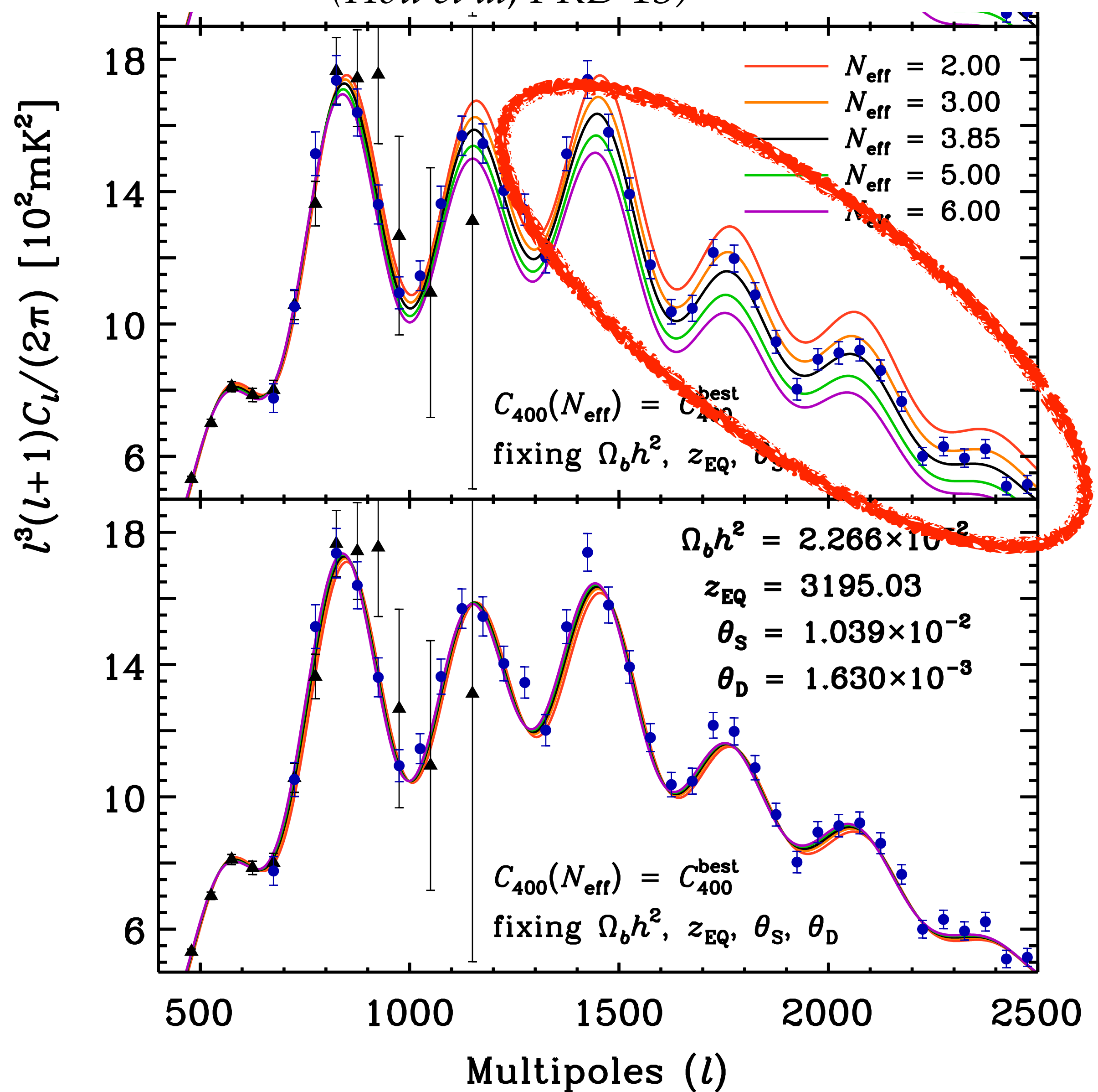
@Cosmic Microwave Background in the damping tail, measured by SPT, ACT & Planck:

Higher N_{eff} will increase the expansion rate AND the damping at high multipoles.



$$r_d^2 \propto \int_0^{a_\star} \frac{da}{a^3 \sigma_T n_e H}$$

(Hou et al, PRD'13)



N_{eff}

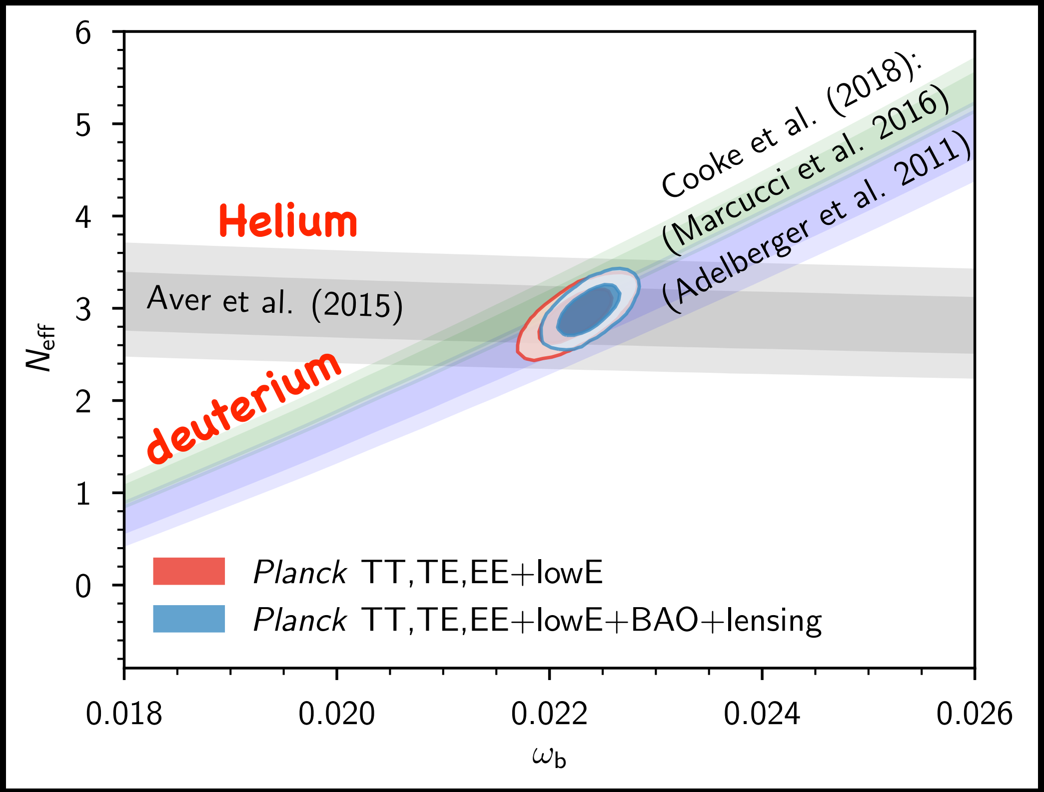
- Planck 2018 CMB temperature polarization and lensing potential data:

$$N_{\rm eff} = 2.89^{+0.36}_{-0.38}\ 95\%{\rm CL}$$

- If we add large scale structure information in the BAO shape form:

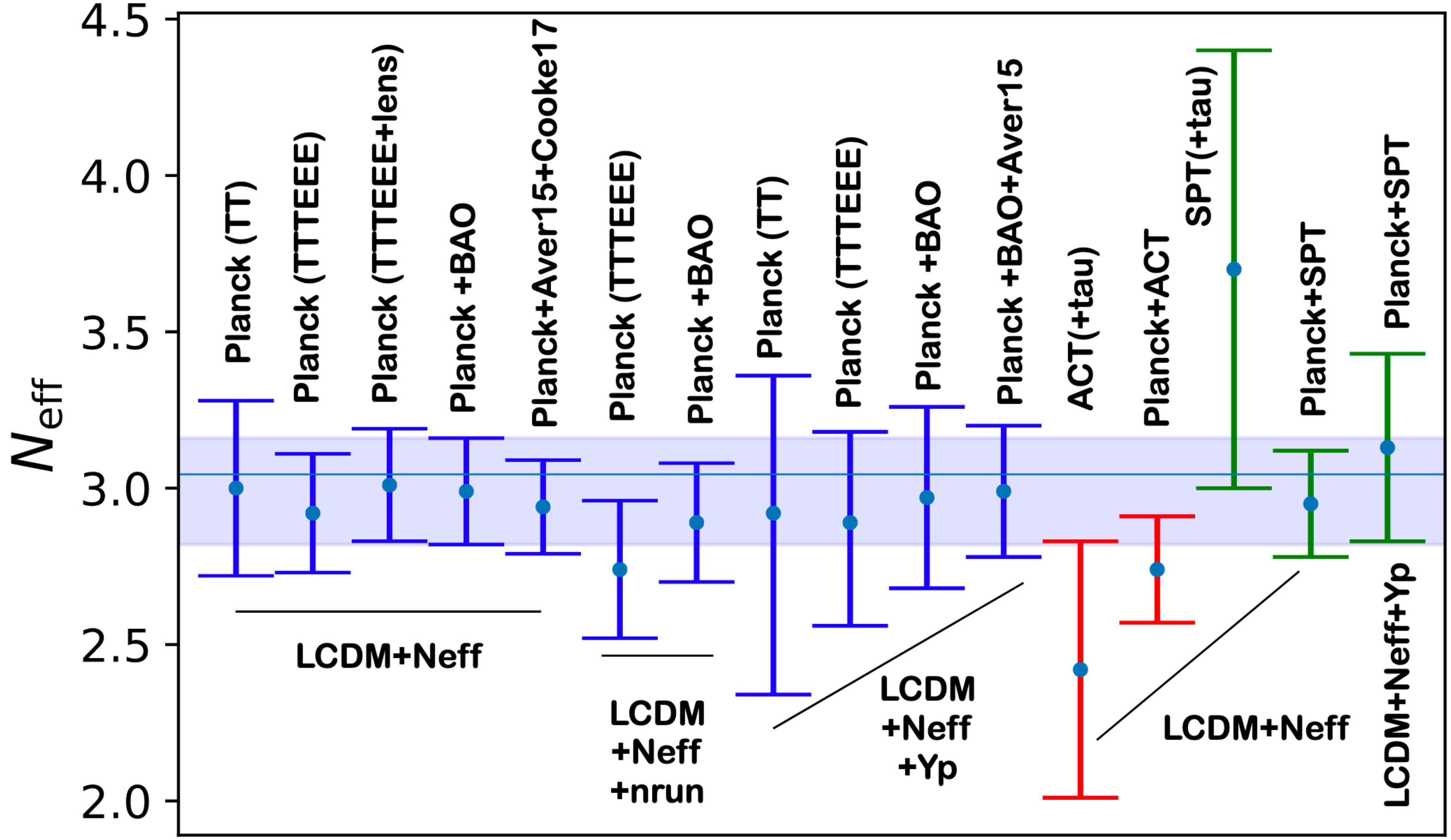
$$N_{\rm eff} = 2.99^{+0.34}_{-0.33}\ 95\%{\rm CL}$$

- Perfectly consistent with BBN estimates:

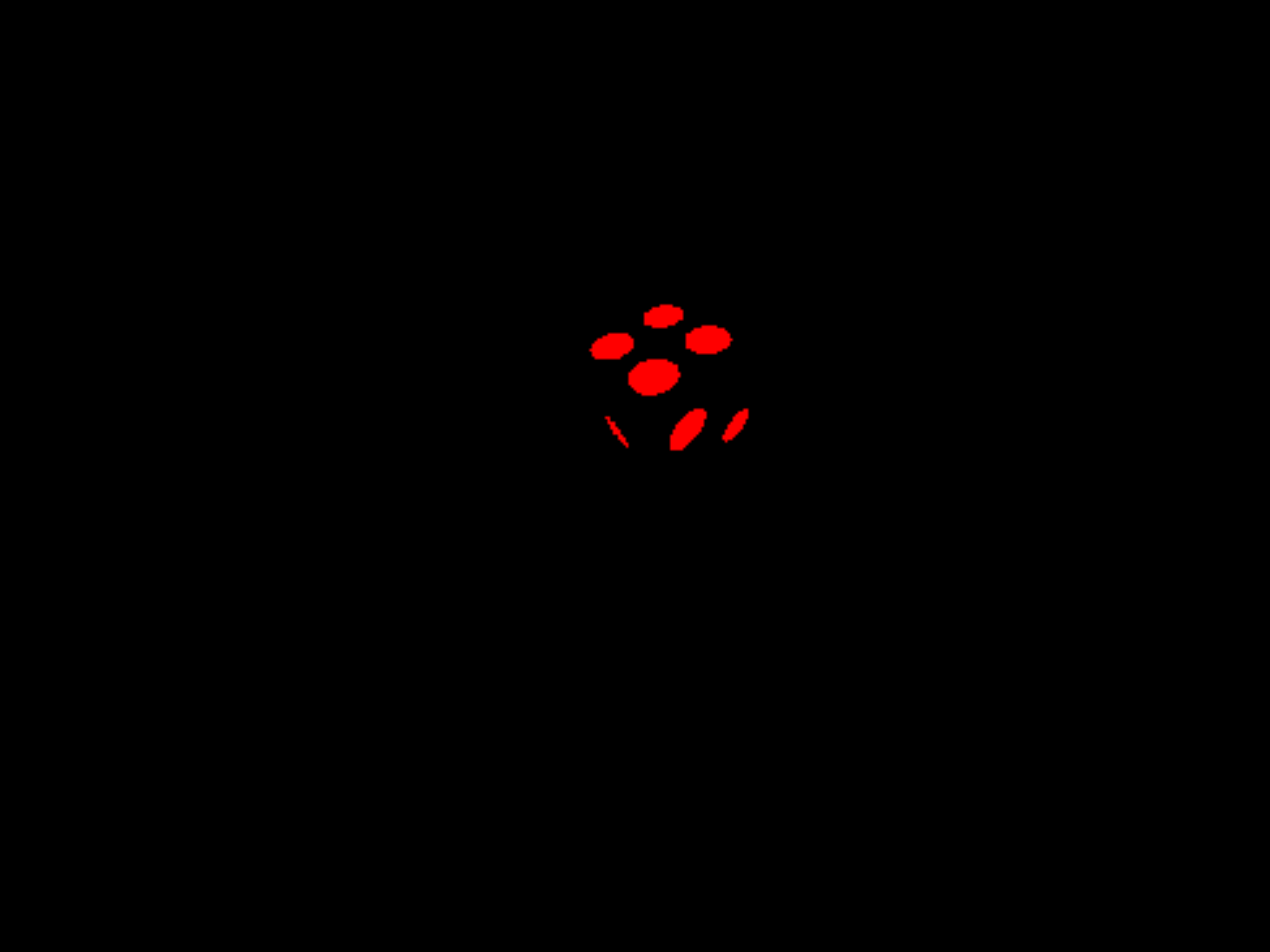


Planck Coll. A&A'20

Neff: current status



Planck collaboration, VI 2018
ACT Collaboration (Aiola+), 2020
SPT Collaboration (Dutcher+, Balkenhol+), 2021



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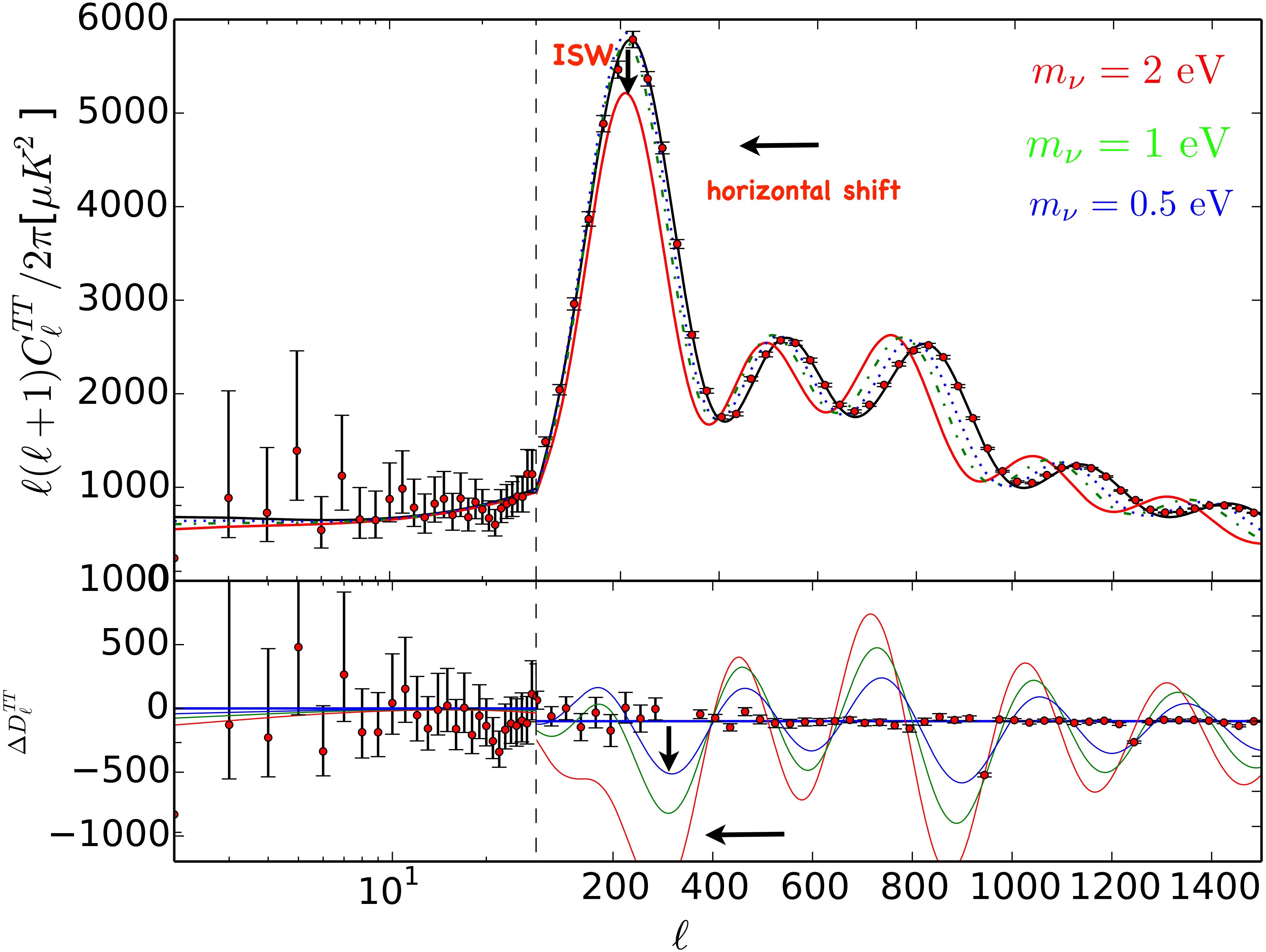
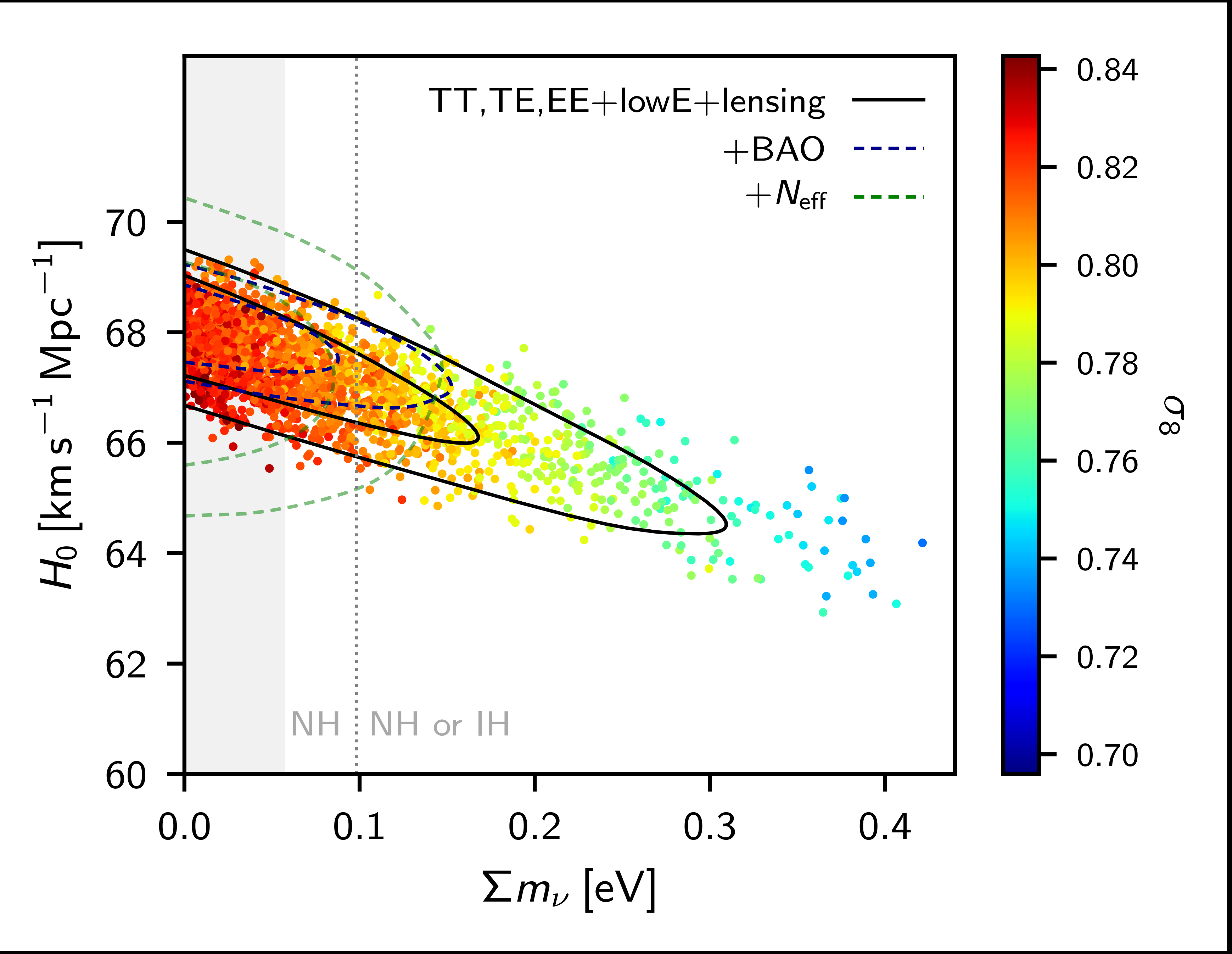
CMB: $\sum m_\nu$

@ CMB: Early Integrated Sachs Wolfe effect (ISW).

Shift in the angular position of the peaks.





Planck Coll. A&A'20

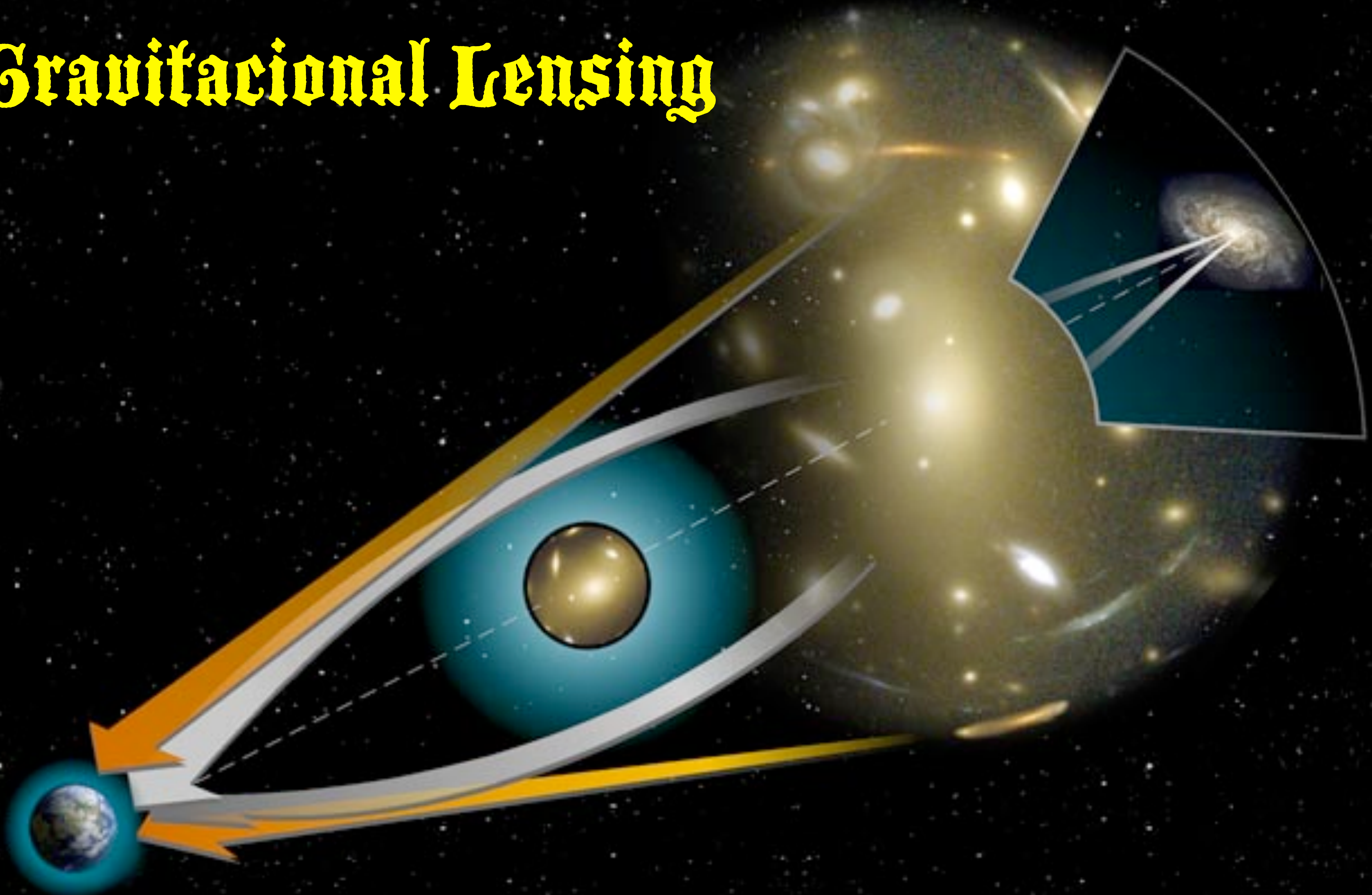
Strong degeneracy between Σm_ν and the Hubble constant H_0!

CMB: $\sum m_\nu$

@ CMB: Early Integrated Sachs Wolfe effect (ISW).

Shift in the angular position of the peaks.

Gravitacional 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.

CMB Lensing: $\sum m_\nu$

Lensing remaps the CMB fluctuations:

$$\Theta_{\rm lensed}(\hat{n}) = \Theta(\hat{n} + \nabla\phi(\hat{n}))$$

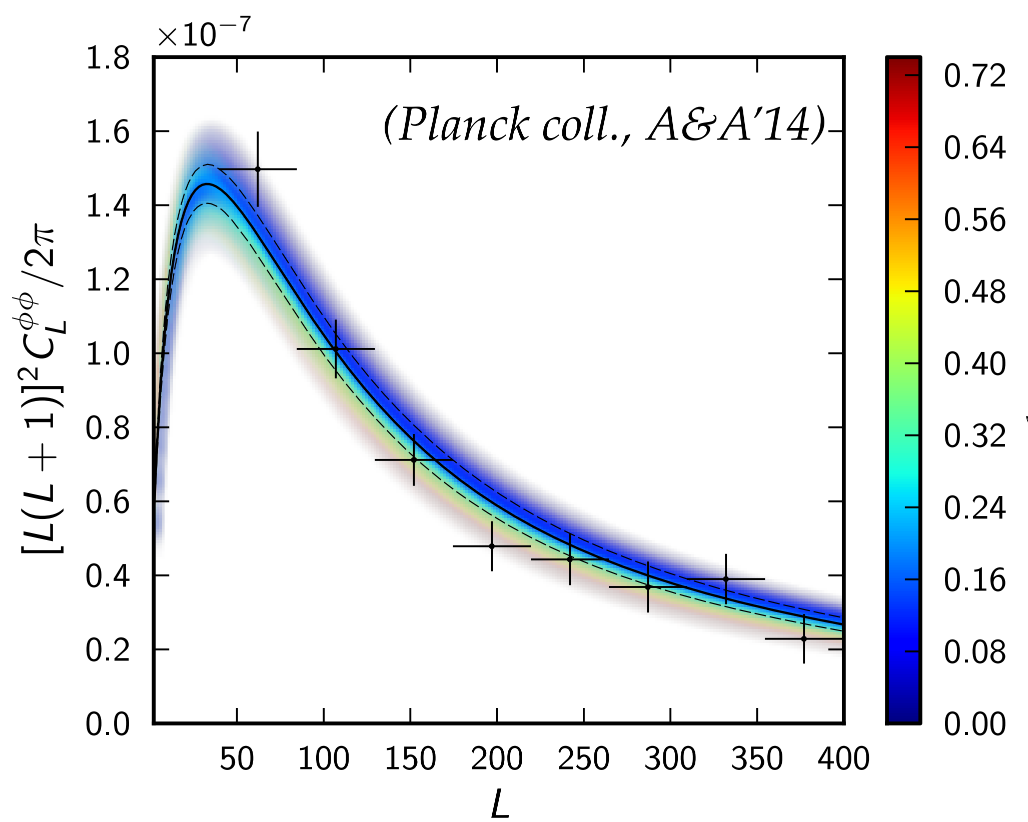
Lensing potential ϕ is a measure of the integrated mass distribution back to the last scattering surface

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

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

Neutrinos are hot relics with large thermal velocities, implying less clustering on small scales, reducing therefore CMB lensing!

(Kaplinghat et al PRL'03, Lesgourgues et al, PRD'06)



CMB: $\sum m_\nu$

Planck TTTEEE+lowT+lowE+lensing

Planck Coll. A&A'20

$$\sum m_\nu < 0.24 \text{ eV } 95\%\text{CL}$$

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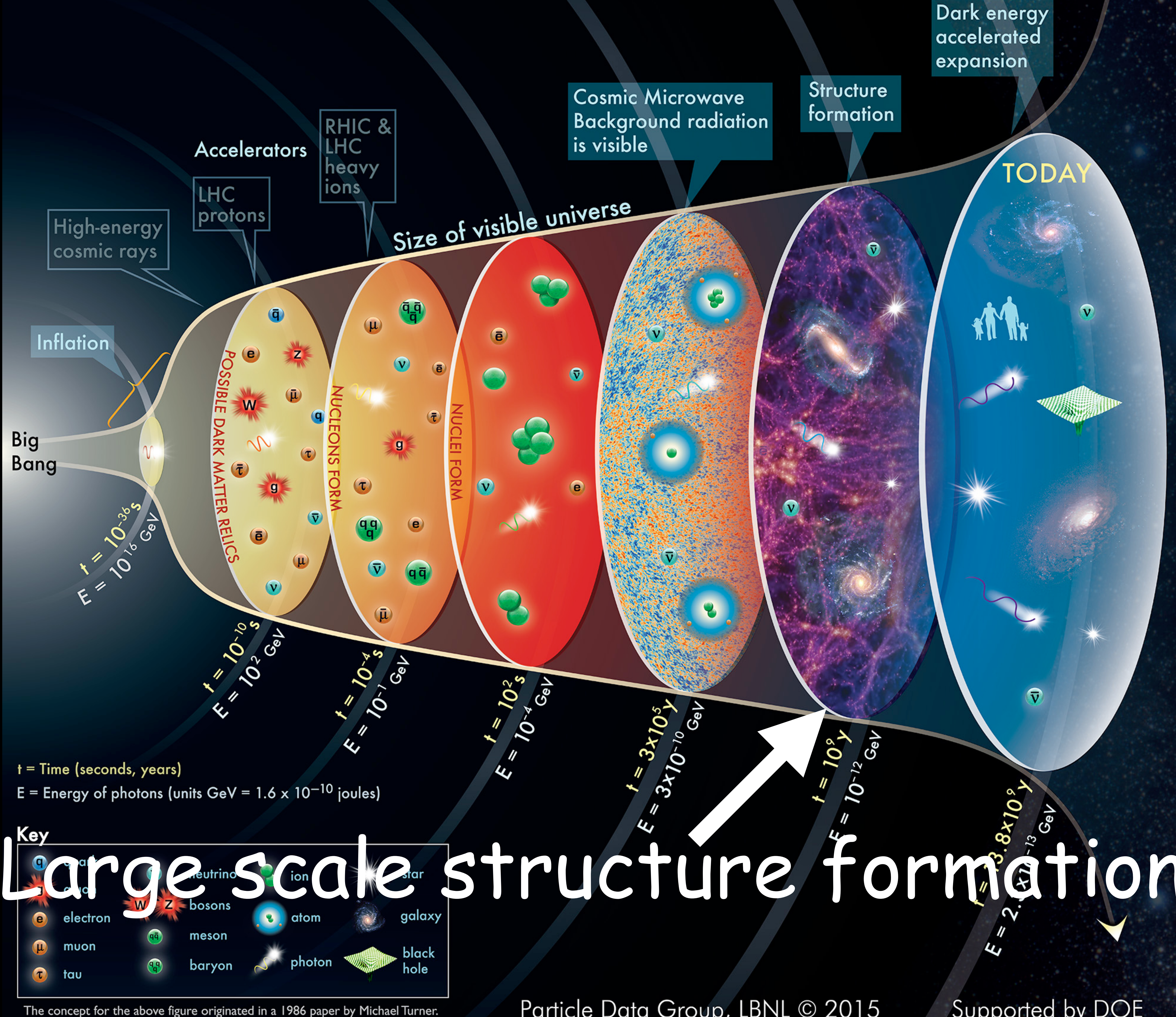
Large scale structure formation: m_ν

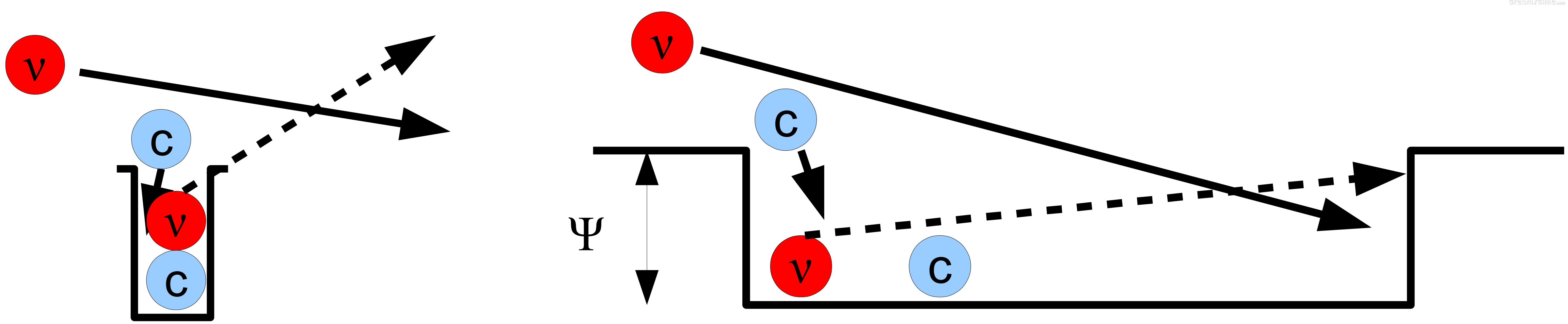


Large scale structure: m_ν

Neutrino masses suppress structure formation on scales larger than their free streaming scale when they turn non relativistic. *(Bond et al PRL'80)*

Neutrinos with eV or sub-eV masses are HOT relics with LARGE thermal velocities!

Cold dark matter instead has zero velocity and therefore it clusters at any scale!



$$\lambda \ll \lambda_{fs,\nu} \to k \gg k_{fs,\nu} \qquad \lambda \gg \lambda_{fs,\nu} \to k \ll k_{fs,\nu}$$

(From Y. Wong)

Large scale structure: m_ν

Growth equation for a single uncoupled fluid, linear regime, with constant sound speed:

Hubble drag

Gravity

$$\ddot{\delta} + \boxed{2\frac{\dot{a}}{a}\dot{\delta}} - \boxed{c_s^2 k^2 \frac{\delta}{a^2}} = \boxed{4\pi G\rho\delta}$$

Pressure

Jeans scale:

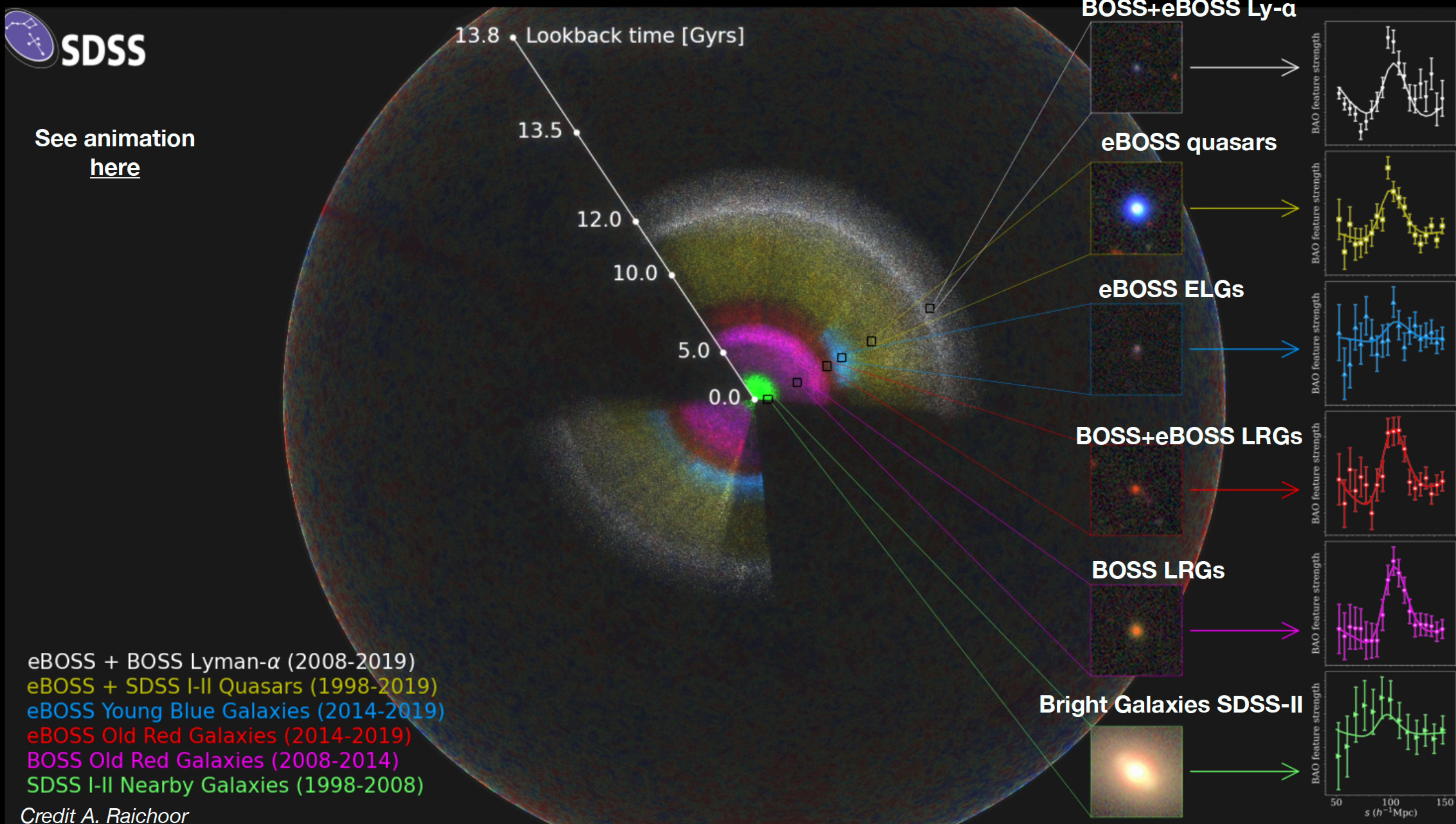
$$k_J \equiv \sqrt{\frac{4\pi G\rho}{c_s^2(1+z)^2}}$$

$k>k_J$ no growth can occur

$k<k_J$ density perturbations growth

Neutrino free streaming scale:

$$k_{fs,\nu}(z) \equiv \sqrt{\frac{3}{2}}\frac{H(z)}{(1+z)\sigma_{v,\nu}(z)}$$



SDSS
See animation
here
13.8
Lookback time [Gyrs]
13.5
12.0
10.0
5.0
0.0
BOSS+eBOSS Ly-α
eBOSS quasars
eBOSS ELGs
BOSS+eBOSS LRGs
BOSS LRGs
Bright Galaxies SDSS-II
BAO feature strength
50
100
150
s (h⁻¹Mpc)
eBOSS + BOSS Lyman-α (2008-2019)
eBOSS + SDSS I-II Quasars (1998-2019)
eBOSS Young Blue Galaxies (2014-2019)
eBOSS Old Red Galaxies (2014-2019)
BOSS Old Red Galaxies (2008-2014)
SDSS I-II Nearby Galaxies (1998-2008)
Credit A. Raichoor

$\sum m_\nu$

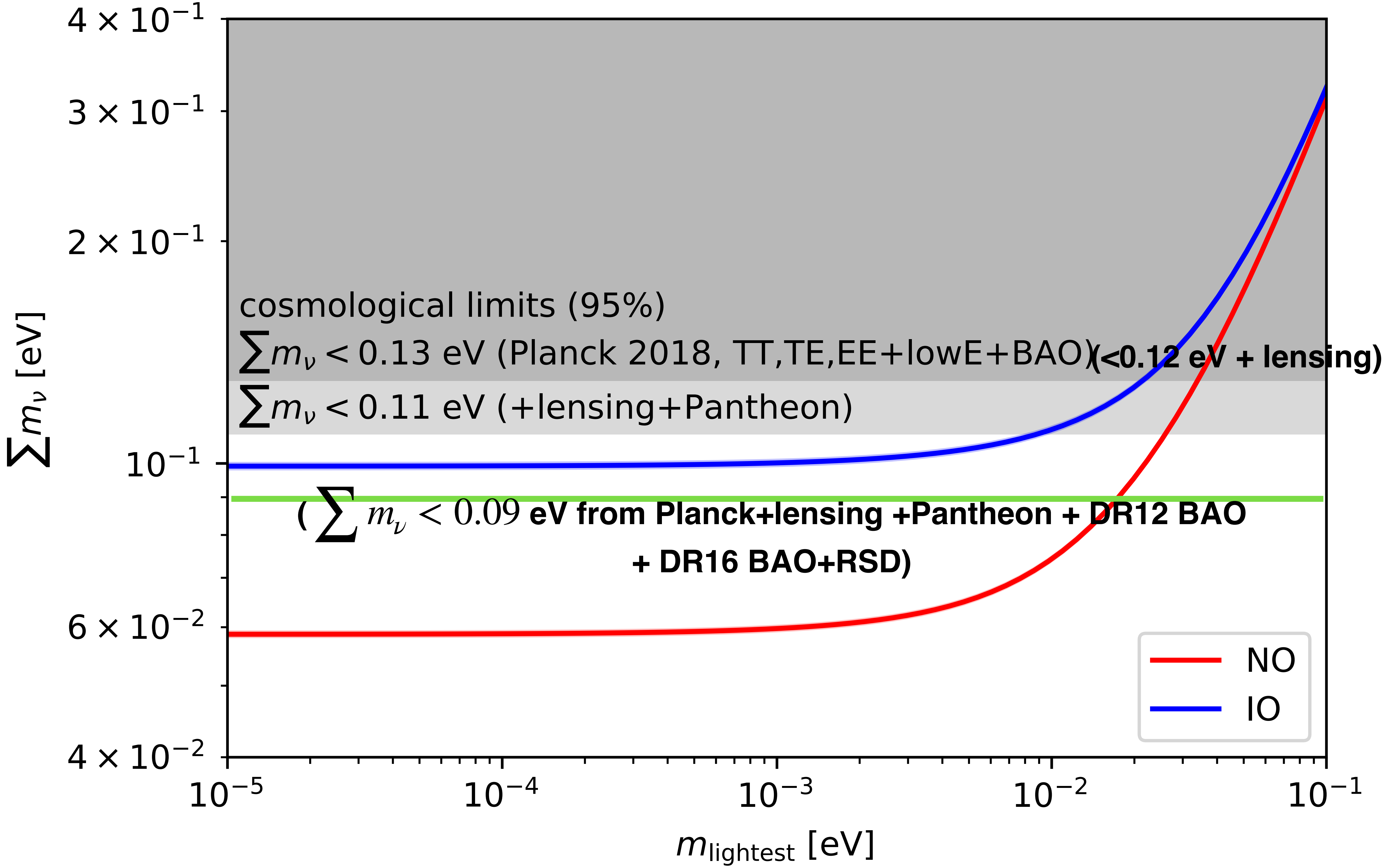
- Planck 2018 CMB temperature polarization and lensing potential data:

$$\sum m_\nu < 0.24 \text{ eV } 95\%\text{CL}$$

- If we add large scale structure information in its BAO form

$$\sum m_\nu < 0.12 \text{ eV } 95\%\text{CL}$$

Planck Coll. A&A'20


cosmological limits (95%)
$\sum m_\nu < 0.13$ eV (Planck 2018, TT,TE,EE+lowE+BAO)
(<0.12 eV + lensing)
$\sum m_\nu < 0.11$ eV (+lensing+Pantheon)
($\sum m_\nu < 0.09$ eV from Planck+lensing +Pantheon + DR12 BAO + DR16 BAO+RSD)
NO
IO
$\sum m_\nu$ [eV]
$m_{\rm lightest}$ [eV]
4×10^{-1}
3×10^{-1}
2×10^{-1}
10^{-1}
6×10^{-2}
4×10^{-2}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}

$\sum m_\nu$

Planck Coll. A&A'20

Planck TTTEEE+lowT+lowE+lensing

$$\sum m_\nu < 0.24 \text{ eV } 95\%\text{CL}$$

+ large scale structure

$$\sum m_\nu < 0.12 \text{ eV } 95\%\text{CL}$$

Planck Coll. A&A'20

+ large scale structure + SNIa

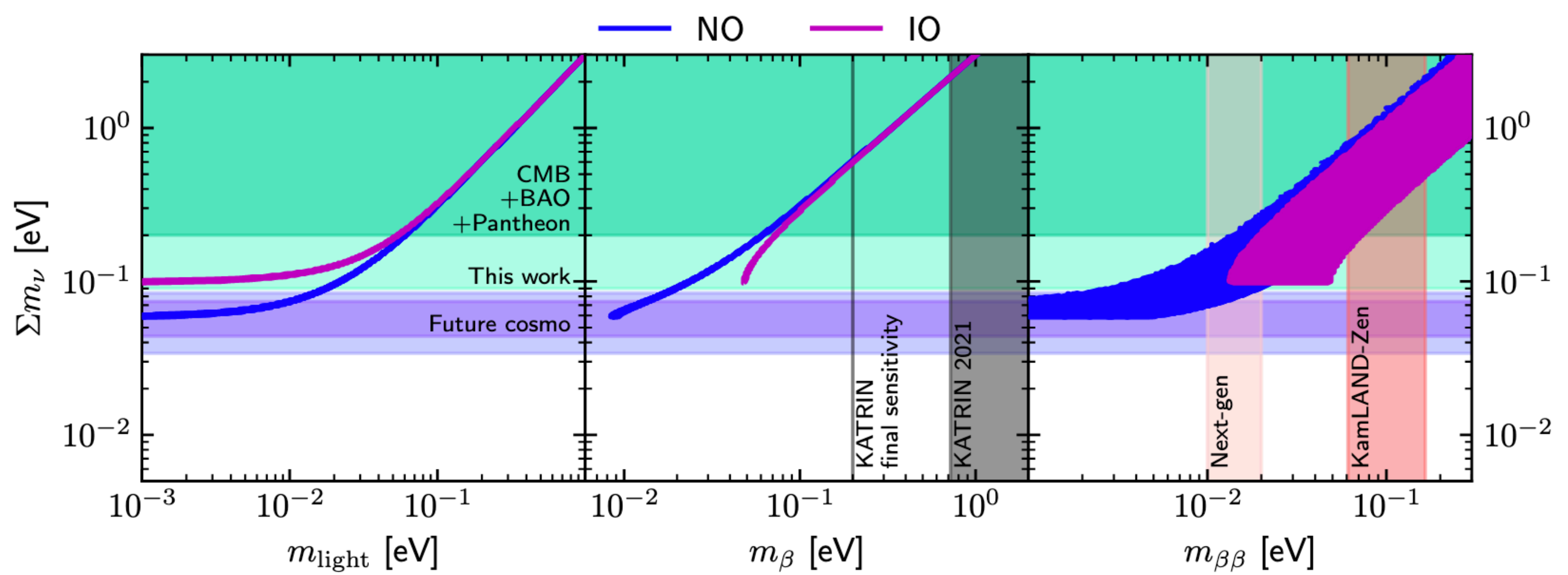
$$\sum m_\nu < 0.11 \text{ eV } 95\%\text{CL}$$

+ SDSS-IV (BAO + RSD) DR16 + DR12 BAO + SNIa

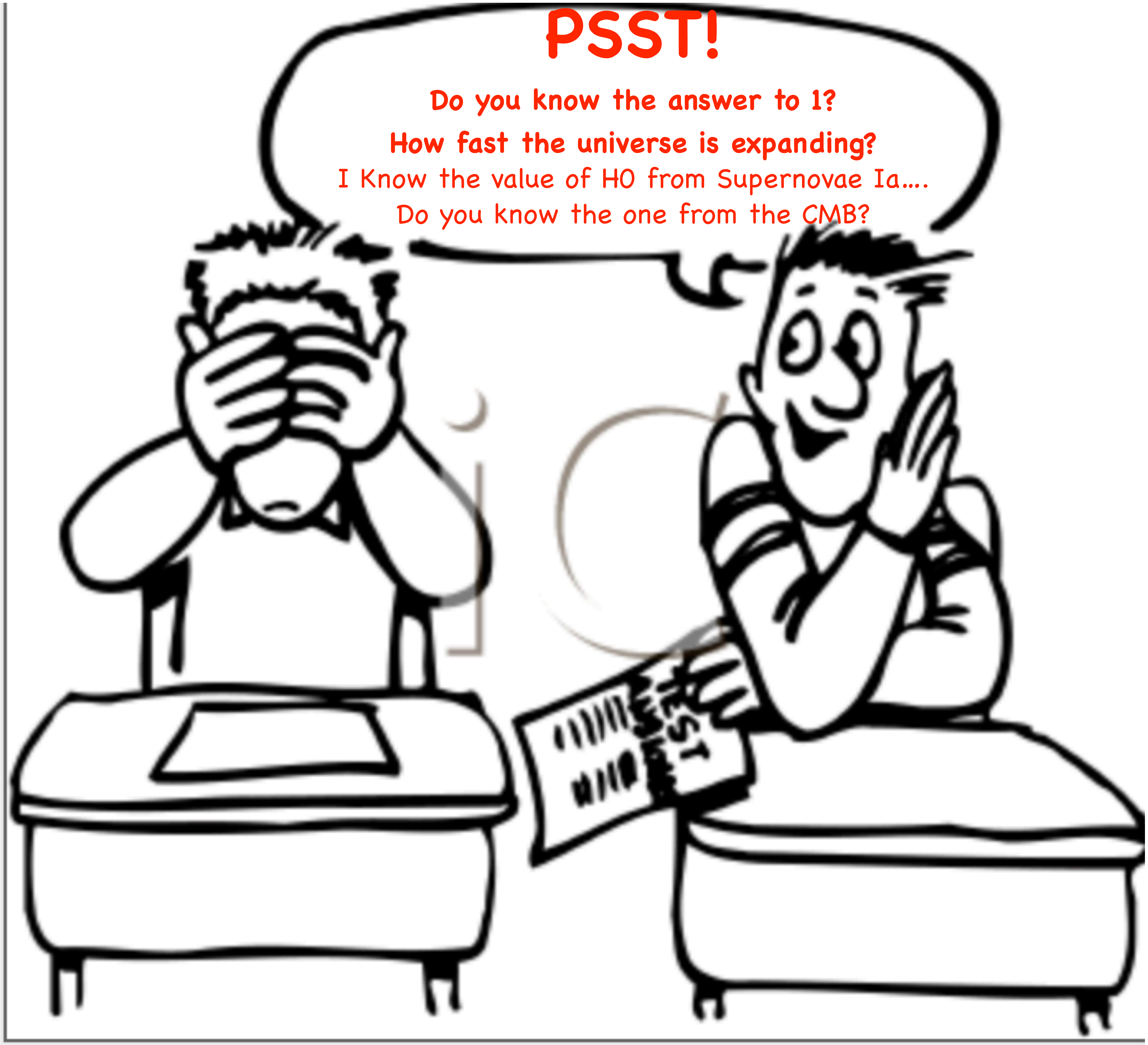
$$\sum m_\nu < 0.09 \text{ eV } 95\% \text{ CL}$$

Di Valentino et al, PRD'21

Planck+lensing +Pantheon	Σm_ν [eV]	H_0 [km/s/Mpc]	Ω_m	σ_8	S_8	$\ln B_{0-NH}$	$\ln B_{NH-IH}$
+ DR12 *BAO only*	< 0.116	67.8 ± 1.0	$0.309^{+0.013}_{-0.012}$	$0.814^{+0.017}_{-0.019}$	0.826 ± 0.022	-1.3	-1.5
+ DR12 *BAO+RSD*	< 0.118	67.8 ± 1.0	$0.310^{+0.013}_{-0.012}$	$0.814^{+0.017}_{-0.019}$	$0.827^{+0.021}_{-0.022}$	-1.3	-1.7
+ DR16 *BAO only*	< 0.158	$67.5^{+1.2}_{-1.3}$	$0.314^{+0.017}_{-0.016}$	$0.811^{+0.020}_{-0.023}$	$0.830^{+0.023}_{-0.024}$	-0.7	-1.6
+DR16 *BAO+RSD*	< 0.101	$67.9^{+1.0}_{-1.1}$	$0.308^{+0.014}_{-0.013}$	$0.817^{+0.016}_{-0.017}$	0.828 ± 0.022	-1.7	-1.9
+DR12 *BAO only* + DR16 *BAO only*	< 0.121	$67.78^{+0.90}$[illegible]	$0.310^{+0.013}$[illegible]	$0.813^{+0.017}$[illegible]	0.826 ± 0.021	-0.9	-1.8
+DR12 *BAO only* + DR16 *BAO+RSD*	< 0.0866	$68.09^{+0.85}_{-0.88}$	0.306 ± 0.011	$0.817^{+0.015}_{-0.016}$	$0.826^{+0.020}_{-0.021}$	-1.9	-2.0
+DR12 *BAO+RSD* + DR16 *BAO only*	< 0.125	67.71[illegible]	0.311[illegible]	$0.813^{+0.017}$[illegible]	0.828 ± 0.021	-1.1	-1.4
+DR12 *BAO+RSD* + DR16 *BAO+RSD*	< 0.0934	$68.00^{+0.87}_{-0.89}$	0.307 ± 0.011	$0.817^{+0.015}_{-0.016}$	0.827 ± 0.021	-1.9	-1.8

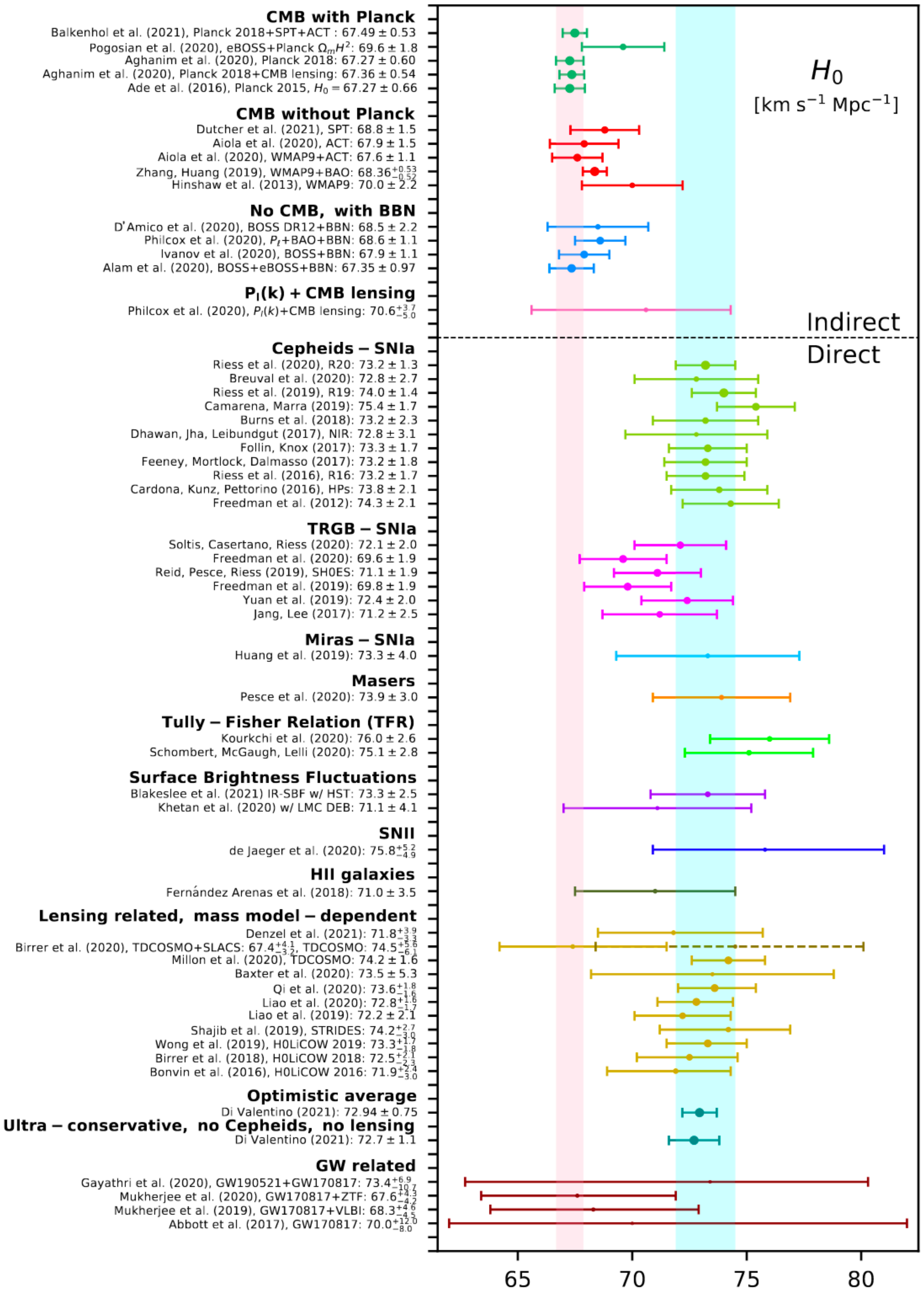


Di Valentino et al, PRD'21


PSST!
Do you know the answer to 1?
How fast the universe is expanding?
I Know the value of H0 from Supernovae Ia….
Do you know the one from the CMB?
TEST

The Hubble tension

Di Valentino et al, 2103.01183



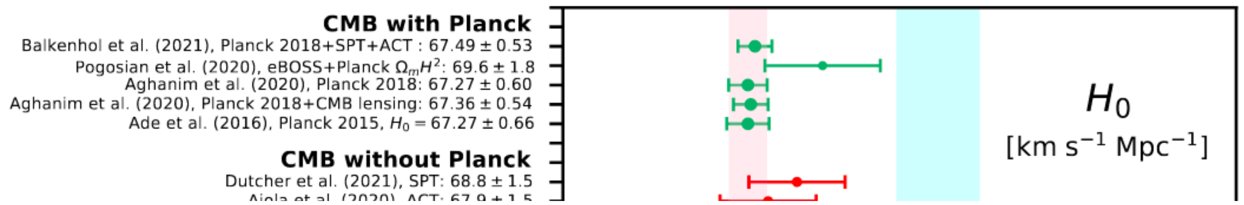
Disagreement of 4σ-6σ depending on the data sets

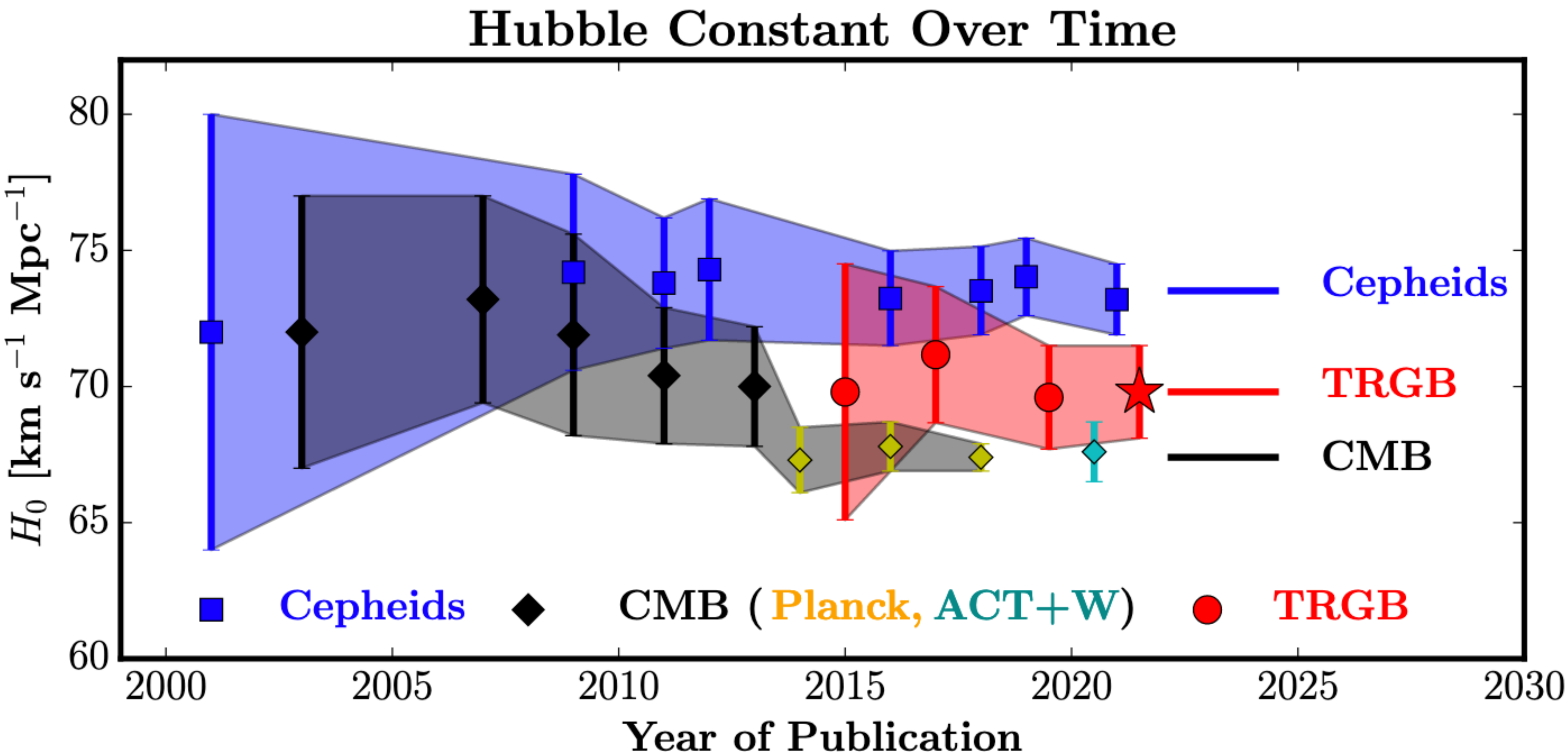
It has grown significance with the improvement of data.

The Hubble tension

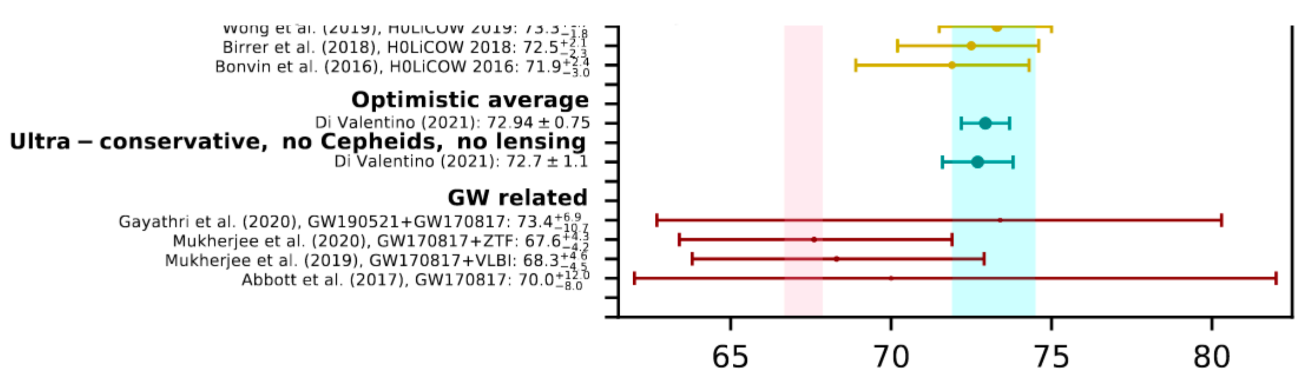
W. Freedman, APJ'21

Di Valentino et al, 2103.01183





'he



Systematics??

From V. Poulin

Several sources are required!

SNIa: Calibration issues

Follin &Knox, MNRAS'18;
Feeney et al, MNRAS'18;
Freedman et al'19&20;
Yuan et al, APJ'19;
Soltis, Casertano & Riess, APjL'21;
Efstathiou'20

Different populations between "local" and Hubble flow SNIa?

Rigault et al, APJ'15
Jones et al, APJ18
Brout & Scolnic, APJ'21

Do we live in a void?

Wu &Huterer, MNRAS'17
Kenworthy, Scolnic & Riess, APJ'19

Strong-lensed quasars: Lens profiles

Blum, Castorina & Simonovic, APjL'20
Birrer et al, A&A'20

Is the cosmological principle wrong?

Colin et at, A&A'19
Heinesen & Bouchert, CQG'20
Secrest wt al, APjL'21

CMB and the Hubble parameter

Within the (let's say) ΛCDM framework, the recipe is the following:

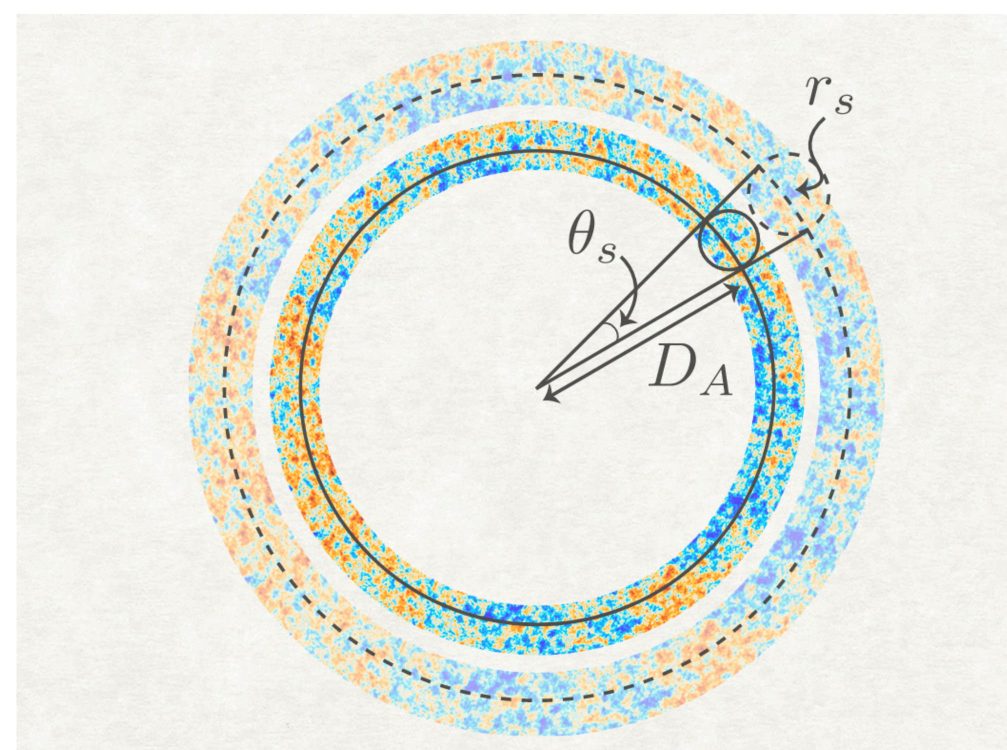
1) From measurements of the matter and baryon densities given a model: derivation of r_s^* at the last scattering redshift z_s
2) From the position of the CMB peaks, the comoving angular diameter distance is extracted:

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

3) 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?




Shhh!! masks on!!!
I'll call the neutrino major and the extra relativistic stuff.
They may know the solution for this!
Social
√-1 π
TEST

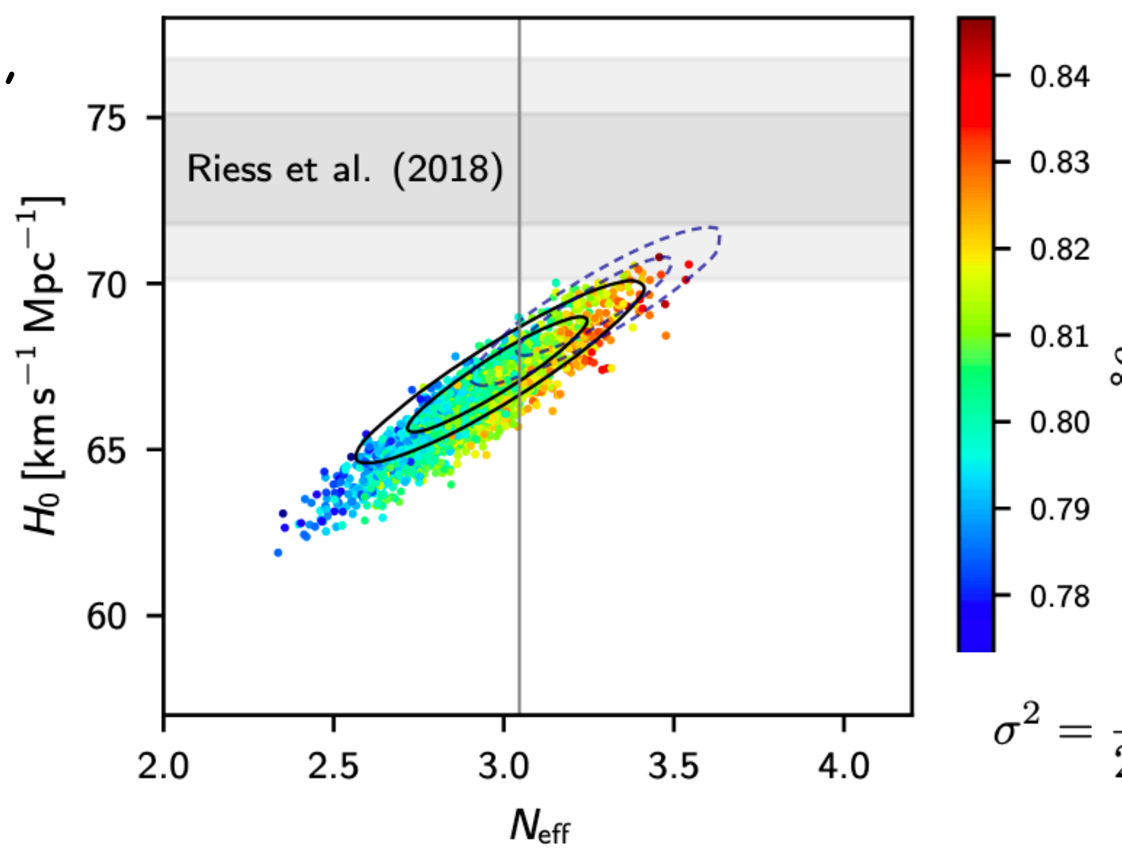
H_0 versus $N_{\rm eff}$

$$\Omega_r h^2 = \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right)\Omega_\gamma h^2$$

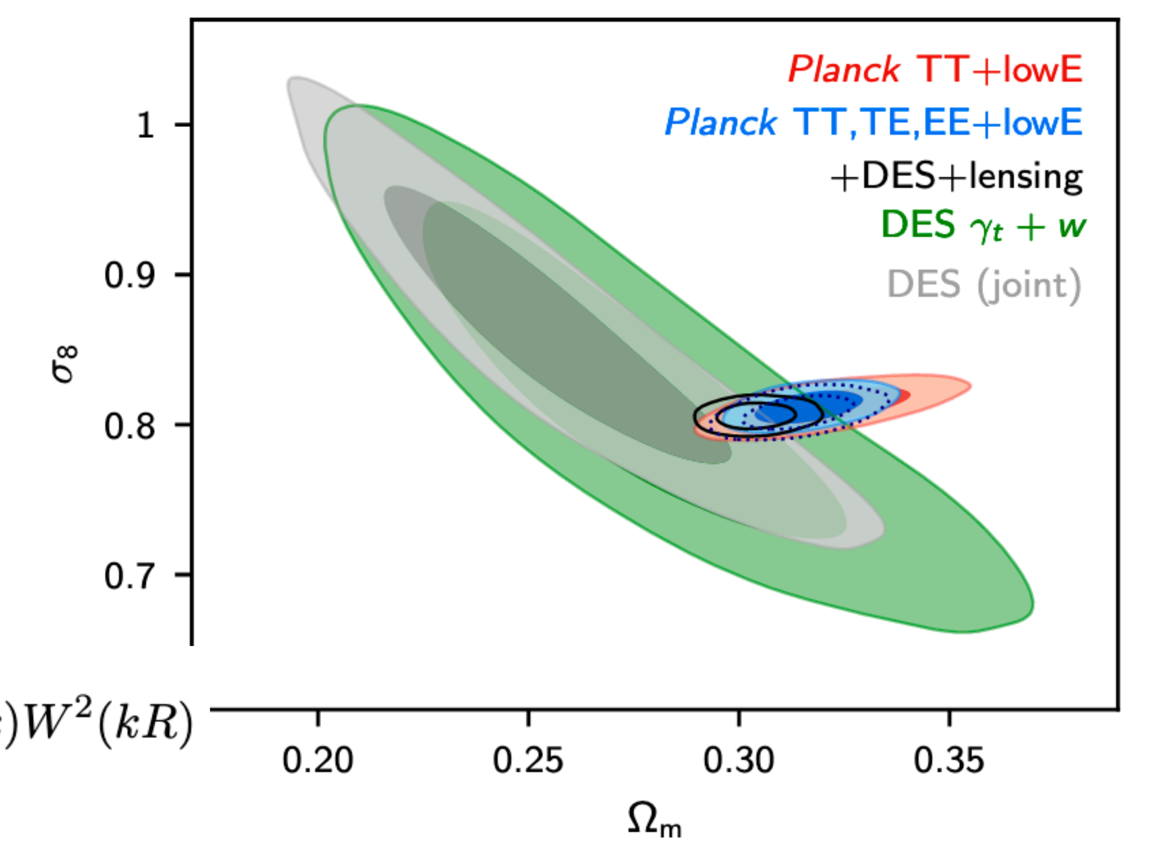
An increase of $N_{\rm eff}$ implies a larger expansion in the early universe: shorter r_s.
D_A at recombination needs to be smaller: higher H_0

$$\theta_s = \frac{r_s}{D_A} \qquad D_A = \int_0^{z_{rec}} \frac{dz}{H(z)}$$

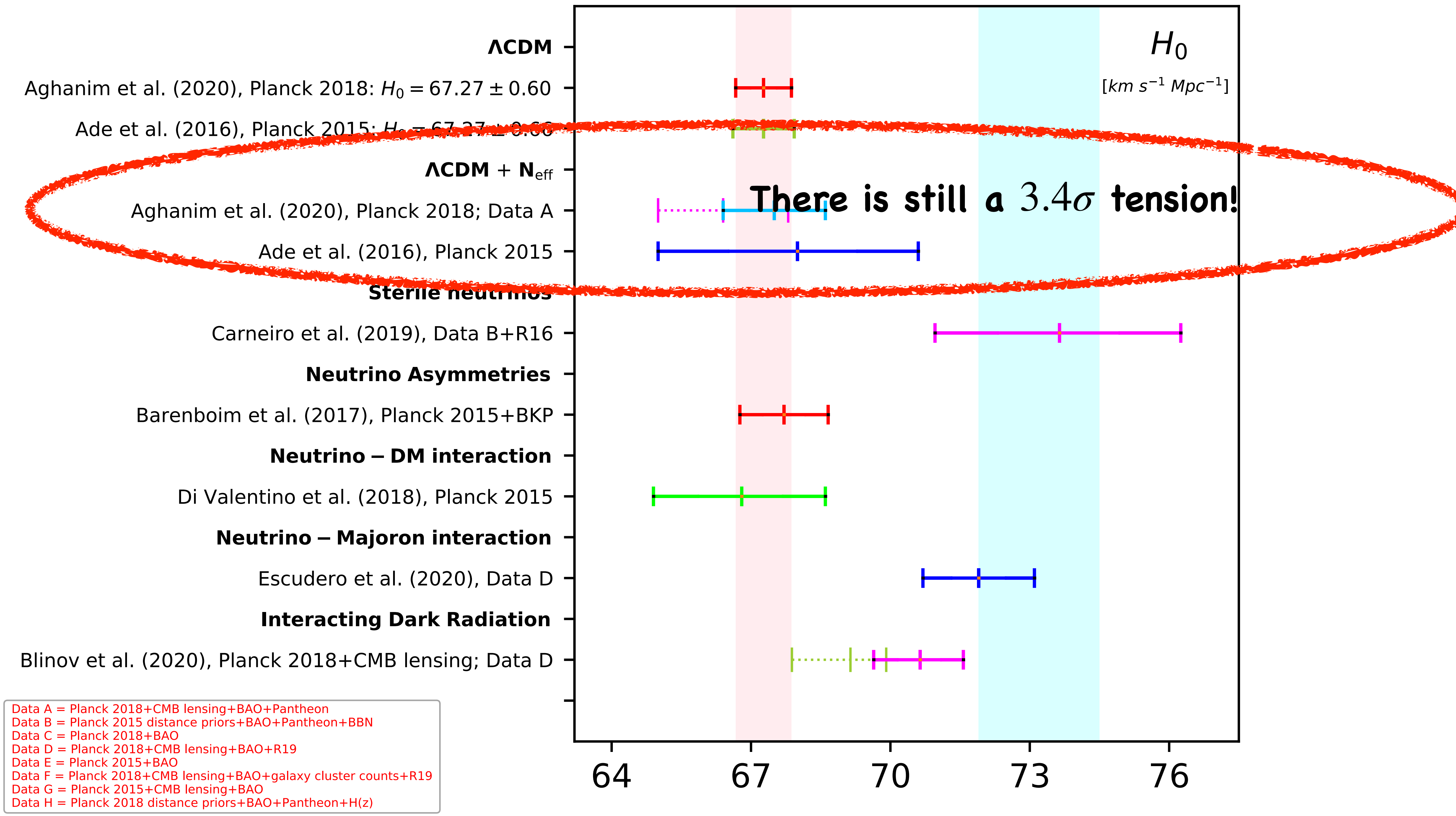
However, this will increase the tensions with weak galaxy lensing and cluster counts data on (in order to keep $\Omega_m h^2$ constant, we need a lower Ω_m, implying a higher σ_8



$$\sigma^2 = \frac{1}{2\pi^2}\int_0^\infty dk k^2 P(k) W^2(kR)$$



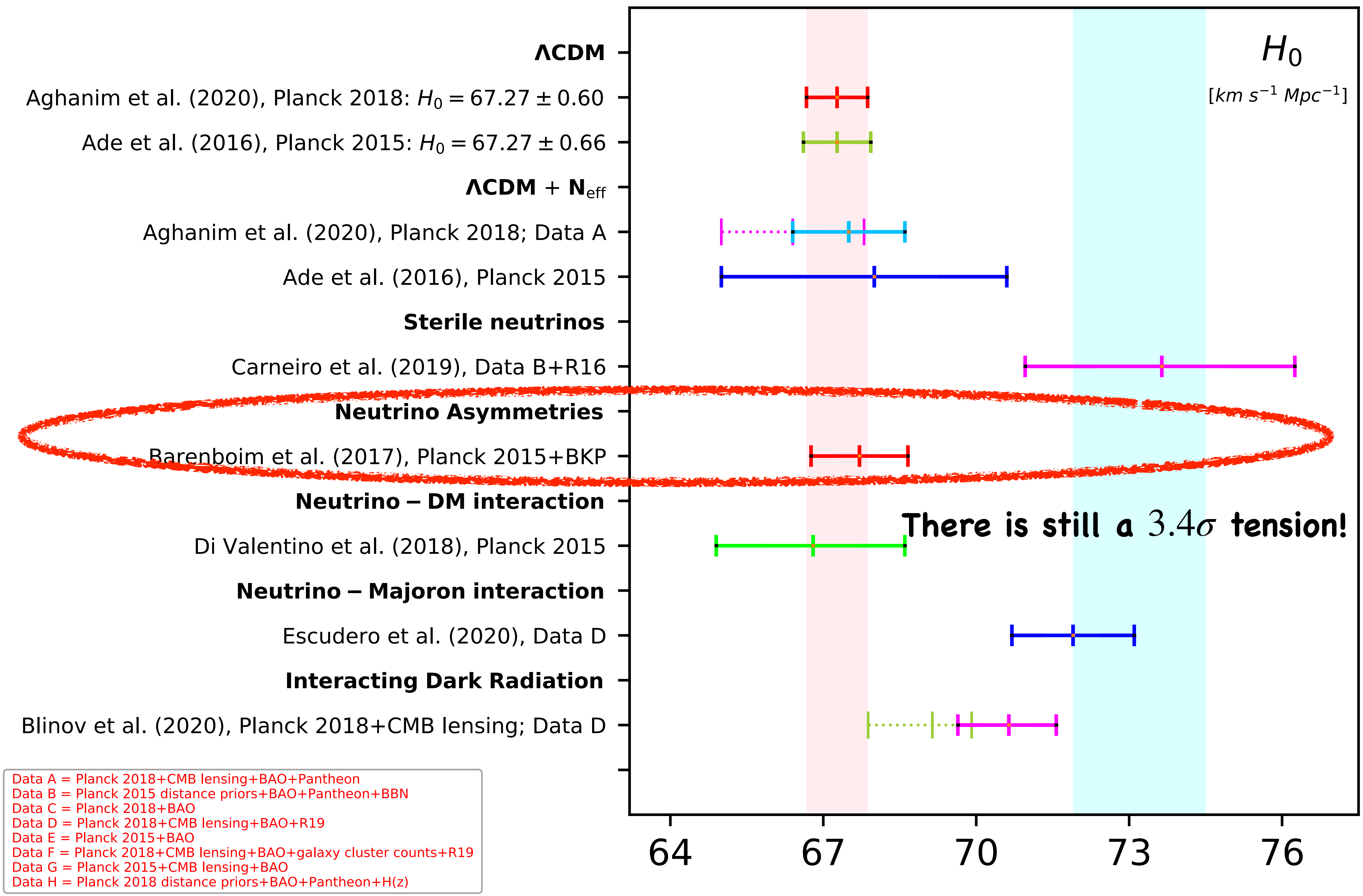
Planck Coll. A&A'20



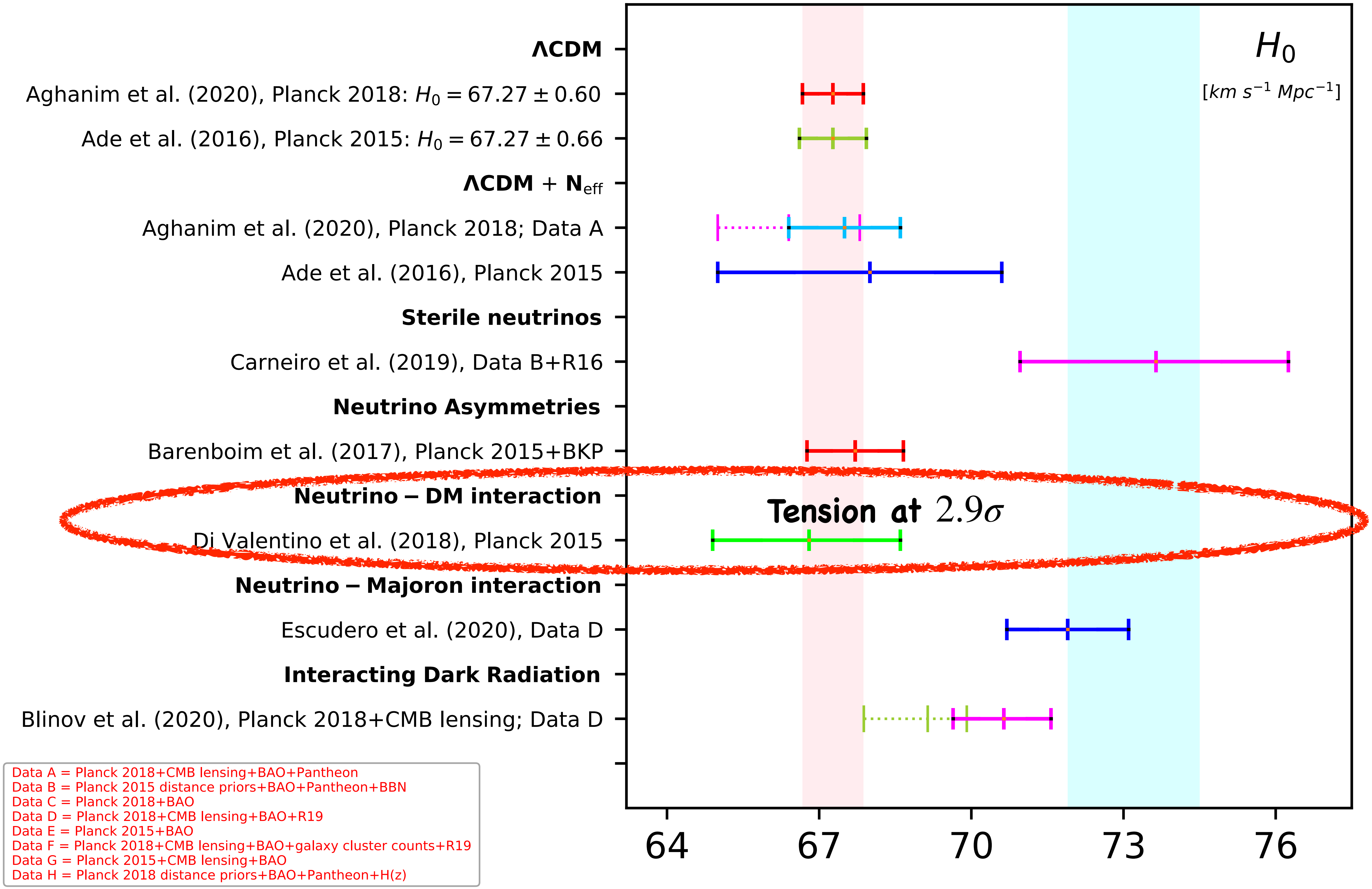
Di Valentino et al, 2103.01183

H_0 versus neutrino asymmetries

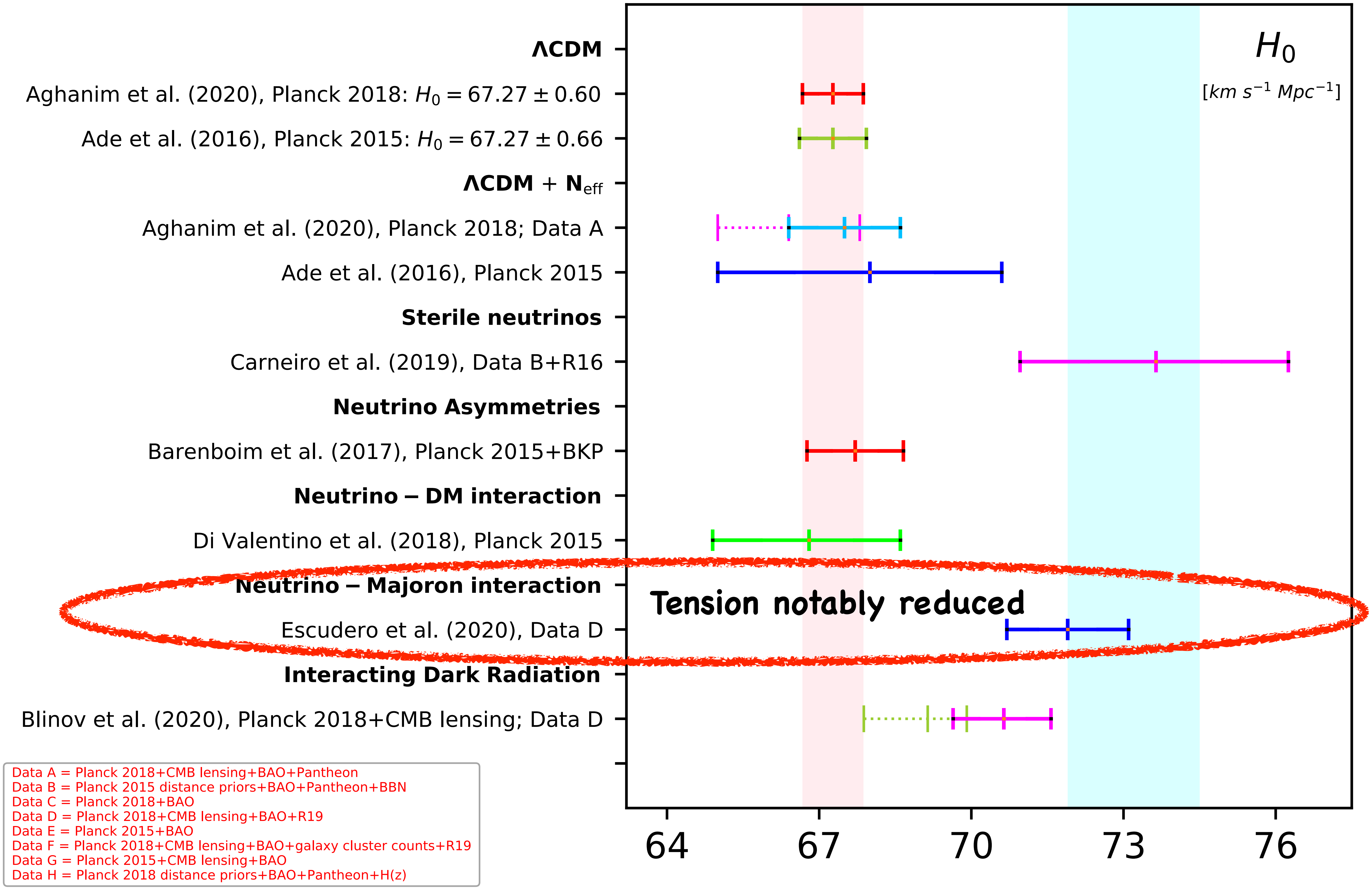
$$\Delta N_{eff} = \frac{15}{7}\left(\frac{\xi_i}{\pi}\right)^2\left(2+\left(\frac{\xi_i}{\pi}\right)^2\right)$$



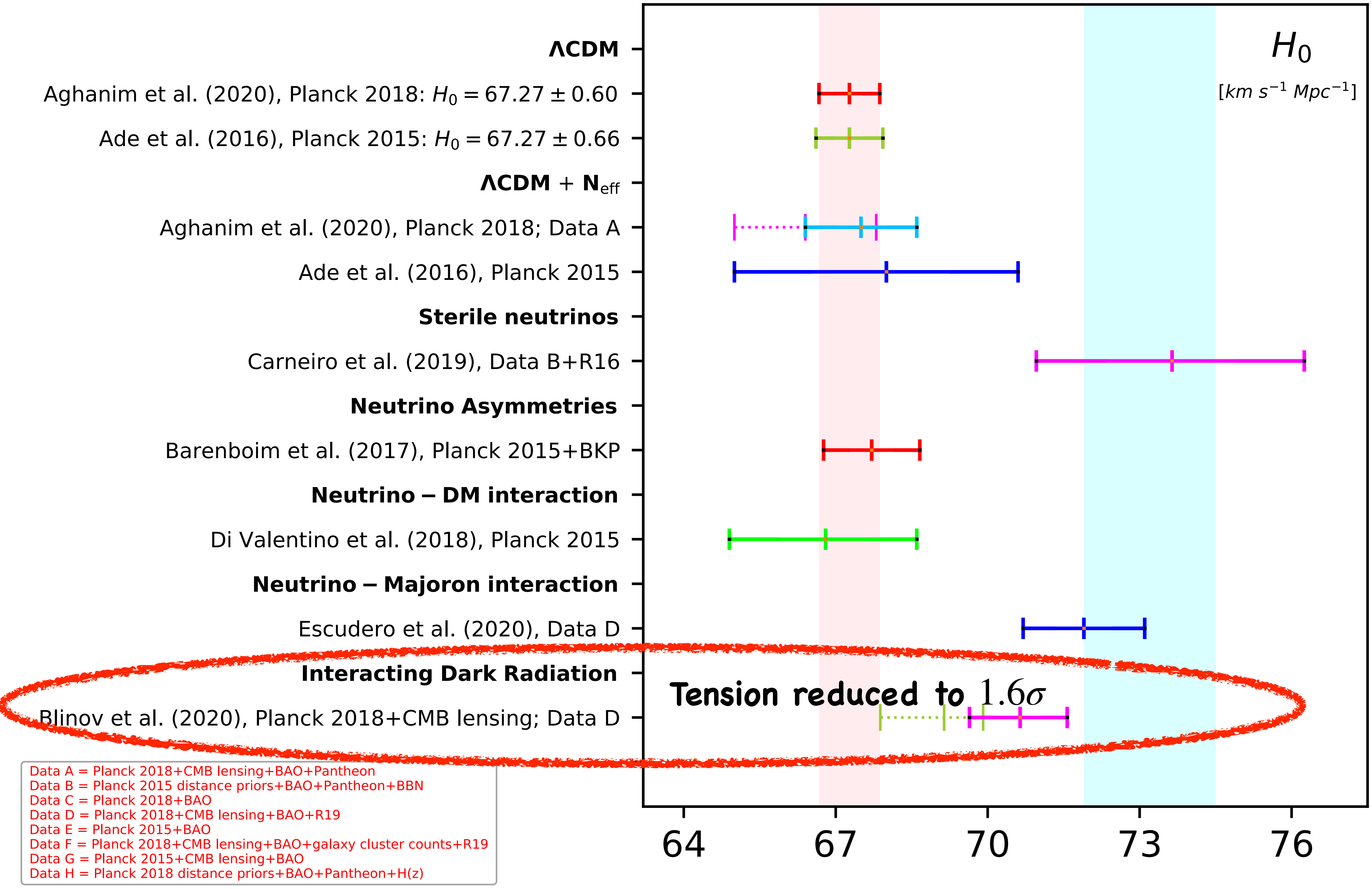
Di Valentino et al, 2103.01183



Di Valentino et al, 2103.01183



Di Valentino et al, 2103.01183



Di Valentino et al, 2103.01183

Interacting neutrinos

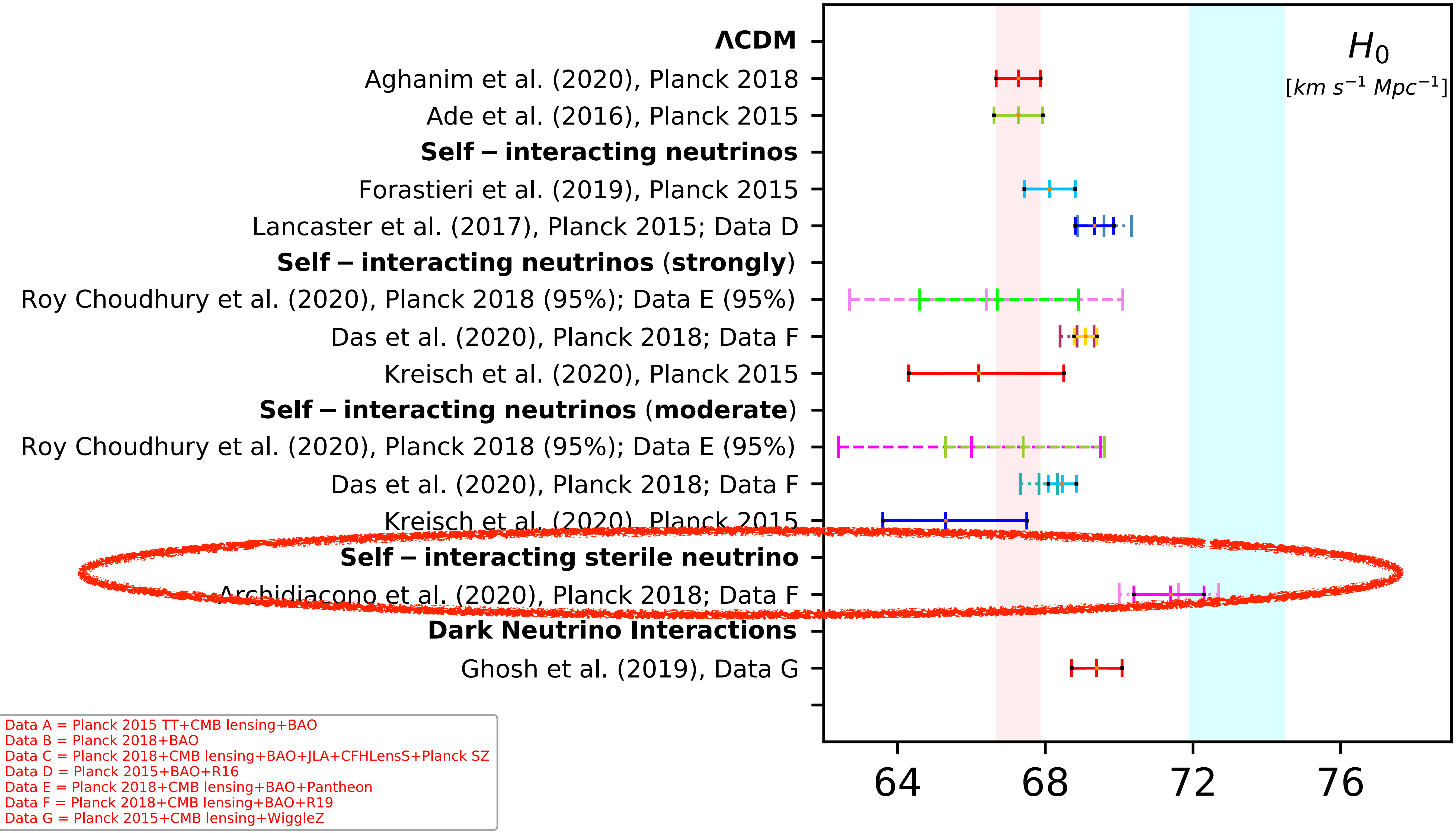
Free-streaming neutrinos travel supersonically through the photon-baryon plasma at early times, inducing a net phase shift in the CMB power spectra towards larger scales (smaller multipoles), as well as a slight suppression of its amplitude.

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

Bashinsky & Seljak, PRD'04

Bashinsky & Seljak, PRD'04; Follin et al, PRL'15;
Baumann et al, JCAP'16; Choi, Chiang & LoVerde, JCAP'18;
Baumann, Green & Zaldarriaga, JCAP'17;
Lancaster et al, JCAP'17; Oldengott, Tram &Wong, JCAP'17;
Kreisch, Cyr-Racine & Doré, PRD'20

Free-streaming neutrinos lead to a physical size of the photon sound horizon at last scattering that is slightly larger.
Interacting neutrinos shift the power spectrum towards towards smaller scales and reduce the physical size of photon sound horizon at last scattering: a smaller value of D_A = higher value of H_0 is required!



Di Valentino et al, 2103.01183

tension $\leq 1\sigma$ *"Excellent models"*	tension $\leq 2\sigma$ *"Good models"*	tension $\leq 3\sigma$ *"Promising models"*
Dark energy in extended parameter spaces [292]	Early Dark Energy [238]	Early Dark Energy [232]
Dynamical Dark Energy [312]	Phantom Dark Energy [11]	Decaying Warm DM [477]
Metastable Dark Energy [317]	Dynamical Dark Energy [11, 284, 312]	Neutrino-DM Interaction [509]
PEDE [395, 397]	GEDE [400]	Interacting dark radiation [520]
Elaborated Vacuum Metamorphosis [403–405]	Vacuum Metamorphosis [405]	Self-Interacting Neutrinos [703, 704]
IDE [317, 639, 640, 642, 655, 660, 664–666]	IDE [317, 656, 659, 664, 666, 673]	IDE [659]
Self-interacting sterile neutrinos [714]	Critically Emergent Dark Energy [997]	Unified Cosmologies [750]
Generalized Chaplygin gas model [747]	$f(\mathcal{T})$ gravity [817]	Scalar-tensor gravity [859]
Galileon gravity [879, 885]	Über-gravity [59]	Modified recombination [986]
Power Law Inflation [966]	Reconstructed PPS [978]	Super ΛCDM [1007]
$f(\mathcal{T})$ [821]		Coupled Dark Energy [653]

Table B1. Models solving the H_0 tension with R20 within the 1σ, 2σ and 3σ confidence levels considering the *Planck* dataset only.

Di Valentino et al, 2103.01183

The “Take Home” messages

- ν **masses & abundances** leave key signatures in cosmological observables.
- **NO** hints so far for neutrino masses or extra dark radiation species!
- N_{eff} @BBN: Light element abundances (^{4}He) abundances.
- N_{eff} @CMB: damping tail
- **$N_{eff} = 2.99^{+0.34}_{-0.33}$, (95% CL) from** 2018 Planck TTTEEE+lensing, perfectly consistent with BBN.
- Cosmology provides currently the tightest bounds to neutrino masses.
- ν masses@CMB: Early ISW, gravitational lensing
- ν masses@LSS: Free streaming

- **$\sum m_\nu < 0.099$ eV (95%CL)** from 2018 Planck TTTEEE+lensing plus RSD+BAO +SNIa data

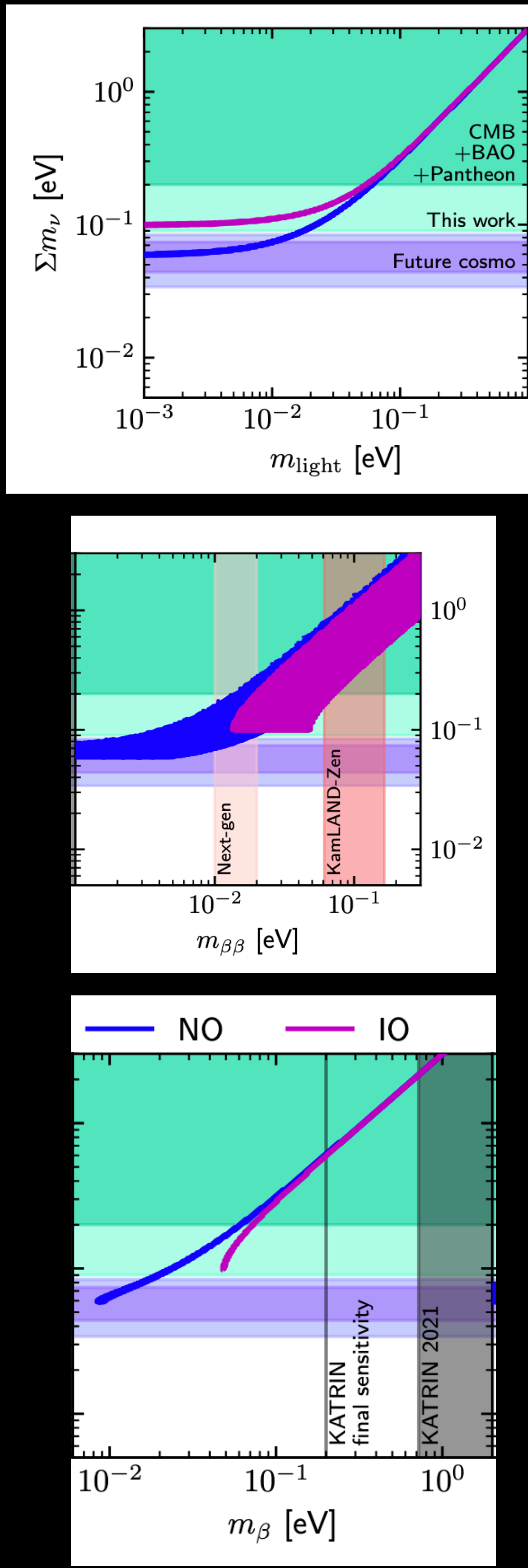
MERCI

BEAUCOUP

MERCI

BE🗼UCOUP

80



From cosmology:
Plank
CMB+BAO - $\Sigma m_\nu < 0.12$ eV (95% CL)

From 0νββ measurements:
KamLAND-Zen
$m_{\beta\beta} < 0.16$ eV (90% CL)

MODEL DEPENDENT

From kinematic measurements:
KATRIN
$m_\beta < 0.8$ eV (90% CL)

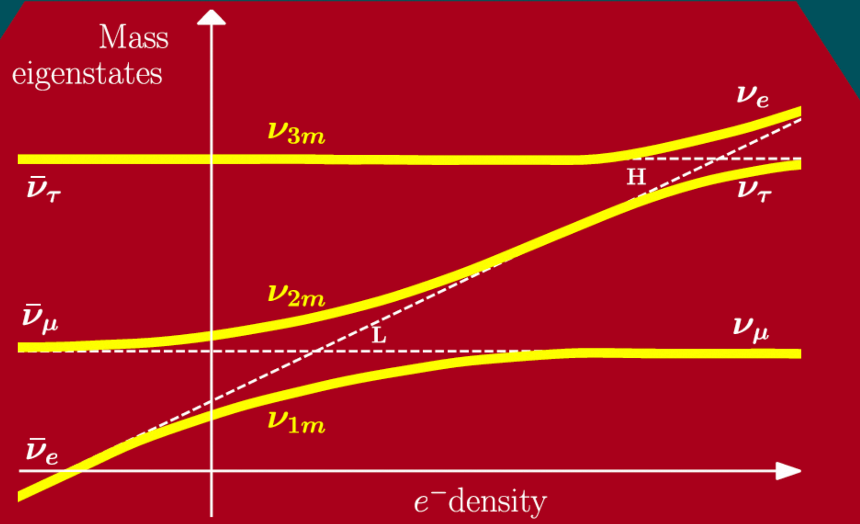
Time-of-flight constraints:
Kamiokande-II (SN1987A)
$m_\nu < 5.7$ eV (95% CL)

MODEL INDEPENDENT

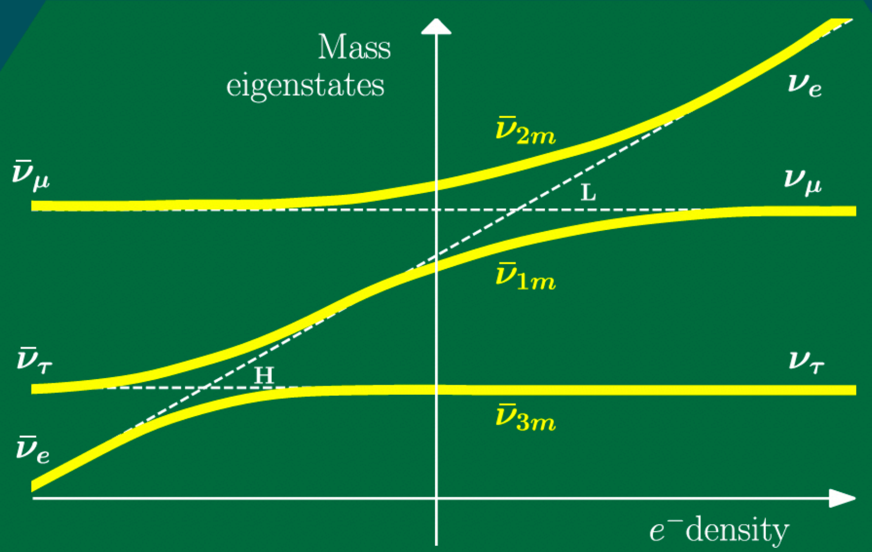
Supernova time delays

$$\Delta t = \frac{D}{2c}\left(\frac{m_\nu}{E_\nu}\right)^2$$

Oscillation probabilities inside the star

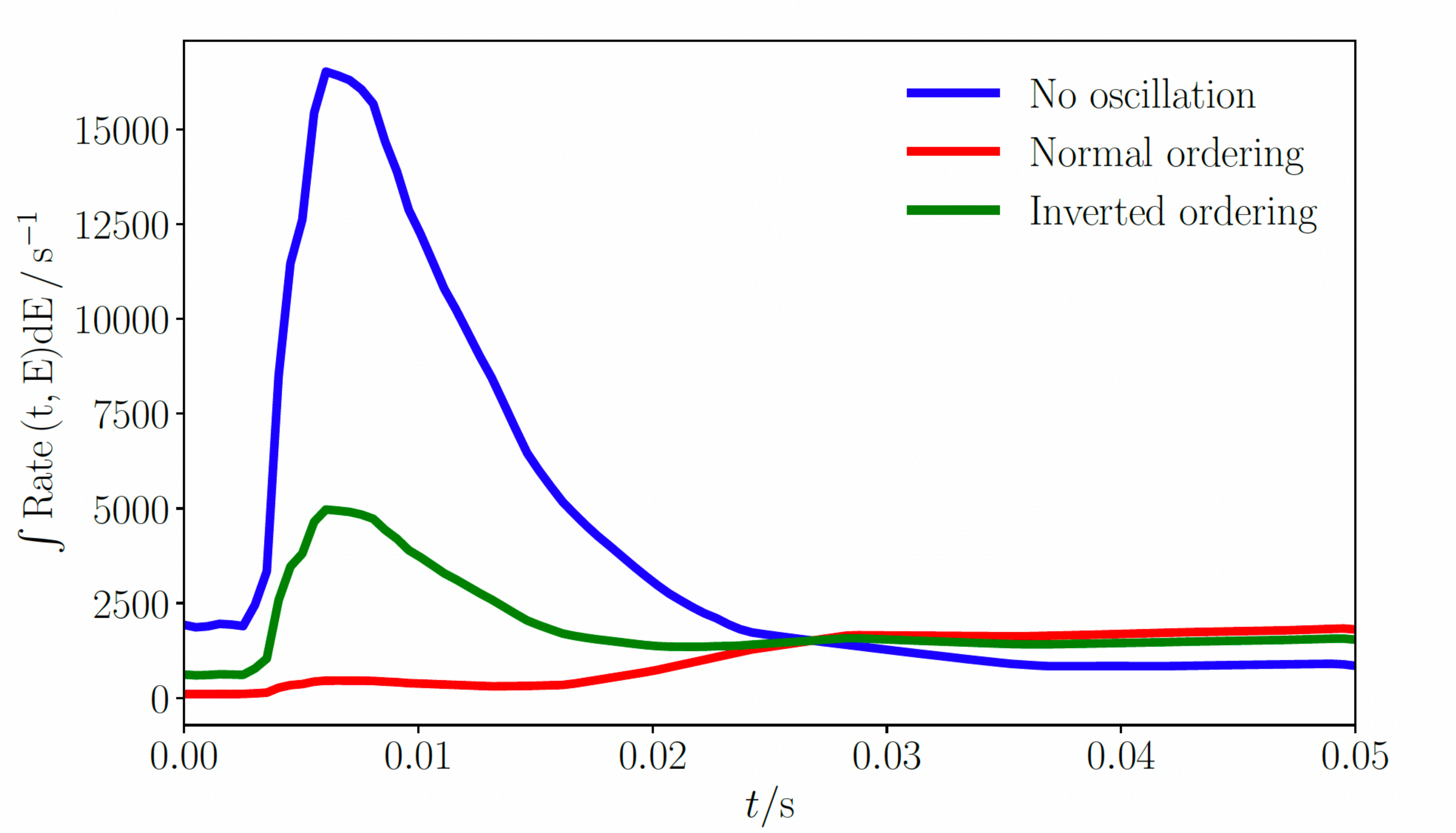


$$\Phi^{\mathrm{NO}}_{\nu_e} = p^{\mathrm{NO}}\Phi^0_{\nu_e} + (1 - p^{\mathrm{NO}})\Phi^0_{\nu_x}$$
$$p^{\mathrm{NO}} = |U_{e3}|^2$$



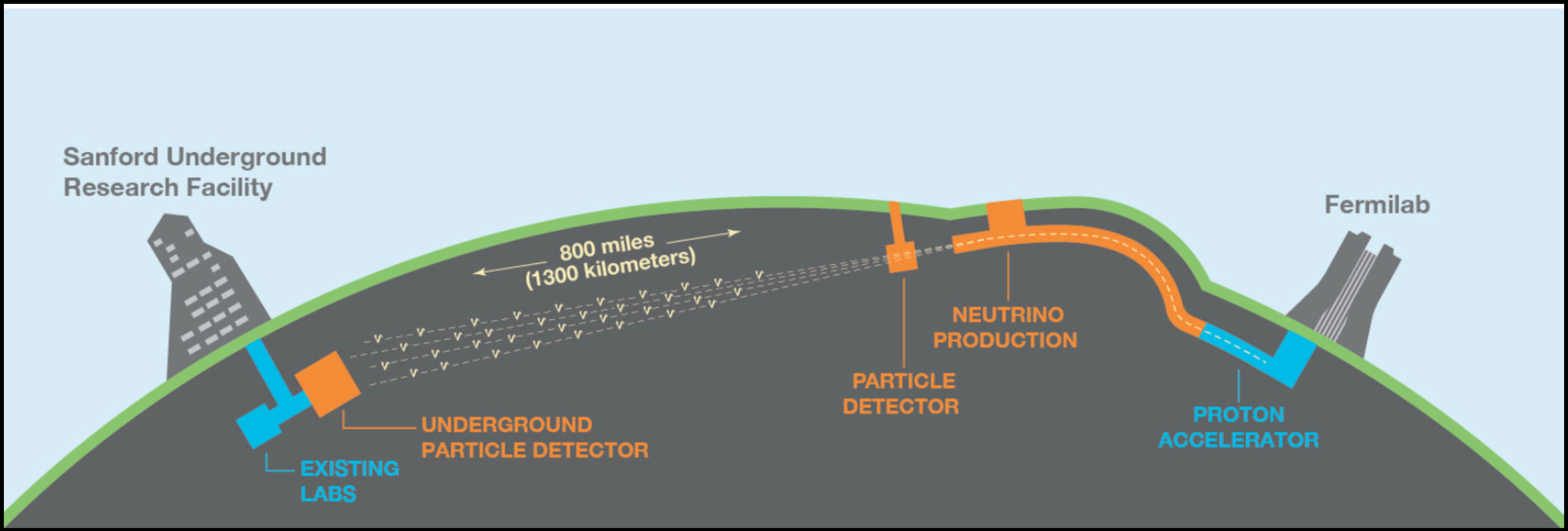
$$\Phi^{\mathrm{IO}}_{\nu_e} = p^{\mathrm{IO}}\Phi^0_{\nu_e} + (1 - p^{\mathrm{IO}})\Phi^0_{\nu_x}$$
$$p^{\mathrm{IO}} = |U_{e2}|^2$$

SN RATES



No oscillation
Normal ordering
Inverted ordering
$\int \mathrm{Rate}\,(\mathrm{t},\mathrm{E})\mathrm{dE}\,/\,\mathrm{s}^{-1}$
0
2500
5000
7500
10000
12500
15000
0.00
0.01
0.02
0.03
0.04
0.05
t/s

DUNE DETECTOR



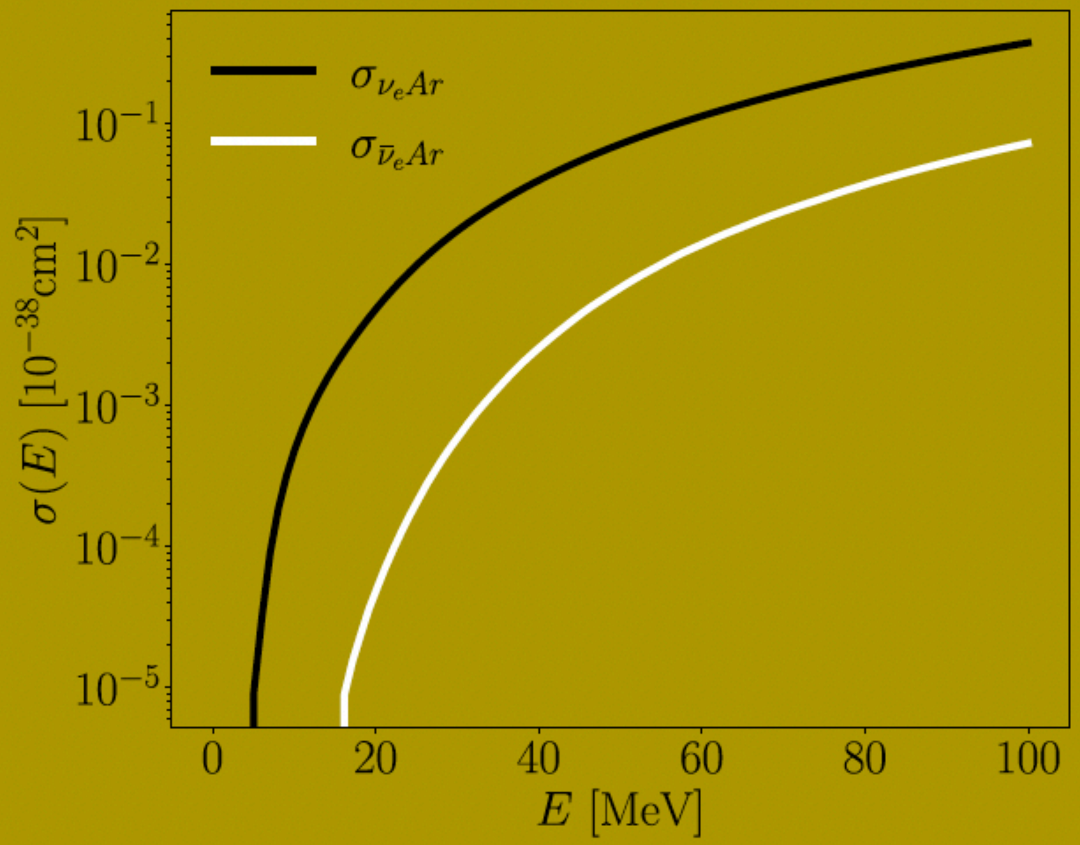
DUNE DETECTOR

Interaction channels in LArTPC:

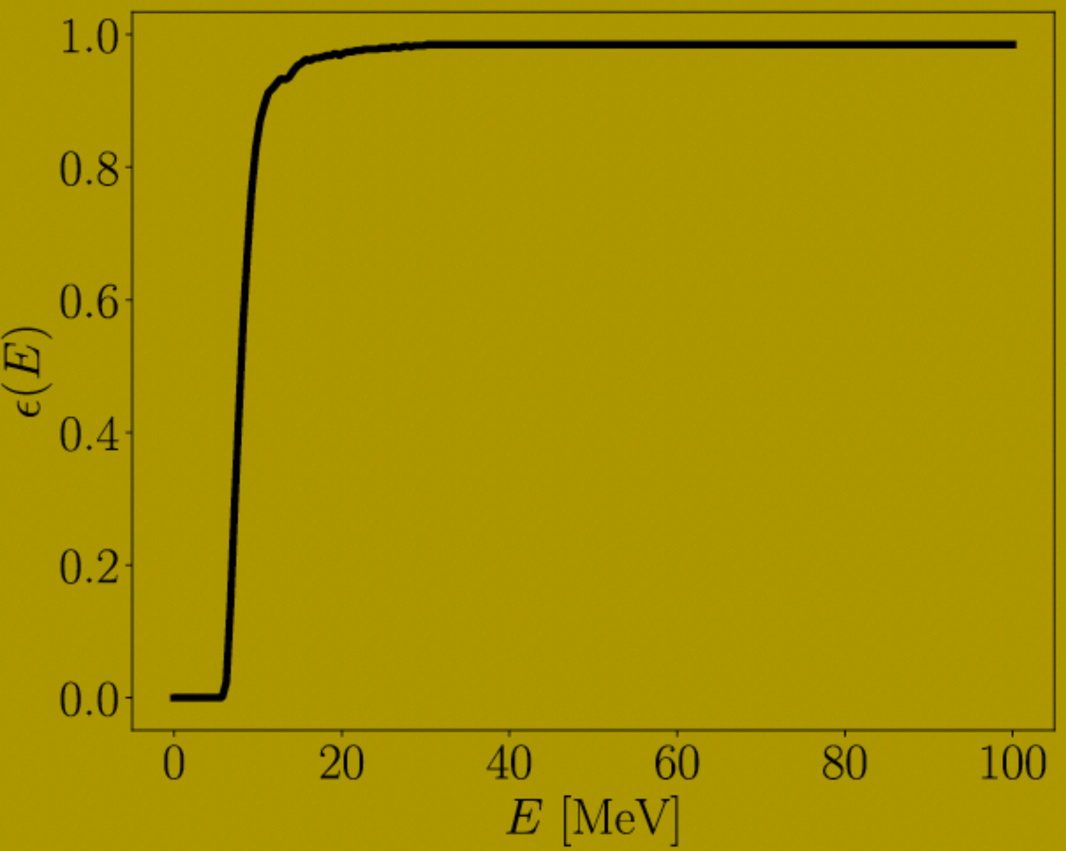
$$\nu_e \ {}^{40}\mathrm{Ar} \longrightarrow e^- \ {}^{40}\mathrm{K}^*$$

$$\bar{\nu}_e \ {}^{40}\mathrm{Ar} \longrightarrow e^+ \ {}^{40}\mathrm{Cl}^*$$

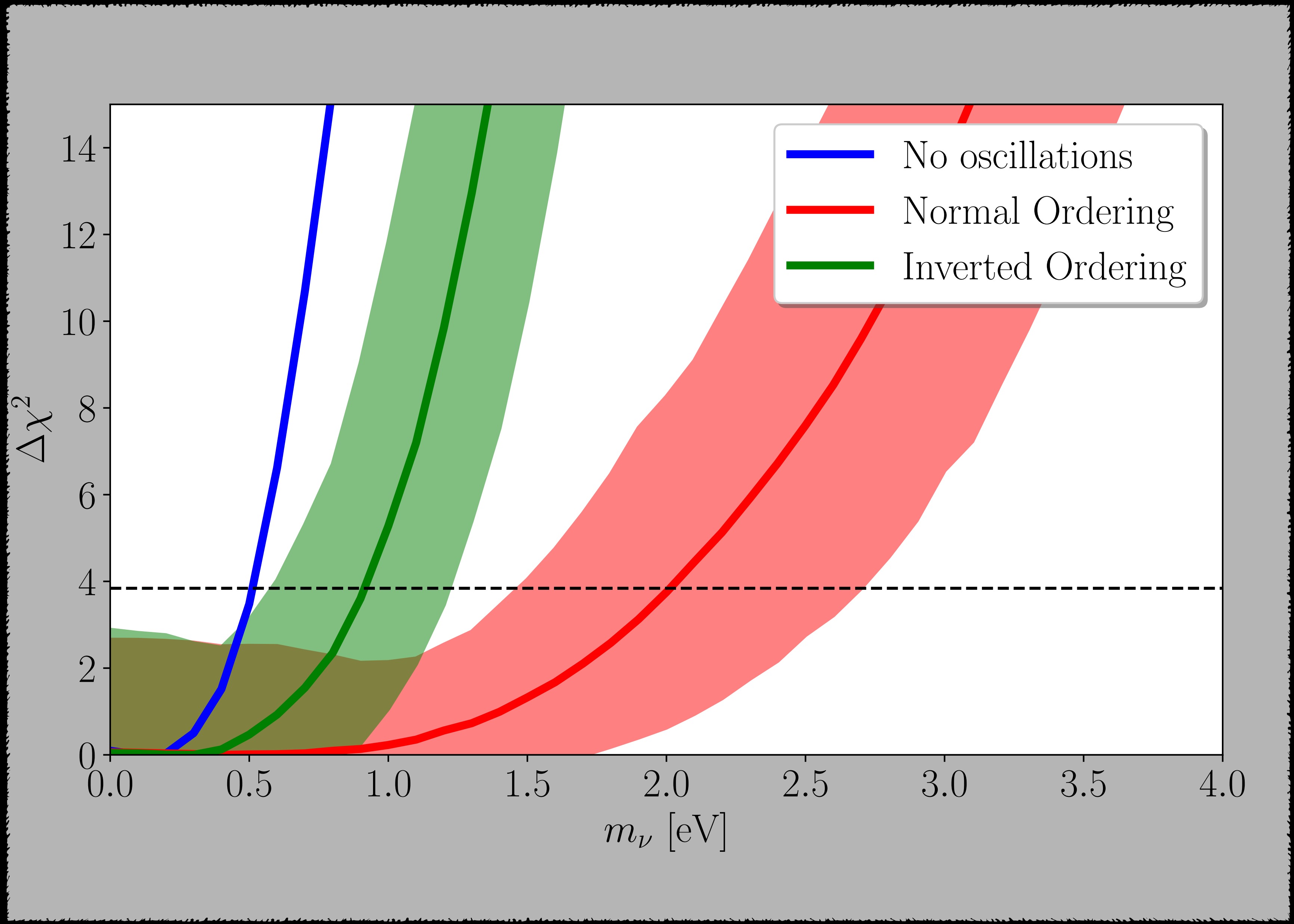
Cross section



DUNE efficiency



Sensitivities (preliminary!)

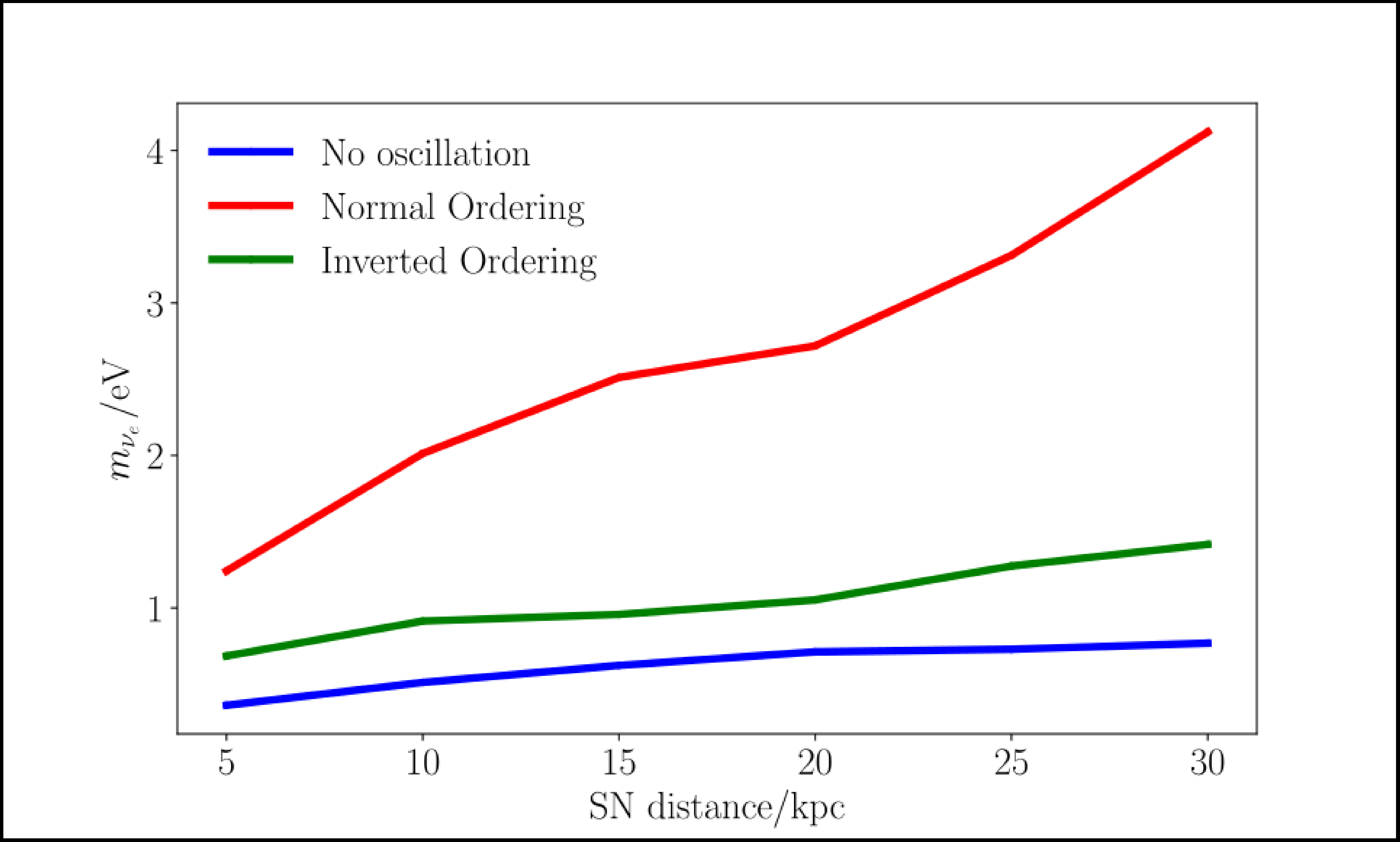


no osc : m_nue < 0.51 eV

NO : m_nue < 2.01 eV

IO : m_nue < 0.91 eV

Sensitivities (preliminary!)



MERCI

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BACKUP SLIDES

invisiblesPlus

elusives

neutrinos, dark matter & dark energy physics

IFIC INSTITUT DE FÍSICA CORPUSCULAR

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

VNIVERSITAT DE VALÈNCIA

EXCELENCIA SEVERO OCHOA

The Hubble parameter compendium

Knox & Millea, PRD'20

$$\theta_s \equiv \boxed{r_s} / \boxed{D_A}$$

Pre-recombination solutions

Low sound horizon solutions

Confusions in determinations of w_m (neutrino interactions, modify gravity, different P(k),..)

Sound speed reduction

Higher recombination temperature

Photon cooling previous to recombination

Increassing H(z) with additional components (e.g. via N_{eff} or early dark energy)

Post-recombination solutions

High sound horizon solutions

Wiggles in H(z)

Violation in the distance-duality relation (axion dimming)

Cepheid mis-calibration

Low sound horizon solutions

Confusions in determinations of w_b w_m

Post recombination evolution of r_s

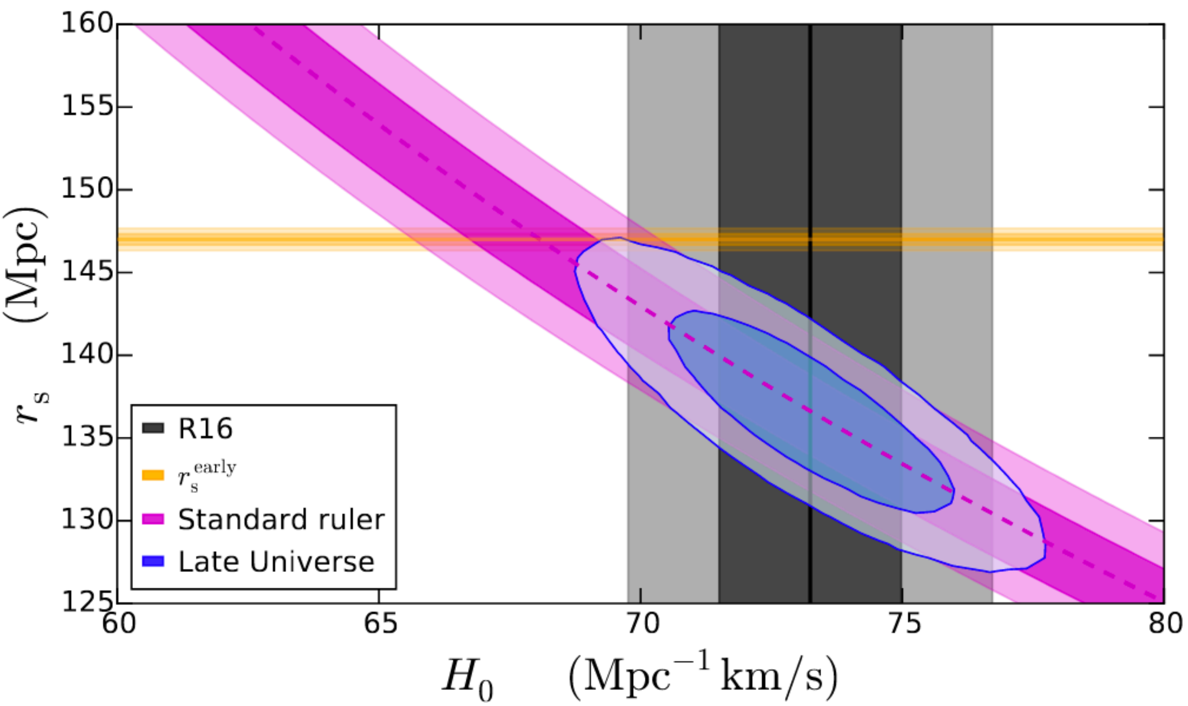
All solutions are required to leave unchanged θ_s , θ_{EQ} & θ_D

The ~~H~~r_s tension?

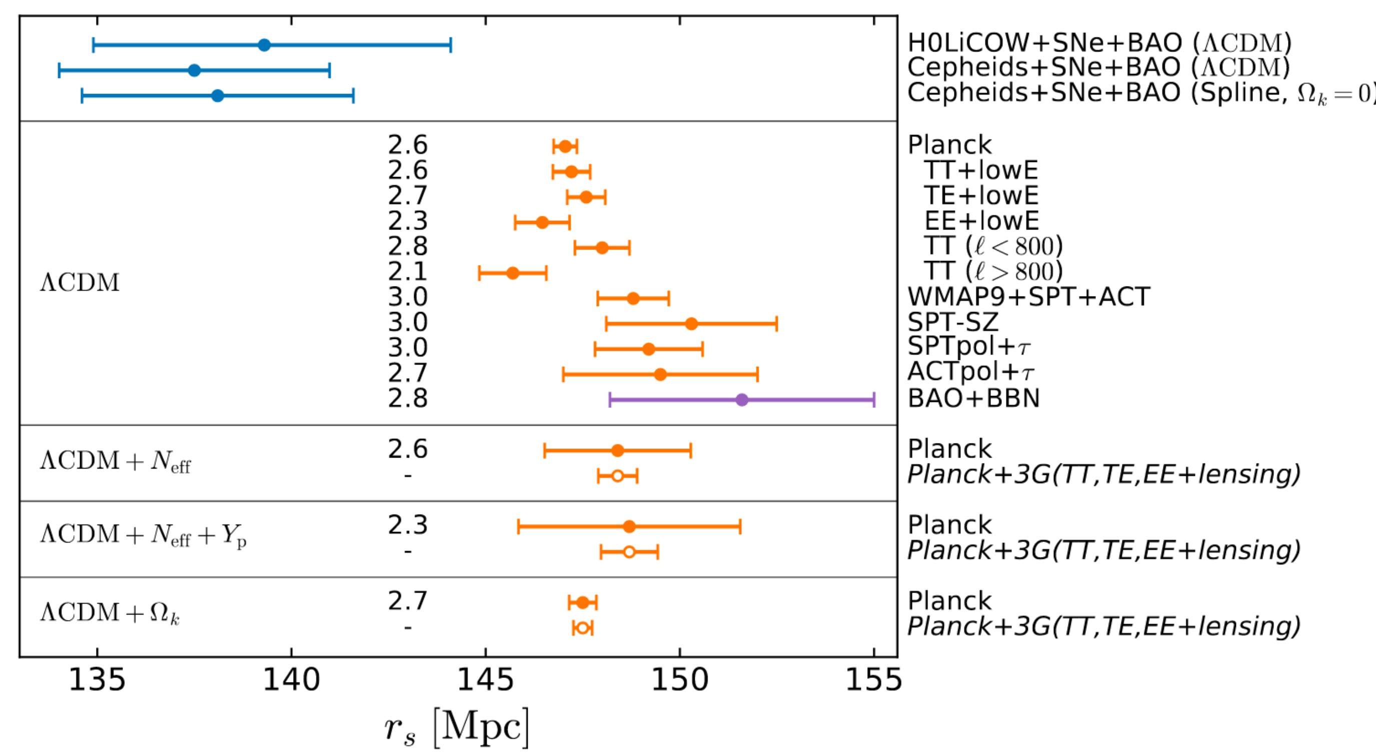
BAO observations determine D_V/r_s (or Hr_s & D_Ar_s). One can use BAO, SNIa & Cepheids data to infer r_s:

$$r_s = 137.7 \pm 3.6 \text{ Mpc}$$

Casting the tension between Cosmic distance leaders and ΛCDM + CMB datasets in terms of r_s, weakens the statistical significance, but helps to clarify the physics that could reconcile these datasets.



Bernal, Verde & Riess, JCAP'16



Aylor et al, APJ'19

Baryon Acoustic Oscillations

2020= SDSS IV

Zhao et al, SDSS IV Coll. MNRAS'21

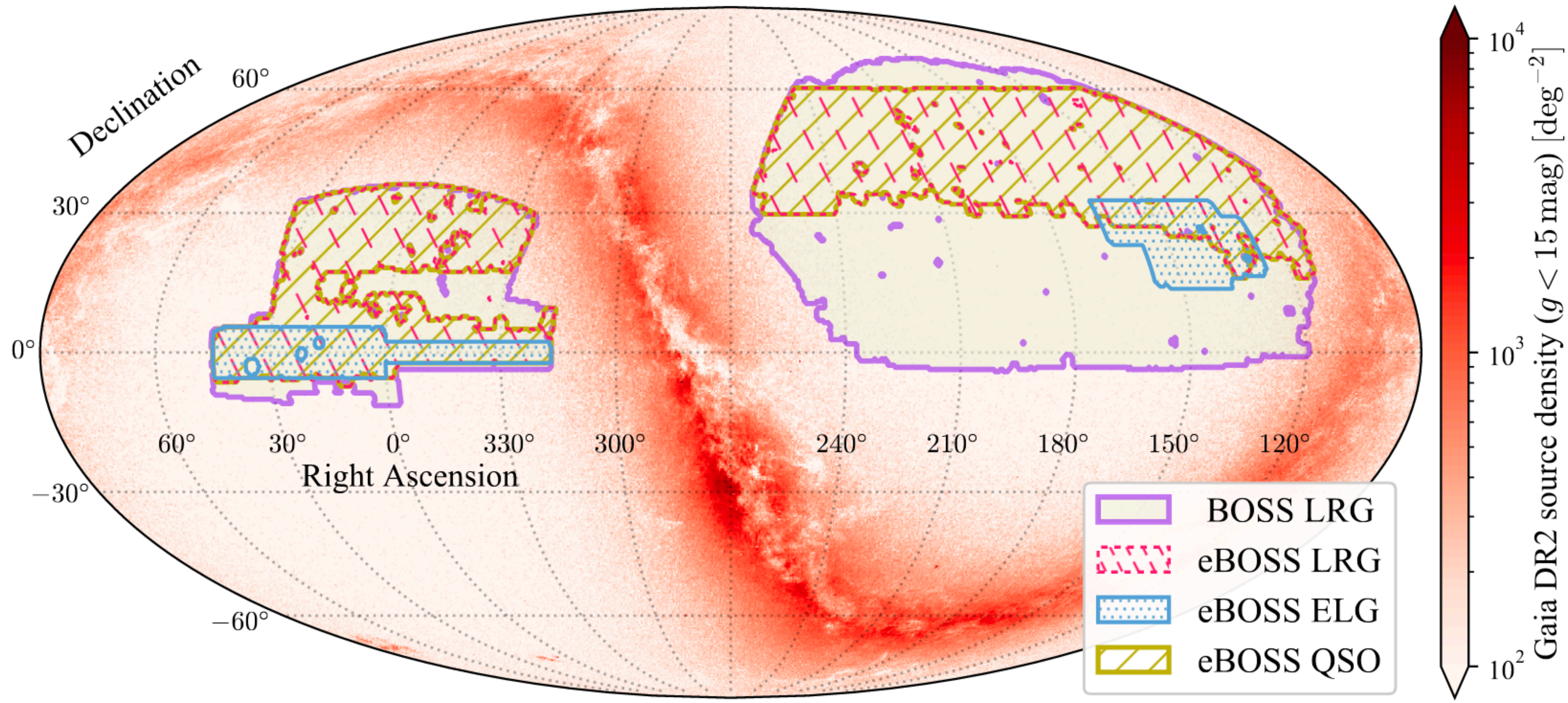
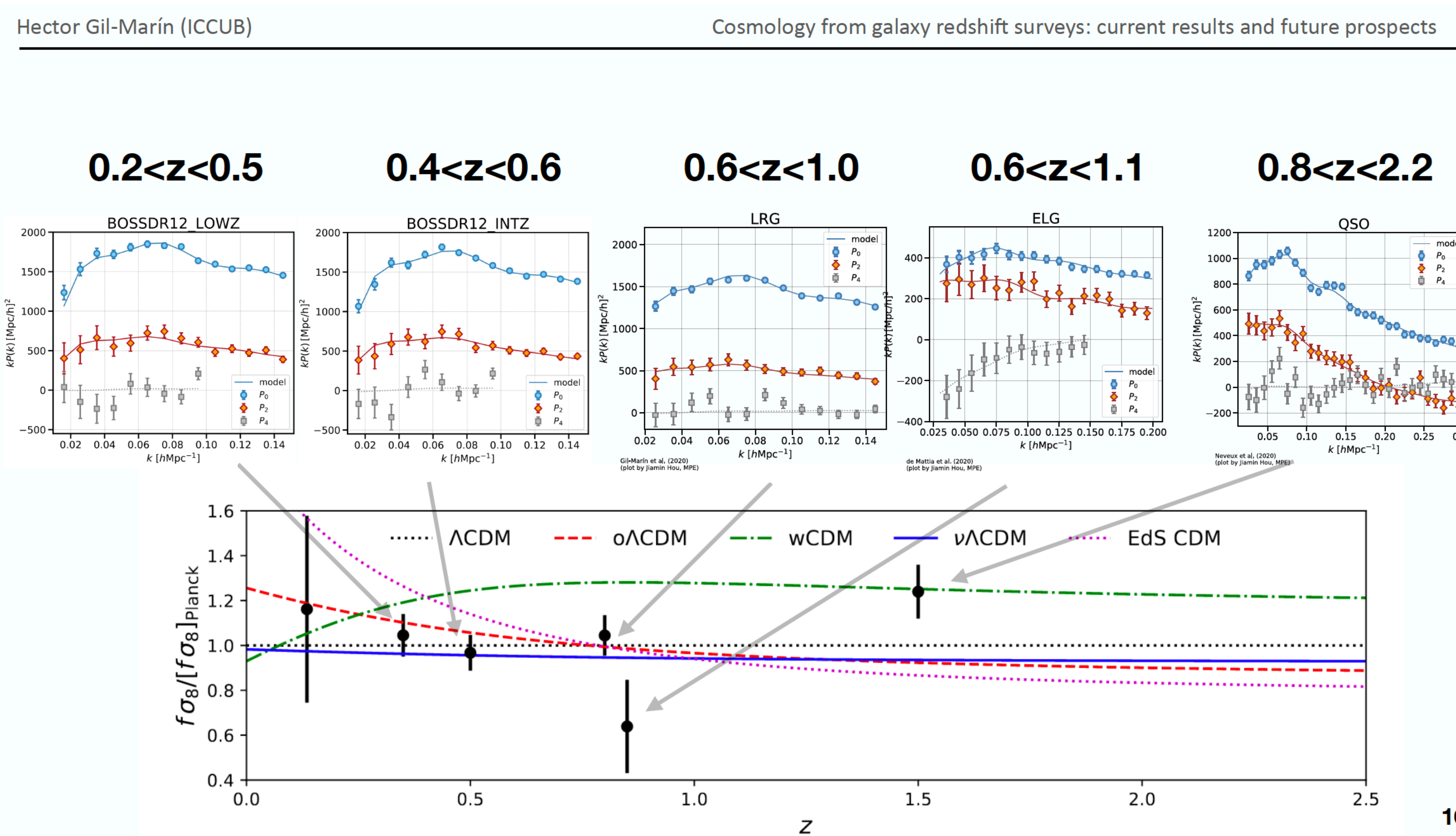


Figure 1. The sky coverage of eBOSS DR16 tracers and BOSS DR12 LRGs, as well as the density map of Gaia DR2 sources with $g < 15$ mag.

Baryon Acoustic Oscillations



NATURE | LETTER

日本語要約

A gravitational-wave standard siren measurement of the Hubble constant

The LIGO Scientific Collaboration and The Virgo Collaboration, The 1M2H Collaboration, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, The Las Cumbres Observatory Collaboration, The VINROUGE Collaboration & The MASTER Collaboration

Affiliations | Contributions | Corresponding authors

Nature **551**, 85–88 (02 November 2017) | doi:10.1038/nature24471
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Citation | Rights & permissions | Article metrics

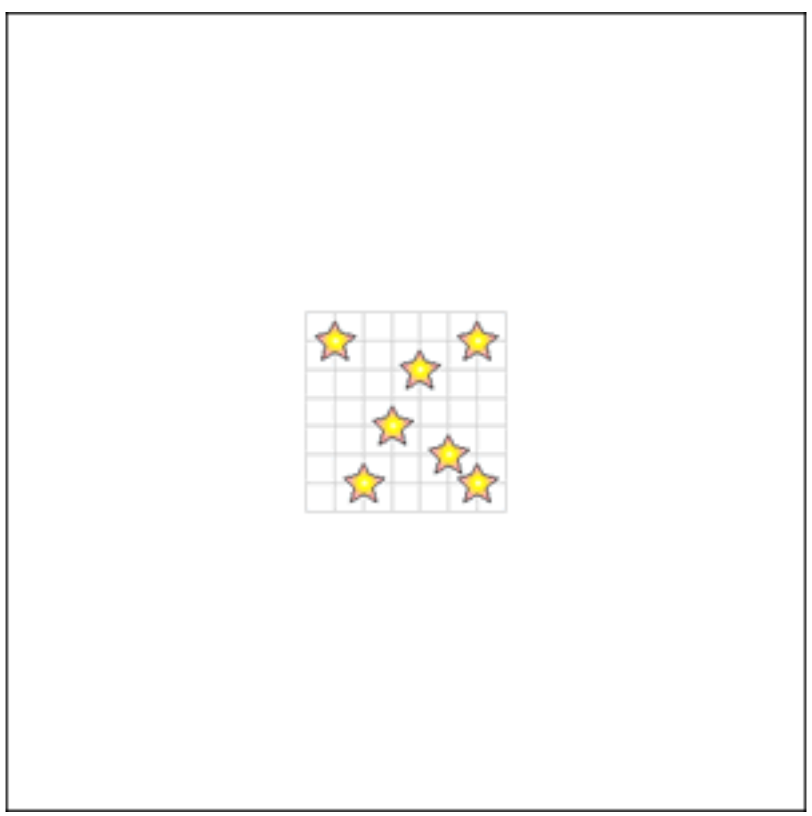
On 17 August 2017, the Advanced LIGO[1] and Virgo[2] detectors observed the gravitational-wave event GW170817—a strong signal from the merger of a binary neutron-star system[3]. Less than two seconds after the merger, a γ-ray burst (GRB 170817A) was detected within a region of the sky consistent with the LIGO–Virgo-derived location of the gravitational-wave source[4, 5, 6]. This sky region was subsequently observed by optical astronomy facilities[7], resulting in the identification[8, 9, 10, 11, 12, 13] of an optical transient signal within about ten arcseconds of the galaxy NGC 4993. This detection of GW170817 in both gravitational waves and electromagnetic waves represents the first 'multi-messenger' astronomical observation. Such observations enable GW170817 to be used as a 'standard siren'[14, 15, 16, 17, 18] (meaning that the absolute distance to the source can be determined directly from the gravitational-wave measurements) to measure the Hubble constant. This quantity represents the local expansion rate of the Universe, sets the overall scale of the Universe and is of fundamental importance to cosmology. Here we report a measurement of the Hubble constant that combines the distance to the source inferred purely from the gravitational-wave signal with the recession velocity inferred from measurements of the redshift using the electromagnetic data. In contrast to previous measurements, ours does not require the use of a cosmic 'distance ladder'[19]: the gravitational-wave analysis can be used to estimate the luminosity distance out to cosmological scales directly, without the use of intermediate astronomical distance measurements. We determine the Hubble constant to be about 70 kilometres per second per megaparsec. This value is consistent with existing measurements[20, 21], while being completely independent of them. Additional standard siren measurements from future gravitational-wave sources will enable the Hubble constant to be constrained to high precision.

Subject terms: High-energy astrophysics · Cosmology

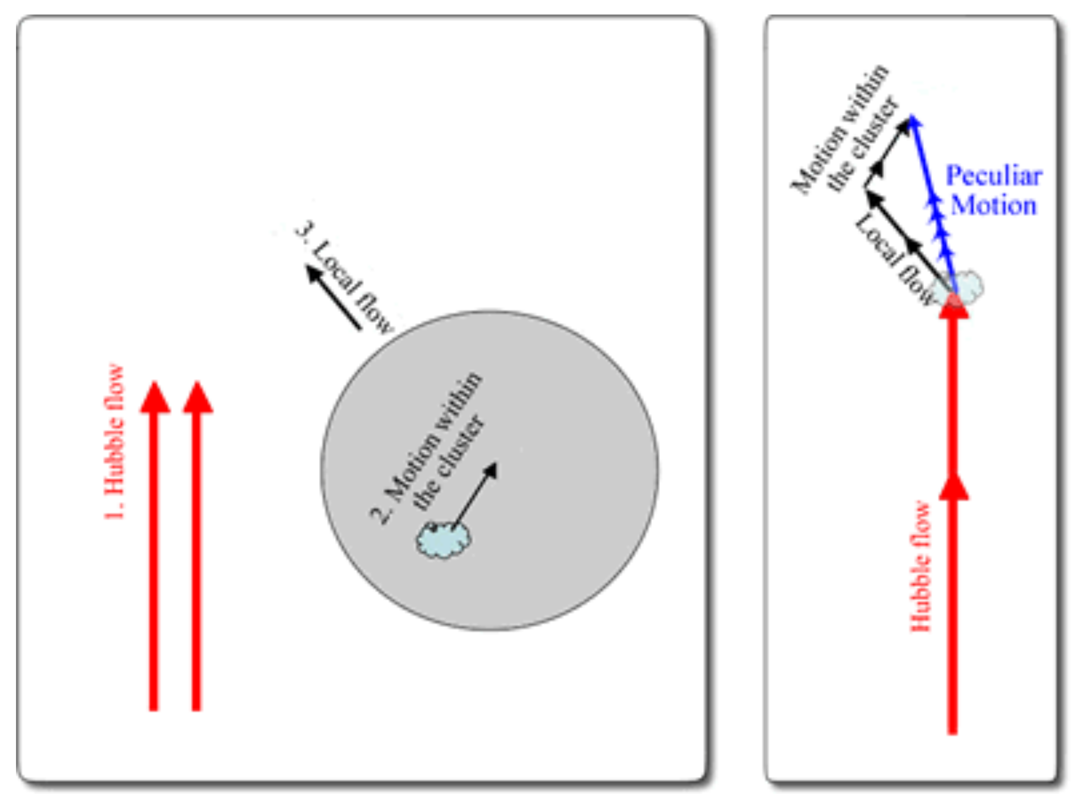
The method combines the distance to the source inferred purely from the gravitational-wave signal with the recession velocity inferred from measurements of the redshift using electromagnetic data.

$$v_H = H_0 d \qquad\qquad d = 43.8^{+2.9}_{-6.9}\,\mathrm{Mpc}$$

Using the optical identification of the host galaxy NGC 4993, they derive the Hubble flow velocity. PROBLEM: the random relative motion of galaxies (peculiar velocity) needs to be taken into account! In practice, the motions of galaxies are influenced by more than just the Hubble flow: the local flow, and the motion of the galaxy within its cluster and/or group environment. These deviations from the pure Hubble flow are referred to as peculiar motions. The peculiar velocity is about 10% of the measured recessional velocity.



The **Hubble flow** causes all **galaxies** to receed from each other.



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Using this recessional velocity, one can find H_0= 68.9 km/s.

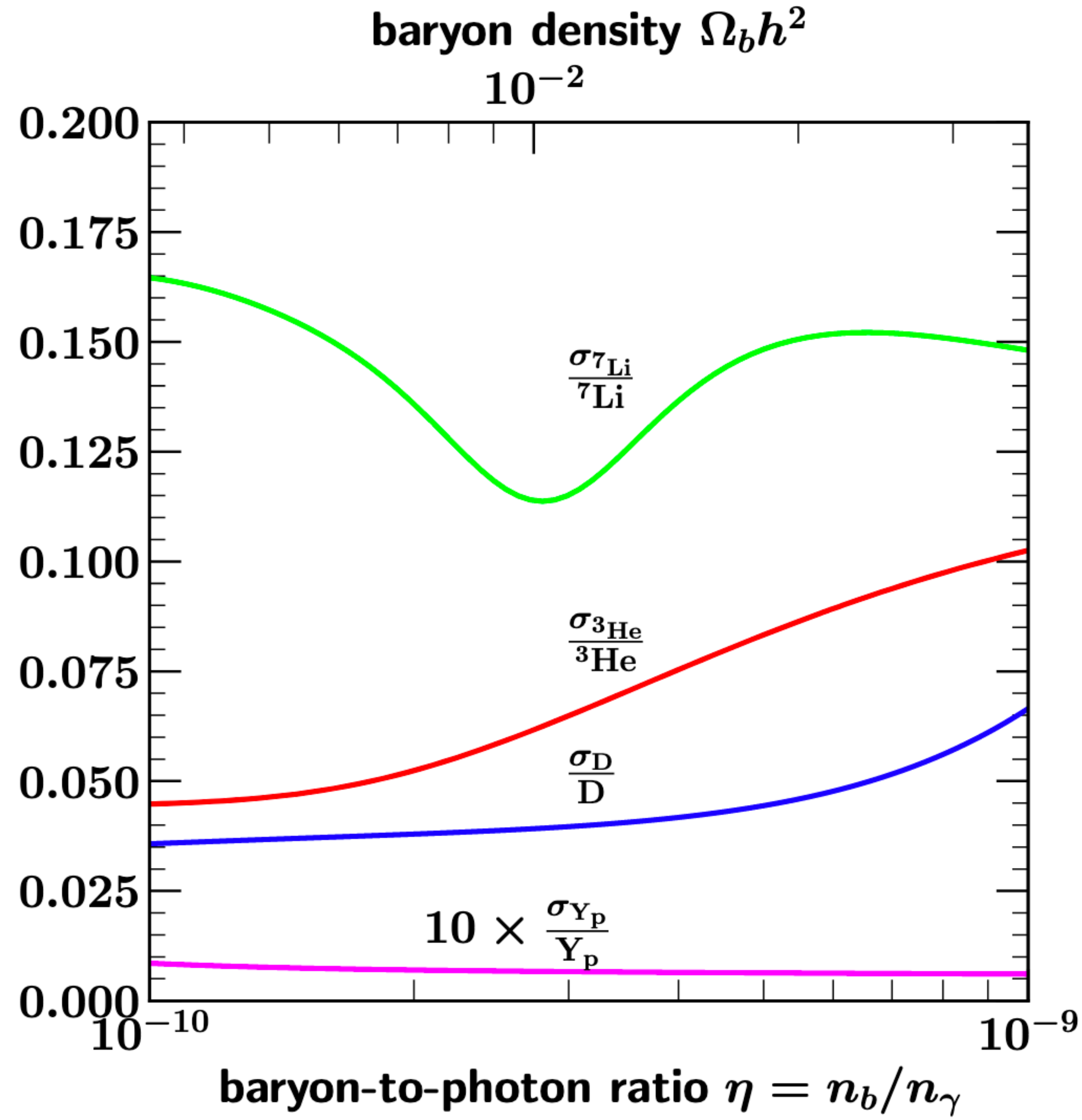

FIG. 3. Fractional uncertainties in the light element abundance predictions shown in Fig. 2. For each species i, we plot ratio of the standard deviation σ_i to the mean μ_i, as a function of baryon-to-photon ratio. The relative uncertainty of the ^{4}He abundance has been multiplied by a factor of 10.

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	$\lesssim 10^{-4}$

Bennett et al, 2012.02726

The ultra relativistic approximation:

$$T_d/m_e \to \infty$$

is not well satisfied in reality!

10^{-4} Uncertainty due to measurement errors on the solar mixing angle

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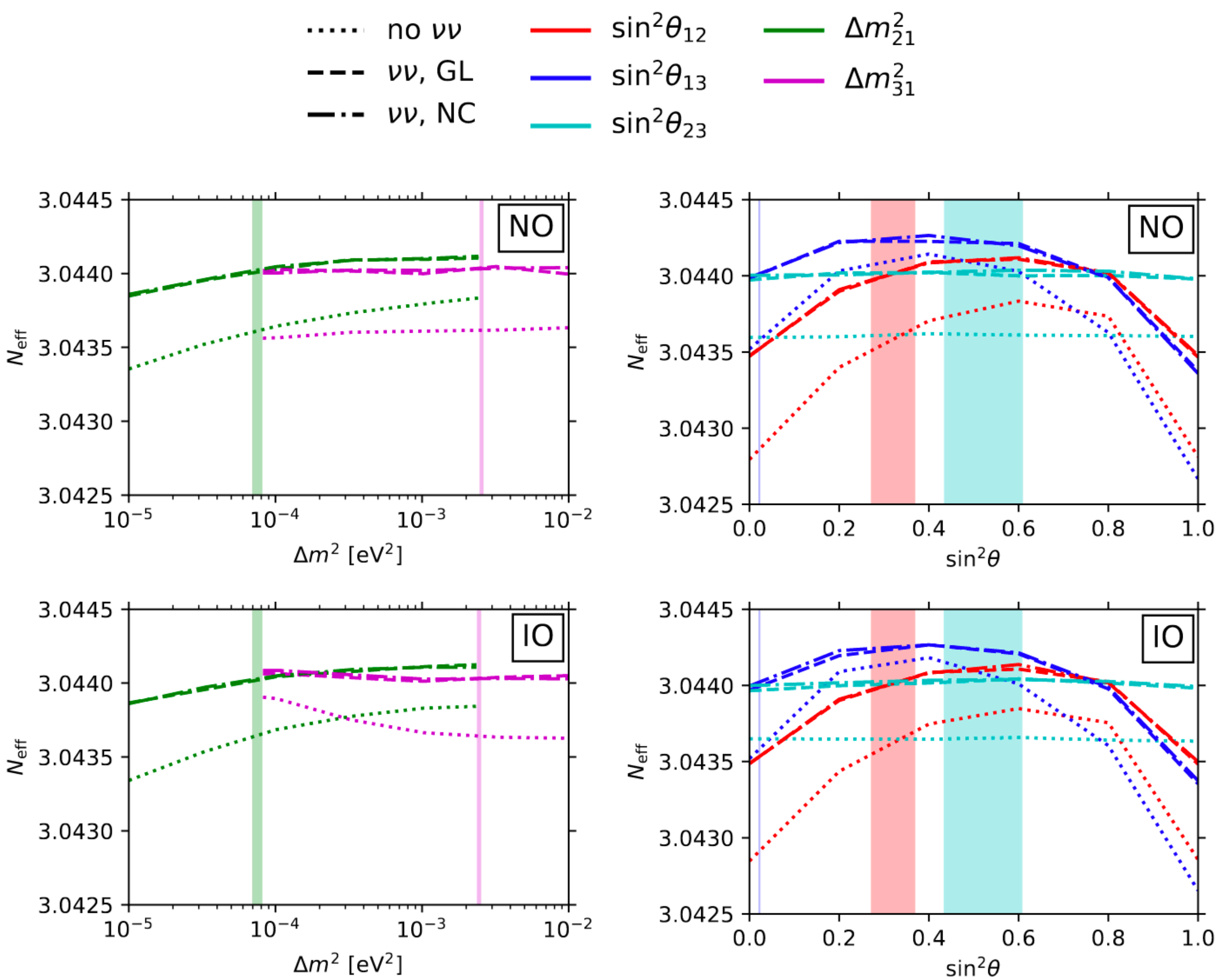

Bennett et al, 2012.02726

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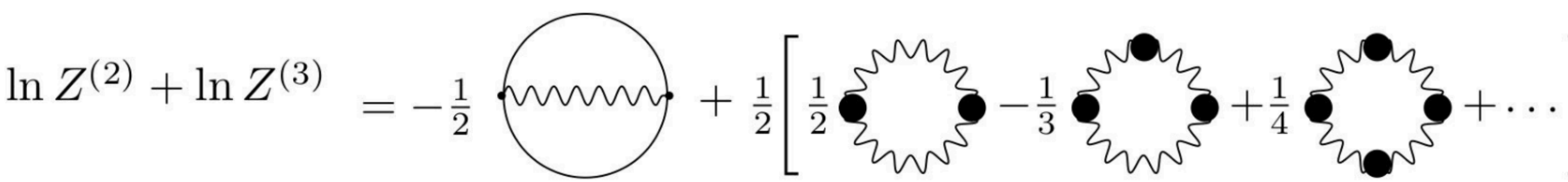
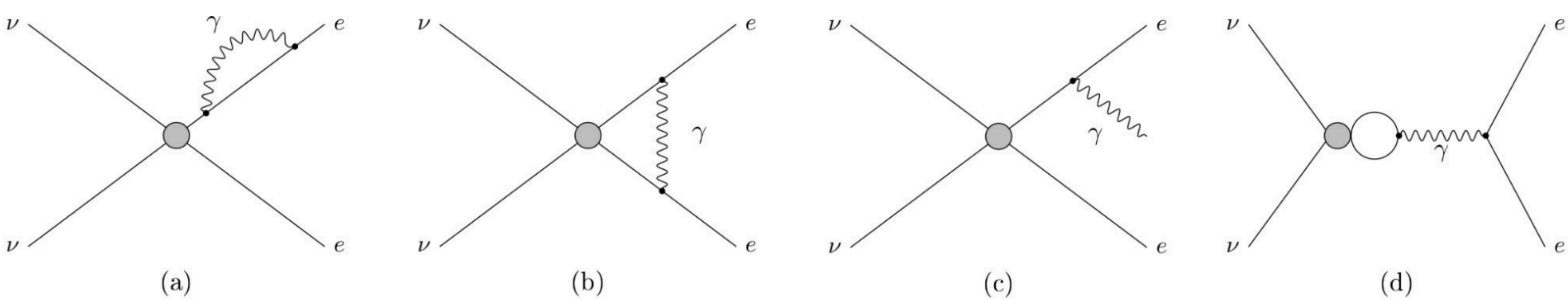
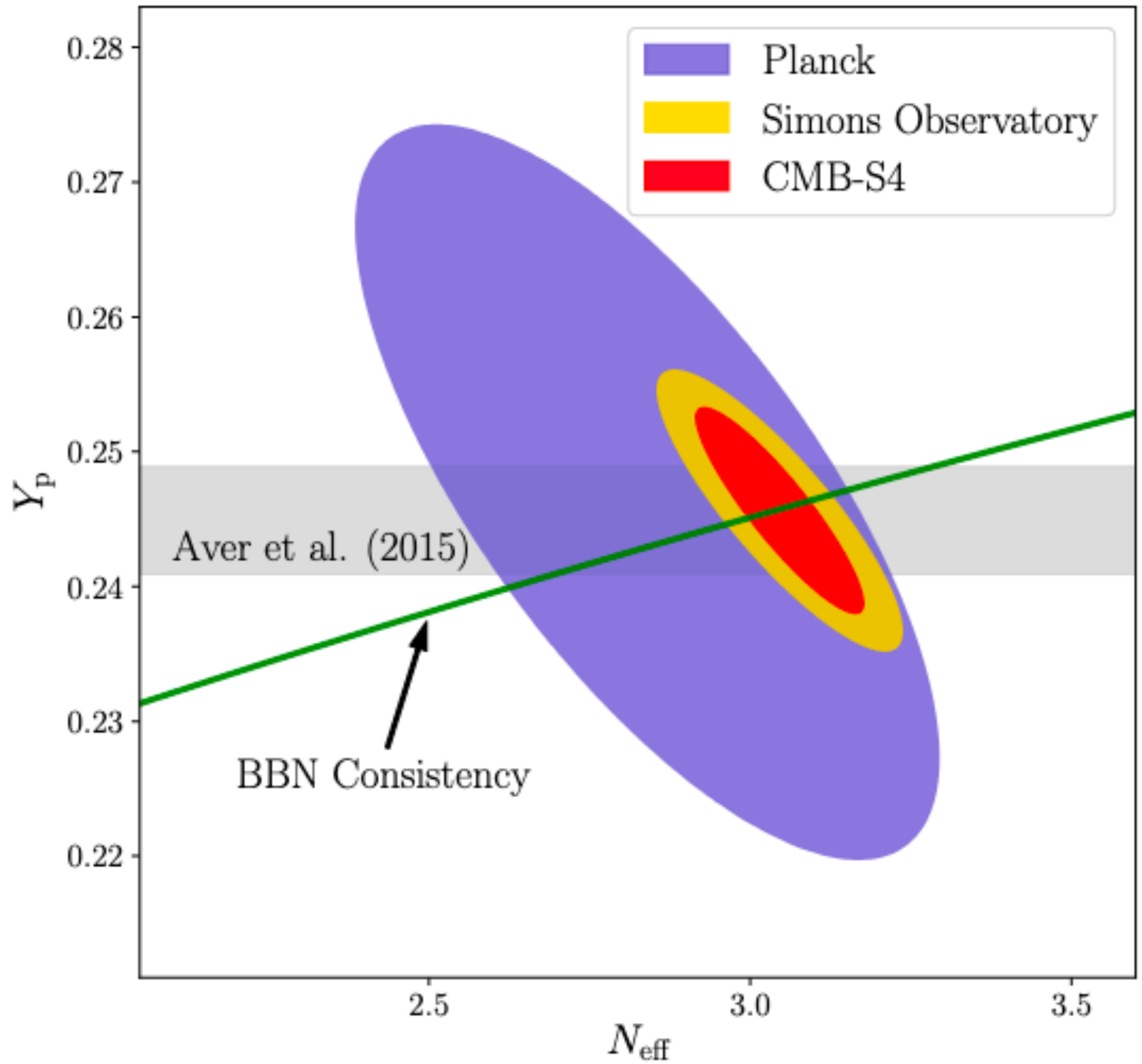
Bennett et al, 1911.04504





CMB Stage IV: N_{eff}

$$\Delta N_{\rm eff} < 0.06 \ 95\%\mathrm{CL}$$



CMB-S4 Science Case, Reference Design, and Project Plan, 1907.04473

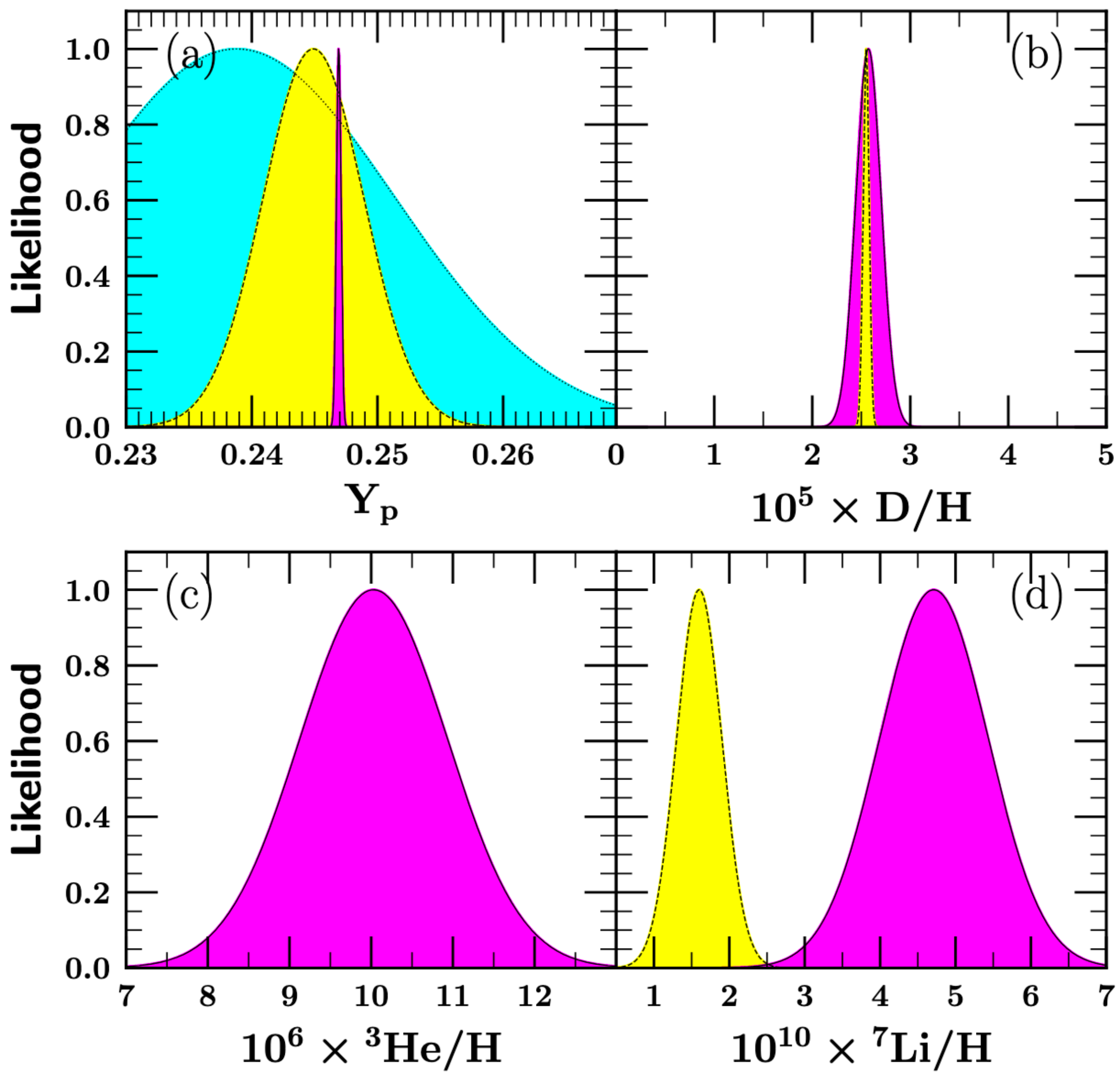
CMB: N_{eff}

$$Y_p = 0.24691 \pm 0.00018 \qquad (0.24691)$$

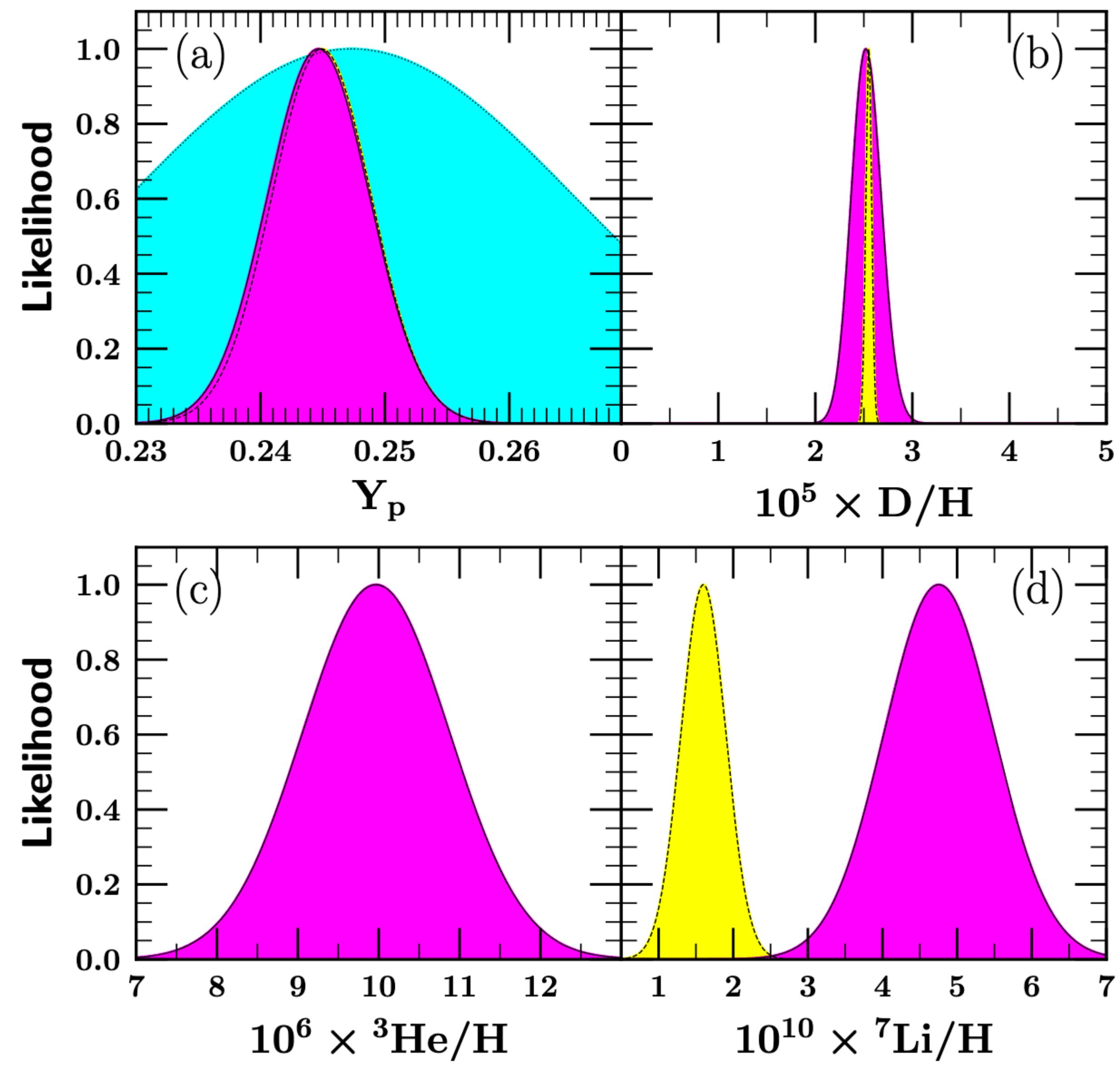
$$Y_p = 0.24465 \pm 0.00410 \qquad (0.24498)$$

Fields, Olive, Yeh & Young JCAP '20

Planck **baseline (N_ν = 3) + BBN**



Planck **baseline (N_ν not fixed) + BBN**

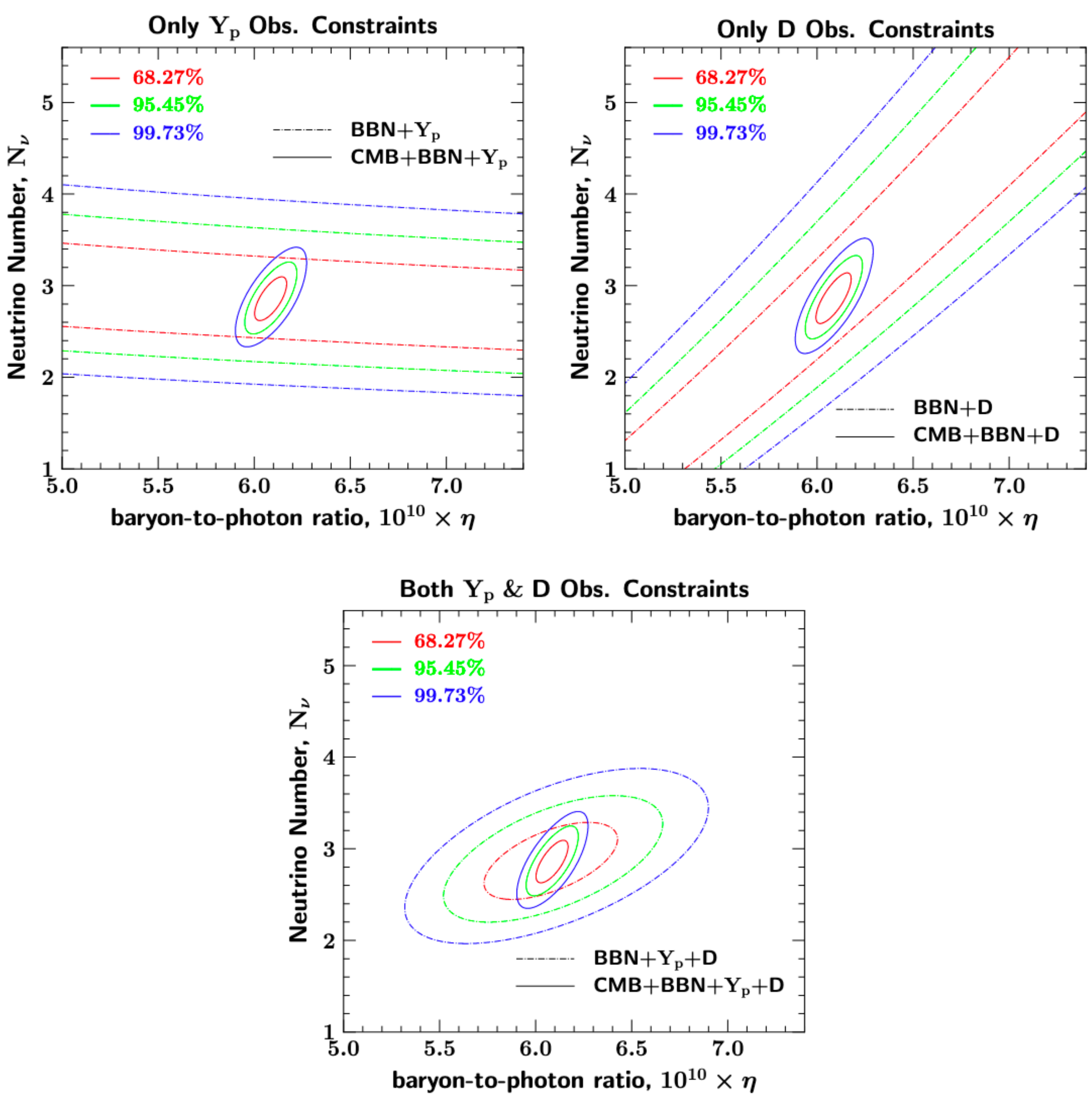


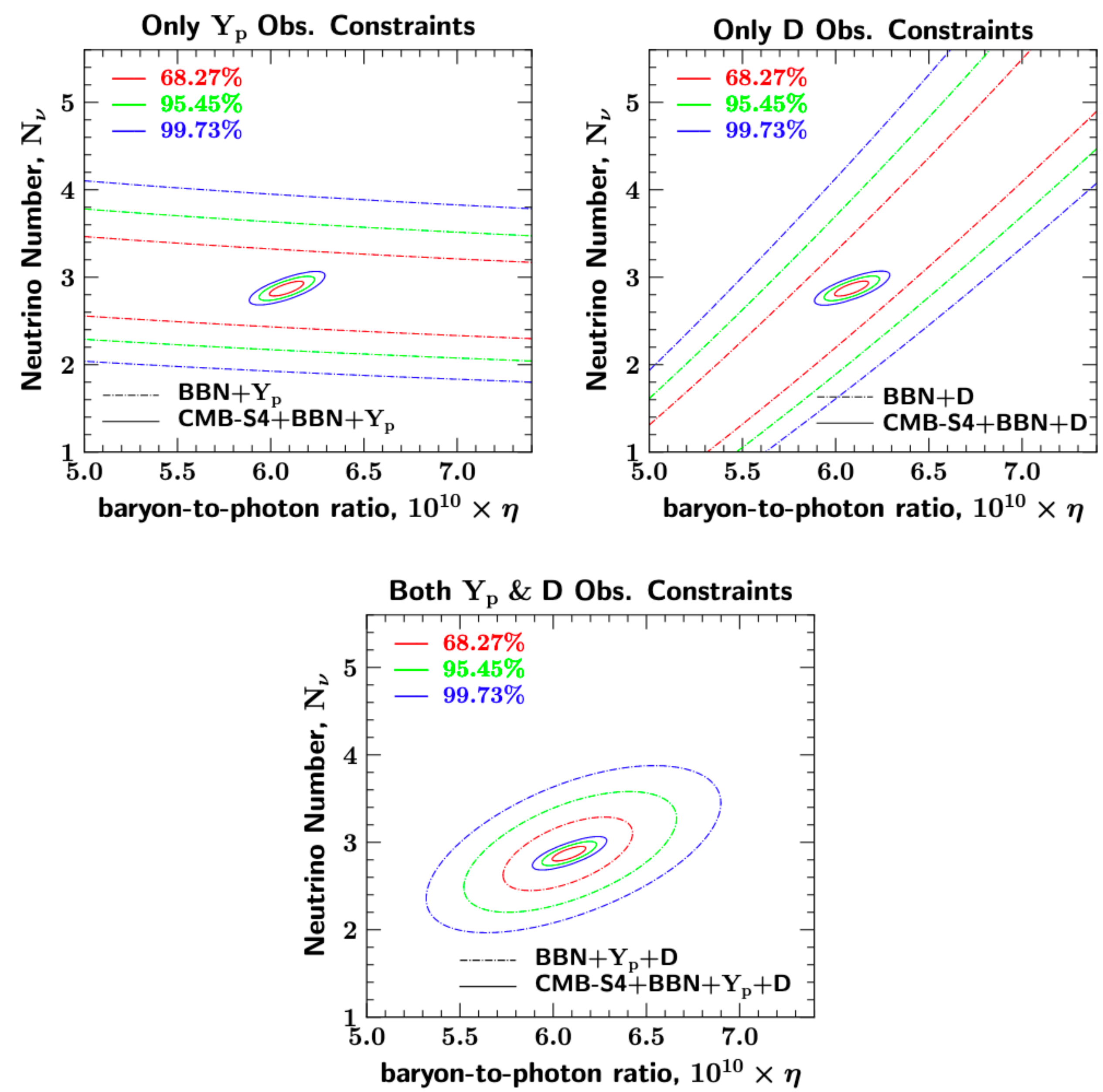
BBN+ CMB

Astronomical measurements

CMB He determinations

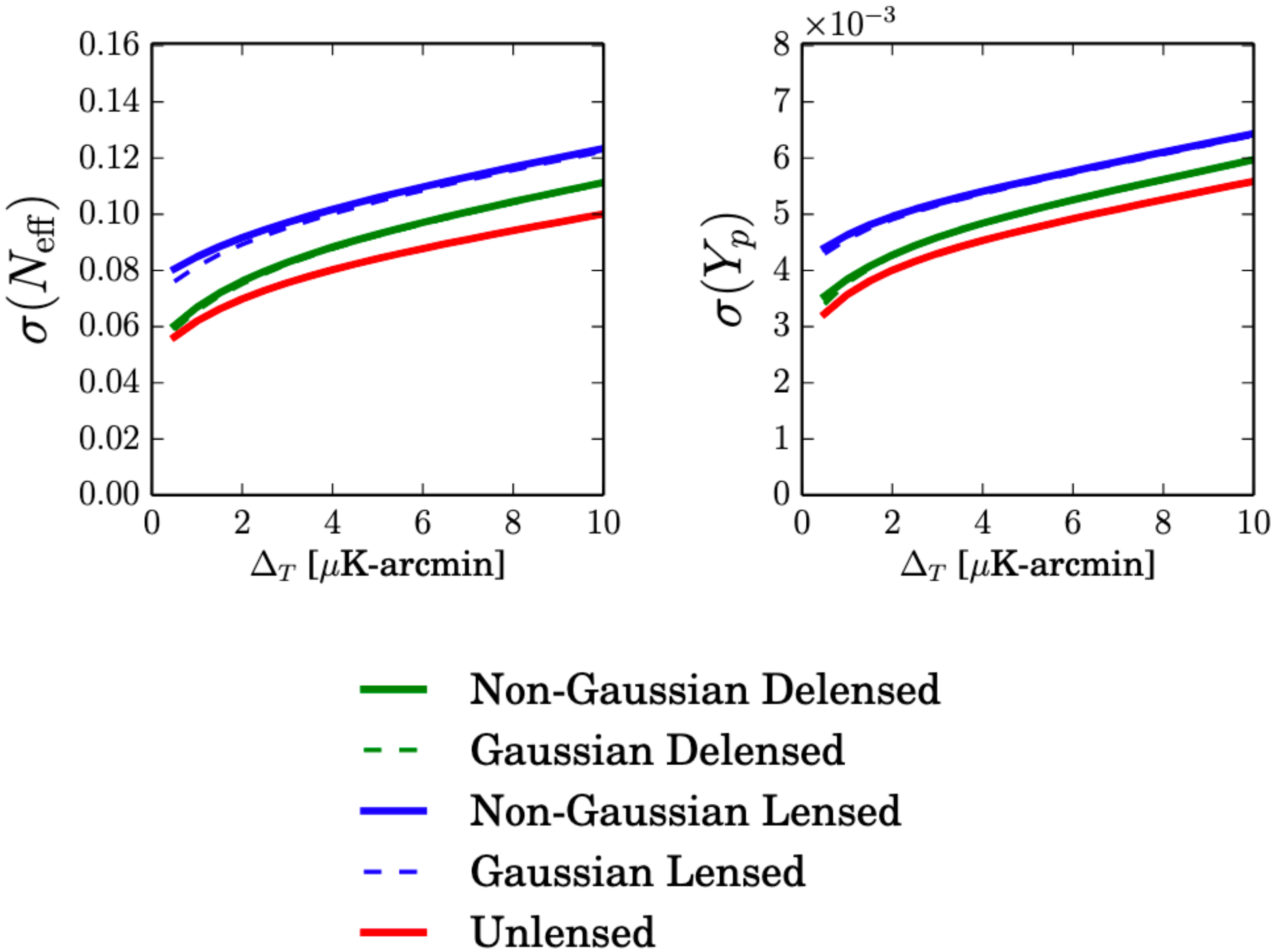
CMB Stage IV: N_{eff}

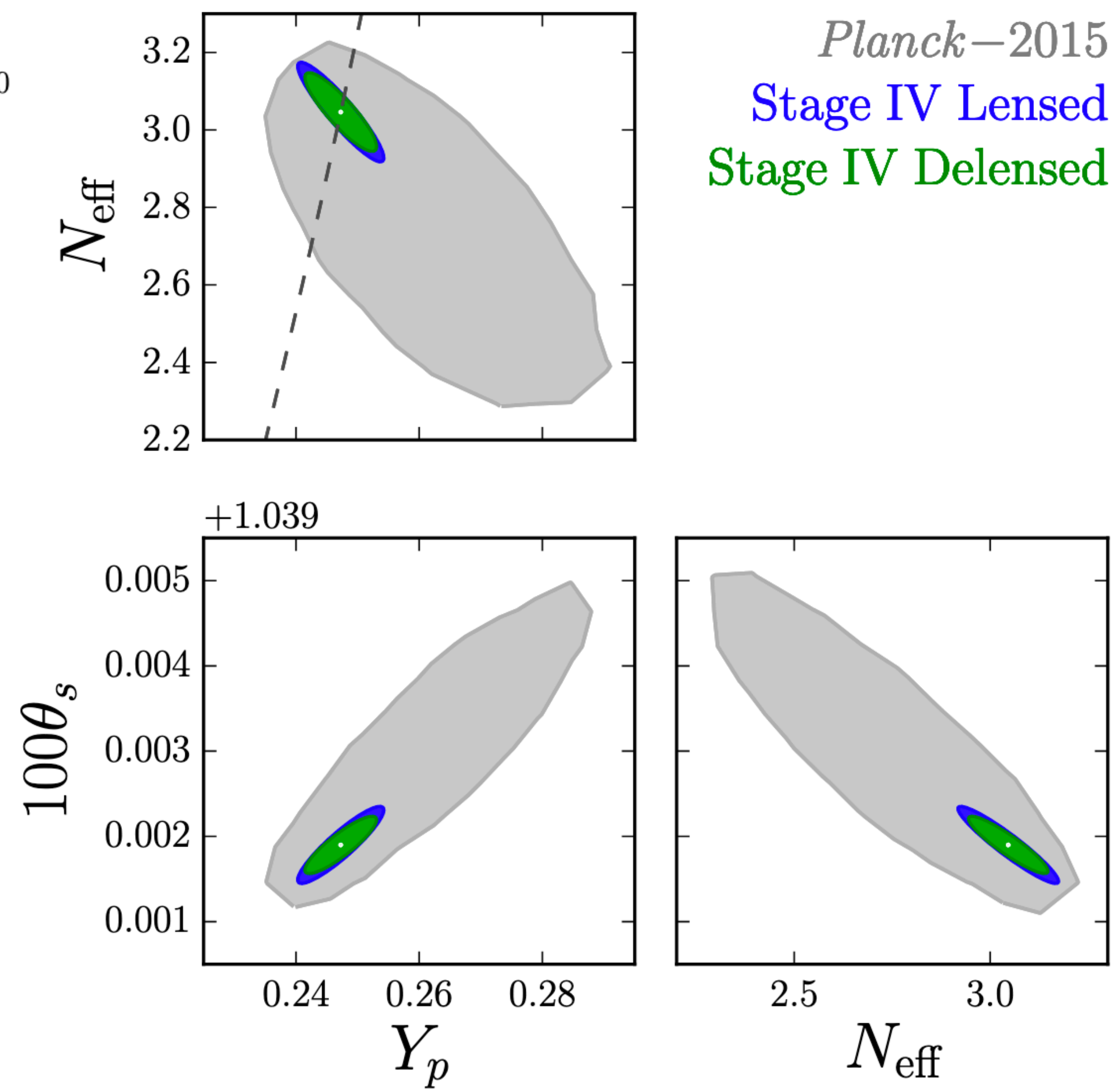




Fields, Olive, Yeh & Young JCAP '20

CMB Stage IV: N_{eff}





Green, Meyers & van Engelen, JCAP'17

B. Strongly interacting neutrino mode

The existence of the SIν mode was first pointed out in Ref. [55], and further studied in Refs. [65, 66]. As discussed there, the SIν cosmology arises due to a multi-parameter degeneracy that opens up in CMB data when the onset of neutrino free-streaming is delayed until redshift $z \sim 8000$. This approximately coincides with the epoch when Fourier modes corresponding to multipole $\ell \approx 400$ enters the causal horizon [65], which lies somewhere between the first and second peak of the CMB temperature spectrum. We review below the properties of this alternate cosmology, emphasizing its differences with the standard ΛCDM model.

neutrinos means that the CMB spectra do not receive the standard phase shift, and thus appear slightly displaced toward larger ℓ as compared to the corresponding ΛCDM spectra. In order to fit the data, we must compensate for this shift by *increasing* the value of θ_*. Thus, the difference between the values of θ_* in the SIν and ΛCDM models directly reflects the absence of the free-streaming neutrino phase shift in the former.

We note that it was a priori far from obvious that such a dramatic change in the angular size of the sound horizon was possible without introducing other artifacts that would significantly worsen the fit to CMB and BAO data. Our analysis shows that the larger value of θ_* is achieved by increasing H_0 and $\Omega_c h^2$ above their ΛCDM values.

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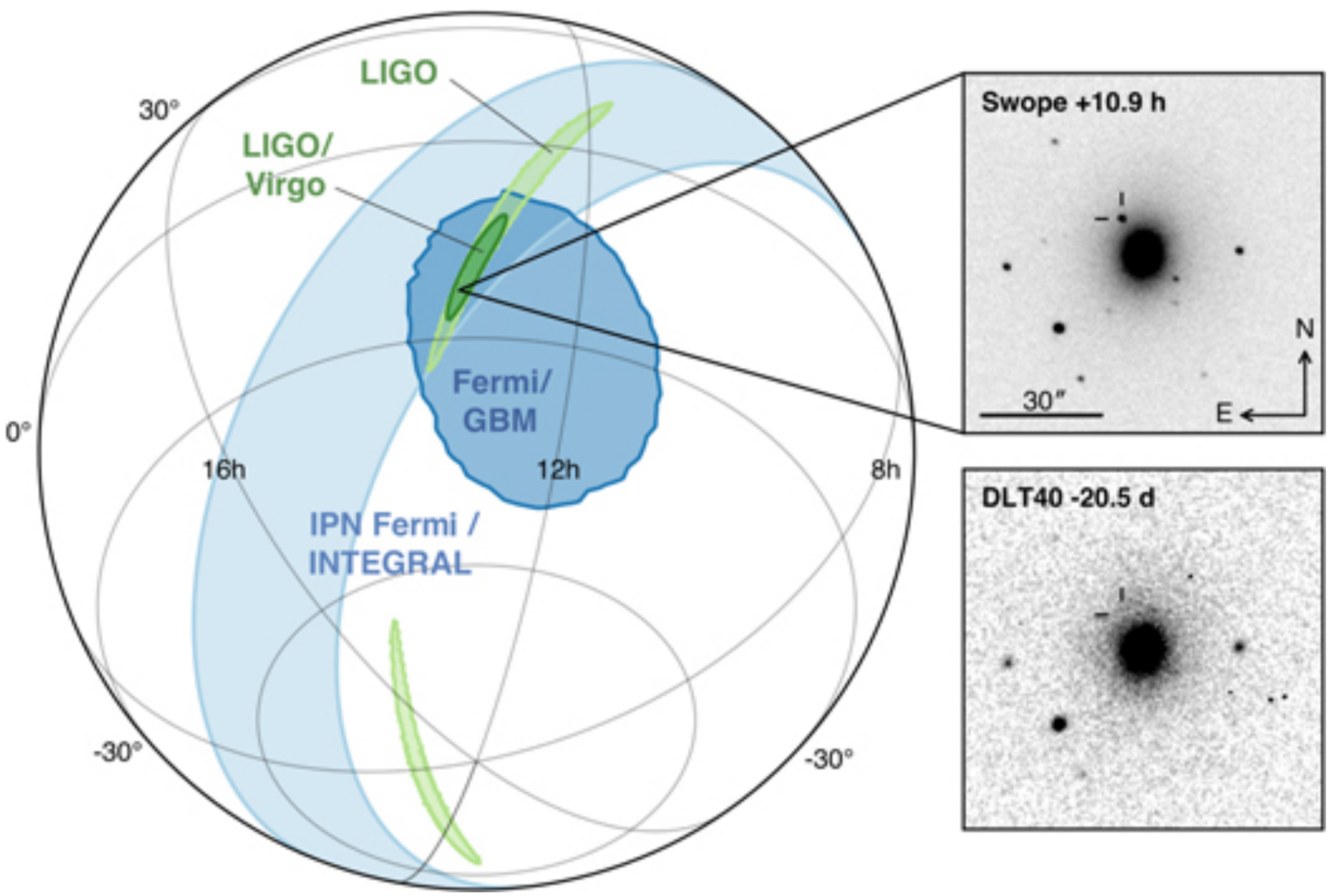
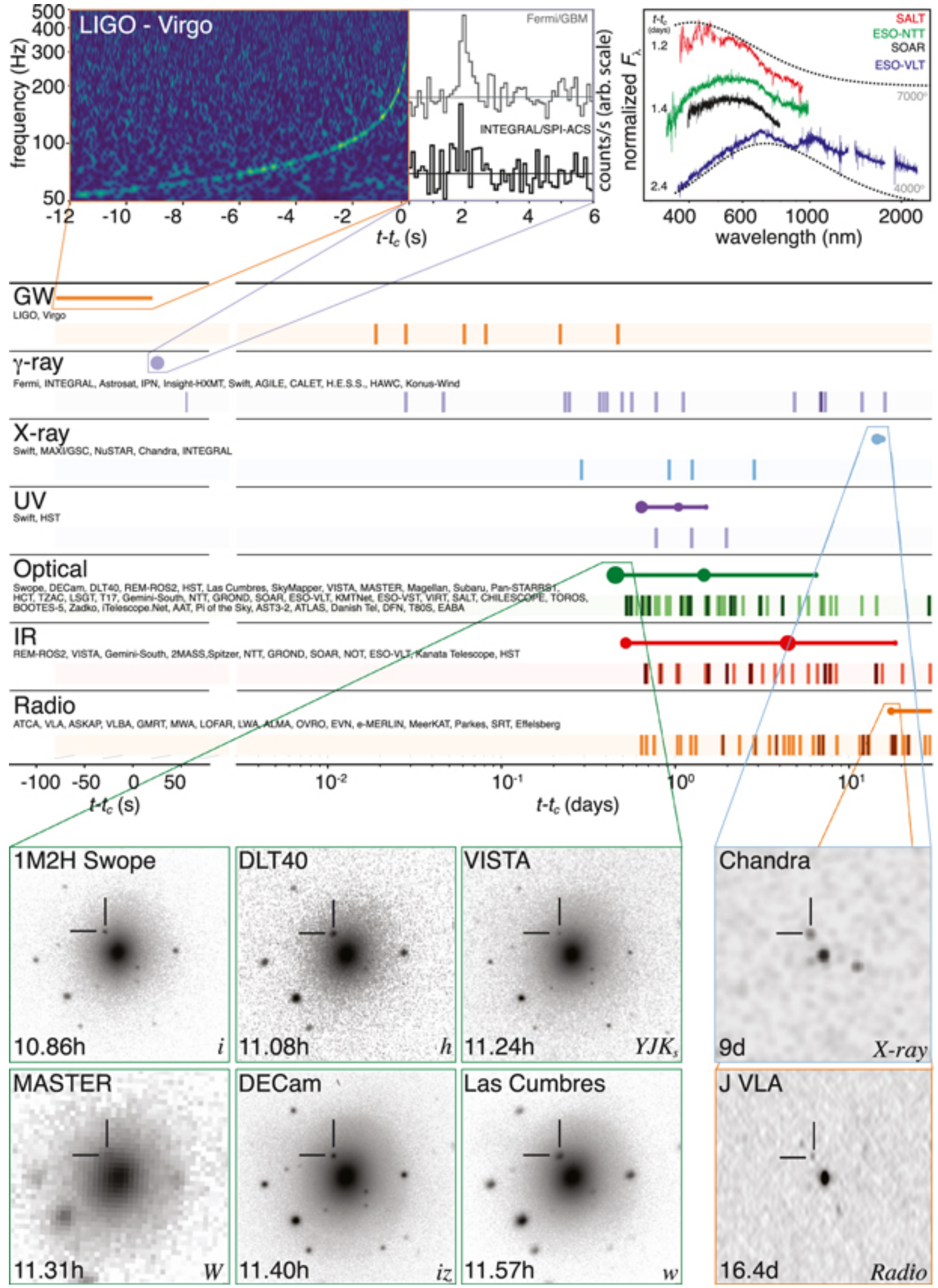
GW170817

The detection of GW170817 in both gravitational waves and electromagnetic waves represents the first 'multi-messenger' astronomical observation



Localization of the gravitational-wave, gamma-ray, an optical signals.
The left panel shows an orthographic projection of th 90% credible regions from LIGO (light green), the initial LIGO-Virgo localization (dark green), IPN triangulation from the time delay between Fermi a INTEGRAL (light blue), and Fermi-GBM (dark blue).
The inset shows the location of the apparent host galaxy NGC 4993 in the Swope optical discovery image at 10.9 hr after the merger (top right) and the DLT40 pre-discovery image from 20.5 days prior to merger (bottom right).
The reticle marks the position of the transient in both images.

GW170817



LIGO - Virgo
frequency (Hz)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
t-t_c (s)
normalized F_λ
SALT
ESO-NTT
SOAR
ESO-VLT
wavelength (nm)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
IR
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
t-t_c (s)
t-t_c (days)
1M2H Swope
10.86h
DLT40
11.08h
VISTA
11.24h
Chandra
9d
X-ray
MASTER
11.31h
DECam
11.40h
Las Cumbres
11.57h
J VLA
16.4d
Radio

日本語要約

A gravitational-wave standard siren measurement of the Hubble constant

The LIGO Scientific Collaboration and The Virgo Collaboration, The 1M2H Collaboration, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, The Las Cumbres Observatory Collaboration, The VINROUGE Collaboration & The MASTER Collaboration

Affiliations | Contributions | Corresponding authors

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Citation | Rights & permissions | Article metrics

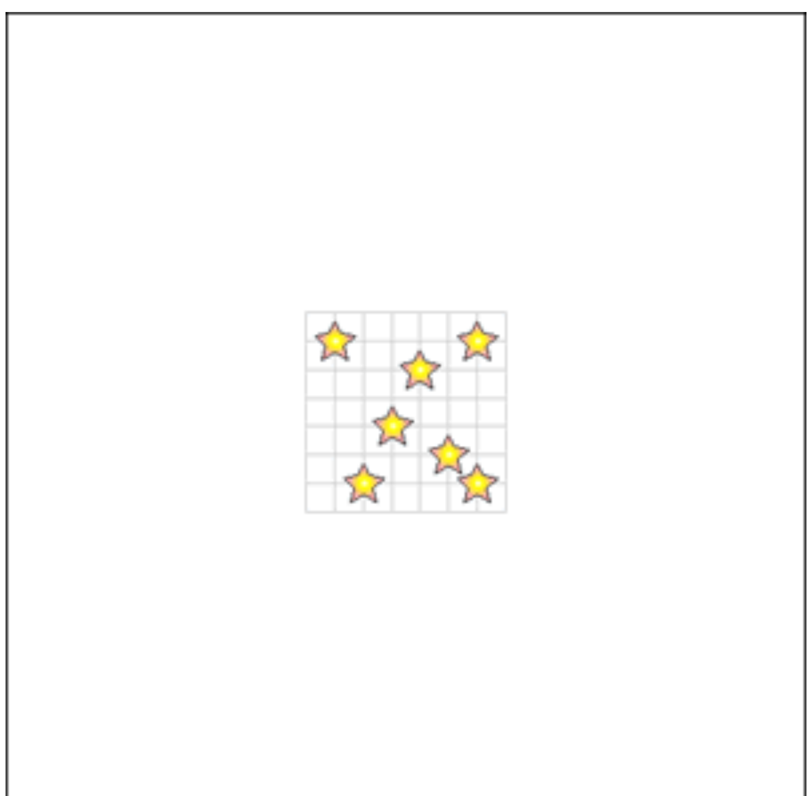
On 17 August 2017, the Advanced LIGO[1] and Virgo[2] detectors observed the gravitational-wave event GW170817—a strong signal from the merger of a binary neutron-star system[3]. Less than two seconds after the merger, a γ-ray burst (GRB 170817A) was detected within a region of the sky consistent with the LIGO–Virgo-derived location of the gravitational-wave source[4, 5, 6]. This sky region was subsequently observed by optical astronomy facilities[7], resulting in the identification[8, 9, 10, 11, 12, 13] of an optical transient signal within about ten arcseconds of the galaxy NGC 4993. This detection of GW170817 in both gravitational waves and electromagnetic waves represents the first 'multi-messenger' astronomical observation. Such observations enable GW170817 to be used as a 'standard siren'[14, 15, 16, 17, 18] (meaning that the absolute distance to the source can be determined directly from the gravitational-wave measurements) to measure the Hubble constant. This quantity represents the local expansion rate of the Universe, sets the overall scale of the Universe and is of fundamental importance to cosmology. Here we report a measurement of the Hubble constant that combines the distance to the source inferred purely from the gravitational-wave signal with the recession velocity inferred from measurements of the redshift using the electromagnetic data. In contrast to previous measurements, ours does not require the use of a cosmic 'distance ladder'[19]: the gravitational-wave analysis can be used to estimate the luminosity distance out to cosmological scales directly, without the use of intermediate astronomical distance measurements. We determine the Hubble constant to be about 70 kilometres per second per megaparsec. This value is consistent with existing measurements[20, 21], while being completely independent of them. Additional standard siren measurements from future gravitational-wave sources will enable the Hubble constant to be constrained to high precision.

Subject terms: High-energy astrophysics · Cosmology

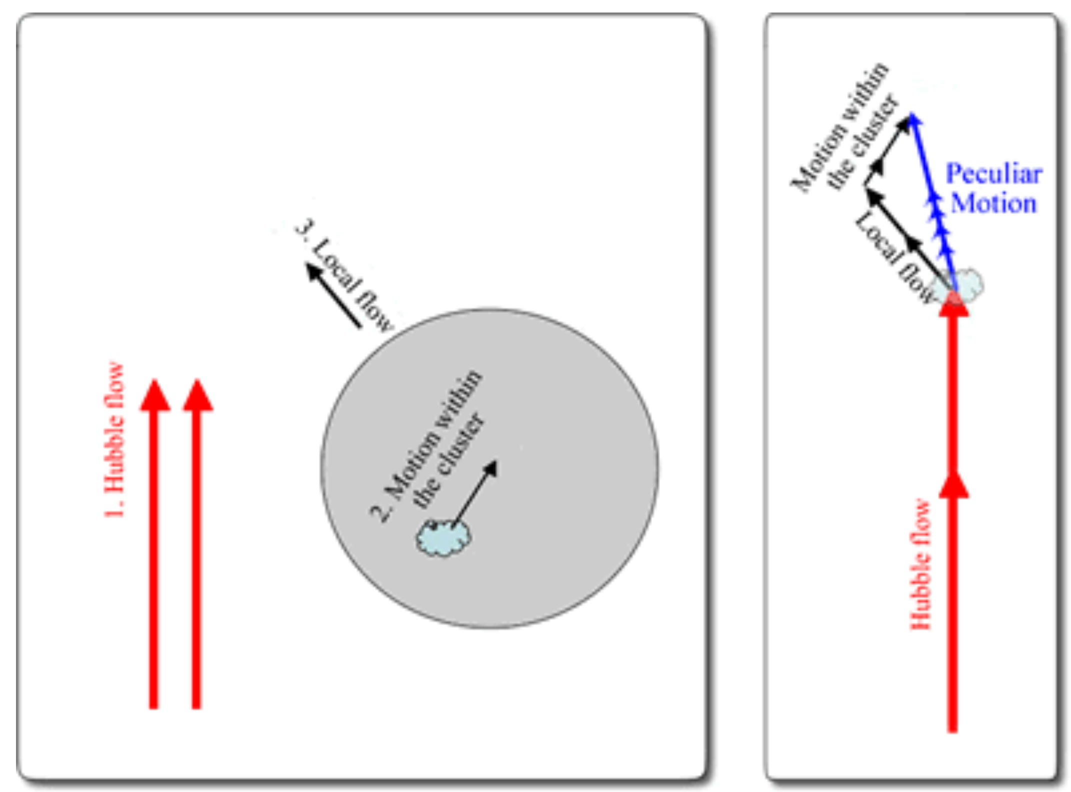
The method combines the distance to the source inferred purely from the gravitational-wave signal with the recession velocity inferred from measurements of the redshift using electromagnetic data.

$$v_H = H_0 d \qquad\qquad d = 43.8^{+2.9}_{-6.9}\,\mathrm{Mpc}$$

Using the optical identification of the host galaxy NGC 4993, they derive the Hubble flow velocity. PROBLEM: the random relative motion of galaxies (peculiar velocity) needs to be taken into account! In practice, the motions of galaxies are influenced by more than just the Hubble flow: the local flow, and the motion of the galaxy within its cluster and/or group environment. These deviations from the pure Hubble flow are referred to as peculiar motions. The peculiar velocity is about 10% of the measured recessional velocity.



The **Hubble flow** causes all **galaxies** to receed from each other.



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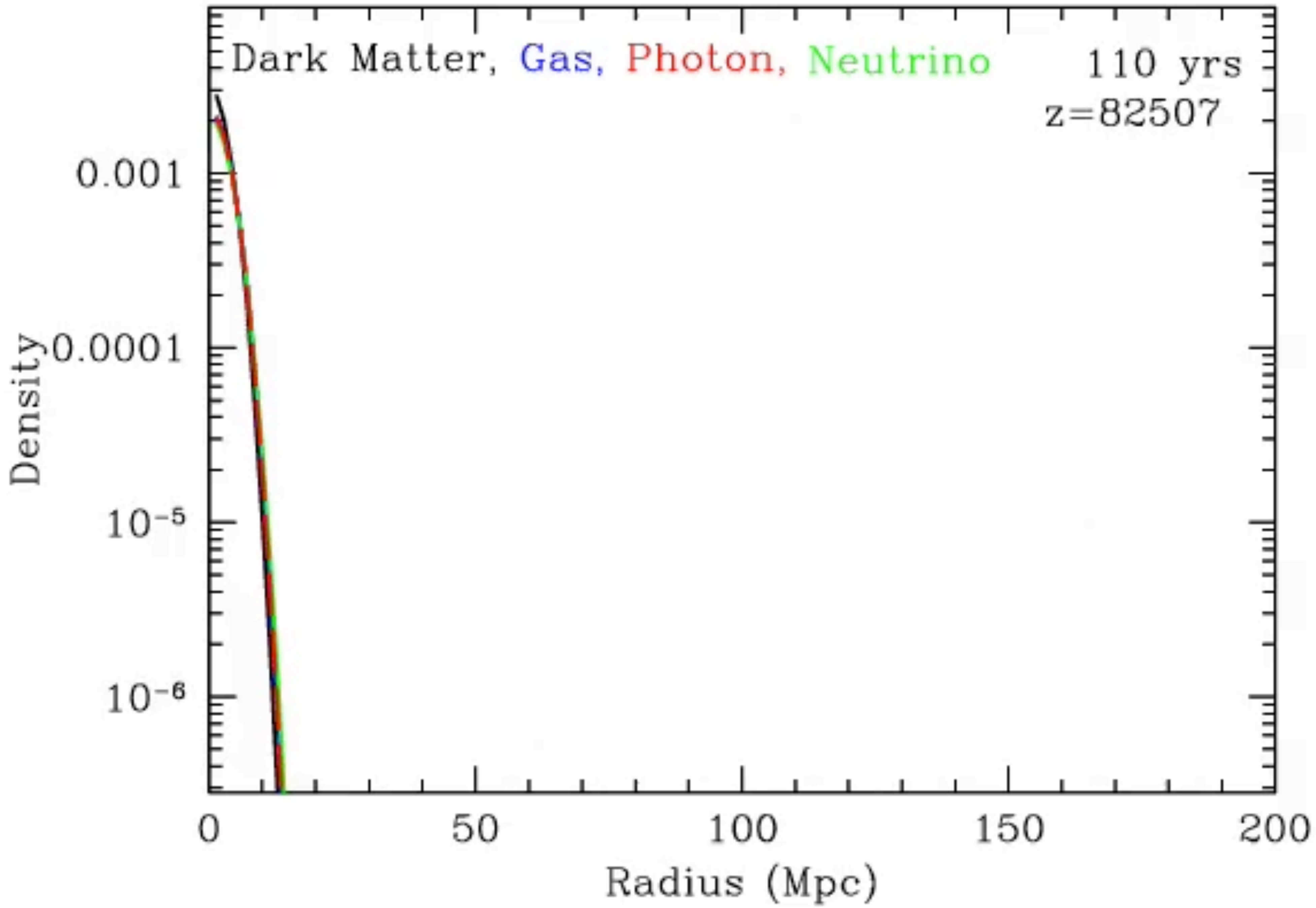
From this, they obtain a Hubble velocity v_H= 3 017 ± 166 km/s.

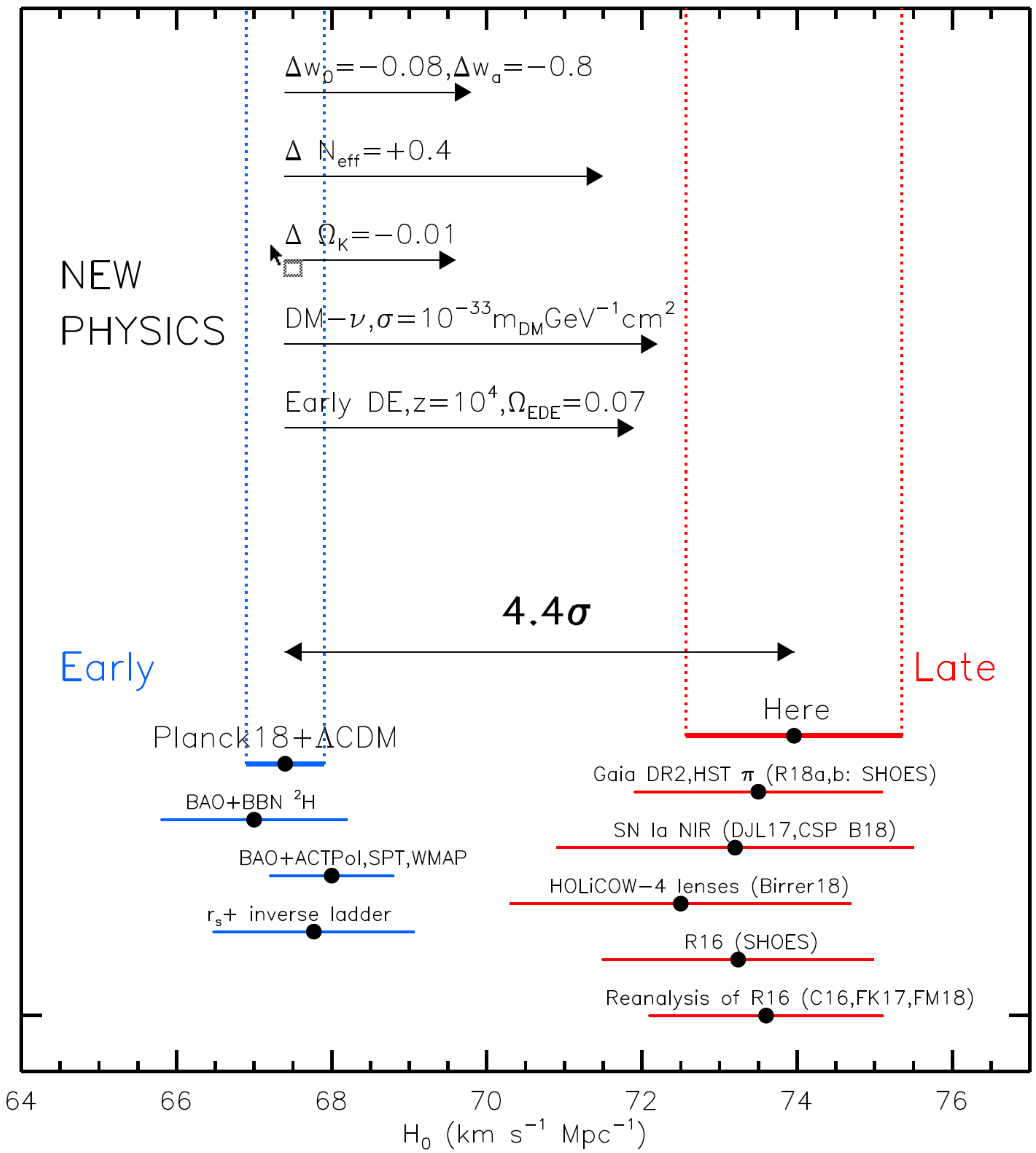
Using this recessional velocity, one can find H_0= 68.9 km/s.

Baryon Acoustic Oscillations



From D. Eisenstein and M. White

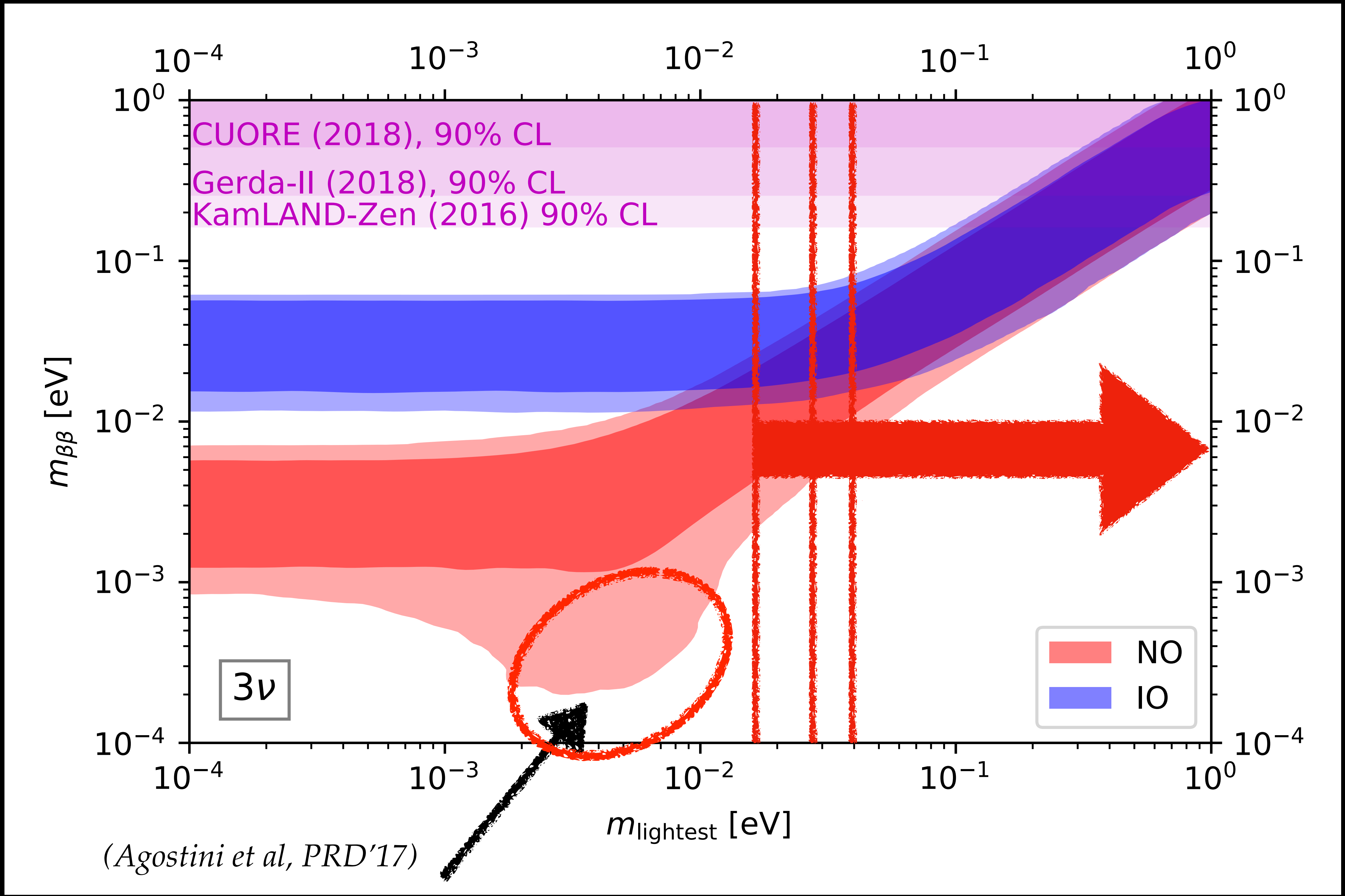
A. G. Riess, S. Casertano, W. Yuan, L. M. Macri and D. Scolnic, c.



Decaying dark matter
Interacting dark energy
Curvature
Early dark energy
Modifications of gravity

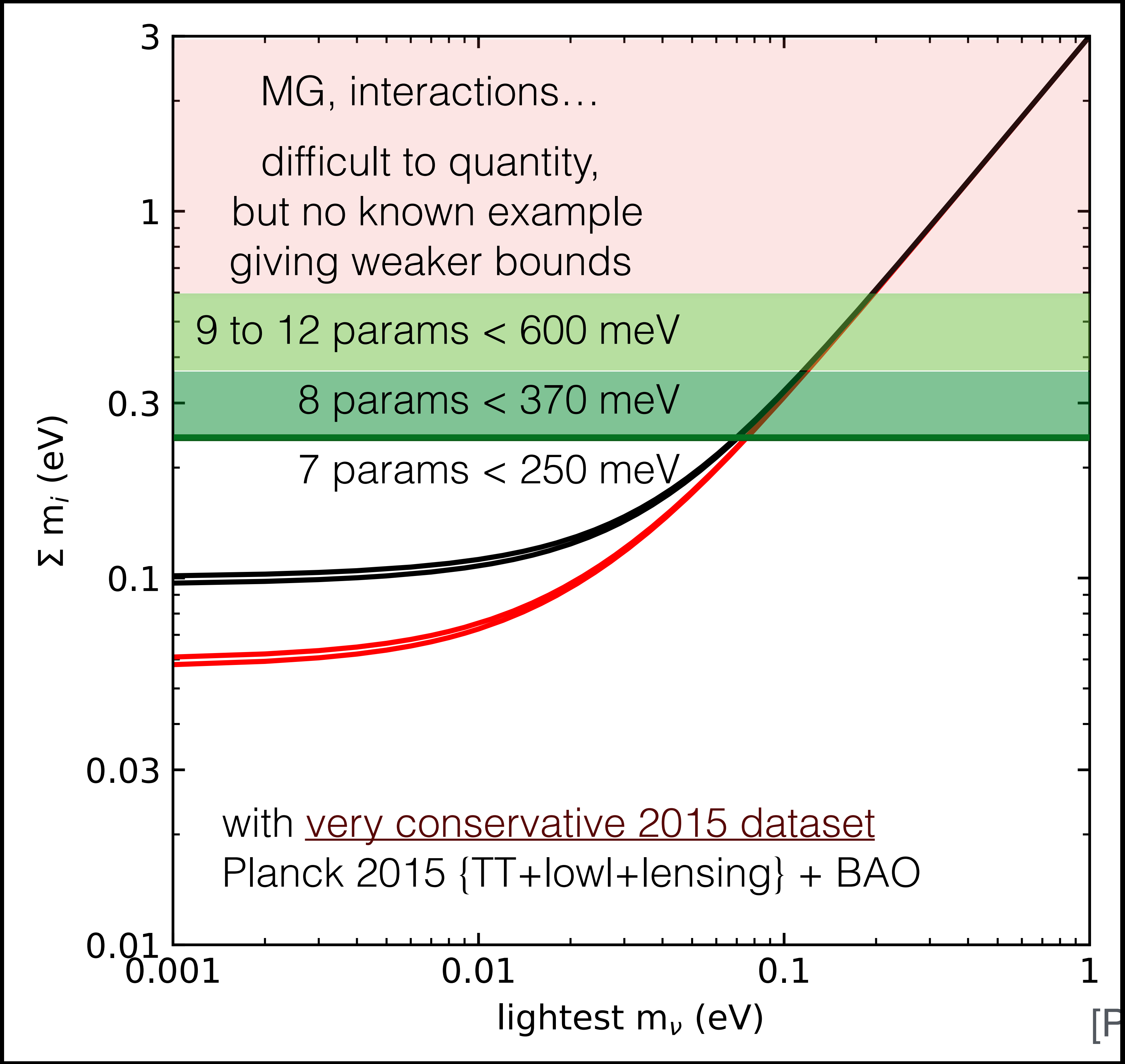
$H_0 = 67.37 \pm 0.54$ km/s/Mpc $\quad$ $H_0 = 74.03 \pm 1.42$ km/s/Mpc

What we know



$m_{\beta\beta}$ < 2 10^{-4} would require some fine tuning in the Majorana phases

$\sum m_\nu$



J. Lesgourgues, talk at Neutrino 2018

Methods to detect non-non-relativistic neutrinos: PTOLEMY

Today neutrinos have a mean temperature:

$$T_{\nu 0} = \left(\frac{4}{11}\right)^{1/3} T_0 = 1.945 \text{ K} \rightsquigarrow 1.697 \times 10^{-4} \text{ eV}$$

And two neutrinos have a mass above: $\sqrt{\Delta m^2_{12}} \simeq 0.008 \text{ eV}$

at least one of these neutrinos has a mass larger than $\sqrt{|\Delta m^2_{13}|} \simeq 0.05 \text{ eV}$

Therefore there are at least two non-relativistic neutrino states.

A process without energy threshold is mandatory!

(Anti)neutrino capture on β-decaying nuclei

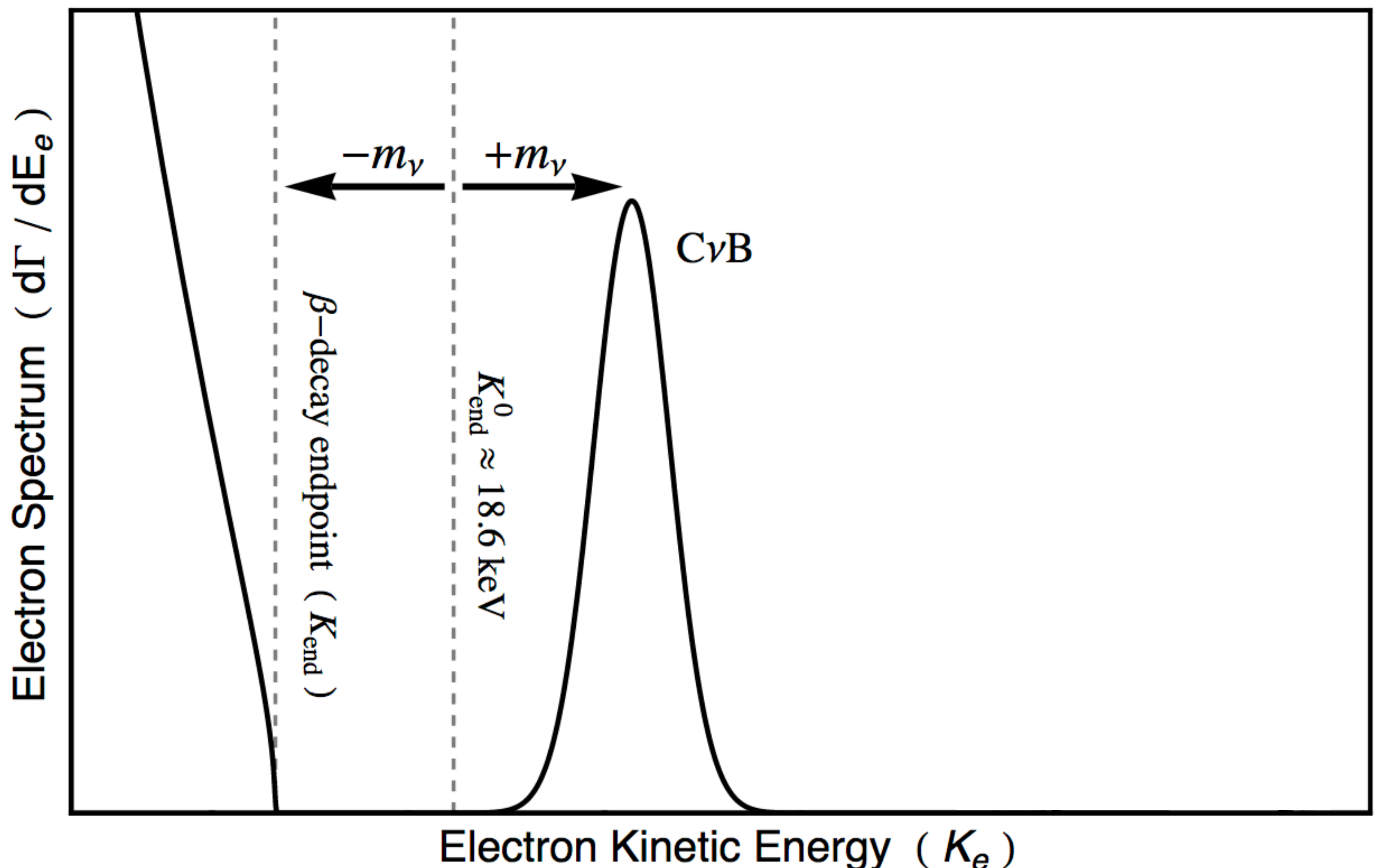
$$\nu_e + N \to N' + e^- \qquad \bar{\nu}_e + N \to N' + e^+$$

$$M(N) - M(N') = Q_\beta > 0$$

Cocco et al 2007

Methods to detect non-non-relativistic neutrinos:

(Anti)neutrino capture on β-decaying nuclei



Long, Lunardini & Sabancillar, JCAP'14

For finite m_ν, the electron kinetic energy is$Q_\beta+E_\nu \geq Q_\beta+m_\nu$, while electrons emerging from the analogous beta decay have at most an energy $Q_\beta-m_\nu$, neglecting nucleus recoil energy. A minimum gap of $2m_\nu$ is thus present and this at least in principle allows to distinguish between beta decay and NCB interaction: GOOD ENERGY RESOLUTION!

PTOLEMY (PonTecorvo Observatory for Light, Early-universe Massive-neutrino Yield) @ LNGS

PTOLEMY: A Proposal for Thermal Relic Detection of Massive Neutrinos and Directional Detection of MeV Dark Matter

E. Baracchini[3], M.G. Betti[11], M. Biasotti[5], A. Boscá[16], F. Calle[16], J. Carabe-Lopez[14], G. Cavoto[10,11], C. Chang[22,23], A.G. Cocco[7], A.P. Colijn[13], J. Conrad[18], N. D'Ambrosio[2], P.F. de Salas[17], M. Faverzani[6], A. Ferella[18], E. Ferri[6], P. Garcia-Abia[14], G. Garcia Gomez-Tejedor[15], S. Gariazzo[17], F. Gatti[5], C. Gentile[25], A. Giachero[6], J. Gudmundsson[18], Y. Hochberg[1], Y. Kahn[26], M. Lisanti[26], C. Mancini-Terracciano[10], G. Mangano[7], L.E. Marcucci[9], C. Mariani[11], J. Martínez[16], G. Mazzitelli[4], M. Messina[20], A. Molinero-Vela[14], E. Monticone[12], A. Nucciotti[6], F. Pandolfi[10], S. Pastor[17], J. Pedrós[16], C. Pérez de los Heros[19], O. Pisanti[7,8], A. Polosa[10,11], A. Puiu[6], M. Rajteri[12], R. Santorelli[14], K. Schaeffner[3], C.G. Tully[26], Y. Raitses[25], N. Rossi[10], F. Zhao[26], K.M. Zurek[21,22]

[1]Racah Institute of Physics, Hebrew University of Jerusalem, Jerusalem, Israel
[2]INFN Laboratori Nazionali del Gran Sasso, L'Aquila, Italy
[3]Gran Sasso Science Institute (GSSI), L'Aquila, Italy
[4]INFN Laboratori Nazionali di Frascati, Frascati, Italy
[5]Università degli Studi di Genova e INFN Sezione di Genova, Genova, Italy
[6]Università degli Studi di Milano-Bicocca e INFN Sezione di Milano-Bicocca, Milano, Italy
[7]INFN Sezione di Napoli, Napoli, Italy
[8]Università degli Studi di Napoli Federico II, Napoli, Italy

PTOLEMY (PonTecorvo Observatory for Light, Early-universe, Massive-neutrino Yield) @ LNGS

The expected rate is:

$$\Gamma_{\mathrm{C}\nu\mathrm{B}} = [n_0(\nu_{h_R}) + n_0(\nu_{h_L})]\, N_T\, \bar{\sigma} \sum_{i=1}^{3} |U_{ei}|^2 f_c(m_i)\,,$$

For unclustered neutrinos (i.e. $f_c = 1$) and 100 g of tritium, the expected number of events per year:

$$\Gamma^{\mathrm{D}}_{\mathrm{C}\nu\mathrm{B}} \simeq 4\,\mathrm{yr}^{-1}, \qquad \Gamma^{\mathrm{M}}_{\mathrm{C}\nu\mathrm{B}} = 2\Gamma^{\mathrm{D}}_{\mathrm{C}\nu\mathrm{B}} \simeq 8\,\mathrm{yr}^{-1}$$

If neutrinos are Majorana particles, the expected number of events is doubled with respect to the Dirac case. The reason is related to the fact that, during the transition from ultra-relativistic to non-relativistic particles, helicity is conserved, but not chirality. The population of relic neutrinos is then composed by left- and right-helical neutrinos in the Majorana case, and only left-helical neutrinos in the Dirac case. Since the neutrino capture can only occur for left-chiral electron neutrinos, the fact that in the Majorana case the right-handed neutrinos can have a left-chiral component leads to a doubled number of possible interactions.

masses (meV)	matter halo	overdensity f_c	$\Gamma^{\mathrm{D}}_{\mathrm{C}\nu\mathrm{B}}$ (yr^{-1})	$\Gamma^{\mathrm{M}}_{\mathrm{C}\nu\mathrm{B}}$ (yr^{-1})
		{best fit	best fit + baryons	optimistic}
any	any	no clustering	4.06	8.12
degenerate	NFW	2.18 | 2.44 | 2.88	8.8 | 9.9 | 11.7	17.7 | 19.8 | 23.4
$m_{\nu_{1,2,3}} = 150$	Einasto	1.68 | 1.87 | 2.43	6.8 | 7.6 | 9.9	13.6 | 15.1 | 19.7
minimal (IO)	NFW	1.15 | 1.18 | 1.21	4.07 | 4.08 | 4.08	8.15 | 8.15 | 8.16
$m_{\nu_3} = 60$	Einasto	1.09 | 1.12 | 1.18	4.07 | 4.07 | 4.08	8.14 | 8.14 | 8.15
minimal (NO)	NFW	1.15 | 1.18 | 1.21	4.66 | 4.78 | 4.89	9.31 | 9.55 | 9.77
$m_{\nu_{1,2}} = 60$	Einasto	1.09 | 1.12 | 1.18	4.42 | 4.54 | 4.78	8.84 | 9.07 | 9.55

de Salas et al, JCAP'17

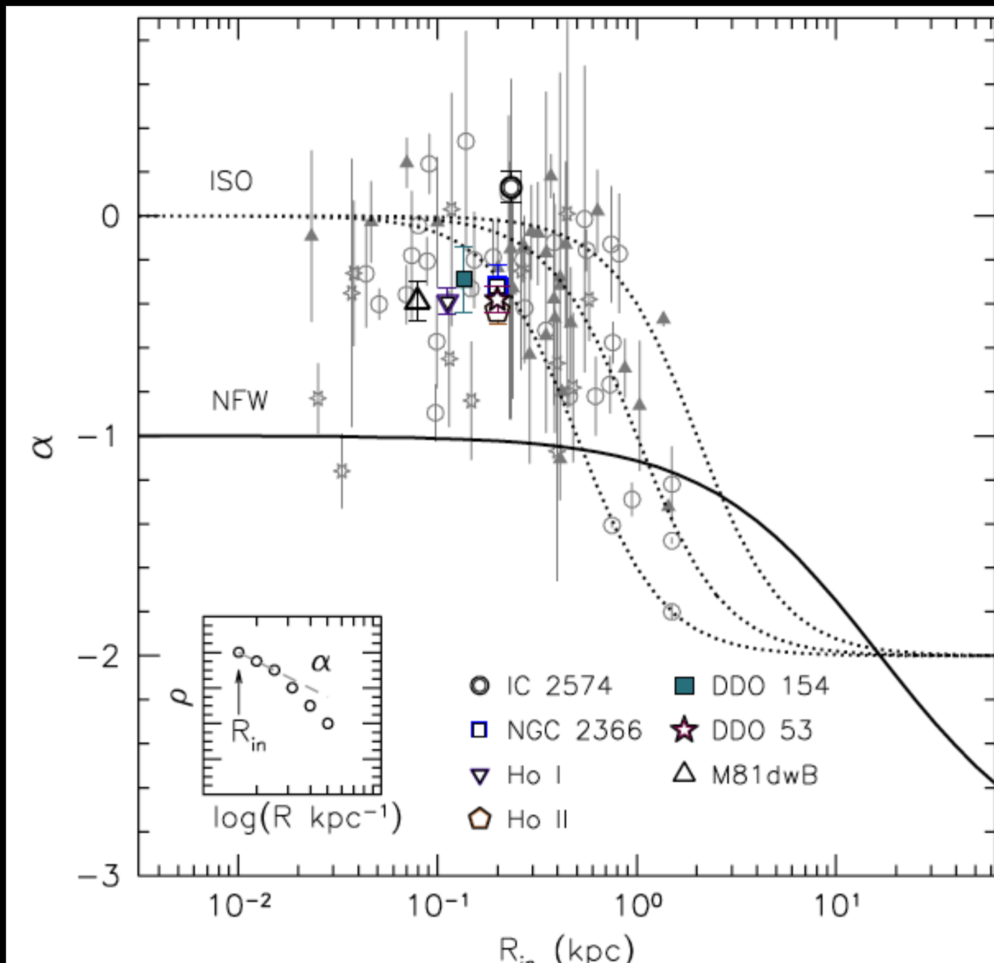
$$r_s(z_{drag}) = \int_0^{\eta(z)} d\eta \; c_s(1+z) \; , \tag{16}$$

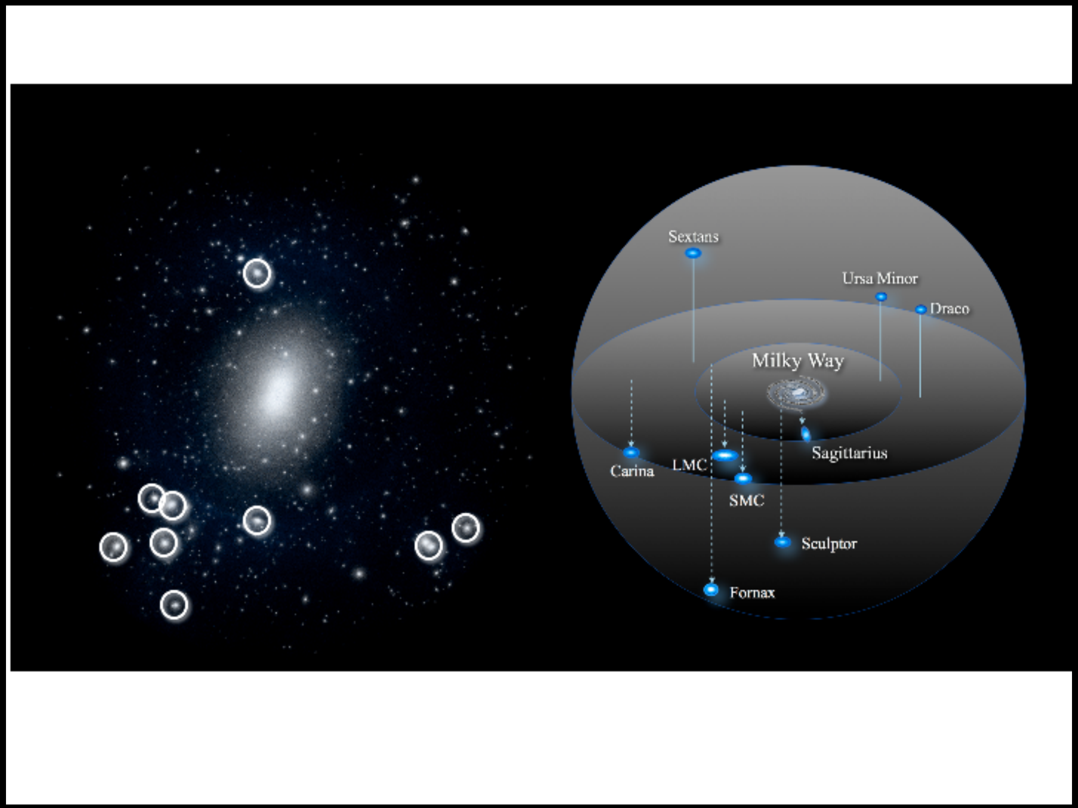
where $c_s = 1/\sqrt{3(1+R)}$ is the sound speed, and $R \equiv 3\rho_b/4\rho_\gamma$. The drag epoch corresponds to the redshift at which the *drag* optical depth τ_d is equal to one:

$$\tau_d(z_{drag}) = \int_0^{z_{drag}} dz \frac{d\eta}{da} \frac{x_e(z)\sigma_T}{R} \equiv 1 \; . \tag{17}$$


COLD dark matter
HOT dark matter
CDM
HDM
WDM
WARM dark matter
DARK MATTER
CREATED BY

Small scale crisis of ΛCDM@galactic and sub-galactic scales



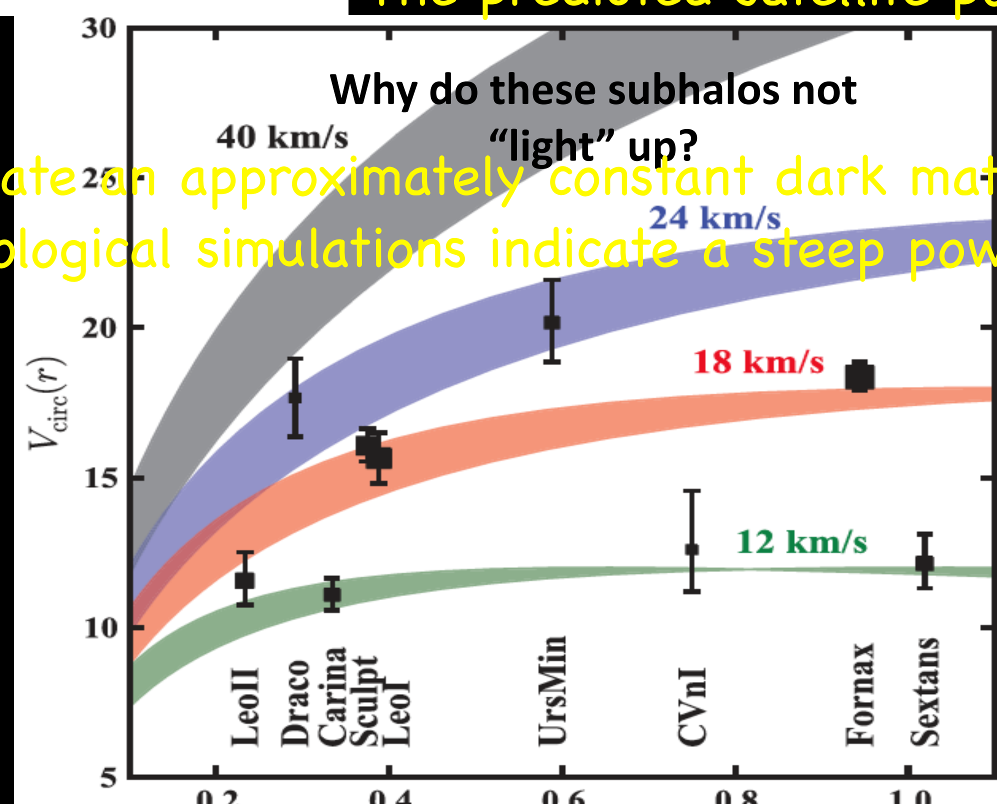


Missing satellite problem

The predicted satellite population far exceeds the observed one

Core/Cusp problem

Observations seem to indicate an approximately constant dark matter density in the inner parts of galaxies (core), while cosmological simulations indicate a steep power-law-like behaviour (cusp)



Too big to fail (TBTF) problem

Massive dark subhalos are too dense to match data.
Expected 10 subhalos in the Milky Way with v >30 km/s, only 3 known!

(Boylan et al, MNRAS'11)

Sterile keV (0.01 m_e) neutrino as a warm dark matter candidate?

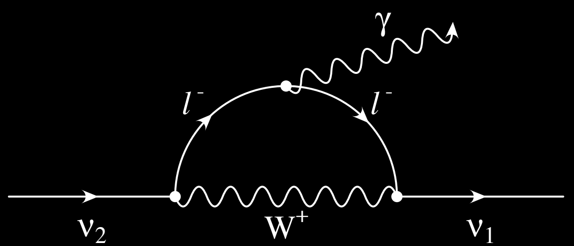
A controversial unidentified line has been detected at with a significance > 3σ in two independent samples of X-ray clusters with XMM-Newton.

It is independently seen by the same group in the Perseus Cluster with Chandra data.

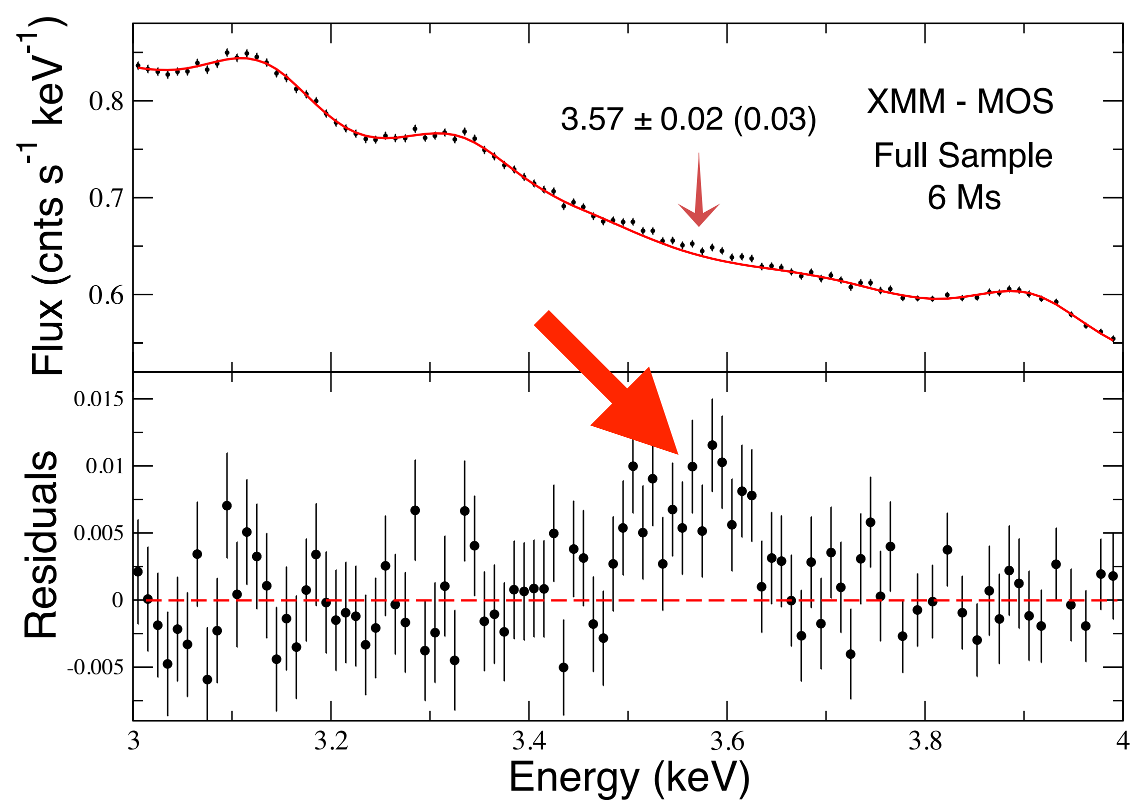
(Bulbul et al, APJ'14)

An independent group finds a line at the same energy toward Andromeda and Perseus with XMM-Newton, with a combined statistical evidence of 4.4σ. *(Boyarsky et al, PRL'14)*

$$\nu_s \to \nu_\alpha + \gamma$$



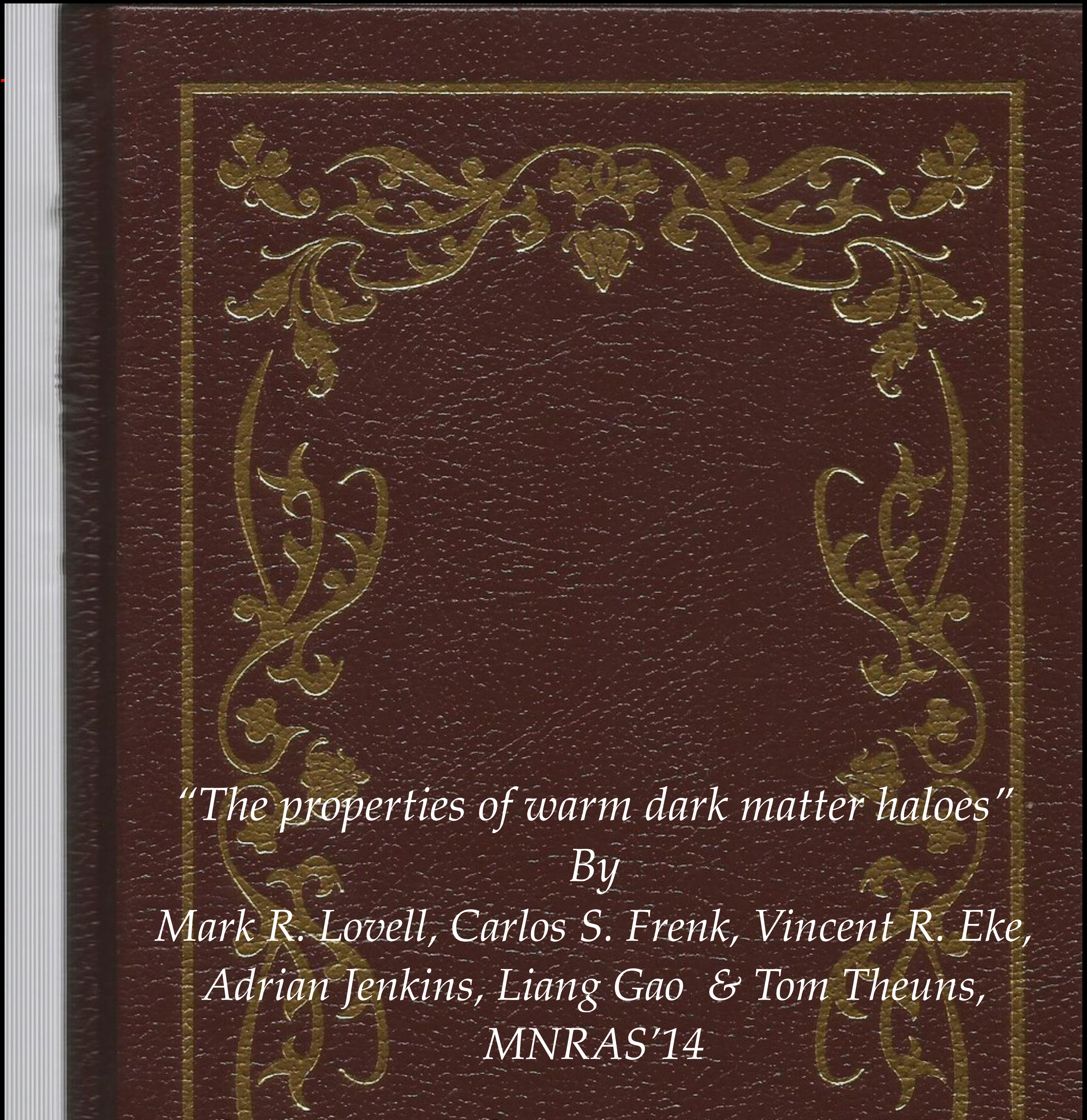
(Bulbul et al, APJ'14)



$$m_s = 2E = 7.1 keV$$

Sterile keV (0.01 m_e) neutrino as a warm dark matter candidate?

WDM leads to an identical large scale structure pattern than CDM, but very different subhaloes abundance, structure and dynamics: the free streaming of a keV sterile neutrino will reduce power at the small scales, delaying structure formation and lowering the haloes concentration.



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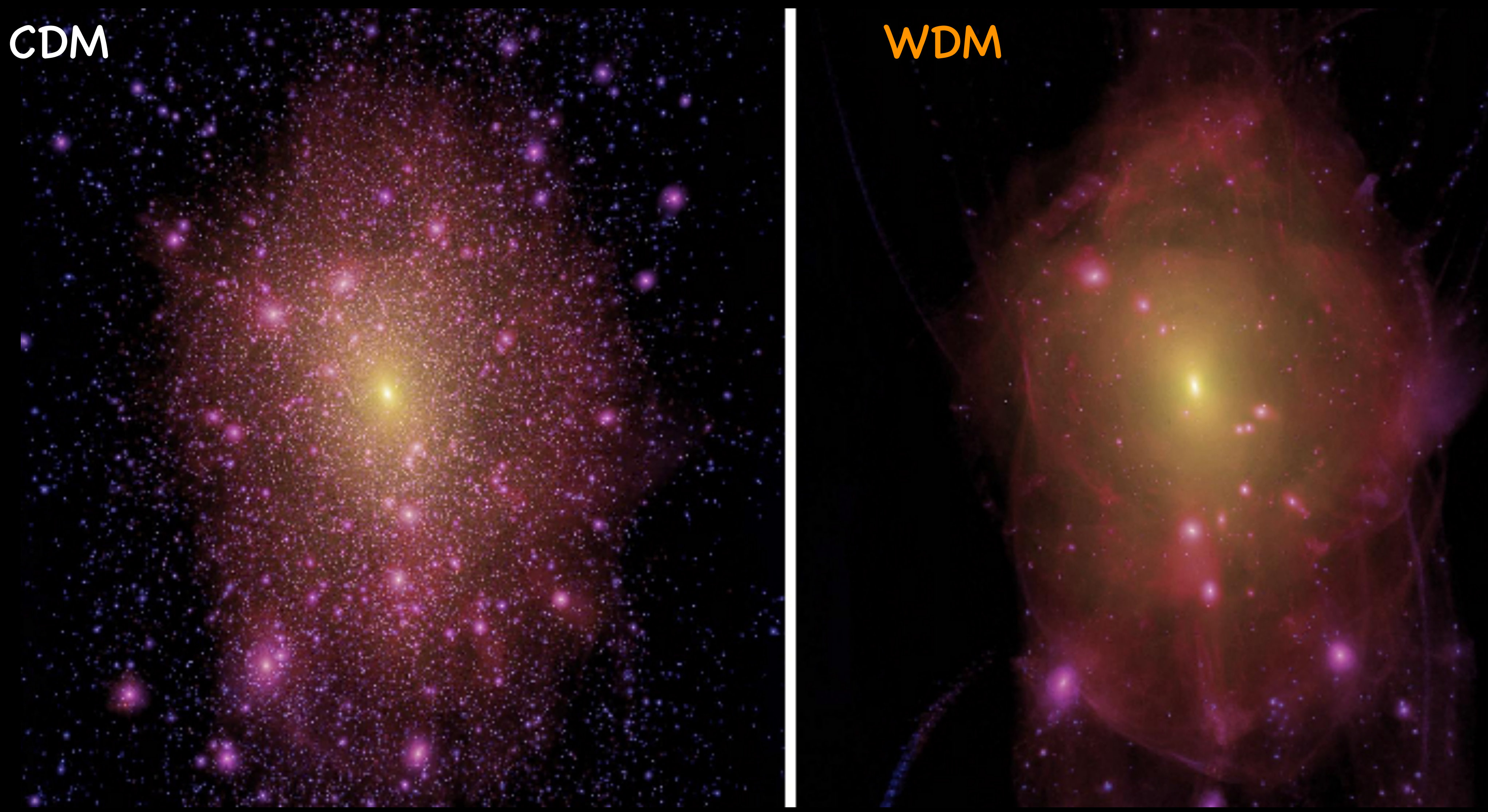
WDM leads to an identical large scale structure pattern than CDM, but very different subhaloes abundance, structure and dynamics: the free streaming of a keV sterile neutrino will reduce power at the small scales, delaying structure formation and lowering the haloes concentration.

Simulations have shown that WDM can solve/alleviate the small scale crisis of ΛCDM

Sterile keV (0.01 m_e) neutrino as a warm dark matter candidate?

WDM could reconcile theory with observations!



"The Haloes of Bright Satellite Galaxies in a Warm Dark Matter Universe", Mark R. Lovell, Vincent R. Eke, Carlos S. Frenk, Liang Gao, Adrian Jenkin Jie Wang, D.M. White , Alexey Boyarsky & Oleg Ruchayskiy MNRAS'12

"The properties of warm dark matter haloes", Mark R. Lovell, Carlos S. Frenk, Vincent R. Eke, Adrian Jenkins, Liang Gao & Tom Theuns, MNRAS'14

Big Bang Nucleosynthesis: N_{eff}

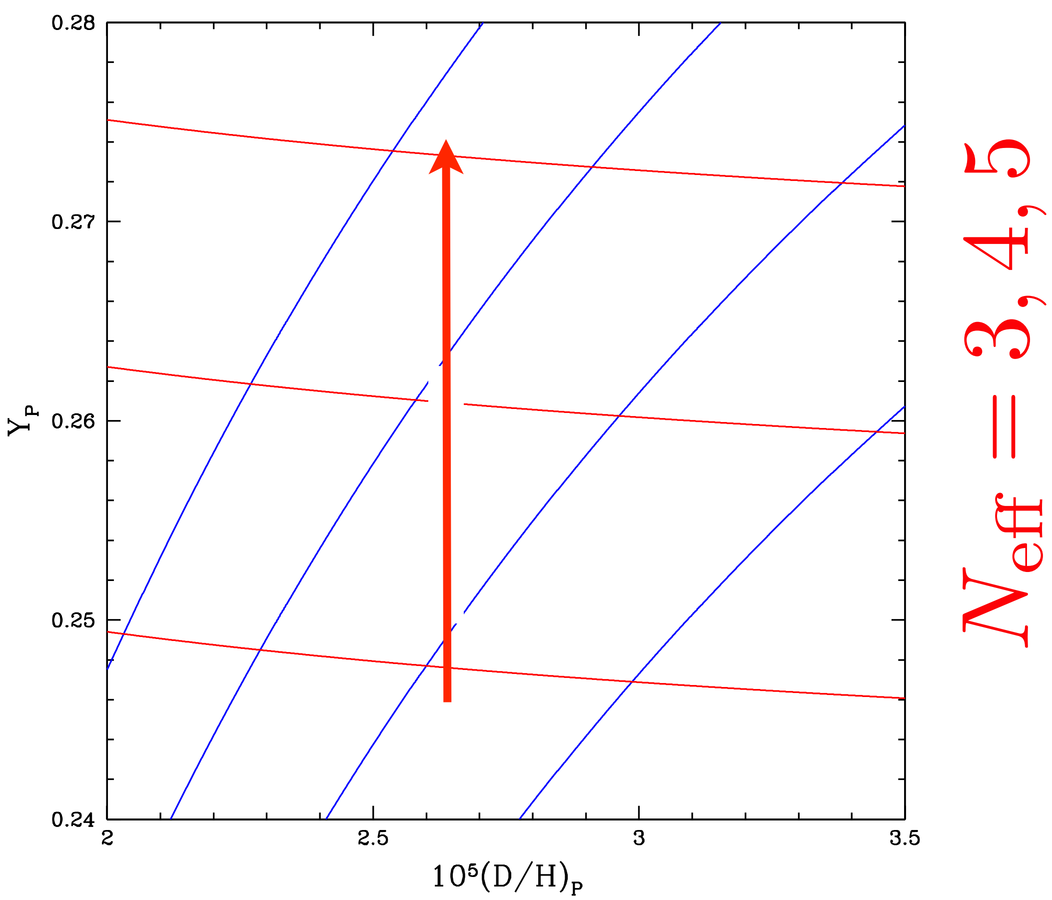
N_{eff} changes the freeze out temperature of weak interactions:

$$\Gamma_{n\leftrightarrow p} \sim H$$

MORE NEUTRINOS:

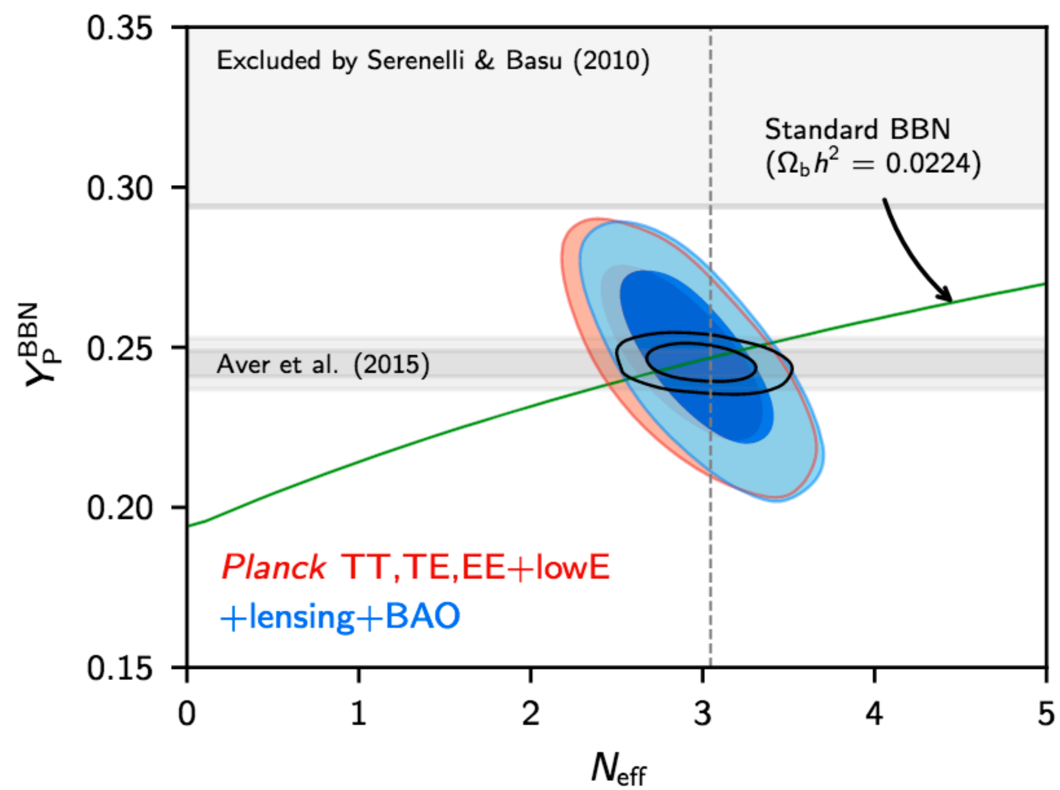
Higher N_{eff}: larger expansion rate & freeze out temperature, MORE HELIUM 4

$$n/p \simeq e^{-\frac{m_n - m_p}{T_{freeze}}} \qquad Y_p = \frac{2(n/p)}{1+n/p}$$



(G. Steigman'12)

Planck 2018 results, 1807.06209

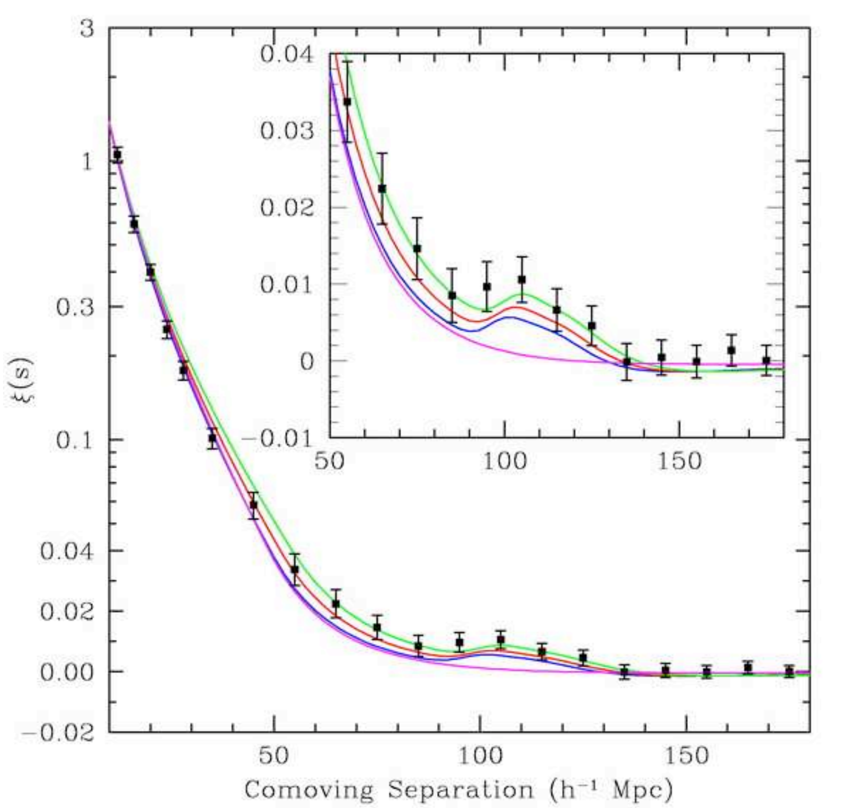


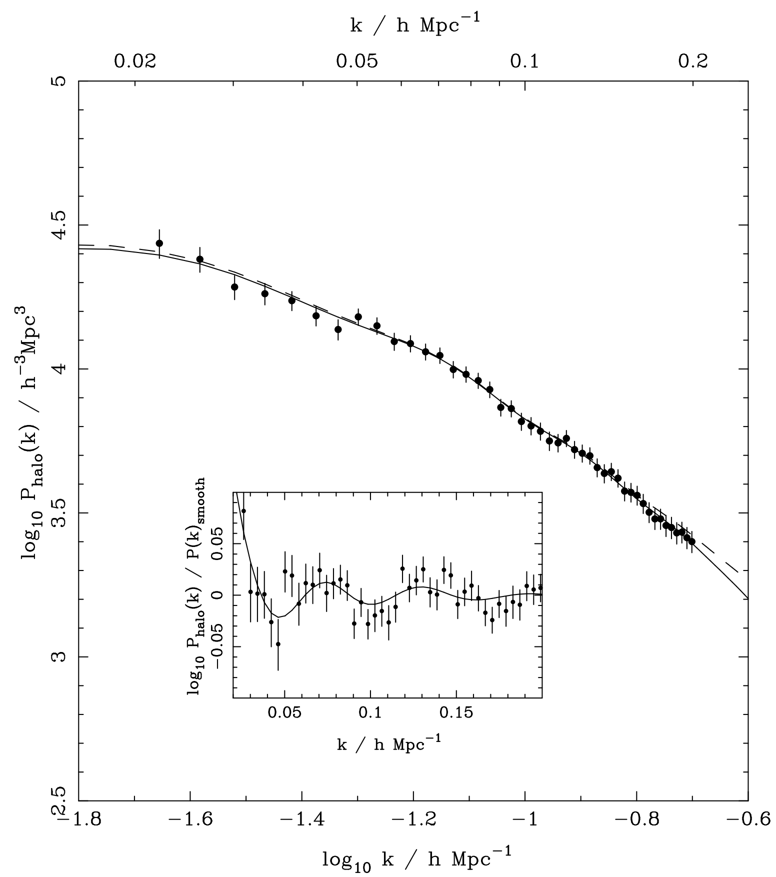
$N_{\rm eff} = 2.99^{+0.43}_{-0.40} \quad Y_p = 0.2437^{+0.0077}_{-0.0080}$

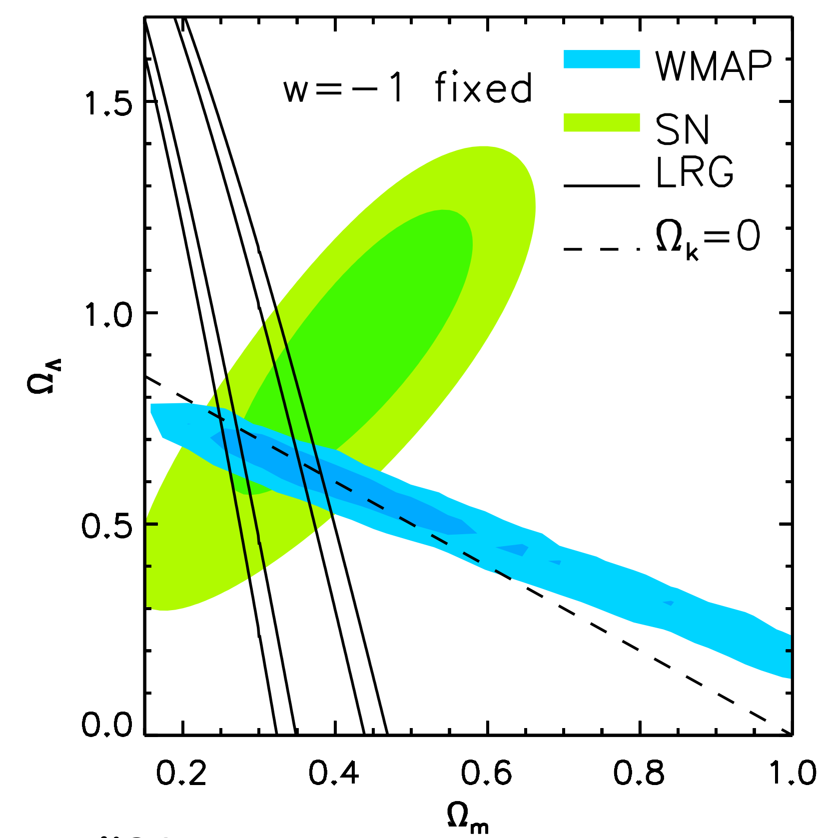
Los catálogos de galaxias miden la función de correlación:

$$\xi(\vec{r}) \equiv \langle \delta(\vec{x})\delta(\vec{x}+\vec{r}) \rangle_{\mathrm{Volume}} \qquad \langle \tilde{\delta}(\vec{k})\tilde{\delta}(\vec{k}') \rangle_{\mathrm{Volume}} = (2\pi)^3 P(k)\delta^3(\vec{k}-\vec{k}')$$

$$\delta(\vec{x}) \equiv \frac{\rho(\vec{x})-\bar{\rho}(\vec{x})}{\bar{\rho}(\vec{x})} \qquad \tilde{\delta}(\vec{k}) \equiv \int d^3\vec{r}\; e^{i\vec{k}\vec{r}}\; \delta(\vec{r})$$







Eisenstein et al'05 **Reid et al'09**

SSDS 2005: Primera detección de la señal BAO (3.4s) (47000 LRGs, 4000 deg^2 , z=0.35)

SDSS II 2009: 110 000 LRGs, 8000 deg^2 , z=0.35.