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The Cosmic NeuTRIVIA game

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

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

ΛCDM NeuTRIVIA: PLAYERS

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

Heavy elements

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

Stars

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

Free H and He

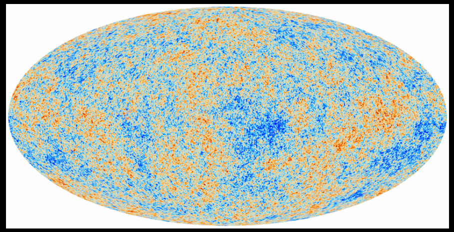
$$\Omega_{\text{H, He}} = 0.04$$

Dark energy

$$\Omega_{\Lambda} = 0.7$$

v

Neutrinos!



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

Cold Dark matter

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

How large is the MASSIVE neuTRIVIA pie piece?

Neutrinos!

ν

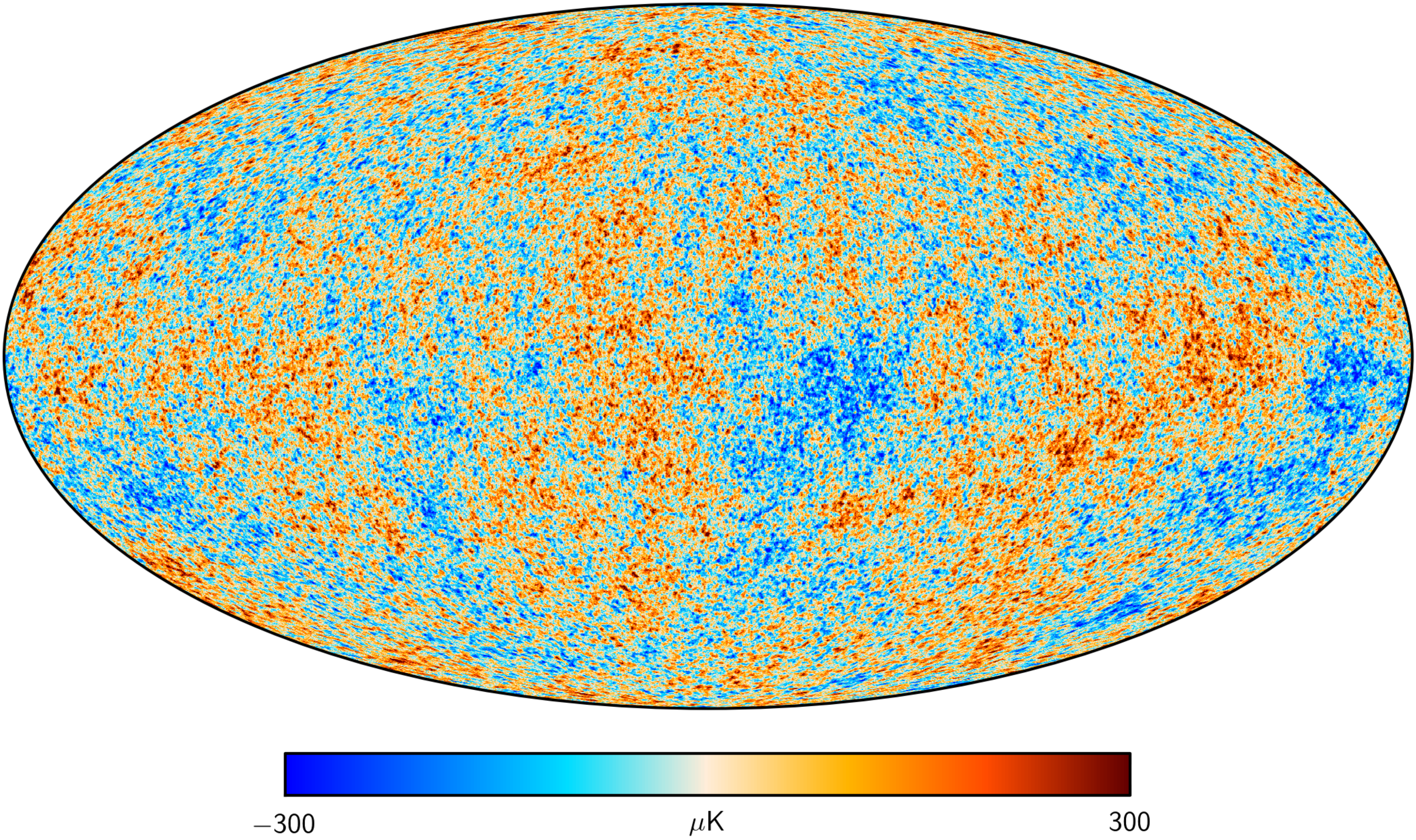
Cosmology tells us

$\Omega_\nu \lesssim 0.0024$ 95% CL

Neutrino oscillations tell us

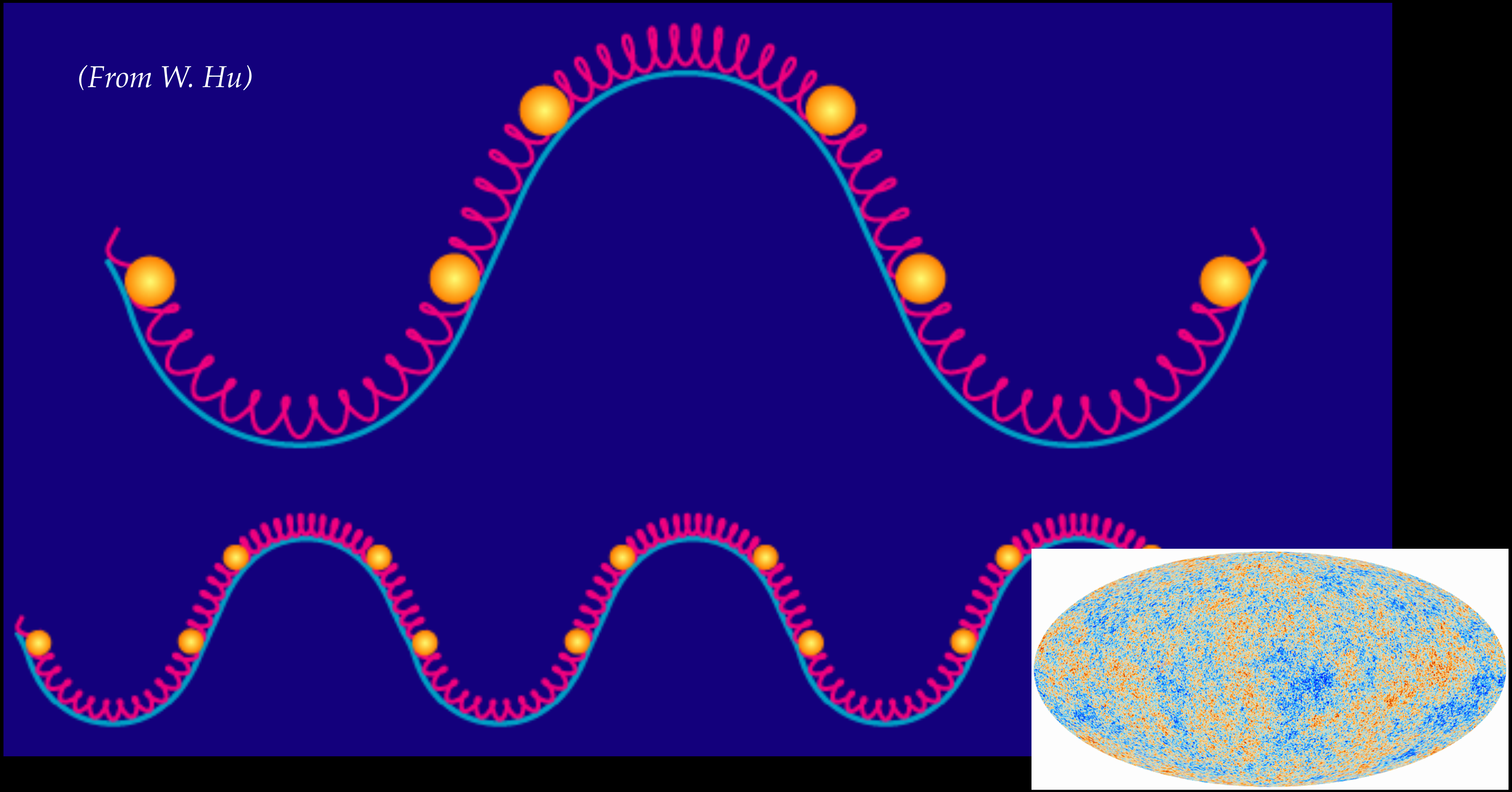
$\Omega_\nu \gtrsim 0.0012$ 95% CL

I guess all you know about dark matter/
what about dark radiation?
But radiation is visible, and it has a mean T≃ 2.725 K!



This map is just telling us how the CMB temperature fluctuations vary with the angular size of patches in the sky...

The CMB fluctuations are due to the acoustic oscillations in the baryon-photon fluid before recombination.


(From W. Hu)

Potential wells → High density → COLD SPOTS in CMB maps

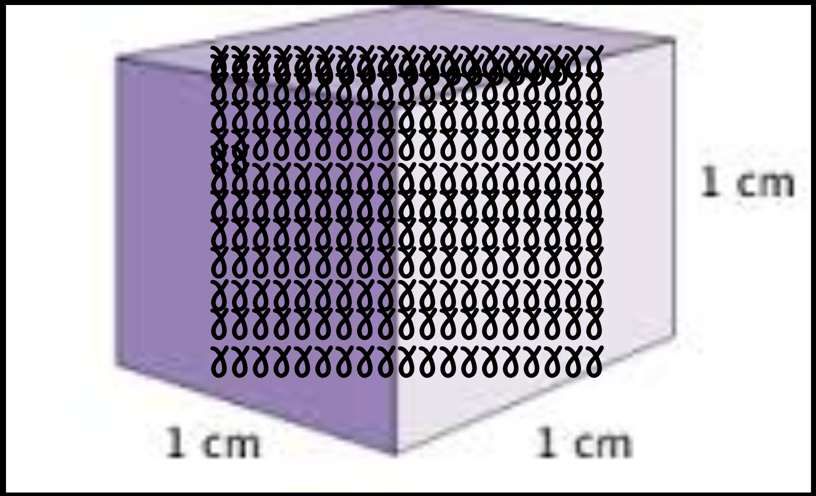
Potential hills → Low density → HOT SPOTS in CMB maps

I guess all you know about dark matter/

what about dark radiation?

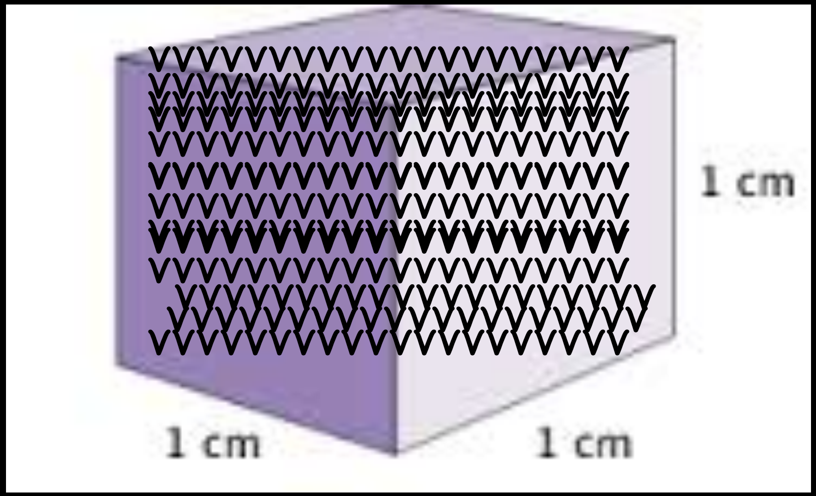
But radiation is visible!

410 photons/cm^3



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

340 neutrinos/cm³

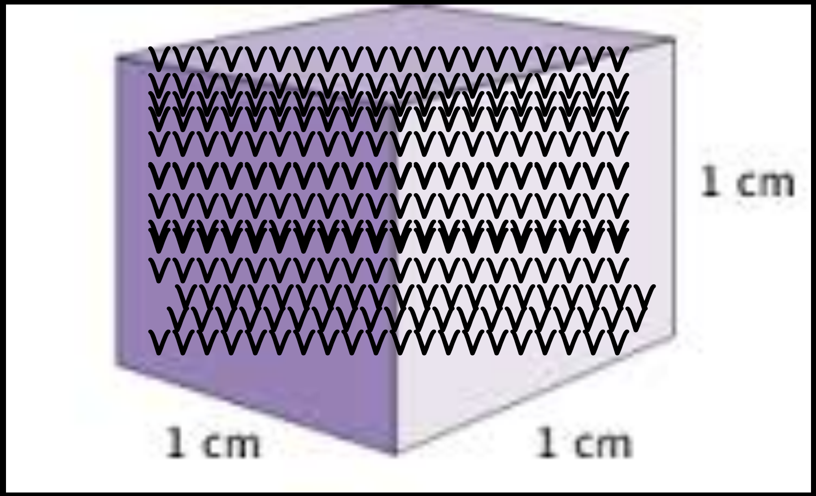


This cosmic relic neutrino background has never been detected directly.

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/cm³



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:

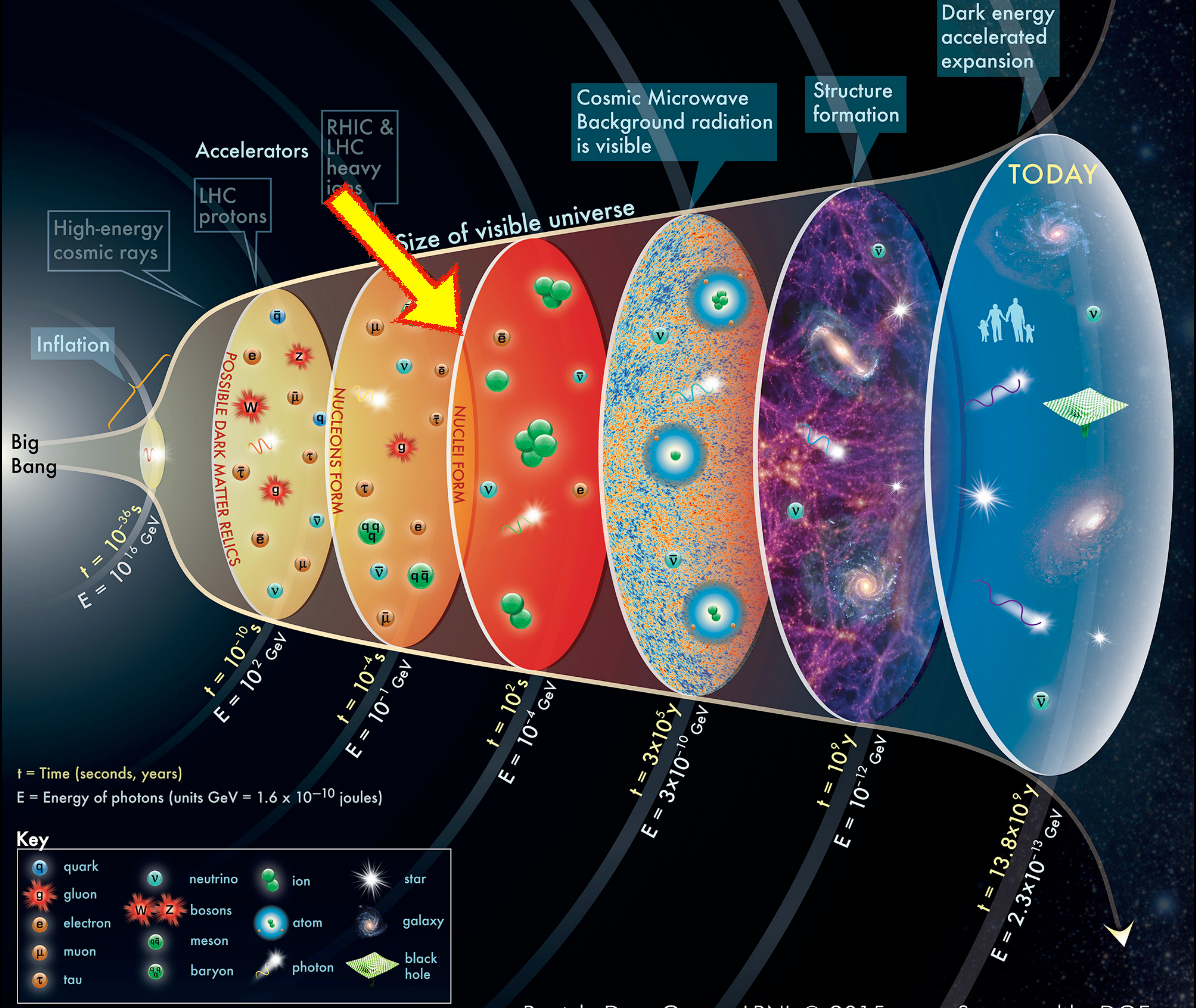
$$\Gamma_\nu = n\sigma v \simeq T^3 G_F^2 T^2 \sim G_F^2 T^5$$

- 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.**



t = Time (seconds, years)

E = Energy of photons (units GeV = 1.6 x 10^{-10} joules)

Key

- q quark
- g gluon
- e electron
- μ muon
- τ tau
- ν neutrino
- W Z bosons
- q q̄ meson
- q q q baryon
- ion
- atom
- photon
- star
- galaxy
- black hole

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}	$100 GeV$
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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: $$\langle v_{\text{thermal}} \rangle \simeq 81(1+z)\left(\frac{\text{eV}}{m_\nu}\right) \text{ km s}^{-1}$$

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

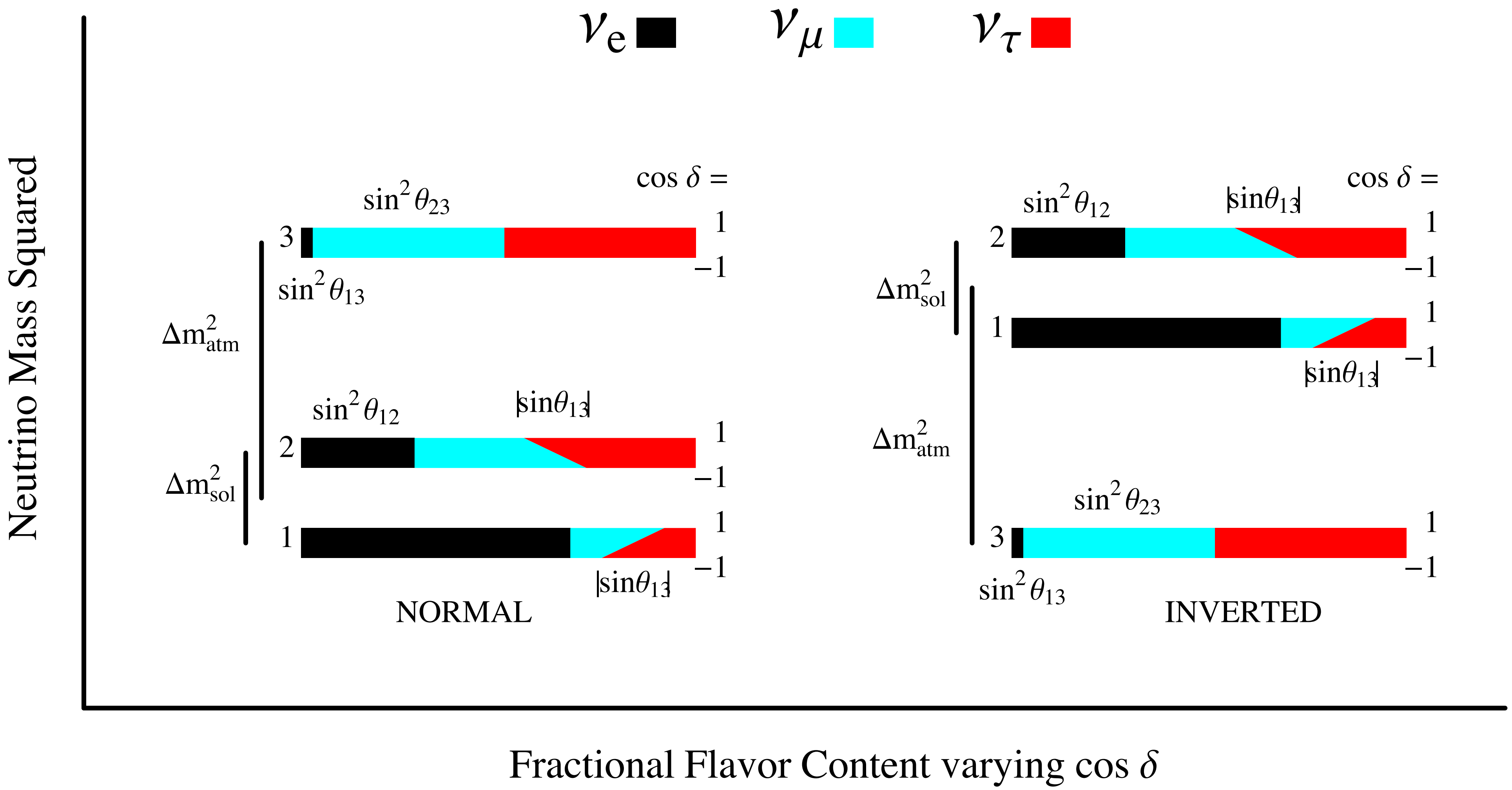
Too much thermal energy to be squeezed into small volumes to form the smaller structures we observe today!

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)

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

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

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

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

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

$$\sqrt{\Delta m_{12}^2} \simeq 0.008 \ \mathrm{eV}$$

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

$$\sqrt{|\Delta m_{13}^2|} \simeq 0.05 \ \mathrm{eV}$$

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

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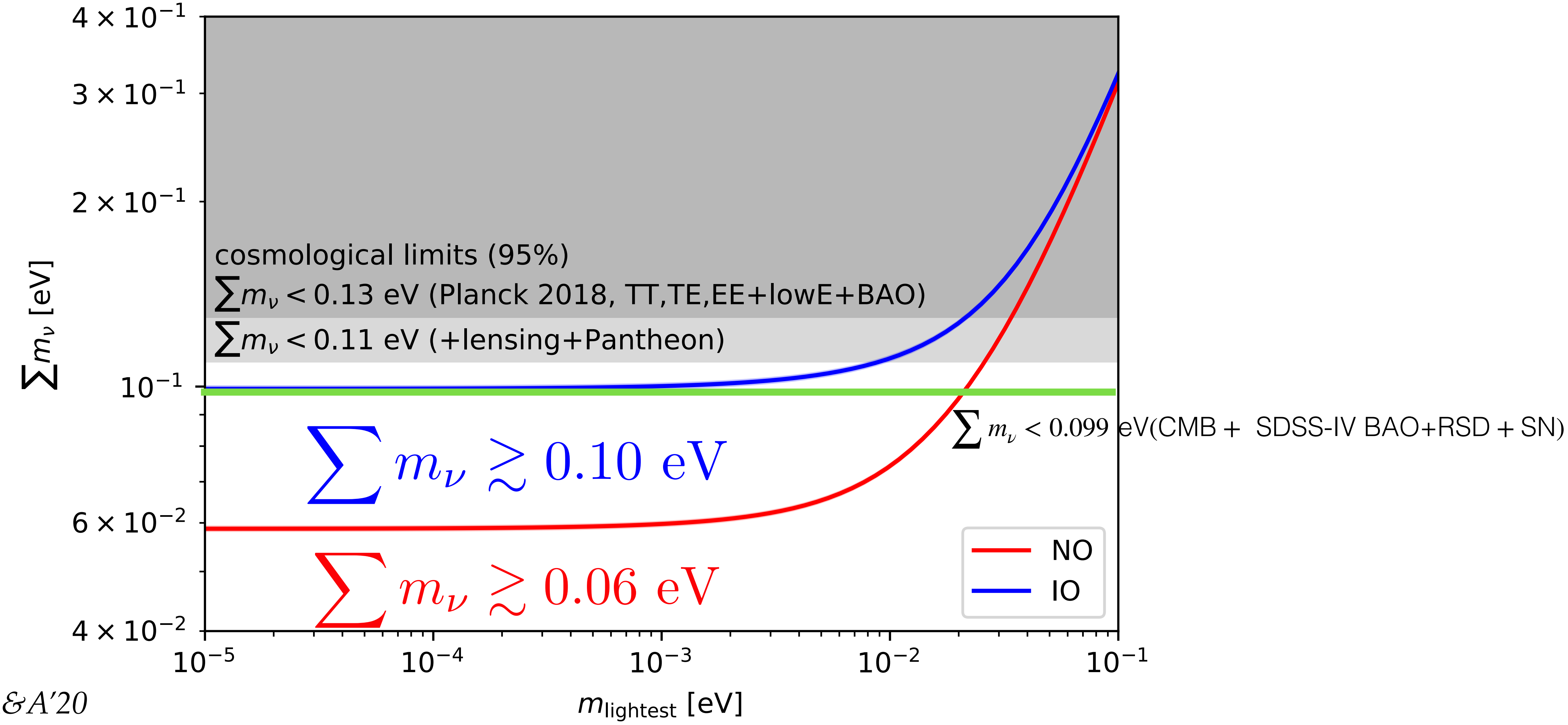
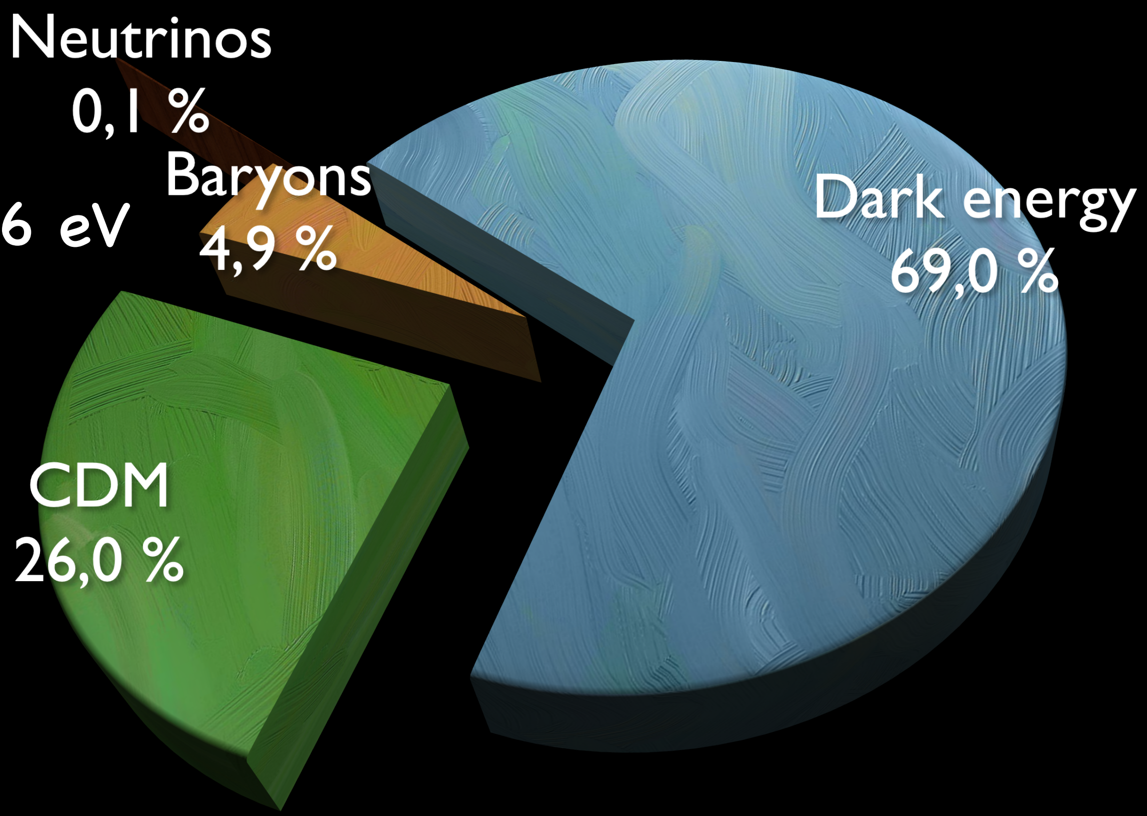
which translates into a lower bound on the total neutrino mass, depending on the ordering:

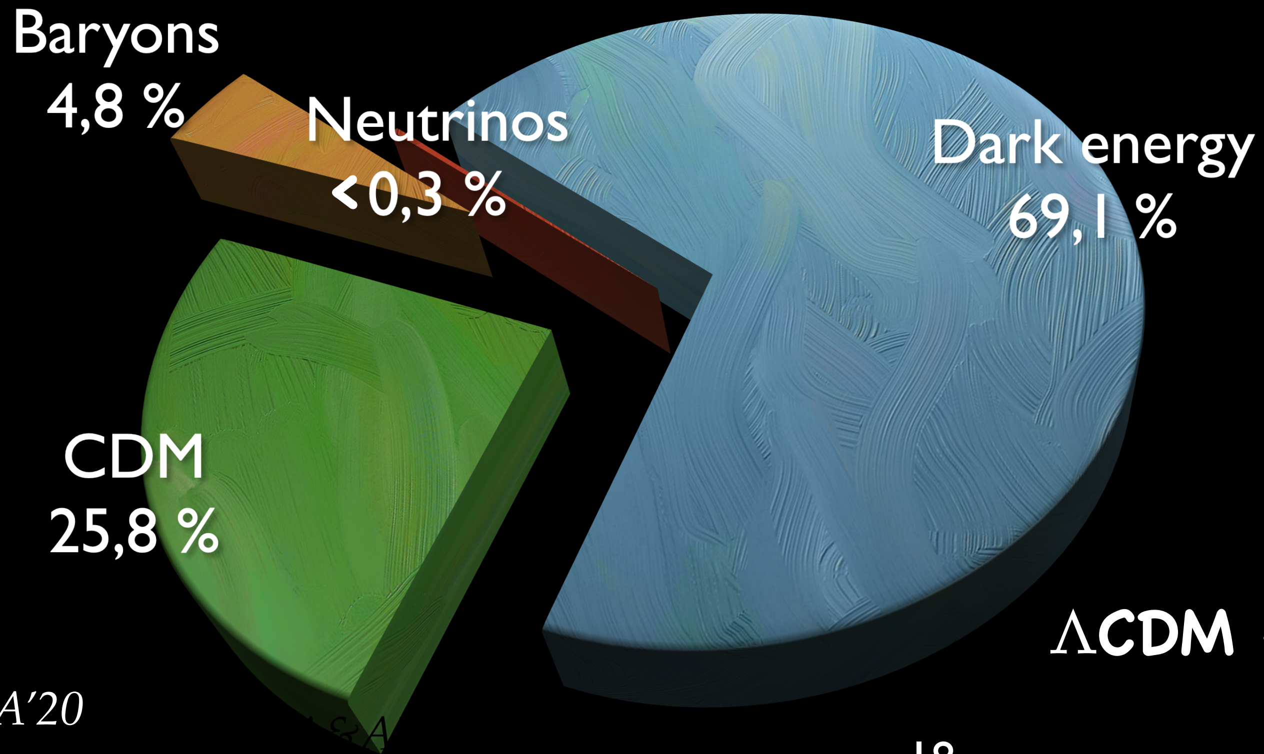


Planck Coll. A&A'20

Planck 2018 Cosmic Trivia

ΛCDM + $\sum m_{\nu,\mathrm{fiducial}} = 0.06$ eV





ΛCDM + $\sum m_{\nu,\mathrm{fiducial}} < 0.12$ eV @95% CL

Planck Coll. A&A'20

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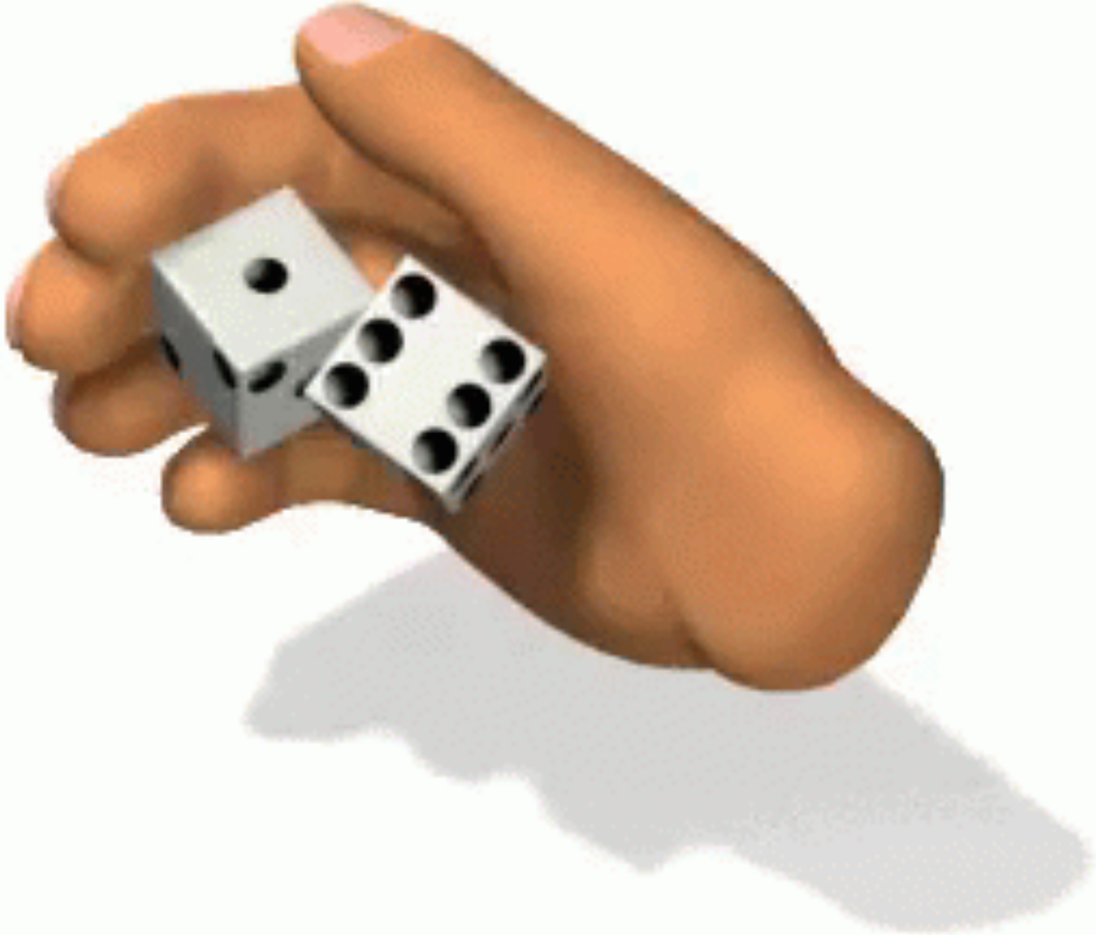


Number of neutrinos: N_{eff}

The total radiation in the universe can be written as:

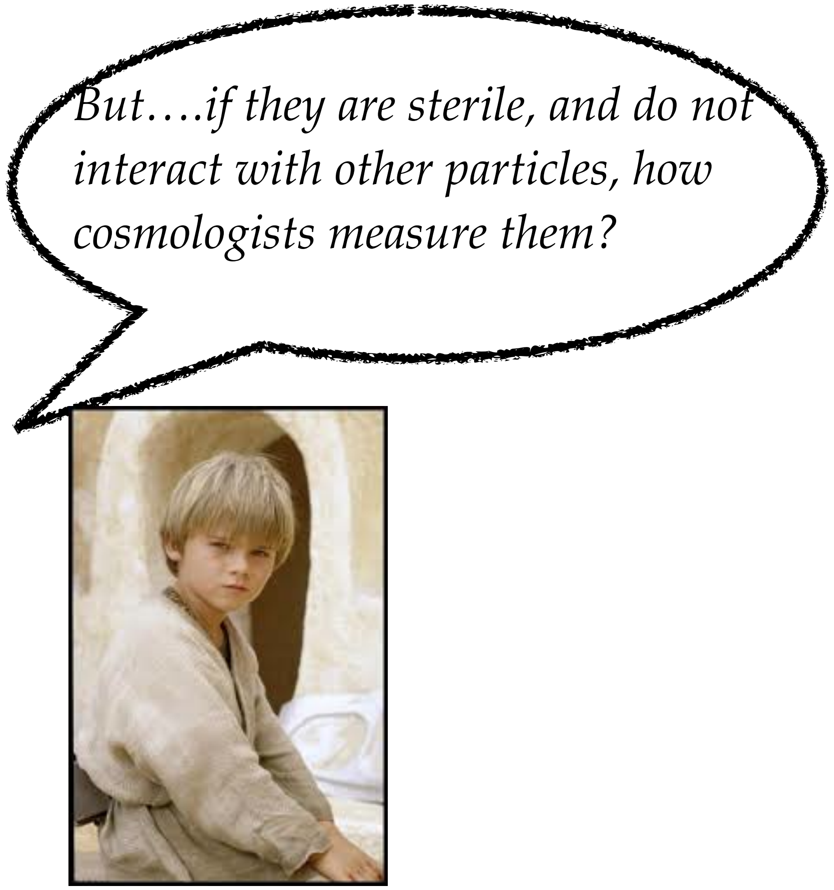
$$\Omega_r h^2 = \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\mathrm{eff}}\right)\Omega_\gamma h^2$$

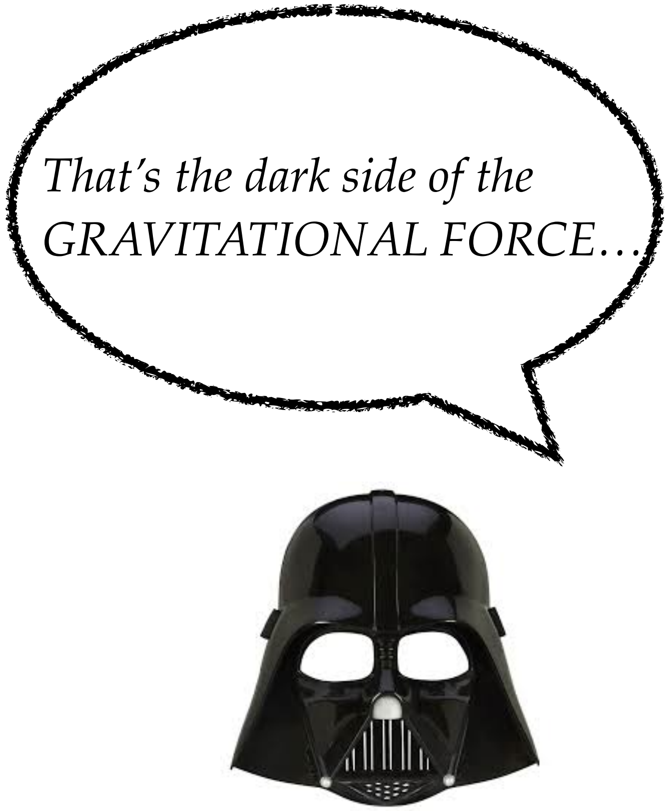
Bennett et al, 2012.02726

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

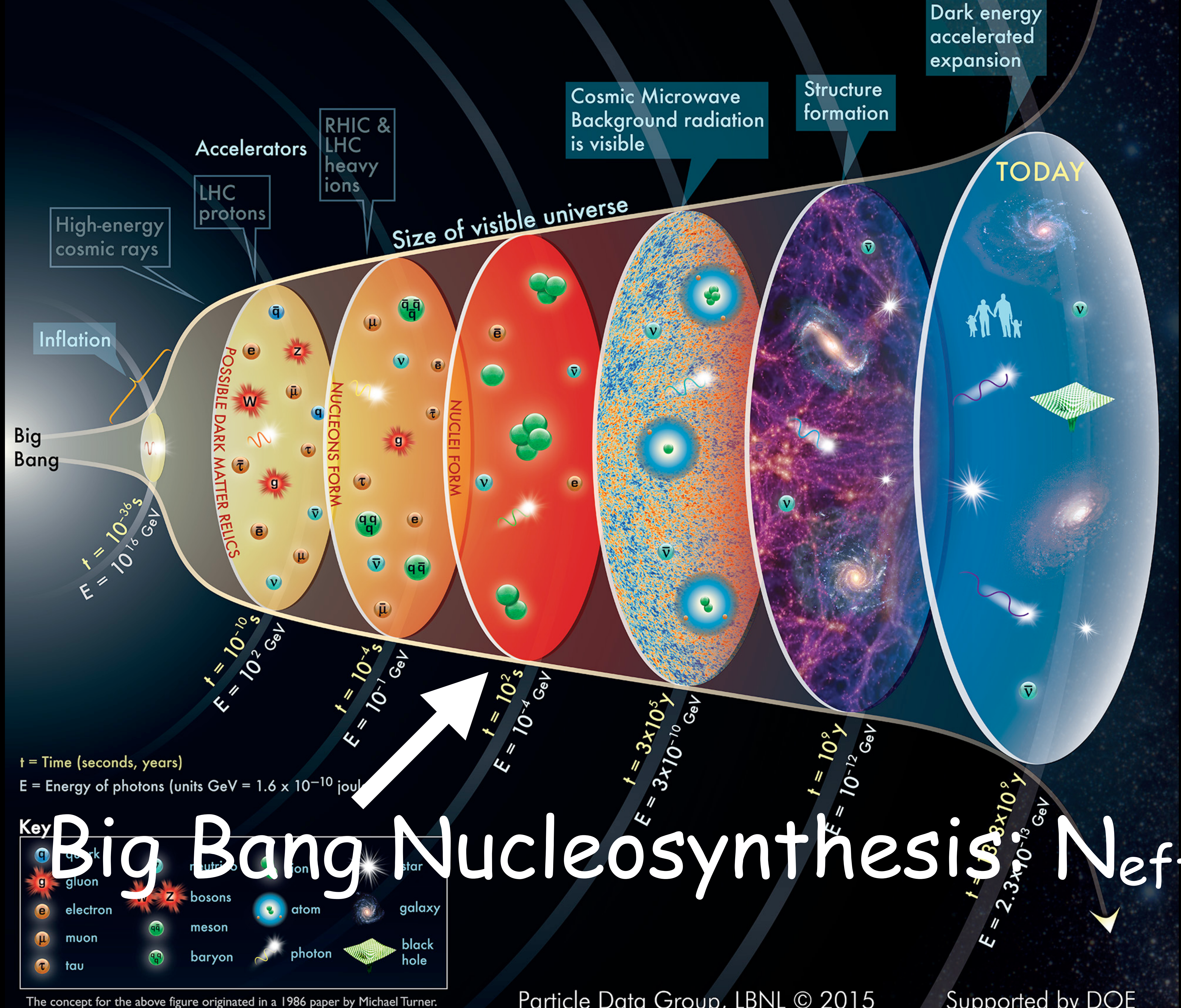
$N_{\mathrm{eff}} < 3.044$ (less neutrinos): Neutrino decays ?

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





Big Bang Nucleosynthesis: N_{eff}



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
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Big Bang Nucleosynthesis: N_{eff}

BBN theory predicts the abundances of D, ^{3}He, ^{4}He and ^{7}Li which are fixed by t$\simeq$180 s.

They are observed at late times: low metallicity sites with little evolution are "ideal".

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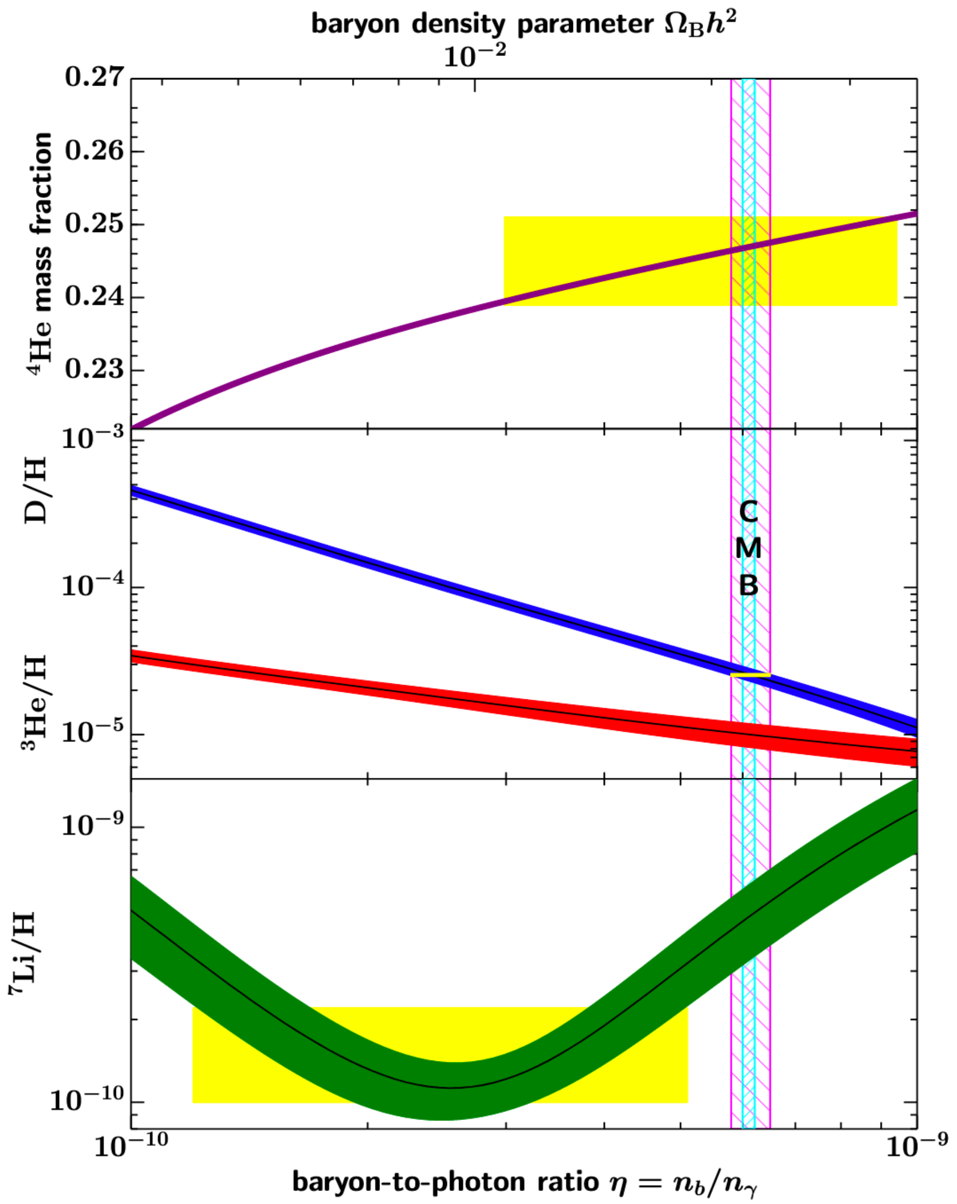


Figure 24.1: The primordial abundances of ^{4}He, D, ^{3}He, and ^{7}Li as predicted by the standard model of Big-Bang nucleosynthesis — the bands show the 95% CL range [47]. Boxes indicate the observed light element abundances. The narrow vertical band indicates the CMB measure of the cosmic baryon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

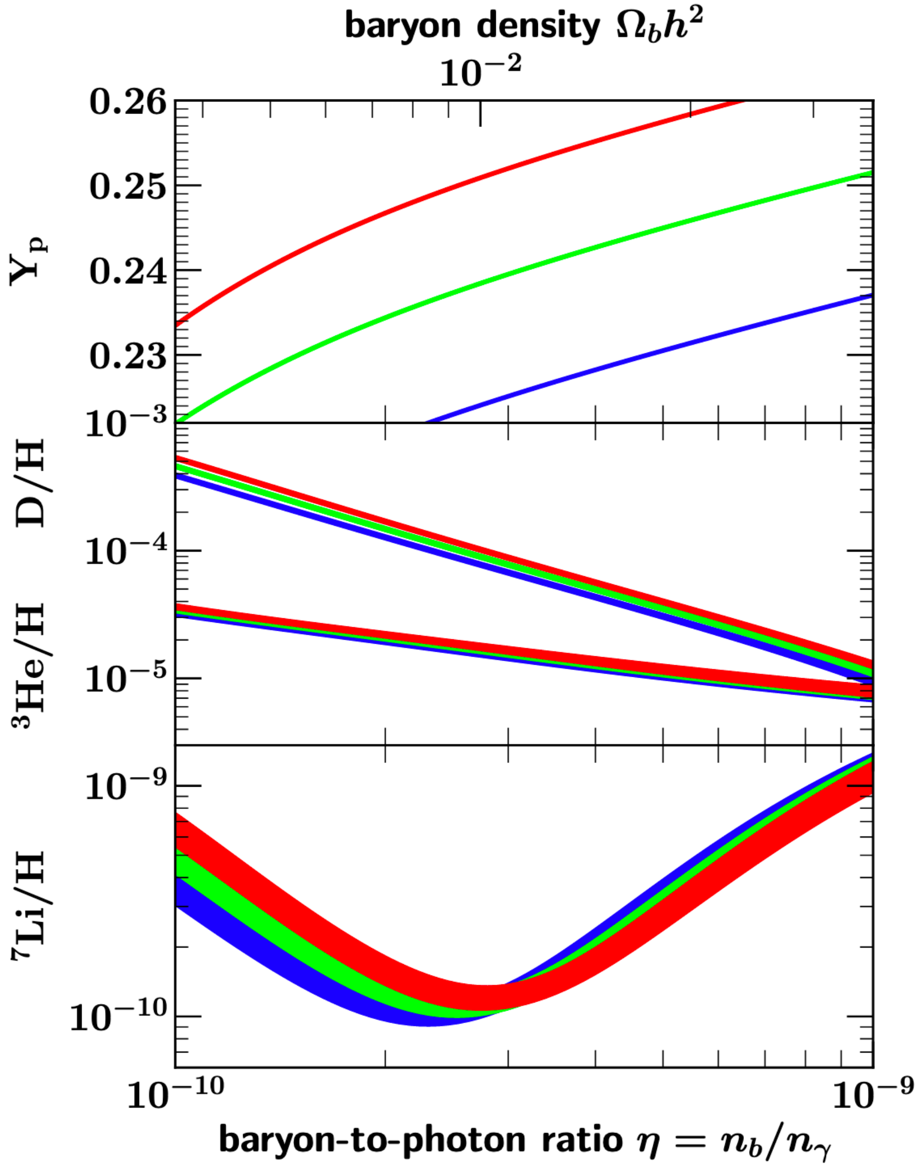
Higher N_{eff}: larger expansion rate & freeze out temperature, MORE HELIUM 4

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

$N_{\rm eff} = 2$

$N_{\rm eff} = 3$

$N_{\rm eff} = 4$



Fields, Olive, Yeh & Young JCAP '20

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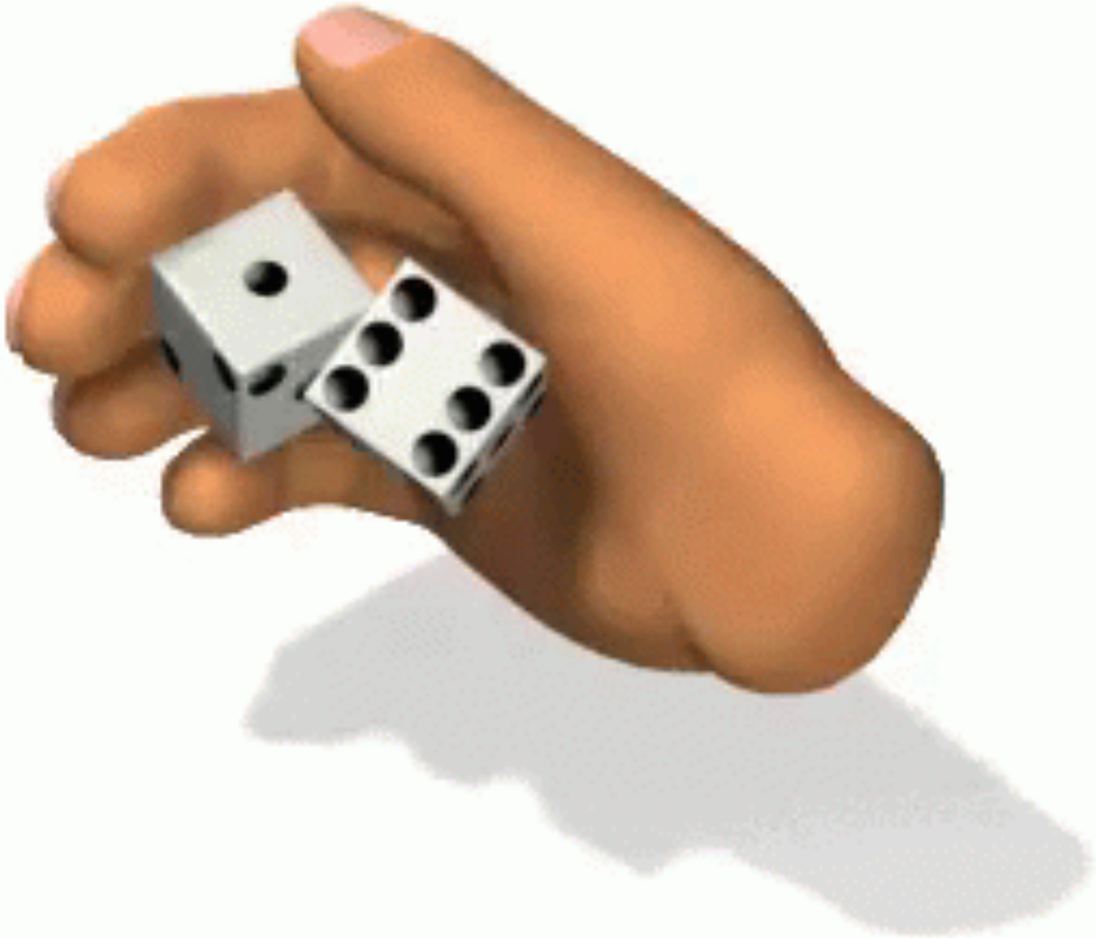
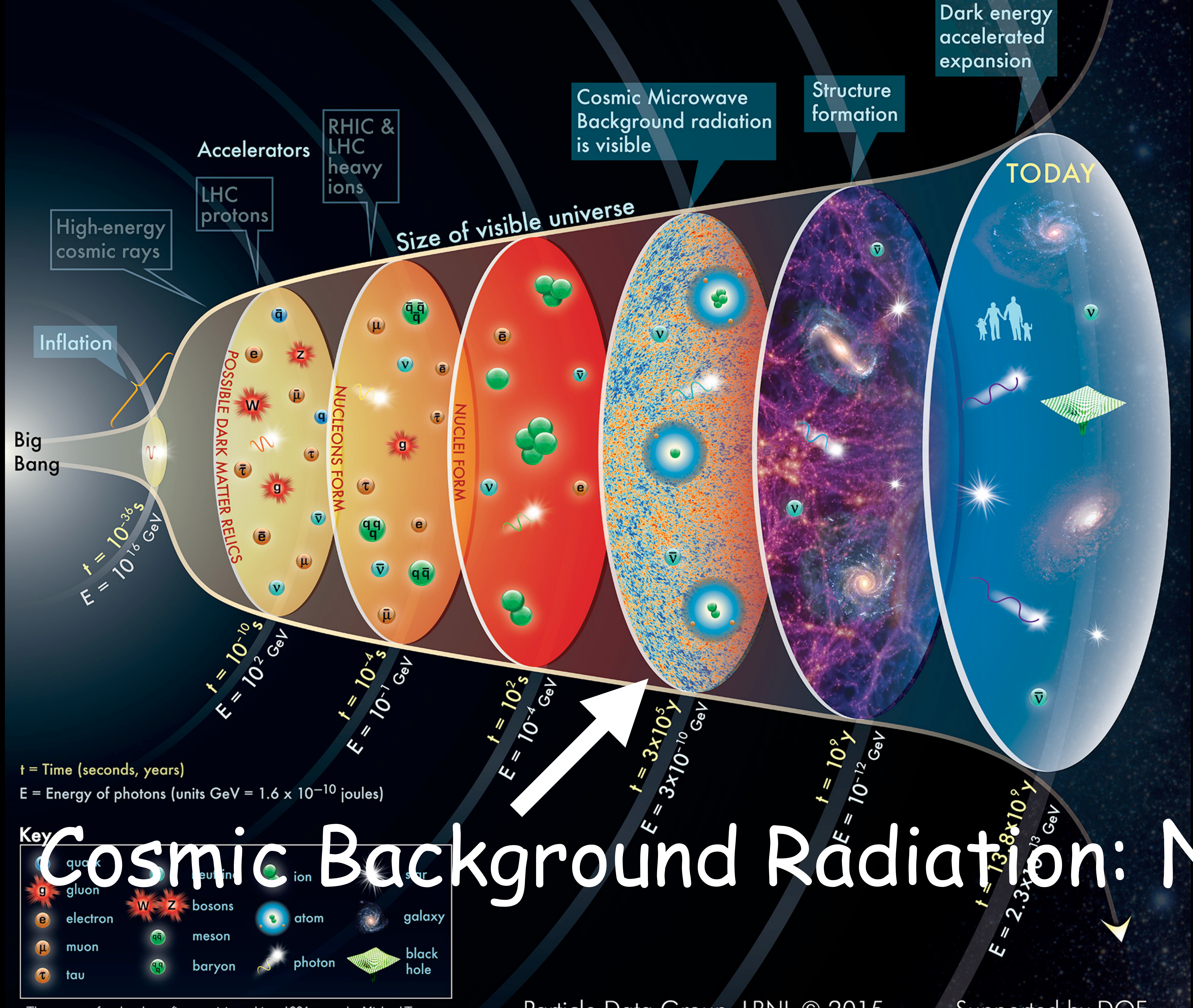


Cosmic Background Radiation: N_{eff}



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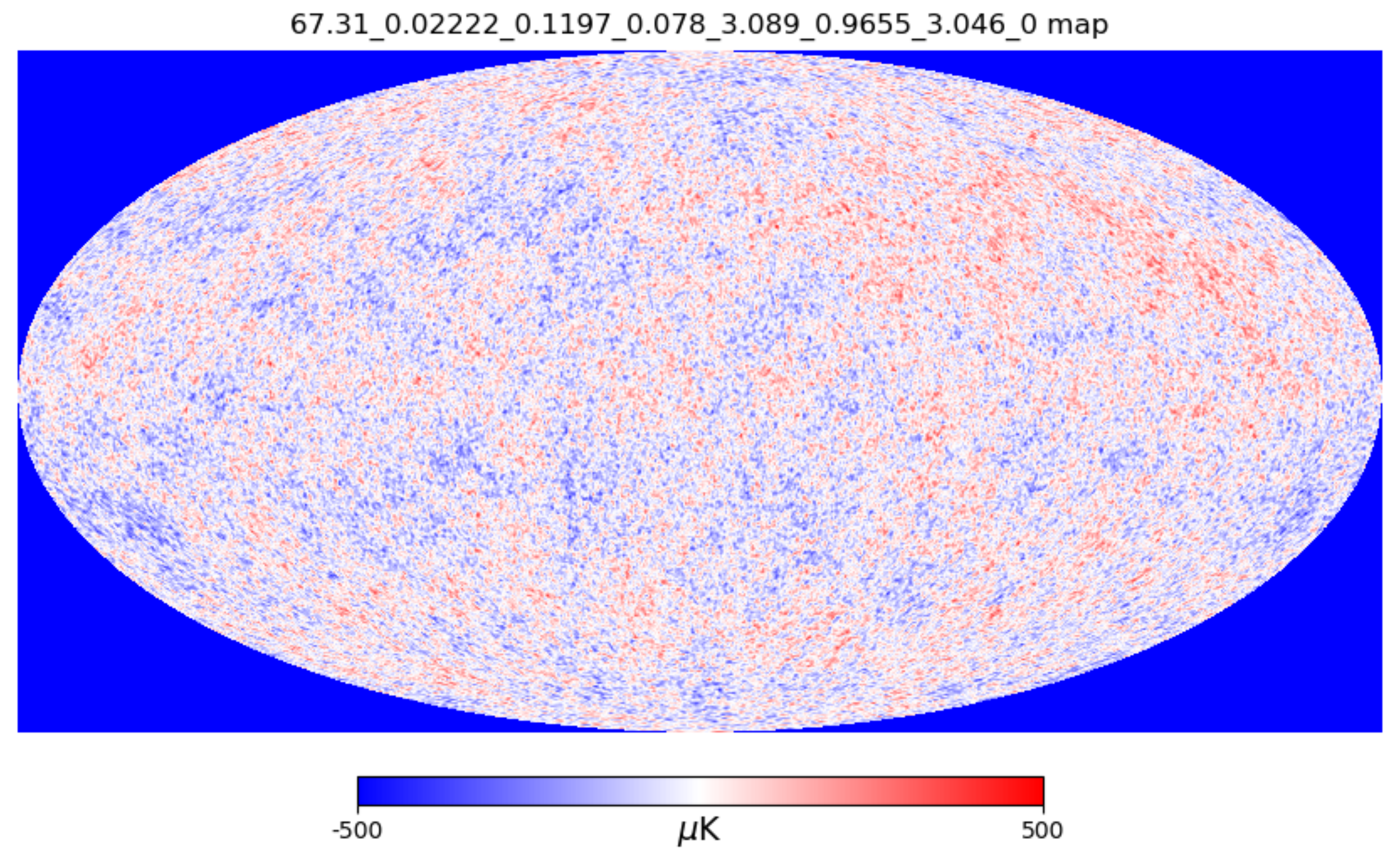
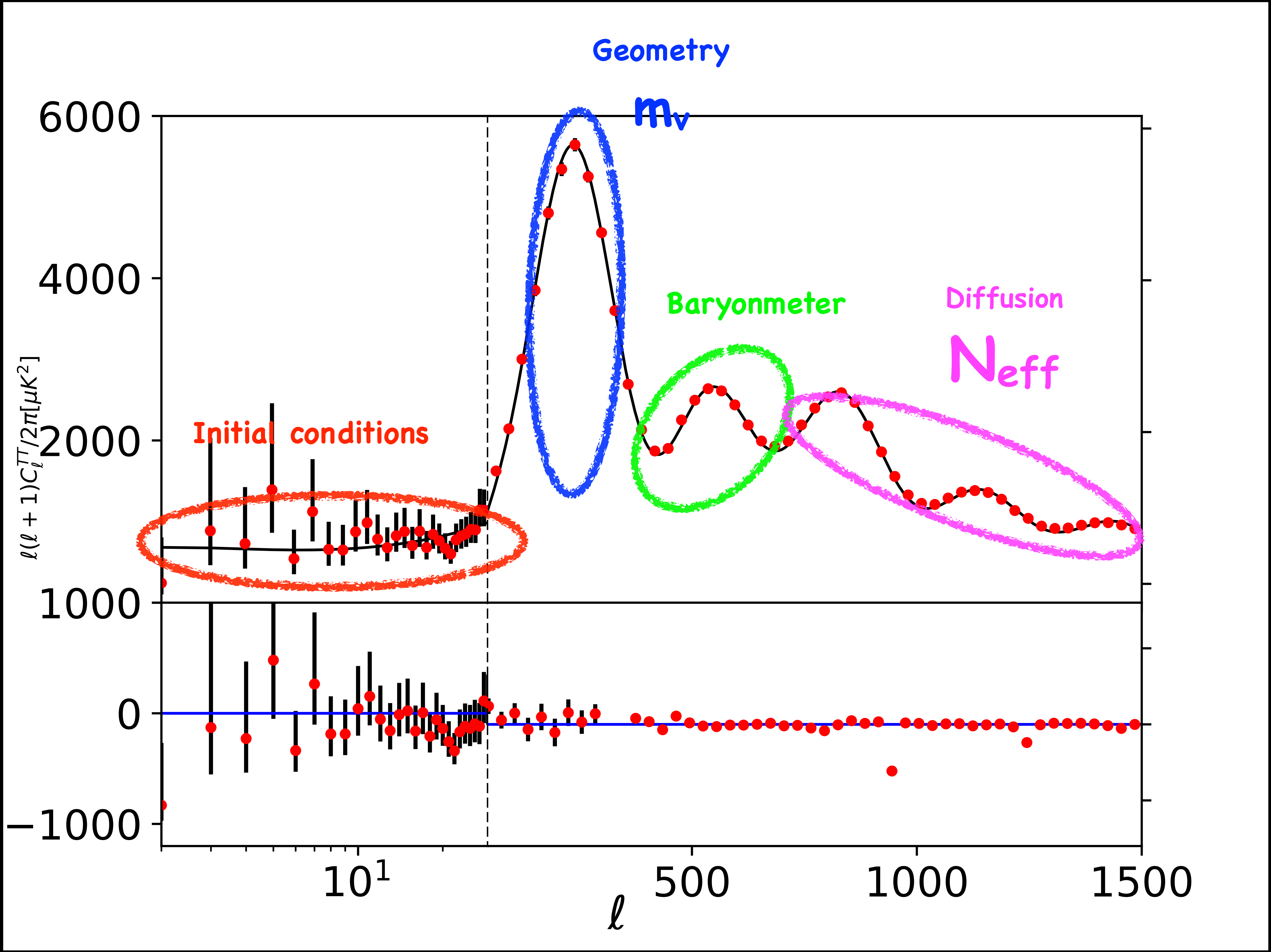
Also known as "photon decoupling", as photons started freely travel through the universe without interacting with matter and the CMB is "frozen"

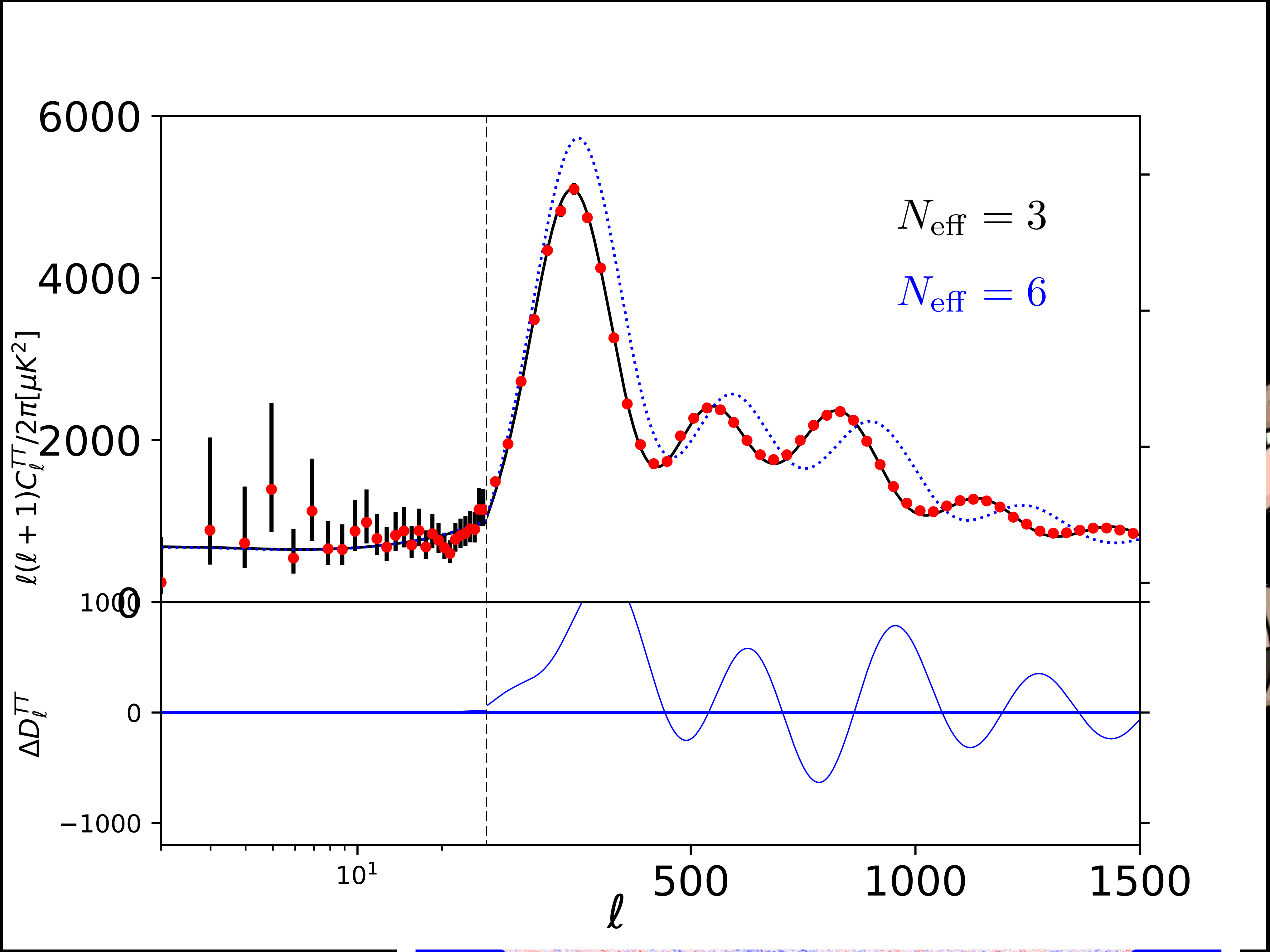
CMB: N_{eff}

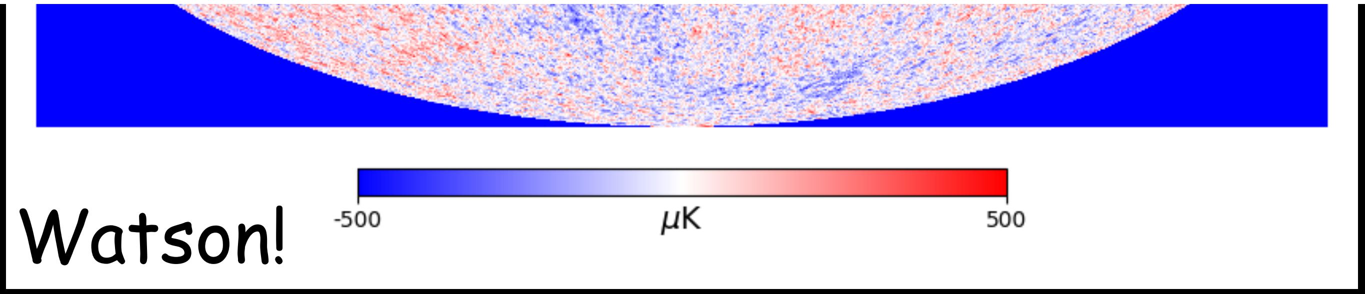


CMB: a lot to learn about….



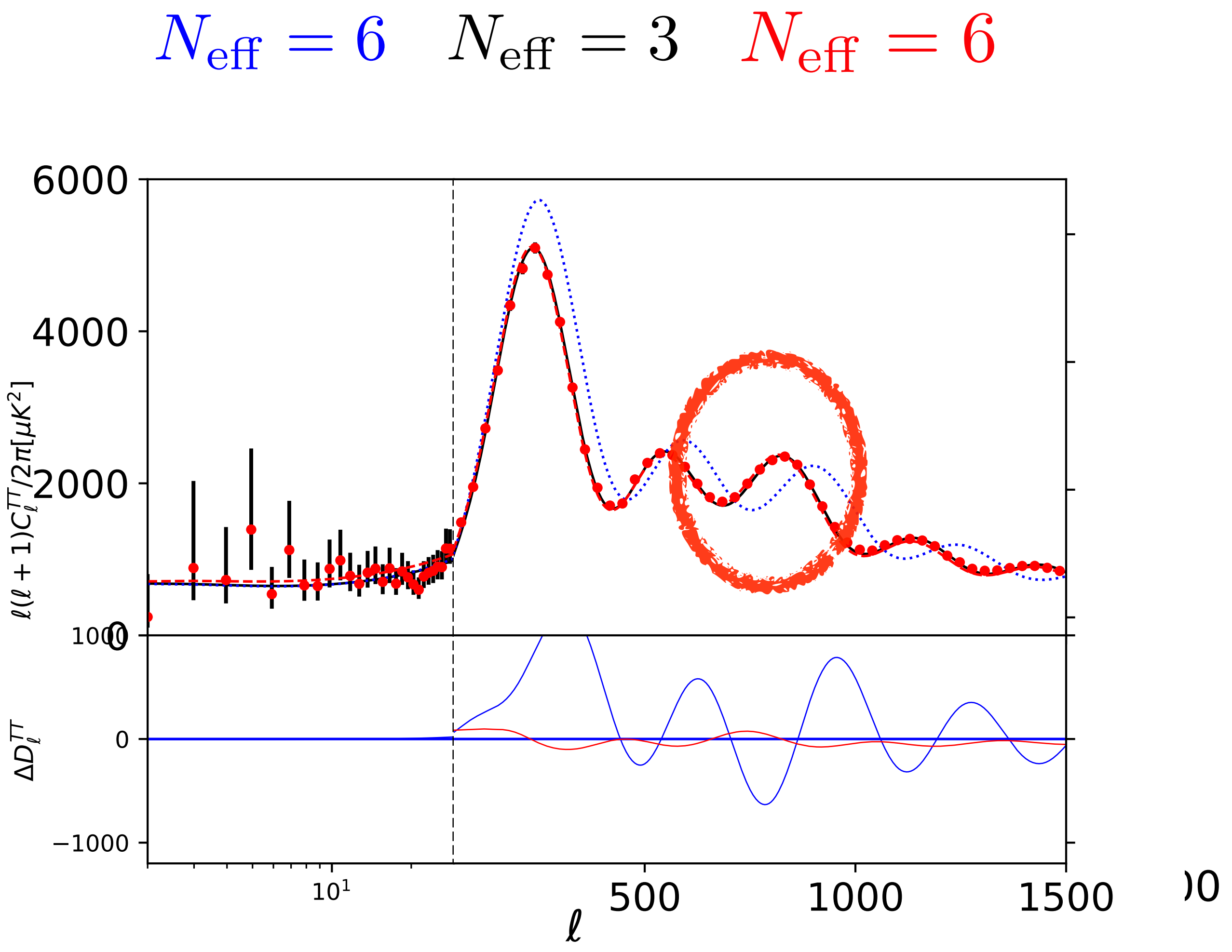
CMB: N_{eff}





Elementary, my dear Watson!

CMB: $N_{\rm eff}$

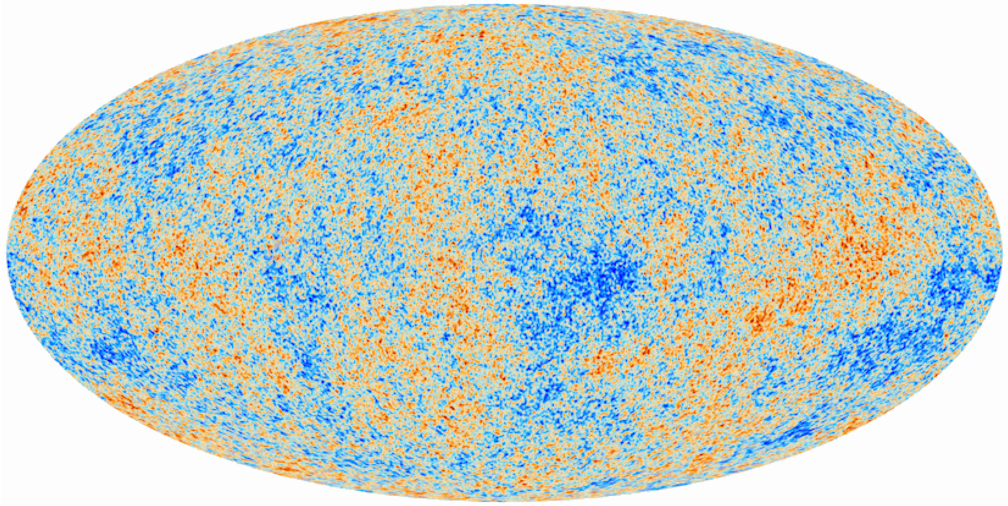


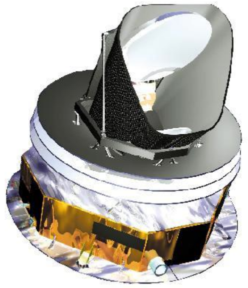
$$(\omega_b, \omega_m, h, A_s, n_s, \tau, N_{\rm eff})$$

Warning!

It is ~~elementary~~, Sherlock Holmes!

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



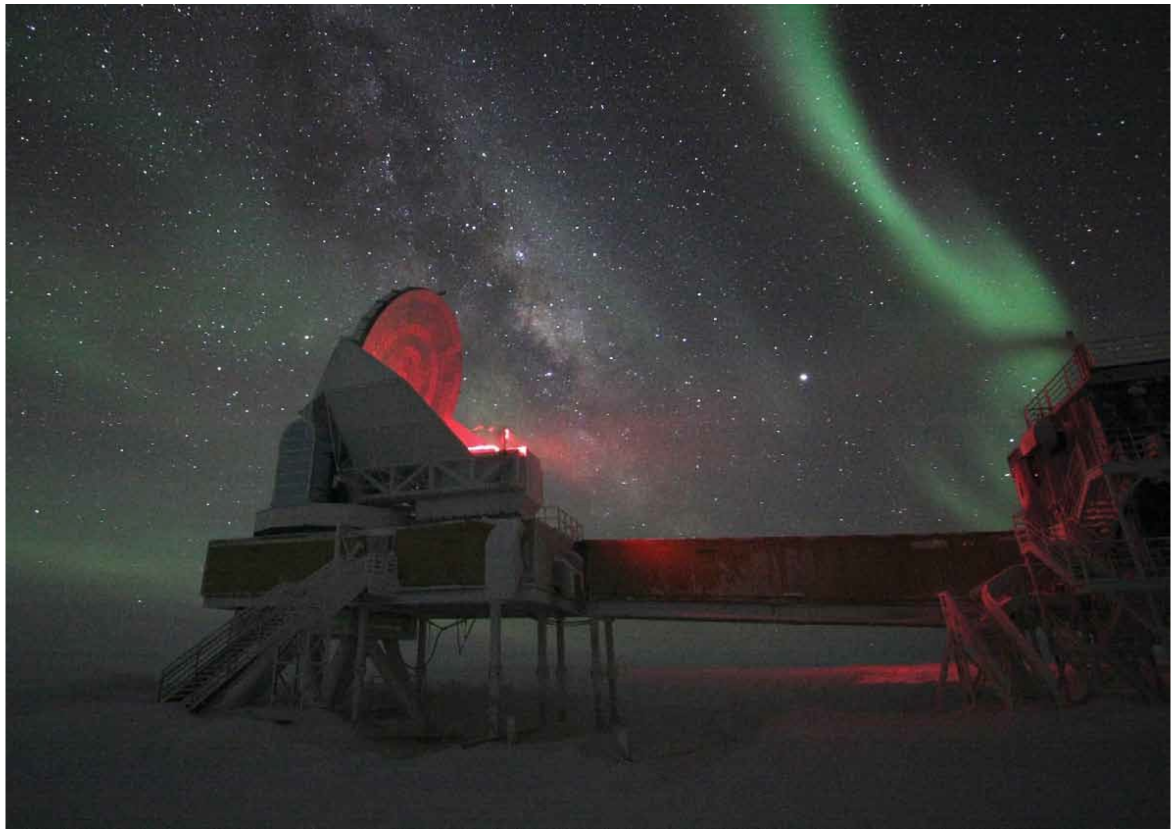


Neutrinos are free-streaming particles propagating at the speed of light, faster than the sound speed in the photon fluid, suppressing the oscillation amplitude of CMB modes that entered the horizon in the radiation epoch.

CMB: N_{eff}

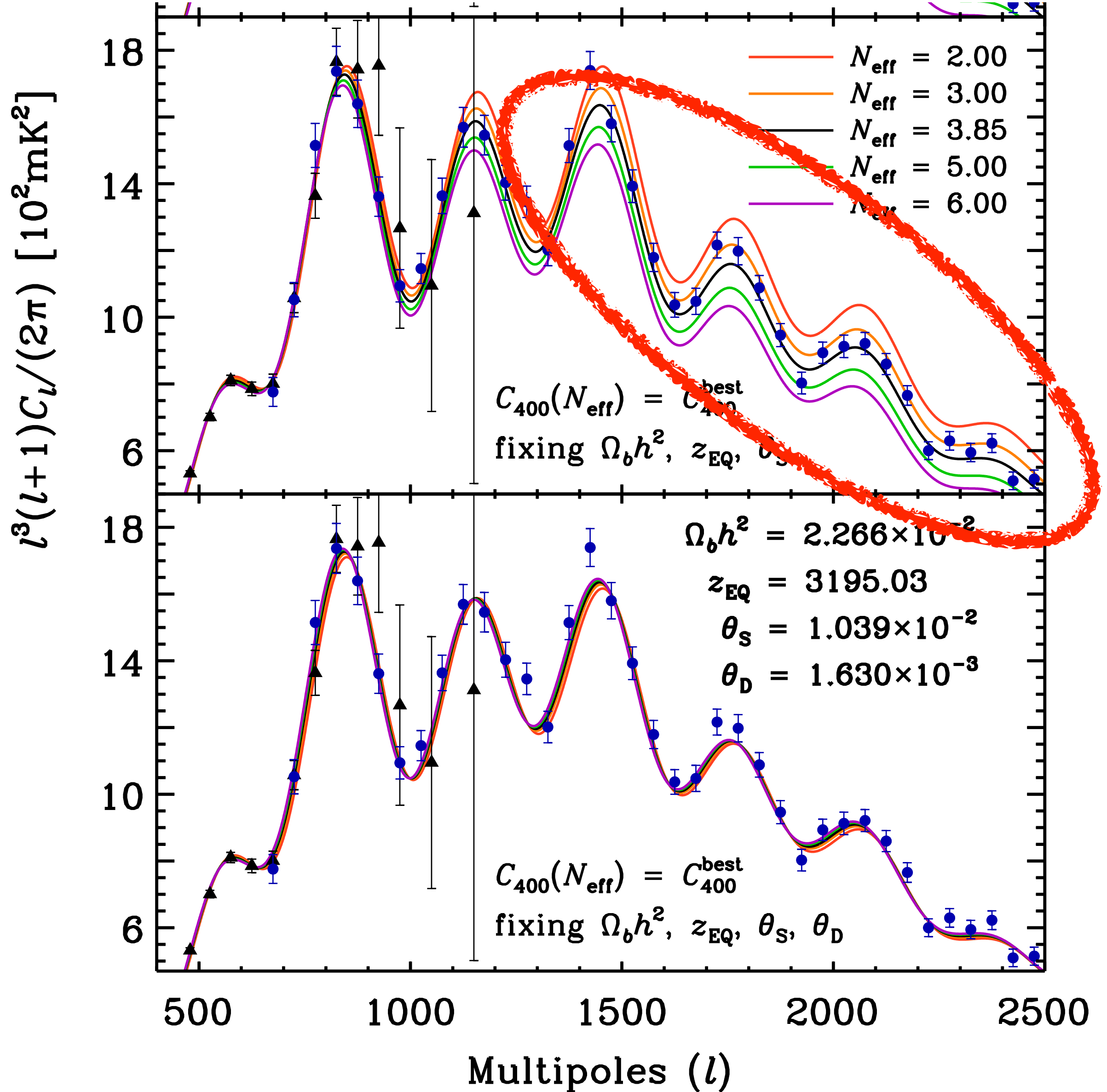
@Cosmic Microwave Background in the damping tail, measured by SPT, ACT & Planck:

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}

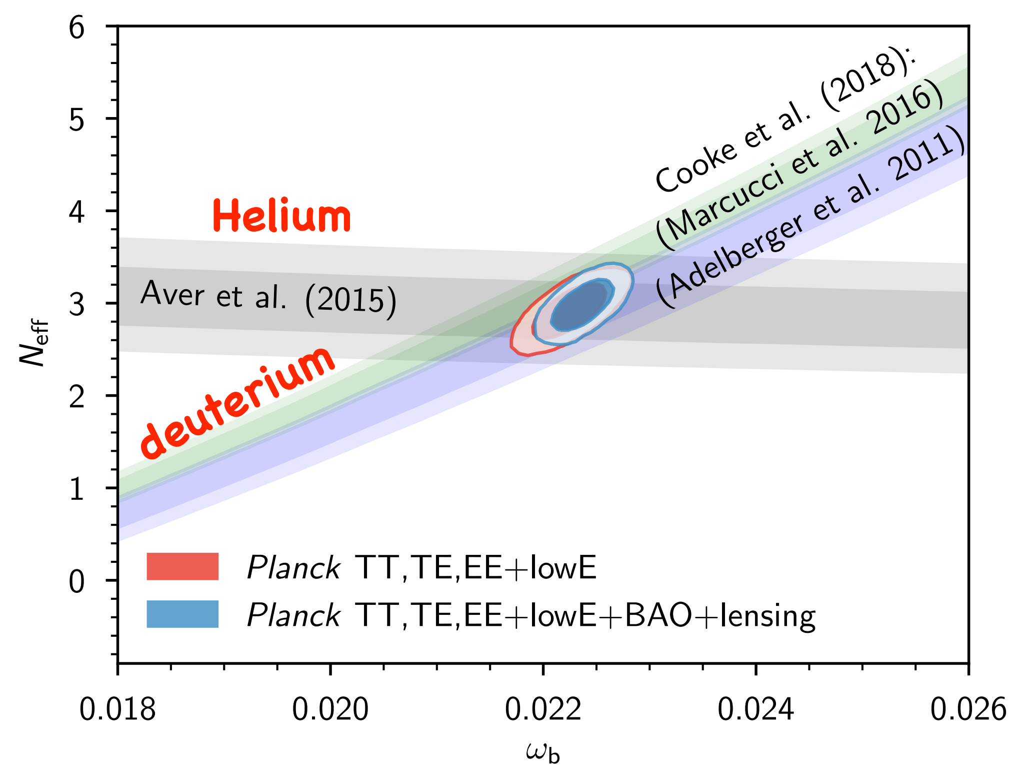
- **Planck 2018 CMB temperature polarization and lensing potential data:**

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

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

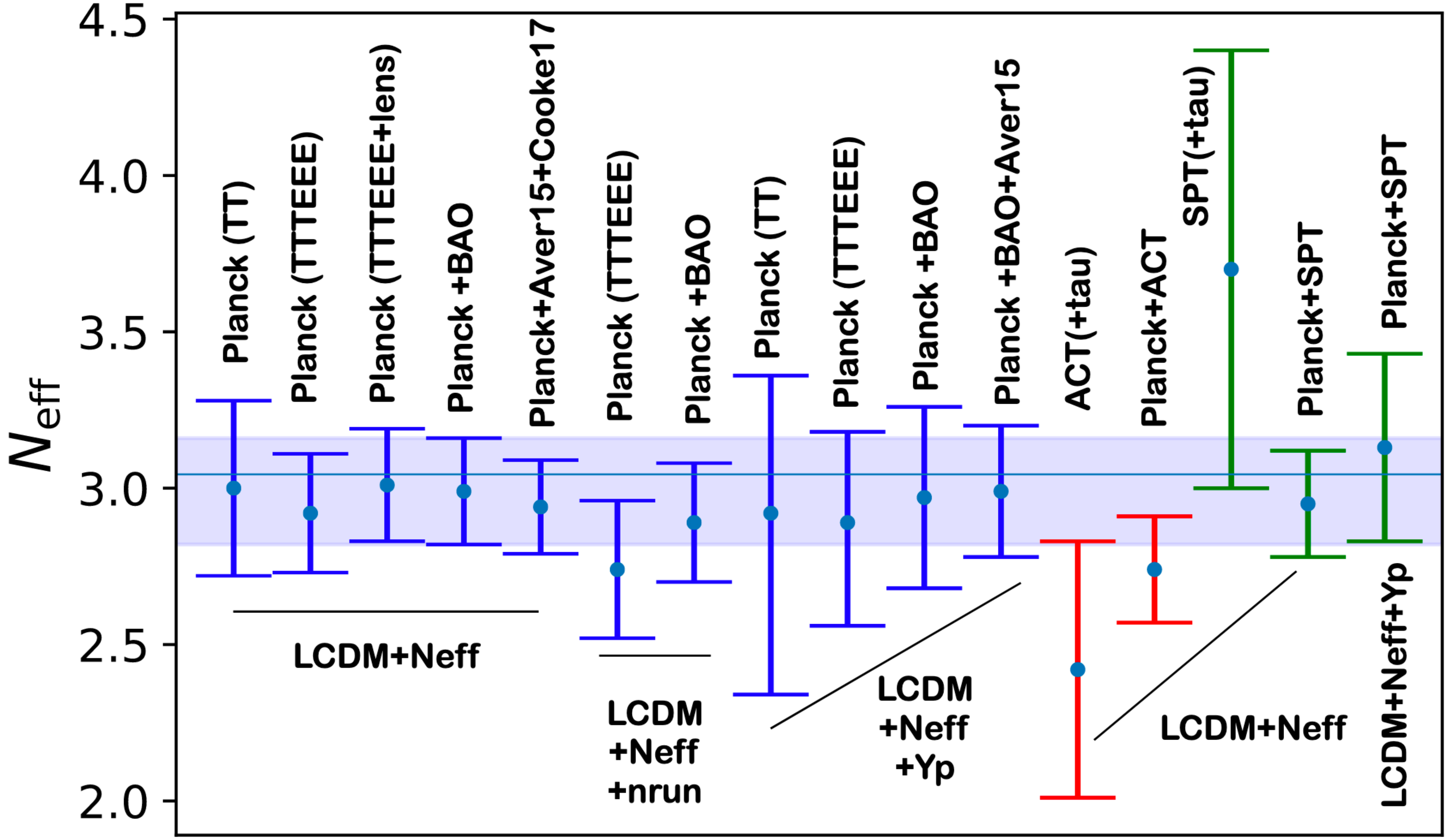
$$N_{\mathrm{eff}} = 2.99^{+0.34}_{-0.33}\ 95\%\mathrm{CL}$$

- **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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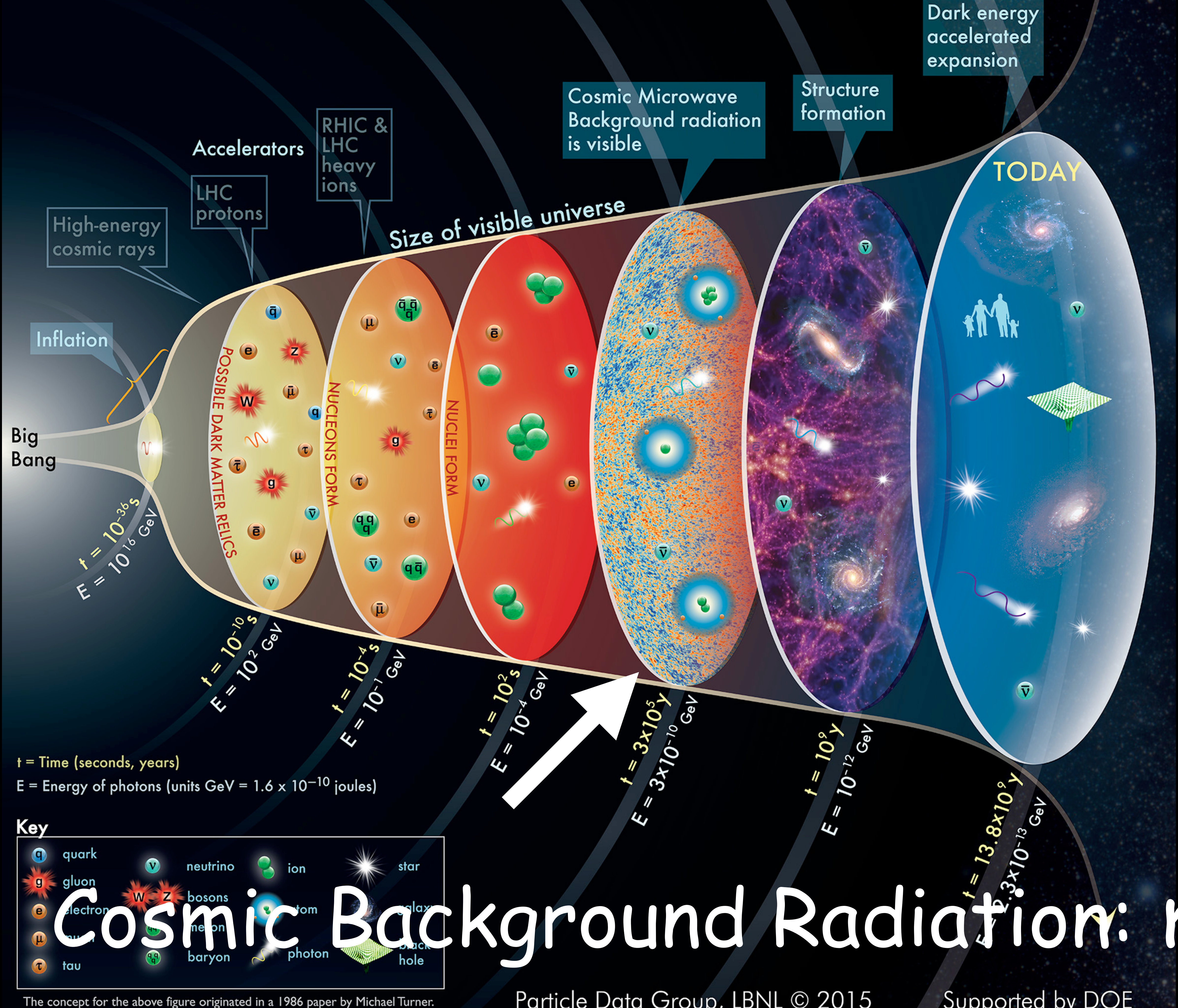
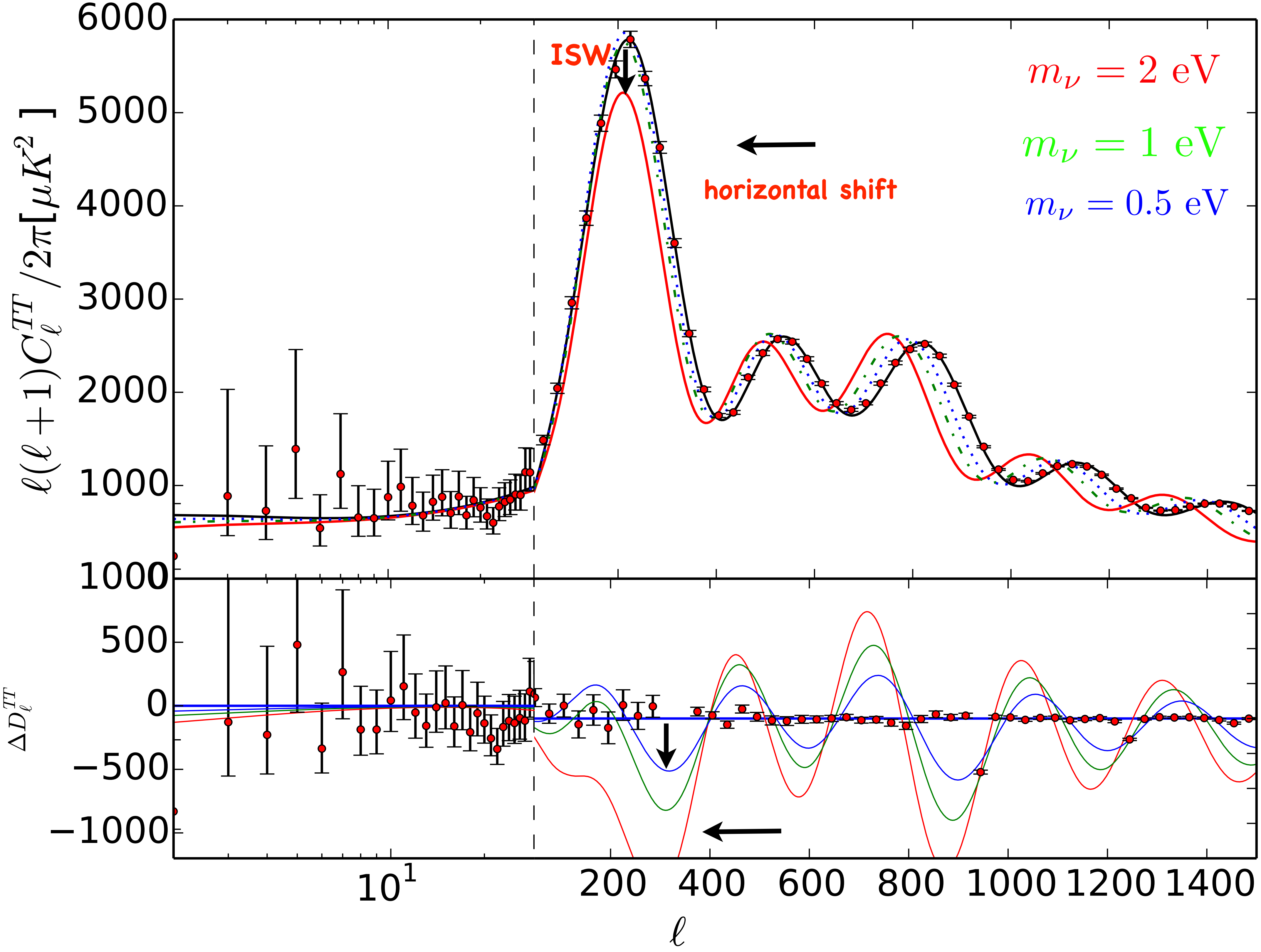


Cosmic Background Radiation: m_ν

CMB: $\sum m_\nu$

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

Shift in the angular position of the peaks.



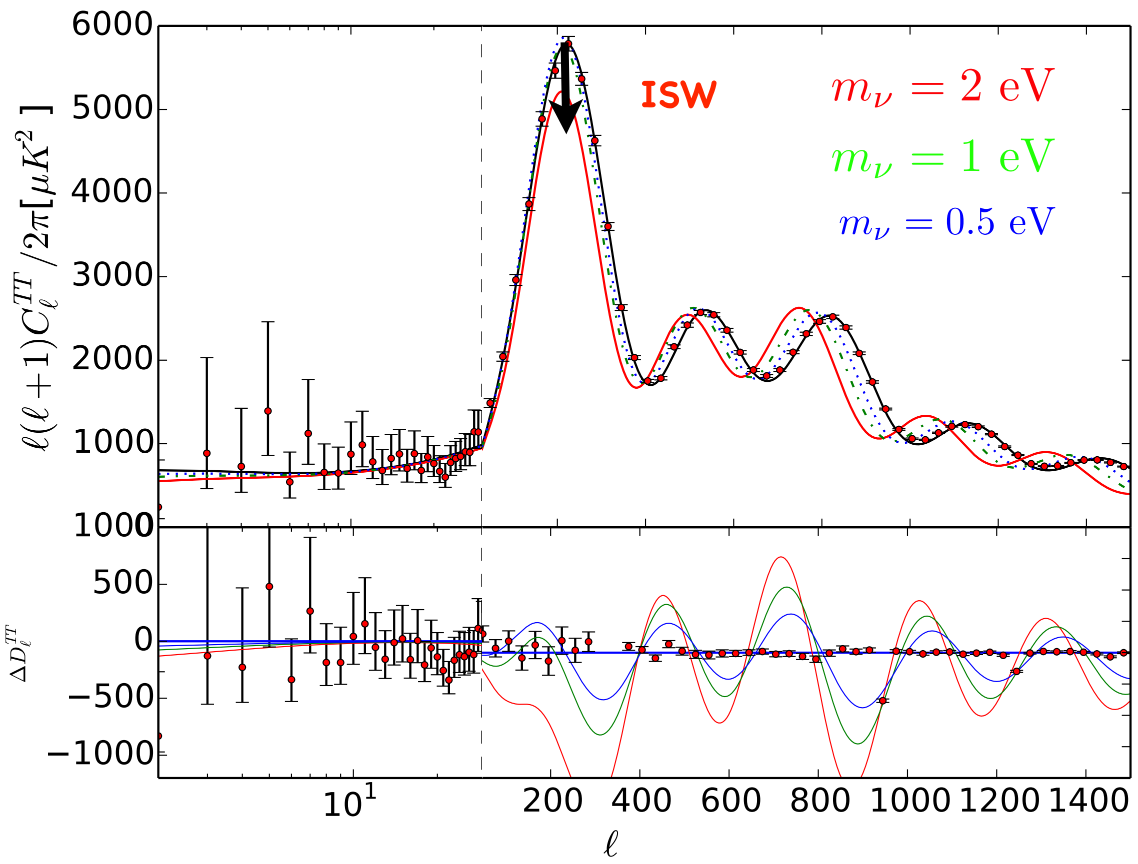
CMB: $\sum m_\nu$

@ CMB: Early Integrated Sachs Wolfe effect (ISW)

$$\Theta(\hat{n}) = \frac{\delta T}{T}(\hat{n}) \simeq \Theta_0 + \Psi + \hat{n}(\hat{v}_e - v) + \int \dot{\Psi} + \dot{\Phi}\, d\eta$$

In matter domination, the gravitational potential is constant: NO ISW effect!

The transition from the relativistic to the non relativistic neutrino regime gets imprinted in the decays of the gravitational potentials near the recombination period, contributing to the ISW effect!



This early ISW effect leads to a depletion of:

$$\frac{\Delta C_\ell}{C_\ell} = -(\sum m_\nu / 0.1 \text{ eV})\%$$

on multipoles:

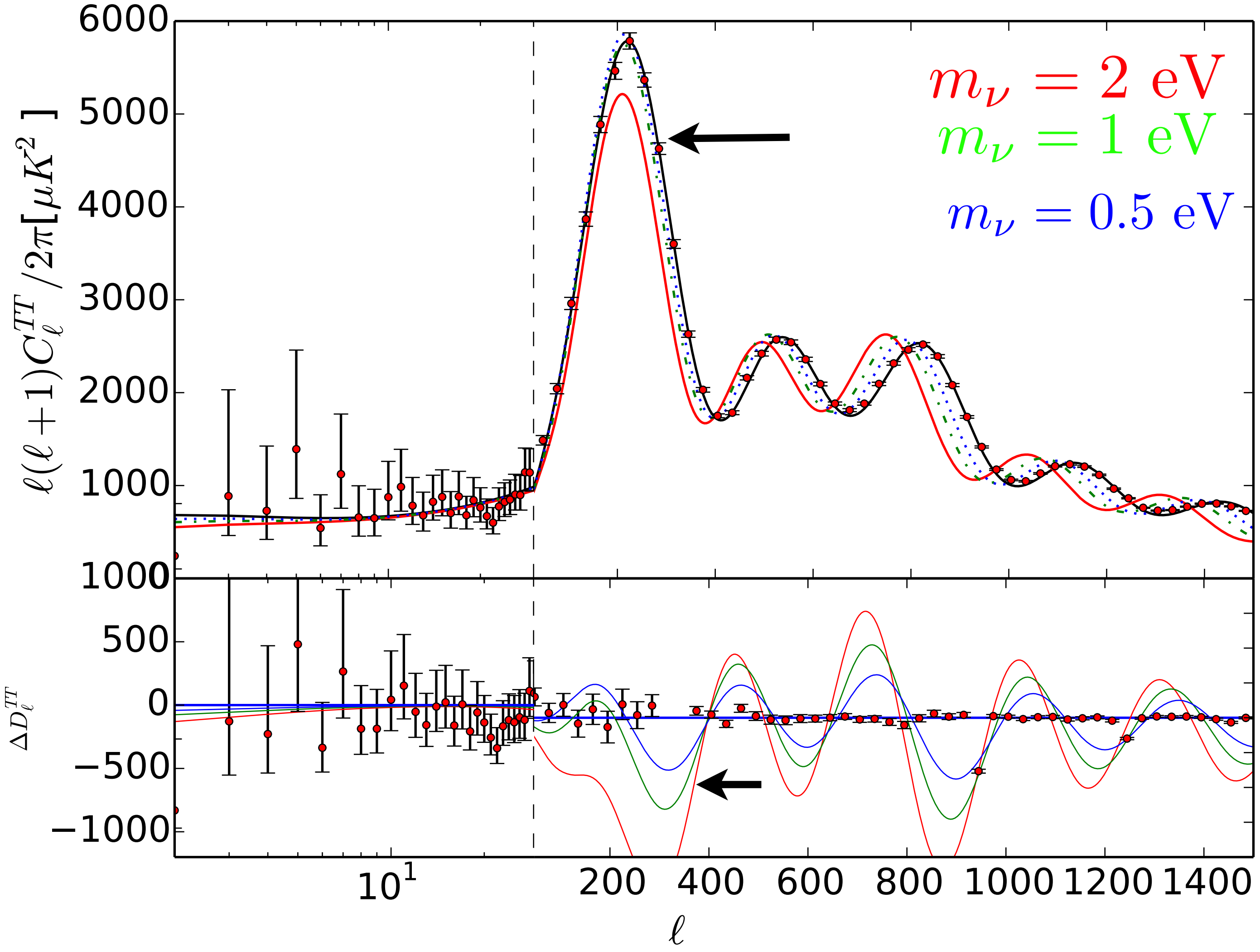
$$20 < \ell < 200$$

(Lesgourgues & Pastor, Phys.Rept'06)

CMB: Σm_ν

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

Shift in the angular position of the peaks.



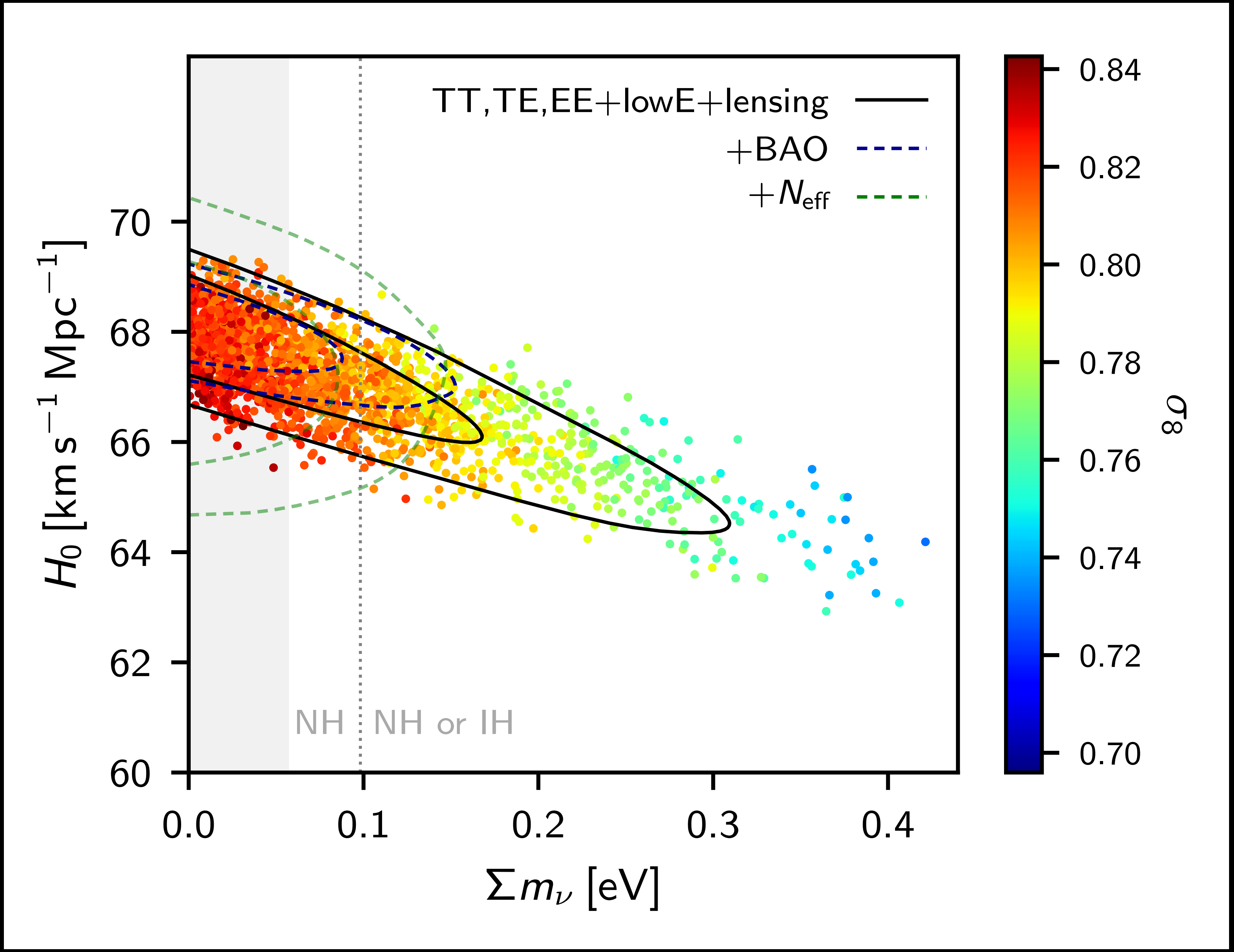
$$\theta_s = \frac{r_s}{D_A}$$

$$r_s = \int_0^{t(z_d)} c_s\,(1+z)dt = \frac{2}{3k_{\rm eq}}\sqrt{\frac{6}{R_{\rm eq}}}\ln\frac{\sqrt{1+R_d}+\sqrt{R_d+R_{\rm eq}}}{1+\sqrt{R_{\rm eq}}}$$

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

The higher the neutrino mass, the lower the angular diameter distance. Peaks shift to lower multipoles. But this effect can be compensated with a lower Hubble constant:

Strong degeneracy between Σm_ν and the Hubble constant H_0!



Planck Coll. A&A'20

Strong degeneracy between Σm_ν and the Hubble constant H_0!

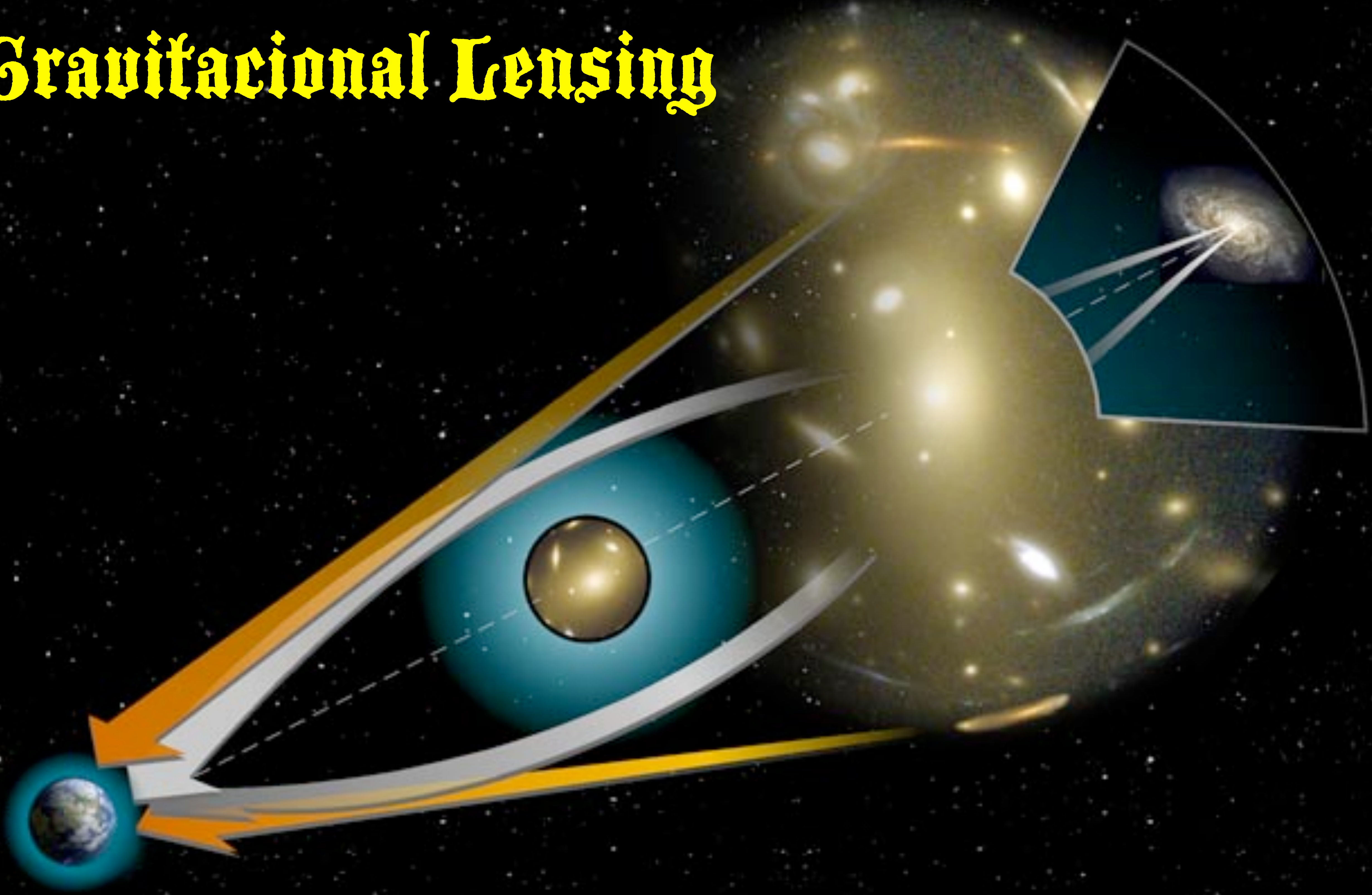
CMB: $\sum m_\nu$

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

Shift in the angular position of the peaks.

CANCELLED

Gravitacional Lensing

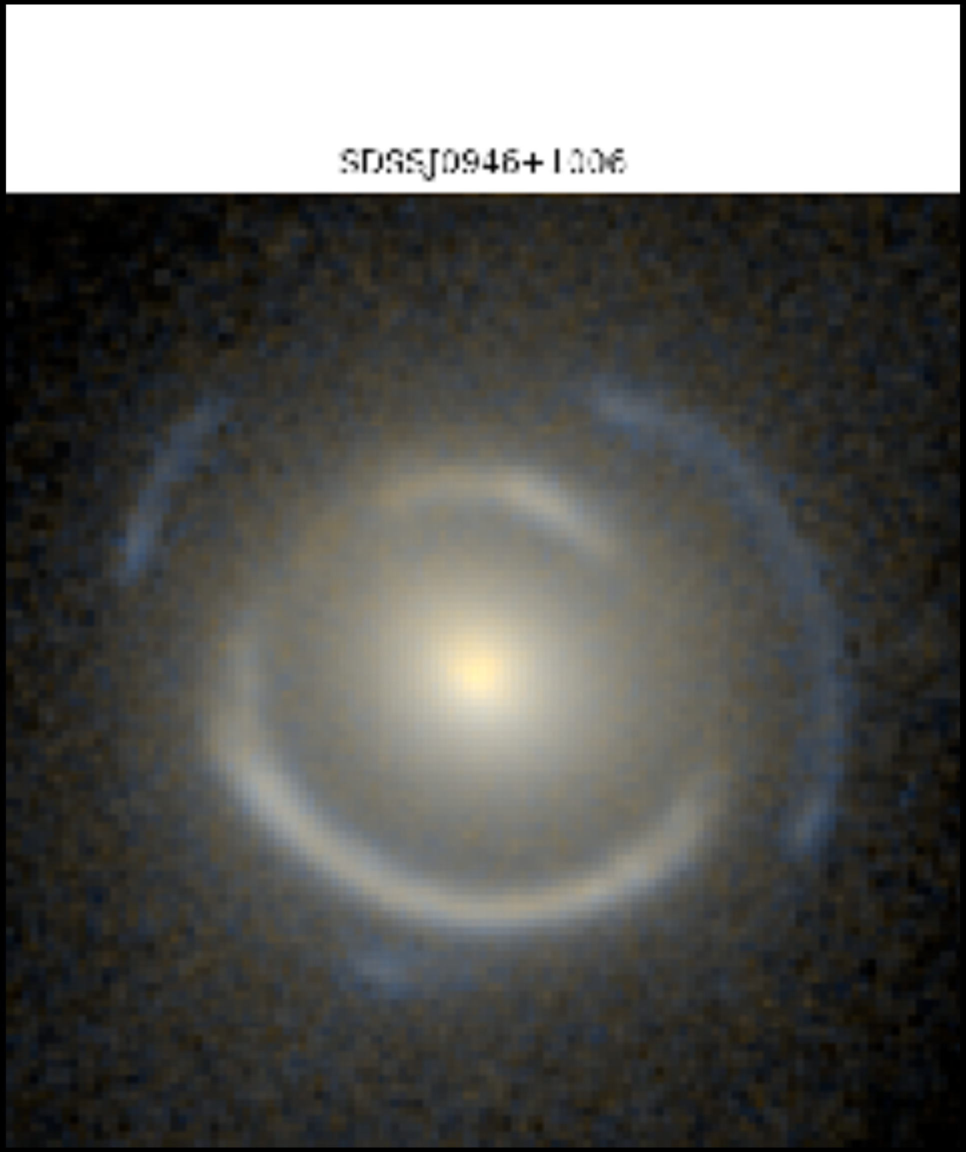


Einstein's relativity predicts that the presence of a massive body will curve space time, distorting the light trajectory. The shape of the background objects will change/ multiplied by the presence of intervening galaxies.

Einstein rings: Perfect alignment: Syzygy!

This movie shows a spiral galaxy acting as a lense of a background quasar (Quasi-stellar radio source) moving behind the galaxy. When the alignment source-lens-observer is perfect, we see the formation of the Einstein ring!

Gravitacional Lensing



Double Einstein ring! 3 perfectly aligned galaxies (probably less than 100 cases in all the universe, and we have seen one!)

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

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

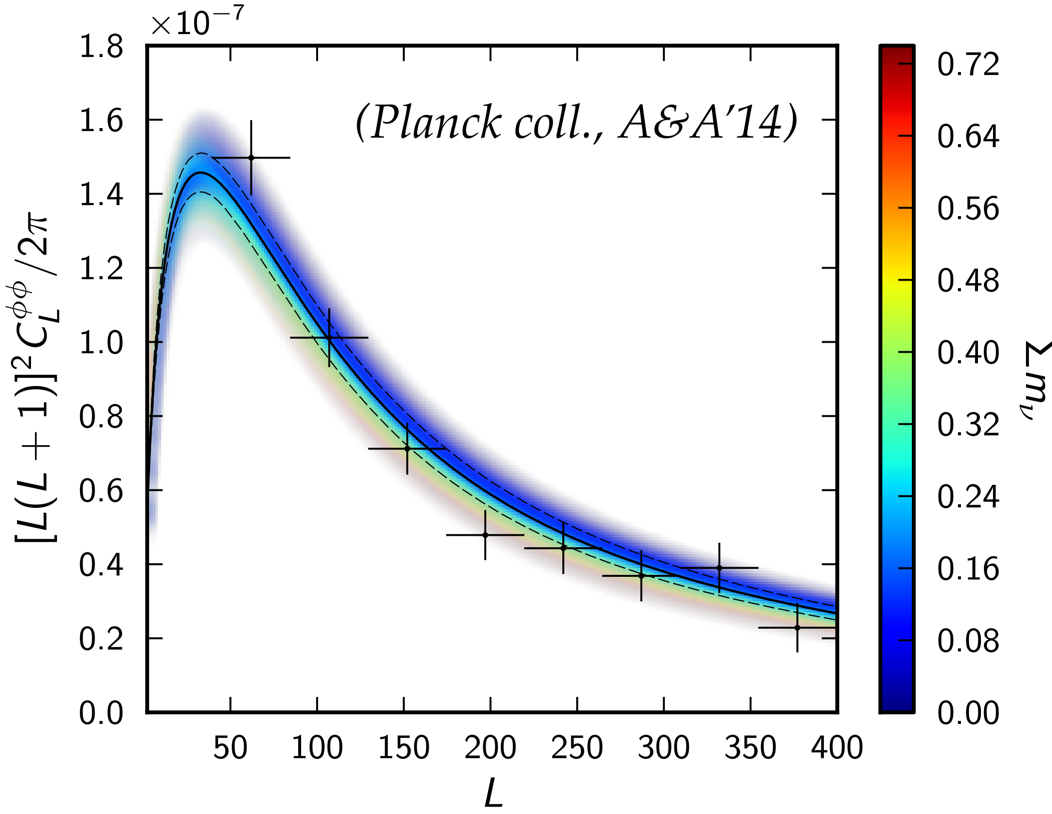
Geometry

Matter distribution

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

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)



(Planck coll., A&A'14)

CMB: $\sum m_\nu$

Planck TTTEEE+lowT+lowE+lensing

Planck Coll. A&A'20

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

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:

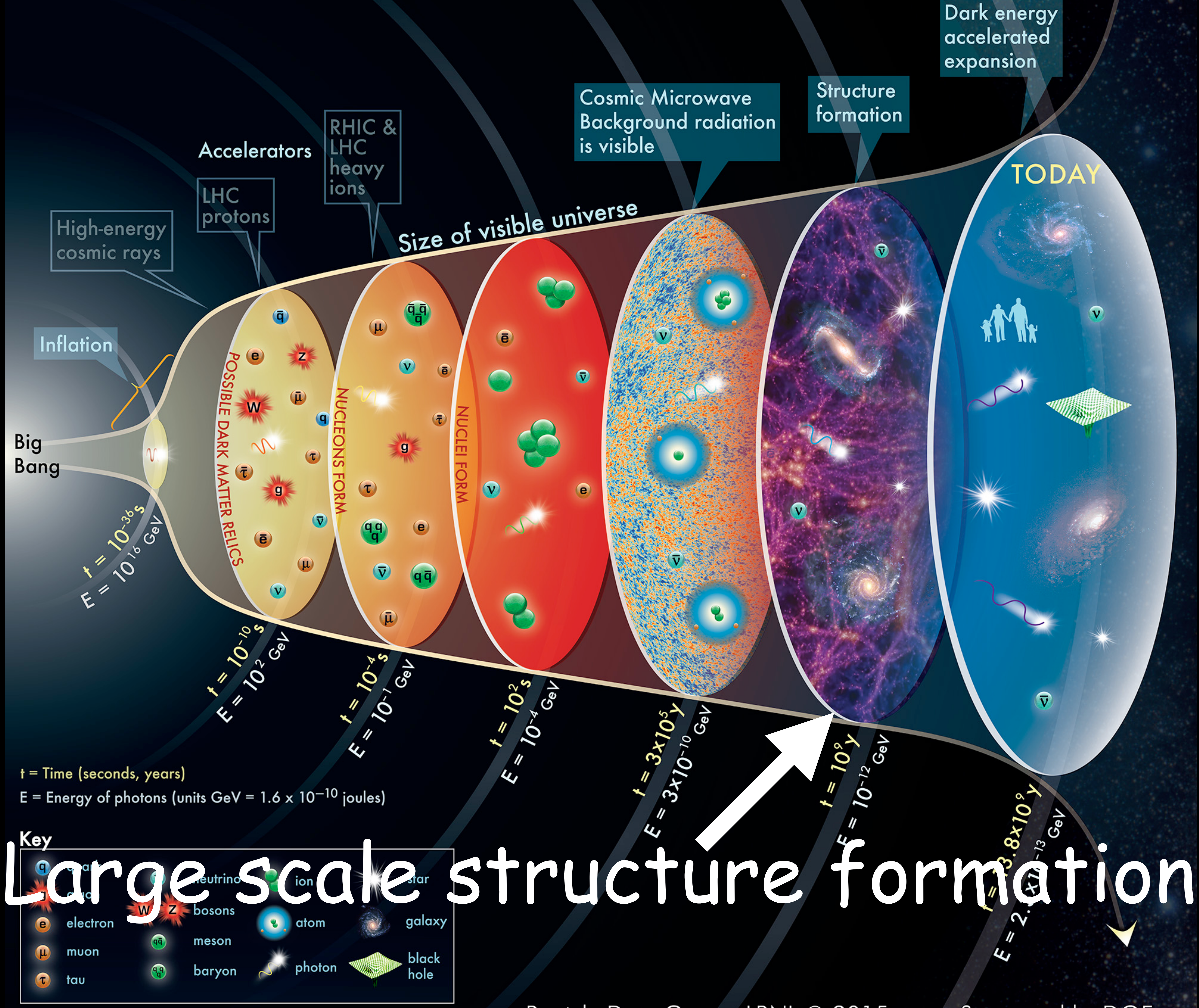
- Number of neutrinos and Big-Bang Nucleosynthesis
- Number of neutrinos and Cosmic Microwave Background Radiation
- Neutrino masses and Cosmic Microwave Background Radiation?
- Neutrino masses and structure formation in the universe?

3. Is anyone cheating? Neutrinos and Tensions

4. Final score:

- Take home messages

Large scale structure formation: m_ν



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

Particle Data Group, LBNL © 2015

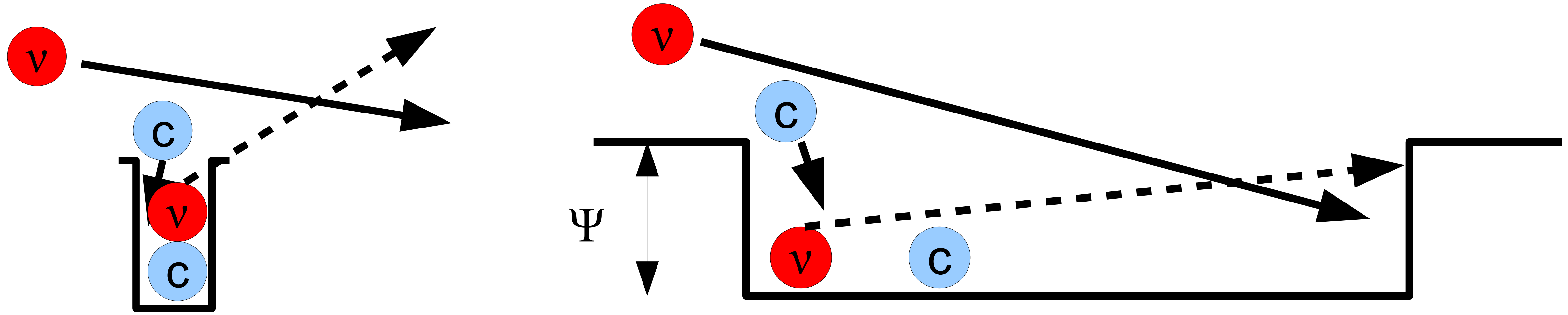
Supported by DOE

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!



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

(From Y. Wong)

Large scale structure: m_ν

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

$$\ddot{\delta} + \overbrace{\boxed{2\frac{\dot{a}}{a}\dot{\delta}}}^{\text{Hubble drag}} - \underbrace{\boxed{c_s^2 k^2 \frac{\delta}{a^2}}}_{\text{Pressure}} = \overbrace{\boxed{4\pi G\rho\delta}}^{\text{Gravity}}$$

Jeans scale:

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

$k>k_J$ no growth can occur

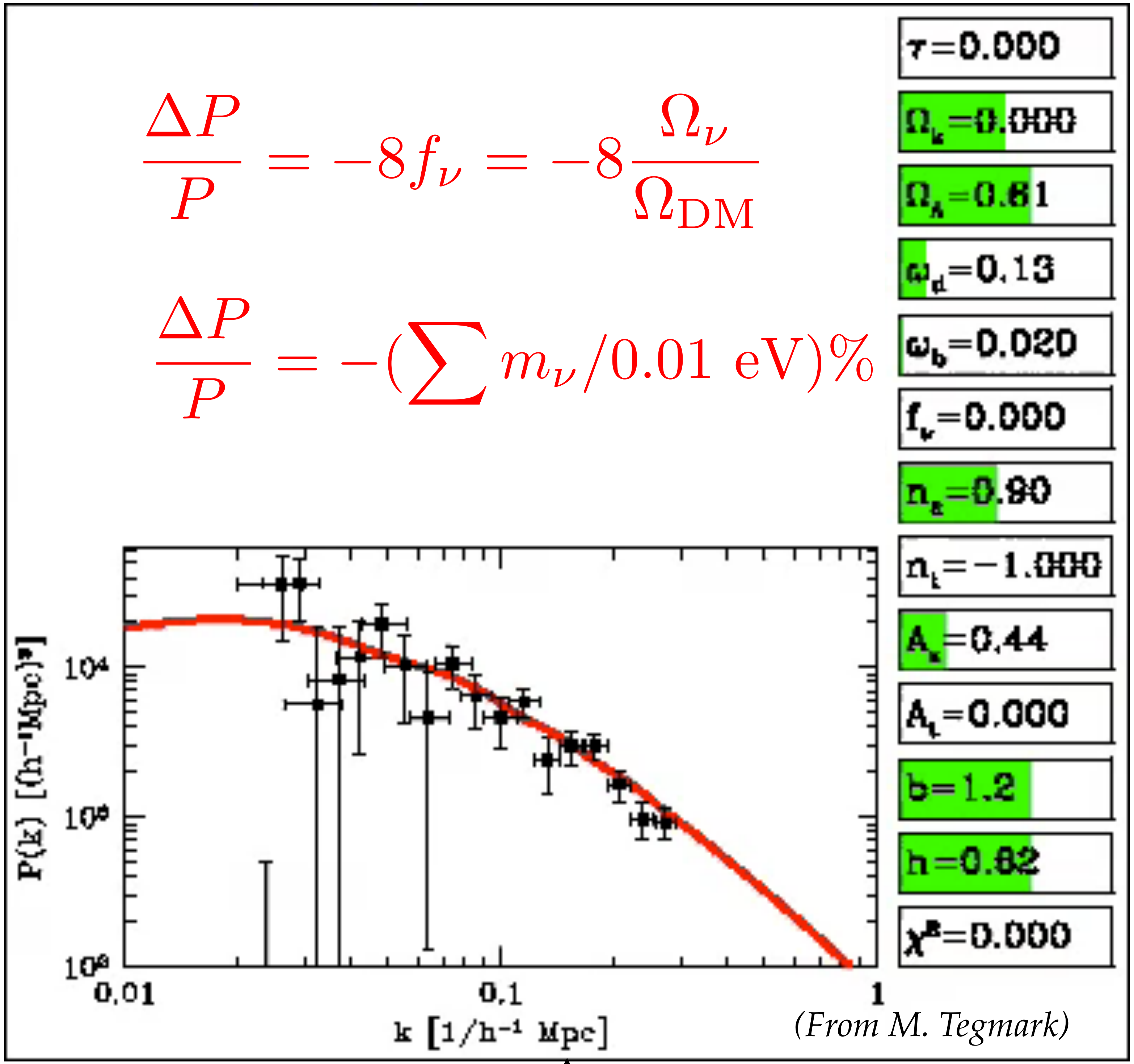
$k<k_J$ density perturbations growth

Neutrino free streaming scale:

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

Large scale structure: m_ν

Matter power spectrum suppression:



$$\frac{\Delta P}{P} = -8 f_\nu = -8 \frac{\Omega_\nu}{\Omega_{\rm DM}}$$

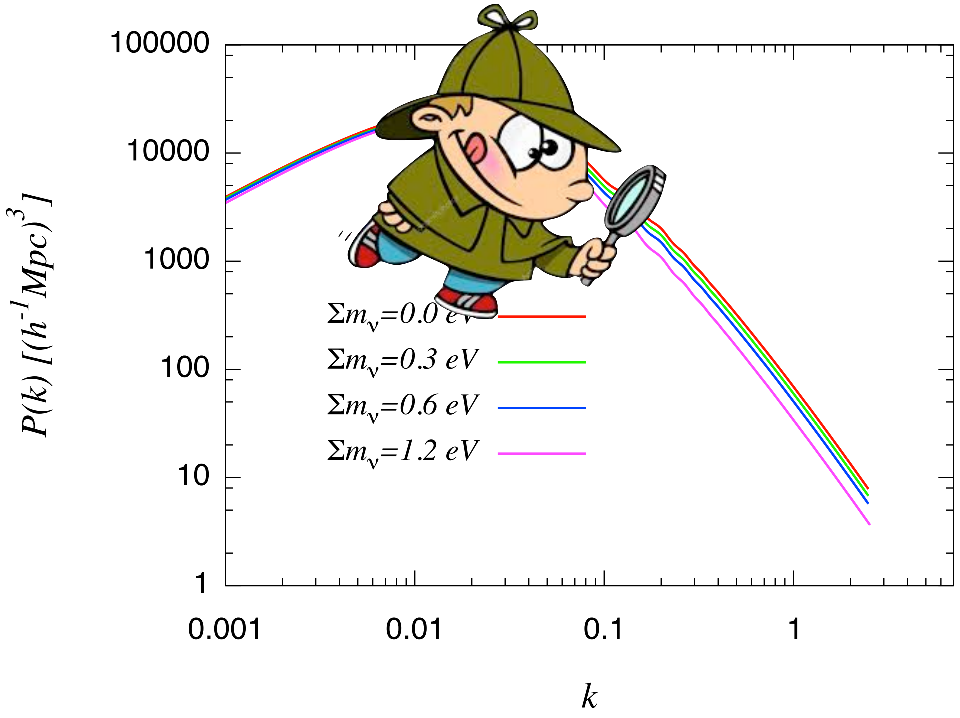
$$\frac{\Delta P}{P} = -(\sum m_\nu / 0.01 \text{ eV})\%$$

(From M. Tegmark)

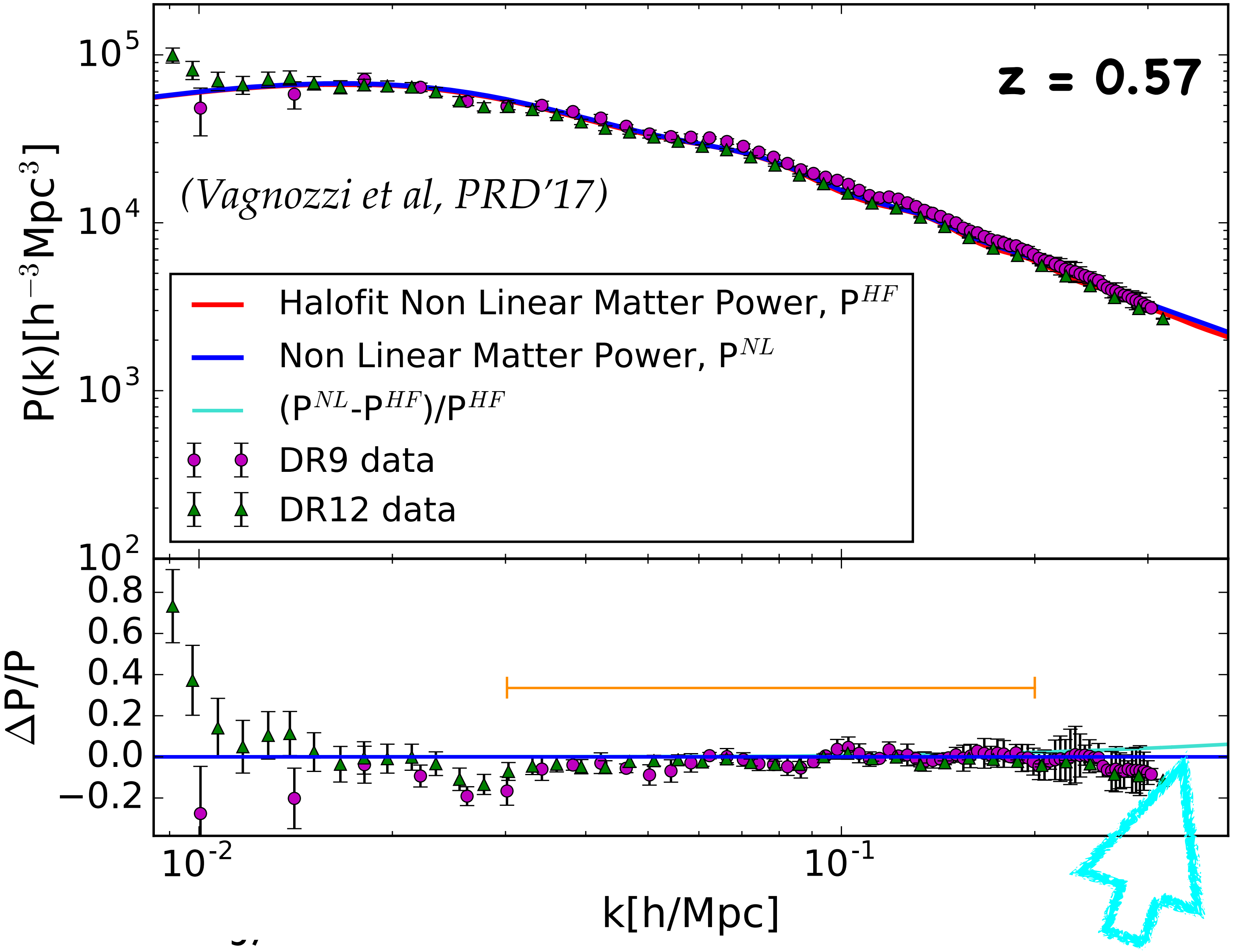
Small scales

Large scale structure: m_ν

@LSS: Caveats, NON-LINEARITIES



Beyond a given scale k_{nl}, linear perturbation theory breaks down!


(Vagnozzi et al, PRD'17)

Large scale structure: m_ν

@LSS: Caveats, BIAS!

$$P_{gg}(k,z) = bias^2 P(k,z)$$

Galaxies are biased tracers of the underlying matter density field! *(Kaiser, APJ'84)*

Neutrinos themselves induce a scale-dependent bias *(LoVerde & Zaldarriaga; Castorina et al)*

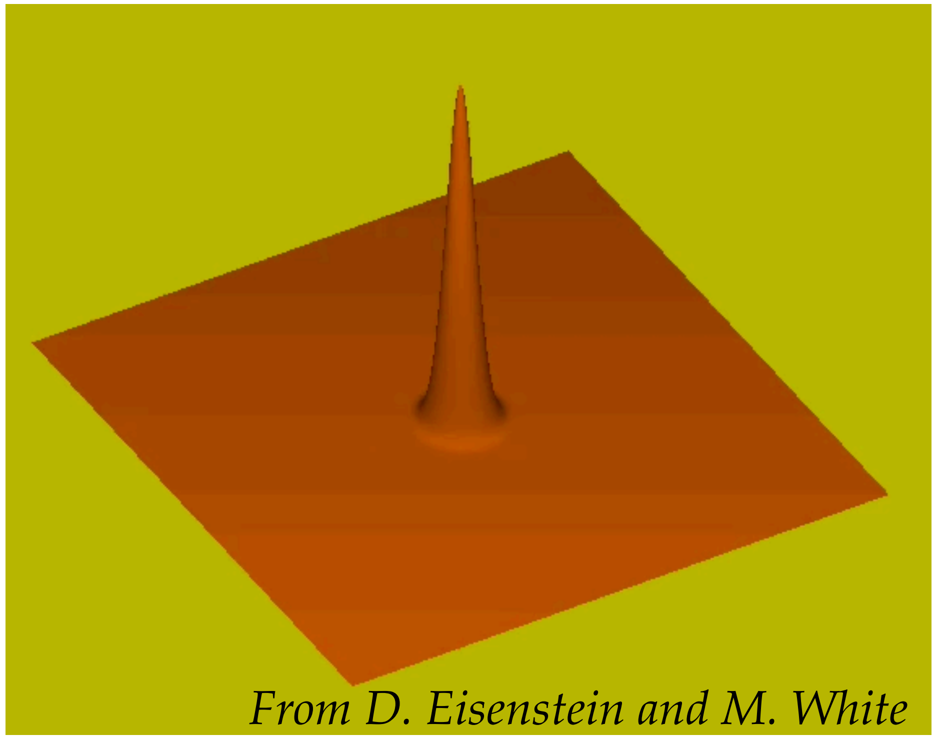
Baryon Acoustic Oscillations

Photons and baryons in the early universe behave as a tightly coupled fluid, resembling acoustic waves, generated as the baryon-photon fluid is attracted and falls onto the overdensities:

$$\ddot{\delta} + [\text{Pressure - Gravity}]\delta = 0 \qquad \delta(\vec{x}) \equiv \frac{\rho(\vec{x})-\bar{\rho}(\vec{x})}{\bar{\rho}(\vec{x})}$$

The time when the baryons are "released" from the drag of the photons is known as the drag epoch. From then on photons expand freely while the acoustic waves "freeze in" the baryons at a scale given by the size of the horizon at the drag epoch:

$$R \equiv 3\rho_b/4\rho_\gamma$$


From D. Eisenstein and M. White

$$r_s = \int_0^{t(z_d)} c_s\,(1+z)dt = \frac{2}{3k_{\rm eq}}\sqrt{\frac{6}{R_{\rm eq}}}\ln\frac{\sqrt{1+R_d}+\sqrt{R_d+R_{\rm eq}}}{1+\sqrt{R_{\rm eq}}}$$

$$r_s = 147.09 \pm 0.26\ \text{Mpc}$$

Planck Coll. A&A'20

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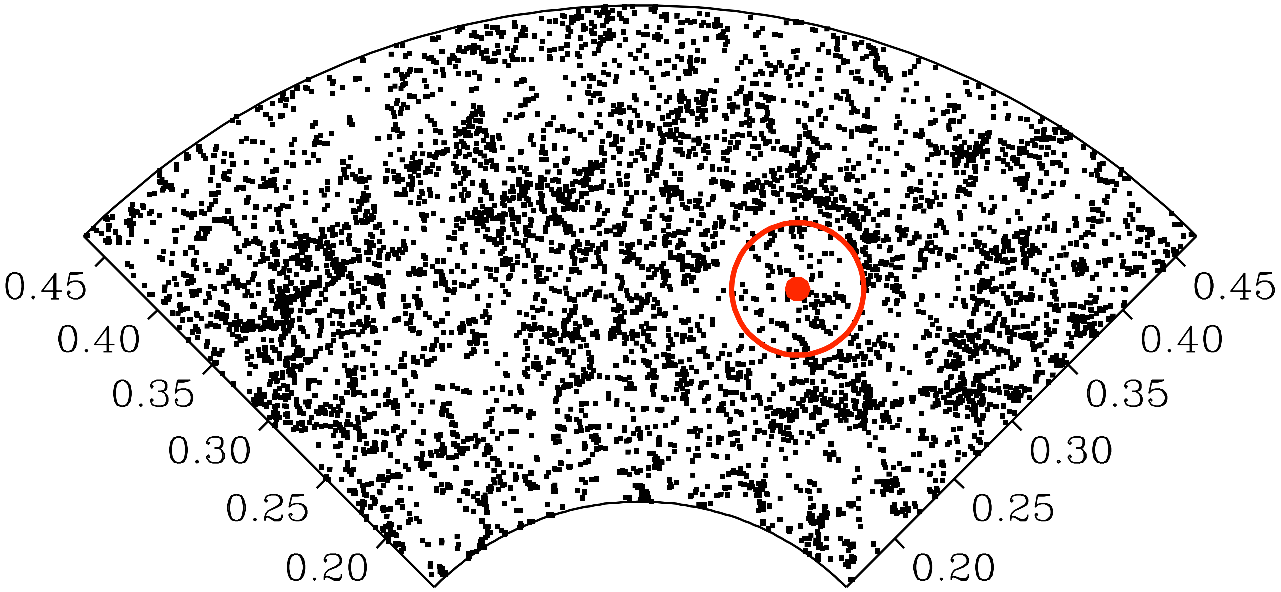
$$r_s = 147.09 \pm 0.26 \text{ Mpc}$$

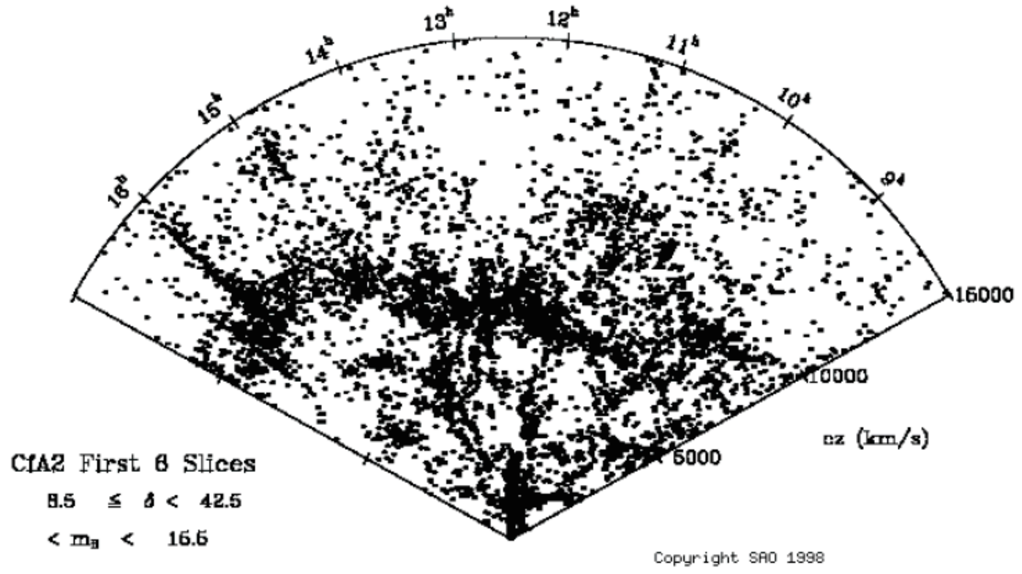
Planck Coll. A&A'20

There should be a small excess in the two-point galaxy correlation function around 150 Mpc!

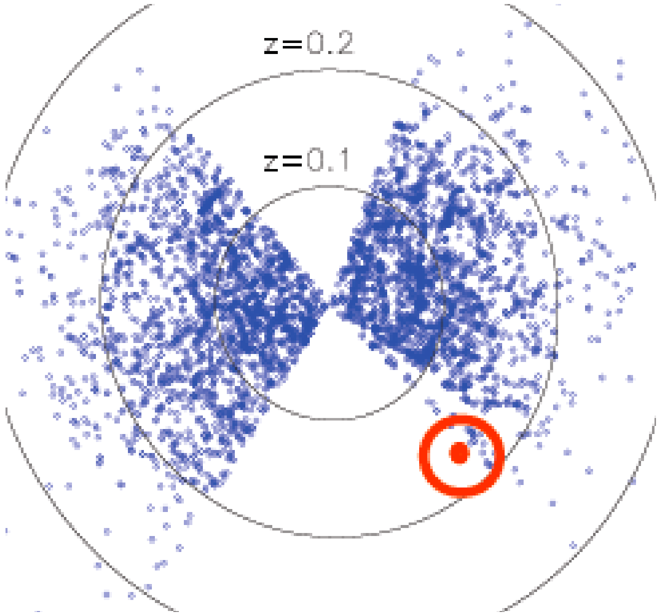


Baryon Acoustic Oscillations

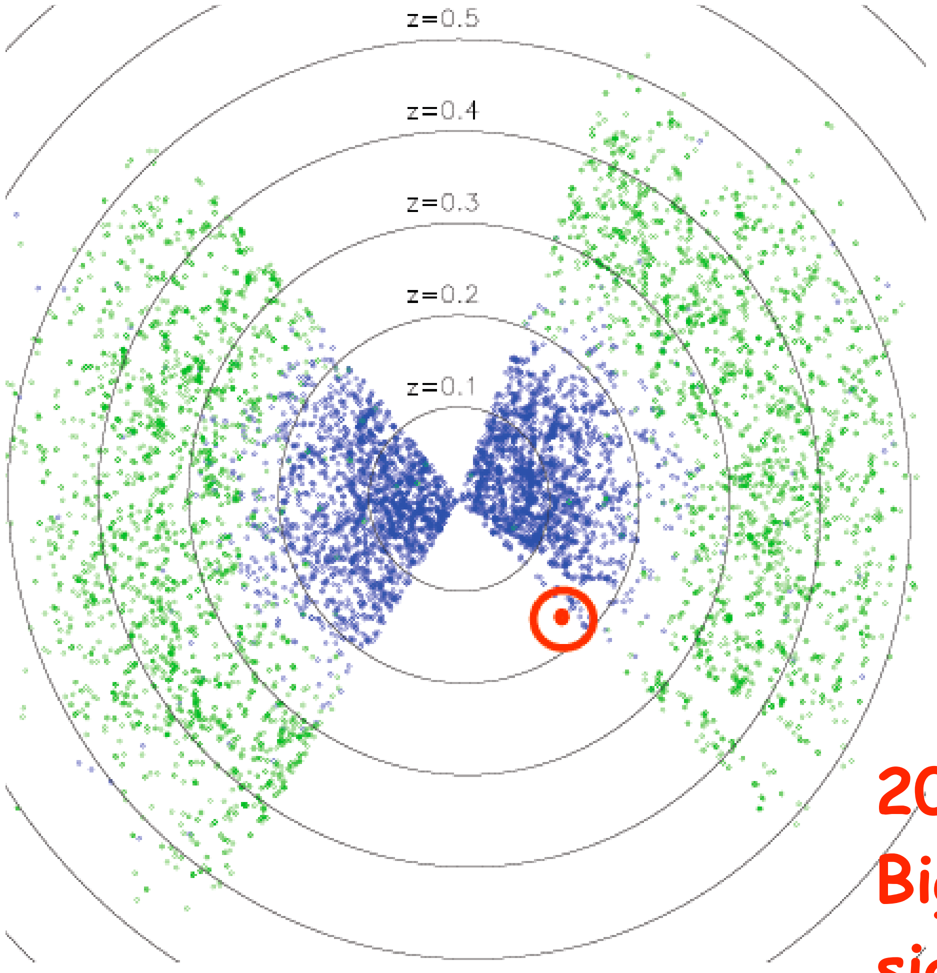
80's: Tiny surveys



BAO scale



2000: Main galaxies @SDSS.
Big number, but small volume

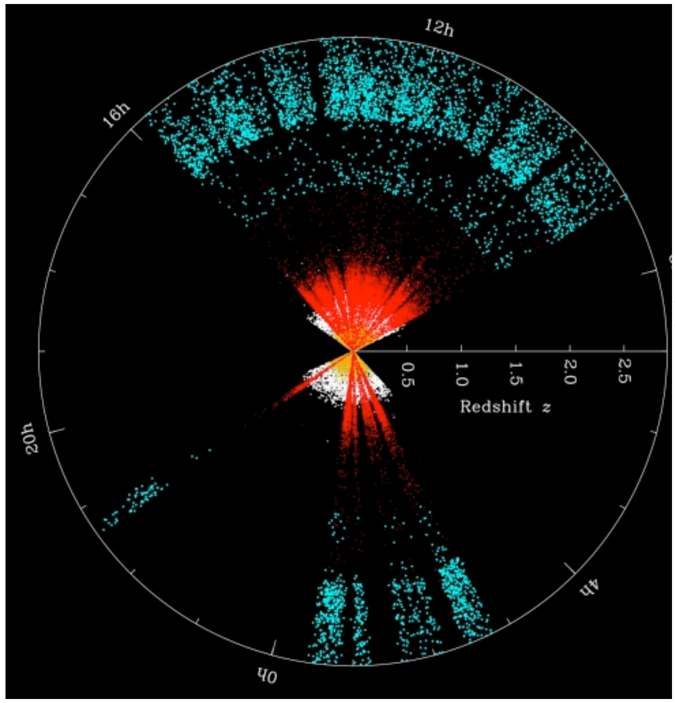


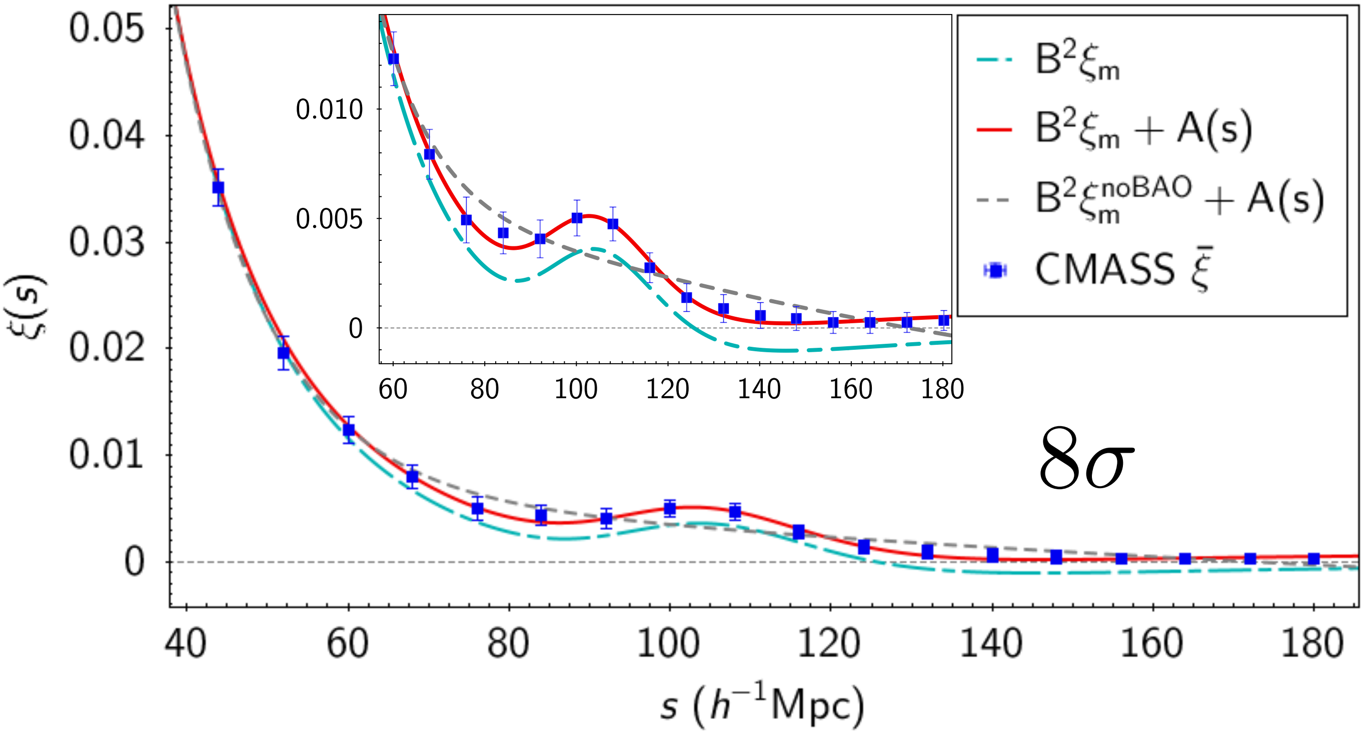
2005: Luminous Red Galaxies @ SDSS.
Big Volume: first detection of the BAO signature

Baryon Acoustic Oscillations

2009-2014= SDSS III

BOSS (SDSSIII) Collaboration

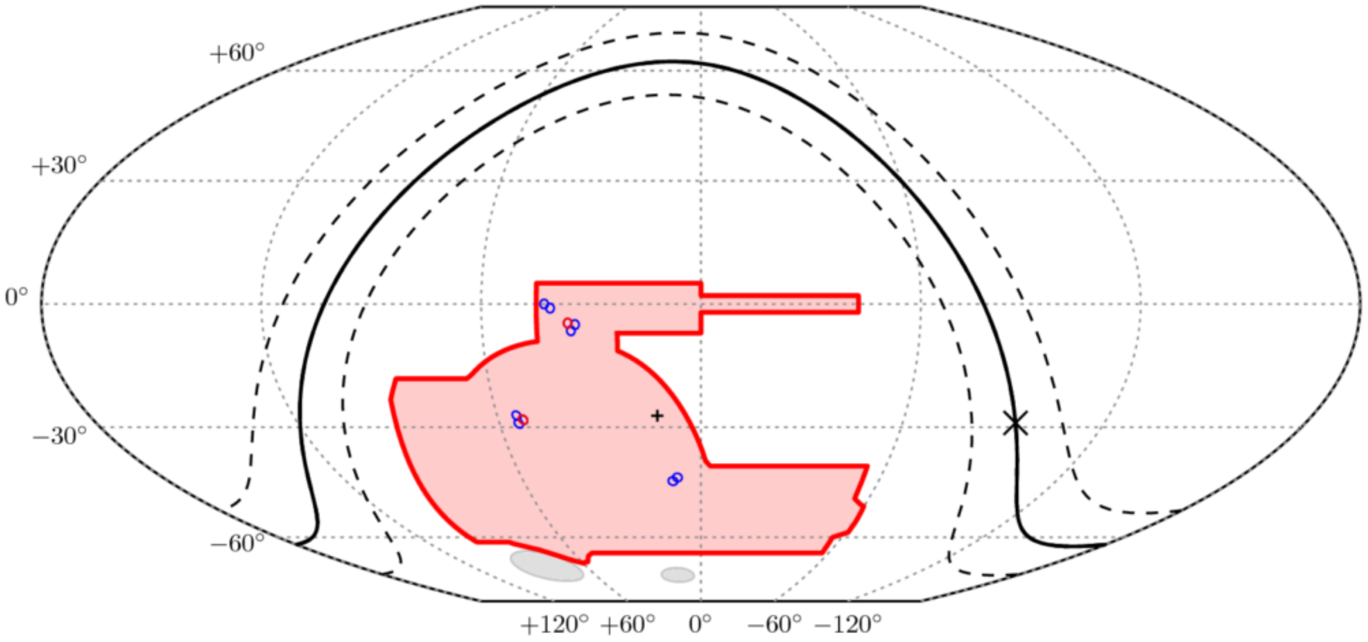




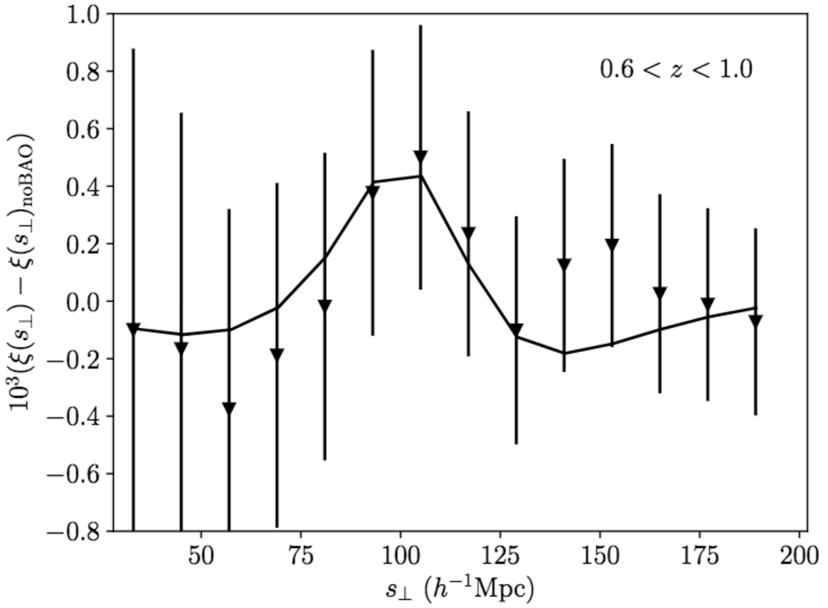
8σ

2013 - 2019= DES

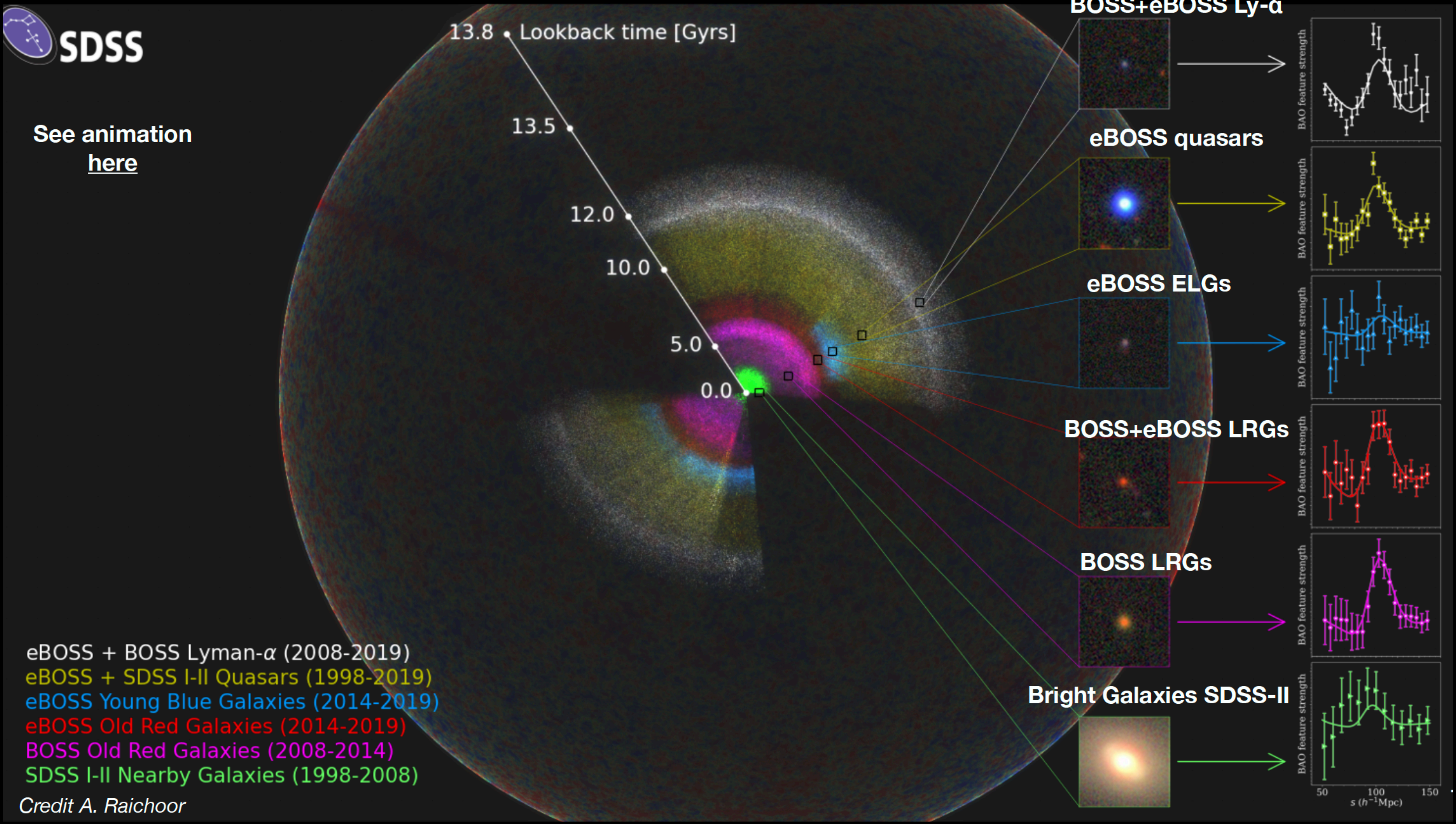
$> 2\sigma$



(DES Collaboration, MNRAS'19)



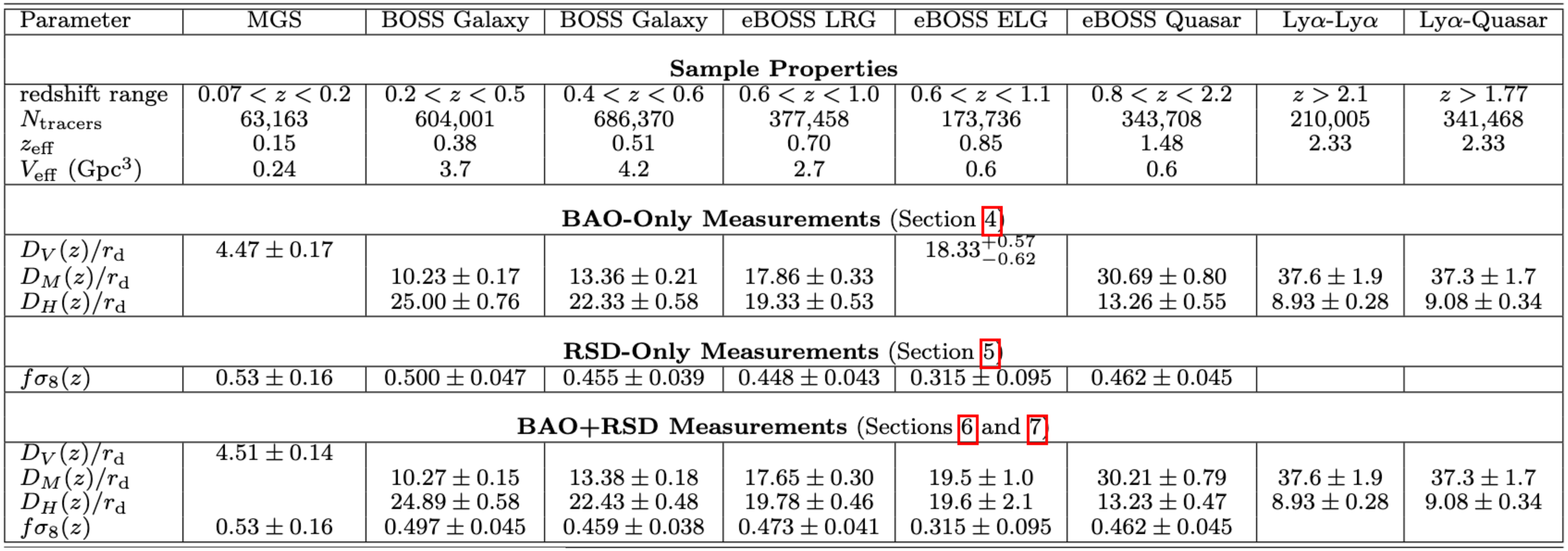
See animation here



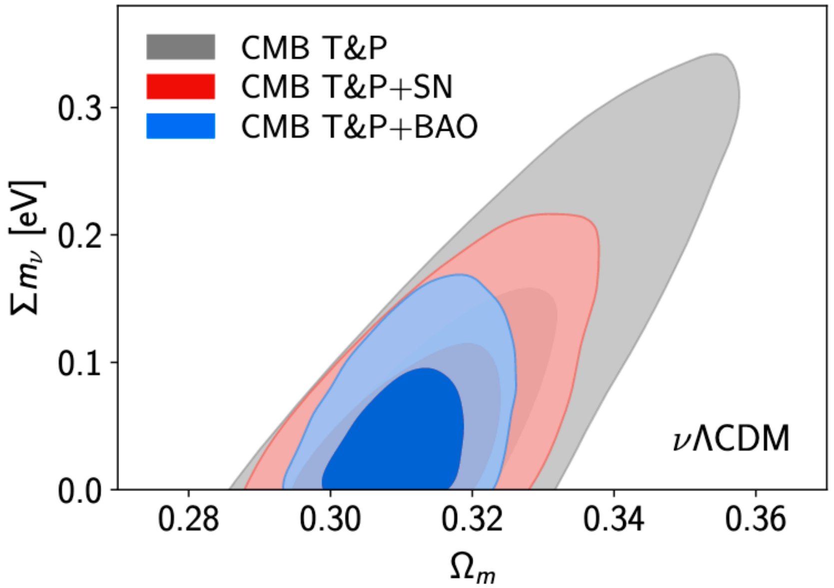
Credit A. Raichoor

Baryon Acoustic Oscillations

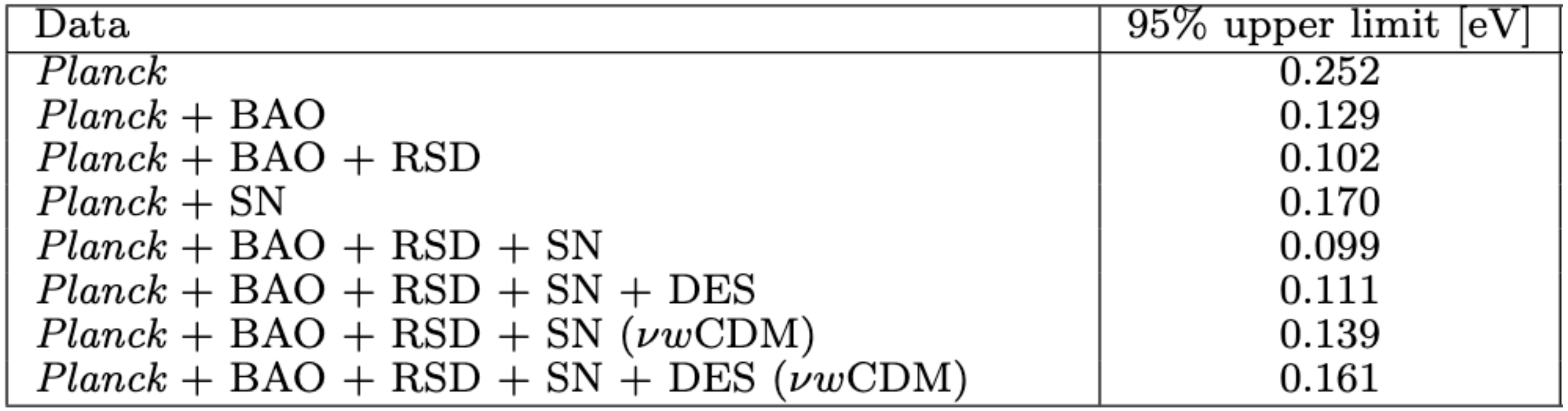
2020= SDSS IV



Parameter	MGS	BOSS Galaxy	BOSS Galaxy	eBOSS LRG	eBOSS ELG	eBOSS Quasar	Lyα-Lyα	Lyα-Quasar
Sample Properties								
redshift range	$0.07 < z < 0.2$	$0.2 < z < 0.5$	$0.4 < z < 0.6$	$0.6 < z < 1.0$	$0.6 < z < 1.1$	$0.8 < z < 2.2$	$z > 2.1$	$z > 1.77$
$N_{\rm tracers}$	63,163	604,001	686,370	377,458	173,736	343,708	210,005	341,468
$z_{\rm eff}$	0.15	0.38	0.51	0.70	0.85	1.48	2.33	2.33
$V_{\rm eff}$ (Gpc^3)	0.24	3.7	4.2	2.7	0.6	0.6		
BAO-Only Measurements (Section 4)								
$D_V(z)/r_{\rm d}$	4.47 ± 0.17				$18.33^{+0.57}_{-0.62}$			
$D_M(z)/r_{\rm d}$		10.23 ± 0.17	13.36 ± 0.21	17.86 ± 0.33		30.69 ± 0.80	37.6 ± 1.9	37.3 ± 1.7
$D_H(z)/r_{\rm d}$		25.00 ± 0.76	22.33 ± 0.58	19.33 ± 0.53		13.26 ± 0.55	8.93 ± 0.28	9.08 ± 0.34
RSD-Only Measurements (Section 5)								
$f\sigma_8(z)$	0.53 ± 0.16	0.500 ± 0.047	0.455 ± 0.039	0.448 ± 0.043	0.315 ± 0.095	0.462 ± 0.045		
BAO+RSD Measurements (Sections 6 and 7)								
$D_V(z)/r_{\rm d}$	4.51 ± 0.14							
$D_M(z)/r_{\rm d}$		10.27 ± 0.15	13.38 ± 0.18	17.65 ± 0.30	19.5 ± 1.0	30.21 ± 0.79	37.6 ± 1.9	37.3 ± 1.7
$D_H(z)/r_{\rm d}$		24.89 ± 0.58	22.43 ± 0.48	19.78 ± 0.46	19.6 ± 2.1	13.23 ± 0.47	8.93 ± 0.28	9.08 ± 0.34
$f\sigma_8(z)$	0.53 ± 0.16	0.497 ± 0.045	0.459 ± 0.038	0.473 ± 0.041	0.315 ± 0.095	0.462 ± 0.045		

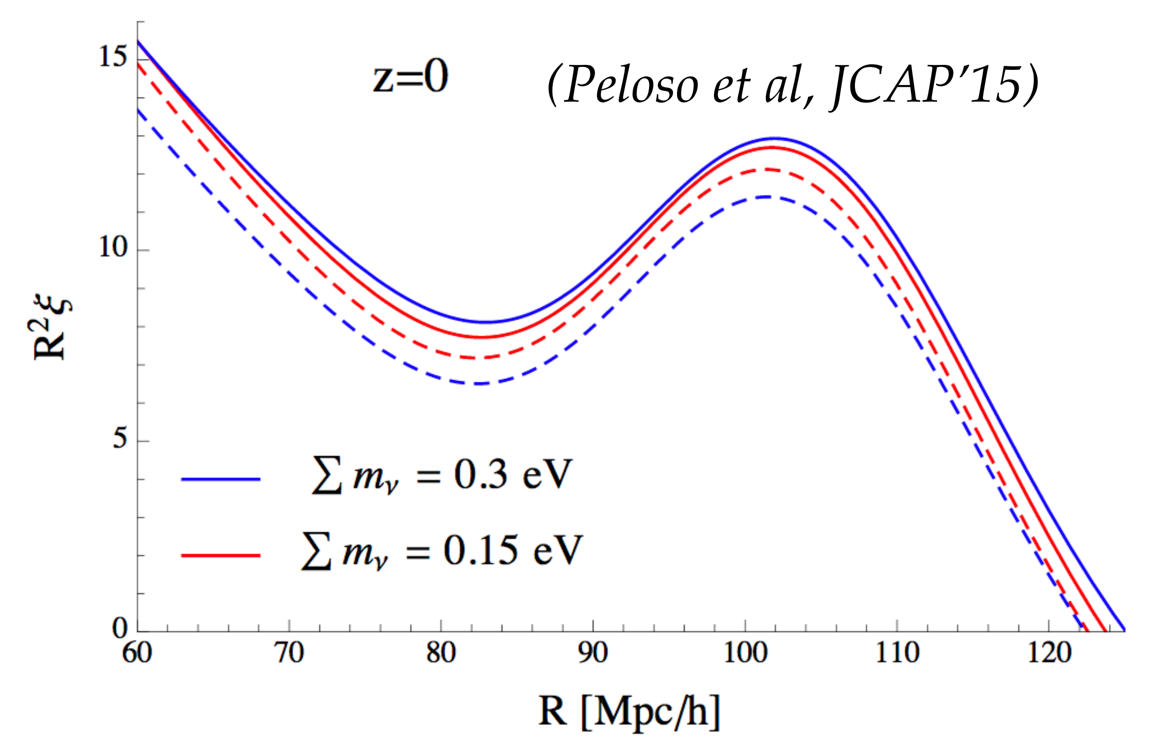


Alam et al, SDSS IV Coll. PRD'21

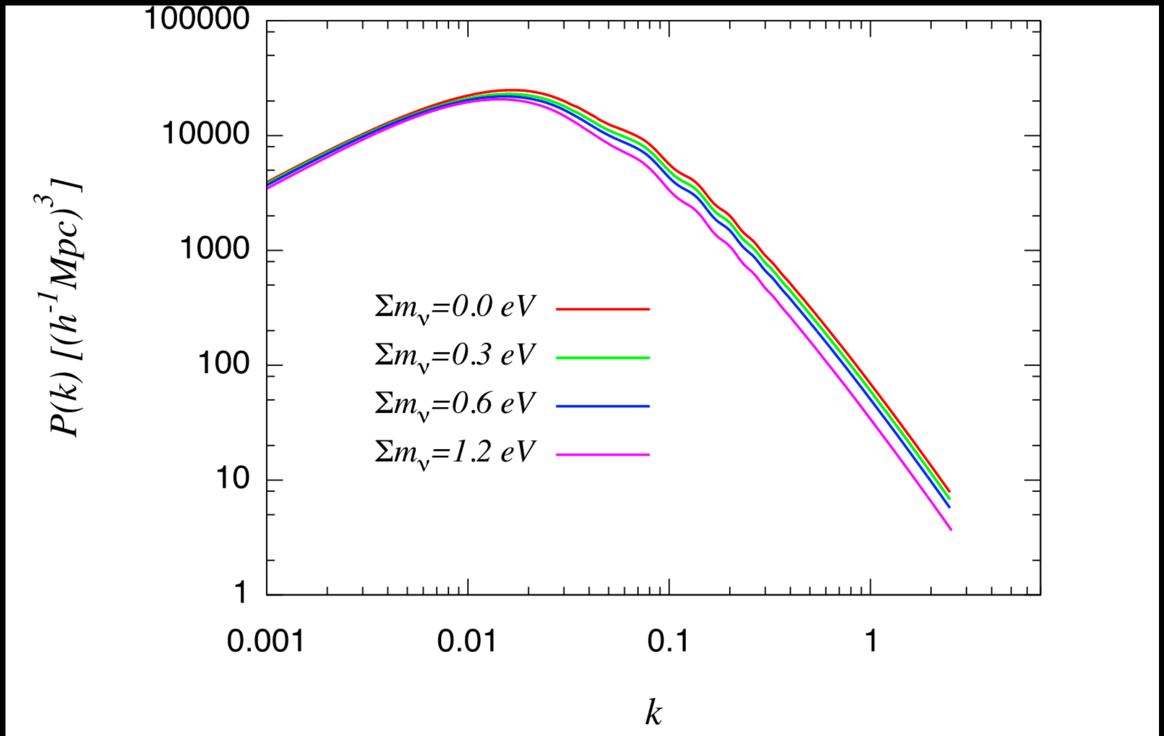


Data	95% upper limit [eV]
Planck	0.252
Planck + BAO	0.129
Planck + BAO + RSD	0.102
Planck + SN	0.170
Planck + BAO + RSD + SN	0.099
Planck + BAO + RSD + SN + DES	0.111
Planck + BAO + RSD + SN (νwCDM)	0.139
Planck + BAO + RSD + SN + DES (νwCDM)	0.161

Large scale structure: m_ν



(Peloso et al, JCAP'15)



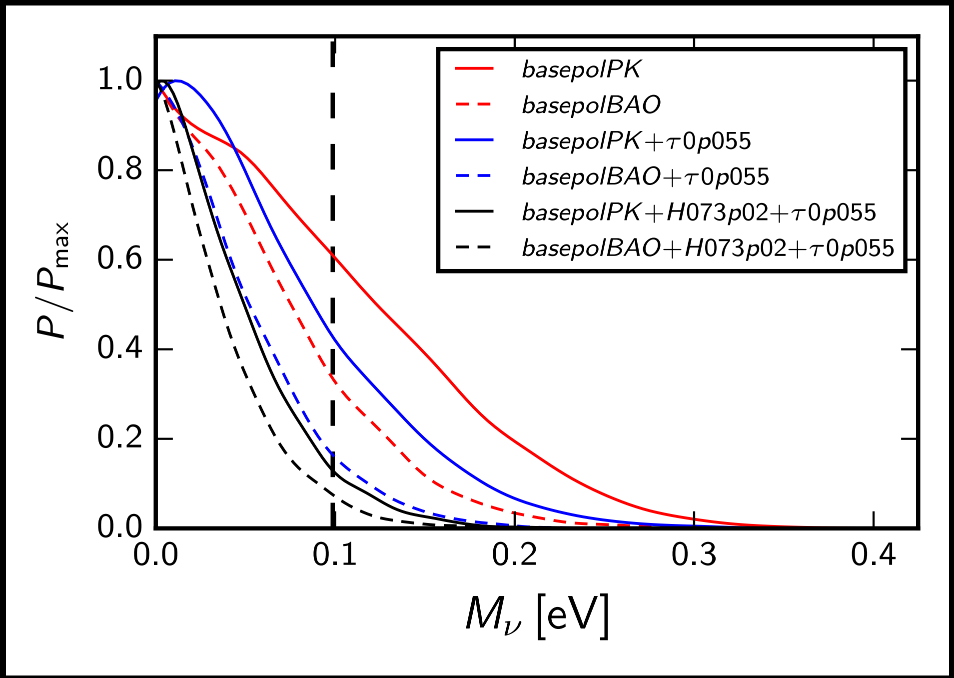
Large scale structure measurements can be interpreted either in the geometrical or shape forms

2 point correlation function

$\downarrow$ **Fourier Transform**

Matter power spectrum

BAO information more powerful



S. Vagnozzi, E. Giusarma, O. Mena, K. Freese, M. Gerbino, S. Ho and M. Lattanzi, PRD'17

$\sum m_\nu$

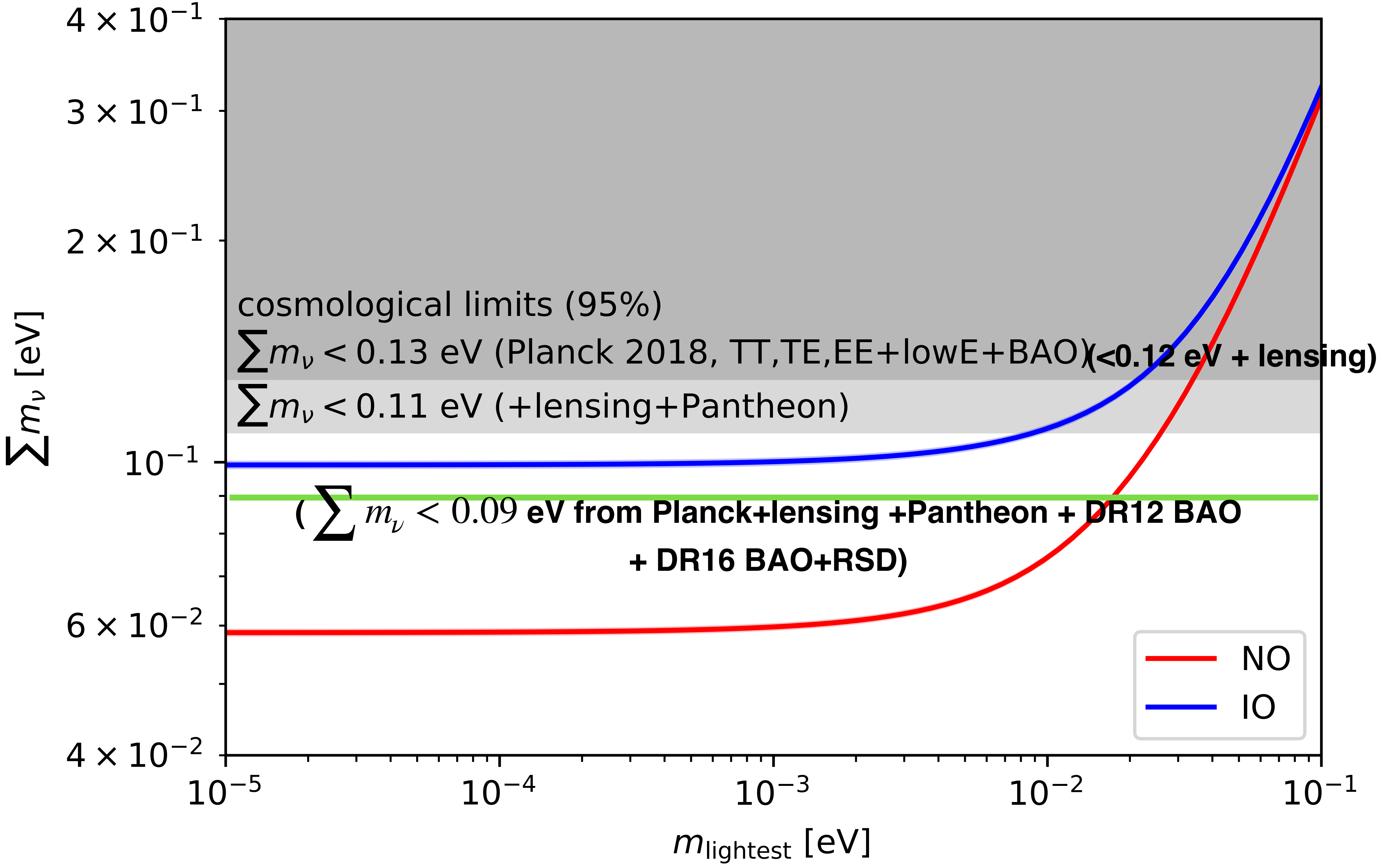
- Planck 2018 CMB temperature polarization and lensing potential data:

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

- 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


4×10^{-1}
3×10^{-1}
2×10^{-1}
10^{-1}
6×10^{-2}
4×10^{-2}
$\sum m_\nu$ [eV]
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
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
$m_{\rm lightest}$ [eV]

Σm_ν

Planck Coll. A&A'20

Planck TTTEEE+lowT+lowE+lensing

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

+ BAO

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

+ BAO + SNIa

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

+ SDSS-IV (BAO + RSD) + SNIa

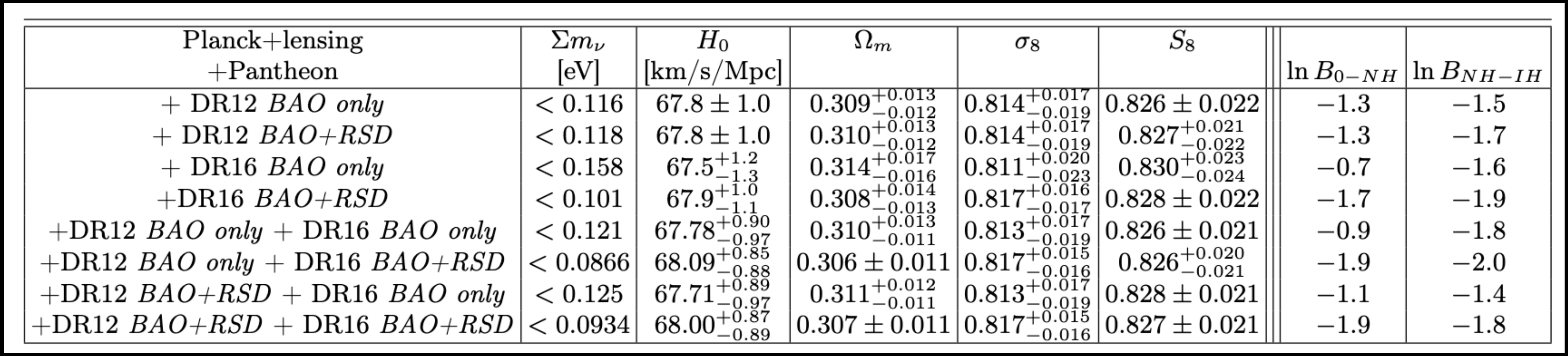
$$\sum m_\nu < 0.099 \text{ eV } 95\,\%\,\text{CL}$$

eBOSS Coll. PRD'21

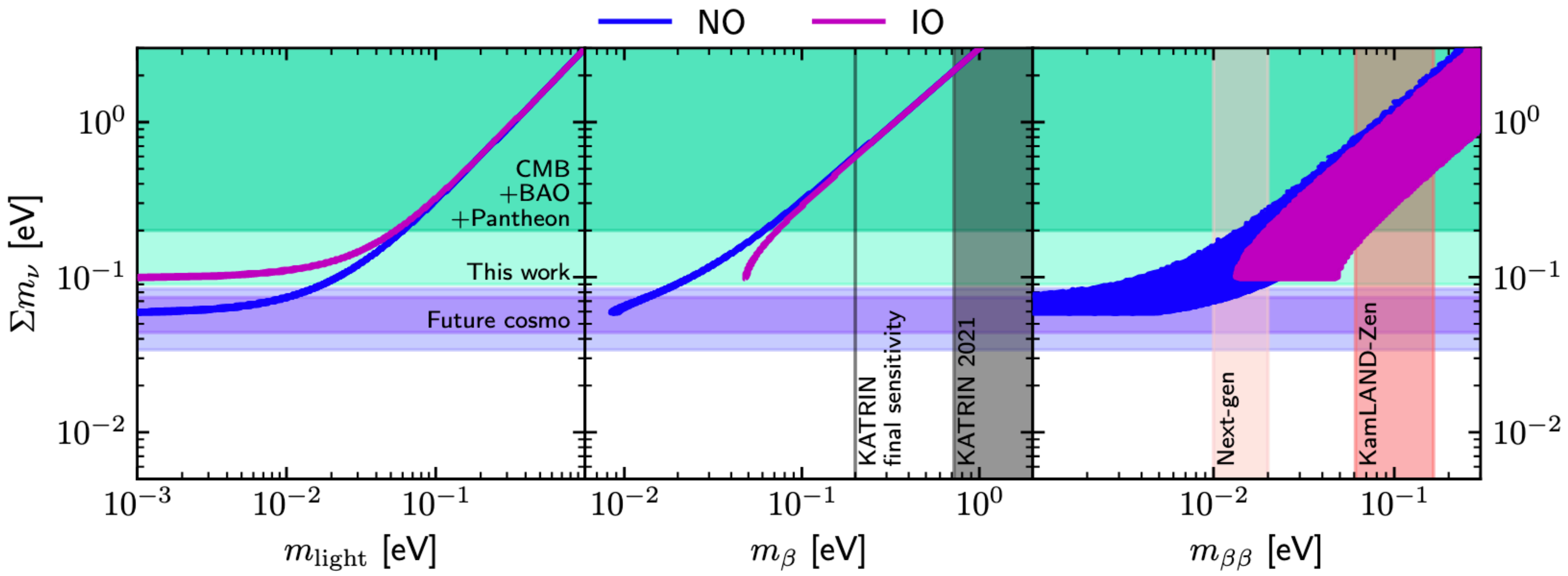
+ SDSS-IV (BAO + RSD) DR16 + DR12 BAO + SNIa

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

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	$67.78^{+0.90}_{-0.97}$	$0.310^{+0.013}_{-0.011}$	$0.813^{+0.017}_{-0.019}$	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	$67.71^{+0.89}_{-0.97}$	$0.311^{+0.012}_{-0.011}$	$0.813^{+0.017}_{-0.019}$	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

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

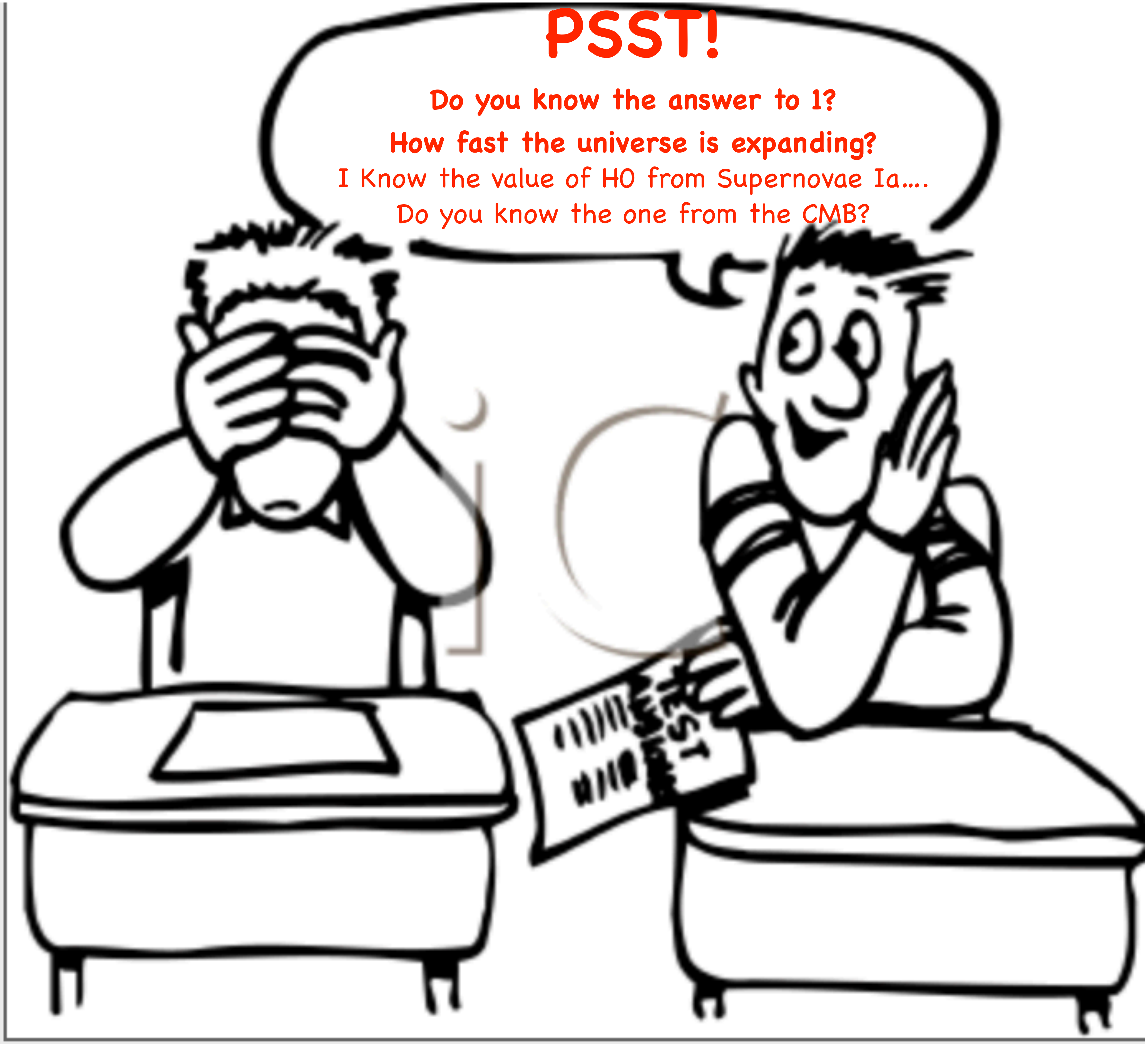
2. Roll the dice and get:

- 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:

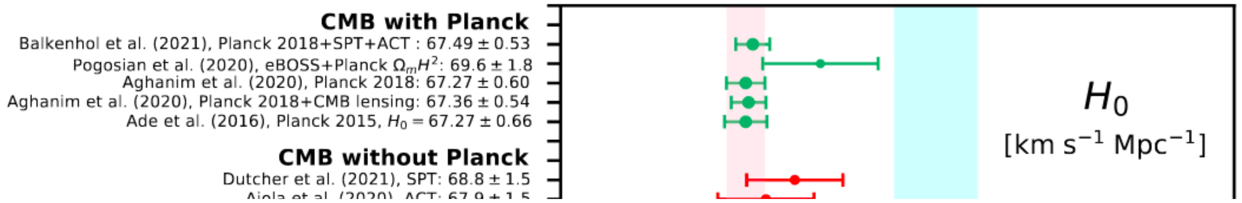
- Take home messages

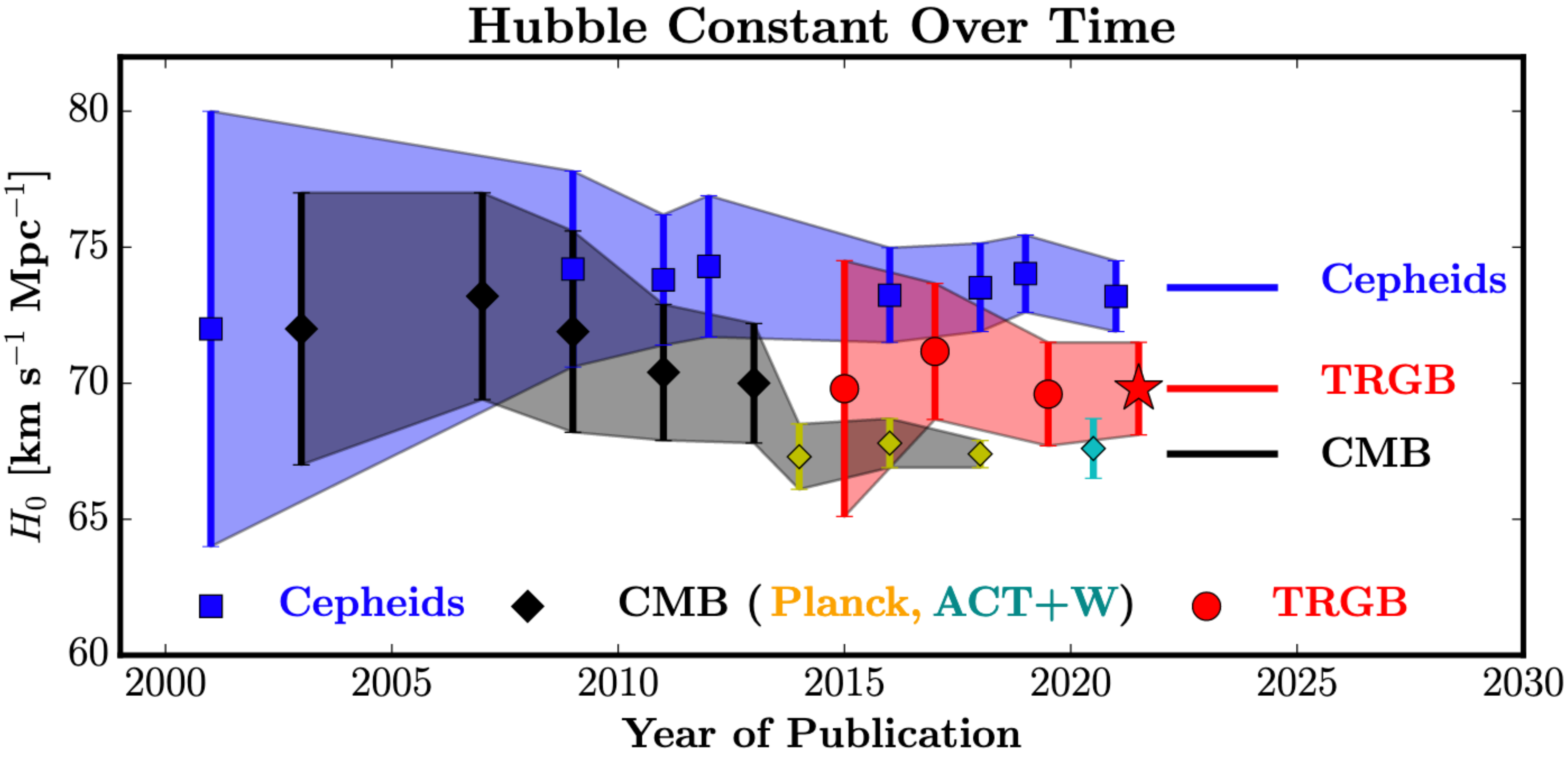

PSST!
Do you know the answer to 1?
How fast the universe is expanding?
I Know the value of H0 from Supernovae Ia....
Do you know the one from the CMB?
TEST ANSWERS

The Hubble tension

W. Freedman, APJ'21

Di Valentino et al, 2103.01183





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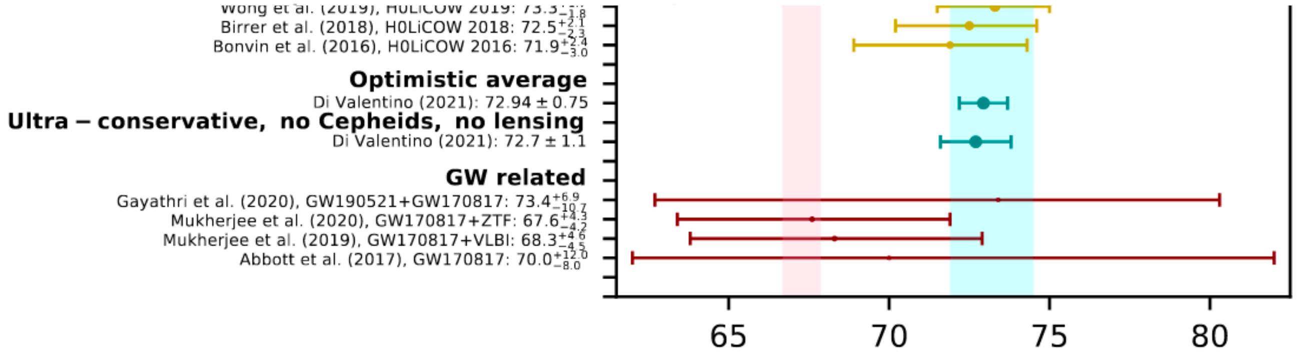
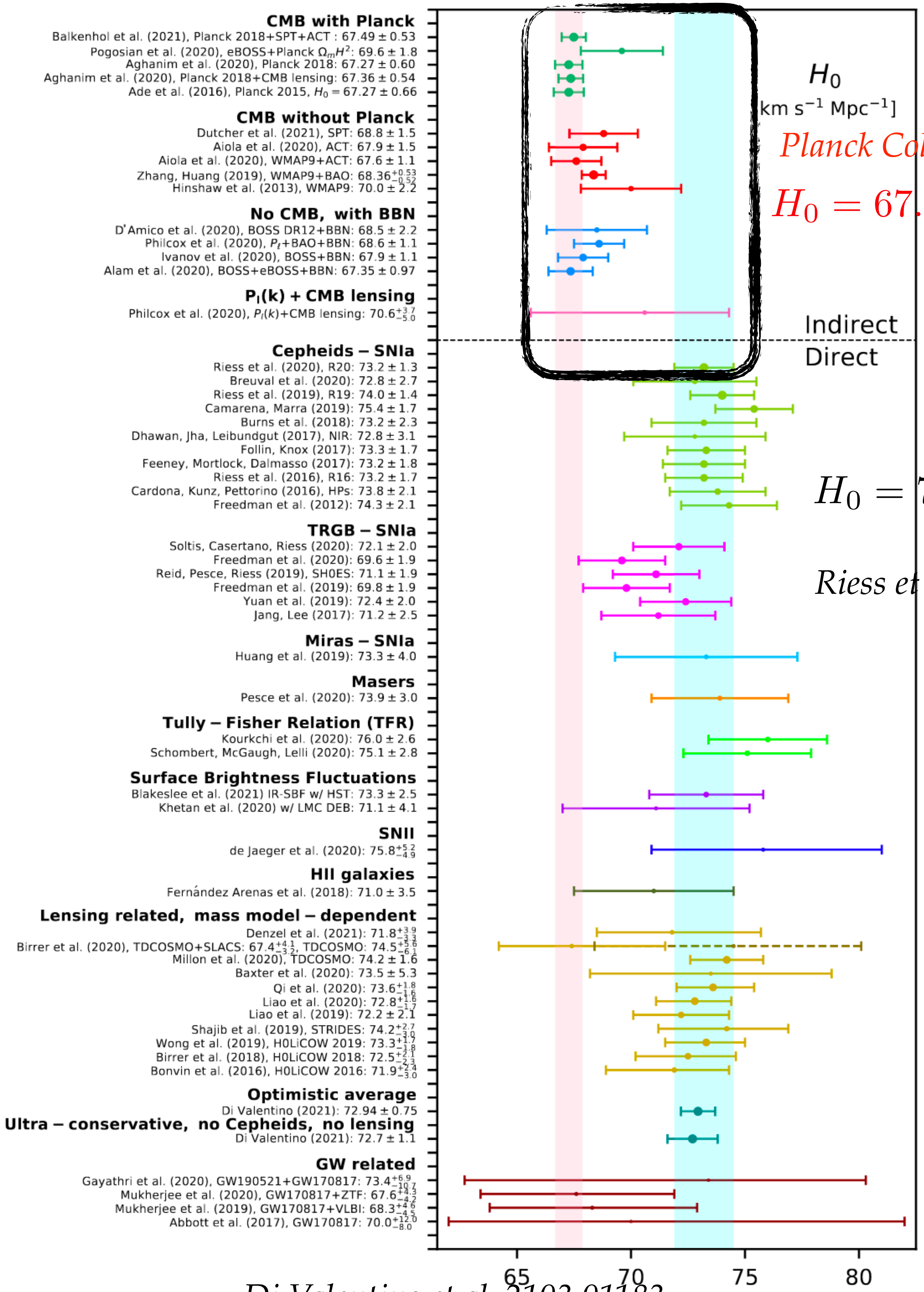


The Hubble tension



Planck Coll. A&A'20

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

$$H_0 = 73.2 \pm 1.3 \text{ km/s/Mpc}$$

Riess et al, APJ'20

Di Valentino et al, 2103.01183

Early, indirect

(they are a prediction within the ΛCDM framework) inferences tend to increase (rather than decrease) from the baseline value derived from Planck 2018 temperature anisotropy data with the inclusion of CMB polarization, BAO data, etc...

The Hubble tension

Late (I)

Best-established and unique empirical methods to measure H_0

The "distance ladder": parallax (=geometry) is used to calibrate luminosities of stars that after can be seen at much larger distances.

Cepheids/SNIa: SH0ES team

$$H_0 = 73.2 \pm 1.3 \ \mathrm{km/s/Mpc}$$ *Riess et al, APJ'20*

Reanalyses of SH0ES data have fully agreed!

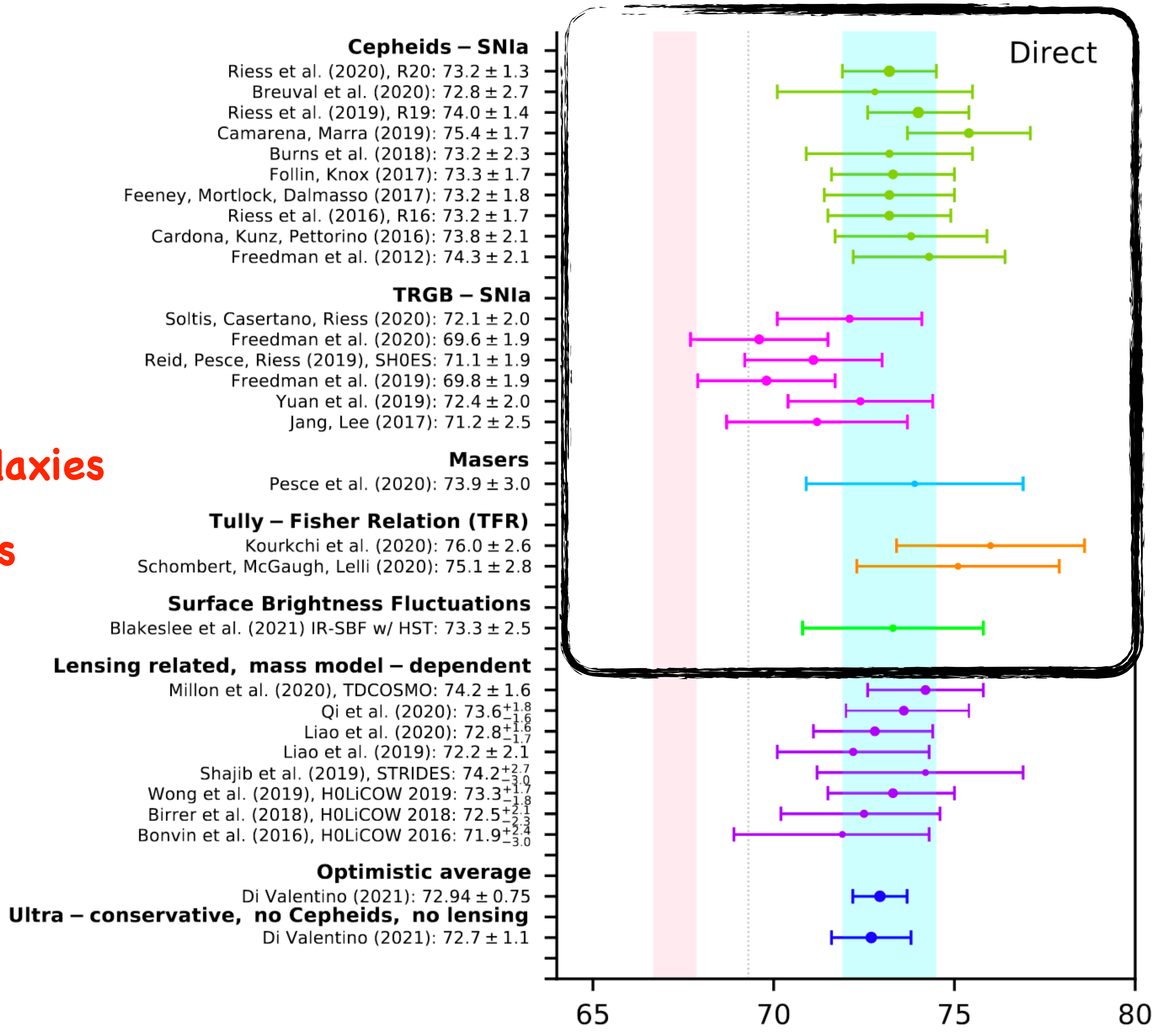
Other distance ladders:

Tip of the RedGiant Branch (TRGB)

Geometric distances to Mega-Maser hosting galaxies

Empirical relation luminosity-rotational velocities

SBF method as a distance indicator

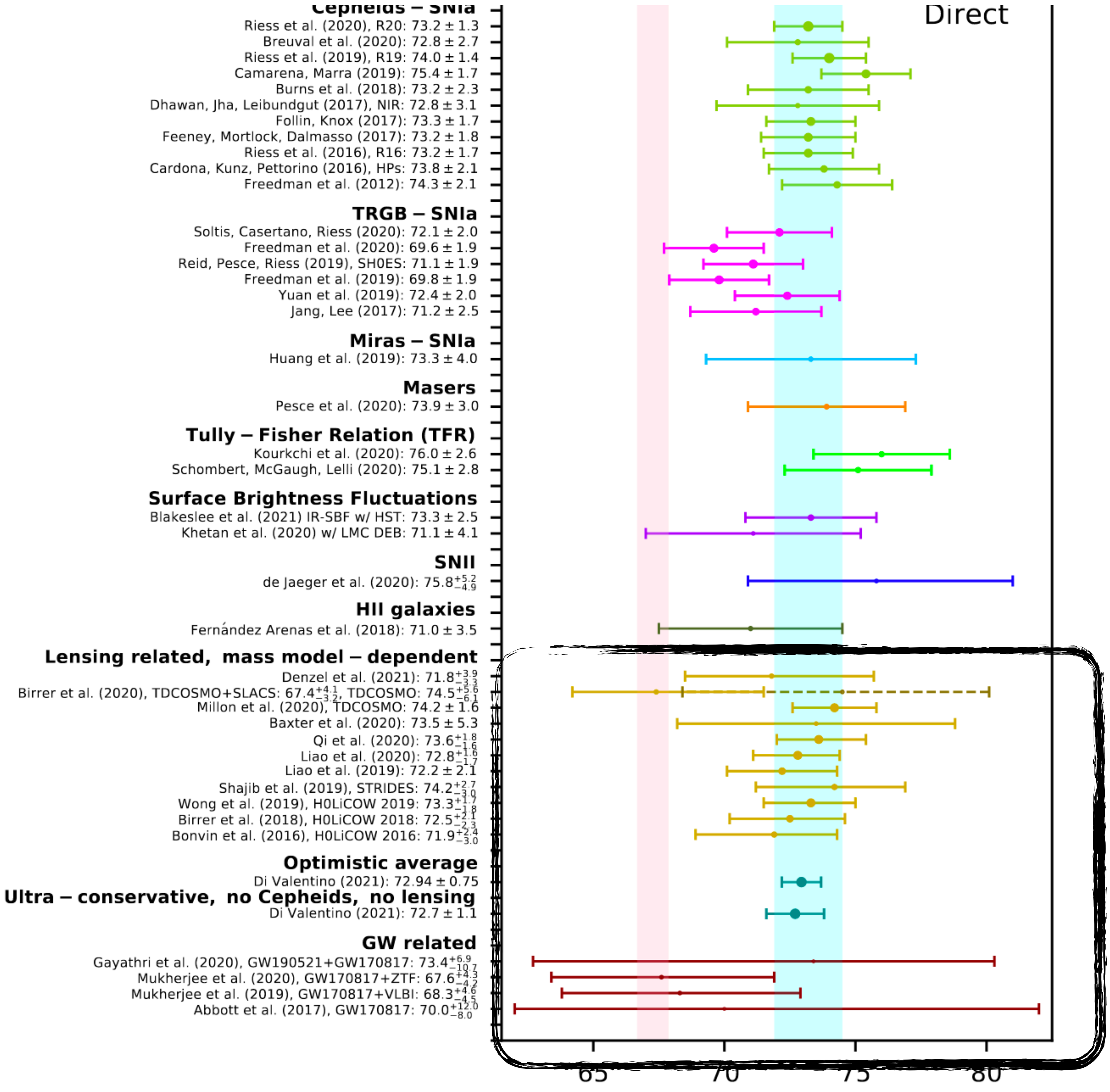


Di Valentino et al, 2103.01183

The Hubble tension

Late (II): “Gastrophysics” model-dependent

Di Valentino et al, 2103.01183



Time delays in strong lensed systems (quasars)(lens mass distribution/foregrounds)

Late (III): Standard sirens

combination of the distance to the source inferred purely from gravity waves, with the recession velocity from redshift data using electromagnetic signal

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:

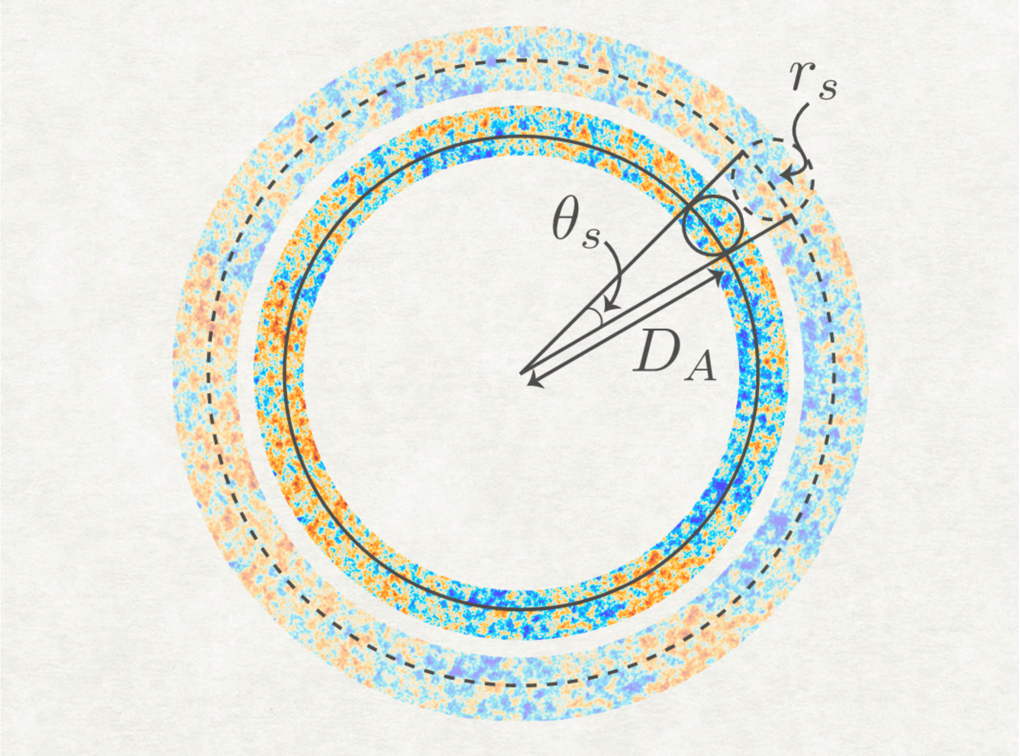
1) From measurements of the matter and baryon densities given a model: derivation of r_s^* at the last scattering redshift z_s
2) From the position of the CMB peaks, the comoving angular diameter distance is extracted:

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

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?



The Hubble parameter compendium

Knox & Millea, PRD'20

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

Early universe solutions

Change both r_s & D_A at recombination to have a higher H_0

Late universe solutions

Change $D_A(z)$ at redshifts after recombination to have a lower H_0

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


Shhh!! masks on!!!
I'll call the neutrino major and the extra relativistic stuff. They may know the solution for this!
Social
d=√(x₂-x)²+(y₂-y)²
BE RATIONAL
BE REAL
√-1 π
TEST ANSWERS

H_0 versus $N_{\rm eff}$

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

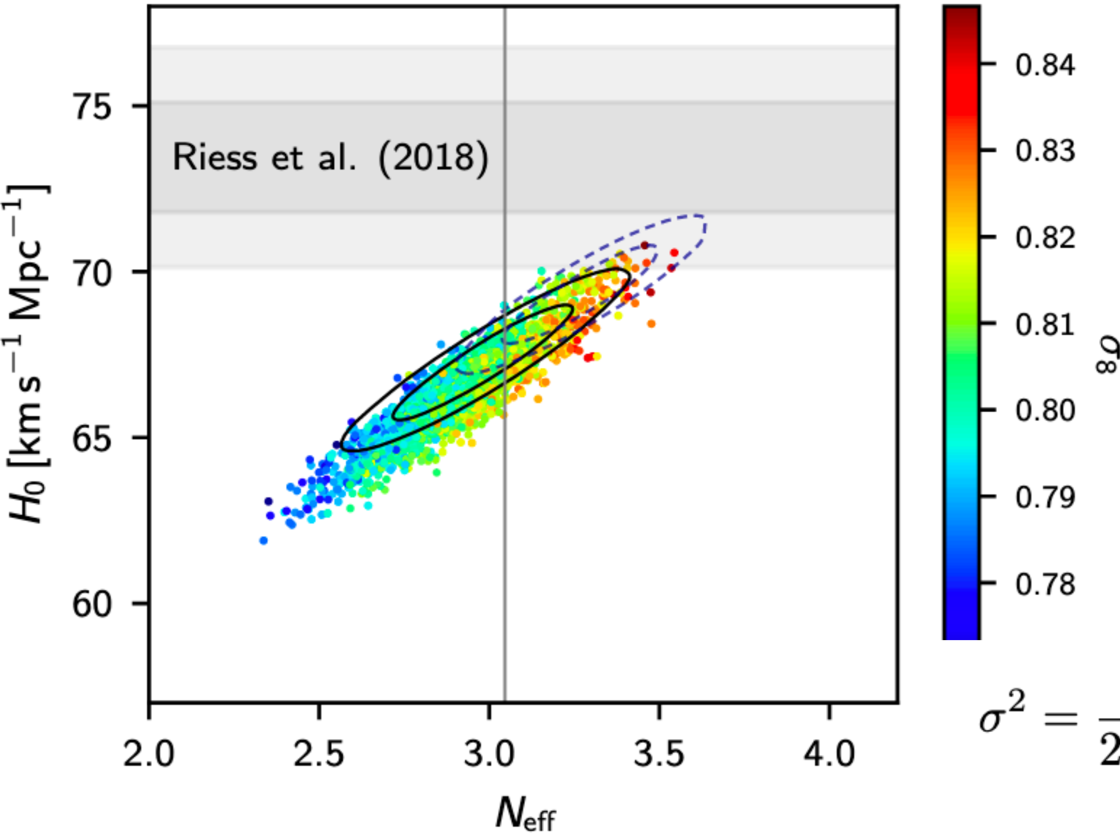
An increase of $N_{\rm eff}$ implies a larger expansion in the early universe: shorter r_s.

D_A at recombination needs to be smaller: higher H_0

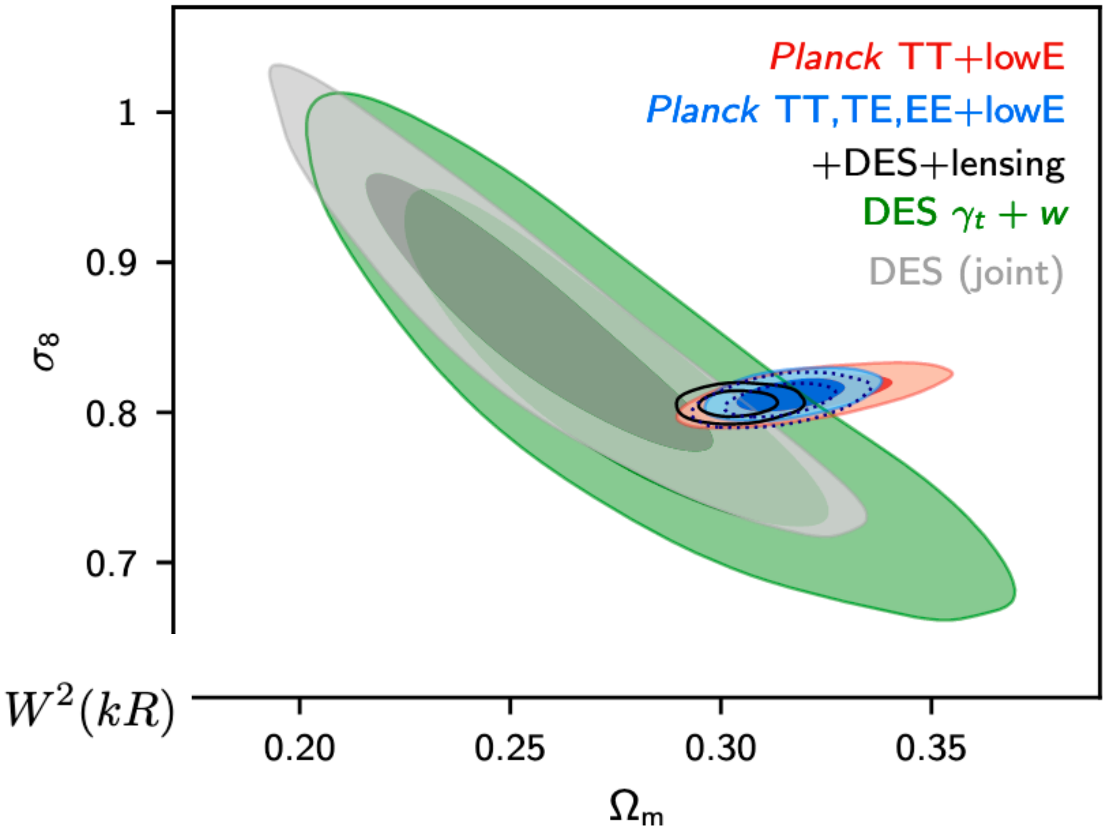
$$\theta_s = \frac{r_s}{D_A} \qquad D_A = \int_0^{z_{rec}} \frac{dz}{H(z)}$$

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

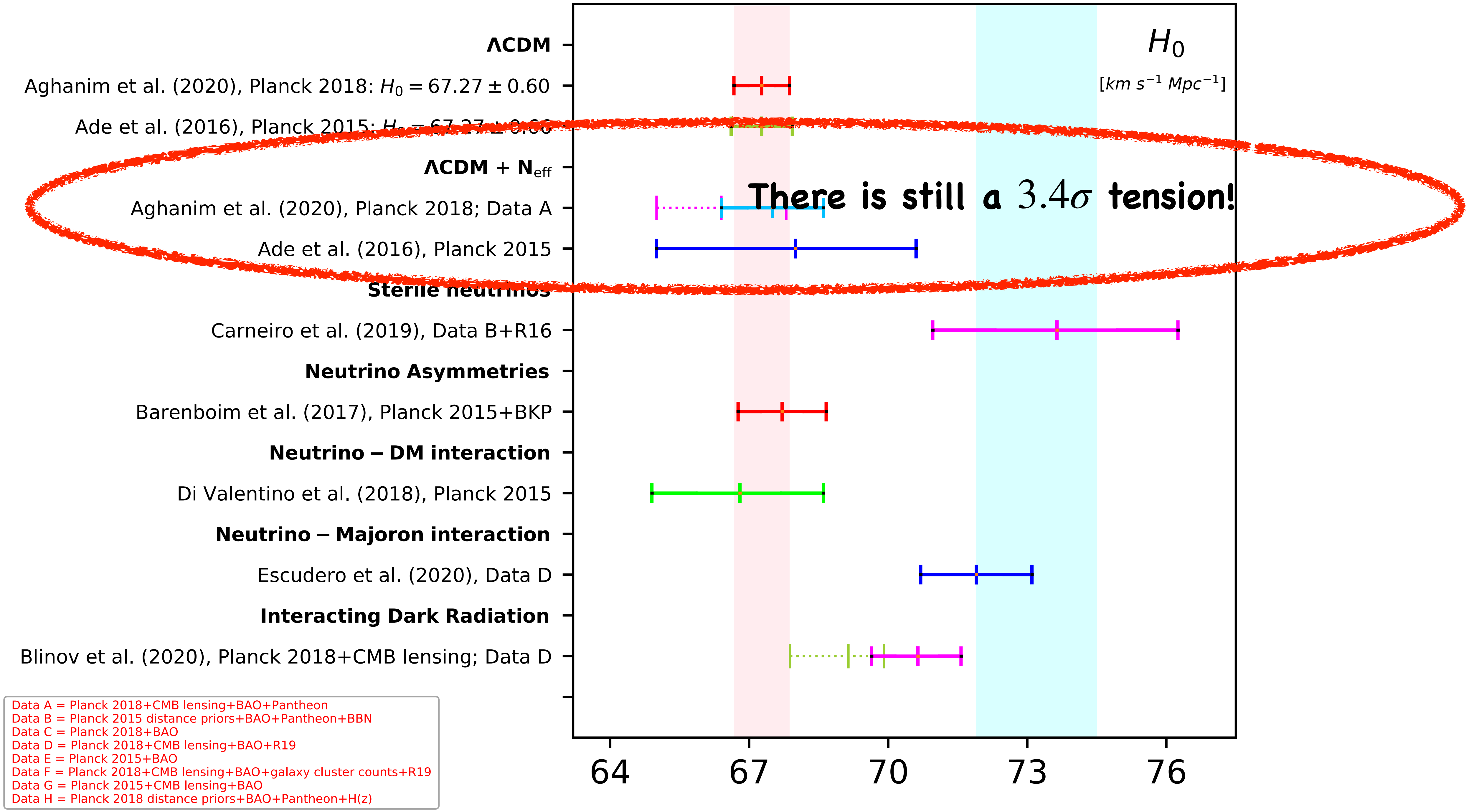
,



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



Planck Coll. A&A'20

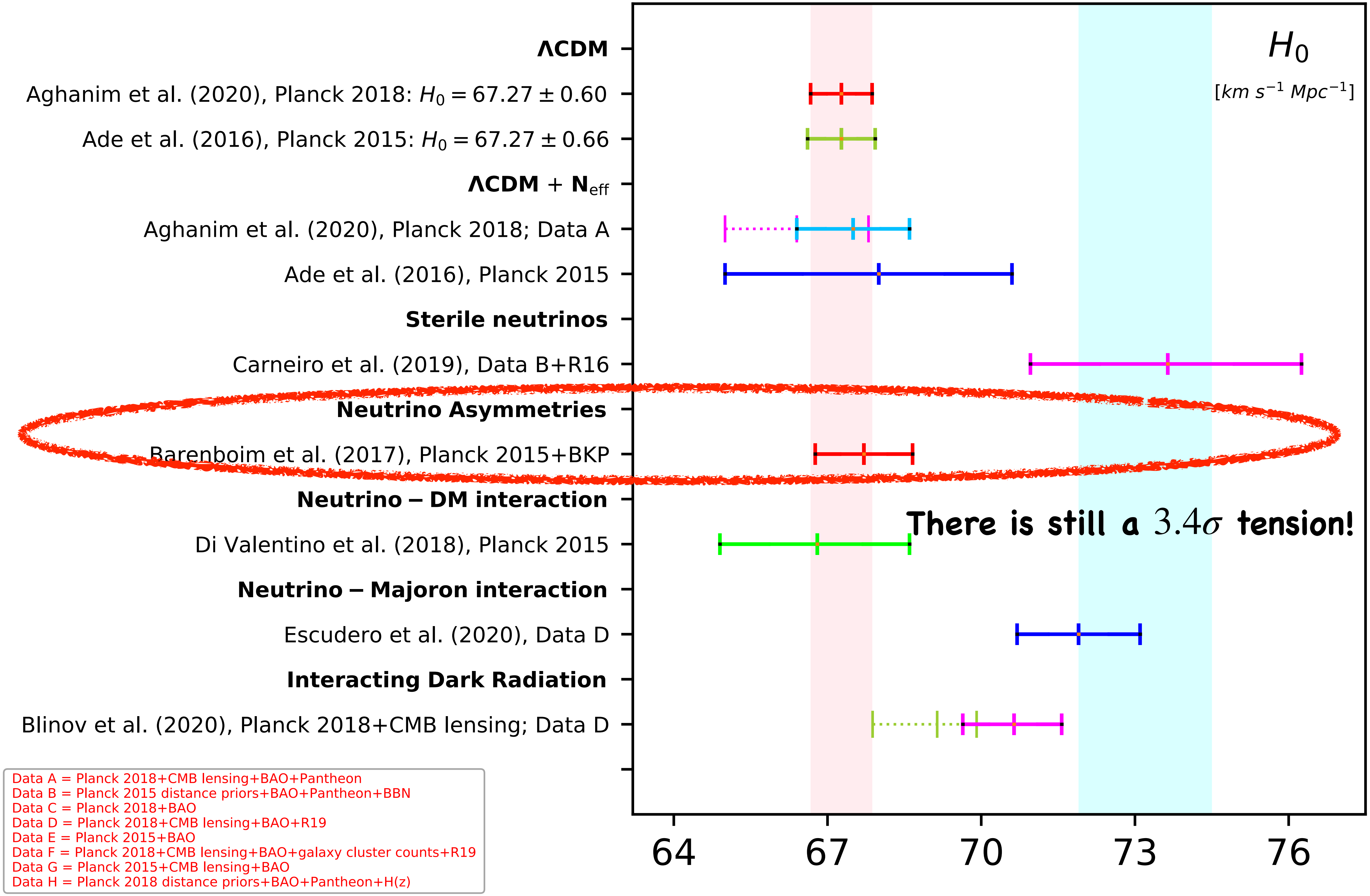


There is still a 3.4σ tension!

Di Valentino et al, 2103.01183

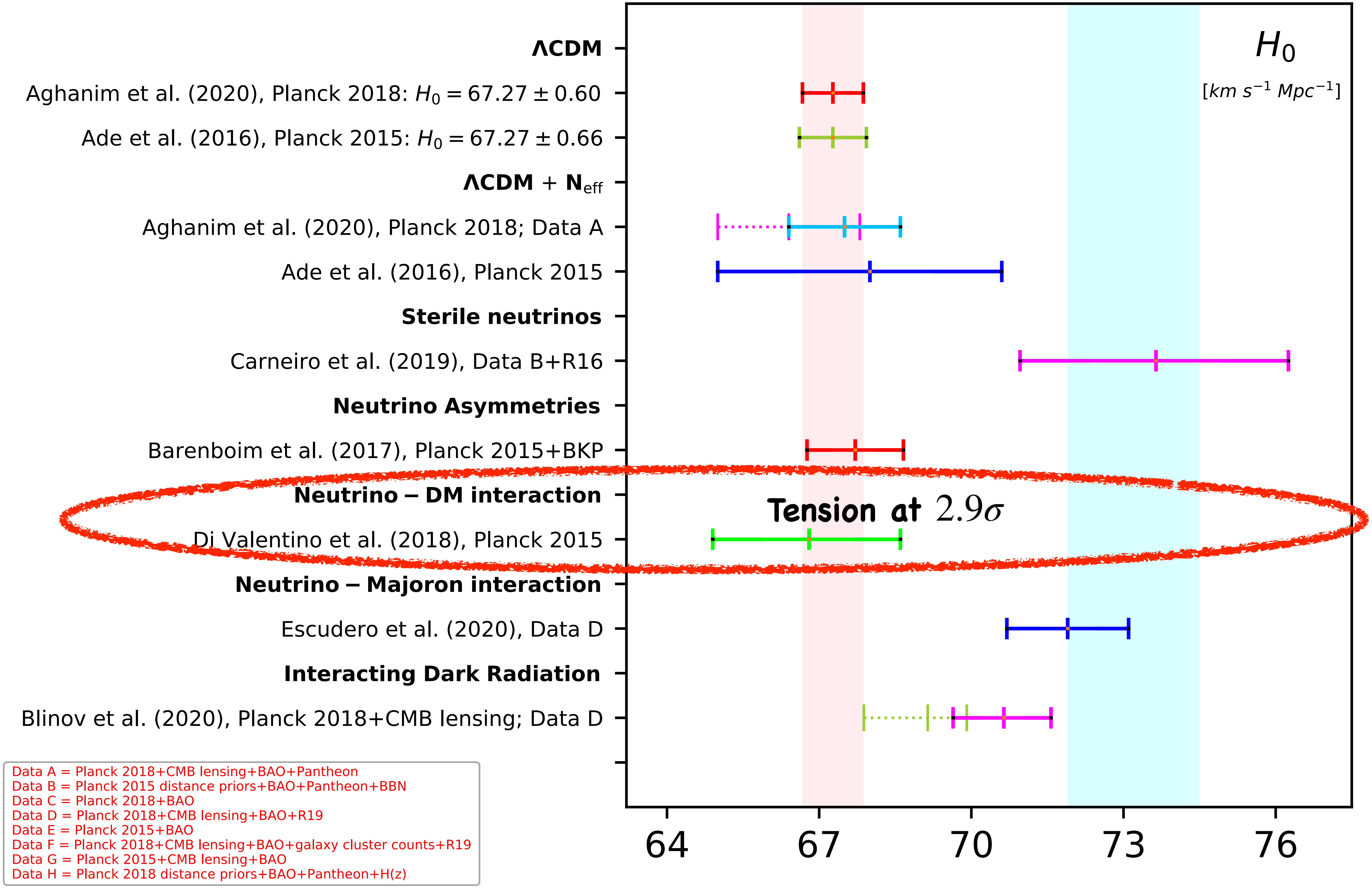
H_0 versus neutrino asymmetries

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

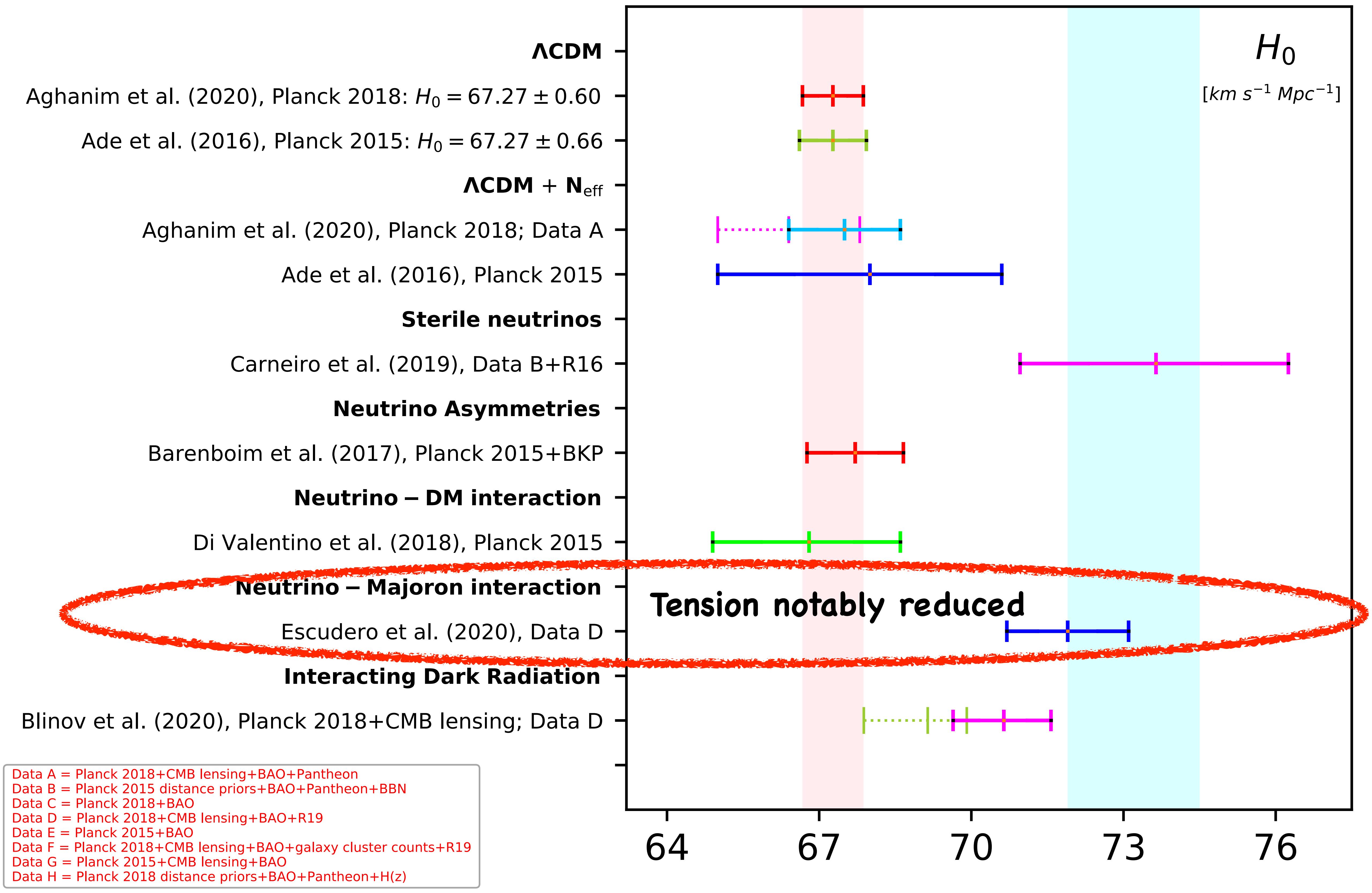


There is still a 3.4σ tension!

Di Valentino et al, 2103.01183

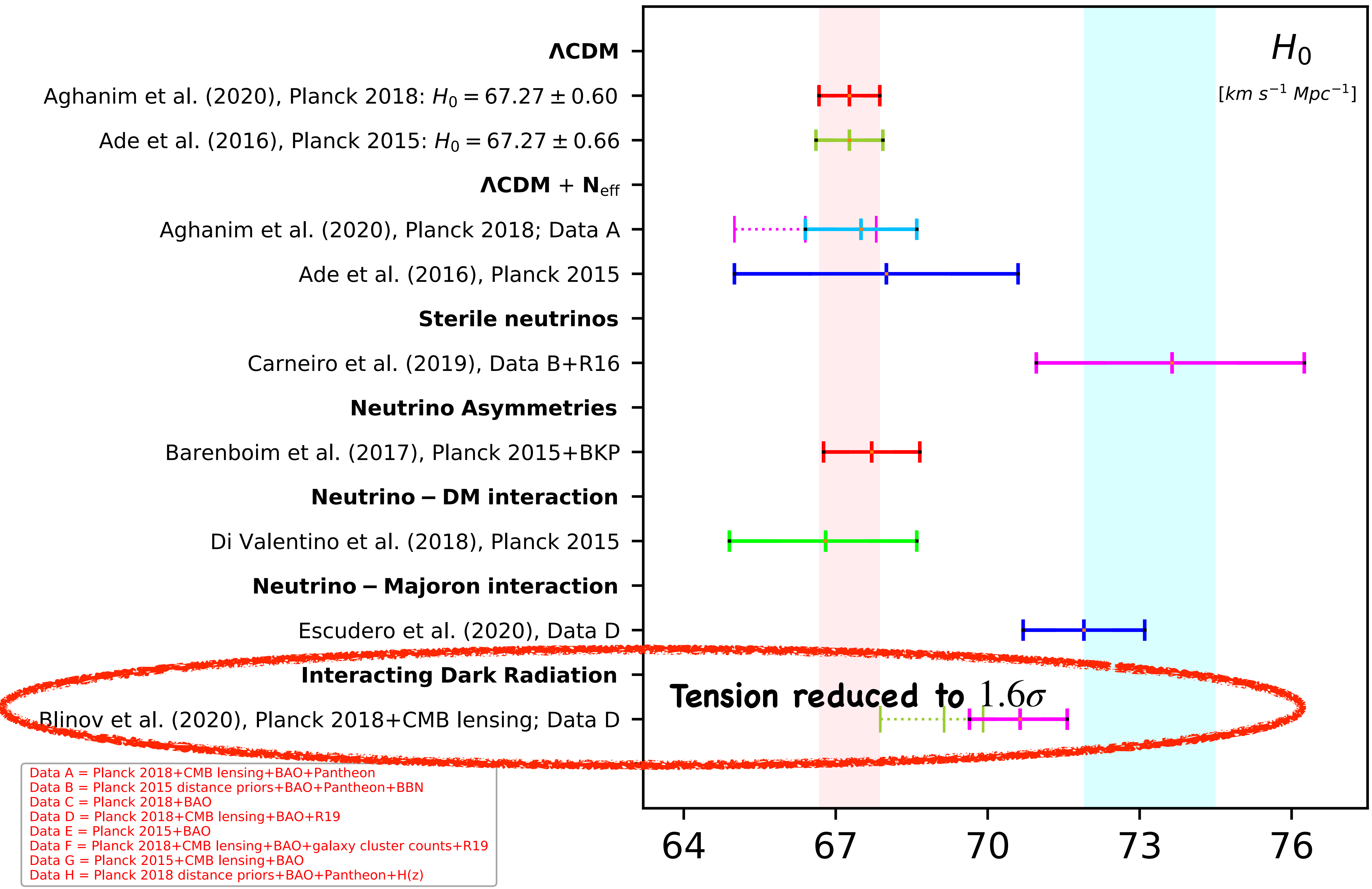


Di Valentino et al, 2103.01183



Tension notably reduced

Di Valentino et al, 2103.01183



Tension reduced to 1.6σ

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.

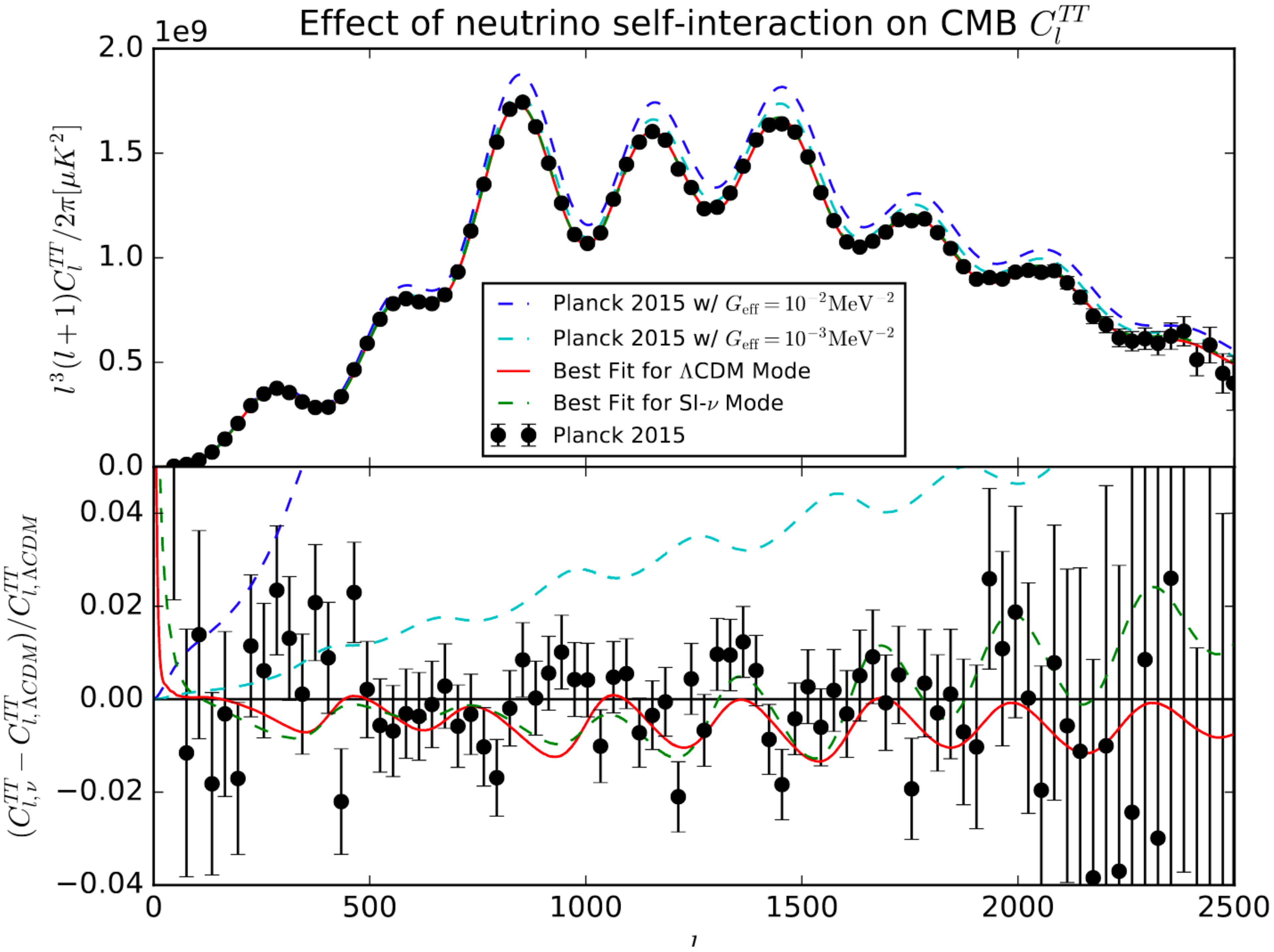
$$\delta\phi \simeq 0.1912\pi \frac{\rho_\nu}{\rho_r}$$

Bashinsky & Seljak, PRD'04

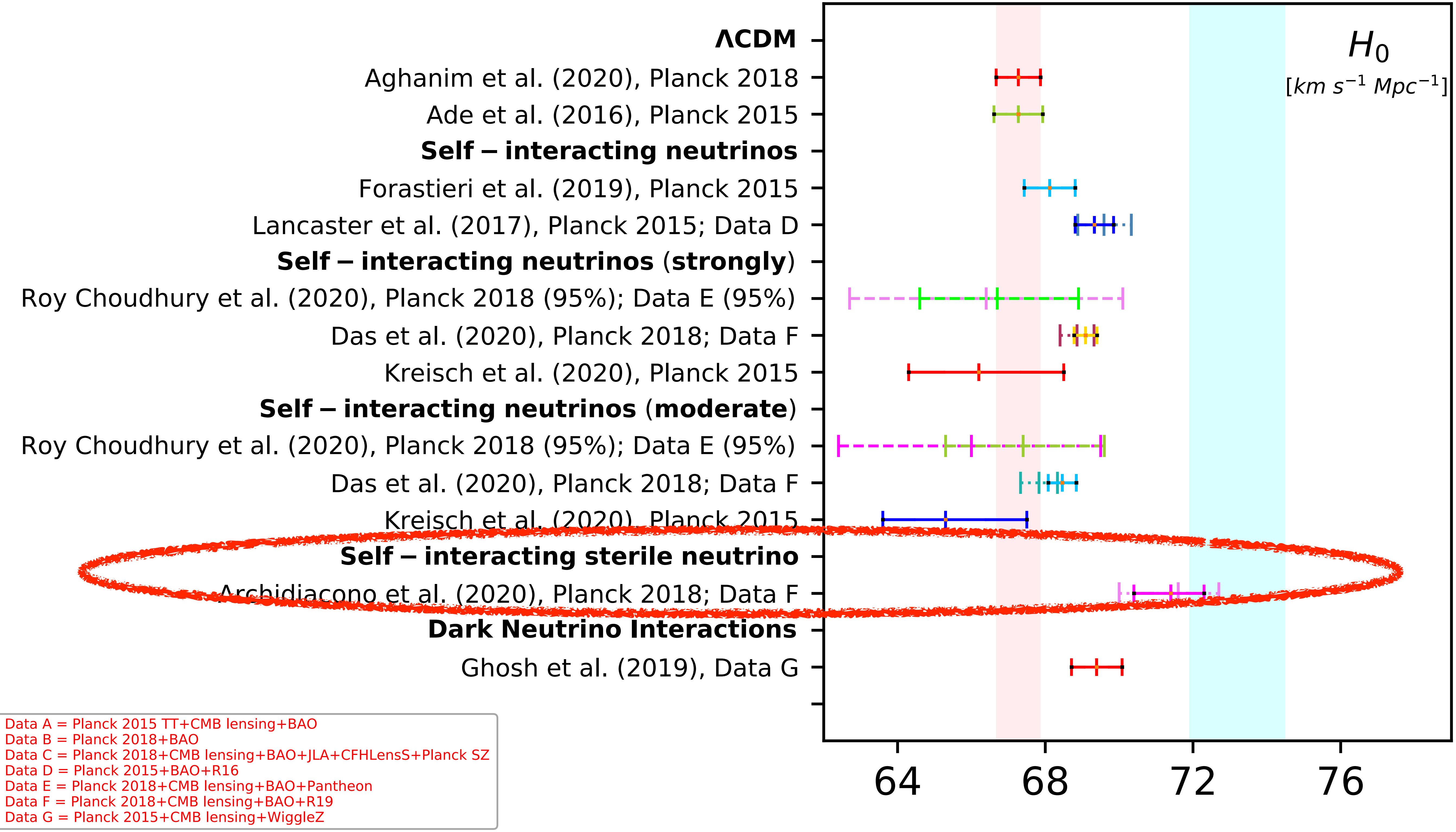
Bashinsky & Seljak, PRD'04; Follin et al, PRL'15;
Baumann et al, JCAP'16; Choi, Chiang & LoVerde, JCAP'18;
Baumann, Green & Zaldarriaga, JCAP'17;
Lancaster et al, JCAP'17; Oldengott, Tram &Wong, JCAP'17;
Kreisch, Cyr-Racine & Doré, PRD'20

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!

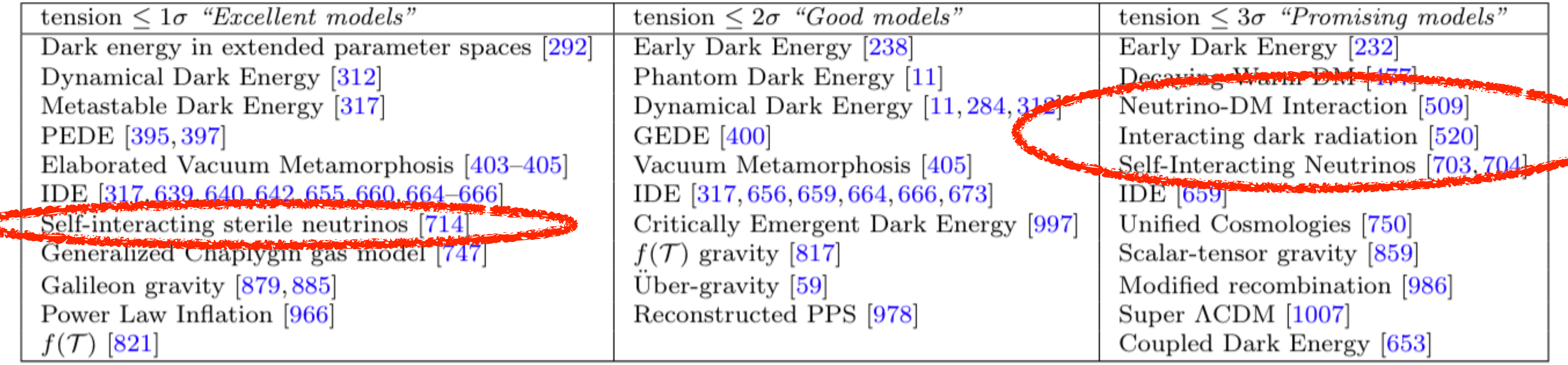
Interacting neutrinos



Lancaster et al, JCAP'17



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

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

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


рахмат
danke
謝謝
ngiyabonga
Баярлалаа
mersi
kia ora
barka
welalin
tack
spas
teşekkür ederim
mahalo
tapadh lea
спасибо
faafetai lava
vinaka
спасибі
blagodaram
dank je
misaotra
matondo
paldies
grazzi
kiitos
dankie
nanni
nandri
dhanyavad
mauruuru
köszönöm
thank you
gracias
хвала
asante
manana
obrigada
tenki
bedankt
bayarlalaa
gràçie
hvala
dankon
aciu
akun
djiere dieuf
tau
mochchakkeram
murakoze
enkosi
dziękuję
дякую
mamnun
chokrane
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gratias ago
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taiku
go raibh maith agat
sobodi
dēkuji
obrigado
sagolun
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ありがとう
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didi madloba
najis tuke
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rahmet
terima kasih
kam sah hamnida
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감사합니다
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merci

BACKUP SLIDES

inνisiblesPlus
elusiνes
neutrinos, dark matter & dark energy physics

IFIC INSTITUT DE FISICA CORPUSCULAR

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

VNIVERSITAT ID 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

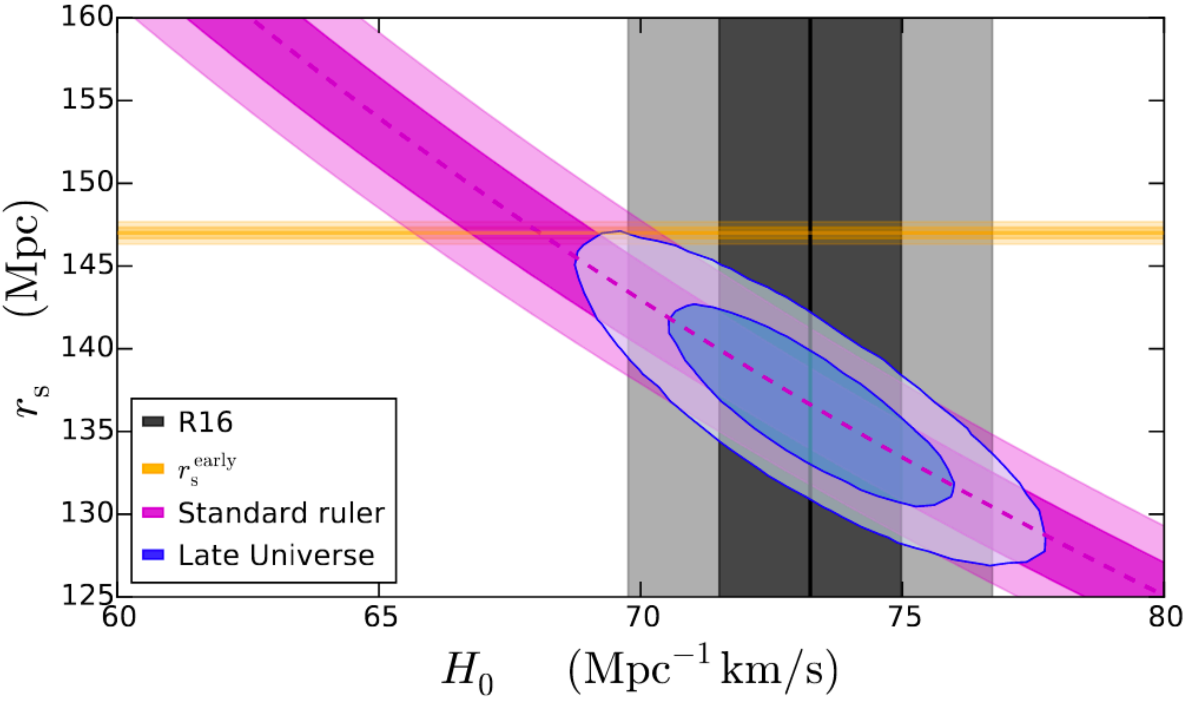
All solutions are required to leave unchanged θ_s , θ_{EQ} & θ_D

The ~~H~~ r_s tension?

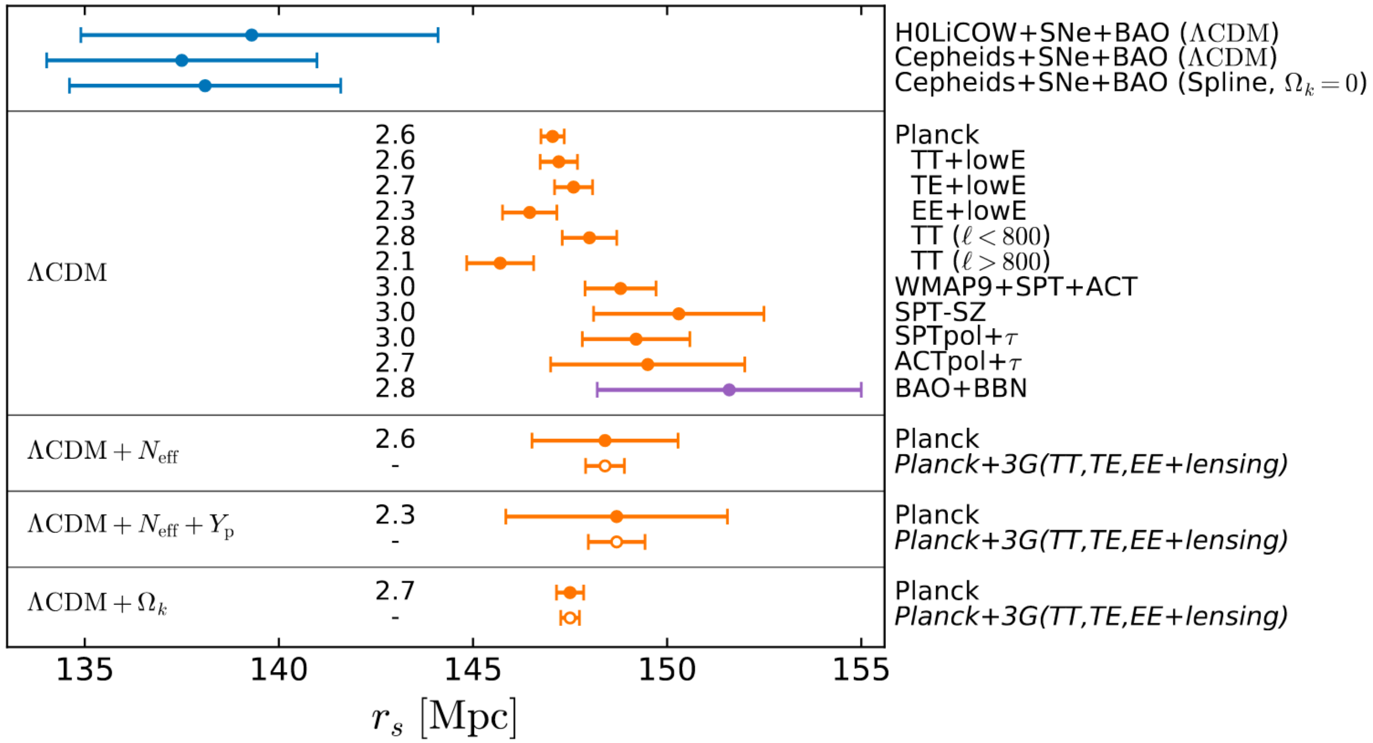
BAO observations determine D_V/r_s (or Hr_s & D_Ar_s). One can use BAO, SNIa & Cepheids data to infer r_s:

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

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

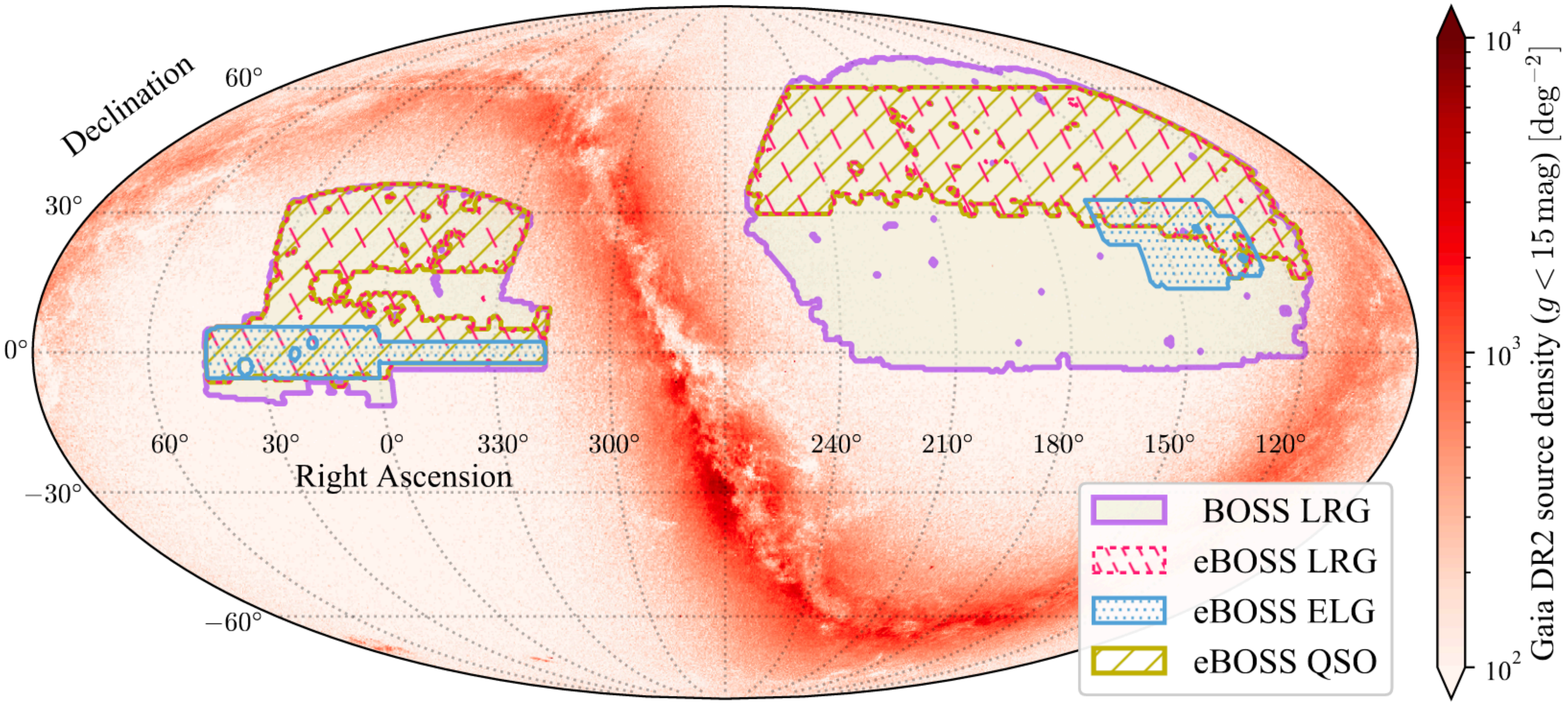
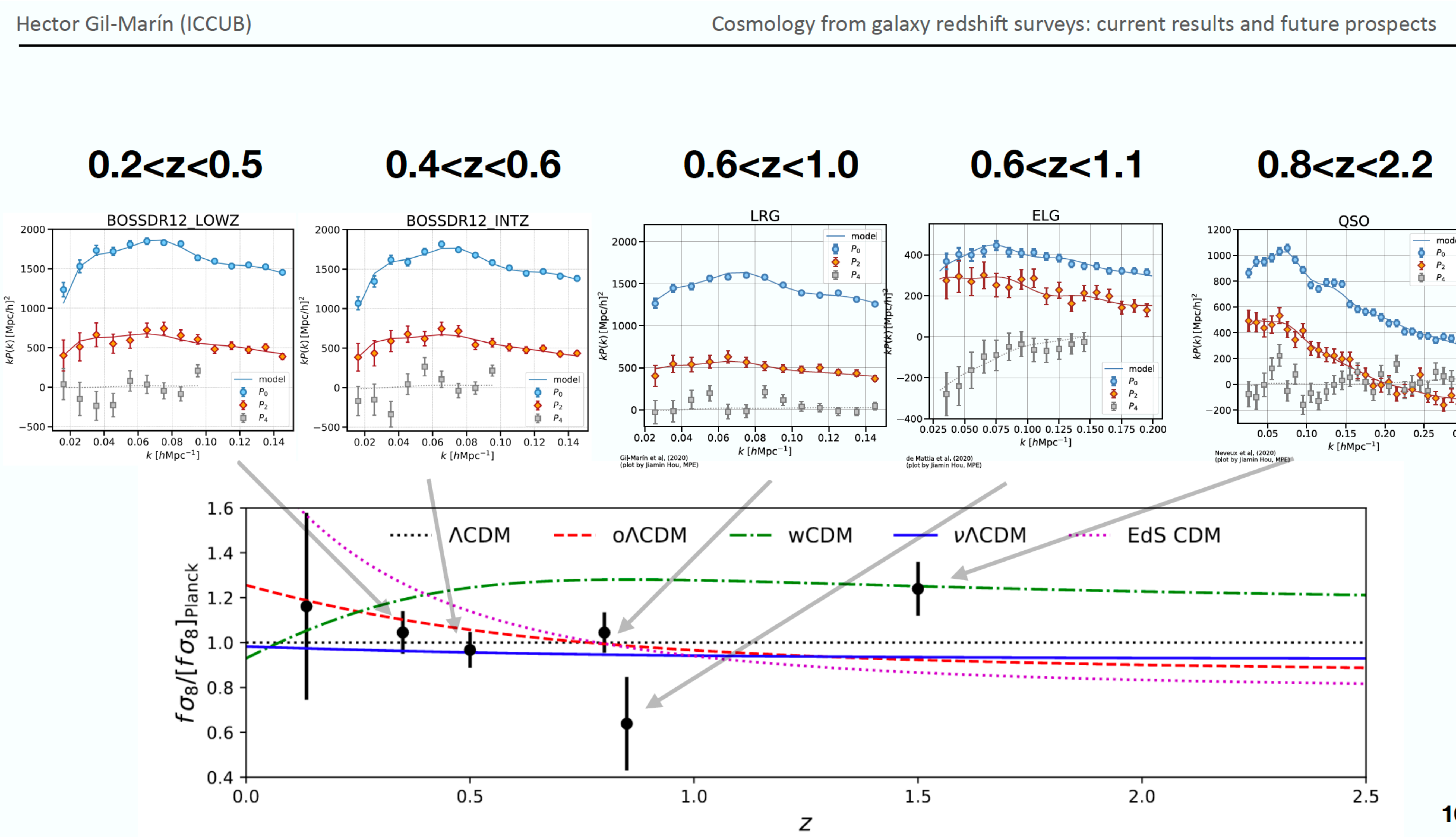


Figure 1. The sky coverage of eBOSS DR16 tracers and BOSS DR12 LRGs, as well as the density map of Gaia DR2 sources with $g < 15$ mag.

Baryon Acoustic Oscillations



Hector Gil-Marín (ICCUB)

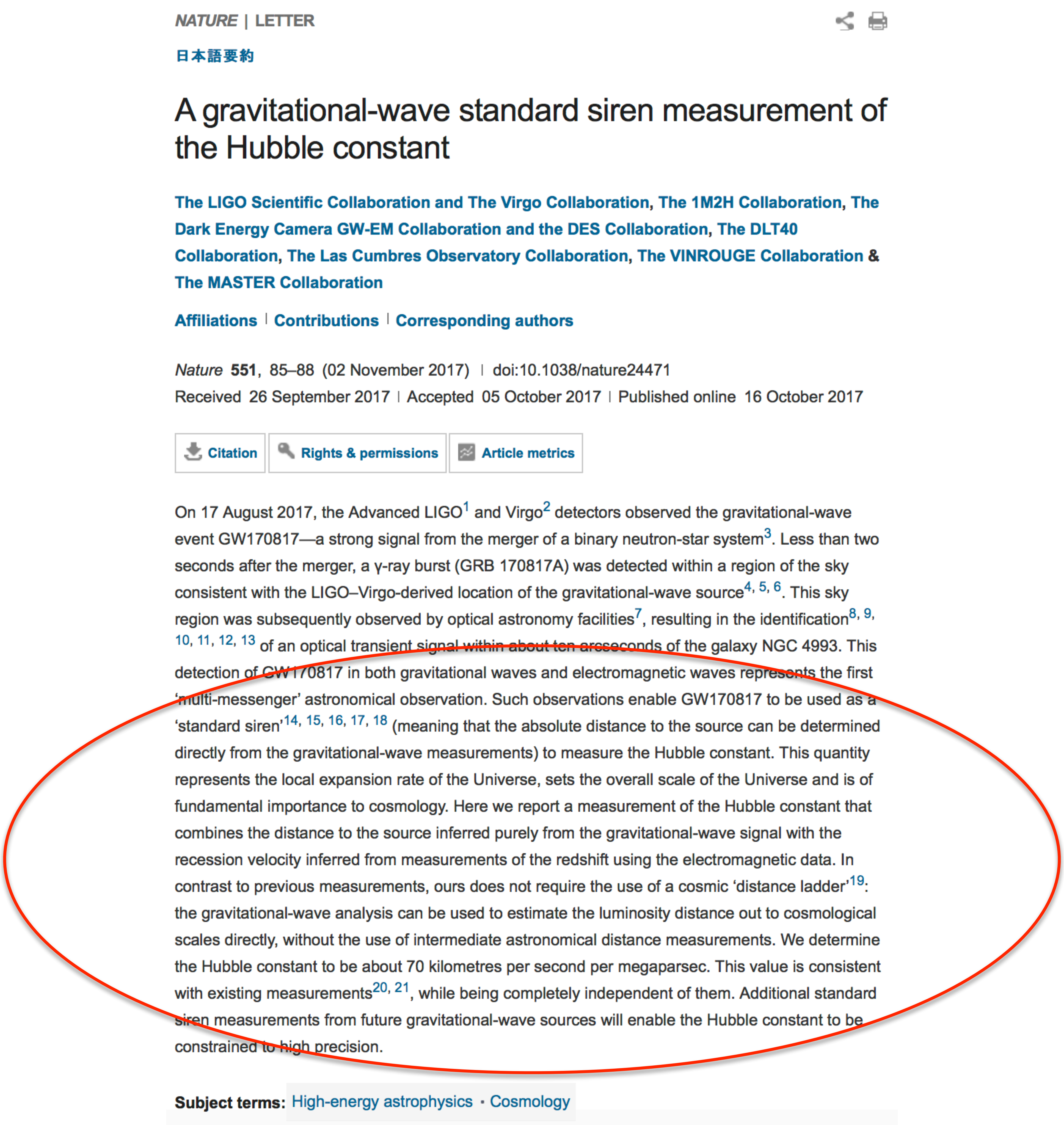
Cosmology from galaxy redshift surveys: current results and future prospects

0.2<z<0.5 **0.4<z<0.6** **0.6<z<1.0** **0.6<z<1.1** **0.8<z<2.2**

Gil-Marín et al, (2020) (plot by Jiamin Hou, MPE)

de Mattia et al. (2020) (plot by Jiamin Hou, MPE)

Neveux et al, (2020) (plot by Jiamin Hou, MPE)



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
Received 26 September 2017 | Accepted 05 October 2017 | Published online 16 October 2017

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.

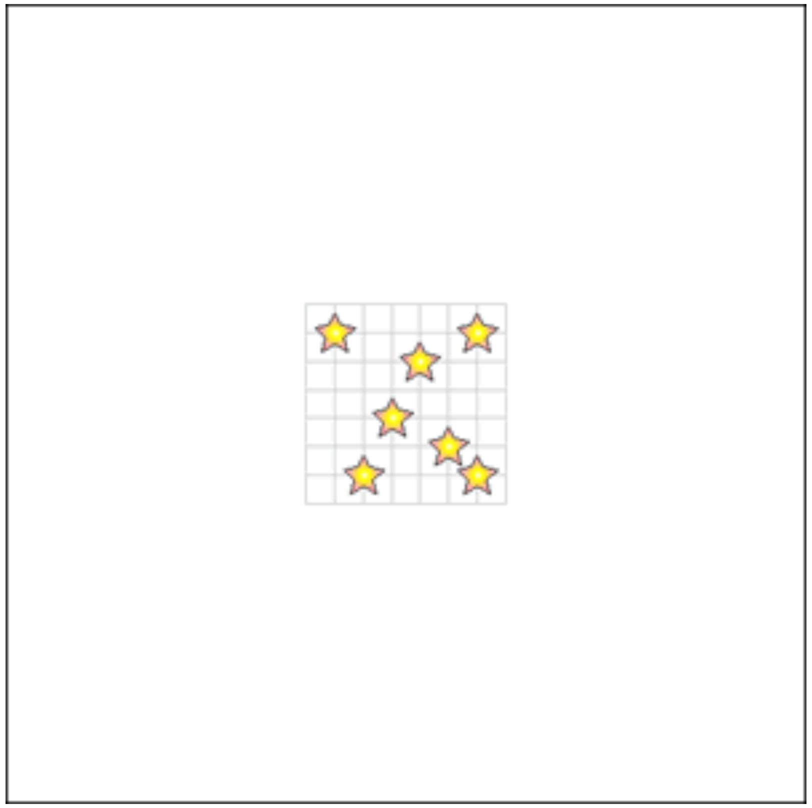
Subject terms: High-energy astrophysics • Cosmology

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.

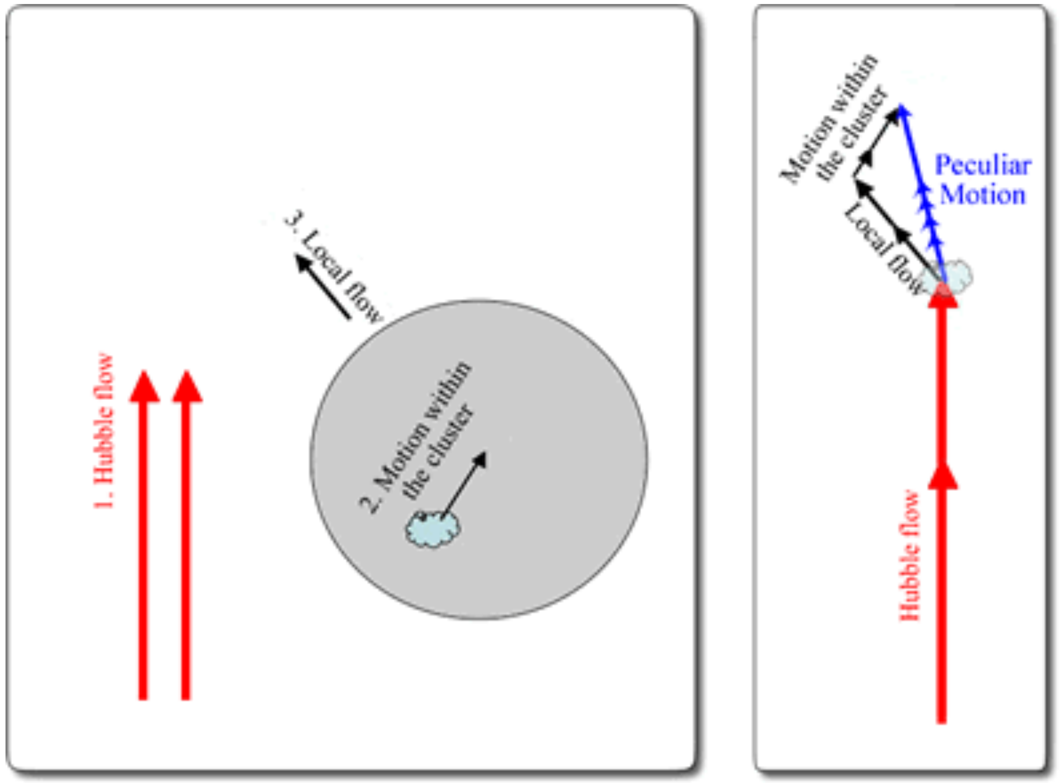
$$v_H = H_0 d$$

$$d = 43.8^{+2.9}_{-6.9}\mathrm{Mpc}$$

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.



The **local flow** and the motion of the galaxy within its **cluster environment** also contribute.

NGC 4993 is part of a collection of galaxies, ESO 508, which has a center-of-mass recession velocity relative to the frame of the cosmic CMB of 3 327 ± 72 km/s. The authors correct the group velocity by 310 km/s, due to the local gravitational fields.

The standard error on their estimate of the peculiar velocity is 69 km/s, but recognizing that this value may be sensitive to details of the bulk flow motion, in their analysis adopt a more conservative estimate of 150 km/s for the uncertainty on the peculiar velocity at the location of NGC 4993 and fold this in their estimate of the uncertainty on v_H.
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.

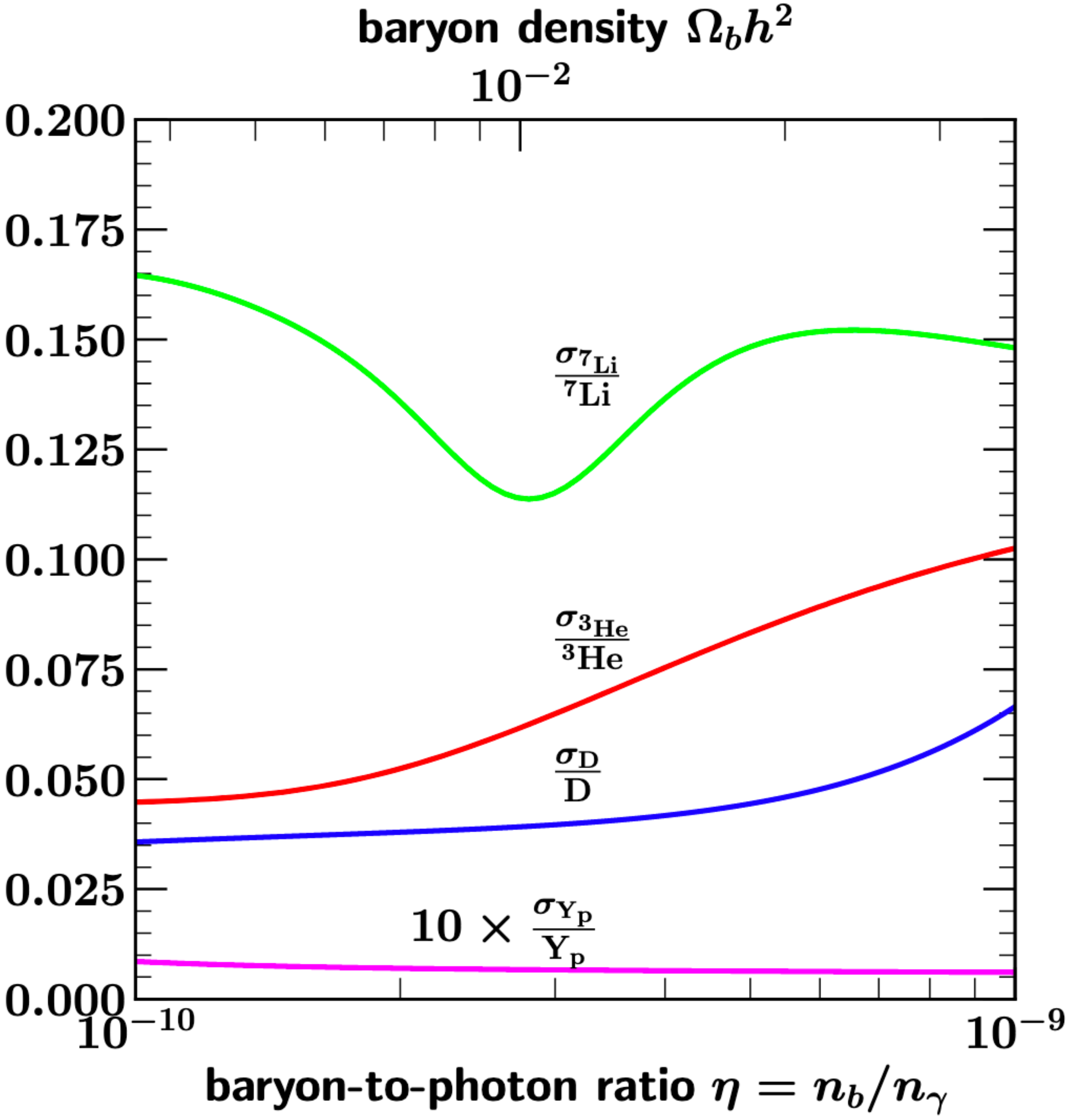
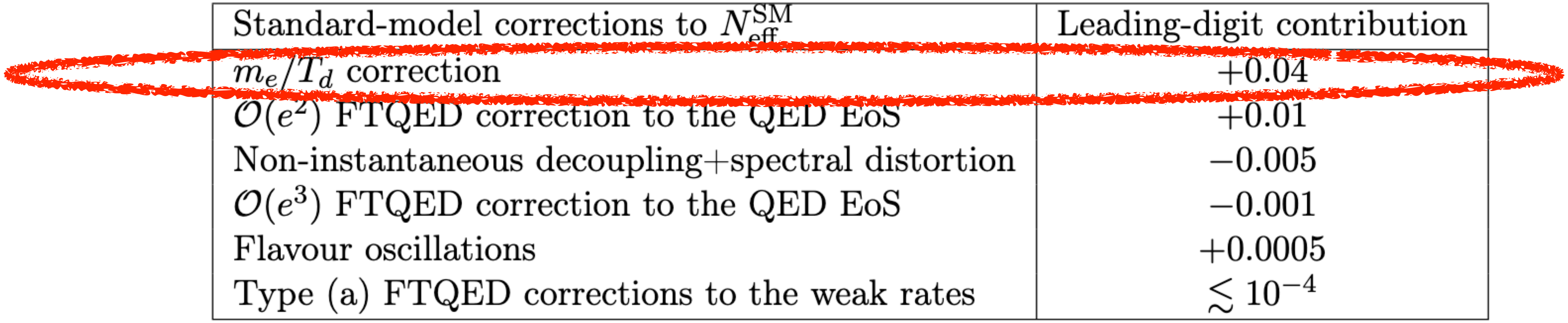


FIG. 3. Fractional uncertainties in the light element abundance predictions shown in Fig. 2. For each species i, we plot ratio of the standard deviation σ_i to the mean μ_i, as a function of baryon-to-photon ratio. The relative uncertainty of the ^{4}He abundance has been multiplied by a factor of 10.

Fields, Olive, Yeh & Young' JCAP 20



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

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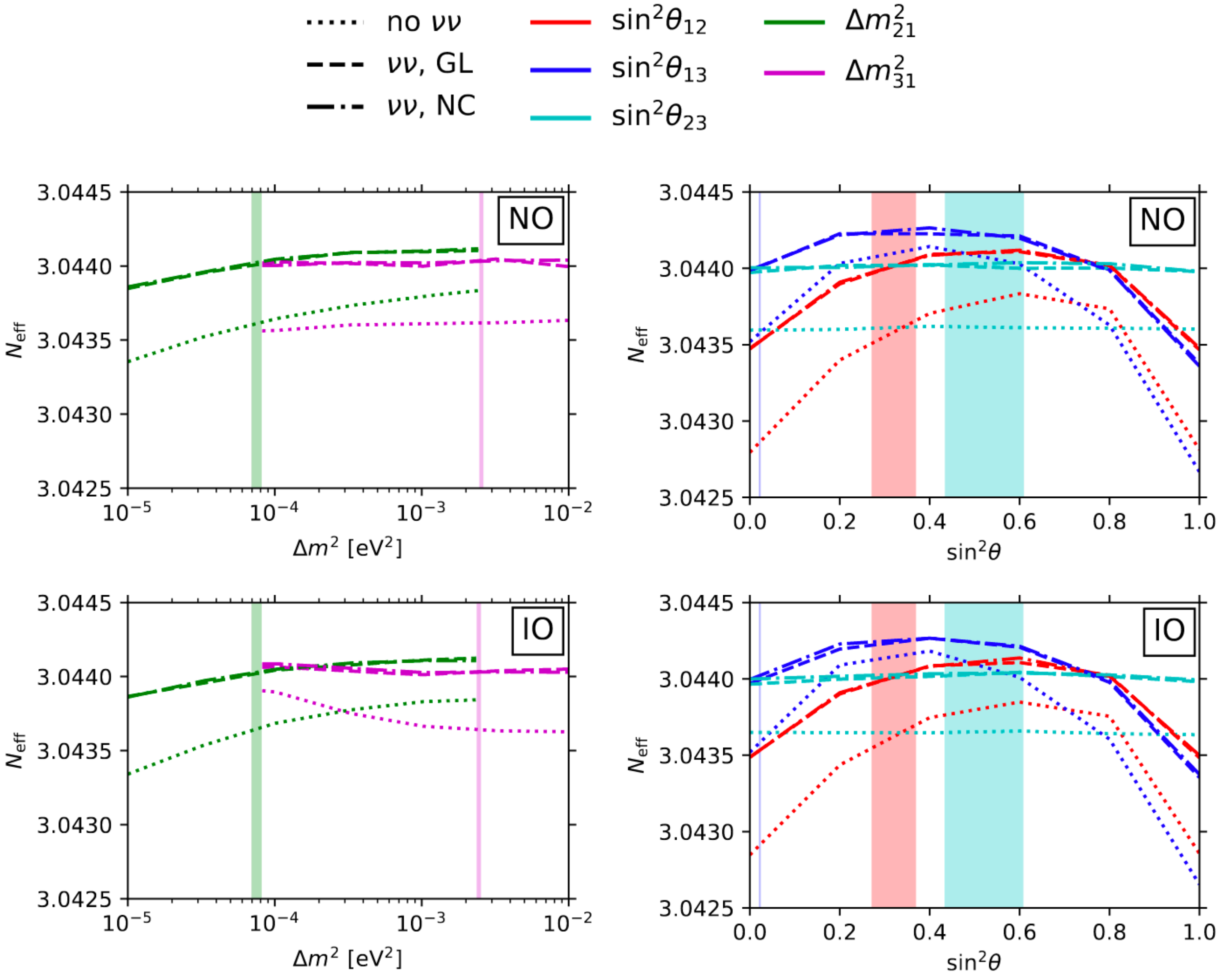
$\mathcal{O}(e^3)$ FTQED correction to the QED EoS	-0.001
Flavour oscillations	$+0.0005$
Type (a) FTQED corrections to the weak rates	$\lesssim 10^{-4}$



Bennett et al, 2012.02726

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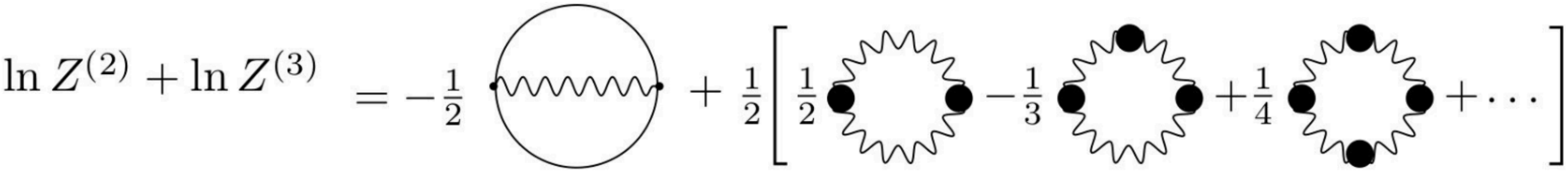
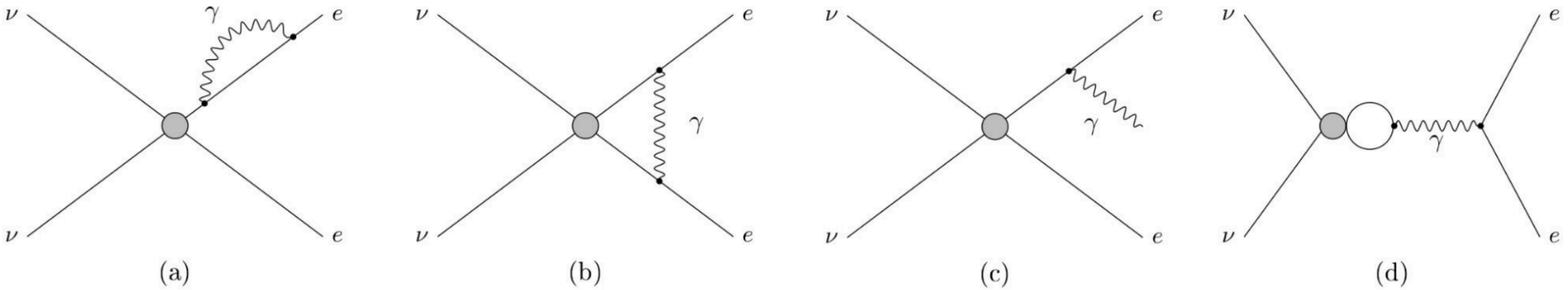
$\mathcal{O}(e^2)$ FTQED correction to the QED EoS	$+0.01$
Non-instantaneous decoupling+spectral distortion	-0.005
$\mathcal{O}(e^3)$ FTQED correction to the QED EoS	-0.001
Flavour oscillations	$+0.0005$
Type (a) FTQED corrections to the weak rates	$\lesssim 10^{-4}$

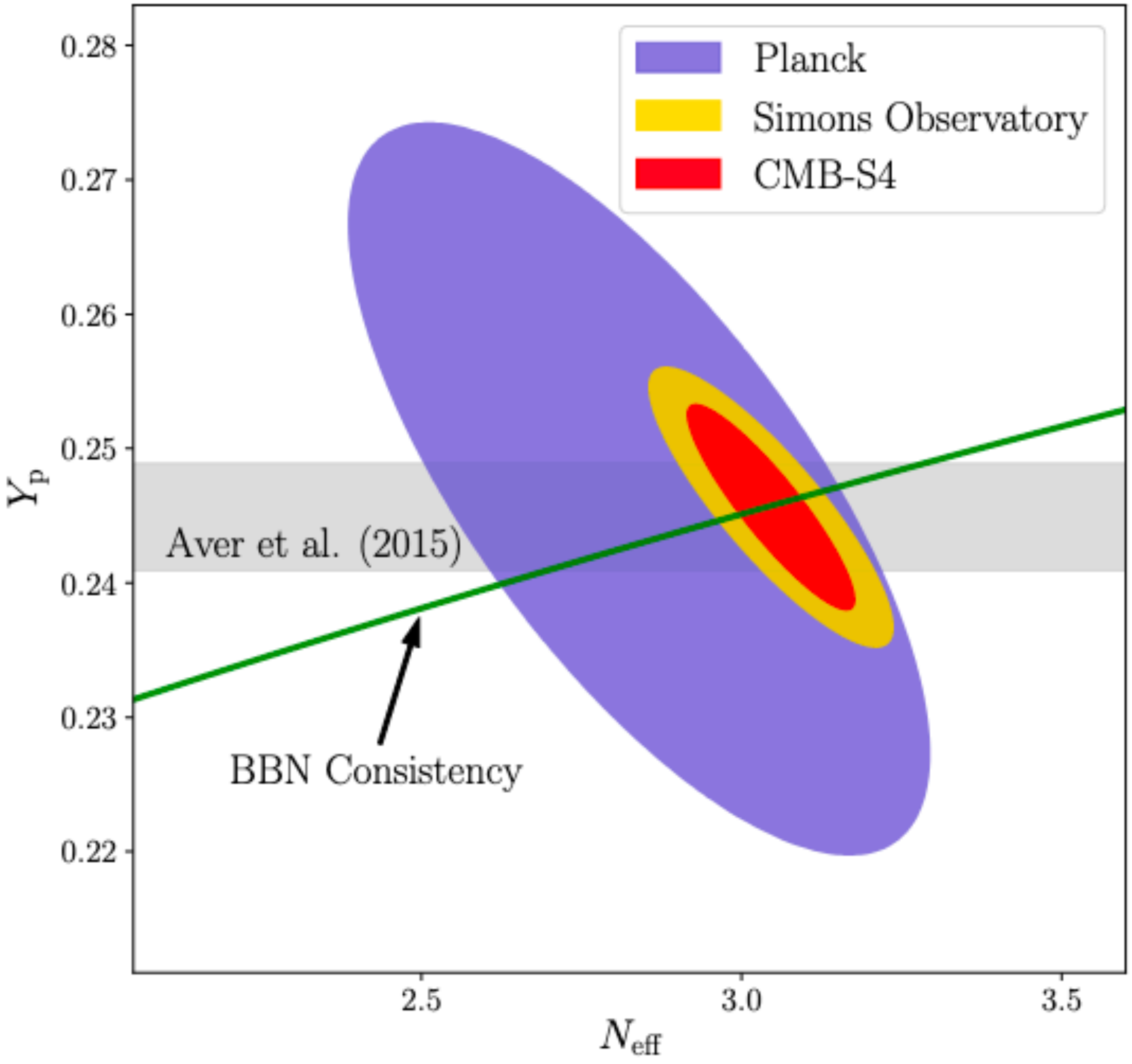
Bennett et al, 1911.04504





CMB Stage IV: N_{eff}

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



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

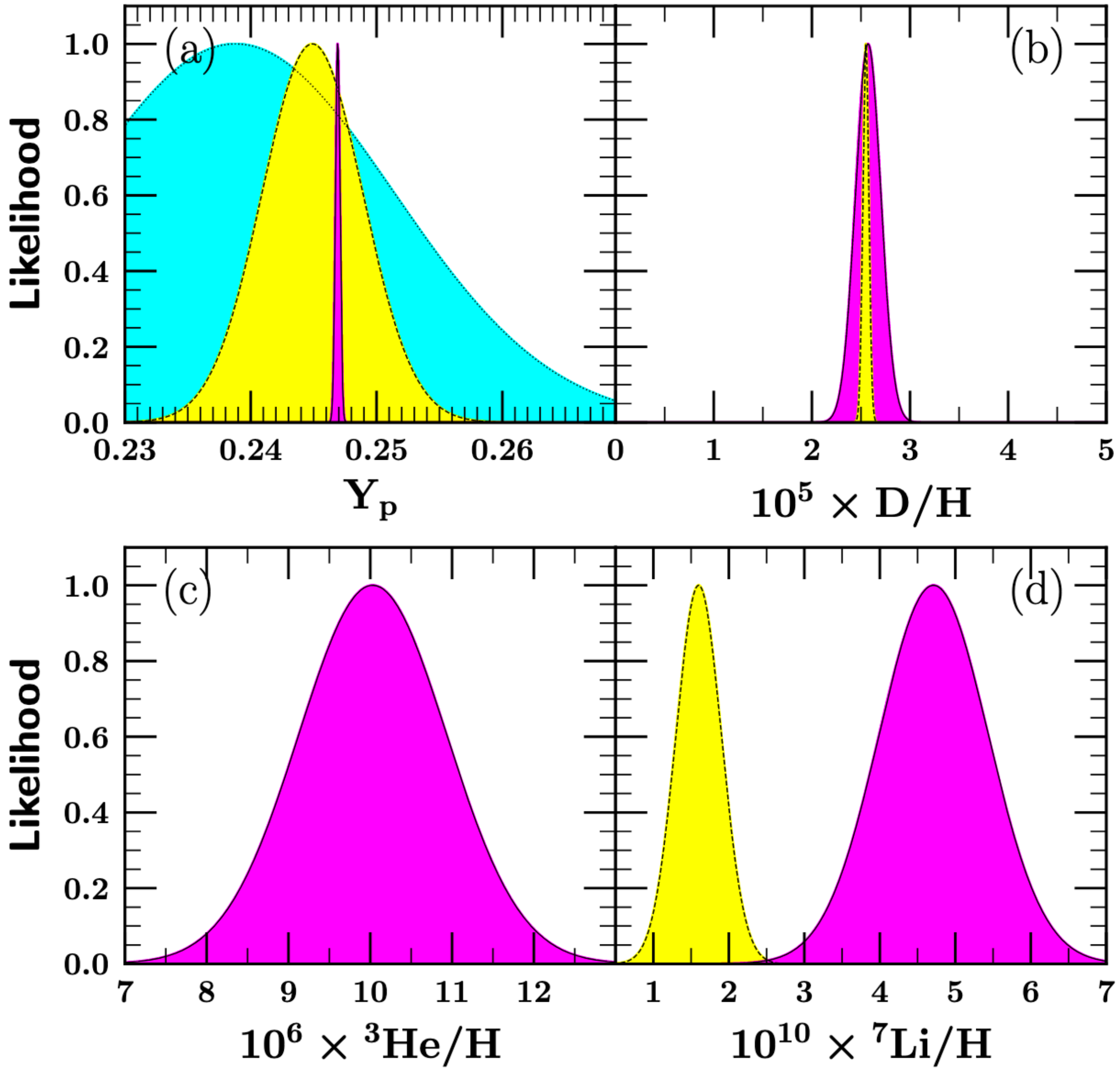
CMB: N_{eff}

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

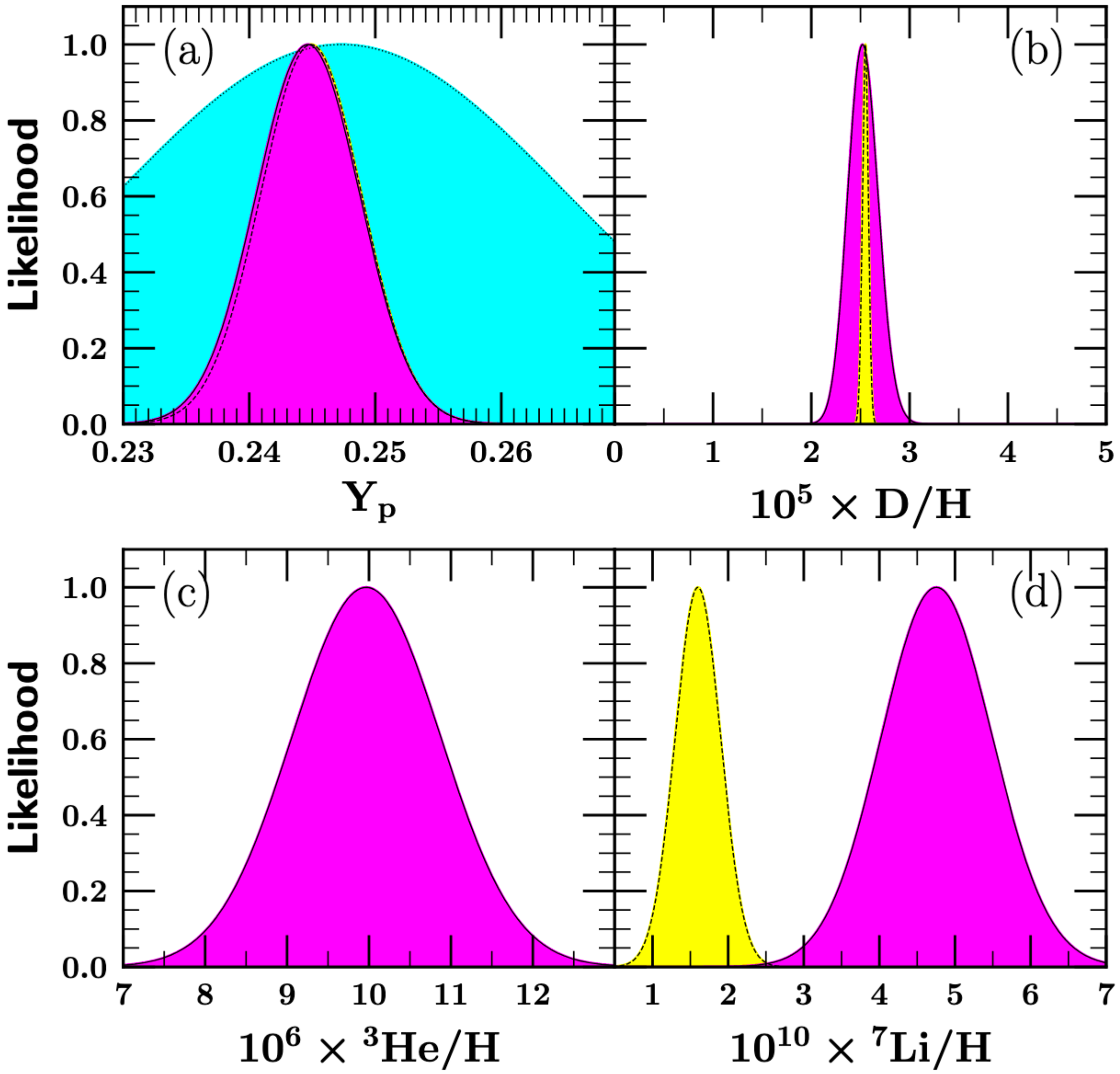
$$Y_p = 0.24465 \pm 0.00410 \qquad (0.24498)$$

Fields, Olive, Yeh & Young JCAP '20

Planck **baseline (N_ν = 3) + BBN**



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

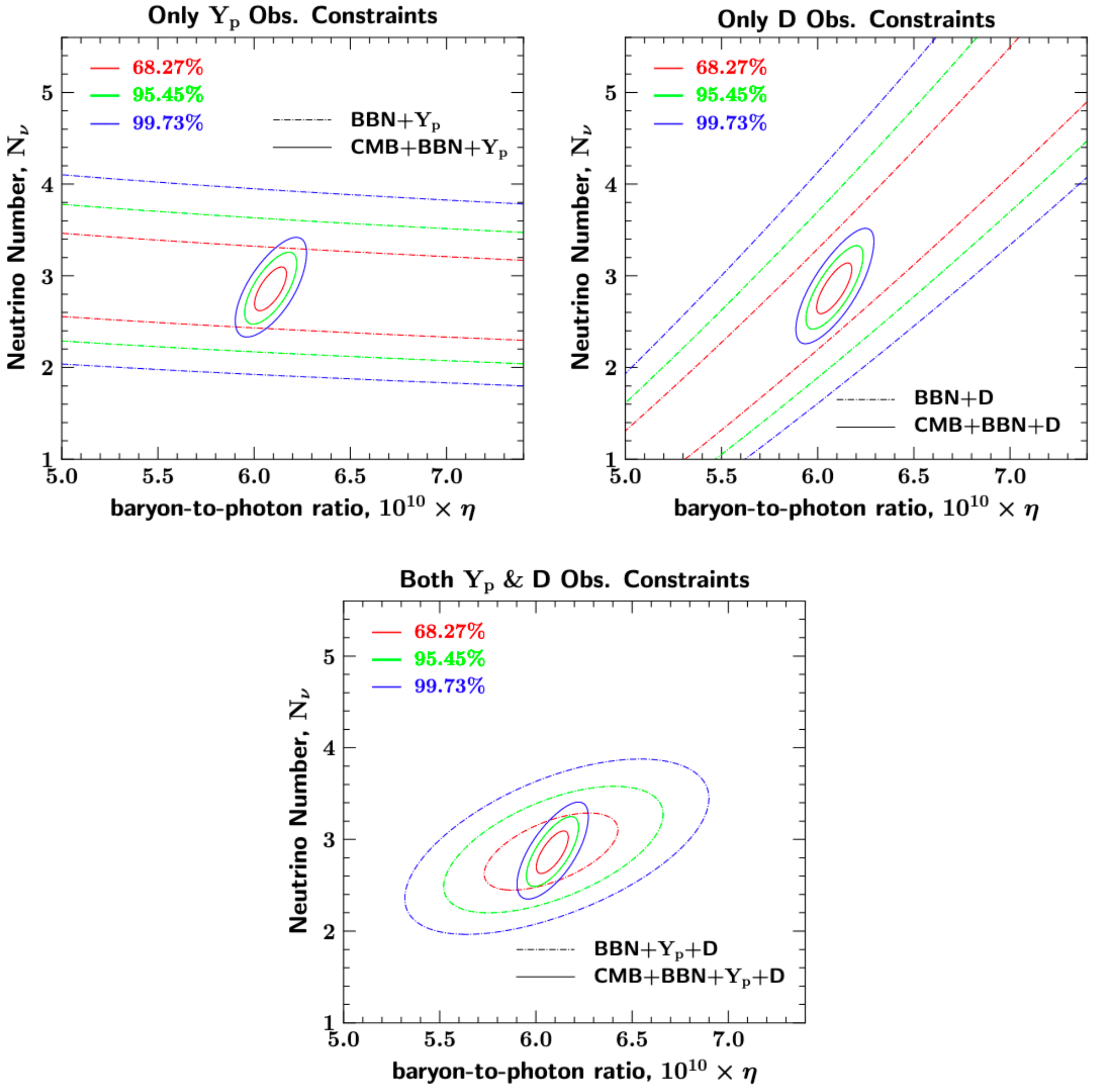


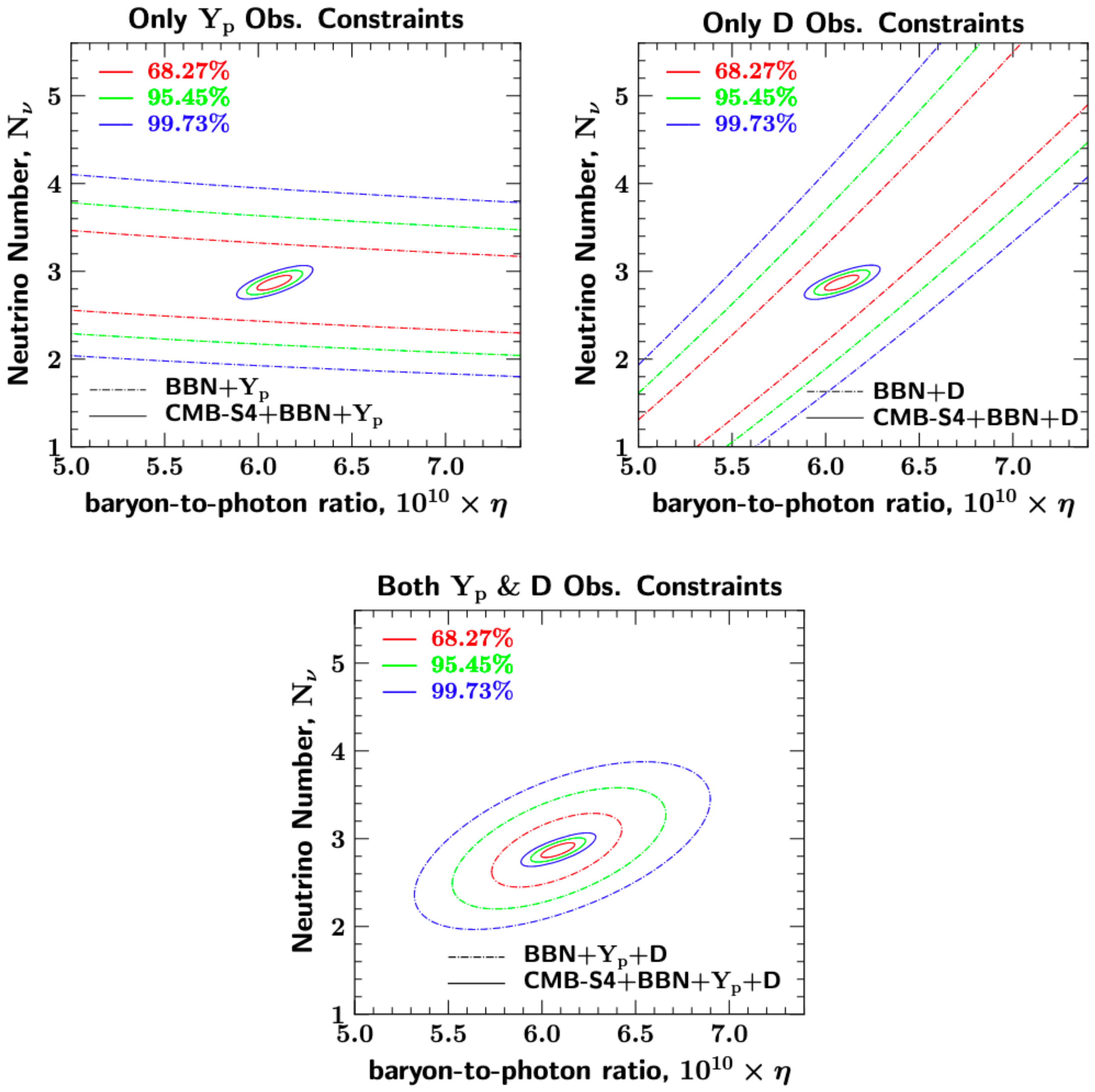
BBN+ CMB

Astronomical measurements

CMB He determinations

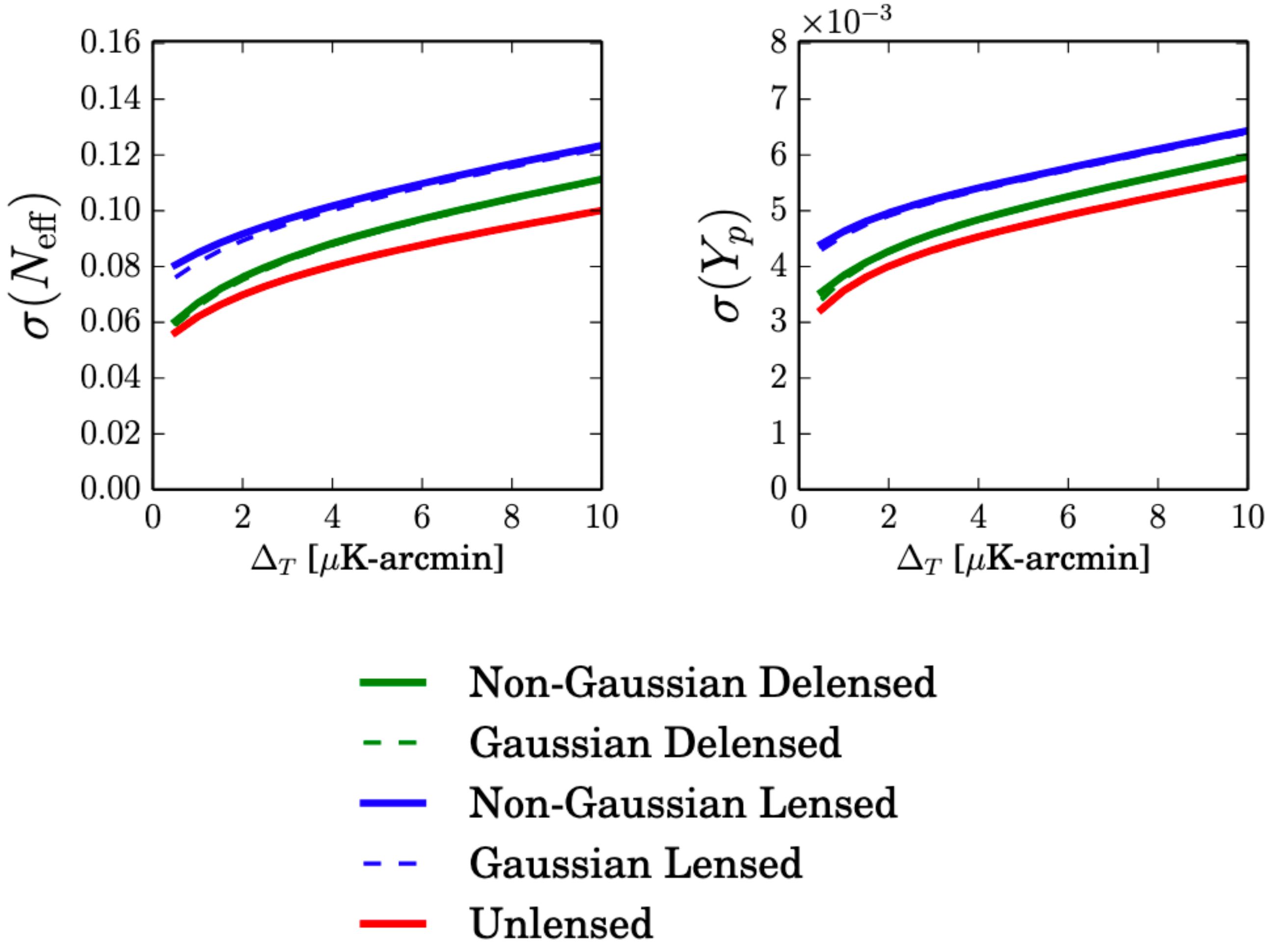
CMB Stage IV: N_{eff}

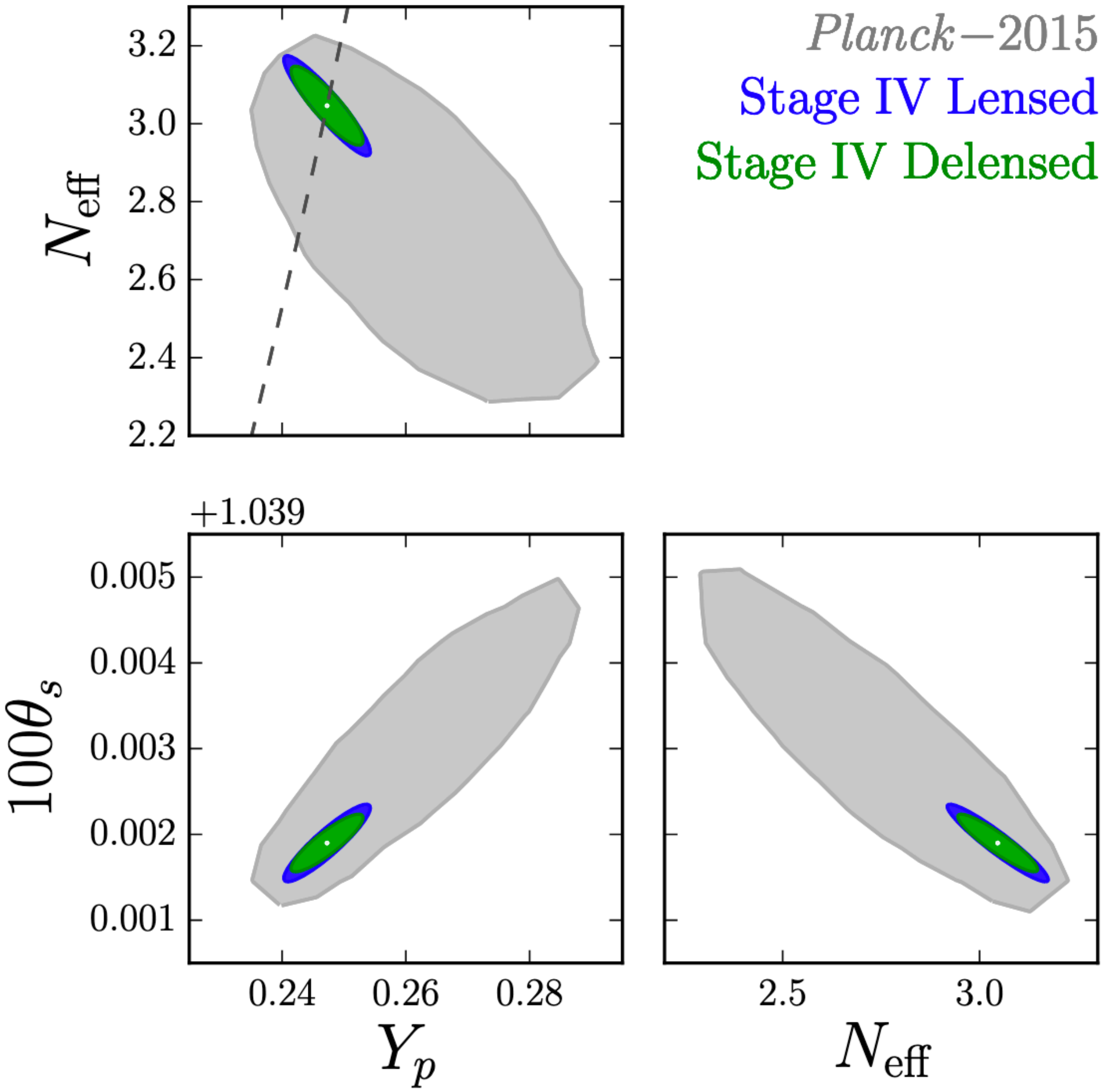




Fields, Olive, Yeh & Young JCAP '20

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 multiparameter 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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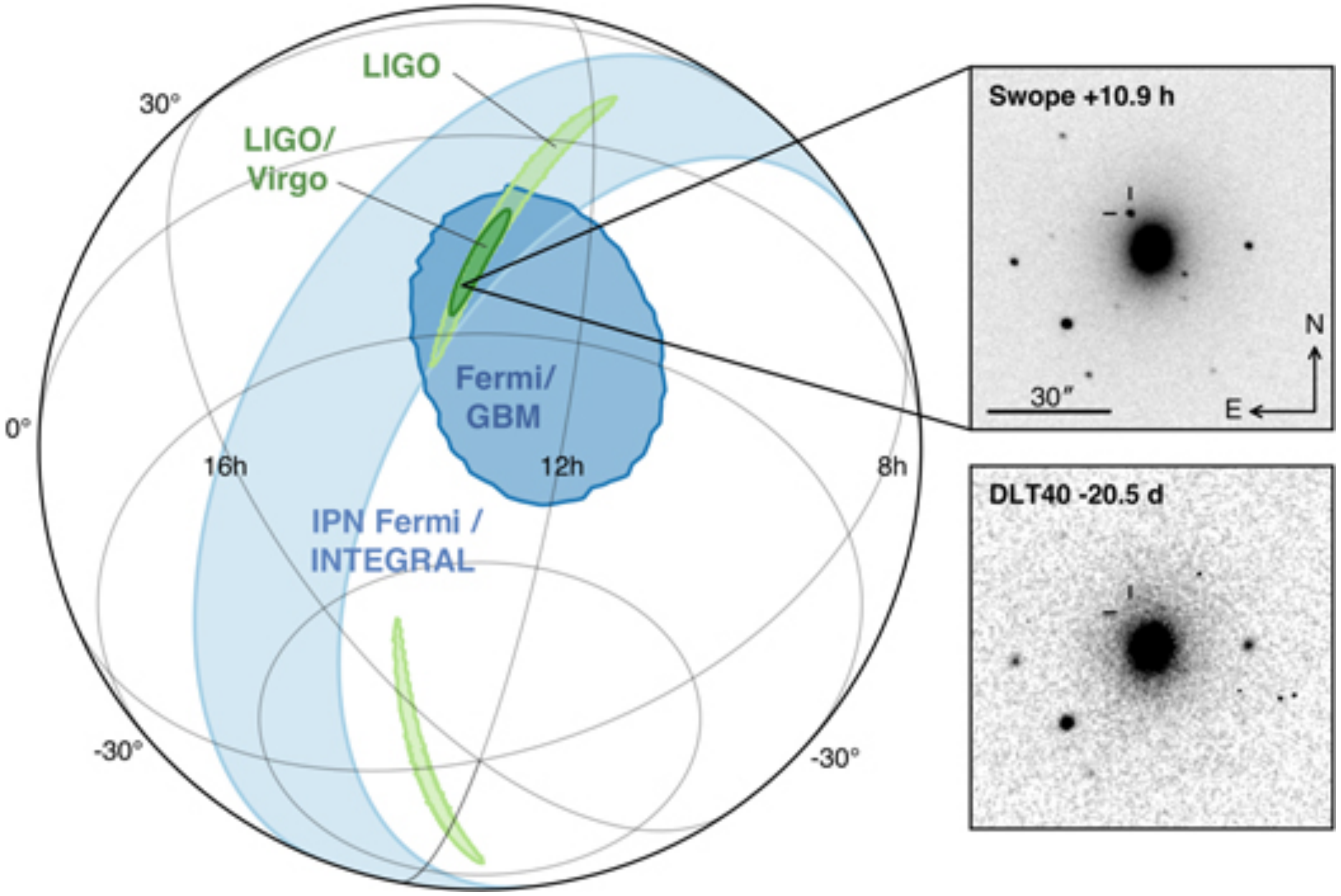
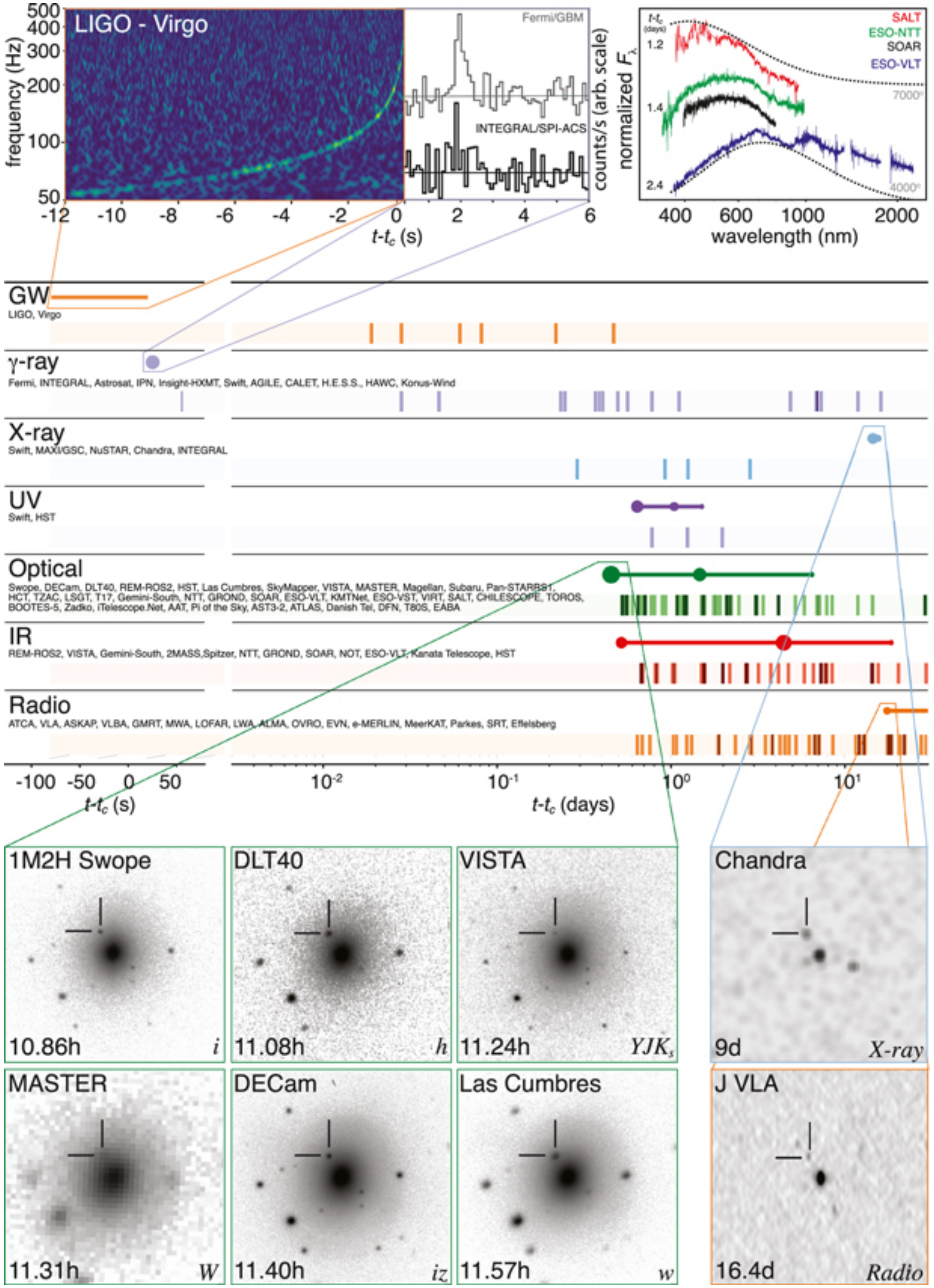
GW170817

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

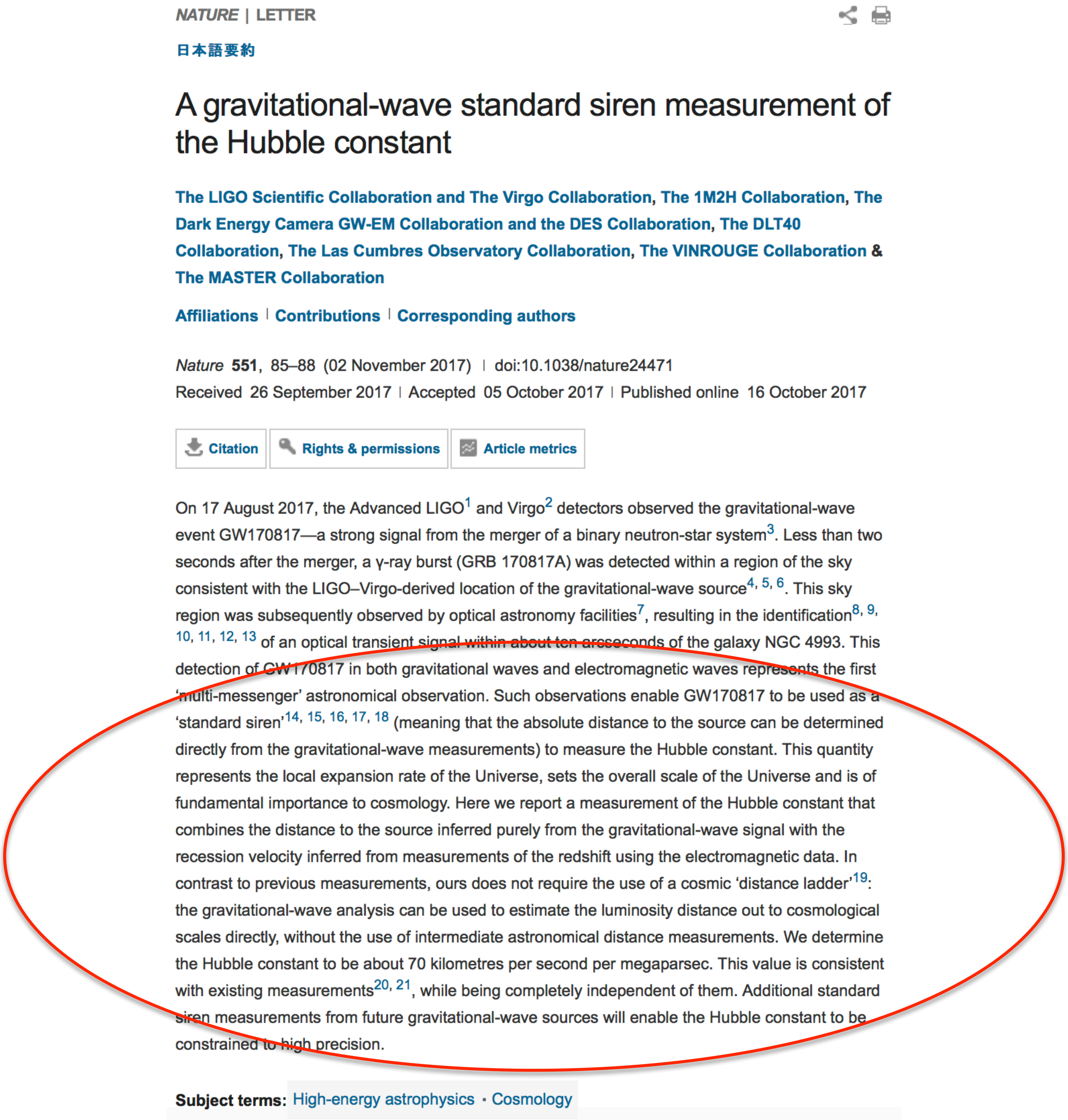


Localization of the gravitational-wave, gamma-ray, an
optical signals.
The left panel shows an orthographic projection of th
90% credible regions from LIGO (light green),
the initial LIGO-Virgo localization (dark green),
IPN triangulation from the time delay between Fermi a
INTEGRAL (light blue), and 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)
500
400
300
200
100
50
-12
-10
-8
-6
-4
-2
0
2
4
6
t-t_c (s)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
normalized F_λ
t-t_c (days)
1.2
1.4
2.4
SALT
ESO-NTT
SOAR
ESO-VLT
7000°
4000°
400
600
1000
2000
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
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
-100
-50
0
50
t-t_c (s)
10^-2
10^-1
10^0
10^1
t-t_c (days)
1M2H Swope
10.86h
i
DLT40
11.08h
h
VISTA
11.24h
YJK_s
Chandra
9d
X-ray
MASTER
11.31h
W
DECam
11.40h
iz
Las Cumbres
11.57h
w
J VLA
16.4d
Radio



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**

Nature **551**, 85–88 (02 November 2017) | doi:10.1038/nature24471
Received 26 September 2017 | Accepted 05 October 2017 | Published online 16 October 2017

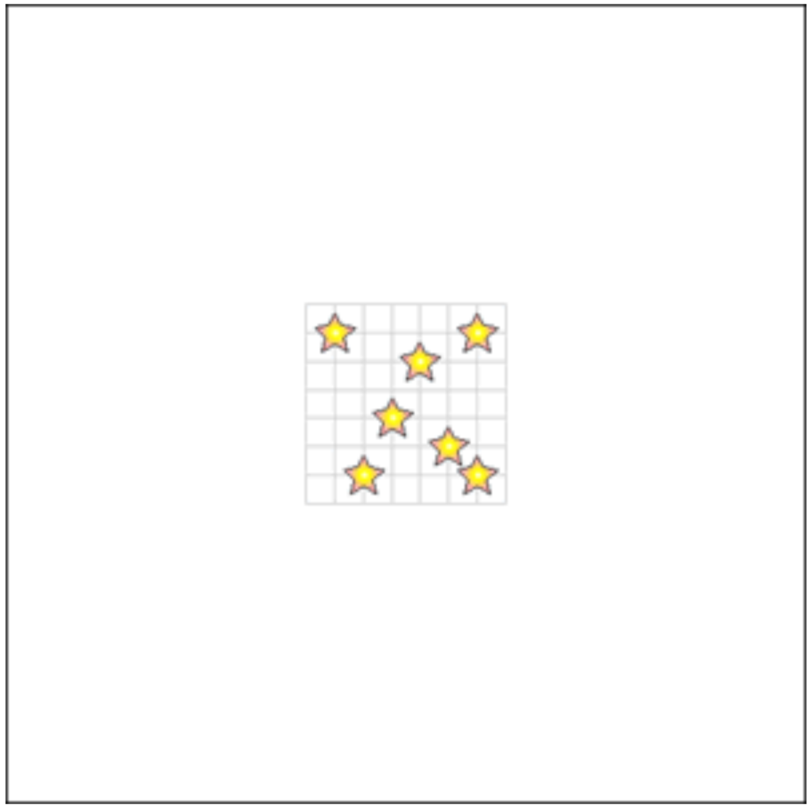
On 17 August 2017, the Advanced LIGO[1] and Virgo[2] detectors observed the gravitational-wave event GW170817—a strong signal from the merger of a binary neutron-star system[3]. Less than two seconds after the merger, a γ-ray burst (GRB 170817A) was detected within a region of the sky consistent with 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

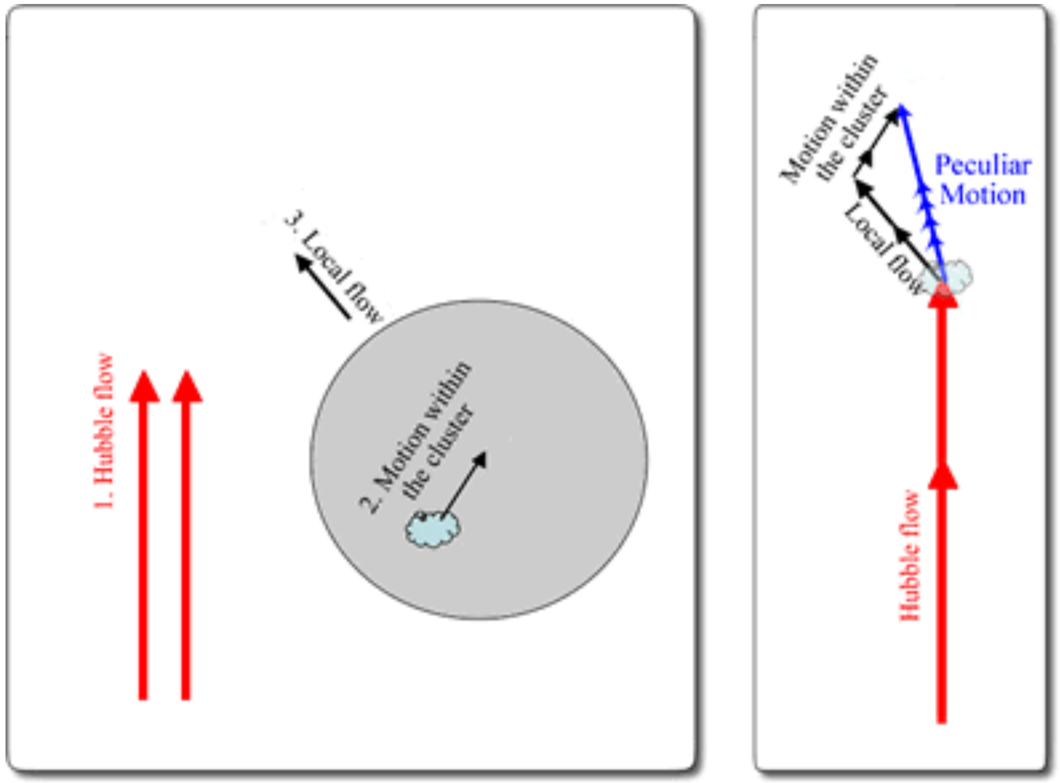
The method combines the distance to the source inferred purely from the gravitational-wave signal with the recession velocity inferred from measurements of the redshift using electromagnetic data.

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

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.



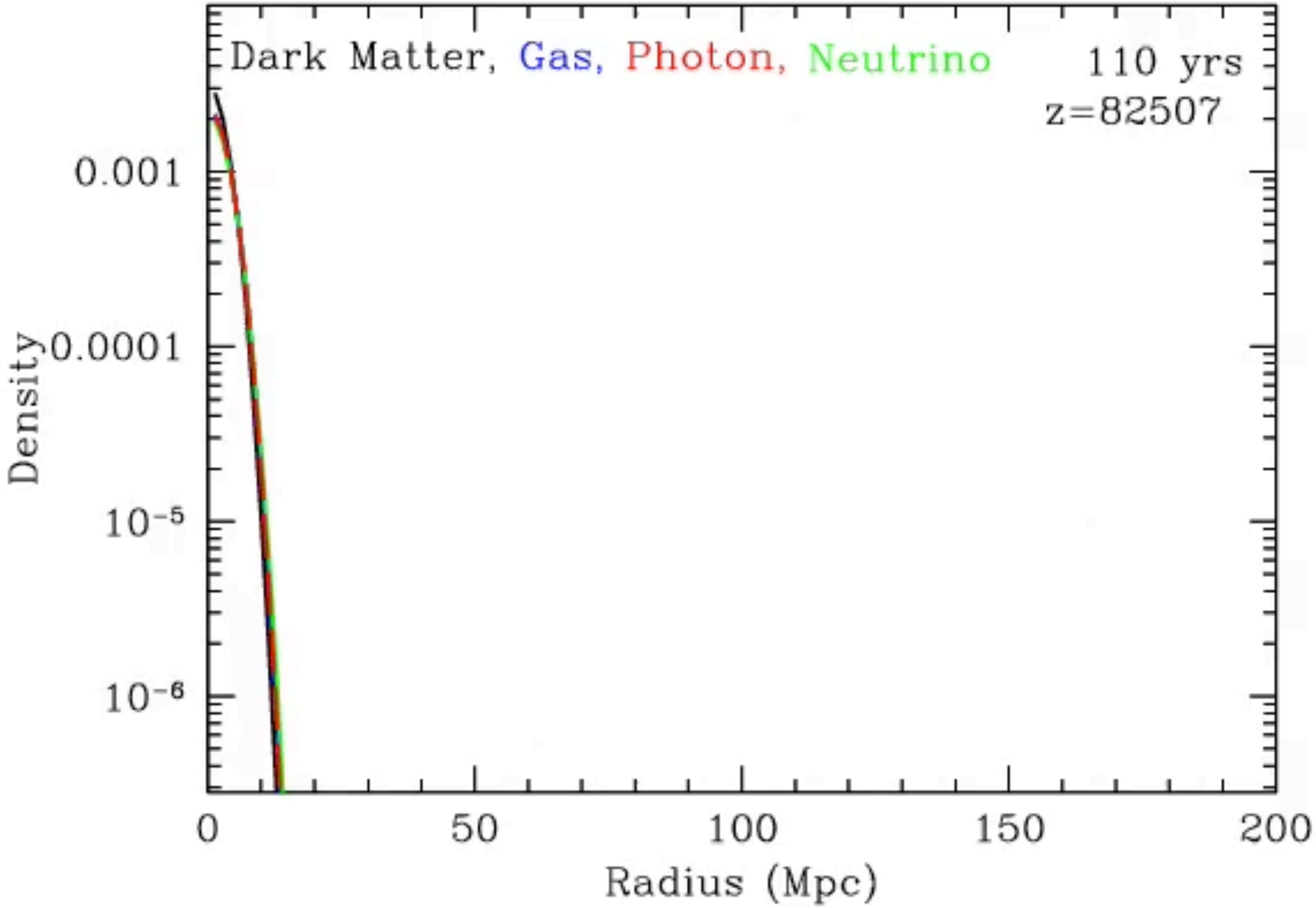
The **local flow** and the motion of the galaxy within its **cluster environment** also contribute.

NGC 4993 is part of a collection of galaxies, ESO 508, which has a center-of-mass recession velocity relative to the frame of the cosmic CMB of 3 327 ± 72 km/s. The authors correct the group velocity by 310 km/s, due to the local gravitational fields.

The standard error on their estimate of the peculiar velocity is 69 km/s, but recognizing that this value may be sensitive to details of the bulk flow motion, in their analysis adopt a more conservative estimate of 150 km/s for the uncertainty on the peculiar velocity at the location of NGC 4993 and fold this in their estimate of the uncertainty on v_H.
From this, they obtain a Hubble velocity v_H= 3 017 ± 166 km/s.

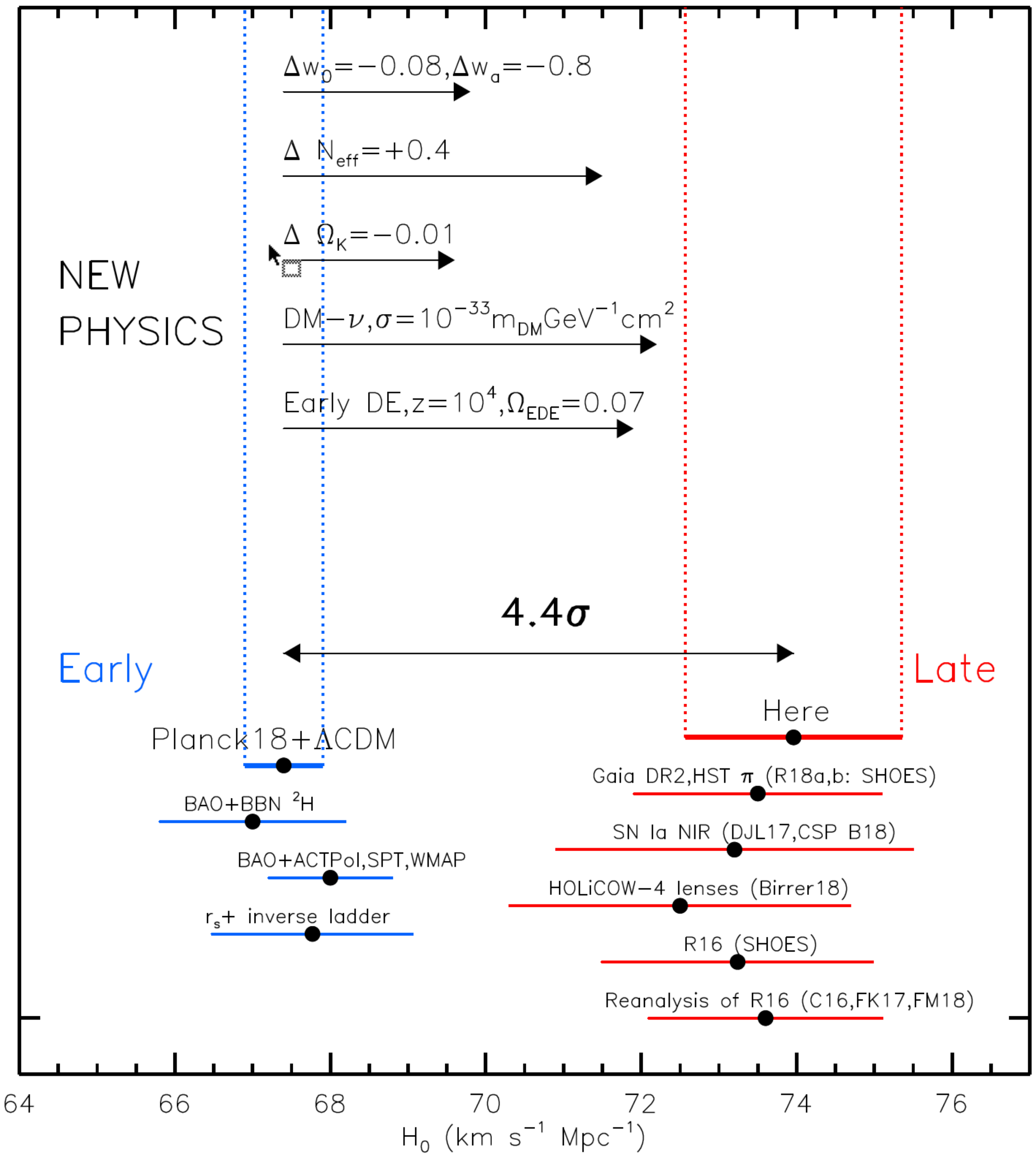
Using this recessional velocity, one can find H_0= 68.9 km/s.

Baryon Acoustic Oscillations



From D. Eisenstein and M. White

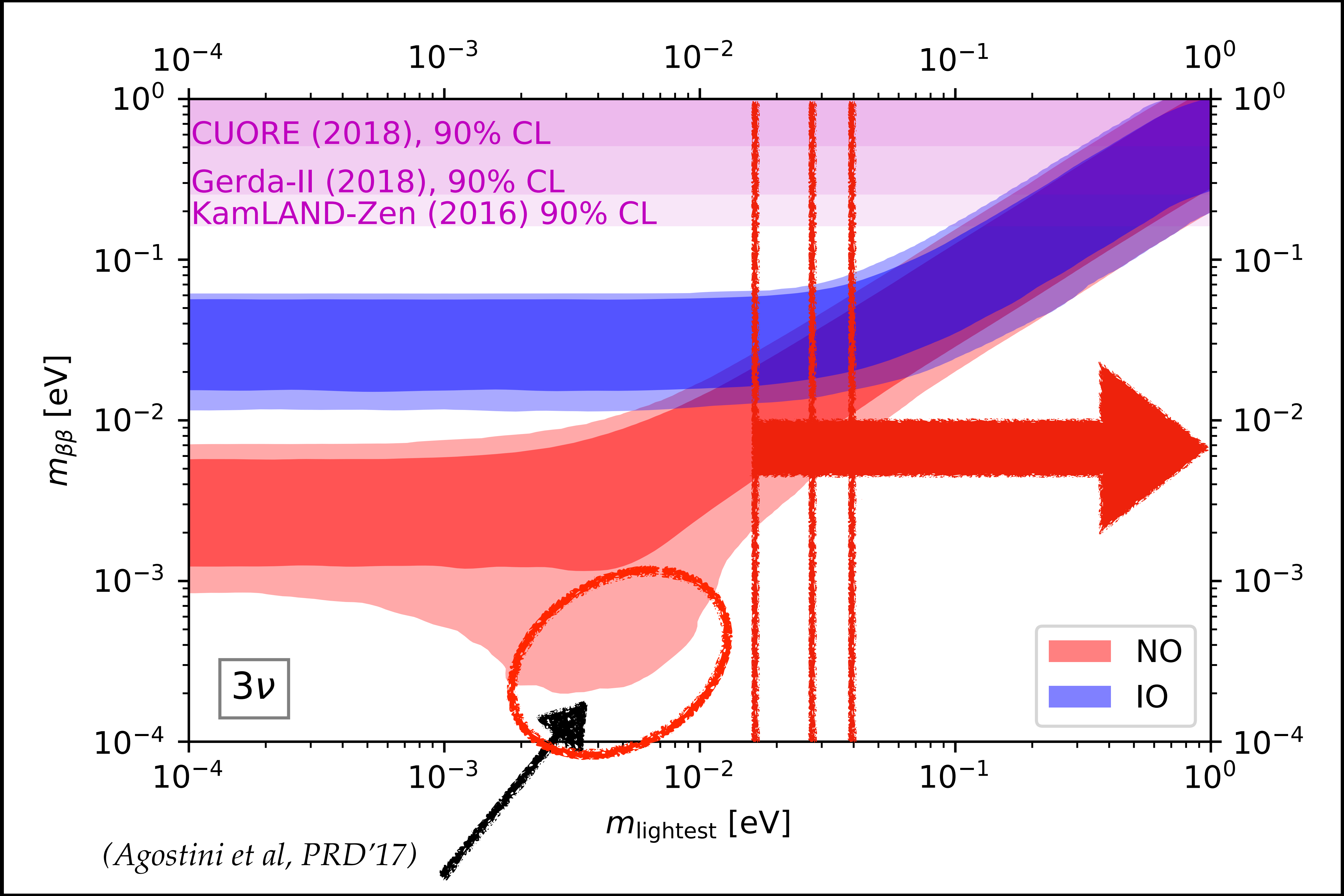
A. G. Riess, S. Casertano, W. Yuan, L. M. Macri and D. Scolnic, c.



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

$H_0 = 67.37 \pm 0.54 \text{ km/s/Mpc}$ $H_0 = 74.03 \pm 1.42 \text{ km/s/Mpc}$

What we know

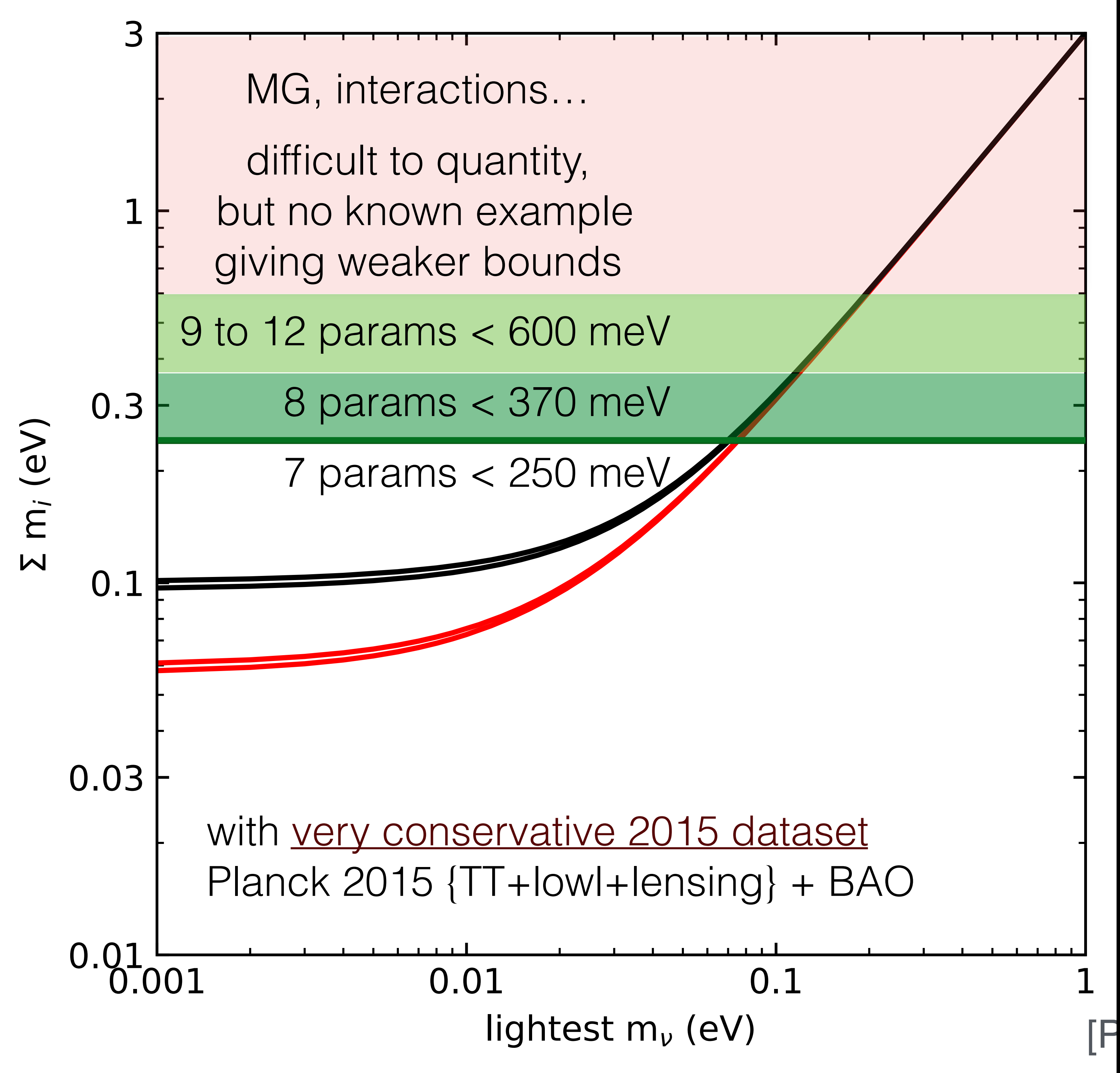


(Agostini et al, PRD'17)

$m_{\beta\beta}$ < 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

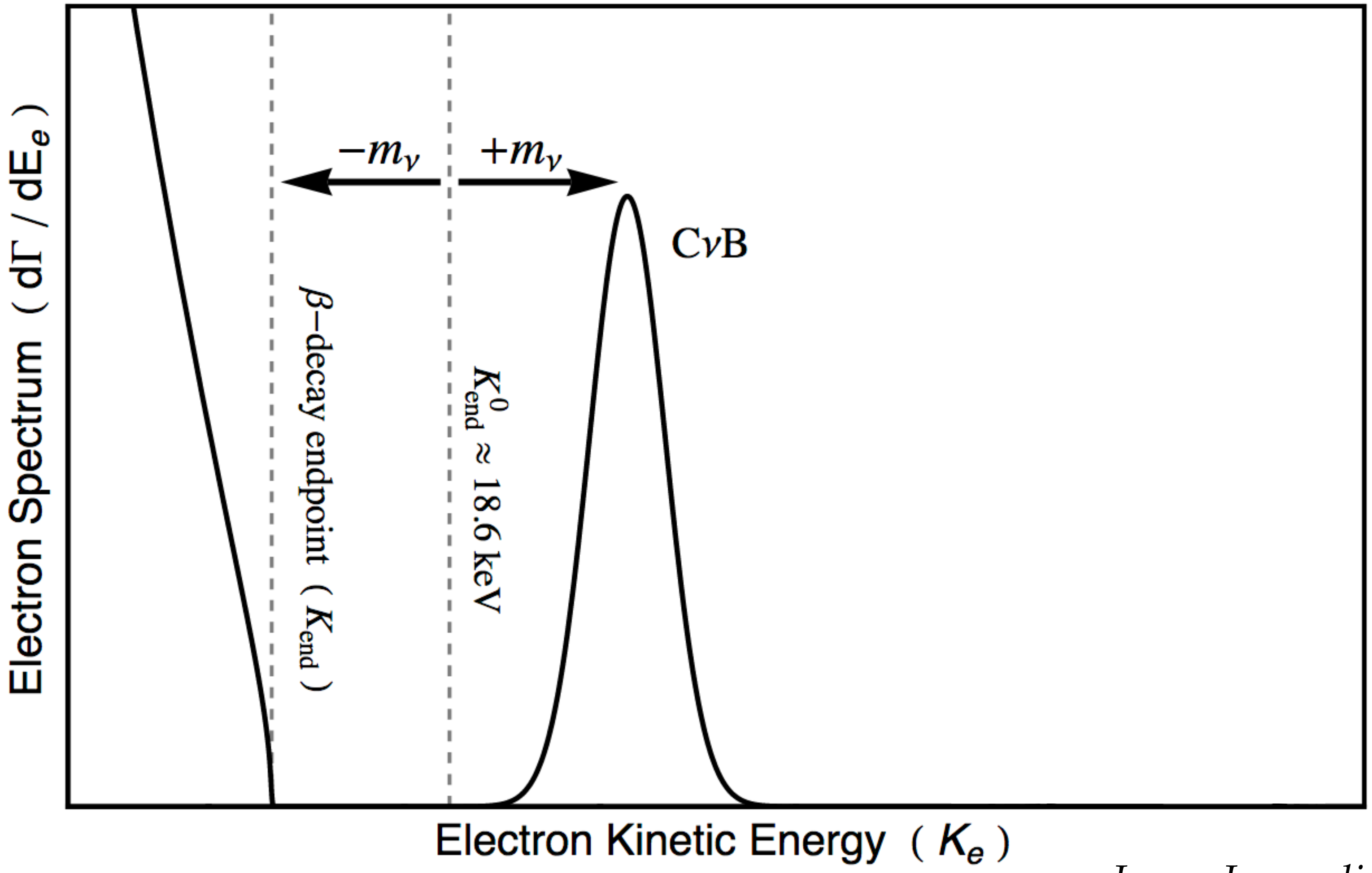
$$\nu_e + N \to N' + e^- \qquad \bar{\nu}_e + N \to N' + e^+$$

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

Cocco et al 2007

Methods to detect non-non-relativistic neutrinos:

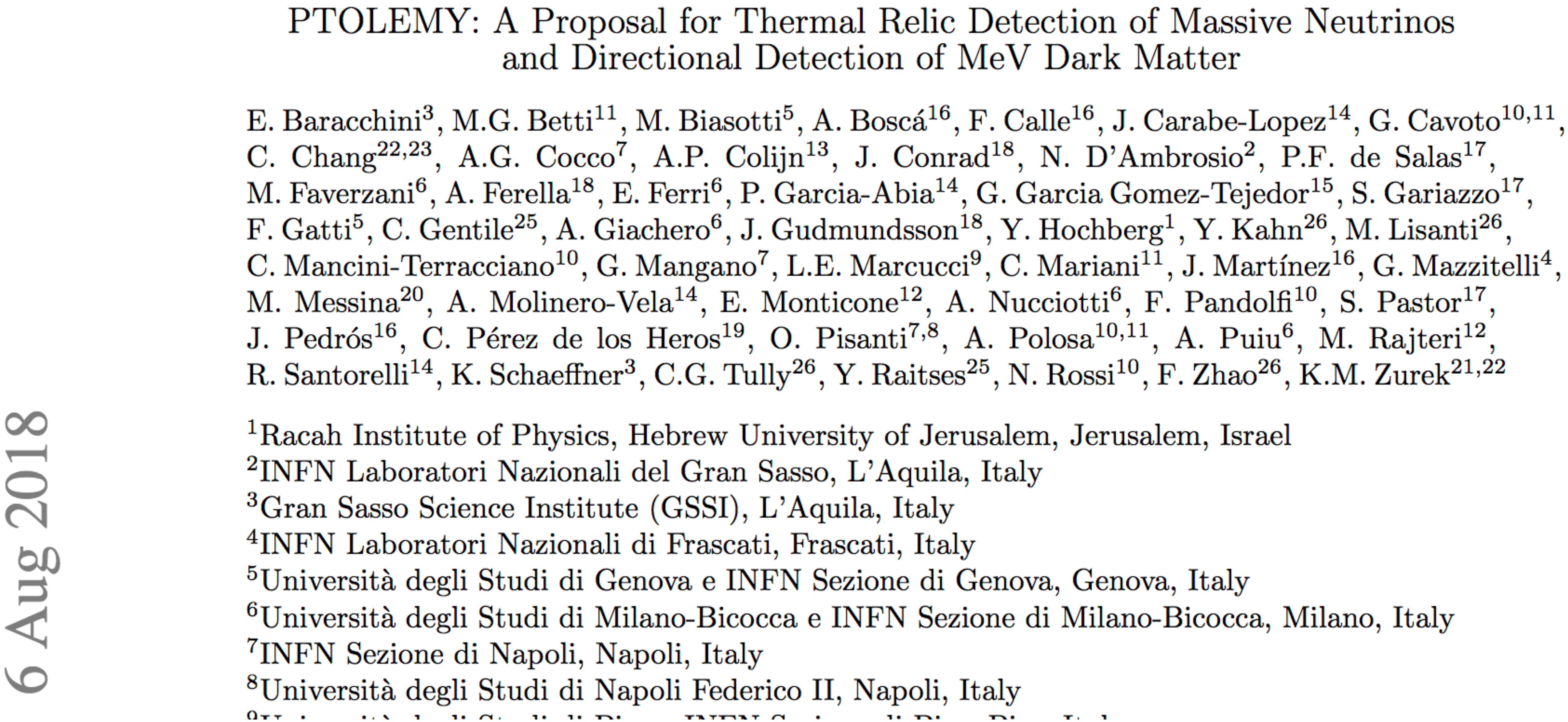
(Anti)neutrino capture on β-decaying nuclei



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

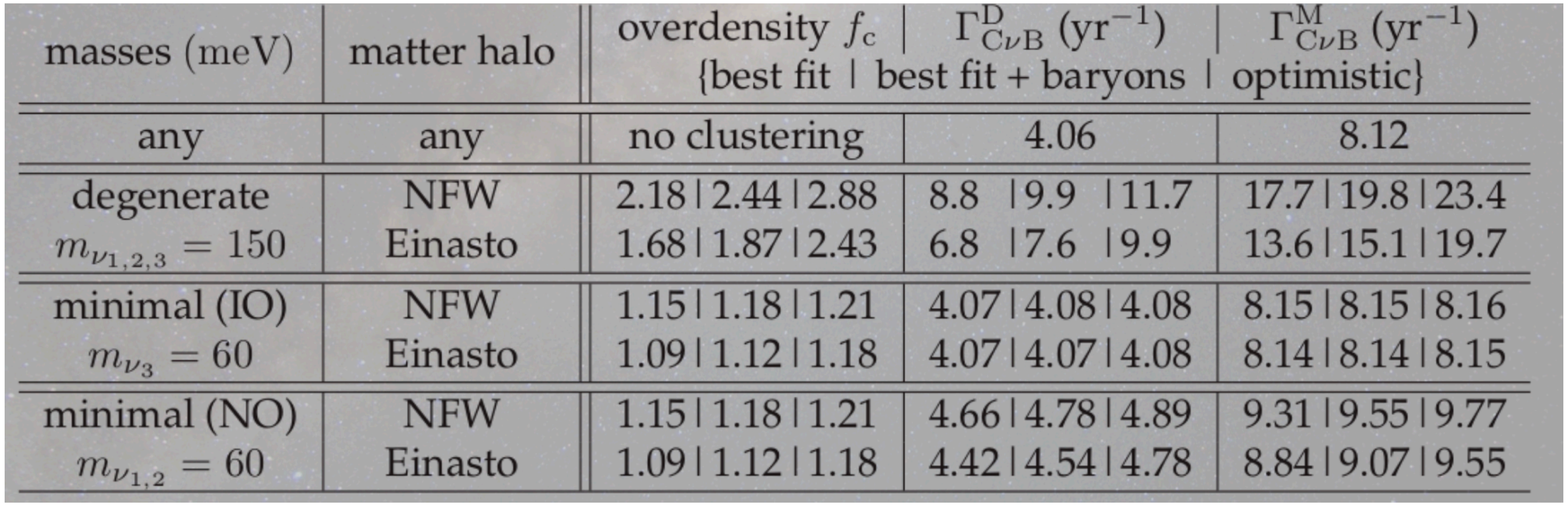
The expected rate is:

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

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

CDM

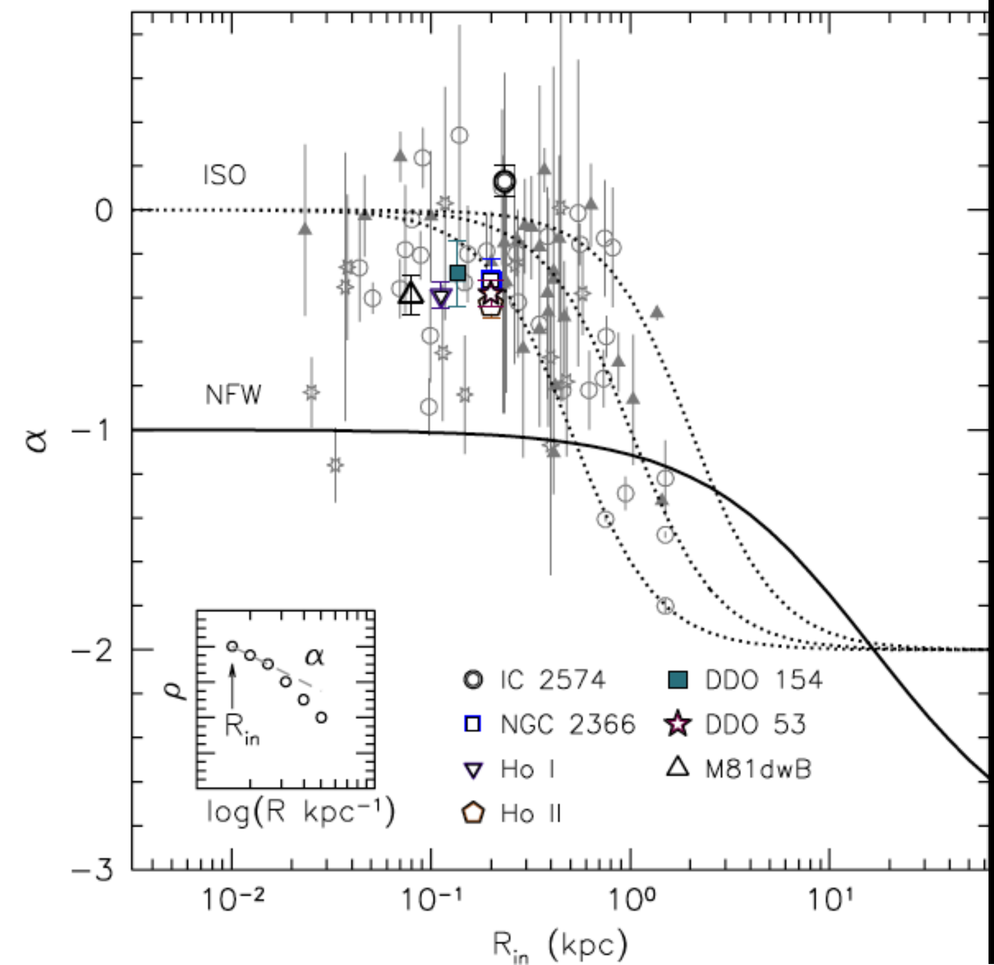
HOT dark matter

HDM

WDM

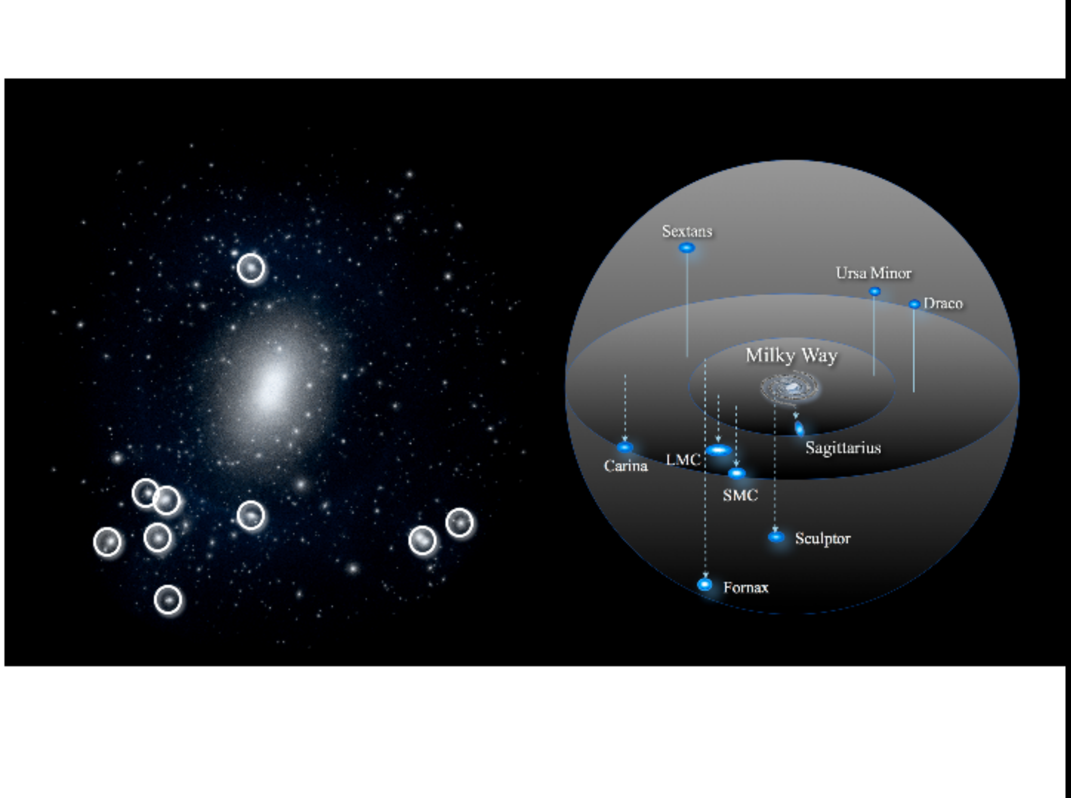
WARM dark matter

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



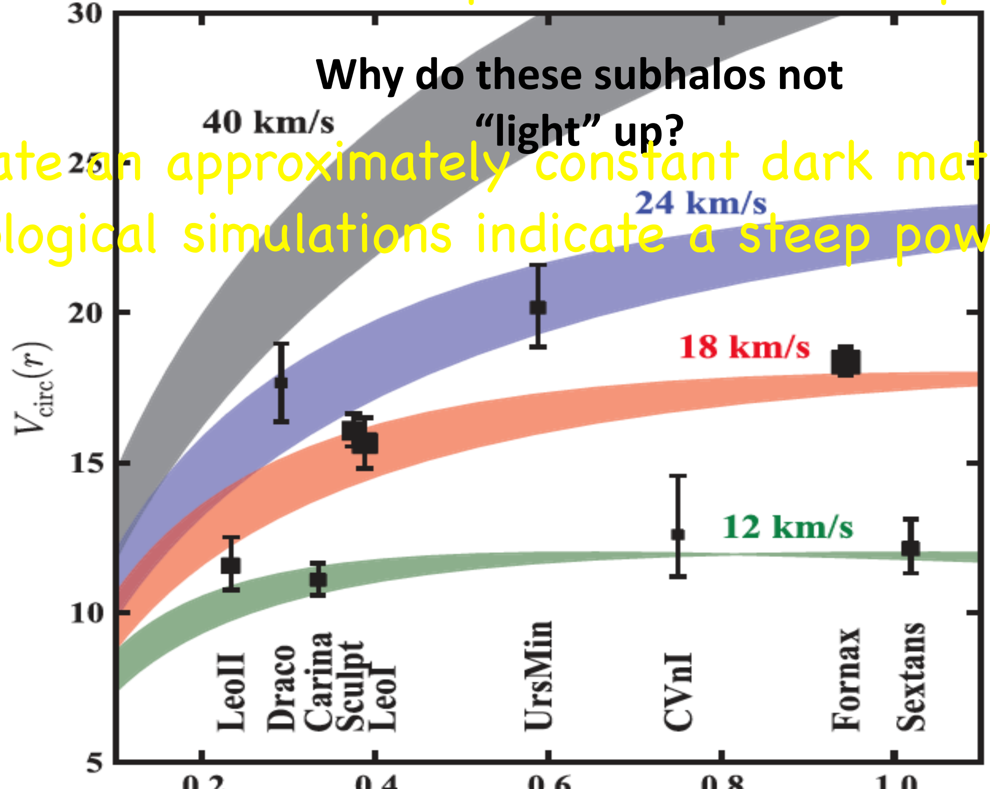
Core/Cusp problem

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)



Missing satellite problem

The predicted satellite population far exceeds the observed one


Why do these subhalos not “light” up?

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?

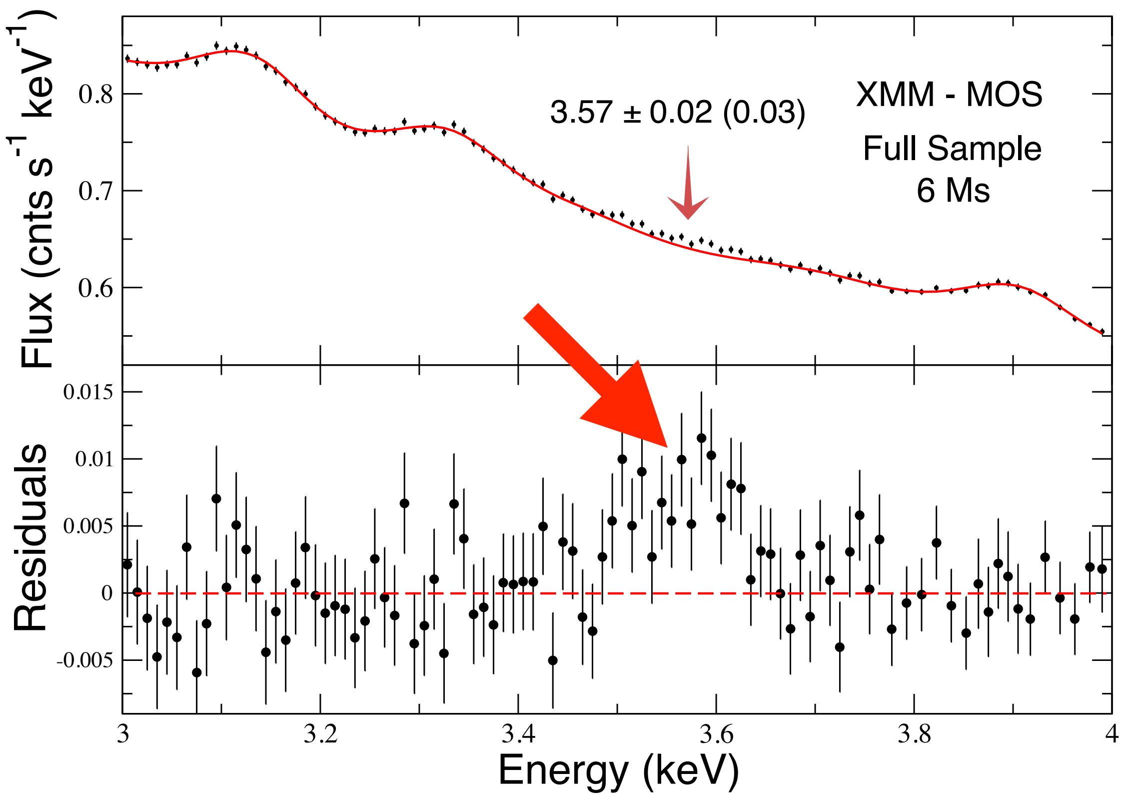
A controversial unidentified line has been detected at with a significance > 3σ in two independent samples of X-ray clusters with XMM-Newton.

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

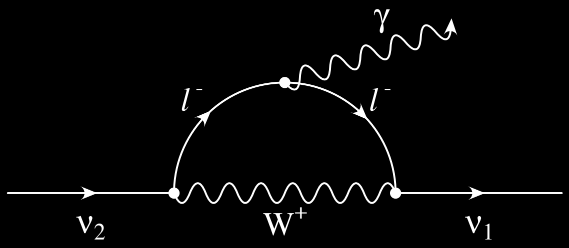
(Bulbul et al, APJ'14)

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)*

(Bulbul et al, APJ'14)



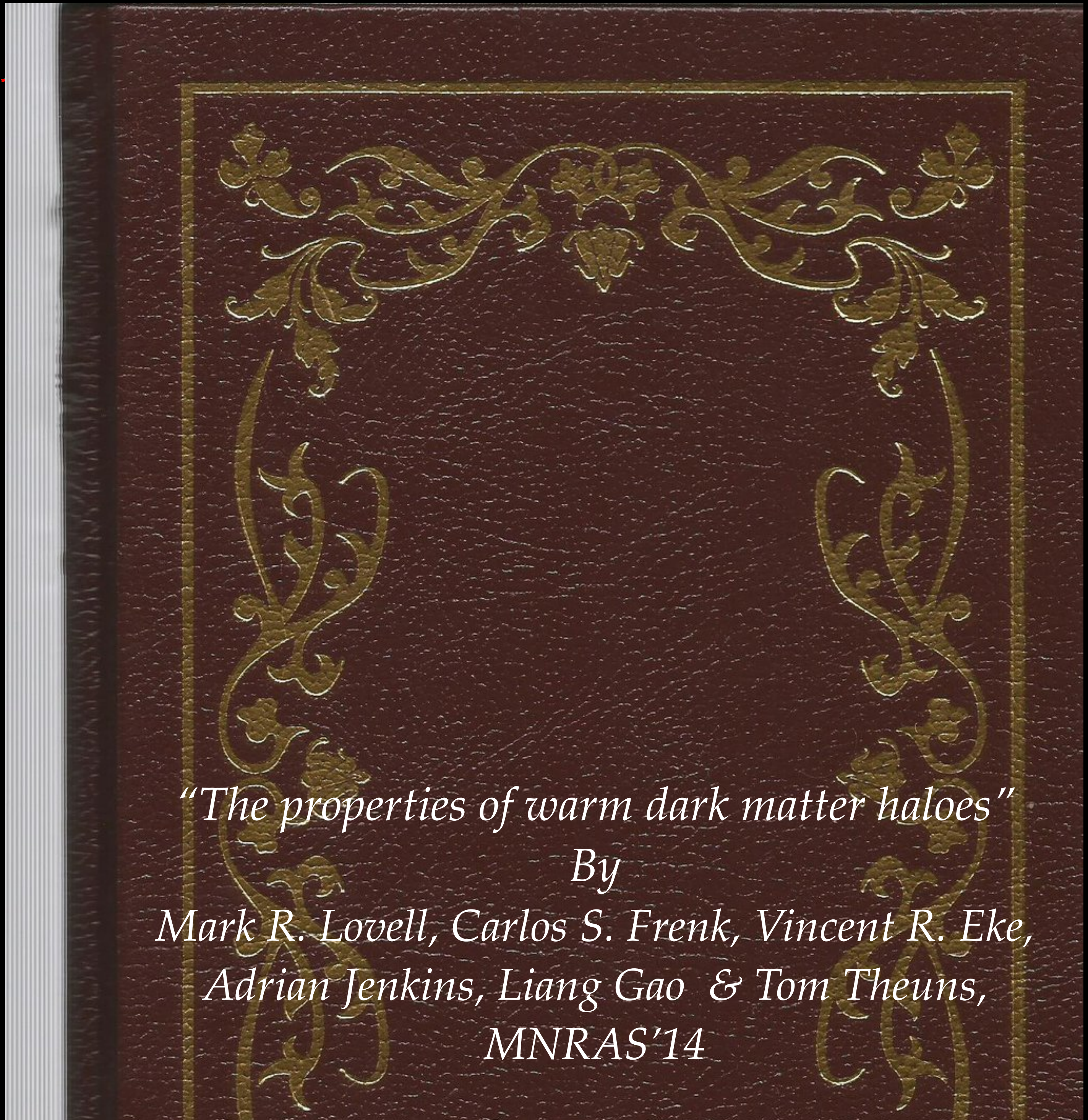
$$\nu_s \rightarrow \nu_\alpha + \gamma$$



$$m_s = 2E = 7.1keV$$

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.



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

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

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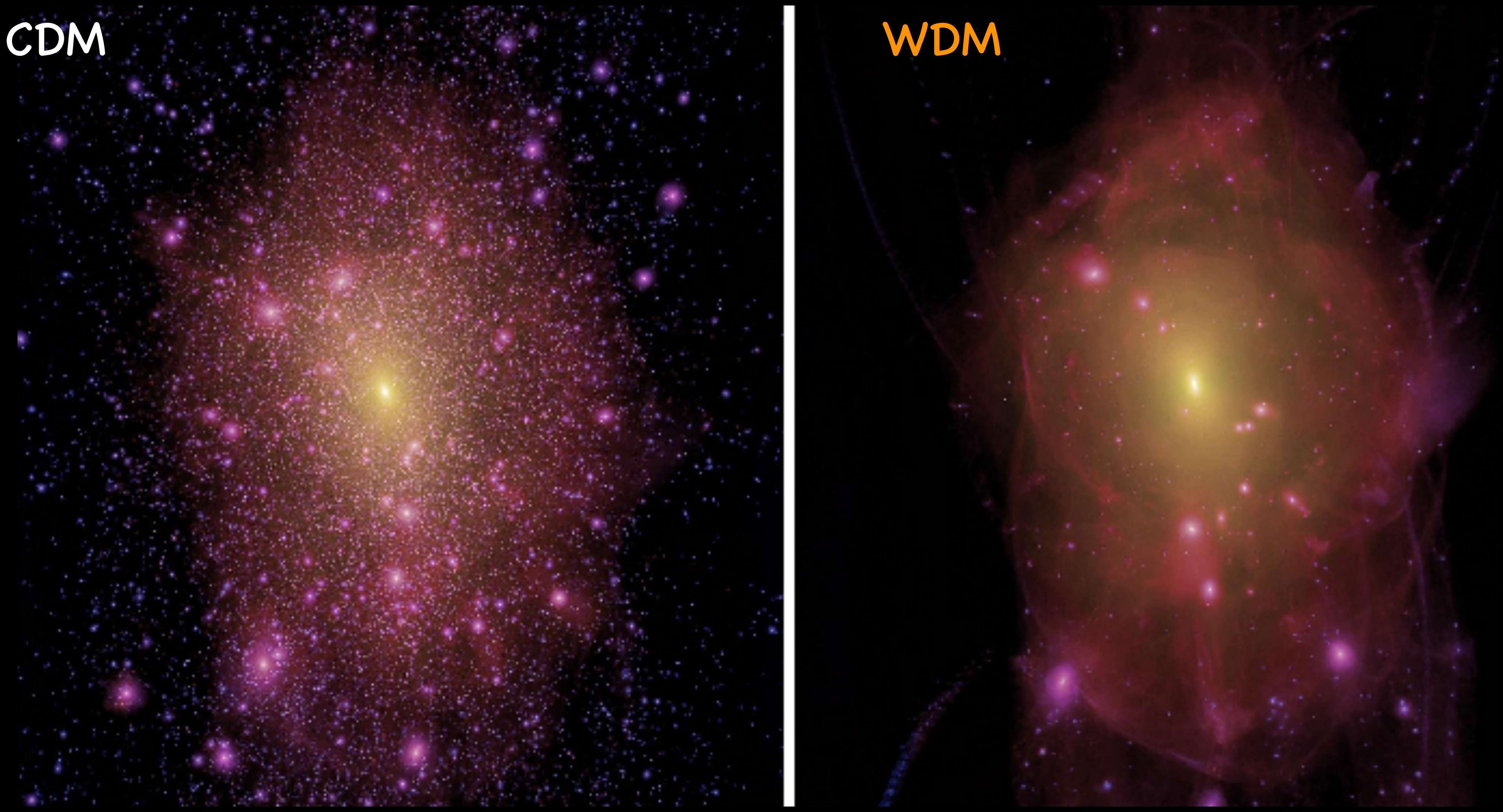
Simulations have shown that WDM can solve/alleviate the small scale crisis of ΛCDM

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 Jenki 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: $N_{\rm eff}$

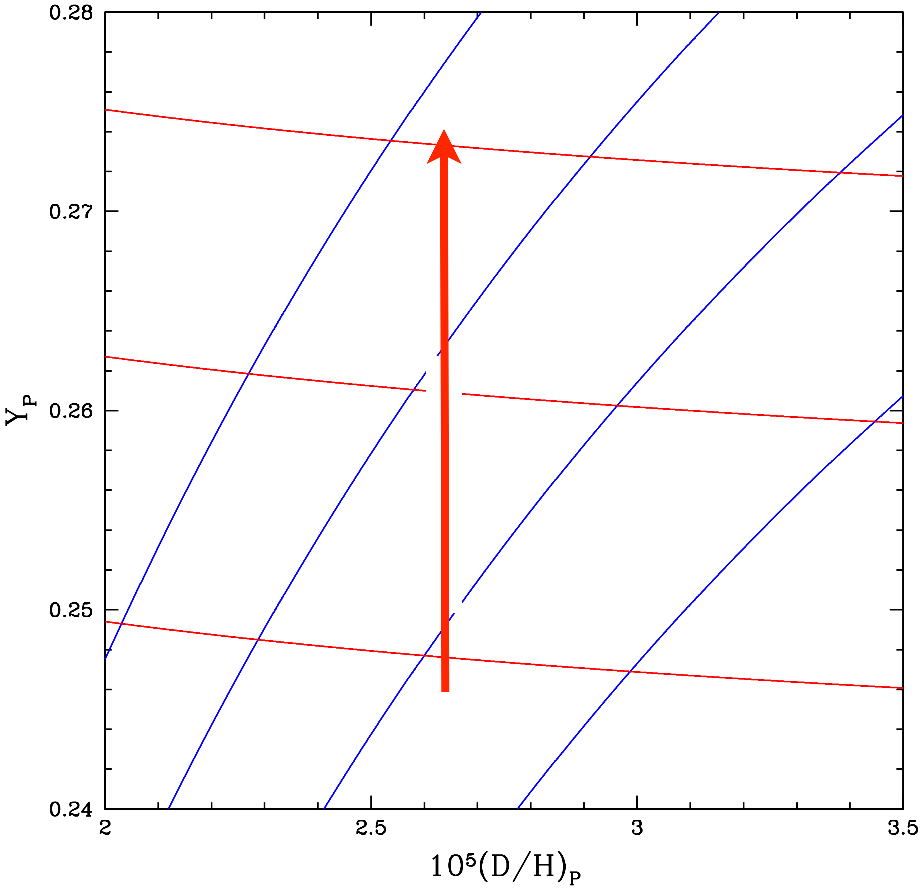
$N_{\rm eff}$ changes the freeze out temperature of weak interactions:

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

MORE NEUTRINOS:

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

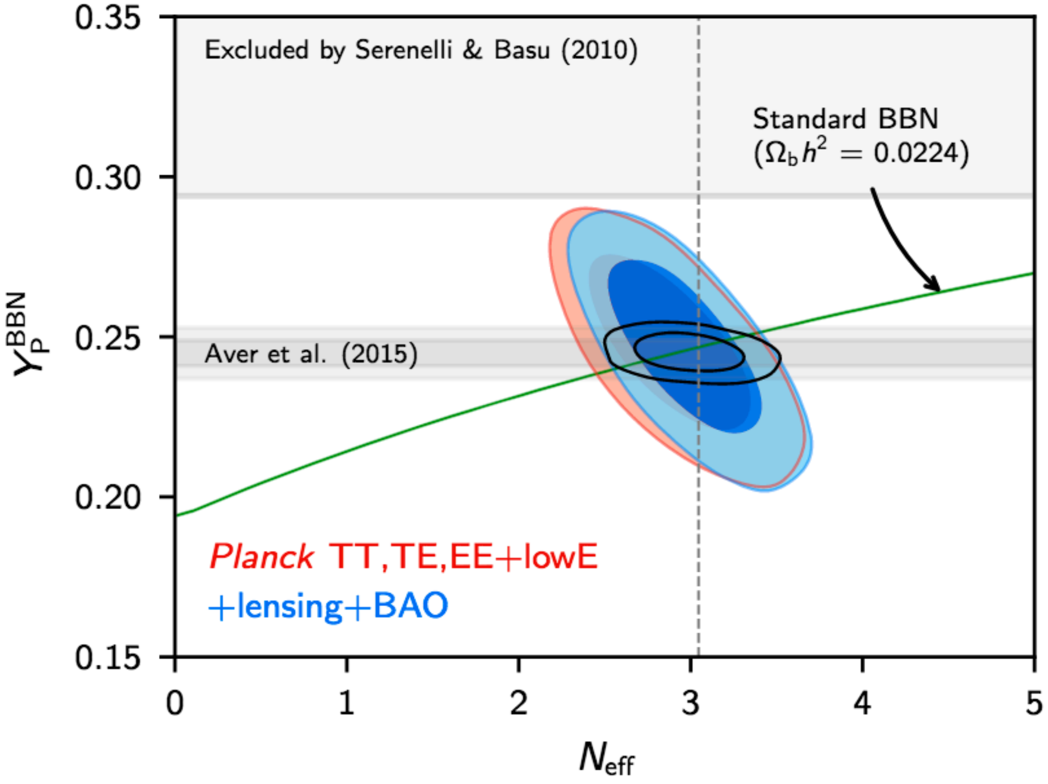
$$n/p \simeq e^{-\frac{m_n - m_p}{T_{freeze}}} \qquad Y_p = \frac{2(n/p)}{1+n/p}$$



$N_{\rm eff} = 3, 4, 5$

(G. Steigman'12)

Planck 2018 results, 1807.06209

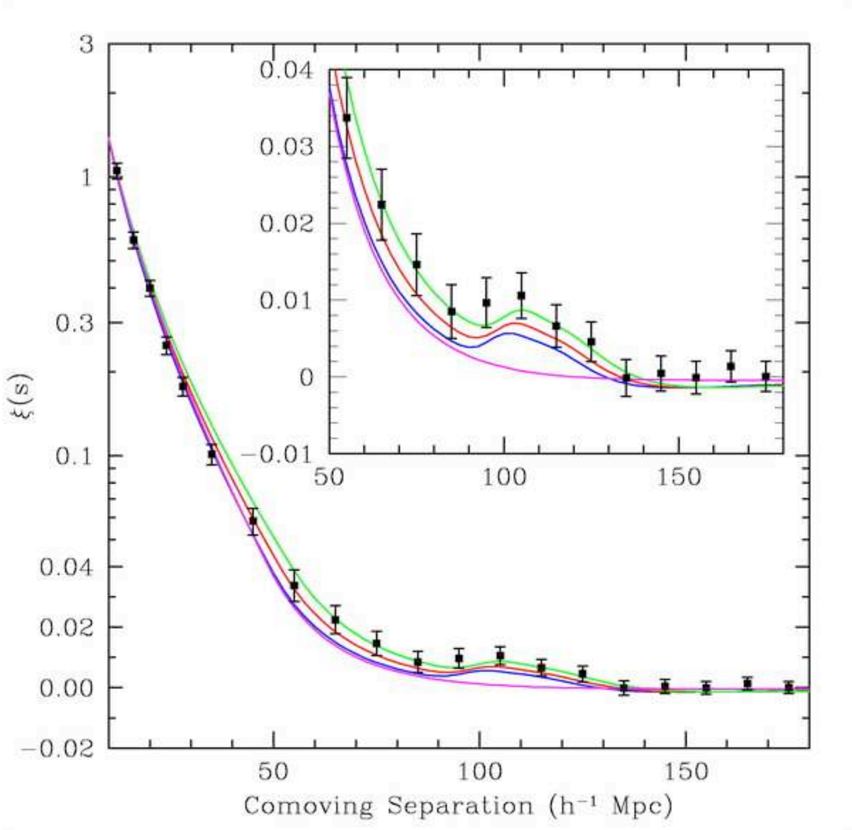


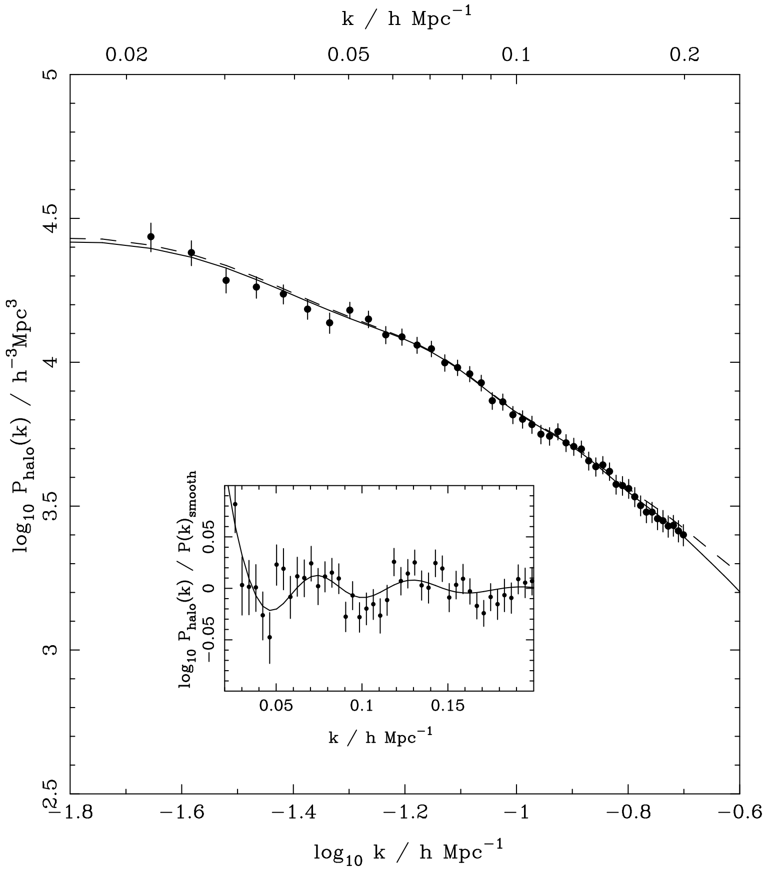
$$N_{\rm eff} = 2.99^{+0.43}_{-0.40} \quad Y_p = 0.2437^{+0.0077}_{-0.0080}$$

Los catálogos de galaxias miden la función de correlación:

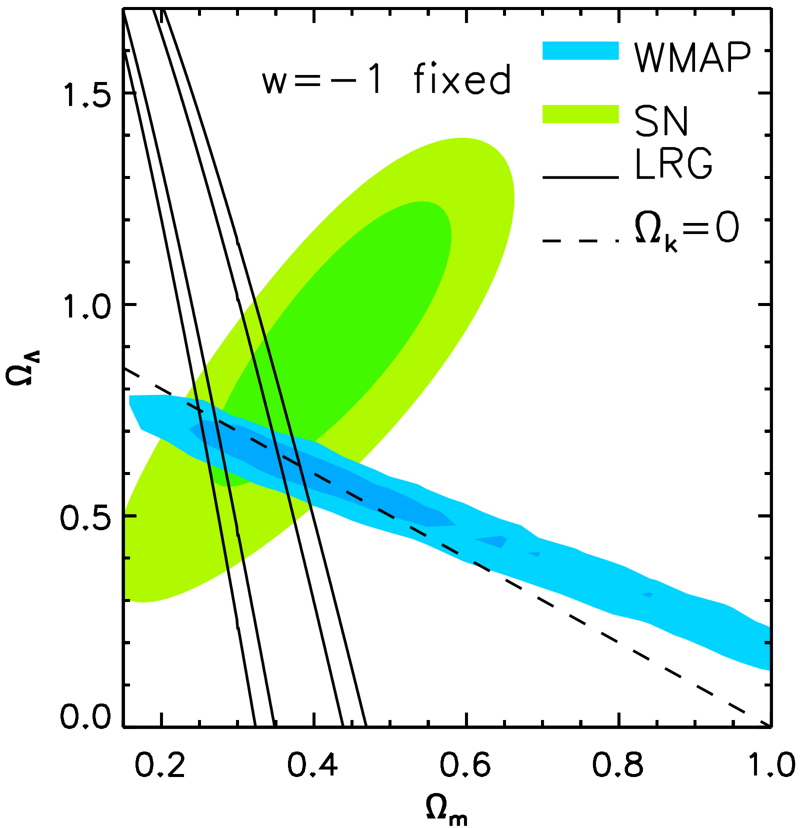
$$\xi(\vec{r}) \equiv \langle \delta(\vec{x})\delta(\vec{x}+\vec{r}) \rangle_{\text{Volume}} \qquad \langle \tilde{\delta}(\vec{k})\tilde{\delta}(\vec{k}') \rangle_{\text{Volume}} = (2\pi)^3 P(k)\delta^3(\vec{k}-\vec{k}')$$

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





Eisenstein et al'05



Reid et al'09

SSDS 2005: Primera detección de la señal BAO (3.4s) (47000 LRGs, 4000 deg² , z=0.35)

SDSS II 2009: 110 000 LRGs, 8000 deg² , z=0.35.