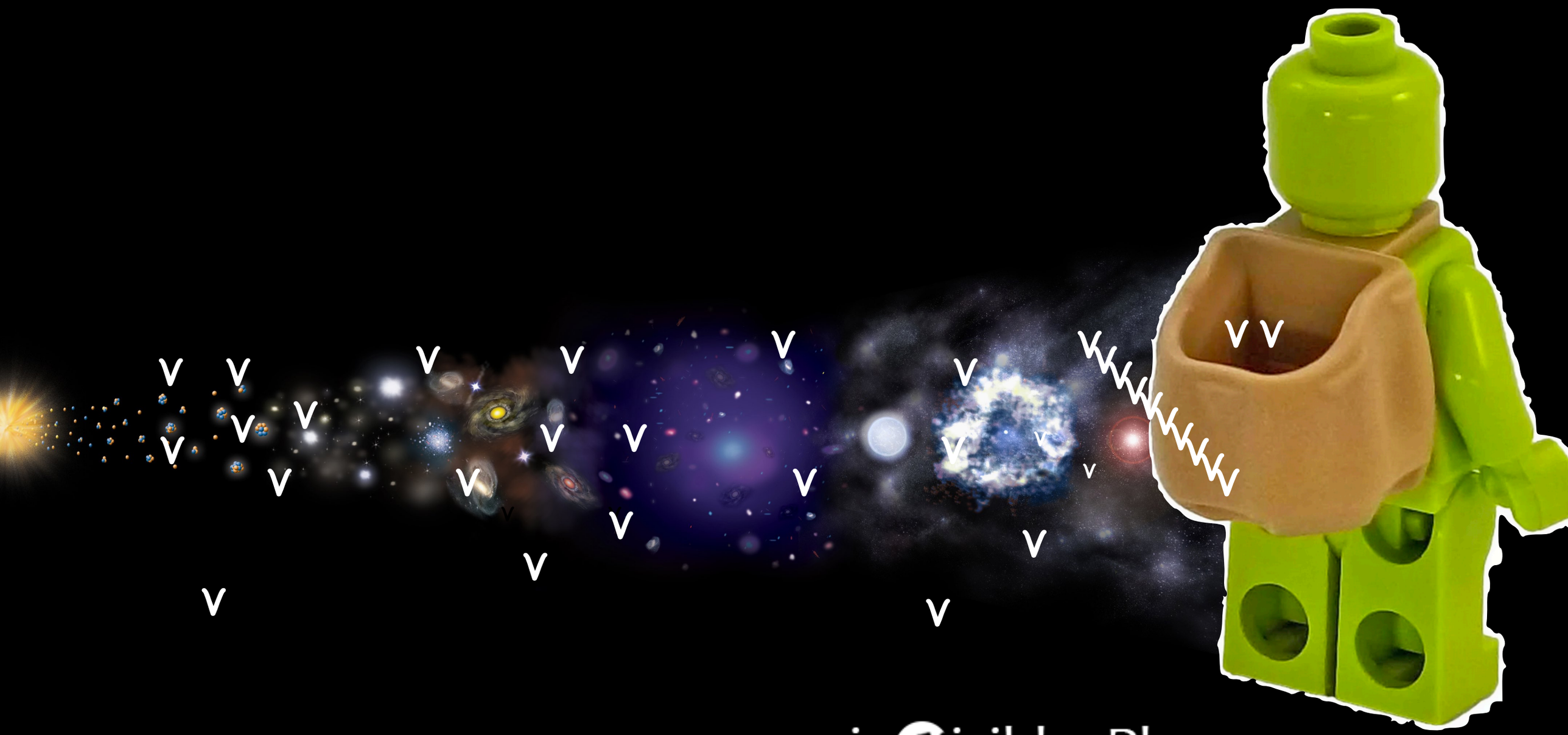
Back to school neutrino hunting!



Olga Mena
IFIC-CSIC/UV Valencia (Spain)

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

Back to school Schedule

Elementary School

- The **classical** cosmic pizza
- The neutrino slice
- Neutrino decoupling in the early universe

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- Take home messages

ΛCDM Pizza

Ω_i

Heavy elements

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

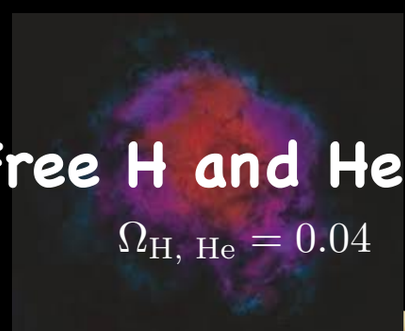
Neutrinos!

Dark energy

$\Omega_\Lambda = 0.7$

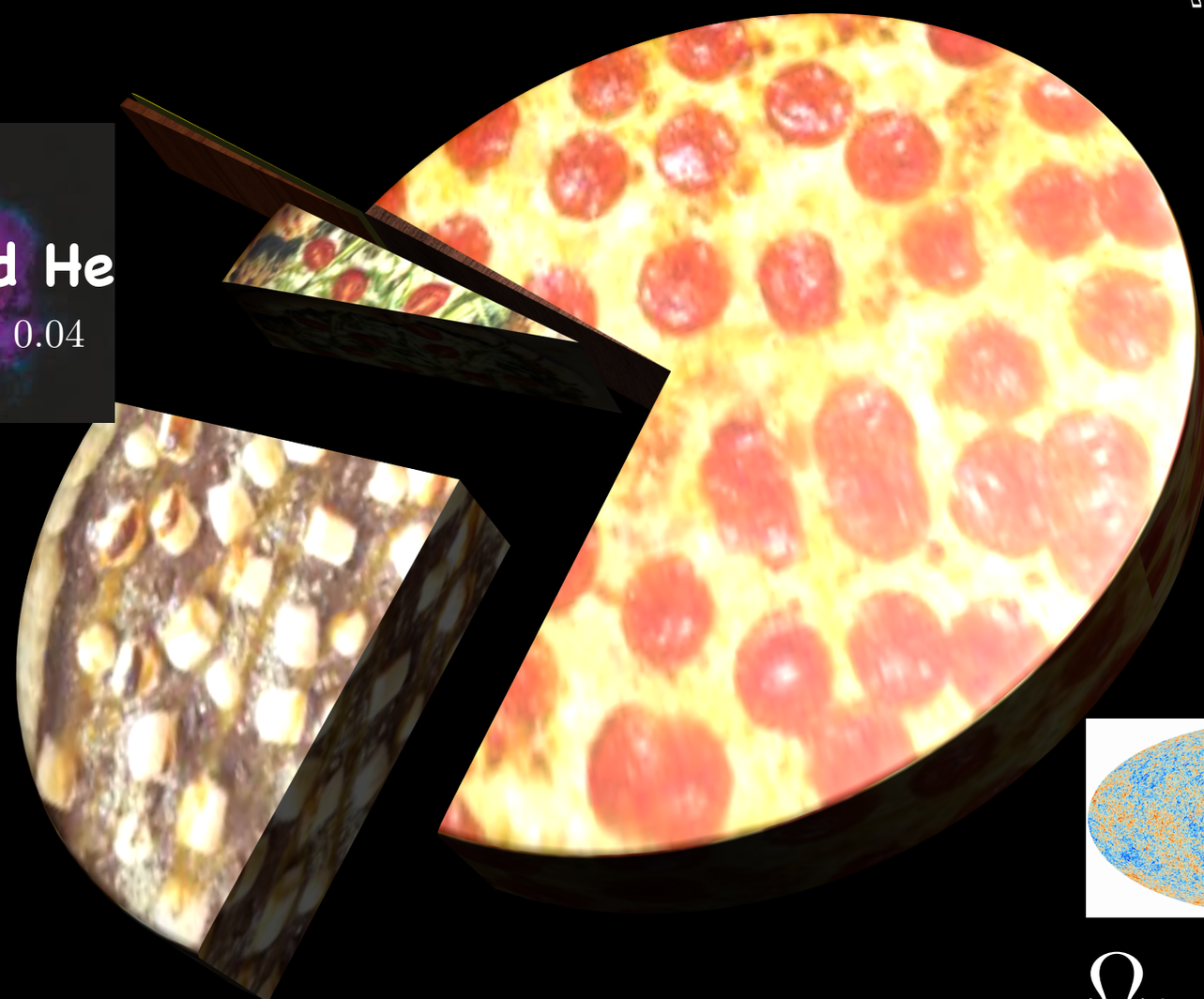
Stars

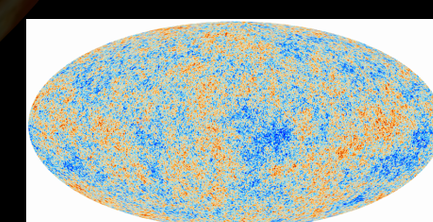
$\Omega_{\text{Stars}} = 0.005$



Free H and He

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



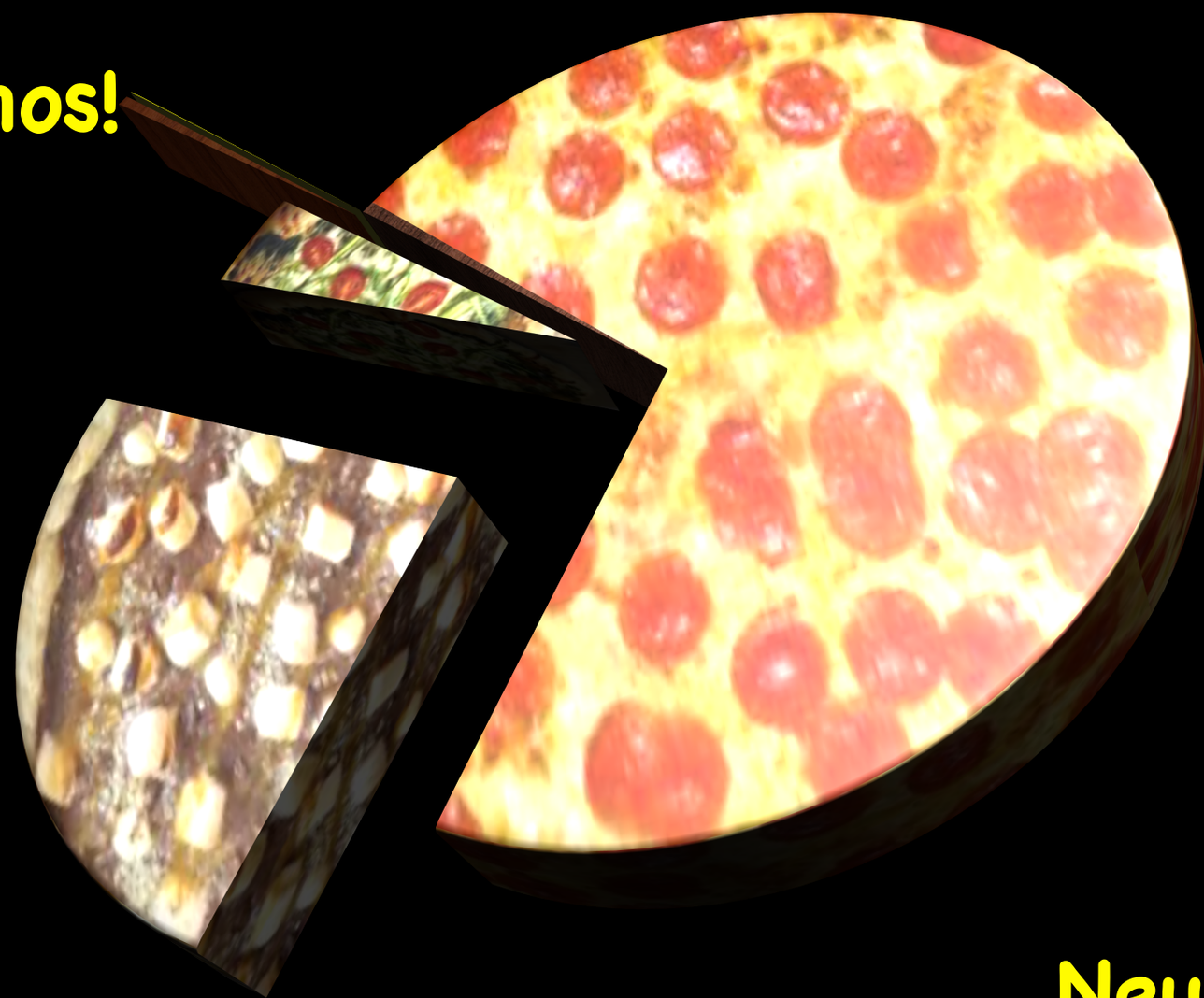


Cold Dark matter

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

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

How large is the MASSIVE neutrino contribution?



Cosmology tells us

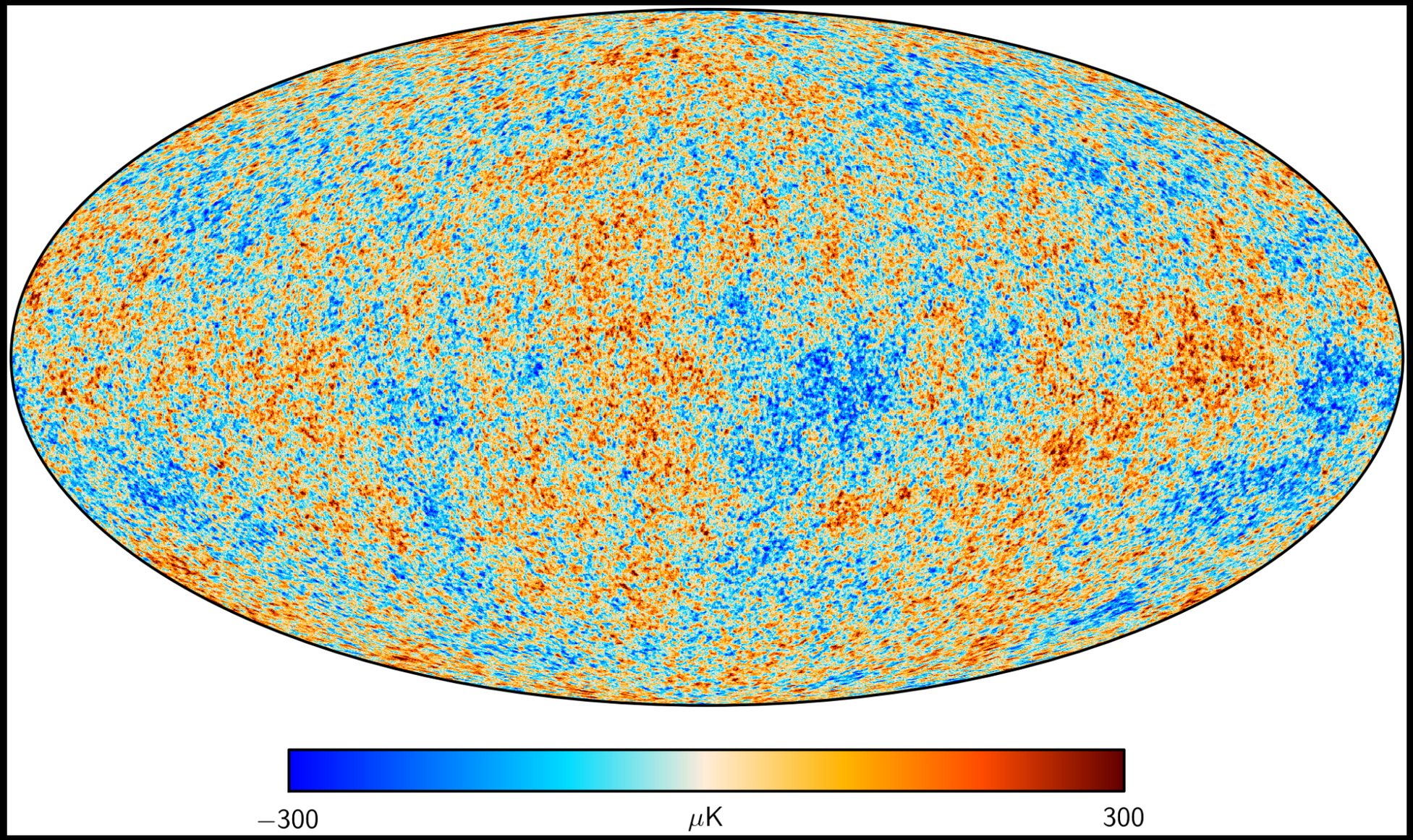
$\Omega_\nu \lesssim 0.0024$ 95% CL

Neutrino oscillations tell us

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

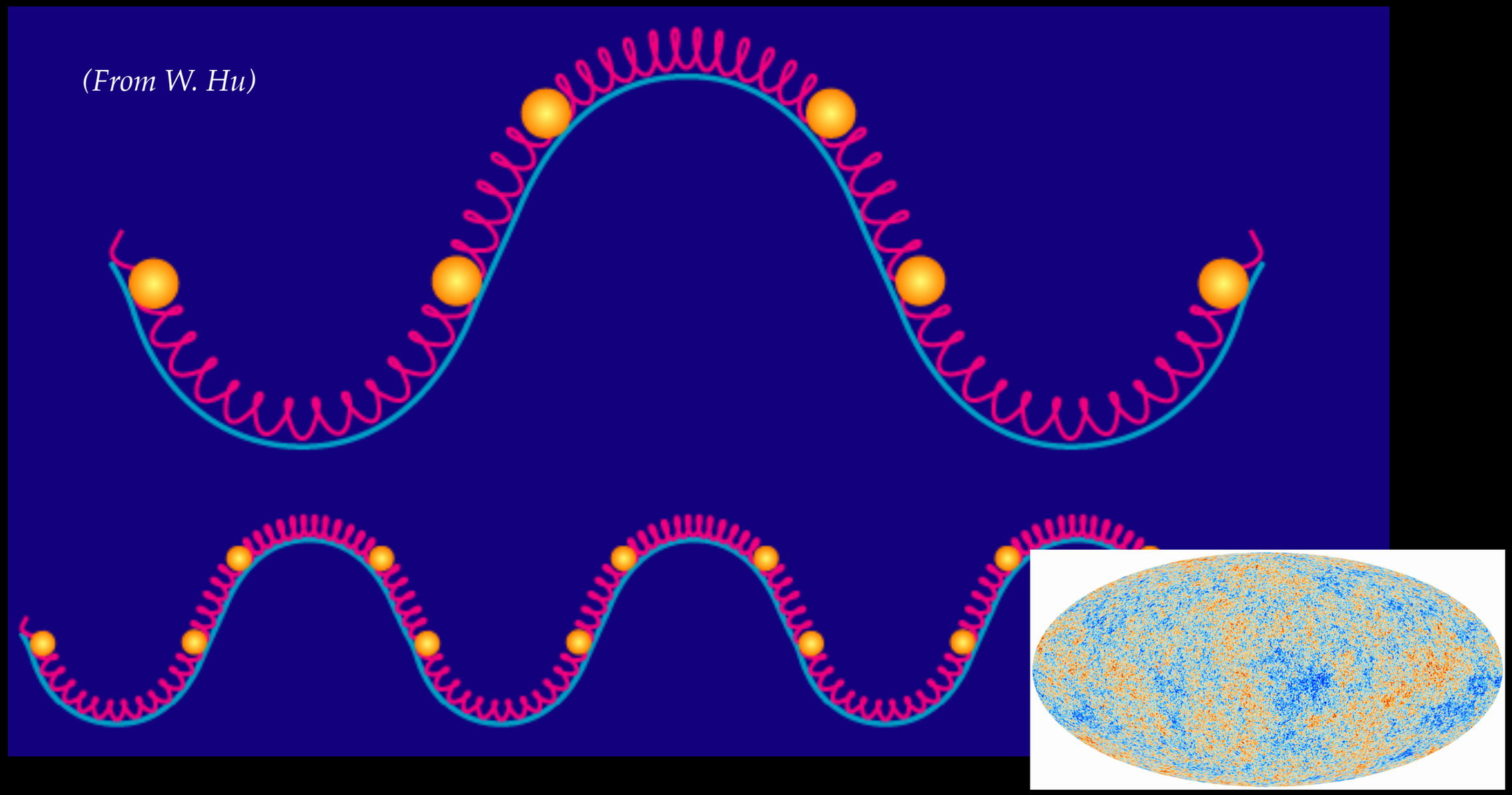
How large is the MASSIVE neutrino rice paella?

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.

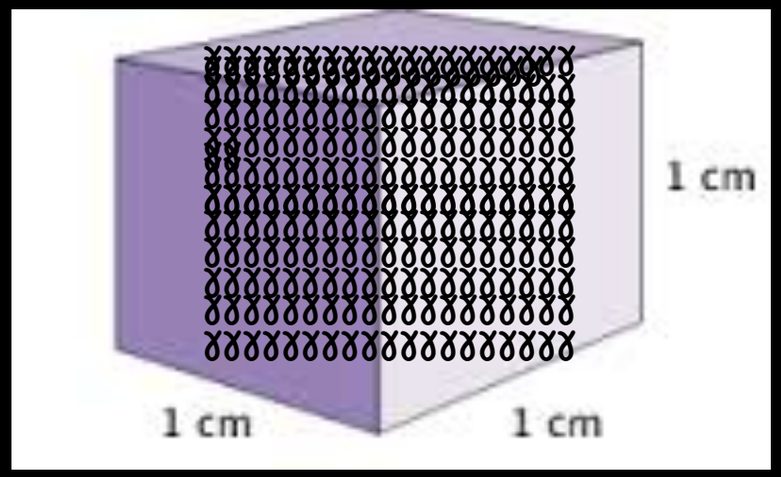


Potential wells ⟶ High density ⟶ COLD SPOTS in CMB maps

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!

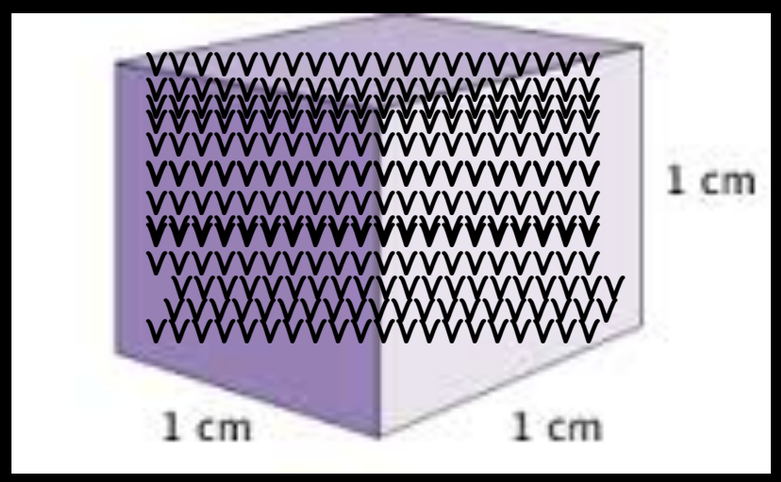
410 photons/cm^3



6720 photons/in^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

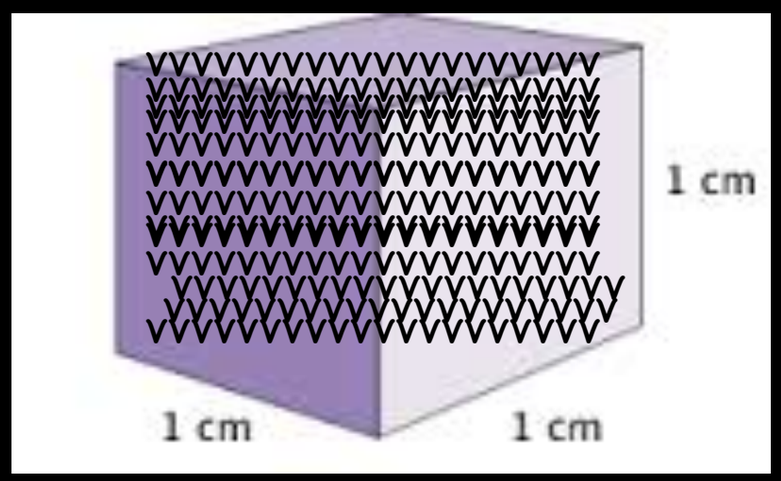


5572 neutrinos/in³

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:

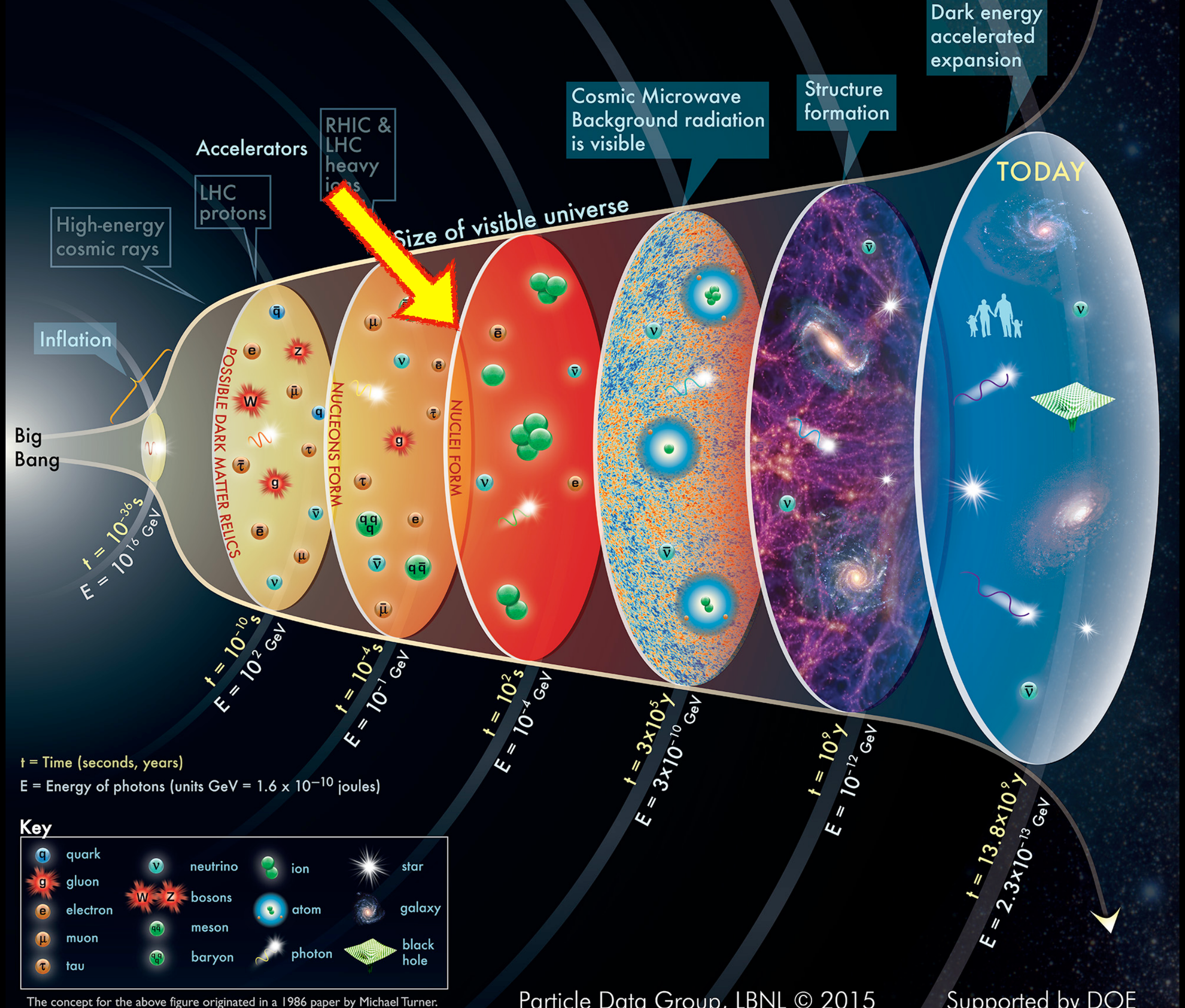
$$\Gamma_\nu = n\sigma v \simeq T^3 G_F^2 T^2 \sim G_F^2 T^5$$

- 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.**


Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
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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CMB	$3.8 \times 10^{5} yrs$	1100	$.26 eV$

They 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

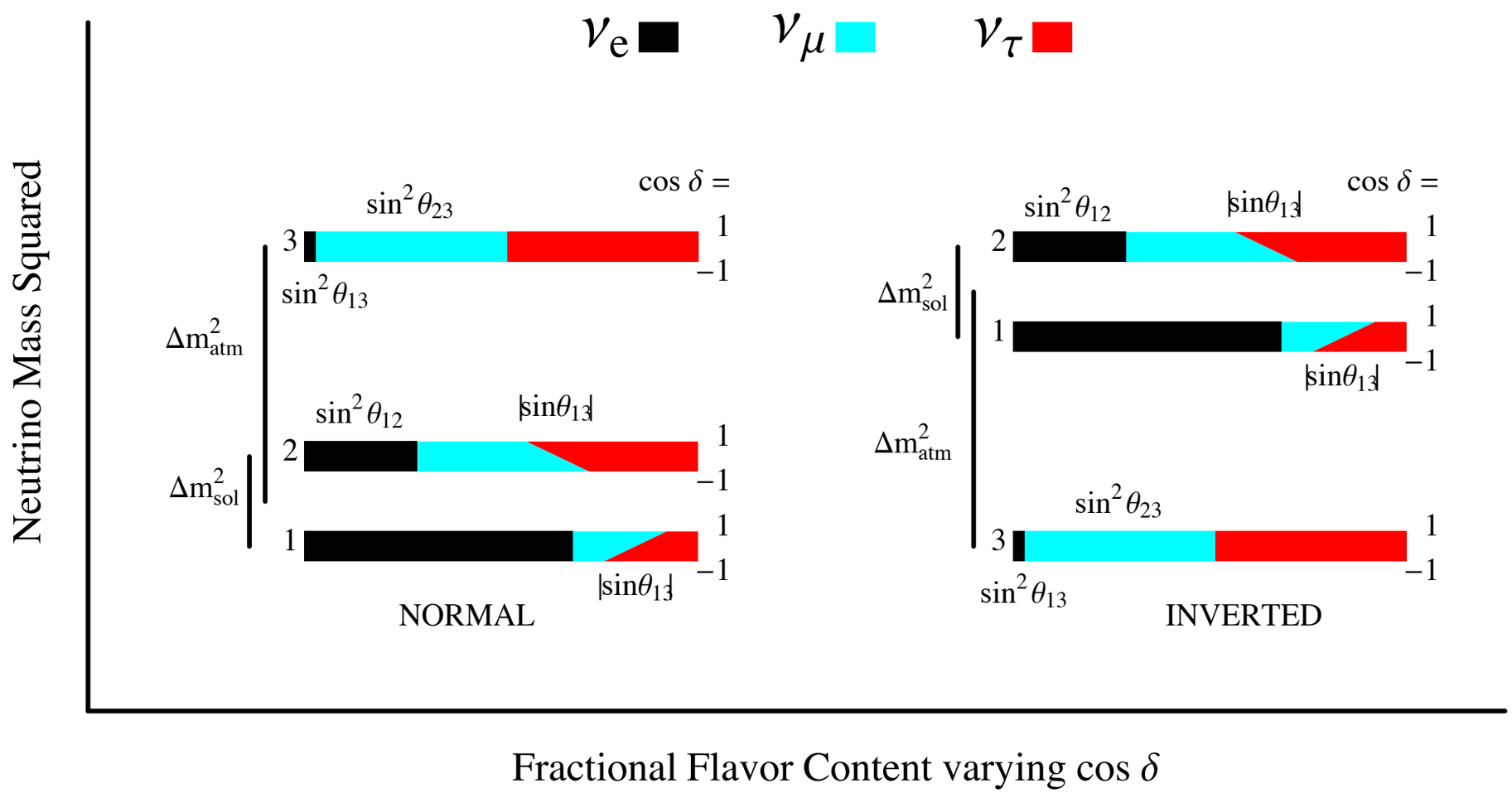
vvvvvvvvvvvvvvvvvvv

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

Peter Denton's talk today @ 14:30!

According to neutrino oscillation physics, we know that there are at lest 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

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

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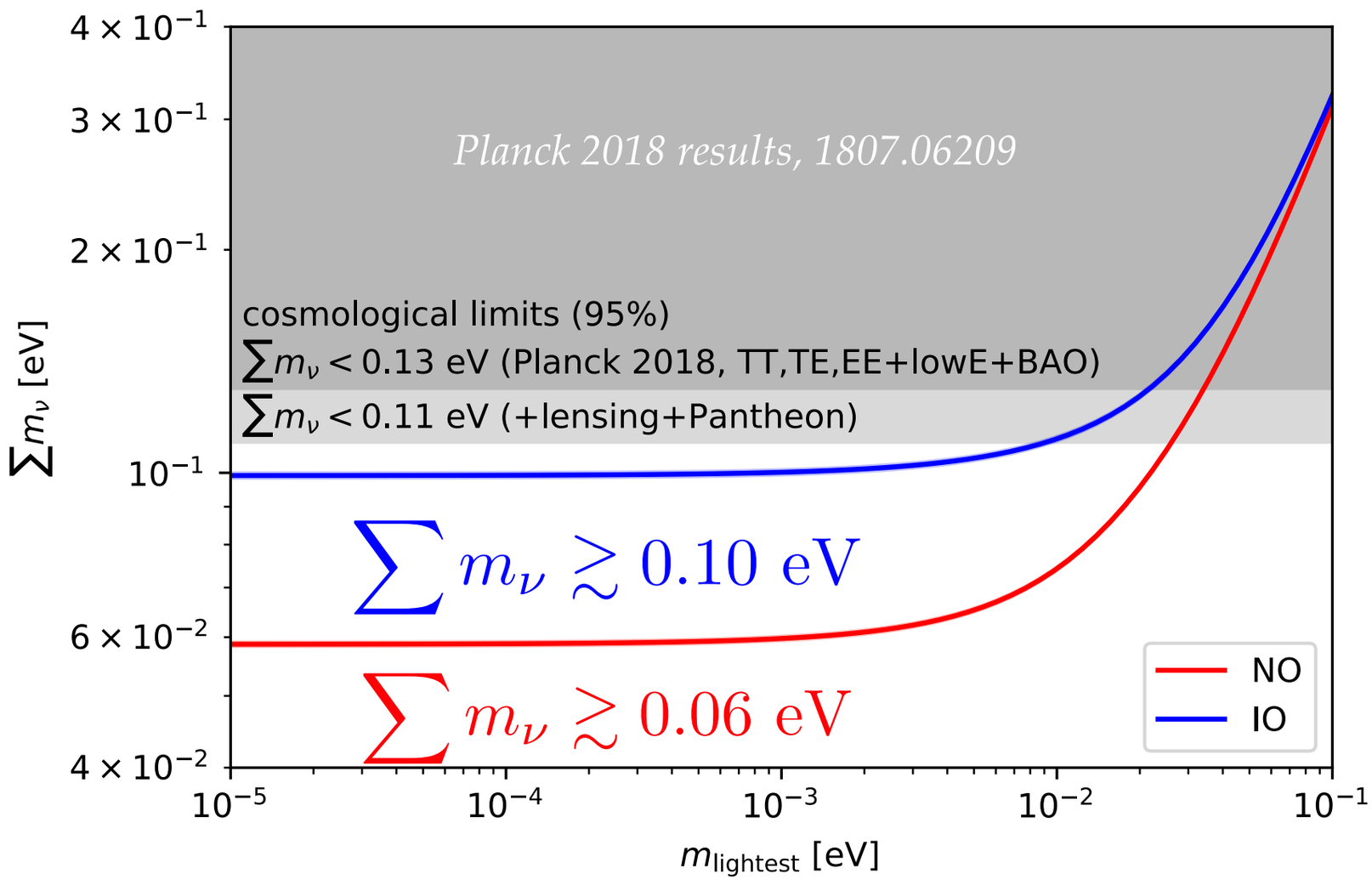
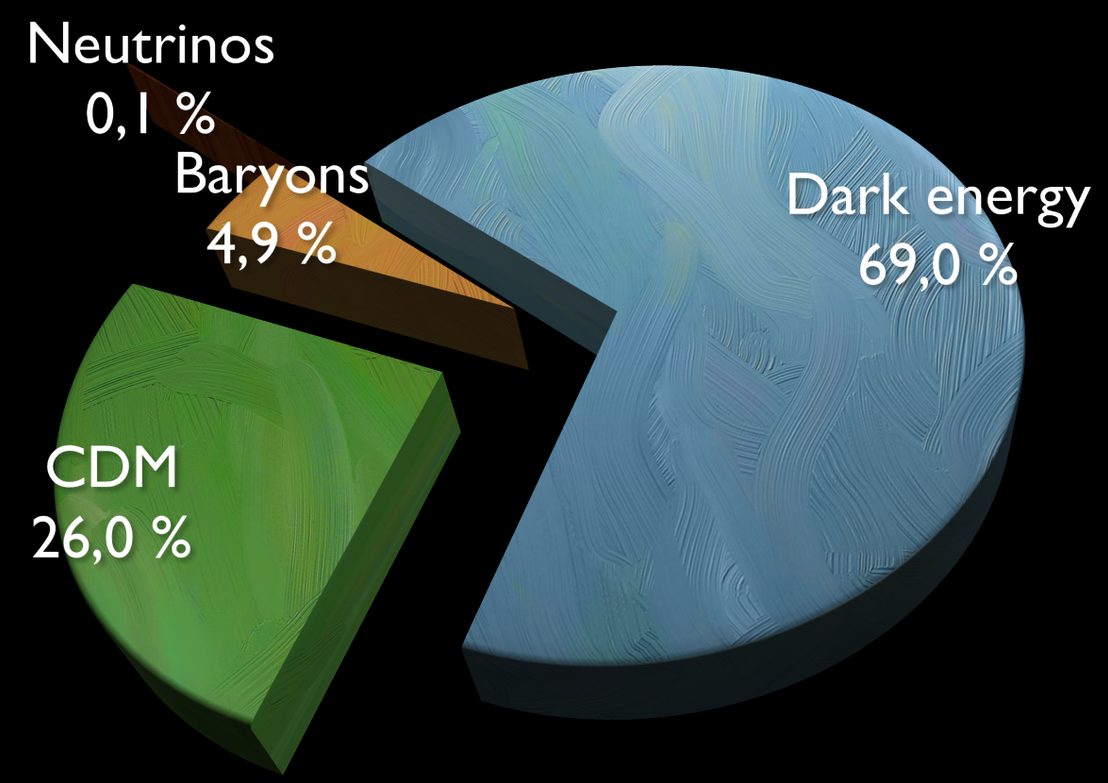
which translates into a lower bound on the total neutrino mass, depending on the ordering:

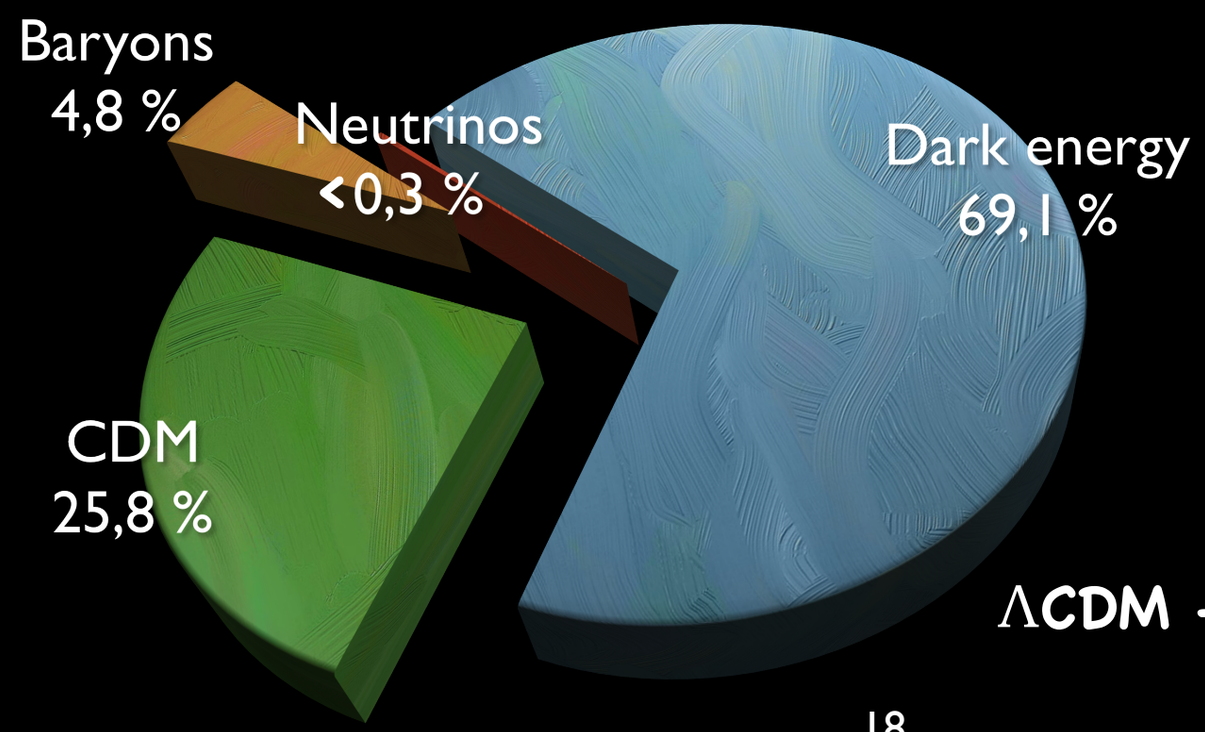


Planck 2018 Cosmic Pizzas

Planck 2018 results, 1807.06209

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





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

To hunt and bound their abundances and their masses, we need to look at several epochs in our universe's evolution:

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Number of neutrinos: N_{eff}

The total radiation in the universe can be written as:

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

N_{eff} = 3.046 standard scenario: electron, muon and tau neutrinos

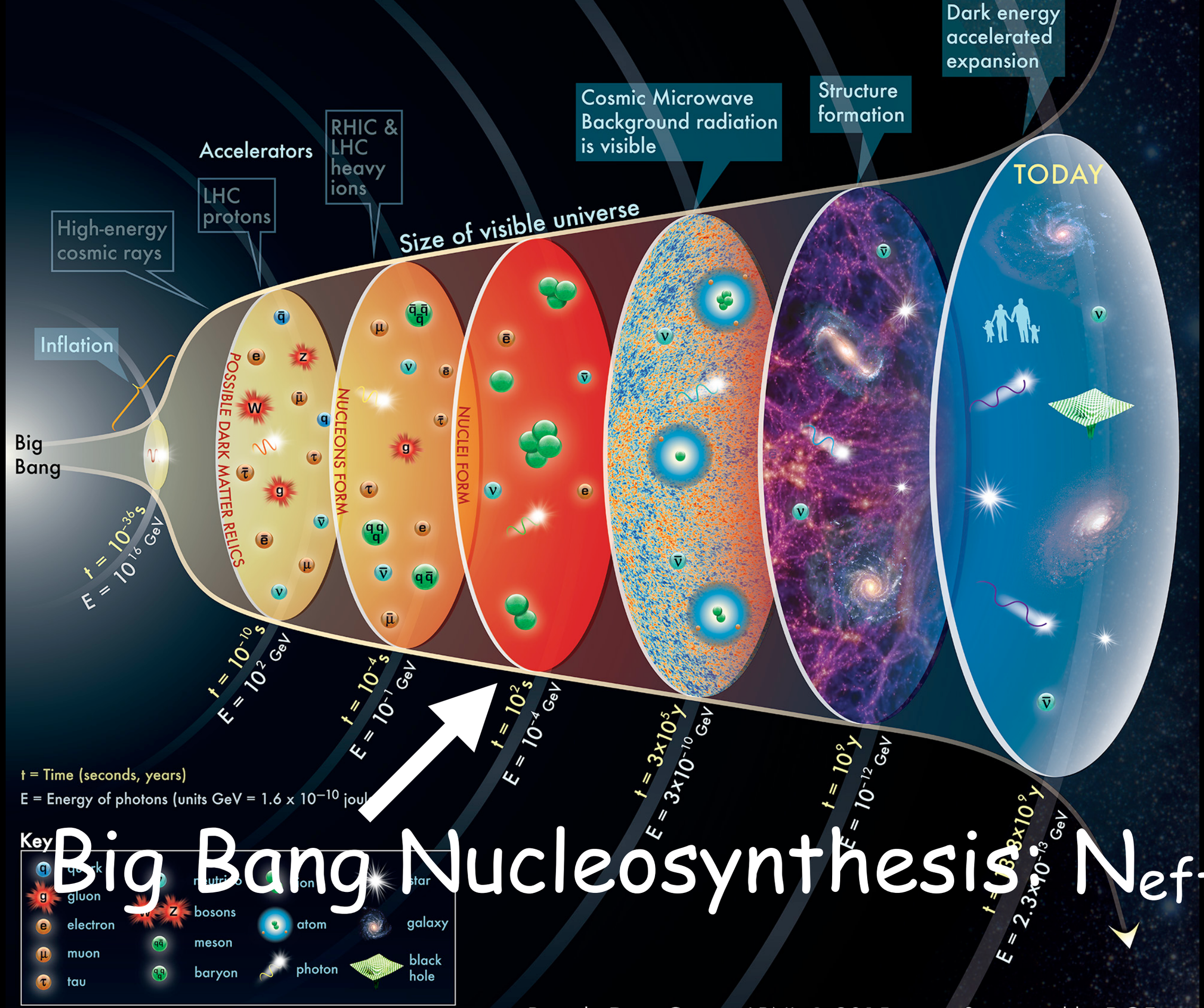
N_{eff} < 3.046 (less neutrinos): Neutrino decays ?

N_{eff} > 3.046 (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}



Event	Time	Redshift	Temperature
Baryogenesis	?	?	?
EW phase transition	$2 \times 10^{-11} s$	10^{15}	$100 GeV$
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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≃180 s.

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

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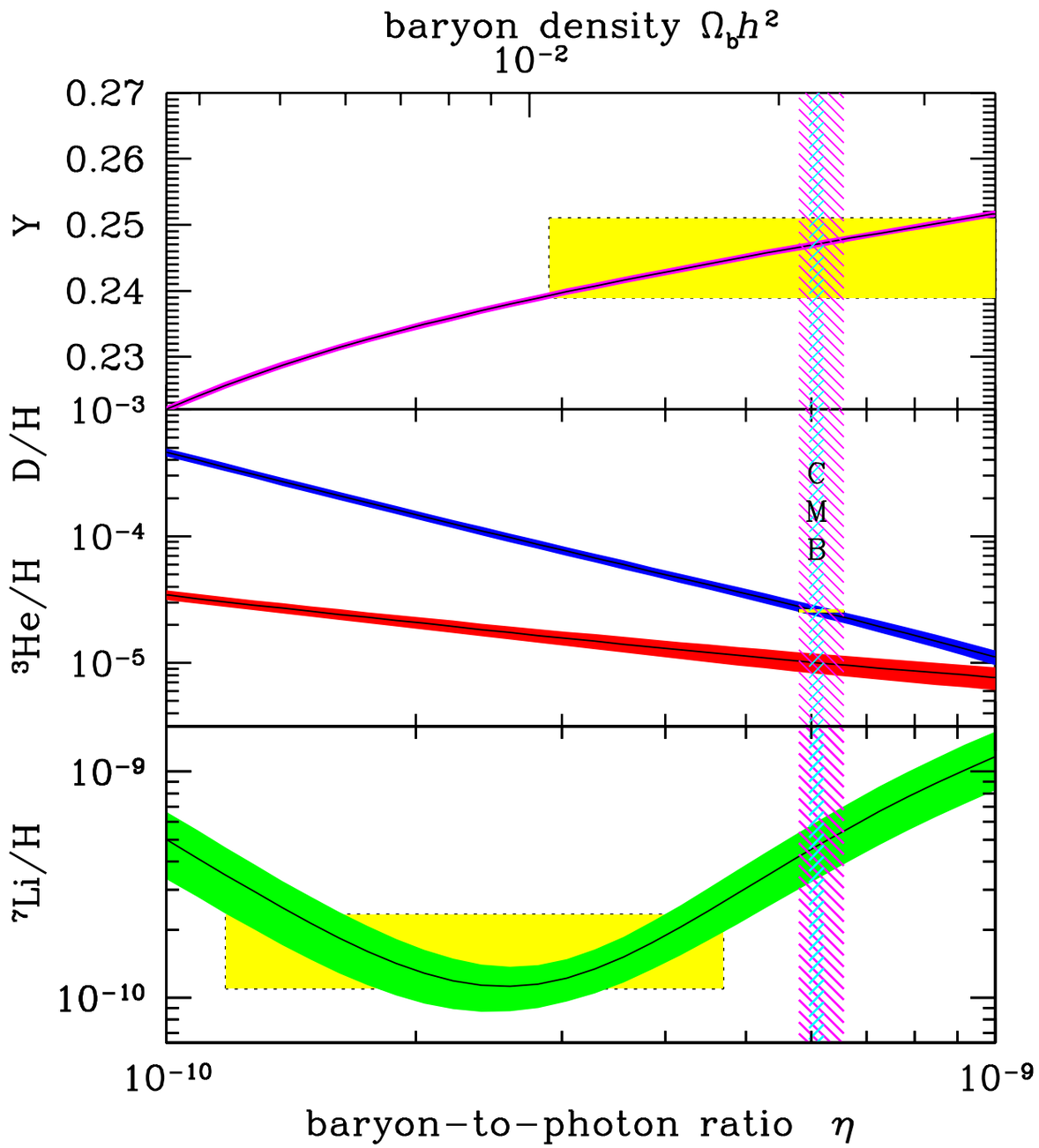


Figure 24.1: The primordial abundances of ^{4}He, D, ^{3}He, and ^{7}Li as predicted by the standard model of Big-Bang nucleosynthesis — the bands show the 95% CL range [5]. Boxes indicate the observed light element abundances. The narrow vertical band indicates the CMB measure of the cosmic baryon density, while the wider band indicates the BBN D+^{4}He concordance range (both at 95% CL).

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}

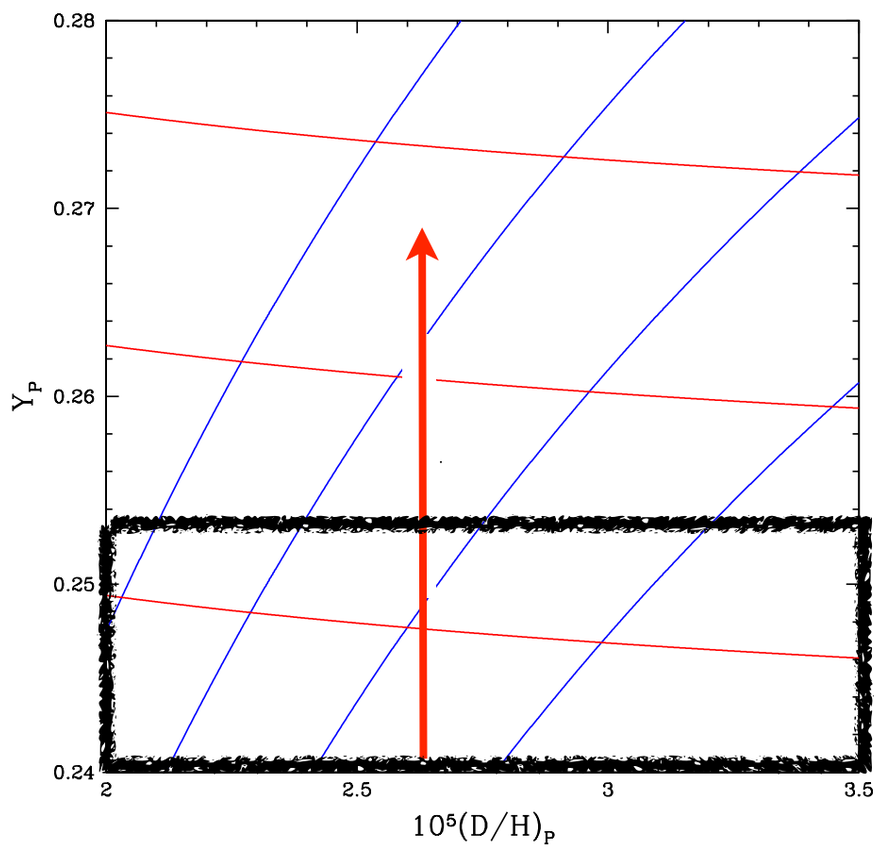
N_{eff} changes the freeze out temperature of weak interactions:

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

MORE NEUTRINOS:

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

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



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

(G. Steigman'12)

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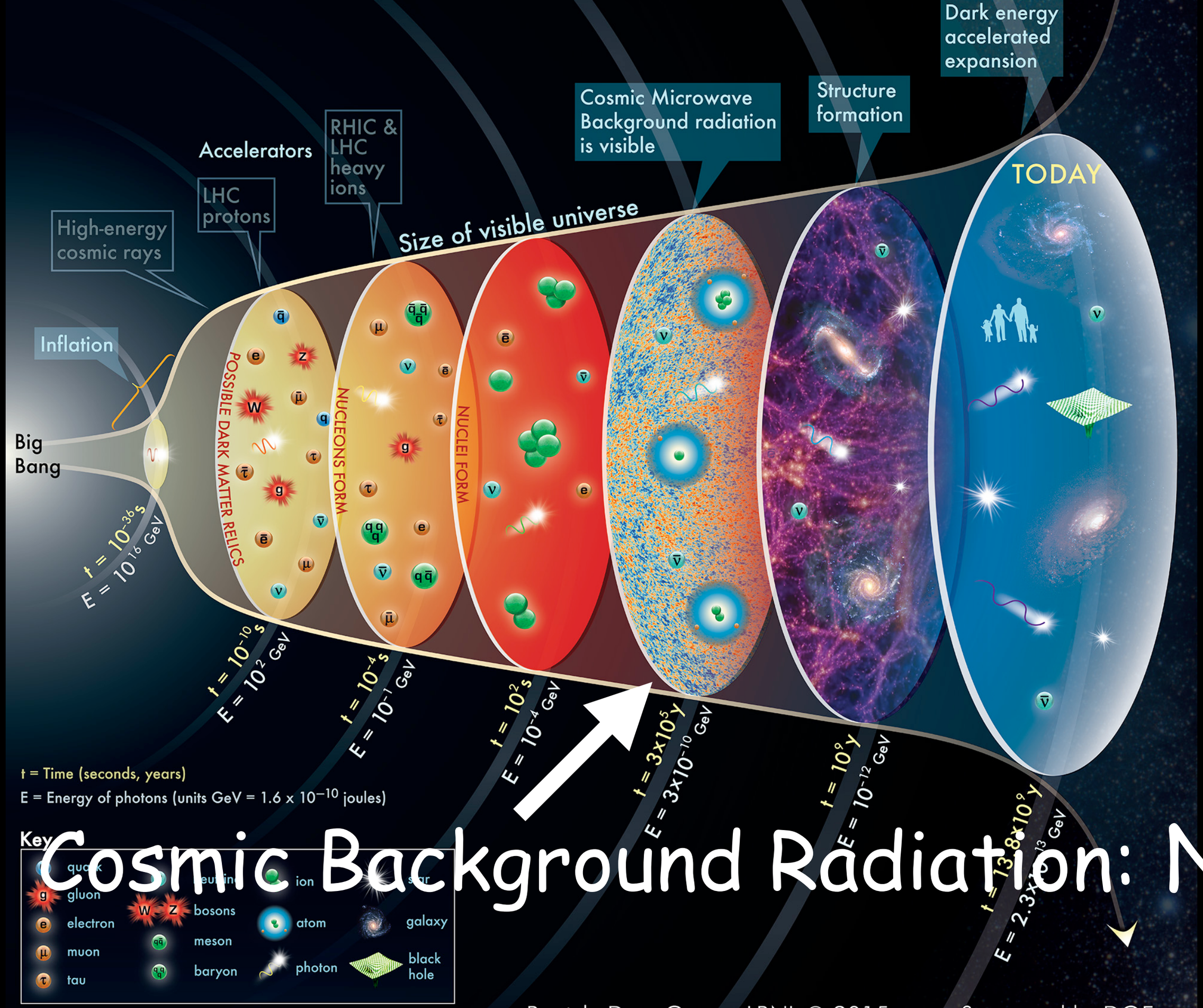
Cosmic Background Radiation: N_{eff}



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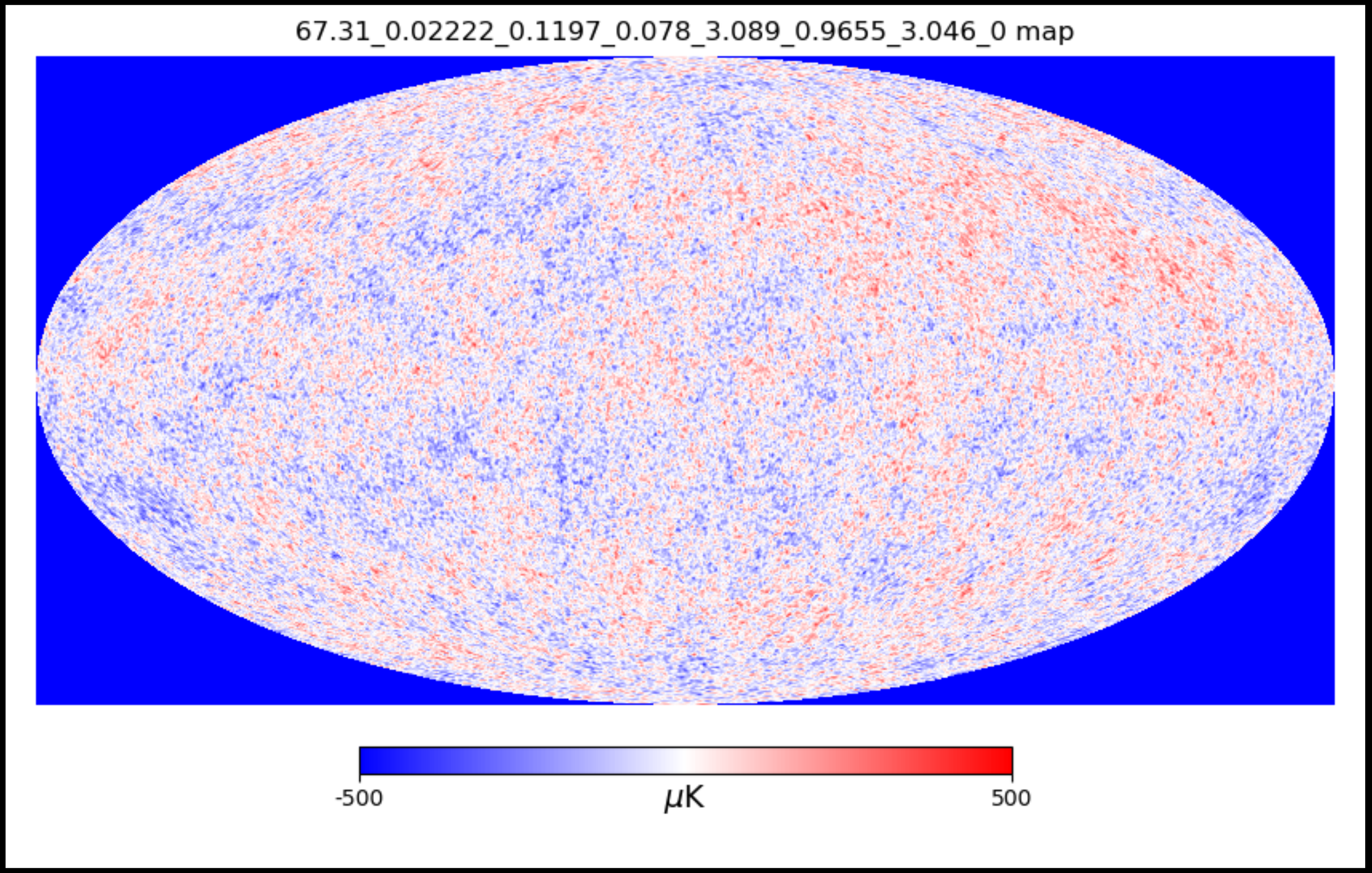
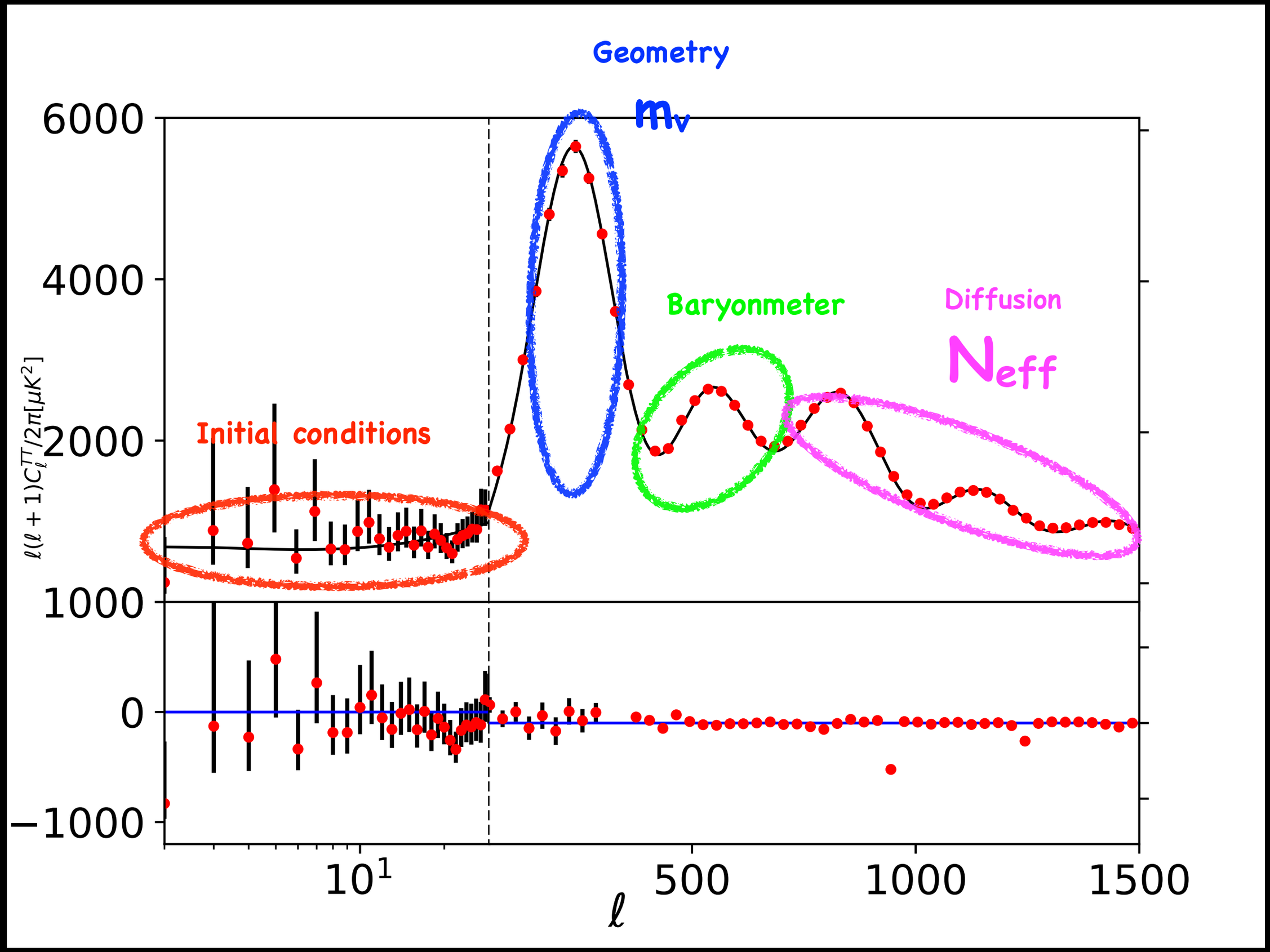
Also known as "photon decoupling", as photons started freely travel through the universe without interacting with matter and the CMB is "frozen"

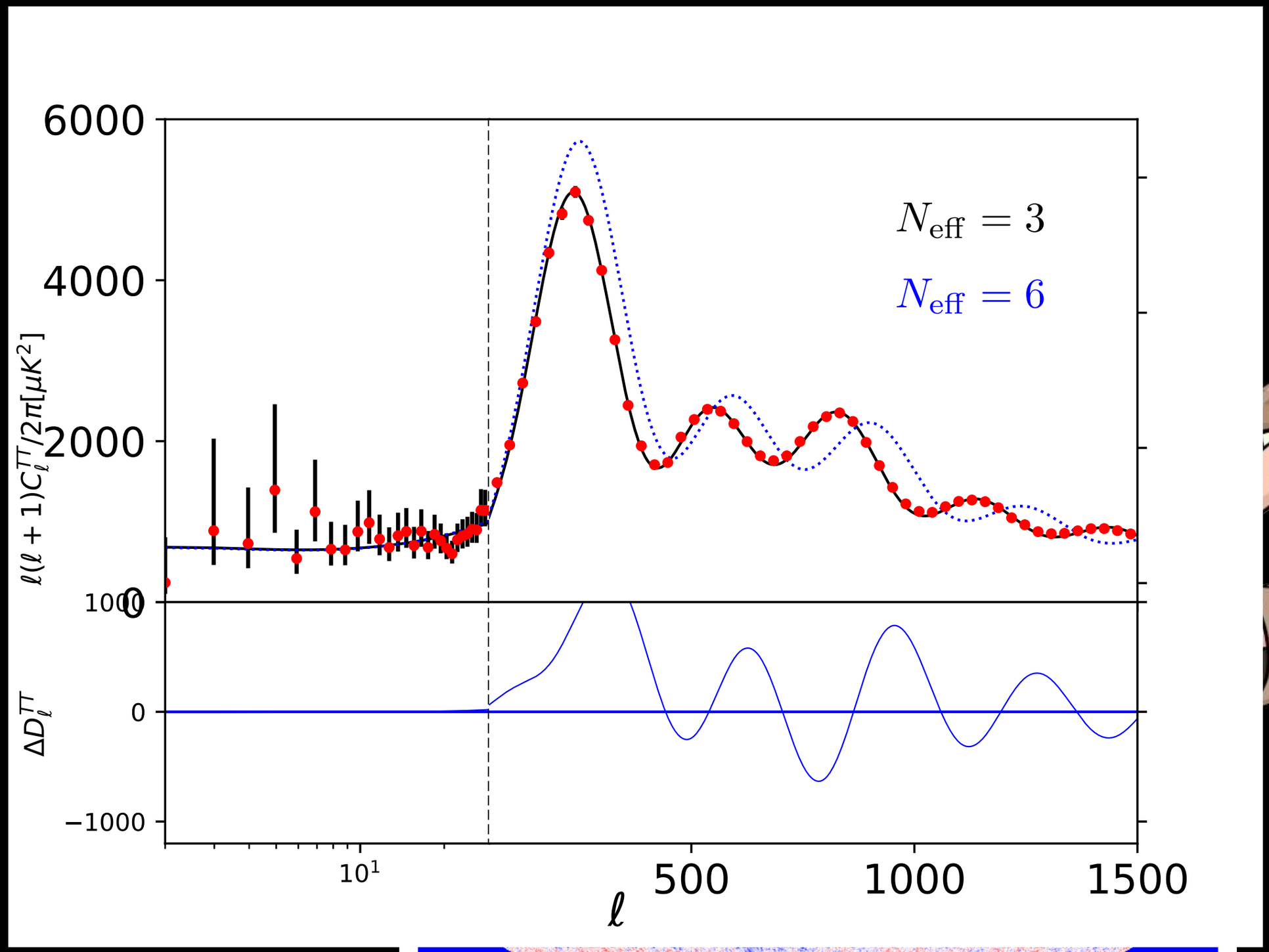
CMB: N_{eff}

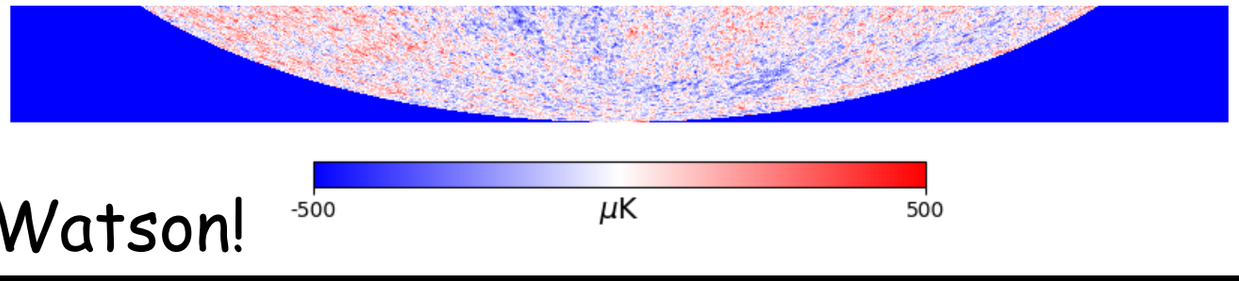


CMB: a lot to learn about….



CMB: N_{eff}

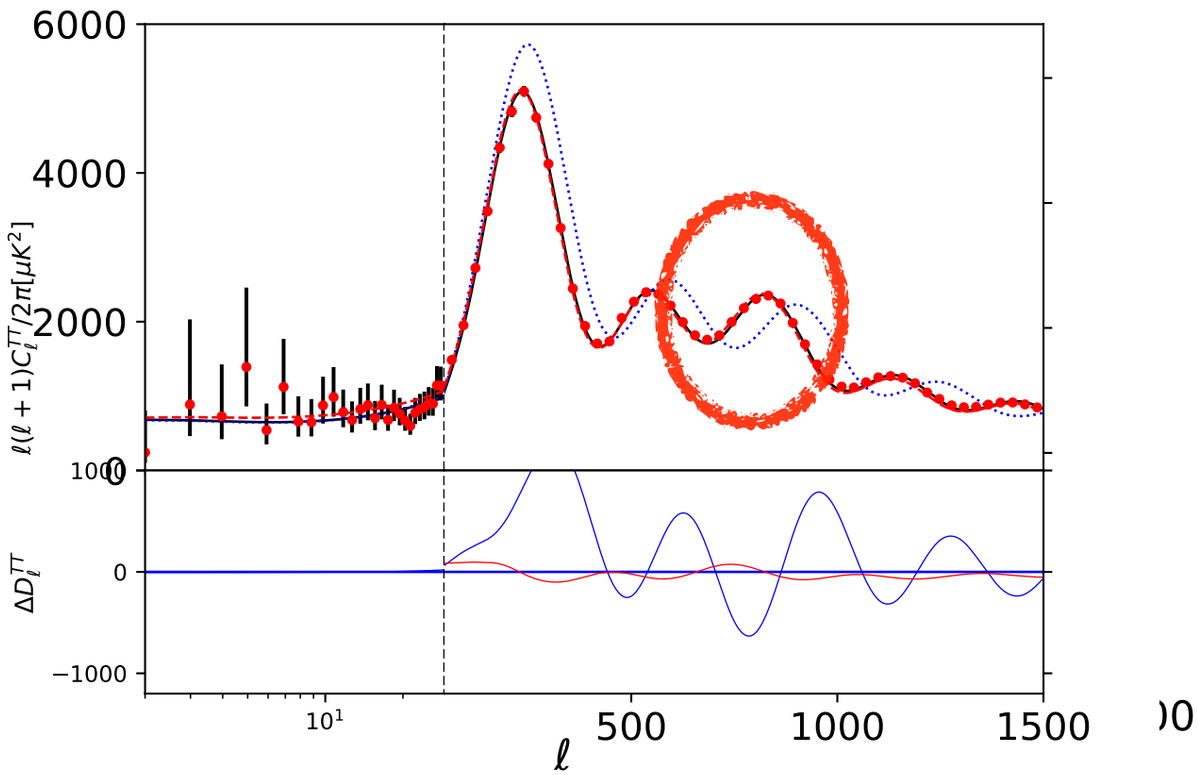




Elementary, my dear Watson!

CMB: $N_{\rm eff}$

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

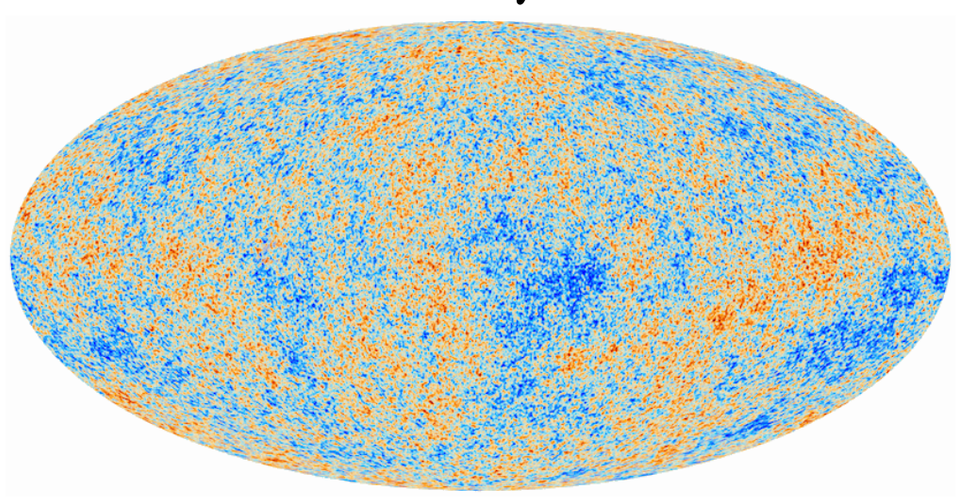


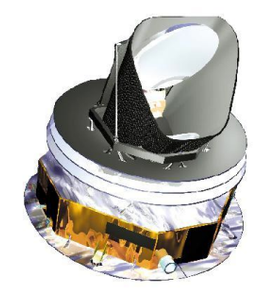
$$(\omega_b, \omega_m, h, A_s, n_s, \tau, N_{\rm eff})$$

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.

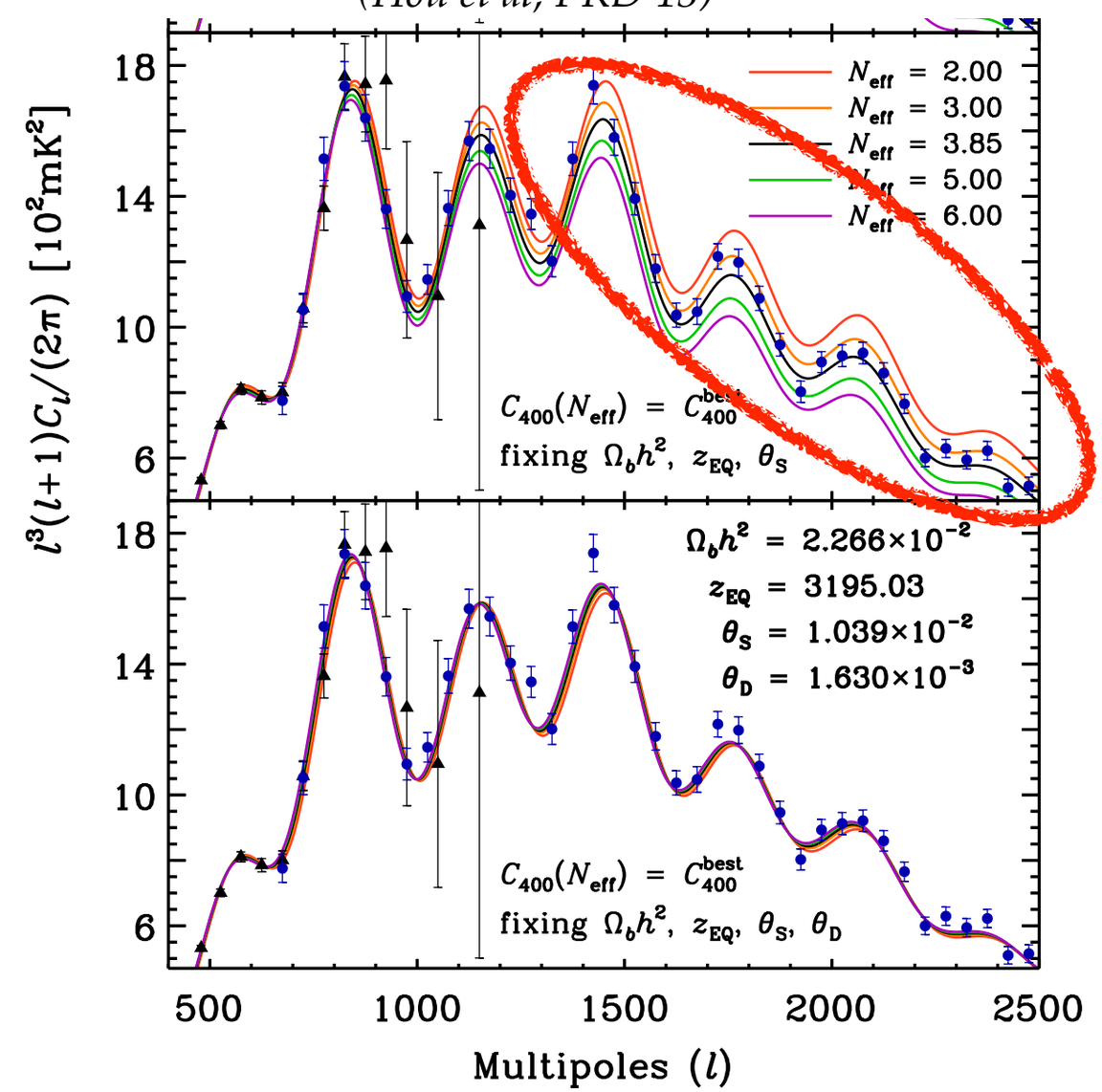
CMB: N_{eff}

@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 results, 1807.06209

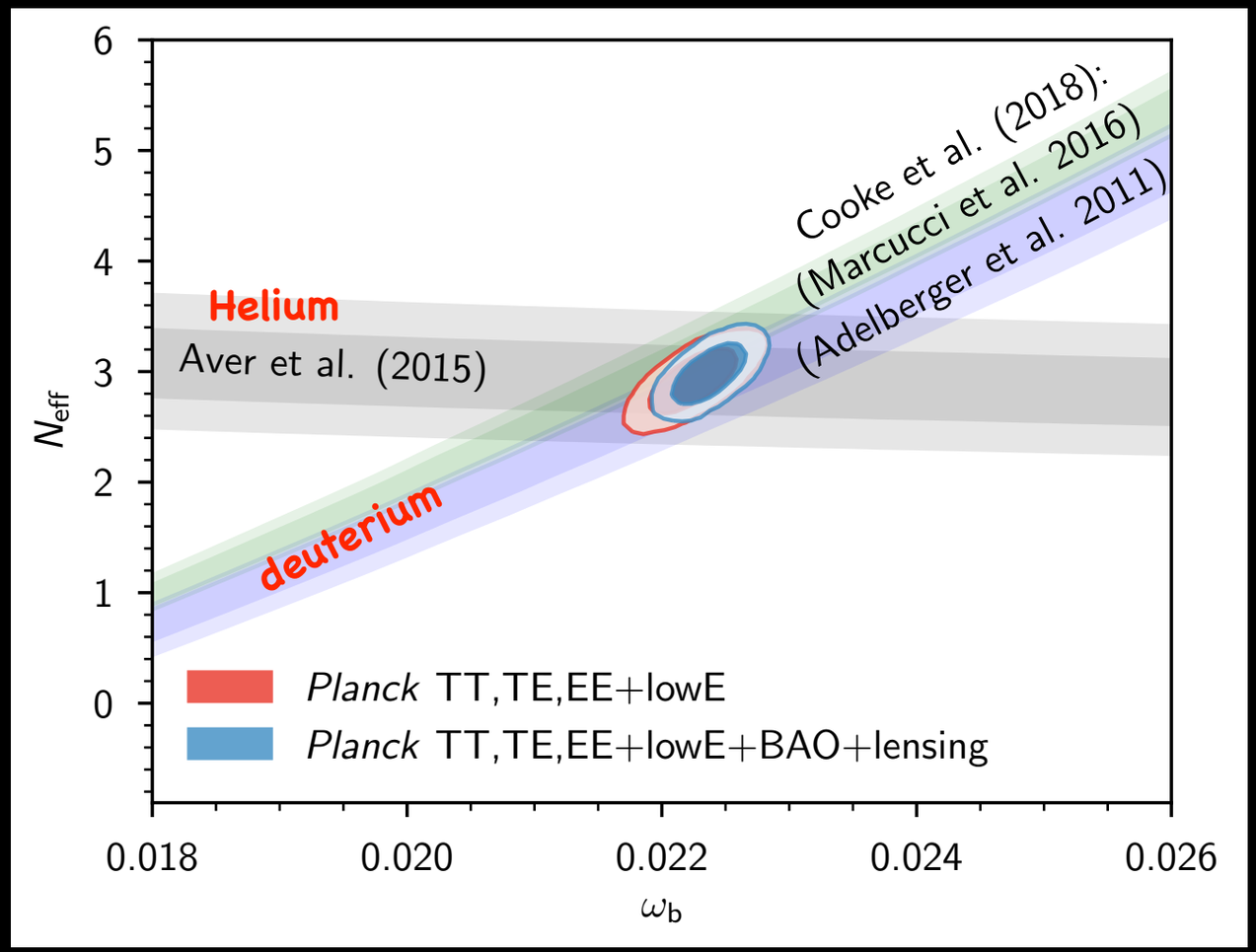
- Planck 2018 CMB temperature polarization and lensing potential data:

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

- 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:



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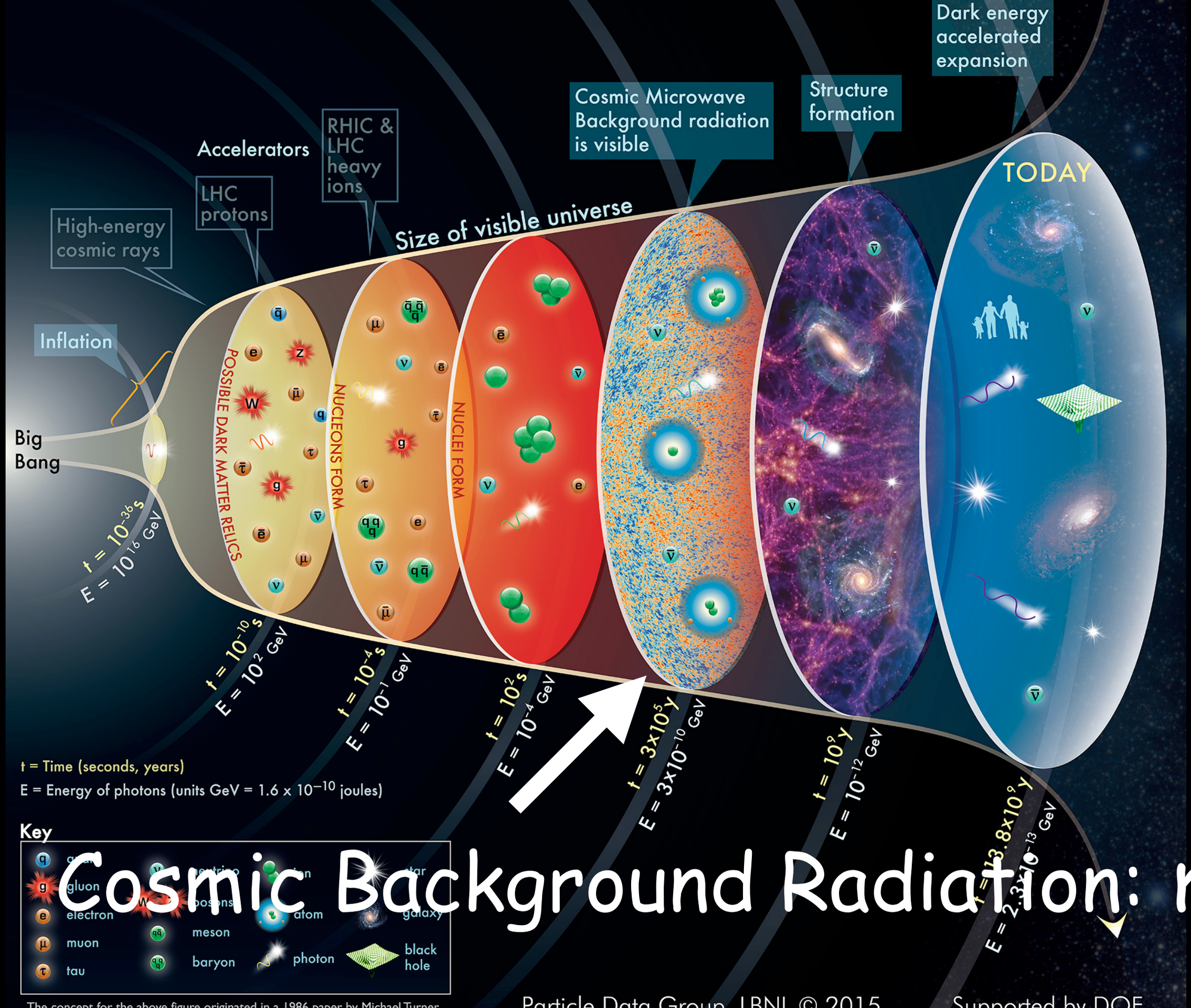
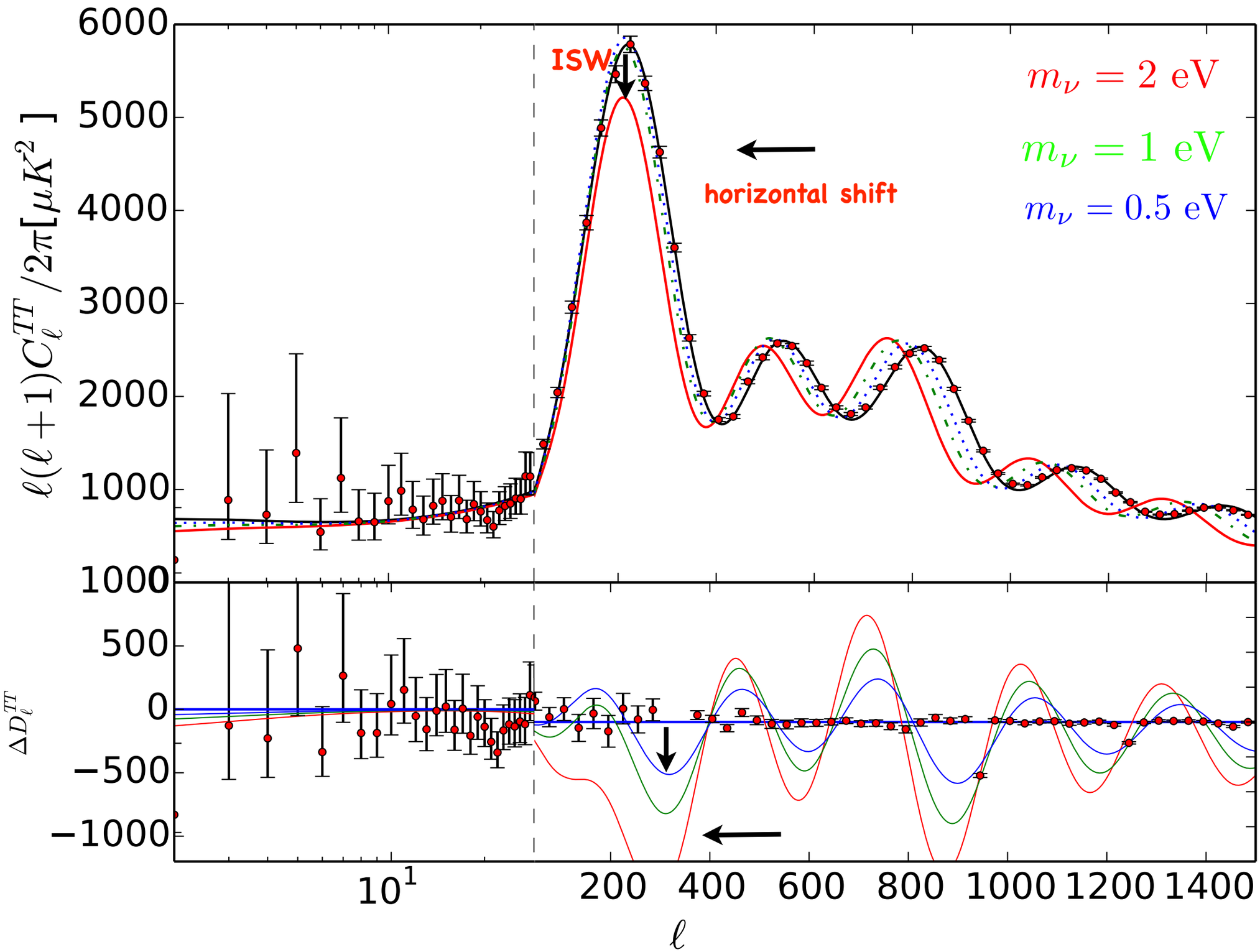
Cosmic Background Radiation: m_ν



CMB: Σm_ν

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

Shift in the angular position of the peaks.

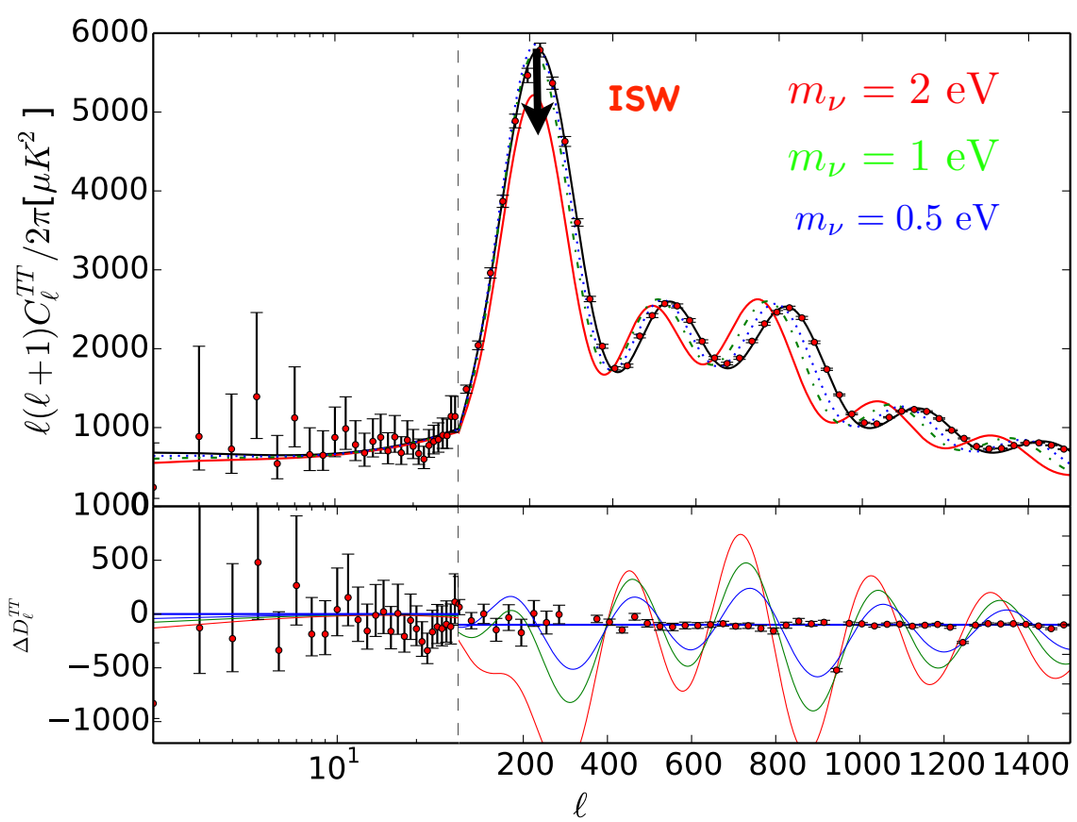


CMB: Σm_ν

@ 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:

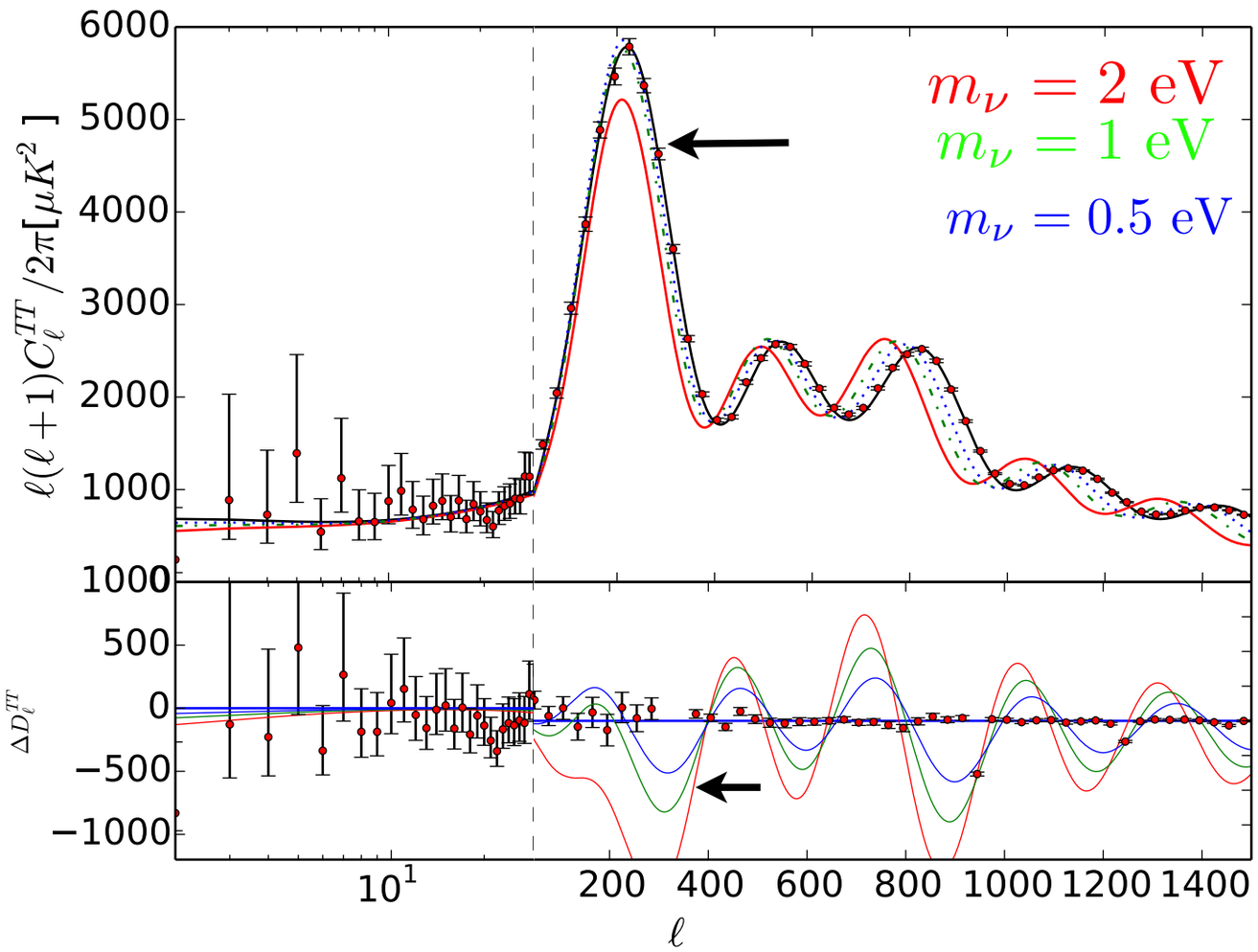
$$20 < \ell < 200$$

(Lesgourgues & Pastor, Phys.Rept'06)

CMB: Σm_ν

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

Shift in the angular position of the peaks.



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

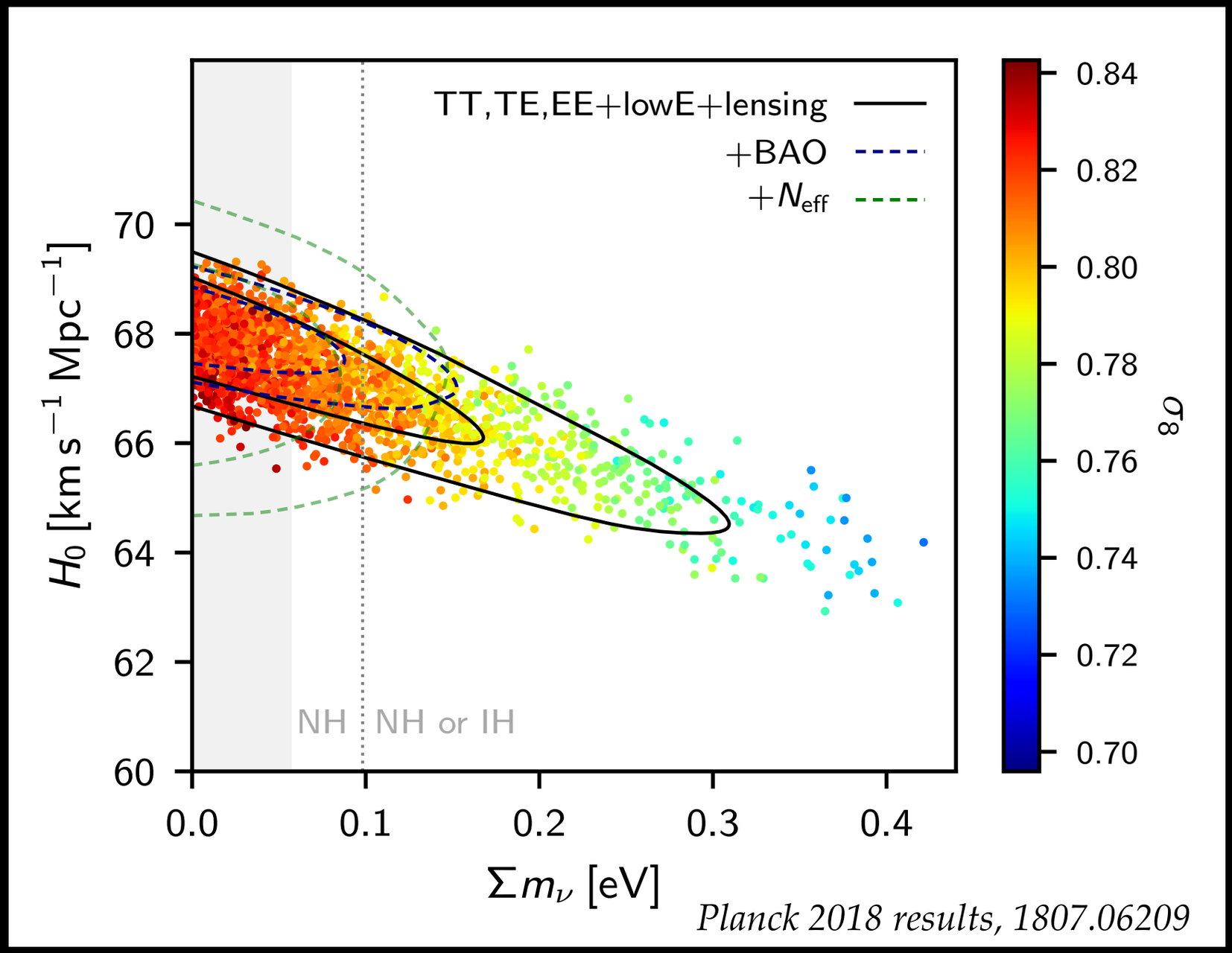
$$r_s = \int_0^{t(z_d)} c_s\,(1+z)dt = \frac{2}{3k_{\rm eq}}\sqrt{\frac{6}{R_{\rm eq}}}\ln\frac{\sqrt{1+R_d}+\sqrt{R_d+R_{\rm eq}}}{1+\sqrt{R_{\rm eq}}}$$

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

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 2018 results, 1807.06209



Planck 2018 results, 1807.06209

Strong degeneracy between Σm_ν and the Hubble constant H_0!

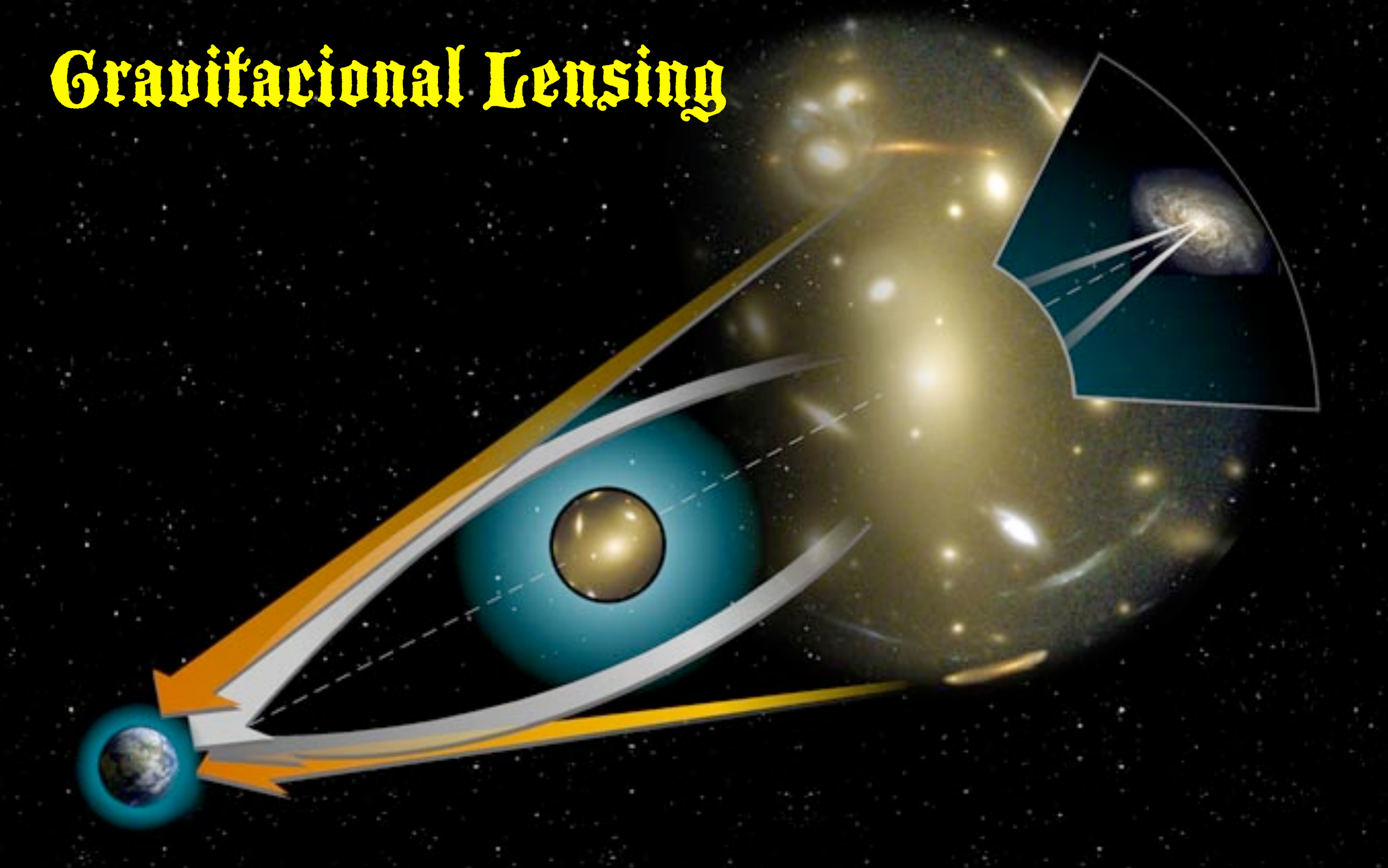
CMB: Σm_ν

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

Shift in the angular position of the peaks.

CANCELLED

Gravitacional Lensing

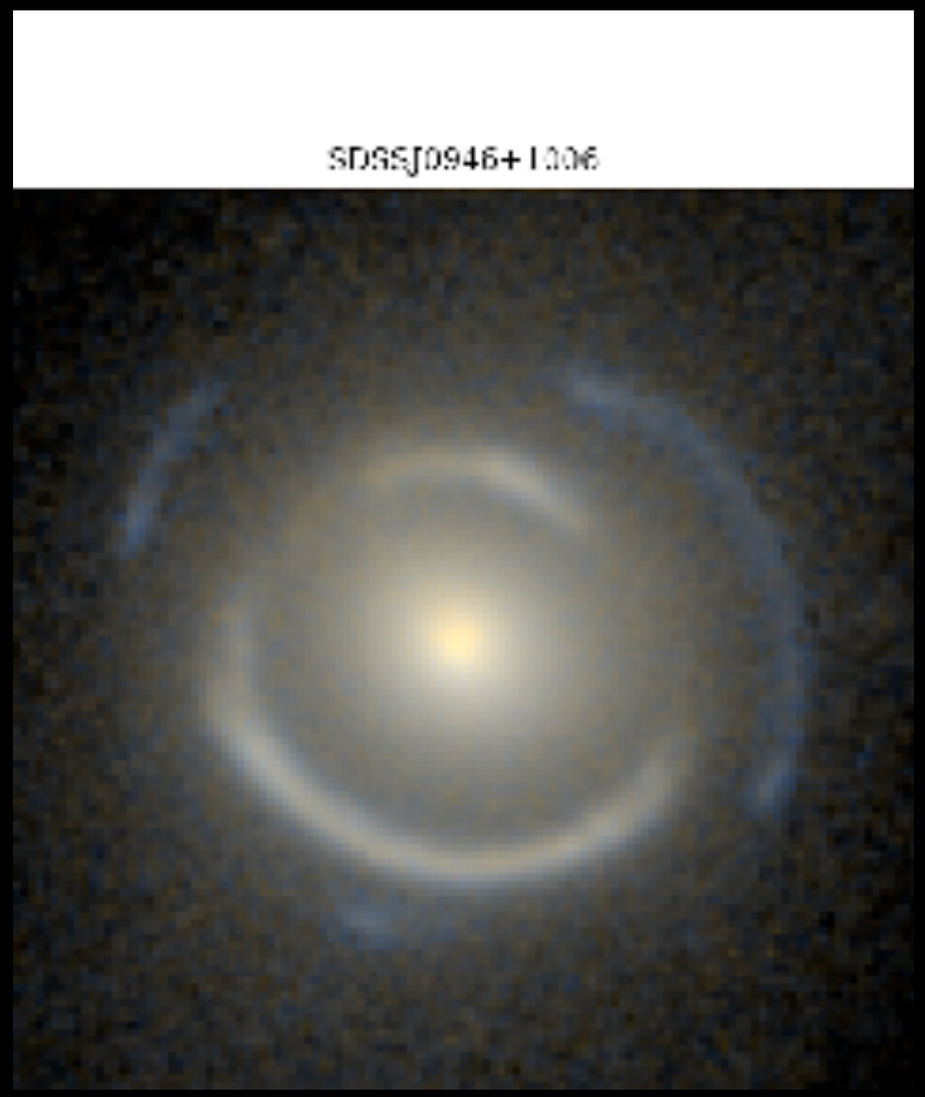


Einstein's relativity predicts that the presence of a massive body will curve space time, distorting the light trajectory. The shape of the background objects will change/ multiplied by the presence of intervening galaxies.

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: Σm_ν

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

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

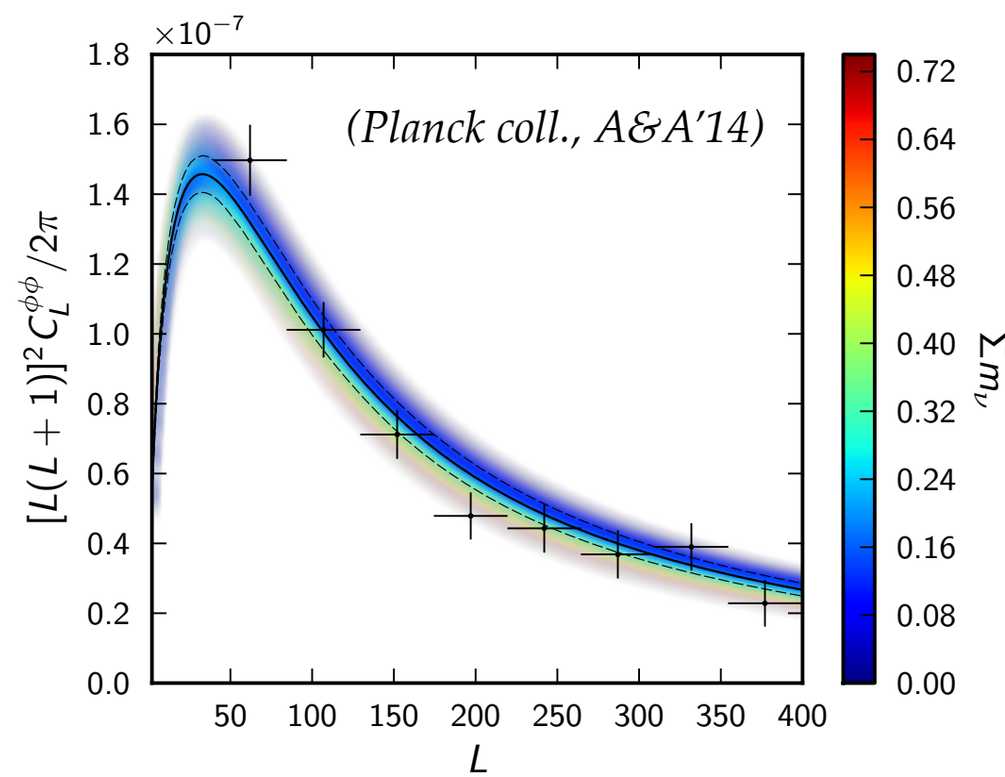
Matter distribution

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: Σm_ν

Planck 2018 results, 1807.06209

Planck TTTEEE+lowT+lowE+lensing

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

Back to school Schedule

Elementary School

- The **classical** cosmic pizza
- The neutrino slice
- Neutrino decoupling in the early universe

Middle School

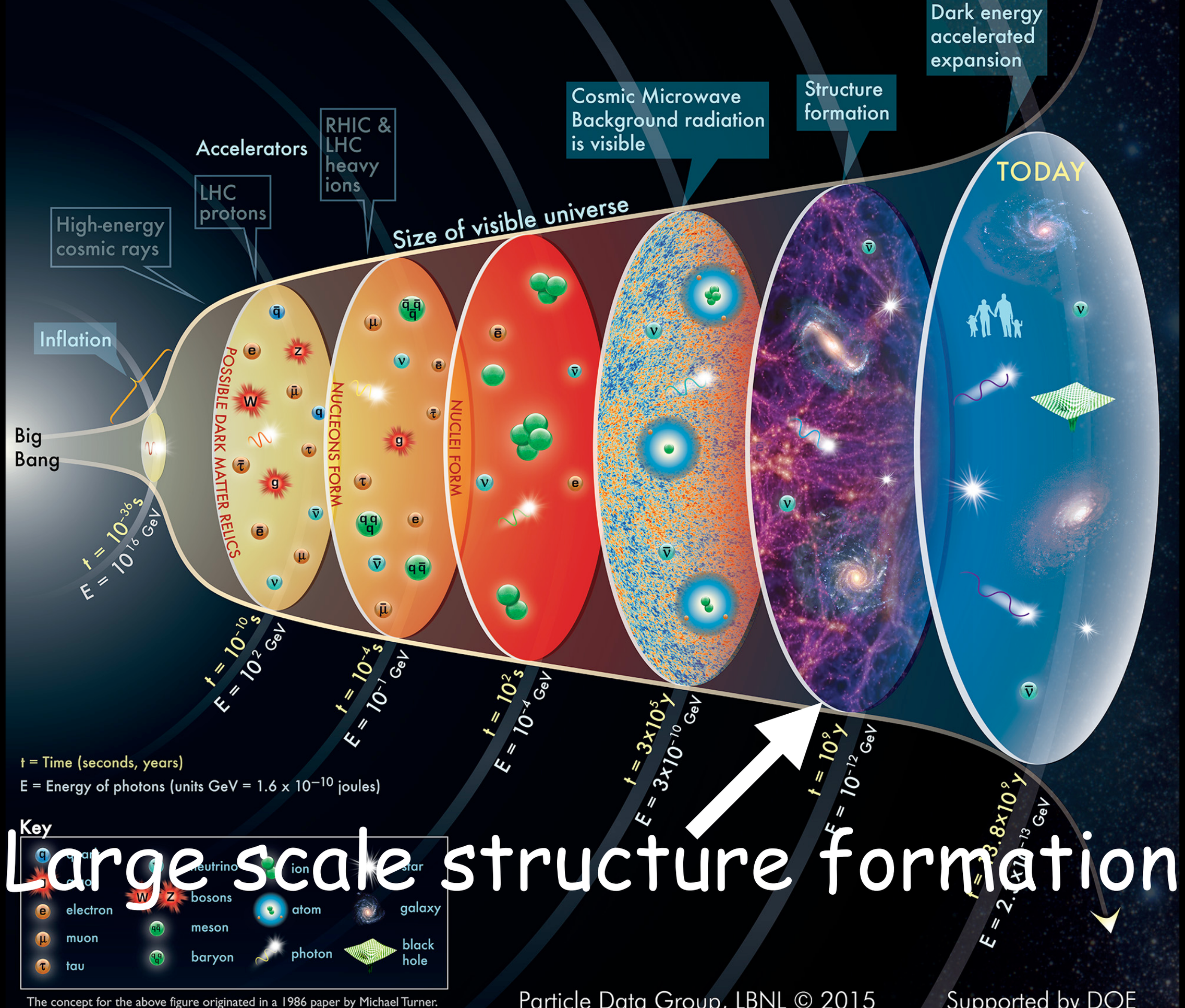
- Number of neutrinos and Big-Bang Nucleosynthesis
- Number of neutrinos and Cosmic Microwave Background Radiation
- Neutrino masses and Cosmic Microwave Background Radiation
- Neutrino masses and structure formation in the universe

High School

- High school League game: Σm_ν versus w(z)
- Senior High school

Homework

- Take home messages



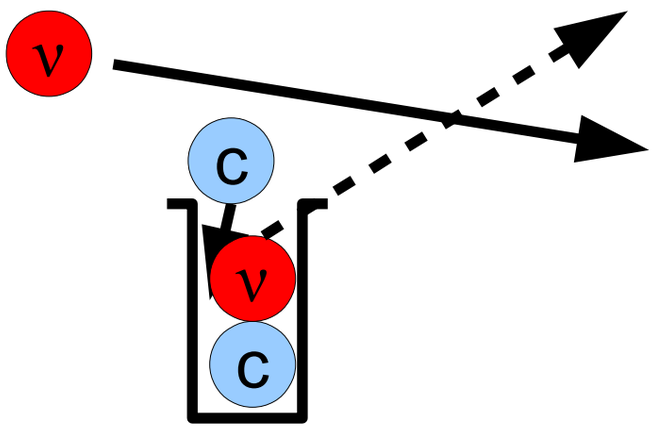
Large scale structure formation: m_ν

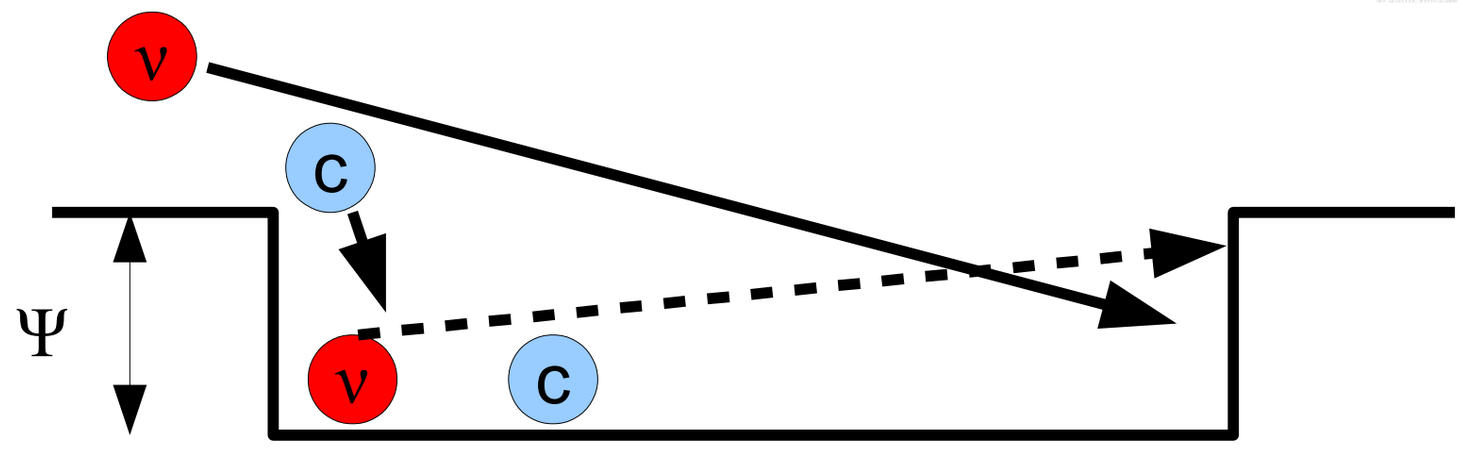
Large scale structure: m_ν

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!





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

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

(From Y. Wong)

Large scale structure: m_ν

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

Hubble drag

Gravity

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

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:

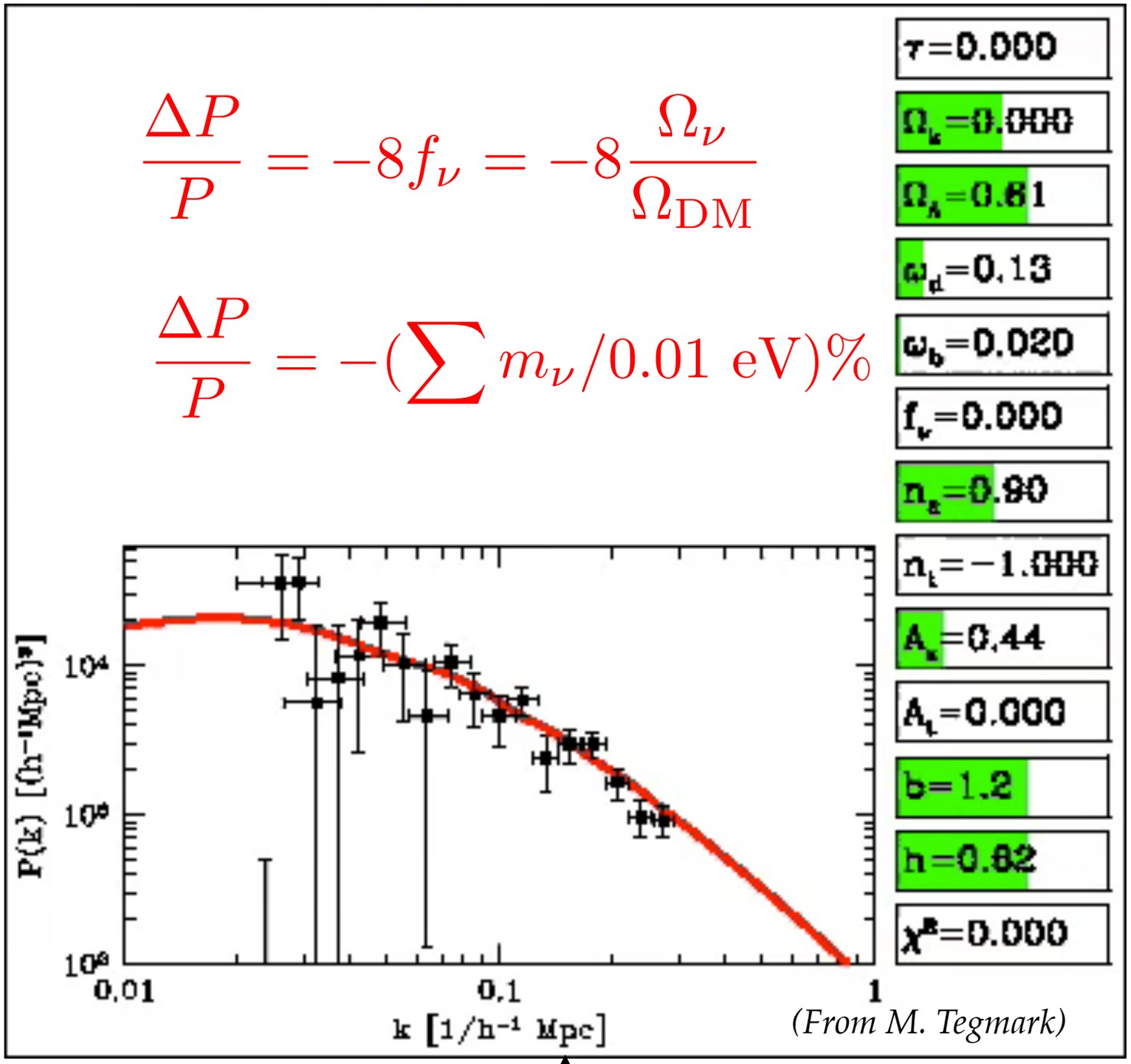
$$k_{fs,\nu}(z) \equiv \sqrt{\frac{3}{2}} \frac{H(z)}{(1+z)\sigma_{v,\nu}(z)}$$

Large scale structure: m_ν

Matter power spectrum suppression:

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

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

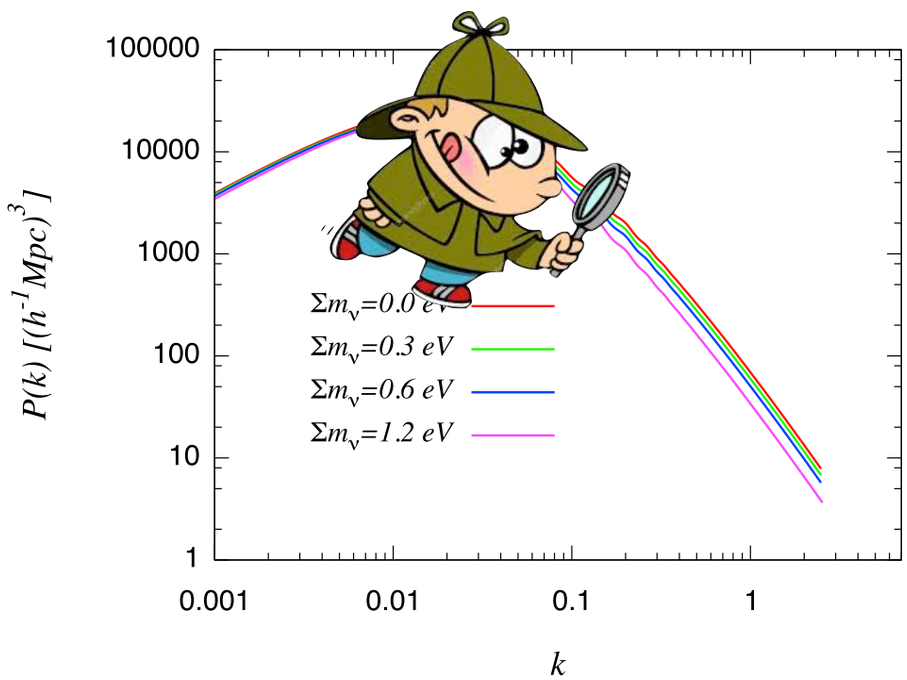


(From M. Tegmark)

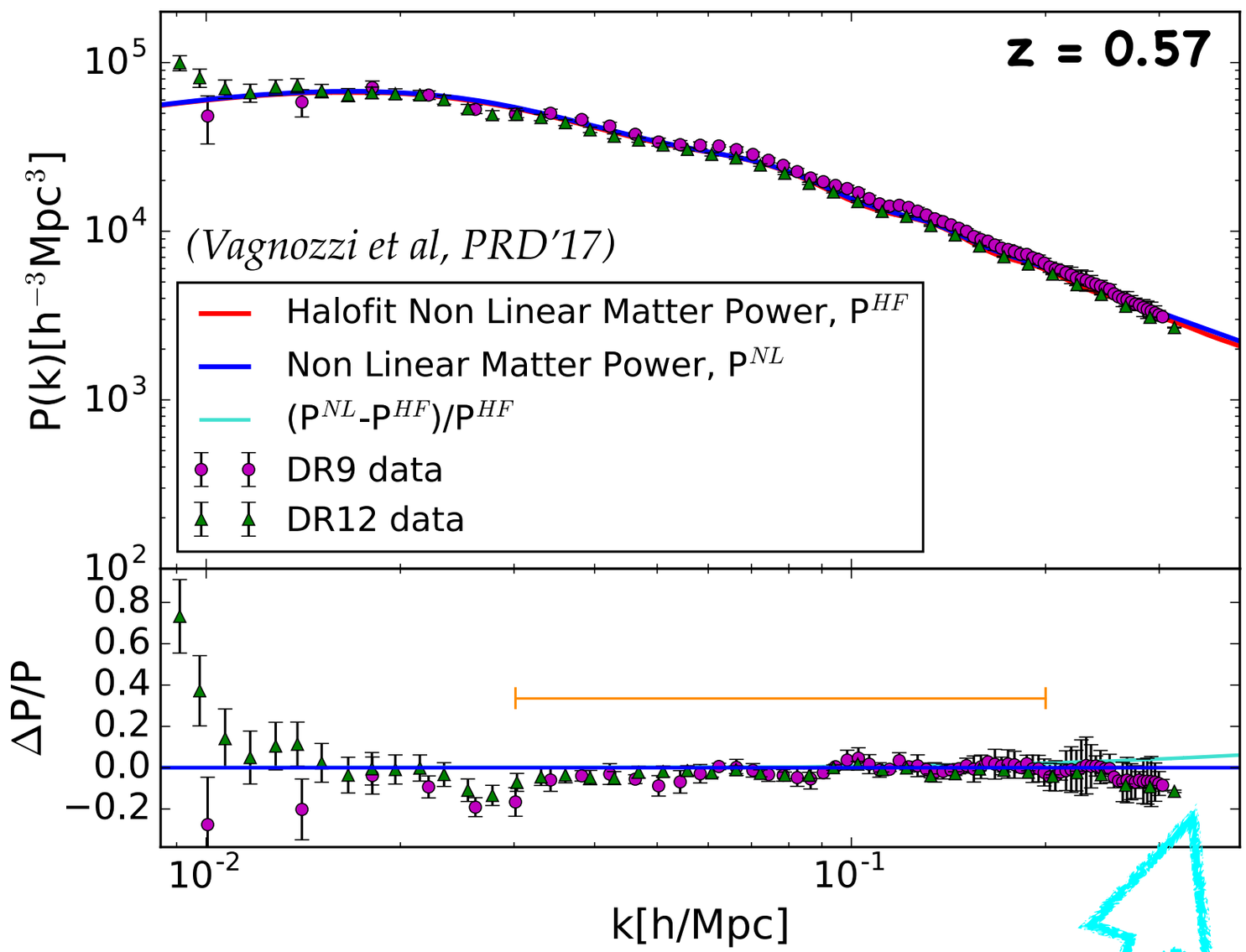
Small scales

Large scale structure: m_ν

@LSS: Caveats, NON-LINEARITIES



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



Large scale structure: m_ν

@LSS: Caveats, BIAS!

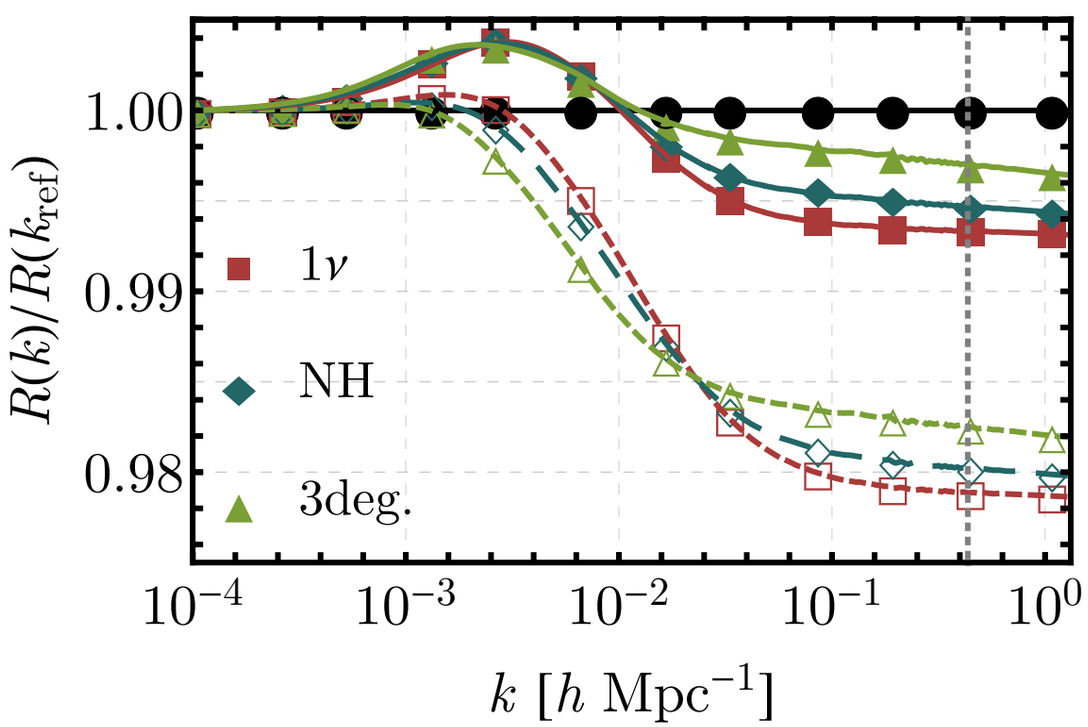
$$P_{gg}(k,z) = bias^2 P(k,z)$$

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

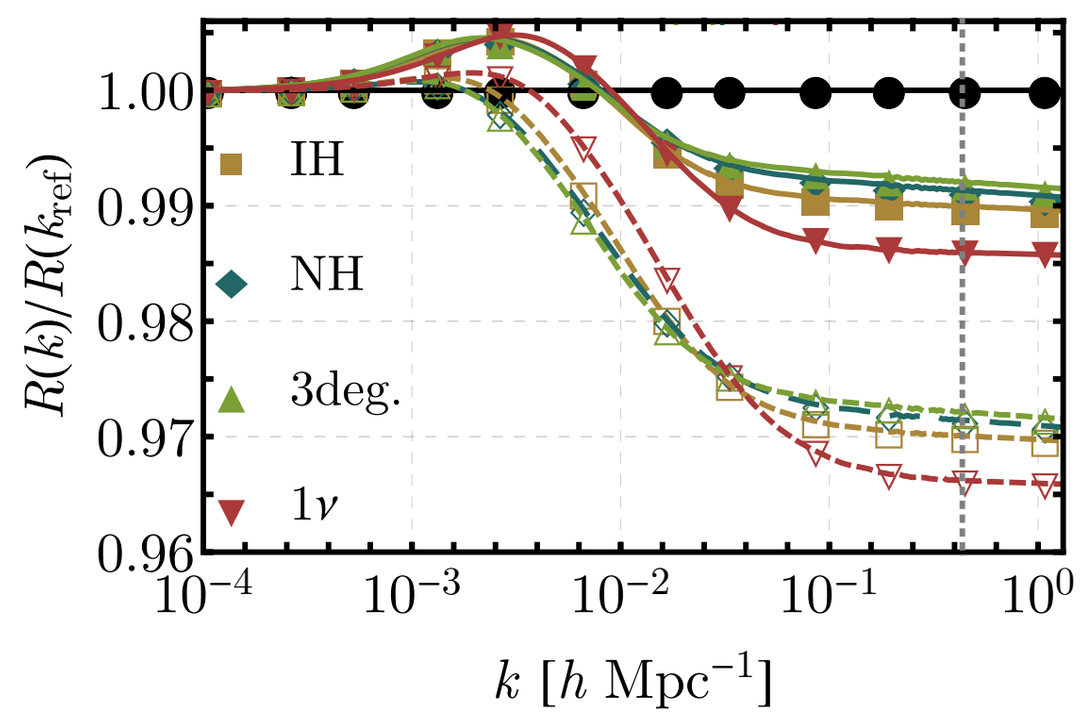
Neutrinos themselves induce a scale-dependent bias *(LoVerde & Zaldarriaga; Castorina et al)*

(Muñoz & Dvorkin PRD'18)

$\sum m_\nu = 0.06$ eV



$\sum m_\nu = 0.09$ eV

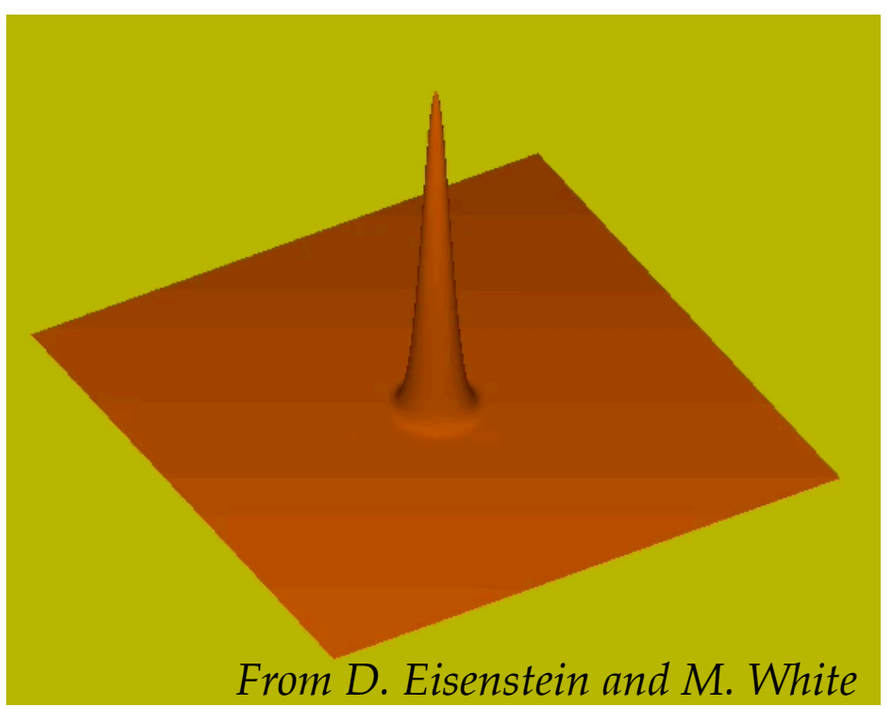


Baryon Acoustic Oscillations

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:

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

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 <u>at a scale given by the size of the horizon at the drag epoch</u>:



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

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

$$r_s = 147.09 \pm 0.26\ \text{Mpc}$$ *(Planck 2018 results)*

Baryon Acoustic Oscillations

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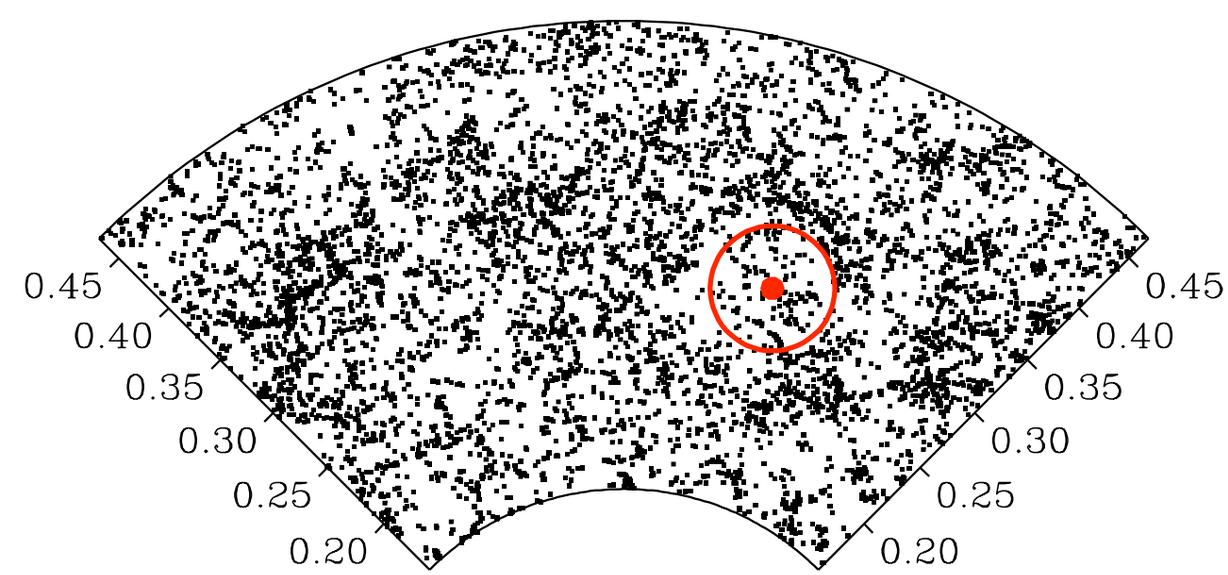
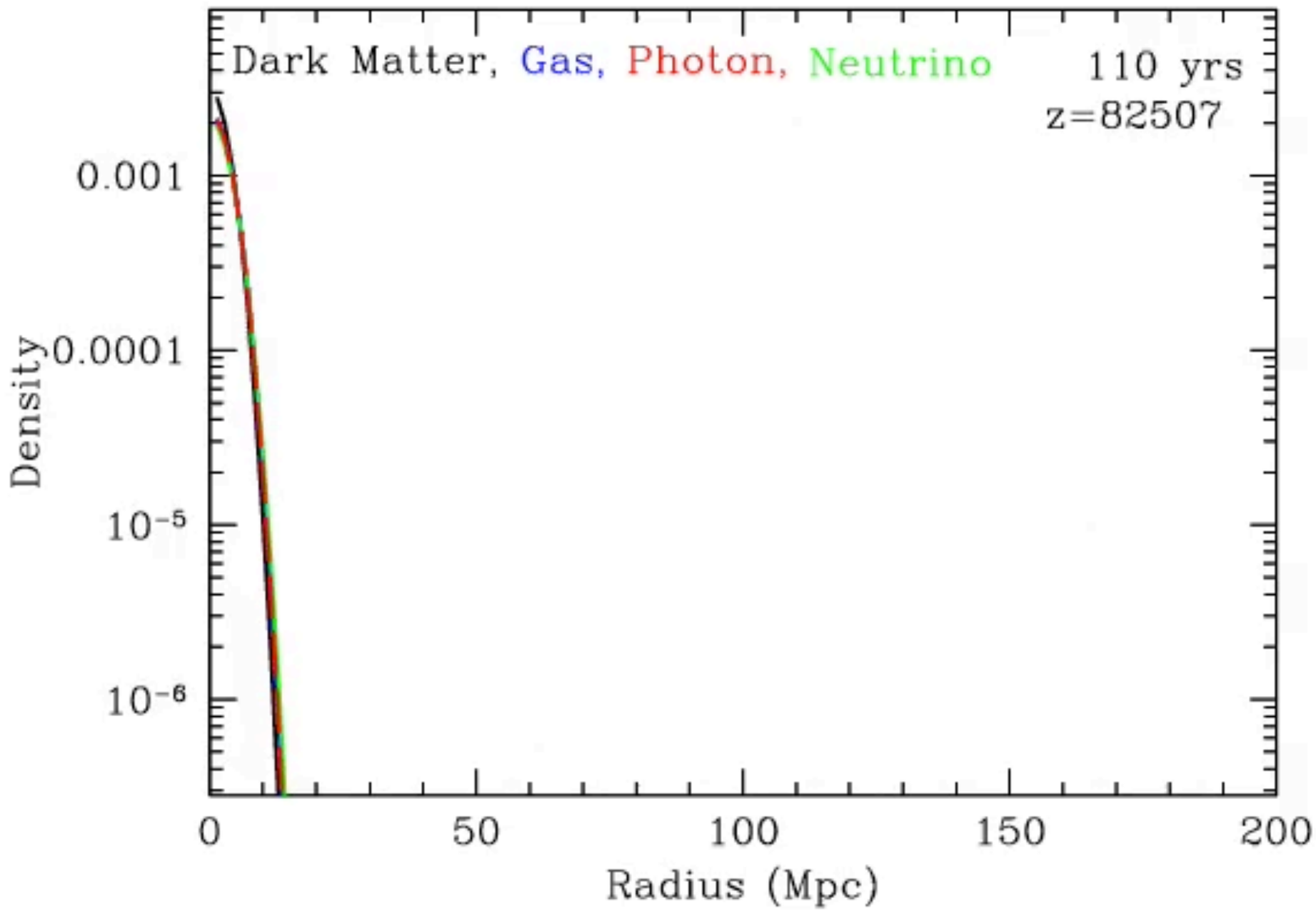
$$r_s = 147.09 \pm 0.26 \text{ Mpc}$$

(Planck 2018 results)

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



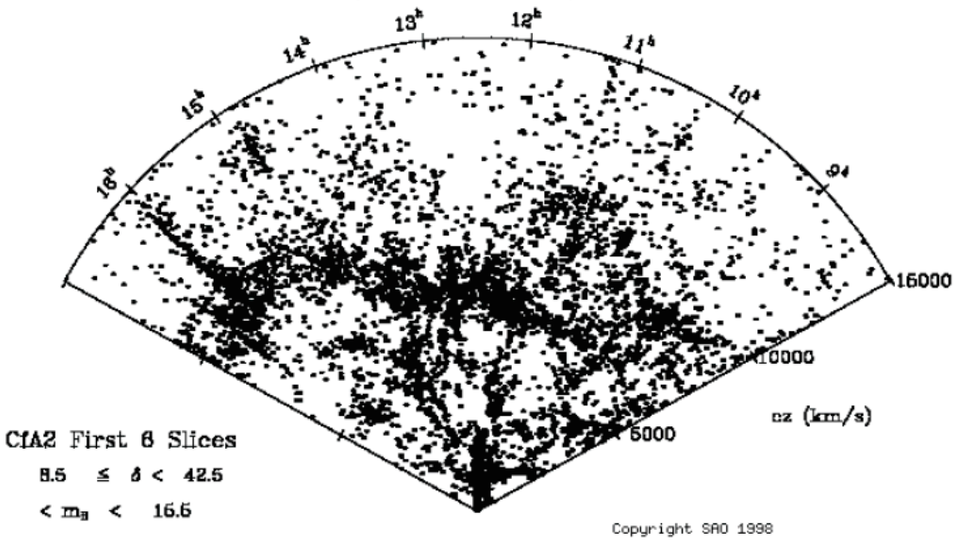
Baryon Acoustic Oscillations



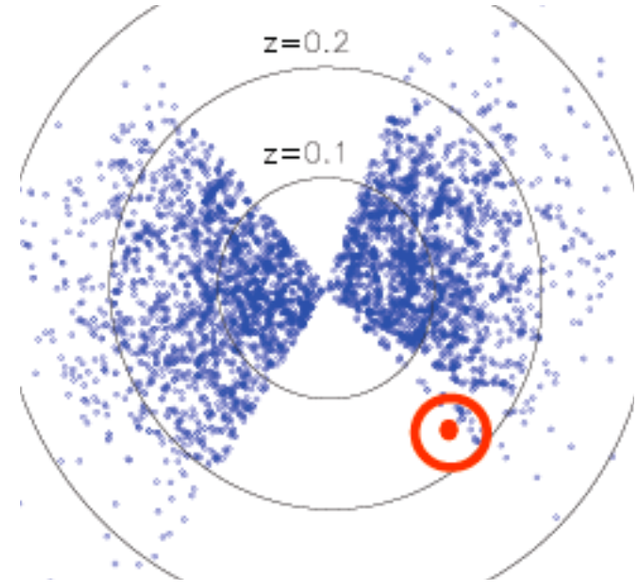
From D. Eisenstein and M. White

Baryon Acoustic Oscillations

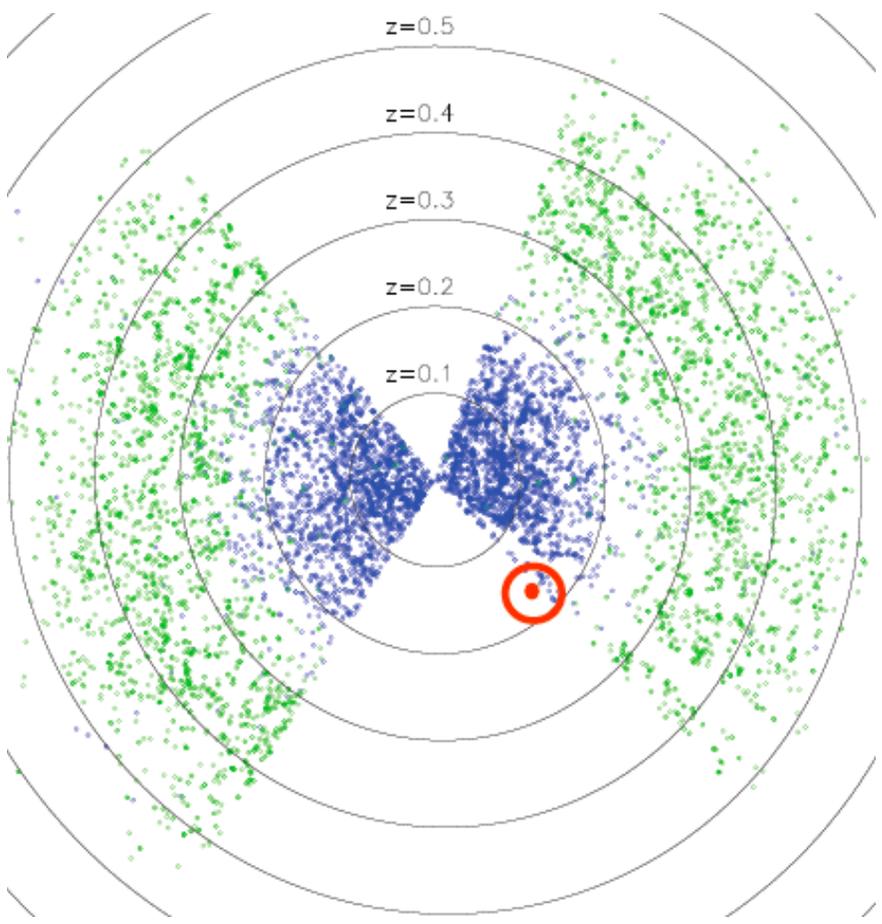
80's: Tiny surveys



BAO scale



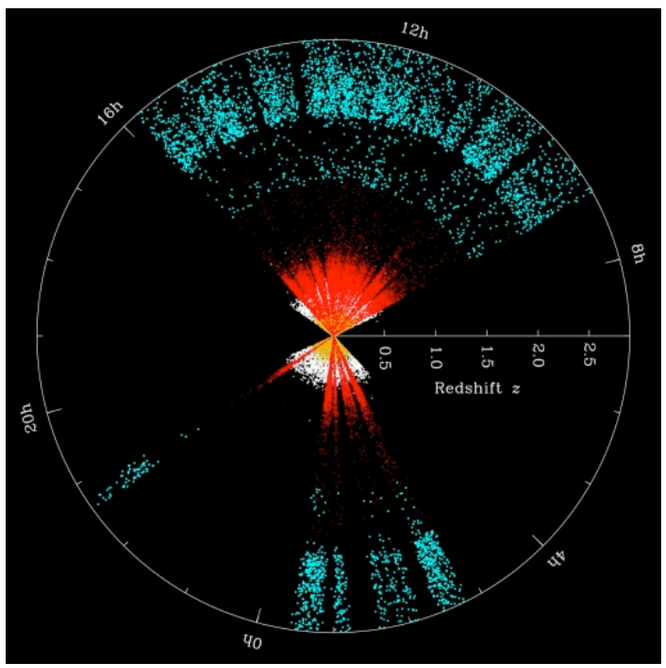
2000: Main galaxies @SDSS.
Big number, but small volume



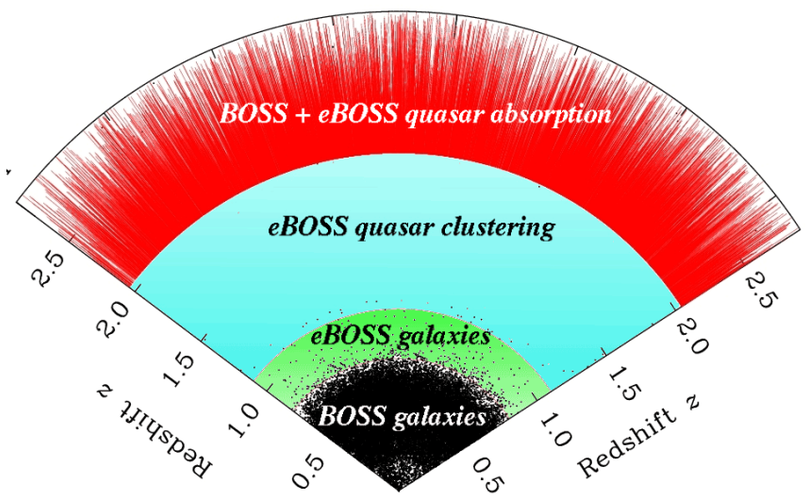
2005: Luminous Red Galaxies @ SDSS.
Big Volume: first detection of the BAO signature

Baryon Acoustic Oscillations

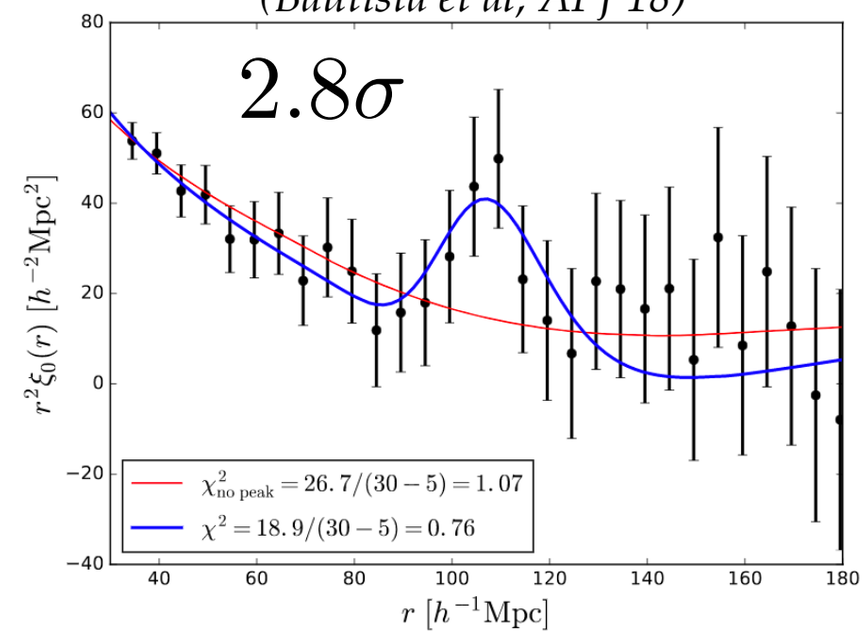
2009-2014= SDSS III

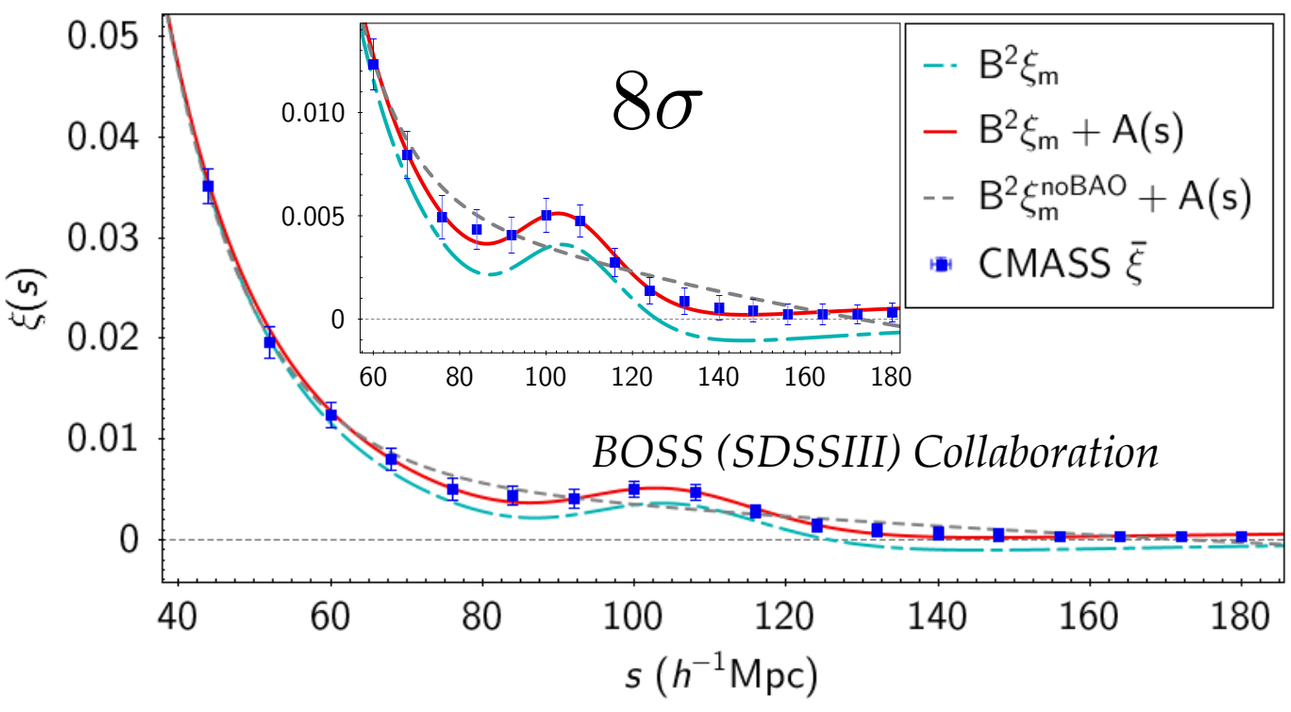


2014 - 2020= SDSS IV eBOSS

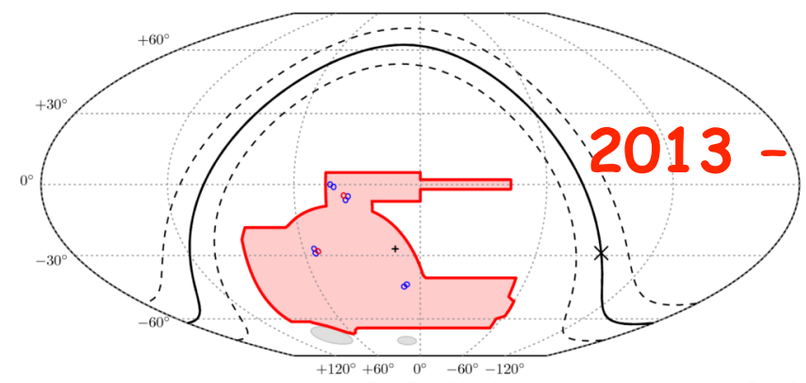


(Bautista et al, APJ'18)



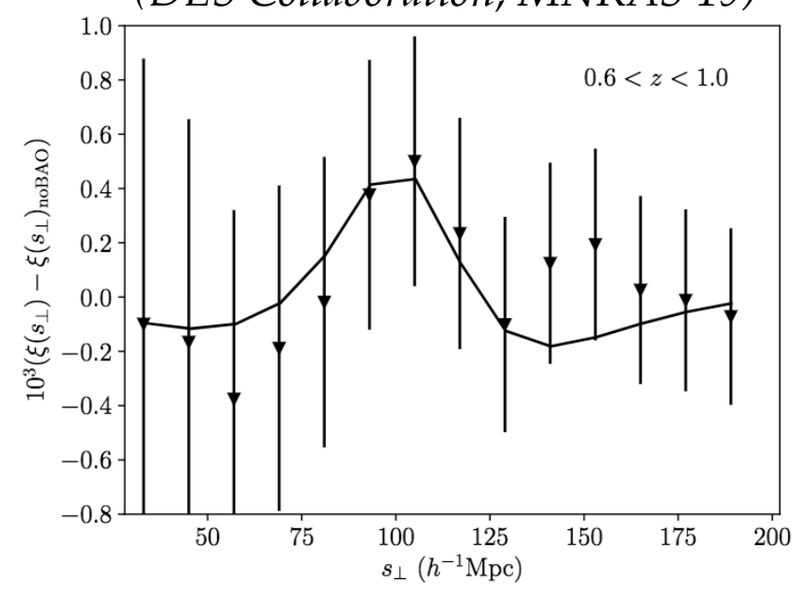


2013 - 2018= DES

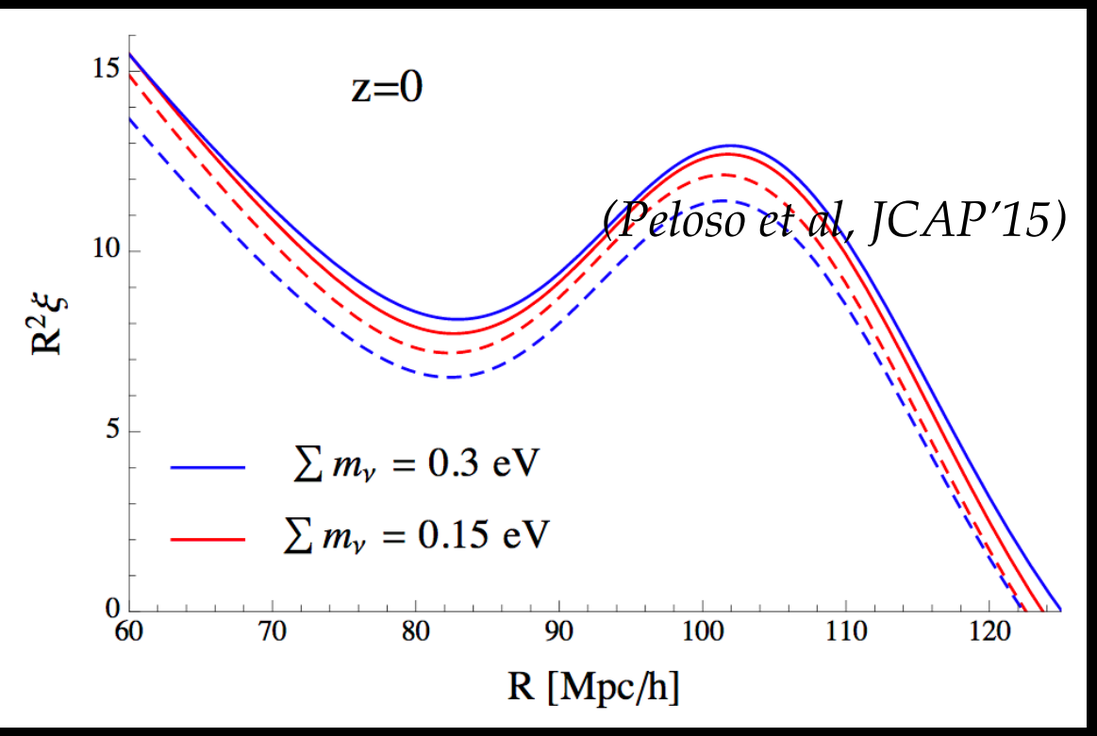


$> 2\sigma$

(DES Collaboration, MNRAS'19)



Large scale structure: m_ν



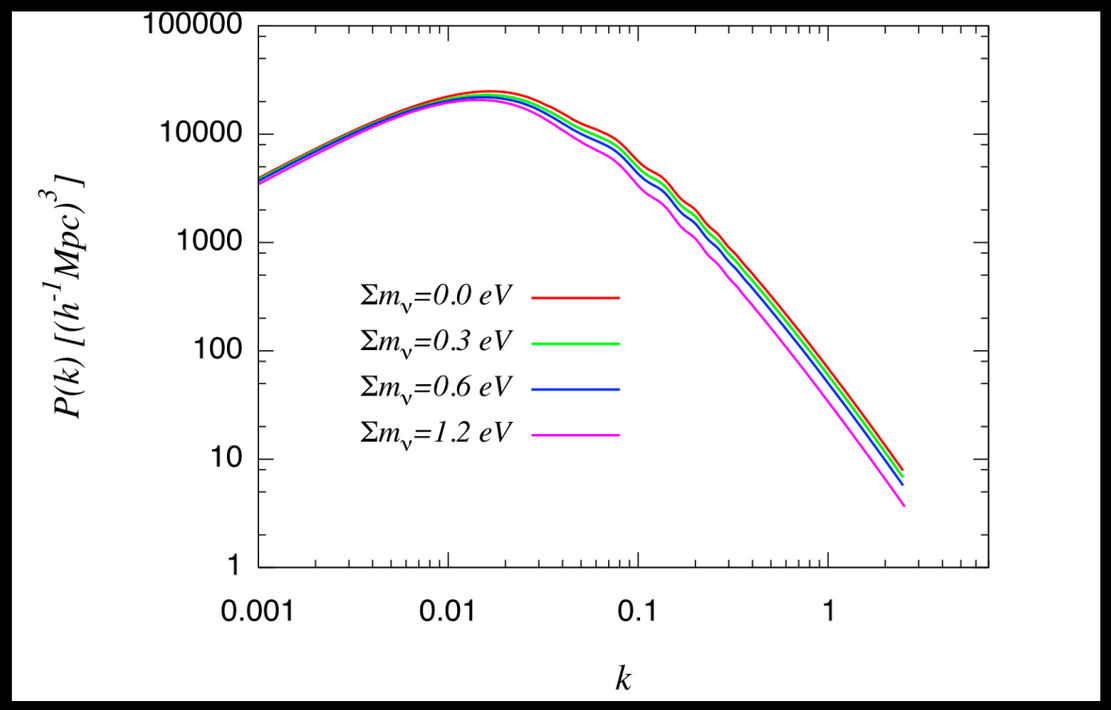
Large scale structure measurements can be interpreted either in the geometrical or shape forms

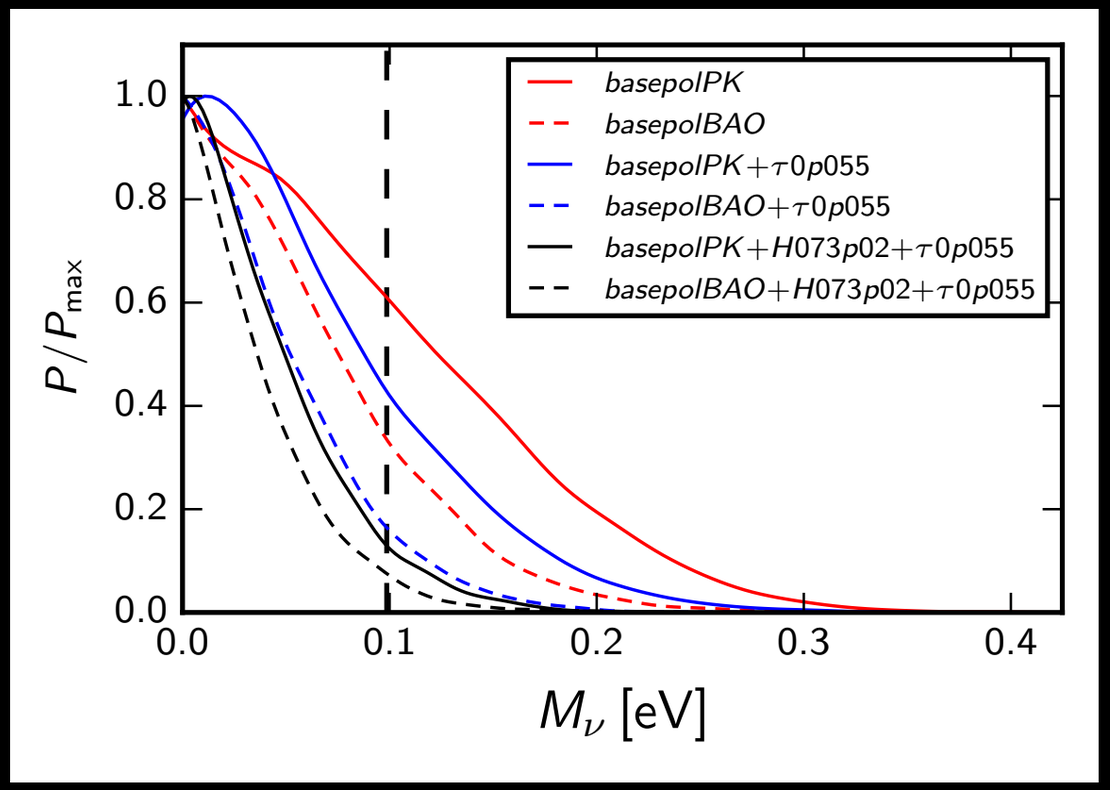
2 point correlation function

↓ 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

Σm_ν

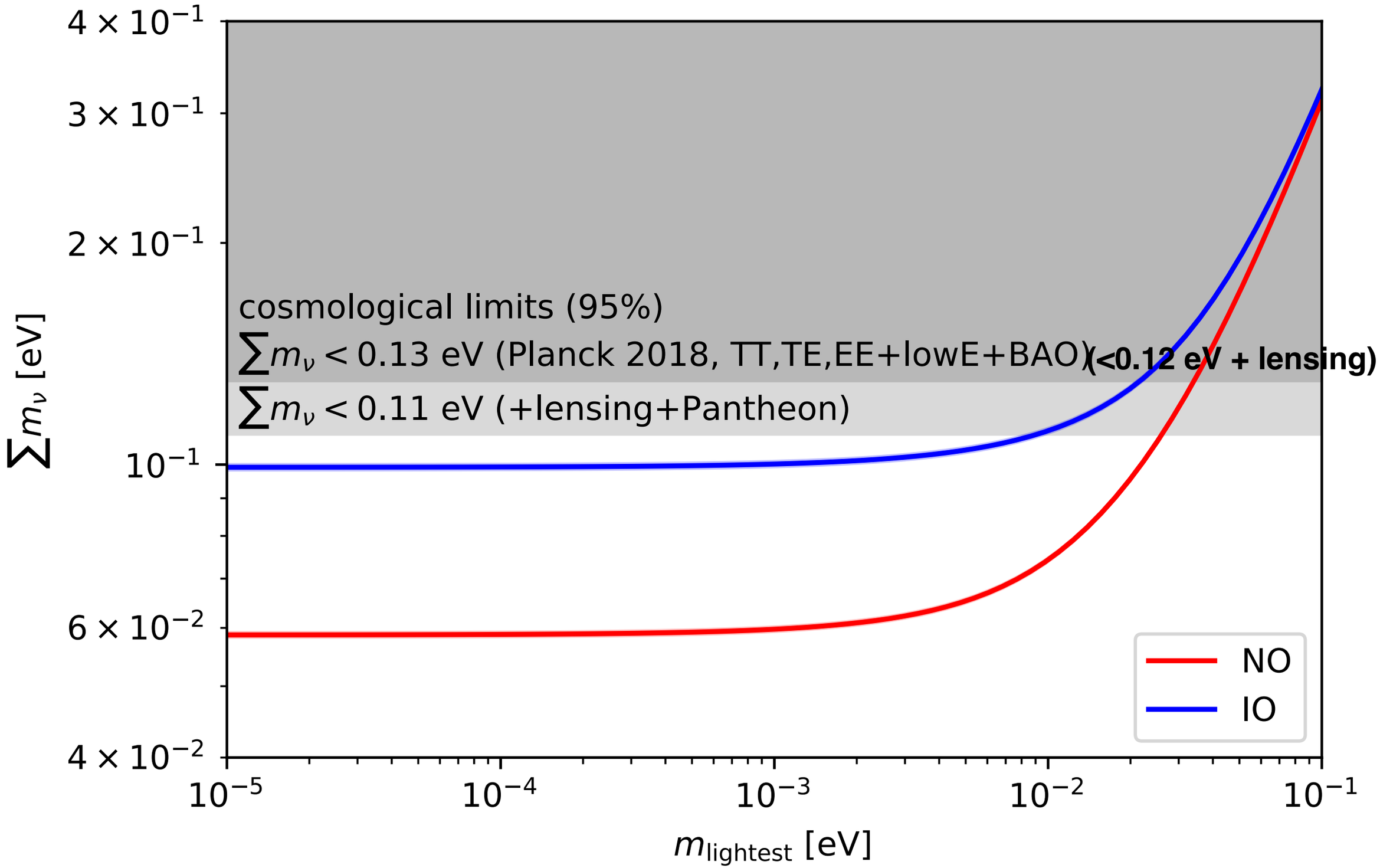
Planck 2018 results, 1807.06209

- **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**

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


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)
NO
IO
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
m_{lightest} [eV]

Σm_ν

Planck 2018 results, 1807.06209

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

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

+ BAO + SNIa + H_0=73.45 ±1.66 km/s/Mpc

Riess et al, APJ'18

$$\sum m_\nu < 0.0970 \text{ eV } 95\%\text{CL}$$

Σm_ν

Planck 2018 results, 1807.06209

Planck TTTEEE+lowT+lowE+lensing

$$\sum m_\nu < 0.26 \text{ eV} \qquad N_{\rm eff} = 2.90 \pm 0.37 \ 95\%\text{CL}$$

+ BAO

$$\sum m_\nu < 0.12 \text{ eV} \qquad N_{\rm eff} = 2.96^{+0.34}_{-0.33} \ 95\%\text{CL}$$

+ BAO + SNIa

$$\sum m_\nu < 0.11 \text{ eV} \qquad N_{\rm eff} = 2.98^{+0.35}_{-0.33} \ 95\%\text{CL}$$

+ BAO + SNIa + H_0=73.45 ±1.66 km/s/Mpc + w + nrun

$$\sum m_\nu < 0.16\text{eV} \qquad N_{\rm eff} = 3.11^{+0.38}_{+0.38} \ 95\%\text{CL}$$

Back to school Schedule

Elementary School

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- 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

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- High school League game: Σm_ν versus w(z)
- Senior High school

Homework

- Take home messages

COSMOLOGICAL CONSTANT Λ w =-1

PLANCK SCALE FUNDAMENTAL CUTOFF

0.000000000000000000000000000000000
000000000000000000000000000000000
000000000000000000000000000000000
000000000000000000000000000000001

123 orders of magnitude larger than the value of Λ observed

BEYOND THE ΛCDM Pizza…

Is Dark Energy Dynamical? w(z)

$$w_\phi = \frac{\dot{\phi}^2/2 - V(\phi)}{\dot{\phi}^2/2 + V(\phi)}$$

The 3-Neutrino representative,

Ω_ν

Madame Dark energy Ω_Λ

Mr Inflation

The radiation member,

N_{eff}

Lady Cold Dark matter,

Ω_{cdm}

The Dark JUSTICE GAME:

The 3-Neutrino representative Σm_ν

versus

the Dark energy equation of state w(z)

GAME RULES:

1. Choose your favourite cosmological model for dark energy
2. Derive cosmological bounds on Σm_ν within that model, discarding neutrino oscillations (i.e. using just with the prior $\Sigma m_\nu > 0$)
3. Are cosmological bounds consistent with oscillation data?

YES!

GREAT! You just won the game!

Your model is not ruled out (yet!)

Go to 1.

NO!

(i.e. $\Sigma m_\nu < 0.06$ eV or $\Sigma m_\nu < 0.1$ eV)

Write a paper

GAME OVER....after referral process

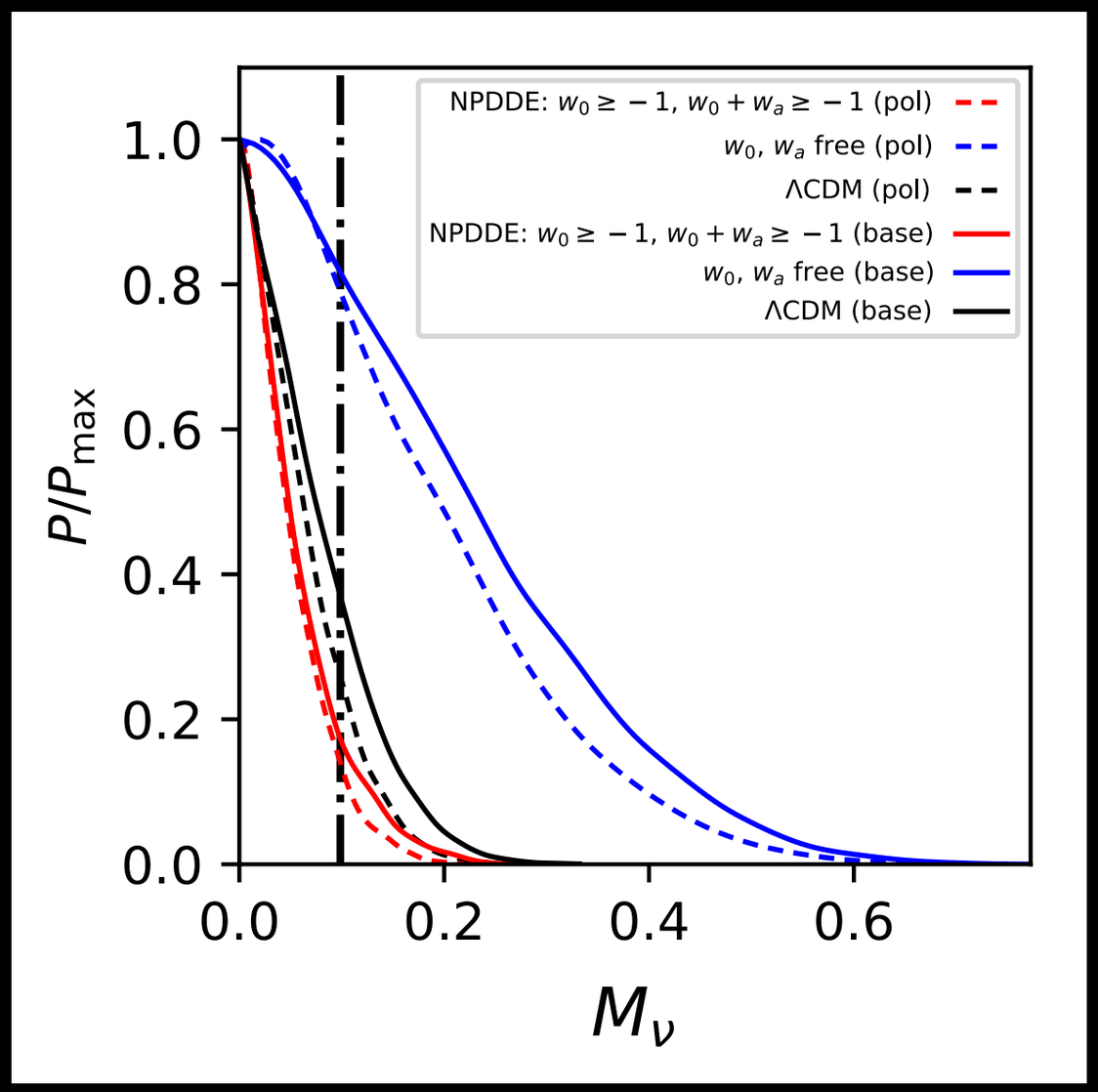
The Dark Justice Game

$$w(z) = w_0 + w_a \frac{z}{1+z}$$

Chevalier & Polarsky'01 &Linder'03

$$w_0 \geq -1 \qquad w_0 + w_a \geq -1$$

NON-PHANTOM REGION



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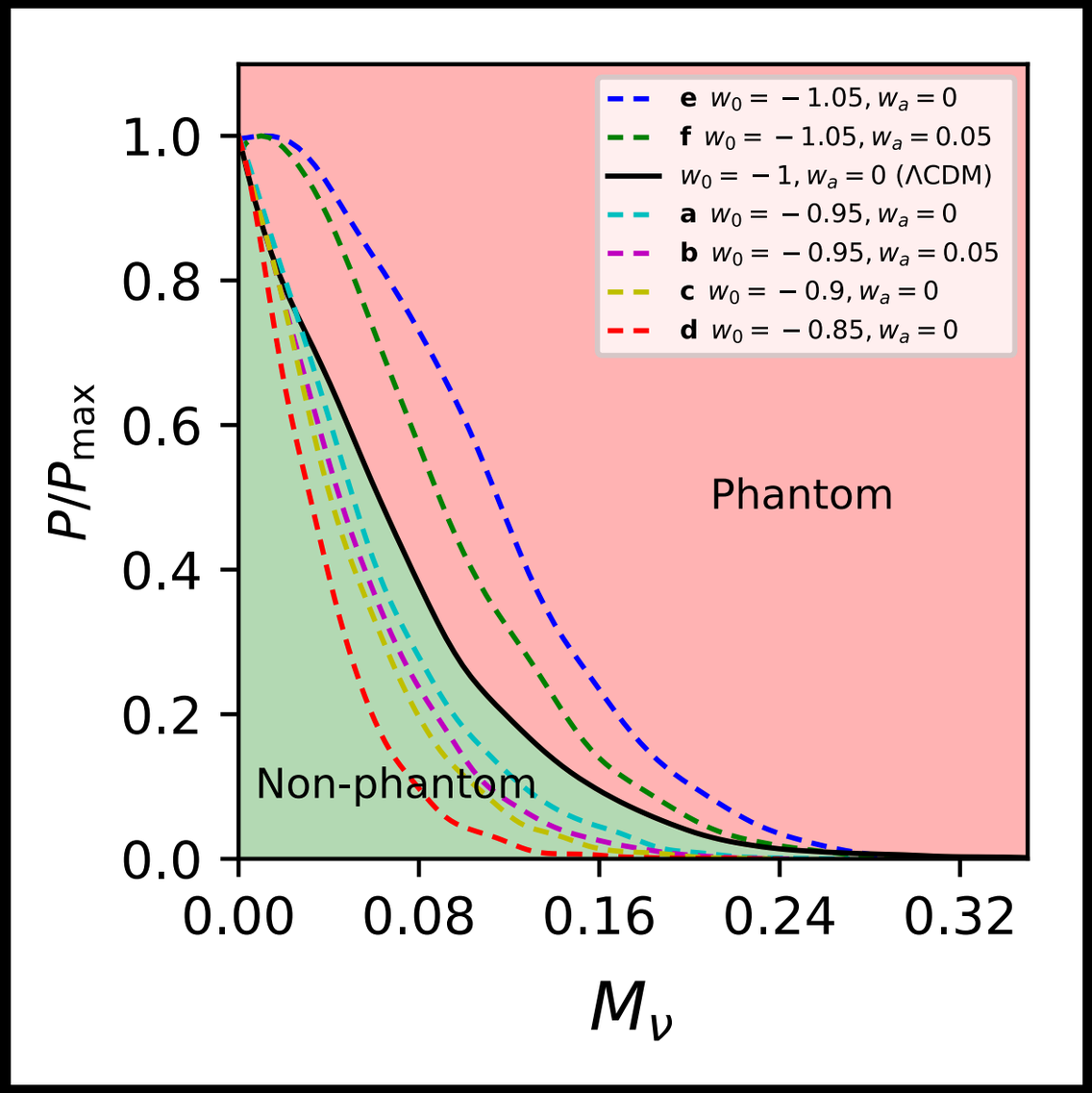

S. Vagnozzi, S. Dhawan, M. Gerbino, K. Freese, A. Goobar and O. Mena, PRD'18

PHANTOM

Back to school Schedule

Elementary School

- The **classical** cosmic pizza
- The neutrino slice
- Neutrino decoupling in the early universe

Middle School

- 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

High School

- High school League game: Σm_ν versus w(z)
- Senior High school

Homework

- Take home messages

Yes, Today, in half-an hour!!

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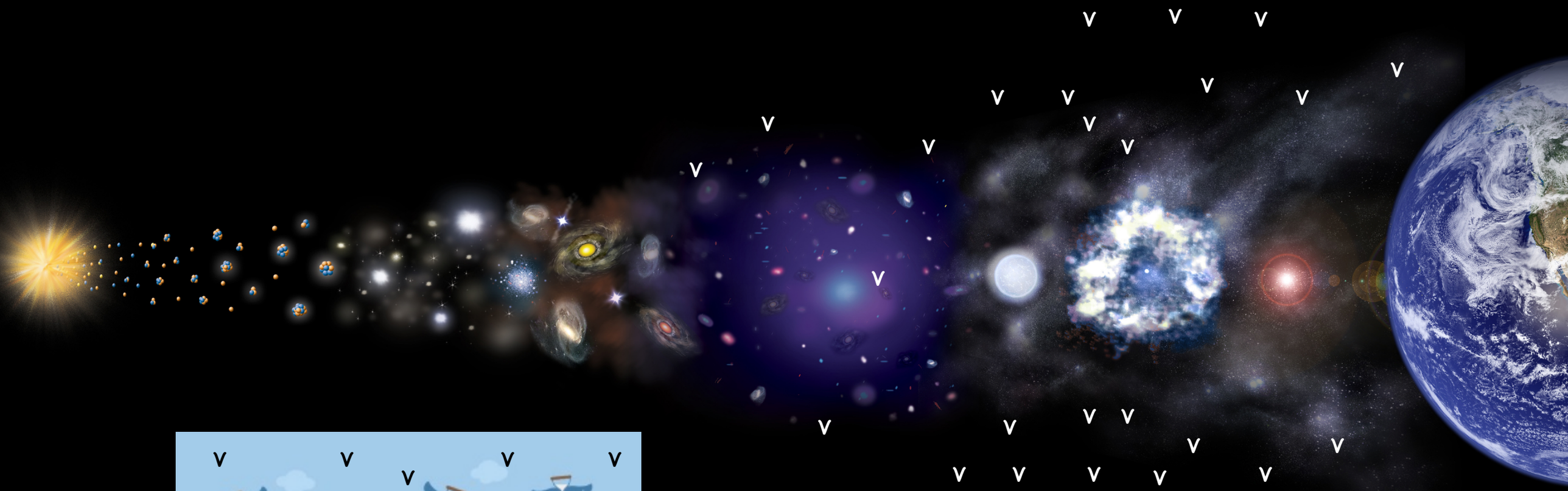
- Take home messages

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 (^4He) 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
- $\Sigma m_\nu < 0.12$ eV (95%CL) from 2018 Planck TTTEEE+lensing plus BAO data
- For non-phantom (physical) dynamical dark energy, Σm_ν bounds get tighter!

thank you
danke
謝謝
ngiyabonga
teşekkür ederim
gracias
спасибо
obrigado
merci
dziękuję
sukriya
kop khun krap
go raibh maith agat
mochchakkeram
grazie
arigatô
takk
dakujem
merci
мерси
감사합니다
ありがとう
terima kasih
najis tuke
kam sah hamnida
তোমাকে ধন্যবাদ
Баярлалаа
рахмат
спасибо
faafetai lava
kiitos
dankie
dhanyavad
nanni
nandri
bayarlalaa
gracie
hvala
mauruuru
köszönöm
enkosi
bedankt
vinaka
спасибі
blagodaram
mersi
kia ora
barka
welalin
tack
spas
dank je
misaotra
matondo
paldies
grazzi
mahalo
tapadh leat
хвала
asante
manana
obrigada
murakoze
tenki
djiere dieuf
tau
akun
dankon
aciü
дякую
mamnun
chokrane
chnorakaloutioun
gratias ago
gràcies
sulpáy
taiku
sobodi
dēkuji
mèsi
didi madloba
sagolun
rahmat
rahmet
tanemirt
diolch
dhanyavadagalu
shukriya
merci
xièxie
ευχαριστώ
arigatô
trugarez
merci

BACKUP SLIDES



invisiblesPlus
elusives
neutrinos, dark matter & dark energy physics

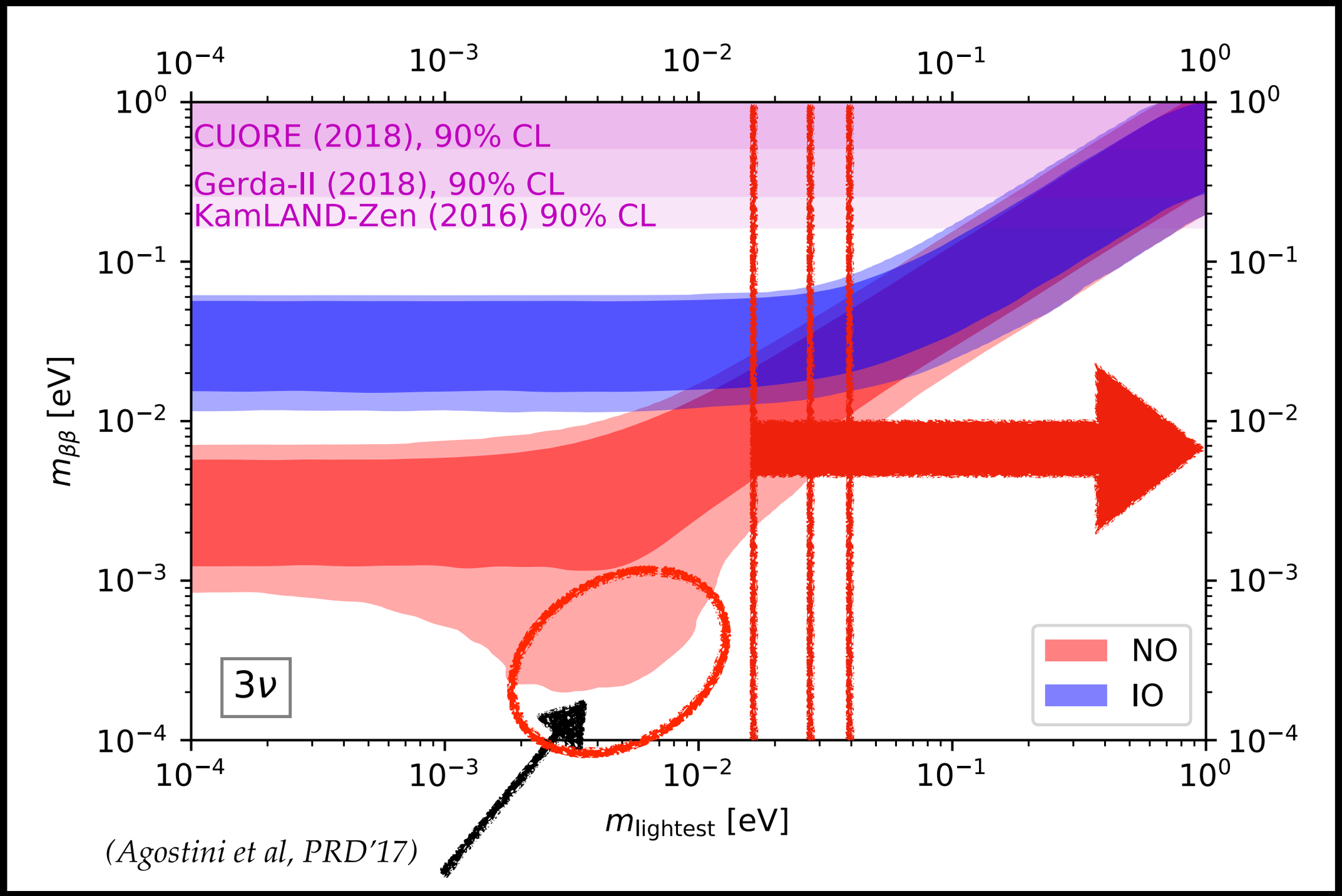
IFIC
INSTITUT DE FÍSICA CORPUSCULAR

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

VNIVERSITAT DE VALÈNCIA

EXCELENCIA SEVERO OCHOA

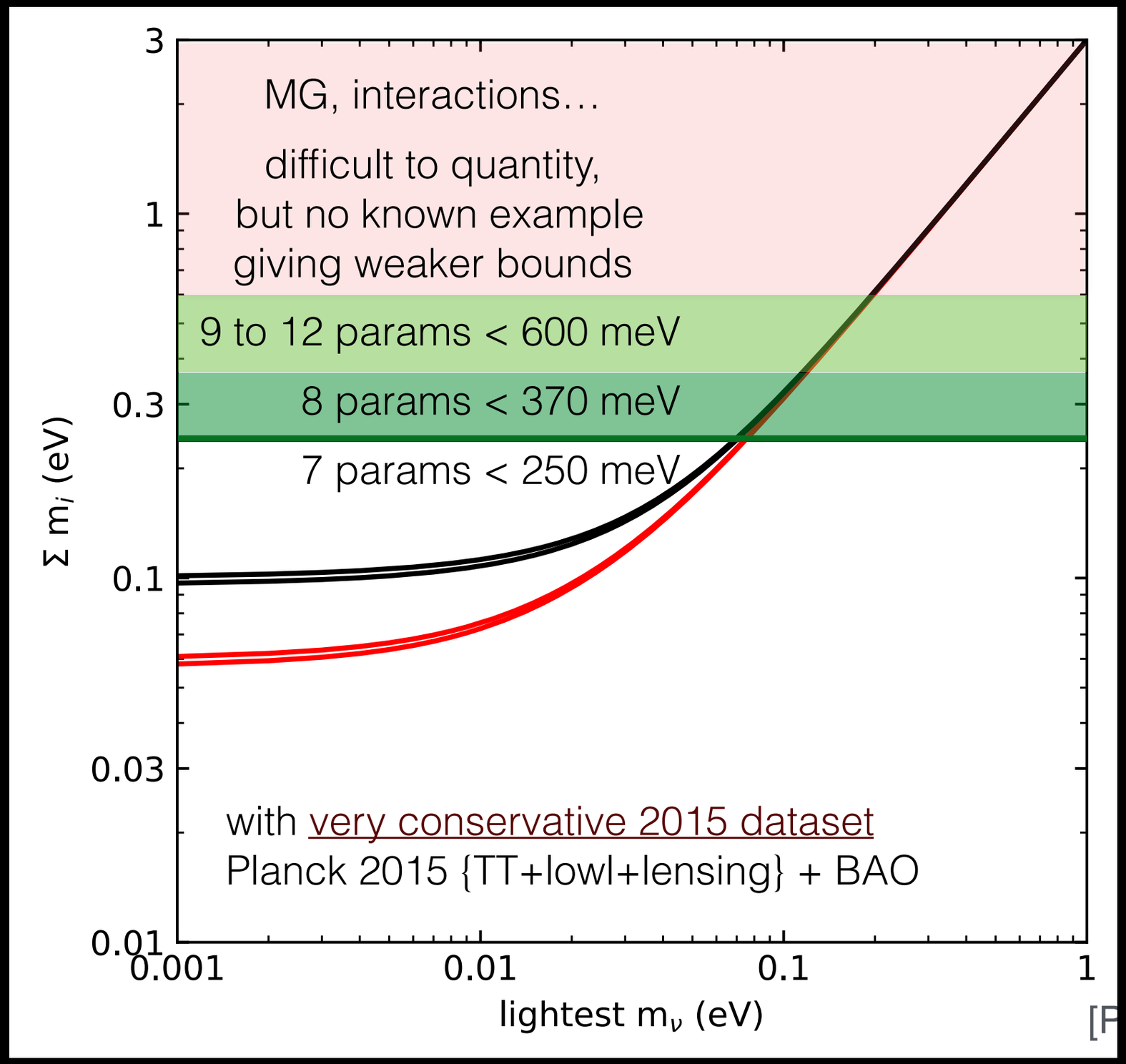
What we know



$m_{\beta\beta} < 2\ 10^{-4}$ would require

some fine tuning in the Majorana phases

Σm_ν



J. Lesgourgues, talk at Neutrino 2018

Methods to detect non-non-relativistic neutrinos: PTOLEMY

Today neutrinos have a mean temperature:

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

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

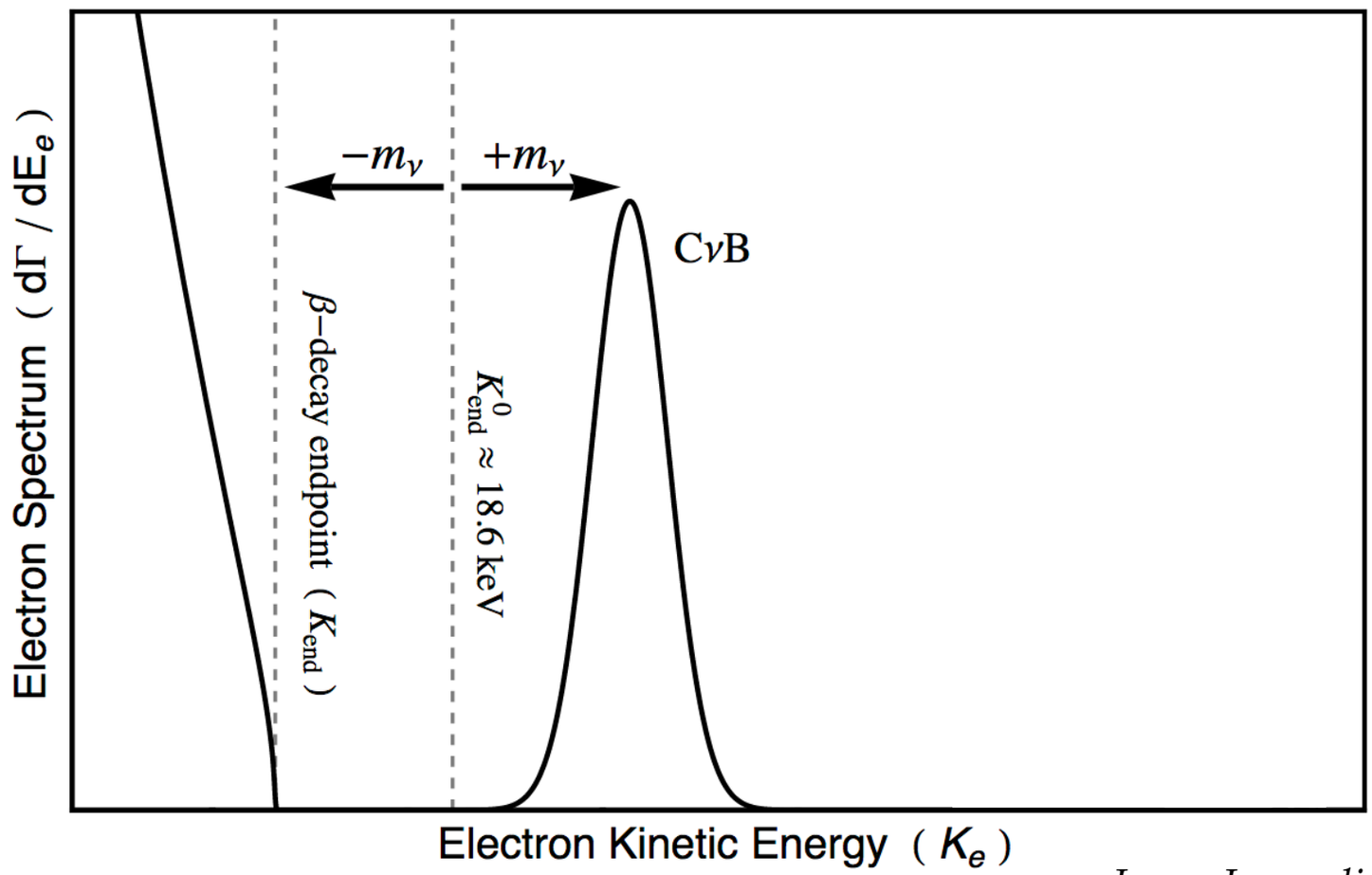
$$\nu_e + N \to N' + e^- \qquad \bar{\nu}_e + N \to N' + e^+$$

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

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

6 Aug 2018

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

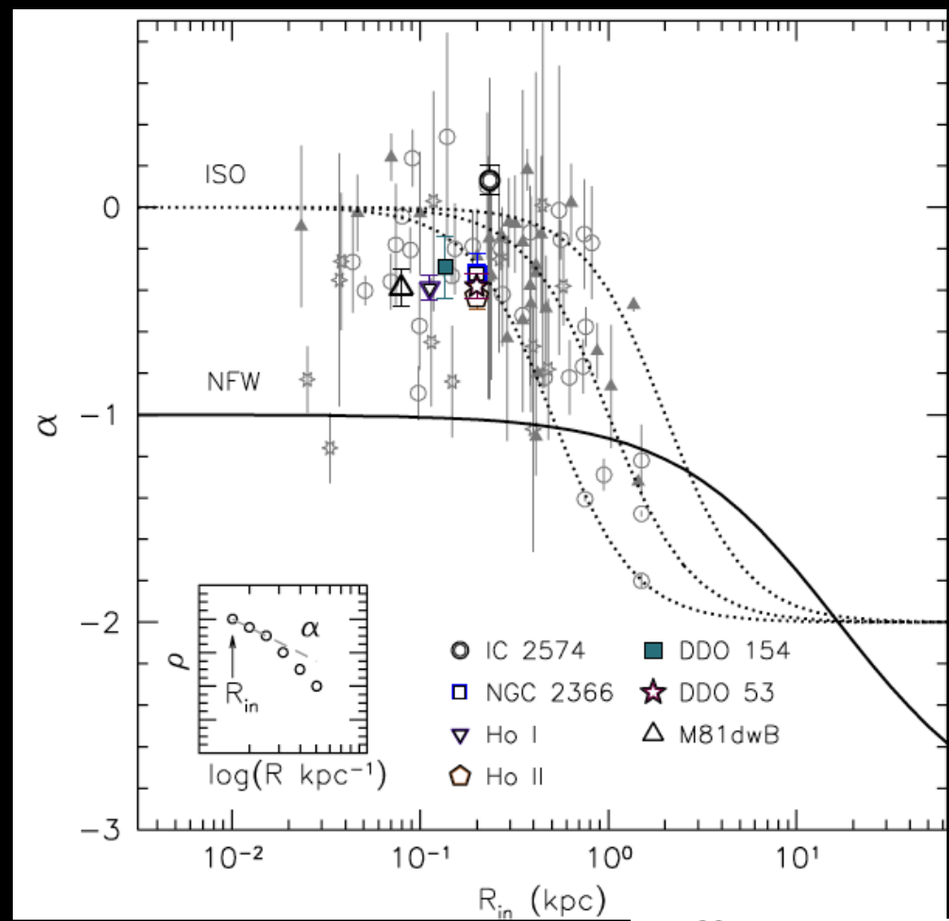
$$r_s(z_{drag}) = \int_0^{\eta(z)} d\eta \; c_s(1+z) \; , \tag{16}$$

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:

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

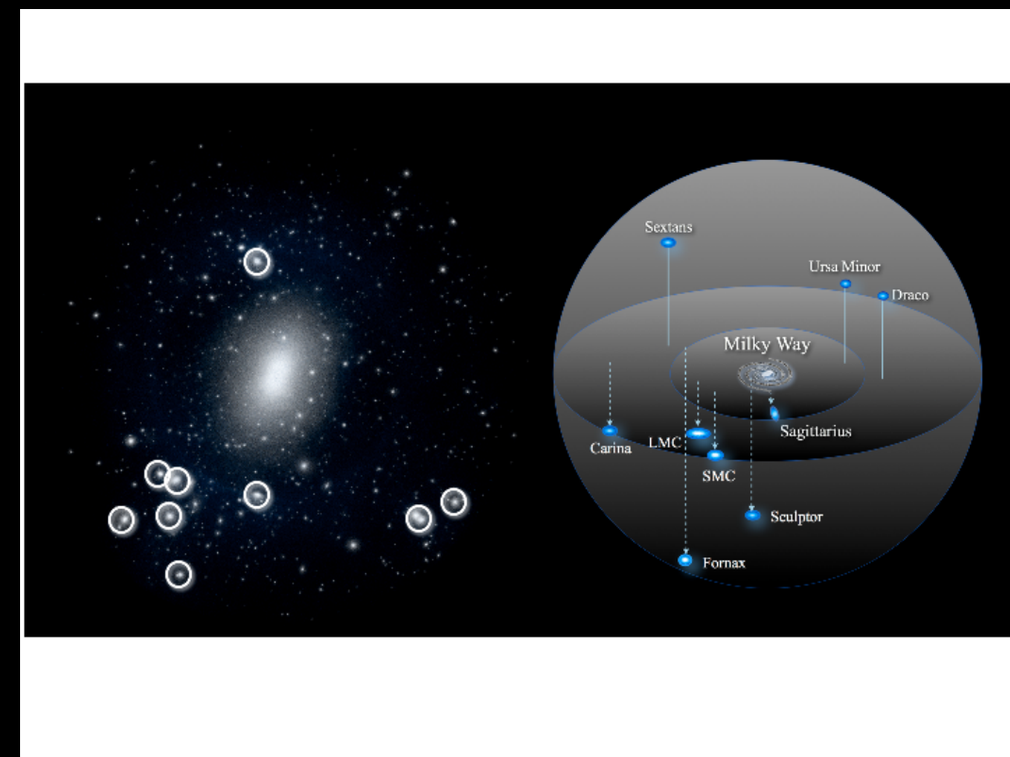
COLD dark matter
CDM
HOT dark matter
HDM
WDM
WARM dark matter
DARK MATTER
CREATED BY

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



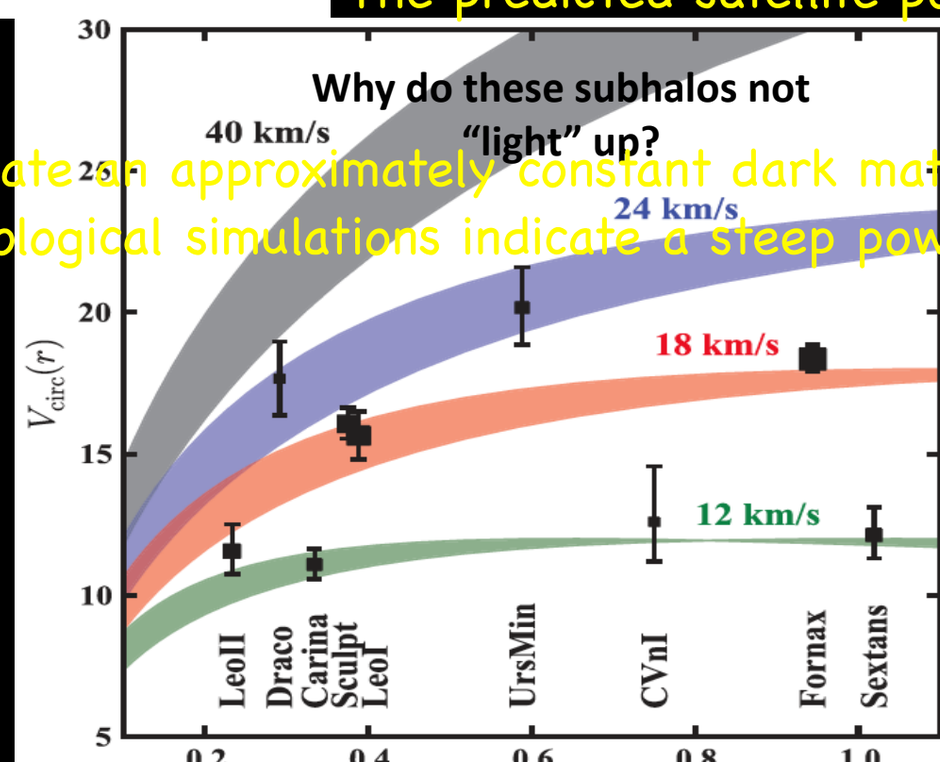
Core/Cusp problem

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



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?

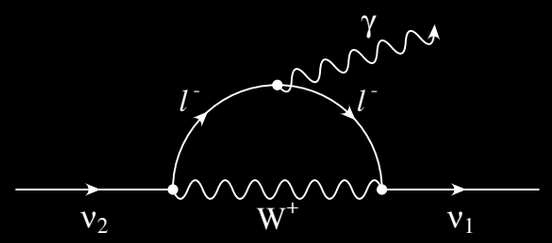
A controversial unidentified line has been detected at with a significance > 3σ in two independent samples of X-ray clusters with XMM-Newton.

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

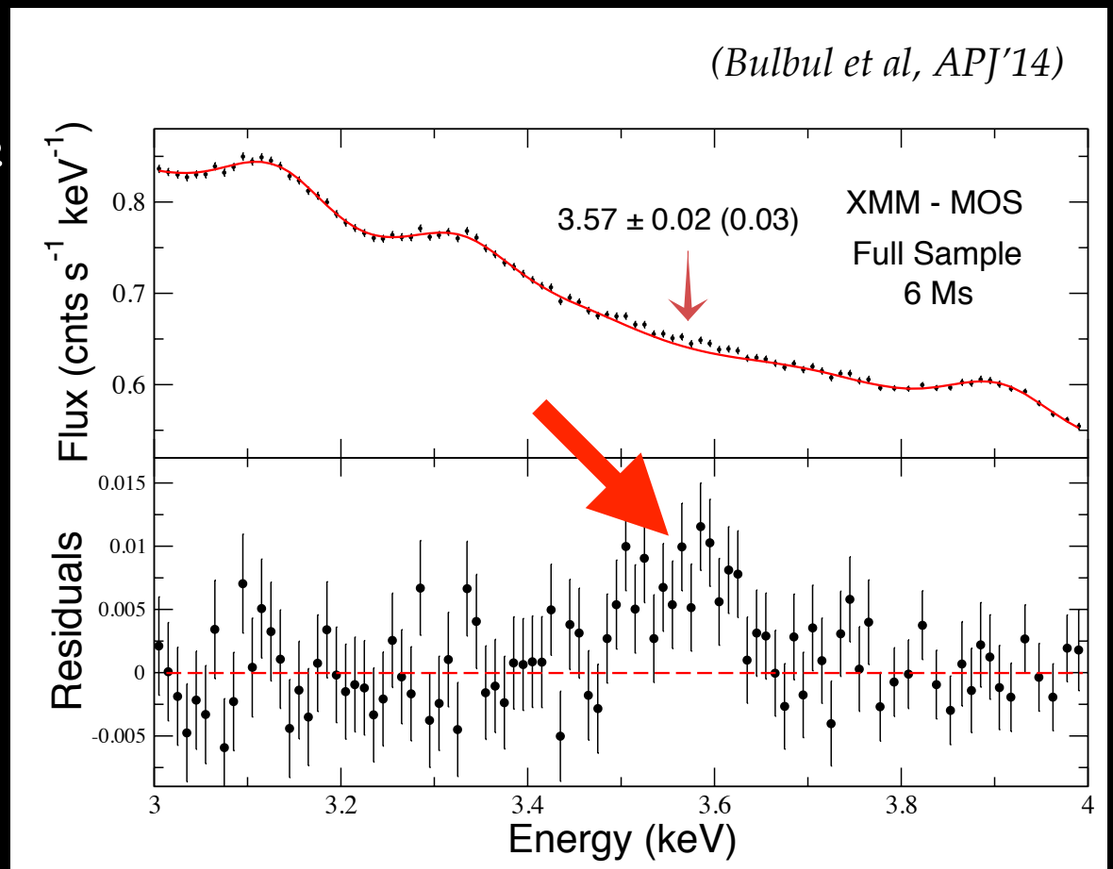
(Bulbul et al, APJ'14)

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)*

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

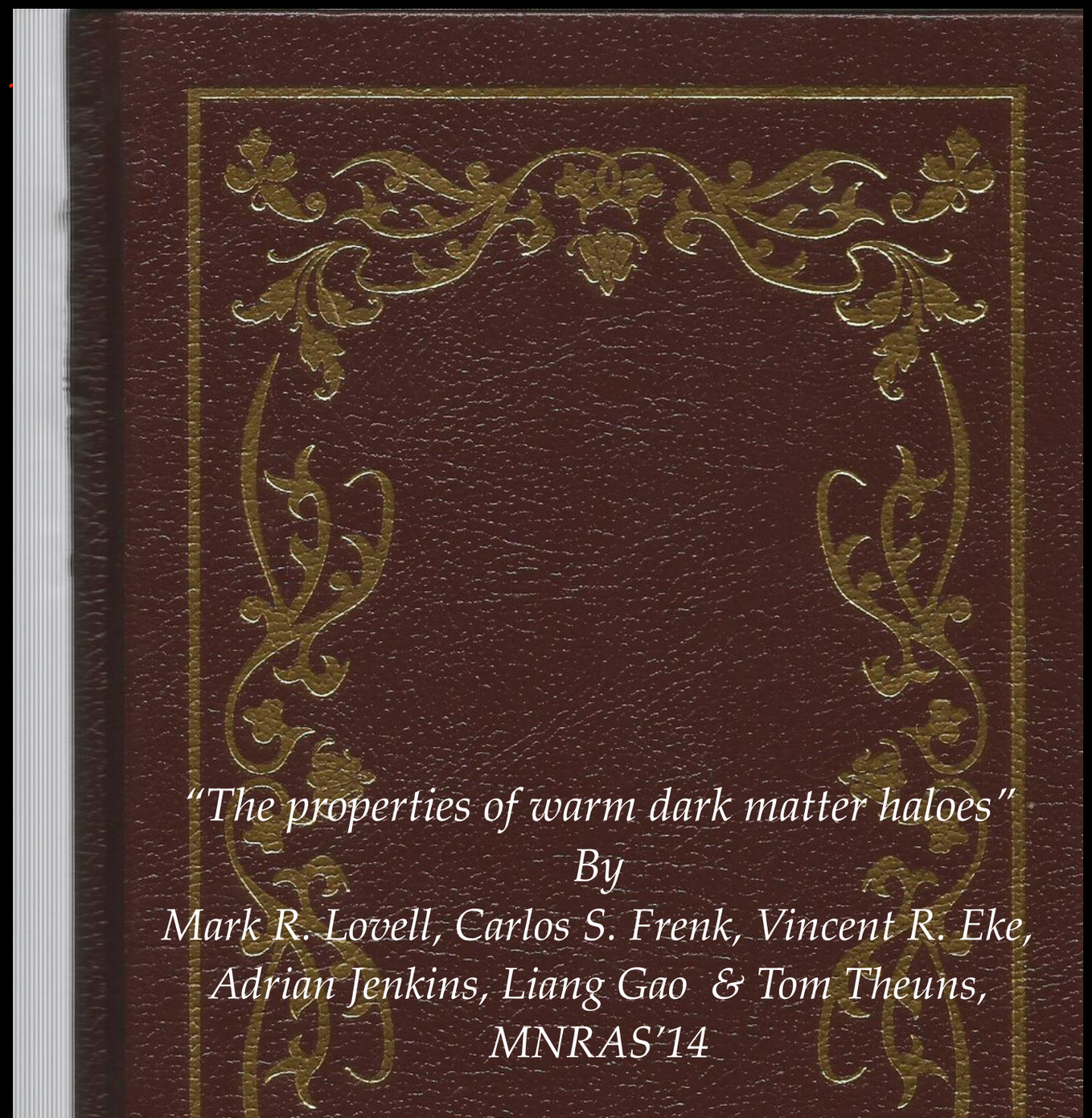


$$m_s = 2E = 7.1 keV$$



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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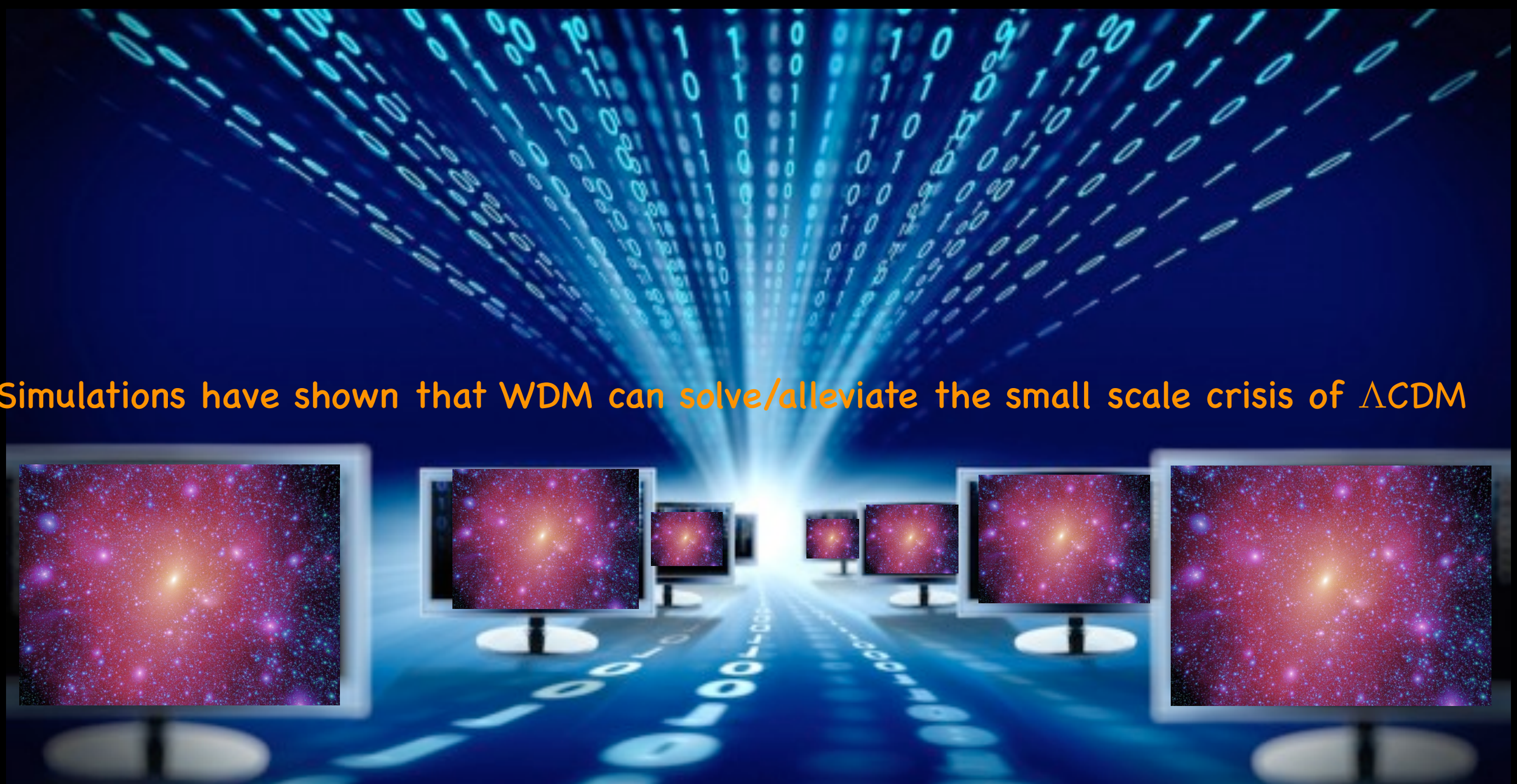
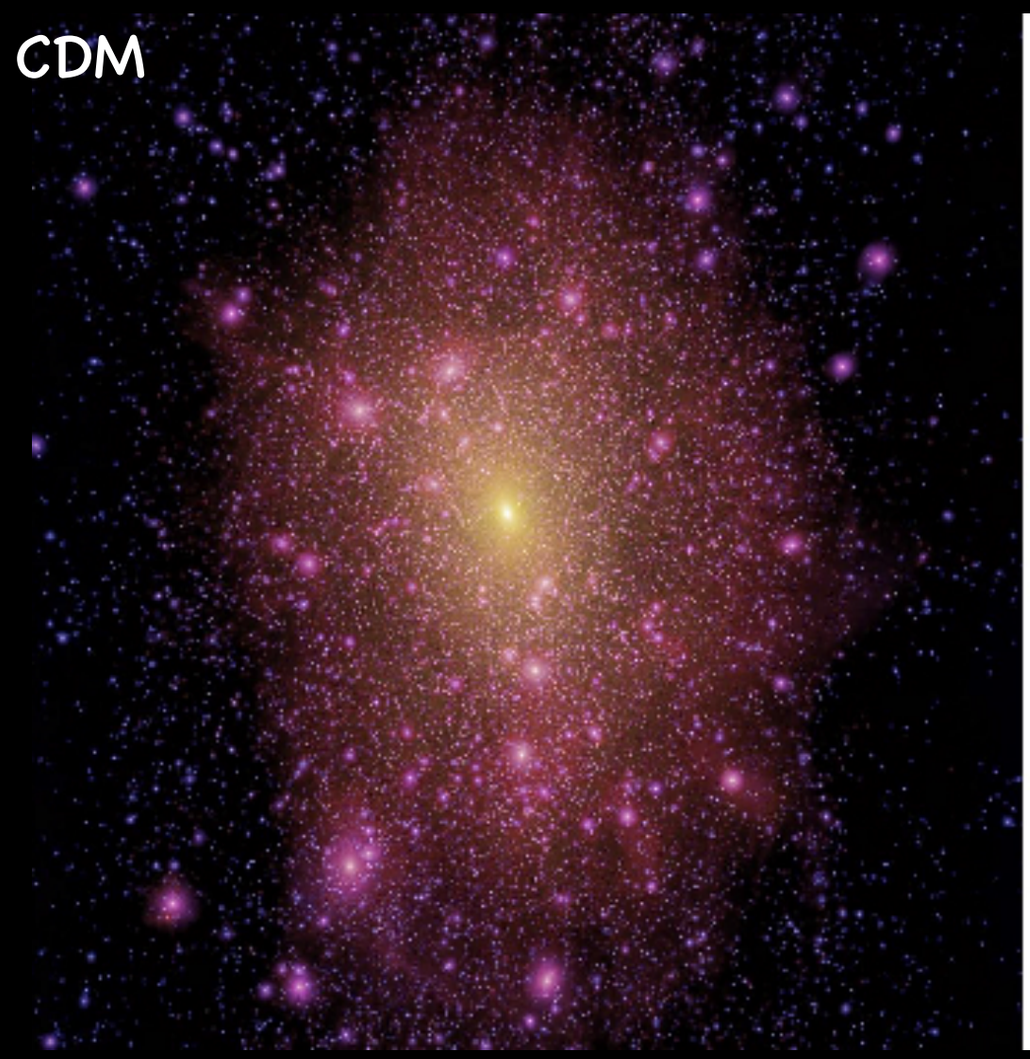
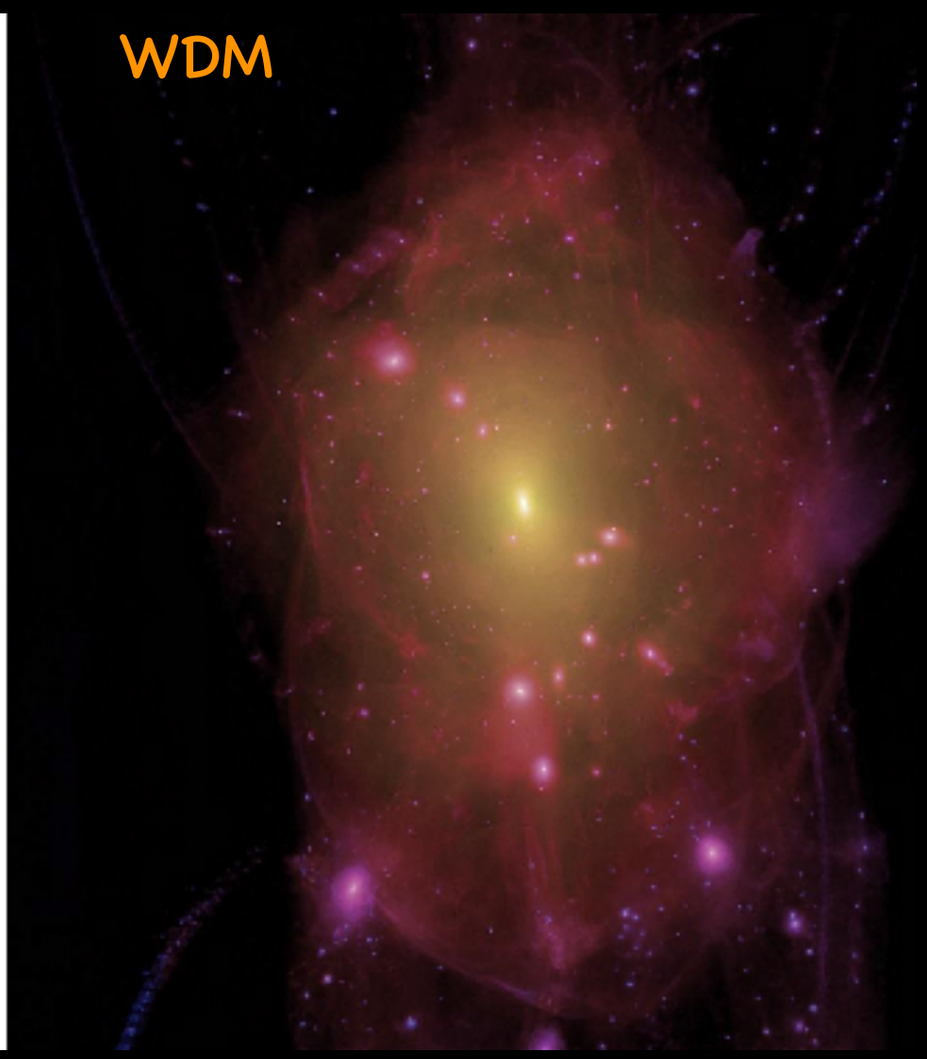


Simulations have shown that WDM can solve/alleviate the small scale crisis of ΛCDM

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}

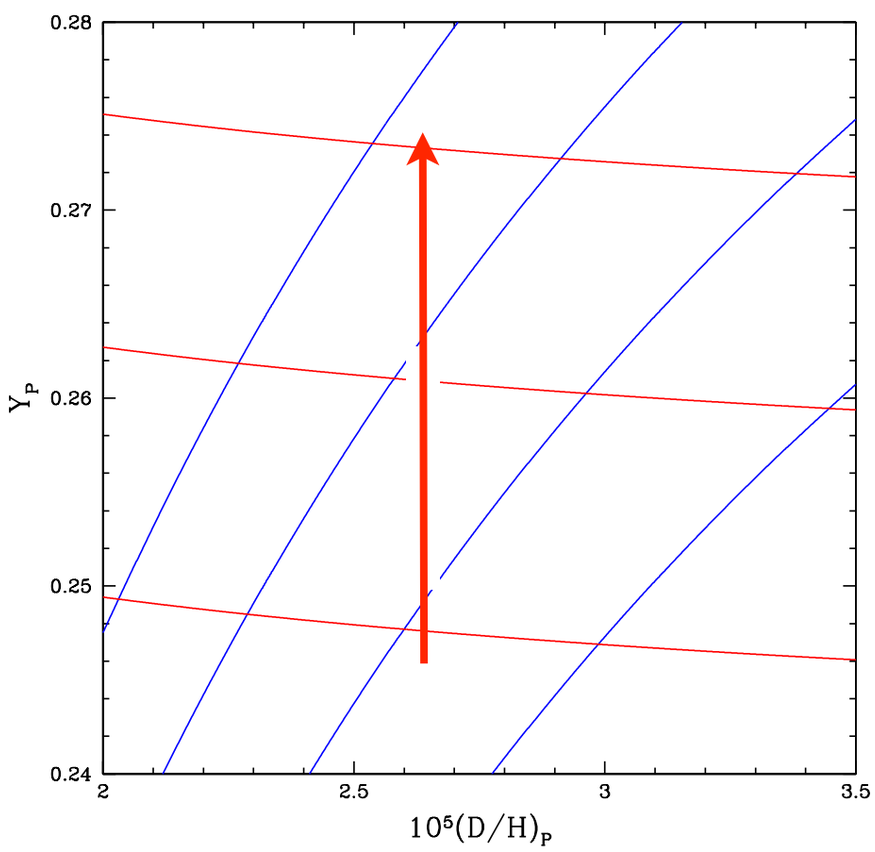
N_{eff} changes the freeze out temperature of weak interactions:

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

MORE NEUTRINOS:

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

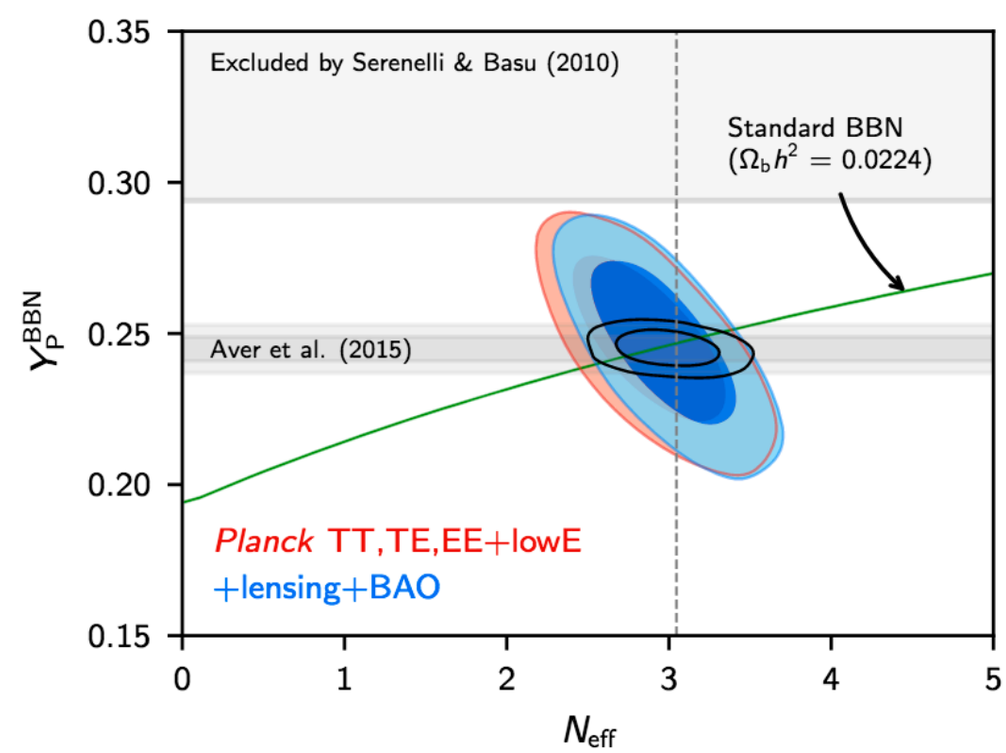
$$n/p \simeq e^{-\frac{m_n - m_p}{T_{freeze}}} \qquad Y_p = \frac{2(n/p)}{1+n/p}$$



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

(G. Steigman'12)

Planck 2018 results, 1807.06209

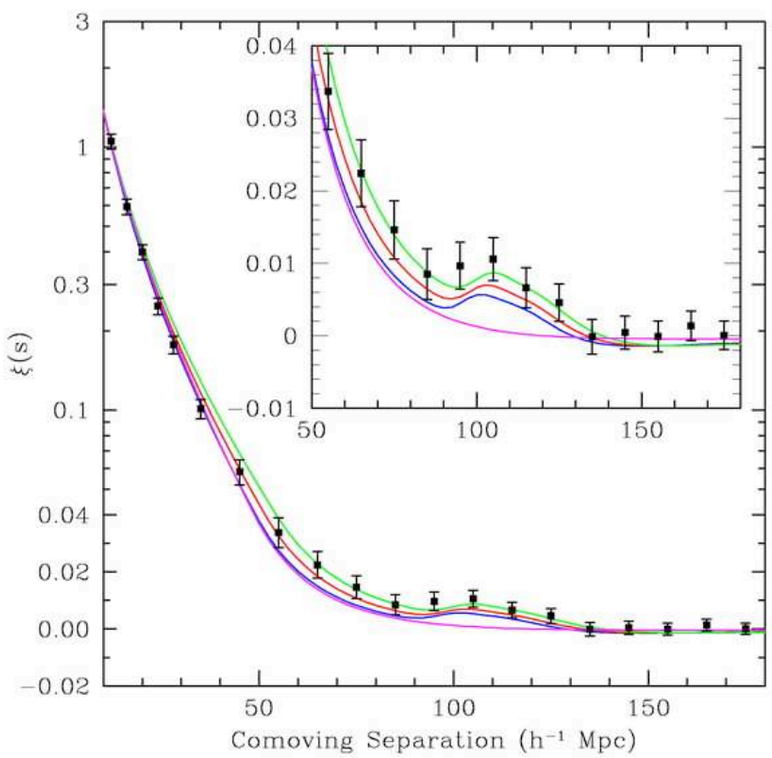


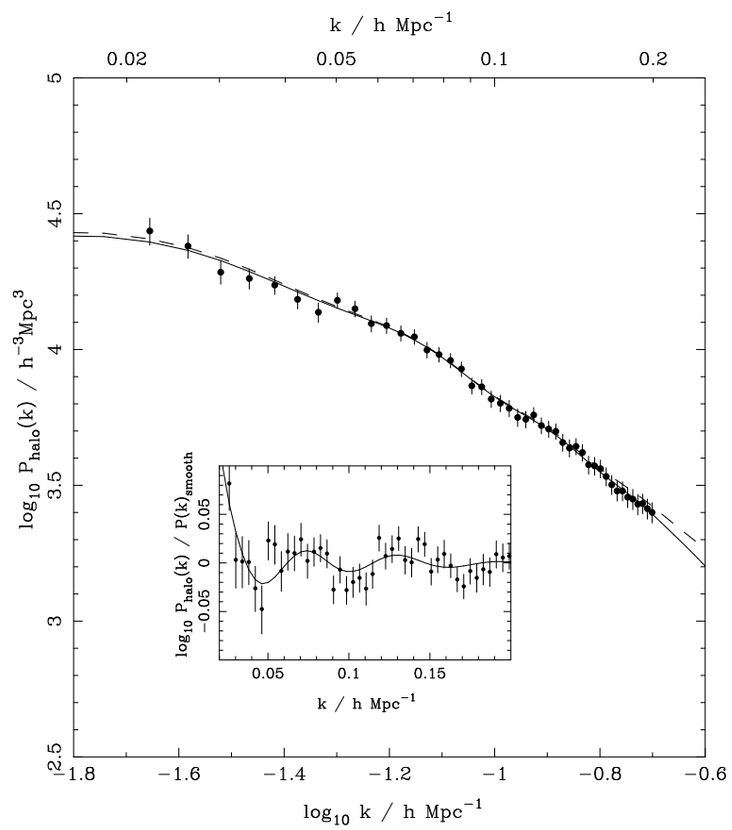
$N_{eff} = 2.99^{+0.43}_{-0.40} \quad Y_p = 0.2437^{+0.0077}_{-0.0080}$

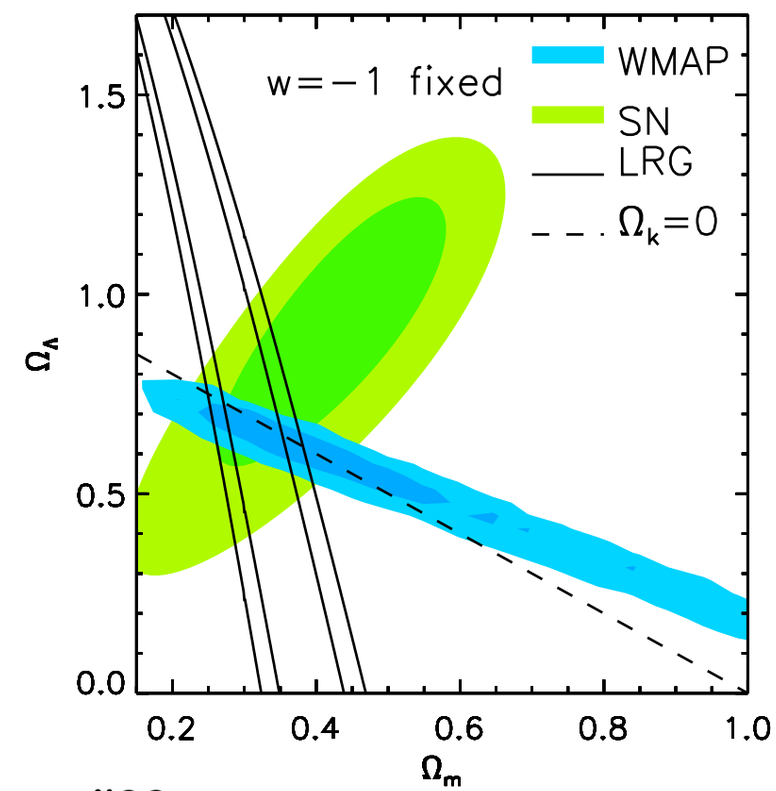
Los catálogos de galaxias miden la función de correlación:

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

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







Eisenstein et al'05

Reid et al'09

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

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