Searching for Neutrinos through Cosmology

Olga Mena
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invisiblesPlus
elusives
neutrinos, dark matter & dark energy physics

IFIC
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VNIVERSITAT DE VALÈNCIA

EXCELENCIA SEVERO OCHOA

Today's menu

Antipasto

- The **classical** cosmic pizza
- The neutrino slice
- Neutrino decoupling in the early universe
- Other cosmic pizzas for tasting

Main course

- 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
- The Dark Justice League game: Σm_ν versus w(z)

Doggy Bag

- Take home messages

ΛCDM Pizza

Ω_i

Heavy elements

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

Neutrinos!

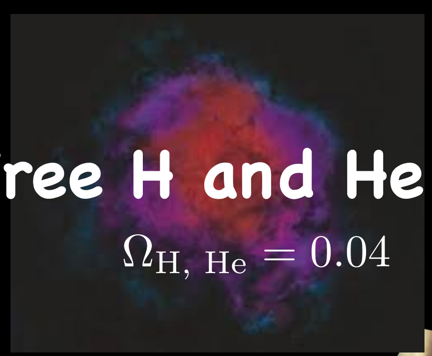
Dark energy

$\Omega_\Lambda = 0.7$

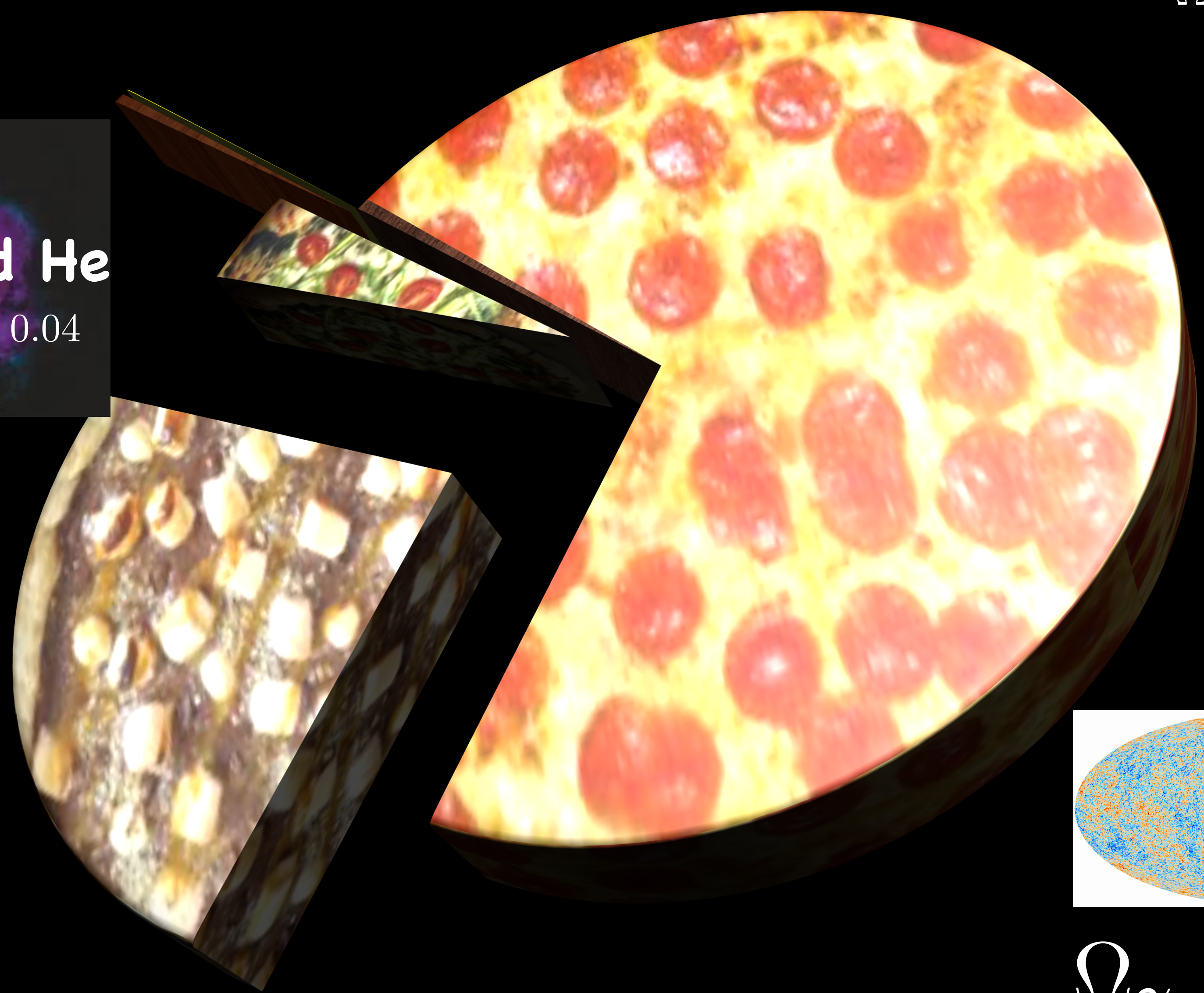
Stars

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

Free H and He

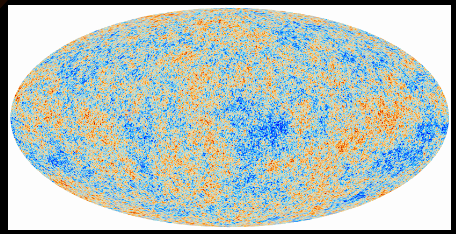


$\Omega_{\text{H, He}} = 0.04$



Cold Dark matter

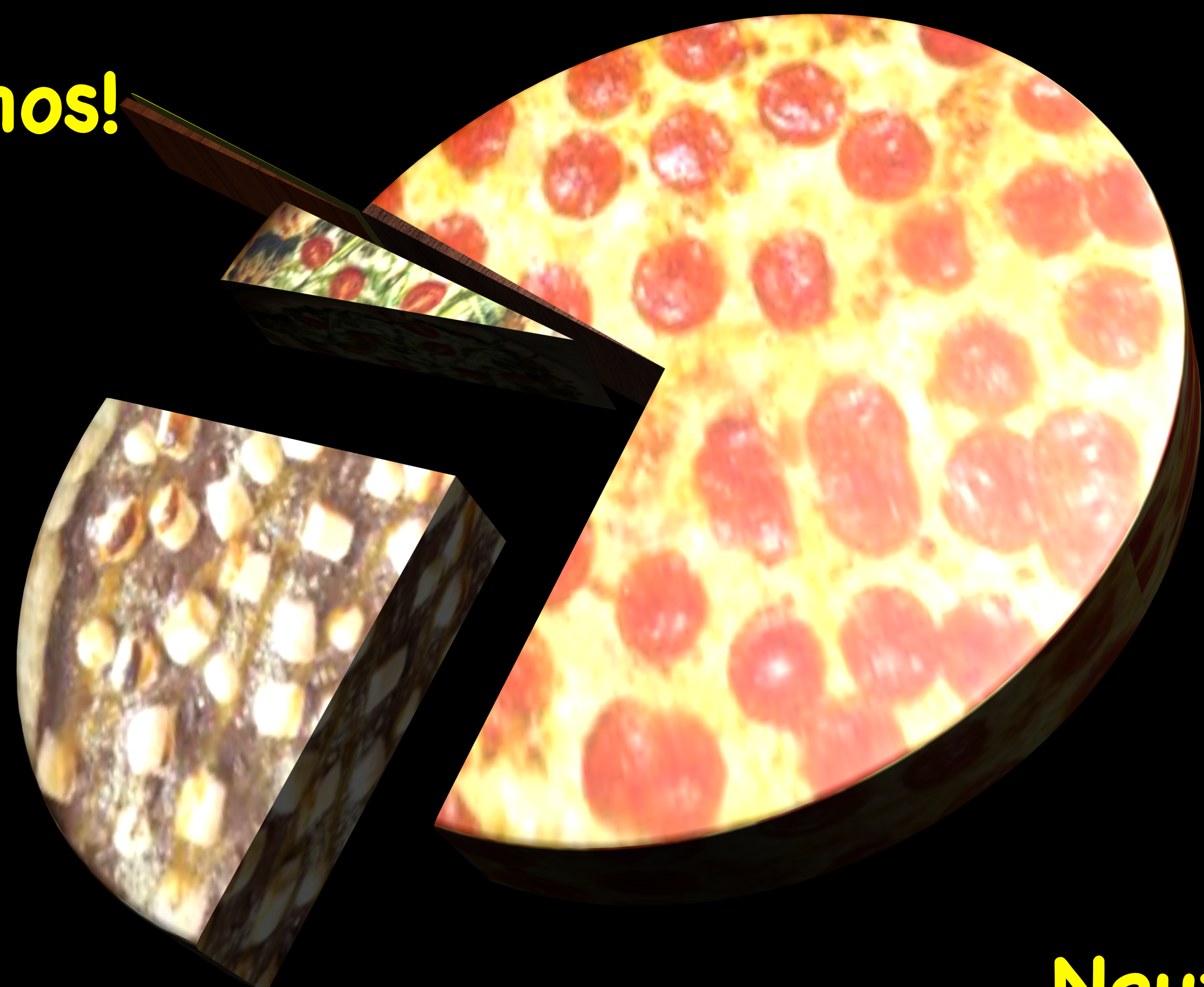
$\Omega_{\text{CDM}} = 0.25$



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

How large is the **MASSIVE** neutrino contribution?

Neutrinos!



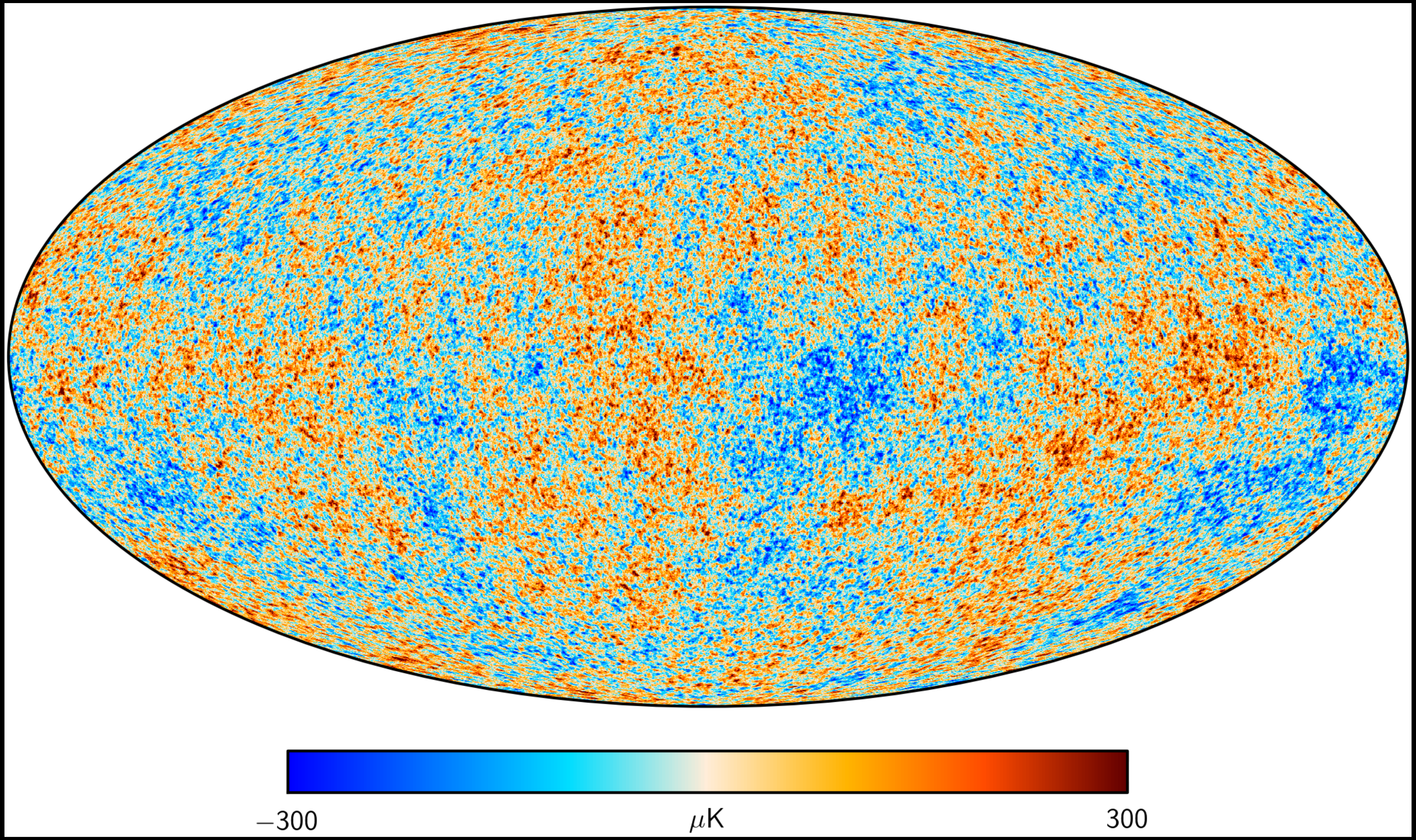
Cosmology tells us

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

Neutrino oscillations tell us

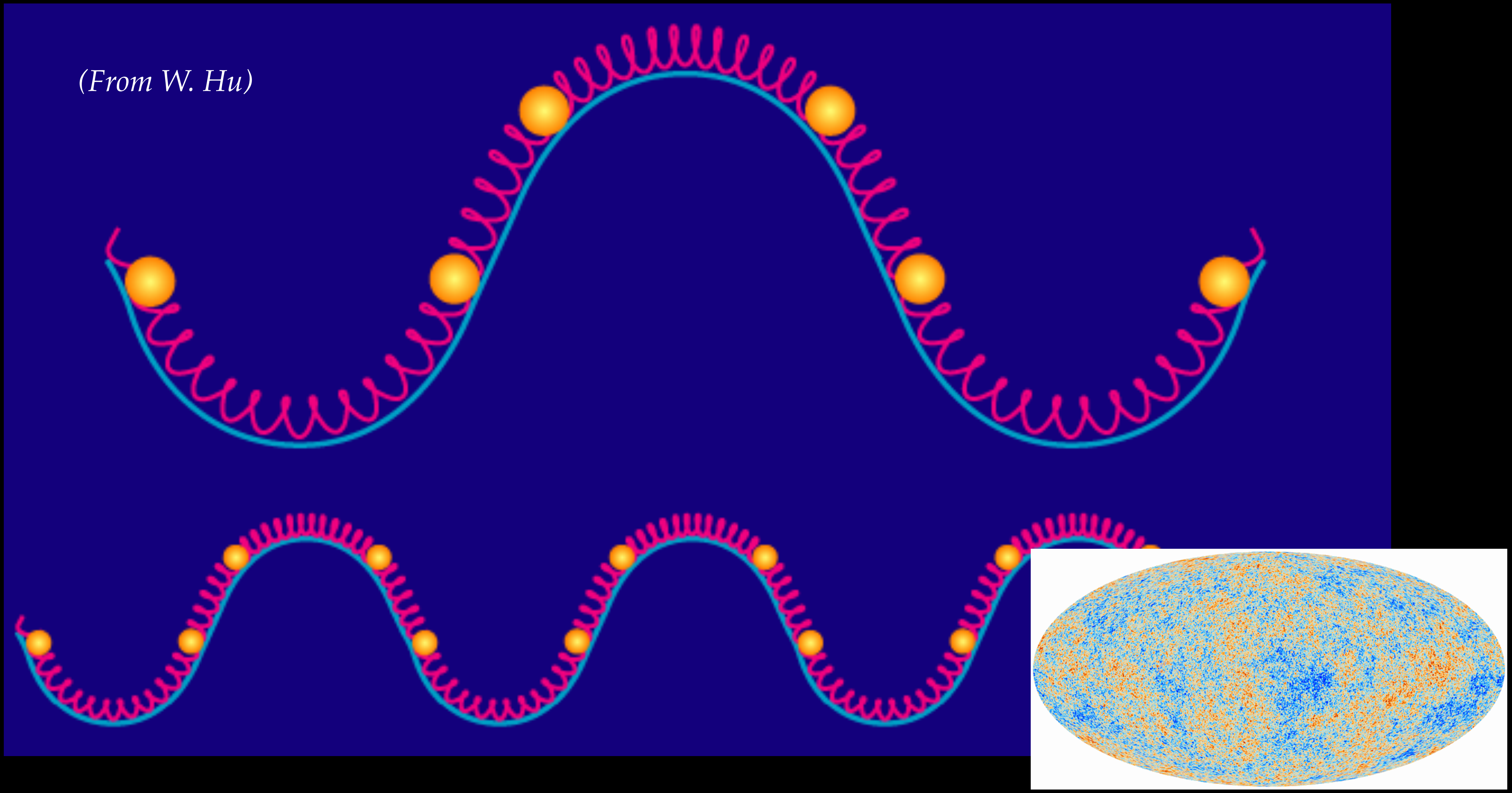
$\Omega_\nu \gtrsim 0.0012$ 95% CL

I guess all you know about dark matter/what about dark radiation?
But radiation is visible, and it has a mean $T \simeq 2.725$ 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.



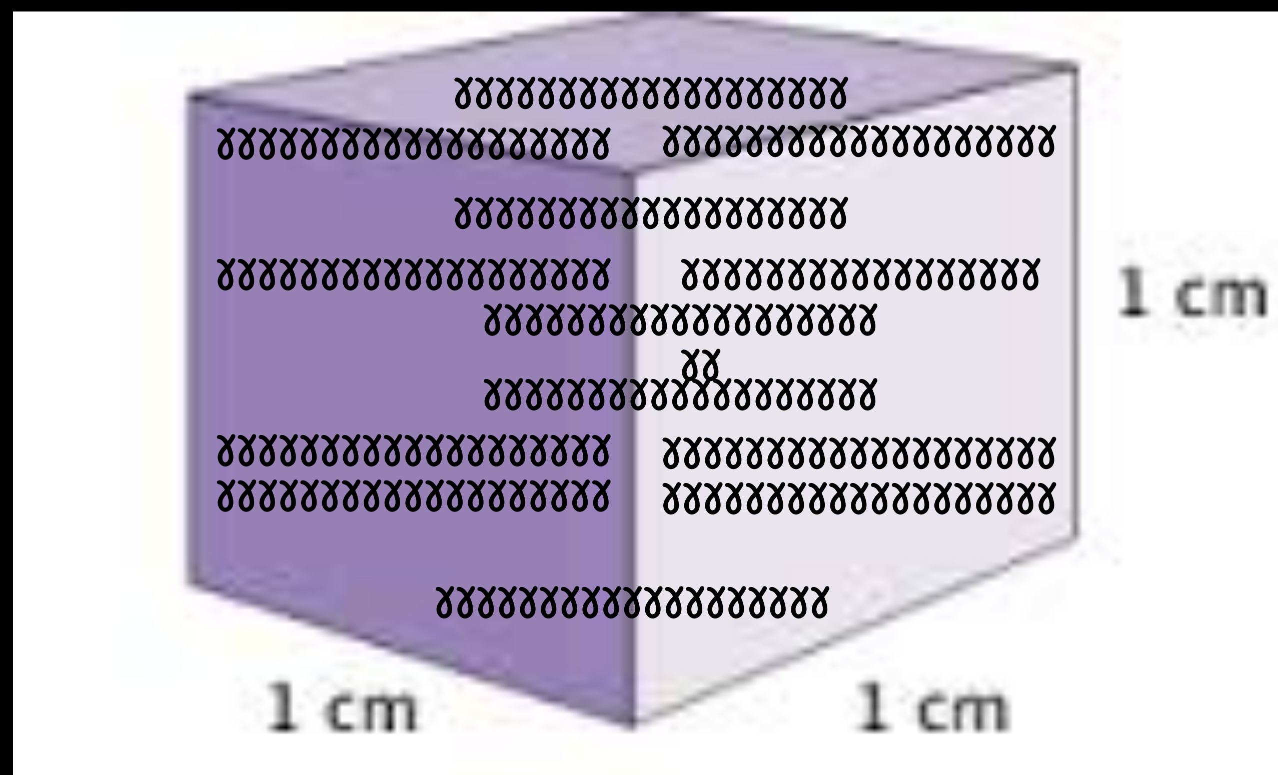
Potential wells → High density → COLD SPOTS in CMB maps

Potential hills → Low density → HOT SPOTS in CMB maps

I guess all you know about dark matter/what about dark radiation?

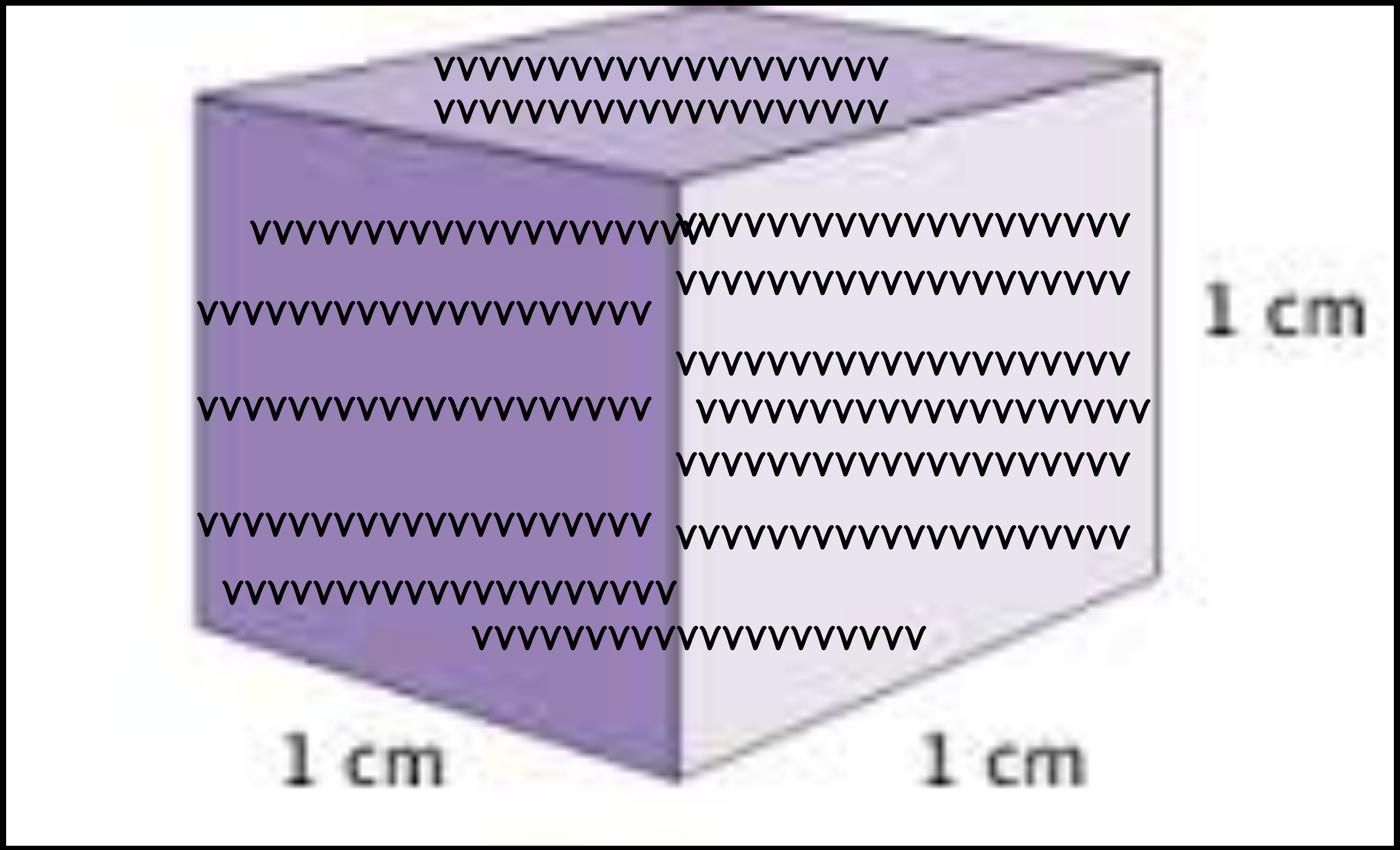
But radiation is visible!

410 photons/cm^3



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

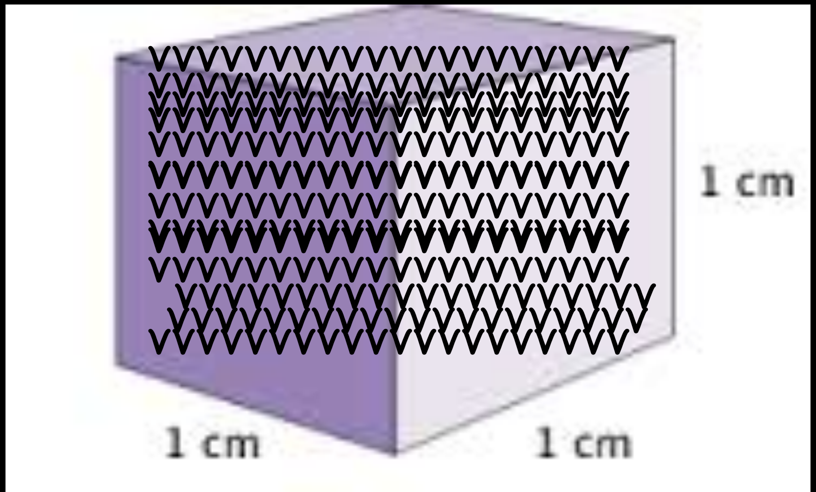
340 neutrinos/cm³



This cosmic relic neutrino background has never been detected directly.

The universe is filled with a dense flux of “relic neutrinos” created in the Big Bang.
This makes neutrinos the most abundant KNOWN form of…

340 neutrinos/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:

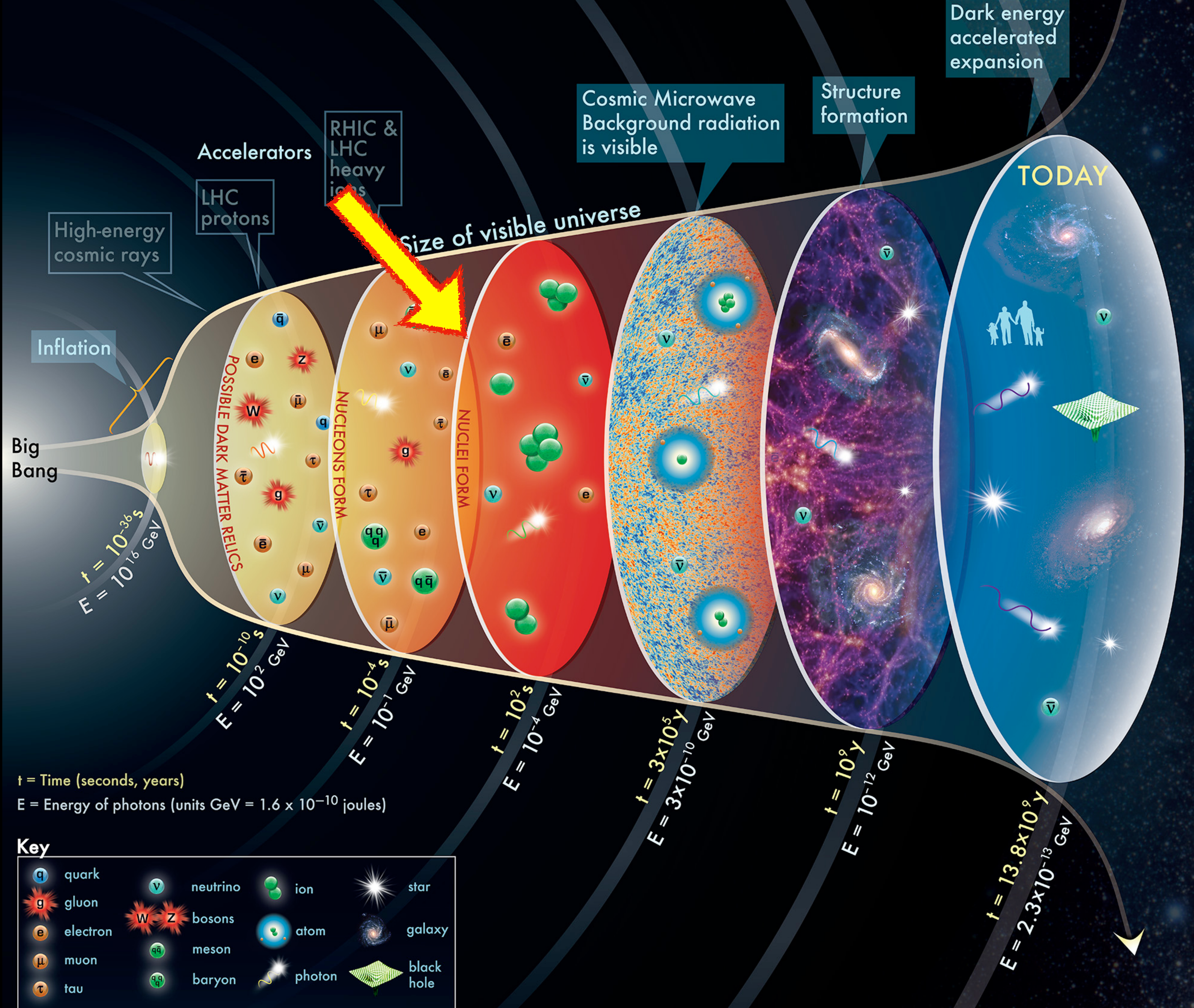
$$\Gamma_\nu = n\sigma v \simeq T^3 G_F^2 T^2 \sim G_F^2 T^5$$

- 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.**



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}	$100GeV$
QCD phase transition	$2 \times 10^{-5}s$	10^{12}	$150MeV$
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Recombination	$2.6 - 3.8 \times 10^{5}yrs$	1100-1400	$.26 - .33eV$
CMB	$3.8 \times 10^{5}yrs$	1100	$.26eV$

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

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

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

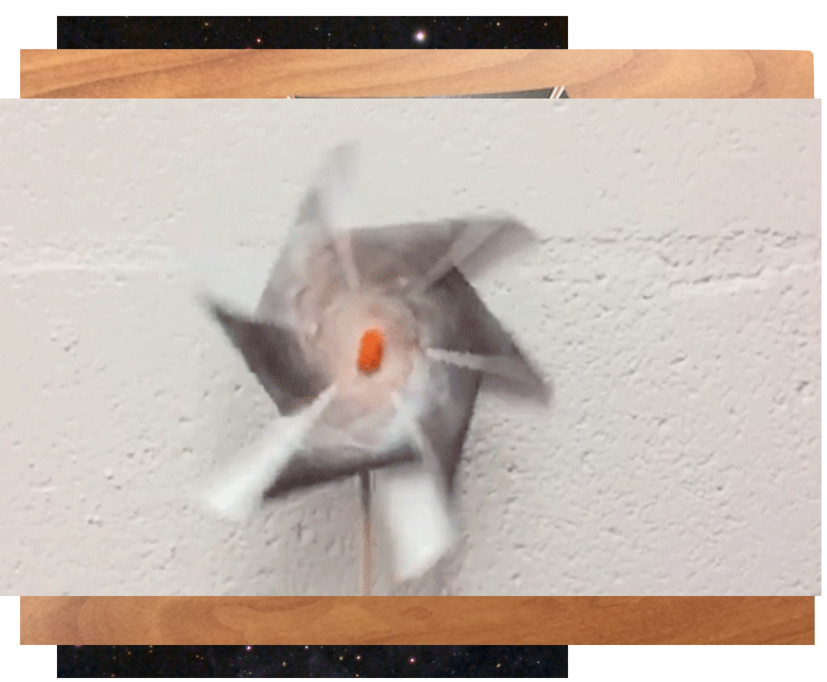
$$\rho_\nu = m_\nu n_\nu \qquad n_{\nu_i}(T_{\nu 0}) \approx 56\ \mathrm{cm}^{-3} \qquad \Omega_\nu h^2 = \frac{\sum m_\nu}{93\ \mathrm{eV}}$$

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

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

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



vvvvvvvvvvvvvvvvvvvvv

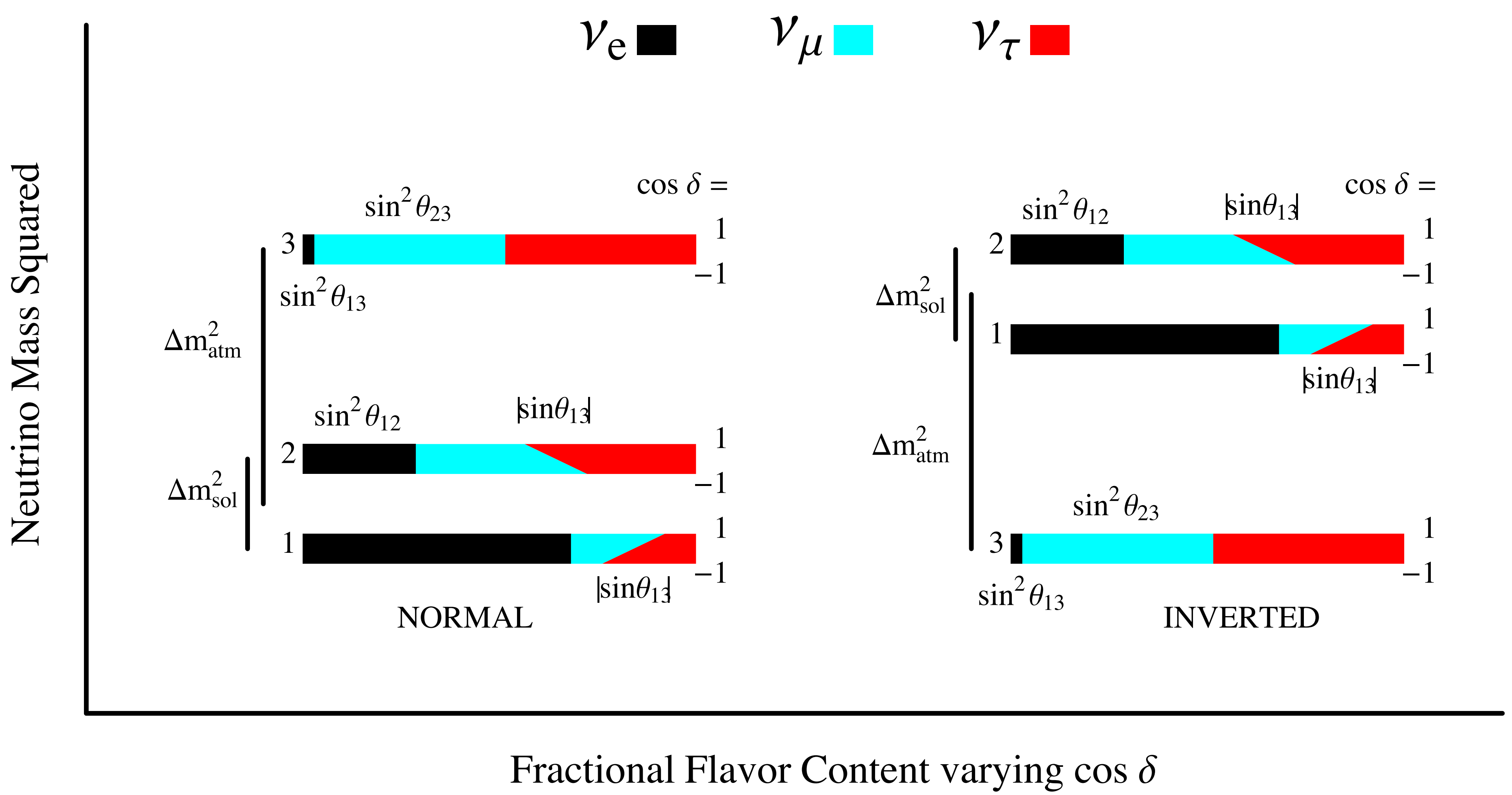
Too much thermal energy to be squeezed into small volumes to form the smaller structures we observe today!

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

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

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

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



(Mena,Parke, PRD'04)

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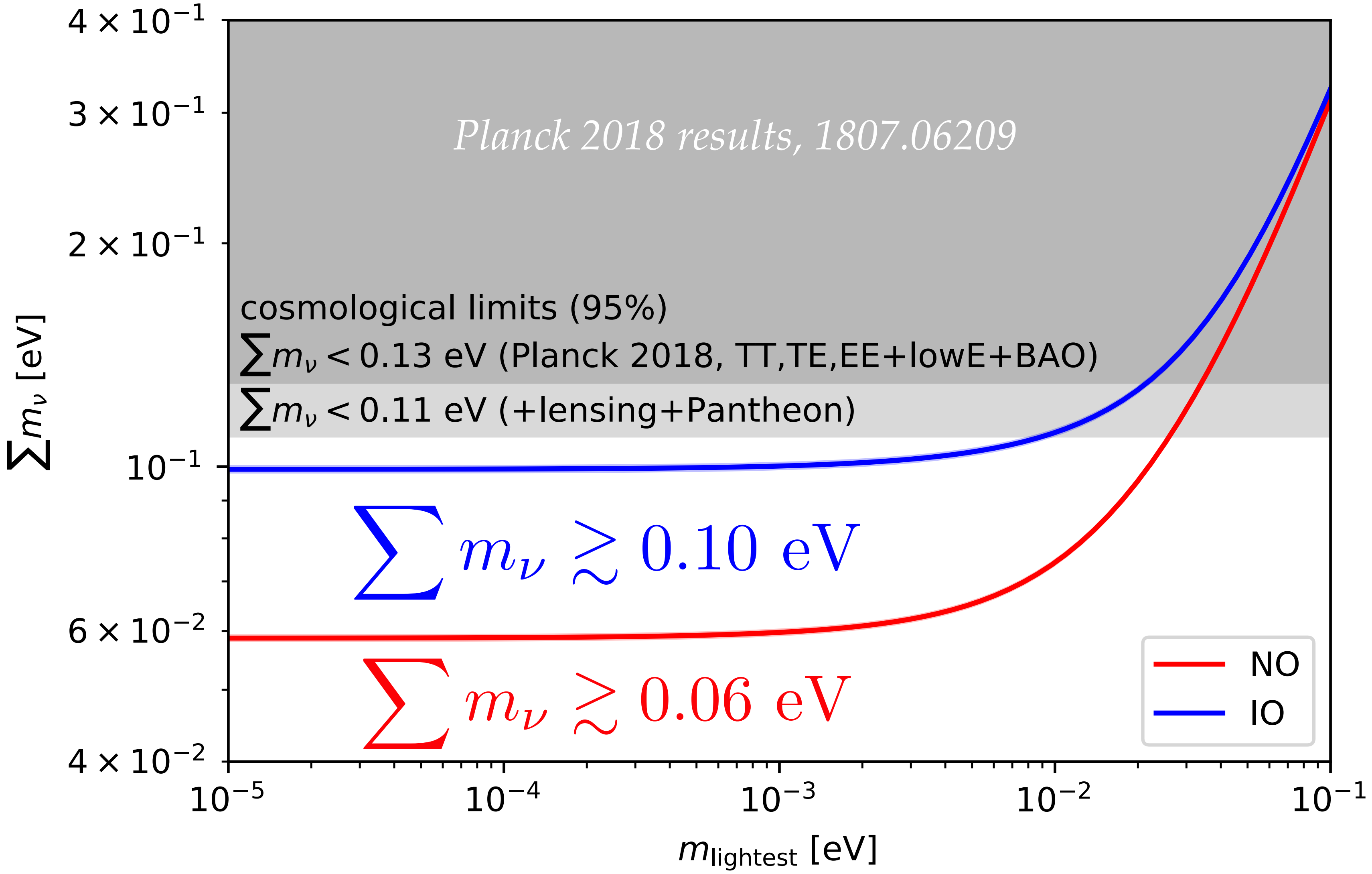
which translates into a lower bound on the total neutrino mass, depending on the ordering:

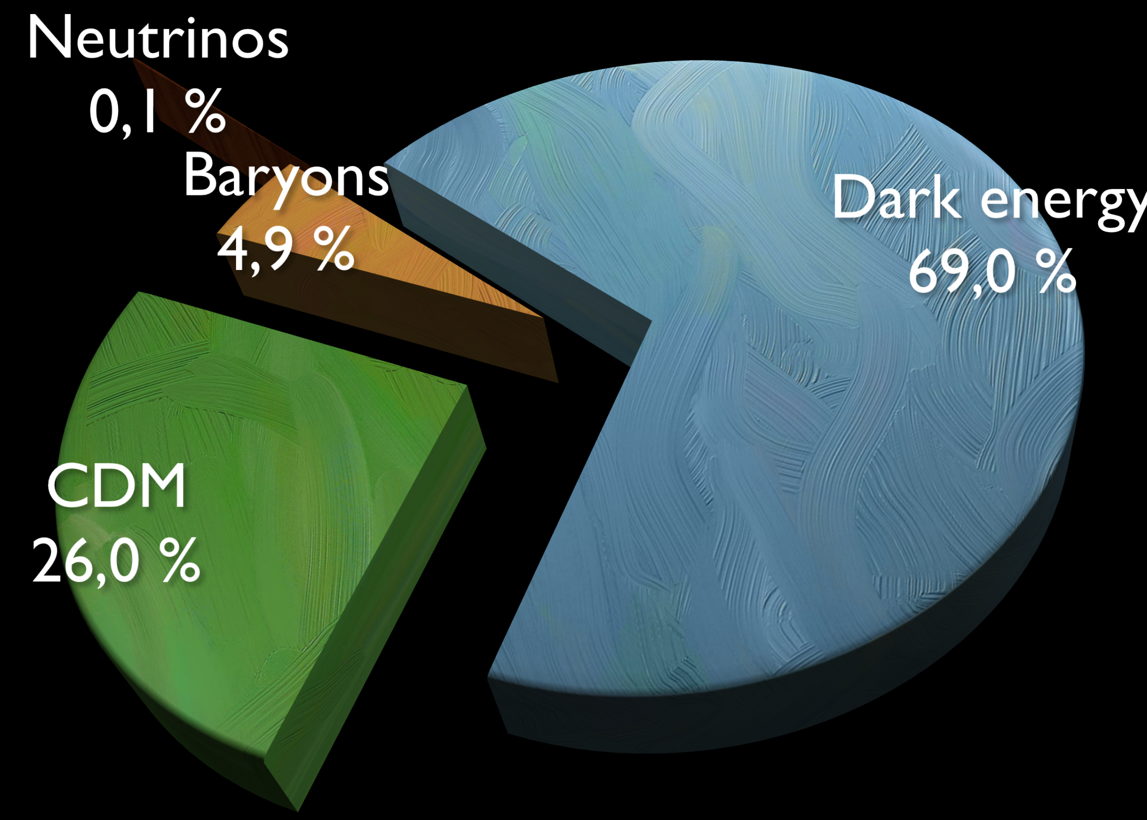


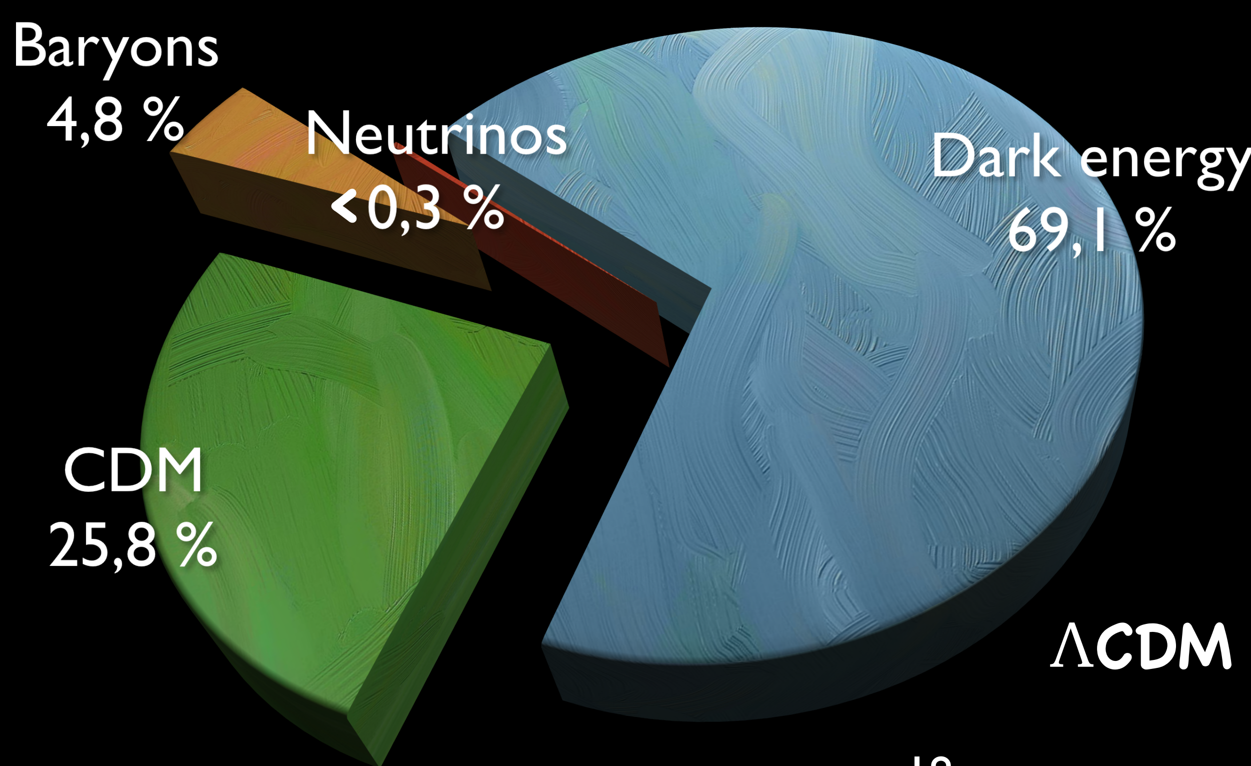
Planck 2018 Cosmic Pizzas

Planck 2018 Cosmic Pizzas

Planck 2018 results, 1807.06209

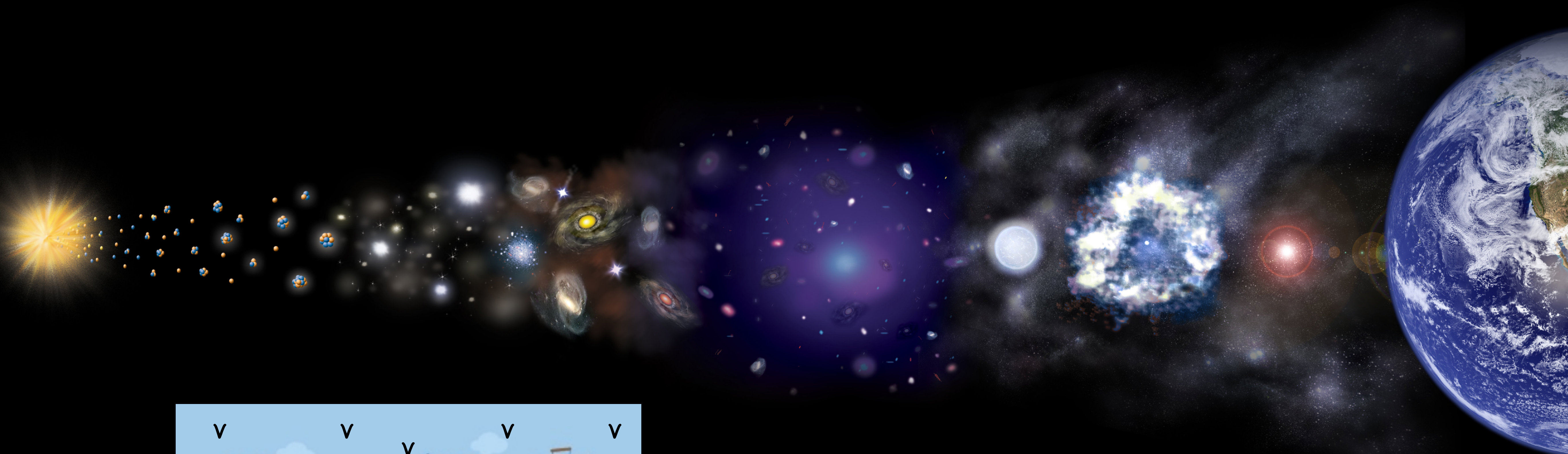
$\Lambda\mathbf{CDM} + \Sigma \mathbf{m}_{\nu,\text{fiducial}} = 0.06$ eV





$\Lambda\mathbf{CDM} + \Sigma \mathbf{m}_{\nu,\text{fiducial}} < 0.12$ eV @95% CL

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



and it's as challenging as trapping time!

Are you willing to join me in the Cosmo neutrino hunting trip?

vvvvvvvvvvvvvvvvvvvvvv

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Number of neutrinos: N_{eff}

The total radiation in the universe can be written as:

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

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

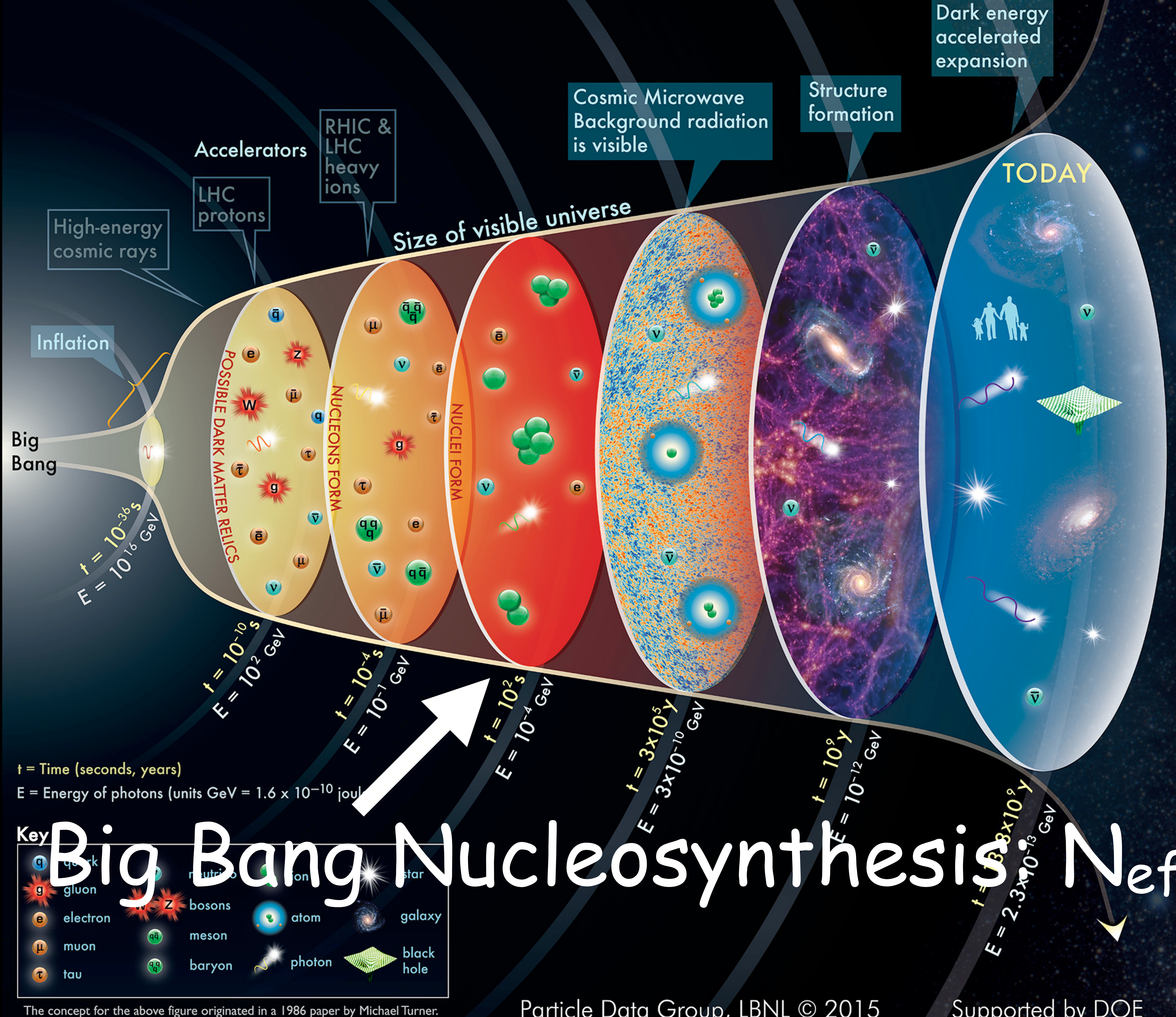
N_{eff} < 3.046 (less neutrinos): Neutrino decays ?

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}



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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".

Big Bang Nucleosynthesis: N_{eff}

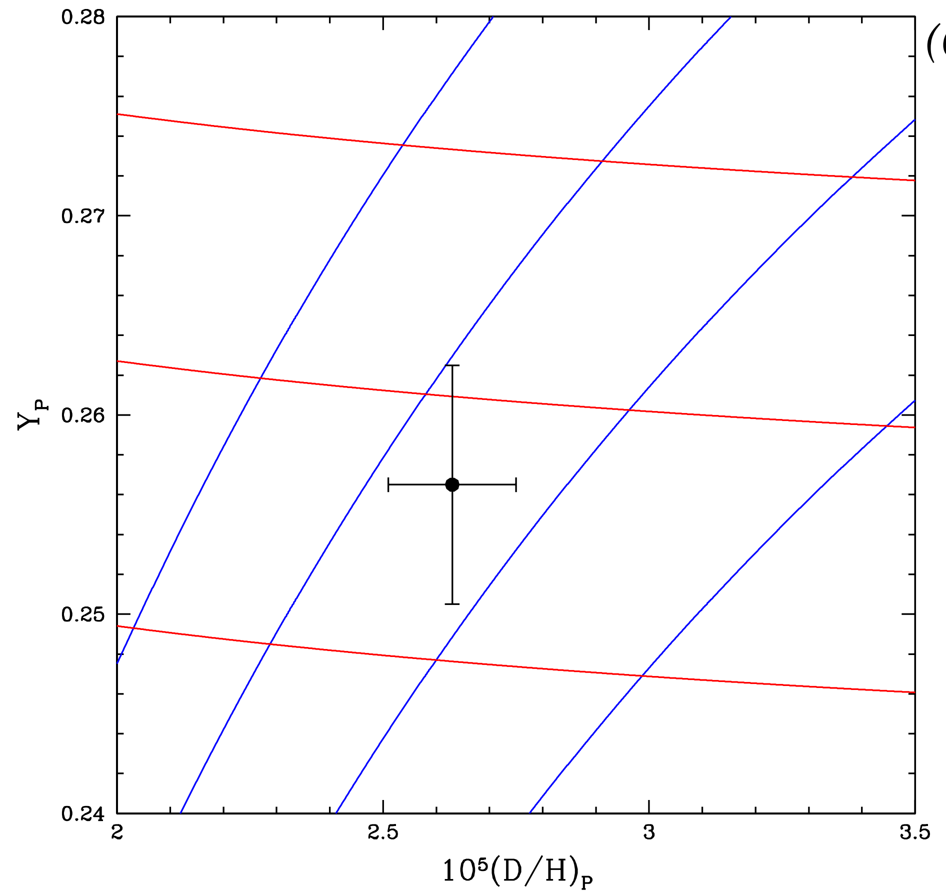
N_{eff} changes the freeze out temperature of weak interactions:

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

MORE NEUTRINOS:

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

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



(G. Steigman'12)

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

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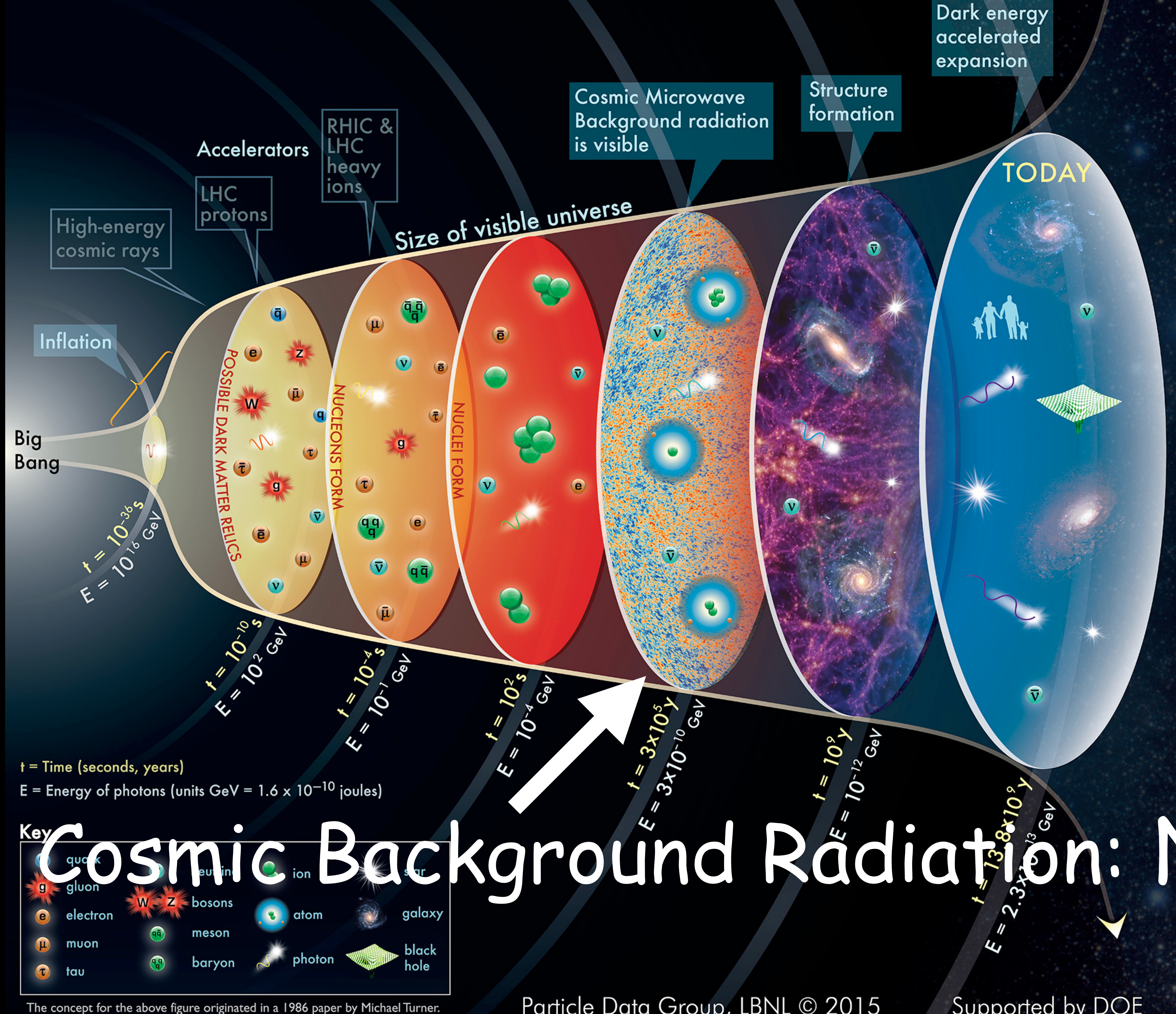
Cosmic Background Radiation: N_{eff}



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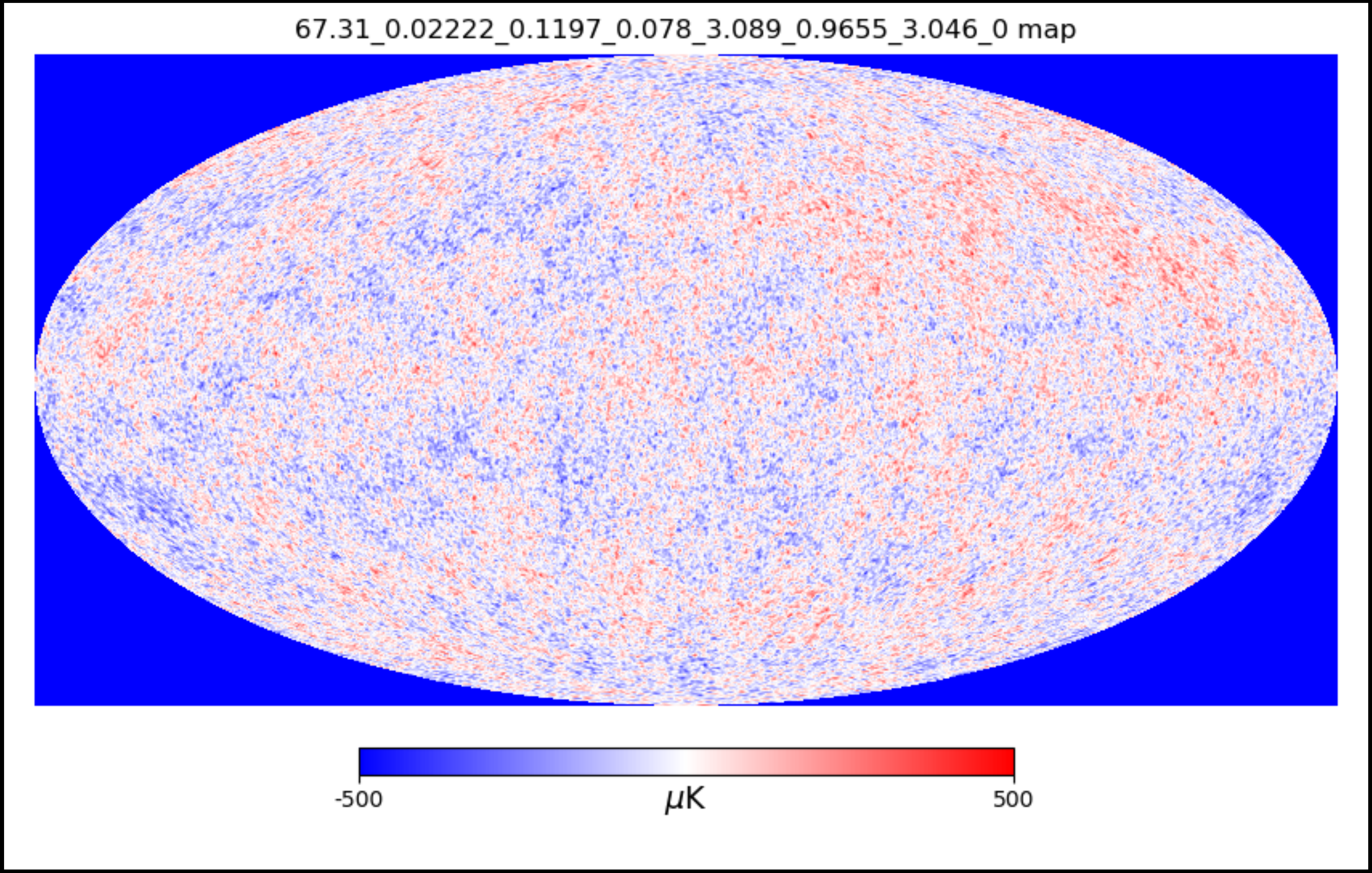
Also known as "photon decoupling", as photons started freely travel through the universe without interacting with matter and the CMB is "frozen"

CMB: N_{eff}



CMB: N_{eff}

Spherical harmonics decomposition:

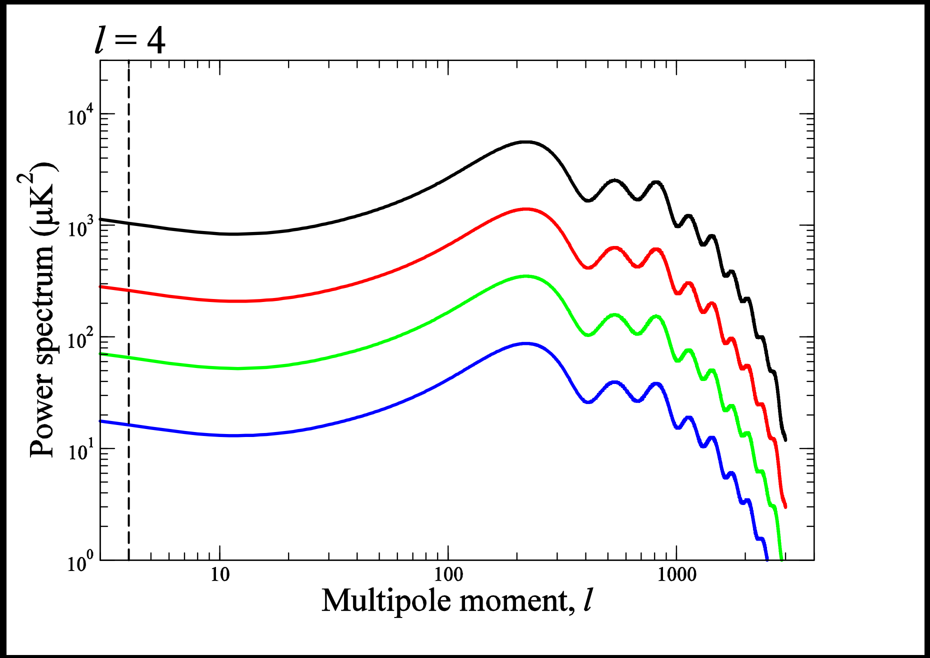
$$T(\hat{n}) = \sum_{\ell=0}^{\ell_{\max}} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\hat{n})$$

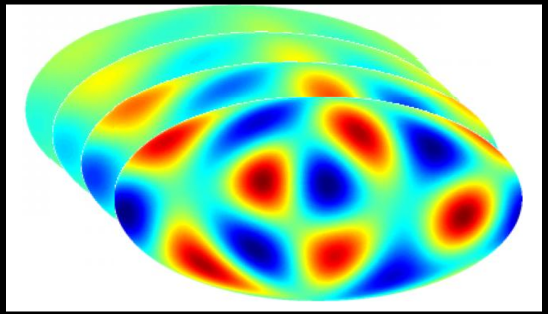
With expansion coefficients:

$$a_{\ell m} = \int_{4\pi} T(\hat{n}) Y^*_{\ell m}(\hat{n}) d\Omega$$

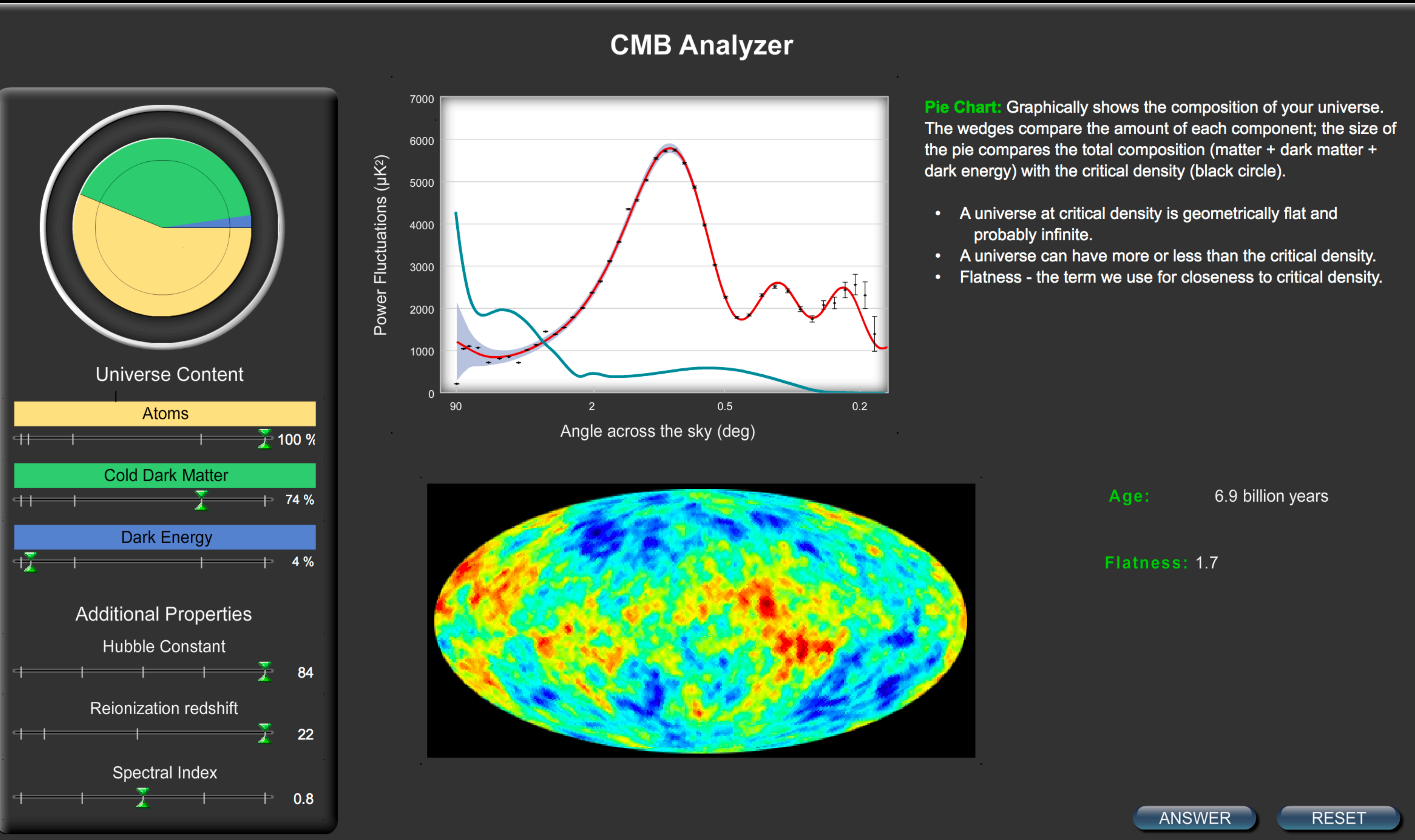
The angular power spectrum measures the amplitude as a function of the wavelength:

$$C_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

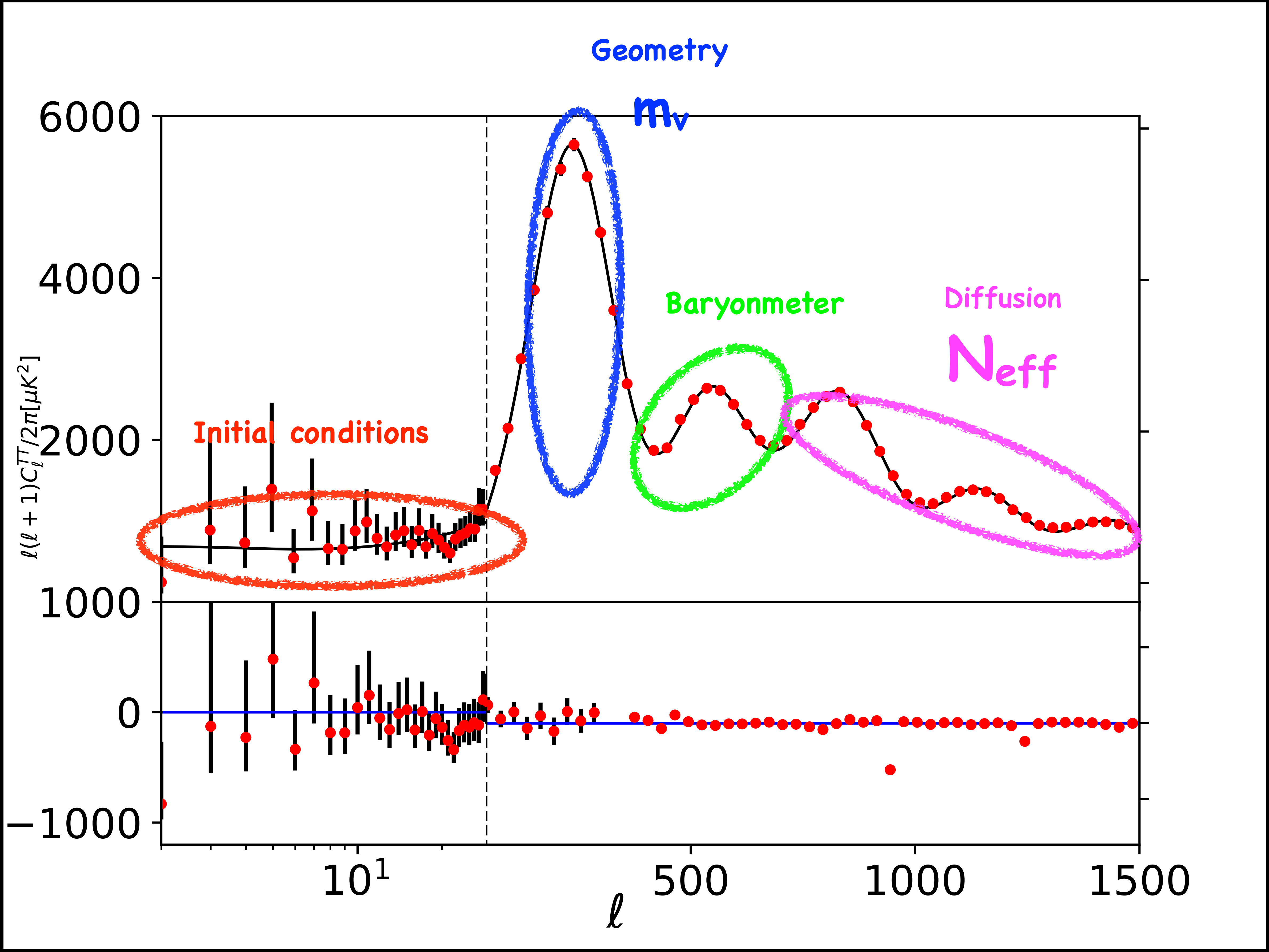




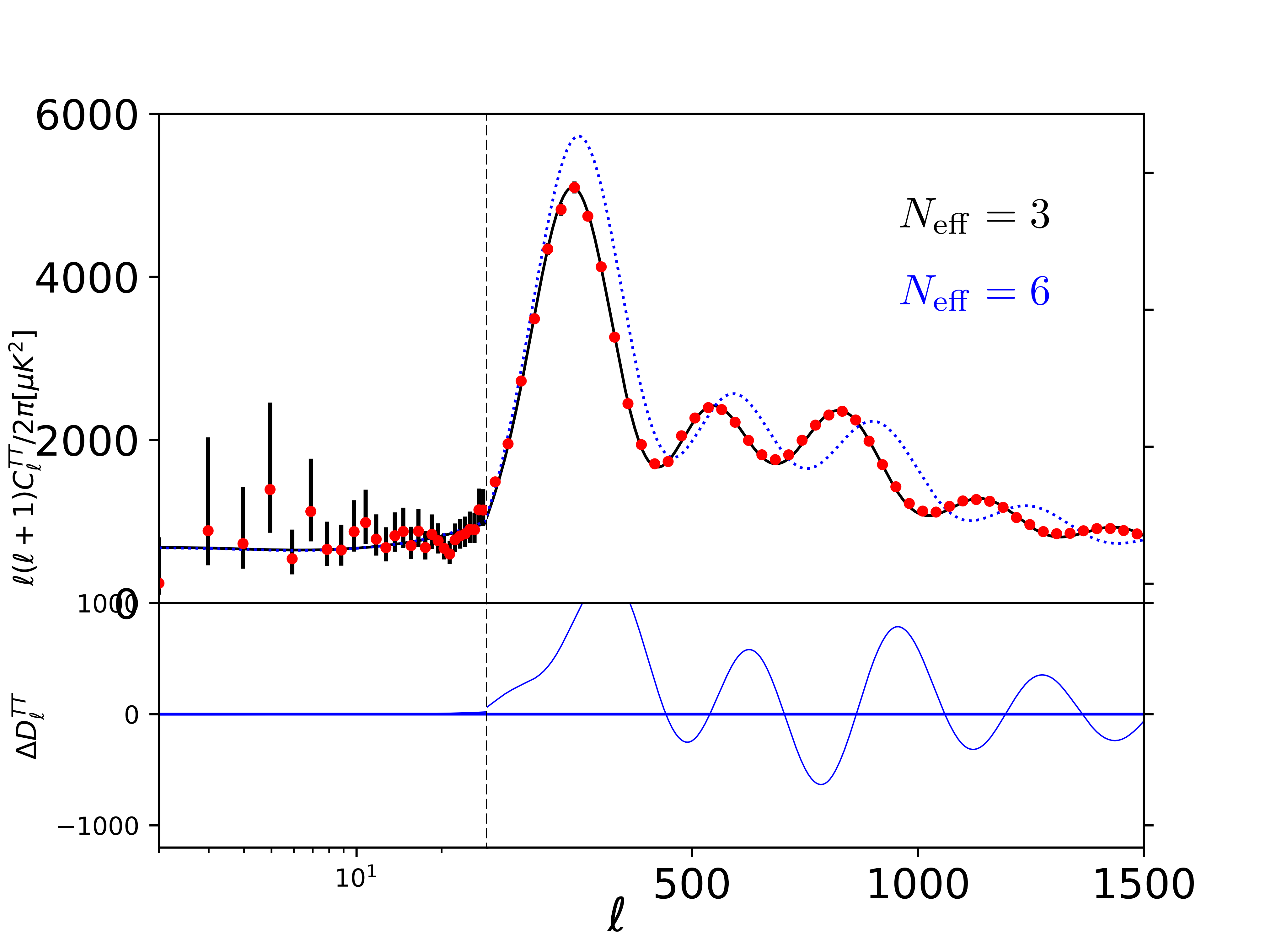
CMB: Neff

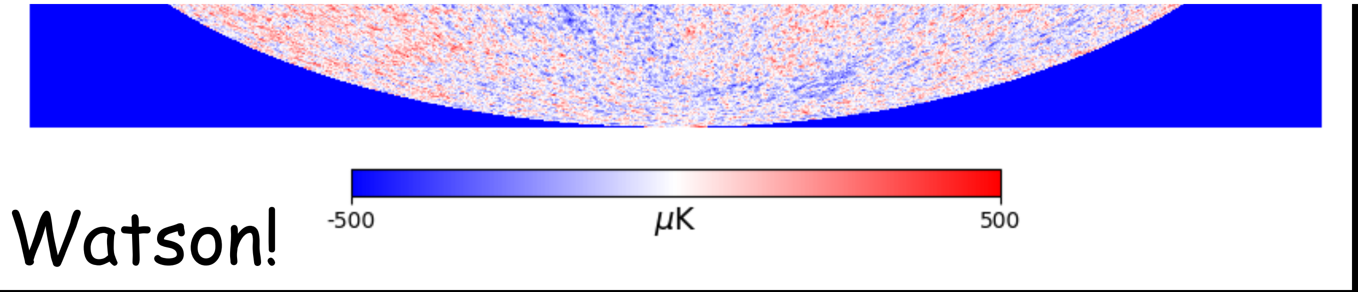

CMB Analyzer
Universe Content
Atoms
100 %
Cold Dark Matter
74 %
Dark Energy
4 %
Additional Properties
Hubble Constant
84
Reionization redshift
22
Spectral Index
0.8
Power Fluctuations (μK2)
7000
6000
5000
4000
3000
2000
1000
0
90
2
0.5
0.2
Angle across the sky (deg)
Pie Chart: Graphically shows the composition of your universe. The wedges compare the amount of each component; the size of the pie compares the total composition (matter + dark matter + dark energy) with the critical density (black circle).
• A universe at critical density is geometrically flat and probably infinite.
• A universe can have more or less than the critical density.
• Flatness - the term we use for closeness to critical density.
Age: 6.9 billion years
Flatness: 1.7
ANSWER
RESET

CMB: a lot to learn about….



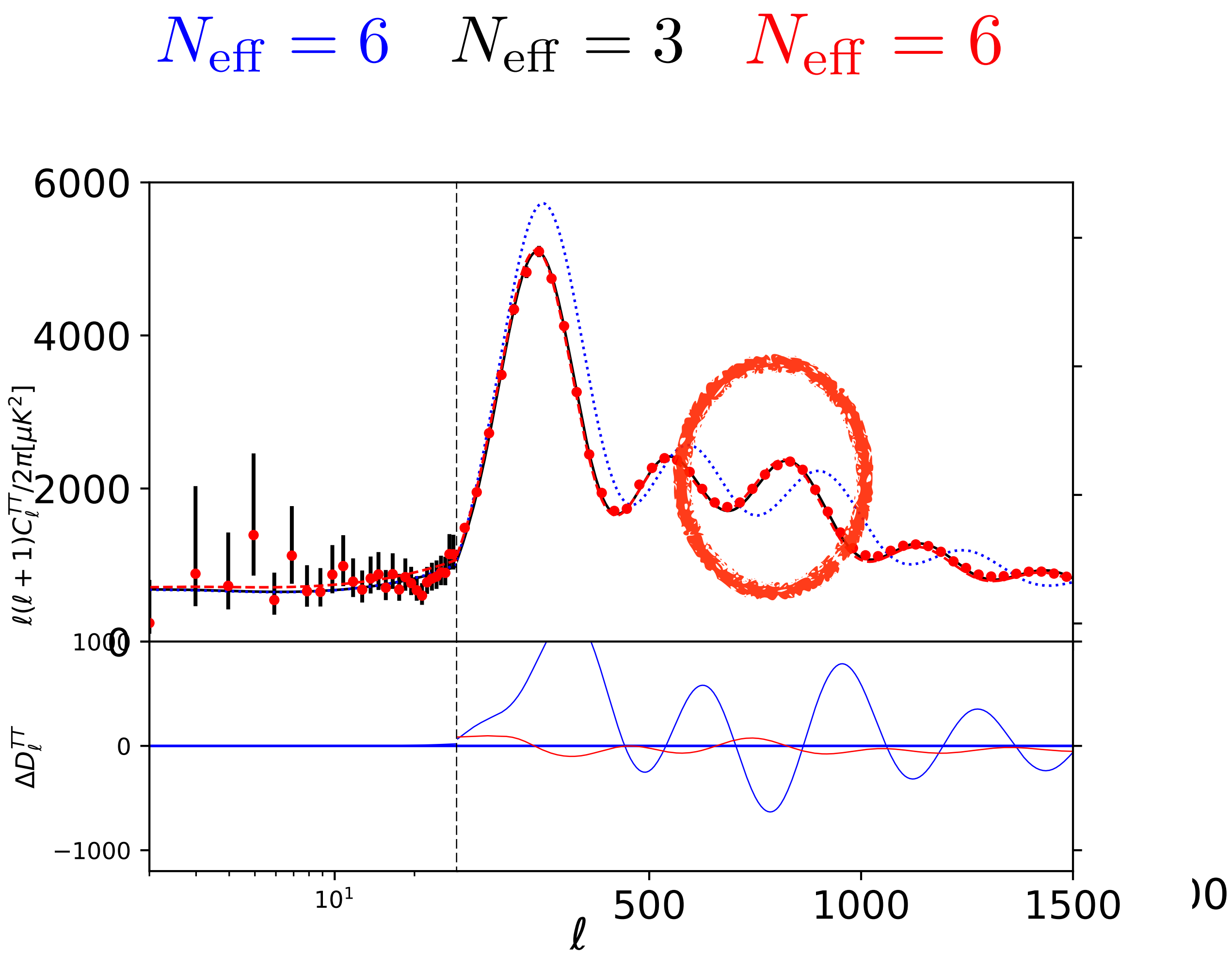
CMB: N_{eff}





Elementary, my dear Watson!

CMB: $N_{\rm eff}$

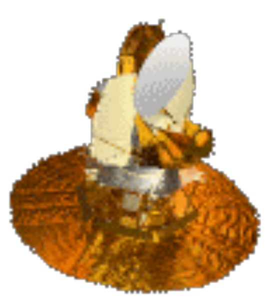


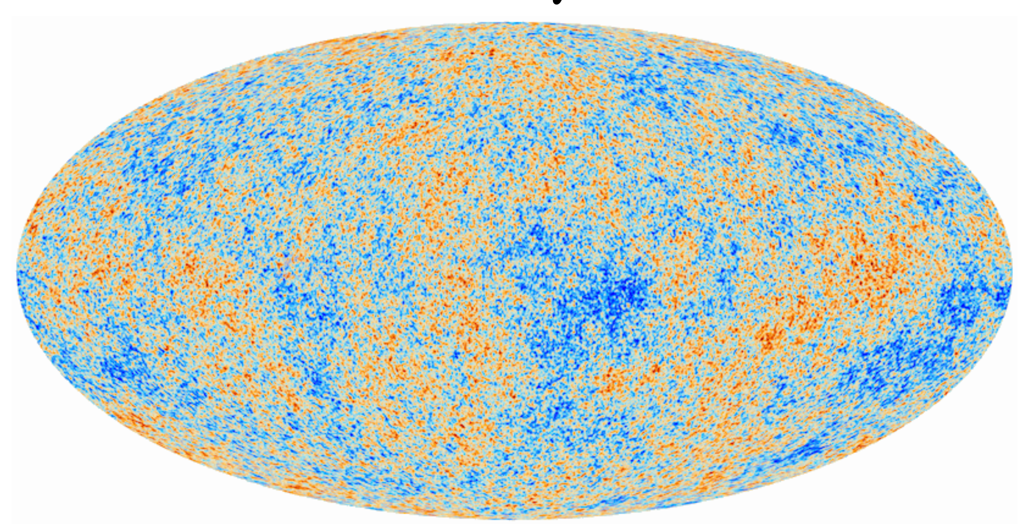
$$(\omega_b, \omega_m, h, A_s, n_s, \tau, N_{\rm eff})$$

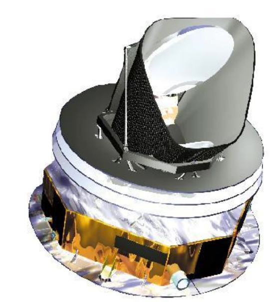
Warning!

It is ~~elementary~~, Sherlock Holmes!

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





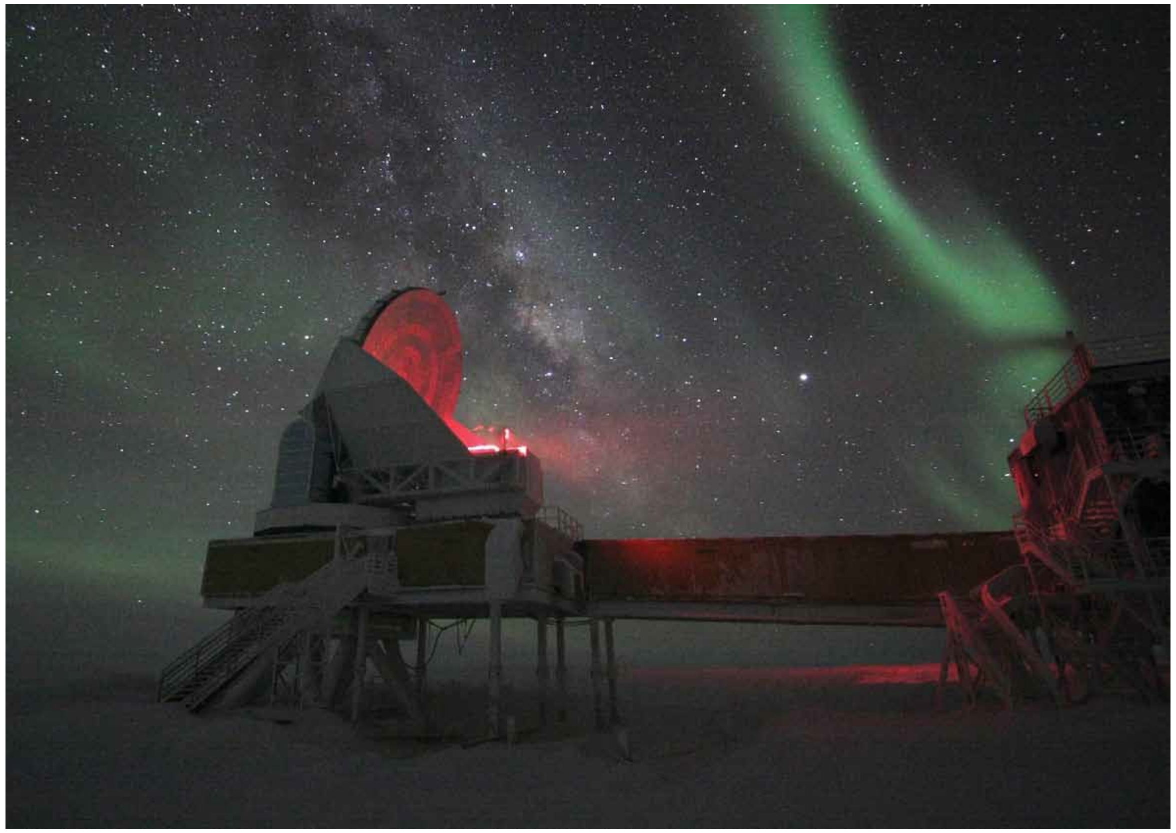


Neutrinos are free-streaming particles propagating at the speed of light, faster than the sound speed in the photon fluid, suppressing the oscillation amplitude of CMB modes that entered the horizon in the radiation epoch.

CMB: N_{eff}

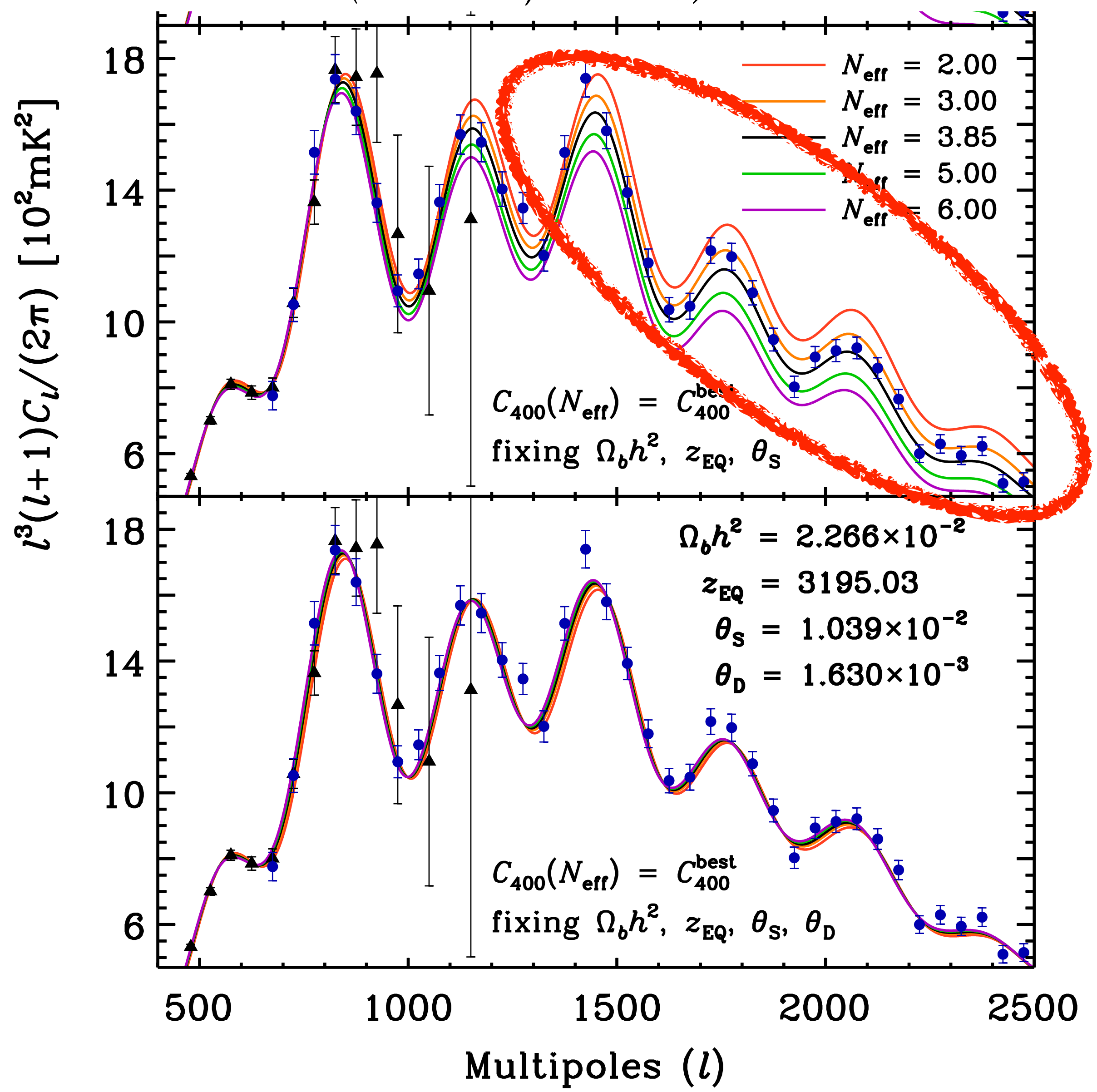
@Cosmic Microwave Background in the damping tail, measured by SPT, ACT & Planck:

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 results, 1807.06209

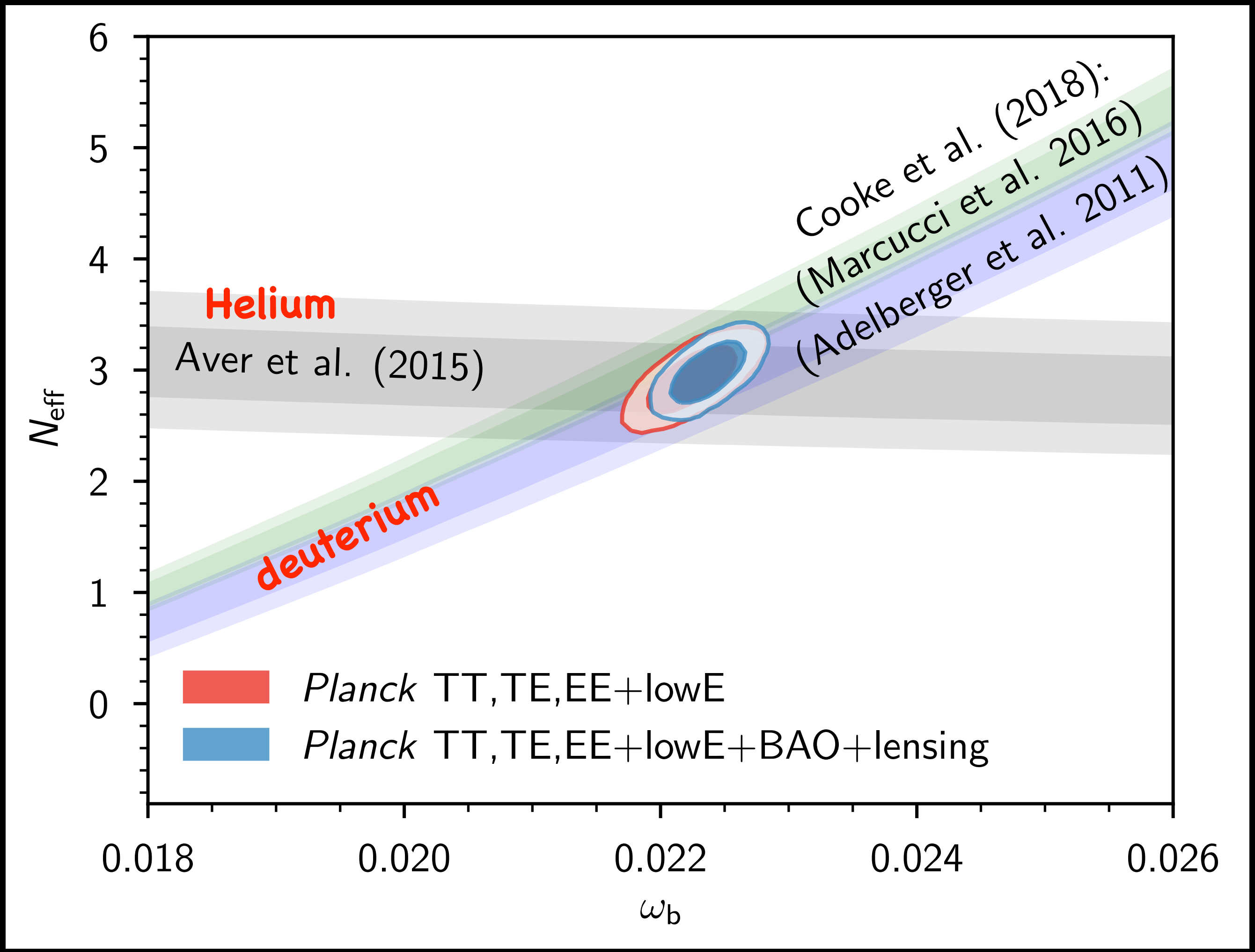
- **Planck 2018 CMB temperature polarization and lensing potential data:**

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

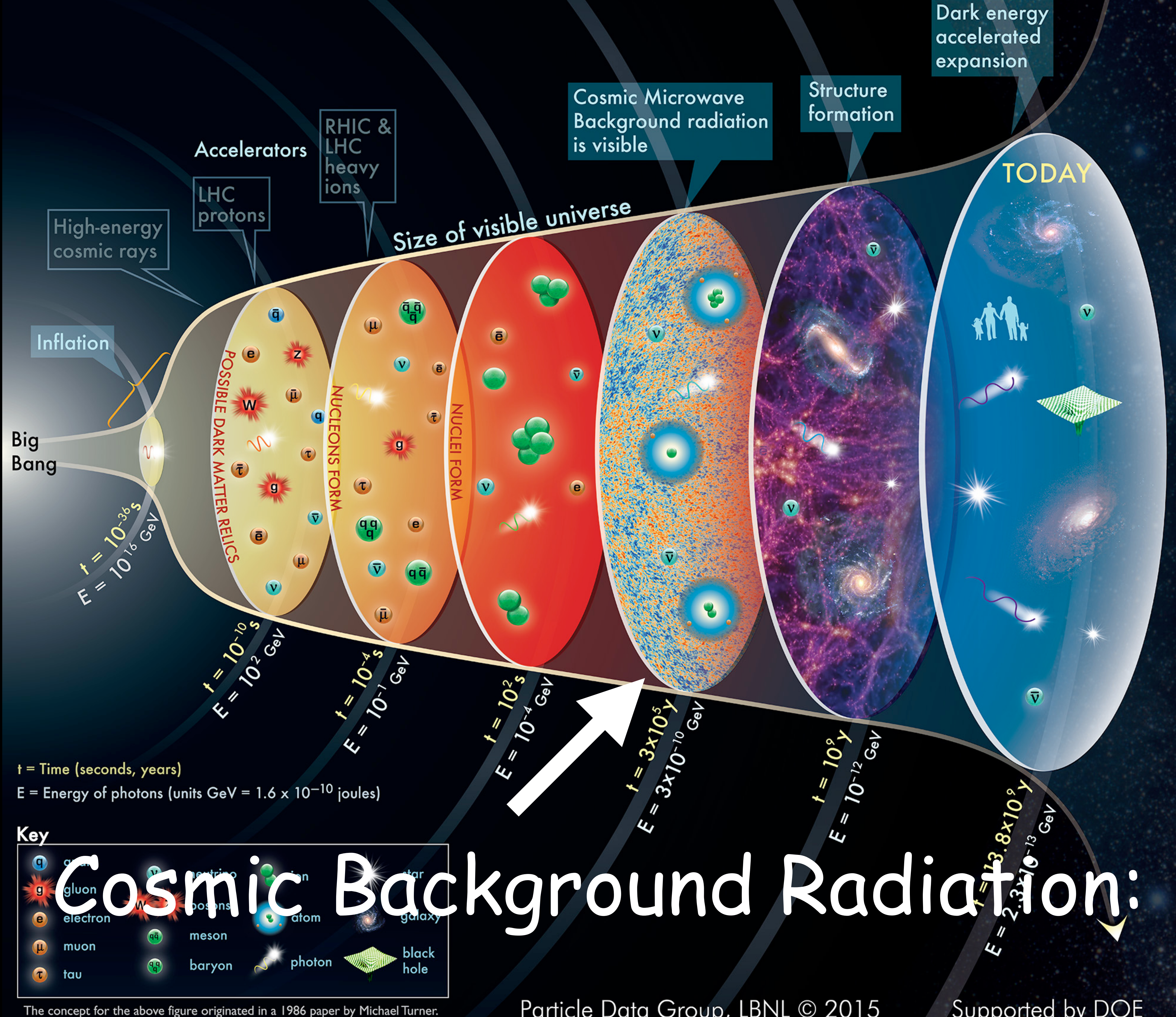
- **If we add large scale structure information in the BAO shape form:**

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

- **Perfectly consistent with BBN estimates:**



Cosmic Background Radiation: m_ν



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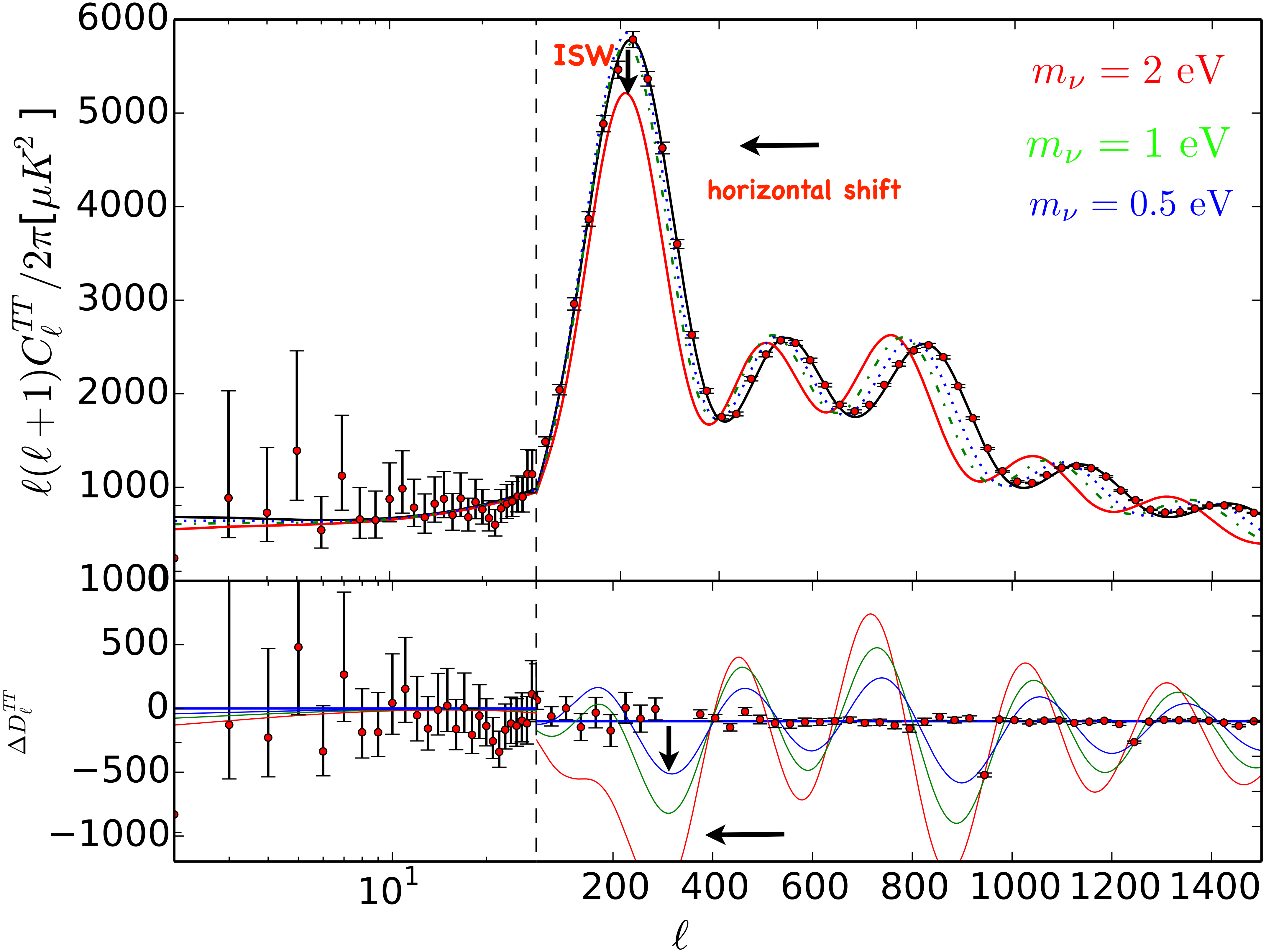
CMB: Σm_ν

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

Shift in the angular position of the peaks.

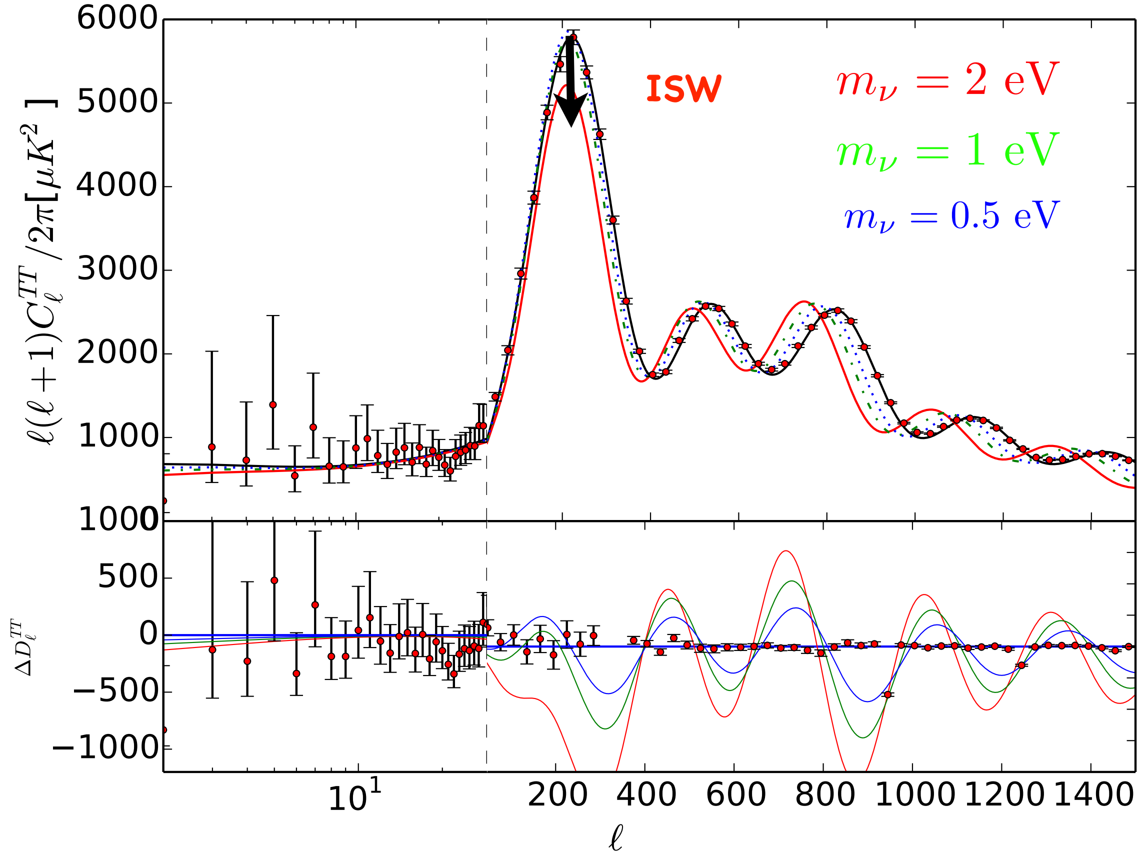


CMB: Σm_ν

@ 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:

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

on multipoles:

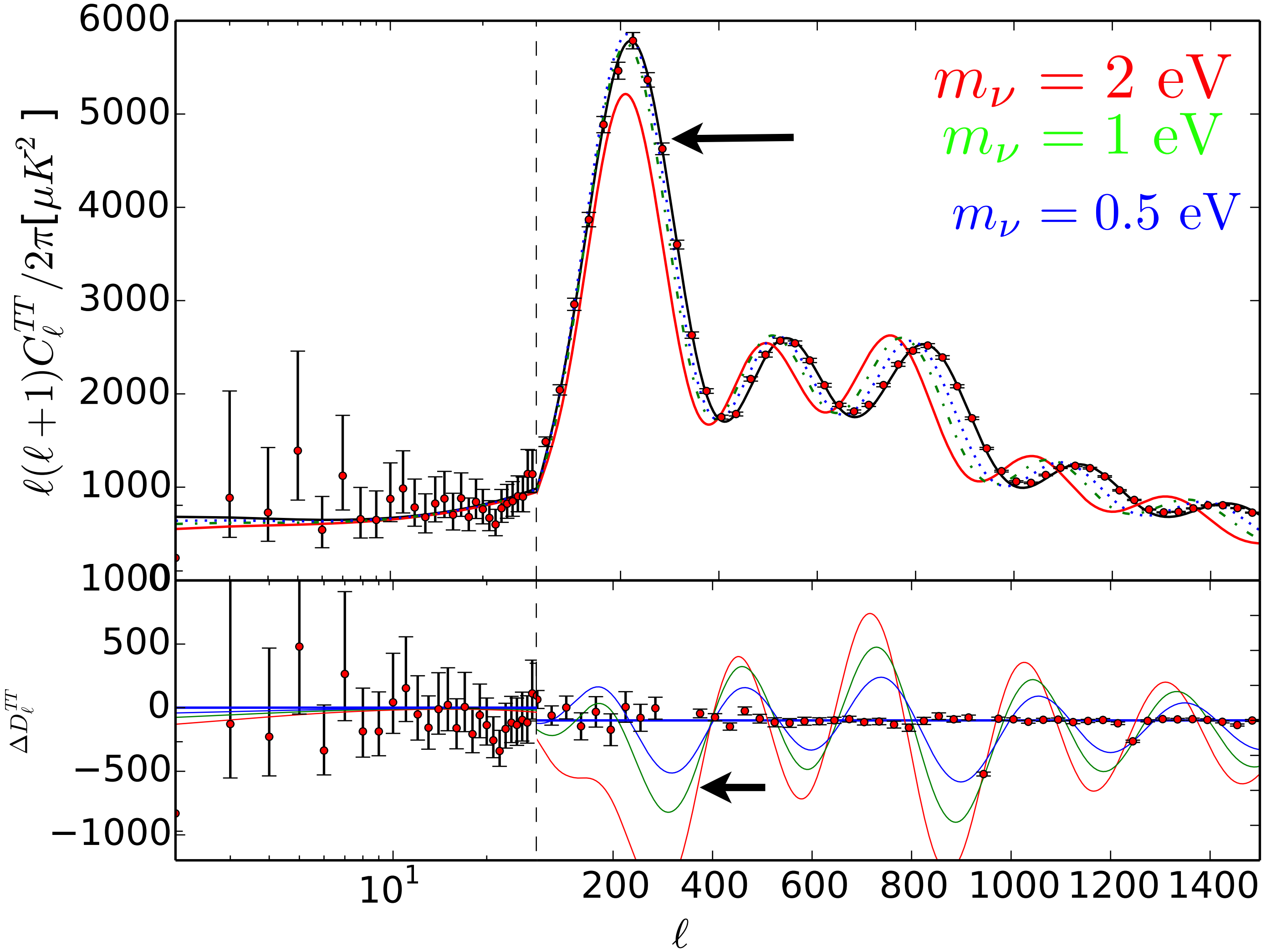
$$20 < \ell < 200$$

(Lesgourgues & Pastor, Phys.Rept'06)

CMB: Σm_ν

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

Shift in the angular position of the peaks.



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

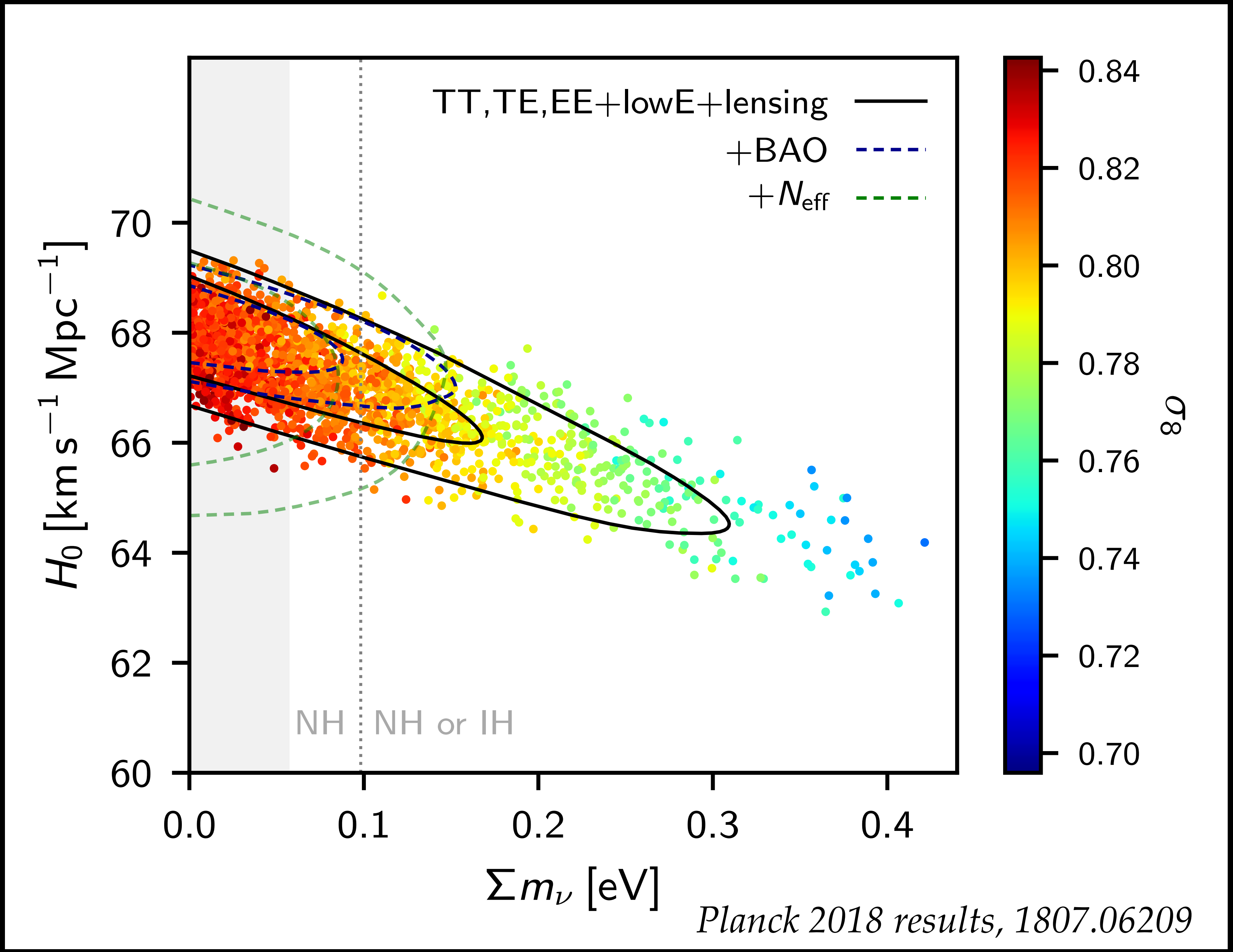
$$r_s = \int_0^{t(z_d)} c_s\,(1+z)dt = \frac{2}{3k_{\rm eq}}\sqrt{\frac{6}{R_{\rm eq}}}\ln\frac{\sqrt{1+R_d}+\sqrt{R_d+R_{\rm eq}}}{1+\sqrt{R_{\rm eq}}}$$

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

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



Strong degeneracy between Σm_ν and the Hubble constant H_0!

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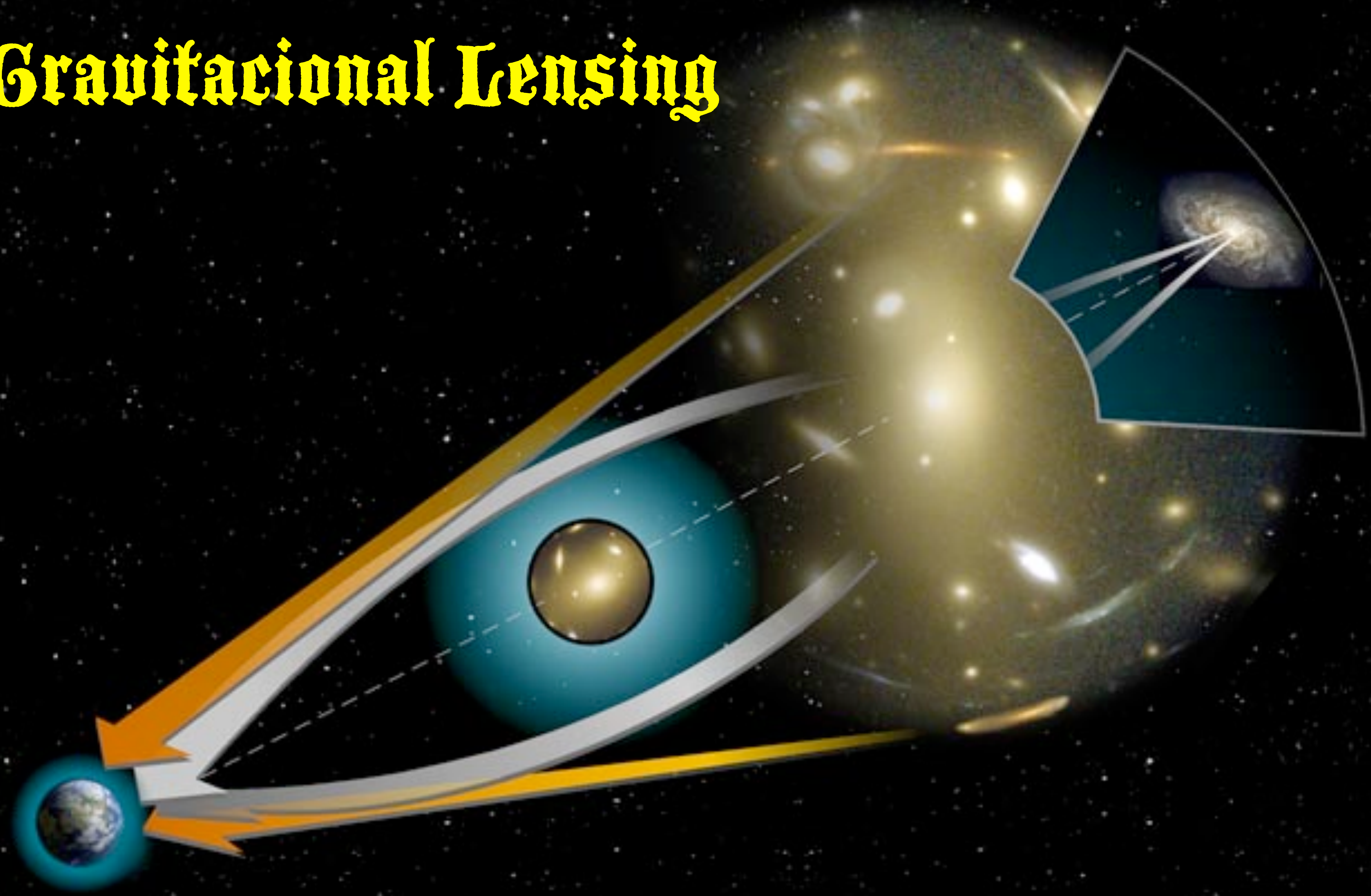
@ CMB: Early Integrated Sachs Wolfe effect (ISW).

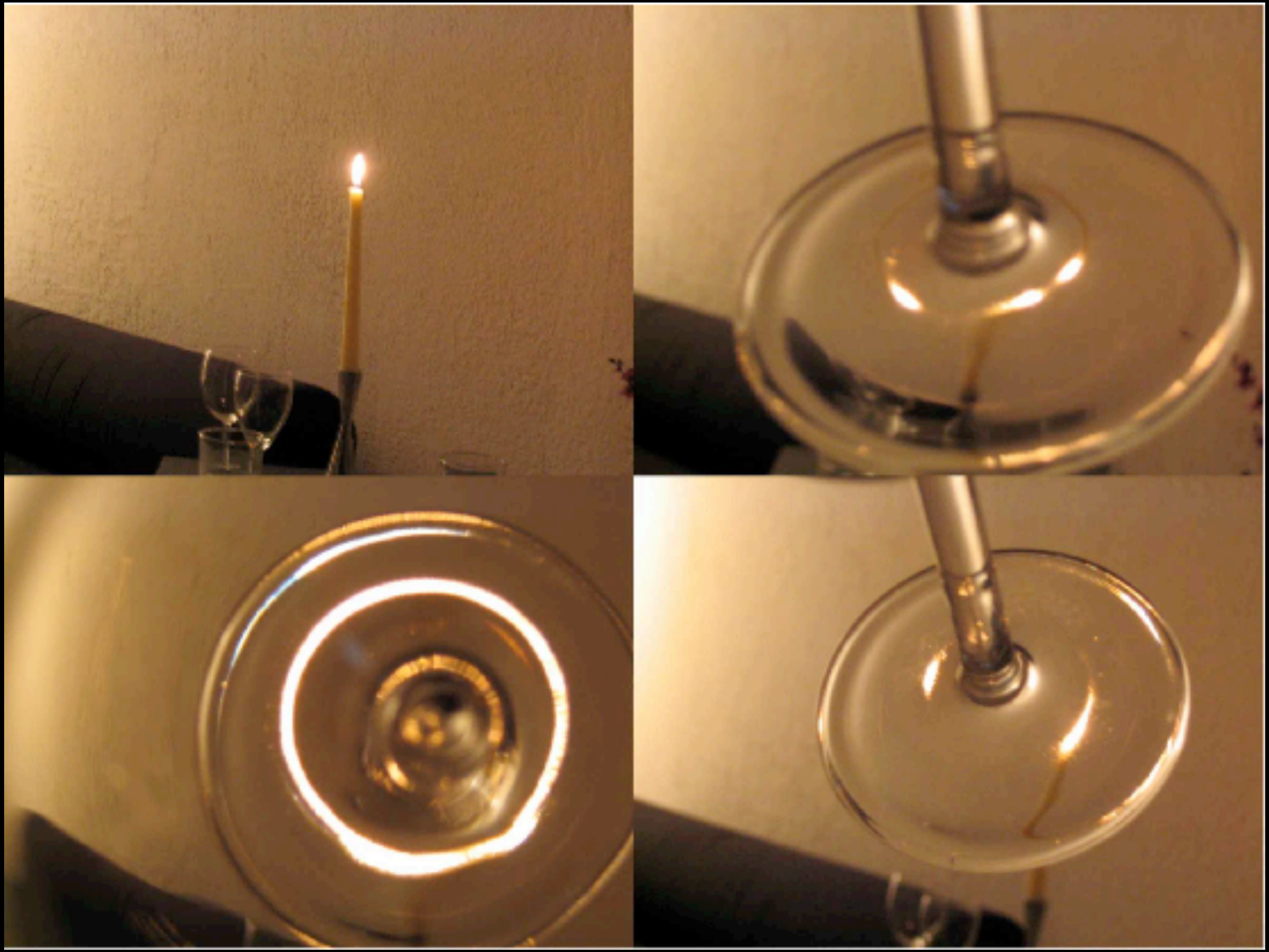
Shift in the angular position of the peaks.

Gravitacional Lensing



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

Gravitacional Lensing



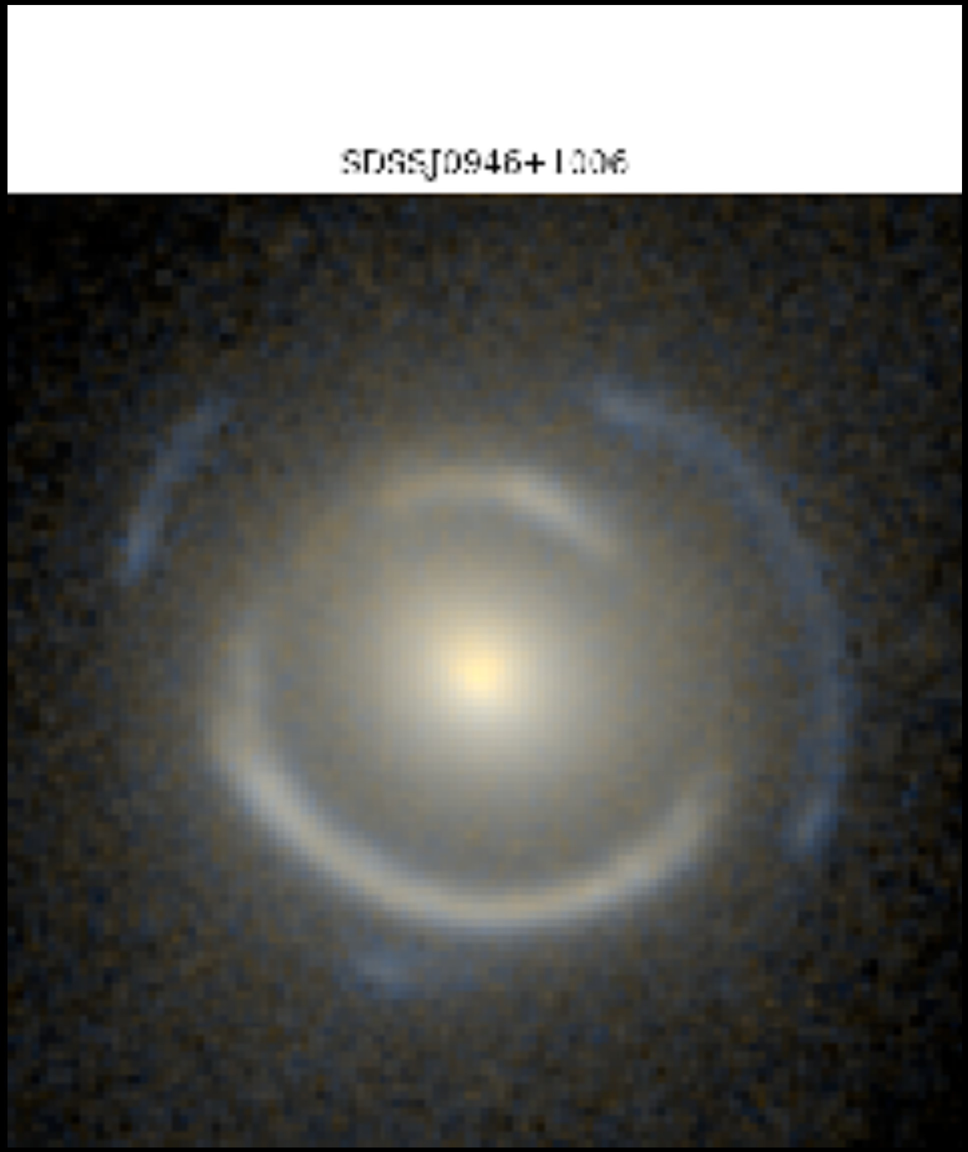
Einstein rings: Perfect alignment

Syzygy!

Lensing Galaxy

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 observed 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

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

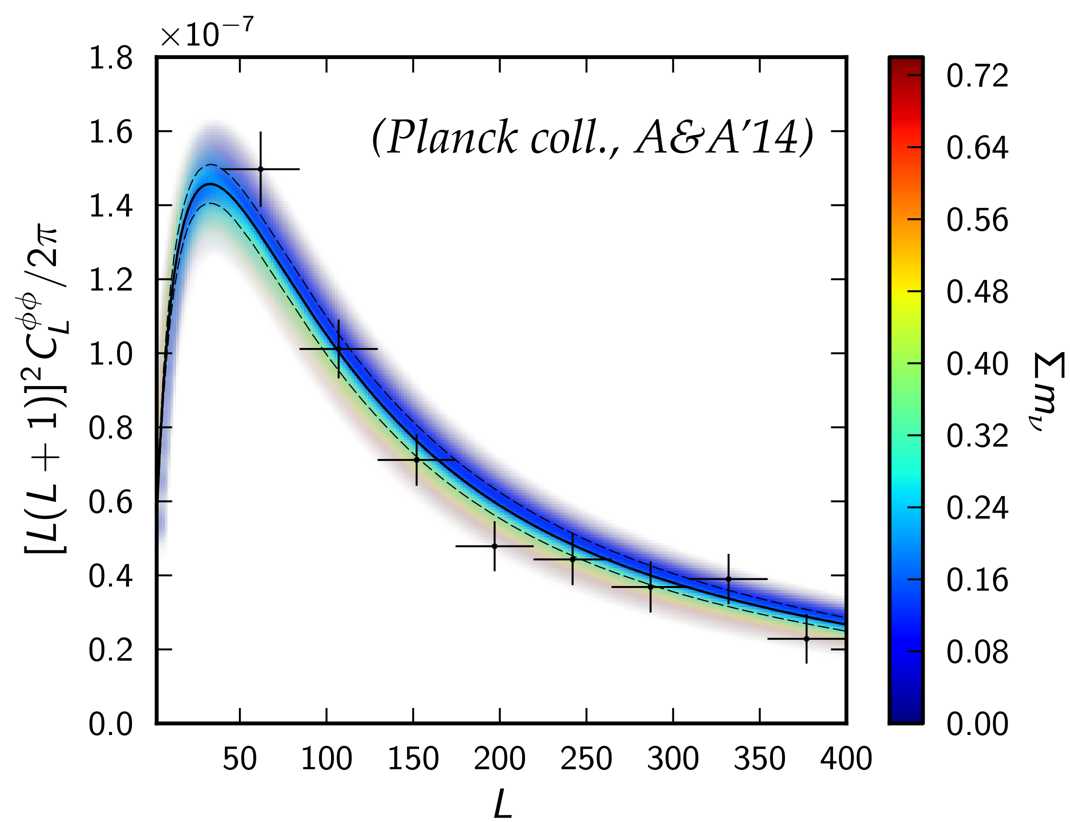
Matter distribution — $\Psi(z, D(z)\hat{n})$

Geometry — $\left(\frac{D(z_{rec}) - D(z)}{D(z_{rec})D(z)}\right)$

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

Neutrino free-streaming implies 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

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

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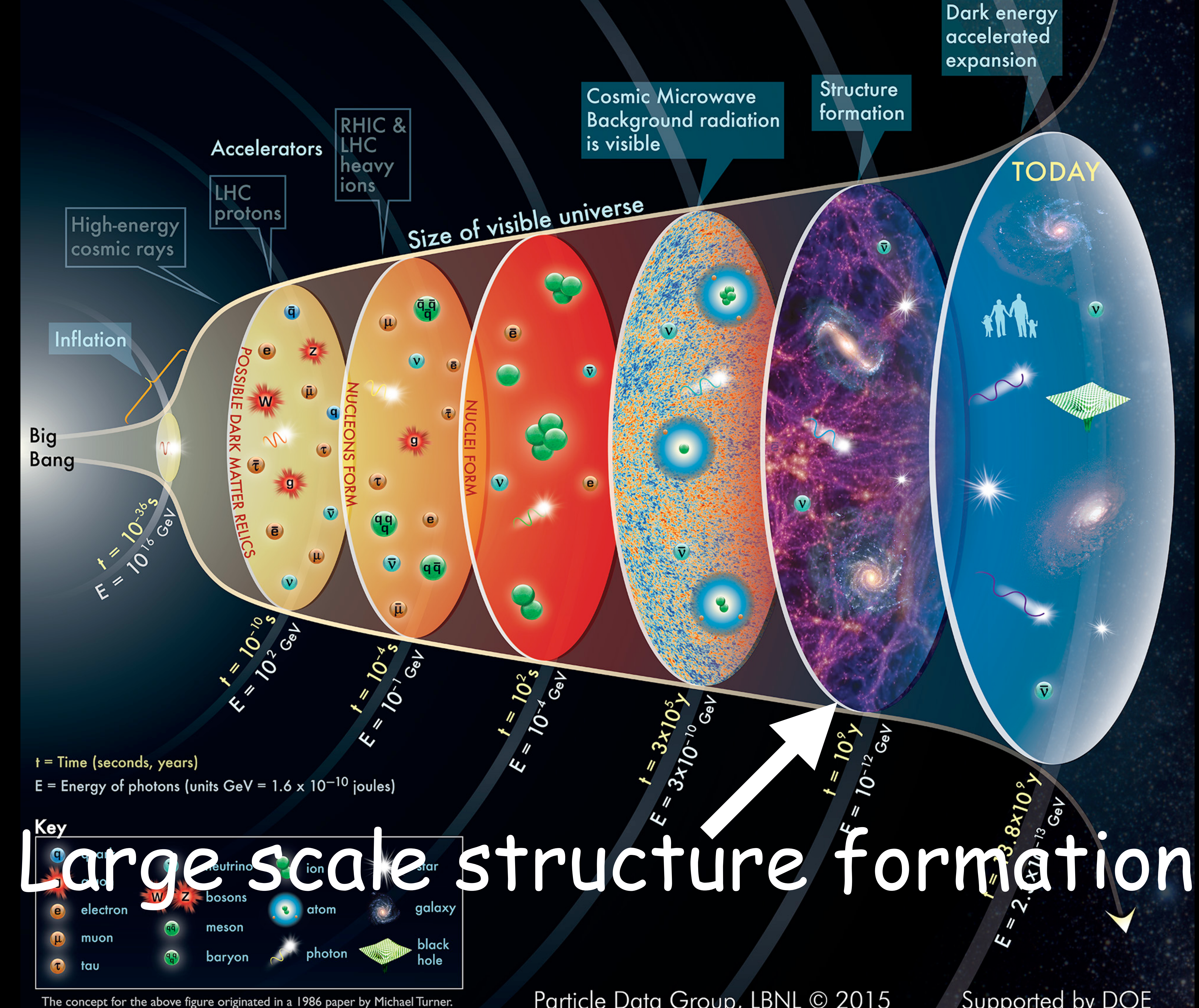
Doggy Bag

- Take home messages

Large scale structure formation: m_ν

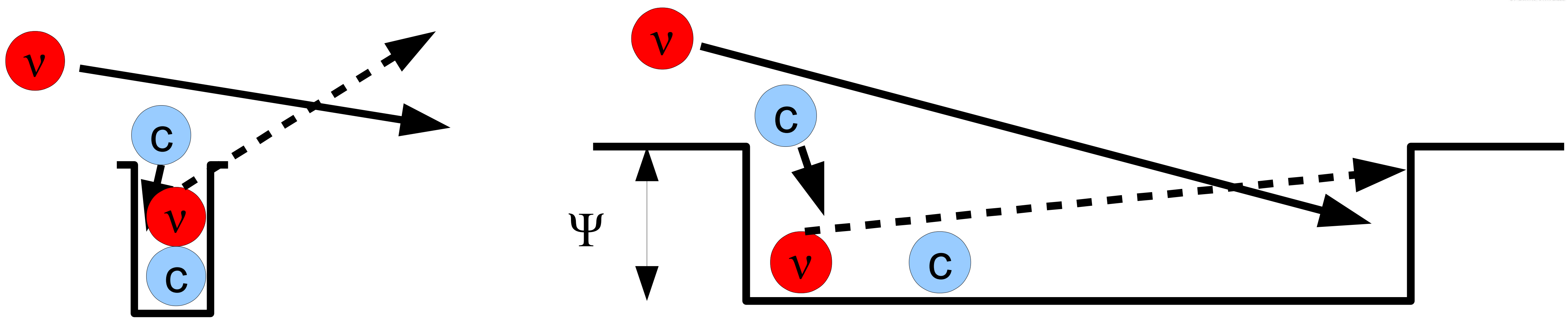


Large scale structure: m_ν

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:

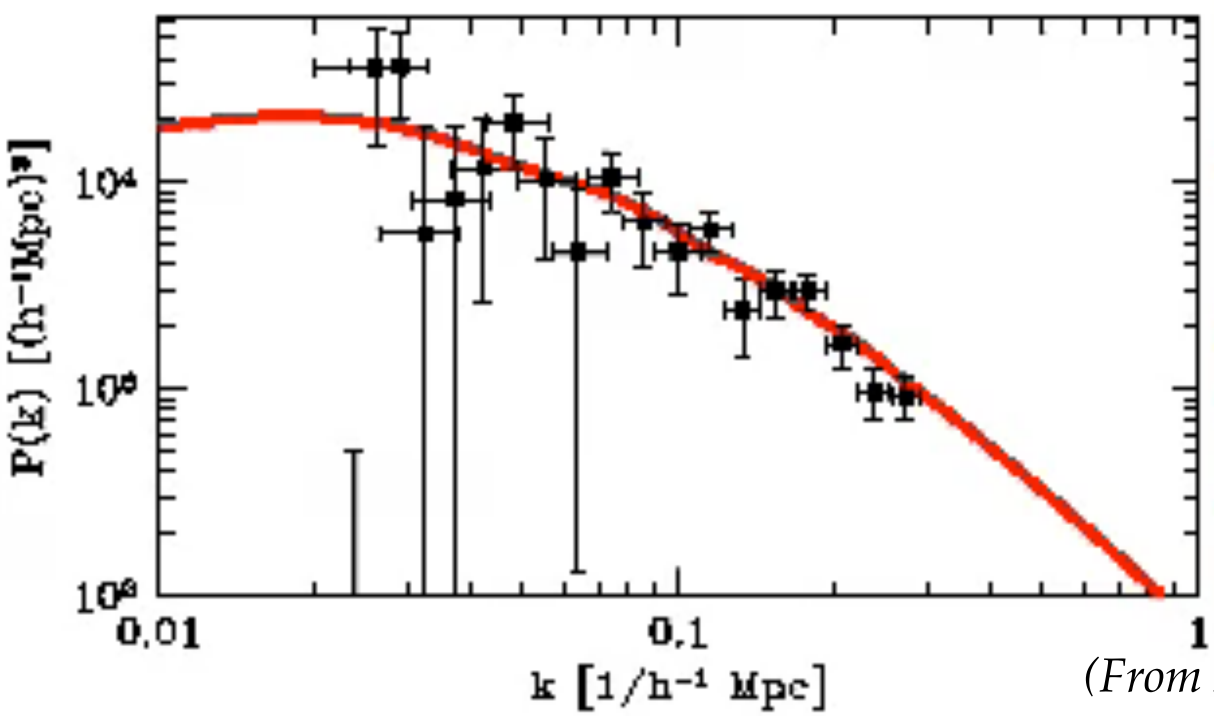
$$k_{fs,\nu}(z) \equiv \sqrt{\frac{3}{2}}\frac{H(z)}{(1+z)\sigma_{v,\nu}(z)}$$

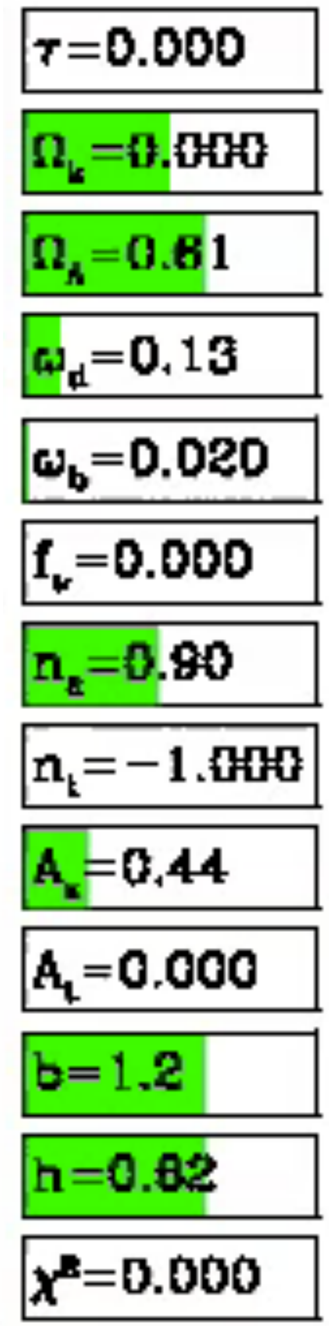
Large scale structure: m_ν

Matter power spectrum suppression:

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

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





(From M. Tegmark)

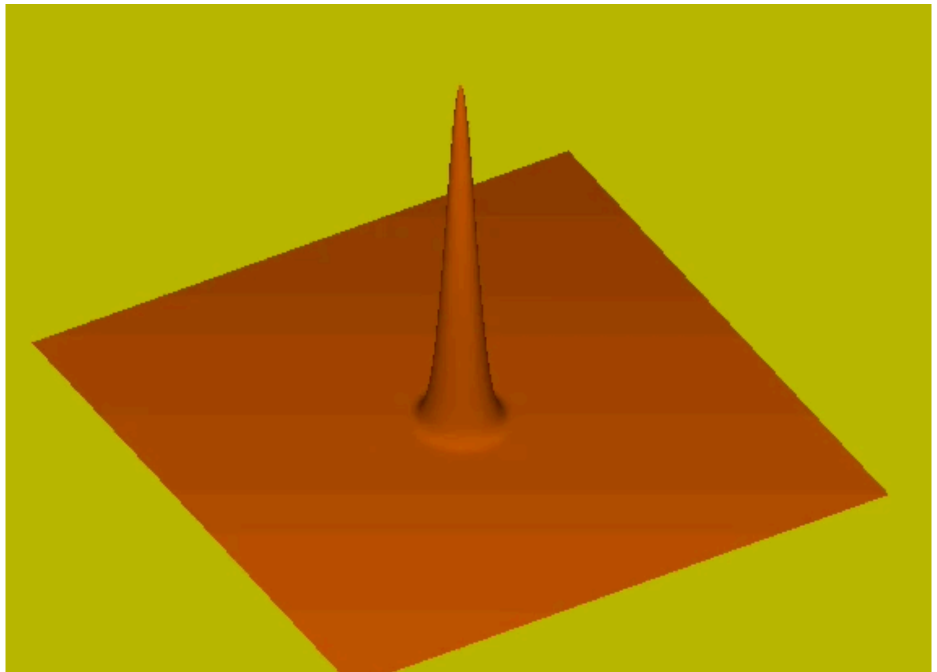
Small scales

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:



From D. Eisenstein and M. White

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

(Planck 2018 results)

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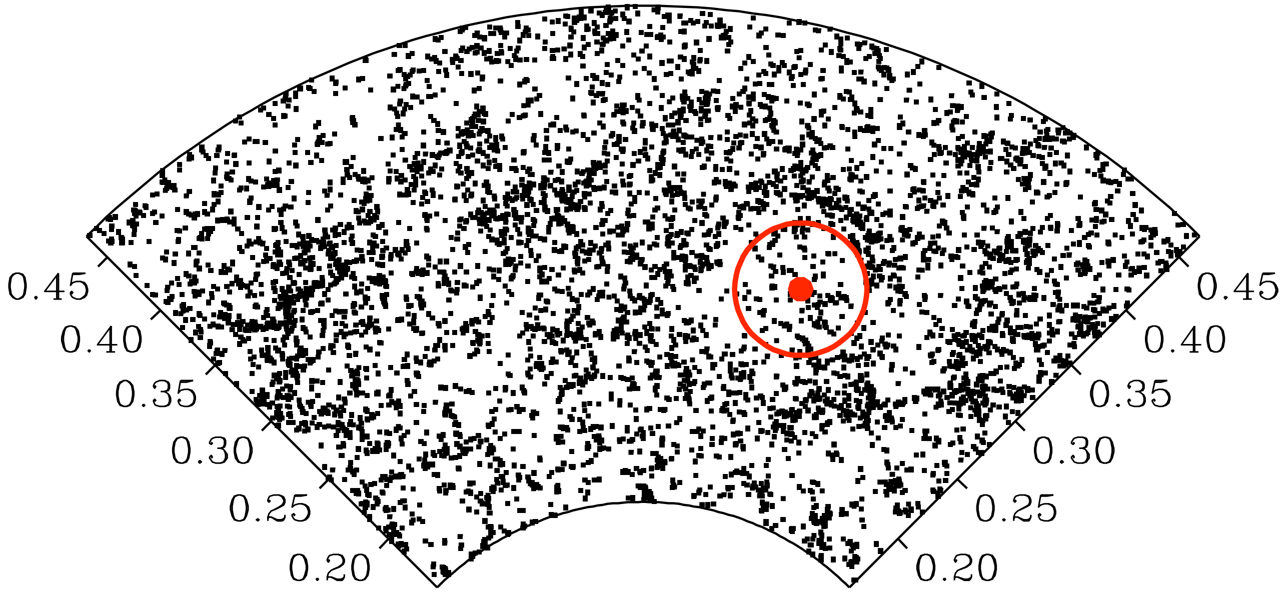
$$r_s = 147.09 \pm 0.26 \text{ Mpc}$$

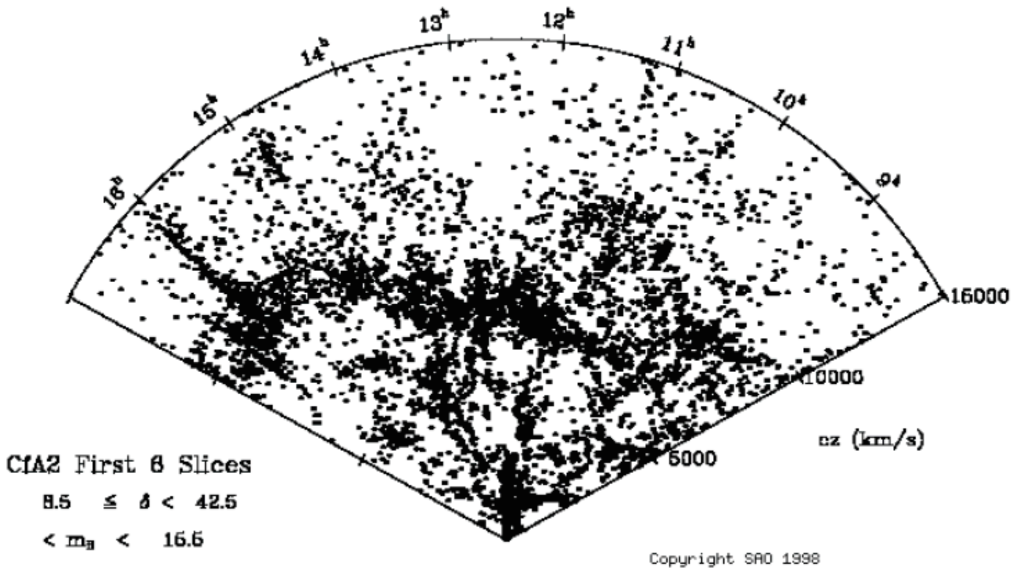
(Planck 2018 results)

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

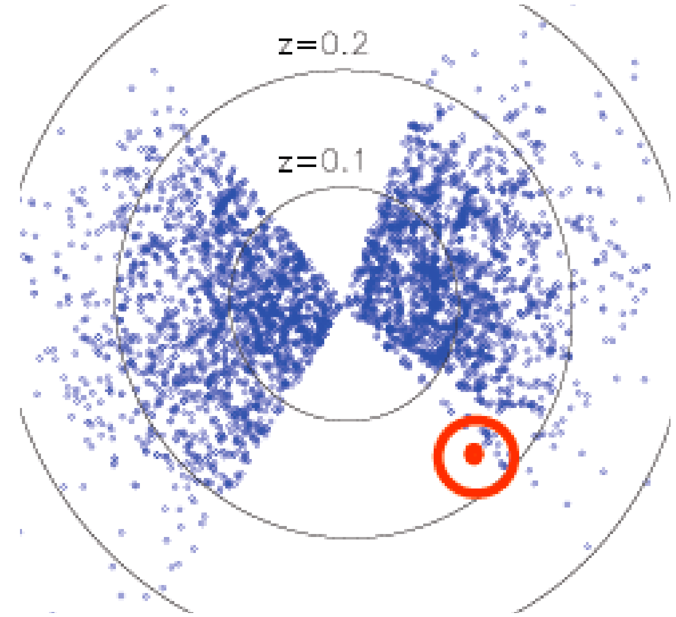


Baryon Acoustic Oscillations

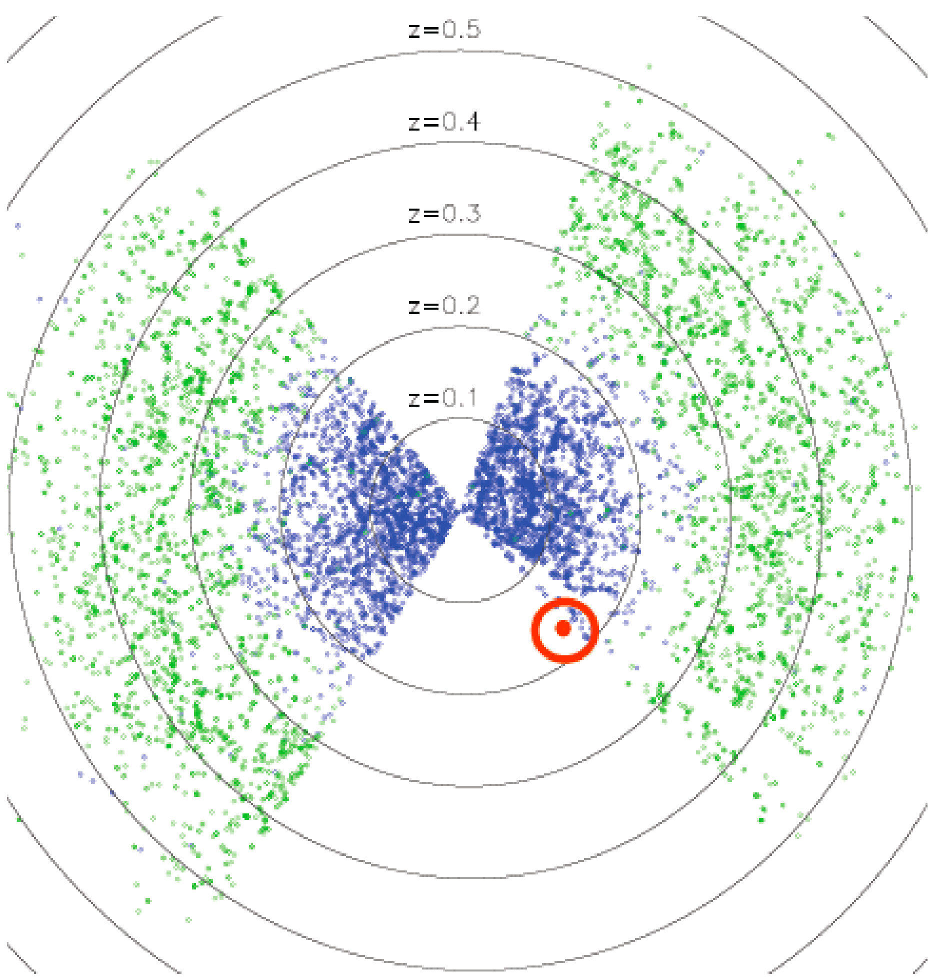
80's: Tiny surveys



BAO scale



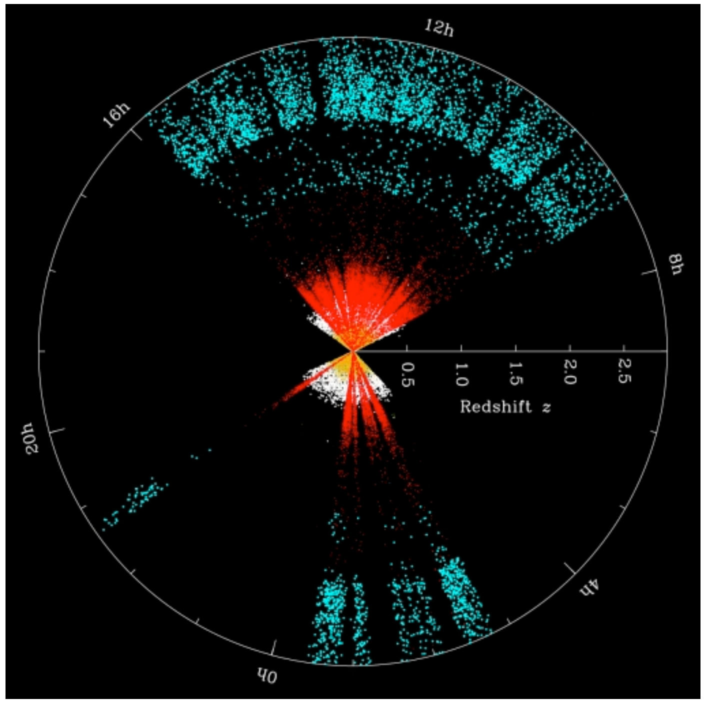
2000: Main galaxies @SDSS.
Big number, but small volume



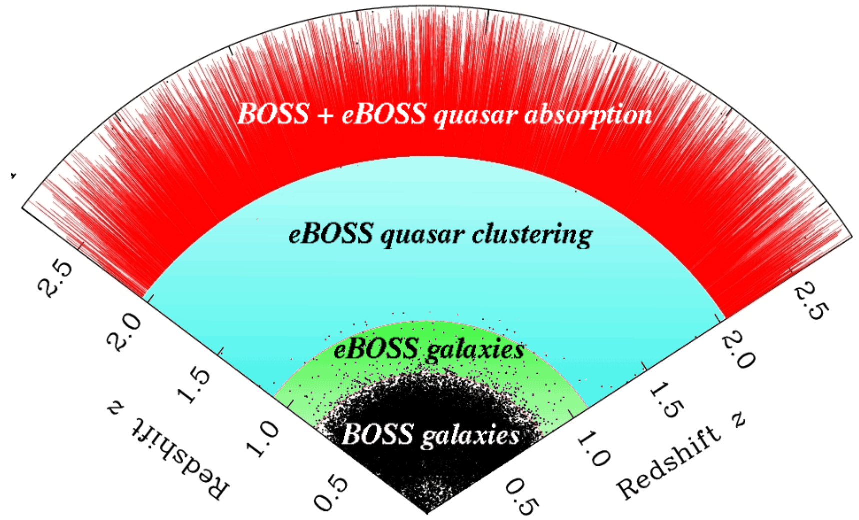
2005: Luminous Red Galaxies @ SDSS.
Big Volume: first detection of the BAO signature

Baryon Acoustic Oscillations

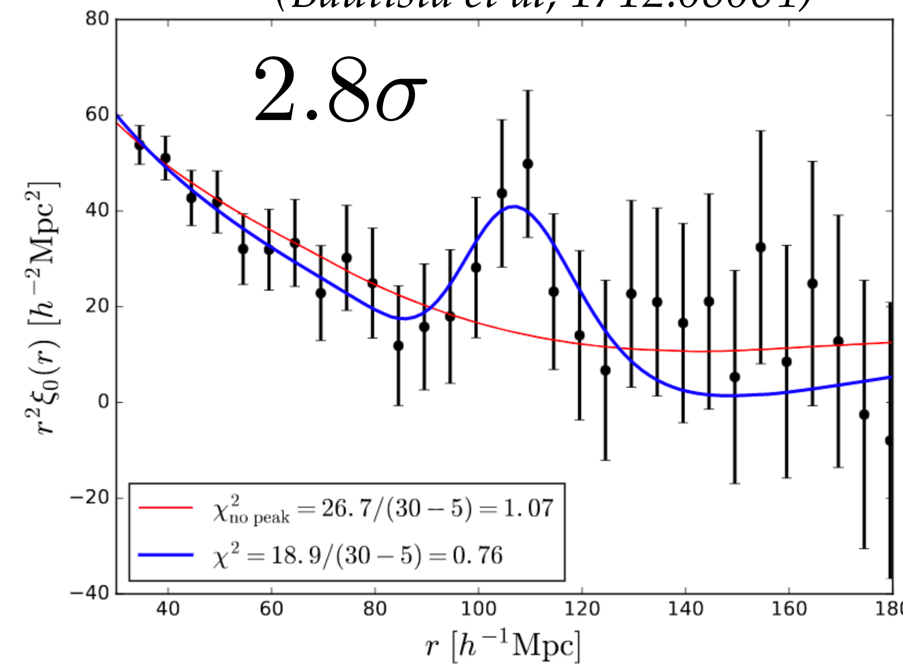
2009-2014= SDSS III

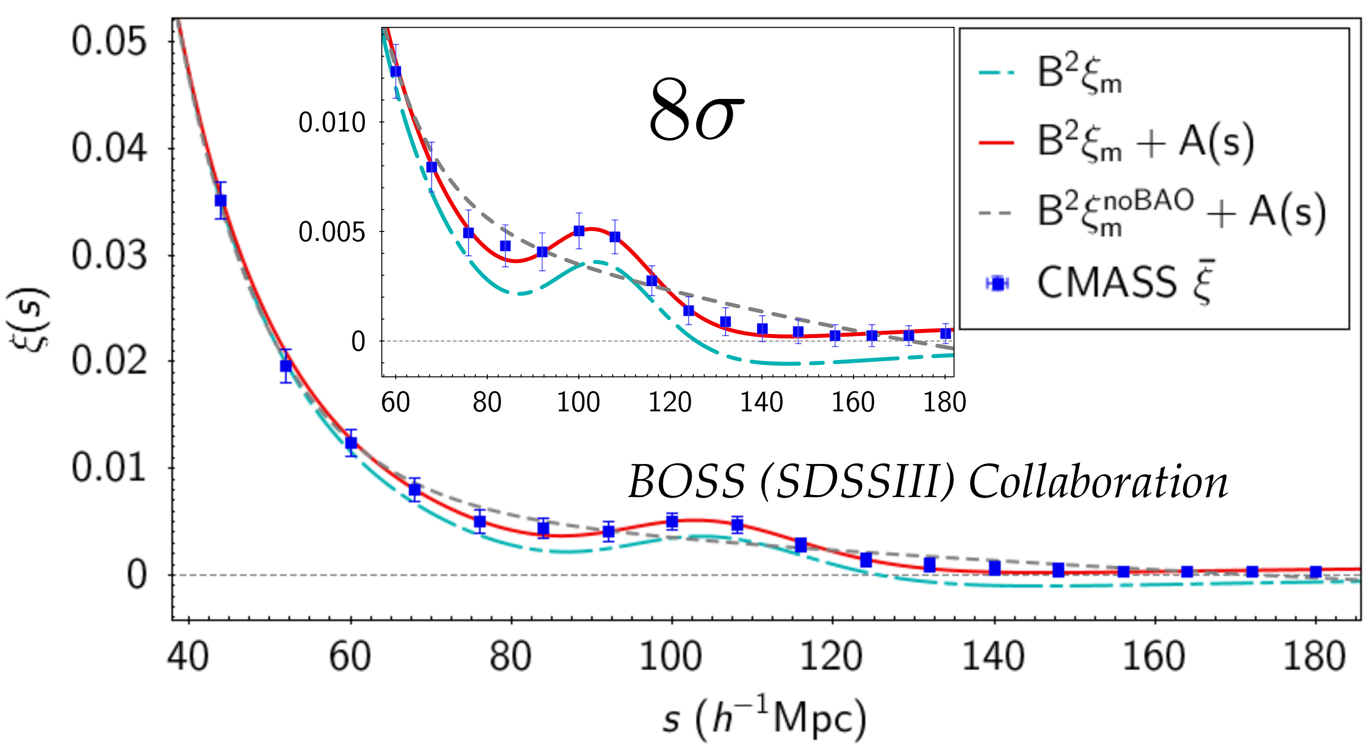


2014 – 2020= SDSS IV eBOSS

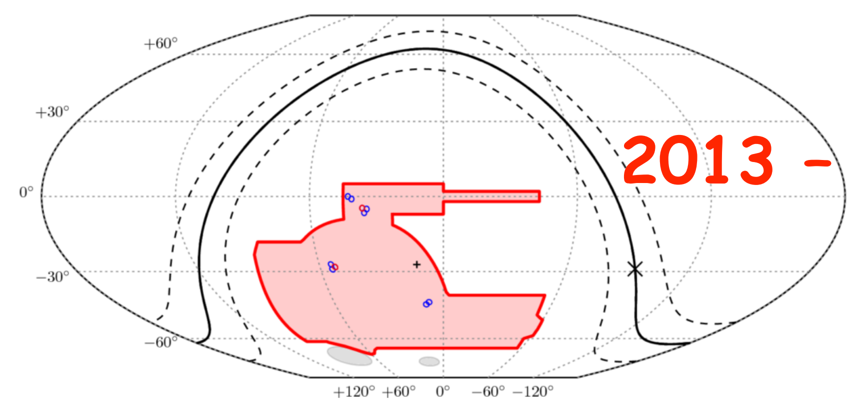


(Bautista et al, 1712.08064)



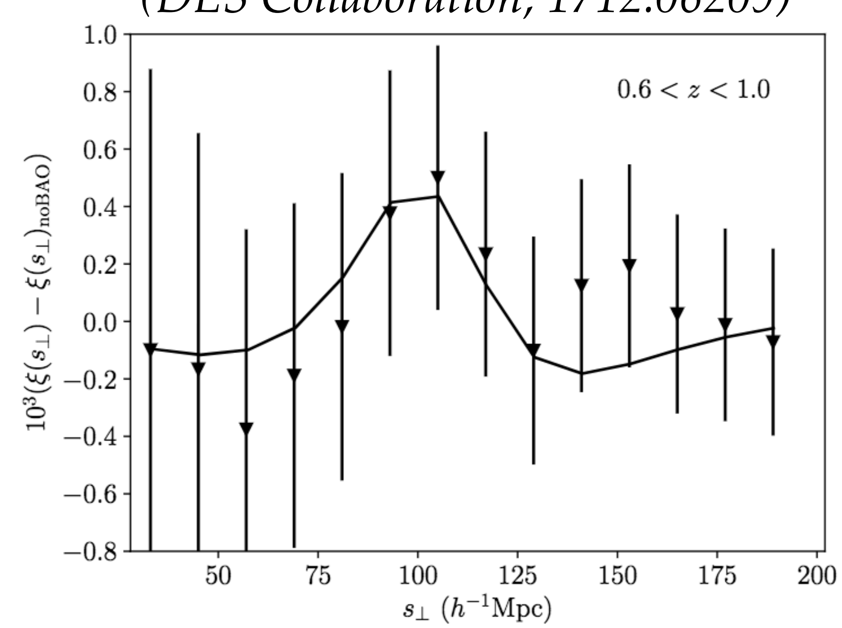


2013 – 2018= DES



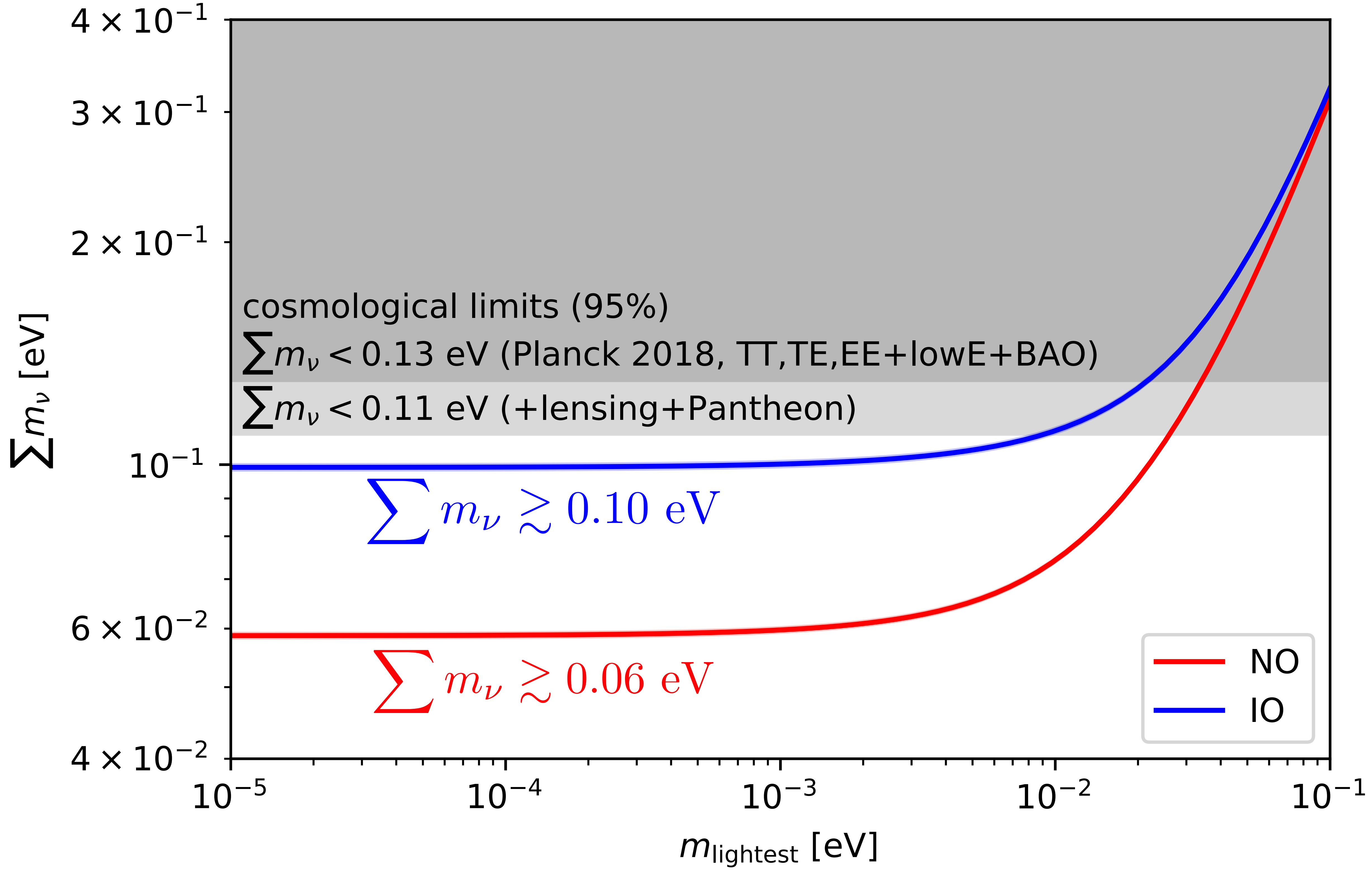
$> 2\sigma$

(DES Collaboration, 1712.06209)



Σm_ν

Planck 2018 results, 1807.06209



CMB: 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*

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

CMB: Σm_ν

Planck 2018 results, 1807.06209

Planck TTTEEE+lowT+lowE+lensing

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

+ BAO

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

+ BAO + SNIa

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

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

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

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Doggy Bag

- Take home messages

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

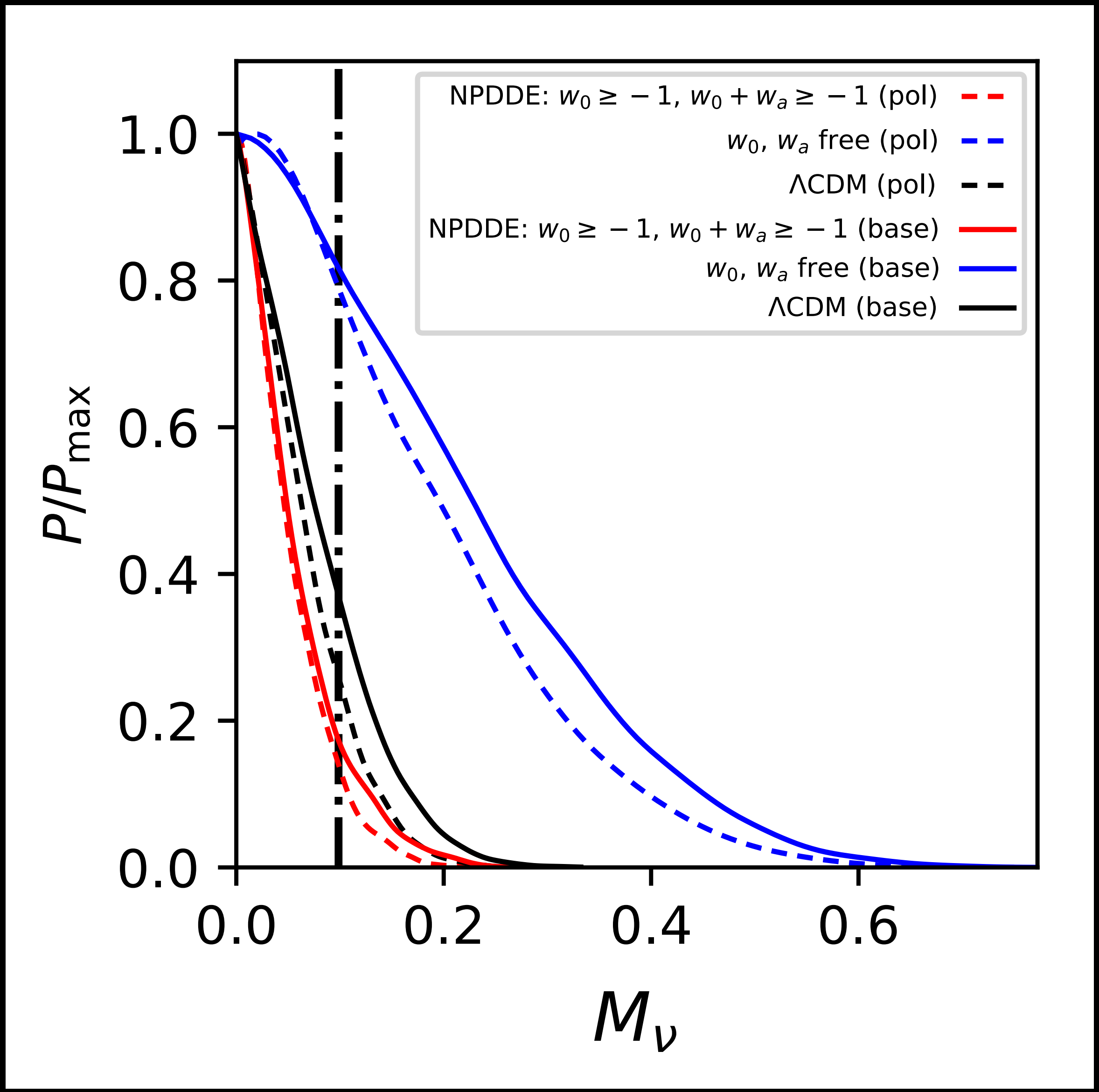
The Dark Justice Game

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

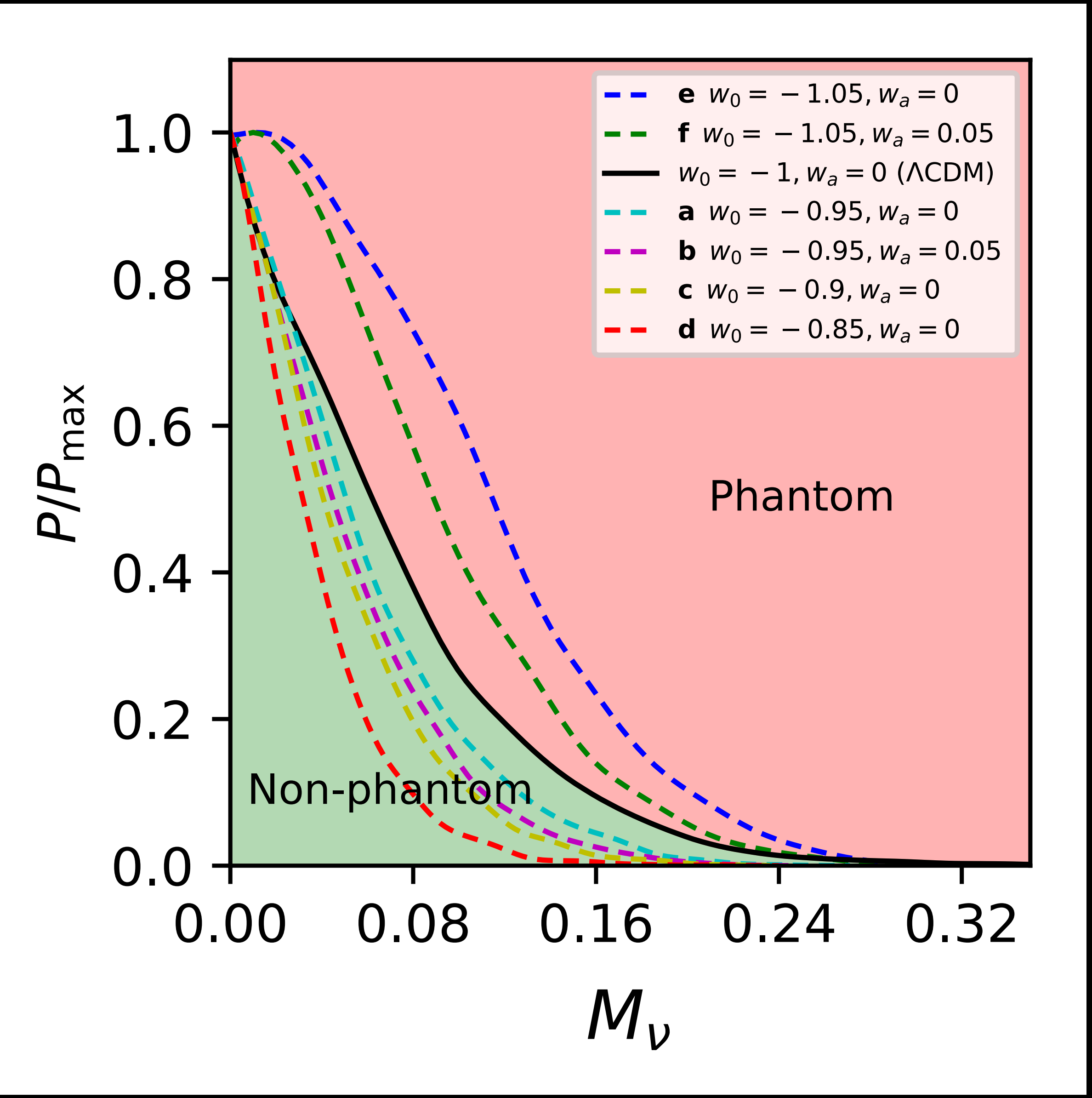
Chevalier & Polarsky'01 &Linder'03

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

NON-PHANTOM REGION



?



Vagnozzi et al PRD'18

Choudury & Choubey, JCAP'18


PHANTOM

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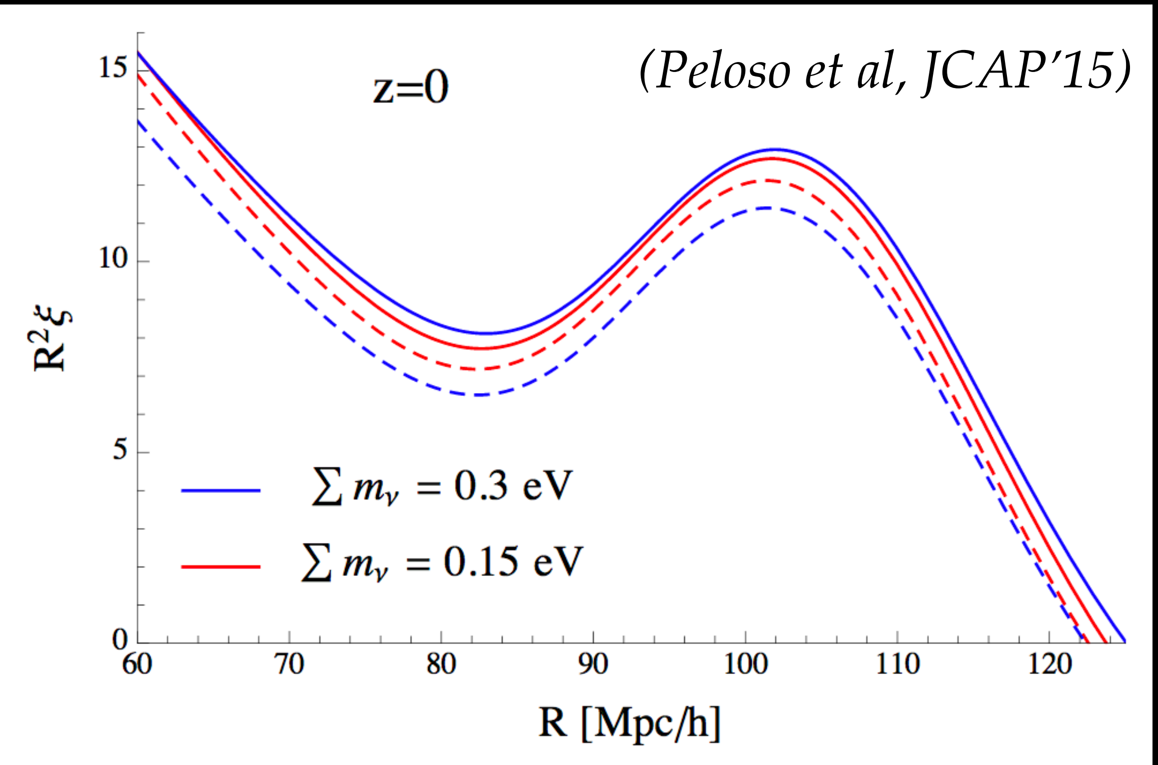
→ • Take home messages

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


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

What we know: Massive neutrinos cosmological signatures

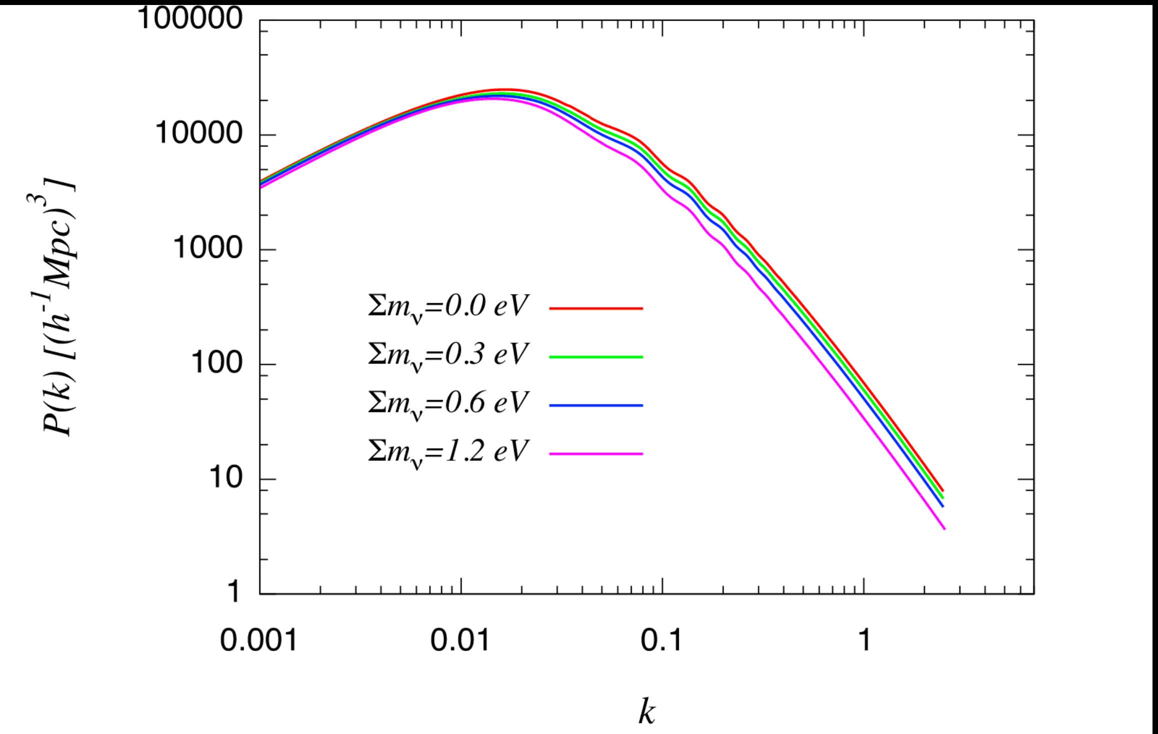


Large scale structure measurements can be interpreted either in the geometrical or shape forms

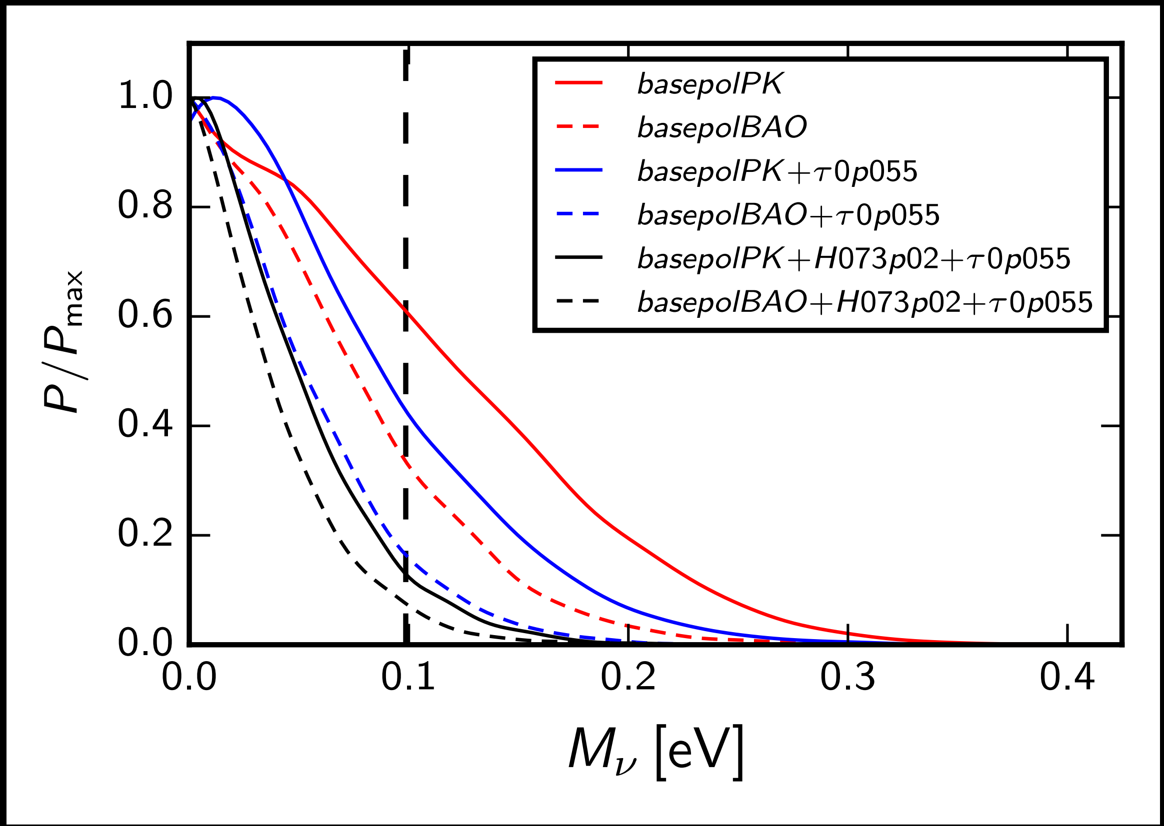
2 point correlation function

Fourier Transform

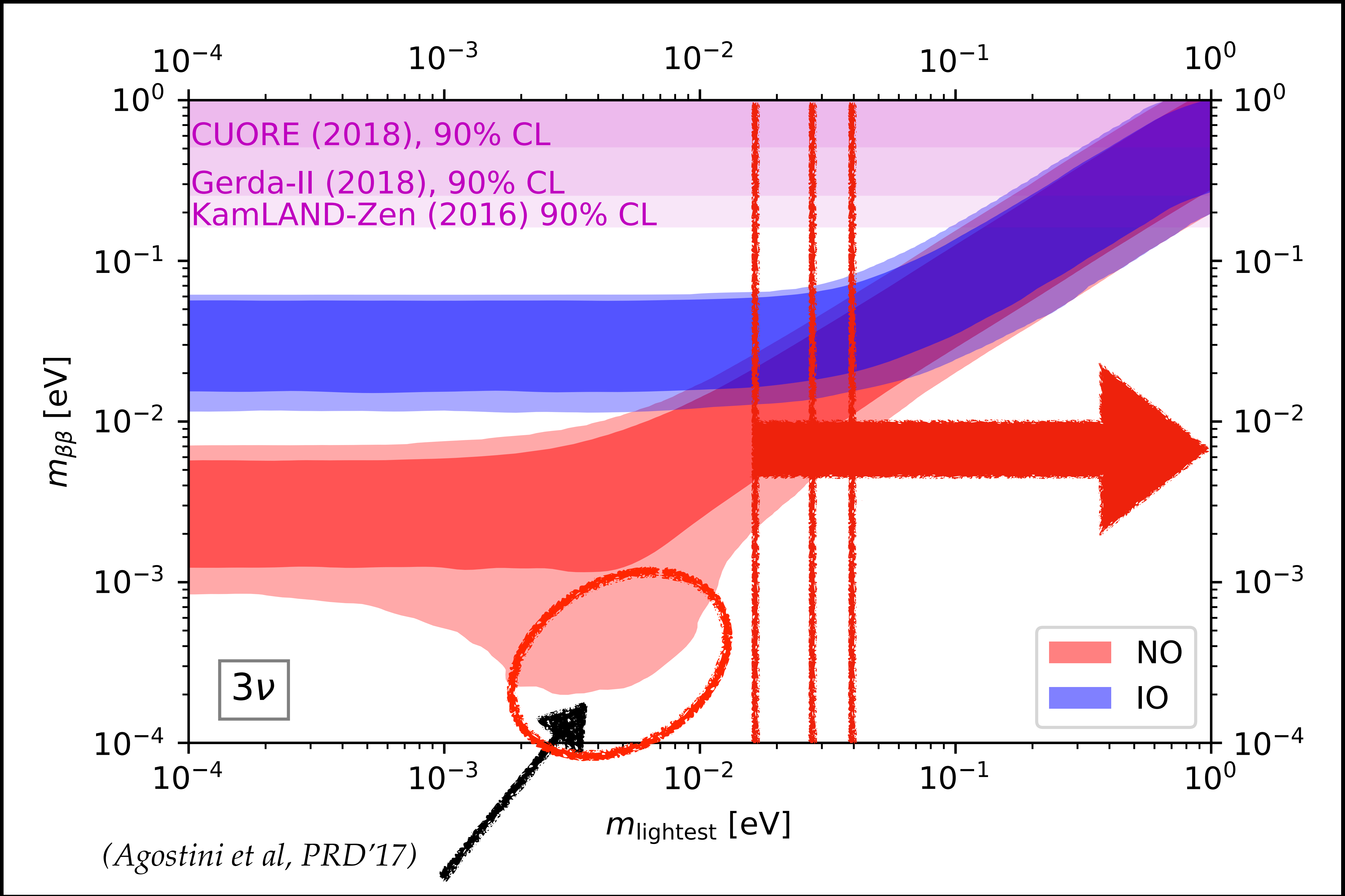
Matter power spectrum



BAO information more powerful



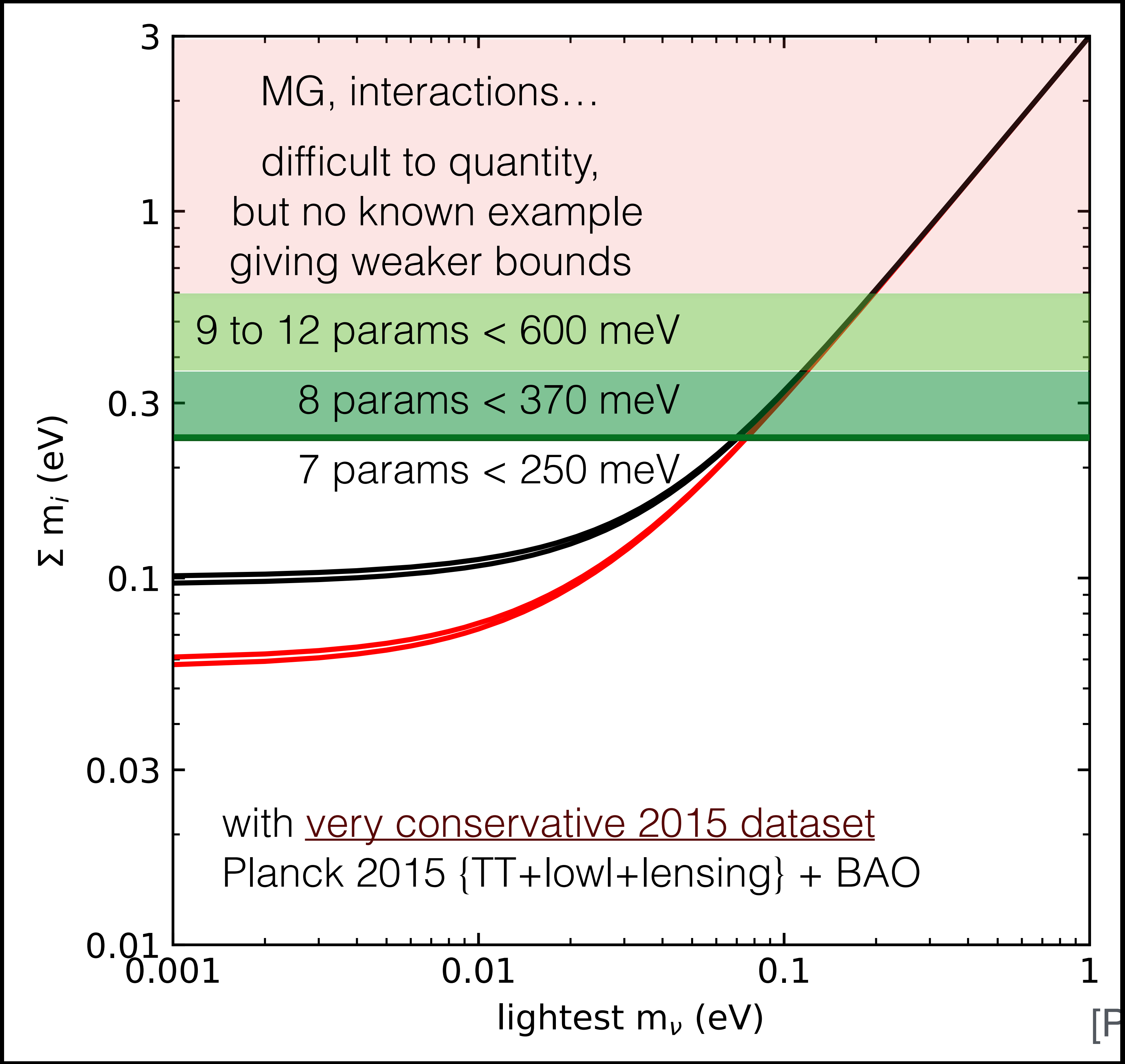
What we know



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

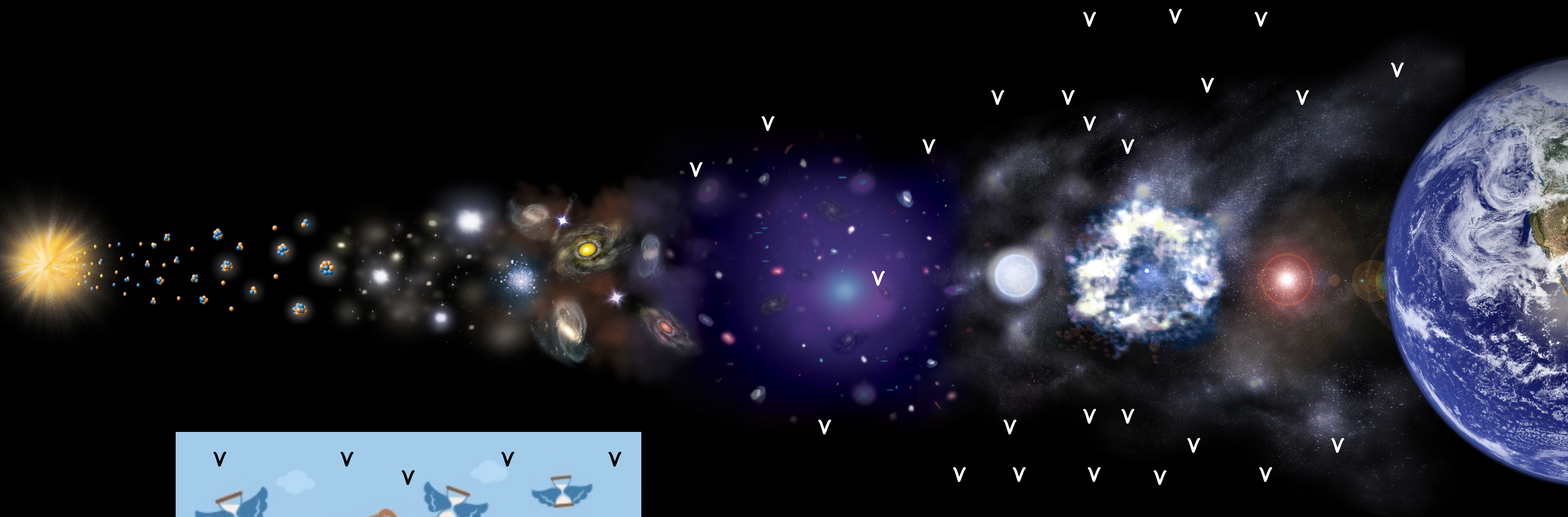
some fine tuning in the Majorana phases

What we know



J. Lesgourgues, talk at Neutrino 2018

BACKUP SLIDES



invisiblesPlus
elusives
neutrinos, dark matter & dark energy physics

IFIC INSTITUT DE FISICA CORPUSCULAR

CSIC

VNIVERSITAT DE VALÈNCIA

EXCELENCIA SEVERO OCHOA

What we know: Massive neutrinos cosmological signatures

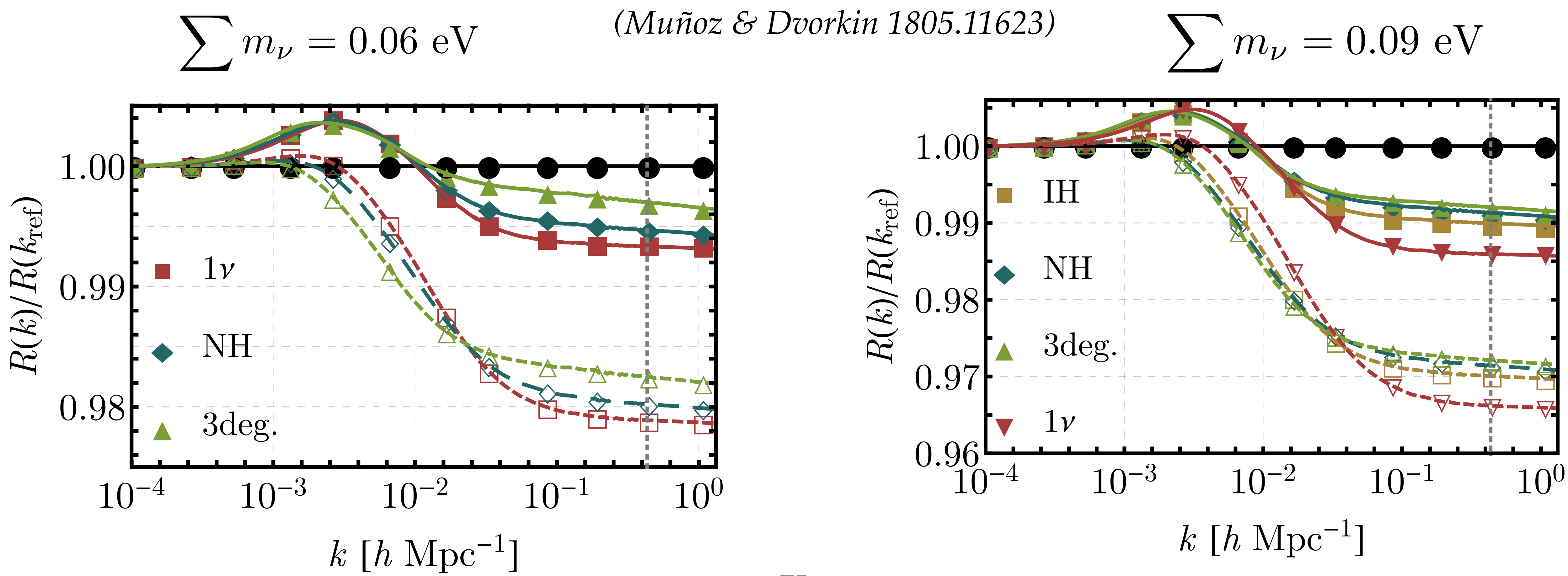
@LSS: Caveats, BIAS!

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

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

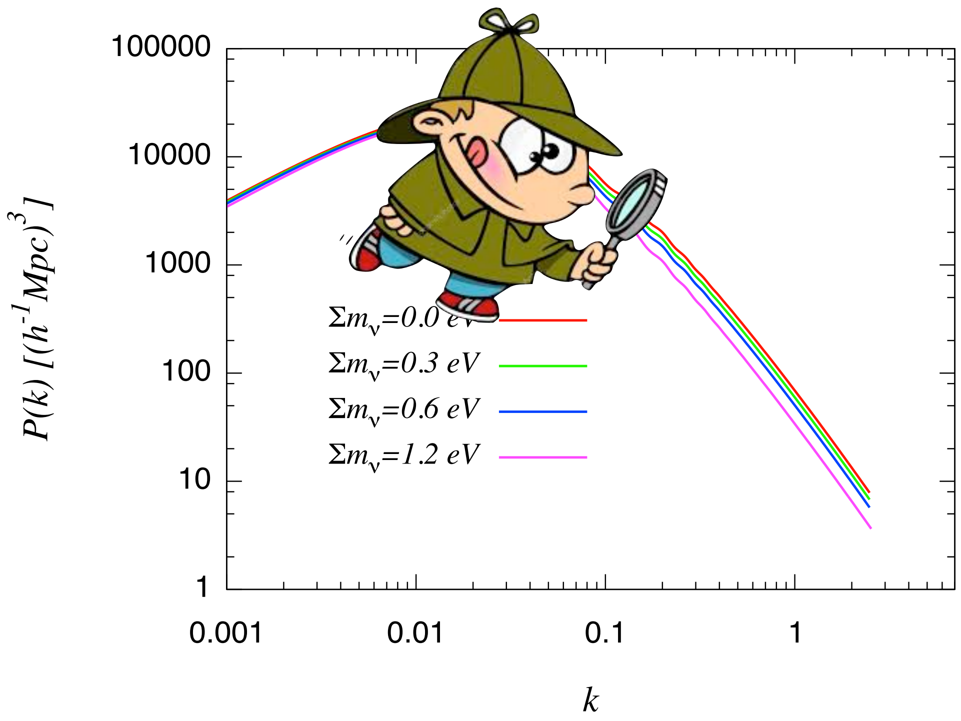
Neutrinos themselves induce a scale-dependent bias *(LoVerde & Zaldarriaga; Castorina et al)*

(Muñoz & Dvorkin 1805.11623)

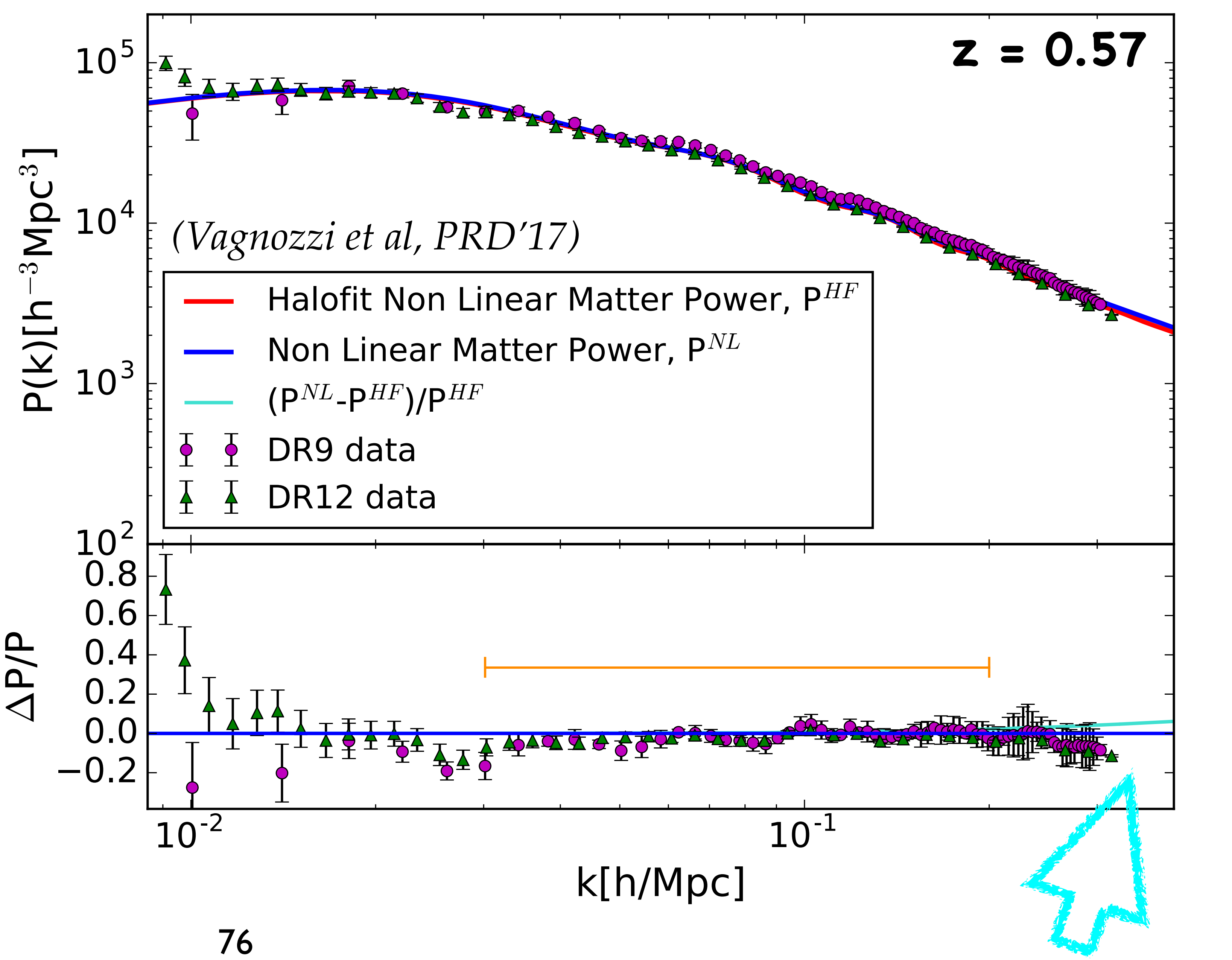


What we know: Massive neutrinos cosmological signatures

@LSS: Caveats, NON-LINEARITIES

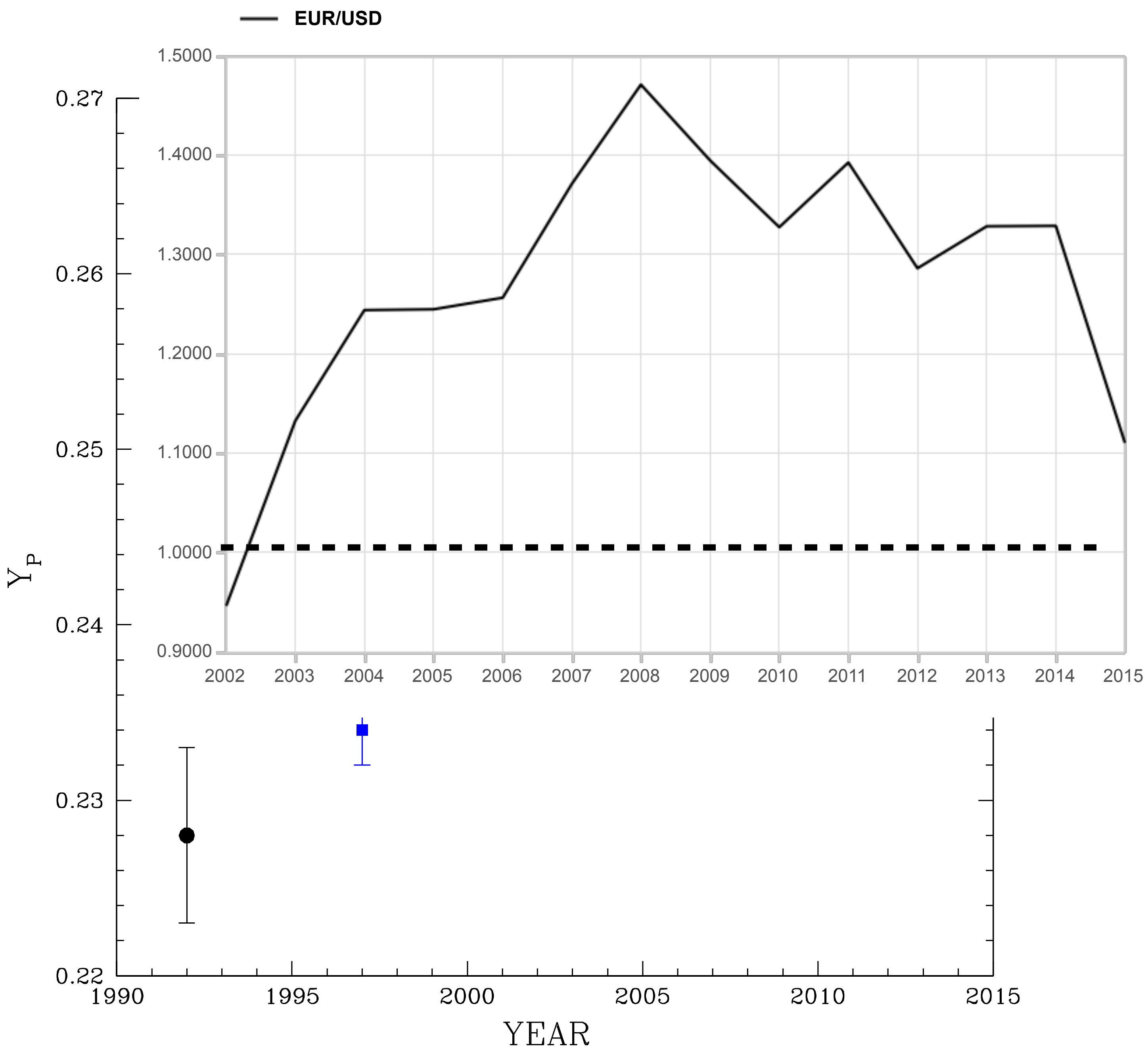


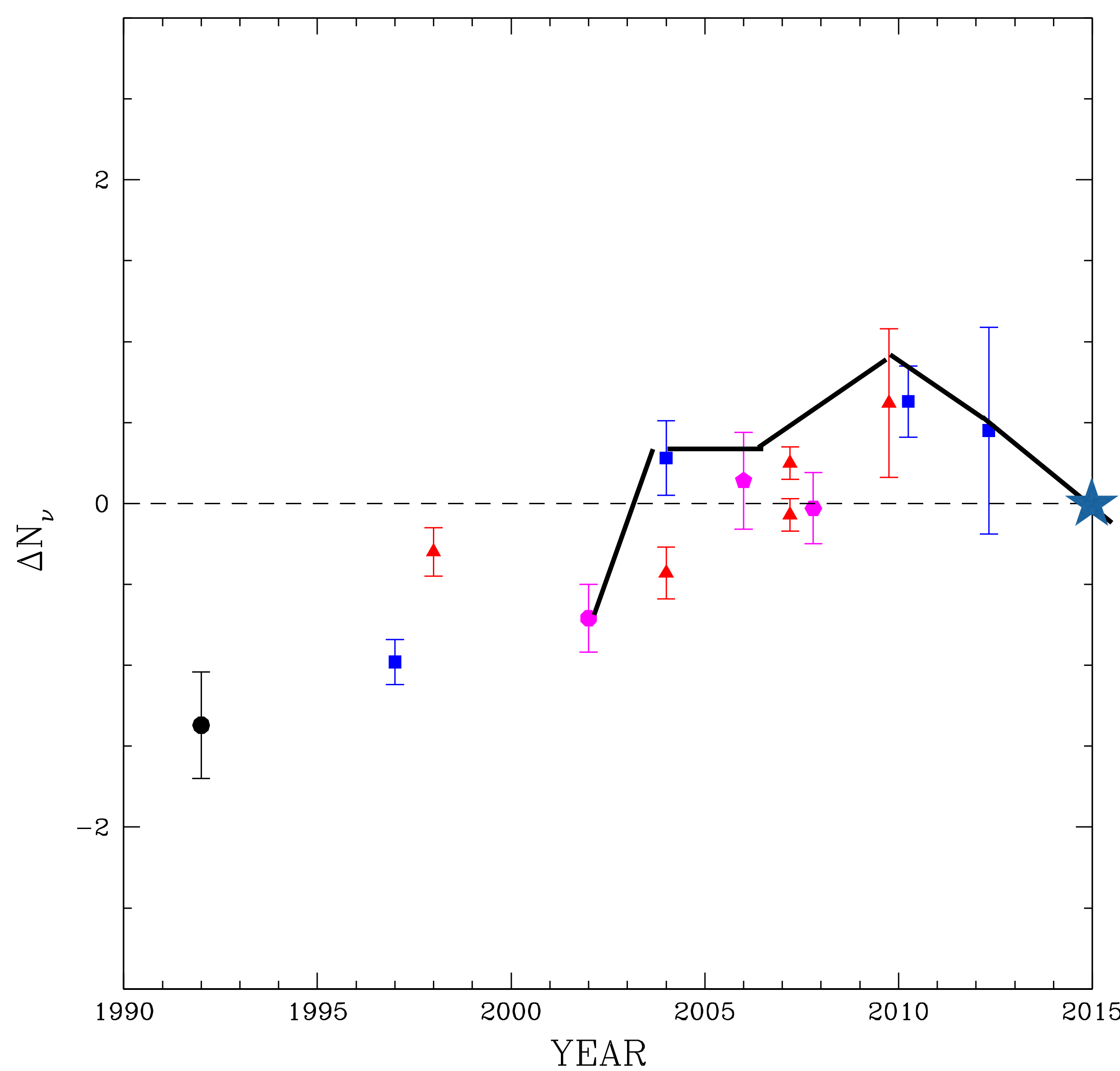
Beyond a given scale k_{nl}, linear perturbation theory breaks down!



Big Bang Nucleosynthesis: N_{eff}

Chronology, over some years, of the published observational determinations of Y_P: the extracted value of ΔN_{eff} mirrors the helium fraction Y_P.





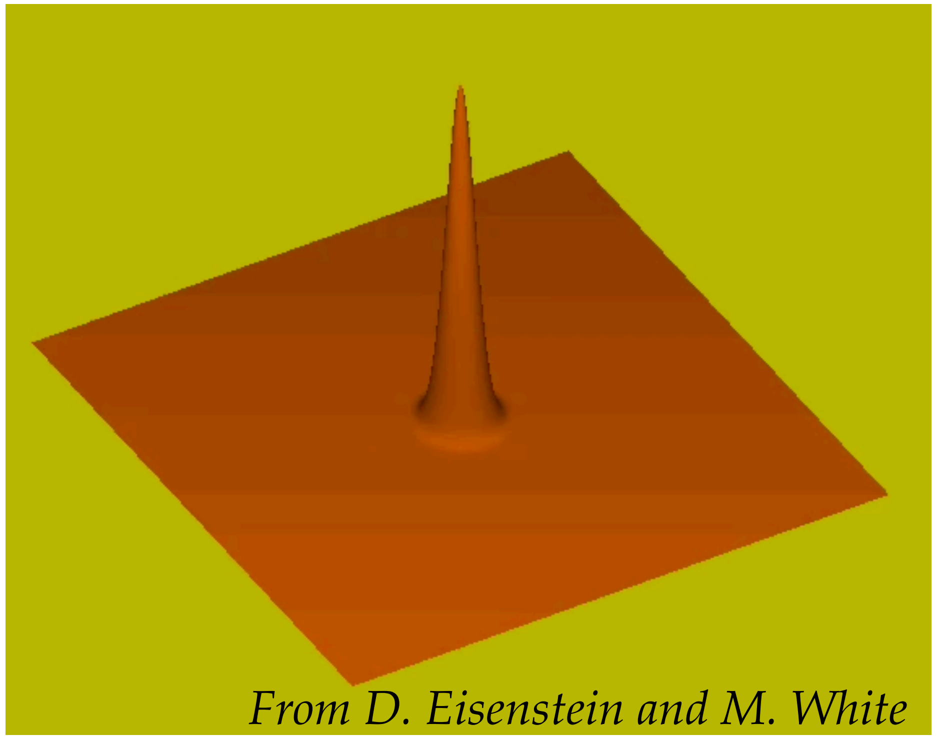
(G. Steigman'12)

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 <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)*

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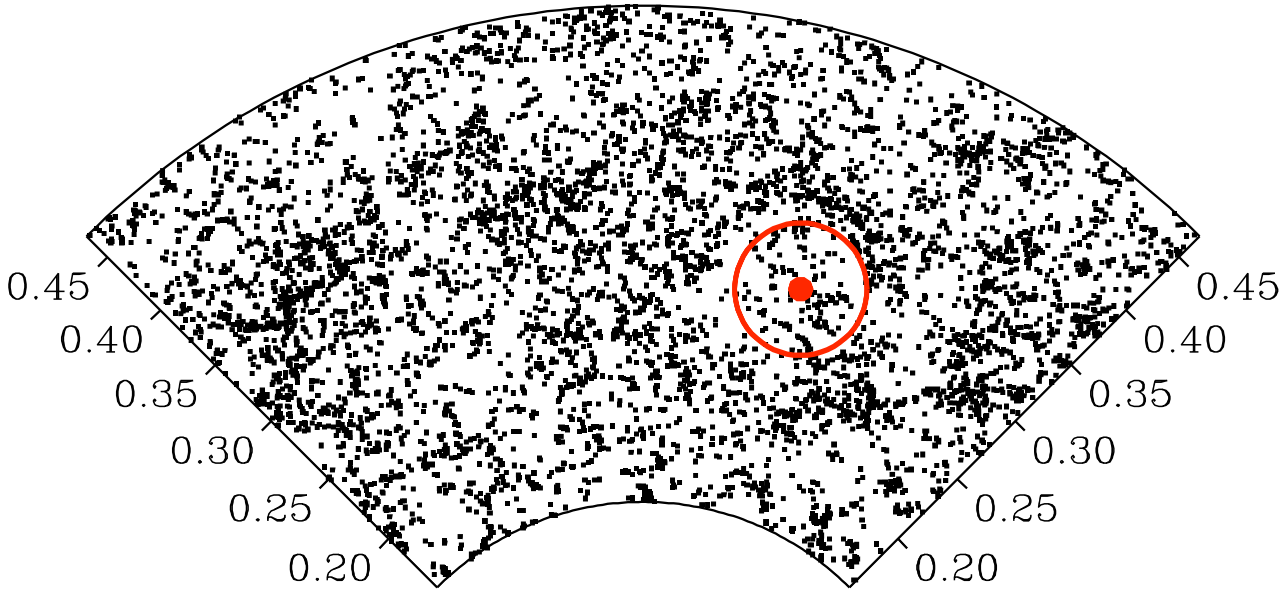
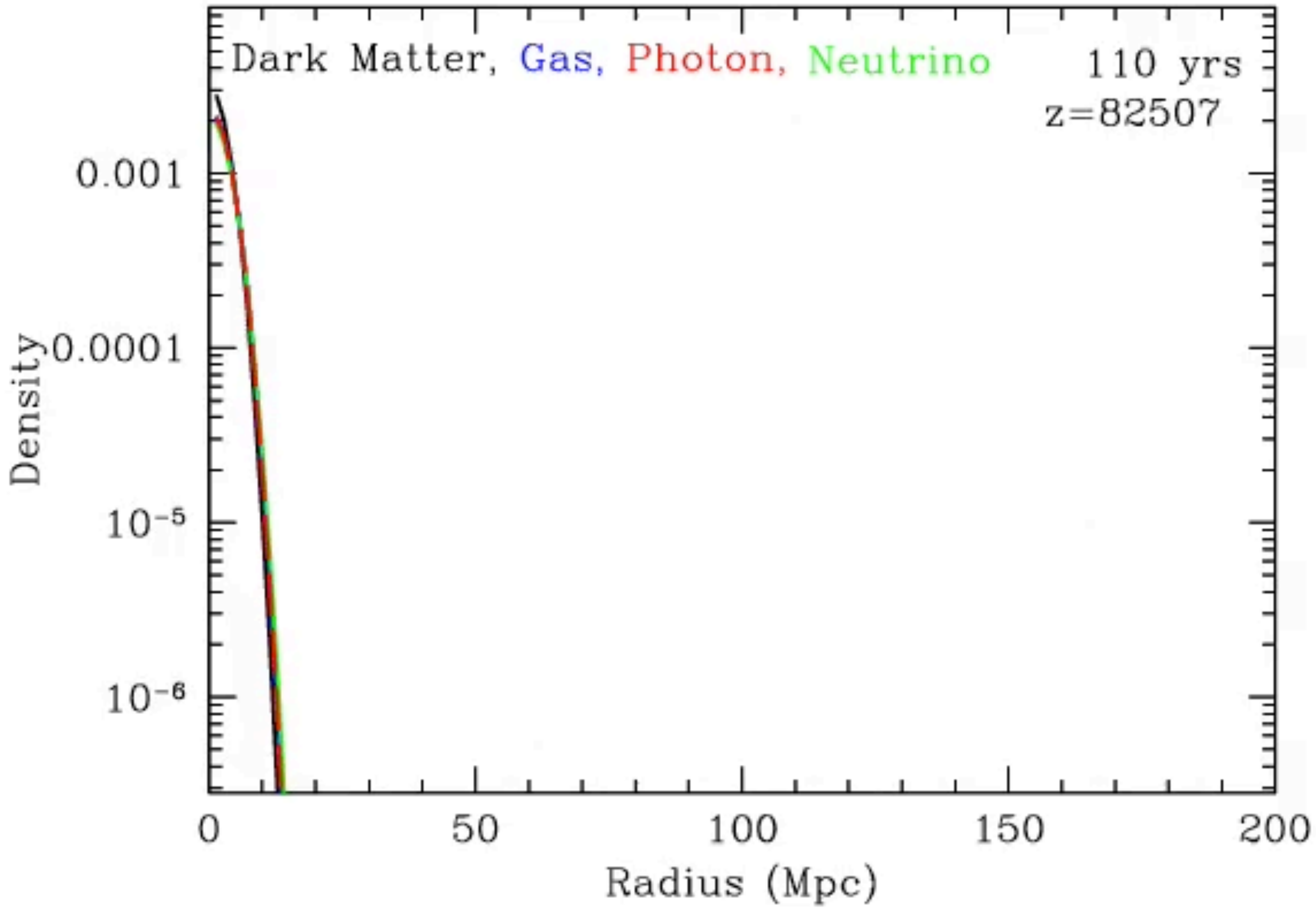
(Planck 2018 results)

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



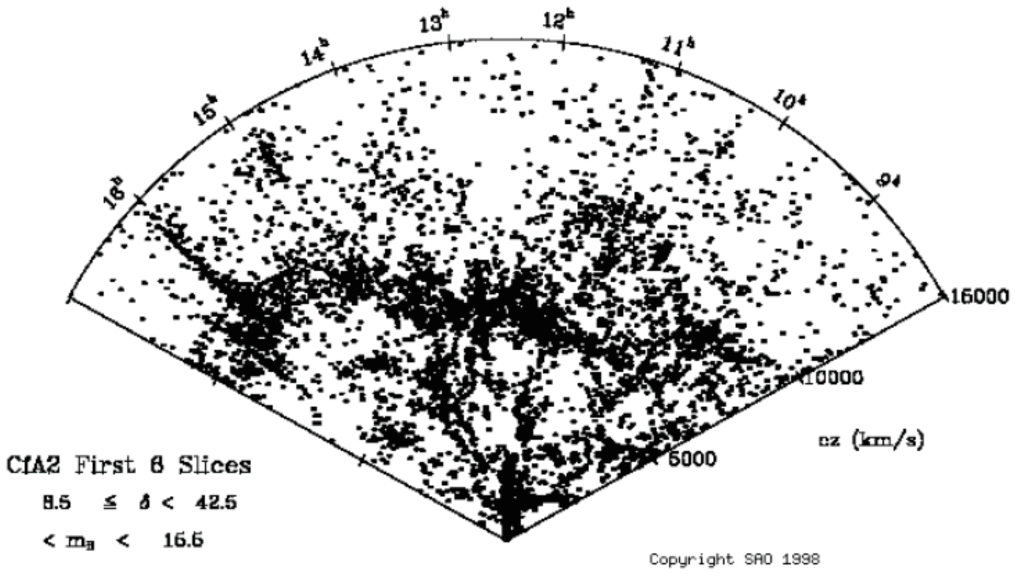
Baryon Acoustic Oscillations



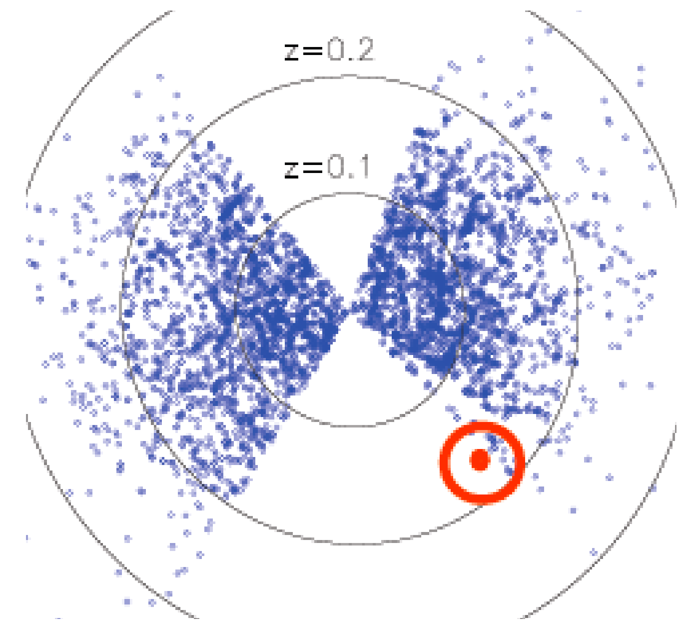
From D. Eisenstein and M. White

Baryon Acoustic Oscillations

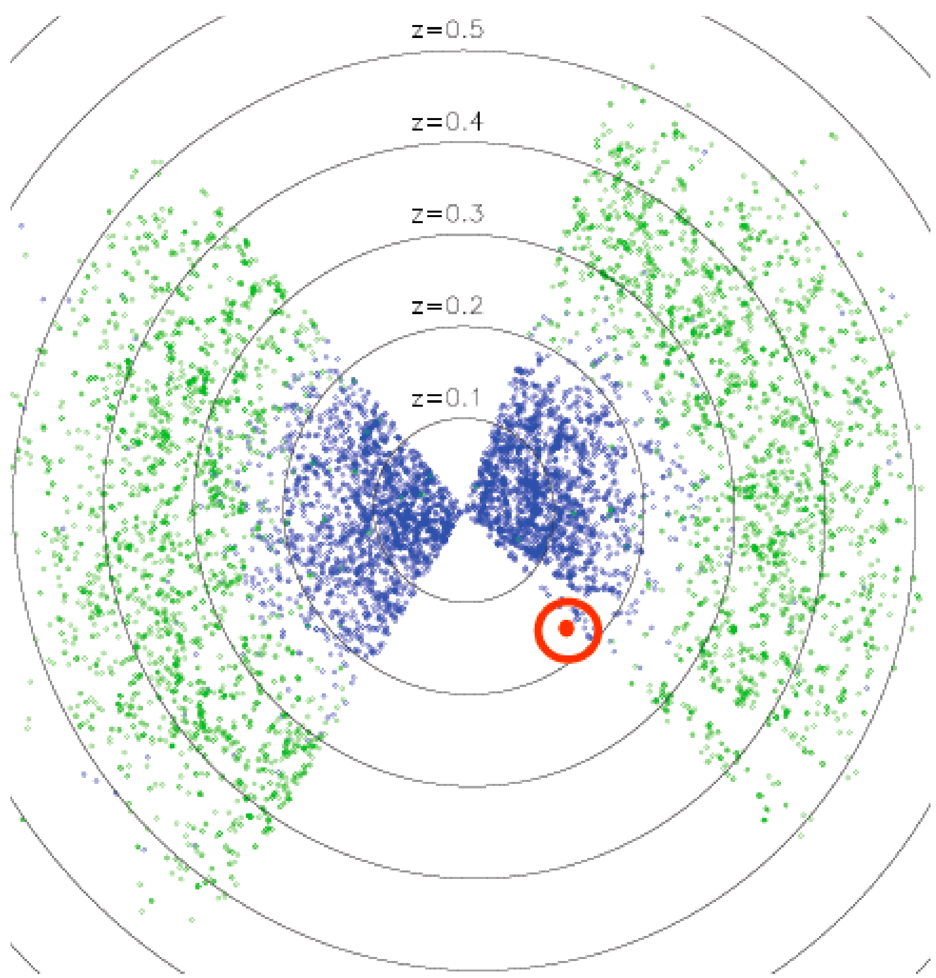
80's: Tiny surveys



BAO scale



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

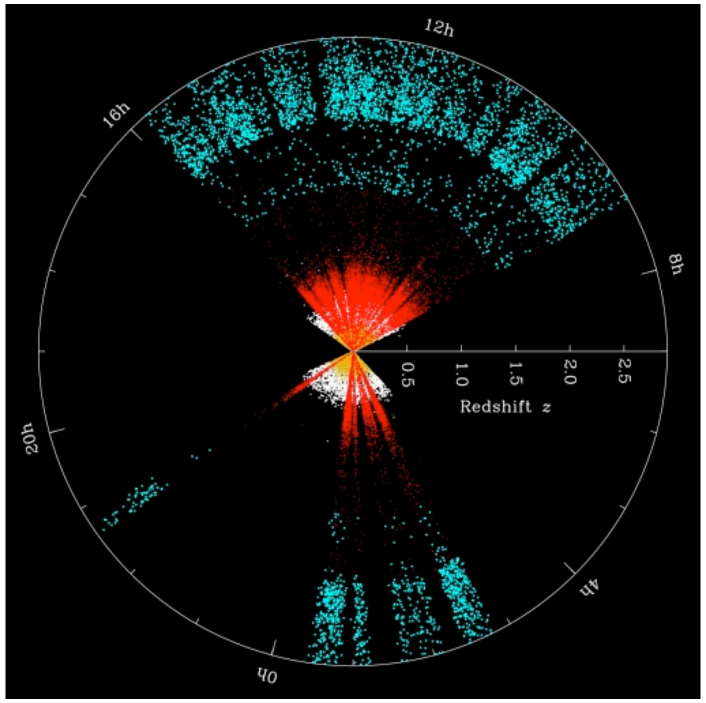


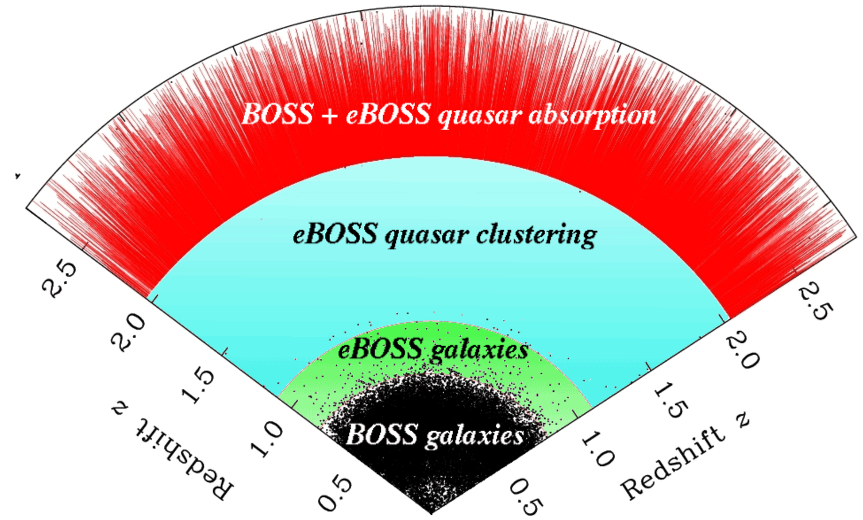
2005: Luminous Red Galaxies @ SDSS.
Big Volume: first detection of the BAO signature

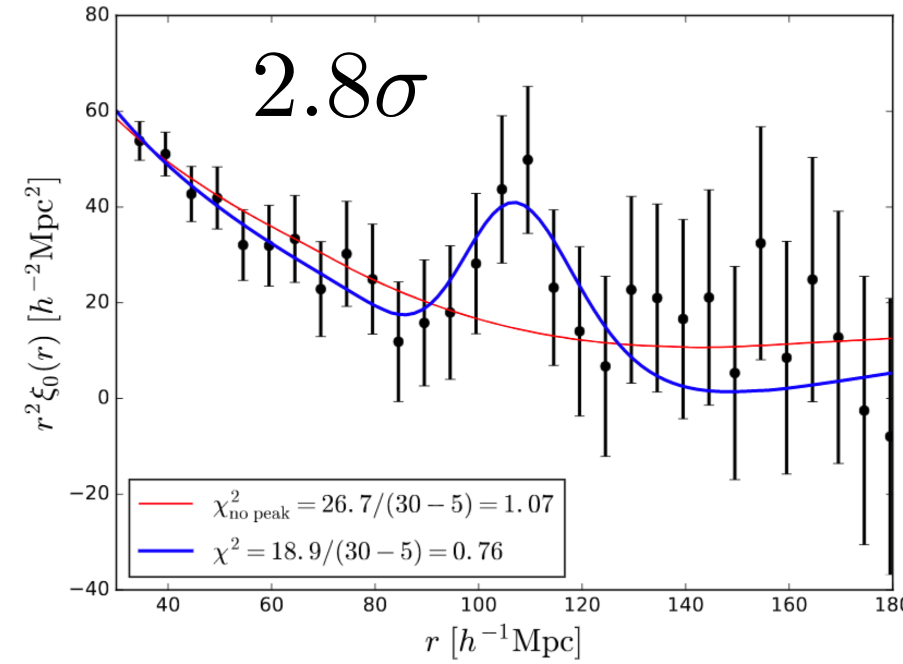
Baryon Acoustic Oscillations

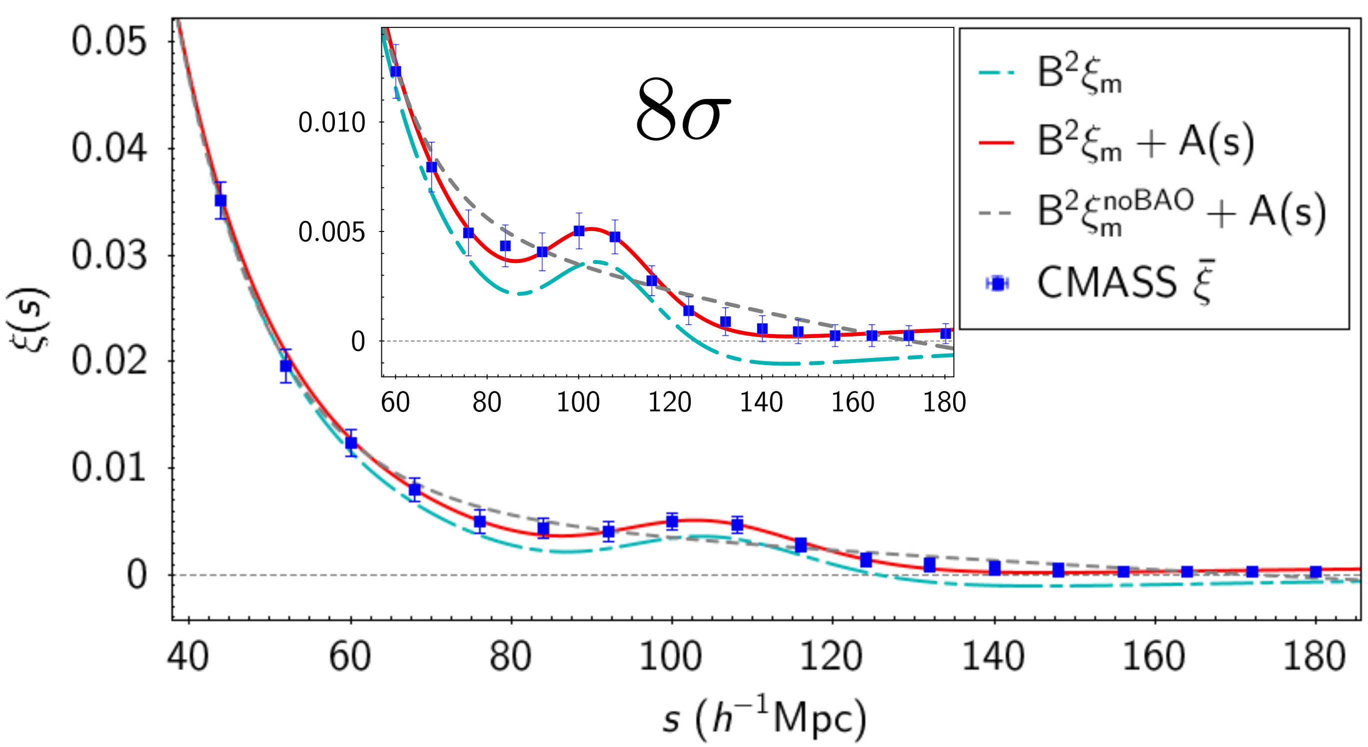
2009-2014= SDSS III

2014 – 2020= SDSS IV eBOSS

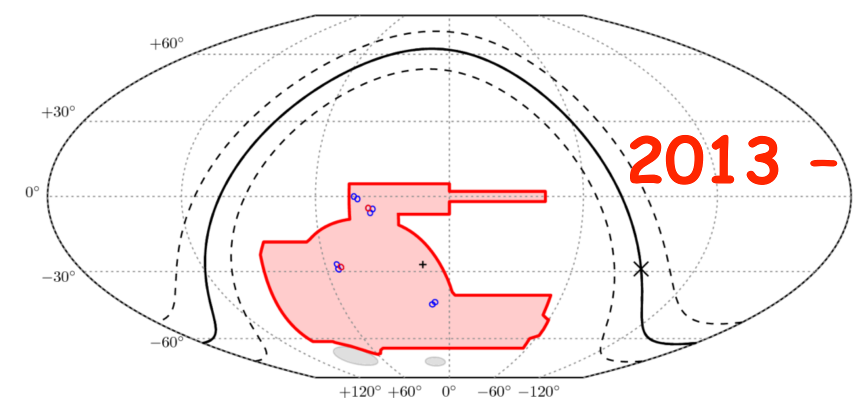




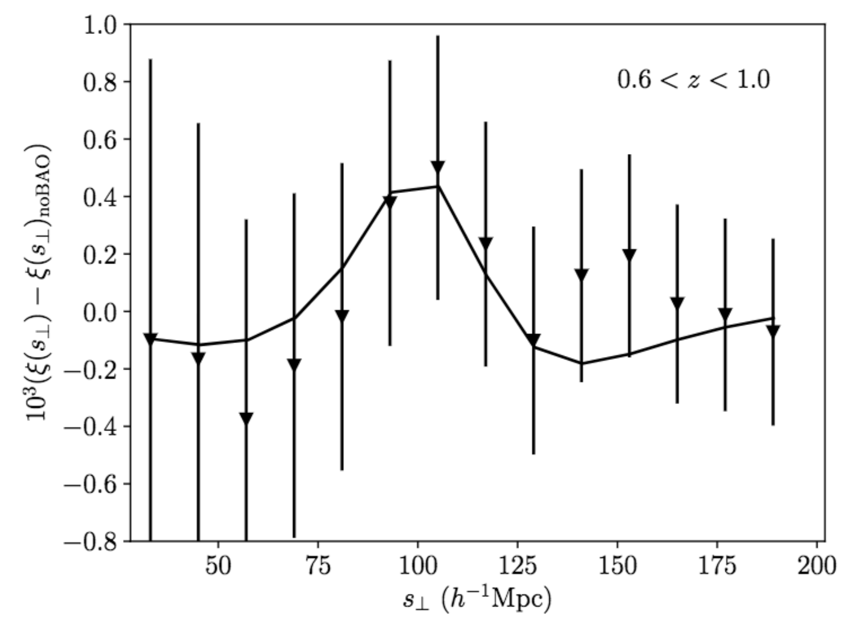




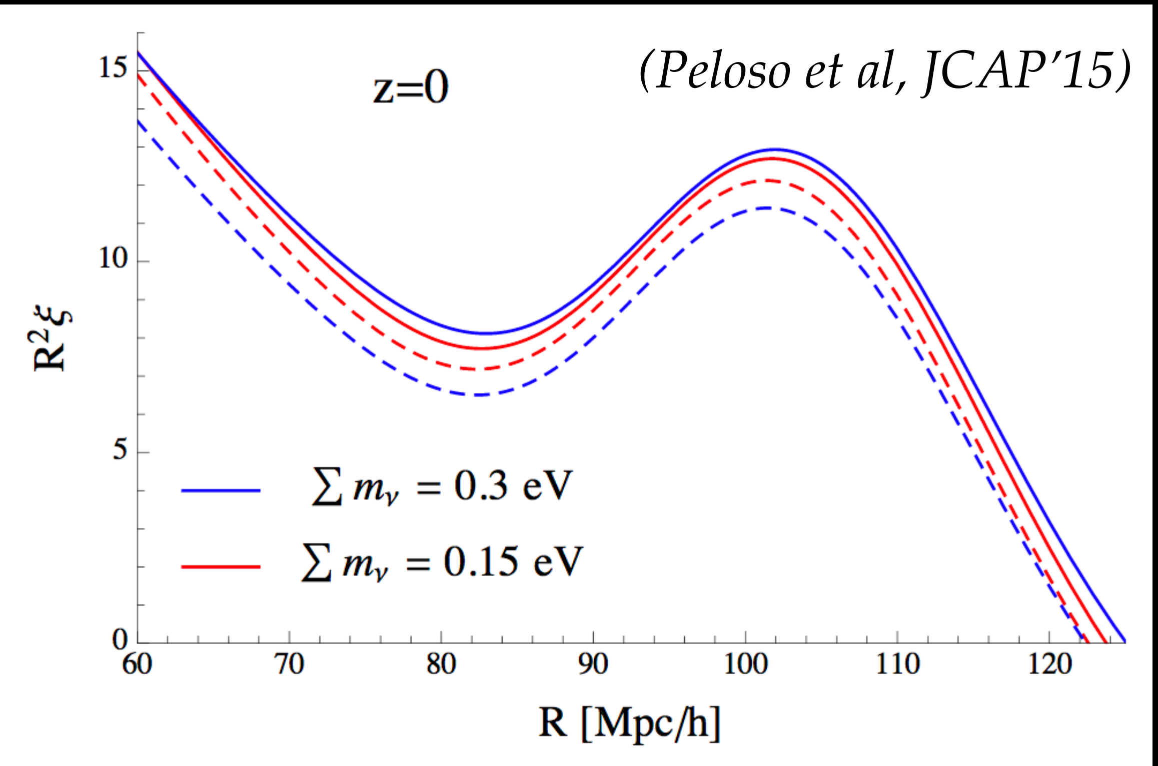
2013 – 2018= DES



$> 2\sigma$



Large scale structure and m_ν



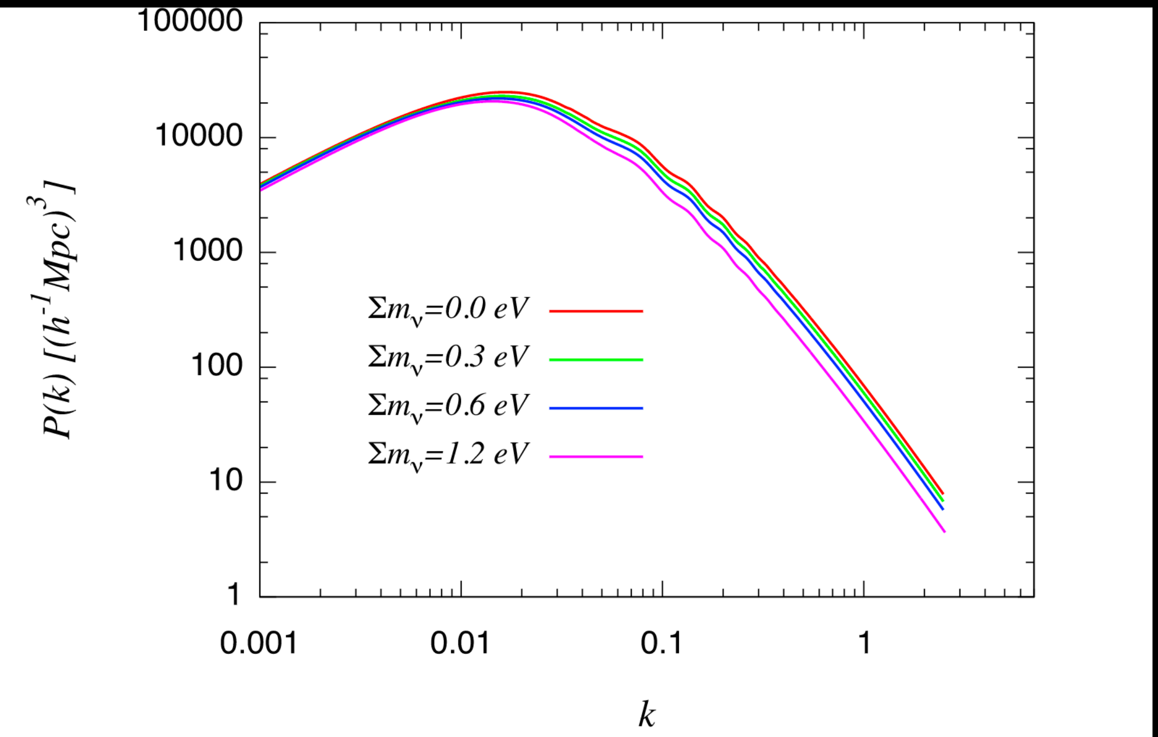
Large scale structure measurements can be interpreted either in the geometrical or shape forms

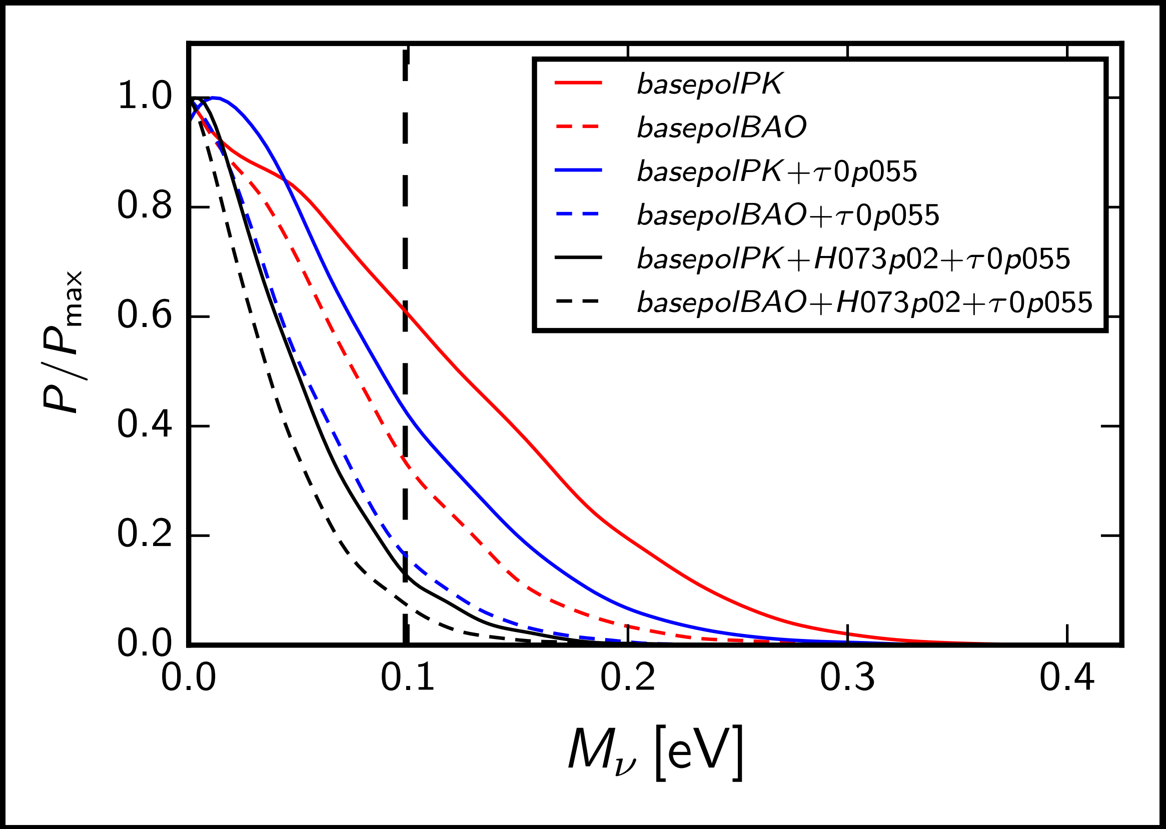
2 point correlation function

Fourier Transform

Matter power spectrum

BAO information still more powerful



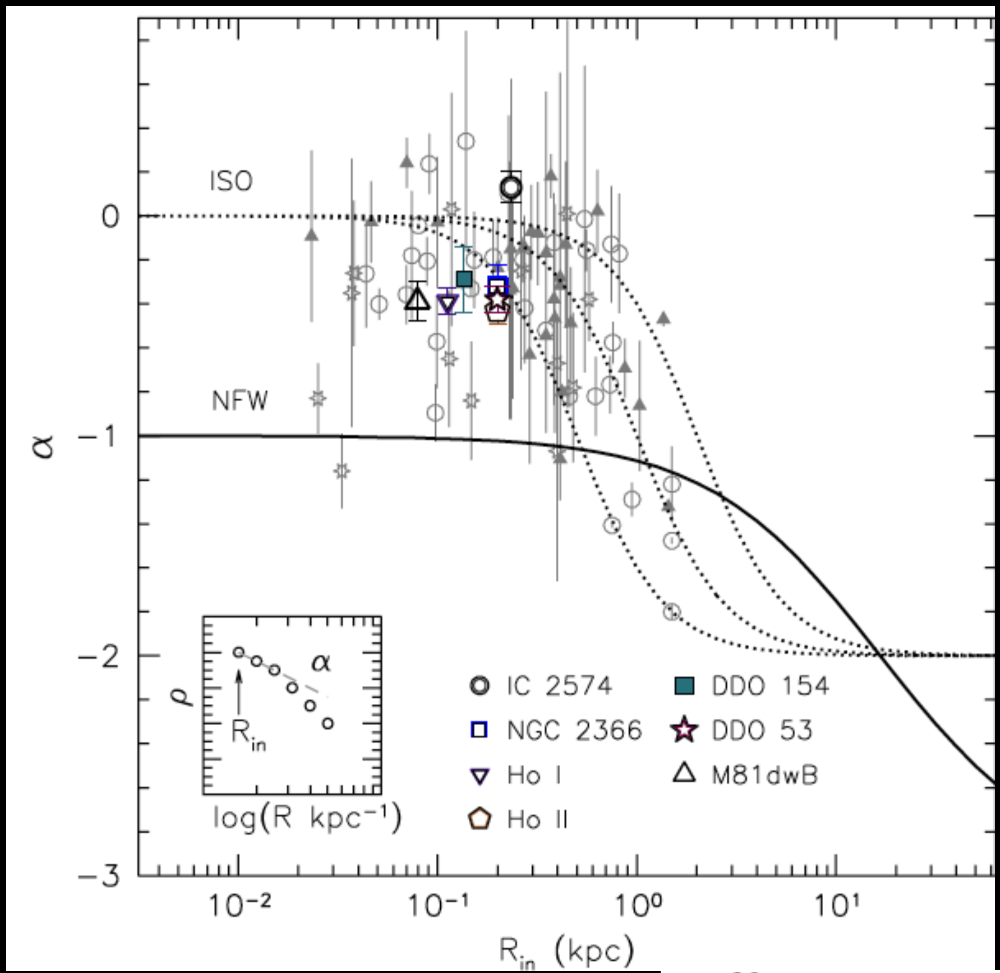


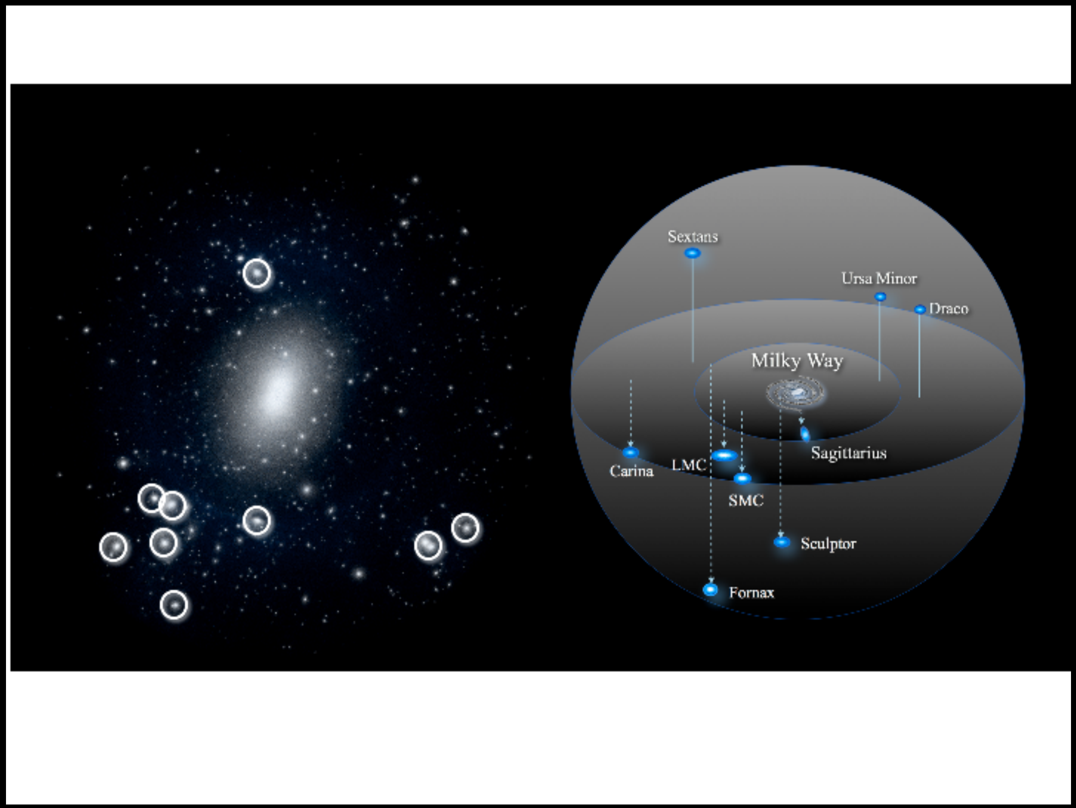
One can look for
(*sterile*) neutrinos in
something not so

shiny and bright....


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

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



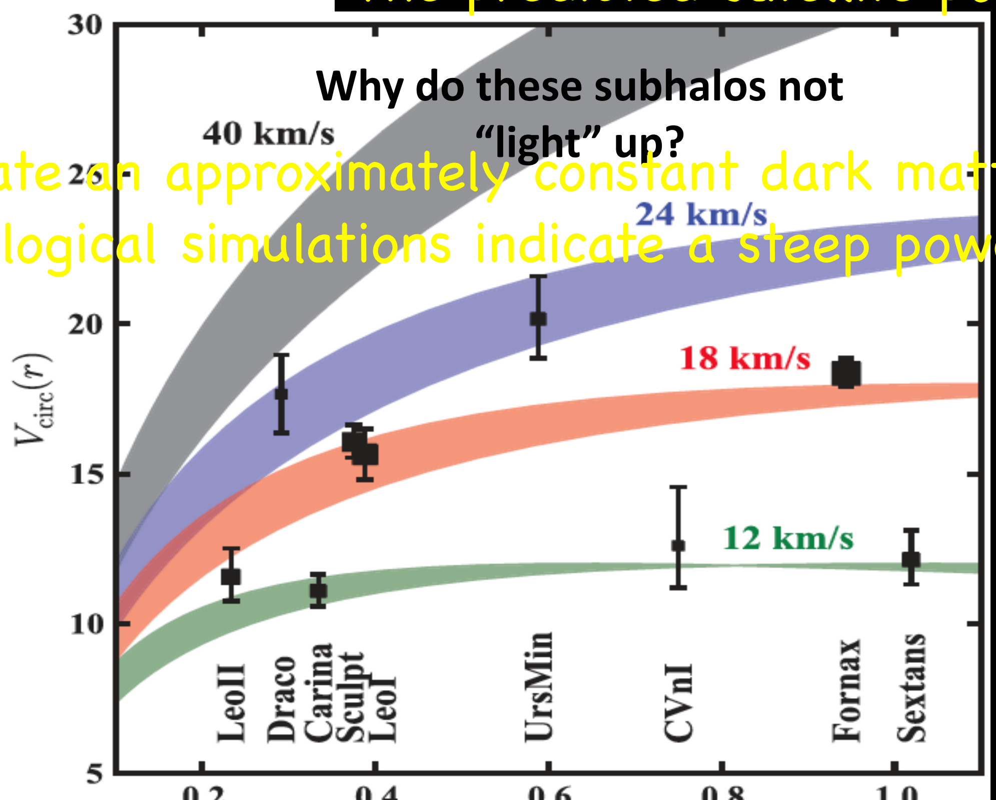


Missing satellite problem

The predicted satellite population far exceeds the observed one

Core/Cusp problem

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



Too big to fail (TBTF) problem

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

(Boylan et al, MNRAS'11)

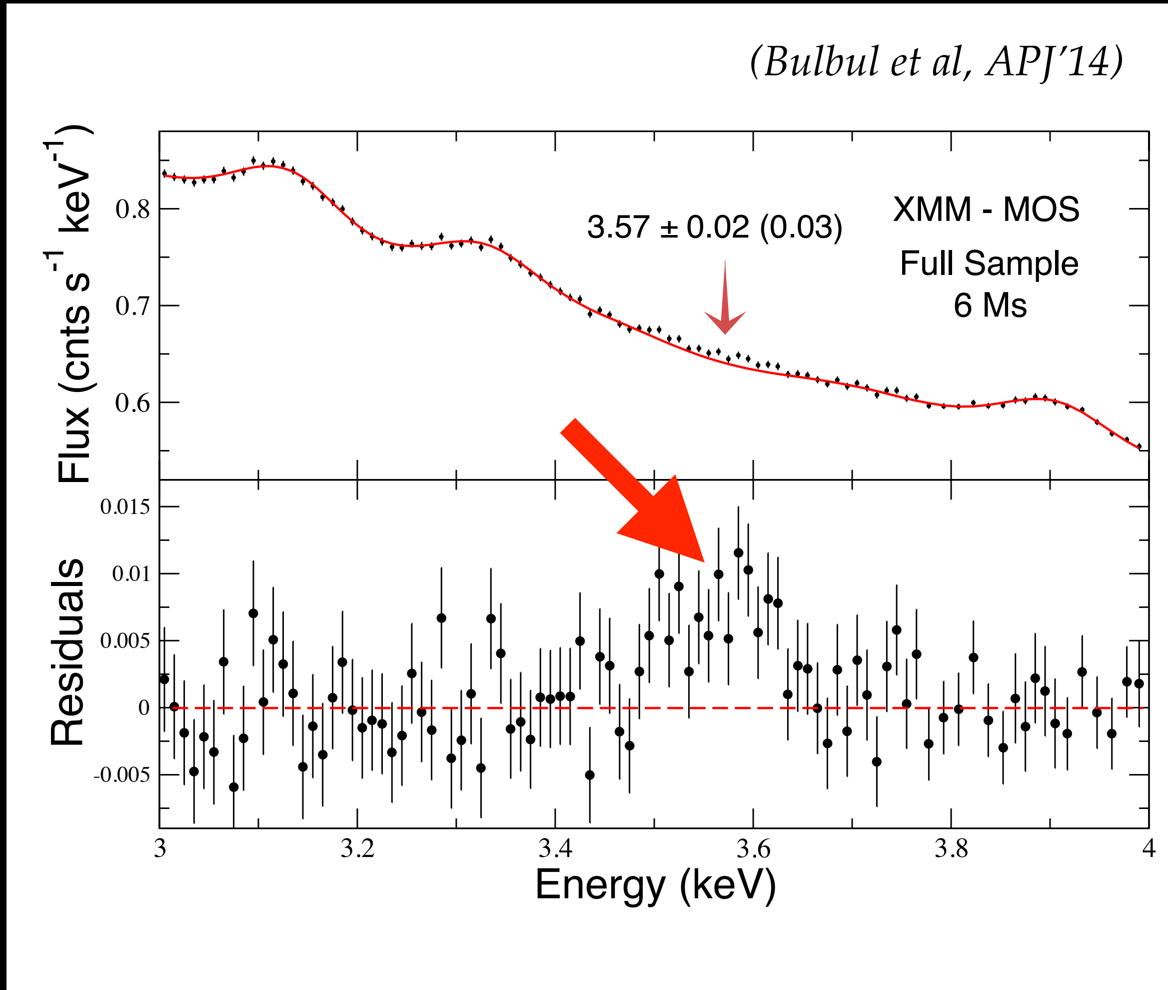
Sterile keV (0.01 m_e) neutrino as a warm dark matter candidate?

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

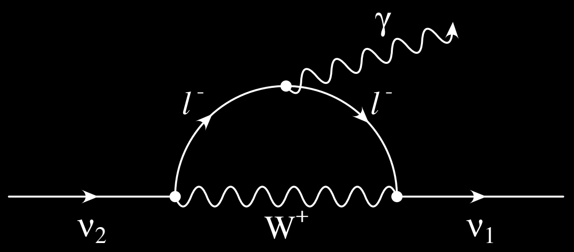
It is independently seen by the same group in the Perseus Cluster with Chandra data.

(Bulbul et al, APJ'14)

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



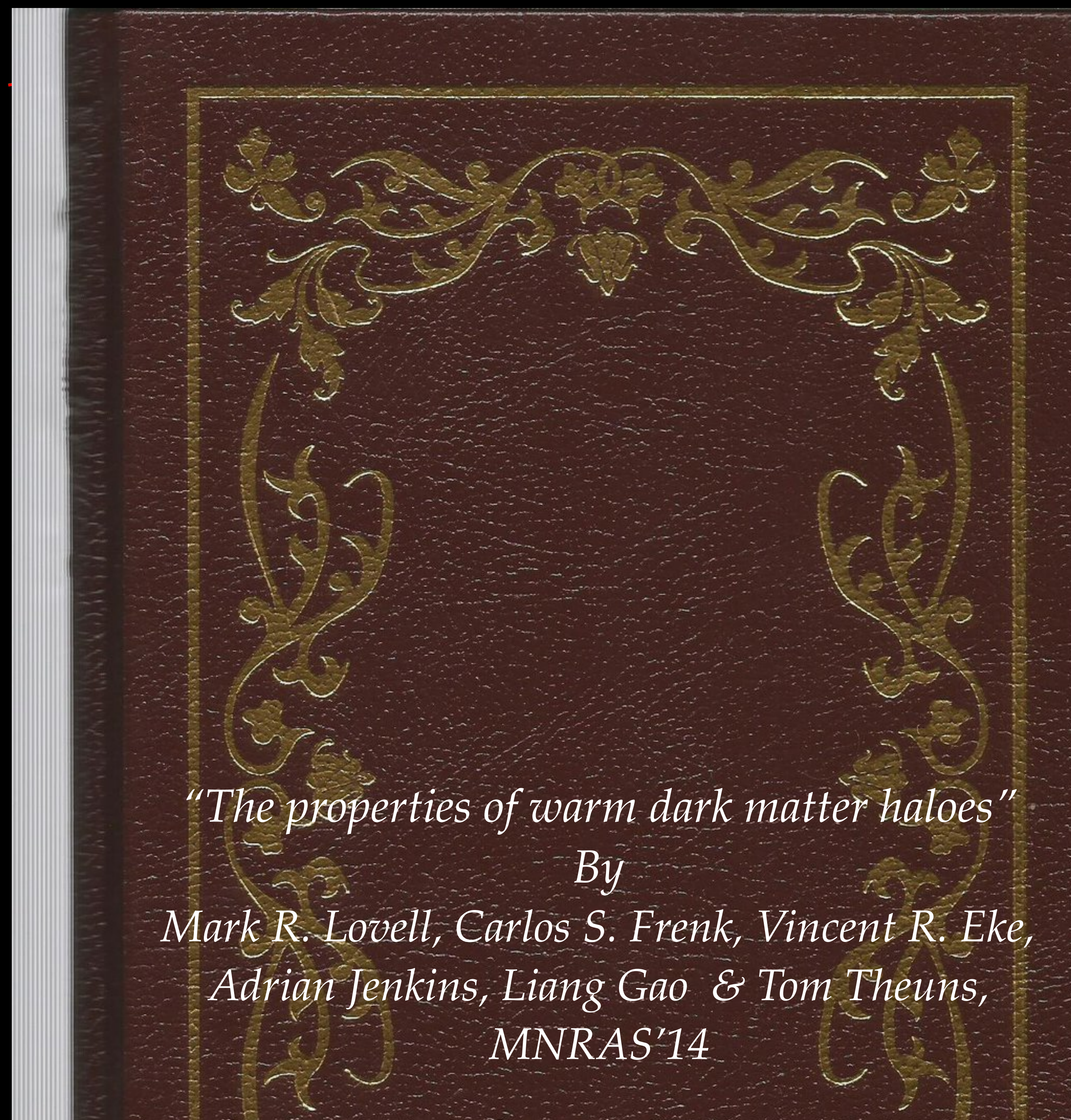
$$\nu_s \rightarrow \nu_\alpha + \gamma$$



$$m_s = 2E = 7.1keV$$

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.



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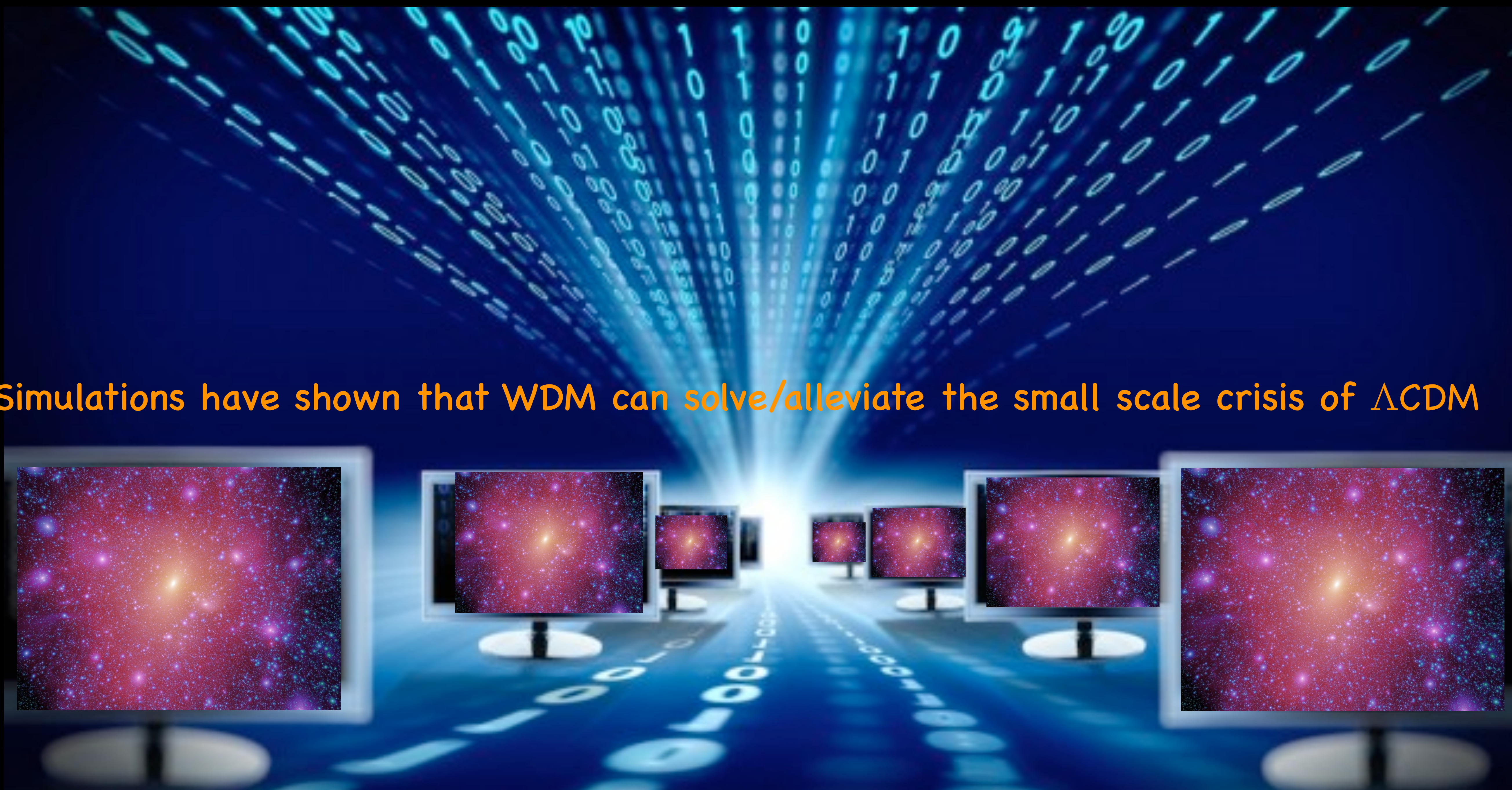
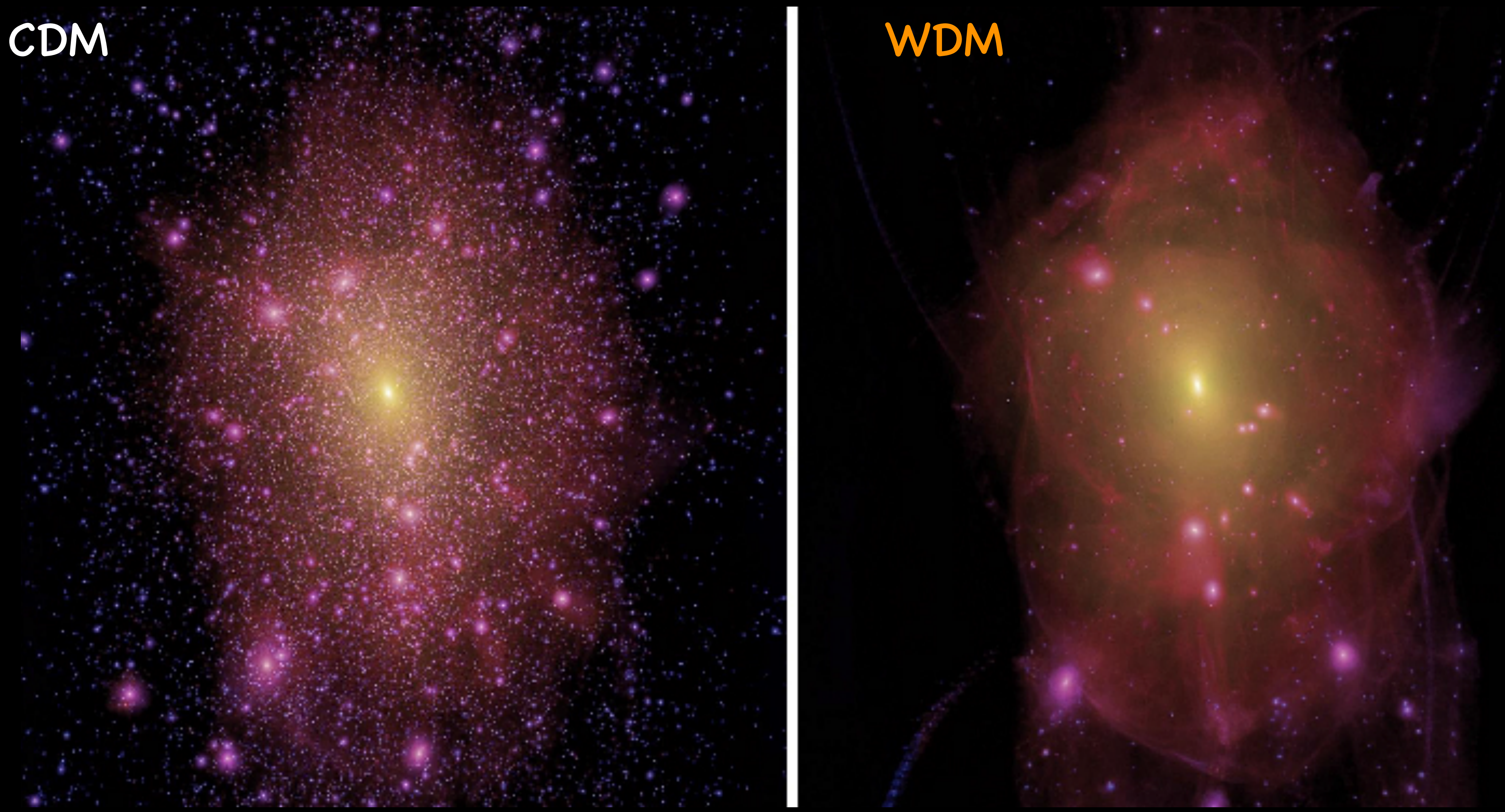


Simulations have shown that WDM can solve/alleviate the small scale crisis of ΛCDM

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

Backup material

- The entropy density is: $$s \equiv \frac{\rho + p}{T}$$

¿How are related the photon and the neutrino temperatures?

- Electron positron annihilation takes place AFTER neutrino decoupling.

- In an expanding universe the entropy density pero comoving volume is conserved:

- Boson's entropy contribution:
- Fermion's entropy contribution:

$$2\pi^2 T^3/45$$

$$7/8 \times 2\pi^2 T^3/45$$

- Before electron/positron annihilation= electrons (g=2), positrons (g=2), neutrinos (3), antineutrinos (3) and photons (g=2) therefore:

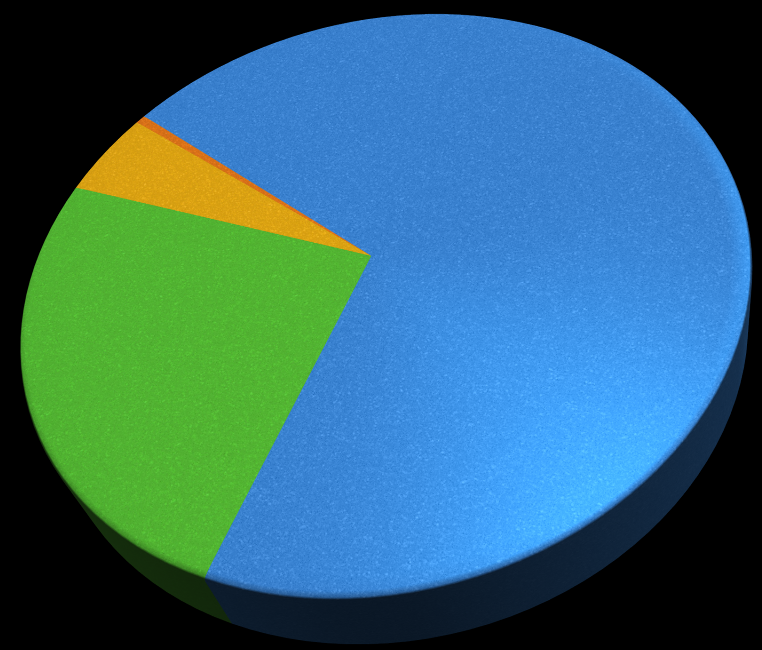
$$s(a_1) = 2\pi^2 T_1^3/45(2 + 7/8(2 + 2 + 3 + 3))$$

- After, only neutrinos, antineutrinos and photons but at different temperature!

$$s(a_2) = 2\pi^2/45(2T_\gamma^3 + 7/8(3 + 3)T_\nu^3)$$

$$s(a_1)a_1^3 = s(a_2)a_2^3 \qquad a_1 T_1 = a_2 T_\nu \longrightarrow \left(\frac{T_\nu}{T_\gamma}\right) = \left(\frac{4}{11}\right)^{1/3}$$

Summary's Dessert Cosmic Cake



- Sterile neutrino masses and abundances leave key signatures in cosmological observables.
- Abundances (N_{eff}) : via Cosmic Microwave Background measurements damping tail & Big Bang Nucleosynthesis light element abundances, N_{eff} <3.41 (@95%CL).
- Masses: neutrino free-streaming nature induce a small-scale suppression matter power spectrum, $m_{\nu,eff} < 0.7$ eV ($< 0.0000014\, m_e$) (@95%CL).
- No current cosmological evidence for sterile neutrinos or dark radiation.
- Warm Dark Matter sterile keV neutrinos: alleviate/solve mostly all the small scale problems of the standard Cold Dark Matter scenario, still a very interesting option!

Massive neutrinos cosmological signatures: m_ν

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

Hubble drag — Pressure — Gravity

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

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:

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

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N_{eff} dark radiation species cosmological signatures

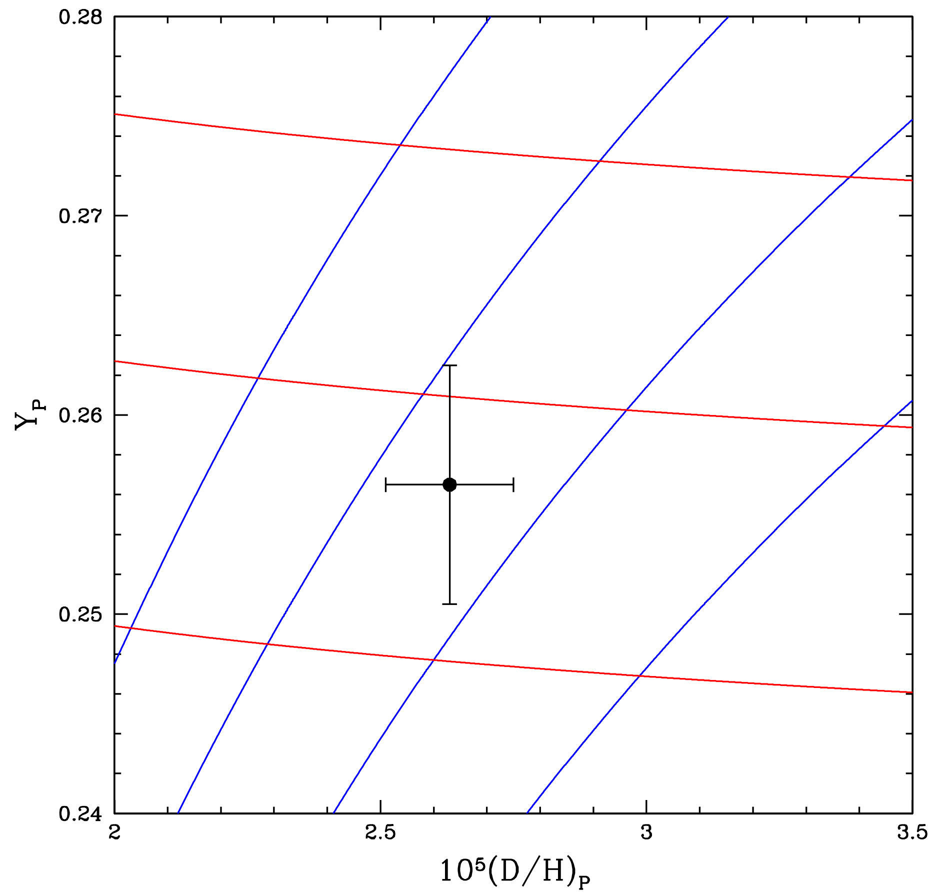
N_{eff} changes the freeze out temperature of weak interactions:

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

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

Higher N_{eff}, Higher expansion rate, higher freeze out temperature, higher ^{4}He fraction:

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



(G. Steigman'12)

$$\Delta N_{\rm eff} = 0, 1, 2$$

- The entropy density is: $$s \equiv \frac{\rho + p}{T}$$

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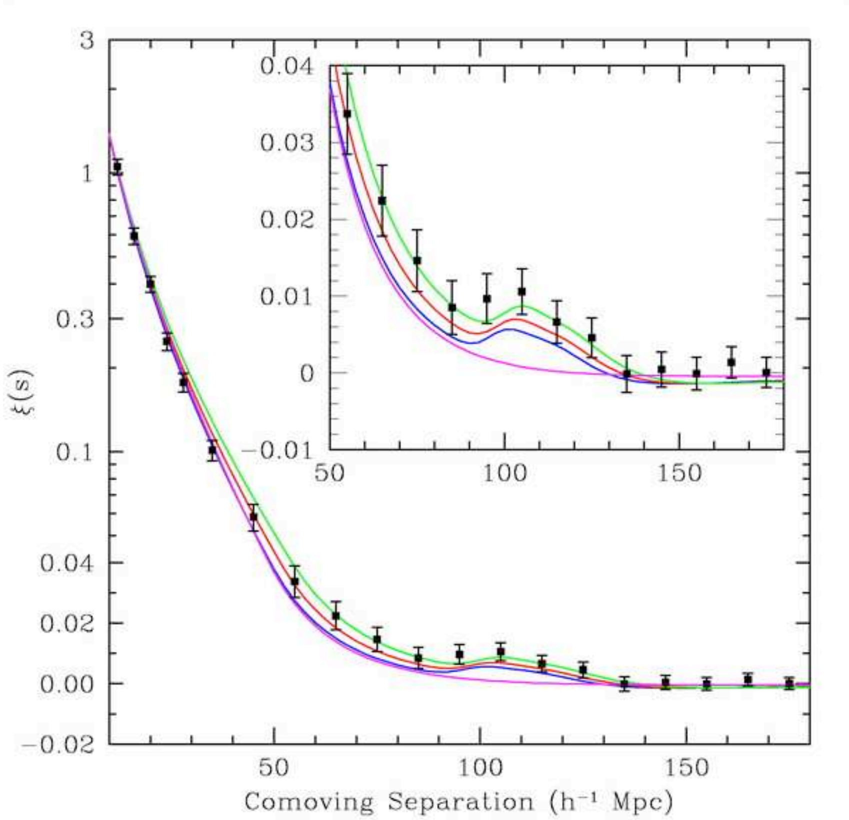
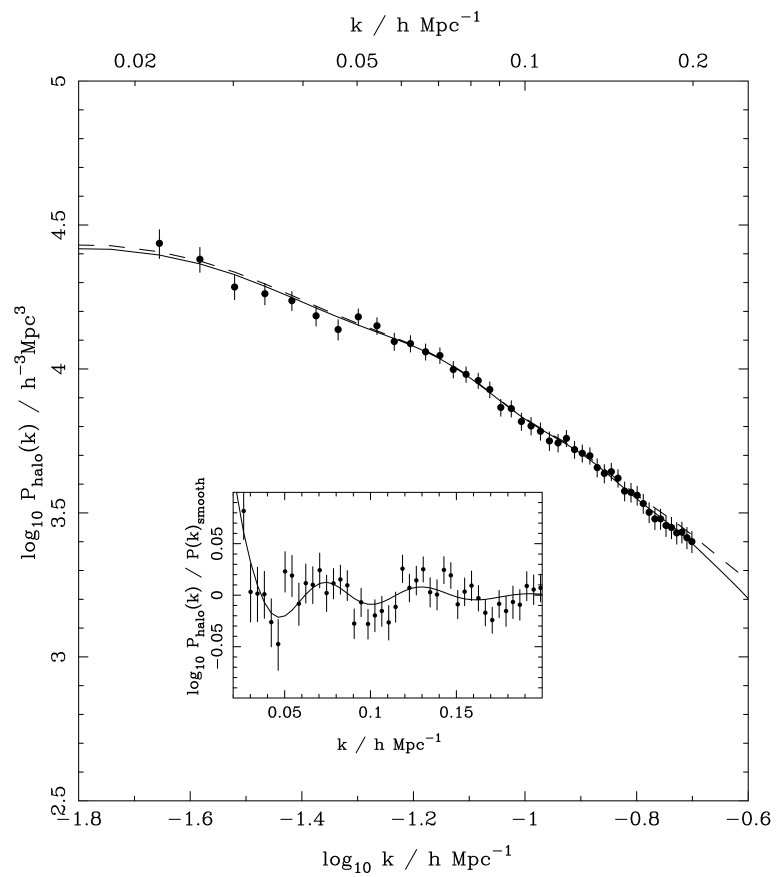
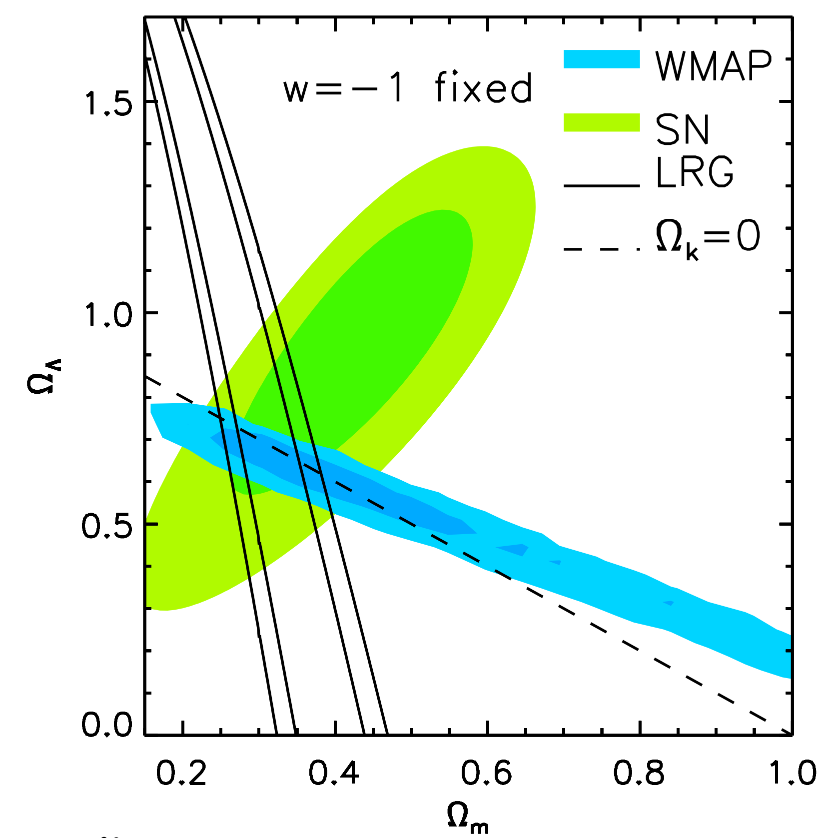
Los catálogos de galaxias miden la función de correlación:

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

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







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

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

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