Messengers from the Early Universe: Cosmic Neutrinos and Other Light Relics

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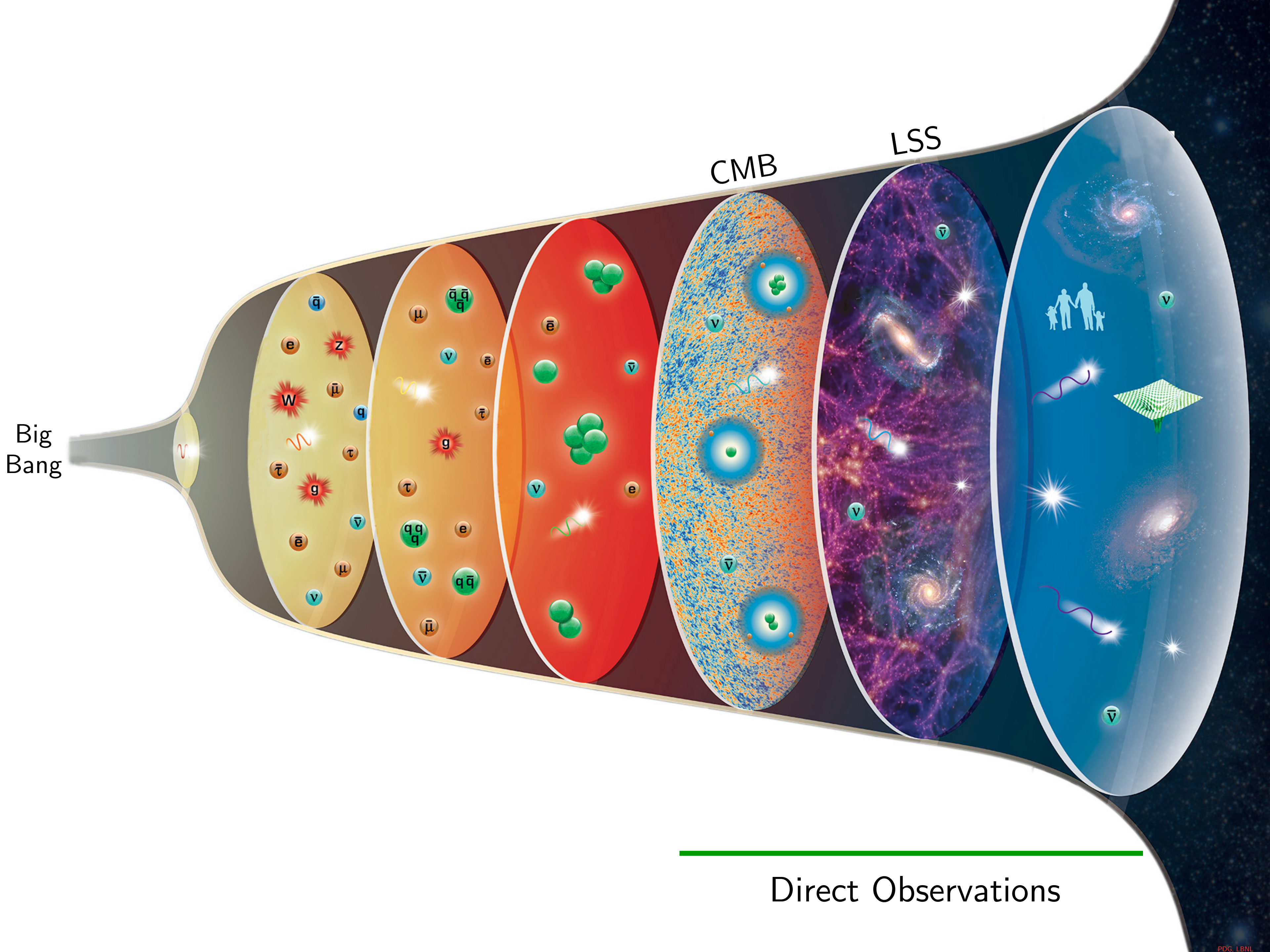
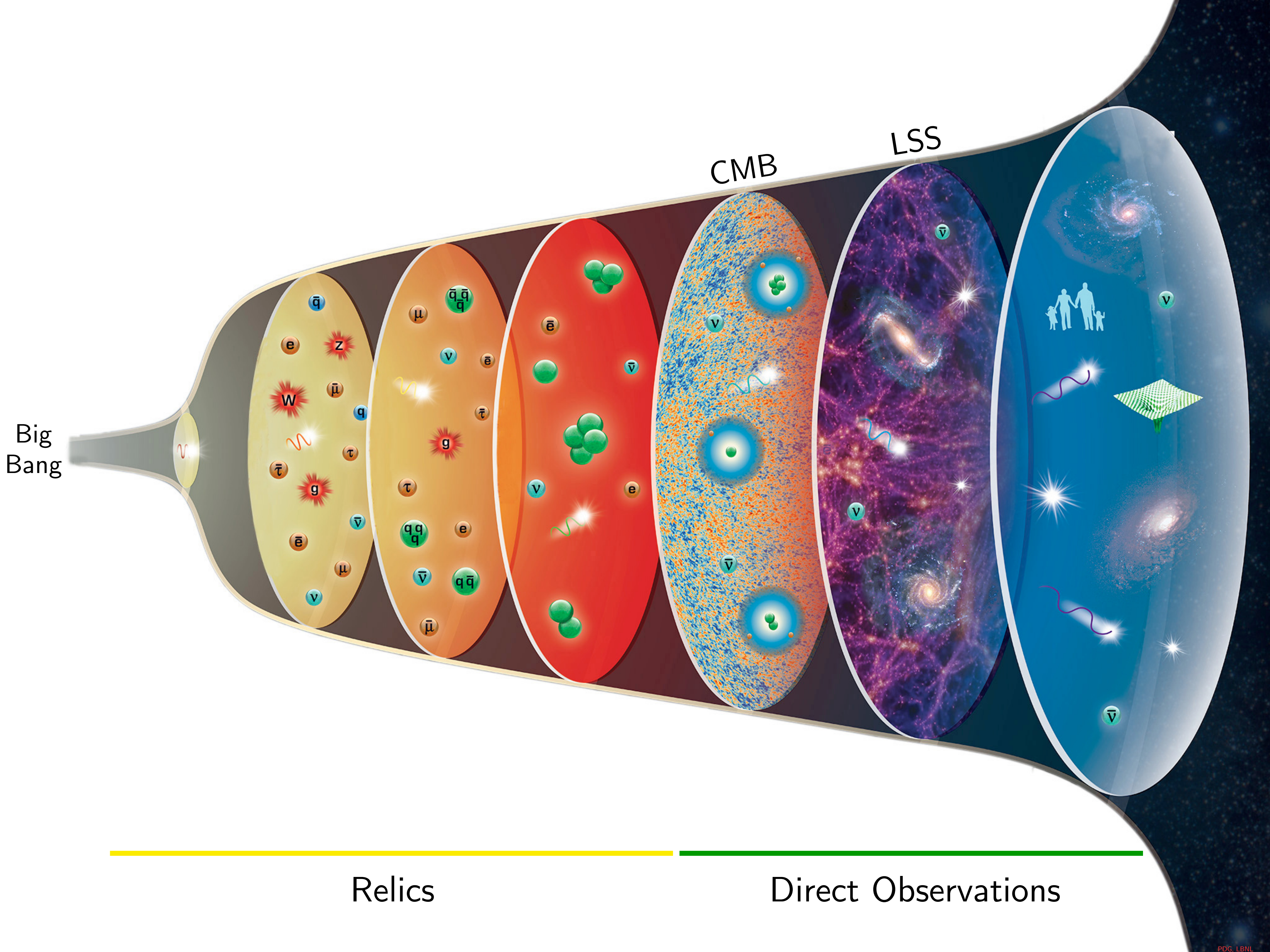
Related to: 1508.06342 (JCAP 2016), 1607.02160 (PRL 2016), 1712.08067 (JCAP 2018), 1803.10741 (Nat. Phys. 2019)

15th Rencontres du Vietnam on Cosmology, August 2019

Big
Bang


Big Bang
CMB
LSS
Direct Observations


Big Bang
CMB
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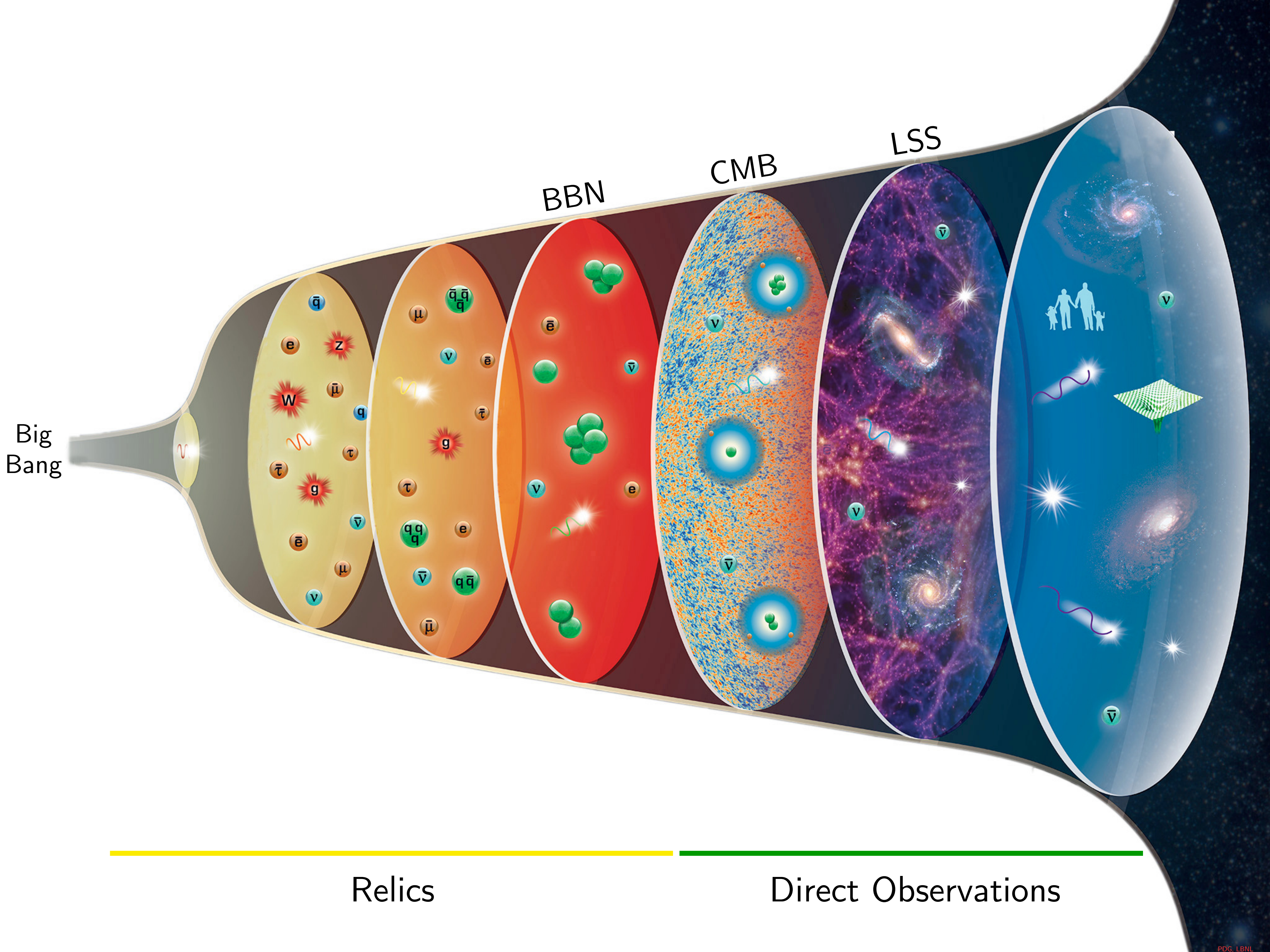
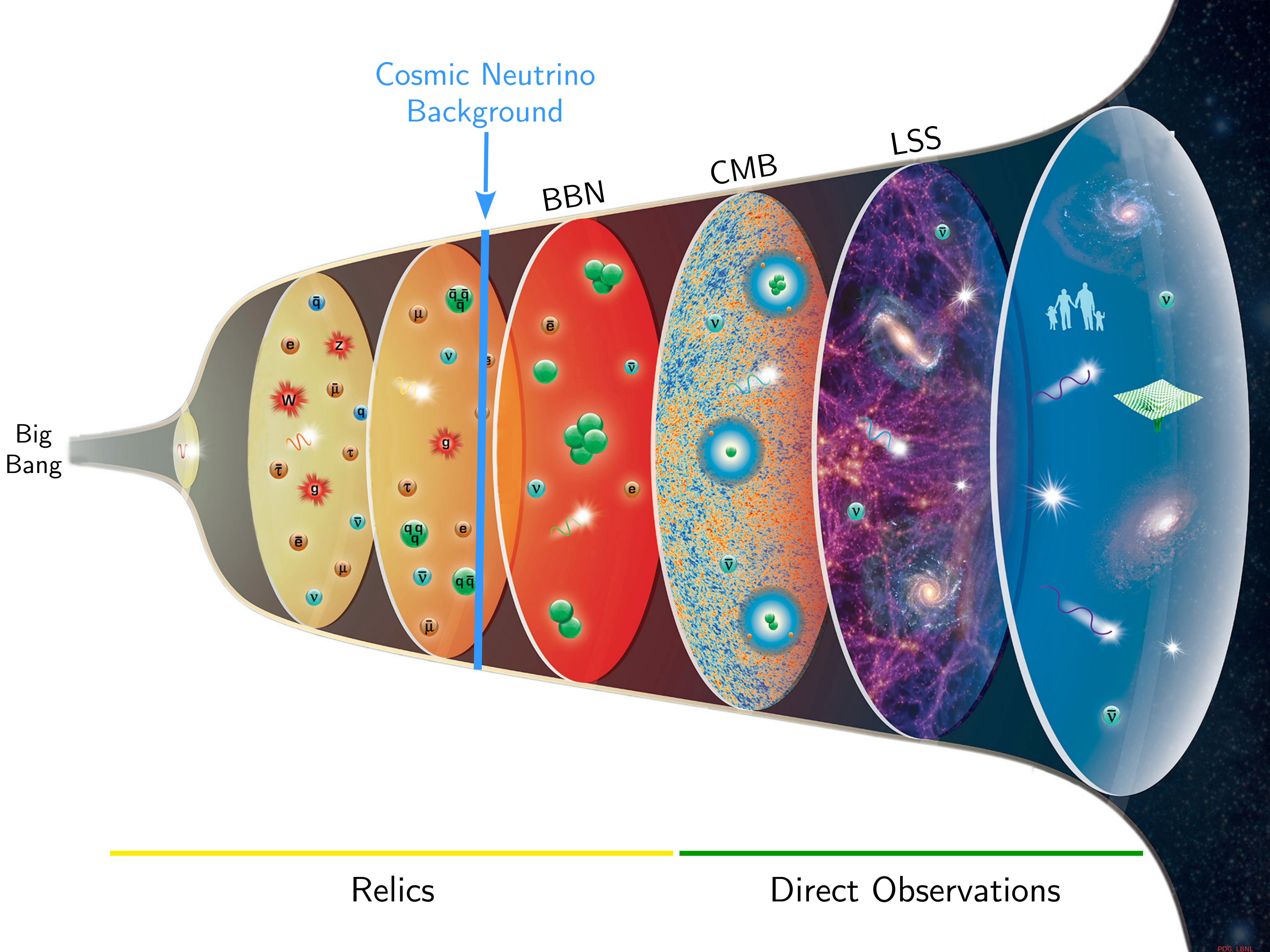
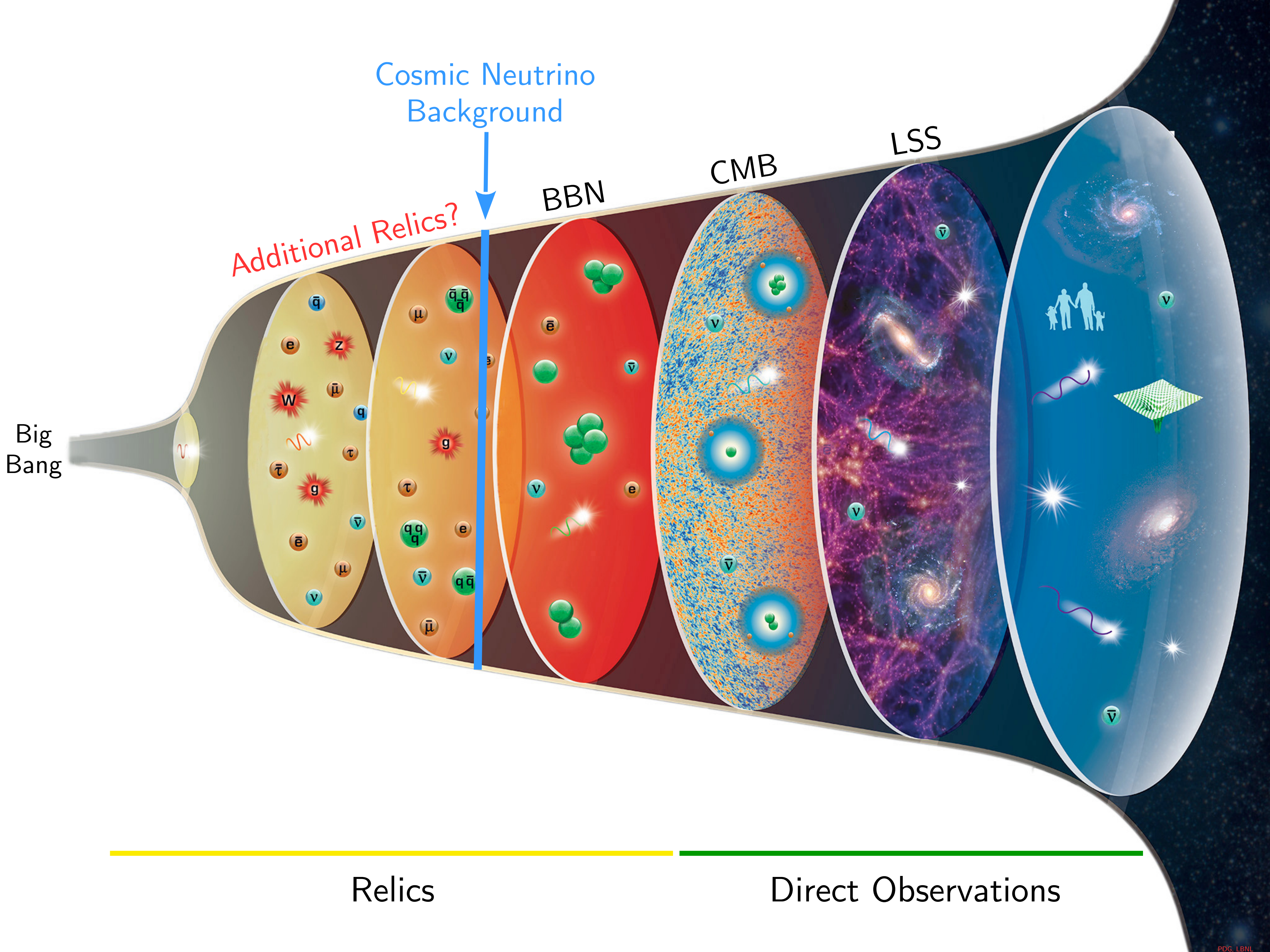
Relics
Direct Observations


Big Bang
BBN
CMB
LSS
Relics
Direct Observations
PDG, LBNL


Cosmic Neutrino Background
Big Bang
BBN
CMB
LSS
Relics
Direct Observations


Cosmic Neutrino Background
Additional Relics?
BBN
CMB
LSS
Big Bang
Relics
Direct Observations

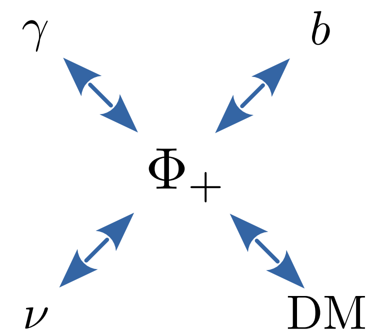
Cosmic Sound Waves

In the early universe, photons and baryons were strongly coupled.

Perturbations excited sound waves in the photon-baryon fluid:

$$\ddot{\delta}_\gamma - c_\gamma^2 \nabla^2 \delta_\gamma = \nabla^2 \Phi_+$$

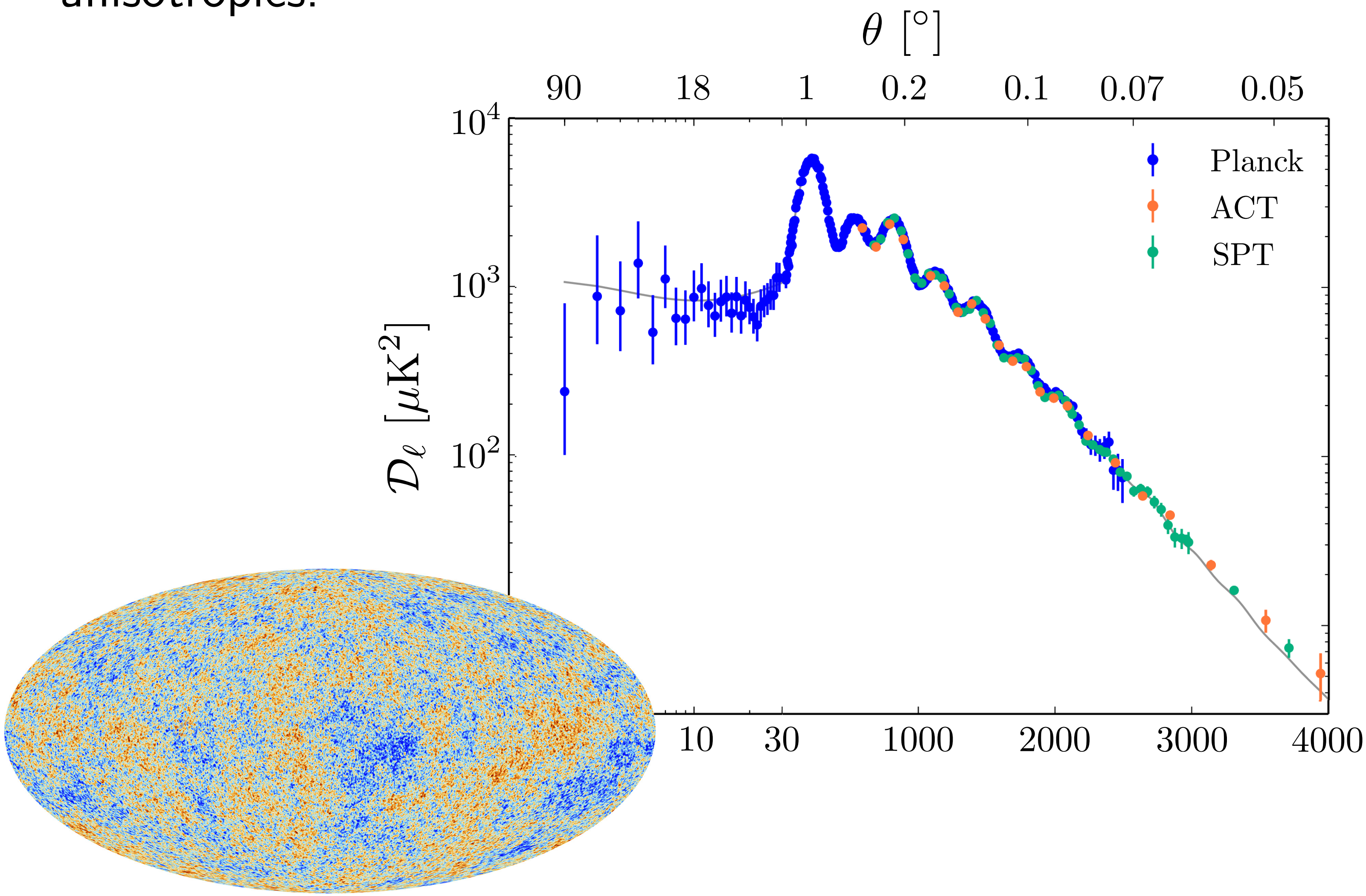
sound waves pressure gravity



These acoustic oscillations have been observed...

Cosmic Sound Waves

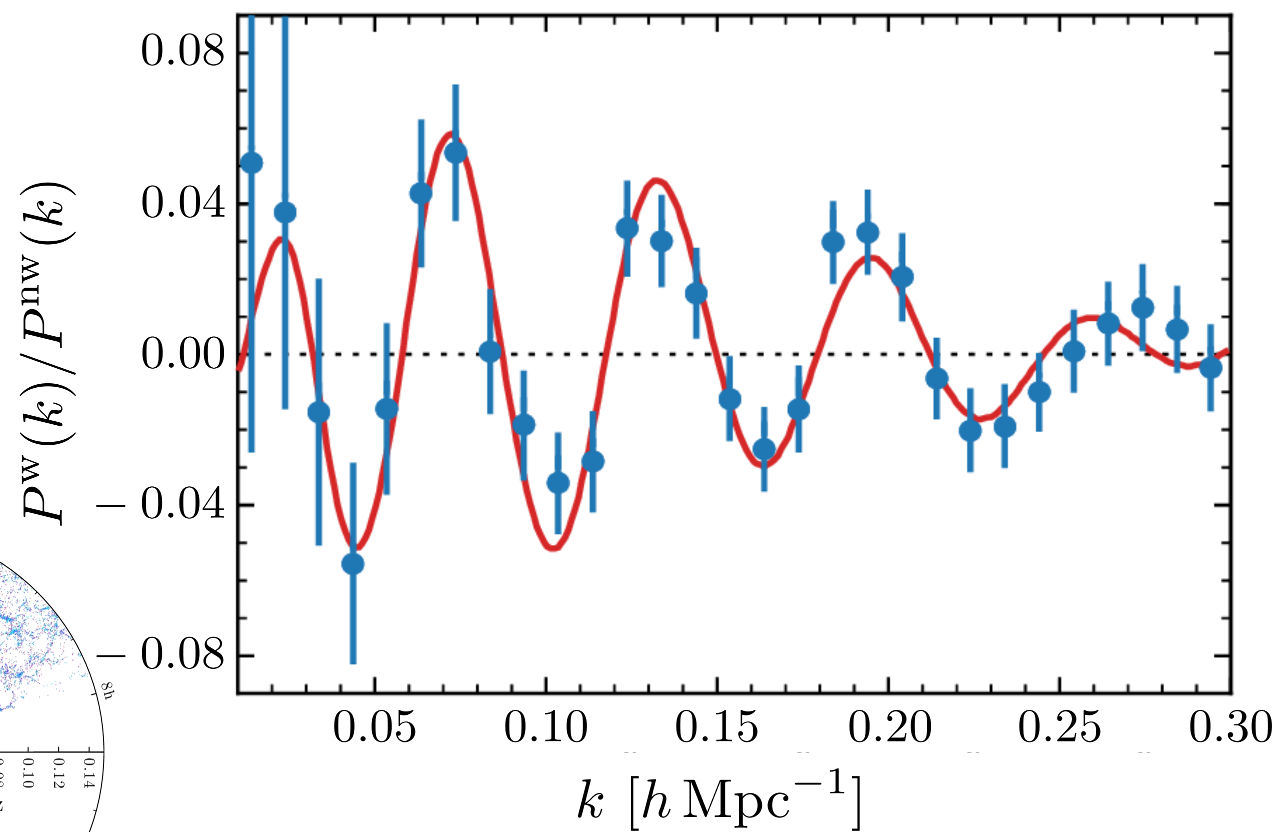
... in the correlations of the cosmic microwave background (CMB) anisotropies:

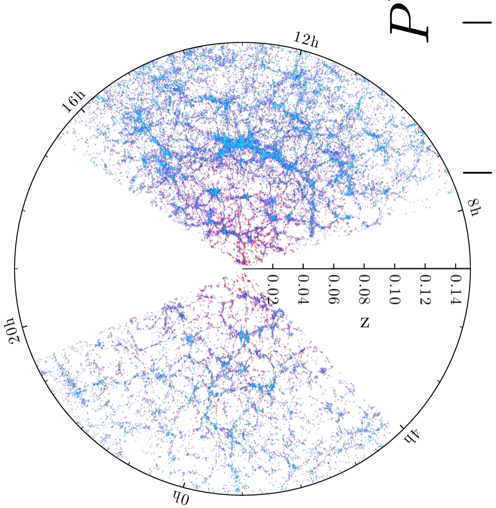


Planck (2015)

Cosmic Sound Waves

... and in the distribution of galaxies in the universe via the spectrum of baryon acoustic oscillations (BAO):





SDSS; Beutler et al. (BOSS, 2016)

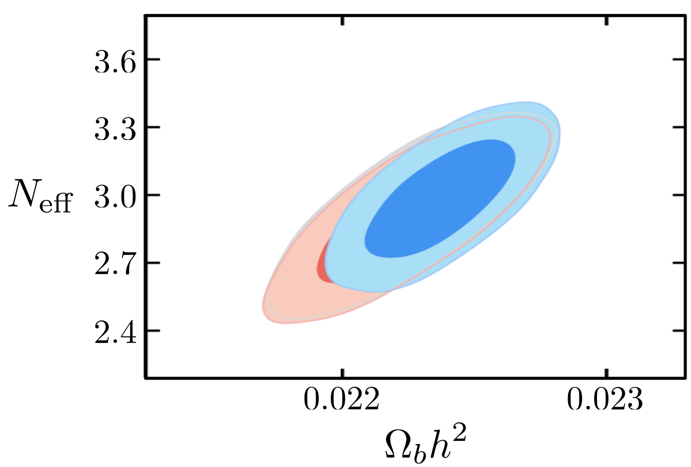
Cosmic Neutrinos

41% of radiation density in the universe:
- $\to$ leave gravitational imprint,
- $\to$ can detect their energy density.

$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\text{eff}}\right]\rho_\gamma$$

Observable: "effective number of neutrinos" $N_{\text{eff}}^{\text{SM}} = 3.045$.

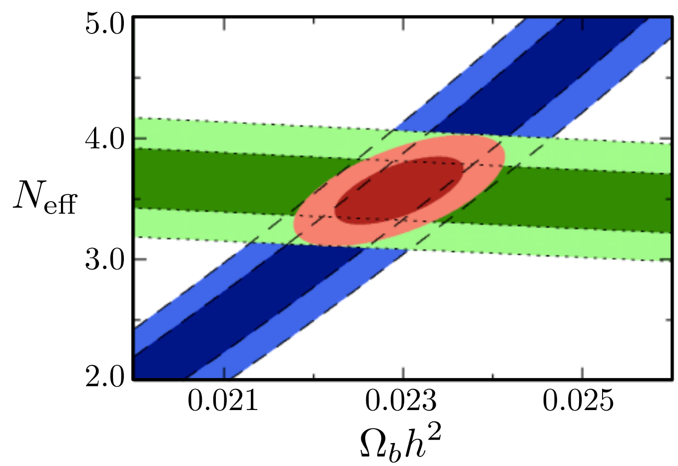
e.g. Mangano et al. (2005), Grohs et al. (2016), de Salas & Pastor (2016)



CMB: anisotropy measurements

$$N_{\text{eff}}^{\text{CMB}} = 2.92 \pm 0.18$$

Planck (2018)



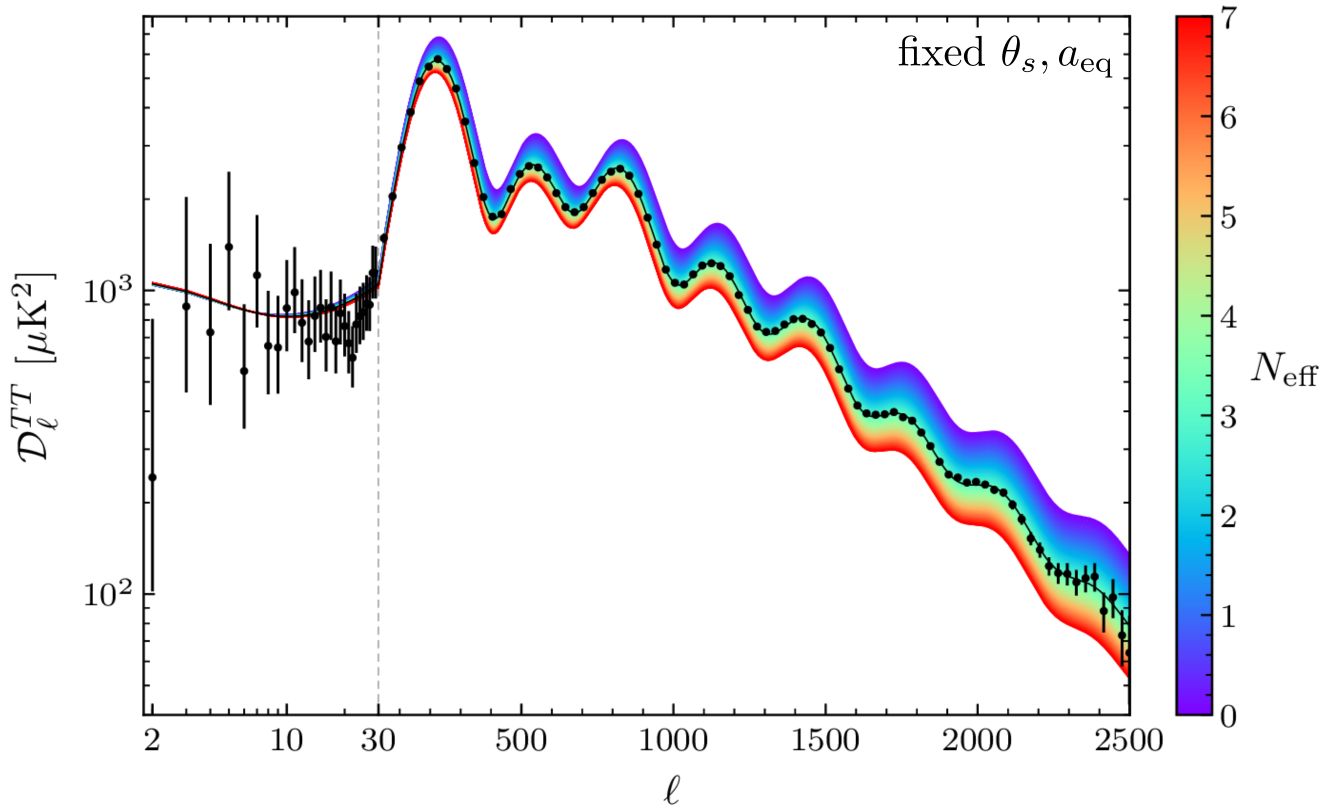
BBN: primordial abundances

$$N_{\text{eff}}^{\text{BBN}} = 3.28 \pm 0.28$$

Cooke et al. (2015)

Cosmic Neutrinos

Main effect of neutrinos in the CMB is on the damping tail:



Degenerate with change in the primordial helium fraction.

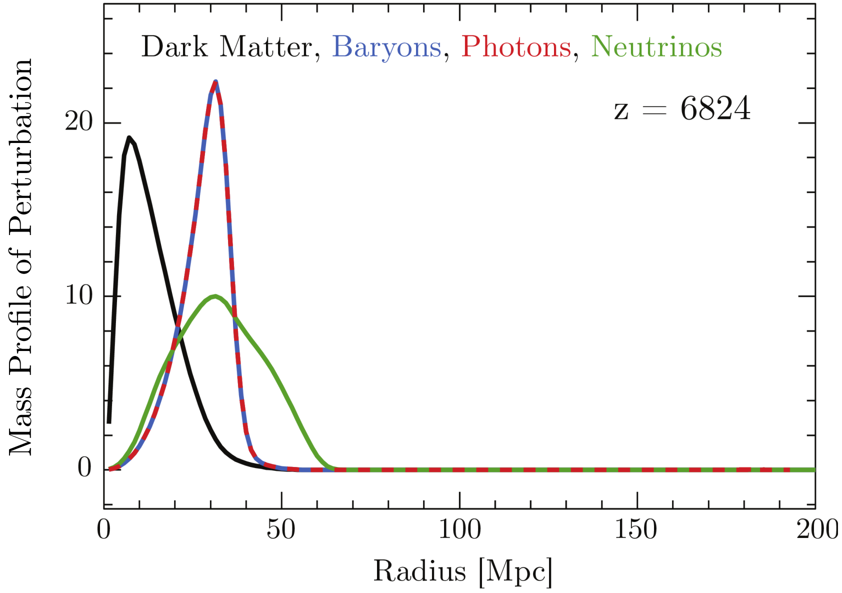
In the past, limiting factor for CMB constraints on neutrinos.

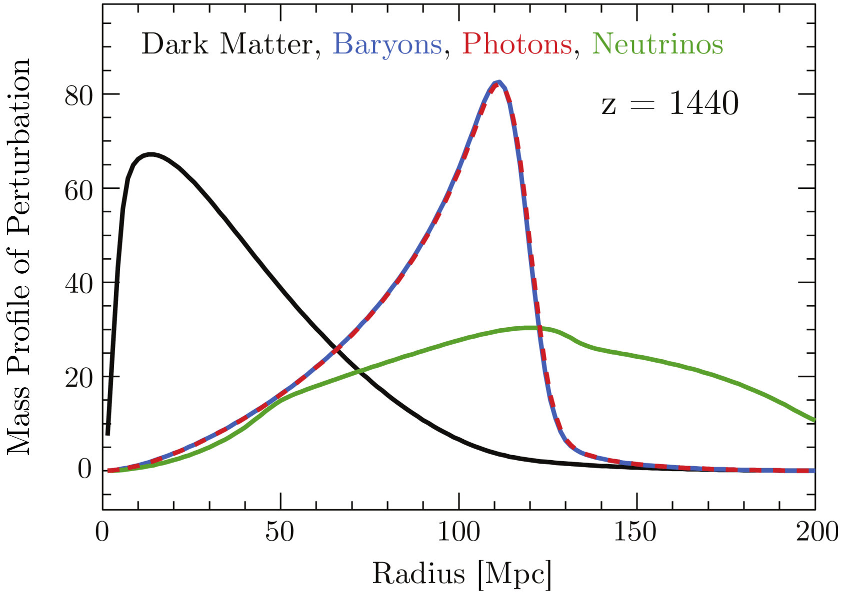
Planck (2015)

Cosmic Neutrinos

Now: Planck is sensitive to neutrino perturbations.

Free-streaming neutrinos overtake the photons and pull them ahead of the sound horizon:





Eisenstein, Seo and White (2007)

$\rightarrow$ Neutrino drag effect on photon perturbations.

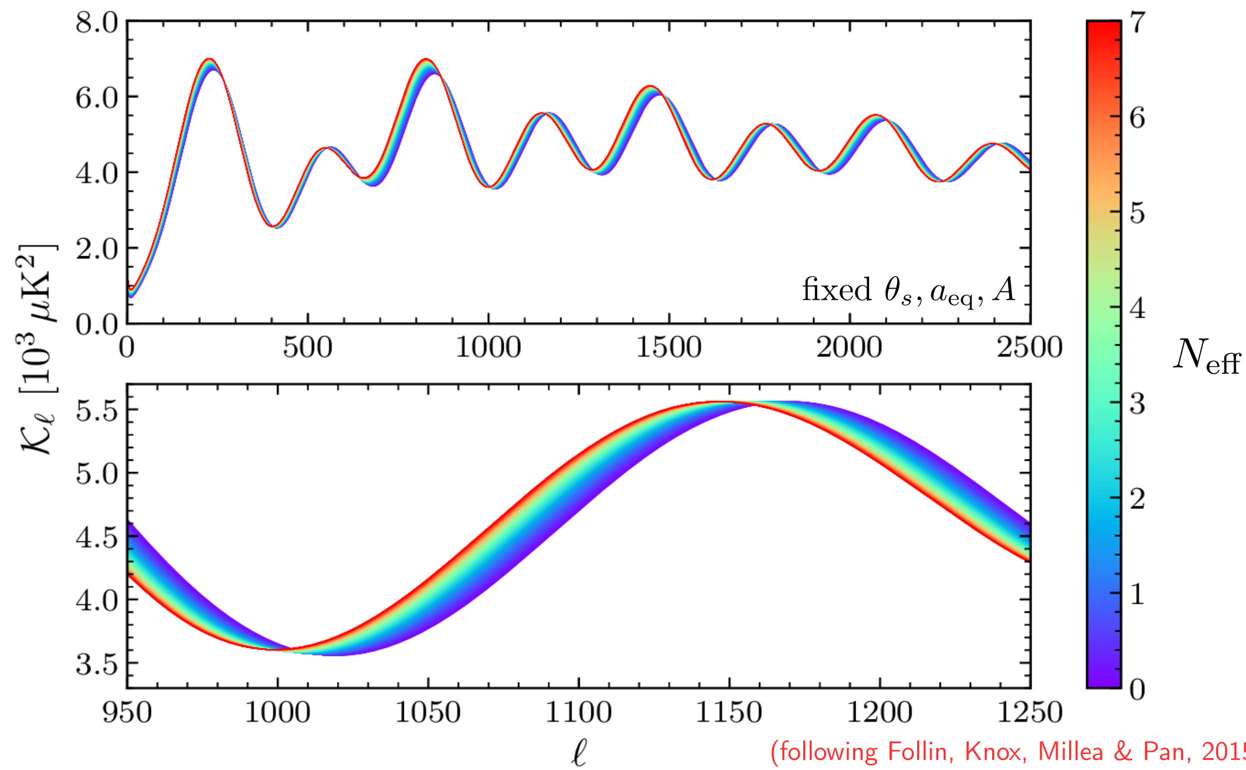
Phase Shift

This corresponds to a phase shift in the CMB power spectrum:

Bashinsky & Seljak (2003)

$$\delta_\gamma(\vec{k}) \approx A(\vec{k})\,\cos(kr_s + \phi)$$

undamped
CMB spectrum



(following Follin, Knox, Millea & Pan, 2015)

Free-streaming neutrinos are a causal way to produce such a shift.

Baumann, Green, Meyers & BW (2016)

Phase Shift and Free-Streaming Neutrinos

Small effect: $\Delta\ell \approx 5.0 \times \Delta N_{\rm eff}$.

But neutrino imprint in phase shift has been detected in Planck data:

$$N_{\rm eff}^{\Delta\ell} = 2.3^{+1.1}_{-0.4}$$ (phase shift-inducing radiation density)

Follin, Knox, Millea & Pan (2015)

Complementary analysis:

$$N_{\rm eff} = 2.80 \pm 0.24$$

(free-streaming radiation density)

$$N_{\rm fluid} < 0.67 \ (95\% \text{ c.l.})$$

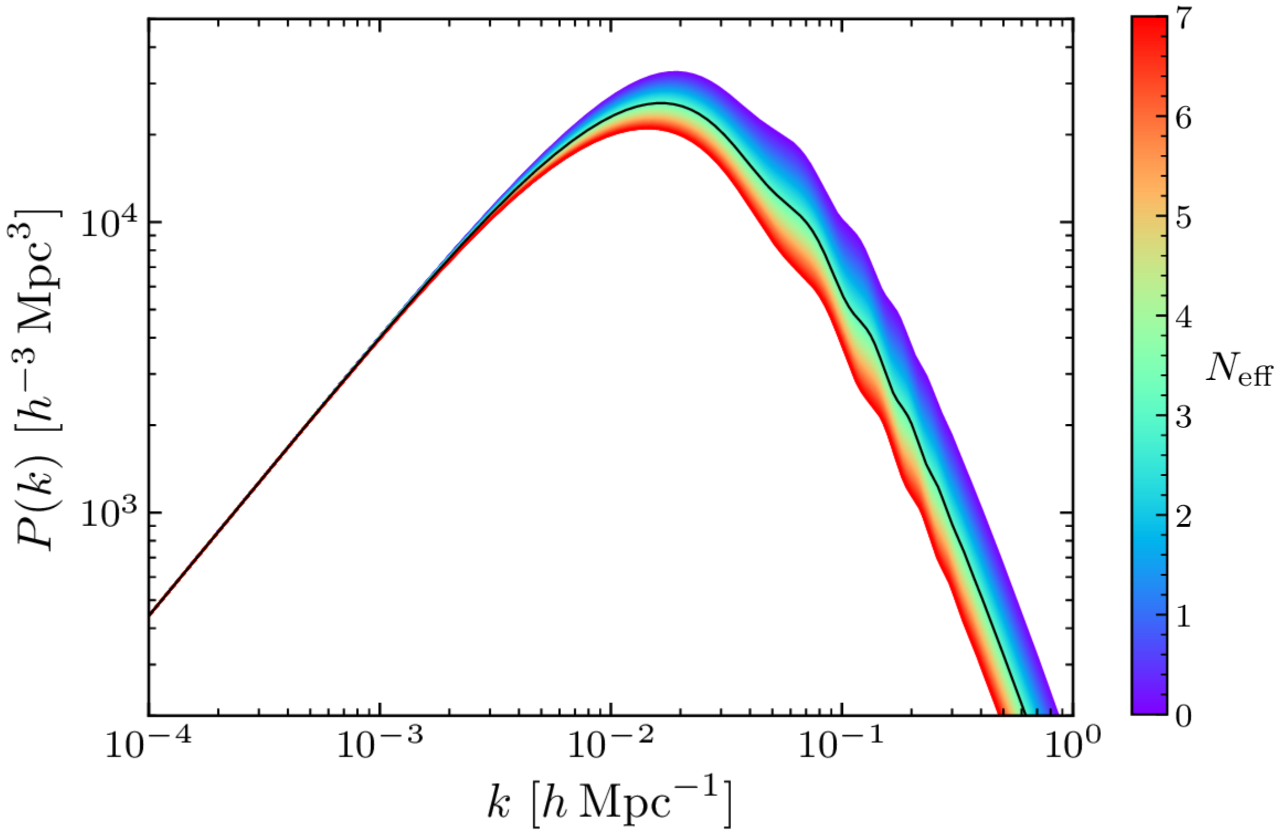
(non-free-streaming radiation density)

Baumann, Green, Meyers & BW (2016)

$\rightarrow$ Standard Model neutrinos are free-streaming.

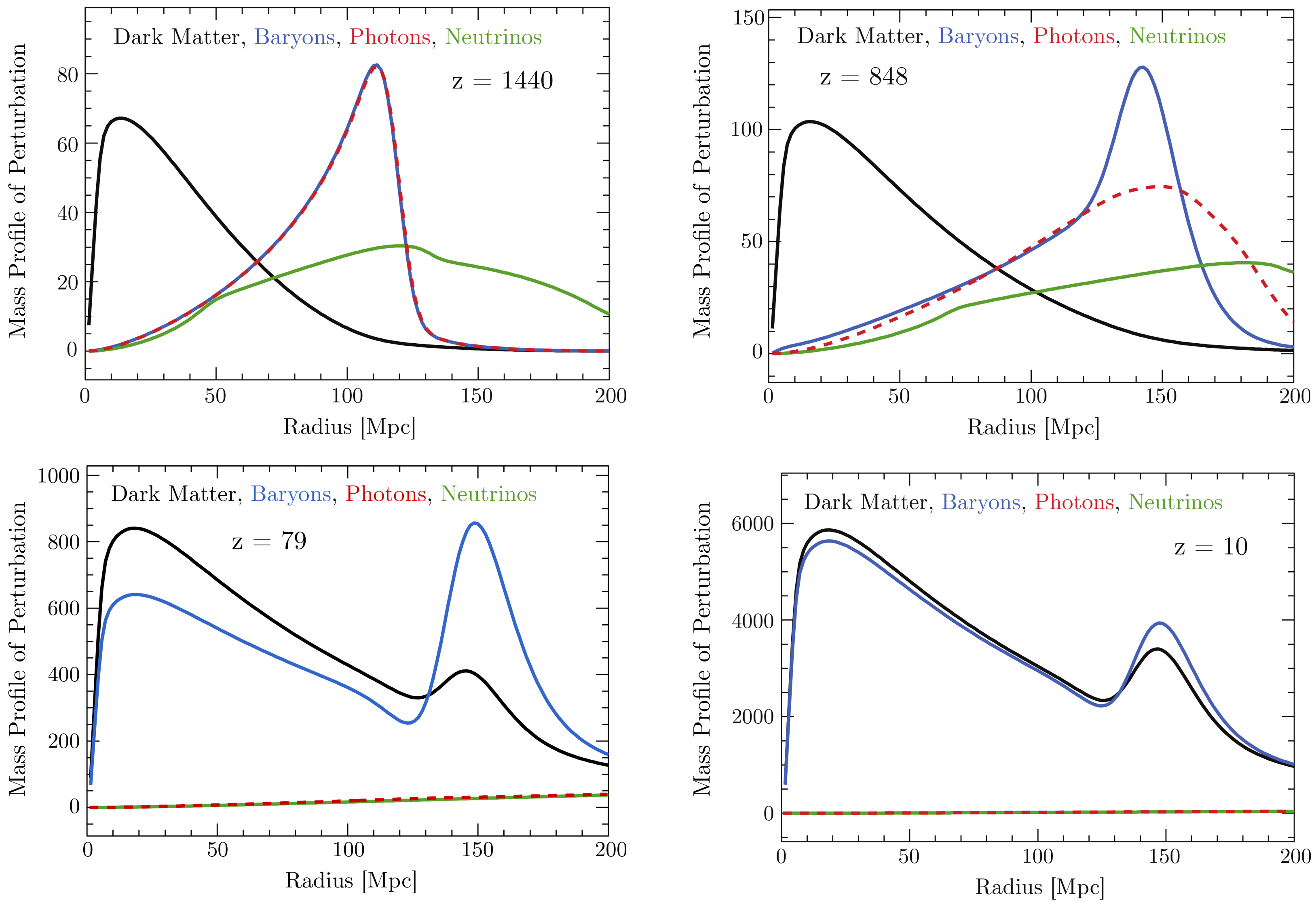
Cosmic Neutrinos in LSS

Main effect of (massless) neutrinos on the matter power spectrum:



Variation of matter-radiation equality and related change in amount of structure growth.

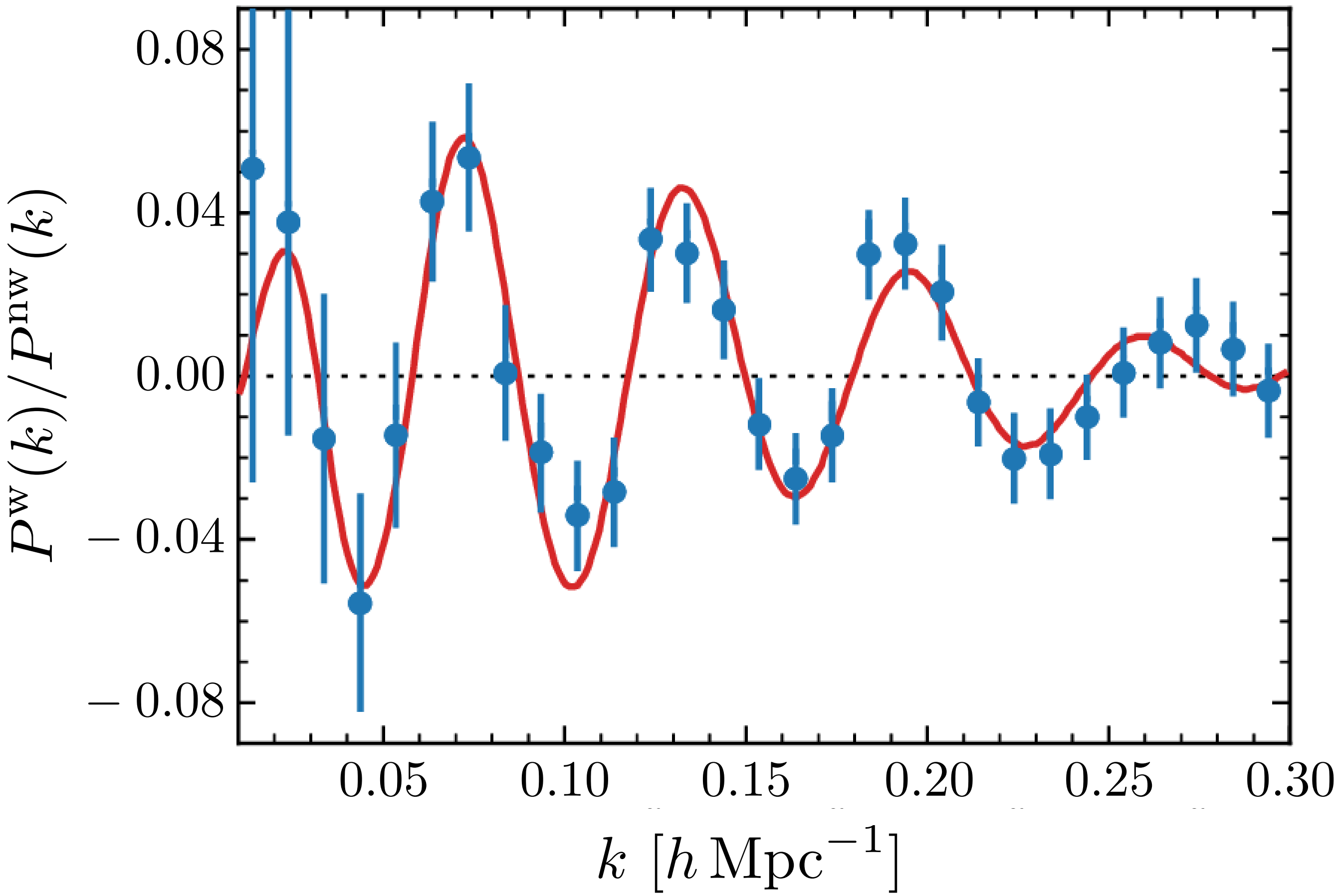
Baryon Acoustic Oscillations



Eisenstein, Seo and White (2007)

Baryon Acoustic Oscillations

In Fourier space, this corresponds to the BAO spectrum, e.g. of the distribution of galaxies:

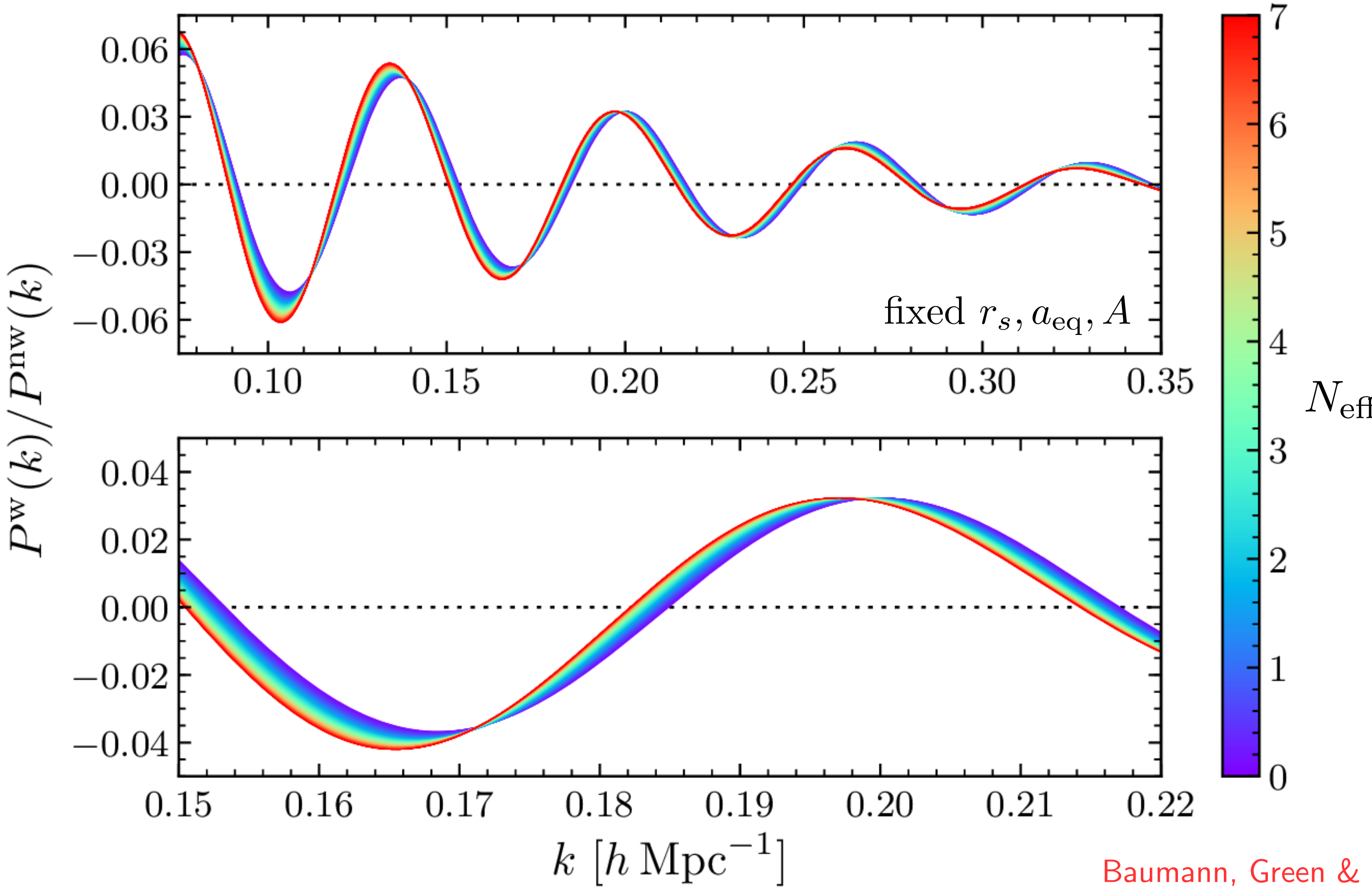


Beutler et al. (BOSS, 2016)

Phase Shift in the BAO Spectrum

Extra relativistic species lead to the same phase shift as in the CMB:

$$\delta_m(\vec{k}) \approx A(\vec{k})\,\sin(kr_s + \phi)$$



Baumann, Green & BW (2018)

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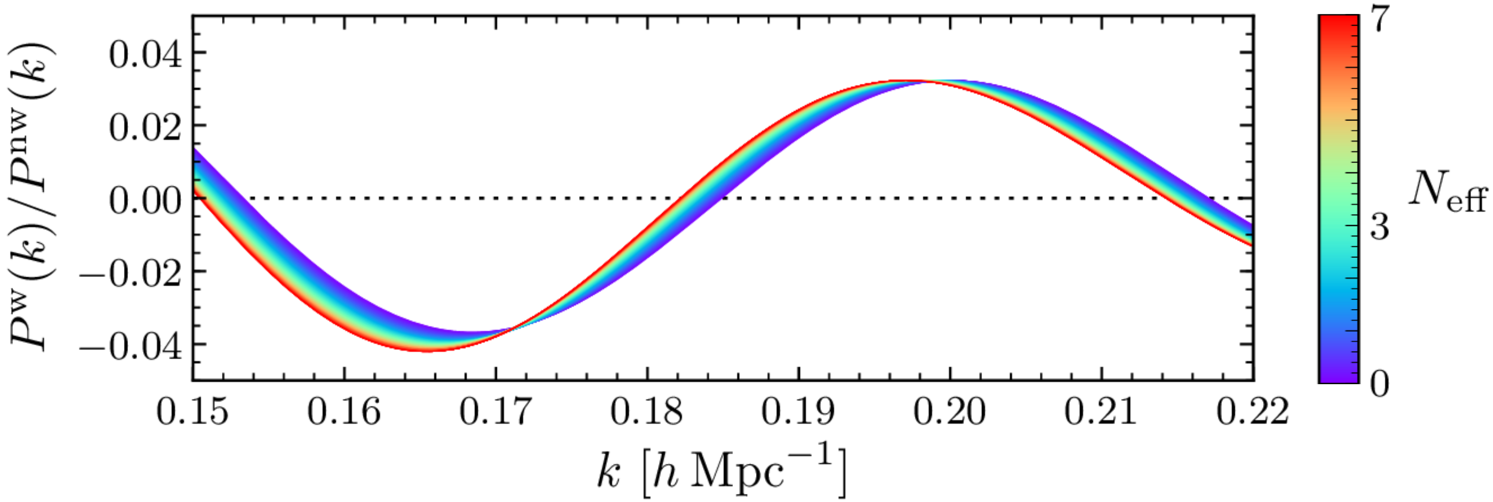


Phase is immune to the effects of nonlinear gravitational evolution.

Baumann, Green & Zaldarriaga (2017)

Certain information encoded in the peak locations is robust to uncertainties in the broadband spectrum.

Baumann, Green & BW (2018)

Generalized BAO Analysis

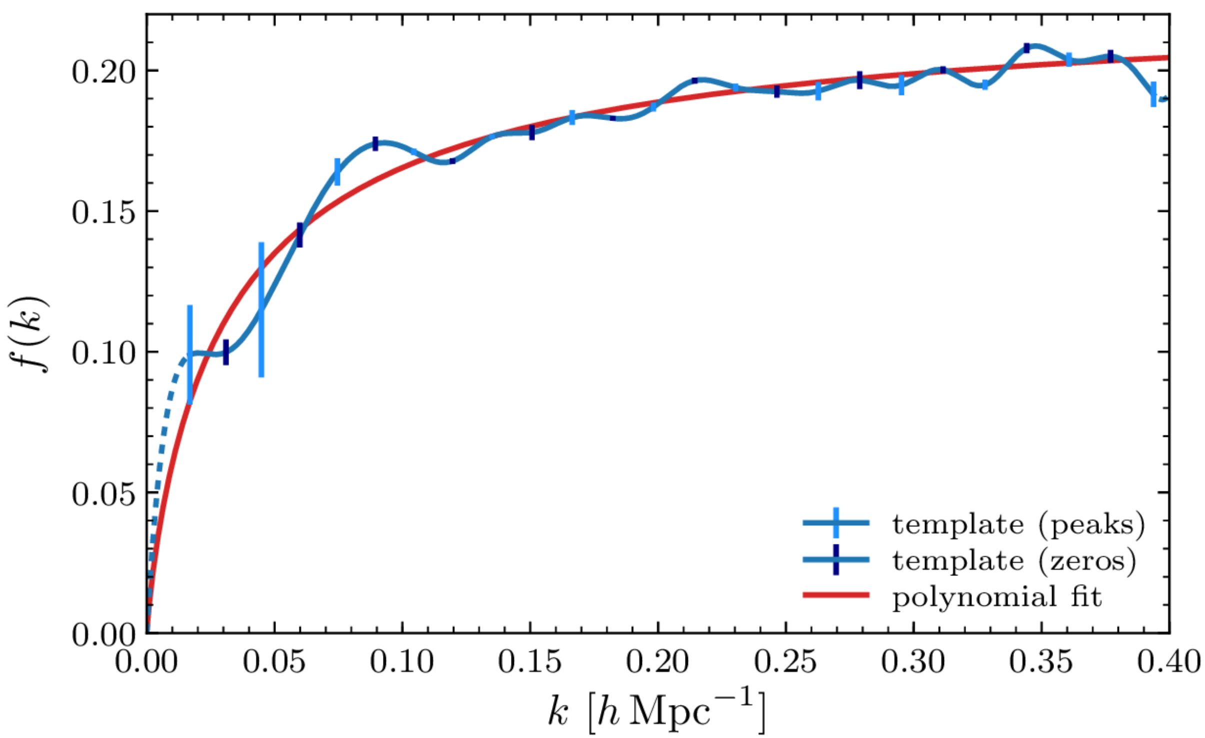
Proposal to adapt the standard BAO analysis:

template

$$P^w(k) \sim A(k)\, \sin(k r_s/\alpha + \beta f(k))$$

standard BAO parameter

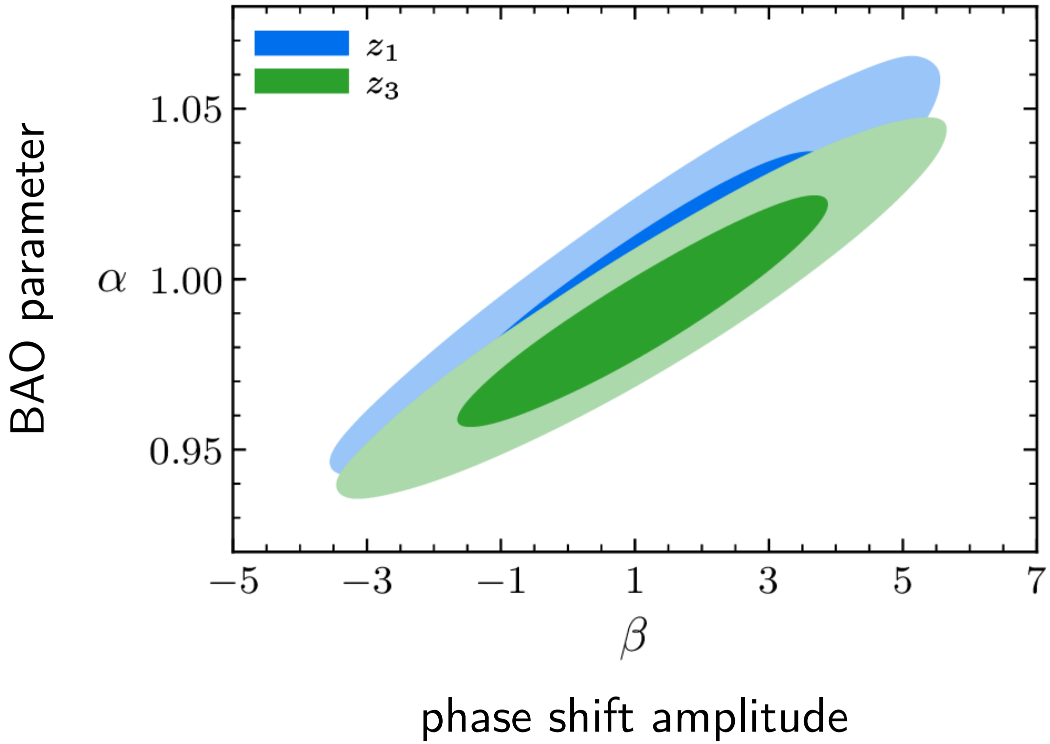
phase shift amplitude



Baumann, Green & BW (2018)

Neutrinos in the BAO Spectrum

The neutrino-induced phase shift can be measured in the BOSS DR12 dataset:



$\beta = 0$: no phase shift

$\beta = 1$: SM phase shift

Baumann, Beutler, Flauger, Green, Vargas-Magaña, Slosar, BW & Yèche (2019)

Neutrinos in the BAO Spectrum

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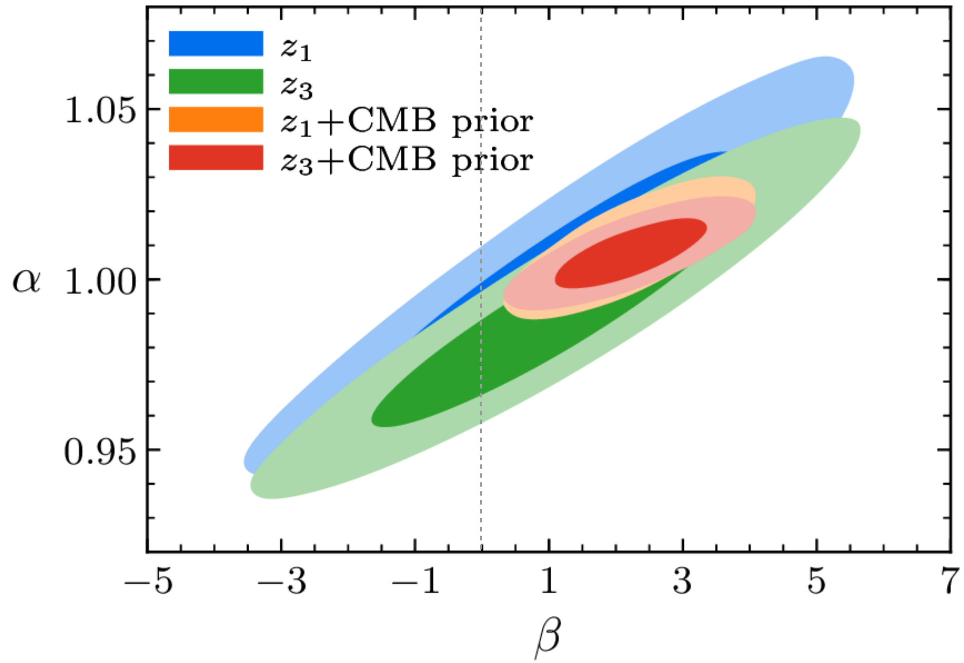


$$\beta > 0 \;\; \text{at} \;\; > 99\% \,\text{c.l.}$$

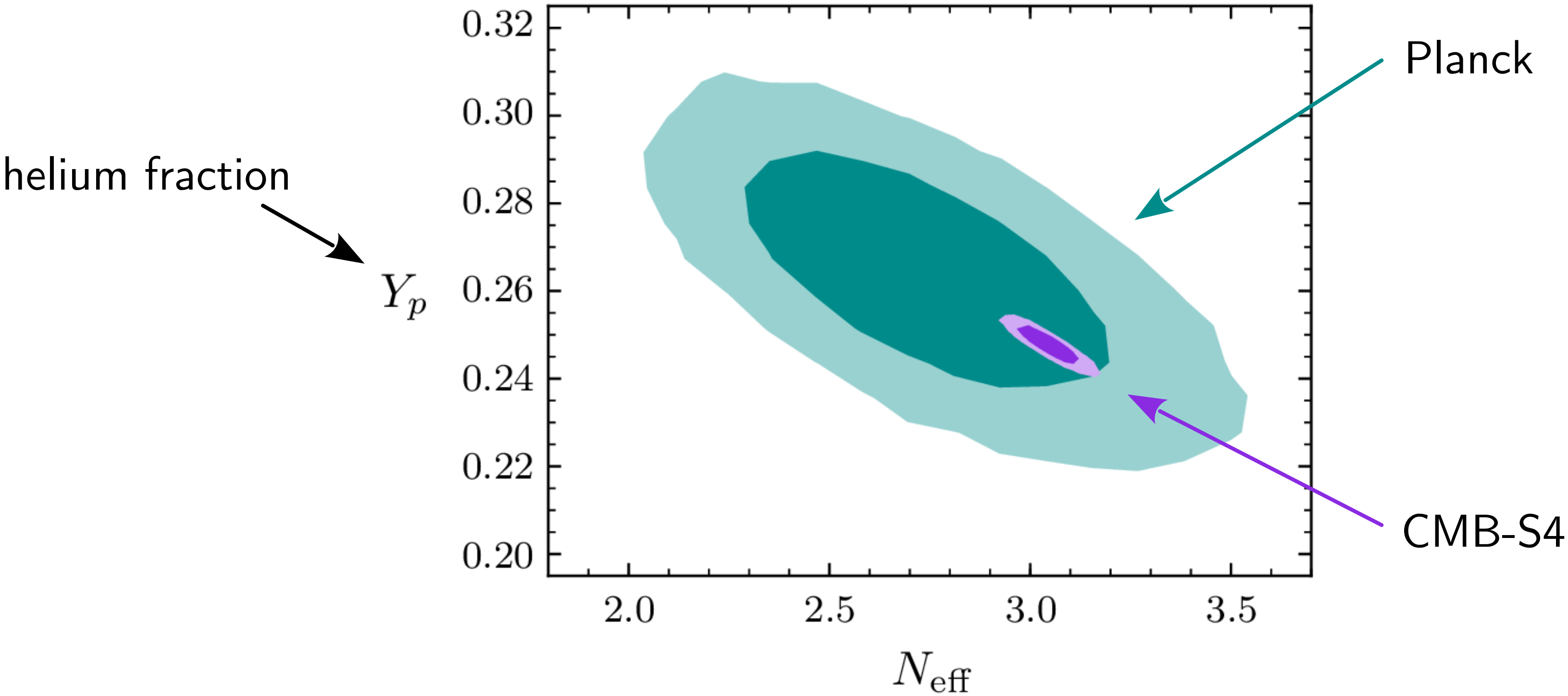
(CMB prior from Planck 2018)

This is a proof of principle for directly extracting information on neutrinos (and other light relics) from galaxy clustering data.

Baumann, Beutler, Flauger, Green, Vargas-Magaña, Slosar, BW & Yèche (2019)

Future Constraints on $\mathrm{N_{eff}}$ from the CMB

Employing all effects of cosmic neutrinos:



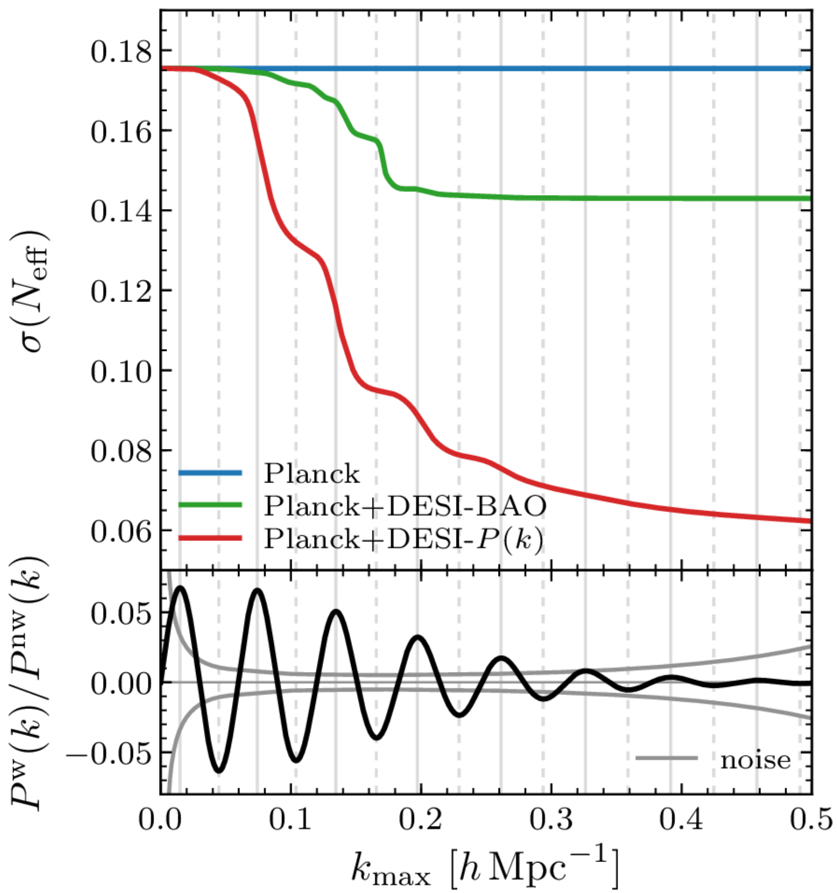
$\rightarrow$ Large improvement from Planck to CMB-S4:

$$\sigma(N_{\mathrm{eff}}) \sim 0.030$$

Baumann, Green, Meyers & BW (2016); CMB-S4 Science Book (2016)

Future Constraints from CMB and LSS

Forecasts indicate that future LSS observations will be sensitive to extra relativistic species:



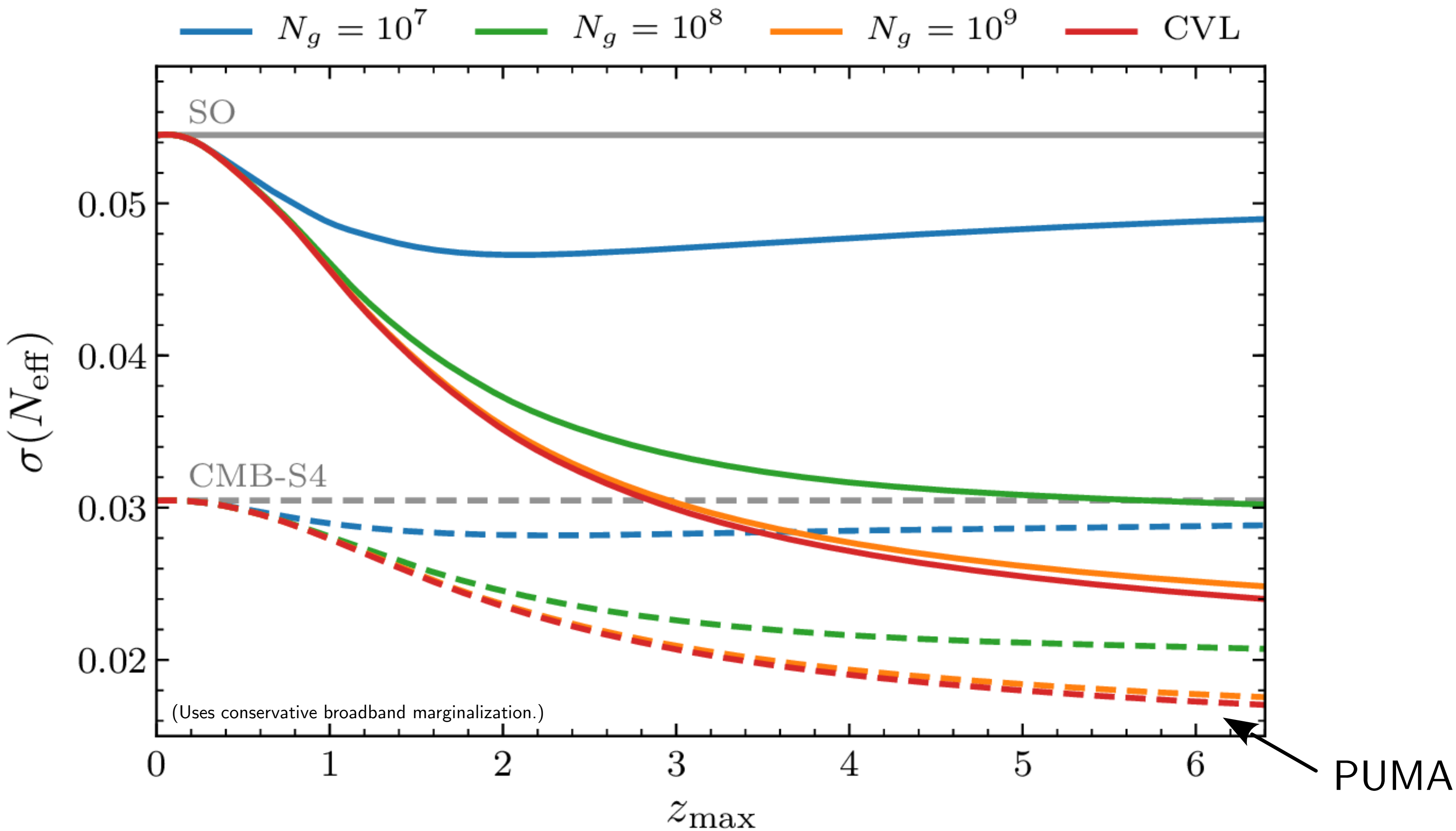
(Uses conservative broadband marginalization.)

→ Planned LSS surveys will provide significant improvements over Planck.

→ Combining with planned CMB experiments, we get further increase of sensitivity.

Baumann, Green & BW (2018)

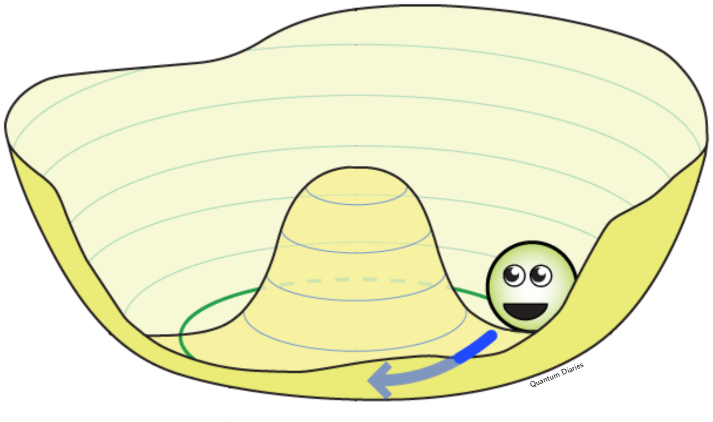
Future Constraints from CMB and LSS



$\rightarrow$ Go beyond neutrinos and probe other light relics!

Baumann, Green & BW (2018)

Extra Light Species



Light and weakly interacting particles arise in many BSM models, e.g. from spontaneously broken global symmetries.

Classification of interactions with the Standard Model in effective field theory:

$$\mathcal{L} \supset \sum \frac{\mathcal{O}_X \mathcal{O}_{\rm SM}}{\Lambda^{\Delta}}$$

allowed interactions constrained by symmetry

symmetry breaking scale

Useful to classify according to spin
$\rightarrow$ dark scalars (e.g. axions), dark fermions, dark forces, gravitinos

Brust, Kaplan & Walters (2013)

Light Thermal Relics

Relic density $\rho_X(\Lambda)$ measured in terms of $N_{\text{eff}} = N_{\text{eff}}^{\text{SM}} + \Delta N_{\text{eff}}$:

$$\Delta N_{\text{eff}}(T_{\text{dec}}) = \frac{\rho_X}{\rho_{\nu_i}} = 0.027\, g_{*,X} \left(\frac{g_{*,\text{SM}}}{g_*(T_{\text{dec}})} \right)^{4/3} \gamma^{-4/3}$$

effective number of relativistic degrees of freedom

entropy production

$$g_{*,X} = 1, \frac{4}{7}, 2, \ldots \text{ for spin-0}, \frac{1}{2}, 1, \ldots \qquad g_{*,\text{SM}} = 106.75$$

Assume:

– Negligible entropy production ($\gamma \approx 1$).

– Minimal extension of the Standard Model ($g_*(T \gg m_t) \approx g_{*,SM}$).

$$\longrightarrow \Delta N_{\text{eff}} \geq 0.027\, g_{*,X}$$

cf. BW (2018)

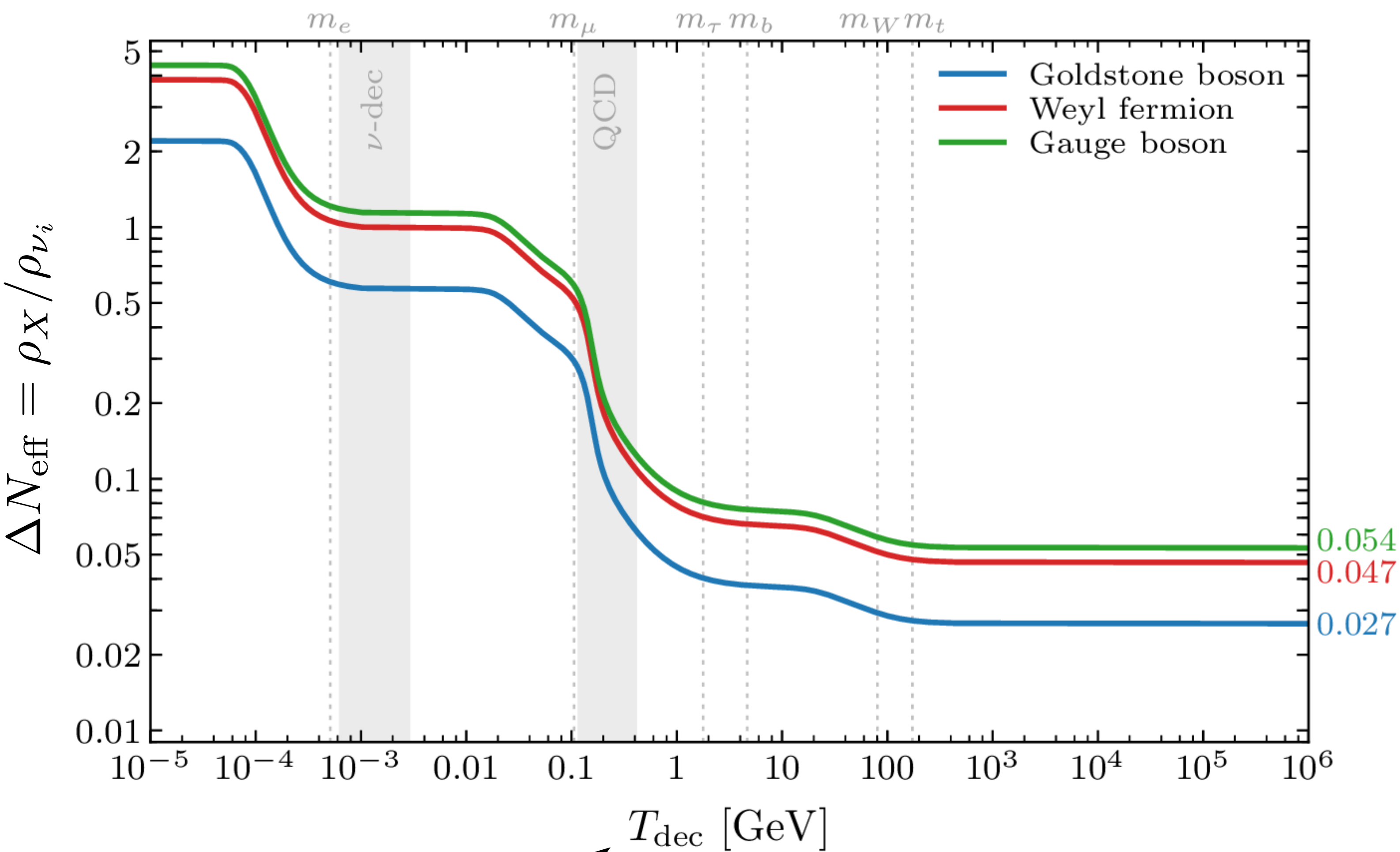
CMB Stage-4

One of the main science targets of the next-generation CMB experiments:

		$\sigma(r)$	$\sigma(N_{\mathrm{eff}})$	$\sigma(\Sigma m_\nu)$
2017 2018	**CMB-S2** 1 000 detectors	0.035	0.14	$0.15\,\mathrm{eV}$
2019 2020 2021 ...	**CMB-S3** 10 000 detectors	0.006	0.06	$0.06\,\mathrm{eV}$
	CMB-S4 500 000 detectors			
Target		$\mathbf{0.0005}$	$\mathbf{0.027}$	$\mathbf{0.015\,eV}$

CMB-S4 Science Book (2016)

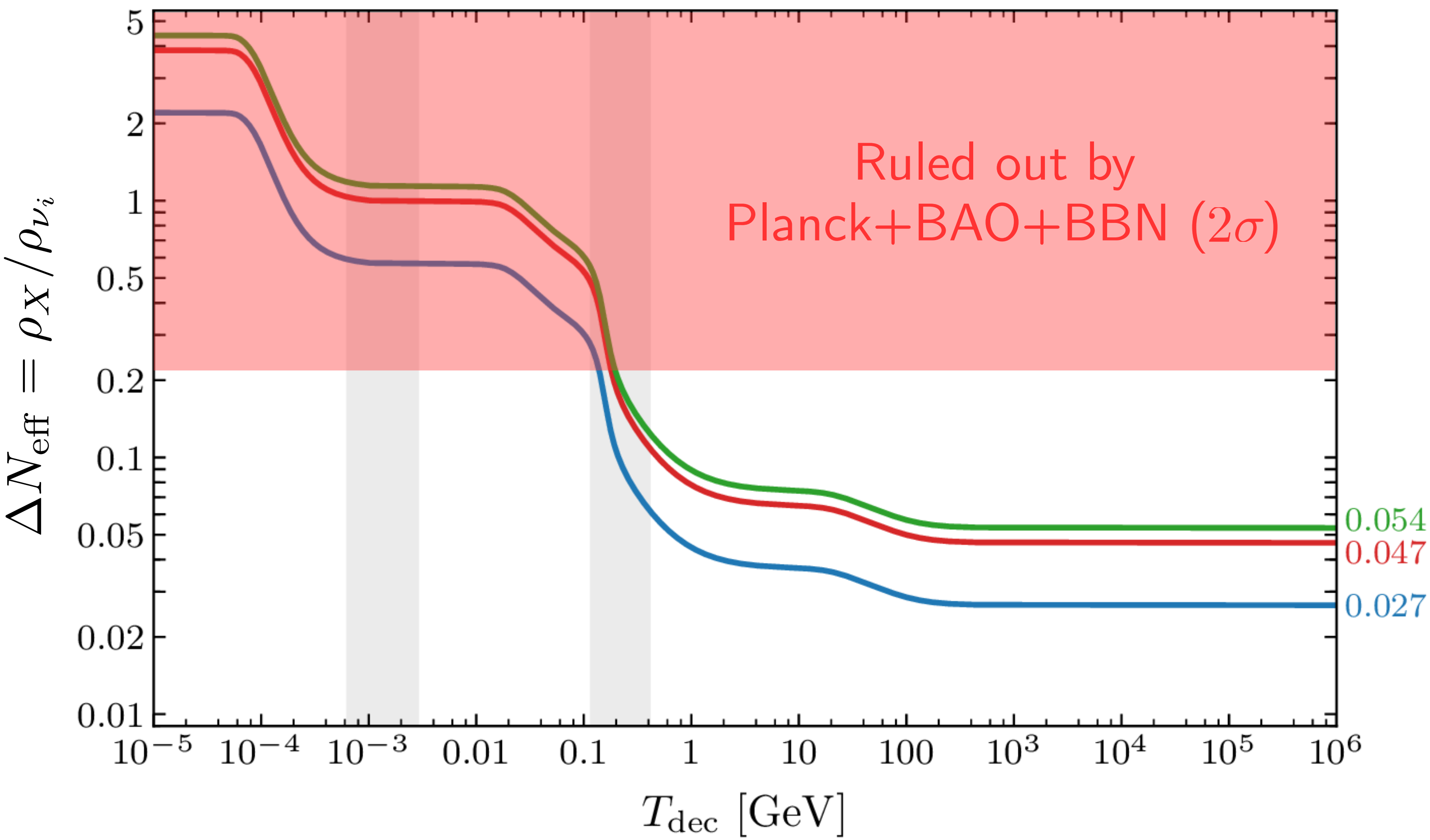
Light Thermal Relics



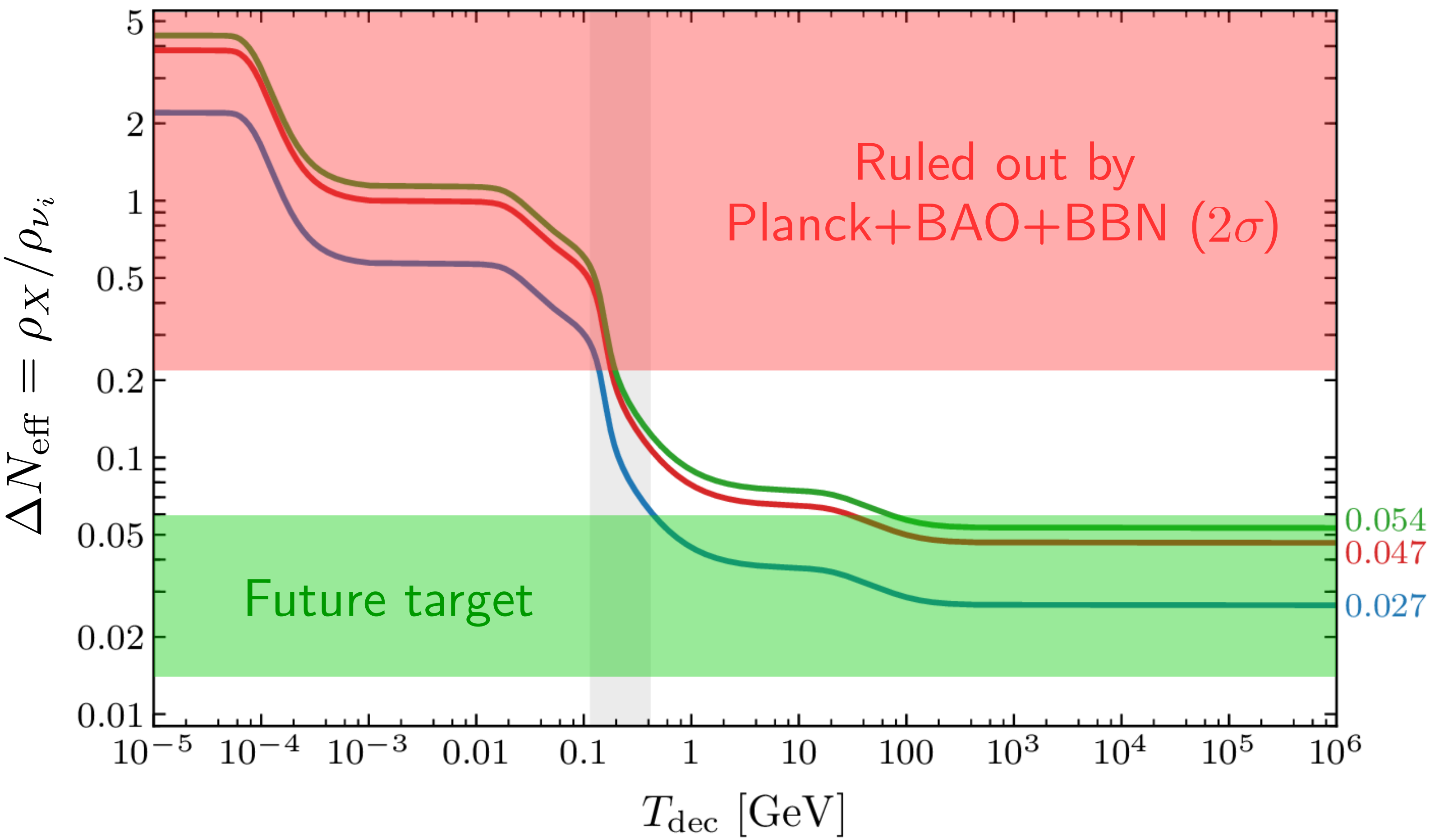
Depends on coupling Λ

$$\Delta N_{\rm eff}(T_{\rm dec}) = 0.027\, g_{*,X} \left(\frac{g_{*,\rm SM}}{g_*(T_{\rm dec})}\right)^{4/3}$$

Light Thermal Relics



Light Thermal Relics



Theoretical Threshold: $\Delta N_{\rm eff} = 0.027$

Detection

Constraints

Example: Constraints on Axions

$$\mathcal{L} = -\frac{\phi}{4\Lambda_\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{\phi}{4\Lambda_g} \mathrm{tr}\{G_{\mu\nu}\tilde{G}^{\mu\nu}\}$$

Assume: $\Delta N_{\mathrm{eff}} = 0.027$ excluded:

$\rightarrow$ Axion was never in thermal equilibrium.

$\rightarrow$ Production rate must be smaller than Hubble rate at reheating:

$$\Gamma(\Lambda_i, T_R) \lesssim H(T_R)\,.$$

$\rightarrow$ Production rate depends on couplings to the Standard Model.

$\rightarrow$ Strong constraints:

$$\Lambda_\gamma > 1.4 \times 10^{13}\,\mathrm{GeV} \left(\frac{T_R}{10^{10}\,\mathrm{GeV}}\right)^{1/2},$$

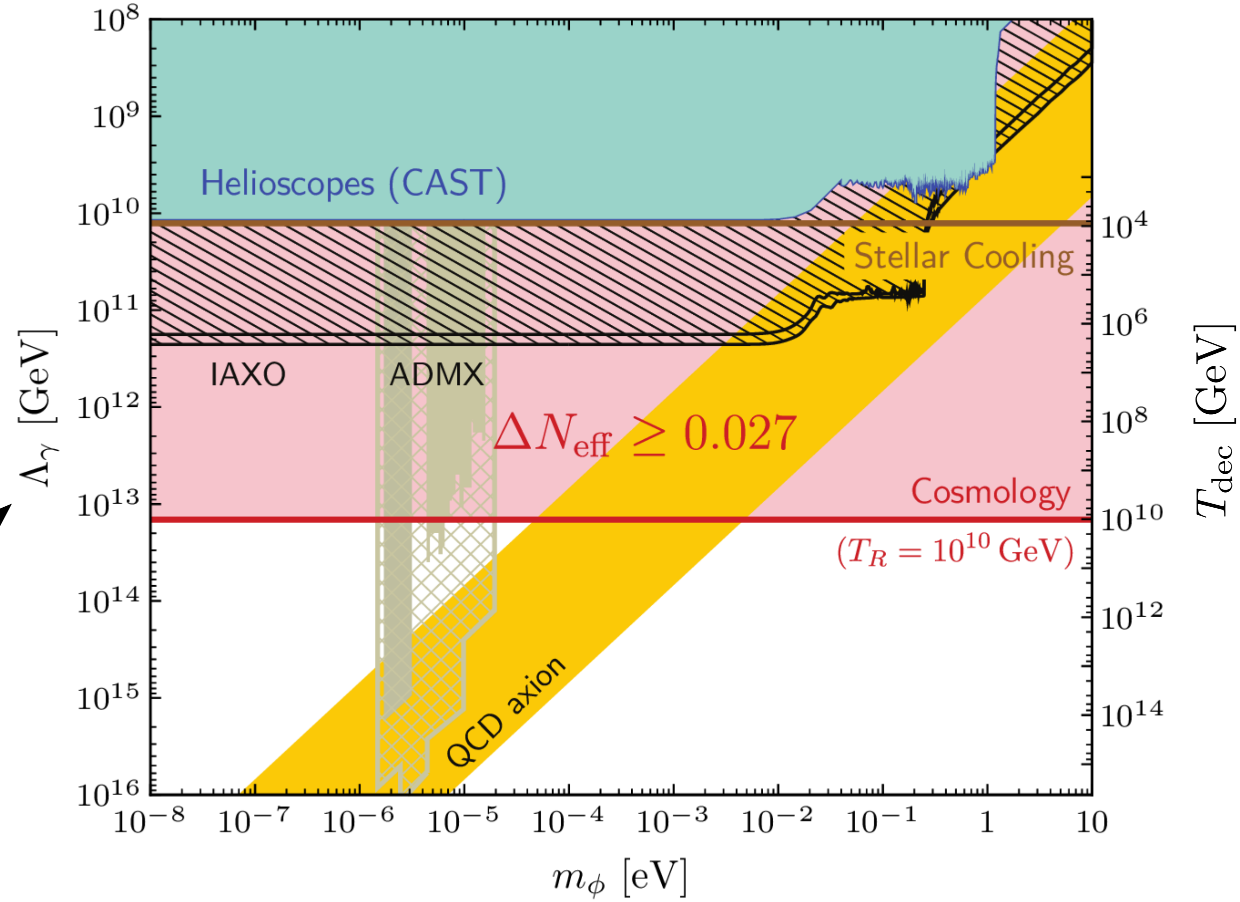
$$\Lambda_g > 5.4 \times 10^{13}\,\mathrm{GeV} \left(\frac{T_R}{10^{10}\,\mathrm{GeV}}\right)^{1/2}.$$

Baumann, Green & BW (2016)

Axion Coupling to Photons

Exclusion of $\Delta N_{\rm eff} = 0.027$ implies strong constraints on couplings to the Standard Model:

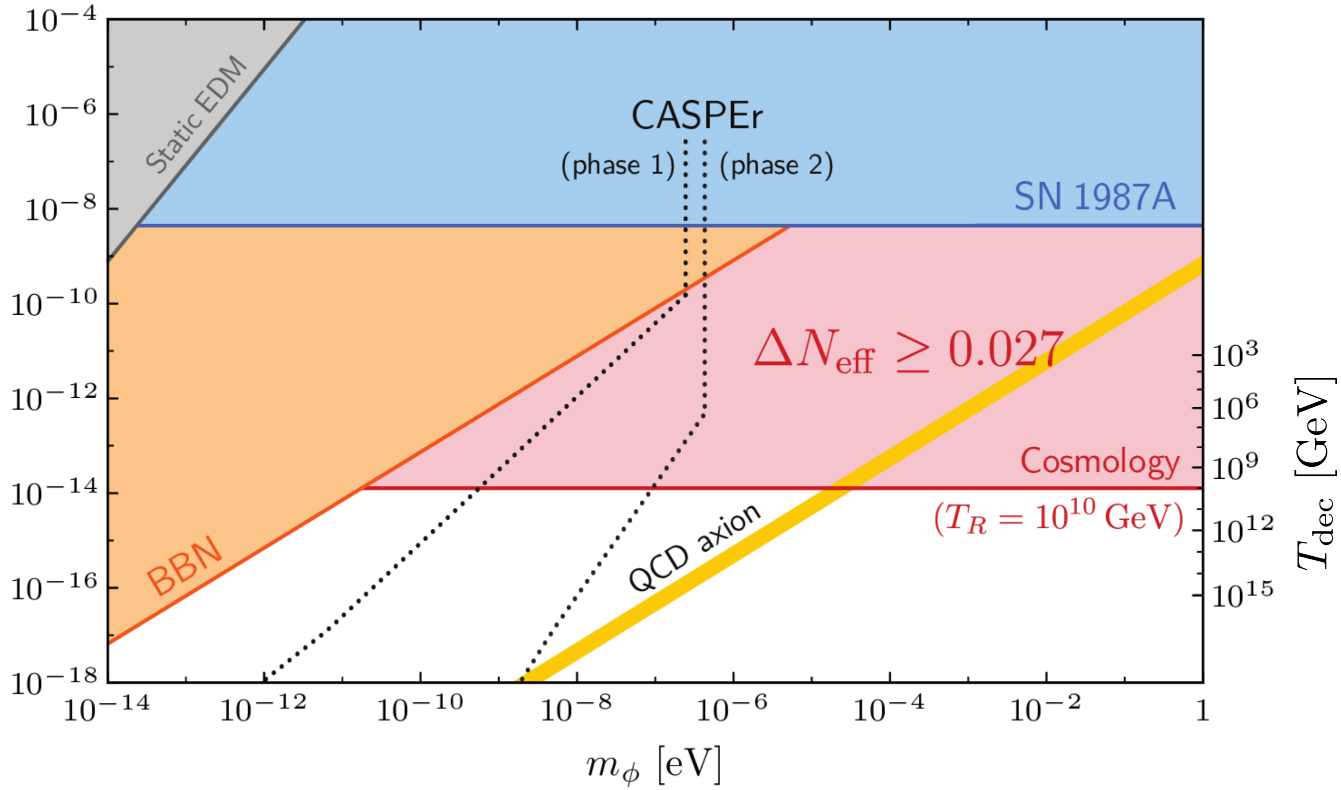
$$-\frac{\phi}{4\Lambda_\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu}$$



Baumann, Green & BW (2016)

Axion Coupling to Gluons

Exclusion of $\Delta N_{\rm eff} = 0.027$ implies strong constraints on couplings to the Standard Model:



$$-\frac{\phi}{4\Lambda_g}\mathrm{tr}\{G_{\mu\nu}\tilde{G}^{\mu\nu}\}$$

$$g_d \approx \frac{2\pi}{\alpha_s} \times \frac{3.8\times 10^{-3}\,\mathrm{GeV}^{-1}}{\Lambda_g}$$

Baumann, Green & BW (2016)

Conclusions

(1) Cosmic neutrino background consists of free-streaming particles (now seen in both the CMB and BAO spectra).

(2) Future cosmological observations have the potential to measure the radiation density of the early universe at the level of

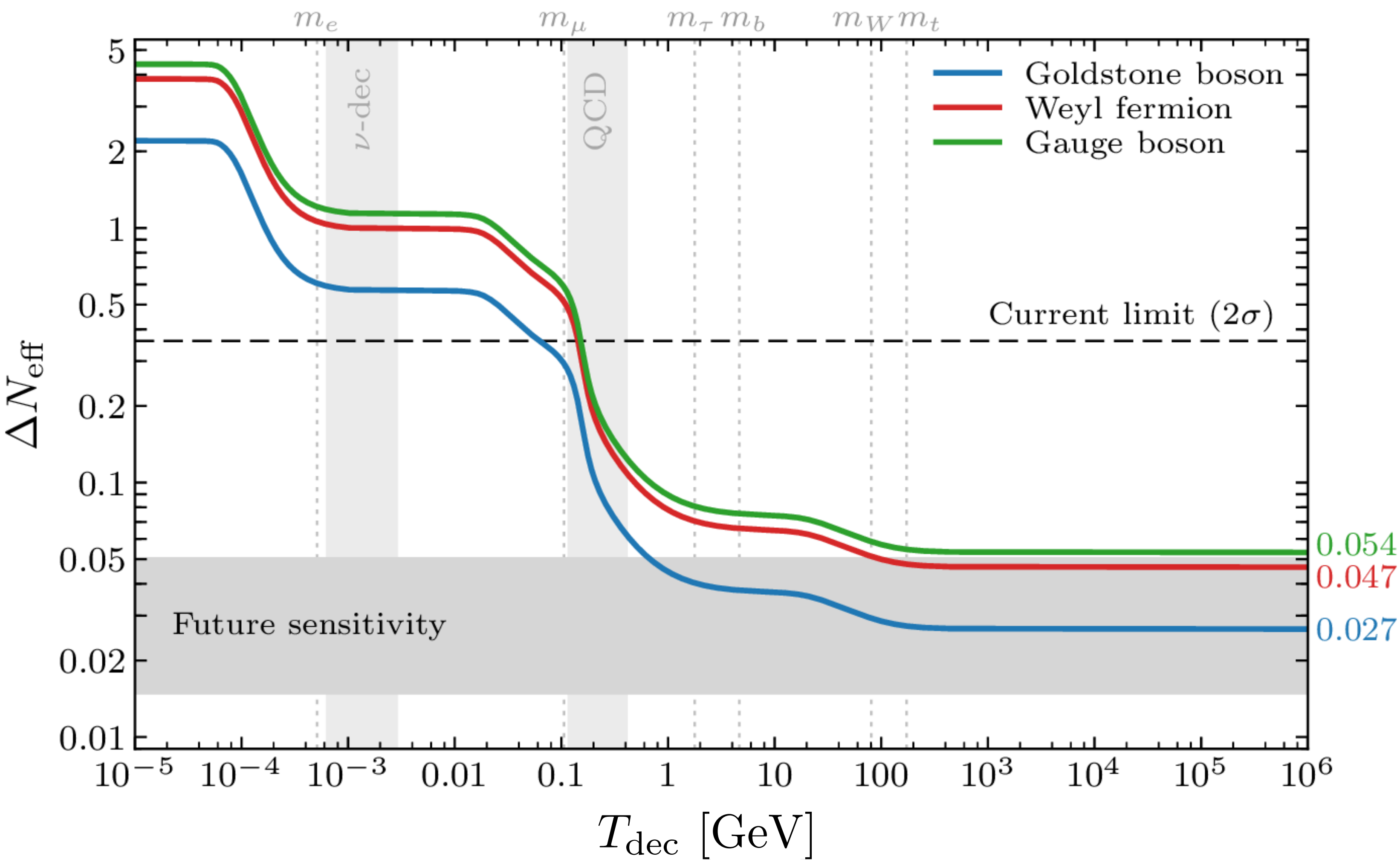
1%

This is an important improvement over current constraints.

How to get there? $\longrightarrow$ Combine future CMB and LSS.

What to do with this? $\longrightarrow$ Probe cosmology and particle physics.

Thank you!



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