Cosmological Probes of Light Relics

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Based on work with:
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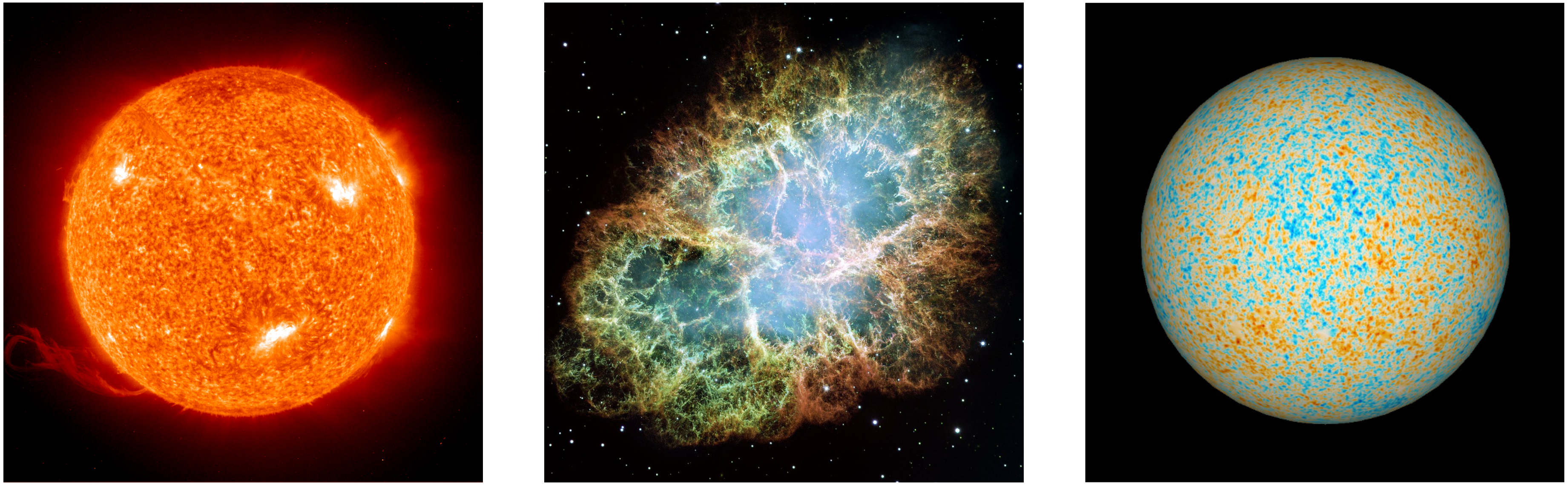
Florian Beutler, Raphael Flauger, Anže Slosar,
Mariana Vargas-Magaña, Christophe Yèche

LBNL Particle Seminar, February 2019

Light particles can be found in many extensions of the Standard Model of particle physics.

Their weak couplings make them hard to detect in terrestrial experiments.

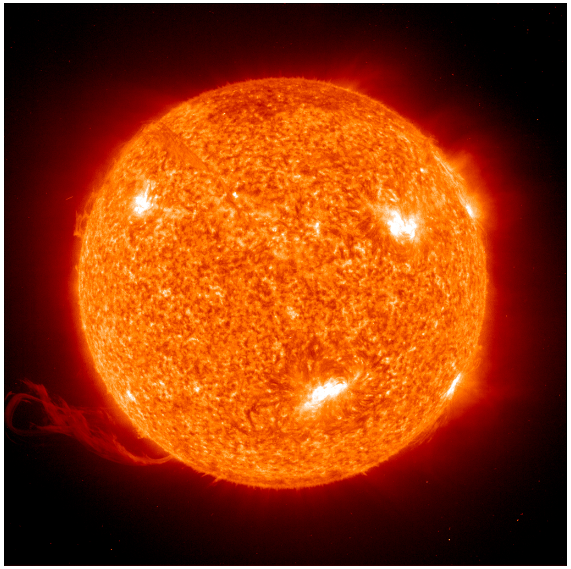
However, they can be efficiently produced in the extreme environments studied in astrophysics and cosmology!



Long time scales Δt and high densities n can compensate small cross sections σ:

$$\frac{\Delta n}{n} \sim \underset{\substack{\swarrow \\ \text{interaction} \\ \text{rate}}}{n\,\sigma} \times \underset{\substack{\searrow \\ \text{interaction} \\ \text{time}}}{\Delta t}$$

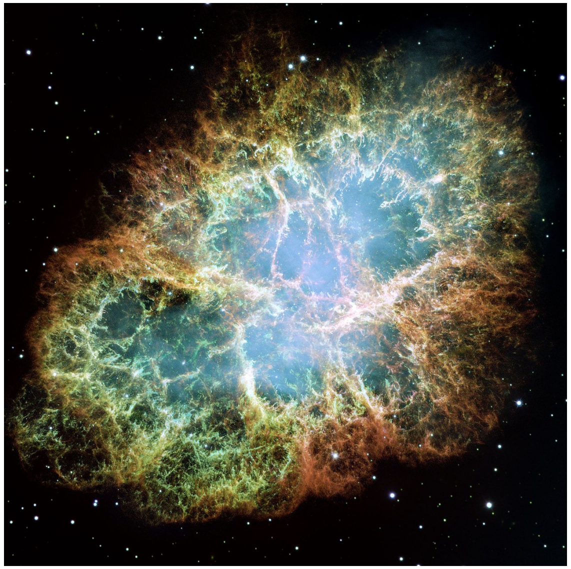
Stellar cooling



$$\Delta t \sim 10^{16}\,\mathrm{s}$$

$$n \sim T^3 \sim (1\,\mathrm{keV})^3$$

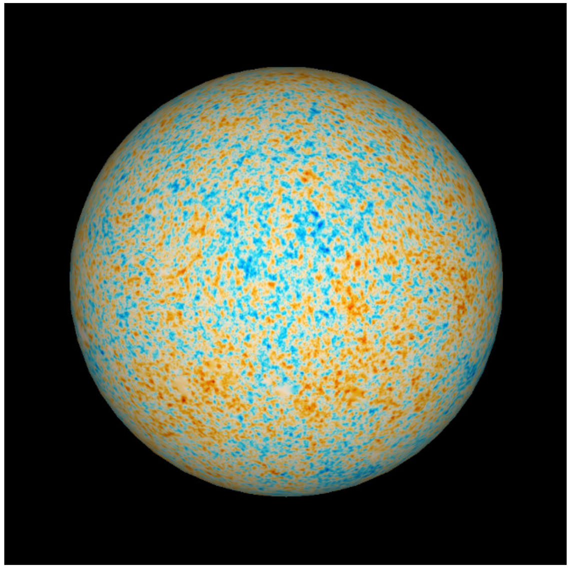
Supernovae



$$\Delta t \sim 10\,\mathrm{s}$$

$$n \sim T^3 \sim (10\,\mathrm{MeV})^3$$

Early universe

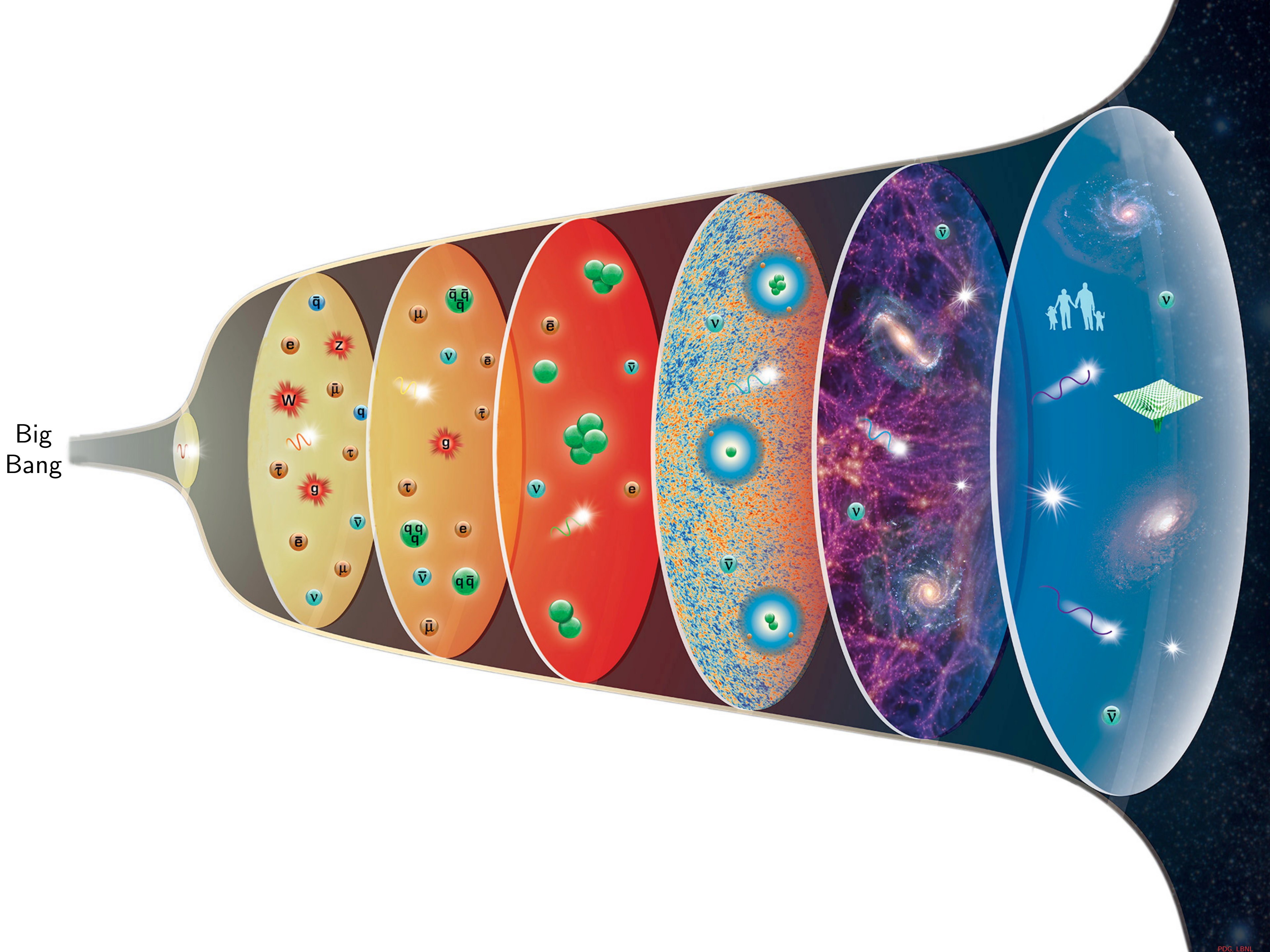


$$\Delta t \lesssim 1\,\mathrm{s}$$

$$n \sim T^3 \gg (1\,\mathrm{MeV})^3$$

Above $10^4\,\mathrm{GeV}$, cosmology beats astrophysics.

→ Probe particle physics and the history of the universe.


Big
Bang
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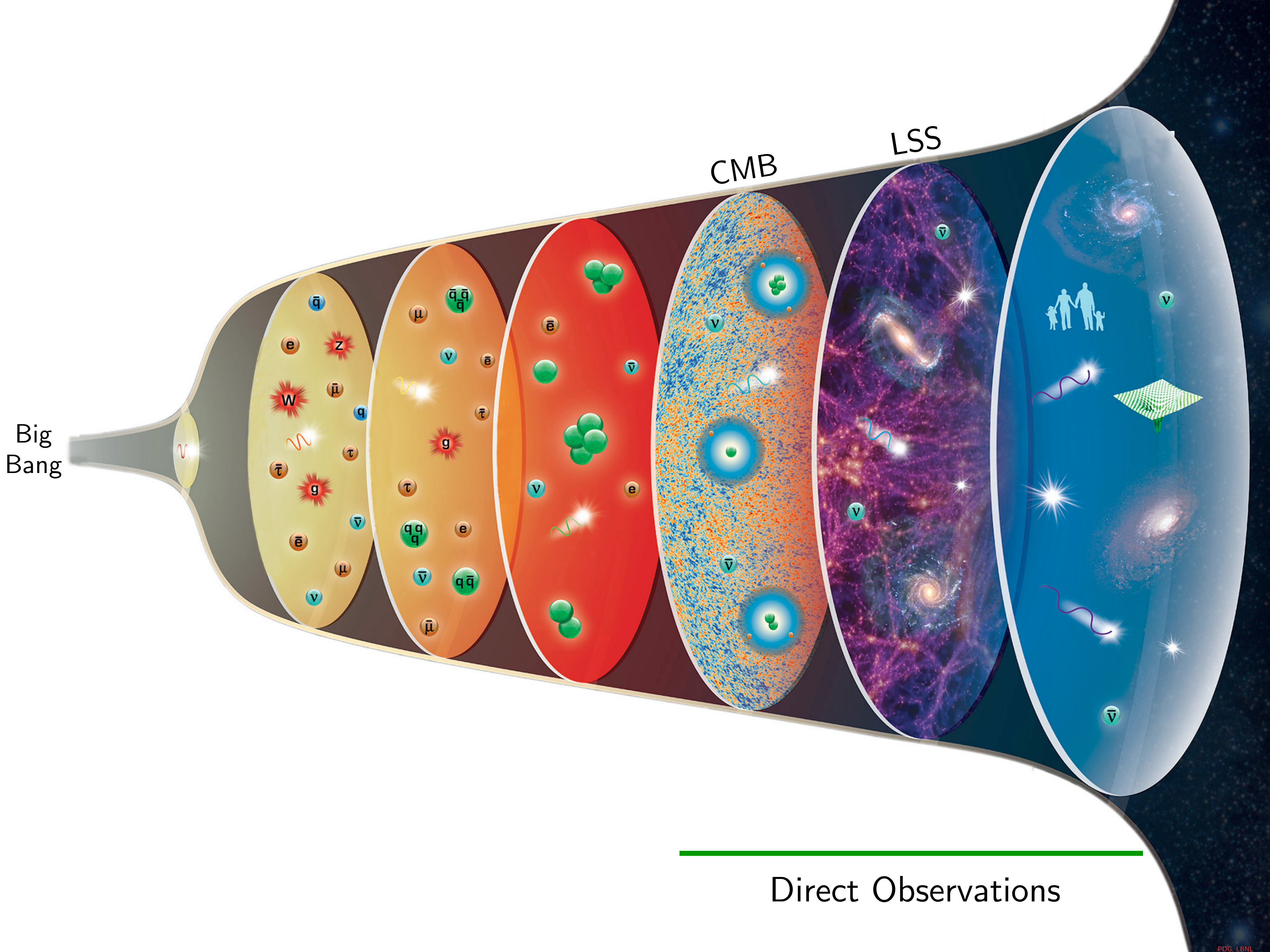
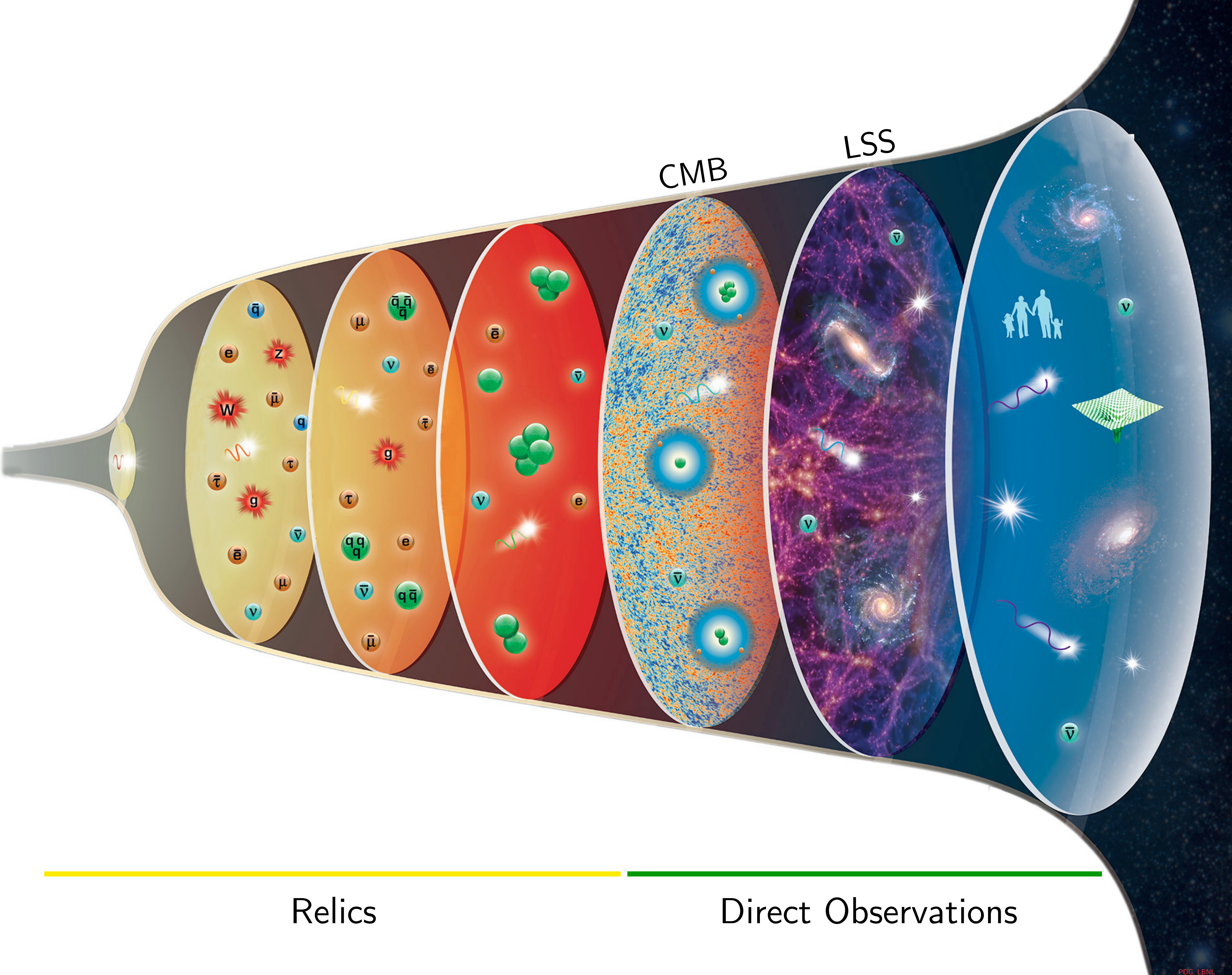
PDG, LBNL


Big Bang
CMB
LSS
Direct Observations
PDG, LBNL

Big
Bang



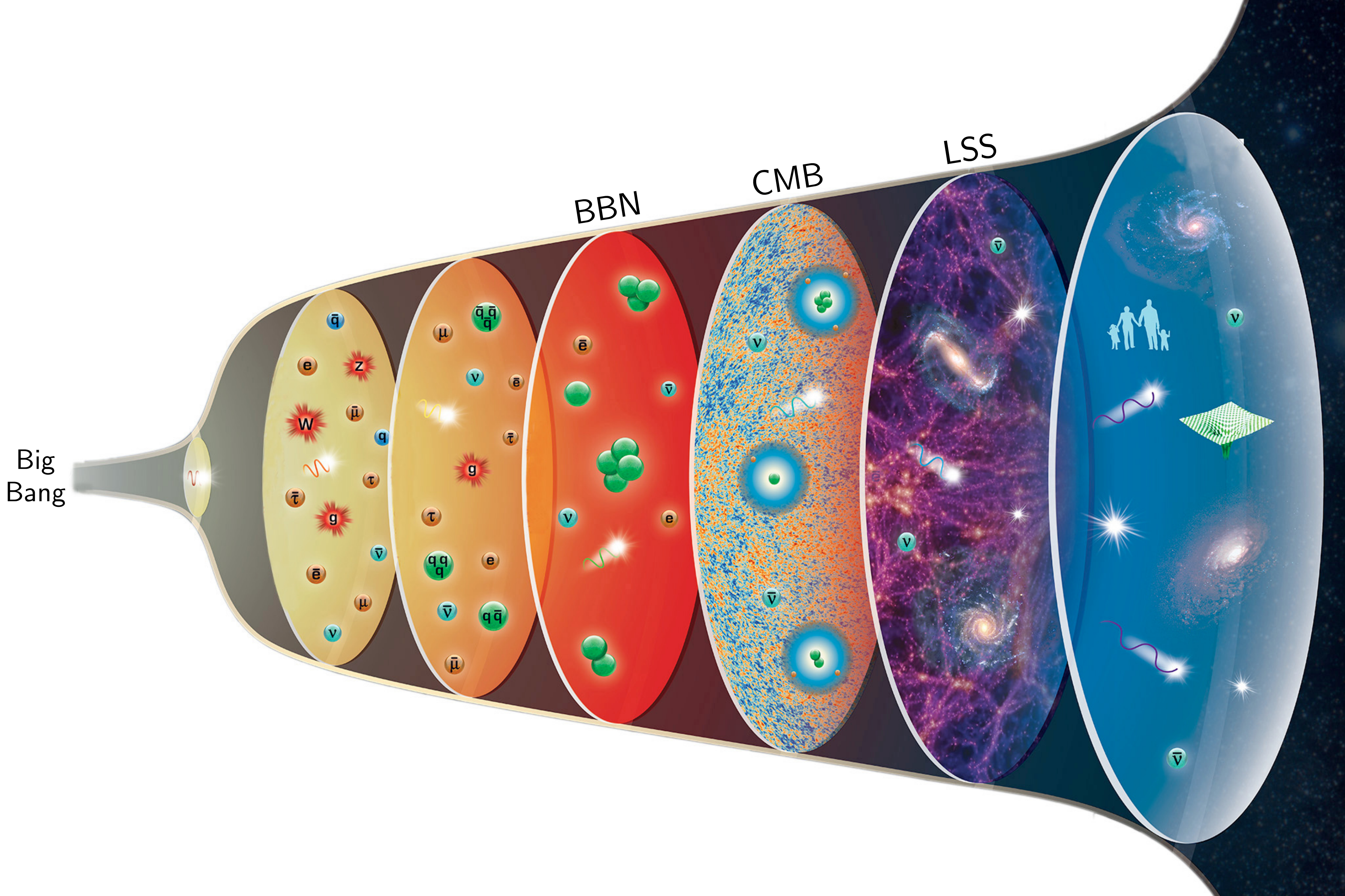
CMB

LSS

Relics

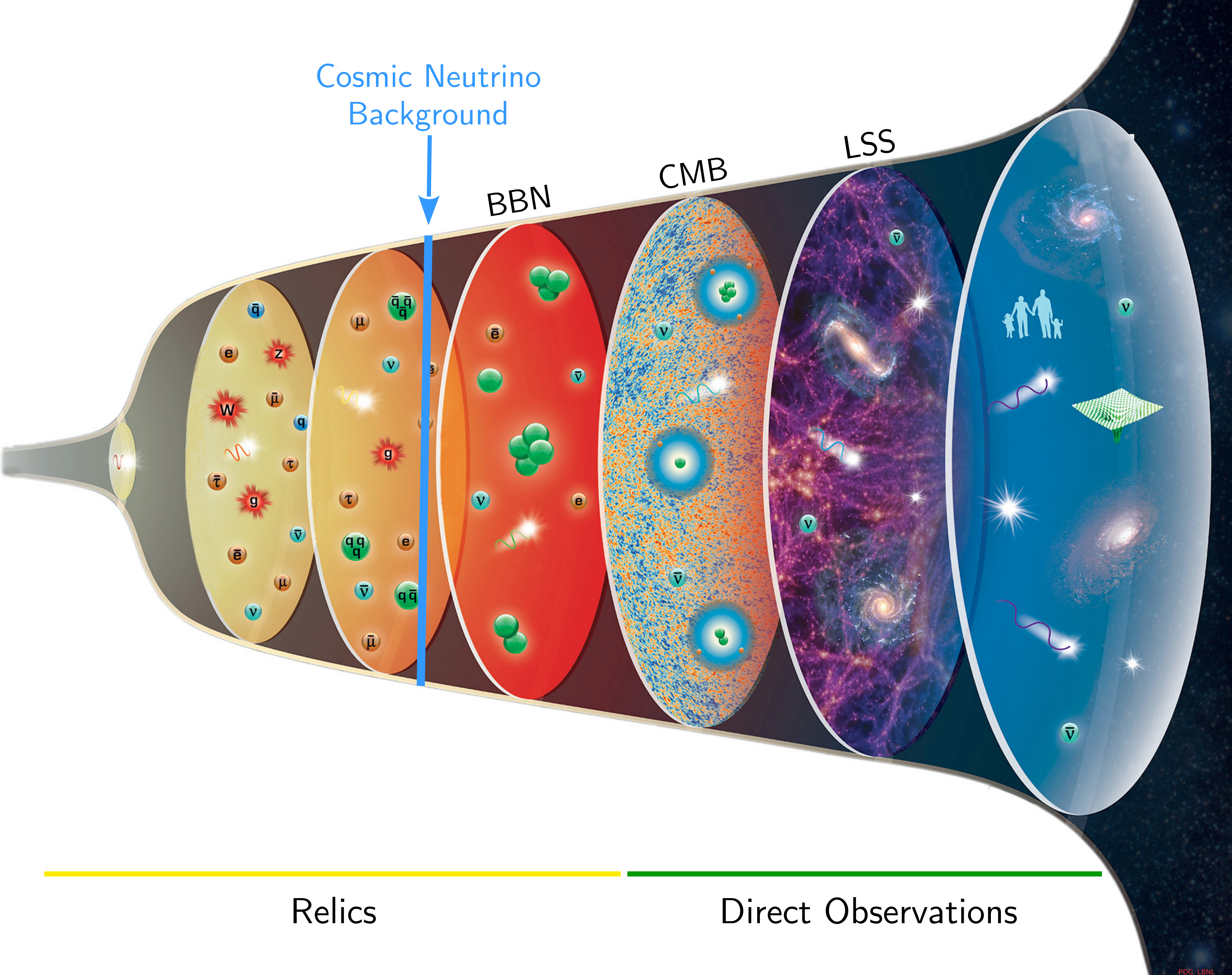
Direct Observations

PDG, LBNL



Relics

Direct Observations



Cosmic Neutrino Background

Big Bang

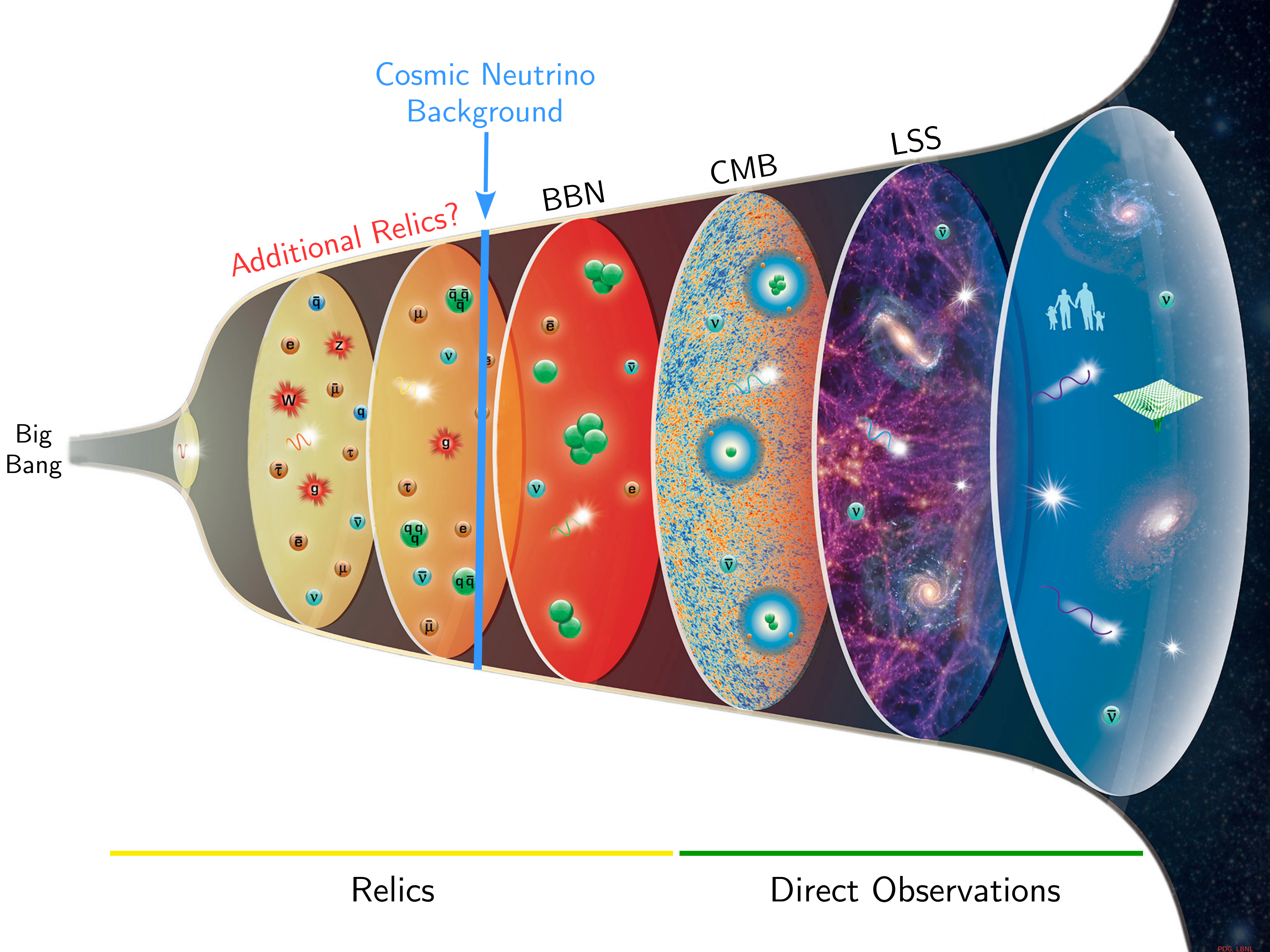
BBN

CMB

LSS

Relics

Direct Observations


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

PDG, LBNL

CMB Stage-4

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

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

CMB-S4 Science Book (2016)

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CMB-S4 Science Book (2016)

Plan of the Talk

- Neutrinos and Other Light Relics

- Probing with the Cosmic Microwave Background

- Probing with the Large-Scale Structure of the Universe

- Measuring Neutrinos in the BAO Spectrum

- Conclusions

Neutrinos and Other Light Relics (aka Dark Radiation)

D. Baumann, D. Green and BW
arXiv:1604.08614 (PRL 2016)

Neutrinos

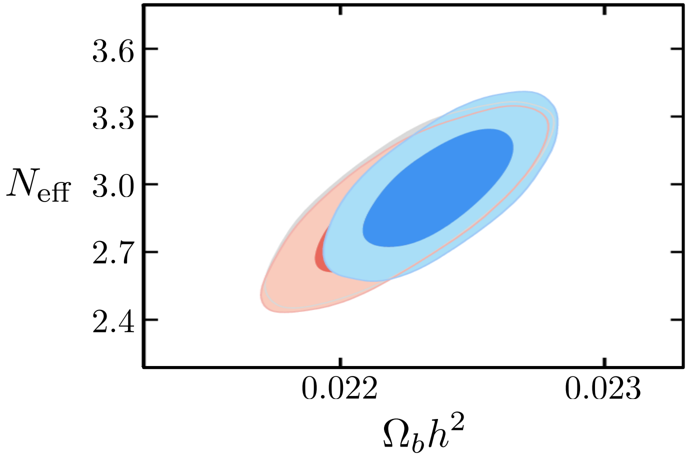
41% of radiation density in the universe:

→ leave gravitational imprint,

→ can detect their energy density.

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

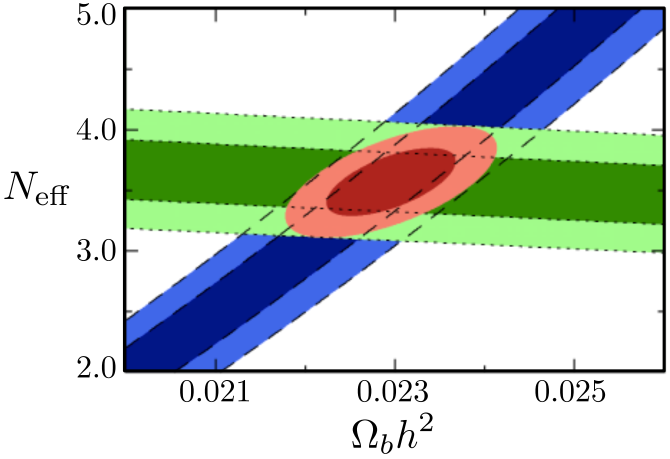
Observable: "effective number of neutrinos" $N_{\mathrm{eff}}^{\mathrm{SM}} = 3.046$



CMB: anisotropy measurements

$$N_{\mathrm{eff}}^{\mathrm{CMB}} = 2.99 \pm 0.17$$

Planck (2018)

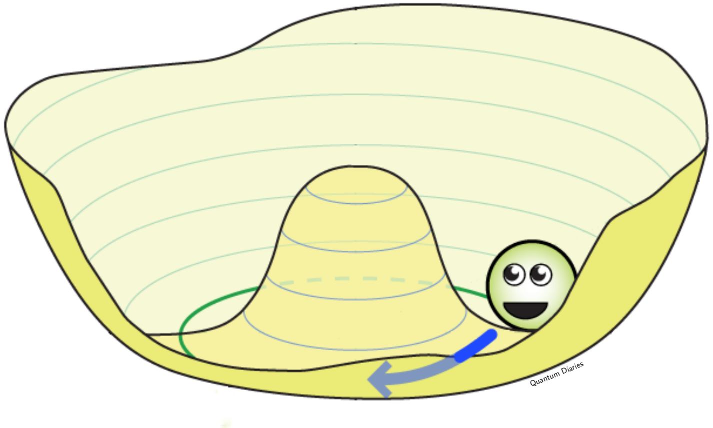


BBN: primordial abundances

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

Cooke et al. (2015)

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:

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

allowed interactions constrained by symmetry

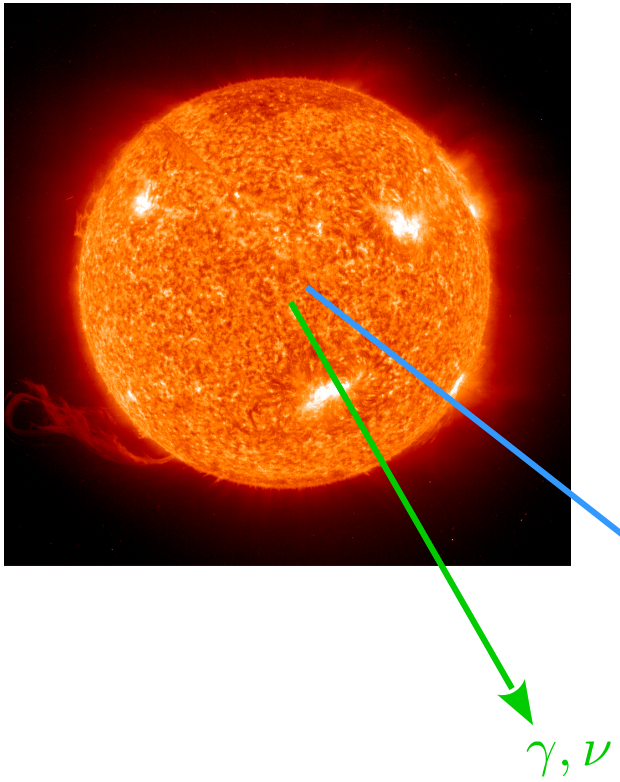
symmetry breaking scale

Useful to classify according to spin

→ dark scalars (e.g. axions), dark fermions, dark forces, gravitinos

Brust, Kaplan & Walters (2013)

Axions in Stars



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

axion-photon
coupling

$$\Big\downarrow$$

$$\Gamma \sim \frac{T^3}{\Lambda_\gamma^2}$$

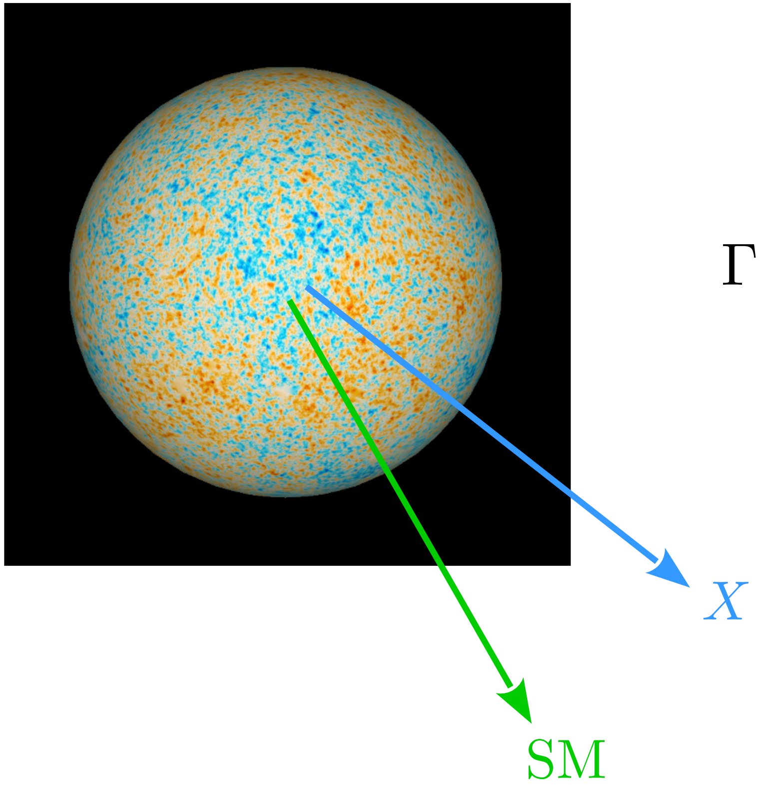
axion
production rate

$$\Big\downarrow$$

$$\Lambda_\gamma \gtrsim 10^{10}\,\mathrm{GeV}$$

constraint from
stellar cooling

Light Thermal Relics



$$\begin{tikzcd} \dfrac{\mathcal{O}_X \mathcal{O}_{\rm SM}}{\Lambda^{\Delta}} \arrow[d] \\ \Gamma(\Lambda, T_{\rm dec}) \approx H(T_{\rm dec}) \arrow[d] \\ \rho_X(\Lambda) \arrow[d] \\ \Delta N_{\rm eff}(T_{\rm dec}) = \dfrac{\rho_X}{\rho_{\nu_i}} \end{tikzcd}$$

coupling to the SM

decoupling

relic density

Light Thermal Relics

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

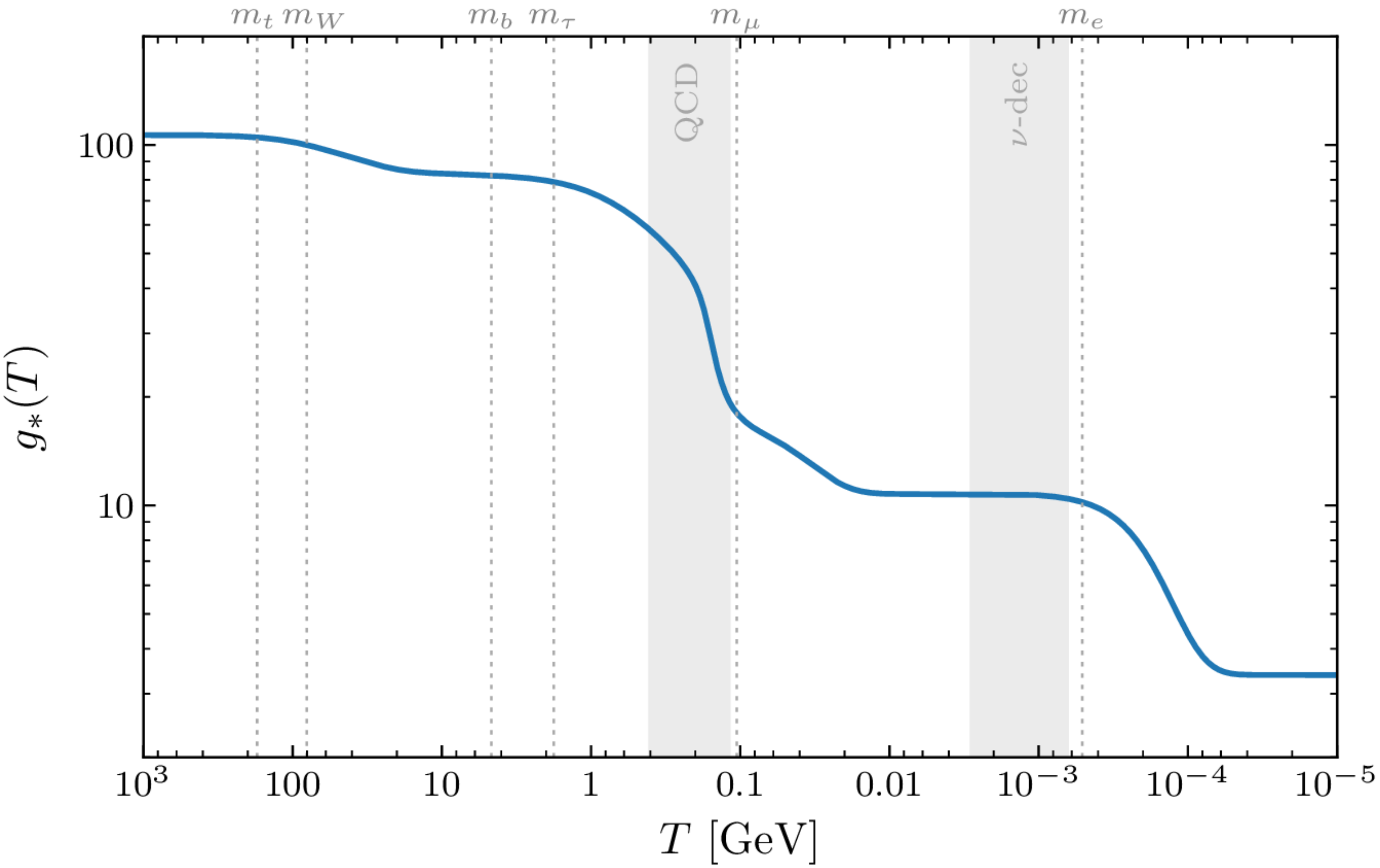
$$\Delta N_{\text{eff}}(T_{\text{dec}}) = \frac{\rho_X}{\rho_{\nu_i}} = 0.027\, g_{*,X} \left(\frac{g_{*,\text{SM}}}{g_*(T_{\text{dec}})} \right)^{4/3} \gamma^{-4/3}$$

effective number of relativistic degrees of freedom

entropy production

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

Effective Number of Relativistic DoFs



$$\max_{\mathrm{SM}}(g_*) = g_{*,\mathrm{SM}} = 106.75$$

Light Thermal Relics

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

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

effective number of relativistic degrees of freedom

entropy production

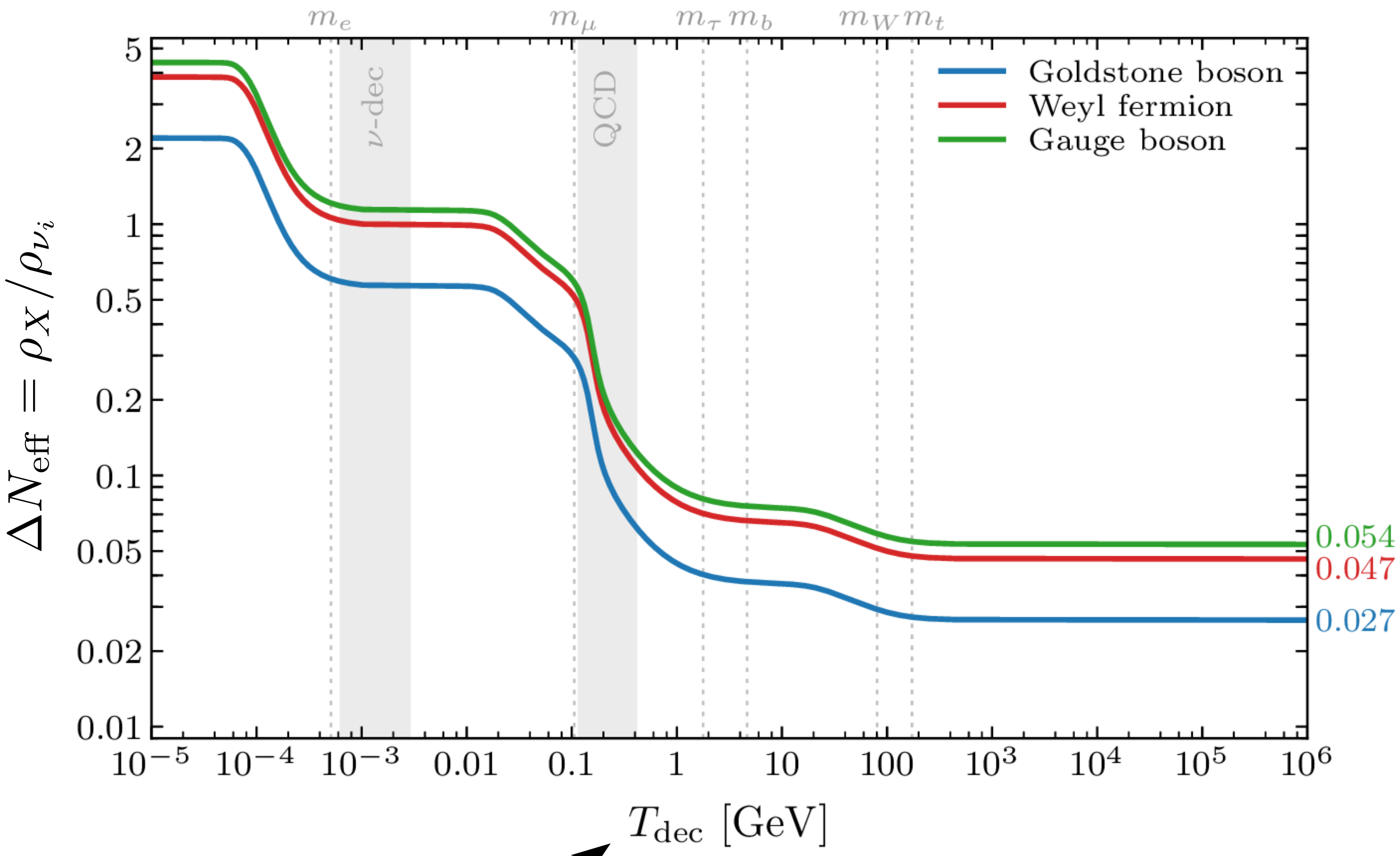
$$g_{*,X} = 1, \frac{4}{7}, 2, \ldots \text{ for spin-0}, \frac{1}{2}, 1, \ldots \qquad g_{*,\rm SM} = 106.75$$

Assume:

- Negligible entropy production ($\gamma \approx 1$).
- Minimal extension of the Standard Model ($g_*(T \gg m_t) \approx g_{*,SM}$).

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

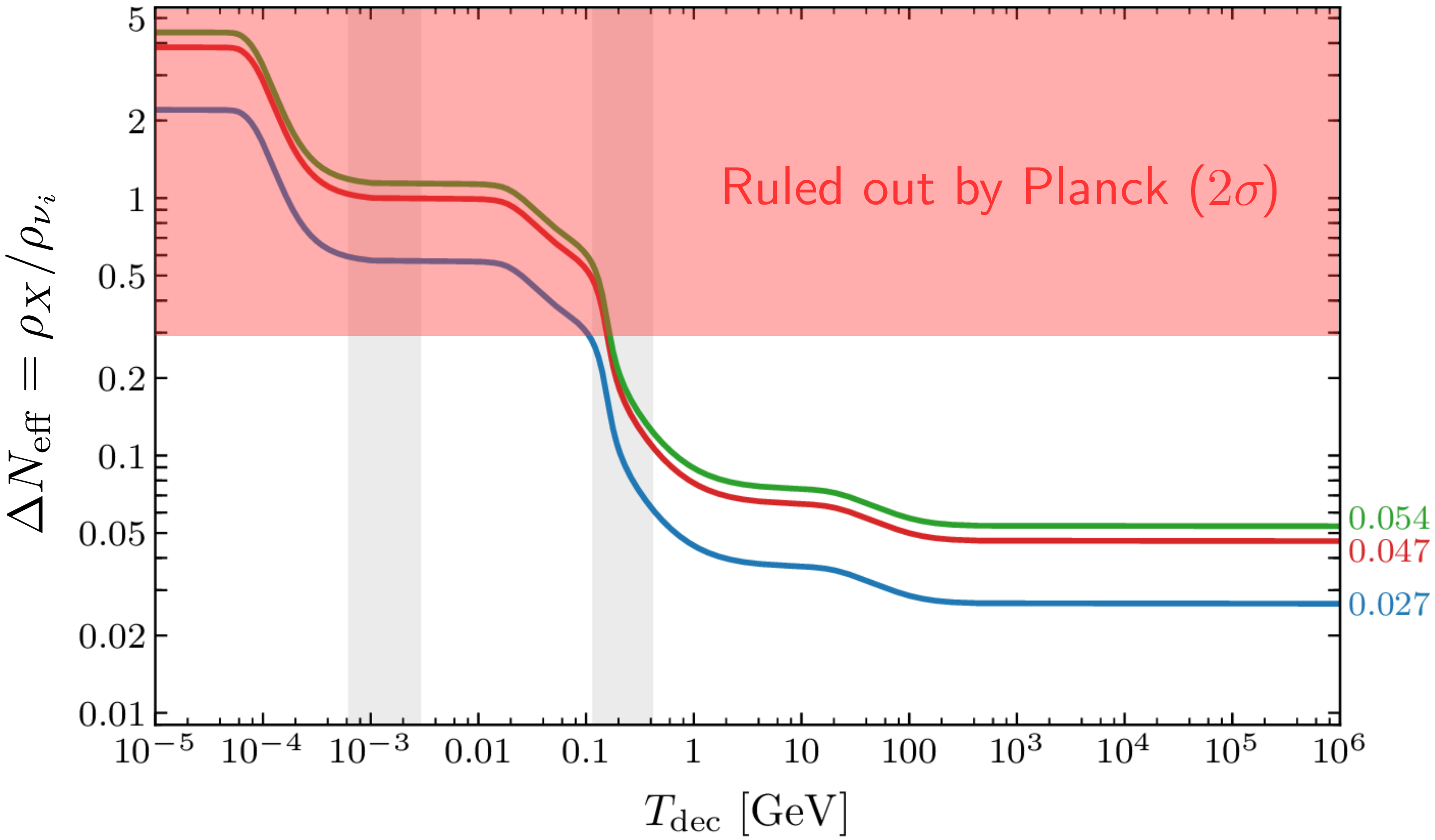
Light Thermal Relics



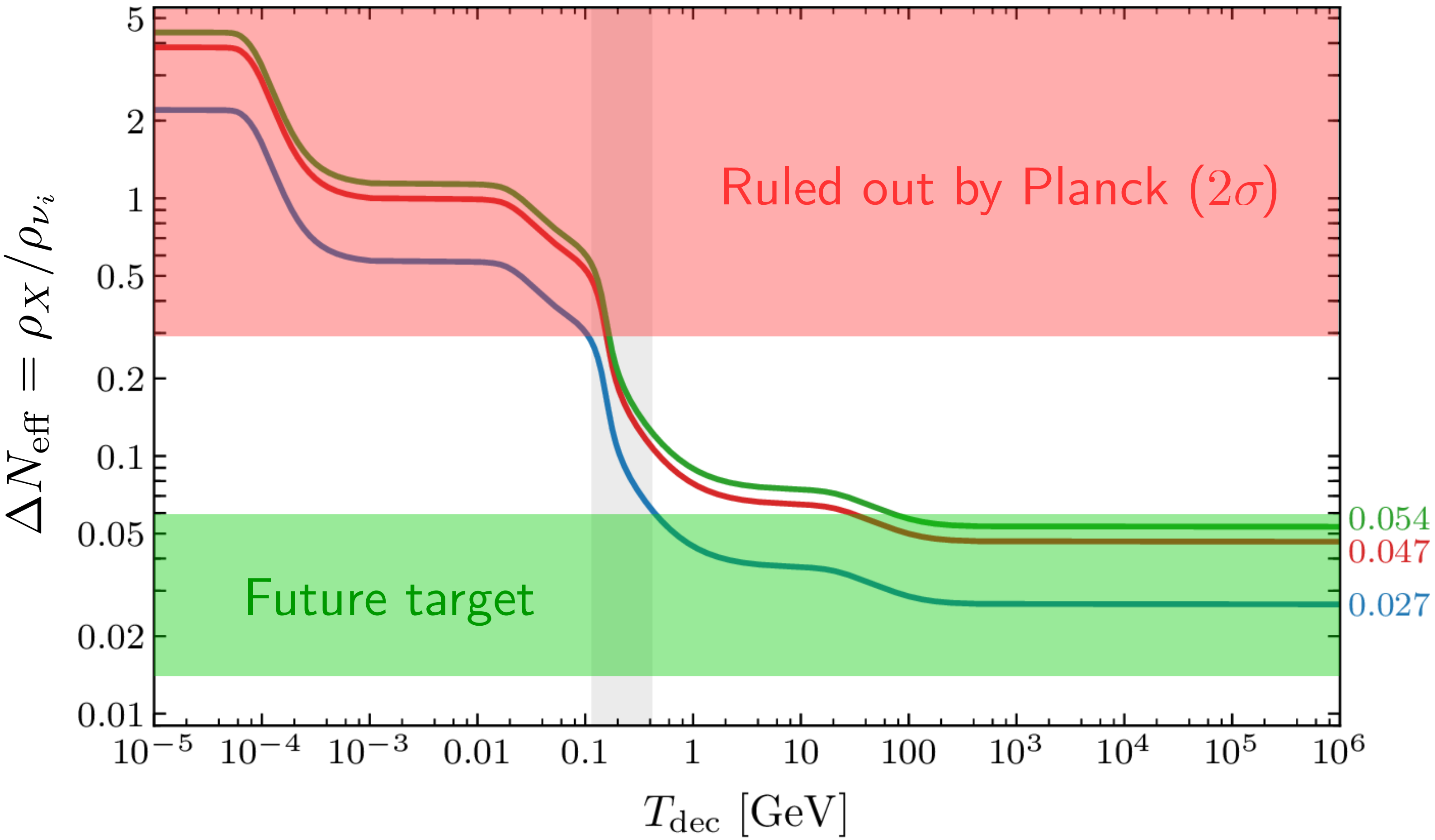
Depends on coupling Λ

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

Light Thermal Relics



Light Thermal Relics



Theoretical Threshold: $\Delta N_{\text{eff}} = 0.027$ → Detection → Constraints

CMB Stage-4

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

		$\sigma(r)$	$\sigma(N_{\rm eff})$	$\sigma(\Sigma m_\nu)$
2017 2018	**CMB-S2** 1 000 detectors	0.035	0.14	0.15 eV
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Target		**0.0005**	**0.027**	**0.015 eV**

CMB-S4 Science Book (2016)

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: $\Delta N_{\rm eff} = 0.027$ excluded:

→ Axion was never in thermal equilibrium.

→ Production rate must be smaller than Hubble rate at reheating:

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

→ Production rate depends on couplings to the Standard Model.

→ Strong constraints:

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

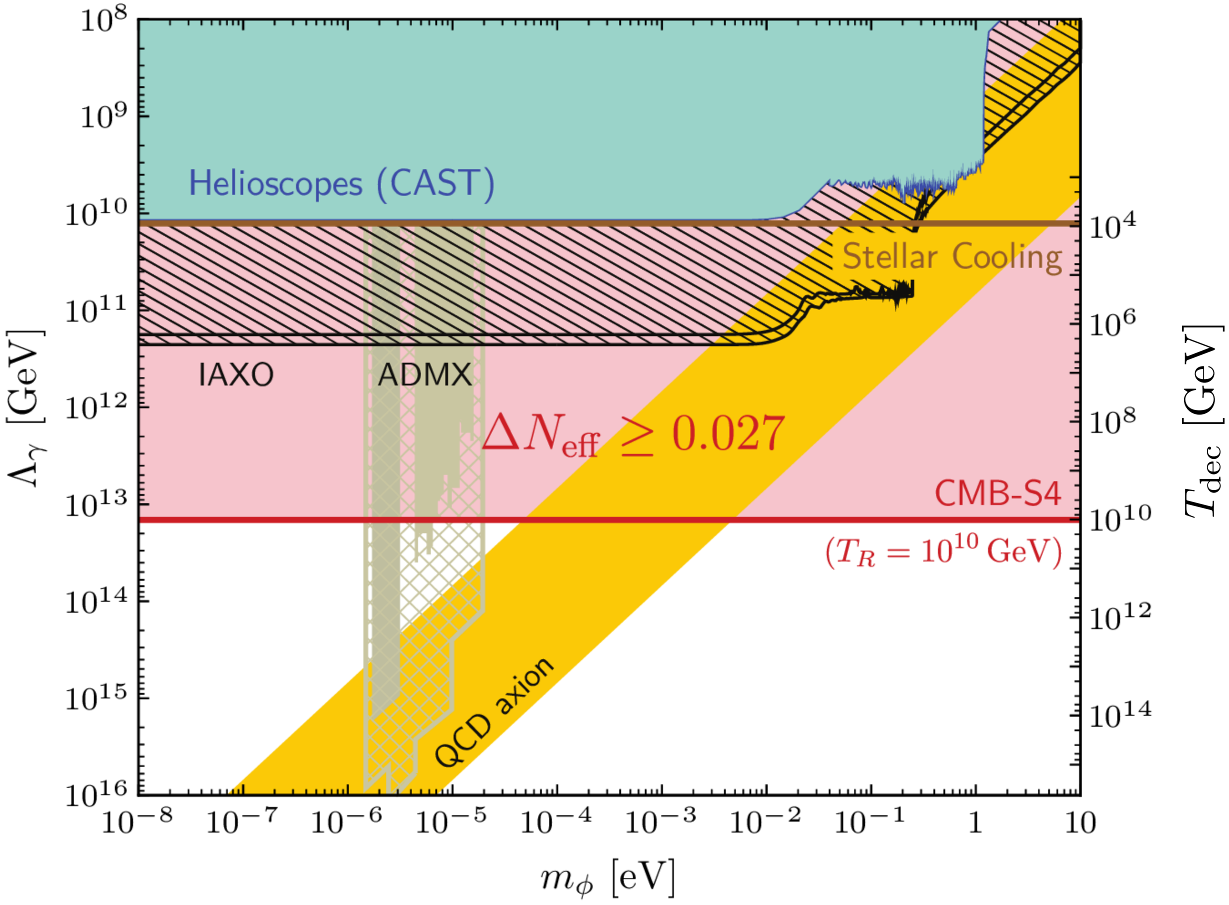
$$\Lambda_g > 5.4 \times 10^{13}\,\mathrm{GeV} \left(\frac{T_R}{10^{10}\,\mathrm{GeV}}\right)^{1/2}.$$

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

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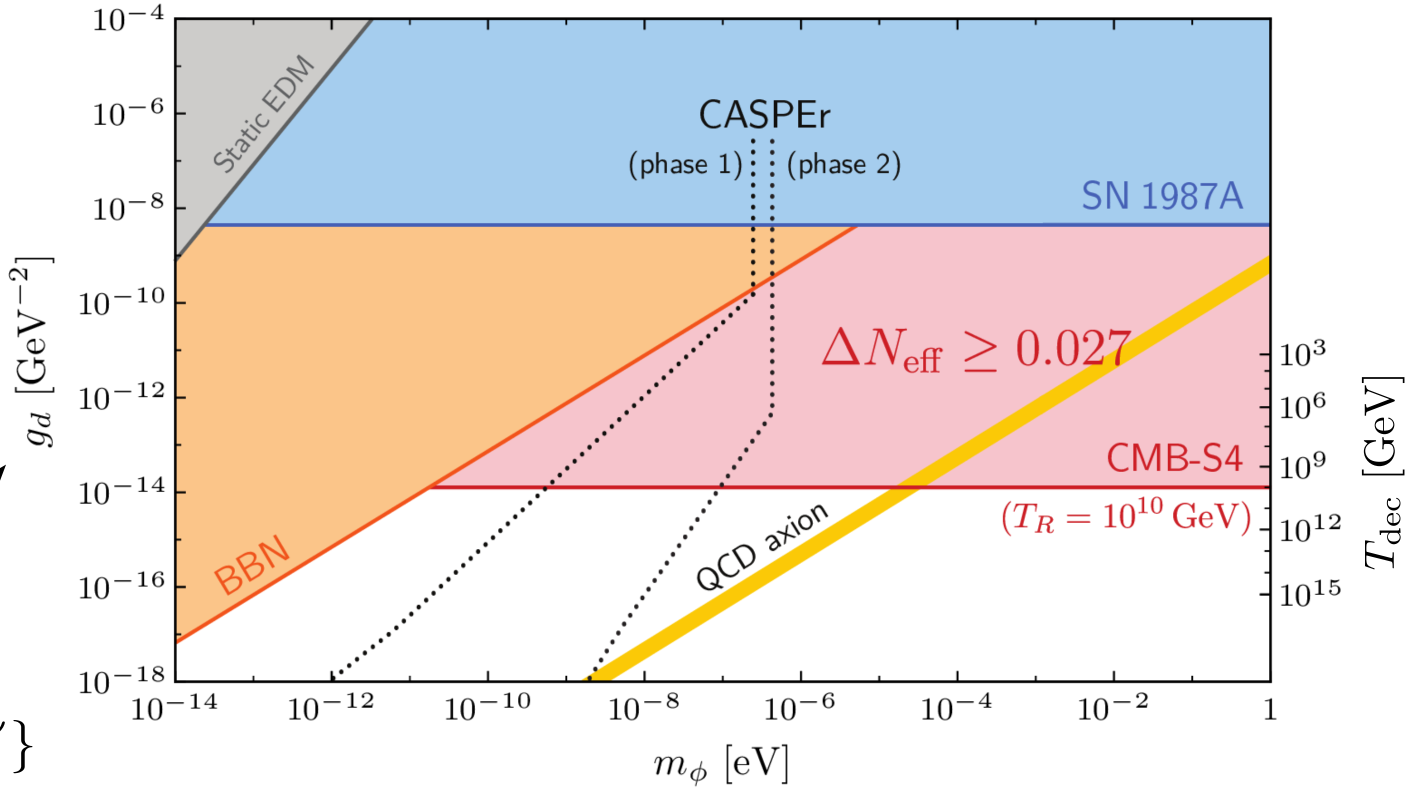


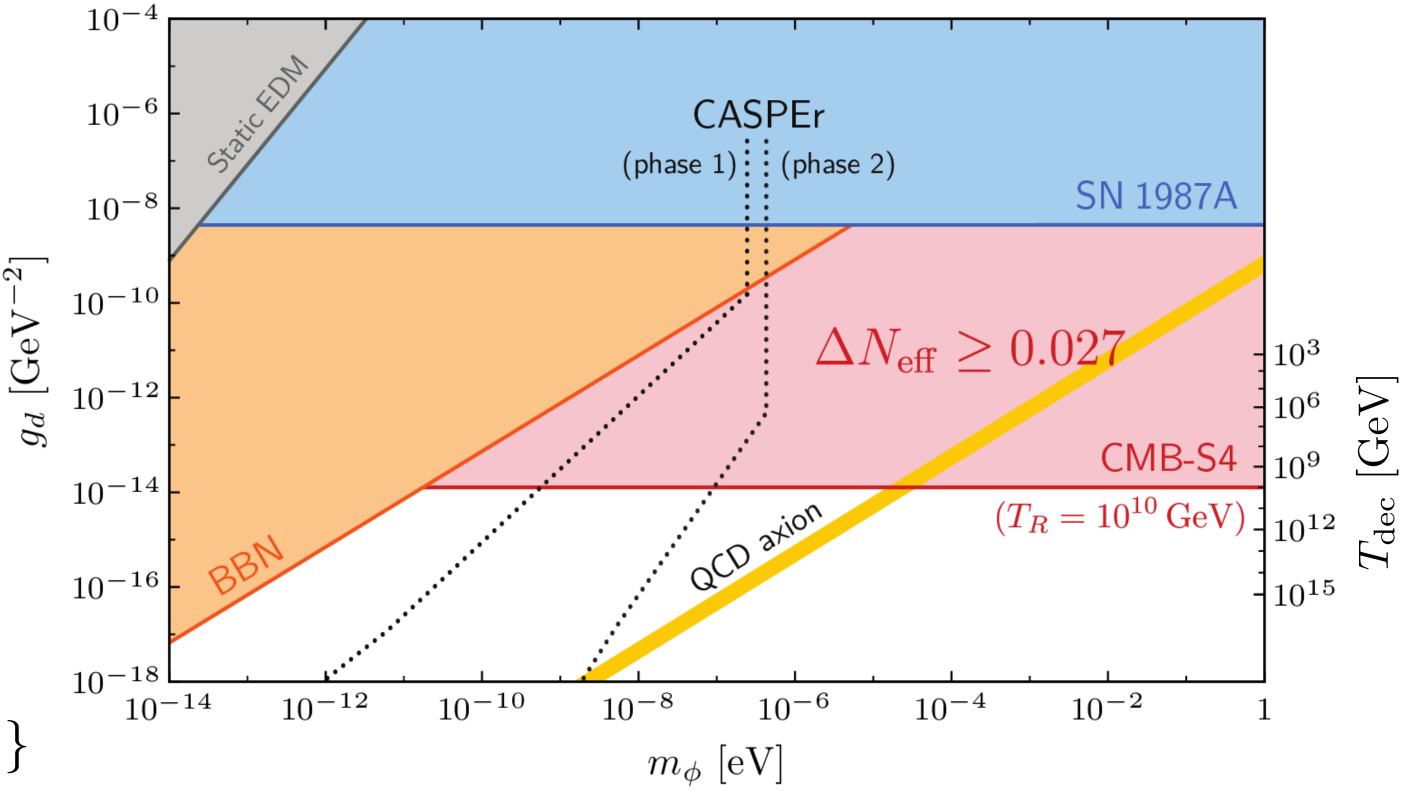
$$-\frac{\phi}{4\Lambda_g}\mathrm{tr}\{G_{\mu\nu}\tilde{G}^{\mu\nu}\}$$

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

Baumann, Green & BW (2016)

Axion Coupling to Gluons

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



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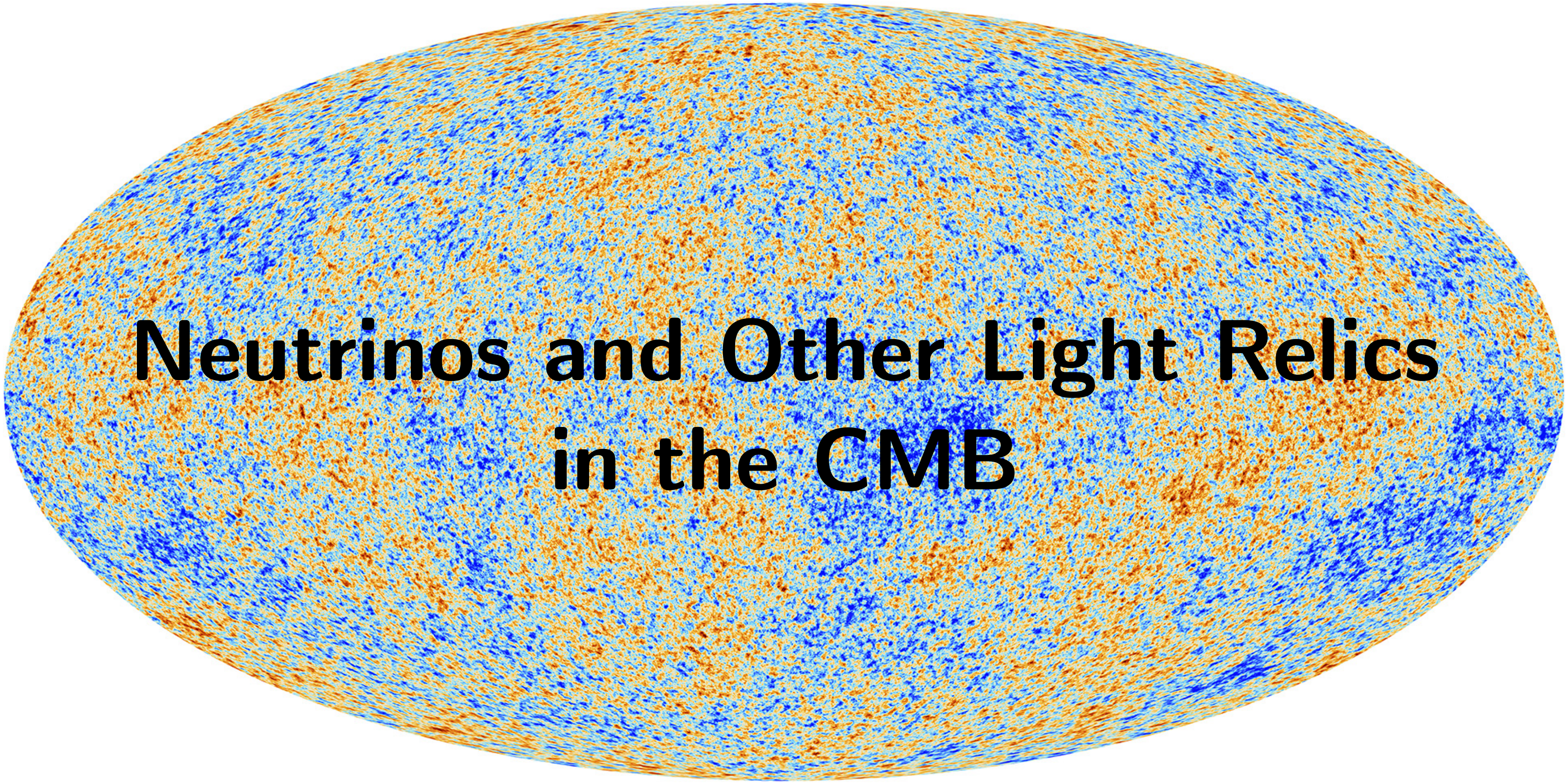
$$g_d \approx \frac{2\pi}{\alpha_s} \times \frac{3.8\times 10^{-3}\,\mathrm{GeV}^{-1}}{\Lambda_g}$$

→ How can we reach $\Delta N_{\rm eff} = 0.027$?

Baumann, Green & BW (2016)



Neutrinos and Other Light Relics in the CMB

D. Baumann, D. Green, J. Meyers and BW
arXiv:1508.06342 (JCAP 2016)

Planck (2015)

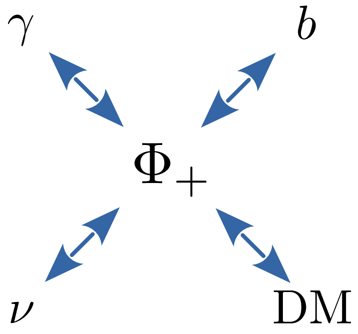
Cosmic Sound Waves

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

Perturbations excited sound waves in the photon-baryon fluid:

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

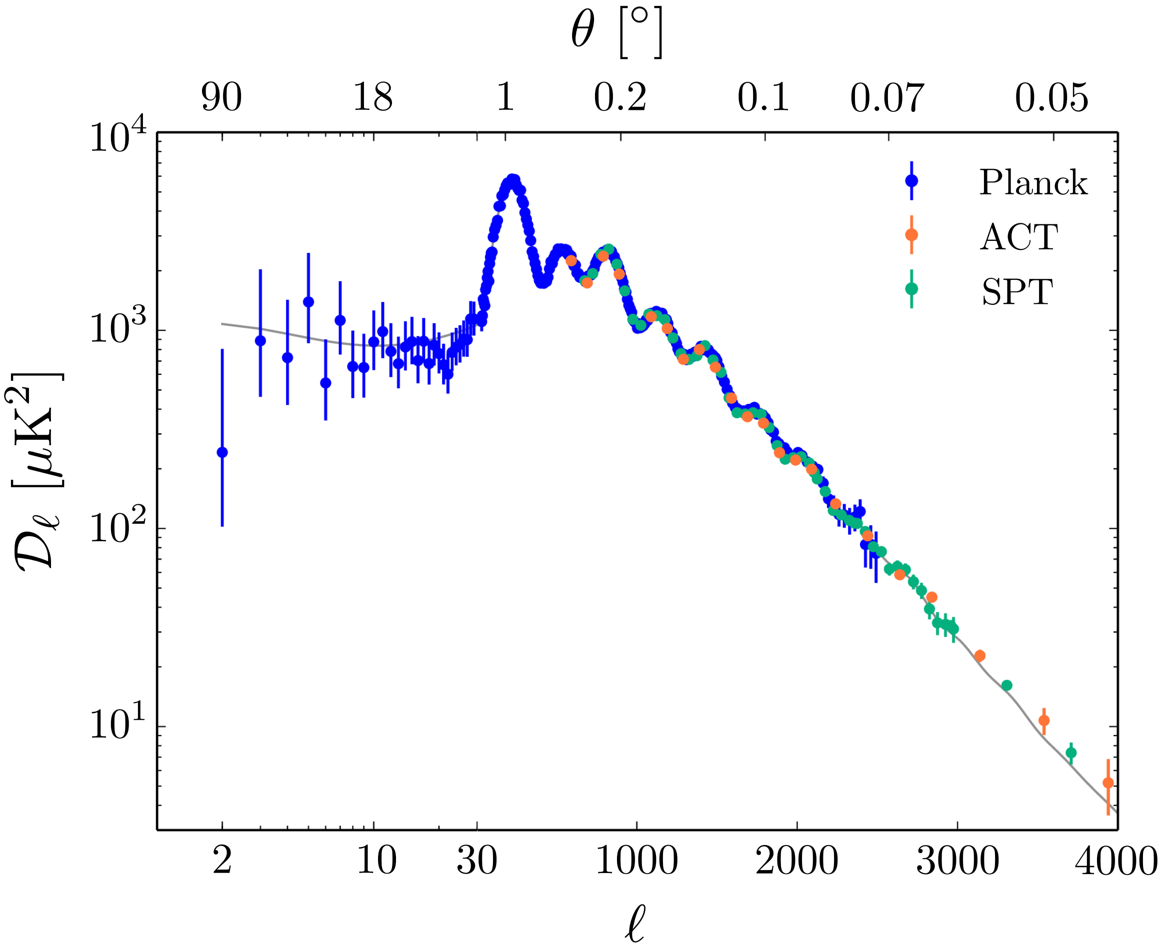
sound waves pressure gravity



These acoustic oscillations have been observed...

Cosmic Sound Waves

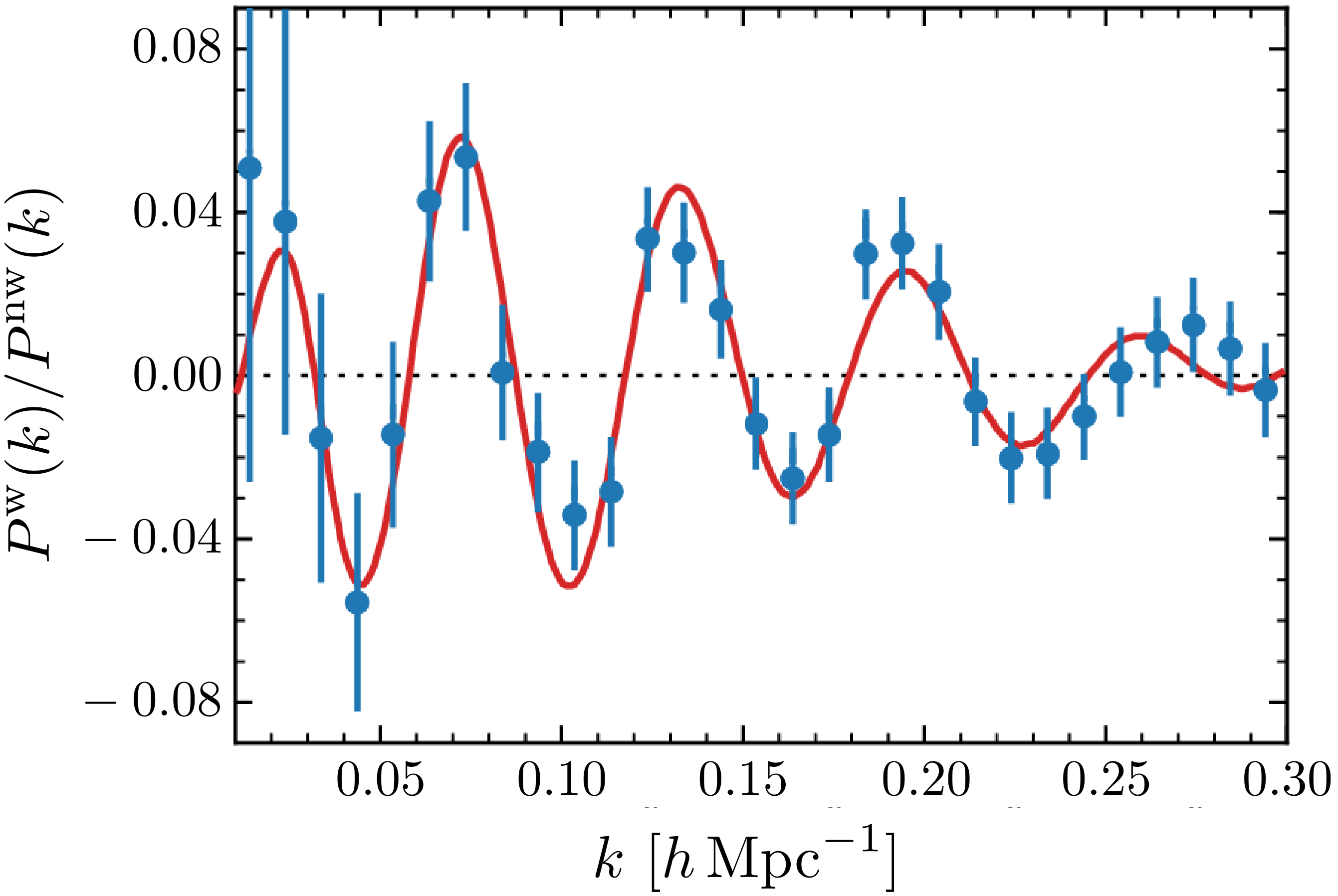
... in the correlations of the cosmic microwave background (CMB) anisotropies:



Planck (2015)

Cosmic Sound Waves

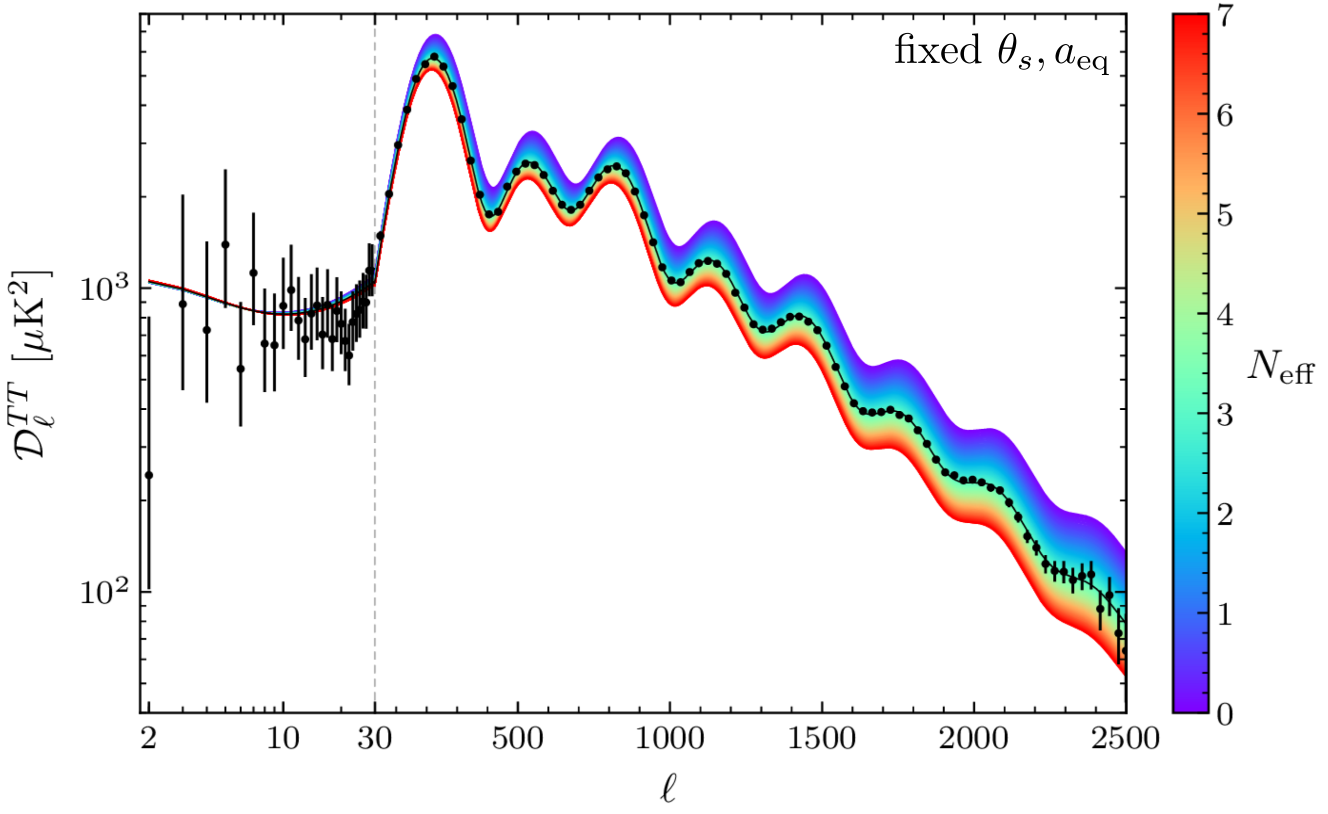
... and in the distribution of galaxies in the universe via the spectrum of baryon acoustic oscillations (BAO):



BOSS (2016)

Cosmic Neutrinos

Main effect of neutrinos is on the CMB damping tail:



Degenerate with change in the primordial helium fraction.

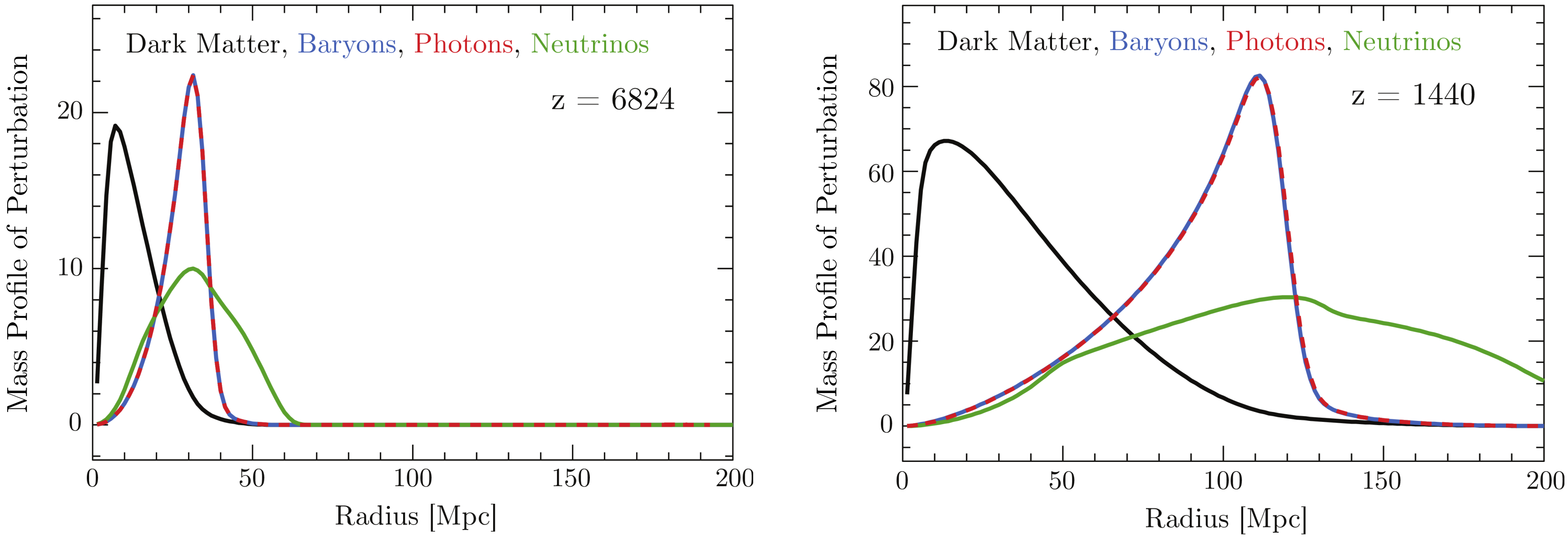
In the past, limiting factor for CMB constraints on neutrinos.

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:

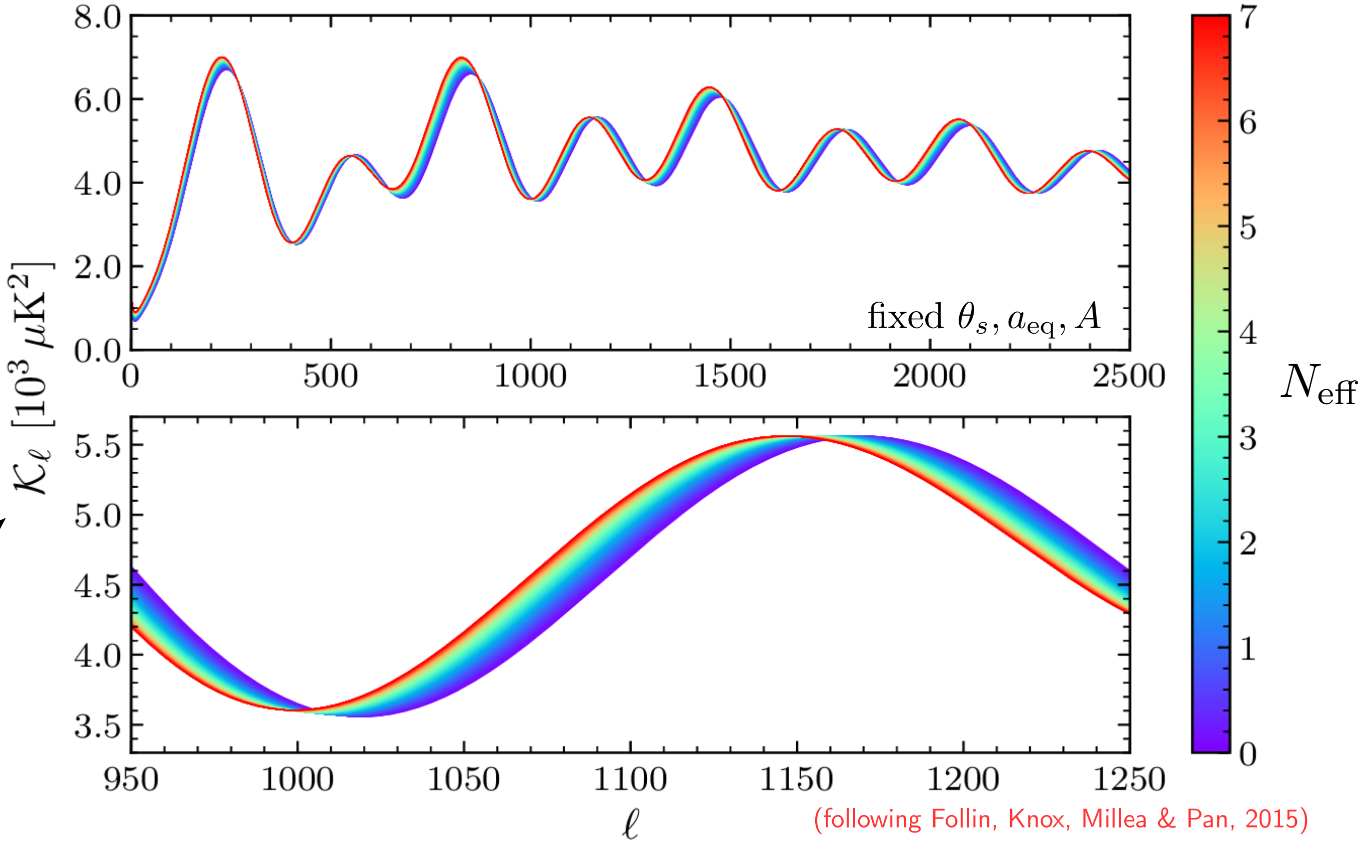


Eisenstein, Seo and White (2007)

Phase Shift

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

Bashinsky & Seljak (2003)



undamped
CMB spectrum

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

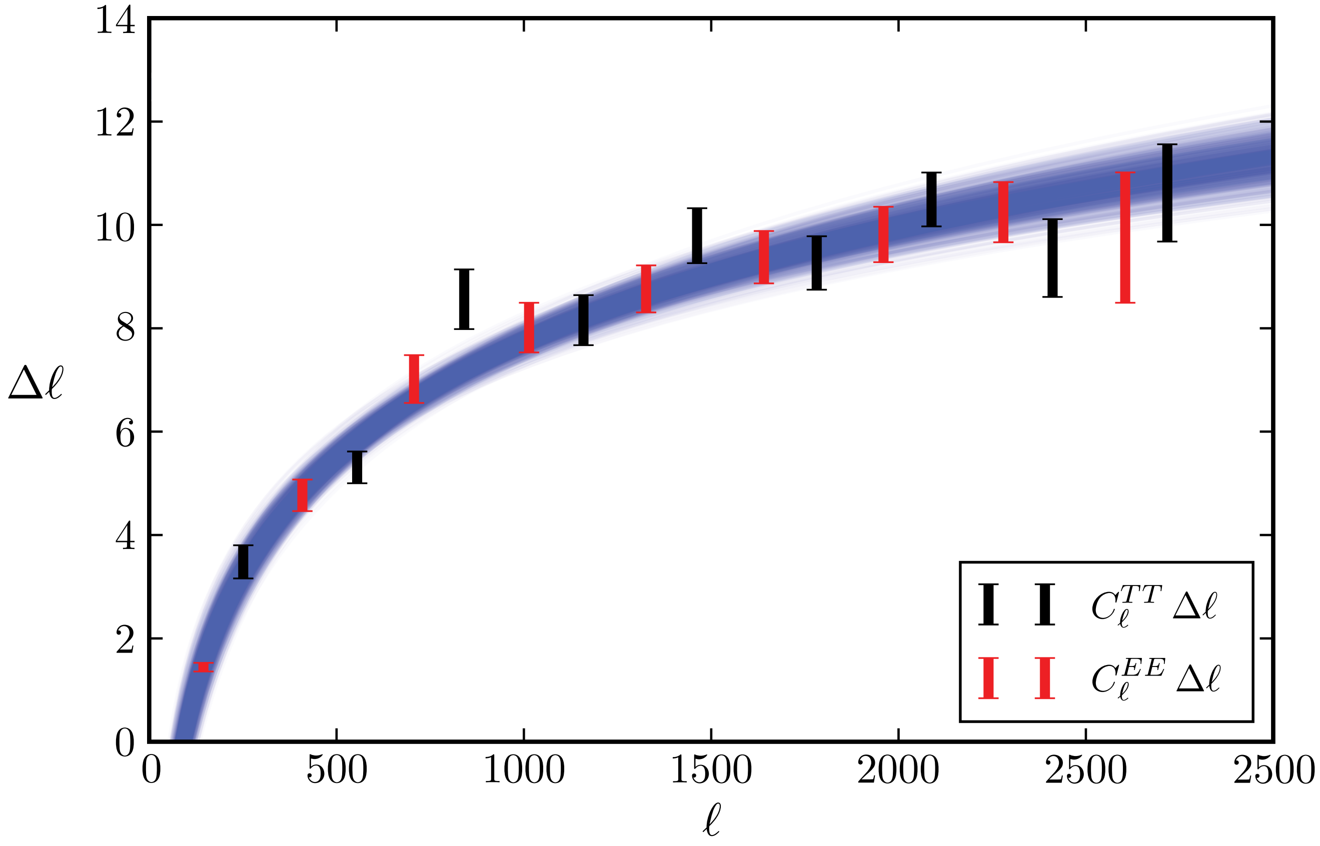
Free-streaming neutrinos are a causal way to produce such a shift.

Baumann, Green, Meyers & BW (2016)

Phase Shift

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

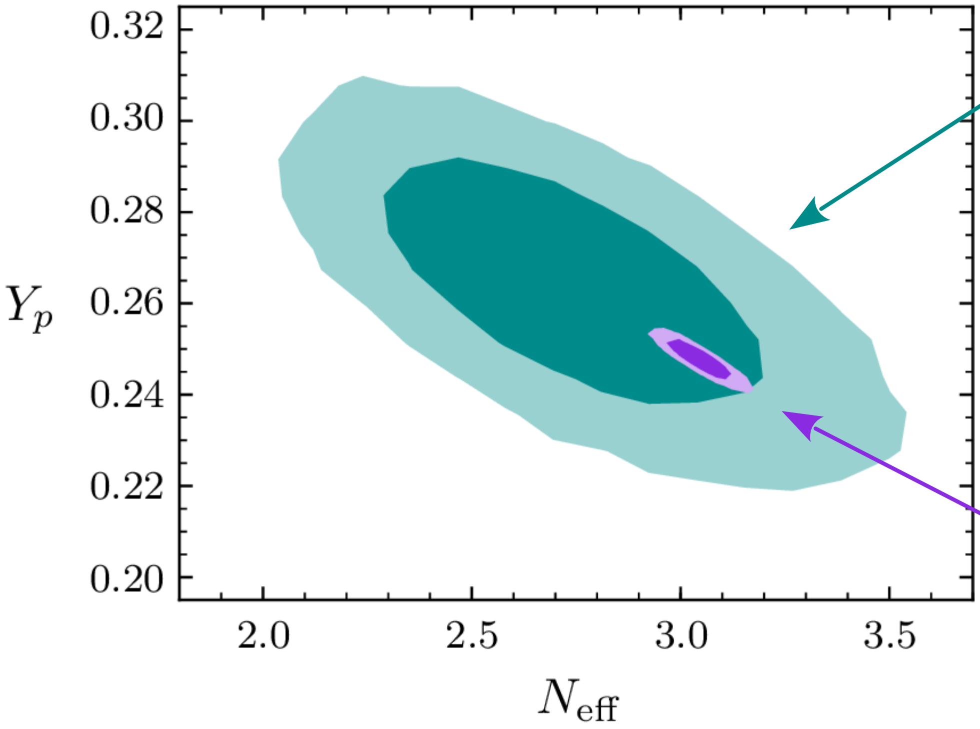
But neutrino imprint in phase shift has been detected in Planck data:



Follin, Knox, Millea & Pan (2015); cf. Baumann, Green, Meyers & BW (2016)

Constraints on $\mathrm{N}_{\mathrm{eff}}$

helium fraction



Planck

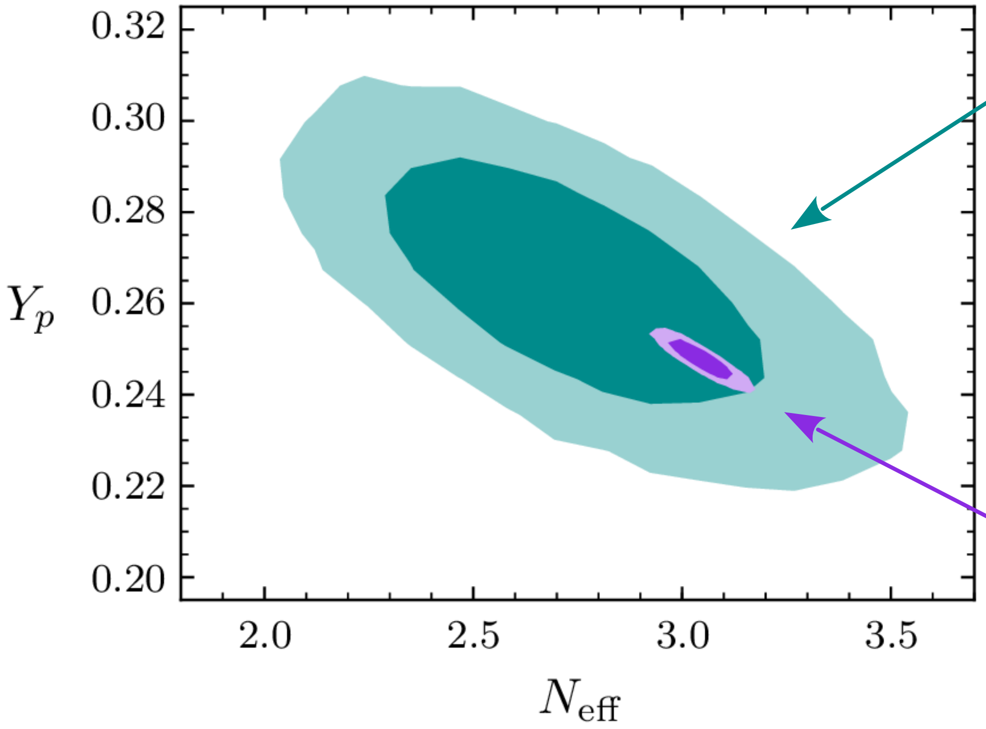
CMB-S4

→ Large improvement from Planck to CMB-S4:

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

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

Constraints on $\mathrm{N}_{\mathrm{eff}}$



helium fraction

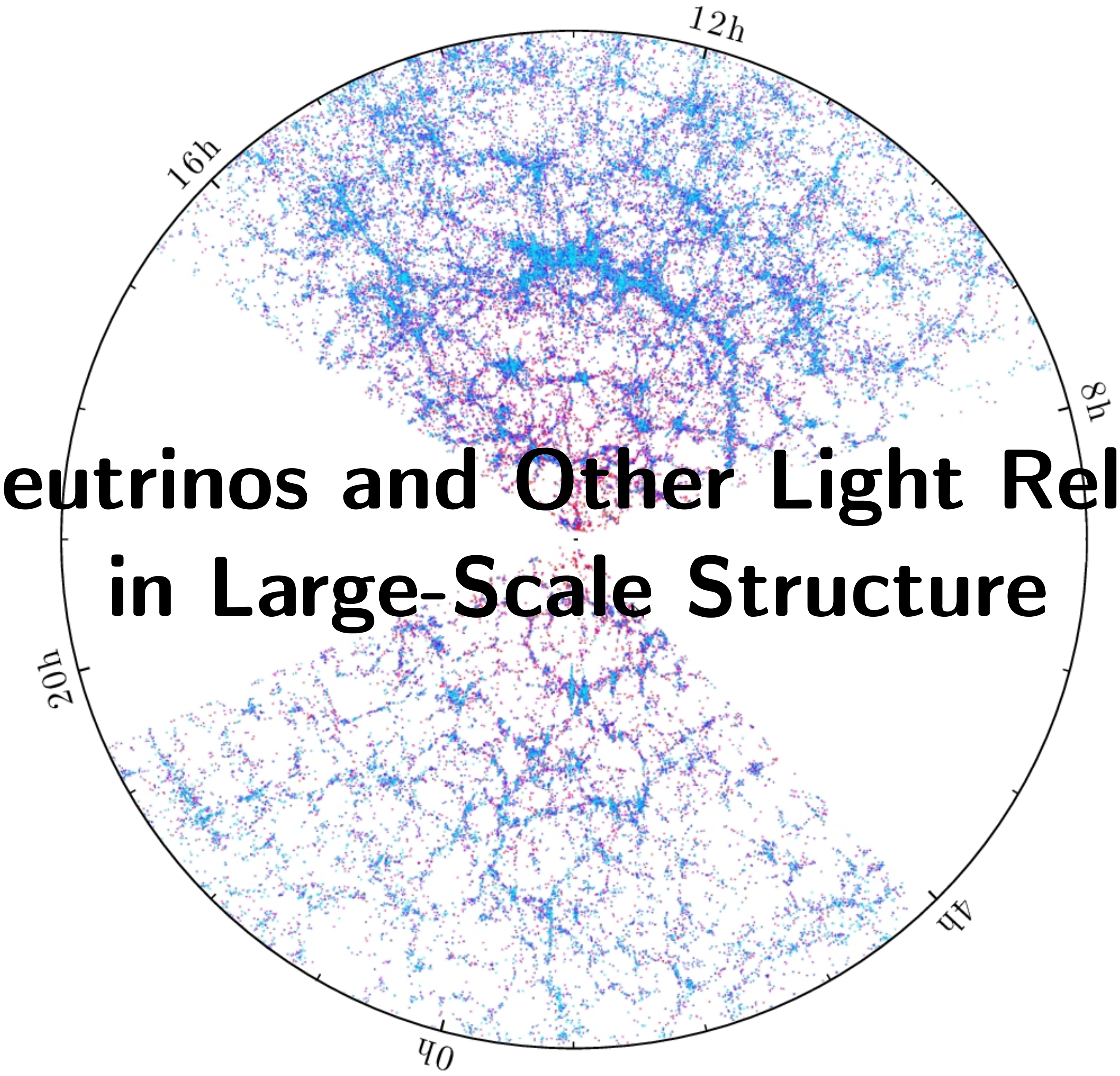
Planck

CMB-S4

→ Large improvement from Planck to CMB-S4:

$$\sigma(N_{\mathrm{eff}}) \sim 0.030 \longrightarrow \text{Can we do even better?}$$

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



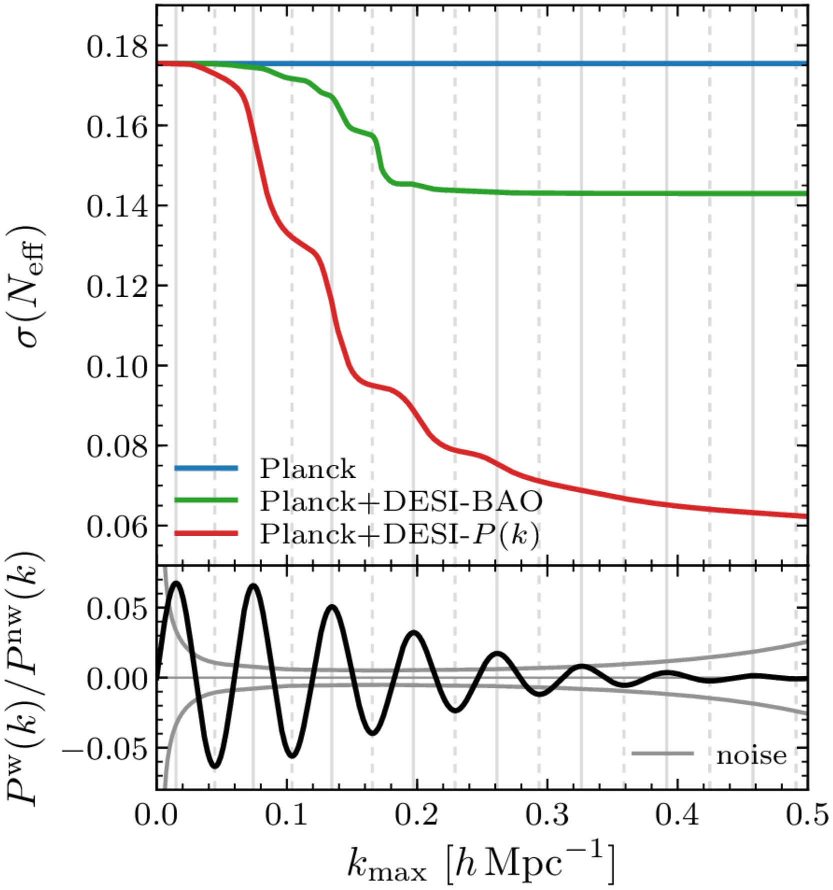
Neutrinos and Other Light Relics in Large-Scale Structure

D. Baumann, D. Green and BW
arXiv:1712.08067 (JCAP 2018)

SDSS

Future Constraints from CMB and LSS

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



(Uses conservative broadband marginalization.)

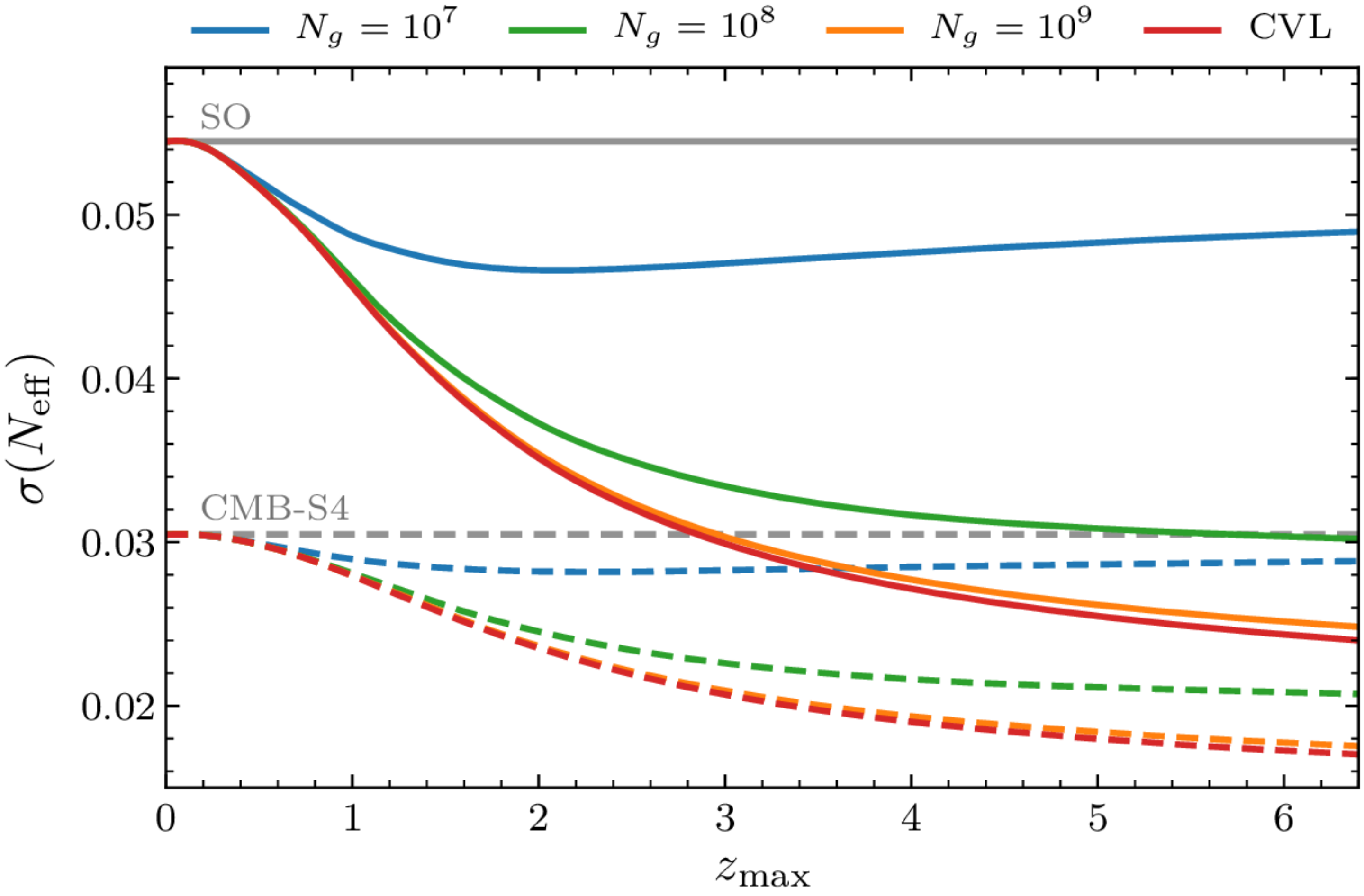
→ Planned LSS surveys will provide significant improvements over Planck.

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

Baumann, Green & BW (2018)

Future Constraints from CMB and LSS

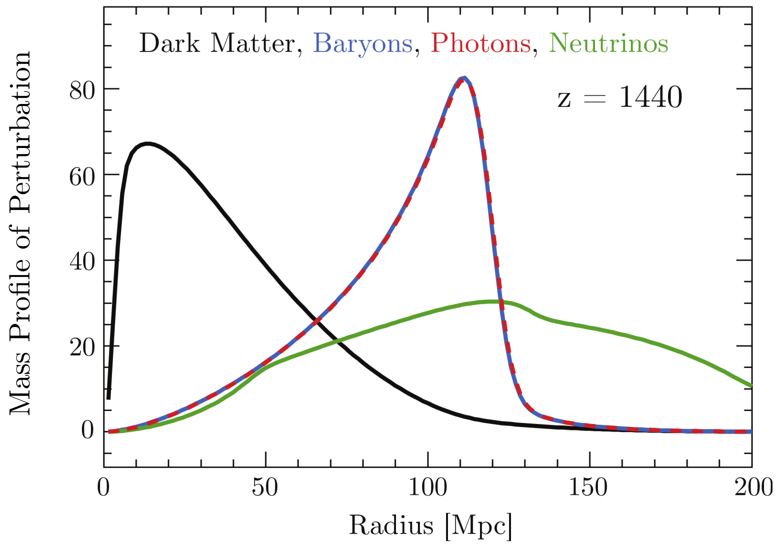
The target $\Delta N_{\text{eff}} = 0.027$ is within reach (at 95% c.l.) for future observations:

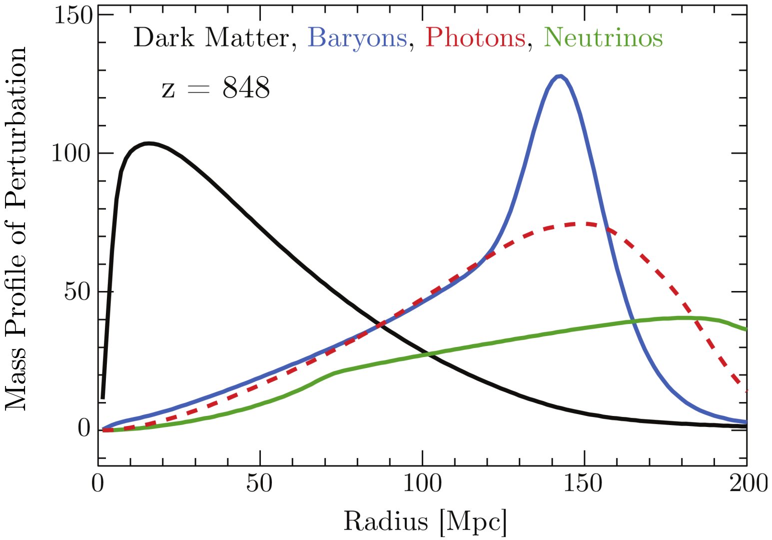


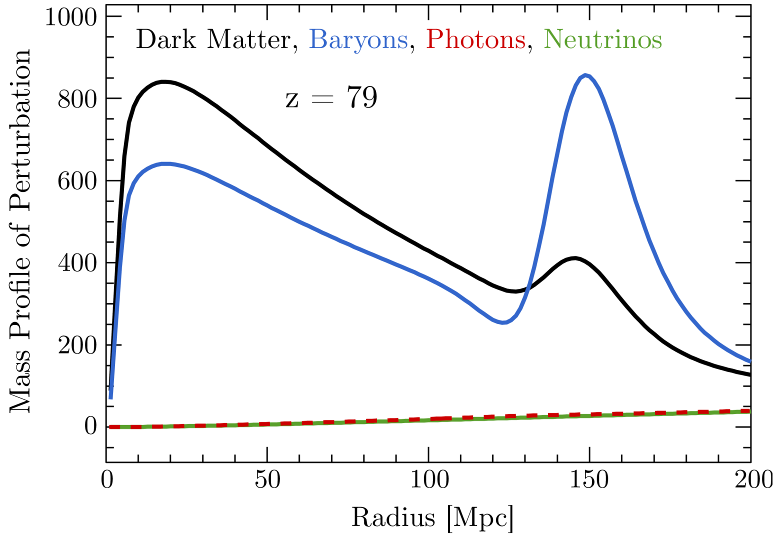
(Uses conservative broadband marginalization.)

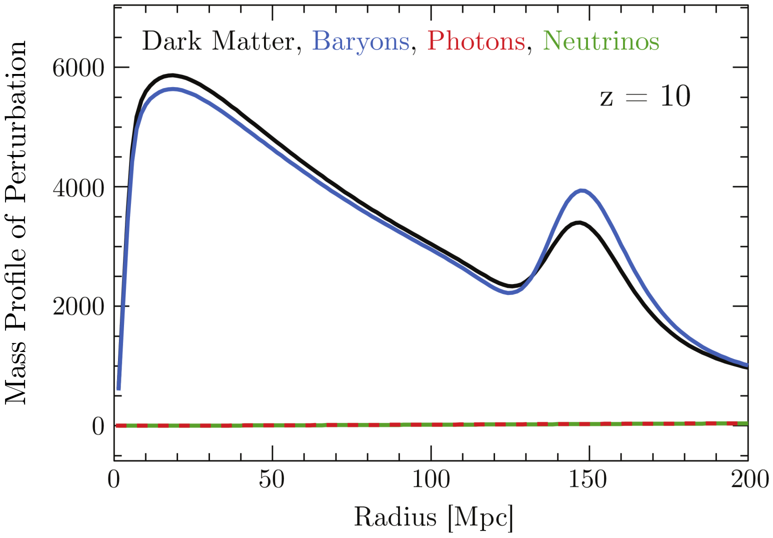
Baumann, Green & BW (2018)

Baryon Acoustic Oscillations





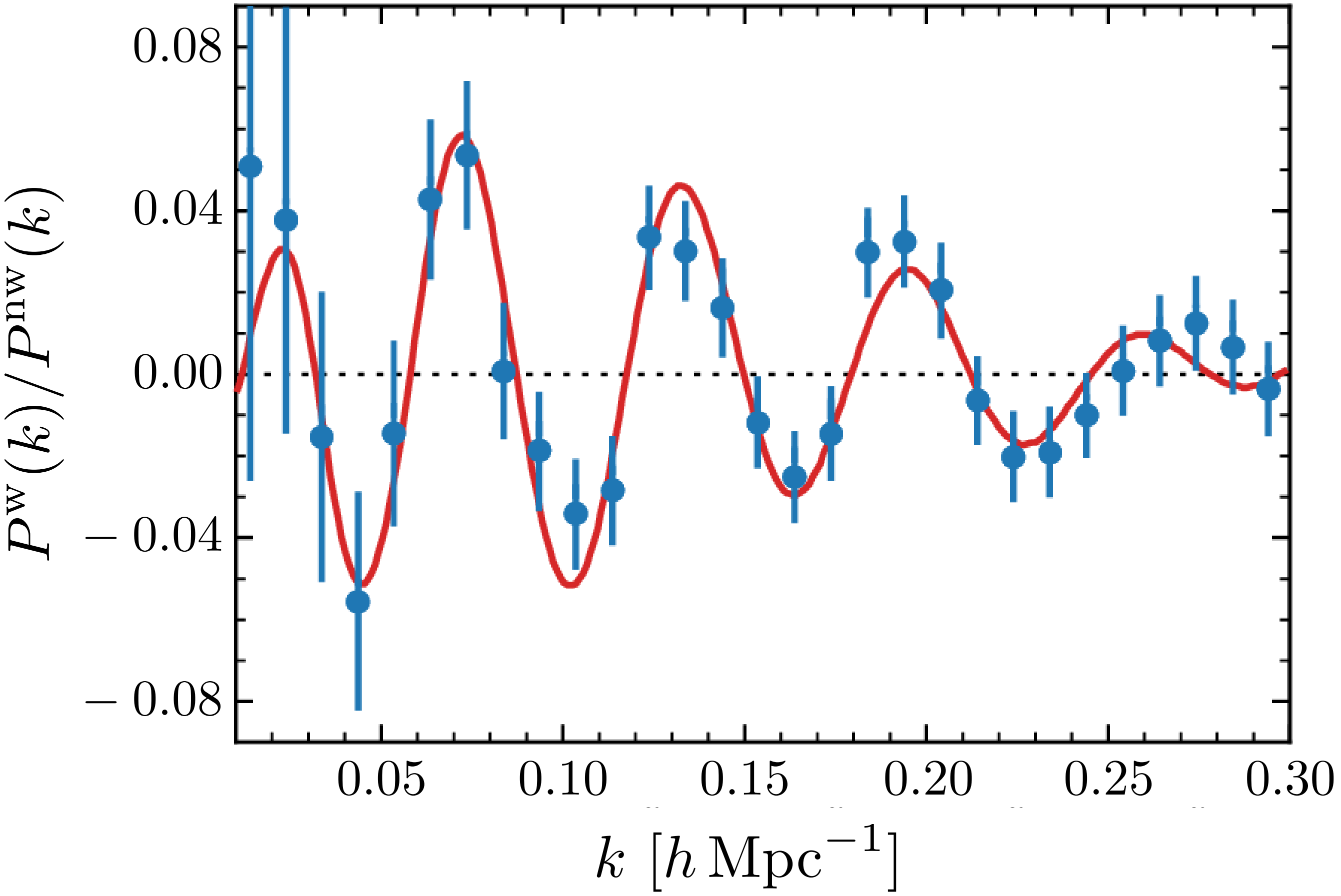




Eisenstein, Seo and White (2007)

Baryon Acoustic Oscillations

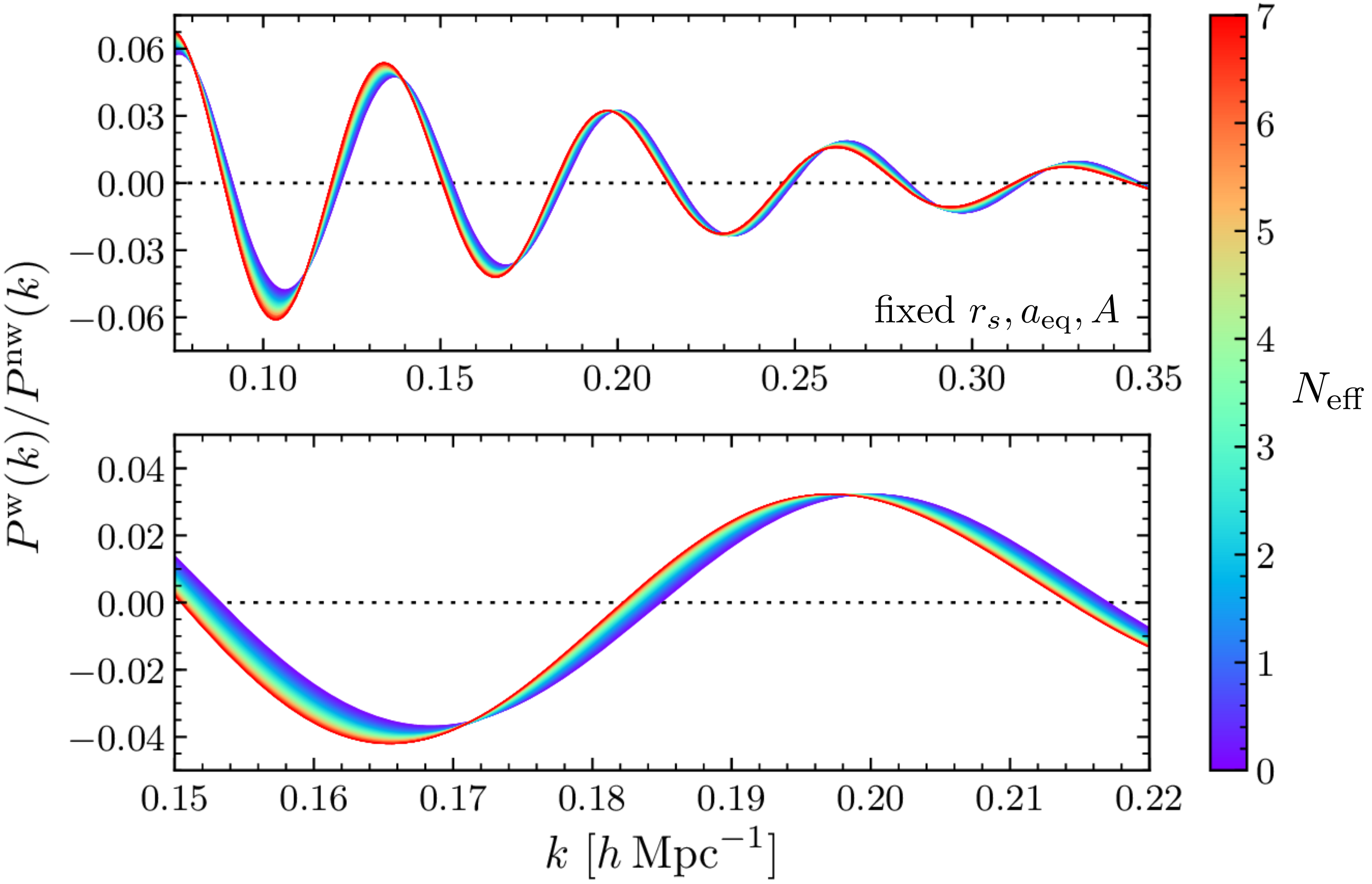
In Fourier space, this corresponds to the BAO spectrum, e.g. of the distribution of galaxies:



BOSS (2016)

Phase Shift in the BAO Spectrum

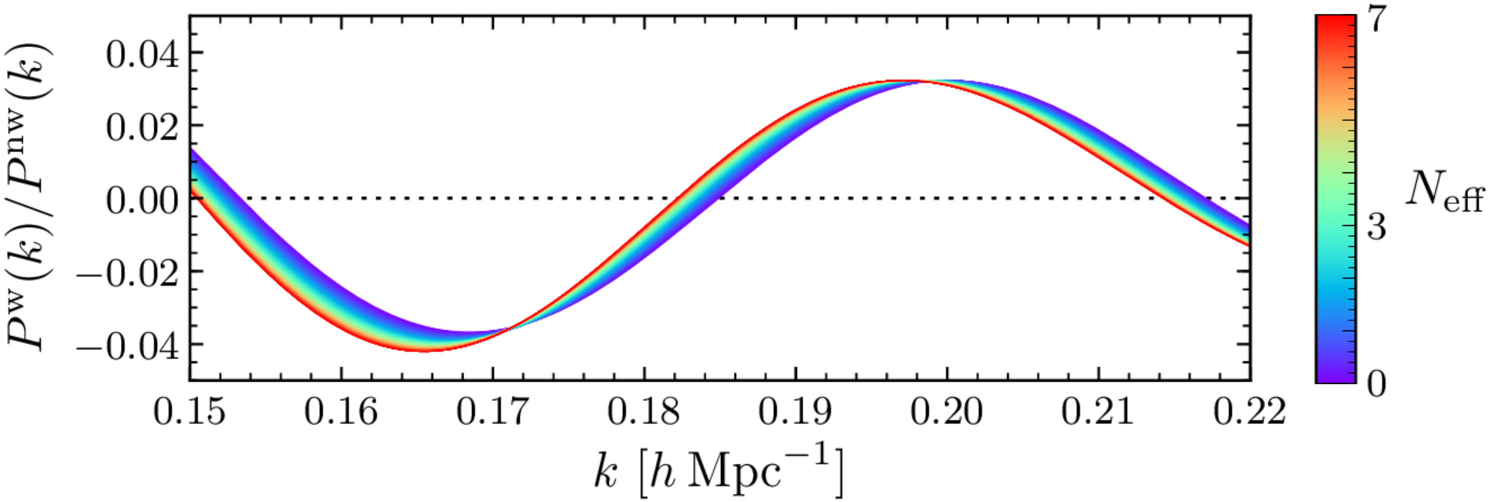
Extra relativistic species lead to the same phase shift as in the CMB:



Baumann, Green & BW (2018)

Phase Shift in the BAO Spectrum

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



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

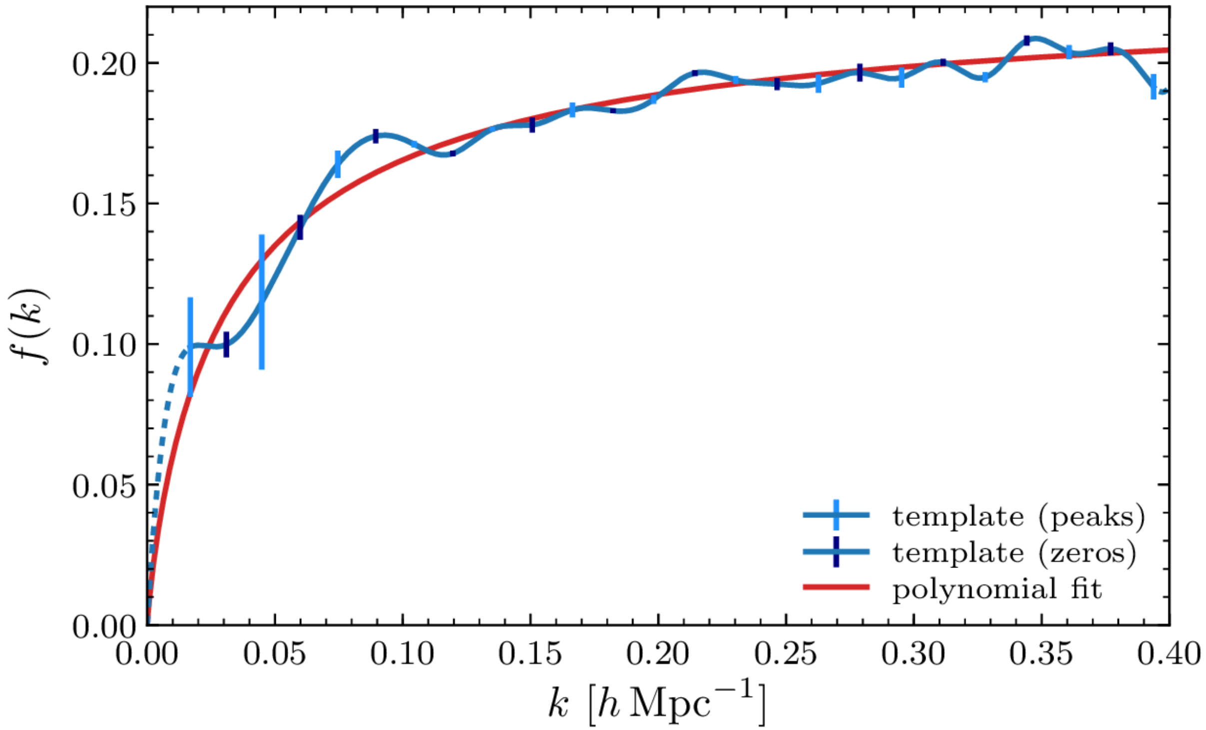
Proposal to adapt the standard BAO analysis:

template

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

standard BAO parameter

phase shift amplitude



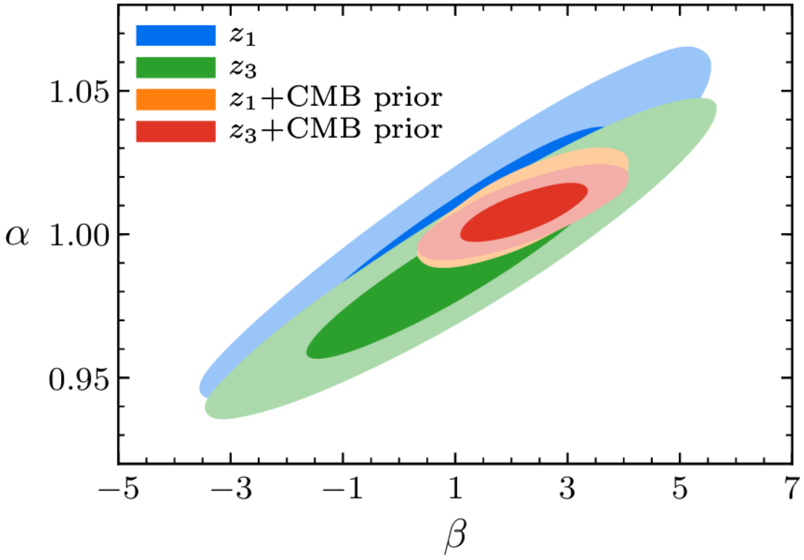
Baumann, Green & BW (2018)

Measuring Neutrinos in the BAO Spectrum

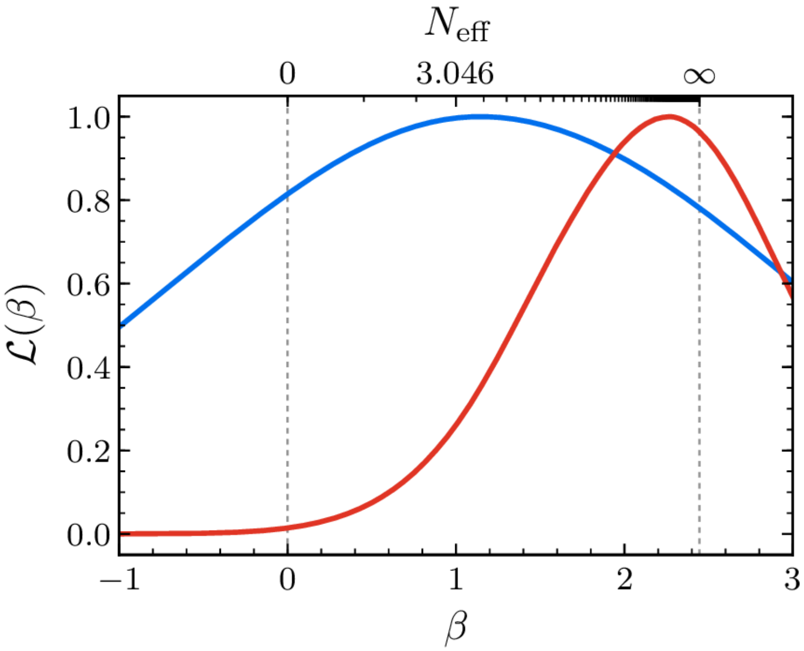
D. Baumann, F. Beutler, R. Flauger, D. Green,
A. Slosar, M. Vargas-Magaña, BW and C. Yèche
arXiv:1803.10741 (Nat. Phys. 2019)

First Measurement

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



$$\beta = 2.22 \pm 0.75$$



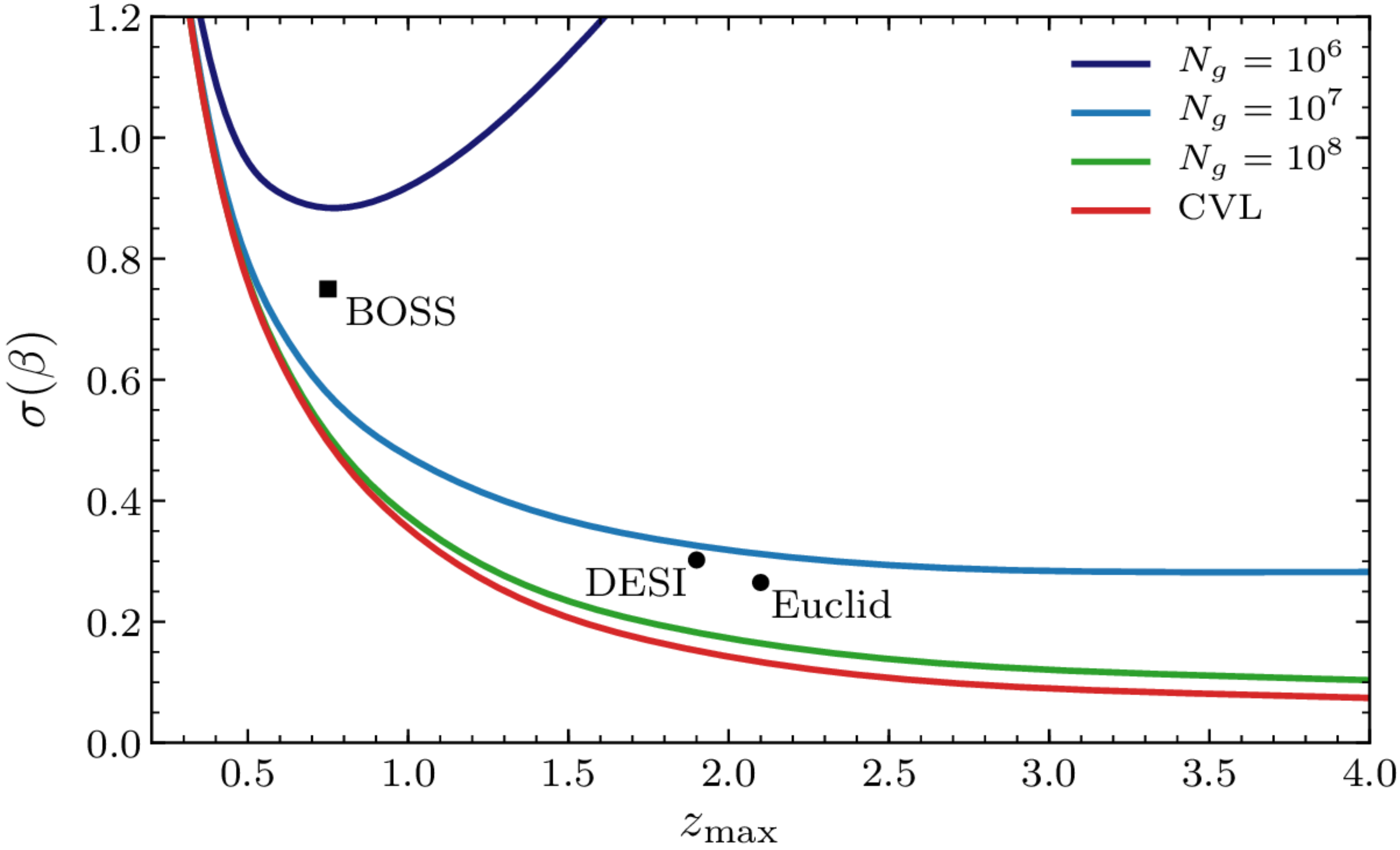
$$\beta > 0 \ \text{ at } \ > 99\% \, \text{c.l.}$$

This is a proof of principle for directly extracting information on light relics from galaxy clustering data.

Baumann, Beutler, ..., BW, ... (2019)

Future Prospects

Future observations will greatly improve on this first measurement:



Baumann, Green & BW (2018); Baumann, Beutler, ..., BW, ... (2019)

Conclusions

(1) BAO spectrum can be robustly employed beyond its current use.

→ New observable for the early universe.

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

1%

This is an improvement of an order of magnitude over current constraints.

How to get there? → Combine future CMB and LSS.

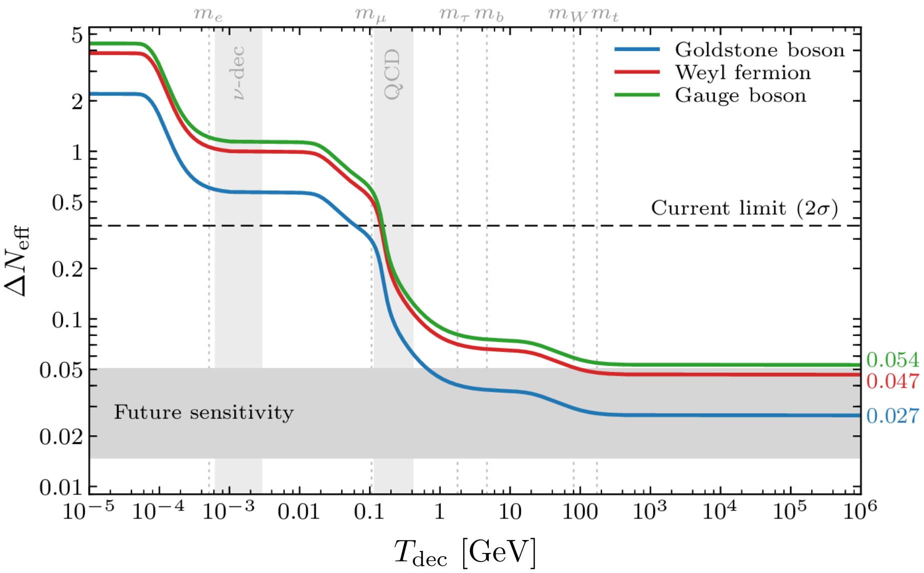
What to do with this? → Probe cosmology and particle physics.

K. Abazajian et al. (CMB-S4 Collaboration),
CMB-S4 Science Book, First Edition,
arXiv:1610.02743 [astro-ph.CO].

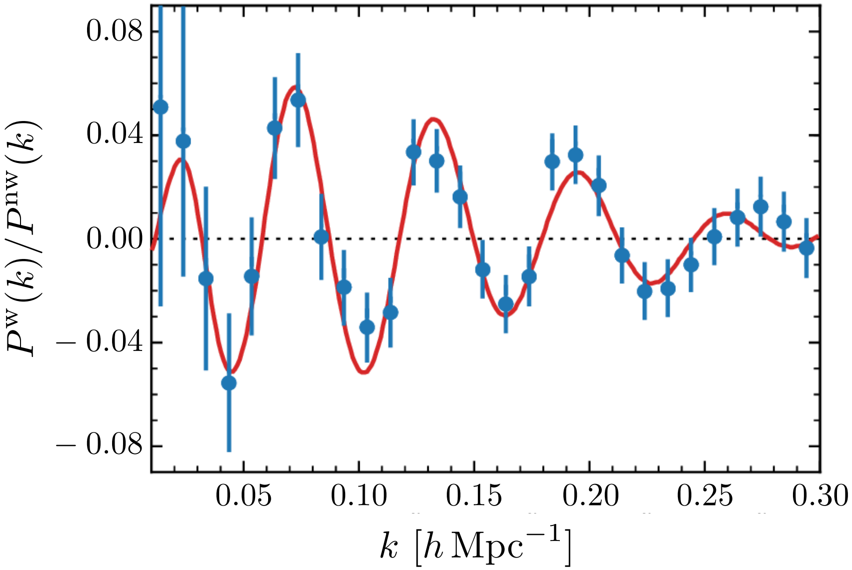
K. Abazajian et al. (CMB-S4 Collaboration),
CMB-S4 Science Book, First Edition,
arXiv:161**0.027**43 [astro-ph.CO].

Thank you!

Light Thermal Relics



BAO Spectrum



Benjamin Wallisch
bwallisch@ias.edu

(cf. arXiv:1810.02800)

Backup Slides

Couplings to the Standard Model

Classification of interactions according to spin:

- spin-0: axions, ALPs, pNGBs — shift symmetry

$$\mathcal{L} \supset -\frac{\phi}{4\Lambda_\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{\partial_\mu \phi}{\Lambda_\psi}\bar{\psi}\gamma^\mu\gamma^5\psi$$

- spin-1/2: sterile neutrinos — chiral symmetry

$$\mathcal{L} \supset -\frac{1}{\Lambda_\chi^2}\chi^\dagger\bar{\sigma}^\mu\chi\,\partial^\nu B_{\mu\nu} + \ldots$$

- spin-1: dark forces — gauge symmetry

$$\mathcal{L} \supset -\frac{\epsilon}{2}F'^{\mu\nu}B_{\mu\nu} - \frac{1}{\Lambda_{A'}^2}F'_{\mu\nu}H\bar{\psi}\sigma^{\mu\nu}\psi + \ldots$$

- spin-3/2: gravitino — supersymmetry

$$\mathcal{L} \supset -\frac{1}{F^2}\chi^\dagger\sigma_\mu\partial_\nu\chi T^{\mu\nu}$$

Brust, Kaplan & Walters (2013)

Couplings to Matter Fields

Similar constraints apply to couplings of Goldstone bosons to charged fermions and neutrinos:

	Current Constraints		Future CMB Constraints		
Coupling	Bound [GeV]	Origin	Freeze-Out [GeV]	Freeze-In [GeV]	$\Delta\tilde{N}_{\rm eff}$
Λ_{ee}	1.2×10^{10}	White dwarfs	6.0×10^{7}	2.7×10^{6}	1.3
$\Lambda_{\mu\mu}$	2.0×10^{6}	Stellar cooling	1.2×10^{10}	3.4×10^{7}	0.5
$\Lambda_{\tau\tau}$	2.5×10^{4}	Stellar cooling	2.1×10^{11}	9.5×10^{7}	0.05
Λ_{bb}	6.1×10^{5}	Stellar cooling	9.5×10^{11}	–	0.04
Λ_{tt}	1.2×10^{9}	Stellar cooling	3.5×10^{13}	–	0.03
$\Lambda^V_{\mu e}$	5.5×10^{9}	$\mu^+\to e^+\phi$	6.2×10^{9}	4.8×10^{7}	0.5
$\Lambda_{\mu e}$	3.1×10^{9}	$\mu^+\to e^+\phi\gamma$	6.2×10^{9}	4.8×10^{7}	0.5
$\Lambda_{\tau e}$	4.4×10^{6}	$\tau^-\to e^-\phi$	1.0×10^{11}	1.3×10^{8}	0.05
$\Lambda_{\tau\mu}$	3.2×10^{6}	$\tau^-\to\mu^-\phi$	1.0×10^{11}	1.3×10^{8}	0.05
Λ^A	6.0×10^{5}	D^0 $\bar{D}^0$	1.3×10^{11}	2.0×10^{8}	0.05

Feng et al.; Brust et al.; Hansen et al.; Archidiacono & Hannestad; ...

Baumann, Green & BW (2016)

Free-Streaming Neutrinos

Standard Model neutrinos are free-streaming – can we detect this?

Introduce parametrisation:

N_{eff} ↓ free-streaming radiation density

N_{fluid} ↓ non-free-streaming radiation density

Damping tail of CMB power spectrum:

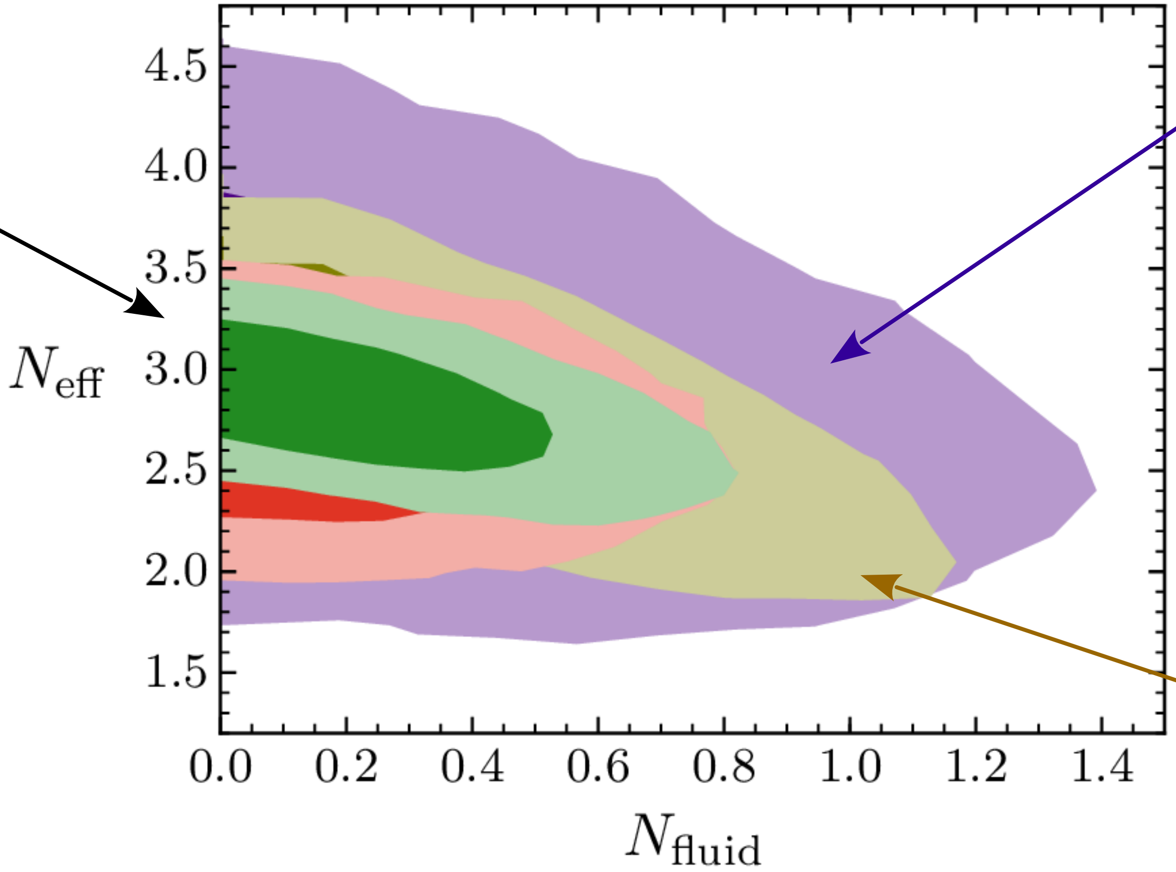
→ only sensitive to background energy density: $N_{\text{eff}} + N_{\text{fluid}}$

Data now precise enough to be sensitive to neutrino perturbations:

$$\underset{\text{sound waves}}{\ddot{\delta}_\gamma} - c_\gamma^2 \nabla^2 \delta_\gamma = \underbrace{\nabla^2 \Phi_+}_{\gamma \qquad \nu}$$

→ discriminating between N_{eff} and N_{fluid} possible!

Planck Constraints



includes polarisation

marginalised over helium fraction

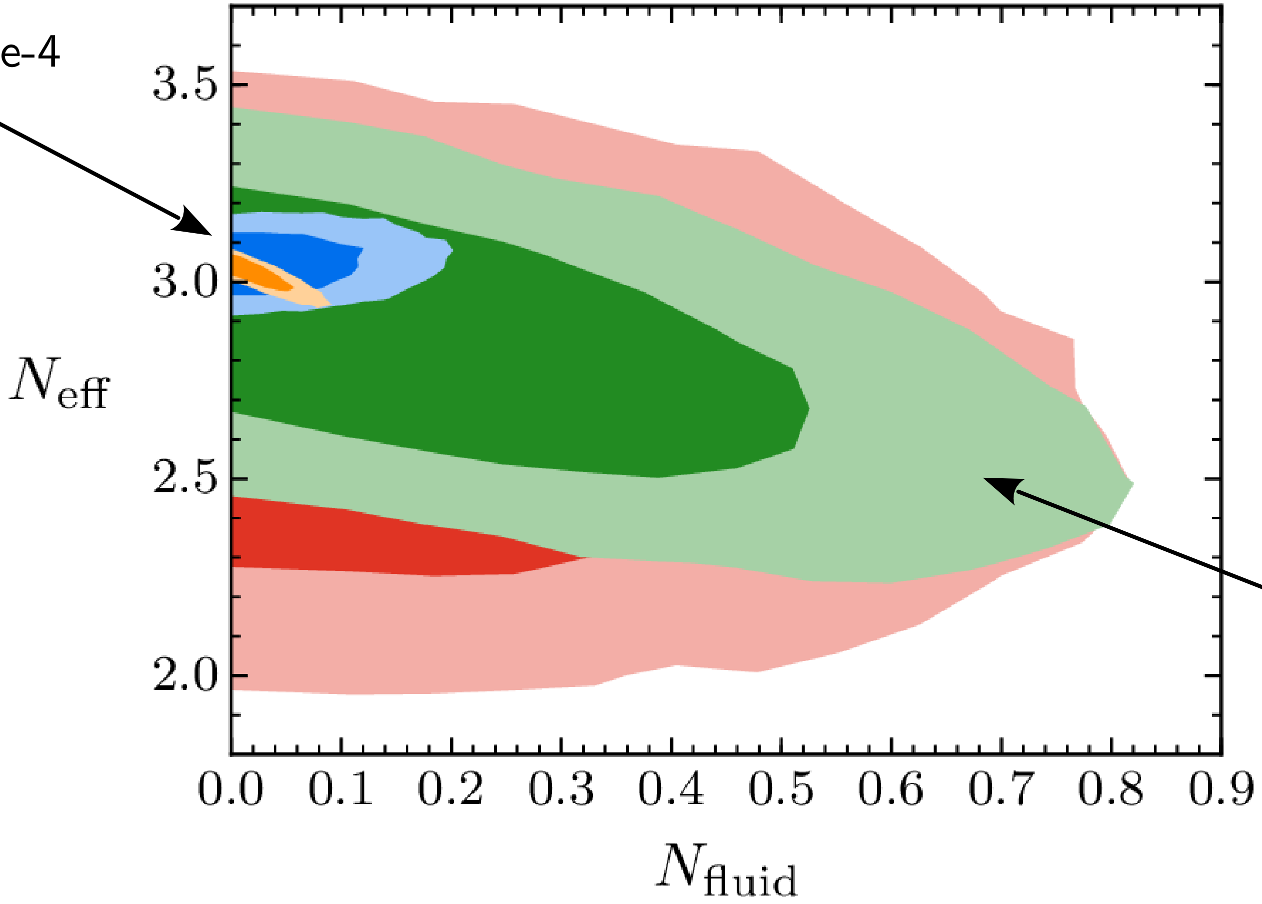
temperature only

$$N_{\rm eff} = 2.80 \pm 0.24 \qquad\qquad N_{\rm fluid} < 0.67 \ (95\% \text{ c.l.})$$

→ Standard Model neutrinos are free-streaming!

Baumann, Green, Meyers & BW (2016)

CMB Stage-4 Forecast

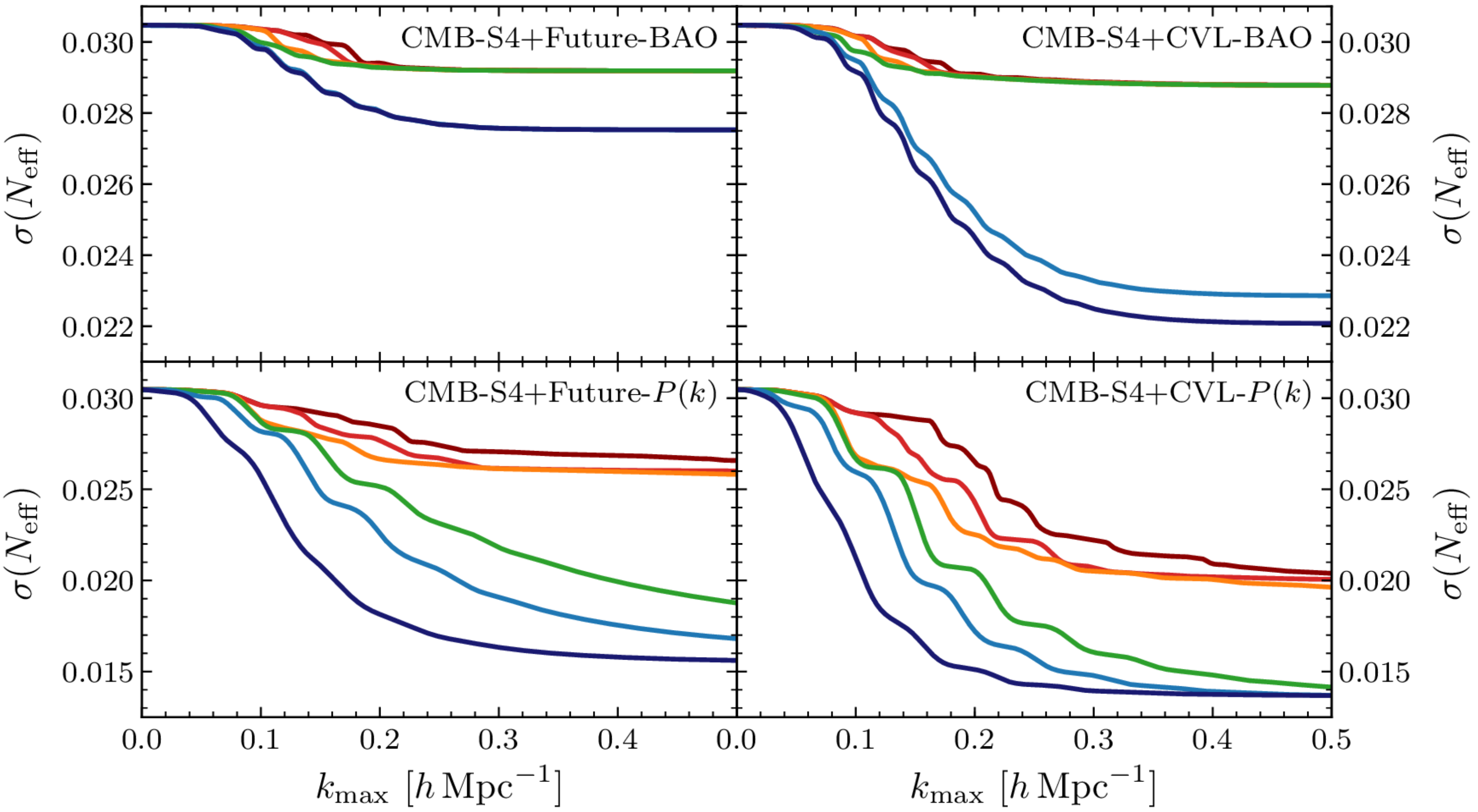


CMB Stage-4

Planck

Baumann, Green, Meyers & BW (2016)

Future LSS Constraints on $\mathrm{N_{eff}}$

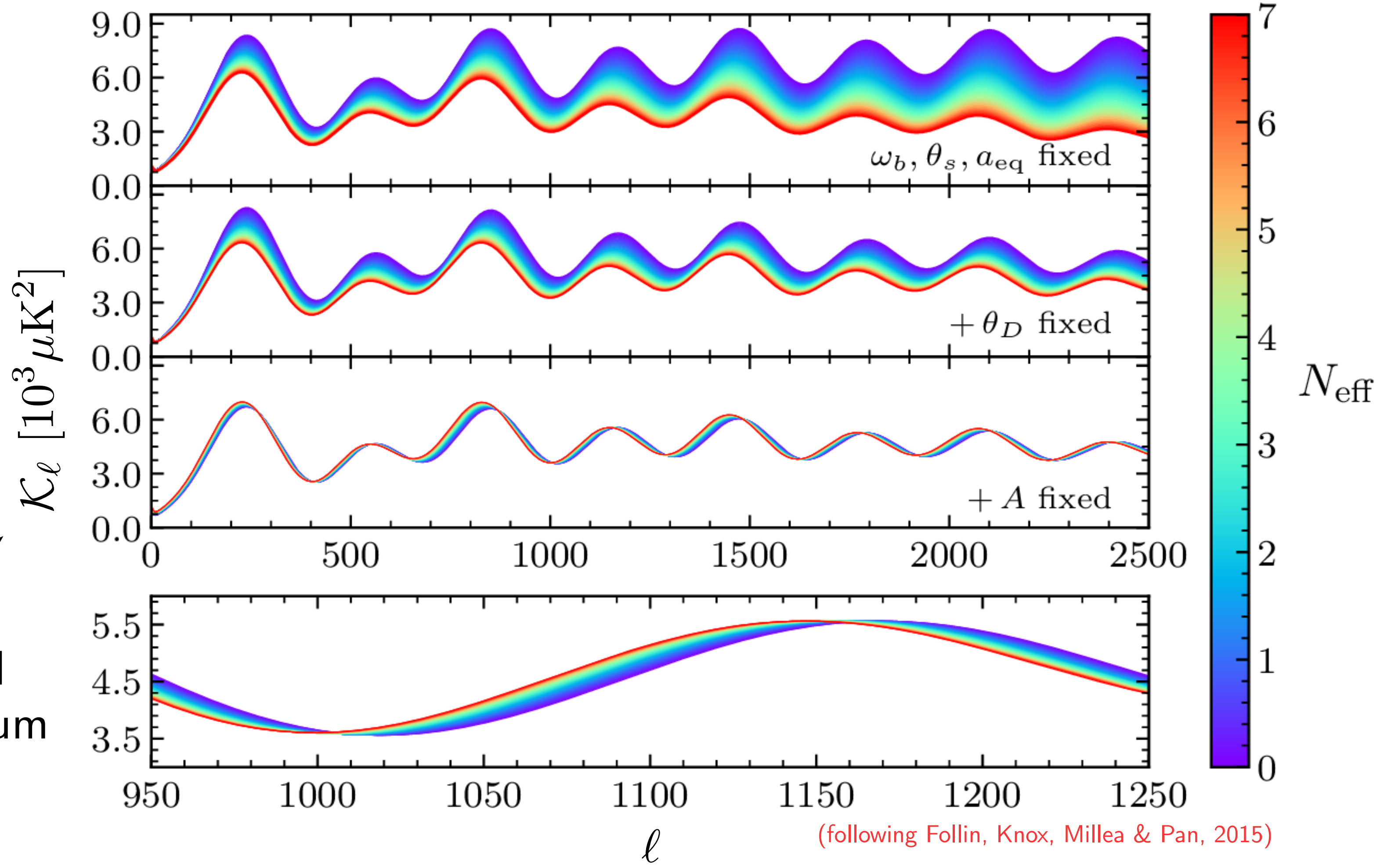


$N_g = 10^8,\ z_{\rm max} = 2,\ f_{\rm sky} = 0.5$

$\mathrm{CVL},\ z_{\rm max} = 6,\ f_{\rm sky} = 0.5$

Baumann, Green & BW (2018)

Phase Shift in the CMB

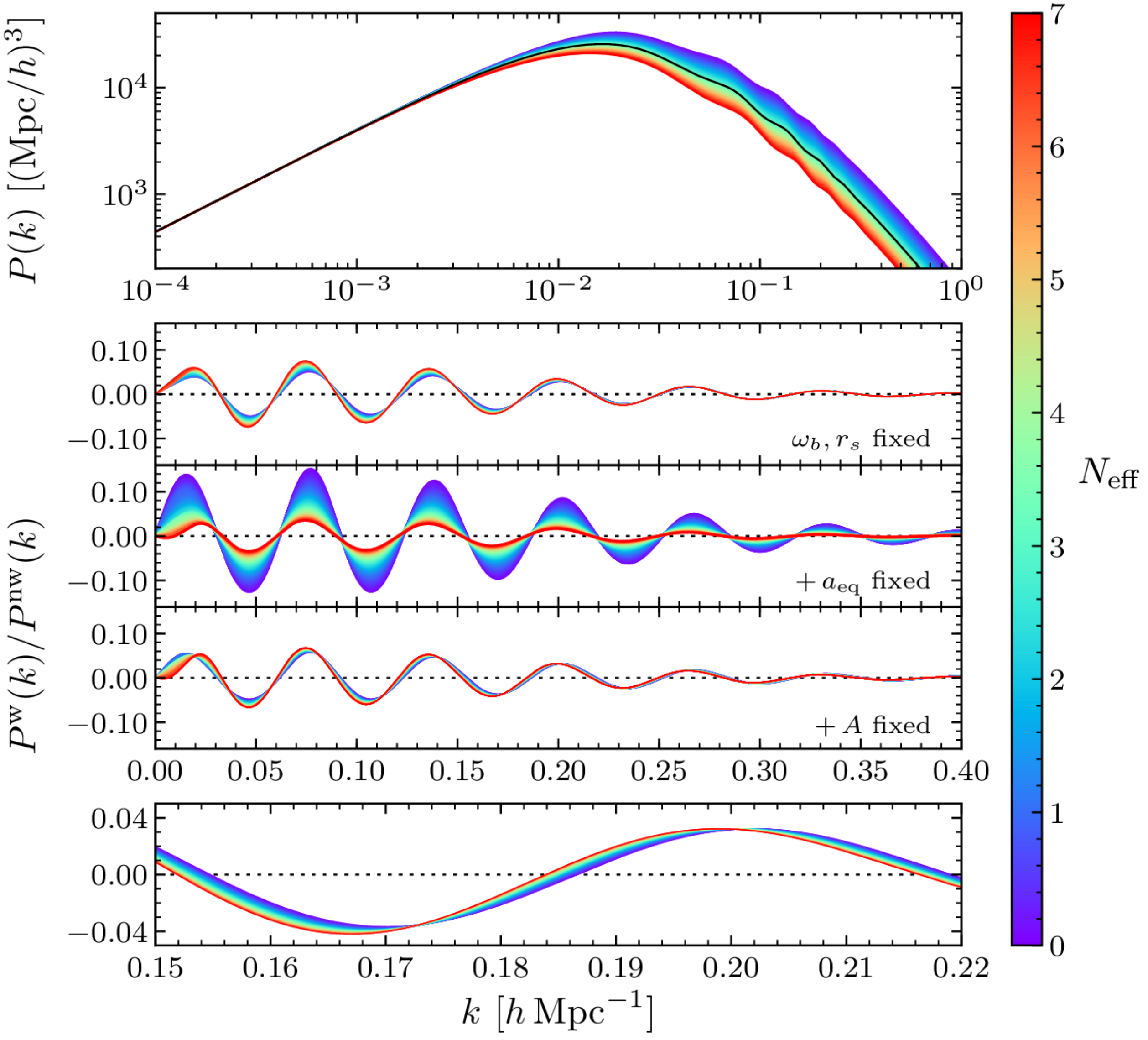


Undamped CMB spectrum

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

Phase Shift in LSS

$$P(k) \equiv P^{\mathrm{w}}(k) + P^{\mathrm{nw}}(k)$$
$$\equiv P^{\mathrm{nw}}(k)\,[1 + O(k)]$$

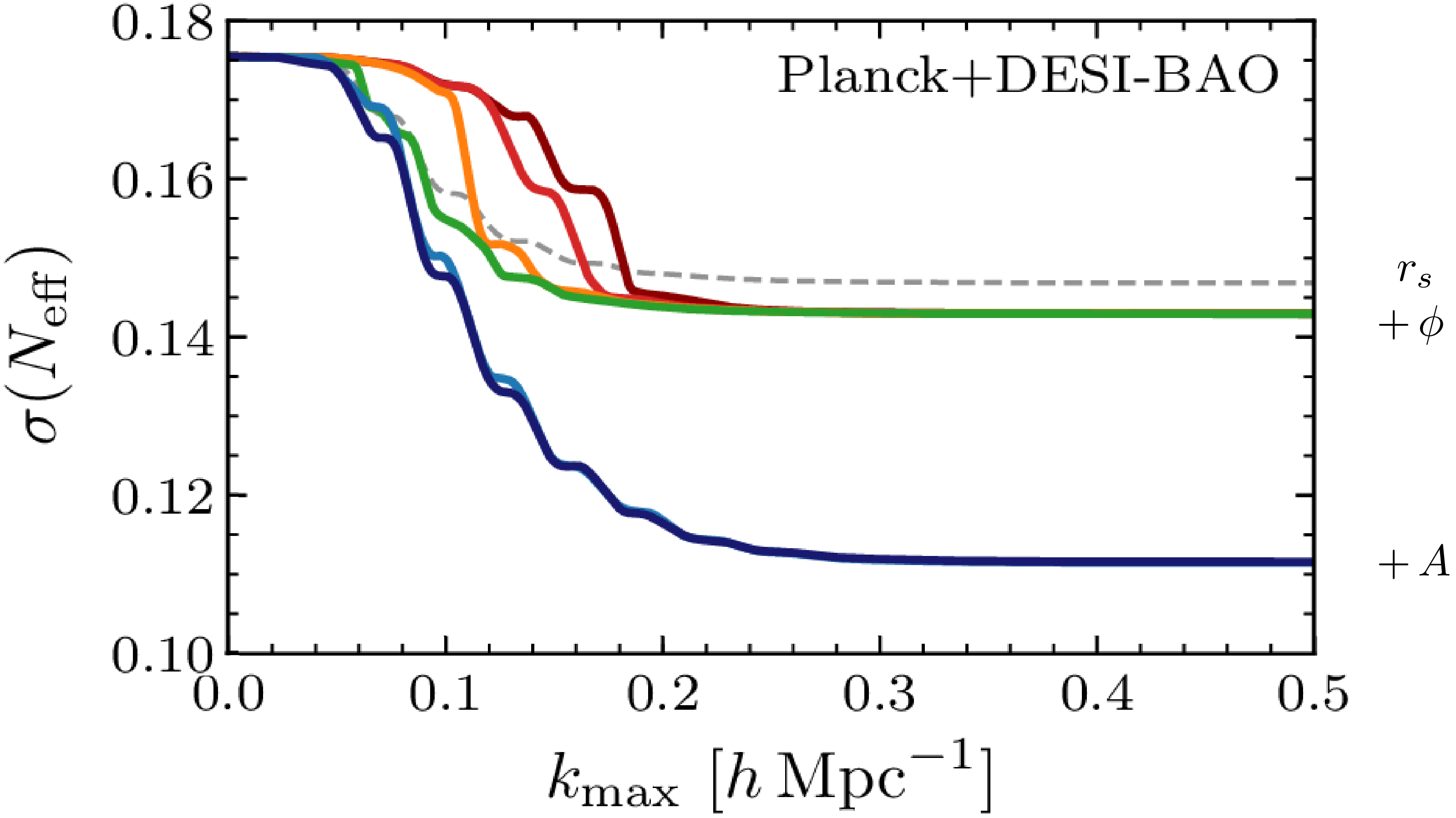


BAO spectrum $O(k)$

Baumann, Green & BW (2018)

Frequency, Amplitude and Phase Shift

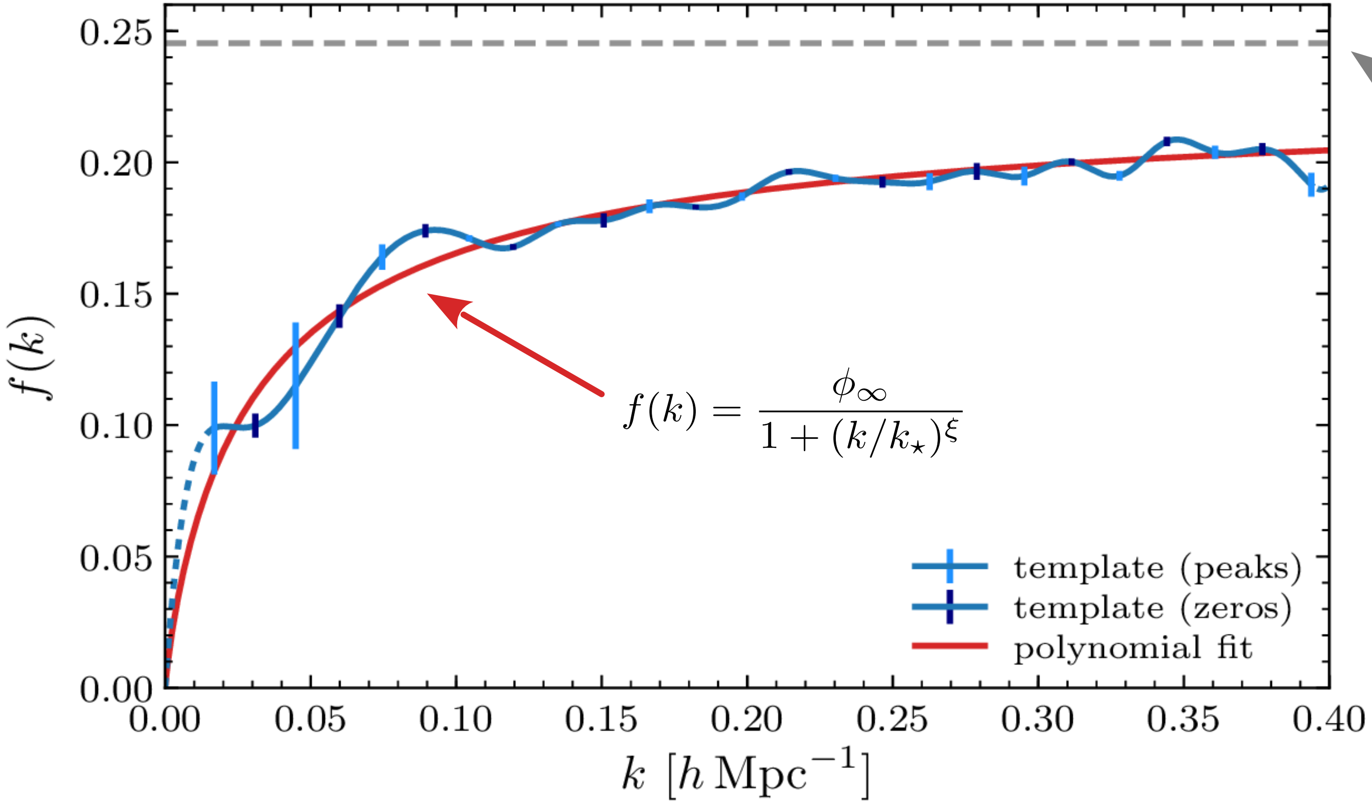
$$O(k) \sim A \sin(k r_s + \phi)$$



Baumann, Green & BW (2018)

Phase Shift Measurement

$$\phi(k) = \beta(N_{\rm eff})\, f(k) \qquad\qquad \beta = \epsilon/\epsilon_{\rm fid}\,, \quad \epsilon \equiv \rho_\nu/\rho_r$$



$$f(k) = \frac{\phi_\infty}{1+(k/k_\star)^\xi}$$

Analytic estimate

$0.191\pi\,\epsilon$

$$O(k) = O_{\rm fid}\left(\alpha^{-1}k + (\beta-1)f(k)/r_s^{\rm fid}\right)$$

standard BAO parameter

Baumann, Green & BW (2018)

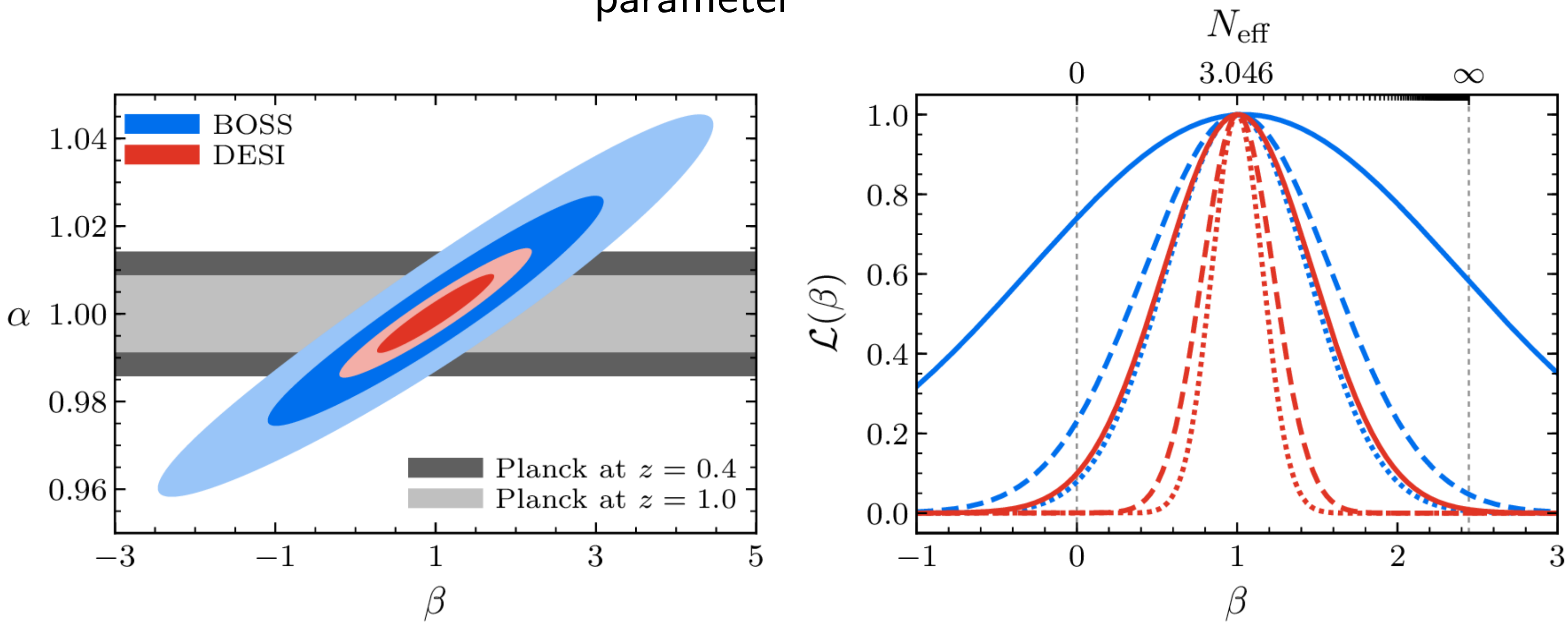
Projected Constraints on the Phase Shift

phase shift amplitude

$$O(k) = O_{\text{fid}}\left(\alpha^{-1}k + (\beta - 1)f(k)/r_s^{\text{fid}}\right)$$

standard BAO parameter

phase template



Baumann, Green & BW (2018)