

# CMB Phase Shift and Future Bounds on Axion Couplings

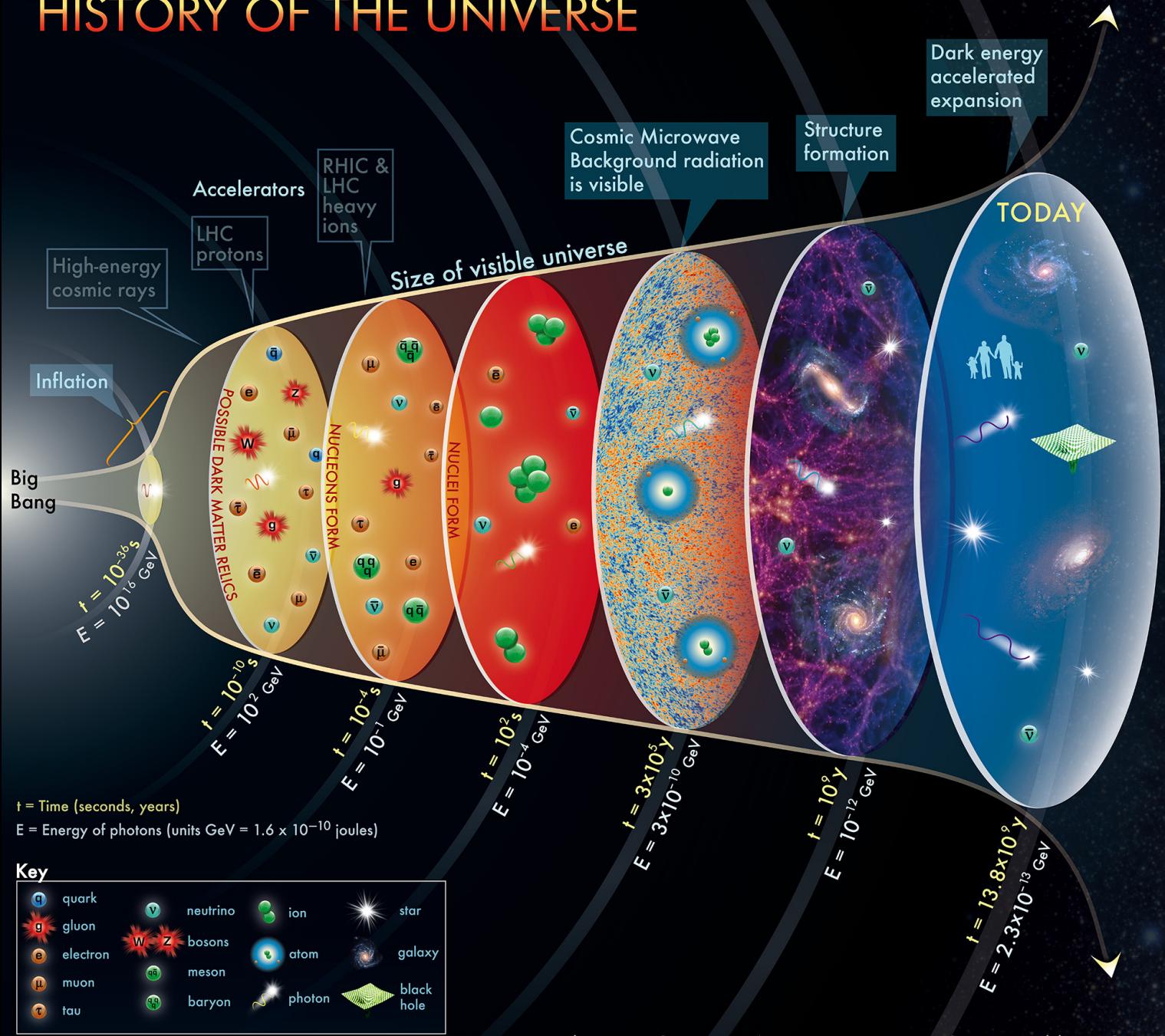
**Benjamin Wallisch**

DAMTP, University of Cambridge

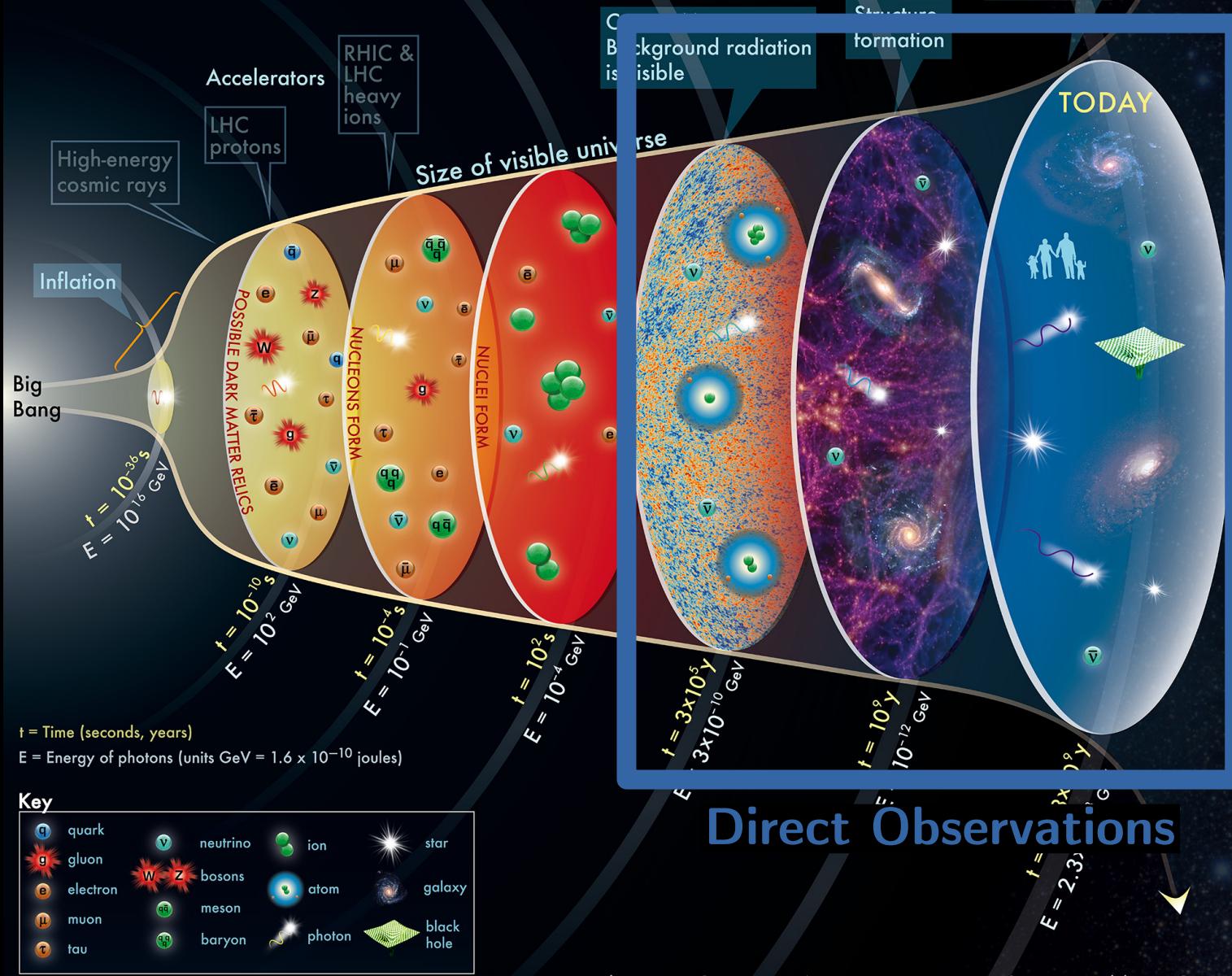
Based on:

arXiv:1508.06342 with Daniel Baumann, Daniel Green and Joel Meyers  
arXiv:1604.xxxxx with Daniel Baumann and Daniel Green

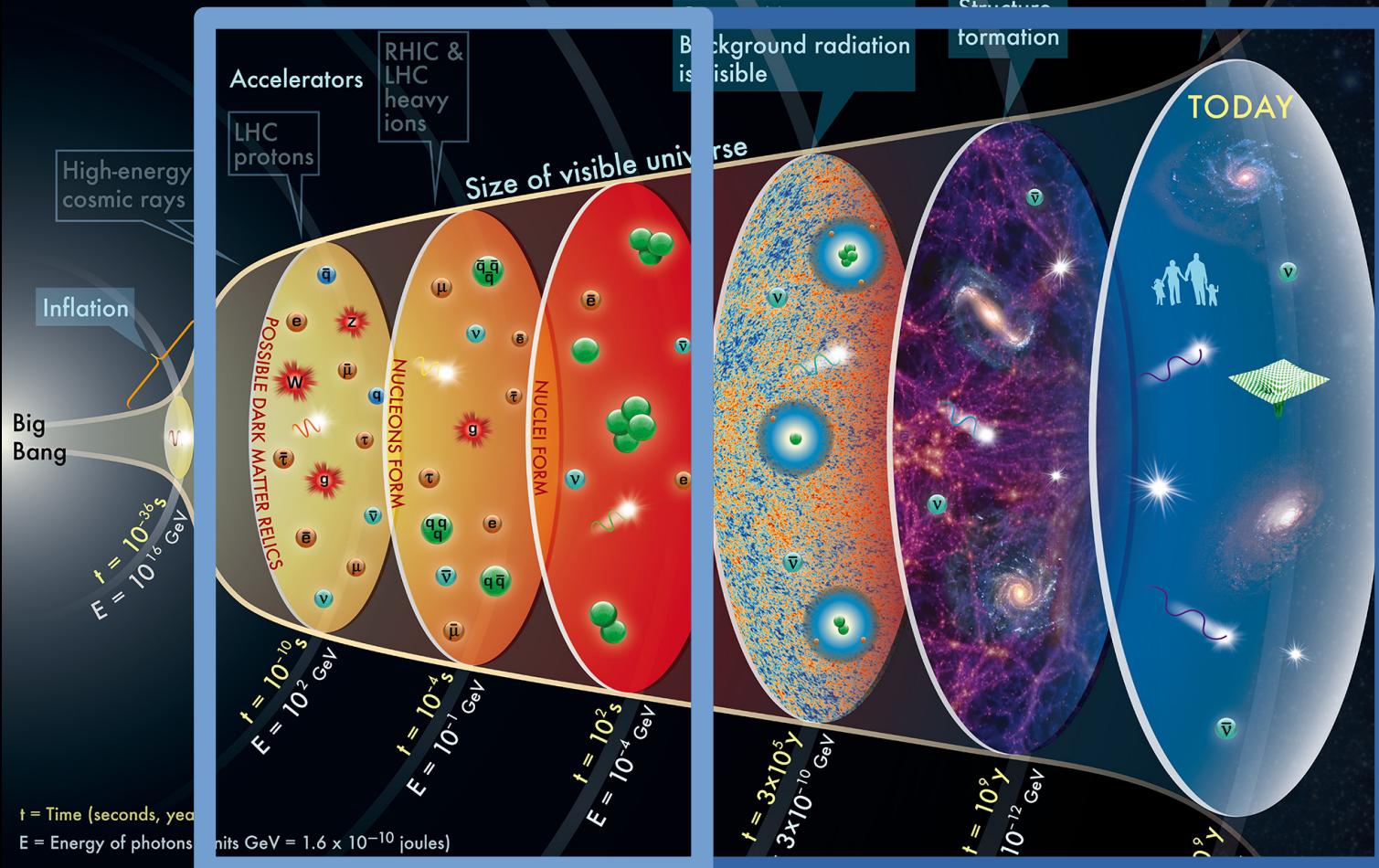
# HISTORY OF THE UNIVERSE



# HISTORY OF THE UNIVERSE



# HISTORY OF THE UNIVERSE



## Direct Observations

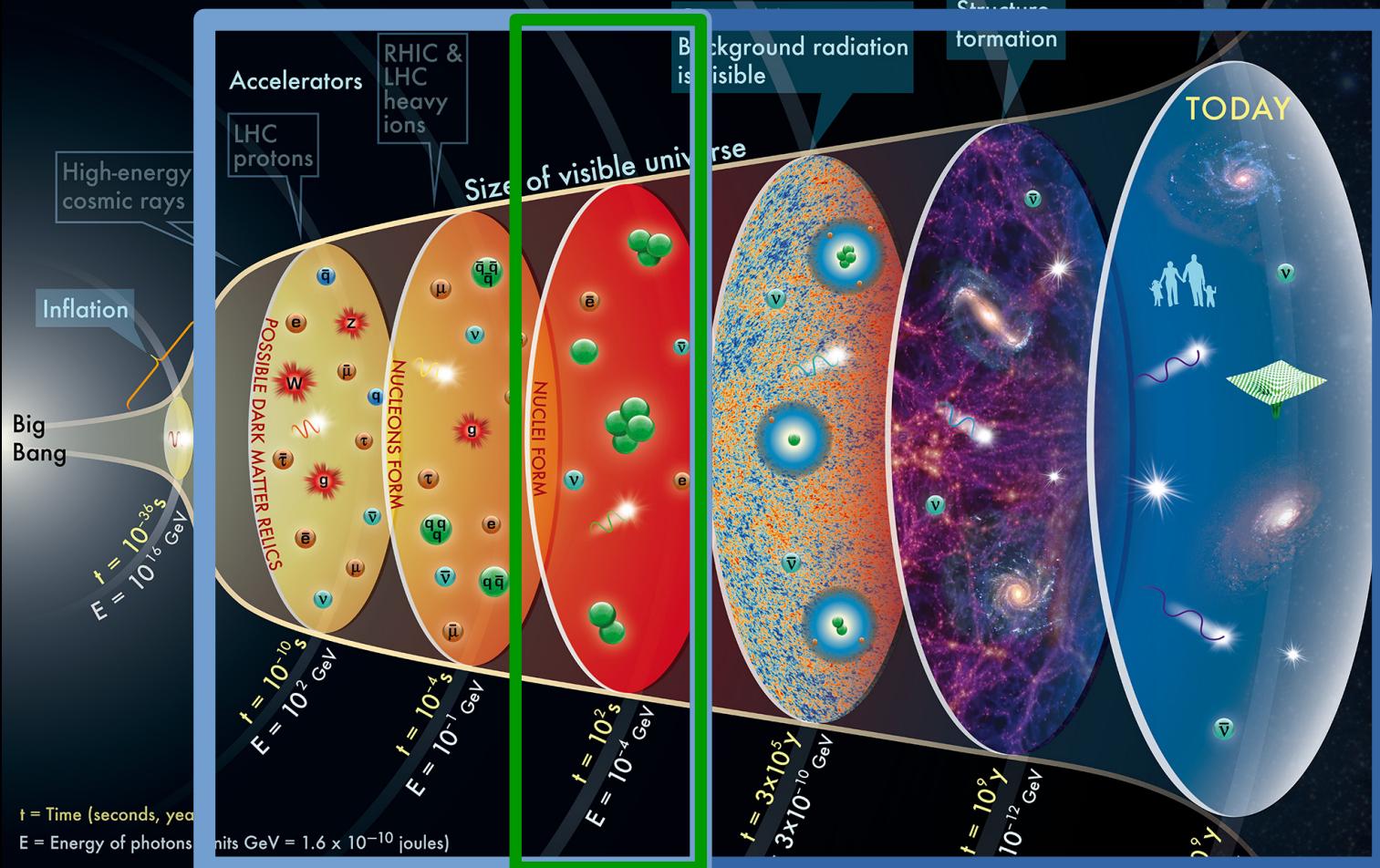
The concept for the above figure originated in a 1986 paper by Michael Turner.

Particle Data Group, LBNL © 2015

Supported by DOE

# HISTORY OF THE UNIVERSE

BBN



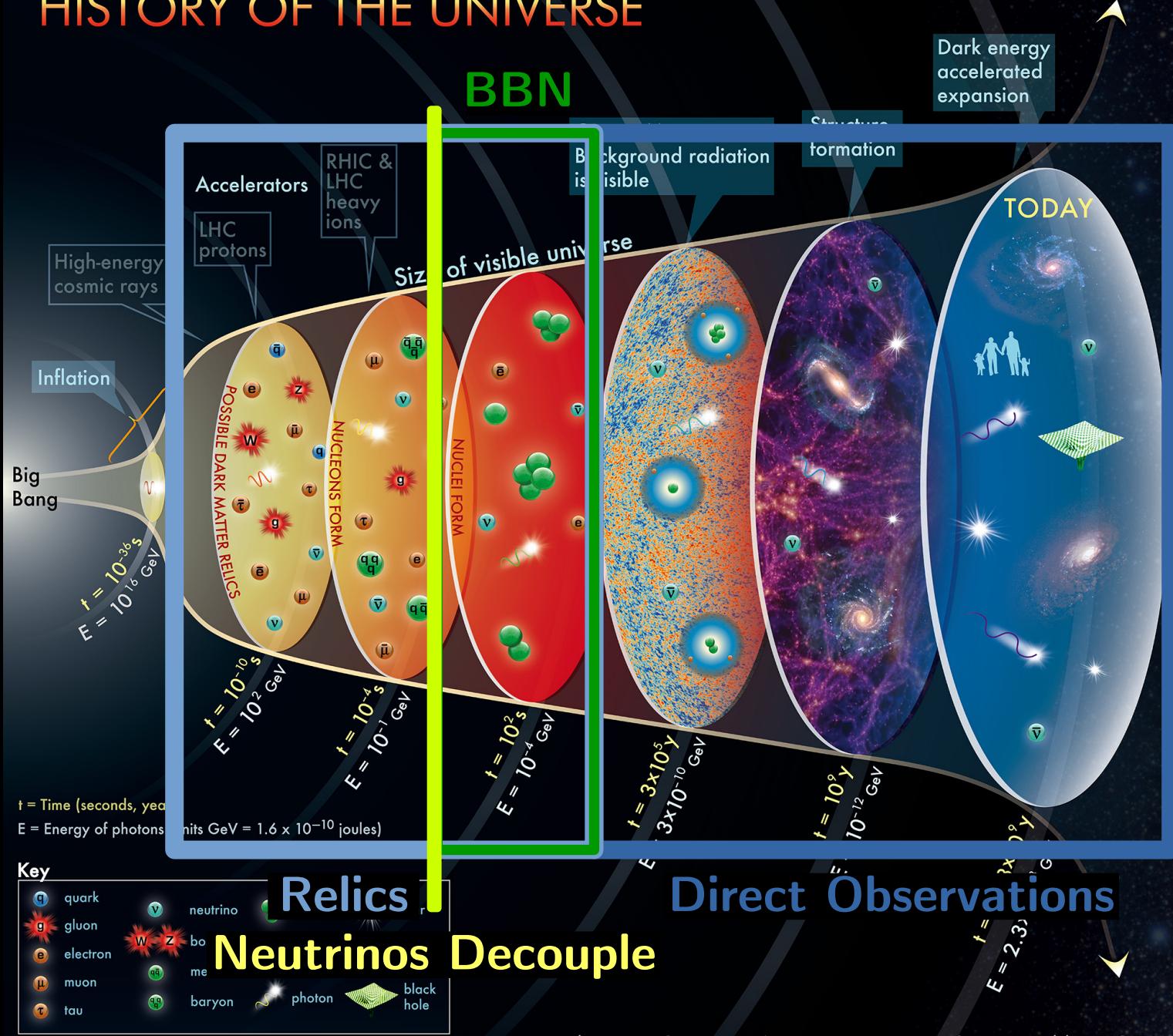
The concept for the above figure originated in a 1986 paper by Michael Turner.

Particle Data Group, LBNL © 2015

Dark energy accelerated expansion

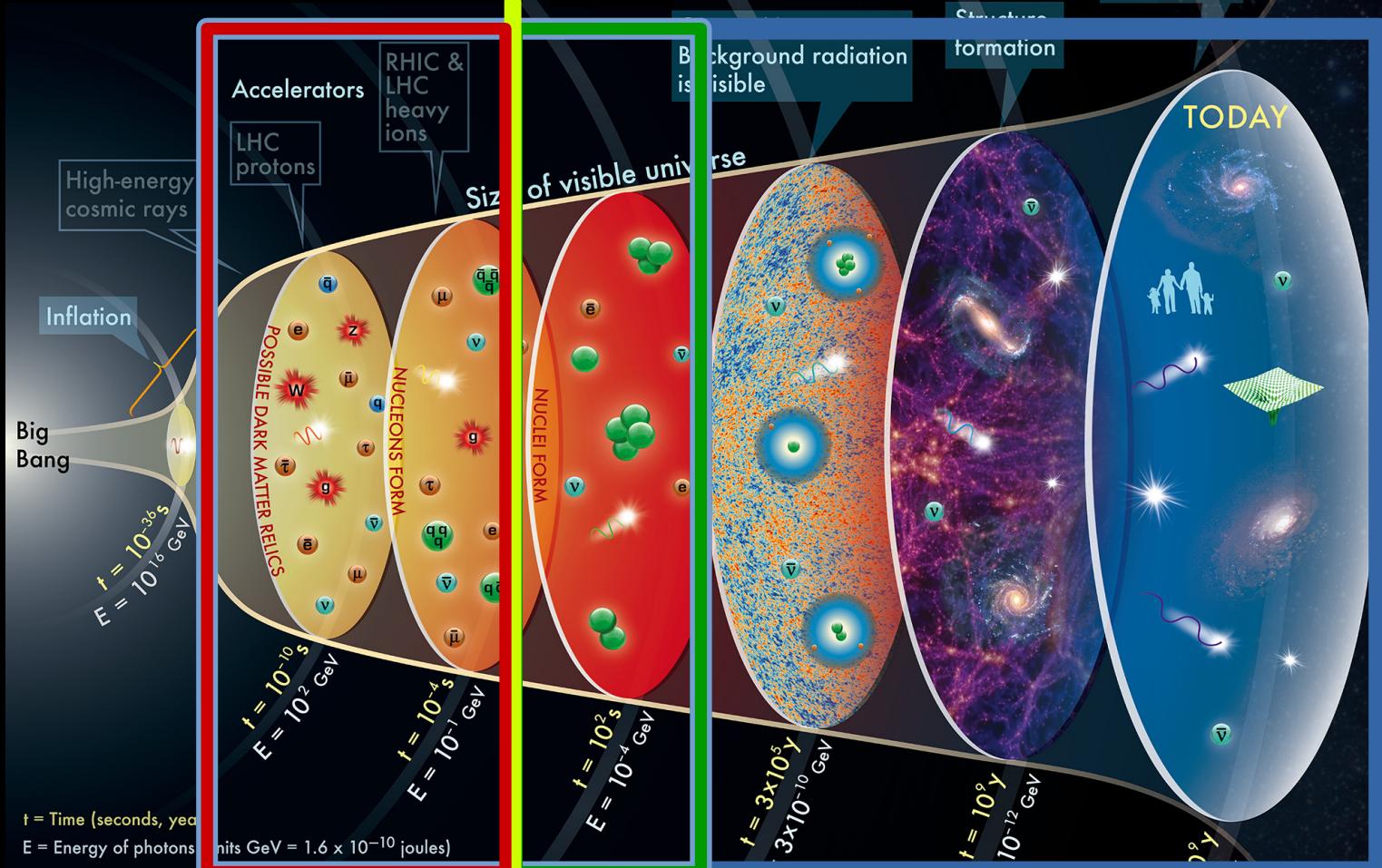
Supported by DOE

# HISTORY OF THE UNIVERSE



# HISTORY OF THE UNIVERSE

## Additional Relics? BBN



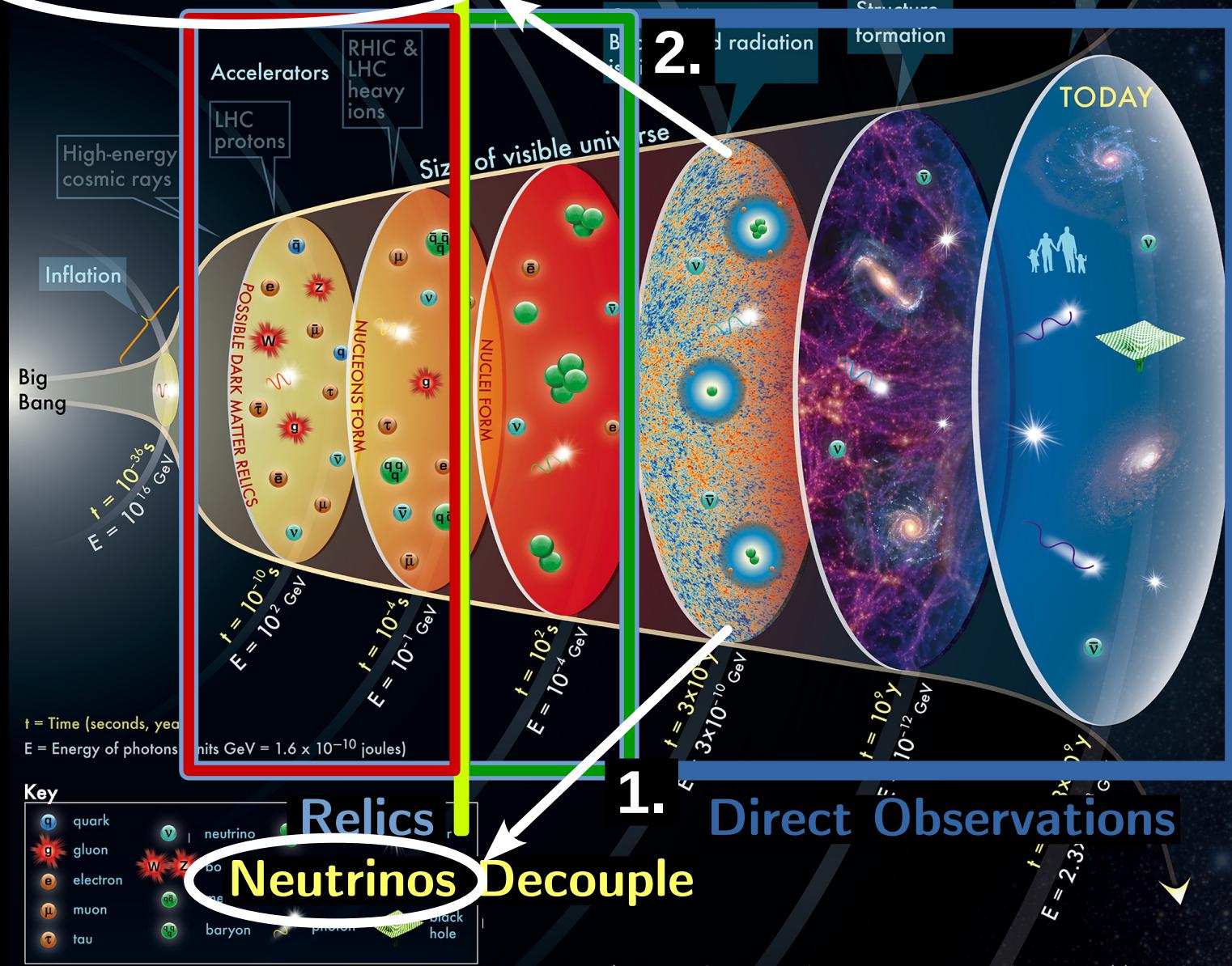
The concept for the above figure originated in a 1986 paper by Michael Turner.

Particle Data Group, LBNL © 2015

Supported by DOE

# HISTORY OF THE UNIVERSE

**Additional Relics? BBN**



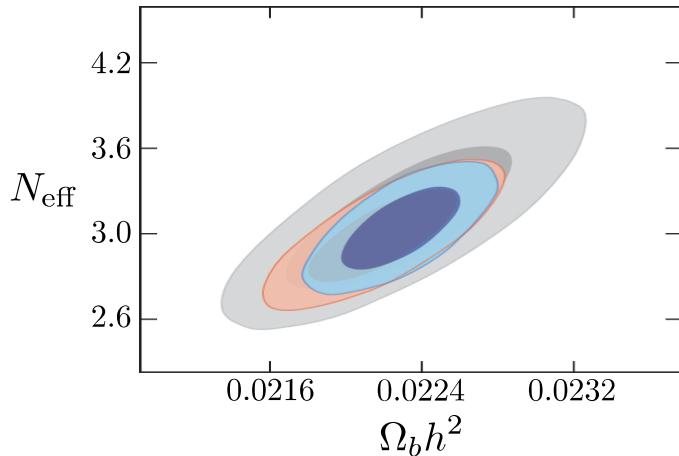
# **Neutrinos and Phase Shift**

# Neutrinos

42% of radiation density in the universe

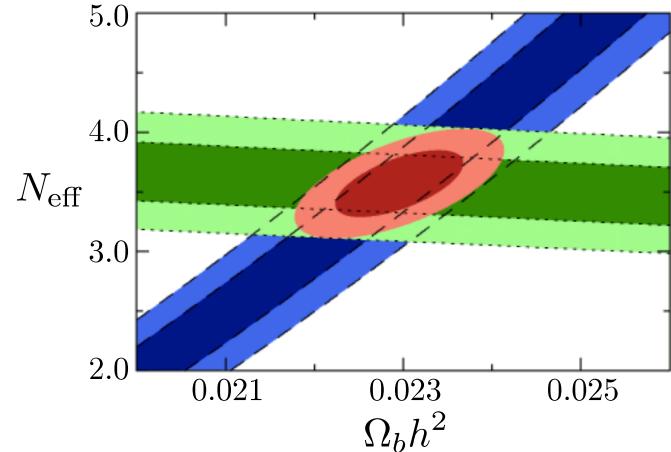
- leave gravitational imprint
- can detect their energy density

Observable: “effective number of neutrinos”  $N_{\text{eff}}^{\text{SM}} = 3.046$



CMB: anisotropy measurements

$$N_{\text{eff}}^{\text{CMB}} = 3.04 \pm 0.18$$



BBN: primordial abundances

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

# Free-Streaming Neutrinos

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

Introduce parametrisation:



Damping tail of CMB power spectrum:

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

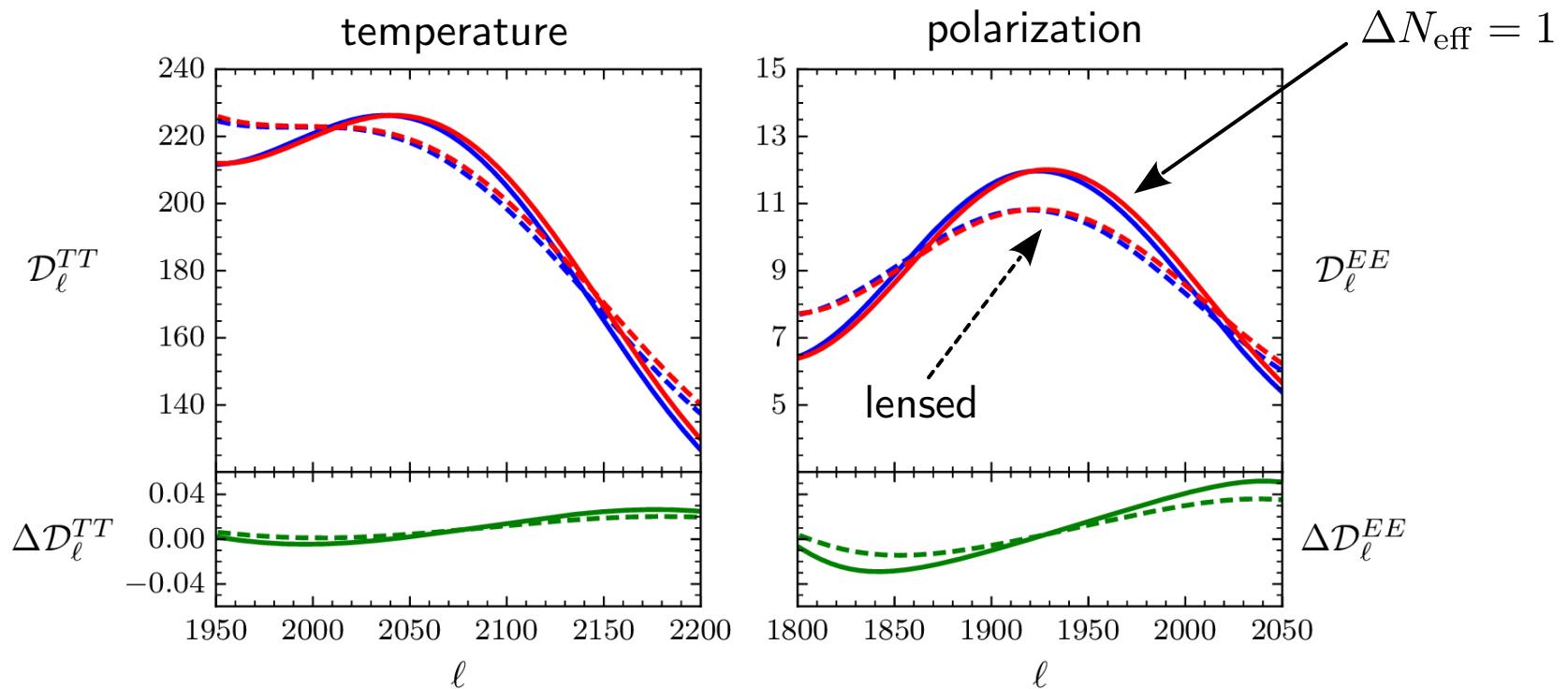
Data now precise enough to be sensitive to neutrino perturbations:

The diagram shows the equation for neutrino perturbations:  $\ddot{\delta}_\gamma - c_\gamma^2 \nabla^2 \delta_\gamma = \nabla^2 \Phi_+$ . A red arrow points from a red box labeled "sound waves" to the term  $\ddot{\delta}_\gamma$ . To the right, two blue circles represent particles: one labeled  $\gamma$  and one labeled  $\nu$ . Blue arrows point from each particle towards the right side of the equation, representing the coupling between neutrinos and photons.

→ discriminating between  $N_{\text{eff}}$  and  $N_{\text{fluid}}$  possible!

# Phase Shift

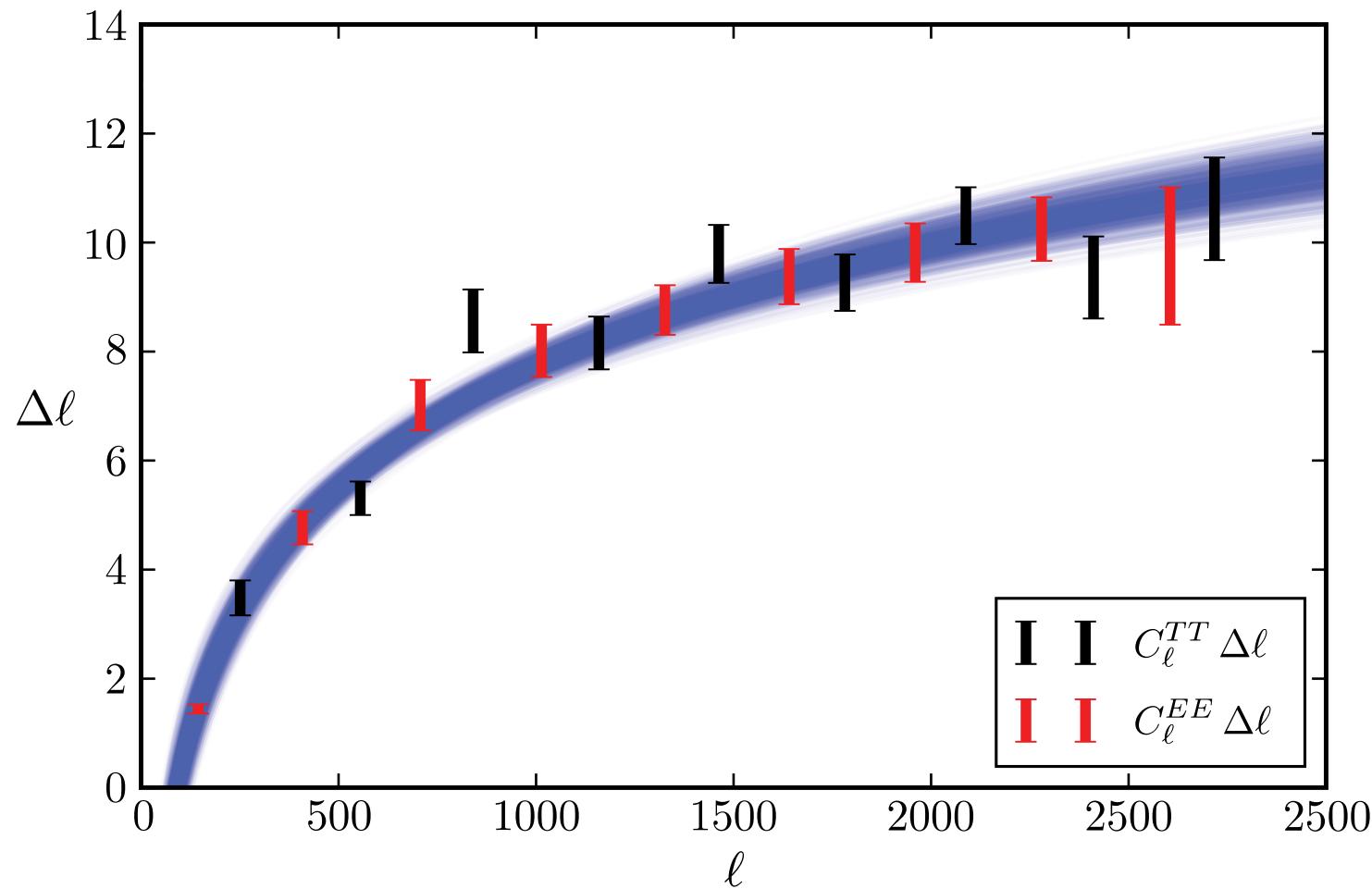
$N_{\text{eff}}$  has more subtle effect: phase shift  $\Delta\ell \approx 5.0 \times \Delta N_{\text{eff}}$



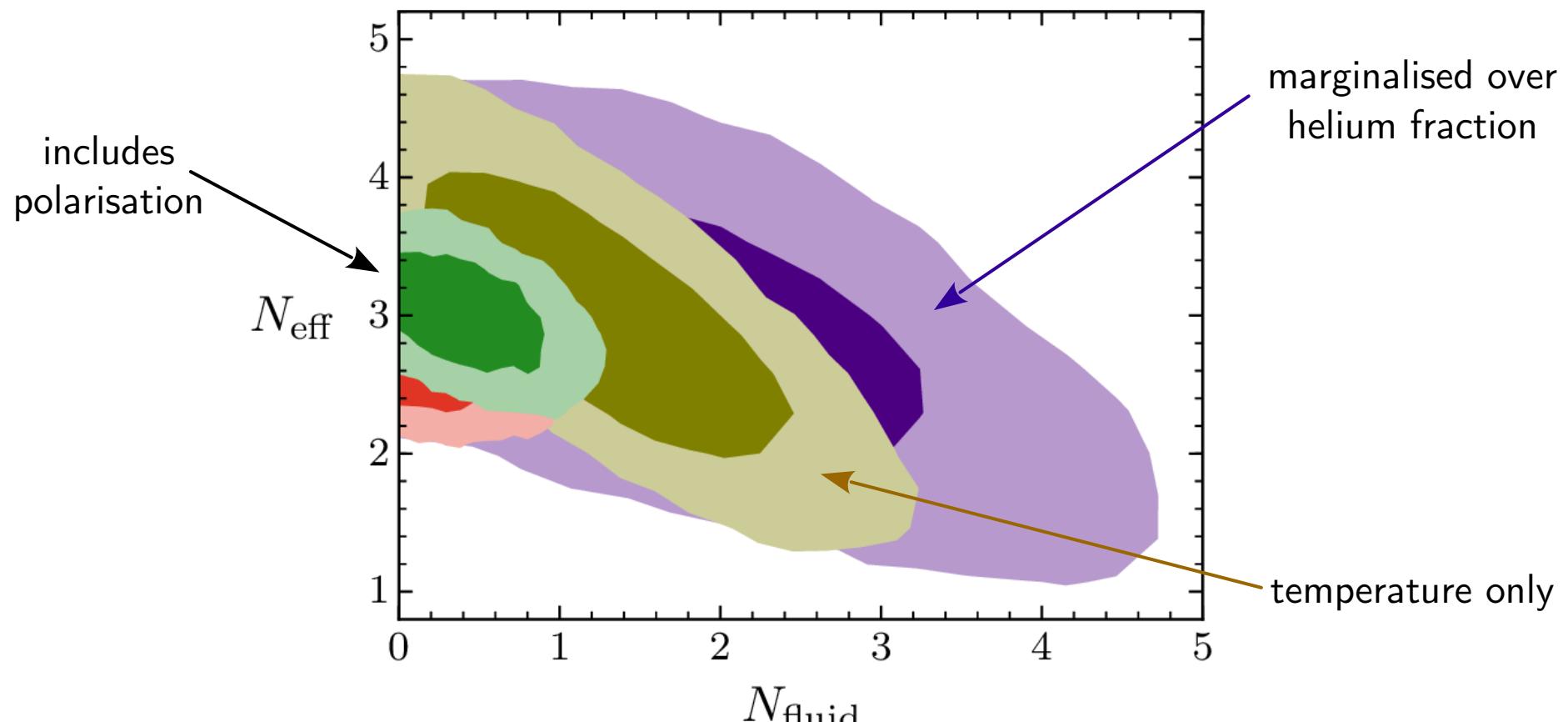
$$\sigma(\Delta\ell) \approx 1 \longrightarrow \sigma(\Delta N_{\text{eff}}) \approx 0.2$$

# Phase Shift

Neutrino imprint in phase shift recently detected in Planck data:



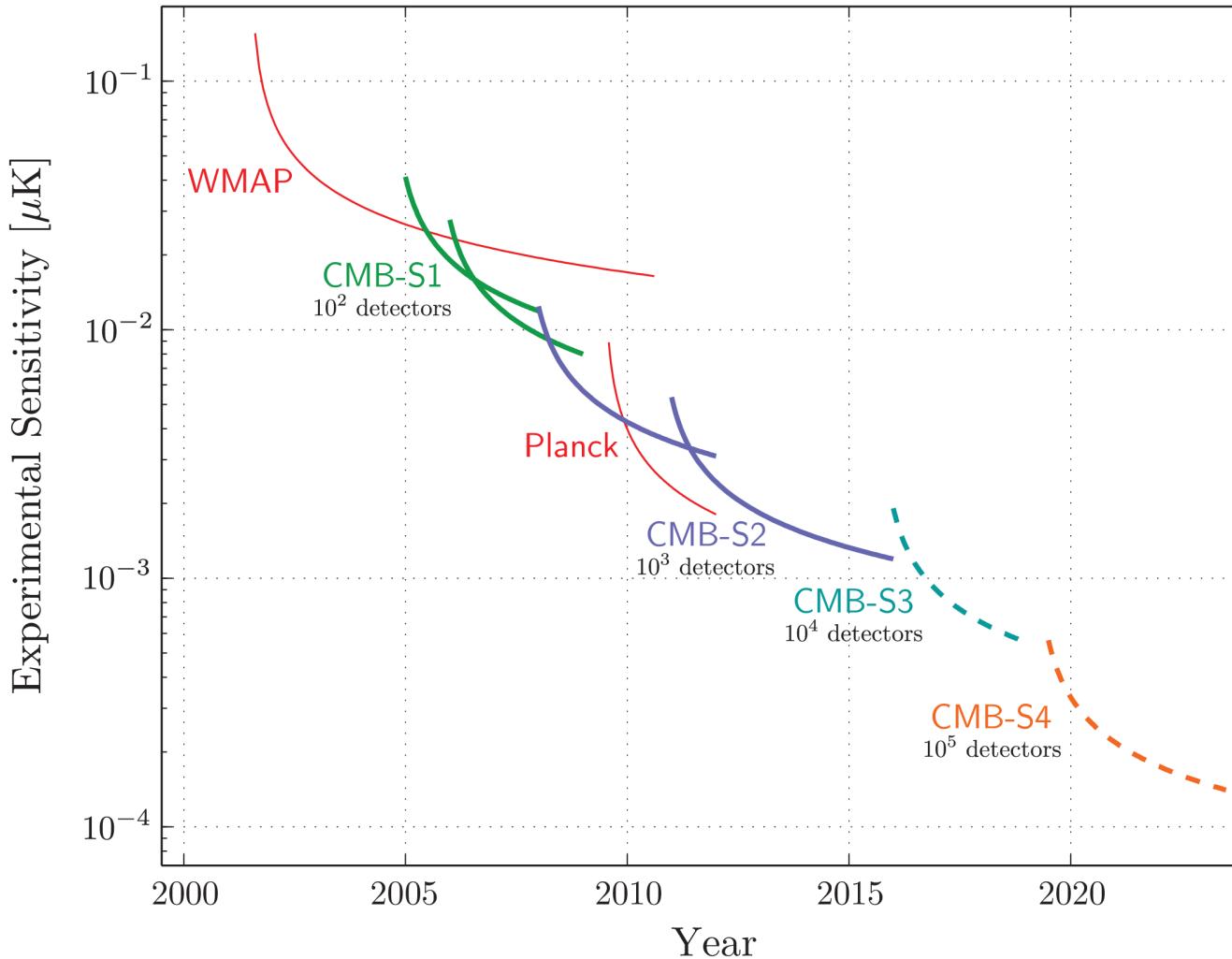
# Planck Constraints



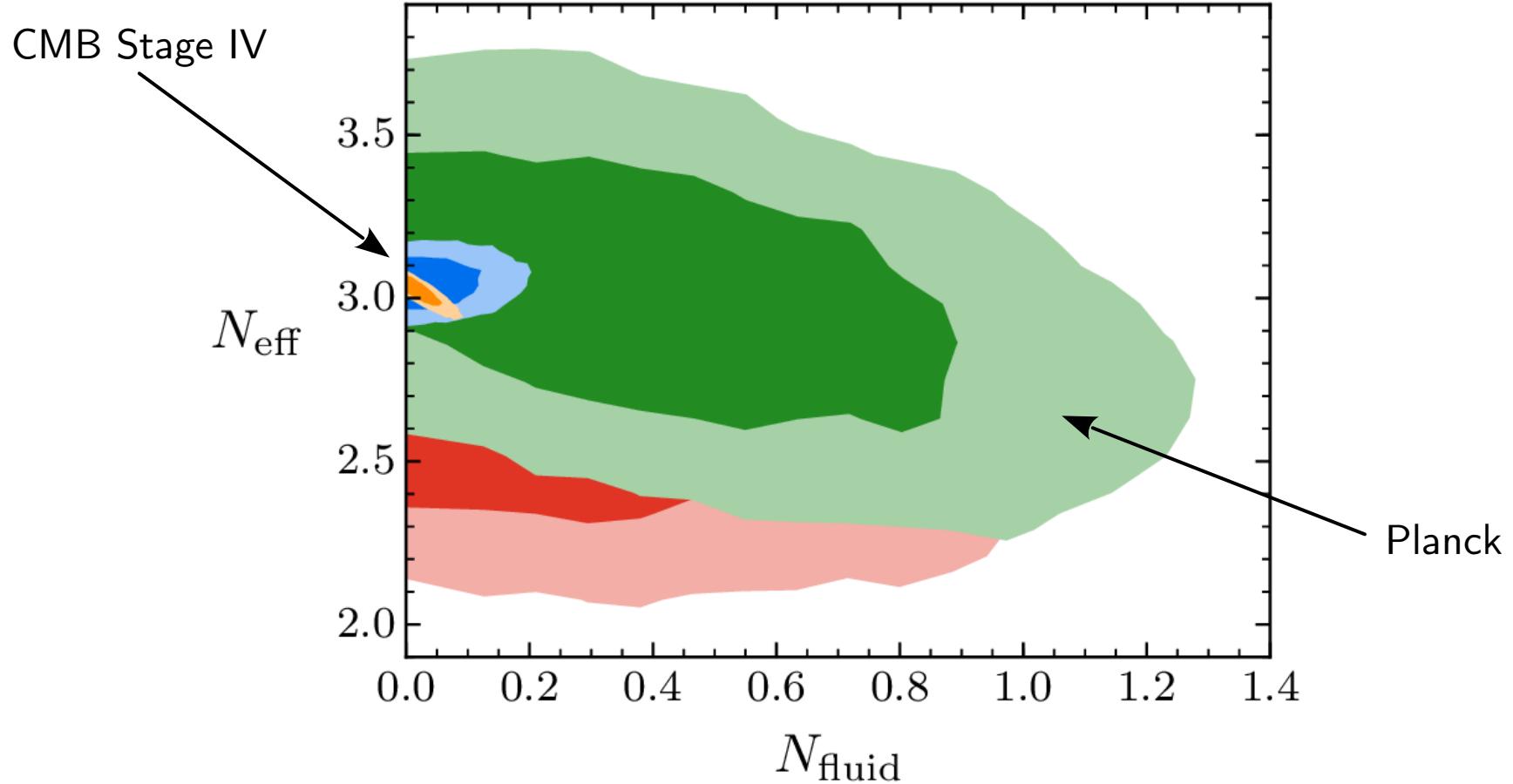
$$N_{\text{eff}} = 2.78 \pm 0.35$$

$$N_{\text{fluid}} < 0.88 \text{ (95% c.l.)}$$

# CMB Stage IV



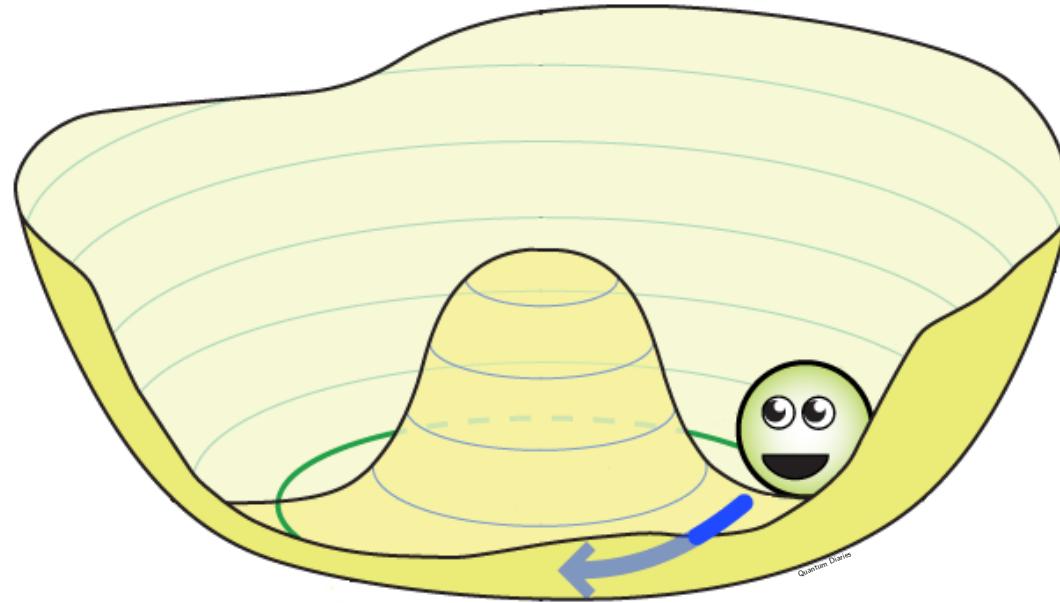
# CMB Stage IV Forecast



$$\sigma(N_{\text{eff}}) = 0.013 \text{ possible!}$$

# **Future Constraints on Axion Couplings**

# Motivation for Extra Light Species



Spontaneously broken global symmetries lead to massless Goldstone bosons.

If symmetries are approximate: extra naturally light particles.

# Couplings to the Standard Model

Additional particles interact with the Standard Model:

$$\frac{\mathcal{O}_\phi \mathcal{O}_{\text{SM}}}{\Lambda^\Delta}$$

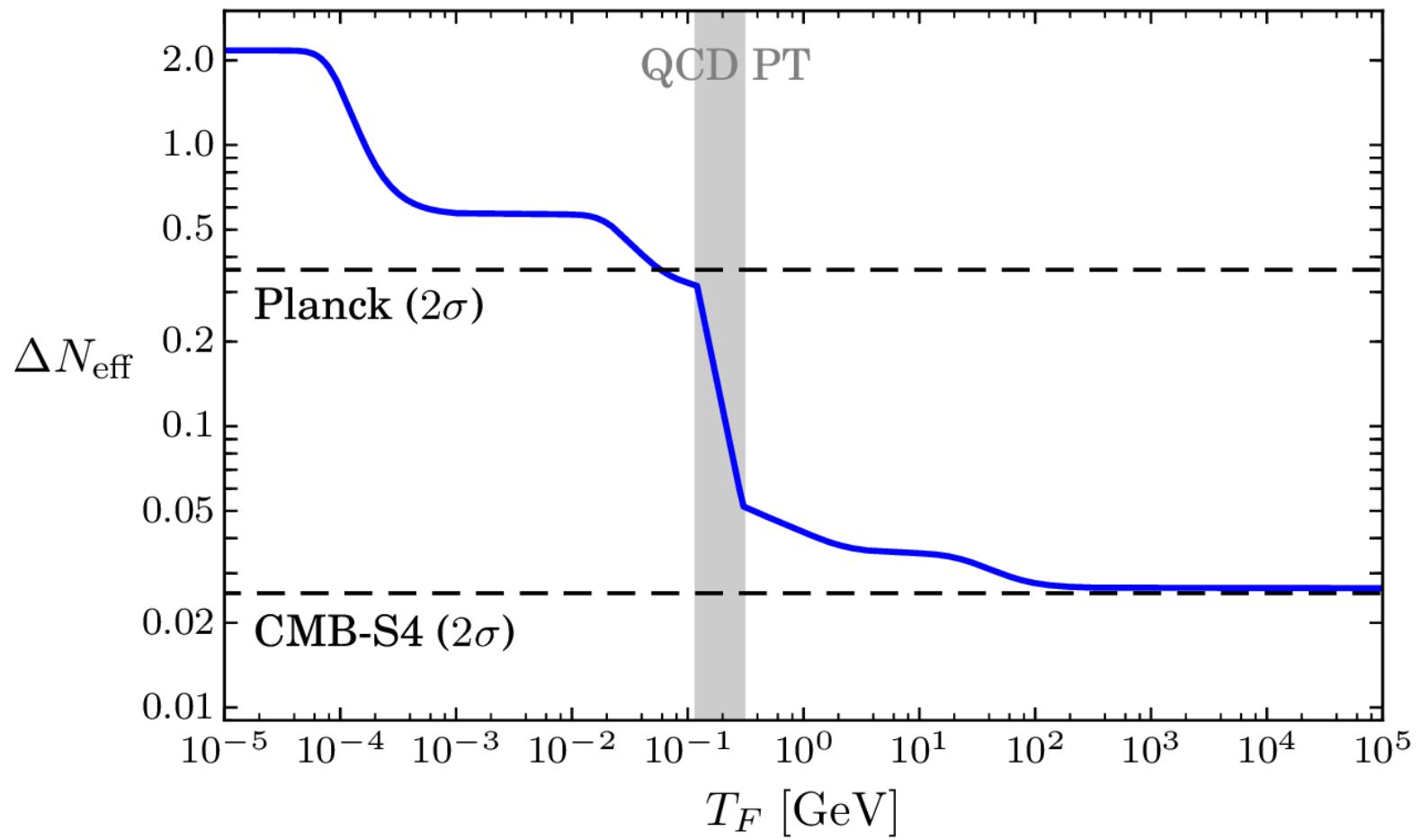
↗  
symmetry breaking scale

Can bring particles into thermal equilibrium

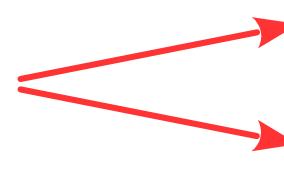
When interaction rate drops below Hubble rate, particle decouples from Standard Model with freeze-out temperature  $T_F$ :

$$\Gamma(\Lambda, T_F) \approx H(T_F)$$

# Thermal Relics



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

 Detection  
Constraints

# Constraints on Axions

$$\mathcal{L} = -\frac{g_{\phi\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{g_{\phi g}}{4}\phi \text{tr}\{G_{\mu\nu}\tilde{G}^{\mu\nu}\}$$

Assume: no detection with CMB Stage IV

- Axion was never in thermal equilibrium
- Production rate must be smaller than Hubble rate at reheating:

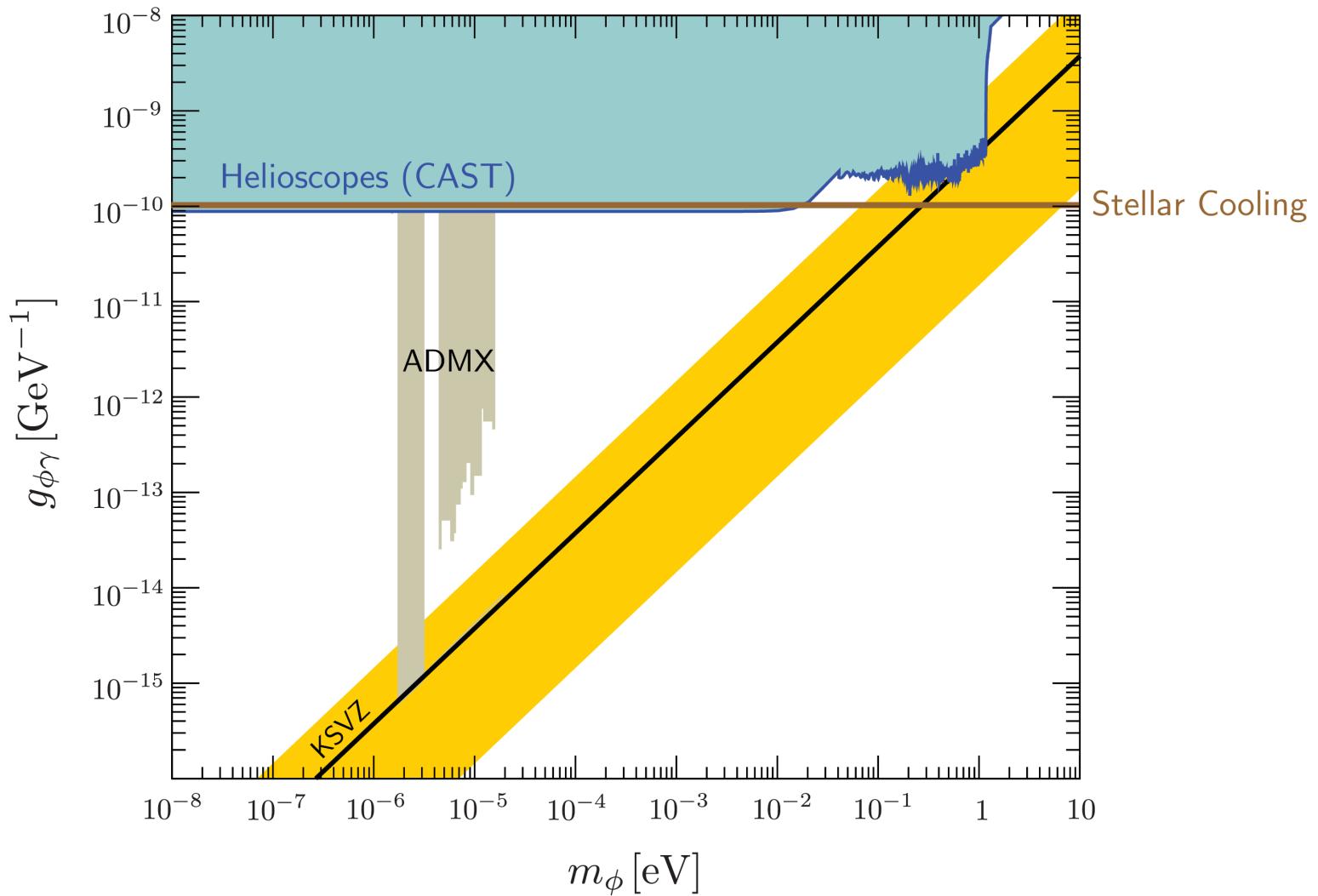
$$\Gamma(g_{\phi\text{SM}}, T_R) \lesssim H(T_R)$$

- Production rate depends on couplings to the Standard Model
- Strong constraints:

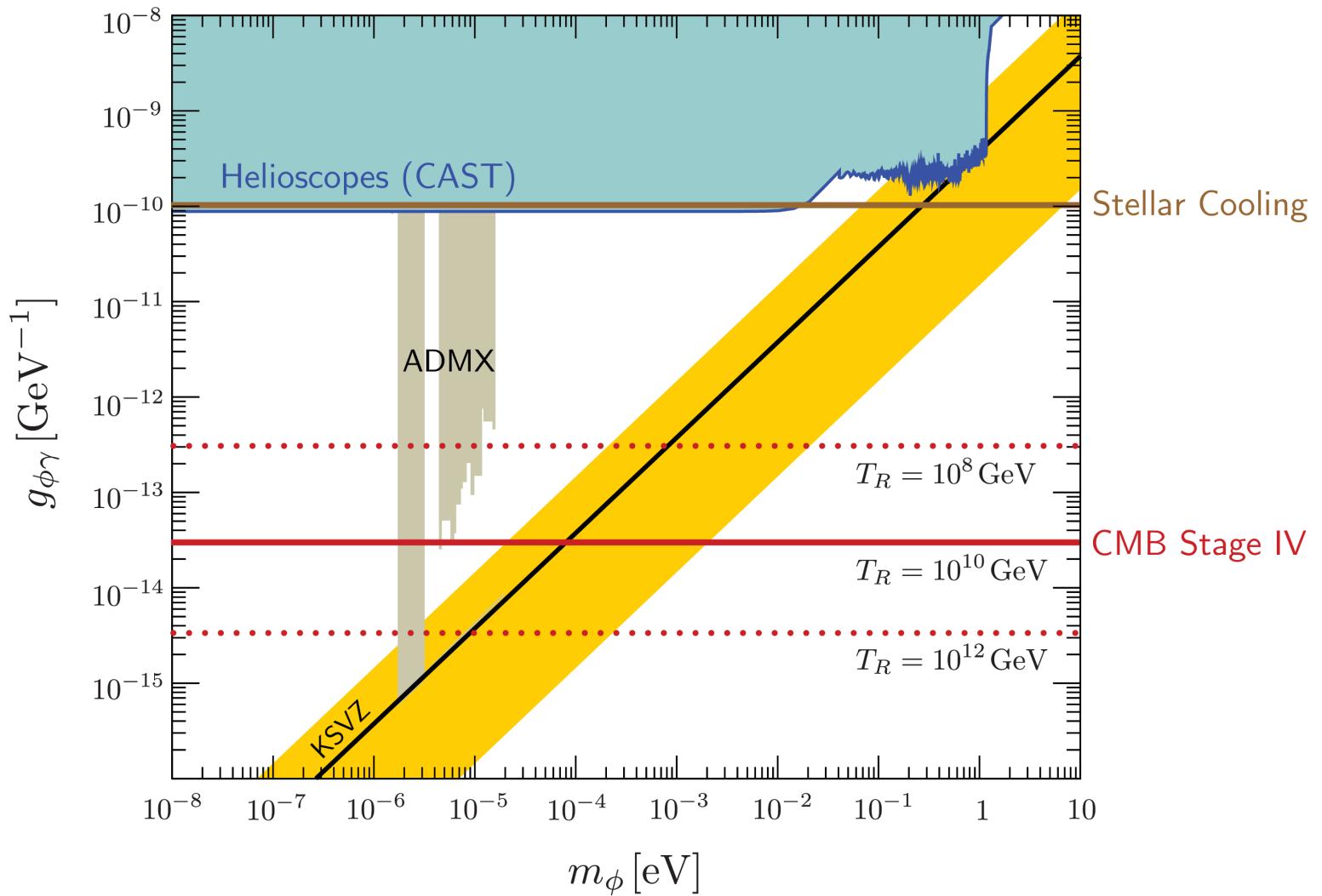
$$g_{\phi\gamma} < 3.0 \times 10^{-14} \text{ GeV}^{-1} \left( \frac{T_R}{10^{10} \text{ GeV}} \right)^{-1/2}$$

$$g_{\phi g} < 1.9 \times 10^{-14} \text{ GeV}^{-1} \left( \frac{T_R}{10^{10} \text{ GeV}} \right)^{-1/2}$$

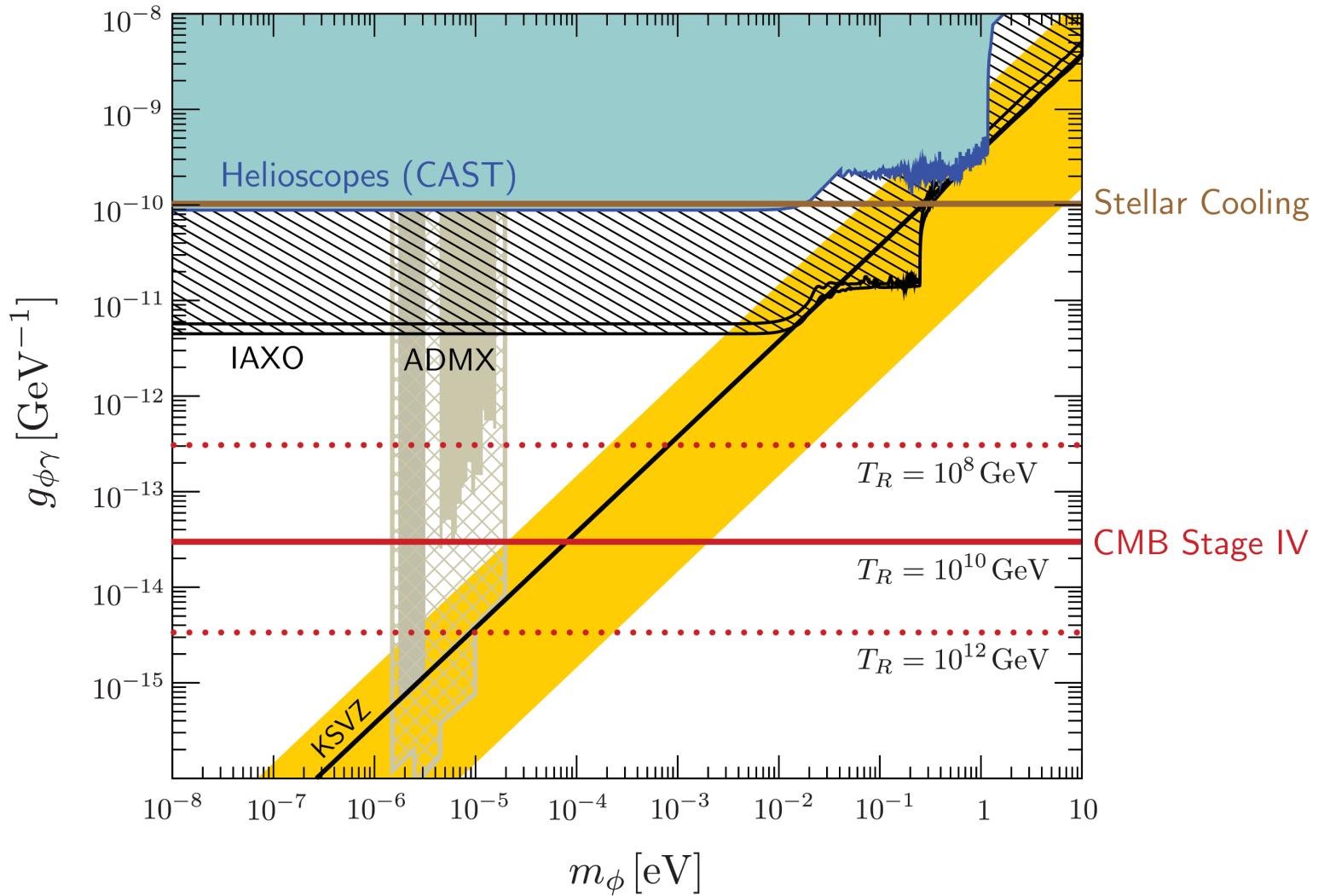
# Axion Coupling to Photons



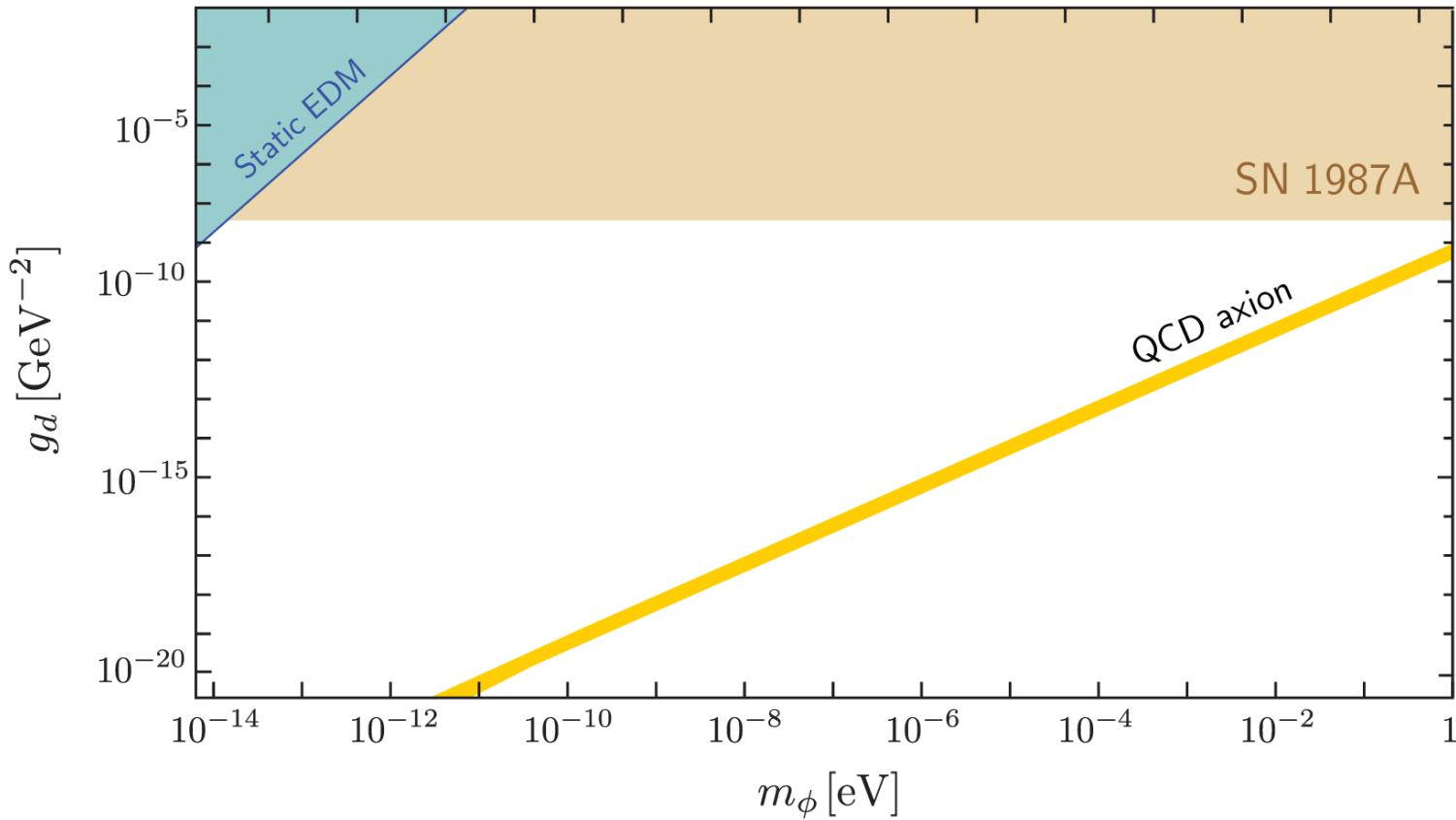
# Axion Coupling to Photons



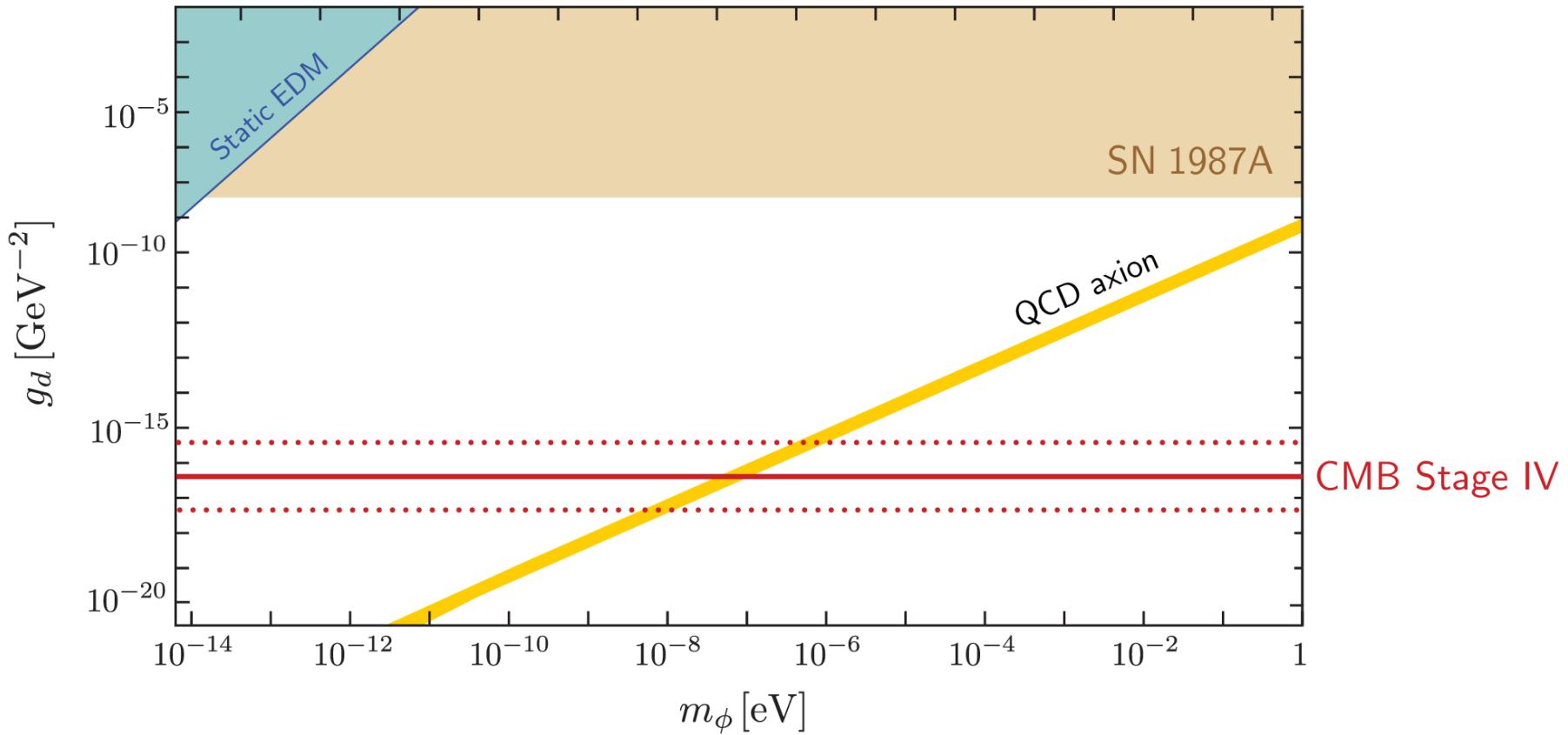
# Axion Coupling to Photons



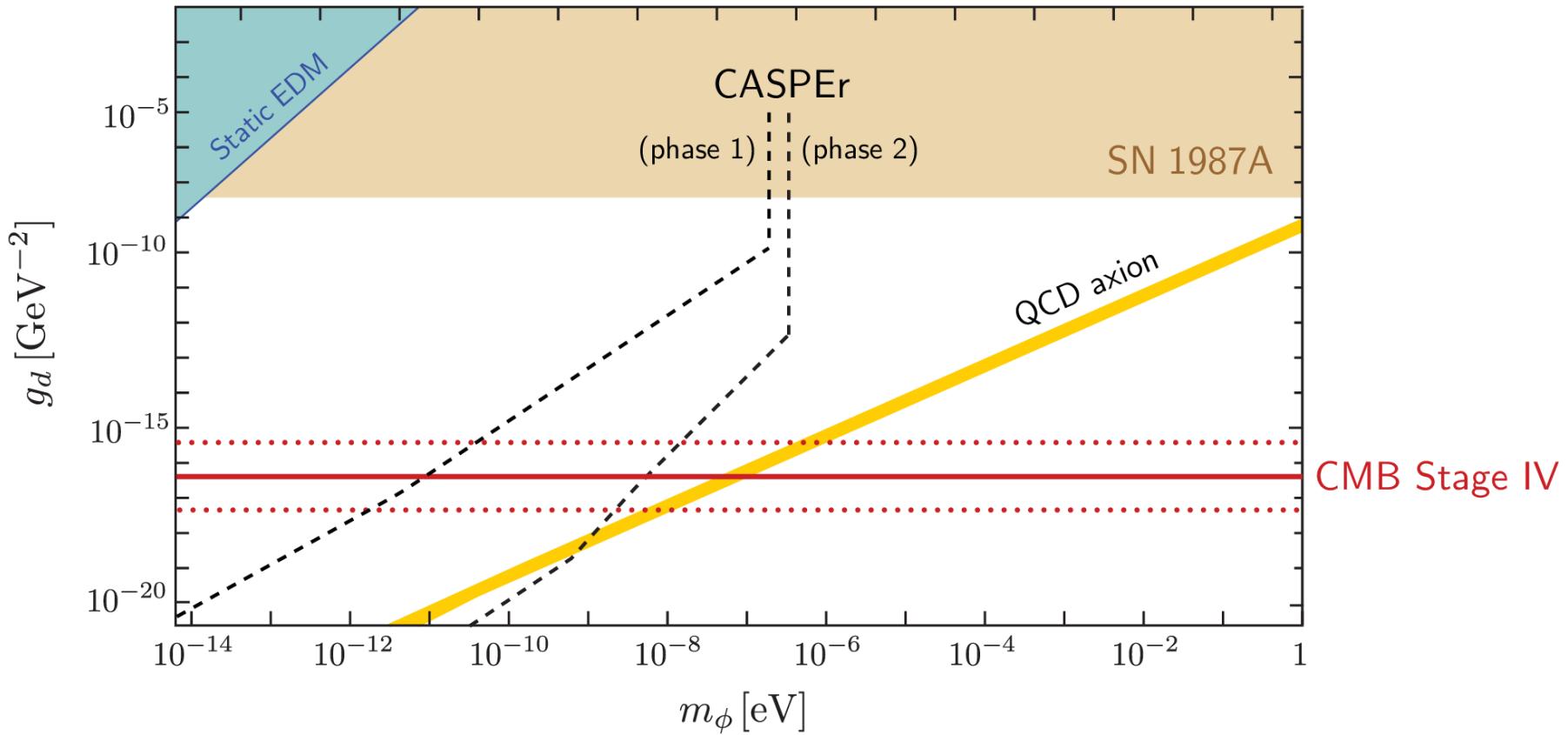
# Axion Coupling to Gluons



# Axion Coupling to Gluons



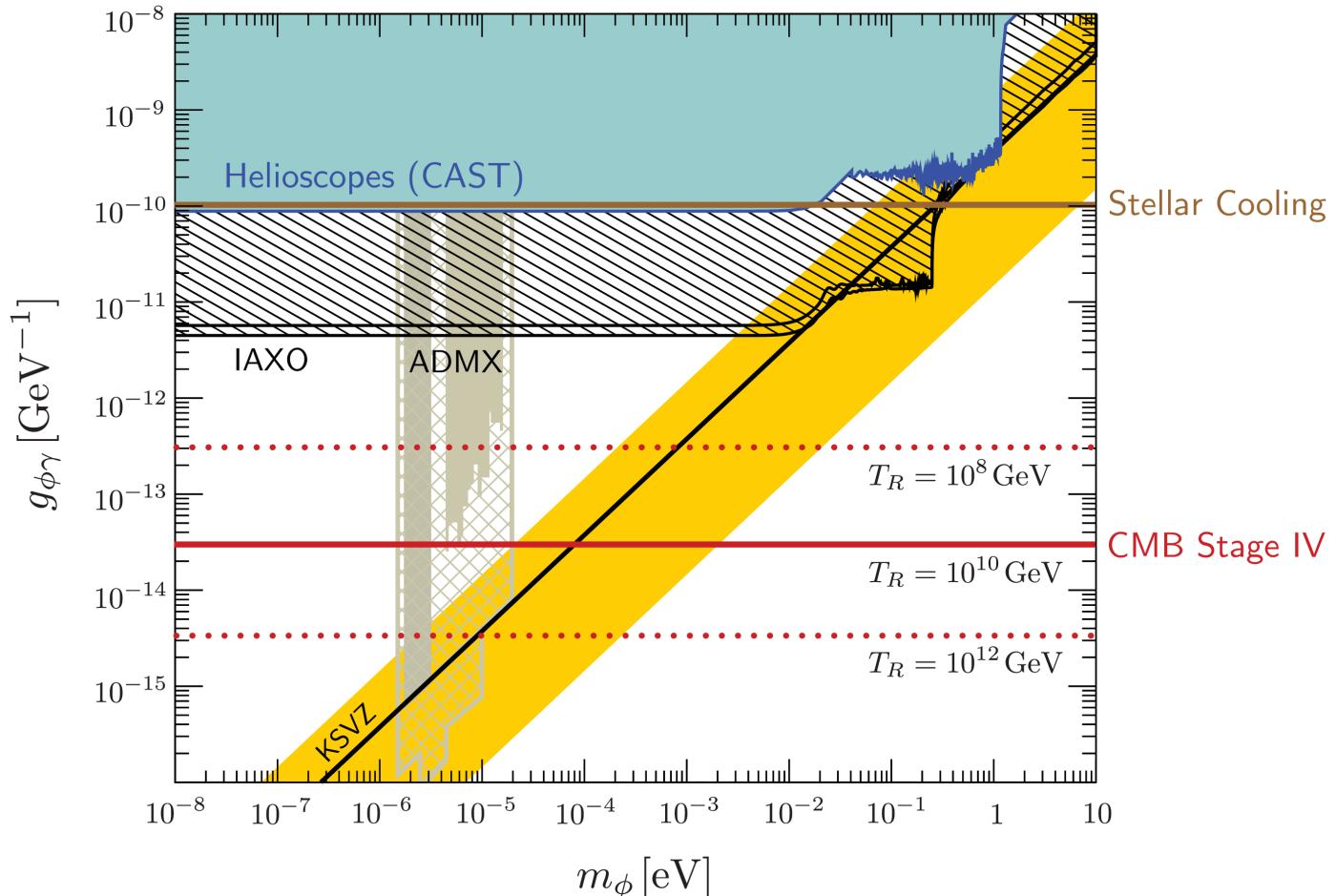
# Axion Coupling to Gluons



# Conclusions

- Constraint on  $N_{\text{eff}}$  now driven by phase shift.
- Constraint on free-streaming nature of neutrinos:  
first time with Planck, improvement with CMB Stage IV.
- Important theoretical threshold:  $\Delta N_{\text{eff}} = 0.027$ .
- Reachable by CMB Stage IV:
  - either: find new particle,
  - or: put strong constraints on couplings to Standard Model.

# Thank you!



Benjamin Wallisch  
[b.wallisch@damtp.cam.ac.uk](mailto:b.wallisch@damtp.cam.ac.uk)