Cosmology overview

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TAUP 2017

Sudbury, Ontario

UNSW SYDNEY

Australian Government

Australian Research Council

The standard model of cosmology: ΛCDM

Ingredients of ΛCDM

General Relativity

$$R_{\mu\nu} - \frac{1}{2} R \, g_{\mu\nu} = 8\pi G \, T_{\mu\nu}$$

Geometry

Content

Ingredients of ΛCDM

General Relativity

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

Geometry   Content

- Cosmological principle
  (homogeneity and isotropy)
- spatially flat

Ingredients of ΛCDM

General Relativity

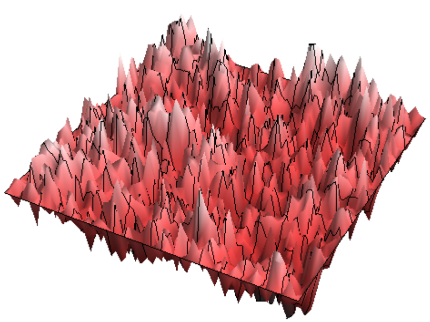
$$R_{\mu\nu} - \frac{1}{2} R \, g_{\mu\nu} = 8\pi G \, T_{\mu\nu}$$

Geometry

Content

- Cosmological principle (homogeneous and isotropic)
- spatially flat

+ initial perturbations



Ingredients of ΛCDM

General Relativity

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

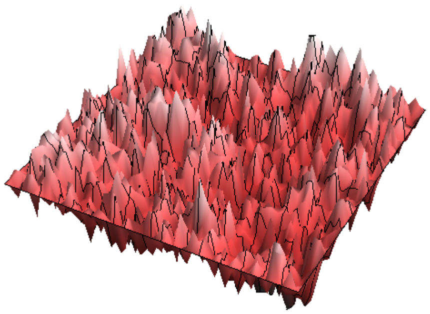
Geometry

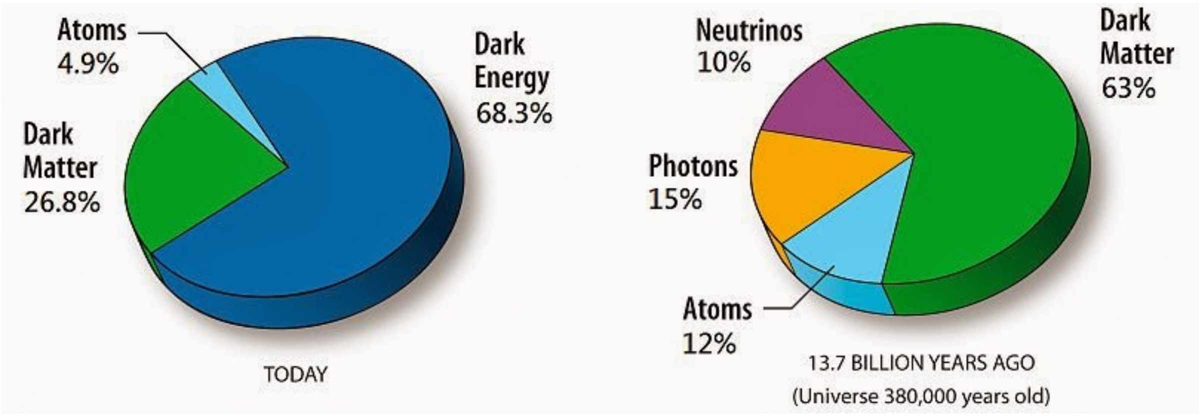
- Cosmological principle (homogeneous and isotropic)
- spatially flat

Content

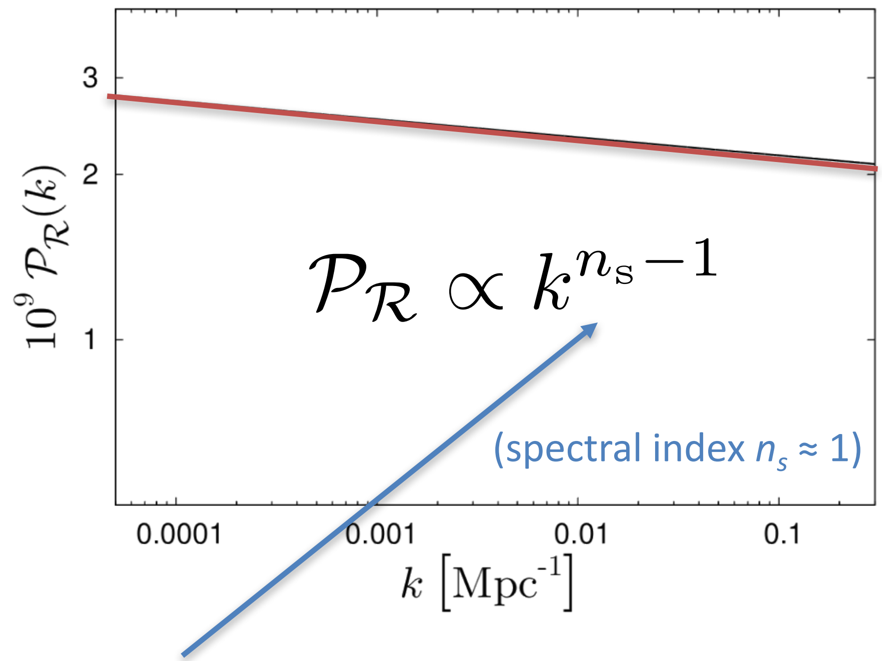
- Standard model particles + interactions
- Cold dark matter
- Cosmological constant

+ initial perturbations





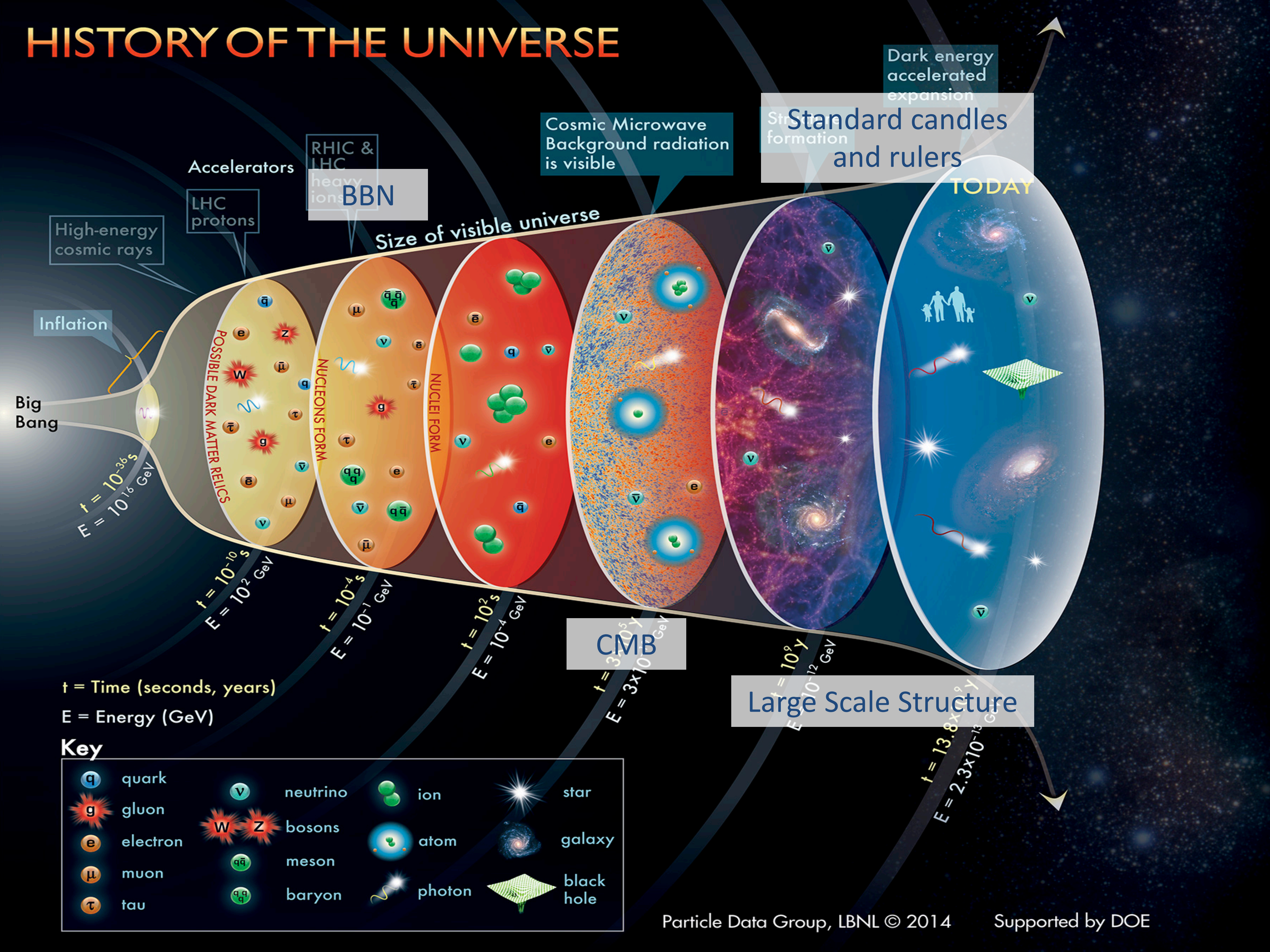
ΛCDM: initial perturbations



Almost scale-invariant power-law spectrum of

- adiabatic (no entropy perturbations)
- Gaussian (no non-trivial higher order correlations)
- statistically isotropic and homogeneous
- scalar (no vector or tensor perturbations)

perturbations



HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Standard candles and rulers
Cosmic Microwave Background radiation is visible
Accelerators
RHIC & LHC
BBN
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
CMB
Large Scale Structure
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy (GeV)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL © 2014
Supported by DOE

Challenging ΛCDM

Challenging ΛCDM?

General Relativity — modified gravity?

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

inhomogeneous background?

Geometry

- Cosmological principle (homogeneous and isotropic)
- spatially flat — spatial curvature?

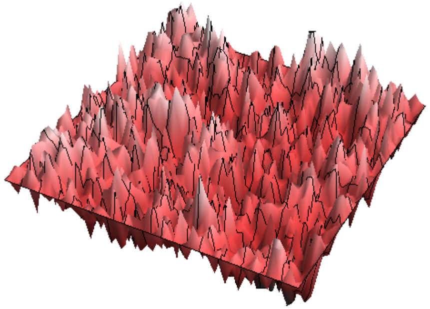
Content

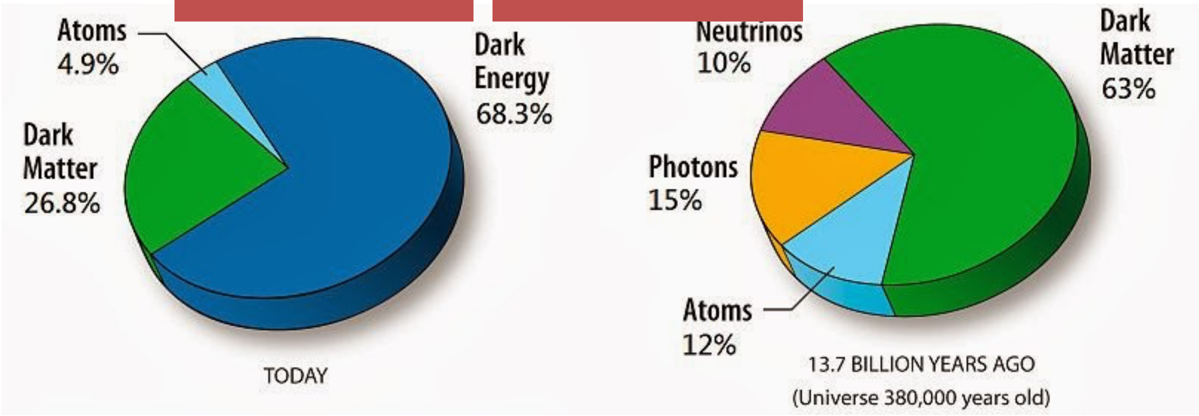
massive neutrinos

- Standard model particles + interactions
- Cold dark matter — warm? — new interactions?
- Cosmological constant — dynamical dark energy?

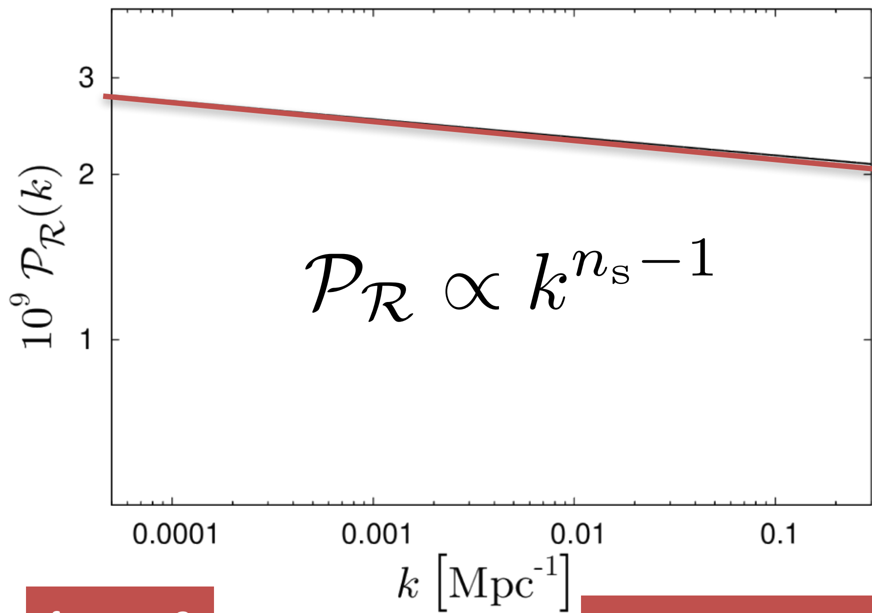
dark radiation? — sterile neutrinos?

+ initial perturbations





Challenging ΛCDM: initial perturbations



features?

scale-dependent tilt?

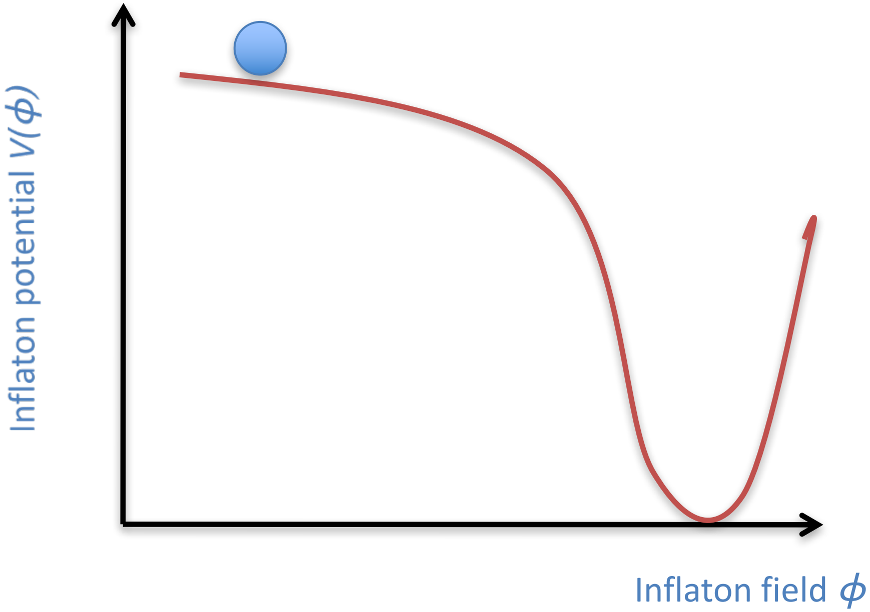
Almost scale-invariant power-law spectrum of

- adiabatic — isocurvature?
- Gaussian — non-Gaussianity?
- statistically isotropic and homogeneous — statistical anisotropy?
- scalar — primordial gravitational waves?

perturbations

Inflation

Inflation



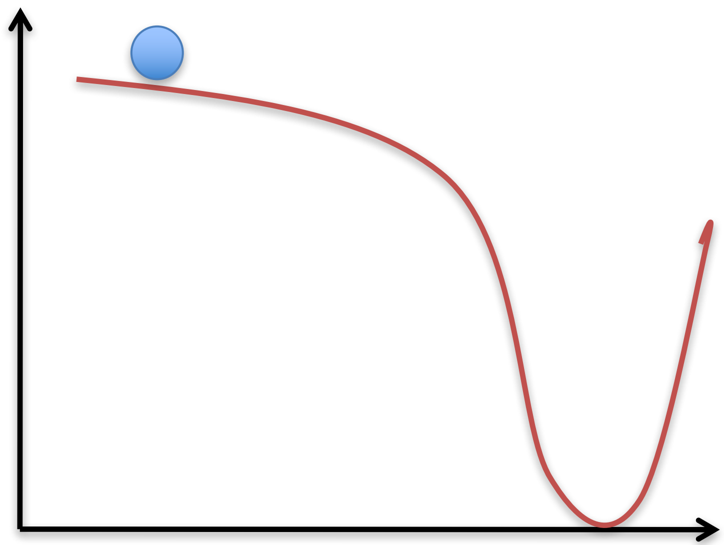
During inflation

- Universe is dominated by potential energy of ϕ
- Exponential growth of scale factor

$$a(t) = a_0 \exp[H_{\text{inf}}\, t]$$

- Space gets stretched by factor $10^{\geq 20}$ in $10^{-(30\ldots40)}$ seconds!

Inflation



During inflation

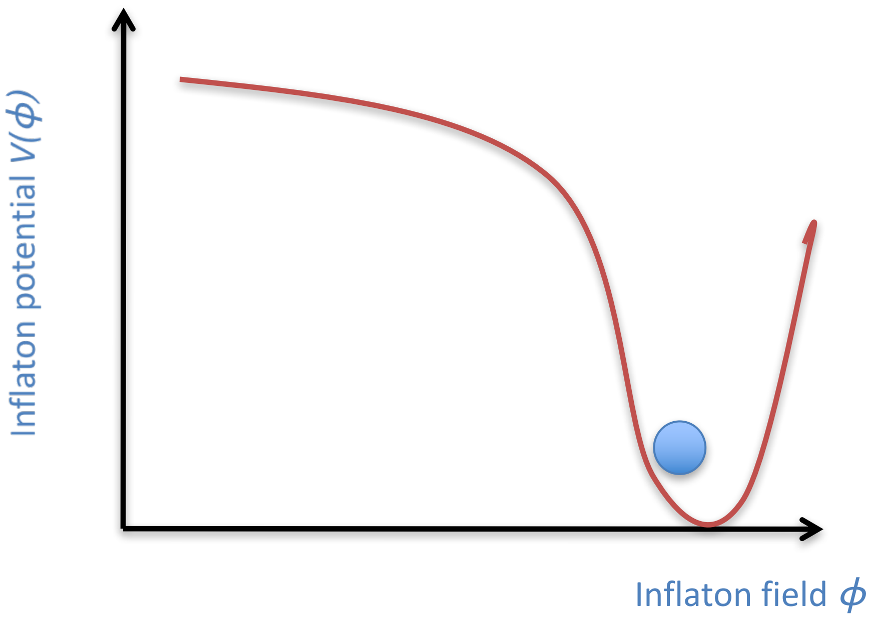
- Universe is dominated by potential energy of ϕ
- Exponential growth of scale factor
  $a(t) = a_0 \exp[H_{inf}\, t]$
- Space gets stretched by factor $10^{\geq 20}$ in $10^{-(30\ldots40)}$ seconds!

  → spatial flatness

- Today's entire observable Universe originated from one tiny (causally connected) patch → homogeneity and isotropy
- Attractor solution, any pre-inflation matter or curvature diluted away

  → independence of initial conditions

Inflation

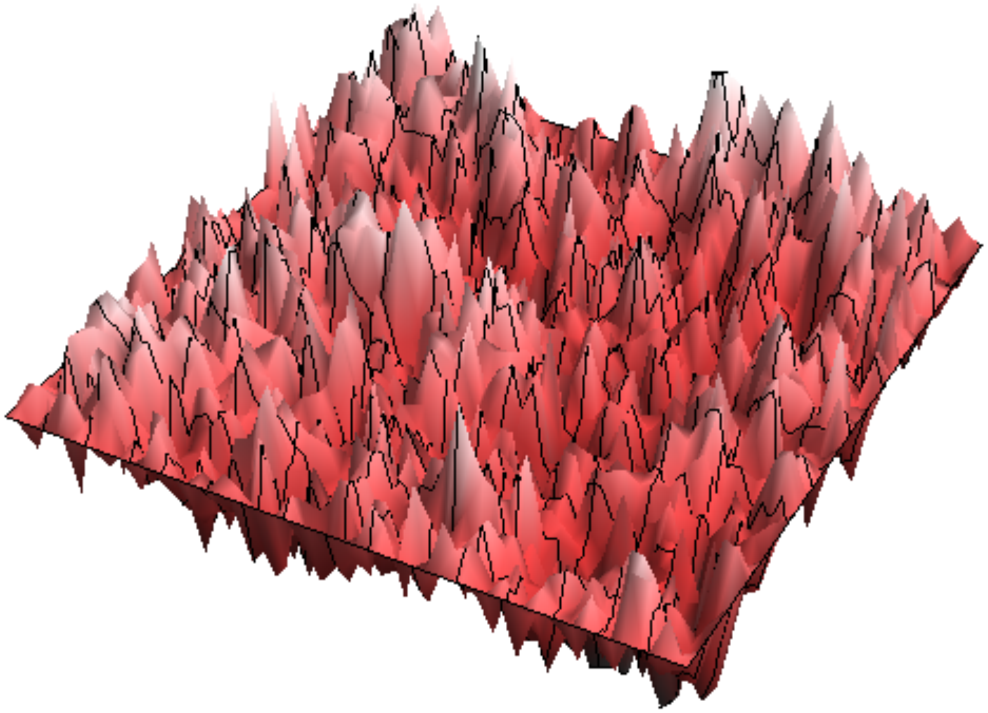


After inflation ends

- Potential energy of ϕ is converted to standard model particles (and dark matter)
- Thermalization (*reheating*)
- Radiation dominated era of cosmology begins

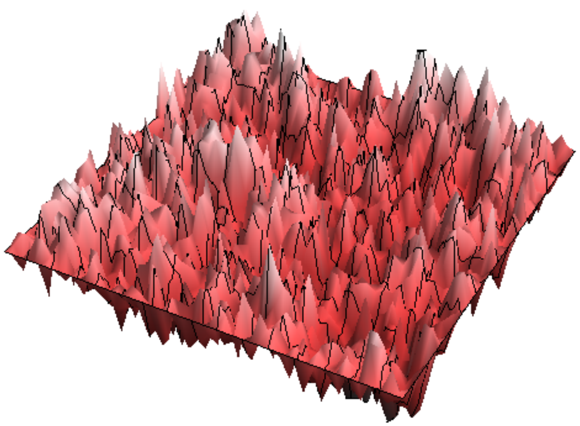
Inflation and primordial perturbations

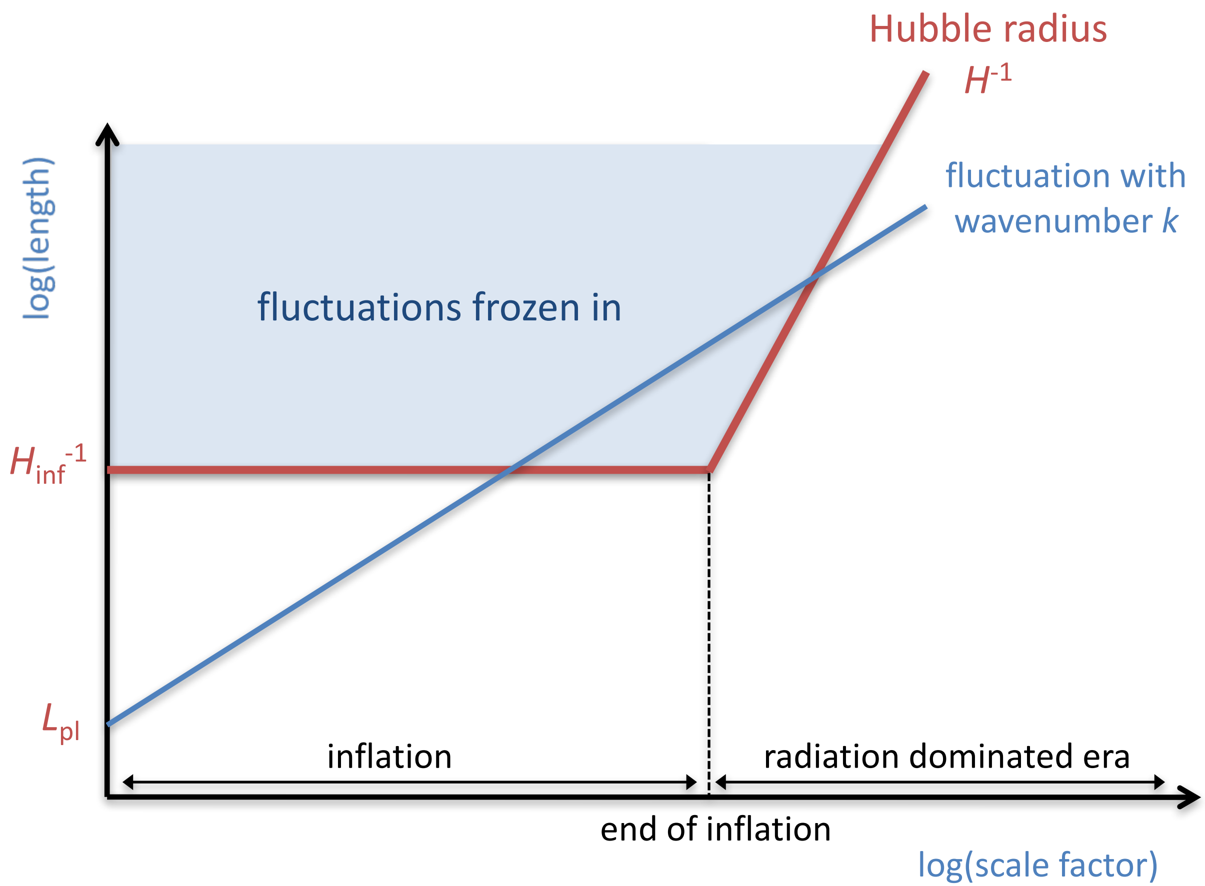
Quantum fluctuations of the inflaton field



- Inflaton's fluctuations get stretched by expansion
- Fluctuations with wavelengths larger than Hubble radius freeze in

Inflation and primordial perturbations

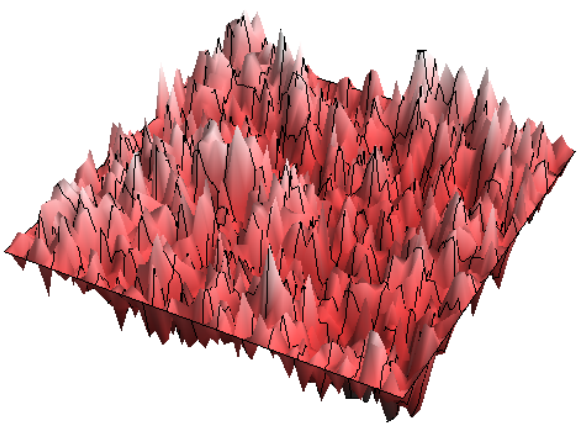




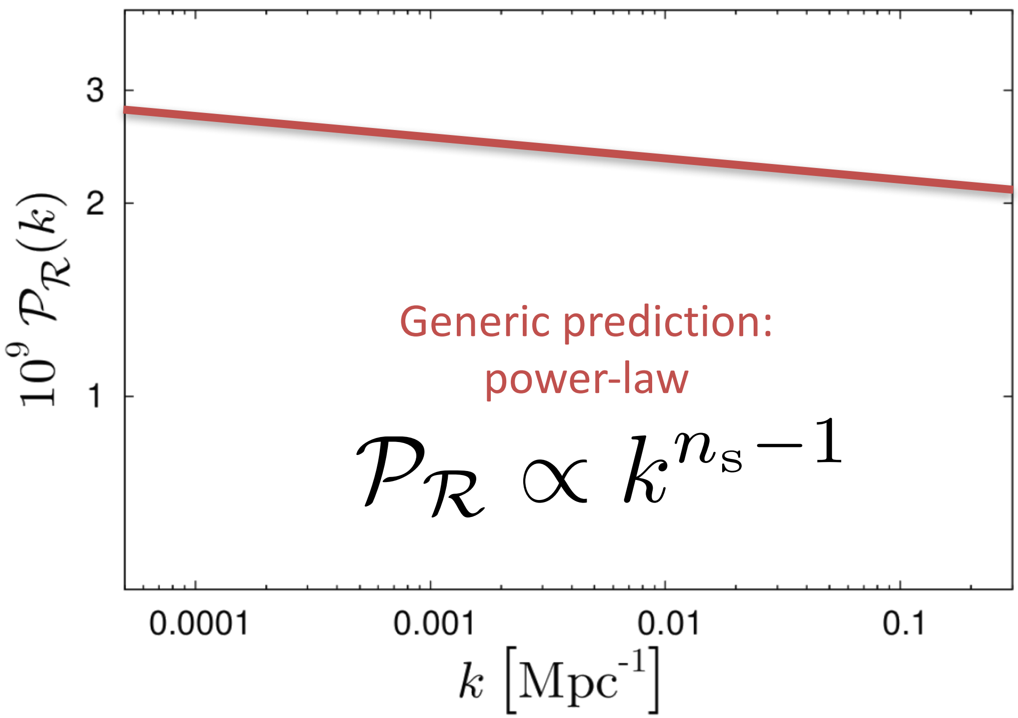
- Perturbations generated during inflation form initial conditions for structure formation in the radiation dominated era

Inflation and primordial perturbations: the scalar power spectrum

$z \approx 10^{25\text{-ish}}$



$z > 10^6$



- In addition: almost scale-invariant spectrum of gravitational waves

  Tensor-to-scalar ratio $r = \mathcal{P}_\mathrm{T}/\mathcal{P}_\mathcal{R}$

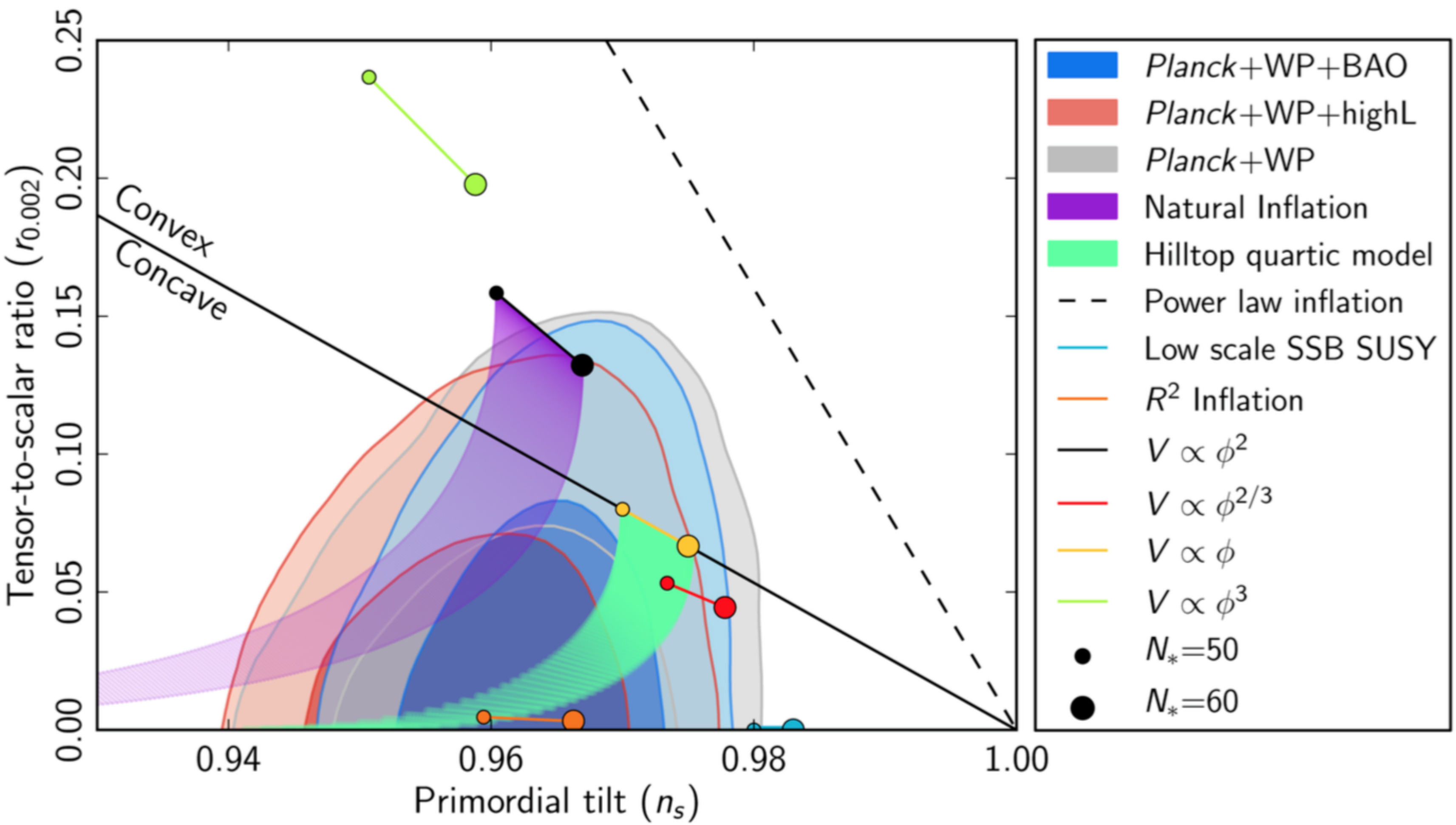
Inflation and primordial perturbations

- single field ⟶ adiabatic
- slow-roll ⟶ almost scale-invariant power-law
- quasi-linear ⟶ Gaussian
- low-scale ⟶ unobservable tensor perturbations

The inflationary mechanism can very elegantly explain seemingly unrelated properties of ΛCDM…

…but what *is* the inflaton?

Planck constraints on simple models of inflation



[*Planck* collaboration 2015]

The neutrino sector

Neutrino parameters

How much energy density do neutrinos contribute…

… at early times?

photon energy density

Fermi-Dirac vs. Bose-Einstein

lower neutrino temperature

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

radiation energy density

Effective number of neutrino species

… at late times?

neutrino energy density

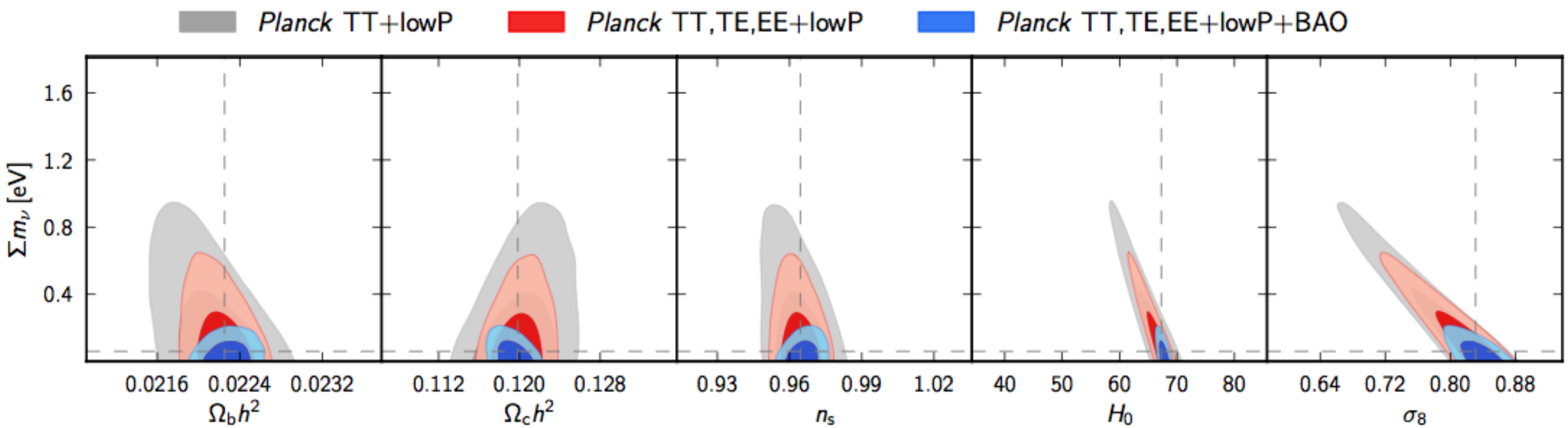
$$\Omega_\nu h^2 \simeq \frac{\sum m_\nu}{93 \text{ eV}}$$

Sum of neutrino masses

ΛCDM: $N_{\rm eff}$ = 3.046
(small deviation from Fermi-Dirac)

ΛCDM: $\sum m_\nu$= 0.06 eV
(assumes lightest mass state is massless)

Planck constraints on the sum of neutrino masses

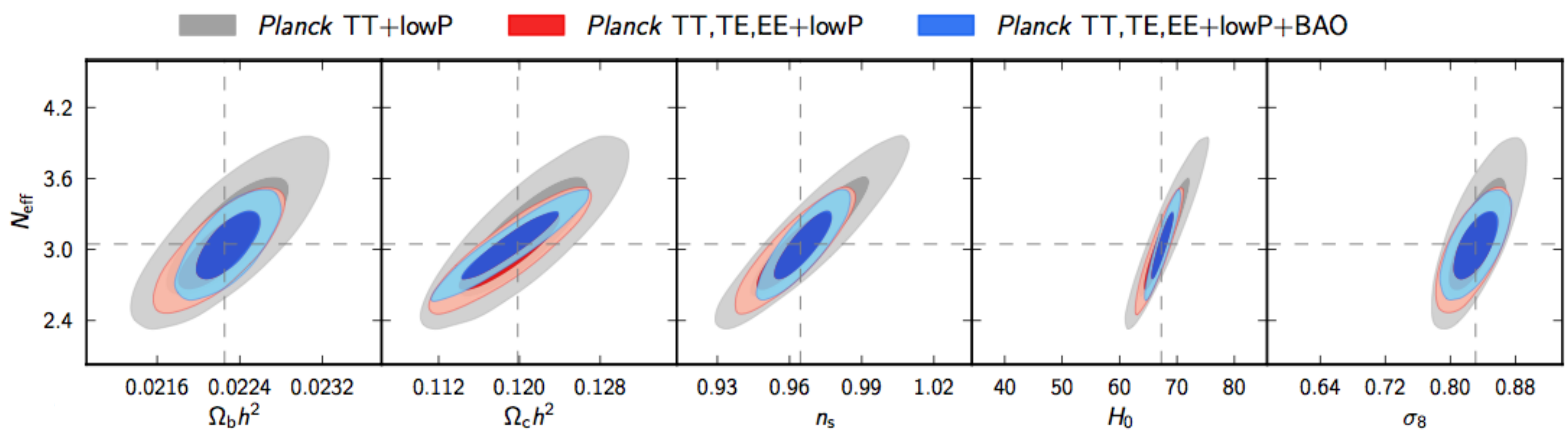


Parameter	TT	TT+lensing	TT+lensing+ext	TT, TE, EE	TT, TE, EE+lensing	TT, TE, EE+lensing+ext
Σm_ν [eV]	< 0.715	< 0.675	< 0.234	< 0.492	< 0.589	< 0.194

No sign of non-zero neutrino masses…

[*Planck* collaboration 2015]

Planck constraints on the effective number of relativistic species

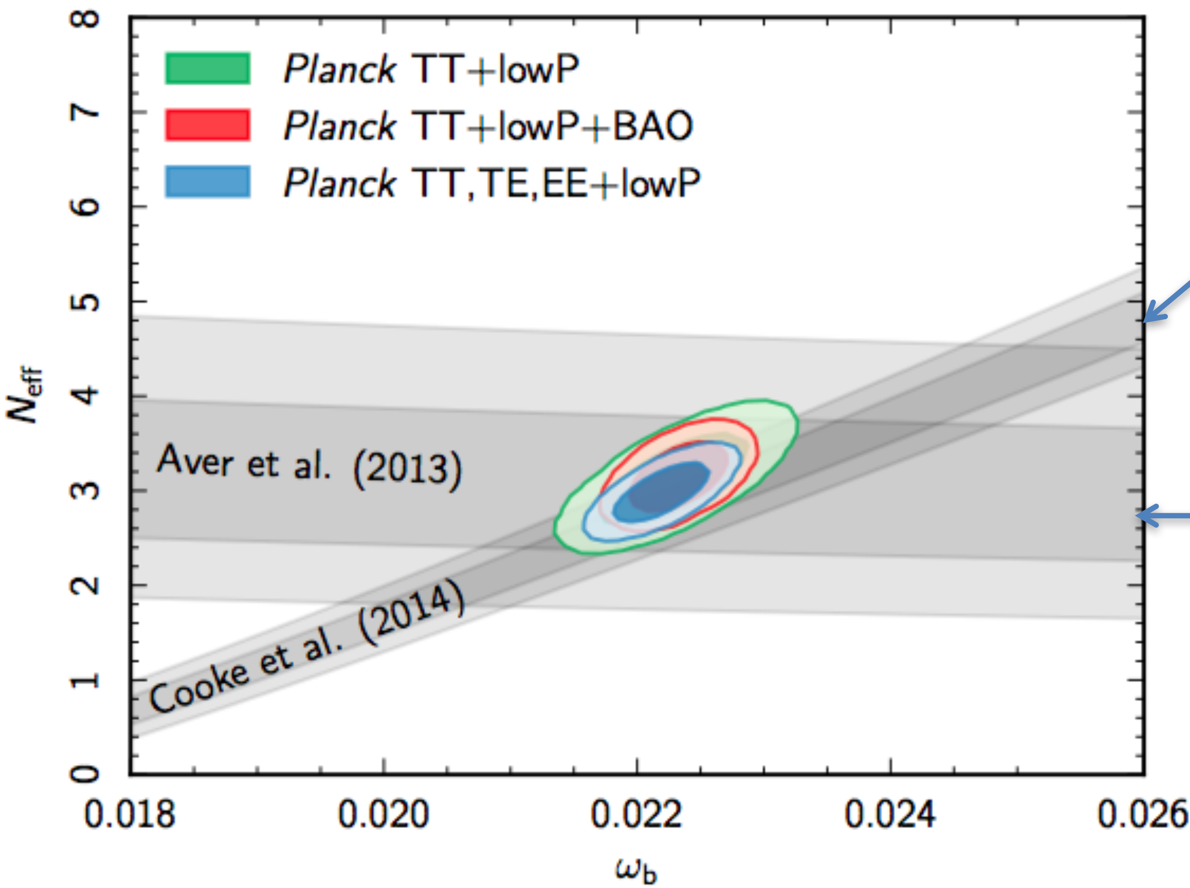


Parameter	TT	TT+lensing	TT+lensing+ext	TT, TE, EE	TT, TE, EE+lensing	TT, TE, EE+lensing+ext
$N_{\rm eff}$	$3.13^{+0.64}_{-0.63}$	$3.13^{+0.62}_{-0.61}$	$3.15^{+0.41}_{-0.40}$	$2.99^{+0.41}_{-0.39}$	$2.94^{+0.38}_{-0.38}$	$3.04^{+0.33}_{-0.33}$

Data confirm standard model expectation
(CνB only, no hints of additional light particles)

[*Planck* collaboration 2015]

Planck results vs. BBN



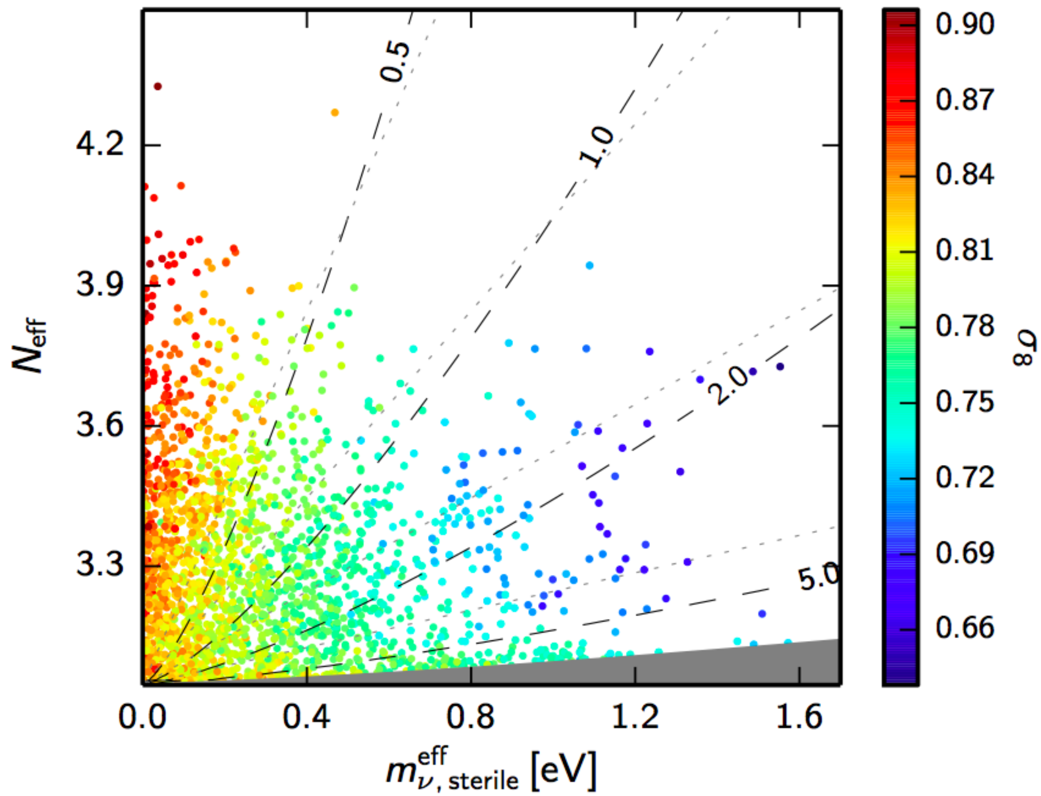
Deuterium abundance from Damped Ly-α system

^{4}He abundance from H II-regions

Excellent match with BBN expectation + astrophysical element abundance measurements

[*Planck* collaboration 2015]

Planck constraints on eV-mass sterile neutrinos



Planck data not compatible with a fully thermalised eV-mass neutrino

Want to save the scenario?
Need to suppress production of steriles (e.g., lepton asymmetry, new interactions, etc.)

$$\left.\begin{aligned} N_{eff} &< 3.7 \\ m^{eff}_{\nu,\,sterile} &< 0.38\ \text{eV} \end{aligned}\right\} \text{95\%, \textit{Planck} TT+lowP+lensing+BAO.}$$

[*Planck* collaboration 2015]

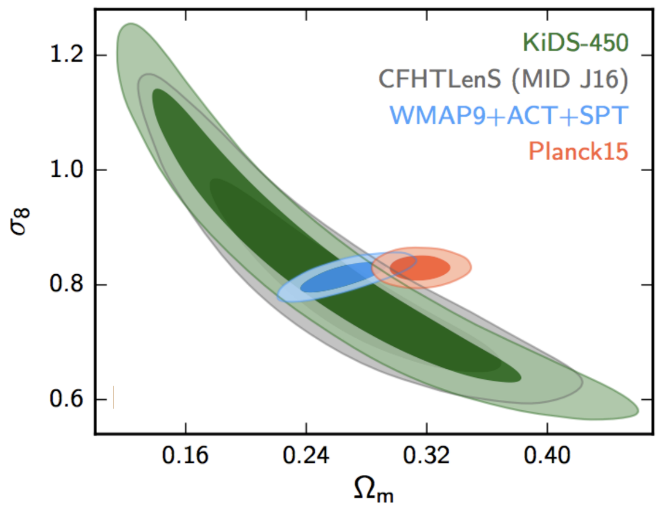
A fly in the ΛCDM-soup?

Discrepancies of *Planck* data with other measurements

- *Planck* data consistent with BAO, SN Ia, WMAP data [*Planck* collaboration 2016]
- Direct measurement of H_0: 2.7σ discrepancy

Planck 2015	$H_0 = 67.3 \pm 0.9$
Riess+ 2016	$H_0 = 73.3 \pm 1.8$

- Galaxy weak lensing: 2.3σ discrepancy



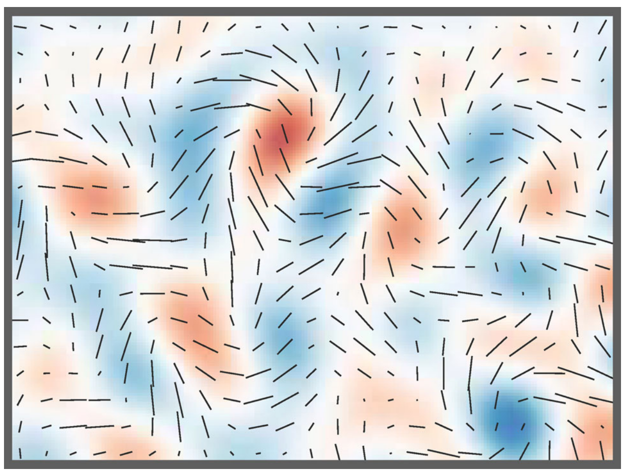
[Hildebrandt+ 2016]

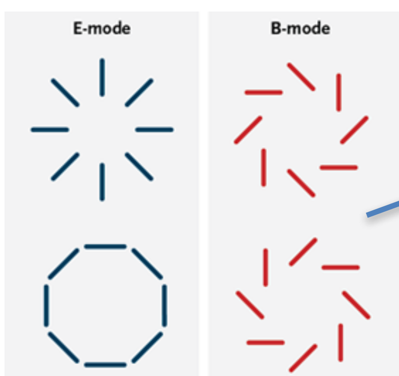
Statistical fluke, systematic effects or hints for new physics?

Future observations

Future CMB observations

- CMB Temperature: exhausted by Planck
- Next frontier: CMB polarisation and CMB lensing

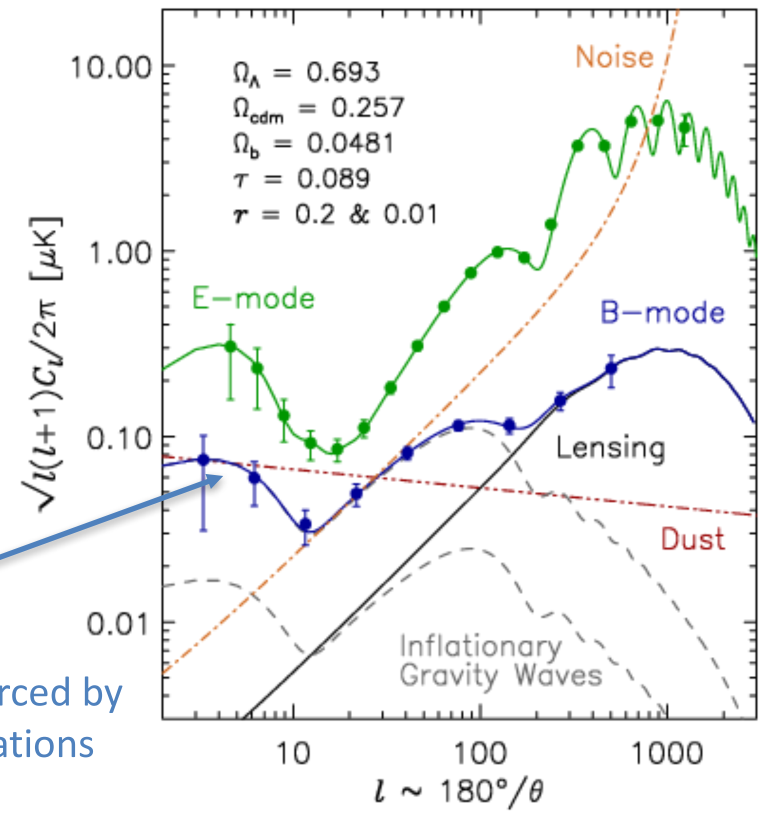




B-mode not sourced by scalar perturbations

⇓

Ideal probe for tensors



Future CMB observations

- CMB Temperature: exhausted by *Planck*
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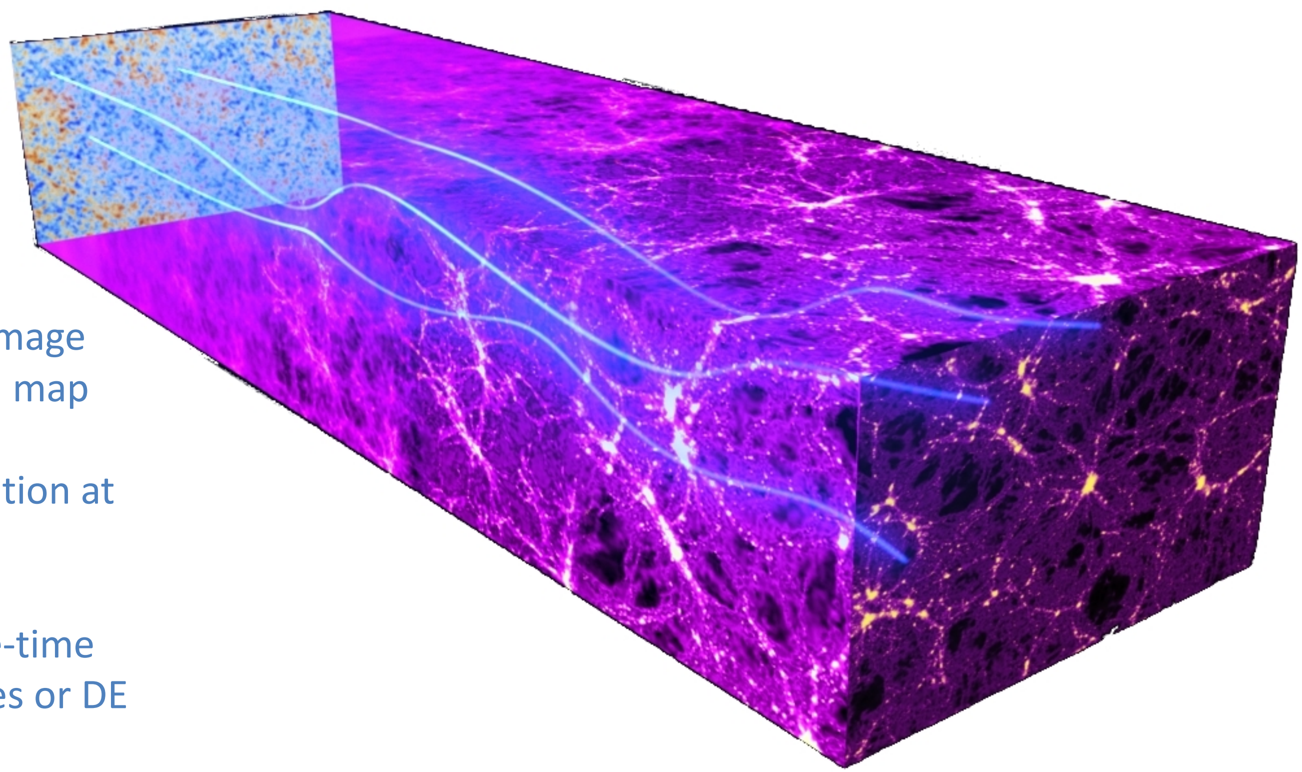


Lensing distorts original image
Infer lens properties from map

↓

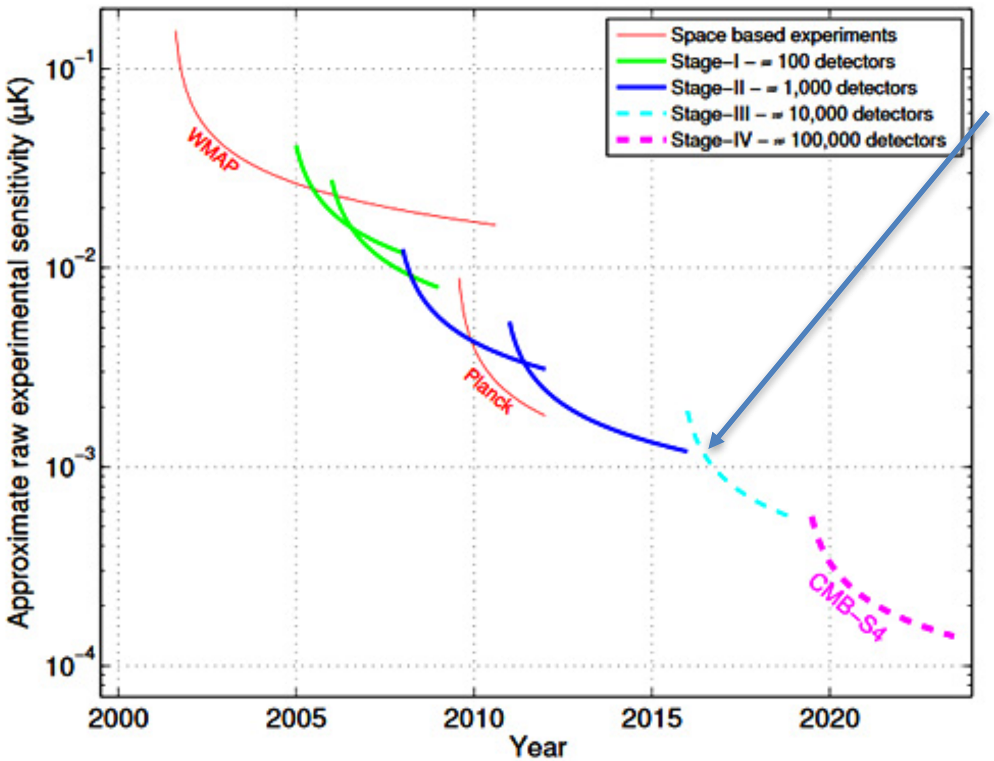
Sensitive to matter distribution at
redshifts $z \approx 1 \ldots 3$

↓

Good for constraining late-time
effects, e.g., neutrino masses or DE

Future CMB observations

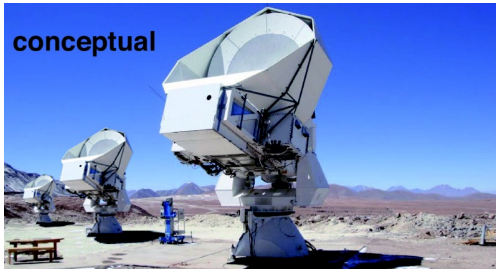
- CMB Temperature: exhausted by Planck
- Next frontier: CMB polarisation and CMB lensing



Stage II-III

Polarbear, BICEP 3/Keck array, SPT, ACT

Stage III

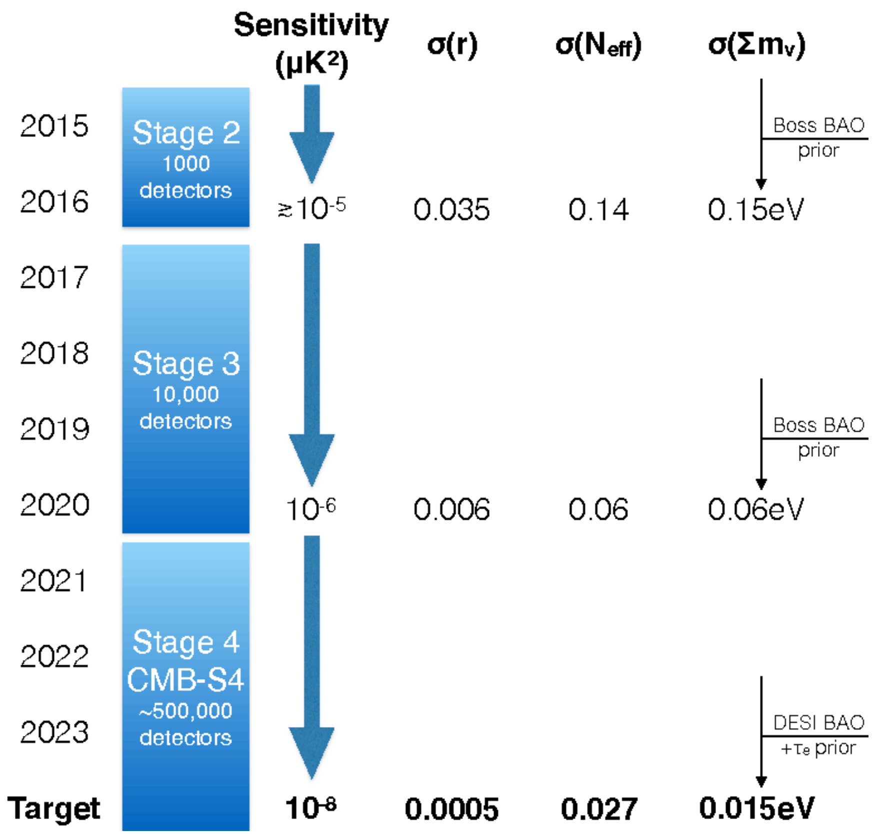


Simons array

[see M. Hasegawa's talk]

Future CMB observations: CMB-S4

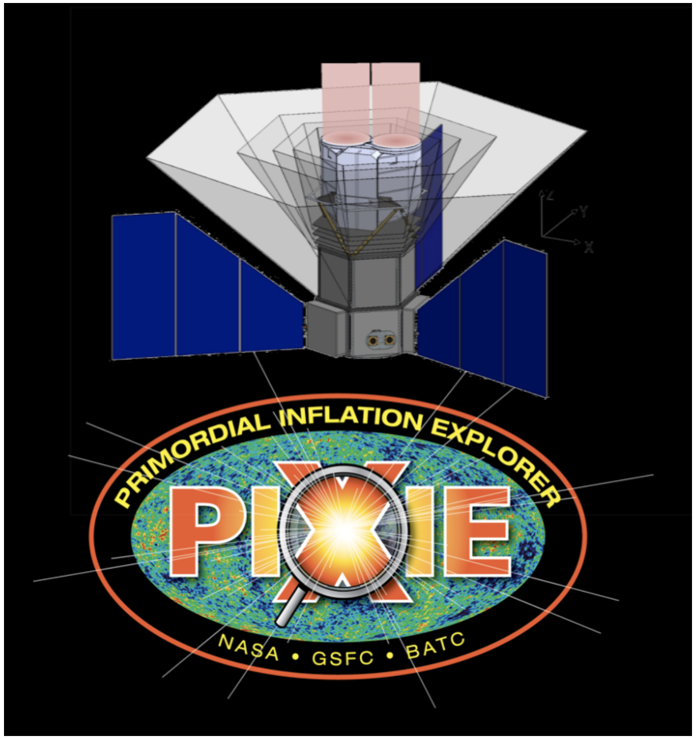
- O(10^5) detectors deployed on telescopes at the South Pole, Atacama desert (+ northern hemisphere site?)



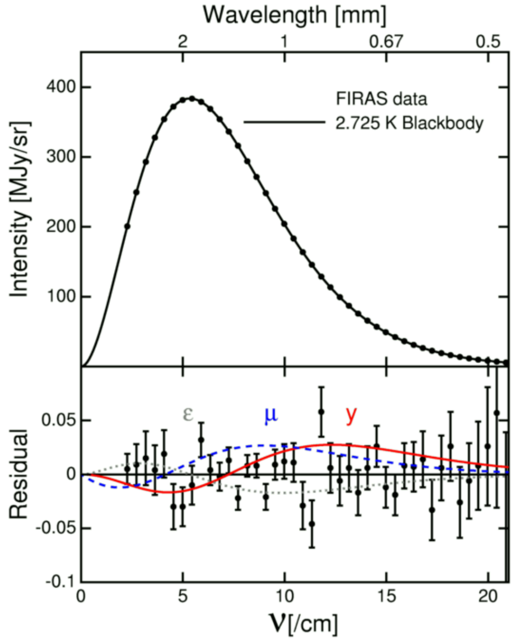
[Abazajian+ 2016]

Future CMB observations: PIXIE

- Proposed space mission for measuring large-scale CMB polarisation and looking for distortions from CMB frequency spectrum



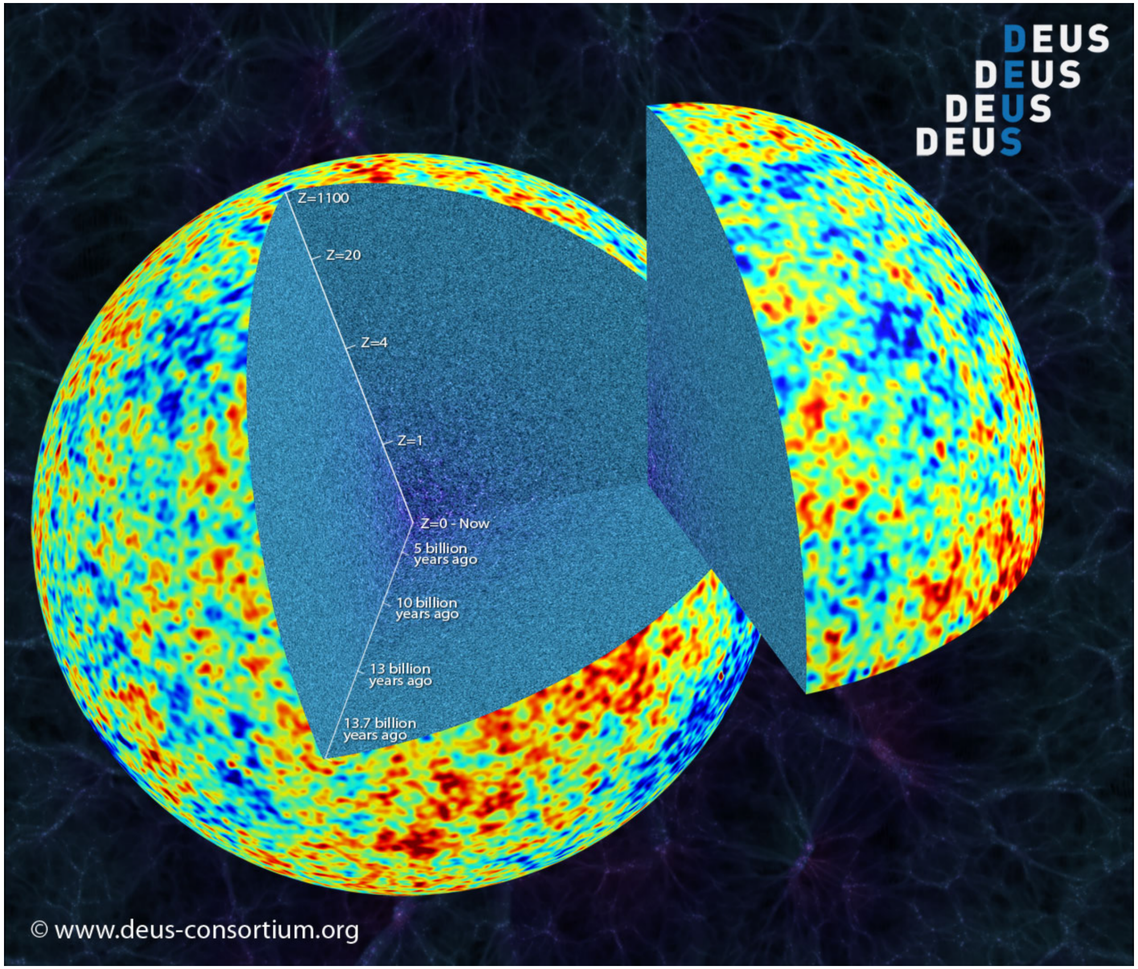
[Kogut+ 2014]



- Improve uncertainty on y- and μ-distortions by 3 orders of magnitude
- Sensitive to DM-ν or DM-γ interactions?

[see J. Diacoumis's talk]

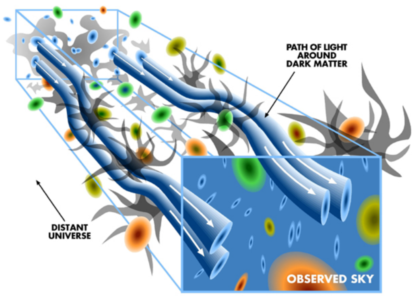
Future large scale structure observations



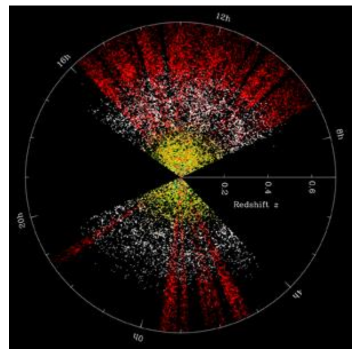
- Tap information contained in 3-dimensional distribution of matter
- Tomography: snapshots at different redshift intervals allows us to see evolution of perturbations
- Need wide and deep survey

Large scale structure observables

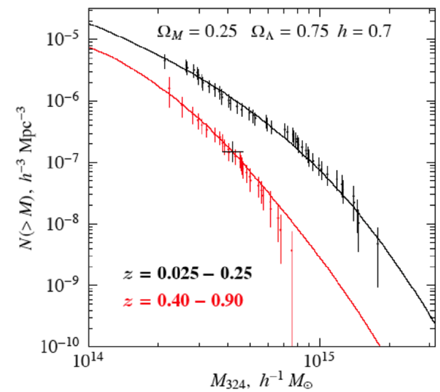
visible,
near infrared



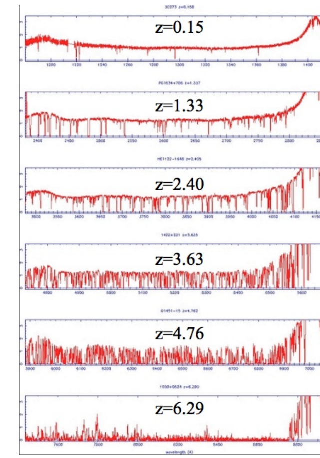
Galaxy weak lensing



Galaxy clustering/BAO

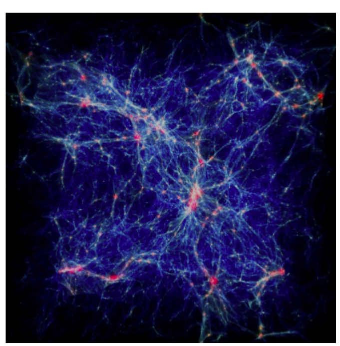


Cluster counts



Lyman-α forest

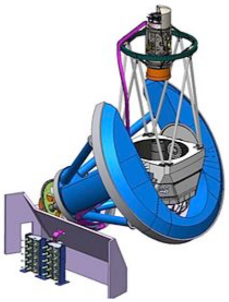
radio



Neutral hydrogen
(21 cm line)

Future galaxy surveys

DES



DESI

LSST

Euclid

Parameter sensitivities for a Euclid-like survey

Data	$10^3 \times \sigma(\omega_m)$	$100 \times \sigma(h)$	$\sigma(\sum m_\nu)/\mathrm{eV}$	$\sigma(N_{\mathrm{eff}}^{\mathrm{ml}})$	$\sigma(w_0)$	$\sigma(w_p)$	$\sigma(w_a)$	FoM/10^3
csgx	1.2	0.86	0.022	0.069	0.077	0.010	0.22	0.45
ccl	0.98	0.32	0.039	0.031	0.038	0.022	0.16	0.29
csgxcl	0.27	0.23	0.0098	0.019	0.025	0.0052	0.085	2.3
cscl	0.35	0.29	0.010	0.022	0.031	0.0087	0.10	1.1

c=CMB (Planck); g=galaxy power spectrum; s=cosmic shear; x=shear-galaxy cross-correlation, cl=clusters

- Sensitivity up to 10 meV for sum of neutrino masses, and up to 0.02 for effective number of neutrino species when observables are combined
- Can cleanly distinguish between effects of dark energy and neutrinos

[Basse+ 2013]

Conclusions

- For almost 20 years, ΛCDM has successfully resisted attempts to falsify it
- Initial perturbations very likely formed by inflation, but what is the inflaton?
- No evidence for neutrino masses (yet!) or additional light species
- Fully thermalised eV-mass sterile neutrino ruled out
- Exciting new measurements in the next 5-10 years (CMB polarisation, lensing, LSS surveys) will
  - detect non-zero neutrino mass at > 4σ
  - find tensor modes, if $r > 10^{-3}$
  - Constrain N_{eff} with a sensitivity of 0.02