Introduction to Cosmology

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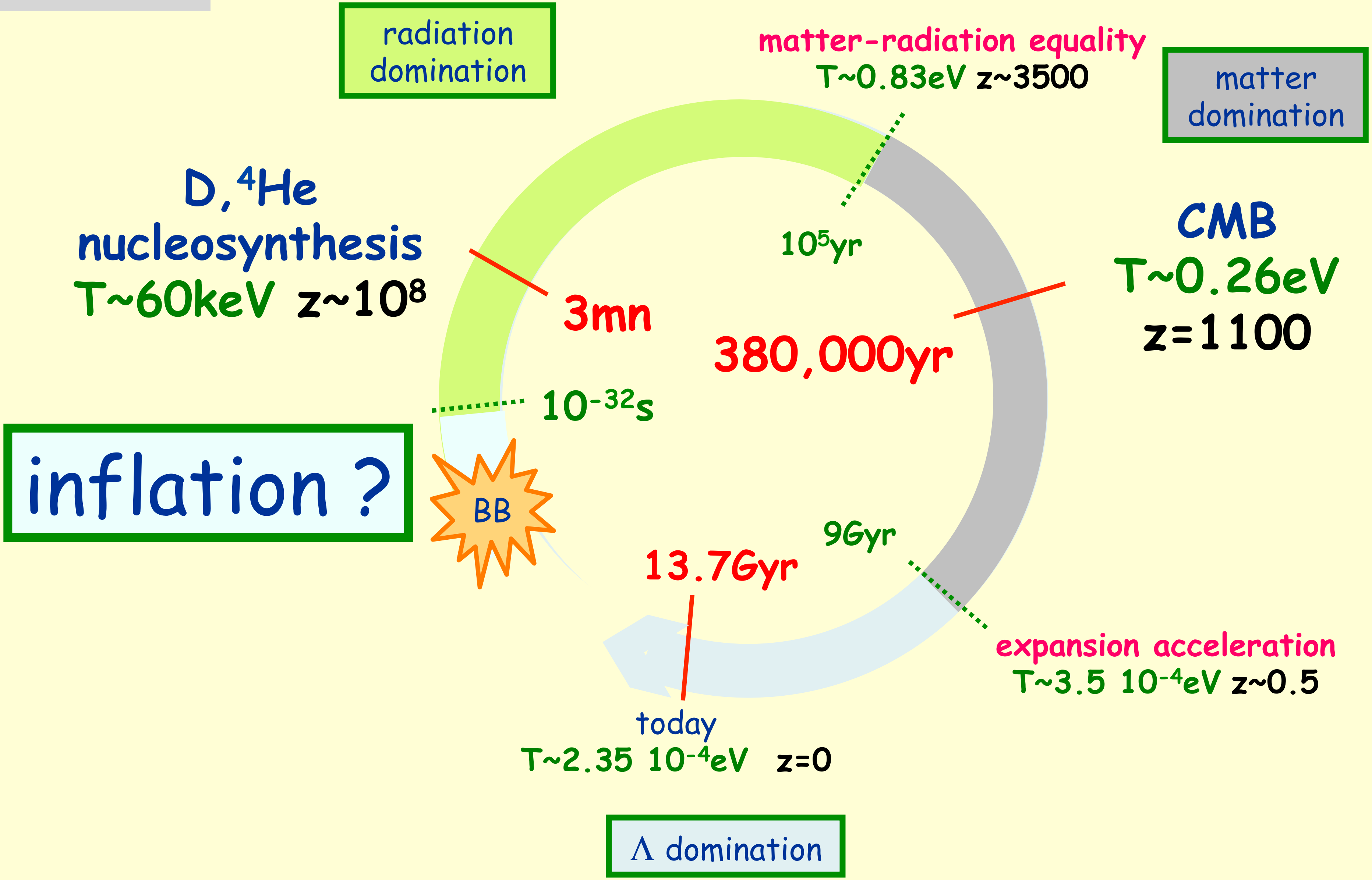
1) The Big Bang model
2) Content of the Universe
3) Cosmological probes
4) **Beyond concordance**

Beyond concordance

Two interesting topics in cosmology

- Inflation
- Neutrino masses from cosmology


radiation domination
matter-radiation equality
T~0.83eV z~3500
matter domination
D,4He nucleosynthesis
T~60keV z~10^8
3mn
10^5yr
CMB
T~0.26eV
z=1100
380,000yr
10^-32s
inflation ?
BB
9Gyr
13.7Gyr
expansion acceleration
T~3.5 10^-4eV z~0.5
today
T~2.35 10^-4eV z=0
Λ domination

Motivations for inflation

- Observational facts : the Universe started out
  - expanding
  - with the same temperature everywhere (within 10^{-5})
  - with a perfectly flat geometry ($\Omega_k^0 \approx 0.002$)
  - with small seeds of structures

- Λ_{CDM} does not explain these properties, esp. 2 and 3 :
  - T_{CMB} equal in regions of the sky not causaly connected at early times in Λ_{CDM} (*horizon problem)*
  - flatness today implies highly fine-tuned flatness at early times in Λ_{CDM} (*flatness problem*)

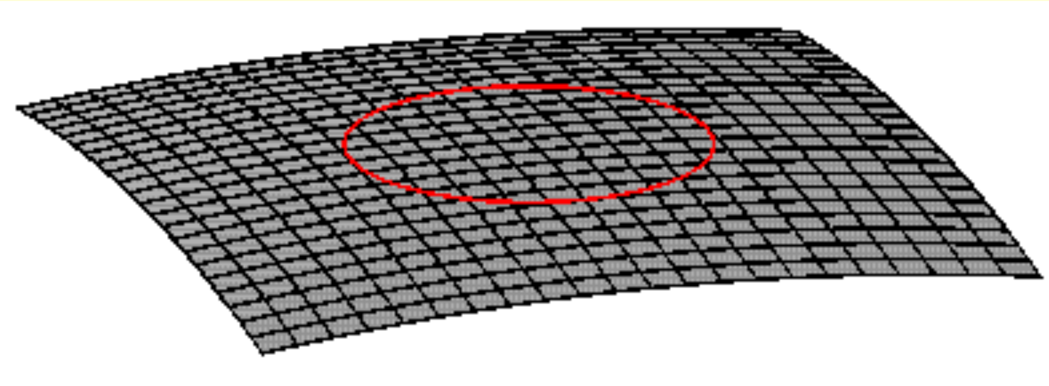
What is inflation ?

- Inflation = rapid exponential expansion of the Universe, sometime within the first ps after the Big Bang, during which the Universe size grows by more than ~ 10^{30}.
  - initial size is small and inflation is fast → distant patches of the sky today were in causal contact in the distant past.
  - the exponential increase of size during inflation quickly drives Ω_k to 0 (cf. Friedmann equations with inflation), and once driven to 0 by inflation, the Universe naturally evolves away from 0 in the absence of inflation.

⇒ horizon and flatness problems solved

More about flatness

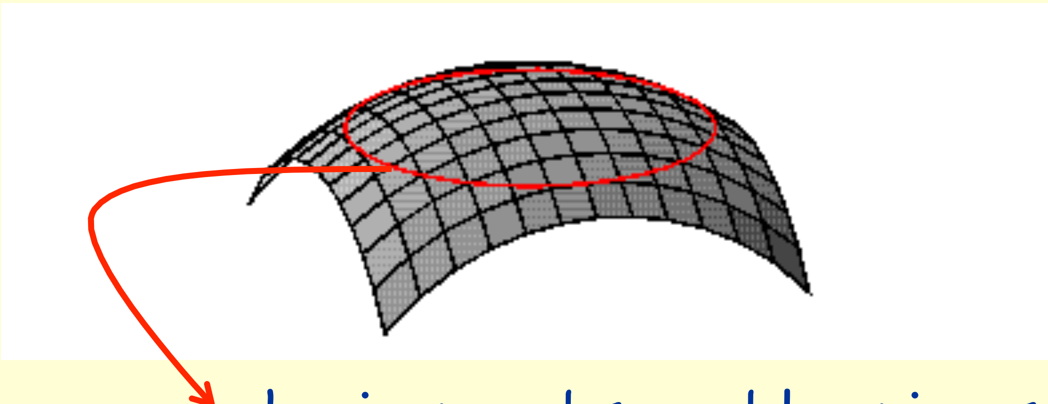
time



after inflation:

size and curvature radius very large

the observable universe looks almost flat



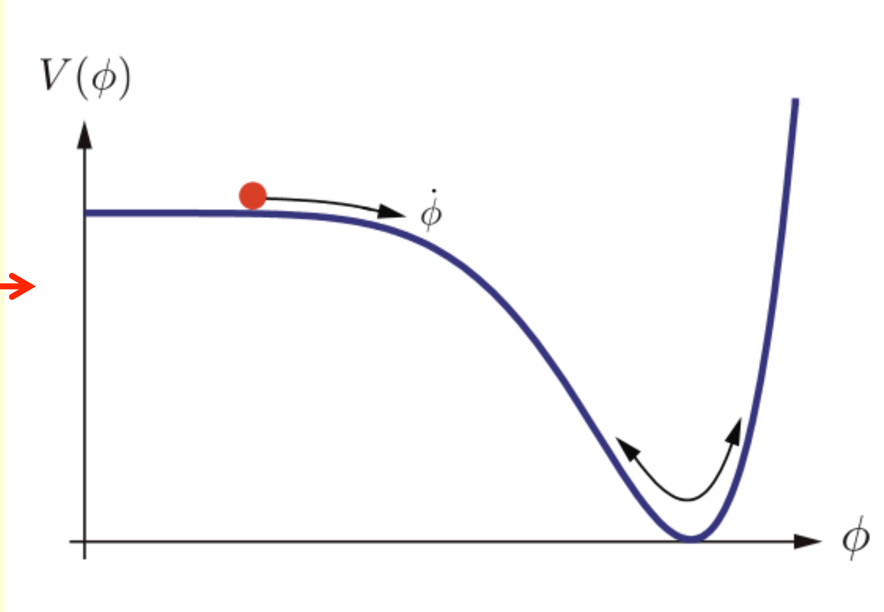
before inflation:

size and curvature radius small

horizon = observable universe

Modeling inflation

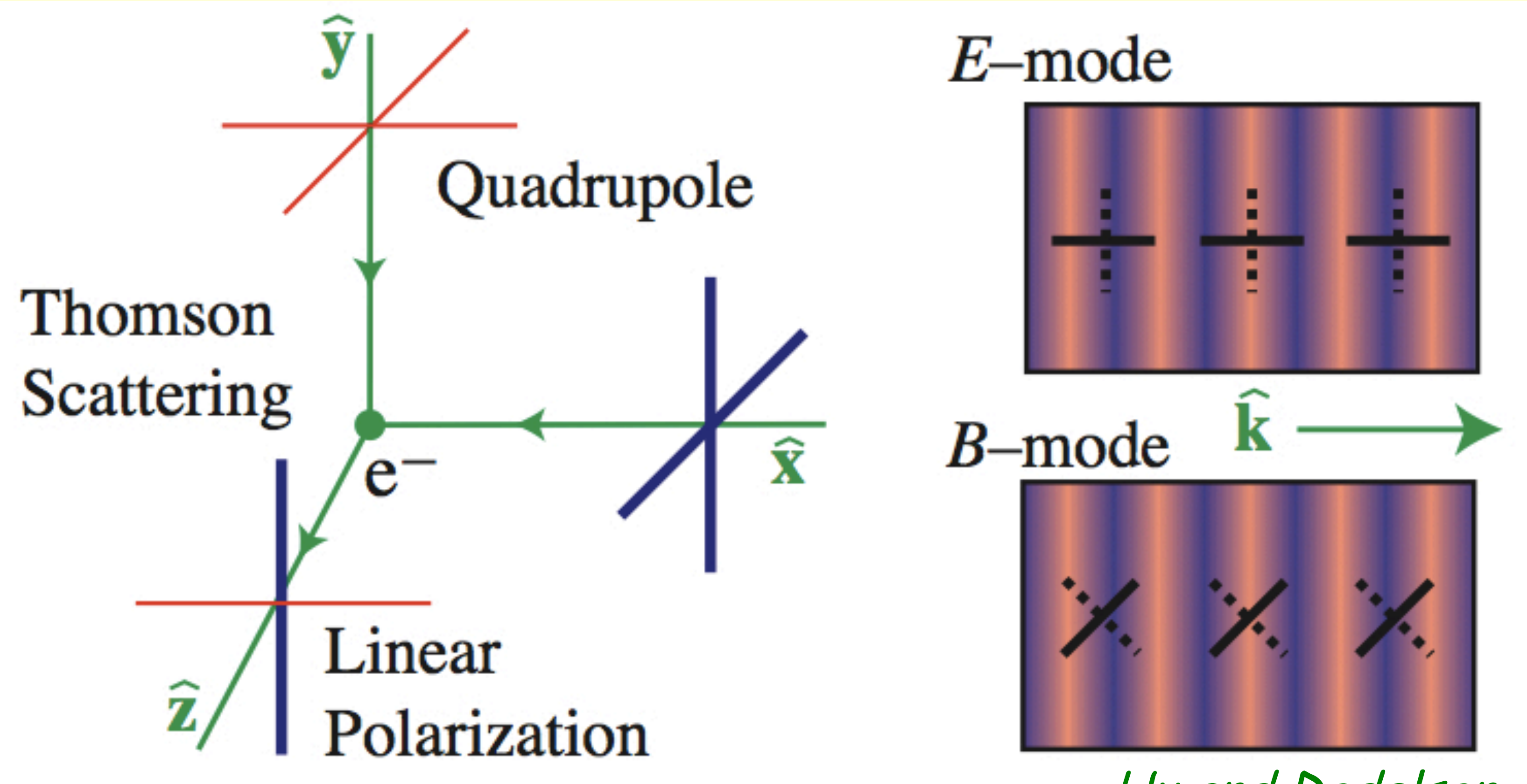
- Inflation driven by a scalar field Φ (inflaton) rolling-down slowly towards a minimum of its potential, e.g.



- In the vacuum:
  - fluctuations of Φ (scalar fluctuations) → particles, density fluctuations
  - fluctuations of the metric → gravitational waves (tensor fluctuations)

- Primordial scalar fluctuation spectrum (linear): $P(k) = Ak^{n_s}$ inflation models predict values of n_s, of $dn_s/d\ln k$ and tensor-to-scalar mode ratio r

Smoking gun : CMB polarisation

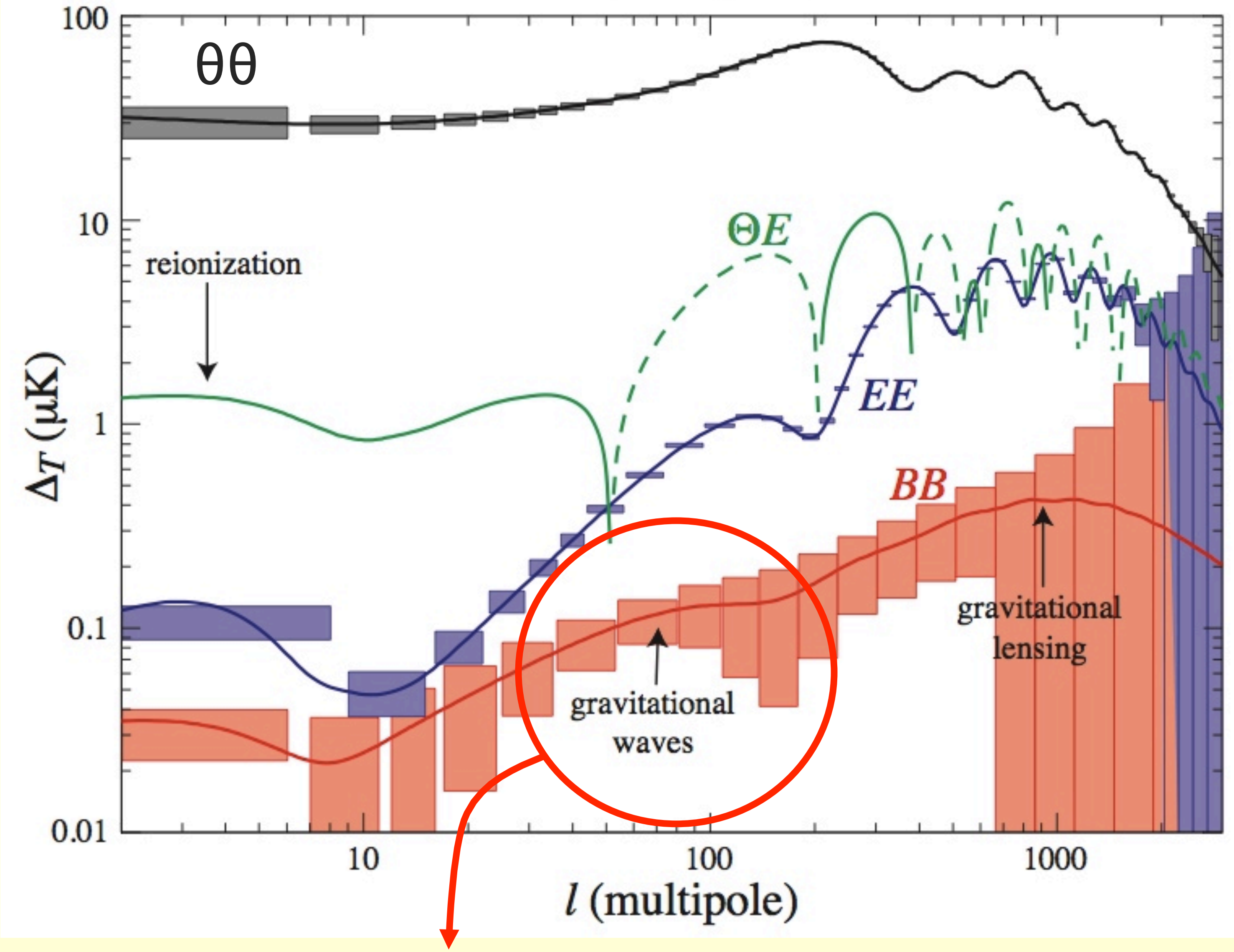


Hu and Dodelson, 2002

- Thomson scattering of a radiation anisotropic in flux → outgoing radiation is polarized
- Density fluctuations & gravitational waves → quadrupole T anisotropy → CMB polarized→ analysis in E and B modes

CMB polarisation components

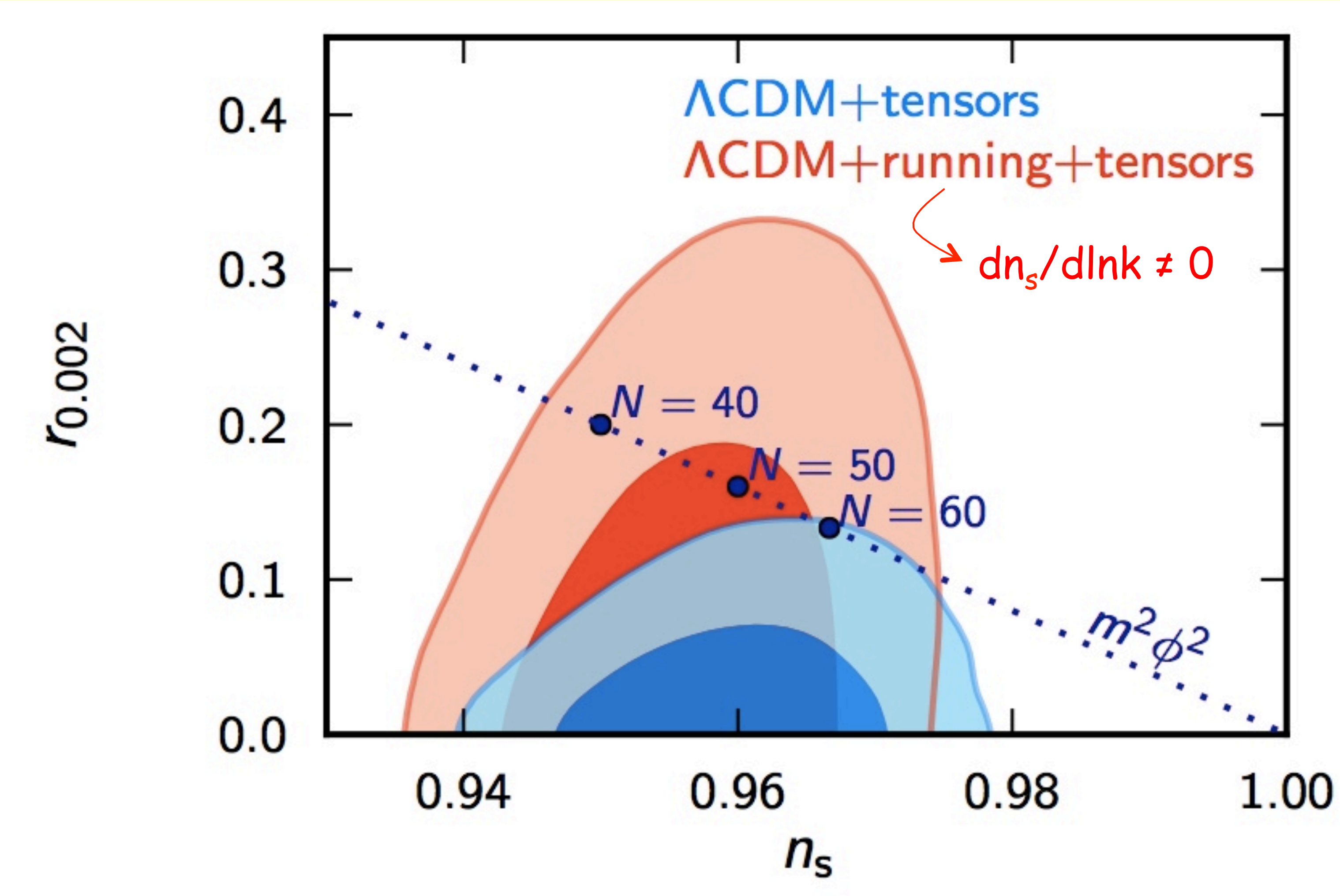
Hu and Dodelson, 2002



A B-mode signal at l≈100 would be a distinctive signature of inflation

Data vs inflation : Planck 2013

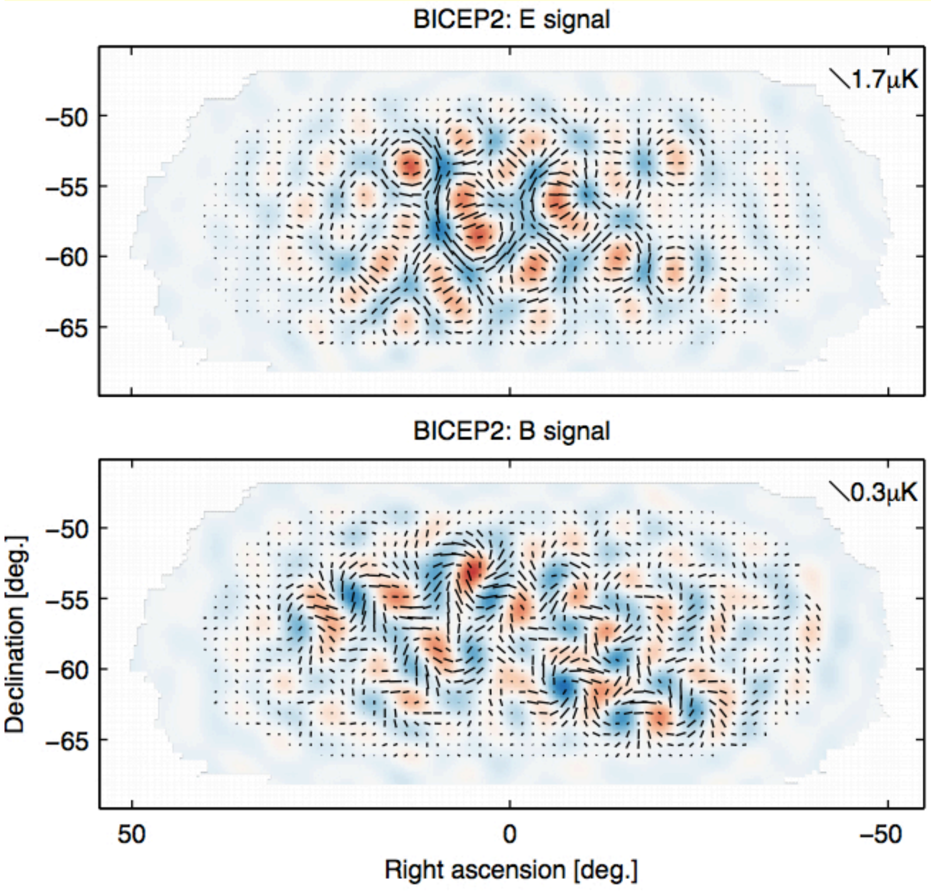
Indirect constraint from CMB TT power spectrum analysis



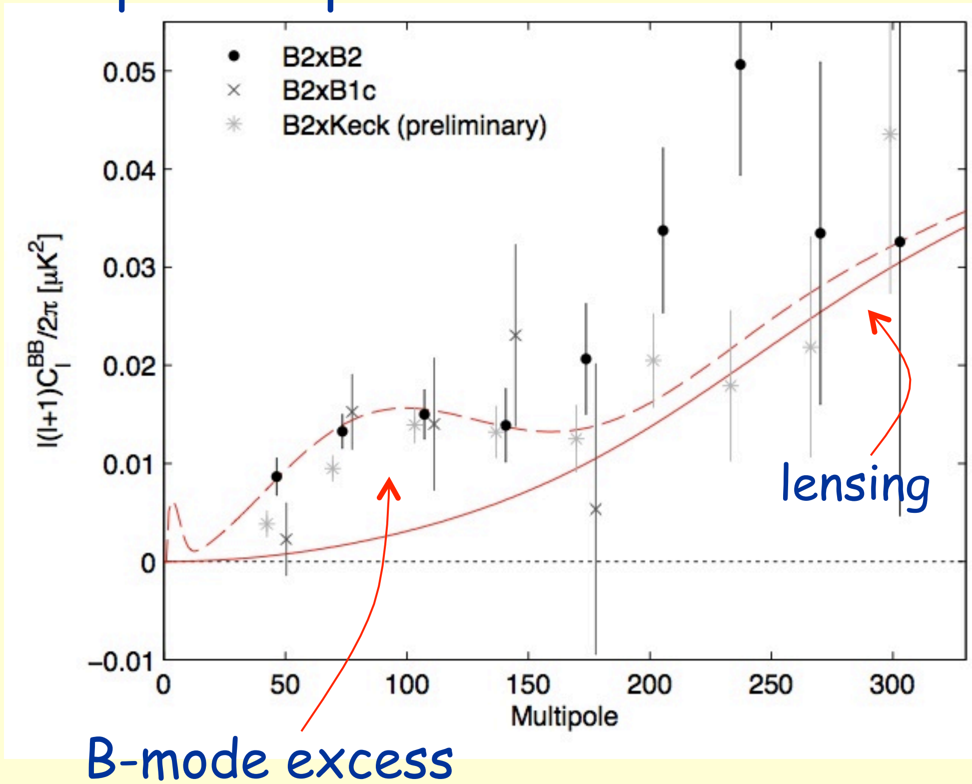
Planck 2013, Cosmological parameters, arXiv:1303.5076

Claim of B-mode polarisation detection : Bicep2 2014

Bicep2 coll., arXiv:1403.3985



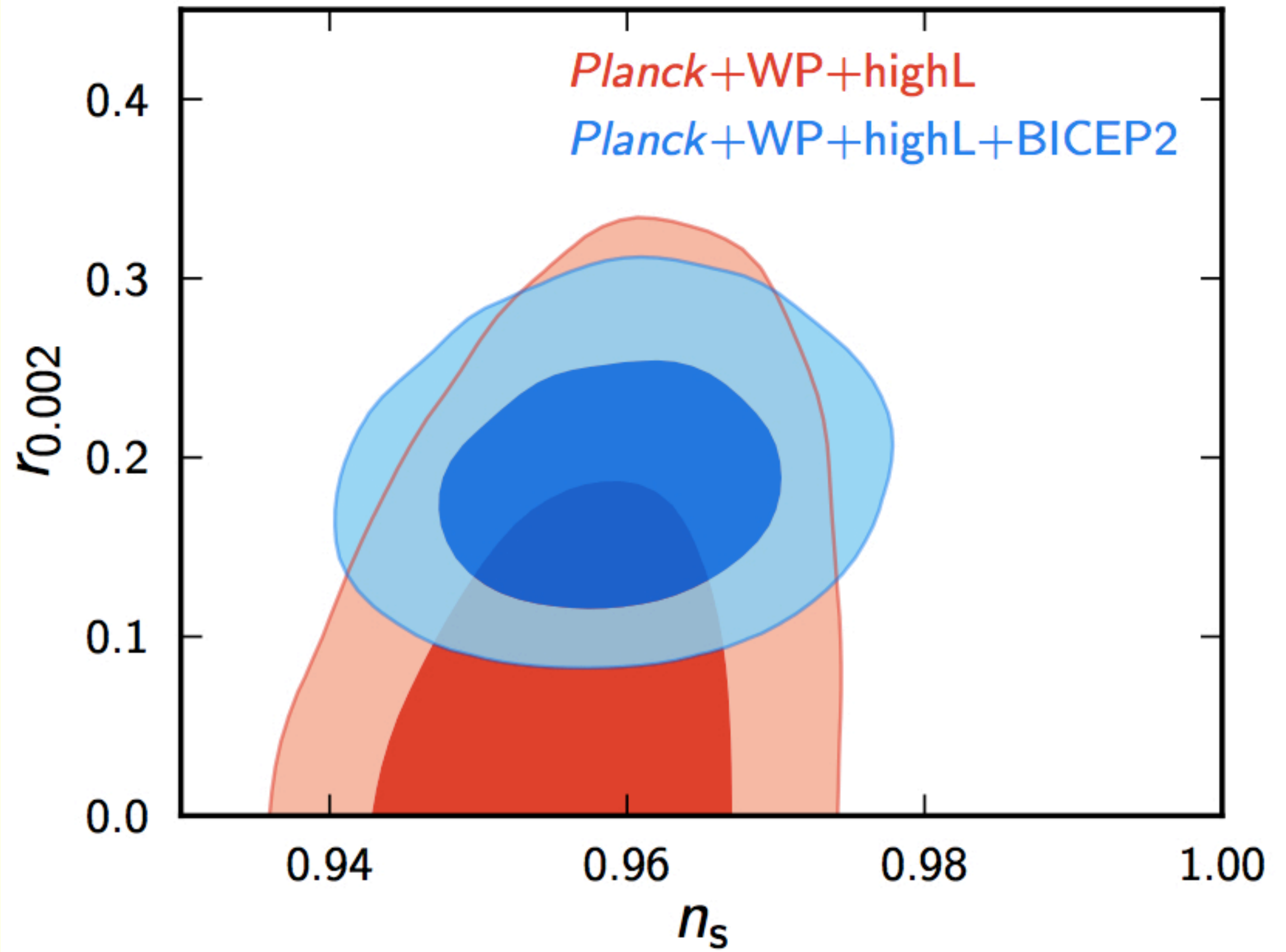
BB power spectrum



5σ excess of B-mode power over Λ_{CDM}+lensing predictions, at degree angular scales

Data vs inflation : Bicep2 2014

Bicep2 coll., arXiv:1403.3985

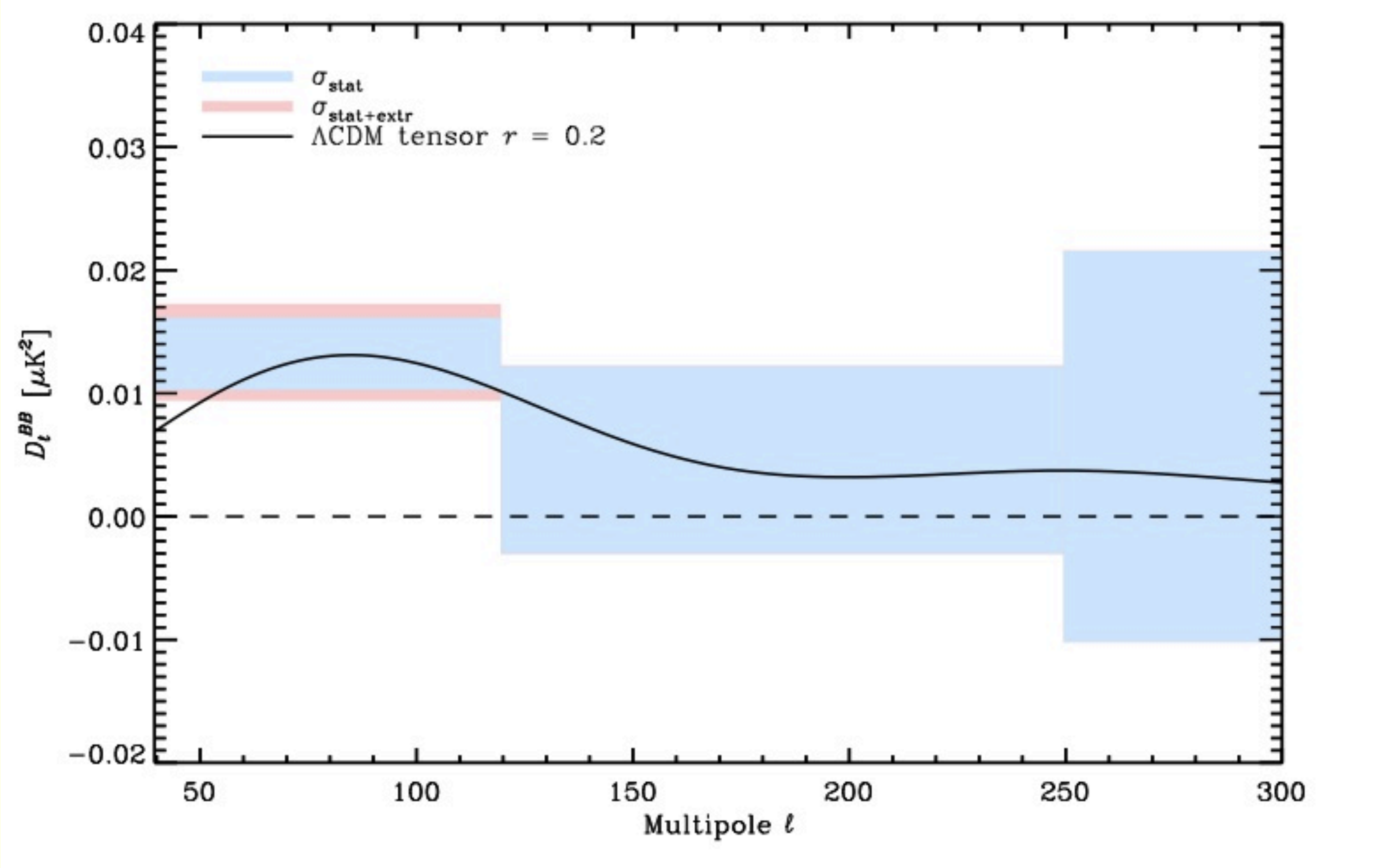


energy scale for inflation ~10^{16} GeV

Bicep2: Planck/Bicep2 data in agreement if running of n_s assumed
Planck: questioned Bicep2 model for dust polarization

Dust polarization in Bicep2 region : Planck 2014

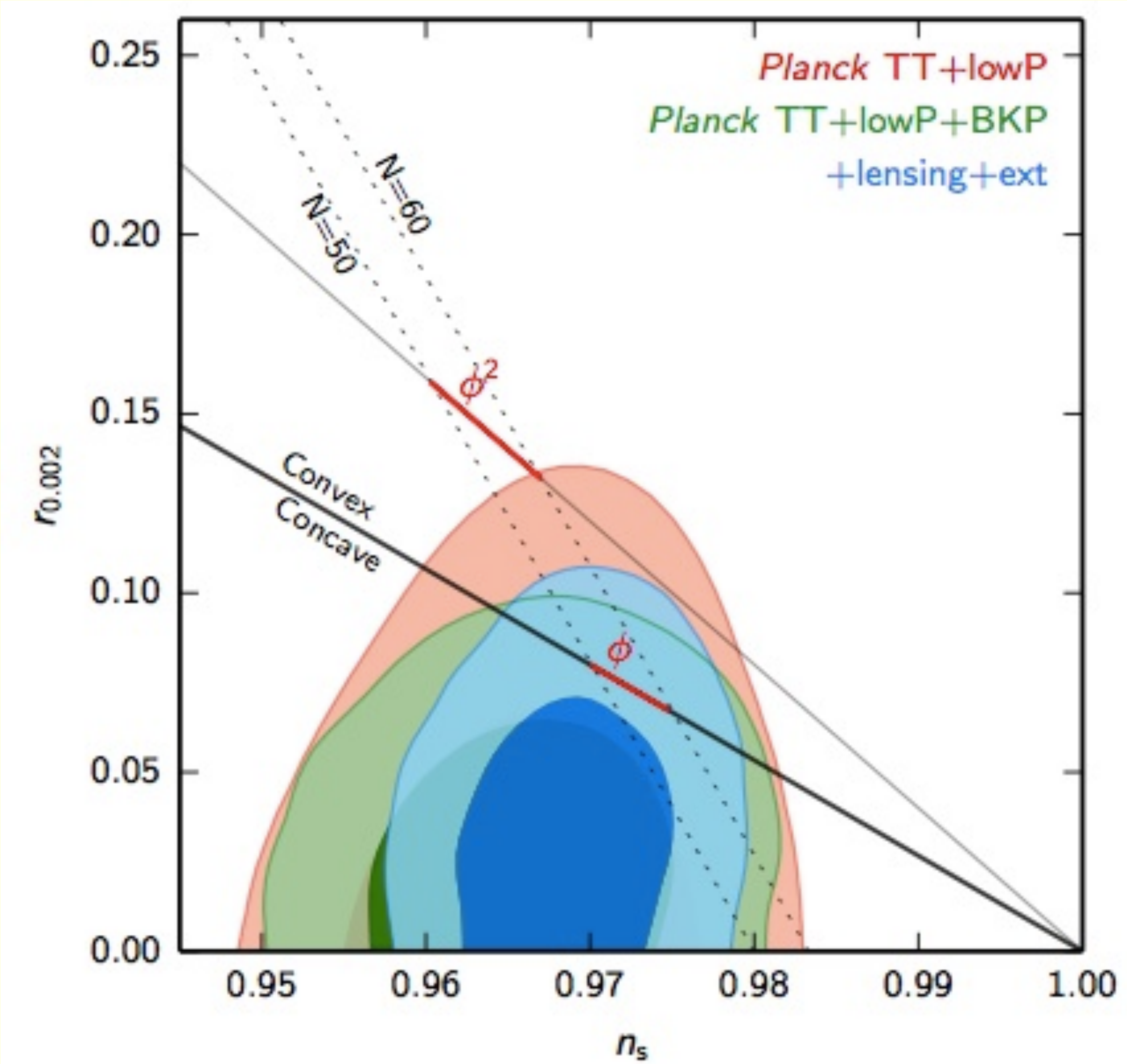
Planck coll., arXiv:1409.5738



Power spectrum of dust emission extrapolated to Bicep2 from Planck data (boxes) vs $\Lambda_{CDM+inflation}$ prediction for r=0.2 (line)
➔ polarized dust emission underestimated in Bicep2 analysis

Data vs inflation : Planck + BK 2015

Planck 2015, Cosmological parameters, arXiv:1502.01589



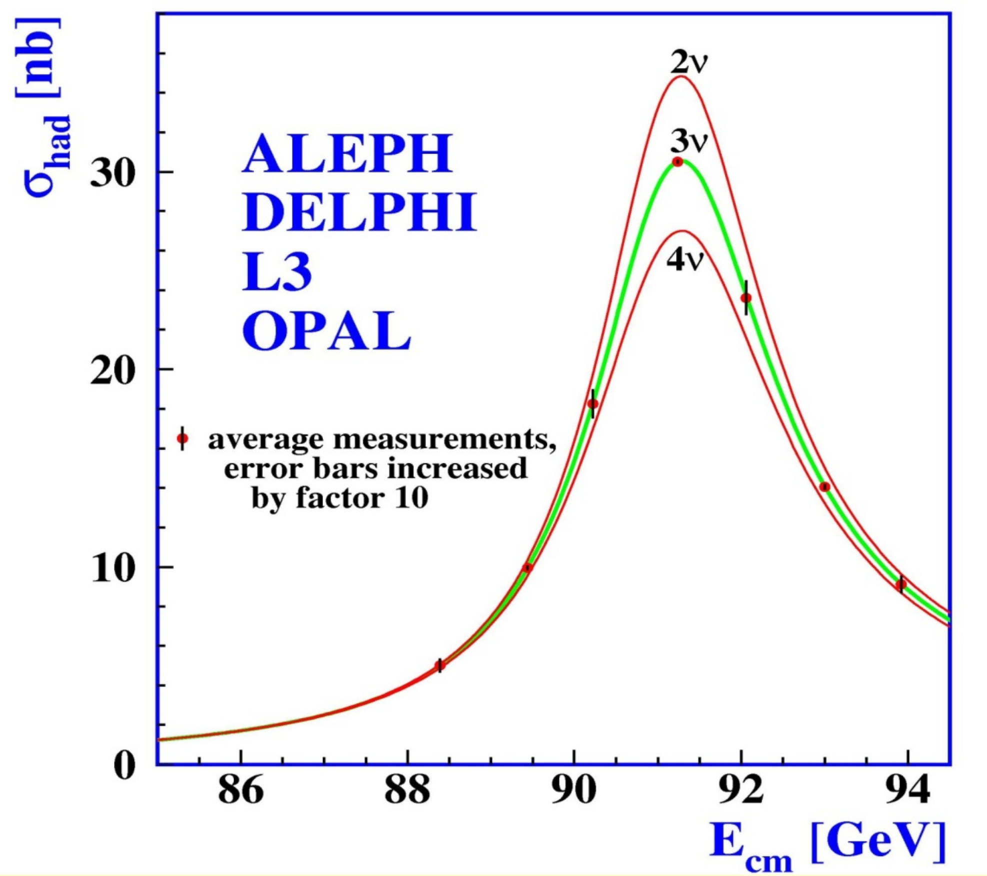
Planck+BICEP2/Keck +BAO+SNe+H_0 data :

$r_{0.002}$<0.09 (95%CL)

To go further: direct B-mode detection (ground-based projects <2025, satellites >2025)

Properties of neutrinos from particle physics

$e^+ e^- \to Z \to$ hadrons



- tree-level SM prediction:

$$\sigma_f(\sqrt{s}) = \frac{s\Gamma_Z^2}{(s-M_Z^2)^2 + \Gamma_Z^2 M_Z^2}\sigma_f^0$$

$$\sigma_f^0 = \frac{12\pi}{M_Z^2}\frac{\Gamma_{e\bar{e}}\Gamma_{f\bar{f}}}{\Gamma_Z^2}$$

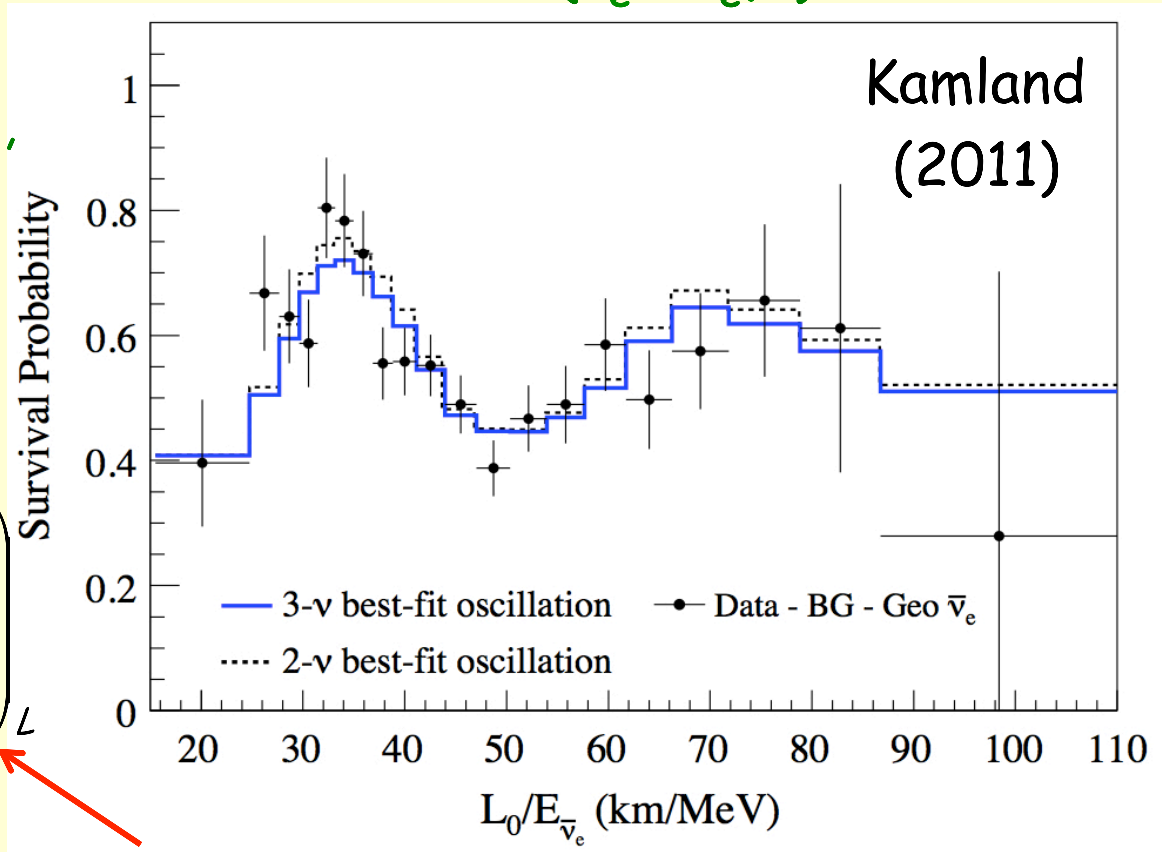
$\Rightarrow$ width and normalization depend on N_ν

- data best agree with N_ν=3 light neutrinos coupled to the Z

$N_\nu = 2.9840 \pm 0.0082$

Neutrino oscillations

$P(\bar{\nu}_e \rightarrow \bar{\nu}_e, t)$



- Multiple evidence for ν flavour conversion: solar, atmospheric & reactor ν's

$\Rightarrow$ $m_\nu \neq 0$, ν mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}_L = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}_L$$

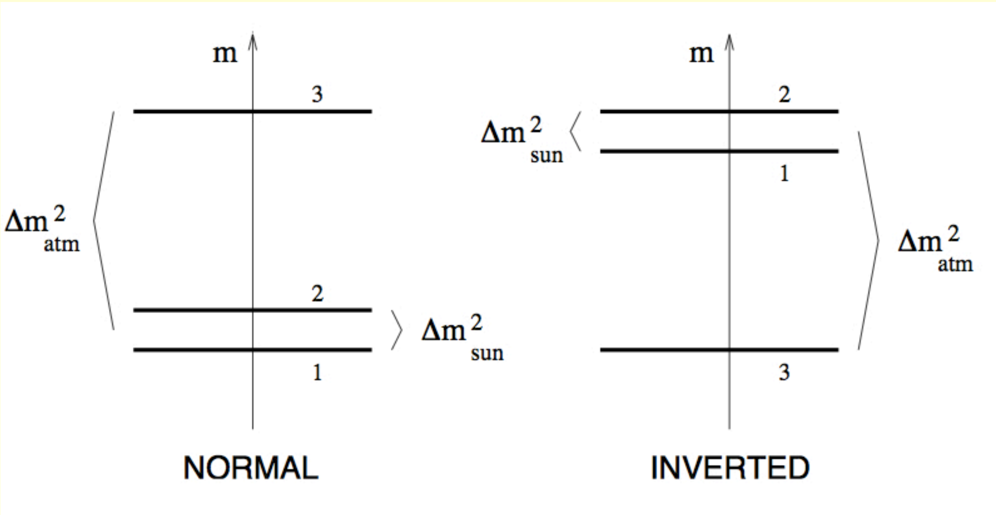
flavour ν's
produced in weak processes (e.g. β decays)

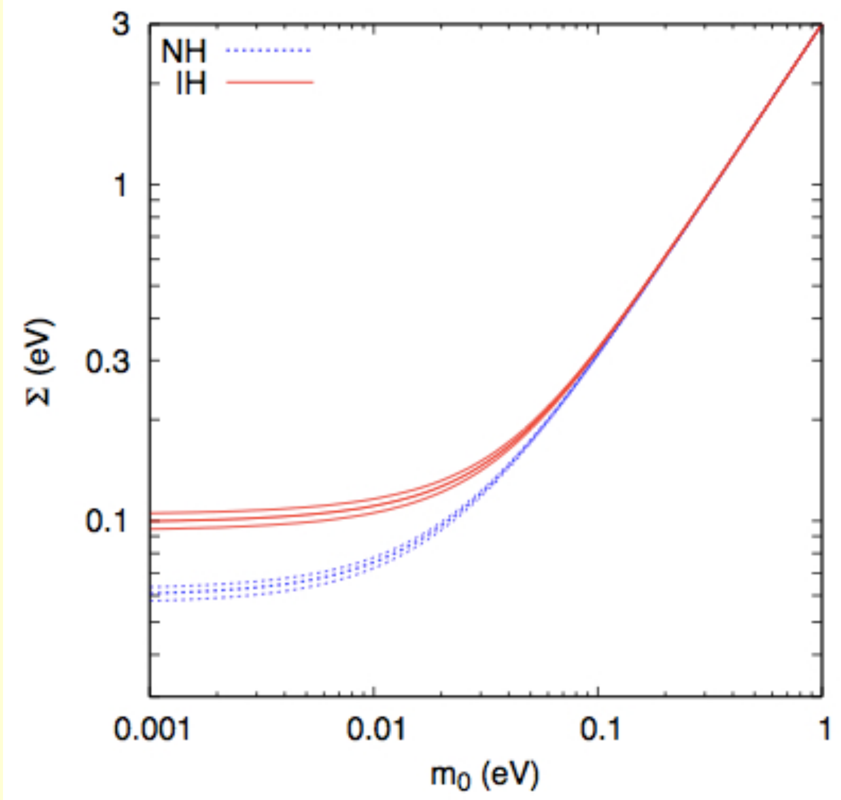
mass eigenstates, $m_{\nu 1,2,3} < 1$eV, ∃i, $0.05\text{eV} < m_i$: responsible for oscillations

- $m_\nu \neq 0$ → generation of the baryon asymmetry of the Universe (if CP violation in ν mixing) & impact on the evolution of the Universe

Neutrino mass hierarchy

- From neutrino oscillation results :





- Approximate range for Σm_i :
  0.06 (0.1) eV ≤ Σm_i ≤ 6 eV

J.Lesgourgues & S.Pastor, Adv. High Energy Phys. 2012 (2012) 608515

Neutrinos & the Universe evolution

- Neutrinos are present in the primordial plasma (p, n, e, γ and ν) and kept in thermodynamical equilibrium by EW interactions e.g. : $\nu\bar{\nu} \leftrightarrow e^+e^-$

- Neutrinos decouple (Γ_{EW} below Γ_{exp}) at T ≈ 1MeV and begin traveling freely through space *(cosmic neutrino background)*

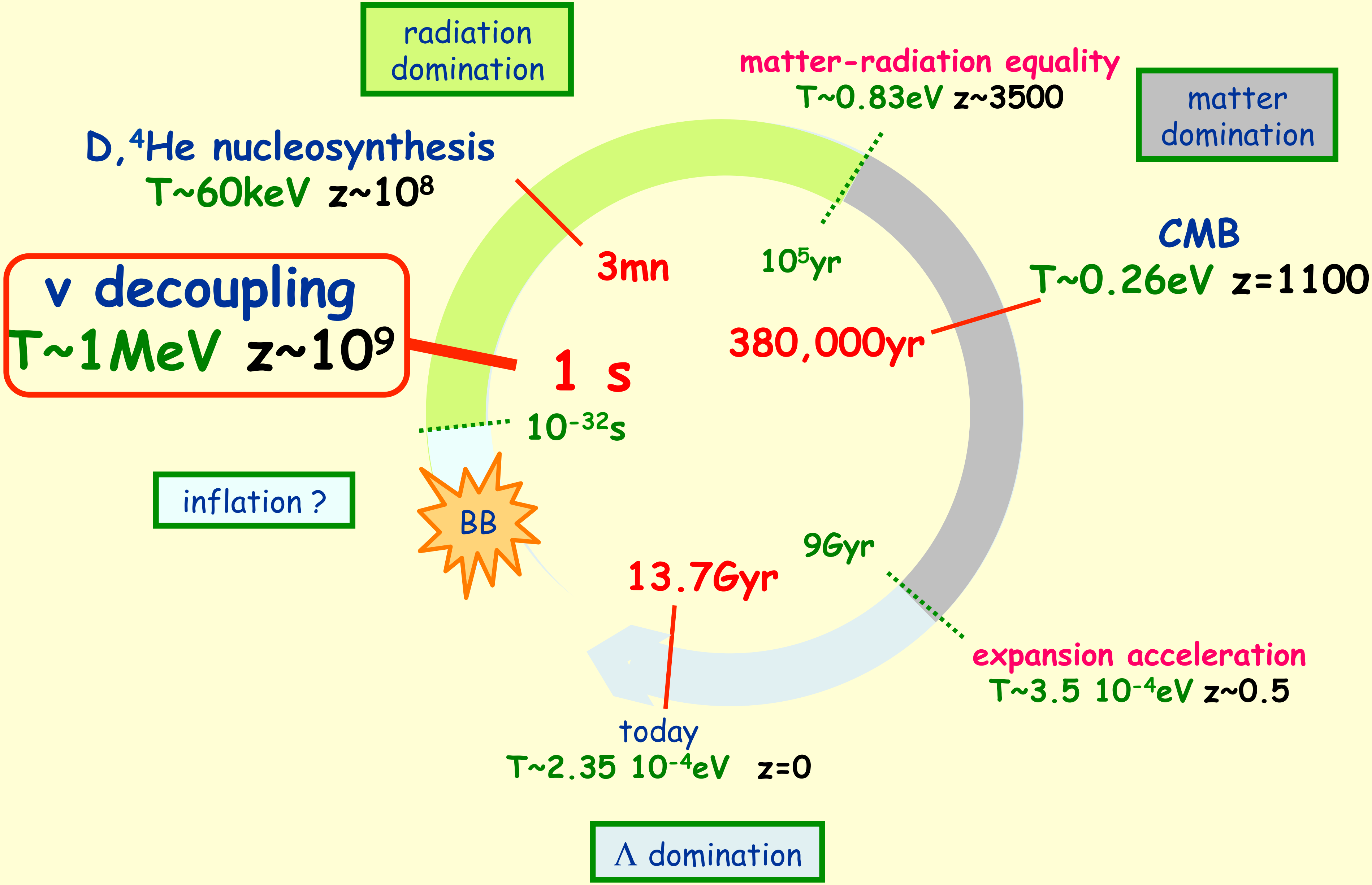
soon after decoupling ($T=T_\gamma \approx m_e$):

$$T_\nu = (4/11)^{1/3} T_\gamma \qquad n_\nu = (3/11) n_\gamma$$ (per flavour, $\nu+\bar{\nu}$)

today :

$$T_{CMB}^{now} = 2.725K \rightarrow n_\gamma^0 = 411 cm^{-3} \Rightarrow n_\nu^0 = 112 cm^{-3}$$

(per flavour, $\nu+\bar{\nu}$)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Λ domination

Light neutrinos as dark matter candidates ?

- Today's density of relic neutrinos (per flavour, $\nu + \bar{\nu}$):
  - **Relativistic** neutrinos ($m_\nu \ll 10^{-4}$**eV**):

$$\Omega_\nu^0 = \frac{7}{16}(T_\nu / T_\gamma)^4 \Omega_\gamma^0 = 0.227 \Omega_\gamma^0$$

$$T_{CMB}^{now} = 2.725K \rightarrow \Omega_\gamma^0 = 5.1 h_{70}^{-2} \times 10^{-5} \Rightarrow \Omega_\nu^0 = 1.2 h_{70}^{-2} \times 10^{-5}$$

➔negligible

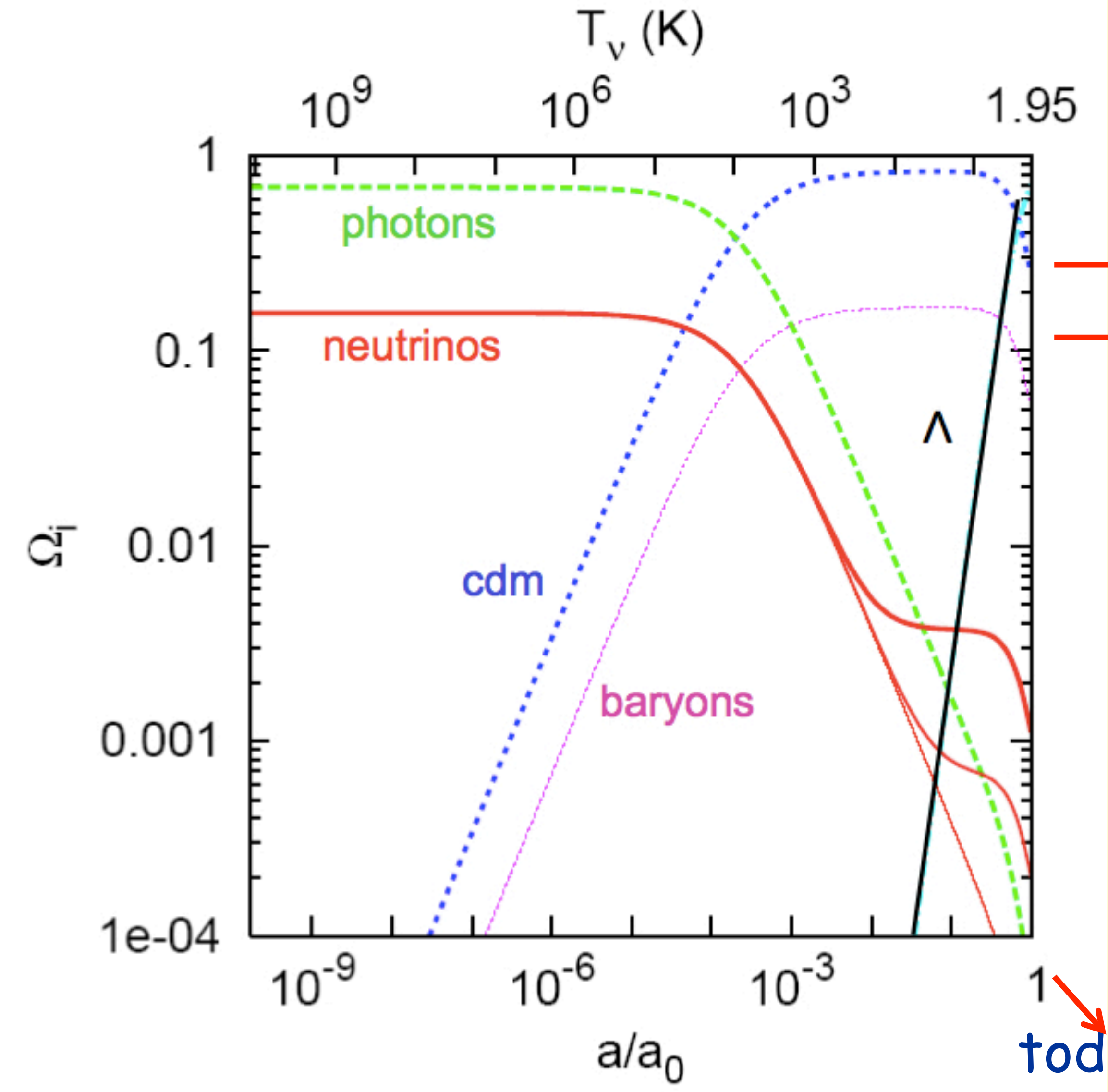
  - **Non-relativistic** neutrinos ($m_\nu \gg 10^{-4}$**eV**):

$$\Omega_\nu^0 = \frac{m_\nu n_\nu^0}{\rho_c^0} = 0.02 h_{70}^{-2} \frac{m_\nu}{1eV}$$

➔marginal for standard neutrinos (< 0.13)

→ SM neutrinos cannot account for dark matter

Relic neutrino densities



today

$\Omega_{cdm} \simeq 0.25$

$\Omega_\nu < 0.13$ ($\Sigma m_i \leq 6$ eV)

SM neutrinos cannot account for dark matter

J.Lesgourgues & S.Pastor, Adv. High Energy Phys. 2012 (2012) 608515

Massive neutrinos in cosmology

- Neutrinos decoupled at T≈1 MeV → no oscillation, free propagation BUT ν's have some effects, e.g.
  - ν's contribute to the cosmic expansion → impact on b-γ oscillations and matter perturbation growth
  - massive ν's do not cluster at low-scales (small-scale ν fluctuations suppressed by *free streaming*)

$$\lambda_{fs}(t)=2\pi\frac{v_{th}(t)}{H(t)} \Rightarrow \lambda_{fs}(t_0)\approx 10Mpc\frac{1eV}{m_\nu}$$

today free-streaming scale of NR ν's

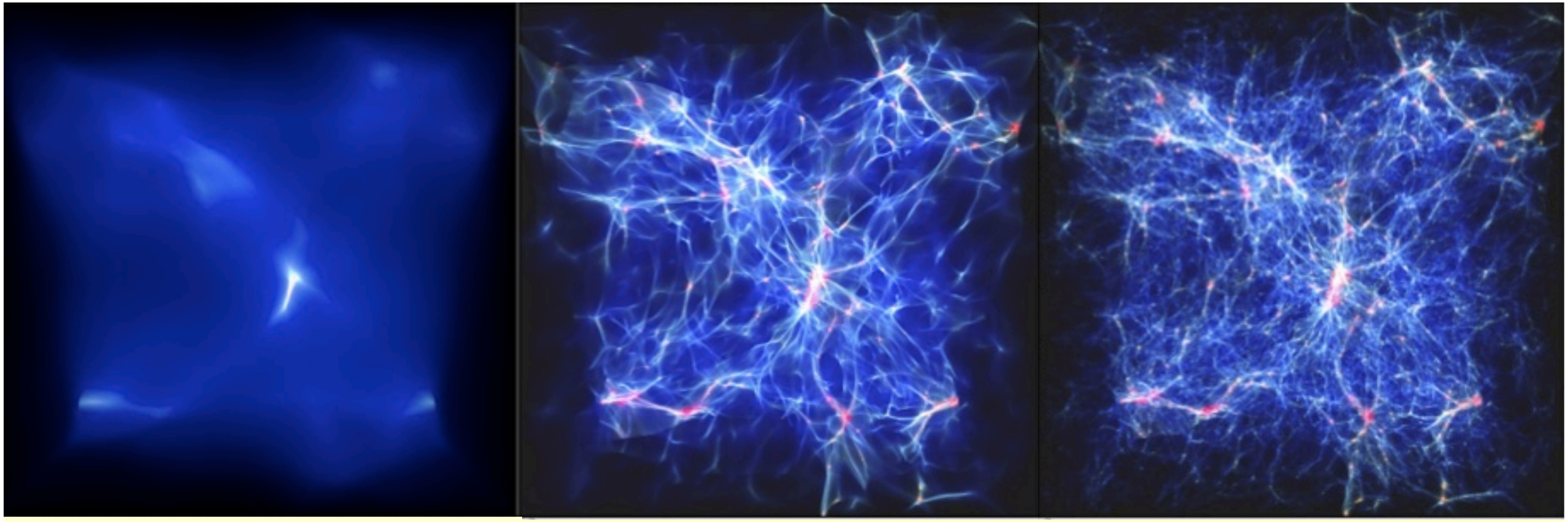
  - growth rate of b, CDM perturbations reduced at low scales by the absence of gravitational clustering from free-streaming ν's

➔ impact on CMB & matter power spectra

Free streaming and structure formation

From hydrodynamical simulations with baryons and DM

HDM : 0.1 keV   WDM : 0.5 keV   CDM : ∞ mass



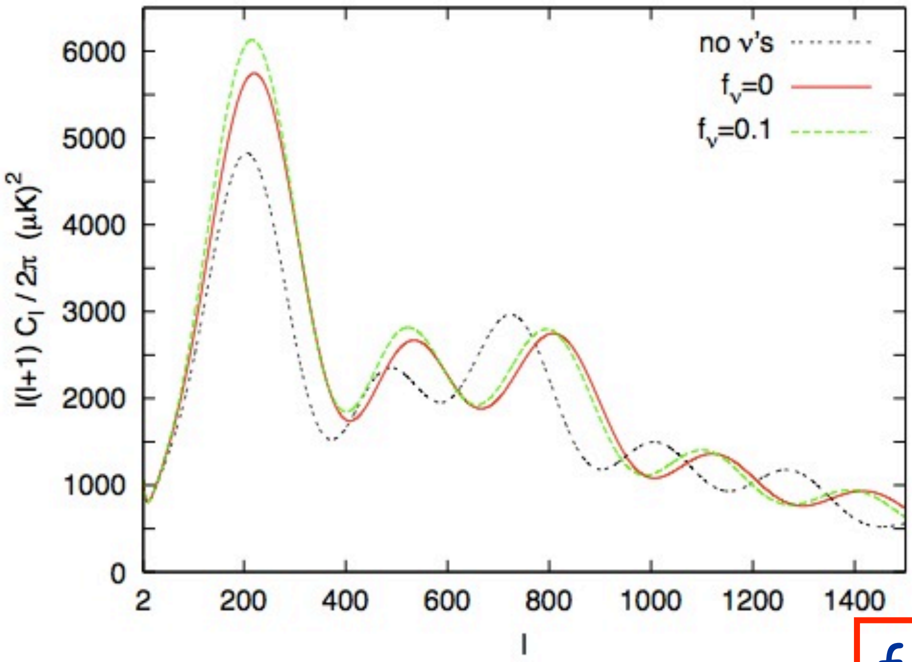
← lighter mass

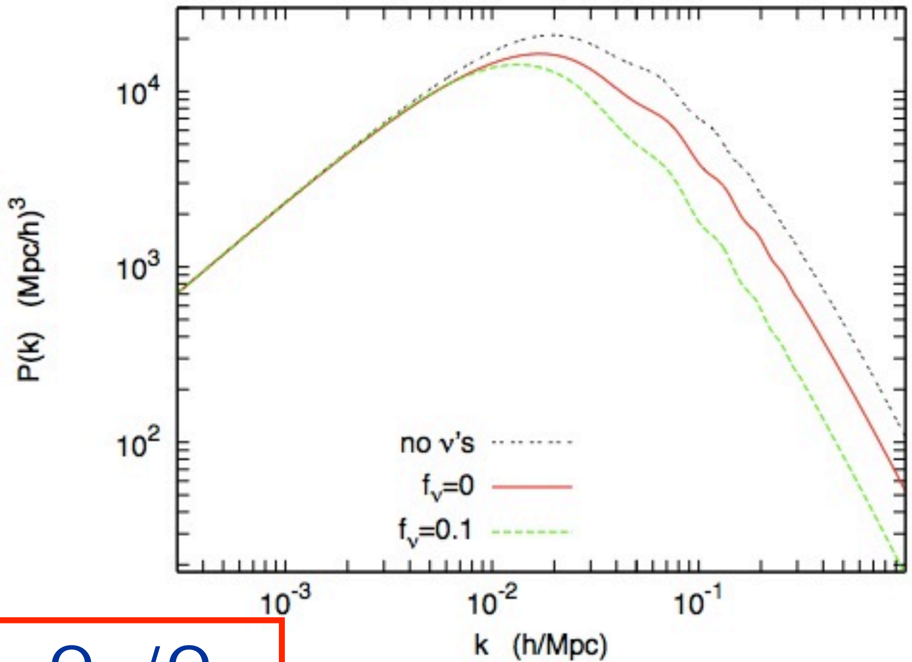
J.Baur et al, JCAP 08 (2016) 012

Effect of massive ν's on CMB and matter spectra

CMB spectrum in monopole space

Matter spectrum in Fourier space





$f_{\nu=} = \Omega_\nu / \Omega_m$

Constraints on Σm_i from CMB / matter spectrum

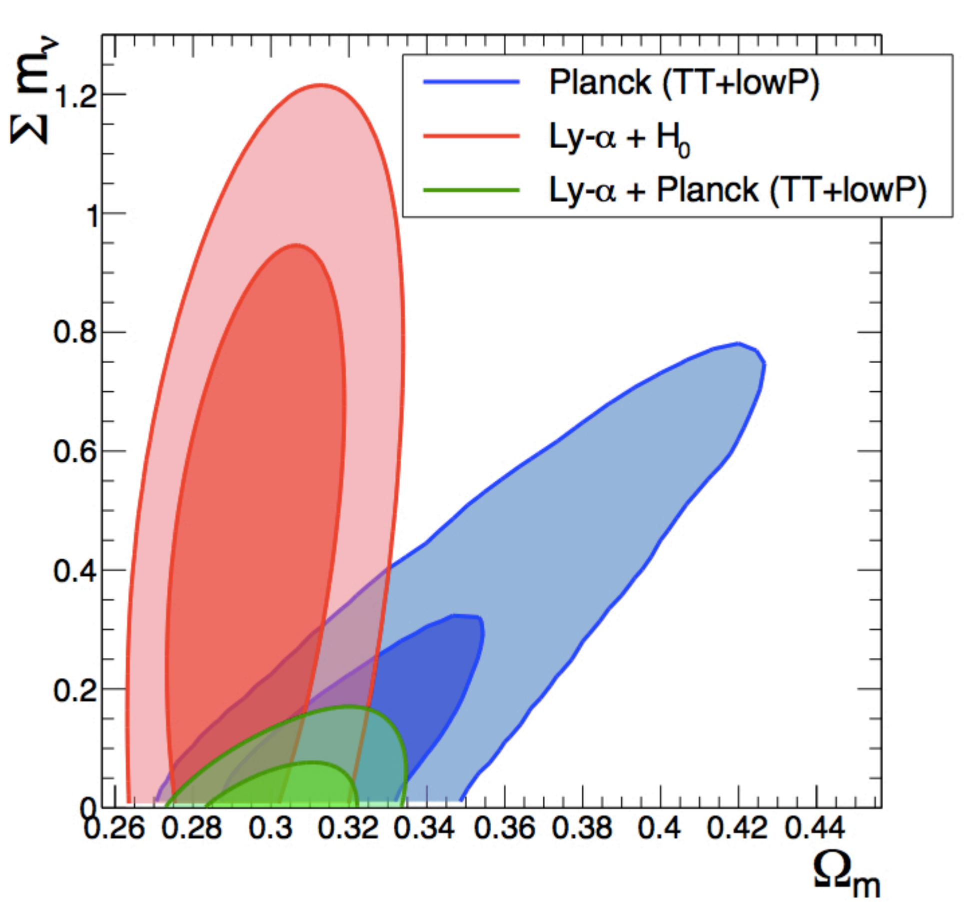
J.Lesgourgues & S.Pastor, Phys.Rept. 429 (2006) 307

Most recent results

Assuming only 3 active neutrinos and a flat Universe

- Planck 2015 (Planck + lensing + BAO + JLA + H_0) :
  $\Sigma m_i < 0.23$ eV (95% CL)

Planck 2015, arXiv:1502.01589

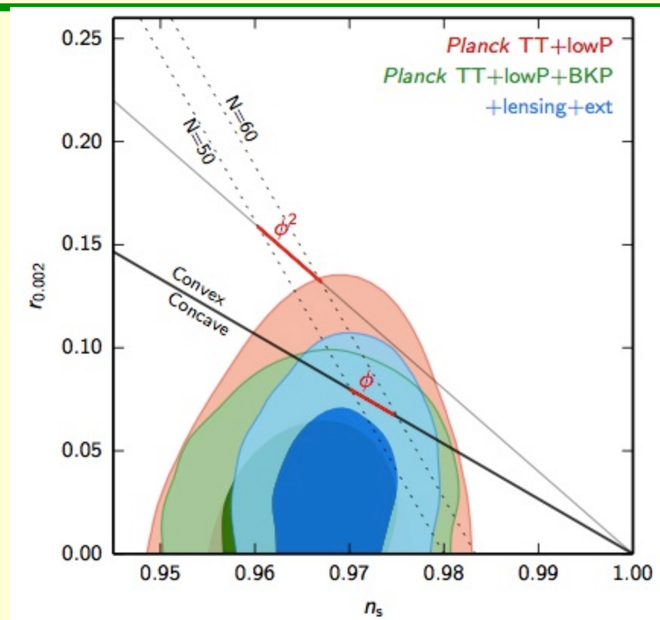


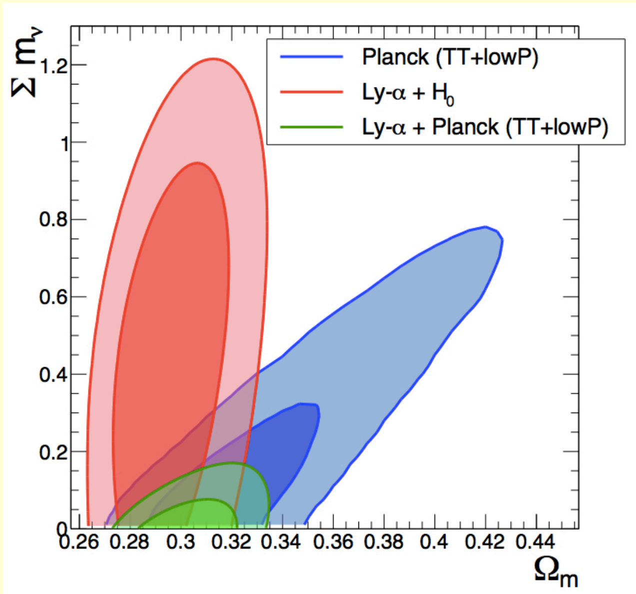
- Planck + matter spectrum :
  $\Sigma m_i < 0.12$ eV (95% CL)

N.Palanque-Delabrouille et al, JCAP 11 (2015) 011

CONCLUSIONS (4)

- Inflation :
  - no sign yet: $r_{0.002}$<0.09 (95%CL)
  - Future : direct B-mode detection





Neutrino masses :
- strong constraint from cosmology: Σm_i < 0.12 eV (95% CL)
- more to be expected from future LSS projects