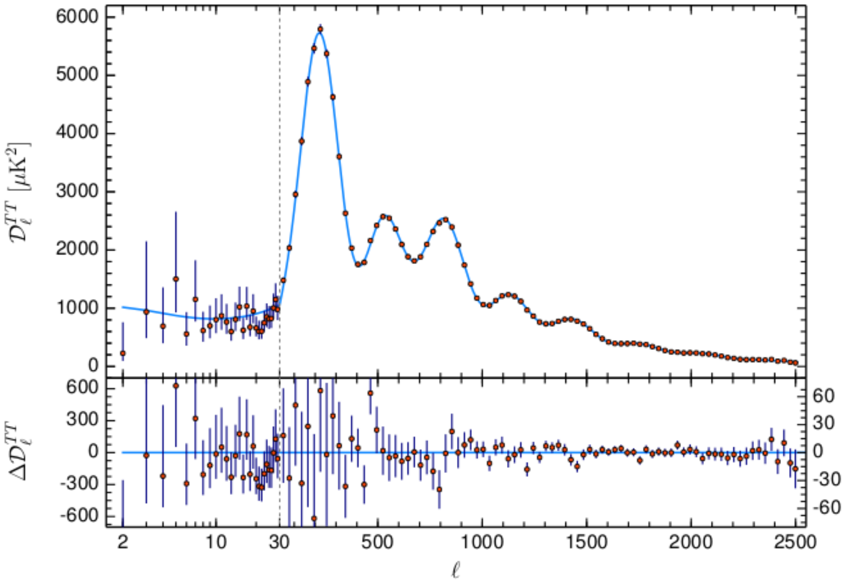
Inflation & PLANCK

Inflation and standard cosmology

Cosmological observations: CMB

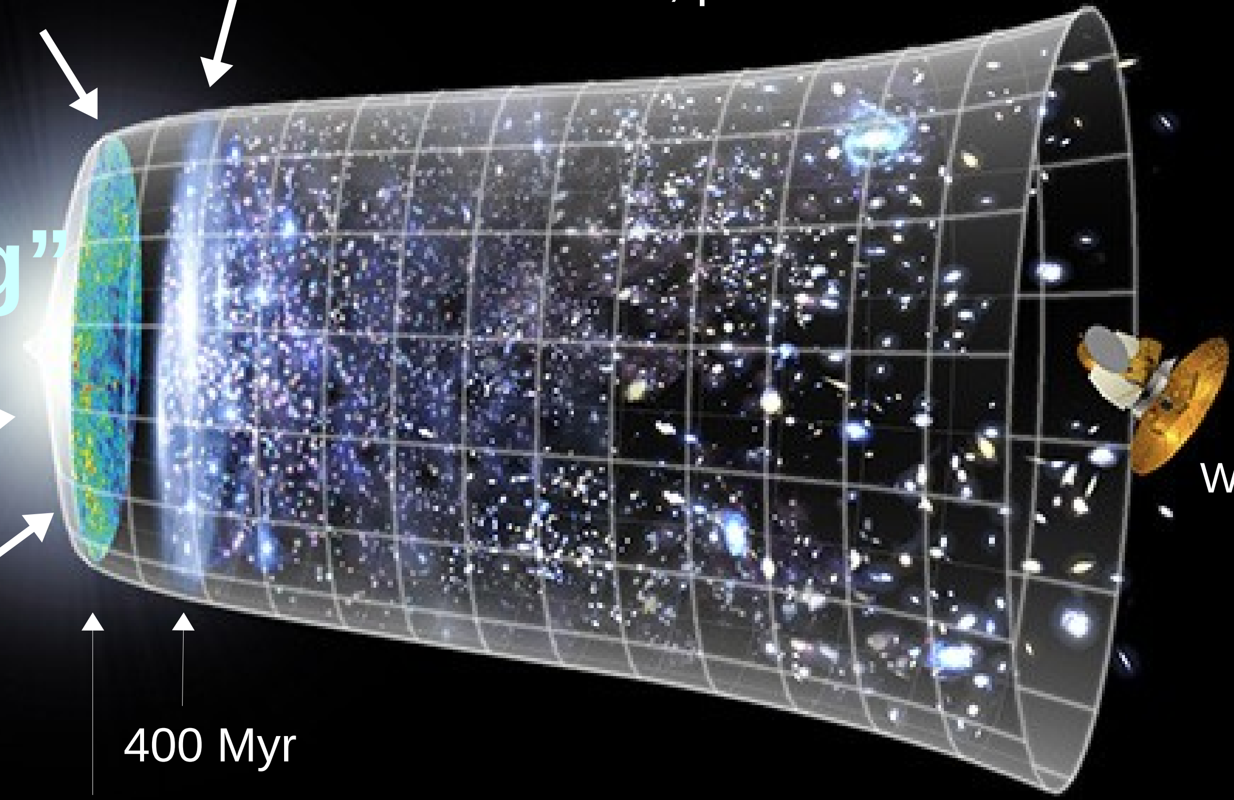
Model building



Mar Bastero Gil

University of Granada

The expanding Universe



First stars

CMB

3000 K

Galaxies, planets

“Big Bang”

Inflation:
Before BBN

BBN

3 minutes

WMAP

400 Myr

300.000 yr

13.7 Gyr

T ~ 1/a

2.73 K

NASA/WMAP Science Team

Cosmological Principle:

The Universe is homogeneous and isotropic at large scales

$l_{hom} > 100 h^{-1} h \mathrm{Mpc}$

Sarkar et al. 0906.3431 [SDSS DR6]; WiggleZ 1205.6812

FLRW metric: $ds^2 = dt^2 - a(t)^2 \delta_{ij} dx^i dx^j$

Flatness problem

$\Omega_T = 1 \Rightarrow \Omega_T(t_{nucl}) - 1 \approx 10^{-16}$

Horizon problem

The observable Universe was larger than the **particle horizon** at LSS

Inflation

Early period of accelerated expansion

$\ddot{a} > 0 : \quad P < -\rho/3$

Superhorizon perturbations?

Too small sub-horizon (**causal**) perturbations

Unwanted relics...

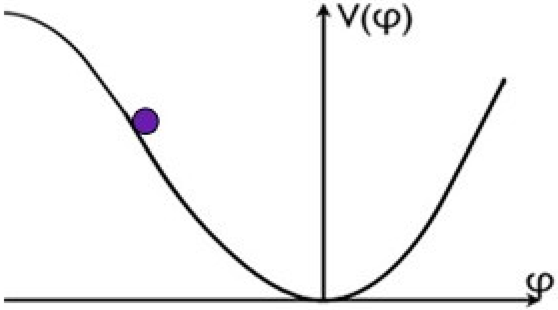
monopoles, moduli, gravitinos,...

Starobinsky ‘80; Guth ‘81; Albrecht, Steinhardt ‘82; Linde 1982

Slow Roll Inflation

Scalar field rolling down its (flat) potential

$$P=\dot{\varphi}^2/2-V(\varphi)\approx -V(\varphi)$$ negative pressure



"Flat" potential The curvature and the slope smaller than the (Hubble) expansion rate H

Kinetic energy << potential energy **$H^2 \sim V/3m_P^2$** **Hubble parameter** $(H=\dot{a}/a)$

$(a=\text{scale factor})$

Slow-roll parameters

$$|\eta_\varphi|=m_P^2\left|\frac{V''}{V}\right|<1$$

curvature

$$\epsilon_\varphi=\frac{m_P^2}{2}\left(\frac{V'}{V}\right)^2<1$$

slope

←

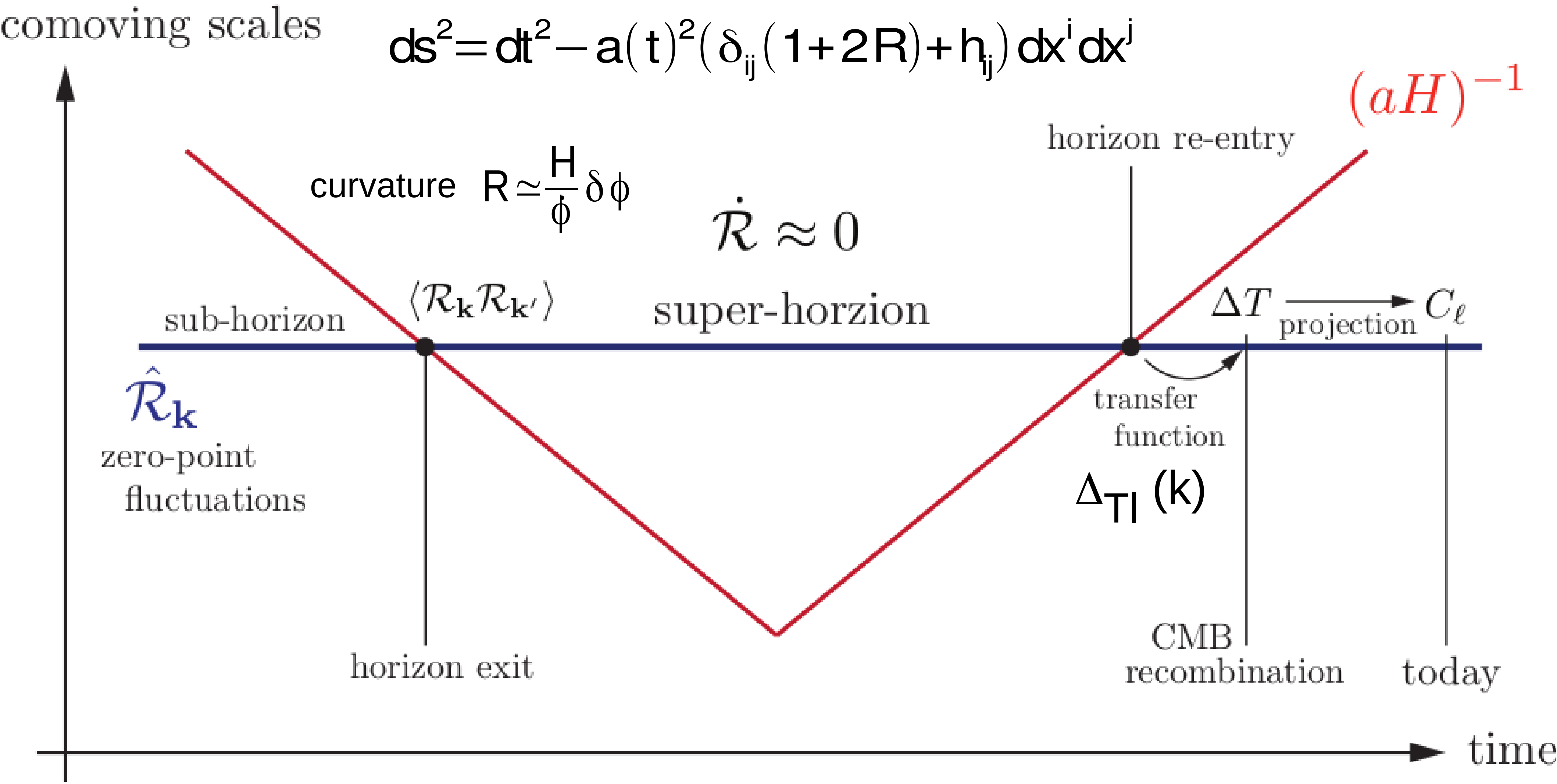
Slow-roll equation

$$\dot{\varphi}\simeq -V'/3H$$

CMB: T anisotropy spectrum

(background + linear fluctuations)

$$ds^2 = dt^2 - a(t)^2 (\delta_{ij}(1+2R)+h_{ij})\, dx^i dx^j$$



$$\Delta T/T \quad \Rightarrow \quad C_l^{TT} = \frac{2}{\pi}\int k^2 dk\, P_R(k) \underbrace{\Delta_{Tl}(k)\Delta_{Tl}(k)}_{(H_{0,}\ \ \Omega_i)}$$

Primordial spectrum

Primordial spectrum
(background + linear fluctuations)

$$ds^2 = dt^2 - a(t)^2\left(\delta_{ij}(1+2R)+h_{ij}\right)dx^i dx^j$$

Inflation

$$P_R(k) = \left(\frac{H_k}{\dot{\phi}}\right)^2 |\delta\phi_k|^2 = \left(\frac{H_k}{\dot{\phi}}\right)^2 \underbrace{\left(\frac{H_k}{2\pi}\right)^2}_{\text{Vacuum fluctuations}}$$

$$n_s - 1 = \frac{d\ln P_R}{d\ln k} = \frac{d\ln P_R}{d\ln N_e} = 2\eta - 6\epsilon$$

(~ scale invariant)

CMB

Spectral index

$$P_R(k) = A_S(k_0)\left(\frac{k}{k_0}\right)^{n_s-1}$$

$$A_s(k_0) = 2.2\,x\,10^{-10}$$

$$n_s = 0.965 \pm 0.004$$

[Planck 2018]

Tensors: **(h ~ massless scalar field)**

$$P_h(k) = 8\left(\frac{H_k}{2\pi m_P}\right)^2$$

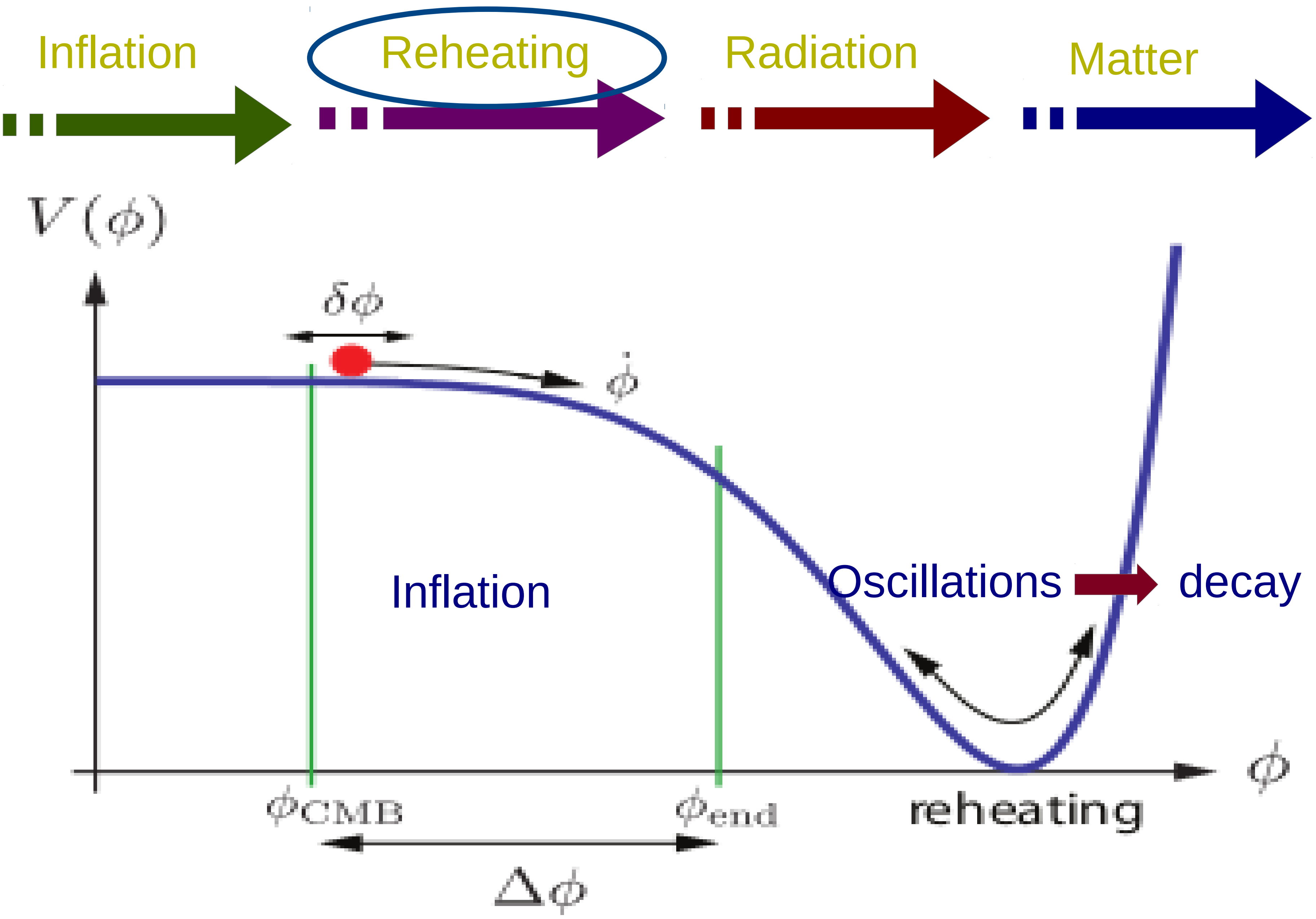
$$P_h(k) = A_T(k_0)\left(\frac{k}{k_0}\right)^{n_T}$$

$$n_T = \frac{d\ln P_h}{d\ln N_e} = -2\epsilon, \quad r = 16\epsilon$$

$$r = \frac{P_h}{P_R} < 0.09$$

$$V^{1/4} \sim 10^{16}\left(\frac{r}{0.1}\right)^{1/4} \text{ Gev}$$

No. de e-folds: $N(k)=\ln\frac{a_{end}}{a_k}$



No. of e-folds: $N(k) = \ln \frac{a_{end}}{a_k}$

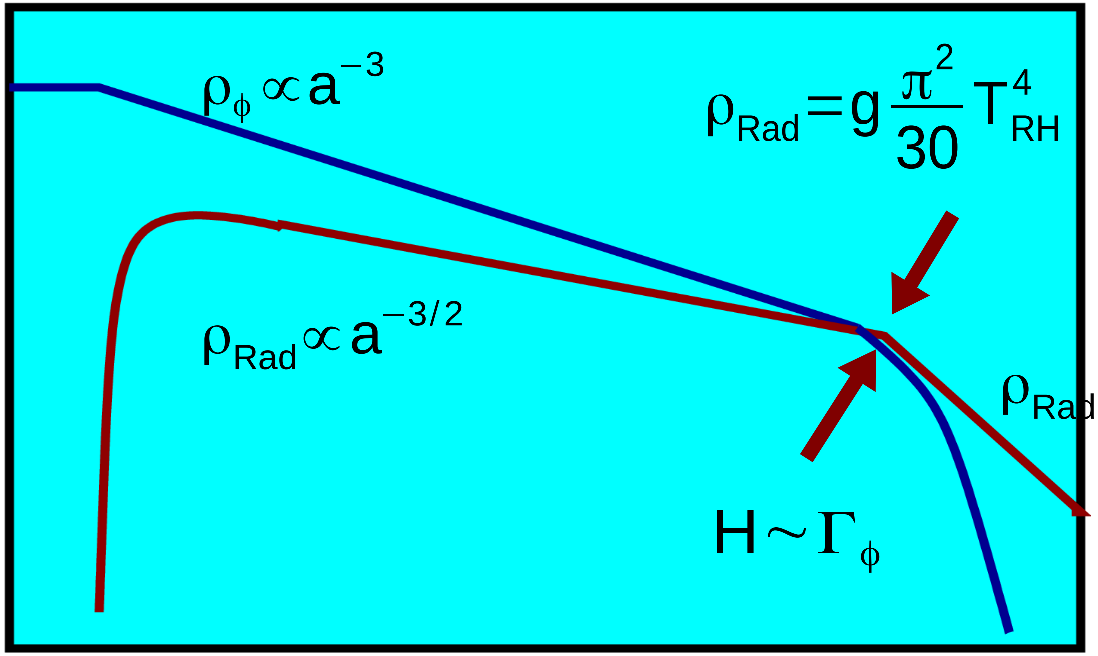
Inflation → Reheating → Radiation → Matter

$k = H_k a_k$

Horizon exit

$k = H_0 a_0$

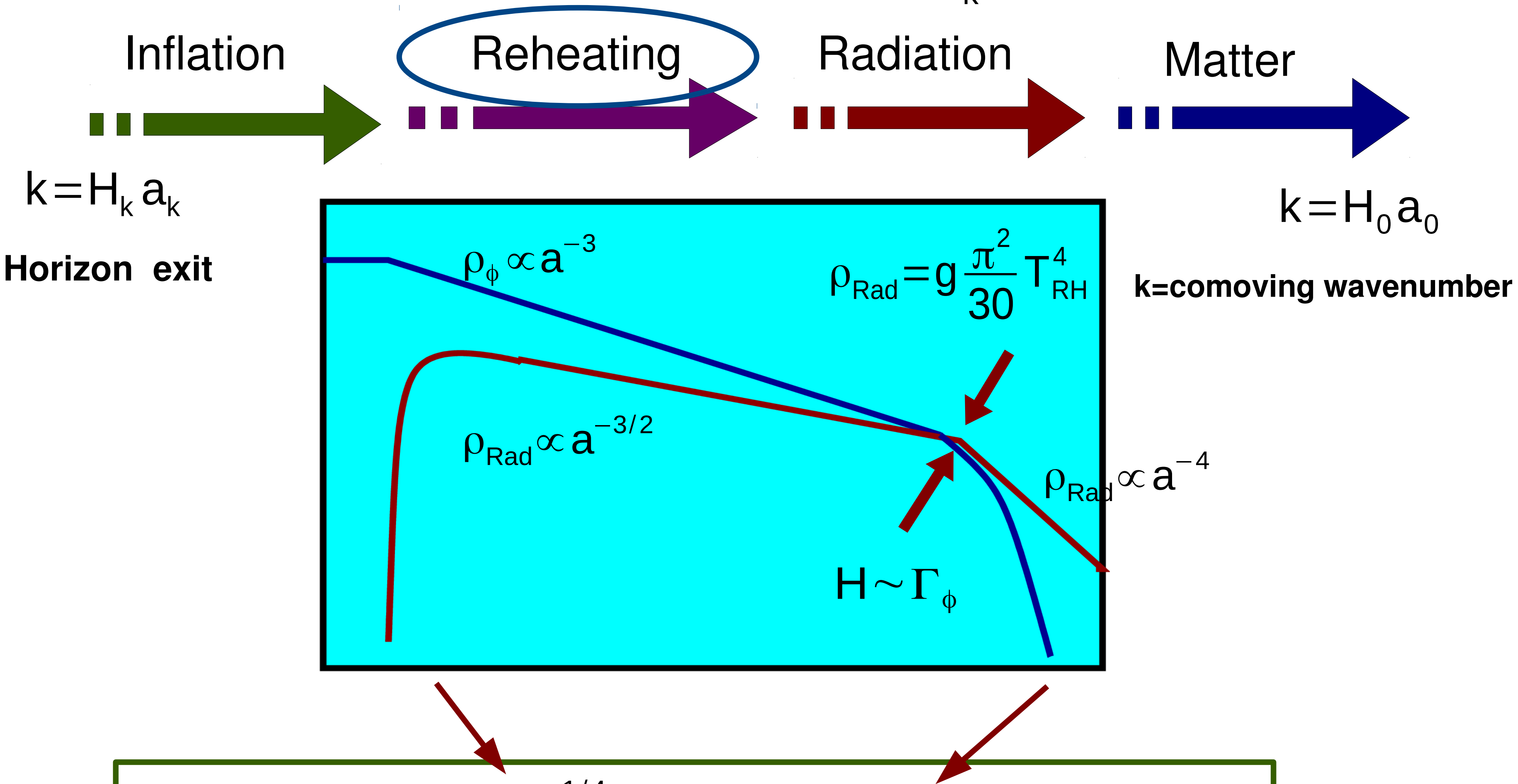
k=comoving wavenumber



$$\frac{k}{a_0 H_0} = \frac{a_k}{a_0} \frac{H_k}{H_0} = \frac{a_k}{a_{end}} \quad \frac{a_{end}}{a_{RH}} \quad \frac{a_{RH}}{a_{EQ}} \quad \frac{a_{EQ}}{a_0} \quad \frac{H_k}{H_0}$$

inflation **reheating** **radiation** **matter**

No. of e-folds: $N(k)=\ln\frac{a_{end}}{a_k}$



Inflation

Reheating

Radiation

Matter

$k=H_k a_k$

Horizon exit

$k=H_0 a_0$

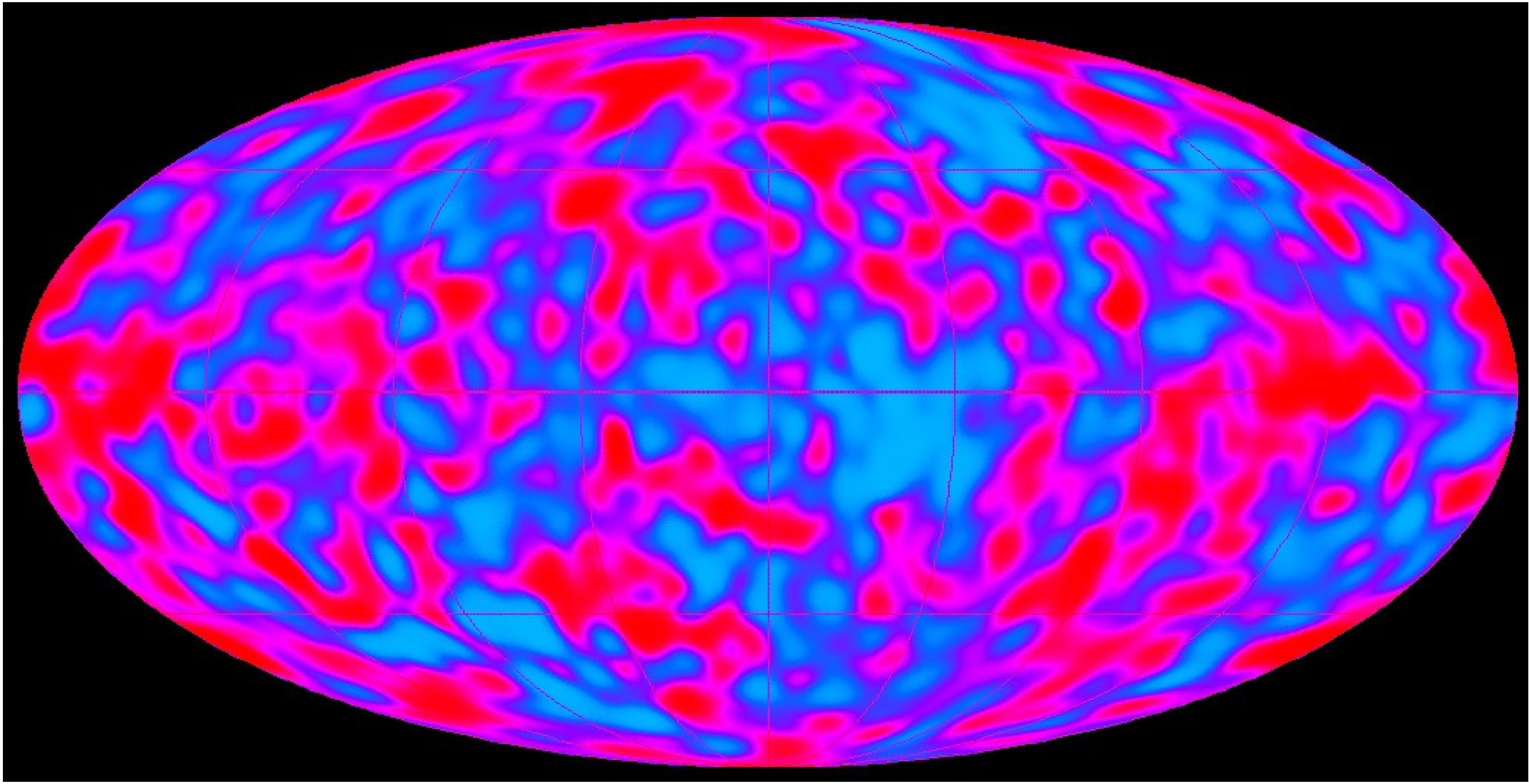
k=comoving wavenumber

$$N_e \simeq 56+\frac{2}{3}\ln\frac{V_{inf}^{1/4}}{10^{15}\,GeV}+\frac{1}{3}\ln\frac{T_{RH}}{10^9\,GeV}\sim 60-40$$

Cosmic microwave background radiation (CMB)

Spectrum of T fluctuations

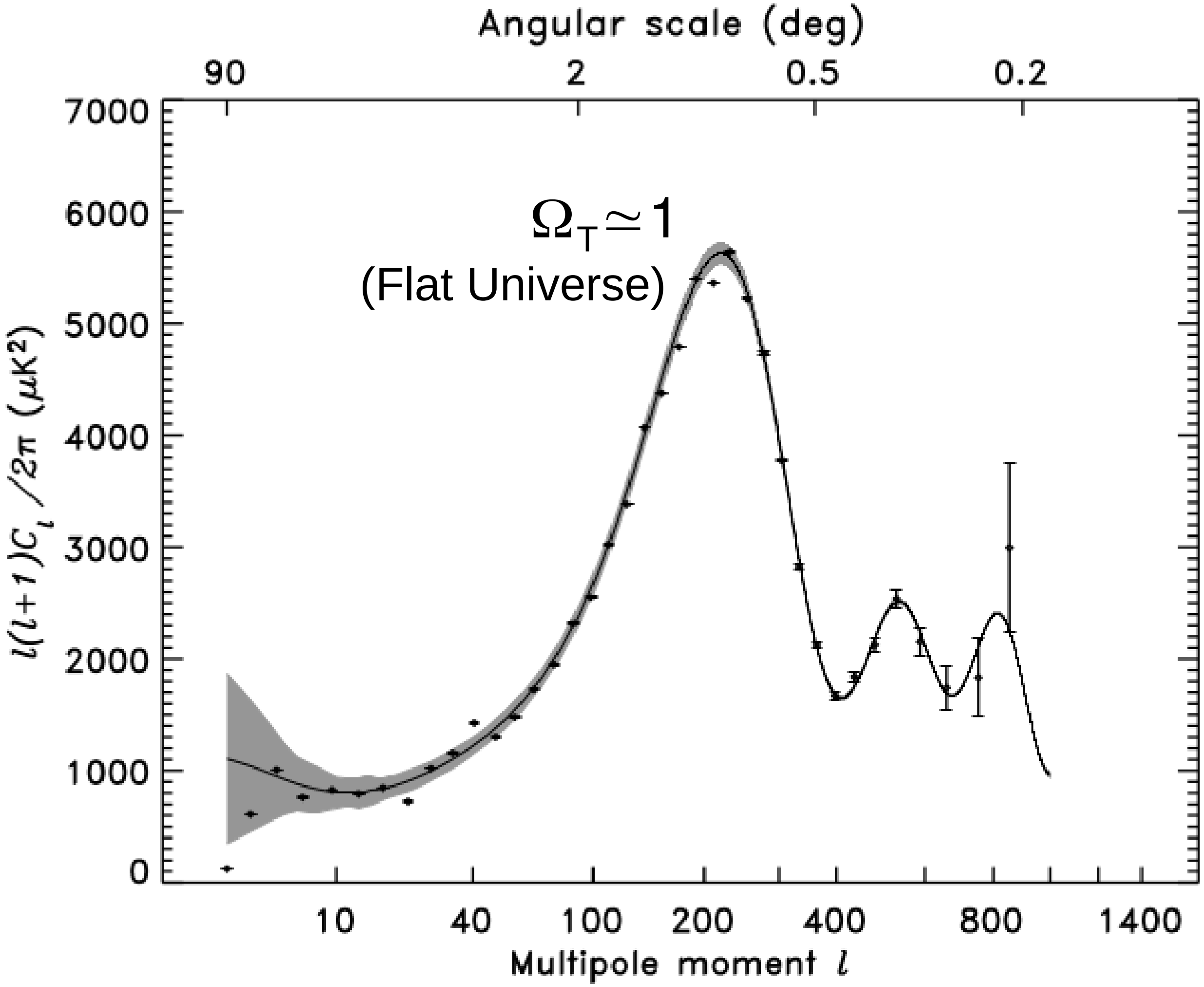
Primordial spectrum: $\delta_H = \frac{2}{5} P_R^{1/2} = 1.7 \times 10^{-5}$



COBE 1994 (NASA)

Cosmic microwave background radiation (CMB)

Spectrum of T fluctuations



$\Omega_T \simeq 1$

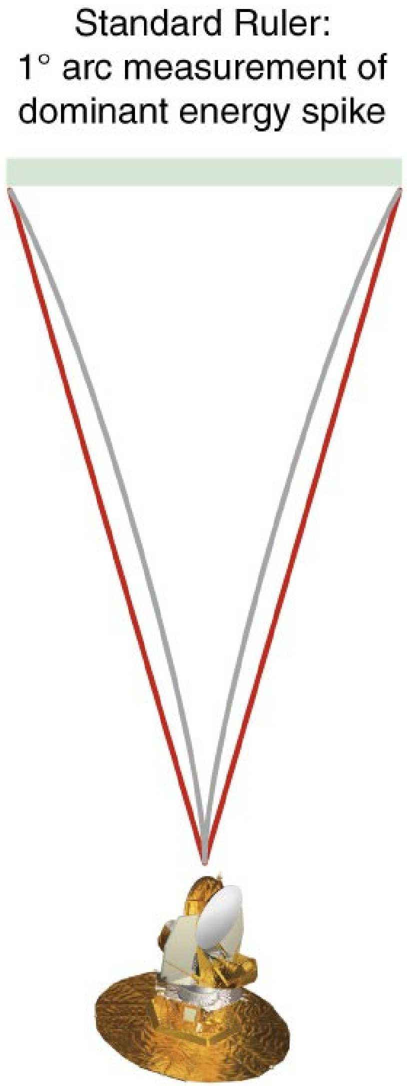
(Flat Universe)

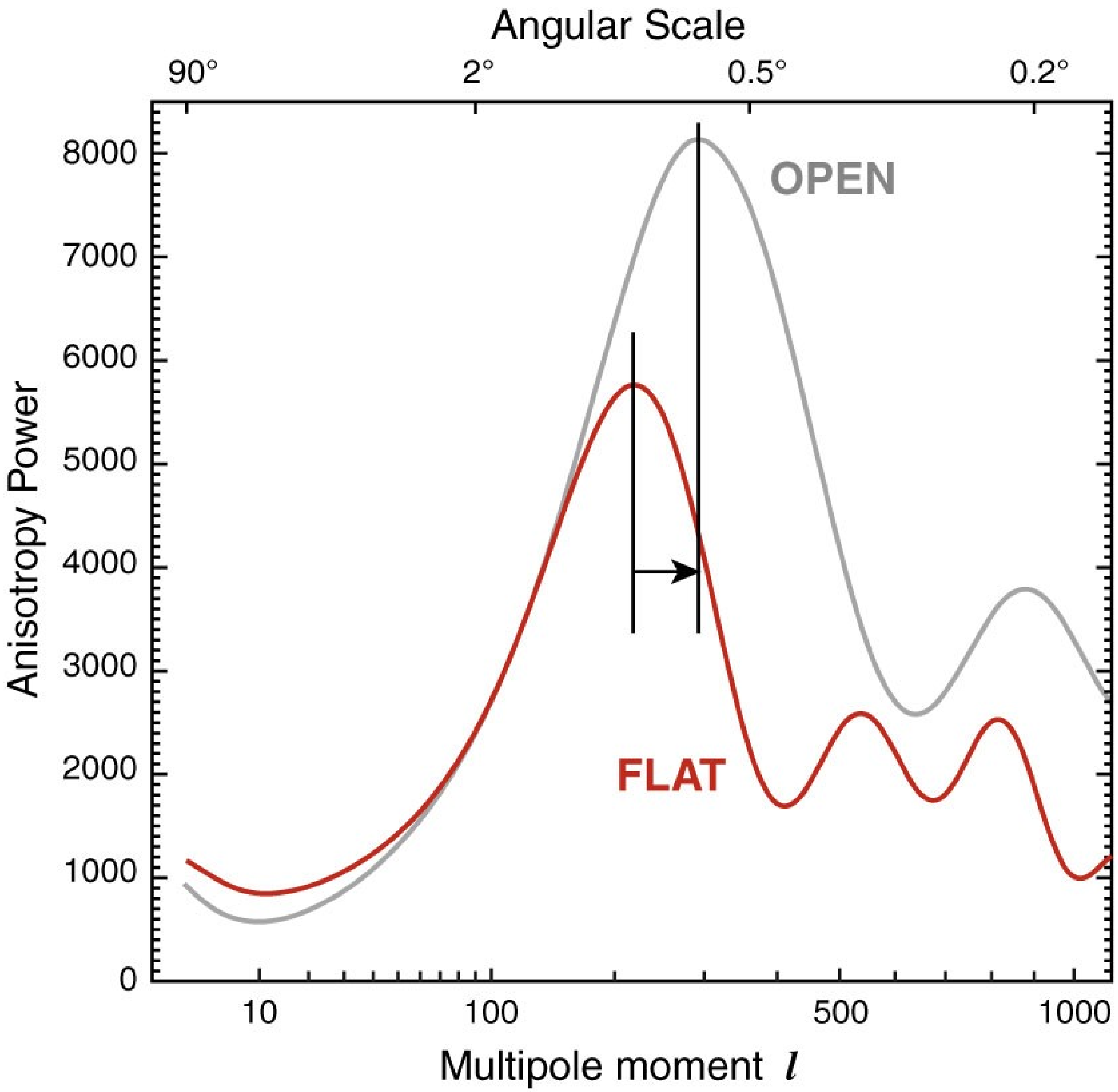
[WMAP1 (2003)]

https://map.gsfc.nasa.gov/

Cosmic microwave background radiation (CMB)

Spectrum of T fluctuations

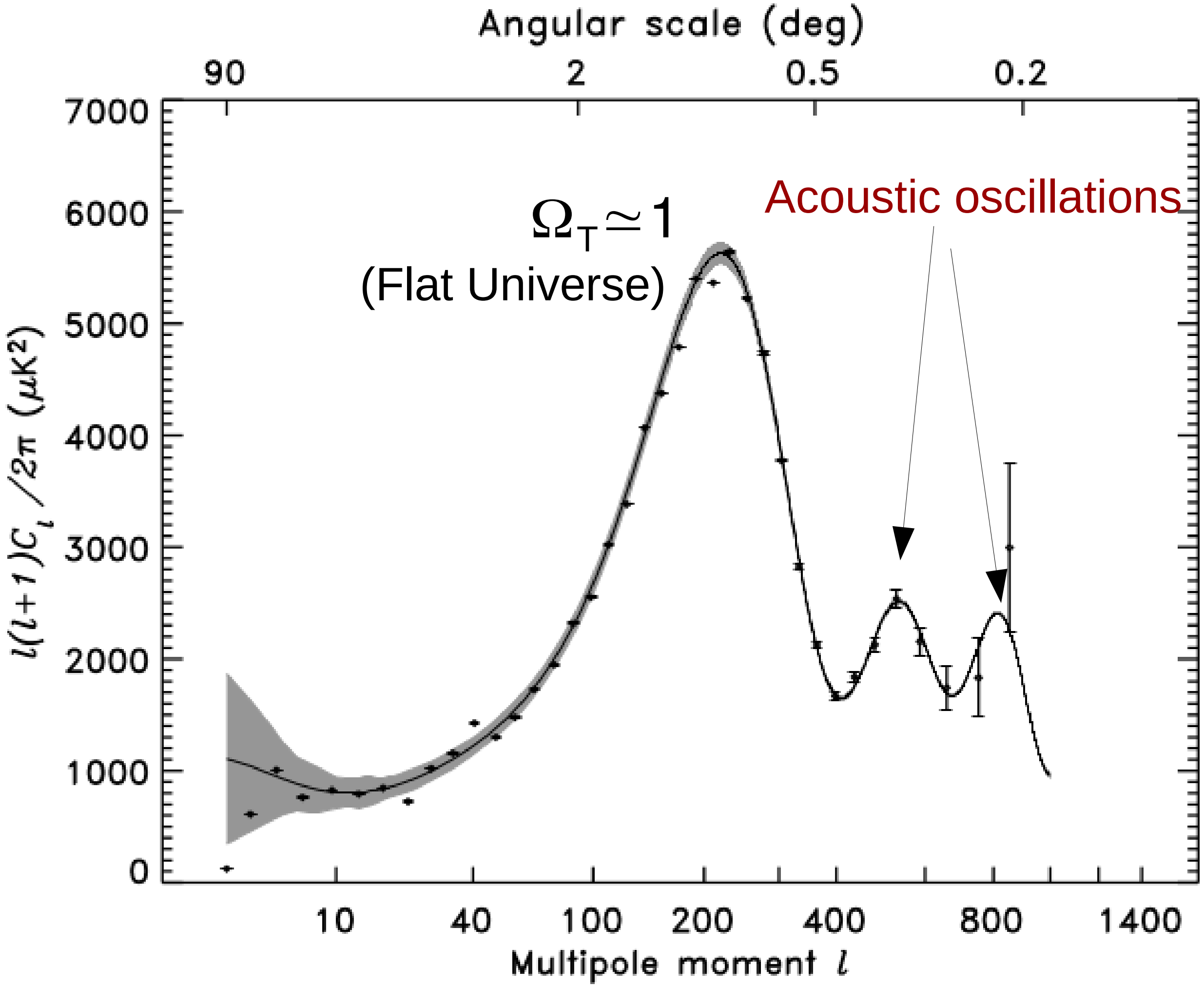




https://map.gsfc.nasa.gov/

Cosmic microwave background radiation (CMB)

Spectrum of T fluctuations



$\Omega_T \simeq 1$

(Flat Universe)

Acoustic oscillations

Adiabatic initial conditions
(rule out cosmic strings,….)

Spectral index

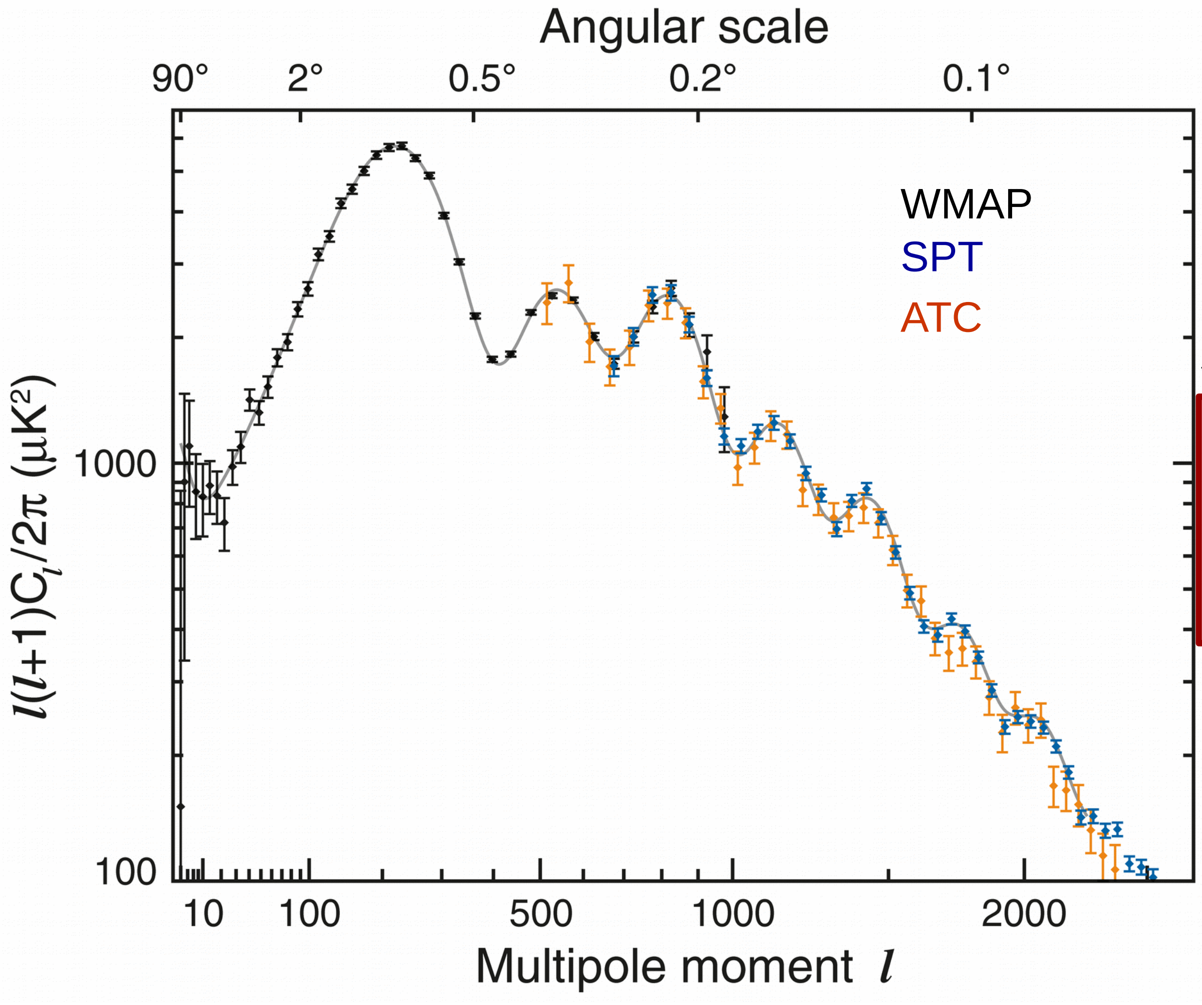
$$n_s = 0.96 \pm 0.03$$

[WMAP1 (2003)]

https://map.gsfc.nasa.gov/

Cosmic microwave background radiation (CMB)

Spectrum of T fluctuations



Spectral index & tensors

$n_s = 0.972 \pm 0.013$

$r < 0.13$

[WMAP9 (2012)]

https://map.gsfc.nasa.gov/

Cosmological parameters (ΛCDM)

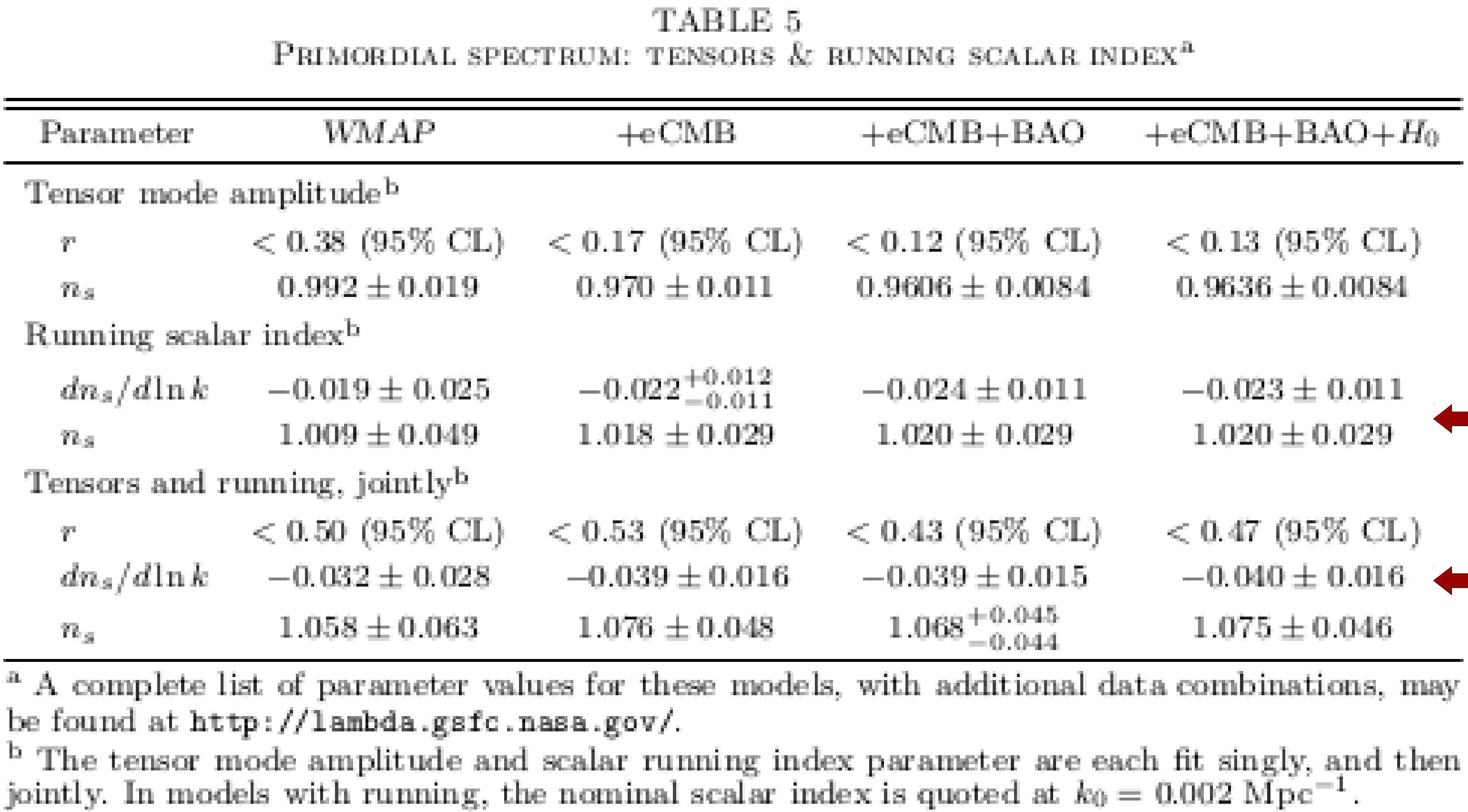


TABLE 5
PRIMORDIAL SPECTRUM: TENSORS & RUNNING SCALAR INDEX[a]

Parameter	*WMAP*	+eCMB	+eCMB+BAO	+eCMB+BAO+H_0
Tensor mode amplitude[b]				
r	< 0.38 (95% CL)	< 0.17 (95% CL)	< 0.12 (95% CL)	< 0.13 (95% CL)
n_s	0.992 ± 0.019	0.970 ± 0.011	0.9606 ± 0.0084	0.9636 ± 0.0084
Running scalar index[b]				
$dn_s/d\ln k$	-0.019 ± 0.025	$-0.022^{+0.012}_{-0.011}$	-0.024 ± 0.011	-0.023 ± 0.011
n_s	1.009 ± 0.049	1.018 ± 0.029	1.020 ± 0.029	1.020 ± 0.029
Tensors and running, jointly[b]				
r	< 0.50 (95% CL)	< 0.53 (95% CL)	< 0.43 (95% CL)	< 0.47 (95% CL)
$dn_s/d\ln k$	-0.032 ± 0.028	-0.039 ± 0.016	-0.039 ± 0.015	-0.040 ± 0.016
n_s	1.058 ± 0.063	1.076 ± 0.048	$1.068^{+0.045}_{-0.044}$	1.075 ± 0.046

[a] A complete list of parameter values for these models, with additional data combinations, may be found at `http://lambda.gsfc.nasa.gov/`.

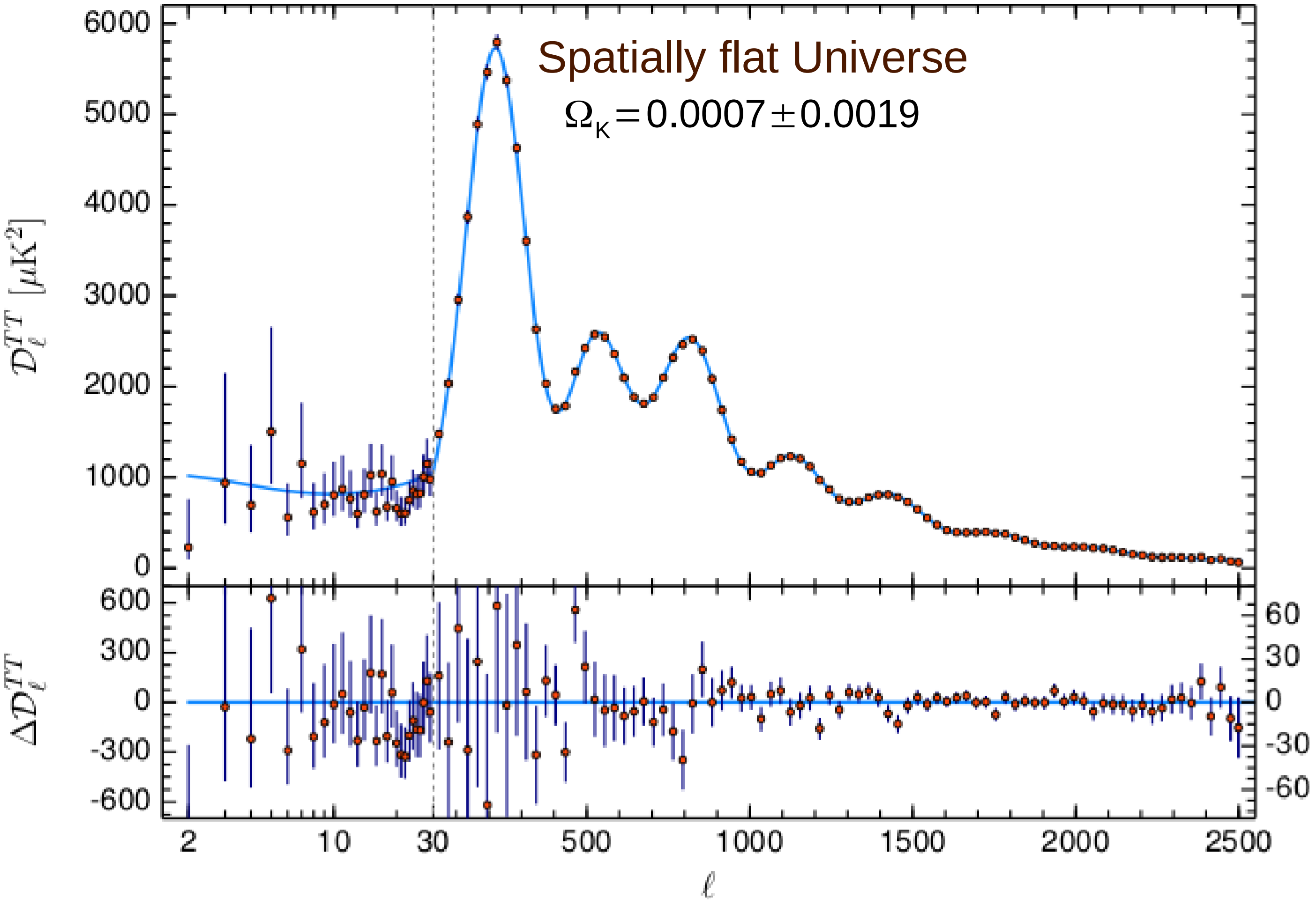
[b] The tensor mode amplitude and scalar running index parameter are each fit singly, and then jointly. In models with running, the nominal scalar index is quoted at $k_0 = 0.002\ \mathrm{Mpc}^{-1}$.

[WMAP9 (2012)]

https://map.gsfc.nasa.gov/

Cosmic microwave background radiation (CMB)

Spectrum of T fluctuations



Spatially flat Universe

$\Omega_K = 0.0007 \pm 0.0019$

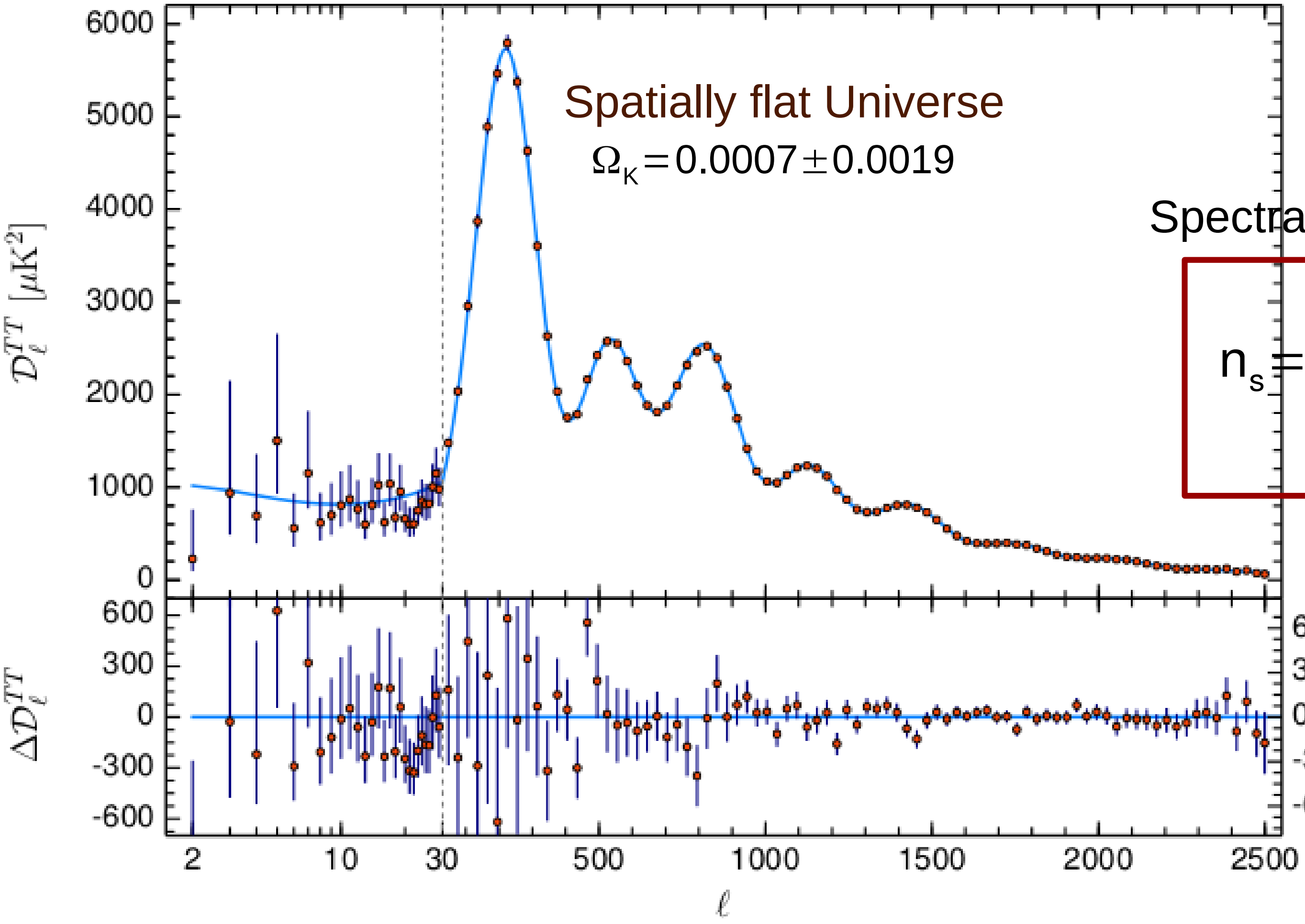
COBE (1992)
Boomerang
Maxima
DASI
CBI
VSA
…..

WMAP
SPT
BICEP/KEK
PLANCK
(14/05/09)

[Planck 2018: astro-ph/1807.06211]

Cosmic microwave background radiation (CMB)

Spectrum of T fluctuations



Spatially flat Universe

$\Omega_K = 0.0007 \pm 0.0019$

Spectral index & tensors

$n_s = 0.965 \pm 0.004$

$r_{0.05} < 0.09$

[Planck 2018: astro-ph/1807.06211]

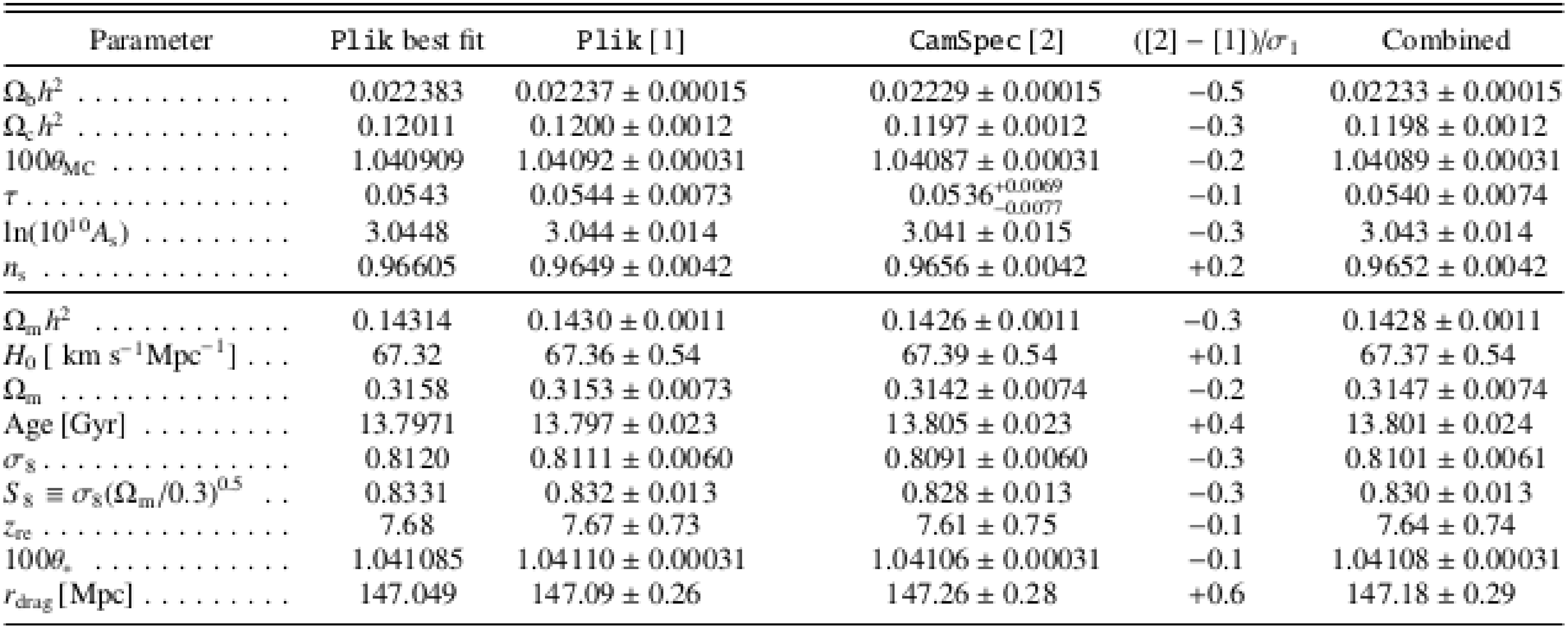
ΛCDM Model: 6 parameters that fit the CMB

$$\left\{ \underbrace{P_R(k_0),\quad n_s,}_{\text{Primordial spectrum}} \quad \underbrace{\Omega_B,\quad \Omega_M,\quad \Omega_\Lambda,}_{\text{Matter content}} \quad \tau_{reio} \right\}$$

Optical depth to LSS due to reionization

Baryons+CDM+DE

$(w_\Lambda = -1)$



Parameter	Plik best fit	Plik [1]	CamSpec [2]	$([2] - [1])/\sigma_1$	Combined
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015	0.02229 ± 0.00015	-0.5	0.02233 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012	-0.3	0.1198 ± 0.0012
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031	1.04087 ± 0.00031	-0.2	1.04089 ± 0.00031
τ	0.0543	0.0544 ± 0.0073	$0.0536^{+0.0069}_{-0.0077}$	-0.1	0.0540 ± 0.0074
$\ln(10^{10} A_s)$	3.0448	3.044 ± 0.014	3.041 ± 0.015	-0.3	3.043 ± 0.014
n_s	0.96605	0.9649 ± 0.0042	0.9656 ± 0.0042	$+0.2$	0.9652 ± 0.0042
$\Omega_m h^2$	0.14314	0.1430 ± 0.0011	0.1426 ± 0.0011	-0.3	0.1428 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}] . . .	67.32	67.36 ± 0.54	67.39 ± 0.54	$+0.1$	67.37 ± 0.54
Ω_m	0.3158	0.3153 ± 0.0073	0.3142 ± 0.0074	-0.2	0.3147 ± 0.0074
Age [Gyr]	13.7971	13.797 ± 0.023	13.805 ± 0.023	$+0.4$	13.801 ± 0.024
σ_8	0.8120	0.8111 ± 0.0060	0.8091 ± 0.0060	-0.3	0.8101 ± 0.0061
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$ . .	0.8331	0.832 ± 0.013	0.828 ± 0.013	-0.3	0.830 ± 0.013
z_{re}	7.68	7.67 ± 0.73	7.61 ± 0.75	-0.1	7.64 ± 0.74
$100\theta_*$	1.041085	1.04110 ± 0.00031	1.04106 ± 0.00031	-0.1	1.04108 ± 0.00031
r_{drag} [Mpc]	147.049	147.09 ± 0.26	147.26 ± 0.28	$+0.6$	147.18 ± 0.29

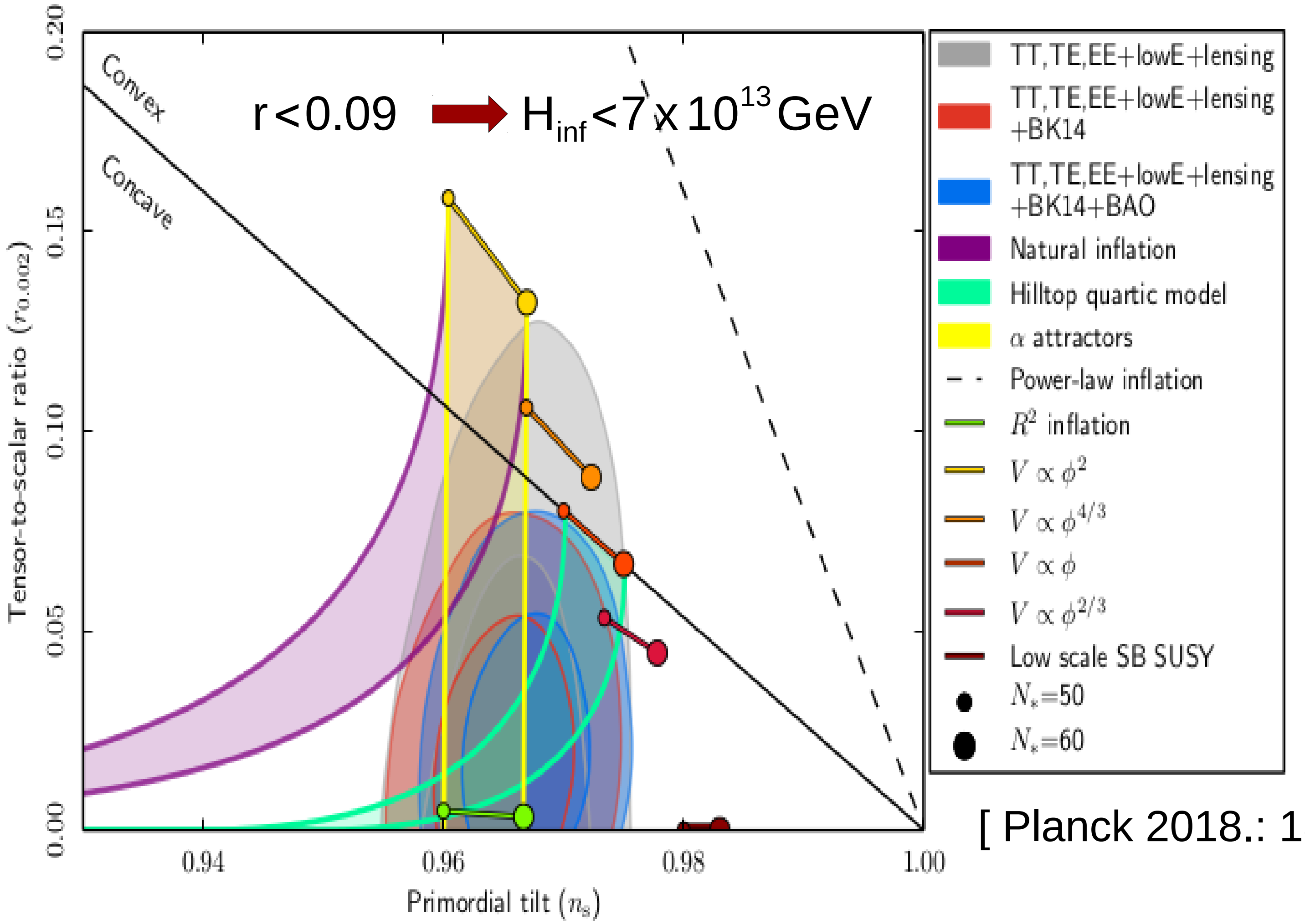
[PLANCK (2018)]

https://www.cosmos.esa.int/web/planck

Primordial spectrum: ~adiabatic, ~scale-invariant, gaussian?, tensors?

$$P_R = P_R(k_0)(k/k_0)^{n_s - 1} \qquad k_0 = 0.05\,\mathrm{Mpc}^{-1}$$

Tensor-to-scalar Ratio: $r = P_T / P_R \qquad P_R = 2.2 \times 10^{-9}$



$r < 0.09 \Rightarrow H_{inf} < 7 \times 10^{13}\,\mathrm{GeV}$

[Planck 2018.: 1807.06211]

BICEPS & KECK & PLANCK (2018): $r_{0.05} < 0.06$ [arXiv:1810.05216]

Primordial spectrum: $P_R = P_R(k_0)(k/k_0)^{n_s - 1 + \frac{1}{2}\alpha_s \ln k/k_0 + \cdots}$ $k_0 = 0.05\,\mathrm{Mpc}^{-1}$

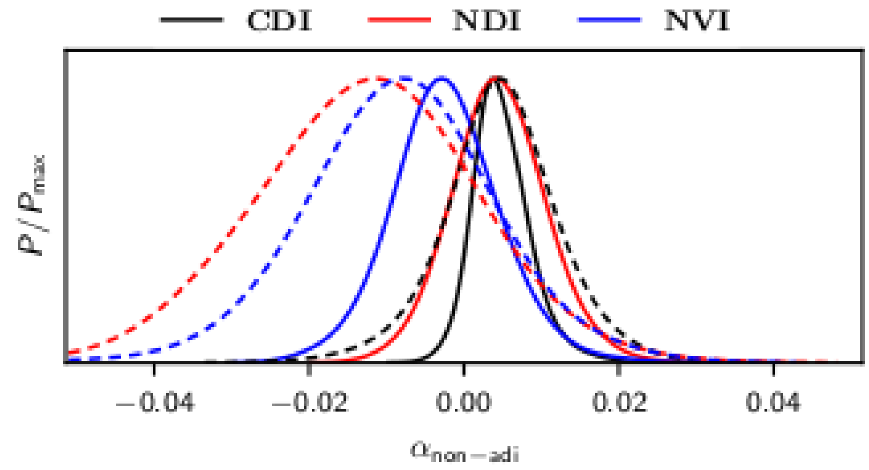
adiabatic, gaussian, ~scale-invariant spectrum

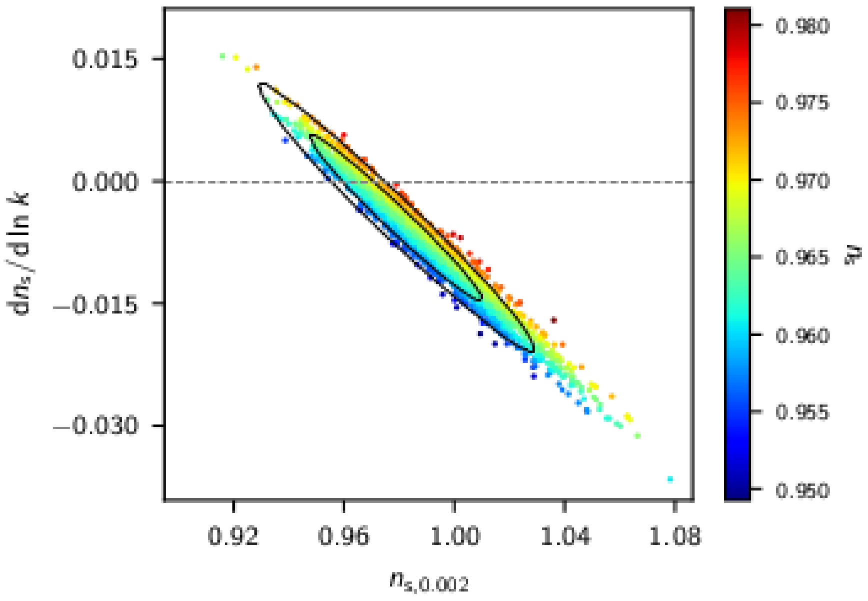
No evidence for:
isocurvature modes, non-gaussianity, or <u>running of the spectral index</u>

$[f_{NL} = 2.5 \pm 5.7]$

$\alpha_s = -0.007 \pm 0.013,$ $r_{0.002} < 0.072$

$[n_t = -r/8 < 0]$

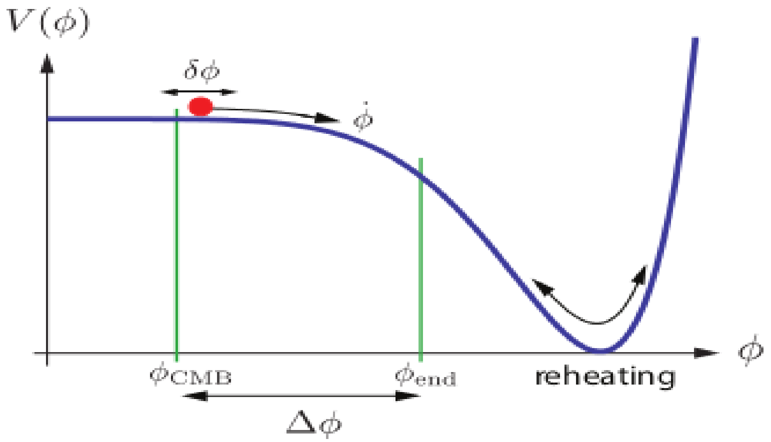




[Planck 2018.: 1807.06211]

Which inflationary potential? : Particle Physics model?

$$V(\phi_i,\dots)=\underbrace{V_{\Delta N_e=10}(\phi_i)}_{\text{Primordial spectrum}}+\underbrace{V_{end}(\phi_i,\dots)}_{\text{End of inflation}}+\underbrace{V_{reh}(\phi_i,\dots)}_{\text{Inflation} \Rightarrow \text{Radiation}}$$

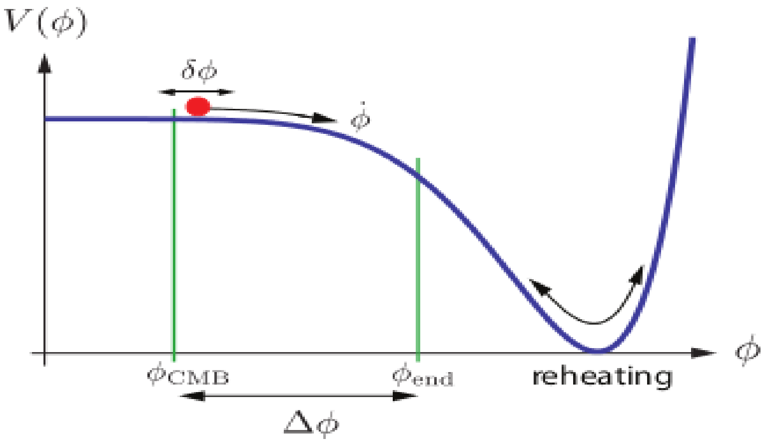


J. Martin, C. Ringeval, & Vennin, arXiv: 1303.3787: “Encyclopedia Inflationaris”

(~ 100 models)

Which inflationary potential? : Particle Physics model?

$$V(\phi_i,\ldots)=\underbrace{V_{\Delta N_e=10}(\phi_i)}_{\text{Primordial spectrum}} + \underbrace{V_{\text{end}}(\phi_i,\ldots)}_{\text{End of inflation}} + \underbrace{V_{\text{reh}}(\phi_i,\ldots)}_{\text{Inflation} \rightarrow \text{Radiation}}$$



So far, no signs of new physics at the LHC!

J. Martin, C. Ringeval, & Vennin, arXiv: 1303.3787: “Encyclopedia Inflationaris”

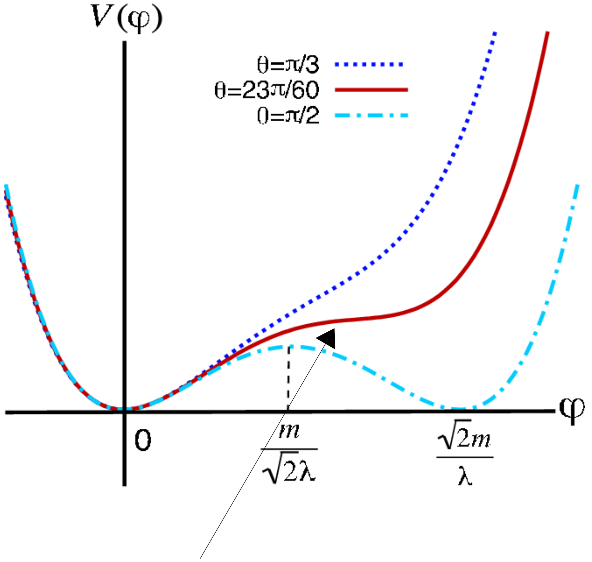
(~ 100 models)

- Simple monomials models $V(\phi)=V_0(\phi/m_P)^p$ rule out for p>2

$$n_s \simeq 1-\frac{2(p+2)}{4N_e+p}, \qquad r \simeq \frac{16p}{4N_e+p}$$

(minimal kinetic + minimal coupling to gravity)

- Adding more terms to the potential can save the model: “Polichaotic models”



““Plateau” : lower H_*

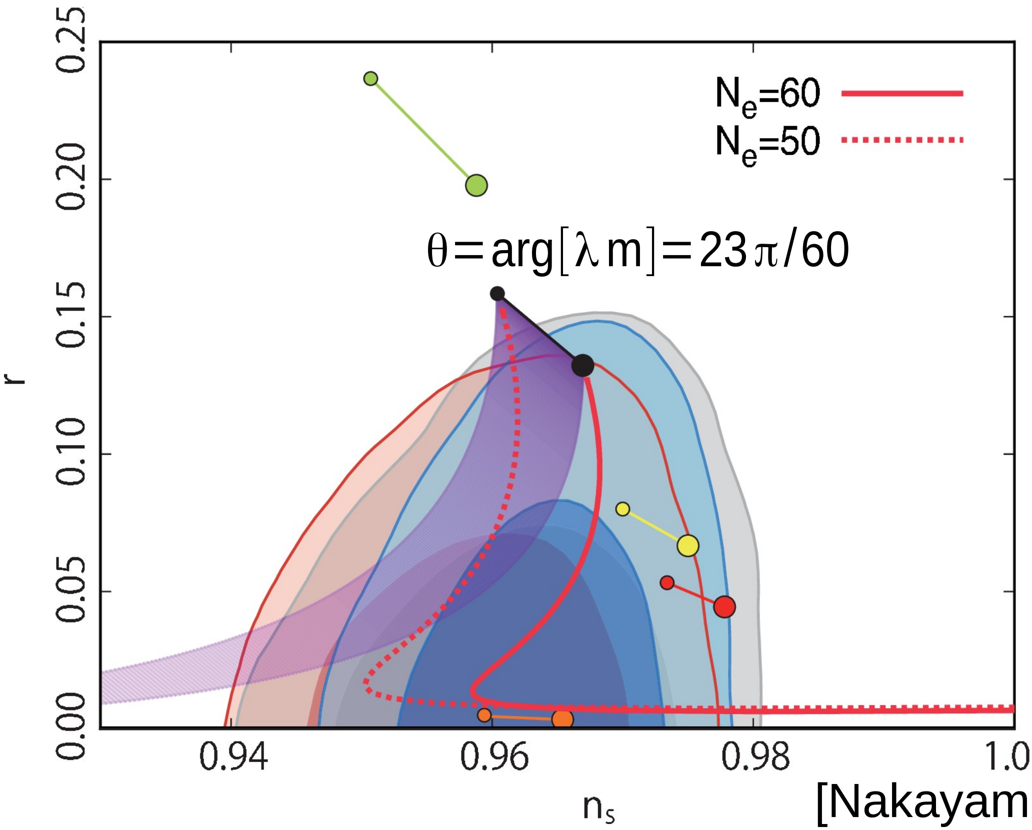
$$r \sim \frac{H^2/m_P^2}{P_R} < 0.1$$

$$m \sim 10^{13}\ \text{GeV}$$

$$\lambda^2 \sim 10^{-14}$$

$$V(\phi)=\frac{1}{2}m^2\phi^2+\frac{1}{4}\lambda^2\phi^4-\frac{1}{\sqrt{2}}m\lambda\sin\theta\phi$$

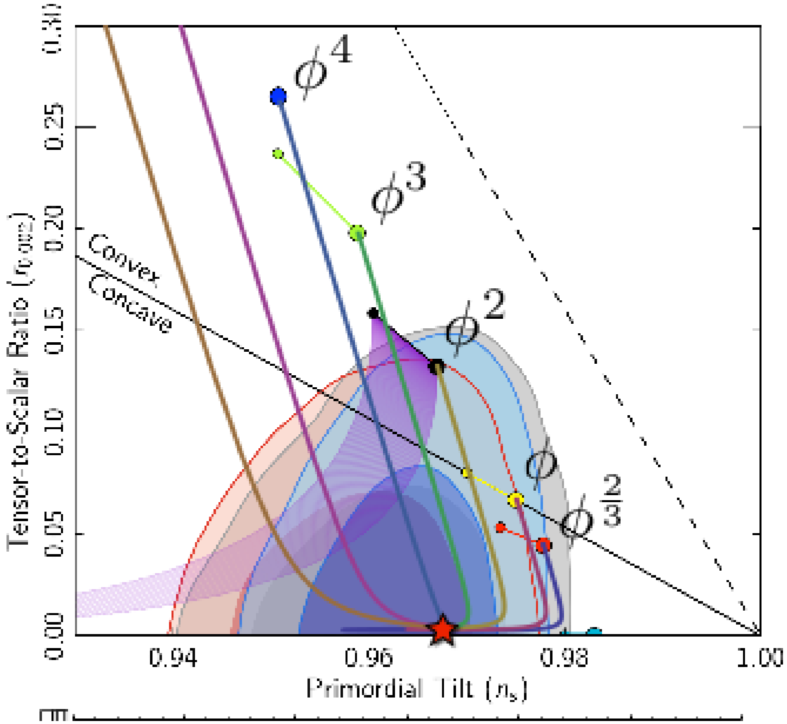
(Sugra + shift sym. + W= X(m Φ+ λ Φ^2+...)



[Nakayama et al. 1303.7315]

“Starobinsky model” ⟷ Non-minimal coupling to gravity

[Kallosh, Linde, Roest, 1310.3950]



$$n_s \simeq 1 - \frac{2}{N_e}, \qquad r \simeq \frac{12}{N_e^2}$$

Non-minimal coupling: Jordan frame

$$L_J = \sqrt{-g}\left(\frac{\Omega(\varphi)}{2}R - \frac{1}{2}(\partial\varphi)^2 - V_J(\varphi)\right)$$

Metric conformal transformation

$$\Omega(\varphi) = 1 + \xi f(\varphi)$$

$$L_E = \sqrt{-g}\left(\frac{m_P^2}{2}R - \frac{1}{2}\left(\Omega(\varphi)^{-1} + \frac{3}{2}(\partial\Omega(\varphi))^2\right)(\partial_\mu\varphi)^2 - \frac{V_J(\phi)}{\Omega(\varphi)^2}\right)$$

Non-minimal kinetic: Einstein frame

Large ξ limit + canonical kinetic term:

$$L_E = \sqrt{-g}\left(\frac{m_P^2}{2}R - \frac{1}{2}(\partial_\mu\varphi)^2 - V_0(1 - e^{-\sqrt{2\varphi/3}})^2\right)$$

[p=4 large ξ limit : $\xi \geq 0.1$]

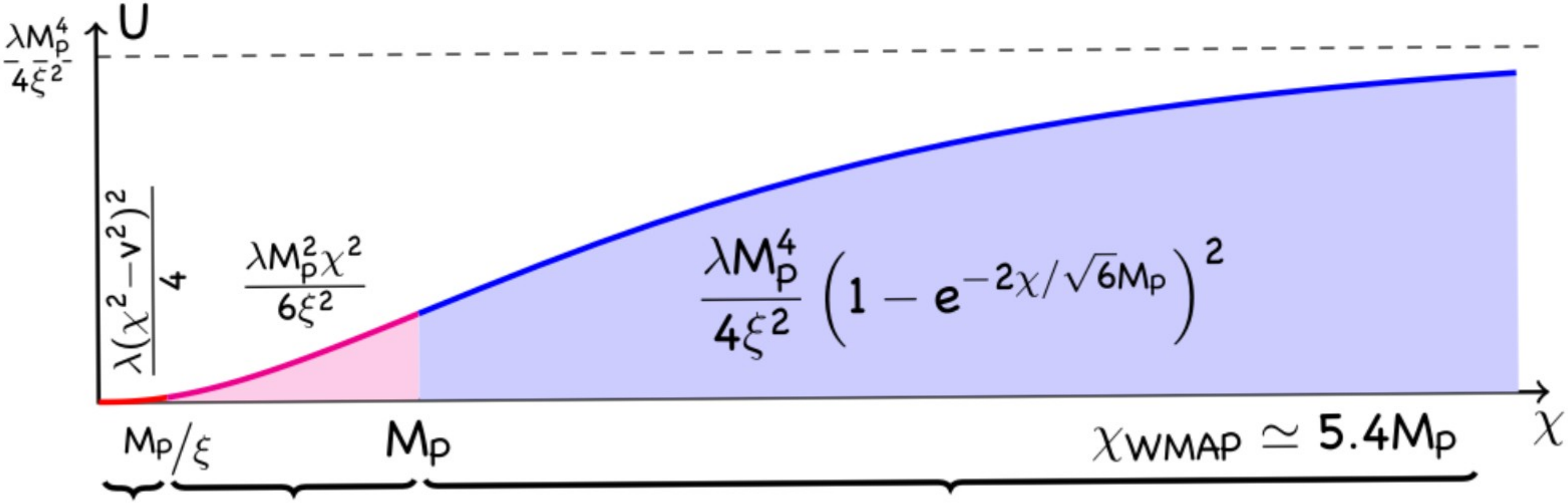
Universal attractor point for models
with spontaneously broken (super)conformal invariance

Sugra embedding: $K = -3\log(F[\Omega(\varphi), \varphi, S])$, $W = \lambda S f(\Phi)$

[Non-minimal kinetic term: $K_{\varphi\bar\varphi}\partial_\mu\varphi\partial^\mu\bar\varphi$]

Inflaton = Higgs

[Bezrukov & Shaposhnikov '08]



$$S=\int\sqrt{-g}\,d^4x\left(\frac{m_P^2}{2}R\;+\;\xi R\phi^2+\frac{1}{2}(\partial_\mu\phi)^2-V(\phi)\right)$$

$$V(\phi)=\frac{\lambda}{4}(\phi^2-v^2)^2 \xrightarrow{\text{Conformal transformation}} V(\chi)=\frac{\lambda_{eff}}{4}m_P^4\left(1-e^{-\sqrt{2/3}\chi/m_P}\right)$$

$\phi\simeq\chi\ll m_P/\xi$

$\lambda\simeq O(0.1)$

$$\boxed{n_S\simeq 0.97,\quad r\simeq 0.003}$$

$\chi\gg m_P/\xi$

$\lambda_{eff}\simeq 10^{-13}$ [COBE]

Reheating: decay into SM degrees of freedom !!

[Casadio, laFelice, Vacca '07; Enqvist, Meriniemi, Nurmi, '13; Figueroa, García-Bellido, Torrenti, '15]

Which inflationary potential? Particle Physics model?

$$V(\phi_i,\ldots)=\underbrace{V_{\Delta N_e=10}(\phi_i)}_{\textbf{Primordial spectrum}} + \underbrace{V_{end}(\phi_i,\ldots)}_{\textbf{End of inflation}} + \underbrace{V_{reh}(\phi_i,\ldots)}_{\textbf{Inflation} \rightarrow \textbf{Radiation}}$$

The inflaton must couple to other species:
gravitational reheating inconsistent
with BBN constraints

How the universe thermalize?

Reheating T?

Baryogenesis? “Relics” ?

“stiff” (w > 1/3) reheating amplifies the
spectrum of primordial gravity waves (radiation)
violating the bound on extra relativistic dof during BBN

[D. Figueroa & E. H Tanin 1811.04093]

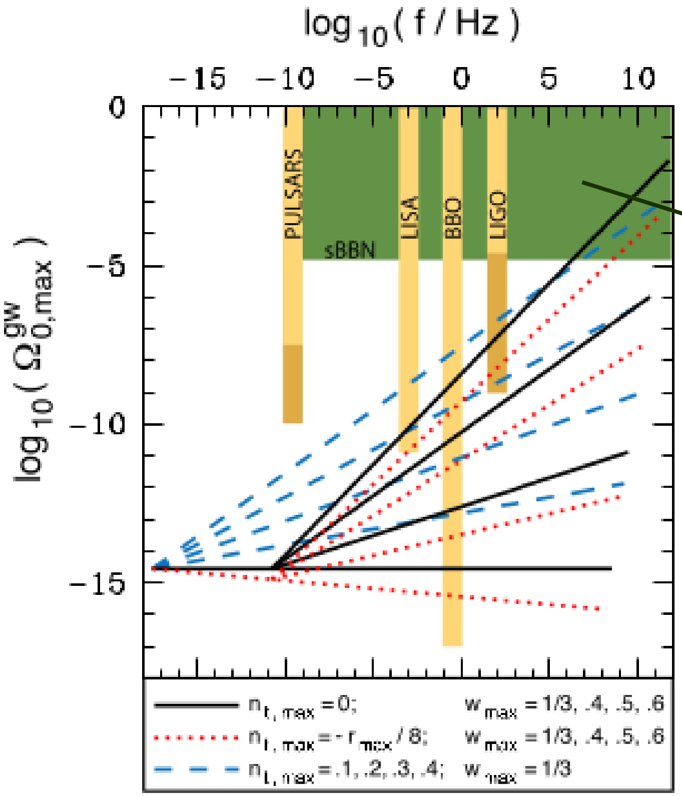
- **Gravitational reheating:** some light dof are excited during inflation and gives rise to radiation, subdominant at the end of inflation $\rho_\phi(t_{end}) \gg \rho_{rad}(t_{end})$

[Ford PRD35 '87; Spokoiny PLB215 '93]

- **"stiff" reheating:** after inflation, inflaton energy density must decrease faster than radiation $\rho_\phi \propto (a_{end}/a(t))^{3(1+w)}, \quad w>1/3$

- Radiation must dominate before BBN $w>0.57$

- Primordial GW are amplified during a "stiff" period



$$\Omega_{GW}(k) = 4.2x\,10^{-2} P_R(k_0)^2 \left(\frac{k}{k_0}\right)^{n_T} r_0 \left(\frac{a_{eq}}{a}\right)\left(\frac{k_{eq}}{k}\right)^{\alpha}$$

$\alpha<0, \qquad w>1/3$

BBN contraints: $\left(\frac{\rho_{tensors}}{\rho_{SM}}\right)_{BBN} < O(0.1)$

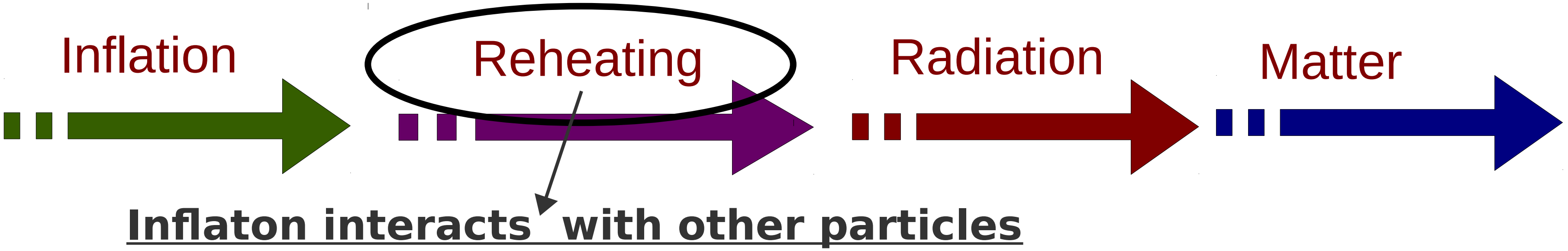
But:

$w>0.57 \Rightarrow \left(\frac{\rho_{tensors}}{\rho_{SM}}\right)_{BBN} > O(0.1)$

"stiff" eof
$w>1/3$

Blue tensors
$n_T>0$

[Boyle & Buonnano: arXiv 0708.2279]



Inflation → Reheating → Radiation → Matter

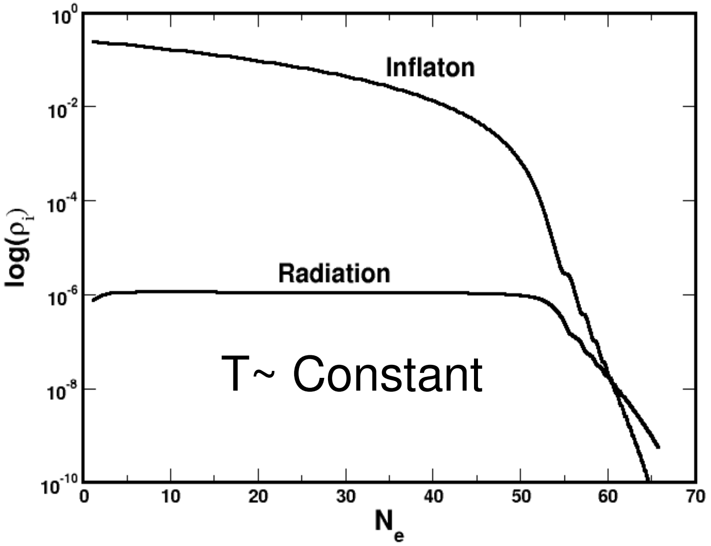
Inflaton interacts with other particles

Interactions with the cosmic plasma induce dissipation

$$\ddot{\varphi}+(3H+\Upsilon)\dot{\varphi}+V_{\varphi}=0$$

"Decay" into light dof= extra friction

"Warm" inflation



A (small) fraction of the vacuum energy is converted into radiation during inflation

$$\dot{\rho}_R+4H\rho_R=\Upsilon\dot{\varphi}^2$$ "Source term"

Slow-roll: $$\begin{cases}(3H+\Upsilon)\dot{\varphi}\simeq -V_{\phi}\\ 4H\rho_R\simeq\Upsilon\dot{\varphi}^2\end{cases}$$

Extra friction term: $Q=\Upsilon/(3H)$ (Particle production versus Hubble friction)

- $Q<<1, T<<H$ → Standard **C**old **I**nflation
- $Q< 1, T > H$ → **W**eak **D**issipative **R**egime

  Standard slow-roll

- $Q>1, T > H$ → **Str**ong **D**issipative **R**egime

Slow-roll : $3H(1+Q)\dot{\varphi}\simeq -V_{\varphi}(\varphi,T)$, $\rho_r \simeq \frac{3}{4} Q \dot{\varphi}^2$

$|\eta_{\varphi}|<(1+Q)$, $\epsilon_{\varphi}<(1+Q)$, $\beta_{\Upsilon}<(1+Q)$, $\delta_T<1$ **(Thermal corrections)**

$\beta_{\Upsilon}=m_P^2(\Upsilon_{\varphi} V_{\varphi})/(\Upsilon V)$ $\delta_T=\underline{T V_{T\varphi}}/V_{\varphi}$

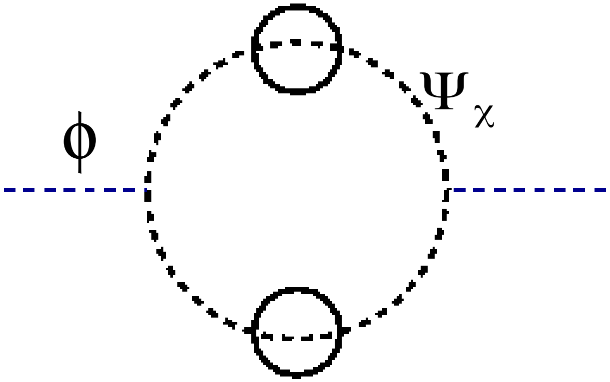
- **Q varies during inflation**
- Extra friction prolongs inflation → Smaller ϕ values
- Dissipation induces thermal inflaton fluctuations

Interactions & Dissipative coefficient

High T regime:

light scalar

$$L = \cdots - \frac{1}{2} m_\varphi^2 \varphi^2 - g \varphi \bar{\psi}_\chi \psi_\chi - h \sigma \bar{\psi}_\chi \psi_\chi + \cdots$$



light $m_\Psi = g\phi < H, T$, $g \ll 1$

$$\boxed{\Upsilon \simeq \frac{3}{1 - 0.34 \log h} \frac{g^2}{h^2} T}$$

Linear T coefficient

Adiabatic approximation:

$$T > H$$

$$\dot{\varphi}/\varphi, \quad H < \Gamma_\chi \simeq \frac{\pi}{512} h^4 \left(\frac{T}{H}\right)$$

Macroscopic

Microscopic

- Small g coupling to keep fermions light
- Not too small h because of adiabatic condition
- How to avoid thermal corrections to inflaton potential due to light fields?

Thermal potential: $$\Delta V_T = -\frac{\pi^2}{90} g_R T^4 + \frac{g^2 \varphi^2}{12} T^2 + \cdots$$

Berera, Gleiser &Ramos PRD'98; Yokoyama & Linde PRD '98

Little Higgs ⟷ Little inflaton

Naturalness problem in the SM (and inflation):

- Scalar field masses are not protected against quadratic radiative corrections by any sym. : why m_h = 125 GeV ? (why the inflaton is light $m_\phi < H$?)

(A) Susy : no. fermions = no. bosons

$$\Delta V_{T=0} \sim \Lambda^2\, \mathrm{STr}\, M^2 + \sum_{F,B} (-1)^{2s_i}(2s_i+1)\frac{M^4}{64\pi^2}\ln\frac{M^2}{Q^2}+\cdots$$

➡ $$\Delta V_T = -\frac{\pi^2}{90} g_R T^4 + \sum_{F,B}\frac{g_i^2\varphi^2}{12}T^2+\cdots$$ ➡ Thermal Higgs mass

(B) Little Higgs: Pseudo-Nambu Goldstone boson of a global symmetry

(m_h ~ soft breaking)

Cancellation of quadratic divergences occurs from particles of the same spin

➡ $$\Delta V_T = -\frac{\pi^2}{90} g_R T^4 + C\,T^2+\cdots$$ ➡ No thermal Higgs mass (high T)

[D. Kaplan & M. Schmaltz JHEP 0310; M. Schmaltz JHEP 0408]

Little warm inflation

High T regime:

Inflaton a PNGB of a broken U(1) symmetry + pair of fermions + exchange sym.

$$L=\cdots-gM\cos(\varphi/M)\bar{\psi}_1\psi_1-gM\sin(\varphi/M)\bar{\psi}_2\psi_2-h\sigma\sum_{i=1,2}(\bar{\psi}_i\psi_\sigma+\bar{\psi}_\sigma\psi_i)+\cdots$$

light Ψ: $gM < T < M$, $g<1$

Thermal potential:

$$\Delta V_T=-\frac{\pi^2}{90}g_R T^4+\underbrace{\frac{g^2M^2}{12}T^2}_{\text{No thermal mass for the inflaton}}+\frac{g^4(\varphi)M^4}{16\pi^2}\left(\log\frac{\mu^2}{T^2}-c_f\right)$$

Light dof

No thermal mass for the inflaton

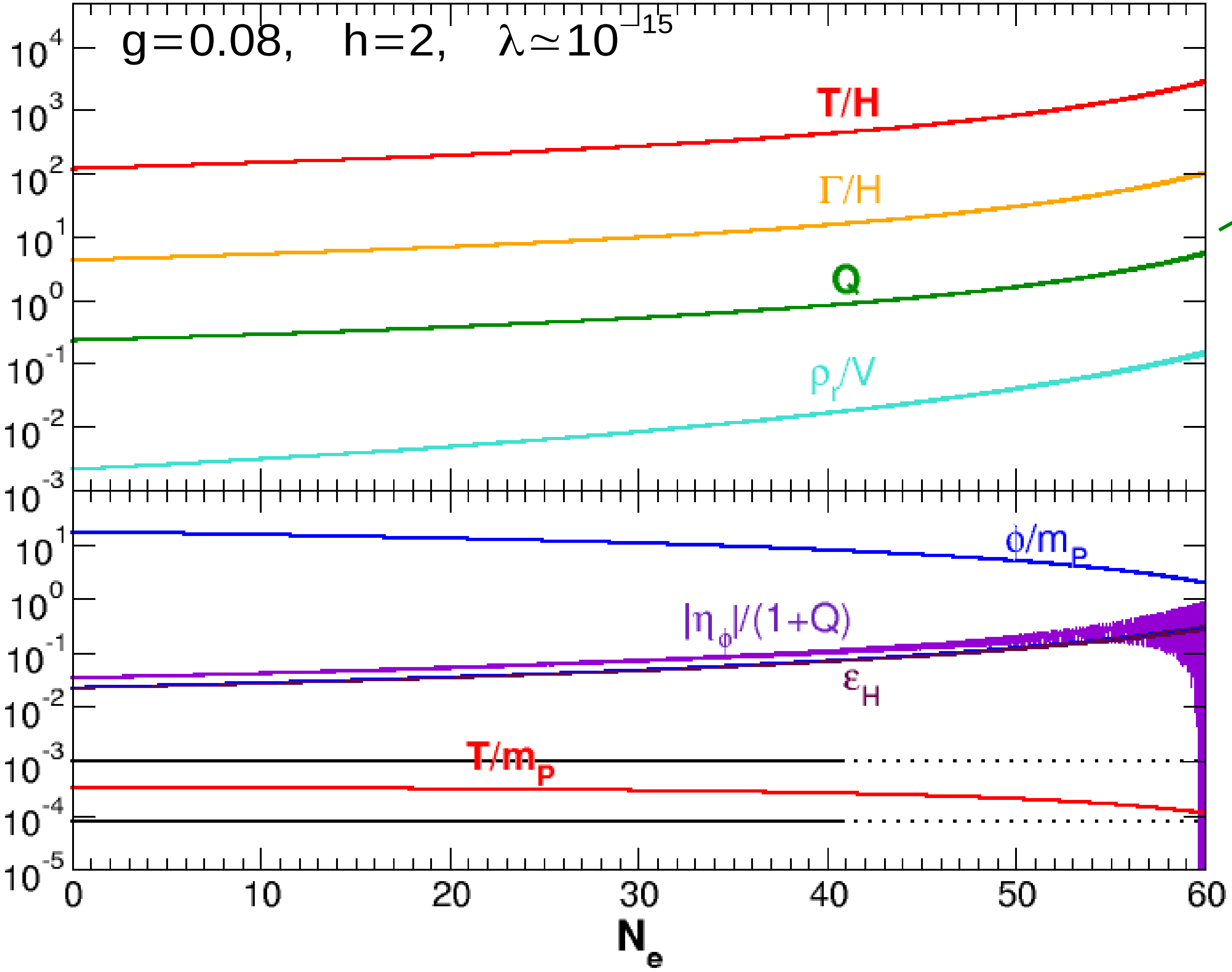
Total energy density:

$$\rho_T=\frac{1}{2}\dot{\varphi}^2+V(\varphi)+\rho_R \qquad \left[\rho_R=\Delta V_T-T\frac{d\Delta V_T}{dT}=\frac{\pi^2}{30}g_R(\varphi,T)T^4\right]$$

Background dynamics

Quartic potential: $V(\varphi)=\frac{\lambda}{4}\varphi^4$

$$\Upsilon=\frac{3}{1-0.34\log h}\frac{g^2}{h^2}T$$



Inflation ends in the strong dissipative regime

$\rho_\phi\simeq\rho_{rad}$

Radiation dominates

$\epsilon_H=-\frac{\dot{H}}{H^2}$

$M\simeq2\,x\,10^{15}\,GeV$

$gM<T<M$

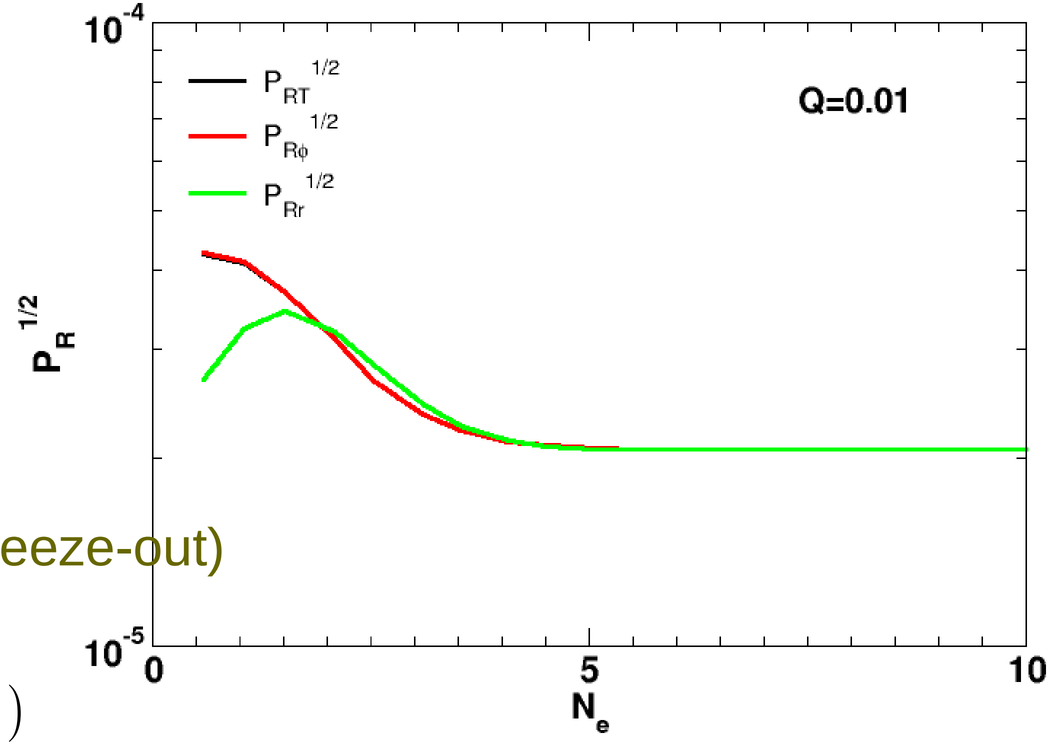
Fluctuations & primordial spectrum: coupled system

Weak dissipative regime (Q=Υ/H<<1) : field decoupled from radiation

$$\delta\ddot{\varphi}_k^{GI}+(3H+\Upsilon)\delta\dot{\varphi}_k^{GI}+(\frac{k^2}{a^2}+V_{\varphi\varphi})\delta\varphi_k^{GI}\simeq(2\Upsilon T)^{1/2}\hat{\xi}_k$$

$$P_{\delta\varphi}\simeq\frac{HT}{2\pi}\frac{Q}{\sqrt{1+4\pi Q/3}}$$

Primordial spectrum: $P_R\simeq\left(\frac{H}{\dot{\varphi}}\right)^2 P_{\delta\varphi}$



R is constant after horizon crossing (freeze-out)

$$P_R\simeq(P_R)_{Q=0}(\underbrace{1+2N}_{}+\frac{T}{H}\frac{4\pi Q}{\sqrt{1+4\pi Q/3}})$$

Dissipative processes may maintain a non-trivial distribution of inflaton particles:

$$N\simeq n_{BE}=(e^{k/aT}-1)^{-1}$$

Ramos, da Silva, 1302.3544; BG, Berera, Moss & Ramos, 1401.1149

Fluctuations & primordial spectrum: coupled system

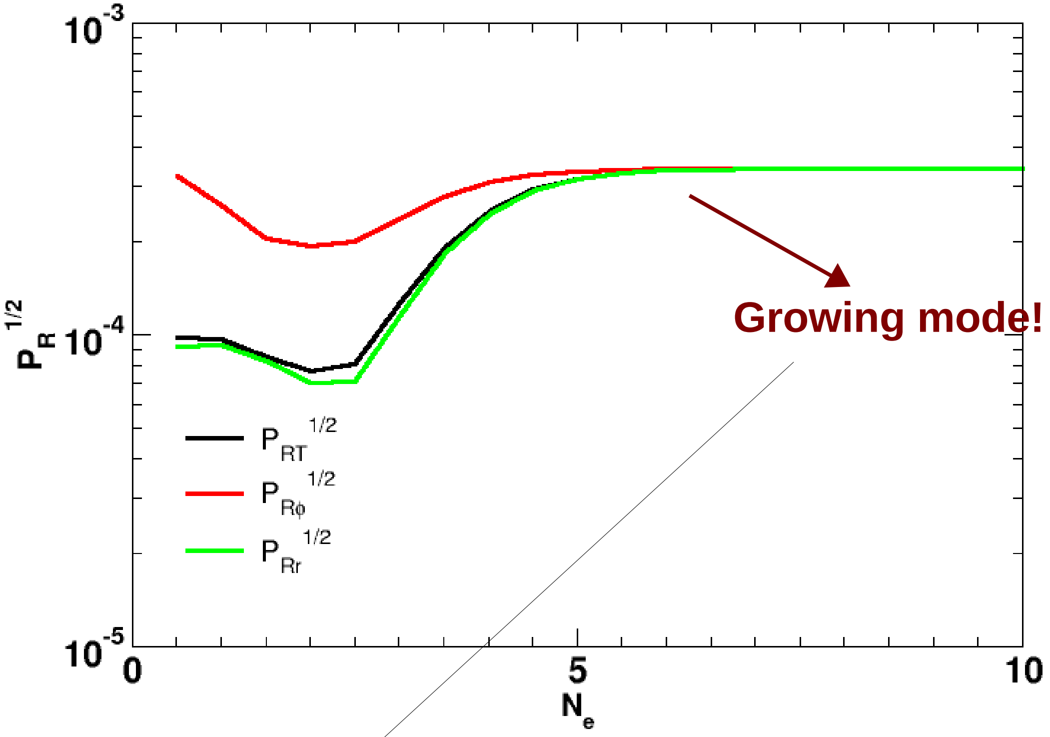
Strong dissipative regime ($Q=\Upsilon/H>1$) : coupled system

$$\delta\ddot{\varphi}_k^{GI}+(3H+\Upsilon)\delta\dot{\varphi}_k^{GI}+\dot{\varphi}\,\delta\Upsilon^{GI}+\left(\frac{k^2}{a^2}+V_{\varphi\varphi}\right)\delta\varphi_k^{GI}\simeq(2\Upsilon T)^{1/2}\hat{\xi}_k$$

Primordial spectrum:

$$P_R=\frac{h_\varphi}{h_T}P_{R_\varphi}+\frac{h_r}{h_T}P_{R_r}\simeq P_{R_r}\simeq P_{R_\varphi}, \qquad (h_i=\rho_i+p_i)$$

$Q=10$



Growing mode!

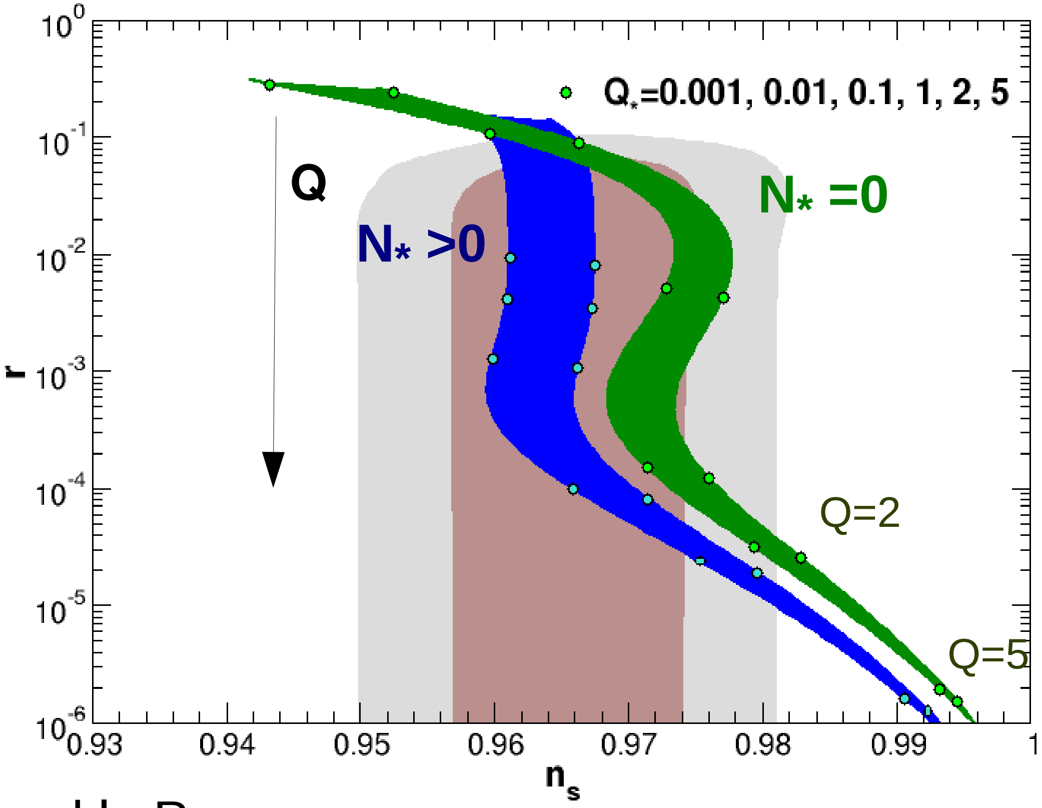
R is constant after horizon crossing

$$P_R\simeq\left(\frac{H}{\dot{\varphi}}\right)^2\left(\frac{H}{2\pi}\right)^2\left(1+2N+\frac{T}{H}\frac{4\pi Q}{\sqrt{1+4\pi Q/3}}\right)\times G[Q], \qquad Q=\Upsilon/(3H)$$

Blue tilted spectrum

Primordial spectrum: quartic chaotic model

$$V(\varphi)=\frac{\lambda}{4}\varphi^{4}, \quad N_e=50-60$$



$$n_s-1=\frac{d\ln P_R}{dN_e}=(n_s-1)_N+(n_s-1)_{diss}+(n_s-1)_G\,, \quad (n_s-1)_G>0$$

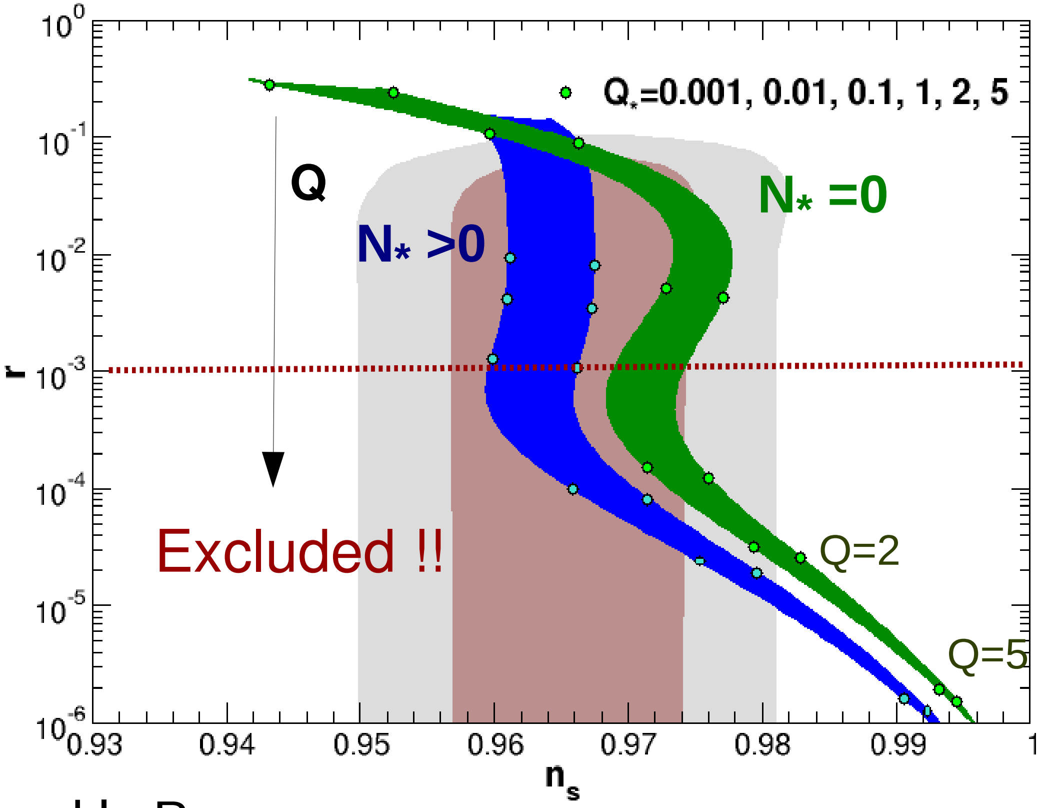
$$r\simeq\frac{16\,\epsilon_\phi}{(1+2\mathcal{N}+\Delta_Q)\,G[Q]}\leq 16\,\epsilon_\varphi$$

Quartic:

$$\mathcal{N}\neq 0,\ Q<1:\ n_s\simeq 1-2/N_e\,, \quad r\simeq 16\,\epsilon_\varphi\left(\frac{H}{T}\right)\ll 0.1$$

Primordial spectrum: quartic chaotic model

$$V(\varphi)=\frac{\lambda}{4}\varphi^{4,}\quad N_e=50-60$$



Q < 0.1, r> 0.001

Parameter space constraint:
gM/T<1, M/T>1

$$n_s-1=\frac{d\ln P_R}{dN_e}=(n_s-1)_N+(n_s-1)_{diss}+(n_s-1)_G\,,\quad (n_s-1)_G>0$$

$$r\simeq\frac{16\epsilon_\phi}{(1+2\mathcal{N}+\Delta_Q)G[Q]}\le 16\epsilon_\varphi$$

Quartic:

$$\boxed{\mathcal{N}\neq 0,\ Q<1\ :\ n_s\simeq 1-2/N_e\,,\quad r\simeq 16\epsilon_\varphi\left(\frac{H}{T}\right)\ll 0.1}$$

Summary

- Planck 2015: the most precise cosmological data up today

6 parameters to fit the Universe: ΛCDM

$$\left\{ P_R(k_0), \quad n_s, \quad \Omega_B, \quad \Omega_M, \quad \Omega_\Lambda, \quad \tau_{reio} \right\}$$

[Some tension with SNIa (H_0) & CFHTLenS (σ_8).....]

- Primordial spectrum: gaussian? Adiabatic? Tensors?

Inflation provides a solution to the standard cosmological problems, and a causal mechanism for the primordial spectrum

Many models still consistent with observations (plateau-like potentials?)

Detection of primordial tensors may help with model selection

Alternatives: loop quantum cosmology? String gas cosmology ($n_T>0$)?...

Reheating? Thermalization of the Universe after inflation?

Summary

- Dissipative effects due to decaying fields can be relevant during inflation, and modify the inflationary predictions

- "High T" regime for dissipation (light fermion ψ decaying into light dof): $\Upsilon = C_T T$

Inflaton a PNGB of a broken U(1) symmetry + pair of fermions + exchange sym.

Light fermions: gM < T + thermal corrections under control + minimal matter content

$\boxed{\lambda\phi^4 \text{ compatible with data, } Q^* \sim 0.01\text{-}0.1,\ r \sim 0.1\text{-}10^{-3}}$

- Non-gaussianity compatible with observations for both weak and strong dissipative regime, with a characteristic shape

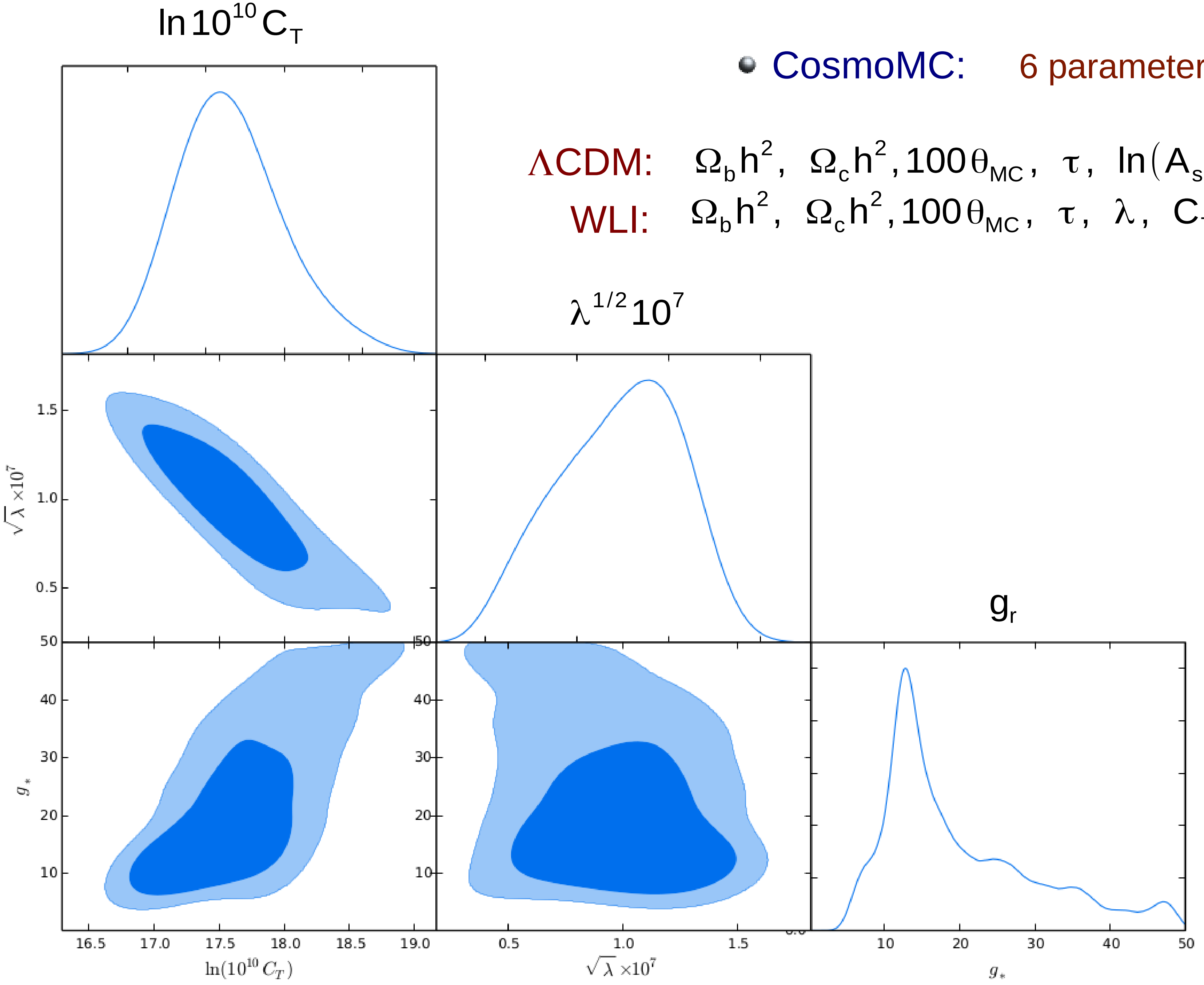
Little warm inflation & CMB data:

non thermal inflaton

- CosmoMC: 6 parameters fit

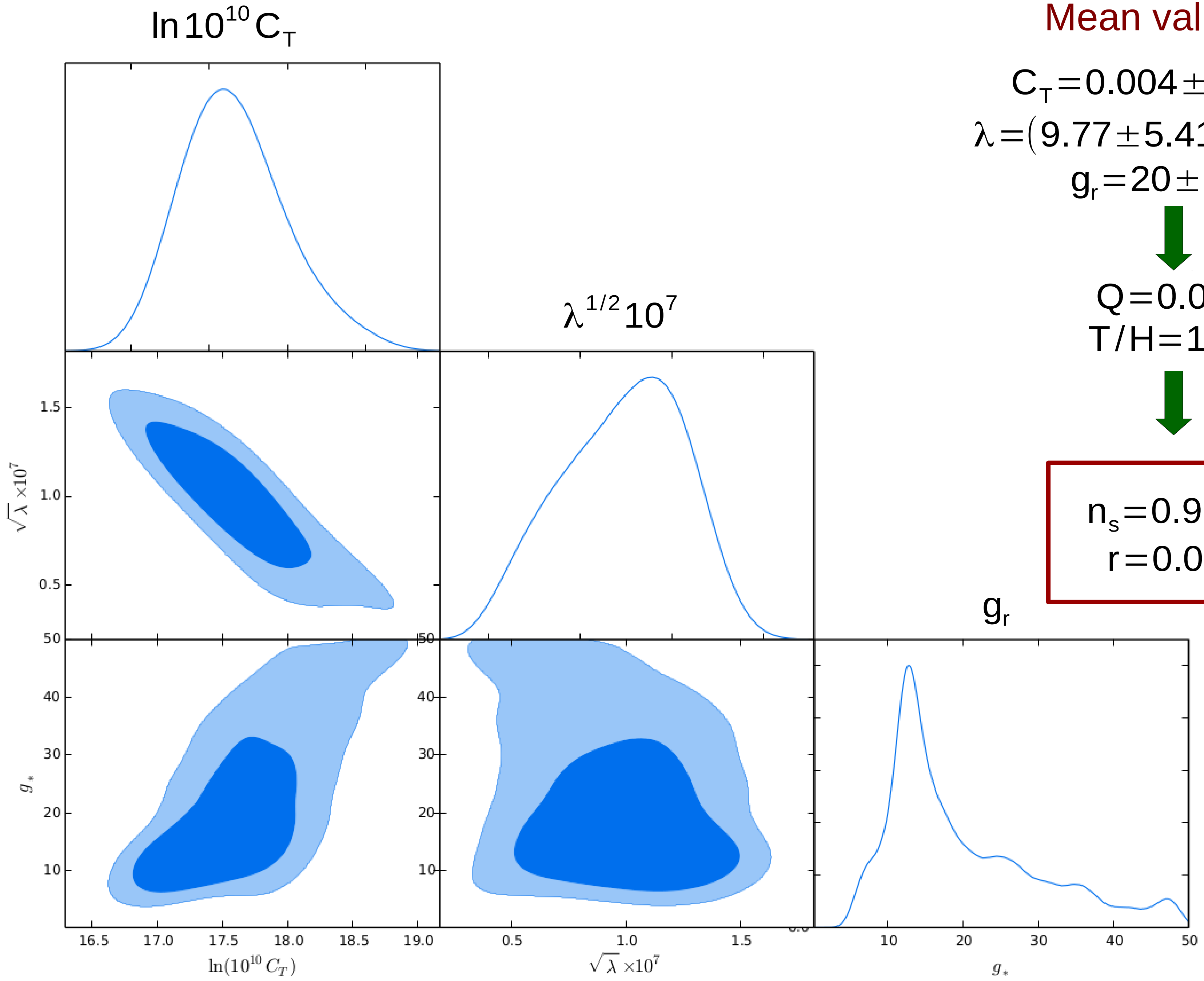
ΛCDM: $\Omega_b h^2$, $\Omega_c h^2$, $100\,\theta_{MC}$, τ, $\ln(A_s \times 10^{10})$, n_s, r,

WLI: $\Omega_b h^2$, $\Omega_c h^2$, $100\,\theta_{MC}$, τ, λ, C_T, g_r



Little warm inflation & CMB data:

non thermal inflaton



Mean values

$C_T = 0.004 \pm 0.002$

$\lambda = (9.77 \pm 5.41) \times 10^{-15}$

$g_r = 20 \pm 10$

$Q = 0.019$

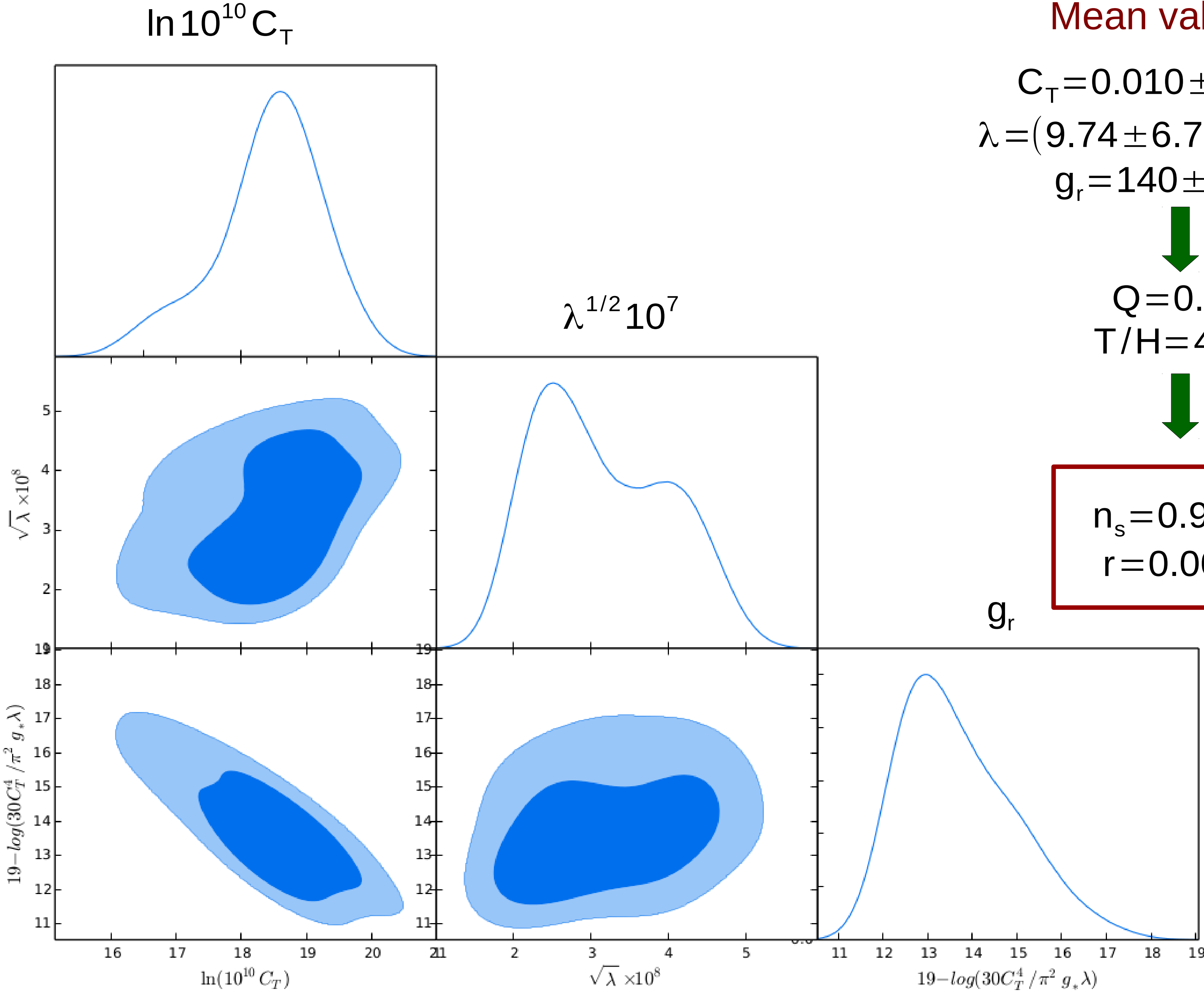
$T/H = 19.3$

$n_s = 0.974$

$r = 0.06$

Little warm inflation & CMB data:

thermal inflaton



Mean values

$C_T = 0.010 \pm 0.008$

$\lambda = (9.74 \pm 6.78) \times 10^{-16}$

$g_r = 140 \pm 488$

$Q = 0.14$

$T/H = 40.7$

$n_s = 0.965$

$r = 0.006$

Warm inflation &Non-gaussiantiy : T dependent diss. coefficient

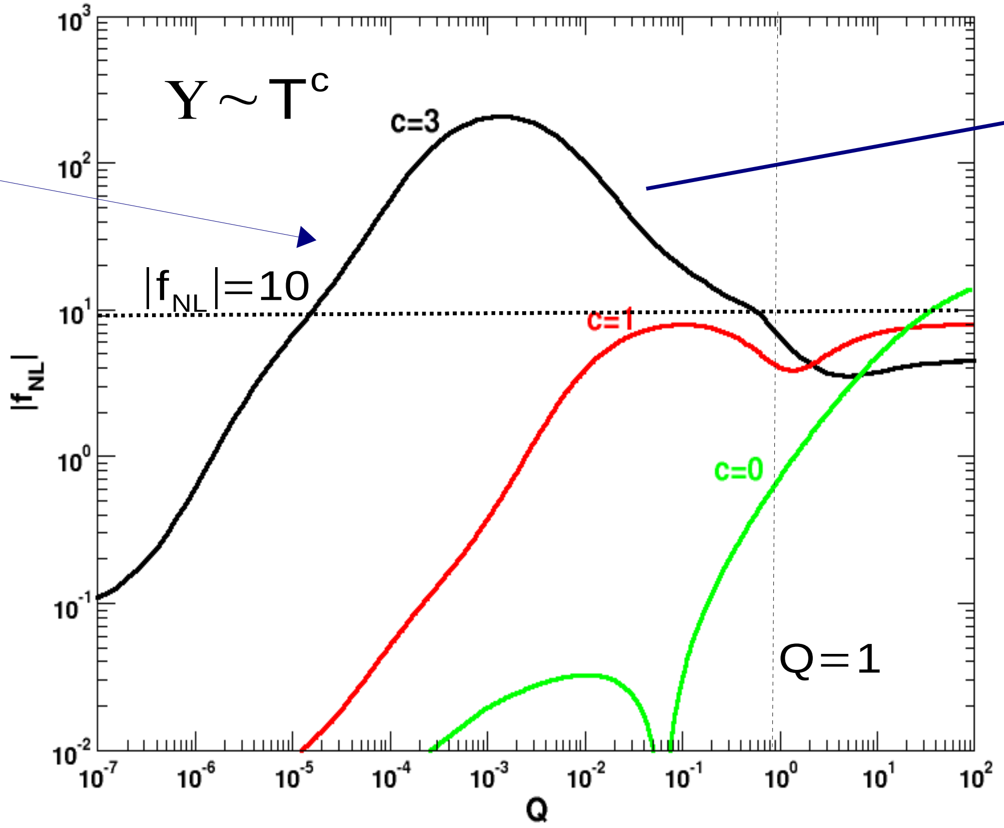
- **Bispectrum:** $B_R(k_1, k_2, k_3) = \sum_{cyc} \langle R_1(k_1) R_1(k_2) R_2(k_3) \rangle = A_B(k) \bar{B}(k_1, k_2, k_3)$ → **shape**

$$f_{NL} = \frac{18}{5} \frac{A_B(k)}{P_R(k)^2}$$

Non-linear parameter

$$P_R \simeq ((P_R)_{vac} + (P_R)_{diss}) F[Q]$$

$(P_R)_{vac} > (P_R)_{diss}$



$(P_R)_{vac} < (P_R)_{diss}$

(Planck: f_{NL}<~O(10))

f_{NL}^{local} = 2.7 +- 5.8 $(k_3 << k_1 \sim k_2)$

f_{NL}^{equil} =-42 +- 75 $(k_3 \sim k_1 \sim k_2)$

f_{NL}^{warm} = 4 +- 33

[BG, Berera, Moss, Ramos '14]