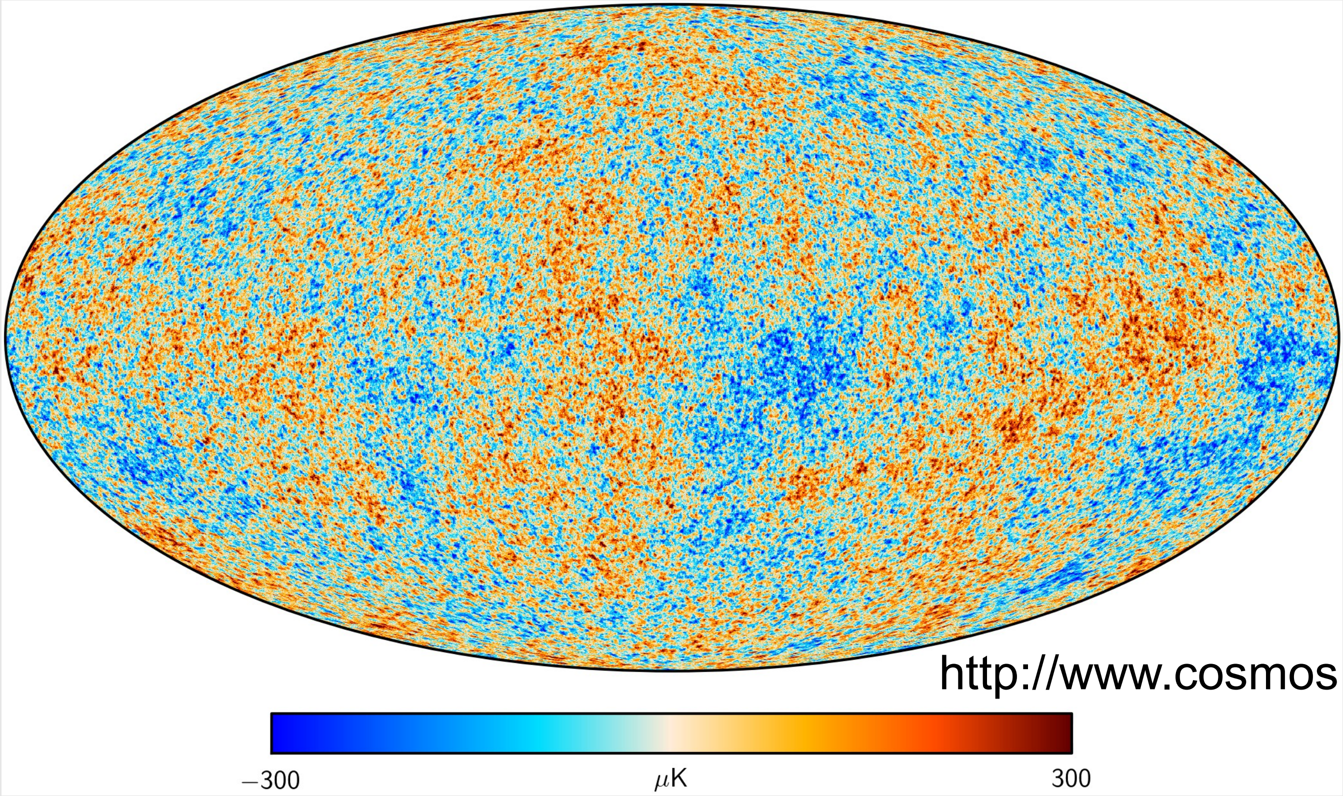
Cosmology: Theory

(PLANCK and all that)



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

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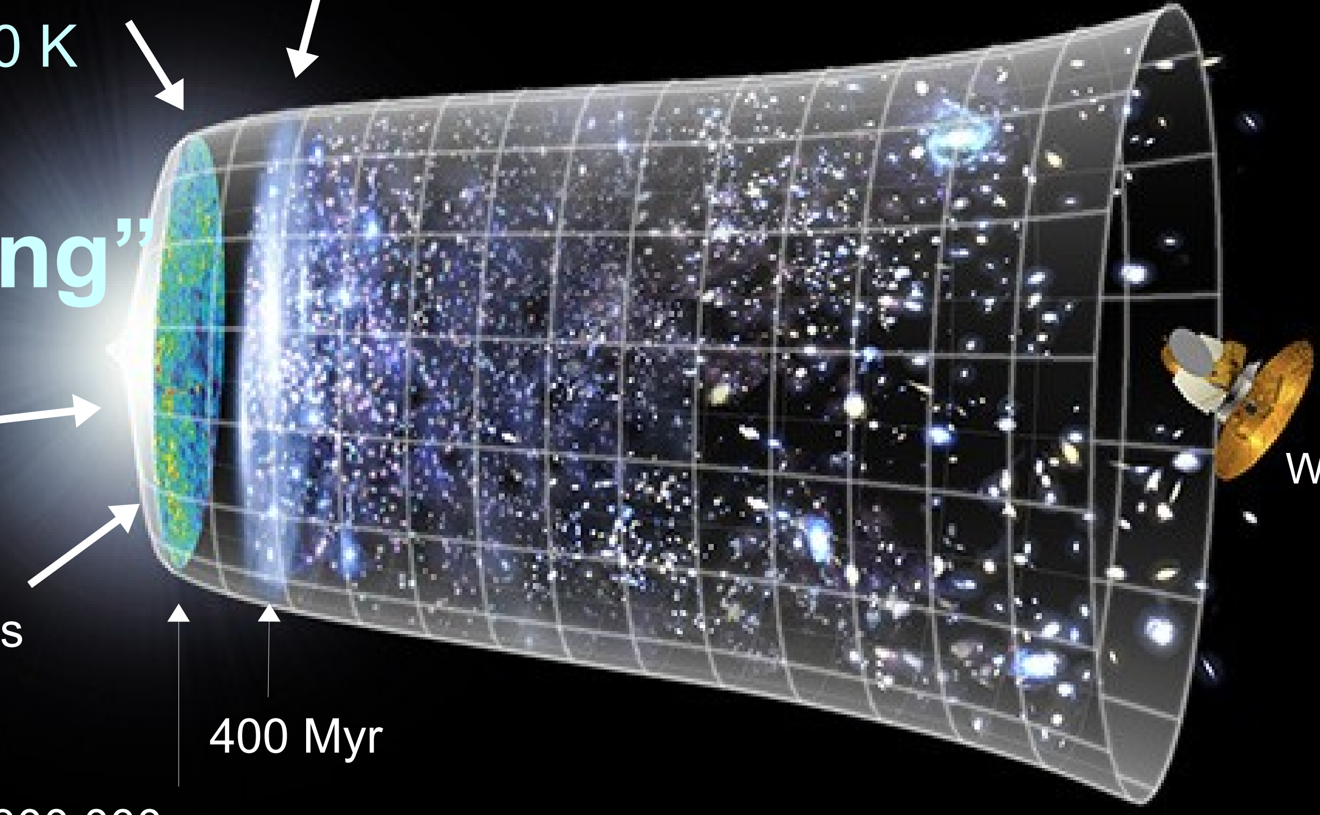
The expanding Universe



First stars

CMB

3000 K

Galaxies, ...

“Big Bang”

Inflation:
before BBN

WMAP

BBN
3 minutes

400 Myr

300.000 yr

13.7 Gyr

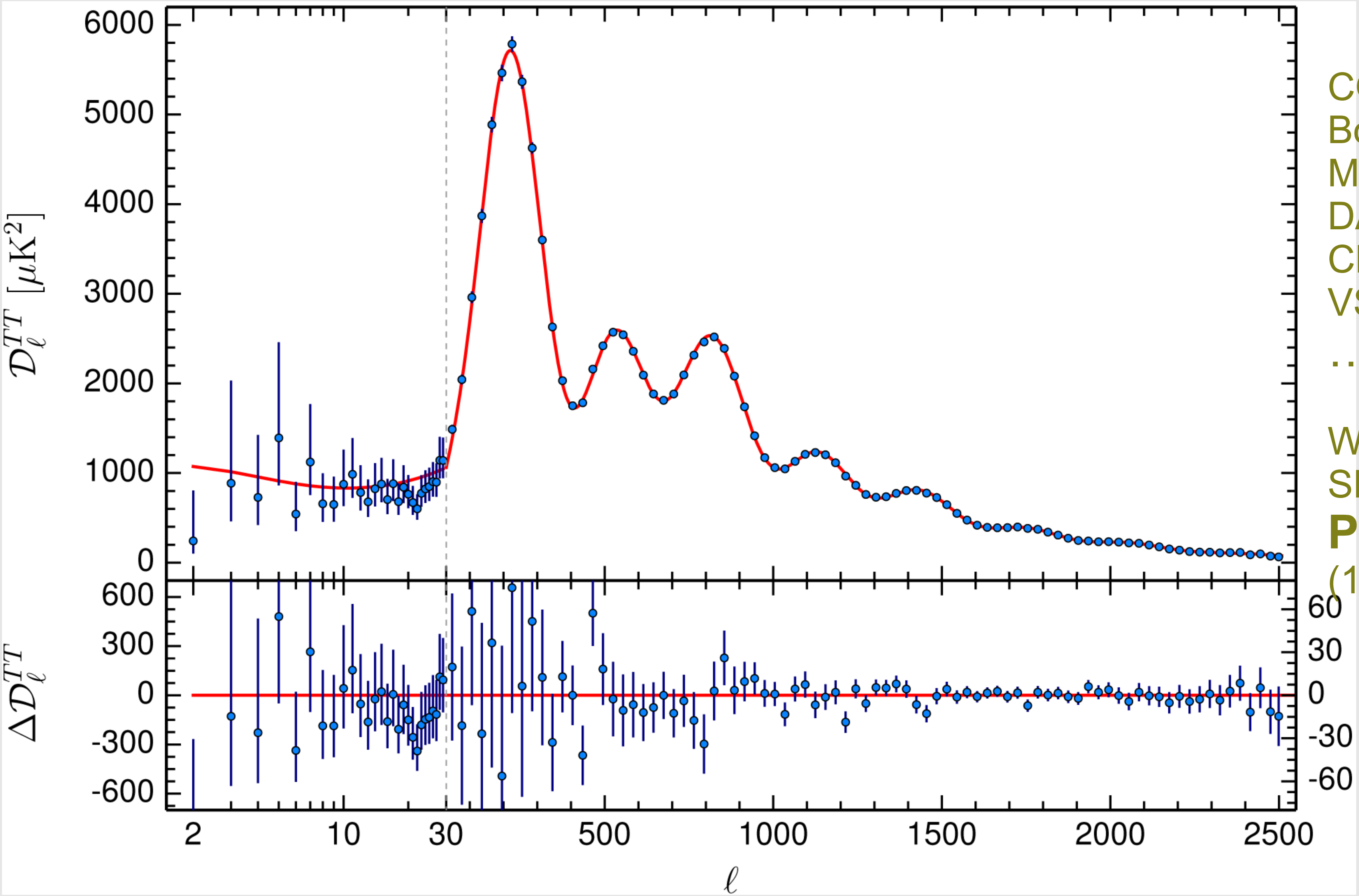
T ~ 1/a

2.73 K

NASA/WMAP Science Team

Cosmic microwave background radiation (CMB)

Spectrum of T fluctuations



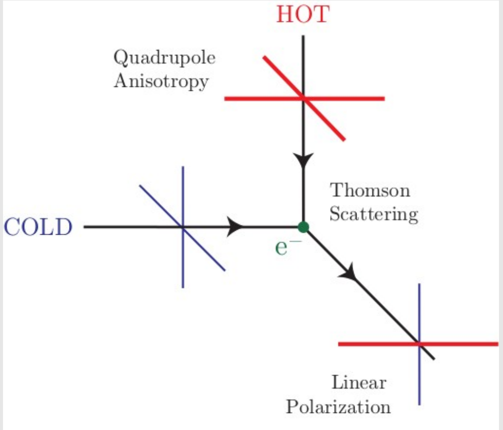
COBE (1992)
Boomerang
Maxima
DASI
CBI
VSA
.....

WMAP
SPT
PLANCK
(14/05/09)

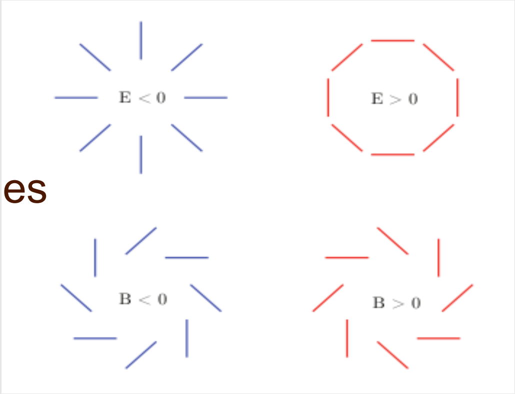
[Planck collab.: astro-ph/1502.01589]

Polarization &Tensors (primordial GW)

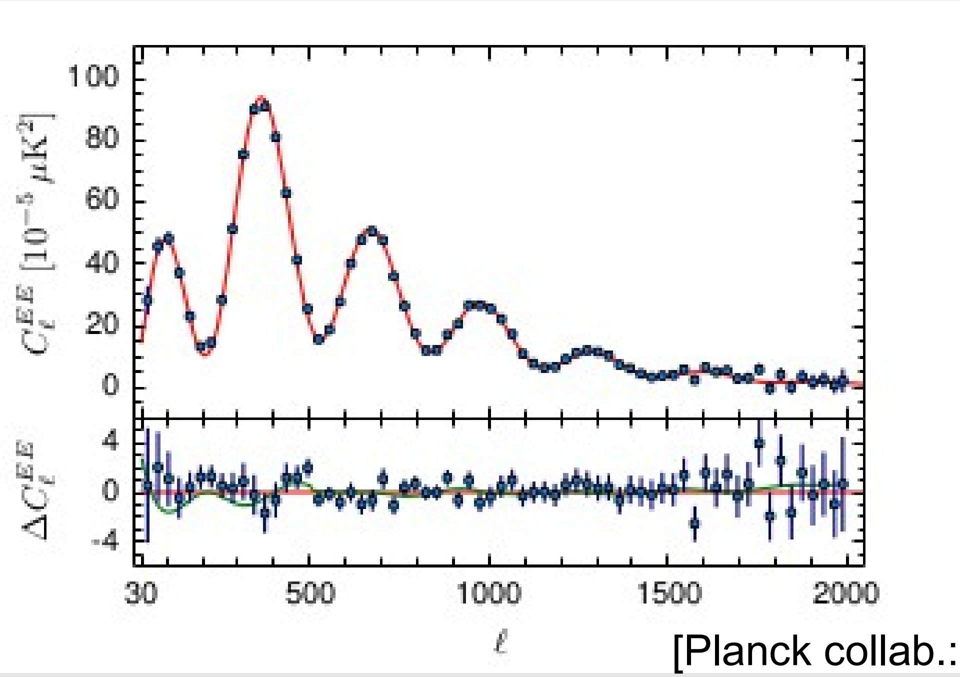
Thompson scattering polarizes linearly the spectrum (DASI 2002)

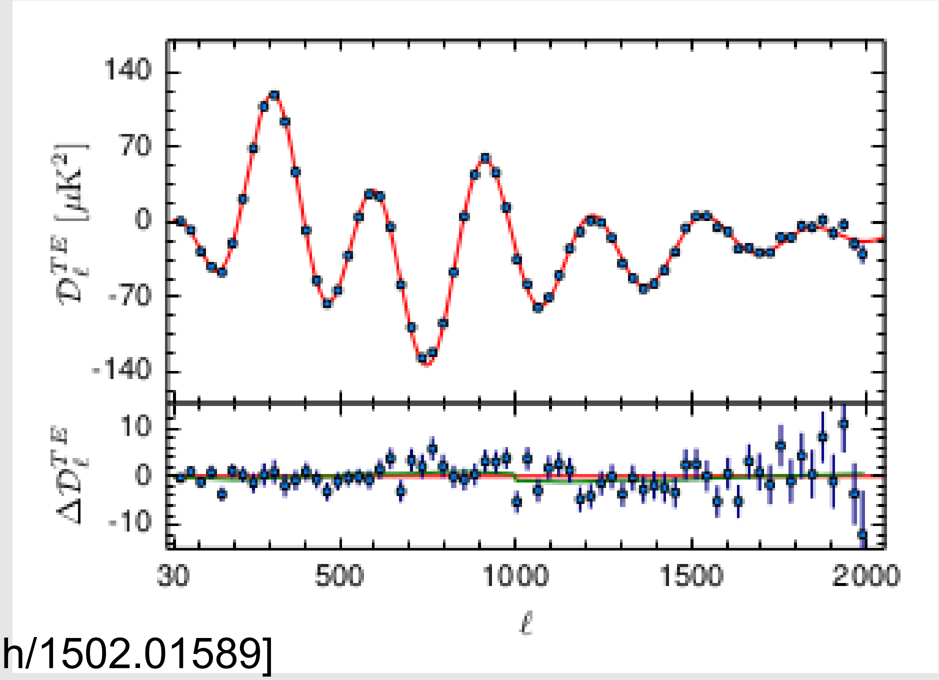


Polarization: E & B modes



Spectra: C^{TT}, C^{EE}, C^{TE} , C^{BB} Tensors?

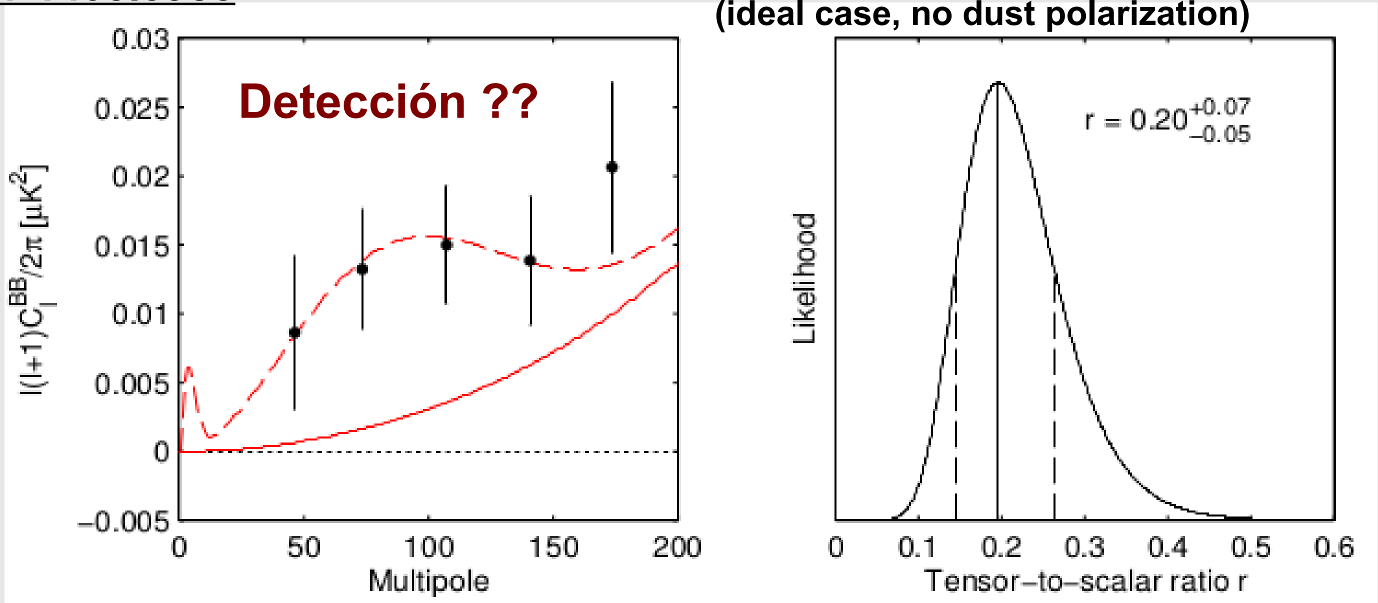




[Planck collab.: astro-ph/1502.01589]

BICEP2 & PLANCK

BICEP2: arXiv 1403.3985



Detección ??

(ideal case, no dust polarization)

$$r = 0.16^{+0.06}_{-0.05} ???$$

So far, only galactic dust: **$r_{0.05} < 0.12$ (95 % CL)**

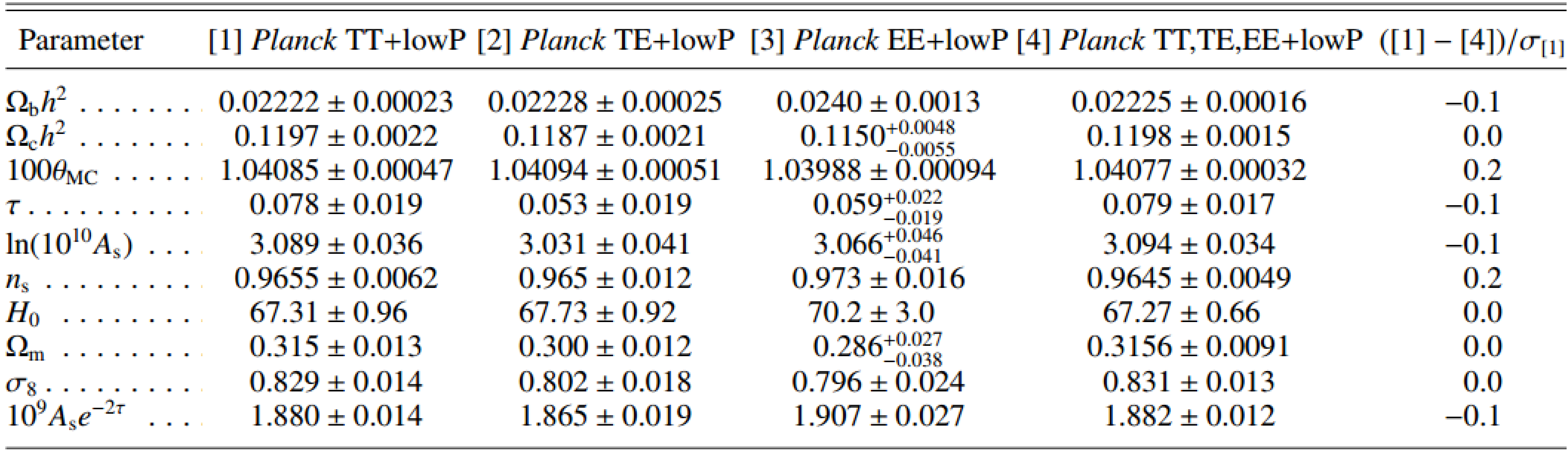
BICEP/KECK & PLANCK: arXiv 1502,00612

ΛCDM Model: 6 parameters that fit the CMB

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

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

Baryons+CDM+DE $(w_\Lambda=-1)$



Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP	[3] *Planck* EE+lowP	[4] *Planck* TT,TE,EE+lowP	$([1] - [4])/\sigma_{[1]}$
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013	0.02225 ± 0.00016	-0.1
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$	0.1198 ± 0.0015	0.0
$100\theta_{MC}$	1.04085 ± 0.00047	1.04094 ± 0.00051	1.03988 ± 0.00094	1.04077 ± 0.00032	0.2
τ	0.078 ± 0.019	0.053 ± 0.019	$0.059^{+0.022}_{-0.019}$	0.079 ± 0.017	-0.1
$\ln(10^{10}A_s)$ . . .	3.089 ± 0.036	3.031 ± 0.041	$3.066^{+0.046}_{-0.041}$	3.094 ± 0.034	-0.1
n_s	0.9655 ± 0.0062	0.965 ± 0.012	0.973 ± 0.016	0.9645 ± 0.0049	0.2
H_0	67.31 ± 0.96	67.73 ± 0.92	70.2 ± 3.0	67.27 ± 0.66	0.0
Ω_m	0.315 ± 0.013	0.300 ± 0.012	$0.286^{+0.027}_{-0.038}$	0.3156 ± 0.0091	0.0
σ_8	0.829 ± 0.014	0.802 ± 0.018	0.796 ± 0.024	0.831 ± 0.013	0.0
$10^9 A_s e^{-2\tau}$ . . .	1.880 ± 0.014	1.865 ± 0.019	1.907 ± 0.027	1.882 ± 0.012	-0.1

FLRW metric (homogeneous & isotropic): a(t)=scale factor), H=dlna/dt Hubble parameter

Flat Universe: $\Omega_M+\Omega_\Lambda=1$

Primordial Fluctuations~ adiabatic, gaussian, scale-invariant spectrum

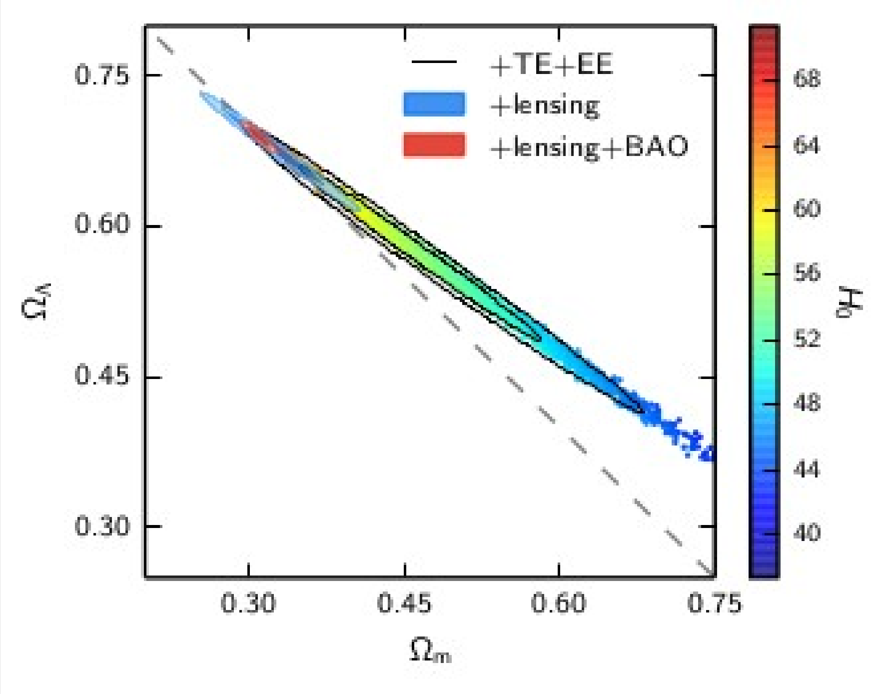
[Planck collab.: astro-ph/1502.01589]

ΛCDM Model: 6 parameters that fit the CMB

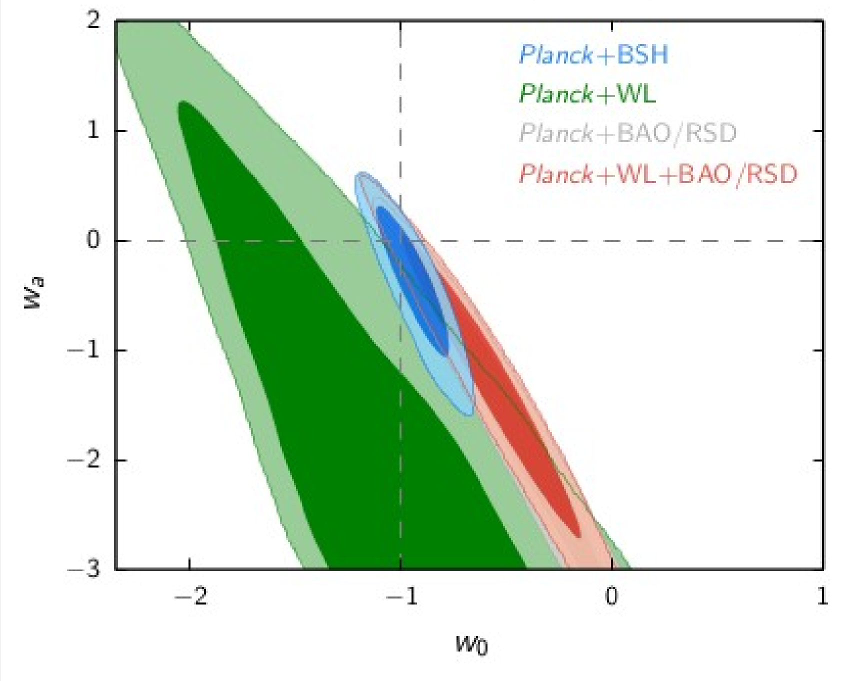
$$\left\{ \underbrace{P_R(k_0),\quad n_s,}_{\text{Primordial spectrum}} \quad \underbrace{\Omega_B,\quad \Omega_M,\quad \Omega_\Lambda,}_{\text{Matter content}} \quad \underbrace{\tau_{reio}}_{\text{Optical depth to LSS due to reionization}} \right\}$$

Baryons+CDM+DE

$(w_\Lambda=-1)$



$(w_\Lambda=w_0+(1-a)w_a)$



Background ~ Flat Universe + "Cosmological constant"

FLRW metric (homogeneous & isotropic): a(t)=scale factor), H=dlna/dt Hubble parameter

Flat Universe: $\Omega_M+\Omega_\Lambda=1$

[Planck collab.: astro-ph/1502.01589]

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**

Problems of the Big Bang Model

Homogeneous & isotropic $\Rightarrow$ Horizon problem

The universe is spatially flat $\Rightarrow$ Why?

$\Delta T/T \sim 10^{-5}$ $\Rightarrow$ Primordial fluctuations?

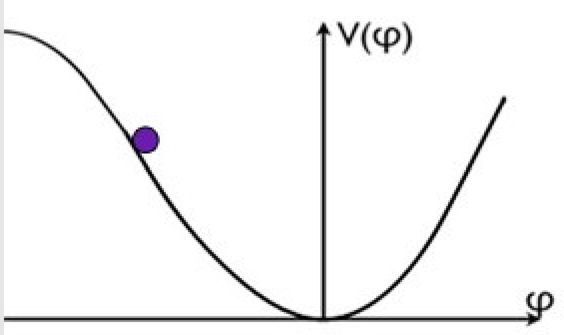
“Relics”: monopoles, topological defects, exotic particles... ?

Solution: Inflation

Period of accelerated expansion

$$\ddot{a} > 0 \Longleftrightarrow \rho + 3p < 0$$

Inflation: “slow-roll”



Kinetic energy << potential

Energy & pressure

$$\rho \approx V(\varphi) \qquad p \approx -V(\varphi)$$

Negative pressure

Flat Potential

The curvature and the slope of the potential less than the Hubble rate

$$H^2 \sim V/3m_P{}^2$$

“Slow-roll” parameters

$$|\eta_\varphi| = m_P^2 \left| \frac{d^2V/d\varphi^2}{V} \right| < 1 \qquad \epsilon_\varphi = \frac{m_P^2}{2} \left(\frac{dV/d\varphi}{V} \right)^2 < 1$$

curvature **slope**

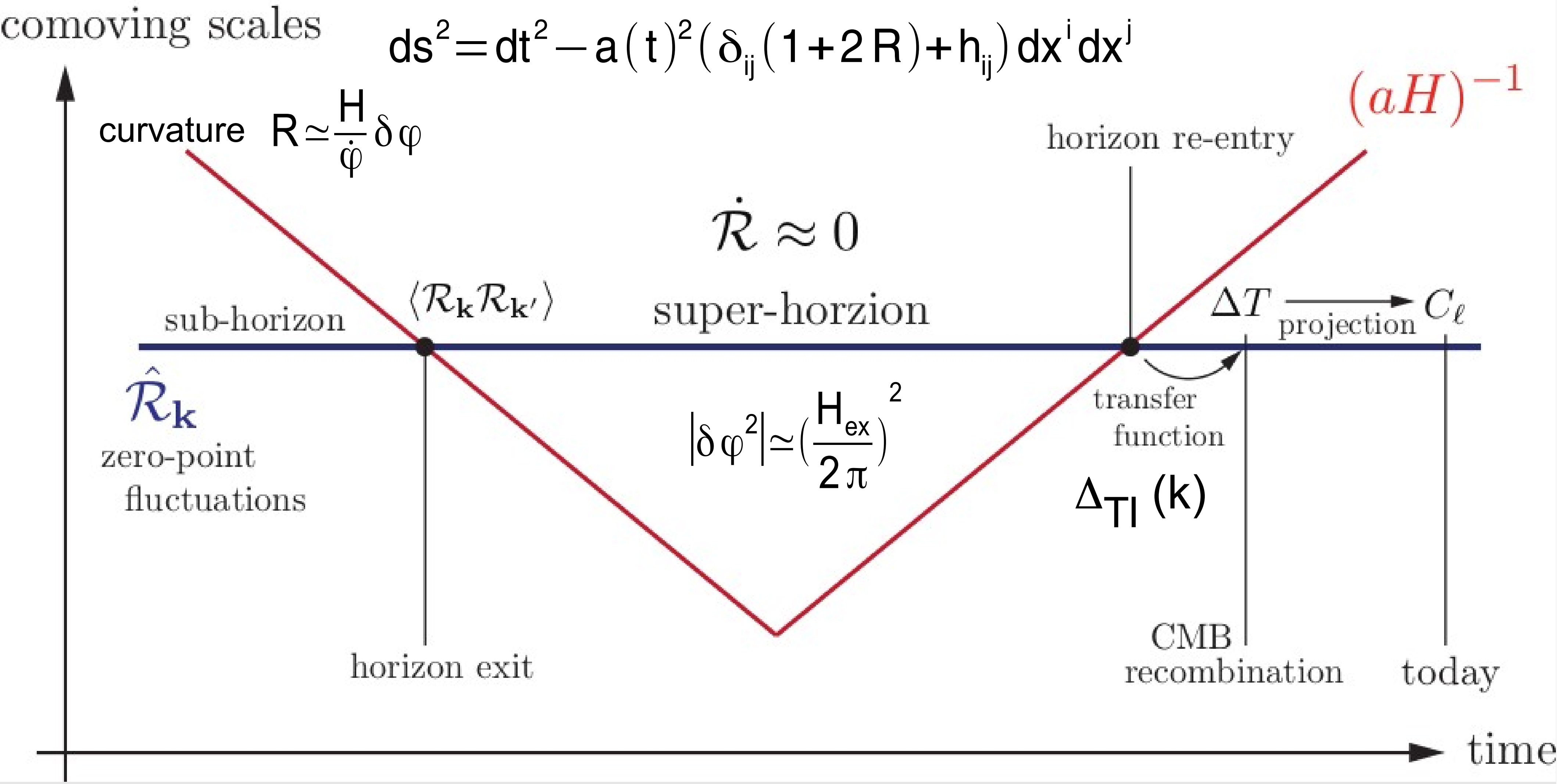
“slow-roll” evolution

$$3H\dot{\varphi} \simeq -dV/d\varphi, \qquad \ddot{\varphi} \ll 3H\dot{\varphi}, \qquad \dot{\varphi}^2 \ll V(\varphi)$$

$$(\dot{\varphi} \equiv d\varphi/dt)$$

CMB: T anisotropy spectrum

(background + linear fluctuations)



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

curvature $R \simeq \frac{H}{\dot{\varphi}} \delta\varphi$

$$|\delta\varphi^2| \simeq \left(\frac{H_{ex}}{2\pi}\right)^2$$

$\Delta_{Tl}(k)$

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

Primordial spectrum

Recipe for inflation

- Choose a potential: V(ϕ) (model building: Particle physics)
- Get “slow-roll” parameters and no. of efolds

  (Observable universe: Ne ~ 50-60)

- Amplitude of the primordial spectrum (input):

  $$P_R \simeq (H/\dot{\varphi})^2 P_{\delta\varphi} \simeq (5 \text{x} 10^{-5})^2$$ (CMB: COBE, WMAP, PLANCK)

  (Fix one parameter of the potential)

- Predictions (output): spectral index , tensor-to-scalar ratio, ….

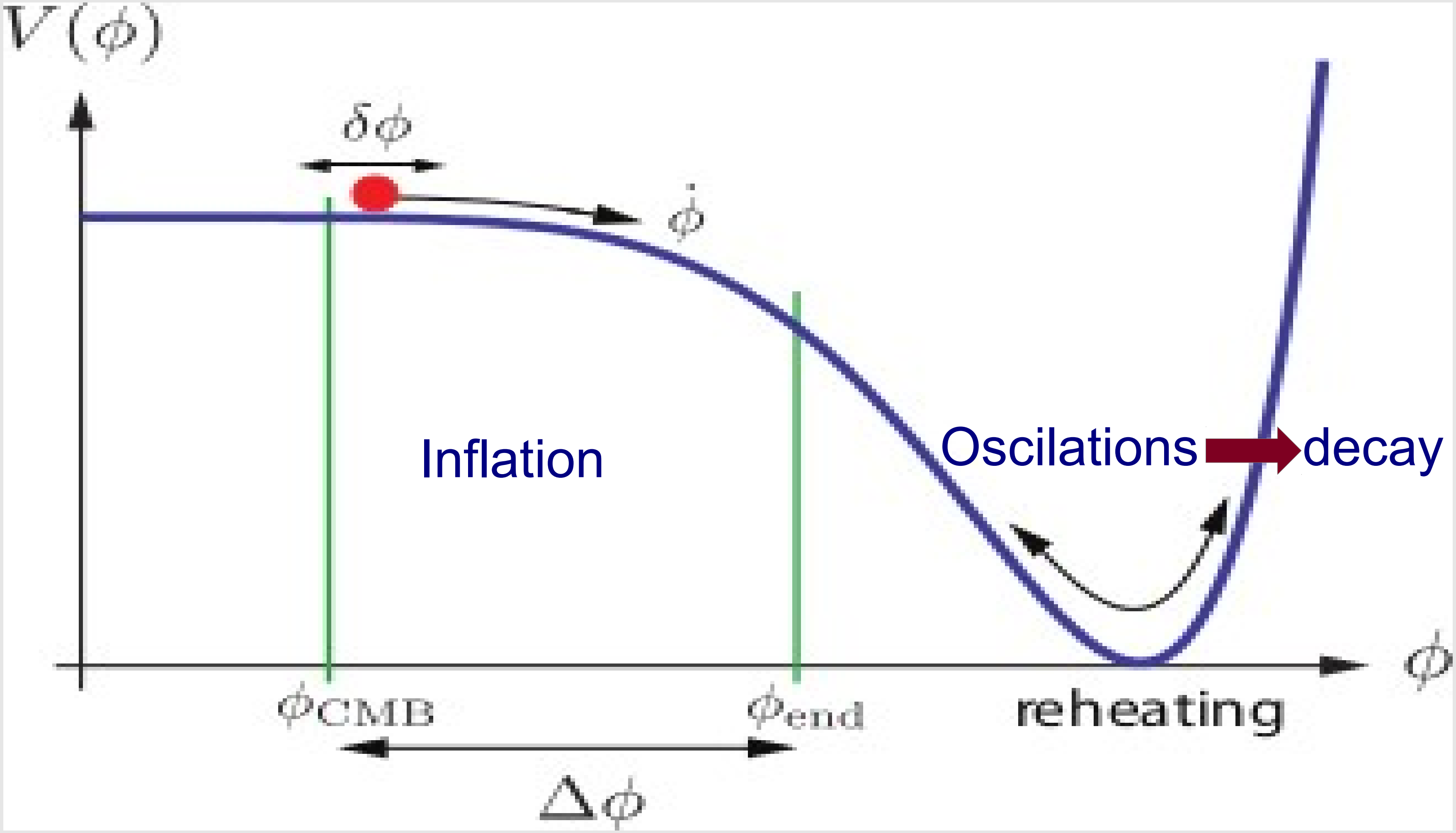
  $$n_S = \frac{d \ln P_R}{d \ln k} \simeq \frac{d \ln P_R}{d \ln a} \simeq 1 + 2\eta_\varphi - 6\epsilon_\varphi$$ (spectral index) $$P_R = P_R(k_0)(k/k_0)^{n_s - 1}$$

  $$P_T = 8\left(\frac{H}{2\pi m_P}\right)^2, \quad r = \frac{P_T}{P_R} < 1$$ (tensors : primordial gravitational waves)

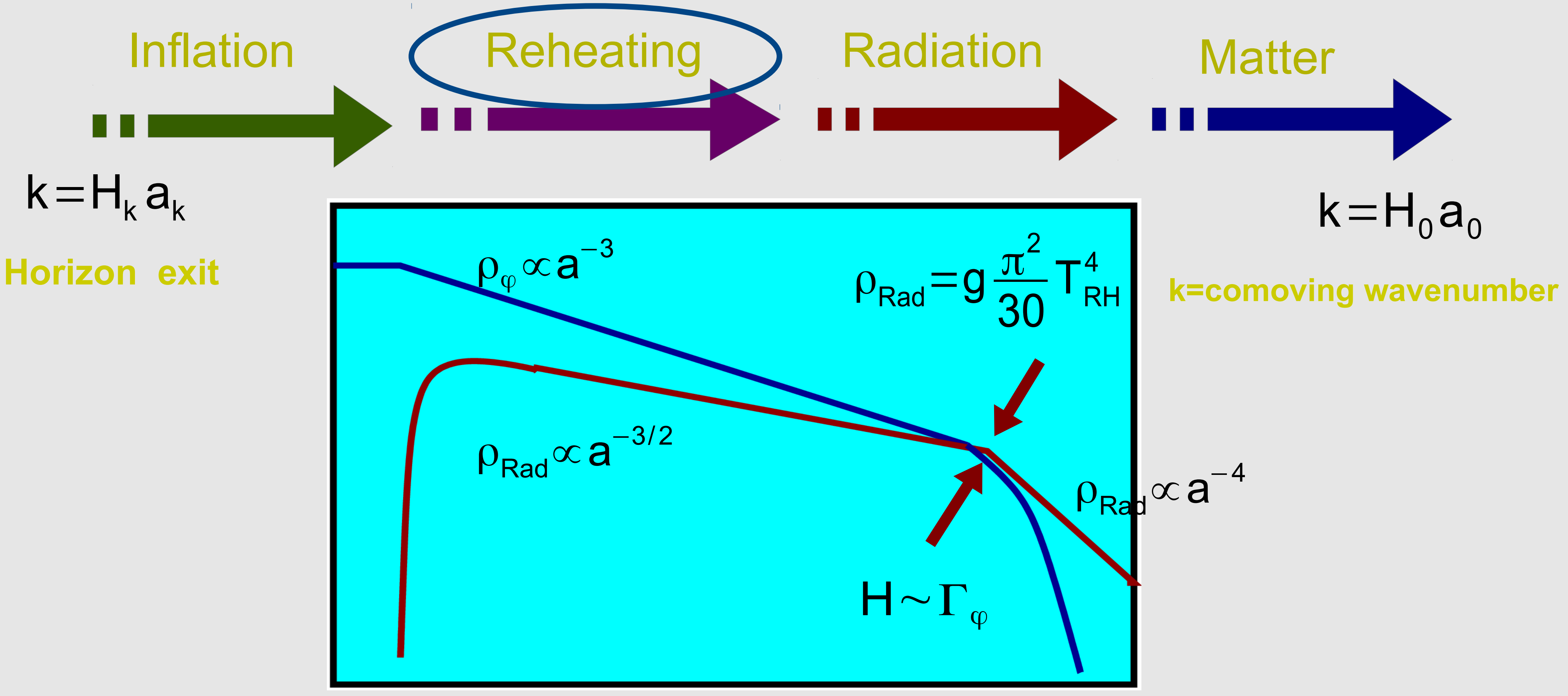
- Compare with observations (CMB)

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

Inflation → Reheating → Radiation → Matter



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



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

Primordial spectrum: $P_R = P_R(k_0)(k/k_0)^{n_s-1}$

adiabatic, gaussian, scale-invariant spectrum

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

- **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

f_{NL}^{local} = 2.5 +- 5.7 $(k_3 << k_1 \sim k_2)$

f_{NL}^{equil} =-16 +- 70 $(k_3 \sim k_1 \sim k_2)$

f_{NL}^{orth} = -34 +- 33

[Planck collab.: astro-ph/1502.02114]

Primordial spectrum: $P_R = P_R(k_0)(k/k_0)^{n_s - 1}$

adiabatic, gaussian, scale-invarian spectrum

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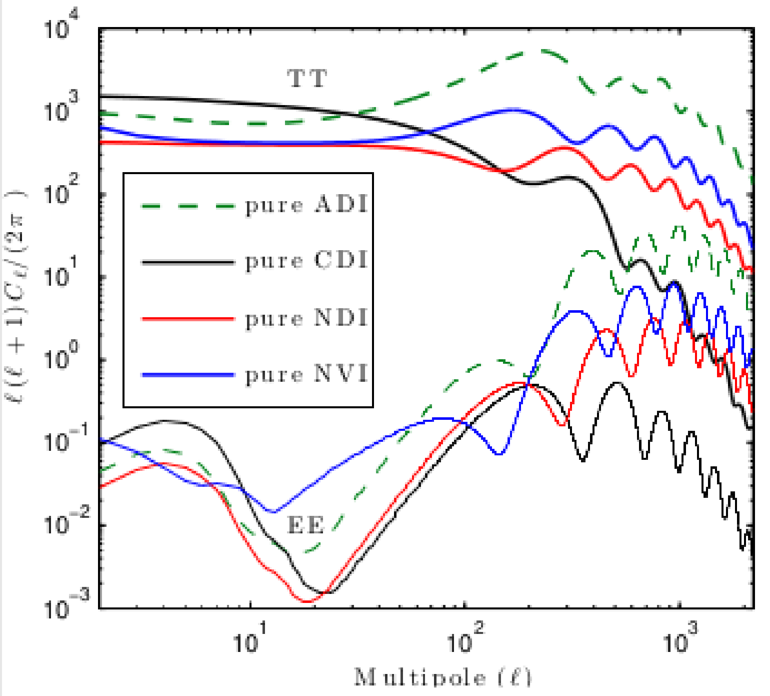
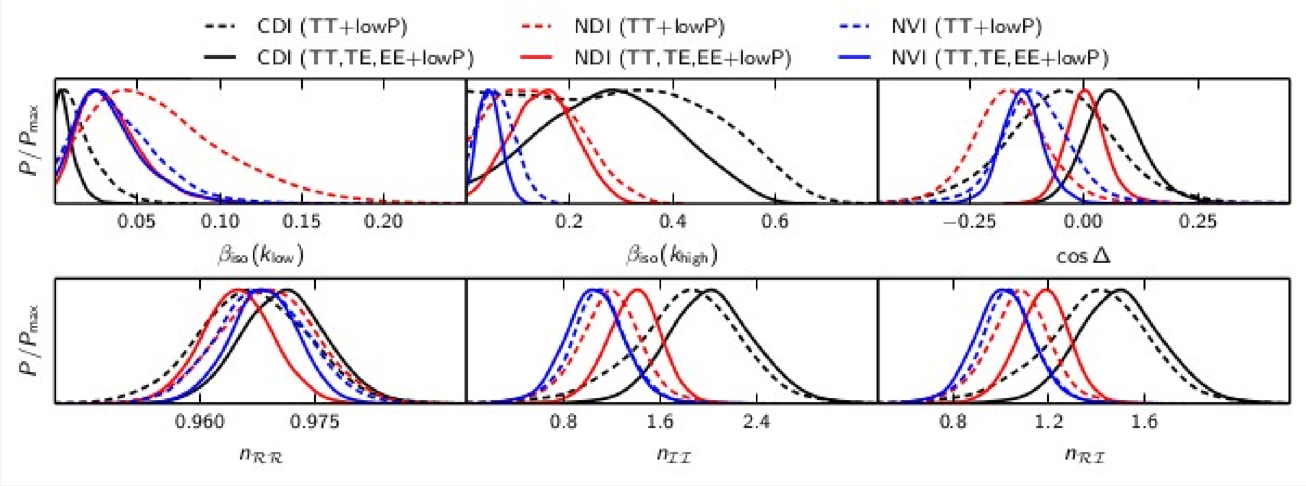


$$\beta_{iso} = \frac{P_{II}(k)}{P_{RR}(k) + P_{II}(k)}, \qquad \cos\Delta = \frac{P_{ab}}{(P_{aa}P_{bb})^{1/2}}$$



$k_{min} = 0.002\,\mathrm{Mpc}^{-1}, \quad k_{max} = 0.1\,\mathrm{Mpc}^{-1}$

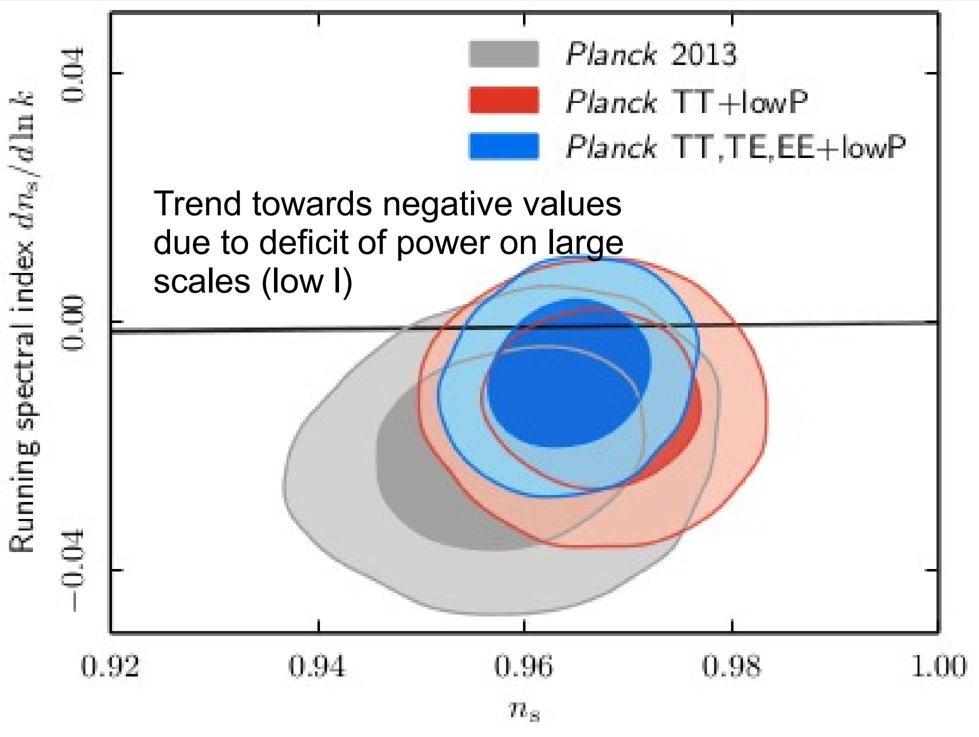
Pure isocurvature mode ruled-out as only source for the spectrum

[Planck collab.: astro-ph/1502.02114]

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

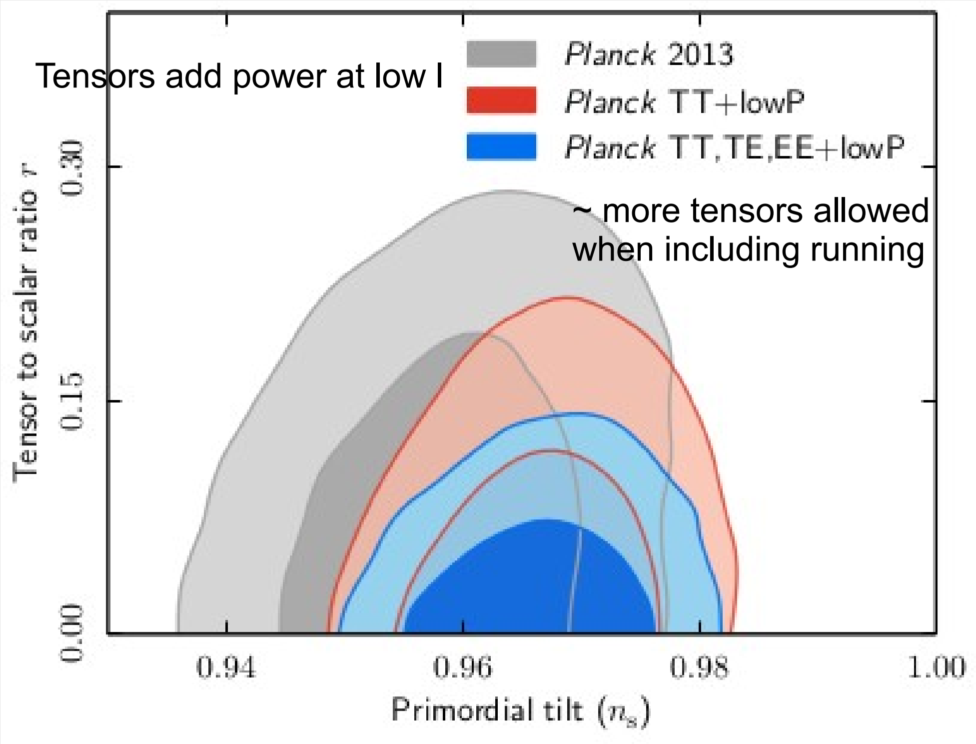
adiabatic, gaussian, scale-invariant spectrum

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



Trend towards negative values due to deficit of power on large scales (low l)

$$\alpha_s = \frac{dn_s}{d\ln k} = -0.0057 \pm 0.0071$$



Tensors add power at low l

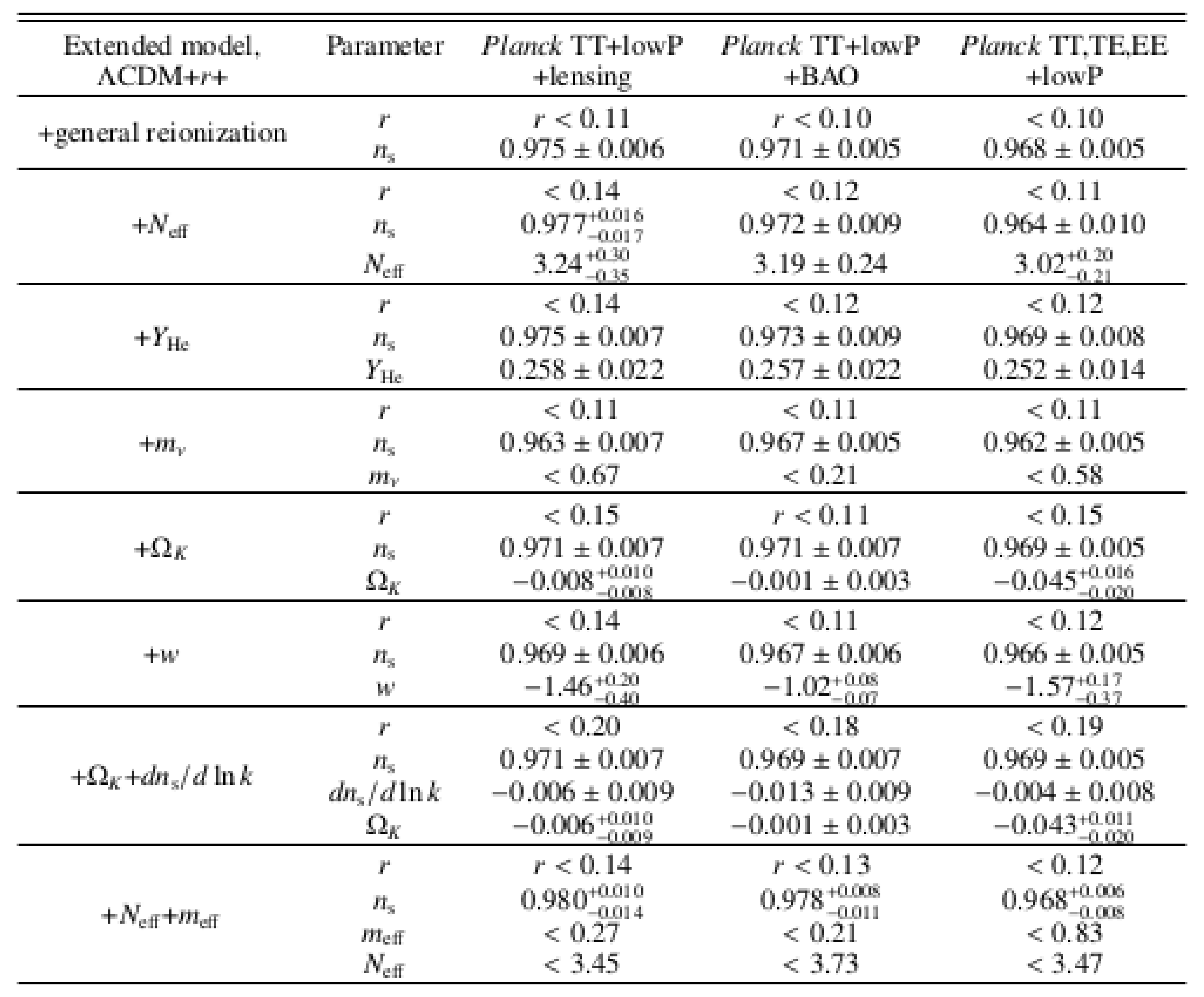
~ more tensors allowed when including running

$$\alpha_s = -0.013 \pm 0.01, \quad r_{0.002} < 0.18$$

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

[Planck collab.: astro-ph/1502.02114]

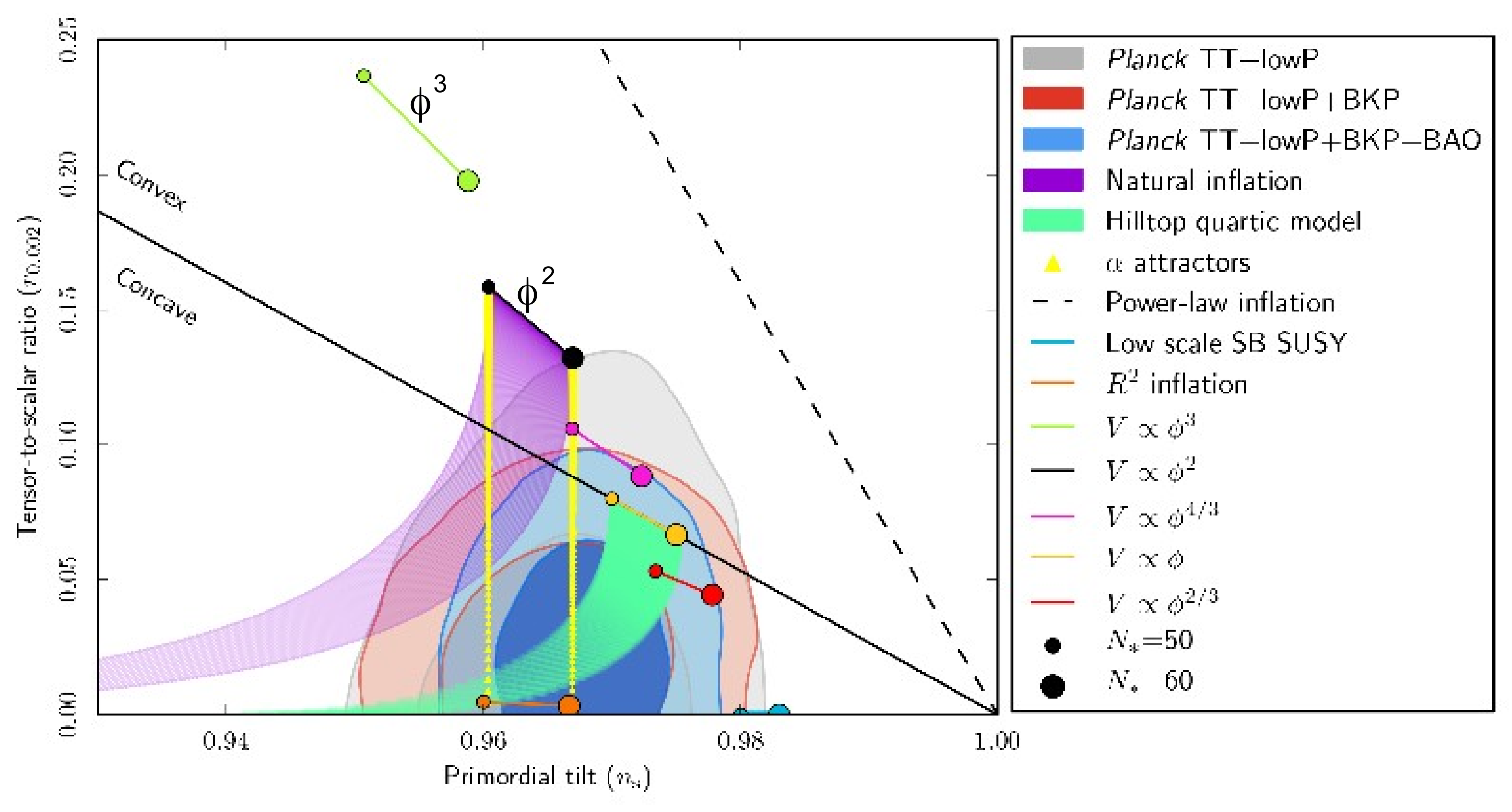
Primordial spectrum: ΛCDM extensions



Extended model, ΛCDM+r+	Parameter	*Planck* TT+lowP +lensing	*Planck* TT+lowP +BAO	*Planck* TT,TE,EE +lowP
+general reionization	r	$r < 0.11$	$r < 0.10$	< 0.10
	n_s	0.975 ± 0.006	0.971 ± 0.005	0.968 ± 0.005
+$N_{\rm eff}$	r	< 0.14	< 0.12	< 0.11
	n_s	$0.977^{+0.016}_{-0.017}$	0.972 ± 0.009	0.964 ± 0.010
	$N_{\rm eff}$	$3.24^{+0.30}_{-0.35}$	3.19 ± 0.24	$3.02^{+0.20}_{-0.21}$
+$Y_{\rm He}$	r	< 0.14	< 0.12	< 0.12
	n_s	0.975 ± 0.007	0.973 ± 0.009	0.969 ± 0.008
	$Y_{\rm He}$	0.258 ± 0.022	0.257 ± 0.022	0.252 ± 0.014
+m_ν	r	< 0.11	< 0.11	< 0.11
	n_s	0.963 ± 0.007	0.967 ± 0.005	0.962 ± 0.005
	m_ν	< 0.67	< 0.21	< 0.58
+Ω_K	r	< 0.15	$r < 0.11$	< 0.15
	n_s	0.971 ± 0.007	0.971 ± 0.007	0.969 ± 0.005
	Ω_K	$-0.008^{+0.010}_{-0.008}$	-0.001 ± 0.003	$-0.045^{+0.016}_{-0.020}$
+w	r	< 0.14	< 0.11	< 0.12
	n_s	0.969 ± 0.006	0.967 ± 0.006	0.966 ± 0.005
	w	$-1.46^{+0.20}_{-0.40}$	$-1.02^{+0.08}_{-0.07}$	$-1.57^{+0.17}_{-0.37}$
+Ω_K+$dn_s/d\ln k$	r	< 0.20	< 0.18	< 0.19
	n_s	0.971 ± 0.007	0.969 ± 0.007	0.969 ± 0.005
	$dn_s/d\ln k$	-0.006 ± 0.009	-0.013 ± 0.009	-0.004 ± 0.008
	Ω_K	$-0.006^{+0.010}_{-0.009}$	-0.001 ± 0.003	$-0.043^{+0.011}_{-0.020}$
+$N_{\rm eff}$+$m_{\rm eff}$	r	$r < 0.14$	$r < 0.13$	< 0.12
	n_s	$0.980^{+0.010}_{-0.014}$	$0.978^{+0.008}_{-0.011}$	$0.968^{+0.006}_{-0.008}$
	$m_{\rm eff}$	< 0.27	< 0.21	< 0.83
	$N_{\rm eff}$	< 3.45	< 3.73	< 3.47

Primordial spectrum: $P_R = P_R(k_0)(k/k_0)^{n_s-1}$ $k_0 = 0.002\,\mathrm{Mpc}^{-1}$

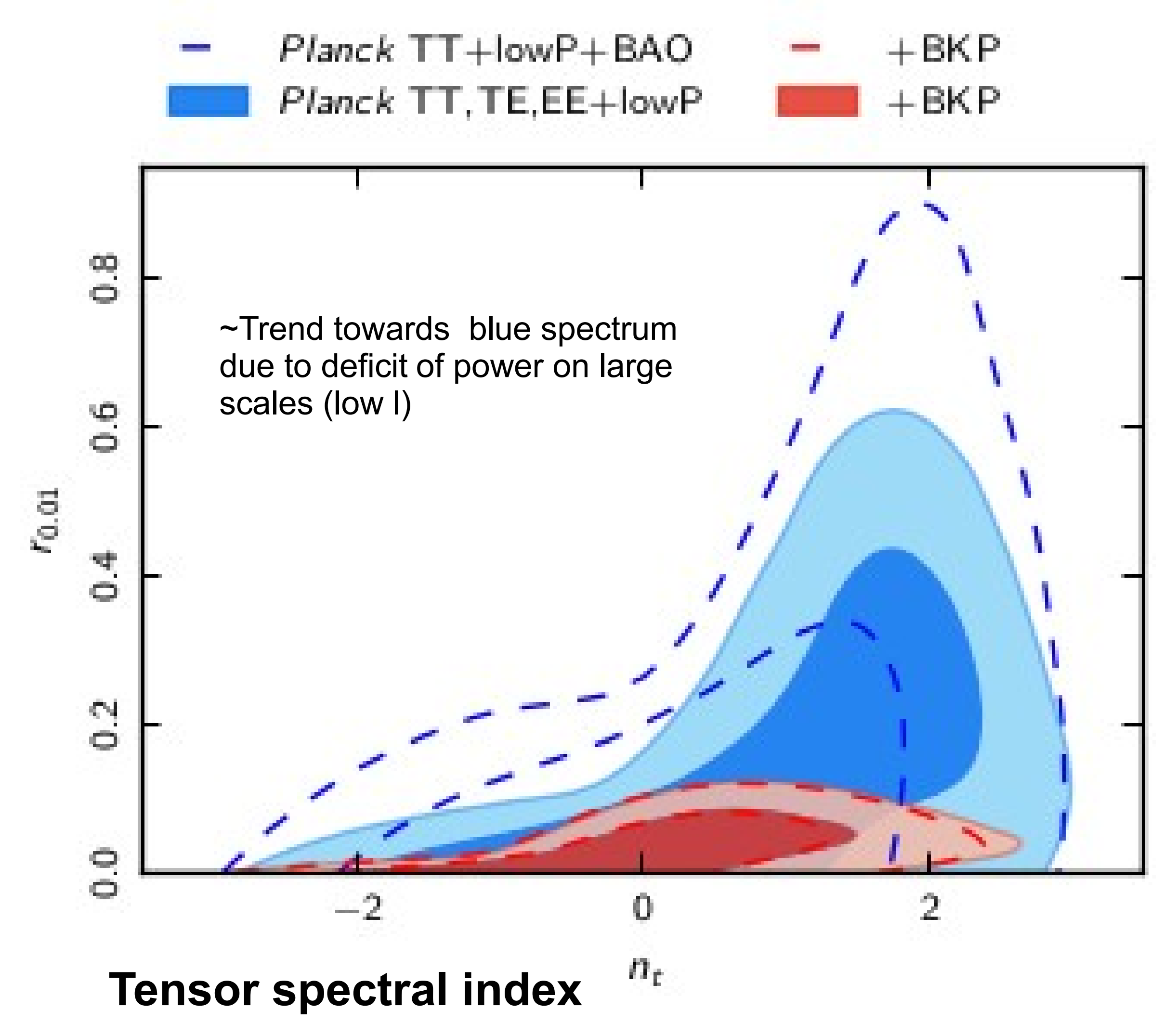
Tensor-to-scalar ratio : $r = P_T/P_R$ $P_R = 2.2\mathrm{x}10^{-9}$ $(n_T = -r/8)$



[Planck collab.: astro-ph/1502.02114]

Primordial spectrum: $P_R = P_R(k_0)(k/k_0)^{n_s - 1}$ $k_0 = 0.01\,\mathrm{Mpc}^{-1}$

Tensor-to-scalar ratio : $r = P_T/P_R$ $P_T = P_T(k_0)(\frac{k}{k_0})^{n_T}$



~Trend towards blue spectrum due to deficit of power on large scales (low l)

Tensor spectral index

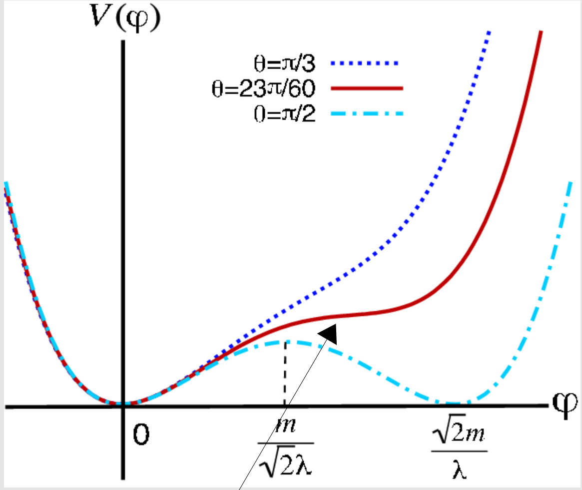
[Planck collab.: astro-ph/1502.02114]

- Simple monomials models $V(\varphi)=V_0(\varphi/m_P)^p$ 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”



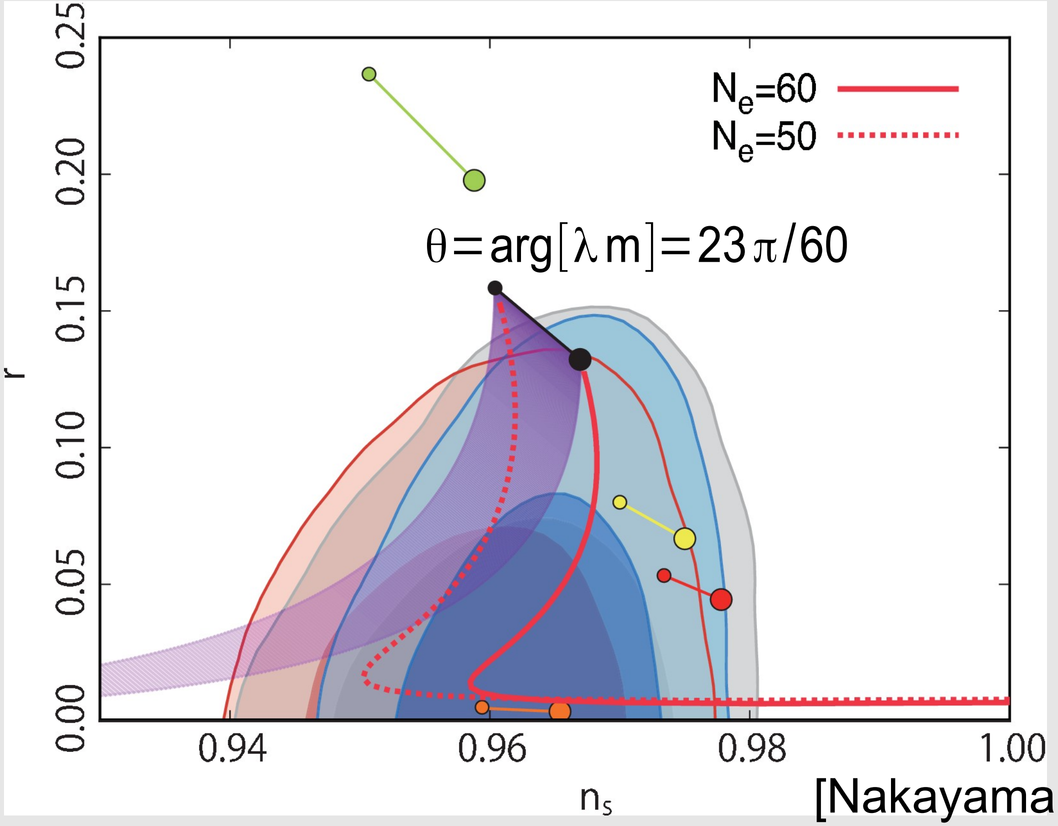
““Plateau” : lower H_*

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

$$m\sim 10^{13}\ \text{GeV}$$
$$\lambda^2\sim 10^{-14}$$

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

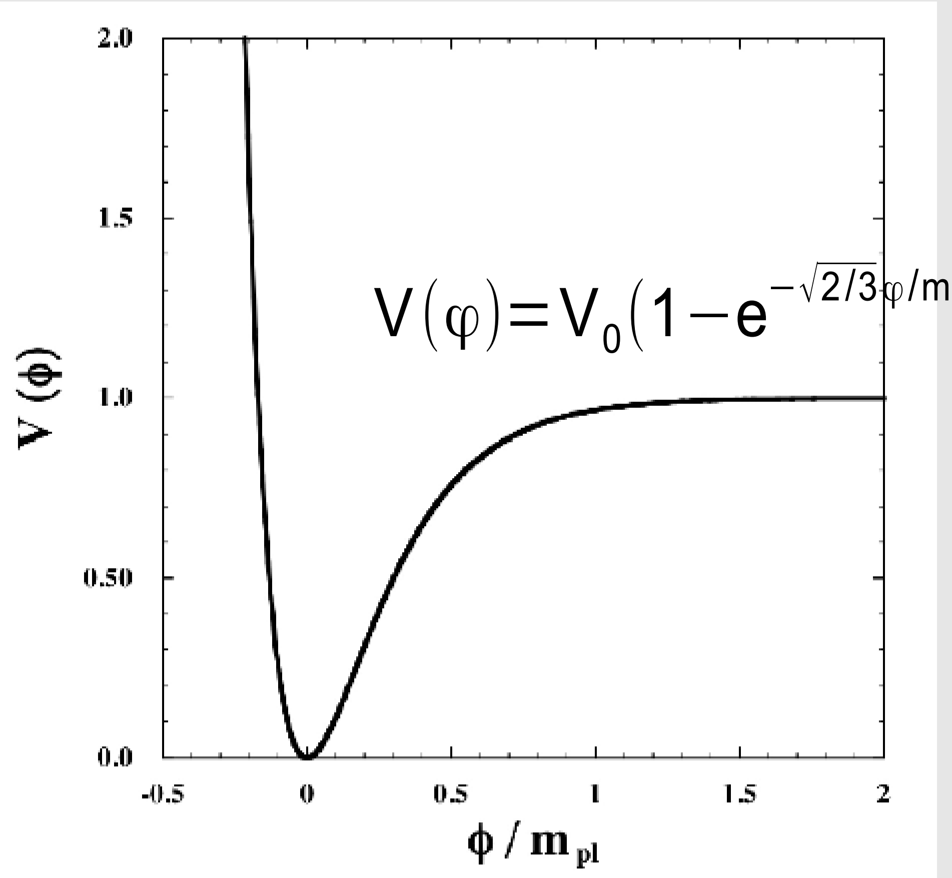
(Sugra + shift sym. + W= X(m Φ+ λ Φ^2+...)



[Nakayama et al. 1303.7315]

R^2 inflation: gravitational action + radiative corrections

[Starobinsky .'80]



$$V(\varphi) = V_0 \left(1 - e^{-\sqrt{2/3}\varphi/m_P}\right)^2$$

Einstein grav. + Radiative corrections

$$S_{gravity} = \int \sqrt{-g}\, d^4x \left(\frac{m_P^2}{2} R + \frac{R^2}{12} + \cdots\right)$$

R= Ricci scalar

Metric conformal transformation

$$S_{gravity} = \int \sqrt{-g}\, d^4x \left(\frac{m_P^2}{2} R + \frac{1}{2}(\partial_\mu \varphi)^2 - V(\varphi)\right)$$

$$\boxed{n_S \simeq 1 - \frac{2}{N_e} \qquad r \simeq \frac{12}{N_e^2}}$$

R^2 inflation from supergravity:

Buchmuller, Domcke, Kamada, 1306.3471

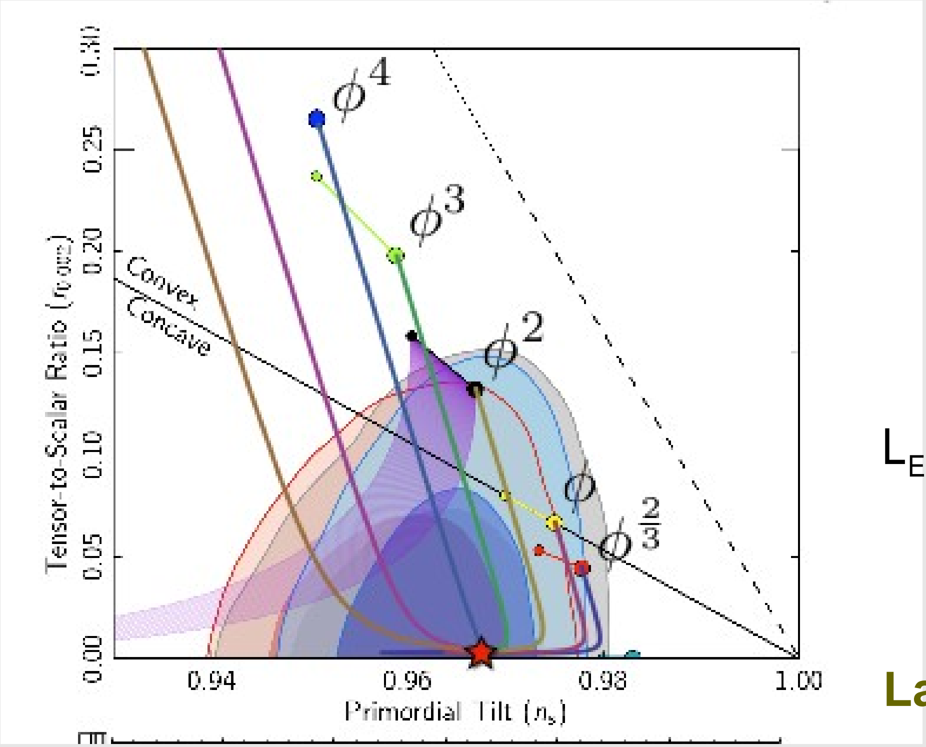
Farakos, Kehagias, Riotto, 1307.1137

Ellis, Nanopoulos, Olive, 1307.3537

Ferrara, Kallosh, Van Proeyen, 1309.4052

“Starobinsky model” ⟷ Non-minimal coupling to gravity

[Kallosh, Linde, Roest, 1310.3950]



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

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

Non-minimal coupling: Jordan frame

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

$$\Big\downarrow$$

Metric conformal transformation

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

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

Non-minimal kinetic: Einstein frame

Large ξ limit + canonical kinetic term:

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

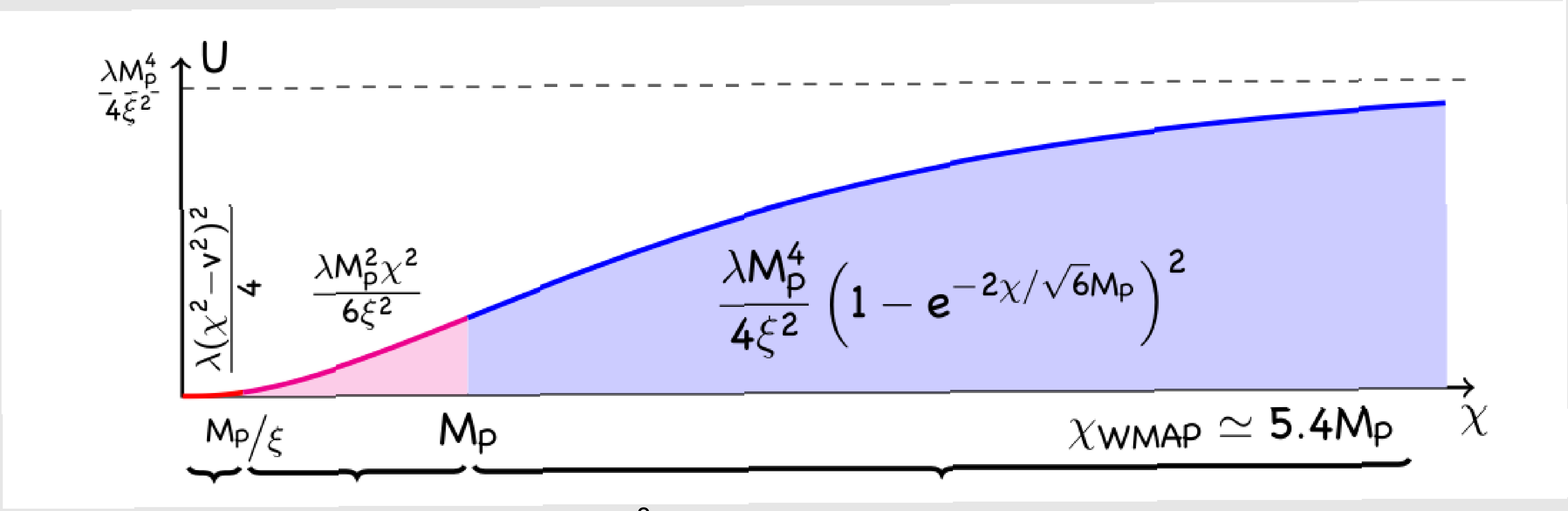
[p=4 large ξ limit : $\xi \geq 0.1$]

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

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

Inflaton = Higgs

[Bezrukov & Shaposhnikov '08]



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

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

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

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

$\chi\gg m_P/\xi$

$\lambda\simeq O(0.1)$

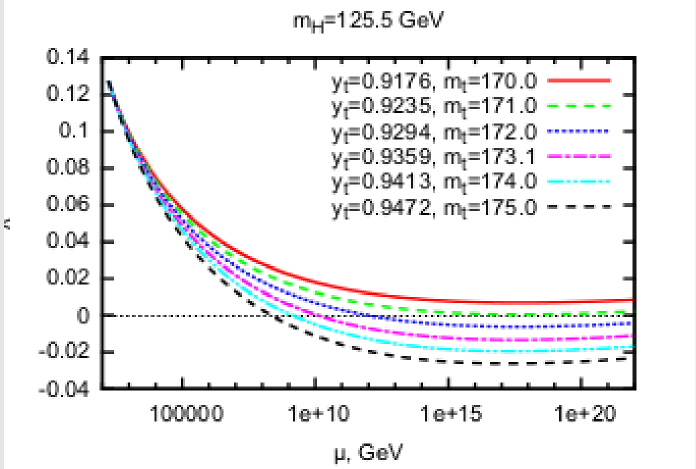
$\lambda_{eff}\simeq 10^{-13}$ [COBE]

Reheating: decay into SM degrees of freedom !!

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

Inflaton = Higgs: Stability of the Higgs potential?

RGE running:



[Bezrukov, Rubio & Shaposhnikov '14]

[Bezrukov & Shaposhnikov, '14]

SM: $\lambda(\mu)<0$ at $\mu\simeq 10^{10}$ GeV for $m_t\geq 172$ GeV

$$V_{SM}=\frac{1}{4}\lambda\phi^4-\frac{1}{2}m^2\phi^2 \longrightarrow V_{inf}\simeq\frac{\lambda_{eff}}{4}m_P^4\left(1-e^{-\sqrt{2/3}\chi/m_P}\left(1+\cdots\right)\right)$$

"Low energy"

$\mu\leq m_P/\xi$

"High Energy"

$m_P/\xi\leq\mu\leq m_P/\sqrt{\xi}$

Matching conditions at $\mu\sim m_P/\xi$: depend on higher order operators (UV completion)

$$\lambda(\mu_1)=\lambda^{SM}(\mu_1)+\delta\lambda\,, \qquad h_t(\mu_1)=h_t^{SM}(\mu_1)+\delta h_t$$

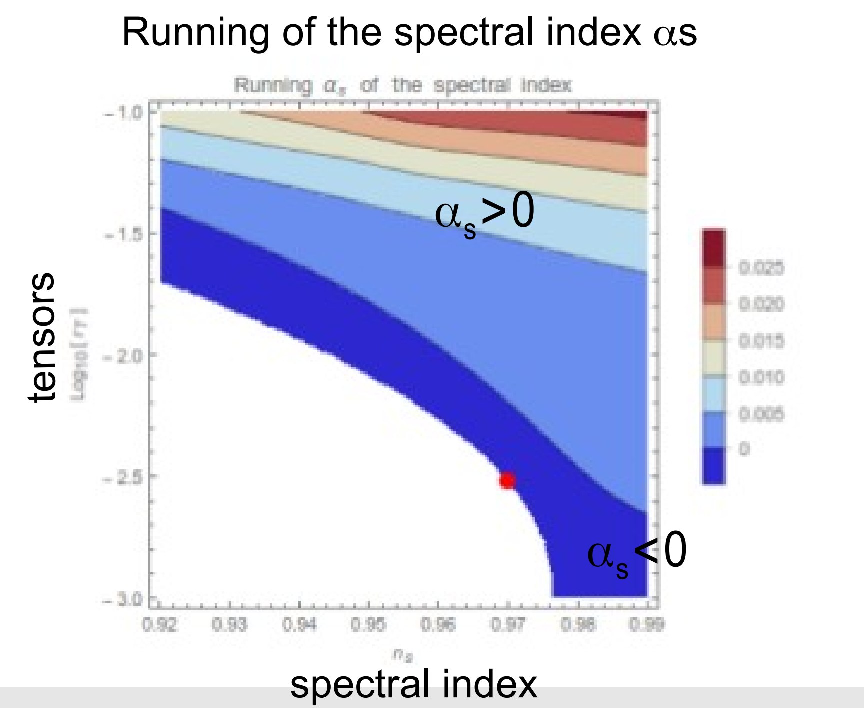
The negative minimum is lifted by thermal corrections after inflation:

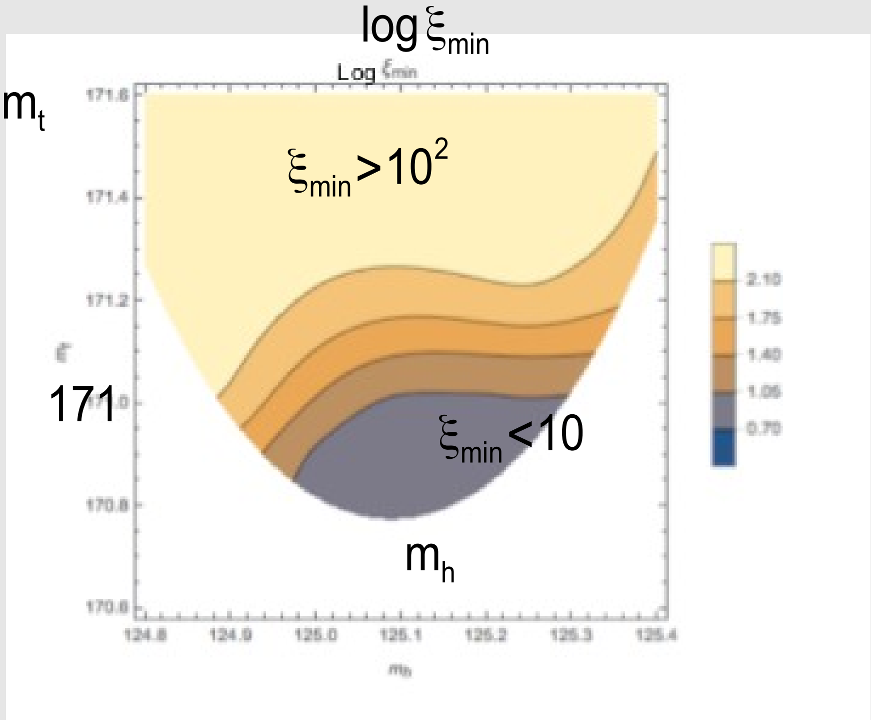
$$\Delta V(T_{reh},\chi_{min})>-V(\chi_{min})$$

[Enqvist, Enckell, Nurmi '16]

[Fumagall & Postma '16]

Inflaton = Higgs: Stability of the Higgs potential?





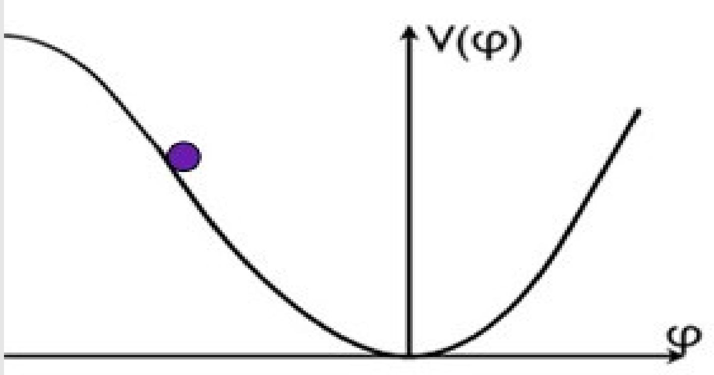
[Enqvist, Enckell, Nurmi '16]

Higgs inflation can be realised for $\xi < 10$ for low top masses

It can be falsified: a detection of a negative running of the spectral index + $m_t < 171.8$ Gev will rule out the model

Which inflationary potential? :

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



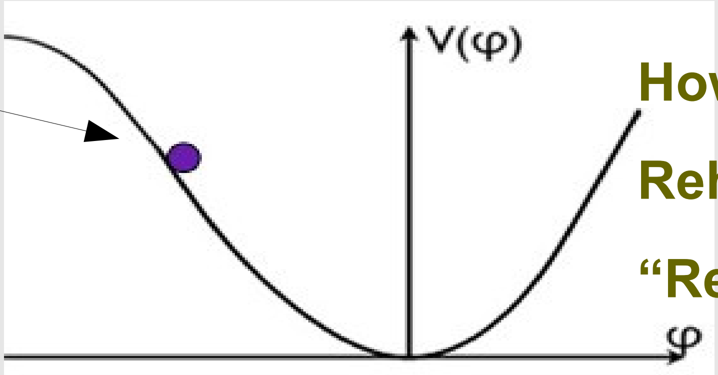
J. Martin, C. Ringeval, & Vennin, arXiv: 1303.3787: “Encyclopedia Inflationaris”

(~ 100 models)

Which inflationary potential? :

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

Initial conditions?



How the universe thermalize?

Reheating T? Baryogenesis?

“Relics” ?

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

(~ 100 models)

Initial conditions for inflation

(canonically normalized, minimally coupled field to gravity)

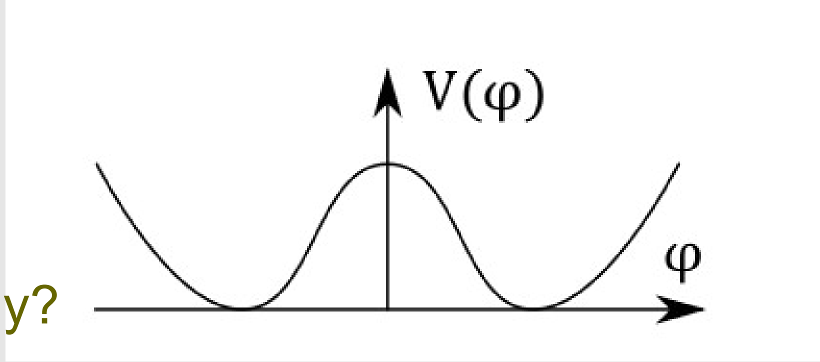
Homogeneous & isotropic background

- Small field models: $\Delta\phi < m_P, \quad H_{inf}/m_P < 10^{13}$ GeV

[Goldwirth & Piran, Phys. Rept. 214 '92]

The initial field velocity has to be tuned: $\dot{\phi} < H^2$

Tunneling from a false vacuum? Quantum cosmology?



[Garriga, Montes, Sasaki, Tanaka '99]

[Hartle&Hawking '83; Linde '84; Vilenkin '82]

- Large field models: $\Delta\phi \sim m_P, \quad H_{inf}/m_P \sim 10^{13}$ GeV

The inflationary slow-roll trajectory is a local attractor in the initial conditions space

There is enough time for the kinetic energy to get redshifted and become subdominant

[Albrecht & Brandenberger '85; Brandenberger & Kung '90; Mukhanov '14]

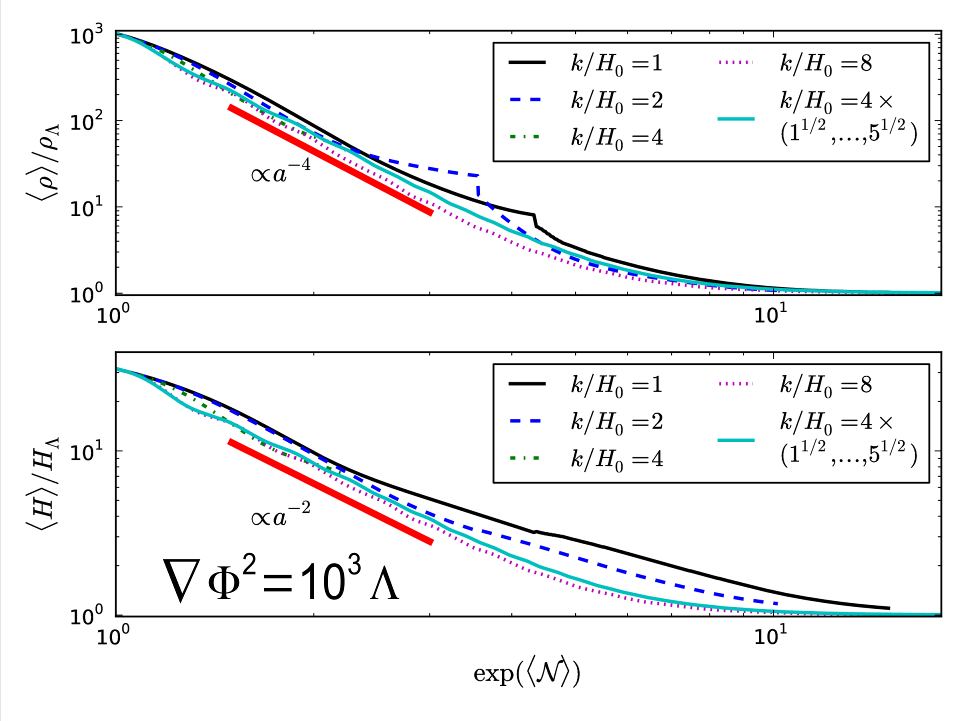
Initial conditions for inflation

(canonically normalized, minimally coupled field to gravity)

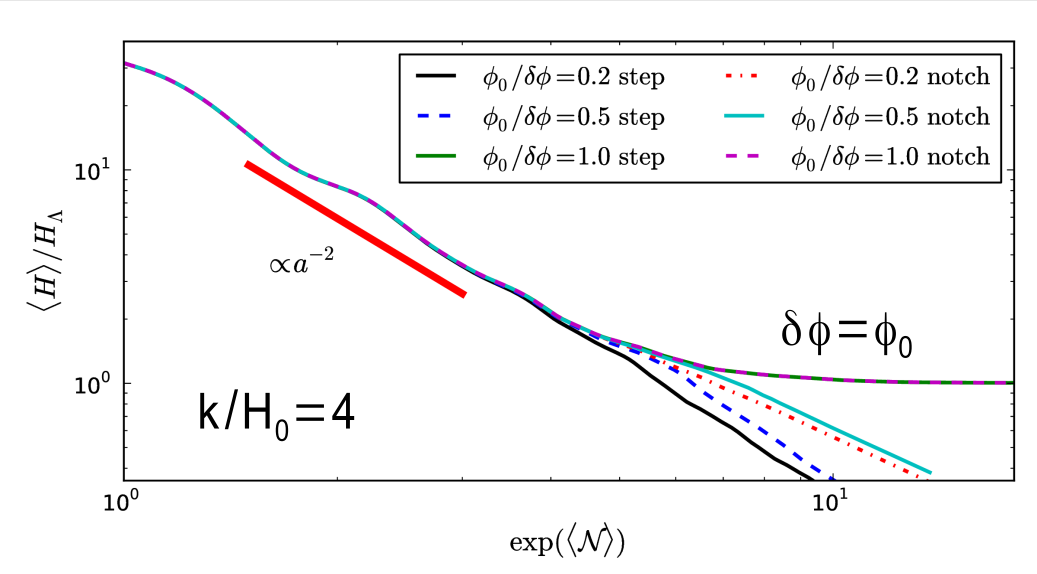
Inomogeneous background: Field + metric (Einstein Eqs.)

$$\nabla\Phi^2 \geq V(\Phi) \quad \Phi(x) = \phi_0 + \delta\phi \sum \cos(k\,x + \theta_k)$$

$\delta\phi$ within the range of inflationary values



$\delta\phi$ outside the inflationary plateau



[East, Kleban, Linde, Senatore 1511.05143]

Exponential expansion occurs even in the presence of large gradients

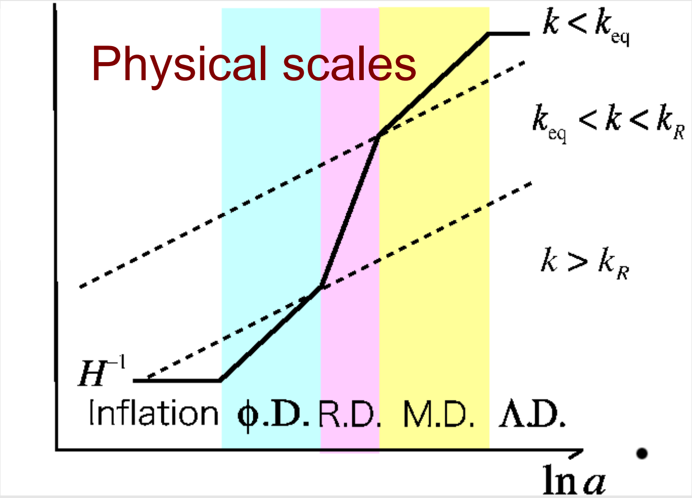
Large initial values of the inhomogeneous field (outside the "plateau") may prevend inflation

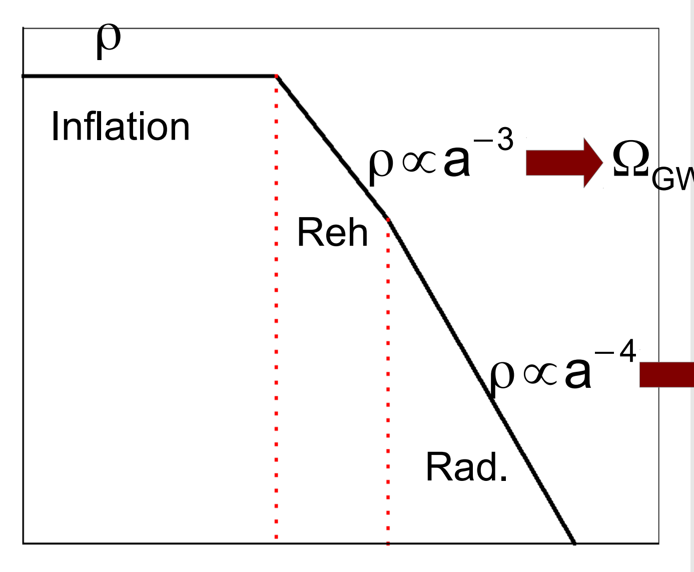
There is no need to assume a Hubble-sized homogeneous initial patch for inflation to occur

[Easther, Price & Rasero '14; Laguna, Kurki-Suonio & Matzner '93]

Primordial gravitational waves: direct detection?

Inflation → Reheating → Radiation → Matter

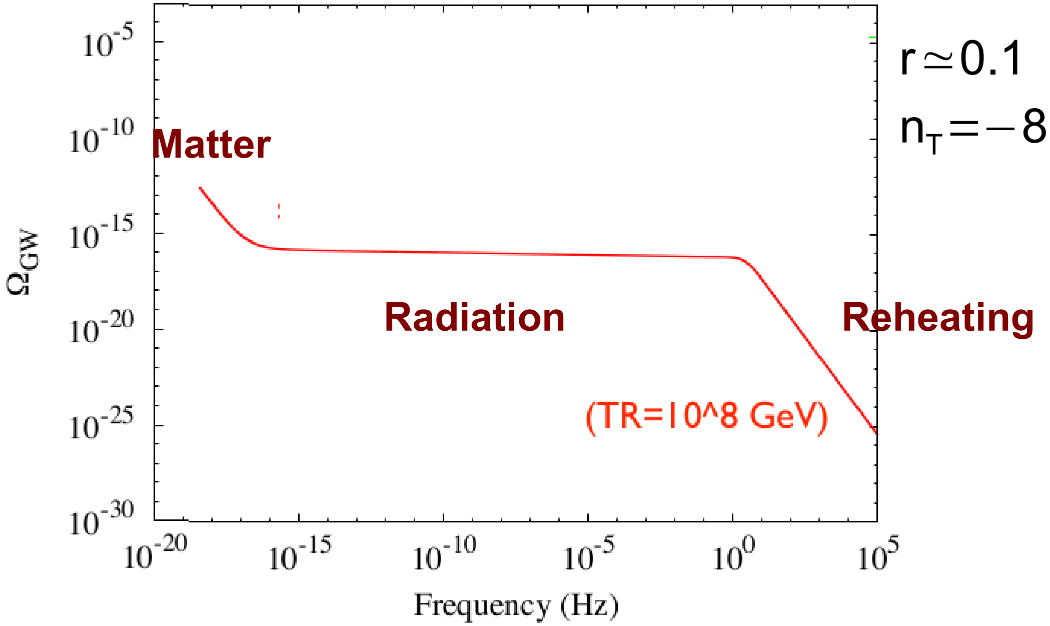




$\rho \propto a^{-3} \Rightarrow \Omega_{GW} \propto k^{-2}$

$\rho \propto a^{-4} \Rightarrow \Omega_{GW} \propto k^{0}$

$$\Omega_{GW} = \frac{1}{\rho_c} \frac{d\rho_{GW}}{d\ln f}$$

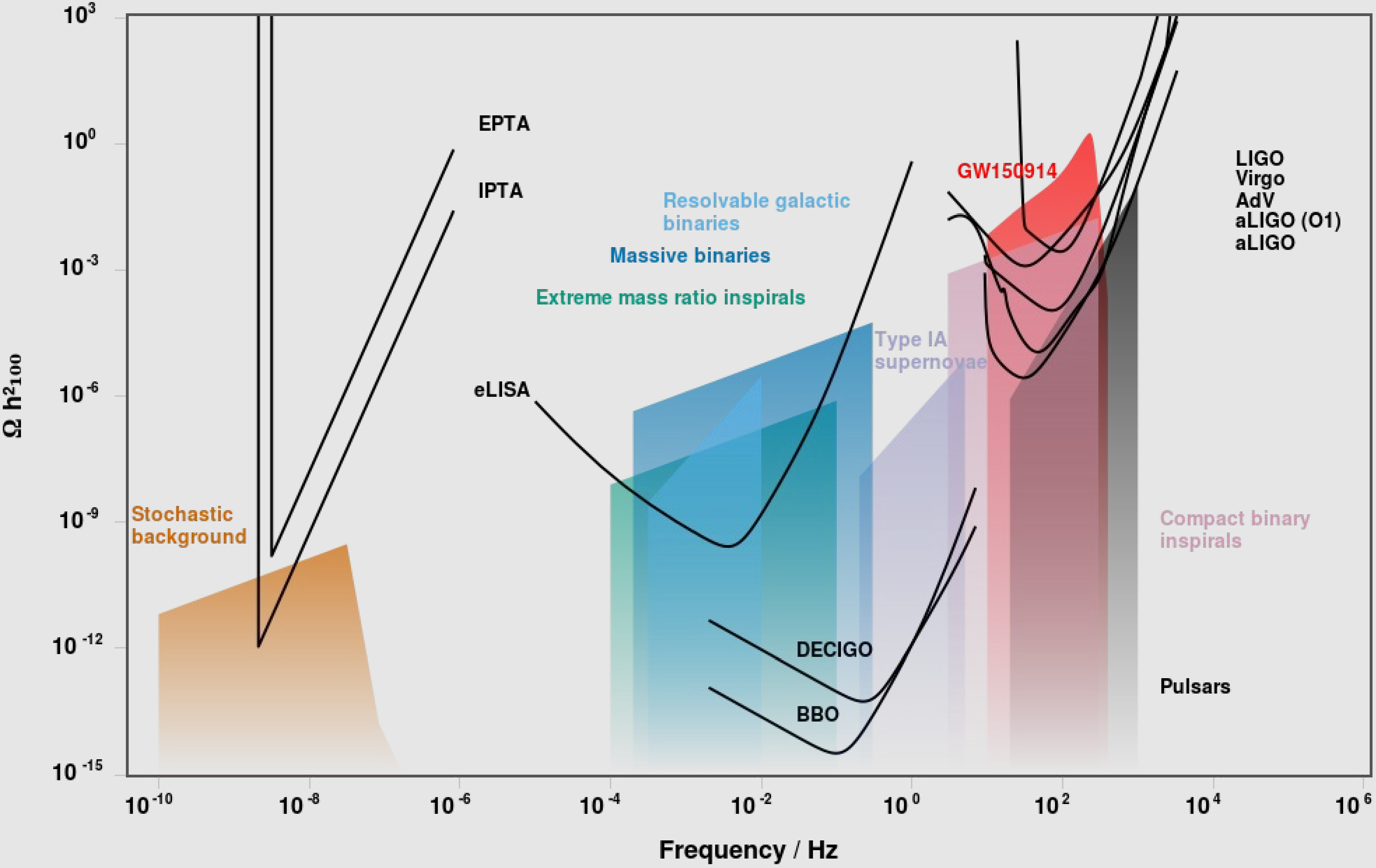


$r \simeq 0.1$

$n_T = -8r$

Fluctuations exit the horizon (freeze-out) during inflation, they reenter during MD/RD

Gravitational Waves: Direct detection

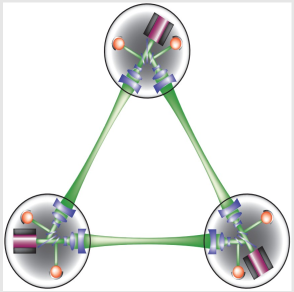


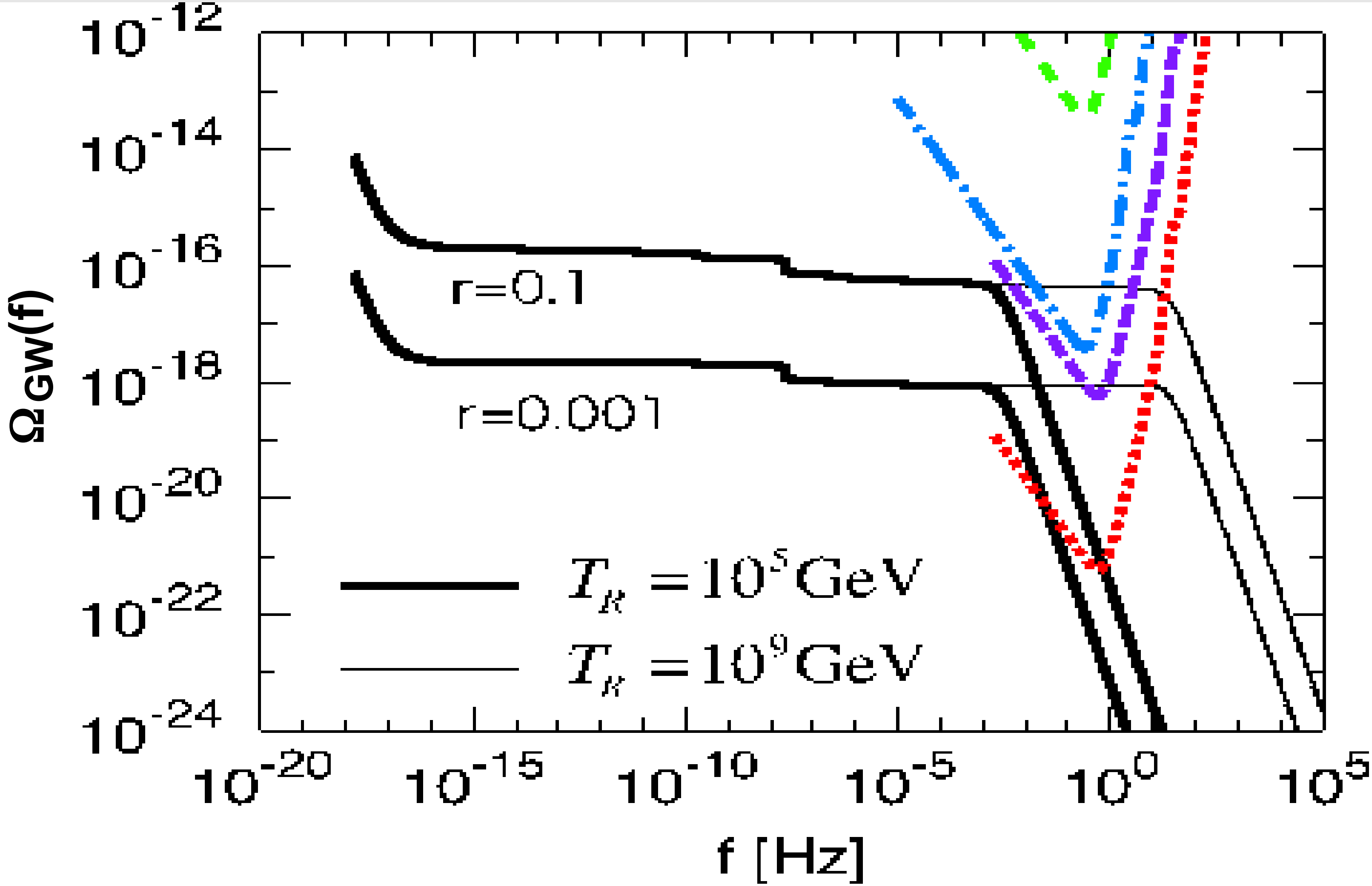
http://rhcole.com/apps/GWplotter/

[Moore, Cole & Berry, 1408.0740]

[Nakayama et al., 0804.1827]

DECIGO

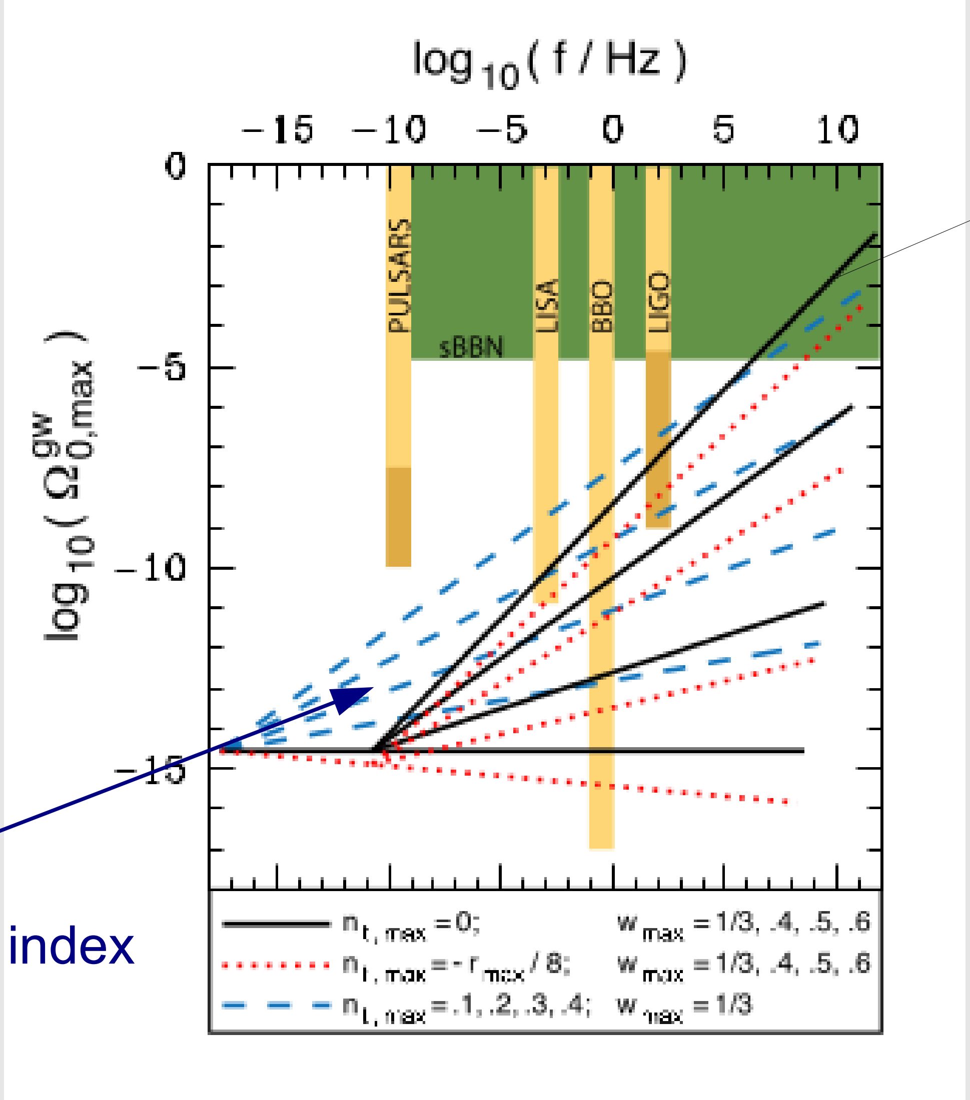




Primordial gravitational waves: direct detection?

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

$$\left\{\begin{array}{lll} \alpha=2, & \text{MD} & w=0 \\ \alpha=0, & \text{RD} & w=1/3 \\ \alpha<0, & & w>1/3 \end{array}\right.$$

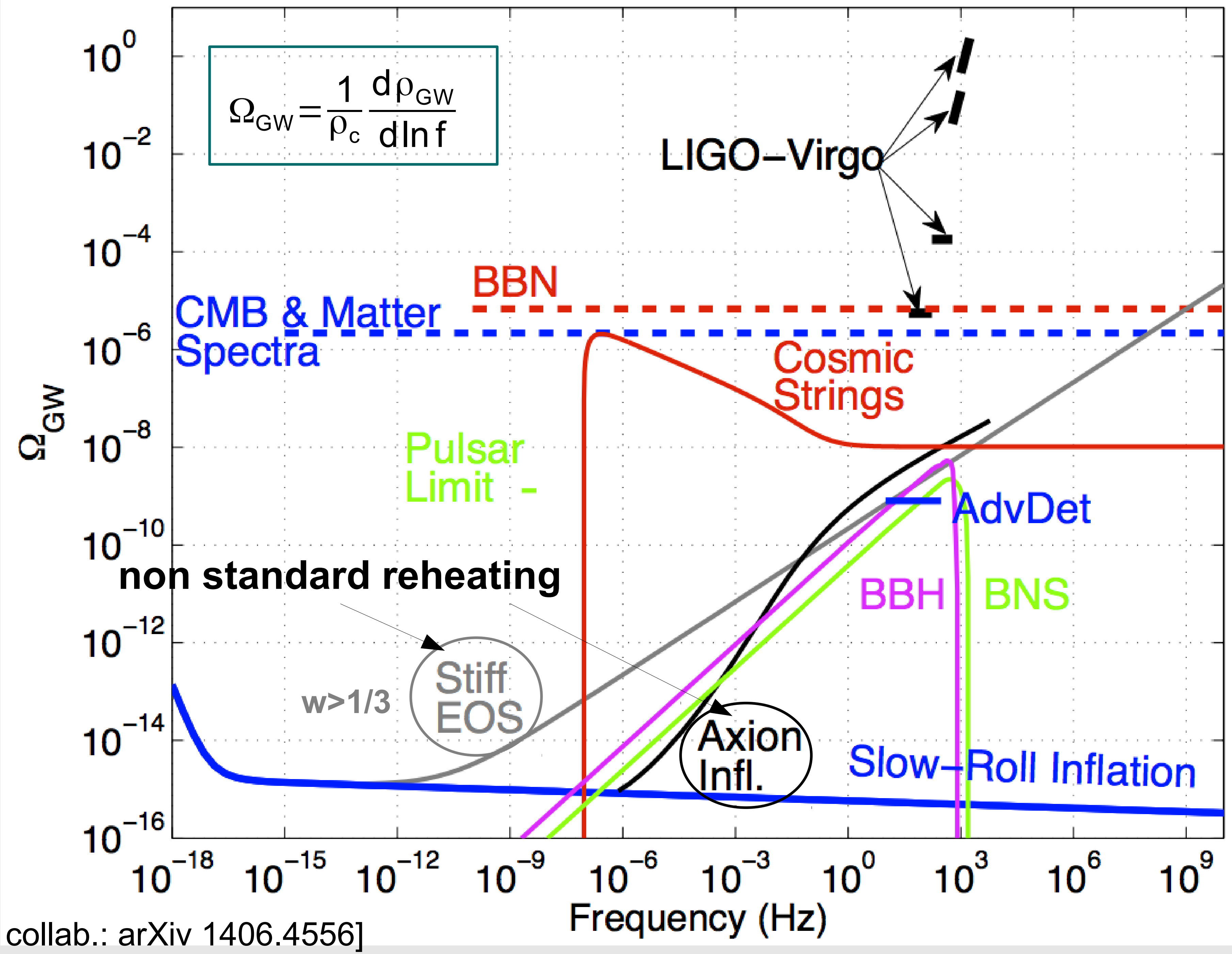


“stiff” EOS
$w>1/3$

Blue tensor spectral index
$n_T>0$

[Boyle & Buonnano: arXiv 0708.2279]

Primordial gravitational waves: direct detection?



[LIGO collab.: arXiv 1406.4556]

Preheating & Gravity Waves

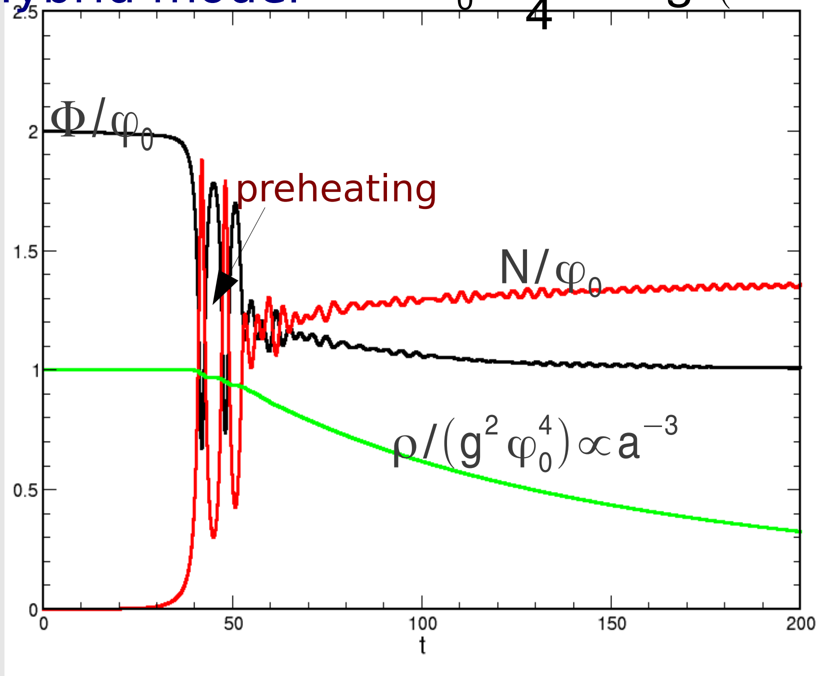
Non-adiabatic change in the time dependent effective masses leads to parametric amplification of the field fluctuations ➡ Source of GW

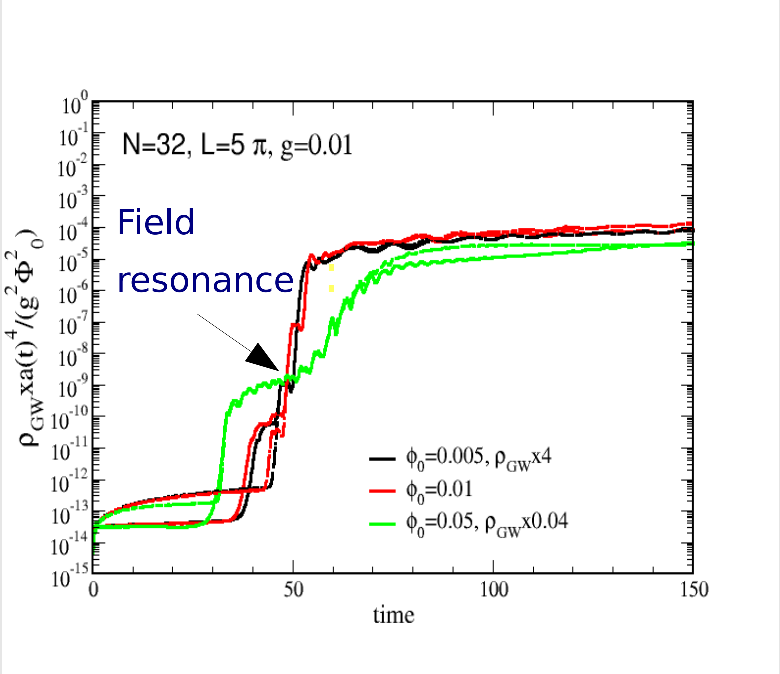
$$\ddot{h}_{ij}+3H\dot{h}_{ij}-\nabla^2 h_{ij}/a^2=S_{ij}^{TT}/a^2$$

Scalars
Fermions
Gauge bosons

Scalar matter $S_{ij}^{M}=16\pi G T_{ij}\sim 16\pi G \nabla_i\chi\nabla_j\chi$

Hybrid model $V=V_0+\frac{g^2}{4}N^4+g^2(\Phi^2-\varphi_c^2)N^2+\frac{1}{2}m_\varphi^2\Phi^2$





Easther, Giblin & Lim '06 ; García-Bellido & Figueroa '07; Dufaux et al. '08
Dufaux, Figueroa & García-Bellido '10; Enqvist, Figueroa & Meriniemi '12

Frequency (scalars):

$$f_0 = \frac{k_0}{2\pi} \simeq \frac{k_{res}}{2\pi} \underbrace{\frac{a_{res}}{a_0}} \simeq 4 \times 10^{10} \frac{k_{res}}{\rho_{res}^{1/4}} \mathrm{Hz} \sim 10^{10} g^{1/2} \mathrm{Hz}$$

$$(k_{res} \simeq g\,\varphi_{0,} \qquad \rho_{res} \simeq g^2 \varphi_0^4)$$

(No entropy production: $g_S(T_R)\, a^3(t_R)\, T_R^3 = g_S(T_0)\, a^3(t_0)\, T_0^3$ **)**

Power spectrum (scalars):

$$\Omega_{GW}^{(0)} h^2 = \Omega_{GW}^{(res)} h^2 \underbrace{\left(\frac{a_{res}}{a_0}\right)}^4 \simeq 10^{-6} \frac{1}{\rho_{res}} \frac{d\rho_{GW}^{res}}{d\ln k} \propto 10^{-6} \left(\frac{\Phi_0}{m_P}\right)^2$$

Redshift: radiation

Low scale hybrid inflation (very weak coupling $g < 10^{-12}$) could lead to a stochastic background of GW within the reach of GW detectors....

Frequency (fermions):

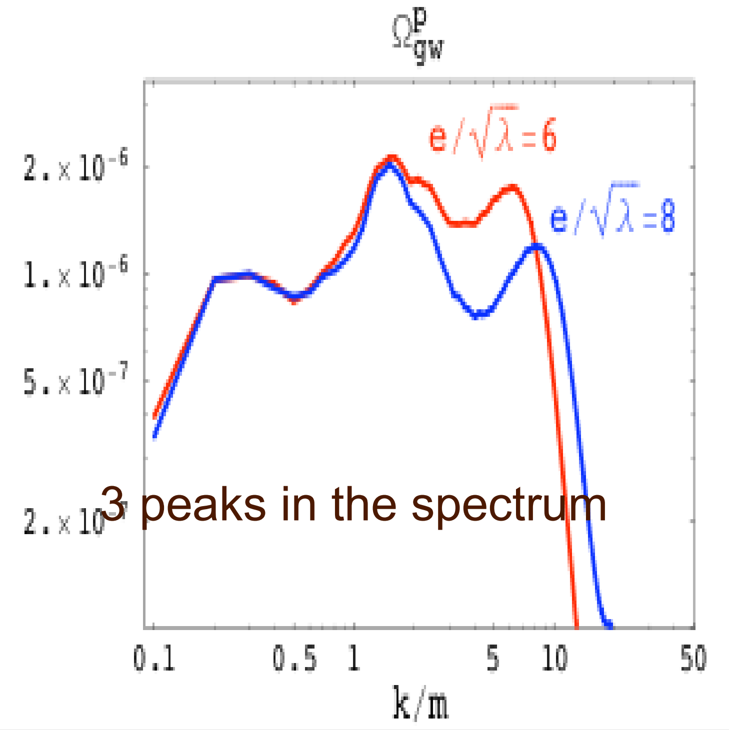
$$f_0 = q^{1/4} \omega_0 \quad (\omega_0 = \text{frequency of inflaton osc.})$$

Frequency too large (outside observable range) for $h_0^2 \Omega_{GW} > 10^{-14}$

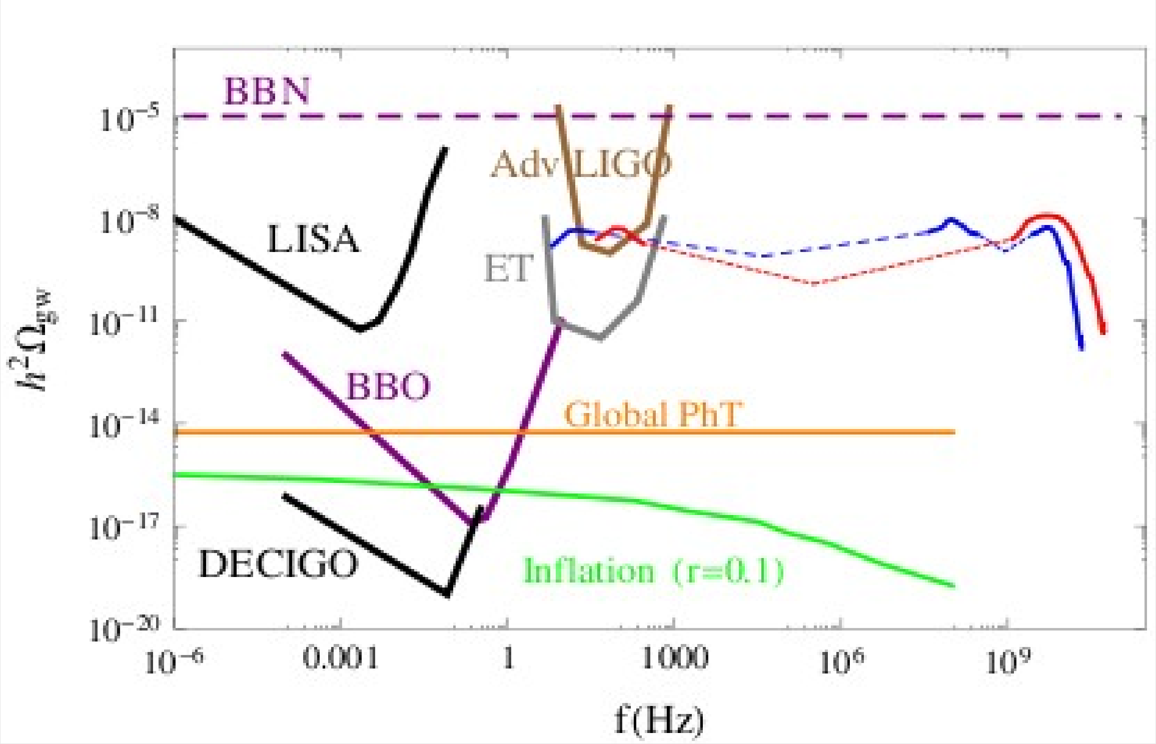
GW from preheating: Abelian Higgs model

$$L = D_\mu N D^\mu N + \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - V(\varphi, N), \qquad D_\mu = \partial_\mu - i e A_\mu$$

Scalar couplings: g, λ;   gauge coupling:e



3 peaks in the spectrum



$$f_{IR} \simeq \begin{cases} \lambda^{1/4} g\, 10^{11}\,\mathrm{Hz}, & g^2 > \lambda \\ \lambda^{-3/4} g\, 10^{10}\,\mathrm{Hz}, & g^2 < \lambda \end{cases}$$

$$f_{mid} \simeq \lambda^{1/4} 10^{11}\,\mathrm{Hz}$$

$$f_{UV} \simeq \frac{e}{\sqrt{\lambda}} \lambda^{1/4} 10^{11}\,\mathrm{Hz}$$

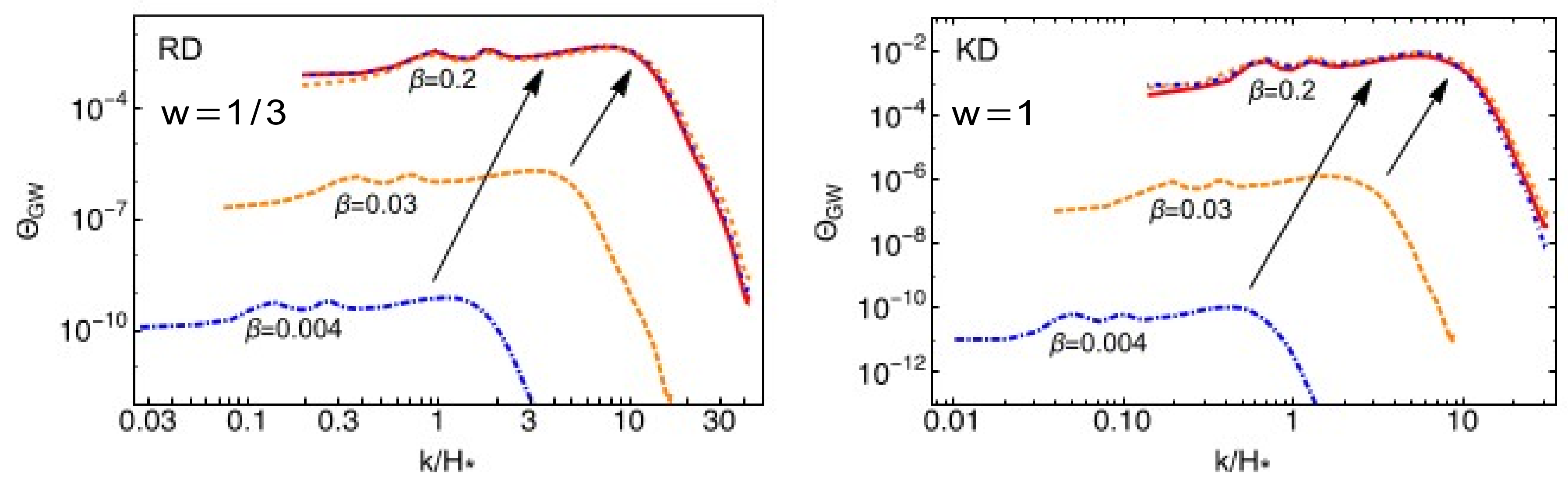
[Dufaux, Figueroa & García-Bellido '10]

GW from preheating: Higgs (condensate) decay into gauge bosons after inflation

$$\Omega_{GW}(k,z)=\left(\frac{H_{end}}{m_P}\right)^4 \left(\frac{a}{a_{end}}\right)^{3w-1} \Theta_{GW}$$

$$\beta=\lambda^{1/2}\frac{\phi_{end}}{H_{end}}$$

w= eos after inflation



$$h^2\Omega_{GW}(f_p)\leq\begin{cases}10^{-29} & \text{RD} \quad f_p\leq 3\times10^{8}\ \text{Hz} \\ 10^{-16} & \text{KD} \quad f_p\leq 3\times10^{11}\ \text{Hz}\end{cases}$$

(too small)

Figueroa, García-Bellido & Torrenti 1602.03085

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).....]

- Open questions: Dark Matter? Dark Energy? WDE=-1?

- 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

Reheating? Thermalization of the Unvierse after inflation?

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

Detection of primordial tensors may help with model selection

- GW may offer a unique window also into the physics of the very early universe (before BBN) !