Probing the Early Universe with Baryogenesis & Inflation

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Outline

- **BARYOGENESIS**

    1. Electroweak baryogenesis
    2. Leptogenesis
    3. Other models

- **INFLATION**

    1. The basic picture
    2. Recent developments

I. The basic picture

Key references

A. Starobinsky ; A. Linde
K. Freese, J.A. Friemann and A.V. Olinto, Phys. Rev. Lett. 65 (1990) 3233
G. R. Dvali, Q. Shafi and R. K. Schaefer, Phys. Rev. Lett. 73 (1994) 1886

Reviews

D. Baumann, arXiv:0907.5424v2 (2012)
V. Mukhanov, *Physical Foundations of Cosmology* (2005)
D. S. Gorbunov and V.A. Rubakov, *Theory of the Early Universe, Vol II* (2012)

'Slowly rolling' scalar fields

Scalar field in curved space-time:

$$S_M = \int d^4x \sqrt{-g} L \,, \quad L = -\frac{1}{2} g_{\mu\nu} \phi \partial^\mu \partial^\nu \phi - V(\phi) \,,$$

with stress energy tensor, i.e. energy density and pressure:

$$T_{\mu\nu} = -\frac{2}{\sqrt{-g}} \frac{\delta S_M}{\delta g_{\mu\nu}} = \partial_\mu \phi \partial_\nu \phi + g_{\mu\nu} L \,,$$

$$\rho = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}(\partial_i \phi)^2 + V(\phi) \,, \quad p = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}(\partial_i \phi)^2 - V(\phi)$$

field equations: Friedman equations and equation for ϕ:

$$\ddot{\phi} + 3H\dot{\phi} + \partial_\phi V = 0$$

‘Slowly rolling’ homogeneous field ($\dot{\phi}^2 \ll V$, $|\ddot{\phi}| \ll |H\dot{\phi}|,\ |\partial_\phi V|$) satisfies ‘slow roll’ conditions:

$$\epsilon = \frac{M_{\rm P}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1\,,$$
$$\eta = M_{\rm P}^2\left|\frac{V''}{V}\right| \ll 1$$

Equations of motion for scalar field and scale factor:

$$3H\dot{\phi} = -V'\,, \quad H^2 + \frac{k}{a^2} = \frac{1}{3M_{\rm P}^2}V$$

Simplest example: *chaotic inflation*

$$V(\phi) = \lambda\phi^p$$

Important parameters for models of inflaton:

Exponential expansion, number of e-folds until end of inflation (time t_e, field value $\phi_e \ll \phi$):

$$a_e = a\ e^N\,, \quad N = \int_t^{t_e} dt H = \frac{1}{M_\mathrm{P}^2}\int_{\phi_e}^{\phi} d\phi \frac{V}{V'} = \frac{1}{2p}\frac{\phi^2}{M_\mathrm{P}^2}$$

Field at N e-folds before end of inflation:

$$\phi(N) = \sqrt{2pN} M_\mathrm{P}\,,$$

i.e. field super-Planckian for $N = 50 \ldots 60$; slow roll parameters:

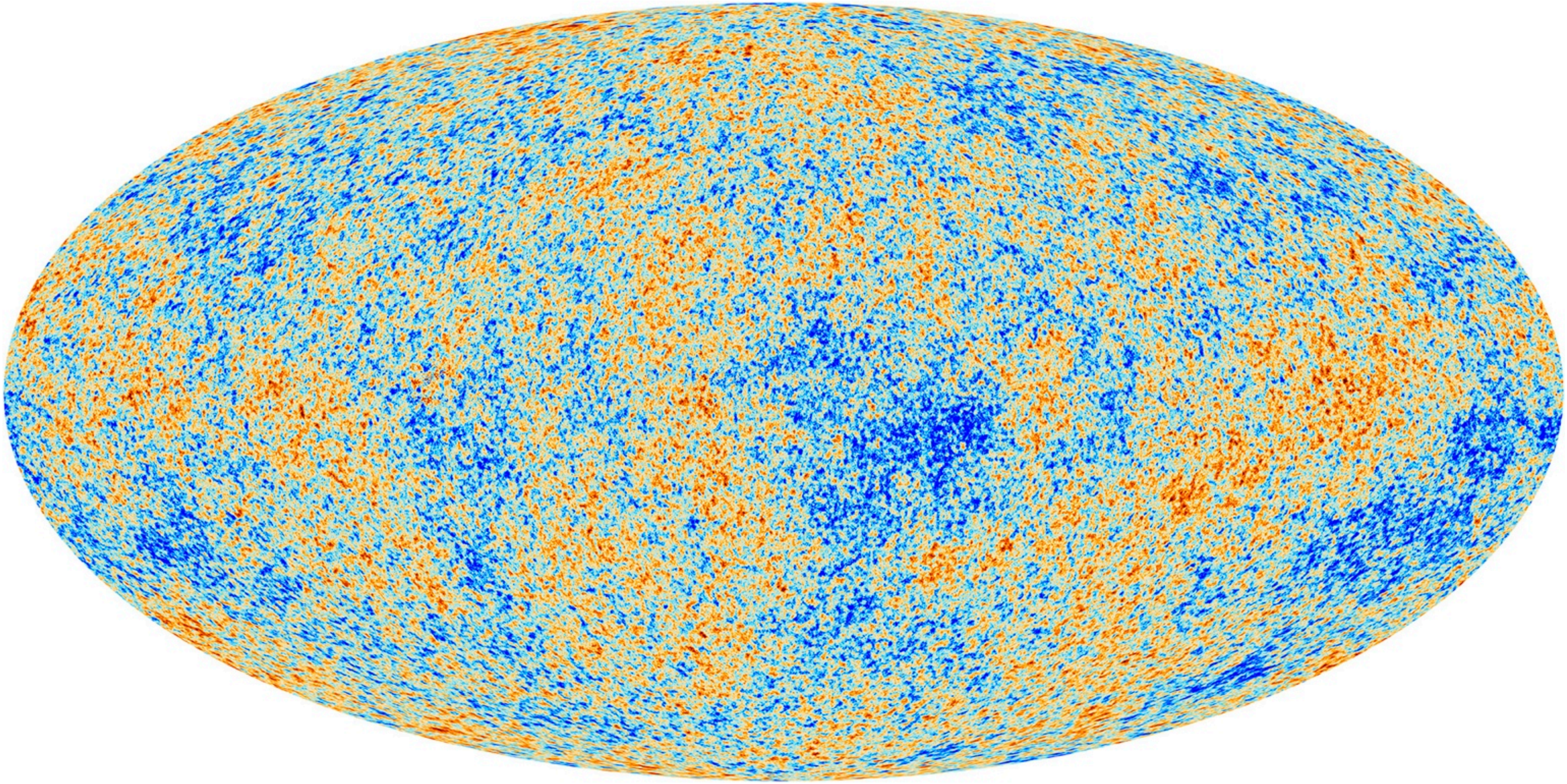
$$\epsilon = \frac{p}{4N}\,, \quad \eta = \frac{p-1}{2N}$$

Spectral indices:

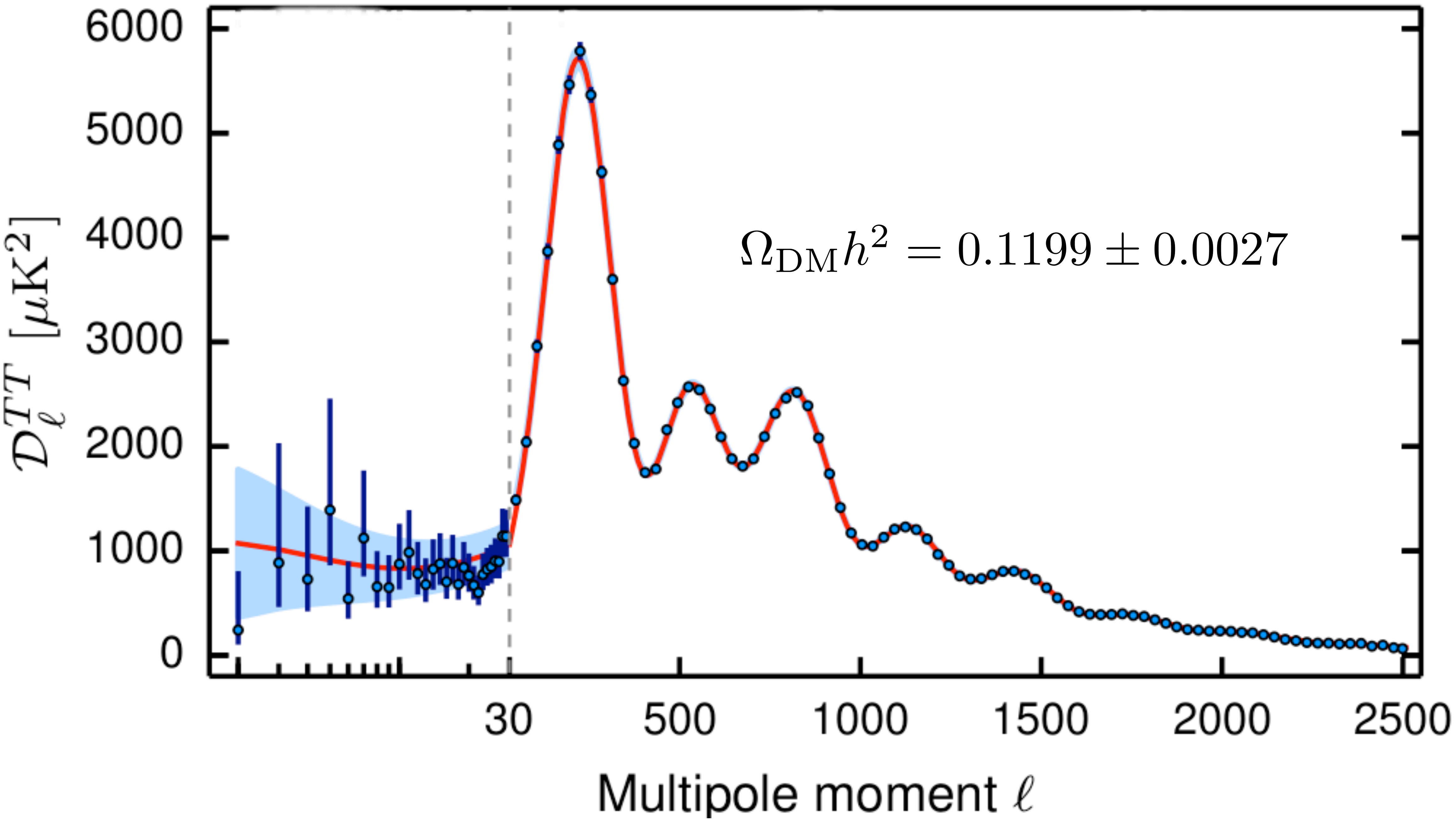
$$n_s - 1 = 2\eta - 6\epsilon = -\frac{p+2}{2N}\,, \quad n_t = -2\epsilon = \frac{p}{2N}$$

tensor-to-scalar ratio:

$$r = 8M_\mathrm{P}^2\left(\frac{V'}{V}\right)^2 = 16\epsilon$$



The microwave background sky as seen by Planck 2013: fluctuations one million times smaller than average; best evidence for hot early universe



$$\Omega_{\mathrm{DM}} h^2 = 0.1199 \pm 0.0027$$

Planck power spectrum 2015; implications: flat universe, abundance of matter & dark matter, ... ; primordial density perturbations from QUANTUM FLUCTUATIONS [Chibisov, Mukhanov ’81,...]

Correlation Functions of Photon Flux

$$\frac{\Delta T(\hat{n})}{T_0} = \sum_{lm} a_{lm} Y_{lm}(\hat{n})$$

$$C_l^{TT} \propto \sum_m \langle a_{lm}^* a_{lm} \rangle \propto \int k^2 dk \Delta_s^2(k) \Delta_{Tl}^2(k)$$

primordial density fluctuations (inflation): $\Delta_s(k)$

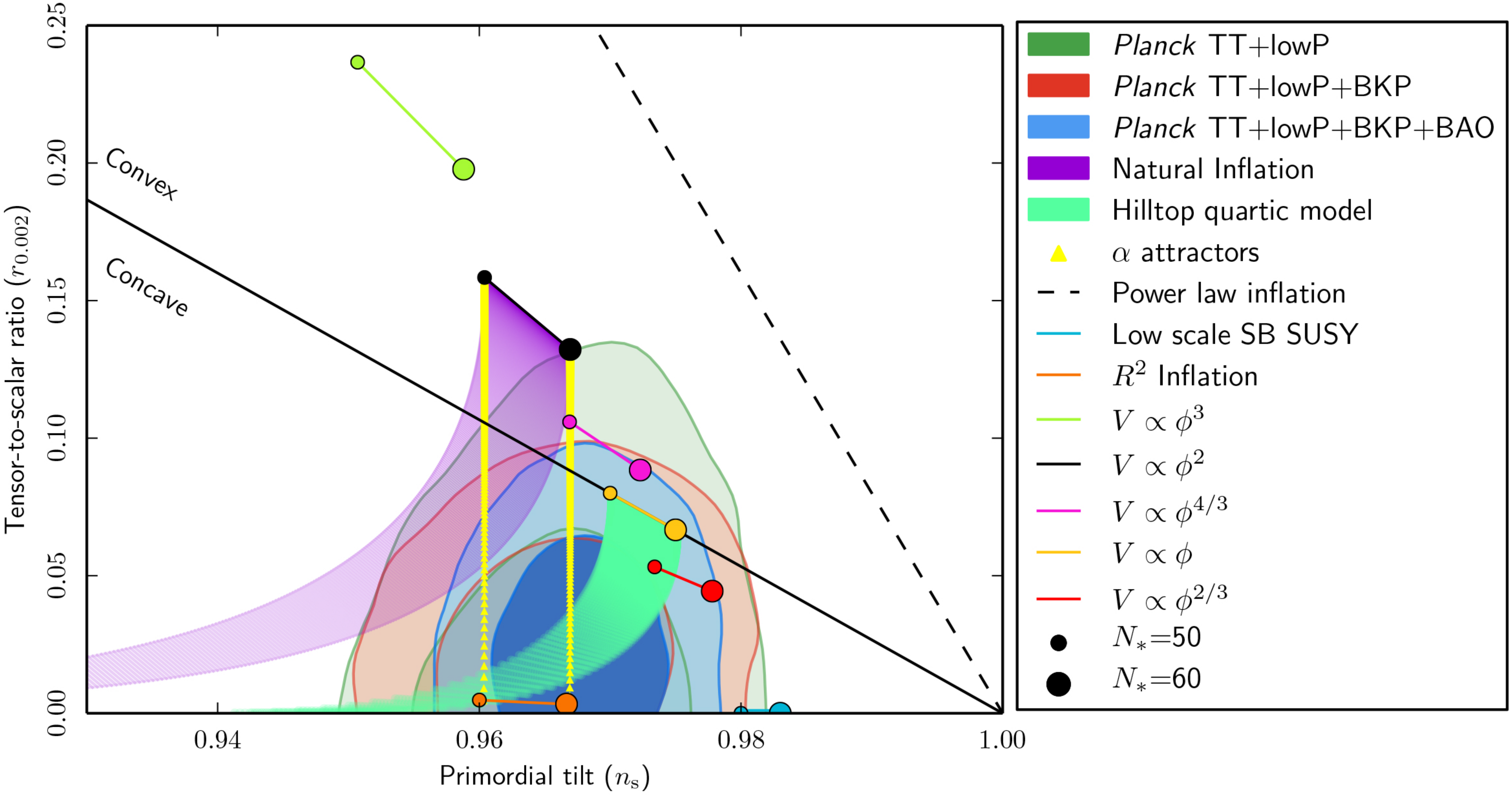
transfer functions (observable at time of photon decoupling): $\Delta_{Tl}(k)$

parametrization of primordial scalar and tensor perturbations:

$$\Delta_s^2(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1}, \quad \Delta_t^2(k) = A_t \left(\frac{k}{k_*}\right)^{n_t}, \quad r = \frac{A_t}{A_s}$$

inflationary models: testable predictions for $A_s, \; n_s, \; r$

How well do inflation models describe the Planck data?



II. Recent developments

- Example of small field inflation: hybrid inflation, connection with leptogenesis and dark matter
- Impact of BICEP2 data
- Example of large field inflation: chaotic inflation in supergravity, connection with supersymmetry breaking and moduli stabilization
- The Starobinsky model
- ...

SFI: supersymmetric hybrid inflation

[WB, Domcke, Kamada, Schmitz '13, '14]

Leptogenesis & gravitinos: for thermal leptogenesis and typical superparticle masses, thermal production yields observed amount of dark matter:

$$\Omega_{3/2}h^2 = C\left(\frac{T_R}{10^{10}\,\mathrm{GeV}}\right)\left(\frac{100\,\mathrm{GeV}}{m_{3/2}}\right)\left(\frac{m_{\tilde{g}}}{1\,\mathrm{TeV}}\right)^2 , \quad C \sim 0.5$$

$\Omega_{3/2}h^2 \sim 0.1$ is natural value; but why is reheating temperature close to minimal LG temperature?

Simple observation: heavy neutrino decay width (for typical LG parameters)

$$\Gamma_{N_1} = \frac{\widetilde{m}_1}{8\pi}\left(\frac{M_1}{v_\mathrm{F}}\right)^2 \sim 10^3\ \mathrm{GeV}\ , \quad \widetilde{m}_1 \sim 0.01\ \mathrm{eV}\ , \quad M_1 \sim 10^{10}\ \mathrm{GeV}$$

yields reheating temperature (for gas of decaying heavy neutrinos)

$$T_R \sim 0.2 \cdot \sqrt{\Gamma^0_{N_1} M_P} \sim 10^{10}\ \mathrm{GeV}$$

wanted for gravitino DM. *Intriguing hint or misleading coincidence?*

Spontaneous B-L breaking & false vacuum decay

Supersymmetric SM with right-handed neutrinos:

$$W_M = h^u_{ij}\mathbf{10}_i\mathbf{10}_j H_u + h^d_{ij}\mathbf{5}^*_i\mathbf{10}_j H_d + h^\nu_{ij}\mathbf{5}^*_i n^c_j H_u + h^n_i n^c_i n^c_i S_1$$

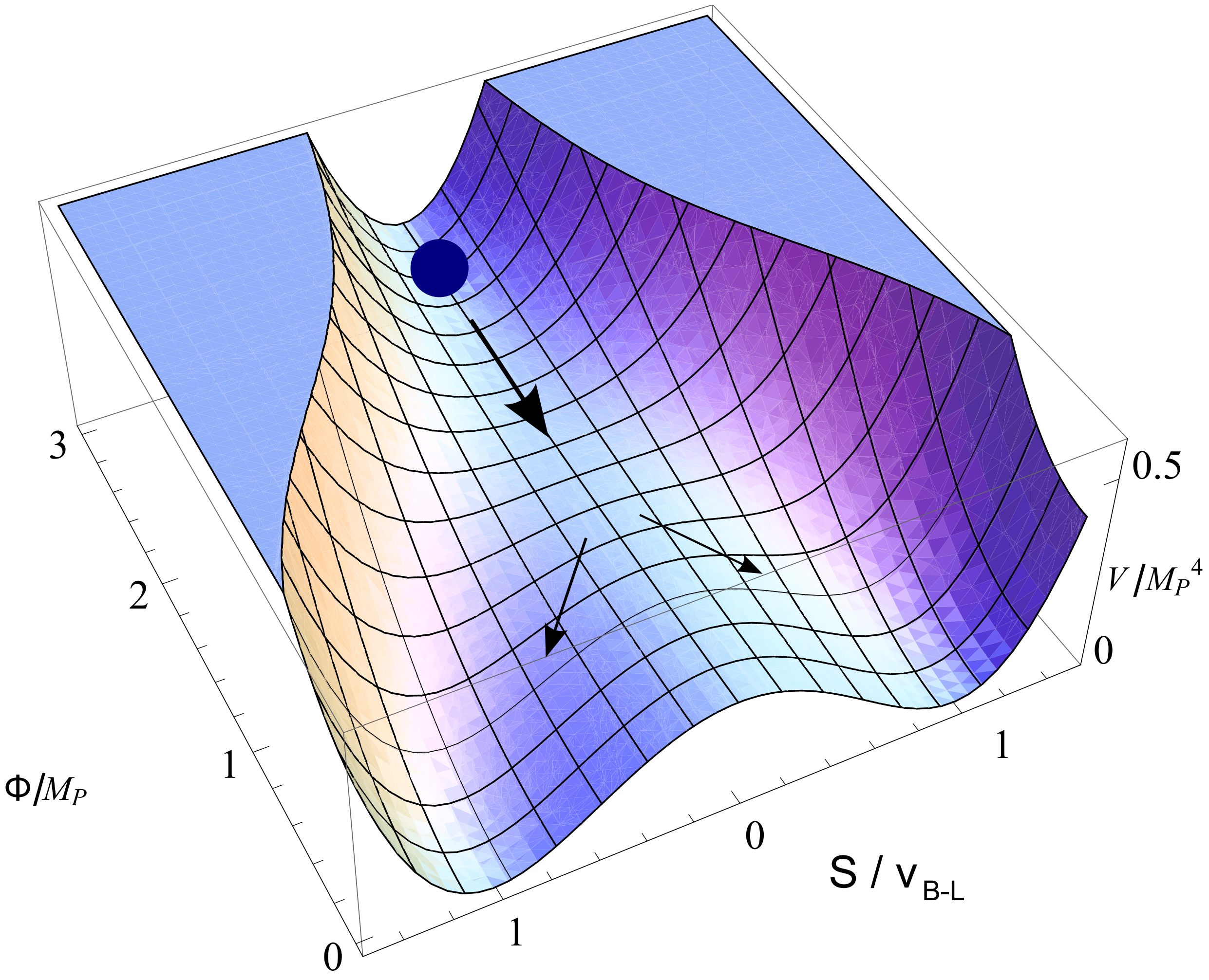
in SU(5) notation: $\mathbf{10} \supset (q, u^c, e^c),\ \mathbf{5}^* \supset (d^c, l),\ n^c \supset (\nu^c)$; B-L breaking:

$$W_{B-L} = \lambda\Phi\left(\frac{1}{2}v^2_{B-L} - S_1 S_2\right)$$

$\langle S_{1,2}\rangle = v_{B-L}/\sqrt{2}$ yields heavy neutrino masses.

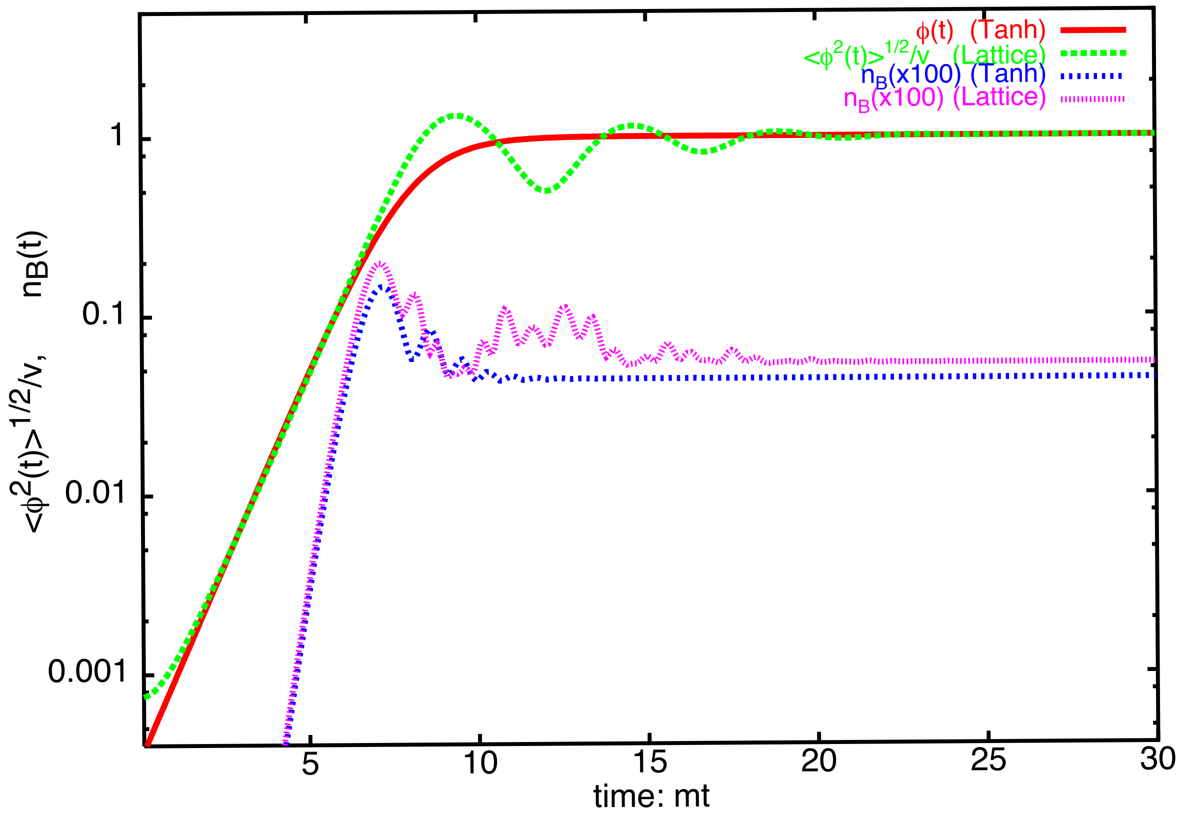
Lagrangian is determined by low energy physics: quark, lepton, neutrino masses etc, but it *contains all ingredients wanted in cosmology*: inflation, leptogenesis, dark matter, ..., all related!

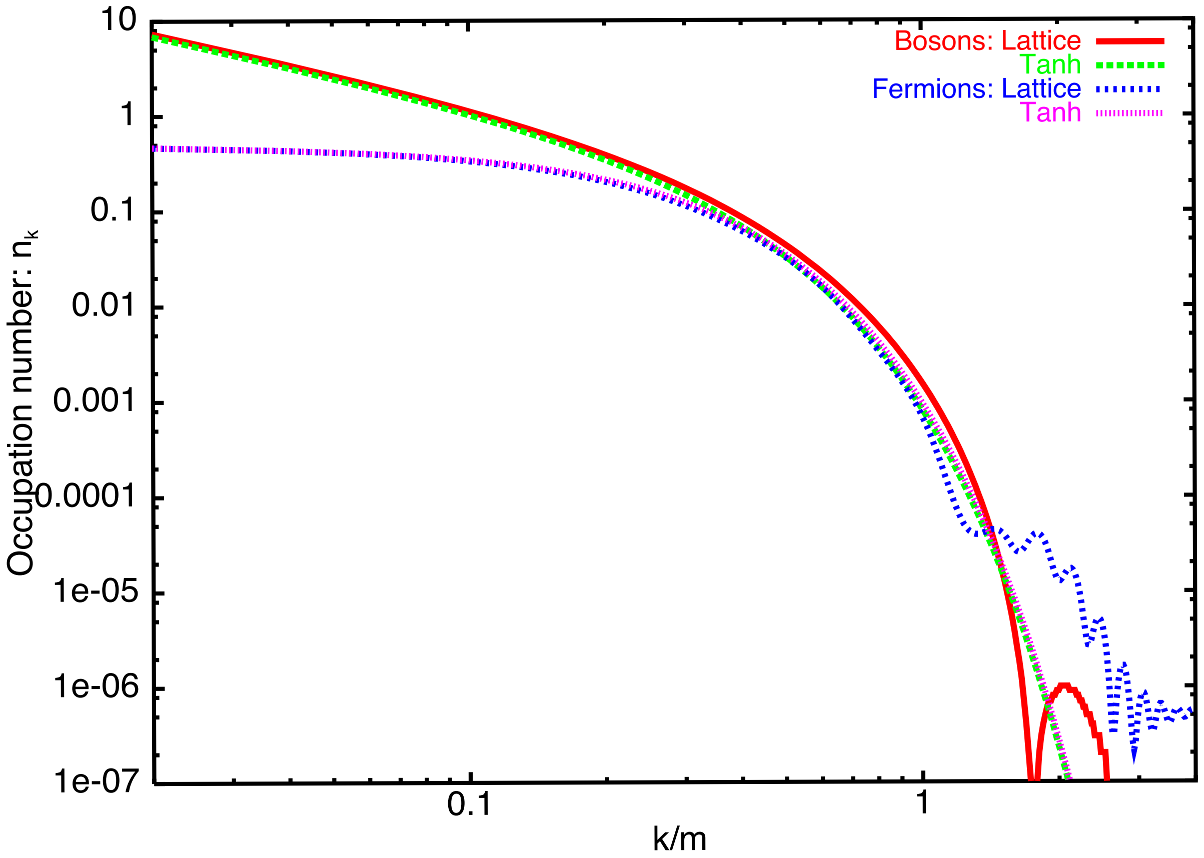
Technically: Abelian Higgs model in unitary gauge; inflation ends with phase transition (“tachyonic preheating”, “spinodal decomposition”)



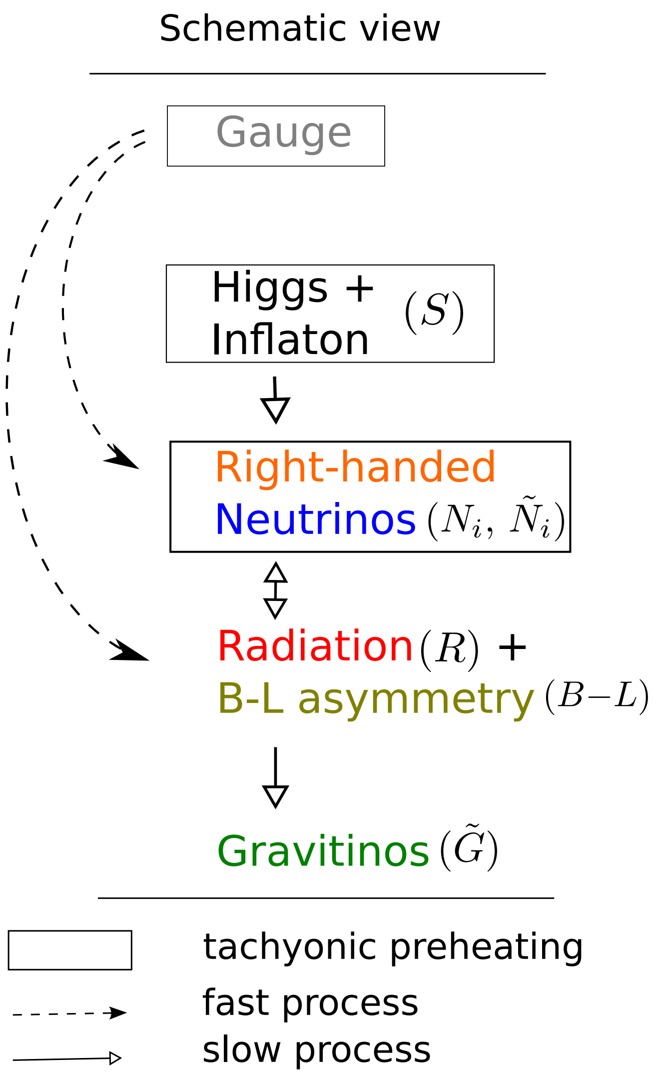
time-dependent masses of B-L Higgs, inflaton, heavy neutrinos ... (bosons and fermions):

$$m_\sigma^2 = \frac{1}{2}\lambda(3v^2(t) - v_{B-L}^2)\ , \quad m_\phi^2 = \lambda v^2(t)\ , \quad M_i^2 = (h_i^n)^2 v^2(t)\ \ldots$$





Rapid transition from false to true vacuum by fluctuations of 'waterfall' B-L Higgs field; production of low momentum Higgs bosons (contain most energy), also other bosons and fermions coupled to B-L Higgs field [Garcia-Bellido, Morales '02], production of cosmic strings: initial conditions for reheating



Schematic view

Gauge

Higgs + Inflaton (S)

Right-handed Neutrinos $(N_i,\, \tilde{N}_i)$

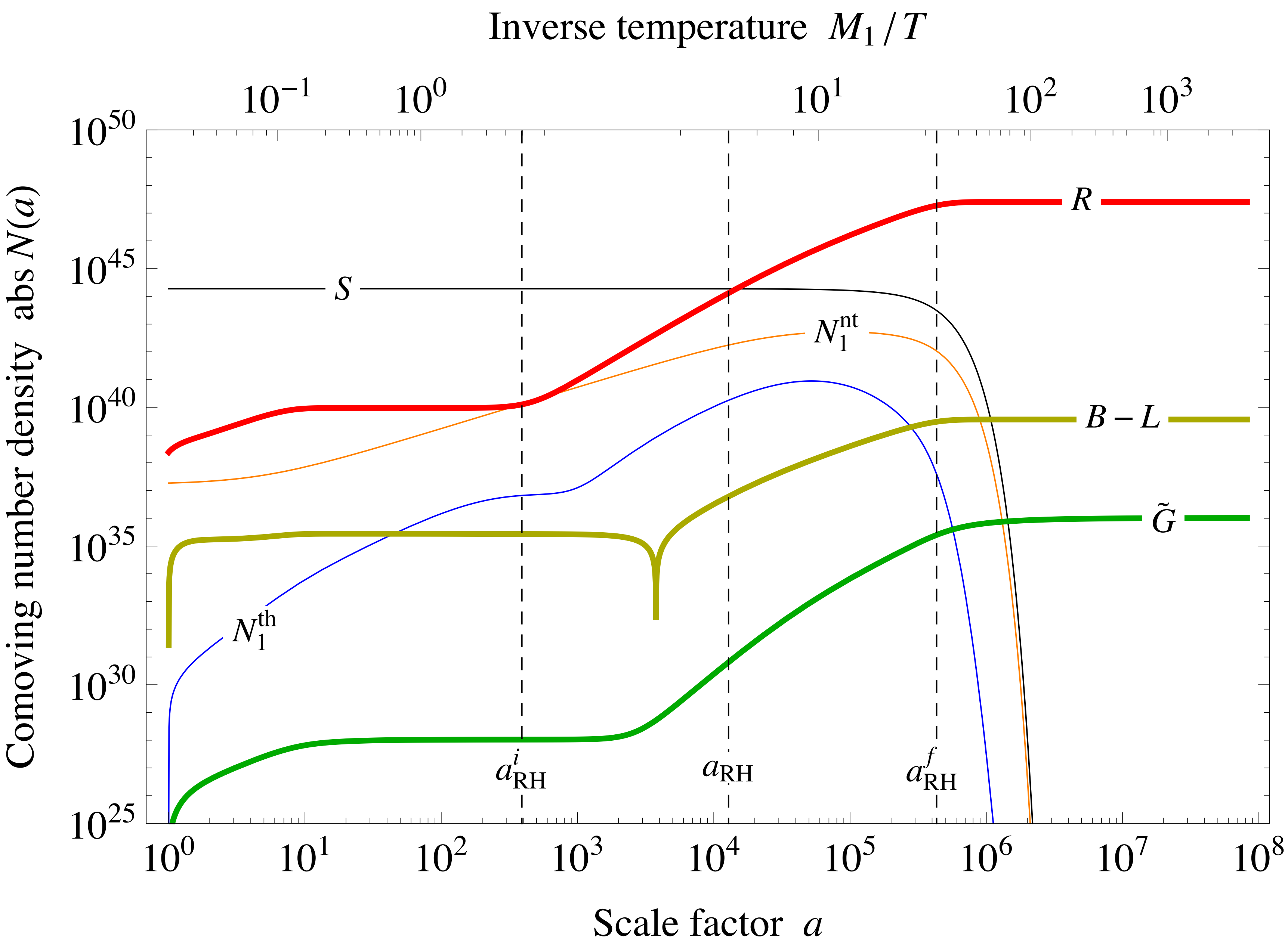
Radiation (R) + B-L asymmetry $(B\!-\!L)$

Gravitinos $(\tilde{G})$

tachyonic preheating

fast process

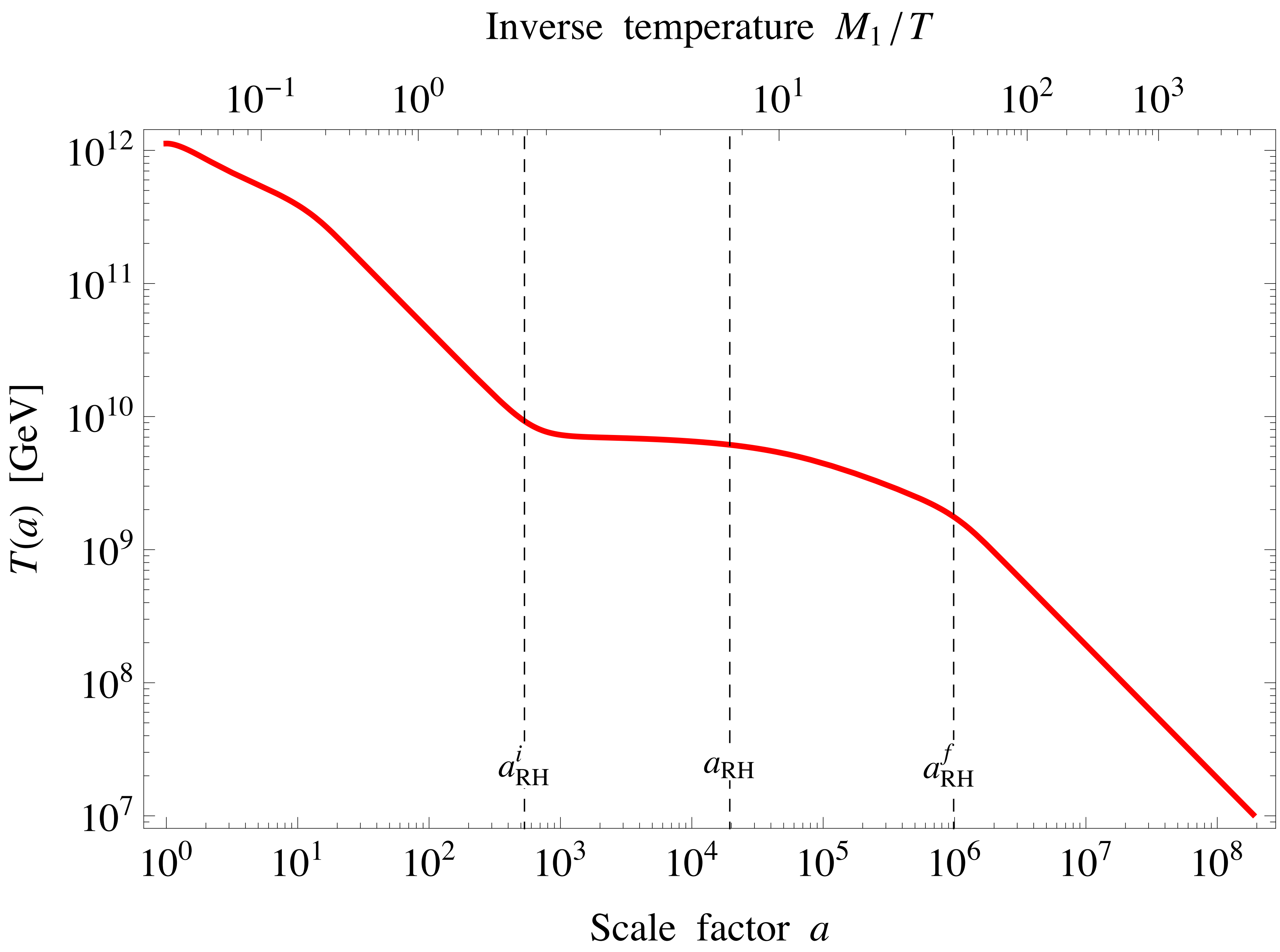
slow process



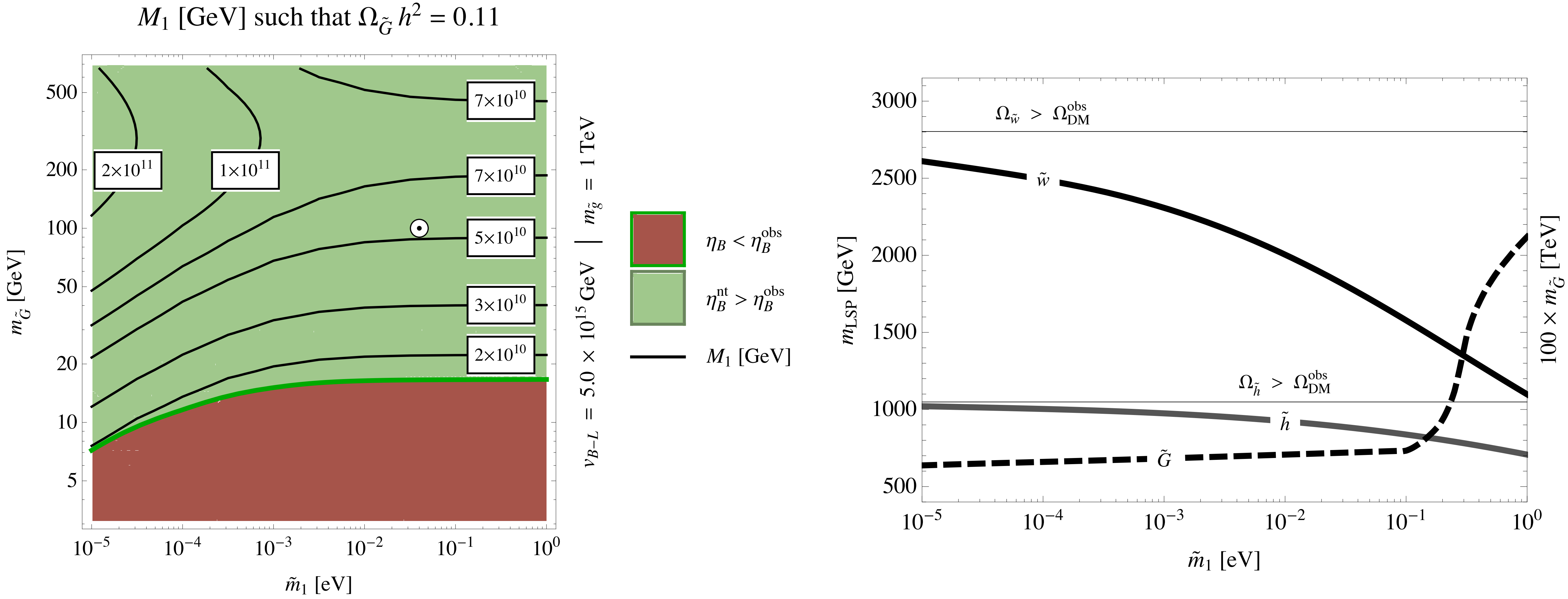
Transition from end of inflation to hot early universe (typical parameters), calculated by means of Boltzmann equations:

$$E\left(\frac{\partial}{\partial t} - Hp\frac{\partial}{\partial p}\right) f_X(t,p) = \sum_{i'j'..}\sum_{ij..} C_X(Xi'j'.. \leftrightarrow ij..)$$

yields *correct baryon asymmetry* and *dark matter abundance*



Time evolution of temperature: intermediate plateau ("maximal temperature"), determined by neutrino properties! Yields correct *gravitino abundance* when combined with 'standard formula'



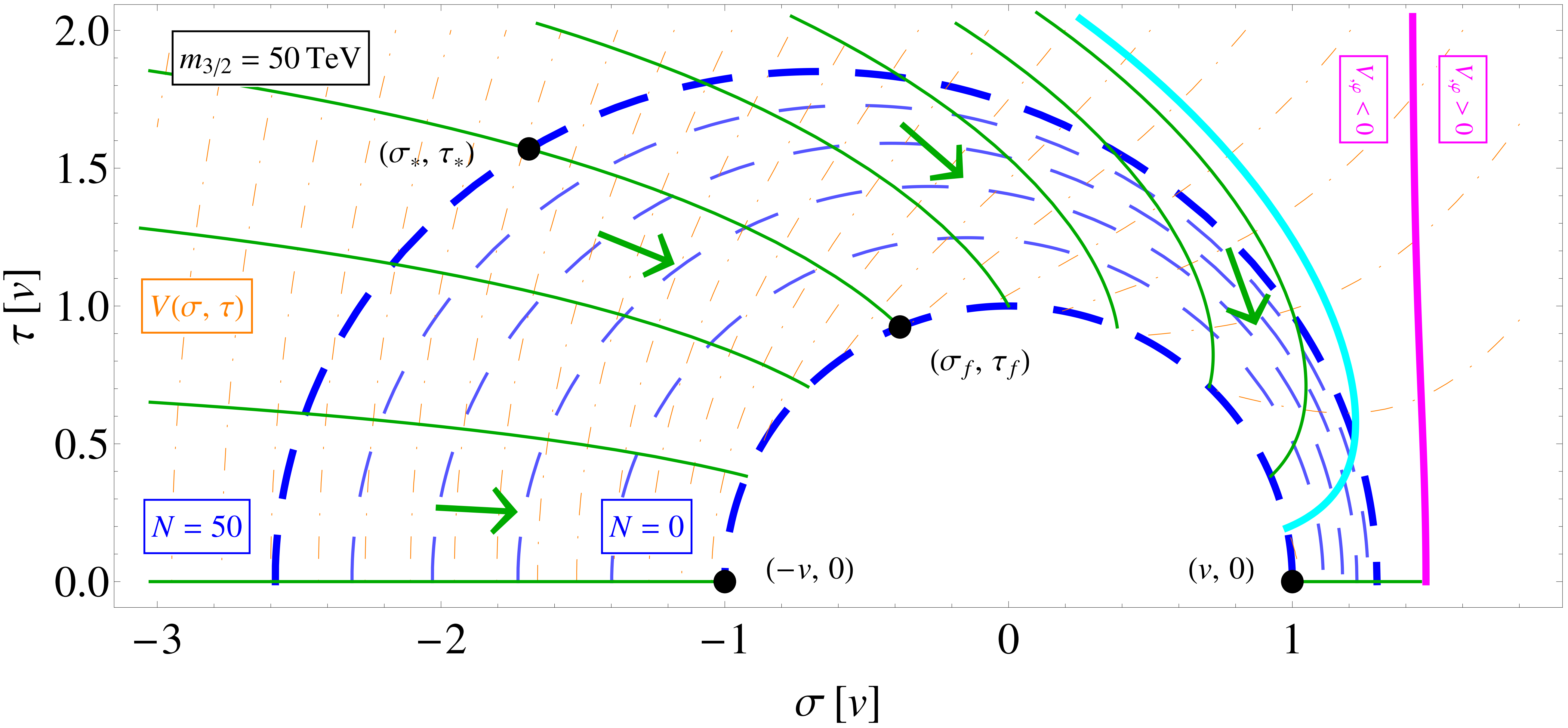
Predictions for LHC (parameter scans): successful leptogenesis and *gravitino DM* (left) or *neutralino DM* (right, upper bounds) [non-thermally produced in decays of thermally produced gravitinos] constrains neutrino and superparticle masses

Spectral index & supersymmetry breaking

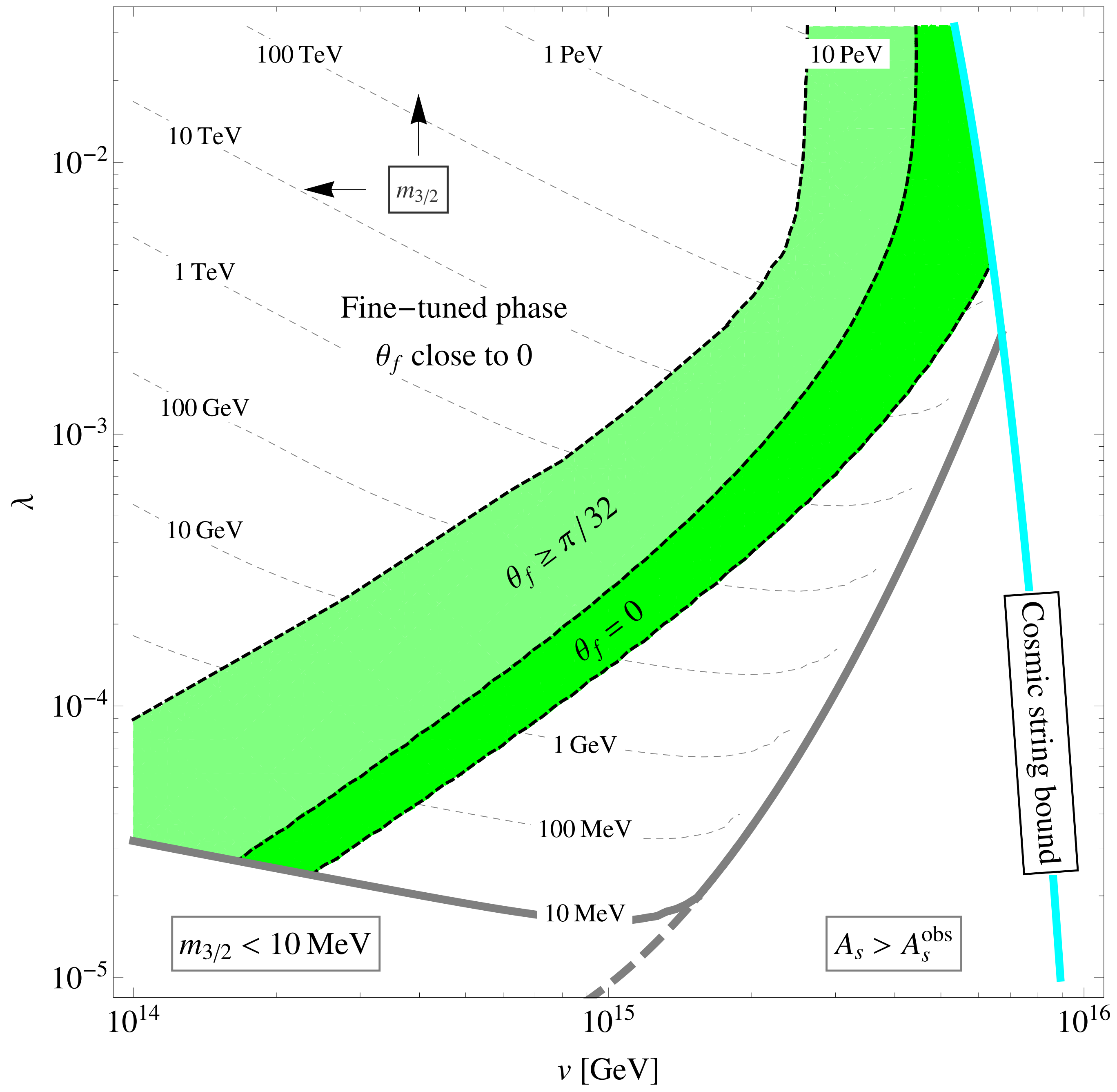
Inflationary potential can be strongly affected by supersymmetry breaking (supergravity correction):

$$
\begin{aligned}
V(\phi) &= V_0 + V_{\mathrm{CW}}(\phi) + V_{\mathrm{SUGRA}}(\phi) + V_{3/2}(\phi) \ , \\
V_0 &= \frac{\lambda^2 v^4}{4} \ , \\
V_{\mathrm{CW}}(\phi) &= \frac{\lambda^4 v^4}{32\pi^2} \ln\left(\frac{|\phi|}{v/\sqrt{2}}\right) + \ldots \ , \\
V_{\mathrm{SUGRA}}(\phi) &= \frac{\lambda^2 v^4}{8M_{\mathrm{P}}^4} |\phi|^4 + \ldots \ , \\
V_{3/2}(\phi) &= -\lambda v^2 m_{3/2}(\phi + \phi^*) + \ldots
\end{aligned}
$$

linear term turns hybrid inflation into two-field model in complex plane; strong effect on inflatonary observables, now dependent on trajectory, i.e. initial conditions! Inflation consistent with Planck data now possible (otherswise very difficult)

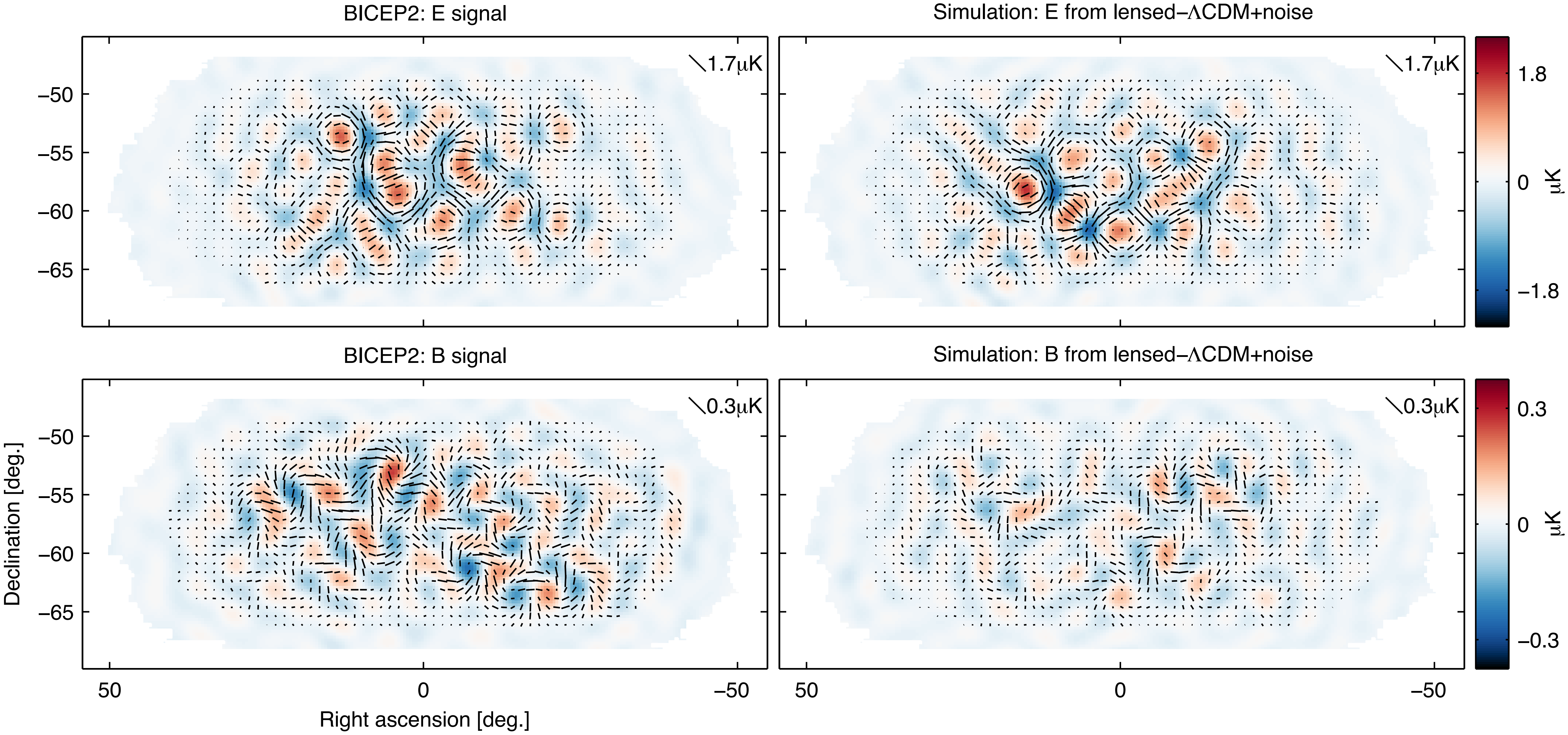


Two-field dynamics of complex inflaton in field space; all trajectories provide enough e-folds of expansion but only one yields the correct spectral index $n_s \simeq 0.96$



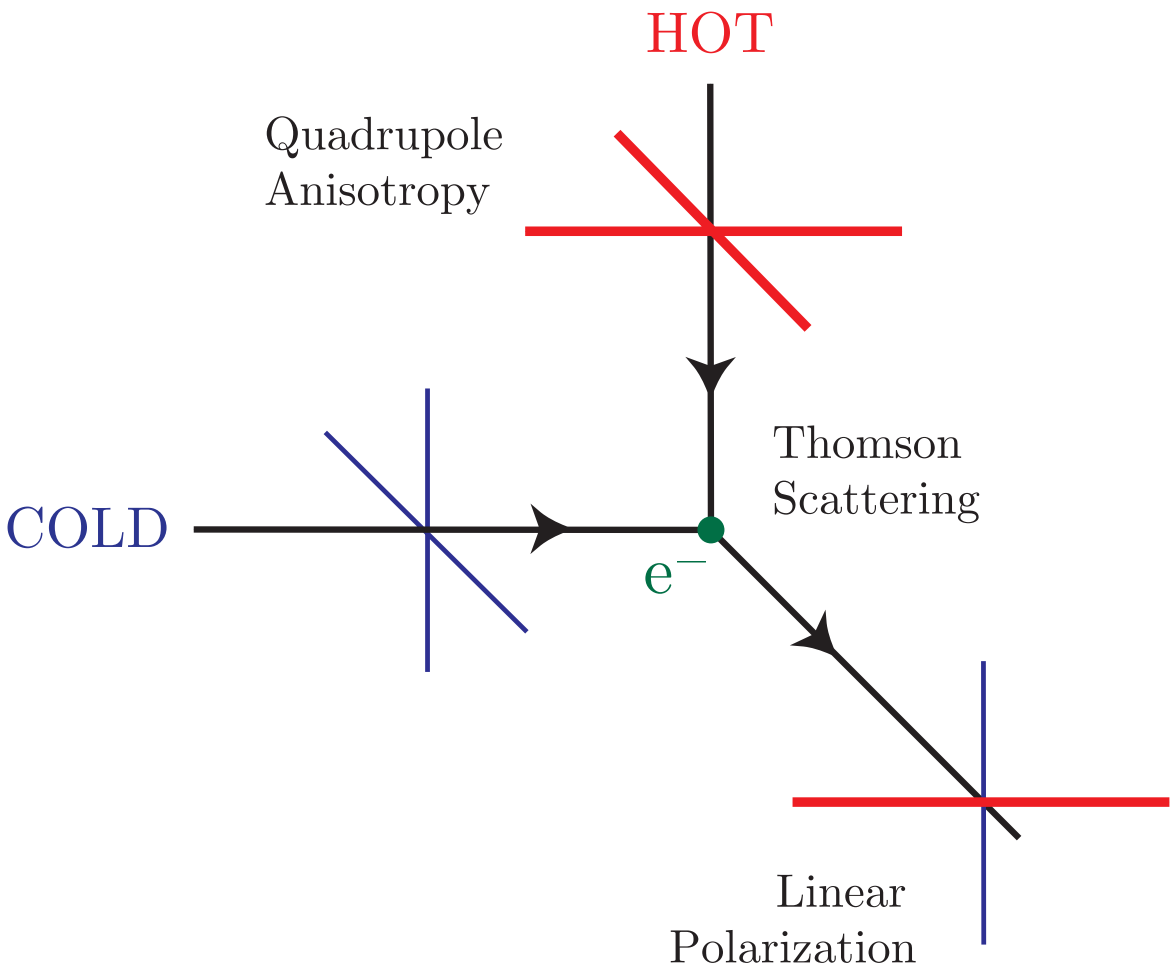
Parameter scan: relations between scale of B-L breaking, gravitino mass and scalar spectral index (no problem!) cosmic string bound automatically fulfilled!
Predicted tensor-to-scalar ratio: $r \lesssim 2 \times 10^{-6}$!! (typical for SF models)

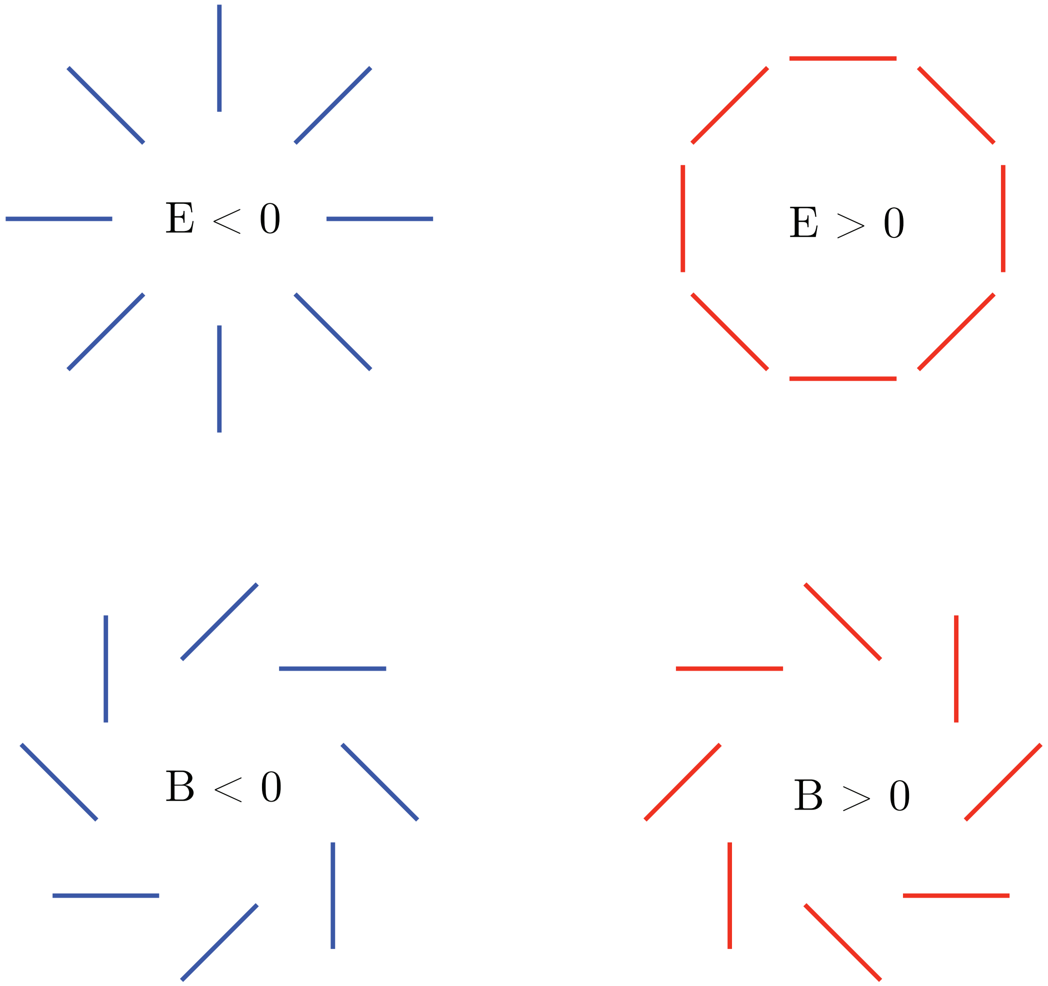
March 2014: BICEP2 Results



Have primordial gravitational waves been discovered in the CMB?

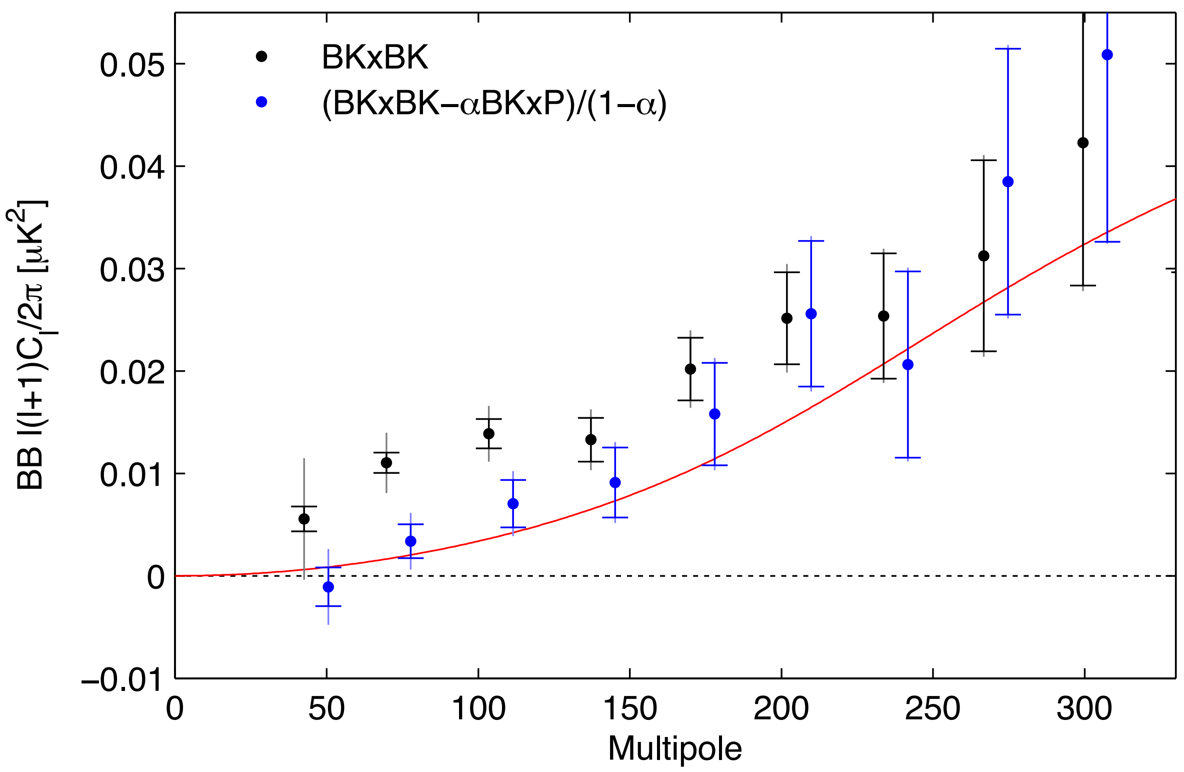
$r \simeq 0.2$? BICEP2/Keck/Planck analysis: mostly dust!

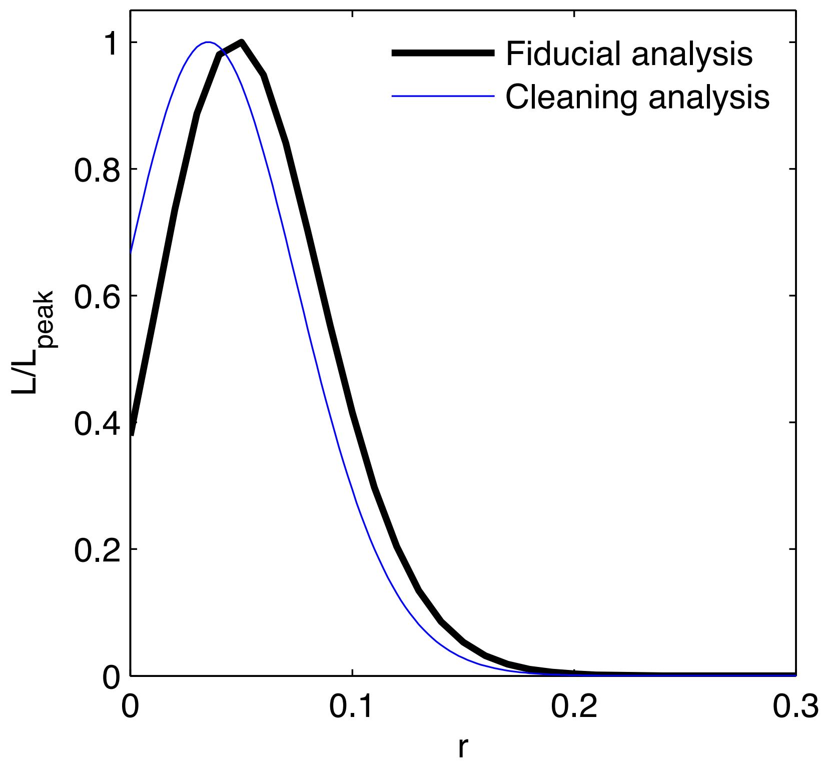




[adapted from Baumann '12]

Polarization: density quadrupole anisotropy generates via Thompson scattering of polarized photons; analysis of tensor spherical harmonics: two patterns of linear polarization, E-modes and B-modes (different under space relection); origin of B-modes: gravitational waves, dust ...





Joint BICEP2/Keck/Planck analysis (2015)

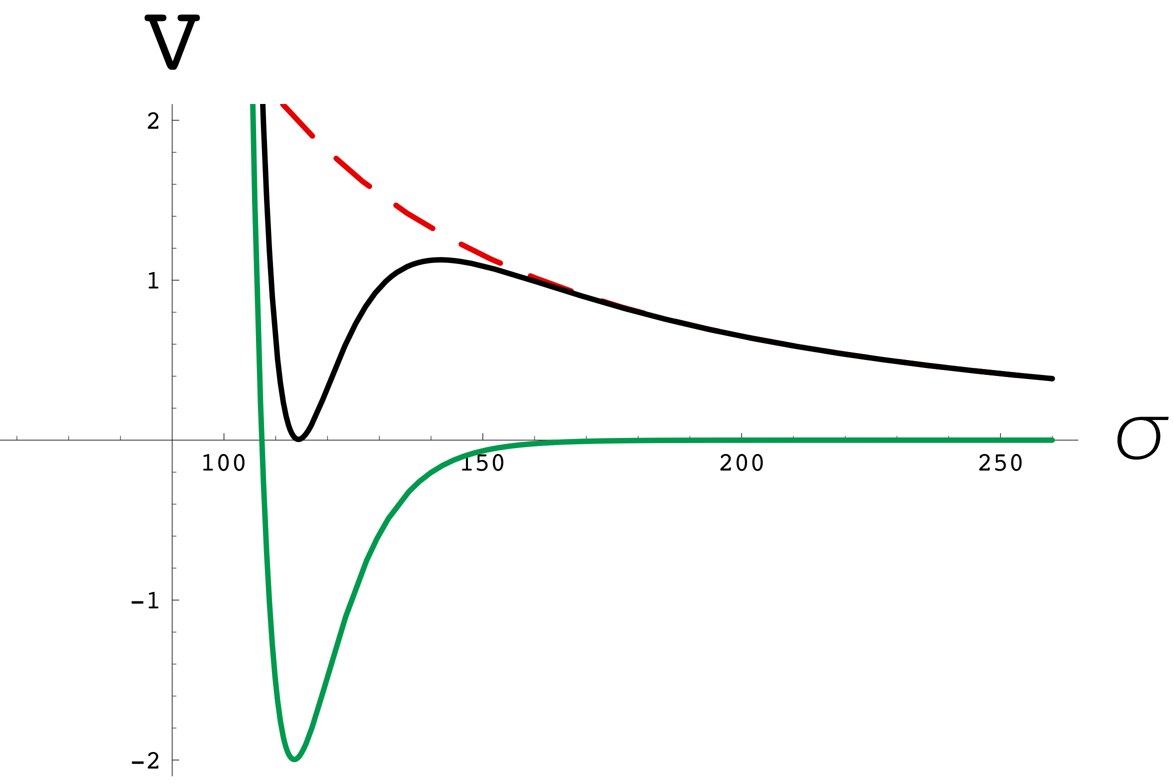
upper: BICEP2/Keck spectrum before and after subtraction of dust contribution

lower: likelihood fit; primordial BB signal almost 2σ effect; favoured value of r about 0.05

More data this year, BB signal not yet excluded !!

LFI: chaotic inflation in supergravity

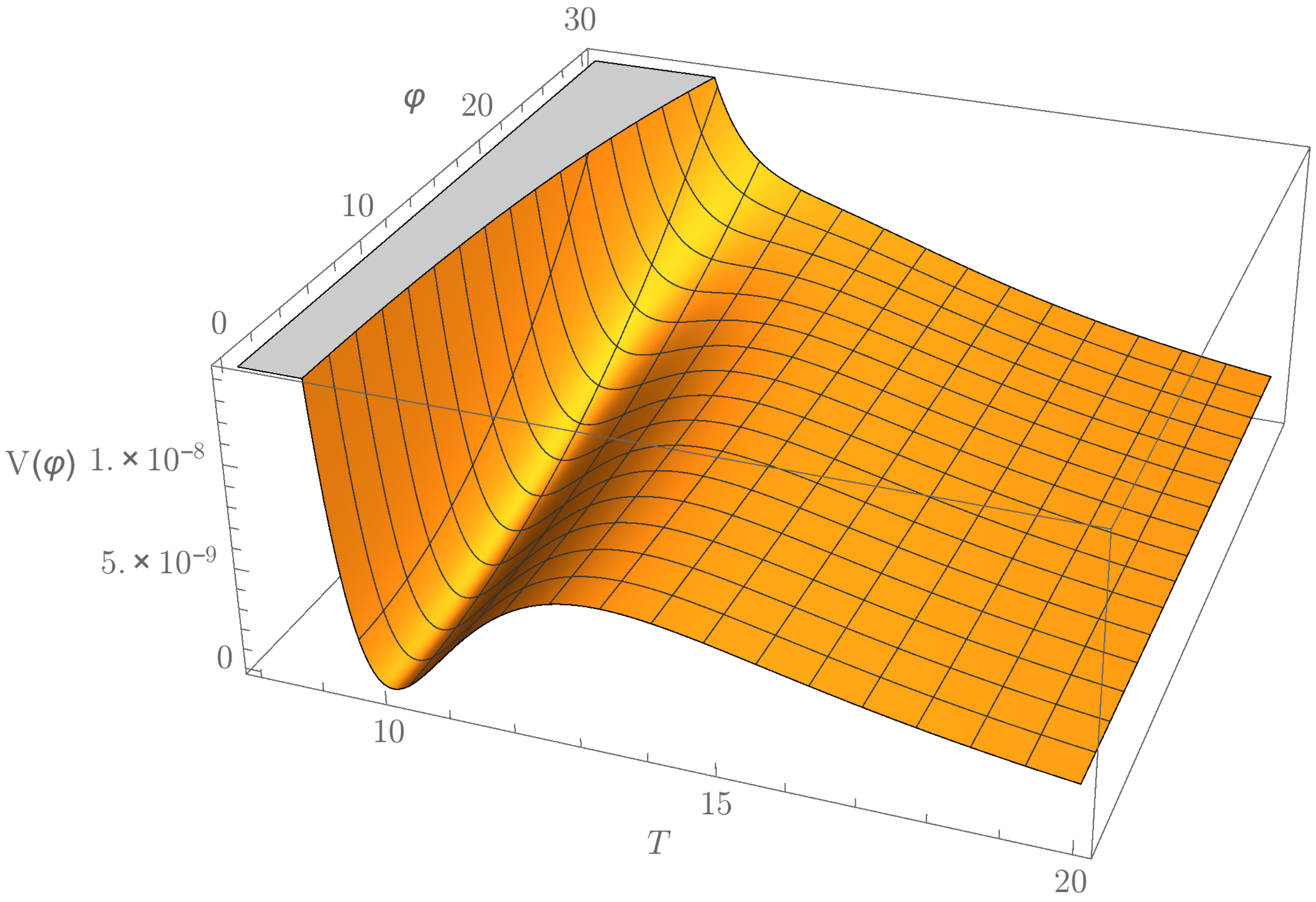
Motivation: Planck/BICEP2 data, LFI in effective field theory (supergravity), recent work in string inflation(axion monodromy, "aligned axions", inflation in F-theory models...). Minimal setup: inflaton, volume modulus (e.g. KKLT), supersymmetry breaking and uplift to Minkowski vacuum from AdS vacuum (eg. Polonyi field) [WB, Dudas, Heurtier, Westphal, Wieck, Winckler '15]



$$W = W_0 + Ae^{-aT} + fX + \frac{1}{2}m\phi^2\,,$$

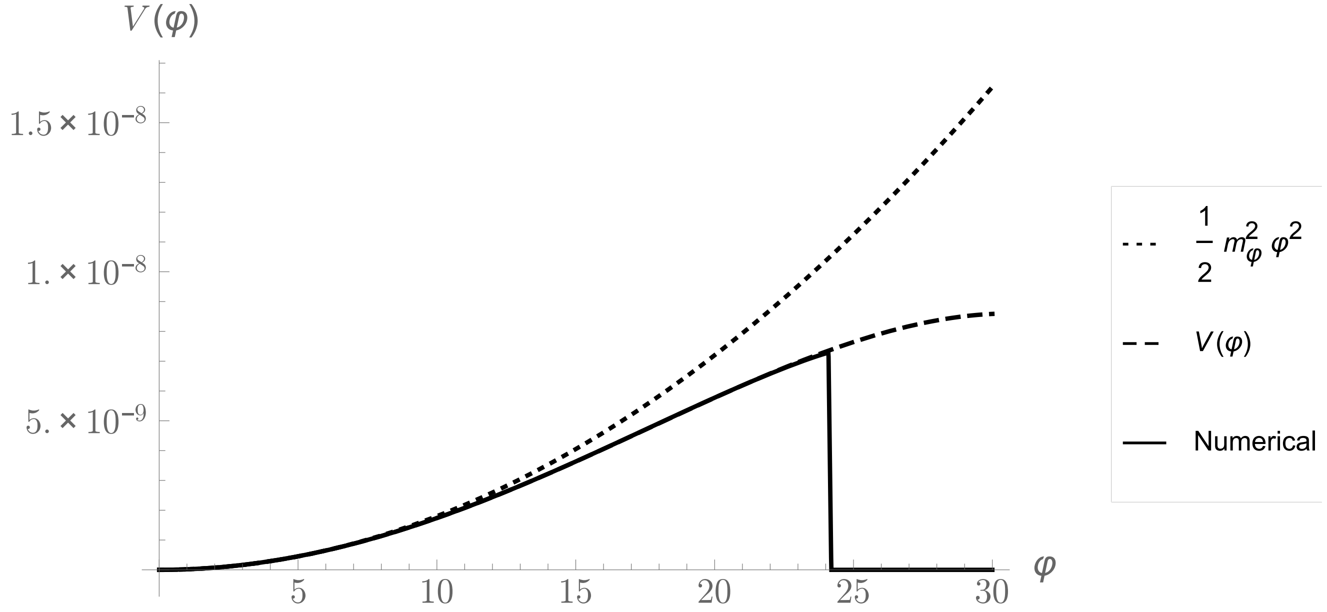
$$K = -3\ln\left(T+\overline{T}\right) + k\left(|X|^2\right) + \frac{1}{2}\left(\phi+\bar{\phi}\right)^2$$

super- & Kahler potential for modulus, Polonyi field and *inflaton* yield supergravity scalar potential



local minimum for modulus exits for sufficiently small inflaton field; integrating out the modulus yields effective inflaton potential:

$$V(\varphi) \approx \frac{3}{2}\tilde{m} m_{3/2}\varphi^2 \left(1 - \frac{1}{8}\frac{\tilde{m}}{m_{3/2}}\varphi^2\right)$$

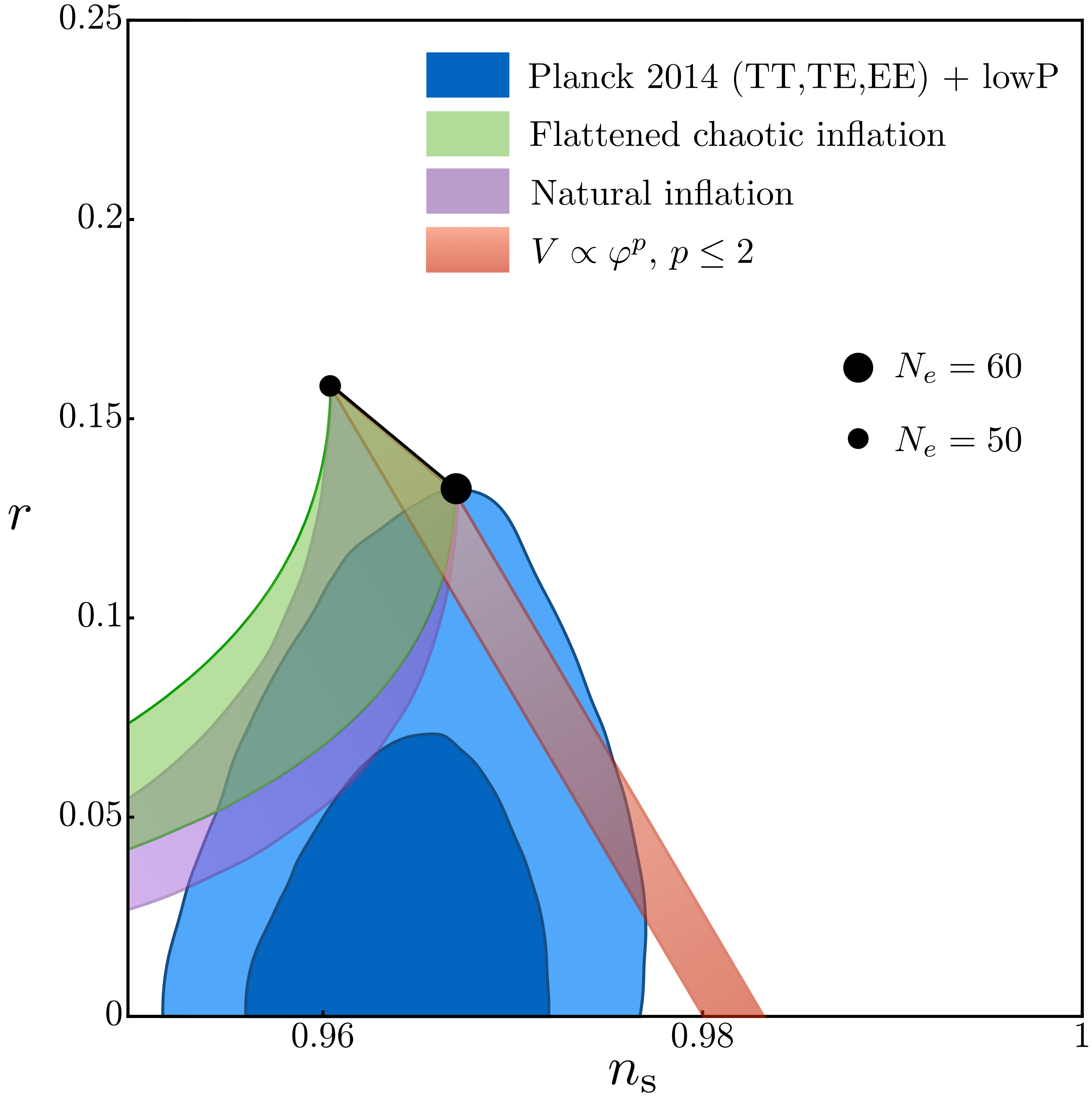


preditions:

$$m_{3/2} > \sqrt{|\tilde{m} m_{3/2}|}\,\varphi_\star$$

$$\sim 5 \times 10^{-5} \approx 10^{14}\ \text{GeV}$$

$$n_s = 0.966\,, \quad r = 0.106$$



flattening of chaotic potential due to moduli effects is generic phenomenon

resulting effective inflation potentials probably still not good enough to fit the Planck data

The Starobinsky model

Consider modified gravitational action:

$$S = -\frac{M_{\mathrm{P}}^2}{2}\int d^4x\sqrt{-g}f(R)\,, \quad f(R) = R - \frac{1}{6M^2}R^2$$

perform Weyl rescaling, $g_{\mu\nu} = \phi\tilde{g}_{\mu\nu}$, then

$$S = -\frac{M_{\mathrm{P}}^2}{2}\int d^4x\left(\sqrt{-\tilde{g}}\tilde{R} + \frac{3}{2\phi^2}\tilde{g}^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + \frac{3M^2}{2}\frac{(1-\phi)^2}{\phi^2}\right)$$

change to canonically normalized field, $\phi = \exp{(2/\sqrt{6})\varphi/M_{\mathrm{P}}}$,

$$S = -\frac{M_{\mathrm{P}}^2}{2}\int d^4x\left(\sqrt{-\tilde{g}}\tilde{R} + \frac{1}{2}\tilde{g}^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + V(\varphi)\right)\,, \quad V(\phi) = \frac{3}{4}M^2M_{\mathrm{P}}^2\left(1 - e^{-\frac{2}{\sqrt{6}}\frac{\varphi}{M_{\mathrm{P}}}}\right)^2$$

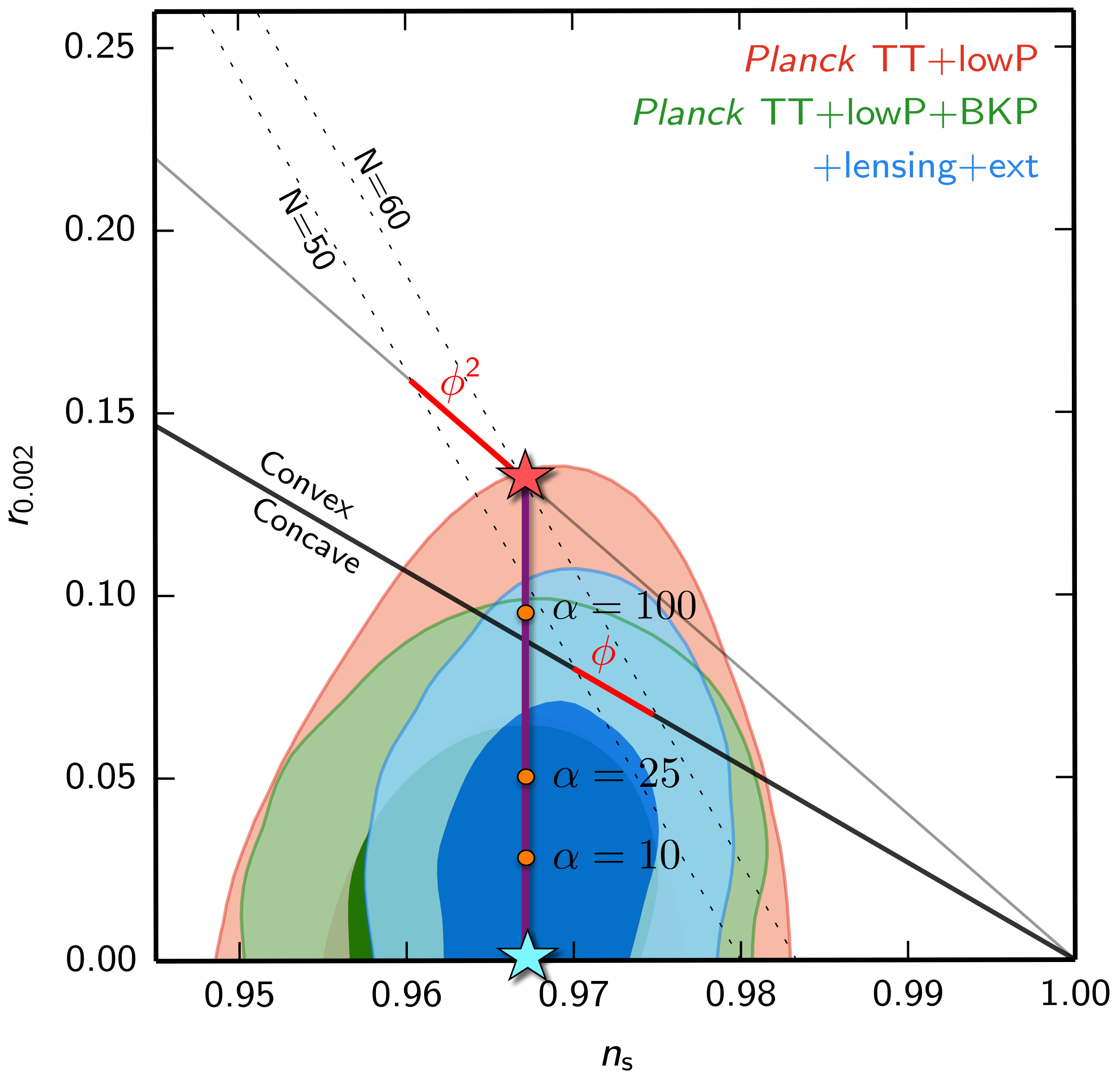
perfect model of inflation:

$$n_s \simeq 1 - \frac{2}{N} \simeq 0.9636\,, \quad r \simeq \frac{12}{N^2} \simeq 0.004$$

Why ???

Escher in the sky

[Kallosh, Linde ’15]



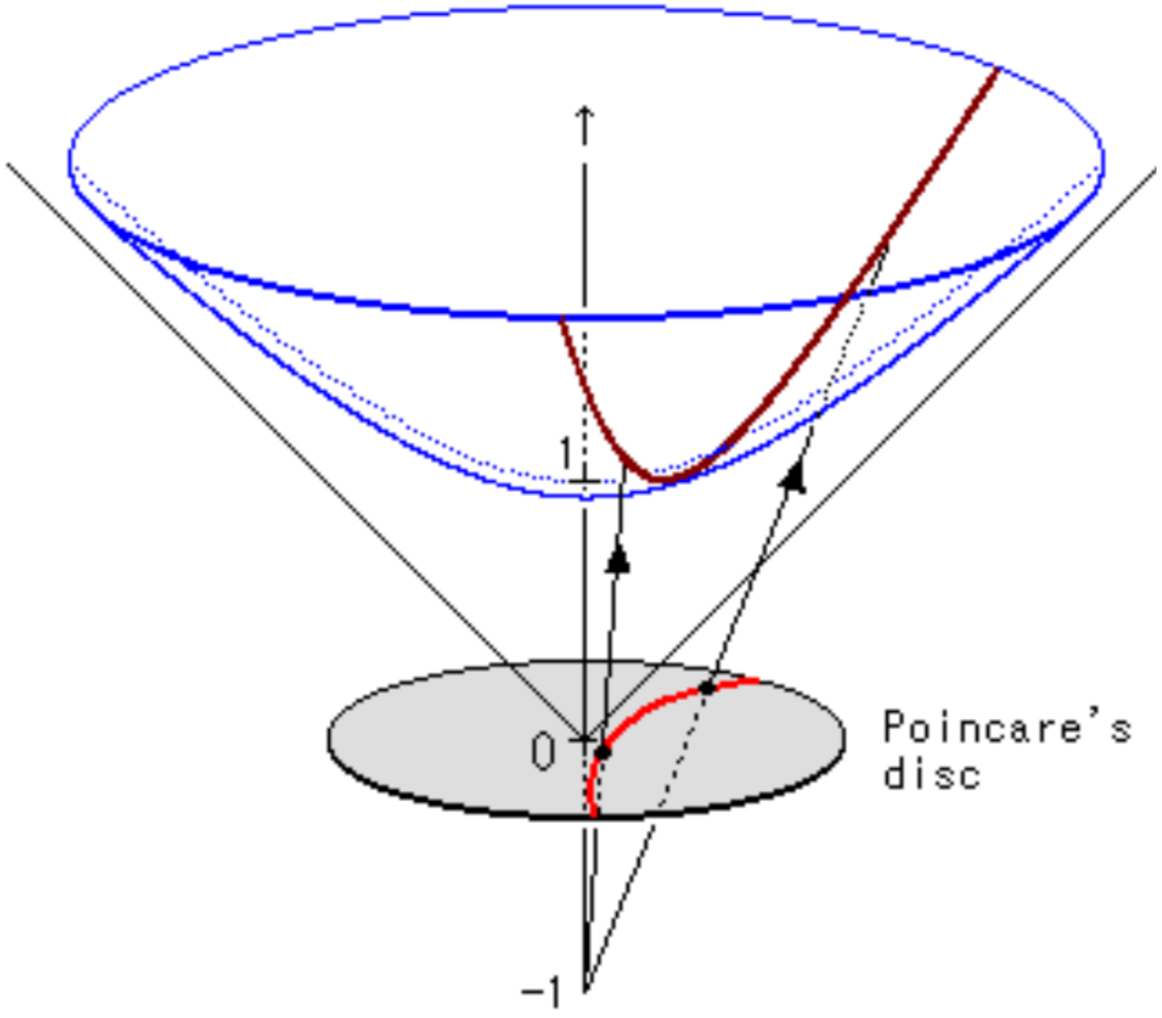
class of potentials that interpolate between chaotic and Starobinsky:

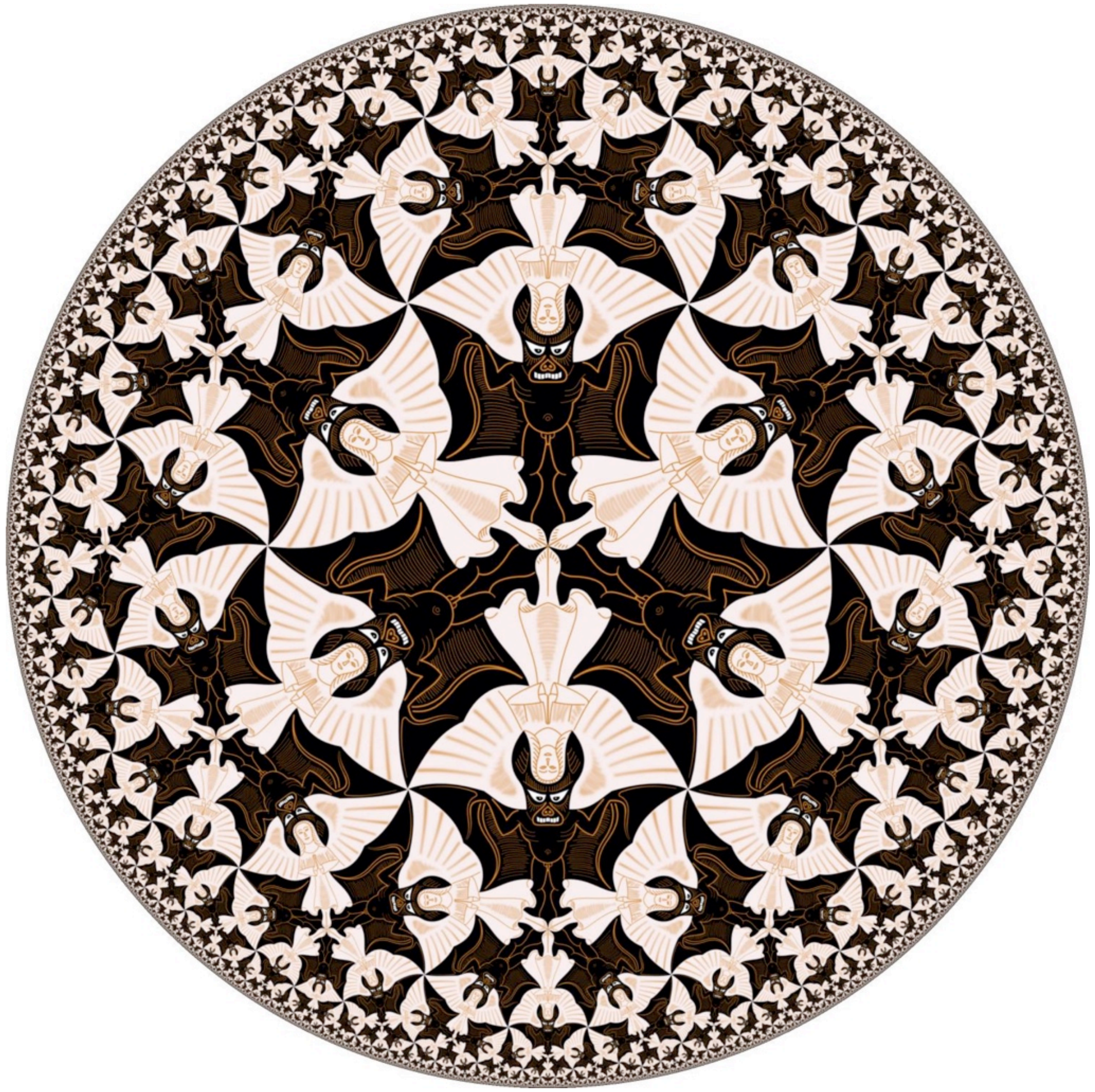
$$\frac{1}{\sqrt{-g}}\mathcal{L} = \frac{1}{2}R - \frac{1}{2}\frac{\partial\phi^2}{(1-\frac{\phi^2}{6\alpha})^2} - \frac{1}{2}m^2\phi^2$$

$$\sim \frac{1}{2}R - \frac{1}{2}\partial\varphi^2 - 3\alpha m^2 \tanh^2 \frac{\varphi}{\sqrt{6\alpha}}$$

preditions:

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





metric on hyperboloid with radius of Poincare's disk:

$$ds^2 = \frac{dx^2 + dy^2}{\left(1 - \frac{x^2+y^2}{3\alpha}\right)^2}\,, \qquad R = \sqrt{3\alpha}$$

... this should inspire your future work about the early universe...