B-Polarisation and primordial inflation

Christophe Ringeval
Centre for Cosmology, Particle Physics and Phenomenology
Institute of Mathematics and Physics
Louvain University, Belgium

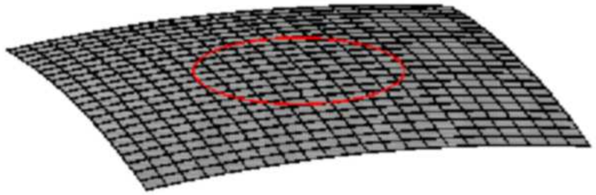
Firenze, 8/09/2016

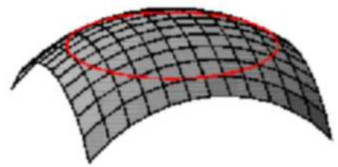
Outline

Motivations

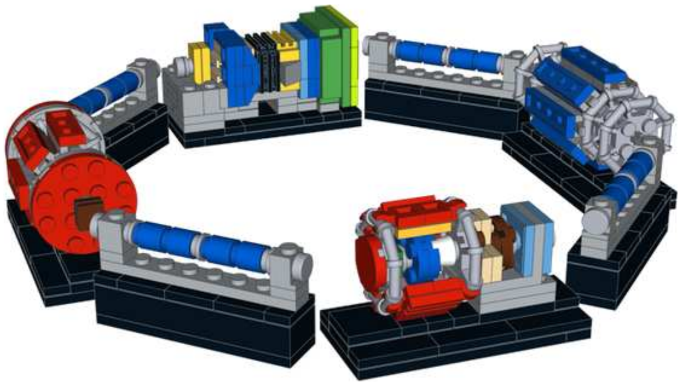
What is primordial inflation?

- A yet to be proven theoretical paradigm describing the early Universe:
  - Our Universe should have undergone a phase a exponentially fast accelerated expansion
  - Length scales $\times e^N$ with $N > 60$ (e-folds)
  - Occured at a redshift: $z_{\rm inf} > 10^{10}$
  - Could have lasted from 10^{-32} s to an infinite amount of time





- Energy involved: $10\,\mathrm{MeV} \ll E_{\rm inf} < 10^{16}\,\mathrm{GeV}$
  - $10^{16}\,\mathrm{GeV} = 1000$ billion times the energy of the LHC (7.5 billion €)



Solves the shortcomings of the Big-Bang model

- Originally proposed to solve the "monopole" problem [Guth:1981], inflation ends up adressing various issues of the Friedmann-Lemaître cosmology [Linde:1982].
- Unexplanable or inconsistent with the standard Big-Bang model:
  - Flatness of the spatial sections: $\Omega_{\mathrm{K}} = 0.0008 \pm 0.004$
  - Statistical isotropy of the observable Universe (horizon problem)
  - Origin of the CMB anisotropies and large scale structures
  - Gaussianity of the CMB fluctuations: $f_{\mathrm{NL}} = 0.8 \pm 5.0$
  - Adiabaticity of the cosmological perturbations: isocurv. $< 4\%$
  - Almost scale invariance of the primordial perturbations: $n_{\mathrm{S}} = 0.9667 \pm 0.004$
- Within General Relativity (GR) inflation requires "repulsive gravity"

Solves the shortcomings of the Big-Bang model

- Originally proposed to solve the "monopole" problem [Guth:1981], inflation ends up adressing various issues of the Friedmann-Lemaître cosmology [Linde:1982].
- Unexplanable or inconsistent with the standard Big-Bang model:
  - Flatness of the spatial sections: $\Omega_K = 0.0008 \pm 0.004$
  - Statistical isotropy of the observable Universe (horizon problem)
  - Origin of the CMB anisotropies and large scale structures
  - Gaussianity of the CMB fluctuations: $f_{\mathrm{NL}} = 0.8 \pm 5.0$
  - Adiabaticity of the cosmological perturbations: isocurv. $< 4\%$
  - Almost scale invariance of the primordial perturbations: $n_{\mathrm{S}} = 0.9667 \pm 0.004$
- Within General Relativity (GR) inflation requires "repulsive gravity"
  - Negative energy

Solves the shortcomings of the Big-Bang model

- Originally proposed to solve the "monopole" problem [Guth:1981], inflation ends up adressing various issues of the Friedmann-Lemaître cosmology [Linde:1982].
- Unexplanable or inconsistent with the standard Big-Bang model:
  - Flatness of the spatial sections: $\Omega_{\mathrm{K}} = 0.0008 \pm 0.004$
  - Statistical isotropy of the observable Universe (horizon problem)
  - Origin of the CMB anisotropies and large scale structures
  - Gaussianity of the CMB fluctuations: $f_{\mathrm{NL}} = 0.8 \pm 5.0$
  - Adiabaticity of the cosmological perturbations: isocurv. $< 4\%$
  - Almost scale invariance of the primordial perturbations: $n_{\mathrm{S}} = 0.9667 \pm 0.004$
- Within General Relativity (GR) inflation requires "repulsive gravity"
  - ~~Negative energy~~

Solves the shortcomings of the Big-Bang model

- Originally proposed to solve the "monopole" problem [Guth:1981], inflation ends up adressing various issues of the Friedmann-Lemaître cosmology [Linde:1982].
- Unexplanable or inconsistent with the standard Big-Bang model:
  - Flatness of the spatial sections: $\Omega_{\rm K} = 0.0008 \pm 0.004$
  - Statistical isotropy of the observable Universe (horizon problem)
  - Origin of the CMB anisotropies and large scale structures
  - Gaussianity of the CMB fluctuations: $f_{\rm NL} = 0.8 \pm 5.0$
  - Adiabaticity of the cosmological perturbations: isocurv. $< 4\%$
  - Almost scale invariance of the primordial perturbations: $n_{\rm S} = 0.9667 \pm 0.004$
- Within General Relativity (GR) inflation requires "repulsive gravity"
  - ~~Negative energy~~
  - Negative pressure

Solves the shortcomings of the Big-Bang model

- Originally proposed to solve the "monopole" problem [Guth:1981], inflation ends up adressing various issues of the Friedmann-Lemaître cosmology [Linde:1982].
- Unexplanable or inconsistent with the standard Big-Bang model:
  - Flatness of the spatial sections: $\Omega_{\mathrm{K}} = 0.0008 \pm 0.004$
  - Statistical isotropy of the observable Universe (horizon problem)
  - Origin of the CMB anisotropies and large scale structures
  - Gaussianity of the CMB fluctuations: $f_{\mathrm{NL}} = 0.8 \pm 5.0$
  - Adiabaticity of the cosmological perturbations: isocurv. $< 4\%$
  - Almost scale invariance of the primordial perturbations: $n_{\mathrm{S}} = 0.9667 \pm 0.004$
- Within General Relativity (GR) inflation requires "repulsive gravity"
  - ~~Negative energy~~
  - Negative pressure
  - Or deviations from GR?

Scalar field inflation

- The only known "type of matter" generating a negative pressure

$$S = \int \mathrm{d}x^4 \sqrt{-g} \left[\frac{M_\mathrm{P}^2}{2} R + \mathcal{L}(\phi) \right] \quad \text{with} \quad \mathcal{L}(\phi) = -\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi)$$

  - ✦ Proven to exist since 2012: the Higgs field is a scalar
  - ✦ In slow-roll: $\dot{\phi}^2 \ll V$

$$\rho = \frac{1}{2} H^2 \left(\frac{\mathrm{d}\phi}{\mathrm{d}N} \right)^2 + V(\phi) \simeq V(\phi), \quad P = \frac{1}{2} H^2 \left(\frac{\mathrm{d}\phi}{\mathrm{d}N} \right)^2 - V(\phi) \simeq -V(\phi)$$

- Can the Higgs field h be responsible of inflation?
  - ✦ Yes, provided $R \to \left(1 + \xi h^2\right) R$ [Bezrukov:2008]
  - ✦ Almost equivalent to modify gravity $R \to R + \frac{R^2}{\mu^2}$ [Starobinsky:1979]
  - ✦ In the Einstein frame

$$V(\phi) = \frac{0.7 M_\mathrm{P}^4}{4\xi^2} \left(1 - e^{-\sqrt{2/3}\phi/M_\mathrm{P}} \right)$$

Inflationary quantum fluctuations

- Inflation is quasi de-Sitter spacetime due to ϕ
  - Scalar metric-field quantum fluctuations are amplified [Mukhanov:1981,Starobinky:1982]
  - Quantum origin $\Rightarrow$ Gaussianity
  - Power spectrum of the curvature perturbations at leading order

$$\mathcal{P}_\zeta = \frac{H_*^2}{8\pi^2 M_{\mathrm{P}}^2 \epsilon_{1*}}, \quad \text{where} \begin{cases} H_*^2 \simeq \dfrac{V(\phi_*)}{3M_{\mathrm{P}}^2} \\ \epsilon_{1*} = \dfrac{1}{2M_{\mathrm{P}}^2} \left.\dfrac{\mathrm{d}\phi}{\mathrm{d}N}\right|_*^2 \simeq \dfrac{M_{\mathrm{P}}^2}{2}\left(\dfrac{V'}{V}\right)^2 \end{cases}$$

$\Rightarrow$ origin of the CMB and of all structures in the Universe

- Quantum fluctuations in de-Sitter $\Rightarrow$ gravitational waves [Starobinsky:1979]

$$\mathcal{P}_h = \frac{2H_*^2}{\pi^2 M_{\mathrm{P}}^2} \ll \mathcal{P}_\zeta \qquad r \equiv \frac{\mathcal{P}_h}{\mathcal{P}_\zeta} = 16\epsilon_{1*} \ll 1$$

$\Rightarrow$ unavoidable consequence of field inflation

Tensor-to-scalar ratio for Higgs inflation

- Amplitude of the CMB temperature anisotropies (Planck 2015)

$$\mathcal{P}_\zeta \simeq (2.2 \pm 0.1) \times 10^{-9} = \frac{V(\phi_*)}{24\pi^2 M_{\mathrm{P}}^4 \epsilon_1(\phi_*)} \Rightarrow \xi \simeq 40000$$

- Amplitude of the primordial gravitational waves
  - ✦ No free parameter!

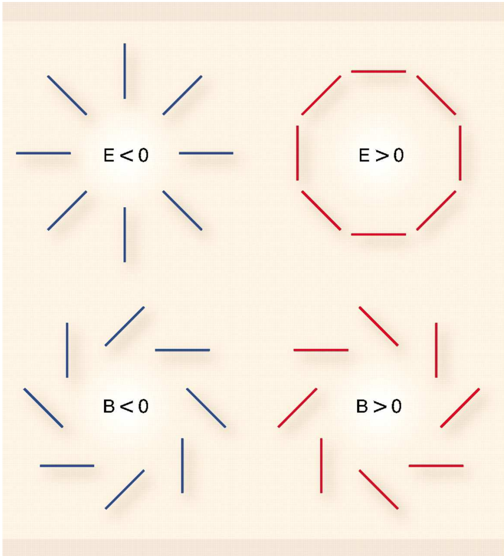
$$\xi = 40000 \quad \Rightarrow \quad \mathcal{P}_h \simeq 8.8 \times 10^{-12} \quad \Rightarrow \quad r = 0.004$$

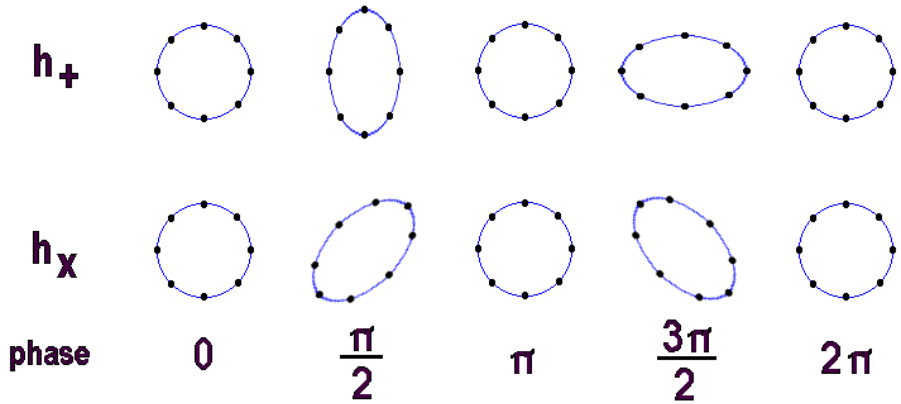
  - ✦ Higgs inflation energy scale: $E_{\mathrm{inf}} \simeq 8 \times 10^{15}\,\mathrm{GeV}$
- These are gravitational waves produced at a redhift $z_{\mathrm{inf}} = 10^{27}$
  - ✦ Current Planck 2015 constraints: $r < 0.12$
  - ✦ Out of sensitivity for interferometers such as LIGO/VIRGO
  - ✦ Only one way to go: using the Universe at $z = 1100$ as a detector:

B-Polarization of the Cosmic Microwave Background

Why searching for primordial B-modes?

- Because only gravitational waves and vector perturbations can make ionized matter in the cosmic plasma moving such as it generates a curly polarization





- Gravitational waves at $z = 1100$ can only come from inflation
- Vector perturbations at that time can only come active sources such as Cosmic Strings, primordial magnetic fields and/or modified gravity

primordial B-modes = inflation or new physics

Roadbook

- Does Higgs/Starobinsky inflation and $r = 0.004$ universal predictions?
  - No, they are currently the simplest and most favoured models
- May Higgs and Starobinsky (and α-attractor) inflation being disambiguated?
  - Yes, owing to the reheating, but requires high precision in all channels T, E, B (see next slides)
- How many models of inflation there are? Can we find the "correct" one?
  - Hundreds of slow-roll single field models have been proposed since the 80s
  - Planck 2015 + BICEP2/KECK have ruled out almost 40% of them
  - CMB stage 4 in the worst case scenario: inflation is slow-roll single field, no feature, no non-Gaussianities, no measureable isocurvature modes, no topological defects, no understanding of reheating microphysics

$\Rightarrow$ 80% of existing models would be ruled-out

Inflationary predictions matching CMB S4 precision

Slow-roll at next-to-next to leading order

- Perturbative solutions for the background and field-metric perturbations

$$\epsilon_0 = \frac{H_{\mathrm{ini}}}{H}, \qquad \epsilon_{i+1} = \frac{\mathrm{d}\ln|\epsilon_i|}{\mathrm{d}N} \qquad \text{measure deviations from de-Sitter}$$

- Background trajectory: $N - N_{\mathrm{end}} \simeq \int_{\phi}^{\phi_{\mathrm{end}}} \frac{V(\psi)}{V'(\psi)}\,\mathrm{d}\psi$
- Accelerated expansion ($\ddot{a} > 0$) stops for $\epsilon_1(\phi_{\mathrm{end}}) = 1$
  - ✦ Or, there is another mechanism ending inflation (tachyonic instability) and ϕ_{end} is a model parameter
- Equations of motion for the linear perturbations

$$\left.\begin{aligned} \mu_{\mathrm{T}} &\equiv a h \\ \mu_{\mathrm{S}} &\equiv a\sqrt{2}\phi_{,N}\zeta \end{aligned}\right\} \Rightarrow \mu_{\mathrm{TS}}'' + \left[k^2 - \frac{(a\sqrt{\epsilon_1})''}{a\sqrt{\epsilon_1}}\right]\mu_{\mathrm{TS}} = 0$$

  - ✦ Are solved order by order in ϵ_i around a particular time $\eta_* = \eta(N_*)$

Slow-roll power spectra

- Can be consistently solved using slow-roll and pivot expansion [Stewart:1993, Gong:2001, Schwarz:2001, Leach:2002, Martin:2002, Habib:2002, Casadio:2005, Lorenz:2008, Martin:2013, Beltran:2013]

✦ Scalar modes

$$\mathcal{P}_\zeta = \frac{H_*^2}{8\pi^2 M_P^2 \epsilon_{1*}} \left\{ 1 - 2(1+C)\epsilon_{1*} - C\epsilon_{2*} + \left(\frac{\pi^2}{2} - 3 + 2C + 2C^2\right)\epsilon_{1*}^2 + \left(\frac{7\pi^2}{12} - 6 - C + C^2\right)\epsilon_{1*}\epsilon_{2*} \right.$$
$$+ \left(\frac{\pi^2}{8} - 1 + \frac{C^2}{2}\right)\epsilon_{2*}^2 + \left(\frac{\pi^2}{24} - \frac{C^2}{2}\right)\epsilon_{2*}\epsilon_{3*}$$
$$+ \left[-2\epsilon_{1*} - \epsilon_{2*} + (2+4C)\epsilon_{1*}^2 + (-1+2C)\epsilon_{1*}\epsilon_{2*} + C\epsilon_{2*}^2 - C\epsilon_{2*}\epsilon_{3*}\right] \ln\left(\frac{k}{k_*}\right)$$
$$\left. + \left[2\epsilon_{1*}^2 + \epsilon_{1*}\epsilon_{2*} + \frac{1}{2}\epsilon_{2*}^2 - \frac{1}{2}\epsilon_{2*}\epsilon_{3*}\right] \ln^2\left(\frac{k}{k_*}\right) \right\},$$

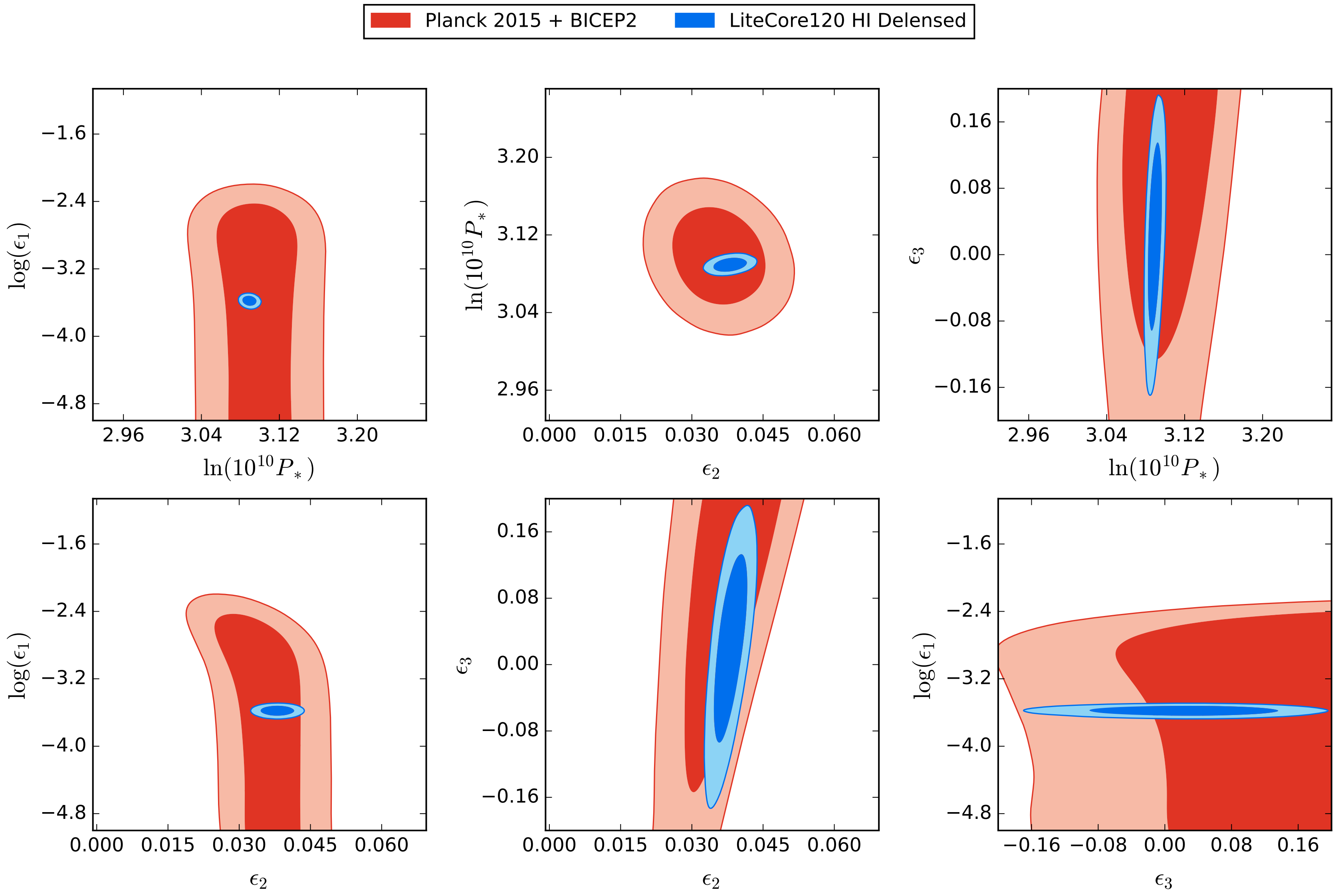
✦ Tensor modes

$$\mathcal{P}_h = \frac{2H_*^2}{\pi^2 M_P^2} \left\{ 1 - 2(1+C)\epsilon_{1*} + \left[-3 + \frac{\pi^2}{2} + 2C + 2C^2\right]\epsilon_{1*}^2 + \left[-2 + \frac{\pi^2}{12} - 2C - C^2\right]\epsilon_{1*}\epsilon_{2*} \right.$$
$$\left. + \left[-2\epsilon_{1*} + (2+4C)\epsilon_{1*}^2 + (-2-2C)\epsilon_{1*}\epsilon_{2*}\right] \ln\left(\frac{k}{k_*}\right) + \left(2\epsilon_{1*}^2 - \epsilon_{1*}\epsilon_{1*}\right) \ln^2\left(\frac{k}{k_*}\right) \right\}$$

- Notice that: $H_* \equiv H(N_*)$ and $\epsilon_{i*} \equiv \epsilon_i(N_*)$ in which

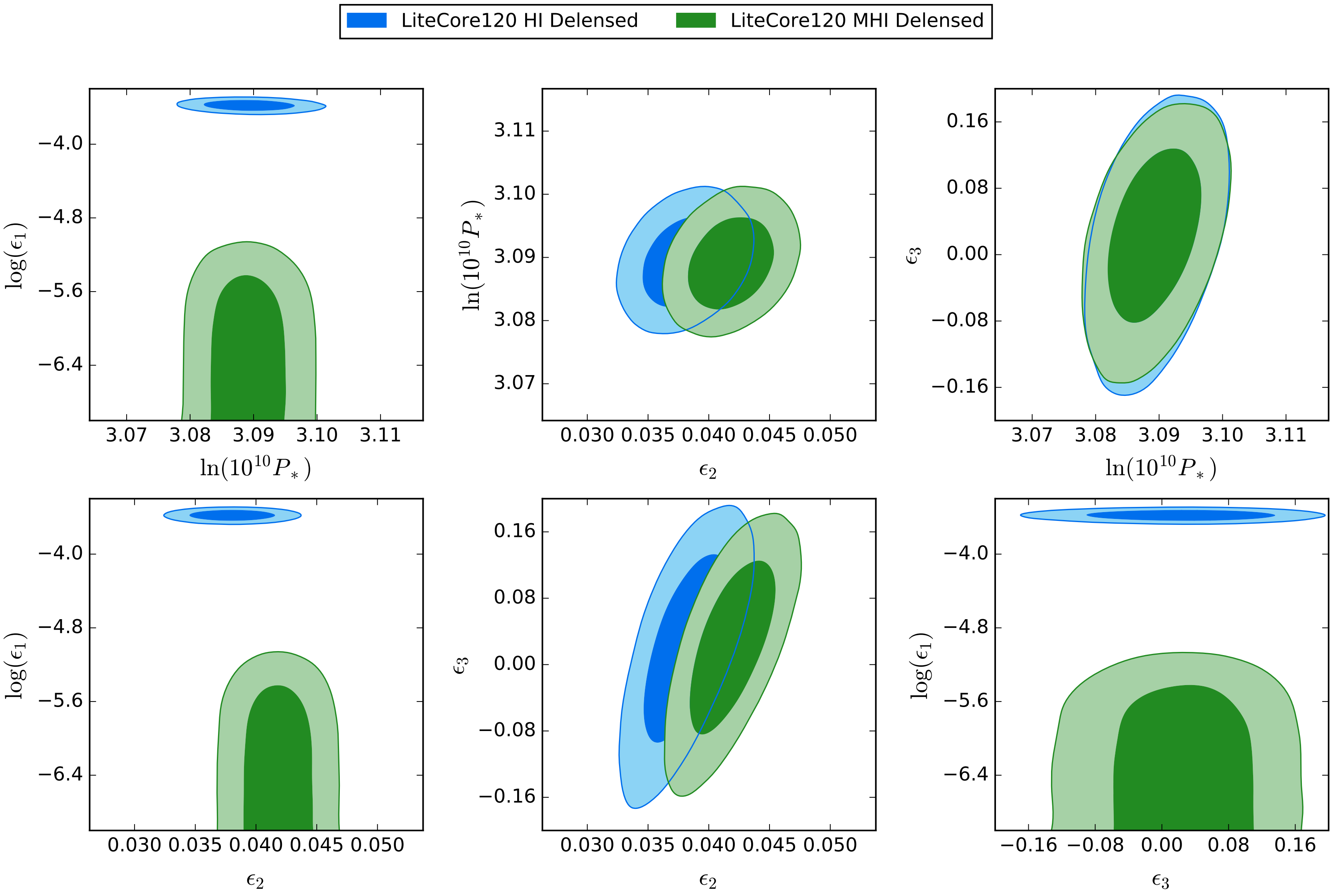
$$k_* \eta(N_*) = -1, \qquad \text{Hubble exit of an observable scale } k_*$$

Model-independent constraints



[Clesse, Ringeval, Vennin:2016]

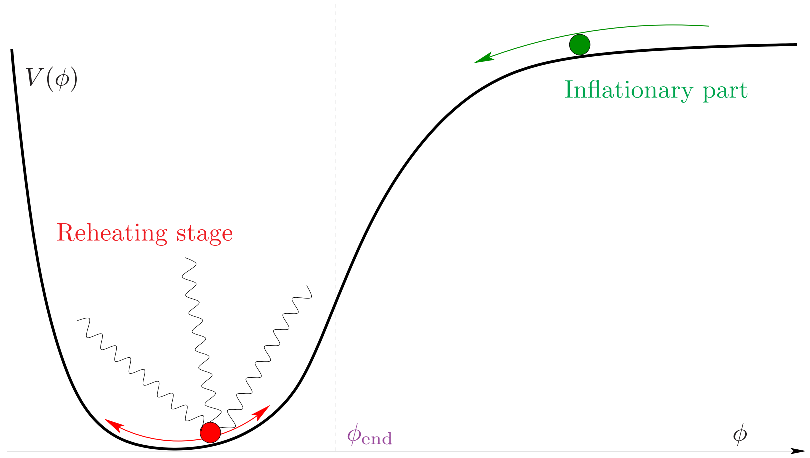
Model-independent constraints



[Clesse, Ringeval, Vennin:2016]

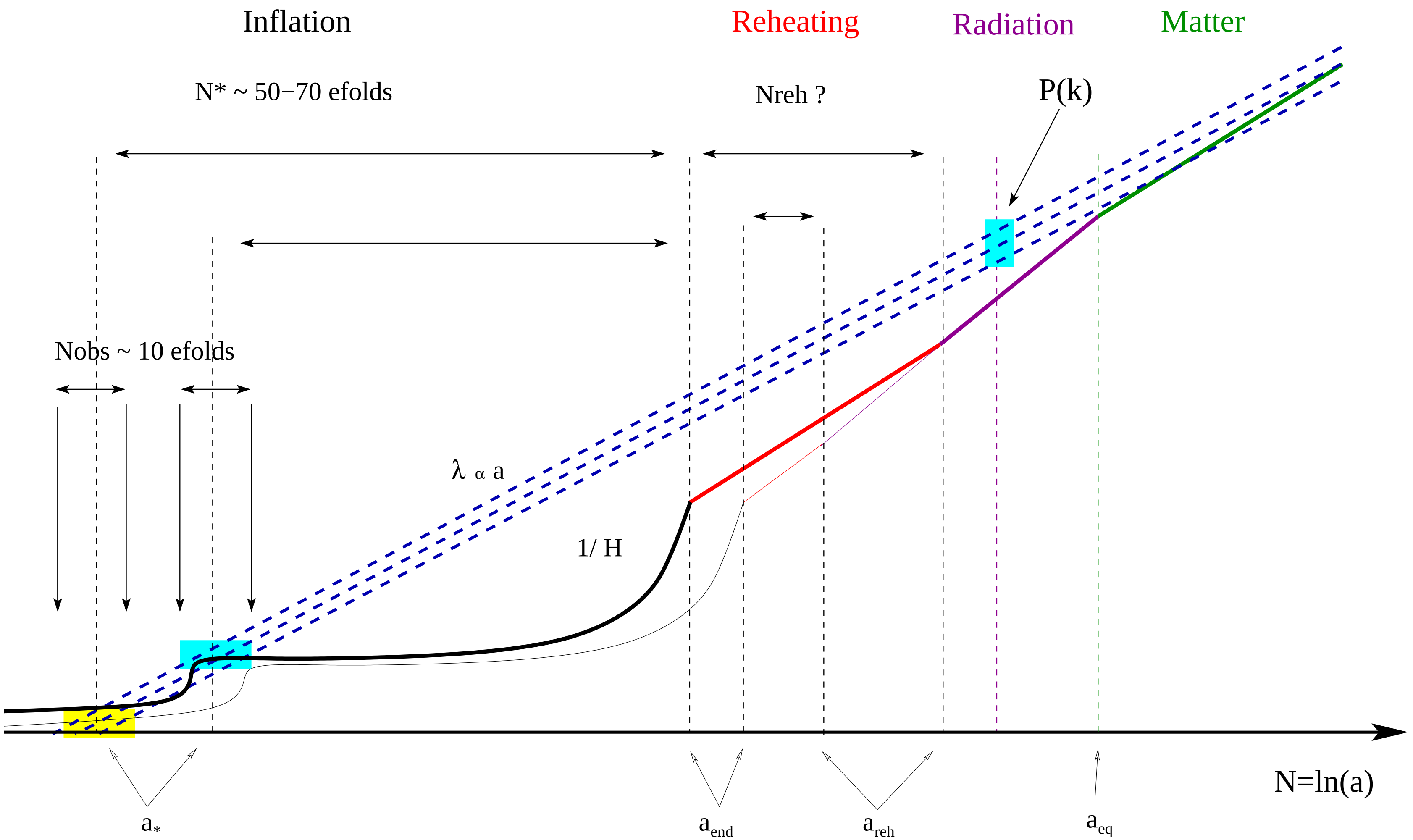
The reheating era

- Must exist within inflationary cosmology
  - ✦ Decelerating expansion era immediately following inflation
  - ✦ Transition from field vacuum domination to radiation domination
- Basic picture
  - ✦ In details, a very complicated process, microphysics dependent
  - ✦ Theoretically, reheating is completely specified by the couplings between the inflaton and Standard Model particles



- Two inflationary models may share the same potential while having a completely different reheating era!
  - ✦ Starobinski Inflation: $\rho_{\text{reh}}^{1/4} \simeq 10^9\,\text{GeV}$ [Terada et al., arXiv:1411.6746]
  - ✦ Higgs Inflation: $\rho_{\text{reh}}^{1/4} \lesssim 10^{13}\,\text{GeV??}$ [Garcia-Bellido et al., arXiv:0812.4624]

Reheating effects on inflationary observables



- Cosmological observations "measure" $\mathcal{P}_{\zeta,h}(k)$ from the radiation era; inflationary models predict $\mathcal{P}_{\zeta,h}(k)$ at Hubble exit
- Reheating unavoidably affects the observable length scales

Solving for the time of pivot crossing

- To make inflationary predictions, one has to solve $k_* \eta_* = -1$

$$\frac{k_*}{a_0} = \frac{a(N_*)}{a_0} H_* = \frac{e^{\Delta N_*} H_*}{1 + z_{\mathrm{end}}} = e^{\Delta N_*} R_{\mathrm{rad}} \left(\frac{\rho_{\mathrm{end}}}{\tilde{\rho}_\gamma}\right)^{-\frac{1}{4}} H_*$$

- R_{rad} can be expressed in terms of $(\rho_{\mathrm{reh}}, \overline{w}_{\mathrm{reh}})$ or $(\Delta N_{\mathrm{reh}}, \overline{w}_{\mathrm{reh}})$

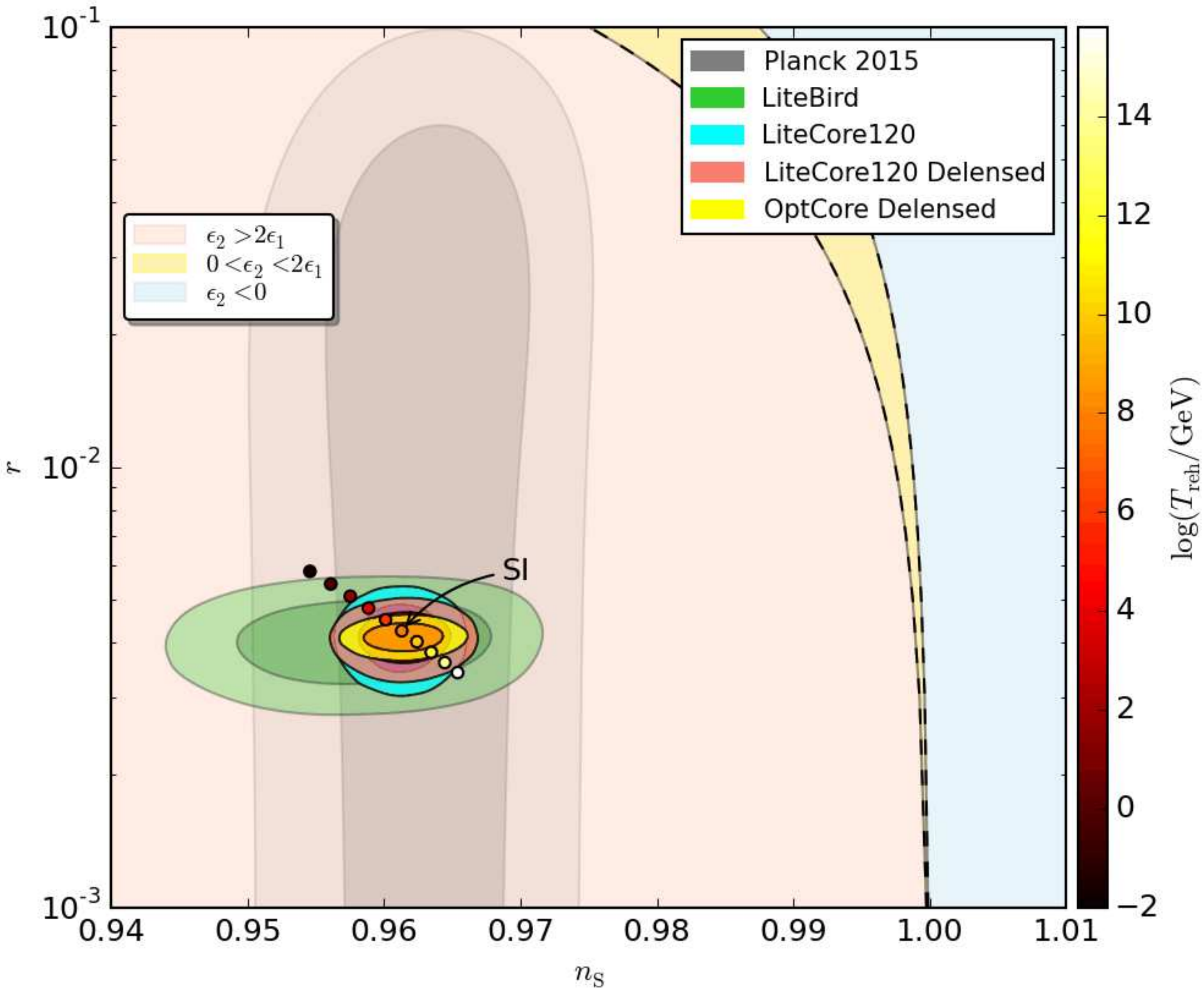
$$\ln R_{\mathrm{rad}} = \frac{\Delta N_{\mathrm{reh}}}{4}(3\overline{w}_{\mathrm{reh}} - 1) = \frac{1 - 3\overline{w}_{\mathrm{reh}}}{12(1 + \overline{w}_{\mathrm{reh}})} \ln\left(\frac{\rho_{\mathrm{reh}}}{\rho_{\mathrm{end}}}\right)$$

- Defining $N_0 \equiv \ln\left[k_*/(a_0 \tilde{\rho}_\gamma^{1/4})\right]$ (number of e-folds of deceleration), this is a non-trivial integral equation that depends on: model + how inflation ends + reheating + data [Martin,Ringeval:2006]

$$-\left[\int_{\phi_{\mathrm{end}}}^{\phi_*} \frac{V(\psi)}{V'(\psi)} \mathrm{d}\psi\right] = \ln R_{\mathrm{rad}} - N_0 + \frac{1}{4}\ln(8\pi^2 P_*) - \frac{1}{4}\ln\left\{\frac{9}{\epsilon_1(\phi_*)[3 - \epsilon_1(\phi_{\mathrm{end}})]} \frac{V(\phi_{\mathrm{end}})}{V(\phi_*)}\right\}$$

Disambiguating Higgs and Starobinksy inflation

- Fiducial model has $T_{\rm reh} = 10^8\,\mathrm{GeV}$ and $\overline{w}_{\rm reh} = 0$



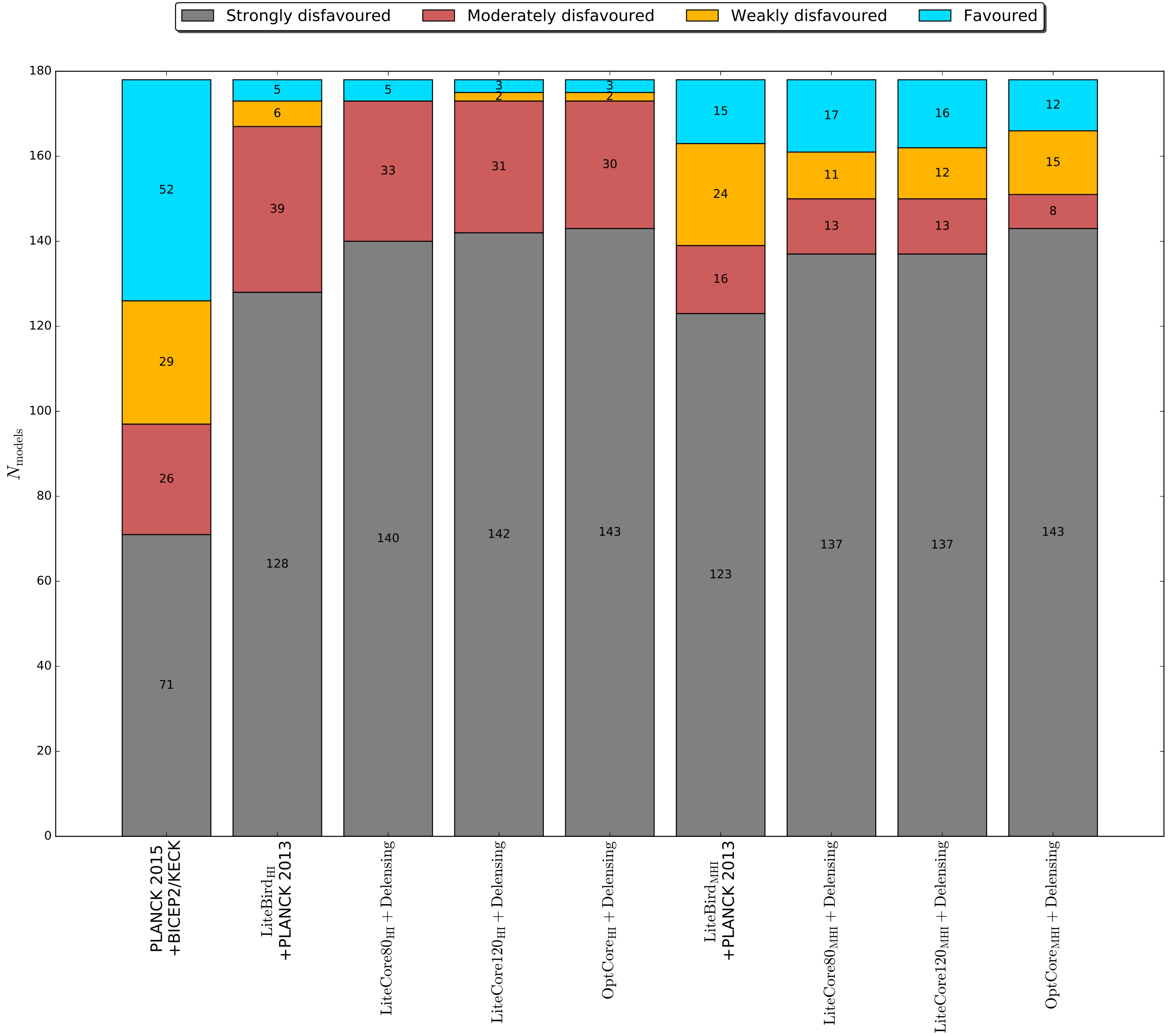
Data analysis in model space

- Data should be analyzed within the parameter space of each model, including the reheating parameter: $(\boldsymbol{\theta}_{\rm inf}, R_{\rm rad})$
- Using the public code ASPIC of Encyclopaedia Inflationaris [arxiv:1303.3787]

$$(\boldsymbol{\theta}_{\rm inf}, R_{\rm rad}) \longrightarrow \texttt{ASPIC} \longrightarrow \epsilon_{i*} \longrightarrow \begin{cases} \mathcal{P}_\zeta(k) \\ \mathcal{P}_h(k) \end{cases} \longrightarrow \texttt{CAMB} \longleftrightarrow \text{CMB data}$$

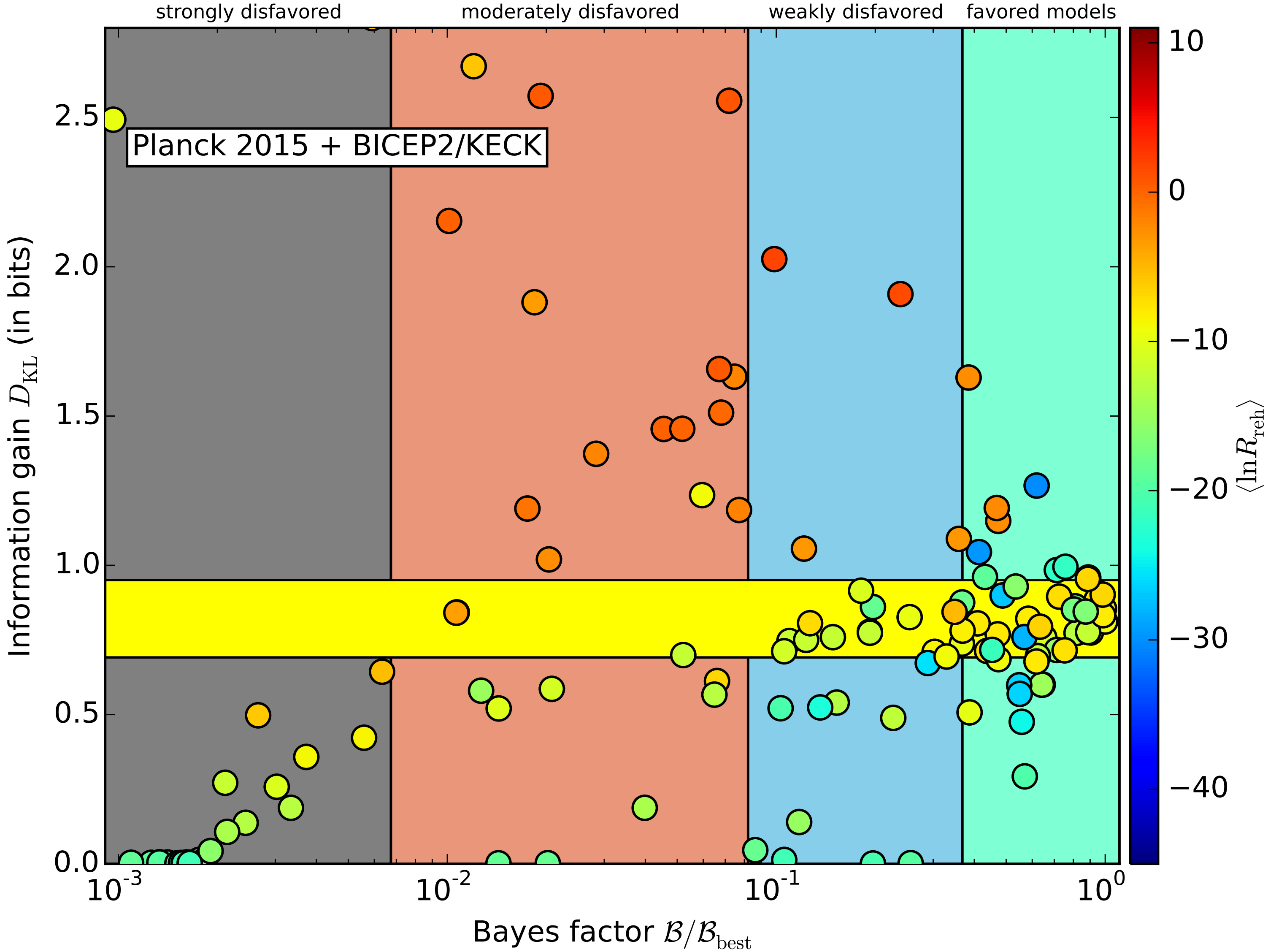
Name	Parameters	Sub-models	$V(\phi)$
HI	0	1	$M^4\left(1-e^{-\sqrt{2/3}\phi/M_{\rm Pl}}\right)$
RCHI	1	1	$M^4\left(1-2e^{-\sqrt{2/3}\phi/M_{\rm Pl}}+\frac{A_{\rm I}}{16\pi^2}\frac{\phi}{\sqrt{6}M_{\rm Pl}}\right)$
LFI	1	1	$M^4\left(\frac{\phi}{M_{\rm Pl}}\right)^p$
MLFI	1	1	$M^4\frac{\phi^2}{M_{\rm Pl}^2}\left[1+\alpha\frac{\phi^2}{M_{\rm Pl}^2}\right]$
RCMI	1	1	$M^4\left(\frac{\phi}{M_{\rm Pl}}\right)^2\left[1-2\alpha\frac{\phi^2}{M_{\rm Pl}^2}\ln\left(\frac{\phi}{M_{\rm Pl}}\right)\right]$
RCQI	1	1	$M^4\left(\frac{\phi}{M_{\rm Pl}}\right)^4\left[1-\alpha\ln\left(\frac{\phi}{M_{\rm Pl}}\right)\right]$
NI	1	1	$M^4\left[1+\cos\left(\frac{\phi}{f}\right)\right]$
ESI	1	1	$M^4\left(1-e^{-q\phi/M_{\rm Pl}}\right)$
PLI	1	1	$M^4e^{-\alpha\phi/M_{\rm Pl}}$
KMII	1	2	$M^4\left(1-\alpha\frac{\phi}{M_{\rm Pl}}e^{-\phi/M_{\rm Pl}}\right)$
HF1I	1	1	$M^4\left(1+A_1\frac{\phi}{M_{\rm Pl}}\right)^2\left[1-\frac{2}{3}\left(\frac{A_1}{1+A_1\phi/M_{\rm Pl}}\right)^2\right]$
CWI	1	1	$M^4\left[1+\alpha\left(\frac{\phi}{Q}\right)^4\ln\left(\frac{\phi}{Q}\right)\right]$
LI	1	2	$M^4\left[1+\alpha\ln\left(\frac{\phi}{M_{\rm Pl}}\right)\right]$
RpI	1	3	$M^4e^{-2\sqrt{2/3}\phi/M_{\rm Pl}}\left\lvert e^{\sqrt{2/3}\phi/M_{\rm Pl}}-1\right\rvert^{2p/(2p-1)}$
DWI	1	1	$M^4\left[\left(\frac{\phi}{\phi_0}\right)^2-1\right]^2$
MHI	1	1	$M^4\left[1-\operatorname{sech}\left(\frac{\phi}{\mu}\right)\right]$
RGI	1	1	$M^4\frac{(\phi/M_{\rm Pl})^2}{\alpha+(\phi/M_{\rm Pl})^2}$
MSSMI	1	1	$M^4\left[\left(\frac{\phi}{\phi_0}\right)^2-\frac{2}{3}\left(\frac{\phi}{\phi_0}\right)^6+\frac{1}{5}\left(\frac{\phi}{\phi_0}\right)^{10}\right]$
RIPI	1	1	$M^4\left[\left(\frac{\phi}{\phi_0}\right)^2-\frac{4}{3}\left(\frac{\phi}{\phi_0}\right)^3+\frac{1}{2}\left(\frac{\phi}{\phi_0}\right)^4\right]$
AI	1	1	$M^4\left[1-\frac{2}{\pi}\arctan\left(\frac{\phi}{\mu}\right)\right]$
CNAI	1	1	$M^4\left[3-\left(3+\alpha^2\right)\tanh^2\left(\frac{\alpha}{\sqrt{2}}\frac{\phi}{M_{\rm Pl}}\right)\right]$
CNBI	1	1	$M^4\left[\left(3-\alpha^2\right)\tan^2\left(\frac{\alpha}{\sqrt{2}}\frac{\phi}{M_{\rm Pl}}\right)-3\right]$
OSTI	1	1	$-M^4\left(\frac{\phi}{\phi_0}\right)^2\ln\left[\left(\frac{\phi}{\phi_0}\right)^2\right]$
WRI	1	1	$M^4\ln\left(\frac{\phi}{\phi_0}\right)^2$
SFI	2	1	$M^4\left[1-\left(\frac{\phi}{\mu}\right)^p\right]$
II	2	1	$M^4\left(\frac{\phi-\phi_0}{M_{\rm Pl}}\right)^{-\beta}-M^4\frac{\beta^2}{6}\left(\frac{\phi-\phi_0}{M_{\rm Pl}}\right)^{-\beta-2}$
KMIII	2	1	$M^4\left[1-\alpha\frac{\phi}{M_{\rm Pl}}\exp\left(-\beta\frac{\phi}{M_{\rm Pl}}\right)\right]$
LMI	2	2	$M^4\left(\frac{\phi}{M_{\rm Pl}}\right)^\alpha\exp\left[-\beta(\phi/M_{\rm Pl})^\gamma\right]$
TWI	2	1	$M^4\left[1-A\left(\frac{\phi}{\phi_0}\right)^2e^{-\phi/\phi_0}\right]$
GMSSMI	2	2	$M^4\left[\left(\frac{\phi}{\phi_0}\right)^2-\frac{2}{3}\alpha\left(\frac{\phi}{\phi_0}\right)^6+\frac{\alpha}{5}\left(\frac{\phi}{\phi_0}\right)^{10}\right]$
GRIPI	2	2	$M^4\left[\left(\frac{\phi}{\phi_0}\right)^2-\frac{4}{3}\alpha\left(\frac{\phi}{\phi_0}\right)^3+\frac{\alpha}{2}\left(\frac{\phi}{\phi_0}\right)^4\right]$
BSUSYBI	2	1	$M^4\left(e^{\sqrt{6}\frac{\phi}{M_{\rm Pl}}}+e^{\sqrt{6}\gamma\frac{\phi}{M_{\rm Pl}}}\right)$
TI	2	3	$M^4\left(1+\cos\frac{\phi}{\mu}+\alpha\sin^2\frac{\phi}{\mu}\right)$
BEI	2	1	$M^4\exp_{1-\beta}\left(-\lambda\frac{\phi}{M_{\rm Pl}}\right)$
PSNI	2	1	$M^4\left[1+\alpha\ln\left(\cos\frac{\phi}{f}\right)\right]$
NCKI	2	2	$M^4\left[1+\alpha\ln\left(\frac{\phi}{M_{\rm Pl}}\right)+\beta\left(\frac{\phi}{M_{\rm Pl}}\right)^2\right]$
CSI	2	1	$\frac{M^4}{\left(1-\alpha\frac{\phi}{M_{\rm Pl}}\right)^2}$
OI	2	1	$M^4\left(\frac{\phi}{\phi_0}\right)^4\left[\left(\ln\frac{\phi}{\phi_0}\right)^2-\alpha\right]$
CNCI	2	1	$M^4\left[\left(3+\alpha^2\right)\coth^2\left(\frac{\alpha}{\sqrt{2}}\frac{\phi}{M_{\rm Pl}}\right)-3\right]$
SBI	2	2	$M^4\left\{1+\left[-\alpha+\beta\ln\left(\frac{\phi}{M_{\rm Pl}}\right)\right]\left(\frac{\phi}{M_{\rm Pl}}\right)^4\right\}$
SSBI	2	6	$M^4\left[1+\alpha\left(\frac{\phi}{M_{\rm Pl}}\right)^2+\beta\left(\frac{\phi}{M_{\rm Pl}}\right)^4\right]$
IMI	2	1	$M^4\left(\frac{\phi}{M_{\rm Pl}}\right)^{-p}$
BI	2	2	$M^4\left[1-\left(\frac{\phi}{\mu}\right)^{-p}\right]$
RMI	3	4	$M^4\left[1-\frac{c}{2}\left(-\frac{1}{2}+\ln\frac{\phi}{\phi_0}\right)\frac{\phi^2}{M_{\rm Pl}^2}\right]$
VHI	3	1	$M^4\left[1+\left(\frac{\phi}{\mu}\right)^p\right]$
DSI	3	1	$M^4\left[1+\left(\frac{\phi}{\mu}\right)^{-p}\right]$
GMLFI	3	1	$M^4\left(\frac{\phi}{M_{\rm Pl}}\right)^p\left[1+\alpha\left(\frac{\phi}{M_{\rm Pl}}\right)^q\right]$
LPI	3	3	$M^4\left(\frac{\phi}{\phi_0}\right)^p\left(\ln\frac{\phi}{\phi_0}\right)^q$
CNDI	3	3	$\frac{M^4}{\left\{1+\beta\cos\left[\alpha\left(\frac{\phi-\phi_0}{M_{\rm Pl}}\right)\right]\right\}^2}$

Bayesian model comparison with CMB S4



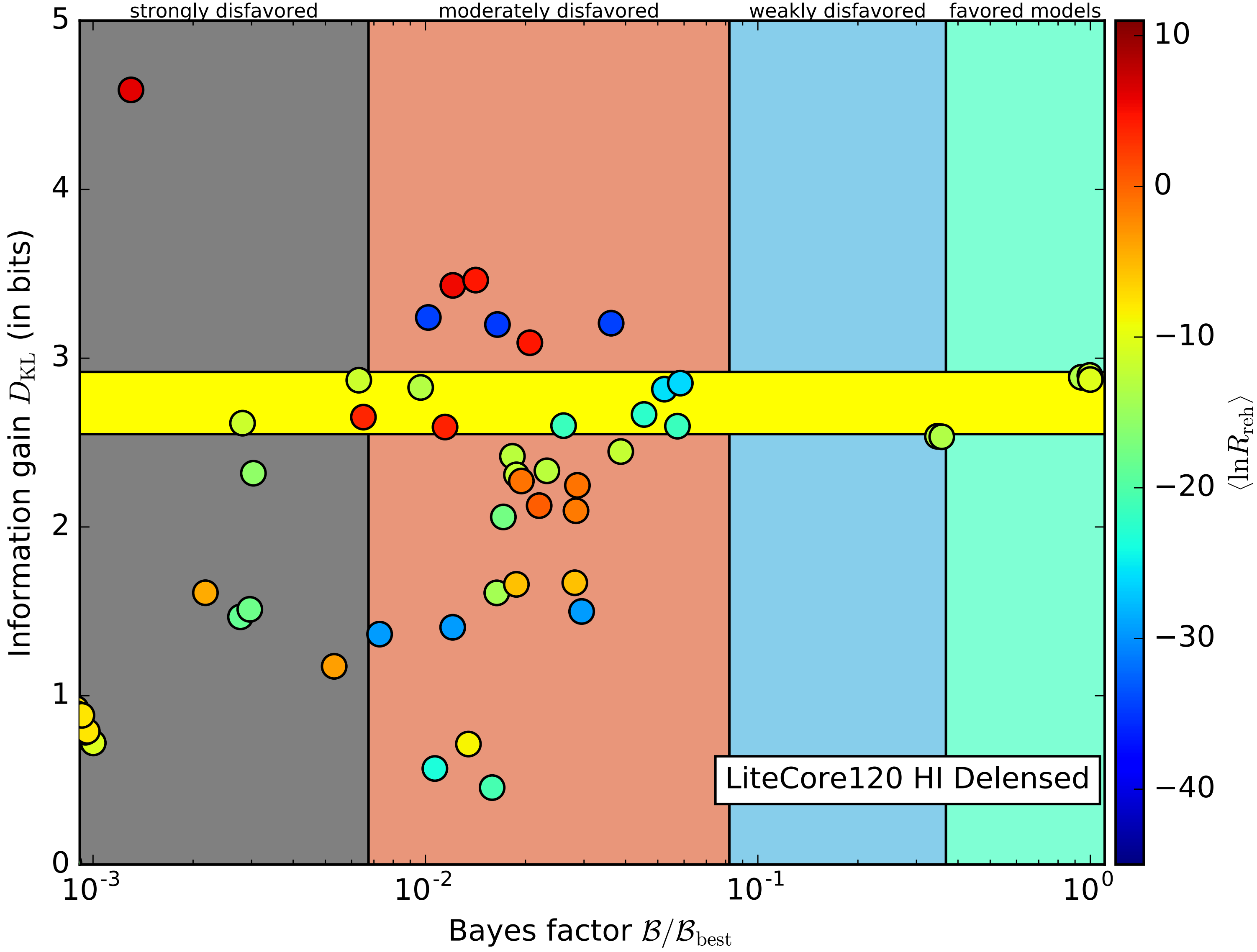
Information gain on reheating

- If reheating microphysics is unknown [Clesse, Martin, Ringeval, Vennin:2016]



Information gain on reheating

- If reheating microphysics is unknown [Clesse, Martin, Ringeval, Vennin:2016]



Other remarks

- Slow-roll single field inflation without feature is a worst case scenario on the route to $r = 10^{-3}$
  - ✦ Any measurement of non-Gaussianities, features, trans-Planckian effects, isocurvature would provide unvaluable information on inflationary microphysics
- Cosmic strings could also be discovered through primordial B-modes, T at large multipoles, or even with GW direct detection

$$\Rightarrow \text{lower bound on } E_{\text{inf}} \Rightarrow \text{lower bound on } r$$

- CMB S4 should not only target low values of $r = 16\epsilon_{1*}$ but also improves accuracy on ϵ_{2*} and the running of $\mathcal{P}_\zeta \Rightarrow \epsilon_{3*}$
  - ✦ Disambiguating models with reheating
  - ✦ Could potentially kill slow-roll!
- Inflation being proven true would dramatically expand what we call "The Universe": a huge impact for Physics