Constraining high-energy physics with cosmic inflation

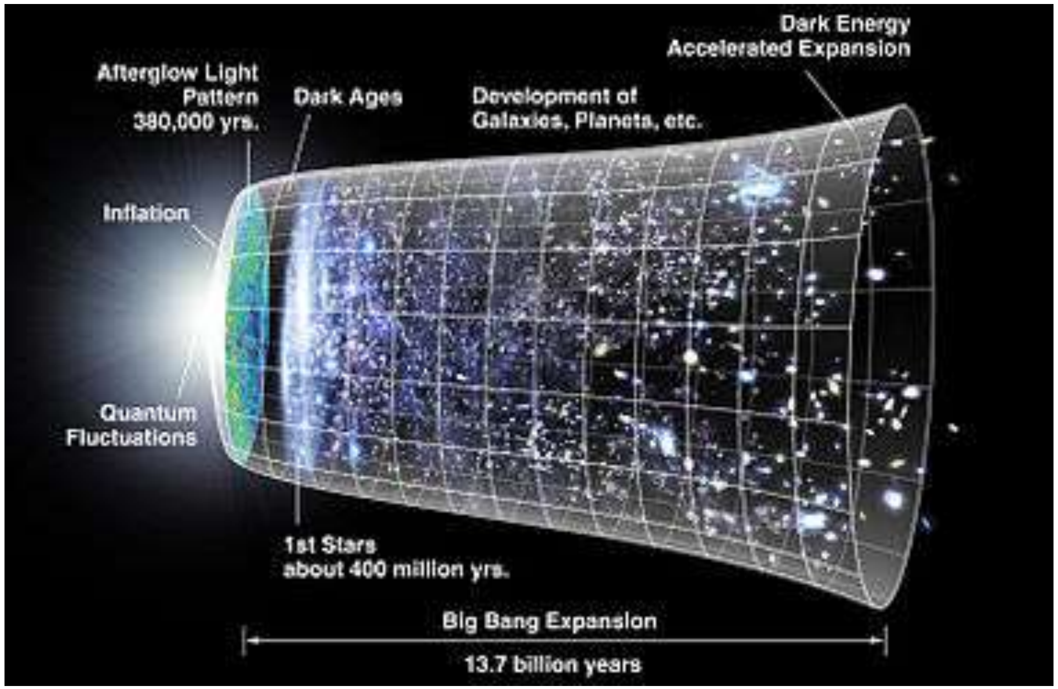
Vincent Vennin

Séminaire LLR, 14 January 2026

The primordial Universe is a high-energy laboratory

- Inflation is a **high-energy** phase of accelerated expansion in the early Universe

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\,\mathrm{d}\vec{x}^2 \quad \text{with} \quad \ddot{a} > 0 \quad \text{and} \quad (10\,\mathrm{MeV})^4 < \rho < \left(10^{16}\,\mathrm{GeV}\right)^4$$



The horizon problem

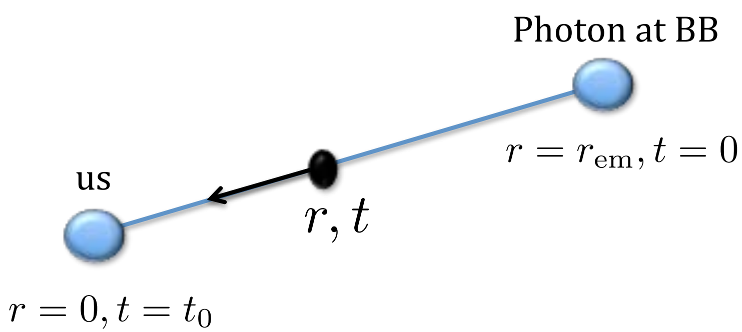
FLRW Universe: $\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2\,(t)\,\mathrm{d}\vec{x}^2$

Einstein equations: $H^2 = \dfrac{\rho}{3M_{\mathrm{Pl}}^2}$ and $\dot{\rho} + 3H(\rho + p) = 0$ with $H = \dot{a}/a$

Examples: pressureless dust: $p = 0 \longrightarrow \rho \propto a^{-3} \longrightarrow a \propto t^{2/3}$

radiation: $p = \rho/3 \longrightarrow \rho \propto a^{-4} \longrightarrow a \propto t^{1/2}$

Null geodesics for photons: $\mathrm{d}t = a\mathrm{d}r \longrightarrow r(t) = r_{\mathrm{em}} - \int_0^t \mathrm{d}t/a$



Causal horizon: current distance to the furthest point a photon reaching us today can have been sent from

$$d_{\mathrm{hor}} = a(t_0) \int_0^{t_0} \frac{\mathrm{d}t}{a(t)}$$

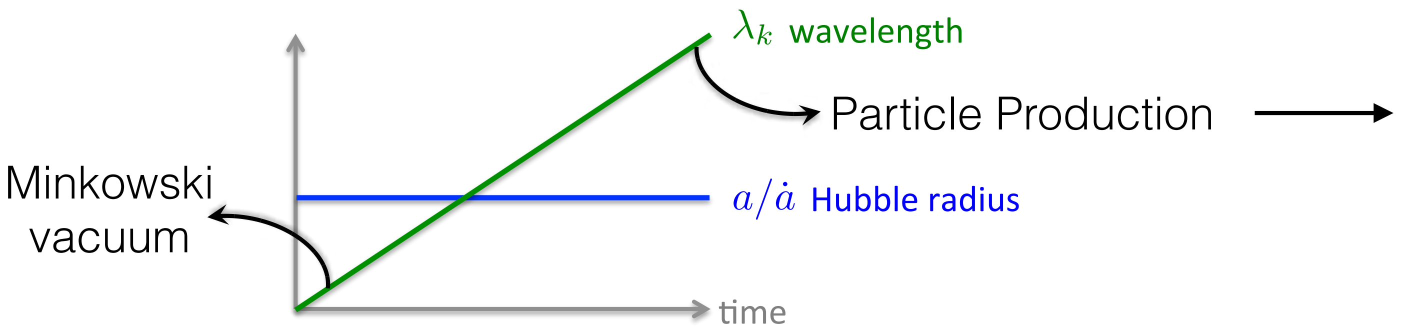
If $a \propto t^p$, d_{hor} is finite unless $p > 1$

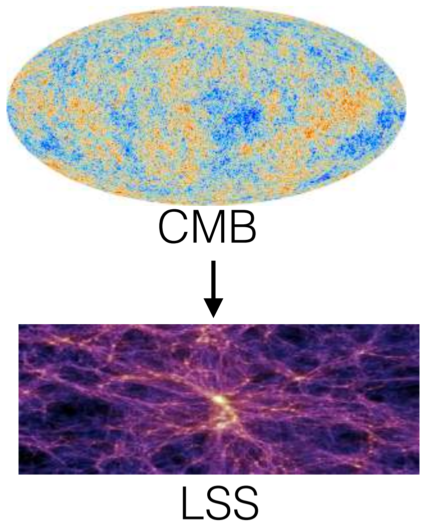
The primordial Universe is a high-energy laboratory

- Inflation is a **high-energy** phase of accelerated expansion in the early Universe

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\,\mathrm{d}\vec{x}^2 \quad \text{with} \quad \ddot{a} > 0 \quad \text{and} \quad \rho \leq \left(10^{16}\,\mathrm{GeV}\right)^4$$

- Quantum vacuum fluctuations are stretched to cosmological distances and seed the large-scale structure of our universe





Quantum mechanics on cosmological scales!

How to realise inflation?

Einstein Equations: $$H^2 = \frac{\rho}{3M_{\rm Pl}^2}$$ $$\dot\rho + 3H(\rho + p) = 0$$ $$\longrightarrow \quad \frac{\ddot a}{a} = -\frac{1}{6M_{\rm Pl}^2}(\rho + 3p)$$

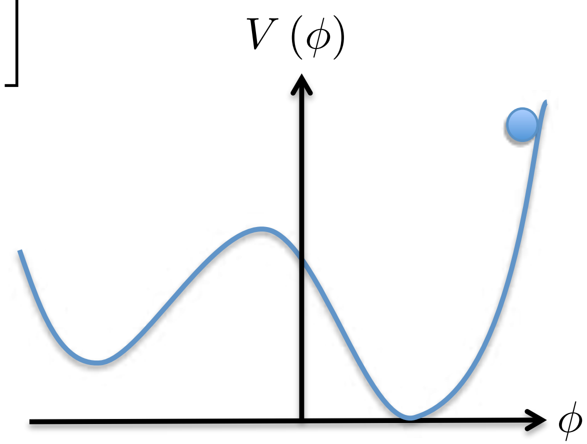
Requires a fluid with negative pressure

Simplest system compatible with symmetries: homogeneous scalar field

$$S = -\int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}(2\Lambda - R) + \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + V(\phi) - \mathcal{L}_{\rm int}(\phi, A_\mu, \psi, \cdots)\right]$$

$$T_{\mu\nu}^{(\phi)} = -\frac{2}{\sqrt{-g}}\frac{\partial S^{(\phi)}}{\partial g_{\mu\nu}} = \partial_\mu\phi\partial_\nu\phi - g_{\mu\nu}\left[\frac{1}{2}g^{\rho\sigma}\partial_\rho\phi\partial_\sigma\phi + V(\phi)\right]$$
$$= (\rho + p)\,u_\mu u_\nu + p g_{\mu\nu}$$

velocity of comoving observer



with $$\begin{cases} \rho = \frac{1}{2}\dot\phi^2 + V(\phi) \\ p = \frac{1}{2}\dot\phi^2 - V(\phi) \end{cases}$$

$$\boxed{\rho + 3p < 0 \Leftrightarrow V(\phi) > \dot\phi^2}$$

Implementing Inflation

$$\boxed{V'' \ll H^2}$$

Effective field theory: integrate out the degrees of freedom > Λ

$$H \ll \Lambda \ll M_{\rm Pl}$$

Quantum corrections tend to drive scalar masses to the cutoff scale Λ, unless the fields are protected by symmetries

$$\Delta m^2 \sim \Lambda^2 \gg H^2 \longrightarrow \Delta\left(\frac{V''}{H^2}\right) \gg 1$$

Higher-dimension operators

$$V \to V\left(1 + c\frac{\phi^2}{\Lambda^2} + \cdots\right) \longrightarrow \Delta\left(\frac{V''}{H^2}\right) = 6c\frac{M_{\rm Pl}^2}{\Lambda^2} \gg 1$$

For a nice review, see Baumann and MacAllsiter 2014, “Inflation and String Theory”

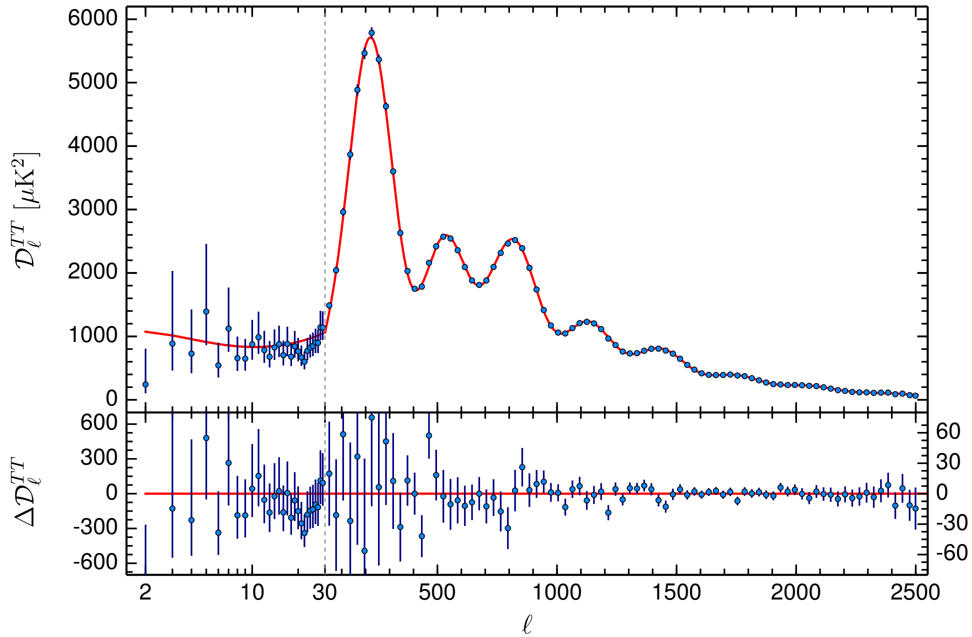
Cosmological perturbations

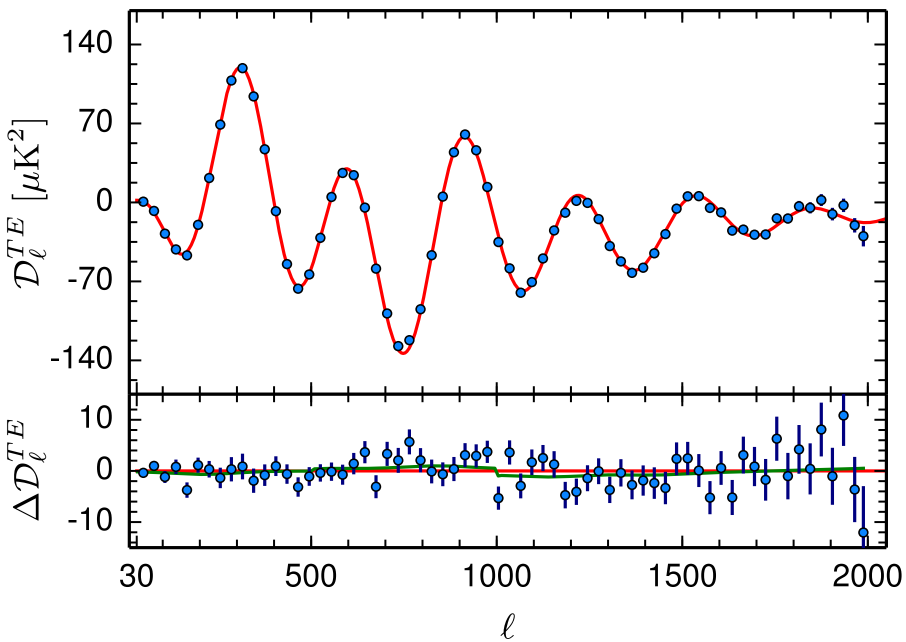
Single scalar gauge-invariant degree of freedom $v \ni \delta\phi, \delta g_{\mu\nu}$

$$\propto \delta T/T$$

Quantised starting from Bunch-Davies vacuum $v \to \hat{v}$

Quantum mean values compared with statistical averages in the sky





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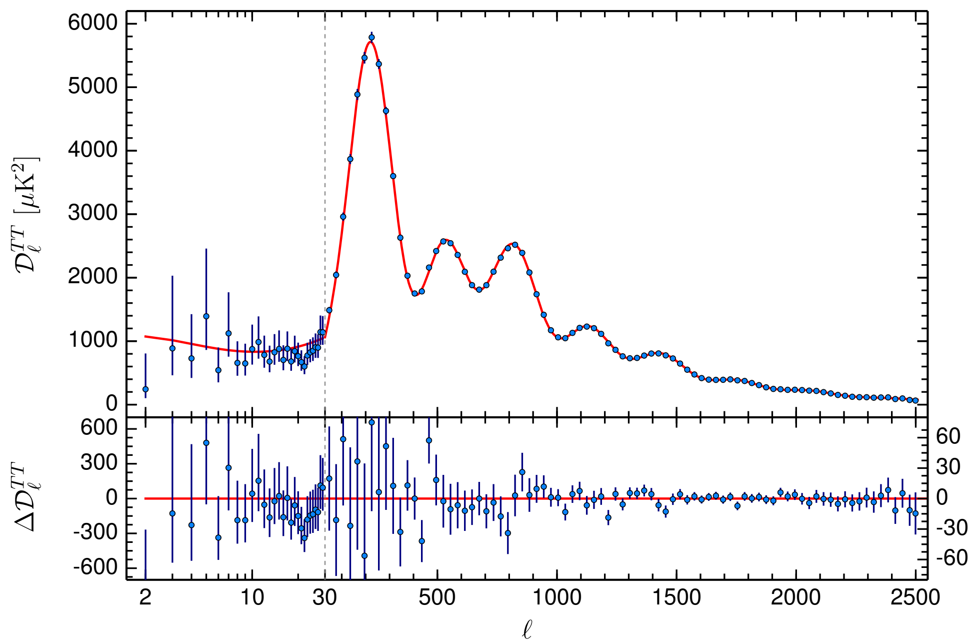
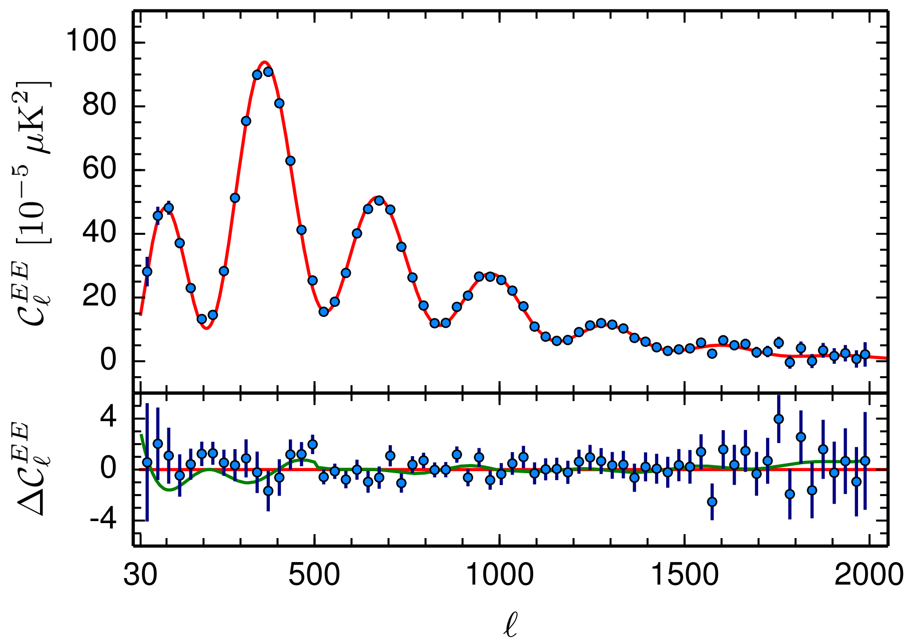
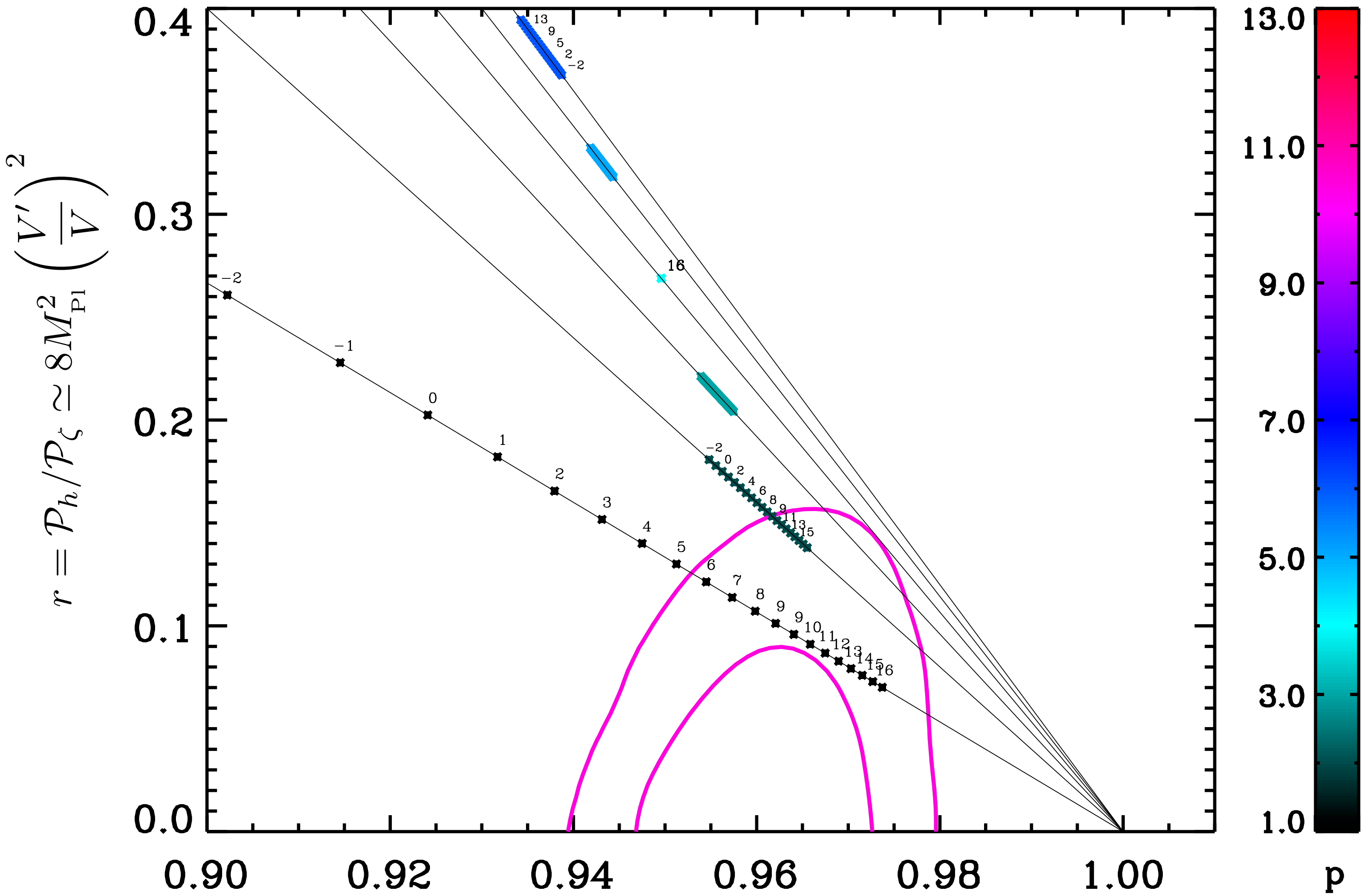




Comparing models

Example: $V \propto \phi^p$



$$n_{\rm S} = 1 + \mathrm{d}\ln\mathcal{P}_\zeta/\mathrm{d}\ln k$$

$$\simeq 1 - 3M_{\rm Pl}^2\left(\frac{V'}{V}\right)^2 + 2M_{\rm Pl}^2\frac{V''}{V}$$

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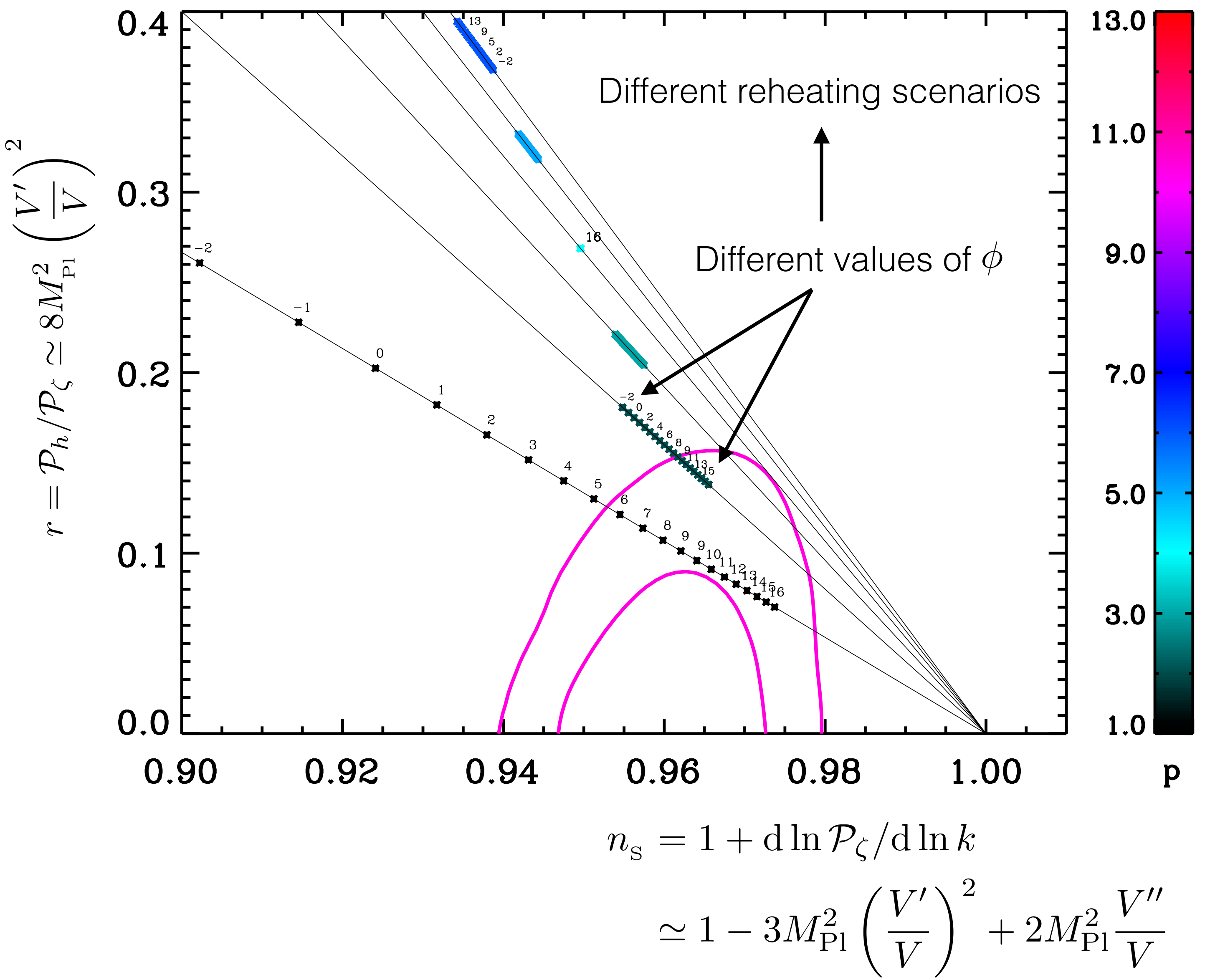
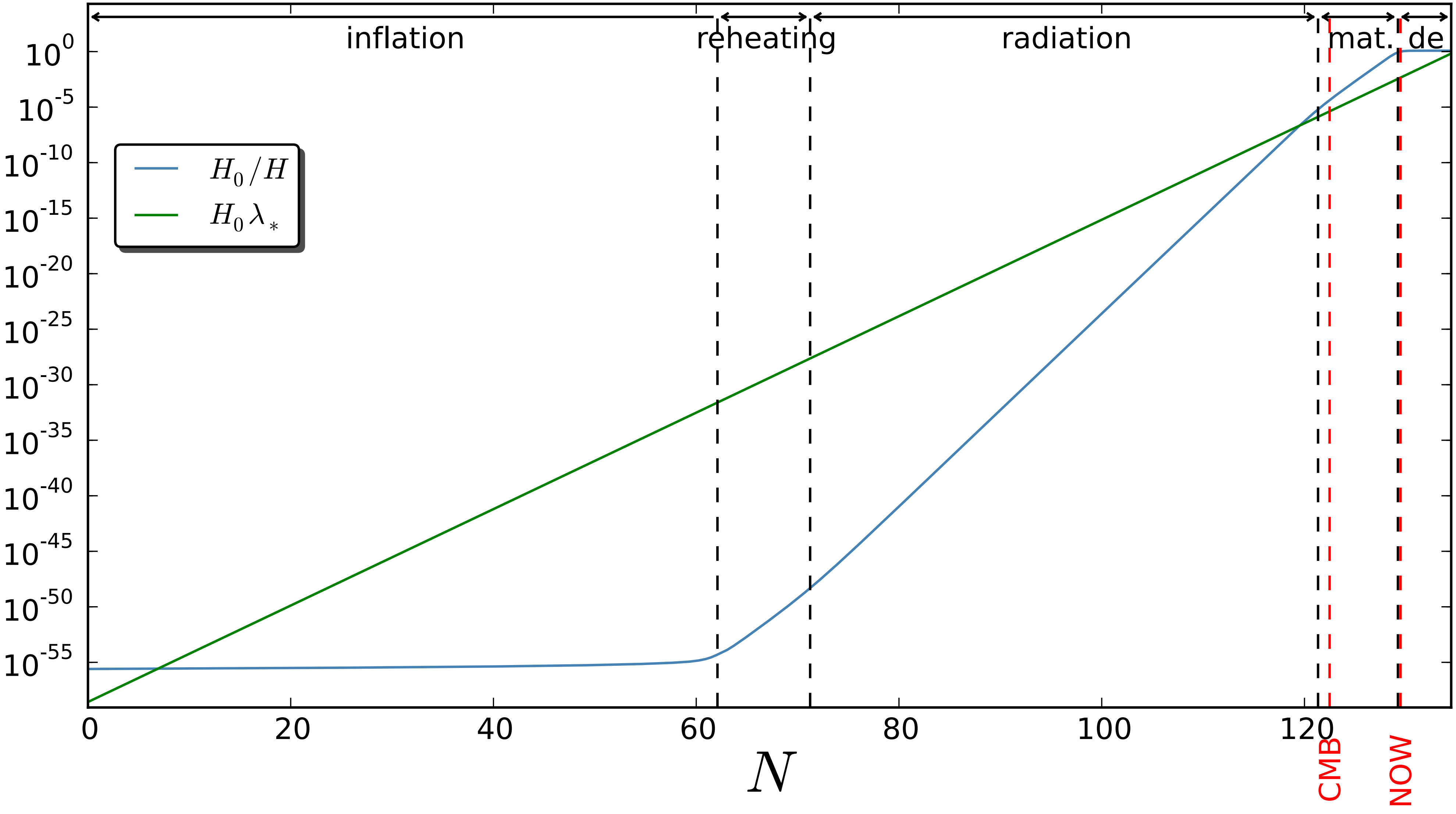


Kinematics reheating



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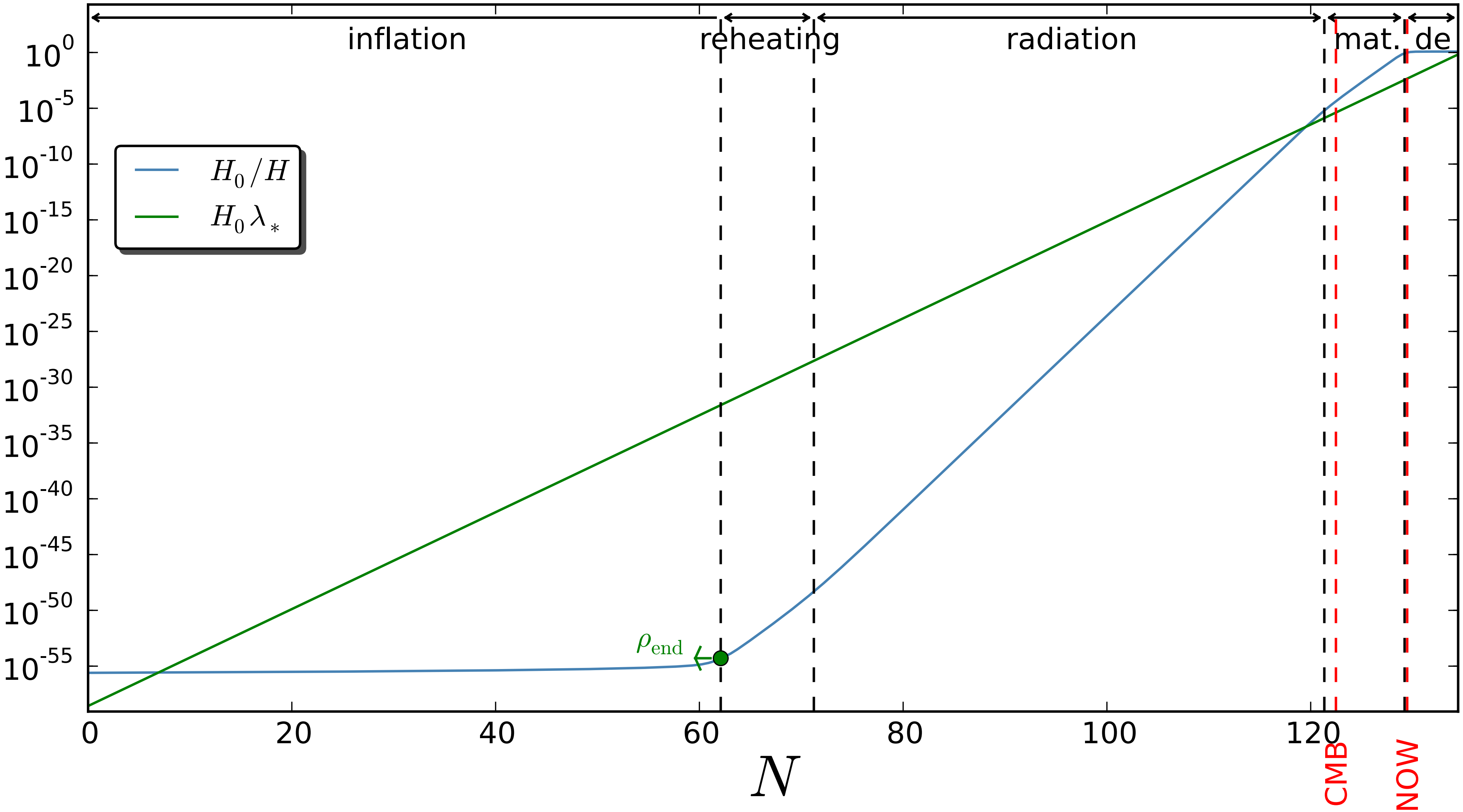

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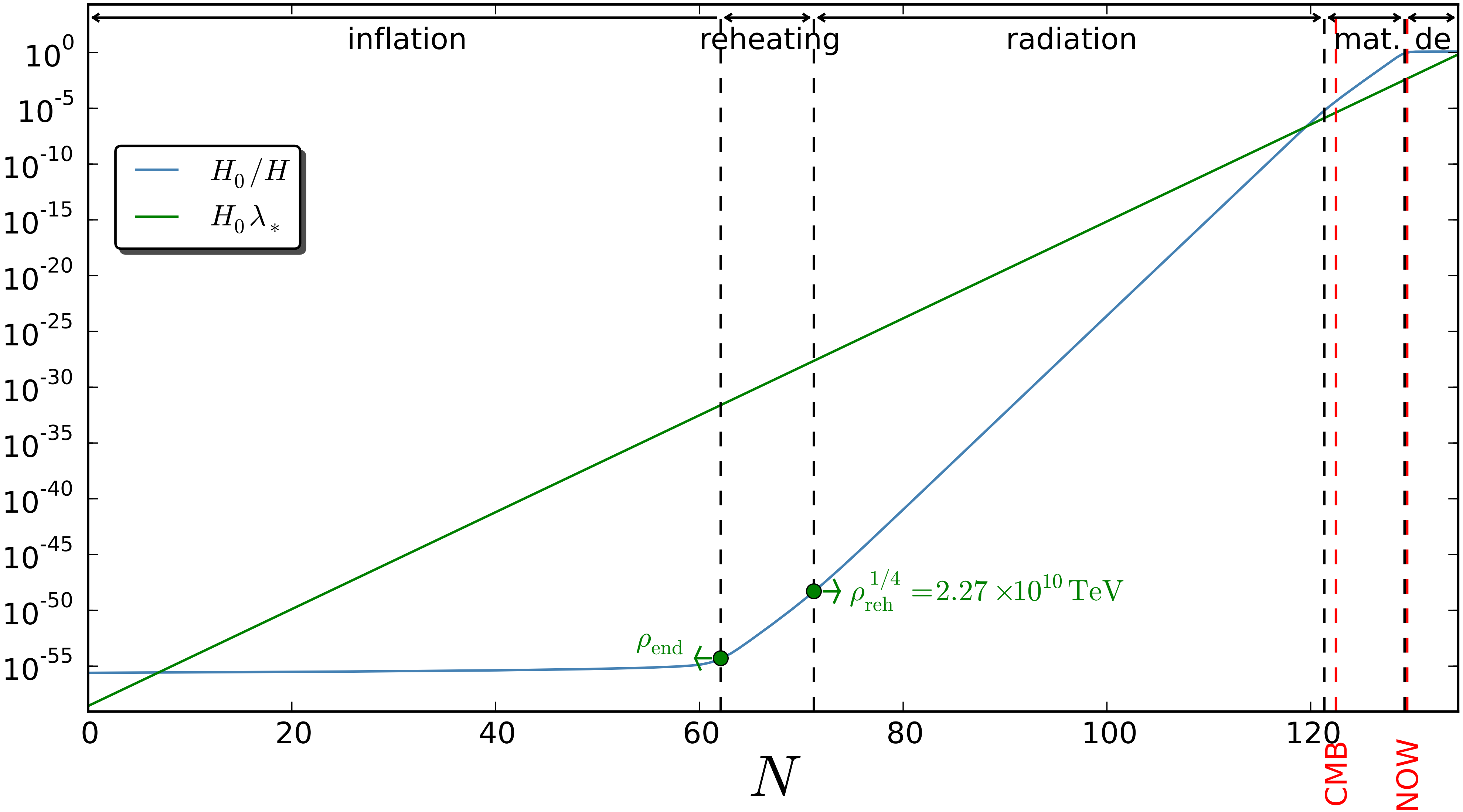

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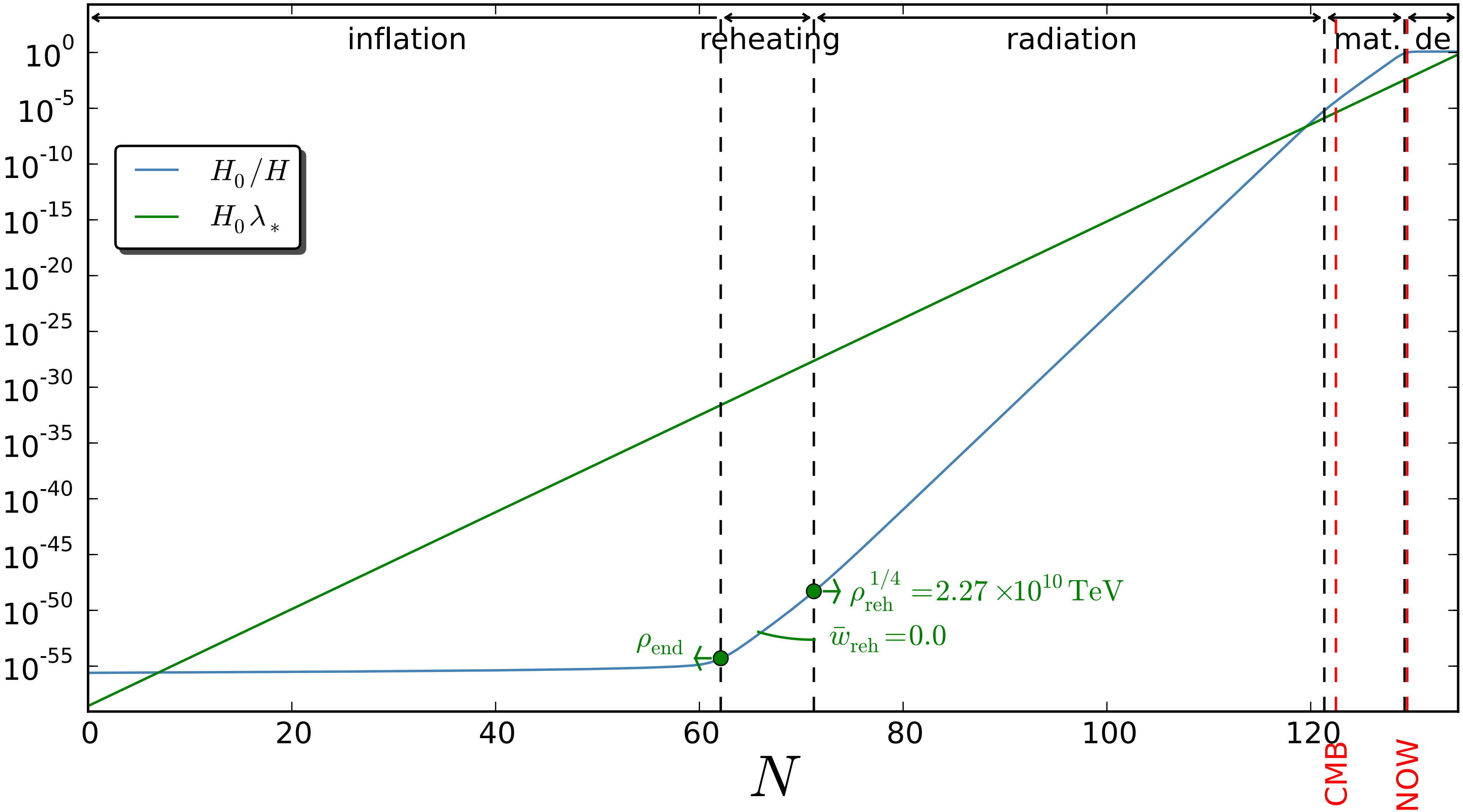

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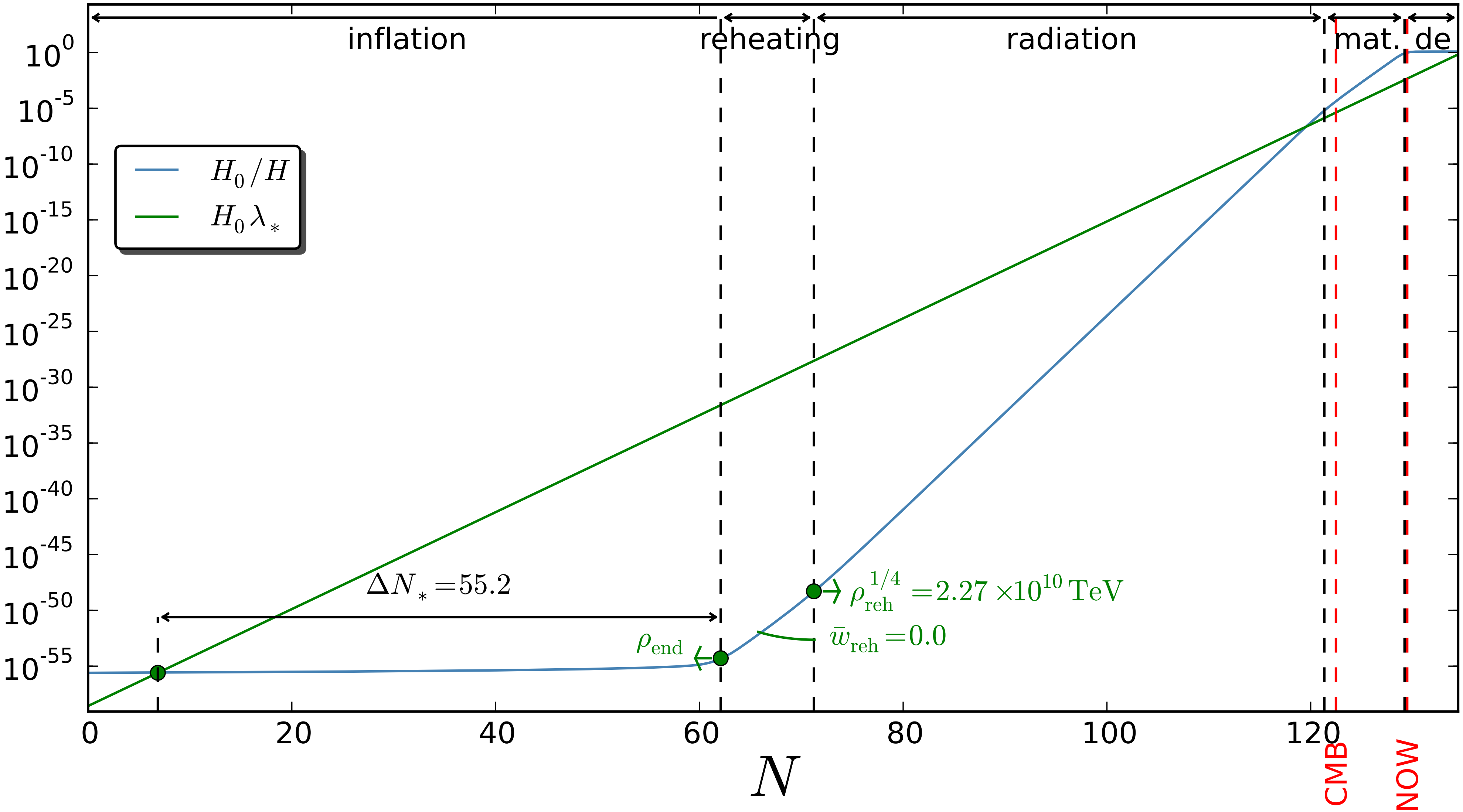
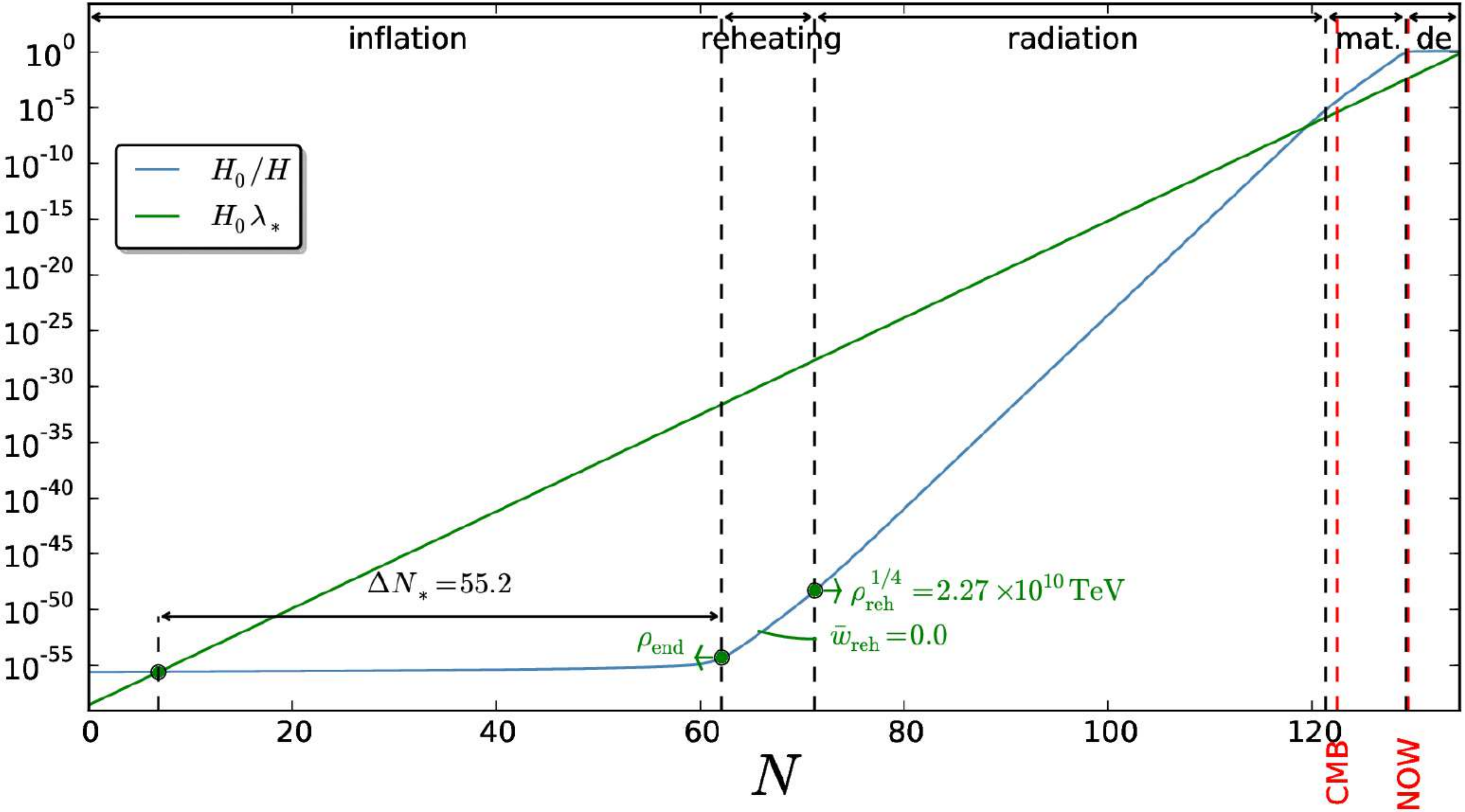


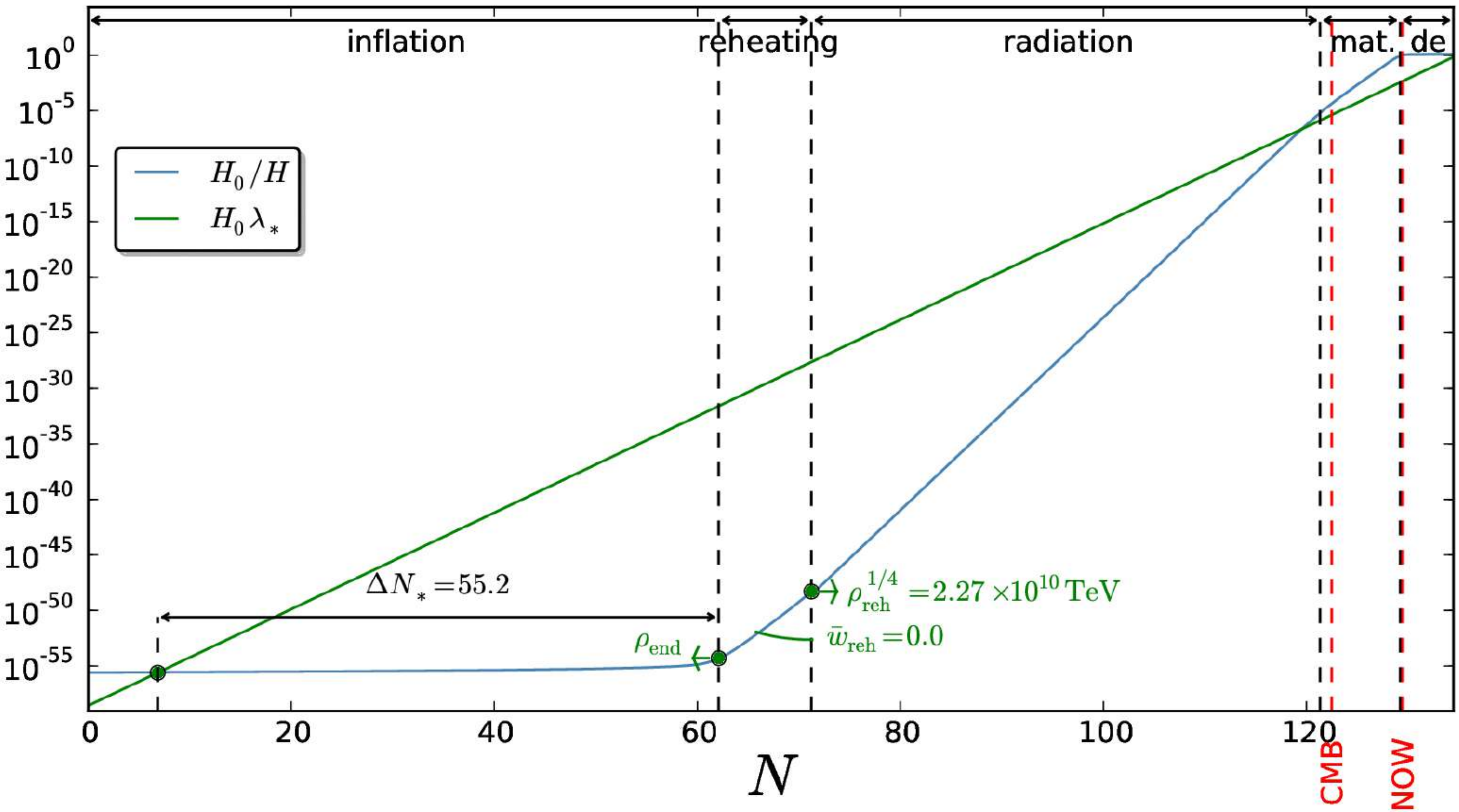
Kinematics reheating

$\rho_{\mathrm{BBN}} < \rho_{\mathrm{reh}} < \rho_{\mathrm{end}}$



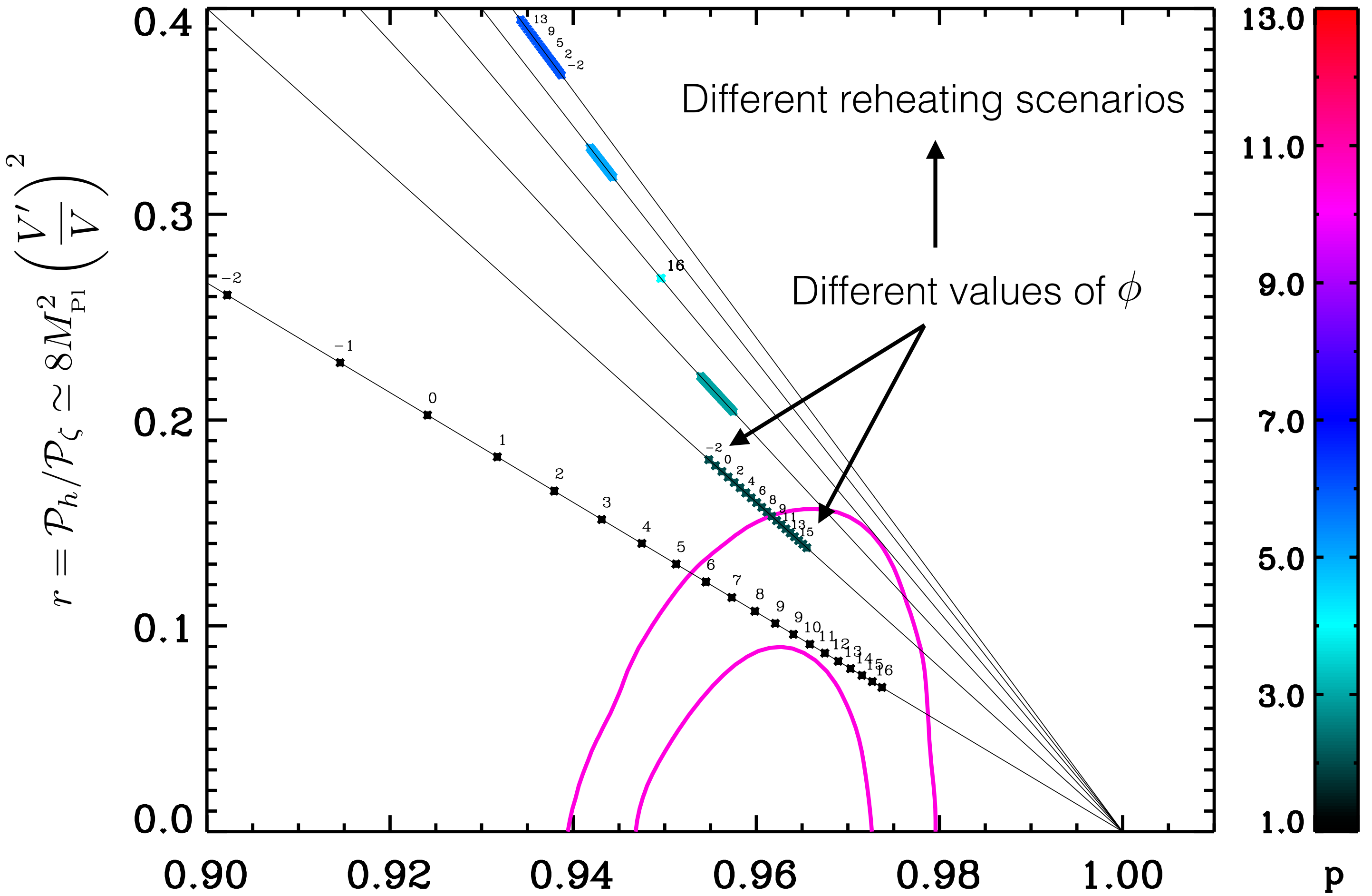
Kinematics reheating

$-1/3 < \bar{w}_{\rm reh} < 1$



Comparing models

Example: $V \propto \phi^p$

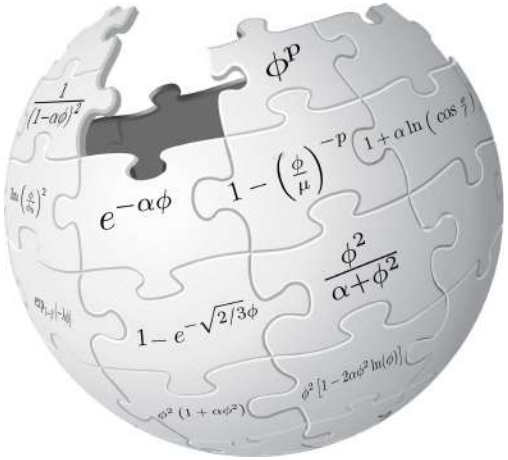


$$n_{\rm S} = 1 + \mathrm{d}\ln\mathcal{P}_\zeta/\mathrm{d}\ln k$$

$$\simeq 1 - 3M_{\rm Pl}^2\left(\frac{V'}{V}\right)^2 + 2M_{\rm Pl}^2\frac{V''}{V}$$

Encyclopedia inflationaris

J Martin, C Ringeval, V Vennin



- First issue 2013, latest version 2024 (arXiv:1303.3787)
- Accurate slow-roll predictions for 287 models (all single-field models proposed in the literature)
- Comes with a public runtime library *ASPIC*
- Results featured in the *Particle Data Group* review

Example: Higgs Inflation

Bezrukov & Shaposhnikov

Higgs field in the Jordan frame

$$S = \bar{M}^2 \int \mathrm{d}^4\mathbf{x}\sqrt{-\bar{g}}\left[\left(1+\xi h^2\right)\frac{\bar{R}}{2} - \frac{1}{2}\bar{g}^{\mu\nu}\partial_\mu h \partial_\nu h - \bar{M}^2\frac{\lambda}{4}\left(h^2 - \frac{v^2}{\bar{M}^2}\right)^2\right] + S_m\left[\psi_m; \bar{g}_{\mu\nu}\right]$$

Conformal transformation

Esposito-Farese & Polarski 2000

$$g_{\mu\nu} = \left(1+\xi h^2\right)\bar{g}_{\mu\nu}$$

$$\frac{\mathrm{d}\phi}{\mathrm{d}h} = \frac{\sqrt{1+\xi\left(1+6\xi\right)h^2}}{\left(1+\xi h^2\right)}M_{\mathrm{Pl}}$$

Higgs field in the Einstein frame

$$S = \bar{M}^2 \int \mathrm{d}^4\mathbf{x}\sqrt{-g}\left[\frac{R}{2} - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right] + S_m\left[\psi_m; A^2(\phi)g_{\mu\nu}\right]$$

$$V(\phi) = M_{\mathrm{Pl}}^2\left(1+\xi h^2\right)^{-2}\bar{M}^2\frac{\lambda}{4}\left(h^2 - \frac{v^2}{\bar{M}^2}\right)^2$$

$$A(\phi) = \left(1+\xi h^2\right)^{-1/2}$$

Higgs Inflation

Planck mass

(as measured in Cavendish-type experiments)

Damour & Esposito-Farese 1992 & 1996

$$\frac{1}{M_{\mathrm{Pl}}^2} = \frac{1}{\bar{M}^2}\boxed{\frac{1}{1+\xi h^2}}\boxed{\frac{1+\left(1+8\xi\right)\xi h^2}{1+\left(1+6\xi\right)\xi h^2}}$$

graviton exchange   scalar particle exchange

Today: $h \simeq \dfrac{v}{\bar{M}} \ll 1$ so $\bar{M} \simeq M_{\mathrm{Pl}}$

Inflaton

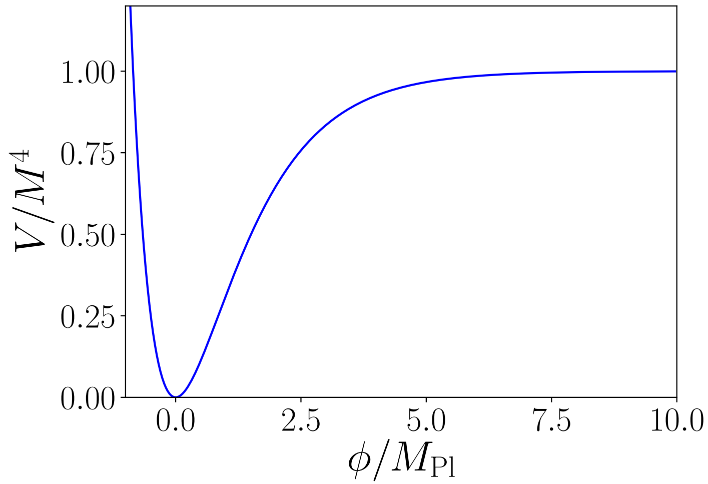
$$\frac{\phi}{M_{\mathrm{Pl}}} = \sqrt{\frac{1}{\xi}+6}\ \mathrm{arcsinh}\left[\sqrt{\xi\left(1+6\xi\right)}h\right] - \sqrt{6}\arctan\left[\frac{\sqrt{6}\xi h}{\sqrt{1+\xi\left(1+6\xi\right)h^2}}\right]$$

Limit $\xi \gg 1$ and $\xi h \gg 1$: $\phi \simeq \sqrt{6}M_{\mathrm{Pl}}\ln\left(1+\xi h^2\right)$

Potential

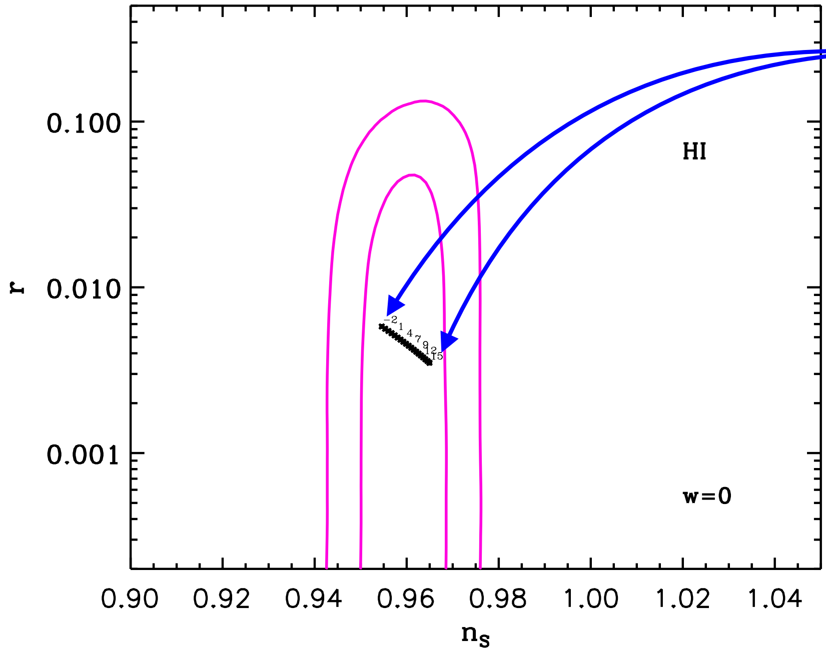
$$V\left(\phi\right) = \boxed{\frac{\bar{M}^4\lambda}{4\xi^2}}\left(1-e^{-\sqrt{\frac{2}{3}}\frac{\phi}{M_{\mathrm{Pl}}}}\right)^2$$

M^4



Higgs Inflation

Predictions



Different reheating temperatures

$$\cdots + S_m\left[\psi_m; A^2(\phi) g_{\mu\nu}\right]$$

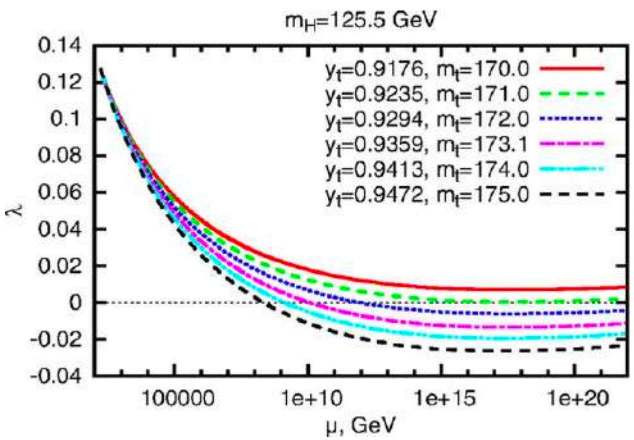
Calculable in principle!

CMB amplitude normalisation

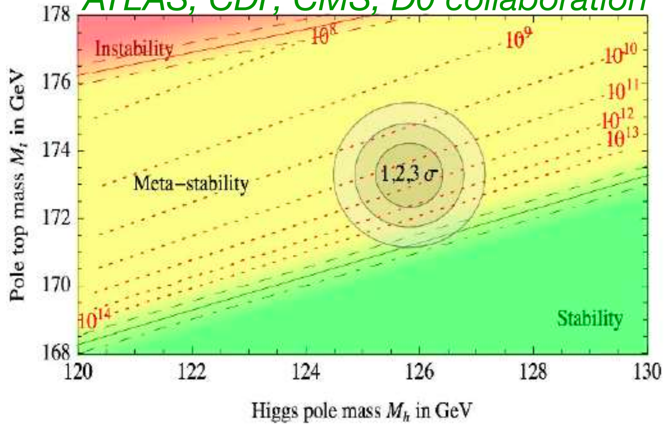
$$\frac{M}{M_{\rm Pl}} \simeq 0.003\sqrt{\frac{60}{\Delta N_*}}\left(\frac{\mathscr{P}_\zeta}{2.2\times 10^{-9}}\right)^{1/4}$$ (GUT scale)

$$\longrightarrow \xi \simeq 48000\sqrt{\lambda} = 24000\frac{m_h}{v}$$

Today:
$m_h \simeq 125\text{GeV},\ v = 175\text{GeV}$



ATLAS, CDF, CMS, D0 collaboration



Starobinsky Inflation

Starobinsky 1980

f(R) theory $$S = \frac{M_{\rm Pl}^2}{2}\int \mathrm{d}^4\mathbf{x}\sqrt{-\bar{g}}\, f\left(\bar{R}\right) \quad \text{with} \quad f(\bar{R}) = \bar{R} + \frac{\bar{R}^2}{6\mu^2}$$

Contains one tensor + one scalar propagating dof

Conformal transformation

De Felice & Tsujikawa 2010

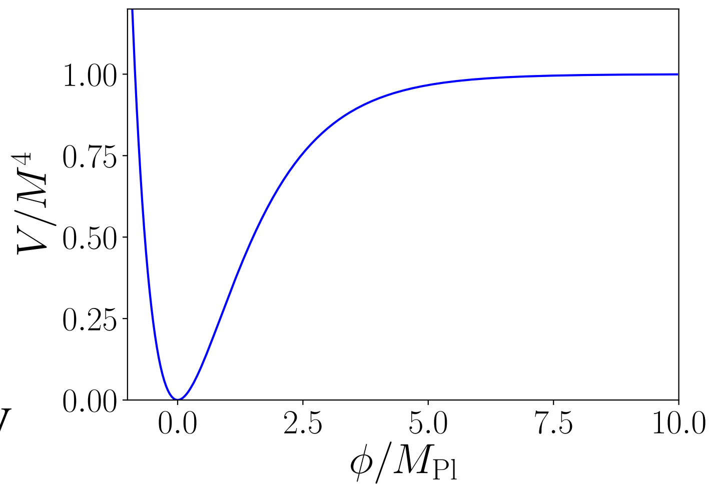
$$g_{\mu\nu} = \frac{\partial f}{\partial \bar{R}}\bar{g}_{\mu\nu}$$

$$\frac{\phi}{M_{\rm Pl}} = \sqrt{\frac{3}{2}}\ln\left(\left|\frac{\partial f}{\partial \bar{R}}\right|\right)$$

Scalar field in the Einstein frame

$$S = \frac{M_{\rm Pl}^2}{2}\int \mathrm{d}^4\mathbf{x}\sqrt{-g}\left[R - \frac{1}{4M_{\rm Pl^2}}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \frac{1}{2M_{\rm Pl^2}}V(\phi)\right] \quad \text{with} \quad V(\phi) = \frac{M_{\rm Pl}^2}{2}\frac{\left|\frac{\partial f}{\partial \bar{R}}\right|}{\frac{\partial f}{\partial \bar{R}}}\frac{\bar{R}\frac{\partial f}{\partial \bar{R}} - f(\bar{R})}{\left(\frac{\partial f}{\partial \bar{R}}\right)^2}$$

$$\longrightarrow V(\phi) = \underbrace{\boxed{\frac{3}{4}M_{\rm Pl}^2\mu^2}}_{M^4}\left(1 - e^{-\sqrt{\frac{2}{3}}\frac{\phi}{M_{\rm Pl}}}\right)^2$$



CMB amplitude normalisation $$\frac{M}{M_{\rm Pl}} \simeq 0.003$$

$$\longrightarrow \mu \sim 10^{-5}M_{\rm Pl} \sim 10^{13}\mathrm{GeV}$$

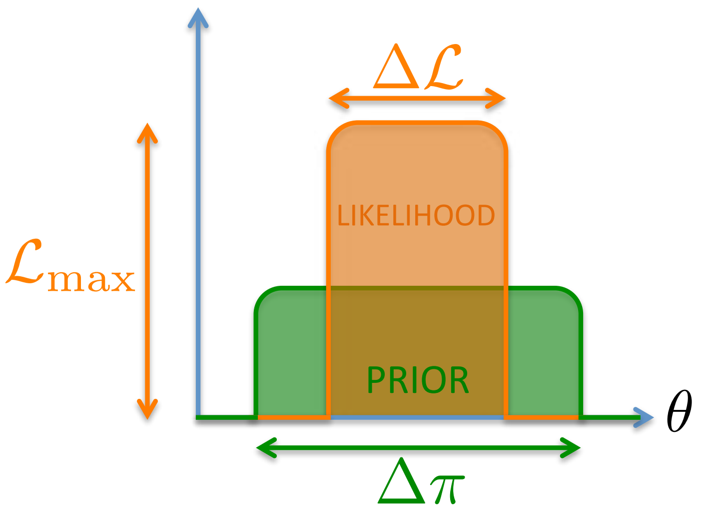
Comparing models

- Probability of a model $\mathscr{M}$ to explain the data $\mathscr{D}$:

$$P(\mathscr{M}\,|\,\mathscr{D}) = \frac{\mathscr{E}(\mathscr{D}\,|\,\mathscr{M})P(\mathscr{M})}{P(\mathscr{D})}$$

- Bayesian evidence

$$\mathscr{E}(\mathscr{D}\,|\,\mathscr{M}) \propto \int \mathscr{L}(\mathscr{D}\,|\,n_{\mathrm{S}}, r, \cdots)\pi_{\mathscr{M}}(\vec{\theta}_{\mathrm{inf}}, \vec{\theta}_{\mathrm{reh}}, \cdots)\mathrm{d}\vec{\theta}$$



$$\mathcal{E}\left(\mathcal{M}\right) = \mathcal{L}_{\max}\,\frac{\Delta\mathcal{L}}{\Delta\pi}$$

Compromise between quality of the fit
and lack of fine tuning

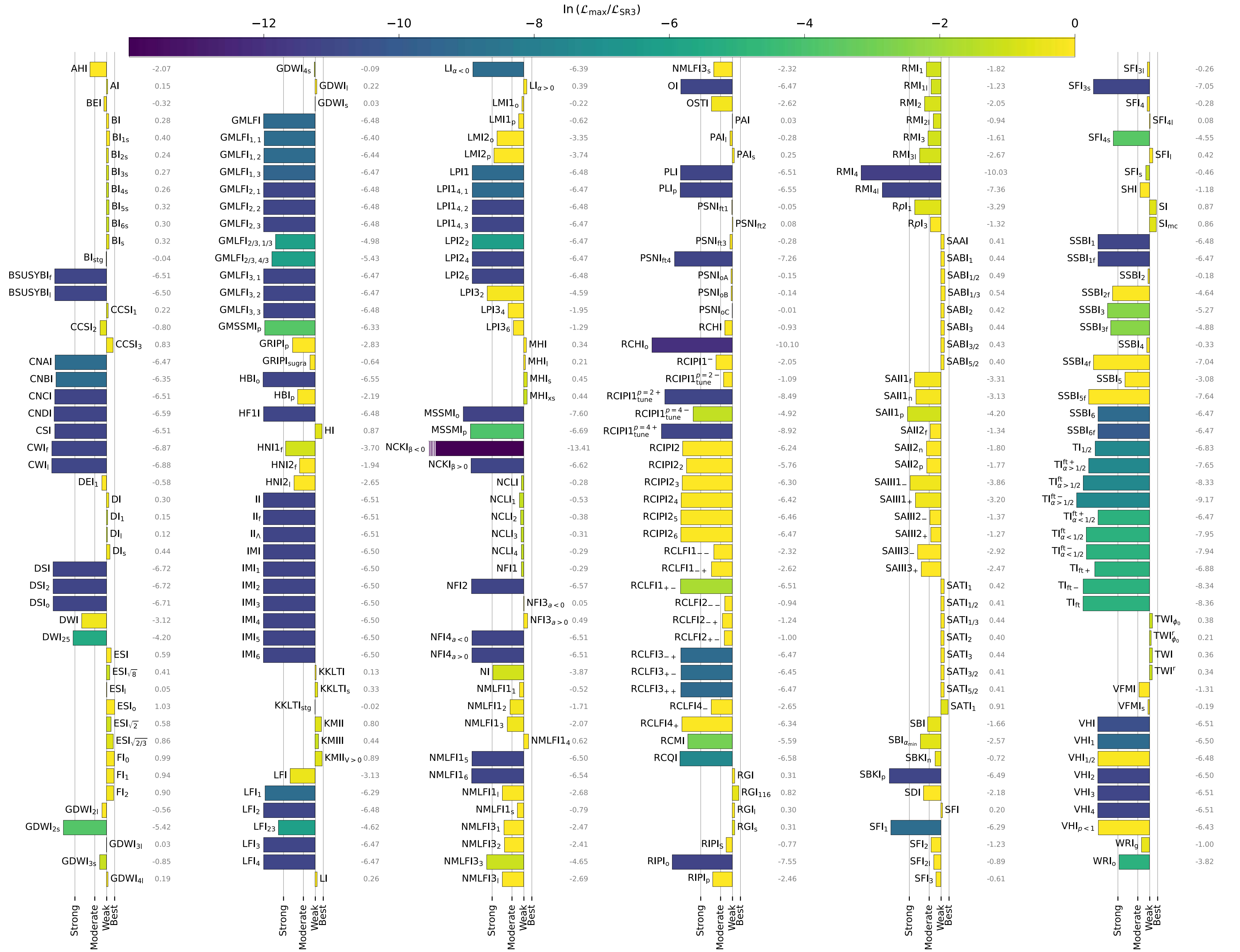
Courtesy C. Ringeval

Machine-learning an effective likelihood

- To speed-up data analysis for 287 models

$$\mathcal{L}_{\mathrm{eff}}(\boldsymbol{D}|P_*, \varepsilon_1, \varepsilon_2, \varepsilon_3) \propto \int P(\boldsymbol{D}|\boldsymbol{\theta}_{\mathrm{s}}, P_*, \varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4)\, \pi(\varepsilon_4)\, \pi(\boldsymbol{\theta}_{\mathrm{s}})\, \mathrm{d}\varepsilon_4 \mathrm{d}\boldsymbol{\theta}_{\mathrm{s}}.$$

- The full likelihood has 55 parameters and is built upon
  - Planck 2020 post-legacy TT, TE, EE data (`PR4/NPIPE` maps)
  - Large scale EE polarization (`lowE`)
  - BICEP/Keck B-mode 2018 (arXiv:2110.00483)
  - Small scale TE and EE from SPT-3G (arXiv:2103.13618)
  - Baryon Acoustic Oscillations (SDSS collaboration)
- MCMC exploration of the 55 dimensions
  - `COSMOMC` up to 25 million samples ($R - 1 < 10^{-3}$)
  - `GetDist` marginalization in 4D: $P_*, \varepsilon_1, \varepsilon_2, \varepsilon_3$
- Basic machine learning: 1 hidden layer with 300 nodes

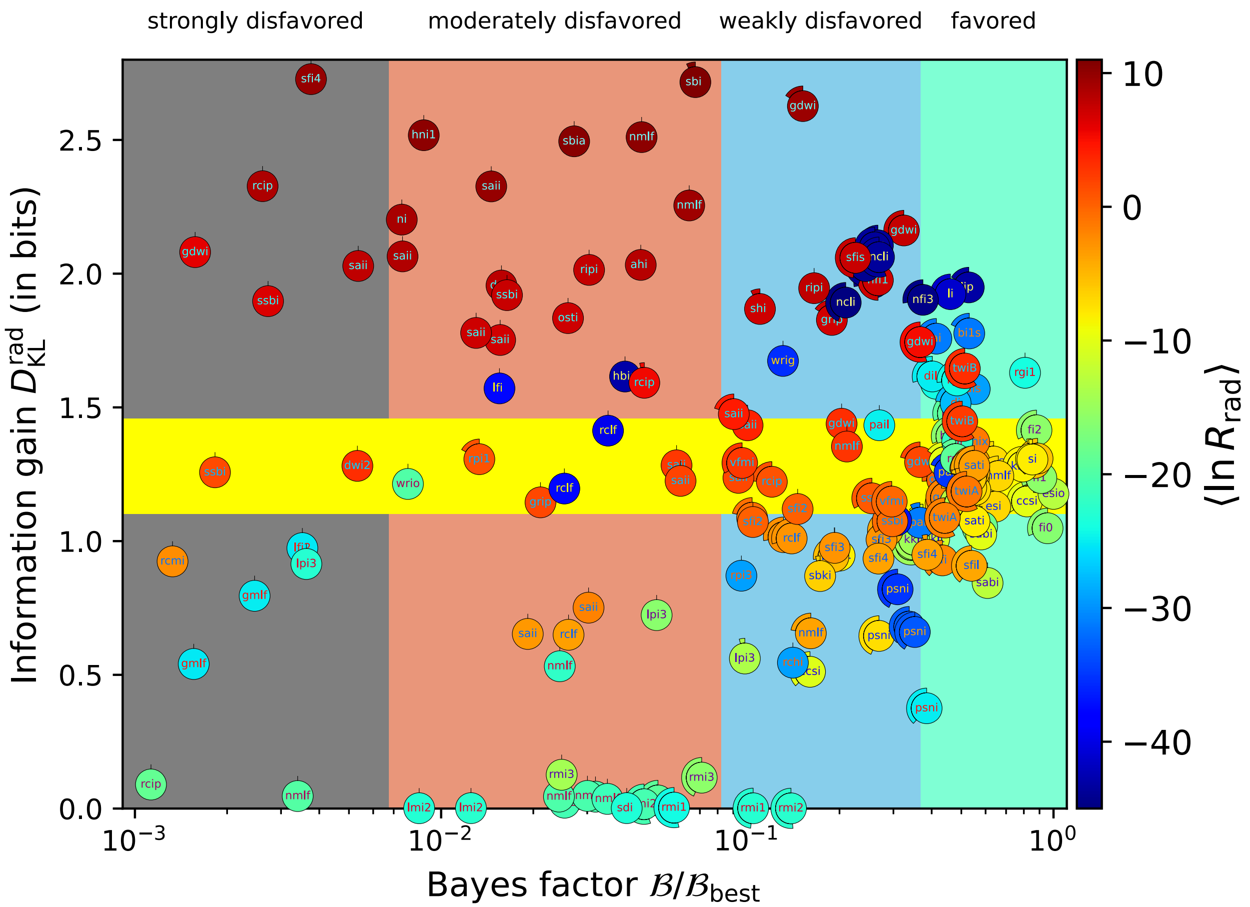


ln ($\mathcal{L}_{max}/\mathcal{L}_{SR3}$)
−12
−10
−8
−6
−4
−2
0
Strong
Moderate
Weak
Best

Information gain on reheating

- Kullback-Leibler divergence between the prior and posterior

$$D_{\rm KL}^{\rm reh} = \int P(\vec{\theta}_{\rm reh}\,|\,\mathscr{D}) \ln \left[\frac{P(\vec{\theta}_{\rm reh}\,|\,\mathscr{D})}{\pi(\vec{\theta}_{\rm reh})} \right] {\rm d}\vec{\theta}_{\rm reh}$$



Information gain on reheating

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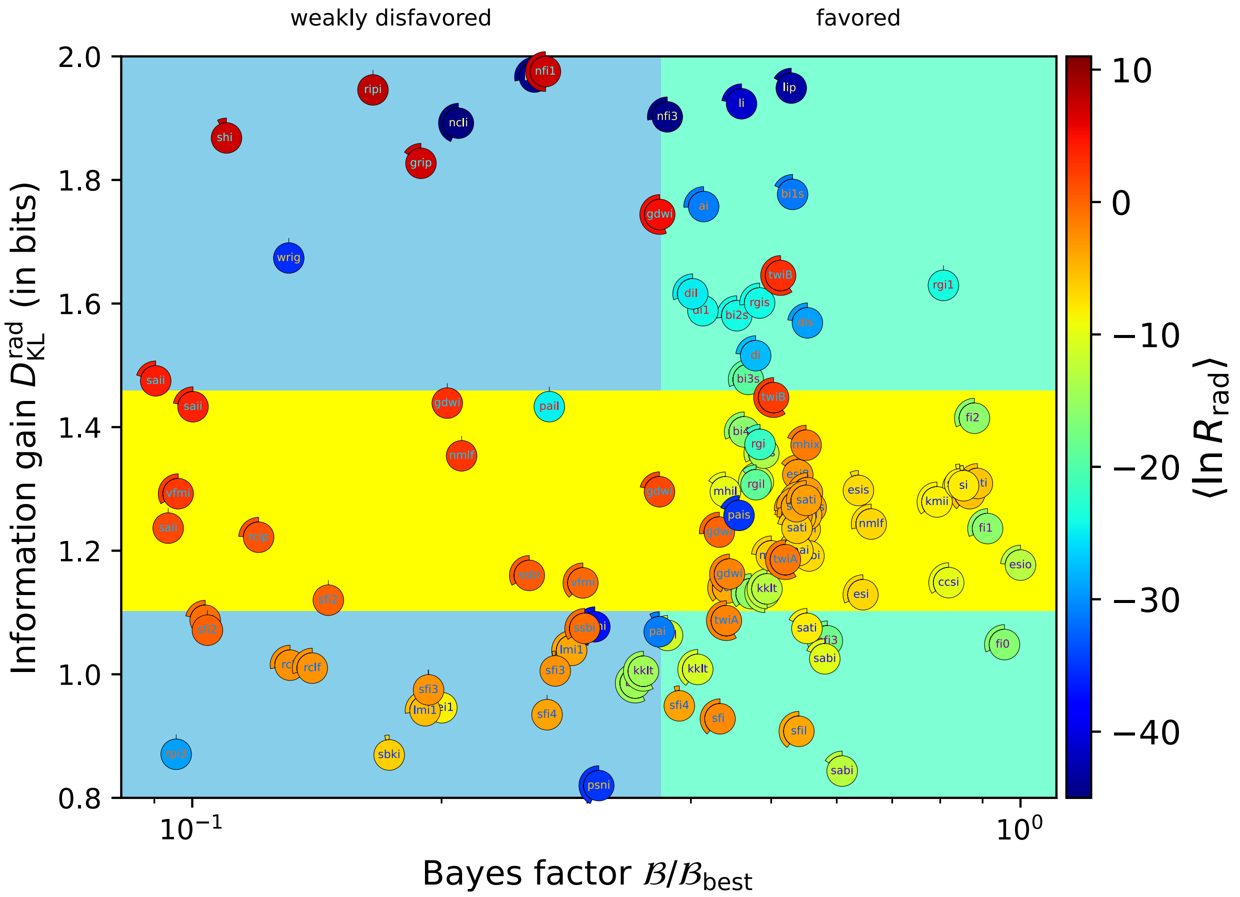
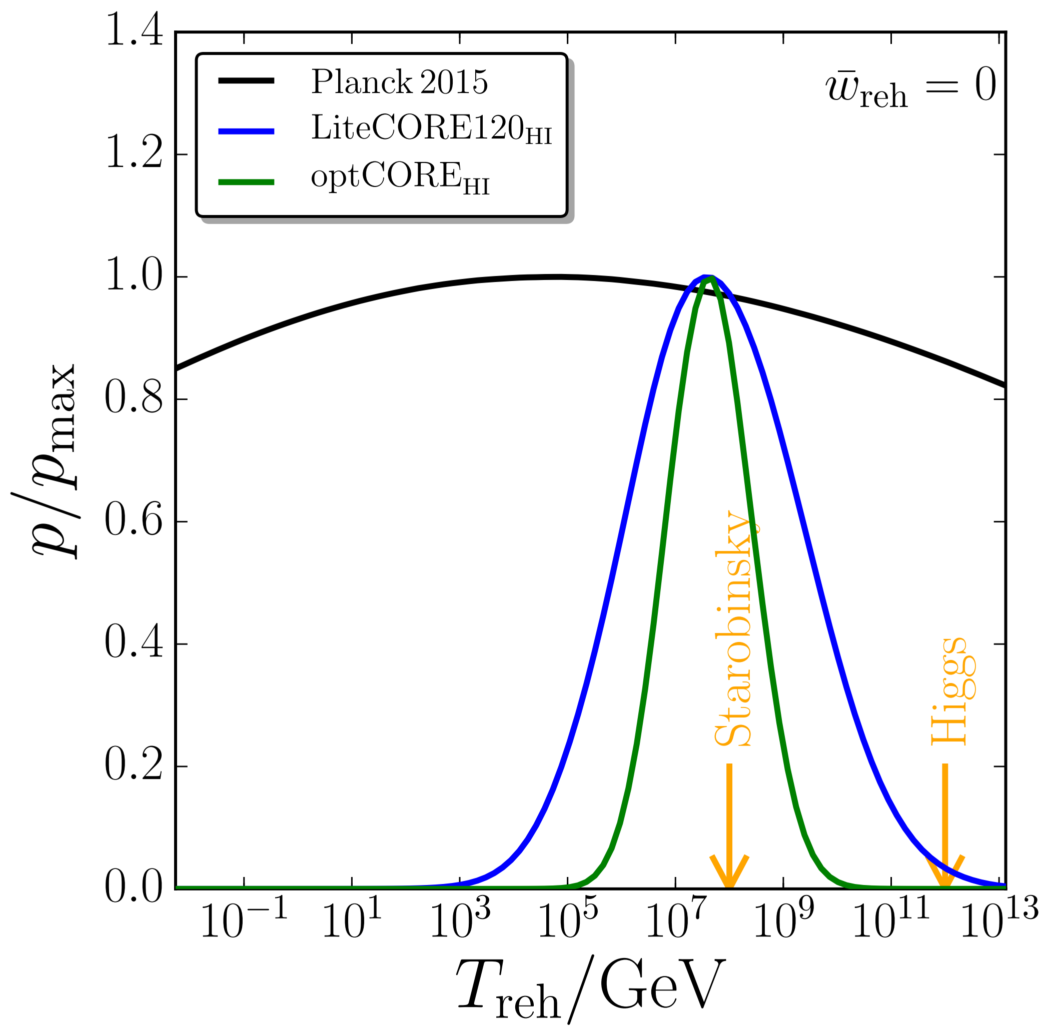


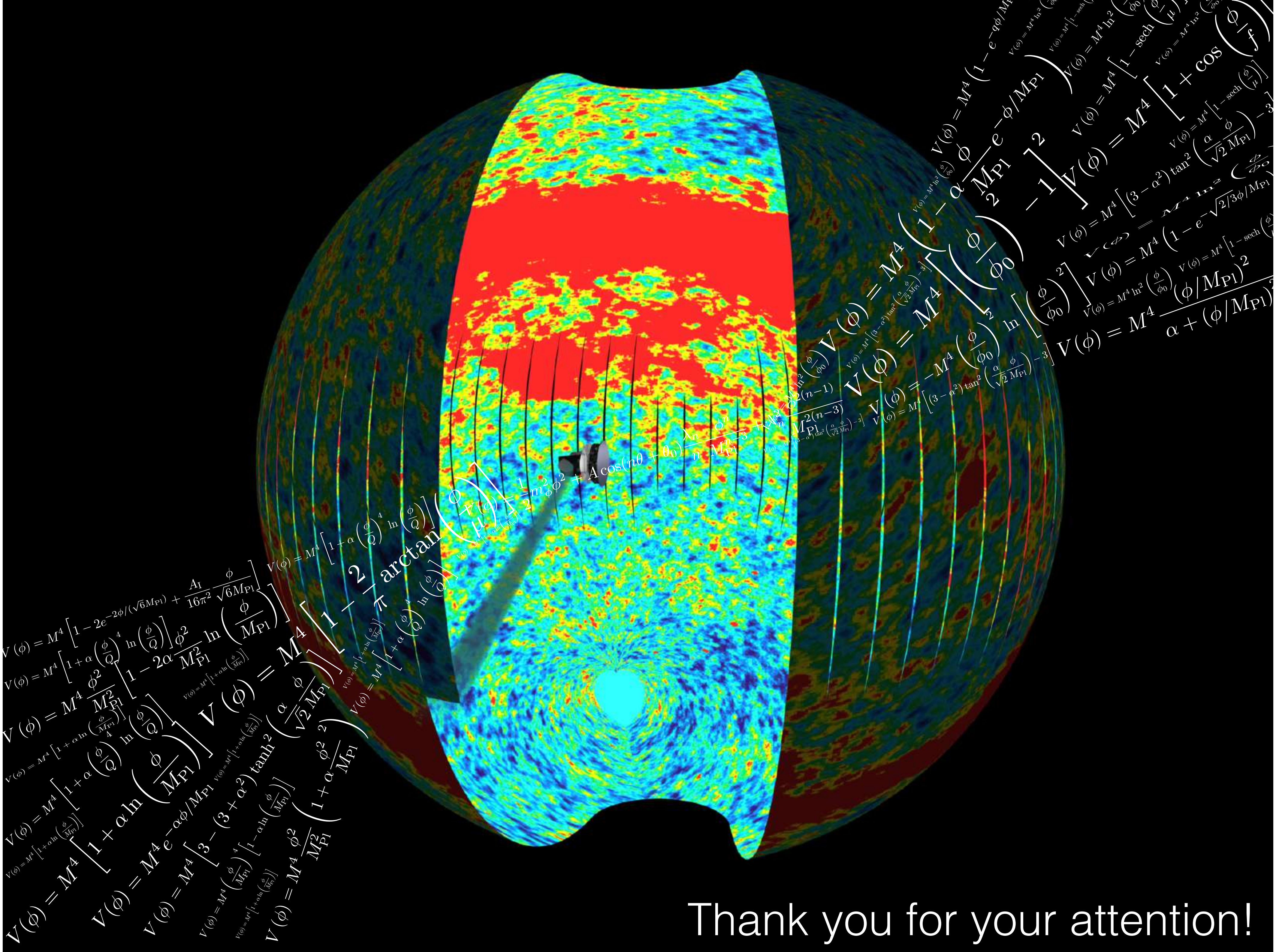
Prospects on constraining reheating

Example: Higgs Inflation vs the Starobinsky model



Conclusion

- Cosmic inflation can be embedded in various high-energy constructions.
- Out of the 287 single-field models proposed so far, 40% are excluded by CMB data, while 25% remain favored.
- The data starts to be sensitive to the reheating dynamics, hence probes how the inflationary sector couples to the standard model.
- These constraints will get better in the future with CMB-S4, Euclid and LiteBIRD on their way!



Thank you for your attention!

Back up slides

Higgs Inflation

Radiative corrections

Barvinsky, Kamenshchik, Starobinsky (2008)
De Simone, Hertzberg, Wilczek (2008)

$$F(h) = 1 + \xi h^2 + \frac{C}{16\pi^2} h^2 \ln\left(\frac{M_{\rm Pl}^2 h^2}{\mu^2}\right)$$

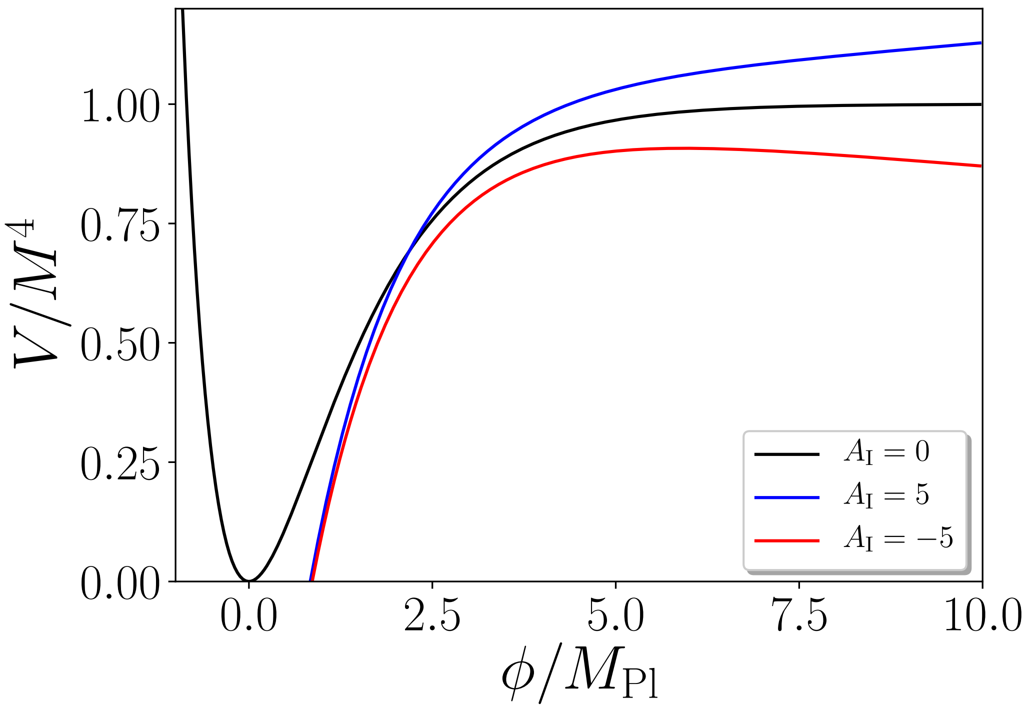
$$U(h) = M_{\rm Pl}^2 \frac{\lambda}{4}\left(h^2 - \frac{v^2}{\bar{M}^2}\right)^2 + \frac{\lambda A}{128\pi^2} M_{\rm Pl}^2 h^4 \ln\left(\frac{M_{\rm Pl}^2 h^2}{\mu^2}\right)$$

with $A = \frac{3}{8\lambda}\left[2g^4 + g^2 + g'^2 - 16 y_{\rm t}^4\right] + 6\lambda + \mathcal{O}\left(\xi^{-2}\right)$ and $C = 3\xi\lambda + \mathcal{O}\left(\xi^0\right)$

μ: renormalisation scale, $y_{\rm t}$: Yukawa coupling of the top quark
g, g' : coupling constants of the $\mathrm{SU}(2)_{\rm L}$ and $\mathrm{U}(1)_{\rm Y}$ groups

$$\longrightarrow V(\phi) \simeq \frac{M_{\rm Pl}^2 \lambda}{4\xi^2}\left(1 - 2e^{-\sqrt{\frac{2}{3}}\frac{\phi}{M_{\rm Pl}}} + \frac{A_{\rm I}}{16\pi^2}\frac{\phi}{\sqrt{6}M_{\rm Pl}}\right)$$

with $A_{\rm I} = A - 12\lambda$



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$$F(h) = 1 + \xi h^2 + \frac{C}{16\pi^2} h^2 \ln\left(\frac{M_{\rm Pl}^2 h^2}{\mu^2}\right)$$

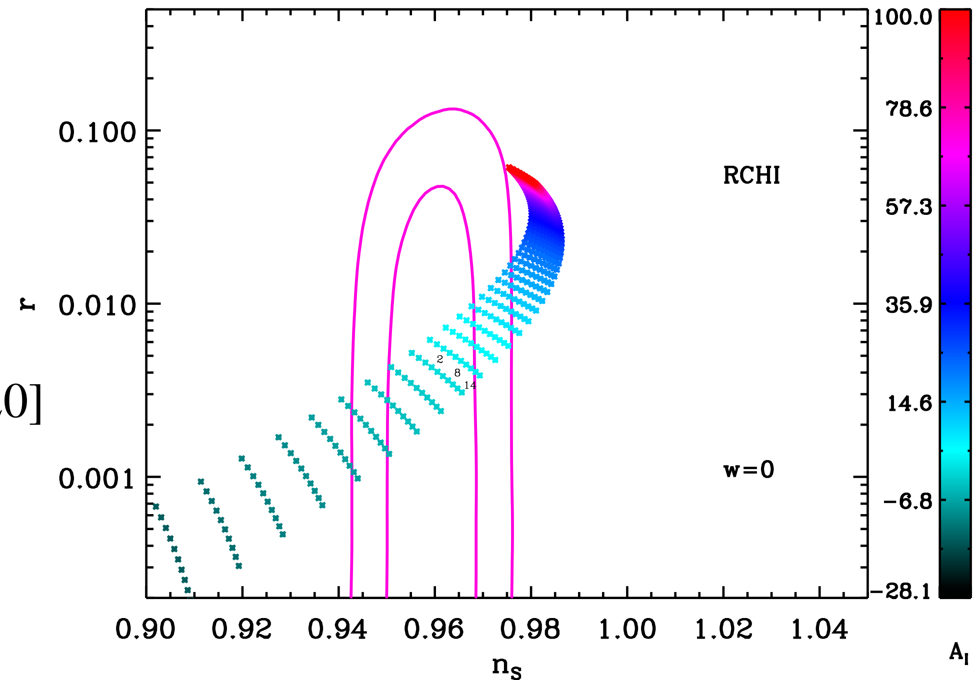
$$U(h) = M_{\rm Pl}^2 \frac{\lambda}{4}\left(h^2 - \frac{v^2}{\bar{M}^2}\right)^2 + \frac{\lambda A}{128\pi^2} M_{\rm Pl}^2 h^4 \ln\left(\frac{M_{\rm Pl}^2 h^2}{\mu^2}\right)$$

with $A = \frac{3}{8\lambda}\left[2g^4 + g^2 + g'^2 - 16 y_{\rm t}^4\right] + 6\lambda + \mathcal{O}\left(\xi^{-2}\right)$ and $C = 3\xi\lambda + \mathcal{O}\left(\xi^0\right)$

μ: renormalisation scale, $y_{\rm t}$: Yukawa coupling of the top quark
g, g' : coupling constants of the $\mathrm{SU}(2)_{\rm L}$ and $\mathrm{U}(1)_{\rm Y}$ groups

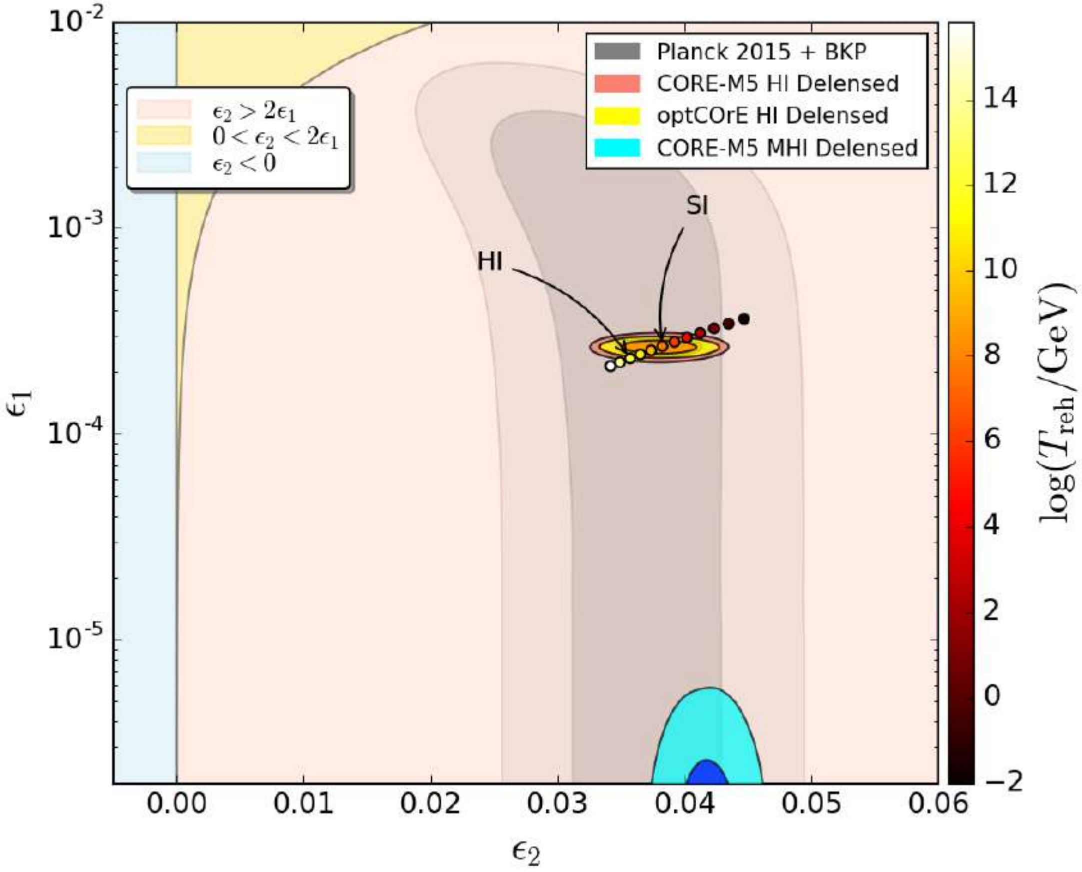
$$\longrightarrow V(\phi) \simeq \frac{M_{\rm Pl}^2 \lambda}{4\xi^2}\left(1 - 2e^{-\sqrt{\frac{2}{3}}\frac{\phi}{M_{\rm Pl}}} + \frac{A_{\rm I}}{16\pi^2}\frac{\phi}{\sqrt{6}M_{\rm Pl}}\right)$$

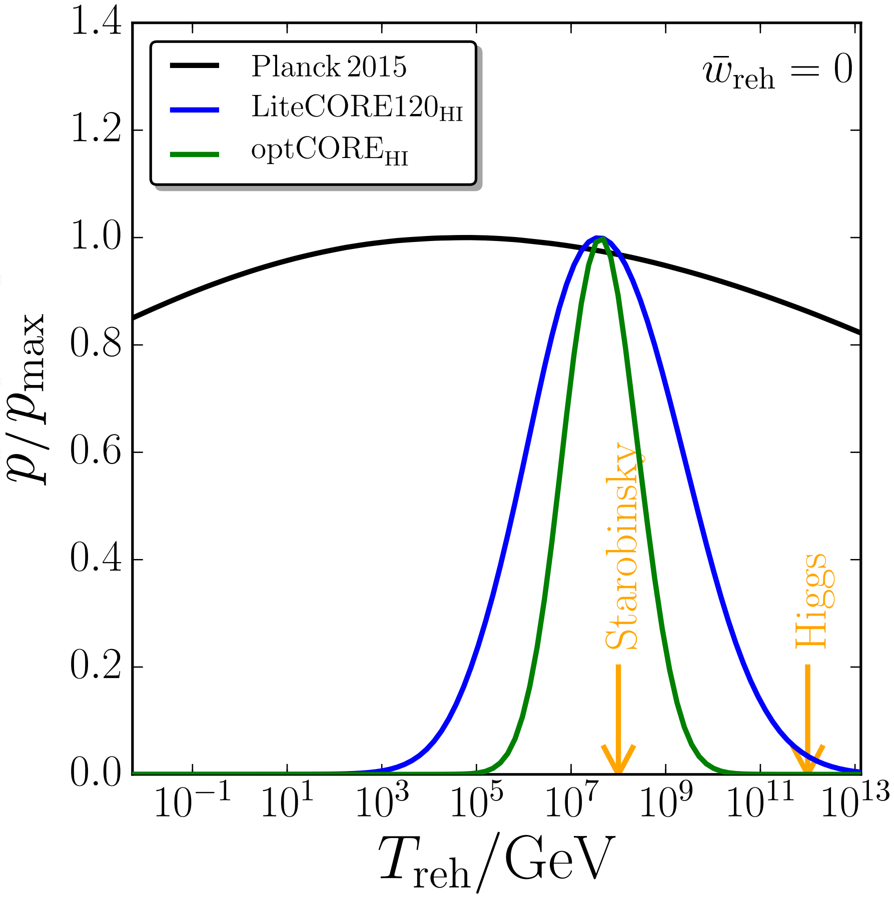
with $A_{\rm I} \simeq \frac{12}{m_h^2 v^2}\left(m_Z^4 + 2m_W^4 - 4m_{\rm t}^4\right) \in [-48, -20]$



Starobinsky Inflation

Reheating

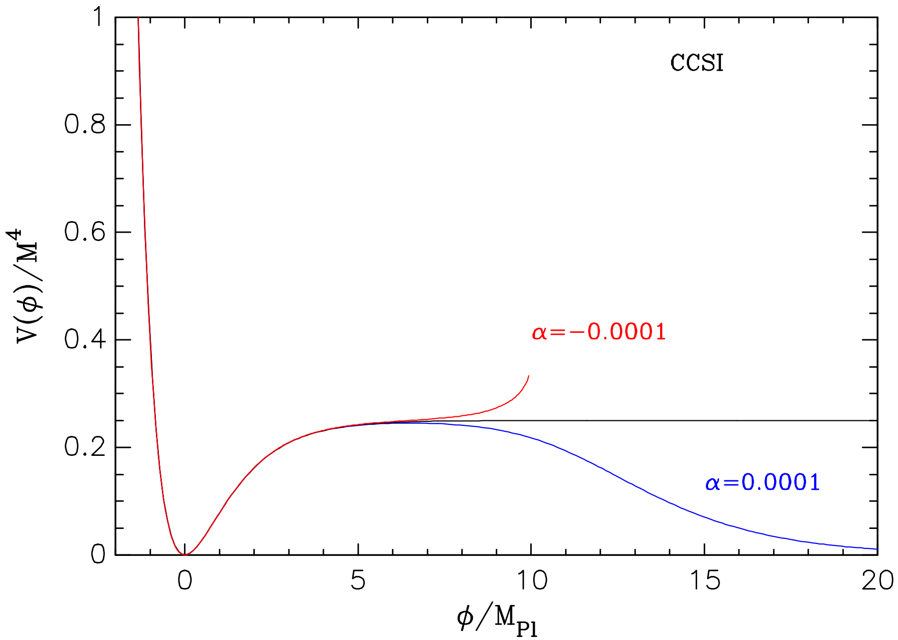




Starobinsky Inflation

Higher-gravitational corrections $f(\bar{R}) = \bar{R} + \frac{\bar{R}^2}{6\mu^2} + \alpha\left(\frac{\bar{R}}{\sqrt{6}\mu}\right)^3$

$$\longrightarrow \quad V(\phi) = \frac{3}{4}M_{\rm Pl}^2\mu^2\left(1 - e^{-\sqrt{\frac{2}{3}}\frac{\phi}{M_{\rm Pl}}}\right)^2 \frac{1 + \sqrt{1 + 3\alpha\left(e^{\sqrt{\frac{2}{3}}\frac{\phi}{M_{\rm Pl}}} - 1\right)} + 2\alpha\left(e^{\sqrt{\frac{2}{3}}\frac{\phi}{M_{\rm Pl}}} - 1\right)}{\left[1 + \sqrt{1 + 3\alpha\left(e^{\sqrt{\frac{2}{3}}\frac{\phi}{M_{\rm Pl}}} - 1\right)}\right]^3}$$



$$\longrightarrow \quad |\alpha| < 10^{-3}$$

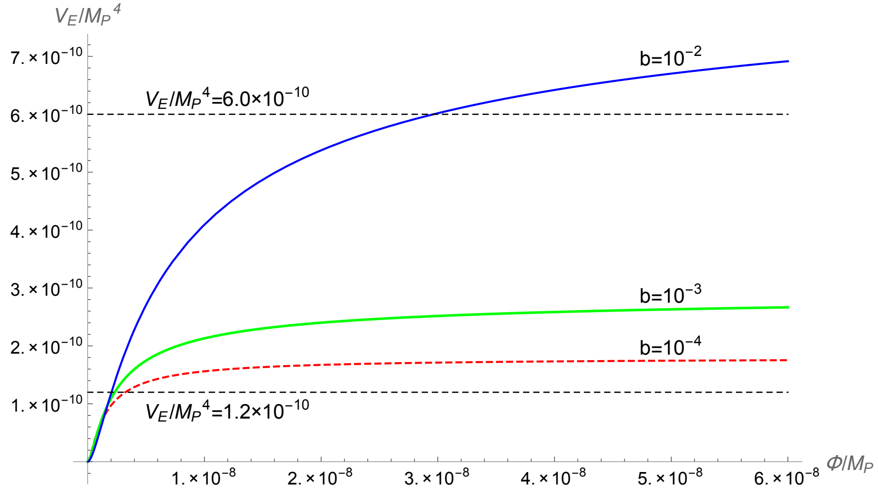
Starobinsky Inflation

Running of μ with curvature

Liu, Prokopec, Starobinsky (2018)

$$f(R) = R + \frac{R^2}{6\mu^2\left[1 + b\ln\left(\frac{R}{\mu^2}\right)\right]}$$

(asymptotically safe)



$\longrightarrow$ $|b| < 10^{-2}$

Higher derivatives in *R*

Gottlöber, Schmidt, Starobinsky (1990)

$$f(R) = R + \frac{R^2}{6\mu^2} + \gamma R \Box R$$

($\gamma R \Box R$ treated perturbatively)

$\longrightarrow$ $|\gamma|\mu^4 < 0.05$

Higgs/Starobinsky Inflation

Scalar geometrisation $$\mathscr{L} = \frac{M_{\text{Pl}}^2}{2}R - \frac{\xi}{2}R\phi^2 + \frac{1}{2}g_{\mu\nu}\partial^\mu\phi\partial^\nu\phi - V(\phi)$$

Assume ϕ is slowly rolling, such that its kinetic term can be neglected compared to its potential energy

$\longrightarrow$ $\xi R\phi = -V'\left(\phi\right) + \mathcal{O}\left(\xi^{-1}\right)$ (no conformal transformation, we remain in the physical - Jordan - frame)

These solutions are the same as for f(R) gravity with $f(R) = R - \xi R\frac{\phi^2(R)}{M_{\text{Pl}}^2} - \frac{2}{M_{\text{Pl}}^2}V\left[\phi(R)\right]$

With a potential $V(\phi) = \frac{\lambda}{4}\left(\phi^2 - \phi_0^2\right)^2$ this precisely gives $f(R) = R + \frac{R^2}{6\mu^2}$ with $\mu = M_{\text{Pl}}\sqrt{\frac{\lambda}{3\xi^2}}$

Mixed Higgs-*R*² inflation

He, Starobinsky, Yokoyama (2018)

$$\mathscr{L} = \frac{M_{\text{Pl}}^2}{2}\left(R + \frac{R^2}{6\mu^2}\right) - \frac{\xi}{2}R\phi^2 + \frac{1}{2}g_{\mu\nu}\partial^\mu\phi\partial^\nu\phi - \frac{\lambda}{4}\phi^4$$

In the attractor regime during inflation —> $f(R) = R + \frac{R^2}{6\tilde{\mu}^2}$

with $$\frac{1}{\tilde{\mu}^2} = \frac{1}{\mu^2} + \frac{3\xi^2}{\lambda}M_{\text{Pl}}^2$$