Reheating Predictions of the Inflation with Non-minimal Coupling

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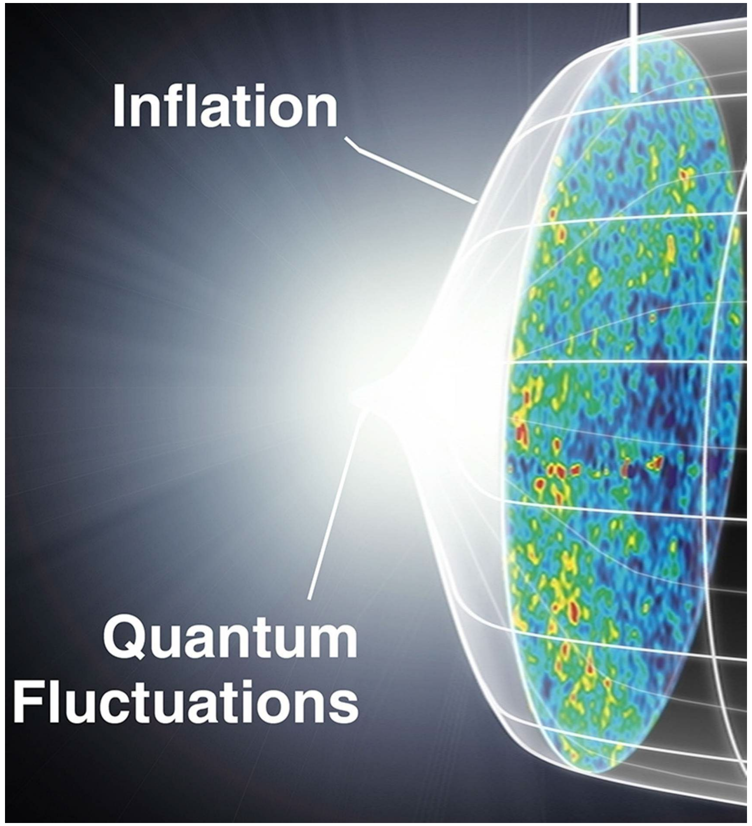
based on **arXiv:2111.00825**

In collaboration with Dhong Yeon Cheong (Yonsei U.), Seong Chan Park (Yonsei U.)

Introduction

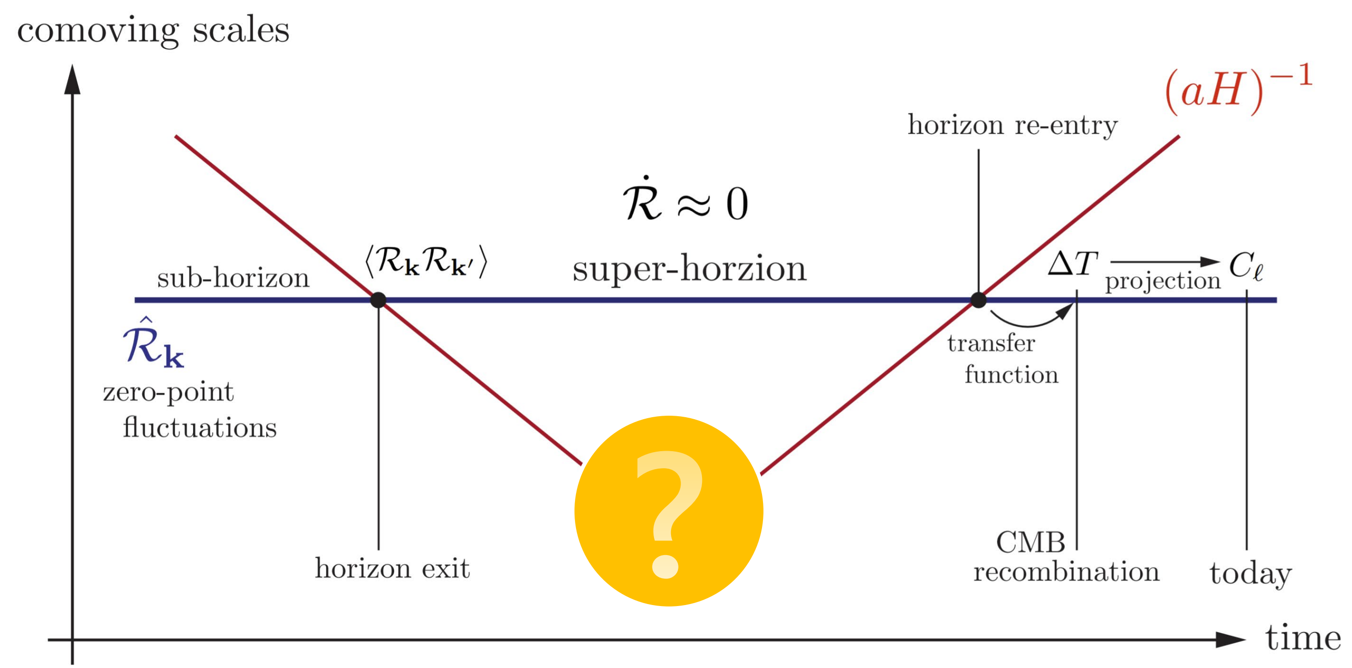
- Inflationary Paradigm in Standard Cosmology
  - Exponential expansion at the early universe
  - Horizon Problem / Flatness Problem
  - Quantum fluctuation: seeds for large scale structure



Introduction

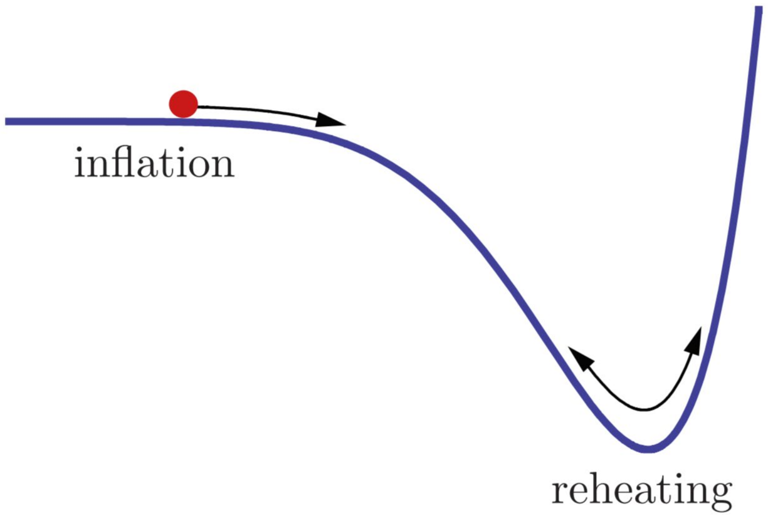
- Detailed reheating process, transition to the thermal universe after the inflation, is usually overlooked.
  - Conservation of the curvature perturbation at the super-horizon
  - Non-linear / Non-perturbative / Model-dependent

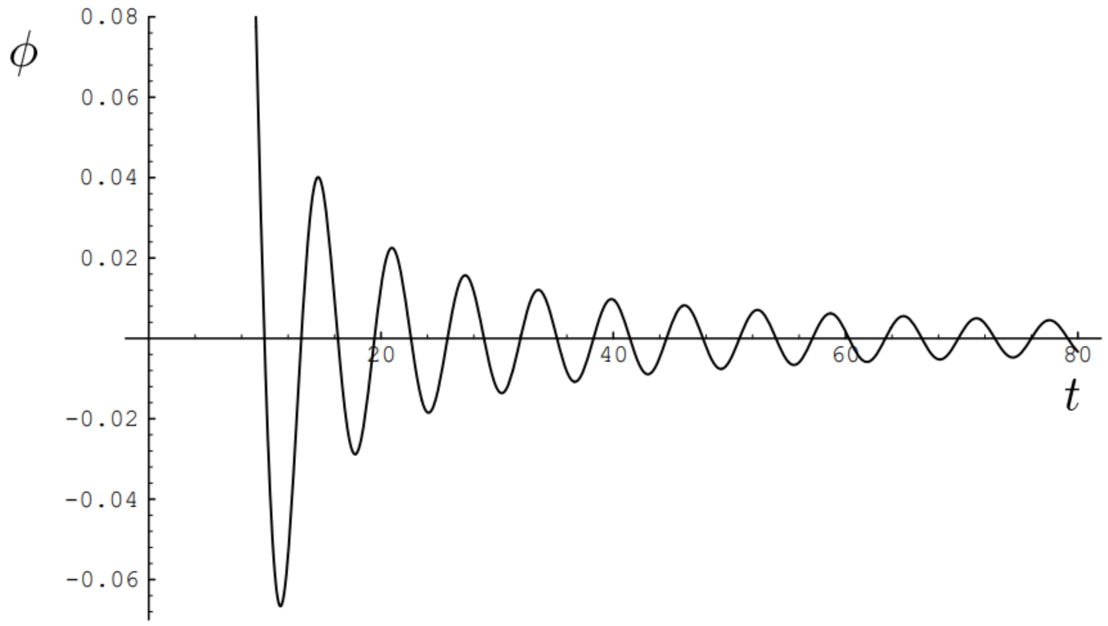
S. Weinberg [astro-ph/0302326]



Reheating & Particle Production

- After the inflation, inflaton starts to oscillate *coherently* and decays





L. Kofman *et al.* [hep-ph/9704452]
K. Lozanov *et al.* [1907.04402]

$$\phi(t) \approx \Phi(t)\sin(mt)$$

Particle Production & Reheating

- Elementary theory of (perturbative) reheating:

$$\ddot{\phi} + 3H\dot{\phi} + \boxed{\Gamma\dot{\phi}} + m^2\phi = 0$$

  - Reheating ends when $\Gamma = H$

- Missing parts
  - Inflaton is not a single particle, but a *condensate*
  - Back-reaction of produced particles

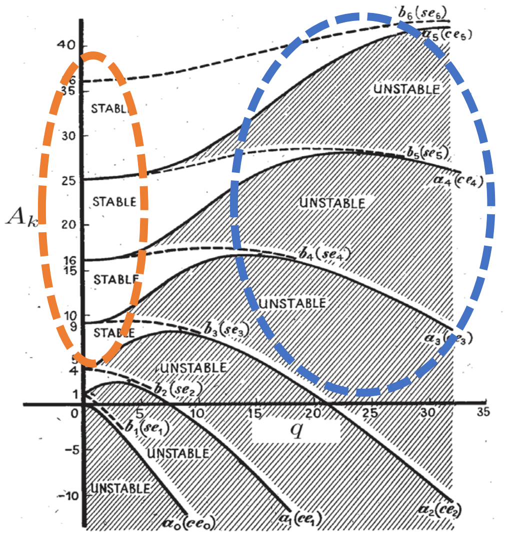
Particle Production & Reheating

- Toy Model $\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - V(\phi) - g^2\phi^2\chi^2$

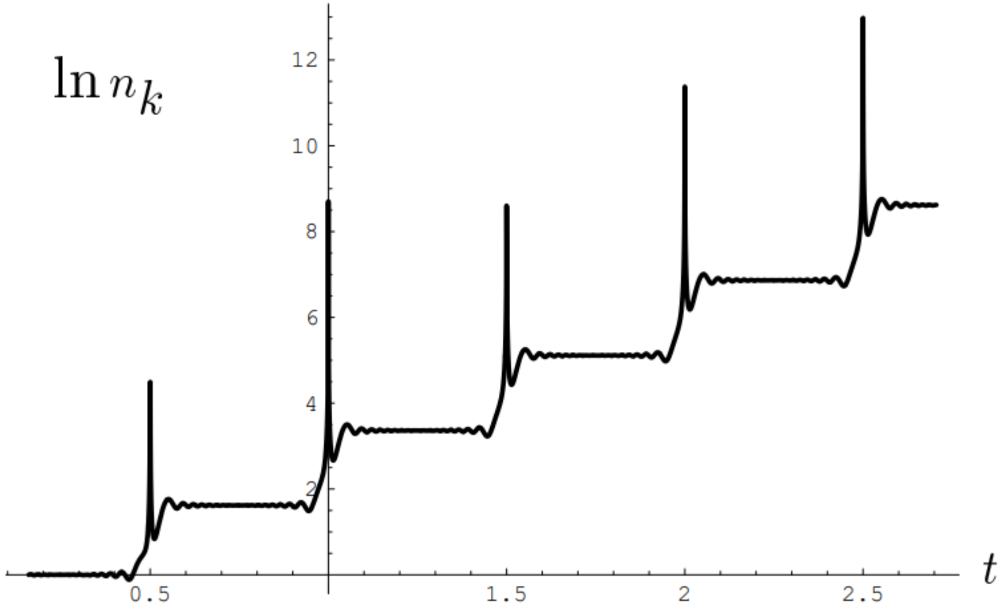
$$\ddot{\chi}_k + \cancel{3H\dot{\chi}_k} + \left(\frac{k^2}{a^2} + g^2\phi^2(t)\right)\chi_k = 0 \qquad \phi(t) \approx \Phi(t)\sin(mt)$$

Harmonic oscillator with time-dependent mass

Narrow resonance



Broad resonance



Particle Production & Reheating

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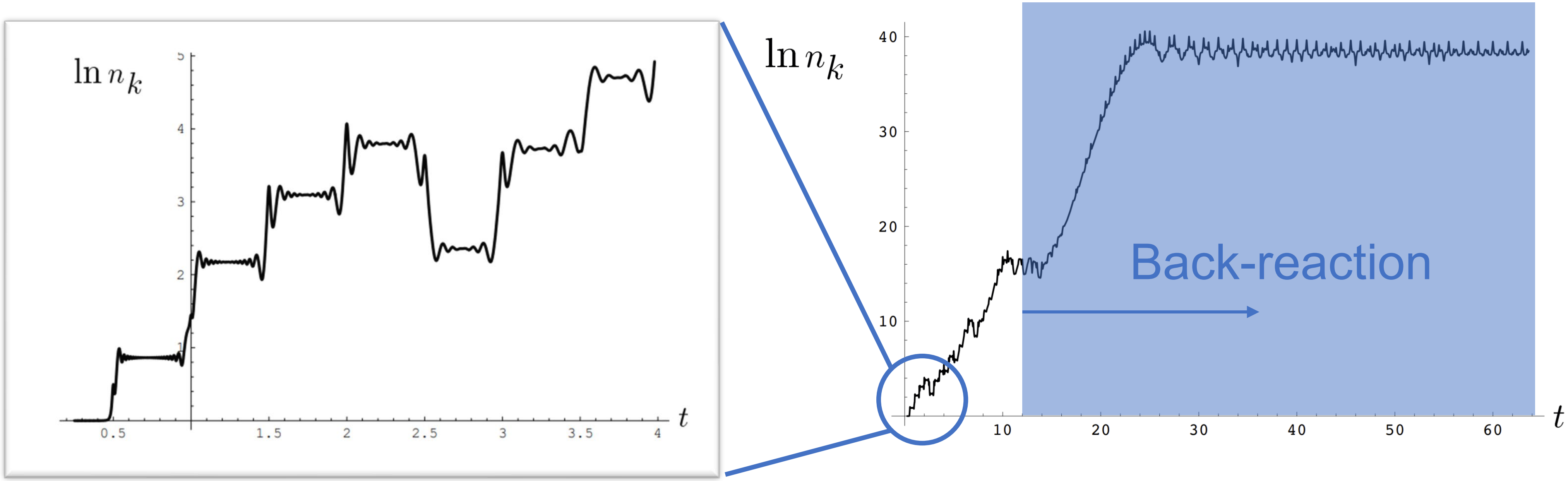


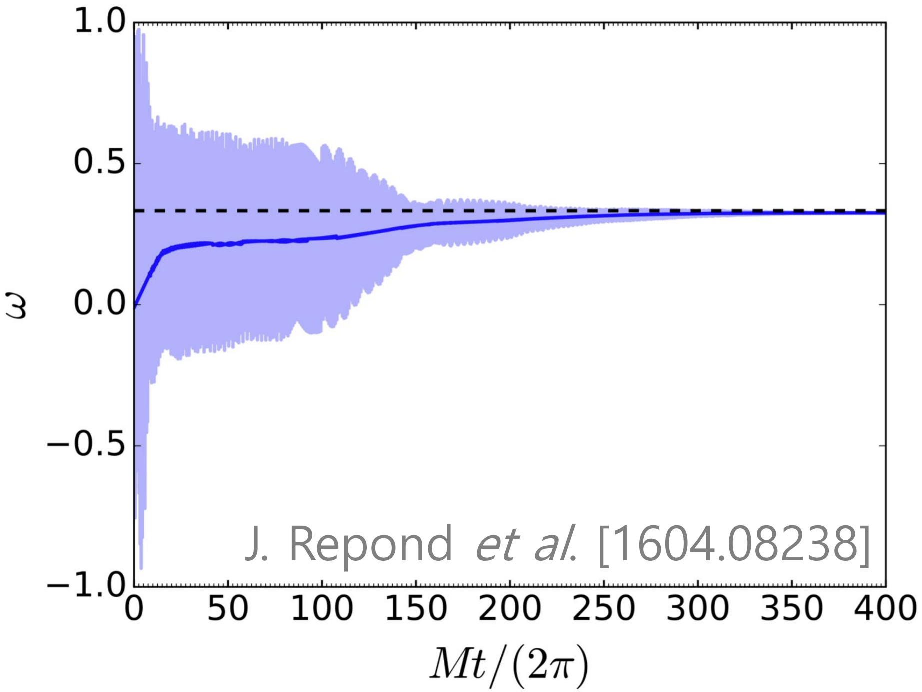
Particle Production & Reheating

- Reheating processes are complicated:

(Non-perturbative) Preheating → (Back-reaction) **(Perturbative) reheating** → **Thermalization**

Reheating

  - Generally, we rely on numerical simulation.



- Then, why do we still care about reheating?

Conceptual Reason : Initial Conditions

- Reheating process *provides initial conditions* of the thermal universe
  - In the inflation cosmology, the beginning of the thermal universe is not a 'BANG'.

- Connection BSM Physics?
  - Baryogenesis **SML**, S.C. Park, K. Oda [2010.07563]
  - Dark matter

- Origin of primordial fluctuation? (e.g.) Curvaton scenario

  D. H. Lyth *et al.* [astro-ph/0208055]

- Intrinsic model dependence

Practical Reason : Inflation Predictions

- Reheating *changes the predictions* from the inflation.
  - Precision era of cosmology

L. Dai *et al.* [1404.6704]
J. L. Cook *et al.* [1502.04673]

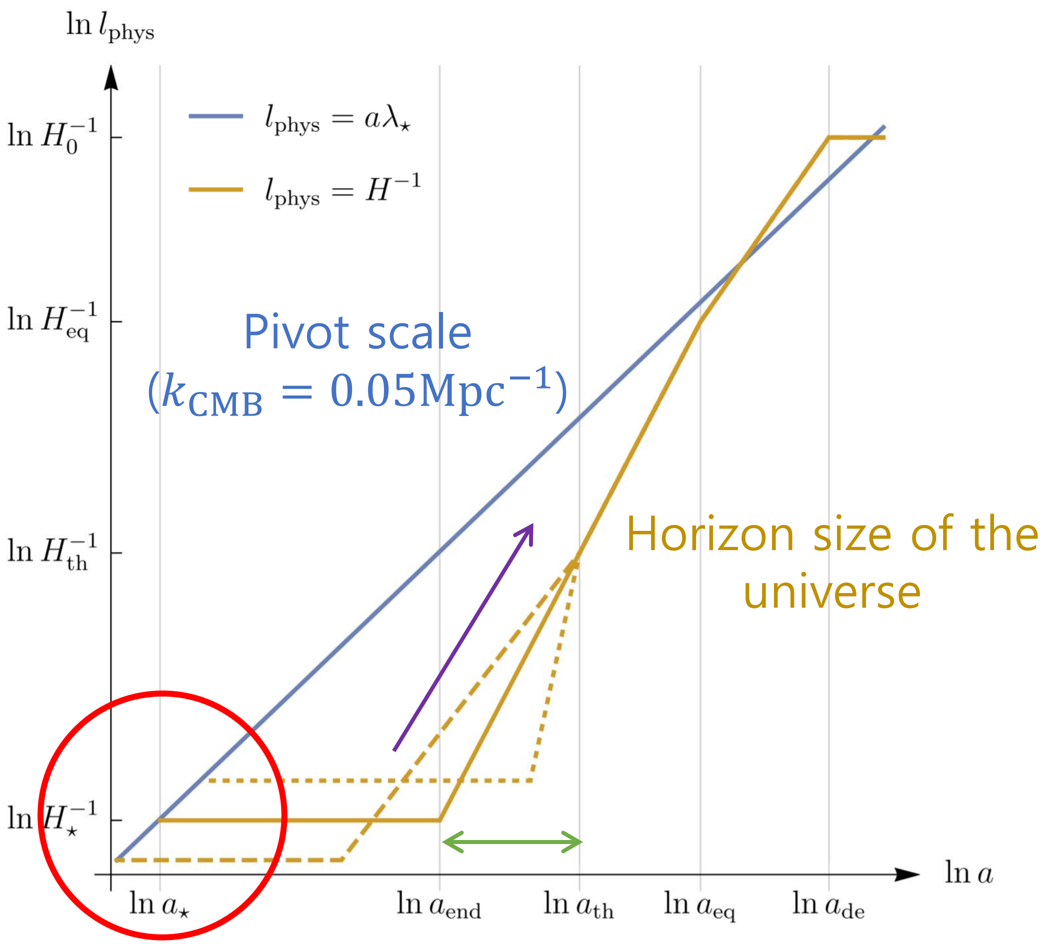
- Reheating parameters
  - E-folding number during the reheating

$$N_{\rm reh} \equiv \ln\left(\frac{a_{\rm reh}}{a_e}\right)$$

  - (Averaged) equation of state

$$w_{\rm reh} \equiv \frac{1}{N_{\rm reh}} \int_{N_k}^{N_k+N_{\rm reh}} w(N)\ dN$$

  - Reheating temperature $T_{\rm reh}$



K.D. Lozanov [1907.04402]

Practical Reason : Inflation Predictions

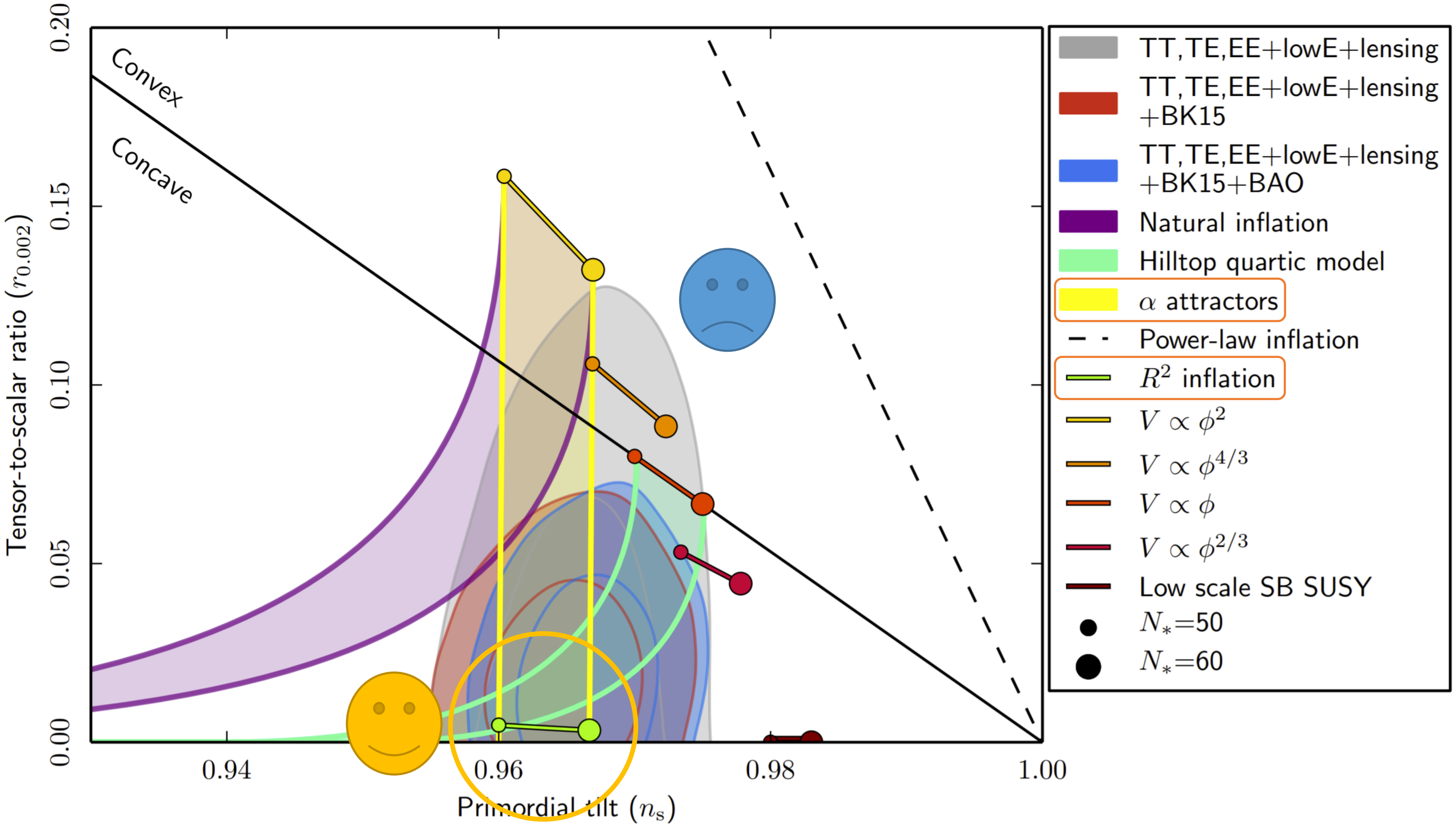
- Consistency relations

$$T_{\rm reh} = \left[\left(\frac{43}{11 g_{\rm reh}} \right)^{1/3} \frac{a_0 T_0}{k} H_k e^{-N_k} \left(\frac{45 U_e}{\pi^2 g_{\rm reh}} \right)^{-\frac{1}{3(1+w_{\rm reh})}} \right]^{\frac{3(1+w_{\rm reh})}{3w_{\rm reh}-1}}$$

$$N_{\rm reh} = \frac{4}{(1-3w_{\rm reh})} \left[61.6 - \ln\left(\frac{U_e^{1/4}}{H_k} \right) - N_k \right]$$

"60 e-folds"

Inflation with Non-minimal Coupling



Inflation with Non-minimal Coupling

- Slow-roll inflation with suppressed tensor-to-scalar ratio requires **asymptotically flat potential** (shift symmetry).

- Models with non-minimal couplings between inflaton and Ricci scalar cover large classes of models with shift symmetry (α*-attractor behavior*)
  - Higgs inflation
  - Starobinsky inflation (equivalent to Higgs inflation classically)
  - Higgs-R^2 Inflation (after integrating out heavy mode)

T. Futamase *et al*. [PRD 39, 399]
S.C. Park *et al*. [1311.0472]
R. Kallosh *et al*. [1311.0472]

- Also, reheating *breaks the degeneracy* of classically equivalent theories.
  - Probes of the microscopic physics

Inflation with Non-minimal Coupling

- Introduction of non-minimal coupling is a way to guarantee asymptotic flat potential with redefinition of the metric:

$$S_J = \int d^4x\sqrt{-g_J}\left[-\frac{M^2+K(\phi)}{2}R + \frac{1}{2}(\partial\phi)^2 - V(\phi)\right]$$

$$g_{E,\mu\nu} = \Omega^2 g_{J,\mu\nu} \qquad \Omega^2 \equiv \frac{M^2+K(\phi)}{M_P^2}$$

$$\downarrow$$

$$S = \int d^4x\sqrt{-g_E}\left[-\frac{M_P^2}{2}R_E + \frac{1}{2}\Pi(\phi)(\partial\phi)^2 - \frac{V(\phi)}{\Omega^4}\right]$$

$$\Pi(\phi) \equiv \frac{1}{\Omega^2} + \frac{3\zeta}{2M_P^2}\frac{K'(\phi)^2}{\Omega^4}$$

$$\zeta = \begin{cases} 1 & \text{(Metric)} \\ 0 & \text{(Palatini)} \end{cases}$$

Metric vs. Palatini formulations

METRIC

- Affine connection is given by Christoffel symbol (as a function of metric)

$$R(\Gamma(g))$$

PALATINI

- Affine connection is independent of metric and given by the equation of motion.

$$R(\Gamma), \qquad g$$

- They are equivalent at pure Einstein gravity but differ in modified ones.
  - Different predictions in the presence of non-minimal coupling F. Bauer *et al.* [0803.2664]

Inflation with Non-minimal Coupling

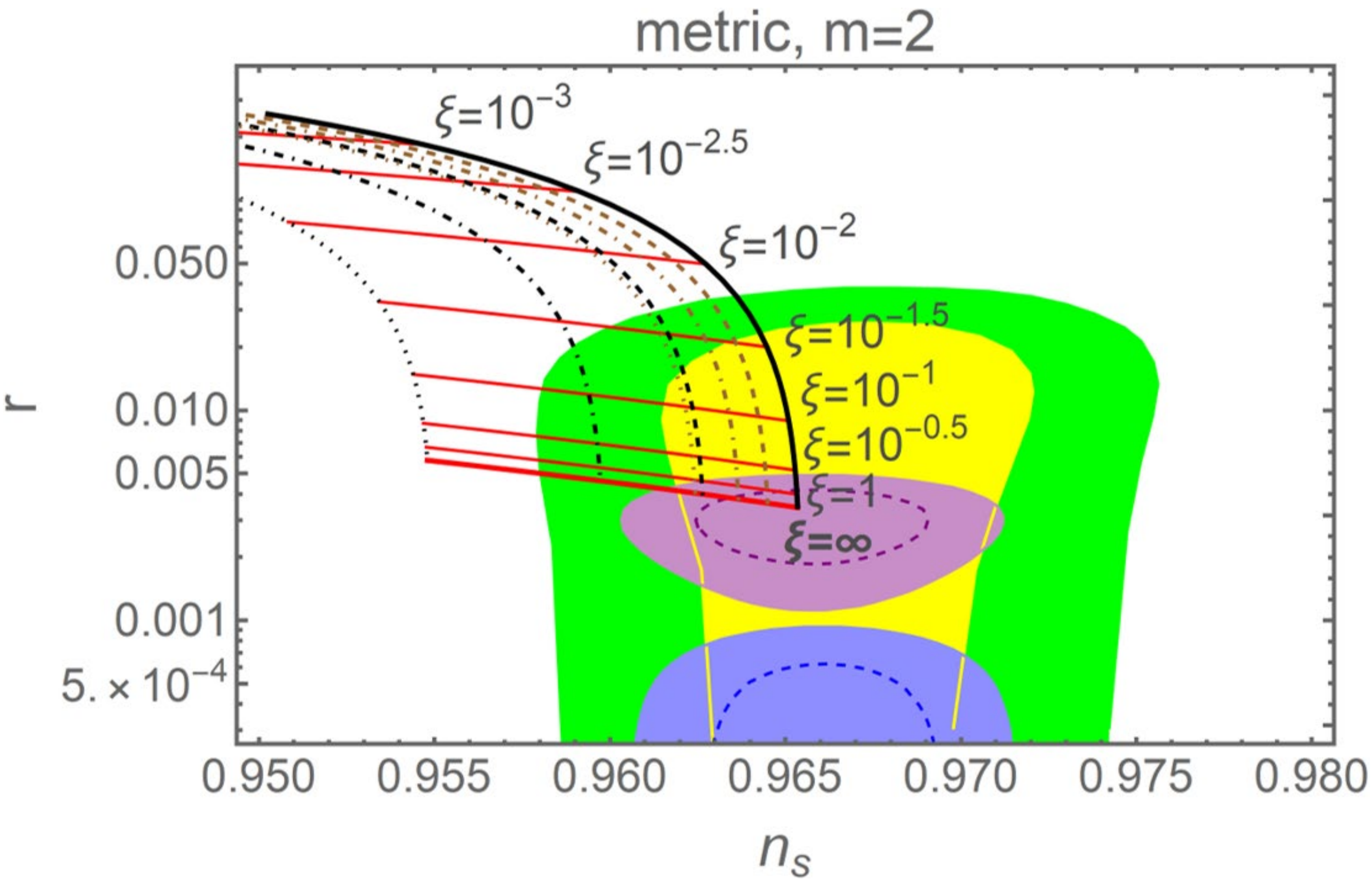
- Condition for asymptotically flat potential: S.C. Park *et al.* [1311.0472]

$$\lim_{\phi\to\infty}\frac{V(\phi)}{K(\phi)^2} = \text{Const.} > 0.$$

- We will consider monomial functions:

$$K(\phi) = \xi M_P^2\left(\frac{\phi}{M_P}\right)^m \qquad V = \frac{\lambda M_P^4}{2m}\left(\frac{\phi}{M_P}\right)^{2m}$$

Results: metric cases (m=2)



D.Y. Cheong, **SML**, S.C. Park [2111.00825]

- **Black bold line: $w = 1/3$**

  (RD-like universe)

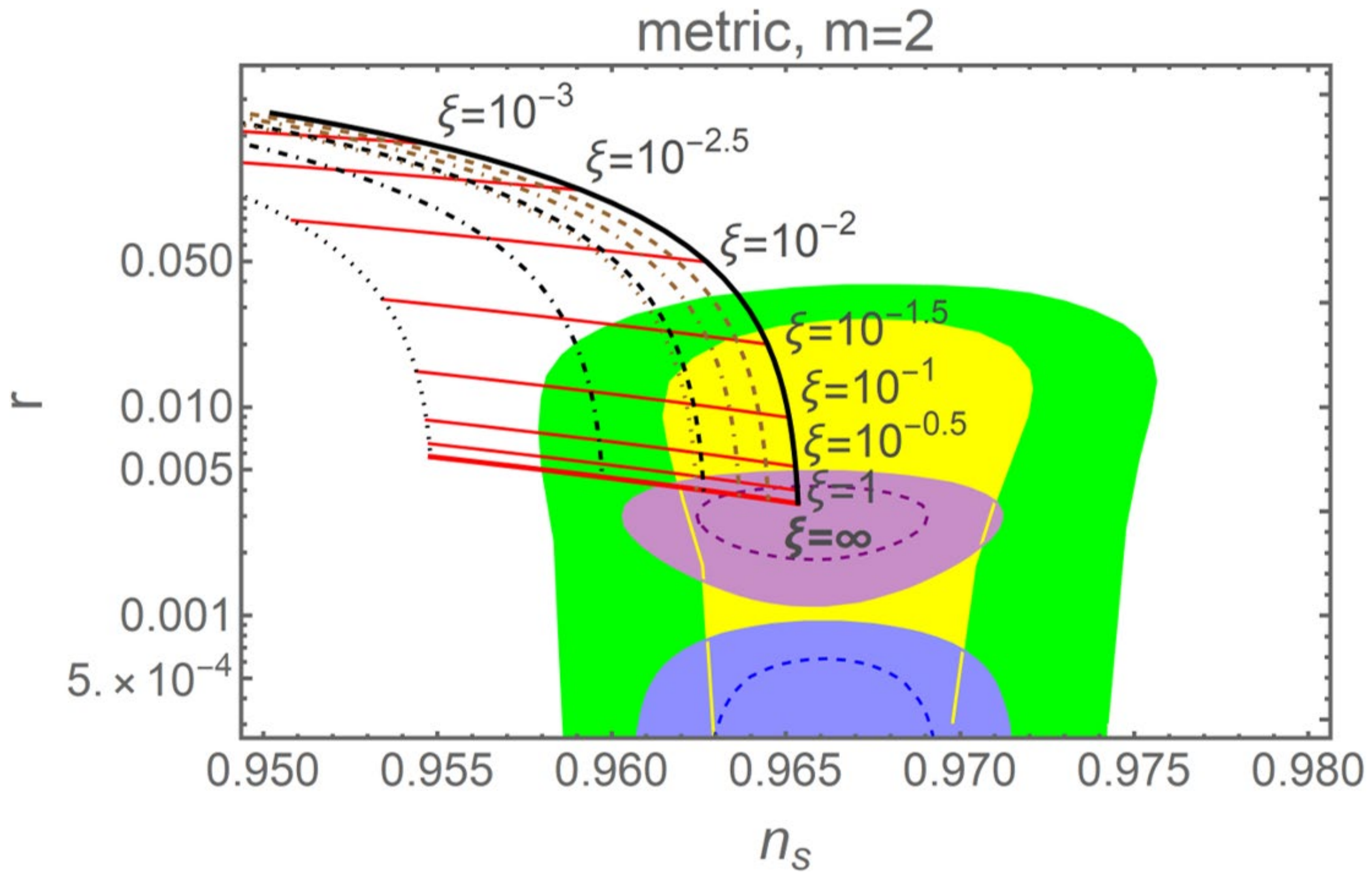
  or

  instantaneous reheating

  (no difference between reheating and RD universe)

- $T_{\rm reh} = T_{\rm max} \simeq 10^{15}$ GeV

Results: metric cases (m=2)



D.Y. Cheong, **SML**, S.C. Park [2111.00825]

- **Black lines: $w = 0$**

  (MD-like universe)

  - Low reheating temperature is disfavored by measurements.

- **Brown lines: $w = 1/5$**
  - Closer to $w = 1/3$, reheating dependence becomes weaker.

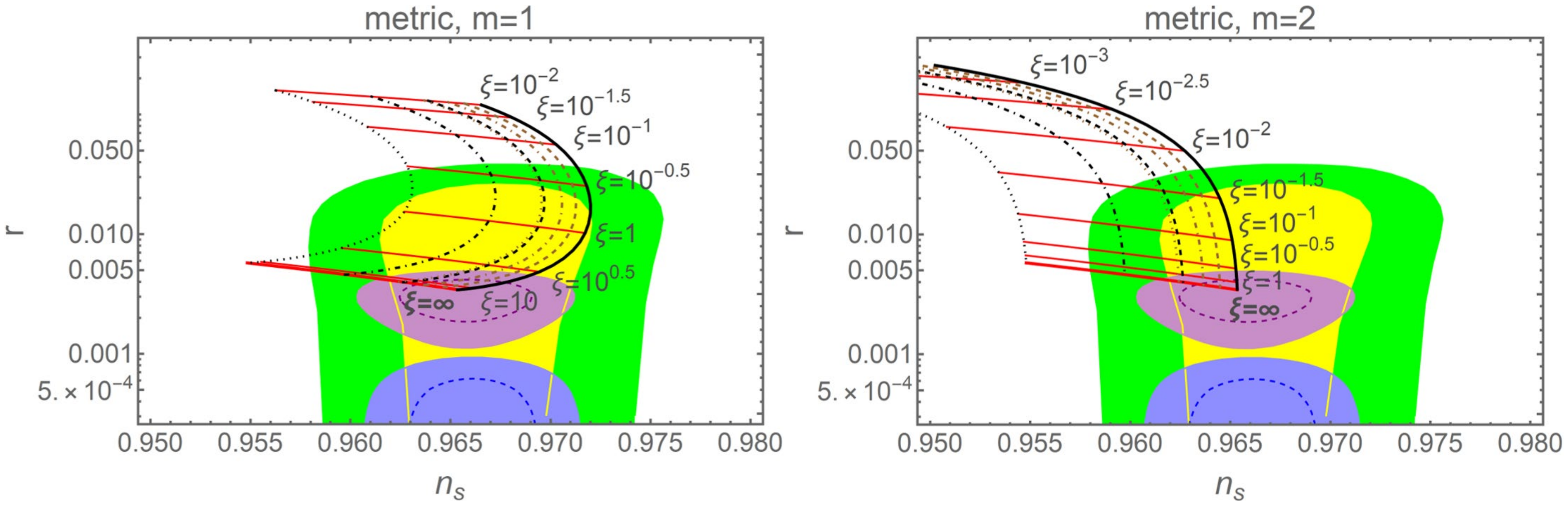
$T_{reh}=10^{-2}$GeV → BBN

$T_{reh}=10^{5}$GeV

$T_{reh}=10^{10}$GeV → Gravitino overproduction

Results: metric cases

D.Y. Cheong, **SML**, S.C. Park [2111.00825]



Results: metric cases

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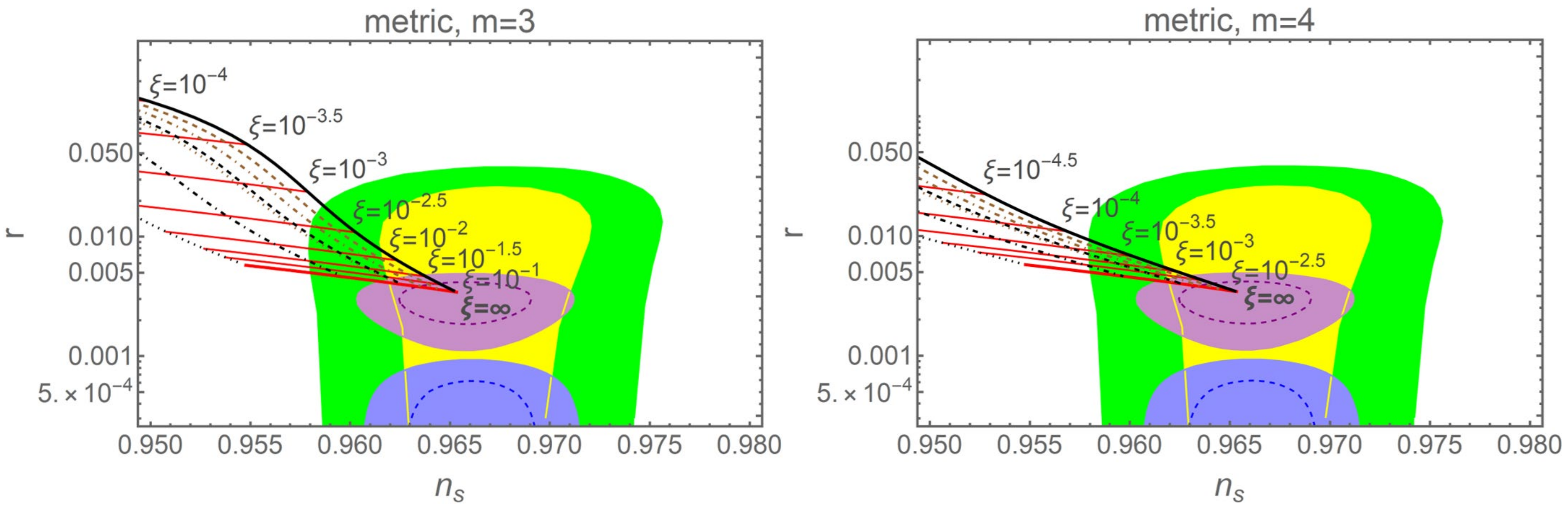
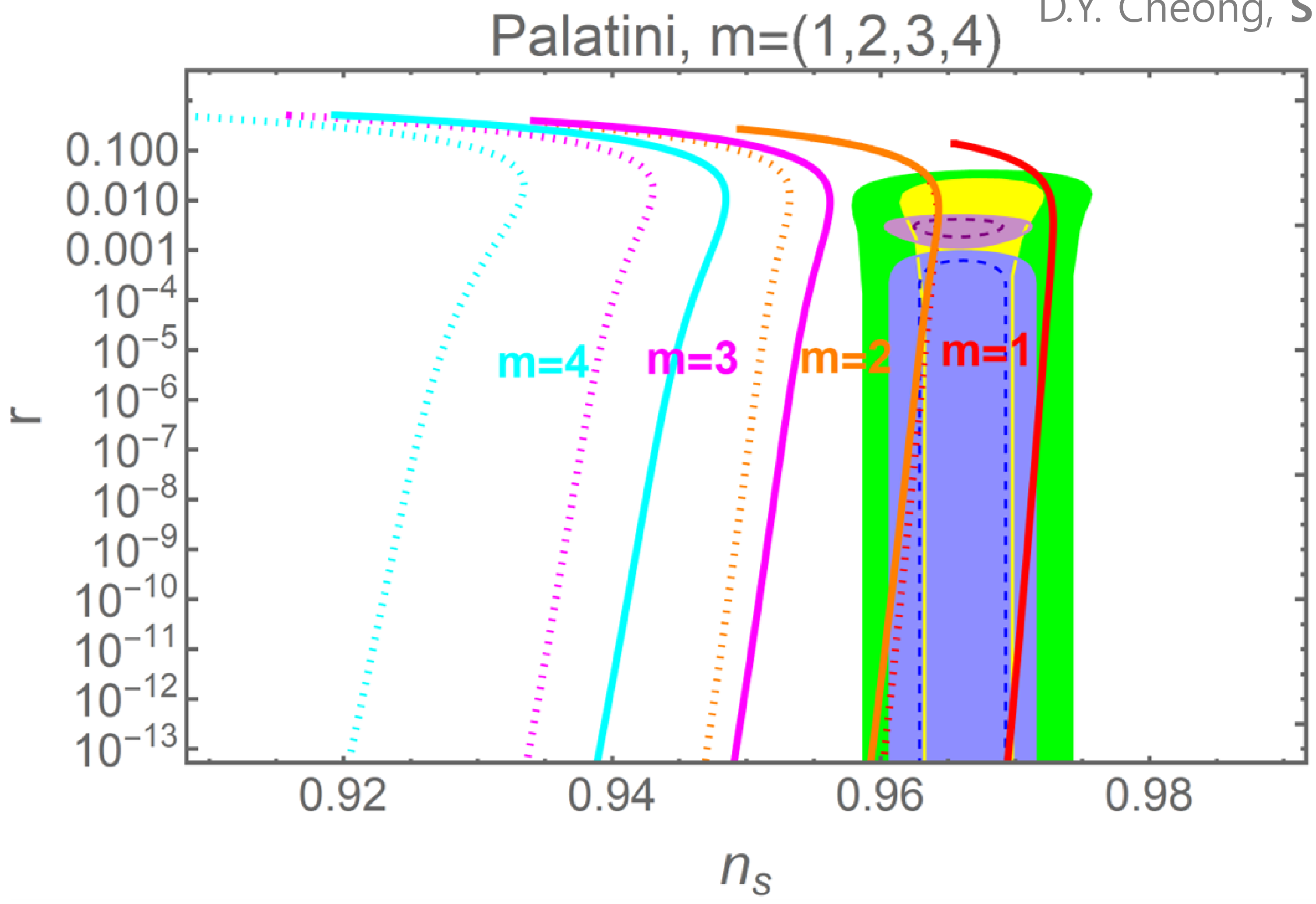


Results: Palatini cases

D.Y. Cheong, **SML**, S.C. Park [2111.00825]



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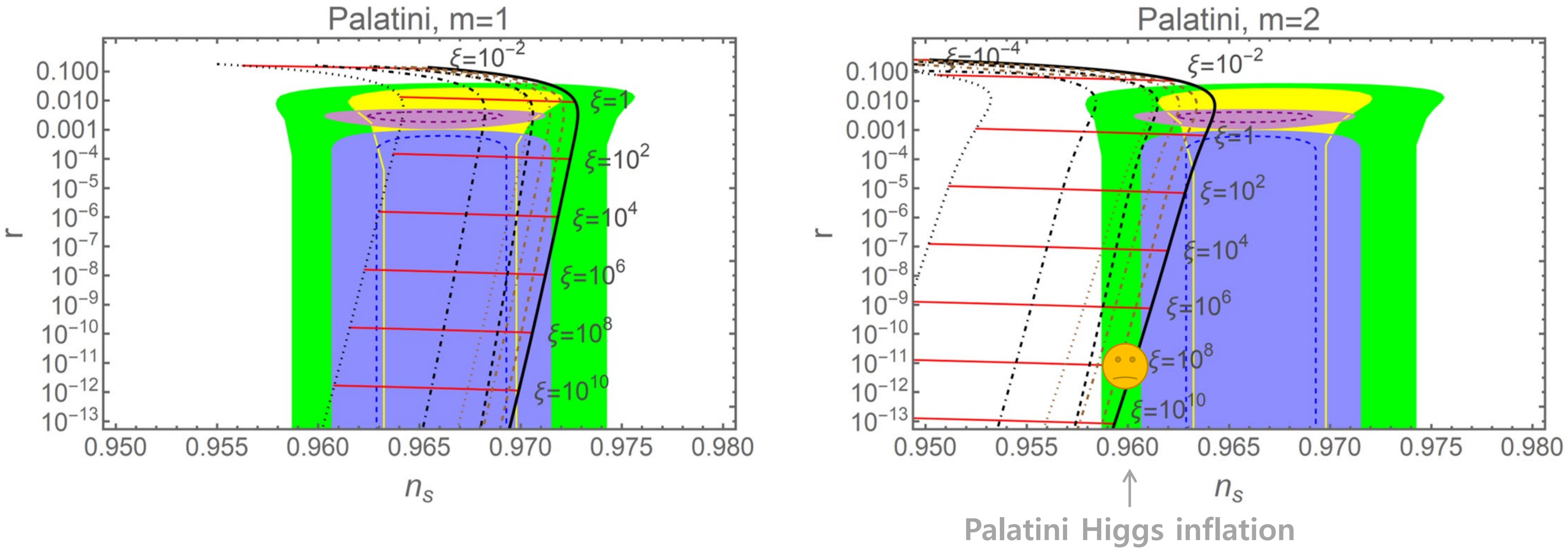
D.Y. Cheong, **SML**, S.C. Park [2111.00825]



- Large suppression of tensor-to-scalar ratio

Conclusion

- In the inflationary paradigm, there are conceptual/practical reasons for studying reheating stage.

- General template for the inflation predictions considering reheating with
  - Metric and Palatini formalism
  - General monomial potential
  - Wide range of non-minimal coupling

- Future constraints (CMB-S4/LiteBird) on (n_s, r) will rule out models or constrain reheating temperature as well.