Reheating Predictions of the Inflation with Non-minimal Coupling

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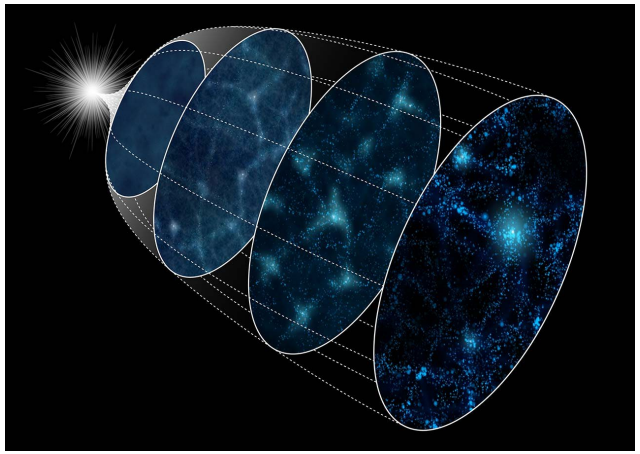
based on **arXiv:2111.00825**

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

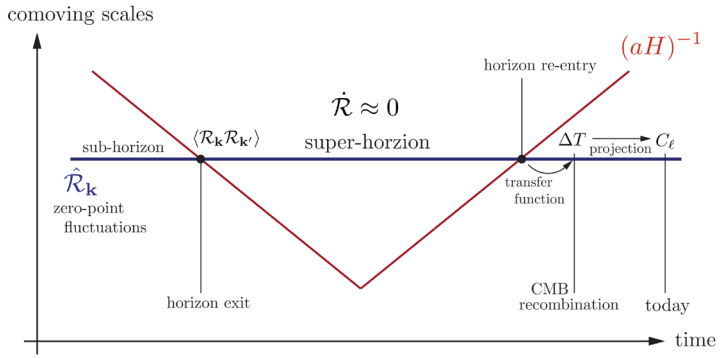
Introduction

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



- Detailed reheating process, transition to the thermal universe after the inflation, is usually overlooked.
  - Conservation of the curvature perturbation at the super-horizon

S. Weinberg
[astro-ph/0302326]



- 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]

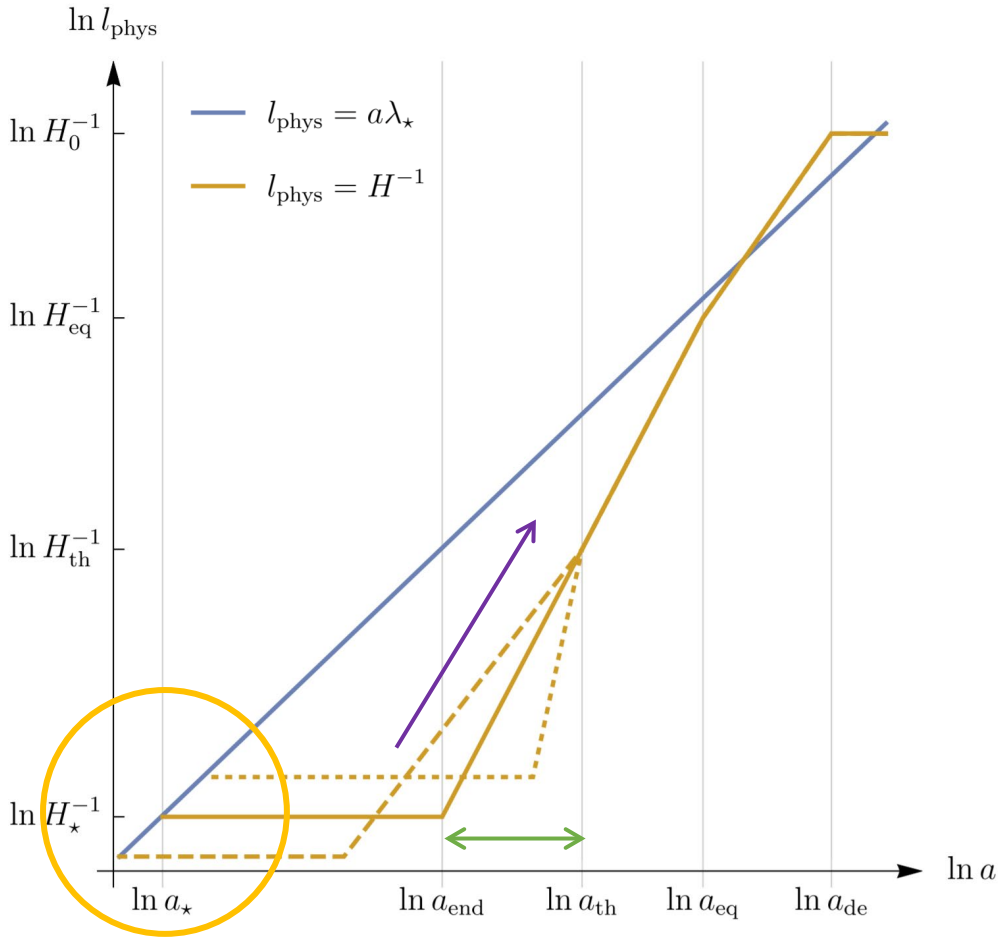
- Reheating parameters
  - E-folding number during the reheating

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

  - (Averaged) equation of state

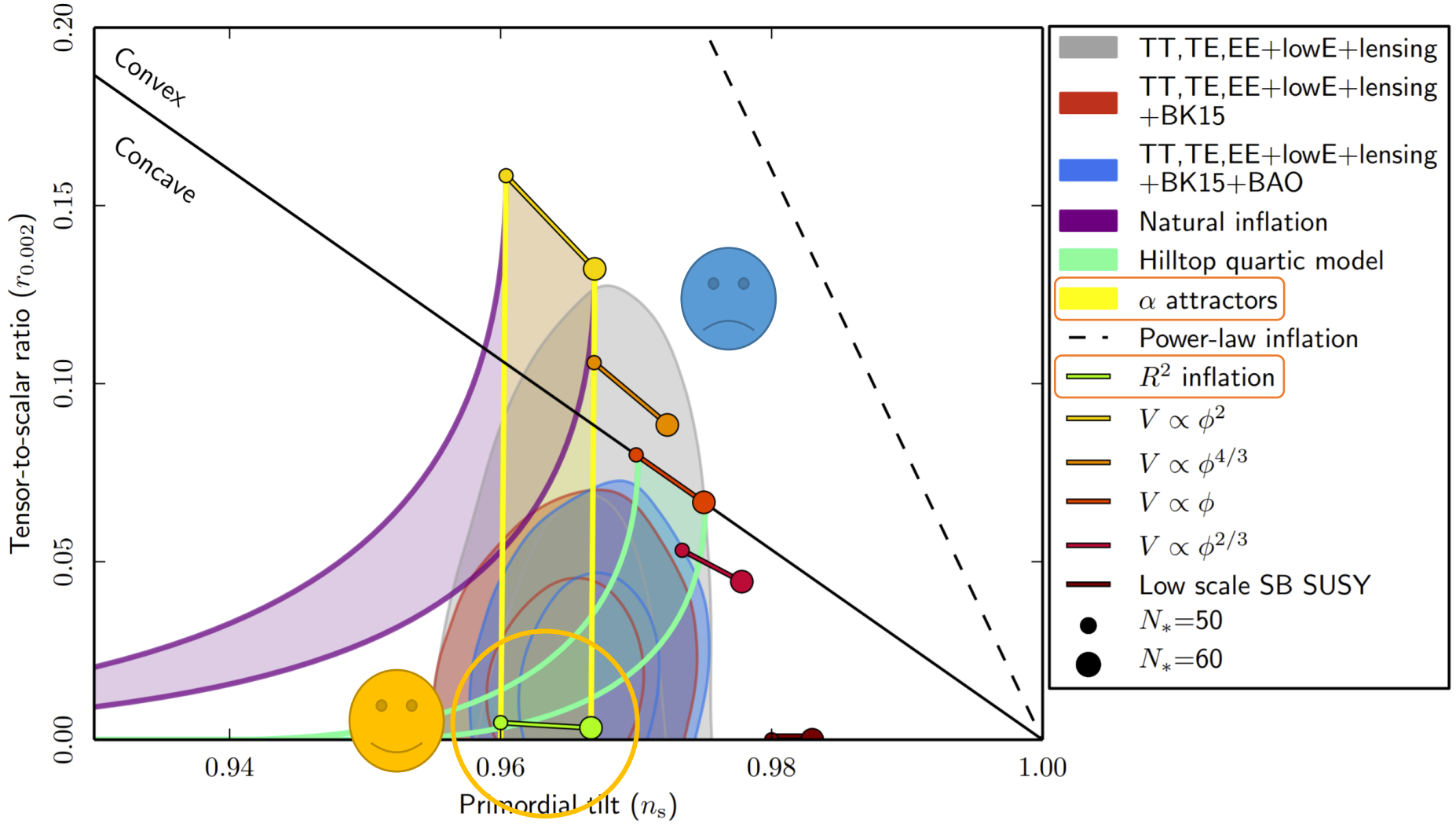
$$w_{\rm reh} \equiv \frac{1}{N_{\rm reh}} \int_{N_k}^{N_k+N_{\rm reh}} w(N)\, dN$$

  - Reheating temperature $T_{\rm reh}$



K.D. Lozanov [1907.04402]

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

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

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

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

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

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

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

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

Inflation with Non-minimal Coupling

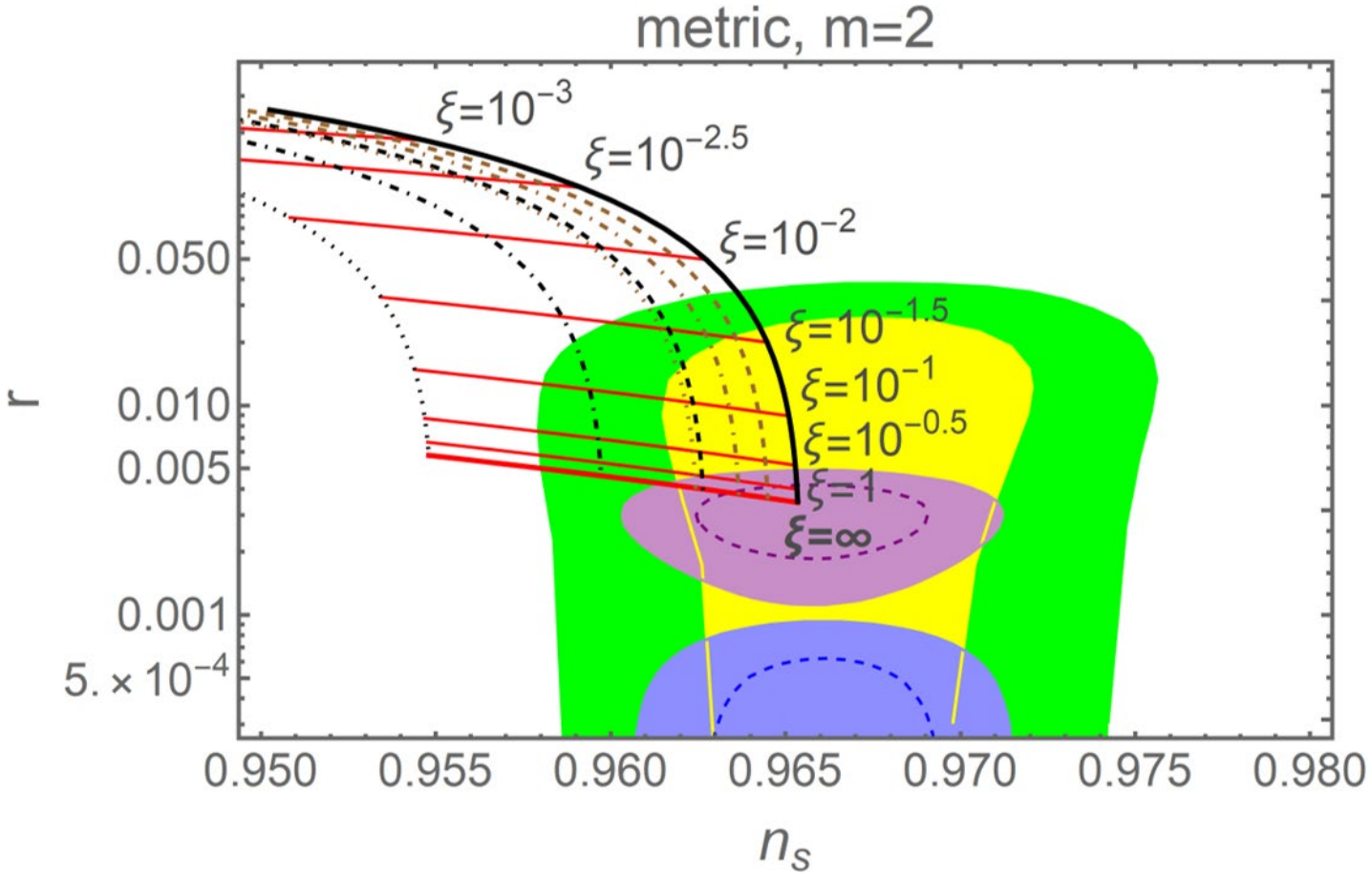
- Condition for asymptotically flat potential: S.C. Park *et al*. [1311.0472]

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

- 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)

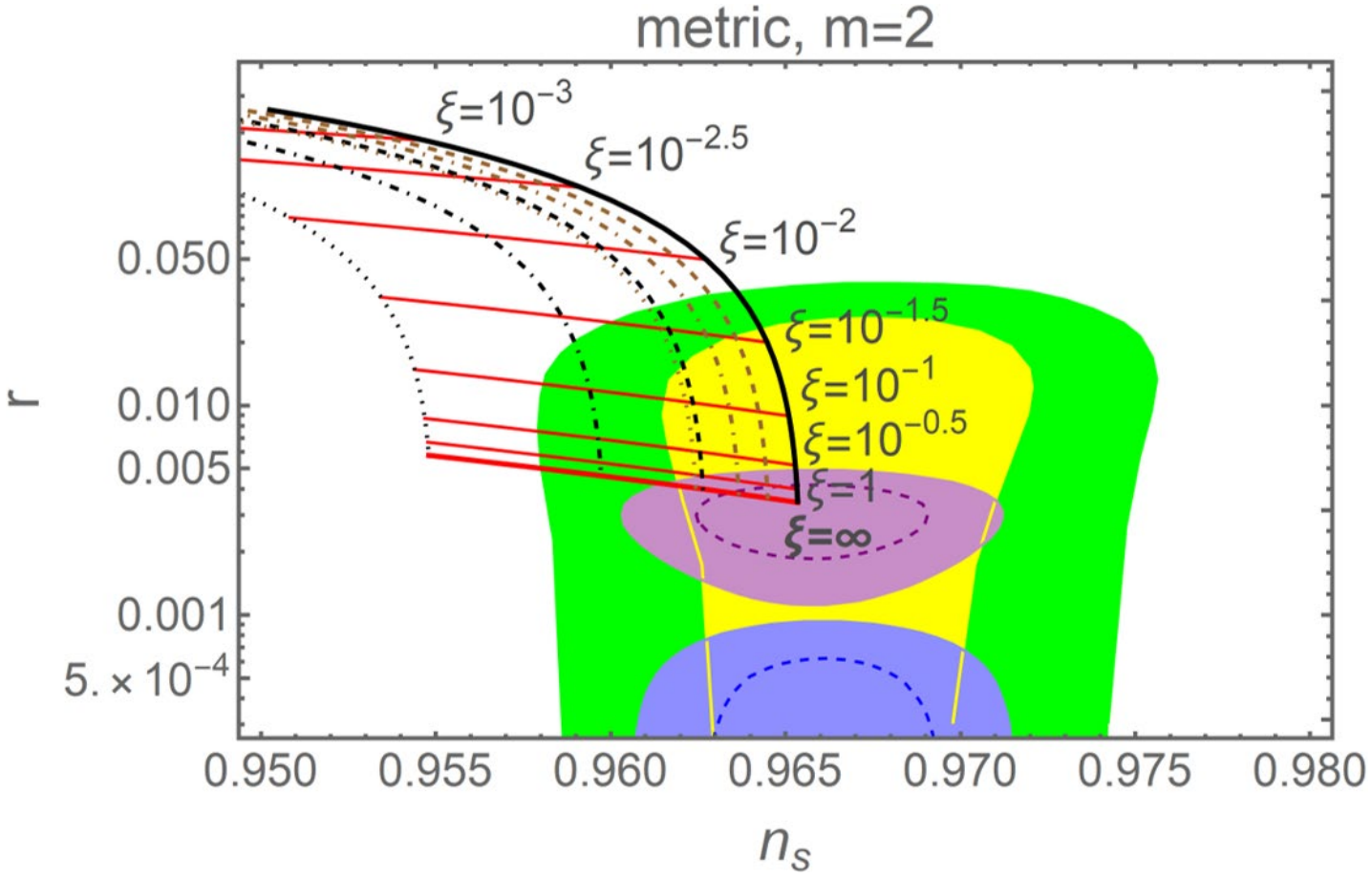
or

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.

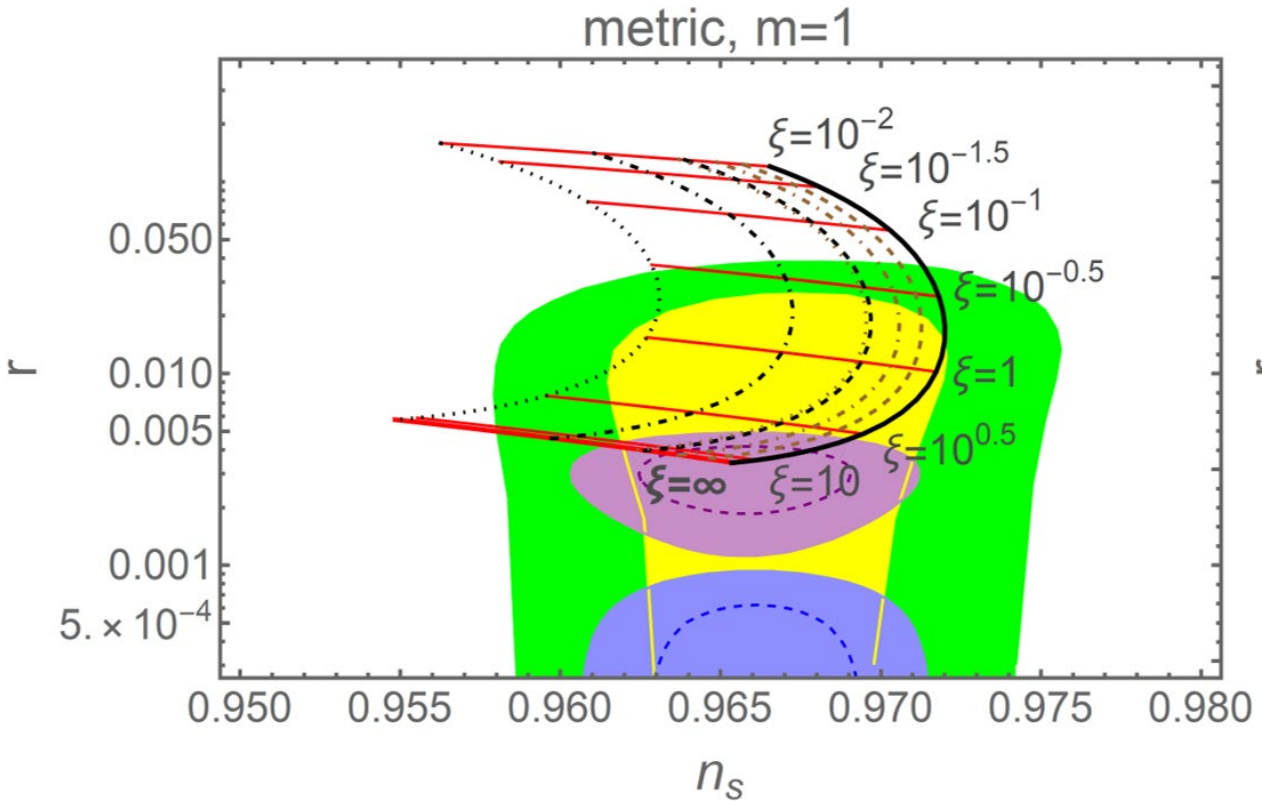
..... $T_{reh}=10^{-2}$GeV ⟶ BBN

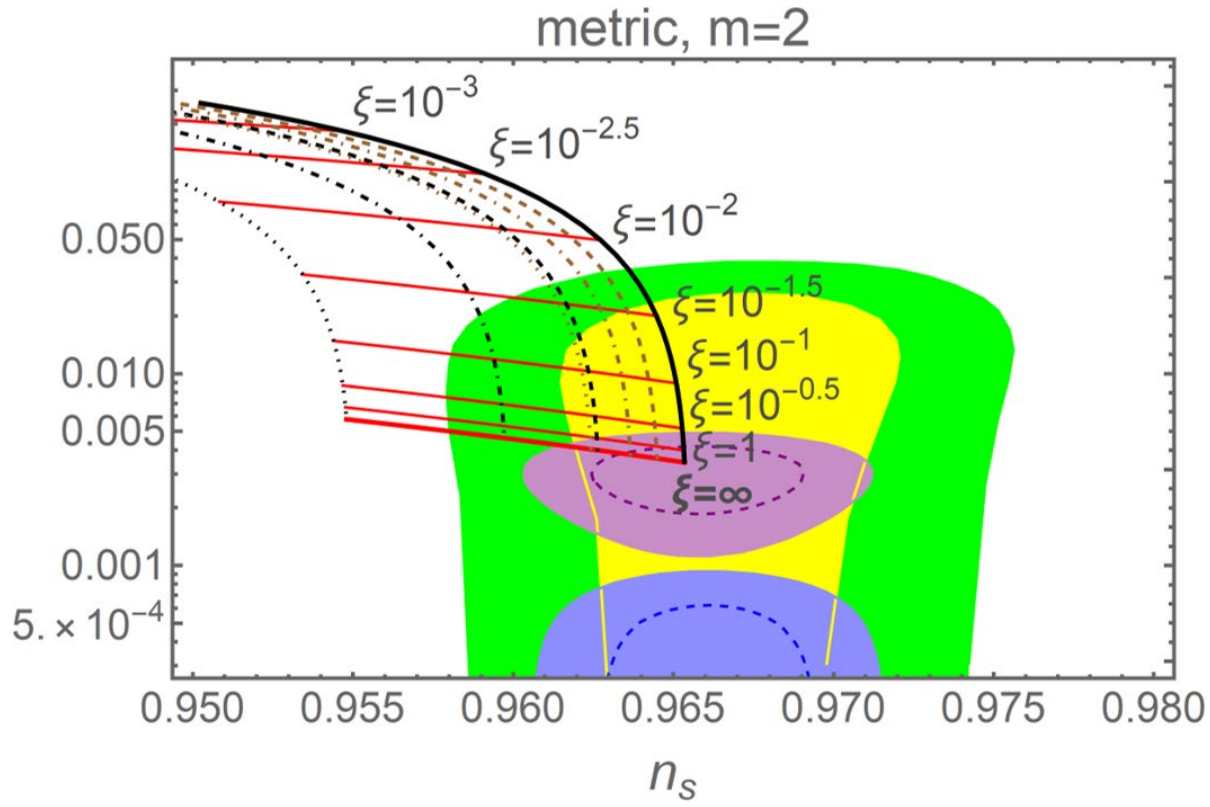
-·-·- $T_{reh}=10^{5}$GeV

----- $T_{reh}=10^{10}$GeV ⟶ Gravitino overproduction

Results: metric cases

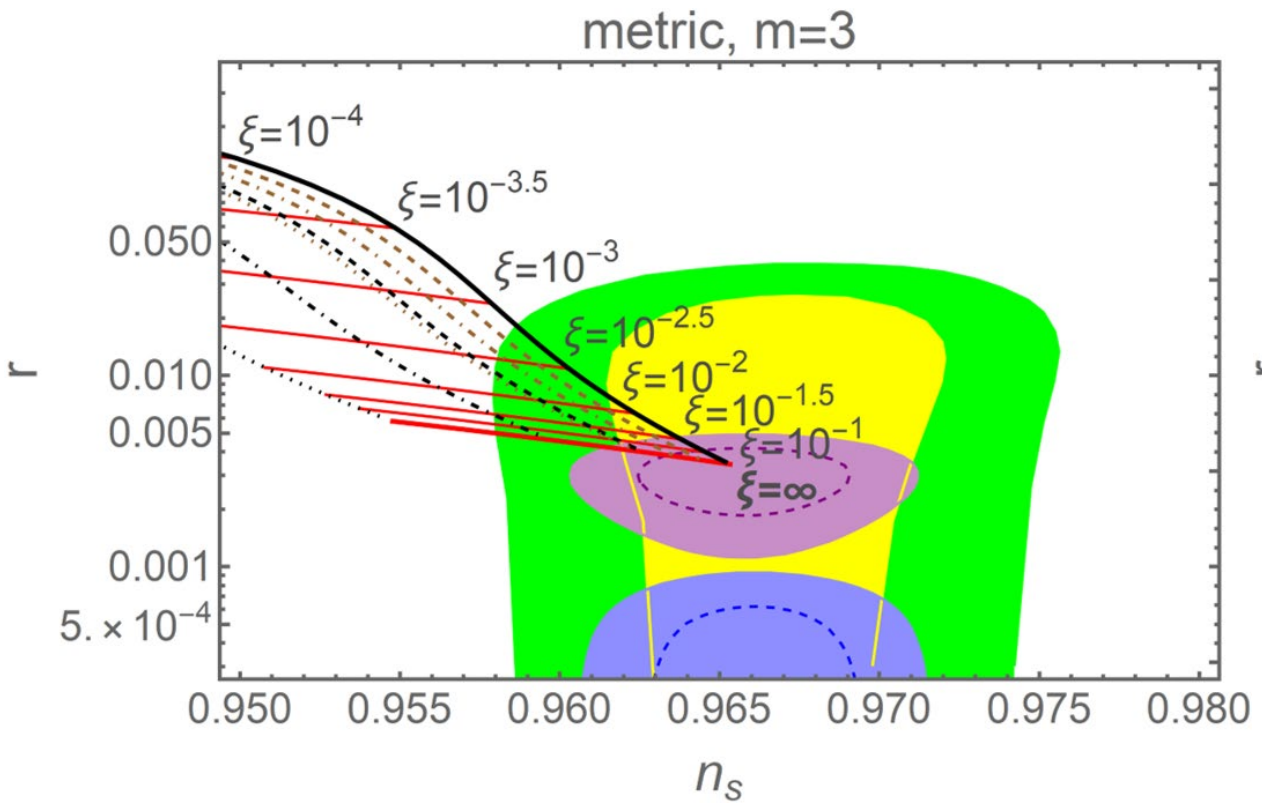
D.Y. Cheong, **SML**, S.C. Park [2111.00825]

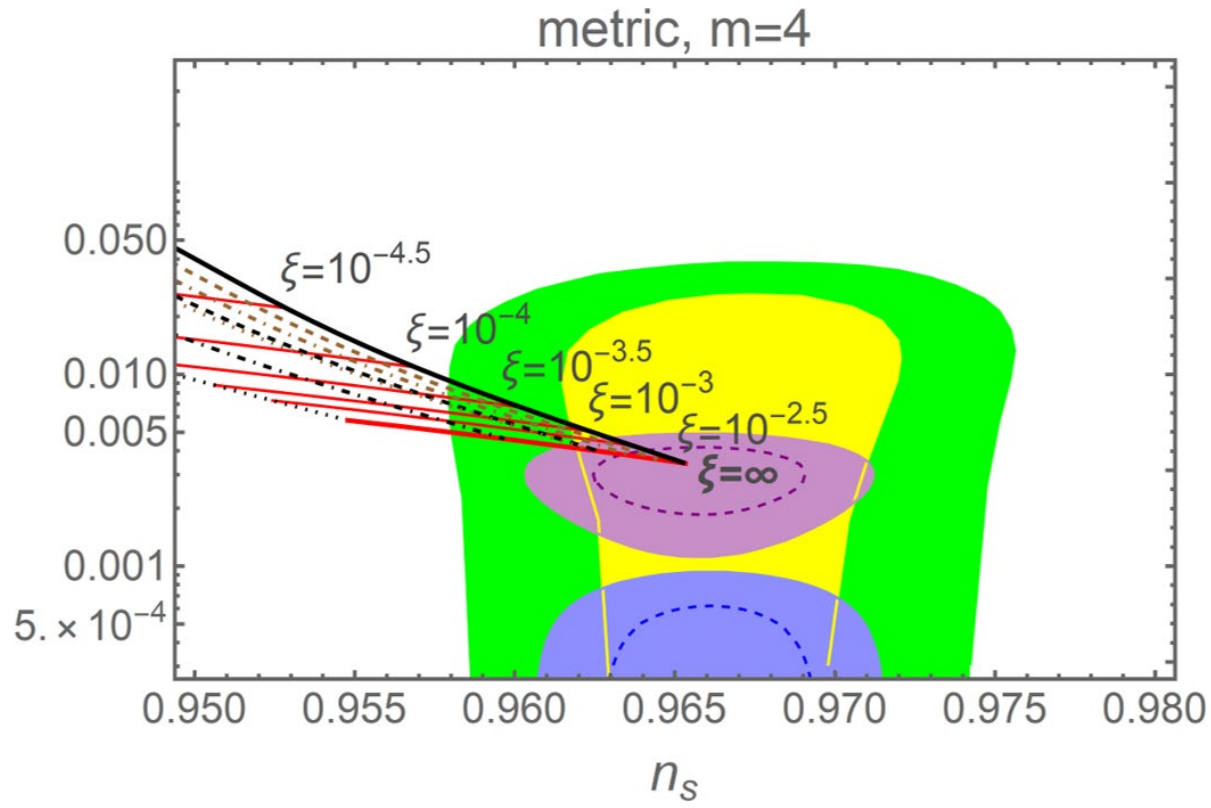




Results: metric cases

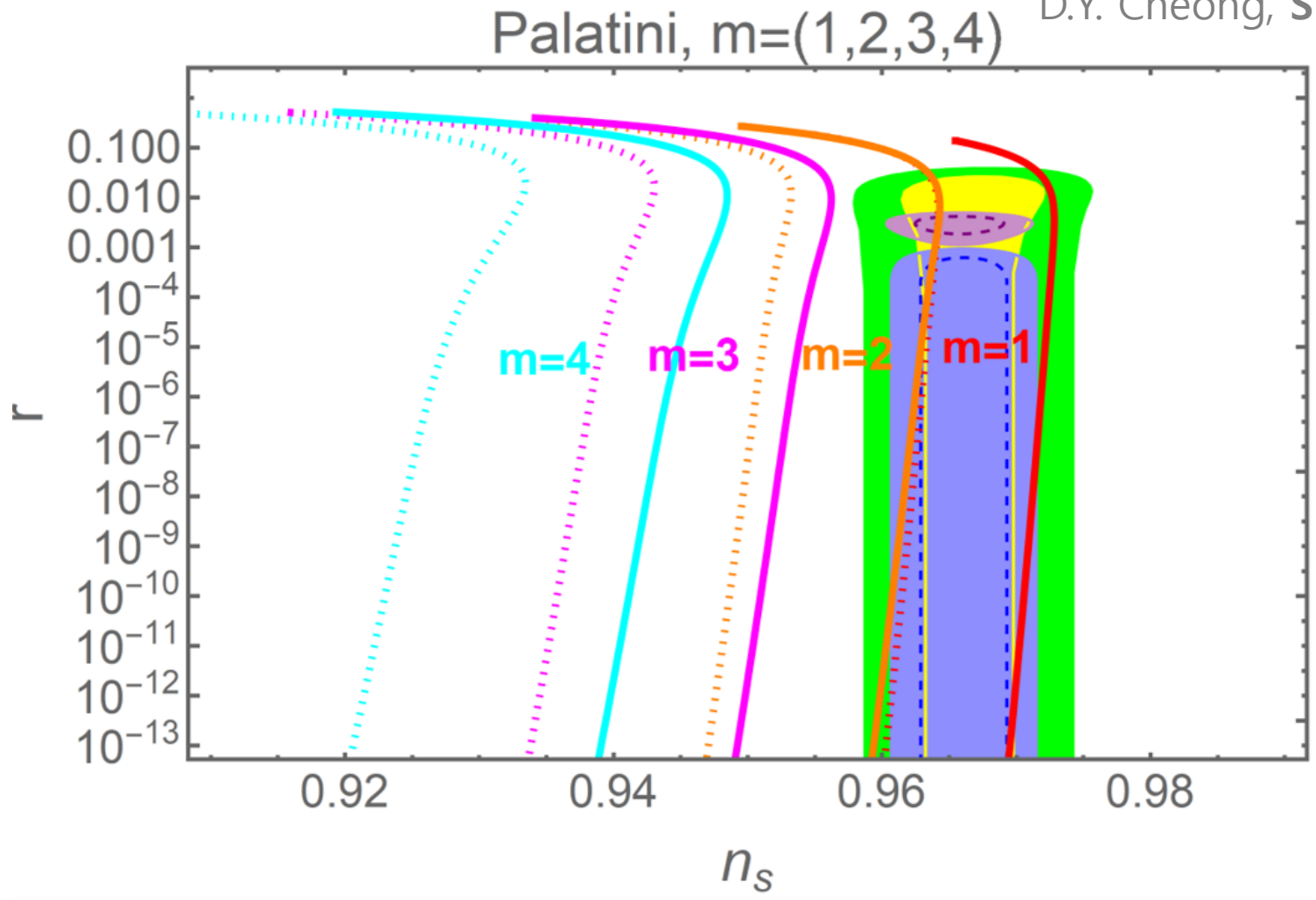
D.Y. Cheong, **SML**, S.C. Park [2111.00825]





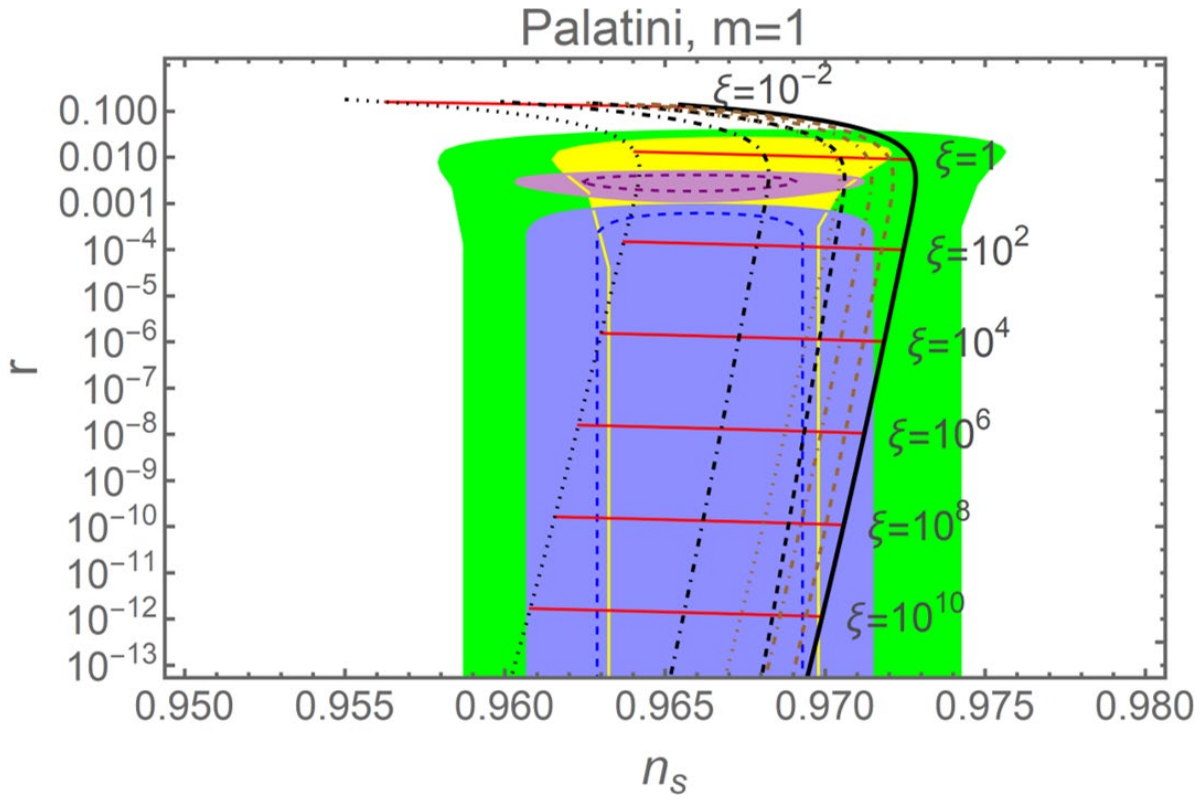
Results: Palatini cases

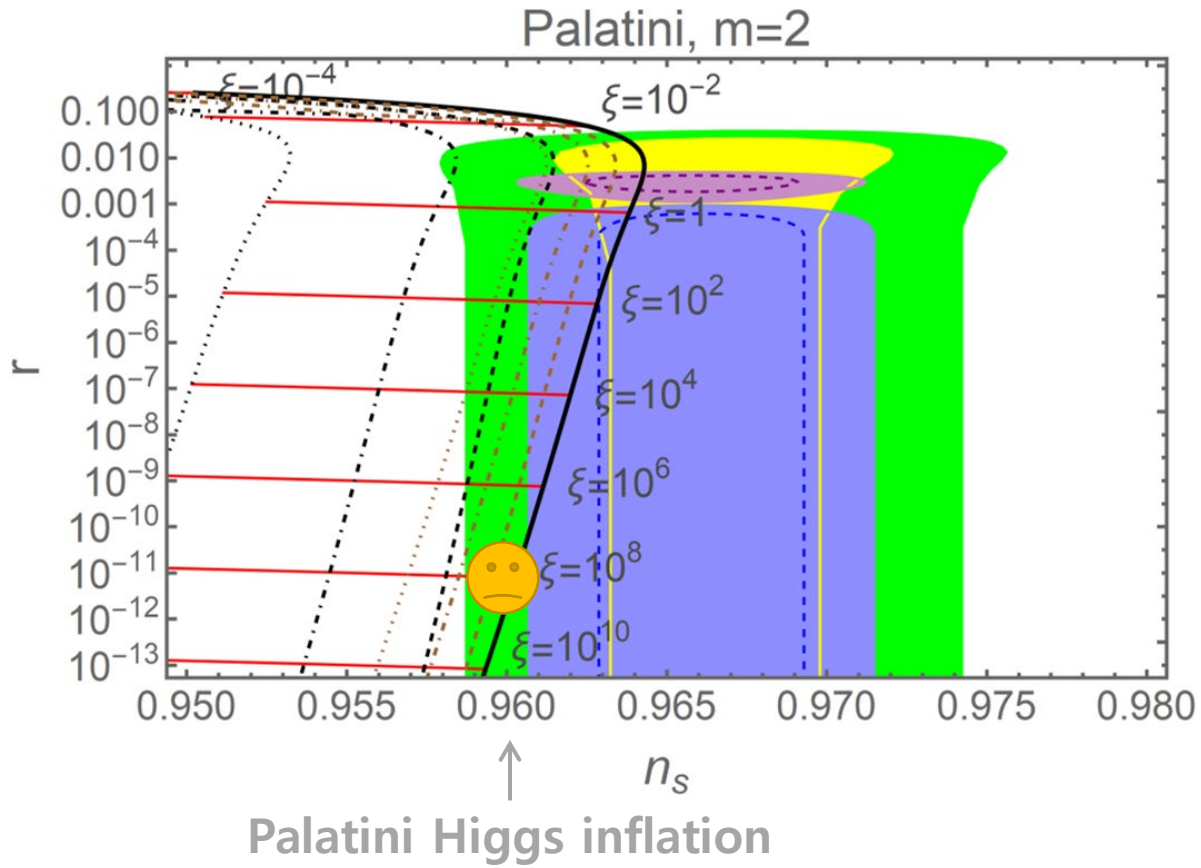
D.Y. Cheong, **SML**, S.C. Park [2111.00825]



Results: Palatini cases

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.