Reheating Predictions and Phenomenology from Inflation with Non-minimal Coupling

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based on **arXiv: 2111.00825 & 2010.07563** (*JHEP* 03 (2021) 083)

In collaborations with Seong Chan Park (Yonsei U.), Kin-ya Oda (Tokyo Woman's Cristian U.) Dhong Yeon Cheong (Yonsei U.)

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- **Part 1**: Reheating in Models with Non-minimal Coupling
  - Model Independent / General
- **Part 2**: Spontaneous Leptogenesis from Higgs inflation
  - Model dependent / Connections to BSM
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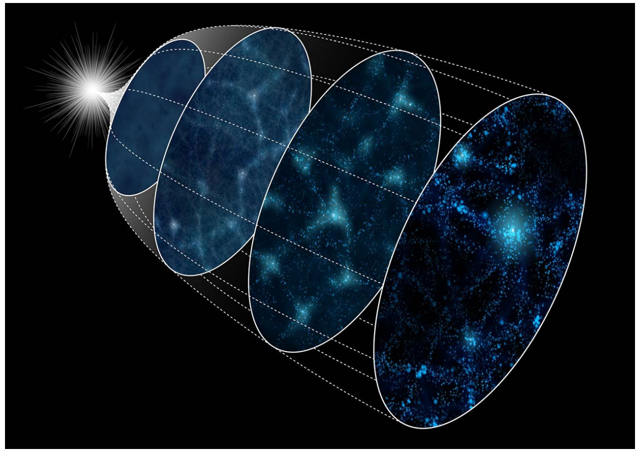
Introduction

Introduction

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

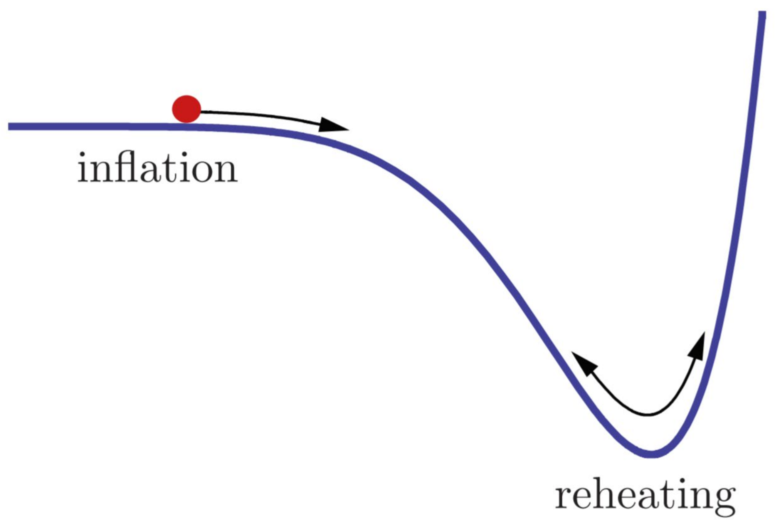


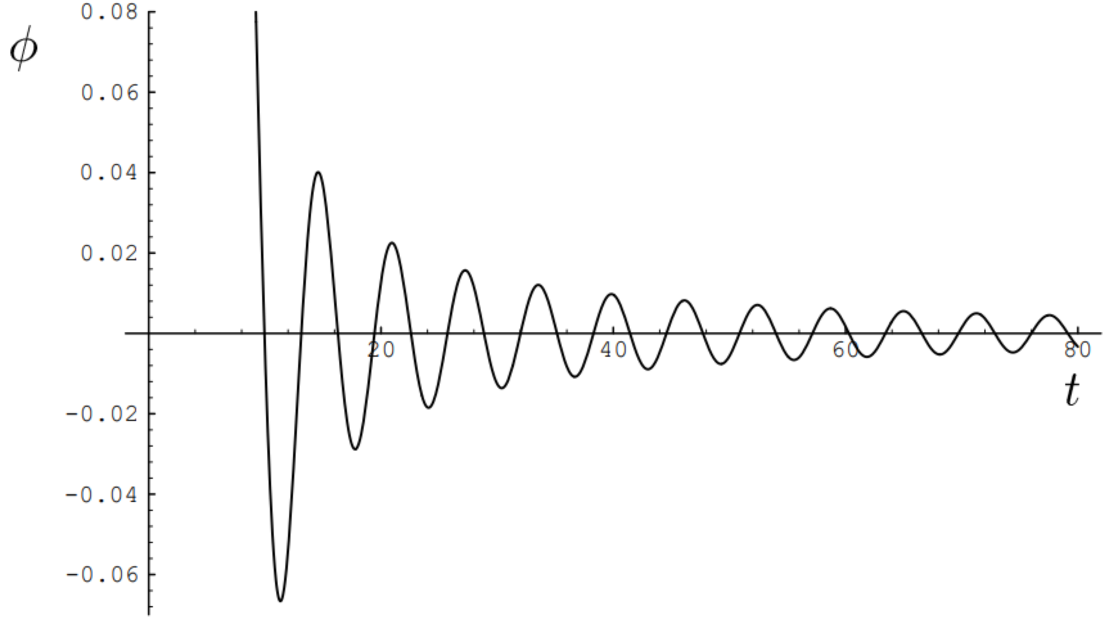
- Detailed reheating process, transition to the thermal universe after the inflation, is usually overlooked.
  - Conservation of the curvature perturbation at the super-horizon
  - Non-linear / Non-perturbative / Model-dependent

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 completes when $\Gamma = H$

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

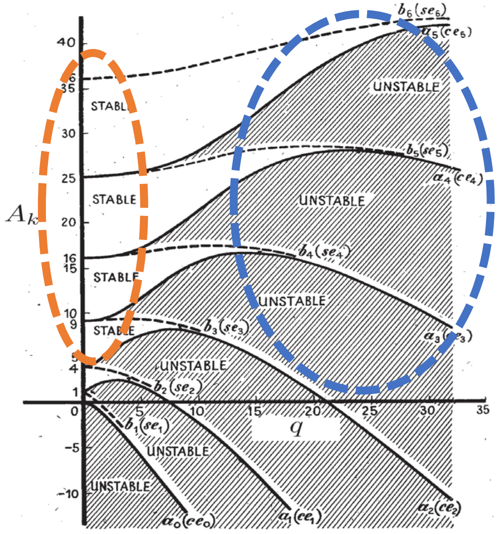
Particle Production & Reheating

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

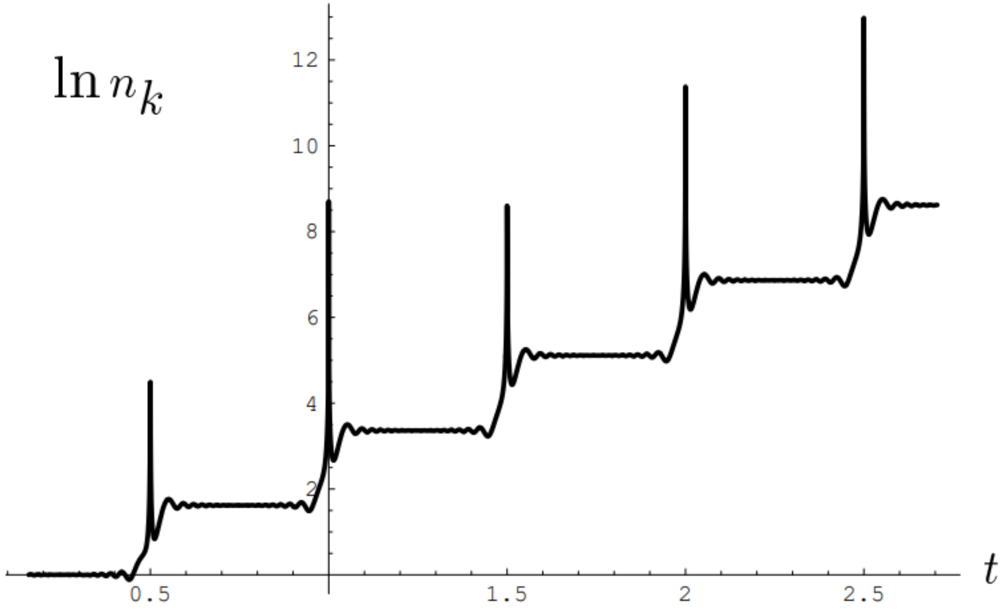
$$\ddot{\chi}_k + \cancel{3H\dot{\chi}_k} + \left(\frac{k^2}{a^2} + g^2\phi^2(t)\right)\chi_k = 0 \qquad \phi(t) \approx \Phi(t)\sin(mt)$$

Harmonic oscillator with time-dependent mass

Narrow resonance



Broad resonance



Particle Production & Reheating

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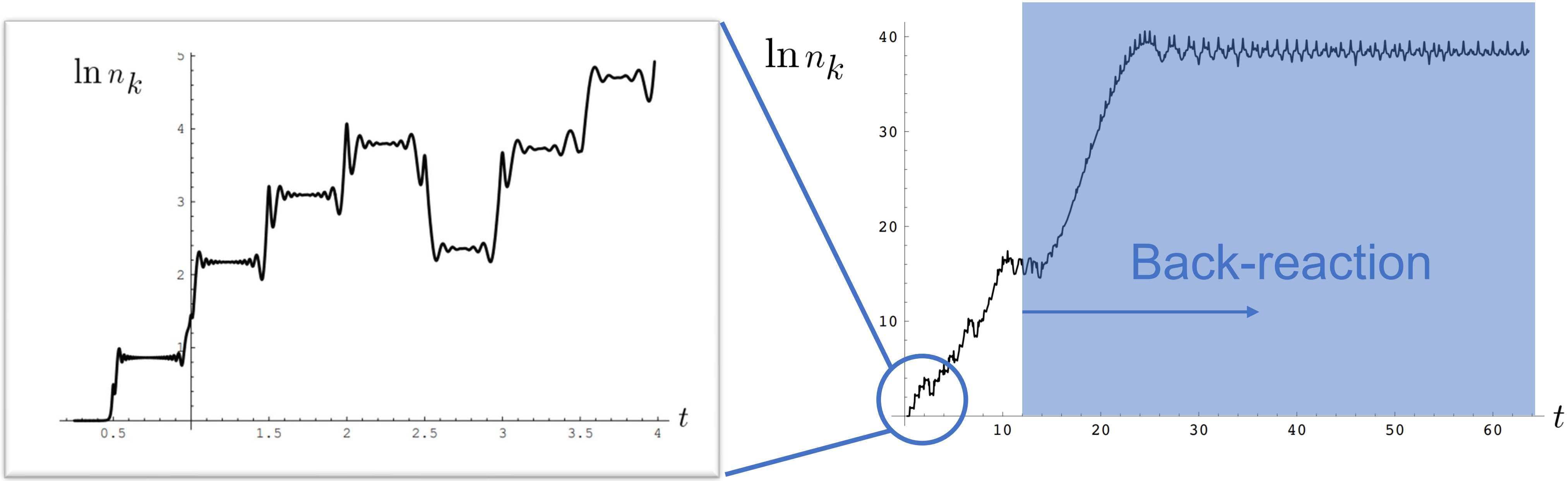
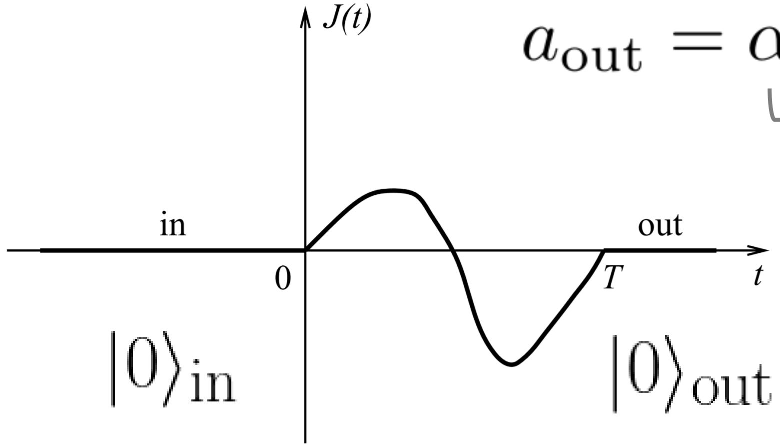


Particle Production & Reheating

- *Non-perturbative* Particle Creation

$$a^{3/2}\chi_k(t) \equiv X_k(t) = \frac{\alpha_k(t)}{\sqrt{2\omega}}\, e^{-i\int^t \omega dt} + \frac{\beta_k(t)}{\sqrt{2\omega}}\, e^{+i\int^t \omega dt}$$

  - Transition from in-vacuum state to out-vacuum state



$$a_{\rm out} = \underbrace{\alpha a_{\rm in} + \beta a_{\rm in}^\dagger}_{\textbf{Bogoliubov coefficients}}$$

$$N_i = \langle 0| a_{\rm in}^\dagger a_{\rm in}^\dagger |0\rangle_{\rm in} = 0$$

$$\downarrow$$

$$N_f = \langle 0| a_{\rm out}^\dagger a_{\rm out}^\dagger |0\rangle_{\rm in} = \underline{|\beta|^2 \neq 0}$$

Particle Production

Particle Production & Reheating

- Reheating processes are complicated:

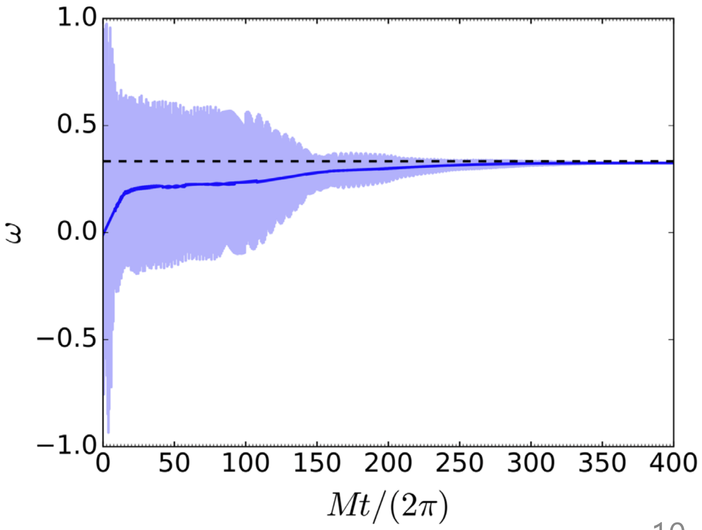
(Non-perturbative) Preheating → **(Perturbative) reheating** → **Thermalization**

Back-reaction

Reheating

- Generally, we rely on numerical simulation.

J. Repond *et al.* [1604.08238]



- 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

  - Dark matter

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

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

- Intrinsic model dependence

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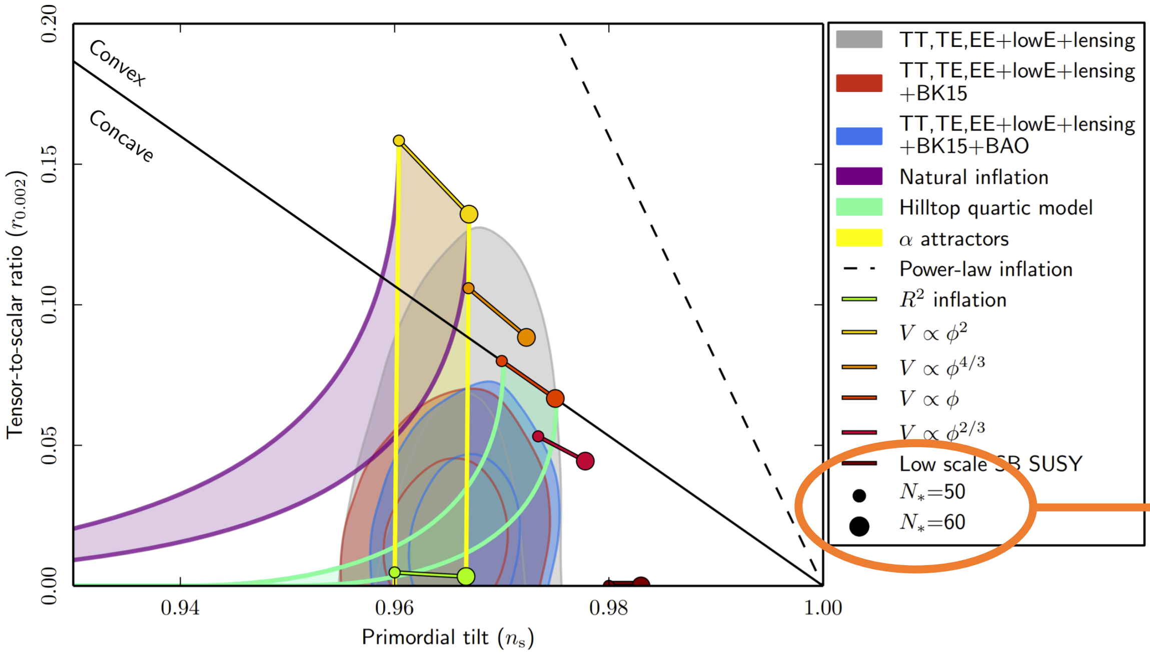
Practical Reason : Inflation Predictions

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

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



Obscured reheating dependence

- Less model dependent

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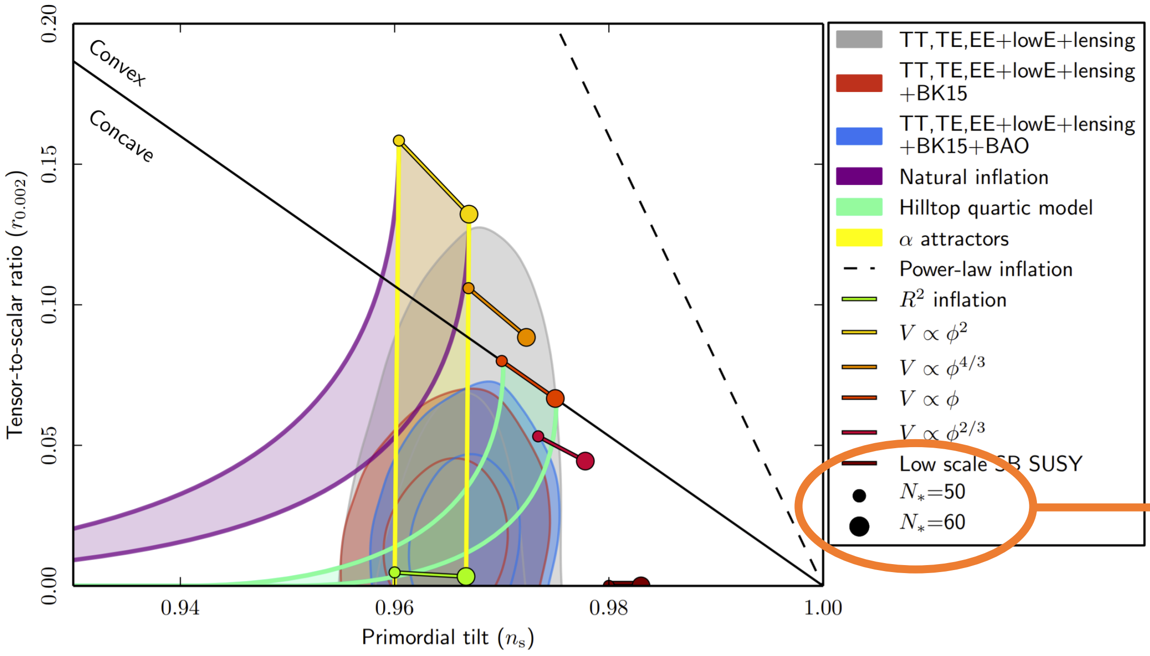

Part 1

Obscured reheating dependence

- Less model dependent

Part 1

Reheating in Models with Non-minimal Coupling

Inflation Predictions with Reheating

- Reheating parameters
  - E-folding number during the reheating

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

  - (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 $T_{\rm reh}$

L. Dai *et al.* [1404.6704]
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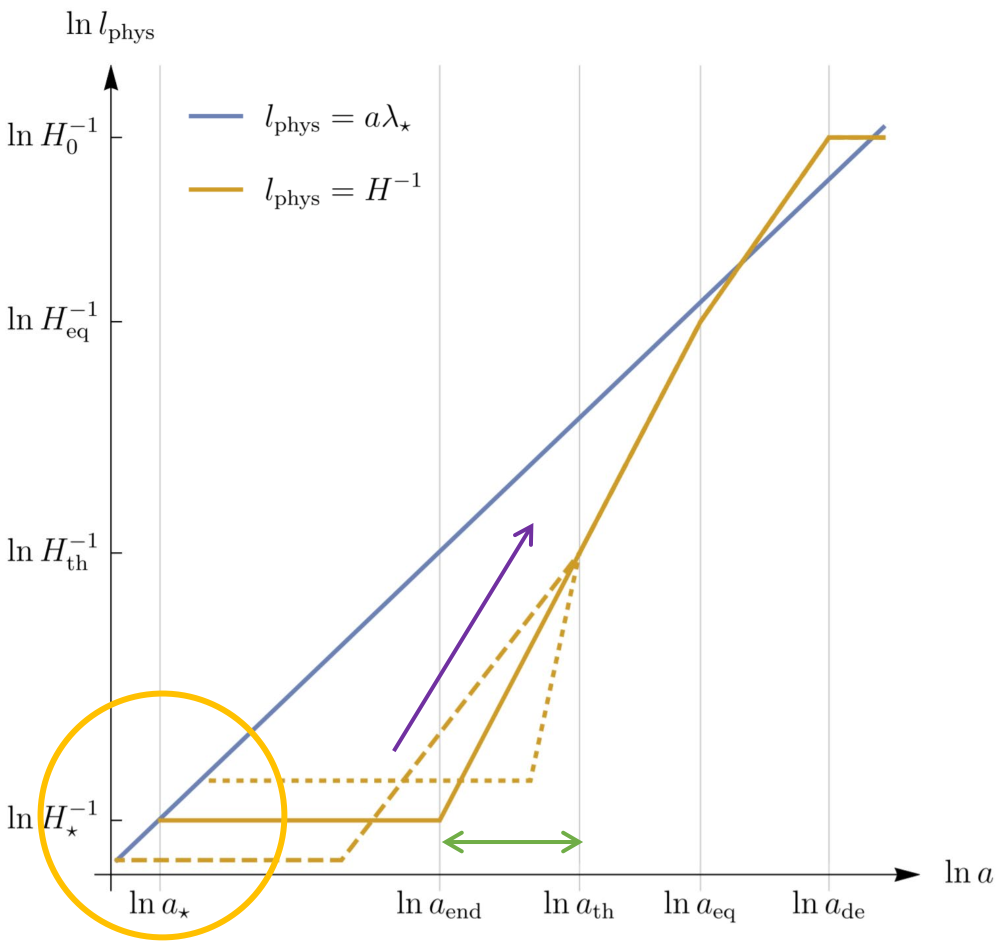
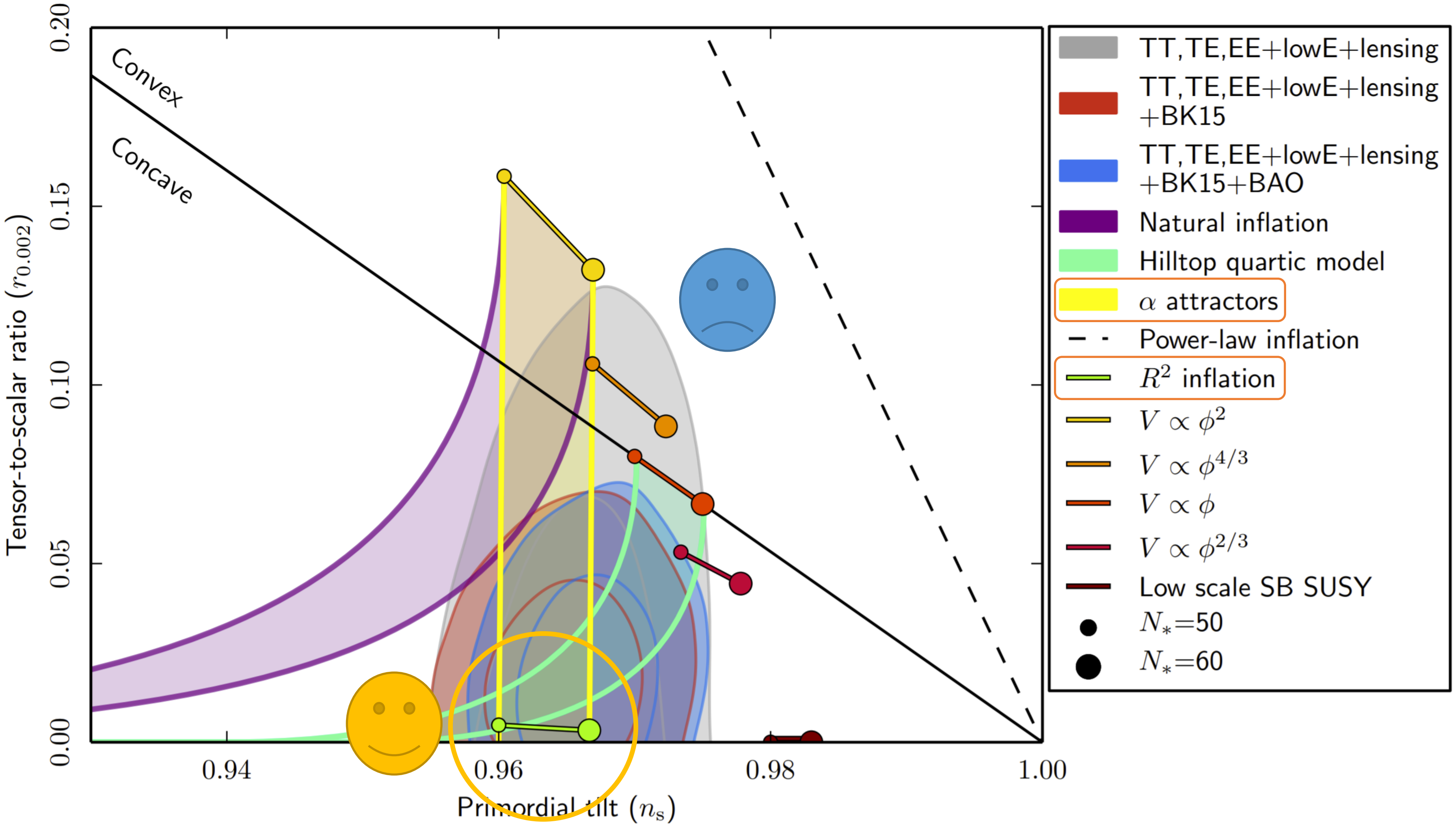


K.D. Lozanov [1907.04402]

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

Inflation with Non-minimal Coupling

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

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

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

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

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

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

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

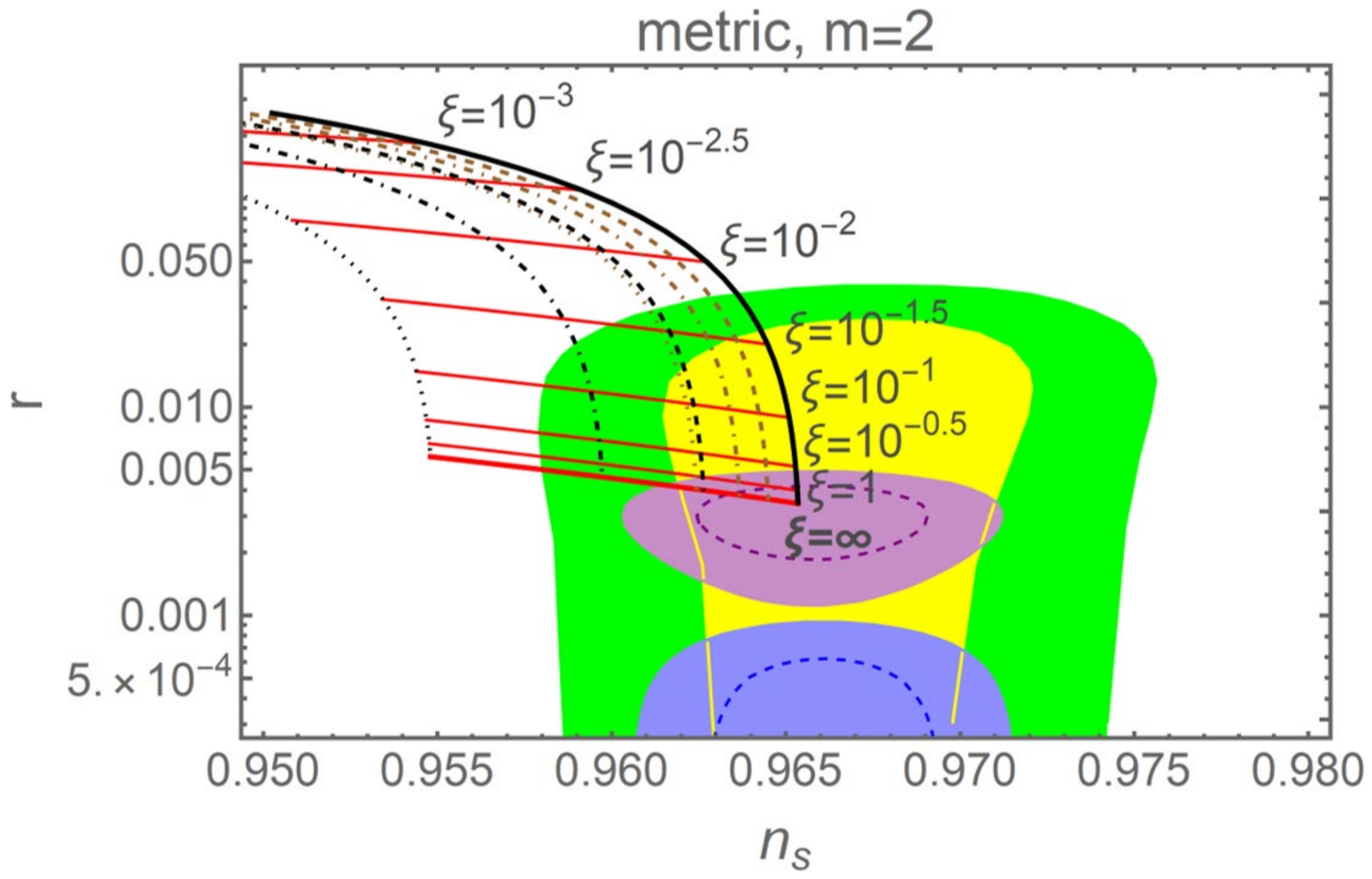
- Condition for asymptotically flat potential: S.C. Park *et al.* [1311.0472]

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

- 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)

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

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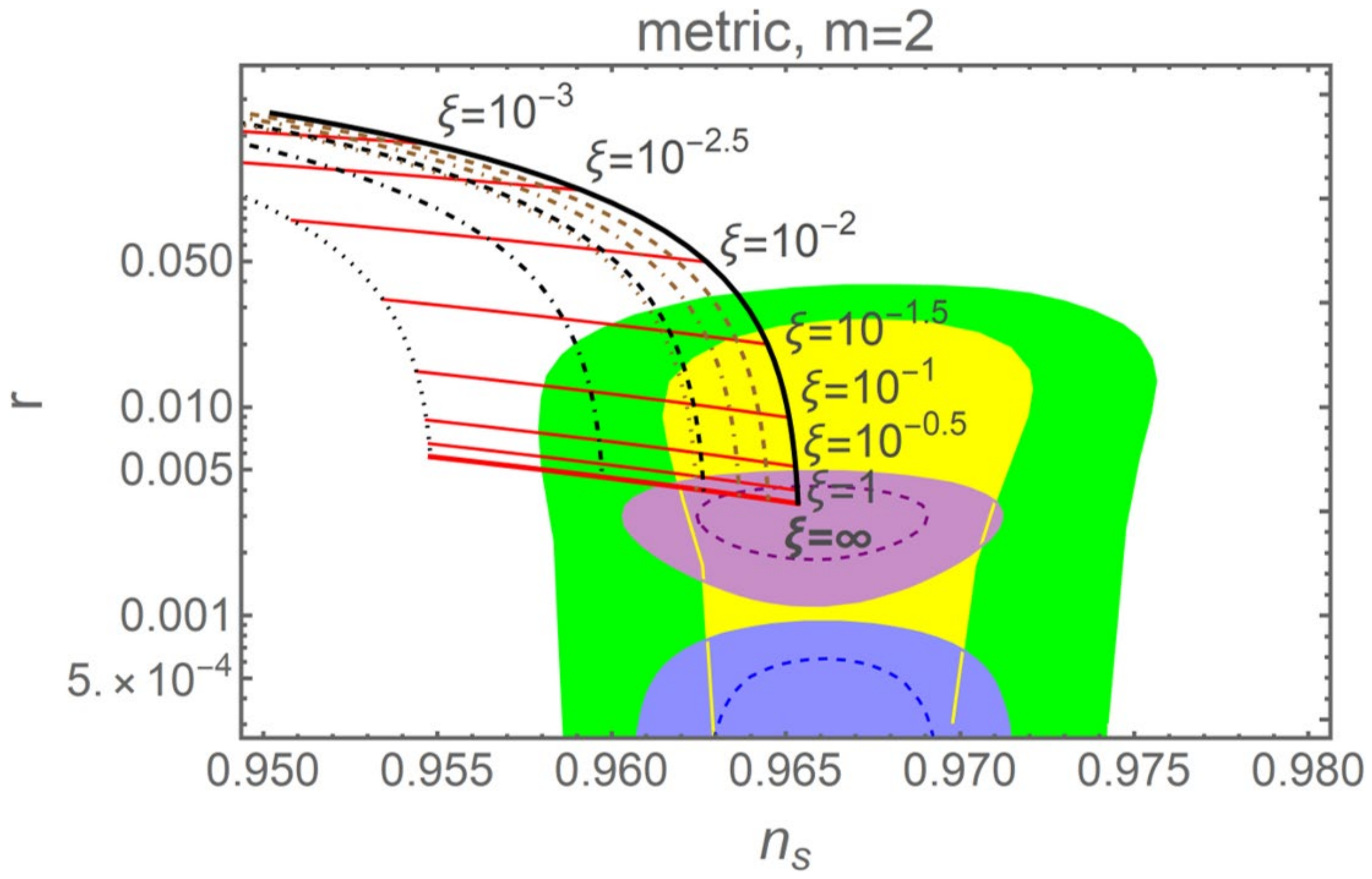


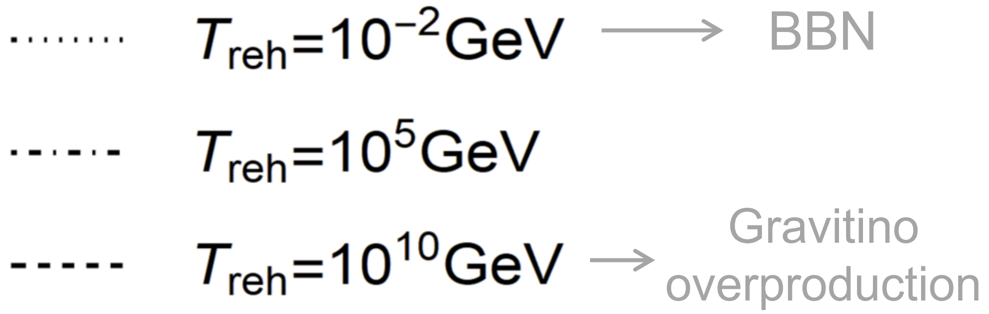
D.Y. Cheong, **SML**, S.C. Park [2111.00825]

- **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.



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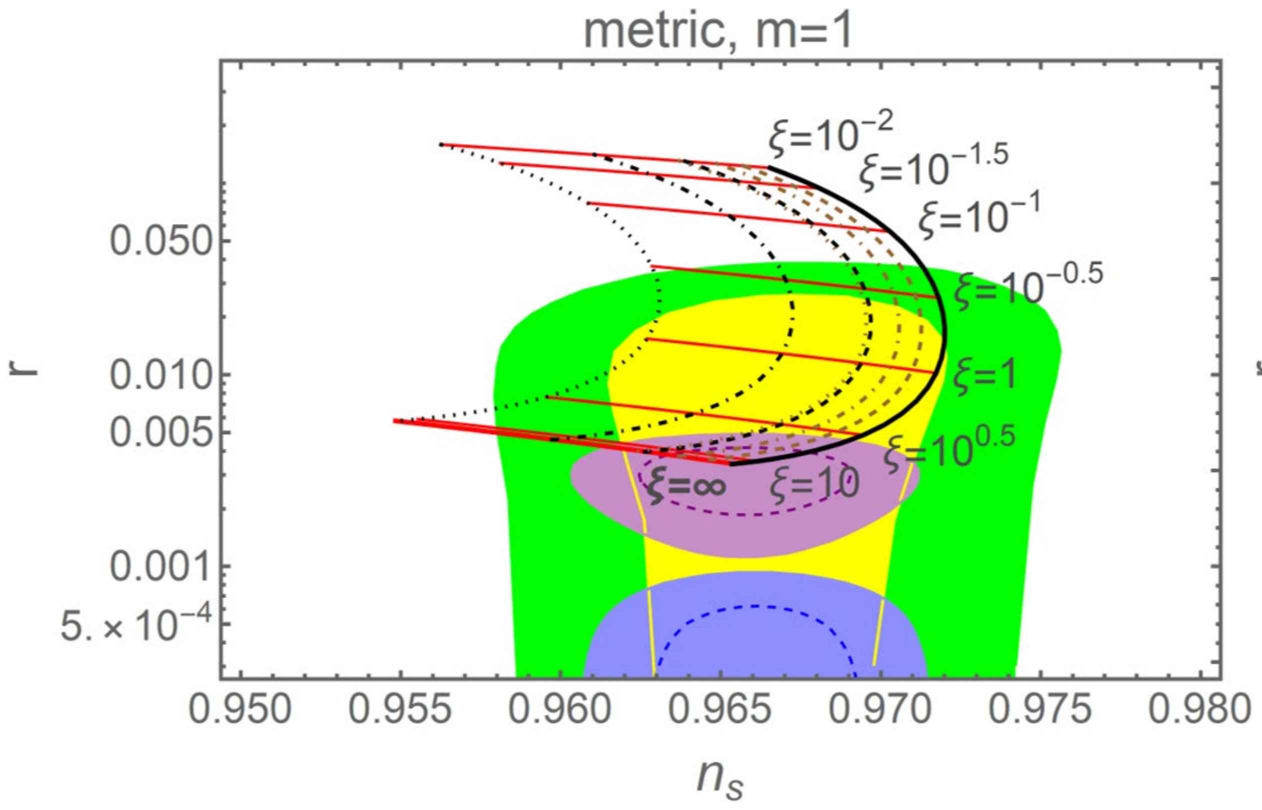

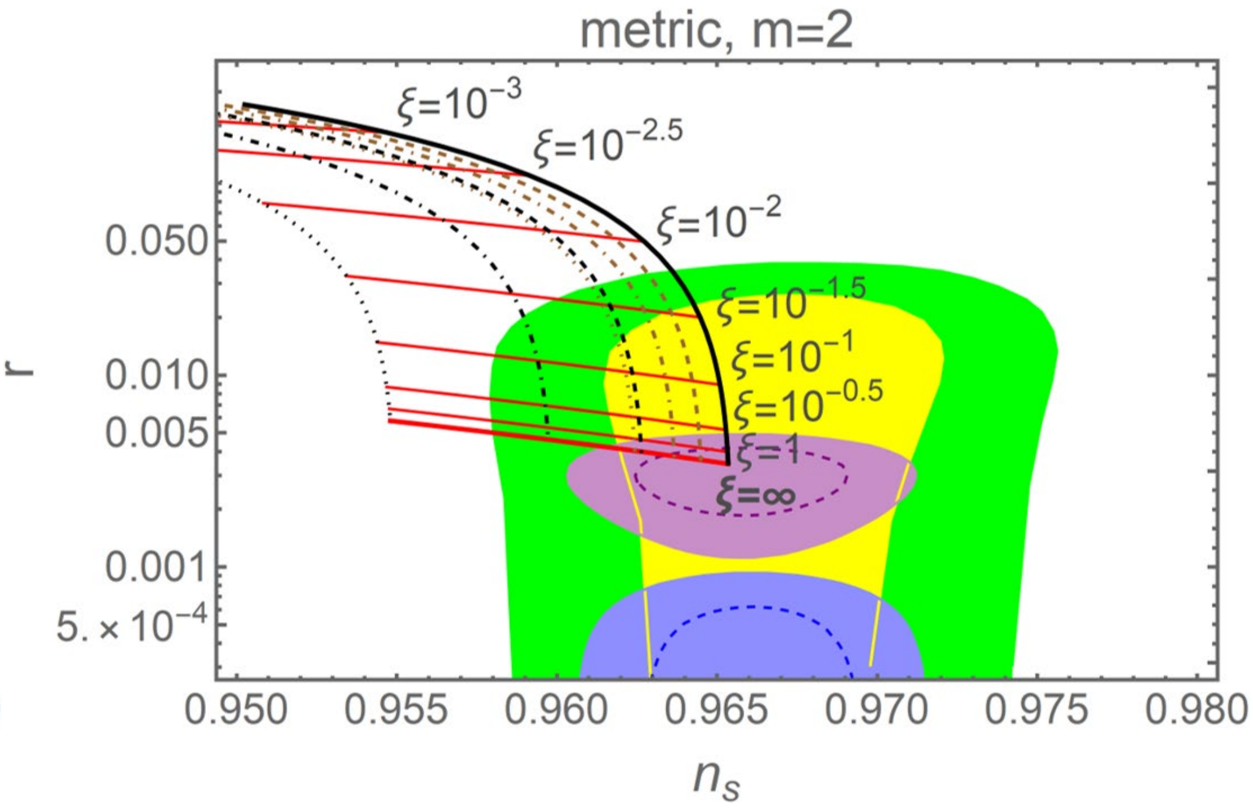

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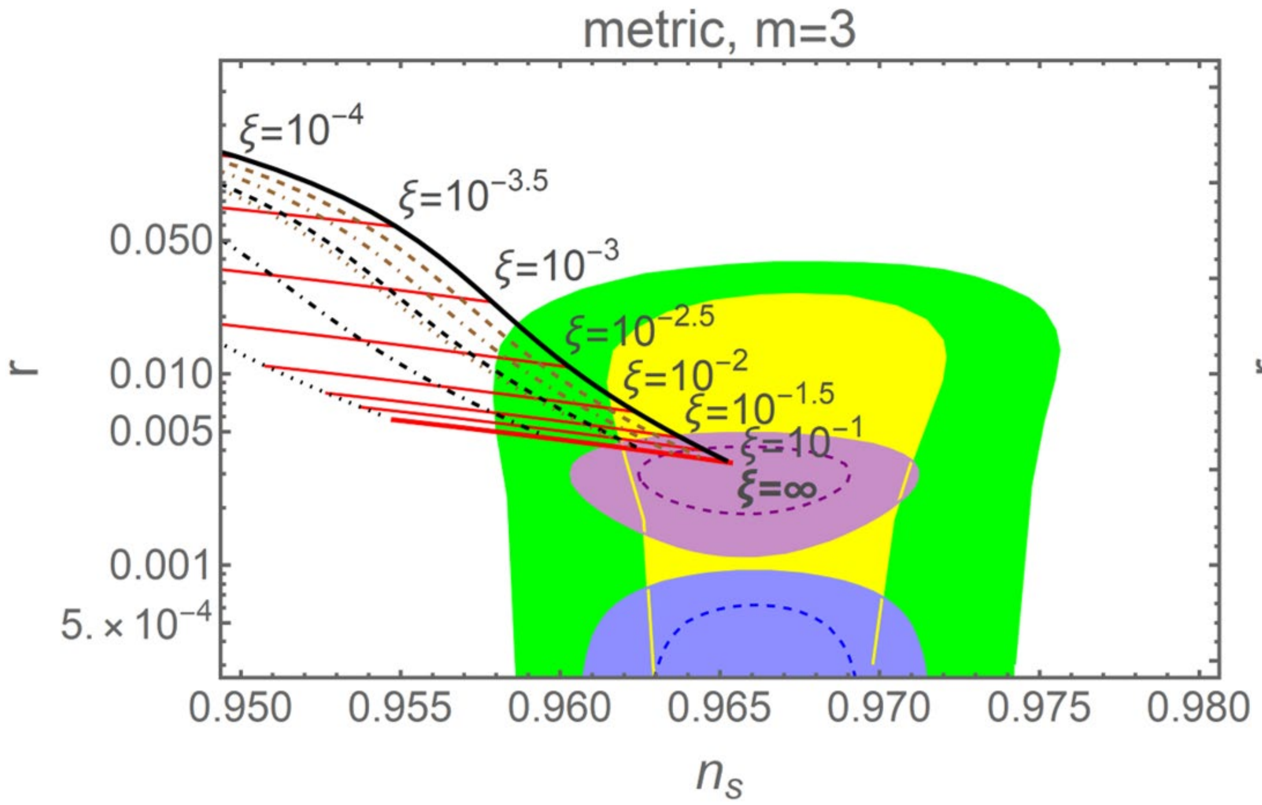
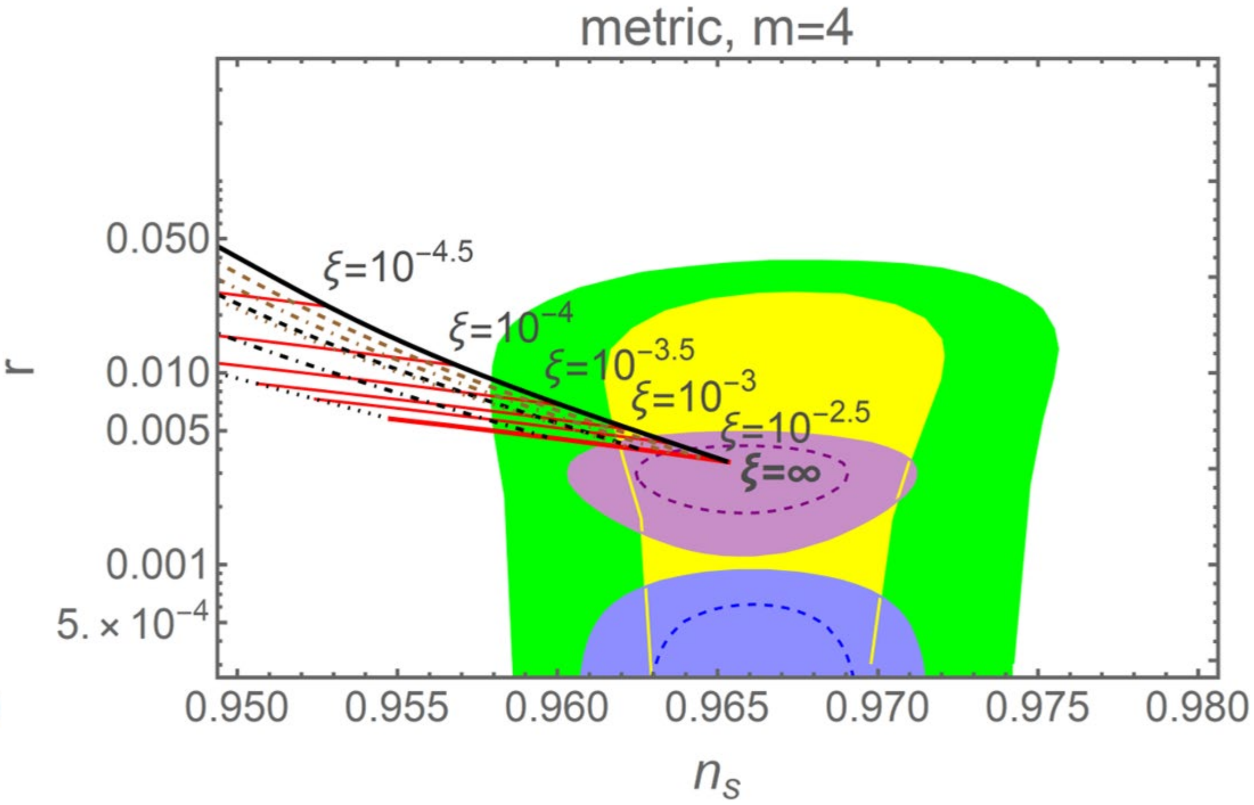
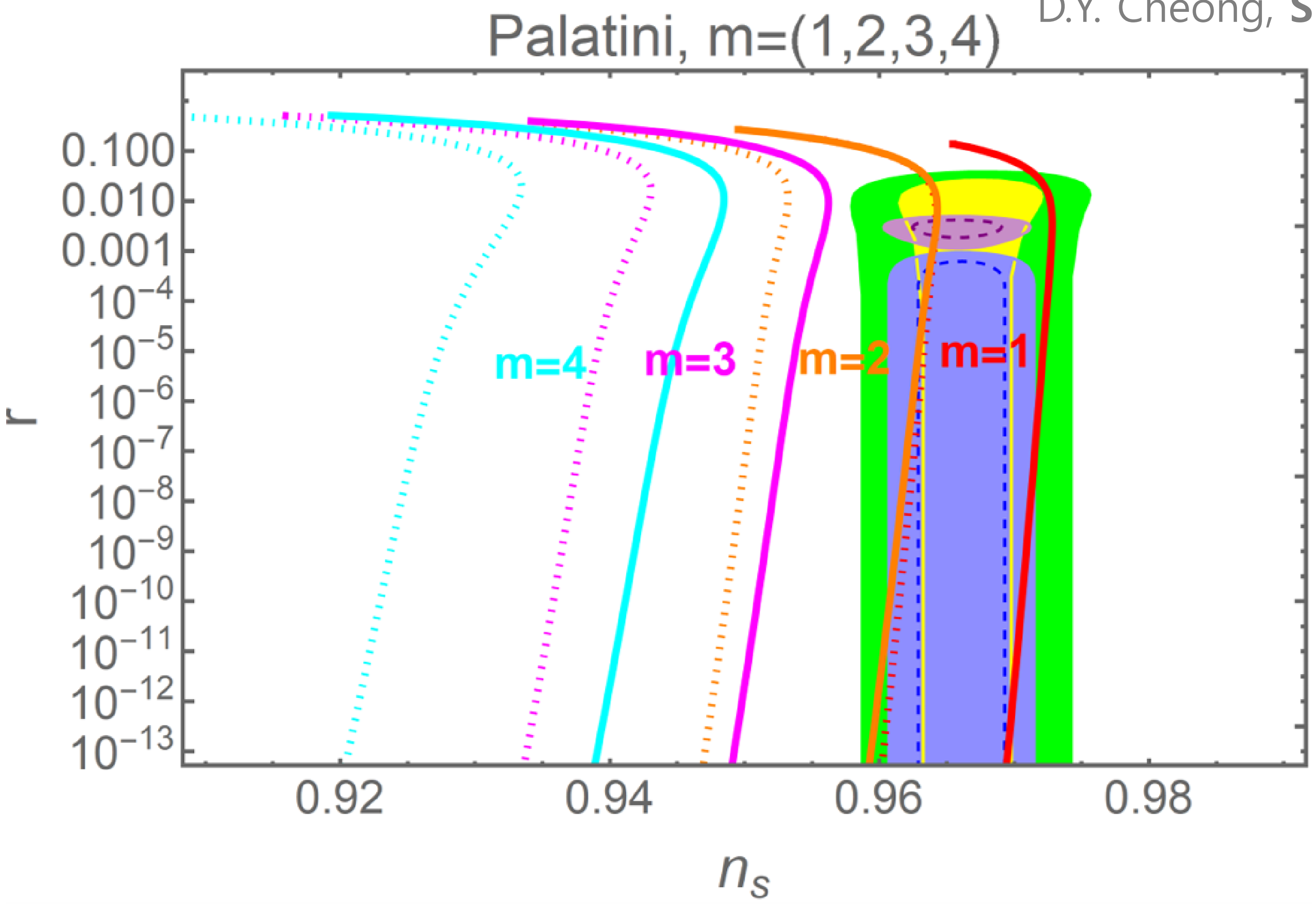




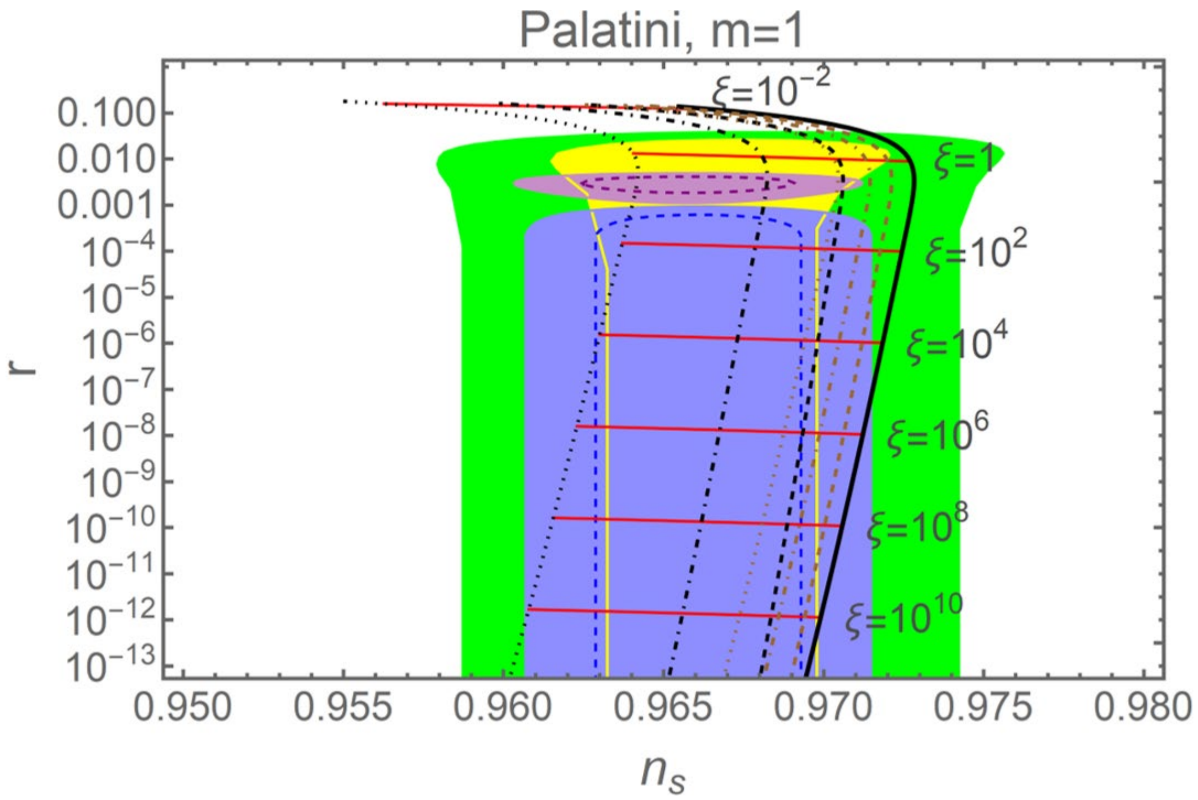
Results: Palatini cases

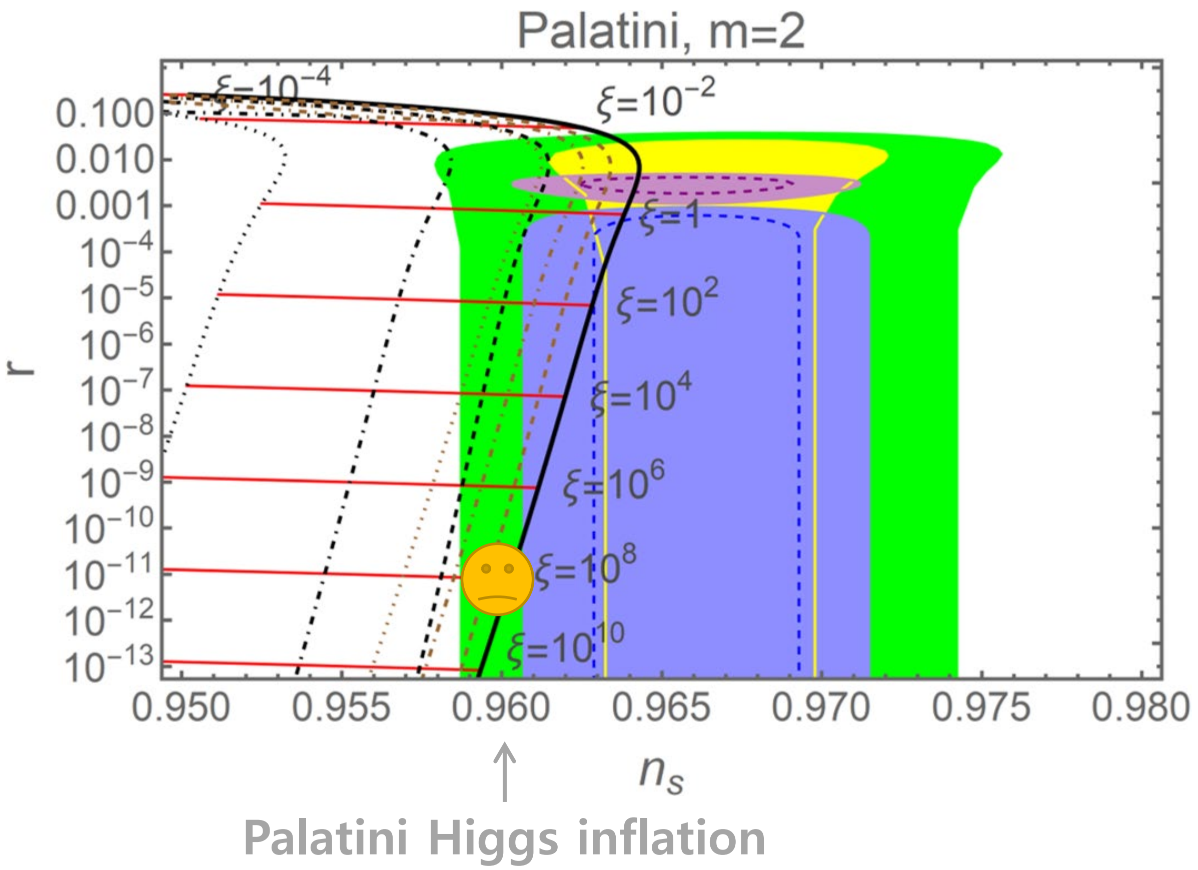
D.Y. Cheong, **SML**, S.C. Park [2111.00825]



Results: Palatini cases

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





- Large suppression of tensor-to-scalar ratio

Summary of Part 1

- Reheating stage changes the inflationary predictions.

- 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.

Part 2

Spontaneous Leptogenesis from Higgs inflation

Baryon Asymmetry

- Baryon asymmetry $\eta_B \equiv \frac{n_B}{n_\gamma} \simeq (6.12 \pm 0.04) \times 10^{-9}$ (from CMB&BBN)
  - Cannot be explained within SM

- Sakharov Conditions
  - Baryon number violation
  - C/CP violation
  - Out of equilibrium

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    - Lepton ~~Baryon~~ number violation — Dim-5 Weinberg operator
    - (Spontaneous) CPT ~~C/CP~~ violation — Dim-6 Operator → Chemical Potential
    - Out of equilibrium

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  - (Spontaneous) CPT C/~~CP~~ violation — Dim-6 Operator → Chemical Potential
  - Out of equilibrium — Reheating

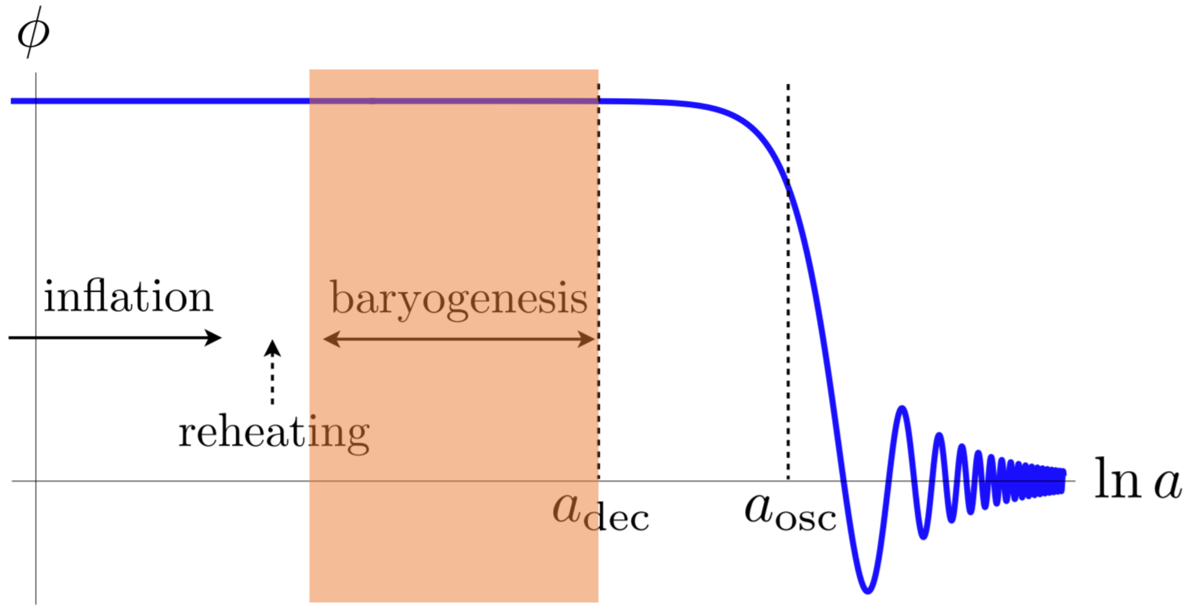
Spontaneous Baryogenesis

- Spontaneous Baryogenesis [A. G. Cohen and D. B. Kaplan (1987)]
  - Hot regime : Thermal Equilibrium $n_B - n_{\bar{B}} \simeq \frac{g}{6}\mu T^2$

(Spatially homogeneous)
Goldstone Boson

$$\frac{1}{\Lambda}(\partial_\mu \phi) j^\mu_B = \frac{\dot{\phi}}{\Lambda}(n_B - n_{\bar{B}})$$

Effective chemical potential μ



Spontaneous Baryogenesis

- Spontaneous Baryogenesis [A. G. Cohen and D. B. Kaplan (1987)]
  - Super-cooled regime : Perturbative/Non-perturbative Decay [A. Dolgov *et al.* hepph/9610405]
    - Possible scenario using SM Higgs was first considered by Kusenko *et al.* [1410.0722, 1505.02461]

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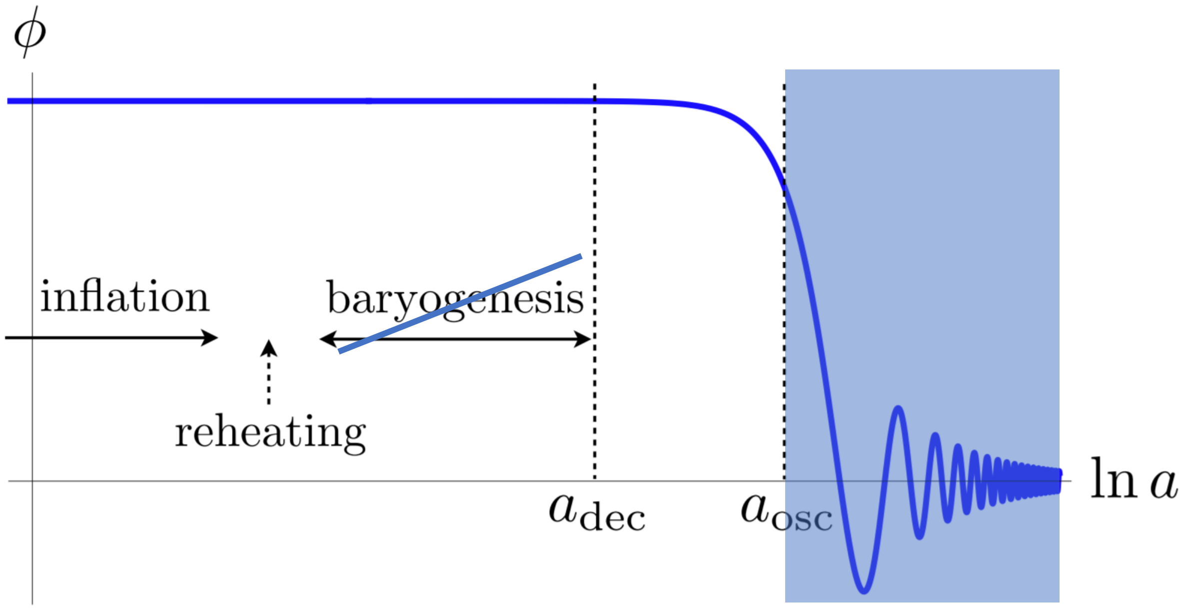

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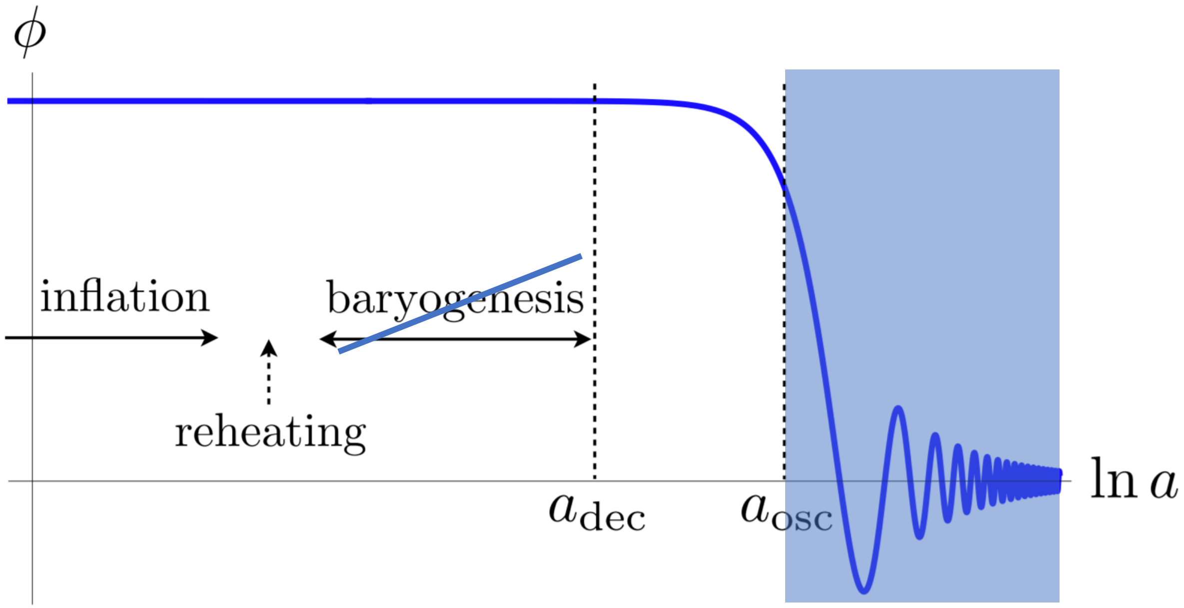


Also realized during the reheating

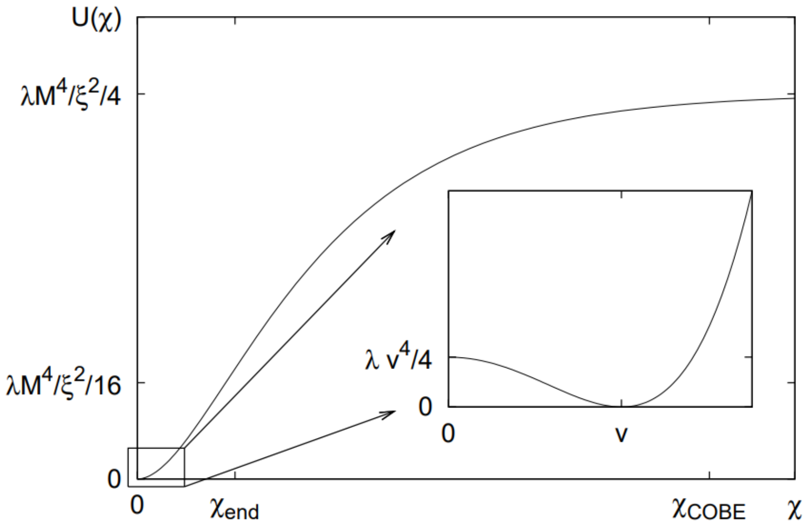
Higgs Inflation (m=2, metric)

- Model

[F.L. Bezrukov *et al.* 0710.3755]

$$S_{J,\text{inf}} = \int d^4x\sqrt{-g_J}\left[\frac{1}{2}\left(M_P^2 + \xi\phi_J^\dagger\phi_J\right)R_J - \frac{1}{2}|\partial_\mu\phi_J|^2 - V_J(\phi_J)\right] \quad V_J(\phi_J) = \frac{\lambda}{4}\phi_J^4$$

- The only candidate of inflaton in SM
  - Best-fit to Planck result



- SM fermions/gauge bosons also become time-dependent

Higher Dimension Operators : Dim-5

- SM as EFT
  - On inflation, this is an important issue (cf. eta problem)
  - Here, we will consider *Planck-suppressed, symmetry breaking* operators
  - Minimal / intrinsic amount of lepton asymmetry

- Dim-5 operator : Weinberg operator

$$\mathcal{L}_{\text{dim-5}} = \frac{c_5}{M_P}(\overline{L}\tilde{\Phi})(\tilde{\Phi}L)^\dagger \qquad \tilde{\Phi} \equiv i\sigma_2\Phi^*$$

  - Lepton number violation
  - *No wash-out* at late times

Higher Dimension Operators : Dim-6

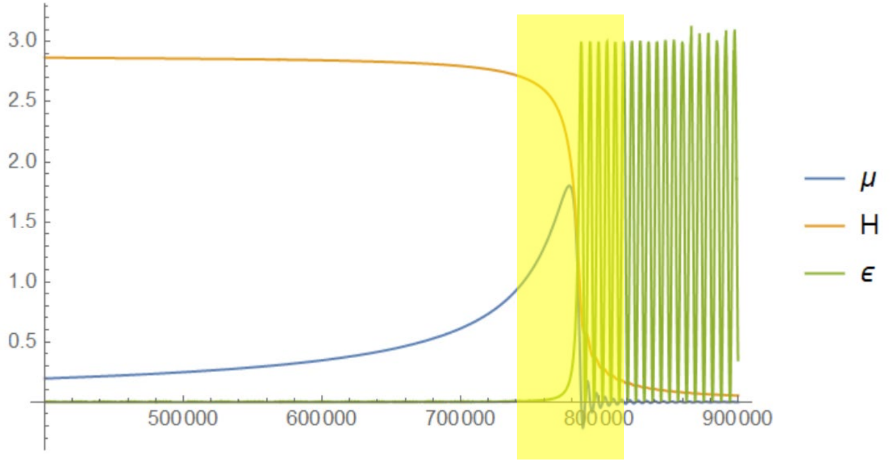
- Dim-6 operator [Pearce *et al.* 1410.0722, 1505.02461]

$$\mathcal{O}_6 = -\frac{c_6}{M_P^2}\Phi_J^\dagger \Phi_J \partial_\mu j_L^\mu = \frac{c_6}{M_P^2}(\partial_\mu \phi_J^2) j_L^\mu = \underbrace{\frac{c_6}{M_P^2}(\partial_t \phi_J^2)}_{} j_L^0$$

Coherent field *spontaneously* breaks Lorentz symmetry

Coefficient of number density: effective chemical potential

- Large chemical potential during reheating



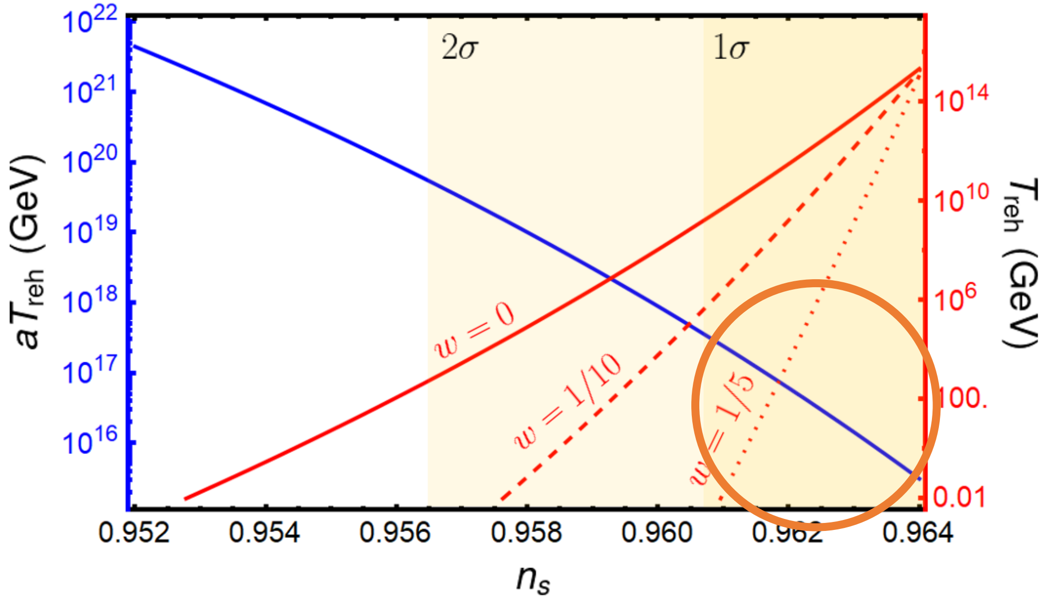
Reheating temperatures

F.L. Bezrukov *et al.* [0710.3755],
Juan Garcia-Bellido *et al.* [0812.4624]
Yohei Ema *et al.* [1609.05209]
Yuta Hamada *et al.* [2007.04701]

- Determining exact reheating temperature is non-trivial
- There exists a *consistency relation* between $\tilde{T} = a_{reh}T_{reh}$ and n_s

$$a_{\rm reh}T_{\rm reh} = \left(\frac{43}{11g(T_{\rm reh})}\right)^{\frac{1}{3}}\left(\frac{a_0T_0}{k_*}\right)H_k e^{-N_e}$$

Jessica L. Cook *et al.* [1502.04673]



- For Higgs Inflation,

$$N_e = \frac{2}{1-n_s} \qquad H_k = \pi M_P\sqrt{\frac{3}{2}A_s(1-n_s)}$$

- Favored Regime $10^{15}\text{GeV} \lesssim \widetilde{T} \lesssim 10^{18}\text{GeV}$

Independent to the equation of state

Neutrino Production

- Bogoliubov Transformation
  - Particle production (Neutrino) from time dependent classical background (Higgs)

$$(i\partial_\tau + \vec{\sigma}\cdot\vec{k})\nu_L = -\widetilde{m}_\nu(i\sigma_2)\nu_L^* - \widetilde{\mu}\nu_L$$

$$\alpha_s'(\tau,k) = -\frac{\beta_s(\tau,k)}{2\omega_s^2}\left[\widetilde{m}_\nu\widetilde{\mu}' - (sk+\widetilde{\mu})\widetilde{m}_\nu'\right]e^{2i\int_0^\tau \omega_s(\tau')d\tau'}$$

$$\beta_s'(\tau,k) = \frac{\alpha_s(\tau,k)}{2\omega_s^2}\left[\widetilde{m}_\nu\widetilde{\mu}' - (sk+\widetilde{\mu})\widetilde{m}_\nu'\right]e^{-2i\int_0^\tau \omega_s(\tau')d\tau'}$$

$$\alpha_s(0,k) = 1 \text{ and } \beta_s(0,k) = 0$$

- Manifest helicity dependence
- Time dependence of neutrino mass is essential

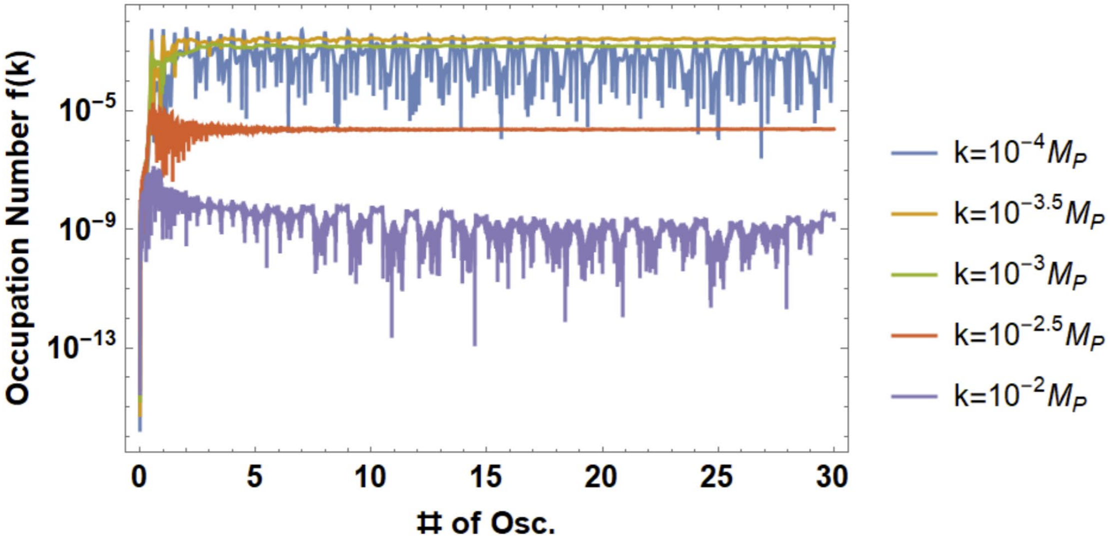
$$n_s(t) = \frac{1}{(a(t)/a_{\rm end})^3}\int\frac{d^3k}{(2\pi)^3}|\beta_s(\tau(t),k)|^2$$

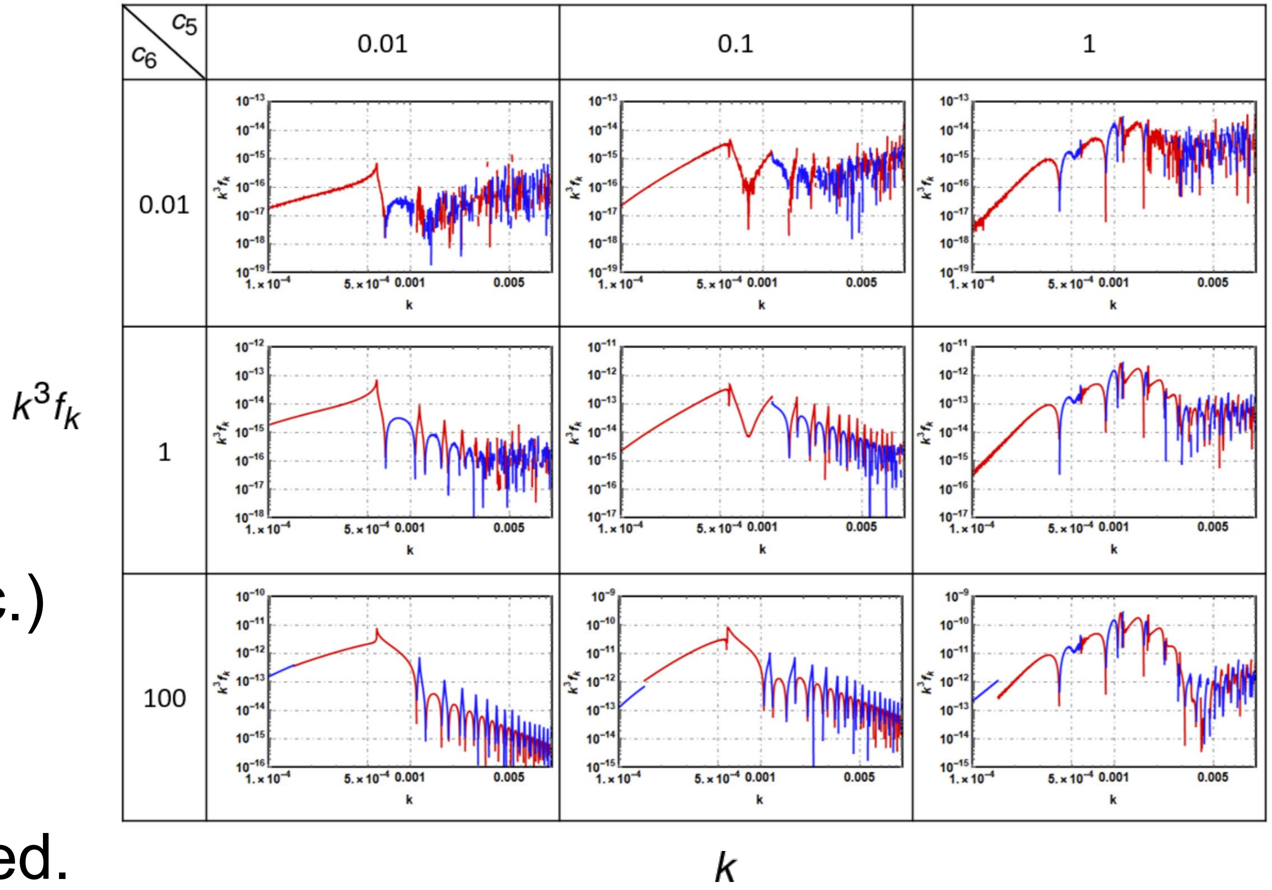
occupation number $f_s(t,k)$

$$\eta_L(t_{\rm reh}) \equiv \left.\frac{n_L}{n_\gamma}\right|_{\rm reh} = \frac{\pi^2}{2\zeta(3)}\left.\frac{\widetilde{n}_L}{\widetilde{T}^3}\right|_{\rm reh}$$

- transforms to B asymmetry via sphaleron

Lepton Asymmetry



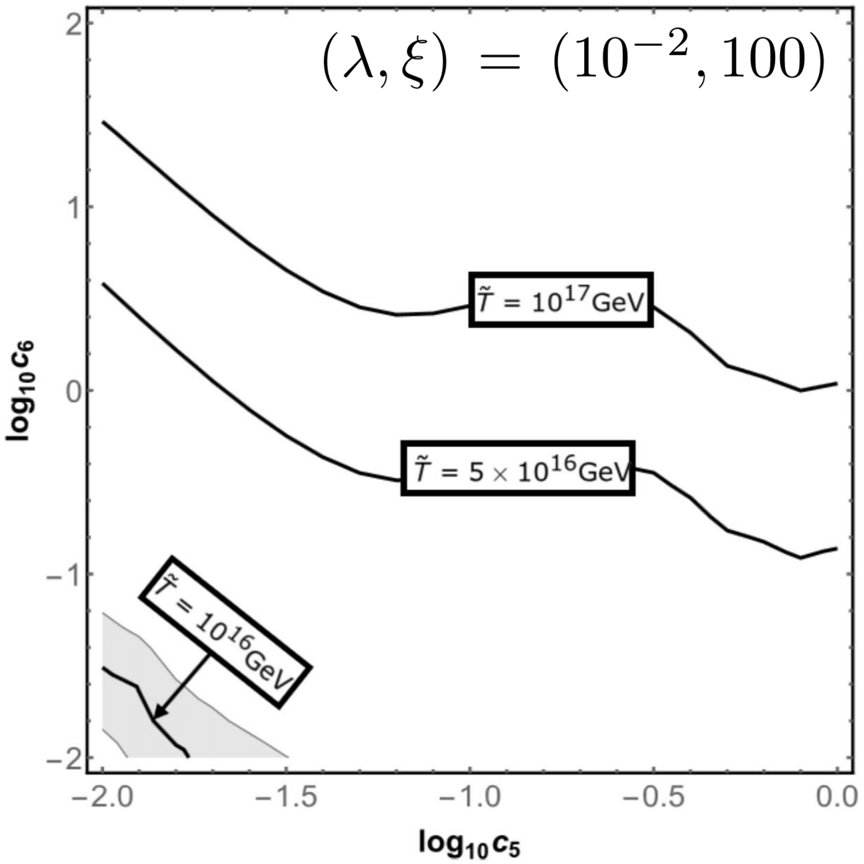


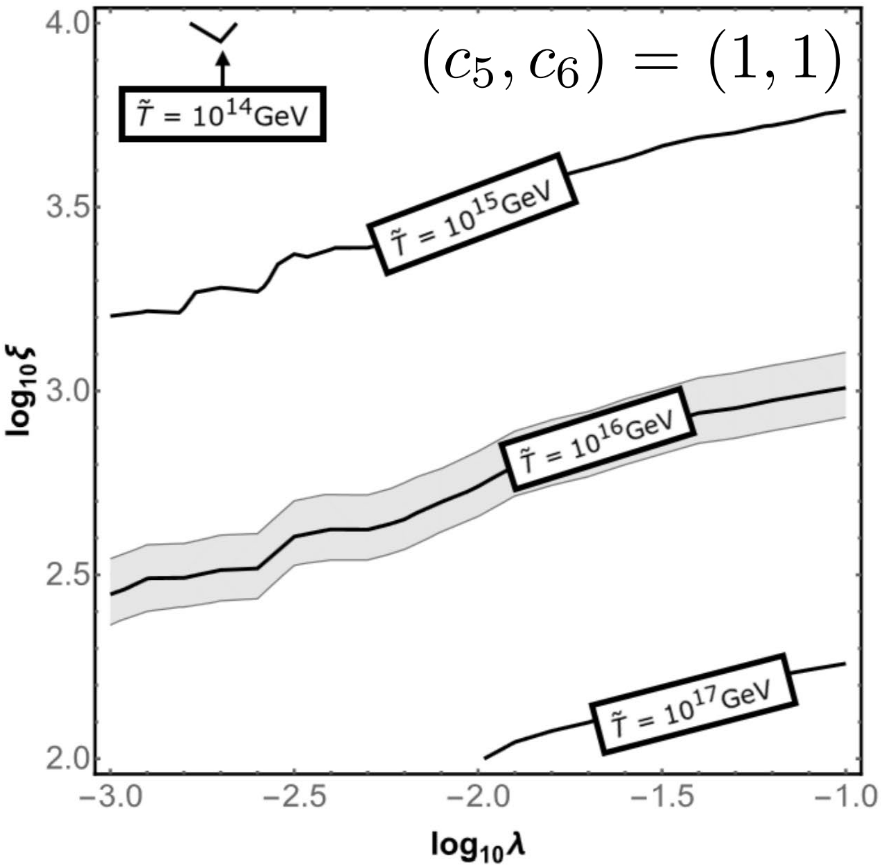
- Almost produced at early time (≤ 5 osc.)
  - Insensitive to reheating history
- Large momentum mode are suppressed.
  - No unitarity violation

[**SML**, K. Oda, SC. Park. 2010.07563]

Results

$$\eta_B(c_5, c_6, \widetilde{T}) \simeq \frac{C^{(\mathrm{SM})}_{\mathrm{sphal}} \pi^2 \widetilde{n}_L}{2\zeta(3)\widetilde{T}^3}$$





[**SML**, K. Oda, SC. Park. 2010.07563]

Summary of Part 2

- We calculated the *intrinsic* amount of the baryon asymmetry from Higgs inflation, in the EFT point of view.
  - Planck suppressed / symmetry breaking operators (no explicit CP violation)
- This is also applicable for other inflation models
- In single field model, minimal asymmetry already explains current observation with high reheating temperature
  - favored high temperature range : $10^{15}\mathrm{GeV} \lesssim \widetilde{T} \lesssim 10^{18}\mathrm{GeV}$

Conclusion

Part 1. Practical aspect

- Precision era of cosmology. A precise theoretical understanding of the observational results including effects of reheating is desired.

Part 2. Conceptual aspect

- There exists potentially rich phenomenology of reheating. A possible connection to BSM physics was discussed.

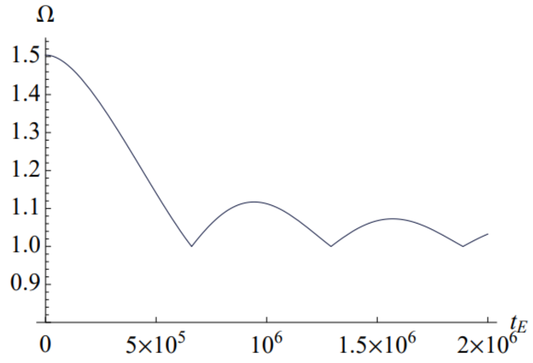
- Future observational prospects are promising. Stay tuned!

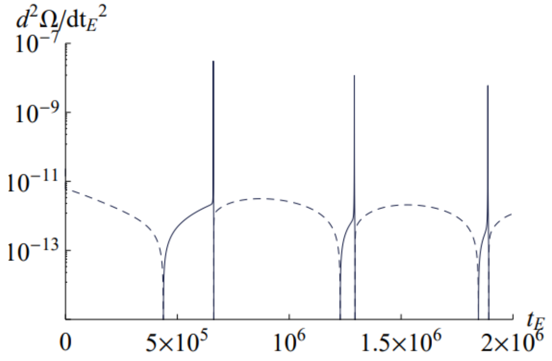
Thank you!

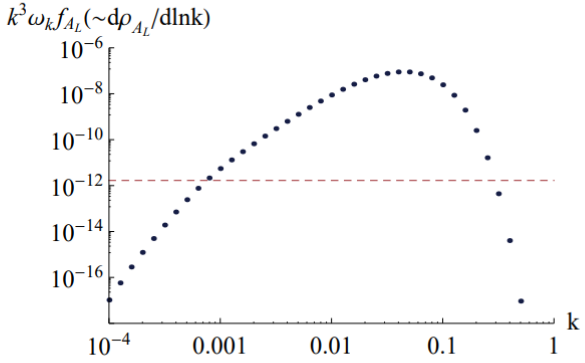
Back Up : Unitarity Problem

- Longitudinal gauge boson decays are non-trivial [Yohei Ema *et al.* 1609.05209]
  - Inflaton lose its energy during the zero crossing

$$m_{A_L}^2 = m_A^2 - \frac{k^2}{k^2+m_A^2}\left(\frac{m_A''}{m_A} - \frac{3m_A'^2}{k^2+m_A^2}\right)$$







- Issues
  - Unitarity Problem $k \sim \sqrt{\lambda} M_P \gg \frac{M_P}{\xi}$
  - Higher operator dependence :
    - Reheating cannot be determined by low E theory

[Yuta Hamada *et al.* 2007.04701]