Gravity mediated pre-heating

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Conventional Pre-heating

- Explosive particle production through parametric resonance in the oscillating inflaton background.

  Followed by perturbative re-heating, thermalization

- Non-equilibrium, non-perturbative in nature

  Kofman, Linde and Starobinsky, 1997

- Introduce arbitray couplings between matter and inflaton

$$L = \frac{1}{2}\phi_{,i}\phi^{,i} - V(\phi) + \frac{1}{2}\chi_{,i}\chi^{,i} - \frac{1}{2}m_\chi^2(0)\chi^2 + \frac{1}{2}\xi R\chi^2$$
$$+ \bar{\psi}\big(i\gamma^i\partial_i - m_\psi(0)\big)\psi - \frac{1}{2}g^2\phi^2\chi^2 - h\bar{\psi}\psi\phi \ .$$

Lesson: Oscillating inflaton field dependent mass term

Gravity mediated pre-heating

Claim: Minimal gravitational coupling is sufficient to pre-heat our universe?

$$\xi = g = h = 0$$

- Gravitational coupling is too weak!!
- Mechanism: Increase the magnitude of the graviton fluctuation after inflation

How to do that?

Plan

- Introduction
- Mechanism:

  Step-I: Resonant amplification of gravitional wave

  Step-II: Resonance in resonant background
- Particular models
- Conclusions and future directions

Inflationary paradigm

- Hot Big-Bang : Homogeneity, Flatness, Monopole, how structure forms...??
- Inflation: Superluminal Expansion

  A. H. Guth, Phys.Rev. D 23, 347 (1981).
  A. D. Linde, Phys. Lett. B 108, 389 (1982).
- Origin of structure, scale invariant power spectrum.
- Universe is super-cooled
- Pre-heating -> reheating+thermalization
- Radiation domination

Some issues

- What is Inflaton?
- Flatness condition of the potential
- Initial condition problem
- In addition, we add extra couplings to get back usual hot big-bang,

$$L = \frac{1}{2}\phi_{,i}\phi^{,i} - V(\phi) + \frac{1}{2}\chi_{,i}\chi^{,i} - \frac{1}{2}m_\chi^2(0)\chi^2 + \frac{1}{2}\xi R\chi^2$$
$$+ \bar{\psi}(i\gamma^i\partial_i - m_\psi(0))\psi - \frac{1}{2}g^2\phi^2\chi^2 - h\bar{\psi}\psi\phi \ .$$

- Can we make pre-heating technically more natural? $\xi=g=h=0$

Detailed mechanism

- Modified Lagrangian (minimal, less parameter)

$$\mathcal{L} = M_p^2 R + \mathcal{L}_\phi + \mathcal{L}_{lv} + \mathcal{L}_{mat},$$

- Consider universal minimal coupling with gravity

$$\mathcal{L}_{mat} = \frac{1}{2}\partial_\mu\theta\partial^\mu\theta - m_\theta^2\theta^2.$$

- Gravity is too weak to transfer energy!!

Lesson from usual pre-heating

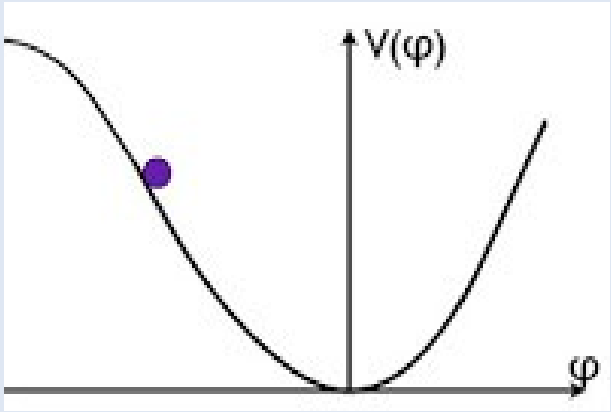
- Introduce (effective) “mass” for gravitational fluctuation: L_lv

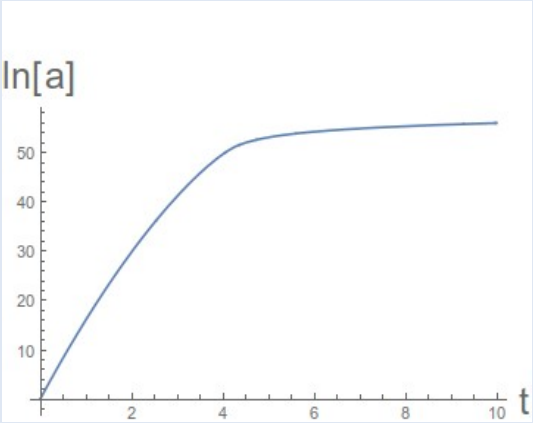
Background dynamics

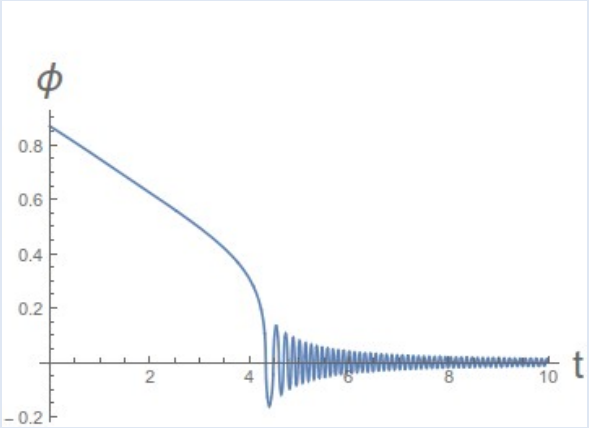
- We have inflation guided by inflaton

$$ds^2 = -dt^2 + a(t)^2(dx^2 + dy^2 + dz^2)$$

- After the end of inflation: Coherent oscillation of inflaton

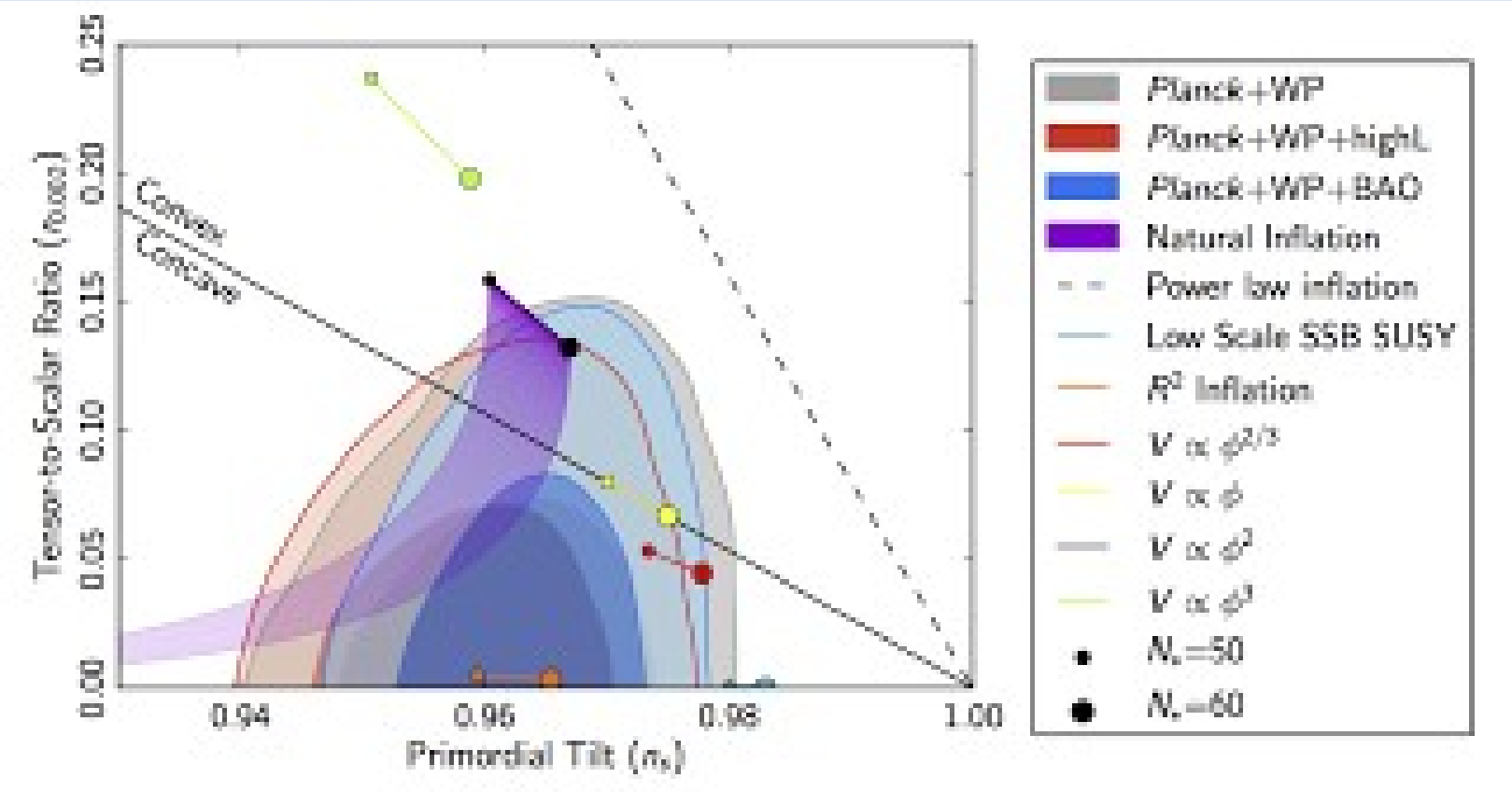






Observational constraints

- Scalar spectral index: $n_s = 0.9603 \pm 0.0073$
- Tensor to scalar ratio: r < 0.11



2-step mechanism: Step-I

Resonant amlification of gravitational Waves

- Metric

$$ds^2 = -dt^2 + a(t)^2(\delta_{ij} + h_{ij})dx^i dx^j$$

- Dynamical eqn for gravitational wave

$$\ddot{h}_k + 3H\dot{h}_k + \left(\frac{k^2}{a^2} + m(\phi)^2\right) h_k = 0,$$

- Effective mass term: must be inflaton field dependent

**In conventional pre-heating: matter field's effective mass is inflaton dependent.

Step-II

Resonance in resonant background

- Matter field equation:

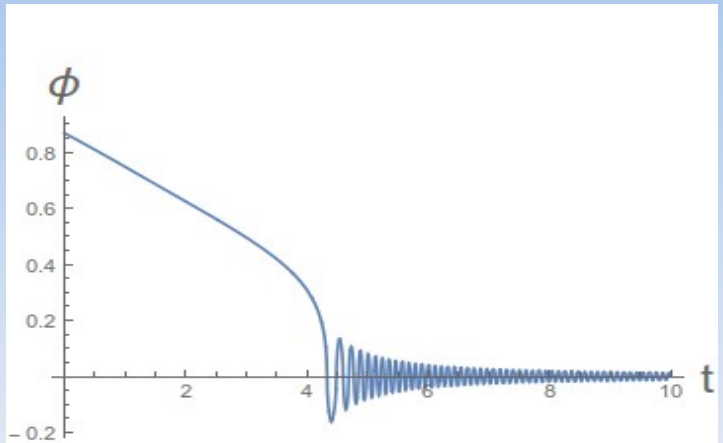
$$\ddot{\theta}_k + 3H\dot{\theta}_k + \left(\frac{k^2}{a^2} + m_\theta^2\right)\theta_k = - \sqrt{\frac{8}{\pi}}\frac{1}{a^2}\int \mathrm{Re}\left[k'^2\, h_k(\mathbf{k}-\mathbf{k}')\right]\, \theta(\mathbf{k}')\, d^3\mathbf{k}'. \quad (9)$$

Expected: Gravitational wave background appears at second 2nd order.

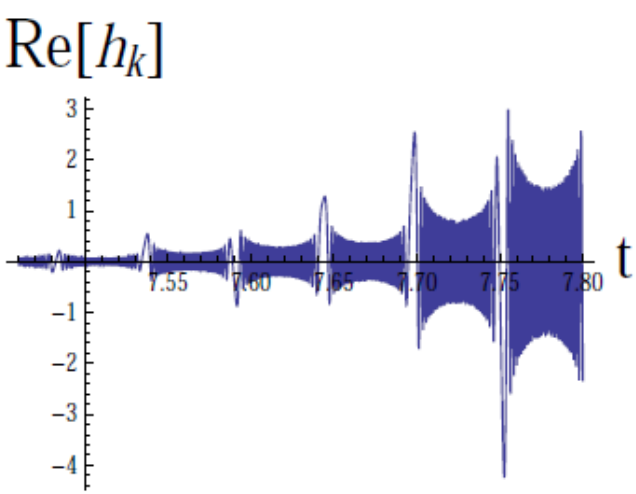
- Inflaton energy-> Gravitational energy -> Matter energy

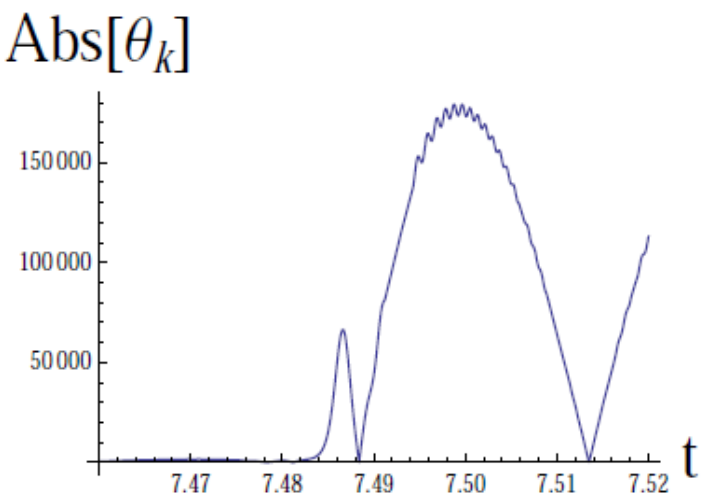
"Minimal coupling + single mass parameter"

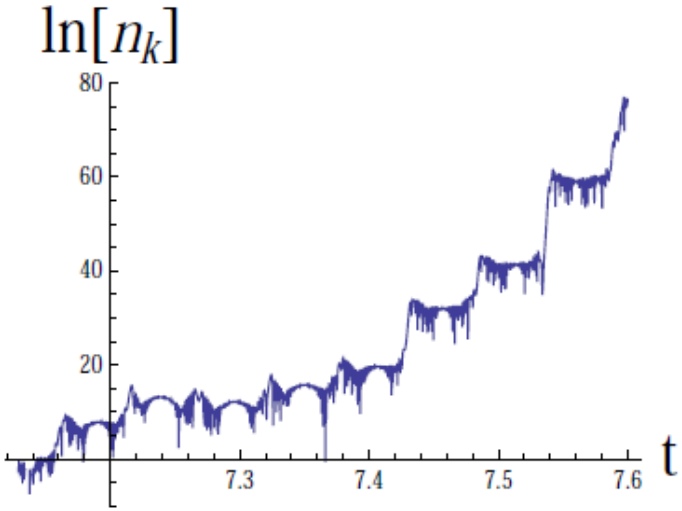
Step-I + Step-II



$$m(\phi)^2 = \lambda\phi^2,$$







- Time is measured in unit of (1/m)

Particle production

- Particel number density in a particular mode,

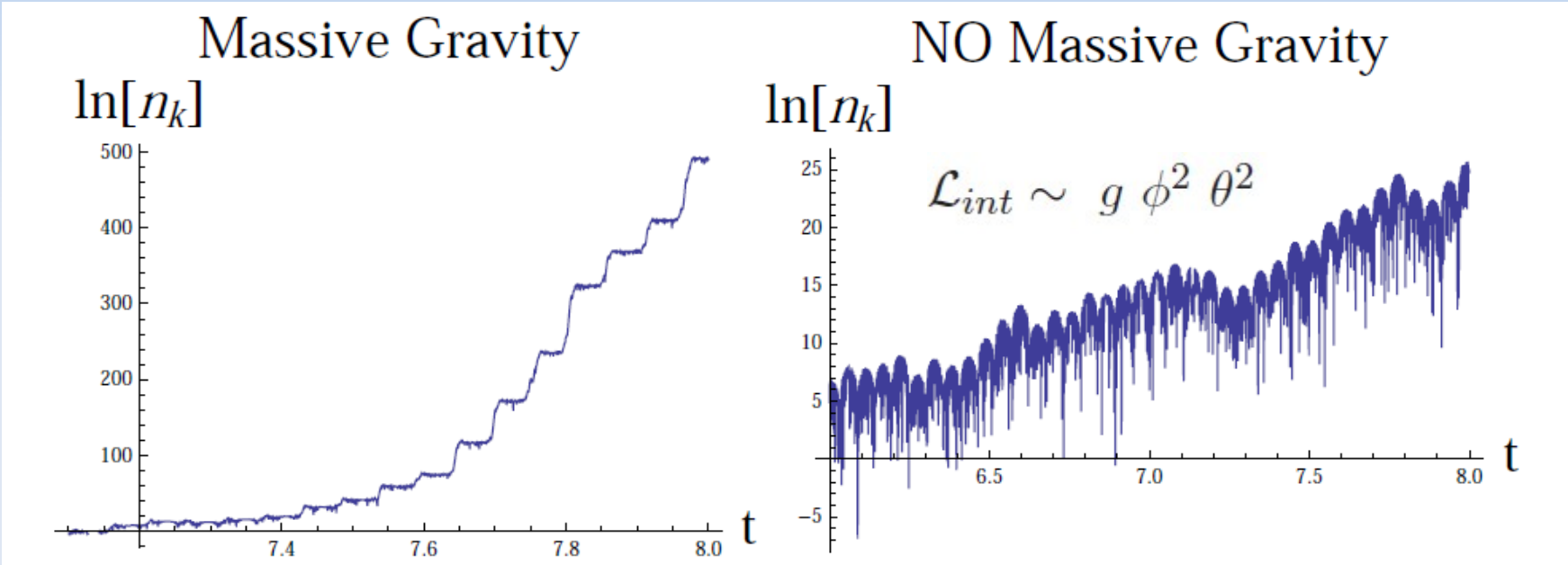
$$n_k = \frac{\omega_k}{2}\left(\frac{|\dot{\theta}_k|^2}{\omega_k^2} + |\theta_k|^2\right) - \frac{1}{2}.$$

- Physical frequency,

$$\omega_k = \sqrt{\frac{k^2}{a^2} + m_\theta^2} = \sqrt{k_{phy}^2 + m_\theta^2},$$

Particle production

- Number density



- Explosive particle production: n_k~Exp[475]
- Thermalization will happen as long as

$$H < \Gamma$$

Model-I: Higher derivative gravity

- We consider inflaton coupled with Gauss-Bonnet term

$$S = \frac{M_{\rm Pl}^2}{2}\int d^4x\sqrt{-g}R - \int d^4x\sqrt{-g}\left[\frac{1}{2}\nabla^\mu\phi\nabla_\mu\phi + V(\phi)\right] - \frac{1}{16}\int d^4x\sqrt{-g}\xi(\phi)R_{\rm GB}^2 + \frac{1}{16}\int d^4x\sqrt{-g}\omega(\phi)R\tilde{R}\,,$$

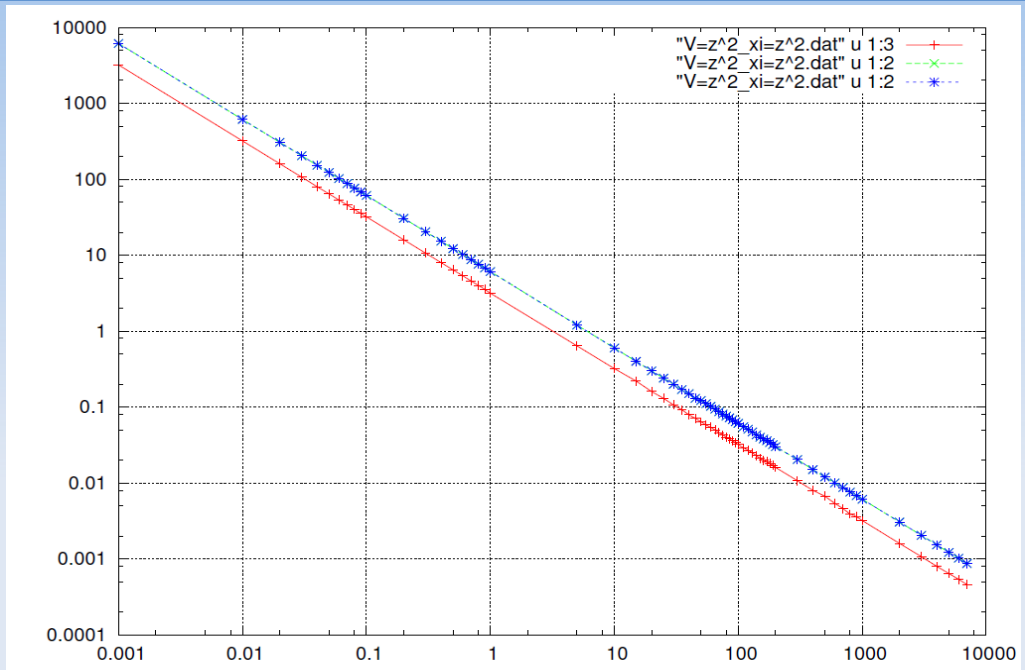
$$R_{\rm GB}^2 \equiv R^{\alpha\beta\gamma\delta}R_{\alpha\beta\gamma\delta} - 4R^{\alpha\beta}R_{\alpha\beta} + R^2$$

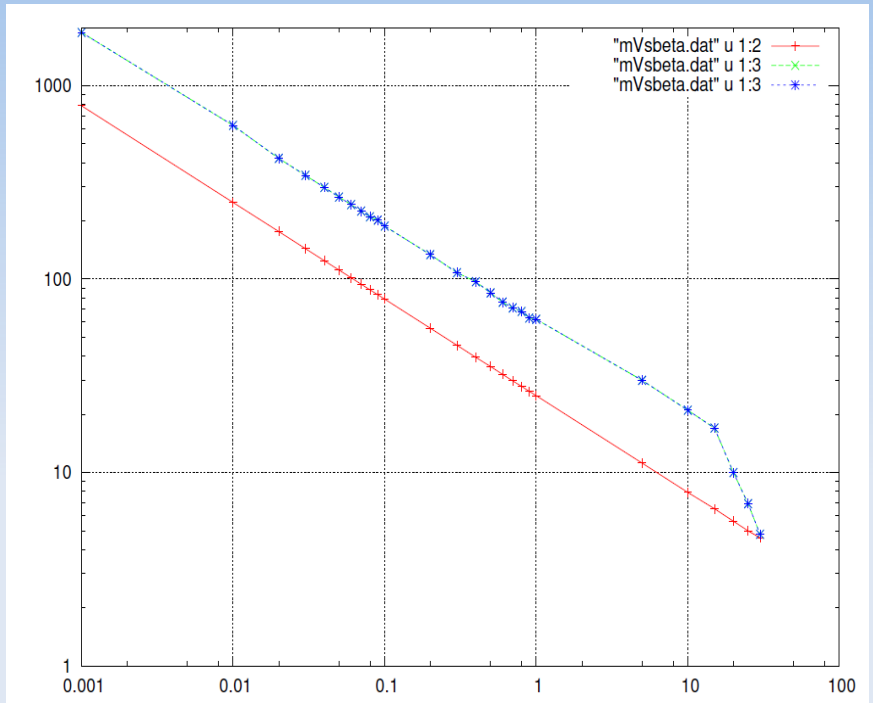
$$3M_{\rm Pl}^2H^2 = \frac{1}{2}\dot{\phi}^2 + V + \frac{3}{2}H^3\dot{\xi}$$

$$\ddot{\phi} + 3H\dot{\phi} + \frac{3}{2}H^2(\dot{H} + H^2)\xi_{,\phi} + V_{,\phi} = 0\,,$$

$$\epsilon \equiv \frac{M_{\rm Pl}^2}{2}\frac{V_{,\phi}^2}{V^2}\,,\quad \eta \equiv M_{\rm Pl}^2\frac{V_{,\phi\phi}}{V}\,,\quad \alpha \equiv \frac{V_{,\phi}\xi_{,\phi}}{4M_{\rm Pl}^2}\,,\quad \beta \equiv \frac{V\xi_{,\phi\phi}}{6M_{\rm Pl}^2}\,,\quad \gamma \equiv \frac{V^2\xi_{,\phi}^2}{18M_{\rm Pl}^6} = \frac{4}{9}\frac{\alpha^2}{\epsilon}$$

Model-I: Constraints on (m,λ)





- (m,λ)-Plane; m ~10^(-3) M; E-folding N=75
- Scalar spectral index: $n_s = 0.9603 \pm 0.0073.$
- Tensor to scalar ratio: r < 0.11

Model-I continue

- Gravitatioal wave equation:

$$\ddot{h} + (3H + \frac{\dot{\alpha}}{\alpha})\dot{h} + \frac{k^2}{a^2\alpha}(1 - \frac{\lambda}{2}\ddot{\xi})h = 0$$

$$\alpha := 1 - \frac{\lambda}{2}H\dot{\xi} = \frac{\dot{\varphi}^2}{6H^2}$$

- Resonant amplification of “h” happens for large λ>1

  Gravity mediated pre-heating happens

  for large λ>1

- Currently we are checking unitarity issue
- Constraint from Re-heating temperature

Model-II: Massive gravity

- Massive gravity: Possible alternative of Dark energy
- Construction of massive gravity is/was difficult!

  Assuming, we have a theory

- Consistent backgroud dynamics
- Growth of various perturbations
- Some new ovservational signatures(Very important)
- New phenomena which was not present in the existing theory

Model-II: Massive Gravity

- Model Lagrangian Lin & Sasaki, 1504.0134

$$\mathcal{L} = M_p^2 R + \mathcal{L}(X, Y^{ij}, \Box\phi, \cdots)$$

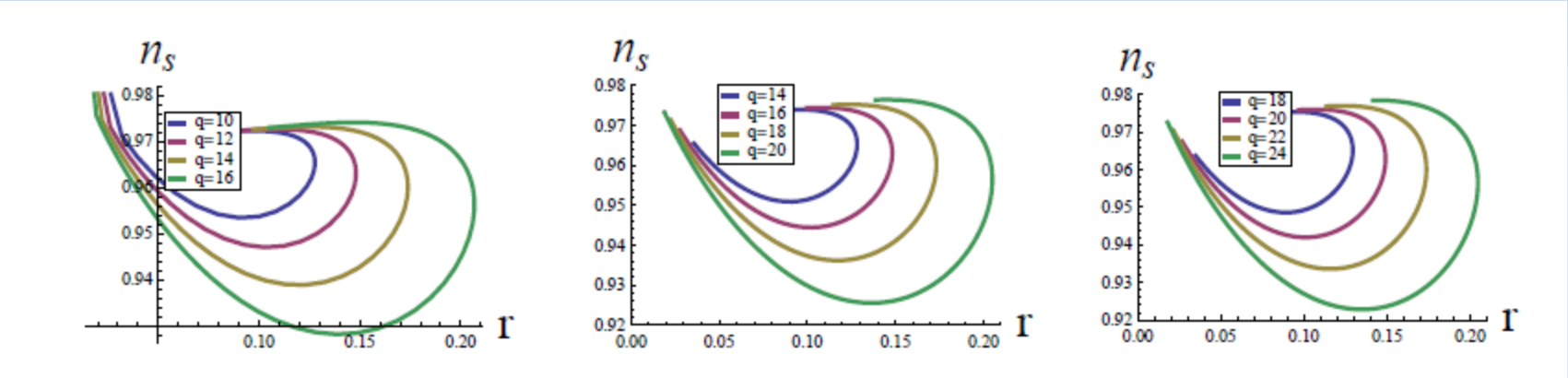
$$X = g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi \quad ; \quad Y^{ij} = g^{ij} - \frac{\partial_i\phi\partial_i\phi}{X}$$

$$\mathcal{L}_{lv}(X, Y^{ij}, \Box\phi, \cdots) = \frac{1}{2}X - \frac{1}{2s^3}M(\phi)X\Box\phi - V(\phi) - \frac{8}{9}M_p^2 m(\phi)^2\frac{\bar{Y}^{ij}\bar{Y}_{ij}}{Y^2}$$

$$V(\phi) = \Lambda^4\left(1 - \cos\left(\frac{\phi}{f}\right)\right) \quad ; \quad \bar{Y}^{ij} = Y^{ij} - 3\frac{Y^{ik}Y^i_k}{Y^2} \quad ; \quad Y = \delta_{ij}Y^{ij}$$

Model-II: Massive Gravity

- For different choices of kinetc function



- E-folding N=50

$$\ddot{h}_k + 3H\dot{h}_k + \left(\frac{k^2}{a^2} + m(\phi)^2\right) h_k = 0,$$

$$m(\phi)^2 = \lambda\phi^2,$$

Conclusion

- We have introduced 2-step mechanism of gravity mediated pre-heating.

  1. Resonant amplification of gravitational wave

  2. Resonance in resonant background

- Mininmal gravitational coupling is sufficient
- Mechanism to work: Inflation field dependent effective mass of the gravitational fluctuation
- Two models: Gauss-Bonnet Gravity, Massive gravity

Future Directions

- Lot more needs to be done
  1. Back-reaction (Full analysis)
  2. Baryogenesis
  3. Primordial magnetic field
- Consistentency in massive gravity theory
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