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Preheating in Gauged M-flation around the Supersymmetric Vacuum and its Gravitational Wave Signatures

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Based on a work in progress and

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A.A., H. Firouzjahi, M.M. Sheikh-Jabbari JCAP 1005 (2010) 002, arXiv:0911.4284 [hep-th]
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A.A., U.Danielsson, M. M. Sheikh-Jabbari, Phys.Lett. B713 (2012) 353, arXiv:1112.2272 [hep-th]

Introduction

- Planck data strongly supports the idea of inflation as the theory of early universe and structure formation.
- The data reduces the lower bound on tensor/scalar ratio, r, to 0.11 $(\%95\ CL)$ which puts some favourite models like $m^2\phi^2$ in trouble, considering Bunch-Davies vacuum. c.f. Ashoorioon, Dimopoulos, Sheikh-Jabbari & Shiu (2013)
- Still any detection of the gravity waves above $r \geq 0.01$ poses theoretical model-building challenges for inflationary scenarios:

  - To embed such a model in supergravity, one has to insure the flatness of the theory on scales beyond the limit of validity of the theory. Lyth (1997)

$$\frac{\Delta\phi}{M_{pl}} > 1.06\left(\frac{r}{0.01}\right)^{1/2}$$

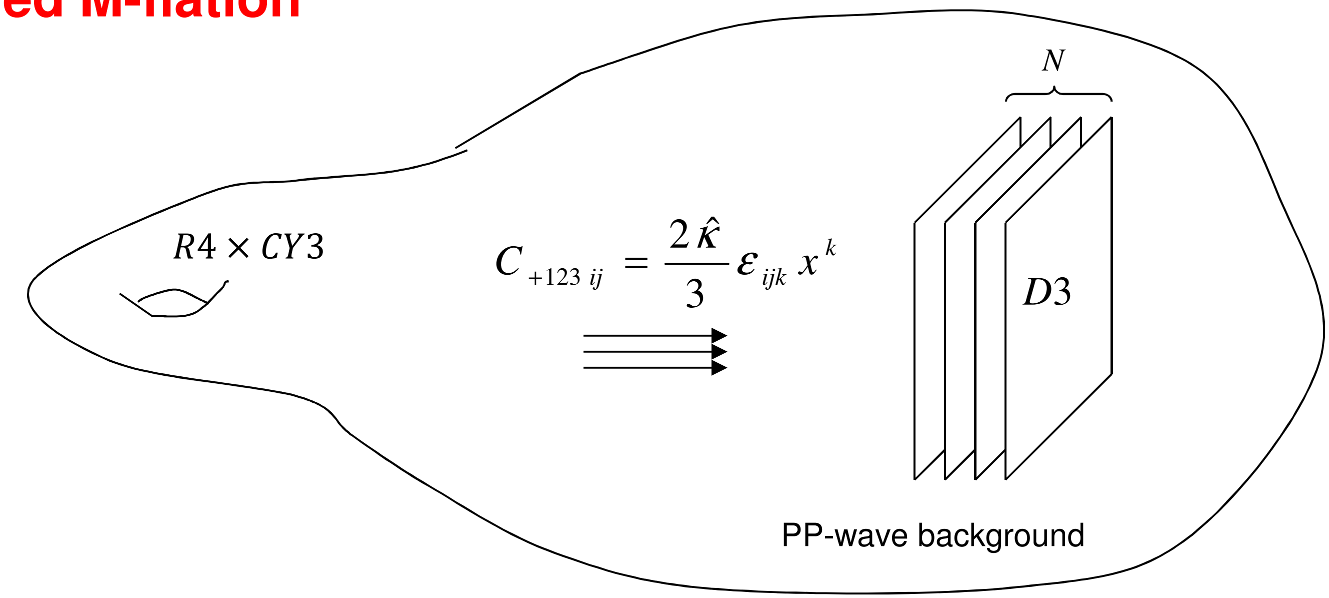
c.f. Choudhury & Mazumdar (2013)

  - In supergravity and stringy models of inflation, one usually finds the size of the region in which inflation can happen to be much smaller than M_{pl}

McAllister & Baumann (2007)

- In this talk I will focus on a string theory motivated model of inflation that may solve this problem using Matrices as inflatons.
- The model has an embedded preheating mechanism in some regions which leads to the production of high frequency gravitational waves.

• Gauged M-flation



10-d IIB supergravity background

$$ds^2 = 2dx^+dx^- - \hat{m}^2\sum_{i=1}^{3}(x^i)^2(dx^+)^2 + \sum_{K=1}^{8} dx_K dx_K$$

$i, j = 1,2,3$ parameterize 3 out 6 dim $\perp$ to the D3-branes and x^K denotes 3 spatial dim along and five transverse to the D3-branes.

$$S = \frac{1}{(2\pi)^3 l_s^4 g_s}\int d^4x\, \mathrm{STr}\left(1-\sqrt{-|g_{ab}|}\sqrt{|Q^I_J|} + \frac{ig_s}{4\pi l_s^2}\left[X^I, X^J\right]C^{(6)}_{IJ0123} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}\right)$$

Myers (1999)

$g_{ab} = G_{MN}\partial_a X^M \partial_b X^N$ $\quad M,N = 0,1,\ldots,9$ $\quad I, J = 4,5,\ldots,9$

$a,b = 0,1,2,3$

$$Q^{IJ} = \delta^{IJ} + \frac{i}{2\pi\, l_s^2}\left[X^I, X^J\right]$$

Matrix Inflation from String Theory

With $\hat{m}^2 = \frac{4g_s^2\hat{\kappa}^2}{9}$ the above background with constant dilaton is solution to the SUGRA

$$V = -\frac{1}{4\left(2\pi\, l_s^2\right)^2}\left[X_i, X_j\right]\left[X_i, X_j\right] + \frac{ig_s\hat{\kappa}}{3.2\pi\, l_s^2}\varepsilon^{ijk} X_i\left[X_j, X_k\right] + \frac{1}{2}\hat{m}^2 X_i^2$$

Upon the field redefinition $\Phi_i \equiv \frac{X_i}{\sqrt{(2\pi)^3 g_s l_s^2}}$

$$V = \mathrm{Tr}\left(-\frac{\lambda}{4}[\Phi_i, \Phi_j][\Phi_i, \Phi_j] + \frac{i\kappa}{3}\varepsilon_{jkl}[\Phi_k, \Phi_l]\Phi_j + \frac{m^2}{2}\Phi_i^2\right)$$

$$\boldsymbol{\lambda} = 8\boldsymbol{\pi g}_s \qquad \boldsymbol{\kappa} = \hat{\boldsymbol{\kappa}}\, \boldsymbol{g}_s.\sqrt{8\boldsymbol{\pi}\, \boldsymbol{g}_s} \qquad \hat{m}^2 = m^2$$

From the brane-theory perspective, it is necessary to choose $\hat{m}$ and $\hat{\kappa}$ such that

$$\hat{m}^2 = \frac{4g_s^2\hat{\kappa}^2}{9}$$

In the stringy picture, we have *N* D3-branes that are blown up into a single giant D5-brane under the influence of *RR* 6-form. The inflaton corresponds to the radius of this two sphere.

Truncation to the SU(2) Sector:

Φ_i are *N X N* matrices and therefore we have $3N^2$ scalars. It makes the analysis very difficult 

Liam's talk

However from the specific form of the potential and since we have three Φ_i, it is possible to show that one can consistently restrict the classical dynamics to a sector with single scalar field:

$$\Phi_i = \hat{\phi}(t) J_i, \qquad i = 1,2,3$$

J_i are *N* dim. irreducible representation of the SU(2) algebra:

$$[J_i, J_j] = i\varepsilon_{ijk} J_k \qquad \mathrm{Tr}\left(J_i J_j\right) = \frac{N}{12}\left(N^2 - 1\right)\delta_{ij}$$

Plugging these to the action, we have:

$$S = \int d^4x \sqrt{-g}\left[\frac{M_P}{2} R + \mathrm{Tr} J^2 \left(-\frac{1}{2}\partial_\mu \hat{\phi}\,\partial^\mu \hat{\phi} - \frac{\lambda}{2}\hat{\phi}^4 + \frac{2\kappa}{3}\hat{\phi}^3 - \frac{m^2}{2}\hat{\phi}^2\right)\right] \qquad \mathrm{Tr}\left(J^2\right) \equiv \sum_{i=1}^{3} \mathrm{Tr}\left(J_i^2\right)$$

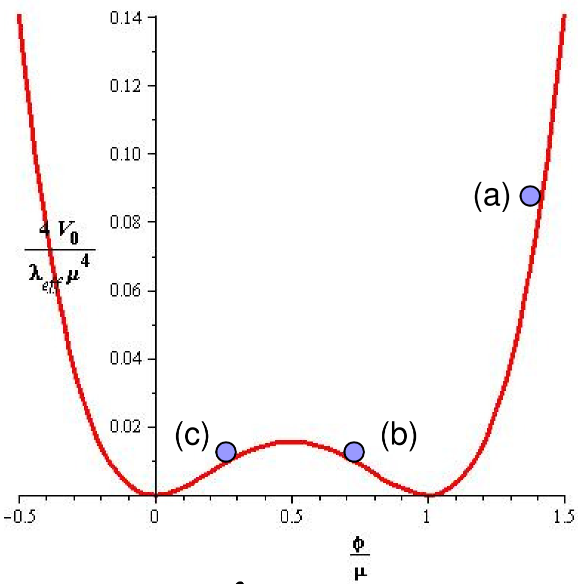
Defining $\phi \equiv \left(\mathrm{Tr}\, J^2\right)^{1/2} \hat{\phi}$ to make the kinetic term canonical, the potential takes the form

$$V_0(\phi) = \frac{\lambda_{eff}}{4}\phi^4 - \frac{2\kappa_{eff}}{3}\phi^3 + \frac{m^2}{2}\phi^2 \qquad \lambda_{eff} \equiv \frac{2\lambda}{\mathrm{Tr}\boldsymbol{J}^2} = \frac{8\lambda}{N(N^2-1)}, \qquad \kappa_{eff} \equiv \frac{\kappa}{\sqrt{\mathrm{Tr}\boldsymbol{J}^2}} = \frac{2\kappa}{\sqrt{N(N^2-1)}},$$

Analysis of the Gauged M-flation around the Single-Block Vacuum

$$V(\phi) = \frac{\lambda_{\text{eff}}}{4}\phi^2(\phi - \mu)^2 \qquad \mu \equiv \frac{\sqrt{2}m}{\sqrt{\lambda_{\text{eff}}}}$$

Hill-top or Symmetry-Breaki[ng]
inflation, Linde (1992)
Lyth & Boubekeur (2005)



In the stringy picture, we have *N* D3-branes that are blown up into a giant D5-brane under the influence of *RR* 6-form.

(a) $\phi_i > \mu$

$\phi_i \approx 43.57\, M_P$ $\qquad \phi_f \approx 27.07\, M_P$ $\qquad \mu \approx 26\, M_P$

$\lambda_{eff} \approx 4.91\times10^{-14}$ $\qquad m \approx 4.07\times10^{-6}\, M_P$

(b) $\mu/2 < \phi_i < \mu$

$\phi_i \approx 23.5\, M_P$ $\qquad \phi_f \approx 35.03\, M_P$ $\qquad \mu \approx 36 M_P$

$\lambda_{eff} \approx 7.18\times10^{-14}$ $\qquad m \approx 6.82\times10^{-6}\, M_P$

(c) $0 < \phi_i < \mu/2$

$\phi_i \approx 12.5\, M_P$ $\qquad \phi_f \approx .97\, M_P$ $\qquad \mu \approx 36 M_P$

$\lambda_{eff} \approx 7.18\times10^{-14}$ $\qquad m \approx 6.82\times10^{-6}\, M_P$

$\lambda \approx 1$

↓

$N \approx 5\times10^4$

↓

$\Delta\phi \le 10^{-6} M_p$

Mass Spectrum of χ Spectators

(a) $(N-1)^2 - 1$ α-modes $\quad l \in Z \quad 0 \le l \le N-2$

Degeneracy of each l-mode is $2l+1$

$$M^2_{\alpha,l} = \frac{1}{2}\lambda_{\text{eff}}(l+2)(l+3)\phi^2 - 2\kappa_{\text{eff}}(l+2) + m^2$$

(b) $(N+1)^2 - 1$ β-modes $\quad l \in Z \quad 1 \le l \le N$

Degeneracy of each l-mode is $2l+1$

$$M^2_{\beta,l} = \frac{1}{2}\lambda_{\text{eff}}(l-2)(l-1)\phi^2 + 2\kappa_{\text{eff}}(l-1) + m^2$$

(c) $3N^2 - 1$ vector modes

Degeneracy of each l-mode is $2l+1$

$$M^2_{A,l} = \frac{\lambda_{eff}}{4}\phi^2 l(l+1)$$

$$\left[(N-1)^2 - 1\right] + \left[(N+1)^2 - 1\right] + \left[3N^2 - 1\right] = 5N^2 - 1$$

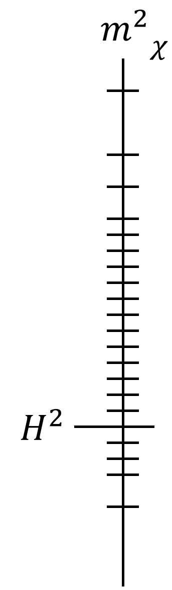
$\alpha-$modes $\quad \beta-$modes $\quad$ vector-field modes

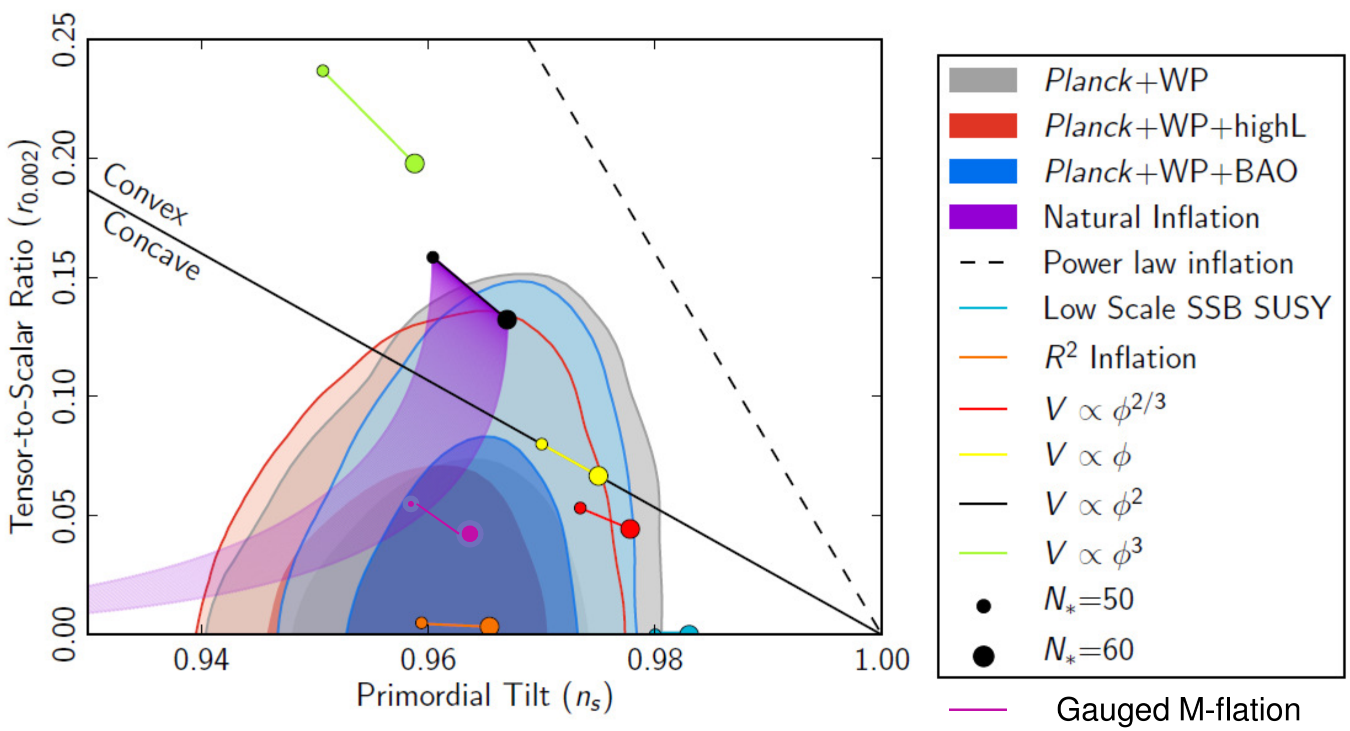
C) Power Spectra in Symmetry-Breaking Inflation $0<\phi<\mu/2$

$$\lambda_{eff} \approx 7.187\times10^{-14} \;\&\; \mu \approx 36\, M_P \Longrightarrow n_{\Re} \approx 0.961 \;\&\; P_{\Re} \approx 2\times10^{-9}$$

$l=1$ α	$6\lambda_{eff}\phi^2 - 6\kappa_{eff}\phi + m^2$	1.23×10^{-11}	0.953	3

$$\frac{P_{S_{\alpha,1}}}{P_R} = 5.12\times10^{-3}$$





Liam McAllister talk

$r \approx 0.048$

$n_T \simeq -0.006$

CMBPOL or QUIET should be able to verify this scenario.

Particle Creation and Preheating Scenario around S~~US~~Y Vacuum

The backreaction of the spectator modes on the inflaton dynamics can become large when $\varepsilon, \eta \approx 1$

- This could be the bonus of our model, as spectator modes help to drain the energy of the inflaton, since their masses change very fast.
- One can show that if inflation ends in the susy-breaking vacuum, this process is not effective to produce spectator particles through parametric resonance:

$$M^2_{\alpha,\beta}\Big|_{\phi=\mu} = \frac{\lambda_{eff}\mu^2}{2}(\omega+1)^2 \qquad \omega_\alpha = -(l+2) \quad \omega_\beta = (l-1) \qquad M^2_A\Big|_{\phi=\mu} = \frac{\lambda_{eff}\mu^2}{4} l(l+1)$$

rest masses are large around susy-breaking vacuum.

- For α and β modes: $\ddot{\chi} + 3H\dot{\chi} + \Omega_k^2 \chi = 0$
- For the gauge mode $\ddot{A} + H\dot{A} + \Omega_k^2 A = 0$

for example for α and β modes:

$$\Omega_k^2 = \frac{k^2}{a^2} + M_\chi^2 + g_3\varphi + g_4^2\varphi^2 \qquad \varphi \equiv \phi - \mu \qquad g_4^2 = \frac{\lambda_{eff}(\omega^2-\omega)}{2} \qquad g_3 = \frac{\lambda_{eff}\mu}{2}(2\omega^2+\omega)$$

$$\forall\omega, \qquad \frac{\dot{\Omega}_k}{\Omega_k^2}\Big|_{\phi\approx\mu} << 1 \Longrightarrow$$

No parametric resonance around the susy-breaking vacuum

Particle Creation and Preheating Scenario around SUSY Vacuum

- The situation is quite different around the SUSY vacuum

$$M^2_{\alpha,\beta}\Big|_{\phi=0} = \frac{\lambda_{eff}\mu^2}{2}$$

$$M^2_{A}\Big|_{\phi=0} = 0$$

- For large values of ω for α and β modes and for all values of l for the gauge modes

$$\left.\frac{\dot{\Omega}_k}{\Omega_k^2}\right|_{\phi\approx 0} >> 1 \Longrightarrow$$ parametric resonance happens.

- $X_\ell = a^{3/2}\chi_\ell$ & $\mathcal{A}_\ell = a^{1/2}A_\ell$ & $t' \equiv \mu\sqrt{\frac{\lambda_{eff}}{2}}\,t$ & $' \equiv \frac{d}{dt'}$ & $\ell^2 \equiv \frac{2k^2}{\lambda_{eff}\mu^2}$

$$X''_\ell + \Omega^2_\omega X_\ell + \frac{2qX^3_\ell}{a^3\mu^2} = 0$$

$$\mathcal{A}''_\ell + \Omega^2_l \mathcal{A}_\ell = 0$$

$$\Omega^2_\omega \equiv \frac{\ell^2}{a^2} + \frac{\varphi^2}{\mu^2}(\omega^2 - \omega) + \frac{3\varphi\omega}{\mu} + 1 - \frac{3}{4}\frac{a'^2}{a^2} - \frac{3}{2}\frac{a''}{a}$$

$$\Omega^2_l \equiv \frac{\ell^2}{a^2} + \frac{\varphi^2}{2\mu^2}(l^2 + l) + \frac{1}{4}\frac{a'^2}{a^2} - \frac{a''}{2a}$$

$$\lim_{t'\to 0} X_\ell = \frac{\exp(-i\Omega_\omega t')}{\sqrt{2\Omega_\omega}}$$

$$\lim_{t'\to 0} \mathcal{A}_\ell = \frac{\exp(-i\Omega_l t')}{\sqrt{2\Omega_l}}$$

$$n^\omega_\ell = \frac{\Omega_\omega}{2}\left(\frac{\mu^2\lambda}{2}\frac{|X'_\ell|^2}{\Omega^2_\omega} + |X_\ell|^2\right) - \frac{1}{2}$$

$$n^l_\ell = \left(\frac{\Omega_l}{2}\left(\frac{\mu^2\lambda}{2}\frac{|\mathcal{A}'_\ell|^2}{\Omega^2_l} + |\mathcal{A}_\ell|^2\right) - \frac{1}{2}\right)\frac{1}{a^2}$$

GW production from Preheating

- Parametric resonance at the end of inflation could be a source of gravitational waves.

- Parametric resonance leads to exponential particle production for some specific momenta in Fourier space, which leads to large inhomogeneities in the energy density of the universe.

$$\ddot{h}_{ij} - 2\left(\frac{\dot{a}^2}{a^2} + 2\frac{\ddot{a}}{a}\right)h_{ij} + 3\frac{\dot{a}}{a}\dot{h}_{ij} - \frac{1}{a}\nabla^2 h_{ij} = \frac{16\pi G}{a^2}\delta S_{ij}^{TT} \quad \text{where} \quad \delta S_{ij} = \delta T_{ij} - \frac{\delta_{ij}}{3}T_k^k$$

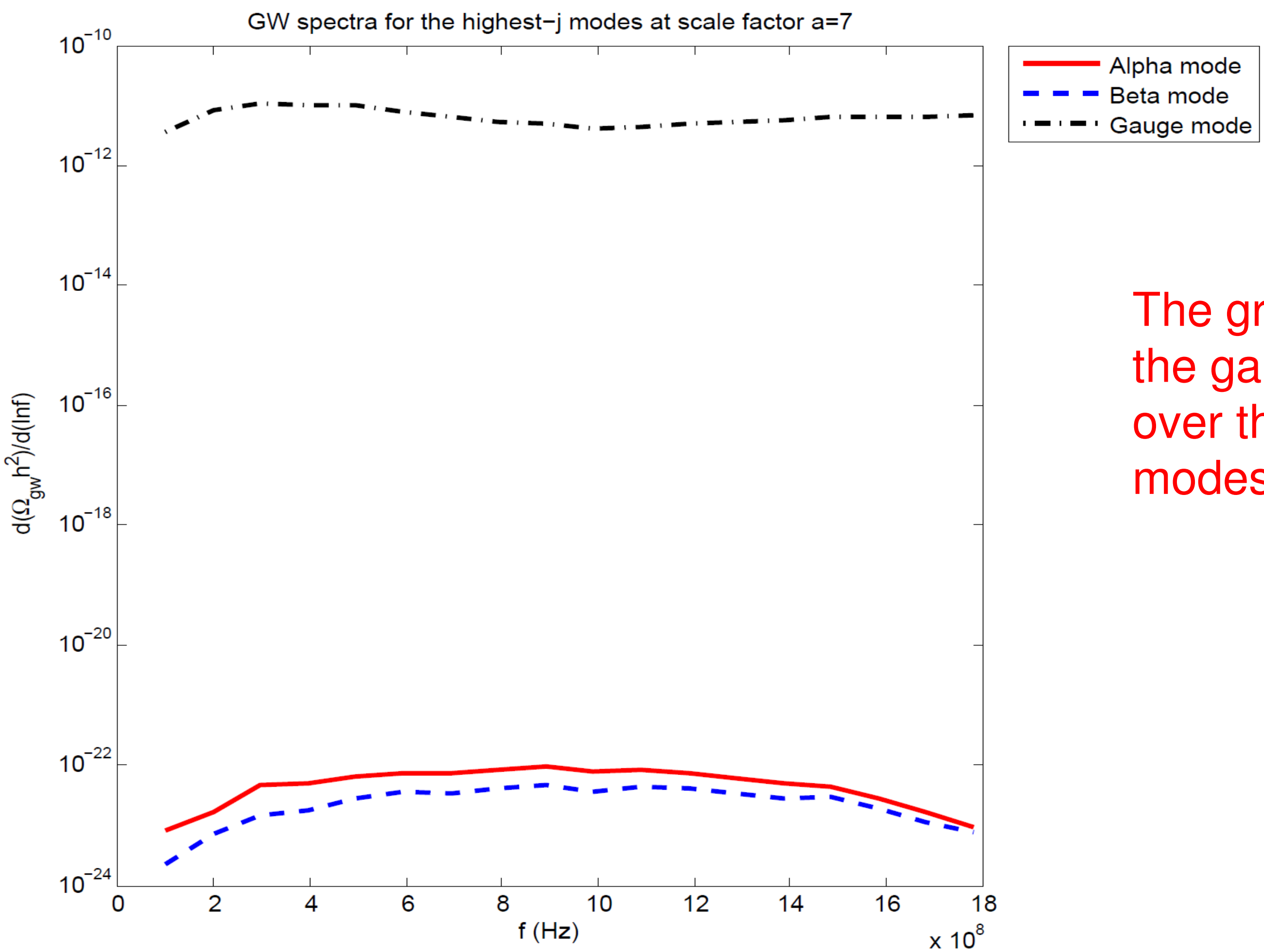
$$\frac{d\Omega_{GW}}{d\ln k} = \frac{1}{\rho_{crit}}\frac{d\rho}{d\ln k} = \frac{\pi k^3}{3H^2L^2}\sum_{i,j}\left|h_{ij,0}(k)\right|^2$$

- This is in addition to the stochastic background of GW produced during inflation which probes the inflationary potential 60 e-folds before the end of inflation.

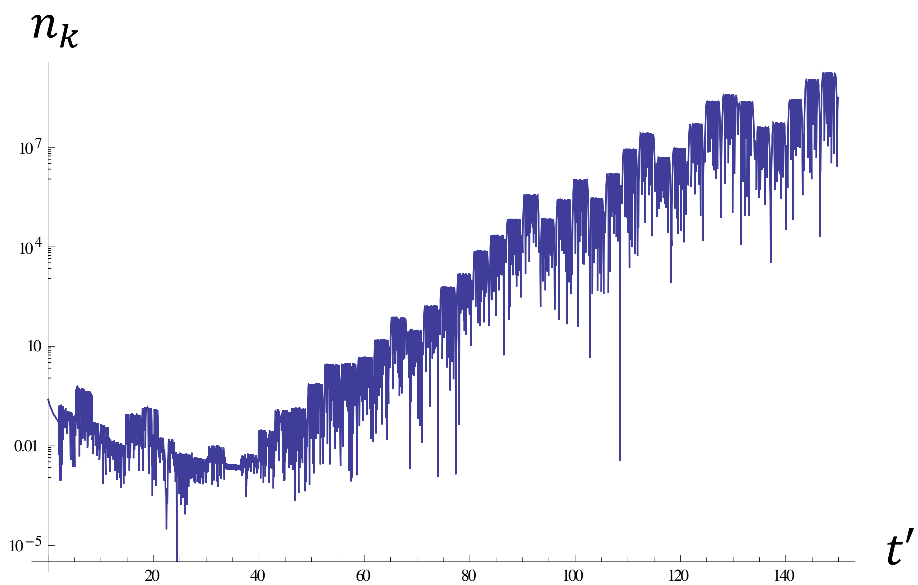
- Since the universe is transparent to gravitational radiation during its history, they can be a useful source of information from early universe.

GW production from Preheating: Single Mode

- We used HLattice (developed by Zhiqi Huang (2007)) to compute the GW spectrum produced by individual highest j modes as the preheat field

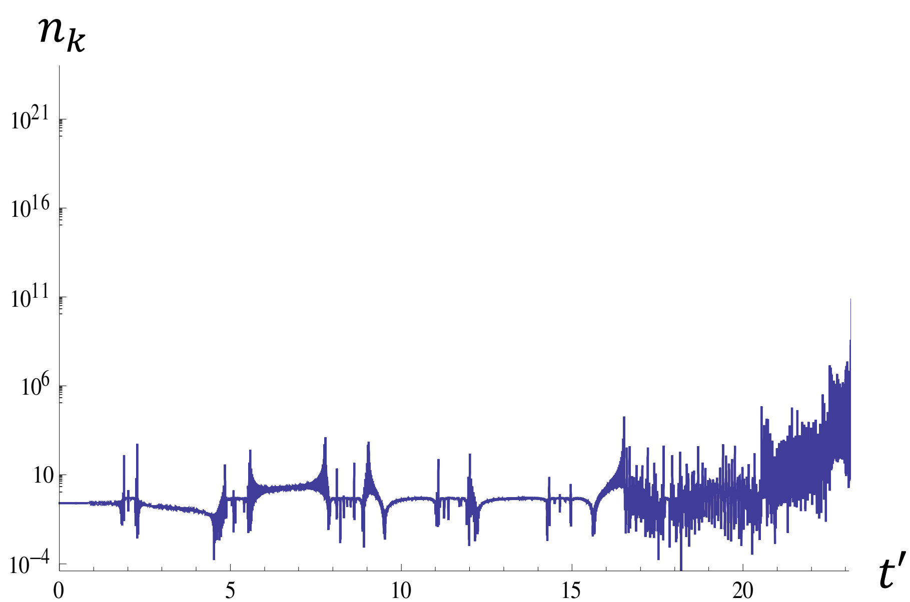


The gravitational wave from the gauge modes dominates over the ones from α and β modes.



Largest j Gauge modes

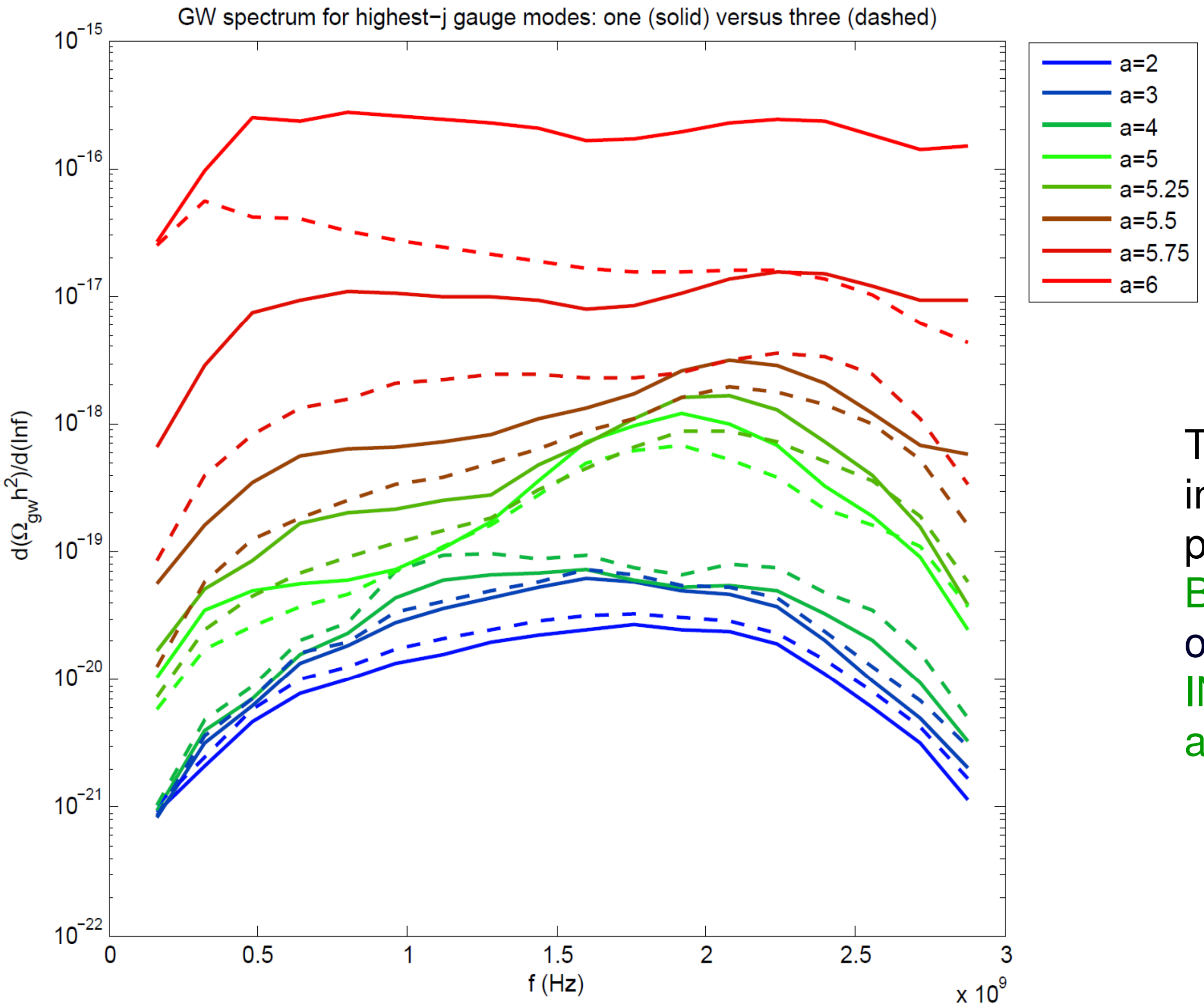
$\ell = 0$



Largest j beta mode

$\ell = 0$

GW production from Preheating: Three largest j Gauge Mode



The signal may be seen in HFGW detectors that probe the GHz band

Birmingham HFGW detector

or

INFN Genoa HFGW resonant antenna

Conclusions

• M-flation can solve the fine-tunings associated with chaotic inflation couplings and produce super-Planckian effective field excursions during inflation.

• M-flation which is qualitatively new third venue within string theory inflationary model-building using the internal matrix degrees of freedom. the first two being open string and closed string models

• Due to Matrix nature of the fields there would be many scalar fields in the model. This leads to the production of isocurvature productions at the CMB scales.

• Due to hierarchical mass structure of the isocurvature modes, one can avoid the "beyond-the-cutoff" problem, even if the cutoff is reduced by the presence of the species.

A.A., M.M. Sheikh-Jabbari, JCAP 1106 (2011) 014, arXiv:1101.0048 [hep-th]

• The loop corrections from the interactions of the graviton with the scalar field create the quadratically divergent, $\frac{\Lambda^2}{M_p^2} R$ conformal mass type term which leads to the problem, if the UV cutoff of the theory is of order Planck mass. In M-flation such an induced term is naturally suppressed.

A.A., U.Danielsson, M. M. Sheikh-Jabbari, Phys.Lett. B713 (2012) 353, arXiv:1112.2272 [hep-th]

• M-flation has a natural built-in mechanism of preheating to end inflation around the SUSY vacuum. The parametric resonance produces large GHz frequency gravitational wave spectrum which could be seen by ultra-high frequency gravitational probes.

Thank you