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# M-flation, Signatures and Advantages

**Amjad Ashoorioon (Lancaster University)**

**Based on**

A.A., H. Firouzjahi, M.M. Sheikh-Jabbari JCAP 0906:018,2009, arXiv:0903.1481 [hep-th],
A.A., H. Firouzjahi, M.M. Sheikh-Jabbari JCAP 1005 (2010) 002, arXiv:0911.4284 [hep-th]
A.A., M.M. Sheikh-Jabbari, JCAP 1106 (2011) 014, arXiv:1101.0048 [hep-th]
A.A., U.Danielsson, M. M. Sheikh-Jabbari, Phys.Lett. B713 (2012) 353, arXiv:1112.2272 [hep-th]
A.A., B. Fung, R. B. Mann, M. Oltean, M. M. Sheikh-Jabbari, arXiv:1312.2284 [hep-th], to appear in JCAP

# Introduction

- Planck data strongly supports the idea of inflation
- $r \leq 0.11$ $(\%95\ CL)$ 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 $r \geq 0.01$ poses theoretical model-building challenges:
  - To embed such a model in supergravity, one has to insure the flatness of the theory on scales

    Lyth (1997)

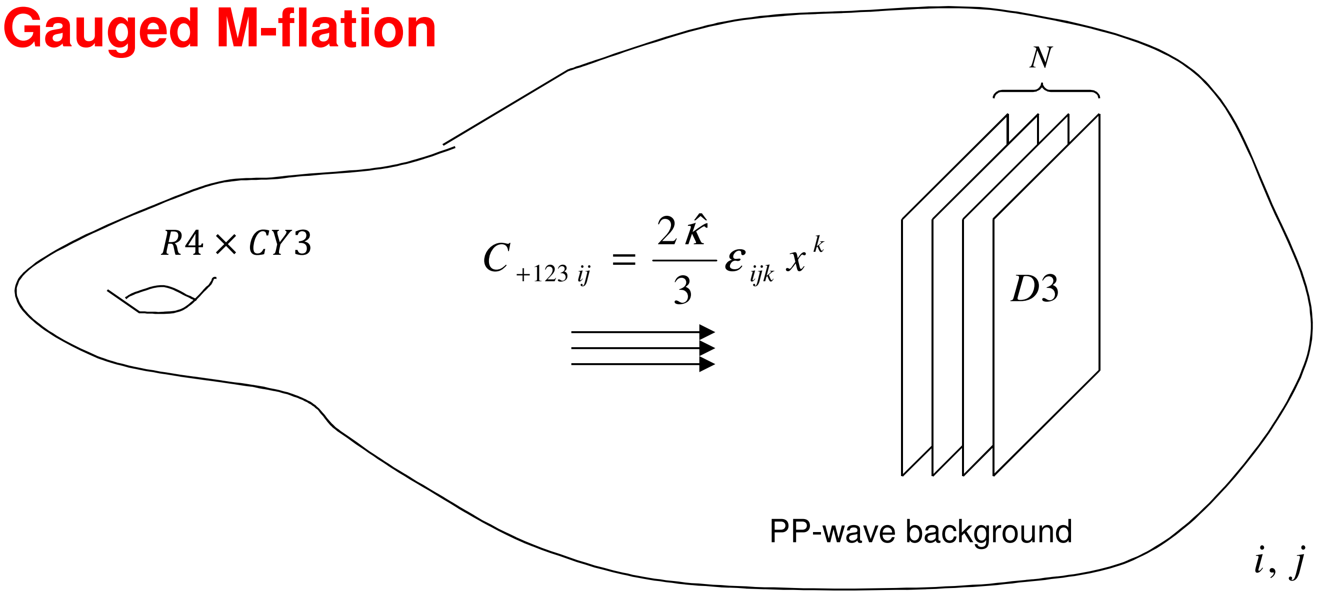
$$\frac{\Delta\phi}{M_{pl}} > 1.06\left(\frac{r}{0.01}\right)^{1/2}$$

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

    McAllister & Baumann (2007)

- I focus on M-flation that uses Matrices as inflaton.
- Embedded preheating in some regions ⇒ high frequency gravitational waves.

## • Gauged M-flation




$i, j = 1,2,3$ 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.

10-d IIB supergravity background

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

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

Myers (1999)

$$g_{ab} = G_{MN}\partial_a X^M \partial_b X^N \qquad M,N = 0,1,\dots,9$$

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

$I, J = 4,5,\dots,9$

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

- We assume there is a hierarchy between three of the extra-dimensions and the other three, so basically we have deal with the large three of the dimensions perpendicular to the D3 branes.

# 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 $\Phi_i \equiv \frac{X_i}{\sqrt{(2\pi)^3 g_s l_s^2}}$

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

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

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 **JCAP 0906:018,2009, arXiv:0903.1481 [hep-th],** we relaxed this condition and took $\lambda, \kappa$ and $m^2$ as independent parameters. In this talk, I will mainly focus on the SUSY case.

- 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:

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

However from the specific form of the potential and since we have three $\Phi_i$, 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

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

# Consistency of the Truncation to the SU(2) Sector

- SU(2) sector is a sector in which the computations are tractable. But is it consistent?

To see that let us defines

$$\Psi_i = \Phi_i - \hat{\phi} J_i \qquad \hat{\phi} = \frac{4}{N(N^2-1)} \mathrm{Tr}(\Phi_i J_i) \qquad \mathrm{Tr}(\Psi_i J_i) = 0$$

$$V = V_0(\phi) + V_{(2)}(\hat{\phi}, \Psi_i) \qquad V_{(2)}(\hat{\phi}, \Psi_i = 0) = 0 \qquad \left(\frac{\delta V_{(2)}}{\delta \Psi_i}\right)_{\Psi_i=0} = 0$$

If we start with the initial consitions $\Psi_i = \dot{\Psi}_i = 0$ and $\hat{\phi} \neq 0$, $\Psi_i$ will remain zero.

- What is the special role of SU(2) generators among other *N X N* matrices?

$$\Phi_i = \Gamma_i - \Xi_i \qquad \mathrm{Tr}(\Gamma_i \Xi_i) = 0$$

$$V = V_0(\Gamma_i) + V_{(1)}(\Gamma_i, \Xi_i)$$

$$V_{(1)} = \mathrm{Tr}\left[\left(-\lambda[\Gamma_i,[\Gamma_i,\Gamma_k]] + i\,\varepsilon_{ijk}[\Gamma_i,\Gamma_j]\right)\Xi_k\right] + O(\Gamma^2)$$

To have $\Gamma_i$ -sector decoupled ⟹ $[\Gamma_i, \Gamma_j] = f_{ijk}\Gamma_k$ ⟹ Three $\Gamma_i$ should form a Lie-Algebra

a) $f_{ijk} = i\,\varepsilon_{ijk}$ ⟹ $\Gamma_i$ are forming a $SU(2)$ algebra $\Phi_i = \sum_\alpha \phi_\alpha J_i^\alpha, \quad i = 1,2,3 \quad N = \sum_\alpha N_\alpha$

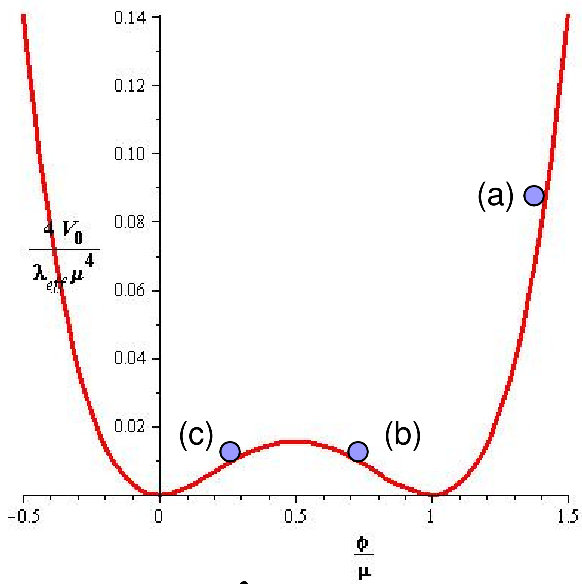
A.A., H. Firouzjahi, M.M. Sheikh-Jabbari, arXiv:0911.4284 [hep-th

b) $f_{ijk} = 0$ ⟹ $\Gamma_i$ are three Abelian subgroups of *U(N)* ⟹ No interesting inflationary dynamics.

# 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-Breaking inflation, Linde (1992)
Lyth & Boubekeur (2005)




(a) $\phi_i > \mu$

$\phi_i \approx 43.5\, M_P$ $\qquad \phi_f \approx 27.1\, M_P$

$\lambda_{eff} \approx 4.9\times10^{-14}$ $\qquad \mu \approx 26\, M_P$

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

$\phi_i \approx 23.5\, M_P$ $\qquad \phi_f \approx 35 M_P$

$\lambda_{eff} \approx 7.2\times10^{-14}$ $\qquad \mu \approx 36 M_P$

(c) $0 < \phi_i < \frac{\mu}{2}$

$\phi_i \approx 12.5\, M_P$ $\qquad \phi_f \approx 1 M_P$

$\lambda_{eff} \approx 7.2\times10^{-14}$ $\qquad \mu \approx 36 M_P$

$\lambda \approx 1$

↓

$N \approx 5\times10^4$

↓

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

# Mass Spectrum of Spectators

We initially have $3N^2$ and $4N^2$ gauge fields. Truncating to the SU(2) sector and using the EOM and the gauge symmetry of the action leaves us with $5N^2-1$ isocurvature modes, or "*spectators*".

The other $5N^2-1$ even though classically frozen, have quantum fluctuations. To compute these effects, let us calculate the mass spectrum of these modes.

- **Spectrum of scalar spectators**

Expanding the action up to second order, $\Phi_i = \hat{\phi} J_i + \Psi_i$, we have:

$$V_{(2)} = \mathrm{Tr}\left[\frac{\lambda}{2}\hat{\phi}^2\Omega_i\Omega_i + \frac{m^2}{2}\Psi_i\Psi_i + \left(-\frac{\lambda}{2}\hat{\phi}^2 + \kappa\hat{\phi}\right)\Psi_i\Omega_i\right]$$

where

$$\Omega_k \equiv i\varepsilon_{ijk}\left[J_i, \Psi_j\right]$$

If we have the eigenvectors of the $\Omega_i$

$$\Omega_i = \omega\Psi_i$$

$$V_2 = \left(\frac{\lambda_{eff}}{4}\phi^2(\omega^2-\omega) + \kappa_{eff}\,\omega\phi + \frac{m^2}{2}\right)\mathrm{Tr}\,\Psi_i\Psi_i$$

It turns out that finding the eigenvectors of $\Omega_i$ is mathematically the same as finding the the vector spherical harmonics:

Dasgupta, Sheikh-Jabbari & Von Raamsdonk (2002)

## Mass Spectrum of Spectators

(a) $N^2-1$ zero modes with $\omega=-1$

$$M^2=\lambda_{eff}\phi^2-2\kappa_{eff}\phi+m^2=\frac{V'}{\phi}$$

These modes are unphysical as they correspond to gauge transformation over the background solution $\Phi_i=\hat{\phi}J_i$. To see that, recall under an infinitesimal gauge transformation $\Phi_i\to\Phi_i+ig[\Phi_i,\Lambda]$ where $\Lambda$ is an arbitrary traceless Hermitian matrix.

(b) $(N-1)^2$ $\alpha$-modes with $\omega=-(l+2),\quad l\in Z\quad 0\le l\le N-2$

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

$$M_l^2=\frac{1}{2}\lambda_{\rm eff}(l+2)(l+3)\phi^2-2\kappa_{\rm eff}(l+2)+m^2$$

$l=0$ $\alpha-$mode is nothing more than the adiabatic mode. Therefore we have $(N-1)^2-1$ isocurvature $\alpha-$mode.

(c) $(N+1)^2-1$ $\beta$-modes with $\omega=l-1,\quad l\in Z\quad 1\le l\le N$

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

$$M_l^2=\frac{1}{2}\lambda_{\rm eff}(l-2)(l-1)\phi^2+2\kappa_{\rm eff}(l-1)+m^2$$

## Mass Spectrum of Spectators

- **Spectrum of scalar spectators**

Expanding the action in gauge fields up to second order,

$$\mathcal{L}^{(2)}_{A_\mu} = -\frac{1}{4}\mathrm{Tr}(\partial_{[\mu}A_{\nu]})^2 + \frac{1}{2}g^2_{YM}\hat{\phi}^2\mathrm{Tr}([J_i, A_\mu][J_i, A_\mu]) \,.$$

we can read the mass spectrum, solving for the eigenvalue problem

$$[J_i, [J_i, X]] = \omega X$$

which has eigenvalues $j(j+1)$ with degeneracy $2j+1$ for each mode. Therefore we we have a system of vector fields with the mass parameter

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

$j = 0$ is massless and corresponds to the $U(1)$ sector in the $U(N)$ matrices and has two polarizations. Other vector field modes are massive and have three d.o.f each. Therefore in total we have $3N^2 - 1$ vector d.o.f.

# Mass Spectrum of χ Spectators

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

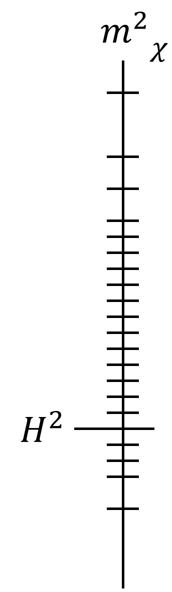
$$M^2_{\alpha,l} = \frac{1}{2}\lambda_{\text{eff}}(l+2)(l+3)\phi^2 - 2\kappa_{\text{eff}}(l+2) + m^2$$

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

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

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

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




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

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

## Power Spectra in the Presence of $\Psi_{r,lm}$ Modes

$$L=-\frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi-\frac{1}{2}\partial_\mu\Psi^*{}_{r,lm}\,\partial^\mu\Psi_{r,lm}-V_0(\phi)-\frac{1}{2}M^2_{r,lm}(\phi)\Psi^*{}_{r,lm}\Psi_{r,lm}\qquad \boldsymbol{r}=\boldsymbol{\alpha},\boldsymbol{\beta},\boldsymbol{A}$$

If you start from the initial condition $\Psi_{r,lm}=\dot{\Psi}_{r,lm}=0$, they remain zero. Therefore the inflationary trajectory is a straight line in the field space and there is no cross-correlation between adiabatic and entropy spectra.

Mukhanov-Sasaki variable

$$\ddot{Q}_\phi+3H\dot{Q}_\phi+\frac{k^2}{a^2}Q_\phi+\left(V_{0,\phi\phi}-\frac{1}{a^3M_P^2}\left(\frac{a^3}{H}\dot{\phi}^2\right)^{\cdot}\right)Q_\phi=0;\qquad Q_\phi\equiv\delta\phi+\frac{\dot{\phi}}{H}\Phi$$

$$\delta\ddot{\Psi}_{r,lm}+3H\,\delta\dot{\Psi}_{r,lm}+\left(\frac{k^2}{a^2}+M_{r,l}(\phi)^2\right)\delta\Psi_{r,lm}=0\qquad \Re=\frac{H}{\dot{\phi}}Q_\phi\qquad S_{r,lm}=\frac{H}{\dot{\phi}}\Psi_{r,lm}$$

$$\dot{\Re}=\frac{H}{\dot{H}}\frac{k^2}{a^2}\Phi\longrightarrow$$

scalar metric perturbations in longitudinal gauge

$$P_{Q_\phi}=\frac{k^3}{2\pi^2}\delta^3(\mathbf{k}-\mathbf{k}')\left\langle Q^*{}_{\phi\mathbf{k}}Q_{\phi\mathbf{k}'}\right\rangle\qquad P_{\Psi_{r,lm}}=\frac{k^3}{2\pi^2}\delta^3(\mathbf{k}-\mathbf{k}')\left\langle \Psi^*{}_{r,lm\mathbf{k}}\;\Psi^*{}_{r,lm\mathbf{k}'}\right\rangle$$

$$C_{\psi^i Q_Q}=\frac{k^3}{2\pi^2}\delta^3(\mathbf{k}-\mathbf{k}')\left\langle Q^*{}_{\phi\mathbf{k}}\Psi_{r,lm}\right\rangle=0$$

## (a) Power Spectra in Symmetry-Breaking Inflation $\phi > \mu$

$\lambda_{eff} \approx 4.9\times 10^{-14}$ $\mu \approx 26\, M_P$ ⟹ $n_{\Re} \approx 0.96$

$P_T(k_{60}) \approx 4.8\times 10^{-10}$ ⟹ $r \approx 0.2$ $n_T \approx -0.025$

| | | | | |
|---|---|---|---|---|
| $l = 1$ $\beta$ | $m^2$ | 1.1 $\times 10^{-12}$ | 0.978 | 3 |

$$\frac{P_{S_{\beta,1}}}{P_R} \simeq 4.7\times 10^{-4}$$

This region of parameter space is ruled out with Planck if one considers Bunch-Davies (BD) vacuum.

- It is possible to reconcile this model and other high energy models of inflation with Planck considering non-BD vacua for tensor and scalar fluctuations, with $M \simeq \text{few} \times 10H$

Ashoorioon, Dimopoulos, Sheikh-Jabbari & Shiu, arXiv:1306.4914

## Power Spectra in Symmetry-Breaking Inflation

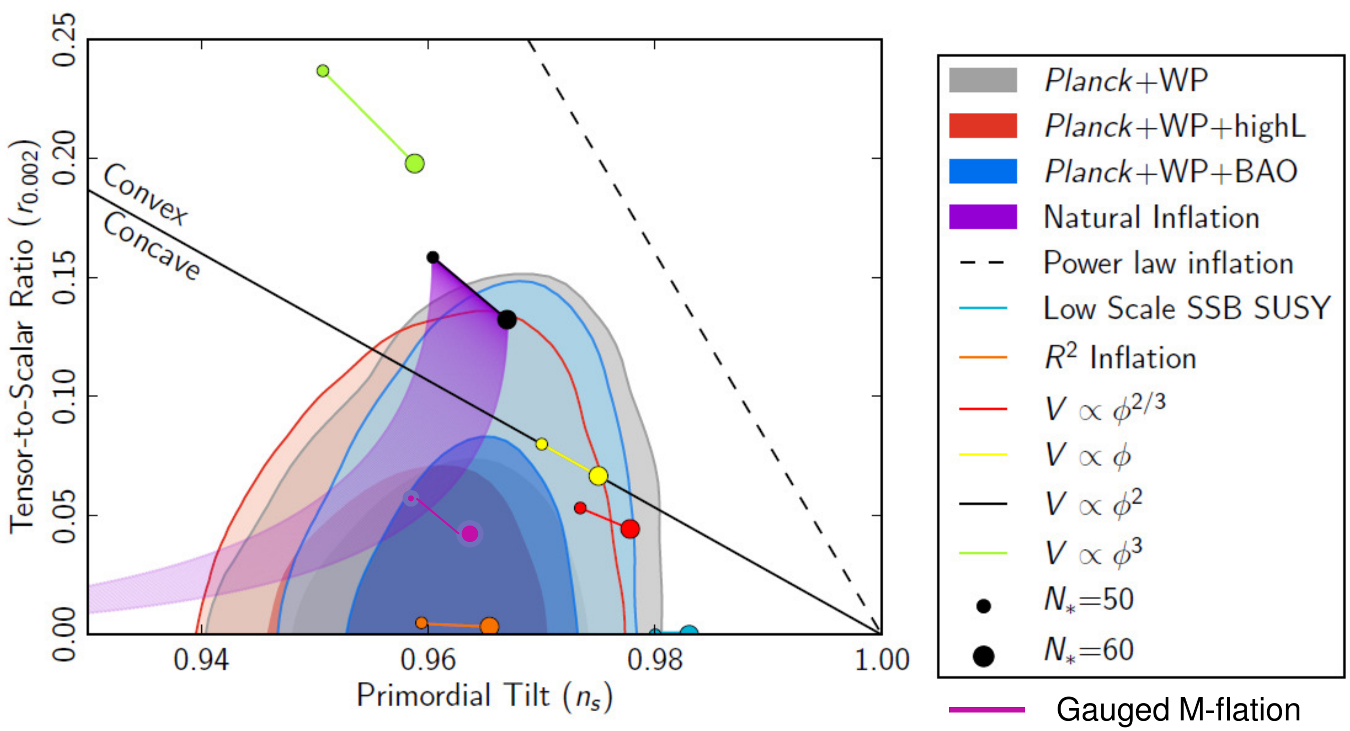
$\mu/2 < \phi < \mu$

$\lambda_{eff} \approx 7.2\times10^{-14}$ $\mu \approx 36\, M_P$ → $n_{\Re} \approx 0.961$

| | | | | |
|---|---|---|---|---|
| $l=1$ $\beta$ | $m^2$ | $6.6 \times10^{-16}$ | $1.05$ | 3 |

$P_T(k_{60}) \approx 1.3\times10^{-11}$ → $r \simeq 0.048$ $n_T \approx -0.006$

$$\frac{P_{S_{\beta,1}}}{P_R} \simeq 2.7\times10^{-7}$$



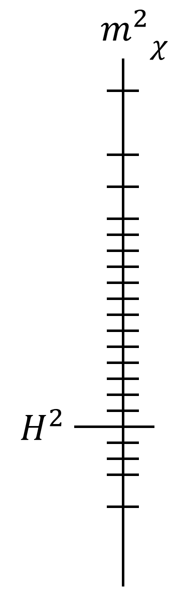

CMBPOL or QUIET should be able to verify this scenario.

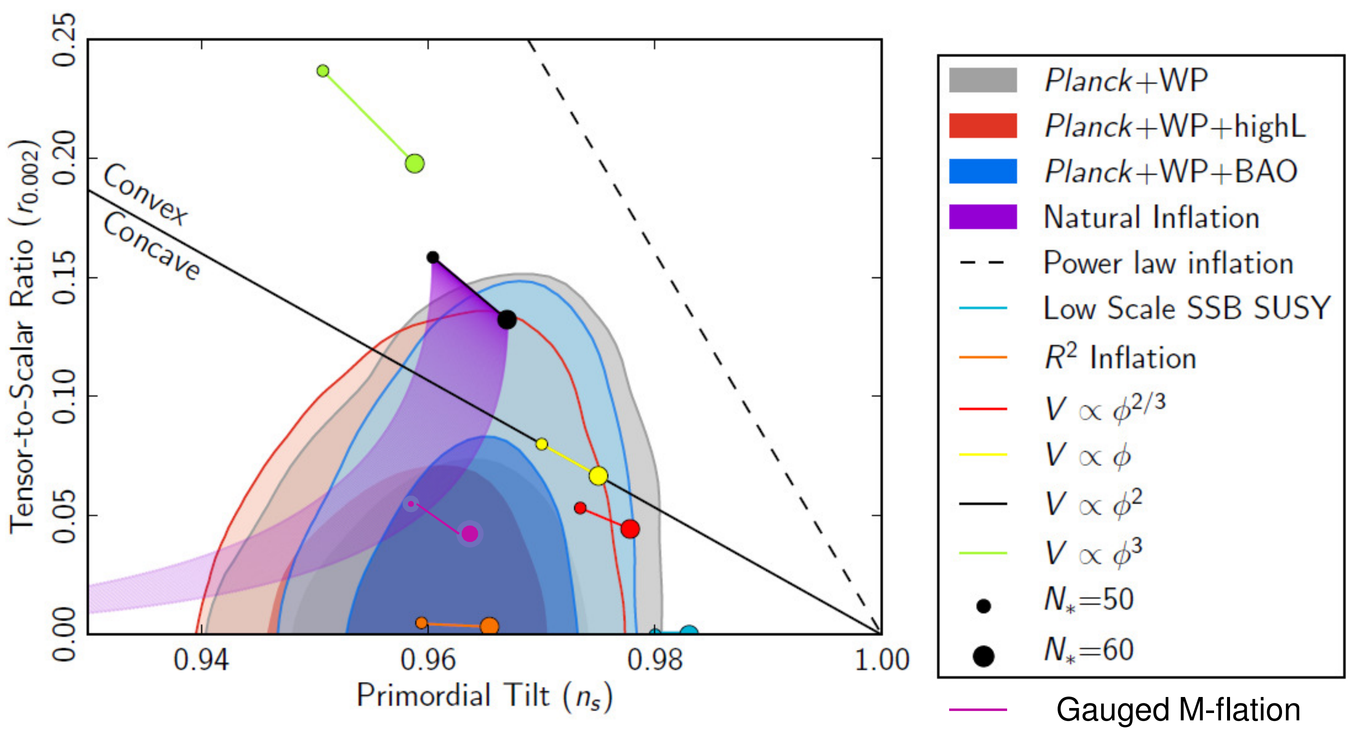
## C) Power Spectra in Symmetry-Breaking Inflation $0 < \phi < \mu/2$

$$\lambda_{eff} \approx 7.2\times10^{-14} \;\&\; \mu \approx 36\ M_P \Longrightarrow n_{\Re} \approx 0.96 \;\&\; P_{\Re} \approx 2\times10^{-9}$$

| | | | | |
|---|---|---|---|---|
| $l=1$ $\alpha$ | $6\lambda_{eff}\phi^2 - 6\kappa_{eff}\phi + m^2$ | $1.2 \times10^{-11}$ | 0.95 | 3 |

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




$r \approx 0.048$

$n_T \simeq -0.006$

CMBPOL or QUIET should be able to verify this scenario.

## Particle Creation and Preheating Scenario around $\phi = \mu$ 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 $\alpha$ and $\beta$ modes: $\ddot{\chi}_k + 3H\dot{\chi}_k + \Omega_k^2\chi_k = 0$
- For the gauge mode $\ddot{A}_k + H\dot{A}_k + \Omega_k^2 A_k = 0$

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 $\phi = 0$

- 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

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

- The mass of $\alpha$-modes and $\beta$-modes become tachyonic for $\ell > \ell_{\min}$, where $\ell^{\alpha}{}_{min} = 94$ and $\ell^{\beta}{}_{min} = 16$.

- We have to find the corrections up to quartic order which stabilizes this instability

$$S_\chi^{(3)} = \int d^4x\sqrt{-g}\{-K_\chi(\phi)\,\mathrm{Tr}(\chi^3)\,\}$$

$$S_\chi^{(4)} = \int d^4x\sqrt{-g}\{-\Lambda_\chi(\phi)\,\mathrm{Tr}(\chi^4)\,\}$$

$$\frac{K_\chi}{M_{Pl}} \ll \Lambda_\chi \simeq 1.0069 \times 10^{11}\frac{\lambda_{\mathrm{eff}}}{4}$$

$$\ddot{\chi}_k + 3H\dot{\chi}_k + \Omega_k^2 \chi_k + 4\Lambda_\chi \chi_k^3 = 0$$

$$\ddot{A}_k + H\dot{A}_k + \Omega_k^2 A_k = 0$$

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

$$X_\ell'' + \Omega_\omega^2 X_\ell + \frac{2qX_\ell^3}{a^3\mu^2} = 0$$

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

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

$$n_\ell^\omega = \frac{\Omega_\omega}{2}\left(\frac{\mu^2\lambda}{2}\frac{|X_\ell'|^2}{\Omega_\omega^2} + |X_\ell|^2\right) - \frac{1}{2}$$

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

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

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

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

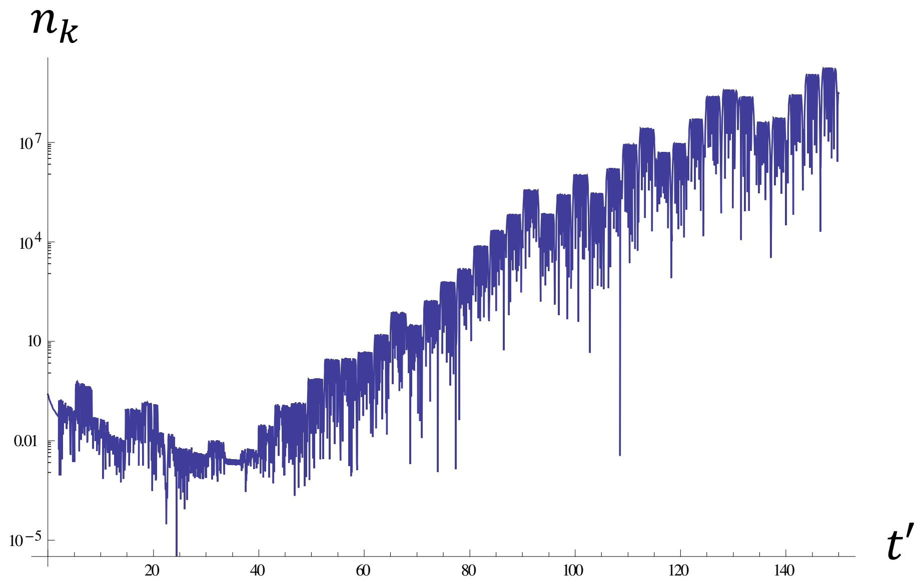
## GW production from Preheating

- Parametric resonance could be a source of gravitational waves.
- Exponential particle production for some momenta ⟹ large inhomogeneities

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

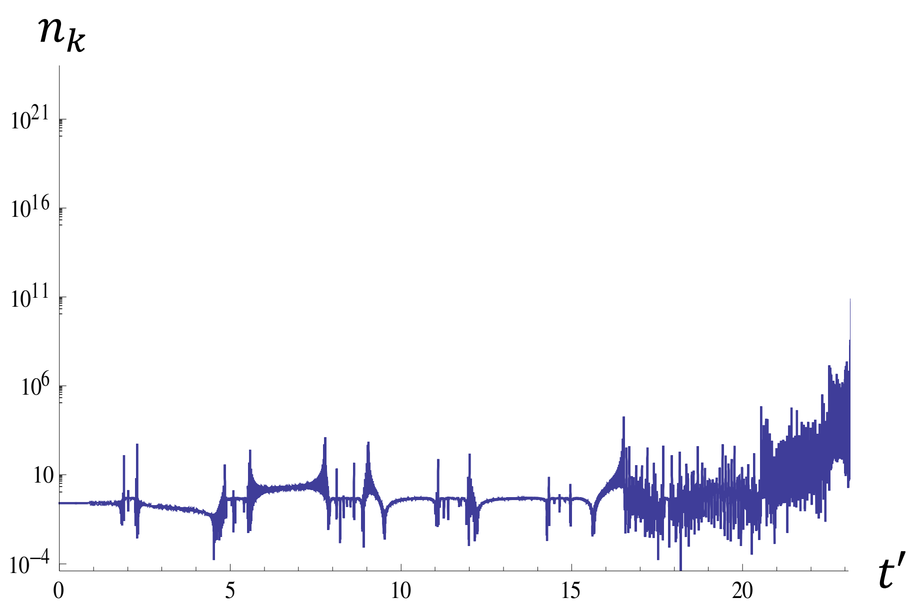
$$\frac{d\Omega_{GW}}{d\ln k} = \frac{1}{\rho_{crit}}\frac{d\rho}{d\ln k} = \frac{\pi k^3}{3H^2L^2}\sum_{i,j}\left|h_{ij,0}(k)\right|^2$$

- This is in addition to the stochastic background of GW produced during inflation
- Such GW is a probe of the inflaton potential and its couplings at the end of inflation.
- Universe is transparent to GW ⟹ useful source of information from early universe.




Largest j Gauge modes

$\ell = 0$

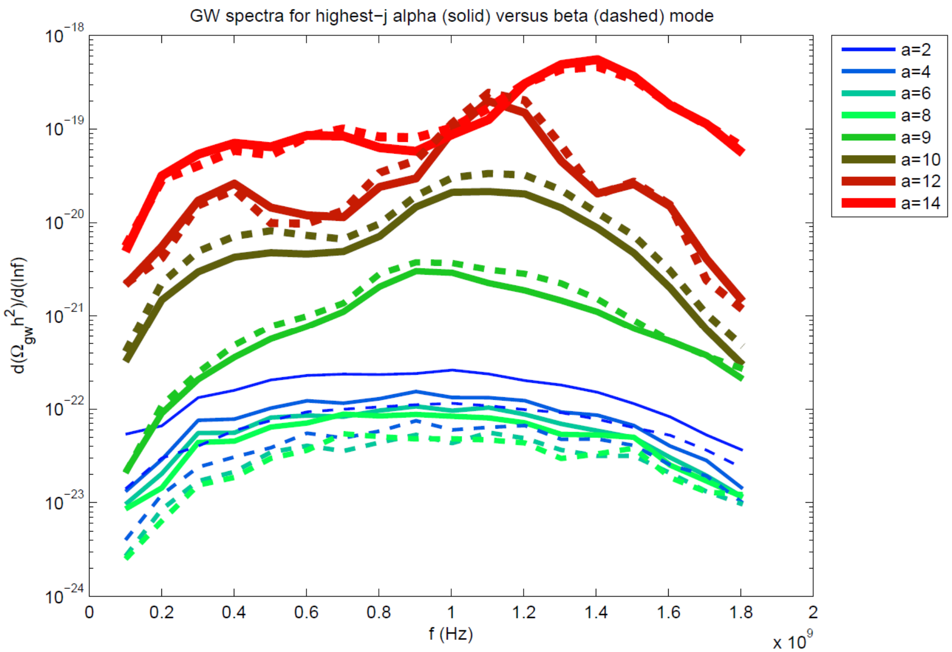


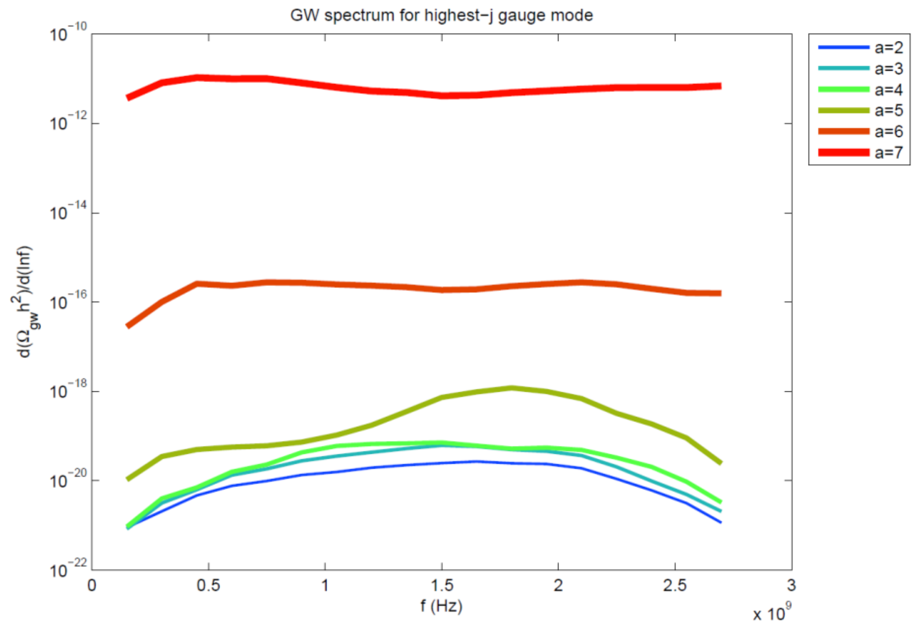

Largest j beta mode with quartic interaction

$\ell = 0$

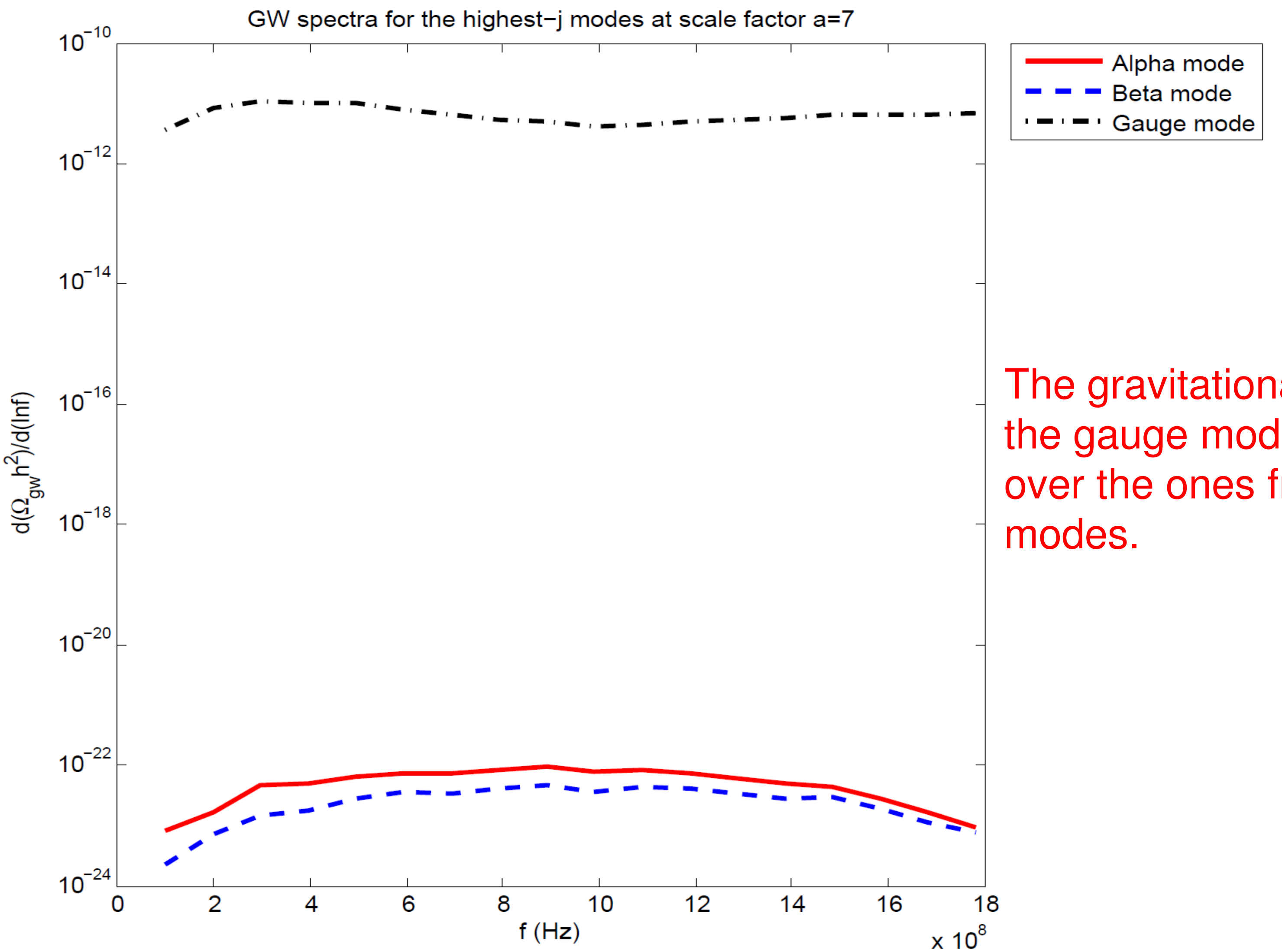
## GW production from Preheating: Single Mode

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



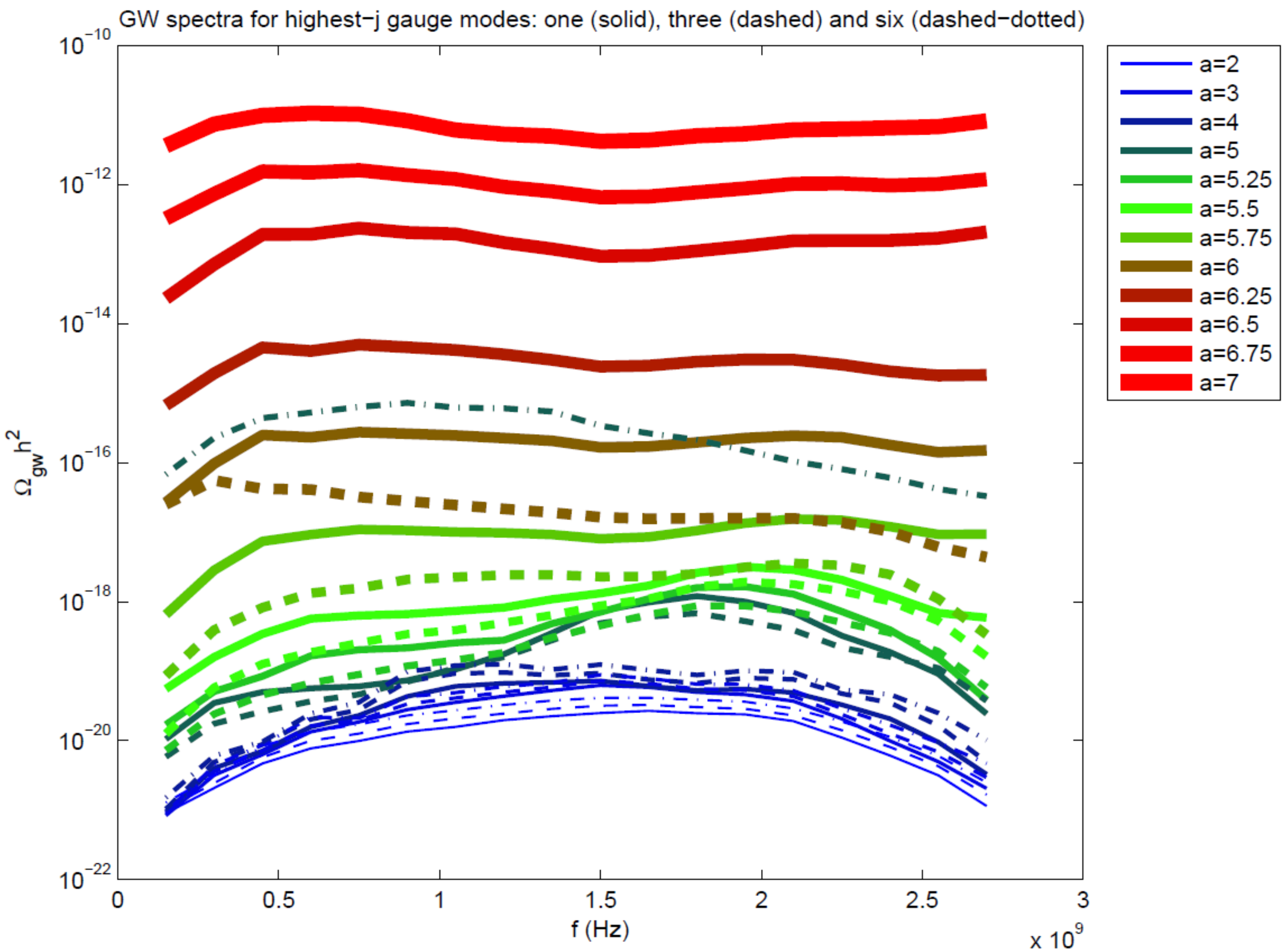



# GW production from Preheating: Single Mode




The gravitational wave from the gauge modes dominates over the ones from $\alpha$ and $\beta$ modes.

# GW production from Preheating: More large j Gauge Mode



## Time Evolution:

- **Linear Period**: while inflaton oscillates coherently around its minimum, the effect of multi-preheat modes is larger than a single mode.

- **Non-Linear Period:** inhomogeneities of the inflaton grow, gravitational radiation is counteracted by the backreaction. Nonlinear effects suppress the degeneracy effects.

## Frequnecy Dependence:

- Our current data already shows that the GWs of our model are in the 1–3 GHz band and they are almost flat with amplitudes around $10^{-16}$.

  - The signal may be seen in Birmingham HFGW resonant antenna or the one at Chongqin University

## Conclusions

- M-flation solves 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.

- Matrix nature of the fields suggests isocurvature productions at the CMB scales.

- Hierarchical mass structure of the isocurvature modes, one can avoid the "beyond-the-cutoff" problem.

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

# Conclusions

- Interactions of the graviton with the scalar field $\frac{\Lambda^2}{M_p^2} R\phi^2 \Longrightarrow \eta$ −problem if $\Lambda = M_{pl}$
- In many-field models like M-flation, the problem can be avoided

$$\Lambda = \frac{M_{pl}}{\sqrt{N_s}}$$

Ashoorioon, Danielsson, Sheikh-Jabbari, Phys.Lett. B713 (2012)

- M-flation has a natural built-in mechanism of preheating around the SUSY vacuum.
- The couplings of the preheat fields are related to self couplings of inflaton, thus known.
- The parametric resonance produces large GHz frequency GW which could be seen by ultra-high frequency gravitational probes like Birmingham or the one at Chognqing University.
- Other signatures in this inflationary region:
  1. Observable GW at cosmological scales with $r = 0.048$.
  2. Iscocurvature perturbations with $\frac{P_S}{P_R} \simeq 5 \times 10^{-3}$.

*Thank you*