GRAVITATIONAL WAVES FROM REHEATING AFTER INFLATION

An (Observable?) Signature from Inflation

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ASTROPHYSICAL TESTs of FUNDAMENTAL PHYSICS

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PUBLICATIONS

· Khlebnikov, Tkachev: hep-ph/9701423 (PRD)

· Easther, Lim: astro-ph/0601617 (JCAP)

· García-Bellido, Figueroa: astro-ph/0701014 (PRL)

· García-Bellido, Figueroa, Sastre: 0707.0839 [hep-ph] (PRD)

· Dufaux, Bergman, Felder, Kofman, Uzan: 0707.0875 [astro-ph] (PRD)

· Easther, Lim, Giblin: astro-ph/0612294 (PRL)

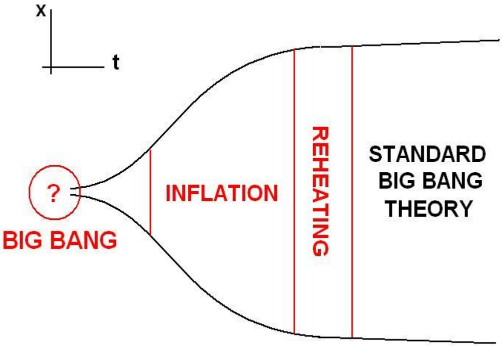
· Easther, Lim, Giblin: astro-ph/0712.2991

· García-Bellido, Figueroa 0801.4109 [gr-qc] (Proceedings of JGRG17)

· Dufaux, Felder, Figueroa, García-Bellido, Kofman, Uzan 0804.XXX [astro-ph] (WORK IN PROGRESS...)

PHYSICAL CONTEXT: AIM of this RESEARCH

INFLATION $\longrightarrow$ REHEATING $\longrightarrow$ BIG BANG THEORY



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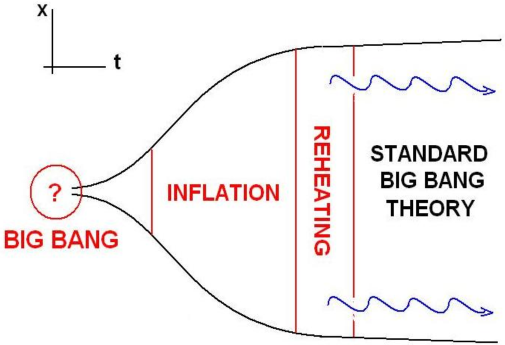

BASICs of REHEATING

1. **Init. Cond. REHEATING**:

   t = 0: NO particles (Empty space),
   ONLY inflaton zero-mode or Vacuum energy

2. **Theory of REHEATING**:

   $0 < t < t_{RH}$: $\mathcal{L} = \mathcal{L}(\phi, \varphi_i, \psi_j, A_\mu, h_{\mu\nu}, ...)$

3. **Physics of REHEATING**: SCALAR SECTORs

   $V = V(\phi) + \frac{1}{2}g^2\phi^2\chi^2 + V(\chi)$ (Chaotic, Hybrid models)

   QFT in a FRW : $\mathbf{k}_i \pm \Delta\mathbf{k}_i \rightarrow \varphi_k(t), n_k(t) \sim exp\{\mu_k\, t\}$

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SCALAR REHEATING (Examples)

$$V(\phi,\chi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{2}m_\chi^2\chi^2 + \frac{1}{2}g^2\phi^2\chi^2 \quad \text{(Massive Chaotic)}$$

$$V(\phi,\chi) = \frac{1}{4}\lambda\phi^4 + \frac{1}{2}m_\chi^2\chi^2 + \frac{1}{2}g^2\phi^2\chi^2 \quad \text{(Massless Chaotic)}$$

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$$\begin{cases} \ddot{\phi}(t) + V'(\phi) = 0 \qquad (\mathrm{Oscillations\ of\ Inflaton\ Zero-Mode:}\ \Phi \downarrow\downarrow) \\ \Box\phi_k + \langle V'' \rangle\, \phi_k = 0 \\ \Box\chi_k + \langle V'' \rangle\, \chi_k = 0 \qquad (\Box \equiv \partial_{tt} + 3H\partial_t + \frac{k^2}{a^2}) \end{cases}$$

DYNAMICS: Non-Linear, Non-Perturbative and Far-From-Equilibrium

Reheating in Chaotic Scenarios: PARAMETRIC RESONANCE

$$\left.\begin{array}{l} \text{Massless}: X_k'' + (\kappa^2 + \frac{g^2}{\lambda} cn^2(z)) X_k = 0 \quad \text{(Lamé Eq.)} \\ \\ \text{Massive}: X_k'' + (A_k - 2q\cos(2z)) X_k = 0 \quad \text{(Mathieu Eq.)} \\ \qquad q = g^2\Phi^2/(2\mu)^2, \qquad A_k = (k/a)^2/\mu^2 + 2q \end{array}\right\} \begin{array}{l} X_k \sim e^{\mu_k\, t} \\ n_k \sim e^{\mu_k\, t} \end{array}$$

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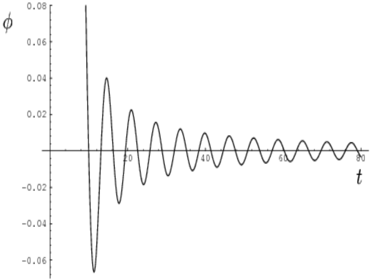
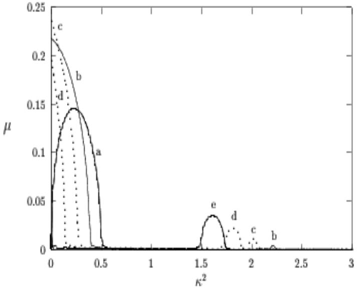
Chaotic Inflation (KLS94,GKLS97)





Reheating in Hybrid Scenarios: SPINODAL INSTABILITY

$$\left.\begin{aligned} &\ddot{\phi}(t) + (\mu^2 + g^2|\chi|^2)\phi(t) = 0 \\ &\ddot{\chi}_k + \left(k^2 + m^2\left(\frac{\phi}{\phi_c} - 1\right) + \lambda|\chi|^2\right)\chi_k = 0 \end{aligned}\right\}$$

$$\chi_k, n_k \sim e^{\sqrt{m^2 - k^2}\,t}$$

$$(k < m = \sqrt{\lambda}v)$$

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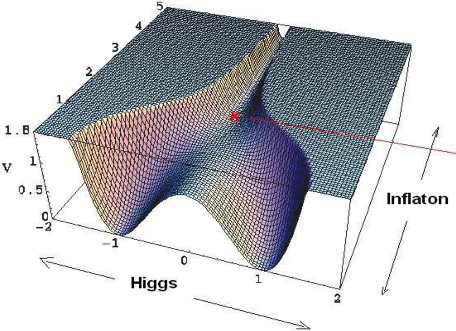
Hybrid Preheating



$\phi < \phi_c = \lambda^{1/2} v/g$

$m^2_\chi(k < \lambda^{1/2} v) < 0$

EXPECTATION: REHEATING $\Rightarrow$ GW

1. **Physics of GW**:
   $h_{ij} \simeq \frac{G}{c^4}\frac{\ddot{Q}_{ij}}{r} \sim M\frac{G}{c^4}\frac{\langle v^2\rangle}{r}, \qquad Q_{ij} = \int d^3x(x_i x_j - x^2\delta_{ij})\rho$

2. **GW Sources**:
   $M, v \uparrow\uparrow \;\Rightarrow\; h_{ij} \uparrow\uparrow \begin{cases} \text{Astrophysics}: & M \uparrow\uparrow, v \uparrow\uparrow \\ \text{Early Universe}: & \Delta\rho \uparrow\uparrow, v \uparrow\uparrow \end{cases}$

3. **Physics of REHEATING**: $\ddot{\varphi}_k + \omega^2(k,t)\varphi_k = 0$

   $\begin{cases} \text{Spinodal Instability}: & \omega^2 = k^2 + m^2(1 - A\,t) < 0 & \text{(Tachyonic)} \\ \text{Parametric Resonance}: & \omega^2 = k^2 + \Phi(t)\,\sin^2\mu t & \text{(Periodic)} \end{cases}$

   At $\mathbf{k}_i$: $\varphi_{k_i}, n_{k_i} \sim e^{\mu(k)t} \Rightarrow$ Inhomogeneities: L_i, v $\uparrow\uparrow$

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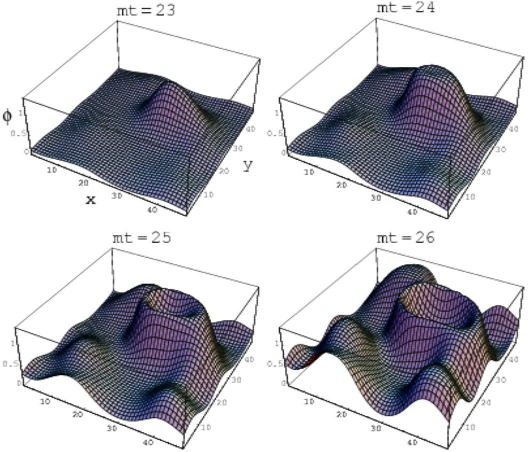
Reheating in the Hybrid Scenarios (Pictorically)

G-B,GA,GP 2002: $\lambda \approx .01$, $V \approx .001$, $v = 10^{-3} M_p$



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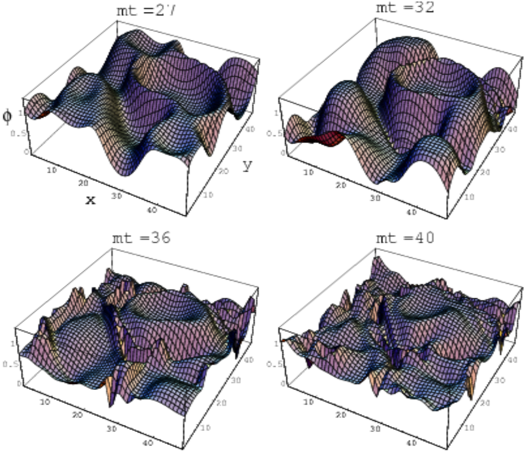

Lattice Simulations: Dynamics

- Scalars $(n_k >> 1)$: $\Box\phi + V_{,\phi} = 0,\ \Box\chi_a + V_{,\chi_a} = 0$

  Semi-classical regime $\pi_k \approx \kappa\phi_k + ...$ **(Squeezed States)**

- FRW: $H^2 = \frac{8\pi}{3}\rho, \quad \frac{\ddot{a}}{a} = -\frac{4\pi}{3}(\rho + 3p),\ ,\ \begin{cases} \rho =< \rho_\phi + \rho_{A_\mu} + ... > \\ p =< p_\phi + p_{A_\mu} + ... > \end{cases}$

- GW: $\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{1}{a^2}\nabla^2 h_{ij} = 16\pi\Pi_{ij}^{\rm TT}, \qquad \Pi_{ij} = T_{ij} - \langle T_{ij}\rangle_{\rm FRW}$

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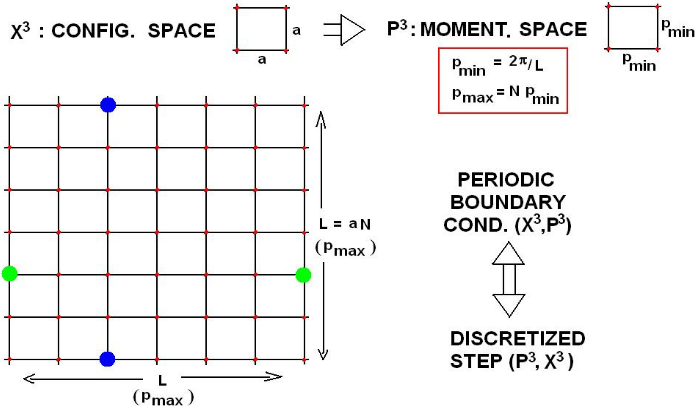
  $ds^2 = a^2(-d\eta^2 + (\delta_{ij} + h_{ij})dx^i dx^j), \qquad {\rm TT} : \begin{cases} h_{ii} = 0 \\ h_{ij,j} = 0 \end{cases}$

  Only TT dof carry energy out of the source!!!

Lattice Simulations: Numerics

$$\partial_\mu O(x) \to (O(x+\mu) - O(x-\mu))/2a_\mu$$

$$\partial_\mu \partial_\mu O(x) \to (O(x+2\mu) + O(x-2\mu) - 2O(x))/4a_\mu^2$$



GW extraction (I)

Scalar Source (Configuration Space):

$$\ddot{h}_{ij}(\mathbf{x},t) + 3H\dot{h}_{ij}(\mathbf{x},t) - \frac{1}{a^2}\nabla^2 h_{ij}(\mathbf{x},t) = \frac{16\pi}{a^2}\,\mathrm{TT}\left\{\nabla_l\phi^a\nabla_m\phi^a\right\}(\mathbf{x},t)$$

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Scalar Source (Fourier):

$$\ddot{h}_{ij}(\mathbf{k},t) + 3H\dot{h}_{ij}(\mathbf{k},t) + \frac{k^2}{a^2}h_{ij}(\mathbf{k},t) = 16\pi\ \Lambda_{ij,lm}(\hat{\mathbf{k}})\left\{\nabla_l\phi^a\nabla_m\phi^a\right\}(\mathbf{k},t)$$

$$\Lambda_{ij,lm} = P_{il}P_{jm} - \frac{1}{2}P_{ij}P_{lm}, \qquad P_{ij} = \delta_{ij} - k_i k_j/k^2$$

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$$\Lambda_{ij,lm} = P_{il}P_{jm} - \frac{1}{2}P_{ij}P_{lm}, \qquad P_{ij} = \delta_{ij} - k_ik_j/k^2$$

Solution: ($h_{ij}(t_0) = \dot{h}_{ij}(t_0) = 0$)

$$h_{ij}(\mathbf{k},t) = \Lambda_{ij,lm}(\hat{\mathbf{k}})\int_{t_0}^{t} dt' G(t-t')\Pi^{\mathrm{eff}}_{lm}(\mathbf{k},t'), \qquad \Pi^{\mathrm{eff}}_{lm} = \nabla_l\phi\,\nabla_m\phi$$

GW extraction (II)

Building the Solution:

1) Non-Physical eq.:
$\ddot{u}_{ij}(\mathbf{x},t) + 3H\dot{u}_{ij}(\mathbf{x},t) - \frac{\nabla^2}{a^2}u_{ij}(\mathbf{x},t) = 16\pi\,\{\phi^a{}_{,i}\,\phi^a{}_{,j}\}\,(\mathbf{x},t)$

2) Fourier transform: $u_{ij}(\mathbf{x},t) \rightarrow u_{ij}(\mathbf{k},t)$

3) Proyection: $h_{ij}(\mathbf{k},t) = \Lambda_{ij,lm}(\hat{\mathbf{k}})u_{lm}(\mathbf{k},t)$

GW extraction (II)

Outputs: $\rho_{GW} = \frac{1}{32\pi G}\frac{1}{L^3}\int d^3\mathbf{x}\,\dot{h}_{ij}\dot{h}_{ij} = \frac{1}{32\pi G}\frac{1}{L^3}\int d^3\mathbf{k}|\dot{h}_{ij}(t,\mathbf{k})|^2$

1) Total GW density:
$\rho_{GW} = \frac{1}{32\pi G L^3} \times \int k^2 dk \int d\Omega\, \Lambda_{ij,lm}(\hat{\mathbf{k}})\dot{u}_{ij}(t,\mathbf{k})\dot{u}^*_{lm}(t,\mathbf{k})$

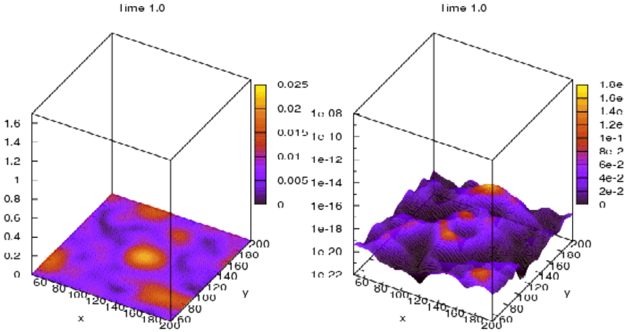
2) Spectrum: $\frac{d\rho}{d\log k} = \frac{1}{8GL^3}k^3\left\langle \Lambda_{ij,lm}(\hat{\mathbf{k}})\dot{u}_{ij}(t,\mathbf{k})\dot{u}^*_{lm}(t,\mathbf{k})\right\rangle_{4\pi}$

3) Snapshots: $h_{ij}(t,\mathbf{x}) = (2\pi)^{-3/2}\int d^3k e^{-i\mathbf{kx}}\Lambda_{ij,lm}(\hat{\mathbf{k}})u_{lm}(t,\mathbf{k})$

Results for Hybrid Reheating (Part I)

$$g^2 = 2\lambda = .25, \ v = 10^{-3} M_p, \ V = .024(\phi_c \sqrt{\lambda} v)$$

Bubble Nucleation and Collisions



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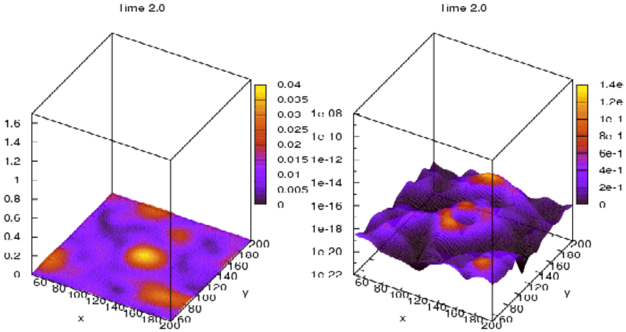

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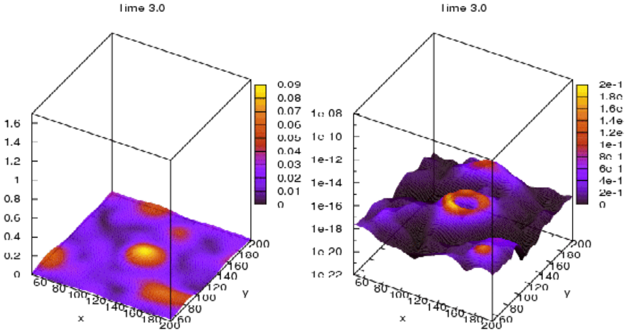

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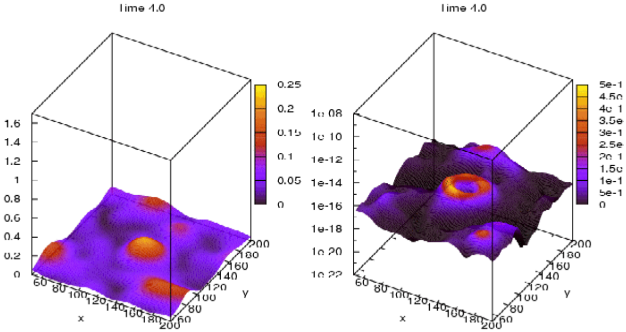

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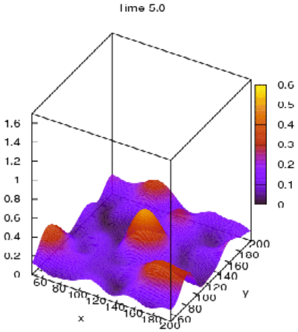

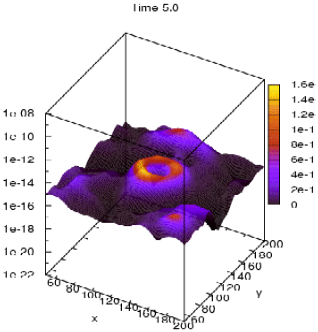

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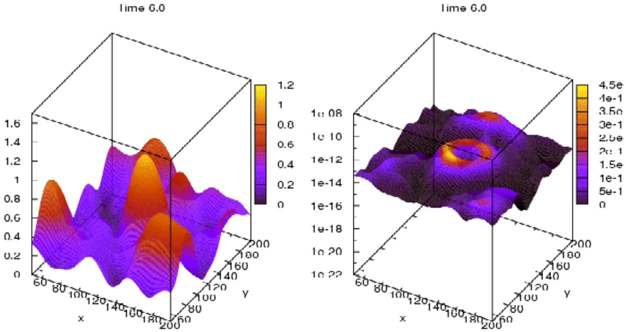

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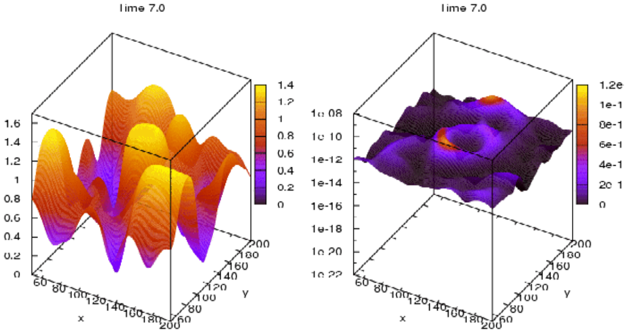

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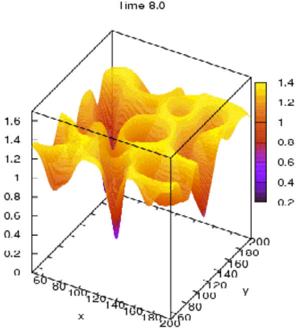

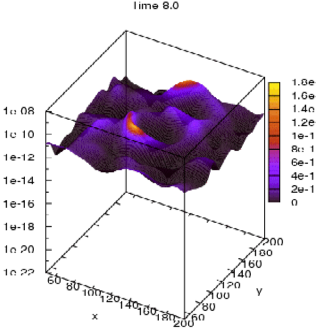

Results for Hybrid Reheating (Part I)

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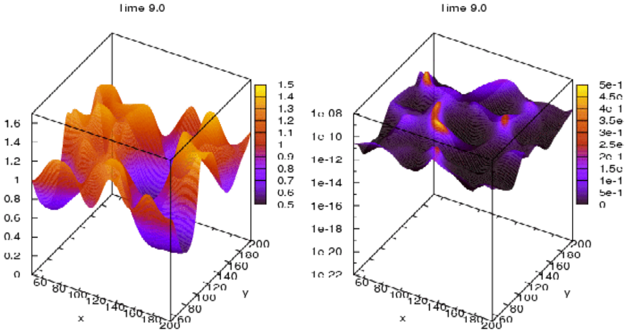

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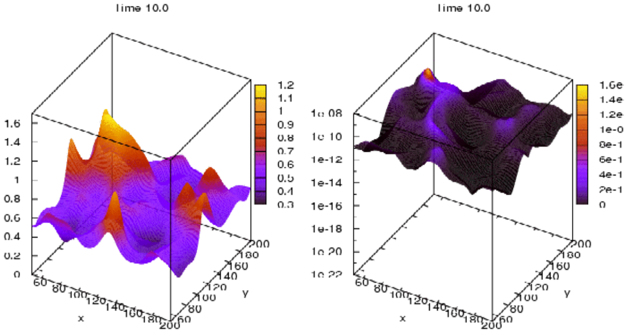

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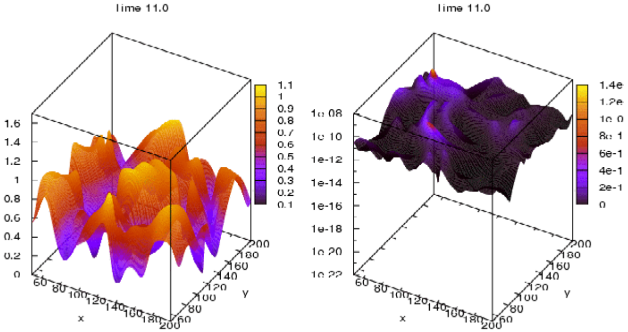

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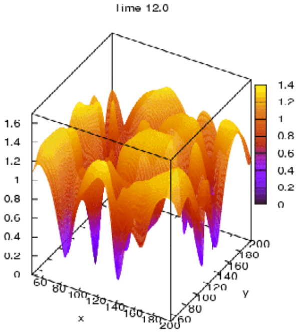

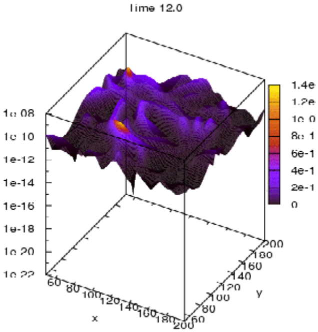

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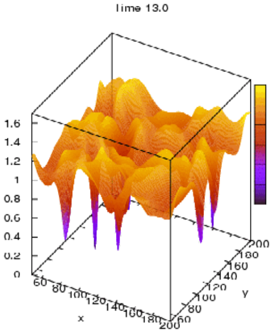

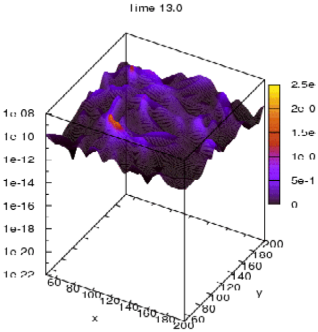

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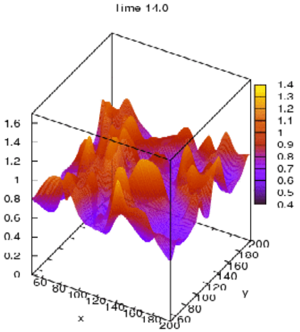

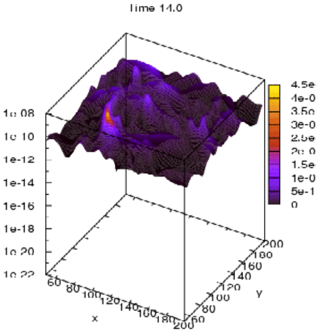

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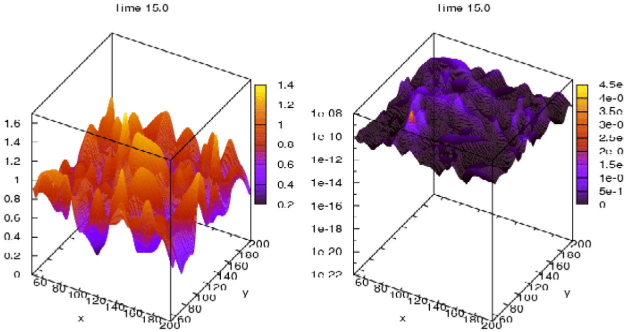

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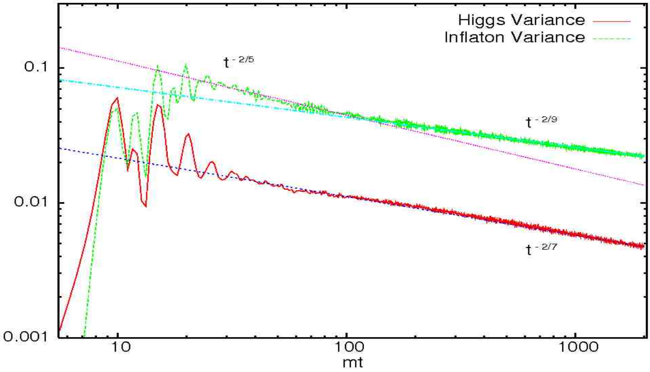
3 stages: **Exp. Instabilities** → **Bubble Collisions** → **Turbulence**



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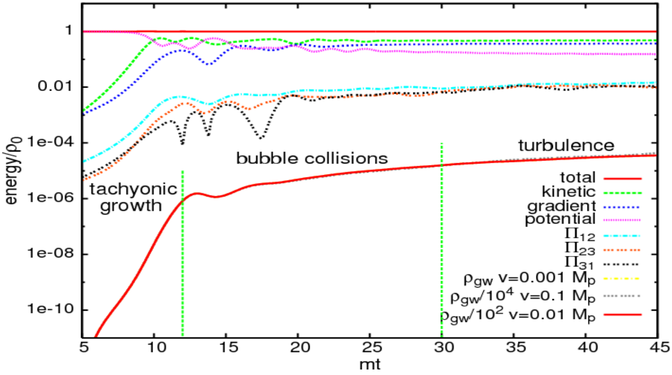

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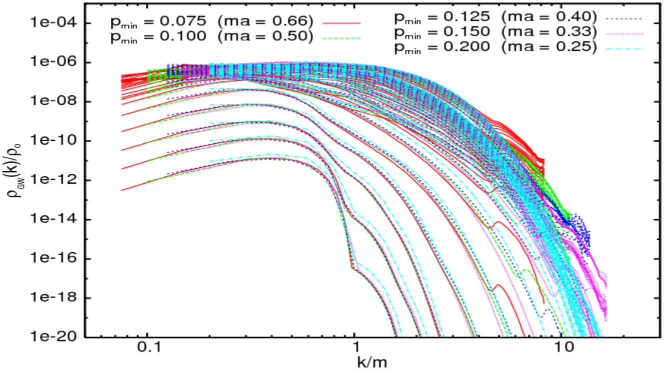
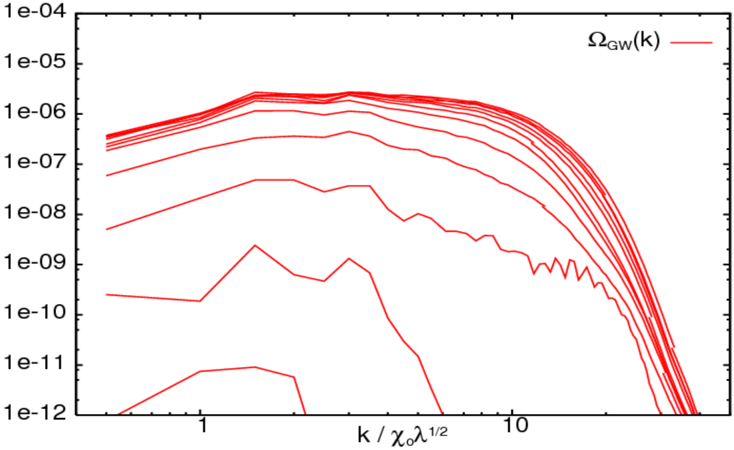


Results for Quartic Chaotic

$\lambda = 10^{-14}$, $g^2/\lambda = 120$ ($V = \frac{1}{4}\lambda\phi^4 + \frac{1}{2}g^2\phi^2\chi^2$)



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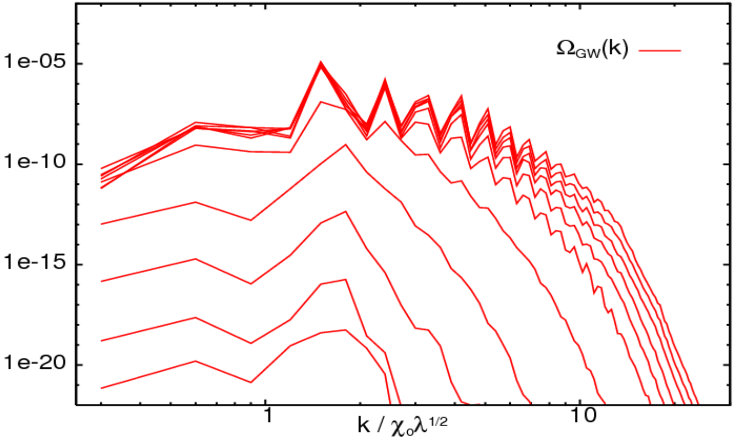
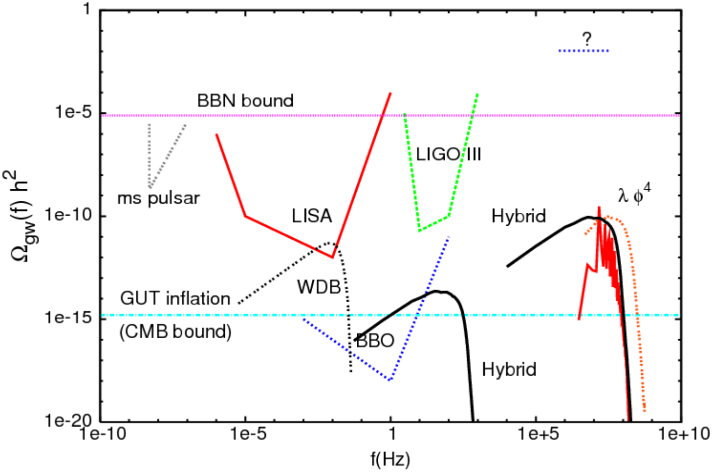


Today's Signal (GW RedShifted)



CONCLUSIONS/NEXT STEPS

1. GW are Early Universe Ideal Probe: decoupled upon production $\Rightarrow$ spectral signature retained till today $\Rightarrow$ GWB: "photo" of Early Universe $t < 1$ s (Disadvantage/Advantage).
2. GW from Reheating: Form, freq. Peak and Amplitude $\longrightarrow$ Specific Model of Inflation (Disadvantage/Advantage)
3. Scalar Reheating Models: GW (high amplitude, too high frequency)
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5. Vector Sources: new channel of GW (not suppressed at Turbulence)
6. GW = f(V_I,g) ANALITICALLY

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