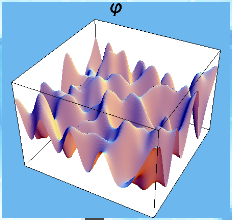
Jean-François Dufaux A.P.C.

Gravitational Waves from Preheating after Inflation: Overview and Recent Results



JFD - Phys.Rev.Lett.103 (2009)

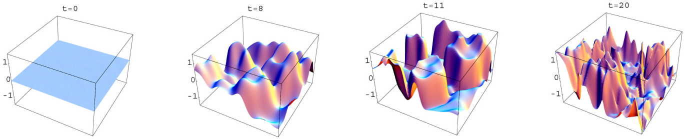
JFD, Figueroa, Garcia-Bellido - Phys.Rev.D (in press)

Brax, JFD, Mariadassou - to appear

Preheating after Inflation

Inflation		Reheating		Hot Big Bang
$\phi(t)$: condensate	$\longrightarrow$	Particle-genesis	$\longrightarrow$	Thermal bath
no particle		Thermalization		of particles
$\hookrightarrow$ **CMB, ...**		$\hookrightarrow$ **????**		$\hookrightarrow$ **BBN, ...**

In many models, the inflaton decays in a violent and highly inhomogeneous way



$\Rightarrow$ Production of gravity waves, carrying relic information about this epoch

Preheating: Explosive decay of the inflaton into large, non-thermal fluctuations of itself and other bosonic fields coupled to it

Non-perturbative production of particles, occupation numbers $n_k \sim 1/g^2 >> 1$

Non-linear classical random fields $\Rightarrow$ Lattice Simulations

Long, turbulent-like evolution towards thermal equilibrium

GW from Preheated Scalar Fields: Methods

[JFD, Bergman, Felder, Kofman, Uzan '07]

Evolve GW on the lattice, together with the scalar fields source

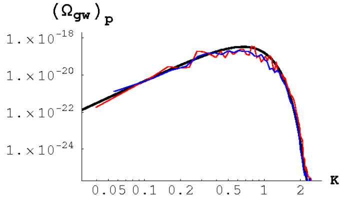
$$\ddot{h}_{ij} + 3\,\frac{\dot{a}}{a}\,\dot{h}_{ij} - \frac{\nabla^2}{a^2}\,h_{ij} = 8\pi G\,\Pi_{ij}^{TT}$$

Calculate $\rho_{\rm gw} \propto \langle \dot{h}_{ij}\dot{h}_{ij}\rangle \Rightarrow$ GW spectrum today: $h^2\,\Omega_{\rm gw} = \left(\frac{h^2}{\rho_c}\,\frac{d\rho_{\rm gw}}{d\ln f}\right)_0$

Linear stage of preheating:

Gaussian random fields and analytical evolution of the source

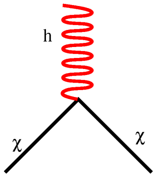
$\Rightarrow$ Check of the lattice results



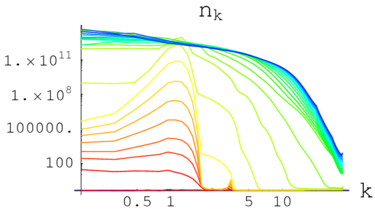
Turbulence and thermal bath

Scalar fields with $\chi_k(t) \propto \mathrm{Exp}[i\omega_k t]$
GW production *forbidden* by helicity conservation

Different for *massless* vector fields



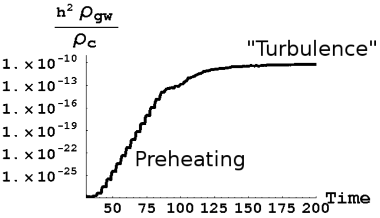
Most GW produced in intermediate non-linear and non-perturbative stage



The spectra of particles produced by preheating are strongly peaked around some typical (comoving) momentum k_*

$R_* = a/k_*$: Characteristic physical size of the source inhomogeneities

The final spectrum depends mainly on the characteristic size R_* ($< 1/H$) of the scalar field inhomogeneities amplified by preheating. This can be calculated analytically as a function of the parameters in a given model of inflation + preheating.



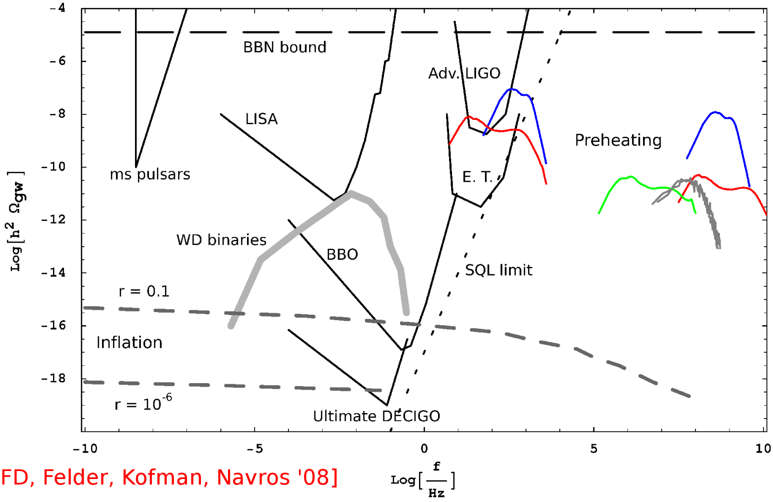
$\hookrightarrow$ **Peak frequency and amplitude of GW spectrum today:**

$$f_* \approx \frac{1}{(R_*\,H)_p}\left(\frac{\rho_{\rm tot}^{1/4}}{10^{11}\,{\rm GeV}}\right) 10^3\,{\rm Hz} \qquad , \qquad h^2\,\Omega^*_{\rm gw} \approx 10^{-6}\,(R_*\,H)_p^2$$

GW from Preheating in 3 Main Categories of Inflationary Models

Preheating after chaotic inflation: $f_* \sim 10^6 - 10^9$ Hz $\quad (\rho_{\rm inf}^{1/4} \sim 10^{15}$ GeV)

Preheating after hybrid inflation: GW cover a wide range of frequencies and amplitudes. Can be observable, but requires very small coupling constants



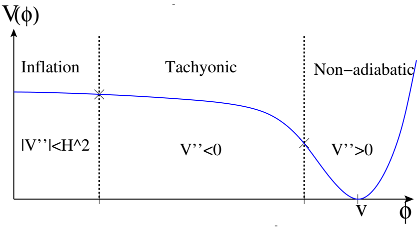
[JFD, Felder, Kofman, Navros '08]

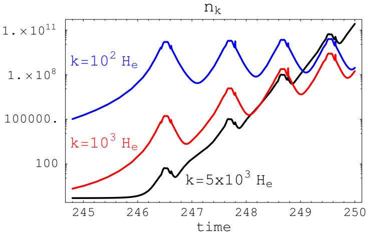
Preheating after Small Field Inflation [Brax, JFD, Mariadassou]

In these models, $V_{\rm inf}^{1/4}$ can be very small (Ex: [German, Ross, Sarkar])

$$V = M^4 \left[1 - f\left(\frac{\phi}{v}\right)\right] \quad \text{with} \quad f\left(\frac{\phi}{v}\right) \propto \frac{\phi^p}{v^p} \quad \text{for} \quad \phi \ll v$$

Preheating by tachyonic growths and *decreases* of inflaton fluctuations



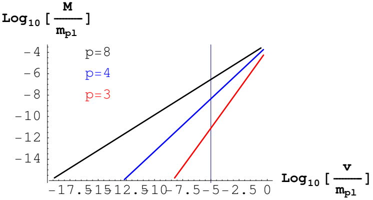


Preheating ends in one oscillation

for $v/m_{\rm Pl} \lesssim 10^{-5} \Rightarrow k_* \approx H$ (!!)

$$\Rightarrow f_* \approx \frac{M}{10^{10}\,{\rm GeV}}\, 10^3{\rm Hz} \quad , \quad h^2\,\Omega^*_{\rm gw} \approx 10^{-6}$$

Otherwise, GW at high frequencies if $p \neq 3$



Other Source: Flat Directions Condensates in Supersymmetric Theories

In SUSY theories, the potential for the scalar fields (e.g. super-partners of quarks and leptons) is flat along some directions in field space. The flatness is lifted by SUSY-breaking and non-renormalizable terms

$$V = m^2\,|\phi|^2 + \left(\frac{A\,m}{M_P^{n-3}}\,\phi^n + \mathrm{h.c.} \right) + \frac{|\lambda|^2}{M_P^{2n-6}}\,|\phi|^{2n-2} + \ldots \qquad (m \sim \mathrm{TeV})$$

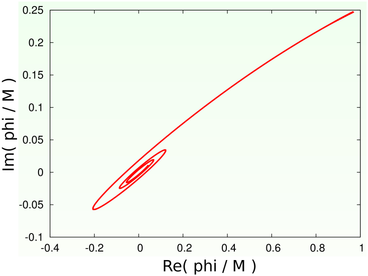
In the early universe:

[Dine, Randall, Thomas '95]

ϕ can acquire a very large VEV during inflation. Subsequent evolution damped untill $H \sim m$. Then, out-of-phase oscillations of Re(ϕ) and Im(ϕ).

Ex: Affleck-Dine baryogenesis

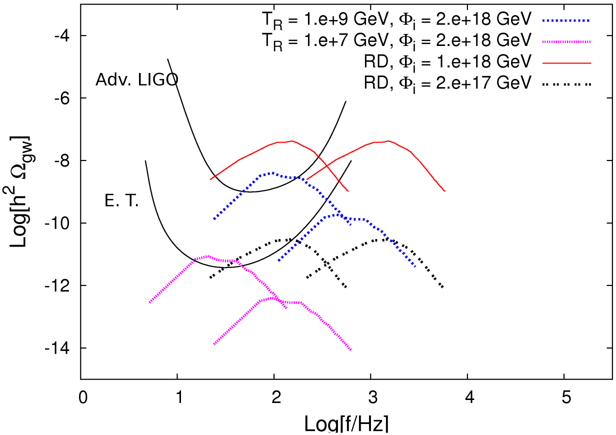
Specific non-perturbative decay channels exist for theses complex scalar fields **[Olive, Peloso '06], [Basboll et al '07], [Gümrükçüoğlu et al '08], ...**



GW from the Non-Perturbative Decay of Flat Directions [JFD '09]

Peak frequency and amplitude today:

$$f_* \sim \left(\frac{a_i}{a_r}\right)^{1/4} \sqrt{\frac{m}{\mathrm{TeV}}}\, 5 \times 10^2\,\mathrm{Hz} \quad , \quad h^2\,\Omega^*_{\rm gw} \sim 10^{-4} \left(\frac{\Phi_i}{M_P}\right)^4 \left(\frac{a_i}{a_r}\right)$$



Main parameters:

Soft SUSY-breaking mass $m \sim TeV$

a_i/a_r: depends on inflaton sector / thermal history of universe

Initial VEV Φ_i of condensate when it starts to oscillate. Needs to be large for GW to be observable (very flat directions)

GW from Abelian Gauge Fields at Preheating [JFD, Figueroa, Garcia-Bellido]

In realistic models, gauge fields also abundantly produced at preheating

Lead to new terms in anisotropic stress sourcing GW (**Ex:** $\Pi_{ij} \supset E_i E_j, B_i B_j$)

May enhance GW production from turbulent evolution towards thermal equilibrium after preheating ; but not in abelian scalar-gauge theories

Out-of-equilibrium gauge fields are also ubiquitous in other sources of GW (**Ex:** phase transitions, local topological defects).

Lattice simulations of gauge theories: (a nightmare...)

$$-\mathcal{L} = (D_\mu X)^* D^\mu X + \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \ldots \quad \text{with} \quad D_\mu = \partial_\mu - i\, e\, A_\mu$$

Gauge invariance is lost by naive discretization (**Ex:** $\partial_\mu^+ X = \frac{X(x+\hat{\mu}) - X(x)}{dx^\mu}$).

Links: $U_\mu(x, x+\hat{\mu}) \equiv e^{-ie \int_x^{x+\hat{\mu}} A_\mu dx^\mu} \quad \Rightarrow \quad D_\mu^+ X = \frac{U_\mu(x,x+\hat{\mu})\, X(x+\hat{\mu}) - X(x)}{dx^\mu}$

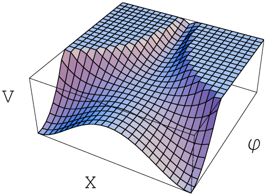
Derive discrete equations of motion from lattice action invariant under a lattice gauge transformation $\Rightarrow$ Constraint equations follow from dynamical equations that are evolved.

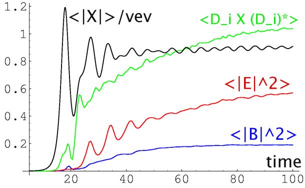
We developed method to compute GW production in scalar-gauge theories on lattice with second order accuracy in lattice spacing and timestep.

Model: Abelian-Higgs Preheating after Hybrid Inflation

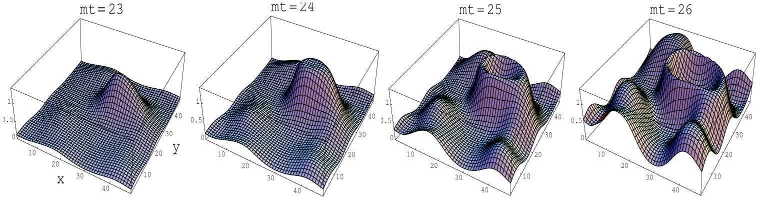
$$V = \frac{\lambda}{4}\left(|X|^2 - v^2\right)^2 + \frac{g^2}{2}\phi^2|X|^2 + V_{\rm sr}(\phi)$$

Inflaton ϕ coupled to waterfall ("Higgs") field X coupled to $U(1)$ gauge field A_μ. As X goes to its VEV after inflation, its fluctuations are amplified by tachyonic preheating and source the production of A_μ.

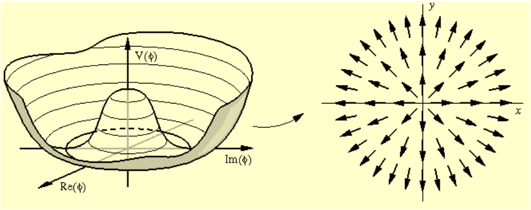




Spatial profile of X during symmetry breaking

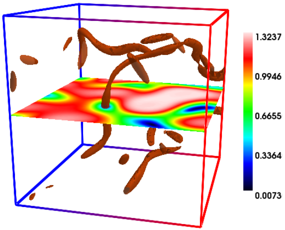


Abelian-Higgs Cosmic Strings during Preheating

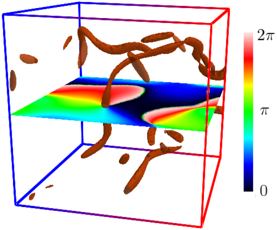


Points where $X = 0$ form line-like configuration with non-zero potential energy A_μ concentrates in those regions to minimize $\rho \supset |\partial_\mu X - ieA_\mu X|^2$

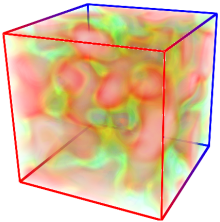
$|X|$-profile around B-strings



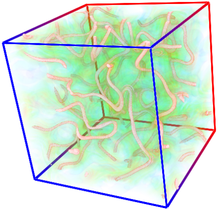
Arg(X)-profile around B-strings



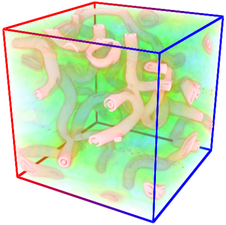
Spatial distributions during symmetry breaking



$|X|$

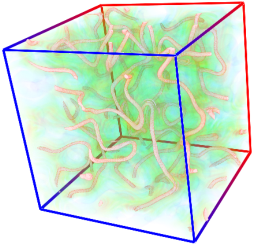


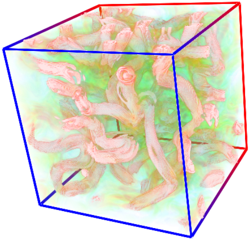
B^2

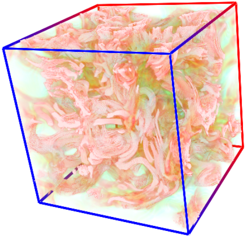


GW

Spatial distributions of $\vec{B}^2$ at different times







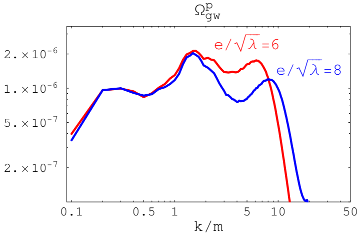
Signatures in the GW Spectra

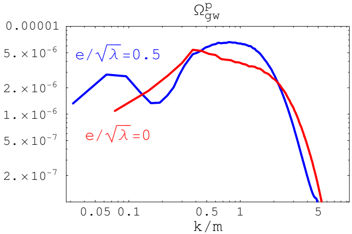
Three well-distinct characteristic scales:

Length of straight string segments $\gtrsim$ size of X-bubbles (R_*)

Width / interactions of X and A_μ around the strings (m_X and $m_A \gg R_*^{-1}$)

$\Rightarrow$ Three peaks in the GW spectra

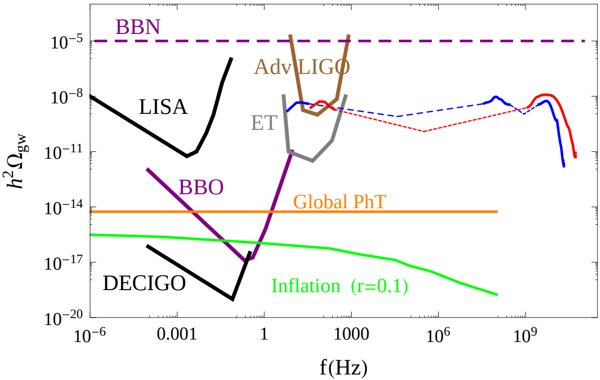




IR peak: $f_1 \lesssim \begin{cases} \lambda^{\frac{1}{4}}\, V_c^{\frac{1}{3}}\, 10^{11}\,\mathrm{Hz} & \text{for } g^2 \gtrsim \lambda \text{ and } V_c \gtrsim 500\, g^3 \\ \lambda^{\frac{1}{4}}\, g\, 10^{11}\,\mathrm{Hz} & \text{for } g^2 \gtrsim \lambda \text{ and } V_c \lesssim 500\, g^3 \\ \lambda^{\frac{1}{4}}\, \frac{g}{\sqrt{\lambda}}\, 10^{10}\,\mathrm{Hz} & \text{for } g^2 \ll \lambda \end{cases}$

Middle peak: $f_2 \approx \lambda^{1/4}\, 10^{11}\,\mathrm{Hz}$; UV peak: $f_3 \approx \frac{e}{\sqrt{\lambda}}\, \lambda^{1/4}\, 10^{11}\,\mathrm{Hz}$

GW Spectrum Today



$$h^2\,\Omega^*_{\rm gw} \sim \begin{cases} 10^{-6}\,V_c^{-2/3}\left(\frac{v}{M_{\rm Pl}}\right)^2 & \text{for} \quad g^2 \gtrsim \lambda \ \text{ and } \ V_c \gtrsim 500\,g^3 \\ \frac{10^{-8}}{g^2}\left(\frac{v}{M_{\rm Pl}}\right)^2 & \text{for} \quad g^2 \gtrsim \lambda \ \text{ and } \ V_c \lesssim 500\,g^3 \\ 10^{-5}\,\frac{\lambda}{g^2}\left(\frac{v}{M_{\rm Pl}}\right)^2 & \text{for} \quad g^2 \ll \lambda \end{cases}$$

Conclusions and Perspectives

- **There can be several instances in the early universe where scalar field condensates decay in an explosive and highly inhomogeneous way**. This generates a stochastic background of GW that carries unique informations about these high-energy phenomena.
- **For preheating after inflation**, these GW can be observable if inflation occurs at low enough energy scales (complementary to GW from inflation itself). Depending on the model, they can cover a wide range of frequencies and amplitude.
- **For the non-perturbative decay of SUSY flat directions**, these GW fall naturally in the Hz-kHz frequency range where ground interferometers operate. They carry informations on both SUSY (scale of SUSY breaking) and inflation (reheat temperature).
- In both cases, **gauge fields can have important consequences on GW production and leave specific imprints in the GW spectra**
- Non-abelian symmetries ($SU(2) \times U(1)$) necessary to produce **massless gauge fields** (photons) at preheating. $\Rightarrow$ GW production from long, turbulent evolution towards thermal equilibrium after preheating??
- **Non-perturbative decay of gauge flat directions** (Ex: MSSM). **[JFD, Gümrükçüoğlu, Peloso]**
- Applications to **other GW sources: cosmic strings, ...**