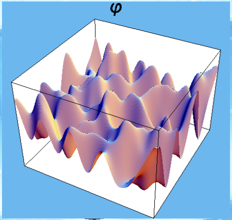
Jean-François Dufaux

IFT - UAM

Gravitational Waves from Cosmological Sources: The Non-Perturbative Decay of SUSY Flat Directions



JFD, Phys.Rev.Lett.103(2009) [arXiv:0902.2574]

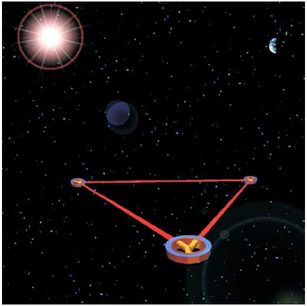
Gravitational Waves from the Early Universe

Propagate freely $\Rightarrow$ Direct probe of high-energy phenomena producing them

Target for several high-sensitivity interferometric experiments (LIGO, VIRGO, LISA, ET, BBO, DECIGO, ...) in frequency range 10^{-5} to 10^{3} Hz

Typical wavelength when produced: $\lambda_p < H_p^{-1}$ (post-inflationary source)
$\hookrightarrow$ Frequency today: $f_0 < 10^3\,\mathrm{Hz} \quad \Rightarrow \quad \rho_p^{1/4} < 10^{11}$ GeV , $H_p < 10$ TeV

Can they tell us something about Supersymmetry??



Supersymmetric Flat Directions

Combinations of complex scalar fields along which the renormalizable potential is exactly flat in the limit of unbroken SUSY.

Flatness lifted by SUSY-breaking and non-renormalizable terms

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

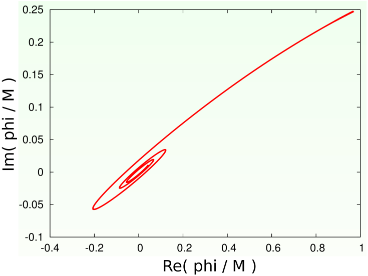
In the early universe:

[Dine, Randall, Thomas '95]

$$V \supset c\, H^2$$

(NB: $V \propto T^2$ for moderate VEV)

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

The Non-Perturbative Decay of Flat Direction Condensates

[Olive, Peloso '06], [Allahverdi, Mazumdar '06 '08], [Basboll et al '07], [Gümrükçüoğlu et al '08]

Model: $V_D = g^2 \left(|\phi_1|^2 - |\phi_2|^2 \right)^2$ (D-term potential)

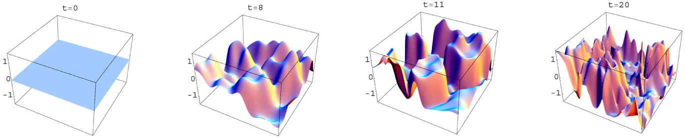
Background: $\phi_1 = \phi_2 = \Phi(t)\, e^{i\,\sigma(t)}$

Fluctuations around this background have the mass matrix:

$$\mathcal{M}^2 = g^2\, \Phi^2(t) \begin{pmatrix} 2\cos^2\sigma(t) & \sin 2\sigma(t) \\ \sin 2\sigma(t) & 2\sin^2\sigma(t) \end{pmatrix}$$

Eigenstates vary non-adiabatically with time $\Rightarrow$ abundant particle production

Once the fluctuations have been sufficiently amplified, they backreact on the condensate and convert most of its energy into large inhomogeneities [JFD '09]



$\Rightarrow$ **These inhomogeneities source a stochastic GW background**

Gravitational Waves from Preheating after Inflation

The non-perturbative decay of a scalar field condensate is typical in reheating after inflation, when the inflaton condensate decays and leads eventually to the thermal bath of the Hot Big Bang.

Non-perturbative effects in this context are called **preheating**

GW from preheating have been intensively studied recently

- **[Khlebnikov, Tkachev '97]**
- **[Garcia-Bellido '98]**, **[Garcia-Bellido, Figueroa '07]**, **[Garcia-Bellido, Figueroa, Sastre '07]**
- **[Easther, Lim '06]**, **[Easther, Giblin, Lim '07]**, **[Easther, Giblin, Lim '08]**
- **[JFD, Bergman, Felder, Kofman, Uzan '07]**, **[JFD, Felder, Kofman, Navros '08]**, **[Felder, Kofman '06]**
- **[Price, Siemens '08]**
- ...

We will apply and extend the methods developed in this context to the non-perturbative decay of SUSY flat directions

GW from Preheating: Methods

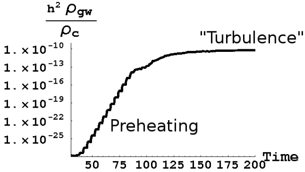
[JFD, Bergman, Felder, Kofman, Uzan '07]

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

$$h_{ij}'' + 2\,\frac{a'}{a}\,h_{ij}' - \nabla^2 h_{ij} = 16\pi G\, T_{ij}^{TT}$$

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

Most GW produced in intermediate "bubbly" stage. Final spectrum depends essentially on characteristic size R_* ($< 1/H$) of scalar field inhomogeneities amplified by preheating **[Felder, Kofman '06]**, similar to bubble collisions



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

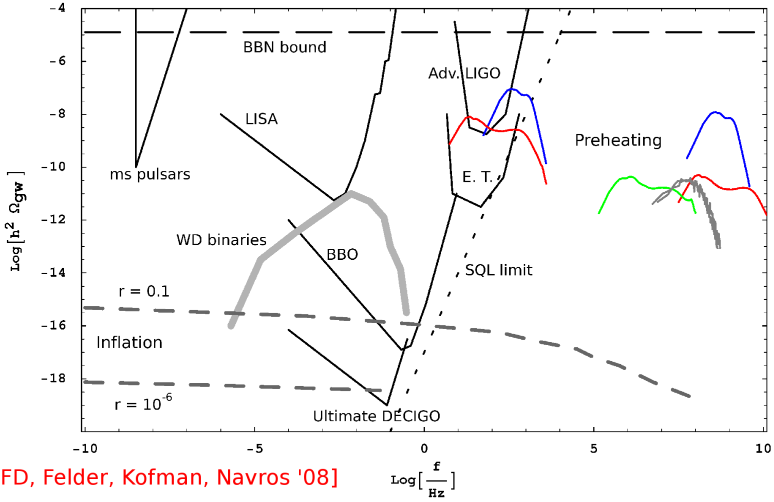
$$f_* \approx \frac{1}{(R_*\,H)_p}\left(\frac{\rho_{\rm tot}^{1/4}}{10^{11}\,{\rm GeV}}\right)10^3\,{\rm Hz} \quad , \quad h^2\,\Omega_{\rm gw}^* \approx 10^{-6}\,(R_*\,H)_p^2$$

$f_* < 10^3$ Hz difficult to achieve in concrete models

GW from Preheating Vs Observations: Status

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]

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

Main differences with respect to preheating after inflation:

- $1/R_* \sim H \sim m \sim \text{TeV} \quad \Rightarrow \quad$ GW frequency in the Hz-kHz range
- When they decay, flat directions are subdominant: $\rho_{\rm flat} < \rho_{\rm tot}$

  $\hookrightarrow \quad \Omega_{\rm gw} \propto (\rho_{\rm flat}/\rho_{\rm tot})^2$

  $\hookrightarrow \quad$ Equation of state and GW depend also on inflaton sector!!

Analytical estimates for the peak frequency and amplitude:

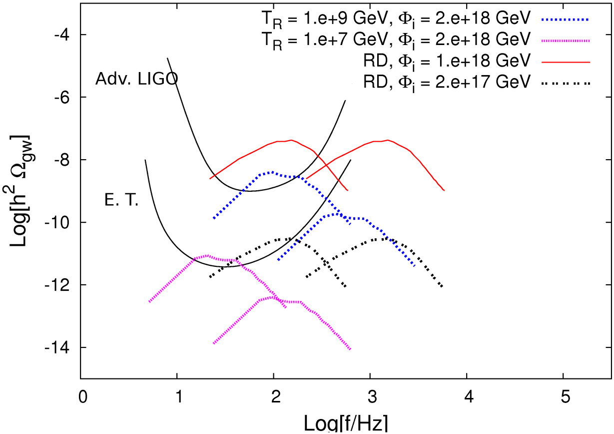
$$f_* \sim \left(\frac{a_i}{a_r}\right)^{1/4} \sqrt{\frac{m}{\rm TeV}}\, 5 \times 10^2\,{\rm Hz} \quad , \quad h^2\,\Omega^*_{\rm gw} \sim 10^{-4}\left(\frac{\Phi_i}{M_P}\right)^4 \left(\frac{a_i}{a_r}\right)$$

Key parameters: initial vev Φ_i of the condensate when it starts to oscillate, soft SUSY-breaking mass m and reheat temperature of the universe T_R

$a_i/a_r = 1 \quad \text{if} \quad T_R > 0.2\sqrt{m\,M_p}$ (radiation-domination during the decay)

$a_i/a_r \simeq \left(5\,T_R/\sqrt{m\,M_p}\right)^{4/3}$ otherwise (matter-domination during the decay)

GW spectra for $m = 100$ GeV (left) and $m = 10$ TeV (right)



Can be observable for high enough initial VEV, $\Phi_i > 10^{17}$ GeV

$\Phi_i \sim (m\, M_P^{n-3})^{1/(n-2)}$ depends on non-renormalizable terms ($W \supset \phi^n / M_P^{n-3}$)

MSSM flattest direction: $n = 9 \Rightarrow \Phi_i \sim 10^{16}$ GeV allowed by gauge invariance

But: may be forbidden by extra symmetries $\Rightarrow \Phi_i \sim M_P$ possible

[Dine, Randall, Thomas '95], [Gaillard, Murayama, Olive '95]

CONCLUSIONS

- **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 energy, but for the models studied so far, this requires very small coupling constants.
- **For the non-perturbative decay of SUSY flat directions**, these GW depend crucially on the initial VEV of flat direction condensates, on their soft SUSY-breaking mass and on the reheat temperature. They can be observable for high enough initial VEVs
- Only scalar field models have been studied so far.
  Vector fields can have important consequences on GW production
  [JFD, Figueroa, Garcia-Bellido], in preparation.
  For flat directions, they play already a crucial role in the linear stage. What is their effect on the subsequent dynamics ?
  [JFD, Gumrukcuoglu, Peloso], in progress