(Some) **Non-Equilibrium phenomena in the Early Universe**

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MITP, Mainz, July 28th, 2014.

I shall be talking about ...

0. **Context: The early Universe**

1. **Gravitational Waves: Probe of the early Universe**

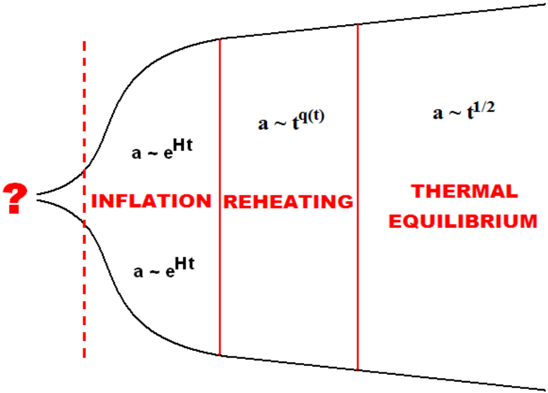
2. **Parametric Excitation $\Rightarrow$ Out-of-Eq. Dynamics $\Rightarrow$ GWs**

3. **Phase Transitions $\Rightarrow$ Cosmic Defects $\Rightarrow$ GWs**

0. Physical Context: The early Universe ($t < t_{\rm BBN} \sim 1{\rm s}$)

INFLATION $\longrightarrow$ **REHEATING** $\longrightarrow$ **THERMAL ERA**

(Particle Production,
PhTs, Cosmic Defects, ...)



1. Gravitational Waves (GWs) [Basics]

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

Eom: $h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = 16\pi G \Pi^{\mathrm{TT}}_{ij}$, $\quad \Pi_{ij} = T_{ij} - \langle T_{ij} \rangle_{\mathrm{FRW}}$

Transverse-Traceless (TT) dof carry energy out of the source!!!

- GW Source(s): (SCALARS , VECTOR , FERMIONS)

$$\Pi^{TT}_{ij} \quad \propto \quad \{\partial_i \chi^a \partial_j \chi^a\}^{TT}, \quad \{E_i E_j + B_i B_j\}^{TT}, \quad \{\bar{\psi}\gamma_i D_j \psi\}^{TT}$$

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   ADVANTAGE: GW DECOUPLE upon Production
   DISADVANTAGE: DIFFICULT DETECTION

2. **ADVANTAGE**: GW $\rightarrow$ Probe for Early Universe

   $$\rightarrow \left\{ \begin{array}{l} \textbf{Decouple} \rightarrow \text{Spectral Form Retained} \\ \textbf{Specific HEP} \;\Leftrightarrow\; \text{Specific GW} \end{array} \right.$$

3. **Physical Processes**:

   $$\left\{ \begin{array}{l} \text{Inflation} \\ \left. \begin{array}{l} \text{Reheating} \\ \text{Phase Transitions} \\ \text{Cosmic Defects} \\ \text{Turbulence?} \end{array} \right\} (\text{Post} - \text{Inflationary}) \end{array} \right.$$

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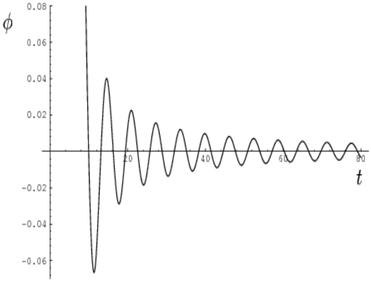
Contents ...

1. Parametric Excitation of fields

Scalar field (condensate) after Inflation:

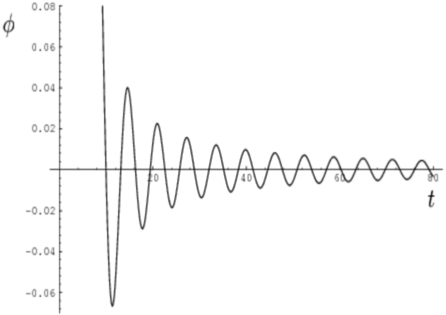
Coherent Oscillations: $\phi(t) \approx \Phi(t) f(t), \quad f(t+T) = f(t)$



1. Parametric Excitation of fields

Fermions: $y\phi\bar{\psi}\psi$: Oscillations $\rightarrow$ ψ – Particle Creation (Non-Pert., Out-of-Eq.)

$$\psi(\mathbf{x},t) = \int \frac{d\mathbf{k}}{(2\pi)^3}\, e^{-i\mathbf{k}\cdot\mathbf{x}} \left[\hat{a}_{\mathbf{k},r}\mathrm{u}_{\mathbf{k},r}(t) + \hat{b}^{\dagger}_{-\mathbf{k},r}\mathrm{v}_{\mathbf{k},r}(t)\right],$$



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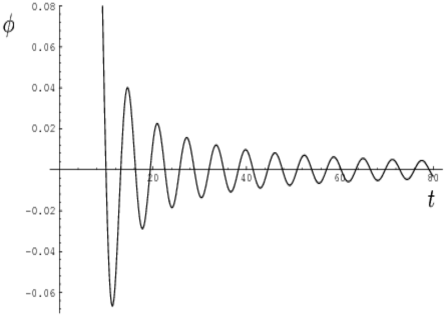

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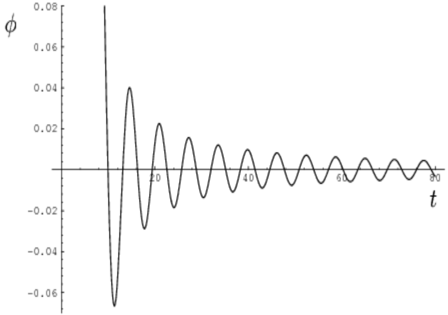

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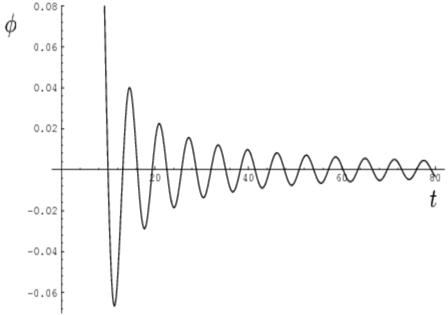

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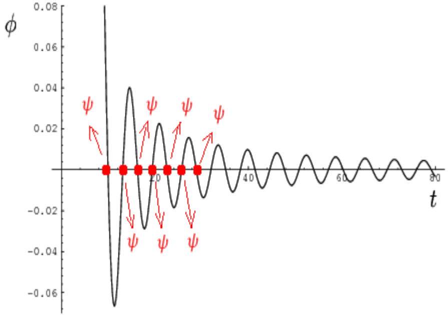

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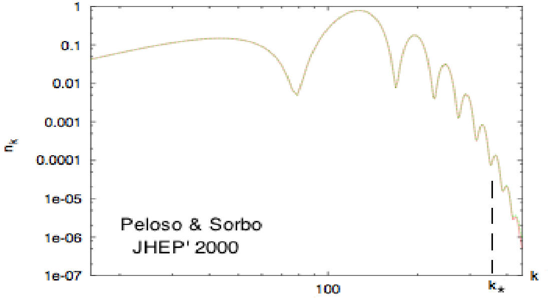

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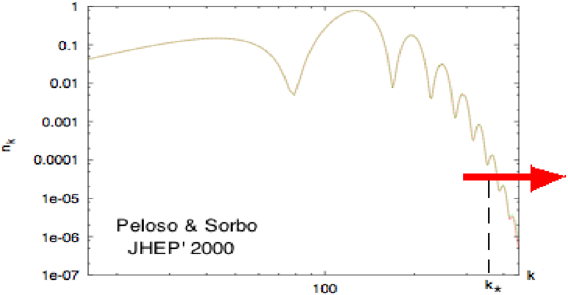
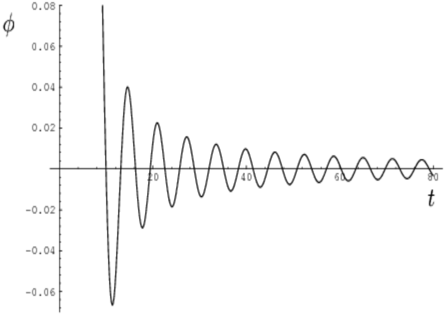


1. Parametric Excitation of fields

Bosons: $g^2\phi^2\chi^2$: Oscillations $\rightarrow$ χ – Particle Creation
(Non-Pert., Out-of-Eq.)

$$\frac{d^2}{dt^2}\chi_{\mathbf{k}} + \omega_{\mathbf{k}}^2(t)\chi_{\mathbf{k}}(t) = 0\,, \quad \omega_{\mathbf{k}}^2(t) = k^2 + a^2(t)g^2\phi^2(t)$$



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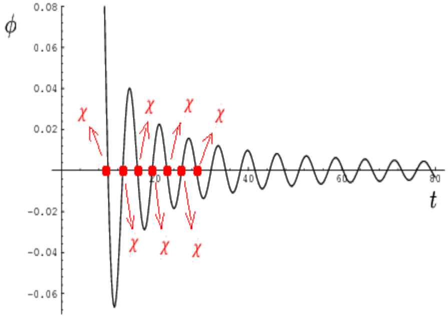

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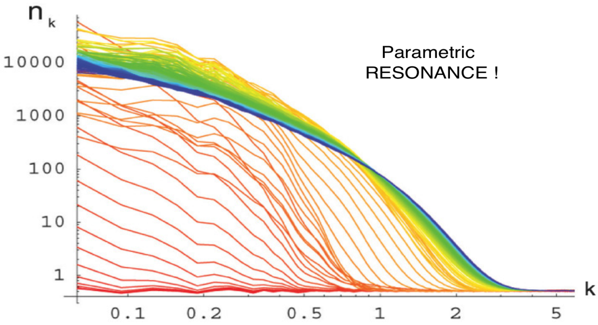

but... 'who' is ϕ?

"Traditionally" $\rightarrow$ ϕ : Inflaton $\Rightarrow$ (p)reheating!... but ...

.... only known scalar field $\rightarrow \phi$: SM higgs, so ...

... Option 1: SM higgs = inflaton? ($\Rightarrow$ Higgs-Inflation), or ...

... Option 2: SM higgs decoupled from Inflation? ($\Rightarrow$ Higgs-spectator)

SM HIGGS during INFLATION

Inflation: dS(H_*), $(H_* \gg v \equiv 246$ GeV)

SM Higgs: $\Phi = \frac{\varphi}{\sqrt{2}} \;\rightarrow\; V(\varphi) = \frac{\lambda(\mu)}{4}\varphi^4, \quad \mu = \varphi \gg v$

Prob. Dist: φ light $(|V''| < H_*^2) \Rightarrow \begin{cases} \text{Random Walk } (k < aH_*) \\ P_{\rm eq}(\varphi) \propto \text{Exp}\{-c\lambda_*(\varphi/H_*)^4\} \end{cases}$

End of Inflation: $\varphi_* = \alpha H_*/\lambda_*^{1/4} \qquad \alpha \in [0.01, 1]$ (98 %)

1.1 Parametric excitation of the SM fields, after Inflation

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End of Inflation: $\varphi_* \neq 0 \;\; (V \propto \varphi^4) \quad \Rightarrow \quad$ Higgs Oscillations (!)

Higgs Osc. $\to$ SM $\Psi^{(j)}, A_\mu^{(j)}$ Param. Exc. !

Fermions:

$$y_j \varphi \bar{\psi}_j \psi_j : \quad \frac{d^2}{d\tau^2} u_{k,\pm}^{(j)} + \left(\kappa^2 + q_j (a\varphi)^2 \pm i\sqrt{q_j}\,\frac{d}{d\tau}(a\varphi)\right) u_{k,\pm}^{(j)} = 0\,, \quad q_j \equiv \frac{y_j^2}{\lambda_{\rm I}}$$

$$j = \left\{ \begin{array}{c} \{t, b, c, s, u, d\} \\ \{e, \mu, \tau\} \end{array} \right\}$$

DGF 2014

Higgs Osc. $\to$ SM $\Psi^{(j)}, A_\mu^{(j)}$ Param. Exc. !

Bosons (Vectors):

$$g_j^2 \varphi A_\mu A^\mu : \quad \frac{d^2}{d\tau^2} u_k^{(j)} + \left(\kappa^2 + q_j (a\varphi)^2\right) u_k^{(j)} = N.L.\,, \quad q_j \equiv \frac{g_j^2}{\lambda_{\rm I}}$$

$$j = \left\{ \begin{array}{c} \{W_\mu^{1,2,3}, B_\mu\} \\ (\{W_\mu^{\pm}, Z_\mu\}) \end{array} \right\}$$

Enqvist et al 2013-2014, DGF et al 2014 (coming)

SM Fermions & Gauge Bosons Out-of-Eq $\rightarrow$ GWs !

IR-Sphere: $\left\{\begin{array}{c} n_k(k \lesssim k_*) \neq 1 \left\{\begin{array}{l} \lesssim 1(F), \\ \gg 1(B) \end{array}\right. \\ \\ n_k(k \gg k_*) \rightarrow 0 \end{array}\right\} \Rightarrow \; T_{**}^{(j)}, \sim \bar{\psi}\gamma\partial\psi,\; \partial A \partial A$

$$\left[\left(T_{\mu\nu}^{(j)}\right)^{\rm TT} \rightarrow \;\; \text{GW Source !} \right]$$

GWs: $\frac{d\rho_{\rm GW}}{d\log k}(k,t) \propto \frac{Gk^3}{a^4(t)} \int_0^t \int_0^t dt_1 dt_2\, \mathcal{G}(k, t_2 - t_1)\, \Pi^2(k, t_1, t_2)$

UTC: $\left\langle T_{ij}^{\rm TT}(\mathbf{k}, t_1)\, T_{ij}^{\rm TT}(\mathbf{k}', t_2) \right\rangle \equiv (2\pi)^3\, \Pi^2(k, t_1, t_2)\, \delta^{(3)}(\mathbf{k}-\mathbf{k}')$

DGF & Meriniemi 2013, DGF 2014 (F), DGF et al 2014 (B) [coming]

Higgs Osc. $\rightarrow$ SM Ψ's, A_μ's (Param. Exc.) $\rightarrow$ GWs

$$j = \left\{ \begin{array}{c} F : \{u, d\}, \{l^\pm\} \\ B : \{W^\pm, Z\} \end{array} \right\} \quad \Rightarrow \quad \Omega_{\rm GW}^{(j)}(k) \equiv \frac{1}{\rho_c}\frac{d\rho_{\rm GW}}{d\log k}(k; q_j)\,,$$

$$q_j \equiv \frac{y_j^2}{\lambda_{\rm I}}, \frac{g_j^2}{\lambda_{\rm I}}$$

Higgs Osc. $\to$ SM Ψ's, A_μ's (Param. Exc.) $\to$ GWs

Fermions:

$$n_k^{(j)}(k \lesssim k_*^{(j)}) \quad \to \quad \Omega_{\rm GW}^{(j)}(k) : \left\{ \begin{array}{l} k_p \sim k_*^{(j)} \;\; \text{(Max.)} \\ \propto k^3, \;\; k \ll k_p \\ \propto k^{-1.5}, \;\; k \gg k_p \end{array} \right\}$$

$$k_*^{(j)} \simeq q_j^{\frac{1}{4}} \sqrt{\lambda_{\rm I}} \varphi_{\rm I}$$

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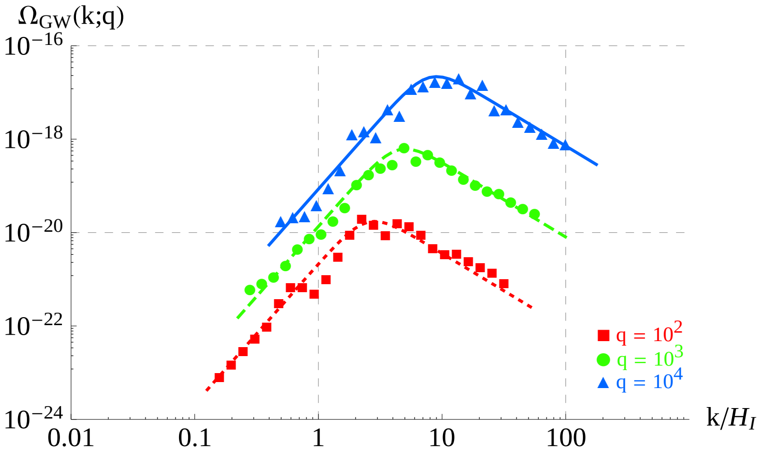
Bosons: Similar analysis !

$$n_k^{(j)}(k \lesssim k_*^{(j)}) \quad \rightarrow \quad \Omega_{\rm GW}^{(j)}(k), \quad j = W^\pm, Z$$

... numerical results only for Fermions (for Bosons coming!)

SM Ψ's Param. Exc. → GWs (Numerical Results)

From Fermions:



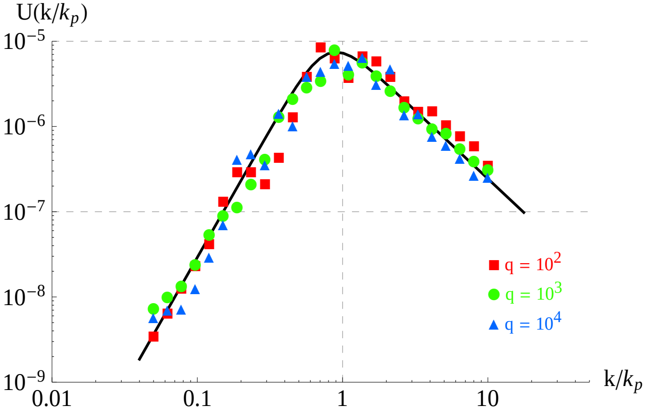
Higgs Osc. $\rightarrow$ SM Ψ's Param. Exc. $\rightarrow$ GWs

SCALING (Universal Shape) :

$$\Omega_{\rm GW}(k; q_j) = (H_{\rm I}/M_p)^4\,(a_{\rm I}/a_{\rm F})^{1-3w} \times {q_j}^{1.55}\,\mathcal{U}(k/k_p)$$

Higgs Osc. → SM Ψ's Param. Exc. → GWs

$$\mathcal{U}(x) \equiv \mathcal{U}_1 \frac{x^3}{(\alpha+\beta x^{4.5})}\,, \begin{cases} \mathcal{U}_1 \equiv \mathcal{U}(1)\ [\sim 10^{-5}(\mathrm{RD}), \sim 10^{-6}(\mathrm{MD})] \\ \alpha+\beta = 1\ \ [\alpha = 0.25, \beta = 0.75\ (\mathrm{RD}, \mathrm{MD})] \end{cases}$$



Higgs Osc. $\rightarrow$ SM Ψ's Param. Exc. $\rightarrow$ GWs

Total GWs :

$$h^2\Omega^{(0)}_{\rm GW}(f) \simeq \epsilon_{\rm I}\, 10^{-6}\, (H_{\rm I}/M_p)^4 \sum_j {q_j}^{1.55}\, \mathcal{U}({q_j}^{-1/4}(k/H_{\rm I}))$$

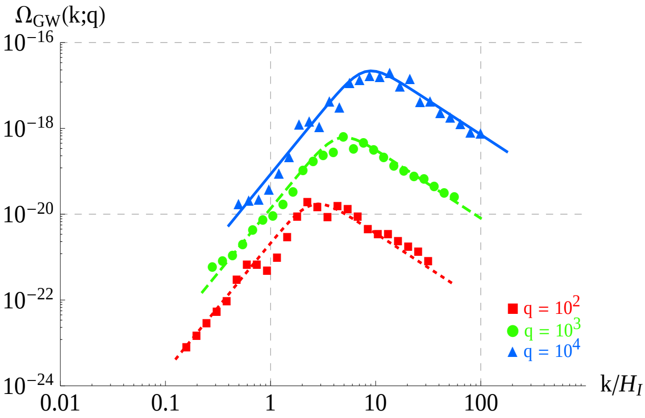
Higgs Osc. $\rightarrow$ SM Ψ's Param. Exc. $\rightarrow$ GWs

$$\text{SM Yukawa Couplings}: y_t > y_b > y_\tau > y_c > y_\mu \gtrsim y_s > y_d > y_u > y_e$$

$$h^2\Omega_{\rm GW}^{(0)}(f) \propto q^{3/2} \propto y^3 \Rightarrow \text{Top Quark dominates (!)}$$

Higgs Osc. → SM Ψ's Param. Exc. → GWs

Top Quark dominates (!)



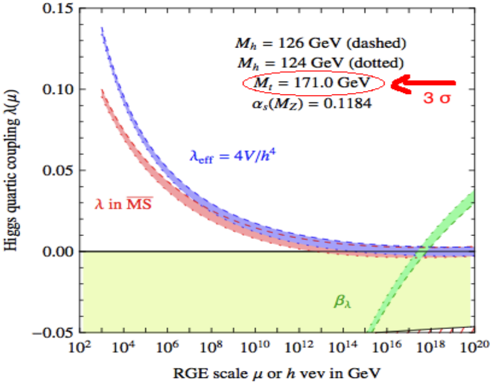
Higgs Osc. $\rightarrow$ SM Ψ's Param. Exc. $\rightarrow$ GWs

Top Quark GW Peak Today:
$(H_* \sim 10^{14}$ GeV, $y_t \sim 0.5)$

Today: $f_p^{(t)} \sim 10^7\,\mathrm{Hz}\,,\qquad h^2\Omega_{\rm GW}^{(\rm p)}\Big|_{\rm t} \sim 10^{-30}\,\lambda_{\rm I}^{-1.55}$

Higgs Osc. $\to$ SM Ψ's Param. Exc. $\to$ GWs

$$\lambda_{\rm I} \lesssim 10^{-7}, 10^{-10}, 10^{-11.5} \quad \Rightarrow \quad h^2\Omega_{\rm GW}^{\rm (p)}\big|_{\rm t} \gtrsim 10^{-20}, 10^{-15}, 10^{-12.5}$$



(Degrassi et al, 2012)

SM A_μ's Param. Resonance. $\to$ GWs (Enhancement?)

Bosonic Enhancement? Ohh Yes!

$$\Omega_{\rm GW}(k) \propto \sum_F {q_F}^{1.5+\delta_F}\,\mathcal{U}_F(k;q_F) \;+\; \sum_B {q_B}^{1.5+\delta_B}\,\mathcal{U}_B(k;q_B)$$

$$A \equiv \frac{\mathcal{U}_B(k;q)}{\mathcal{U}_F(k;q)} \gg 1 \;\Rightarrow\; \Omega_{\rm GW}^{\rm tot}(k) \sim \Omega_{\rm GW}^{(t)} + \Omega_{\rm GW}^{(W,Z)} \sim A \times \Omega_{\rm GW}^{(t)} \gg \Omega_{\rm GW}^{(t)}$$

including also gauge bosons ...

If Param. Resonance of W_μ, Z_μ included... IS THIS ALL?? **NO!**

Decay widths, backreaction, rescattering, thermalization

including also gauge bosons ...

Higgs		Children		Grand-Children
Φ	$\rightarrow$	Ψ_j, A_μ	$\rightarrow$	ψ_i, B_μ
	Non-Perturbative		Perturbative	

CHILDREN-PARTICLES:

$$n_k^{j+1} = \begin{cases} W_j(k) \\ + \ (2W_j(k)+1) n_k^j e^{-\Gamma_j \frac{T}{2}} \\ + \ 2\sqrt{n_k^j e^{-\Gamma_j \frac{T}{2}} (1 + n_k^j e^{-\Gamma_j \frac{T}{2}})} \sqrt{W_j(k)[W_j(k)+1]} \sin\theta_j \end{cases}$$

$W_j(k)$ → SPONTANEOUS

$(2W_j(k)+1) n_k^j e^{-\Gamma_j \frac{T}{2}}$ → STIMULATED

$2\sqrt{\ldots}\,\sin\theta_j$ → STOCHASTIC

GRAND-CHILDREN PARTICLES: $\tilde{n}_k^j = \sum_{i=1}^{j} (1 - e^{-\Gamma_i \frac{T}{2}}) n_k^i$

PERTURBATIVE DECAYS

including also gauge bosons ...

THEN...

Decay widths, backreaction, rescattering, thermalization
MUST BE INCLUDED!

Need: Kurkela & Moore thermalization like-studies!!

Contents ...

0. **Context: The early Universe** $\surd$

1. **Gravitational Waves: Probe of the early Universe** $\surd$

2. **Parametric Excitation $\Rightarrow$ Out-of-Eq. Dynamics $\Rightarrow$ GWs** $\surd$

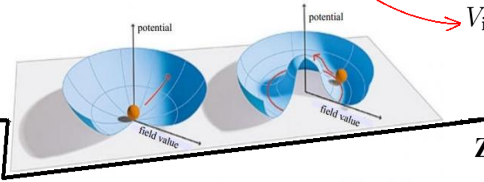
3. **Phase Transitions $\Rightarrow$ Cosmic Defects $\Rightarrow$ GWs**

3. SYMMETRY BREAKING → COSMIC DEFECTS

$$V = \frac{\lambda}{4}\left(|\Phi|^2 - v^2\right)^2 + V_{\rm int}(\Phi, \chi, T)$$

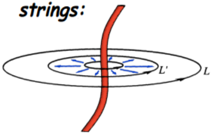
(1st Order, 2nd Order,Cross-Over)

$$V_{\rm int} \sim \begin{cases} g_T^2 |\Phi|^2 T^2 & (\text{THERMAL}) \\ g^2 |\Phi|^2 \chi^2 & (\text{FIELD INT.}) \end{cases}$$

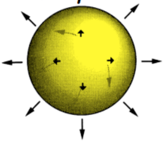


ZOOLOGY:

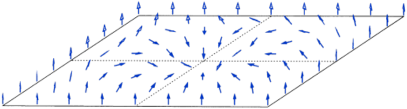
strings:



monopoles:



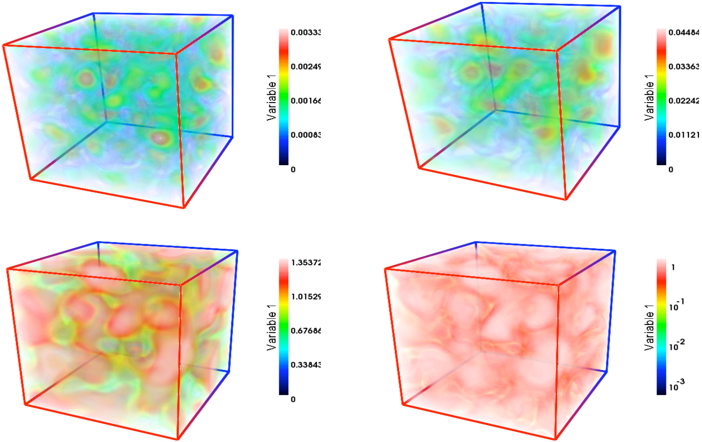
texture: (non-topological)



MICRO-PHYSICS → COSMIC DEFECTS

3. SYMMETRY BREAKING → COSMIC DEFECTS

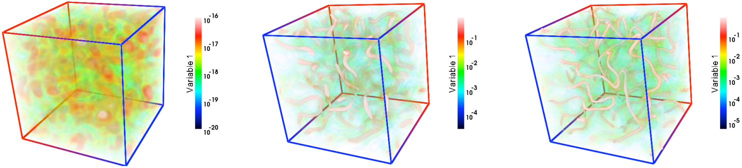
DYNAMICS OF THE HIGGS: Hybrid Preheating (Abelian-Higgs)
[Dufaux et al 2010]



3. SYMMETRY BREAKING → COSMIC DEFECTS

MAGNETIC FIELD DYNAMICS: Hybrid Preheating (Abelian-Higgs)

[Dufaux et al 2010]



Cosmic Defects not observed $\Rightarrow$ constraints !

CMB Temperature constraints:
$v \lesssim (5-10) \times 10^{15}$ GeV [Strings, O(4)-textures] [PLANCK team 2013]

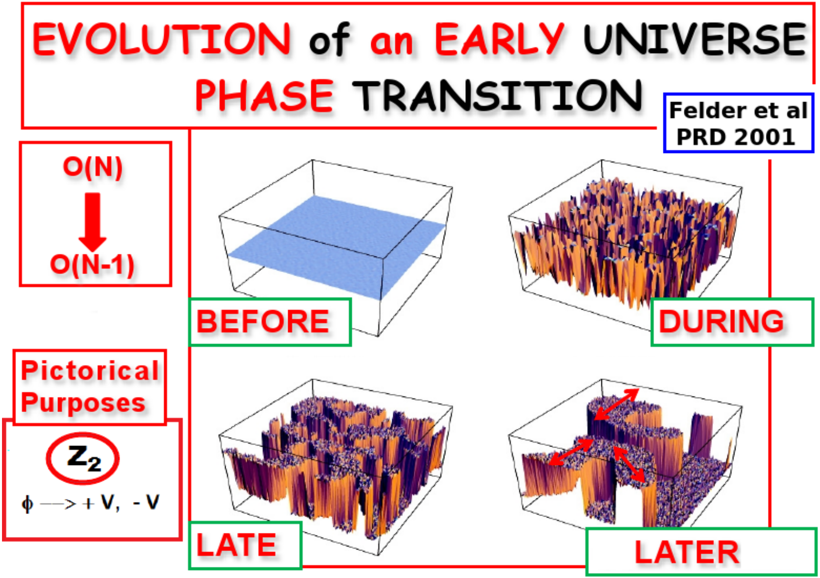
CMB Polarization constraints (BICEP2): $v \lesssim 5 \cdot 10^{15}$ **GeV**
[Lizarraga et al 2014 (local strings), Durrer et al 2014 (Global largeN)]

Let me focus on ...

3. **GRAVITATIONAL WAVES after SYMMETRY BREAKING:**

- **Sourced by NON-TOPOLOGICAL GLOBAL DEFECTS**
- **Sourced by GENERAL COSMIC DEFECTS**

GW from the aftermath of a GLOBAL PhT



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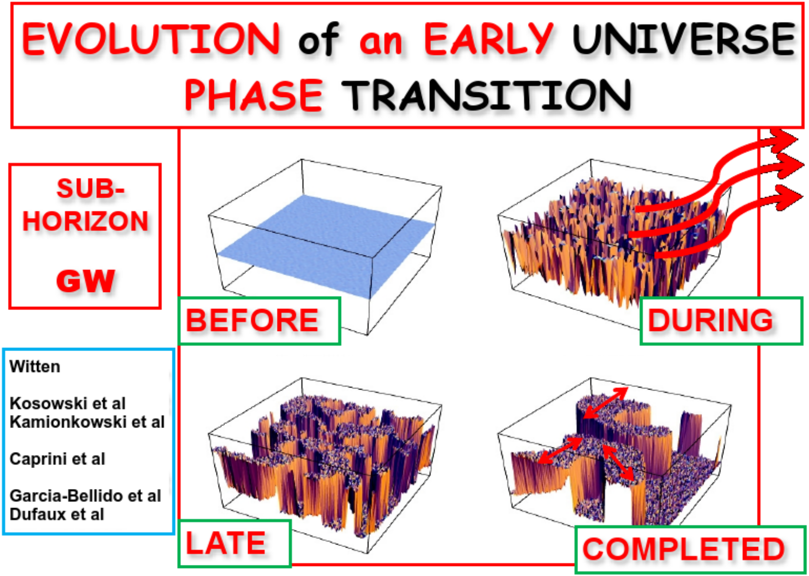

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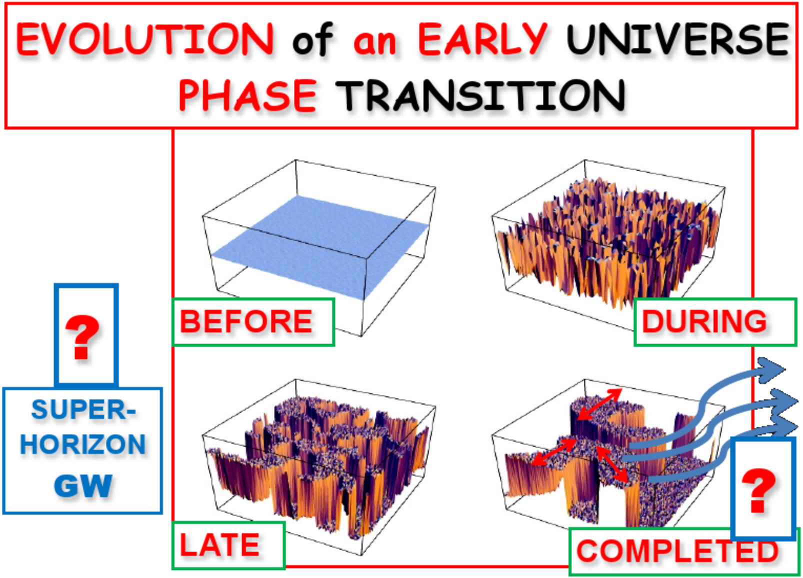
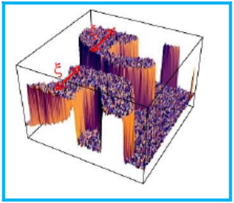


GLOBAL Phase Transition (with non-topological Defects)

After the PHASE TRANSITION
(NON-Linear SIGMA MODEL)



UNIVERSE EXPANDING
(CAUSAL HORIZON)

FIELD SELF-ORDERS
($\xi \uparrow\uparrow$, $\xi < 1/H$)

O(N) → O(N-1): $\begin{cases} \sum_a \phi_a^2 = v^2 & \textbf{(CONSTRAINT)} \\ \Box \phi_a + V'(\phi_a) = 0 & \textbf{(EOM)} \end{cases}$ ⇒ $\Box \phi_a + (\partial_\mu \phi_b \cdot \partial^\mu \phi_b)\, \phi_a = 0$

LARGE-N LIMIT: ($N \geq 4$) $\phi_a(k,\eta) = (k\eta)^{\frac{1}{2}-\gamma}\, C_1(k)\, J_{\gamma+1}(k\eta)$ ($a = \eta^\gamma$)

($k\eta_* < 1$, Super-Horizon Scales)

GLOBAL Phase Transition (with non-topological Defects)

GRAVITATIONAL WAVE BACKGROUND

$\phi_a(\mathbf{k},\eta) \rightarrow T_{\mu\nu}(\phi_a) \rightarrow \Pi^{TT}_{\mu\nu}(\phi_a) \rightarrow \Box h_{\mu\nu} = 16\pi G\, \Pi^{TT}_{\mu\nu}$

FIELD FLUCTUATIONS | STRESS tensor | ANISOTROPIC (TT) STRESS tensor | GW EQUATIONS (TT metric perturb.)

$$\rho_{GW} = \frac{<\dot{h}_{\mu\nu}\dot{h}^{\mu\nu}>}{16\pi G} = \int \frac{d\rho_{GW}(k,\eta)}{d\log k} d\log k \Rightarrow \Omega_{GW}(k,\eta) \equiv \frac{1}{\rho_c}\frac{d\rho_{GW}(k,\eta)}{d\log k}$$

TECHNICALLY

$$\Big(\langle \phi_a(\mathbf{k},\eta)\, \phi_a(\mathbf{k},\eta) \rangle \longrightarrow \langle \Pi^{TT}_{\mu\nu}(\phi_a)\Pi^{TT}_{\mu\nu}(\phi_a) \rangle \longrightarrow \langle \dot{h}_{\mu\nu}\, \dot{h}_{\mu\nu} \rangle \Big)$$

GLOBAL Phase Transition (with non-topological Defects)

GRAVITATIONAL WAVE BACKGROUND

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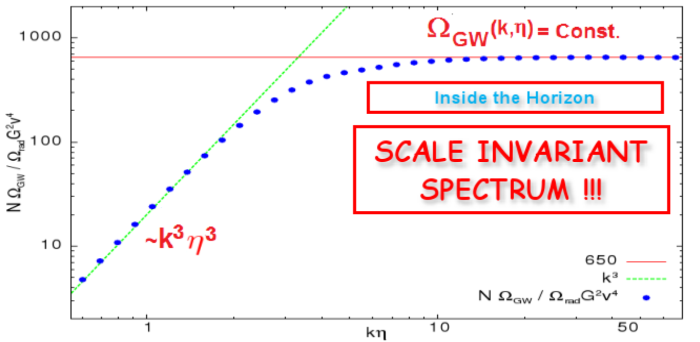

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FIELD FLUCTUATIONS | STRESS tensor | ANISOTROPIC (TT) STRESS tensor | GW EQUATIONS (TT metric perturb.)

SCALE INVARIANT SPECTRUM !!!

(FREQ. INDEPENDENT)

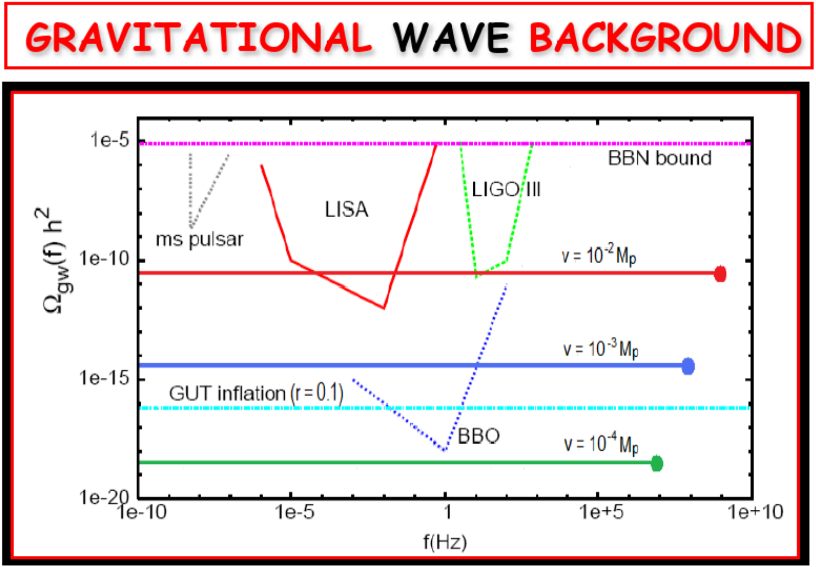
$$\Omega_{\rm GW}(k,\eta_0) \simeq \frac{651}{N}\Omega_{\rm rad}\left(\frac{v}{M_{\rm Pl}}\right)^4$$

$$\mathcal{R} \equiv \frac{\Omega_{\rm GW}(k,\eta_0)}{\Omega^{\rm (inf)}_{\rm GW}(k,\eta_0)} \simeq \frac{356}{N}$$

Jones-Smith et al, 2008

Fenu, DGF, Durrer, Garcia-Bellido 2009

Aftermath of GLOBAL PhT: Scale Inv SubH GW



Let us really focus on what I really want to talk about ...

1. **GRAVITATIONAL WAVES after SYMMETRY BREAKING:**
   - Sourced by NON-TOPOLOGICAL GLOBAL DEFECTS $\surd$
   - **Sourced by GENERAL COSMIC DEFECTS**

CAUSALITY & MICROPHYSICS $\rightarrow$ Cosmic Defects

DEFECTS: Aftermath of PhT $\rightarrow \left\{ \begin{array}{l} \left\{ \begin{array}{l} \text{Domain Walls} \\ \text{Cosmic Strings} \\ \text{Cosmic Monopoles} \end{array} \right. \\ \text{Non} - \text{Topological} \end{array} \right.$

DEFECTS: GW Source $\rightarrow \{T_{ij}\}^{\rm TT} \propto \{\partial_i\phi\partial_j\phi, E_iE_j, B_iB_j\}^{\rm TT}$

CAUSALITY & MICROPHYSICS $\Rightarrow$ Corr. Length: $\xi(t) = \lambda(t)\, H^{-1}(t)$

(Kibble' 76)

SCALING: $\left\{ \begin{array}{c} \lambda(t) = \text{const.} \rightarrow \lambda \sim 1 \Rightarrow k/\mathcal{H} = kt \\ \langle T_{ij}^{\rm TT}(\mathbf{k},t)T_{ij}^{\rm TT}(\mathbf{k}',t')\rangle = (2\pi)^3\ \frac{\rm V^4}{\sqrt{tt'}}\, U(kt,kt')\delta^3(\mathbf{k}-\mathbf{k}') \end{array} \right.$

CAUSALITY & MICROPHYSICS $\rightarrow$ Cosmic Defects

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CAUSALITY & MICROPHYSICS → Cosmic Defects

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Scaling Network of Cosmic Defects $\Rightarrow$ GW

GW spectrum $(kt \gg 1)$: Expansion UTC

$$\frac{d\rho_{\rm GW}}{d\log k}(k,t) \propto \frac{k^3}{M_p^2 a^4(t)} \int dt_1 dt_2 \; a(t_1)a(t_2) \; \cos(k(t_1 - t_2)) \; \Pi^2(k, t_1, t_2)$$

Scaling Network of Cosmic Defects $\Rightarrow$ GW

GW spectrum $(kt \gg 1)$: R.D. SCALING

$$\frac{d\rho_{\rm GW}}{d\log k}(k,t) \propto \frac{k^3}{M_p^2 a^4(t)} \int dt_1 dt_2 \; t_1 t_2 \; \cos(k(t_1 - t_2)) \; \frac{\mathrm{V}^4}{\sqrt{t_1 t_2}} U(kt_1, kt_2)$$

Scaling Network of Cosmic Defects ⇒ GW

GW spectrum $(kt \gg 1)$: $(x_i \equiv kt_i)$ R.D. and SCALING

$$\frac{d\rho_{\rm GW}}{d\log k}(k,t) \propto \left(\frac{\rm V}{M_p}\right)^4 \frac{M_p^2}{a^4(t)} \left[\int dx_1 dx_2 \; \sqrt{x_1 x_2} \; \cos(x_1 - x_2) \; U(x_1, x_2)\right]$$

Scaling Network of Cosmic Defects $\Rightarrow$ GW

GW spectrum $(kt \gg 1)$: SCALE INV.!

$$\frac{d\rho_{\rm GW}}{d\log k}(k,t) \propto \left(\frac{\rm V}{M_p}\right)^4 \frac{M_p^2}{a^4(t)}\, F_U\,, \quad F_U \sim {\rm Const.}\ ({\rm Dimensionless})$$

Scaling Network of Cosmic Defects ⇒ GW

GW today: [∀ PhT (1st, 2nd, ...), ∀ Defects (top. or non-top.)]

$$\Omega_{GW}^{(o)} \equiv \frac{1}{\rho_c^{(o)}}\left(\frac{d\rho_{\rm GW}}{d\log k}\right)_o = \frac{32}{3}\left(\frac{\rm V}{M_p}\right)^4 \Omega_{\rm rad}^{(o)}\, F_U\,, \quad \text{(SCALE INV.!)}$$

$$\frac{\Omega_{GW}^{Sim(N)}}{\Omega_{GW}^{(\rm Analytics)}} = \left\{\begin{array}{ll} 1.3, & ({\rm N}=12) \\ 1.8, & ({\rm N}=8) \\ 3.9, & ({\rm N}=4) \\ 7.3, & ({\rm N}=3) \\ 130, & ({\rm N}=2) \end{array}\right\}$$

LATTICE SIMULATIONS.!
GLOBAL SYM. BREAKING
$1024^3 \to U(x_1, x_2) \to F_U$

[DGF, Hindmarsh, Urrestilla '13]

$\rm V = M_I$, Strings: $\quad \frac{\Omega_{\rm GW}^{(o)}}{\Omega_{\rm GW}^{(\rm inf)}} \sim \mathcal{O}(10^3)$!

Contents ...

Summary I: SM Param. Excitations $\Rightarrow$ GWs

1. Inflation, $dS(H_*) \Rightarrow$ Higgs Osc.$\Rightarrow \Psi's$ (Param. Excitation).
2. $\{\Psi_a\} \rightarrow h^2\Omega_{\rm GW}^{(0)}(f) \propto q_a^{3/2} \propto y_a^3 \Rightarrow$ Top Quark dominates (!)
3. $0 < \lambda_{\rm I} \lll 1$, $H_* \sim 10^{14}$ GeV, Peak's Frequency: $f_* \sim 10^7$ Hz
   $h^2\Omega_{\rm GW}^{(\rm p)}\big|_{\rm t} \gtrsim 10^{-20}, 10^{-15}, 10^{-12.5}$ $(\lambda_{\rm I} \lesssim 10^{-7}, 10^{-10}, 10^{-11.5})$.
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1. Summary: Scale-Inv GW from Defects (PhT aftermath)

1. Global PhT, large-N limit: NLSM → Self-Ordering Scalar Fields

   Any PhT: Lattice Simulations → Numerical UTC

2. SCALING: $kt \gg 1 \Rightarrow \Omega_{GW}(k,t) = \text{Scale Inv.}$

   UNIVERSAL RESULT from ANY PhT!

3. For $VEV = M_I$, then $\Omega_{GW}/\Omega_{GW}^{\rm inf} \sim \mathcal{O}(10) - \mathcal{O}(10^3)$

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"This is the end, my only friend, the end, ...", The Doors

THANKS YOU FOR YOUR ATTENTION!!!

SM Param. Excitation REFERENCES:

- DGF, Meriniemi 2013
- Enqvist, Nurmi, Meriniemi & Rusak 2013, 2014
- DGF 2014
- Enqvist, Nurmi & Weir 2014 [coming]
- DGF, García-Bellido & Torrenti 2014 [coming]

Cosmic Defect REFERENCES:

- Jones-Smith, Dent & Krauss 2008
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- DGF, Hindmarsh & Urrestilla 2013
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