DEFECTS, a non-inflationary source of GW and NG

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GW: $\begin{cases} \text{Fenu, DGF, Durrer, Garcia-Bellido, JCAP '09} \\ \text{DGF, Hindmarsh, Urrestilla, WIP '12} \end{cases}$

NG: DGF, Caldwell, Kamionkowski, PRD '10

CCBPP, Benasque, Huesca, Spain, August 5-25, 2012.

I shall be talking about ...

1. **GRAVITATIONAL WAVES after SYMMETRY BREAKING**

2. **NON-GAUSSIANITY after SYMMETRY BREAKING**

I shall be talking about ...

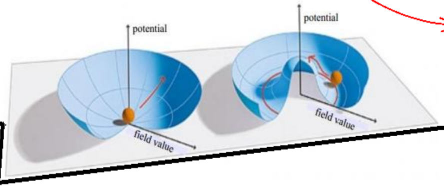
0. **BRIEF INTRODUCTION:**
   Symmetry Breaking (Phase Transition) $\leftrightarrow$ Cosmic Defects

1. **GRAVITATIONAL WAVES after SYMMETRY BREAKING**

2. **NON-GAUSSIANITY after SYMMETRY BREAKING**

0. SYMMETRY BREAKING $\rightarrow$ COSMIC DEFECTS

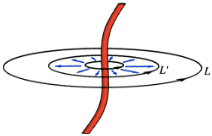
$$V = \frac{\lambda}{4}\left(|\Phi|^2 - v^2\right)^2 + V_{\rm int}(\Phi, \chi, T)$$



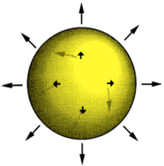
$$V_{\rm int} \sim \begin{cases} g_T^2 |\Phi|^2 T^2 & (\text{THERMAL}) \\ g^2 |\Phi|^2 \chi^2 & (\text{FIELD INT.}) \end{cases}$$

ZOOLOGY:

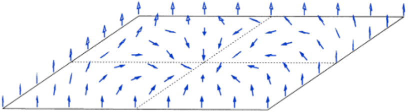
strings:



monopoles:

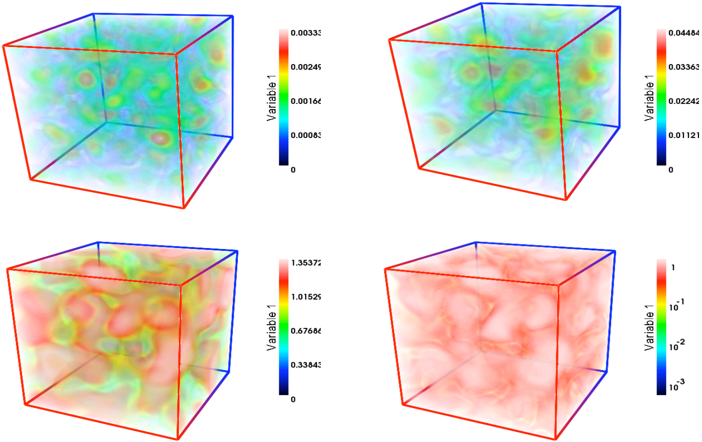


texture: (non-topological)



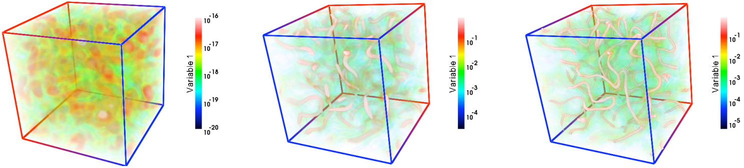
0. SYMMETRY BREAKING $\rightarrow$ COSMIC DEFECTS

DYNAMICS OF THE HIGGS: Hybrid Preheating (Abelian-Higgs)
[Dufaux, DGF, G^{a}-Bellido, PRD'10]



0. SYMMETRY BREAKING $\rightarrow$ COSMIC DEFECTS

MAGNETIC FIELD DYNAMICS: Hybrid Preheating (Abelian-Higgs)
[Dufaux, DGF, G^{a}-Bellido, PRD'10]



0. SYMMETRY BREAKING → COSMIC DEFECTS

SEE MARTIN KUNZ PRESENTATION

Let us focus on what I really shall be talking about ...

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

2. NON-GAUSSIANITY after SYMMETRY BREAKING:
   - Sourced by NON-TOPOLOGICAL GLOBAL DEFECTS
   - Sourced by GENERAL COSMIC DEFECTS

Gravitational Waves (Basics)

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

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

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

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

$$\Pi^{TT}_{ij} \propto \{\partial_i\chi^a\partial_j\chi^a\}^{TT}, \ \{E_iE_j + B_iB_j\}^{TT}, \ \{\bar\psi\gamma_i D_j\psi\}^{TT}$$

- GW Spectrum: $\frac{d\rho_{GW}}{d\log k}(k,t) \propto \frac{M_p^2 k^3}{a^4(t)}|\dot h|^2(k,t)$

$$\langle \dot h_{ij}(k,t)\dot h_{ij}(k',t)\rangle \equiv (2\pi)^3|\dot h|(k,t)\delta^3(\mathbf{k}-\mathbf{k}')$$

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GW from the aftermath of a Global PhT

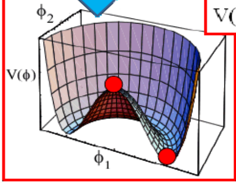
GLOBAL PHASE TRANSITION
(WITH NO TOPOLOGICAL DEFECTS)

$$V_{\rm int} \sim \begin{cases} g_{\rm T}^2|\Phi|^2 T^2 \\ g^2|\Phi|^2\chi^2 \end{cases}$$

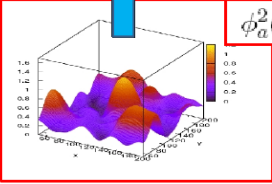
$$\underbrace{\Phi^{\rm T} = (\phi_1, \phi_2, ..., \phi_N)}$$
$$\Phi^{\rm T}\Phi = \sum_a \phi_a^2 = v^2$$

(SSB)

(V.E.V.)

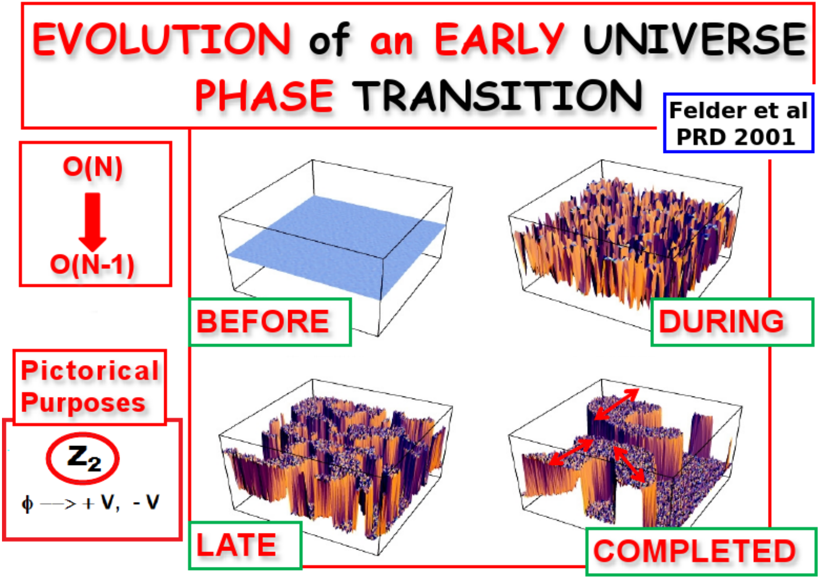


SYMMETRY BREAKING



1st, 2nd, CrossOver, ...

GW from the aftermath of a Global PhT



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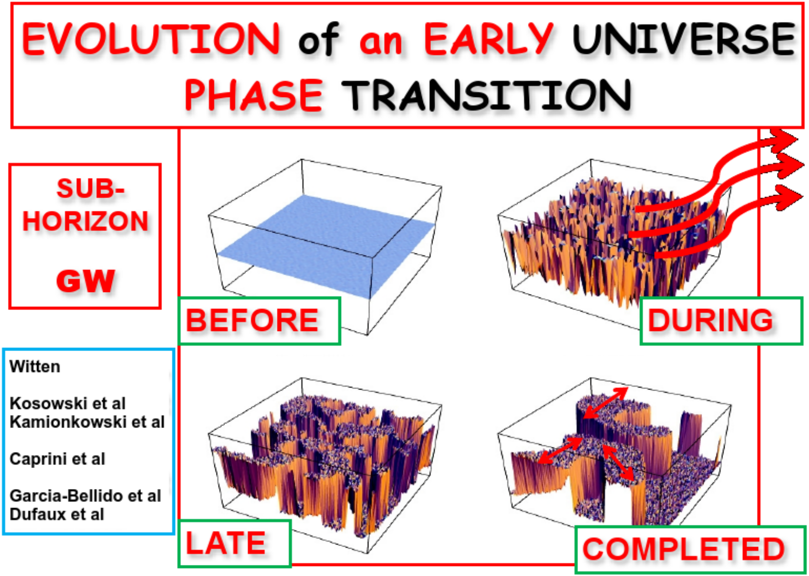


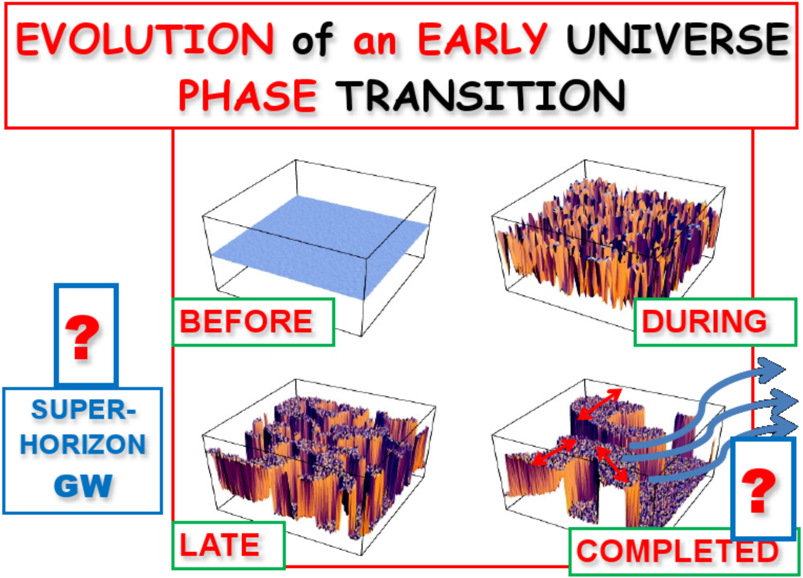
Witten

Kosowski et al
Kamionkowski et al

Caprini et al

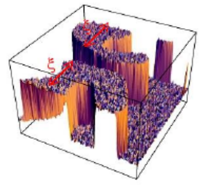
Garcia-Bellido et al
Dufaux et al

GW from the aftermath of a Global PhT



Aftermath of a Global Phase Transition

After the PHASE TRANSITION
(NON-Linear SIGMA MODEL)



UNIVERSE EXPANDING
(CAUSAL HORIZON)

FIELD SELF-ORDERS
(ξ ↑↑ , ξ < 1/H)

O(N) → O(N-1):

$$\begin{cases} \sum_a \phi_a^2 = v^2 & \textbf{(CONSTRAINT)} \\ \Box\phi_a + V'(\phi_a) = 0 & \textbf{(EOM)} \end{cases} \Rightarrow \boxed{\Box\phi_a + (\partial_\mu\phi_b \cdot \partial^\mu\phi_b)\,\phi_a = 0}$$

LARGE-N LIMIT: $(N \geq 4)$

$$\boxed{\phi_a(\mathbf{k},\eta) = (k\eta)^{\frac{1}{2}-\gamma}\, C_1(\mathbf{k})\, J_{\gamma+1}(k\eta)} \quad (a = \eta^{\gamma})$$

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

Aftermath of a Global Phase Transition

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.)

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

TECHNICALLY

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

Aftermath of a Global Phase Transition

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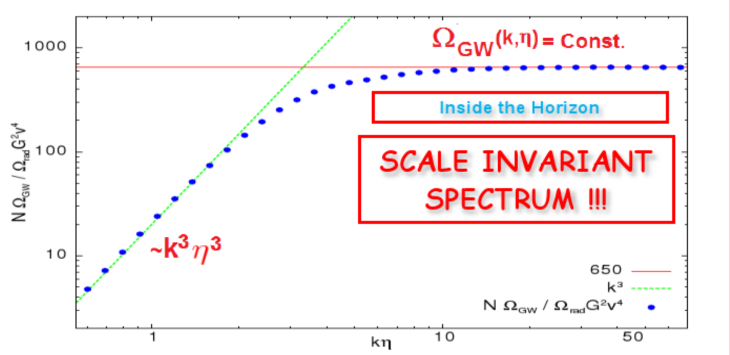

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FIELD FLUCTUATIONS	STRESS tensor	ANISOTROPIC (TT) STRESS tensor	GW EQUATIONS (TT metric perturb.)

SCALE INVARIANT SPECTRUM !!!

(FREQ. INDEPENDENT)

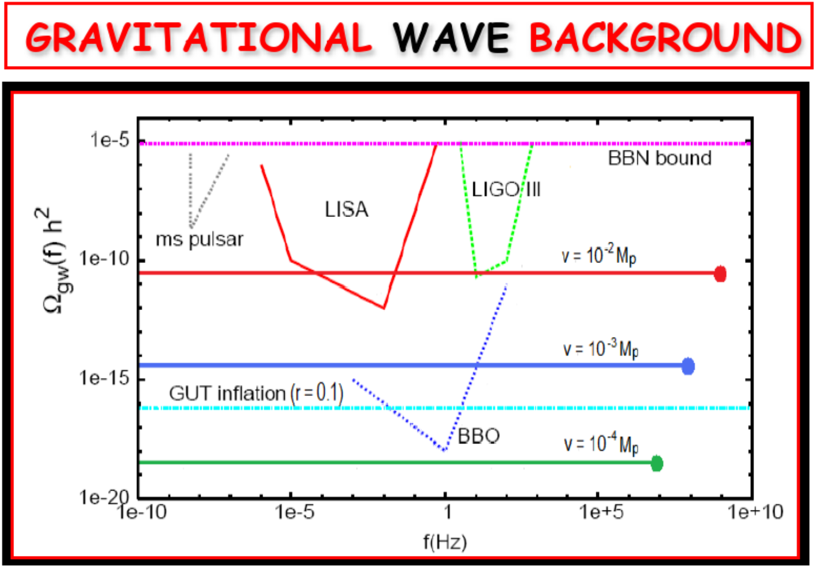
$$\Omega_{\rm GW}(k,\eta_0) \simeq \frac{651}{N}\Omega_{\rm rad}\left(\frac{v}{M_{\rm Pl}}\right)^4$$

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

Jones-Smith et al, 2008

Fenu, DGF, Durrer, Garcia-Bellido 2009

Aftermath of Global PhT: Scale Inv SubH GW



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CAUSALITY & MICROPHYSICS $\rightarrow$ Cosmic Defects

DEFECTS: Aftermath of PhT $\rightarrow \left\{ \begin{array}{l} \left\{ \begin{array}{l} \text{Domain Walls } (N=1) \\ \text{Cosmic Strings } (N=2) \\ \text{Cosmic Monopoles } (N=3) \end{array} \right. \\ \text{Non} - \text{Topological } (N \geq 4) \end{array} \right.$

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: $\xi(t) = \lambda(t)\, H^{-1}(t)$

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

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Scaling Network of Cosmic Defects ⇒ GW

GW spectrum:

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

Scaling Network of Cosmic Defects $\Rightarrow$ GW

GW spectrum: 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 $\Rightarrow$ GW

GW spectrum: $(x_i \equiv k t_i)$ 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: SCALE INV.!

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

Scaling Network of Cosmic Defects ⇒ GW

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

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

$$F_U = \left\{\begin{array}{ll} \frac{6000}{N}, & \text{Large} - \text{N limit} \\ 500, & (\text{N} = 12) \\ 1000, & (\text{N} = 8) \\ 3000, & (\text{N} = 4) \\ 20\cdot 10^3, & (\text{N} = 2) \end{array}\right\}$$

PRELIMINAR RESULTS!
$UTC \rightarrow$ LatticeSims.
(DGF, Hindmarsh, Urrestilla)

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

1. Summary: Scale-Inv GW from Defects (PhT aftermath)

1. Global PhT, large-N limit: NLSM →Self-Ordering Scalar Fields
   Any PhT: Lattice Simulations. Numerics → UETC
2. SCALING: $k\eta_* \ll 1 \to k\eta \gg 1 : \Omega_{GW}(k,\eta) = \text{Scale Inv.}$
   UNIVERSAL RESULT from ANY PhT!
3. For $VEV = M_I$, then $\Omega_{GW}/\Omega_{GW}^{\rm inf} \sim \mathcal{O}(10) - \mathcal{O}(10^3)$
   GW Direct Detection: Scale-Inv GW not a smoking gun of Inflation

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MATTER PERTURB. AFTER GLOBAL PhT

A. Jaffe '93: $\delta(\mathbf{x},\eta) = \frac{2\pi G}{5}\eta^2 \int d\eta' \, \partial_i T_{0i}(\mathbf{x},\eta')\,,$ (MATTER DOMINATION)

Aftermath Global PhT: Matter Perturbations

MATTER PERTURB. AFTER GLOBAL PhT

$$\delta(\mathbf{x},\eta) = \frac{2\pi G}{5}\eta^2 \int d\eta' \, \partial_i T_{0i}(\mathbf{x},\eta') \,, \quad \left(\text{MATTER DOMINATION}\right)$$

Matter Density Perturbations

C

Energy-Momentum Tensor

$$\boxed{T_{0i} = (\partial_0 \phi^a)(\partial_i \phi^a)} \quad \text{(BI-LINEAR)}$$

$$\left(\phi^a(\mathbf{k},\eta) = C_1(\mathbf{k})\,(k\eta)^{\frac{1}{2}-\gamma} J_\nu(k\eta)\right)$$

MATTER PERTURB. AFTER GLOBAL PhT

$$\delta(\mathbf{x},\eta) = \frac{2\pi G}{5}\eta^2 \int d\eta'\, \partial_i(\partial_0\phi^a)(\partial_i\phi^a) \qquad A = \frac{16}{2835\pi^3}$$

$$\langle \delta(\mathbf{k})\delta(\mathbf{k}')\rangle = (2\pi)^3\, \delta_D(\mathbf{k}+\mathbf{k}')\, P^\sigma(k),$$

2-Point Correlator

$$P^\sigma(k,\eta) \equiv \frac{C^2\eta^4}{A^2}\frac{k}{N} g_2,$$

Power Spectrum

$$g_2 \equiv \int \frac{d^3v}{(2\pi)^3}\, [\mathcal{I}(v, |\hat{\mathbf{k}} - \mathbf{v}|)]^2\ (\hat{\mathbf{k}}\cdot\mathbf{v})\ [2(\hat{\mathbf{k}}\cdot\mathbf{v}) - 1]$$

$$\left(\mathcal{I}(a,b) \equiv \int ds \frac{f(as)f'(bs)}{a^{3/2}b^{1/2}}, \quad f(x) \equiv x^{1/2-\alpha}J_\nu(x) \right)$$

MATTER PERTURB. AFTER GLOBAL PhT

Gaussian φ_a

$$\delta(\mathbf{x},\eta) = \frac{2\pi G}{5}\eta^2 \int d\eta'\, \partial_i T_{0i}(\mathbf{x},\eta')\,,$$

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2-Point Correlator

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Power Spectrum

$$\zeta(\mathbf{k}) = -\frac{5}{2}\left(\frac{aH}{k}\right)^2 \delta(\mathbf{k})\,,$$

Curvature Perturbations

$$\Delta^2_{\mathcal{R}\sigma} \equiv \frac{k^3}{2\pi^2}P_{\zeta}(k) \simeq 80\left(\frac{v}{M_{\rm Pl}}\right)^4\frac{1}{N}$$

Curvature Power Spectrum

Physical Constraints

$$\frac{v}{N^{1/4}} = \left(\frac{p_{\sigma}A^2\Delta^2_{\mathcal{R}}}{8G^2_{\rm sw}g_2}\right)^{1/4} M_{\rm Pl} \lesssim \frac{M_{\rm Pl}}{2000} \qquad \begin{pmatrix} G_{\rm sw} = 10 \\ p_{\sigma} = 0.1 \end{pmatrix}$$

Aftermath Global PhT: Non-Gaussianity

NON-GAUSSIANITY AFTER GLOBAL PhT

$$\boxed{\langle \delta(\mathbf{k}_1)\delta(\mathbf{k}_2)\delta(\mathbf{k}_3)\rangle = (2\pi)^3 \delta_D(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3) B(k_1, k_2, k_3)}$$

(3-Point Correlator) (Bispectrum)

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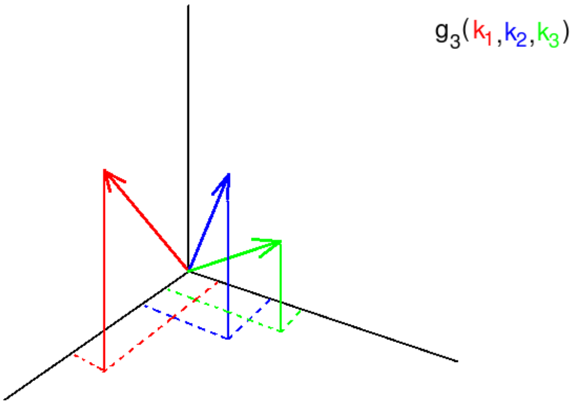

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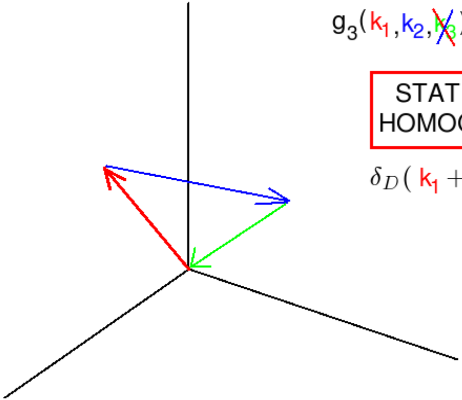


$$g_3(k_1, k_2, \cancel{k_3}) = g_3(k_1, k_2)$$

$$\boxed{\text{STATISTICAL HOMOGENEITY}}$$

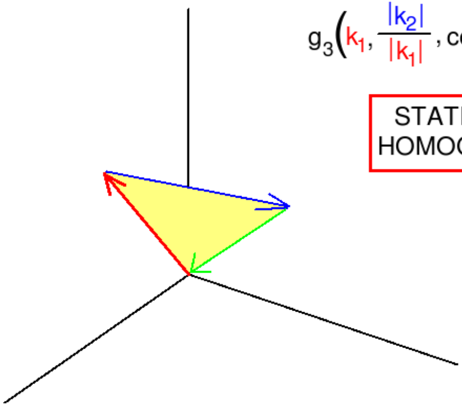
$$\delta_D(k_1 + k_2 + k_3)$$

Aftermath Global PhT: Non-Gaussianity

NON-GAUSSIANITY AFTER GLOBAL PhT

$$g_3\left(k_1, \frac{|k_2|}{|k_1|}, \cos(k_1, k_2), \right)$$

STATISTICAL
HOMOGENEITY



Aftermath Global PhT: Non-Gaussianity

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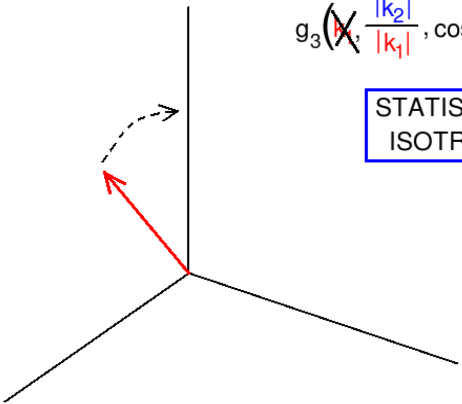


$$g_3\left(\cancel{k_1}, \frac{|k_2|}{|k_1|}, \cos(k_1,k_2), \quad \right)$$

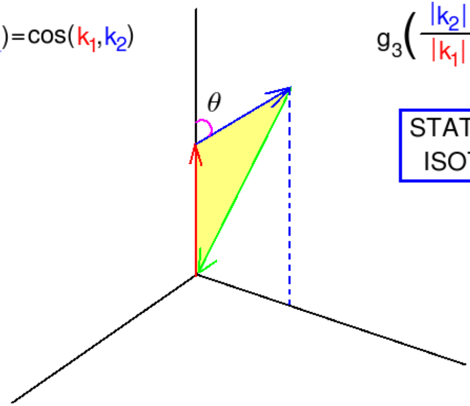
STATISTICAL ISOTROPY

Aftermath Global PhT: Non-Gaussianity

NON-GAUSSIANITY AFTER GLOBAL PhT

$\cos(\theta) = \cos(k_1, k_2)$

$$g_3\left(\frac{|k_2|}{|k_1|}, \theta, \triangle\right)$$



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(3-Point Correlator)

$$B(k_1,k_2,k_3) = \frac{C^3 \eta^6}{A^3 N^2} g_3(k_1,k_2,k_3)$$

$$g_3(k_1,k_2,k_3) \equiv \int \frac{d^3 v}{(2\pi)^3} H(\mathbf{k}_2+\mathbf{v},\mathbf{v}) \times H(\mathbf{v},\mathbf{k}_1-\mathbf{v}) H(\mathbf{k}_1-\mathbf{v},\mathbf{k}_2+\mathbf{v})$$

$$\left[\ H(\mathbf{a},\mathbf{b}) \equiv I(a,b)(b^2-a^2)\ \right]$$

Aftermath Global PhT: Non-Gaussianity

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(Bispectrum)

$$\boxed{\langle \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\rangle = (2\pi)^3 \delta_D(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3) F(k_1,k_2,k_3)}$$

Curvature Bi-Spectrum

$$\boxed{F^\sigma(k_1,k_2,k_3) = -\frac{2\sqrt{2}\pi^3 \Delta^3_{\mathcal{R}\sigma}}{g_2^{3/2} N^{1/2}} \frac{g_3(k_1,k_2,k_3)}{k_1^2 k_2^2 k_3^2}}$$

DGF, Caldwell, Kamionkowski, PRD'10

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(Bispectrum)

Comparing with

Local Model

$$\boxed{f_{\rm nl}^{\sigma} \simeq 390 \times \left(\frac{v}{10^{16}\,\mathrm{GeV}}\right)^6 \left(\frac{N}{5}\right)^{-2}} \times \left(\frac{g_3(k_1,k_2,k_3)}{g_3(1,1,1)}\right)$$

(for equilateral configurations)

$$\left.\begin{array}{l} v \sim \mathrm{GUT} \\ N = 5 \end{array}\right\} \longrightarrow \boxed{f_{\rm nl} \sim O(10^2)} \quad \left(\begin{array}{l} G_{\rm sw} = 10 \\ p_\sigma = 0.1 \end{array}\right)$$

Aftermath Global PhT: Non-Gaussianity

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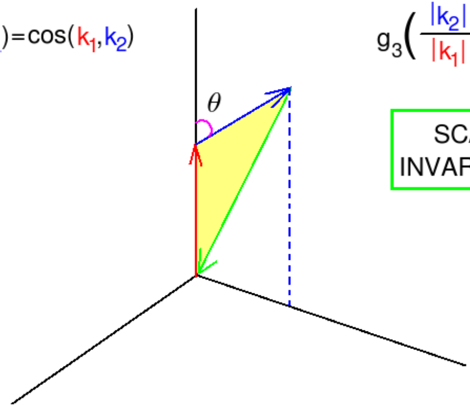
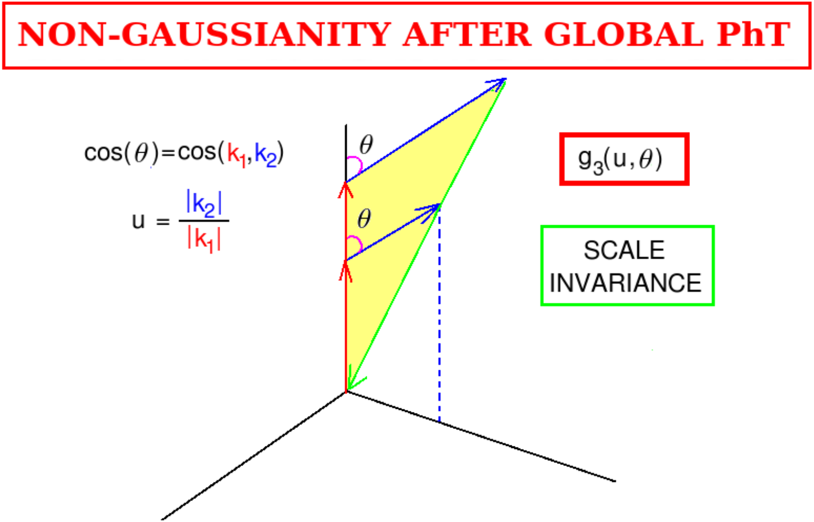
$\cos(\theta) = \cos(k_1, k_2)$



$g_3\left(\frac{|k_2|}{|k_1|}, \theta, \cancel{\triangle}\right)$

SCALE INVARIANCE

Aftermath Global PhT: Non-Gaussianity



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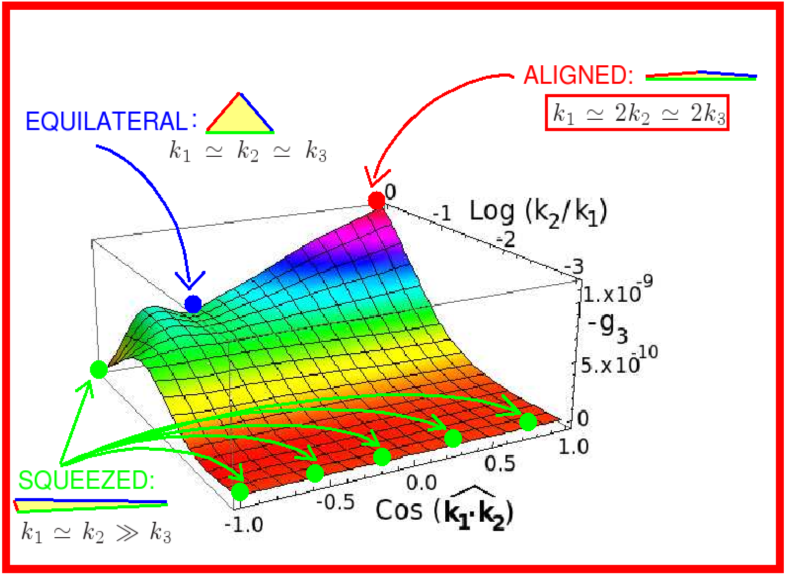

Something else I want to talk about? more NG?

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

2. NON-GAUSSIANITY after SYMMETRY BREAKING:
   - **Sourced by NON-TOPOLOGICAL GLOBAL DEFECTS** $\surd$
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NG from general defects: Work In Progress !

* A. Jaffe's $\delta(\mathbf{x}, t) \leftrightarrow T_{ij}(\varphi_a)$, Correct ?

* Large-N Global PhT: $\Phi_{\rm s}(k, t) \leftrightarrow \varphi_i(k, t)$ (NLSM) $\Rightarrow$
"Exact" NG from Global non-topological defects (DGF, WIP'12)

* 3-point Corr. Functions from lattice Simulations: All Defects!
(Daverio, DGF, Hindmarsh, ..., WIP)

* 3-point Matter Corr. from Strings, analytical considerations
(Hindmarsh & Regan, WIP'12)

2. Summary: NG from Defects (PhT aftermath)

1. Global PhT, large-N limit: $B(k_2/k_1, \cos\theta_{12})$
   Peaked at FOLDED Config. $(k_1 = 2k_2 = 2k_3)$,
   also powered at EQUILATERAL Config. $(k_1 = k_2 = k_3)$
2. NG from general defects (CMB, LSS) $\rightarrow$ WIK!
3. NG $\Rightarrow$ VIOLATION of Slow-Roll, Canonical, Single-Field, Bunch-Davis ... assuming NG is of inflationary origin !.

   NG could come from Cosmic Defects !

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Global Summary and Personal Opinion

1. COSMIC DEFECTS $\Rightarrow$ GW (Scale Invariant, $\Omega_{\rm GW}(f) = {\rm const.}$) & NG (Scale-Invariant, $B(k_1, k_2, k_3) = B(k_2/k_1, \cos\theta_{12})$). They could also dominate the CMB Polarization.

2. COSMIC DEFECTS, Don't play important role in Structure Formation. However, Natural in HEP, and might play a role in GW, NG and CMB-Polarization. Very Important to distinguish them from Inflationary effects!!!

3. ME AND THE COSMIC DEFECTS, WE THANK YOU FOR YOUR ATTENTION!!!

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