GENERATION and IMPRINTS of PRIMORDIAL GRAV. WAVES

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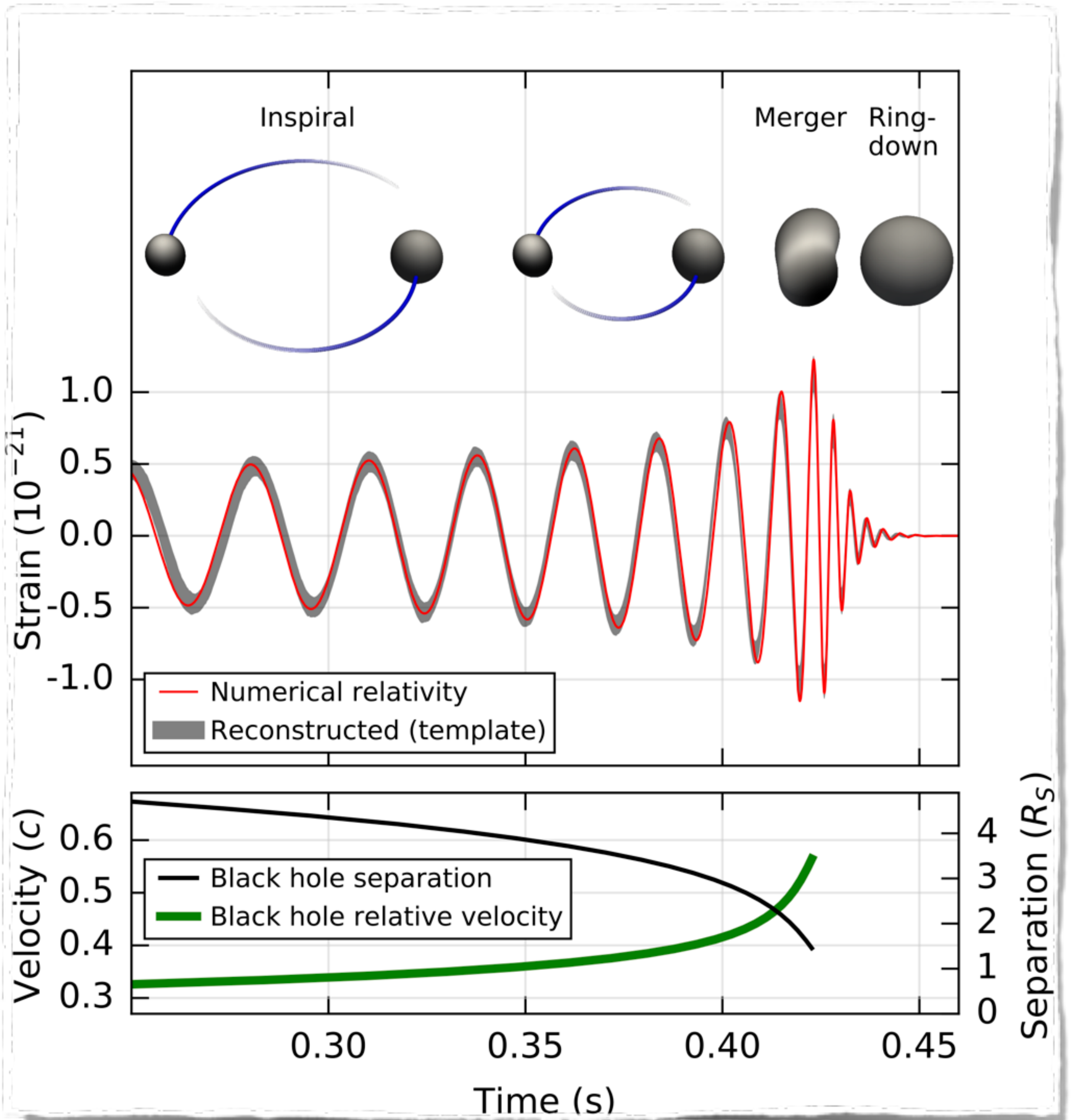
Straight to the point …

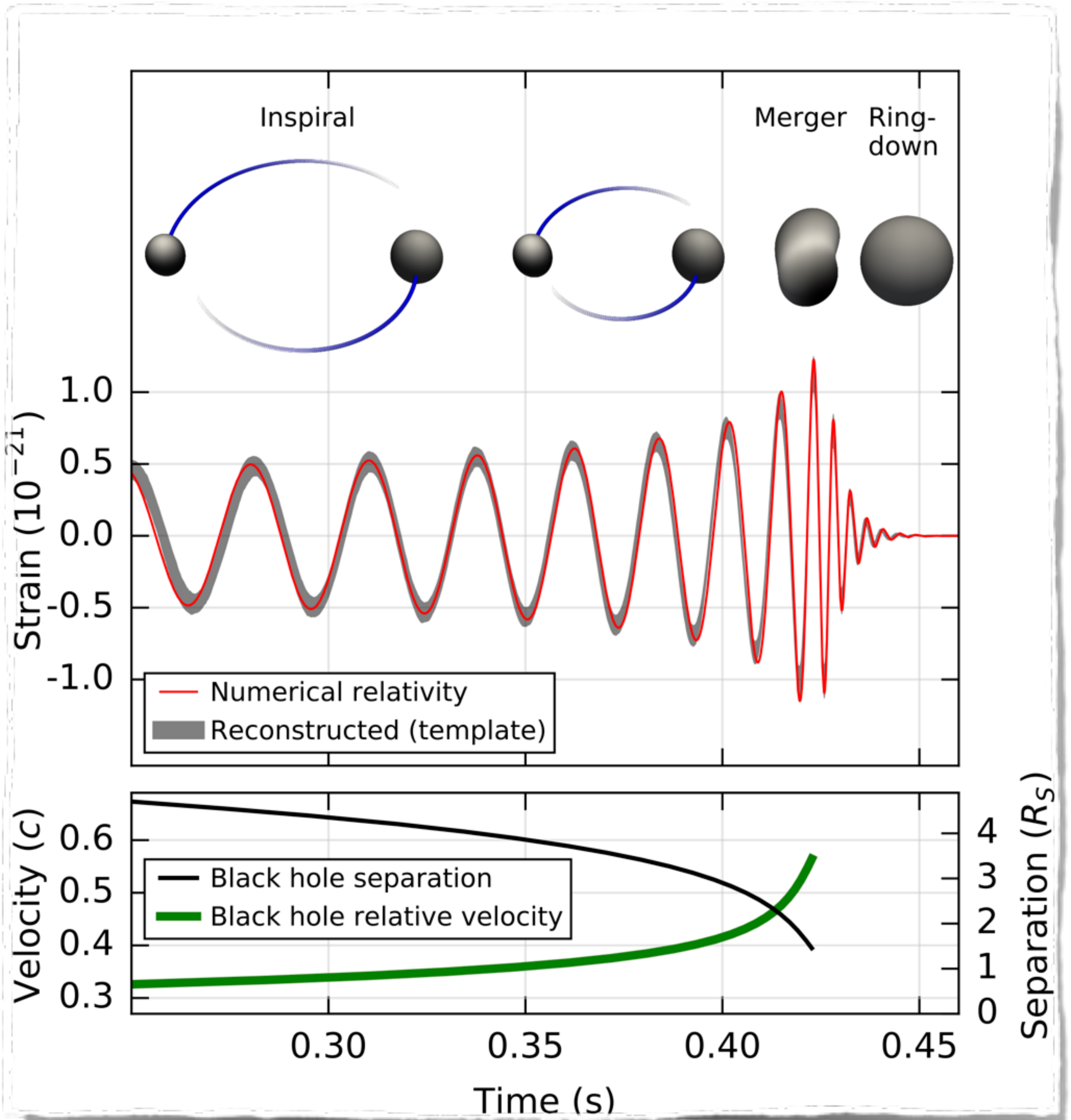


[LIGO & Virgo Scientific Collaborations (arXiv:1602.03841)]

Gravitational Waves (GWs) detected !

[by LIGO/VIRGO]

Straight to the point …



[LIGO & Virgo Scientific Collaborations (arXiv:1602.03841)]

Einstein 1916 … LIGO/VIRGO 2015/16/17

* We can observe the Universe through GWs

* **Cosmology with GWs**

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* Cosmology with GWs

* Late Universe: Hubble diagram from Binaries

* Early Universe: High Energy Particle Physics

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* We can observe the Universe through GWs

* **Cosmology with GWs**

* Late Universe: Hubble diagram from Binaries

* Early Universe: High Energy Particle Physics

Can we really probe High Energy Physics using Gravitational Waves (GWs) ? How ?

GWs: probe of the early Universe

Motivation ?

GWs: probe of the early Universe

1. **WEAKNESS of GRAVITY**:

   ADVANTAGE: GW DECOUPLE upon Production
   DISADVANTAGE: DIFFICULT DETECTION

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

$$\longrightarrow \begin{cases} \textbf{Decouple} \longrightarrow \text{Spectral Form Retained} \\ \textbf{Specific HEP} \;\Leftrightarrow\; \text{Specific GW} \end{cases}$$

GWs: probe of the early Universe

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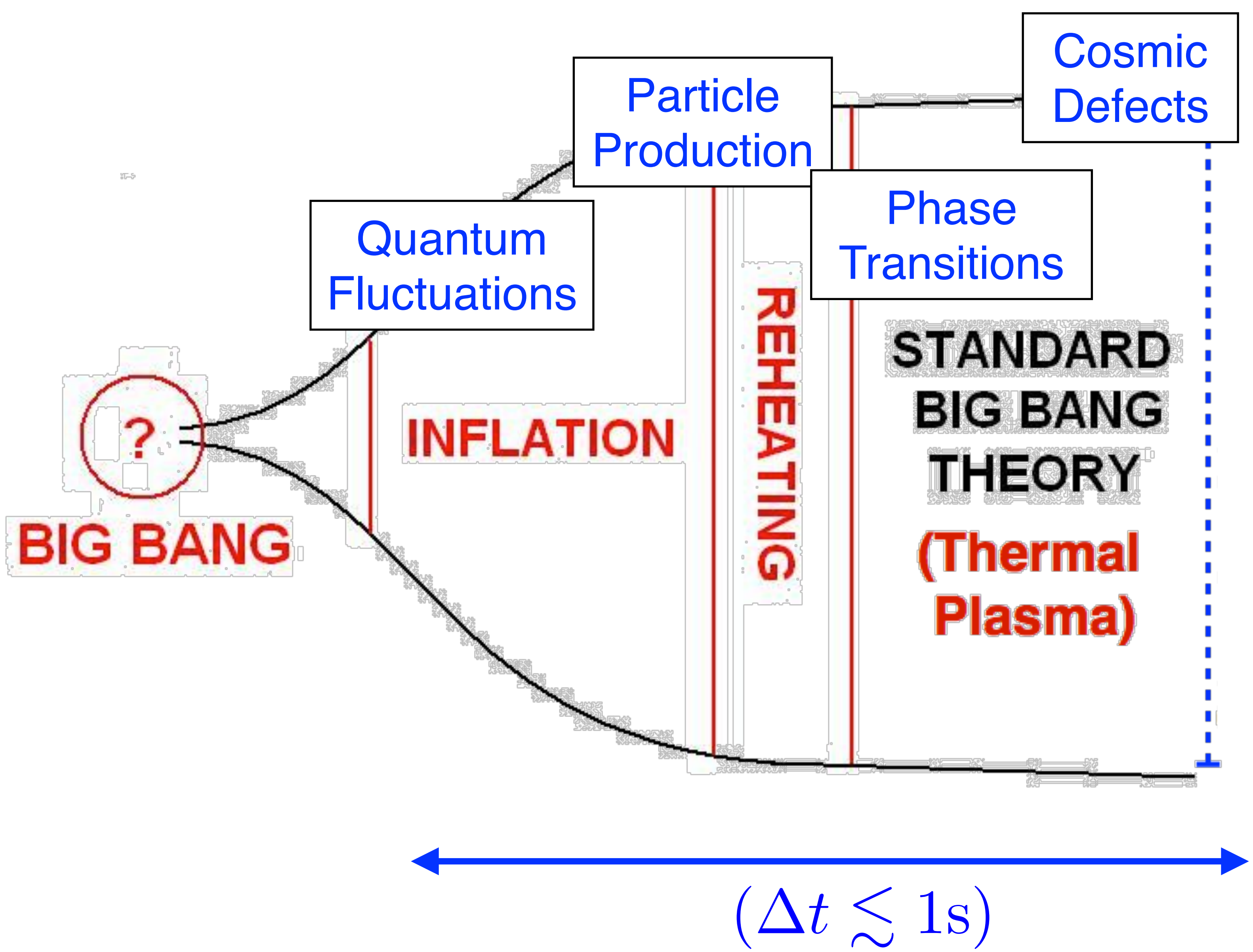
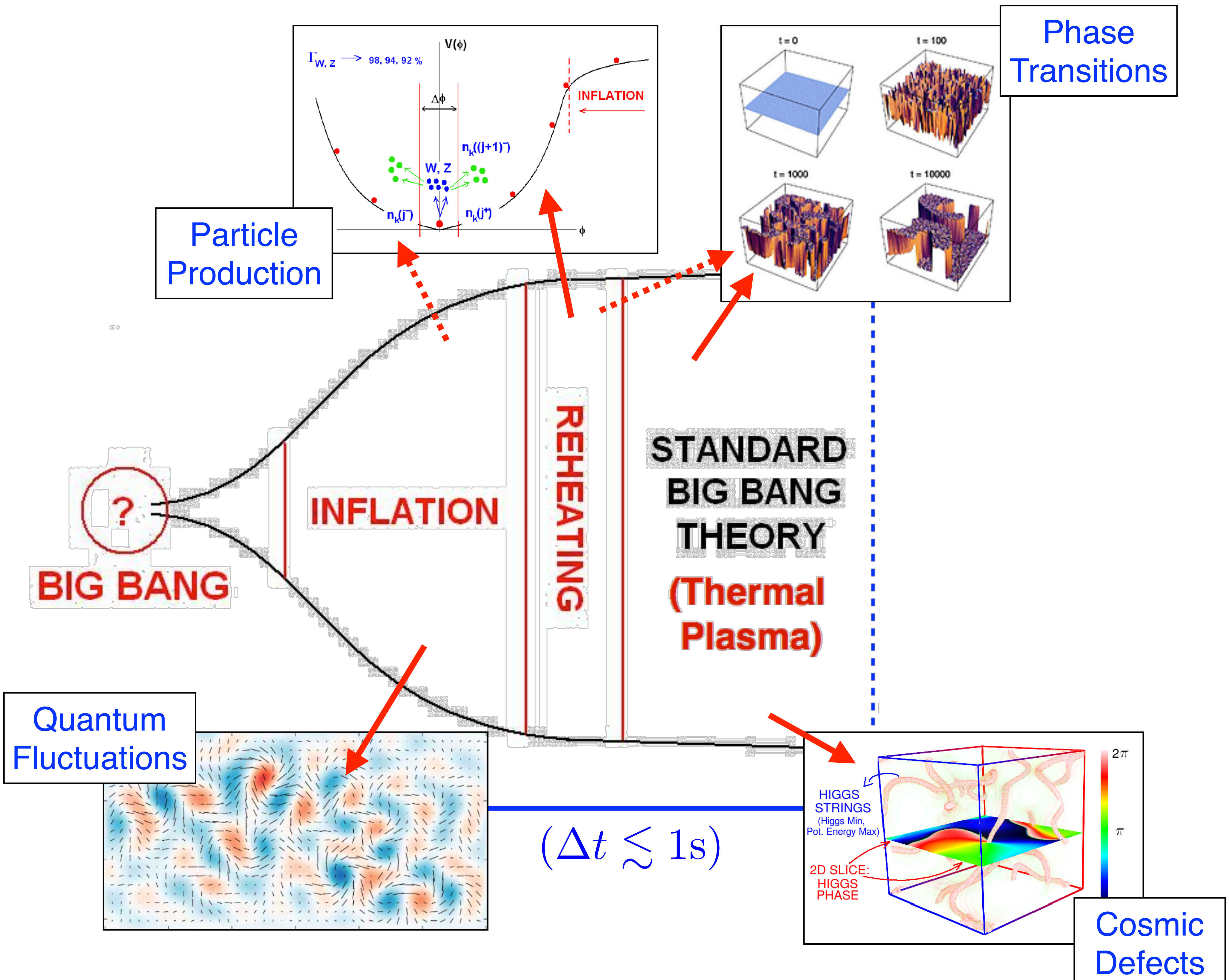
What processes of the early Universe ?

The Early Universe



The Early Universe



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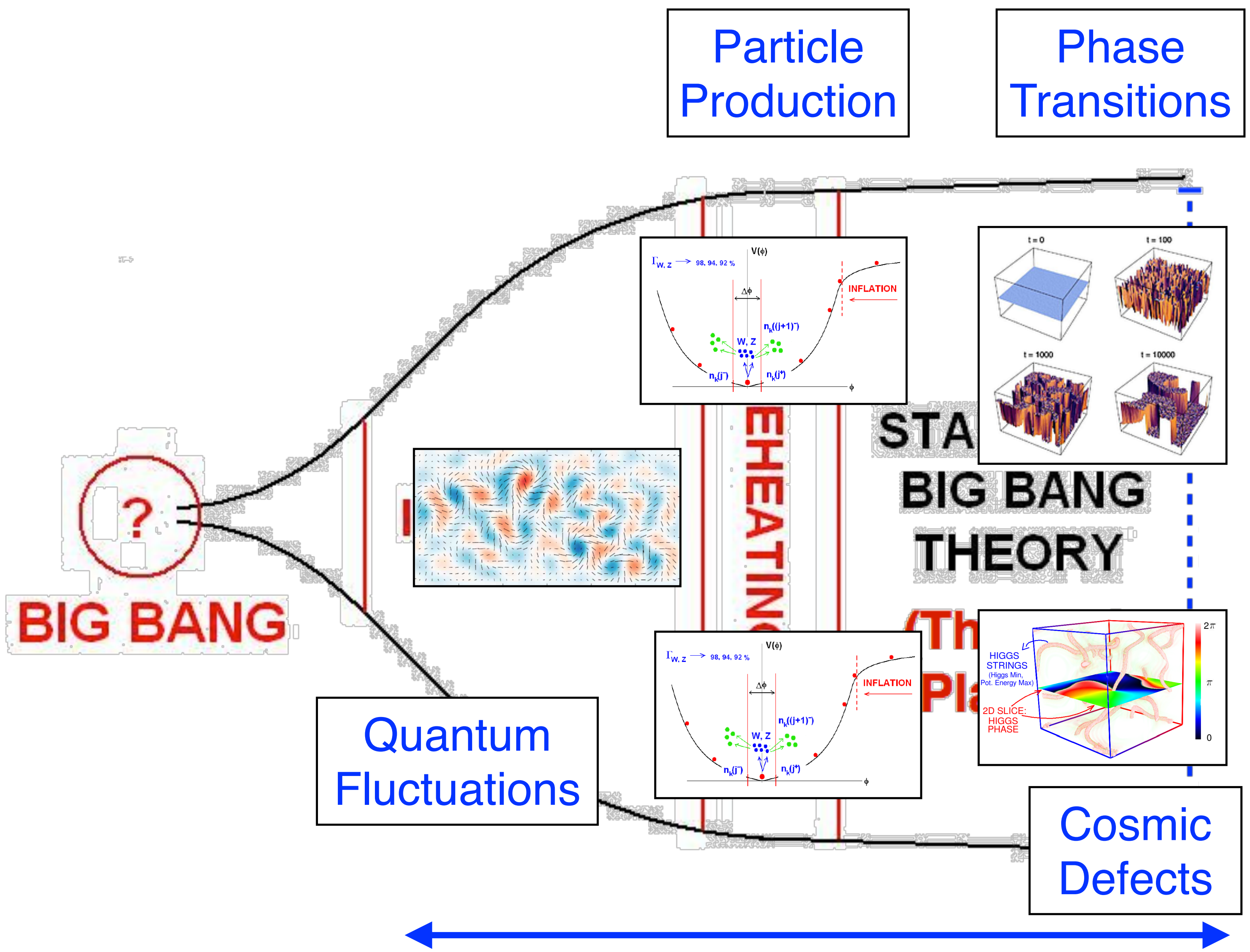
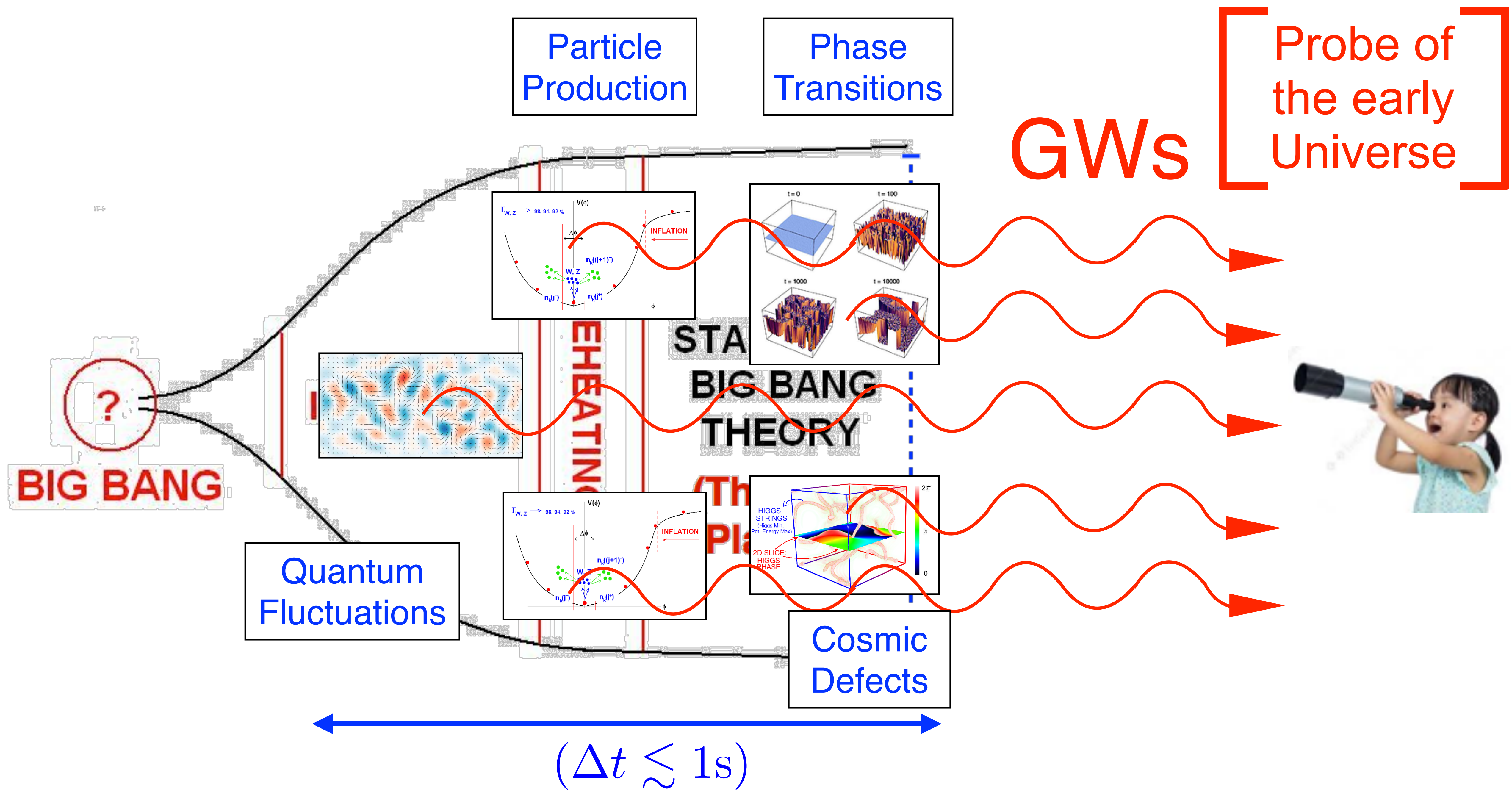


$(\Delta t \lesssim 1\mathrm{s})$

The Early Universe

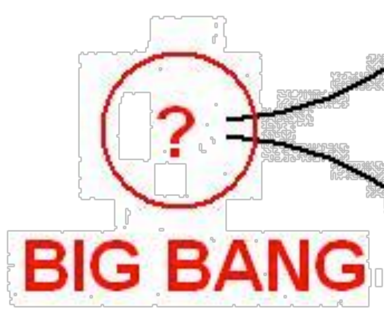


The Early Universe

Particle Production

Phase Transitions

Probe of the early Universe



‘Holy Grail’ of Stochastic GW Backgrounds

(N. Christensen, Moriond'19)

Defects

$(\Delta t \lesssim 1\mathrm{s})$

OUTLINE

0) GWs in Cosmology (def.)

Early Universe

1) GWs from Inflation

2) GWs from Preheating

3) GWs from Phase Transitions

4) GWs from Cosmic Defects

Gravitational Waves in Cosmology

Transverse-Traceless (TT)

FRW: $ds^2 = a^2(-d\eta^2 + (\delta_{ij} + h_{ij})dx^i dx^j),$

$$\boxed{\mathrm{TT}: \begin{cases} h_{ii} = 0 \\ h_{ij},_j = 0 \end{cases}}$$

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Creation/Propagation GWs

Eom: $\boxed{h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = 16\pi G \Pi^{\mathrm{TT}}_{ij},}$

Source: Anisotropic Stress

$$\boxed{\Pi_{ij} = T_{ij} - \langle T_{ij} \rangle_{\mathrm{FRW}}}$$

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

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

Gravitational Waves as a probe of the early Universe

OUTLINE

0) GW definition ✓

Early Universe

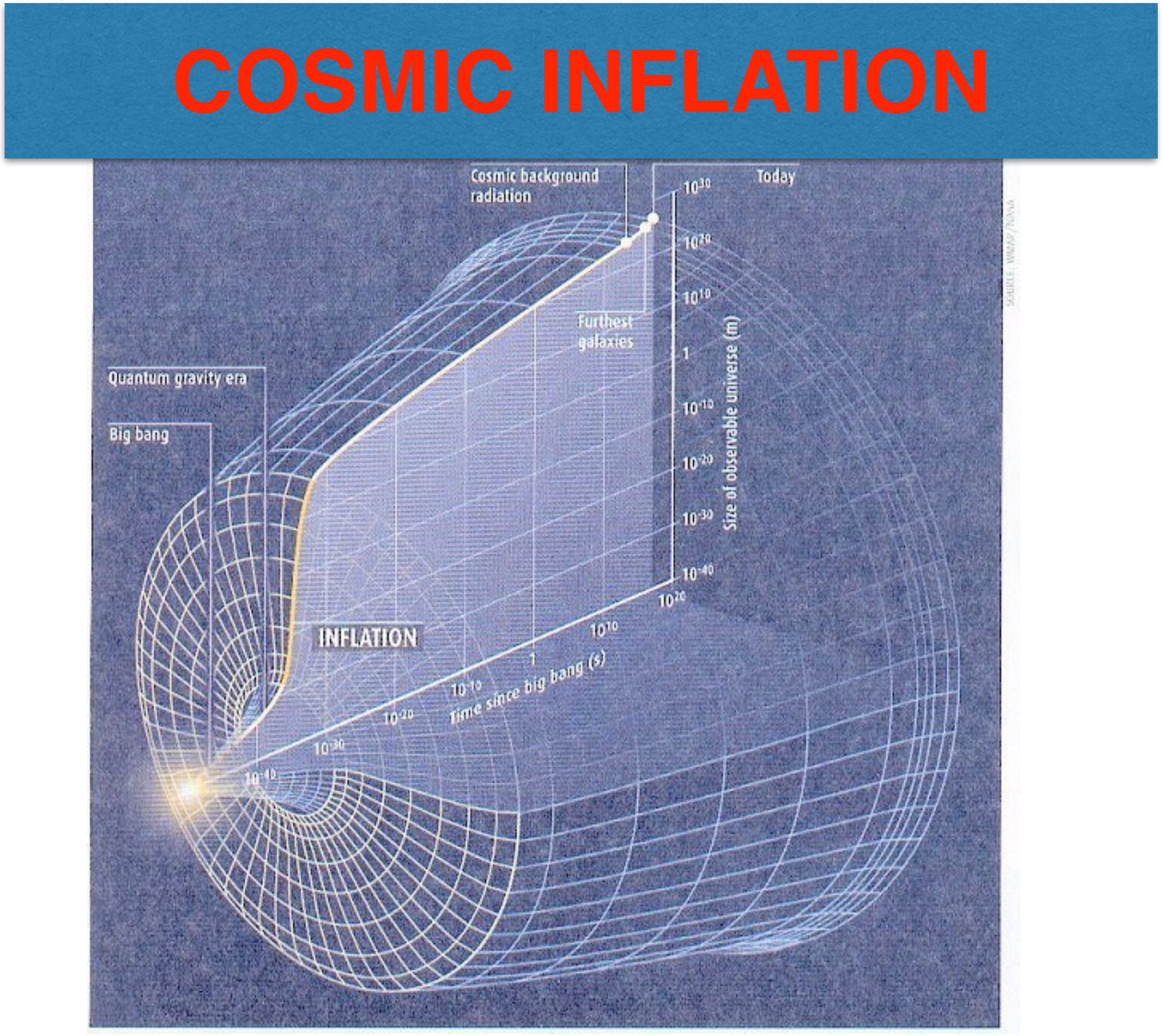
1) GWs from Inflation

2) GWs from Preheating

3) GWs from Phase Transitions

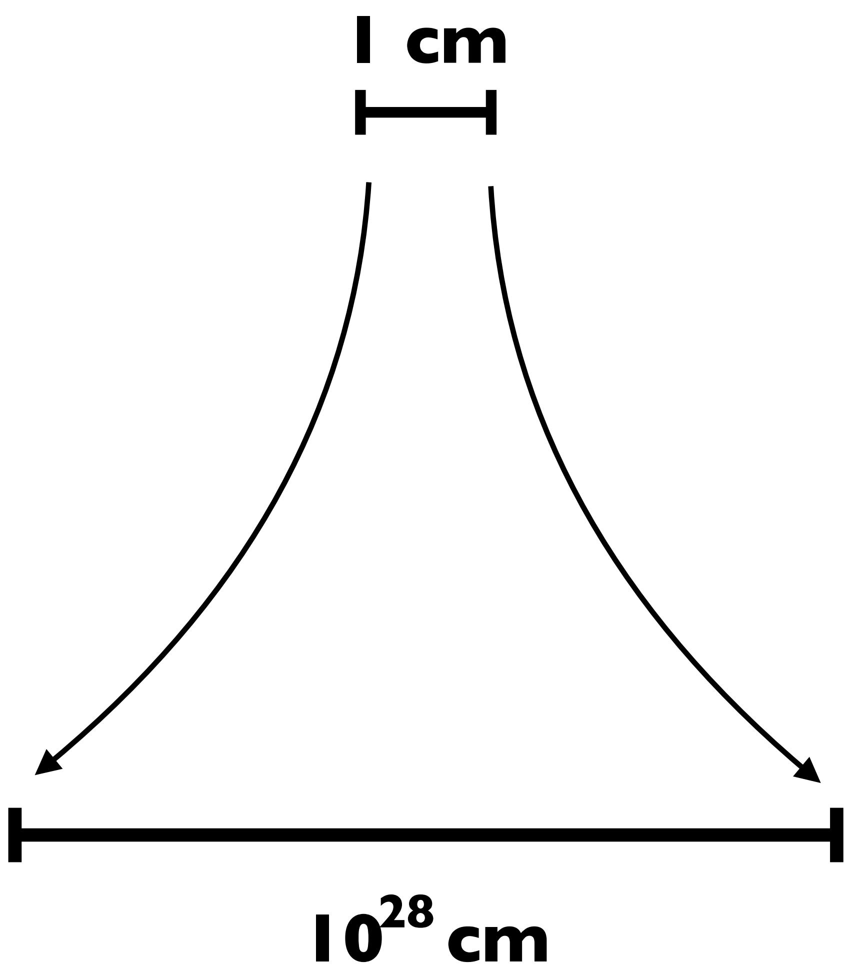
4) GWs from Cosmic Defects

Inflation (basics)



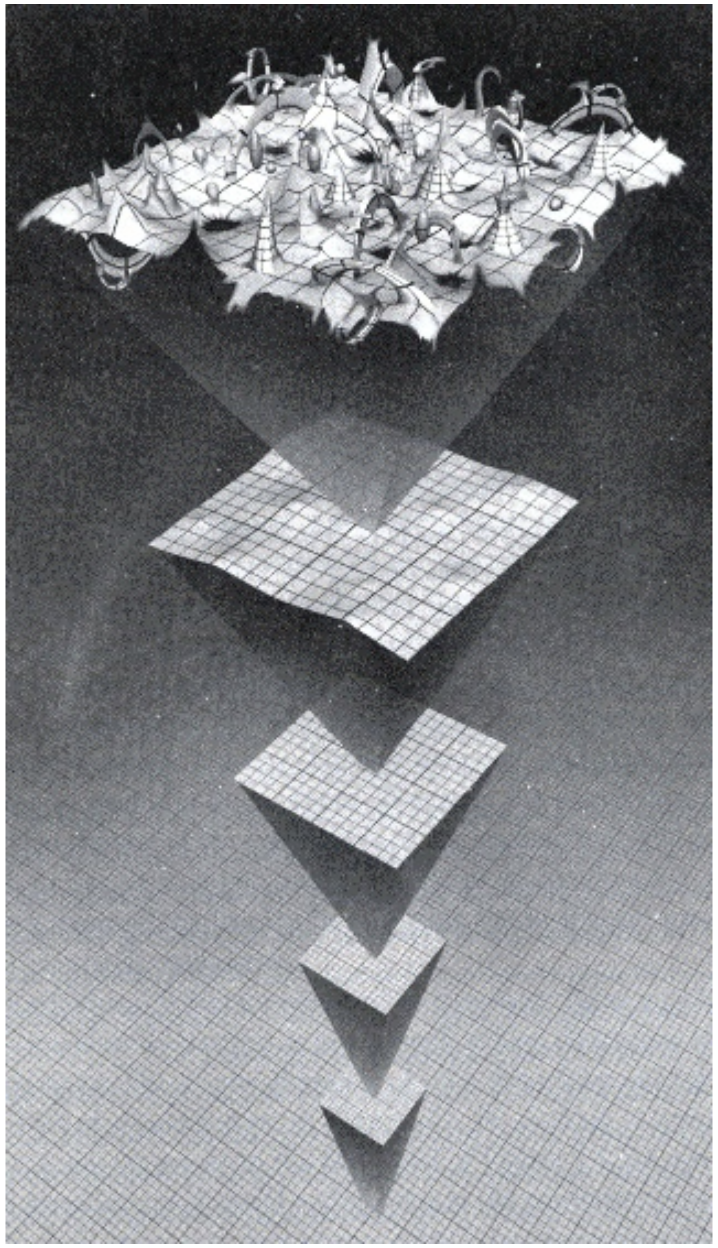
Required for Consistency of the Big Bang theory

$$\boxed{a \sim e^{H_* t} \gtrsim e^{60}}$$



Irreducible GW background from Inflation

$$g_{\mu\nu} = g^{(\mathrm{B})}_{\mu\nu} + \delta g_{\mu\nu} \quad ; \quad [\delta g_{\mu\nu}]^{\mathrm{TT}} = h_{ij} \; , \; \begin{cases} h_{ii} = 0 \\ \partial_i h_{ij} = 0 \end{cases}$$



Quantum Fluctuations

Irreducible GW background from Inflation

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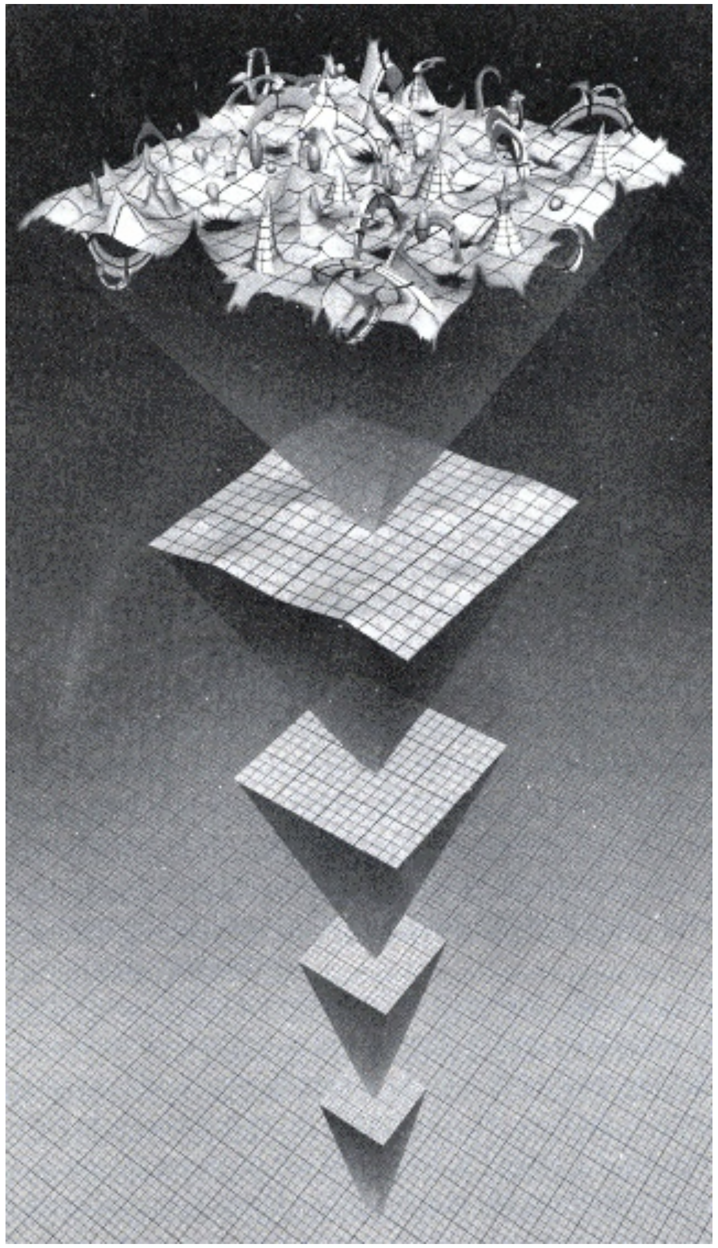

Quantum Fluctuations

$$\left\langle h_{ij}(\vec{k},t) \right\rangle = 0$$

$$\left\langle h_{ij}(\vec{k},t) h_{ij}^*(\vec{k}',t) \right\rangle \equiv (2\pi)^3 \frac{2\pi^2}{k^3} \Delta_h^2(k) \delta(\vec{k}-\vec{k}')$$

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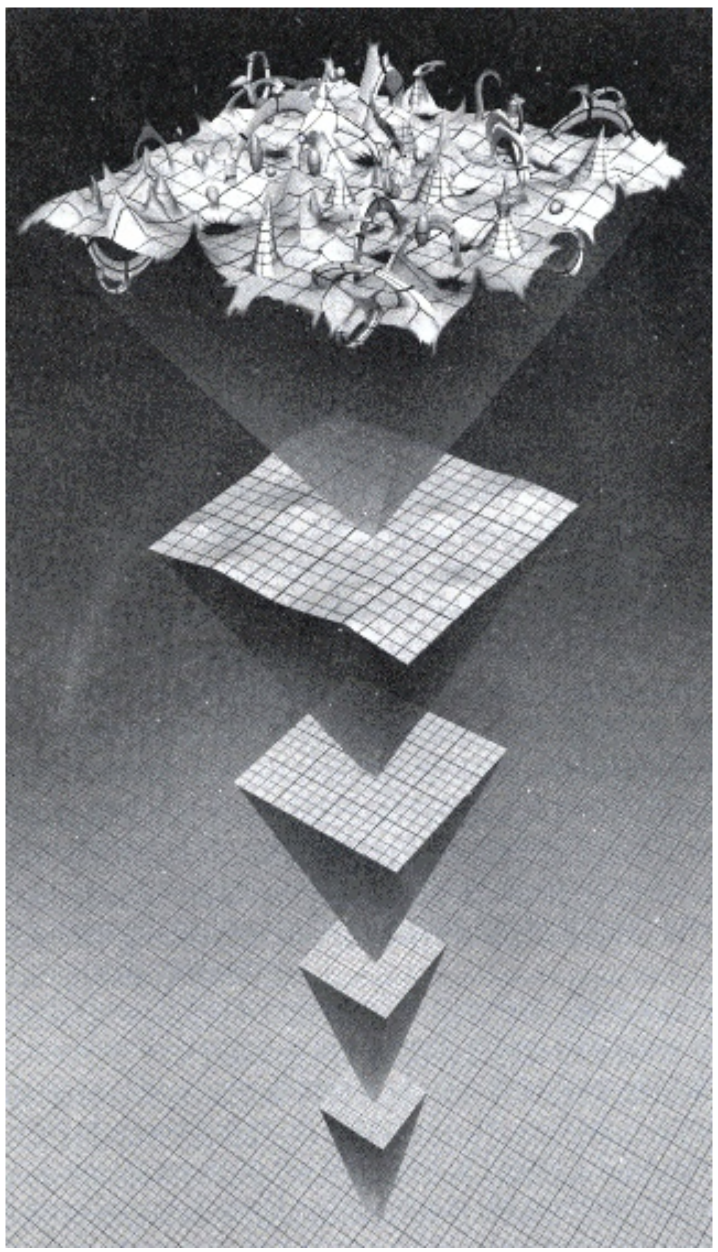

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$$\boxed{\Delta^2_h(k) = \frac{2}{\pi^2}\left(\frac{H}{m_p}\right)^2 \left(\frac{k}{aH}\right)^{n_t}}$$

$$\boxed{n_t \equiv -2\epsilon}$$

energy scale

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Irreducible GW background from Inflation

$$\boxed{\Omega_{\rm GW}^{(o)}(f) \equiv \frac{1}{\rho_c^{(o)}}\left(\frac{d\rho_{\rm GW}}{d\log k}\right)_o = \underbrace{\frac{\Omega_{\rm Rad}^{(o)}}{24}}\Delta_{h_*}^2(k)}$$

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Transfer Funct.: $T(k) \propto k^0\,(\mathrm{RD})$

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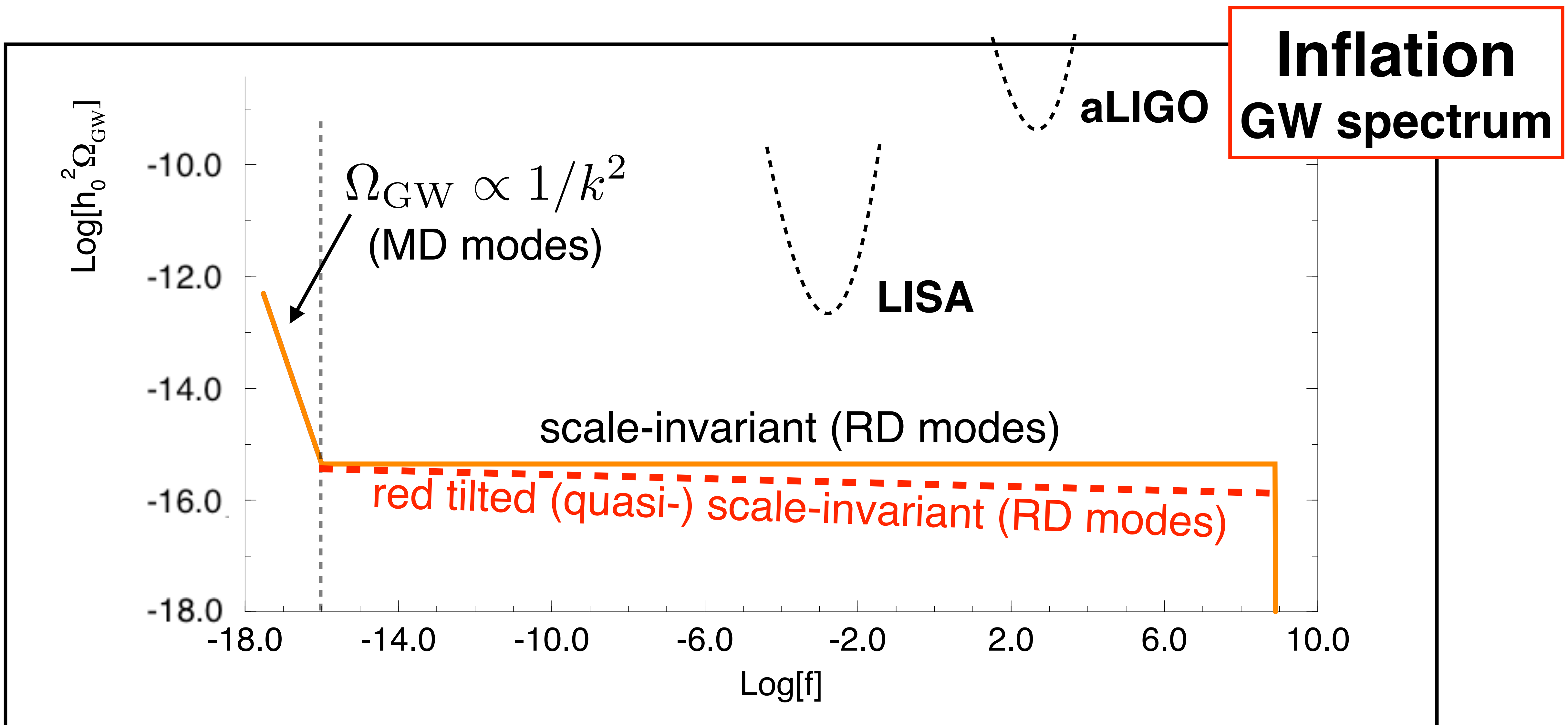

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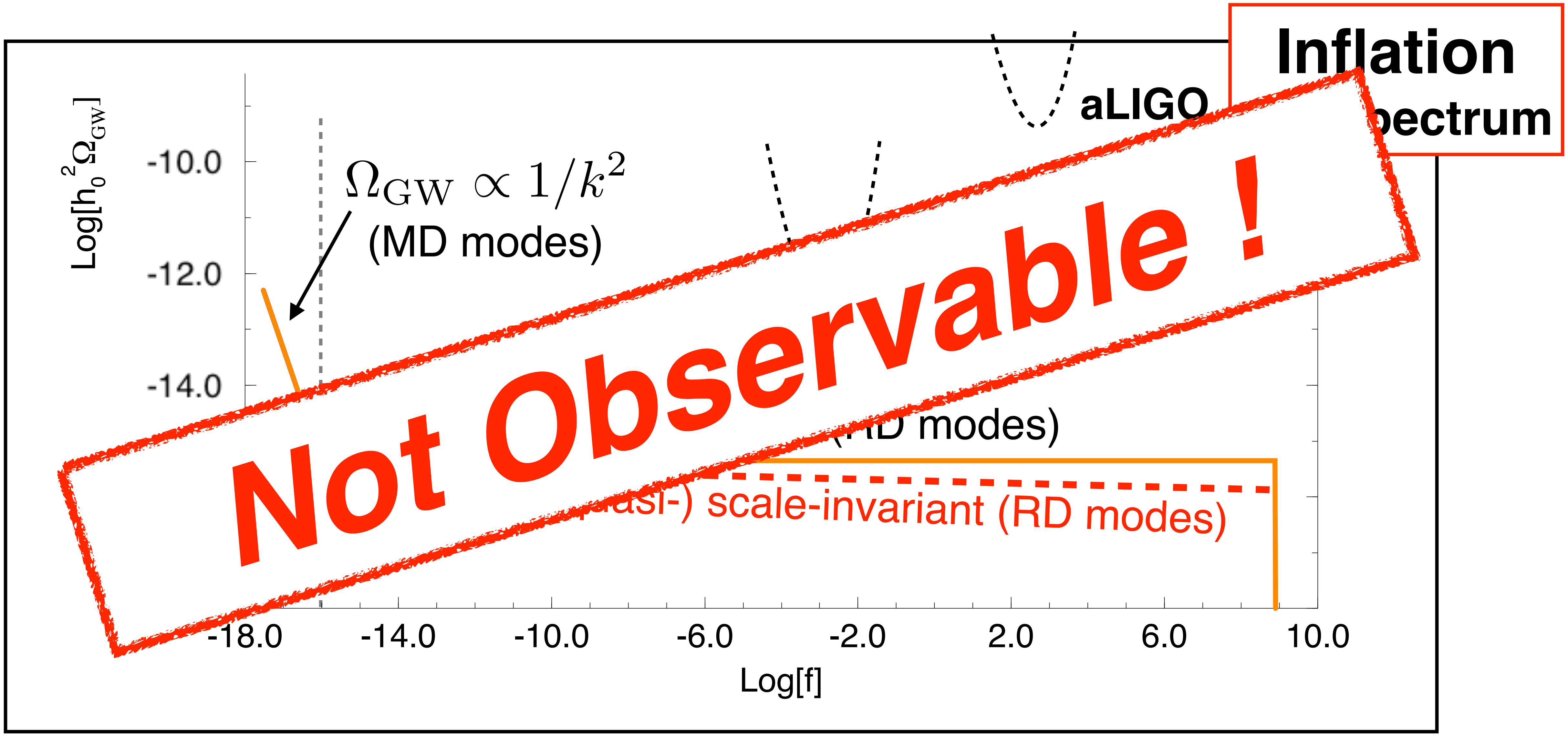

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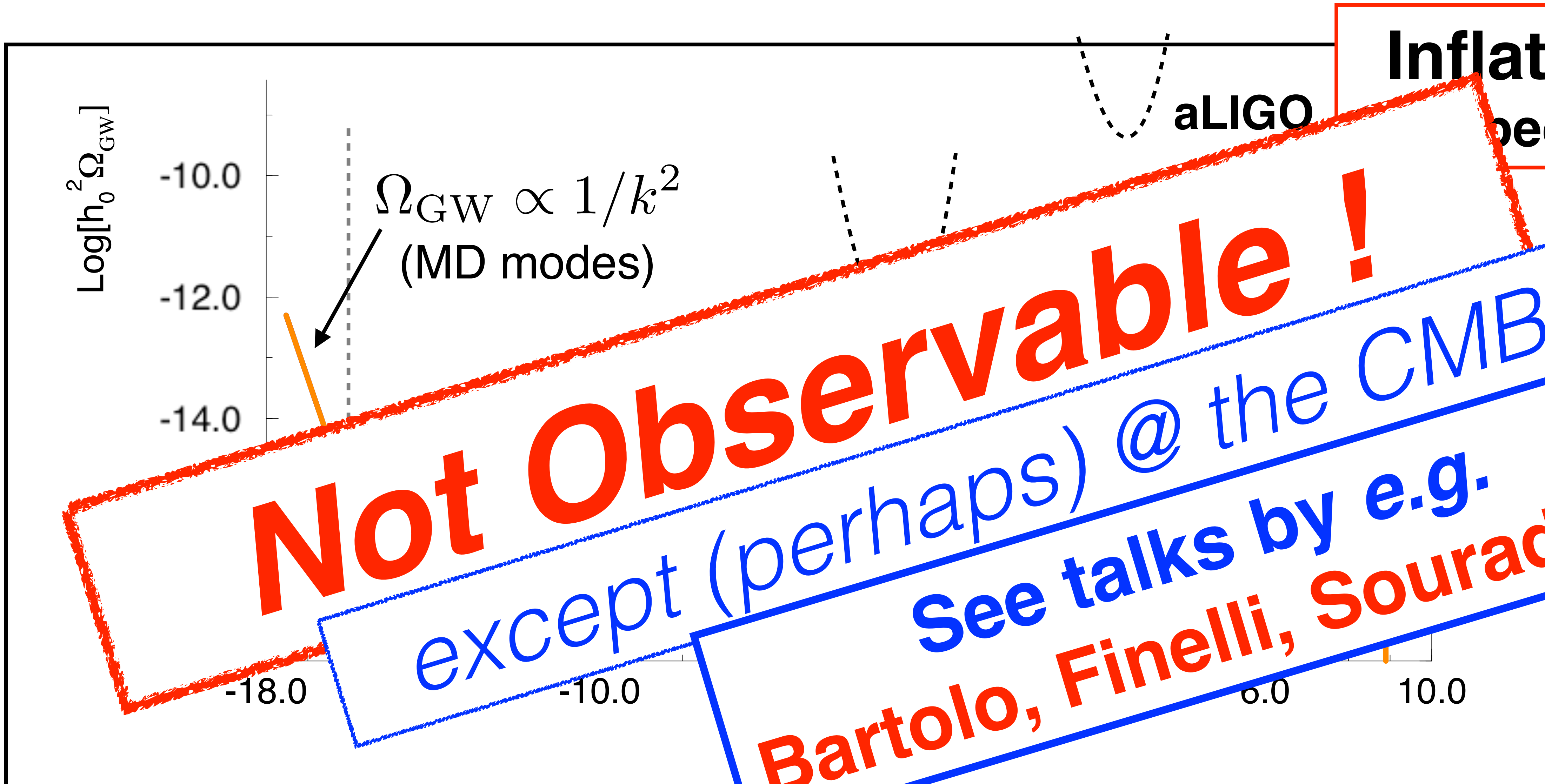

Inflation Spectrum

Not Observable !

except (perhaps) @ the CMB

See talks by e.g.
Bartolo, Finelli, Souradeep

Inflationary GW background

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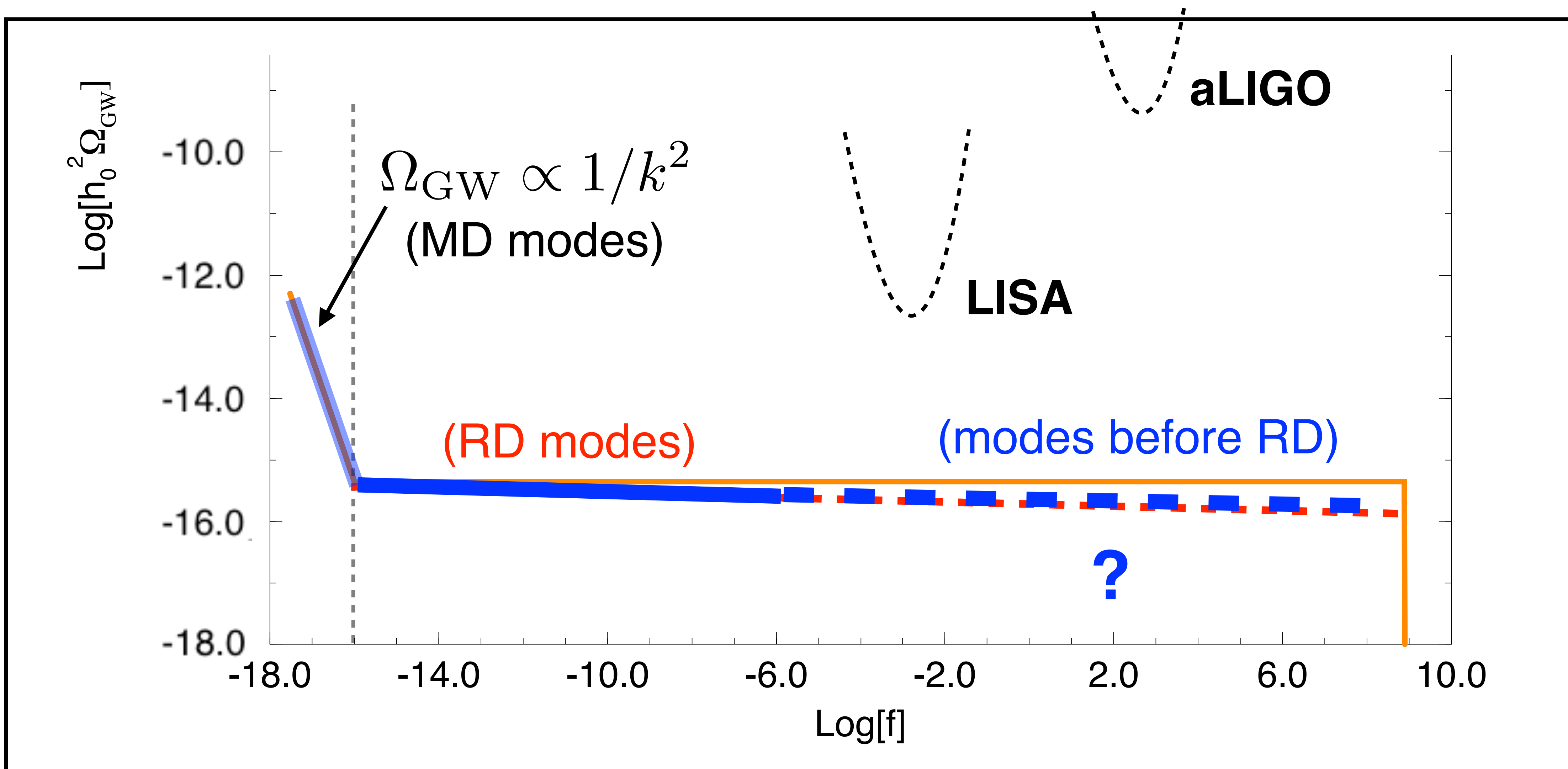
Transfer Funct.: $T(k) \propto k^0 (\mathrm{RD})$

Period before RD: $T(k) \propto k^{2\frac{(w_s-1/3)}{(w_s+1/3)}}$



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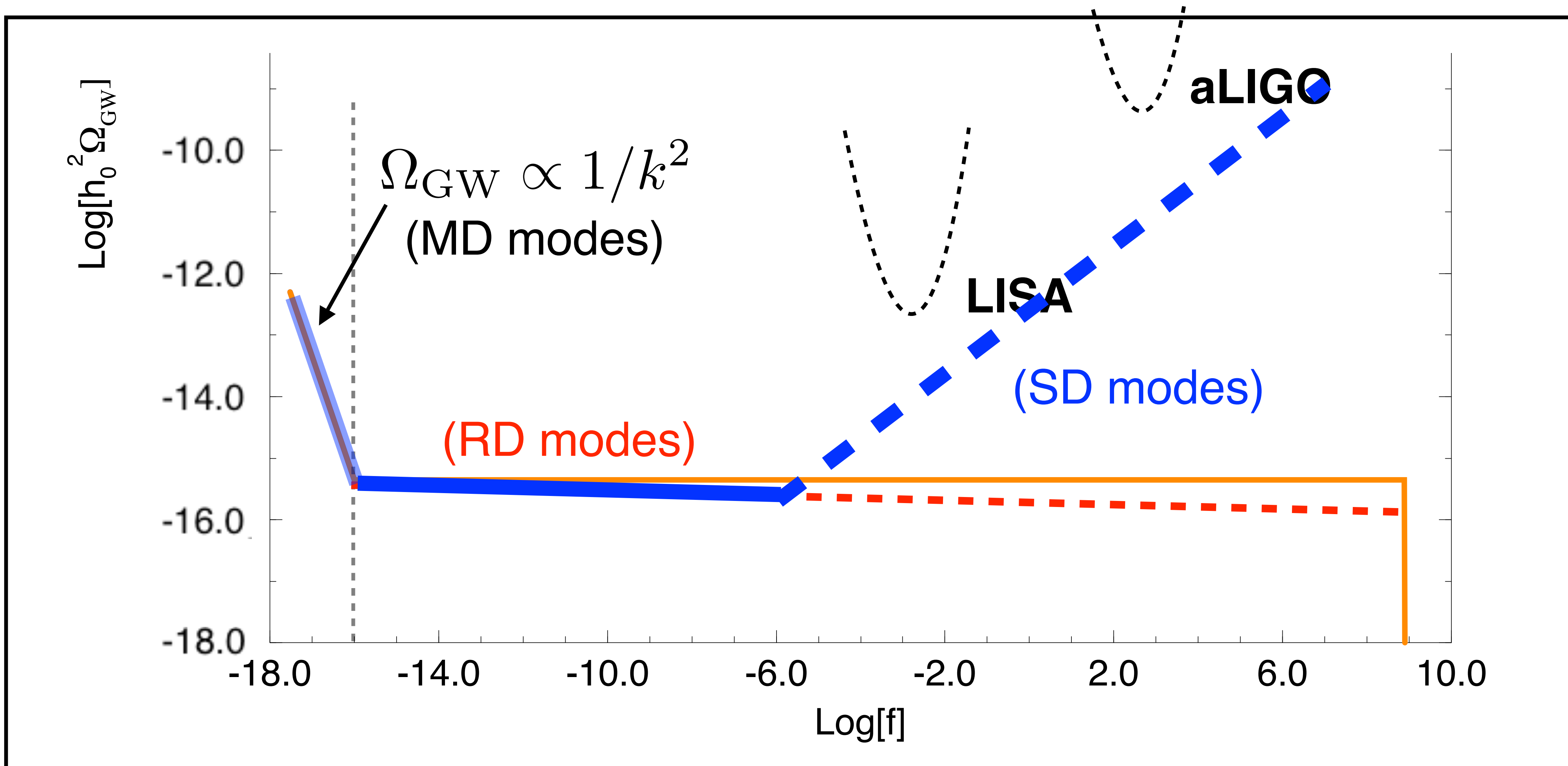
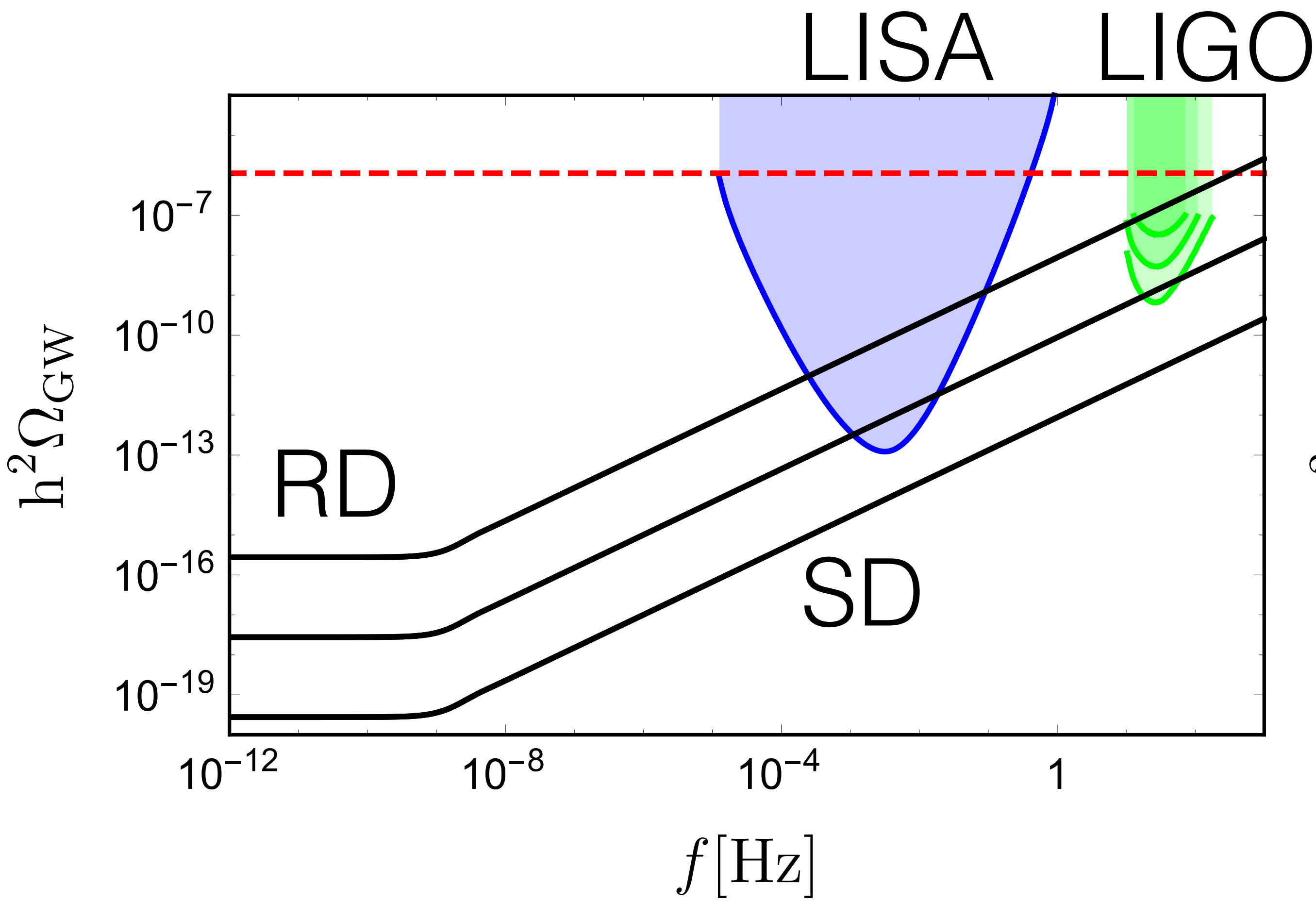
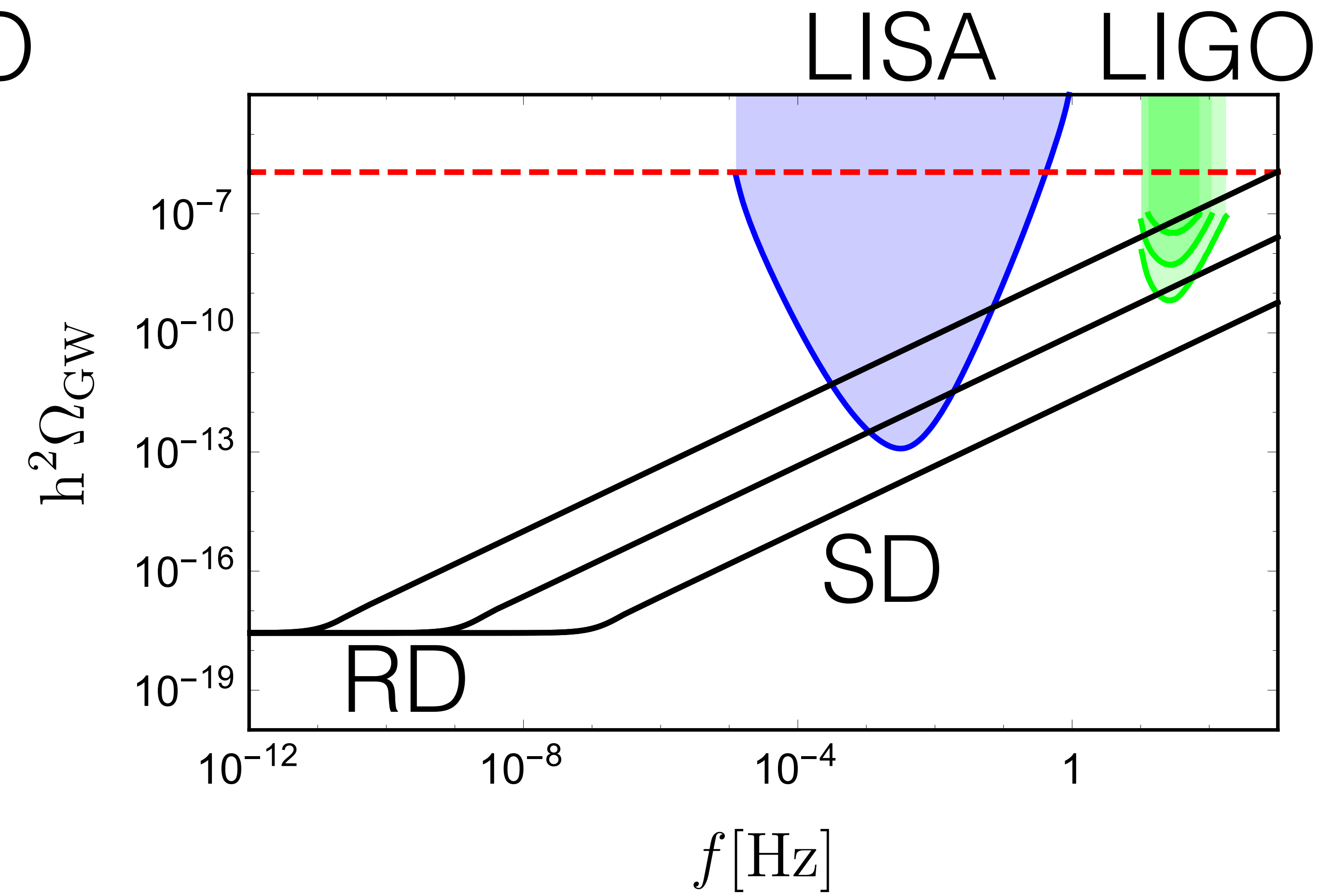
Transfer Funct.: $T(k) \propto k^0(\mathrm{RD})$

Stiff Period: $T(k) \propto k^{2\frac{(w_s-1/3)}{(w_s+1/3)}}$ $(1/3 < \omega_s < 1)$



STIFF EQ of STATE $(1/3 < \omega_s < 1)$

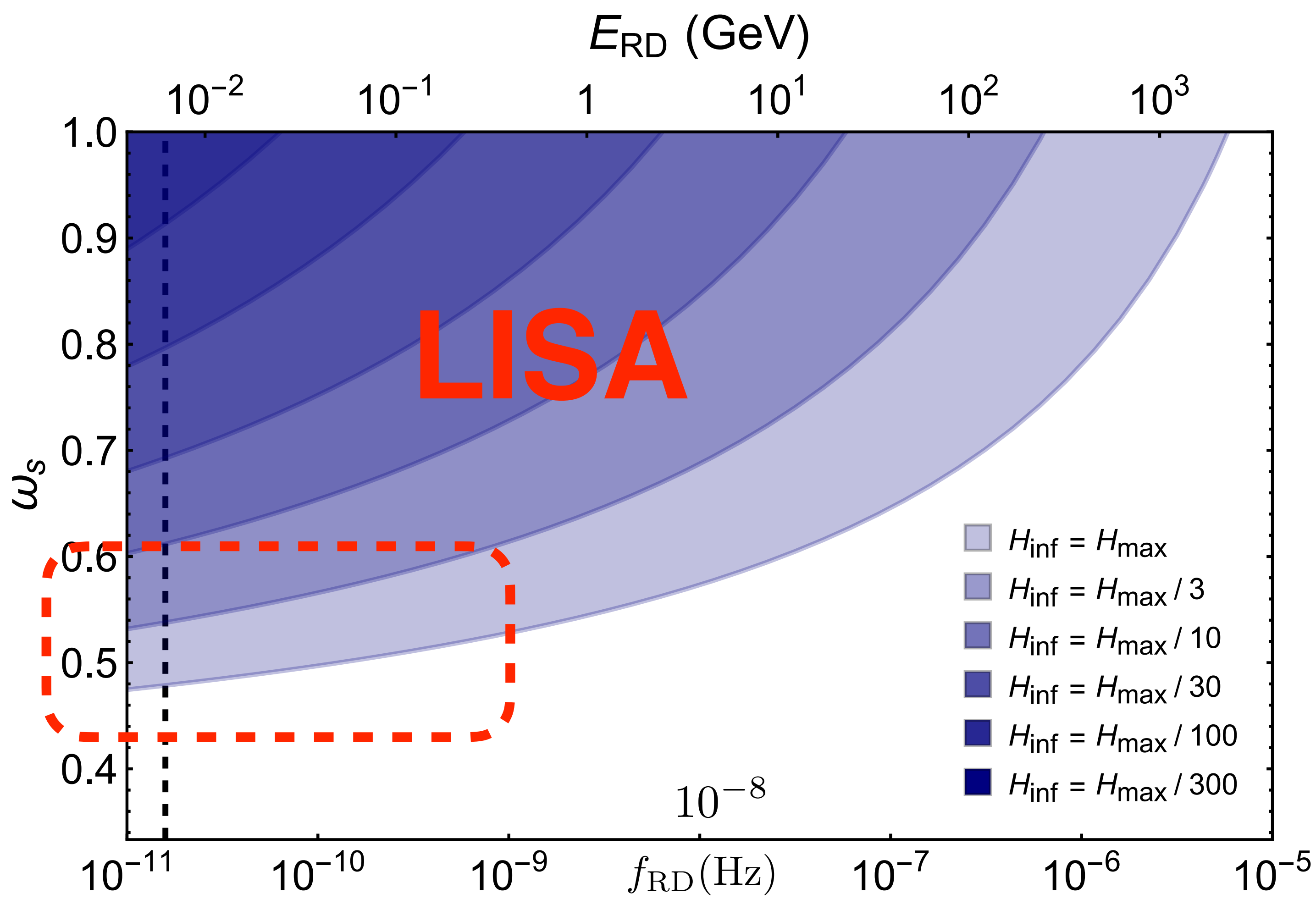


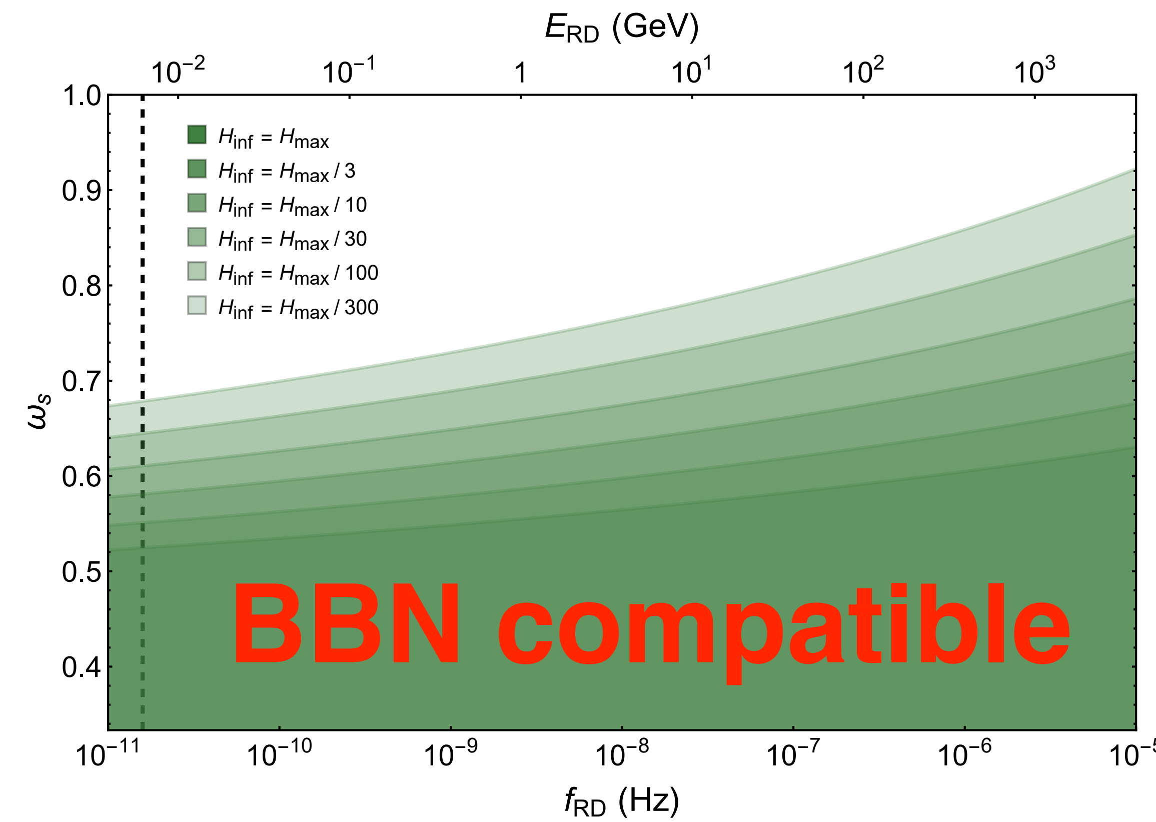


$$\Omega_{\rm GW}(f) \propto H_{\rm inf}^2 \left(\frac{f}{f_{\rm RD}}\right)^{\frac{2(w-1/3)}{(w+1/3)}}$$

Not Scale Invariant !

STIFF EQ of STATE $(1/3 < \omega_s < 1)$





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DGF, Tanin '19, 1905.11960

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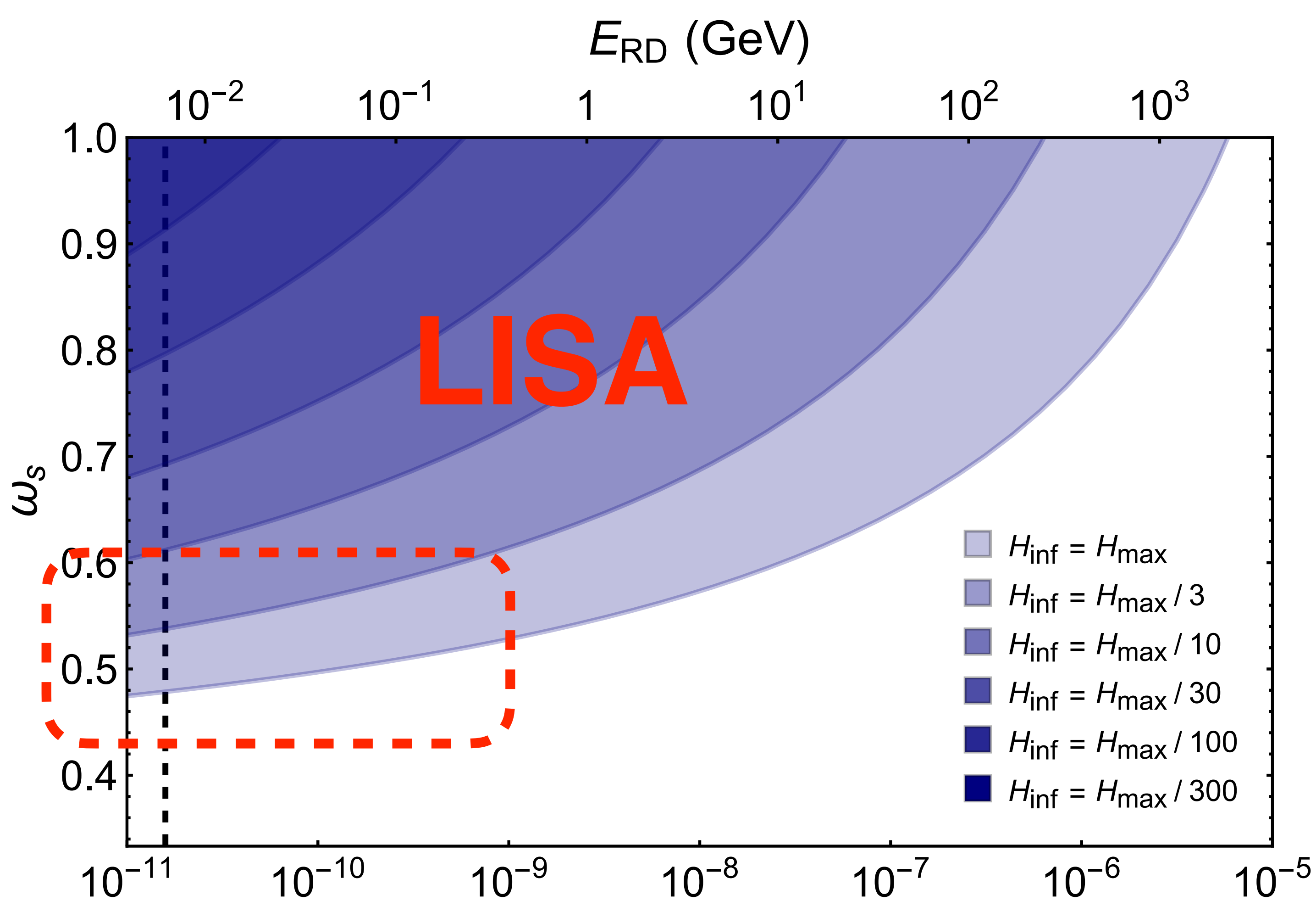
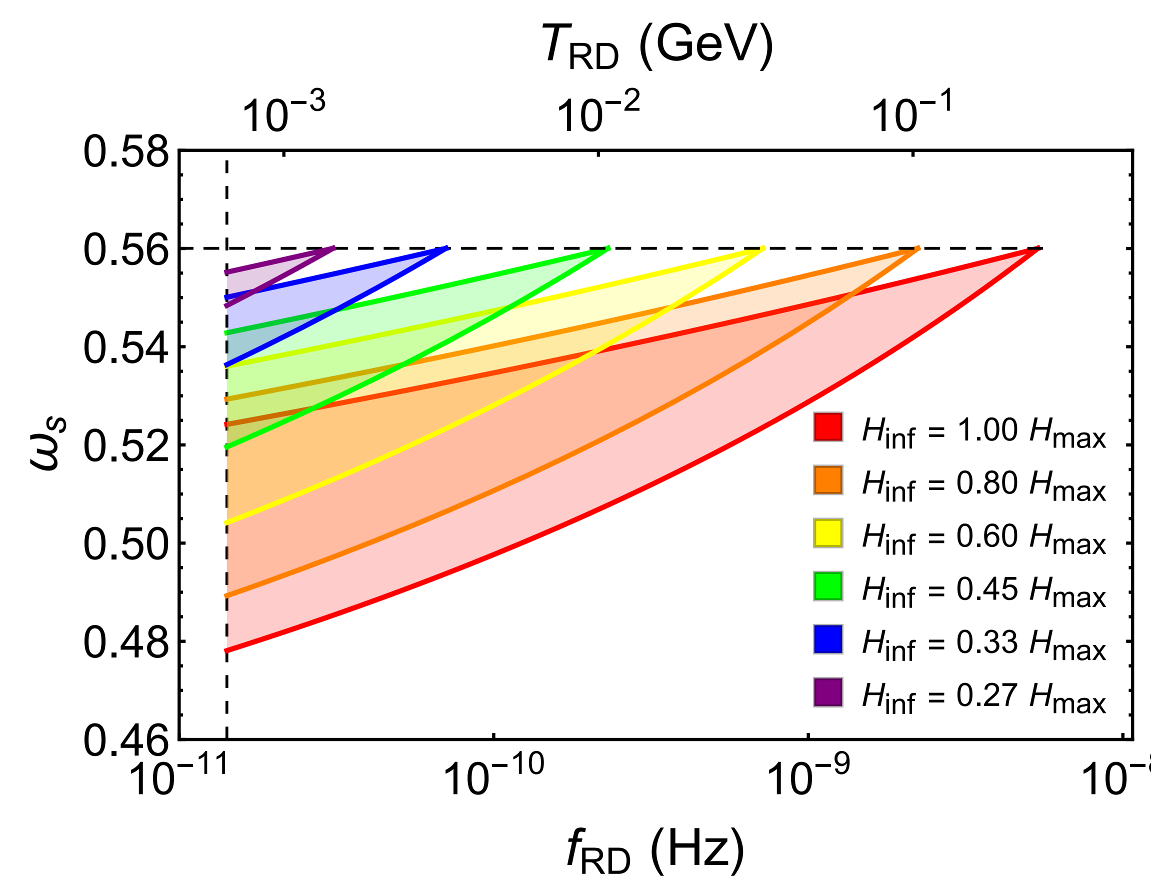


after BBN cut



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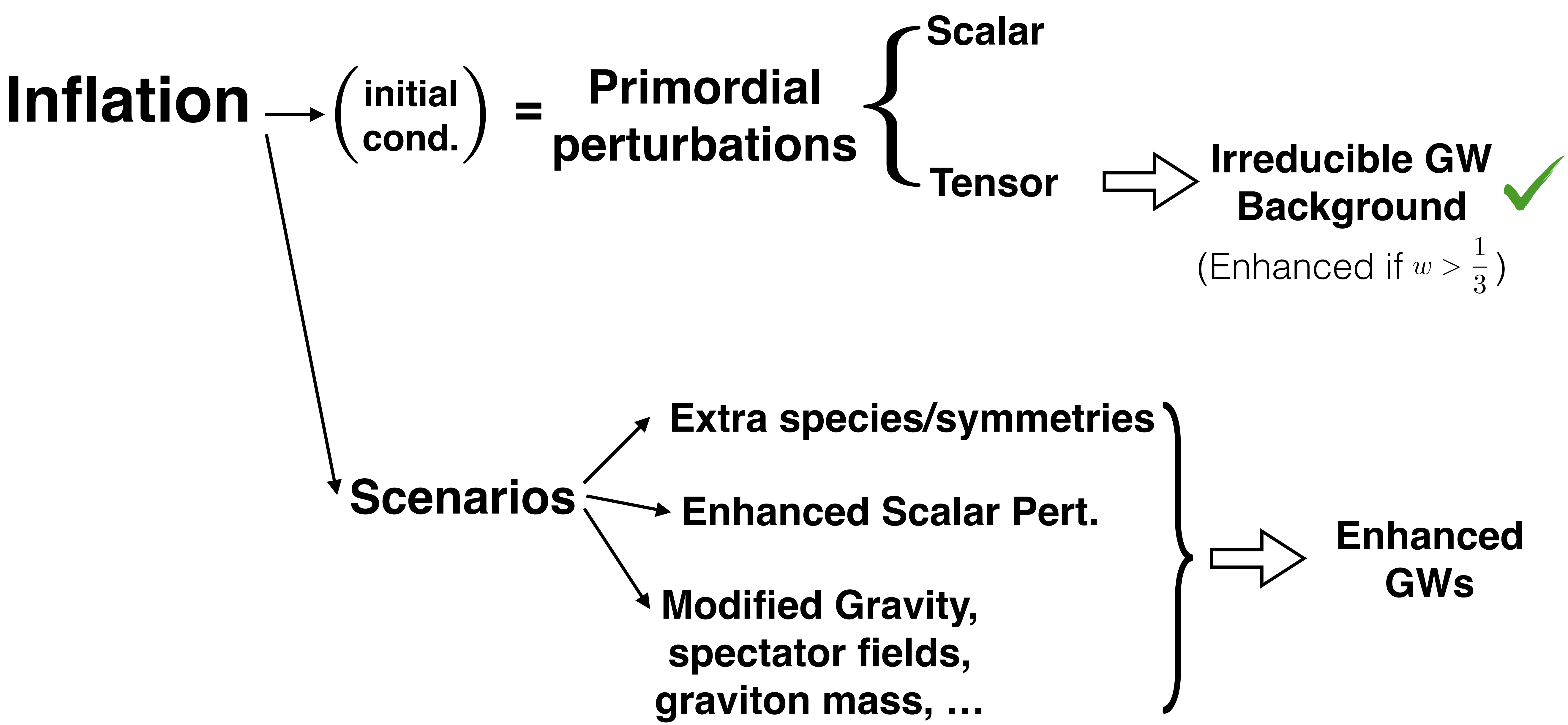
INFLATIONARY COSMOLOGY

Inflation $\longrightarrow \begin{pmatrix}\text{initial}\\ \text{cond.}\end{pmatrix}$ **= Primordial perturbations** $\begin{cases} \textbf{Scalar} \\ \textbf{Tensor} \Longrightarrow \textbf{Irreducible GW Background} \end{cases}$

(Enhanced if $w > \frac{1}{3}$)

INFLATIONARY COSMOLOGY



INFLATIONARY COSMOLOGY

Inflation $\longrightarrow$ (initial cond.) = **Primordial perturbations**

- **Scalar**
- **Tensor** $\Rightarrow$ **Irreducible GW Background** ✓
  (Enhanced if $w > \frac{1}{3}$)

Inflation $\longrightarrow$ **Scenarios**

- **Extra species/symmetries**
- **Enhanced Scalar Pert.**
- **Modified Gravity, spectator fields, graviton mass, …**

$\Rightarrow$ **Enhanced GWs**

INFLATIONARY MODELS

Axion-Inflation Shift symmetry $\varphi \to \varphi + const.$

Freese, Frieman, Olinto '90; . . .

$$V(\varphi) + \frac{\varphi}{f} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

inflaton φ = pseudo-scalar axion

[J. Cook, L. Sorbo (arXiv:1109.0022)] [N. Barnaby, E. Pajer, M. Peloso (arXiv:1110.3327)]

Not the QCD axion;

INFLATIONARY MODELS

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Photon: 2 helicities

$$\left[\frac{\partial^2}{\partial\tau^2} + k^2 \pm \frac{2k\xi}{\tau}\right] A_\pm(\tau, k) = 0,$$

$$\boxed{\xi \equiv \frac{\dot{\varphi}}{2fH}}$$

Chiral instability

$$A_+ \propto e^{\pi\xi}\,, \quad |A_-| \ll |A_+|$$

A+ exponentially amplified,

INFLATIONARY MODELS

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Freese, Frieman, Olinto '90; . . .

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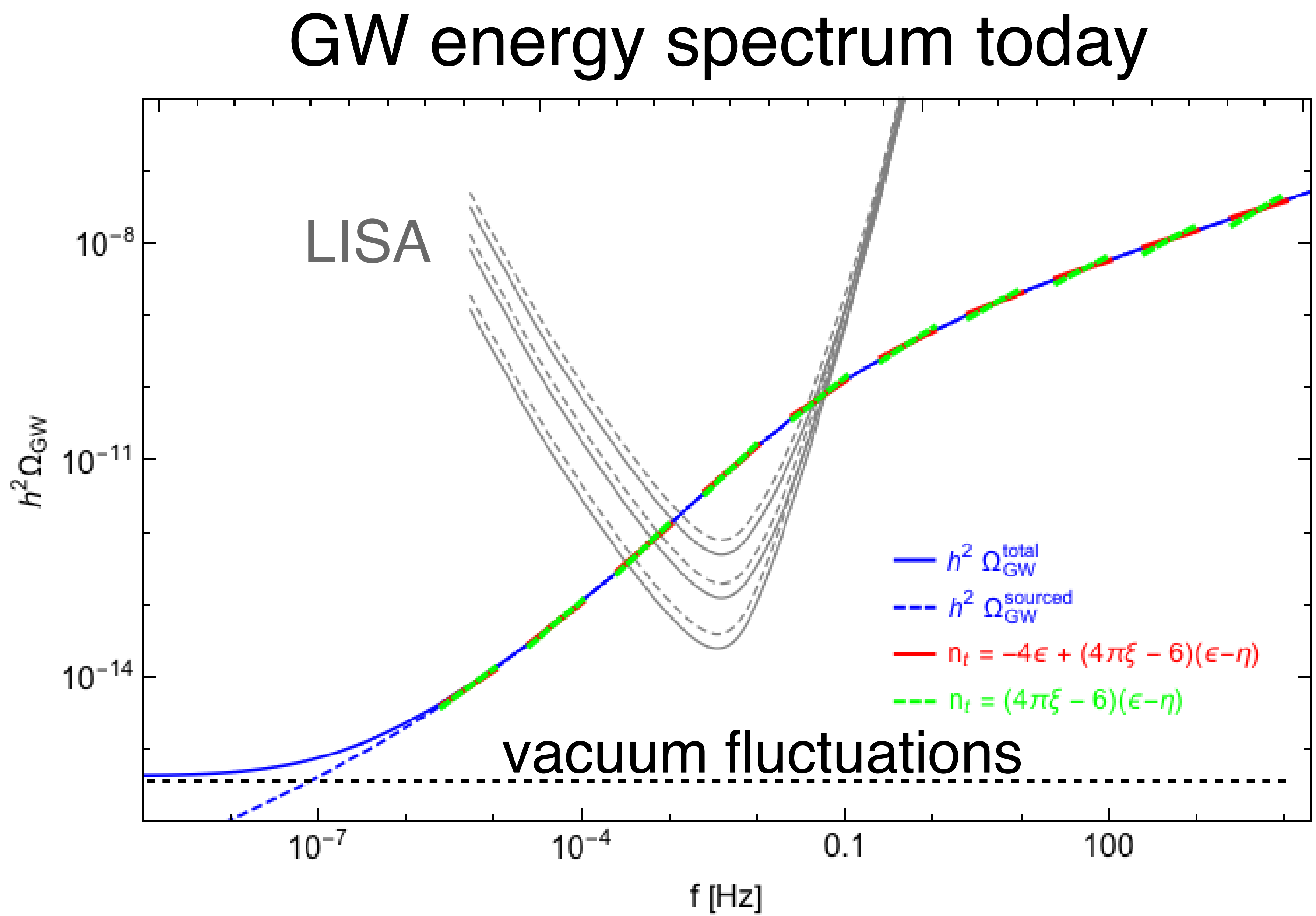
chiral GWs !

$$h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = 16\pi G \Pi^{\rm TT}_{ij} \propto \{E_i E_j + B_i B_j\}^{TT}$$

GW left-chirality only ! ⇐ A_μ **Chiral**

INFLATIONARY MODELS

Axion-Inflation



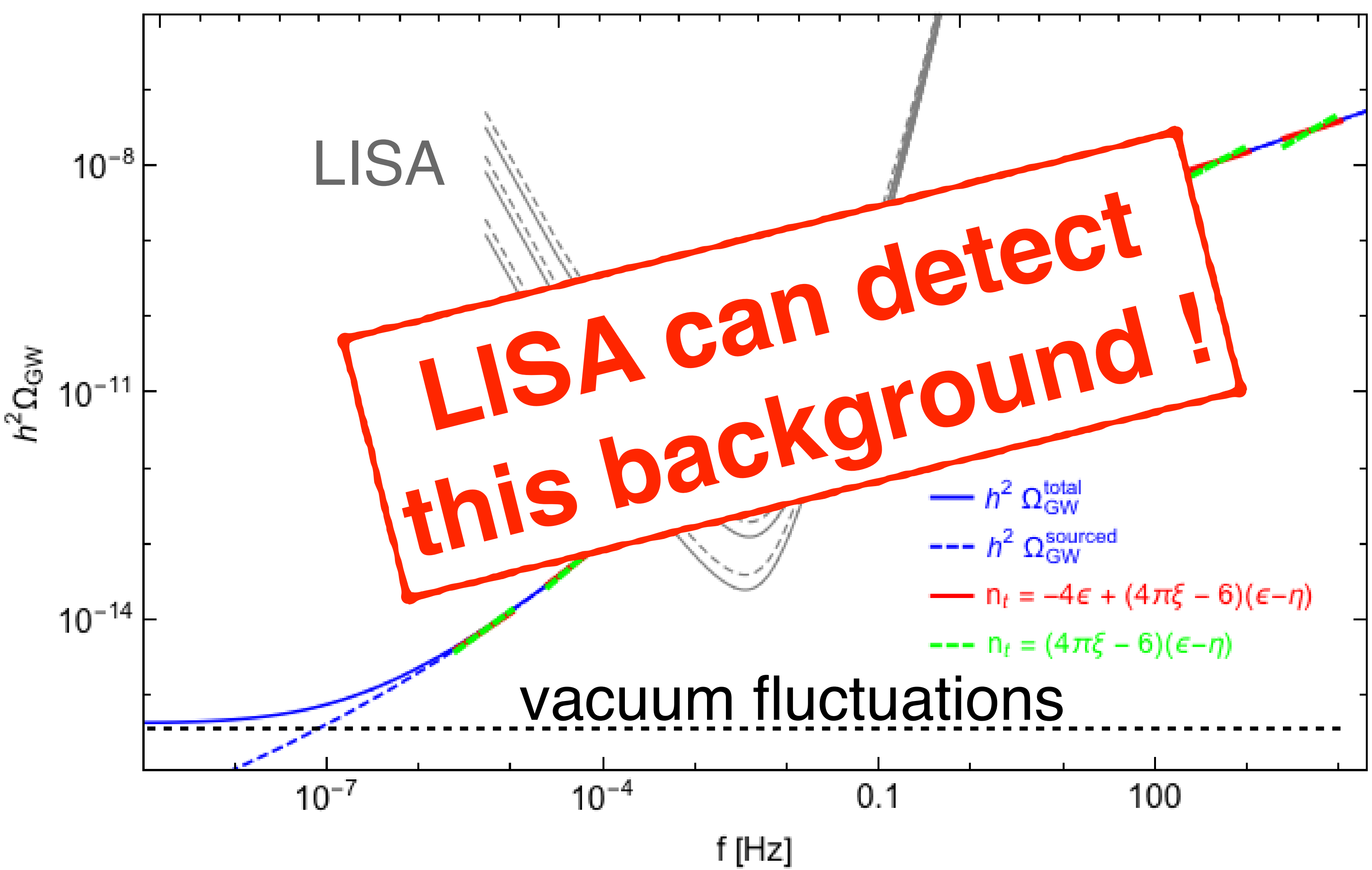
Gauge fields source a Blue-Tilted + Chiral + Non-G GW background

Bartolo et al '16, 1610.06481

INFLATIONARY MODELS

Axion-Inflation

GW energy spectrum today



Gauge fields source a Blue-Tilted + Chiral + Non-G GW background

Bartolo et al ’16, 1610.06481

INFLATIONARY MODELS

What if there are arbitrary fields coupled to the inflaton ?
(i.e. no need of extra symmetry)

$\longrightarrow$

large excitation of fields !?
will they create GWs?

$$\text{inflaton } \phi \longrightarrow V(\phi)$$

$$-\mathcal{L}_\chi = (\partial\chi)^2/2 + g^2(\phi-\phi_0)^2\chi^2/2$$ **Scalar Fld**

$$-\mathcal{L}_\psi = \bar{\psi}\gamma^\mu\partial_\mu\psi + g(\phi-\phi_0)\bar{\psi}\psi$$ **Fermion Fld**

$$\mathcal{L} = -\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} - |(\partial_\mu - gA_\mu)\Phi)|^2 - V(\Phi^\dagger\Phi)$$ **Gauge Fld** ($\Phi = \phi e^{i\theta}$)

INFLATIONARY MODELS

What if there are arbitrary fields coupled to the inflaton ?
(i.e. no need of extra symmetry)

→ large excitation of fields !?
will they create GWs?

$$\boxed{\text{inflaton } \phi \longrightarrow V(\phi)}$$

All 3 cases:

$$m = g(\phi(t) - \phi_0) \Rightarrow \dot{m} \gg m^2 \text{ during } \Delta t_{\rm na} \sim 1/\mu\,, \qquad \text{(non-adiabatic)} \qquad \boxed{\mu^2 \equiv g\dot{\phi}_0}$$

$$\boxed{n_k = \mathrm{Exp}\{-\pi(k/\mu)^2\}}$$ **Non-adiabatic field excitation (particle creation)**

⇓

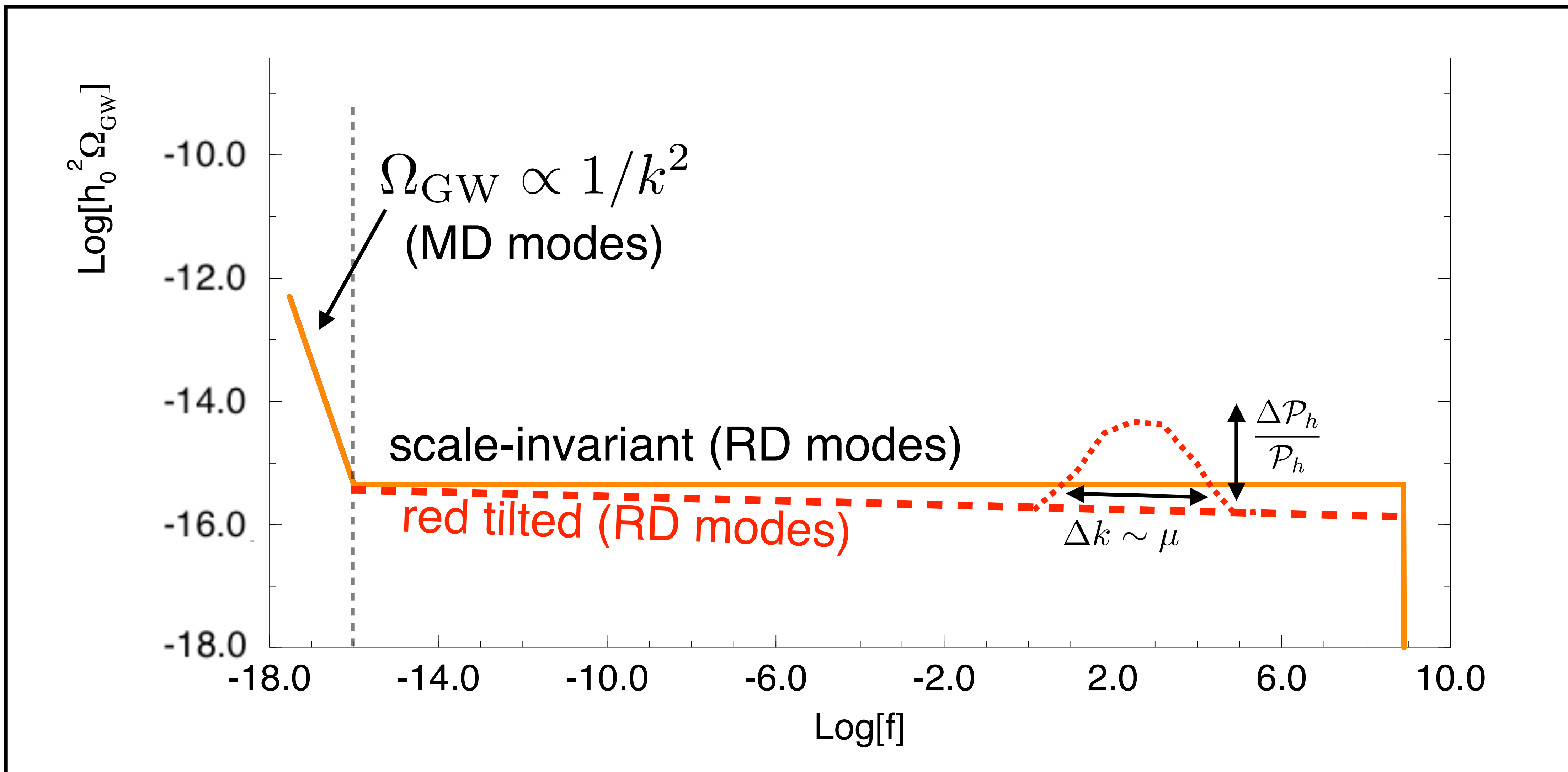
GW

INFLATIONARY MODELS

$$\boxed{\frac{\Delta\mathcal{P}_h}{\mathcal{P}_h} \equiv \frac{\mathcal{P}_h^{(\mathrm{tot})} - \mathcal{P}_h^{(\mathrm{vac})}}{\mathcal{P}_h^{(\mathrm{vac})}} \equiv \frac{\mathcal{P}_h^{(\mathrm{pp})}}{\mathcal{P}_h^{(\mathrm{vac})}} \sim few \times \mathcal{O}(10^{-4})\frac{H^2}{m_{\mathrm{pl}}^2} W(k\tau_0)\left(\frac{\mu}{H}\right)^3 \ln^2(\mu/H)}$$

$$\boxed{\mu^2 \equiv g\dot{\phi}_0}$$

(Sorbo et al 2011, Peloso et al 2012-2013, Caprini & DGF 2018)



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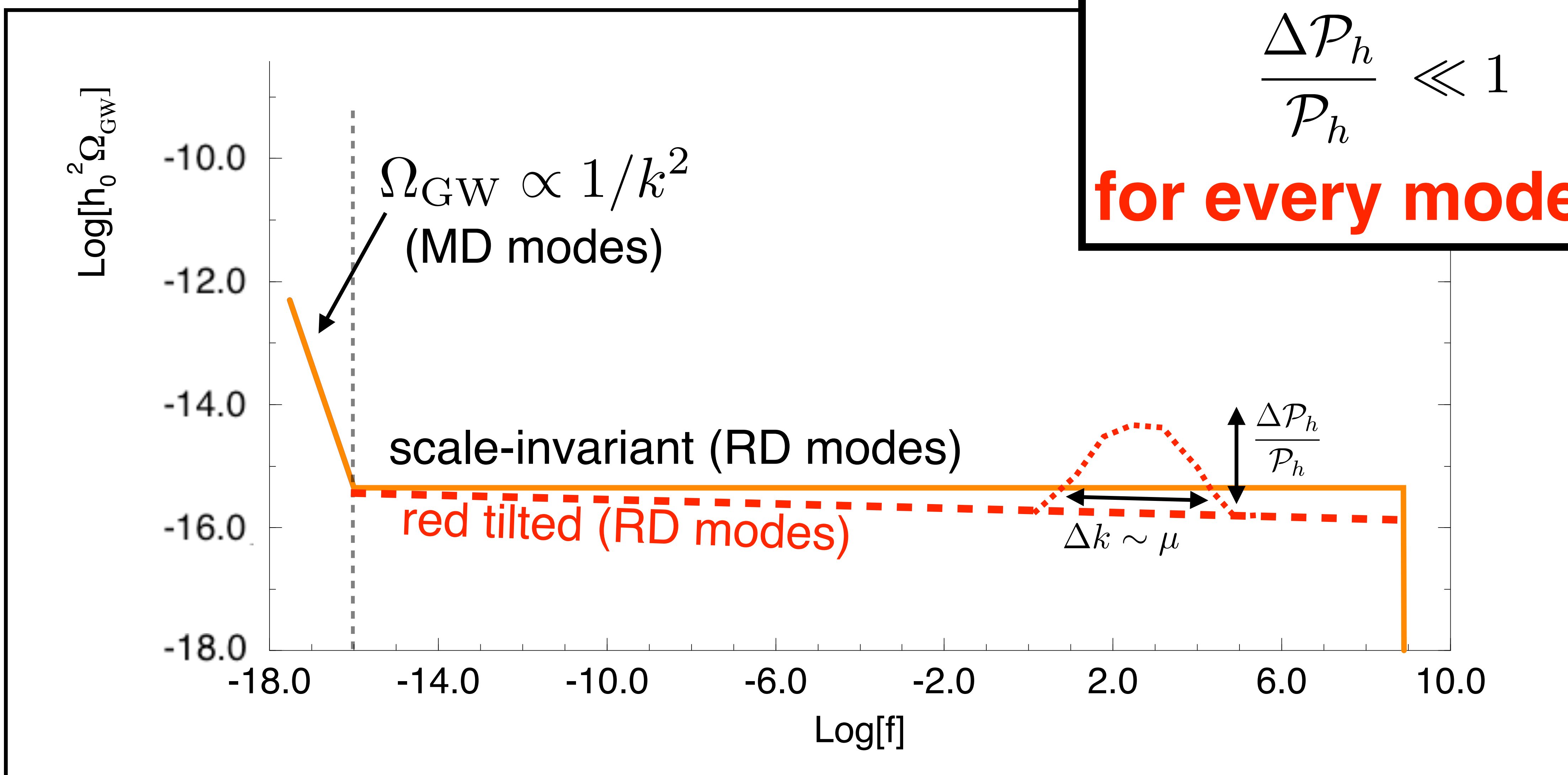
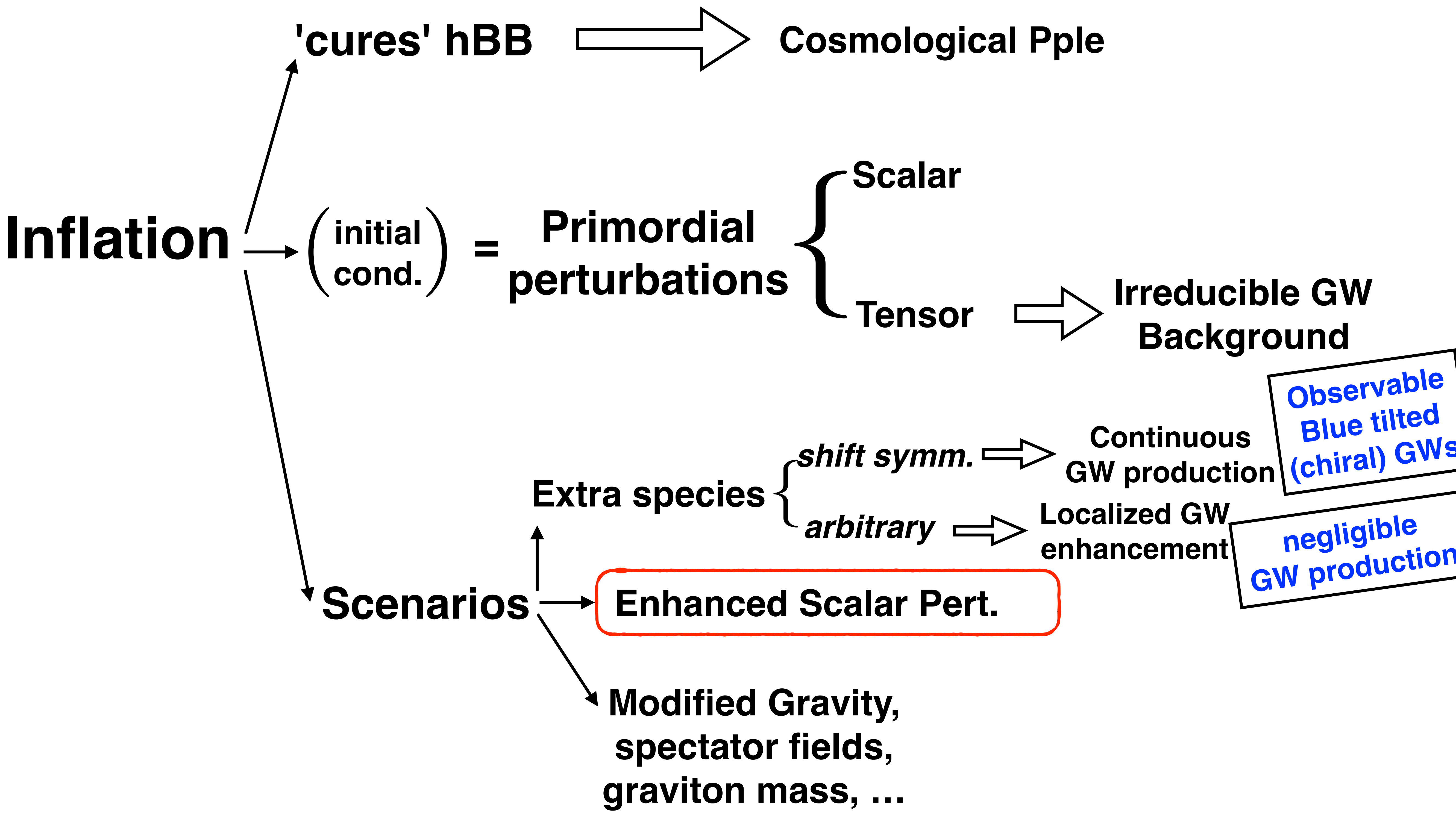
(Sorbo et al 2011, Peloso et al 2012-2013, Caprini & DGF 2018)

$$\frac{\Delta\mathcal{P}_h}{\mathcal{P}_h} \ll 1$$

for every model !



INFLATIONARY COSMOLOGY



INFLATIONARY MODELS

INFLATION → IF $\left\{ \begin{array}{l} \text{non-monotonic} \\ \text{multi-field} \end{array} \right\}$ $\Rightarrow$ possible to enhance $\Delta^2_{\mathcal{R}}$ (at small scales)

Let us suppose $\boxed{\Delta^2_{\mathcal{R}} \gg \Delta^2_{\mathcal{R}}\big|_{\rm CMB} \sim 3 \cdot 10^{-9}}$, @ small scales

$$ds^2 = a^2(\eta)[-(1+2\Phi)d\eta^2 + [(1-2\Psi)\delta_{ij} + 2F_{(i,j)} + h_{ij}]dx^i dx^j]$$

INFLATIONARY MODELS

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$$\boxed{h''_{ij} + 2\mathcal{H}h'_{ij} + k^2 h_{ij} = S^{TT}_{ij}} \sim \Phi * \Phi \quad \textbf{(2nd Order Pert.)}$$

$$\begin{aligned} S_{ij} = {} & 2\Phi\partial_i\partial_j\Phi - 2\Psi\partial_i\partial_j\Phi + 4\Psi\partial_i\partial_j\Psi + \partial_i\Phi\partial_j\Phi - \partial^i\Phi\partial_j\Psi - \partial^i\Psi\partial_j\Phi + 3\partial^i\Psi\partial_j\Psi \\ & - \frac{4}{3(1+w)\mathcal{H}^2}\partial_i(\Psi' + \mathcal{H}\Phi)\partial_j(\Psi' + \mathcal{H}\Phi) \\ & - \frac{2c_s^2}{3w\mathcal{H}}\left[3\mathcal{H}(\mathcal{H}\Phi - \Psi') + \nabla^2\Psi\right]\partial_i\partial_j(\Phi - \Psi) \end{aligned}$$

Phys.Rev. D81 (2010) 023527
Phys.Rev. D75 (2007) 123518
D. Wands et al, 2006-2010

INFLATIONARY MODELS

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$$\boxed{h''_{ij} + 2\mathcal{H}h'_{ij} + k^2 h_{ij} = S^{TT}_{ij}} \sim \Phi * \Phi$$ **(2nd Order Pert.)**

$$\boxed{\Omega_{gw,0}(k) = F_{\rm rad}\,\Omega_{\gamma,0}\,\Delta^4_{\mathcal{R}}(k)}$$

$$\boxed{F_{\rm rad} = \frac{8}{3}\left(\frac{216^2}{\pi^3}\right) 8.3 \times 10^{-3} f_{ns} \sim 30}$$

$f_{ns} \sim 1$

Phys.Rev. D81 (2010) 023527 **Phys.Rev. D75 (2007) 123518** D. Wands et al, 2006-2010

INFLATIONARY MODELS

INFLATION $\rightarrow$ IF $\left\{ \begin{array}{l} \text{non-monotonic} \\ \text{multi-field} \end{array} \right\} \Rightarrow$ possible to enhance $\Delta^2_{\mathcal{R}}$ (at small scales)

BBN $\Omega_{gw,0} < 1.5 \times 10^{-5} \longrightarrow \triangle^2_{\mathcal{R}} < 0.1$

LIGO $\Omega_{gw,0} < 6.9 \times 10^{-6} \longrightarrow \triangle^2_{\mathcal{R}} < 0.07$

$\boxed{\textbf{PTA} \quad \Omega_{gw,0} < 4 \times 10^{-8} \longrightarrow \triangle^2_{\mathcal{R}} < 5 \times 10^{-3}}$

$\boxed{\textbf{LISA} \quad \Omega_{gw,0} < 10^{-13} \longrightarrow \triangle^2_{\mathcal{R}} < 1 \times 10^{-5}}$

BBO $\Omega_{gw,0} < 10^{-17} \longrightarrow \triangle^2_{\mathcal{R}} < 3 \times 10^{-7}$

Phys.Rev. D81 (2010) 023527

INFLATIONARY MODELS

INFLATION $\Rightarrow$ IF $\left\{ \begin{array}{l} \text{non-monotonic} \\ \text{multi-field} \end{array} \right\}$ $\Rightarrow$ possible to enhance $\Delta^2_{\mathcal{R}}$ (at small scales)

IF $\Delta^2_{\mathcal{R}}$ very enhanced $\Rightarrow$ Primordial Black Holes (PBH) may be produced!

See talk *e.g.* by T. Suyama

INFLATIONARY MODELS

INFLATION → IF $\left\{ \begin{array}{l} \text{non-monotonic} \\ \text{multi-field} \end{array} \right\}$ ⇒ possible to enhance $\Delta^2_{\mathcal{R}}$ (at small scales)

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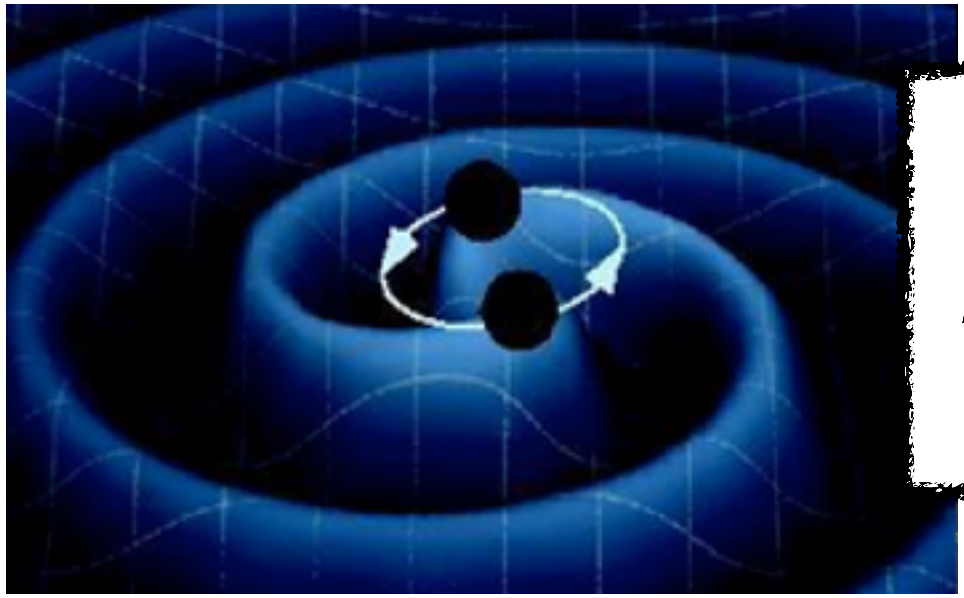
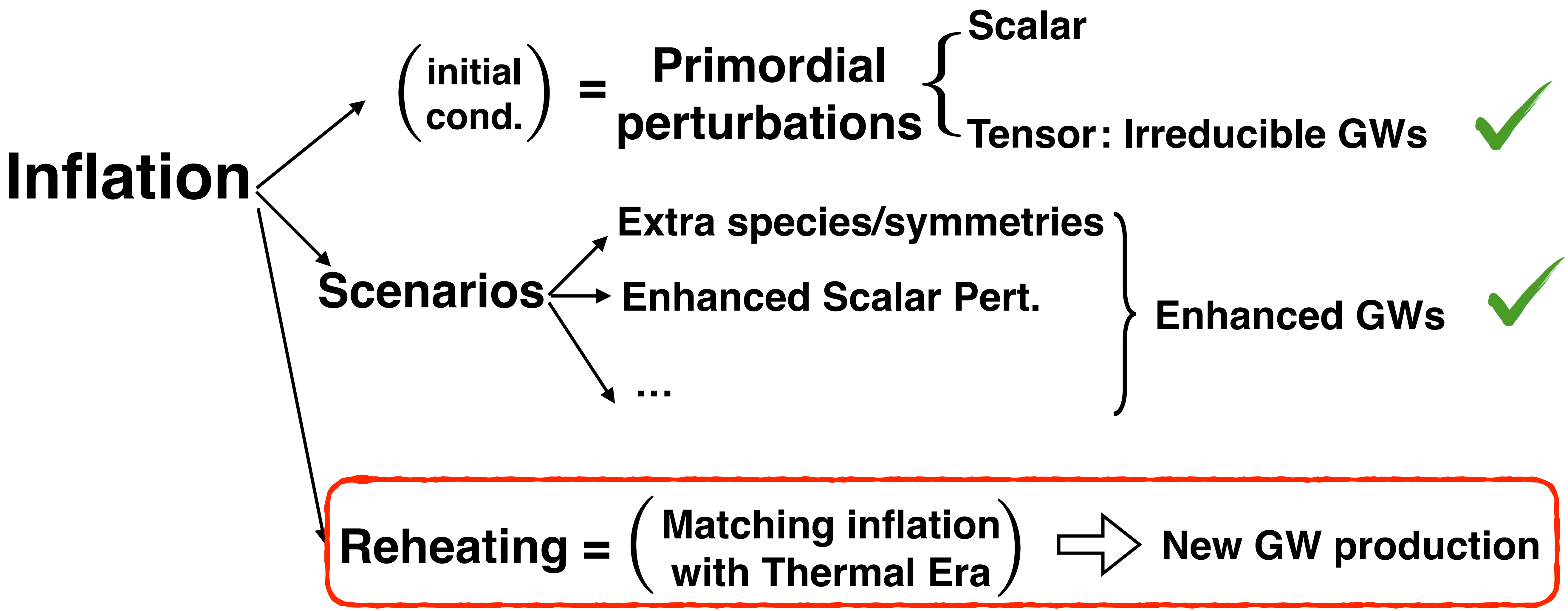
Has LIGO detected PBH's ?



'We should know soon, determining mass/spin distributions'
(M. Fishbach (LIGO), Moriond'19)

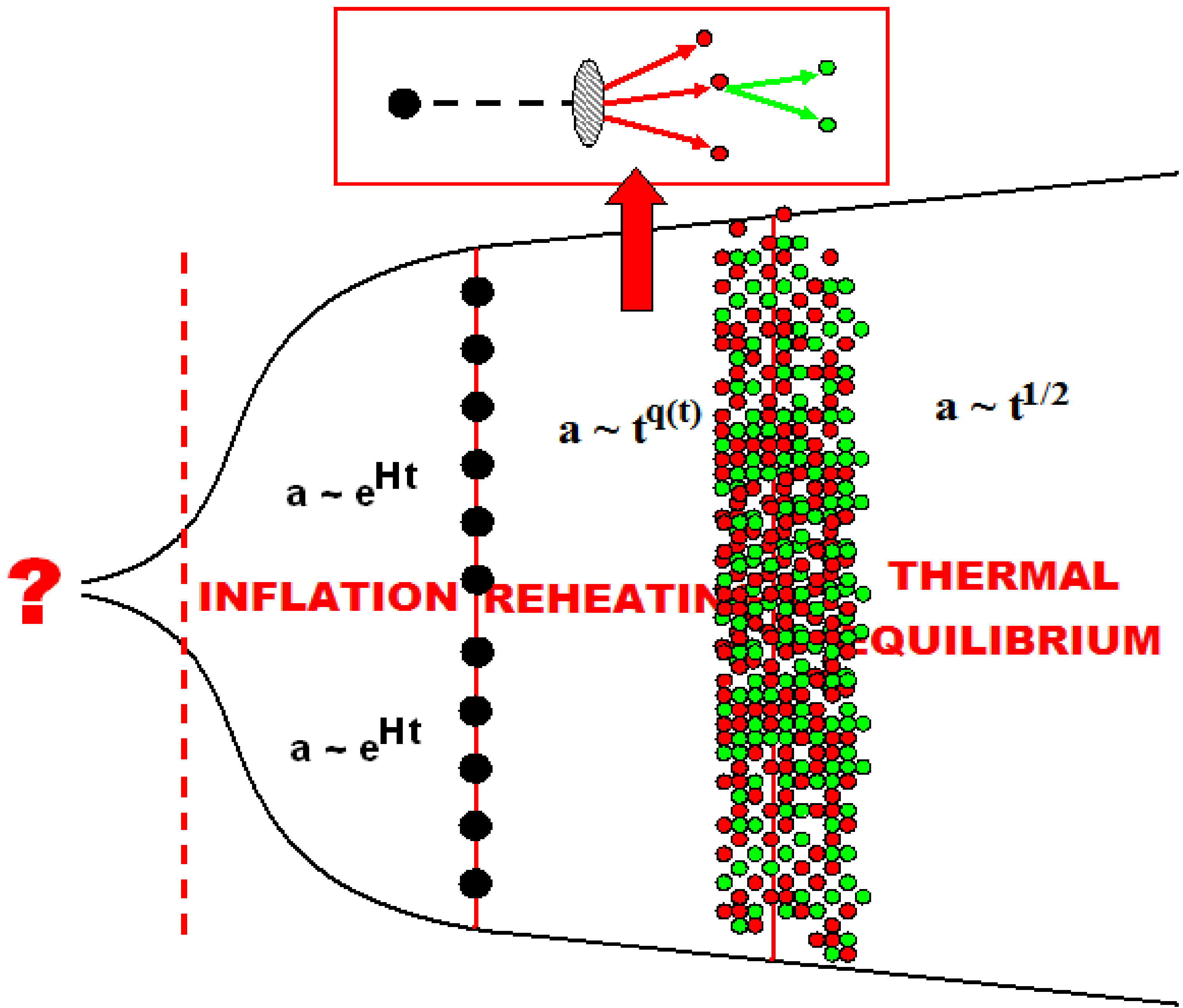
Update: 2005.05641, De Luca *et al*

INFLATIONARY COSMOLOGY



GWs from (p)Reheating

INFLATION ⟶ REHEATING ⟶ BIG BANG THEORY

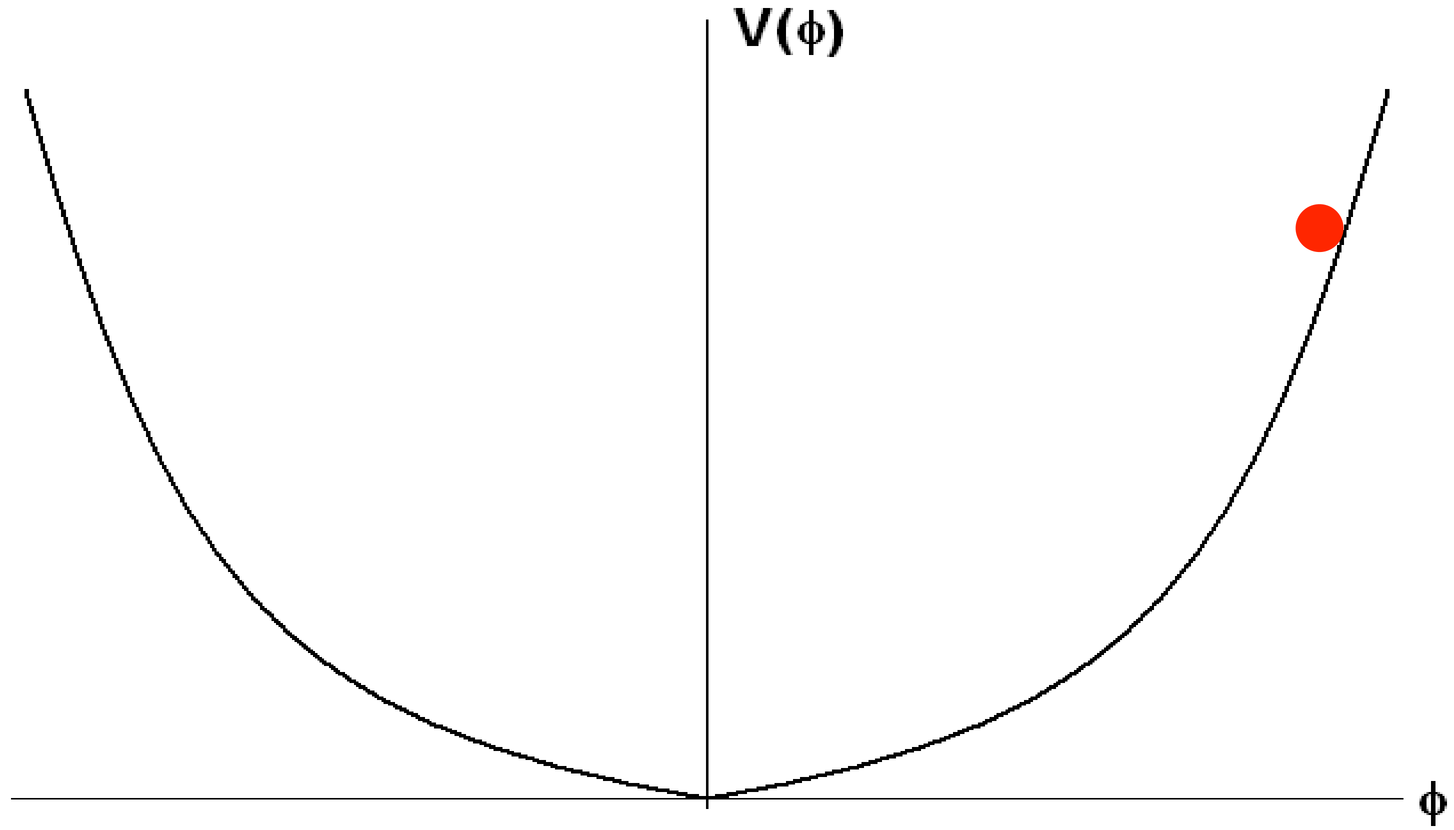


SCALAR (P)REHEATING

1) Chaotic Scenarios: PARAMETRIC RESONANCE

$$V(\phi,\chi) = \quad V(\phi) \quad + \quad \tfrac{1}{2}m_\chi^2\chi^2 \quad + \quad \tfrac{1}{2}g^2\phi^2\chi^2 \qquad \text{(Chaotic Models)}$$

$$X_k'' + [\kappa^2 + m^2(\phi)]X_k = 0 \qquad \text{(Fluctuations of Matter)}$$



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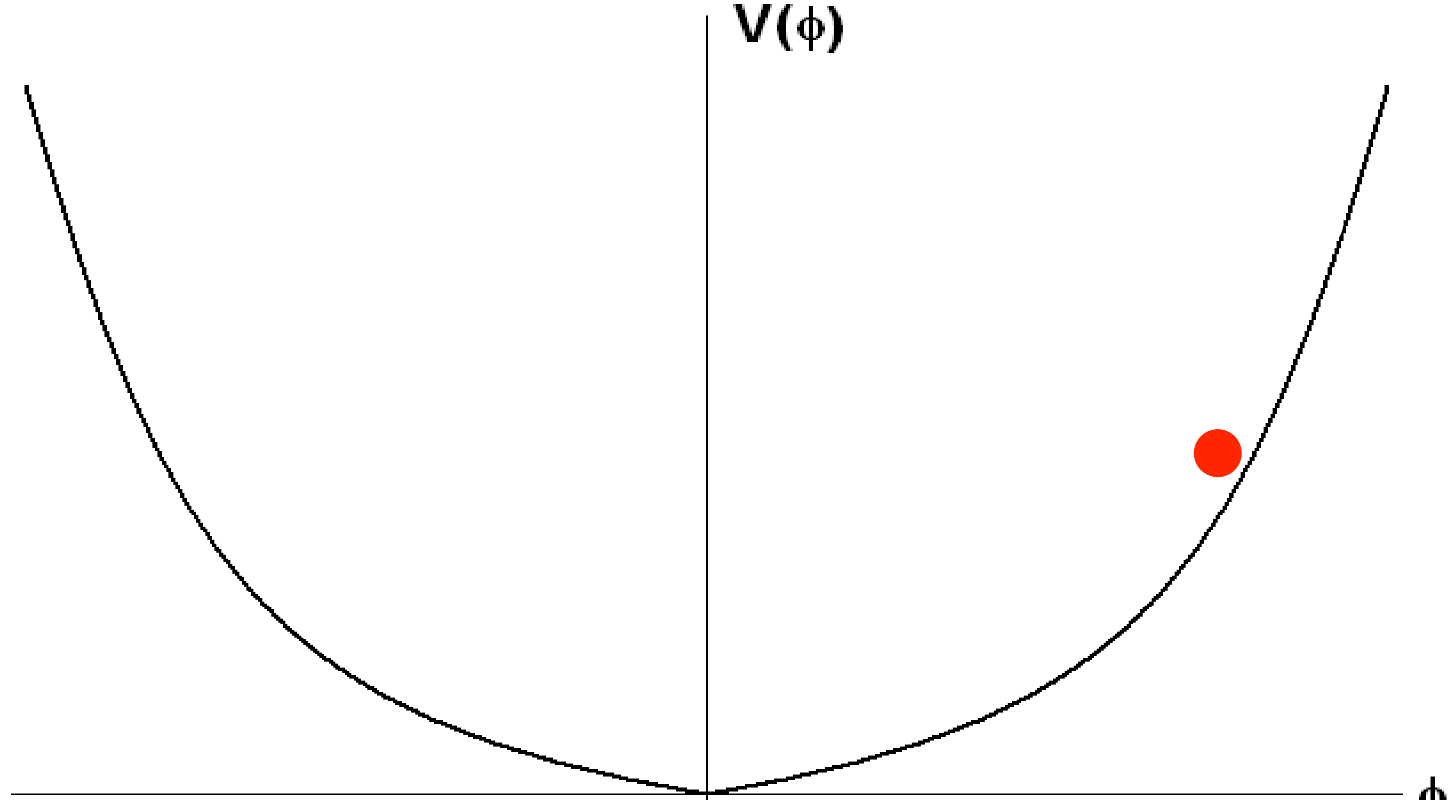

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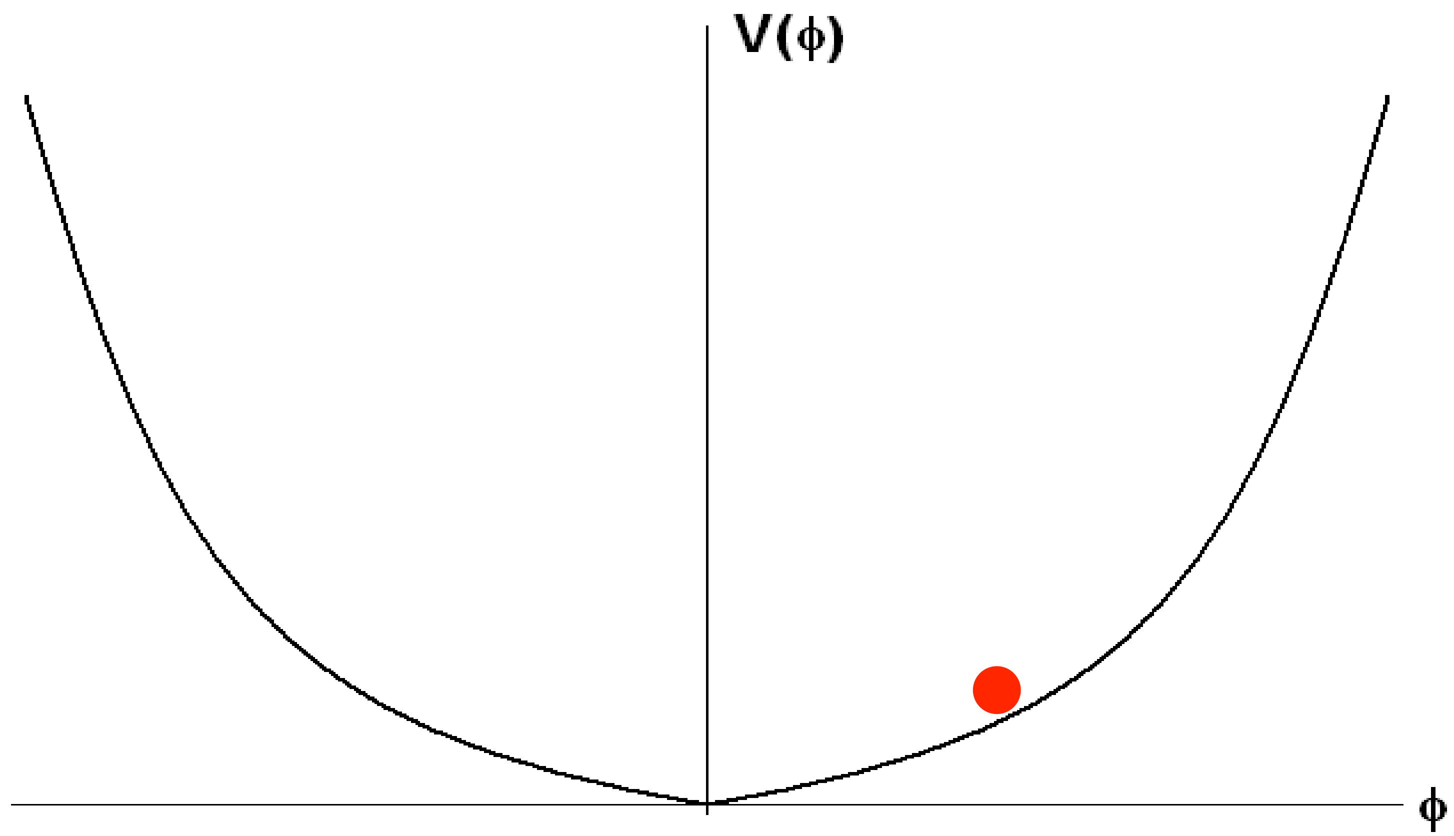

SCALAR (P)REHEATING

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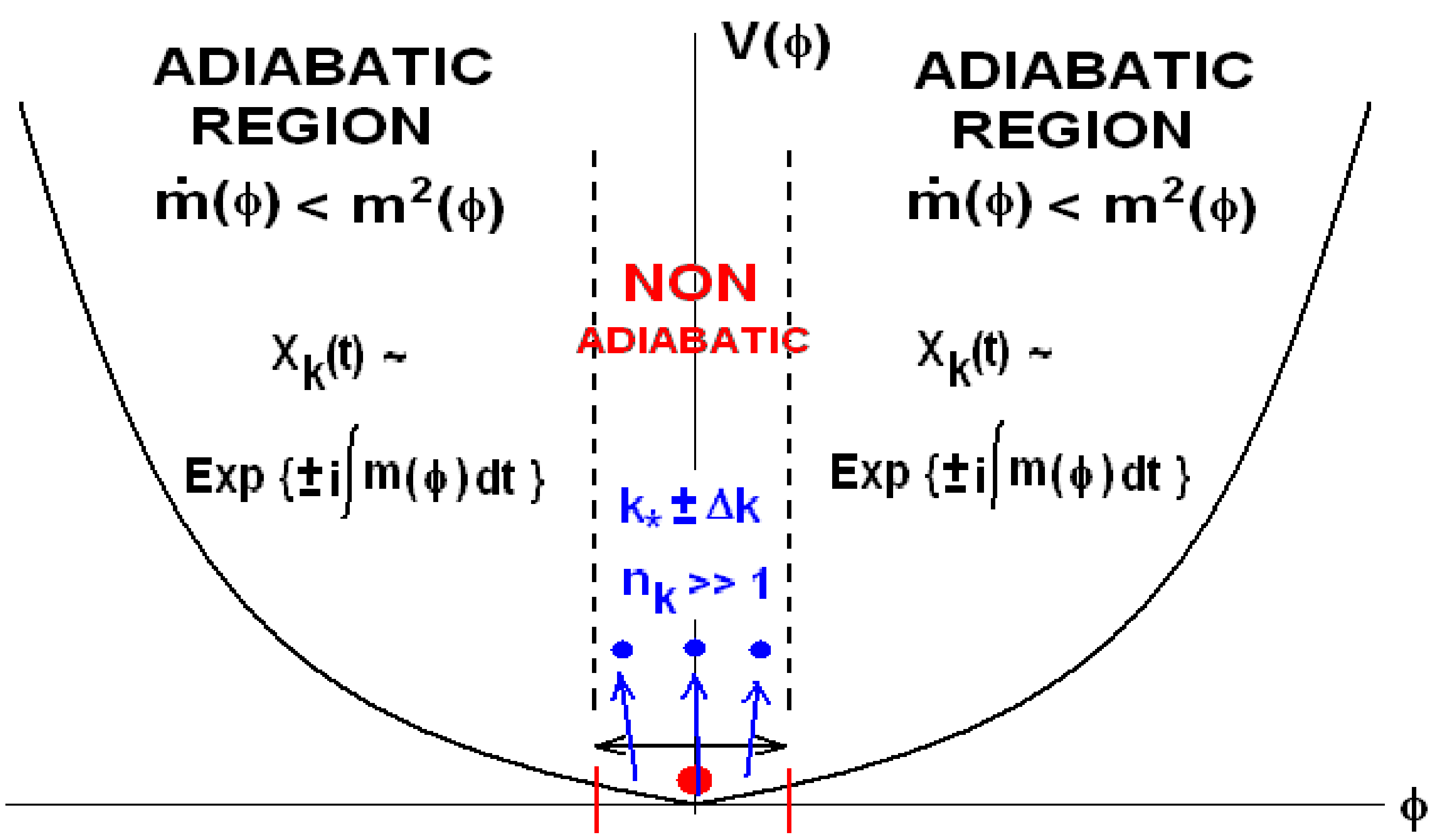

SCALAR (P)REHEATING

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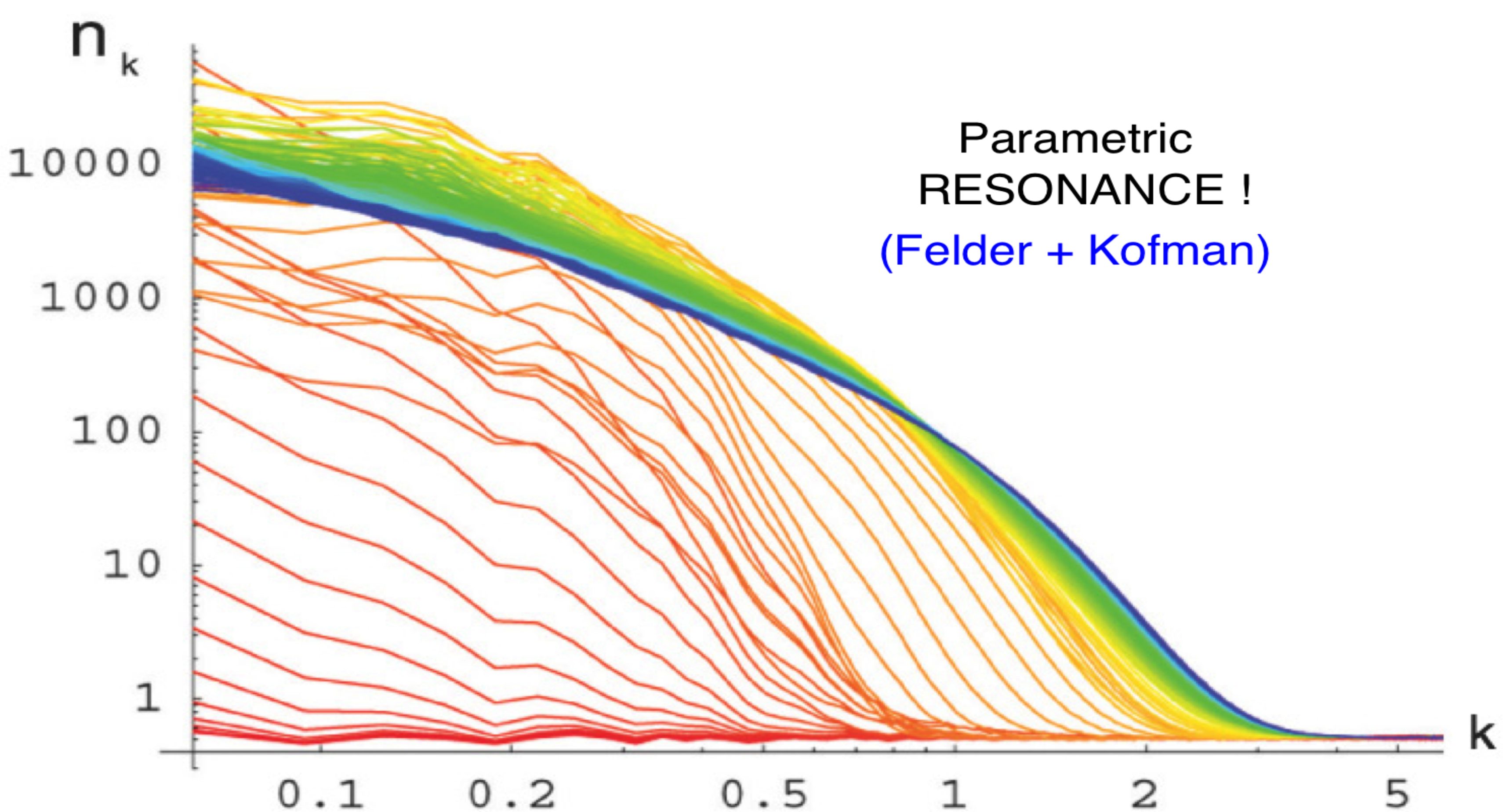


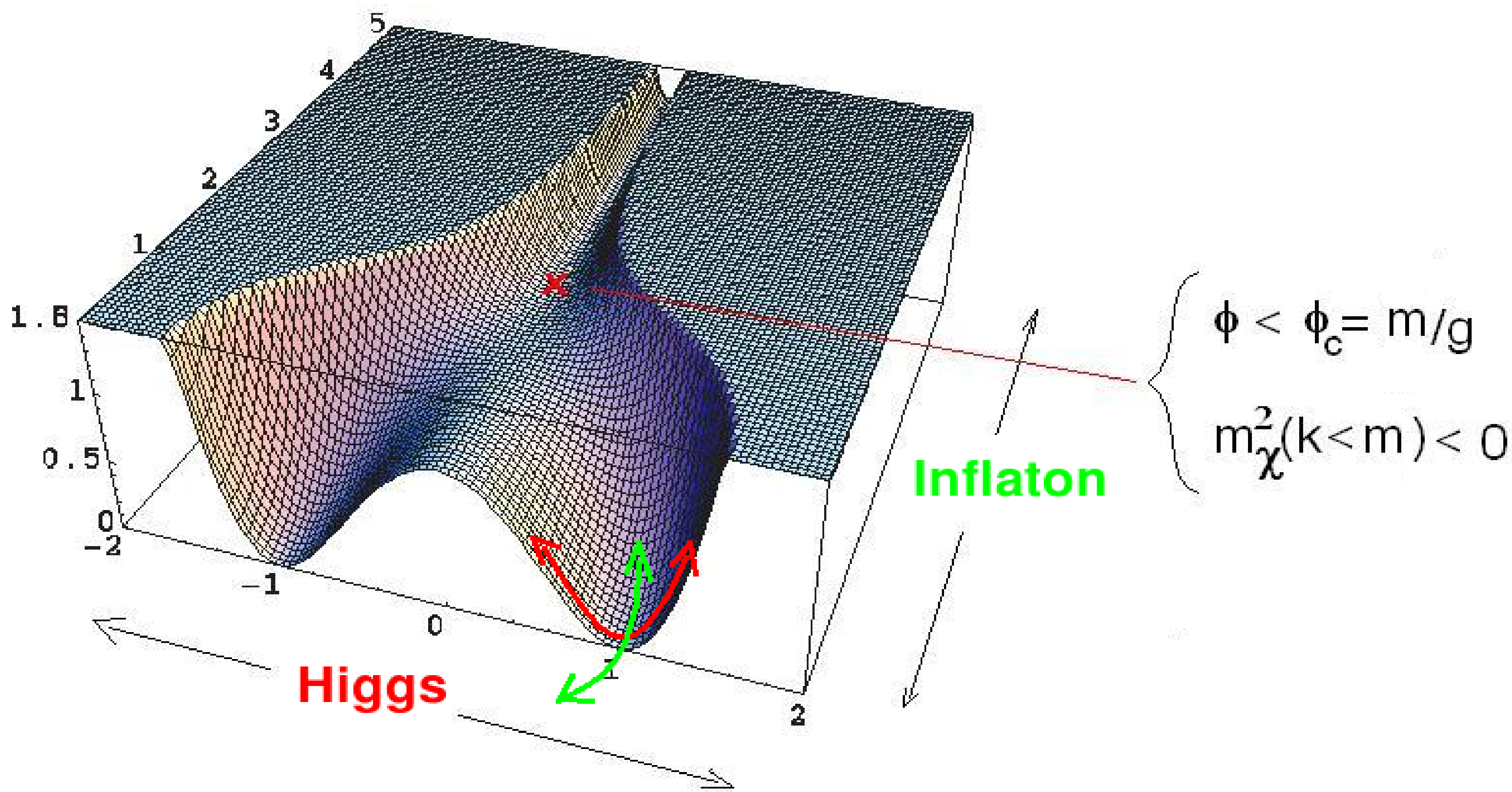
SCALAR (P)REHEATING

2) Hybrid Scenarios : SPINODAL INSTABILITY

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

$$\boxed{\begin{gathered}(k < m = \sqrt{\lambda}v)\\ \chi_k, n_k \sim e^{\sqrt{m^2-k^2}t}\end{gathered}}$$

Hybrid Preheating



INFLATIONARY PREHEATING

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

$$\begin{cases} \textbf{Hybrid Preheating}: & \omega^2 = k^2 + m^2(1 - V\,t) < 0 \quad (\text{Tachyonic}) \\ \textbf{Chaotic Preheating}: & \omega^2 = k^2 + \Phi^2(t)\sin^2\mu t \quad (\text{Periodic}) \end{cases}$$

At $\mathbf{k}_i$: $\varphi_{k_i}, n_{k_i} \sim e^{\mu(k,t)t} \Rightarrow$ Inhomogeneities: $\begin{cases} L_i \sim 1/k_i \\ \delta\rho/\rho \gtrsim 1 \\ v \approx c \end{cases}$

INFLATIONARY PREHEATING

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$\boxed{\textbf{Preheating: Very Effective GW generator !}}$

Easther, Giblin, Lim '06-'08
DGF, Ga-Bellido, et al '07-'10
Kofman, Dufaux et al '07-'09

INFLATIONARY PREHEATING

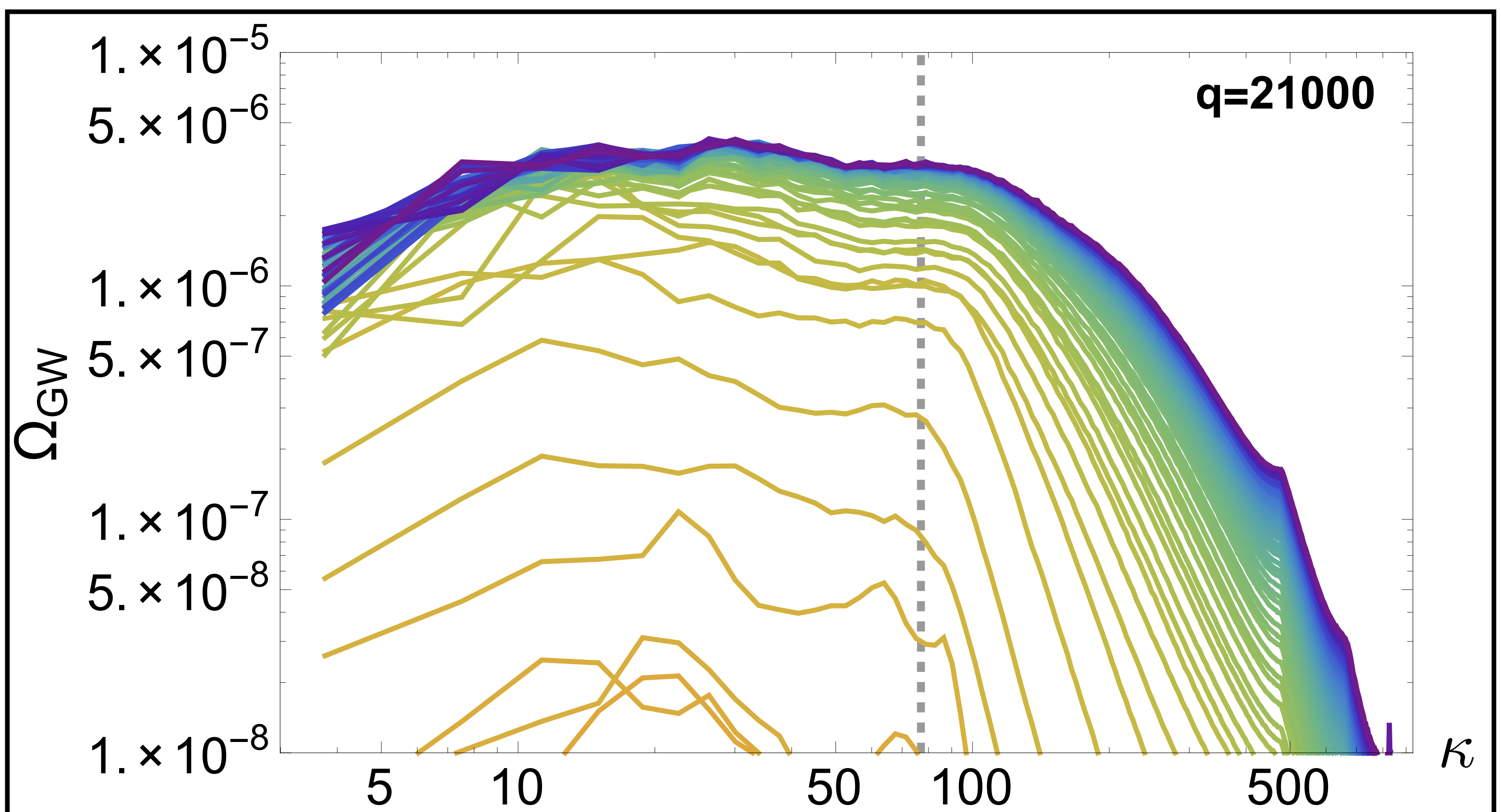
Parameter Dependence (Peak amplitude)

$$\boxed{\omega^2 \equiv V''(\Phi_I)}$$

Chaotic Models: $$\Omega_{\rm GW}^{(o)} \sim A^2 \frac{\omega^6}{\rho m_p^2}\; q^{-1/2}$$

$$\boxed{q \equiv \frac{g^2\Phi_{\rm i}^2}{\omega^2}}$$

Resonance Param.



(DGF, Torrentí, PRD 2017)

INFLATIONARY PREHEATING

Parameter Dependence (Peak amplitude**)**

Chaotic Models: $\Omega_{\rm GW}^{(o)} \sim 10^{-11}\,, \quad @ \quad f_o \sim 10^8 - 10^9~{\rm Hz}$

Large amplitude ! **... at high Frequency !**

INFLATIONARY PREHEATING

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Large amplitude ! **... at high Frequency !**

Very unfortunate... no detectors there !

INFLATIONARY PREHEATING

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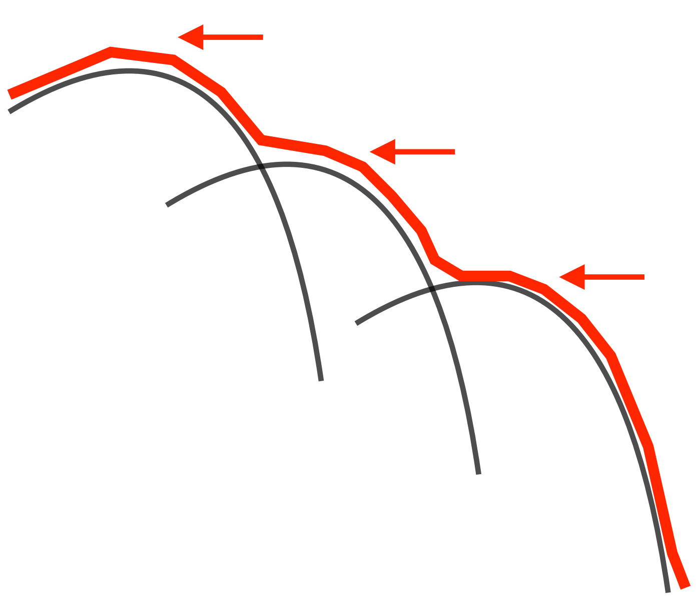
Large amplitude ! **... at high Frequency !**

$\Omega_{\rm GW} \propto q^{-1/2} \longrightarrow$ **Spectroscopy of particle couplings ?**



different couplings
... different peaks ?

DGF & Loayza, work in progress

INFLATIONARY PREHEATING

Parameter Dependence (Peak amplitude**)**

Hybrid Models: $\Omega_{\rm GW}^{(o)} \propto \left(\frac{v}{m_p}\right)^2 \times f(\lambda, g^2) \quad , \qquad f_o \sim \lambda^{1/4} \times 10^9 \text{ Hz}$

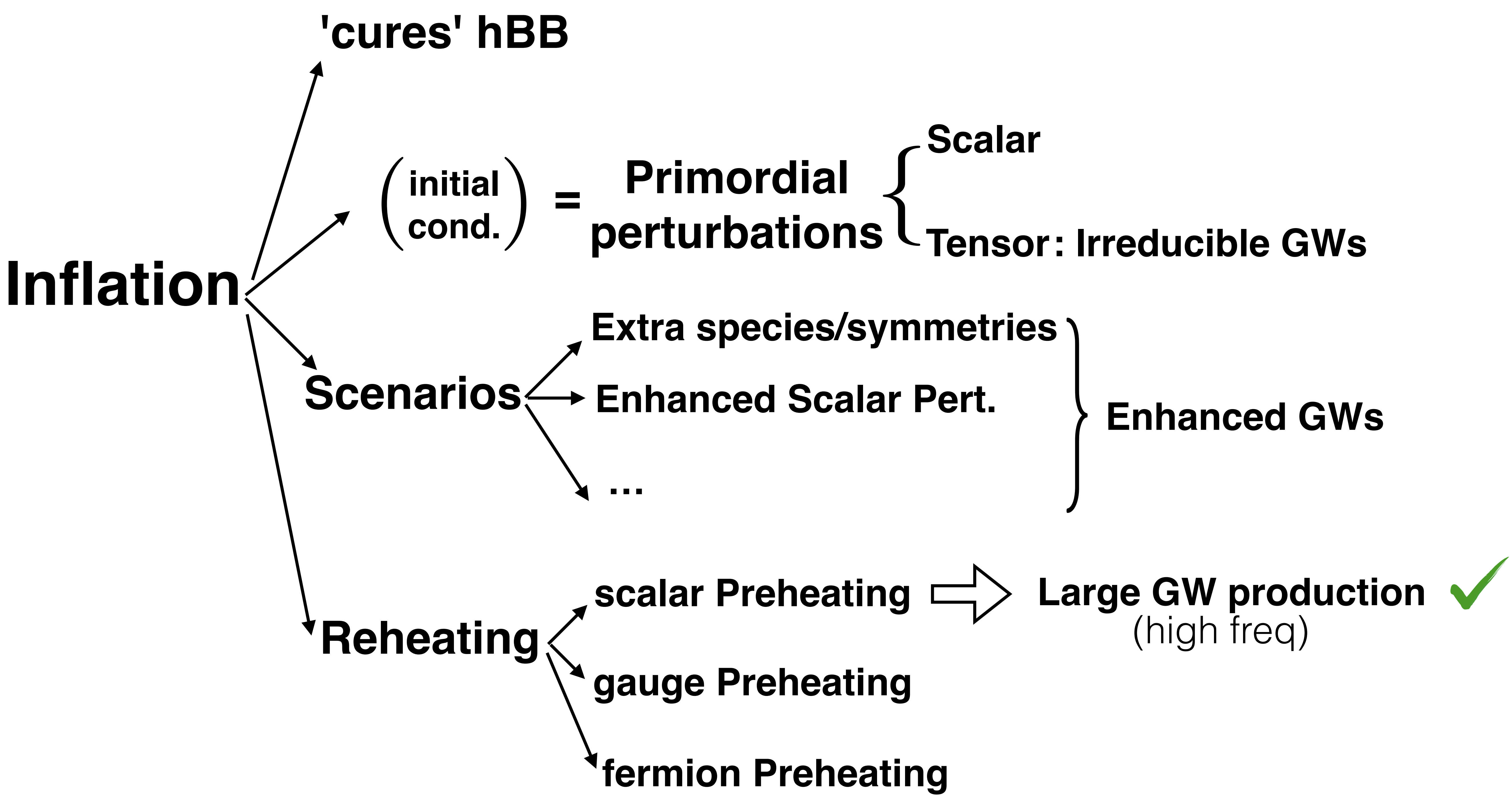
$$\Omega_{\rm GW}^{(o)} \sim 10^{-11}\,, \quad @ \quad \begin{cases} f_o \sim 10^8 - 10^9 \text{ Hz} & \boxed{\lambda \sim 0.1} \text{ (natural)} \\ f_o \sim 10^2 \text{ Hz} & \boxed{\lambda \sim 10^{-28}} \text{ (fine-tuning)} \end{cases}$$

Large amplitude !

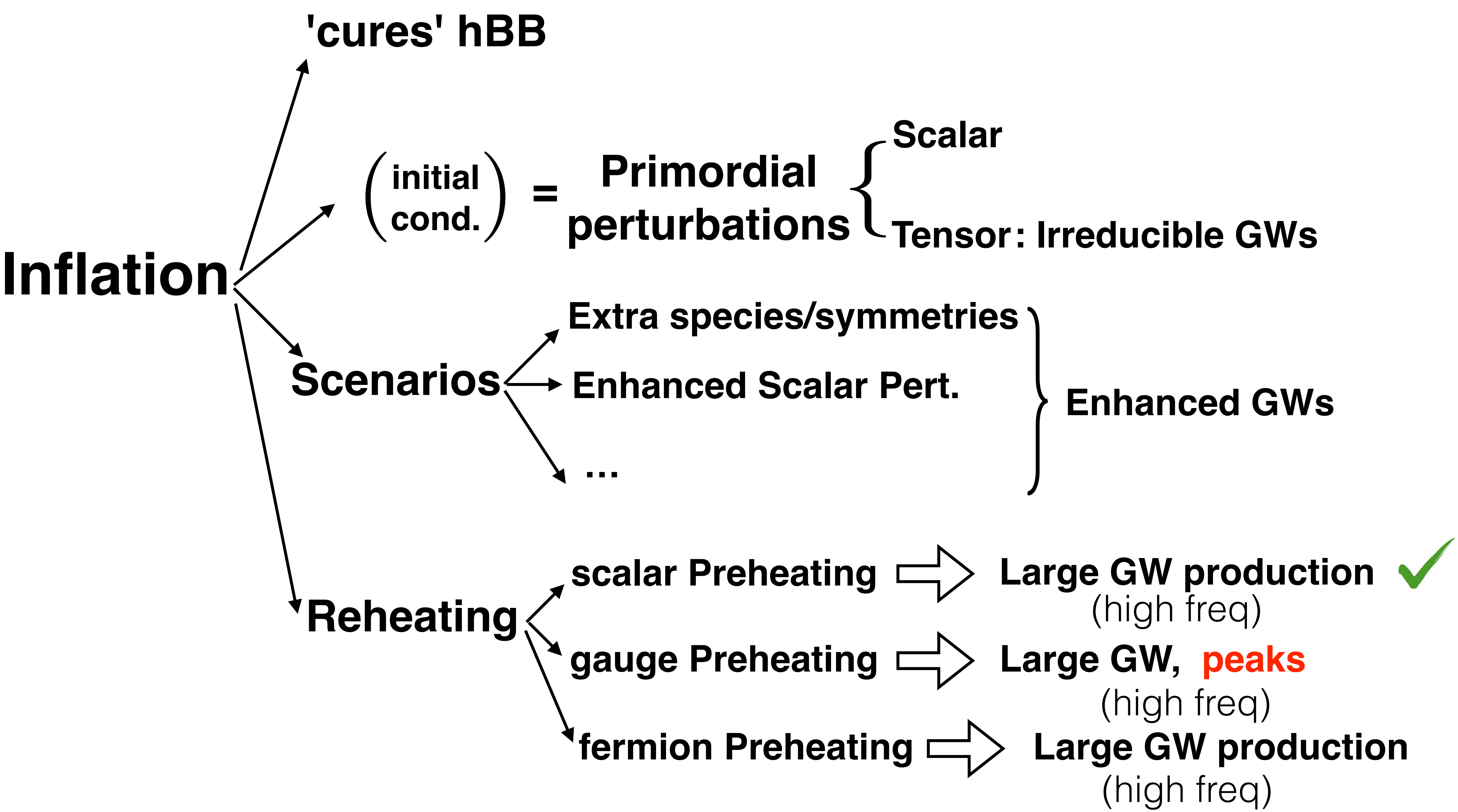
$(\text{for } v \simeq 10^{16} \text{ GeV})$

realistically speaking ...

INFLATIONARY COSMOLOGY



INFLATIONARY COSMOLOGY



INFLATIONARY COSMOLOGY

Inflation

- 'cures' hBB
- (initial cond.) = Primordial perturbations
  - Scalar
  - Tensor : Irreducible GWs
- Scenarios
  - Extra species/symmetries
  - Enhanced Scalar Pert.
  - ...
  - → Enhanced GWs
- Reheating
  - scalar Preheating ⇒ Large GW production ✓ (high freq)
  - gauge **1006.0217, 1706.02365** peaks (high freq)
  - fermion P **1203.4943, 1306.6911** / production freq)

Gravitational Waves as a probe of the early Universe

OUTLINE

0) GW definition ✓

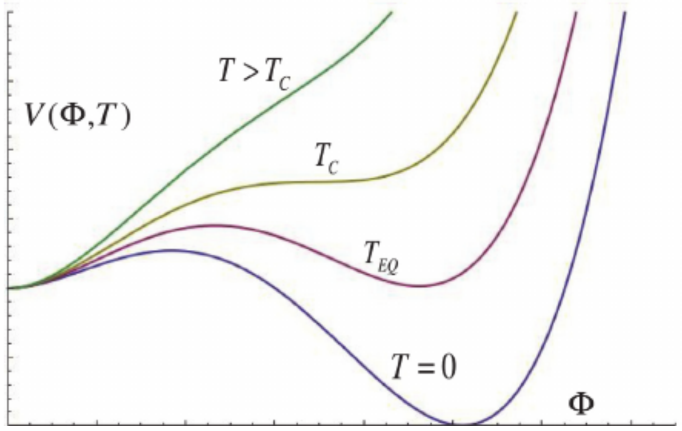
Early Universe

1) GWs from Inflation
2) GWs from Preheating ✓
3) GWs from Phase Transitions
4) GWs from Cosmic Defects

First order phase transitions

Universe expands, temperature decreases: phase transition triggered !

* Potential barrier separates
true and **false** vacua



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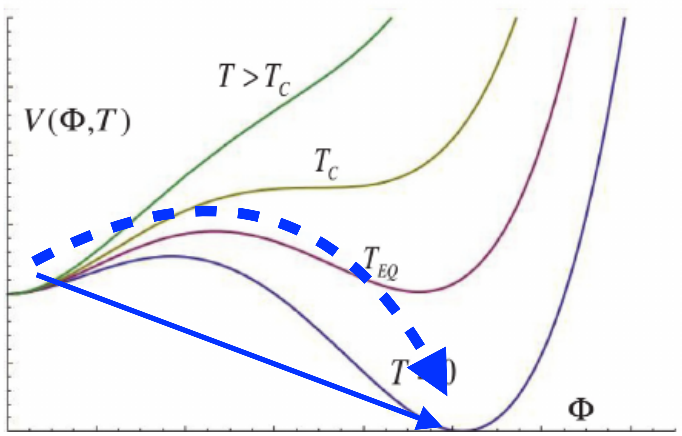

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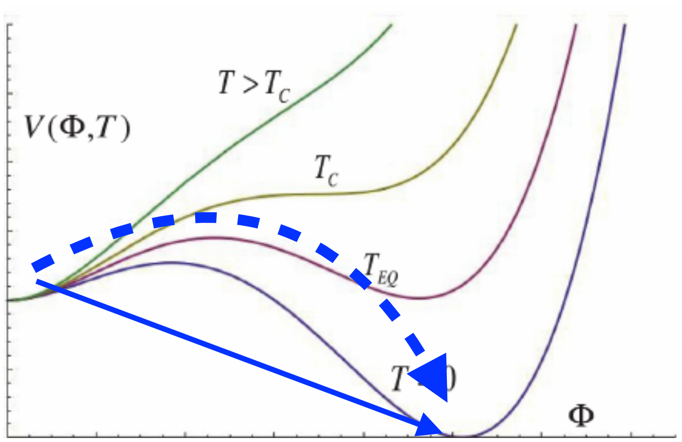
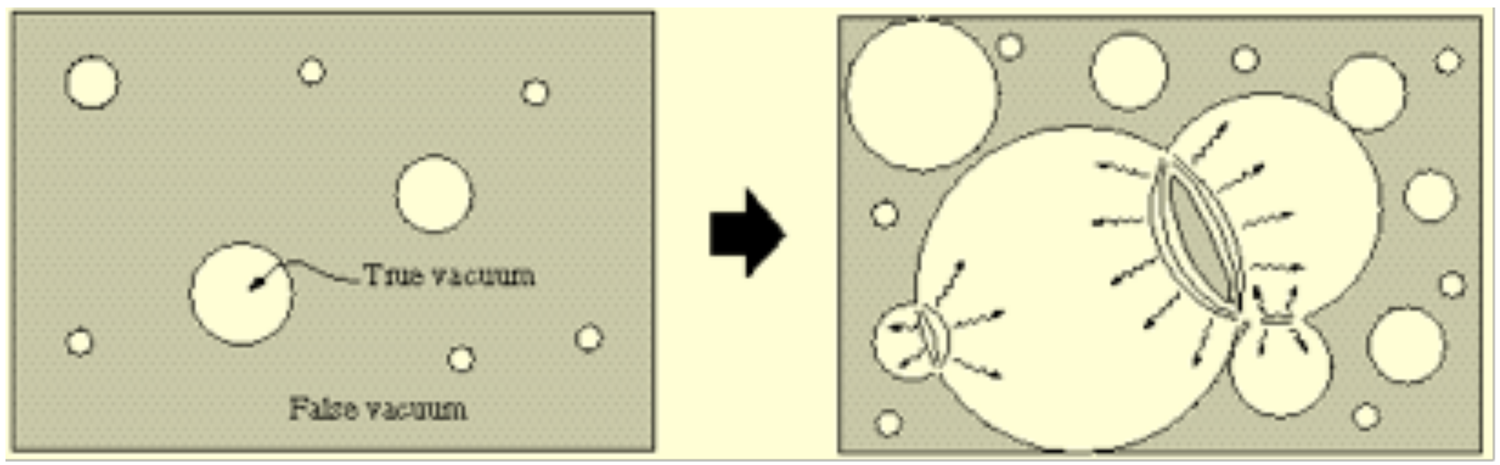


bubble nucleation



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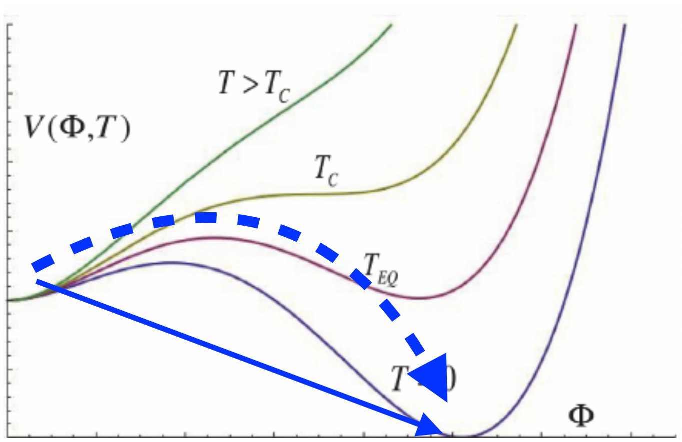

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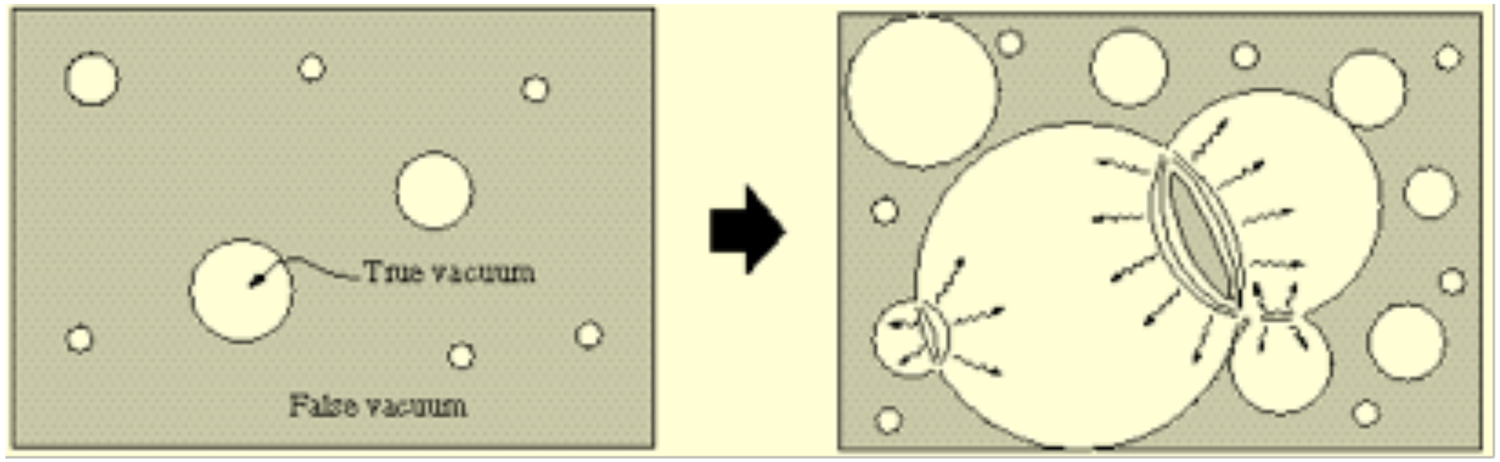

GW

source: Π_{ij} tensor anisotropic stress

- collisions of bubble walls
- sound waves and turbulence in the fluid
- primordial magnetic fields (MHD turbulence)

First order phase transitions

Universe expands, temperature decreases: phase transition triggered !

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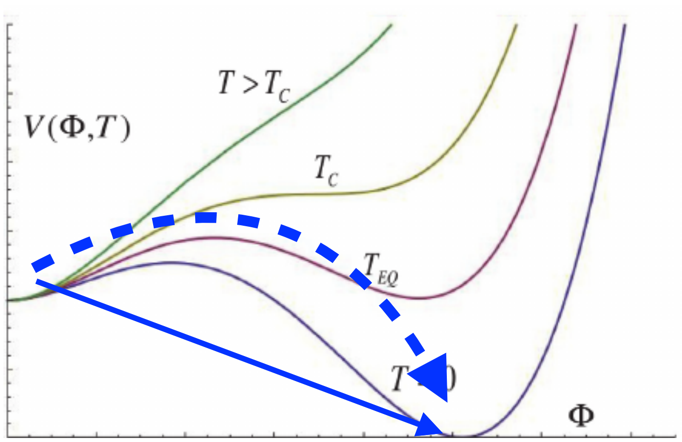

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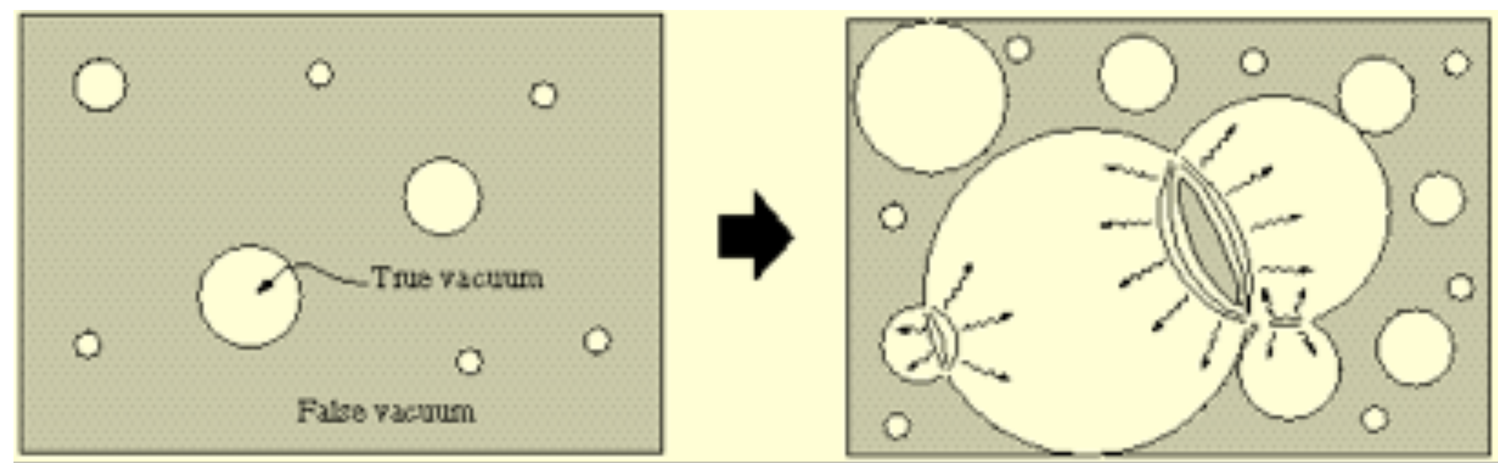

GW
source: Π_{ij} tensor
anisotropic stress

$$\Pi_{ij} \sim \partial_i\phi\,\partial_j\phi$$

$$\Pi_{ij} \sim \gamma^2(\rho+p)\,v_i v_j$$

$$\Pi_{ij} \sim \frac{(E^2+B^2)}{3} - E^i E^j - B^i B^j$$

GWs from first order phase transitions

* **GW causal source**: cannot 'operate' beyond the **horizon**

$$\boxed{f_* = \frac{H(T_*)}{\epsilon_*}}$$

$$\boxed{\epsilon_* \leq 1}$$

parameter characterising source

GWs from first order phase transitions

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parameter characterising source

@ Today

@ Emission time

Hubble rate

temperature

$$f_c = f_* \frac{a_*}{a_0} = \frac{2 \cdot 10^{-5}}{\epsilon_*} \frac{T_*}{1\,\mathrm{TeV}}\,\mathrm{Hz}$$

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Hubble rate

$\updownarrow$

temperature

$$\underset{\text{@ Today}}{f_c} = \underset{\text{@ Emission time}}{f_*}\frac{a_*}{a_0} = \frac{2\cdot 10^{-5}}{\epsilon_*}\frac{T_*}{1\,\mathrm{TeV}}\,\mathrm{Hz} \qquad \simeq \mathrm{mHz}$$

for $\boxed{\epsilon_* \simeq 10^{-2}}$ $\boxed{T_* \simeq 1\,\mathrm{TeV}}$

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$\boxed{\epsilon_* \leq 1}$ parameter characterising source

@ Today

@ Emission time

Hubble rate $\updownarrow$ temperature

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LISA Freq !

for $\boxed{\epsilon_* \simeq 10^{-2}}$ $\boxed{T_* \simeq 1\,\mathrm{TeV}}$ **~ EW scale !**

What is ϵ in 1st Order PhT's?

$$f_c = f_* \frac{a_*}{a_0} = \frac{2 \cdot 10^{-5}}{\epsilon_*} \frac{T_*}{1\,\mathrm{TeV}}\,\mathrm{Hz}$$

GW generation <—> bubbles properties

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GW generation <—> bubbles properties

β^{-1} : duration of PhT

$v_b \leq 1$: speed of bubble walls

$\longrightarrow R_* = v_b\, \beta^{-1}$ size of bubbles at collision

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GW generation <—> bubbles properties

β^{-1} : duration of PhT

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$\longrightarrow R_* = v_b\, \beta^{-1}$ size of bubbles at collision

$$\boxed{\epsilon \simeq \frac{H_*}{\beta}\,,\; H_*\, R_*}$$

BUBBLE COLLISION

SOUND WAVES AND MDH TURBULENCE

Parameters determining the GW spectrum

Freq. (today)

$$f_c = f_* \frac{a_*}{a_0} = \frac{2 \cdot 10^{-5}}{\epsilon_*} \frac{T_*}{1\,\mathrm{TeV}}\,\mathrm{Hz}$$

$$\epsilon \simeq \frac{H_*}{\beta}\,,\ H_*\,R_*$$

Parameter List
(not independent)

$$\boxed{\frac{\beta}{H_*}\,,\quad v_b\,,\quad T_*}$$

Parameters determining the GW spectrum

Freq. (today)

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$$\epsilon \simeq \frac{H_*}{\beta}\,, \quad H_*\,R_*$$

Parameter List
(not independent)

$$\boxed{\frac{\beta}{H_*}\,, \quad v_b\,, \quad T_*}$$

Amplitude (today)

$$\Omega_{\mathrm{GW}} \sim \Omega_{\mathrm{rad}}\,\epsilon_*^2 \left(\frac{\rho_{\mathrm{s}}^*}{\rho_{\mathrm{tot}}^*}\right)^2$$

$$\frac{\rho_{\mathrm{s}}^*}{\rho_{\mathrm{tot}}^*} = \frac{\kappa\,\alpha}{1+\alpha}$$

$$\alpha = \frac{\rho_{\mathrm{vac}}}{\rho_{\mathrm{rad}}^*}$$

$$\kappa = \frac{\rho_{\mathrm{kin}}}{\rho_{\mathrm{vac}}}$$

Parameters determining the GW spectrum

Freq. (today)

$$f_c = f_* \frac{a_*}{a_0} = \frac{2 \cdot 10^{-5}}{\epsilon_*} \frac{T_*}{1\,\mathrm{TeV}}\,\mathrm{Hz}$$

$$\epsilon \simeq \frac{H_*}{\beta}\,, \quad H_*\,R_*$$

Parameter List
(not independent)

$$\frac{\beta}{H_*}\,, \qquad v_b\,, \qquad T_*$$

Amplitude (today)

$\Omega_{\rm GW}$ …

$\rho_{\rm tot}$ … $1+\alpha$

not most general !

Hydro-dynamical effects, turbulence

$$\alpha = \frac{\rho_{\rm vac}}{\rho^*_{\rm rad}}$$

$$\kappa = \frac{\rho_{\rm kin}}{\rho_{\rm vac}}$$

Evaluation of the signal

- **bubble collisions**: **analytical** and **numerical** simulations

  Huber, Konstandin '08   Cutting, Hindmarsh et al 2018, …

- **sound waves**: **numerical** simulations of scalar field and fluid

  Hindmarsh, Weir et al 2012 - 2019,

  analytical Hindmarsh 2016, 2019,

- **MDH turbulence**: **analytical** evaluation

  Kosowsky et al ’07, Caprini et al ’09, Niksa et al '18

  numerical Pol et al 2019

Evaluation of the signal

- **bubble collisions**: **anal**... ions
  ..., ...

- **so**... **...ical** simulations of scalar field and fluid
  Hindmarsh, Weir et al 2012 - 2019,
  analytical **Hindmarsh 2016, 201...**

- **M**...
  ...), Niksa et al '18
  ...r et al 2019

Connection Particle Physics & Cosmology !

GW: new probe of BSM (complementary to colliders)

Evaluation of the signal

- **bubble collisions**: **anal**... ...ions
  ...3, ...
- **so**...**ical** simulations of scalar field and fluid
  Hindmarsh, Weir et al 2012 - 2019,
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- **M**...
  ...**, Niksa et al '18**
  ...**et al 2019**

LISA naturally good for the EW PhT $(f \sim 10^{-3}\ \mathrm{Hz})$

GW: new probe of BSM (complementary to colliders)

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  Hindmarsh, Weir et al 2012 - 2019,

  analytical **Hindmarsh 2016, 201**...

- **M**...

  ... 18

  ... **or et al 201**...

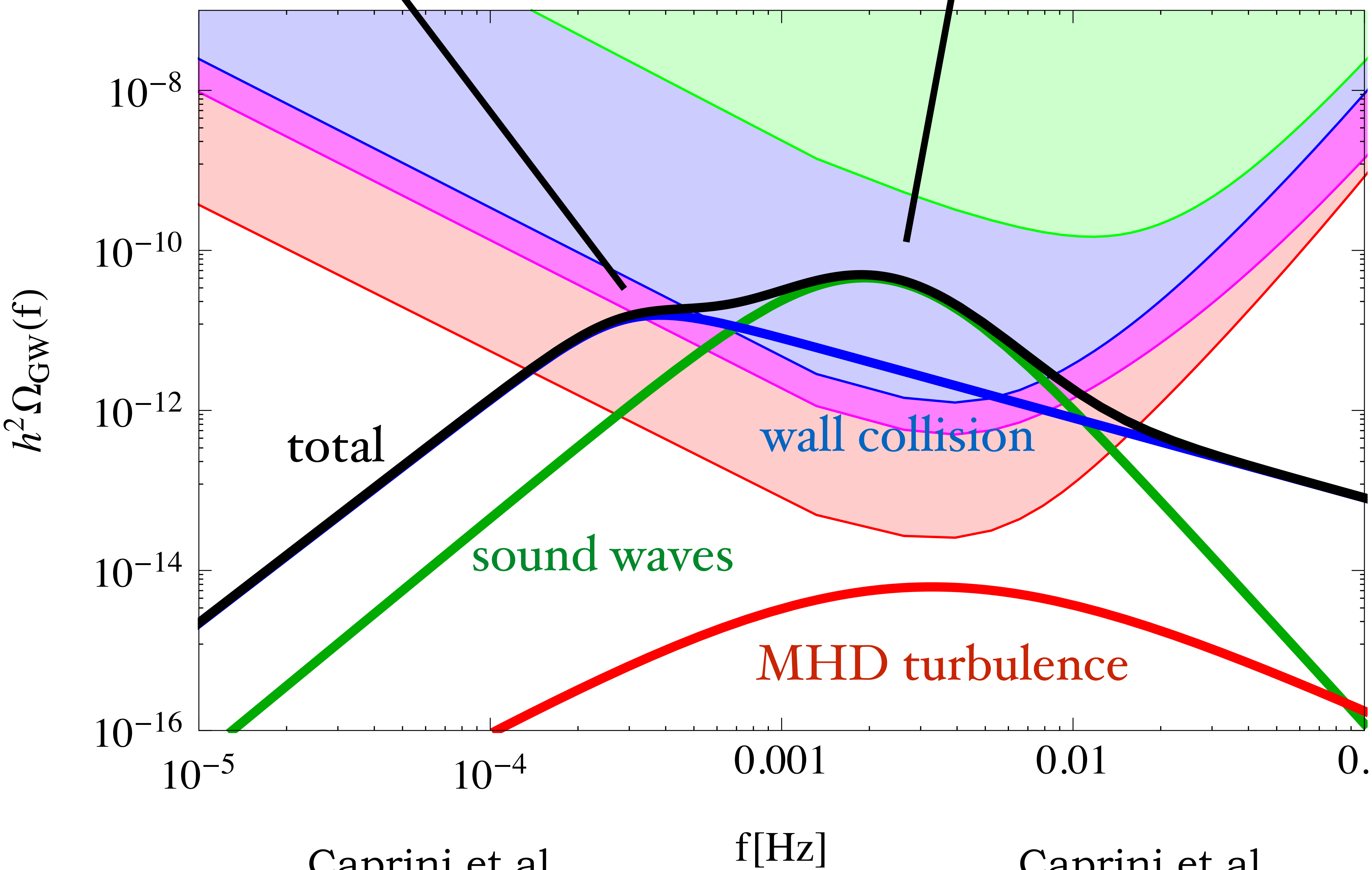
MHz-GHz-THz, high freq range for High-Energy phase transitions

$f \sim 10^{-8} (T/\mathrm{GeV})\ Hz$

Example of spectrum

peak of bubble collisions

peak of fluid-related processes



Caprini et al, arXiv:1512.06239

Caprini et al, arXiv:1910.13125

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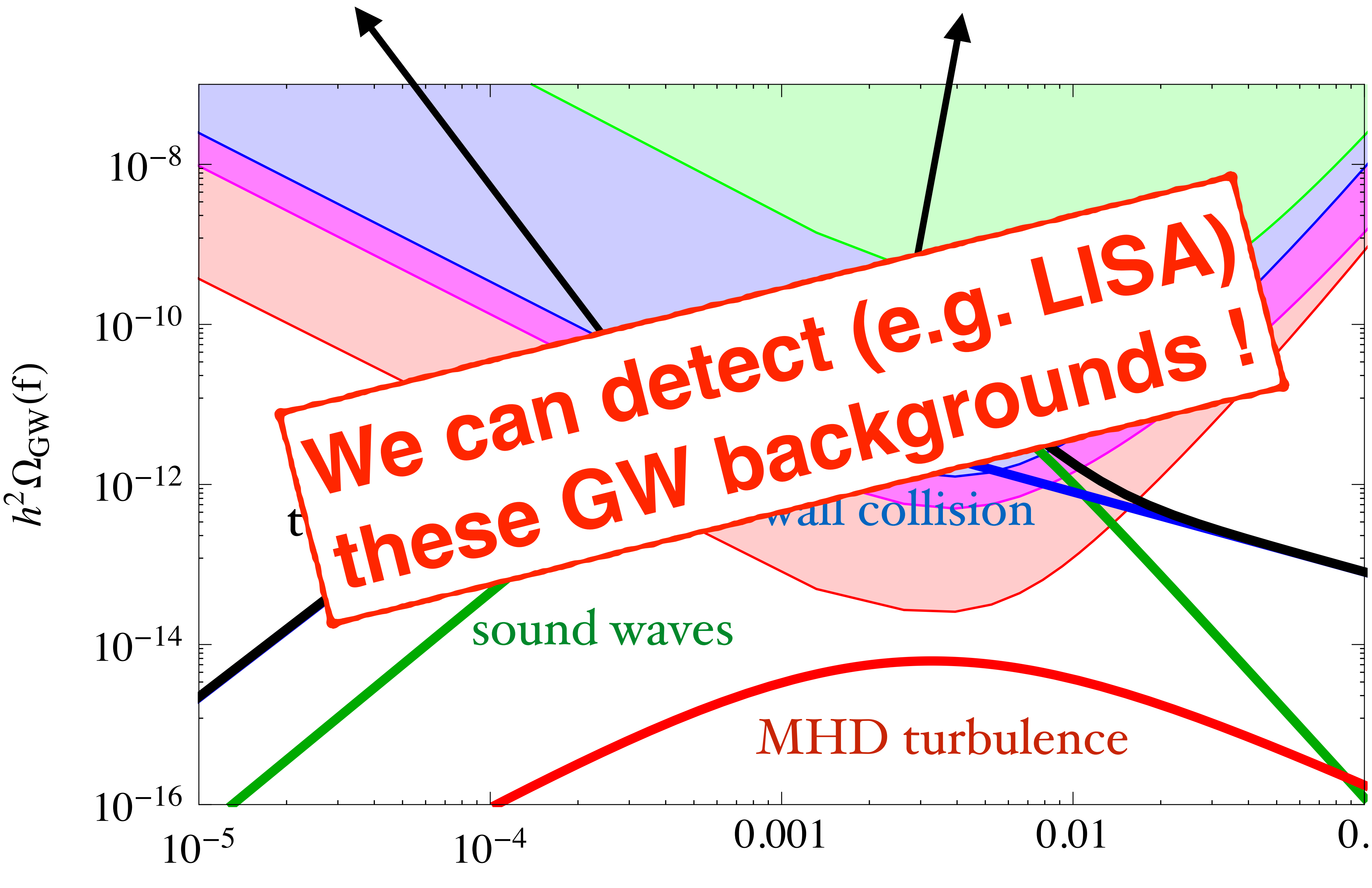


Caprini et al, arXiv:1512.06239

Caprini et al, arXiv:1910.13125

Models for EWPT and beyond

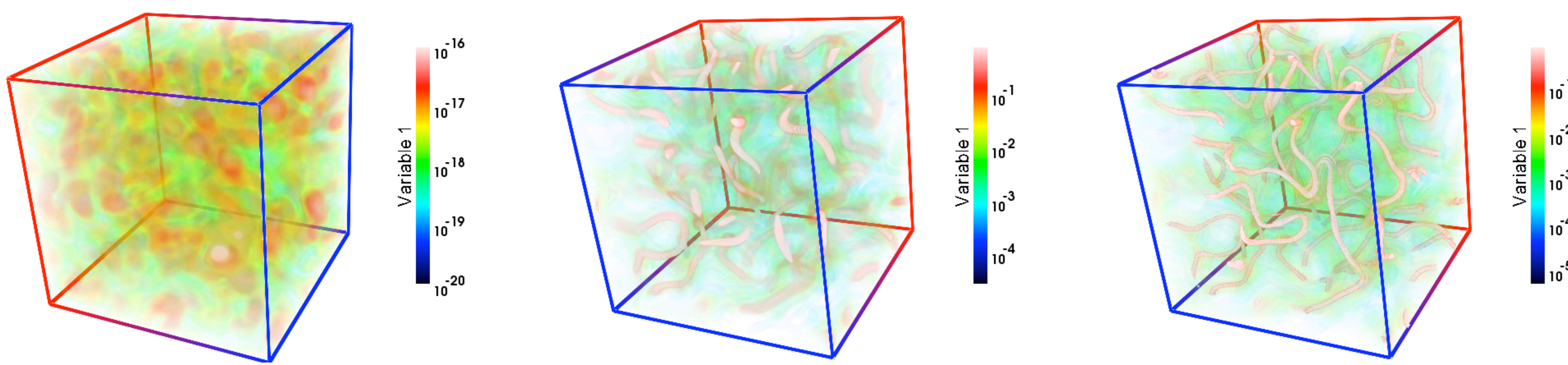
- **LISA** sensitive to energy scale **10 GeV - 100 TeV** ! **(mHZ)**

- LISA can probe the EWPT in BSM models …
  - singlet extensions of MSSM (Huber et al 2015)
  - direct coupling of Higgs to scalars (Kozackuz et al 2013)
  - SM + dimension six operator (Grojean et al 2004)

- … and beyond the EWPT
  - Dark sector: provides DM candidate and confining PT (Schwaller 2015)
  - Warped extra dimensions : PT from the dilaton/radion stabilisation in RS-like models (Randall and Servant 2015)

What about Cosmic Defects ?

(aftermath* products of a PhT)



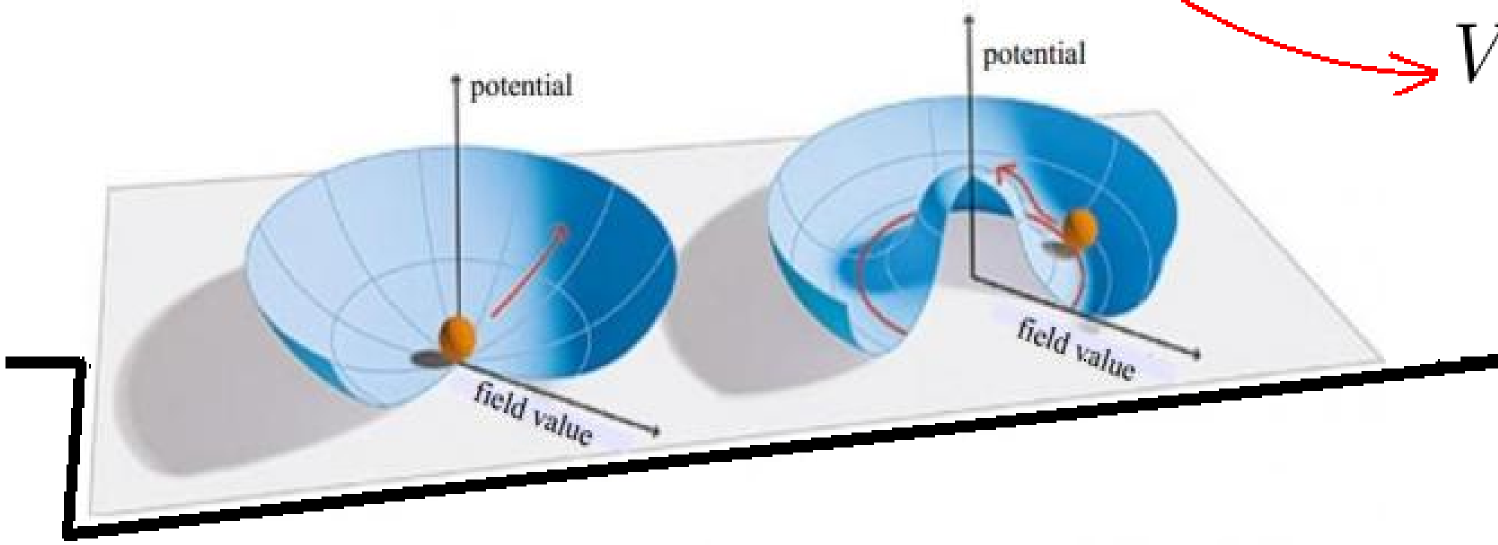
*If certain conditions are met: non-trivial homotopy group(s) of the vacuum manifold

Introduction to Cosmic Defects

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

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

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



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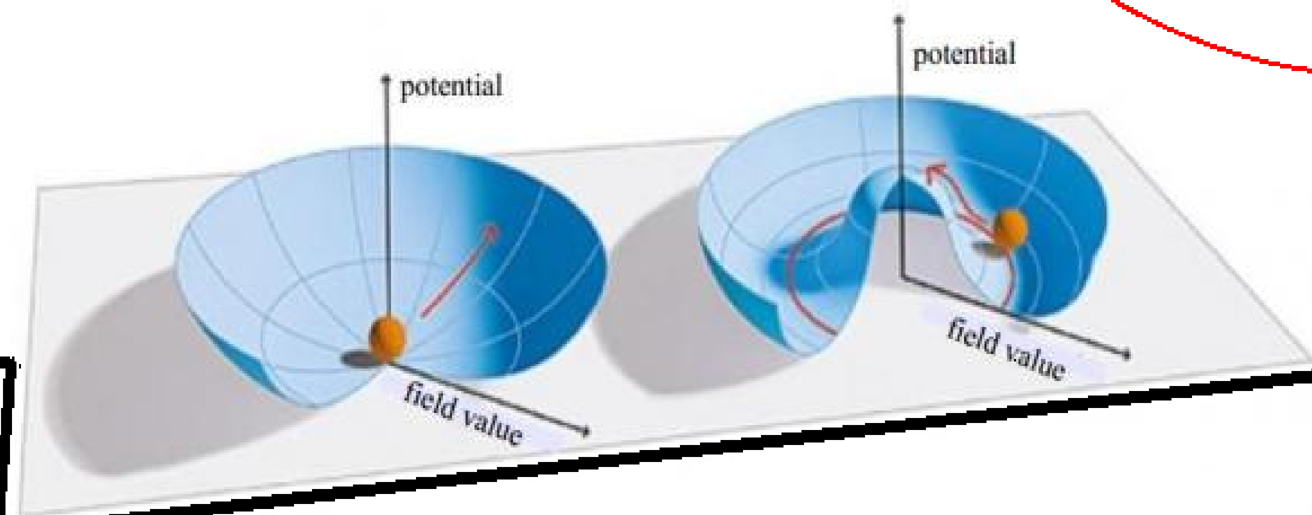
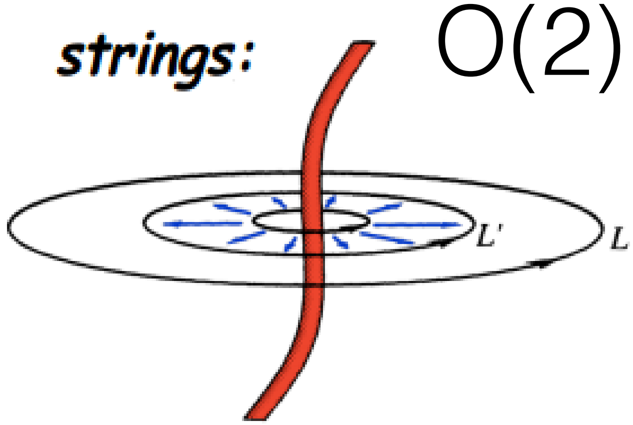
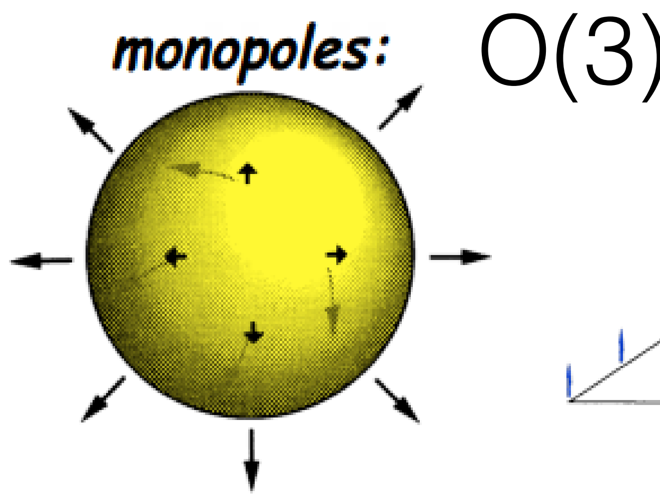
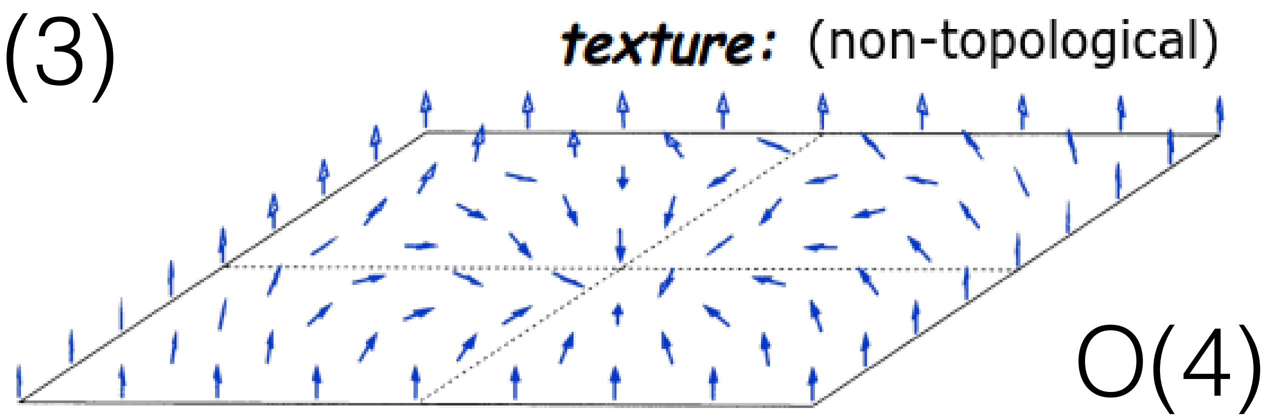


ZOOLOGY:







MICRO-PHYSICS ⟶ **COSMIC DEFECTS**

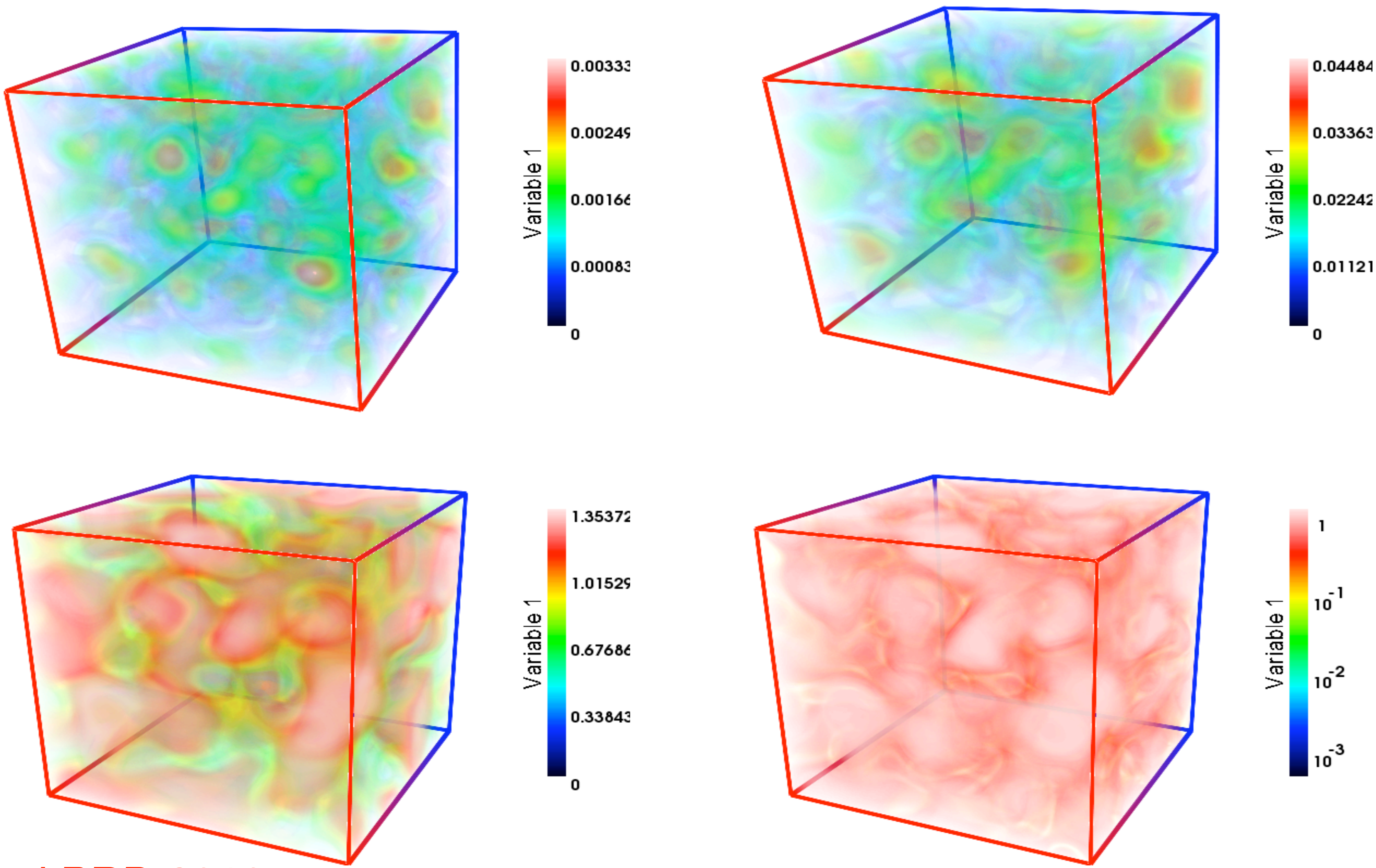
(M = G/H)

Vilenkin & Shellard, '94

Introduction to Cosmic Defects

U(1) Breaking (after Hybrid Inflation)

Higgs Dynamics

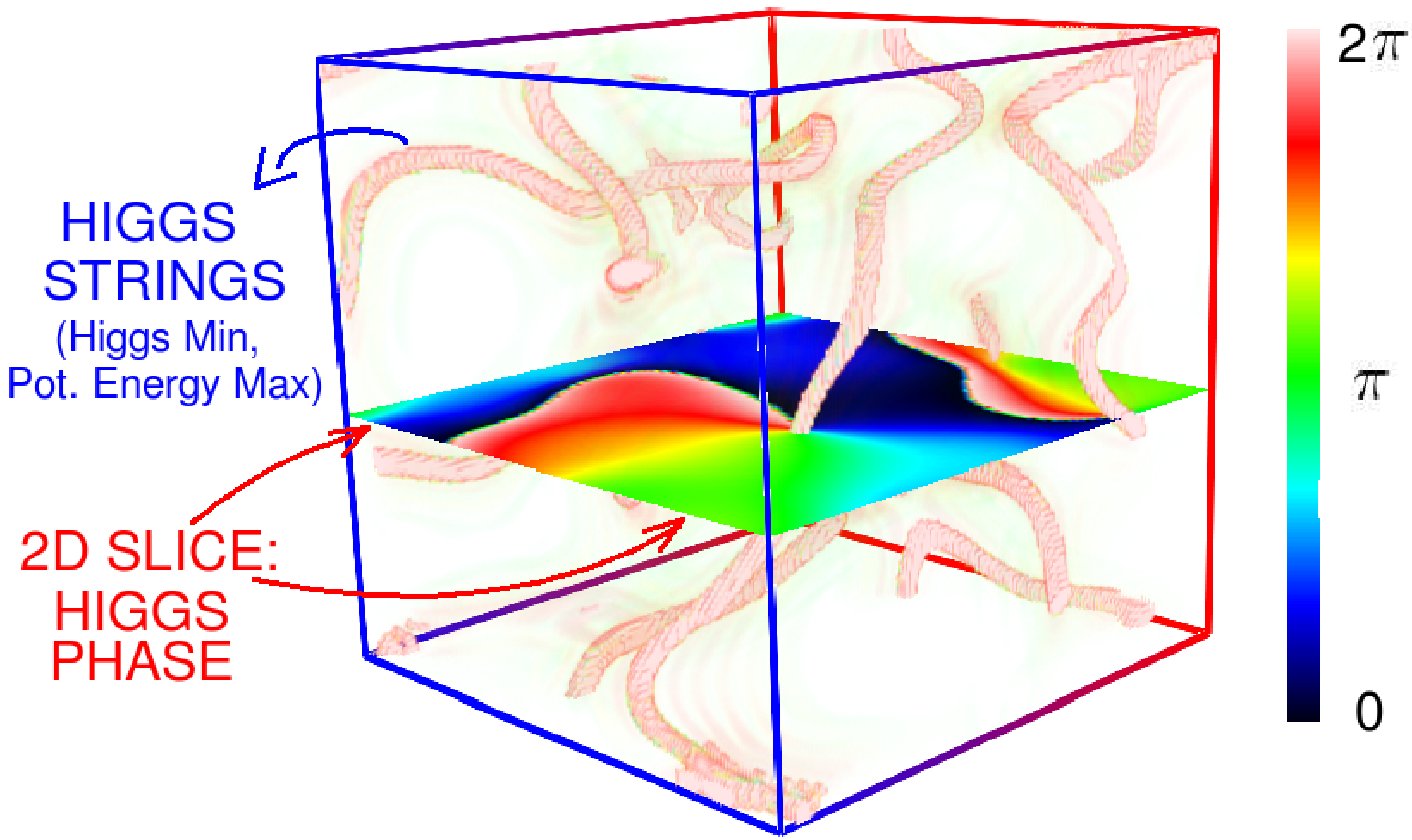


Dufaux et al PRD 2010

Introduction to Cosmic Defects

U(1) Breaking (after Hybrid Inflation)

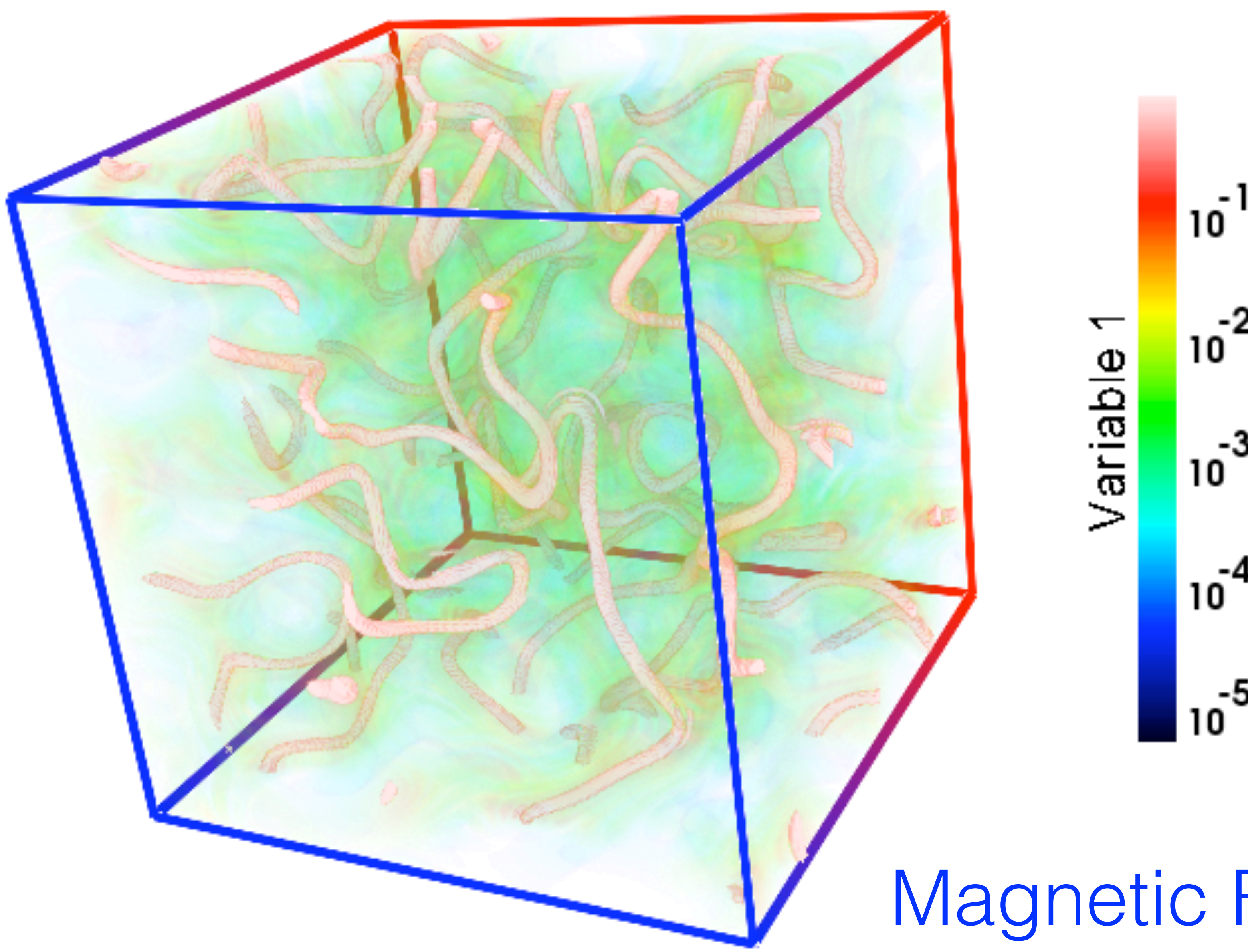
SNAPSHOT OF THE HIGGS $(mt = 17)$



Dufaux et al PRD 2010

Introduction to Cosmic Defects

U(1) Breaking (after Hybrid Inflation)



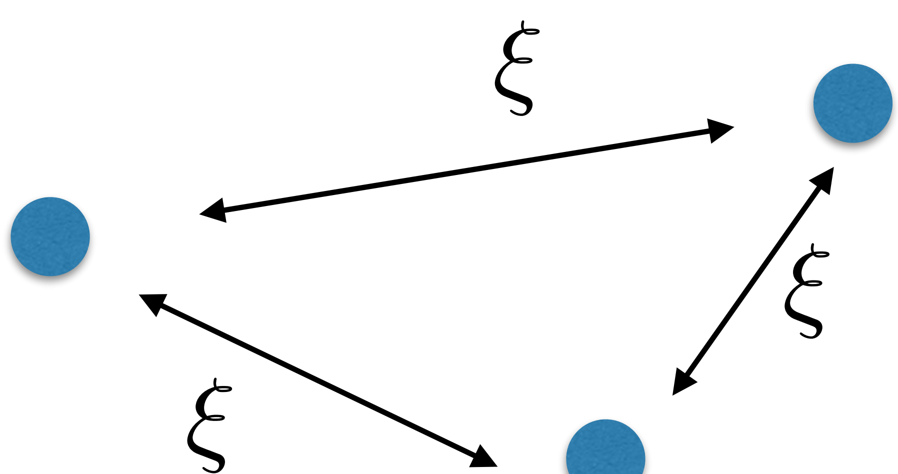
Magnetic Field
energy density

Dufaux et al PRD 2010

Introduction to Cosmic Defects

DEFECTS: Aftermath of PhT $\rightarrow \begin{cases} \begin{cases} \text{Domain Walls} \\ \text{Cosmic Strings} \\ \text{Cosmic Monopoles} \end{cases} \\ \text{Non} - \text{Topological} \end{cases}$

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



Introduction to Cosmic Defects

$$\text{DEFECTS: Aftermath of PhT} \rightarrow \begin{cases} \begin{cases} \text{Domain Walls} \\ \text{Cosmic Strings} \\ \text{Cosmic Monopoles} \end{cases} \\ \text{Non} - \text{Topological} \end{cases}$$

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

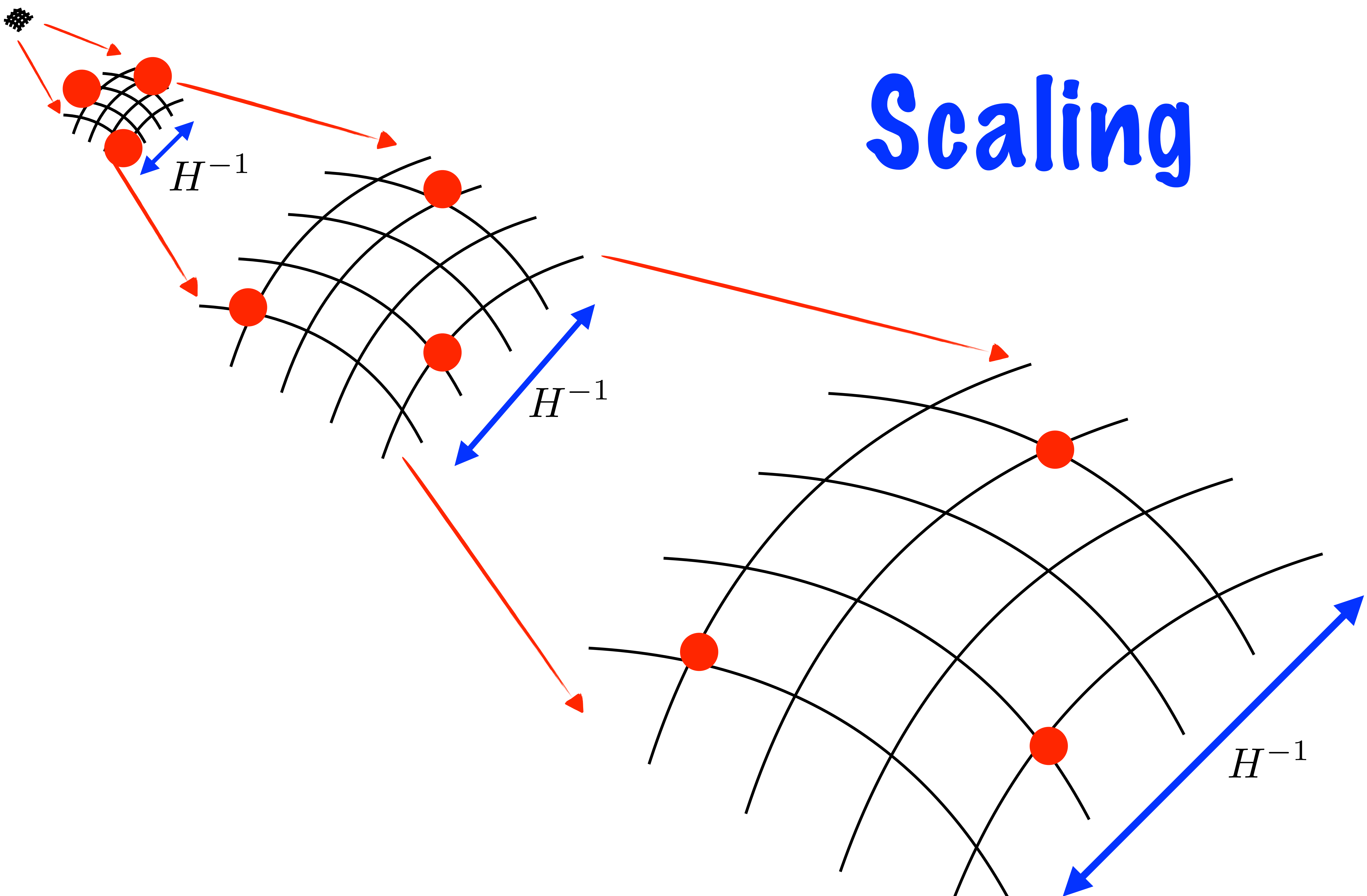
(Kibble' 76)

SCALING: $\lambda(t) = \text{const.} \quad \rightarrow \quad \lambda \sim 1 \quad \Longrightarrow \quad k/\mathcal{H} = kt$

comoving momentum

conformal time

Cosmic Defects



GWs from a scaling network of cosmic defects

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

UTC: $\langle T_{ij}^{\rm TT}(\mathbf{k},t)T_{ij}^{\rm TT}(\mathbf{k}',t')\rangle = (2\pi)^3\,\Pi^2(k,t_1,t_2)\;\delta^3(\mathbf{k}-\mathbf{k}')$

(Unequal Time Correlator)

GW spectrum: Expansion UTC

$$\boxed{\frac{d\rho_{\rm GW}}{d\log k}(k,t) \propto \frac{k^3}{M_p^2a^4(t)}\int dt_1dt_2\; a(t_1)a(t_2)\;\cos(k(t_1-t_2))\;\Pi^2(k,t_1,t_2)}$$

Comoving **Conformal**

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SCALING

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Rad. Dom **SCALING**

Comoving **Conformal**

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$$\boxed{(x_i \equiv kt_i)}$$

GW spectrum: Expansion UTC

$$\frac{d\rho_{\rm GW}}{d\log k}(k,t) \propto \left(\frac{\rm V}{M_p}\right)^4 \frac{M_p^2}{a^4(t)}\left[\int dx_1 dx_2\ \sqrt{x_1x_2}\ \cos(x_1-x_2)\ U(x_1,x_2)\right]$$

Rad. Dom **SCALING**

GWs from a scaling network of cosmic defects

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Rad. Dom **SCALING**

$$\underbrace{\qquad\qquad\qquad\qquad\qquad\qquad}_{F_U \sim \text{Const.}\ \text{(Dimensionless)}}$$

GWs from a scaling network of cosmic defects

VEV **Scaling @ RD**

GW today:

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

Defect type

$$F_U \equiv \int_0^x dx_1 dx_2 \sqrt{x_1 x_2}\, cos(x_1 - x_2) U(x_1, x_2)$$

DGF, Hindmarsh, Urrestilla, PRL 2013

GWs from a scaling network of cosmic defects

GW today:

VEV

Scaling @ RD

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

DGF, Hindmarsh, Urrestilla, PRL 2013

GWs from a scaling network of cosmic defects

energy scale

constants

Total GW Spectrum

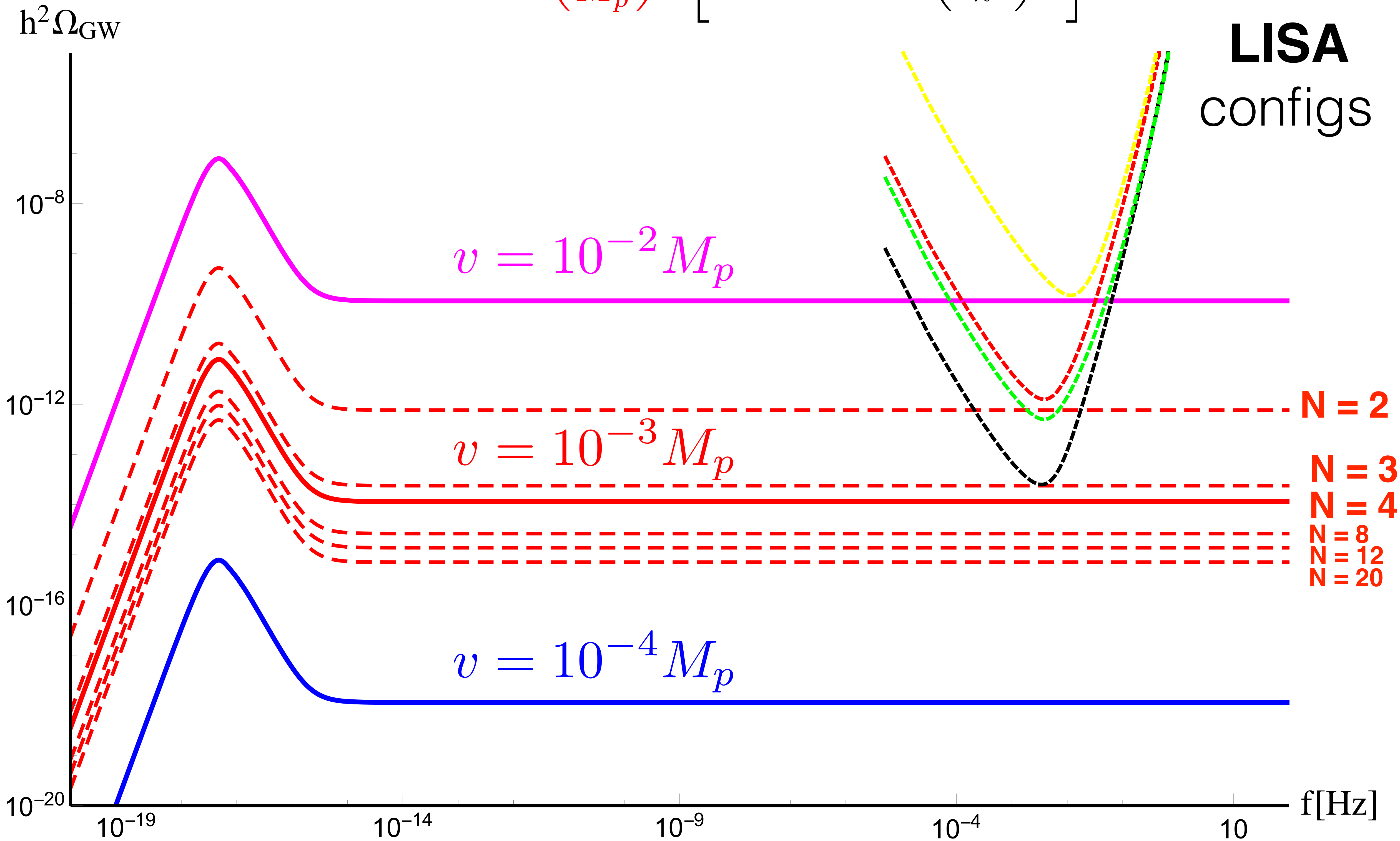
$$\boxed{h^2\Omega_{\rm GW}^{(\rm o)} = h^2\Omega_{\rm rad}^{(\rm o)}\left(\frac{V}{M_p}\right)^4\left[F_U^{(\rm R)} + F_U^{(\rm M)}\left(\frac{k_{\rm eq}}{k}\right)^2\right]}$$

RD $$F_U^{(\rm R)} \equiv \frac{32}{3}\int_0^x dx_1 dx_2\,(x_1x_2)^{1/2}\cos(x_1-x_2)\,U_{\rm RD}(x_1,x_2)$$

MD $$F_U^{(\rm M)} \equiv \frac{32}{3}\frac{(\sqrt{2}-1)^2}{2}\int_{x_{\rm eq}}^x dx_1 dx_2\,(x_1x_2)^{3/2}\cos(x_1-x_2)\,U_{\rm MD}(x_1,x_2)$$

More on GW from Defect Networks

$$h^2\Omega^{(\mathrm{o})}_{\mathrm{GW}} = h^2\Omega^{(\mathrm{o})}_{\mathrm{rad}} \left(\frac{V}{M_p}\right)^4 \left[F_U^{(\mathrm{R})} + F_U^{(\mathrm{M})} \left(\frac{k_{\mathrm{eq}}}{k}\right)^2 \right]$$



DGF, Hindmarsh, Lizarraga, Urrestilla, 2020

What if Defects are Cosmic Strings ?

Extra emission of GWs ! (Vilenkin '81)

What if Defects are Cosmic Strings ?

Intercommutation

Loops are formed !

What if Defects are Cosmic Strings ?

Loops are formed !

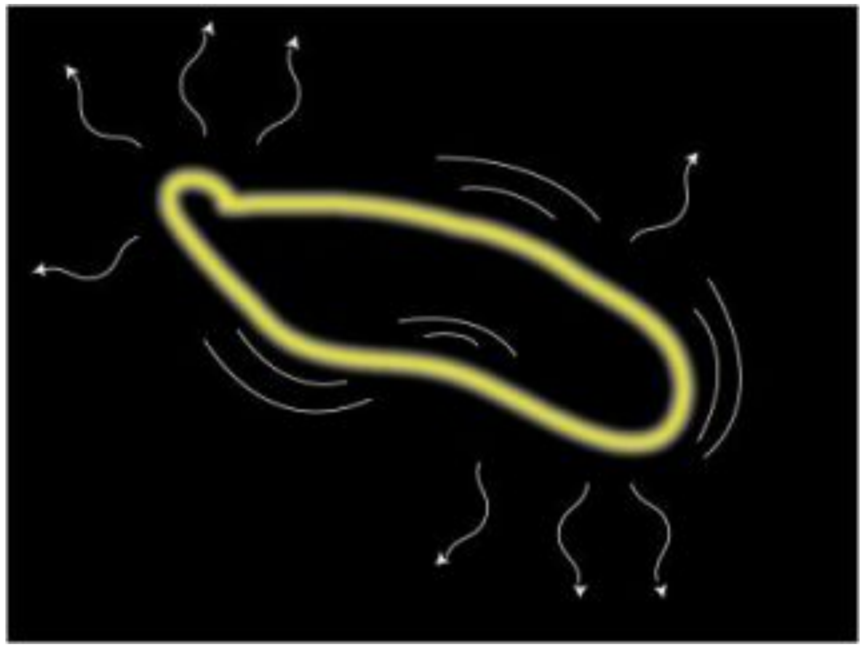


Image Credit: Google

Gravitational Waves emitted !
(releasing the loops' tension)

Cosmic Strings Network: Loop configurations

Cosmic string loop (length *l*) oscillates under tension μ

➡ **emits GWs in a series of harmonic modes**

Extra emission of GWs ! **(Vilenkin '81)**

and many others !

Cosmic Strings Network: Loop configurations

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Extra emission of GWs ! **(Vilenkin '81)**

and many others !

$$\frac{d\rho^{(\mathrm{o})}}{df} \equiv \Gamma G\mu^2 \int_{t_*}^{t_o} dt \left(\frac{a(t)}{a_o}\right)^3 \int_0^{\alpha/H(t)} dl\, l\, n(l,t)\, \mathcal{P}((a_o/a(t))fl)$$

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expansion history

length

number density

GW power emission

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expansion history

length

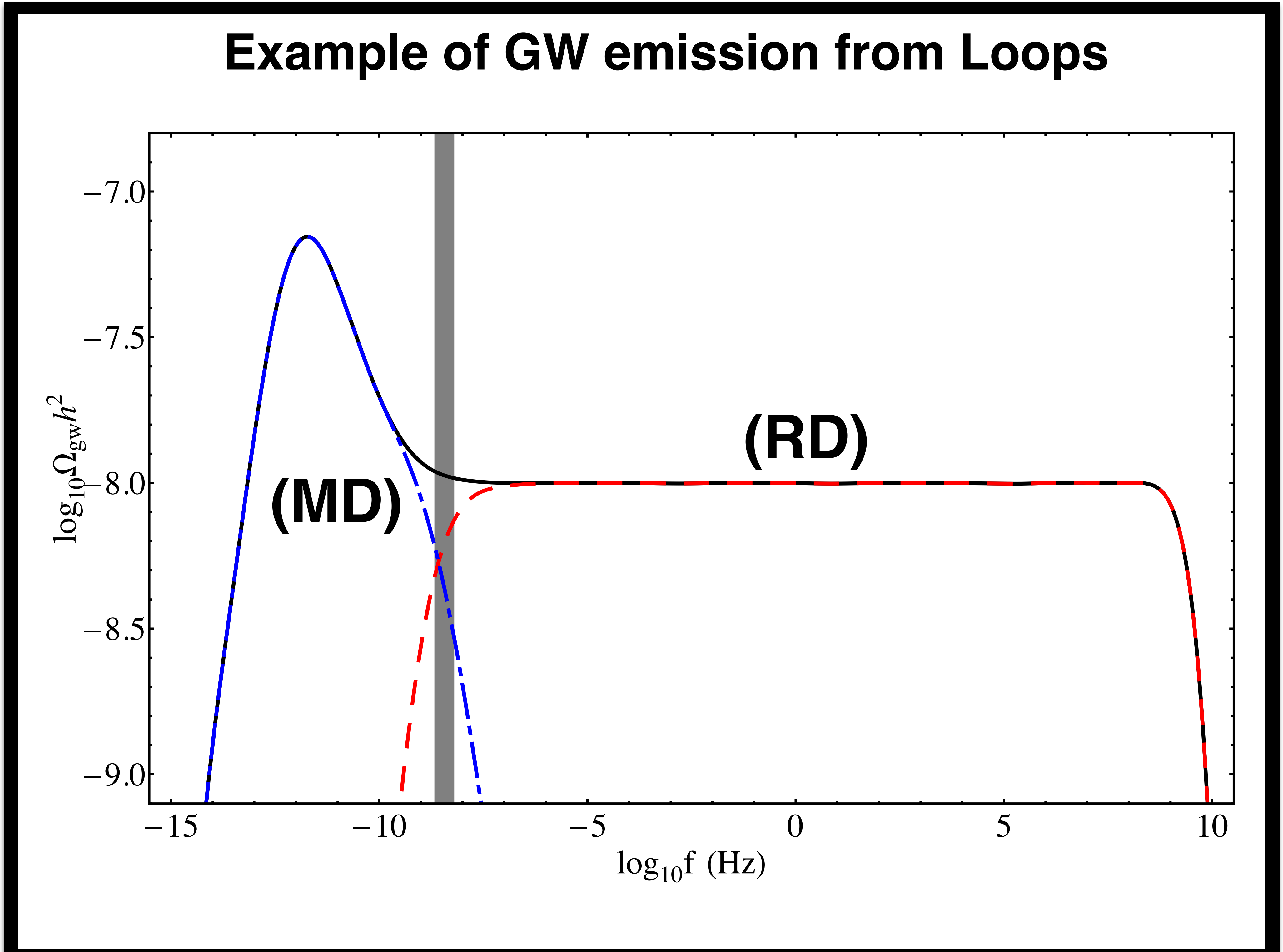
number density

GW power emission

$\propto 1/(fl)^{q+1}$

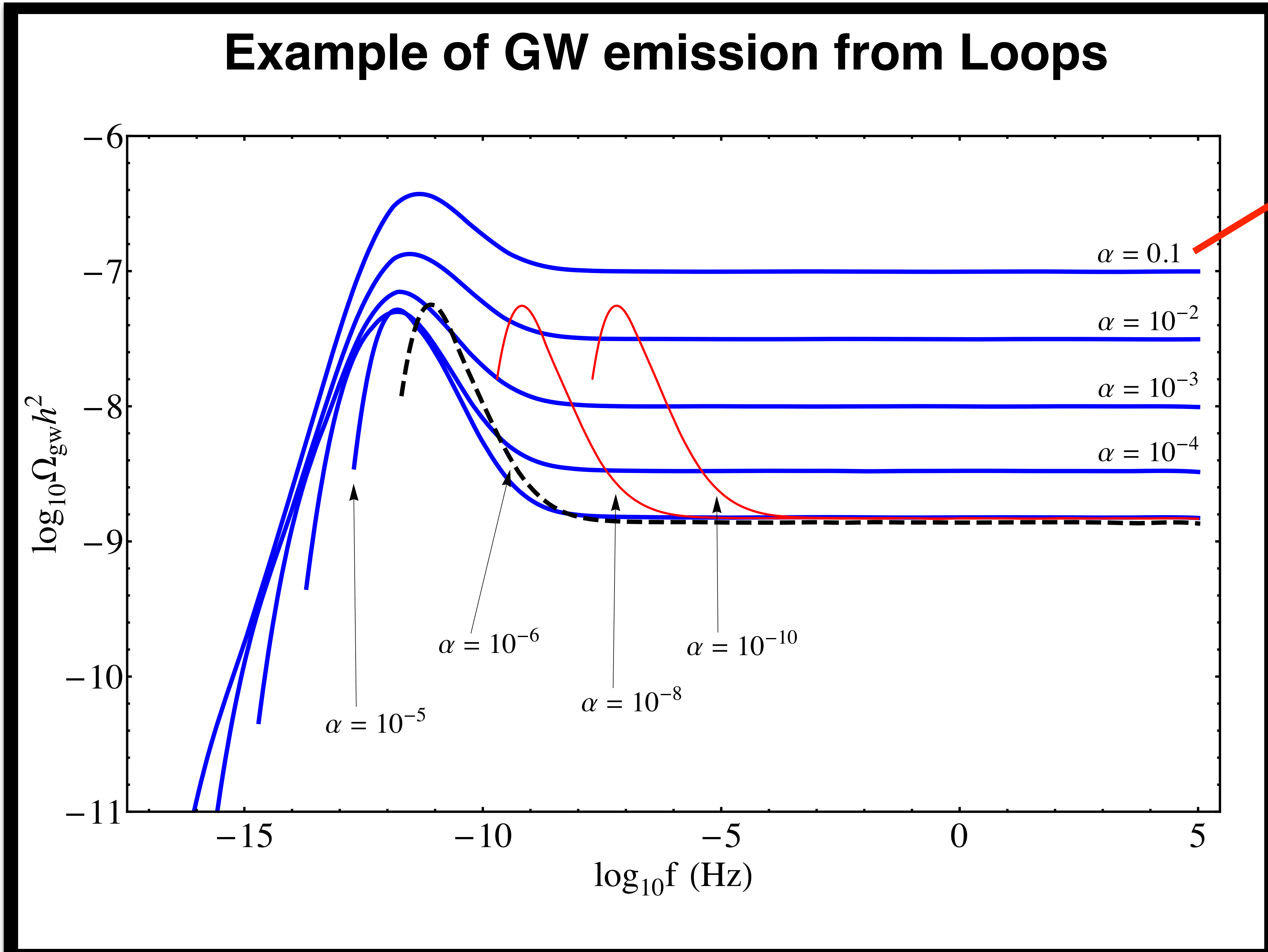
features
(kinks,cusps,…)

Cosmic strings loops: GW background



e.g. Sanidas et al 2012

Cosmic Strings Network: Loop configurations



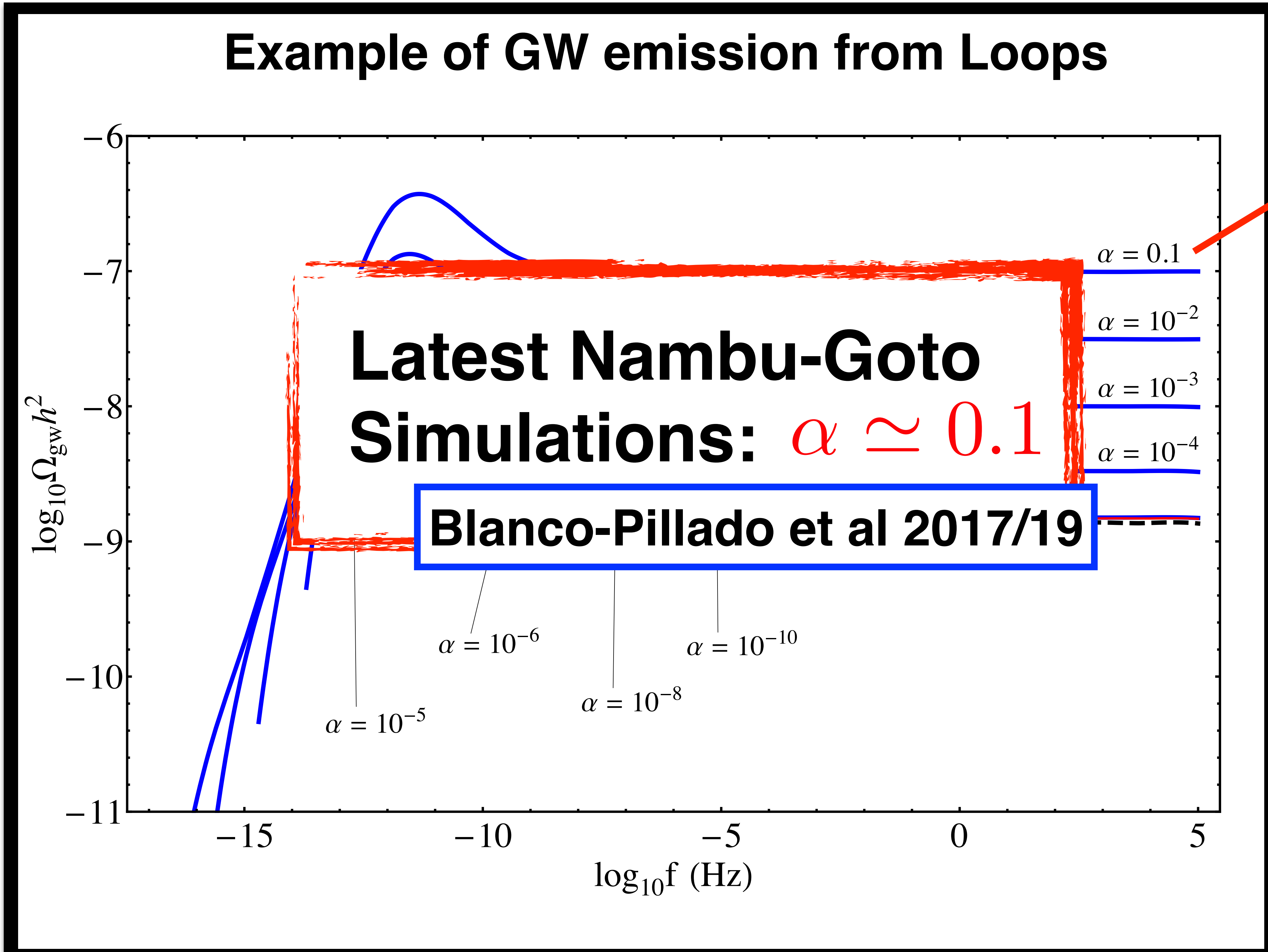
α

loop size

(relative to horizon)

Sanidas et al 2012

Cosmic Strings Network: Loop configurations



α

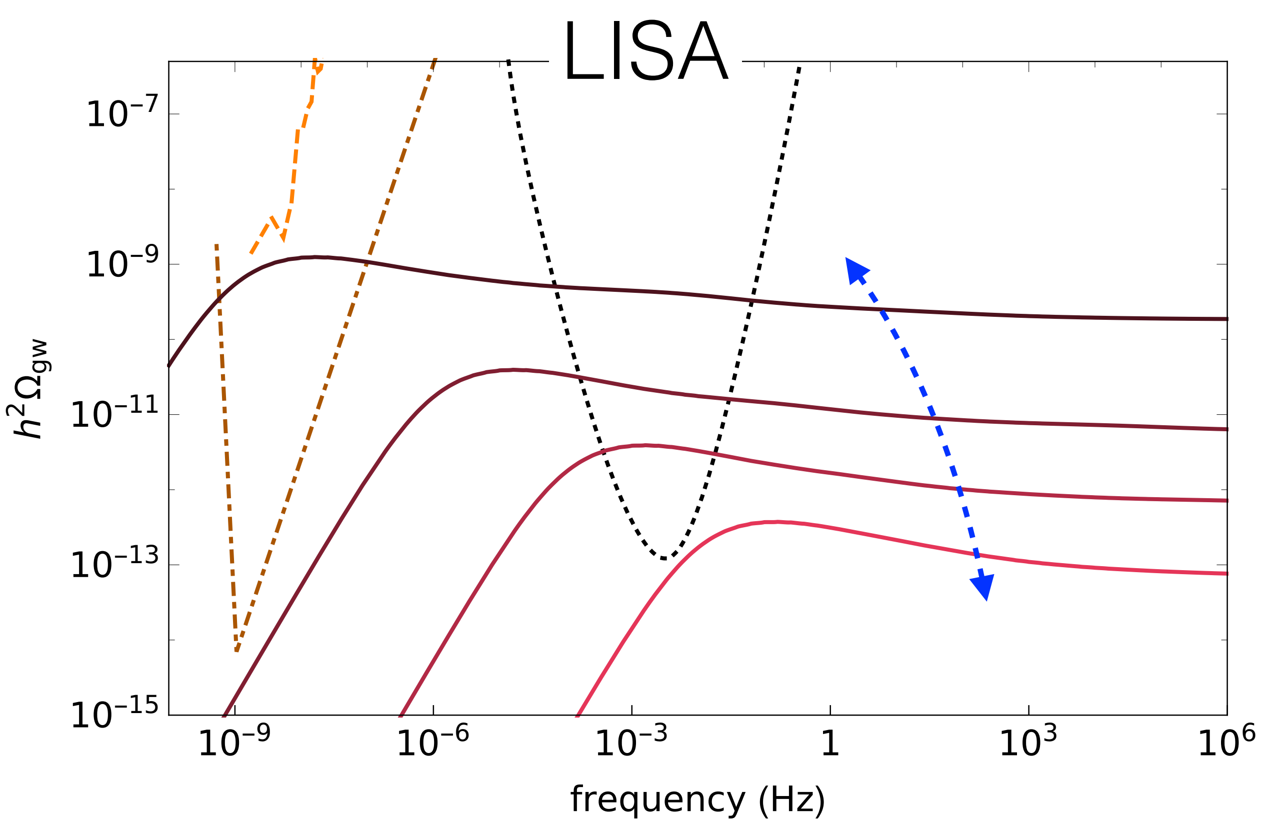
loop size

(relative to horizon)

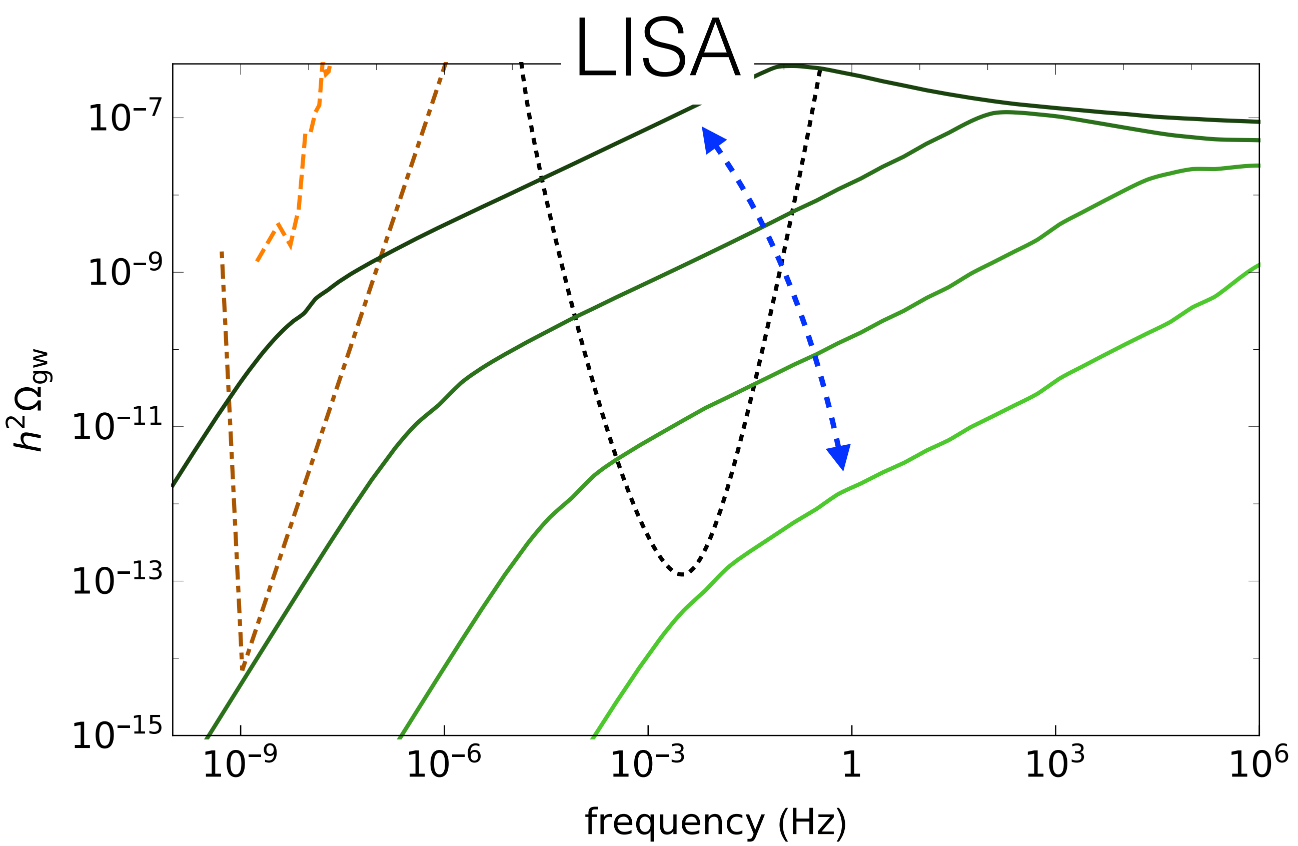
Sanidas et al 2012

Cosmic strings loops: GW background

Blanco-Pillado, Olum, Shlaer



Lorenz, Ringeval, Sakellariadou



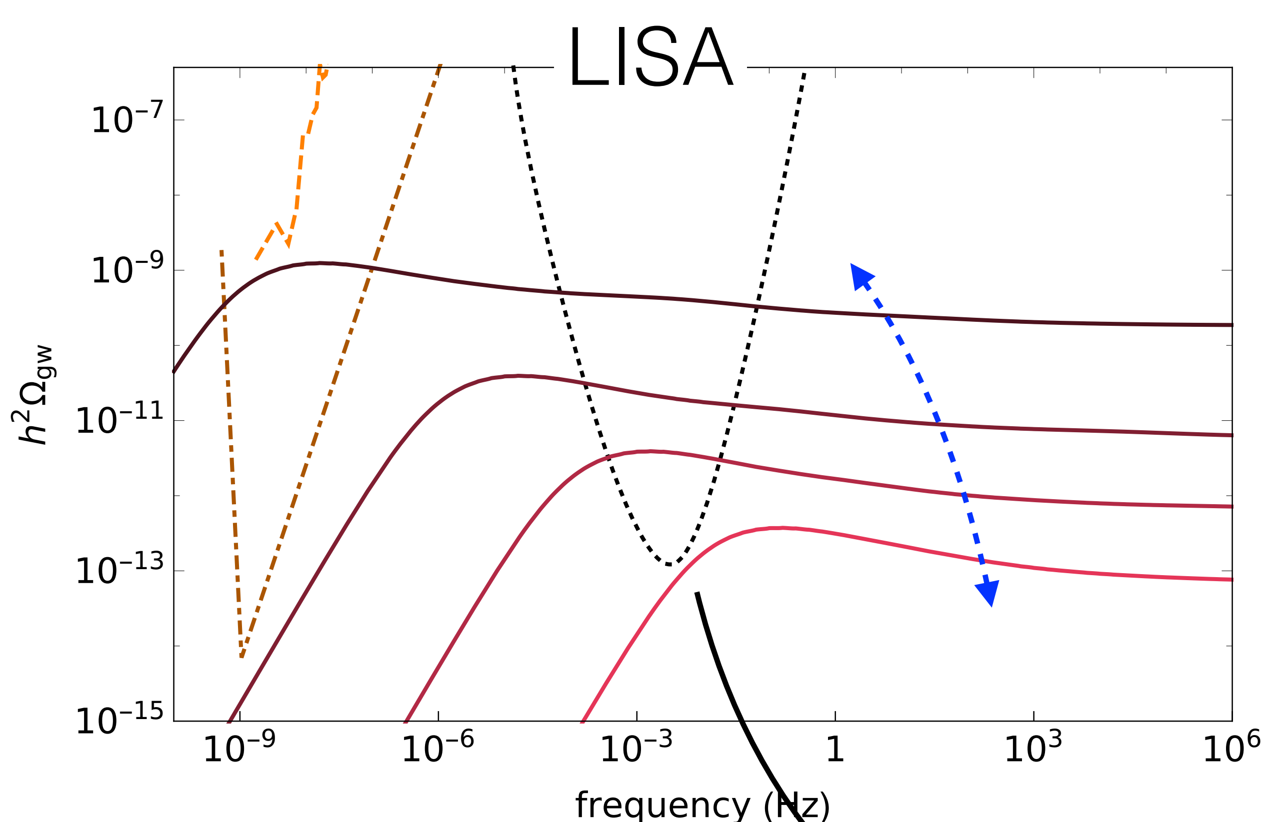
$$G\mu \sim 10^{-11} - 10^{-17}$$

Very large parameter space !

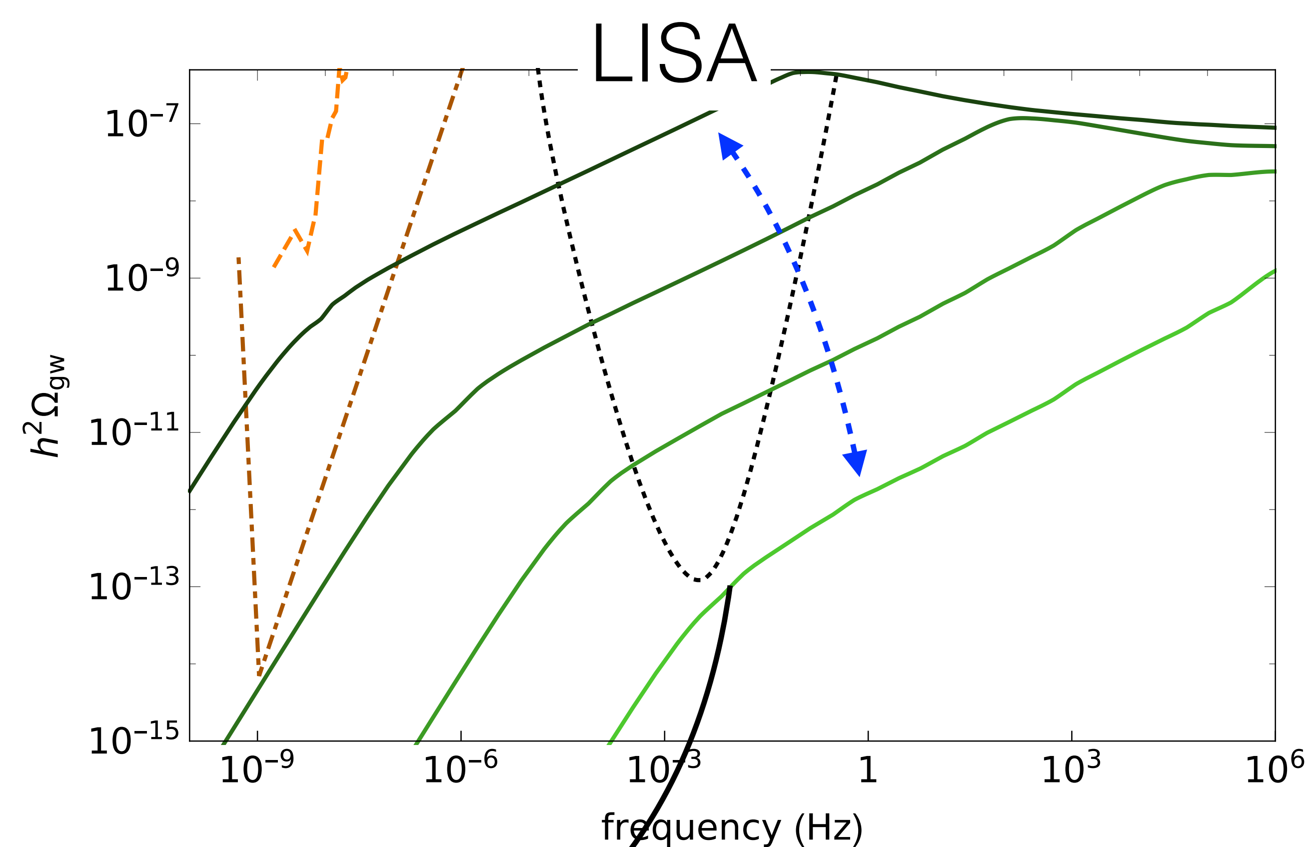
LISA paper 1909.00819

Cosmic strings loops: GW background

Blanco-Pillado, Olum, Shlaer



Lorenz, Ringeval, Sakellariadou



$$\boxed{G\mu \gtrsim 10^{-17}}$$

Very large parameter space !

LISA paper 1909.00819

GW background constrained by LISA

$$\boxed{G\mu \gtrsim 10^{-17} \quad (v \gtrsim 10^{10}\ \mathrm{GeV})}$$

	CMB	PTA (today)	PTA (future)
	$G\mu \sim 10^{-7}$	$G\mu \sim 10^{-11}$	$G\mu \sim 10^{-14}$
LISA improve:	$\mathcal{O}(10^{10})$	$\mathcal{O}(10^{6})$	$\mathcal{O}(10^{3})$

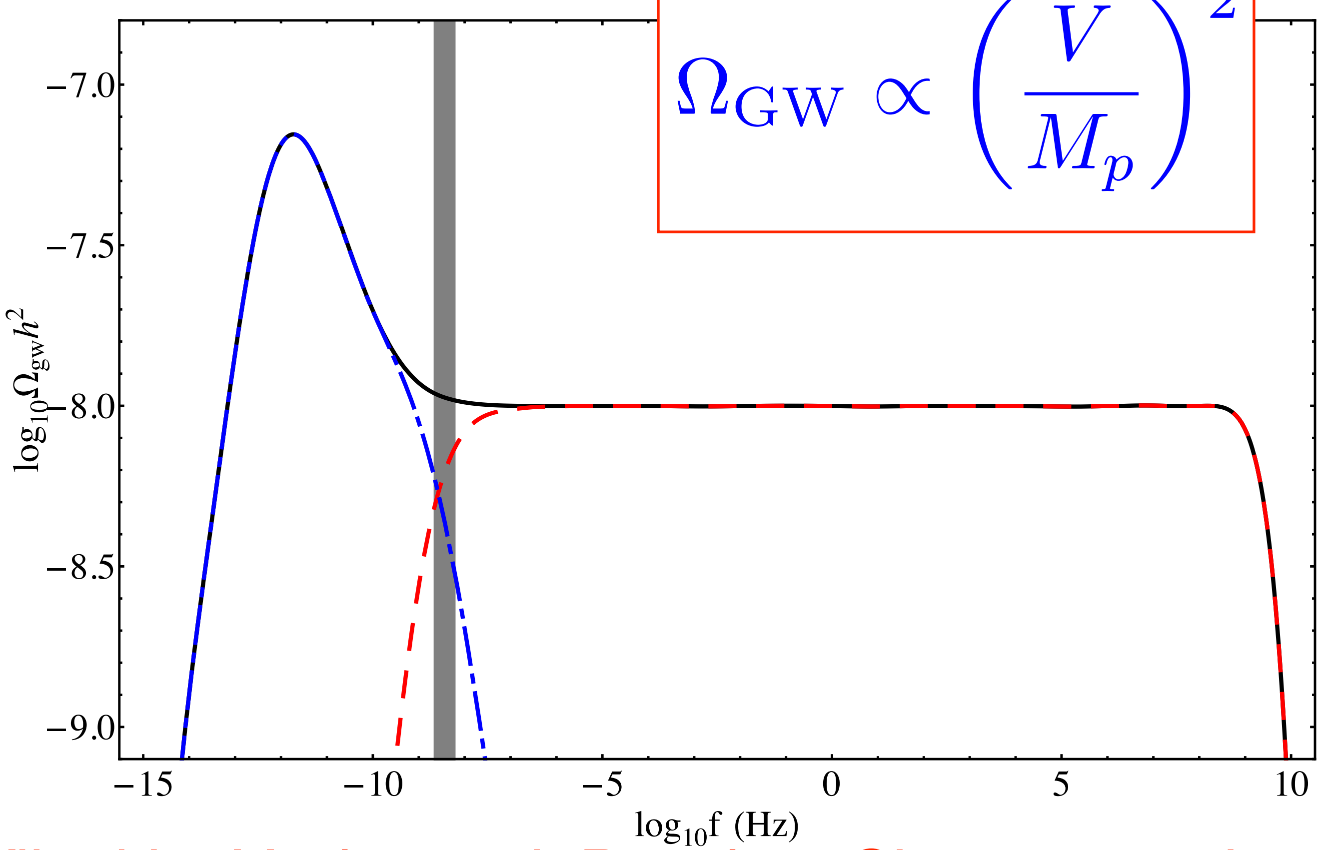
LISA
- * **Best constraints on Comic Strings**
- * **(actually only way to obtain them)**
- * **Discovery, or stringent constraints**

LISA paper 1909.00819

Cosmic Strings Network: Loop configurations

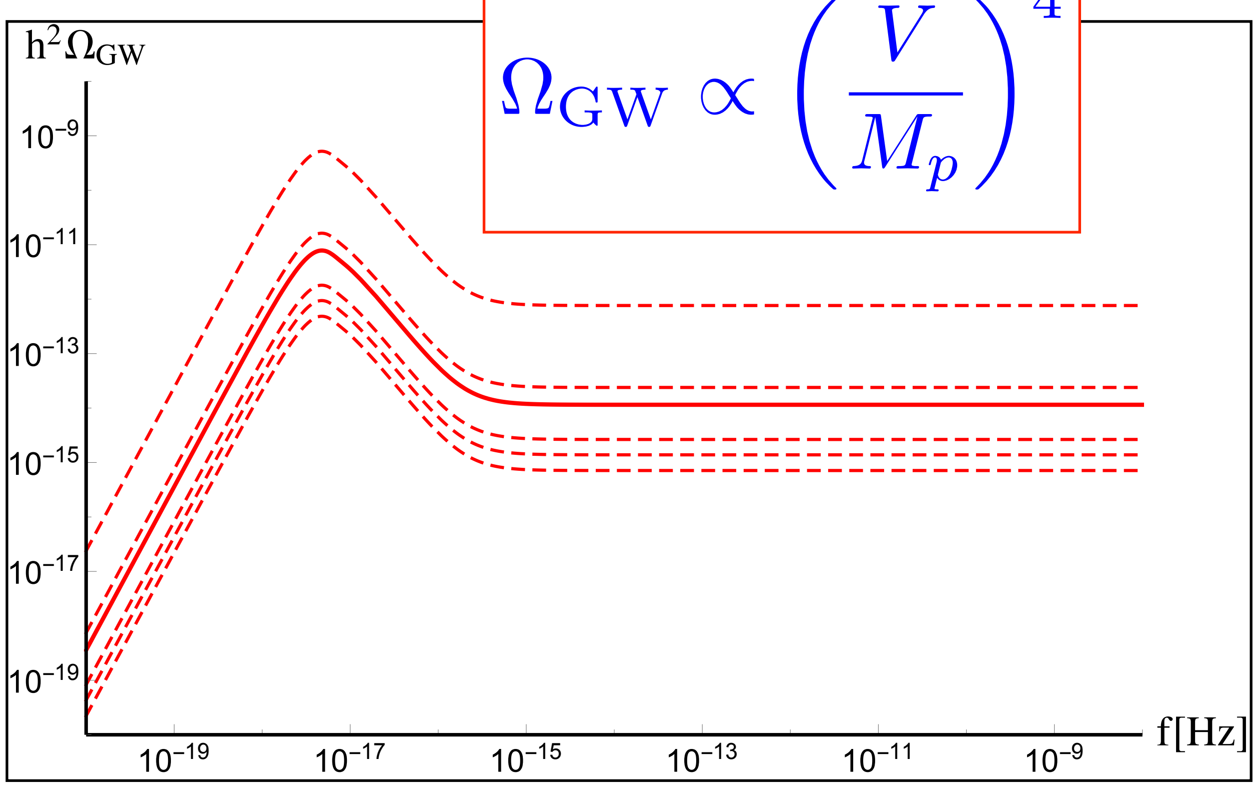
GW from string loops $\neq$ GW from "Infinite"-Strings
(particular emission) **(irreducible emission)**

$$\Omega_{\rm GW} \propto \left(\frac{V}{M_p}\right)^2$$



Vilenkin, Vachaspati, Bouchet, Siemens et al, Sanidas et al, Blanco-Pillado et al, … 1981 - 2020

$$\Omega_{\rm GW} \propto \left(\frac{V}{M_p}\right)^4$$



DGF, Hindmarsh, Lizarraga, Urrestilla, work in progress 2013-2020

Gravitational Waves as a probe of the early Universe

SUMMARY

0) GW definition ✓

Early Universe

1) GWs from Inflation
2) GWs from Preheating ✓

3) GWs from Phase Transitions
4) GWs from Cosmic Defects ✓

Gravitational Waves as a probe of the early Universe

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Intensive search at the CMB

Possible Enhancement

High amplitude, unlike detection

Gravitational Waves as a probe of the early Universe

SUMMARY

Early Universe

0) GW definition

1) GWs from Inflation

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EWPT (1st) observable*

4) GWs from Cosmic Defects

GUT-PT observable**

[*At LISA if EWPT is strong 1st order] [**By PTA/LISA, If large loops present]

Propaganda, Part I

Review on Cosmological Gravitational Wave Backgrounds

Caprini & Figueroa

arXiv:1801.04268

Propaganda, Part II

Almost Nothing

Première Sept 2018 @ CERN / Available from 2021

THANKS FOR YOUR ATTENTION !

Looking forward to seeing you in person in 2021 in Bengaluru !

Back Slides

Topological Defect Formation

Introduction to Cosmic Defects

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

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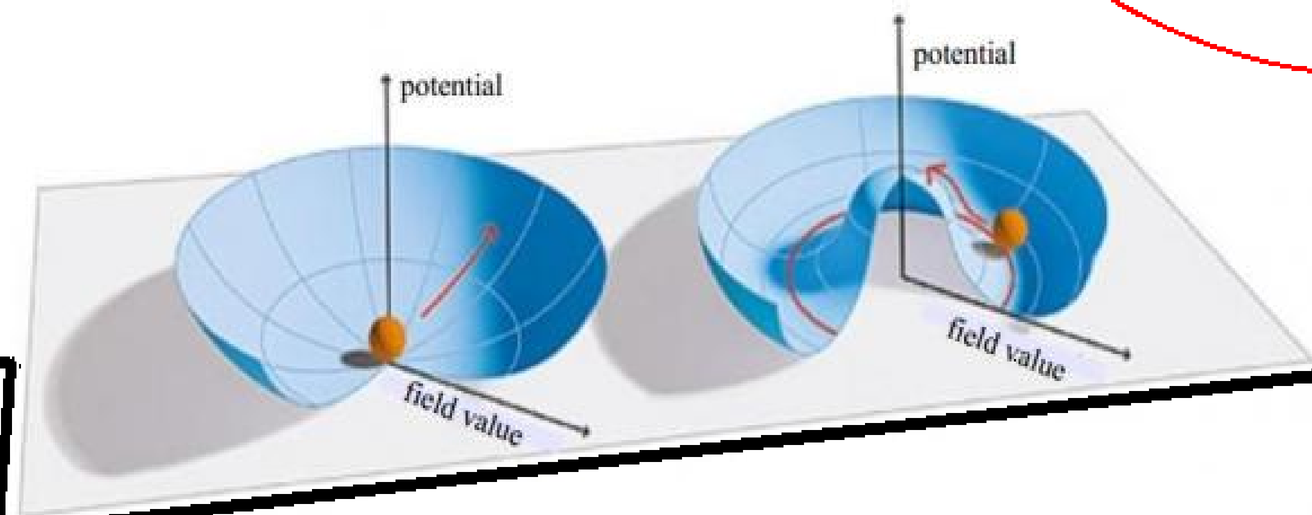

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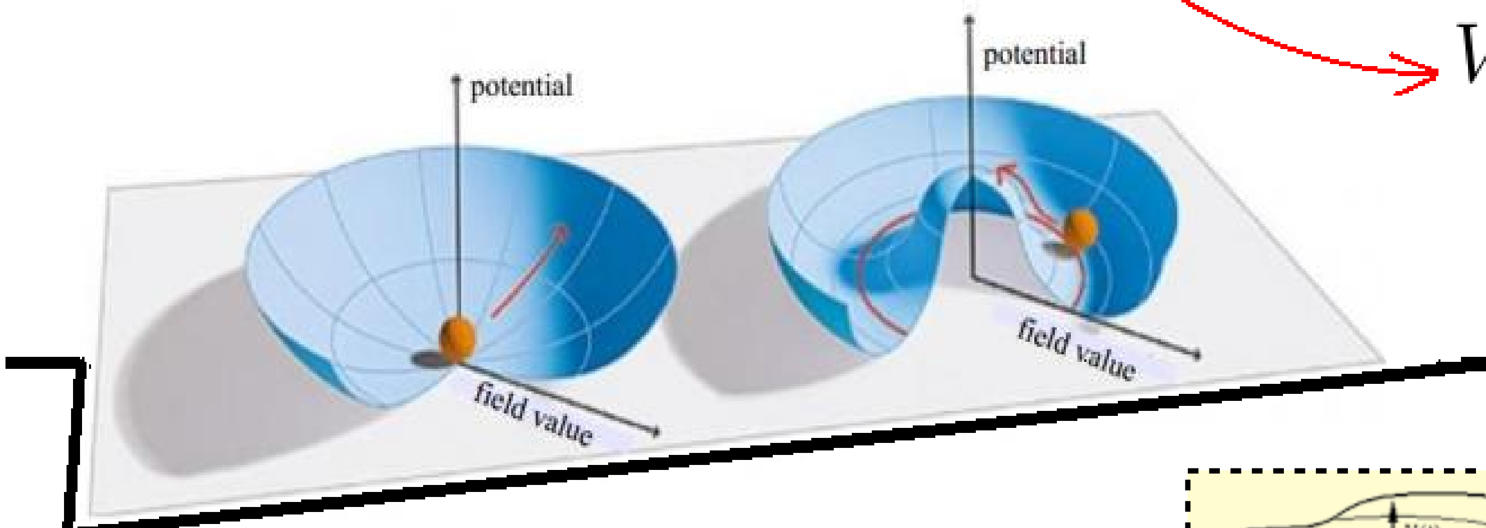

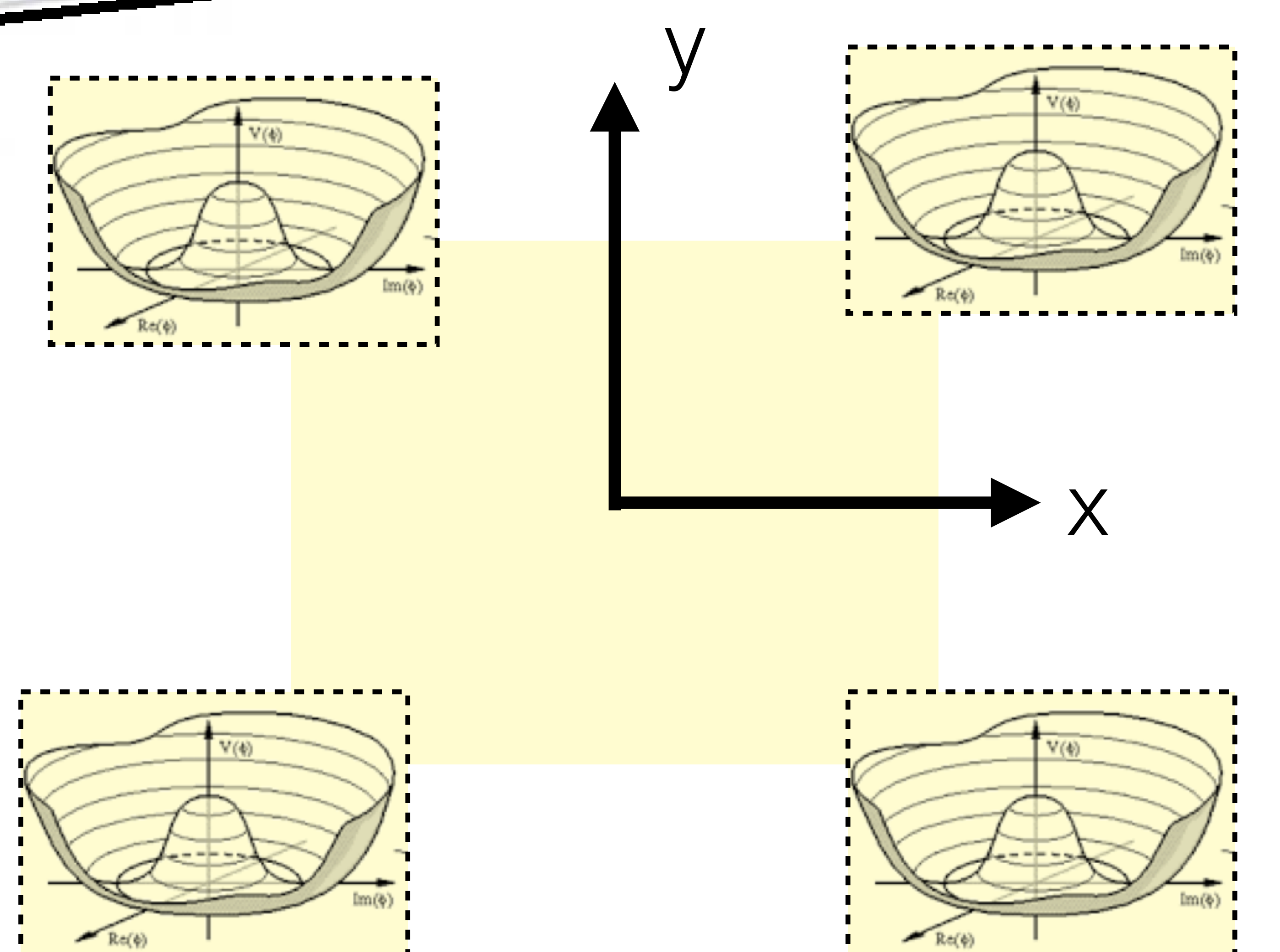

Introduction to Cosmic Defects

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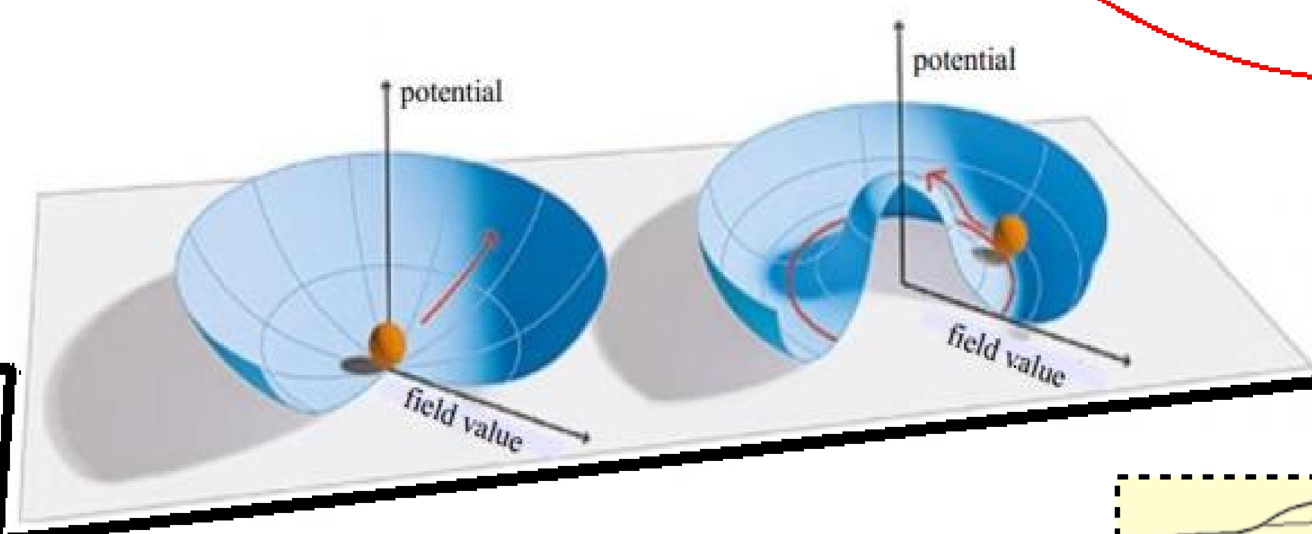

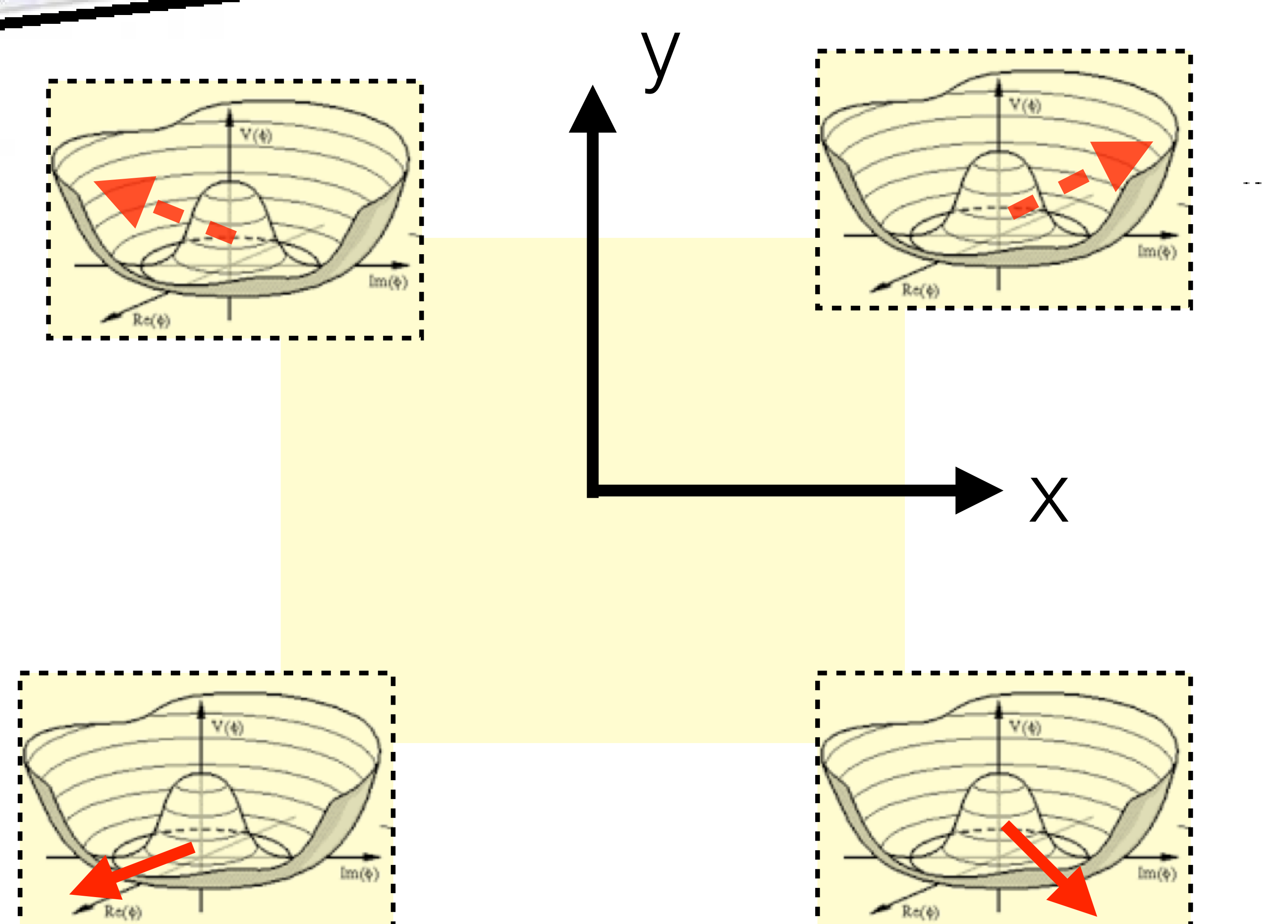

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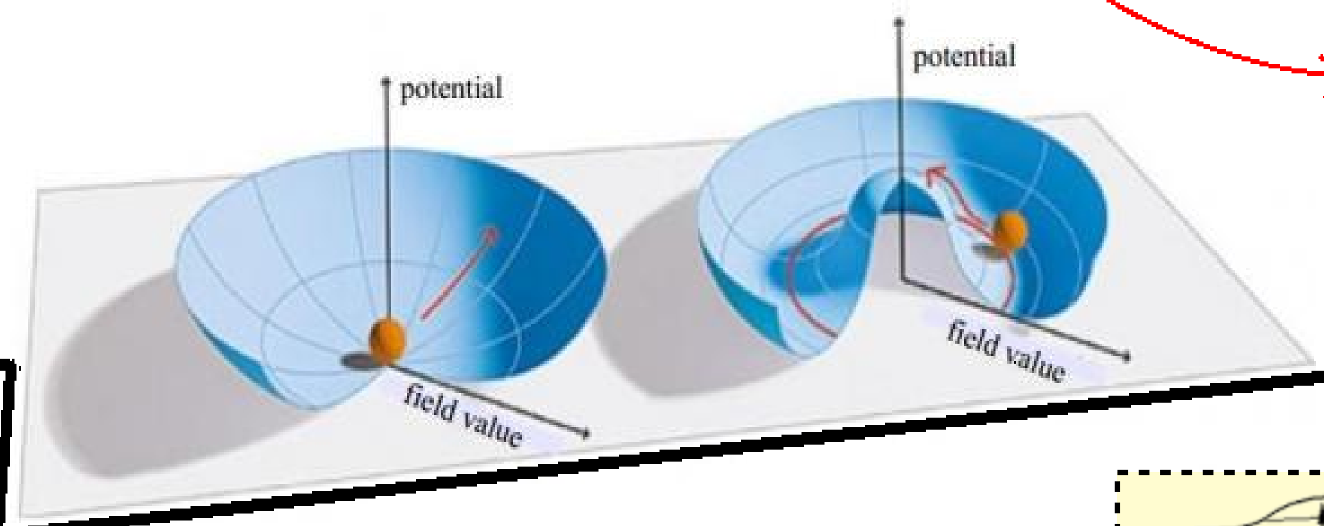

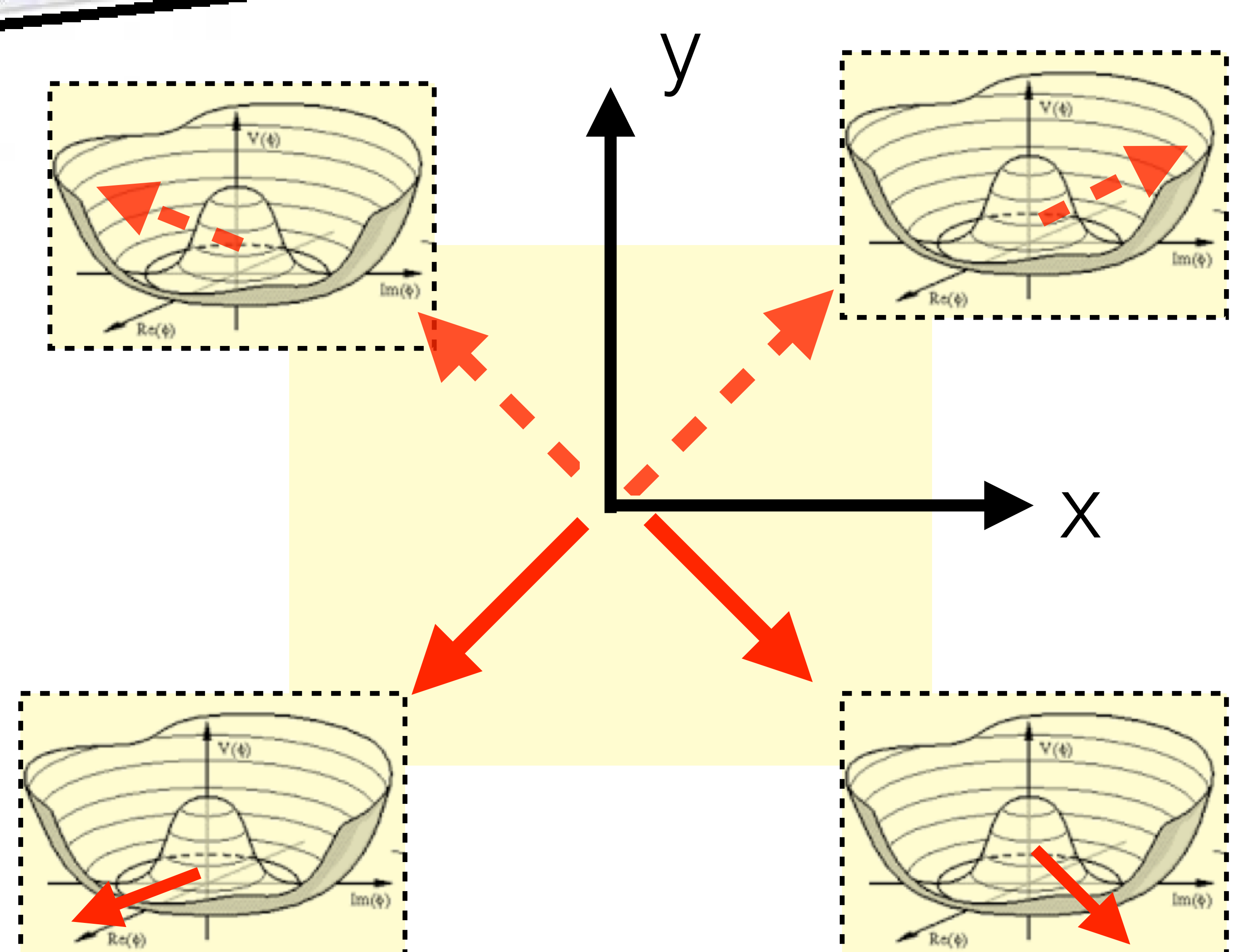

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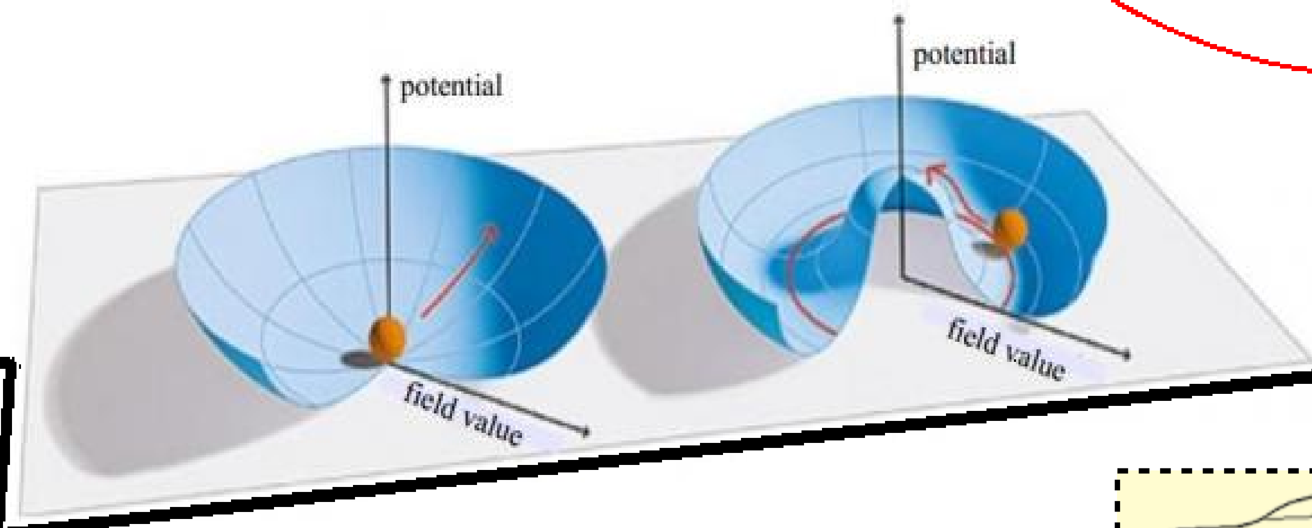

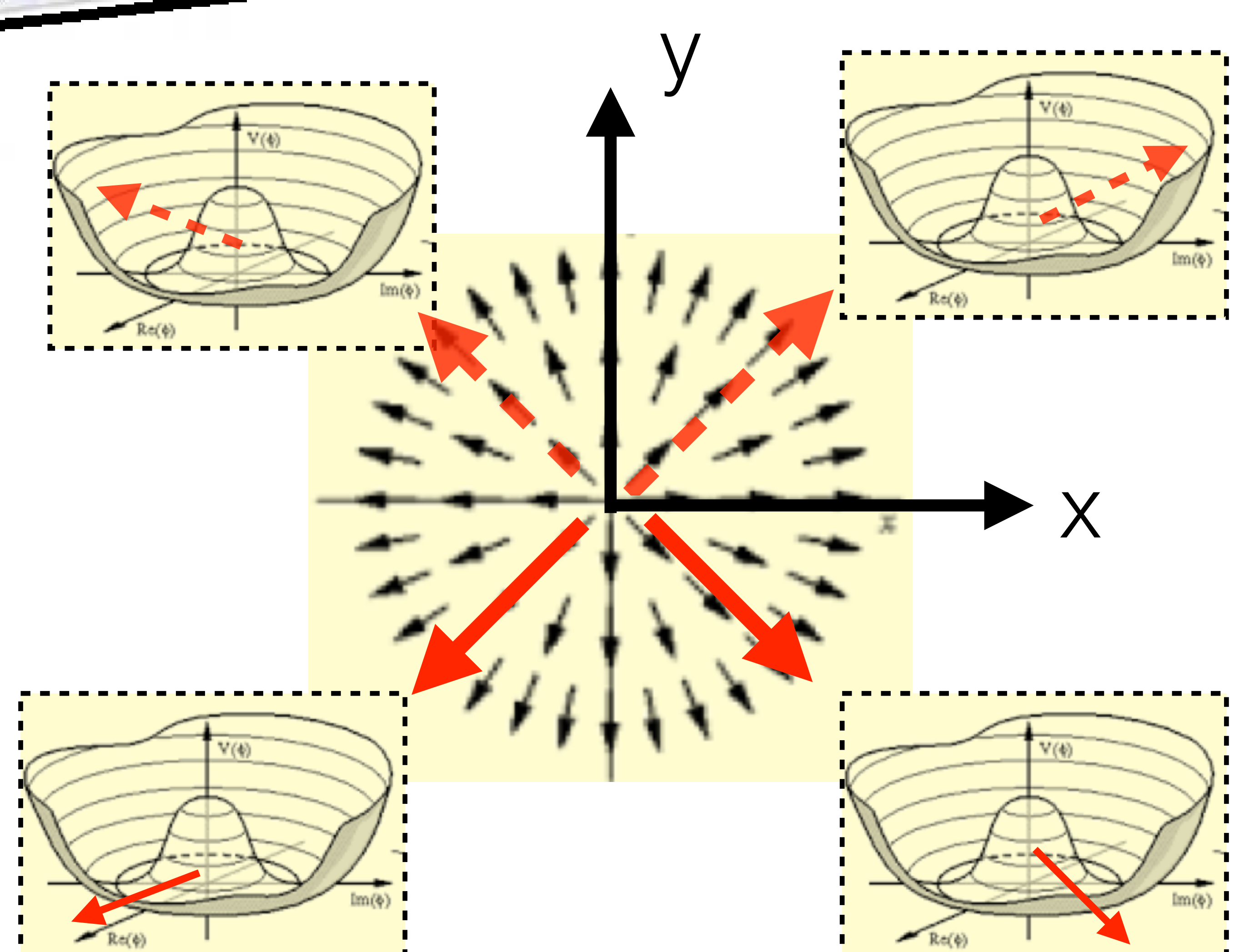

Introduction to Cosmic Defects

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

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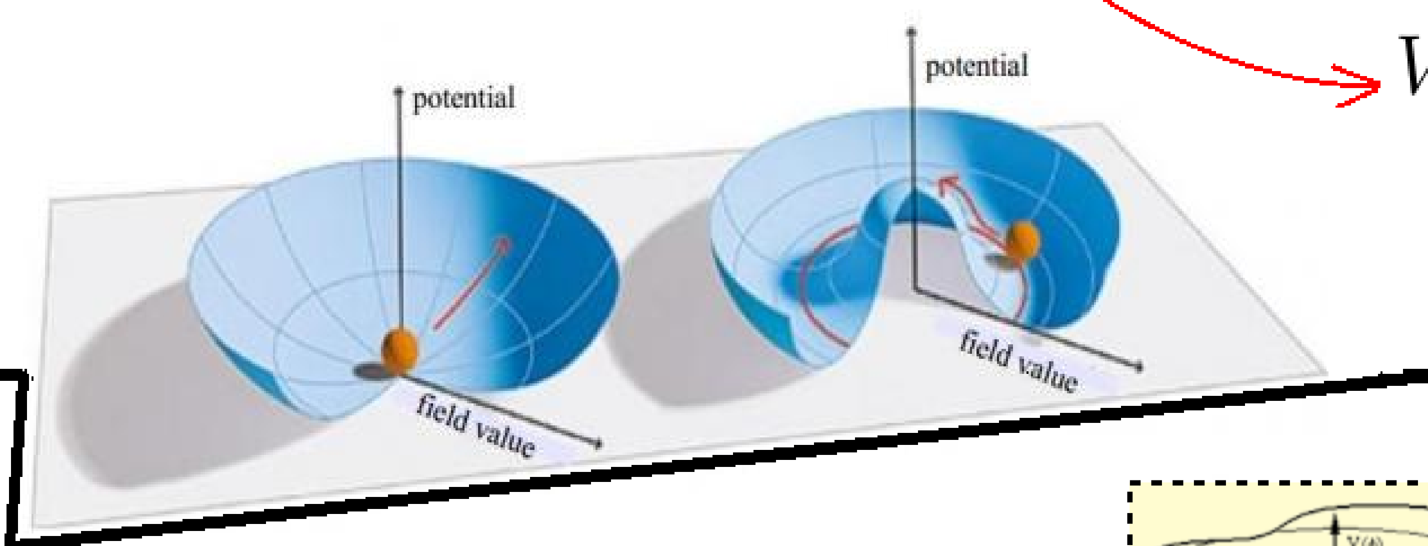

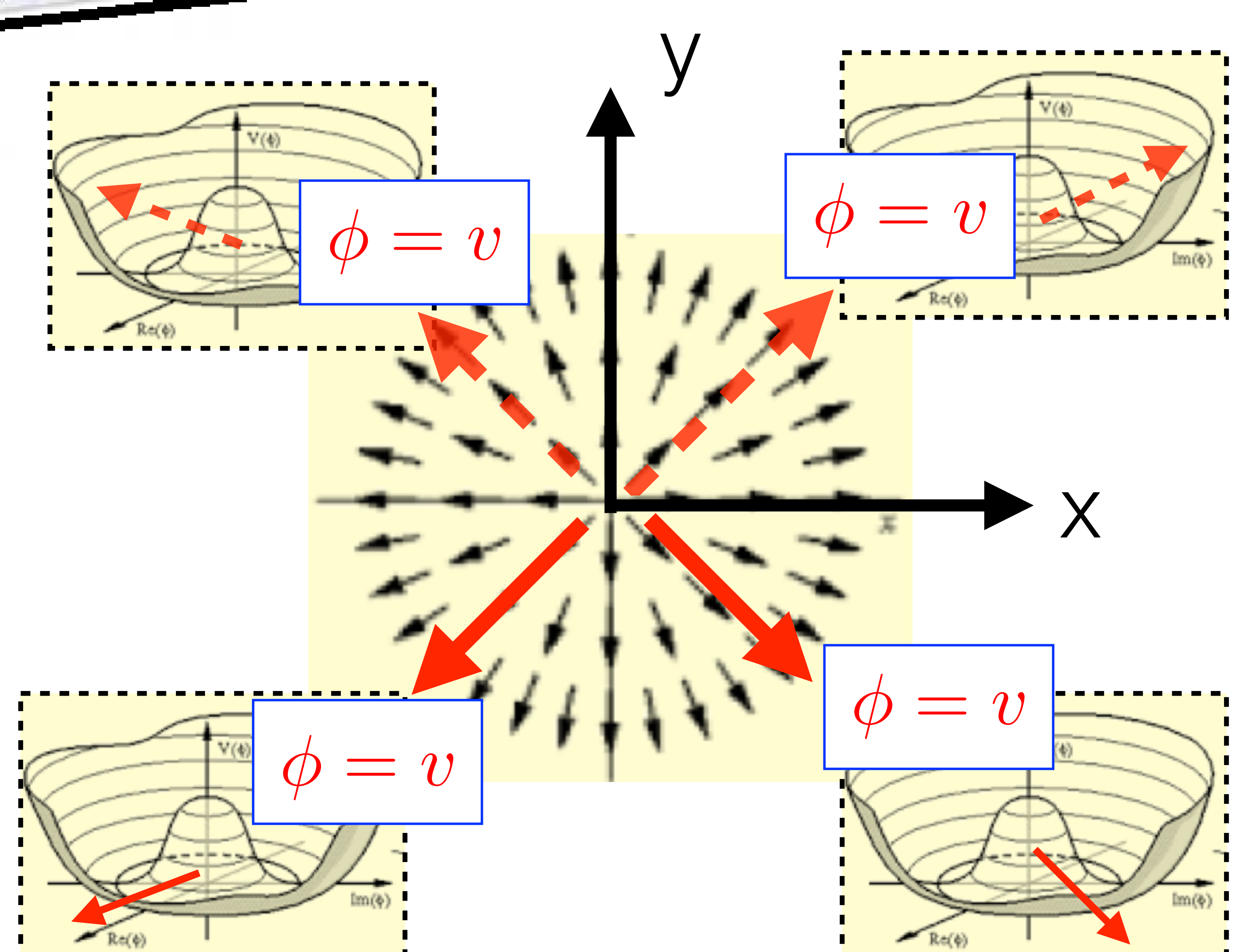

Introduction to Cosmic Defects

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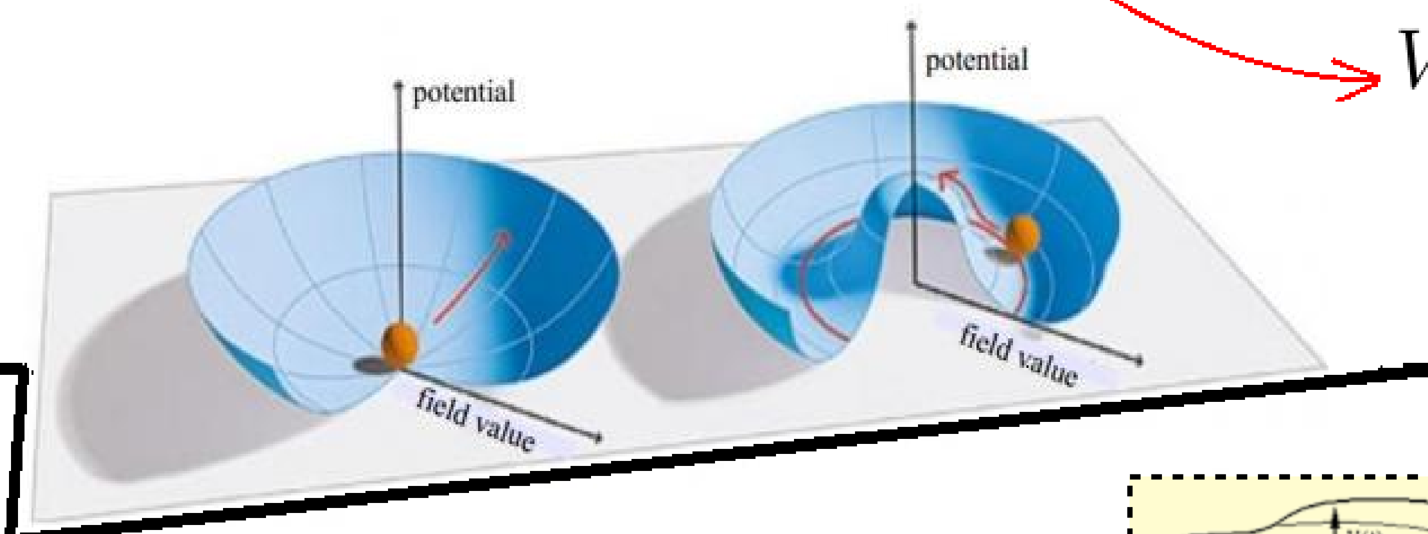
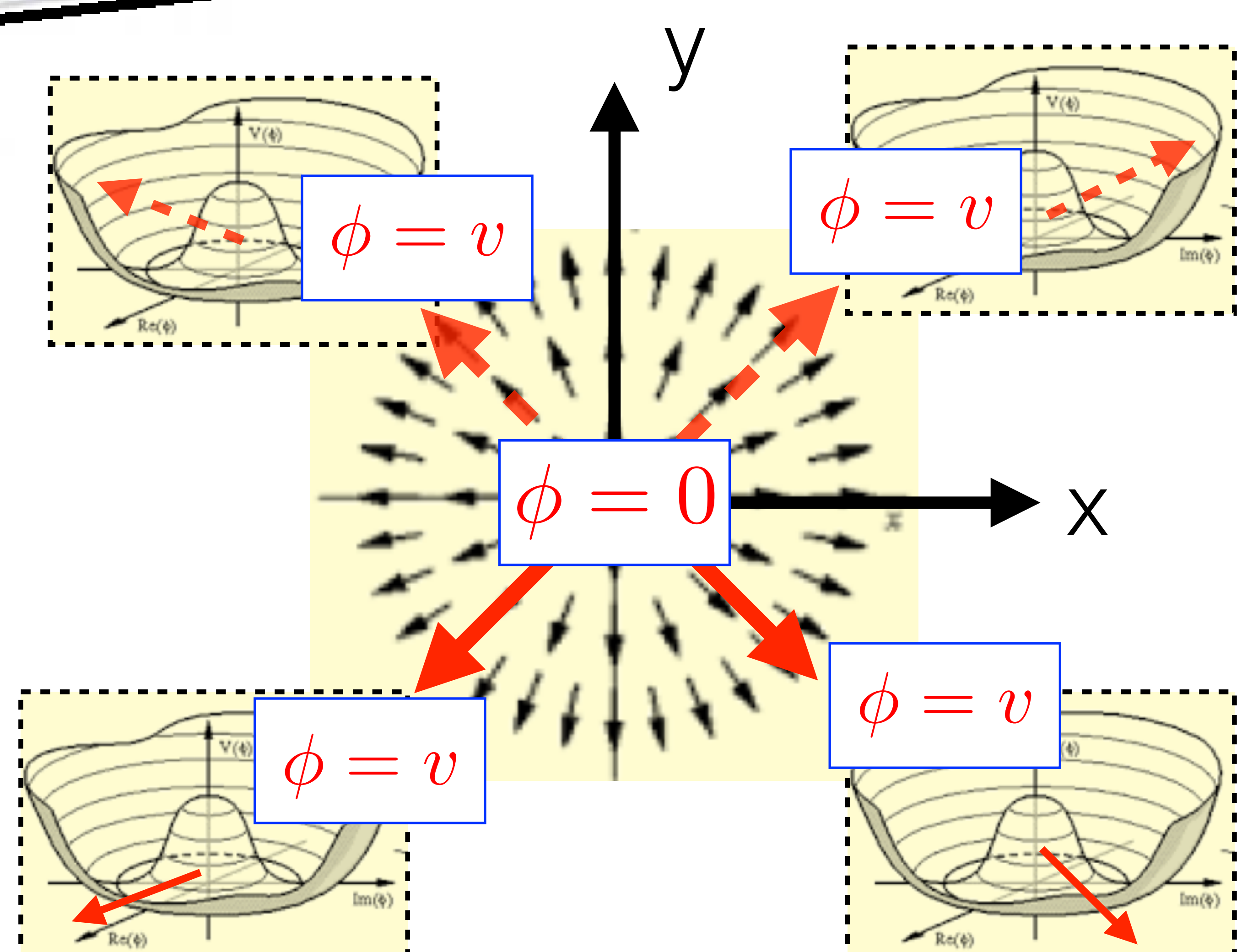
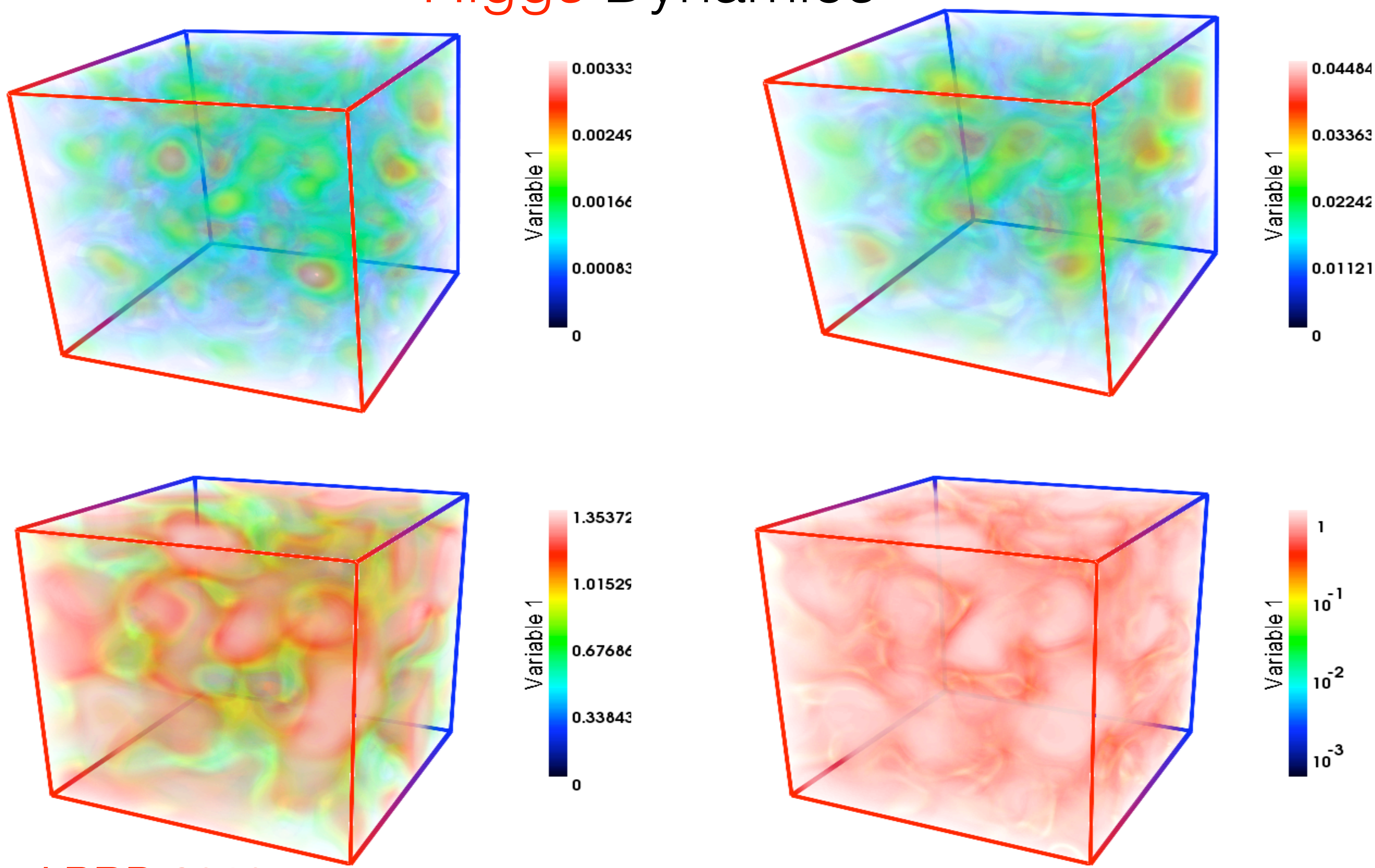




Introduction to Cosmic Defects

U(1) Breaking (after Hybrid Inflation)

Higgs Dynamics

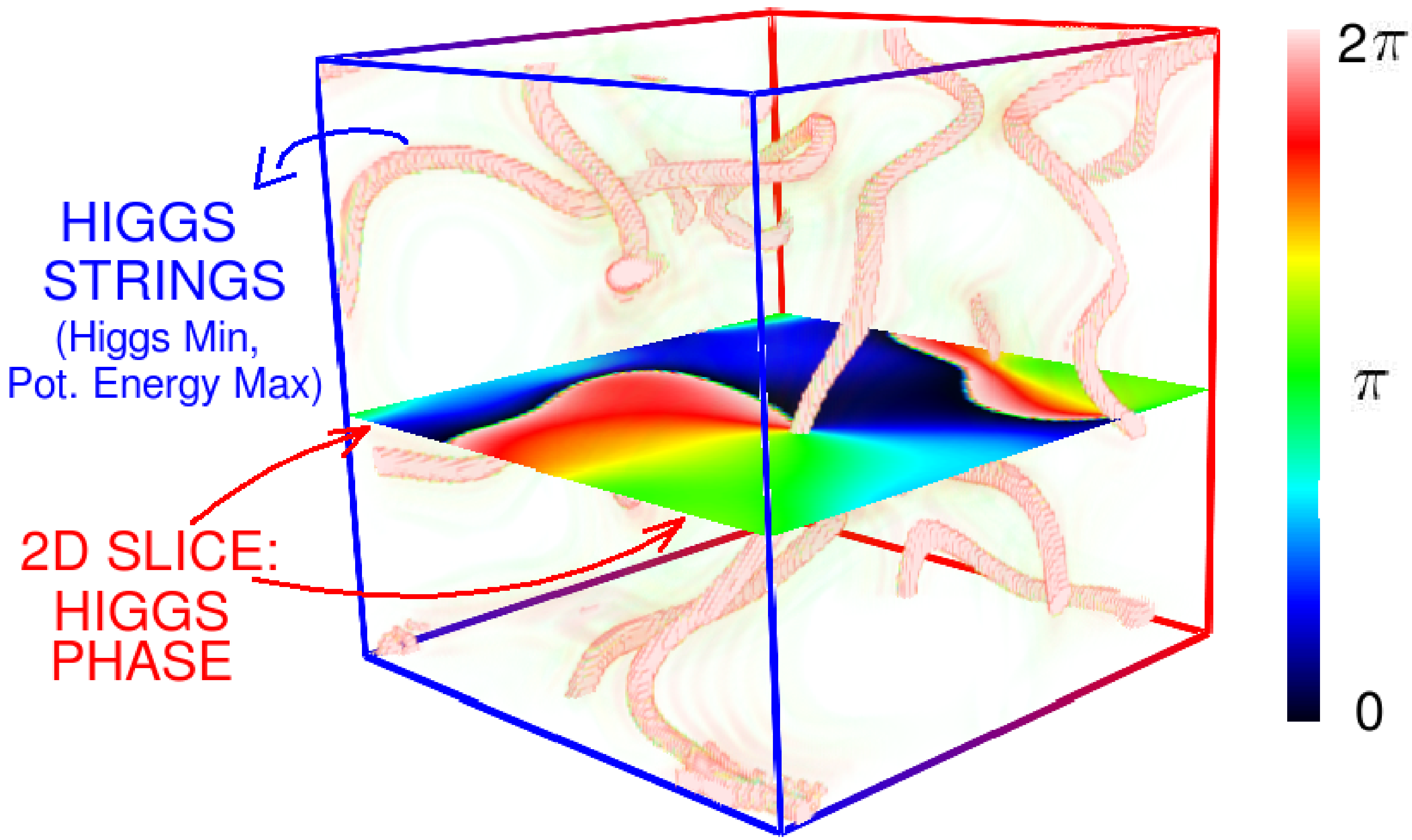


Dufaux et al PRD 2010

Introduction to Cosmic Defects

U(1) Breaking (after Hybrid Inflation)

SNAPSHOT OF THE HIGGS ($mt = 17$)



Dufaux et al PRD 2010

GW from PhT's

Can we really detect a 1st-O Ph-T ?

* LISA can, but LHC pressures typical BSM extensions to promote EW-PhT into First Order

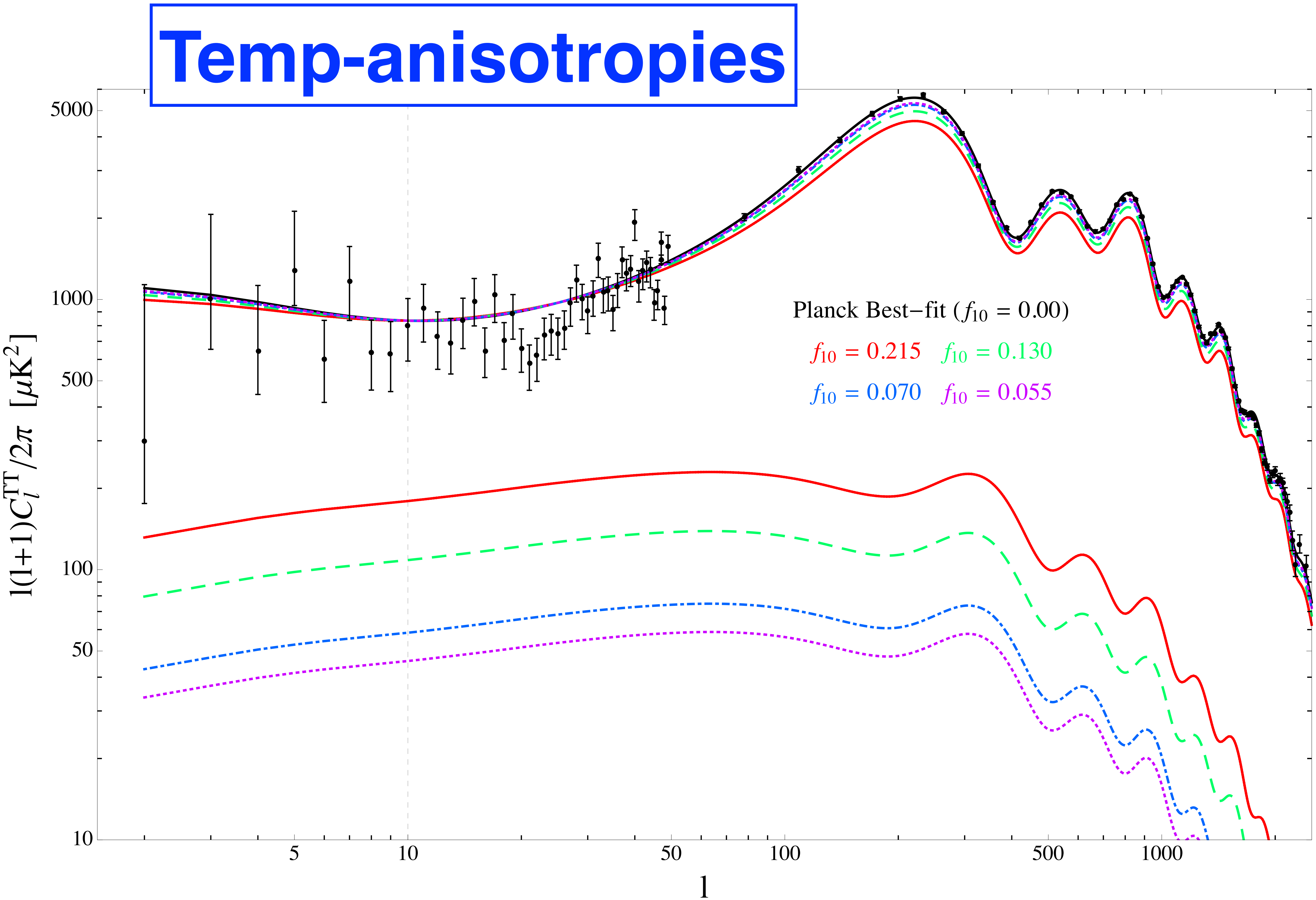
* Assuming LHC does not rule out models before, LISA can detect/constrain significant fraction of Param Space

* Predictions depend on many assumptions (particularly in sound waves), so is our modelling correct?

* Even if we detect it, then we infer α and β , but what BSM model is behind? not univocal !

CMB SLIDES

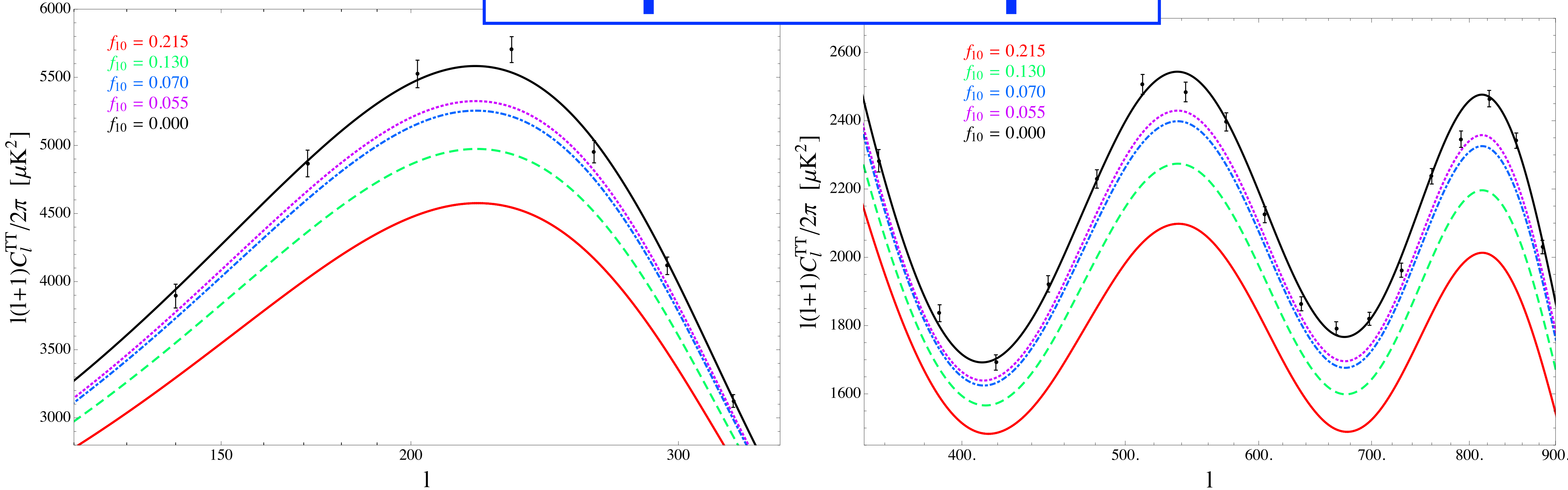
Cosmic Microwave Background



Durrer, DGF, Kunz, JCAP 2014

Cosmic Microwave Background

Temp-anisotropies



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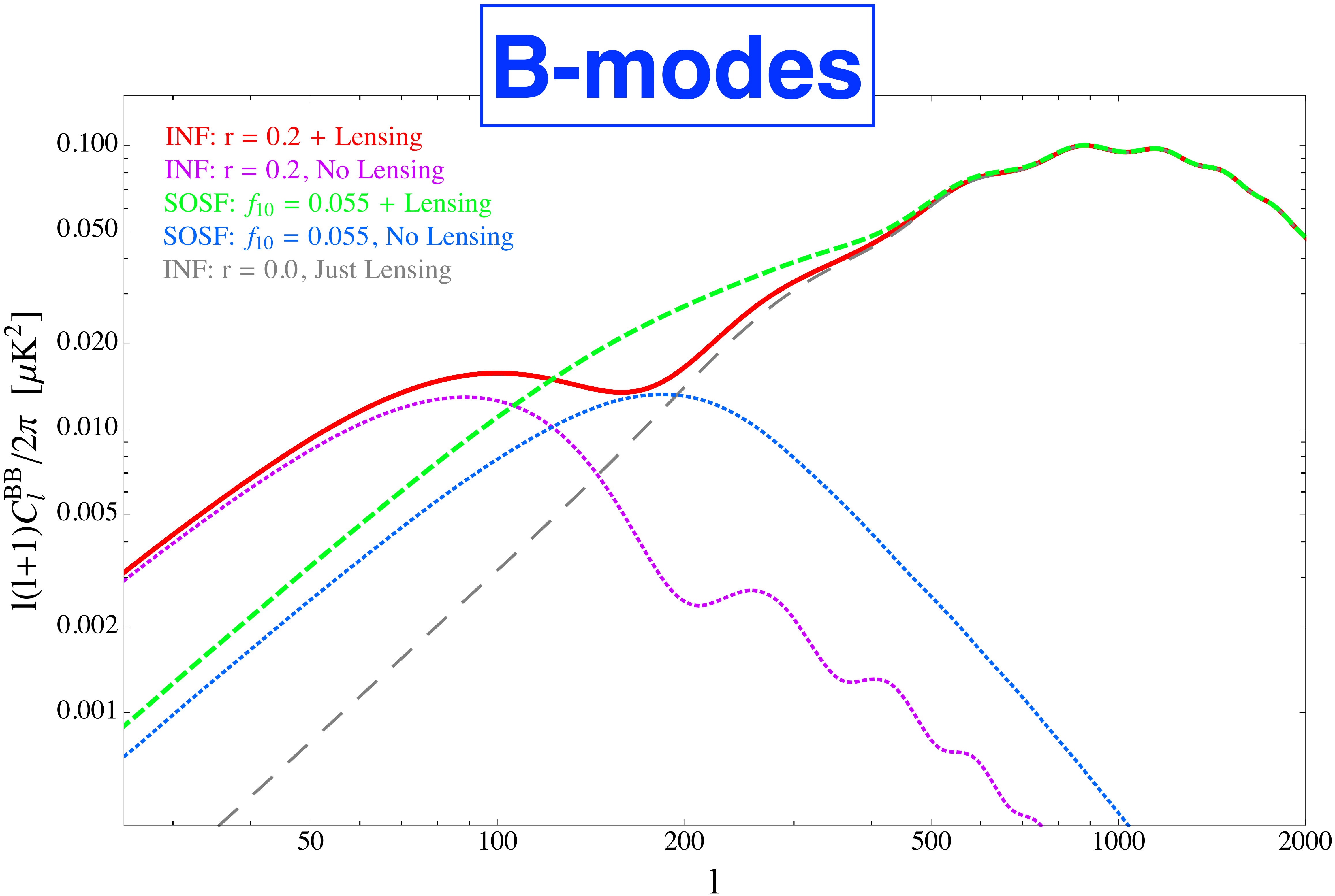

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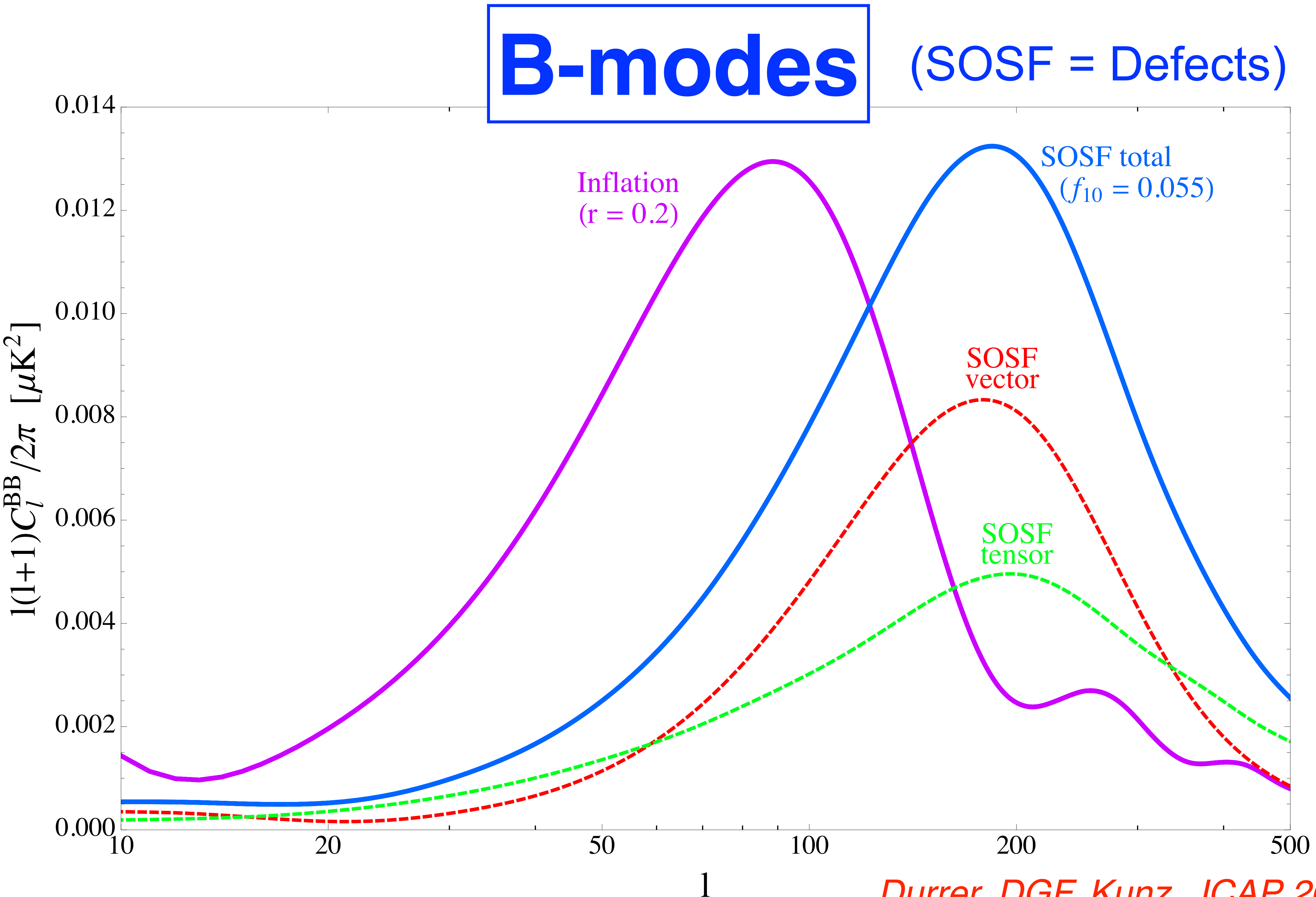

Durrer, DGF, Kunz, JCAP 2014