COSMOLOGICAL GRAVITATIONAL WAVES
(AN INTRODUCTION)

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Challenges and Opportunities of High Frequency Gravitational Wave Detection,
Oct 14-16 2019, ICTP, Trieste, Italy

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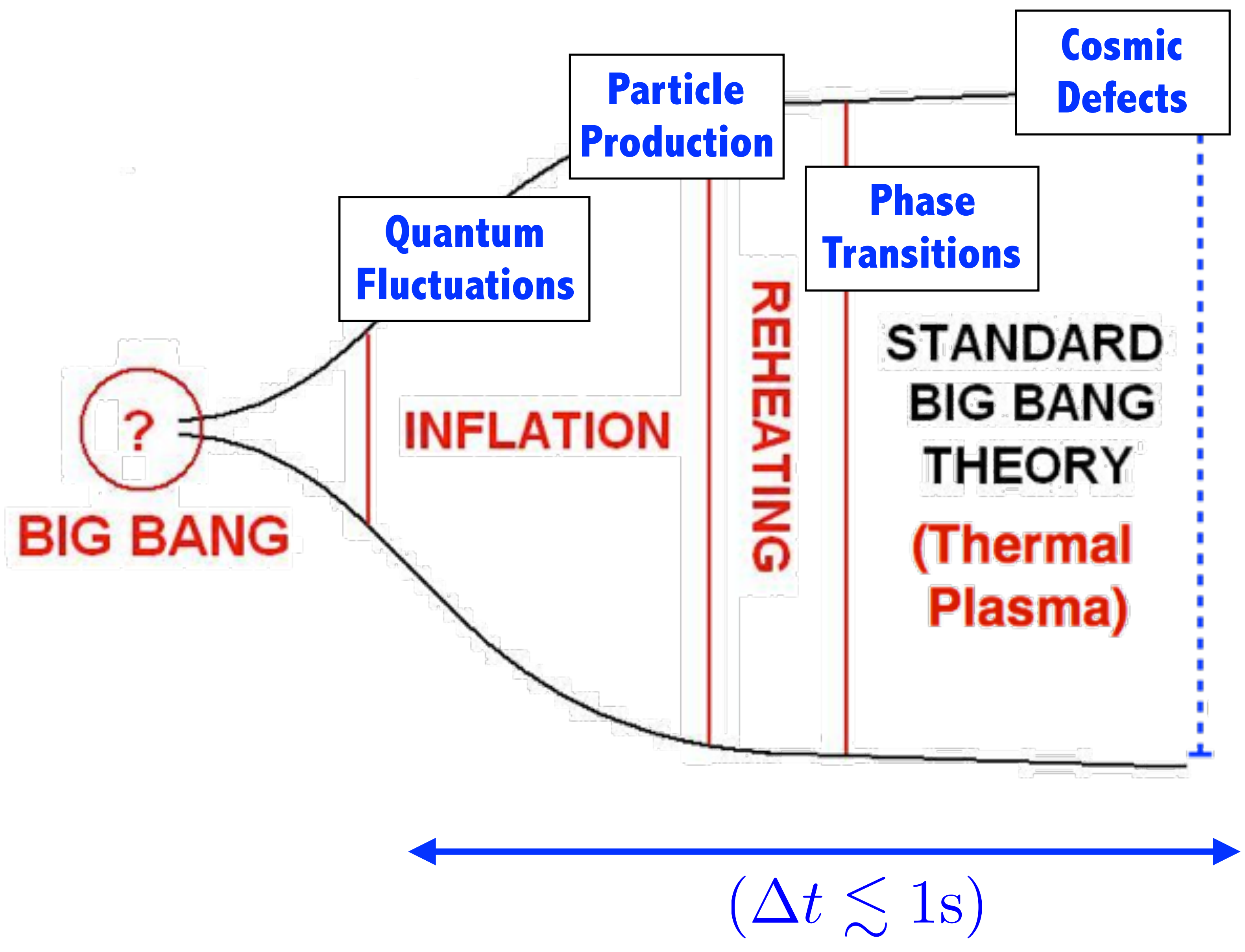
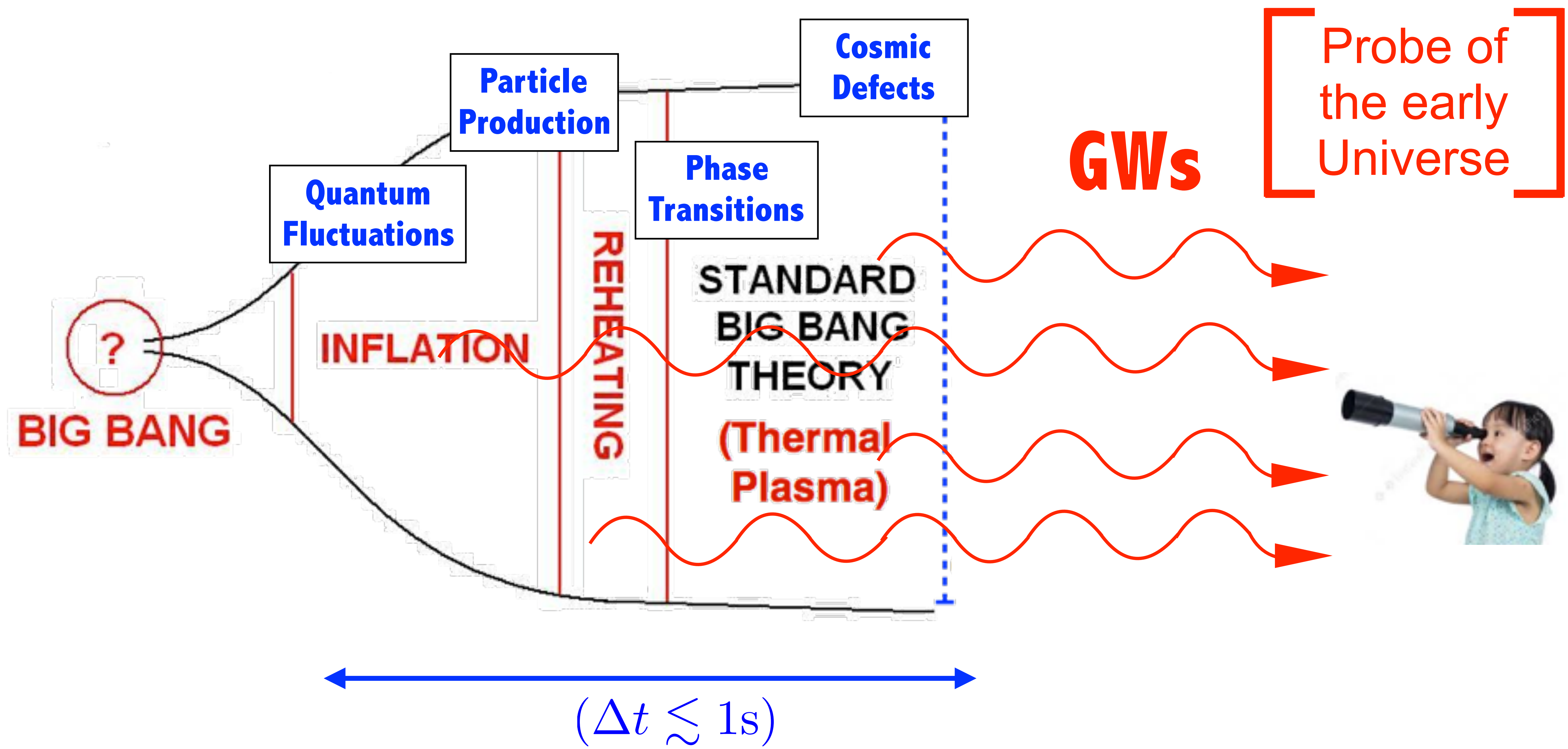
$$\rightarrow \begin{cases} \textbf{Decouple} \rightarrow \text{Spectral Form Retained} \\ \textbf{Specific HEP} \;\Leftrightarrow\; \text{Specific GW} \end{cases}$$

What processes of the early Universe ?

The Early Universe



The Early Universe

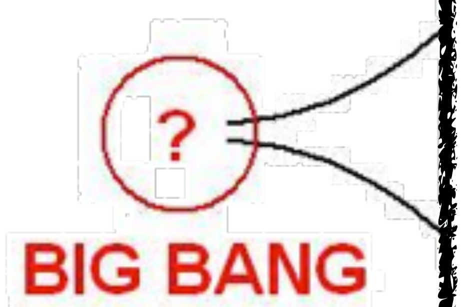


The Early Universe

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) GW definition

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

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

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)

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

Gravitational Waves as a probe of the early Universe

OUTLINE

0) GW definition ✓

Early Universe

1) $\boxed{\text{GWs from Inflation}}$

2) GWs from Preheating

3) GWs from Phase Transitions

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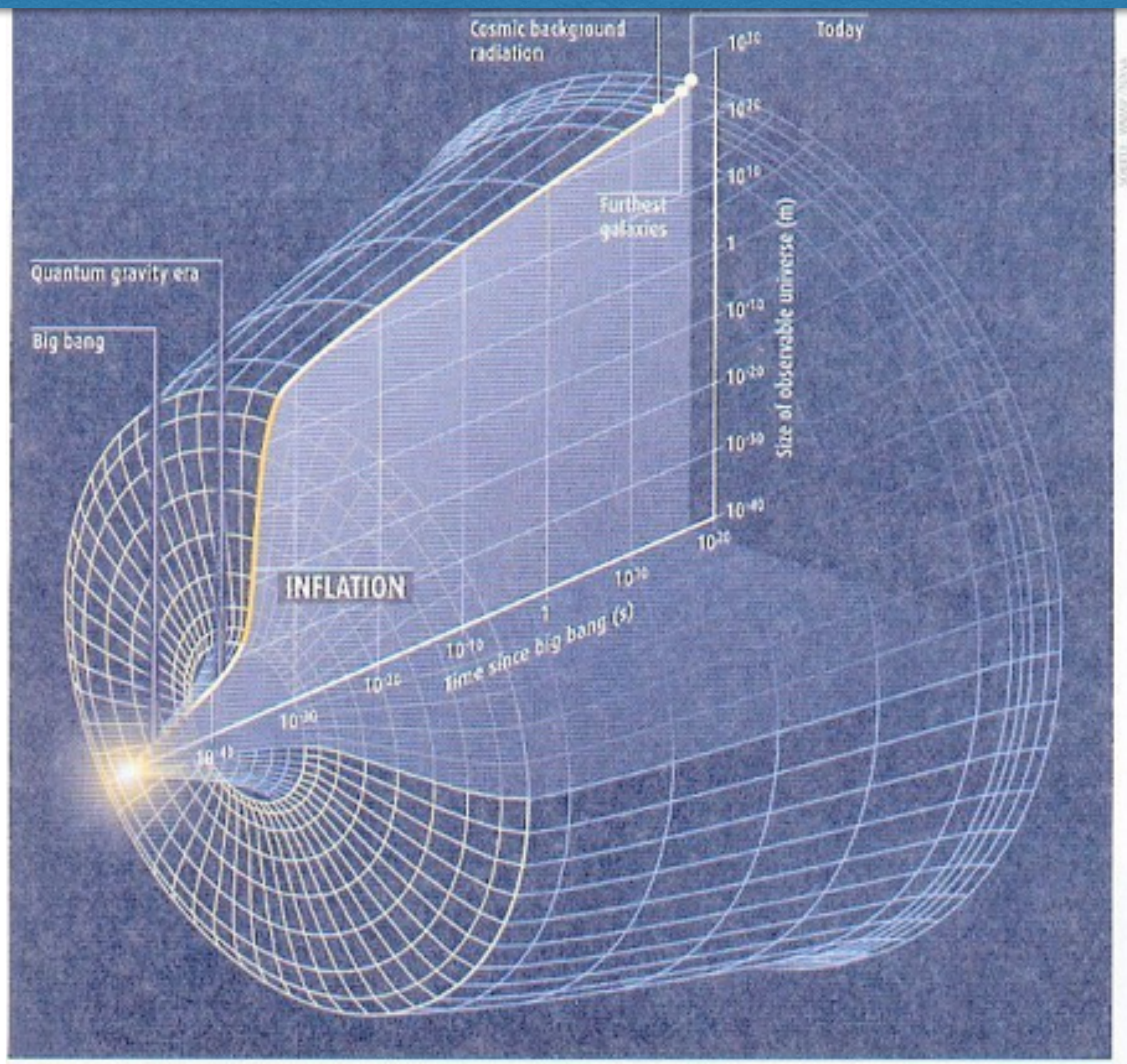
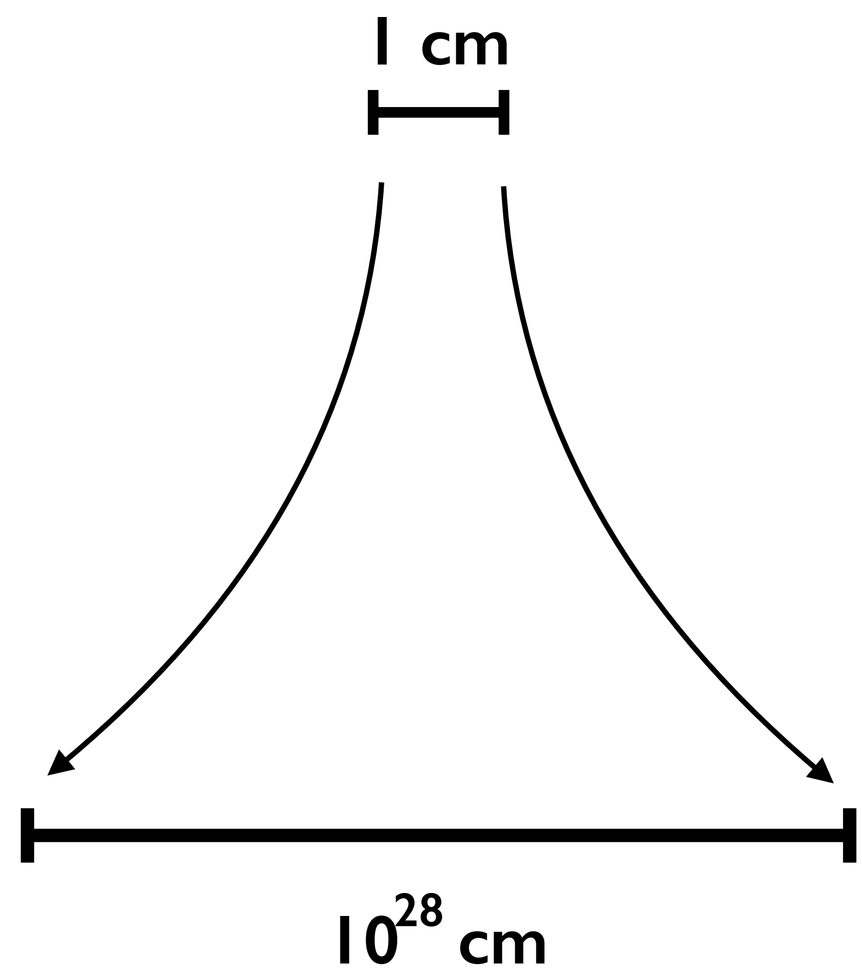
Inflation (basics)

COSMIC INFLATION



Needed for Consistency of the Big Bang theory

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



Irreducible GW background from Inflation

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

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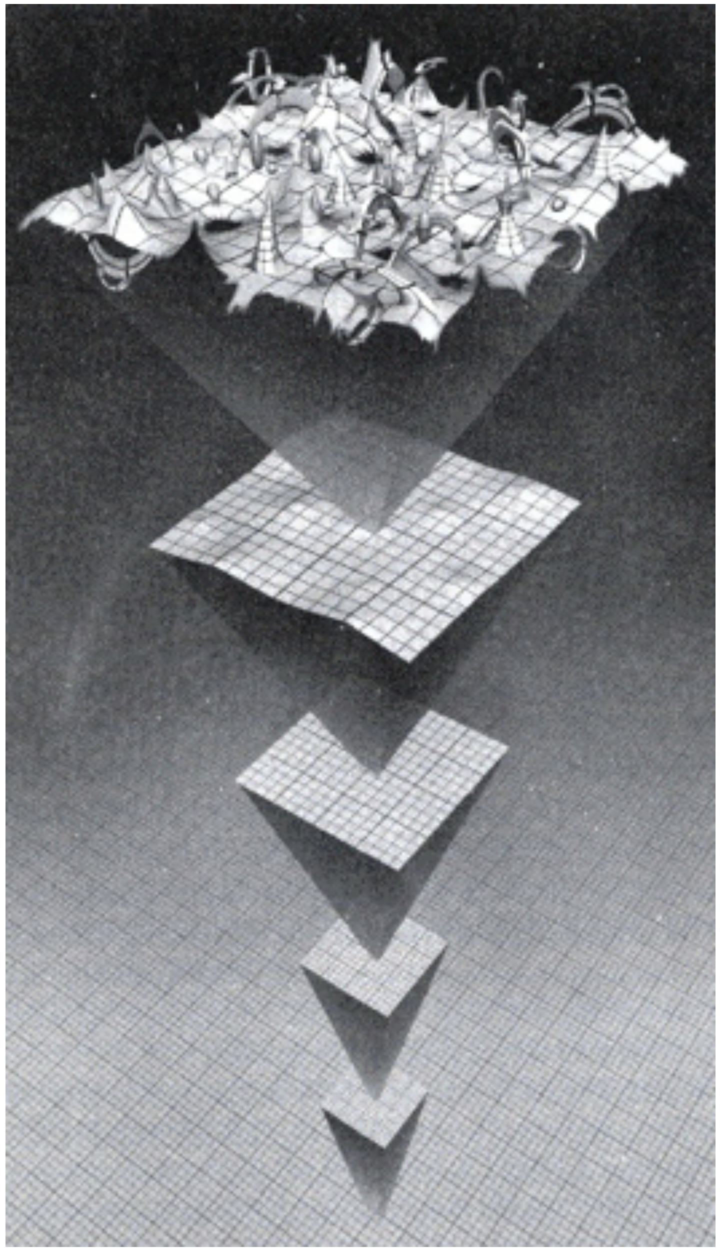

$$\left\langle h_{ij}(\vec{k},t) \right\rangle = 0$$

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

Quantum Fluctuations

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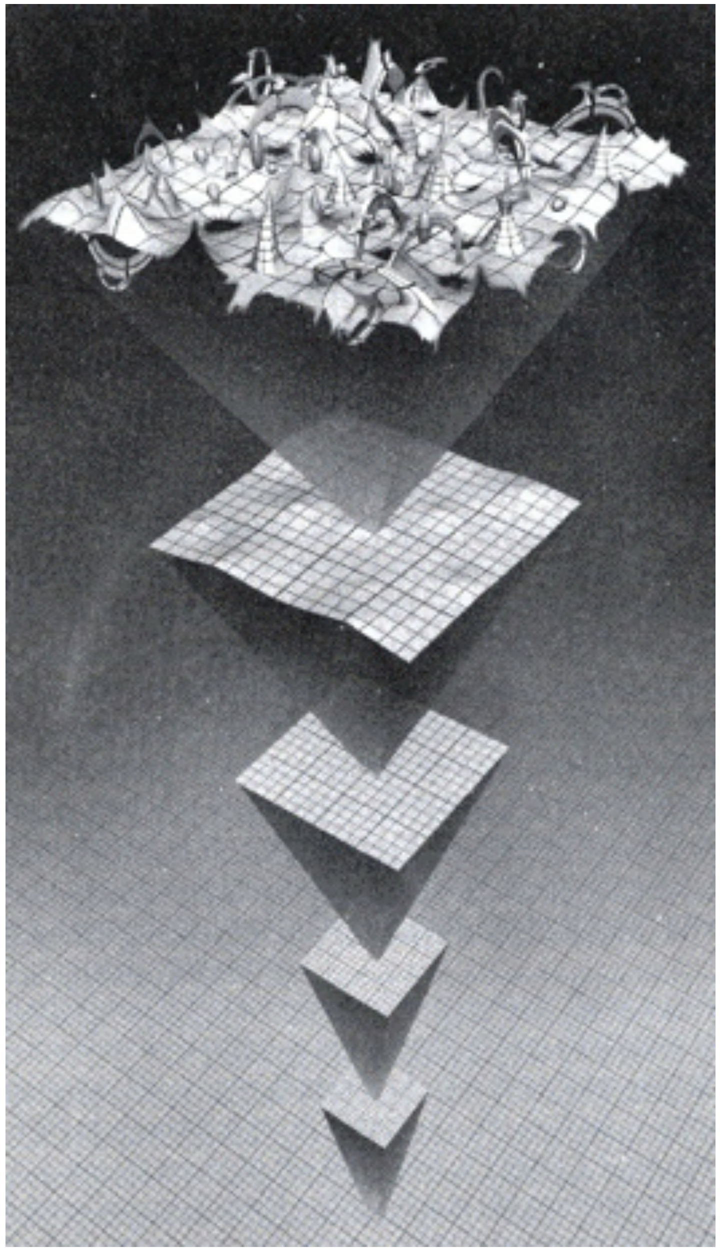

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$$\boxed{\Delta_h^2(k) = \frac{2}{\pi^2}\left(\frac{H}{m_p}\right)^2 \left(\frac{k}{aH}\right)^{n_t}}$$

$n_t \equiv -2\epsilon$

energy scale

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

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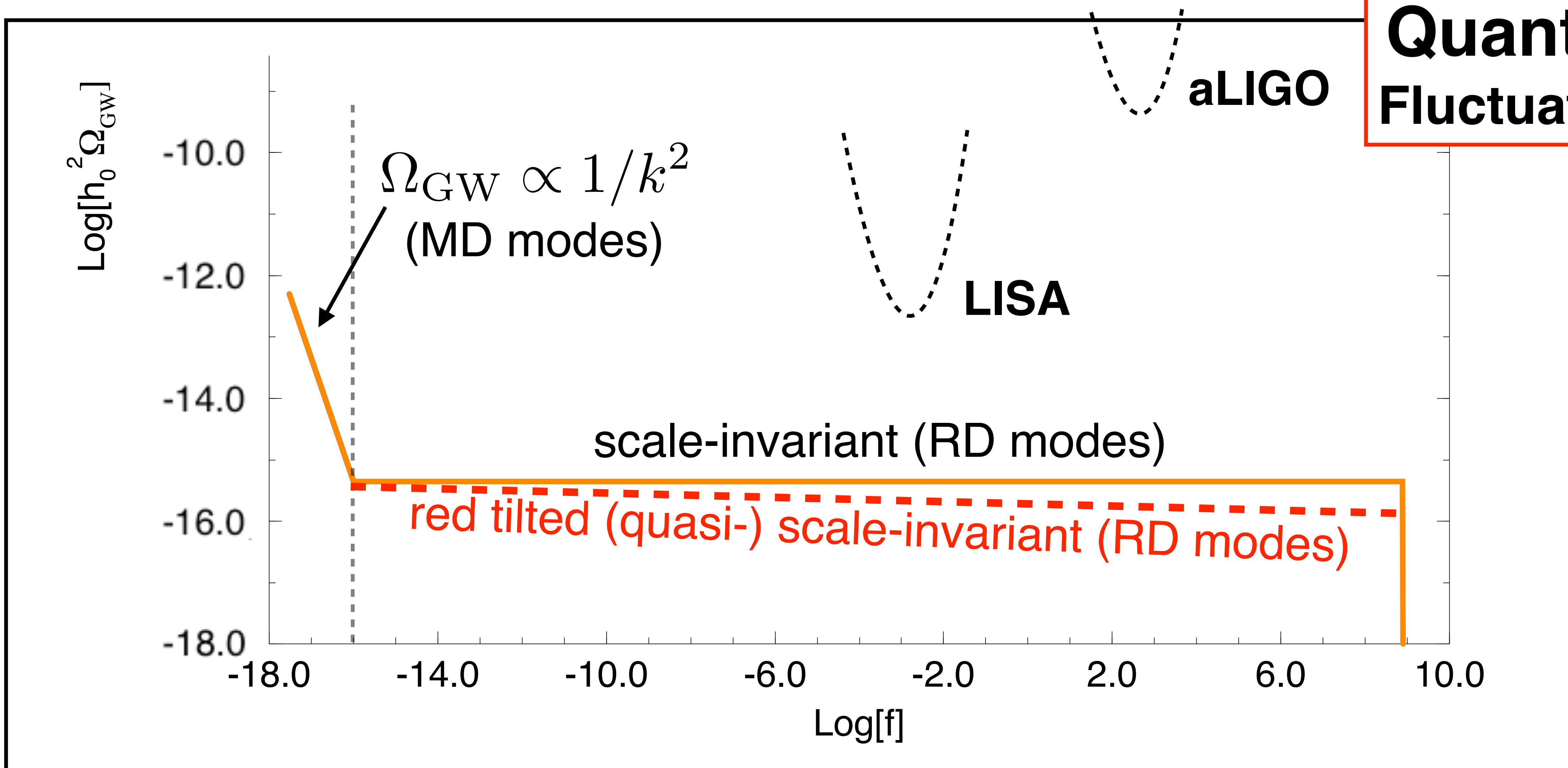

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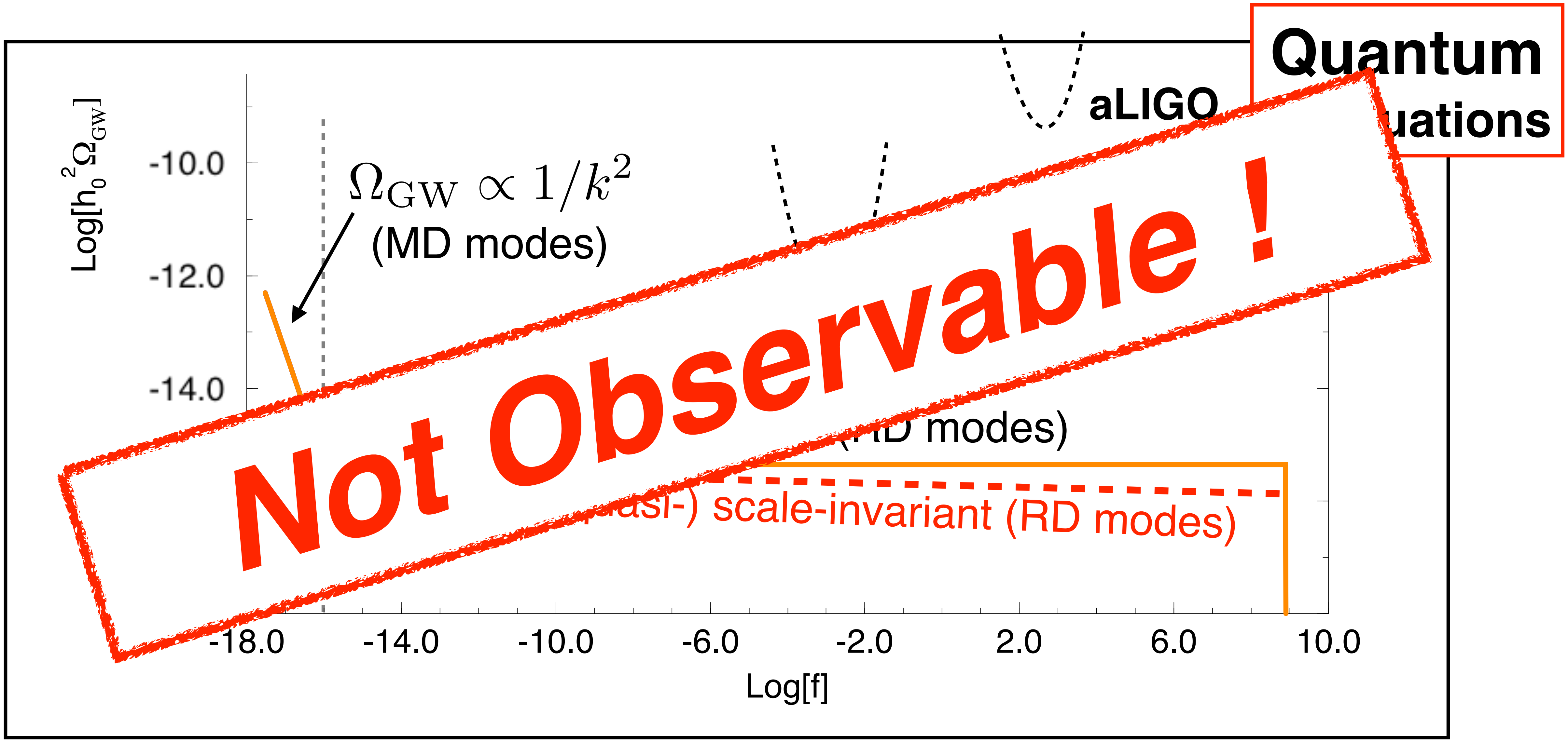

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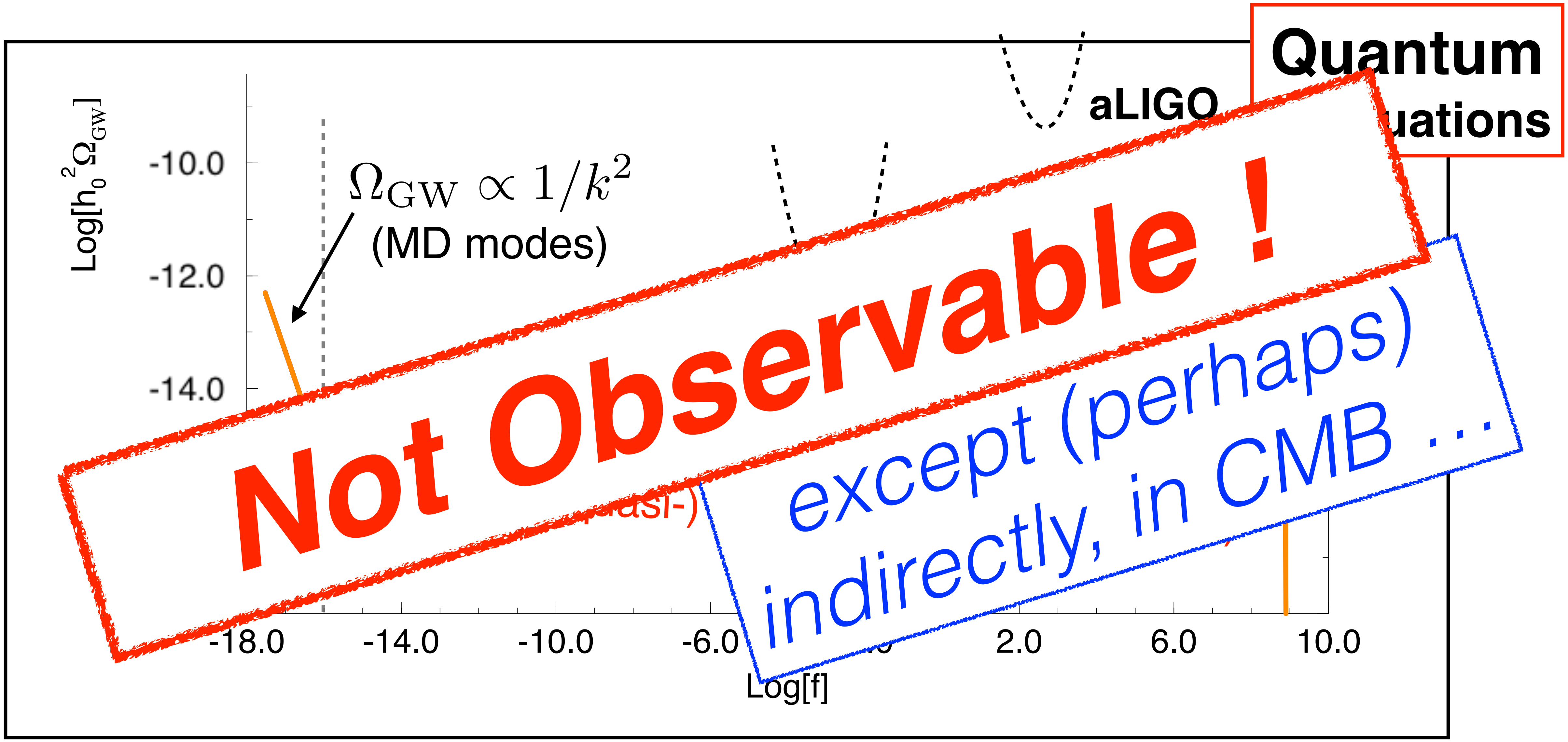
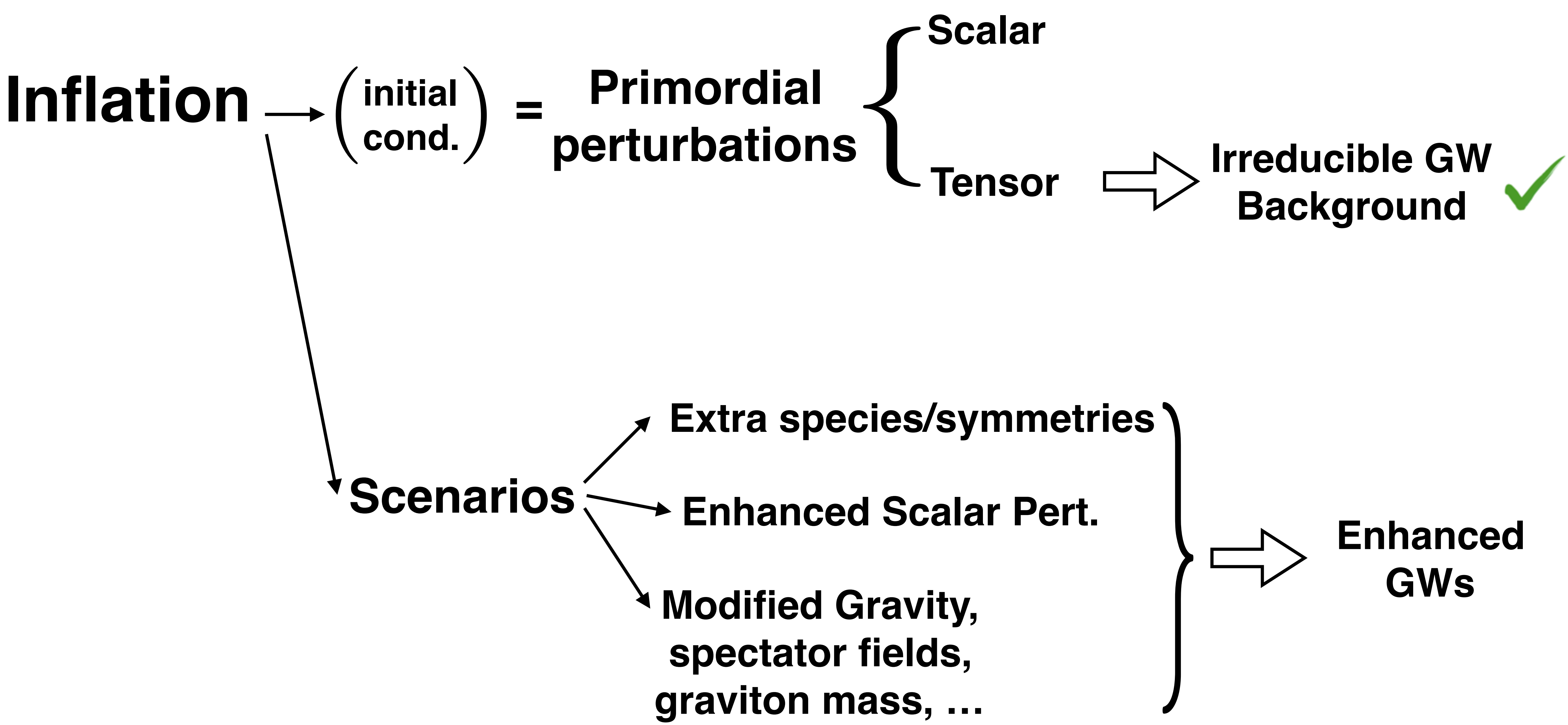
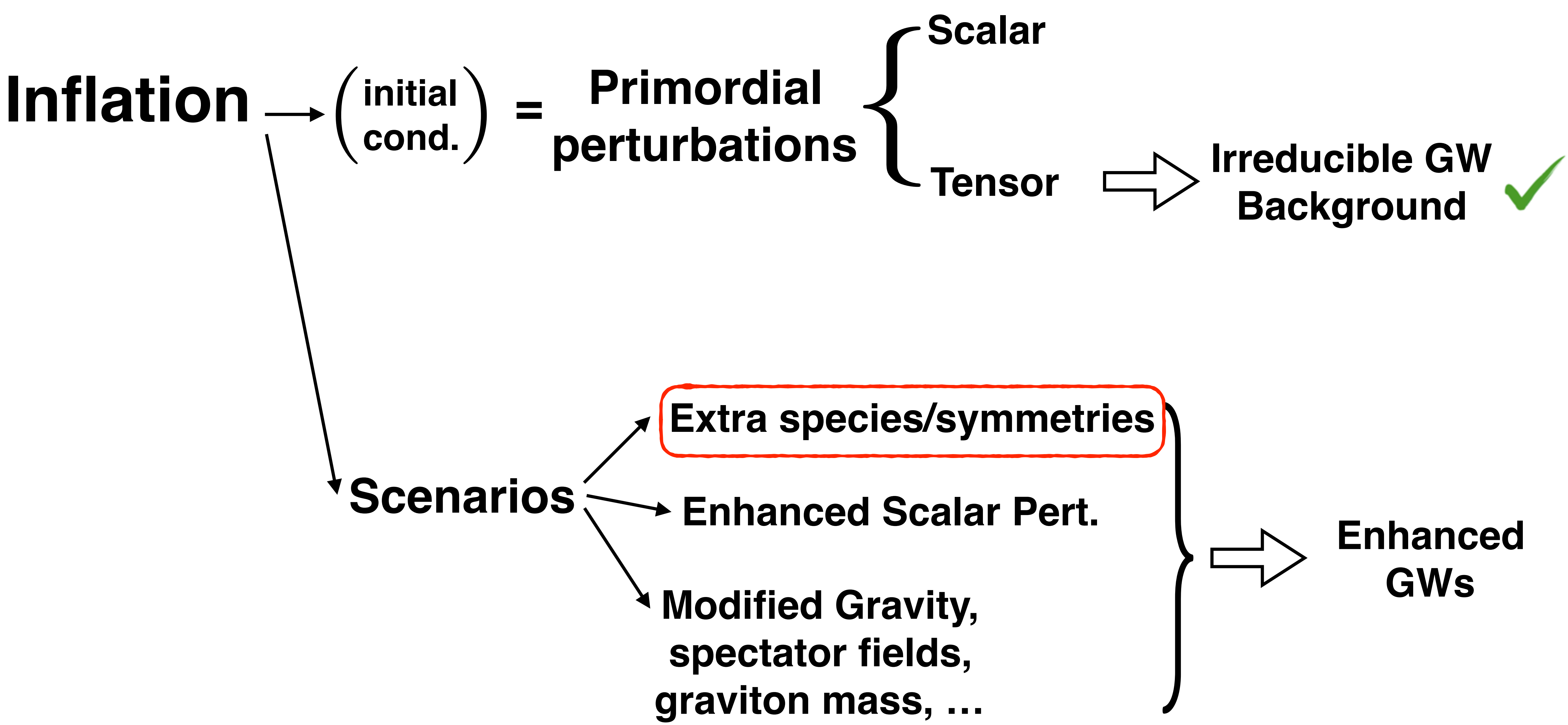


INFLATIONARY COSMOLOGY



INFLATIONARY COSMOLOGY



INFLATIONARY MODELS

Axion-Inflation

Freese, Frieman, Olinto '90; . . .

Shift symmetry $\varphi \to \varphi + const.$

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

inflaton φ = pseudo-scalar axion

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

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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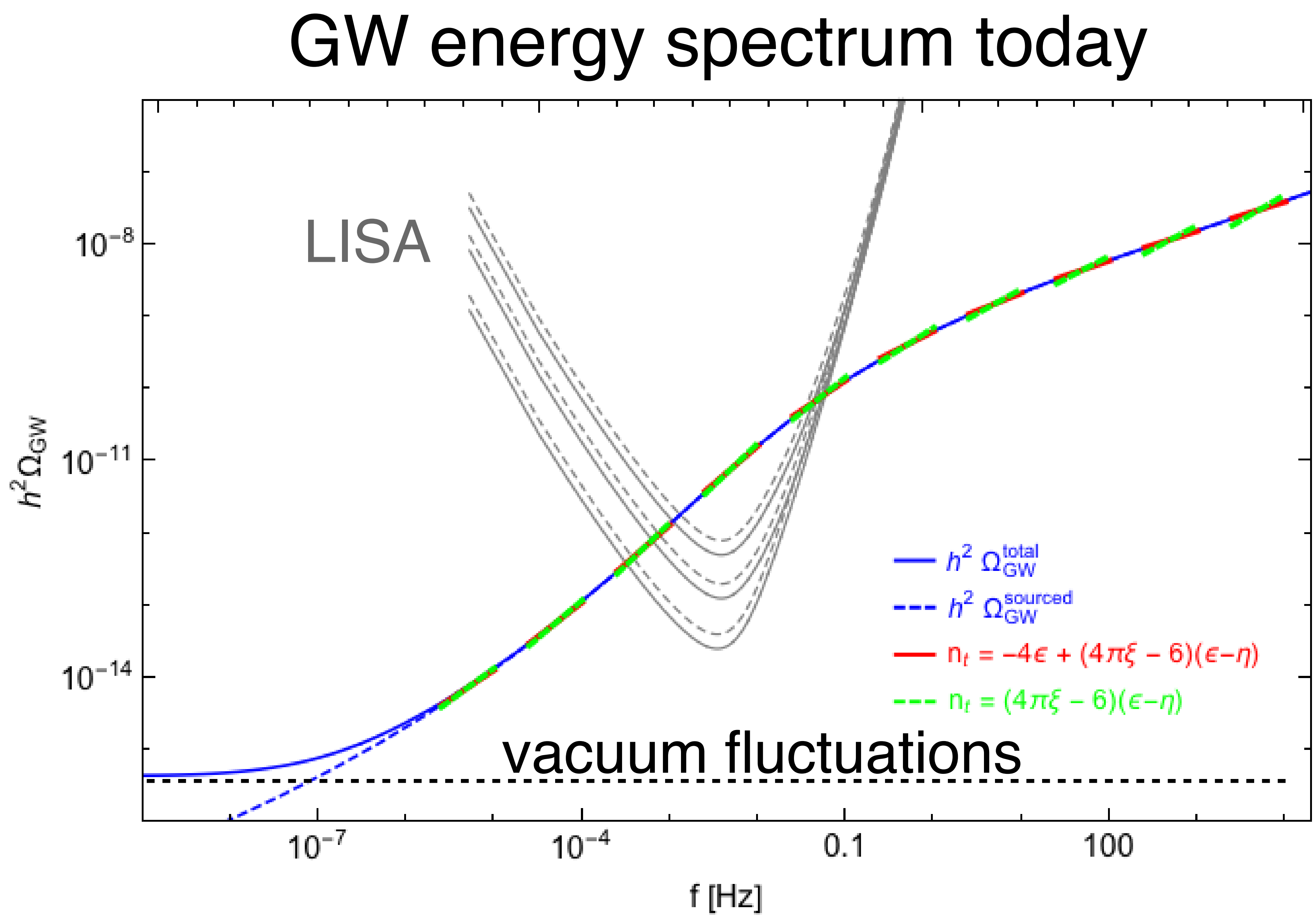
chiral GWs !

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

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

INFLATIONARY MODELS

Axion-Inflation



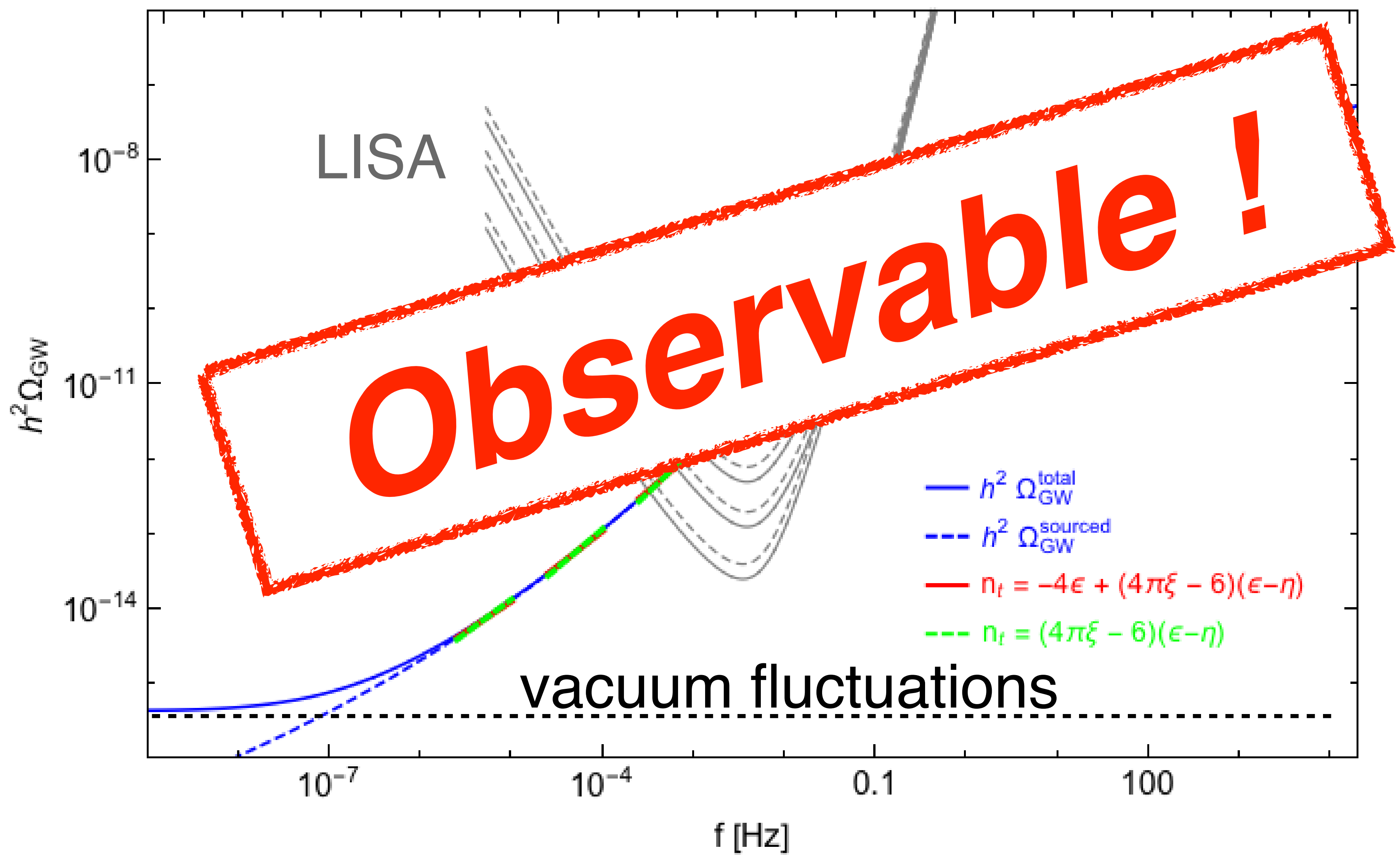
Gauge fields source a blue tilted Non-Gaussian, & Chiral GW Background

Bartolo et al '16, 1610.06481

INFLATIONARY MODELS

Axion-Inflation

GW energy spectrum today



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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?

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

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

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

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

INFLATIONARY MODELS

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→ **large excitation of fields !?**
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$$\boxed{\text{inflaton } \phi \longrightarrow V(\phi)}$$

All 3 cases:

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

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

⇓

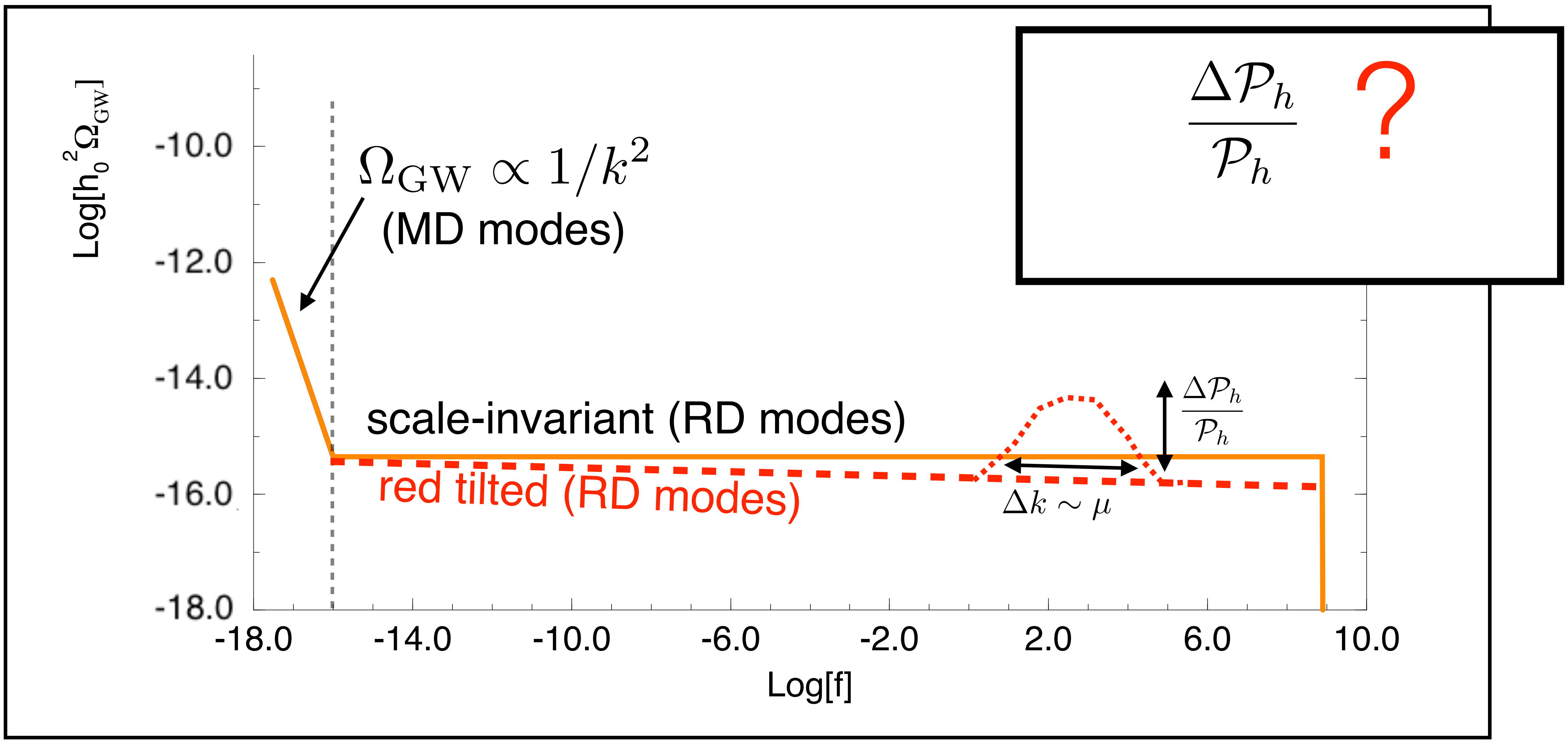
GW

INFLATIONARY MODELS

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

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

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



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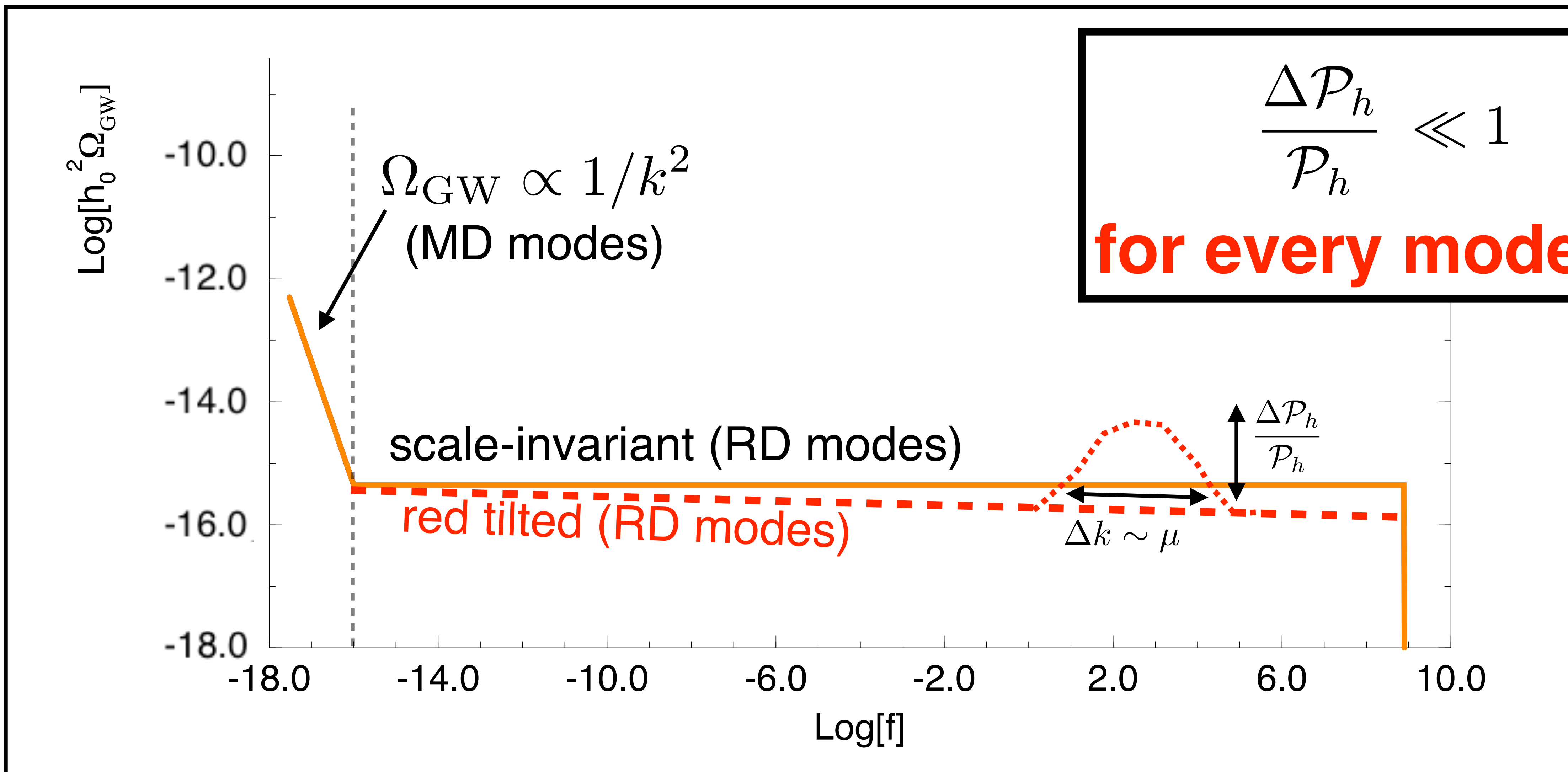

$$\frac{\Delta\mathcal{P}_h}{\mathcal{P}_h} \ll 1$$

for every model !

INFLATIONARY MODELS

$$\boxed{\phi F \tilde{F}}$$

Special one !

INFLATIONARY MODELS

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Special one !

* Are there other variants leading to observable HF-GW?

* Can we measure these GW at different frequencies ?

* What signatures (other than GW) are observable?

* What can we really say about inflation ?

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Peloso et al, 1509.07521, 1606.00459, 1610.03763, 1707.02441, 1803.04501,1904.01488, ...

Domcke et al, 1603.01287, 1806.08769, 1807.03358, 1812.08021, 1905.11372,1910.01205, ...

INFLATIONARY MODELS

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PELOSO's talk !

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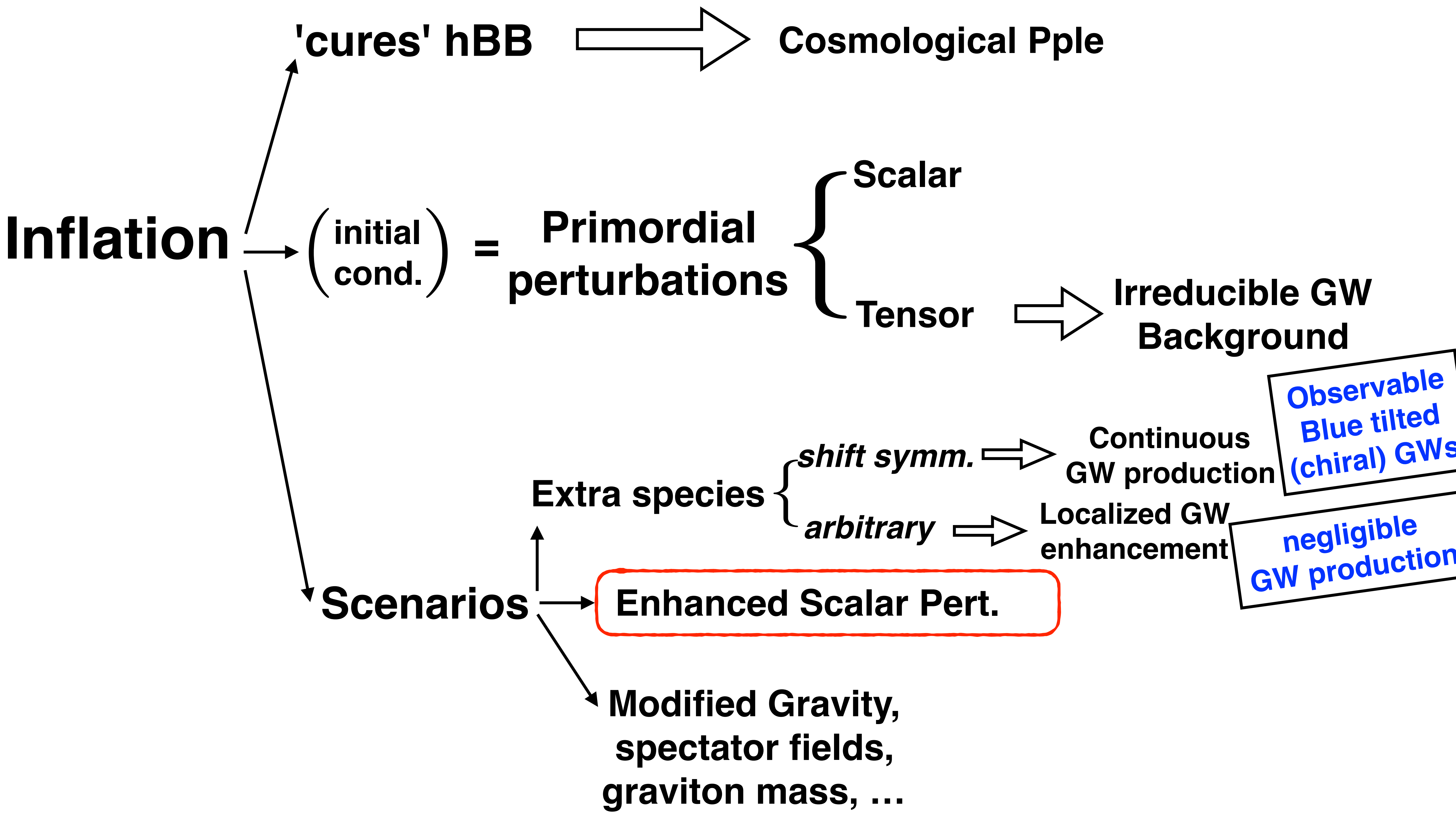
INFLATIONARY COSMOLOGY



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)**

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

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)

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

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

D. Wands et al, 2006-2010
Baumann et al, 2007
Peloso et al, 2018

INFLATIONARY MODELS

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BBN	$\Omega_{gw,0} < 1.5 \times 10^{-5}$ $\longrightarrow$	$\triangle^2_{\mathcal{R}} < 0.1$
LIGO	$\Omega_{gw,0} < 6.9 \times 10^{-6}$ $\longrightarrow$	$\triangle^2_{\mathcal{R}} < 0.07$
PTA	$\Omega_{gw,0} < 4 \times 10^{-8}$ $\longrightarrow$	$\triangle^2_{\mathcal{R}} < 5 \times 10^{-3}$
LISA	$\Omega_{gw,0} < 10^{-13}$ $\longrightarrow$	$\triangle^2_{\mathcal{R}} < 1 \times 10^{-5}$
BBO	$\Omega_{gw,0} < 10^{-17}$ $\longrightarrow$	$\triangle^2_{\mathcal{R}} < 3 \times 10^{-7}$

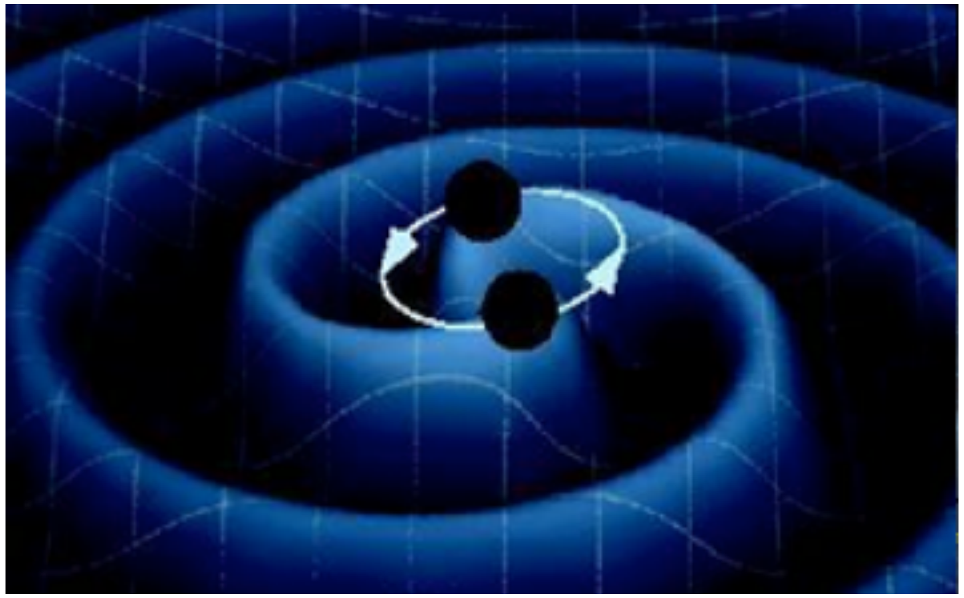
Phys.Rev. D81 (2010) 023527

INFLATIONARY MODELS

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

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

Has LIGO detected PBH's ?



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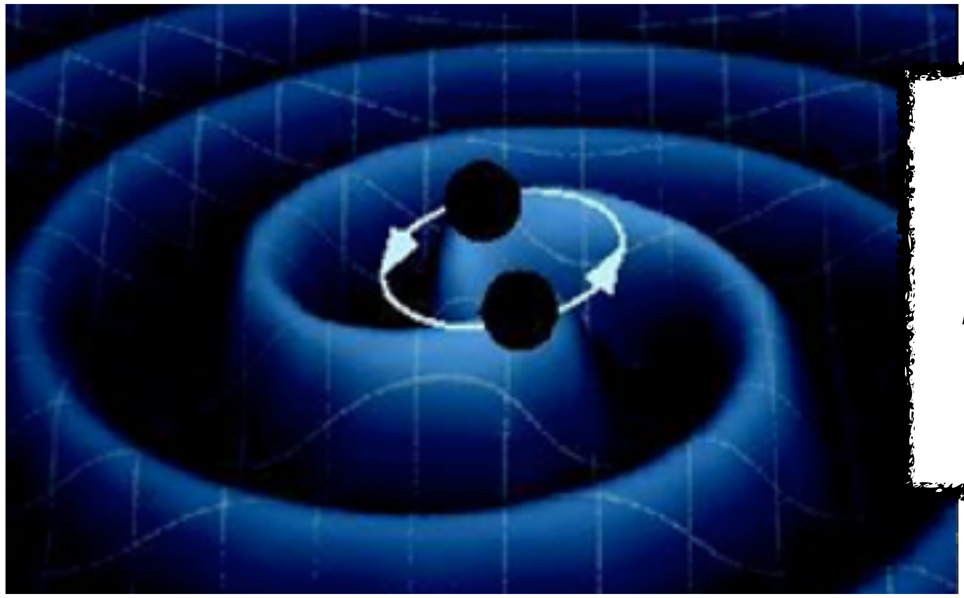

'We will know soon, determining mass/spin distributions'
(M. Fishbach (LIGO), Moriond'19)

INFLATIONARY MODELS

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PBH candidate for Dark Matter ?

Clesse & Garcia-Bellido, 2015-2017
Ali-Haimoud et al 2016-2017
Window is very narrow

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* If PBH are the DM, what is the GW from 2nd O(Φ)? **Bartolo et al, '18**

* If GW from from 2nd O(Φ) PBG, then Non-Gaussianity? **Bartolo et al, '19**

* If GW from from 2nd O(Φ) PBG, then Anisotropies? **Bartolo et al, '19**

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PELOSO's talk !

INFLATIONARY COSMOLOGY

Inflation

$\left(\begin{array}{c}\text{initial}\\ \text{cond.}\end{array}\right)$ = Primordial perturbations

Scalar

Tensor : Irreducible GWs

Scenarios

Extra species/symmetries

Enhanced Scalar Pert.

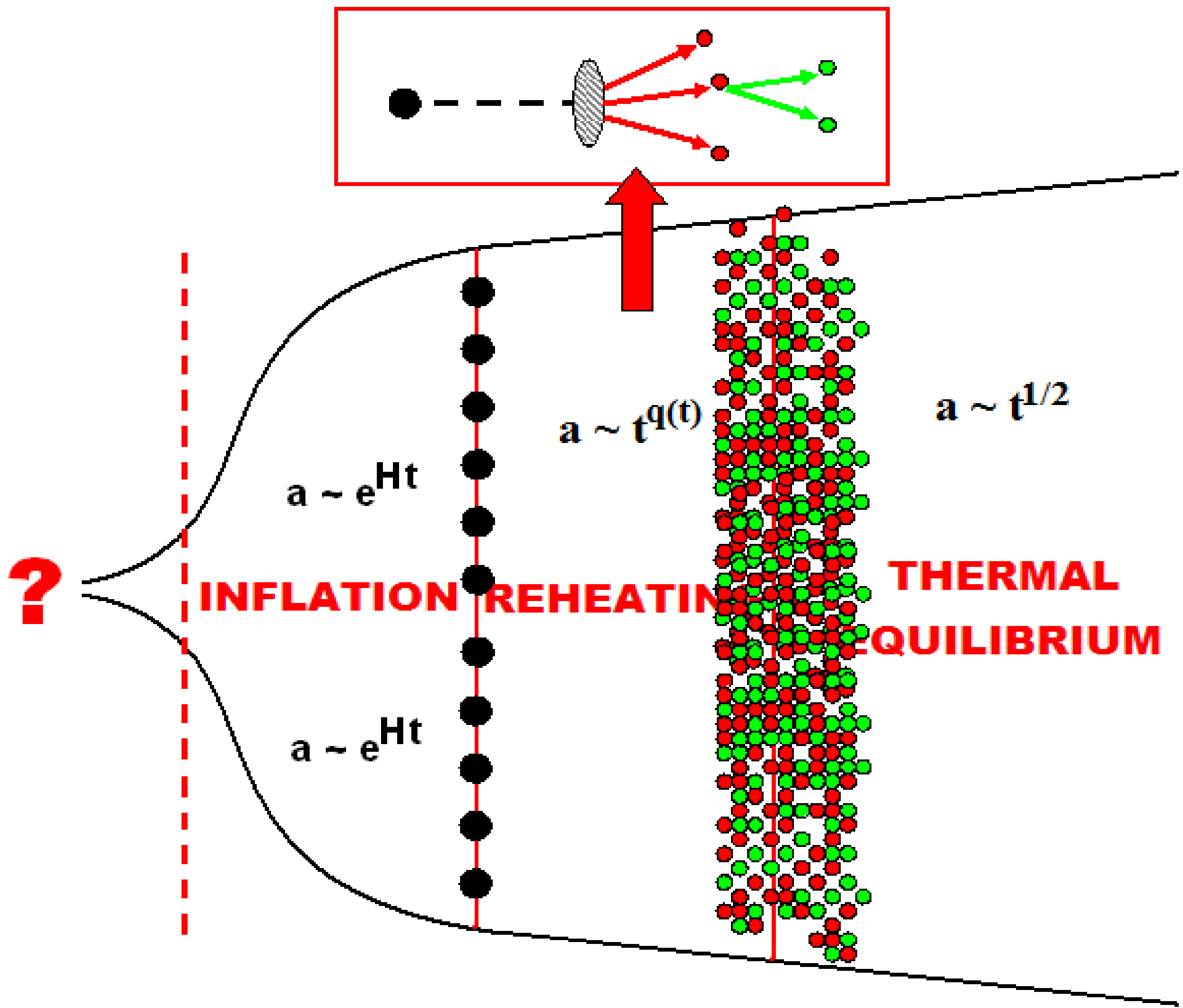
... **others ...**

Enhanced GWs

Reheating = $\left(\begin{array}{c}\text{Matching inflation}\\ \text{with Thermal Era}\end{array}\right)$ ⇨ New GW production

GWs from (p)Reheating

INFLATION $\longrightarrow$ REHEATING $\longrightarrow$ BIG BANG THEORY

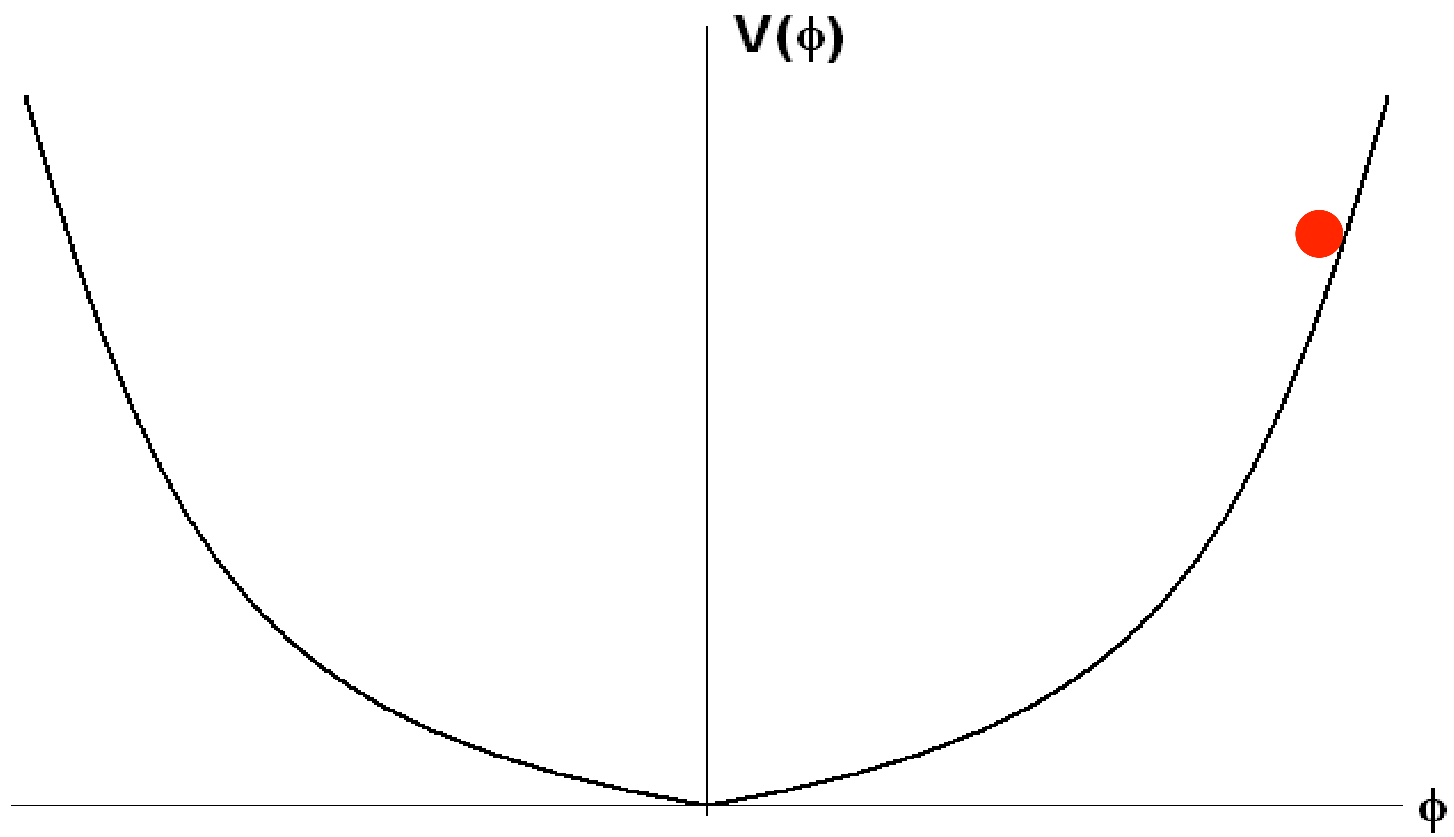


SCALAR (P)REHEATING

1) Chaotic Scenarios: PARAMETRIC RESONANCE

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

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



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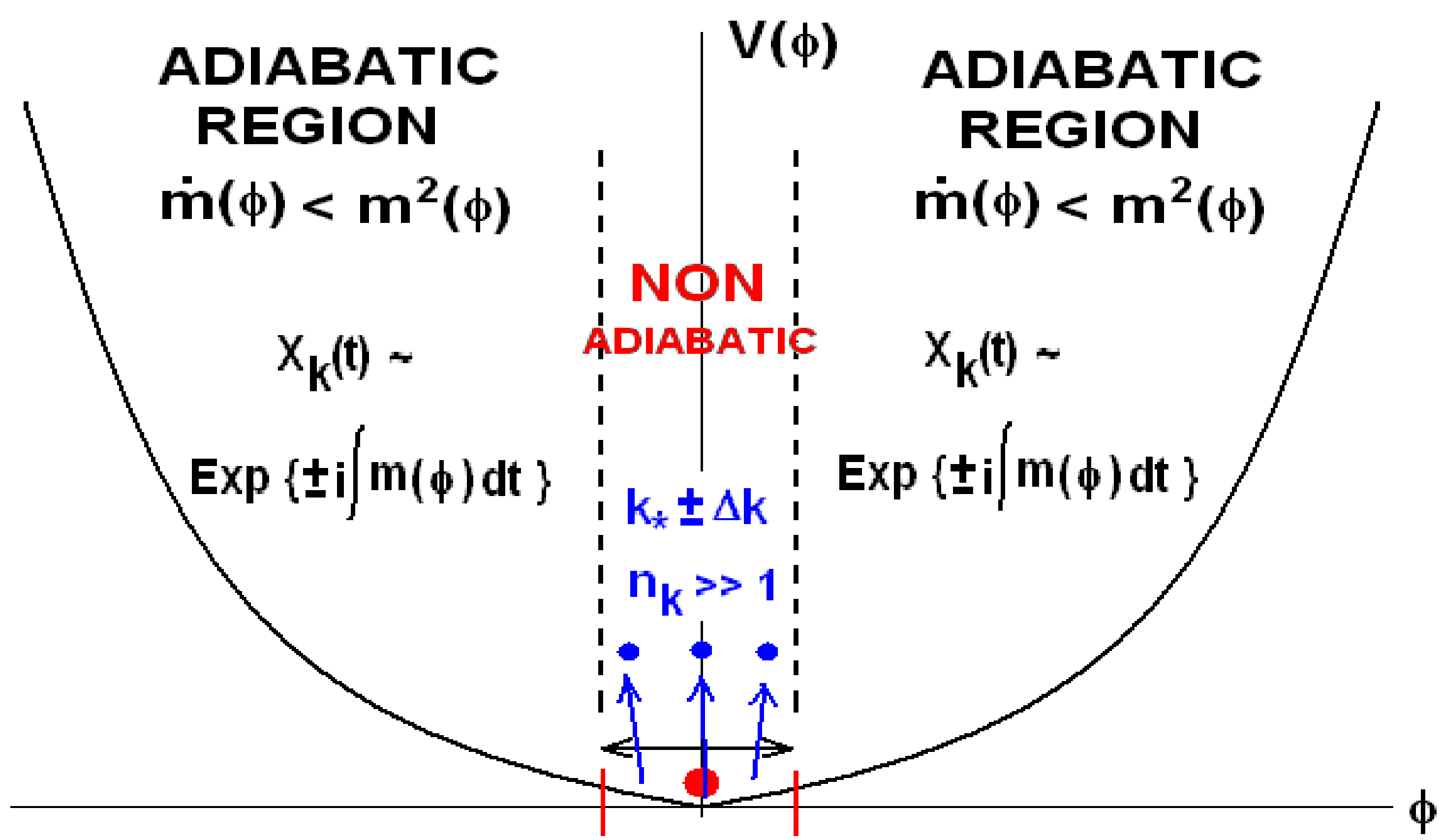

SCALAR (P)REHEATING

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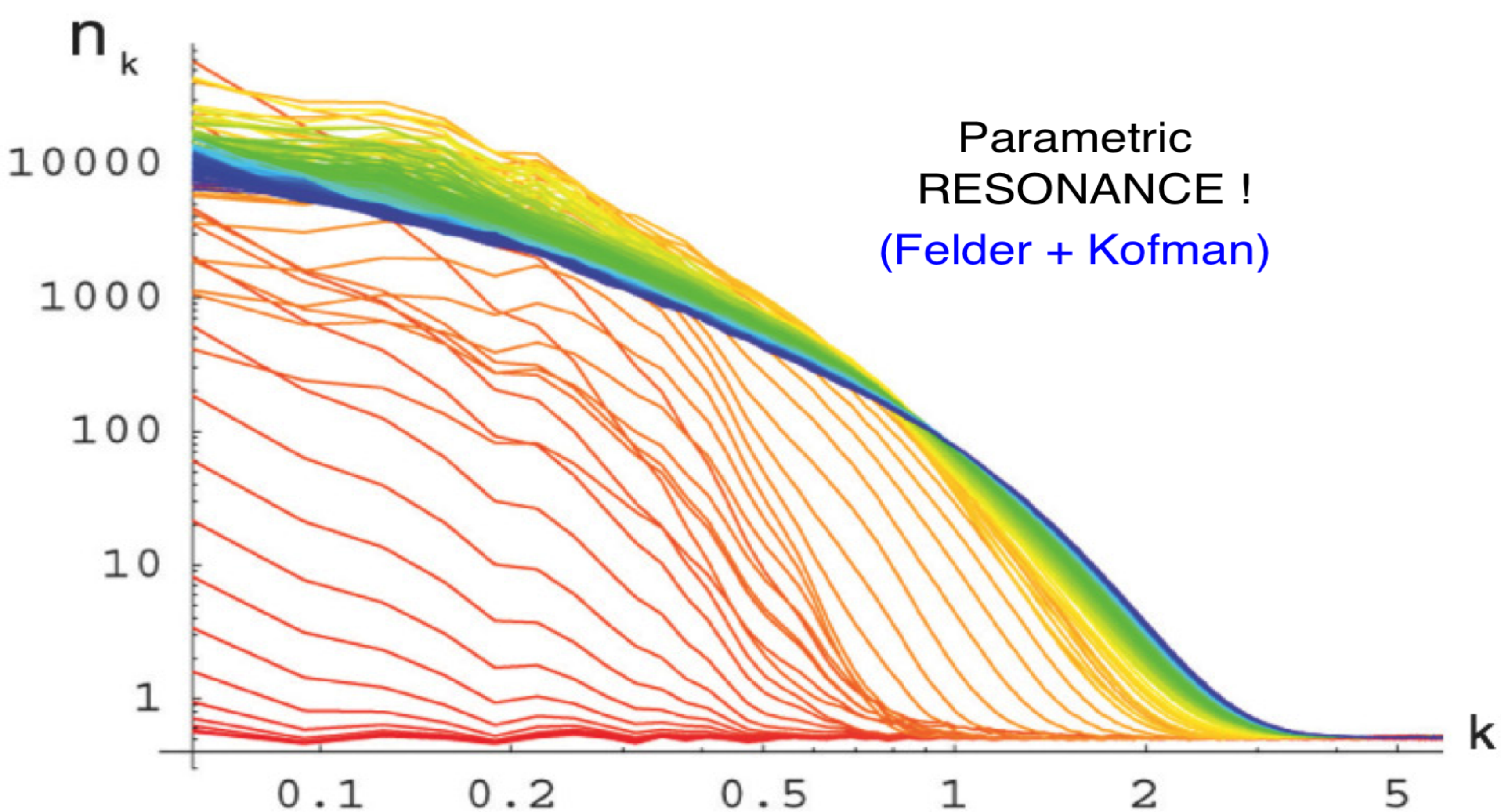


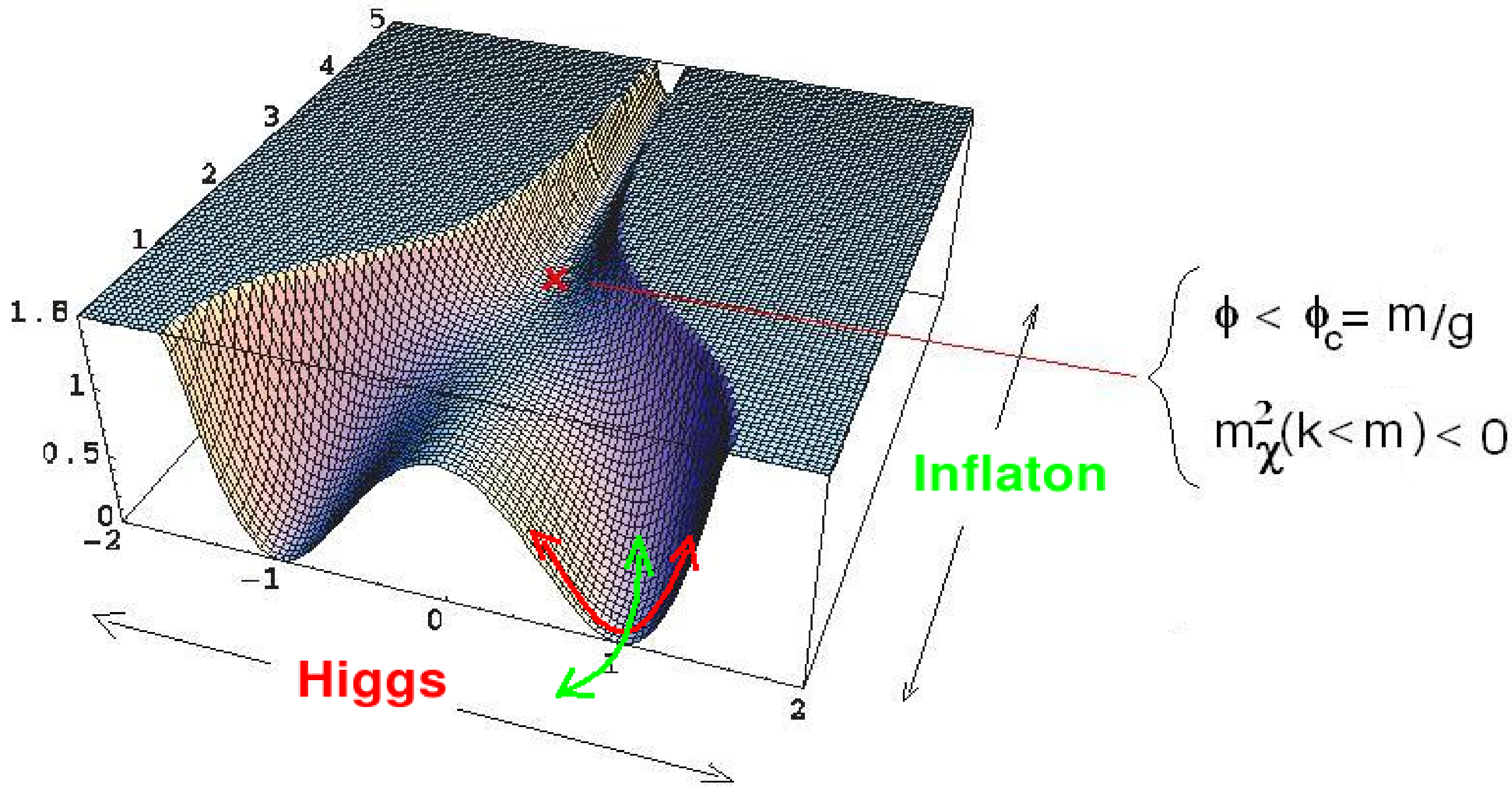
SCALAR (P)REHEATING

2) Hybrid Scenarios : SPINODAL INSTABILITY

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

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

Hybrid Preheating



INFLATIONARY PREHEATING

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

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

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

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

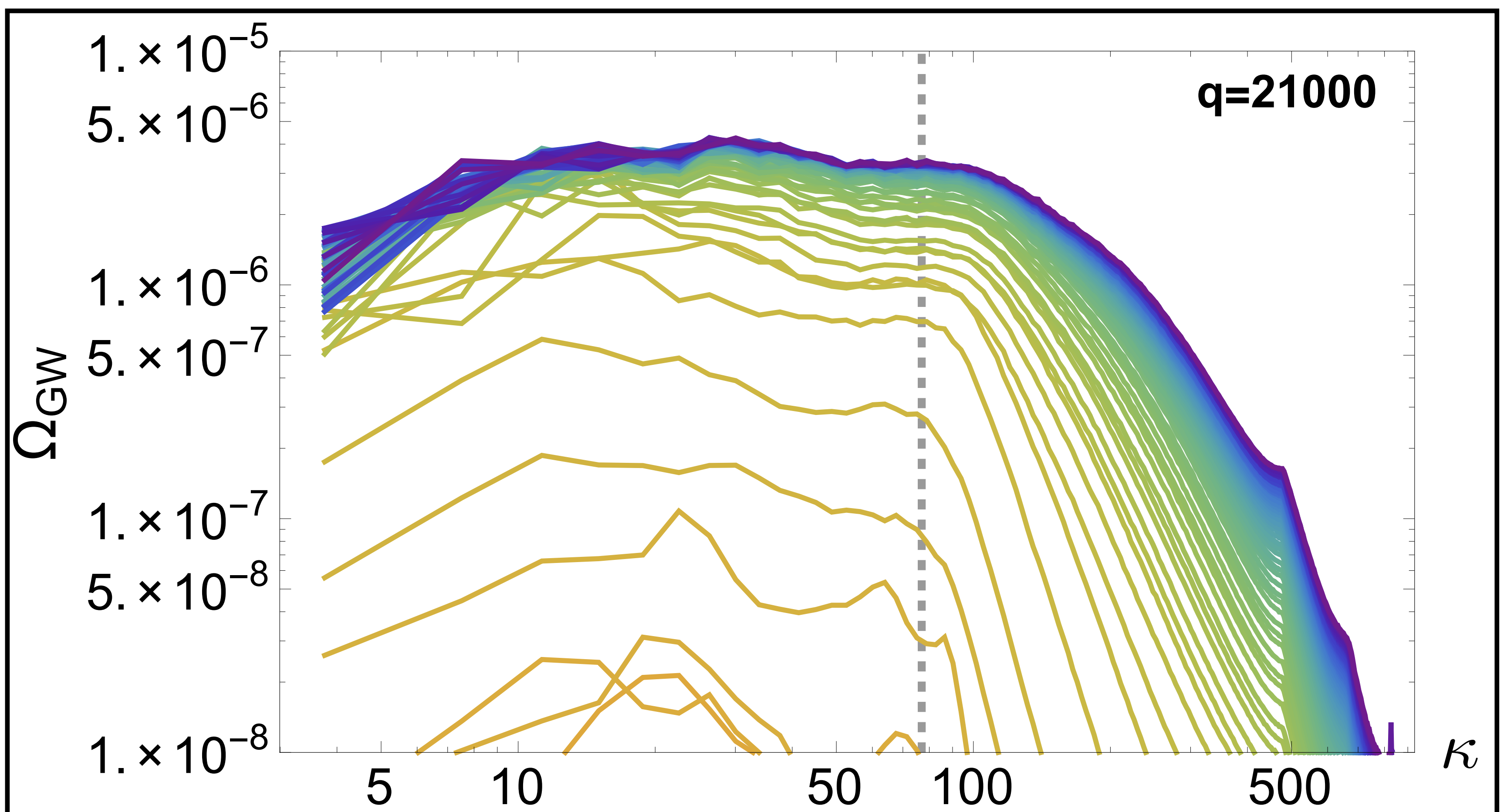
Parameter Dependence (Peak amplitude)

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

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 2017)

INFLATIONARY PREHEATING

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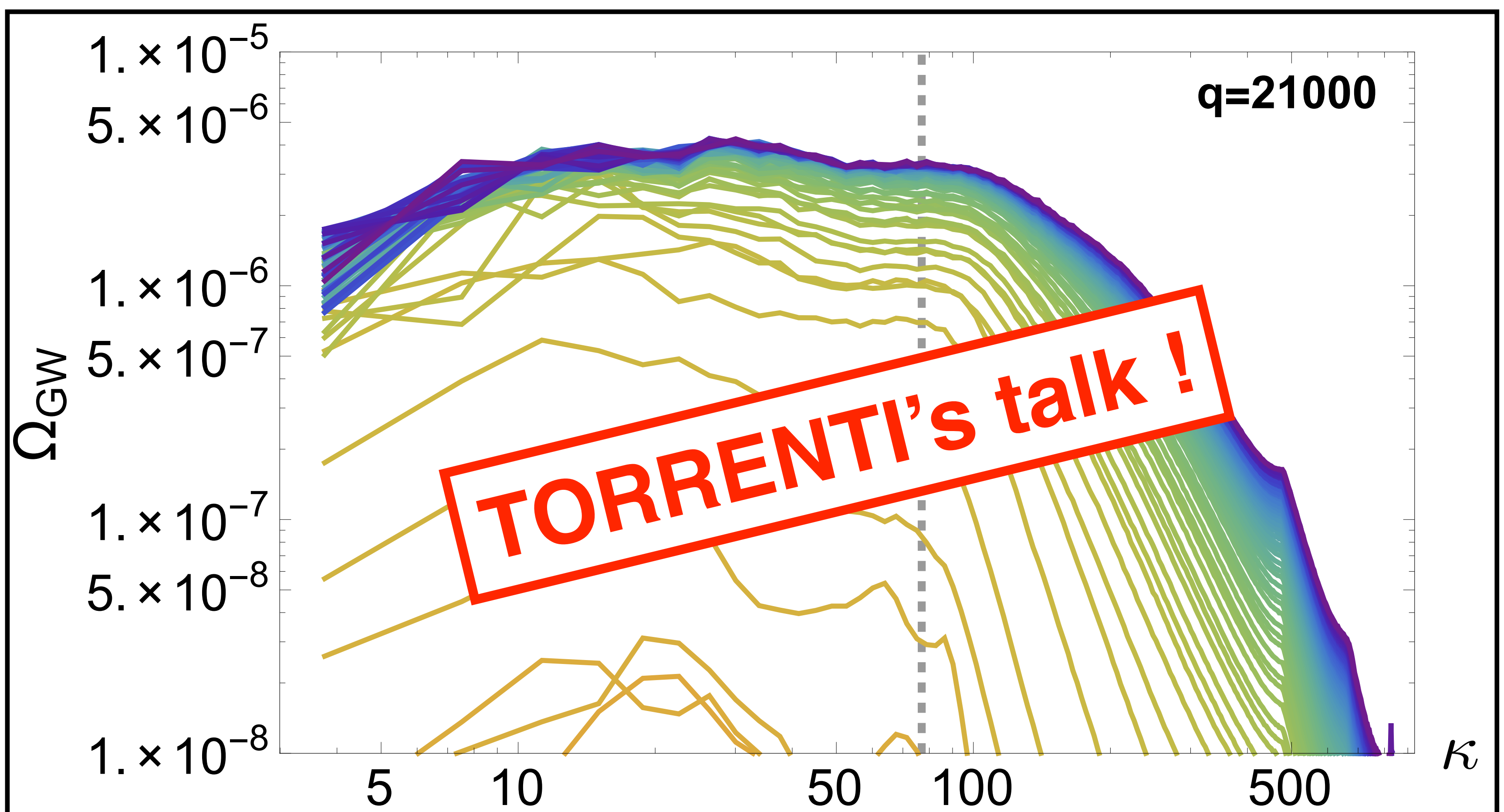

(DGF, Torrentí 2017)

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 ! **... but at high Frequency !**

INFLATIONARY PREHEATING

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

Preheating is a natural source of HF-GW !

Simply because of the small Horizon @ high energy scales

INFLATIONARY PREHEATING

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Preheating is a natural source of HF-GW !

What sensitivity can we aim at high frequency detectors ?

What physics can we probe ?

INFLATIONARY PREHEATING

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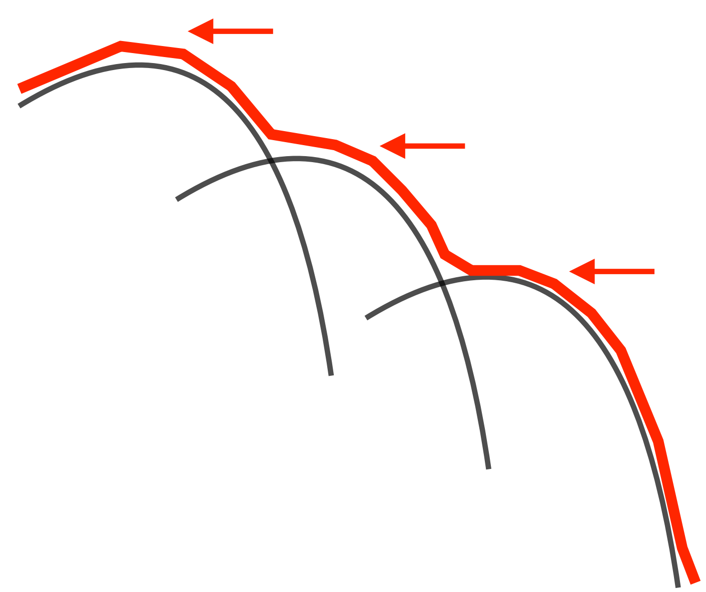
Chaotic Models: $\Omega_{\rm GW}^{(o)} \sim 10^{-11}\,, \quad @ \quad f_o \sim 10^8 - 10^9~{\rm Hz}$

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

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



different couplings
... different peaks !

INFLATIONARY PREHEATING

Parameter Dependence (Peak amplitude**)**

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

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

INFLATIONARY PREHEATING

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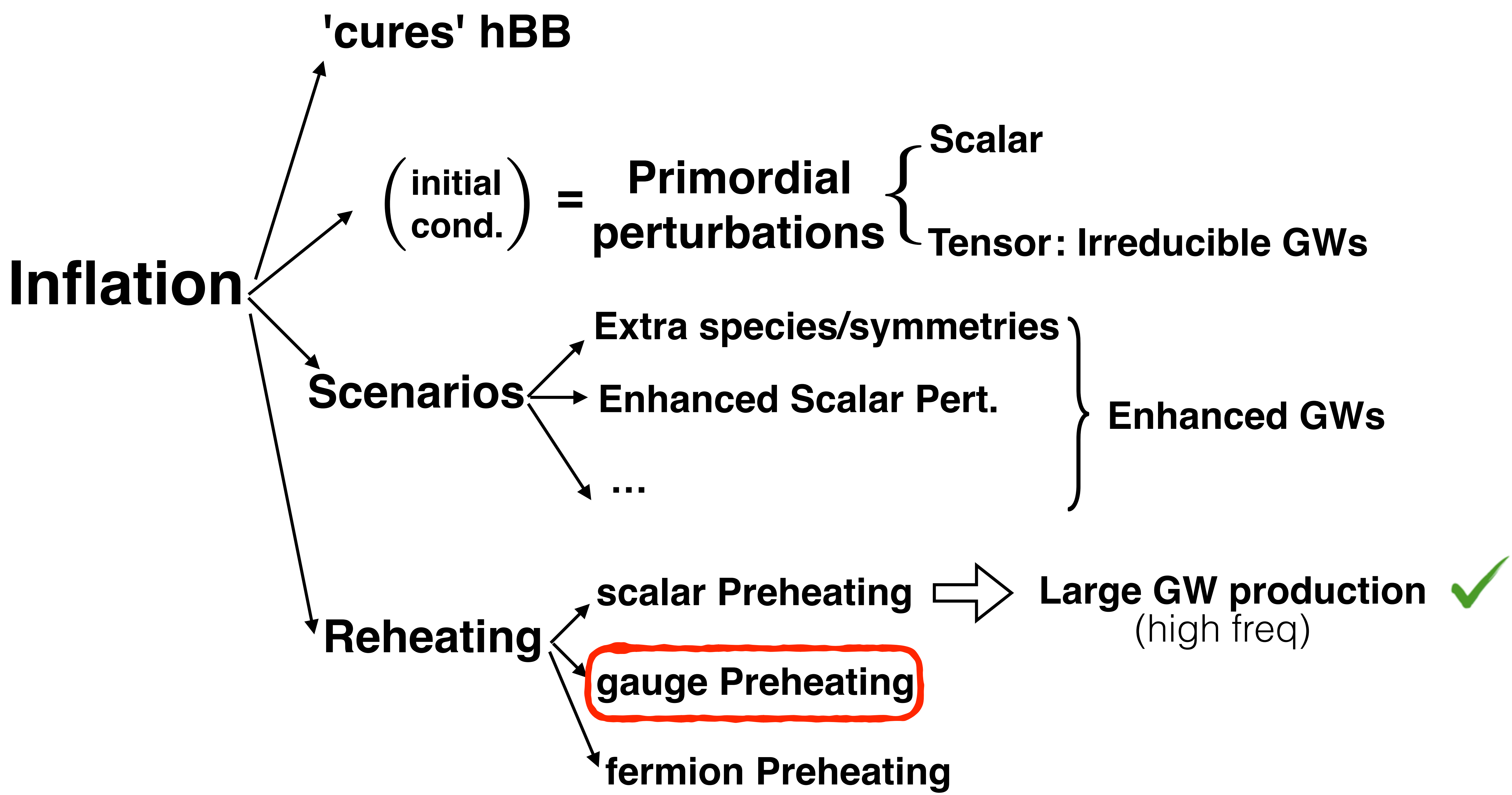
Large amplitude !

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

Naturally a source of HF-GW !

INFLATIONARY COSMOLOGY



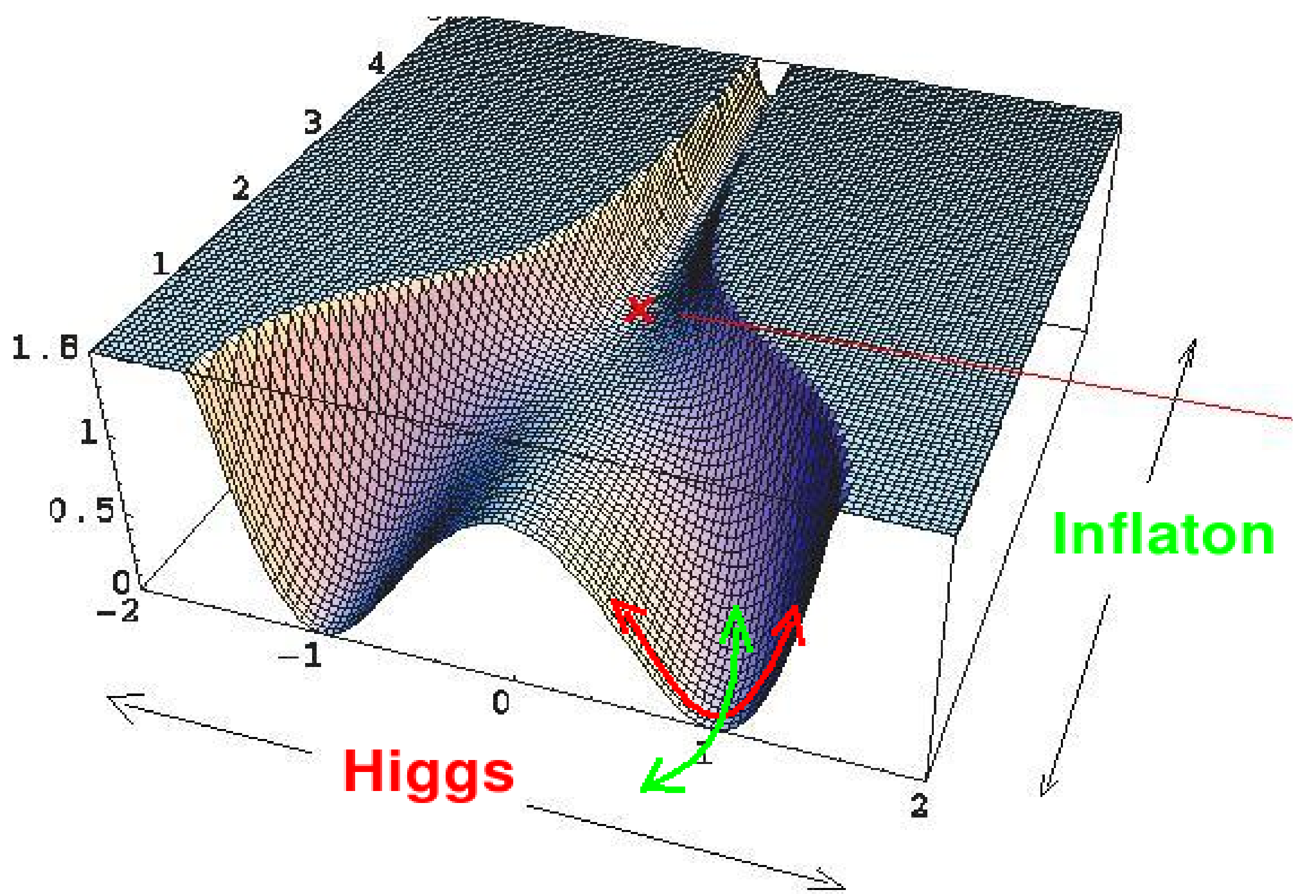
GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

$$L = -\frac{1}{4}F^a_{\mu\nu}F_a^{\mu\nu} + Tr[(D_\mu\Phi)^+ D^\mu\Phi] + \frac{1}{2}(\partial_\mu\chi)^2 - V(\Phi,\chi)$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \qquad D_\mu = \partial_\mu - ieA_\mu$$

$$V(\phi,\chi) = \frac{\lambda}{4}(\phi^2 - v^2)^2 + \frac{g^2}{2}\phi^2\chi^2 + \frac{1}{2}m^2\chi^2$$



… but now there are gauge field(s) !

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

$$L = -\frac{1}{4} F^a_{\mu\nu} F_a^{\mu\nu} + Tr[(D_\mu \Phi)^+ D^\mu \Phi] + \frac{1}{2}(\partial_\mu \chi)^2 - V(\Phi, \chi)$$

EOM: { Minkowski, Temporal Gauge ($A_0 = 0$)

$$\begin{aligned} \ddot{\varphi} - D_i D_i \varphi + V_{,\varphi^*} &= 0 && \rightarrow \text{SCALARS eom} \\ \ddot{A}_i - \partial_j \partial_j A_i + \partial_i \partial_j A_j &= 2e^2\, \mathrm{Im}\,[\varphi^*\, D_i \varphi] && \rightarrow \text{VECTORS eom} \\ \partial_i \dot{A}_i &= 2e^2\, \mathrm{Im}\,[\varphi^*\, \dot{\varphi}]\ . && \rightarrow \text{GAUSS law} \end{aligned}$$

GW EOM

$$\ddot{h}_{ij} - \partial_k \partial_k h_{ij} = 16\pi G\, \Pi^{\mathrm{TT}}_{ij}$$

$$\Pi^{\mathrm{TT}}_{ij} = \left[\partial_i \chi \partial_j \chi + 2\,\mathrm{Re}\left[D_i \varphi\, (D_j \varphi)^*\right] - B_i B_j - E_i E_j\right]^{\mathrm{TT}}$$

COVARIANT

MAGNETIC

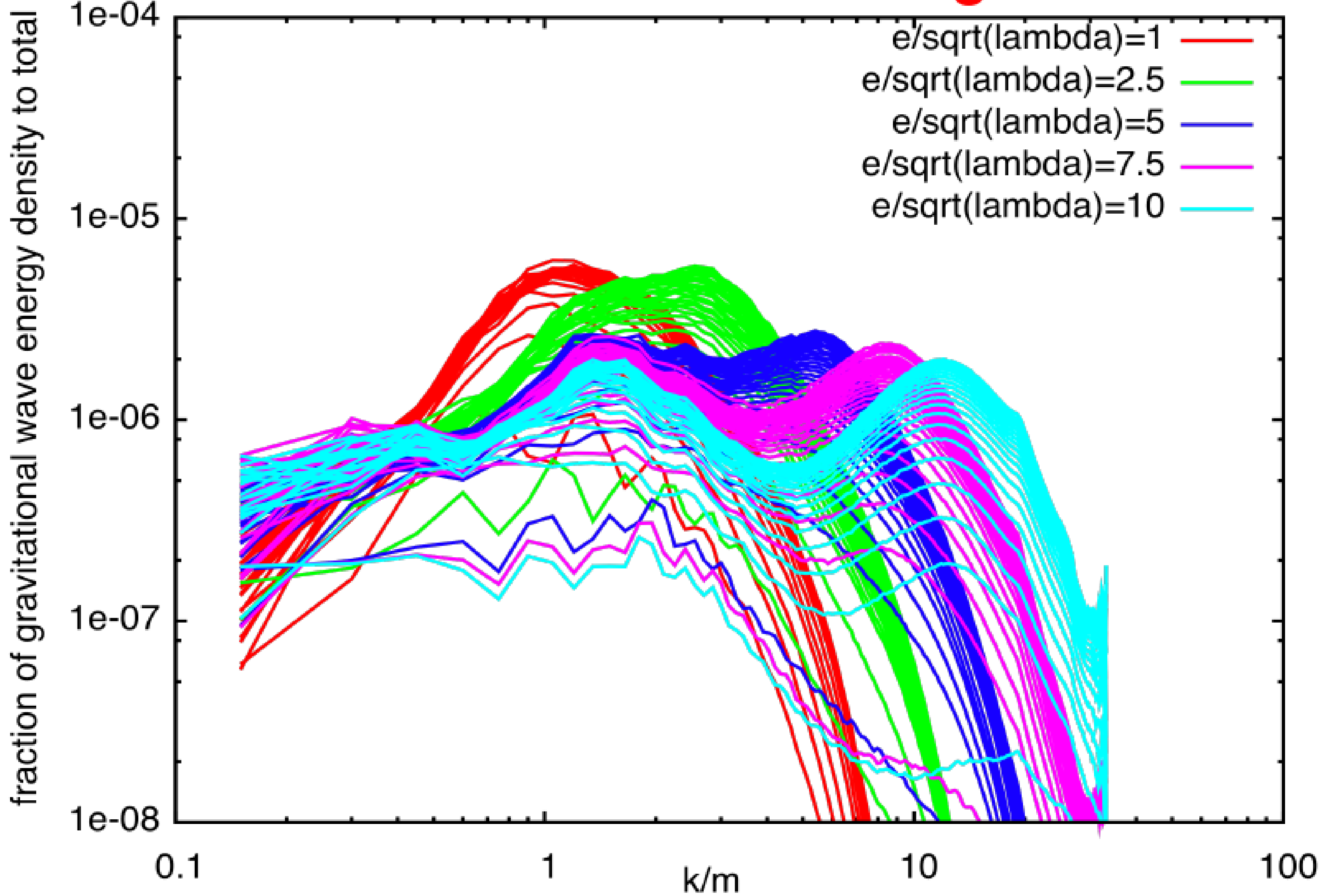
ELECTRIC

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

GRAVITATIONAL WAVES SPECTRA:

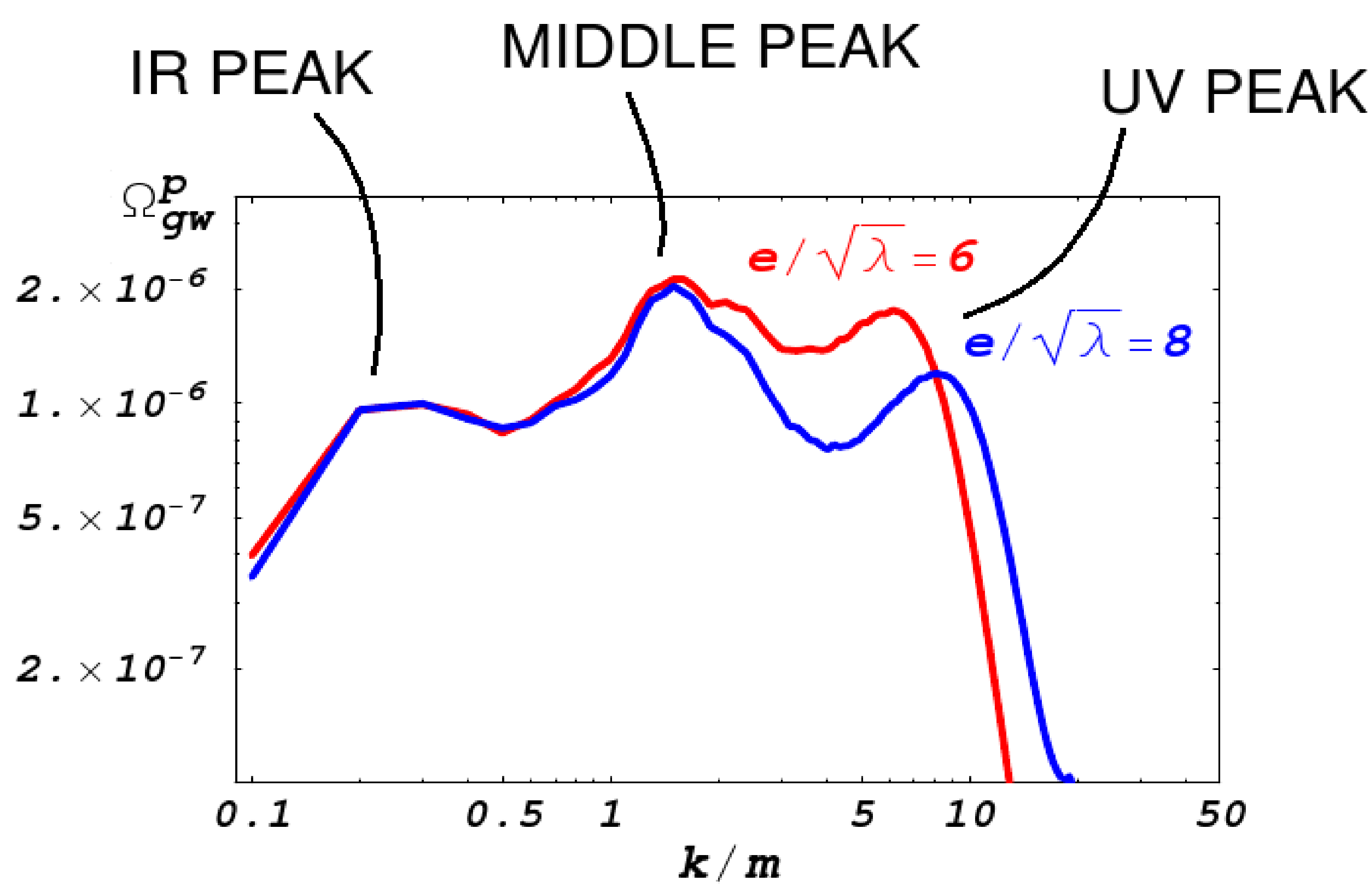
Evolution of GW background



GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

GRAVITATIONAL WAVES SPECTRA:



INFLATIONARY COSMOLOGY

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

INFLATIONARY COSMOLOGY

'cures' hBB

Inflation

(initial cond.) = Primordial perturbations
- Scalar
- Tensor : Irreducible GWs

Scenarios
- Extra species/symmetries
- Enhanced Scalar Pert.
- ...

Enhanced GWs

Reheating
- scalar Preheating ⇨ Large GW, peaks (high freq) ✓
- gauge Preh 1006.0217, 1706.02365 s (high freq) ✓
- fermion Preh 1203.4943, 1306.6911 ks (high freq)

Gravitational Waves as a probe of the early Universe

OUTLINE

0) GW definition ✓

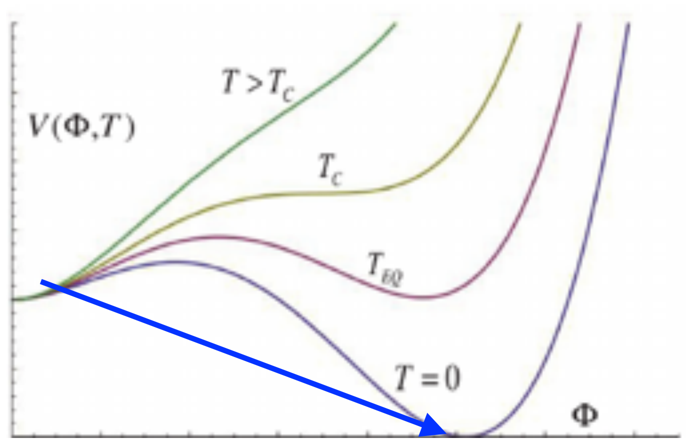
Early Universe

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

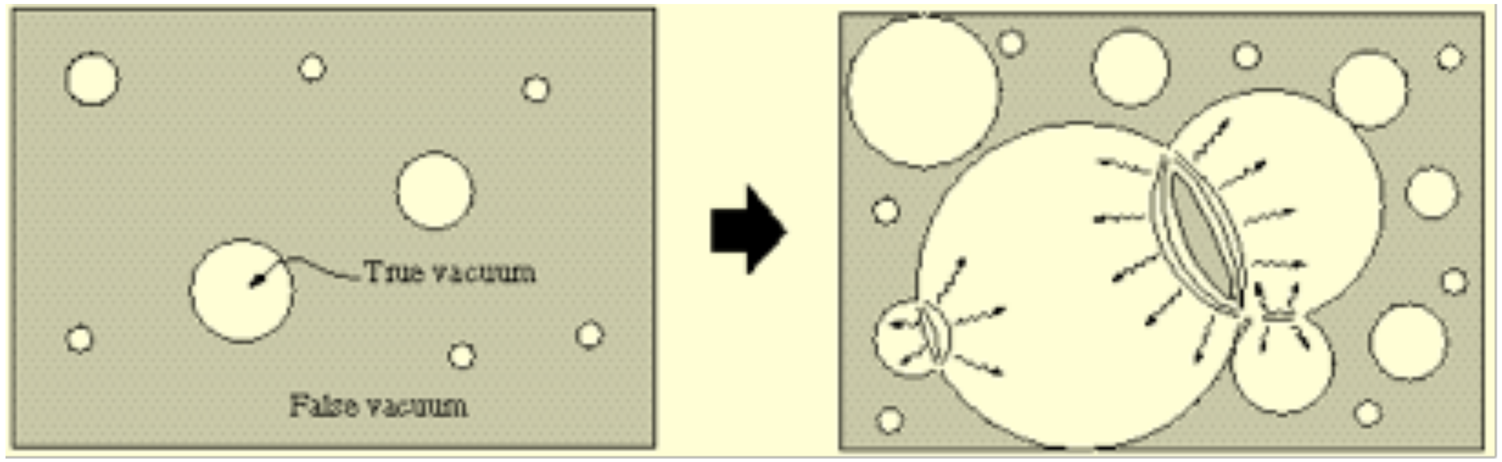
First order phase transitions

Universe expands, T decreases: **phase transition triggered !**

true and **false** vacua



bubble nucleation



source: Π_{ij}
anisotropic stress

$$\Pi_{ij} \sim \partial_i \phi \, \partial_j \phi$$ (Bubble wall collisions)

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

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

What is the freq. 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

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

β^{-1} : duration of PhT

$v_b \leq 1$: speed of bubble walls

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

Parameters determining the GW spectrum

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

$$\downarrow$$

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

Parameter List
(not independent)

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

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

$$\Rightarrow \quad \boxed{\alpha = \frac{\rho_{\mathrm{vac}}}{\rho_{\mathrm{rad}}^*} \qquad \kappa = \frac{\rho_{\mathrm{kin}}}{\rho_{\mathrm{vac}}}}$$

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

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

Parameter List
(not independent)

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

$$\Omega_{GW} \ldots \left(\ldots \rho^*_{tot} \right)$$

not most general !

See HINDMARSH talk !

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

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

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

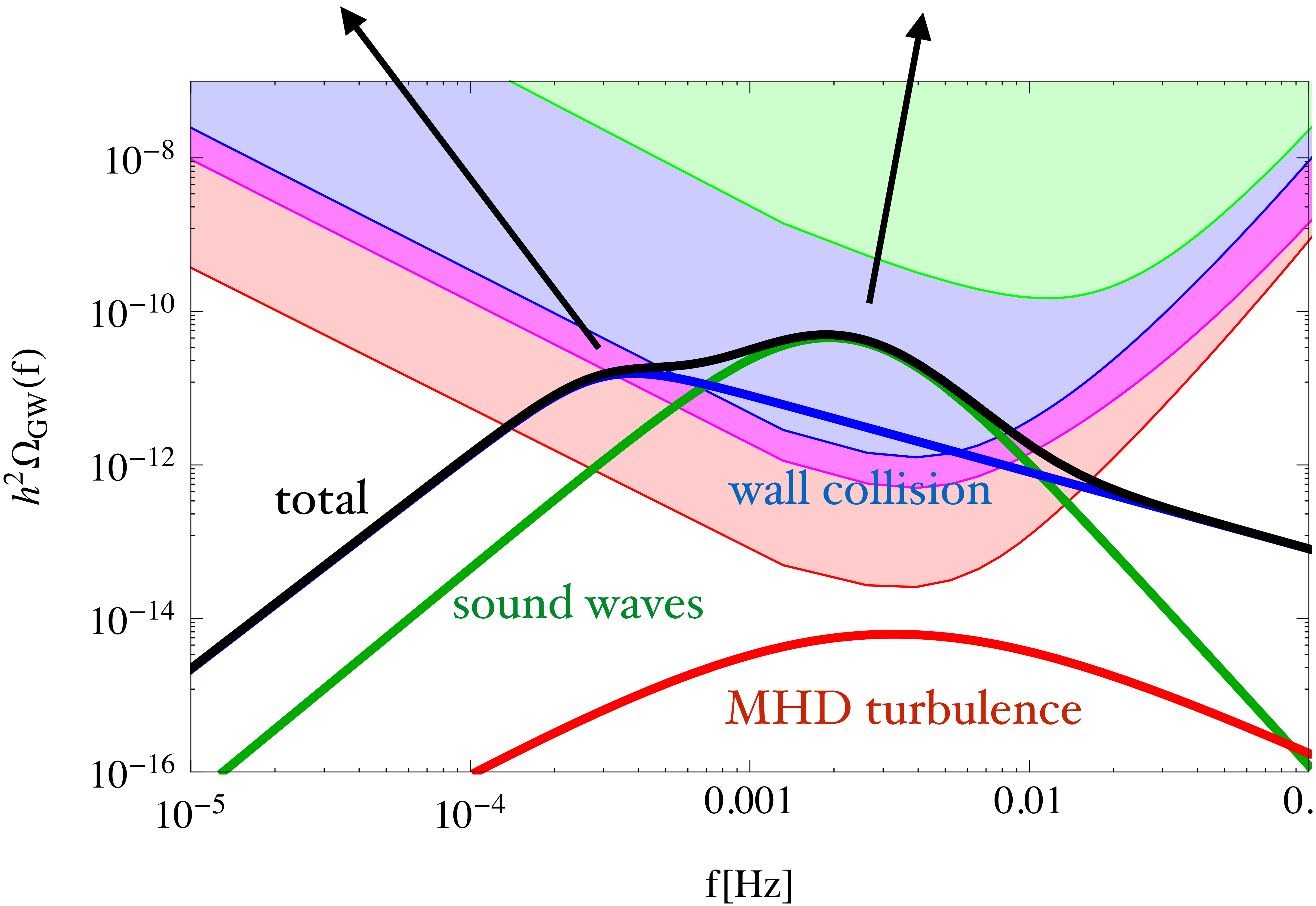
  Kosowsky et al ’07, Caprini et al ’09, Niksa et al '18

  numerical Pol et al 2019

Example of spectrum

peak of bubble collisions

peak of fluid-related processes



Caprini et al, arXiv:1512.06239

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- so... ...cal simulations of scalar field and fluid
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- M...
  ..., Niksa et al '18
  ... Pol et al 2019

Connection Particle Physics & Cosmology !

GW: new probe of BSM (complementary to colliders)

Evaluation of the signal

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

GW: new probe of BSM (complementary to colliders)

Evaluation of the signal

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- **M**...
  ...al 18
  ...Pol et al 201...

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

MHz-GHz-THz, very good range for High-Energy phase transitions

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

Evaluation of the signal

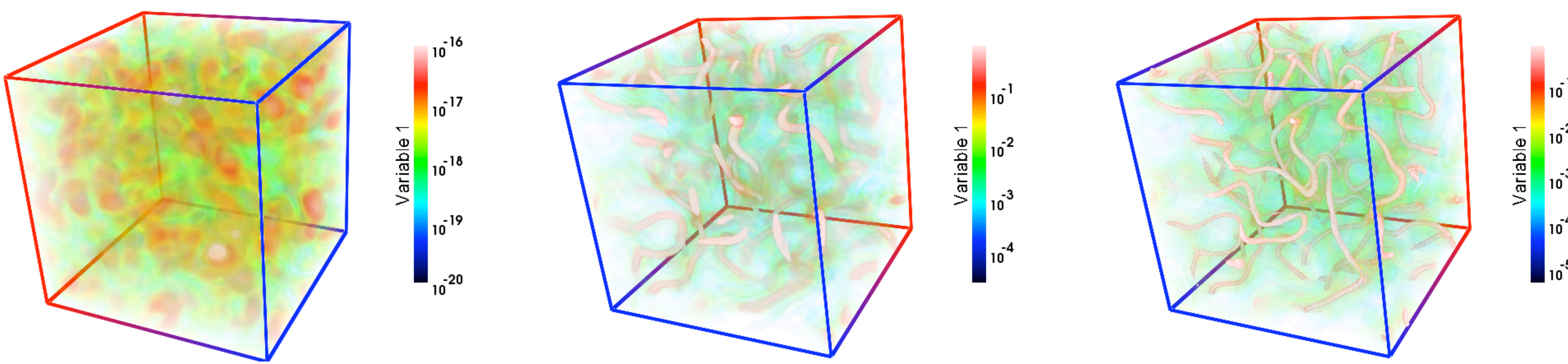
- **bubble collisions**: anal... ions
  ..., ...
- **so**... field and fluid
  H...
  a...
- **M**...
  ...9, Niksa et al '18
  ... Pol et al 2019

Connection Particle
Physics & Cosmology !

See
HINDMARSH talk
for details !

GW: new probe of BSM
(complementary to colliders)

What about
Cosmic Defects ?
(aftermath products of a PhT)

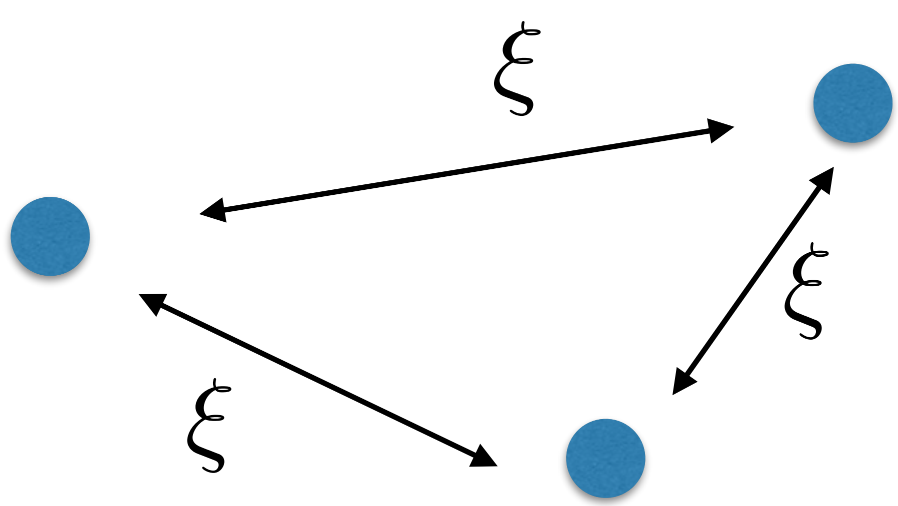


U(1) Breaking (after Hybrid Inflation): Mag. Fields *Dufaux et al, 2010*

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



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

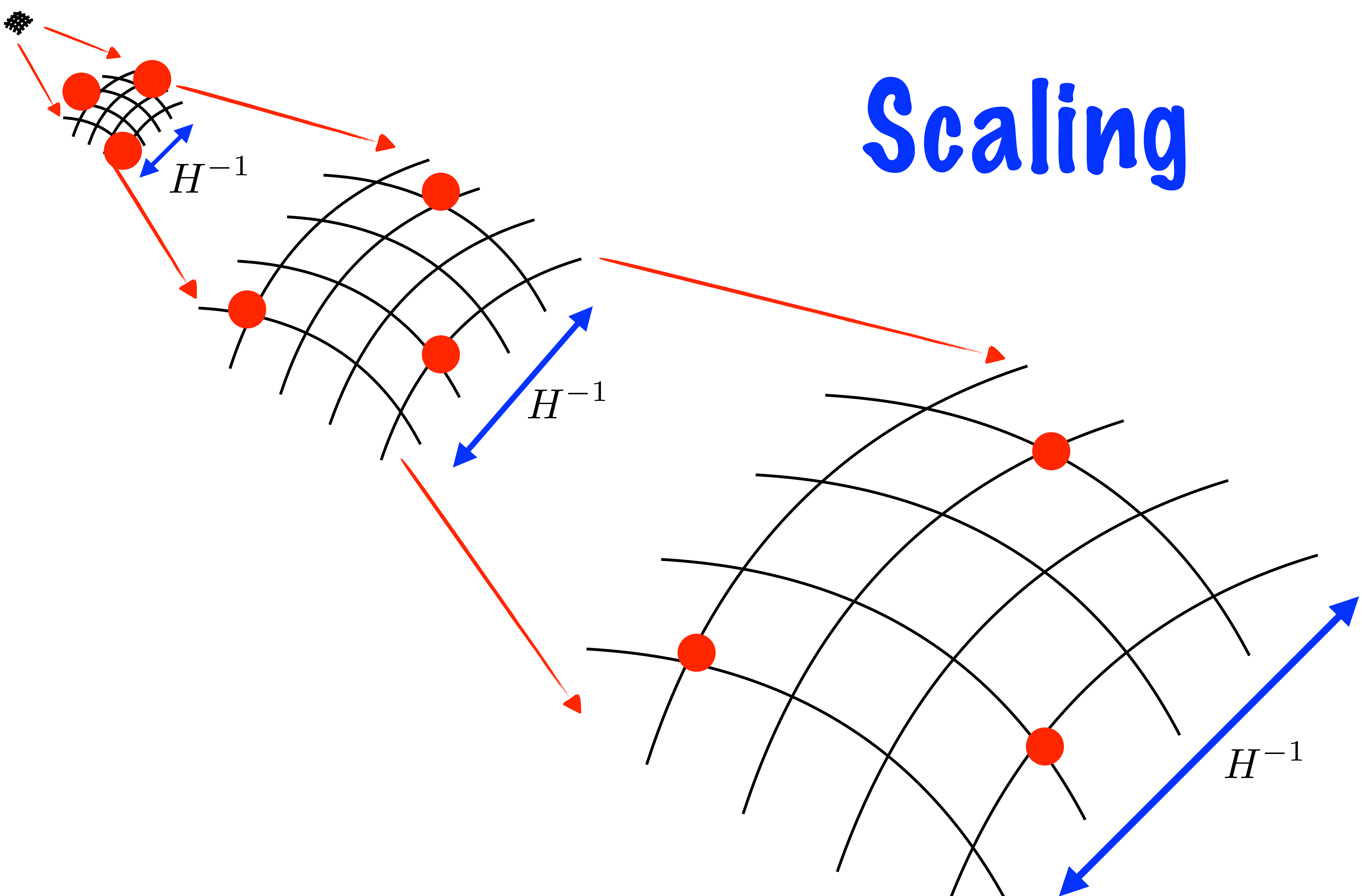
(Kibble' 76)

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

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

Comoving **Conformal**

GWs from a scaling network of cosmic defects

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

SCALING

UTC: $\langle T^{\rm TT}_{ij}(\mathbf{k},t)T^{\rm TT}_{ij}(\mathbf{k}',t')\rangle = (2\pi)^3\,\frac{{\rm V}^4}{\sqrt{tt'}}\,U(kt,kt')\delta^3(\mathbf{k}-\mathbf{k}')$

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SCALING

Comoving **Conformal**

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Rad. Dom **SCALING**

Comoving **Conformal**

GWs from a scaling network of cosmic defects

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

SCALING

UTC: $\langle T^{\rm TT}_{ij}(\mathbf{k},t)T^{\rm TT}_{ij}(\mathbf{k}',t')\rangle = (2\pi)^3\,\frac{{\rm V}^4}{\sqrt{tt'}}\,U(kt,kt')\delta^3(\mathbf{k}-\mathbf{k}')$

GW spectrum: $\boxed{(x_i \equiv kt_i)}$ Expansion UTC

$$\frac{d\rho_{\rm GW}}{d\log k}(k,t) \propto \left(\frac{\rm V}{M_p}\right)^4 \frac{M_p^2}{a^4(t)}\left[\int dx_1dx_2\,\sqrt{x_1x_2}\,\cos(x_1-x_2)\,U(x_1,x_2)\right]$$

Rad. Dom **SCALING**

$F_U \sim$ Const. (Dimensionless)

GWs from a scaling network of cosmic defects

VEV

Scaling @ RD

GW today:

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

Defect type

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

$\forall$ PhT (1st, 2nd, ...), $\forall$ Defects (top. or non-top.)

DGF, Hindmarsh, Urrestilla, 2013

GWs from a scaling network of cosmic defects

energy scale

constants

Total GW Spectrum

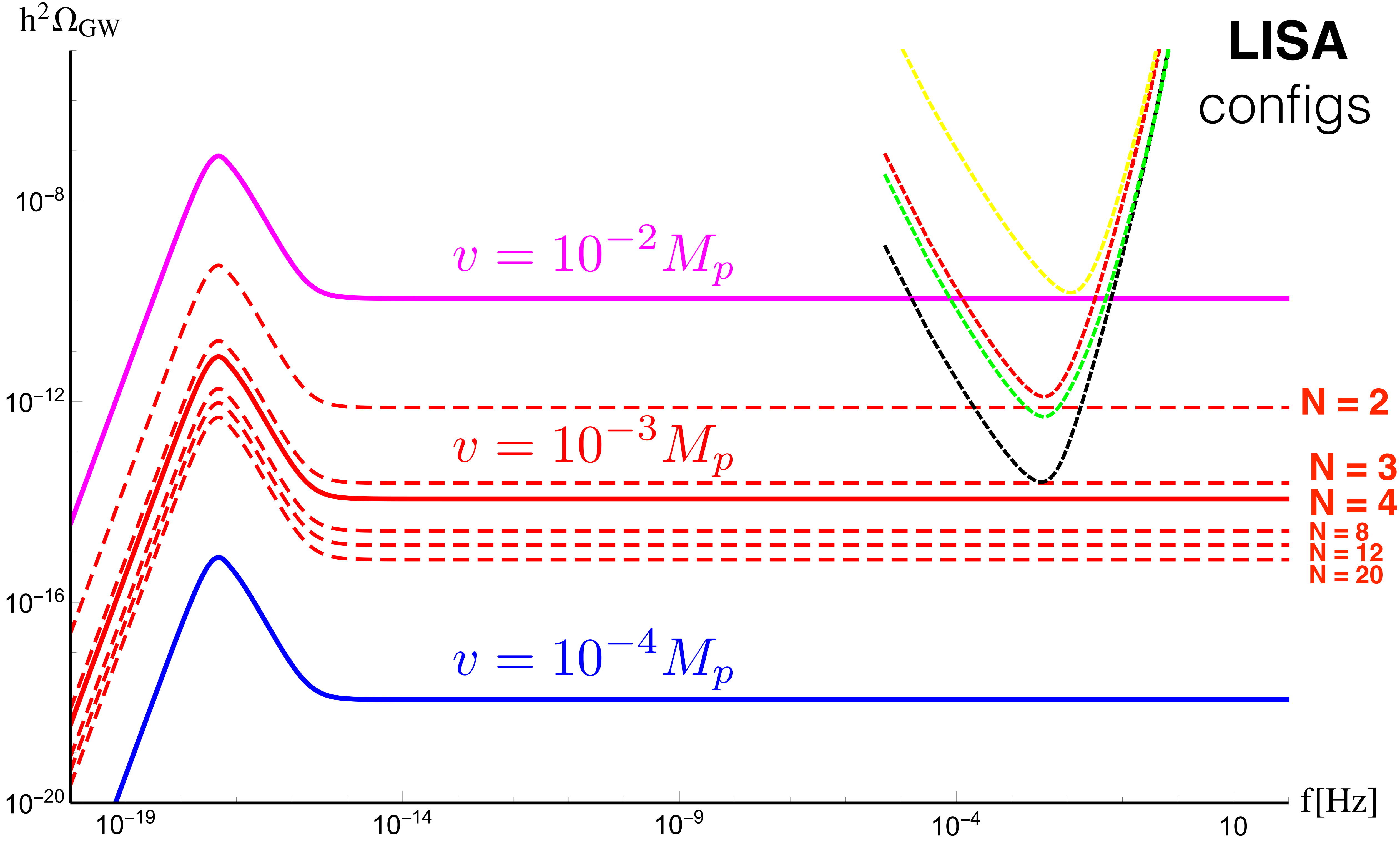
$$\boxed{h^2\Omega_{\rm GW}^{(\rm o)} = h^2\Omega_{\rm rad}^{(\rm o)}\left(\frac{V}{M_p}\right)^4\left[F_U^{(\rm R)} + F_U^{(\rm M)}\left(\frac{k_{\rm eq}}{k}\right)^2\right]}$$

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

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



What if Defects are Cosmic Strings ?

Intercommutation

Loops are formed !

What if Defects are Cosmic Strings ?

Loops are formed !

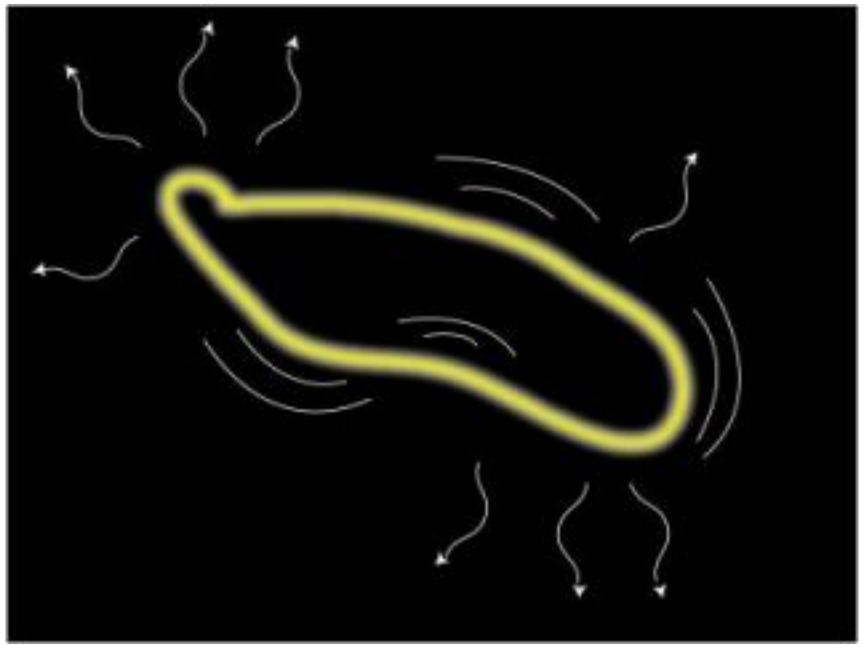


Image Credit: Google

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

Emission of a GW background ! **(Vilenkin '81)**
and many others !

Cosmic Strings Network: Loop configurations

Cosmic string loop (length l) oscillates under tension μ

➡ emits GWs in a series of harmonic modes

Emission of a GW background ! **(Vilenkin '81)**

and many others !

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

expansion history

length

number density

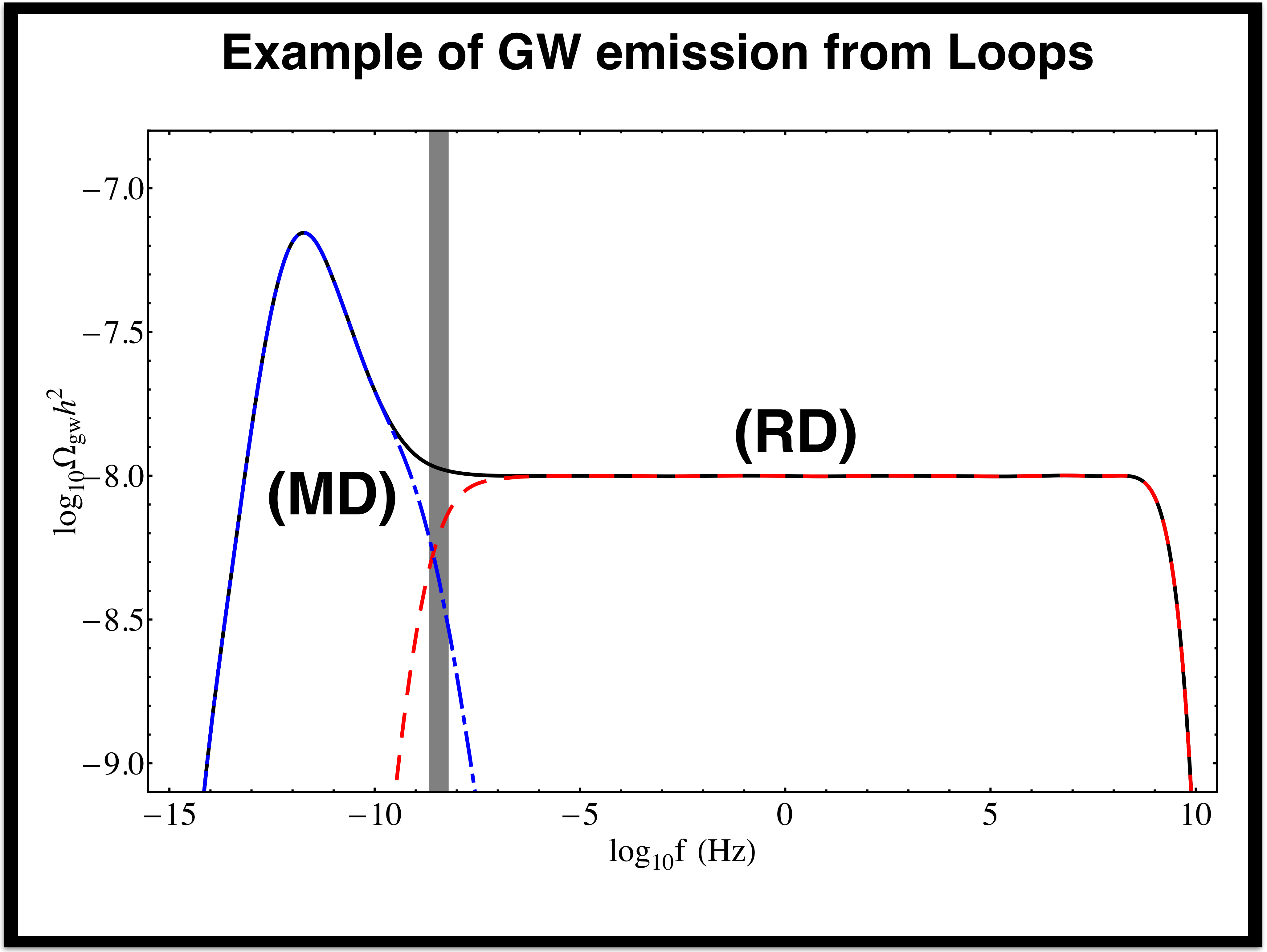
GW power emission

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

features

(kinks,cusps,…)

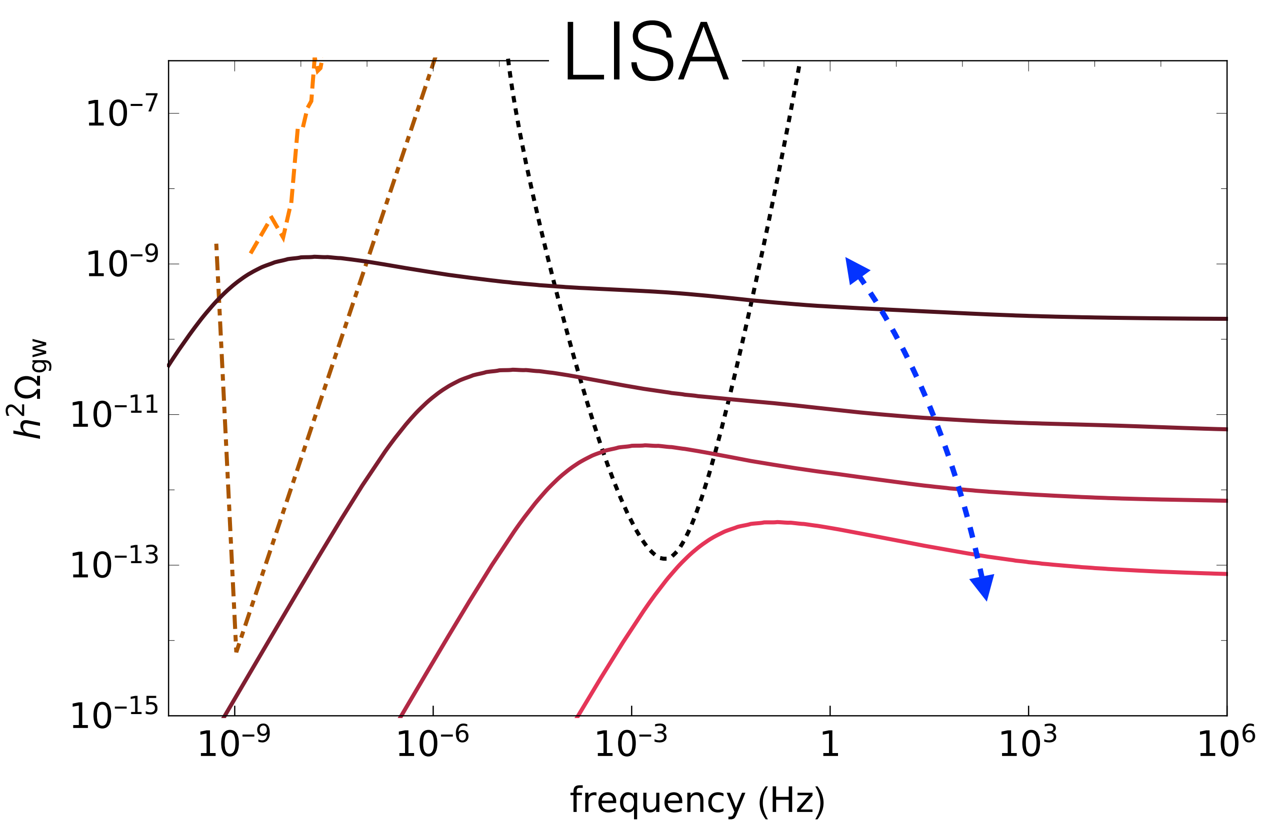
Cosmic strings loops: GW background



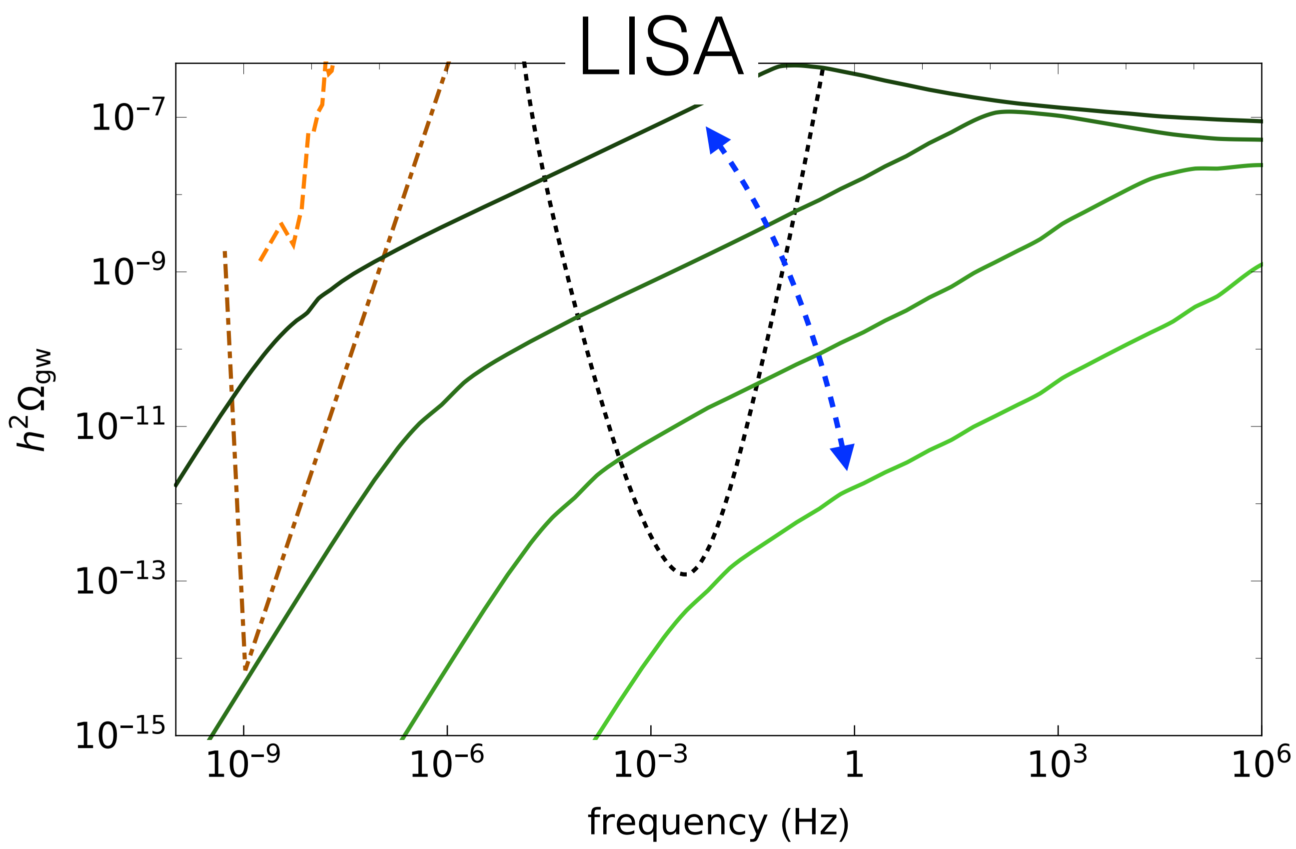
e.g. Sanidas 2012

Cosmic strings loops: GW background

Blanco-Pillado, Olum, Shlaer



Lorenz, Ringeval, Sakellariadou



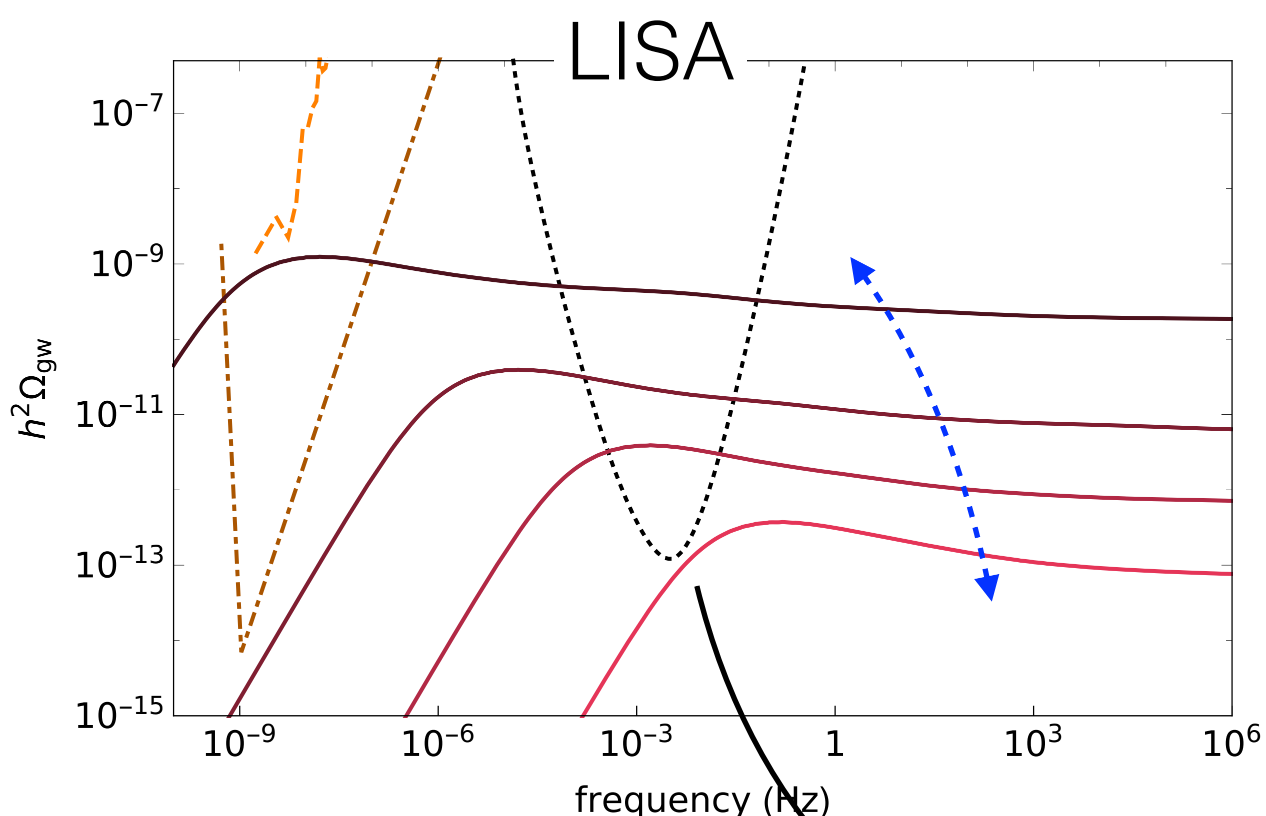
$$G\mu \sim 10^{-11} - 10^{-17}$$

Very large parameter space !

LISA paper 1909.00819

Cosmic strings loops: GW background

Blanco-Pillado, Olum, Shlaer



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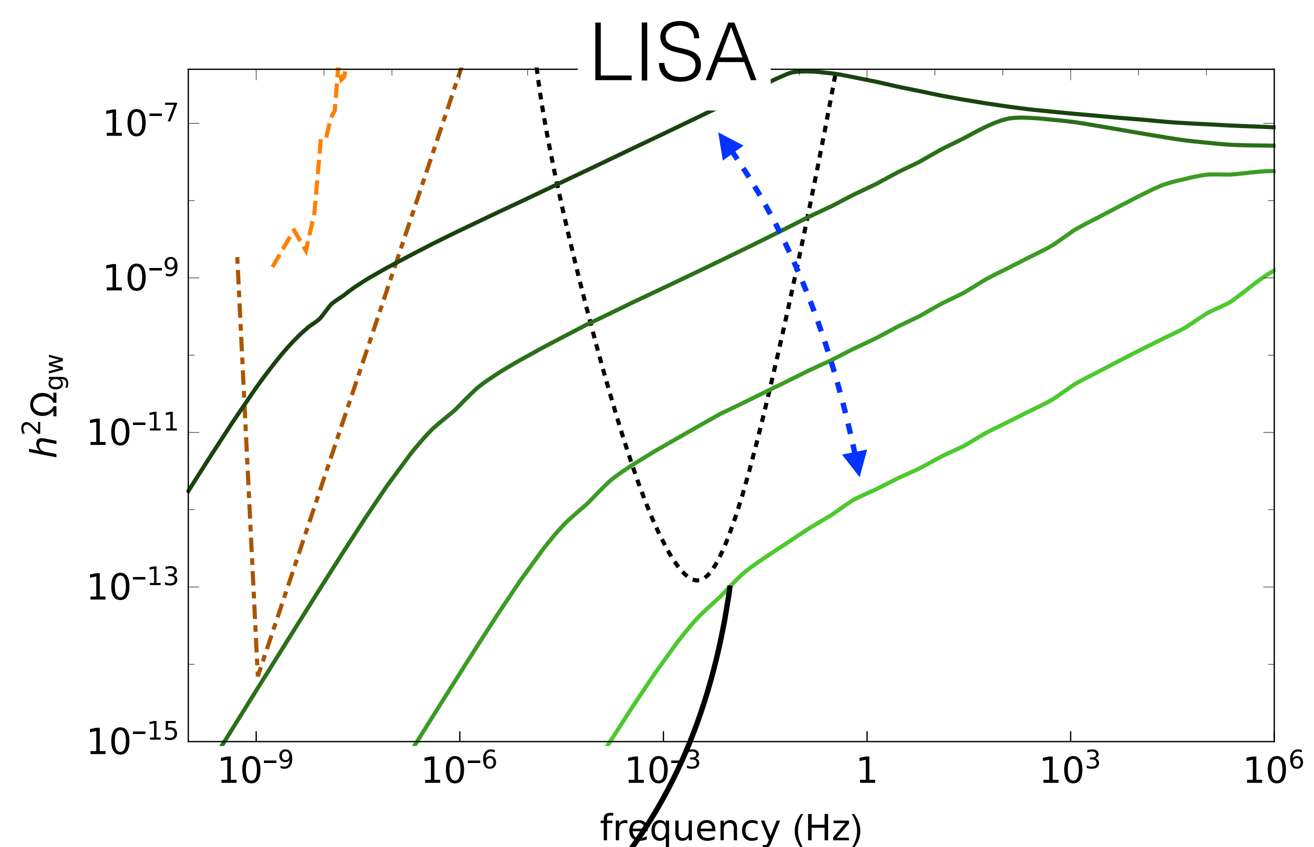

$$\boxed{G\mu \gtrsim 10^{-17}}$$

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 $\left\{ \right.$

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

LISA paper 1909.00819

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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Gravitational Waves as a probe of the early Universe

SUMMARY

0) GW definition

Early Universe

1) GWs from Inflation → Intensive search at the CMB; → Possible Enhancement

2) GWs from Preheating → High amplitude, unlike detection

3) GWs from Phase Transitions → 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]

Sources I did not cover …

* OSCILLONS

* FLAT-DIRECTIONS

* MODIFIED GRAVITY

* SPECTATOR FIELDS ($c_s \ll 1$)

* STIFF ERA

* …..

* YOUR FAVOURITE MODEL

Propaganda, Part I

Review on Cosmological Gravitational Wave Backgrounds

Caprini & Figueroa

arXiv:1801.04268

Propaganda, Part II

Almost Nothing

Première Sept 28th 2018, @ CERN Globe

DISCUSSION

INFLATION

* Wide Freq. Range
* Small Amplitude naturally
* Blue-tilted <—> Special Physics

PREHEATING

Narrow Freq. Range *
Large amplitude @ High Freq *
Very Model Dependent *

$f \sim \frac{1}{\epsilon_*} 10^{-8} (E_*/\mathrm{GeV})\ \mathrm{Hz}$

High Frequency Gravitational Waves

$f \sim \frac{1}{\epsilon_*} 10^{-8} (E_*/\mathrm{GeV})\ \mathrm{Hz}$

* Narrow Freq. Range (~peak)
* Large amplitude IF 1stO PhT
* EWPhT @ LISA / GUT-PhT GHz

PHASE TRANSITIONS

Large Freq. Range *
Large amplitude naturally *
Very Model Dependent *

TOPOLOGICAL DEFECTS

QUESTIONS

Irreducible GW background from Inflation

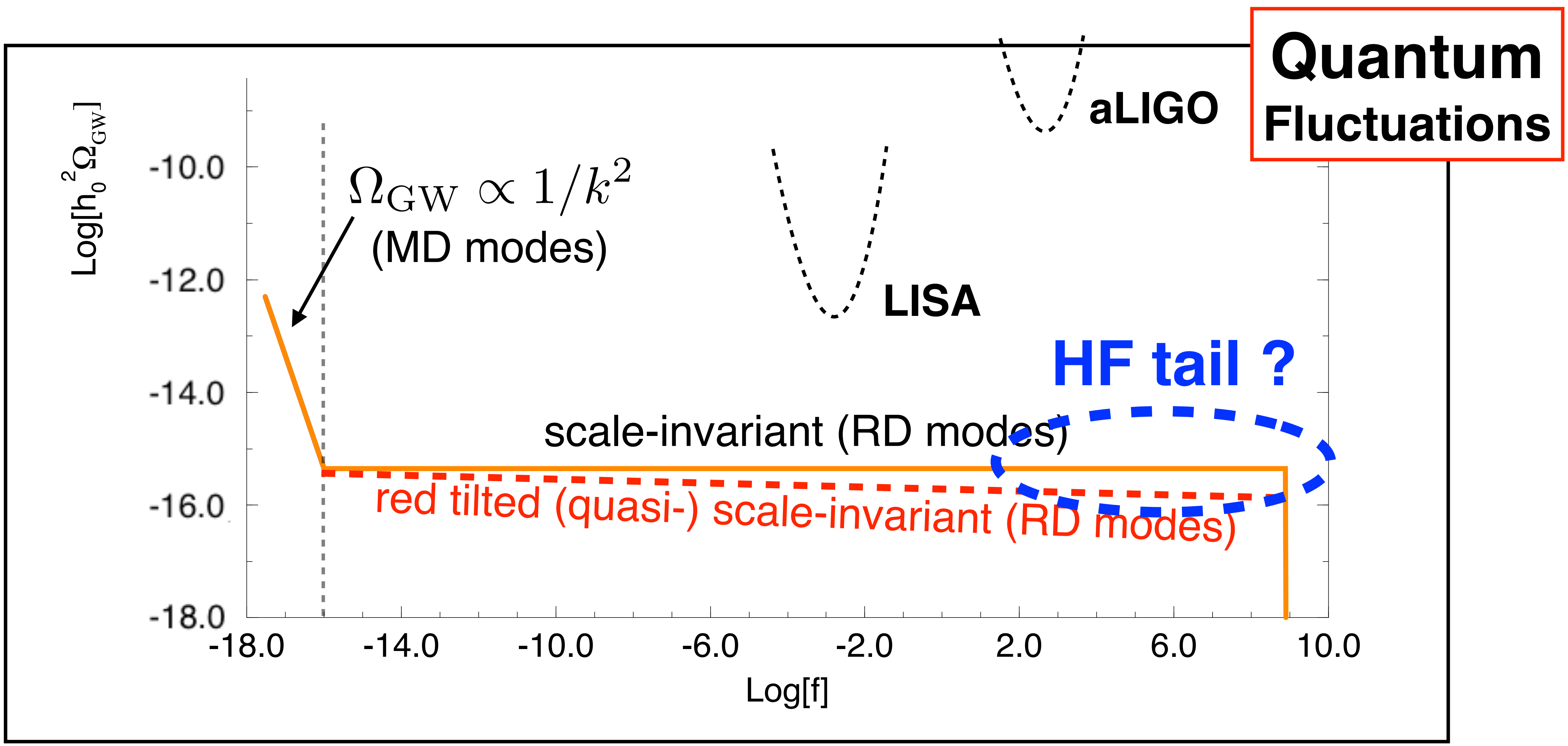
$$\boxed{\Omega_{\rm GW}^{(o)}(f) \equiv \frac{1}{\rho_c^{(o)}}\left(\frac{d\log\rho_{\rm GW}}{d\log k}\right)_o = \underbrace{\frac{\Omega_{\rm Rad}^{(o)}}{24}}\Delta_{h_*}^2(k)}$$

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

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

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

energy scale



STIFF EQ of STATE SLIDES

STIFF EQ of STATE

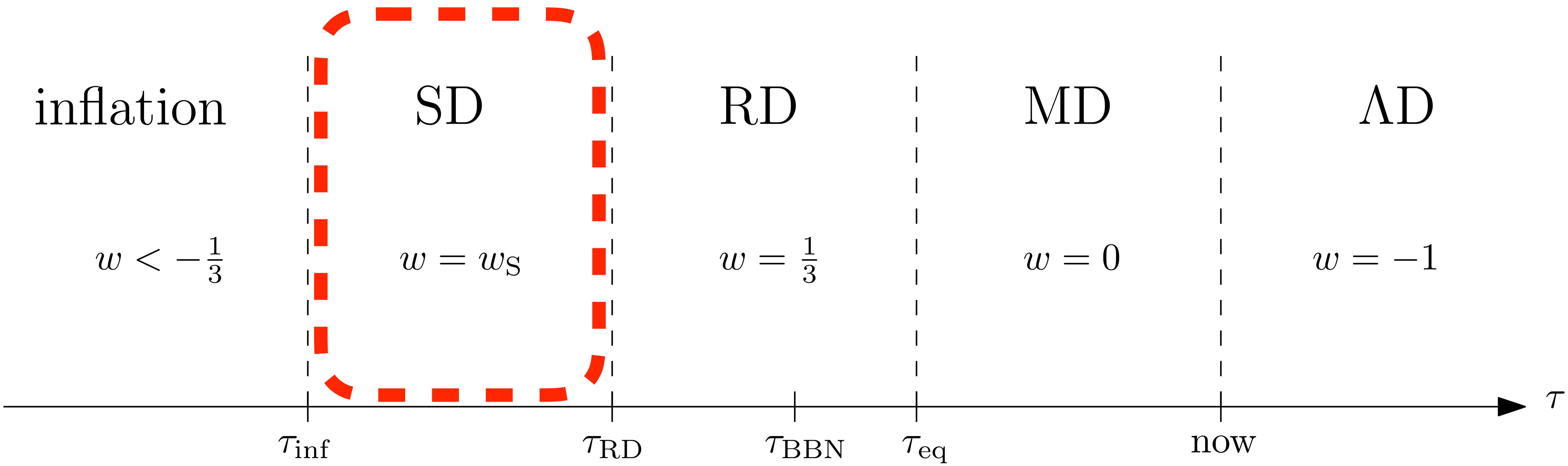
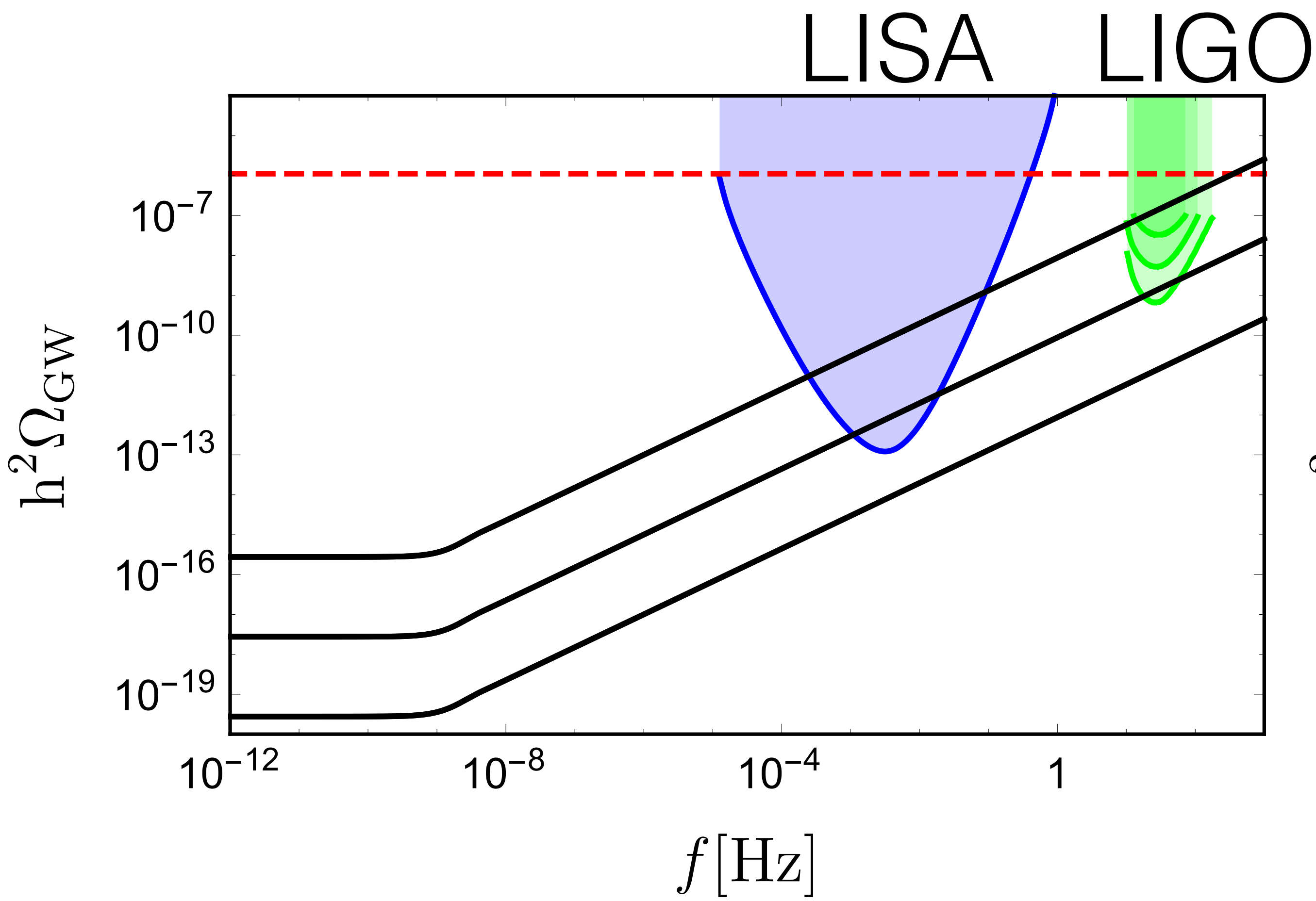
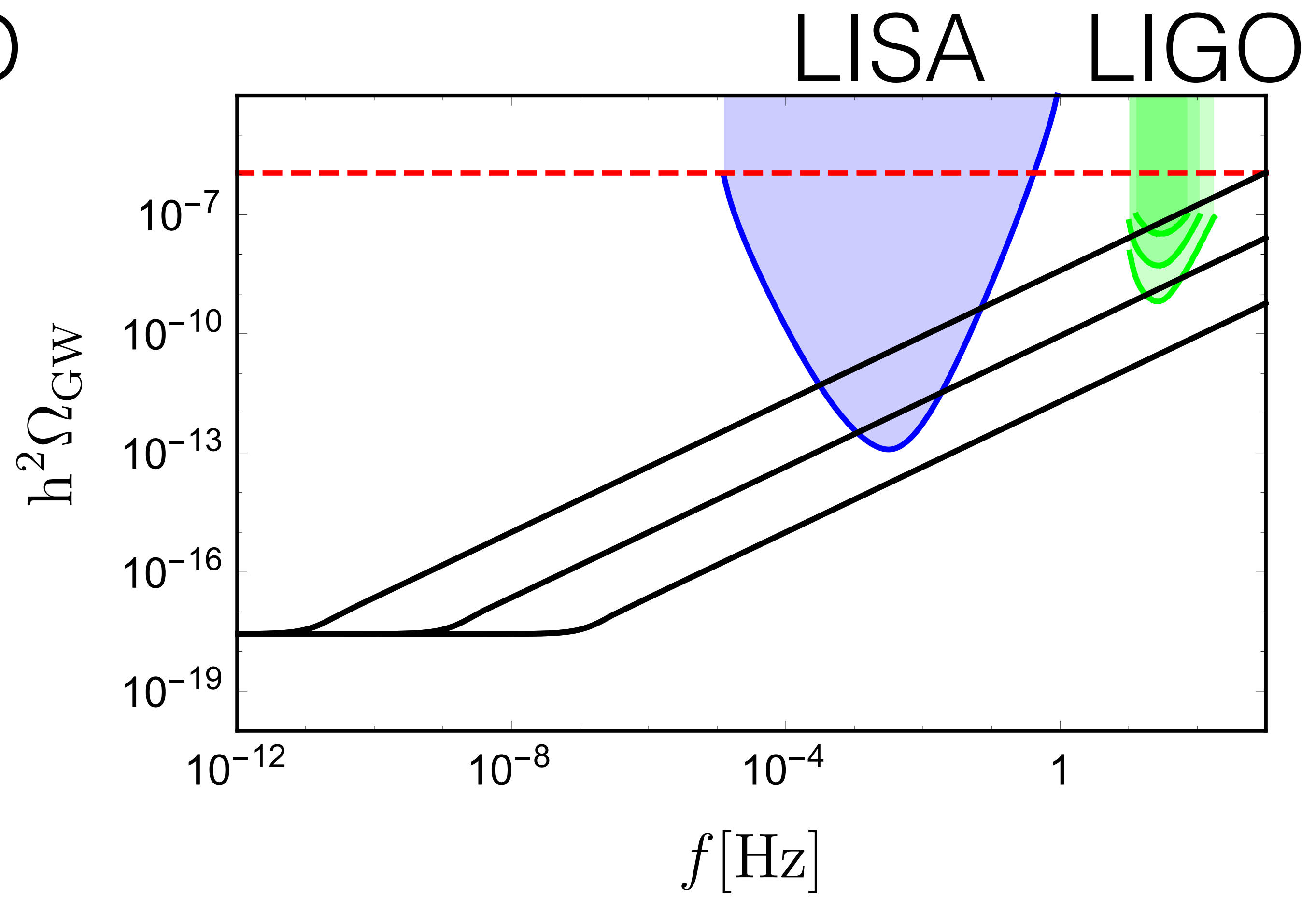


Figure 1. ΛCDM+inflation expansion history with a stiff epoch.

$$\boxed{SD:\ 1/3 < w_{\mathrm{S}} \lesssim 1}$$

STIFF EQ of STATE

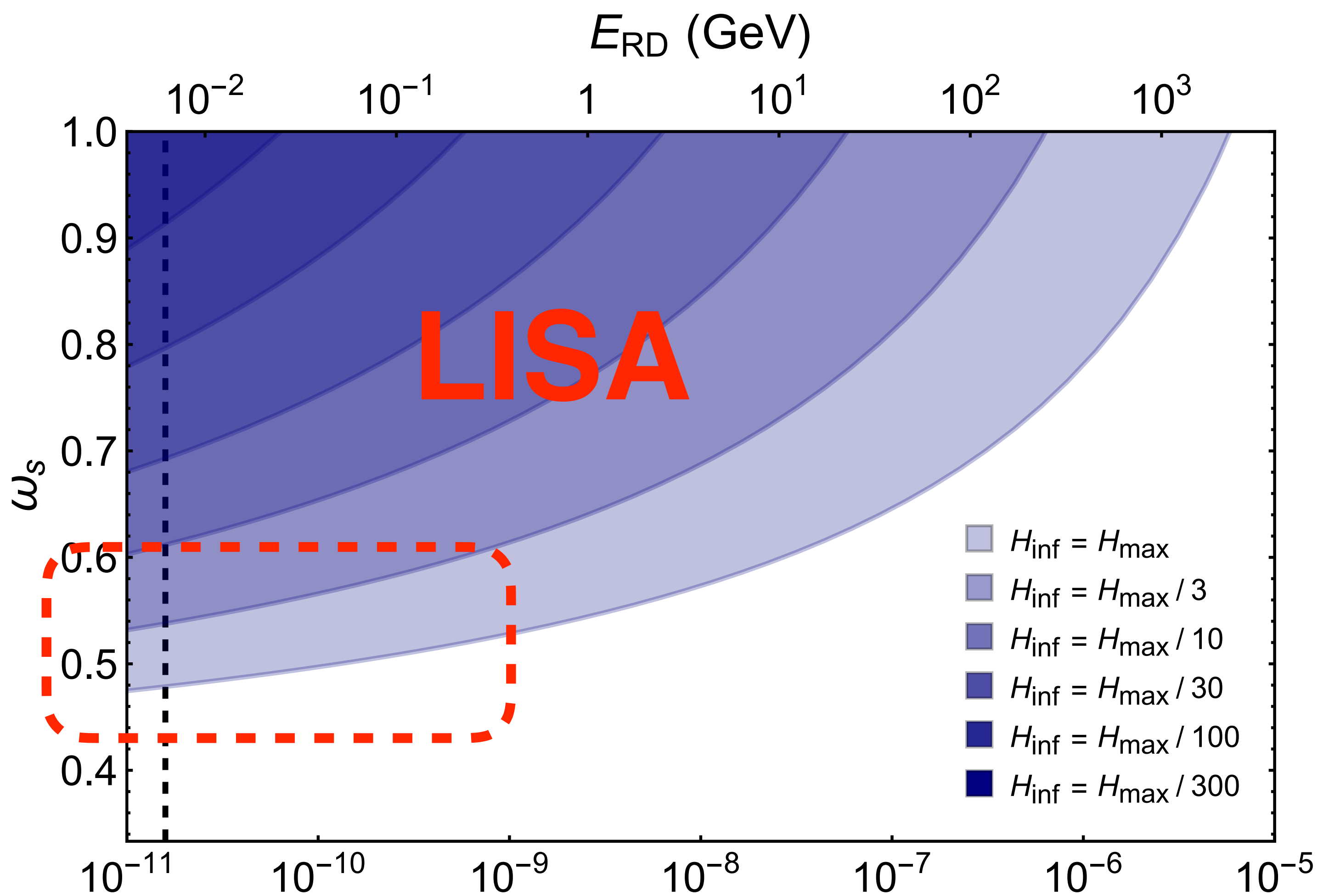


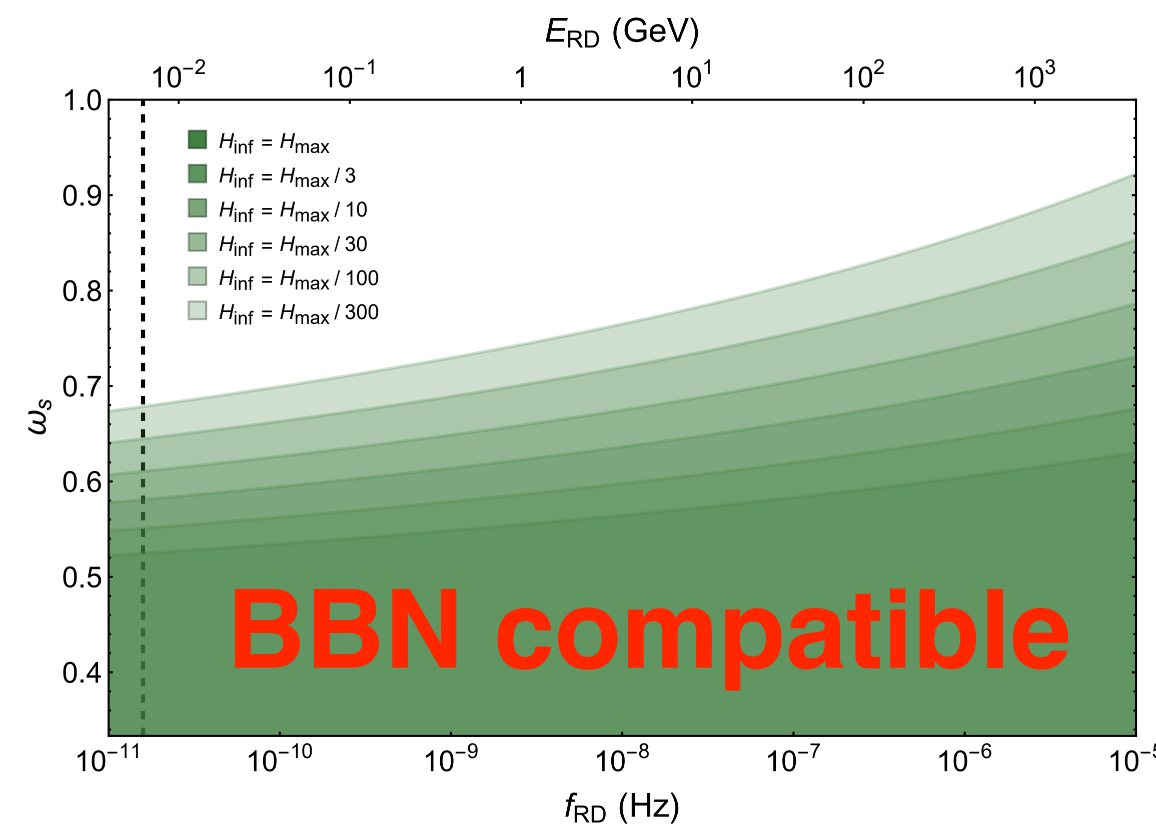


$$\Omega_{\rm GW}(f) \propto H_{\rm inf}^2 \left(\frac{f}{f_{\rm RD}}\right)^{\frac{2(w-1/3)}{(w+1/3)}}$$

Not Scale Invariant !

STIFF EQ of STATE





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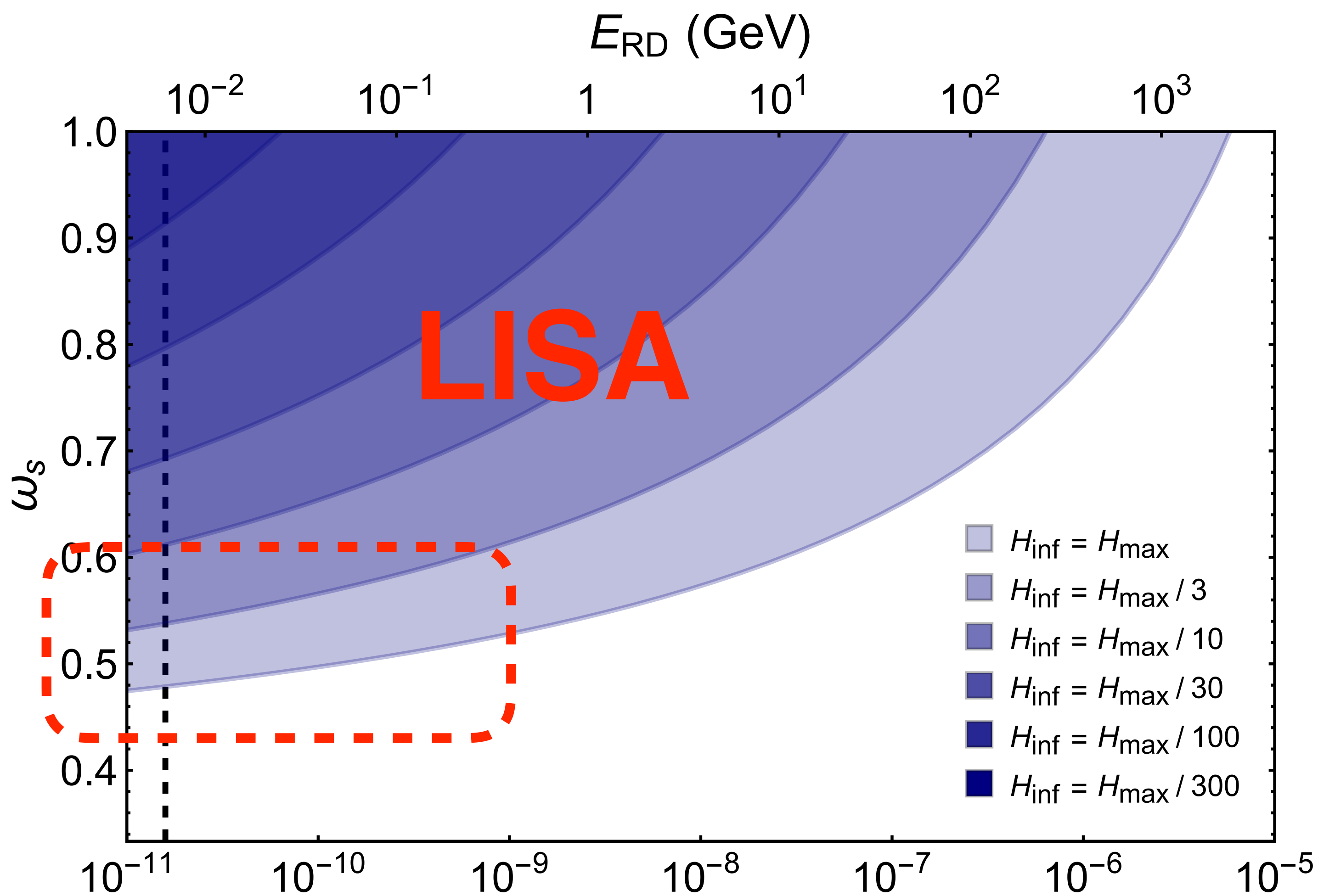
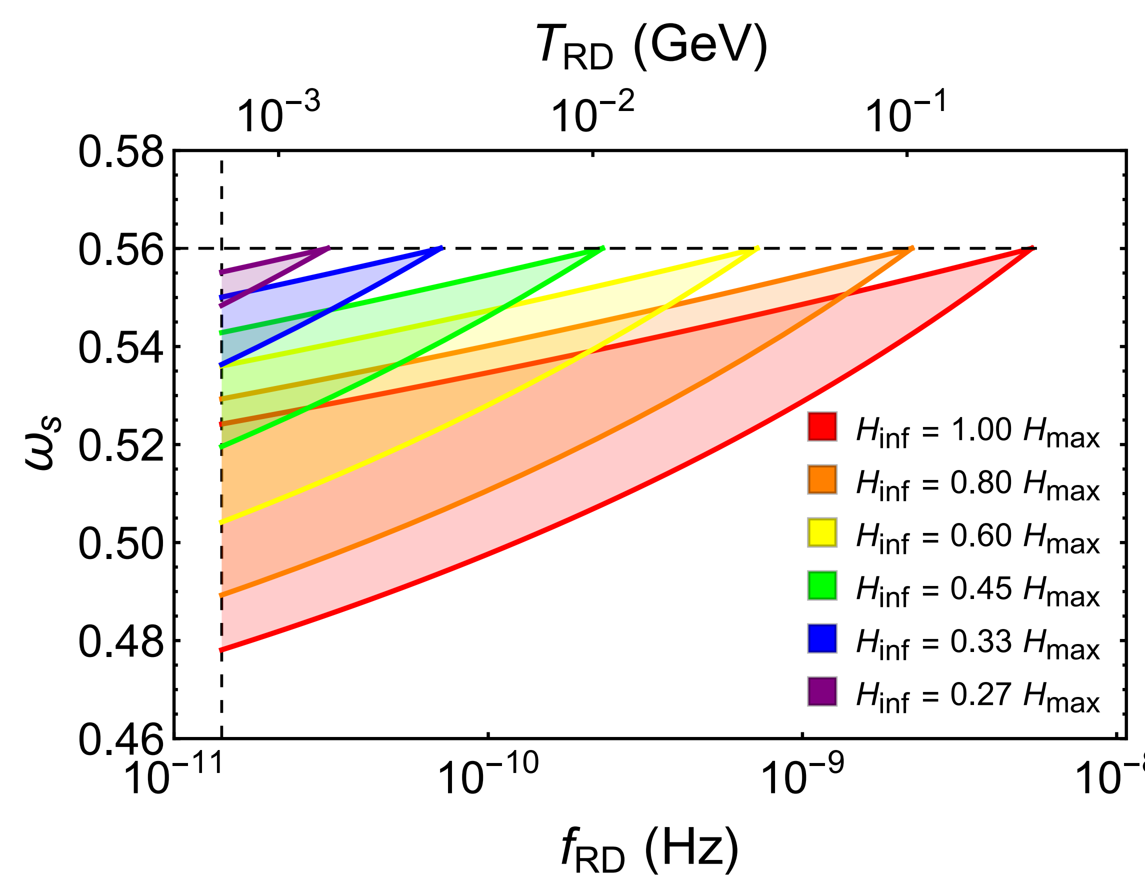
DGF & Tanin
(preliminar)

STIFF EQ of STATE



after BBN cut



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CMB SLIDES

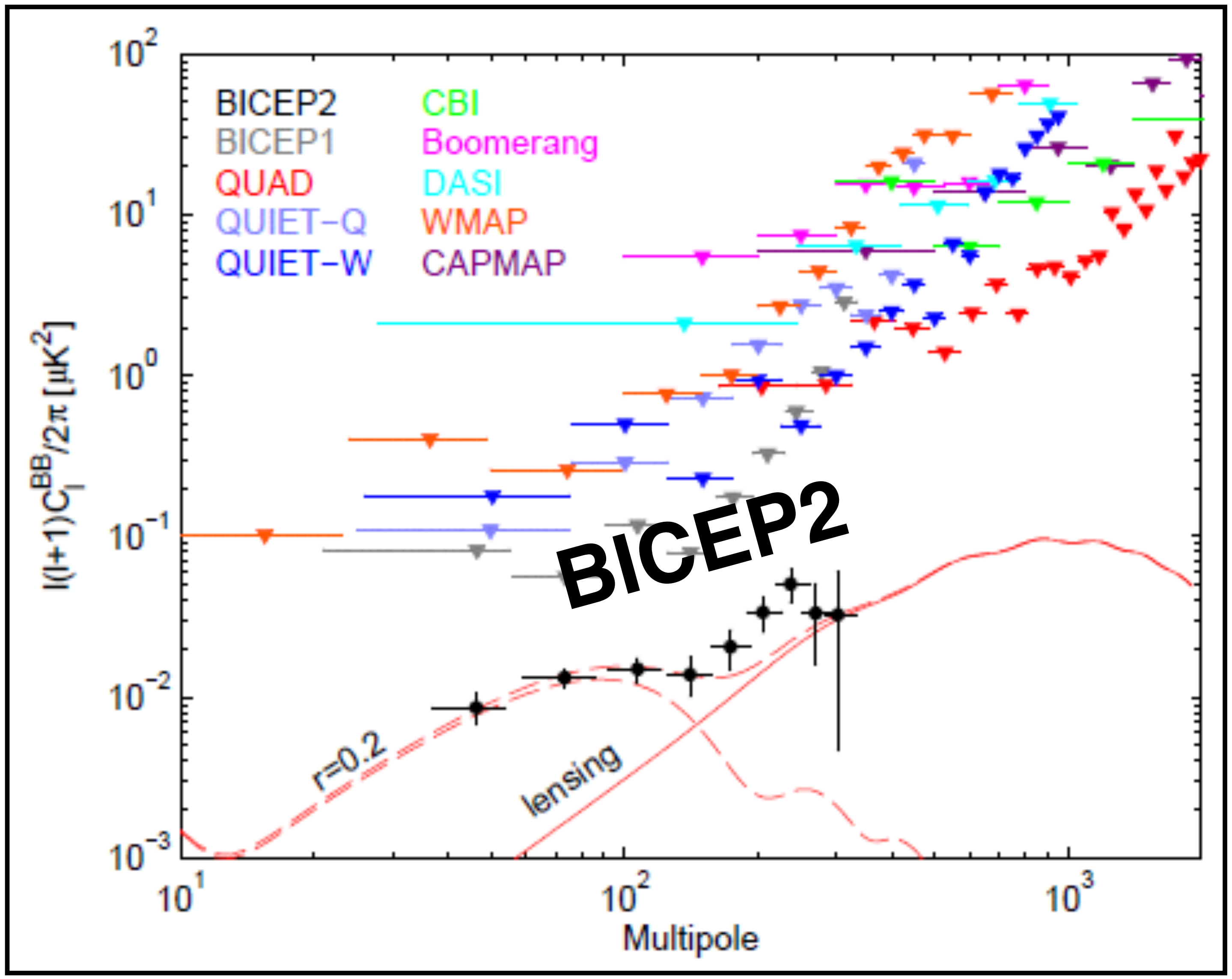
Irreducible GW background from Inflation

$$\langle \mathcal{E}^2 \rangle,\ \langle \mathcal{B}^2 \rangle \ \rightarrow\ \langle |e_{lm}|^2 \rangle \equiv C_l^E,\ \boxed{\langle |b_{lm}|^2 \rangle \equiv C_l^B}$$

CMB Polarization
Angular Power Spectra

$$(Q \pm iU)(\hat{n}) = \sum_{l,m} a_{lm}^{(\pm 2)} Y_{lm}^{(\pm 2)} = \sum_{l,m} (e_{lm} \pm i b_{lm}) Y_{lm}^{(\pm 2)}(\hat{n})$$

B- MODE: Depends only on Tensor Perturbations !



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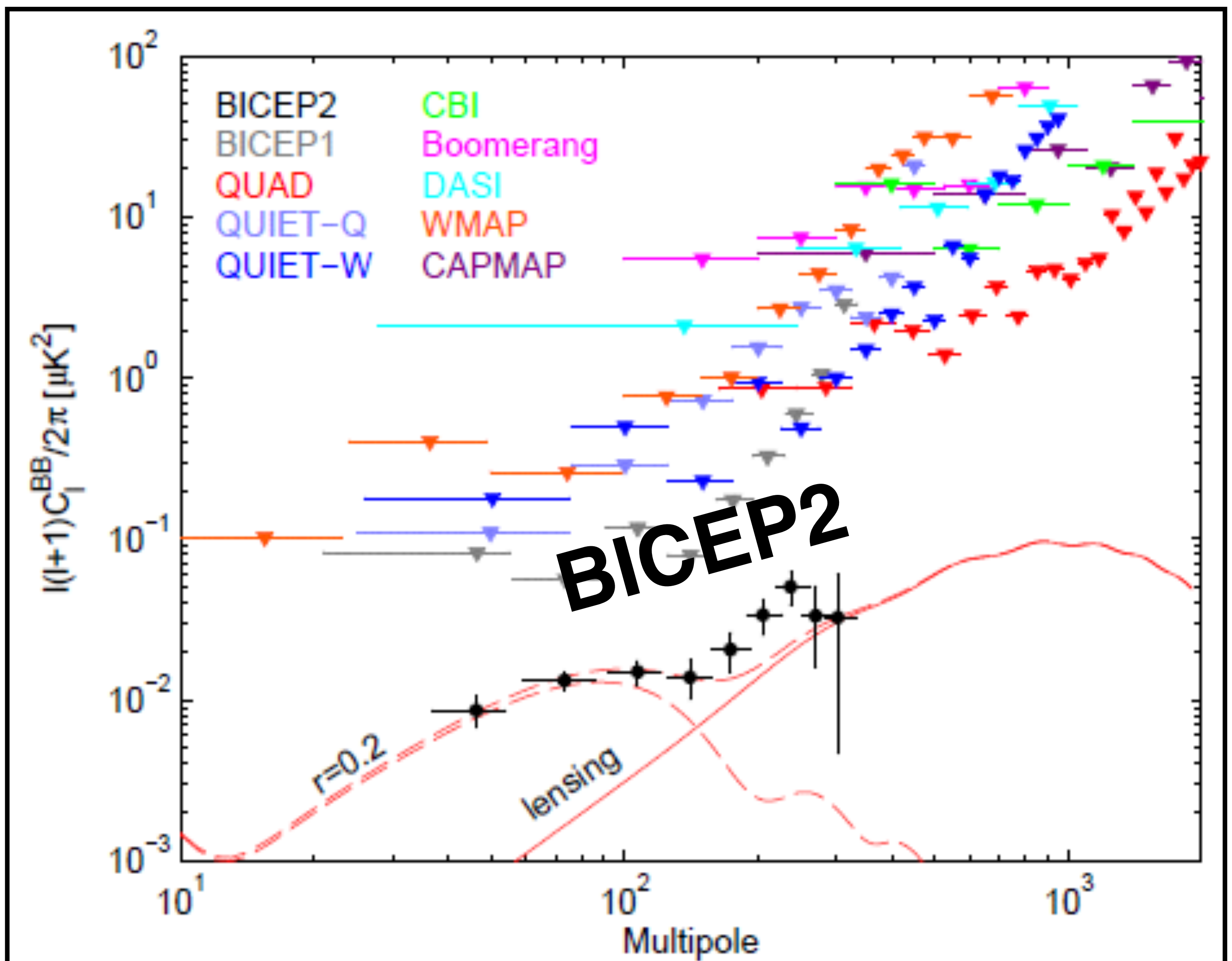

Dashed Line Theoretical Inflation Expectation

Planck/Keck

$$r \equiv \Delta_t^2 / \Delta_s^2 < 0.07 \ (2\sigma)$$

$$\boxed{r \sim 10^{-2} - 10^{-3}} \Rightarrow E_* \sim 5 \cdot 10^{15} \mathrm{GeV} \ (!)$$

next goal

PHASE TRANSITIONS SLIDES

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)

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  - sin... 2015)
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Cosmology and Particle Physics interplay!
Connections with baryon asymmetry & dark matter

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  - sin
  - 13)
  - z et al 2013)
  - 2004)

Conn

nterplay!
& dark matter

Big Problem: LHC is putting great pressure over these scenarios

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  - ...13)
  - ...z et al 2013)
  - ...2004)

...nterplay!
...& dark matter

Conn...

Big Problem: LHC is putting great pressure over these scenarios

- ... and beyond the EWPT
  - Dark sector: provides DM ... PT (Schwall...
  - ... the dilaton/radion ... like models (Randall and Servant 2015)

LISA —> new probe of BSM physics!
(complementary to particle colliders)

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

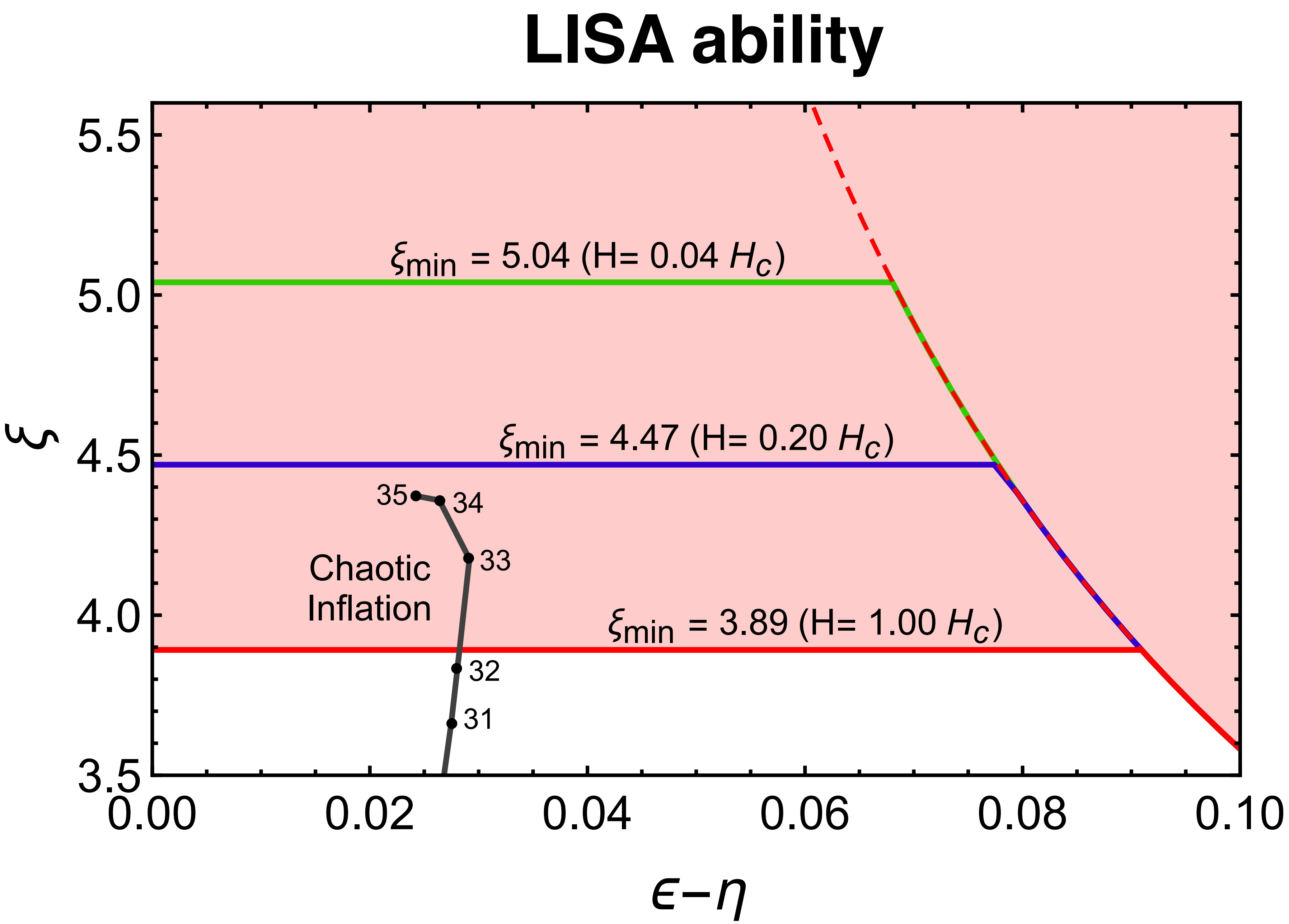
* Predictions depend on many assumptions (particularly in sound waves), so is our modelling correct?

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

AXION INFLATION SLIDES

INFLATIONARY MODELS

Axion-Inflation



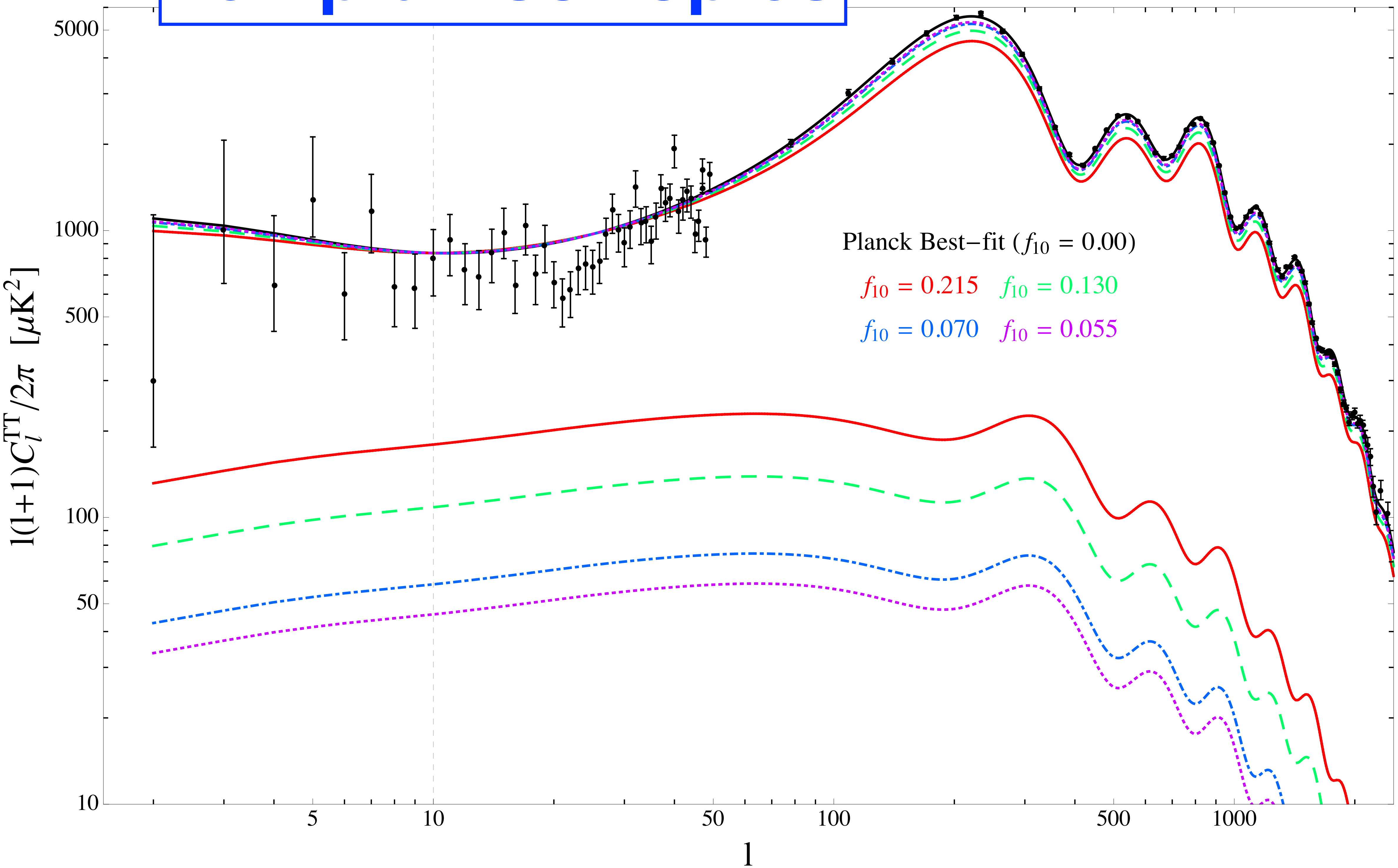
$$\boxed{\xi \equiv \frac{\alpha \dot{\phi}}{2 f H}}$$

Bartolo et al '16, 1610.06481

CMB & COSMIC DEFECTS SLIDES

Cosmic Microwave Background

Temp-anisotropies



Durrer, DGF, Kunz, JCAP 2014

Cosmic Microwave Background

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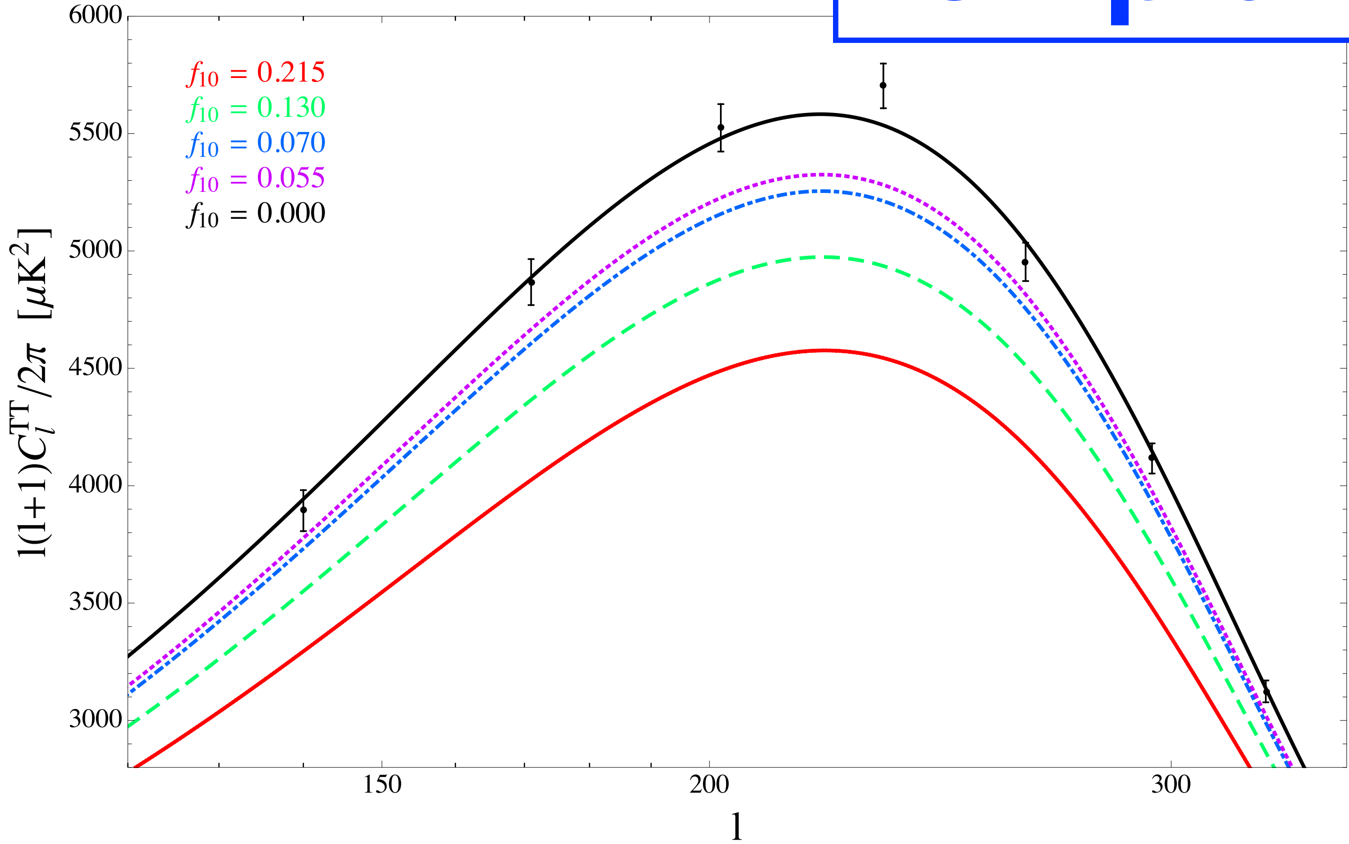

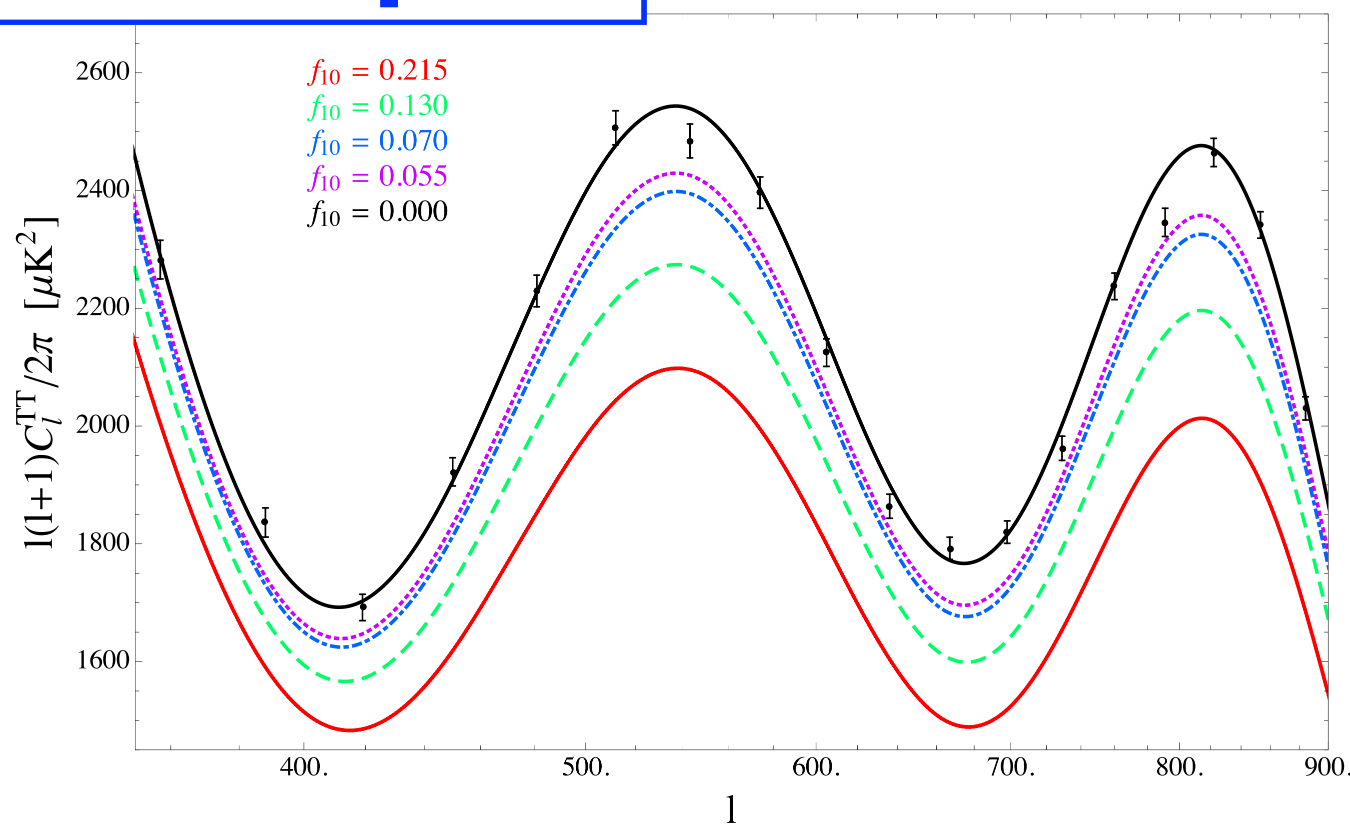

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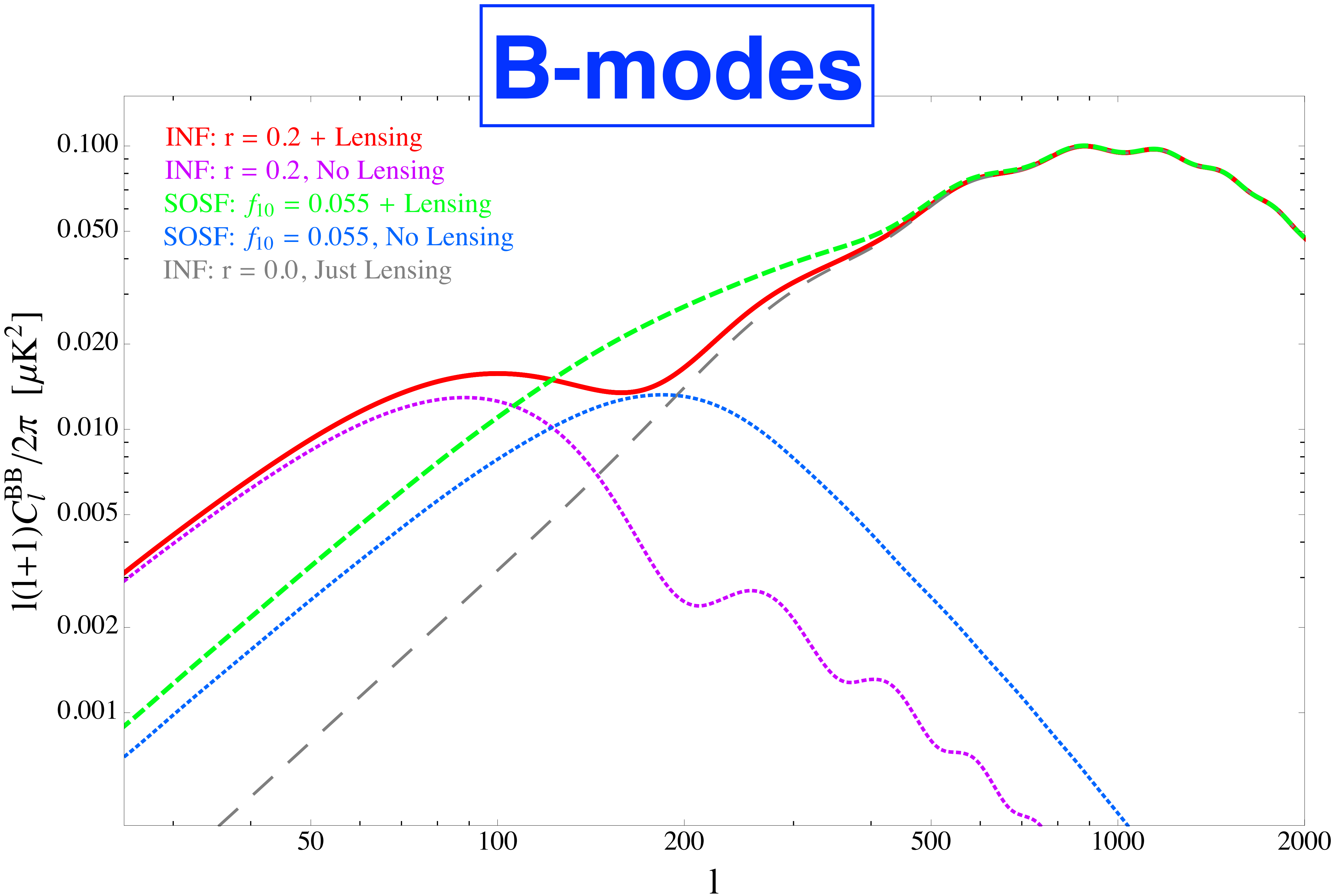

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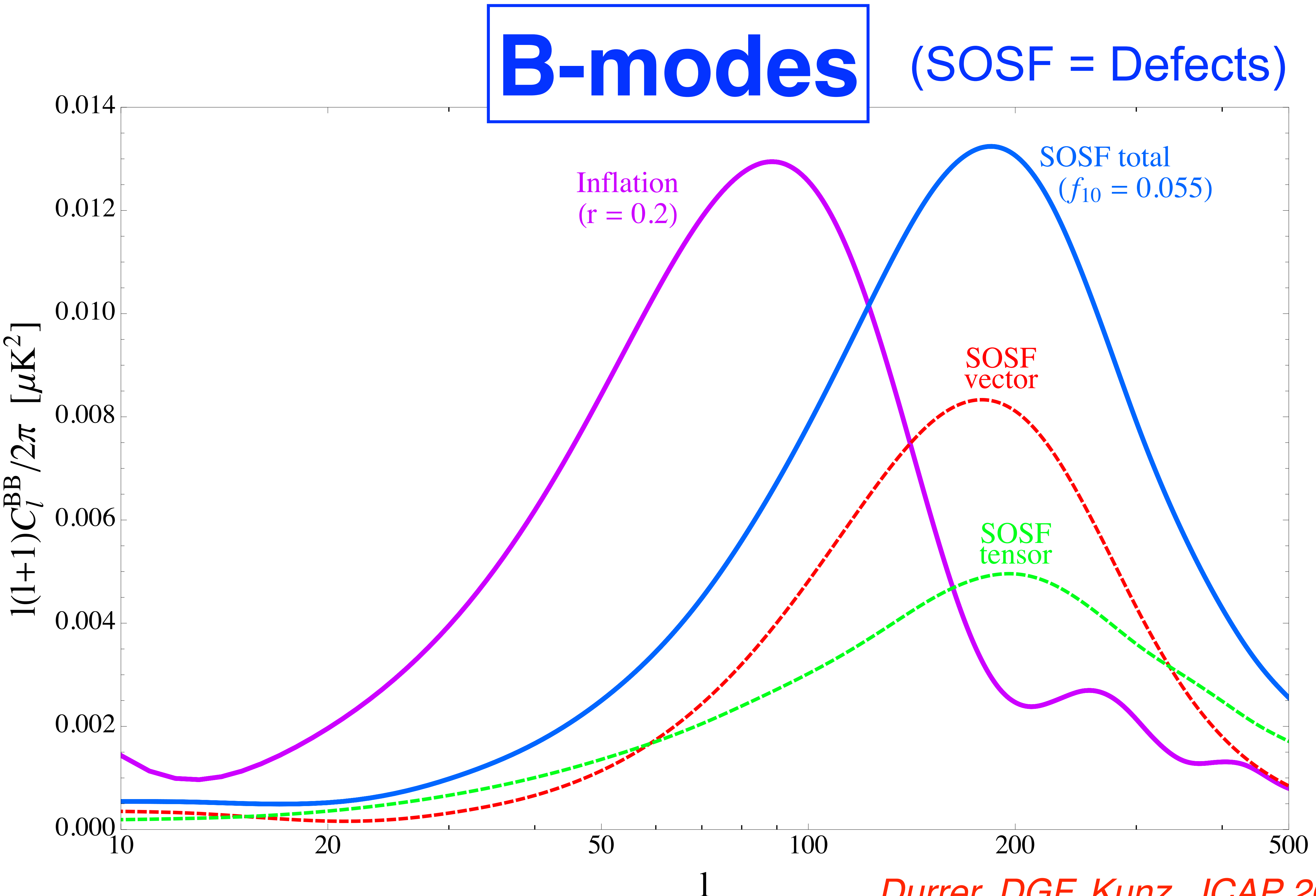

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