GRAVITATIONAL WAVES
AS A PROBE OF HIGH ENERGY PHYSICS

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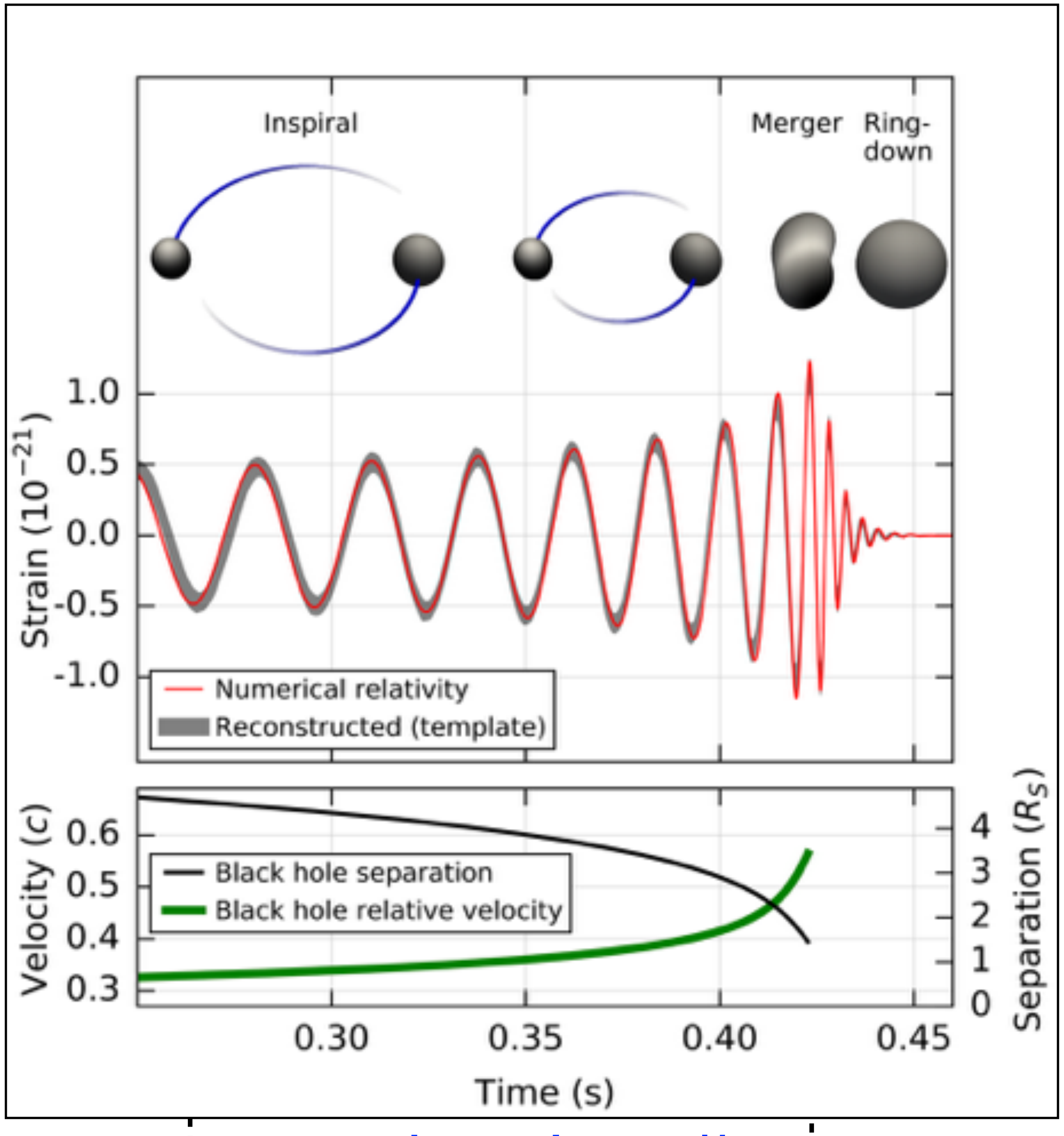
EPFL, Lausanne, Switzerland

WINDOWS ON THE UNIVERSE: 25th Anniversary Rencontres du Vietnam, Aug 5-11 2018

Einstein 1916 … LIGO/VIRGO 2015/16/17



see Lee's talk

Gravitational Waves (GWs) detected !

Milestone

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

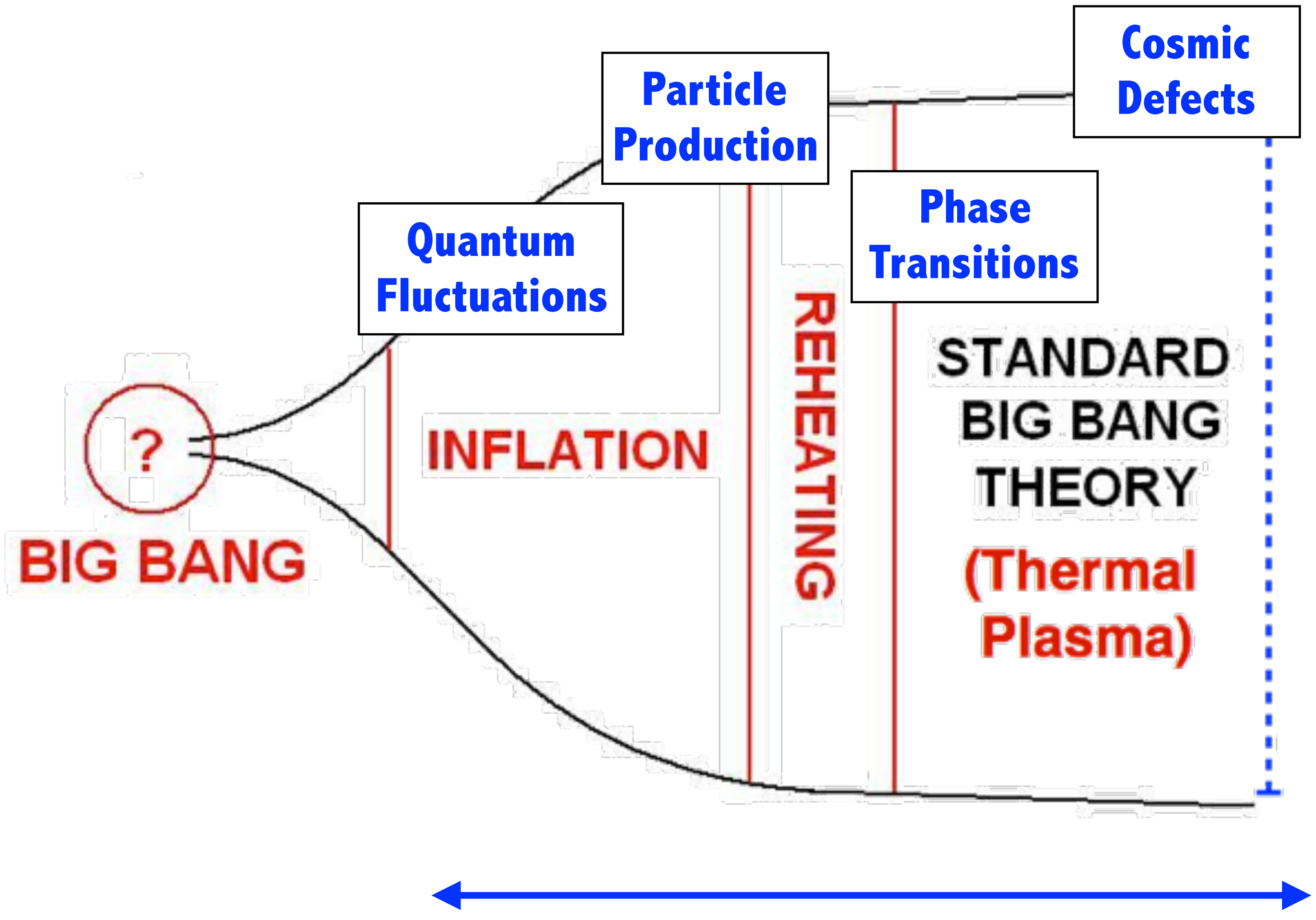
1. **WEAKNESS of GRAVITY**:

   ADVANTAGE: GW DECOUPLE upon Production
   DISADVANTAGE: DIFFICULT DETECTION

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

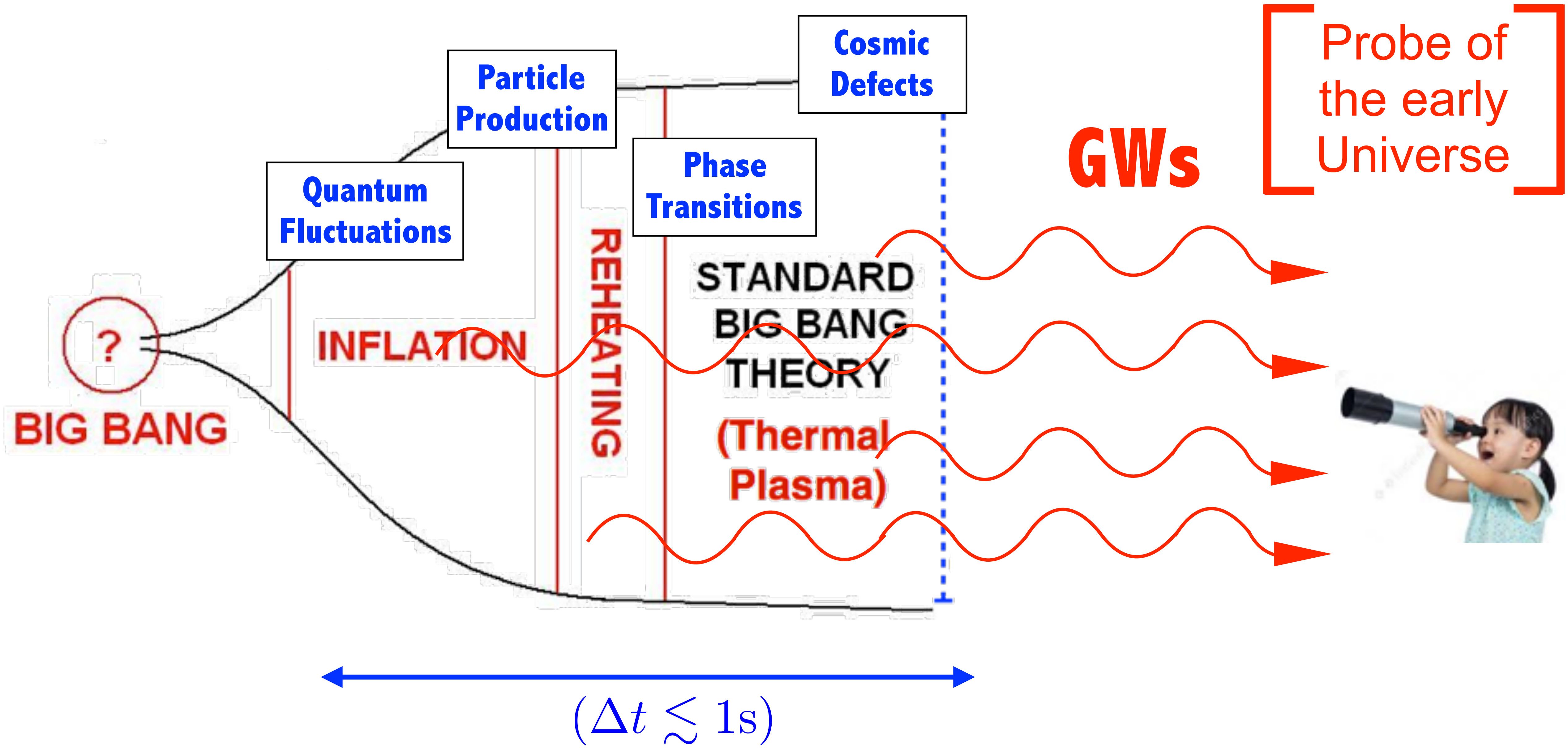
$$\rightarrow \begin{cases} \textbf{Decouple} \rightarrow \text{Spectral Form Retained} \\ \textbf{Specific HEP} \;\Leftrightarrow\; \text{Specific GW} \end{cases}$$

The Early Universe



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

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

Gravitational Waves in Cosmology

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

Transverse-Traceless (TT)

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

Creation/Propagation GWs

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

Source: Anisotropic Stress

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

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

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

Gravitational Waves as a probe of the early Universe

OUTLINE

0) GW definition ✓

Early Universe

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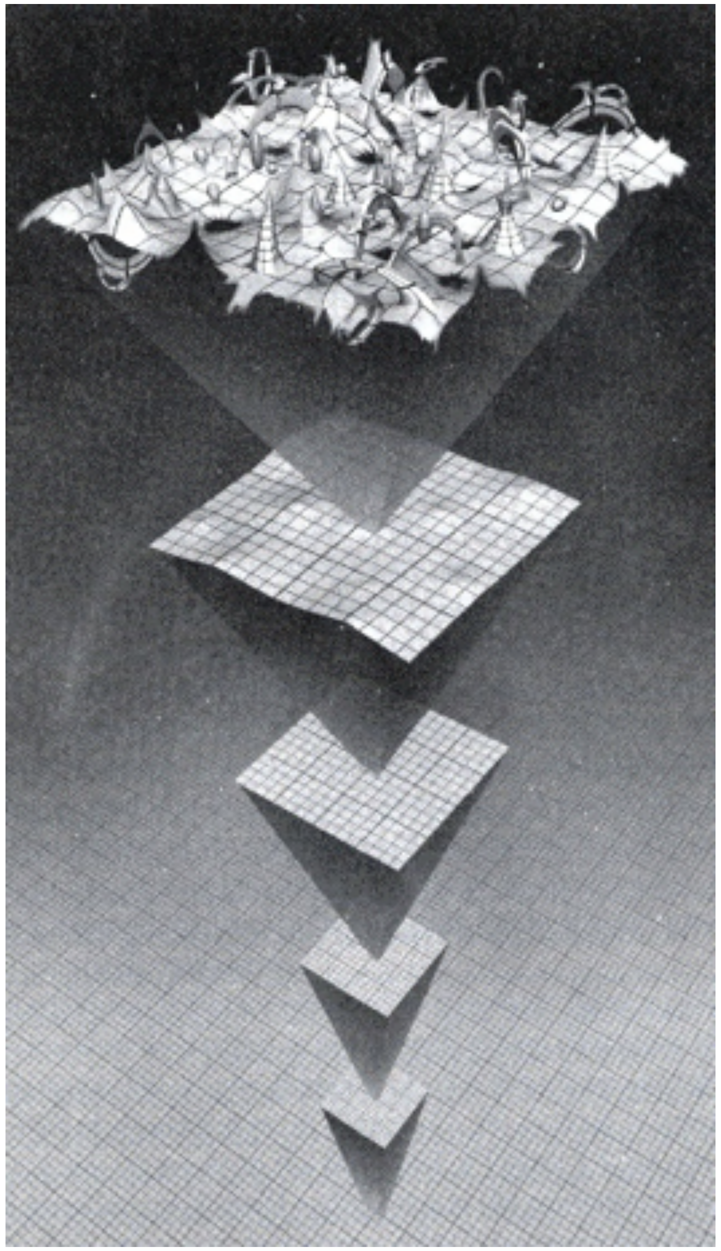
Irreducible GW background from Inflation

recall
Pryke's talk



Quantum
Fluctuations

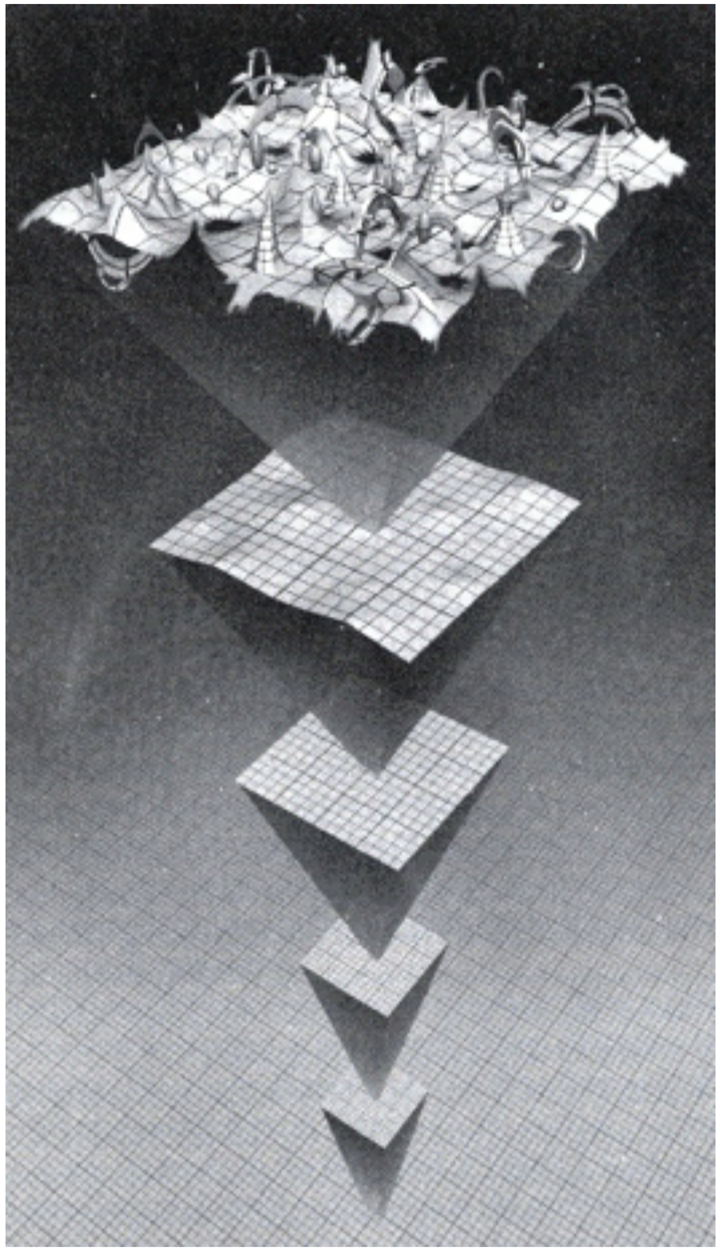
Irreducible GW background from Inflation

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

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

$$n_t \equiv -2\epsilon$$

energy scale



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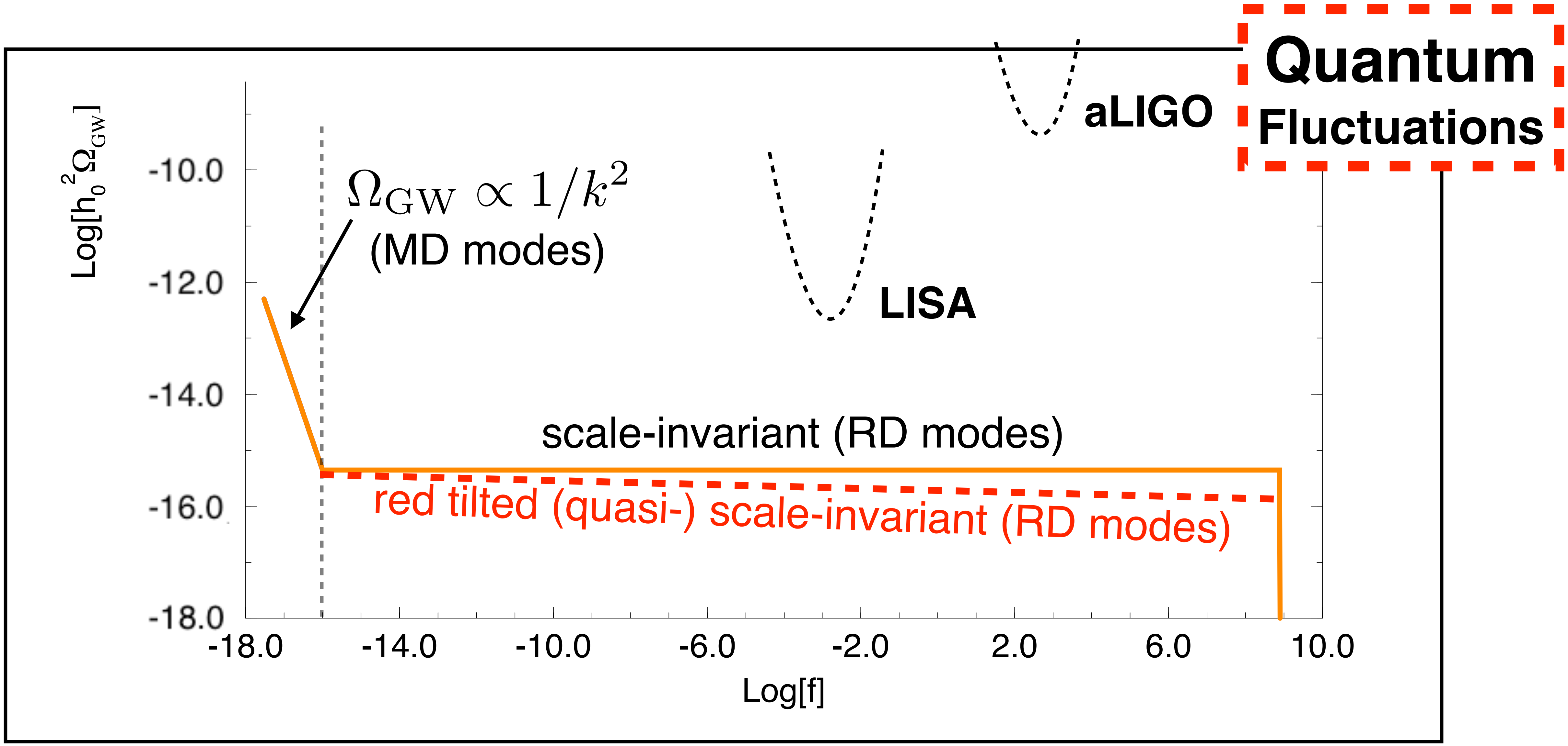
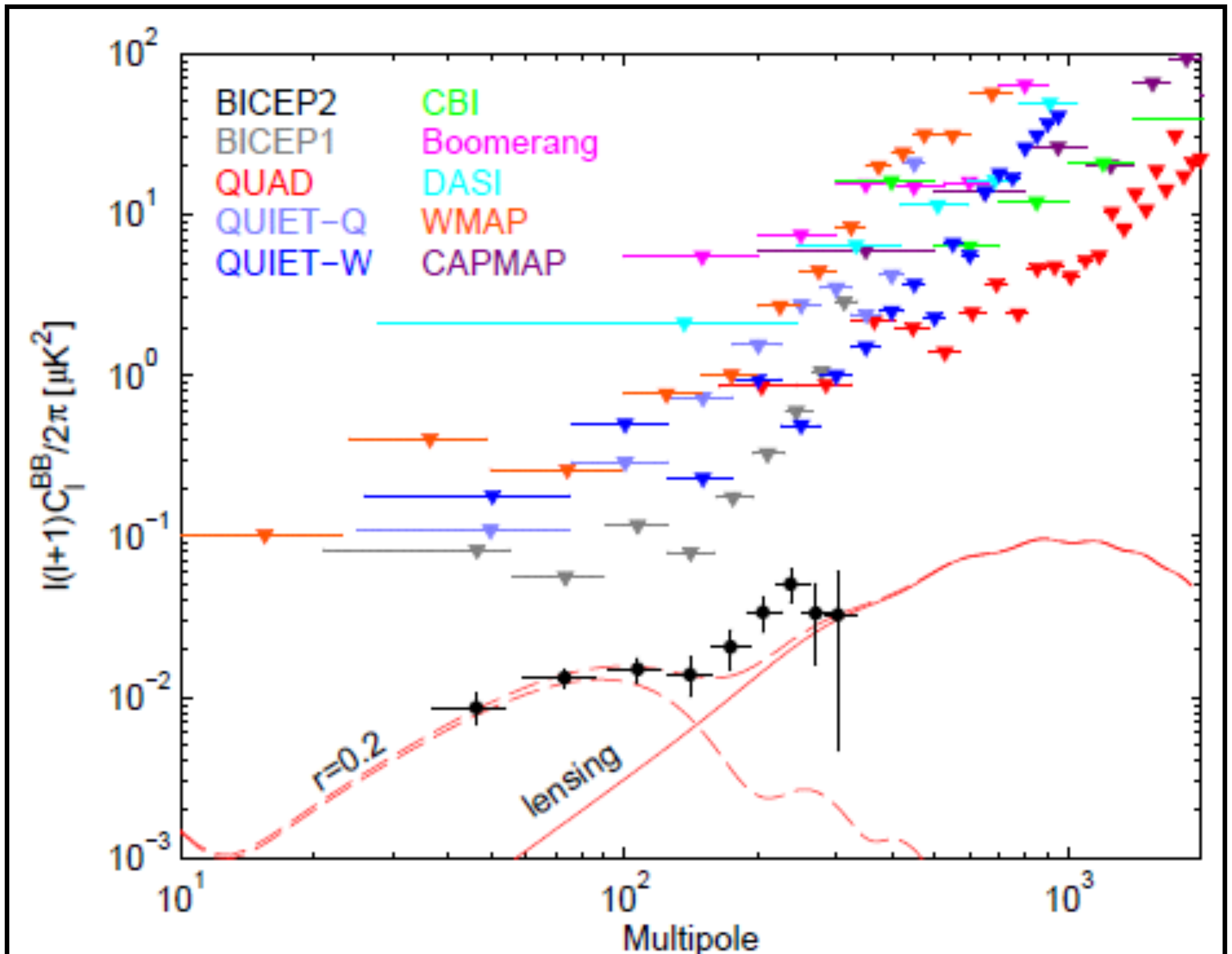


Irreducible GW background from Inflation

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

B- MODE: Depends only on Tensor Perturbations !



Dashed Line Theoretical Inflation Expectation

Planck/Keck

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

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

next goal

Irreducible GW background from Inflation

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

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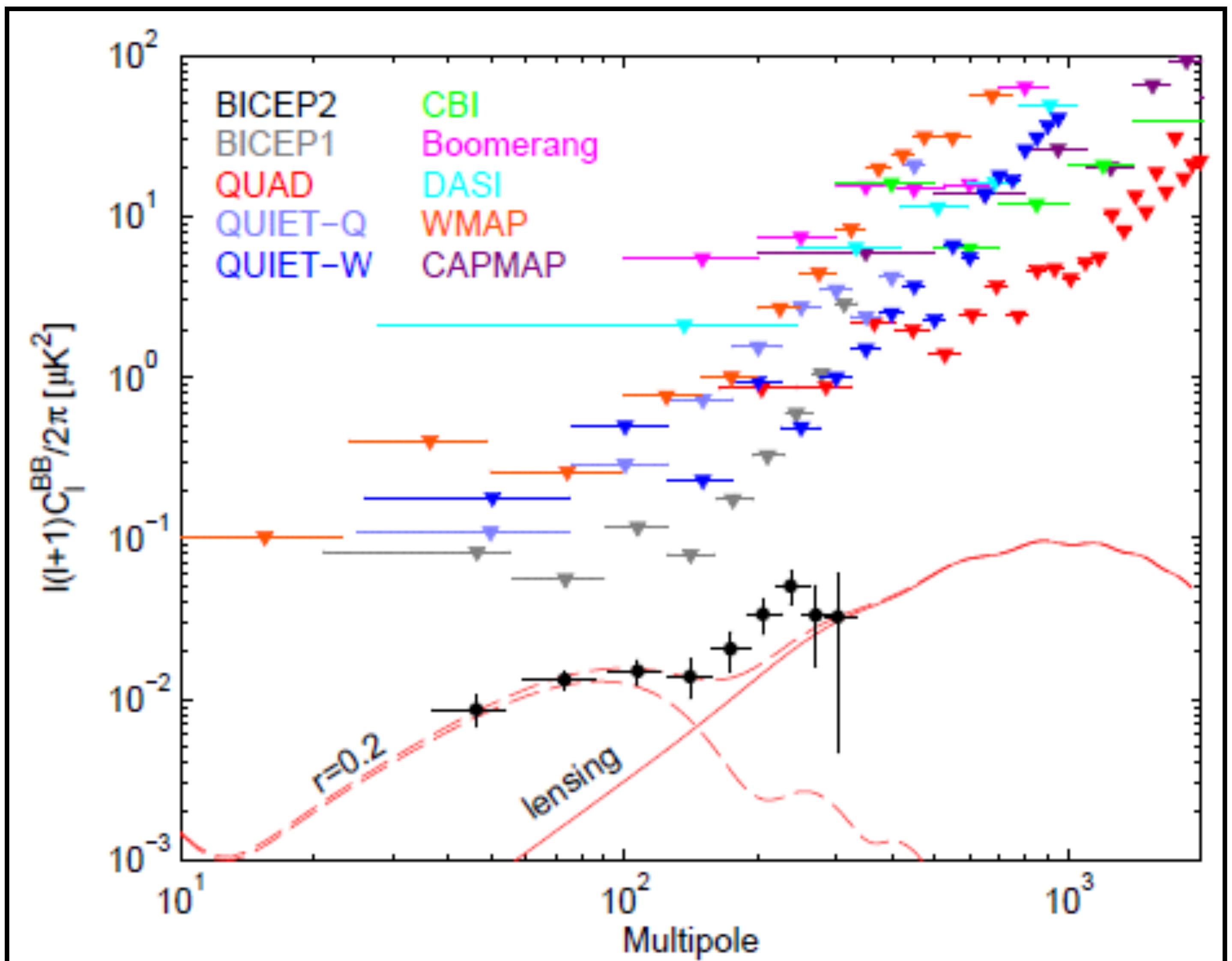


Search of B-modes @ CMB might be only change to detect Inflationary Tensors !

Ground:

AdvACT, CLASS, Keck/BICEP3, Simons Array, SPT-3G

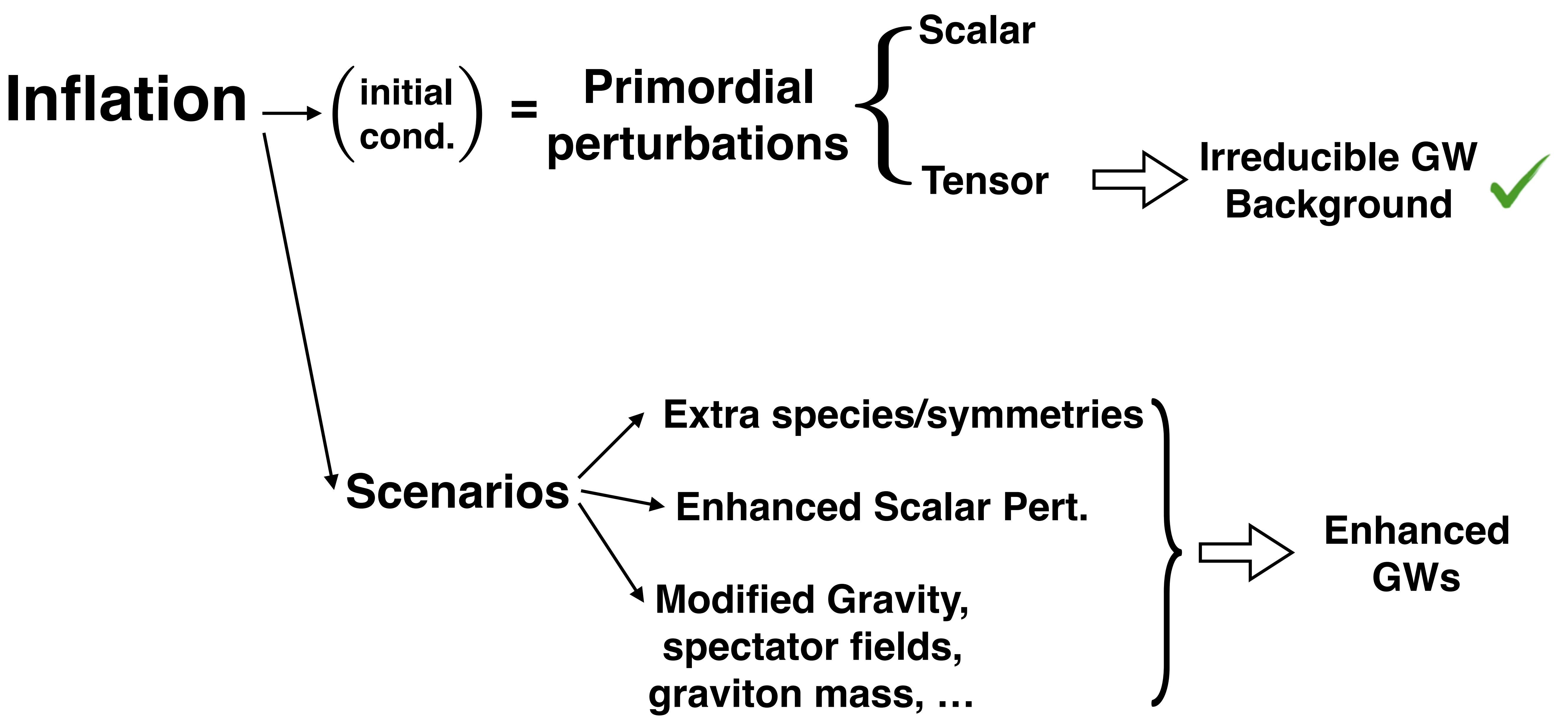
Balloons

EBEX 10k, Spider

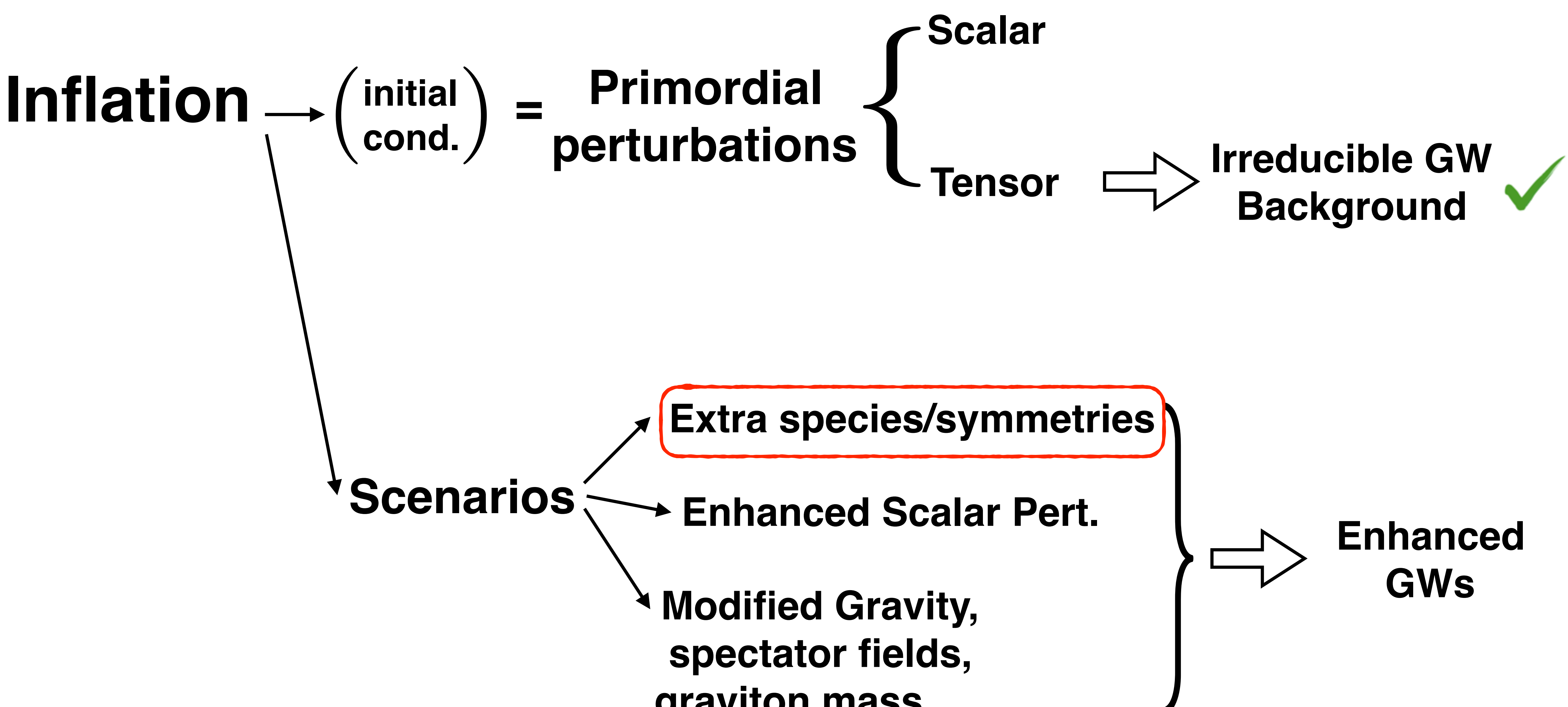
Satellites

CMBPol, COrE, LiteBIRD,

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

Not the QCD axion;

INFLATIONARY MODELS

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

Photon: 2 helicities

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

$$\xi \equiv \frac{\alpha\dot{\phi}}{2fH}$$

Chiral instability

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

A_+ exponentially amplified,

INFLATIONARY MODELS

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chiral GWs !

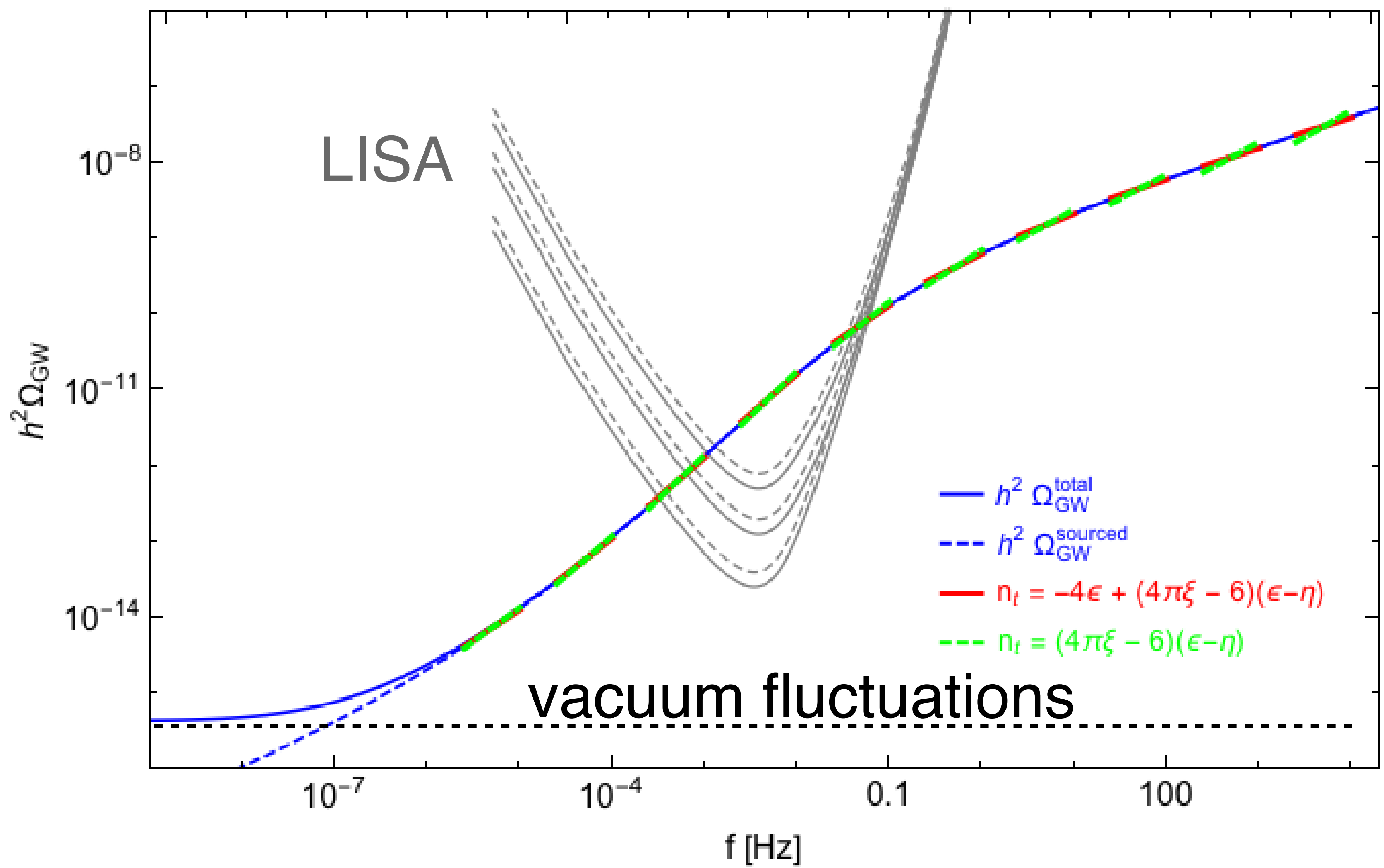
$$h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = 16\pi G \Pi^{\rm TT}_{ij} \propto \{E_i E_j + B_i B_j\}^{TT}$$

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

INFLATIONARY MODELS

Axion-Inflation

GW energy spectrum today



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)

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

inflaton $\phi \longrightarrow V(\phi)$

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

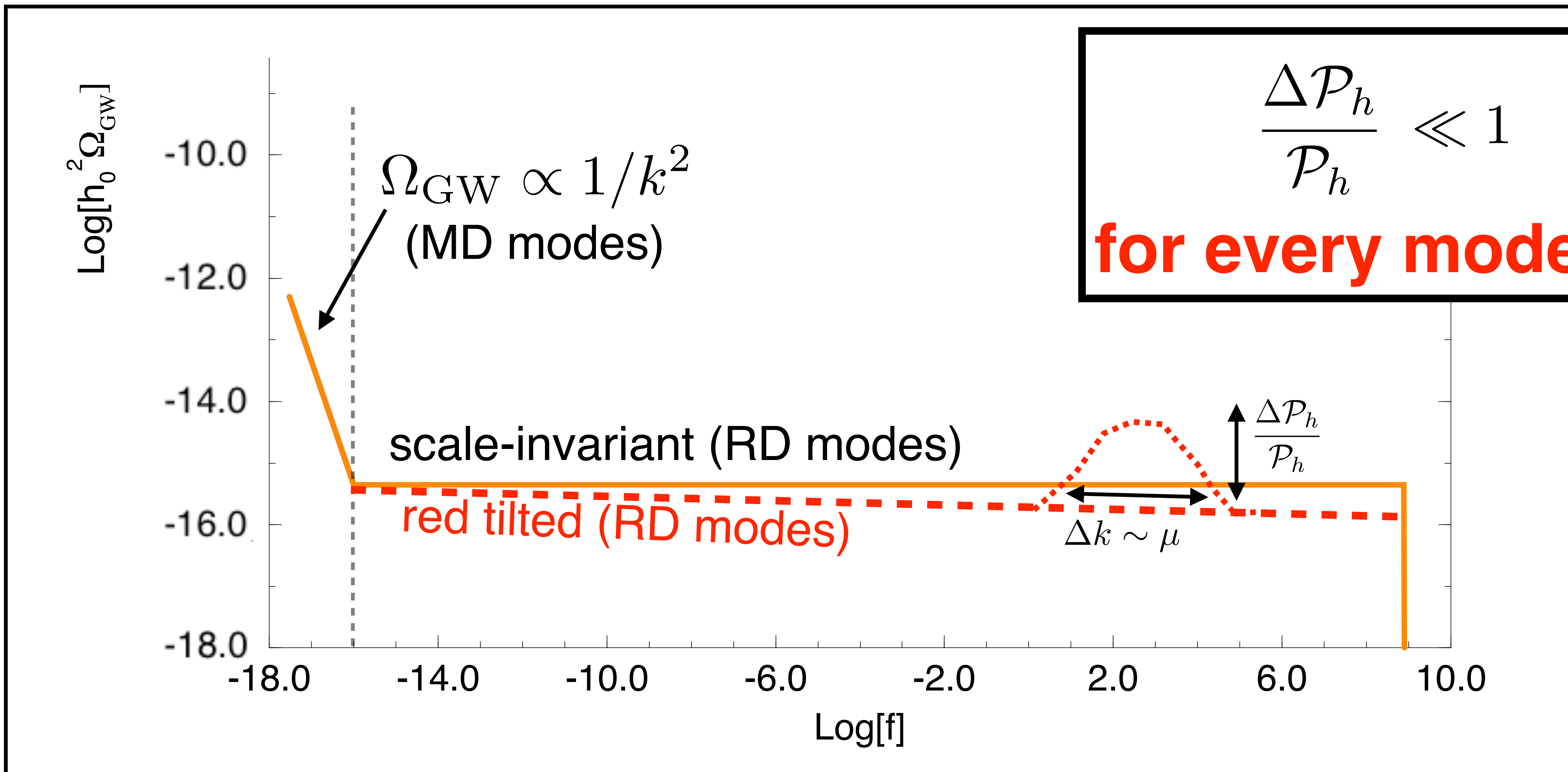
$$-\mathcal{L}_\psi = \bar{\psi}\gamma^\mu\partial_\mu\psi + g(\phi-\phi_0)\bar{\psi}\psi$$ **Fermion Fld**

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

INFLATIONARY MODELS

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

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

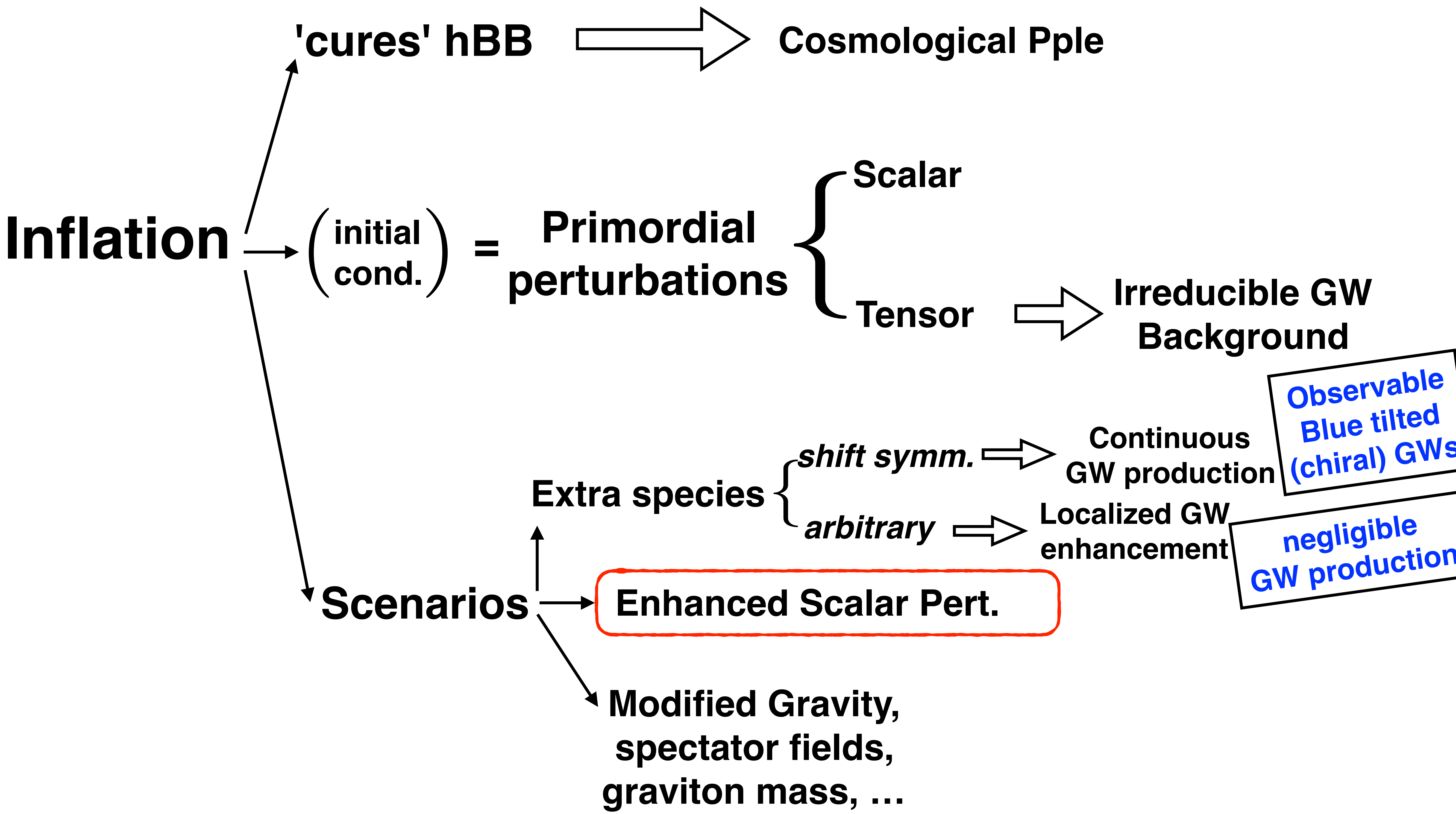


$$\frac{\Delta\mathcal{P}_h}{\mathcal{P}_h} \ll 1$$

for every model !

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

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

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

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

INFLATIONARY MODELS

INFLATION ➡ IF { non-monotonic, multi-field } ⇨ possible to enhance $\Delta^2_{\mathcal{R}}$ (at small scales)

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

Phys.Rev. D81 (2010) 023527

INFLATIONARY MODELS

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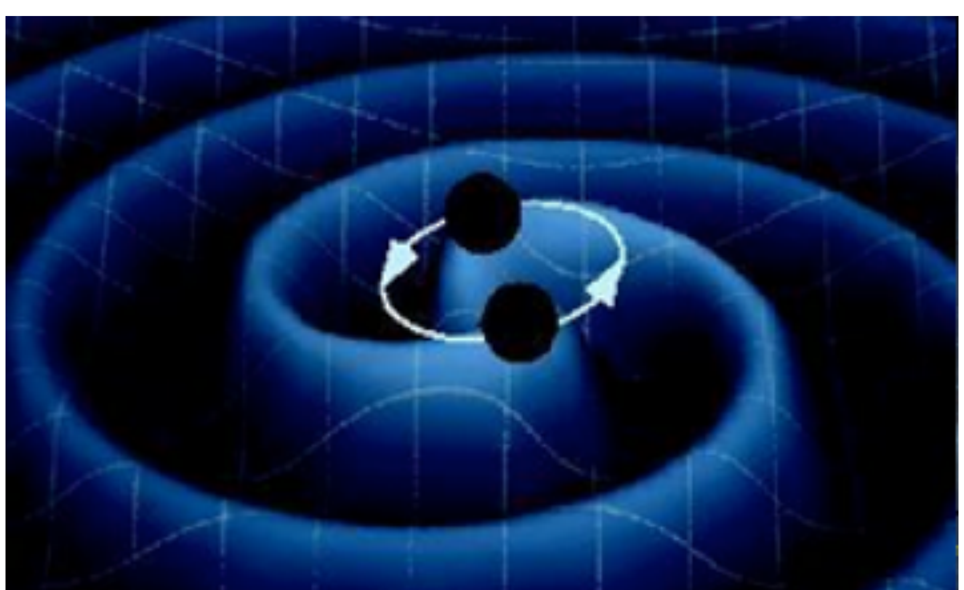
IF $\Delta^2_{\mathcal{R}}$ very enhanced → Primordial Black Holes (PBH) may be produced!

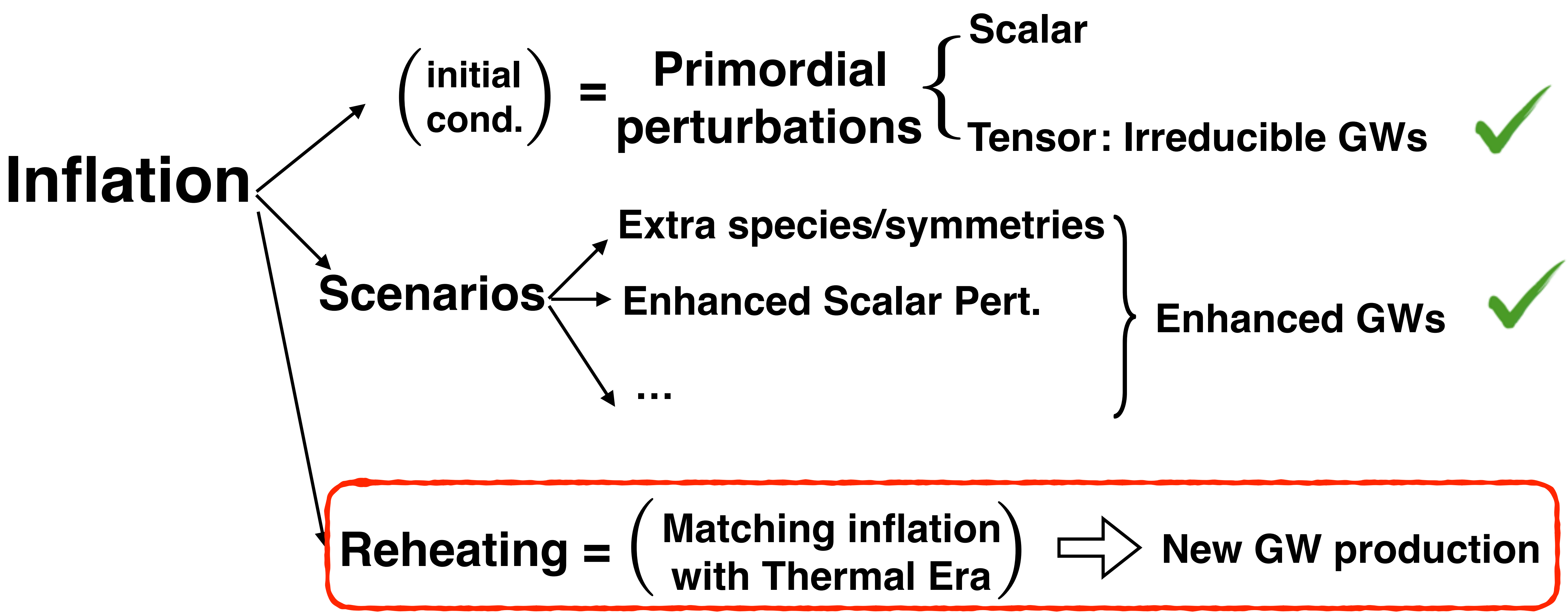
Has LIGO detected PBH's ?



PBH candidate for Dark Matter ?

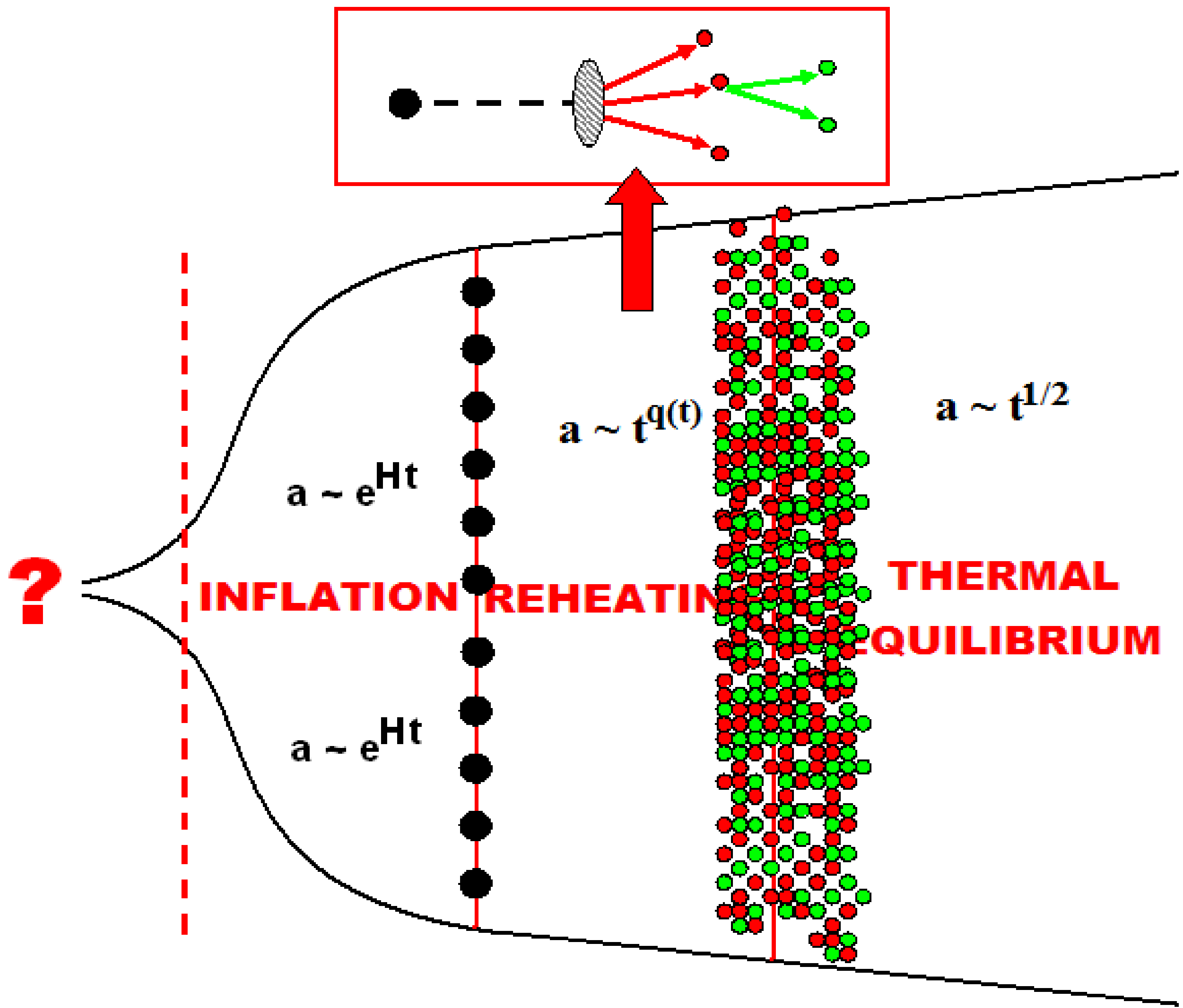
See e.g. papers by
Ali-Haimoud, Byrnes,
Ga-Bellido, Sasaki,
Zumalacarregui, … et al

INFLATIONARY COSMOLOGY



GWs from (p)Reheating

INFLATION ⟶ REHEATING ⟶ BIG BANG THEORY

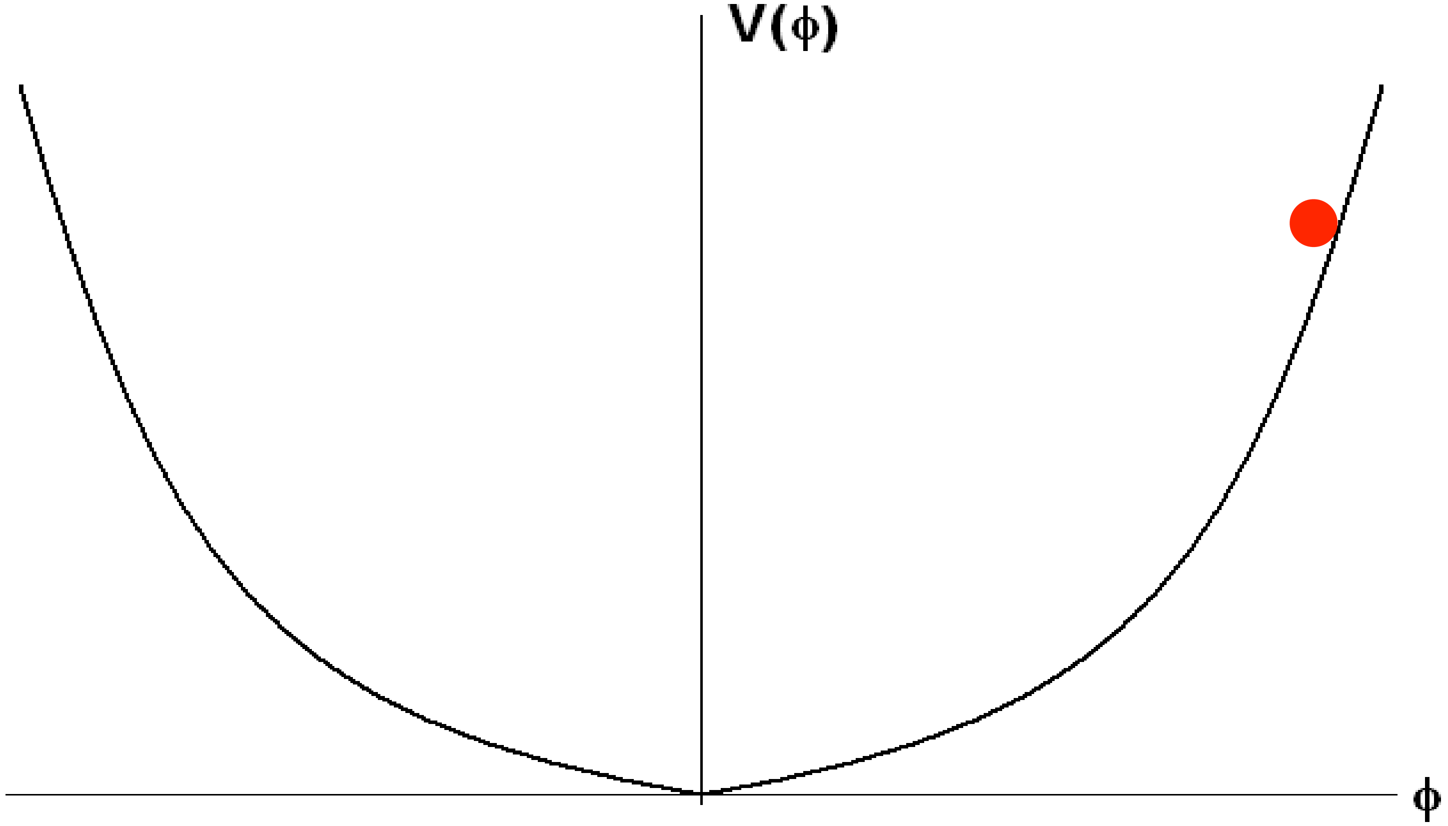


SCALAR (P)REHEATING

1) Chaotic Scenarios: PARAMETRIC RESONANCE

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

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



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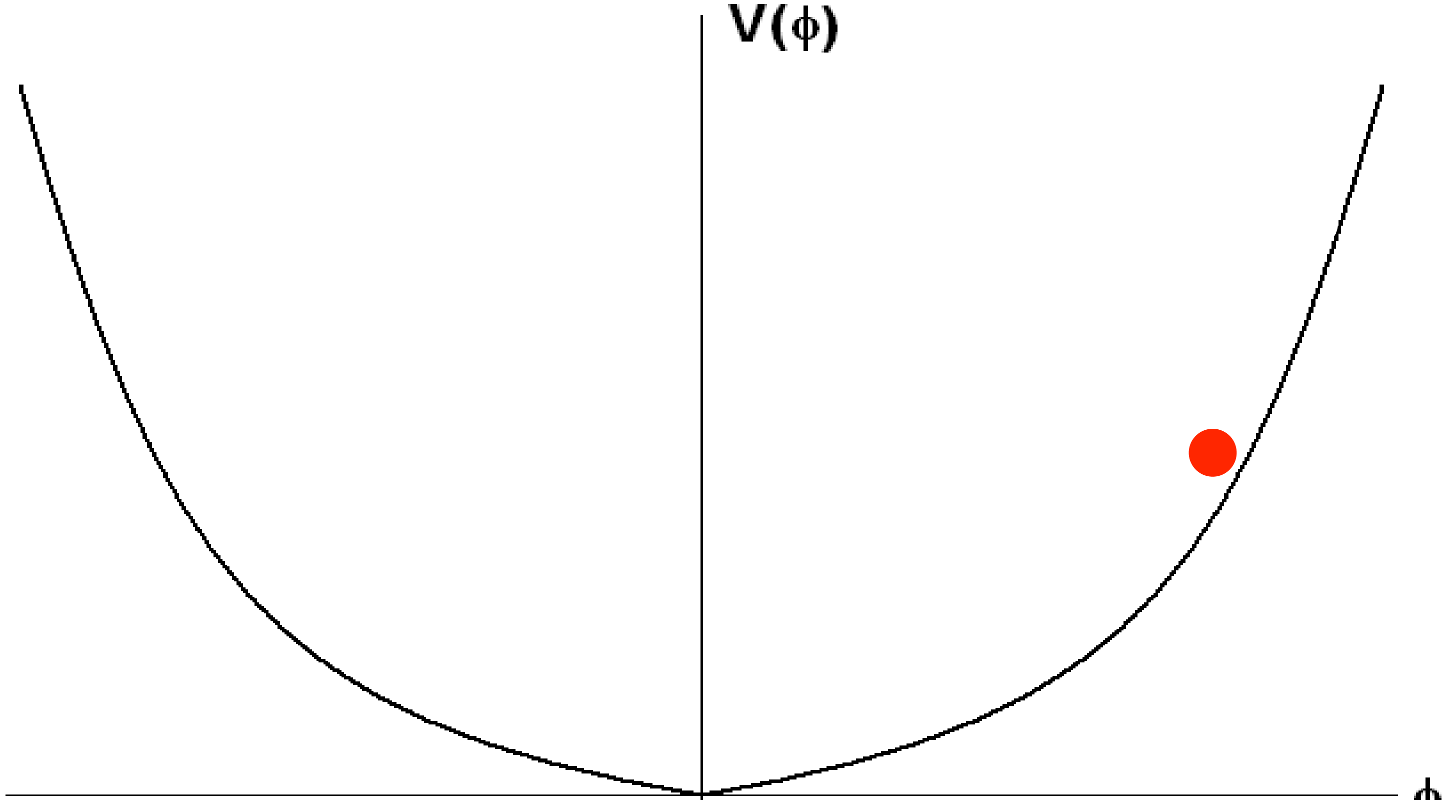

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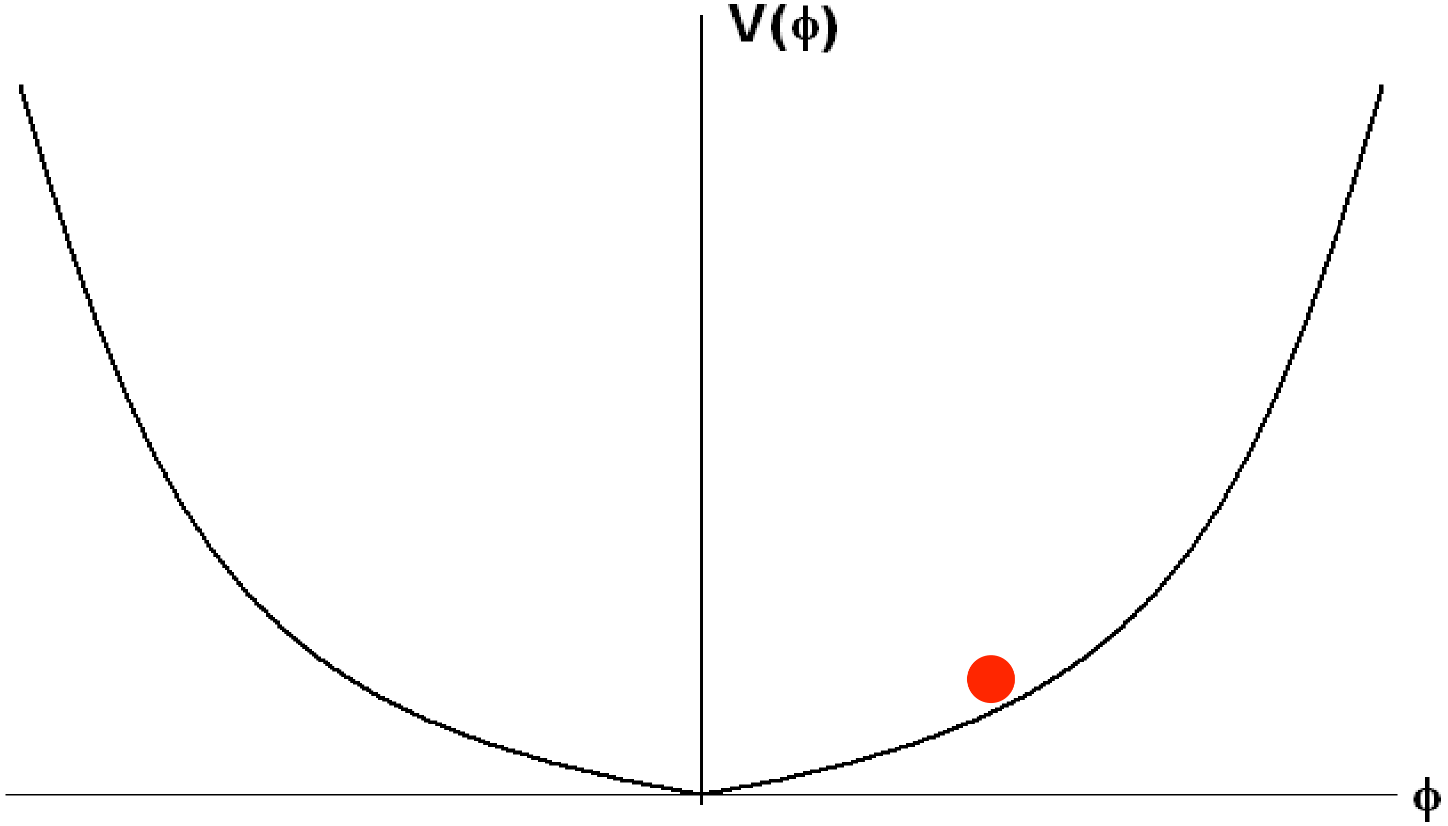

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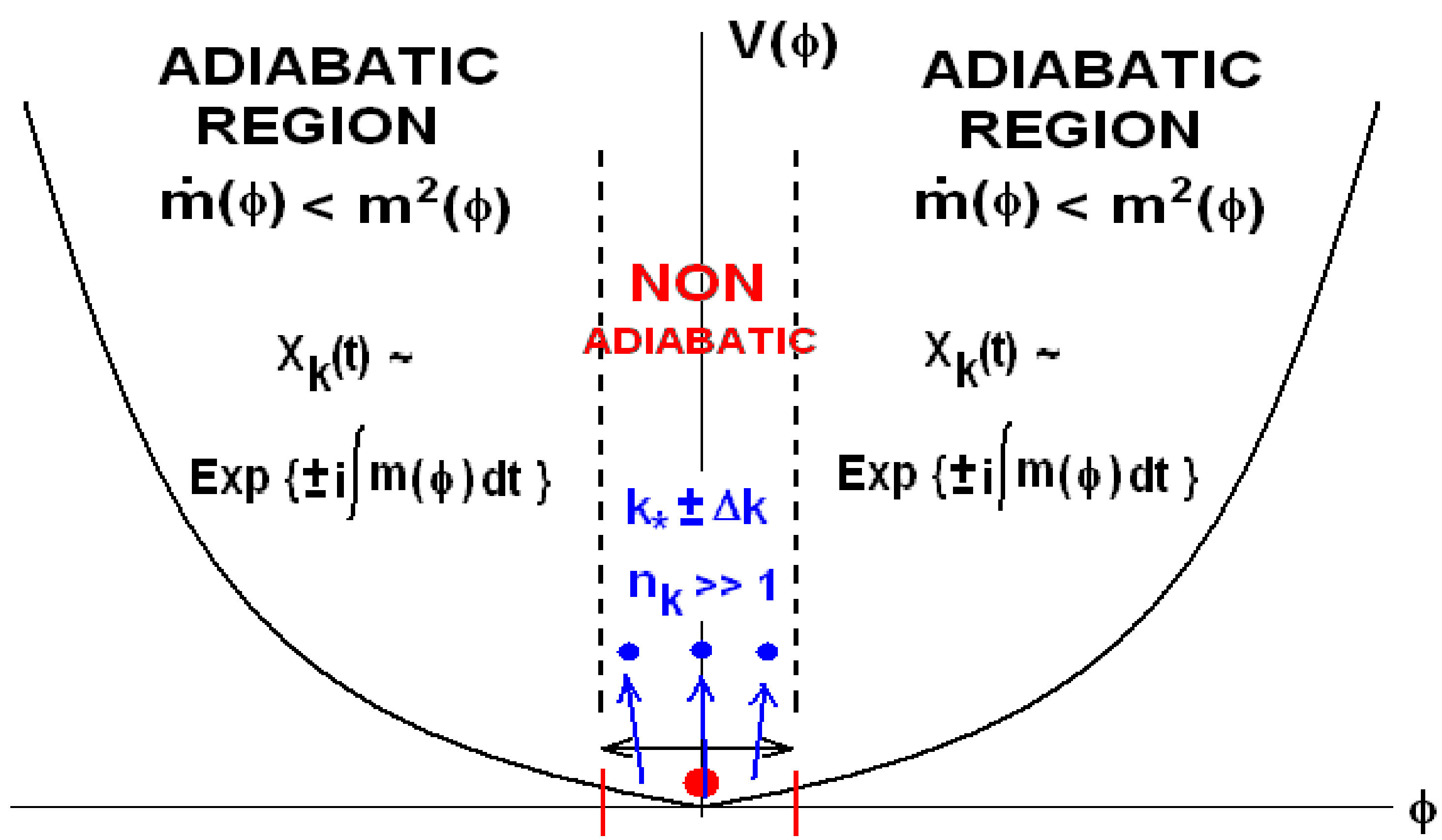

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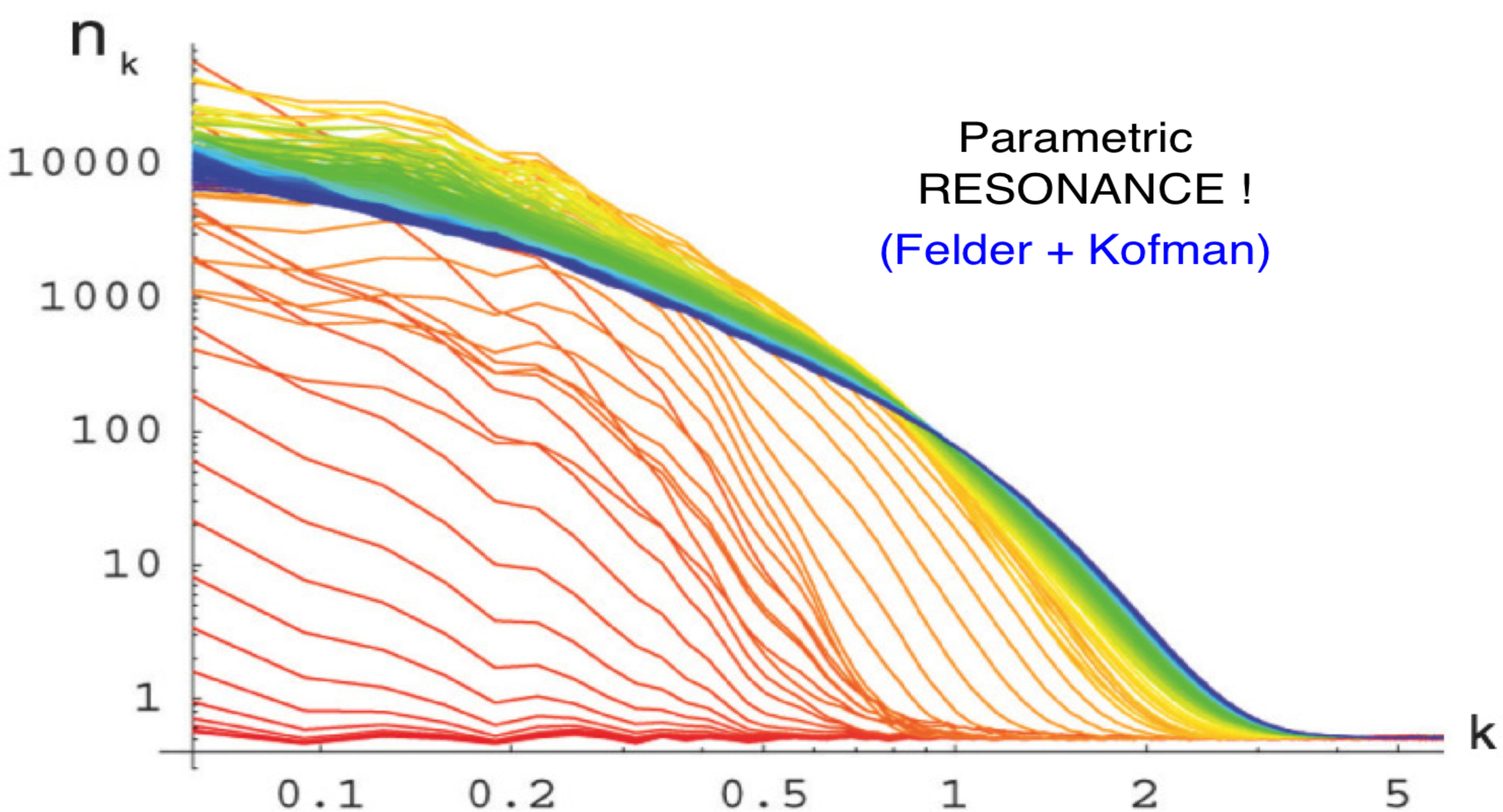


SCALAR (P)REHEATING

2) Hybrid Scenarios : SPINODAL INSTABILITY

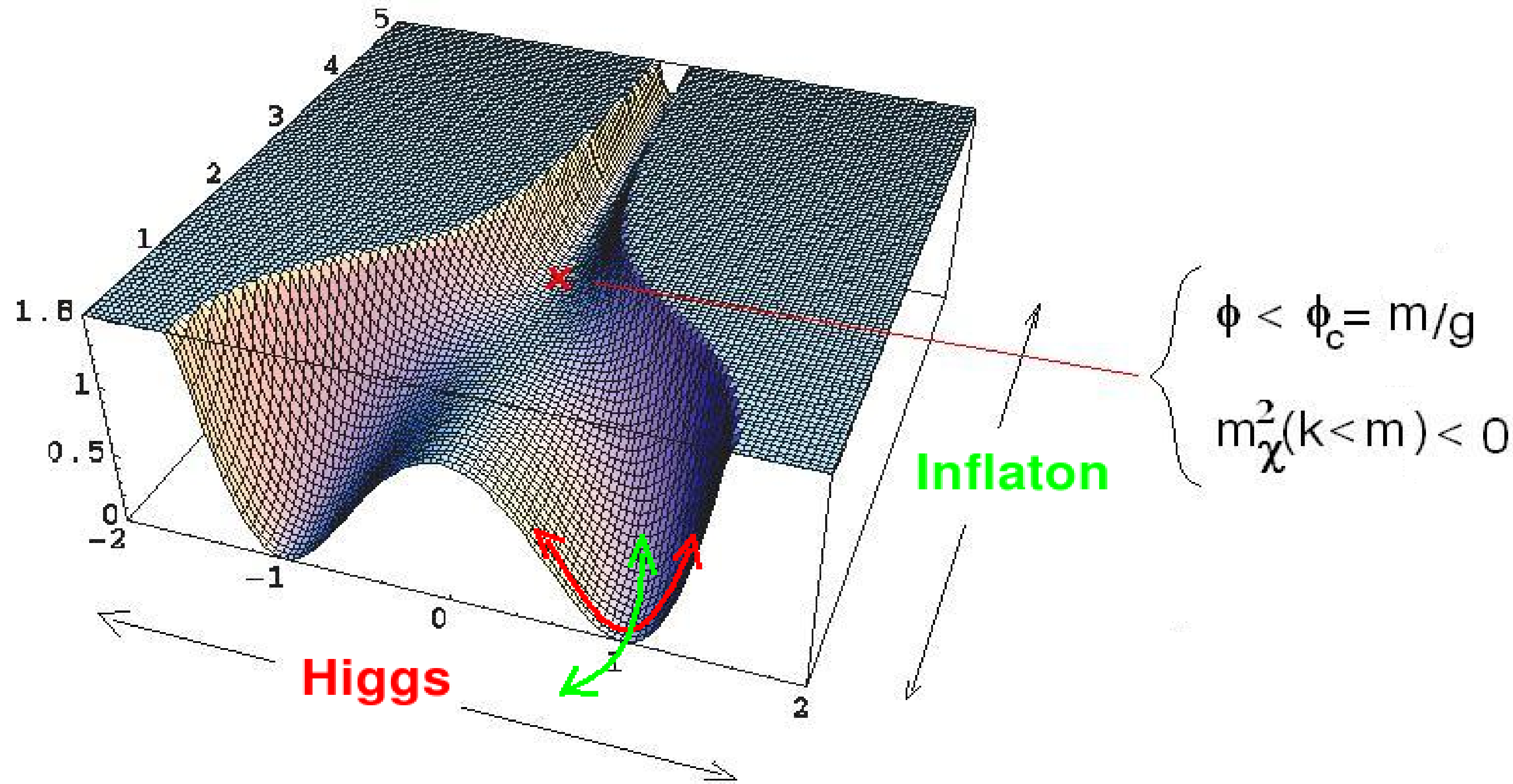
$$\ddot{\phi}(t) + (\mu^2 + g^2|\chi|^2)\phi(t) = 0$$

$$\ddot{\chi}_k + \left(k^2 + m^2\left(\frac{\phi^2}{\phi_c^2} - 1\right) + \lambda|\chi|^2\right)\chi_k = 0$$

$(k < m = \sqrt{\lambda} v)$

$\chi_k, n_k \sim e^{\sqrt{m^2 - k^2}\,t}$

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: $\begin{cases} L_i \sim 1/k_i \\ \delta\rho/\rho \gtrsim 1 \\ v \approx c \end{cases}$

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

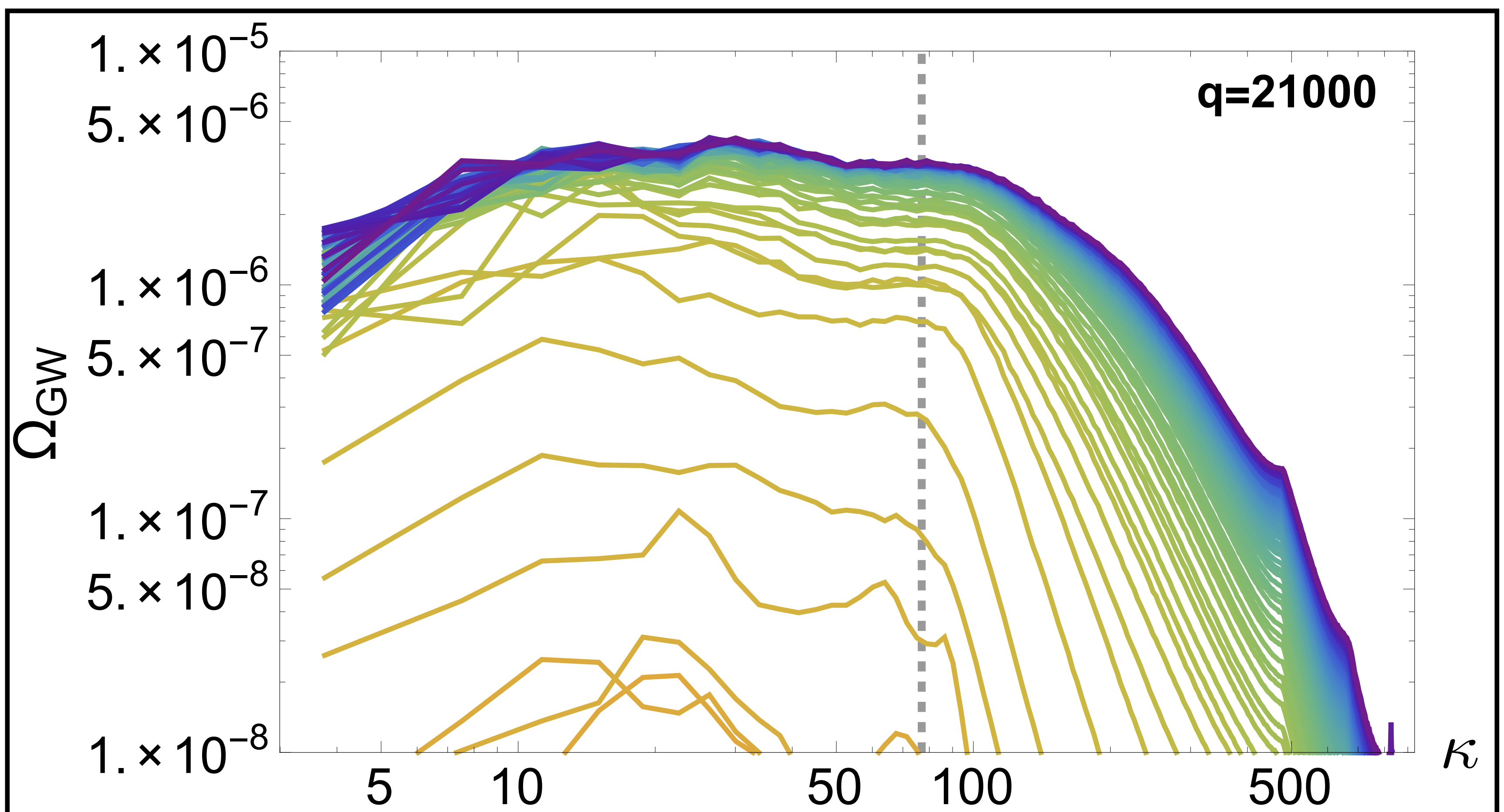
Parameter Dependence (Peak amplitude)

$$\omega^2 \equiv V''(\Phi_I)$$

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

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

Resonance Param.



(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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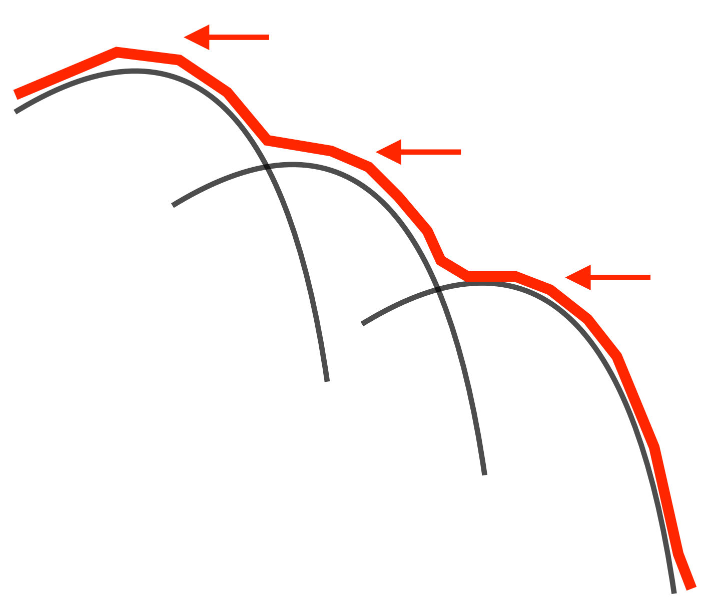
Large amplitude ! ... but at high Frequency !

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



different couplings
... different peaks ?

INFLATIONARY PREHEATING

Parameter Dependence (Peak amplitude**)**

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

Very unfortunate... no detectors there !

INFLATIONARY PREHEATING

Parameter Dependence (Peak amplitude**)**

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

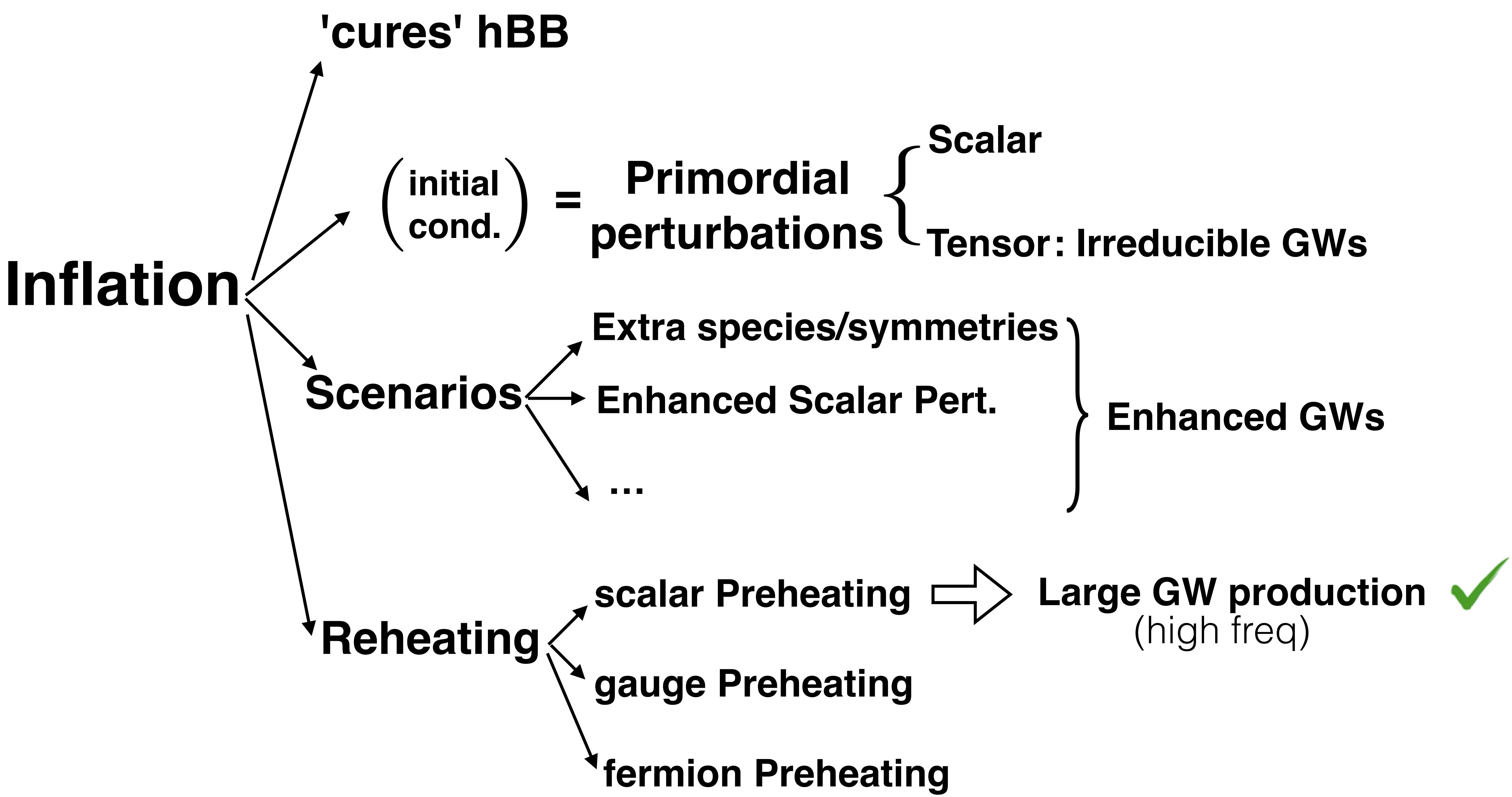
$$\Omega_{\rm GW}^{(o)} \sim 10^{-11}\,, \quad @ \quad \begin{cases} f_o \sim 10^8 - 10^9~{\rm Hz} & \boxed{\lambda \sim 0.1}~\text{(natural)} \\ f_o \sim 10^2~{\rm Hz} & \boxed{\lambda \sim 10^{-28}}~\text{(fine-tuning)} \end{cases}$$

Large amplitude !

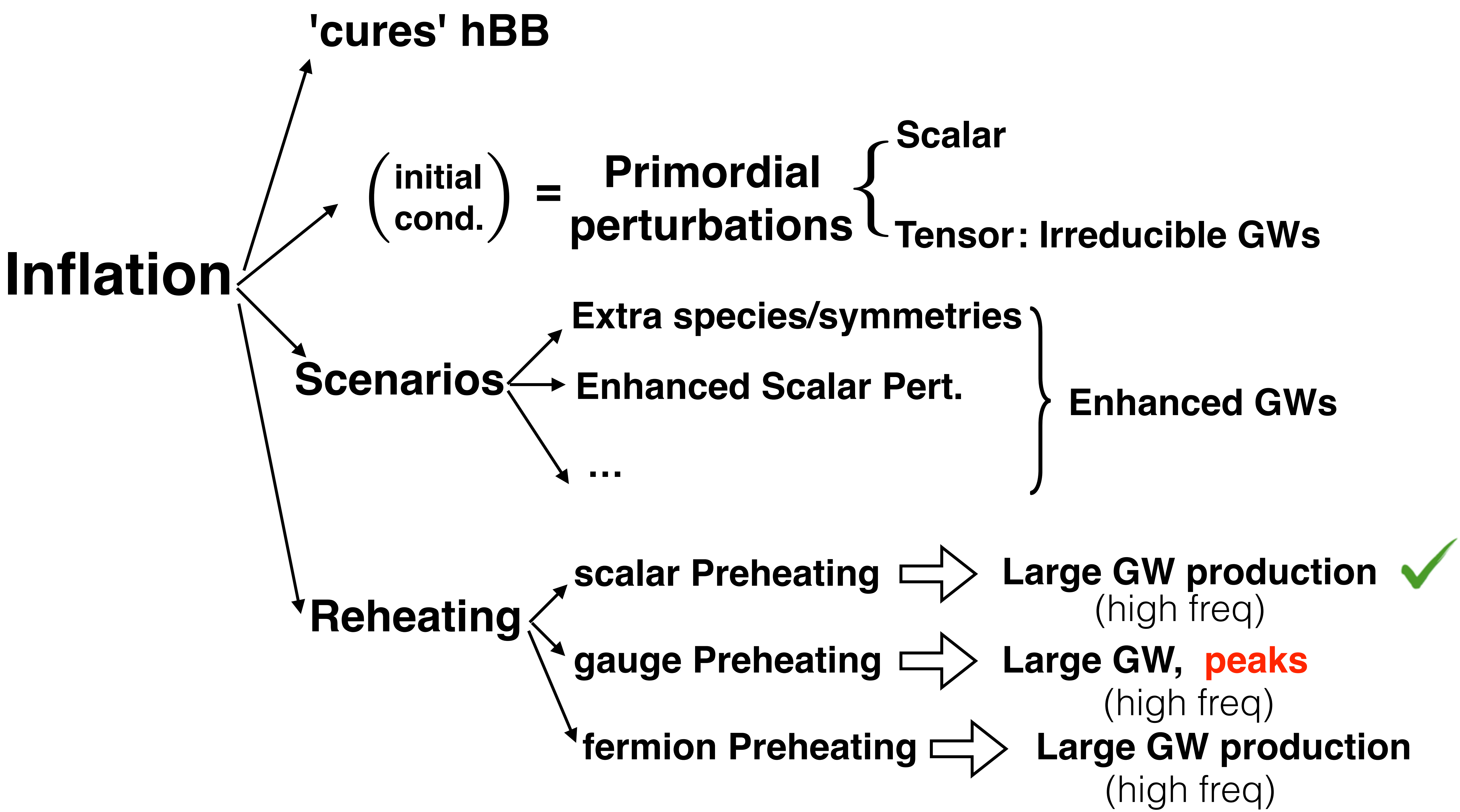
(for $v \simeq 10^{16}$ GeV)

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 ✓

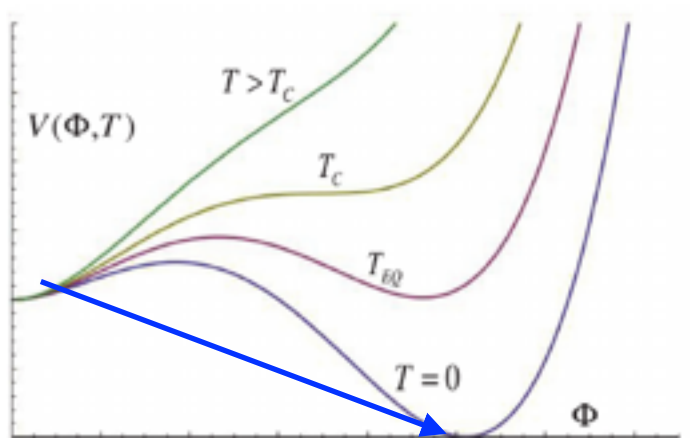
Early Universe

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

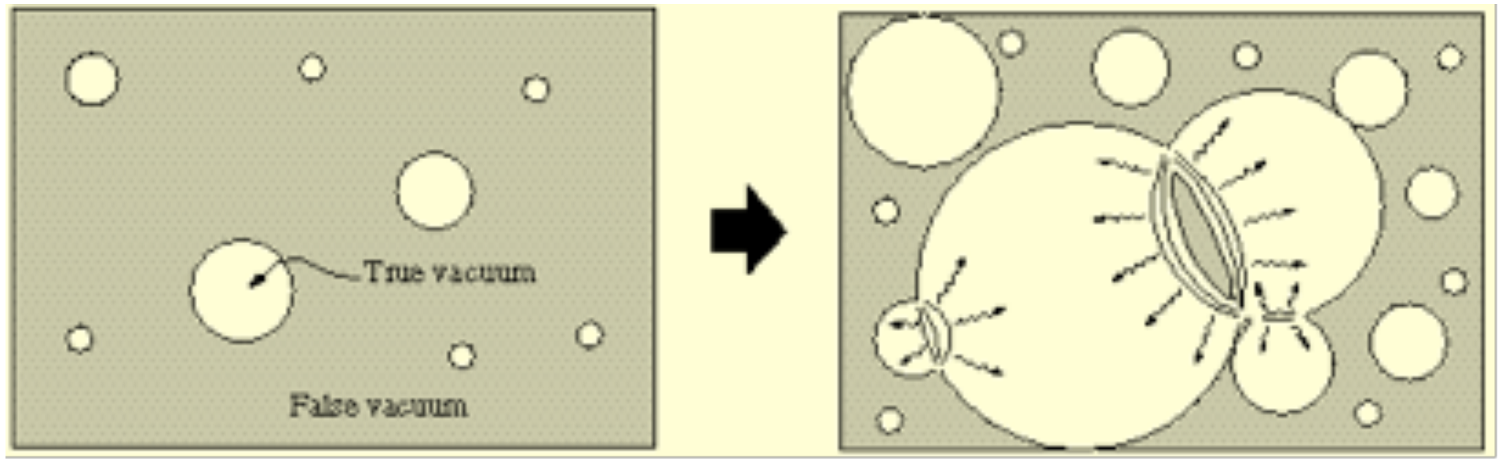
First order phase transitions

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

true and **false** vacua



quantum tunneling



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 ?

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

GW generation <—> bubbles properties

BUBBLE COLLISIONs

SOUND WAVES & MDH TURBULENCE

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

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

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

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

Parameter List
(not independent)

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

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

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

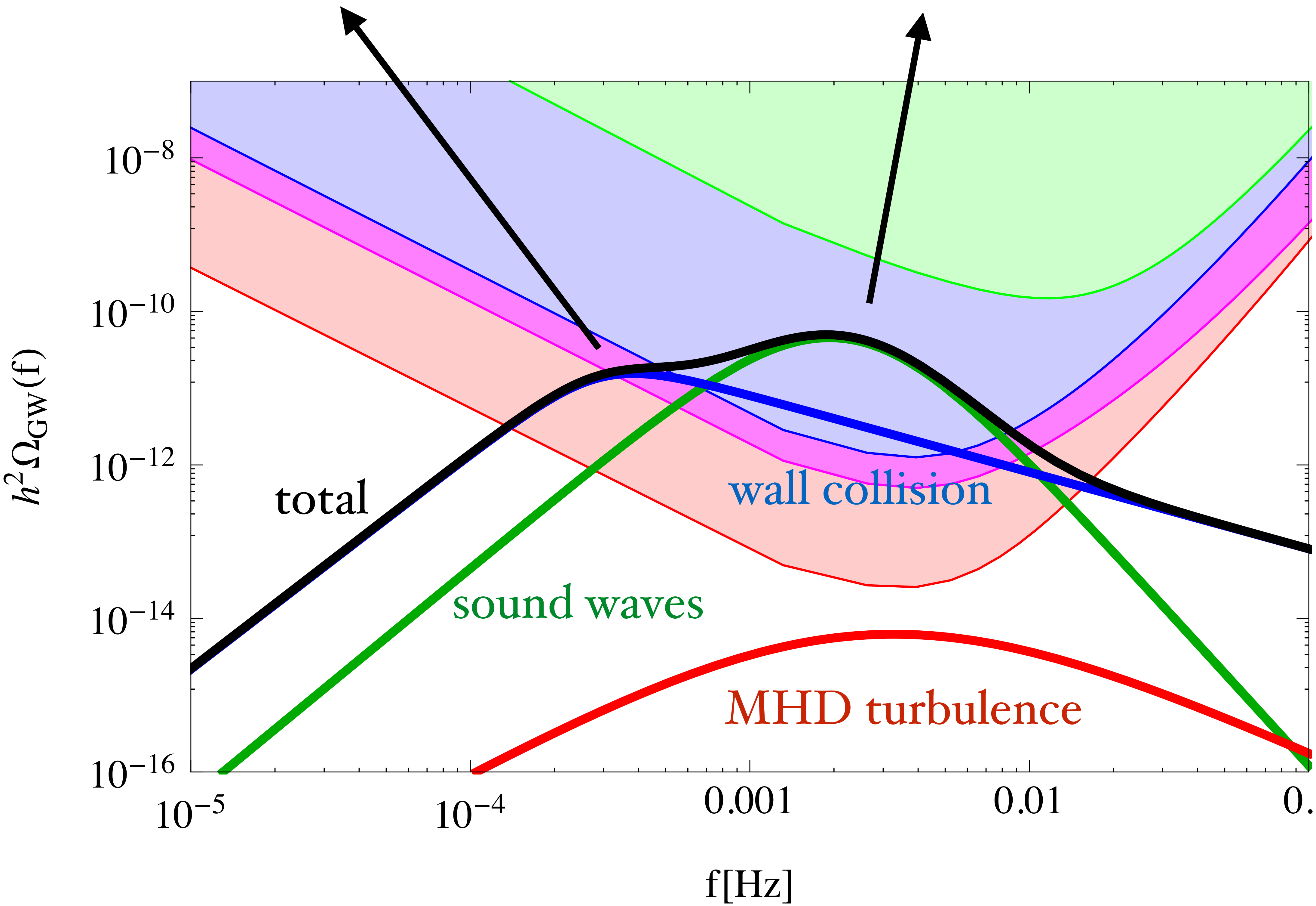
$$\alpha = \frac{\rho_{\mathrm{vac}}}{\rho_{\mathrm{rad}}^*}$$

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

Example of spectrum

peak of bubble collisions β

peak of fluid-related processes $1/R_*$



Caprini et al, arXiv:1512.06239

Evaluation of the signal

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

(Huber and Konstandin arXiv:0806.1828)

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

(Hindmarsh et al arXiv:1504.03291)

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

(Caprini et al arXiv:0909.0622)

Evaluation of the signal

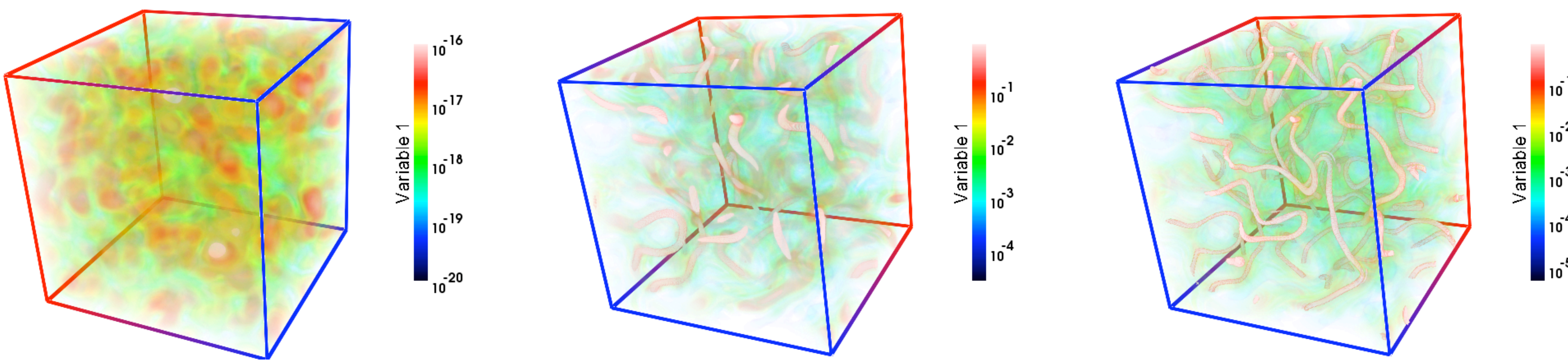
- **bubble collision**... ...tions
  ...n arXiv:0806.1828)
- **sound w**... ...l fluid
  ...Xiv:1504.03291)
- **MDH turb**...
  ... al arXiv:0909.0622)

LISA
new probe
of BSM physics!

(complementary to
particle colliders)

What about Cosmic Defects ?

(aftermath products of a PhT)



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

Cosmic Defects

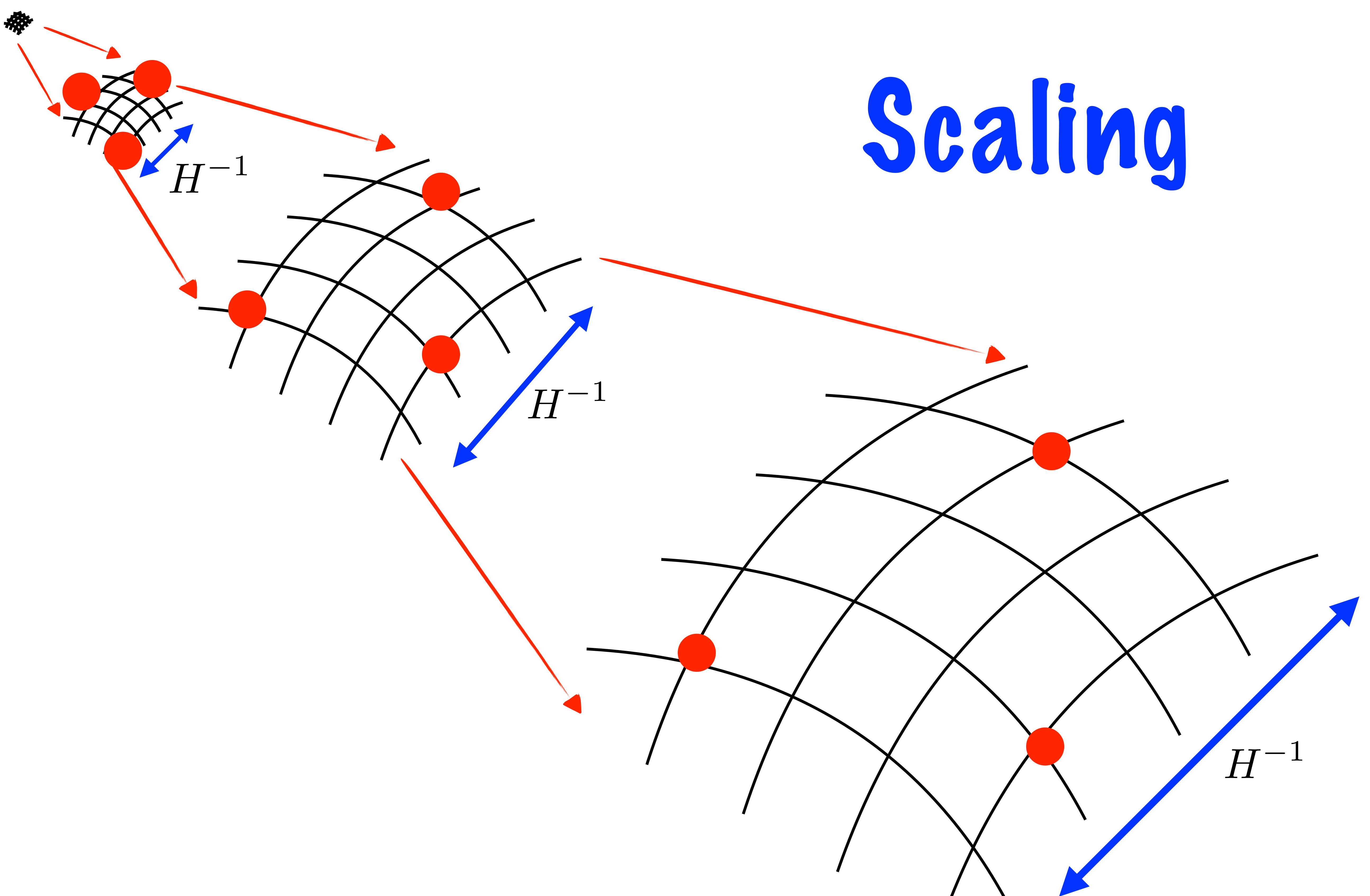
DEFECTS: Aftermath of PhT $\rightarrow \begin{cases} \begin{cases} \text{Domain Walls} \\ \text{Cosmic Strings} \\ \text{Cosmic Monopoles} \end{cases} \\ \text{Non - Topological} \end{cases}$

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

(Kibble' 76)

SCALING: $\lambda(t) = \text{const.} \quad \rightarrow \quad \lambda \sim 1$

Cosmic Defects



GWs from a scaling network of cosmic defects

energy scale

scale inv.

scale dependent

Total GW Spectrum

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

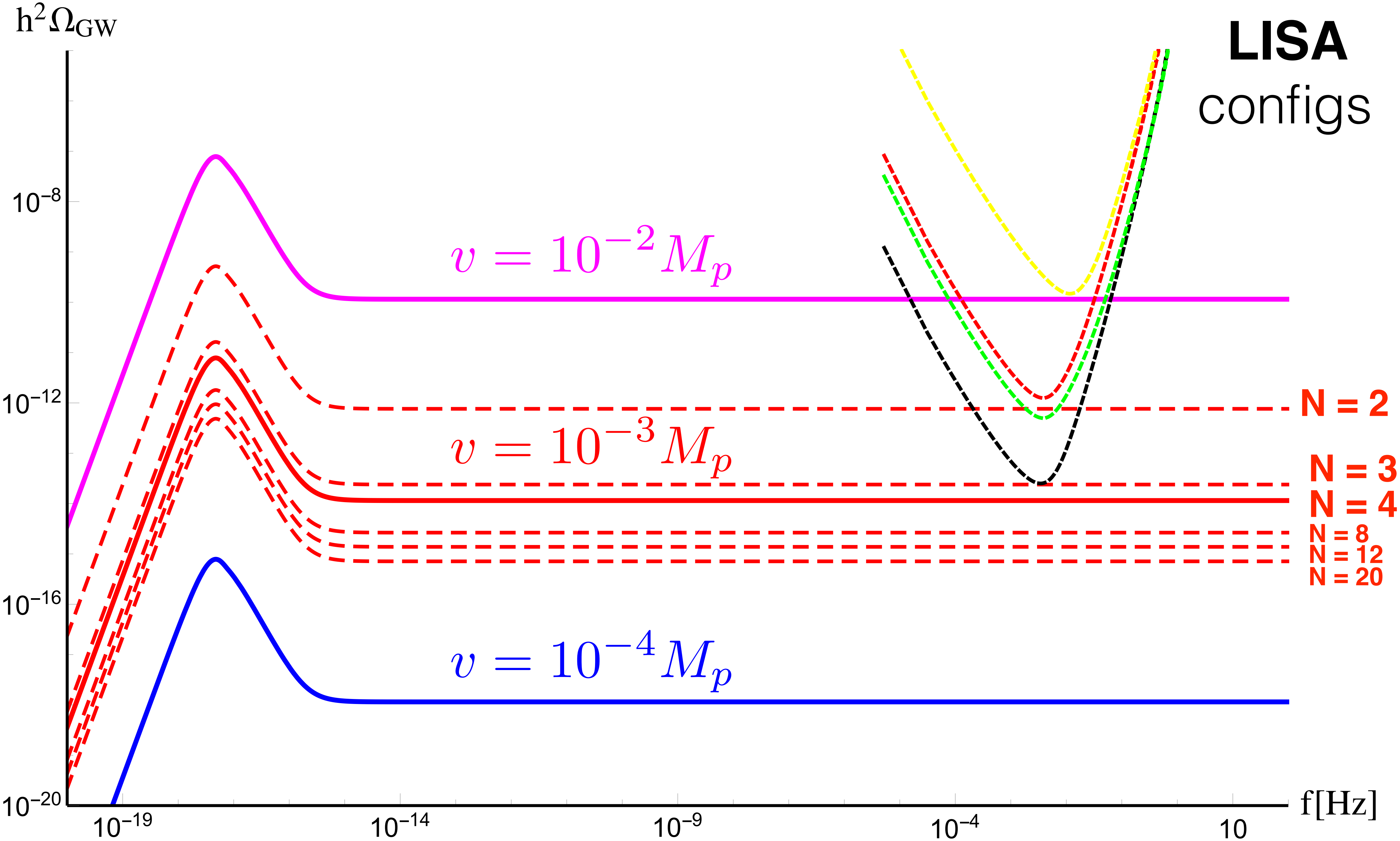
RD $$F_U^{(\rm R)} \equiv \frac{32}{3}\int_0^x dx_1 dx_2\, (x_1 x_2)^{1/2} \cos(x_1 - x_2)\, U_{\rm RD}(x_1, x_2)$$

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

DGF, Hindmarsh, Urrestilla, PRL '13

More on GW from Defect Networks

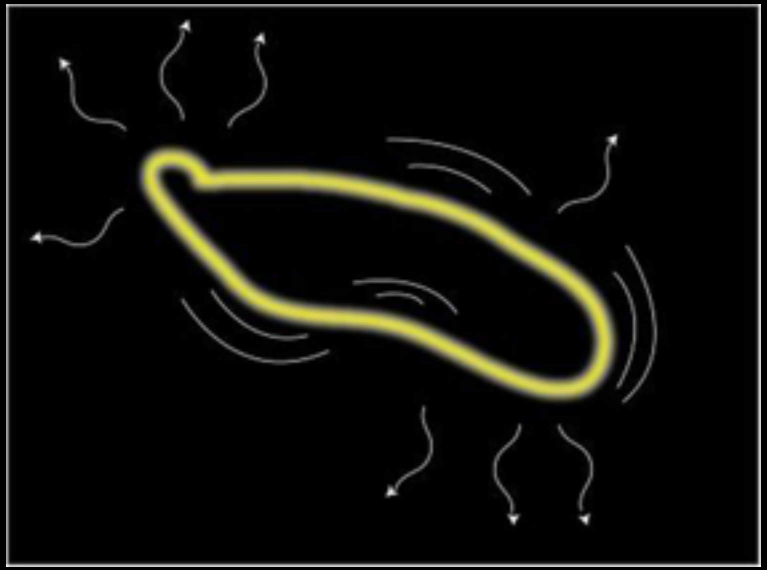
$$h^2\Omega_{\rm GW}^{(o)} = h^2\Omega_{\rm rad}^{(o)}\left(\frac{V}{M_p}\right)^4\left[F_U^{(R)} + F_U^{(M)}\left(\frac{k_{\rm eq}}{k}\right)^2\right]$$



What about if Defects are Cosmic Strings ?

Extra emission of GWs ! (Vilenkin '81)

Loops once formed, decay by radiation emission



→ * Boson emission
* UHCR
* …

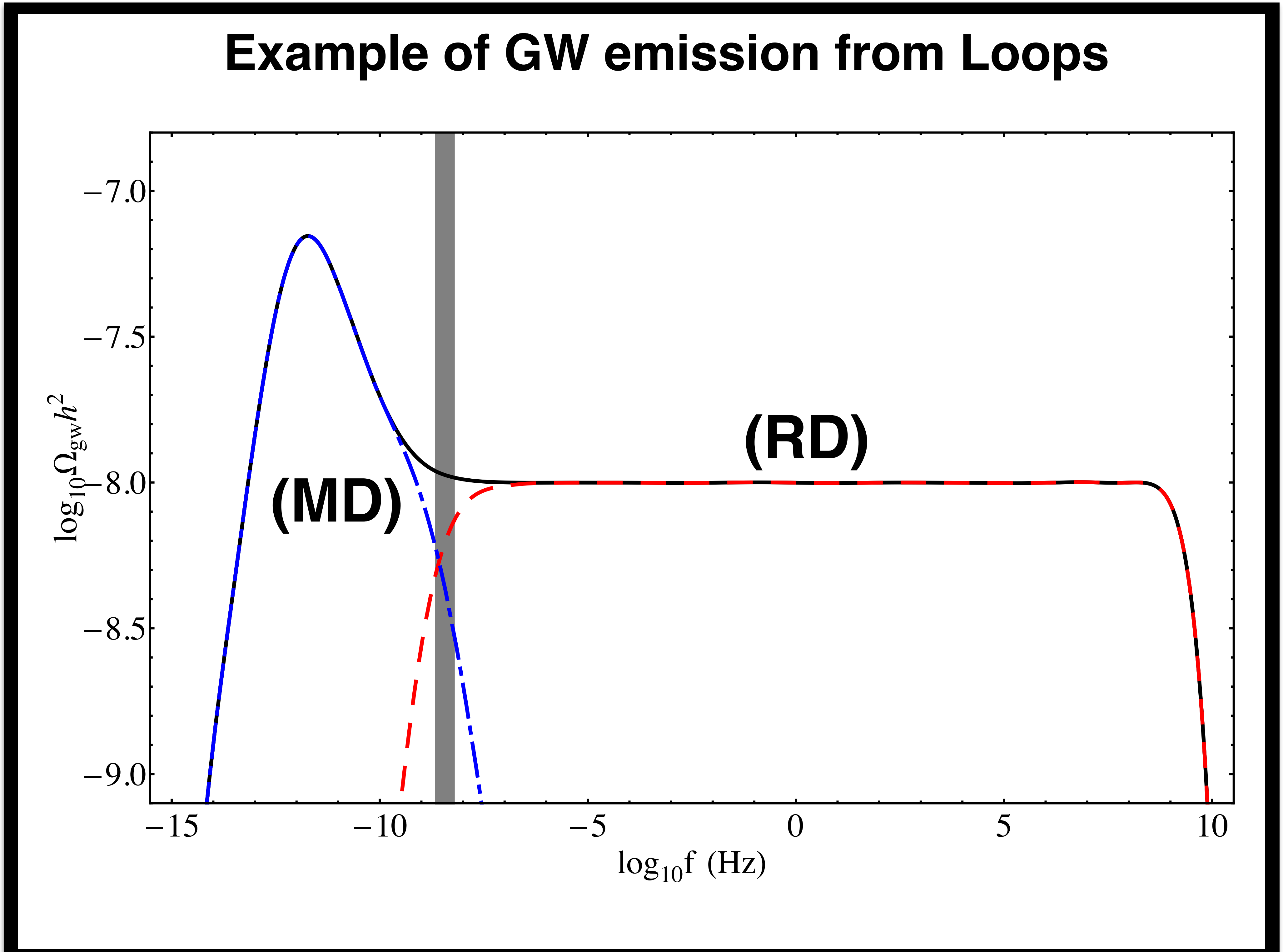
Extra emission of GWs !

String loop (length *l*) oscillates under tension μ

emits GWs in a series of harmonic modes

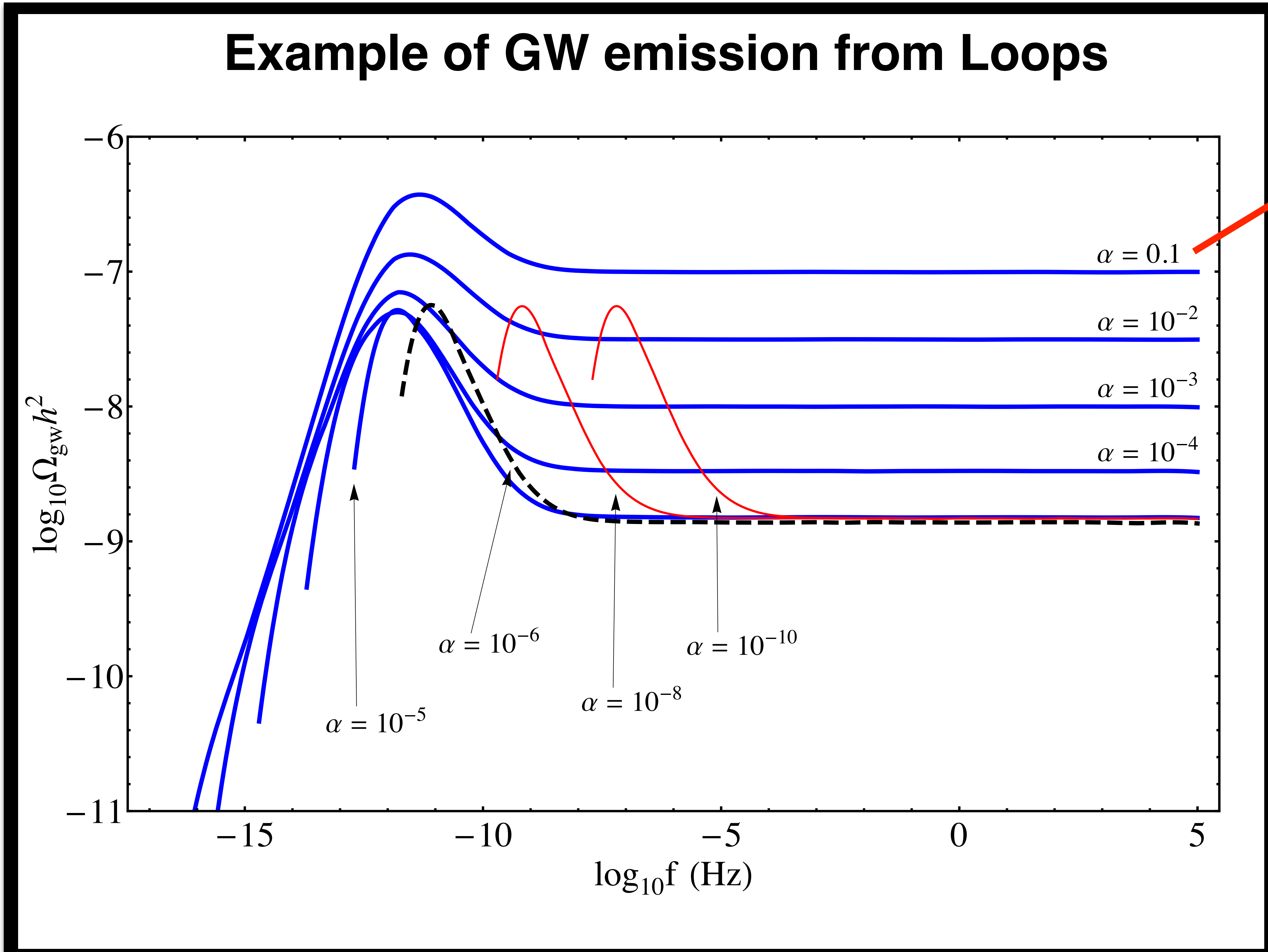
Assuming GW emission dominates …

Cosmic Strings Network: Loop configurations



Sanidas et al 2012

Cosmic Strings Network: Loop configurations



α

loop size

(relative to horizon)

Sanidas et al 2012

Cosmic Strings Network: Loop configurations

Results for 6 links, SNR=20

LISA Prospects

- A1M2
  Conservative limit: $G\mu/c^2 < 4.4 \times 10^{-10}$
  Large loops: $G\mu/c^2 < 1.5 \times 10^{-16}$
- A2M2
  Conservative limit: $G\mu/c^2 < 1.1 \times 10^{-10}$
  Large loops: $G\mu/c^2 < 2.1 \times 10^{-17}$
- A2M5
  Conservative limit: $G\mu/c^2 < 7.0 \times 10^{-11}$
  Large loops: $G\mu/c^2 < 1.3 \times 10^{-17}$
- A5M5
  Conservative limit: $G\mu/c^2 < 1.4 \times 10^{-11}$
  Large loops: $G\mu/c^2 < 4.4 \times 10^{-18}$ $\rightarrow$ $v \lesssim 10^{10} GeV$

(From Sanidas et al, LISA GW cosmology 3rd encounter)

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

SUMMARY

0) GW definition

Early Universe

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

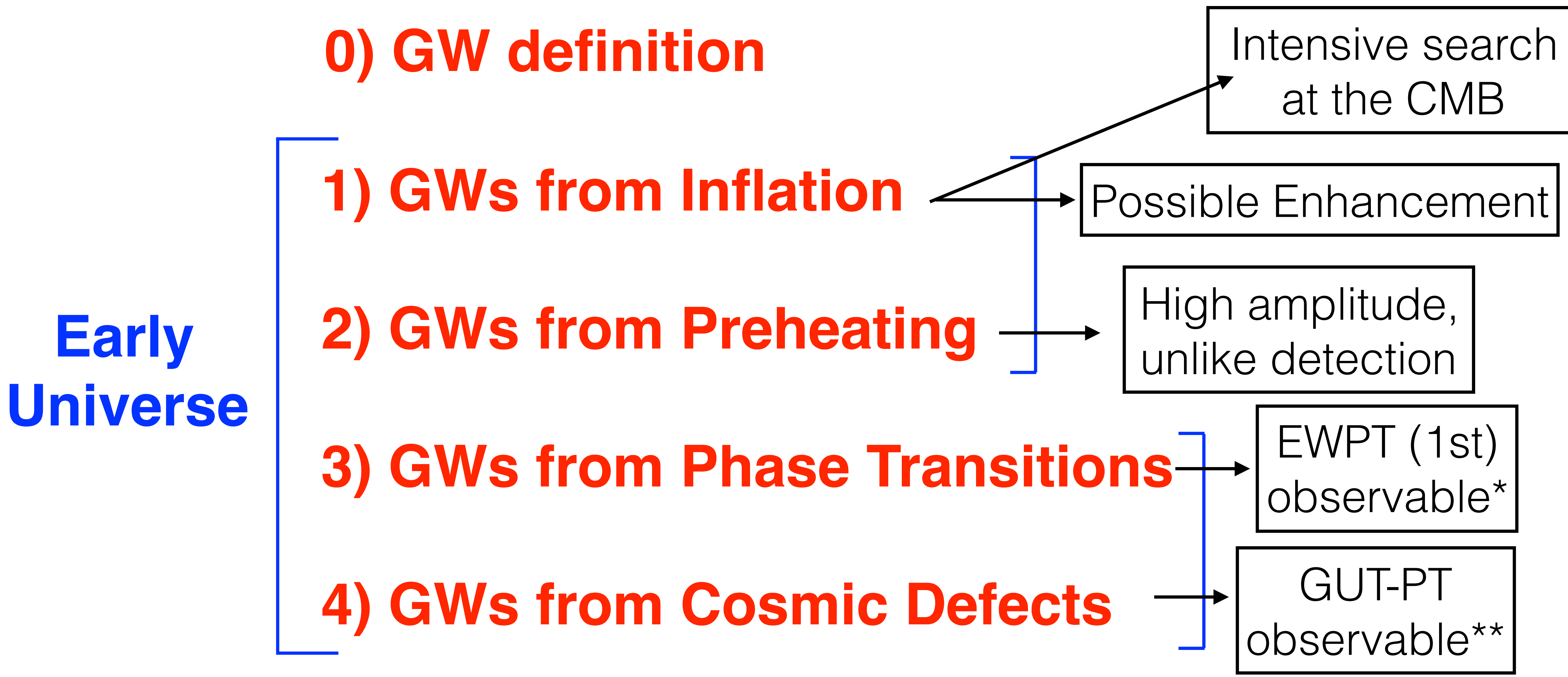
2) GWs from Preheating → High amplitude, unlike detection

3) GWs from Phase Transitions

4) GWs from Cosmic Defects

Gravitational Waves as a probe of the early Universe

SUMMARY



[*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 28th 2018, @ CERN Globe

Cảm ơn bạn rất nhiều vì sự chú ý của bạn !