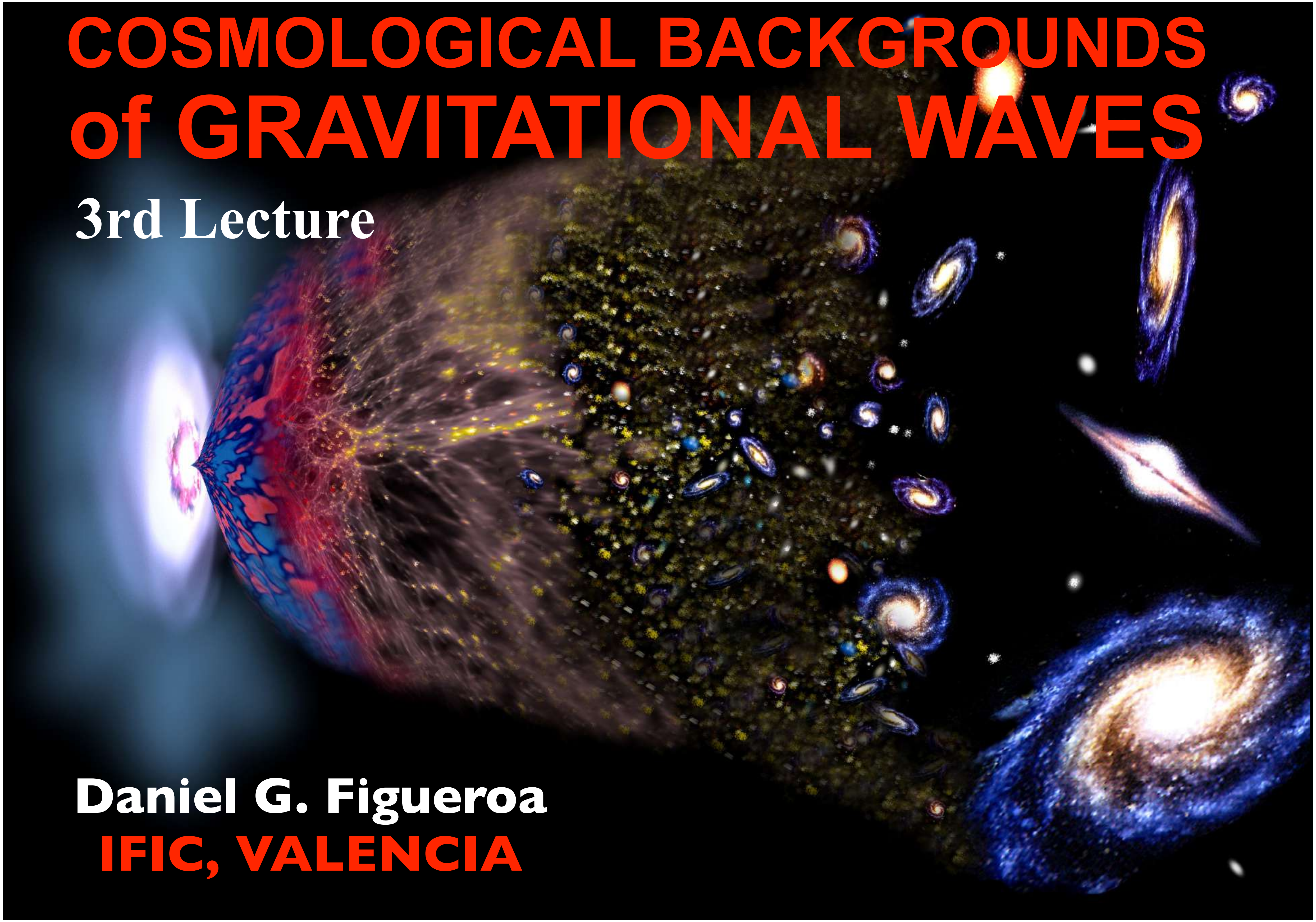
COSMOLOGICAL BACKGROUNDS of GRAVITATIONAL WAVES

3rd Lecture



Daniel G. Figueroa
IFIC, VALENCIA

II Joint ICTP-Trieste/ICTP-SAIFR School on Particle Physics (June 22 - July 3 2020)

Gravitational Waves as a probe of the early Universe

OUTLINE

1) GW definition ✓

Early Universe

2) GWs from Inflation

3) GWs from Preheating ✓

4) GWs from Phase Transitions

5) GWs from Cosmic Defects

3rd lecture

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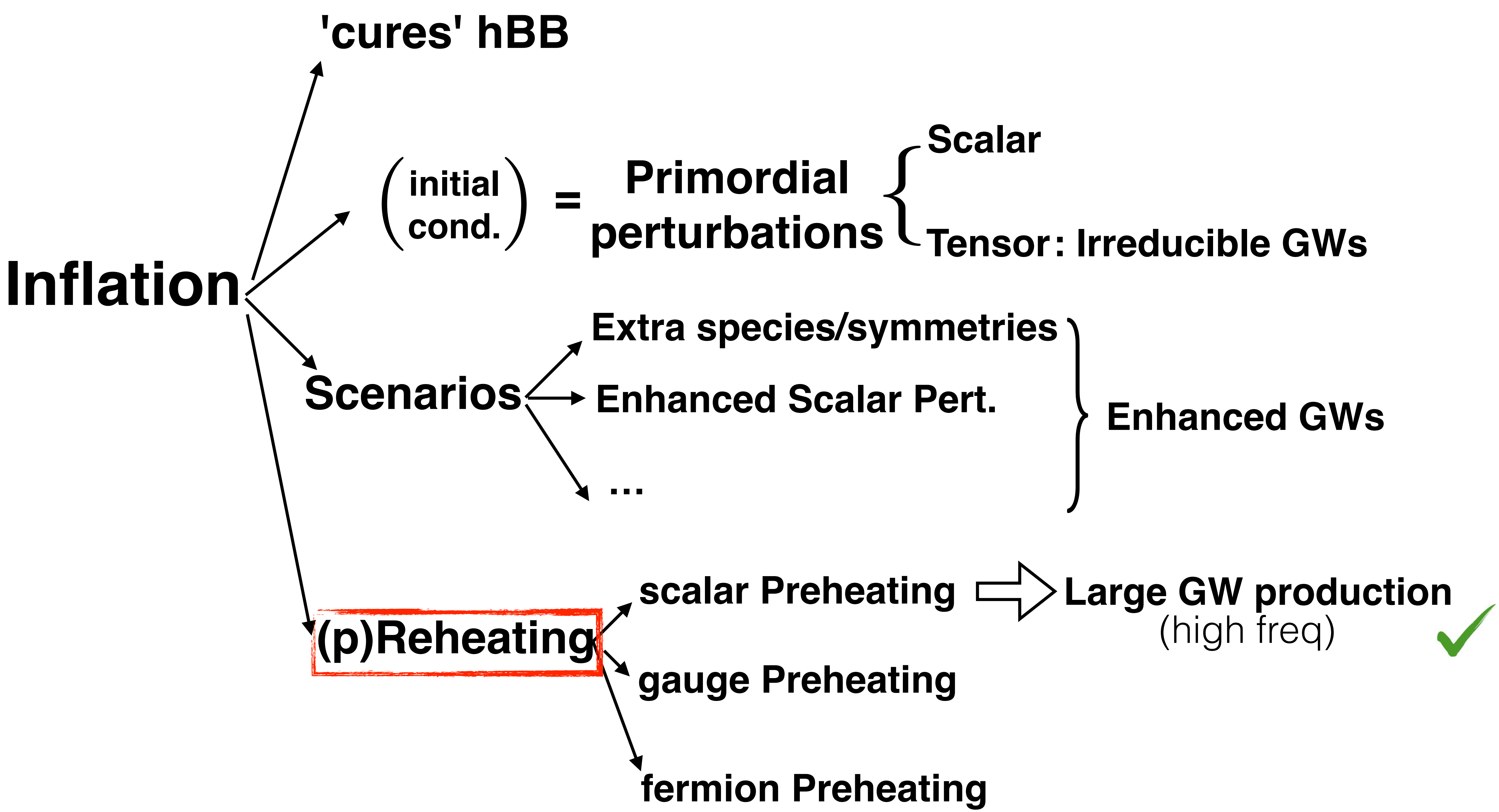
3rd lecture

INFLATIONARY COSMOLOGY



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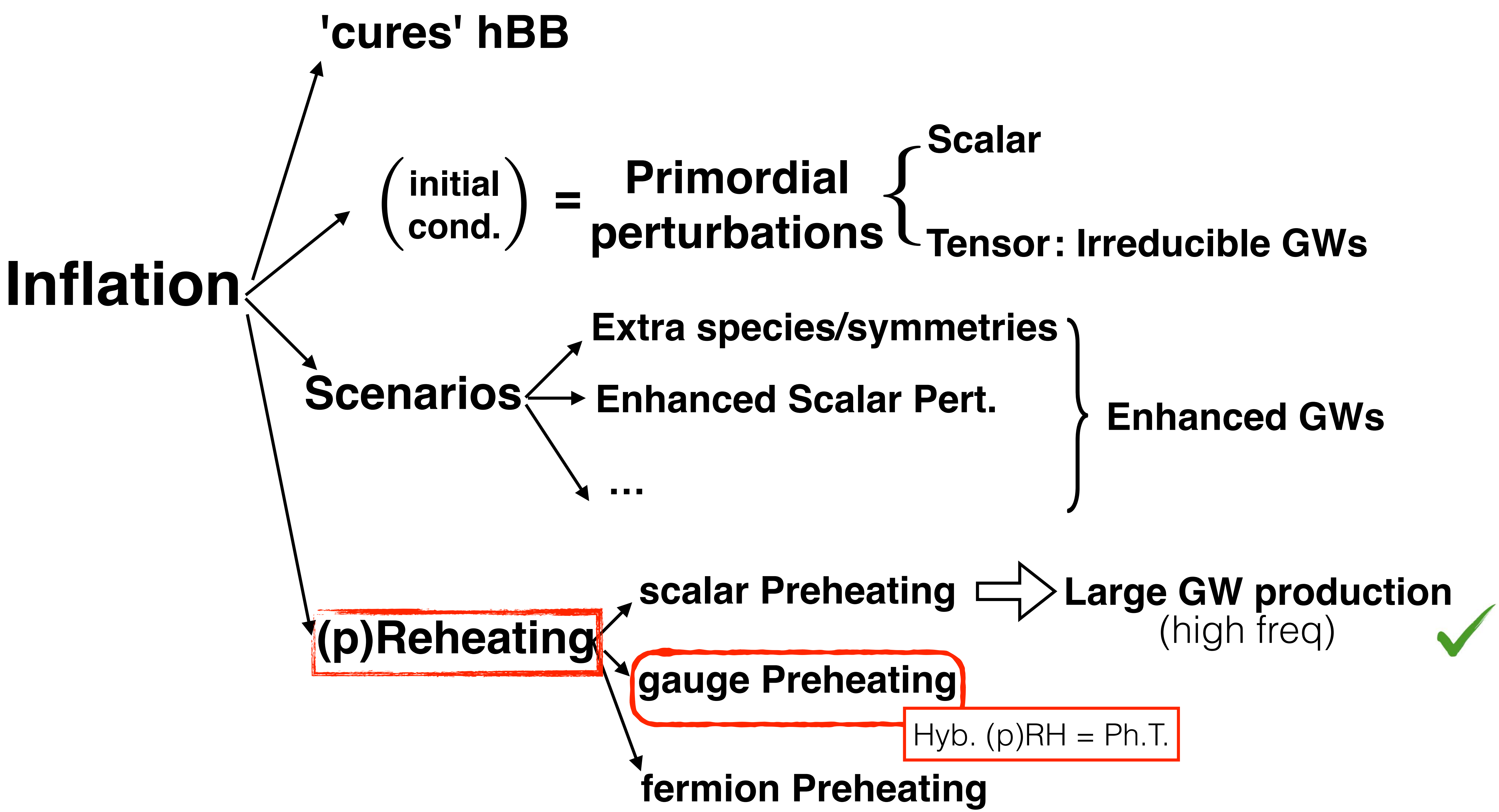

GAUGE (P)REHEATING

Hybrid Preheating = Higgs+Inflaton model

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

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

$m = \sqrt{\lambda}v$

$\phi_c \equiv m/g$

GAUGE (P)REHEATING

Hybrid Preheating = Higgs+Inflaton model

inflaton mass, coupling

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$m = \sqrt{\lambda}v$ (Self-coupling, V.E.V.)

$\phi_c \equiv m/g$ Critical value

GAUGE (P)REHEATING

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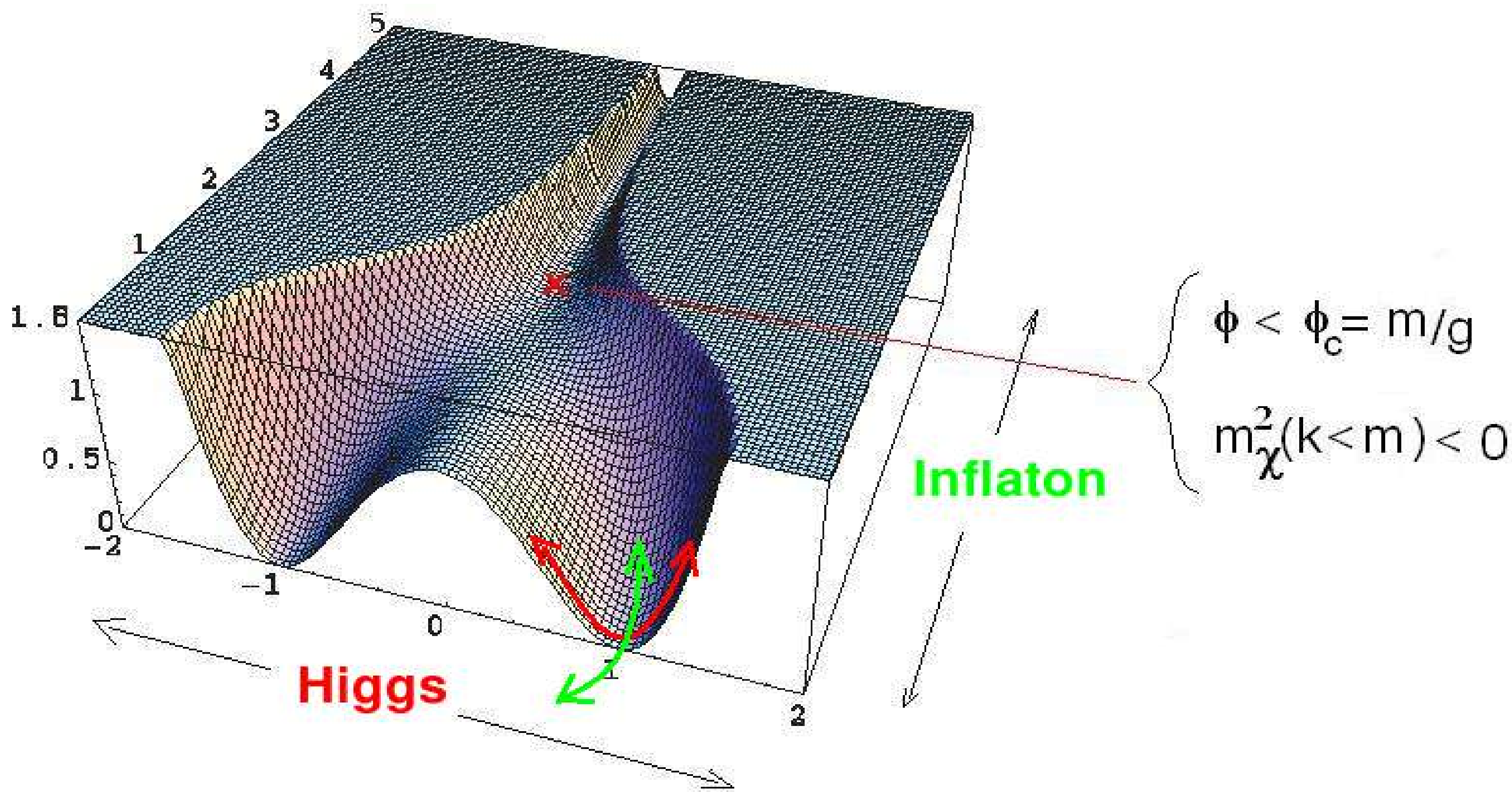
Hybrid Preheating = Phase Transition



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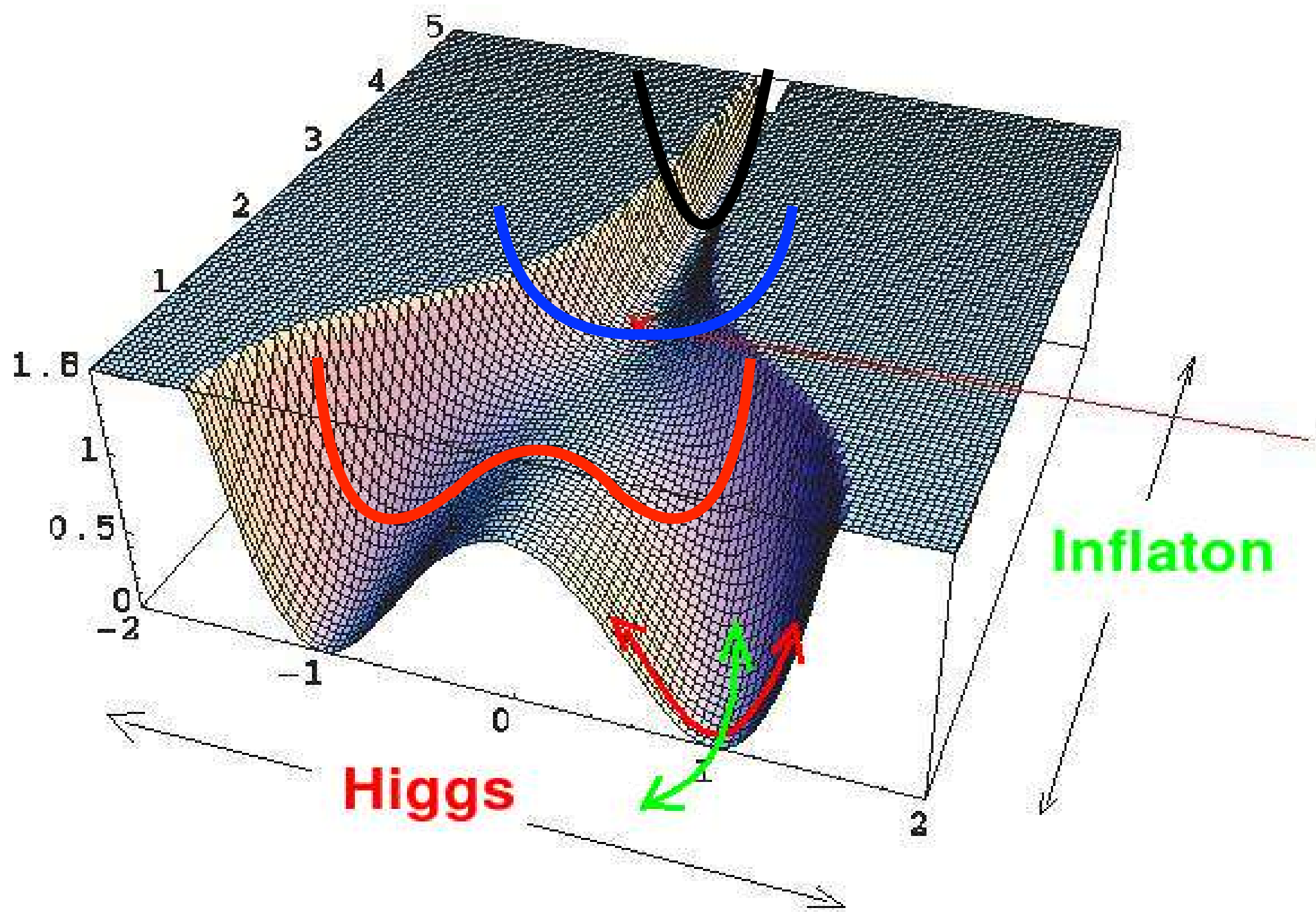

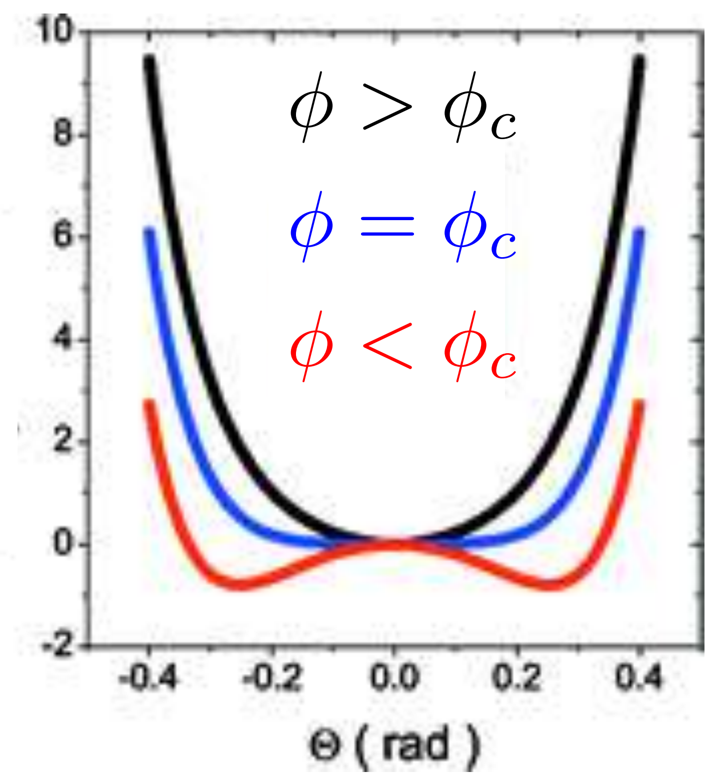

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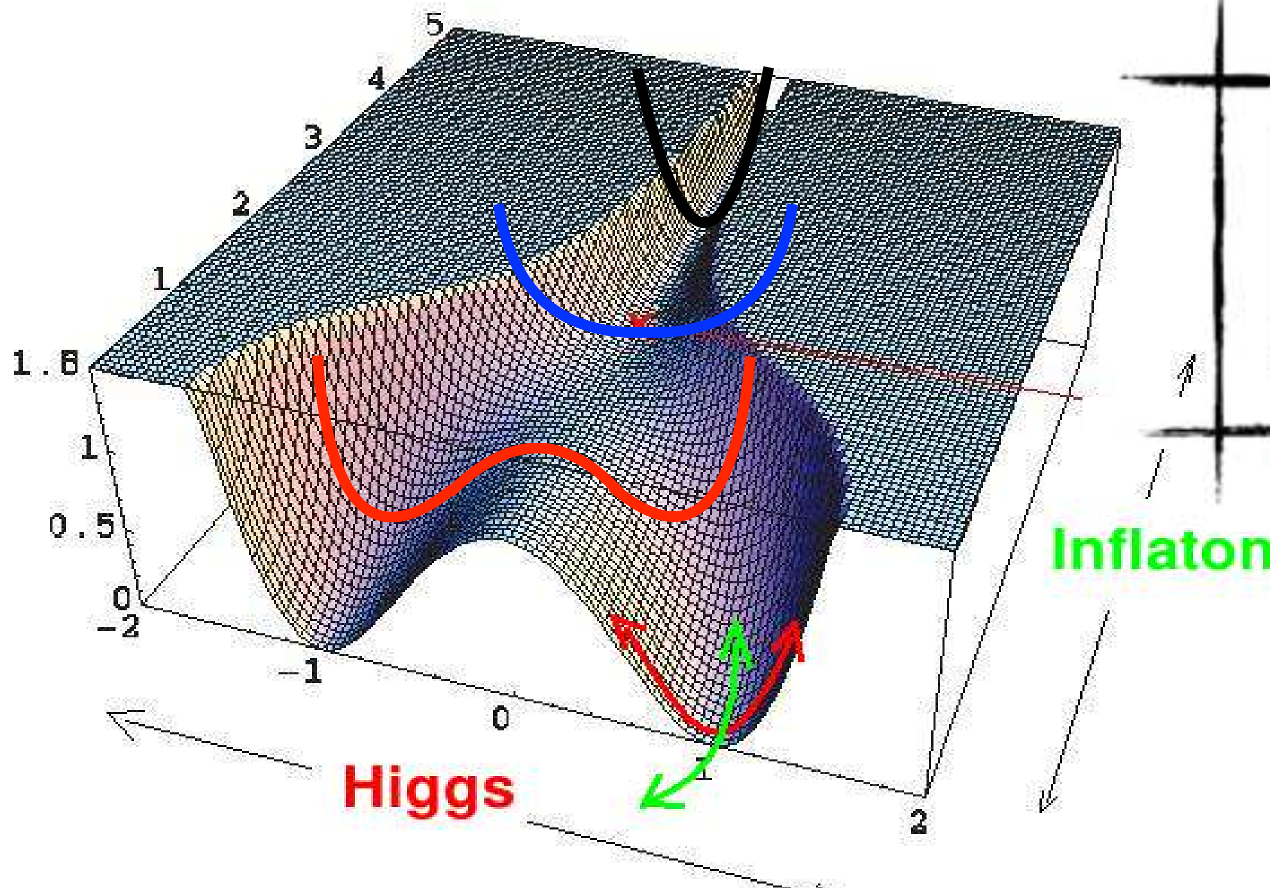
$(k < m = \sqrt{\lambda} v)$

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

Hybrid Preheating = Phase Transition



It is a Phase transition !
by Tachyonic Instability

$\langle\chi\rangle = 0 \;\; \rightarrow \langle\chi\rangle = v$

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

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

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

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

Just to confuse you a little bit: now $\begin{cases} \chi : inflaton \\ \Phi = \frac{\phi}{\sqrt{2}} : Higgs \end{cases}$

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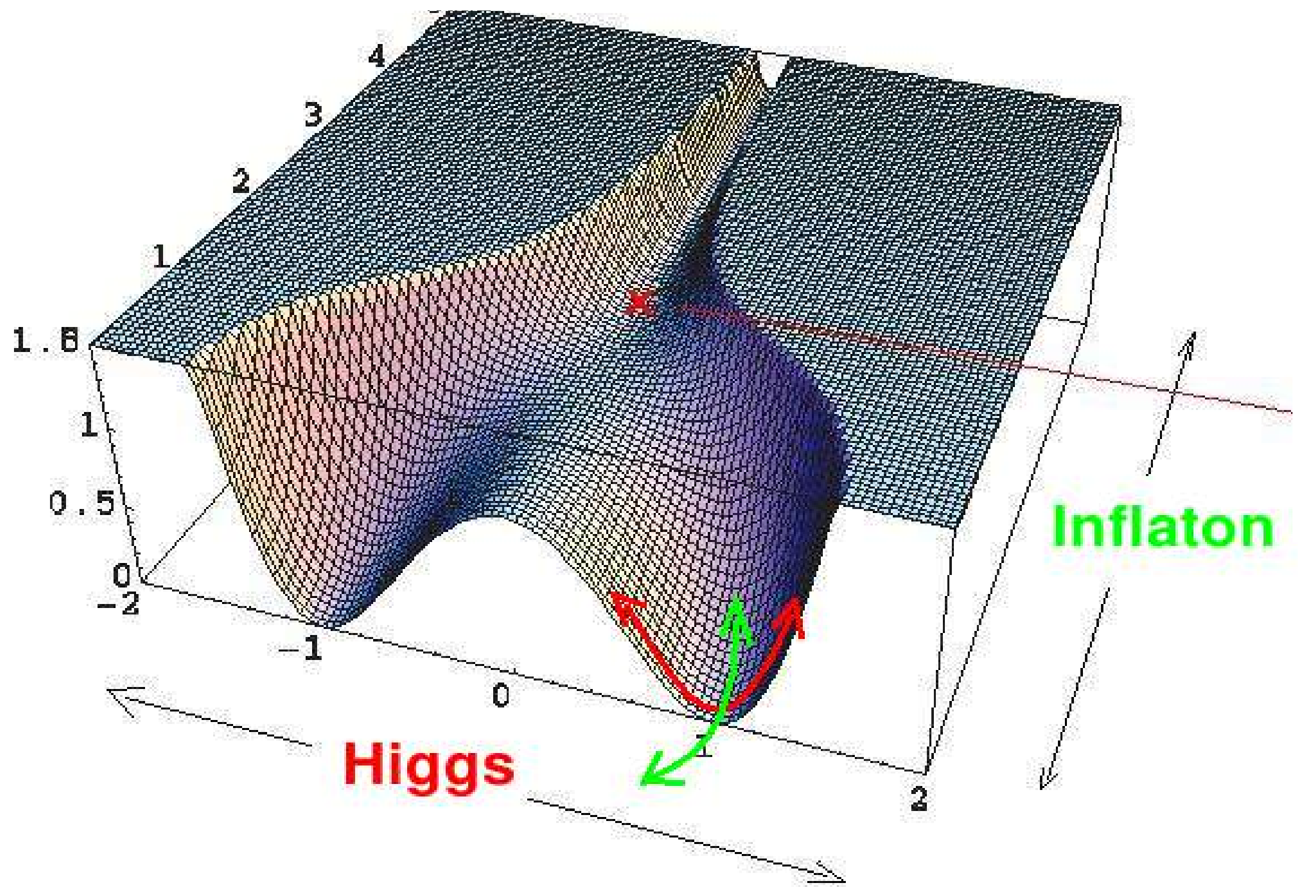

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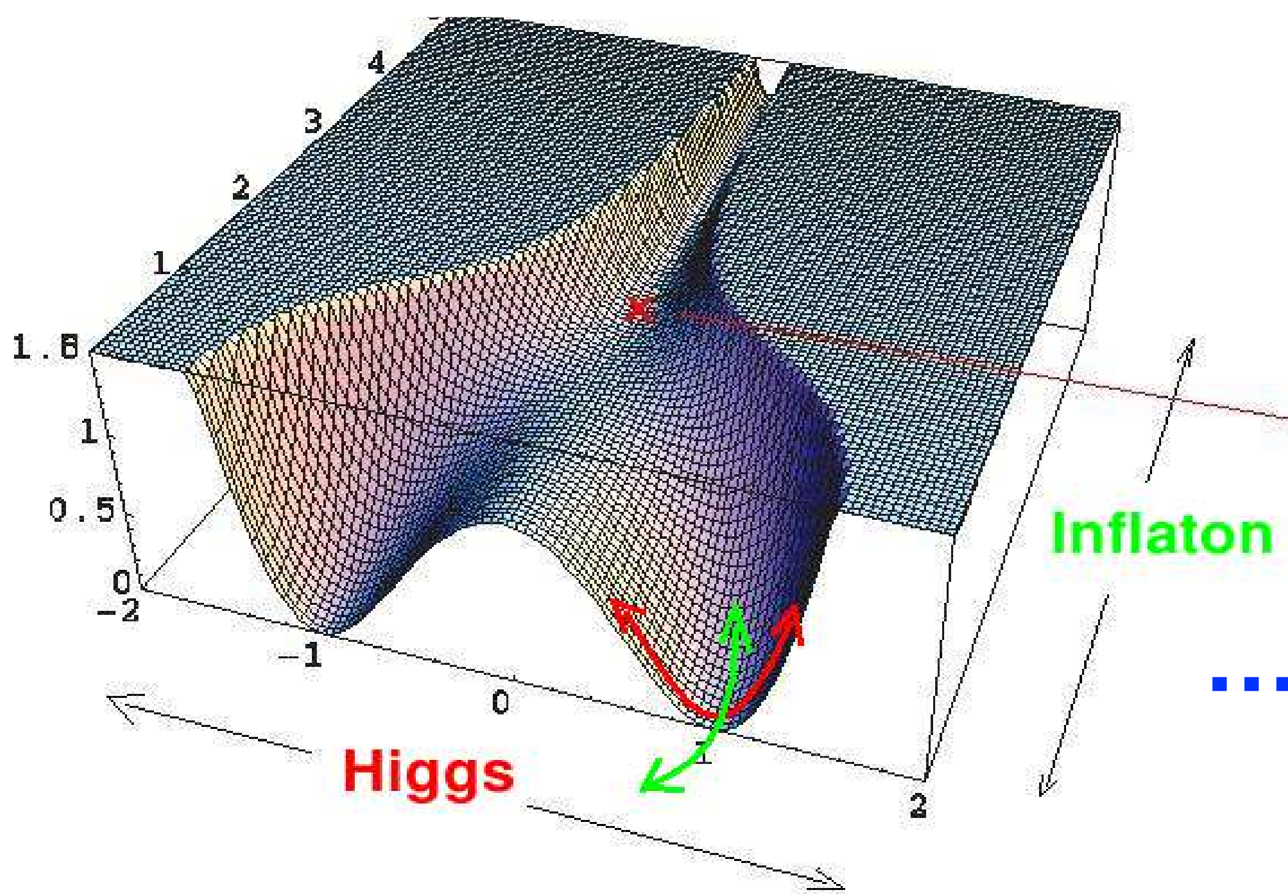

… now there are gauge field(s) !

… so you excite the Higgs, you excite Gauge flds !

GAUGE (P)REHEATING

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

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

→ SCALARS eom

→ VECTORS eom

→ GAUSS law

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GW EOM

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

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

GAUGE (P)REHEATING

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COVARIANT

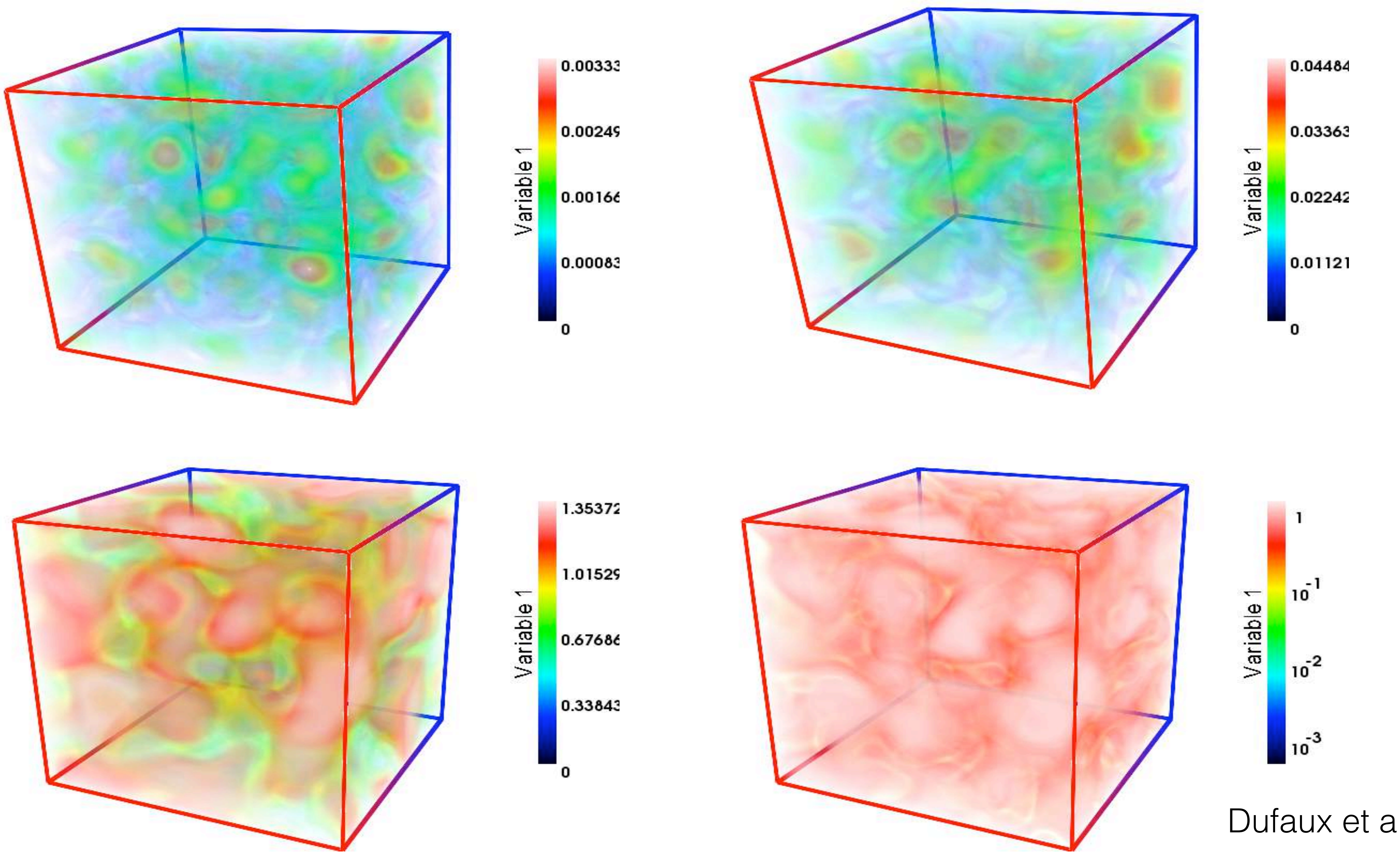
MAGNETIC

ELECTRIC

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

DYNAMICS OF THE HIGGS: $\mathrm{mt} = 5.5 \rightarrow \mathrm{mt} = 23$

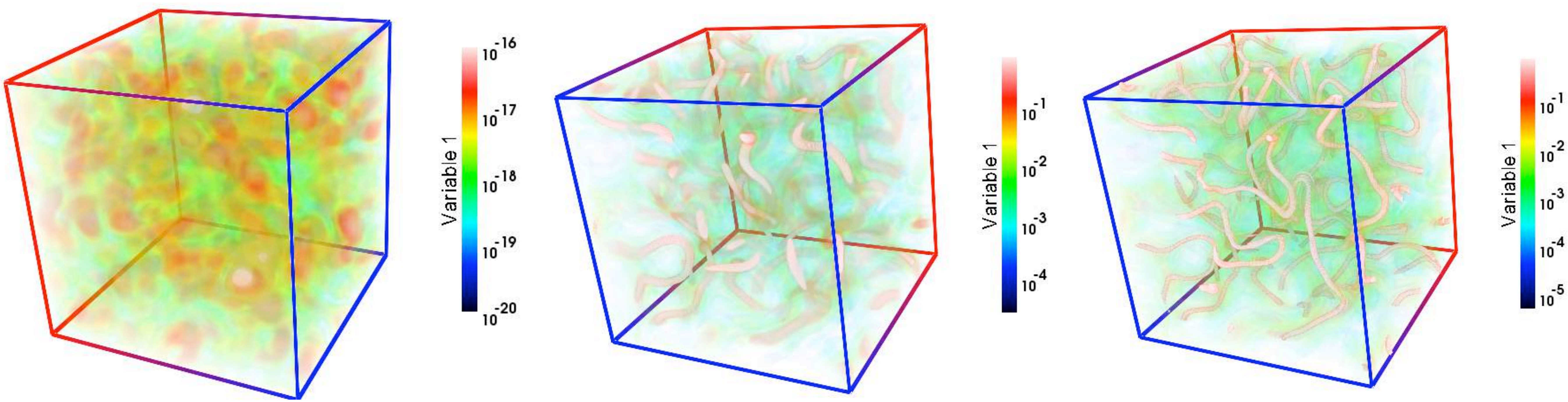


Dufaux et al 2010

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

DYNAMICS OF THE MAGNETIC FIELD: $mt = 5.5 \rightarrow mt = 17$



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What's going on !?

Cosmic Strings are formed

Dufaux et al 2010

GAUGE (P)REHEATING

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What's going on !?

Cosmic Strings are formed

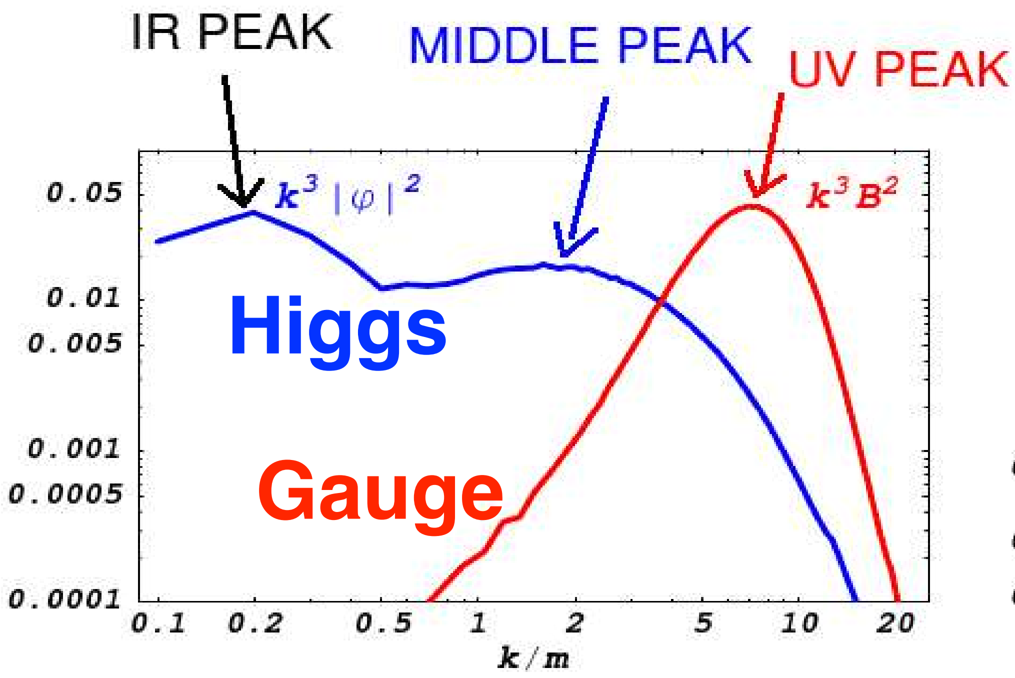
(Topological Defects ⟶ last 1/2 Lecture)

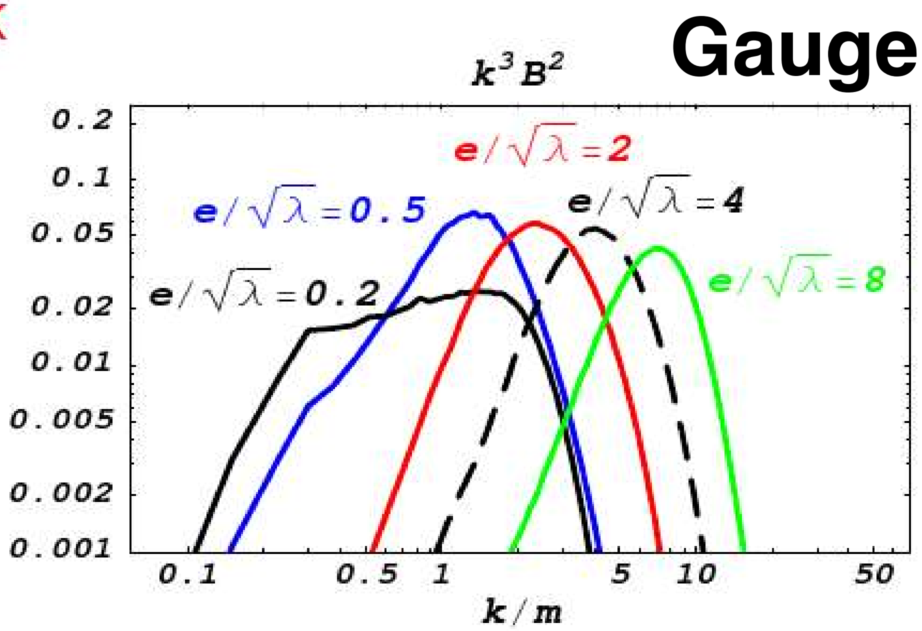
Dufaux et al 2010

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

SCALARS AND VECTORS' SPECTRA:





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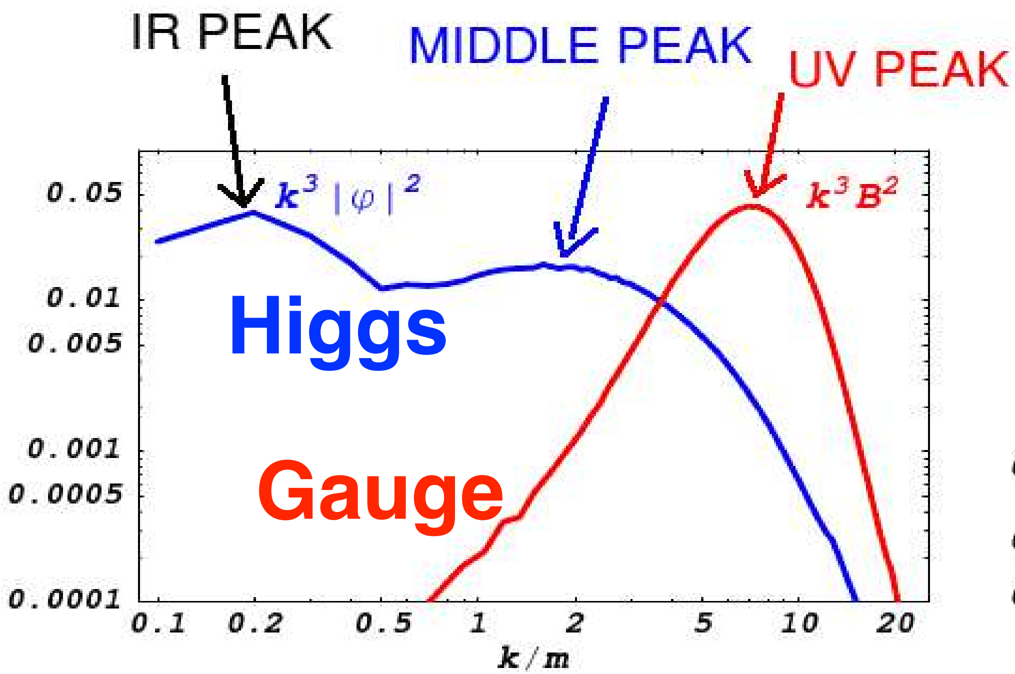
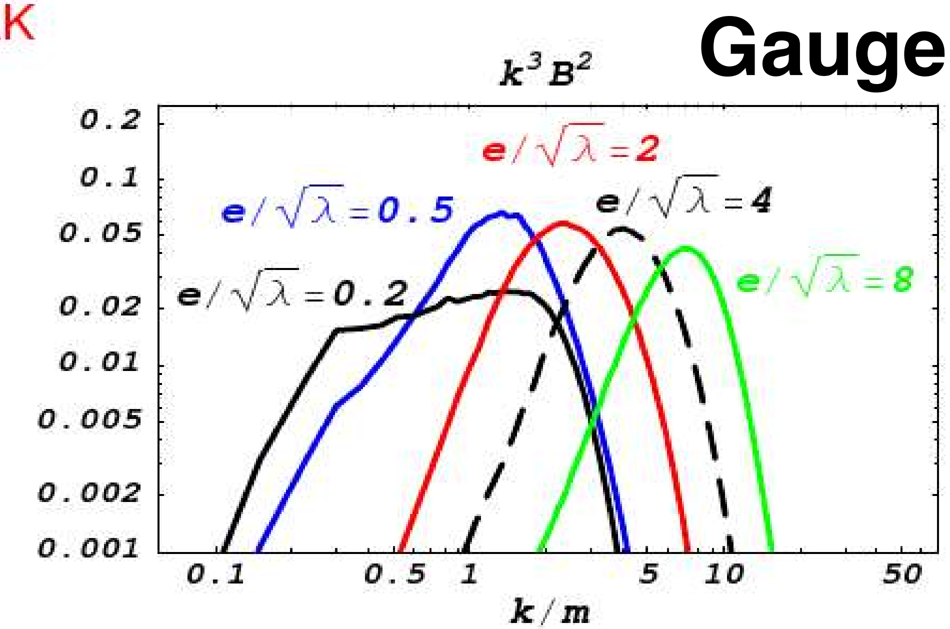




PARAMETERS ABELIAN-HIGGS Model: $m \equiv \sqrt{\lambda} v,\ \lambda/g^2,\ e/\sqrt{\lambda},\ V_c$

MIDDLE PEAK: $\left\{ \begin{array}{l} \text{Higgs mass} \\ (\text{Inflaton Velocity})^{1/3} \end{array} \right\}$ --> Tachyonic Scale, Bubbles' Size

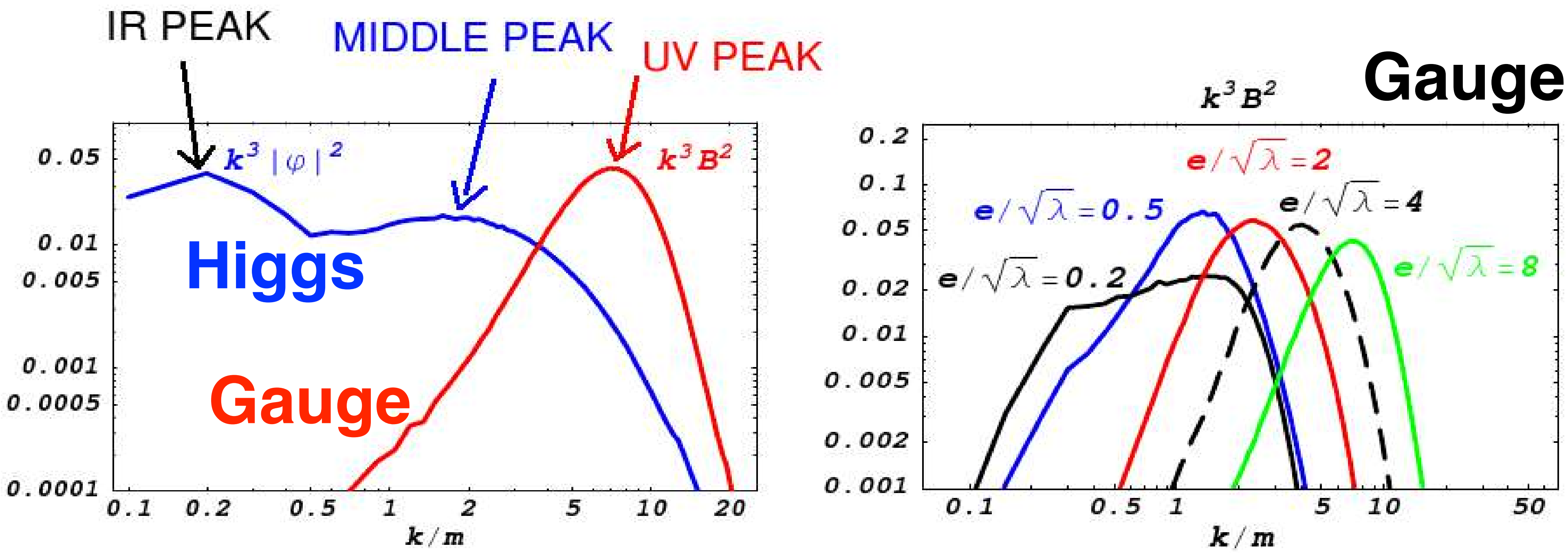
IR PEAK : Inflaton Velocity, Higgs+Inflaton Couplings (Dufaux et al 2009)

UV PEAK: Vector mass / Higgs Mass

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

SCALARS AND VECTORS' SPECTRA:



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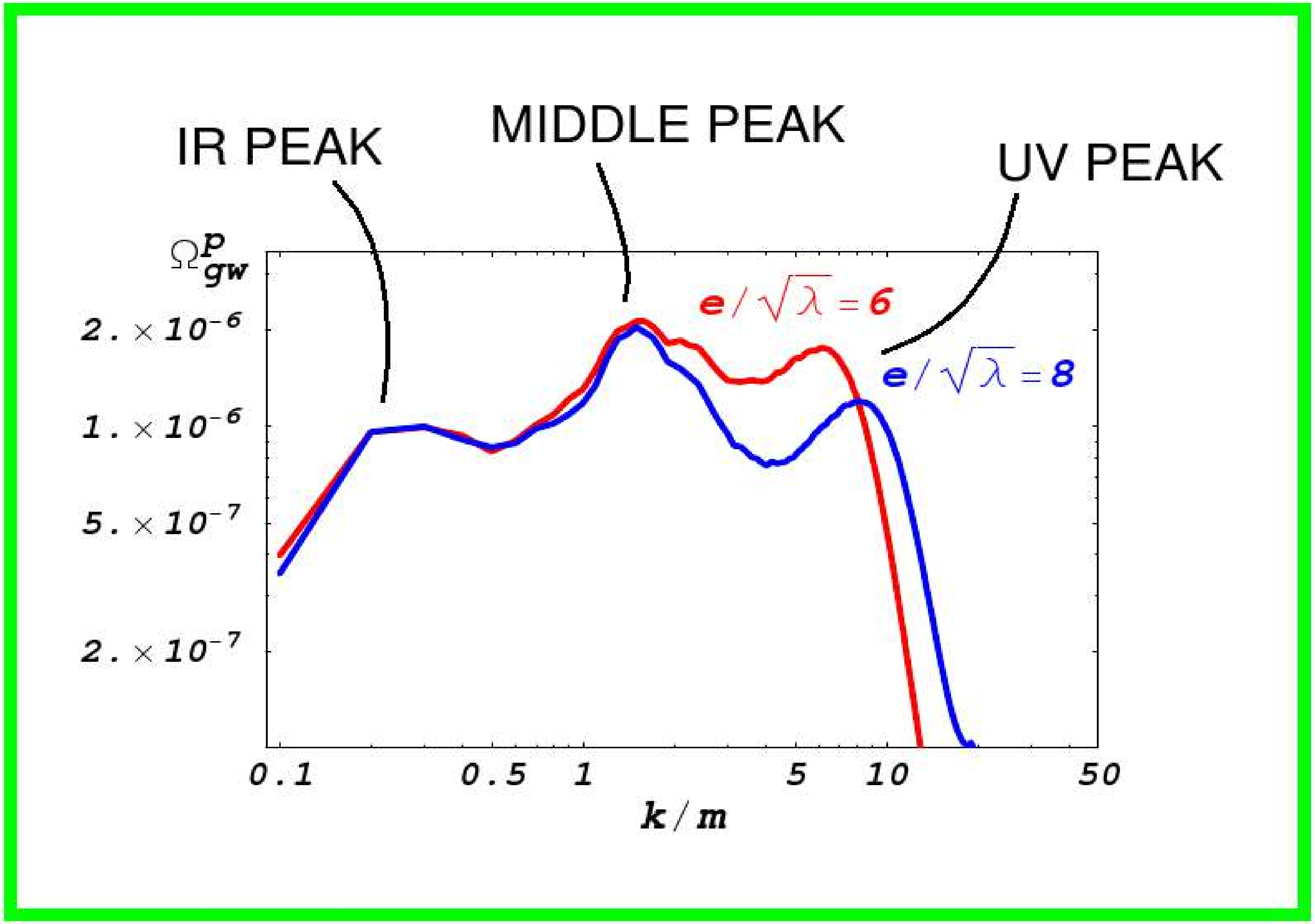
GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

GRAVITATIONAL WAVES SPECTRA:

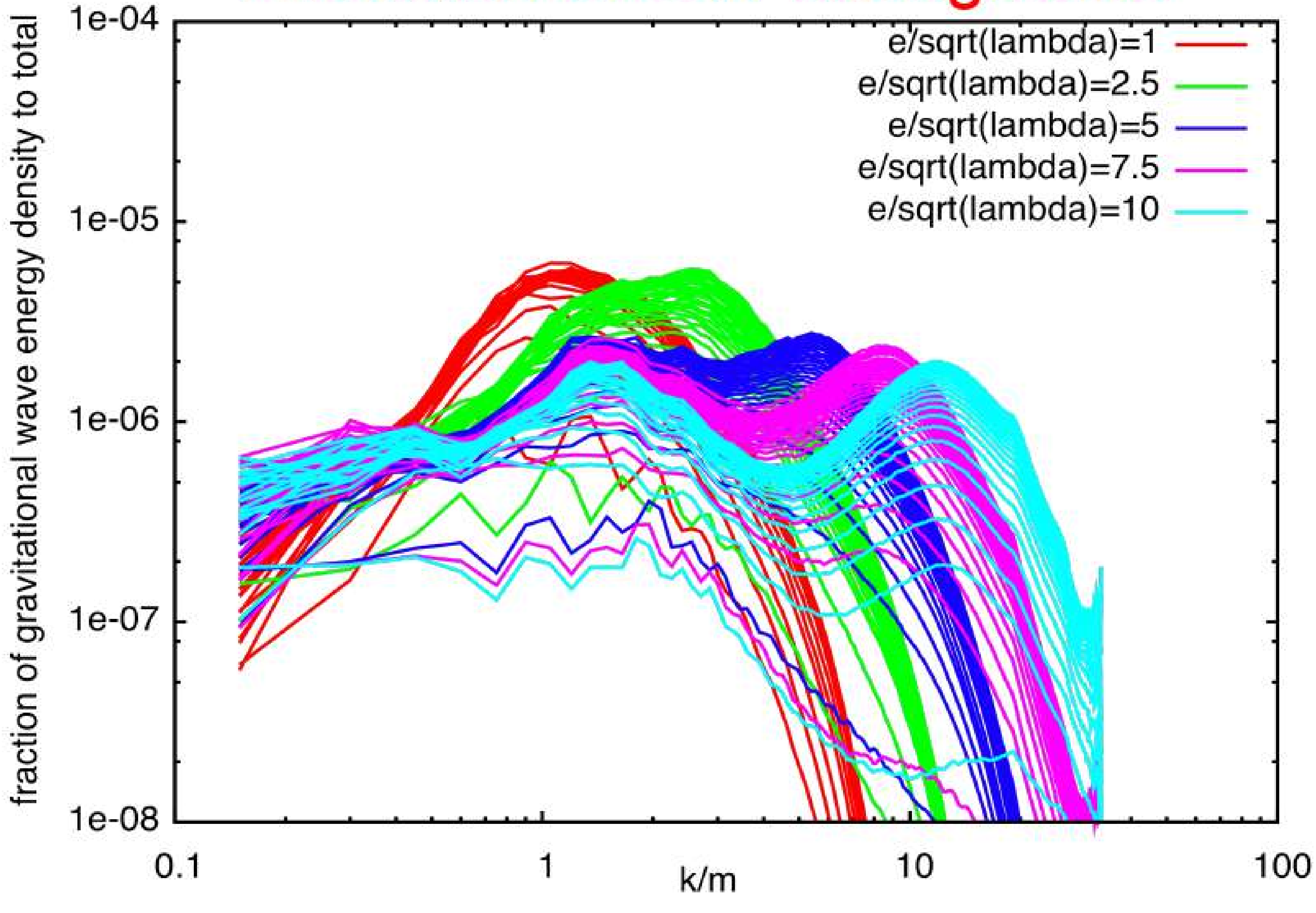


GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

GRAVITATIONAL WAVES SPECTRA:

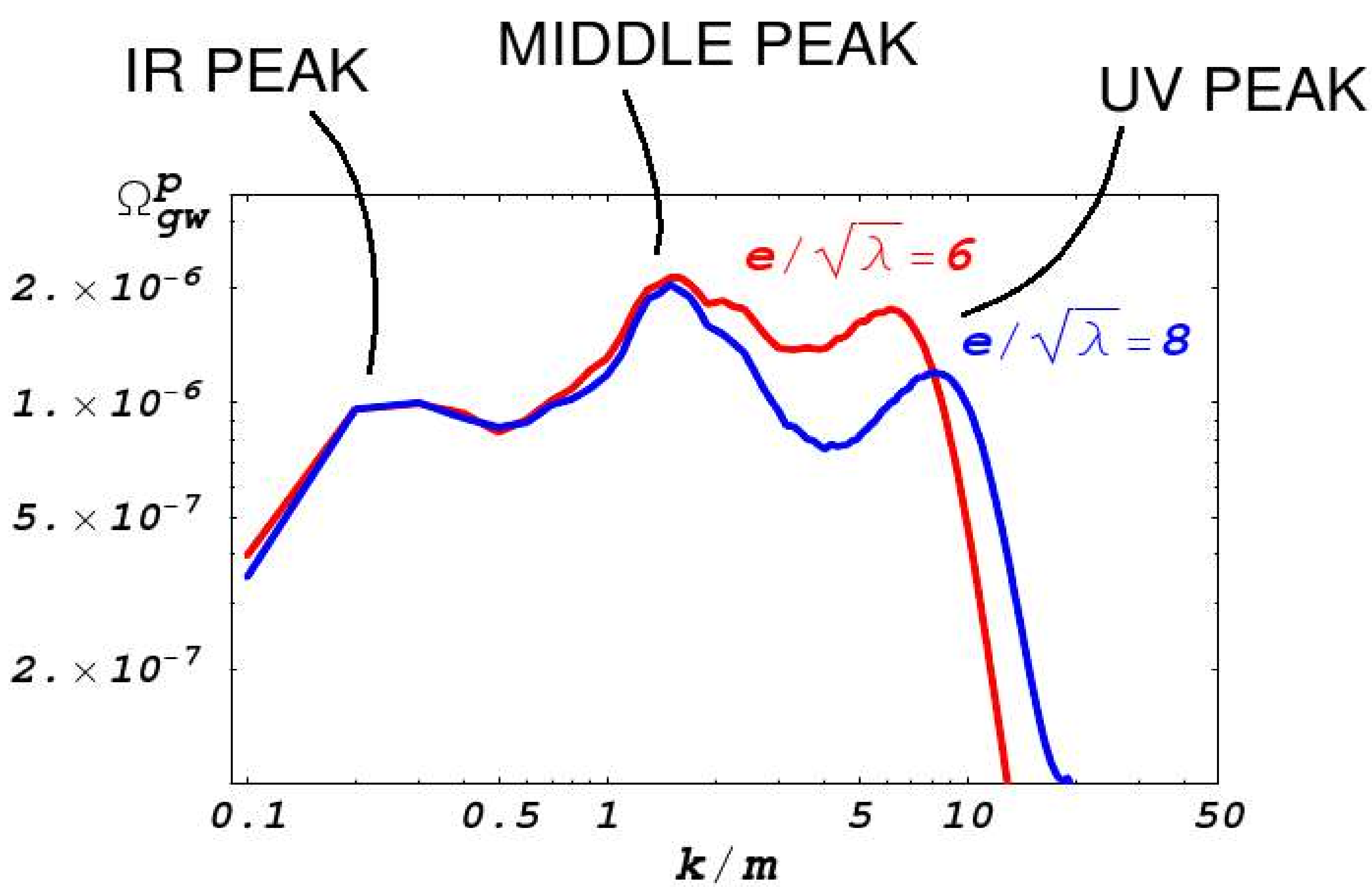
Evolution of GW background



GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

Several Peaks !
(particle physics spectroscopy)



GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

Several Peaks !
(particle physics spectroscopy)

$$\Omega_{\rm GW}^{(o)} \sim 10^{-11} \, ,$$

Large amplitude(s) !

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

Several Peaks !
(particle physics spectroscopy)

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

Large amplitude(s) ! **... but at high Frequency !**

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

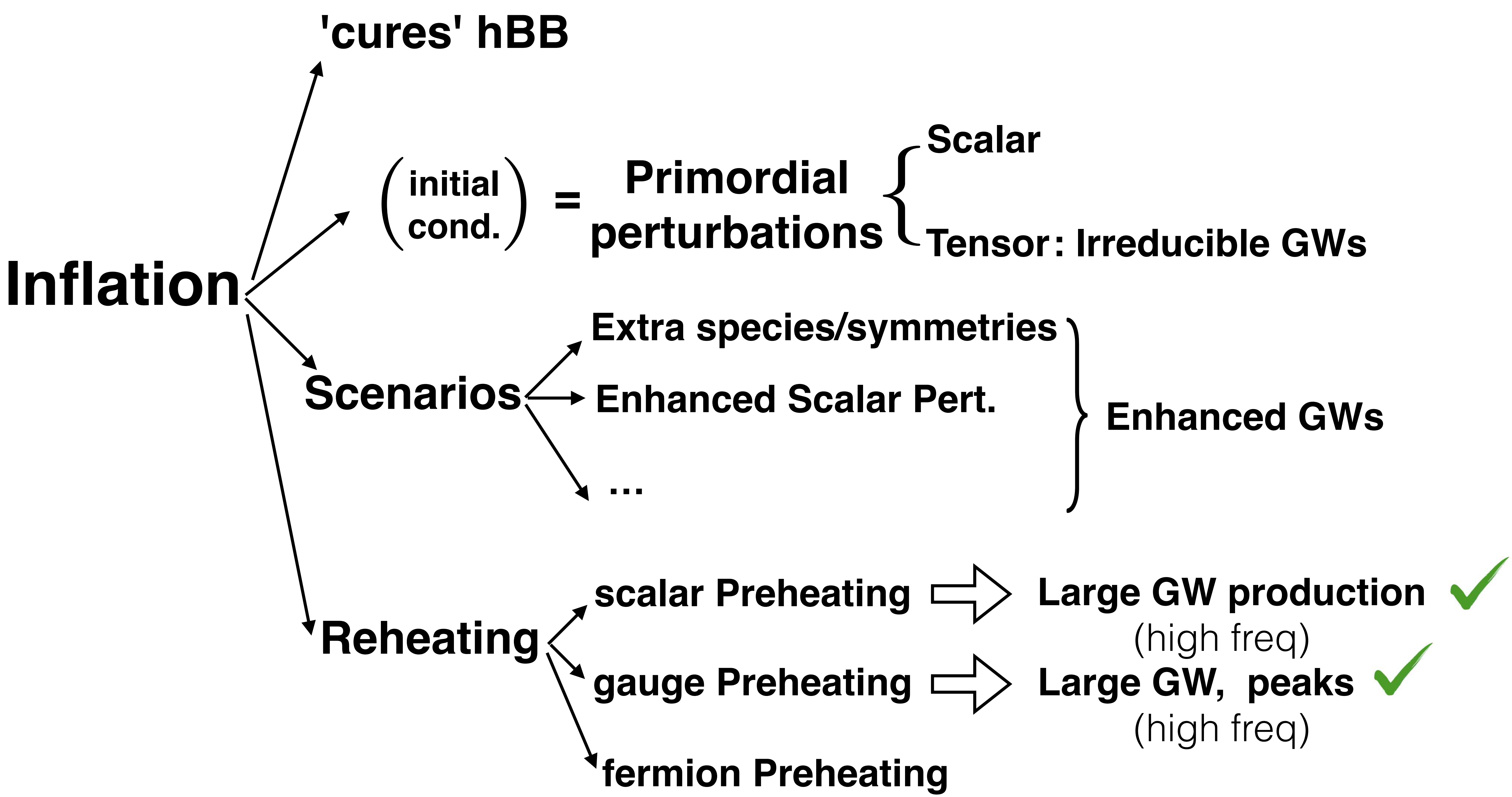
Several Peaks !
(particle physics spectroscopy)

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

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

Very unfortunate... no high frequency detectors !

INFLATIONARY COSMOLOGY



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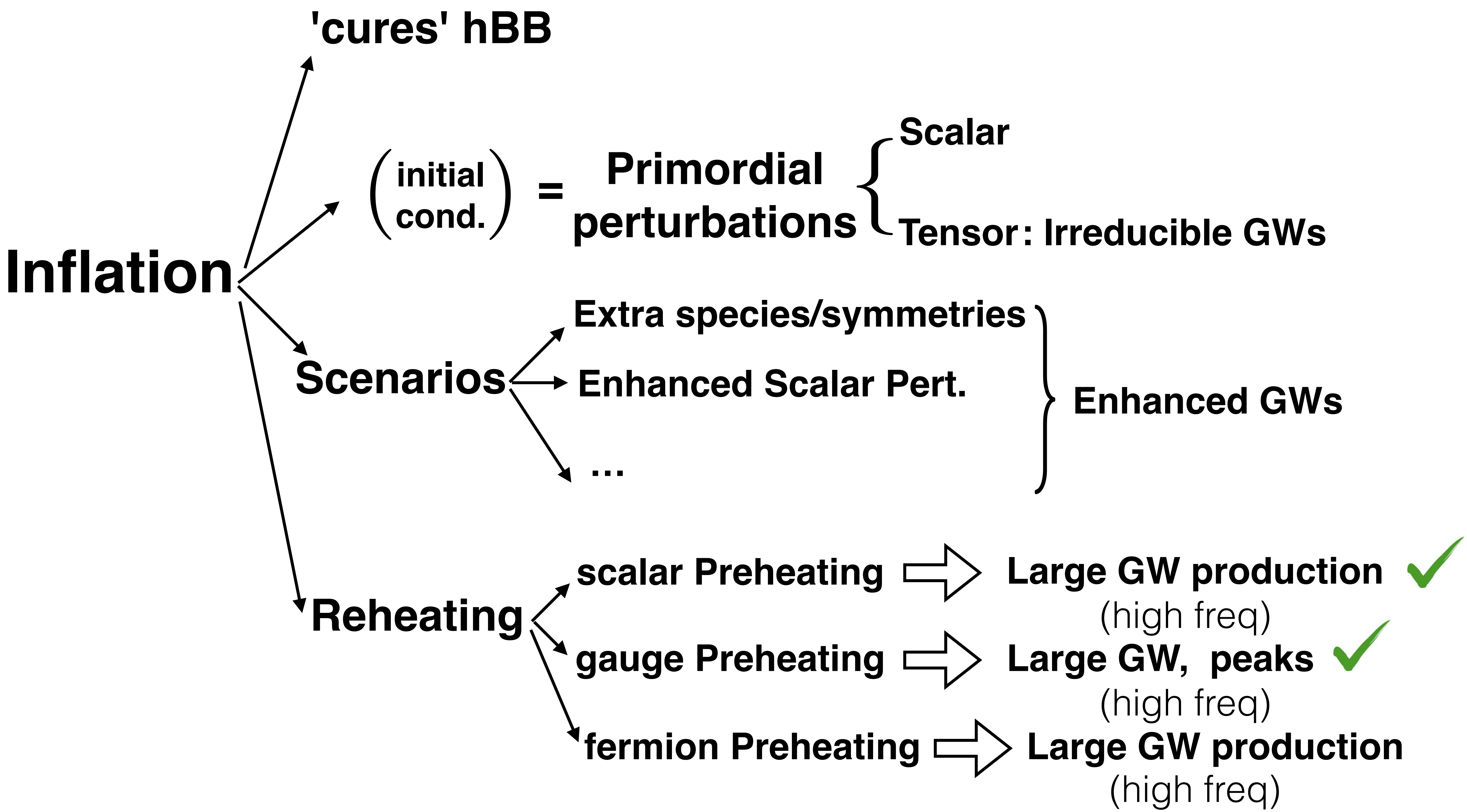

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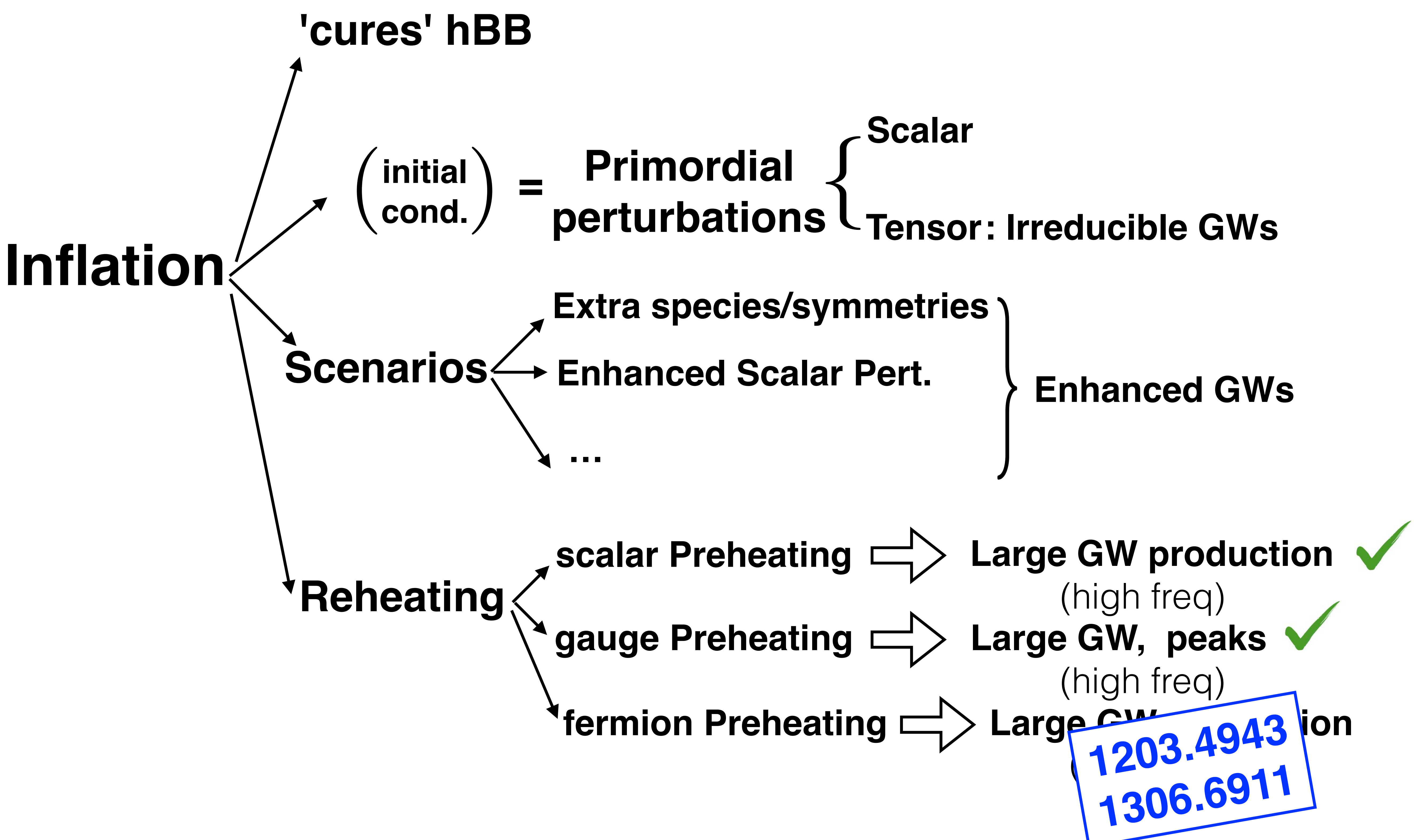

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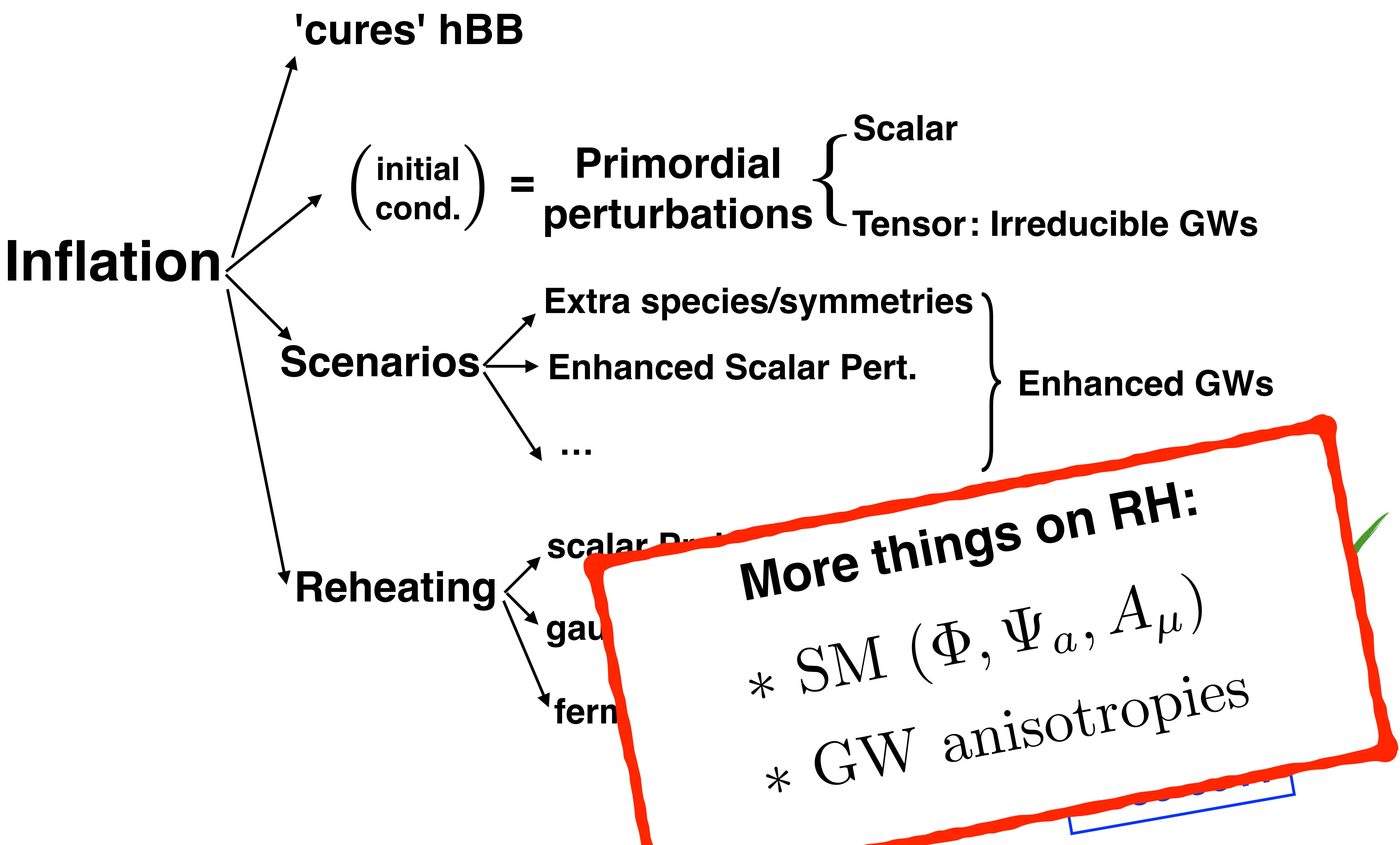

INFLATIONARY COSMOLOGY

Inflation

- 'cures' hBB
- (initial cond.) = Primordial perturbations
  - Scalar
  - Tensor : Irreducible GWs
- Scenarios
  - Extra species/symmetries
  - Enhanced Scalar Pert.
  - ...
  - → Enhanced GWs
- Reheating
  - scalar
  - gau
  - fern

More things on RH:

0812.3622 + 0812.4624

* SM

* GW anisotropies

INFLATIONARY COSMOLOGY

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More things on RH:

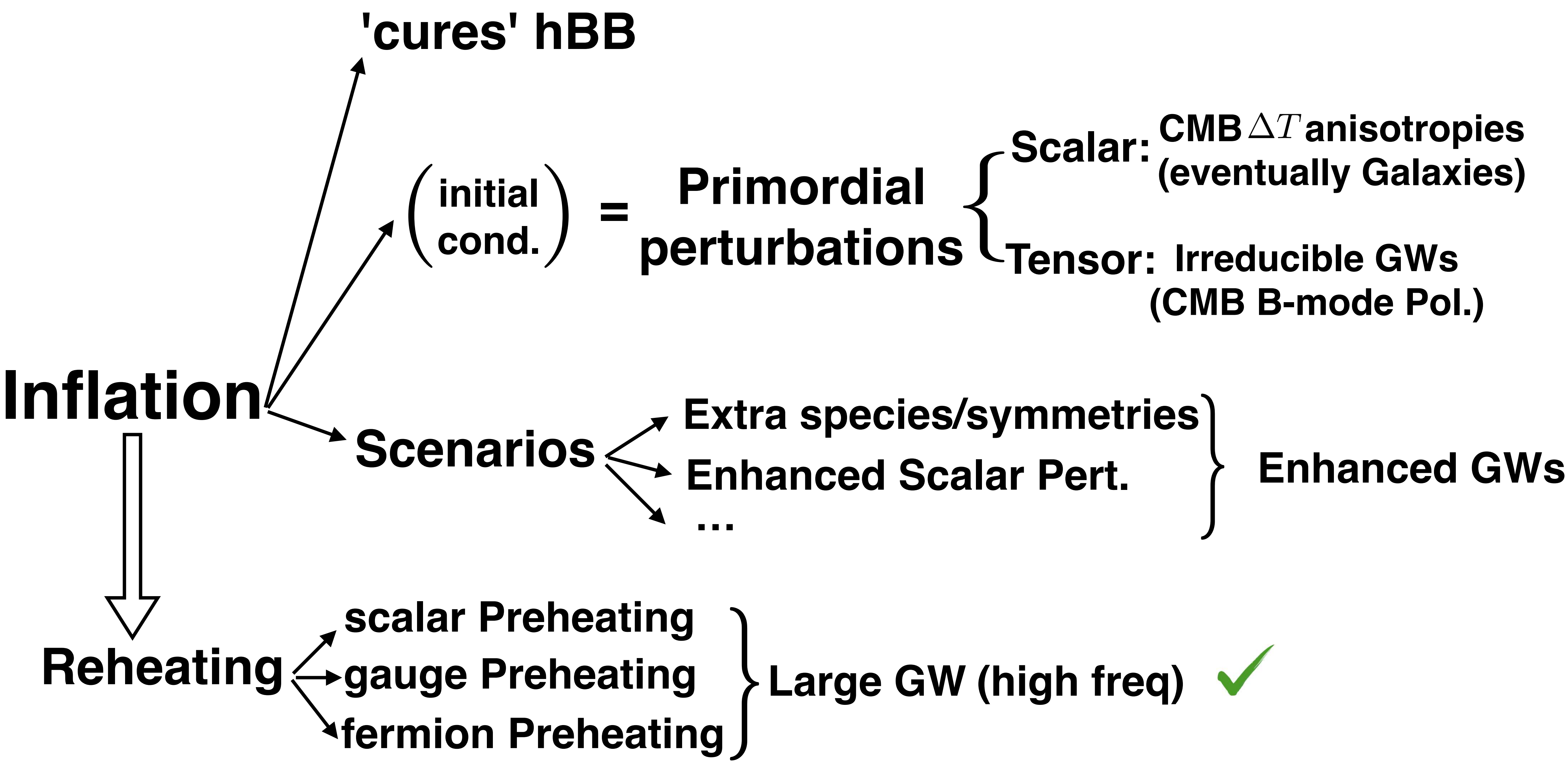
0812.3622 + 0812.4624

* SM (...)

1304.2657 + 1309.1148

* GW an...

EARLY UNIVERSE



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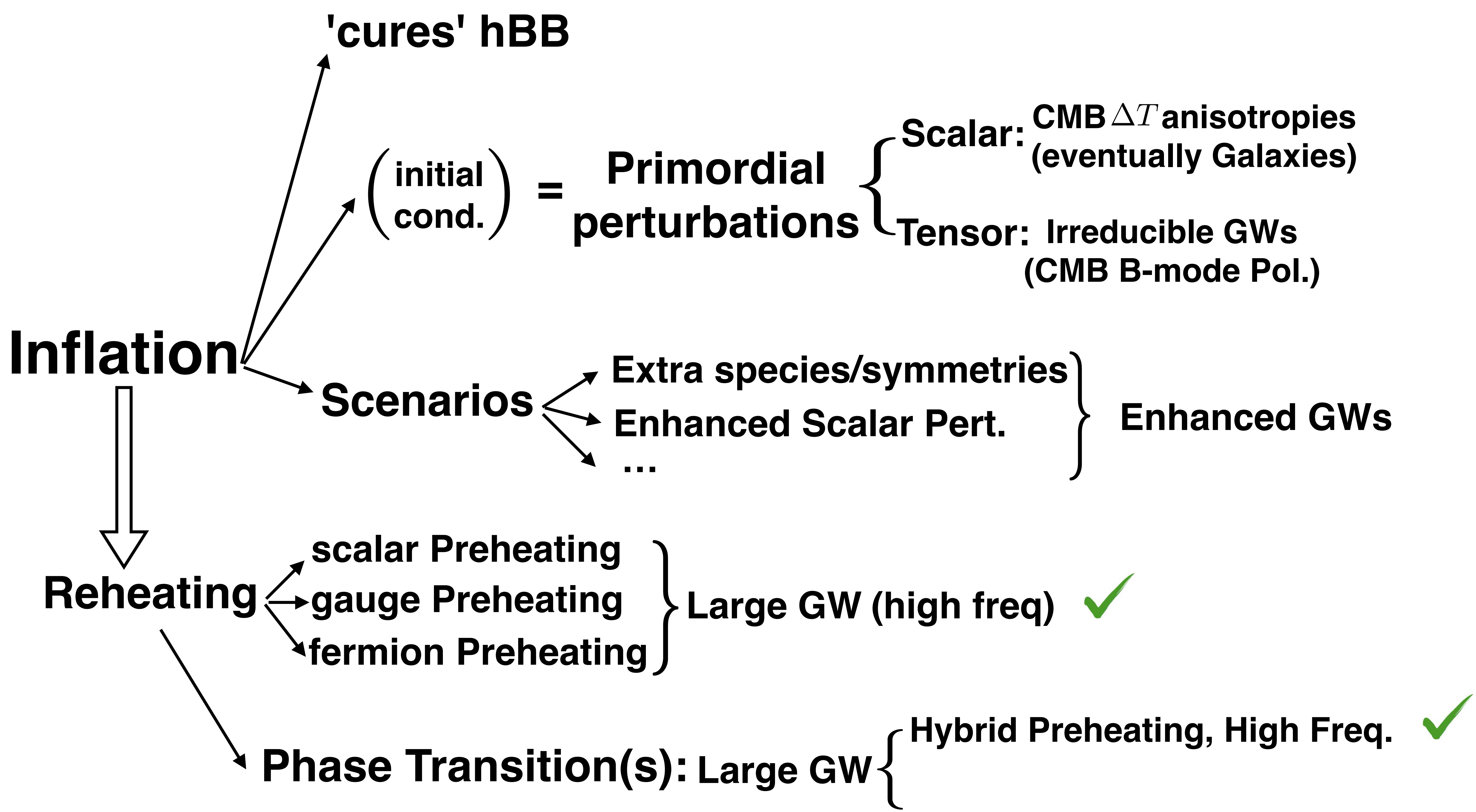


EARLY UNIVERSE

Inflation →

- 'cures' hBB
- (initial cond.) = Primordial perturbations
  - Scalar: CMB ΔT anisotropies (eventually Galaxies)
  - Tensor: Irreducible GWs (CMB B-mode Pol.)
- Scenarios
  - Extra species/symmetries
  - Enhanced Scalar Pert.
  - ...
  - } Enhanced GWs

⇓

Reheating →

- scalar Preheating
- gauge Preheating
- fermion Preheating
- } Large GW (high freq) ✓

Phase Transition(s): Large GW
- Hybrid Preheating, High Freq. ✓
- Thermal 1st-Order PhT

⇓

Thermal Universe

OUTLINE

1st lecture

0) Gravitational Waves (GWs)

1) GWs from Inflation

2nd lecture

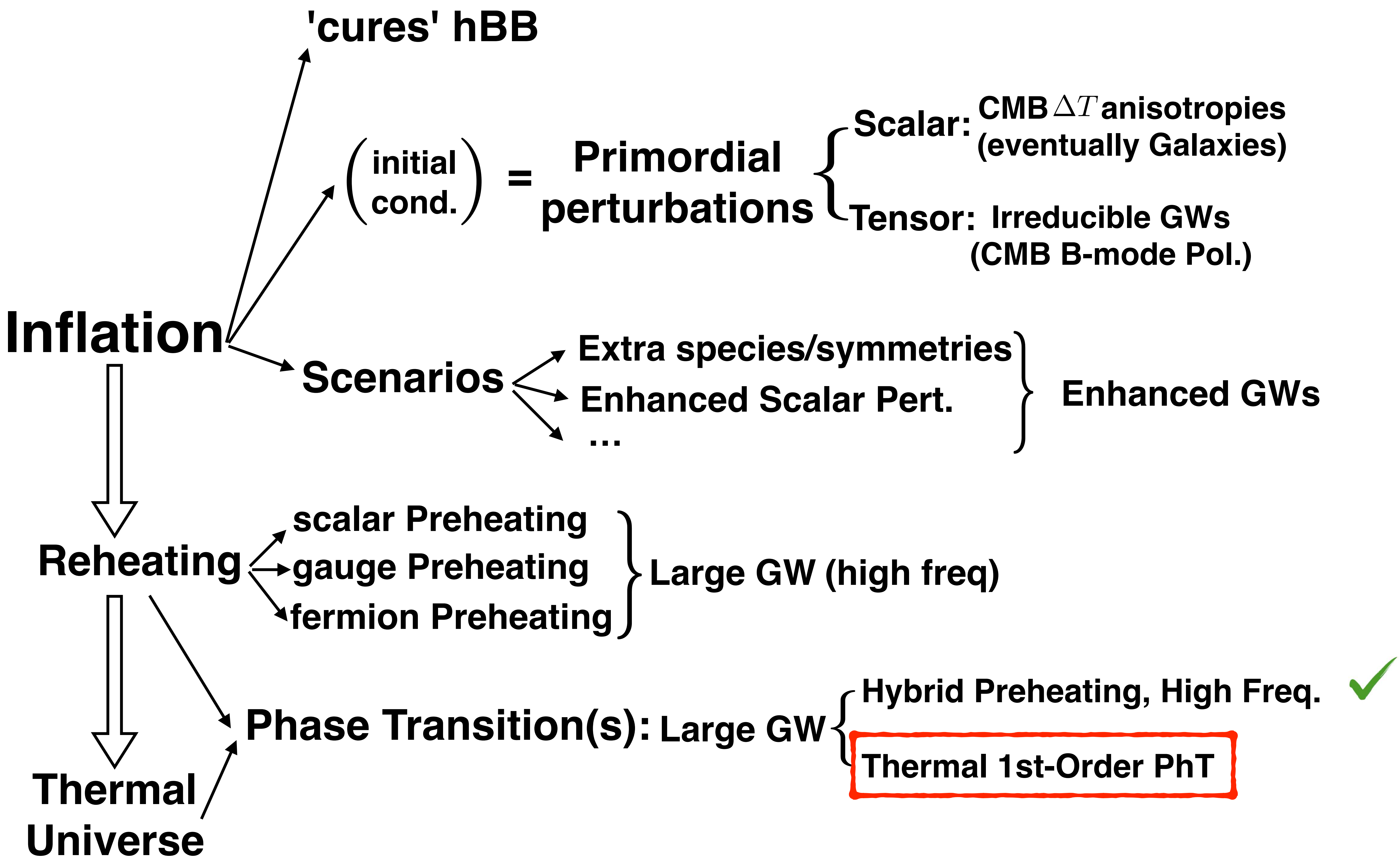
2) GWs from Preheating

3) GWs from Phase Transitions

4) GWs from Cosmic Defects

3rd lecture

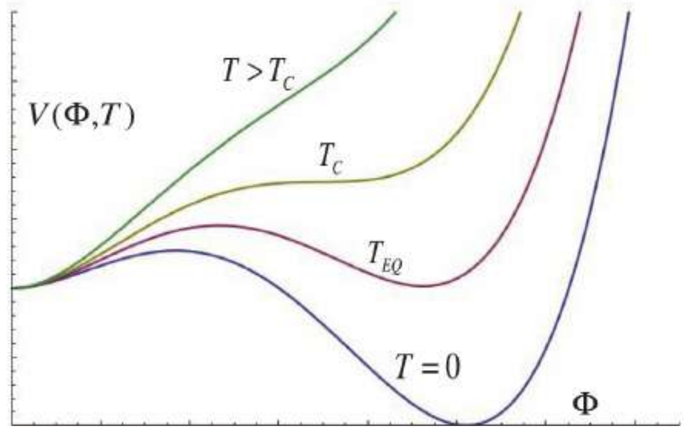
EARLY UNIVERSE



First order phase transitions

Universe expands, temperature decreases: phase transition triggered !

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



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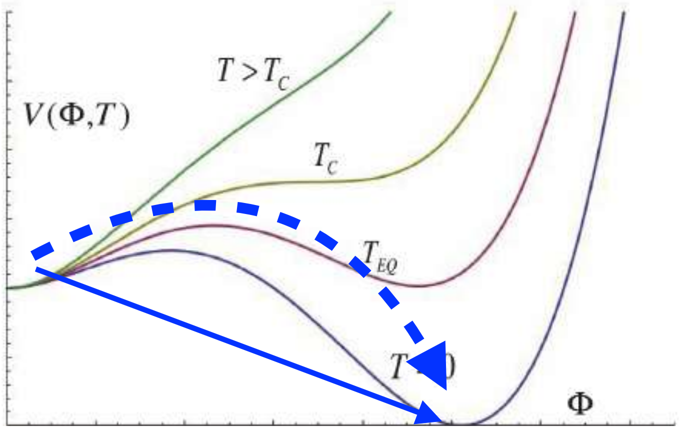

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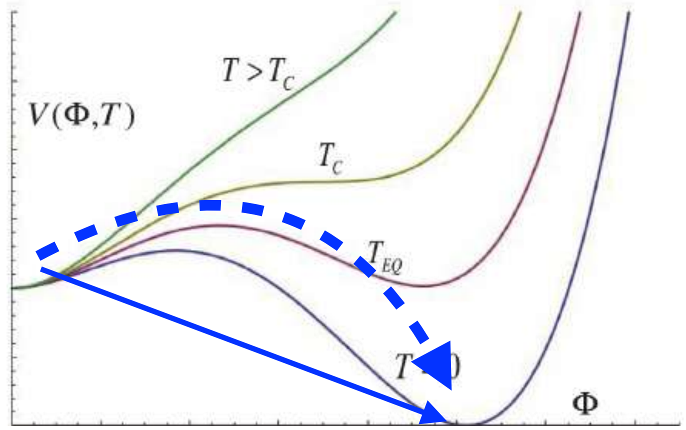
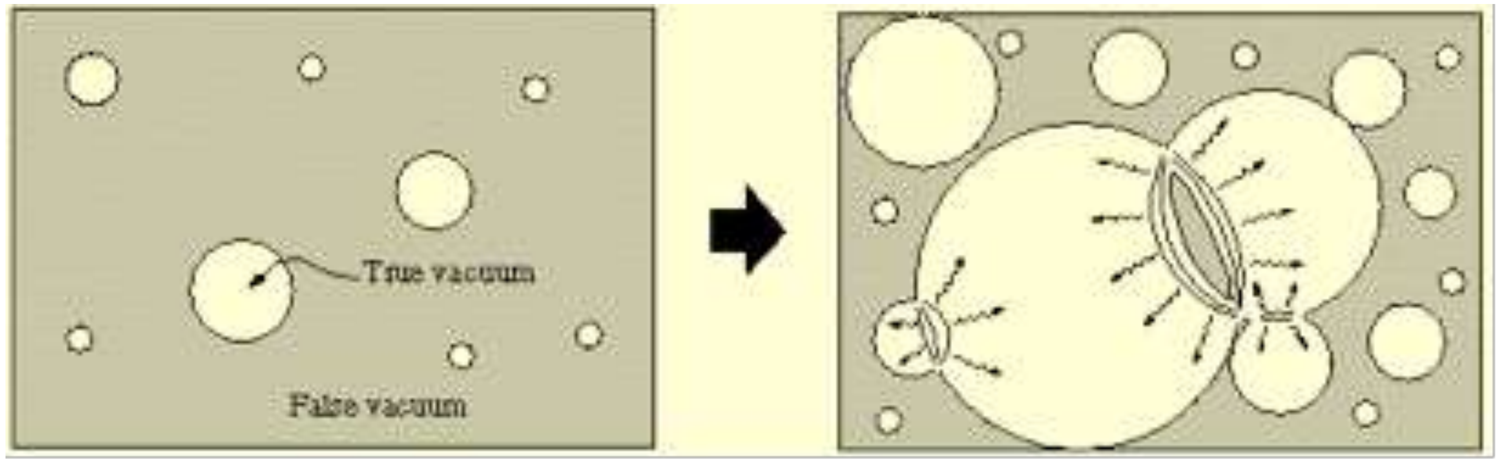


bubble nucleation



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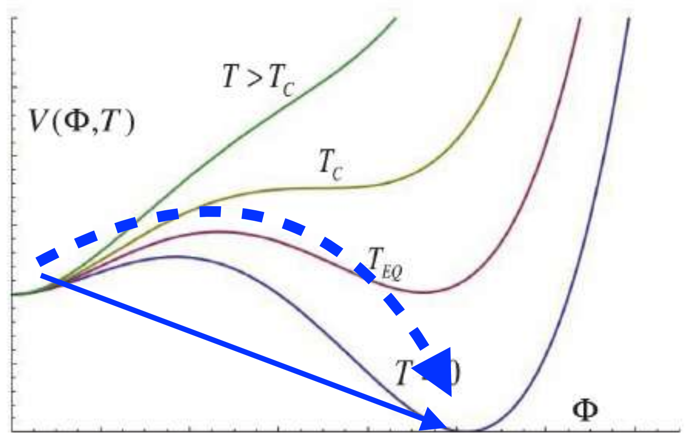

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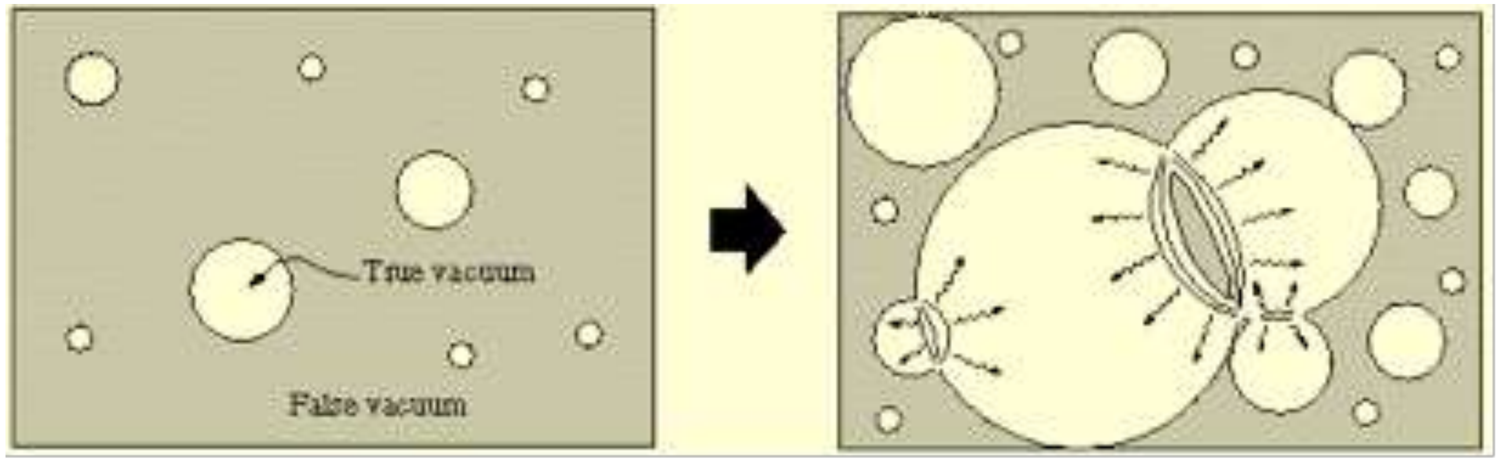

GW
source: Π_{ij} tensor
anisotropic stress

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

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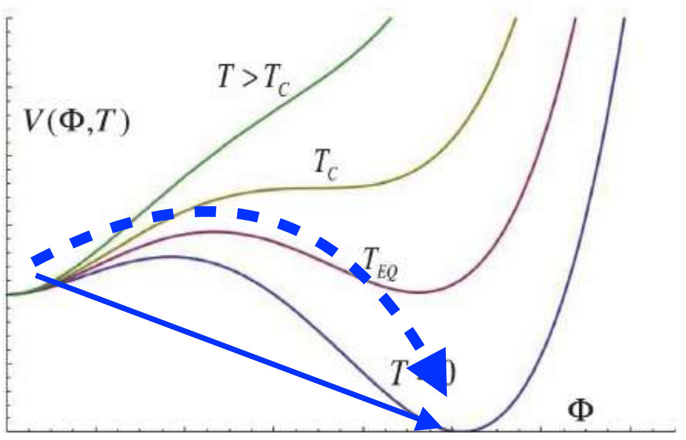
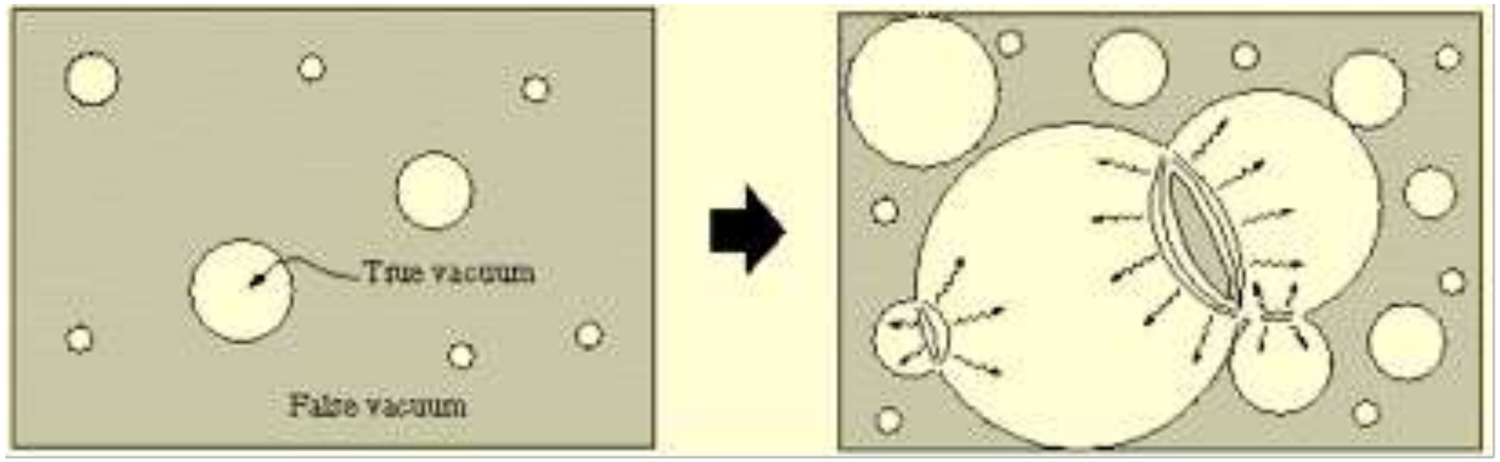


bubble nucleation



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**

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

$$\epsilon_* \leq 1$$

parameter characterising source

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@ 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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@ Today, @ Emission time

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

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Hubble rate ↕ temperature }

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(f_c @ Today; f_* @ Emission time)

LISA Freq !

for $\epsilon_* \simeq 10^{-2}$ $T_* \simeq 1\,\mathrm{TeV}$ **~ 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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β^{-1} : duration of PhT

$v_b \leq 1$: speed of bubble walls

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

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

BUBBLE COLLISION

SOUND WAVES AND MDH TURBULENCE

Parameters determining the GW spectrum

Freq. (today)

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

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

Parameter List (not independent)

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

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

Parameter List
(not independent)

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

Amplitude (today)

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

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

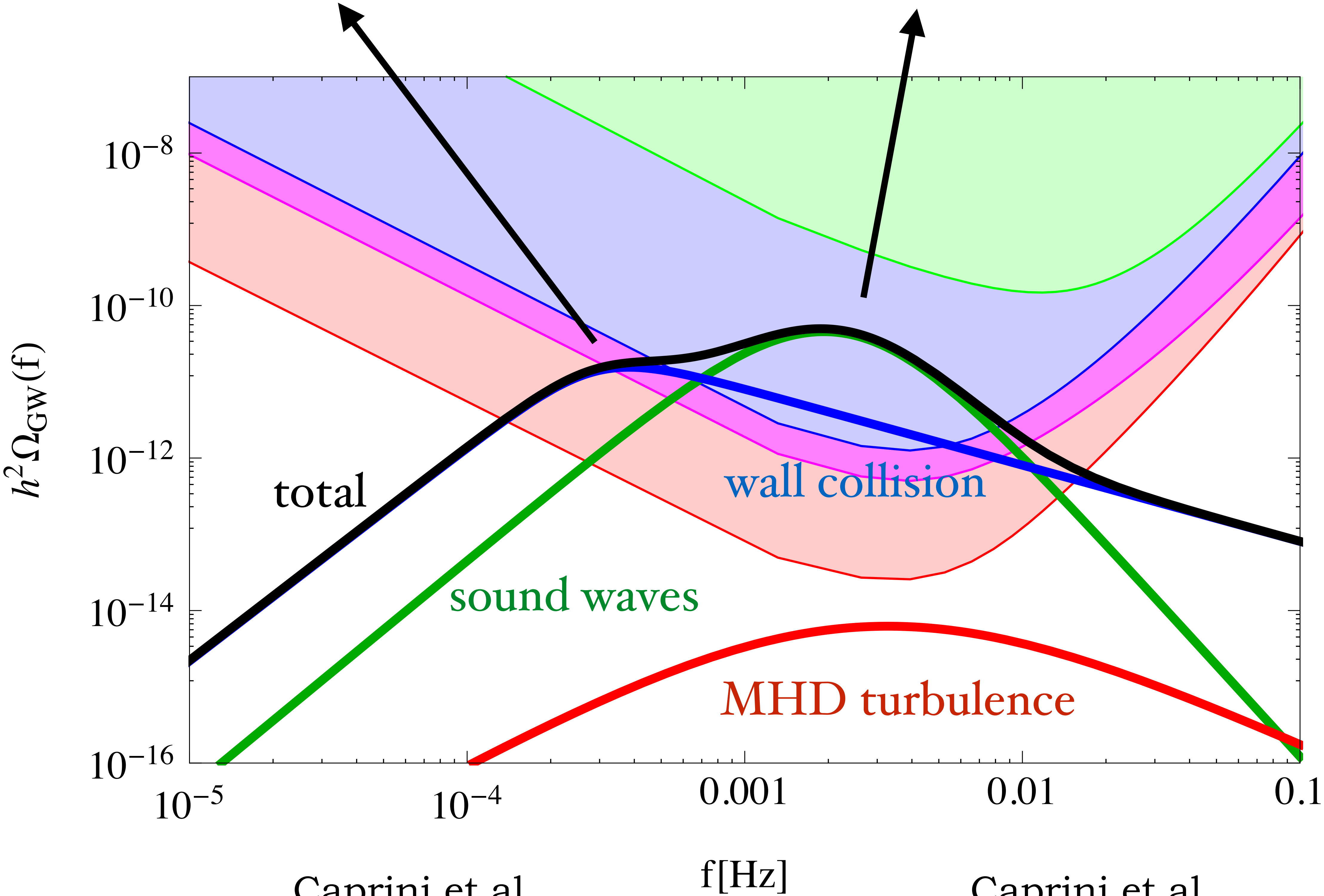
$$\alpha = \frac{\rho_{\mathrm{vac}}}{\rho_{\mathrm{rad}}^*}$$

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

Example of spectrum

peak of bubble collisions β

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



Caprini et al, arXiv:1512.06239

Caprini et al, arXiv:1910.13125

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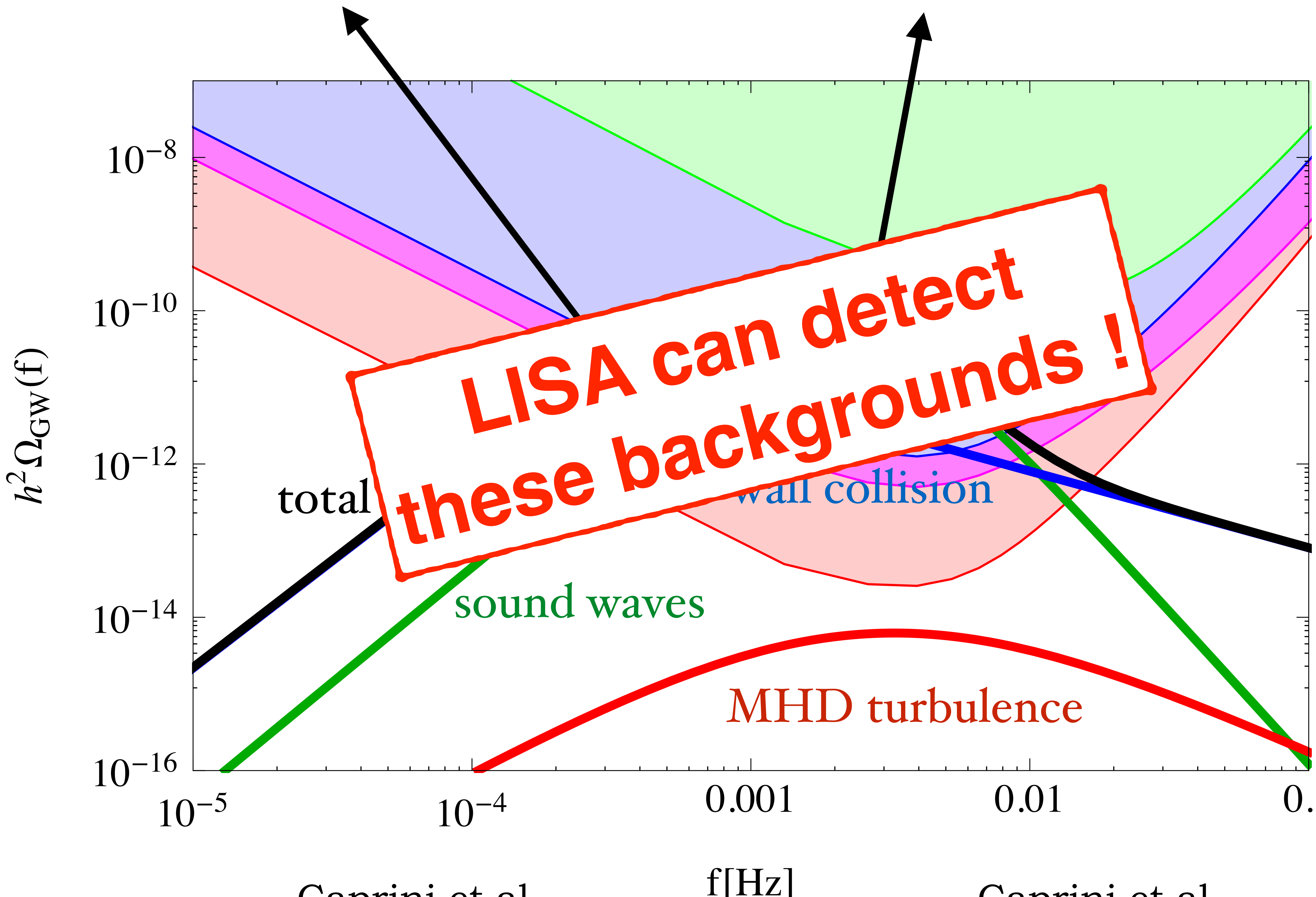

Caprini et al, arXiv:1512.06239

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)

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
  , ...

Connection Particle Physics & Cosmology !

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

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

GW: new probe of BSM (complementary to colliders)

Evaluation of the signal

- **bubble collisions**: anal… …ions
  …3, …
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  analytical **Hindmarsh 2016, 201…**
- **M…**
  …), Niksa et al '18
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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

- **bubble collisions**: **anal**… …ions
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- **M**…
  … 18
  … et al 201…

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

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

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

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

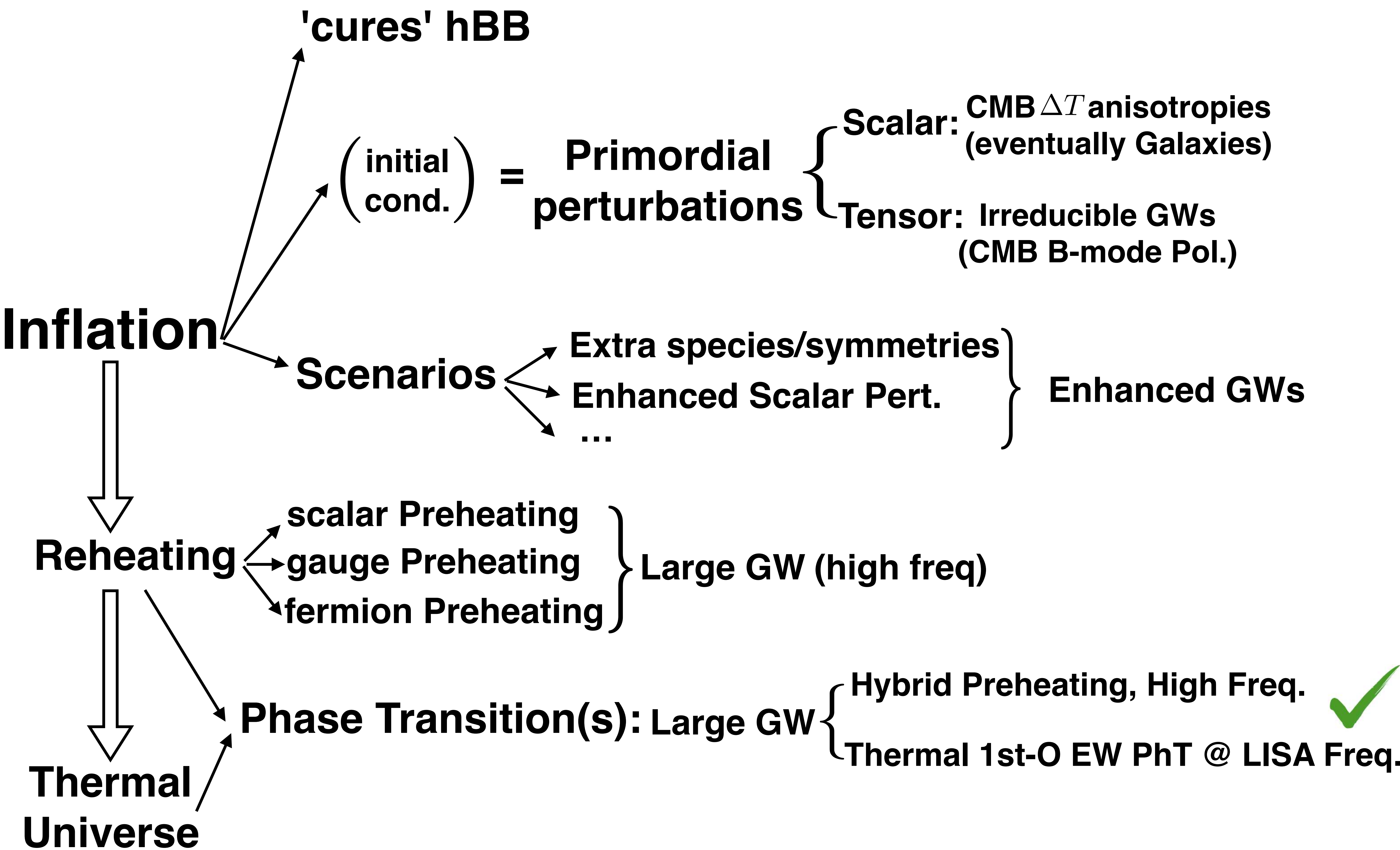
* LISA can, but LHC pressures typical BSM extensions to promote EW-PhT into First Order

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

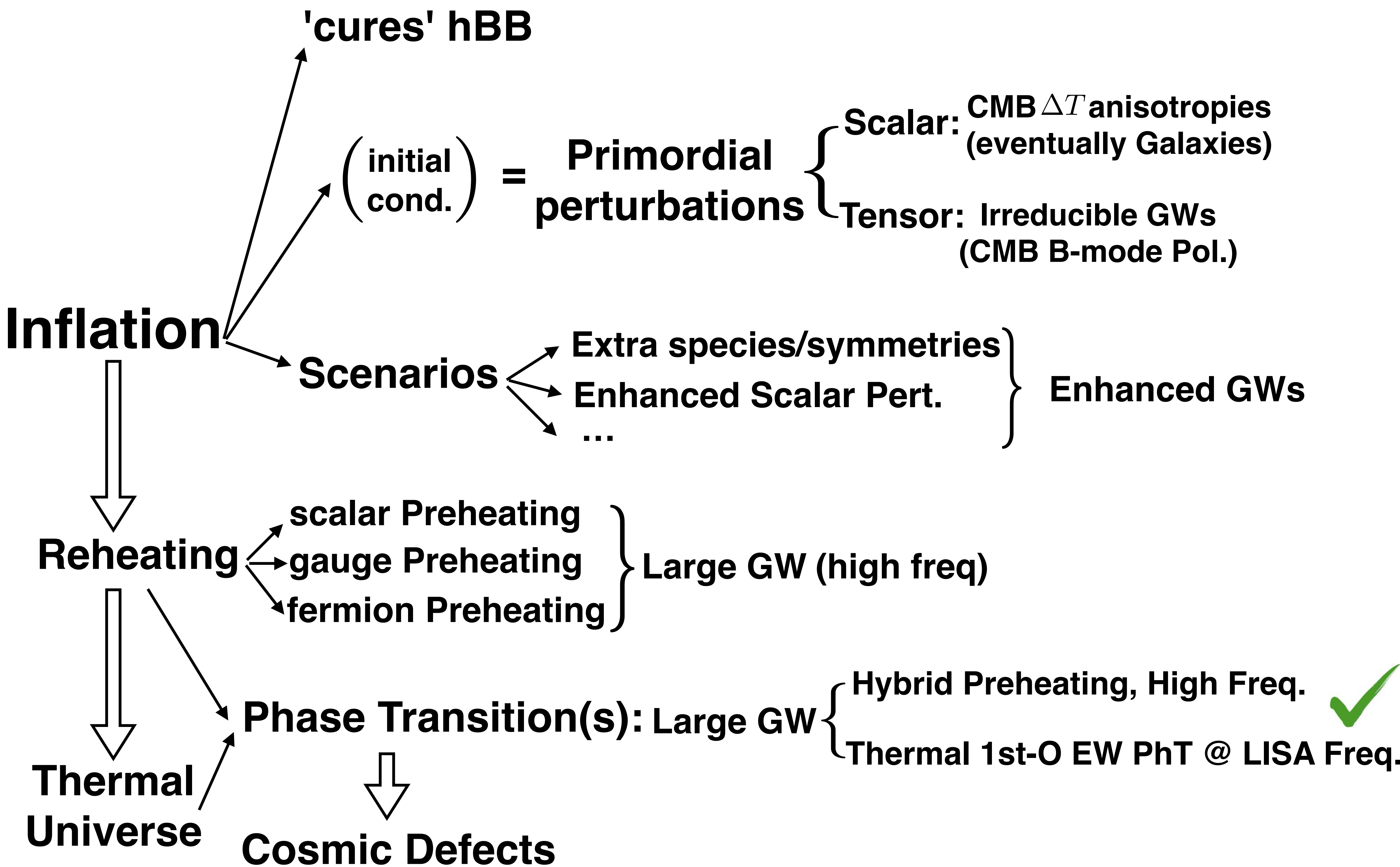
* Predictions depend on many assumptions (particularly in sound waves), so is our modelling correct?

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

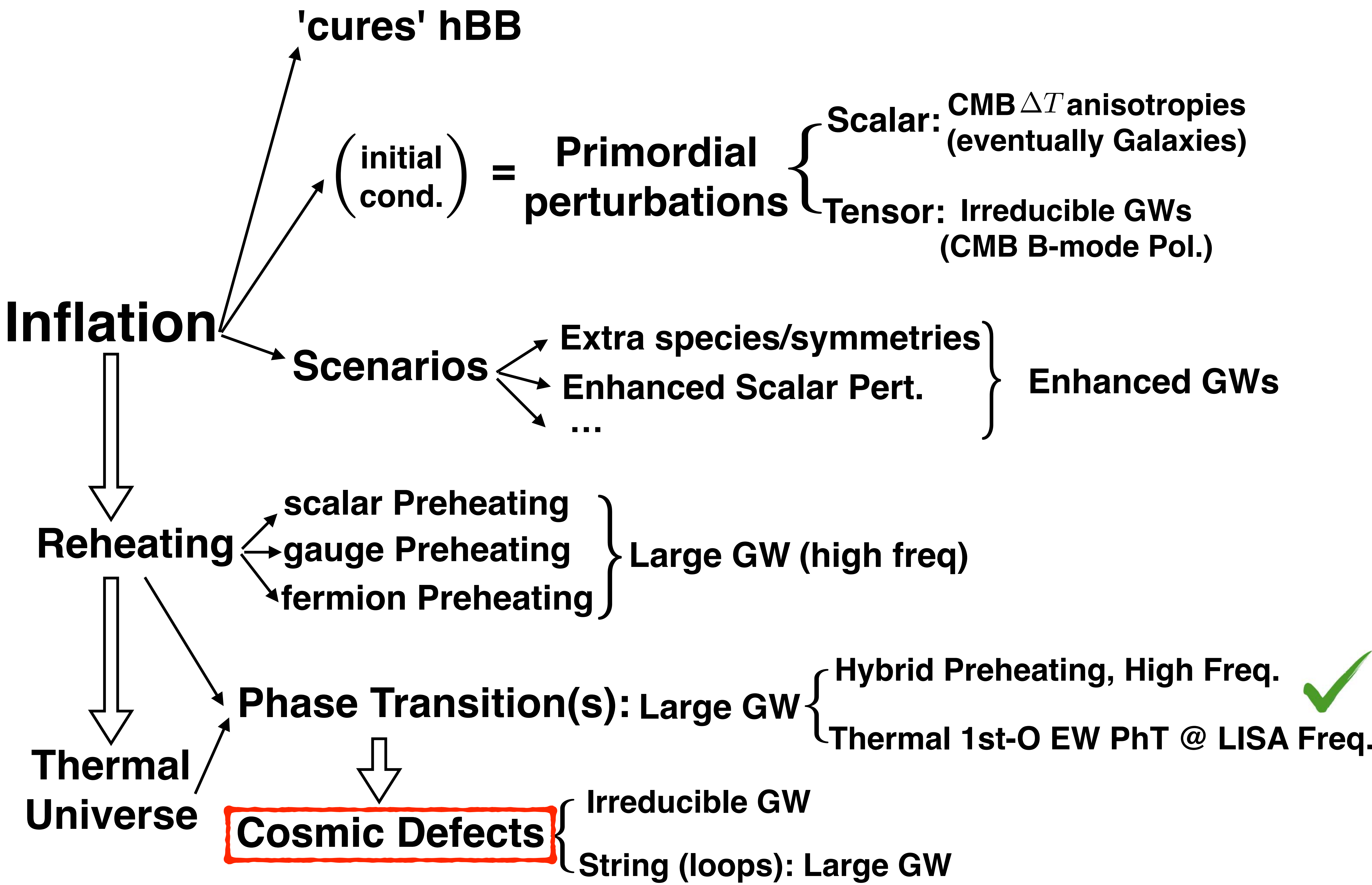
EARLY UNIVERSE



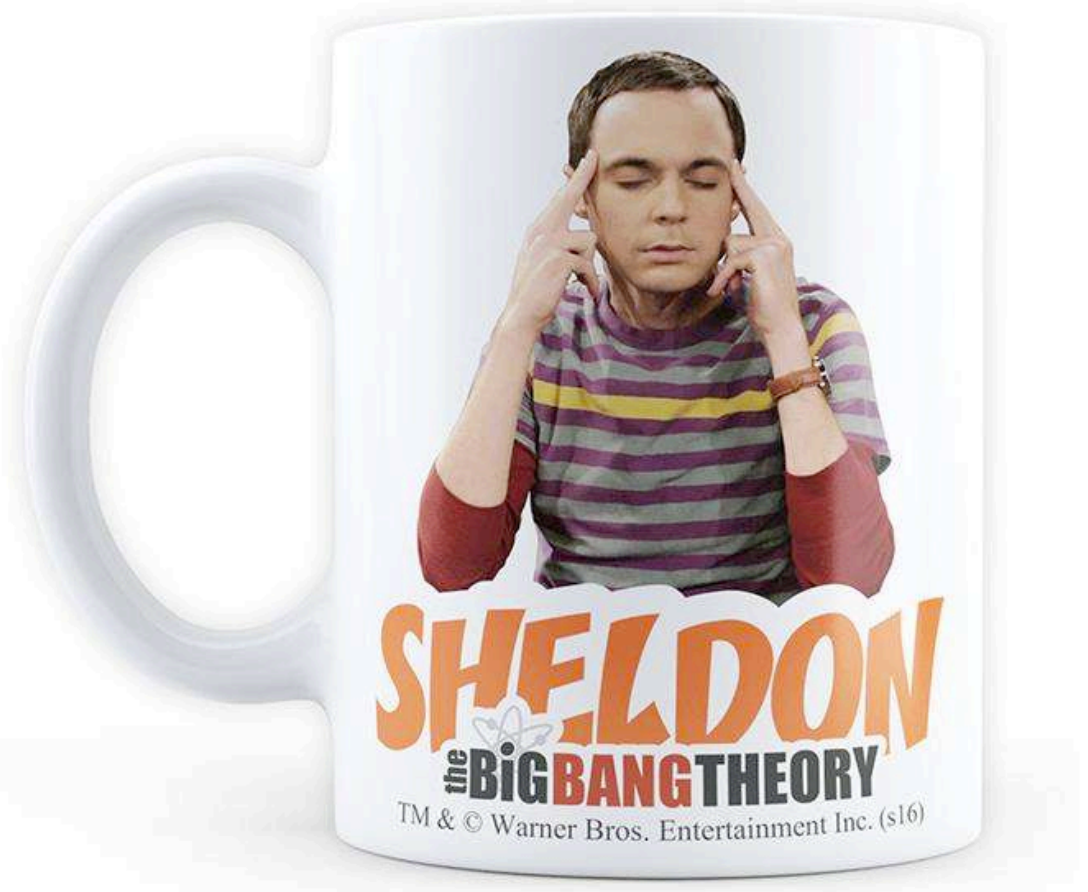
EARLY UNIVERSE



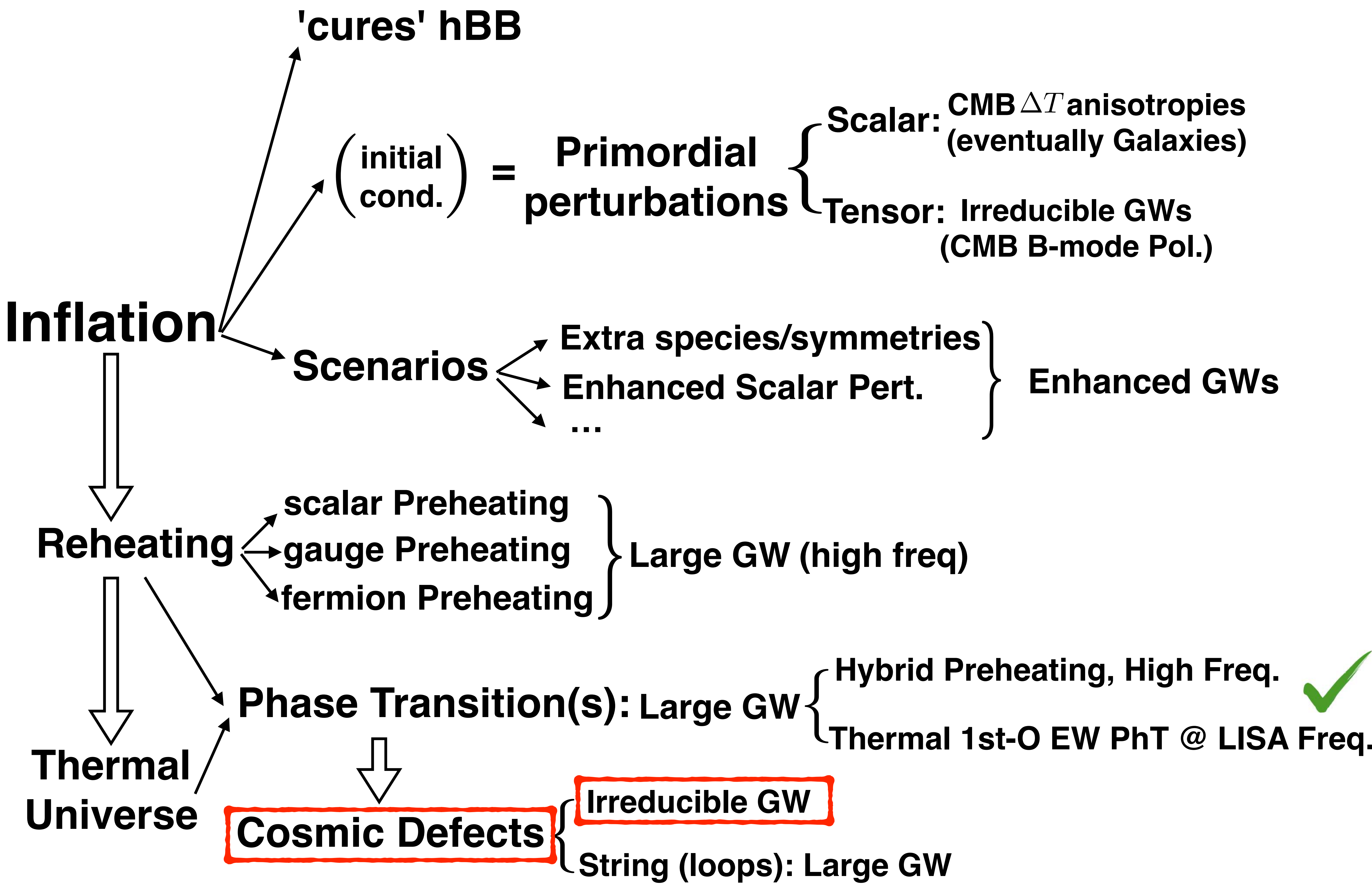
EARLY UNIVERSE



Shall we coffee break ?



EARLY UNIVERSE



Cosmic Defects

Aftermath product of a Ph.T.

Introduction to Cosmic Defects

Topology of cosmic domains and strings

T W B Kibble
Blackett Laboratory, Imperial College, Prince Consort Road, London SW7 2BZ, UK

Received 11 March 1976

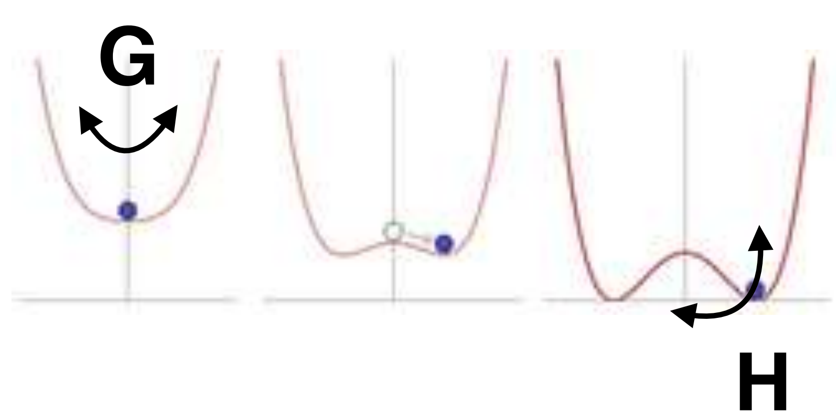
Abstract. The possible domain structures which can arise in the universe in a spontaneously broken gauge theory are studied. It is shown that the formation of domain walls, strings or monopoles depends on the homotopy groups of the manifold of degenerate vacua. The subsequent evolution of these structures is investigated. It is argued that while theories generating domain walls can probably be eliminated (because of their unacceptable gravitational effects), a cosmic network of strings may well have been formed and may have had important cosmological effects.

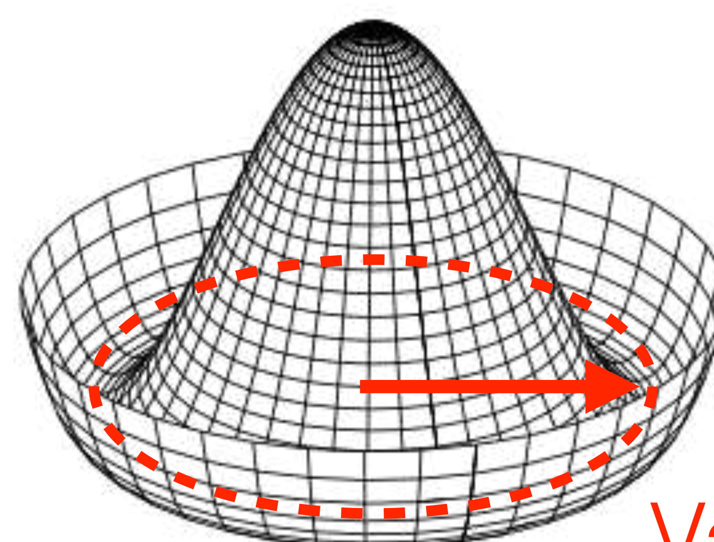
Kibble pioneered the study of topological defect generation in the early universe.

Introduction to Cosmic Defects

Kibble'76

... us recall the more general situation. In a model with symmetry group G, the vacuum expectation value $\langle\phi\rangle$ will be restricted to lie on some orbit of G. If H is the isotropy subgroup of G at one point $\langle\phi\rangle$, i.e. the subgroup of transformations leaving $\langle\phi\rangle$ unaltered, then the orbit may be identified with the coset space $M = G/H$. Physically H is the subgroup of unbroken symmetries, and M is the manifold of degenerate vacua. As we shall see, the topological properties of M (specifically its homotopy groups) largely determine the geometry of possible domain structures.





M = G/H

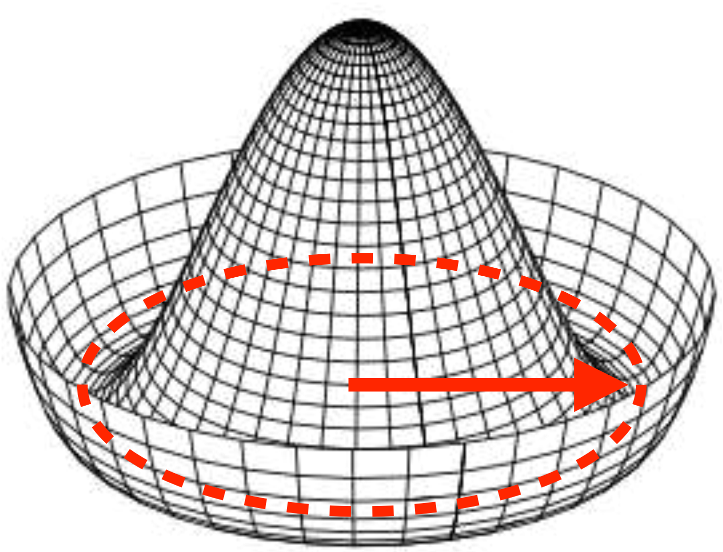
Vacuum Manifold

Introduction to Cosmic Defects

6. Conclusions and discussion

On this basis we showed that a domain structure can be expected to arise. The topological character of this structure depends on the homotopy groups $\pi_k(M)$ of the manifold M of degenerate vacua. Domain walls can form if $\pi_0(M)$ is nontrivial, i.e. if M is non-connected. If it has n connected components we find an n-phase emulsion. The formation of cosmic strings requires that $\pi_1(M)$ be nontrivial, i.e. that M is not formed of simply connected components. Finally, 'monopoles' can form if $\pi_2(M)$ is nontrivial.

Kibble'76



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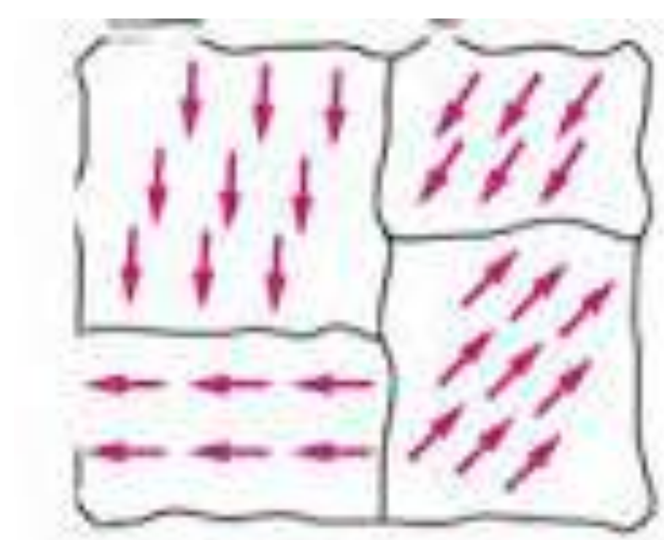
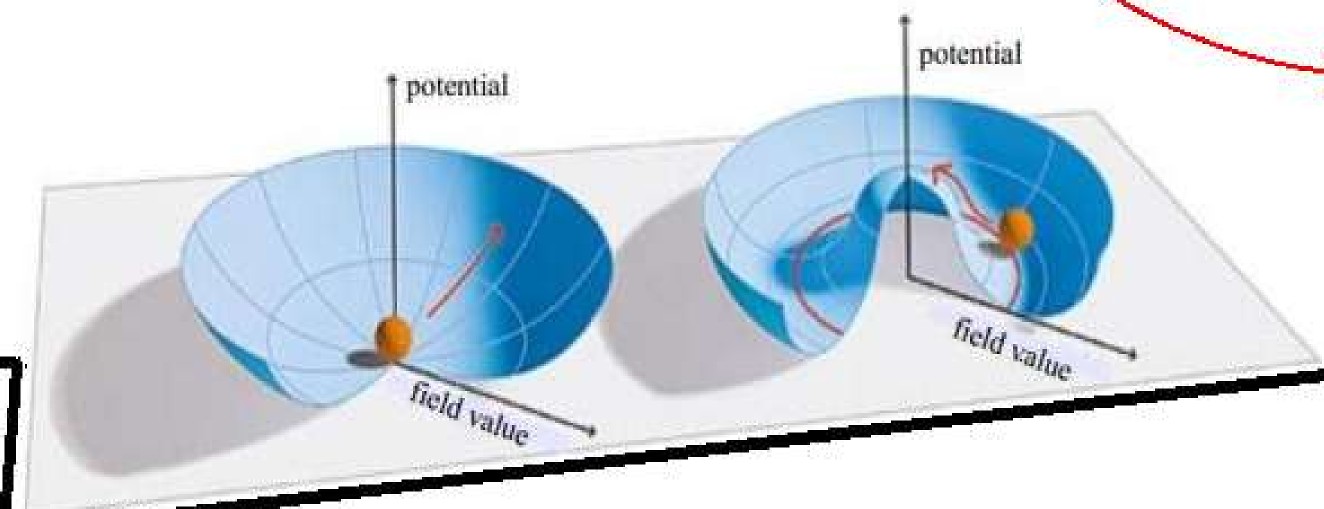


Introduction to Cosmic Defects

(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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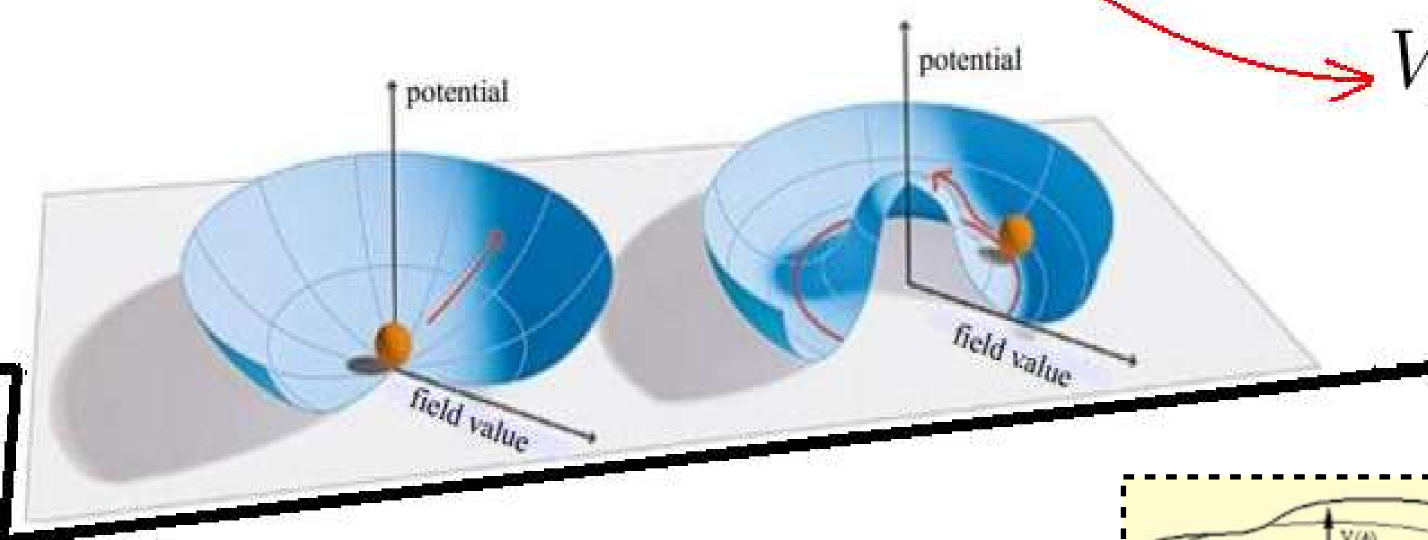

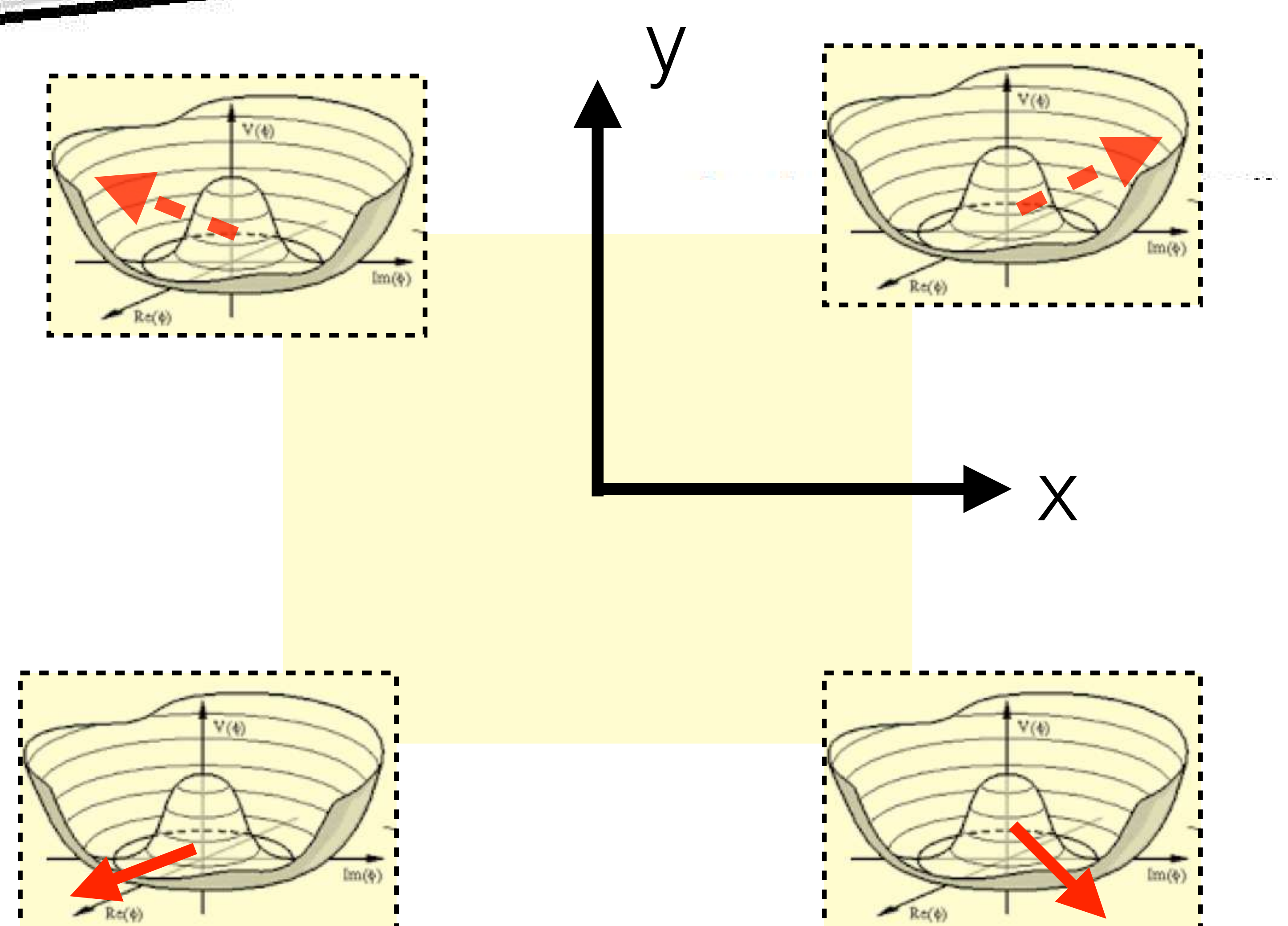

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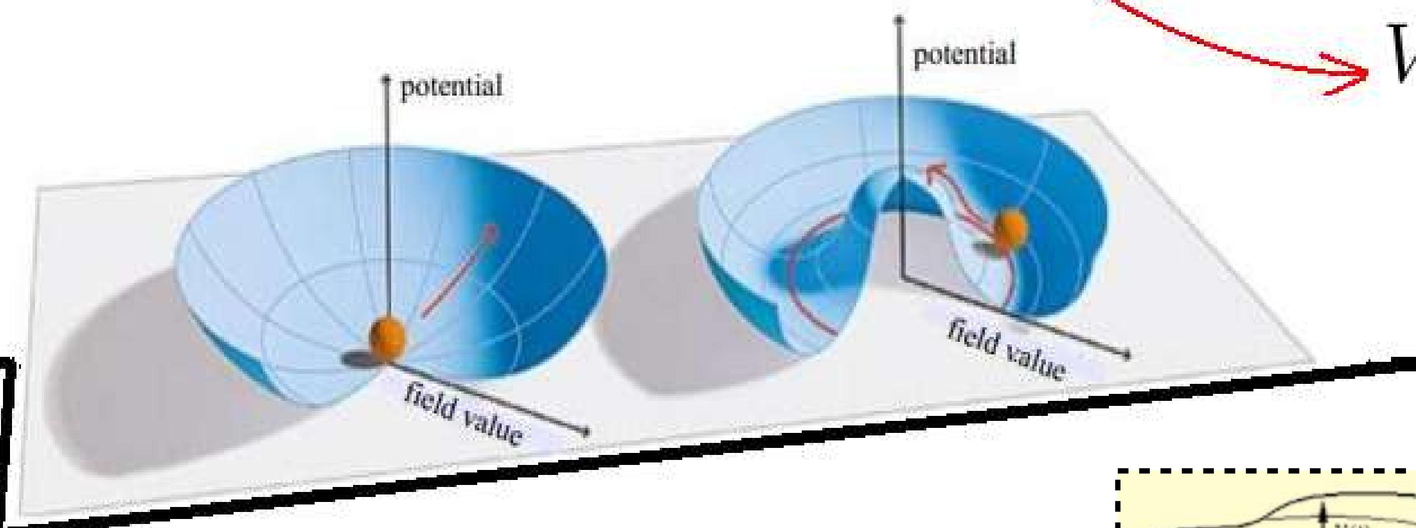

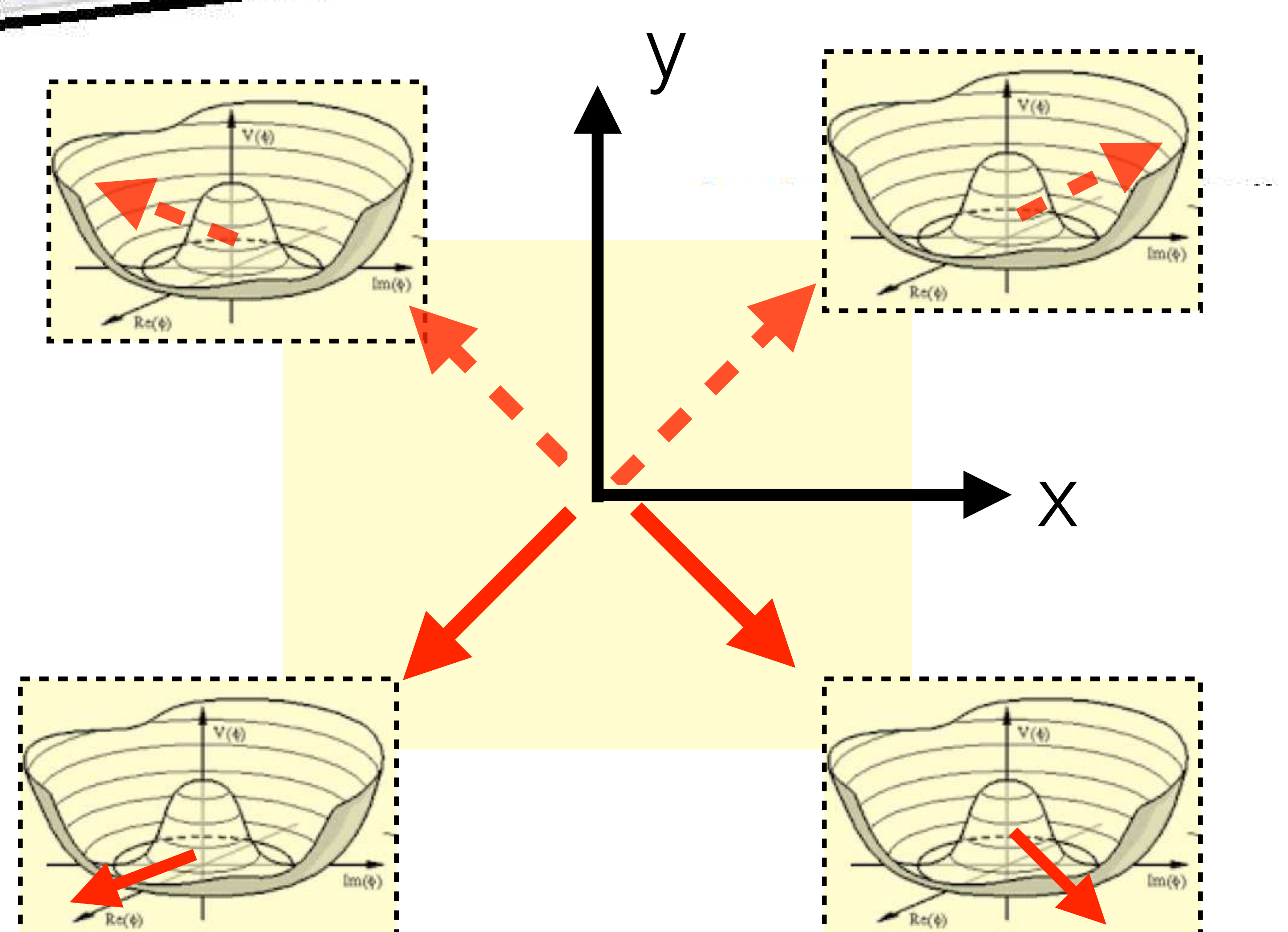

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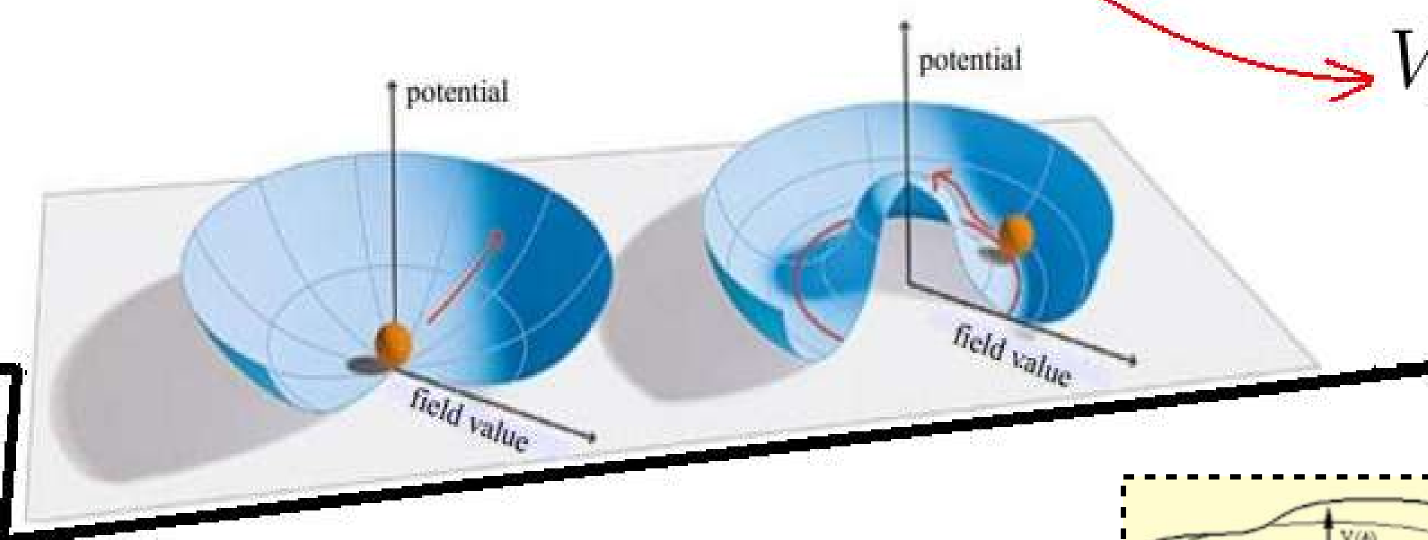

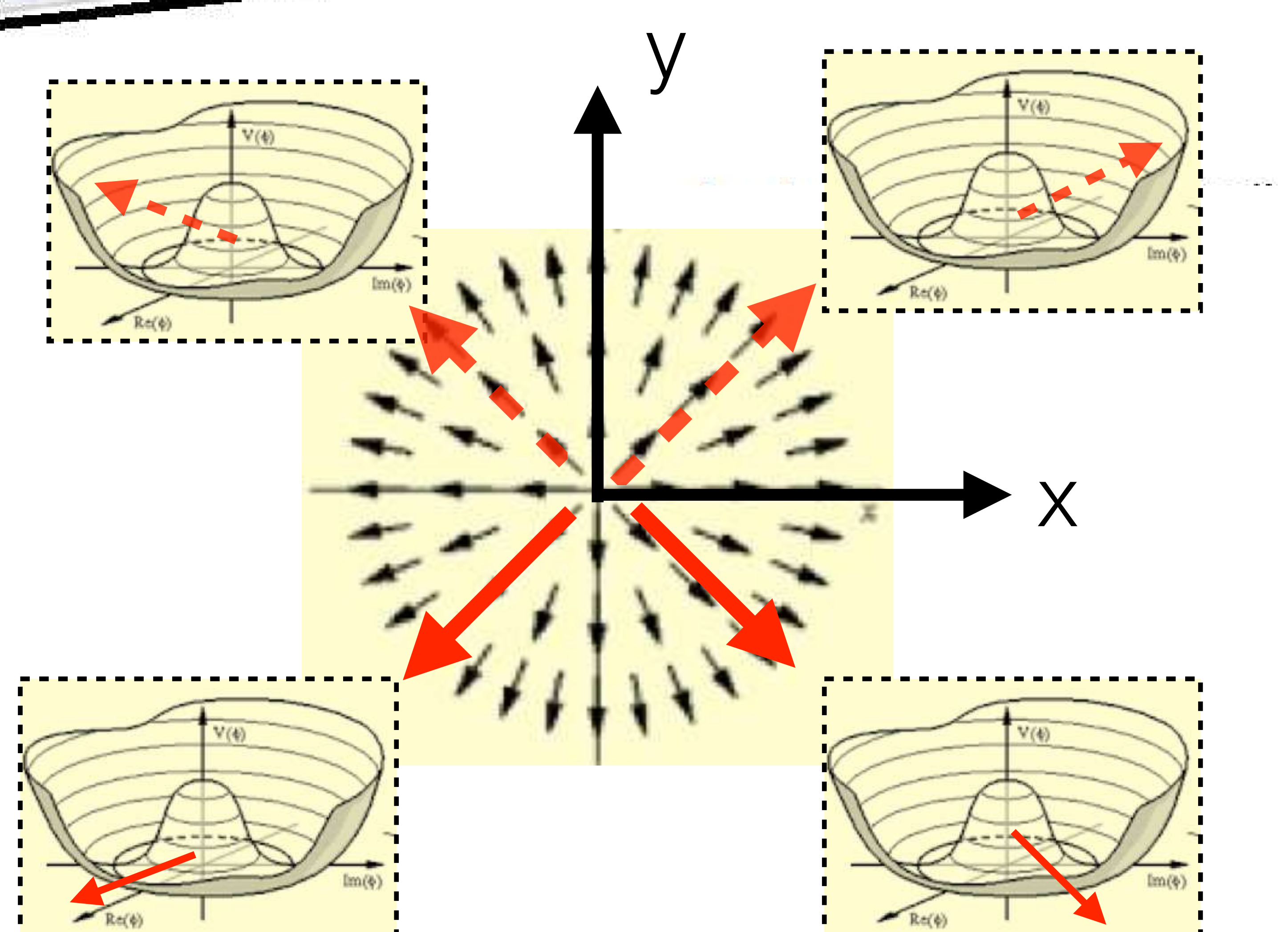

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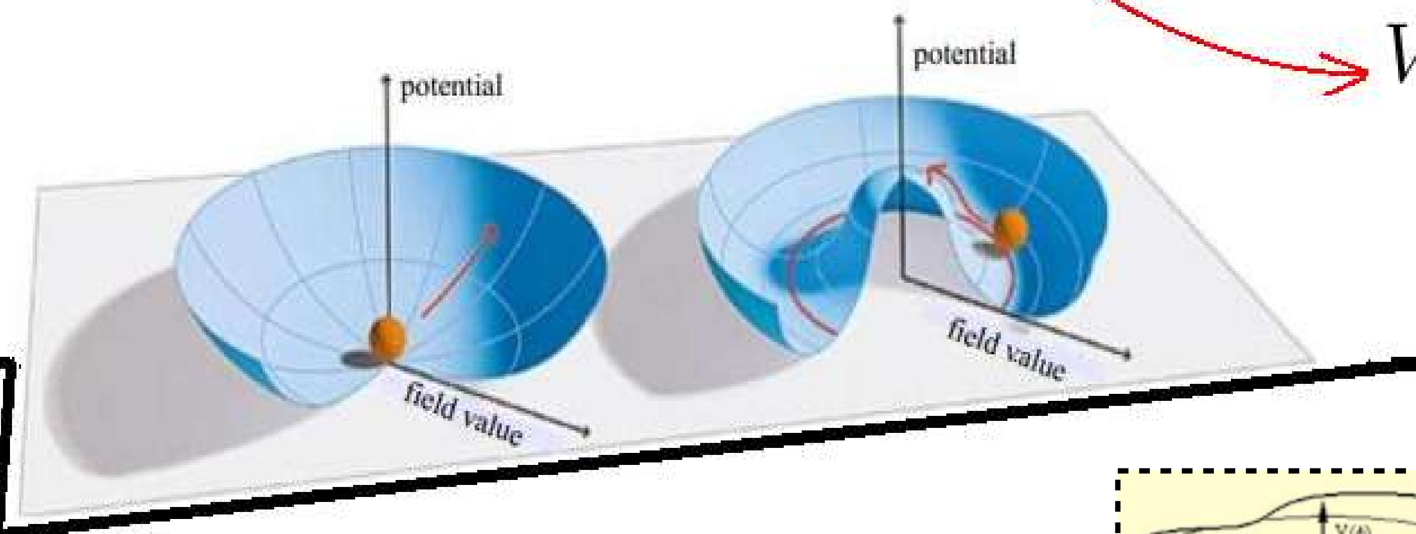

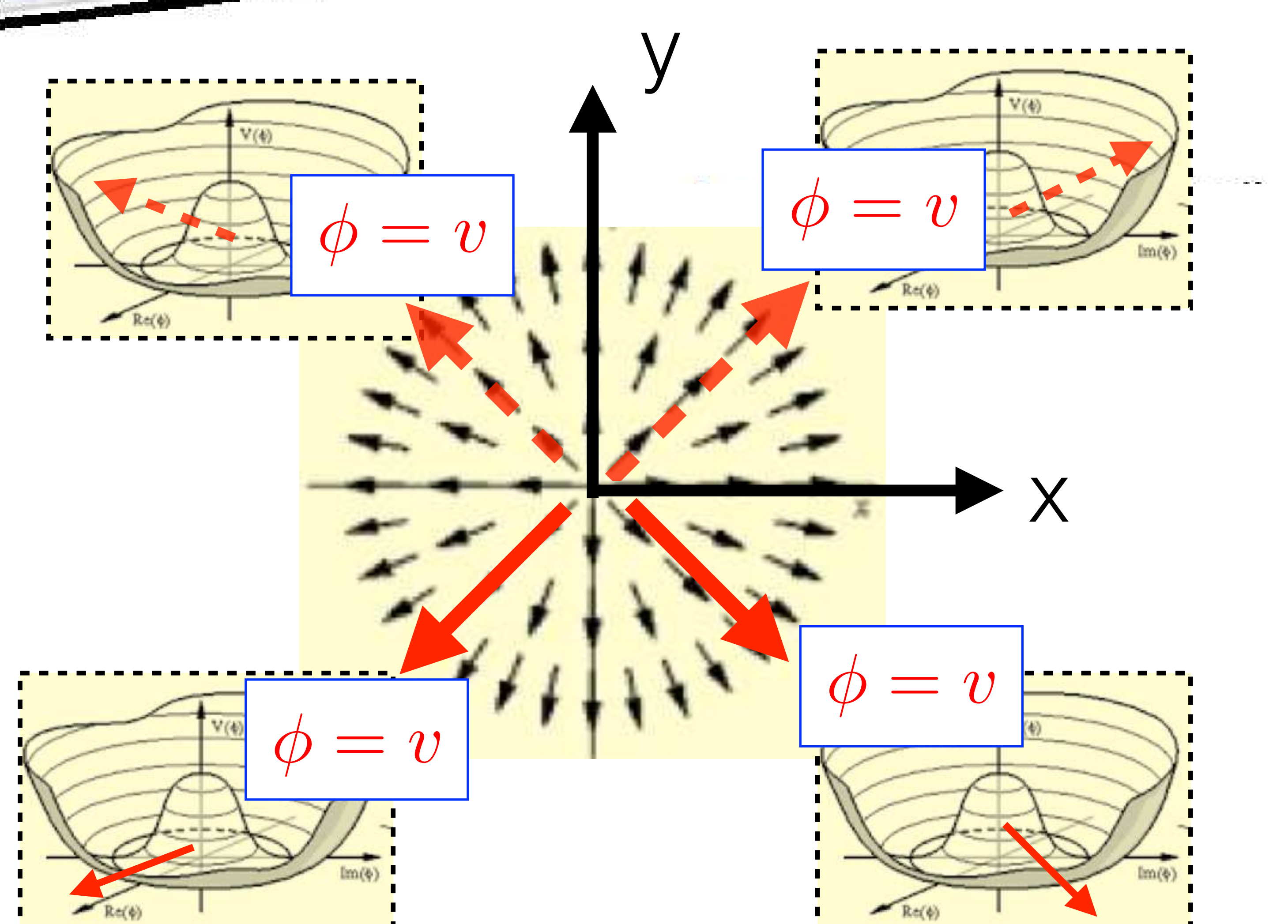

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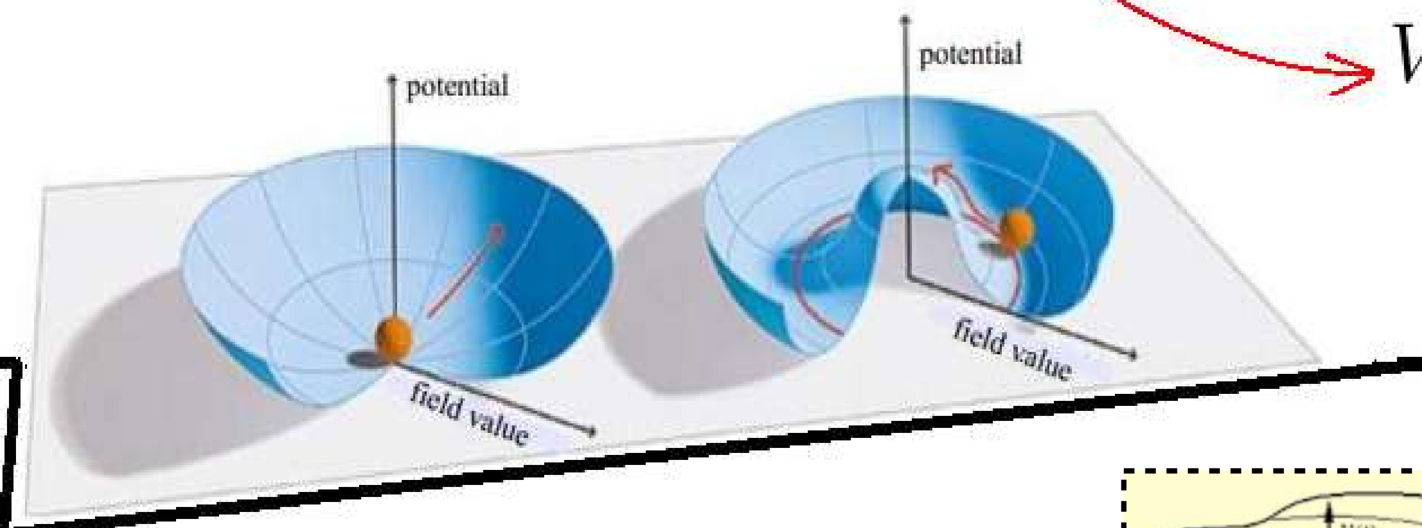

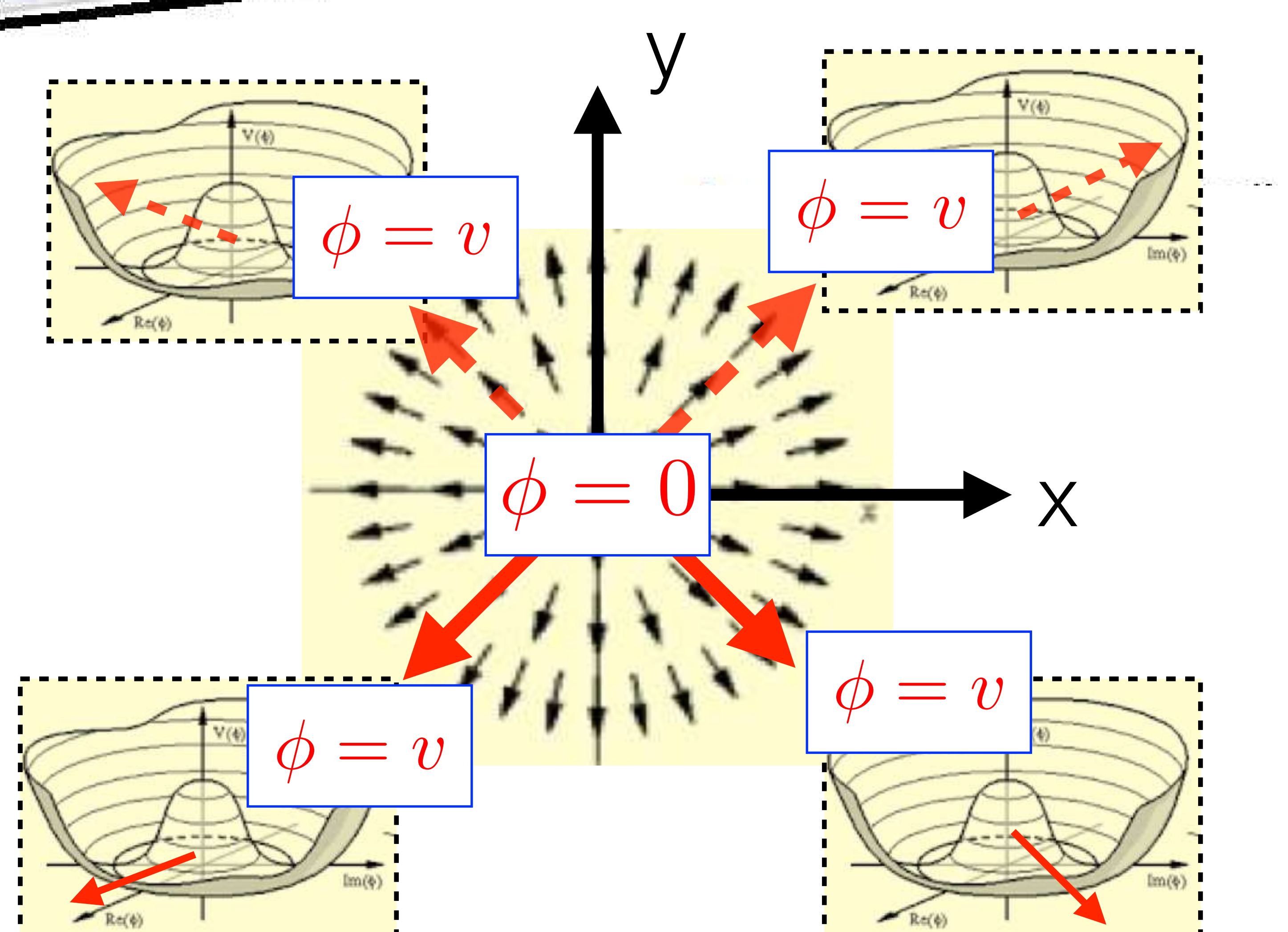

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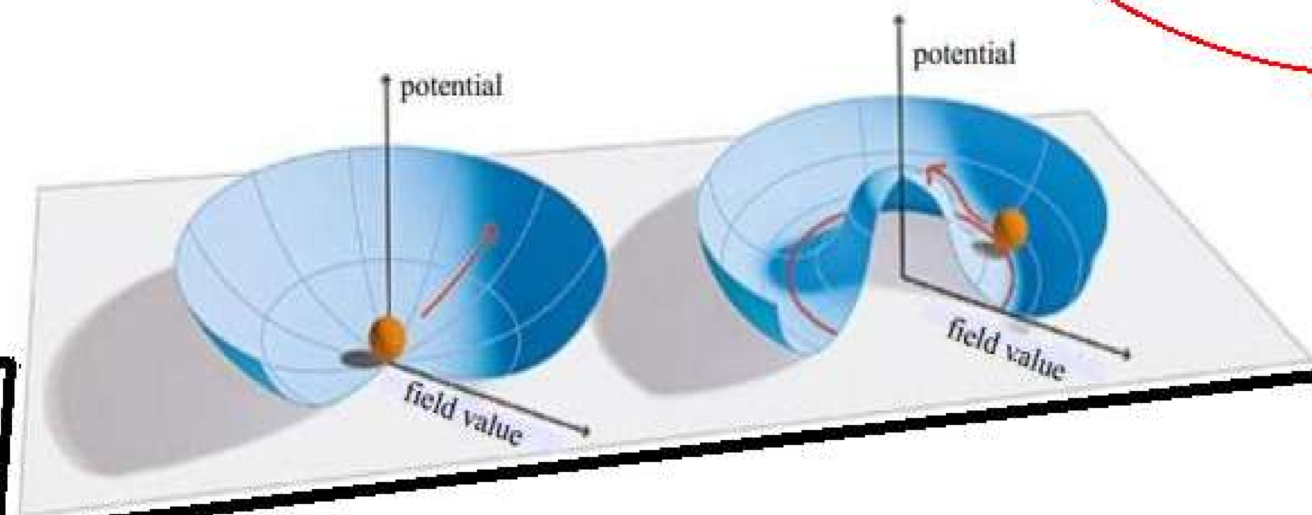
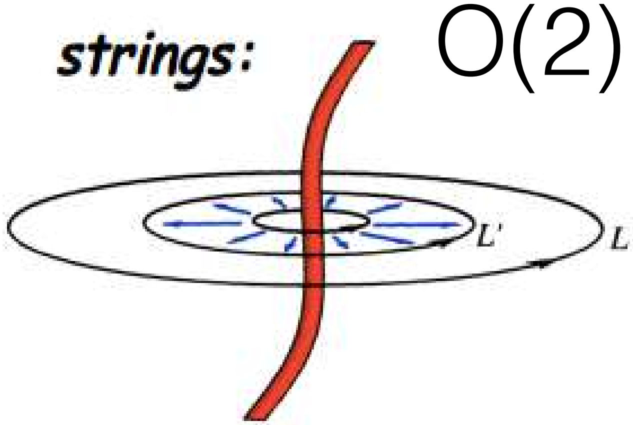
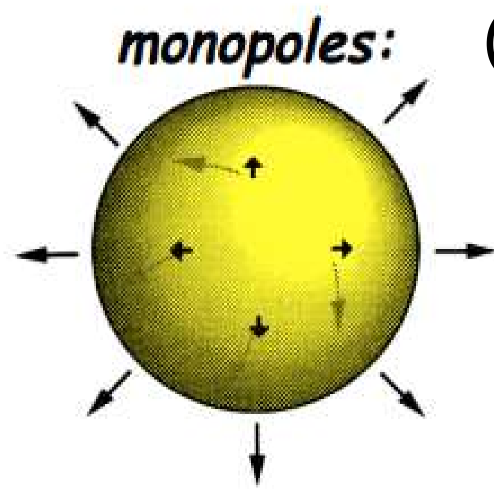


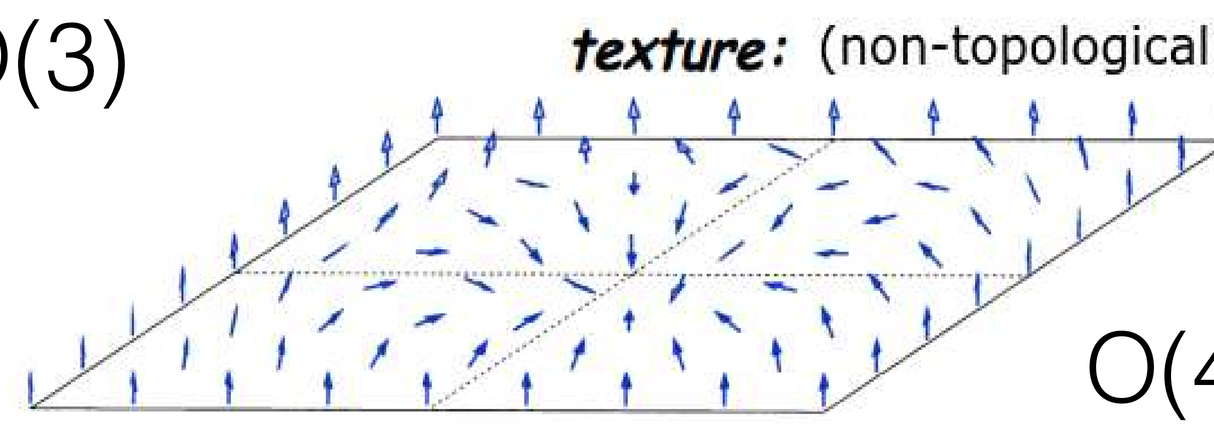
ZOOLOGY:



O(2)



O(3)



O(4)

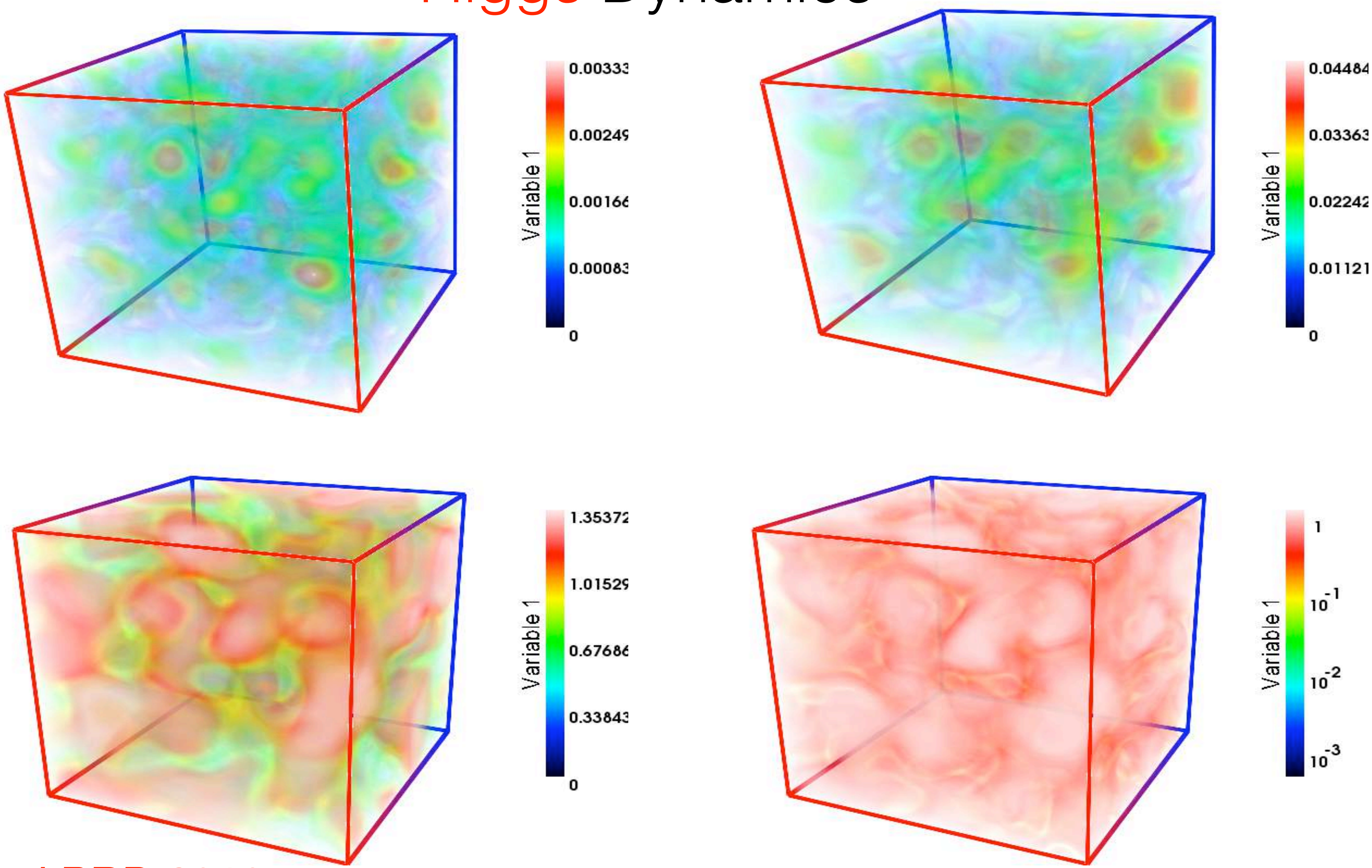
MICRO-PHYSICS → COSMIC DEFECTS

(M = G/H)

Introduction to Cosmic Defects

U(1) Breaking (after Hybrid Inflation)

Higgs Dynamics

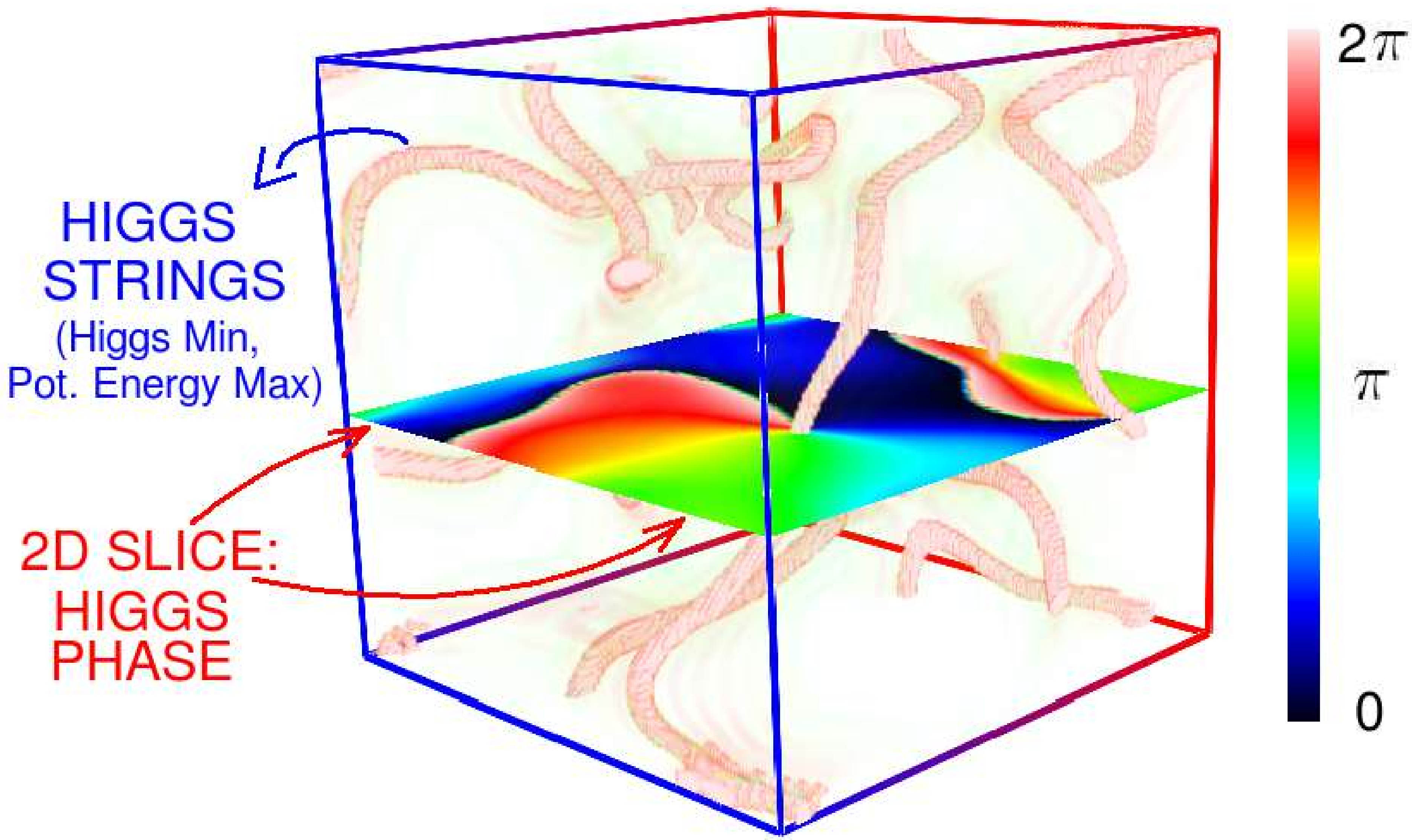


Dufaux et al PRD 2010

Introduction to Cosmic Defects

U(1) Breaking (after Hybrid Inflation)

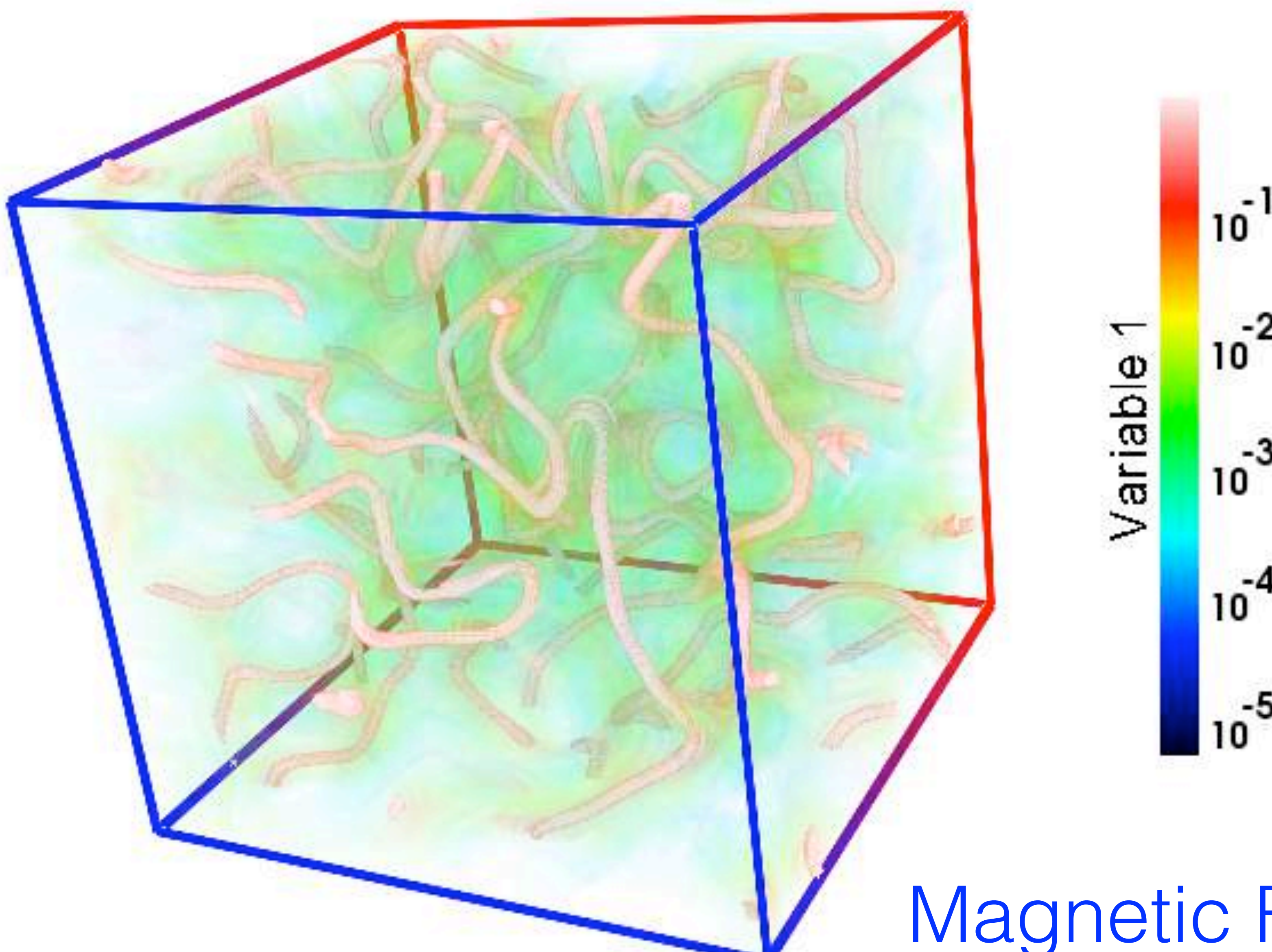
SNAPSHOT OF THE HIGGS ($mt = 17$)



Dufaux et al PRD 2010

Introduction to Cosmic Defects

U(1) Breaking (after Hybrid Inflation)



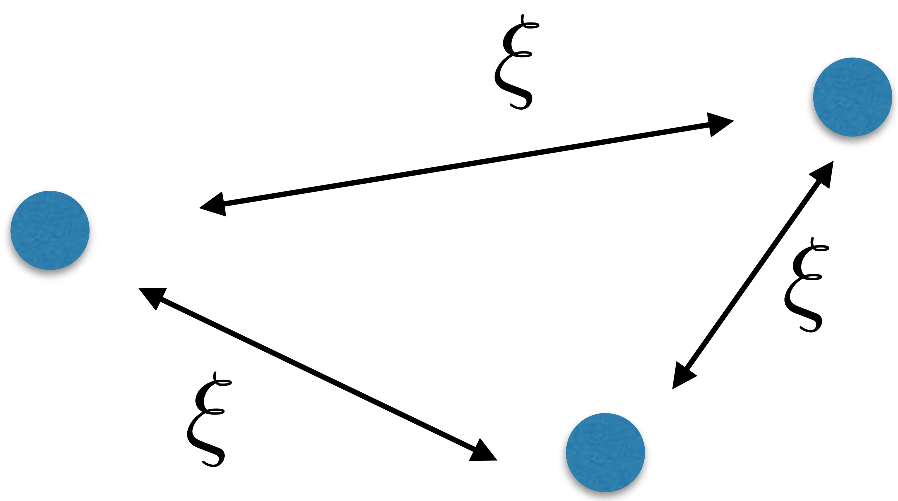
Magnetic Field
energy density

Dufaux et al PRD 2010

Introduction to Cosmic Defects

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

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



Introduction to Cosmic Defects

DEFECTS: Aftermath of PhT $\rightarrow$

- Topological:
  - Domain Walls
  - Cosmic Strings
  - Cosmic Monopoles
- Non – Topological

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

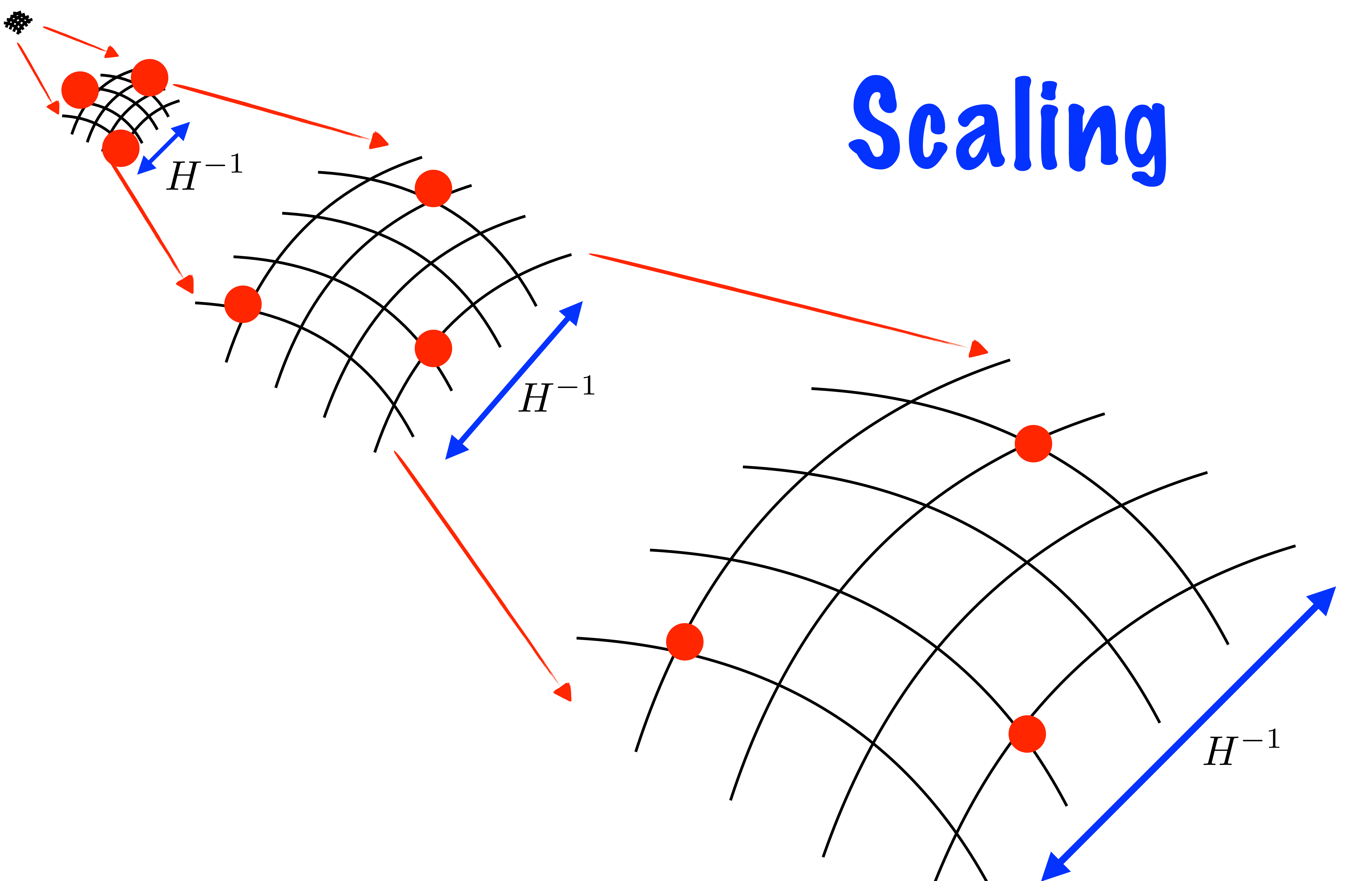
(Kibble' 76)

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 (↑ k) **Conformal** (↑ t)

GWs from a scaling network of cosmic defects

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SCALING

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Comoving **Conformal**

SCALING

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

GW spectrum: Expansion UTC

$$\frac{d\rho_{\rm GW}}{d\log k}(k,t) \propto \frac{k^3}{M_p^2a^4(t)}\int dt_1dt_2 \quad t_1t_2 \quad \cos(k(t_1-t_2))\,\frac{\rm V^4}{\sqrt{t_1t_2}}U(kt_1,kt_2)$$

Comoving **Conformal**

Rad. Dom

SCALING

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$(x_i \equiv kt_i)$

GW spectrum: Expansion UTC

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

Rad. Dom

SCALING

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Rad. Dom **SCALING**

$F_U \sim$ Const. (Dimensionless)

GWs from a scaling network of cosmic defects

GW today:

VEV

Scaling @ RD

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

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

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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

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

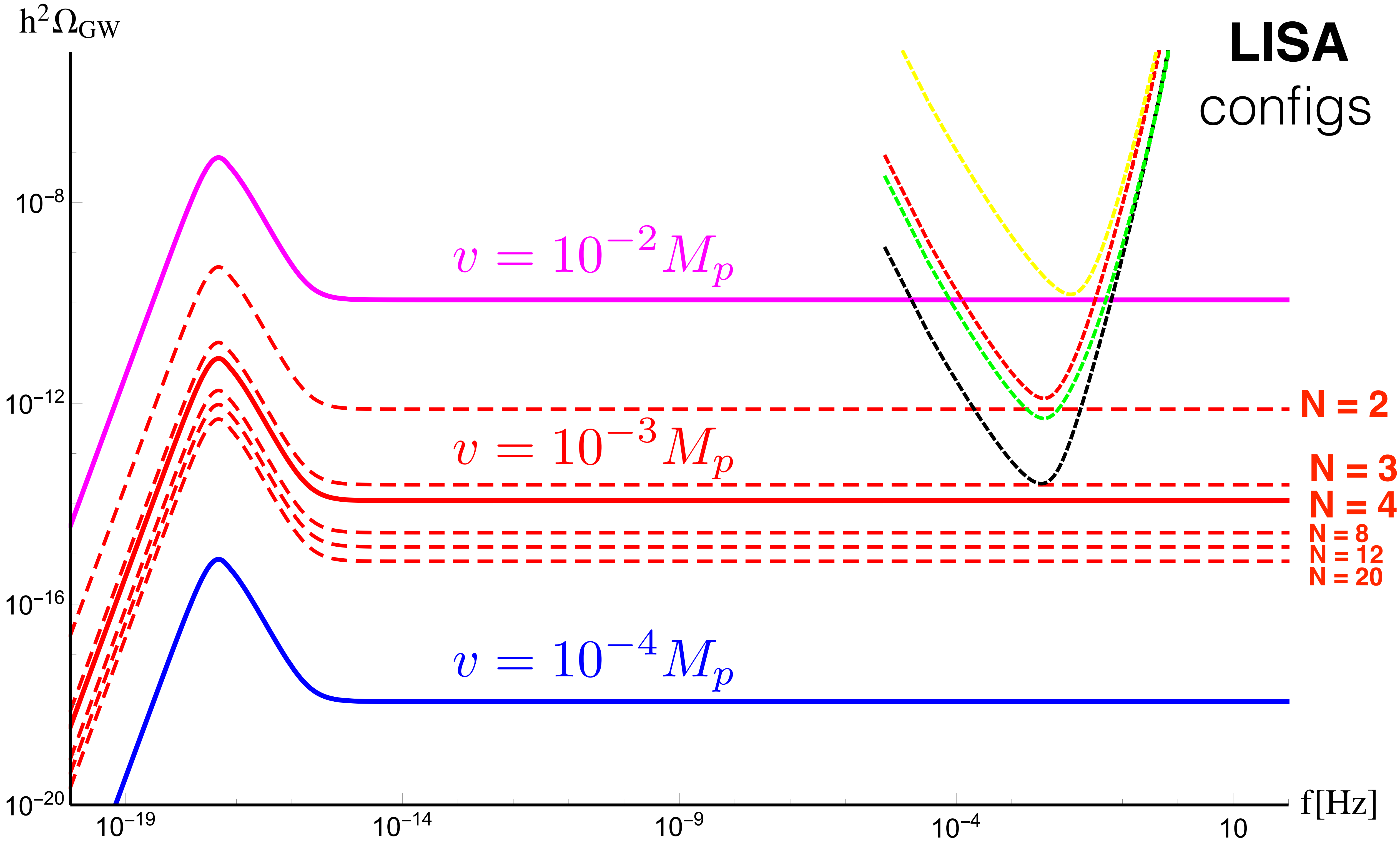
RD $$F_U^{(\rm R)} \equiv \frac{32}{3}\int_0^x dx_1 dx_2\, (x_1x_2)^{1/2} \cos(x_1 - x_2)\, U_{\rm RD}(x_1, x_2)$$

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

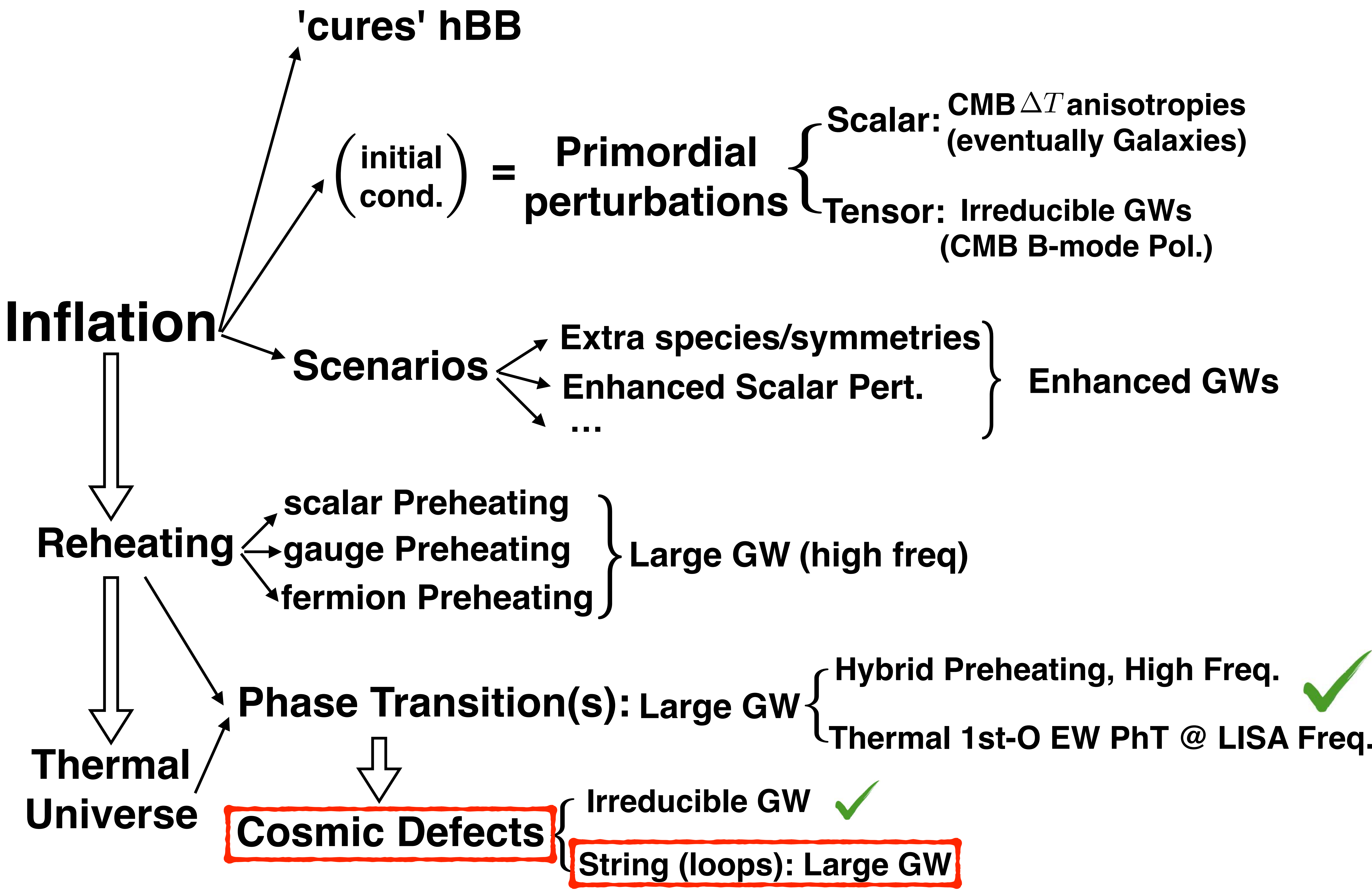
DGF, Hindmarsh, Lizarraga, Urrestilla, 2020 (to appear)

More on GW from Defect Networks

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



EARLY UNIVERSE



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 !

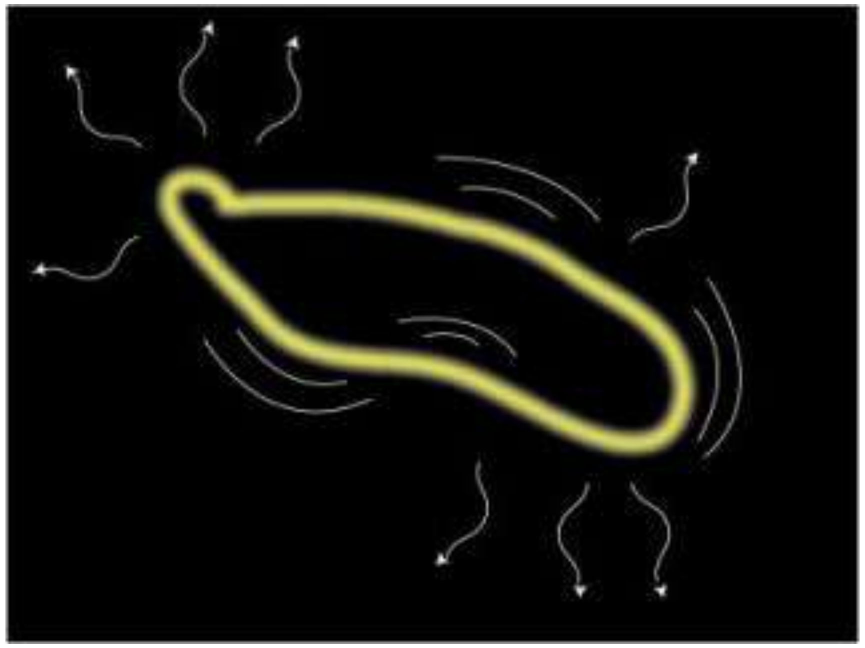


Image Credit: Google

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 !

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

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expansion history

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expansion history (→ dt) **length** (→ dl) **number density** (→ $n(l,t)$)

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expansion history

length

number density

GW power emission

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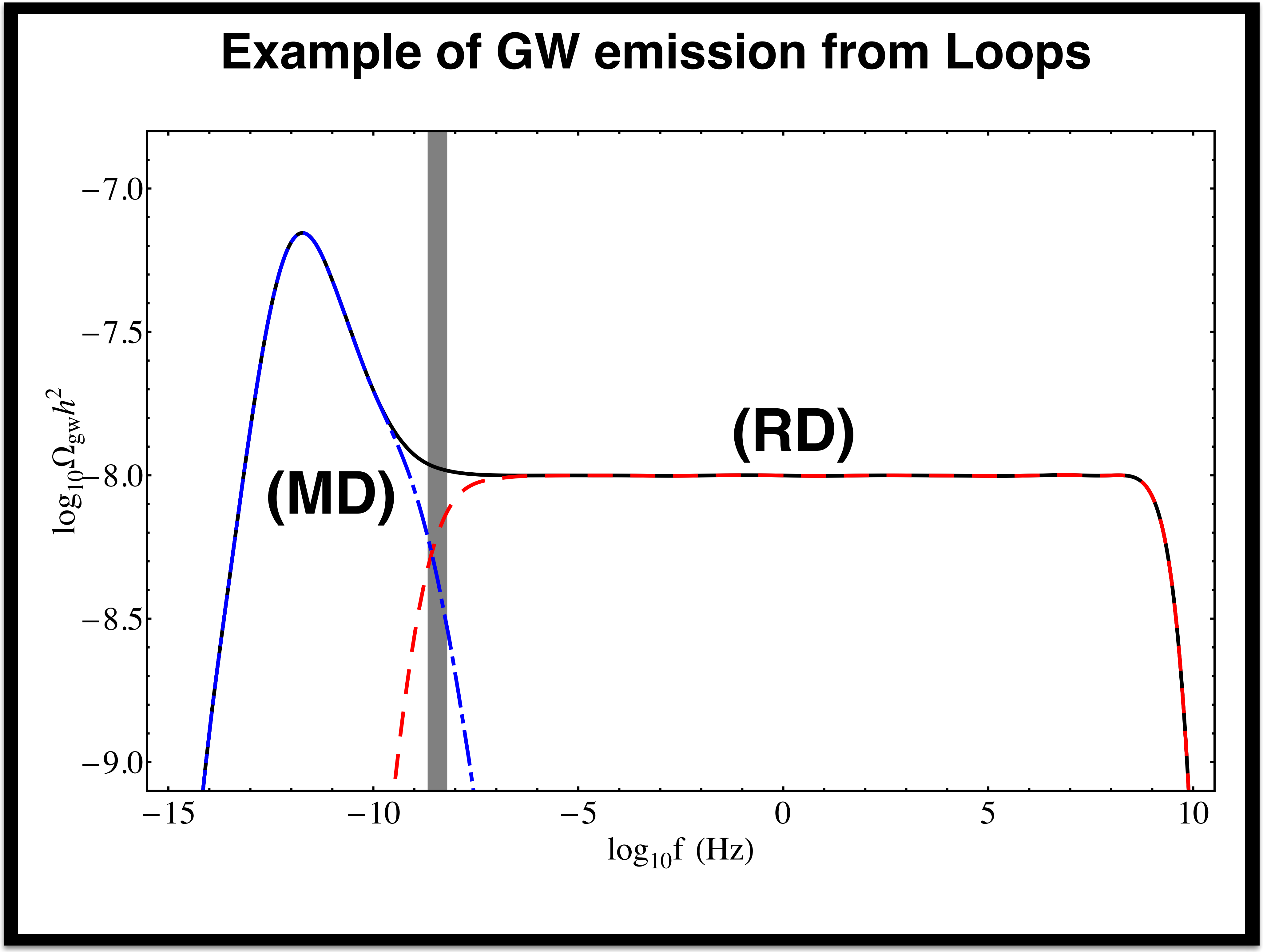
$$\frac{d\rho^{(o)}}{df} \equiv \Gamma G\mu^2 \int_{t_*}^{t_o} dt \left(\frac{a(t)}{a_o}\right)^3 \int_0^{\alpha/H(t)} dl \, l \, n(l,t) \, \mathcal{P}((a_o/a(t)) f l)$$

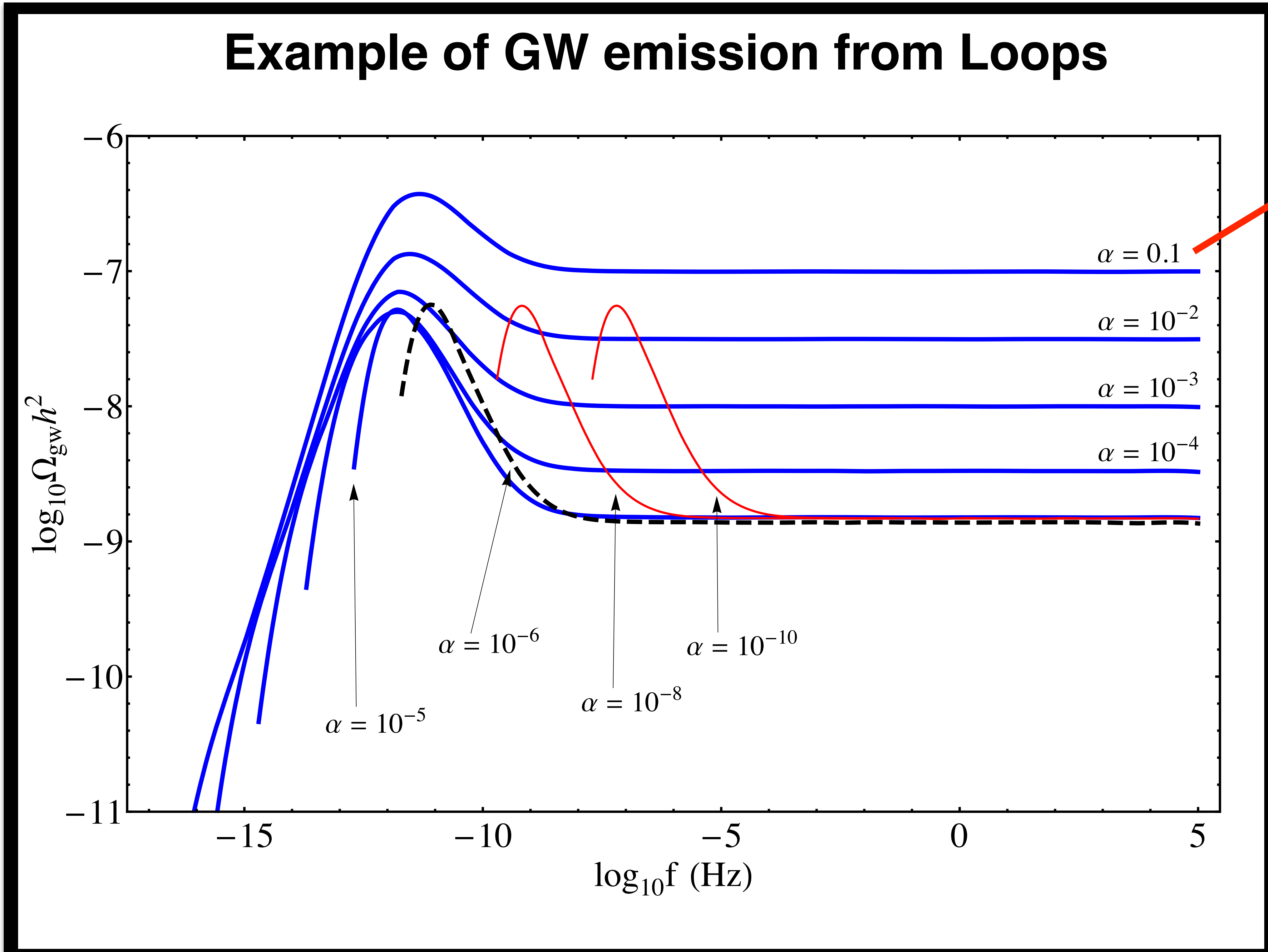
- $dt \left(\frac{a(t)}{a_o}\right)^3$ → **expansion history**
- l → **length**
- $n(l,t)$ → **number density**
- $\mathcal{P}$ → **GW power emission** $\propto 1/(fl)^{q+1}$
  - $q+1$ → **features (kinks,cusps,...)**

Cosmic strings loops: GW background



e.g. Sanidas et al 2012

Cosmic Strings Network: Loop configurations



α

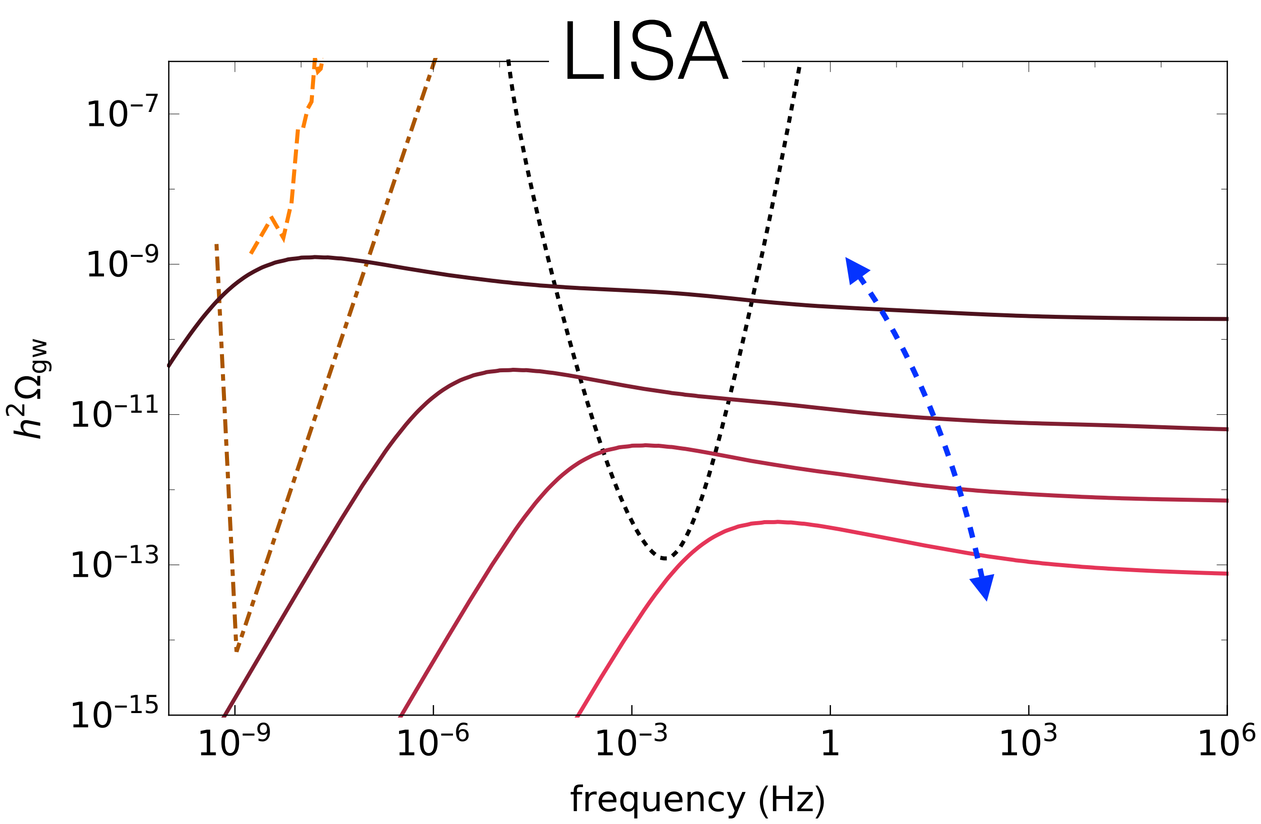
loop size

(relative to horizon)

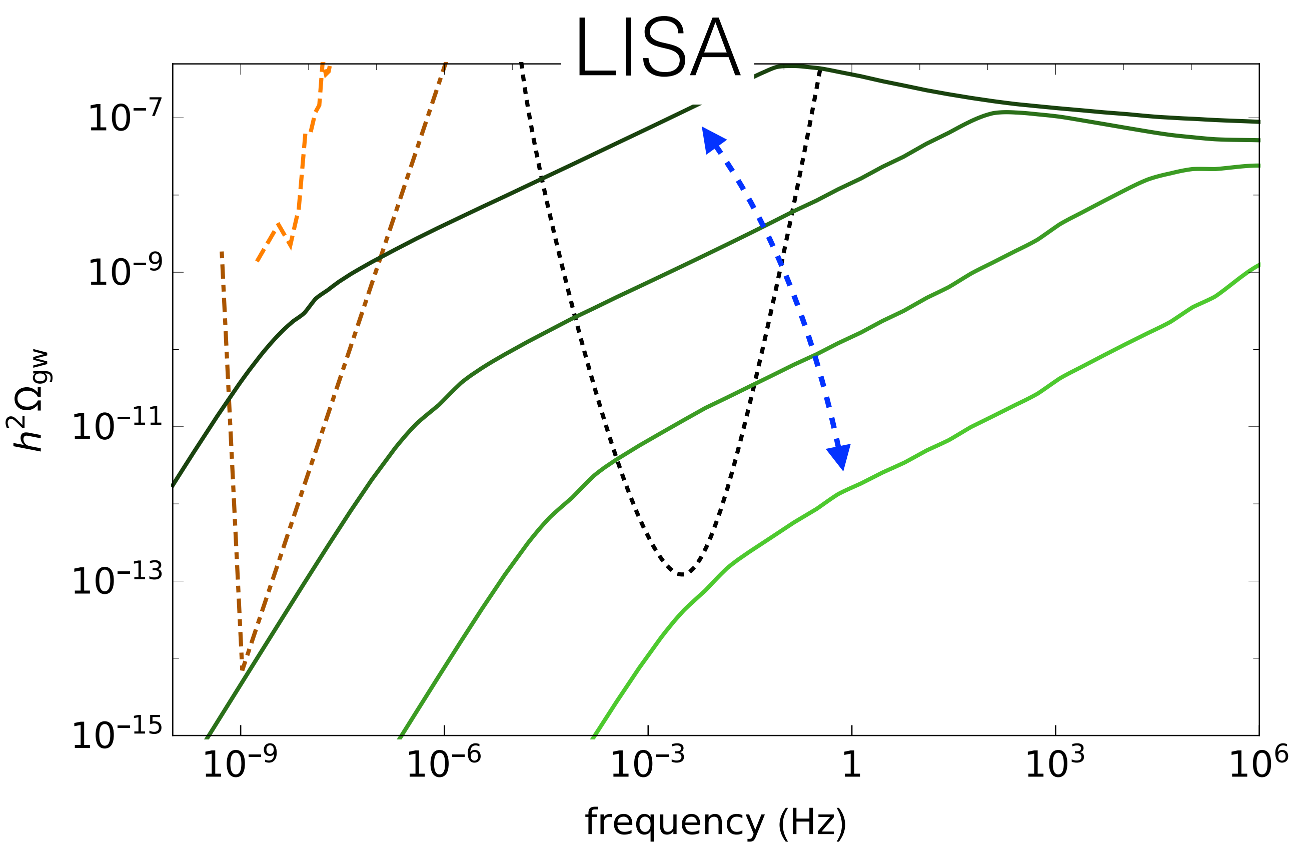
Sanidas et al 2012

Cosmic strings loops: GW background

Blanco-Pillado, Olum, Shlaer



Lorenz, Ringeval, Sakellariadou



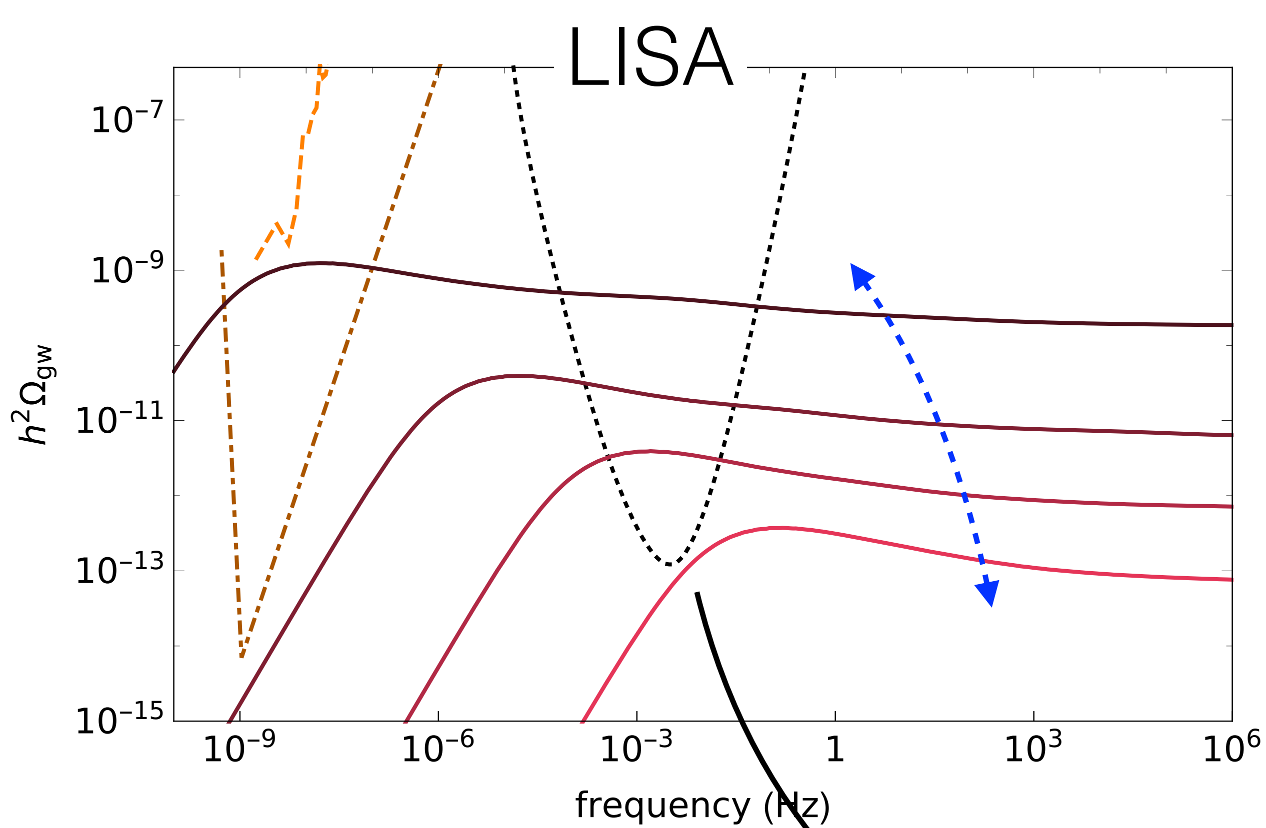
$$G\mu \sim 10^{-11} - 10^{-17}$$

Very large parameter space !

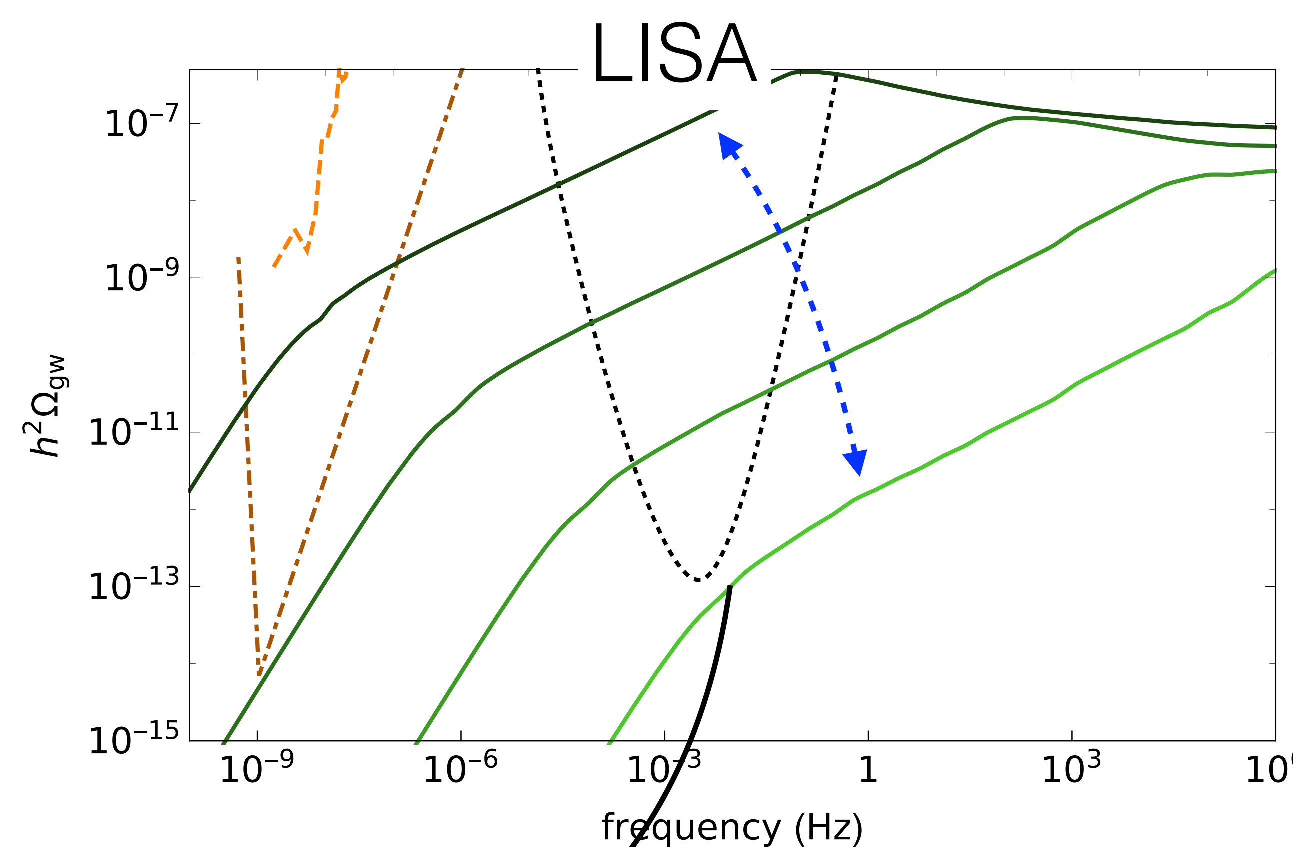
LISA paper 1909.00819

Cosmic strings loops: GW background

Blanco-Pillado, Olum, Shlaer



Lorenz, Ringeval, Sakellariadou



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

Very large parameter space !

LISA paper 1909.00819

GW background constrained by LISA

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

	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**

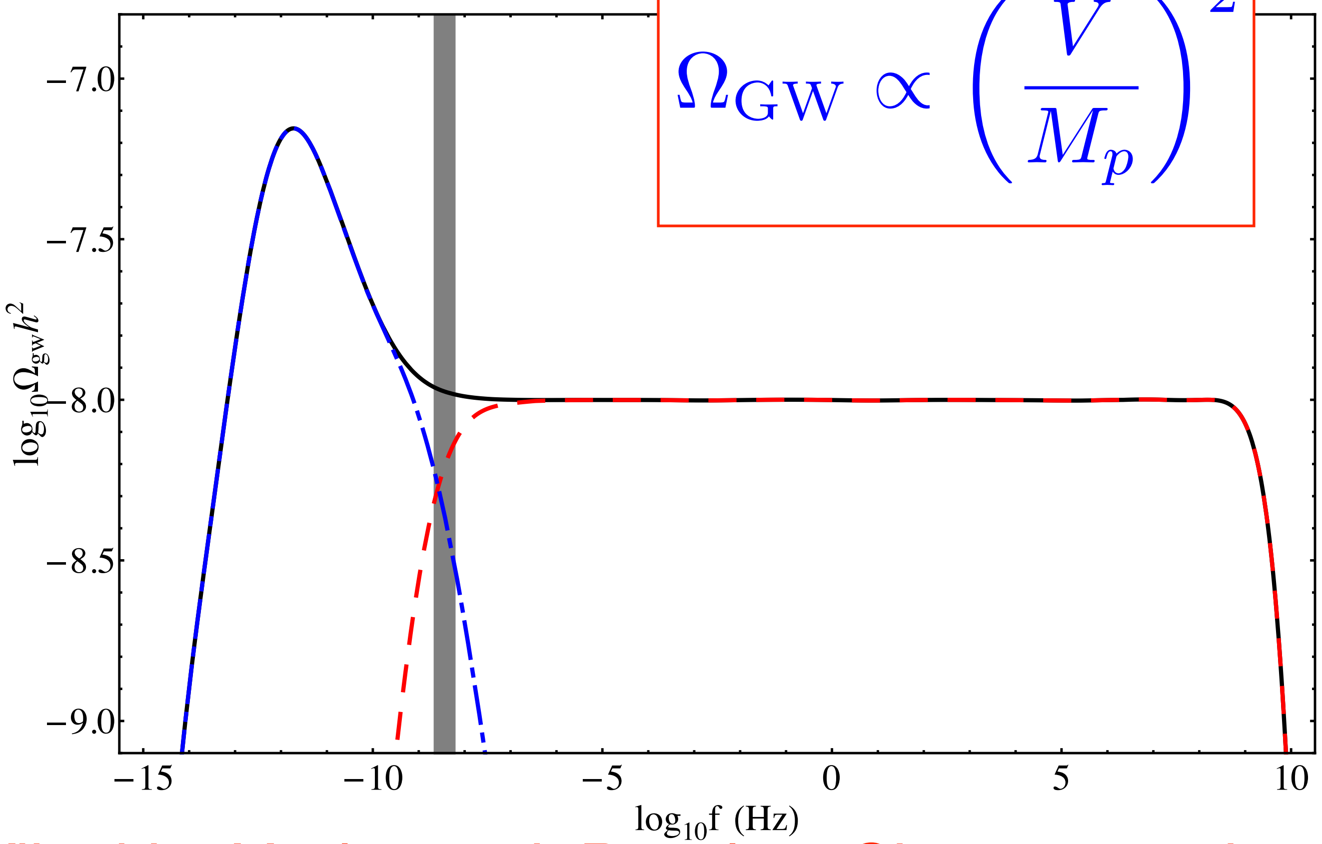
LISA paper
1909.00819

Cosmic Strings Network: Loop configurations

GW from string loops $\neq$ GW from "Infinite"-Strings

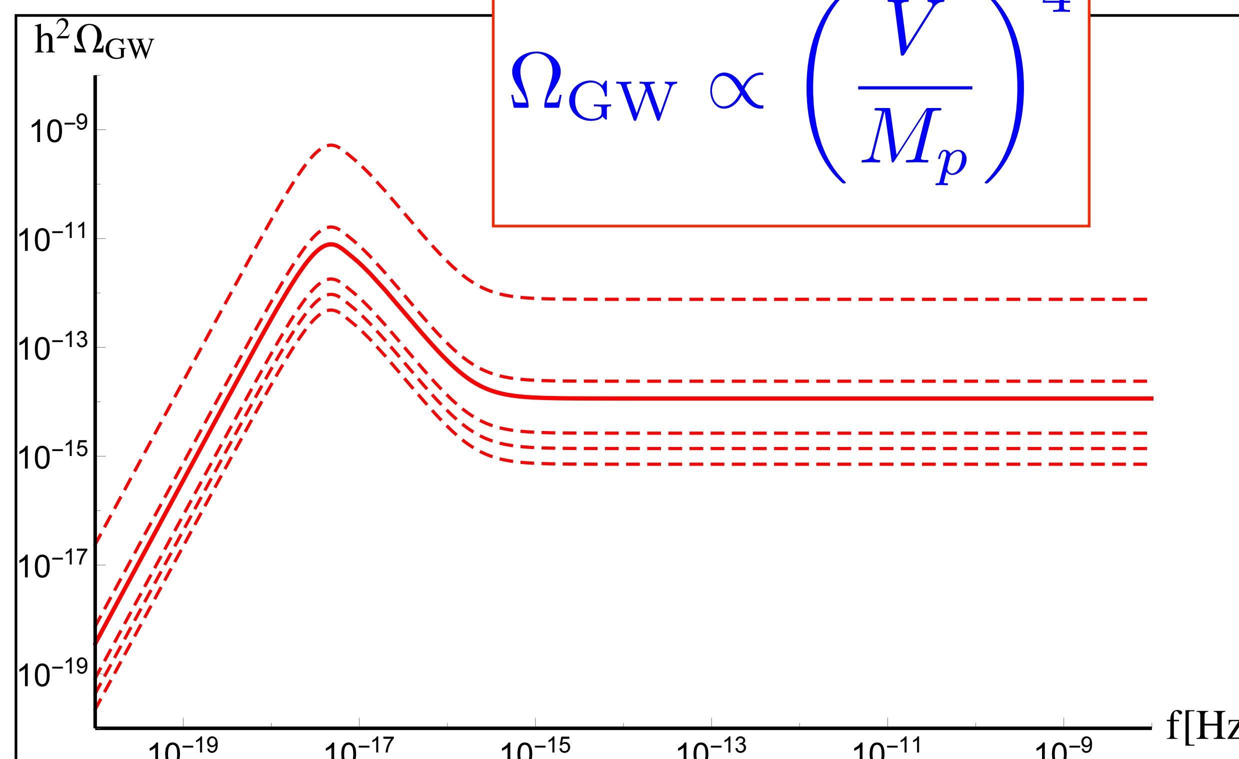
(particular emission) (irreducible emission)

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



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

OUTLINE

1st lecture

1) GWs Definition

2nd lecture

2) GWs from Inflation

3) GWs from Preheating

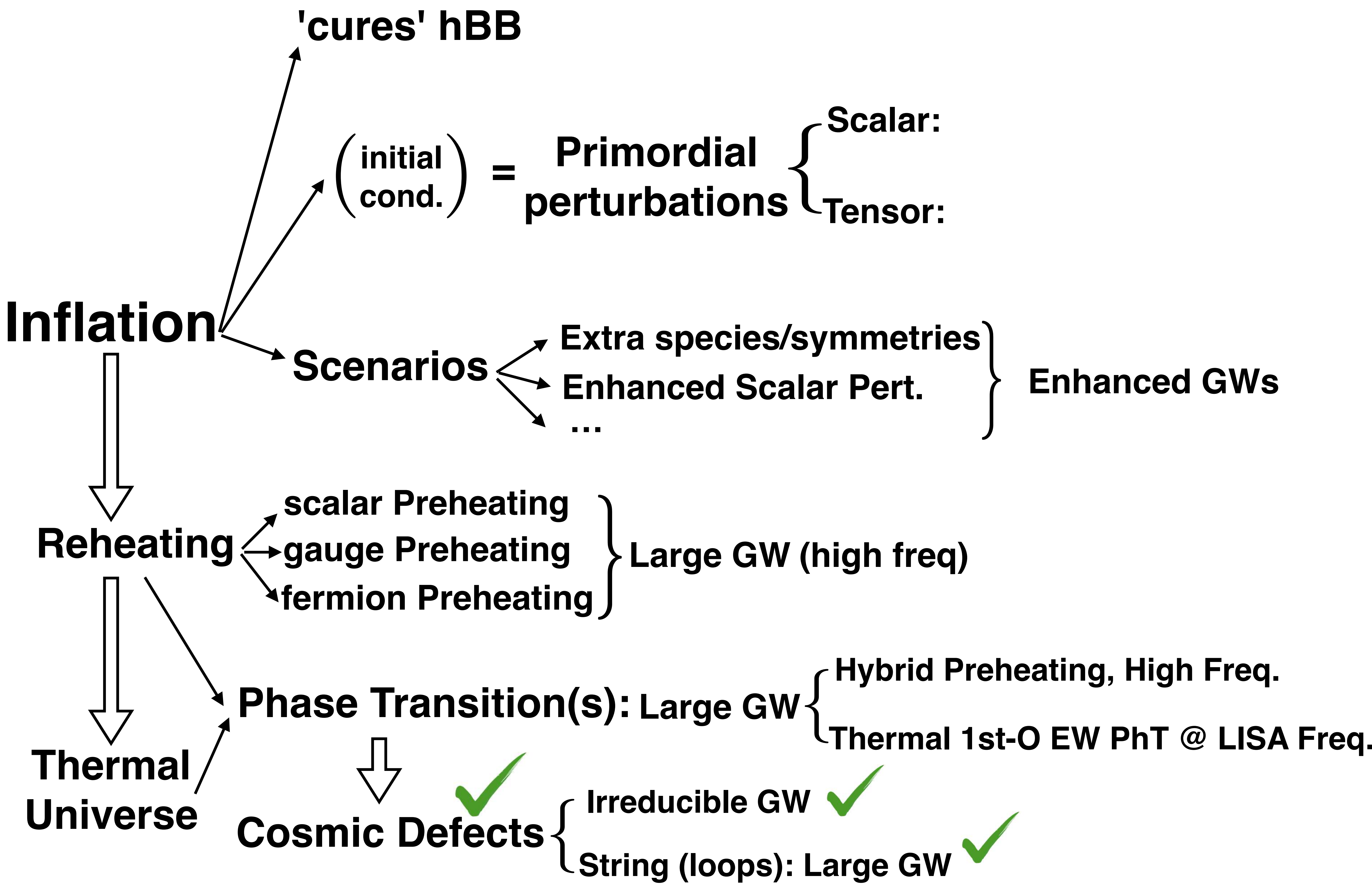
4) GWs from Phase Transitions

5) GWs from Cosmic Defects

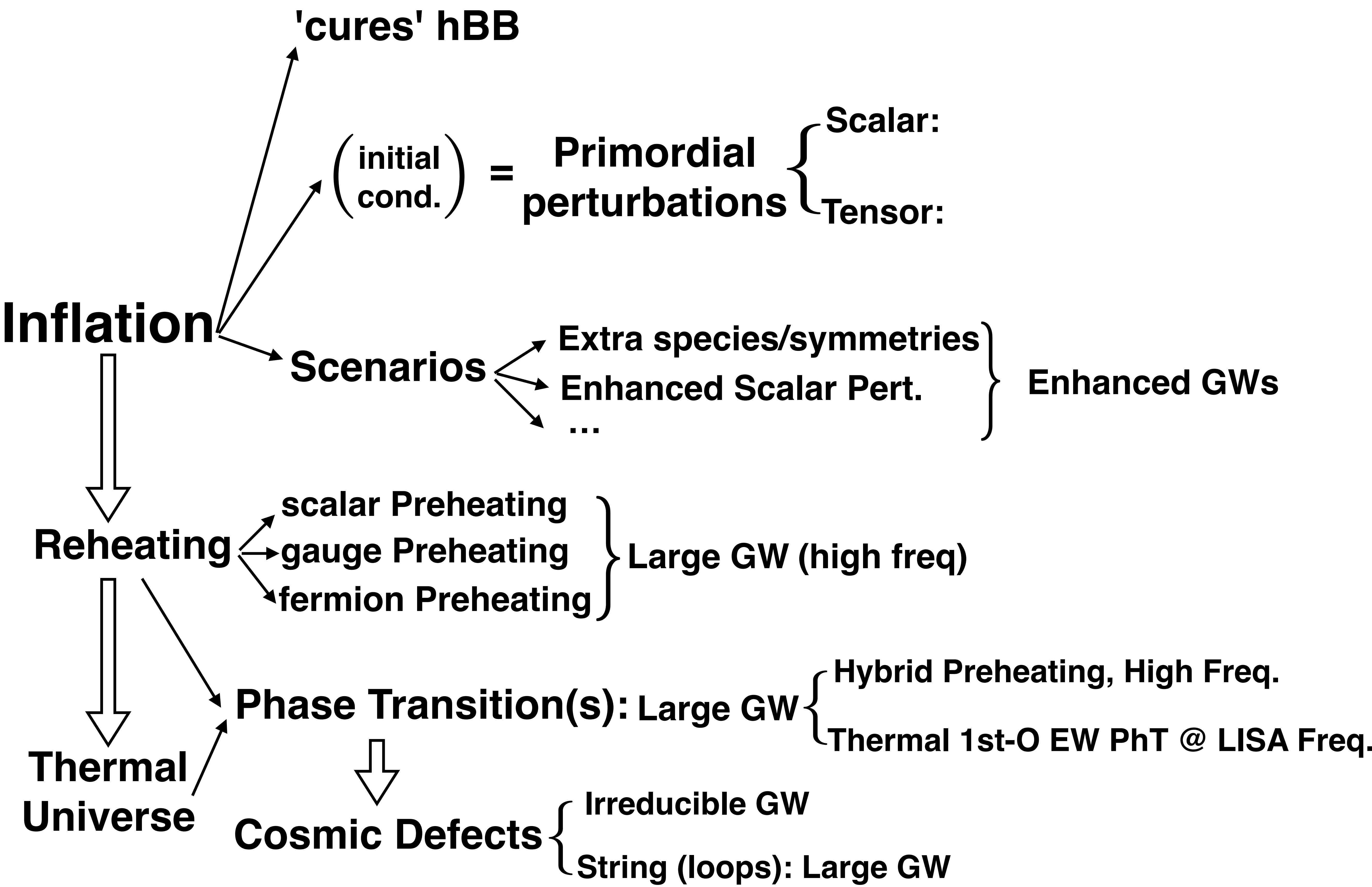
3rd lecture

✓

EARLY UNIVERSE in GWs



EARLY UNIVERSE in GWs ✓



EARLY UNIVERSE in GWs ✓

'cures' hBB

(initial) Primordial

Scalar:

Inflati

d GWs

Rehea

h Freq.

Phase Transition(s): Large GW

Thermal 1st-O EW PhT @ LISA Freq.

Thermal Universe

Cosmic Defects
- Irreducible GW
- String (loops): Large GW

COSMOLOGICAL GRAVITATIONAL WAVES

OUTLINE (~ 4.5 h)

1) GWs definition — 1st lecture (~ 1.5 h)

Early Universe:

2) GWs from Inflation

3) GWs from Preheating

2nd lecture (~ 1.5 h)

4) GWs from Phase Transitions

5) GWs from Cosmic Defects

3rd lecture (~ 1.5 h)

COSMOLOGICAL GRAVITATIONAL WAVES

OUTLINE (~ 4.5 h)

1) GWs definition

Early Universe

2) GWs from Inflation → Intensive search at the CMB. Extra ingredients = enhance GW

3) GWs from Preheating → High amplitude, unlike detection

4) GWs from Phase Transitions

5) GWs from Cosmic Defects

COSMOLOGICAL GRAVITATIONAL WAVES

OUTLINE (~ 4.5 h)

Early Universe

1) GWs definition
2) GWs from Inflation → Intensive search at the CMB. Extra ingredients = enhance GW
3) GWs from Preheating → High amplitude, unlike detection
4) GWs from Phase Transitions → EWPT (1st) observable*
5) GWs from Cosmic Defects → GUT-PT observable**

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

To know more …

Review on Cosmological Gravitational Wave Backgrounds

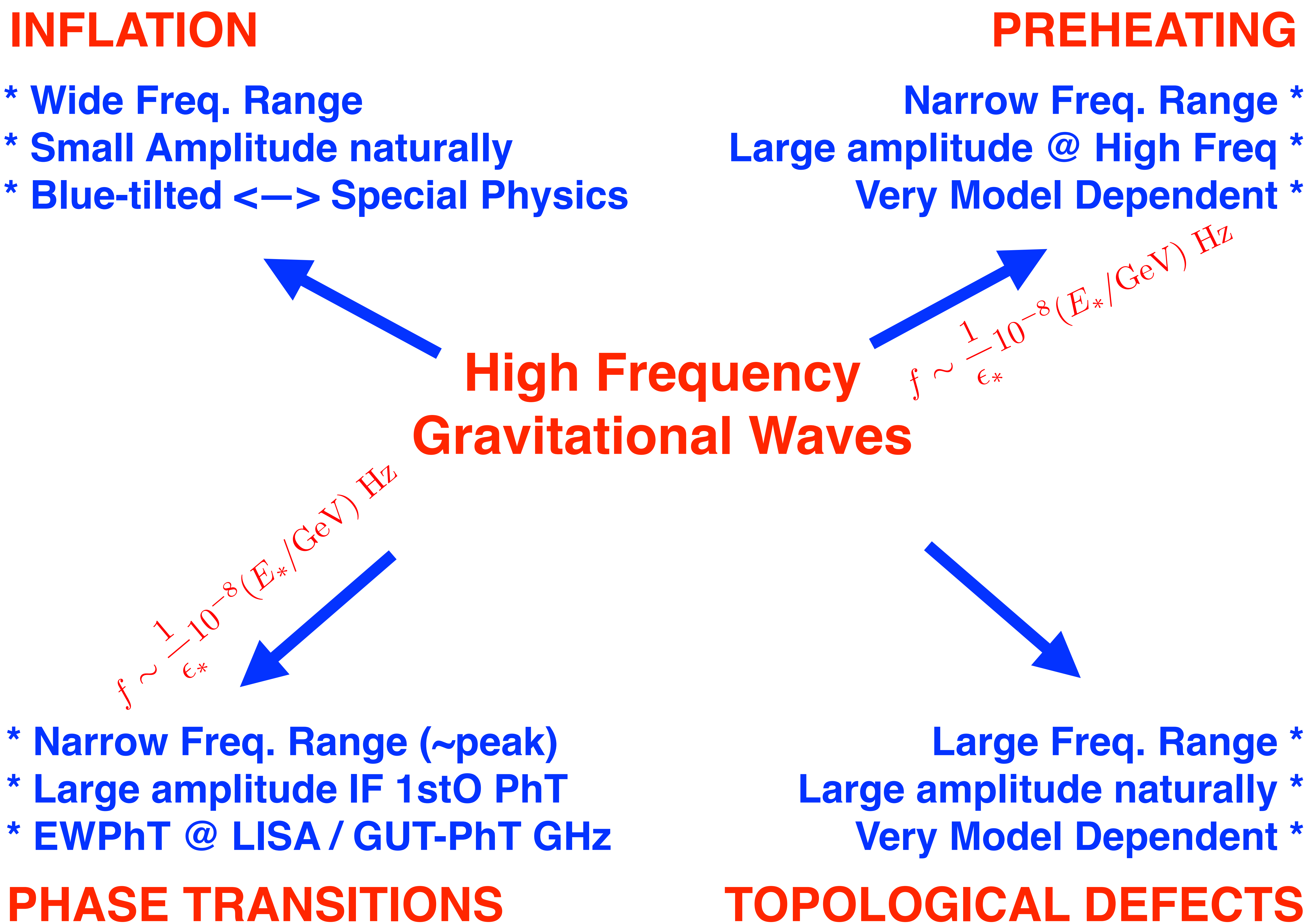
Caprini & Figueroa

arXiv:1801.04268

Obrigado pela sua atenção !

Gracias por vuestra atención !

COSMOLOGICAL GW CLASSIFICATION


INFLATION
* Wide Freq. Range
* Small Amplitude naturally
* Blue-tilted <—> Special Physics
PREHEATING
Narrow Freq. Range *
Large amplitude @ High Freq *
Very Model Dependent *
High Frequency
Gravitational Waves
$f \sim \frac{1}{\epsilon_*} 10^{-8} (E_*/\mathrm{GeV})\ \mathrm{Hz}$
$f \sim \frac{1}{\epsilon_*} 10^{-8} (E_*/\mathrm{GeV})\ \mathrm{Hz}$
* Narrow Freq. Range (~peak)
* Large amplitude IF 1stO PhT
* EWPhT @ LISA / GUT-PhT GHz
Large Freq. Range *
Large amplitude naturally *
Very Model Dependent *
PHASE TRANSITIONS
TOPOLOGICAL DEFECTS