# Gravitational Waves as a probe of fundamental Physics

## YETI 2017, IPPP, Durham

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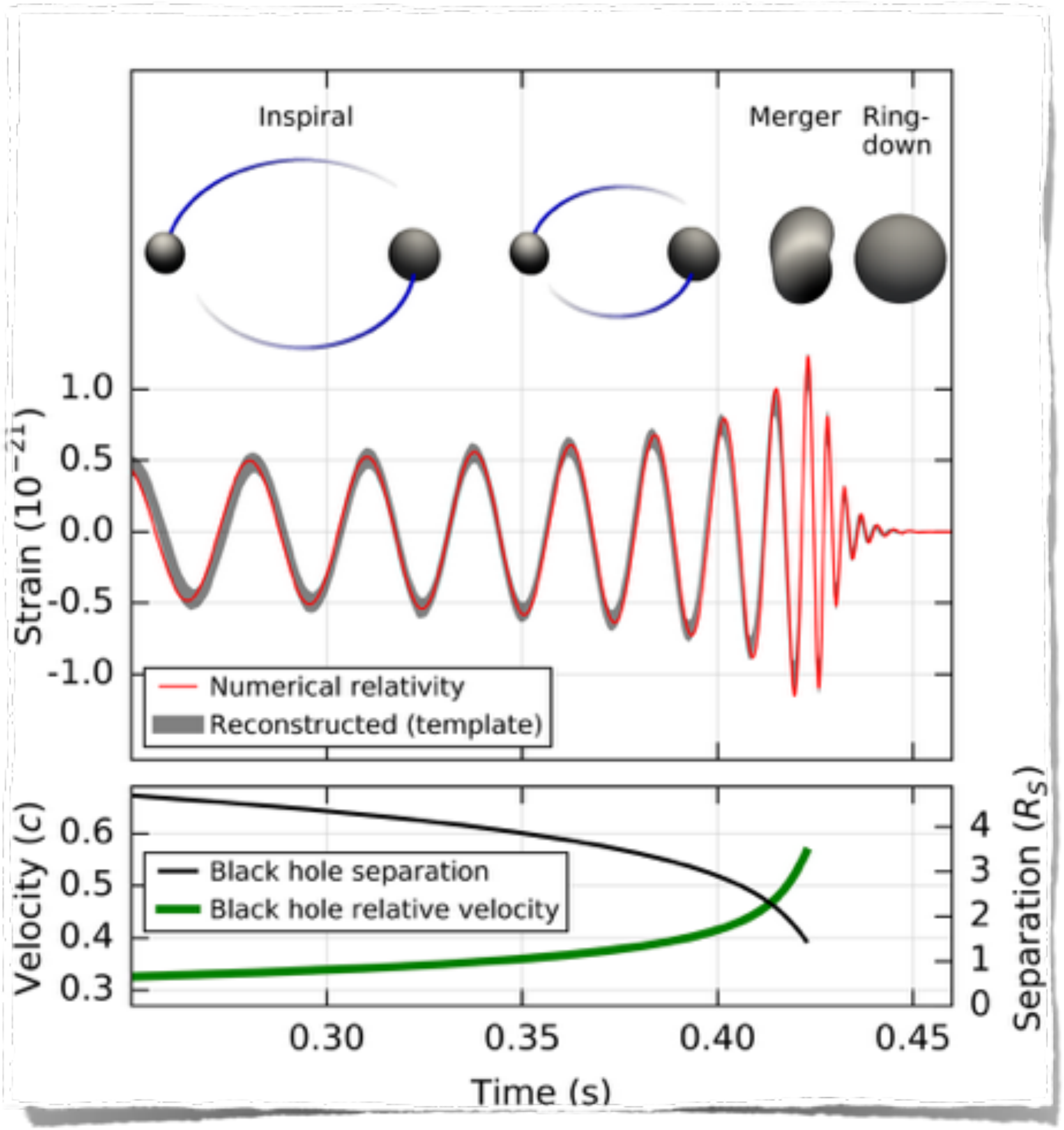
CERN, Theory Division

# Straight to the point …




**Gravitational Waves (GWs) detected !**

**[by aLIGO]**

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

**Einstein 1916 … aLIGO 2015/16**

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*** O(10) Solar mass Black Holes (BH) exist**

*** We can test the BH's paradigm (or Neutron Star physics)**

*** We can further test General Relativity (GR)**
[so far no deviation]

*** We can observe the Universe through GWs**

*** …**

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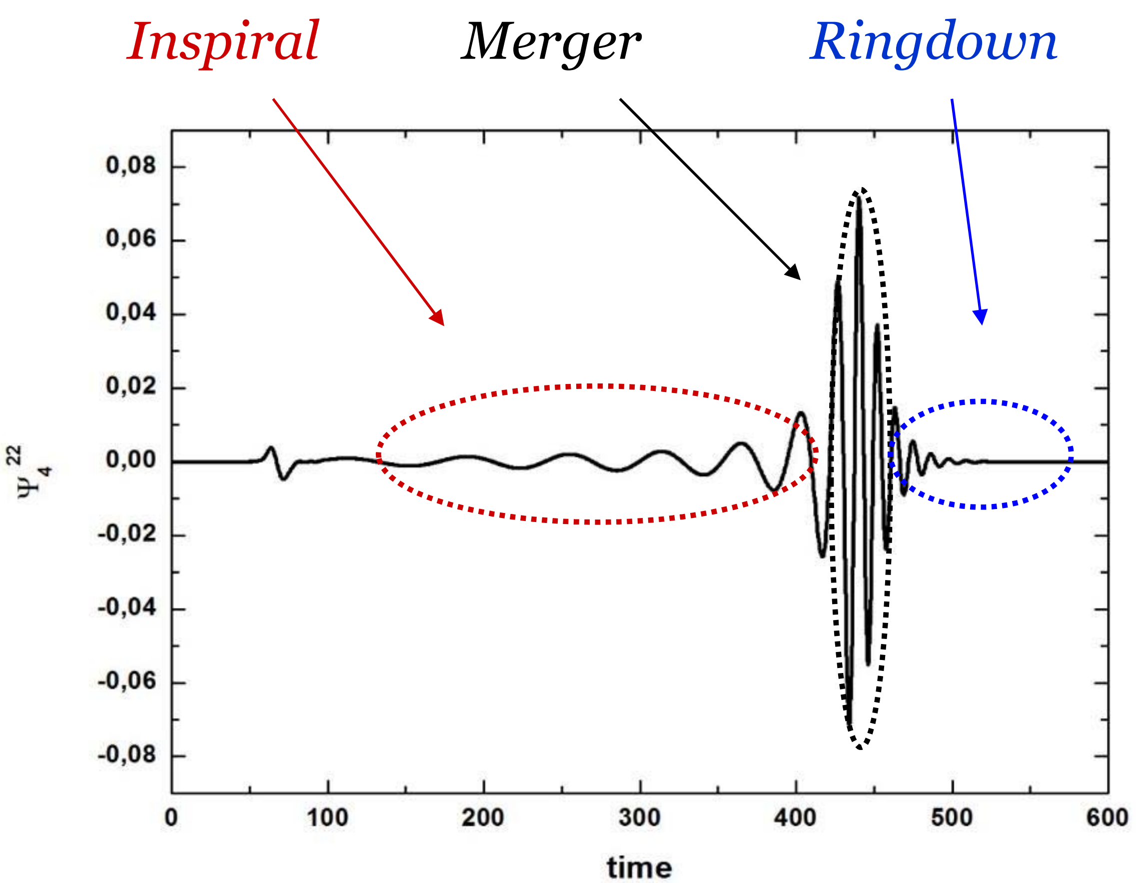
**Binaries**



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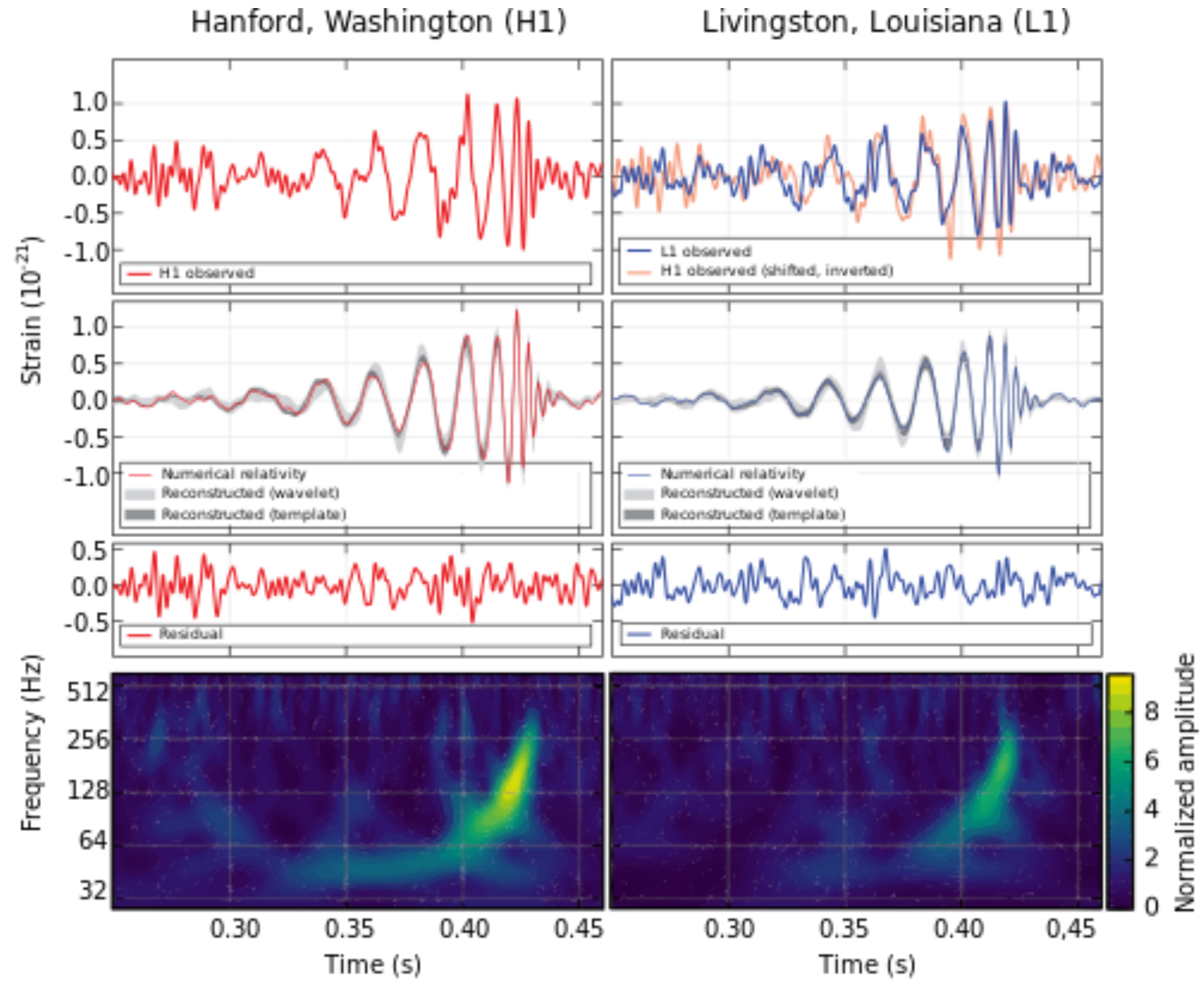


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**Extremely interesting !**

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* O(10) Sc… s
Blac… st

N… (binaries)

* W…
Gen… ity (GR)
[so… no deviation]

See Lectures by

HUSA
SOTIRIOU
BELL
…

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* …

Extremely interesting !
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* We can observe the Universe through GWs

* Cosmology with GWs

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## * Cosmology with GWs

* Late Universe: Hubble diagram from Binaries

* Early Universe:   High Energy Particle Physics

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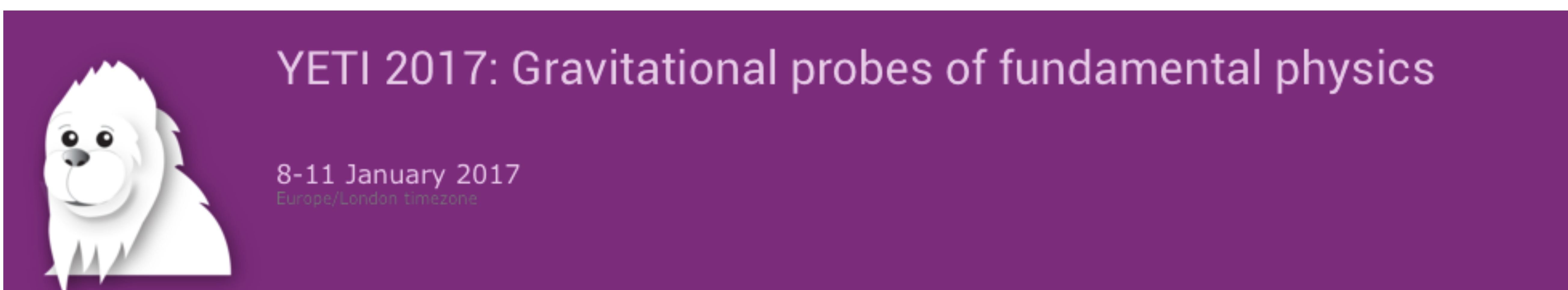

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# Gravitational Waves as a probe of the early Universe

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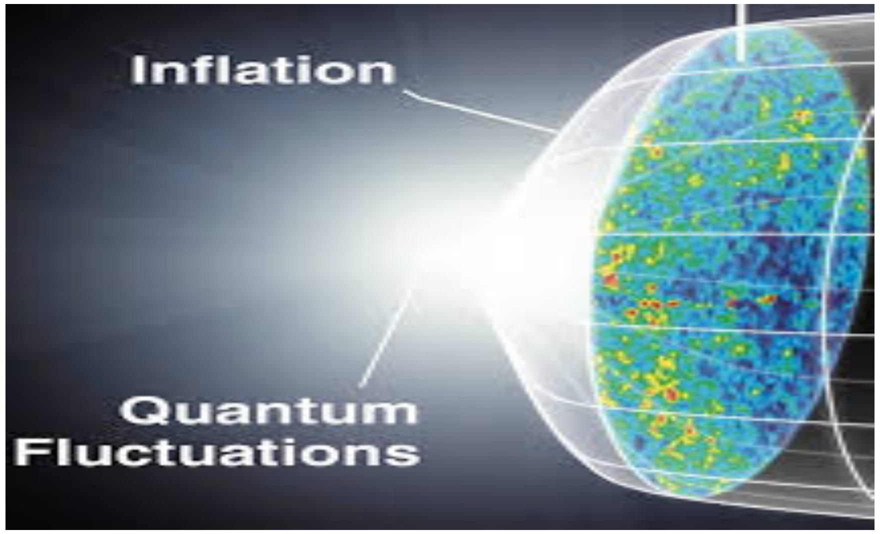
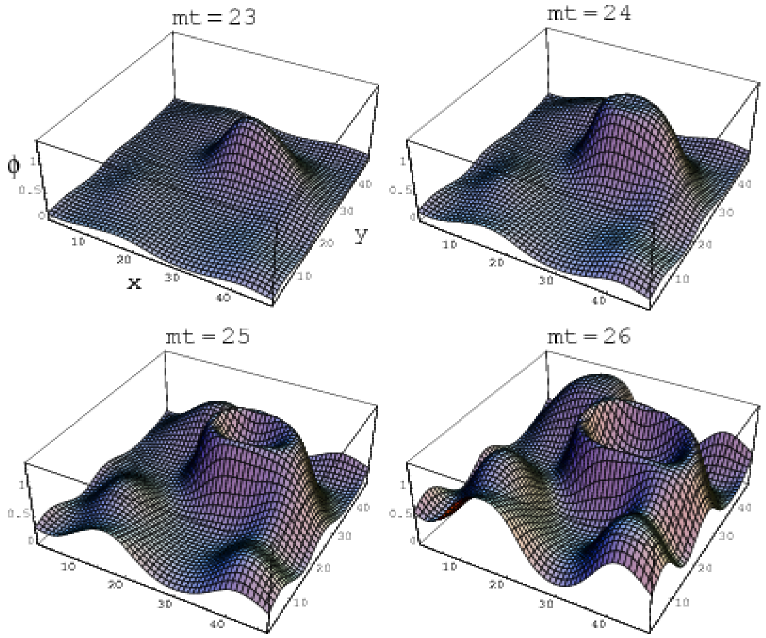
## Inflationary Period



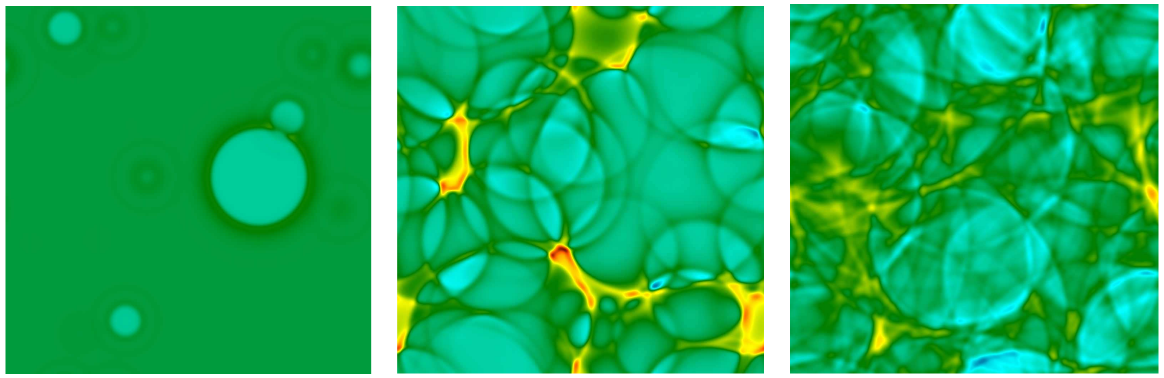

(Image: Google Search)

## Preheating



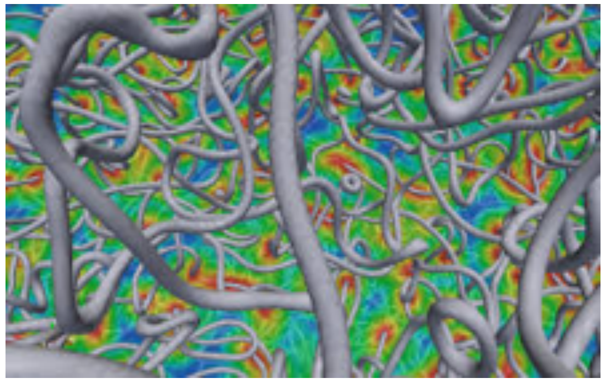

(Fig. credit: Phys.Rev. D67 103501)

## Phase Transitions



(Image: PRL 112 (2014) 041301)

## Cosmic Defects



(Image: Daverio et al, 2013)

# Gravitational Waves as a probe of the early Universe

## OUTLINE

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

## OUTLINE

0) GW definition

Early Universe

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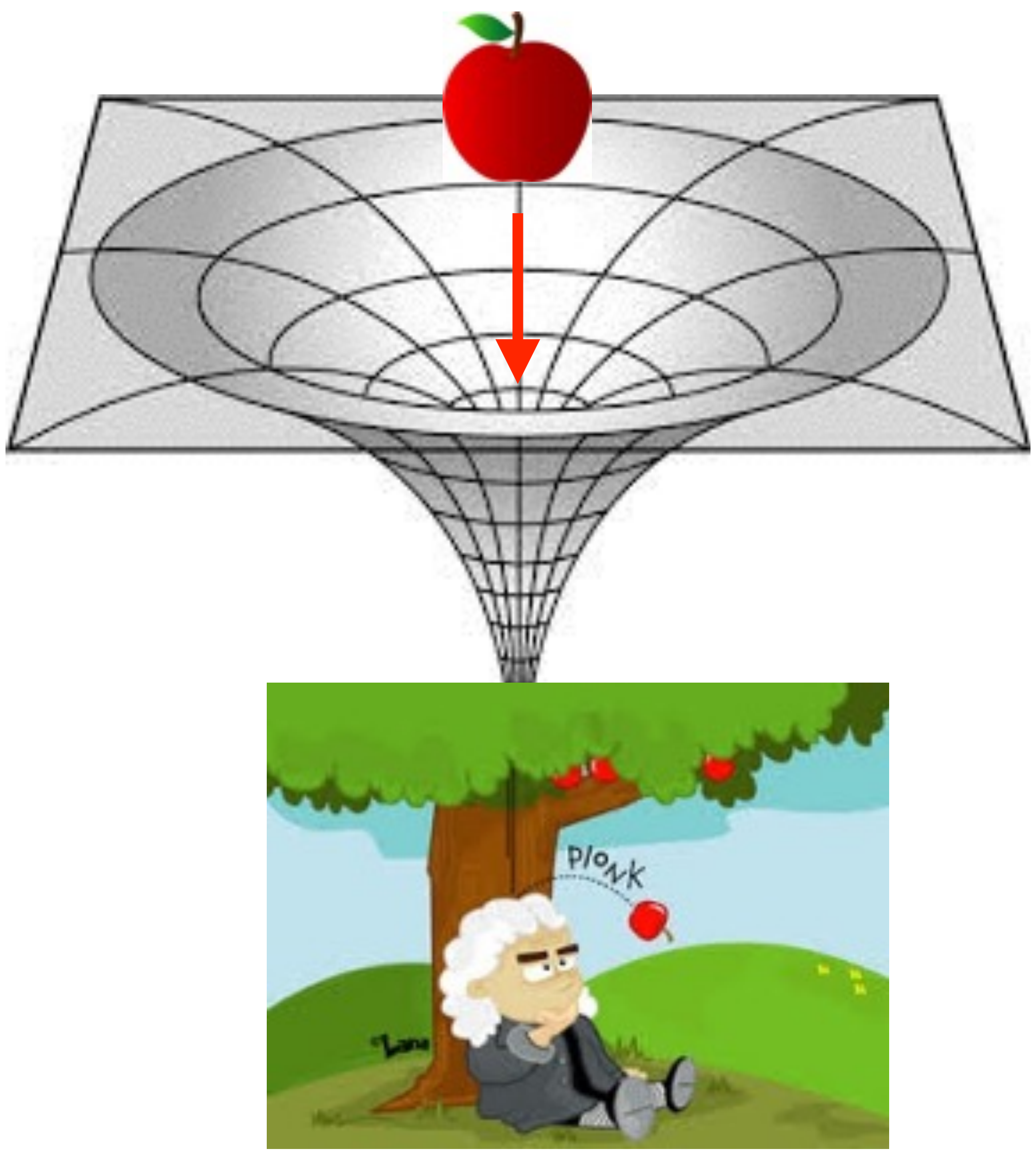
# Gravitational Wave Definition

**General Relativity (GR)**

$$G_{\mu\nu} = \frac{1}{m_p^2} T_{\mu\nu}$$

geometry matter




$$ds^2 = g_{\mu\nu}(x) dx^\mu dx^\nu$$

$$\mathrm{DIFF}: \quad x^\mu \to x'^\mu(x)$$

symmetry

# Gravitational Wave Definition

Minkowski

**1st approach to GWs**

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}(x)$$

fixed frame

$$( \ |h_{\mu\nu}| \ll 1 \ )$$

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$$( \ |\partial_{\mu}\xi_{\nu}(x)| \lesssim |h_{\mu\nu}| \ )$$

residual symm.

$$\boxed{h_{\mu\nu}(x) \to h'_{\mu\nu}(x') = h_{\mu\nu}(x) - \partial_{[\mu}\xi_{\nu]}}$$

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Trace-reversed

$$\bar{h}_{\mu\nu} \equiv h_{\mu\nu} - \frac{1}{2} h \eta_{\mu\nu} \quad \Rightarrow \quad \partial^\alpha \partial_\alpha \bar{h}_{\mu\nu} + \eta_{\mu\nu} \partial^\alpha \partial^\beta \bar{h}_{\alpha\beta} - \partial^\alpha \partial_{(\mu} \bar{h}_{\alpha\nu)} = -\frac{2}{m_p^2} T_{\mu\nu}$$

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$$\Rightarrow \quad \boxed{h^{0\mu} = 0\,, \quad h^i_i = 0\,, \quad \partial_j h_{ij} = 0}$$

$$\boxed{\partial_\mu \partial^\mu h_{ij} = 0}$$

(6 - 4 = 2 d.o.f. )

(transverse-traceless gauge)

# Gravitational Wave Definition

(TT gauge: 6 - 4 = 2 d.o.f. )

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**(Can GW effects be 'gauged away'? No !)**

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**2 dof = 2 polarizations**

$$h_{ab}(t, \mathbf{x}) = \int_{-\infty}^{\infty} df \int d\hat{n}\, h_{ab}(f, \hat{n}) e^{-2\pi i f (t - \hat{n}\mathbf{x})}$$

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$$h_{ab}(f, \hat{n}) = \sum_{A=+,\mathrm{x}} h_A(f, \hat{n}) \epsilon^{(A)}_{ab}(\hat{n}) = \begin{pmatrix} h_+ & h_x & 0 \\ h_x & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Transverse-Traceles (2 dof)

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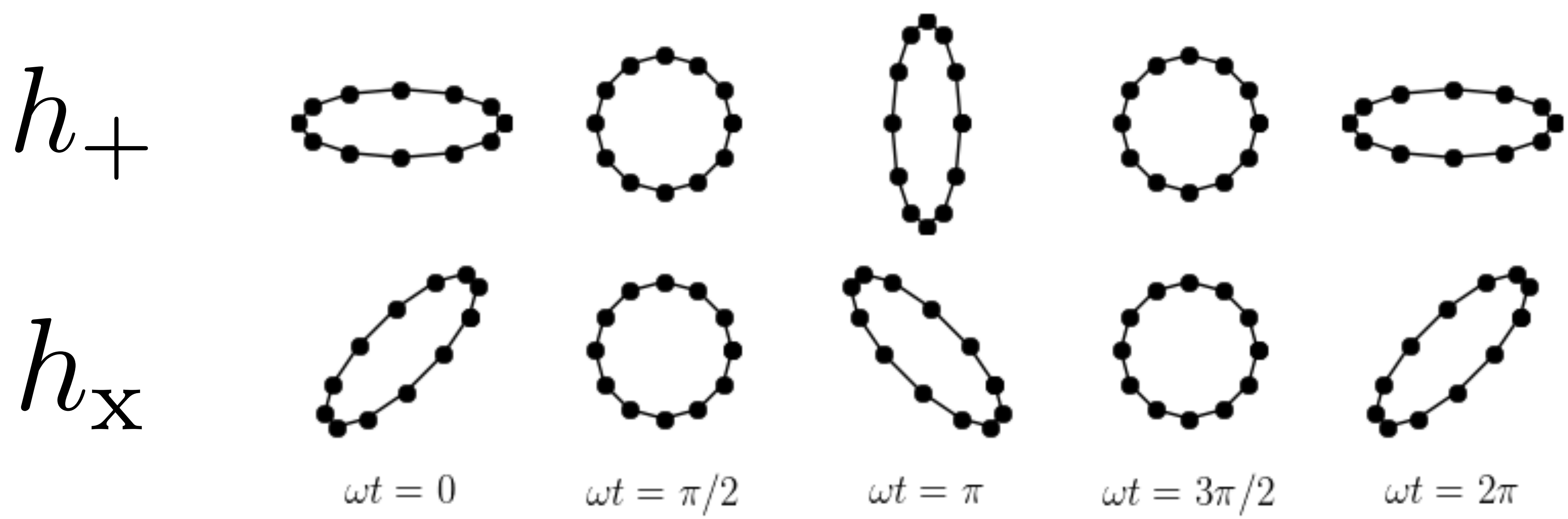

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**2nd approach to GWs** $$g_{\mu\nu}(x) = \bar{g}_{\mu\nu}(x) + h_{\mu\nu}(x)\,, \quad |h_{\mu\nu}| \ll 1$$

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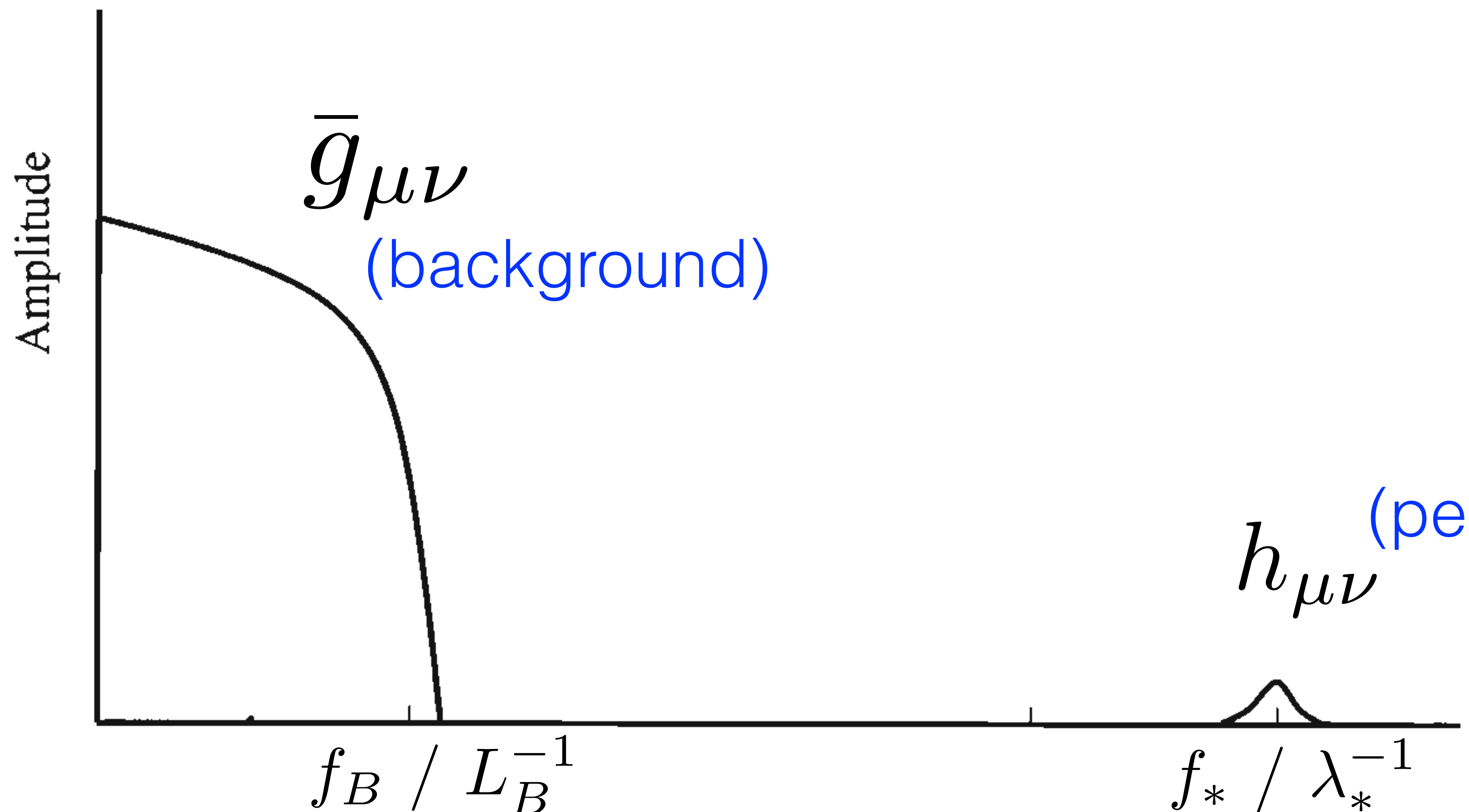

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$$R_{\mu\nu} = \frac{8\pi G}{c^4}\left(T_{\mu\nu} - \frac{1}{2}g_{\mu\nu}T\right) \Rightarrow R_{\mu\nu} = \underbrace{\bar{R}_{\mu\nu}}_{\text{(background)}} + \underbrace{R^{(1)}_{\mu\nu}}_{\mathcal{O}(h)} + \underbrace{R^{(2)}_{\mu\nu}}_{\mathcal{O}(h^2)} + \ldots\,,$$

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High Freq. / Short Scale: $$R^{(1)}_{\mu\nu} = -[R^{(2)}_{\mu\nu}]^{\mathrm{High}} + \frac{8\pi G}{c^4}\left(T_{\mu\nu} - \frac{1}{2}g_{\mu\nu}T\right)^{\mathrm{High}}$$

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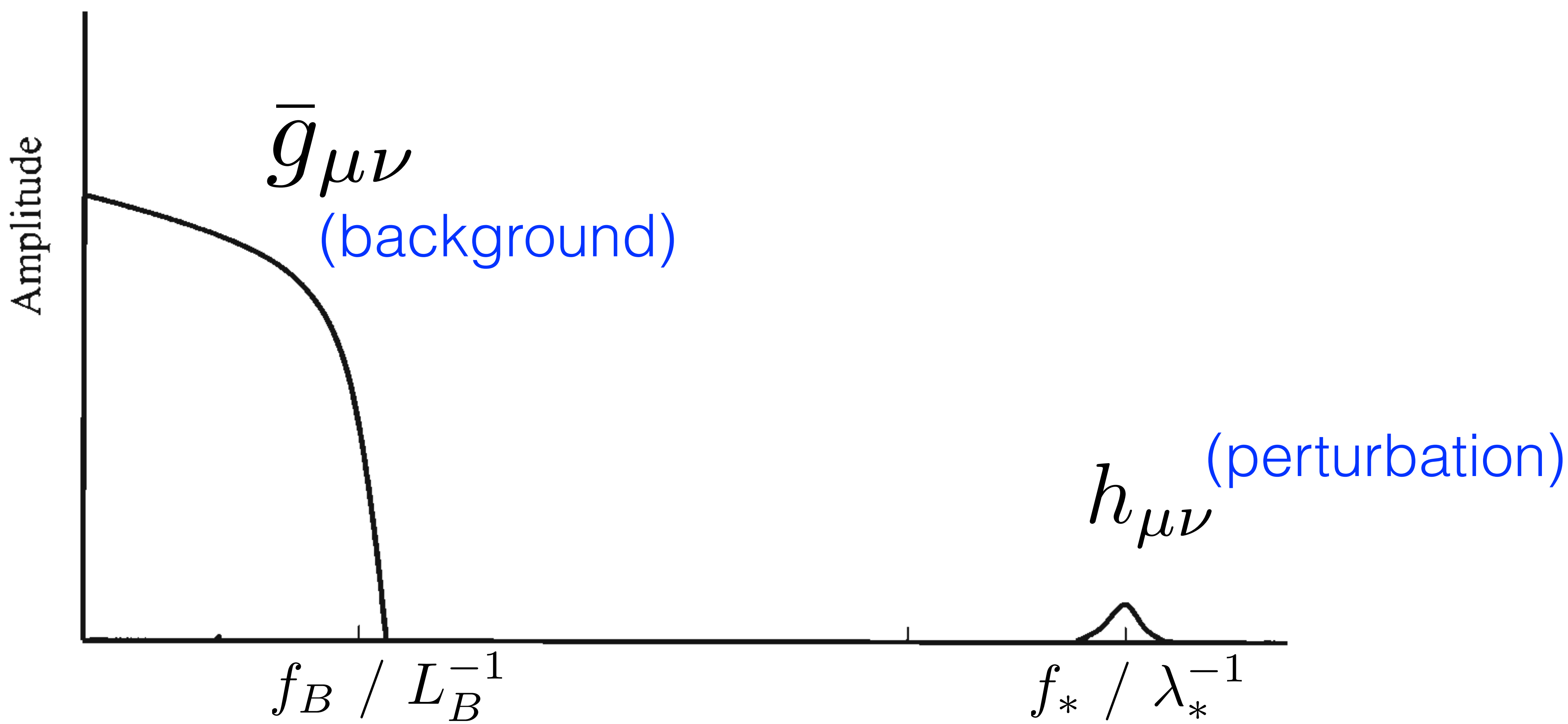

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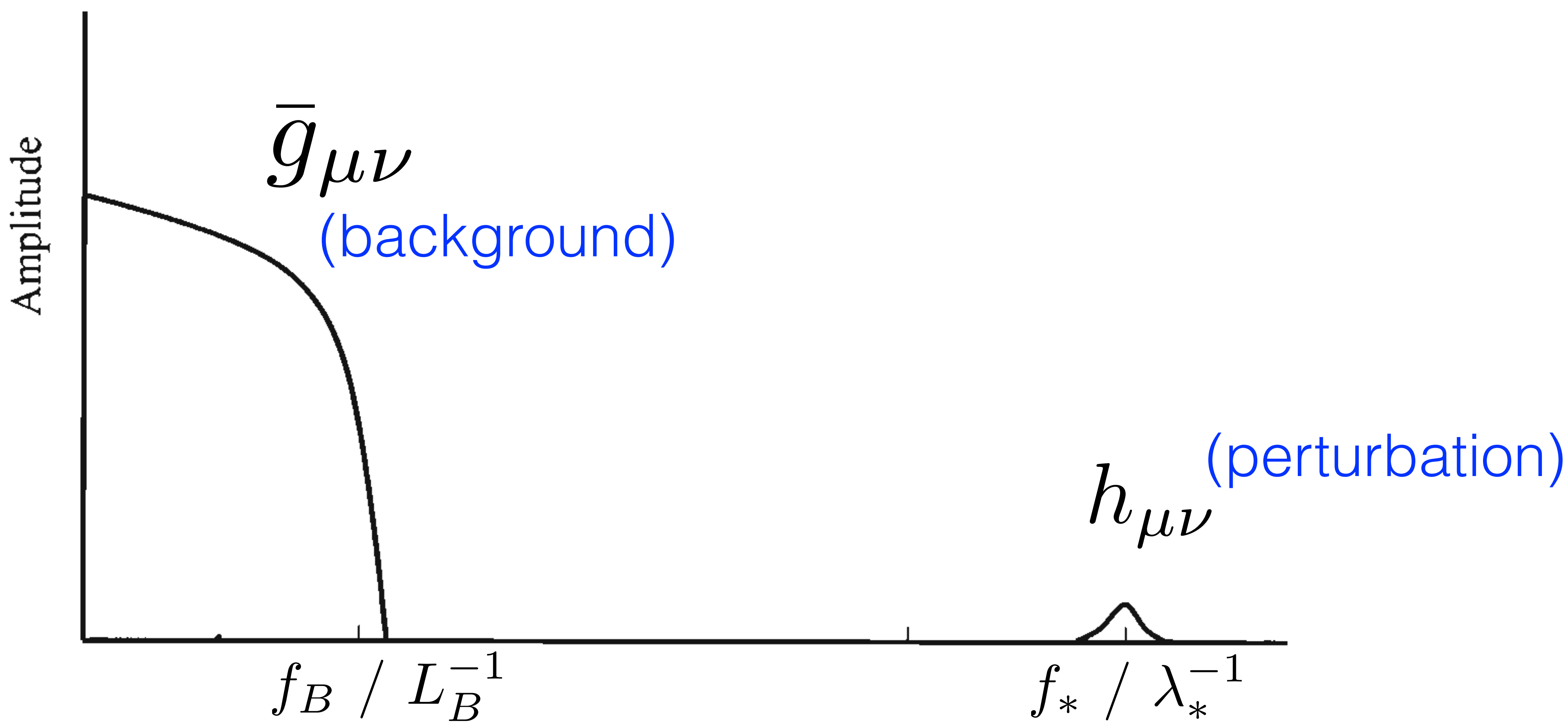

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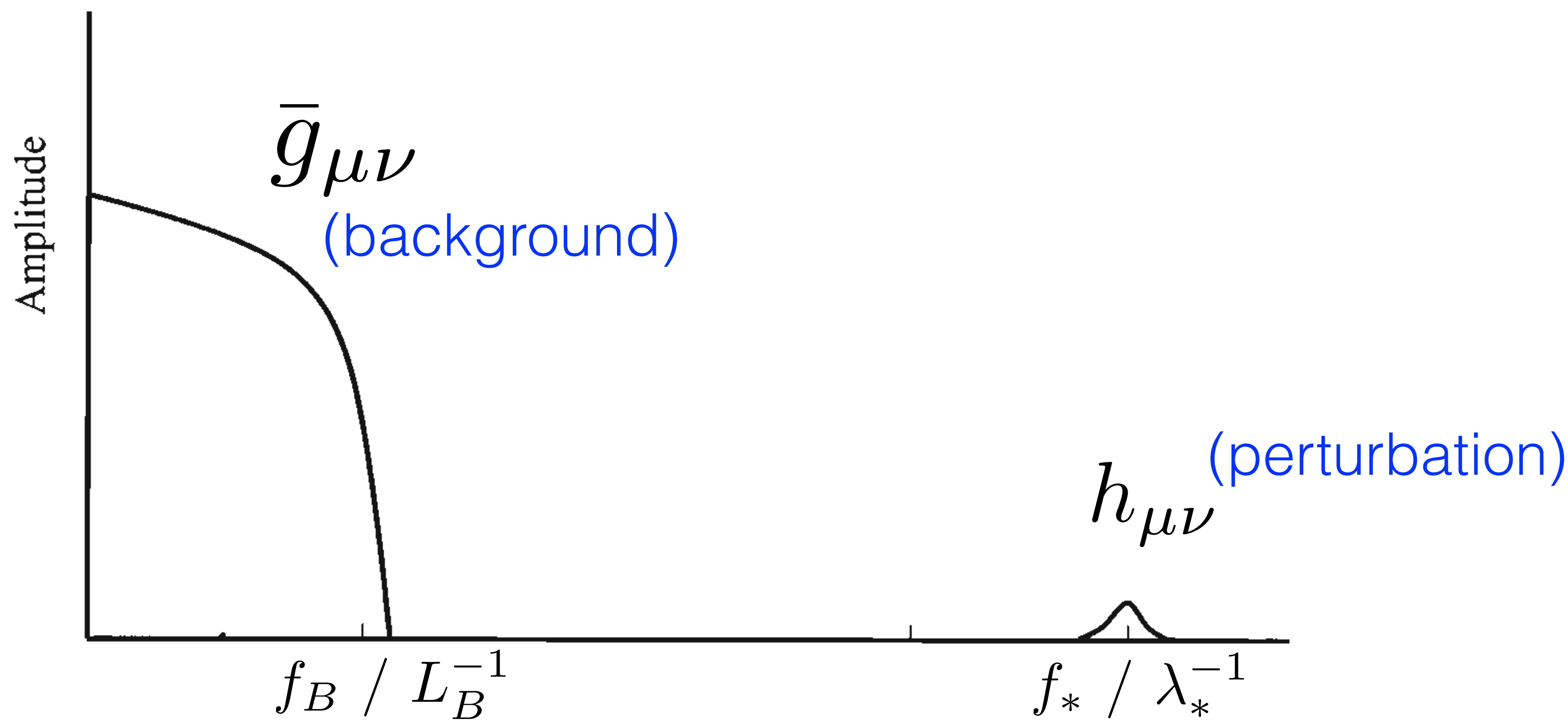

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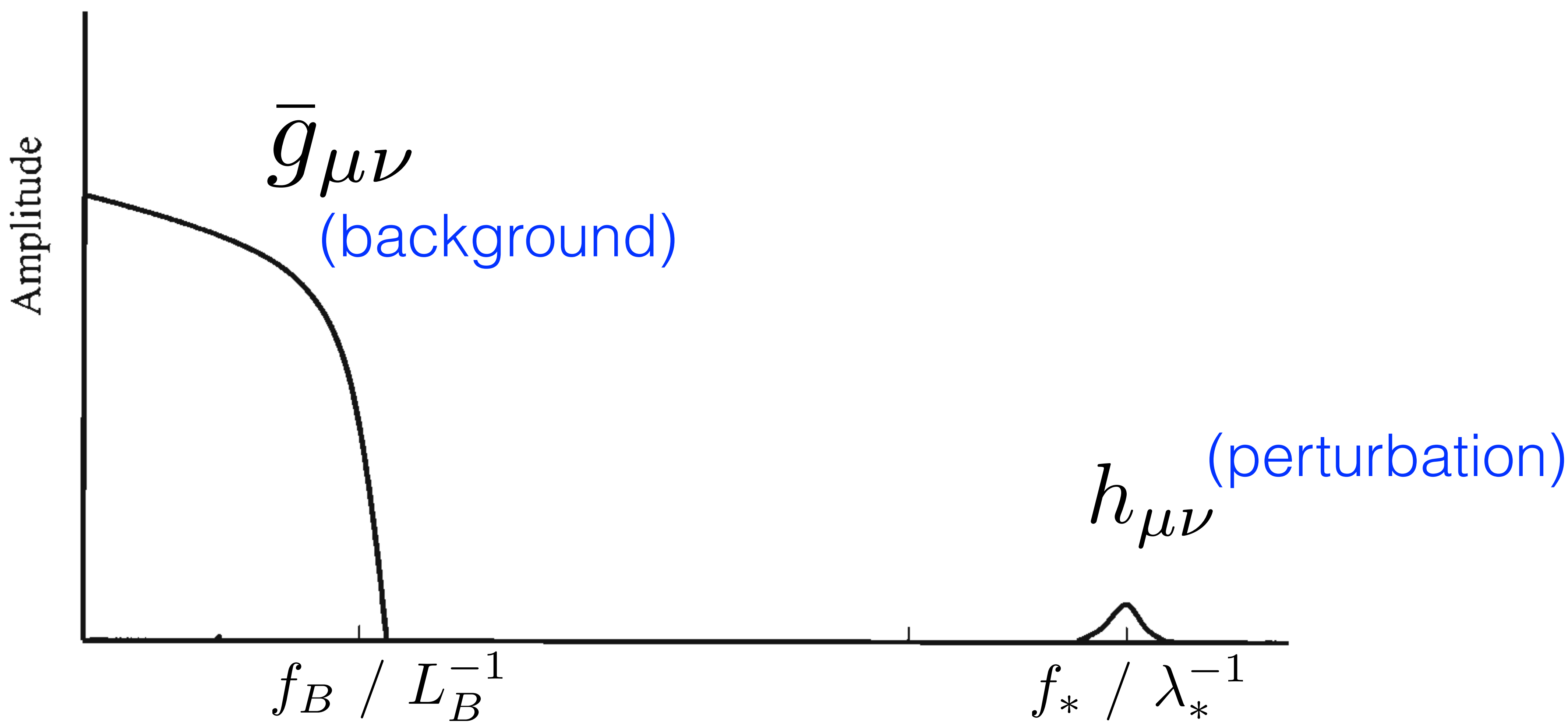

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**It can be shown that only TT *dof* contribute to < … >**

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$$t_{\mu\nu} \equiv -\frac{c^4}{8\pi G}\langle R^{(2)}_{\mu\nu} - \frac{1}{2}\bar{g}_{\mu\nu}R^{(2)}\rangle \qquad \langle T_{\mu\nu} - \frac{1}{2}g_{\mu\nu}T\rangle = \bar{T}^{\mu\nu} - \frac{1}{2}\bar{g}_{\mu\nu}\bar{T}$$

---

$$\langle R^{(2)}_{\mu\nu}\rangle = -\frac{1}{4}\langle\partial_\mu h_{\alpha\beta}\partial_\nu h^{\alpha\beta}\rangle \quad \Rightarrow \quad t_{\mu\nu} = \frac{c^4}{32\pi G}\langle\partial_\mu h_{\alpha\beta}\partial_\nu h^{\alpha\beta}\rangle$$

**It can be shown that only TT *dof* contribute to < … >**

$$\boxed{t_{\mu\nu} = \frac{c^4}{32\pi G}\left\langle\partial_\mu h^{\rm TT}_{ij}\partial_\nu h^{\rm TT}_{ij}\right\rangle} \quad \Rightarrow \quad \boxed{\frac{dE}{dAdt} = \frac{c^4}{32\pi G}\left\langle\dot{h}^{\rm TT}_{ij}\dot{h}^{\rm TT}_{ij}\right\rangle}$$

GW energy-momentum tensor

GW power/area radiated

# Gravitational Wave Definition

What about the
High Freq. / Short Scale?

$$R^{(1)}_{\mu\nu} = -[R^{(2)}_{\mu\nu}]^{\rm High} + \frac{8\pi G}{c^4}\left(T_{\mu\nu} - \frac{1}{2}g_{\mu\nu}T\right)^{\rm High}$$

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$$R^{(1)}_{\mu\nu} = \bar{g}^{\alpha\beta}\left(D_\alpha D_{(\mu}h_{\nu)\beta} - D_\mu D_\nu h_{\alpha\beta} - D_\alpha D_\beta h_{\mu\nu}\right)$$

$$D_\mu \bar{h}_{\mu\nu} = 0 \quad \left(\ \bar{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2}\bar{g}_{\mu\nu}h\ \right)$$ Lorentz gauge

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$$\boxed{D_\alpha D^\alpha \bar{h}_{\mu\nu} = 0}$$

Propagation of GWs
in curved space-time

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High Freq. / Short Scale?

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$$D_\mu \bar{h}_{\mu\nu} = 0 \quad \left(\ \bar{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2}\bar{g}_{\mu\nu}h\ \right)$$ Lorentz gauge

$$\longrightarrow \quad \boxed{D_\alpha D^\alpha \bar{h}_{\mu\nu} = \Pi_{\mu\nu}}$$

Creation of GWs
in curved space-time

# Gravitational Waves as a probe of the early Universe

## OUTLINE

0) GW definition ✓

Early Universe

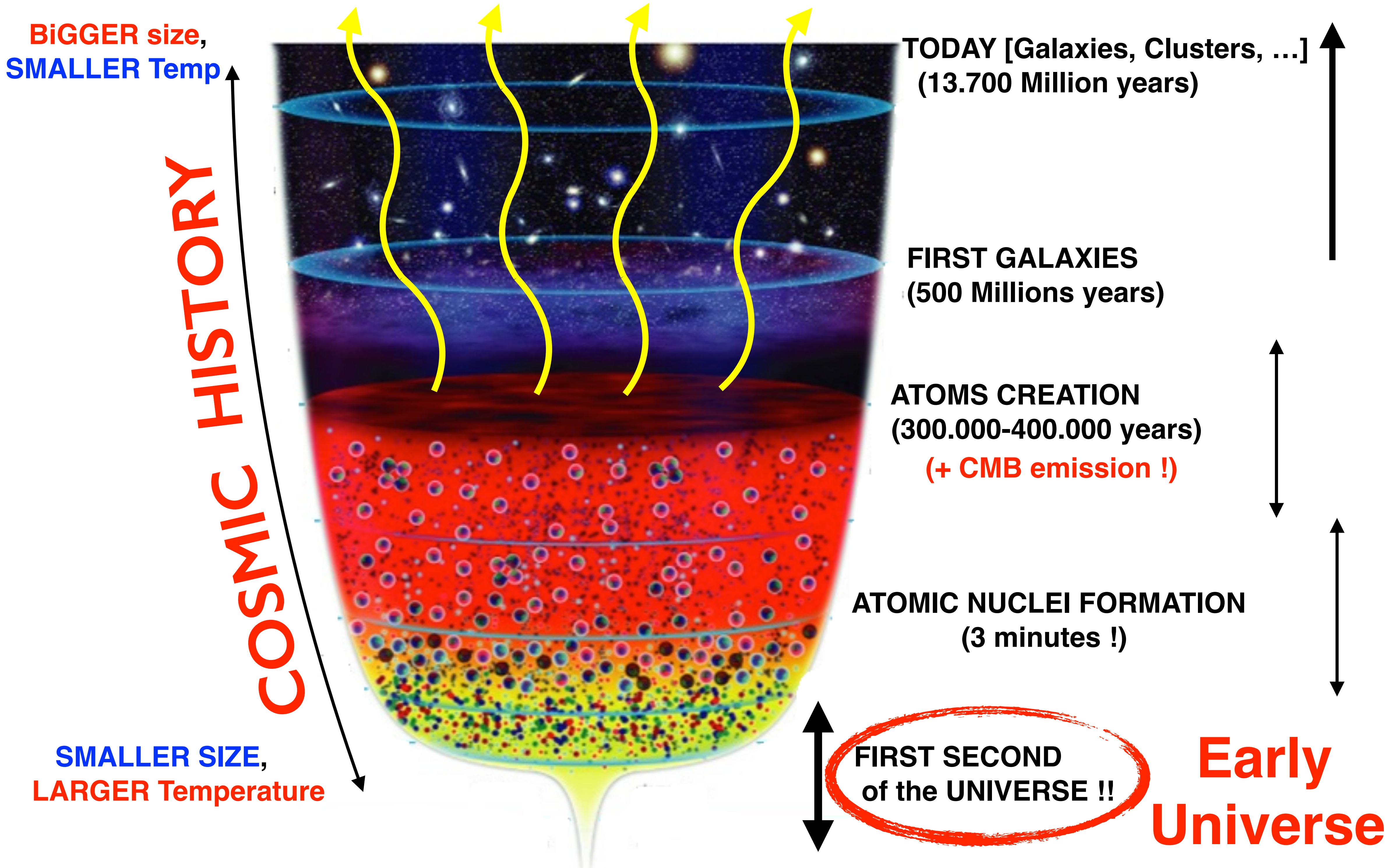
1) GWs from Inflation

2) GWs from Preheating

3) GWs from Phase Transitions

4) GWs from Cosmic Defects

# The Early Universe



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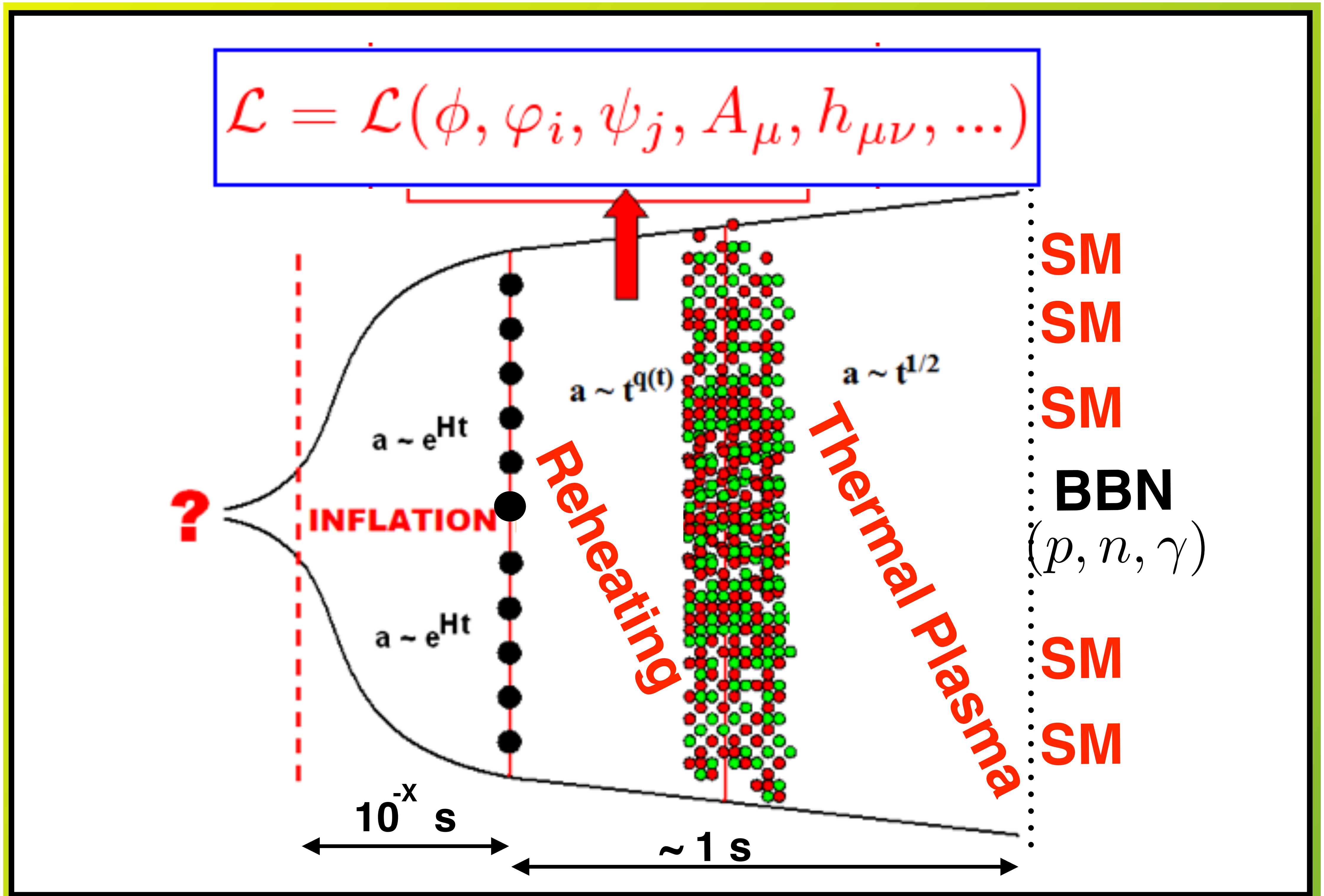

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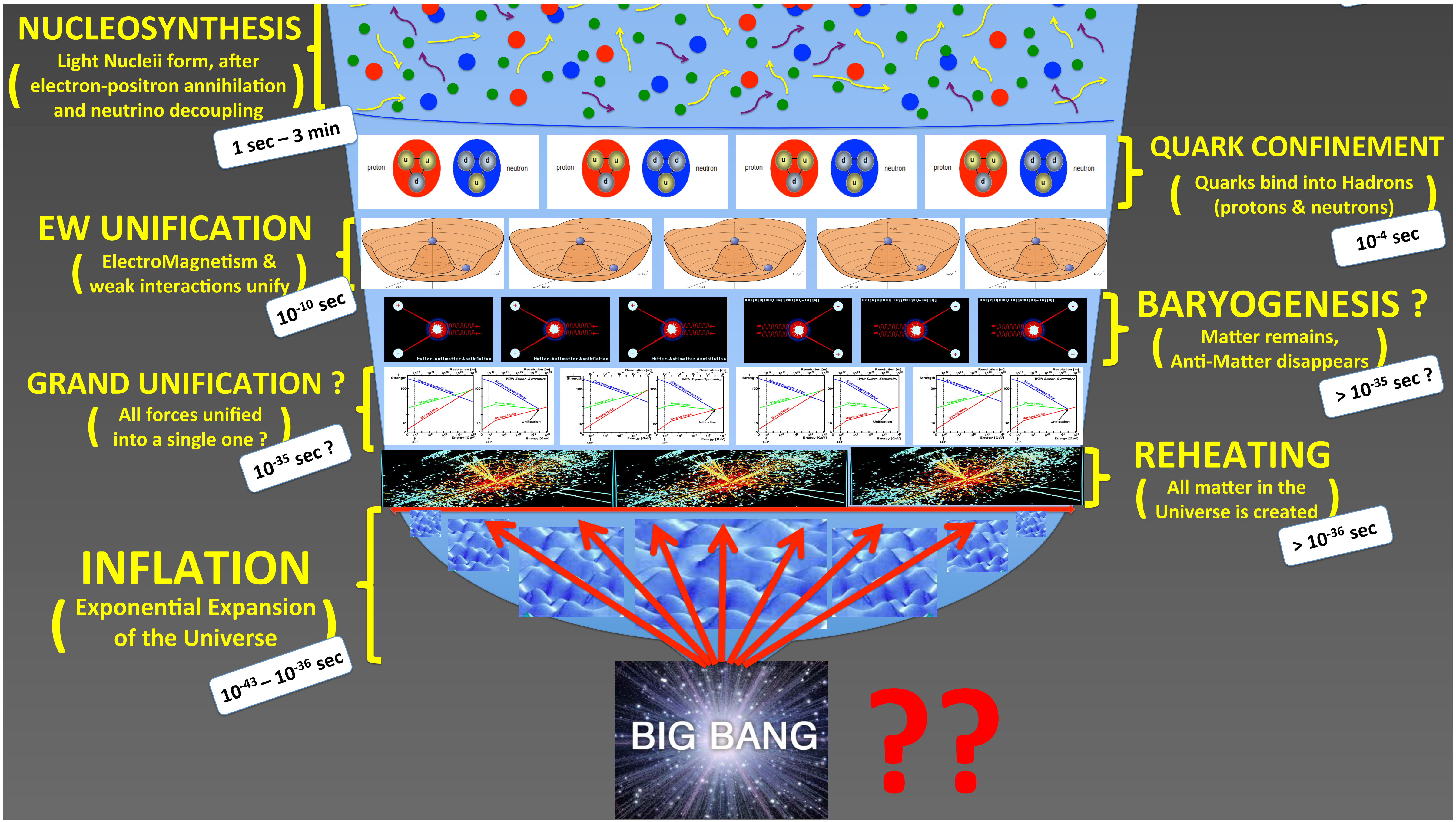


# GWs as a probe of the early Universe

1. **WEAKNESS of GRAVITY**:

   **ADVANTAGE**: GW DECOUPLE upon Production
   **DISADVANTAGE**: DIFFICULT DETECTION

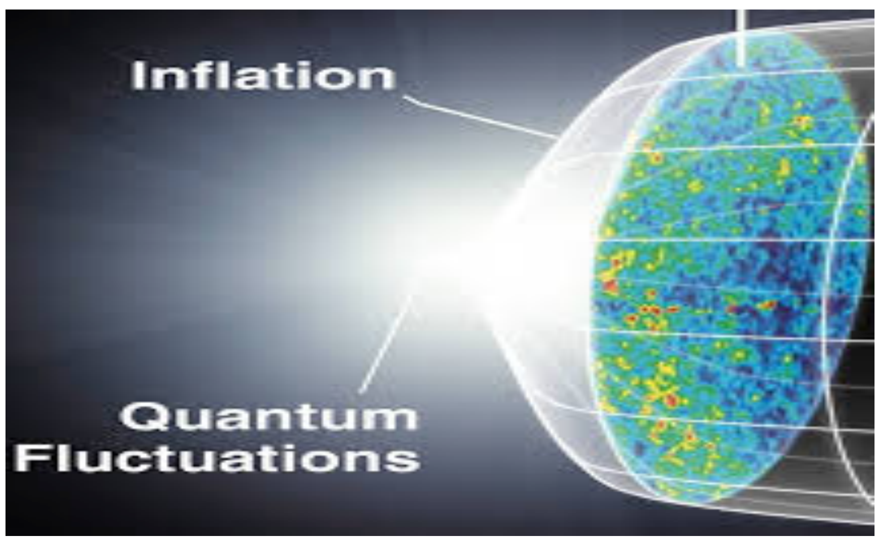
2. **ADVANTAGE**: GW $\longrightarrow$ Probe for Early Universe

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

3. **Physical Processes**: $\begin{cases} \text{Inflation} \\ \text{Reheating} \\ \text{Phase Transitions} \\ \text{Cosmic Defects} \end{cases}$

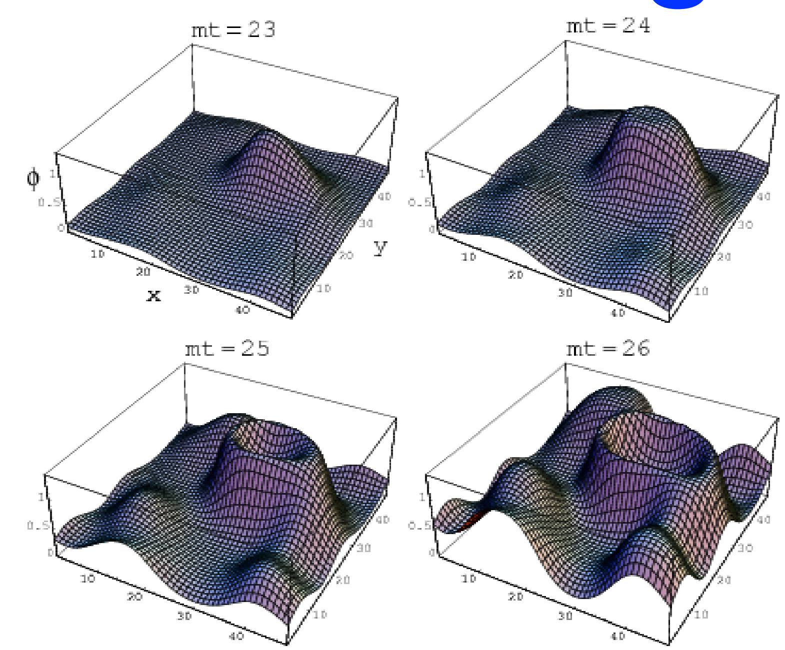
# Gravitational Waves as a probe of the early Universe

## Inflationary Period



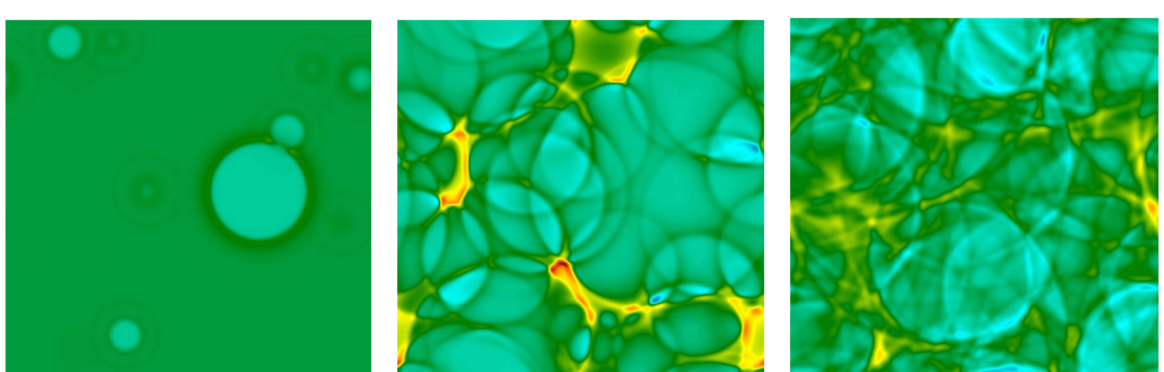

*(Image: Google Search)*

## Preheating



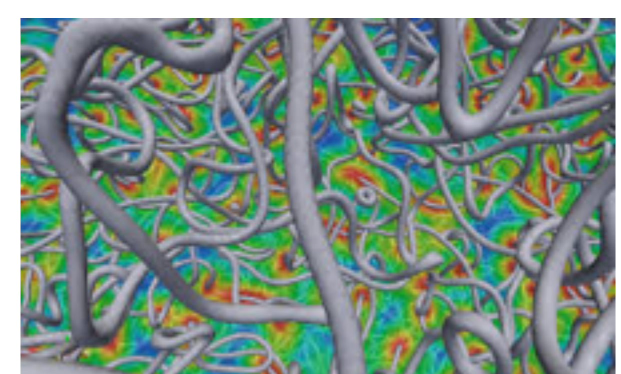

*(Fig. credit: Phys.Rev. D67 103501)*

## Phase Transitions



*(Image: PRL 112 (2014) 041301)*

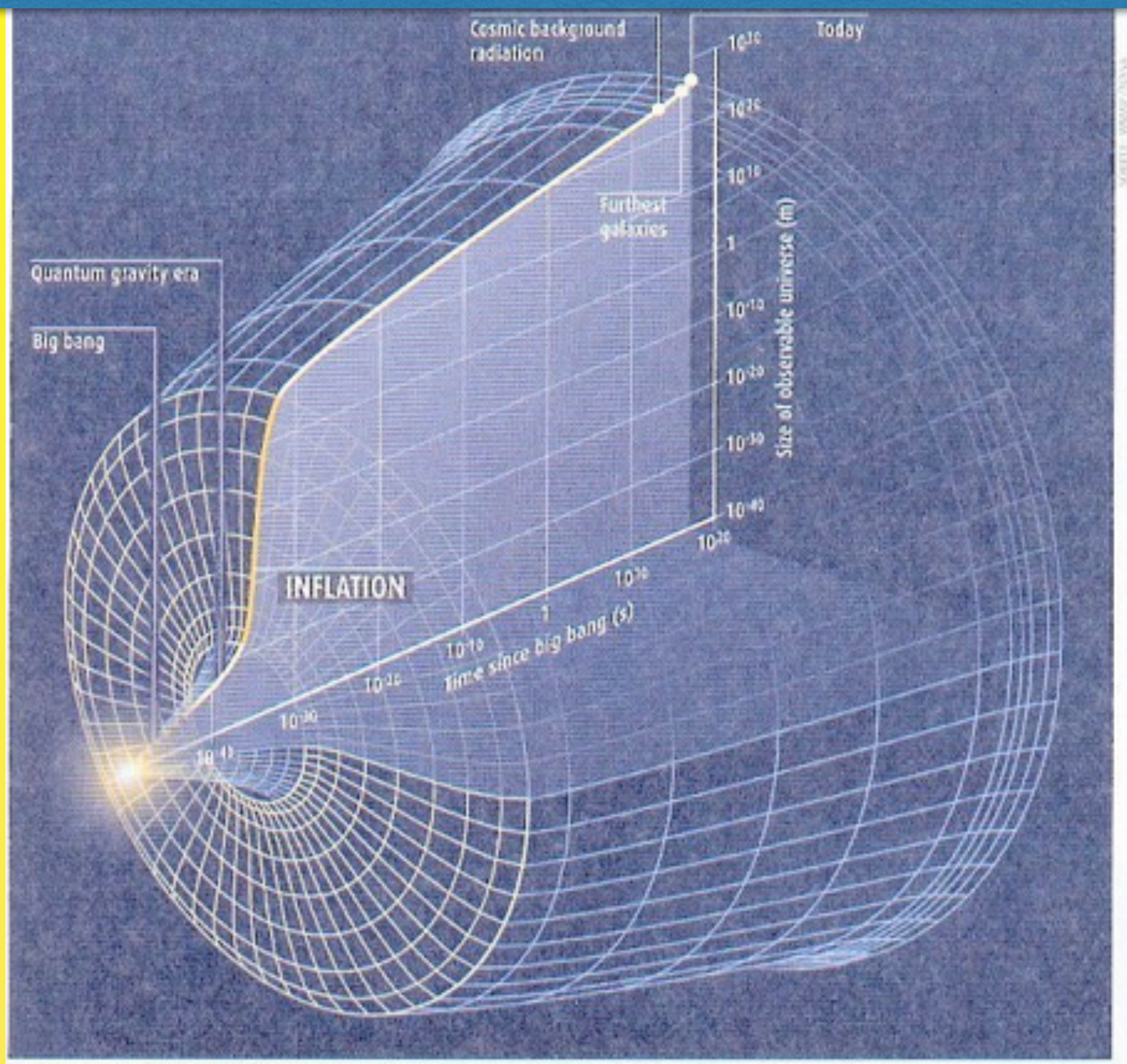
## Cosmic Defects



*(Image: Daverio et al, 2013)*

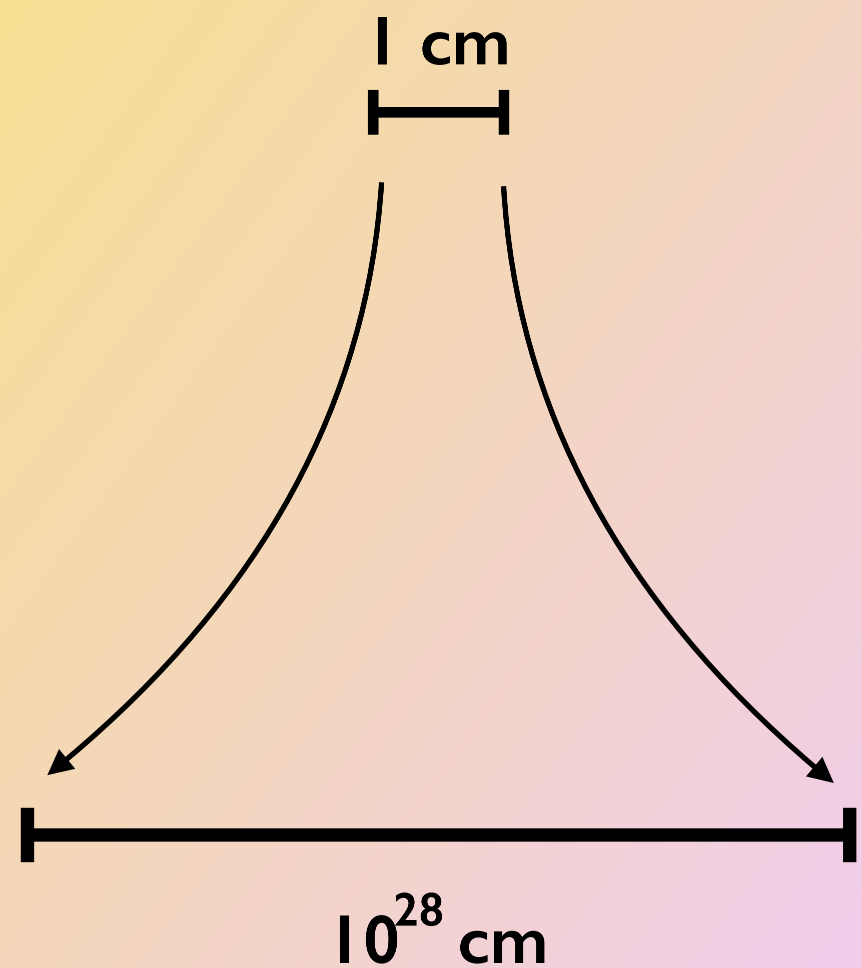
# Inflation: Basics

**COSMIC INFLATION !**




Needed for Consistency of the Big Bang theory !

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



# Inflation: Basic Predictions

**Inflation: A generator of Primordial Fluctuations**

## Tensor Fluctuations:

$$d\tau \equiv dt/a(t)$$

$$S^{(t)}_{(2)} = \frac{m_p^2}{8}\int dt dx^3 a^3 \left[(\dot{h}_{ij})^2 - a^{-2}(\partial_l h_{ij})^2\right] = \frac{1}{2}\int d\tau dx^3 \left[(v')^2 - (\nabla v)^2 + \frac{a''}{a}v^2\right]$$

$$h_{ij}(\vec{k},\tau) = \epsilon^{(s)}_{ij} h^{(s)}_{\vec{k}} \longrightarrow v^{(s)} \equiv \frac{a}{2} m_p h^{(s)}_{\vec{k}}$$

There is no source !

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.... but ....

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(Similarly as with Scalar Pert.)

[ Quantize → Bunch-Davies → Power Spectrum ]

**Quantization of Gravity dof !**

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**Inflation: A generator of Primordial Fluctuations**

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$$h_{ij}(\vec{k},\tau) = \epsilon^{(s)}_{ij} h^{(s)}_{\vec{k}} \rightarrow v^{(s)} \equiv \frac{a}{2} m_p h^{(s)}_{\vec{k}}$$

$$\langle h(\mathbf{k}) h^*(\mathbf{k}')\rangle = \frac{2\pi^2}{k^3}\delta^{(3)}(\mathbf{k}+\mathbf{k}')P_h(\mathbf{k})$$

$$\boxed{\Delta^2_h(k,\tau) \equiv \frac{k^3}{2\pi^2}P_h(k,\tau)} \xrightarrow[\text{(Super-Horizon)}]{k\tau \ll 1} \boxed{\Delta^2_h(k) = \frac{2}{\pi^2}\left(\frac{H}{m_p}\right)^2\left(\frac{k}{aH}\right)^{-2\epsilon}}$$

Red-tilted !

# Inflation: Observables

H & I

INFLATION

$$g_{\mu\nu} = g_{\mu\nu}^{FRW} + \delta g_{\mu\nu}[\mathcal{R}, h_{ij}]$$

$$\boxed{\Delta^2_{\mathcal{R}}(k) = \frac{H^4}{(2\pi)^2\dot{\phi}^2}\left(\frac{k}{aH}\right)^{n_s-1}}$$

$$\boxed{n_s - 1 \equiv 2(\eta - 2\epsilon)}$$

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

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Inflation scale !

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Inflation scale !

Red-tilted

Inflation → Reheating → FRW (hBB)

$a \propto e^{Ht}$

$\rho_\phi \to \rho(\psi, A_\mu, ...)$

$\rho_\gamma, \rho_b, \rho_{DM}, ...$

$$g_{\mu\nu} = g_{\mu\nu}^{FRW} + \delta g_{\mu\nu}[\mathcal{R}, h_{ij}] \xrightarrow{\text{GR}} \rho_i + \delta\rho_i \xrightarrow{\text{GR, Int.}} \delta\rho_i(t)\ [\text{Evolution}]$$

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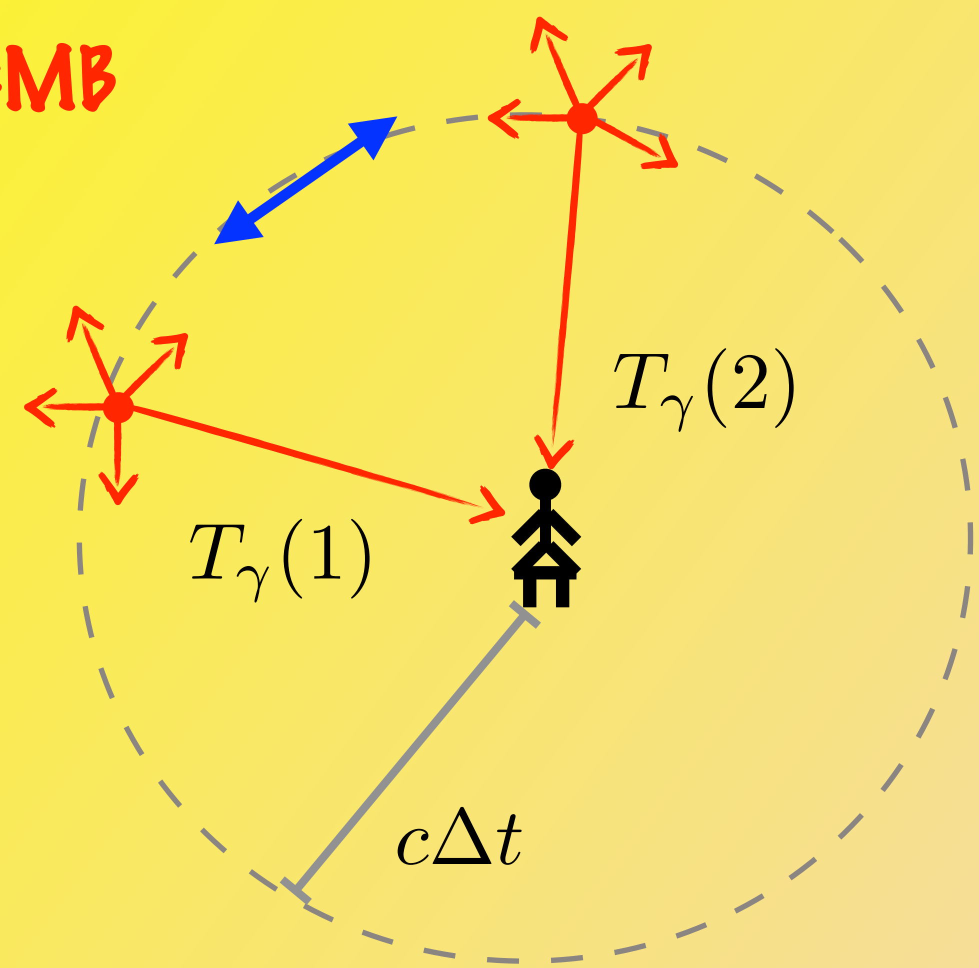
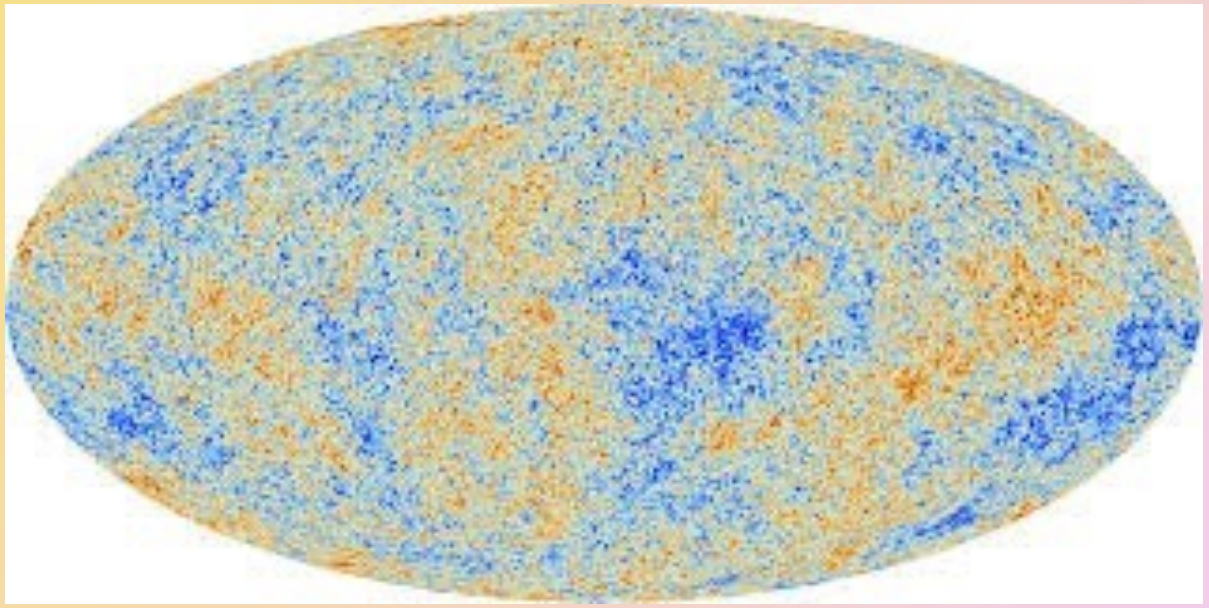
**CMB**




$$\rho_\gamma + \delta_\gamma \ \Rightarrow\ T_\gamma(\hat{n}) = \bar{T} + \delta T(\hat{n})$$



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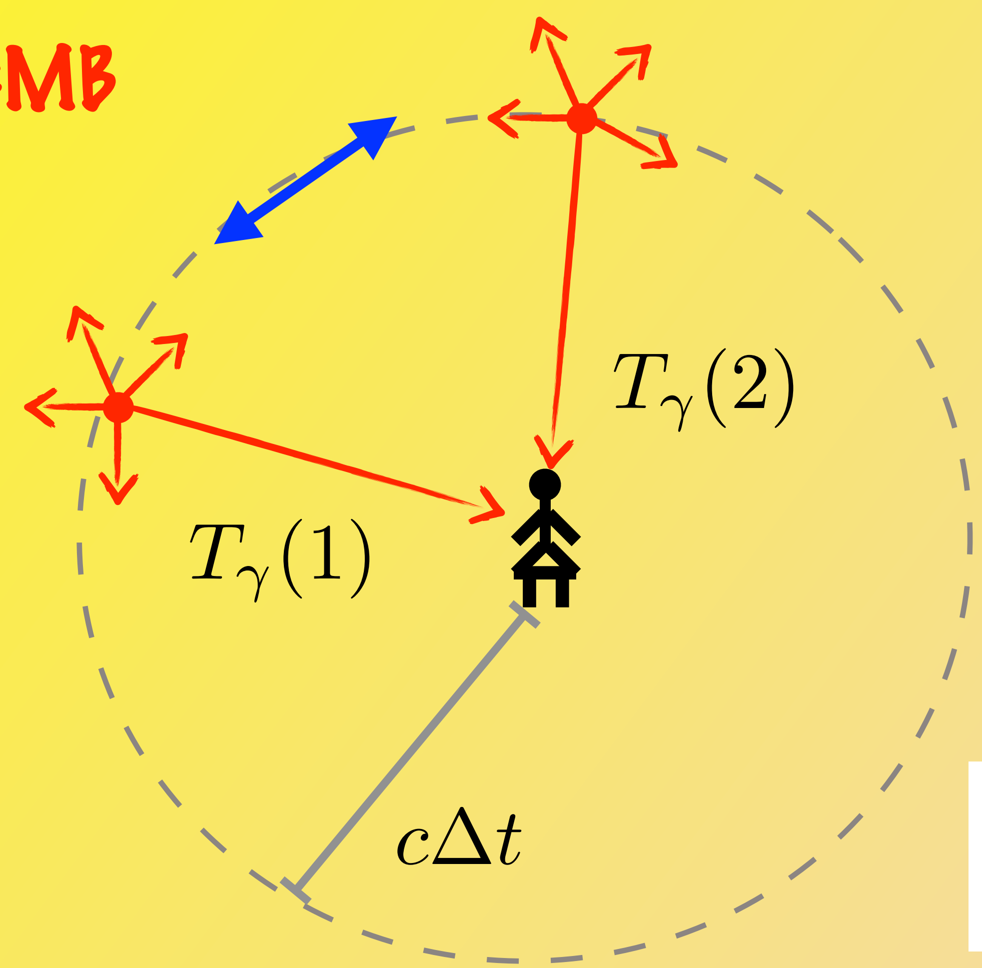


$$\rho_\gamma + \delta_\gamma \ \Rightarrow \ T_\gamma(\hat{n}) = \bar{T} + \delta T(\hat{n})$$

**Temperature Angular Power Spectrum**

$$\delta T(\hat{n}) = \sum_{l,m} a_{lm} Y_{lm}(\hat{n}) \ \Rightarrow \ \langle [\delta T]^2 \rangle \ \to \ \langle |a_{lm}|^2 \rangle \equiv C_l$$

# Inflation: Observables

$\delta\rho_\gamma, \delta\rho_e \Rightarrow$ [Thomson Scattering] $\Rightarrow$ Linear Polarization

Linear Polarization $\rightarrow Q, U$ (Stokes Parameters)

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

$$\mathcal{E}(\hat{n}) = \sum_{l,m} e_{lm} Y_{lm}(\hat{n}), \ \mathcal{B}(\hat{n}) = \sum_{l,m} b_{lm} Y_{lm}(\hat{n})$$

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

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**Polarization Angular Power Spectrum**

**Depends on Scalar (also tensor) Perturbations**

**Depends only on Tensor Perturbations !!!**

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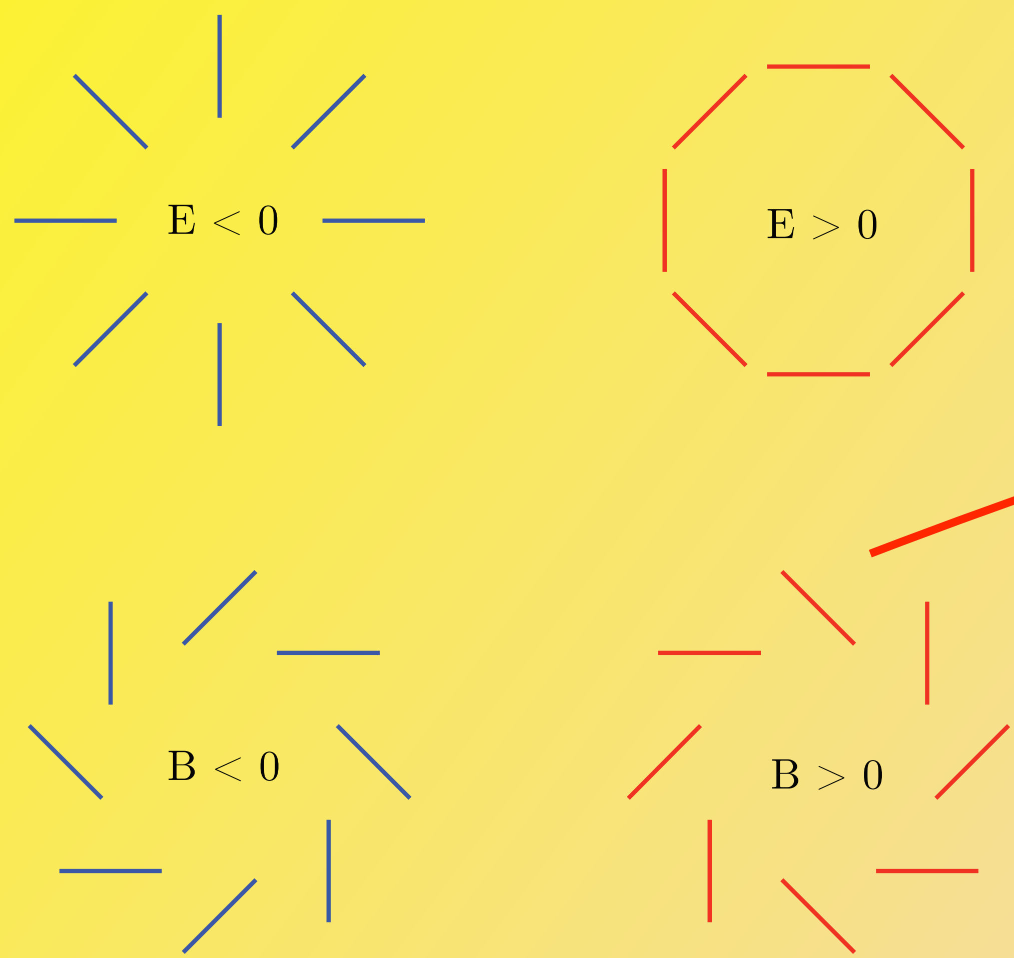


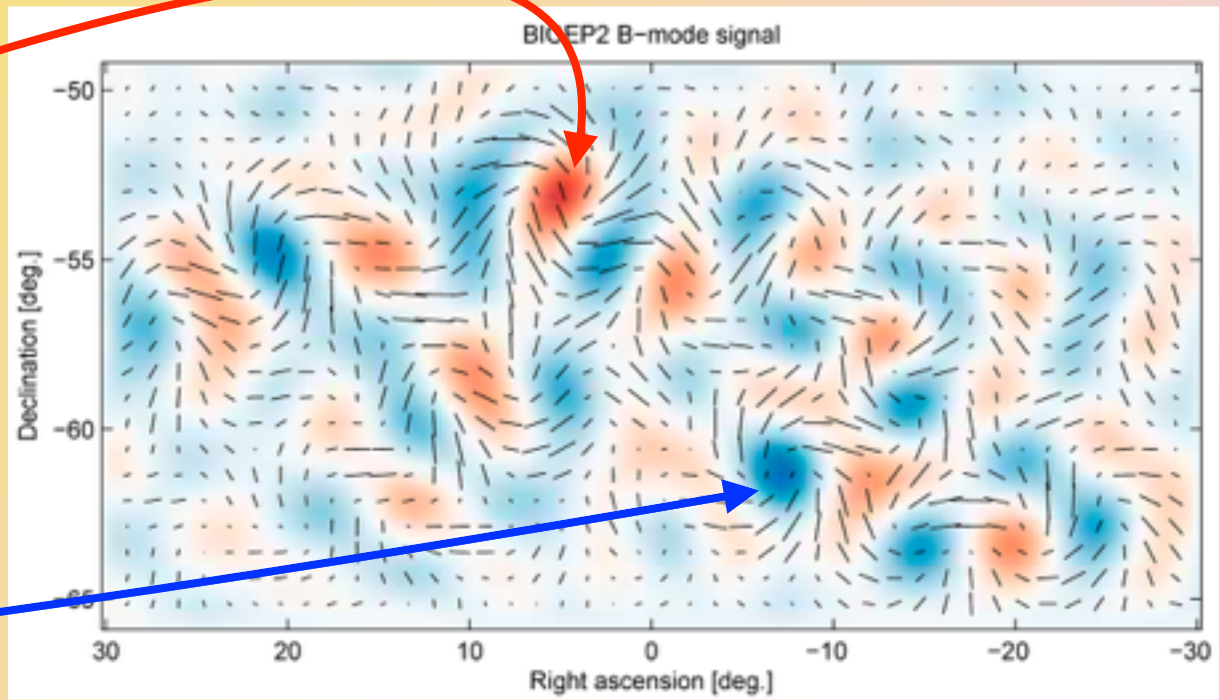

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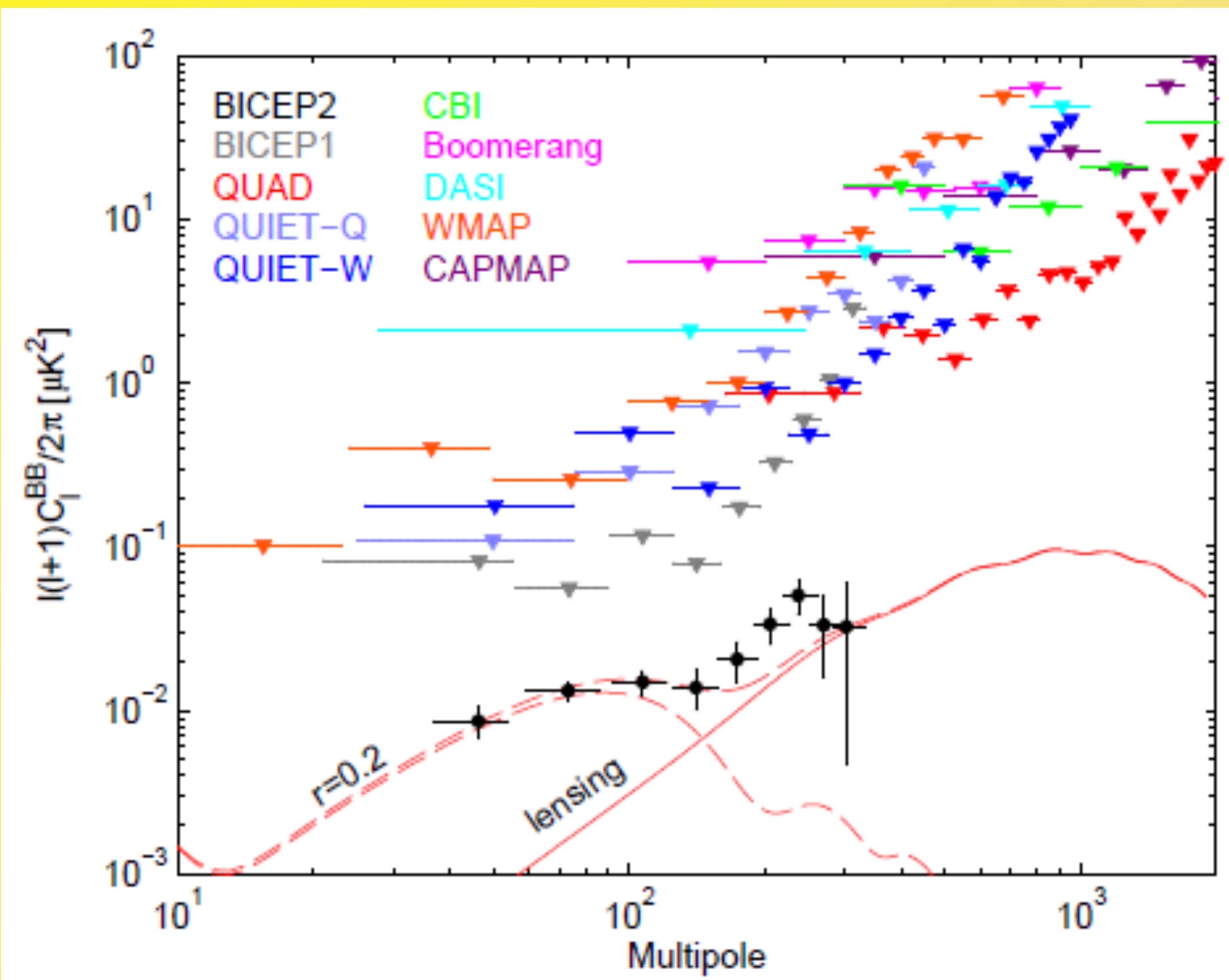

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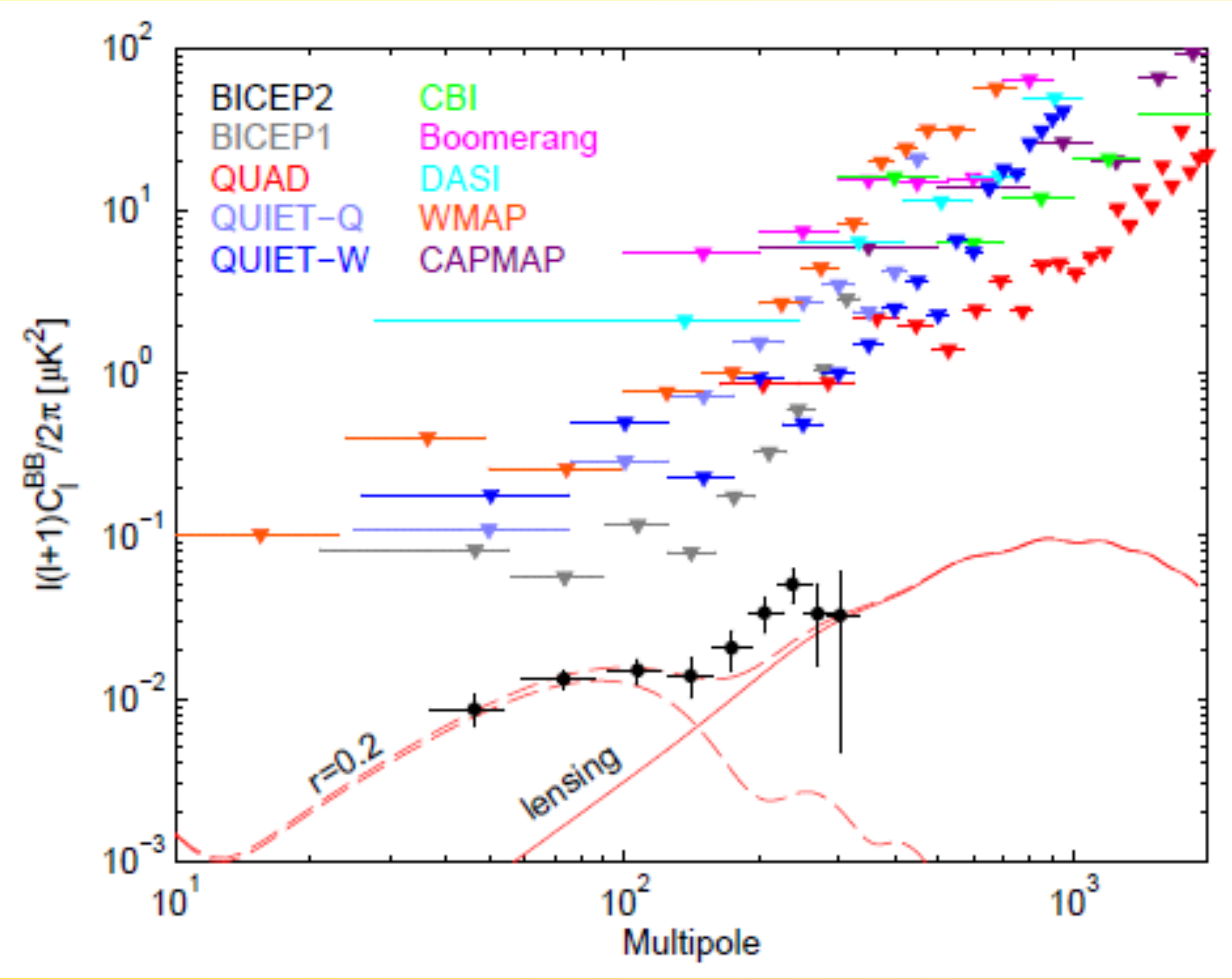


Dashed Line Theoretical Expectation from Inflation

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

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

(!)

# Inflation: Summary

Inflation: Solves Causality Problem. Bonus: Universe Flat

$a \propto e^{Ht}$ → $g_{\mu\nu} = g^{FRW}_{\mu\nu} + \delta g_{\mu\nu}[\mathcal{R}, h_{ij}]$ → $\Delta T,\ \mathcal{E},\ \mathcal{B}\quad [\text{also } \delta\rho]$

Exponetial Expansion

Quantum Origin of Fluctuations

Angular Temperature/ Polarization Anisotropies

Observations:

| $\lvert\Omega_k\rvert \ll 1$ | $n_s - 1 \sim -0.04$ | $\langle \mathcal{R}^3 \rangle \approx 0$ | $4\delta_m = 3\delta_\gamma$ |
|---|---|---|---|
| Locally Flat | Almost Scale-Inv | Gaussian | Adiabatic |

But CMB polarization B-modes due to GWs not yet found !

# Inflation: What else?

Many more things George!

# Inflation: What else?

## Many more things !

### Inflationary period

* GWs from Particle production during inflation

* GWs from Spectator fields

* GWs in the EFT of space-reparam

### Post-Inflationary period

* GWs from merging of primordial BHs

* Kination-domination

* GWs from (p)reheating

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* GWs from merging of primordial BHs

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# Particle production during inflation

[J. Cook, L. Sorbo (arXiv:1109.0022)]

[N. Barnaby, E. Pajer, M. Peloso (arXiv:1110.3327)]

## Axion-inflation model

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

inflaton $\varphi$ = pseudo-scalar axion

The rolling inflaton excites the gauge field(s)

$$\xi \equiv \frac{\dot{\varphi}}{2\Lambda H} \longrightarrow \ddot{A}_\pm(k,t) + \left[k^2 \pm 2\xi \frac{k}{t}\right] A_\pm(k,t) = 0$$

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

$A_+$ exponentially amplified,

$A_-$ has no amplification

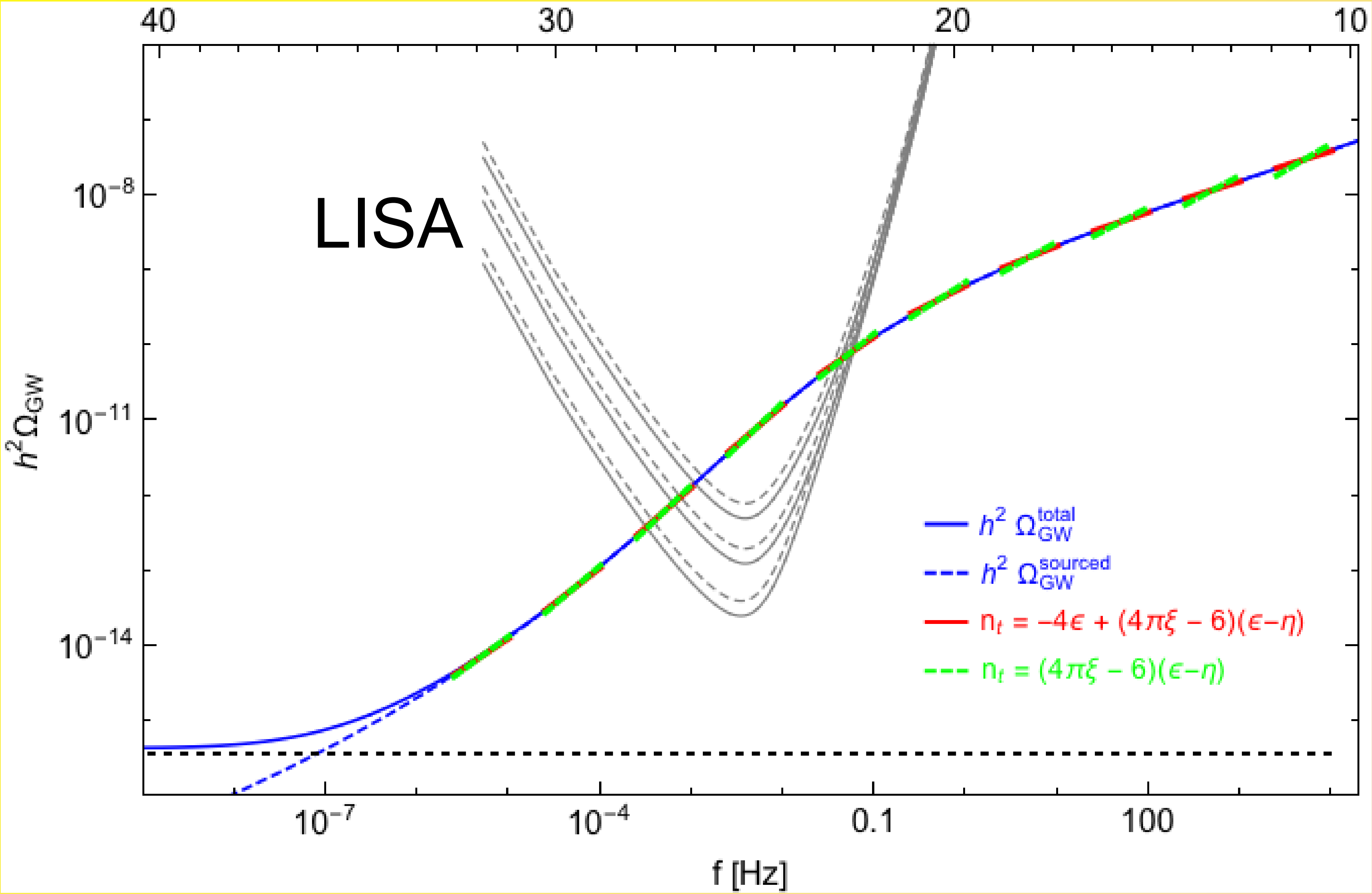
Gauge field excitation creates chiral GWs !

# Particle production during inflation

[J. Cook, L. Sorbo (arXiv:1109.0022)]

[N. Barnaby, E. Pajer, M. Peloso (arXiv:1110.3327)]

## Axion-inflation model




Gauge fields source a blue tilted & chiral GW background

# Particle production during inflation

## Axion-inflation model $V(\varphi) + \frac{\varphi}{\Lambda} F_{\mu\nu}\tilde{F}^{\mu\nu}$

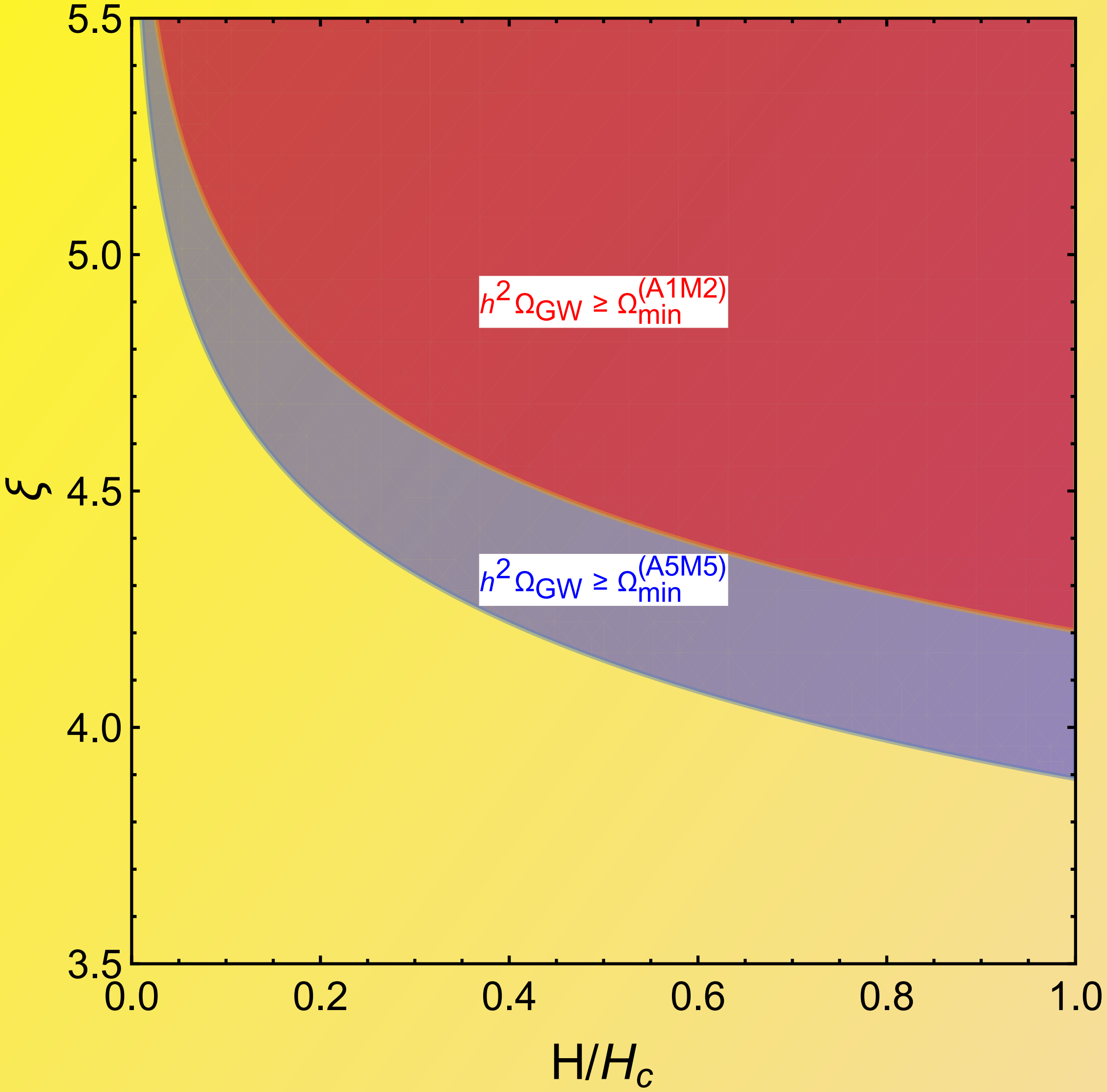
$$h^2\Omega_{\rm gw} = A_* \left(\frac{f}{f_*}\right)^{n_T}$$

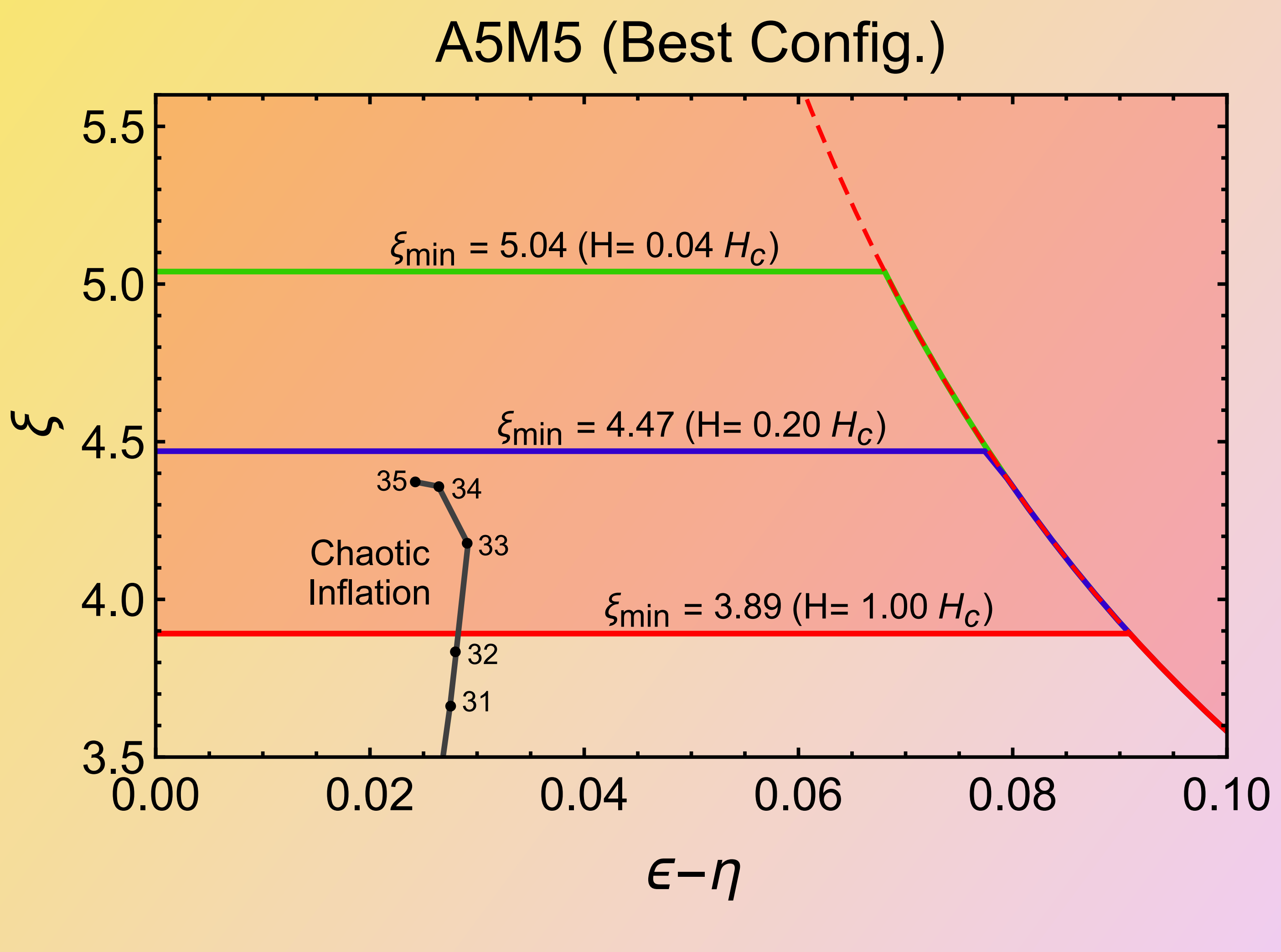
Bartolo et al ‘16

$$\Omega_{\rm GW} h^2 \simeq 1.5 \cdot 10^{-13} \frac{H^4}{M_{Pl}^4} \frac{e^{4\pi\xi}}{\xi^6} \quad , \quad \xi \gg 1$$

$$n_T \simeq (4\pi\xi - 6)(\epsilon_H - \eta)$$

3 parameters
$H,\ \xi,\ \epsilon_H - \eta$



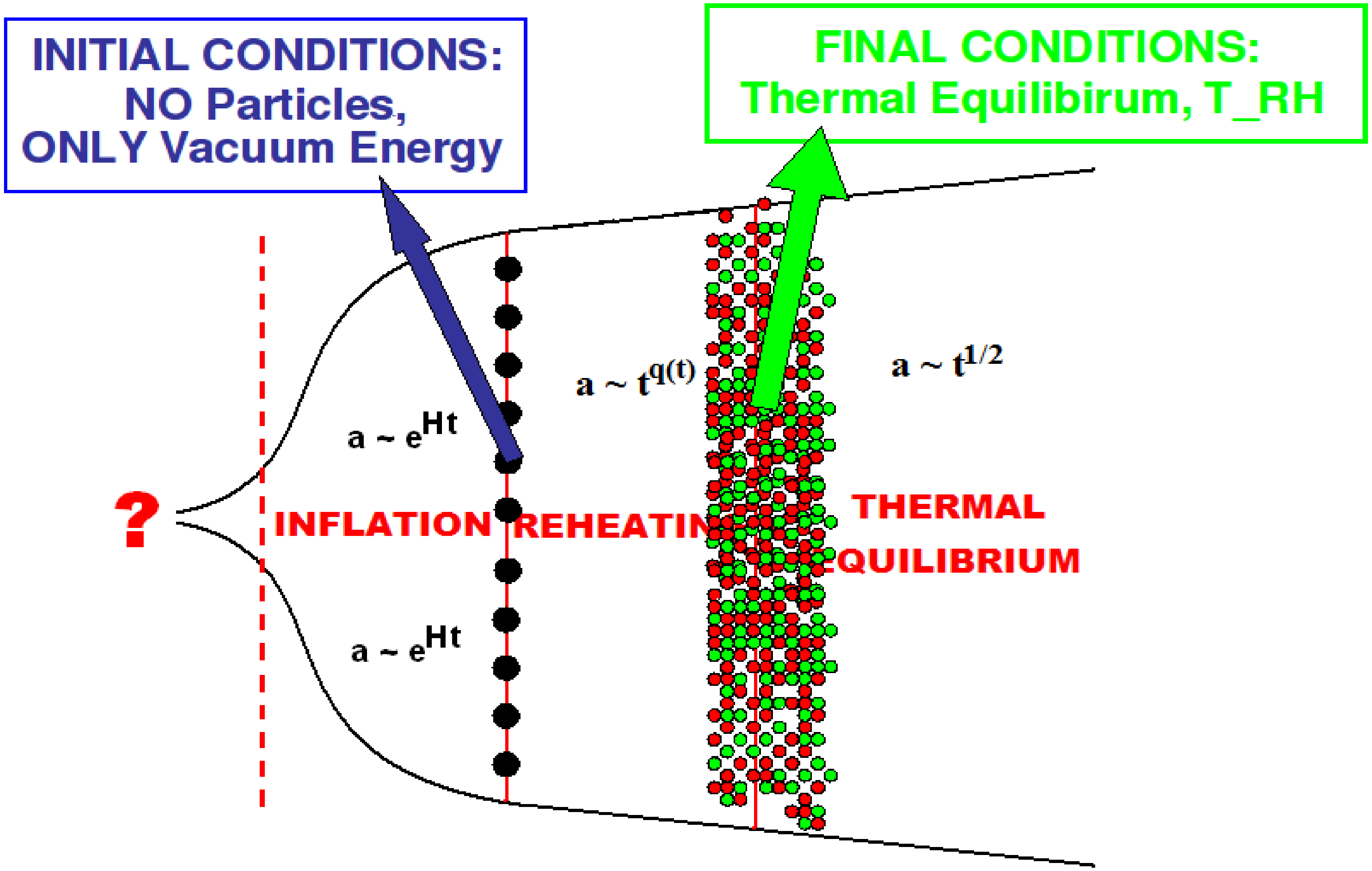
Alright, Inflation ends ...

... so what follows afterwards ?

(p)Reheating !

# GWs from Preheating

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



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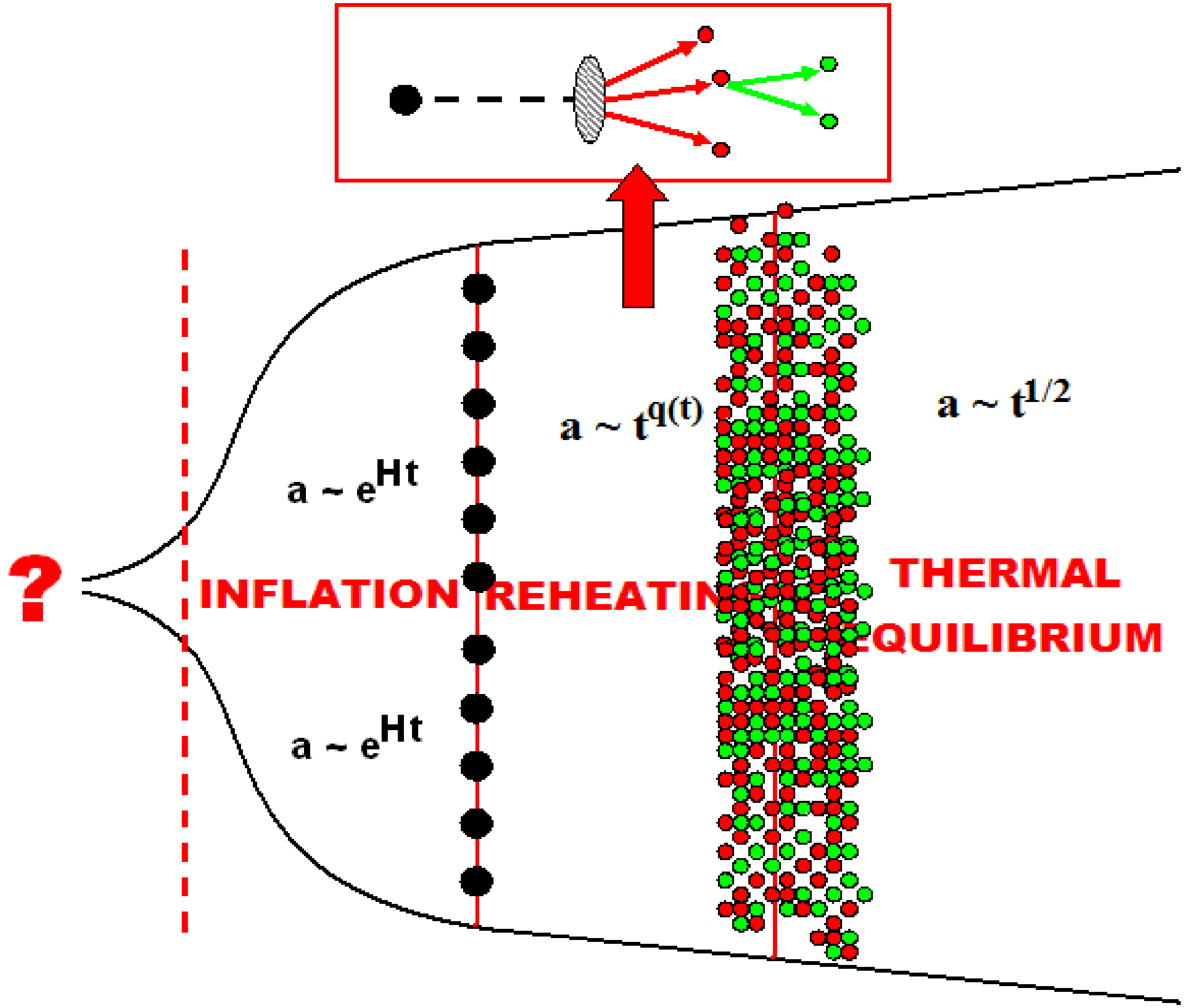
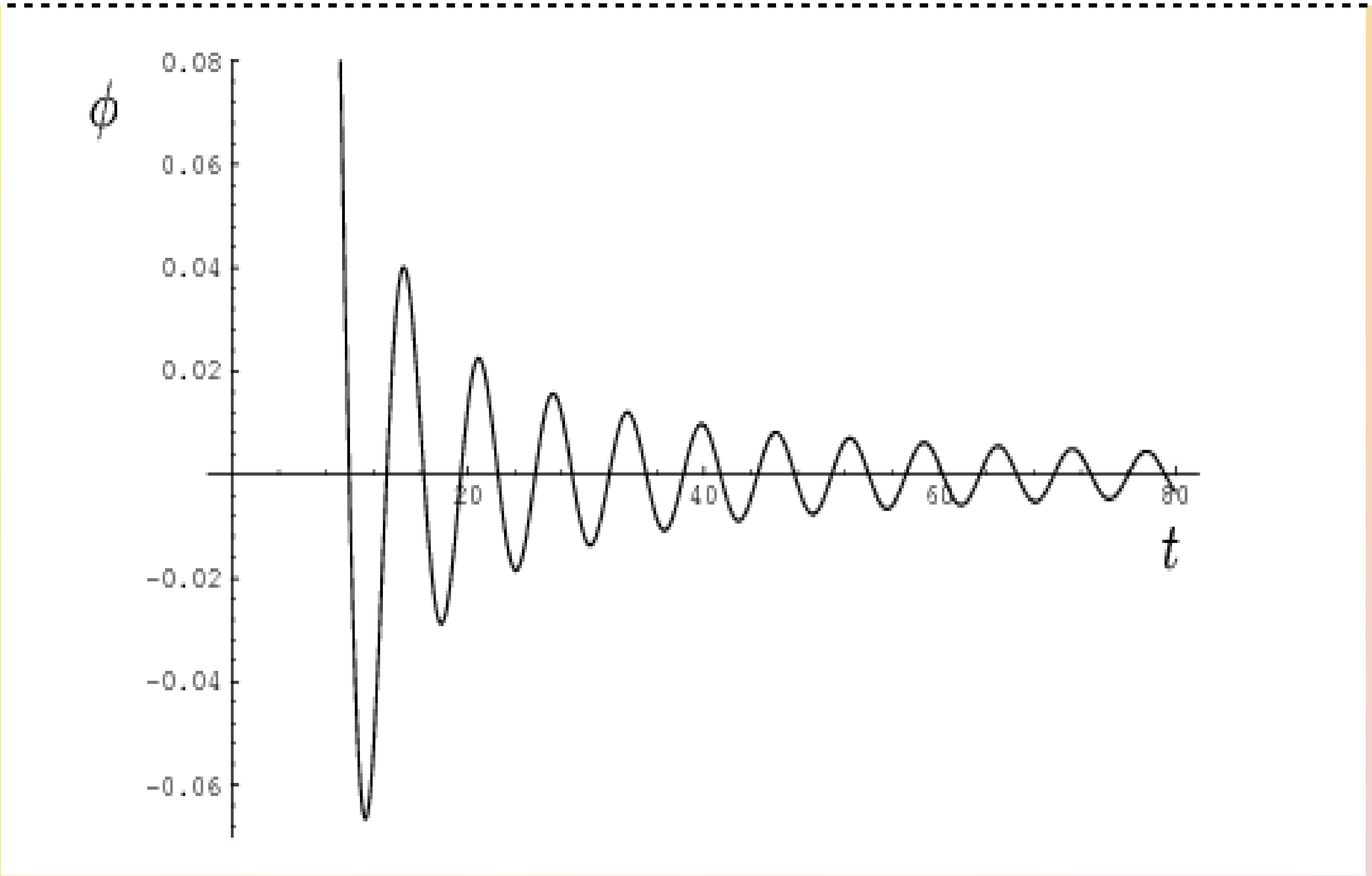


# GWs from Preheating

Inflaton: $V(\phi) \propto \phi^n$

**Scalar field (condensate) after Inflation**:

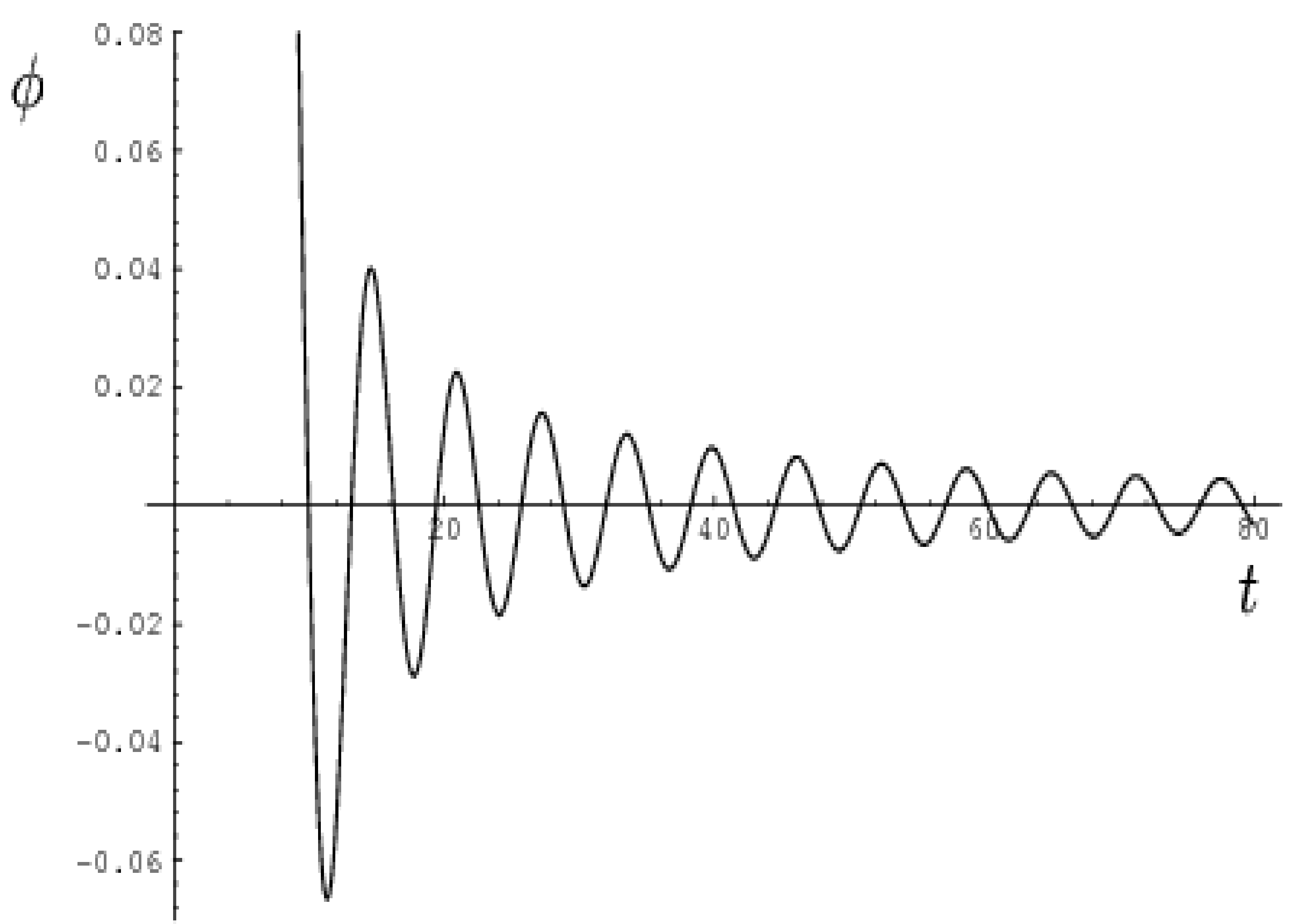
Coherent Oscillations: $\phi(t) \approx \Phi(t) f(t), \quad f(t+T) = f(t)$



# GWs from Preheating

**Fermions**: $y\phi\bar{\psi}\psi$ :  Oscillations $\rightarrow$ $\psi$ $-$ Particle Creation
(Non-Pert., Out-of-Eq.)

$$\psi(\mathbf{x},t) = \int \frac{d\mathbf{k}}{(2\pi)^3}\, e^{-i\mathbf{k}\cdot\mathbf{x}} \Big[\, \hat{a}_{\mathbf{k},r} \begin{pmatrix} u_{\mathbf{k},+}(t) S_r \\ \\ u_{\mathbf{k},-}(t) S_r \end{pmatrix} + \hat{b}^{\dagger}_{-\mathbf{k},r} \begin{pmatrix} v_{\mathbf{k},+}(t)\, S_r \\ \\ v_{\mathbf{k},-}(t)\, S_r \end{pmatrix} \Big],$$

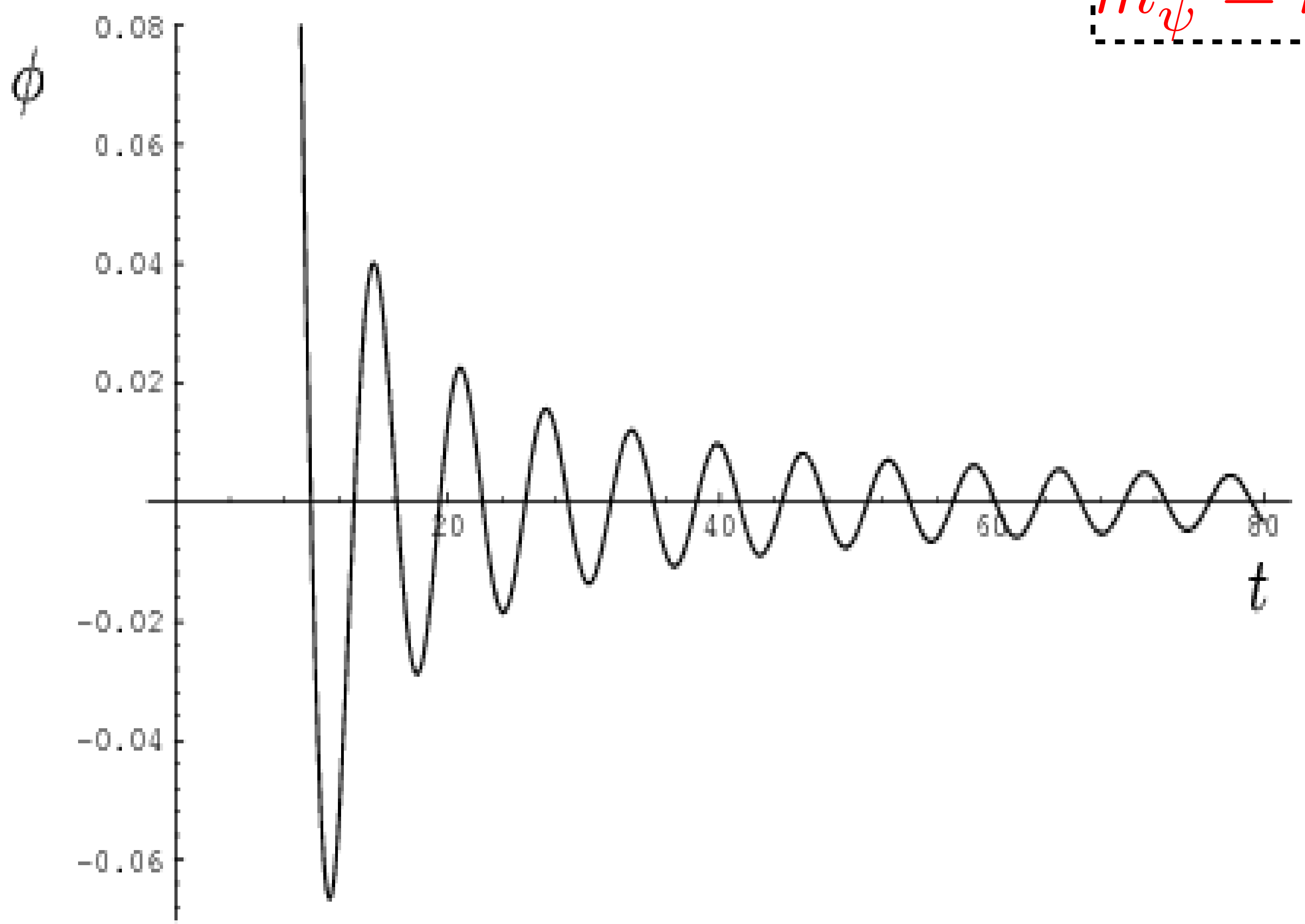


# GWs from Preheating

**Fermions**: $y\phi\bar{\psi}\psi$ : Oscillations $\rightarrow$ $\psi$ − Particle Creation
(Non-Pert., Out-of-Eq.)

$$\frac{d^2}{dt^2}u_{\mathbf{k},\pm} + \left(\omega_{\mathbf{k}}^2(t) \pm i\frac{d(am_\psi)}{dt}\right)u_{\mathbf{k},\pm}(t) = 0\,, \quad \omega_{\mathbf{k}}^2(t) = k^2 + a^2(t)m_\psi^2(t)$$

$$\boxed{m_\psi^2 = h^2\phi^2}$$



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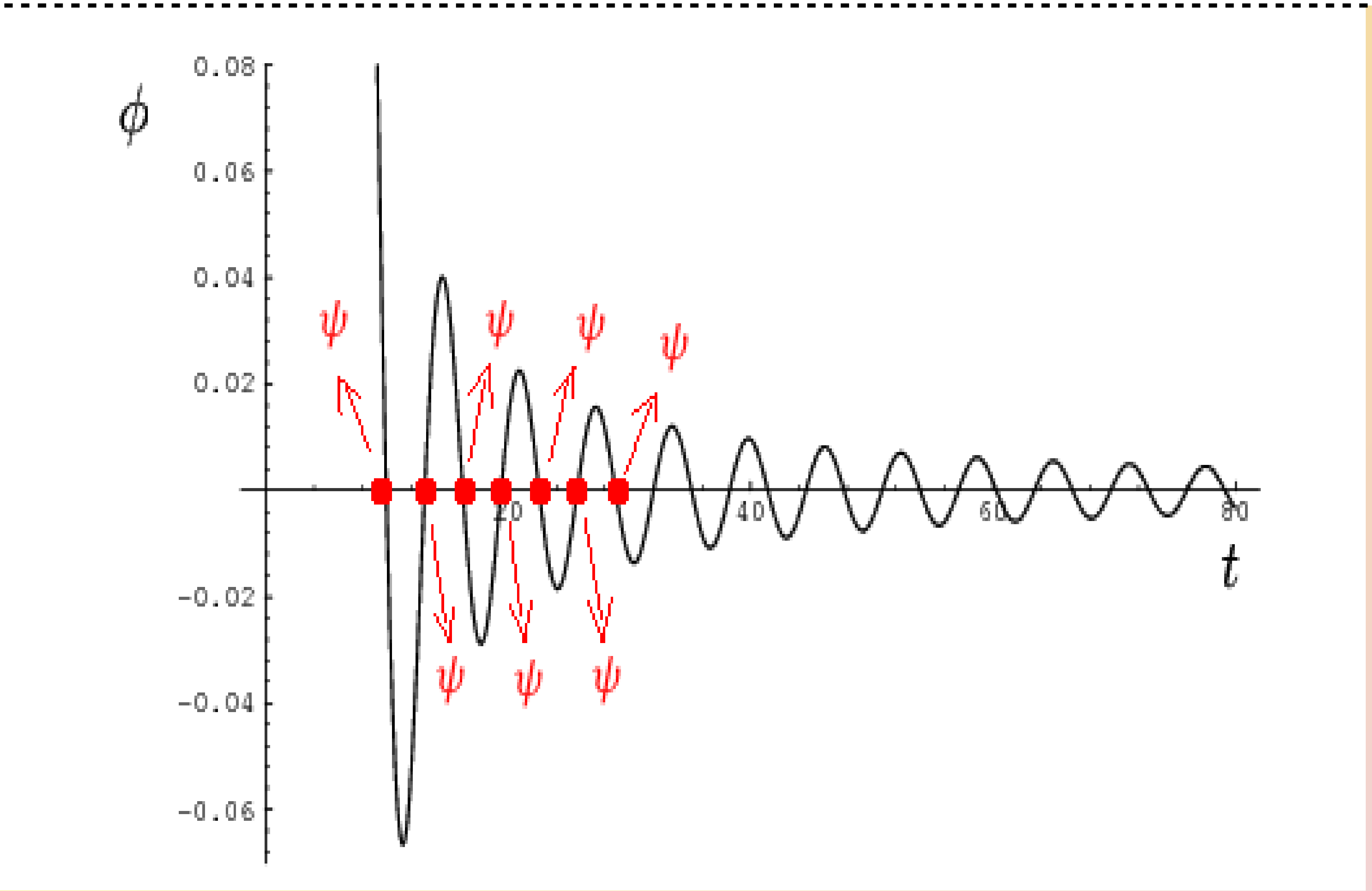

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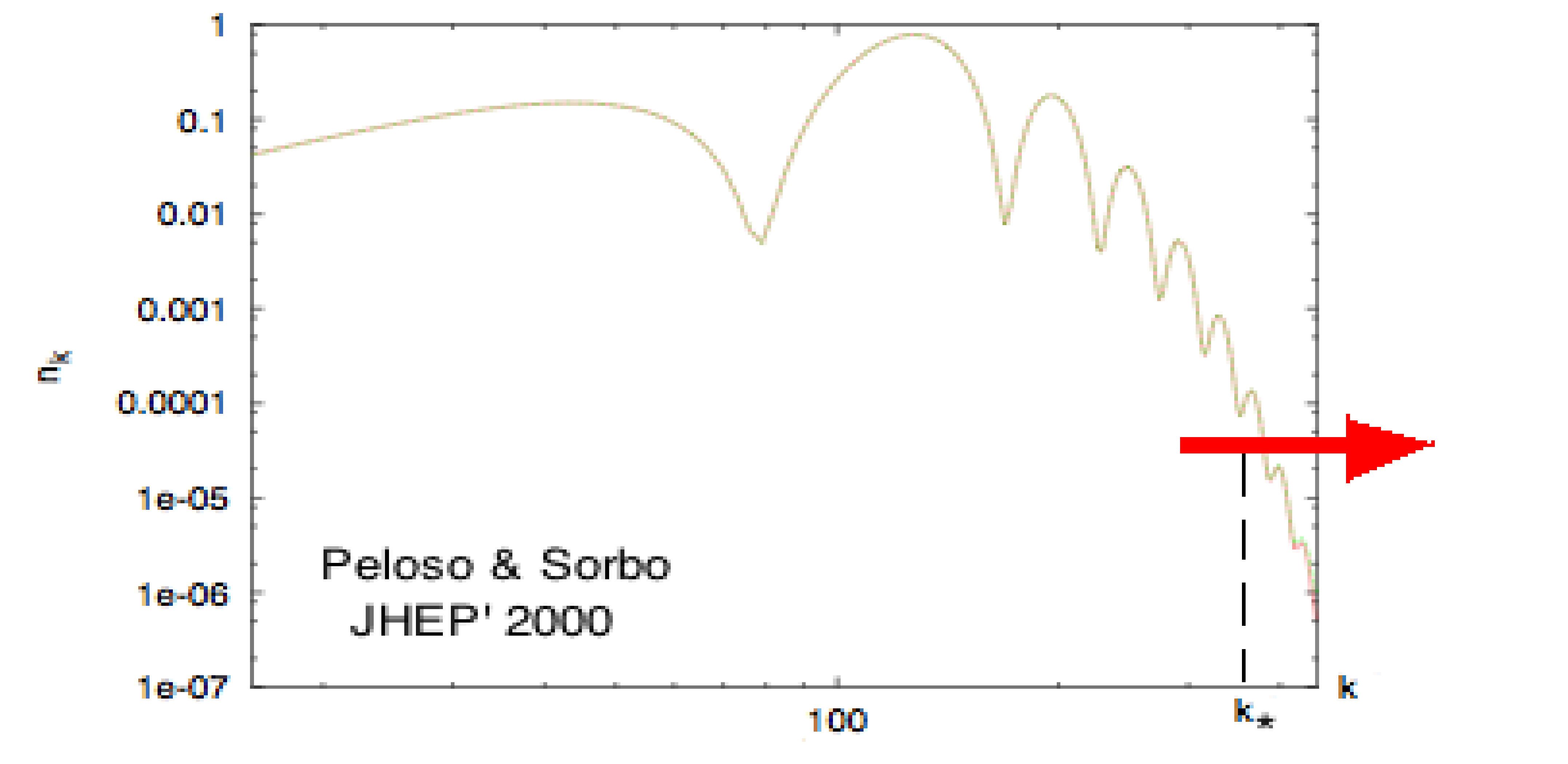
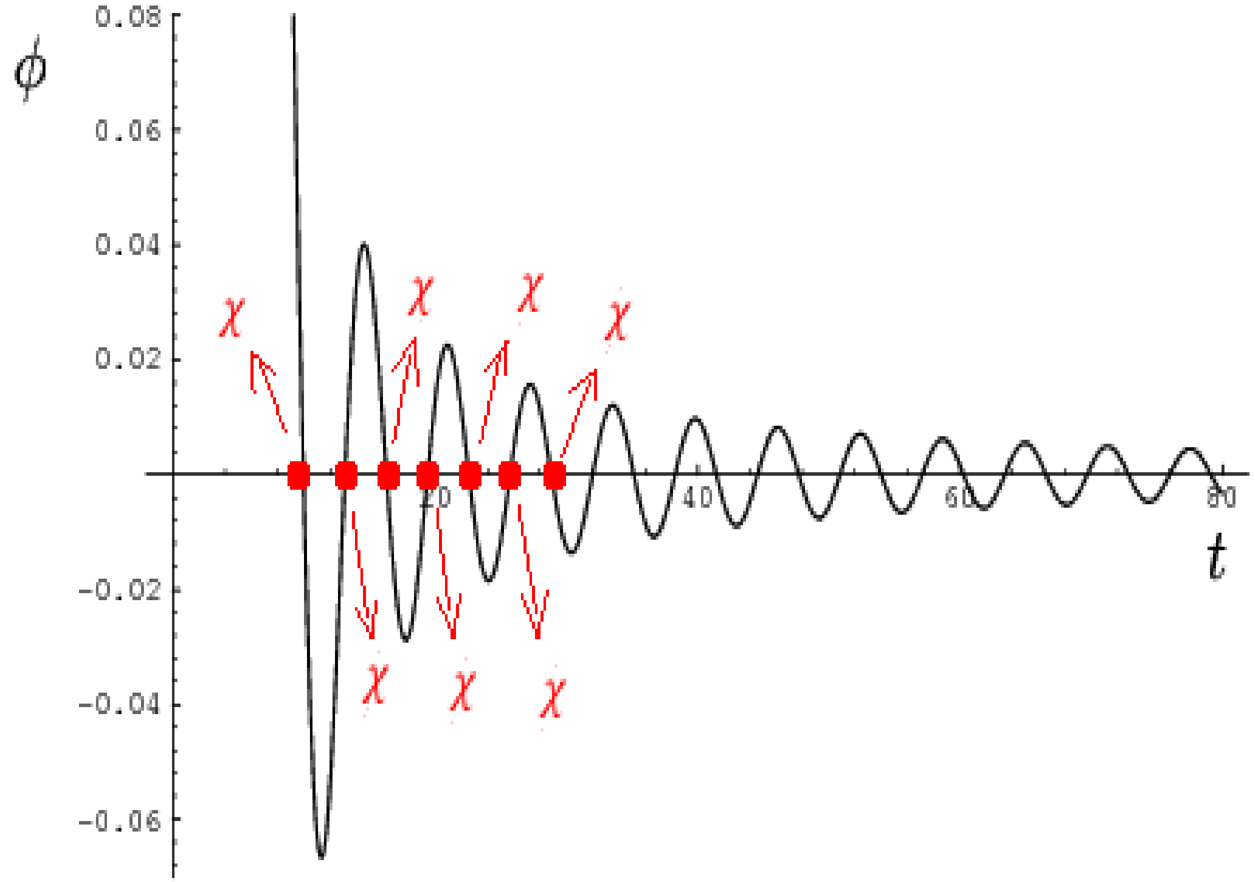


# GWs from Preheating

**Bosons**: $g^2\phi^2\chi^2$ : Oscillations $\rightarrow$ $\chi$ – Particle Creation
(Non-Pert., Out-of-Eq.)

$$\frac{d^2}{dt^2}\chi_{\mathbf{k}} + \omega_{\mathbf{k}}^2(t)\chi_{\mathbf{k}}(t) = 0\,, \qquad \frac{d}{dt}\omega_{\mathbf{k}} \gg \omega_{\mathbf{k}}^2(t)$$



# GWs from Preheating

**Bosons**: $g^2\phi^2\chi^2$ : Oscillations $\rightarrow$ $\chi$ – Particle Creation
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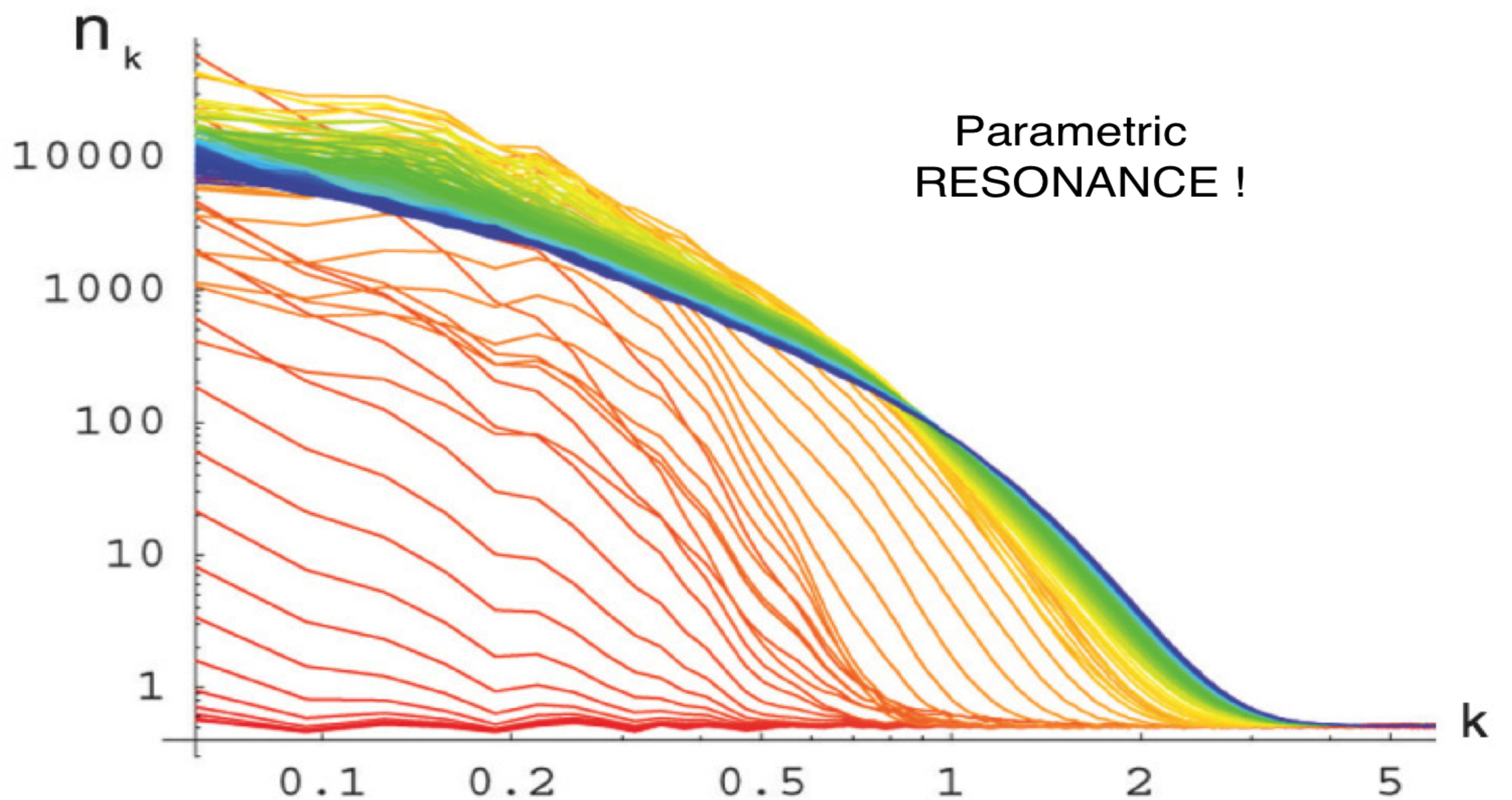
$$\frac{d^2}{dt^2}\chi_{\mathbf{k}} + \omega_{\mathbf{k}}^2(t)\chi_{\mathbf{k}}(t) = 0\,, \qquad \frac{d}{dt}\omega_{\mathbf{k}} \gg \omega_{\mathbf{k}}^2(t)$$



# GWs from Preheating

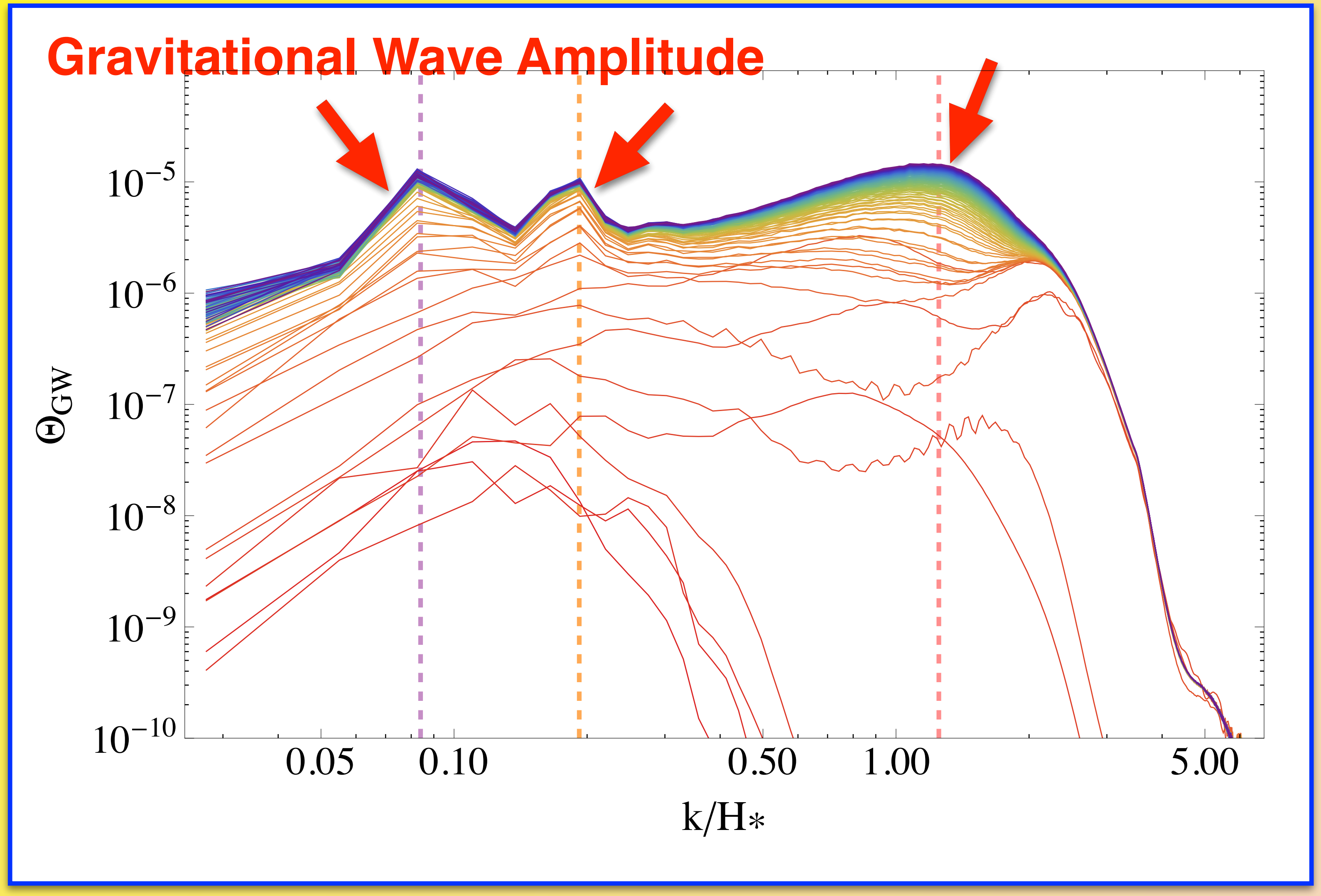
**Gravitational Waves from Inflaton decay Products**

Huge Production !

**Explosive Particle Production !**

**Gravitational Wave Generation**

$$\Omega_{\rm GW} \sim 10^{-11} \quad !!$$



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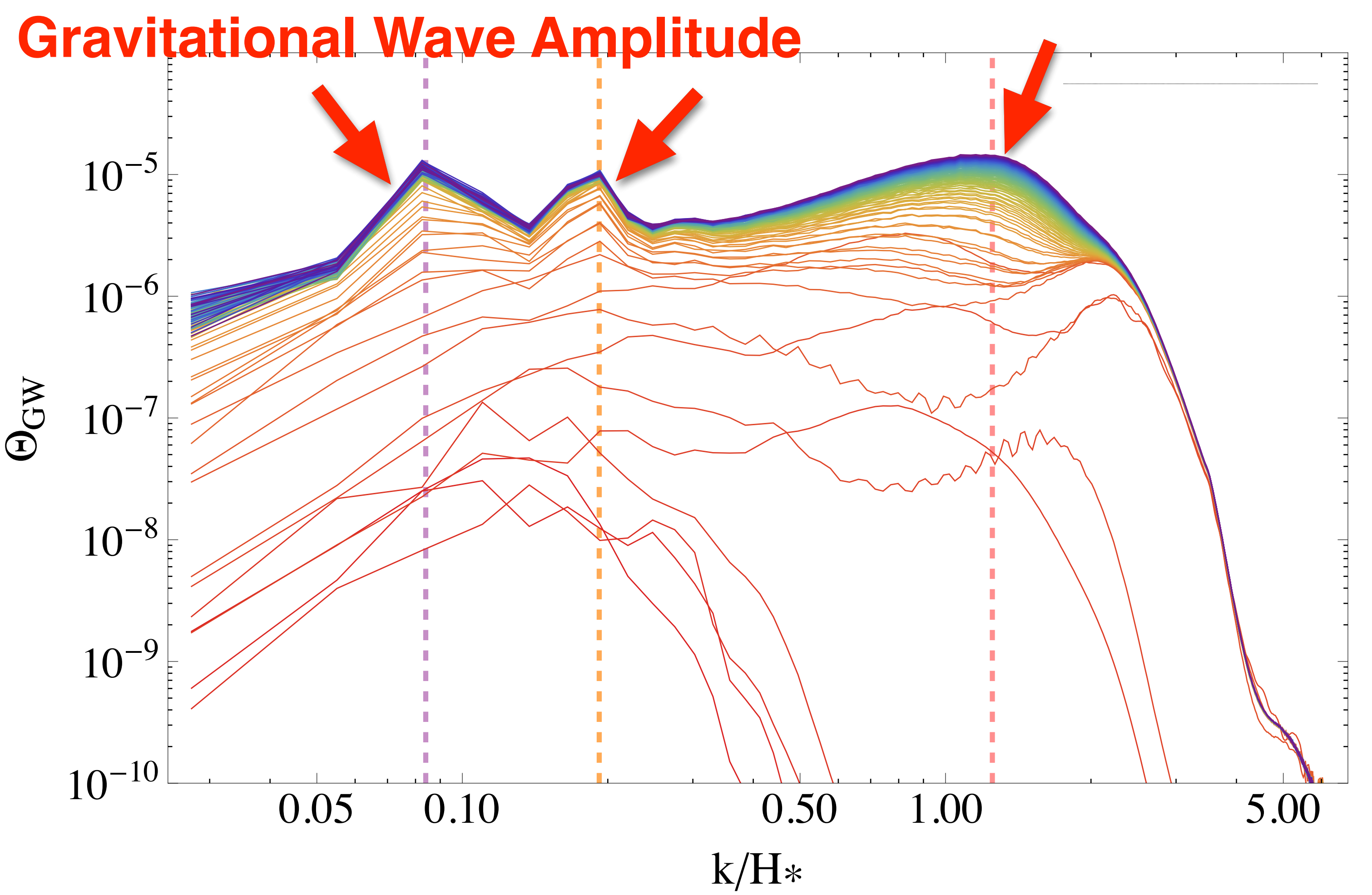
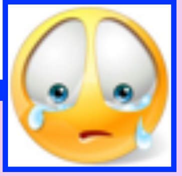



$$\Omega_{GW} \sim 10^{-11} \quad !!$$

**but ...**

$$f_* \sim 10^8 \text{ Hz}$$



# GWs from Preheating

**Gravitational Waves from Inflaton decay Products**

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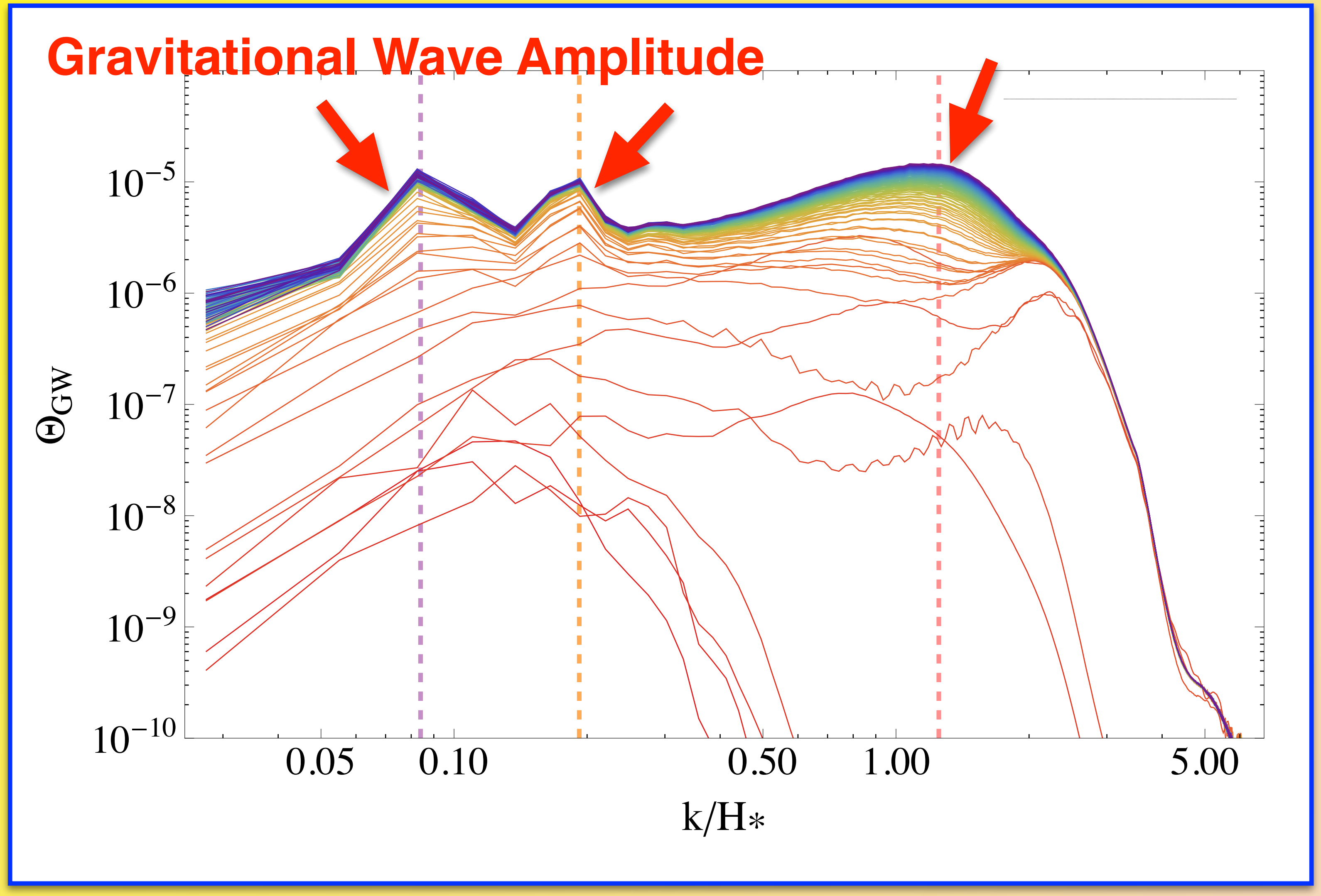



$$\Omega_{\rm GW}[f;\phi_*,V,g^2]\,,\quad f_*\sim 10^8(g/10^{-3})^{1/2}\ \mathrm{Hz}$$

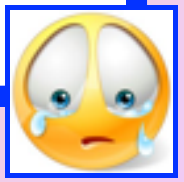
**Explosive Particle Production !**

**Gravitational Wave Generation**

$$\Omega_{\rm GW}\sim 10^{-11}\quad !!$$

**but ...**

$$f_*\sim 10^8\ \mathrm{Hz}$$



# 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

# GW background from first order phase transitions

* GW causal source: cannot 'operate' beyond the horizon (Hubble scale)

$$f_* = \frac{H(T_*)}{\epsilon_*} \qquad \epsilon_* \leq 1$$

parameter characteristic of source dynamics

Hubble rate $\longleftrightarrow$ temperature in the universe :
(assuming standard thermal history)

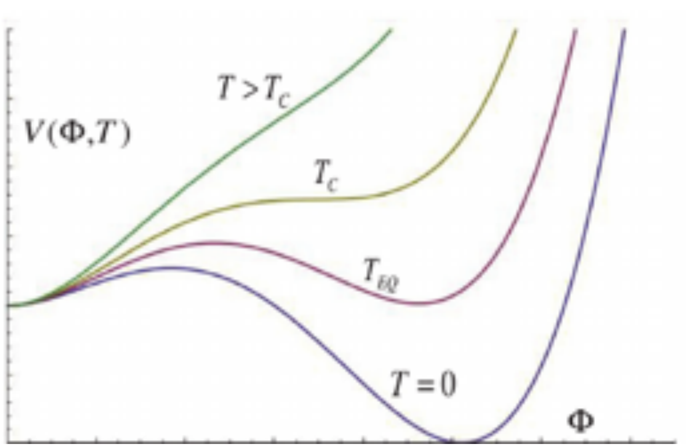
$$f_c = f_* \frac{a_*}{a_0} = \frac{2 \cdot 10^{-5}}{\epsilon_*} \frac{T_*}{1\,\mathrm{TeV}}\,\mathrm{Hz} \qquad \simeq \mathrm{mHz}$$

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

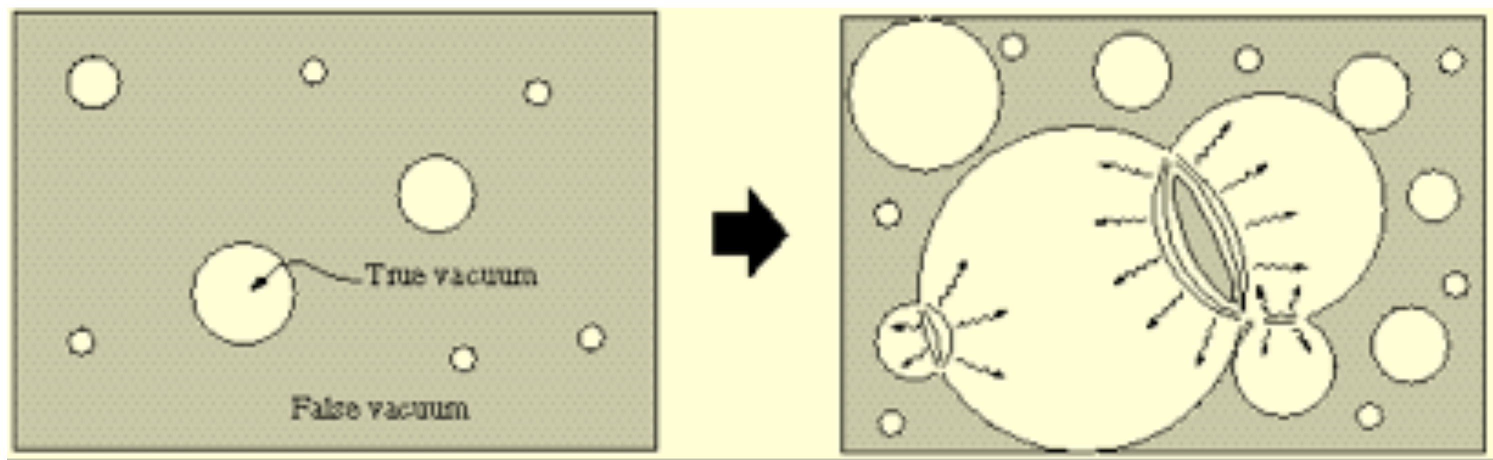
# GW background from first order phase transitions

Universe expands, temperature decreases: phase transition triggered !

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




**quantum tunneling** across the barrier : nucleation of bubbles of true vacuum




source: $\Pi_{ij}$ tensor anisotropic stress

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

# GW background from first order phase transitions

Universe expands, temperature decreases: phase transition triggered !

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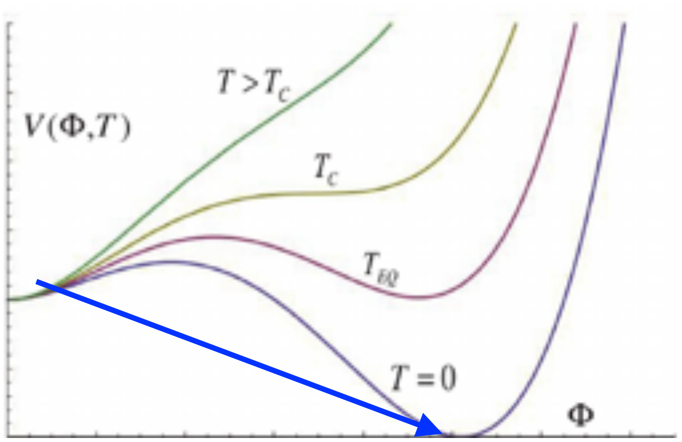
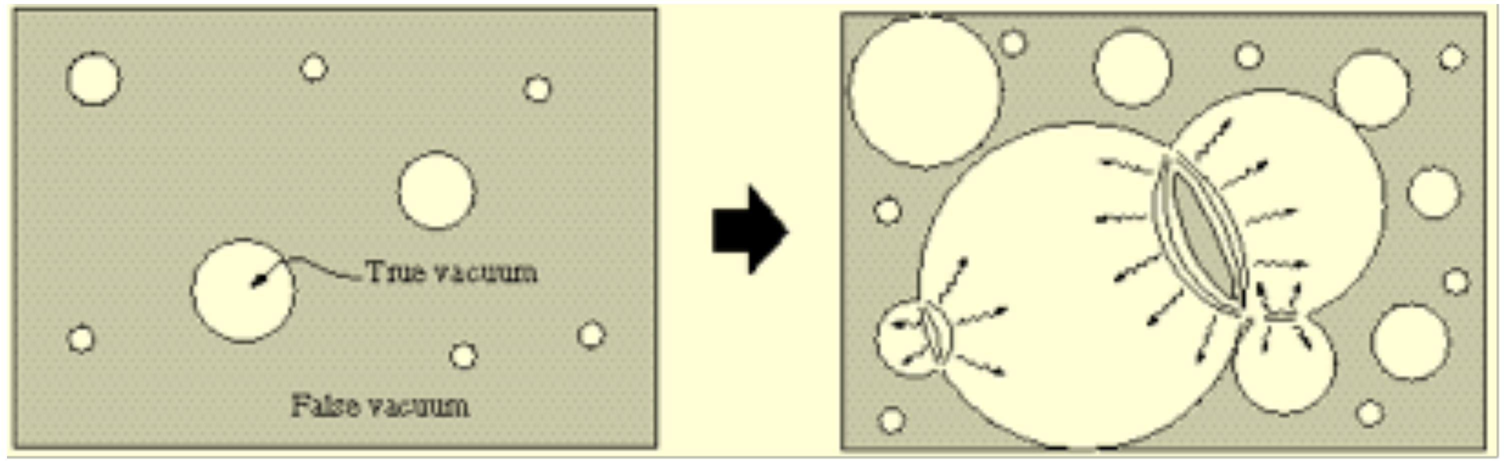



**quantum tunneling** across the barrier: nucleation of bubbles of true vacuum




source: $\Pi_{ij}$ tensor
anisotropic stress

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

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

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

# 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

$\beta^{-1}$ : duration of PhT

$v_b \leq 1$ : speed of bubble walls

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

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

BUBBLE COLLISION

SOUND WAVES AND MDH TURBULENCE

# Parameters determining the GW spectrum

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

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

Parameter List
(not independent)

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

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

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

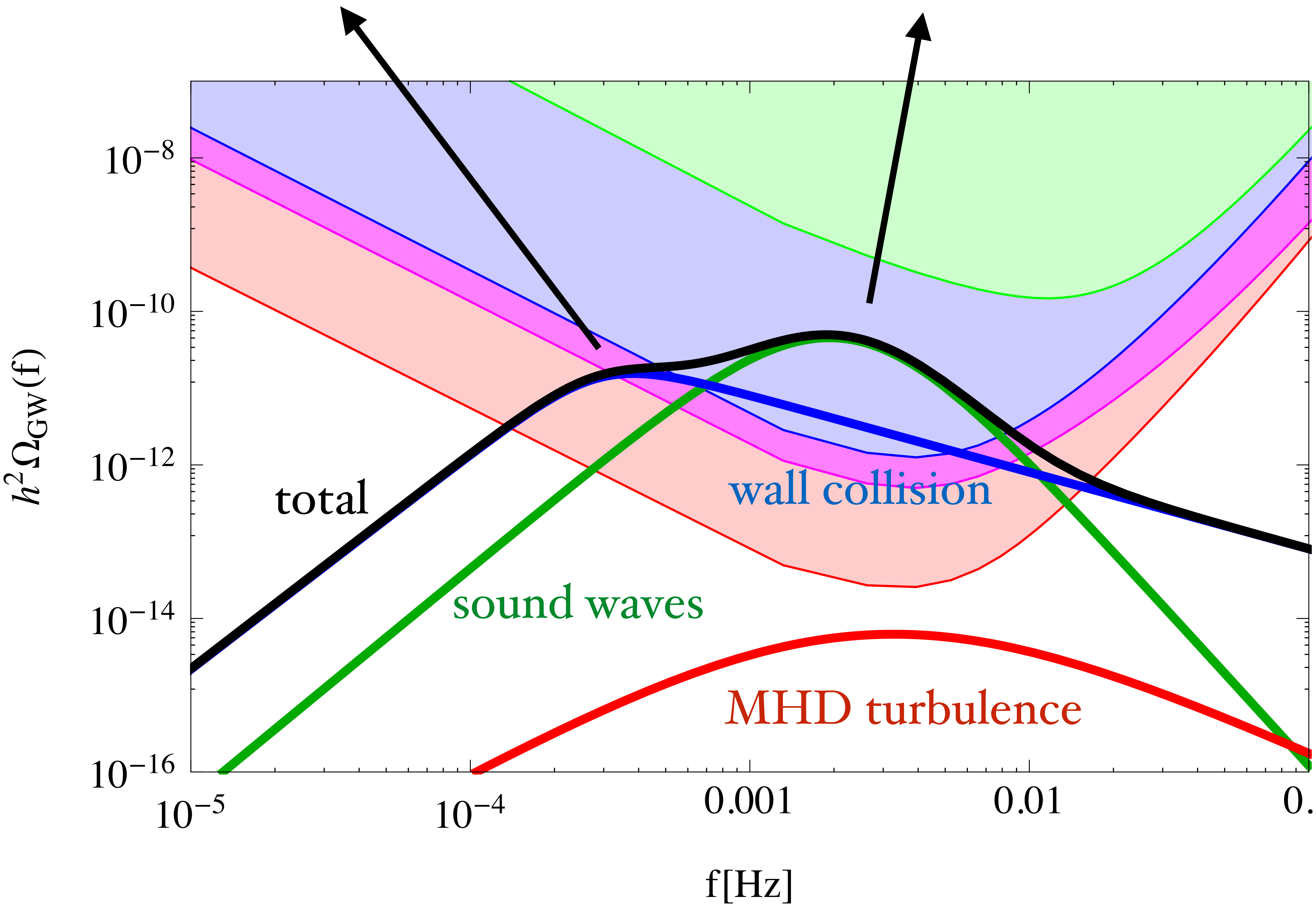
$$\alpha = \frac{\rho_{\mathrm{vac}}}{\rho_{\mathrm{rad}}^*}$$

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

# Example of spectrum ('runaway' solution)

peak of bubble collisions $\beta$

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 with both scalar field and fluid

(Hindmarsh et al arXiv:1504.03291)

- MDH turbulence: analytical evaluation

(Caprini et al arXiv:0909.0622)

# Models for EWPT and beyond

- LISA sensitive to energy scale 10 GeV - 100 TeV !

- 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)

# Models for EWPT and beyond

- LISA sensitive to energy scale 10 GeV - 100 TeV !

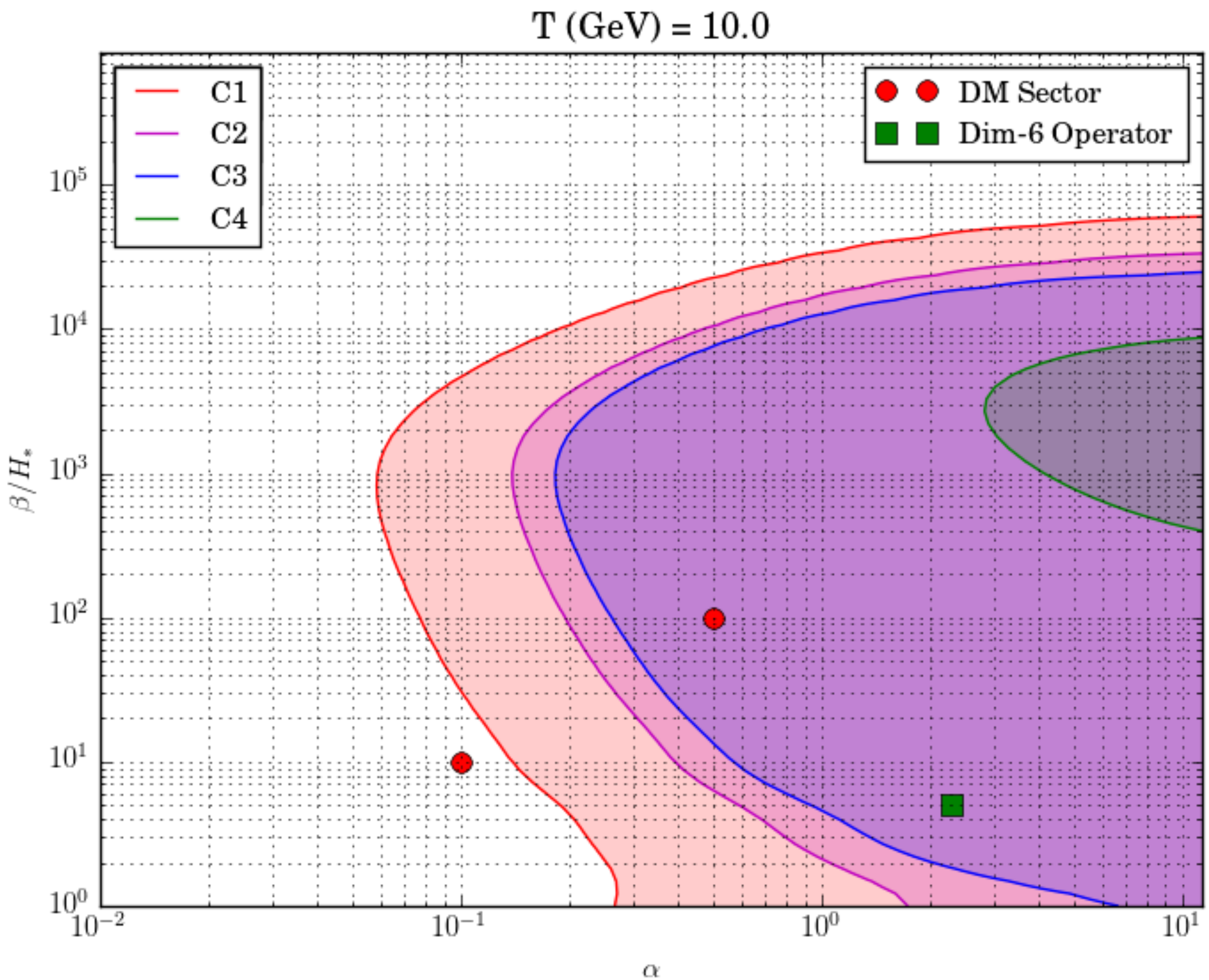
- LISA can probe the EWPT
  - sin ... 2015)
  - ... scalars (Kozackuz et al 2013)
  - ... sion six operator (Grojean et al 2004)

Cosmology and Particle Physics interplay!
Connections with baryon asymmetry & dark matter

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

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

# Detection prospects for LISA: no runaway




Caprini et al, 2015/2016 (LISA 1PhT working group)

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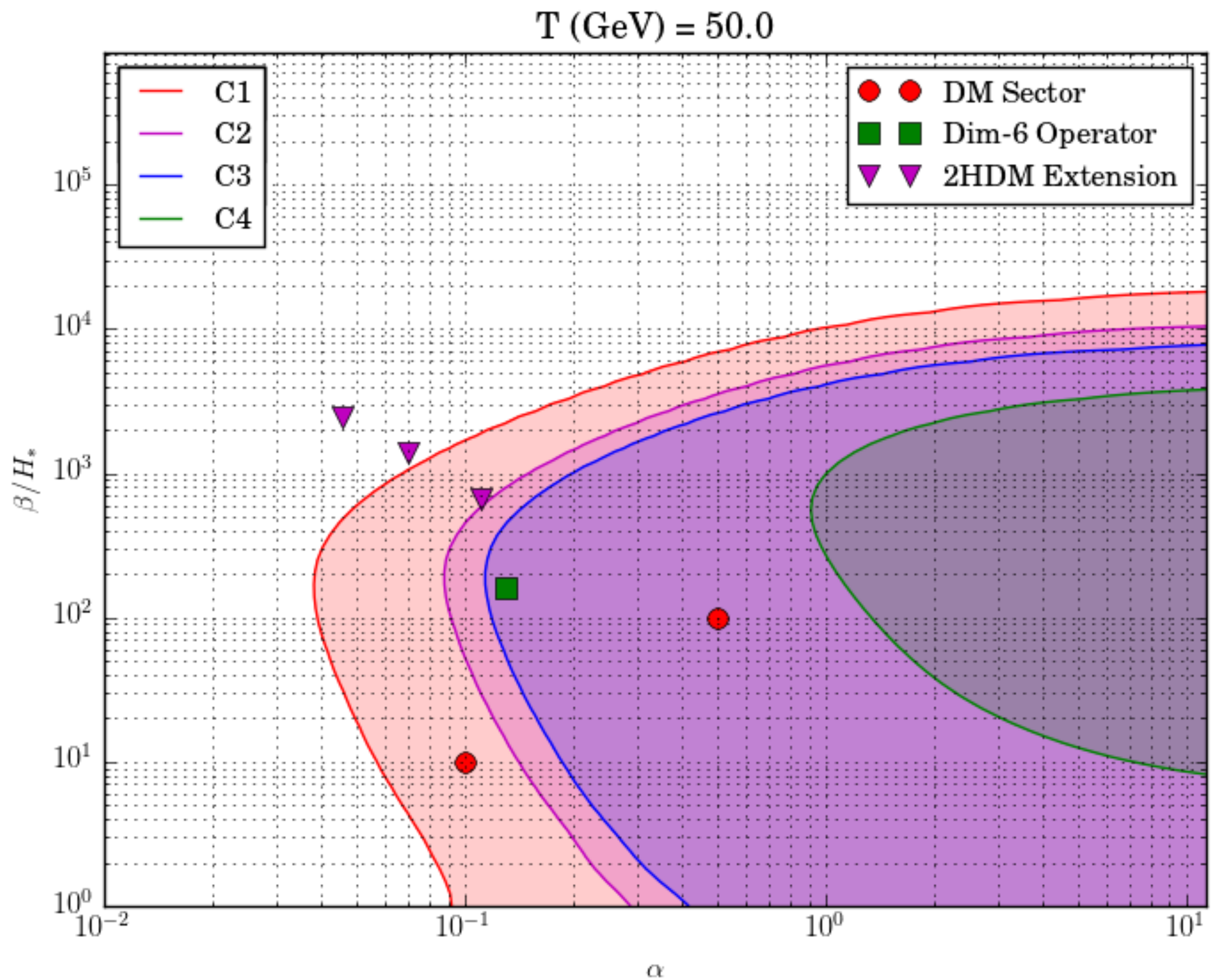


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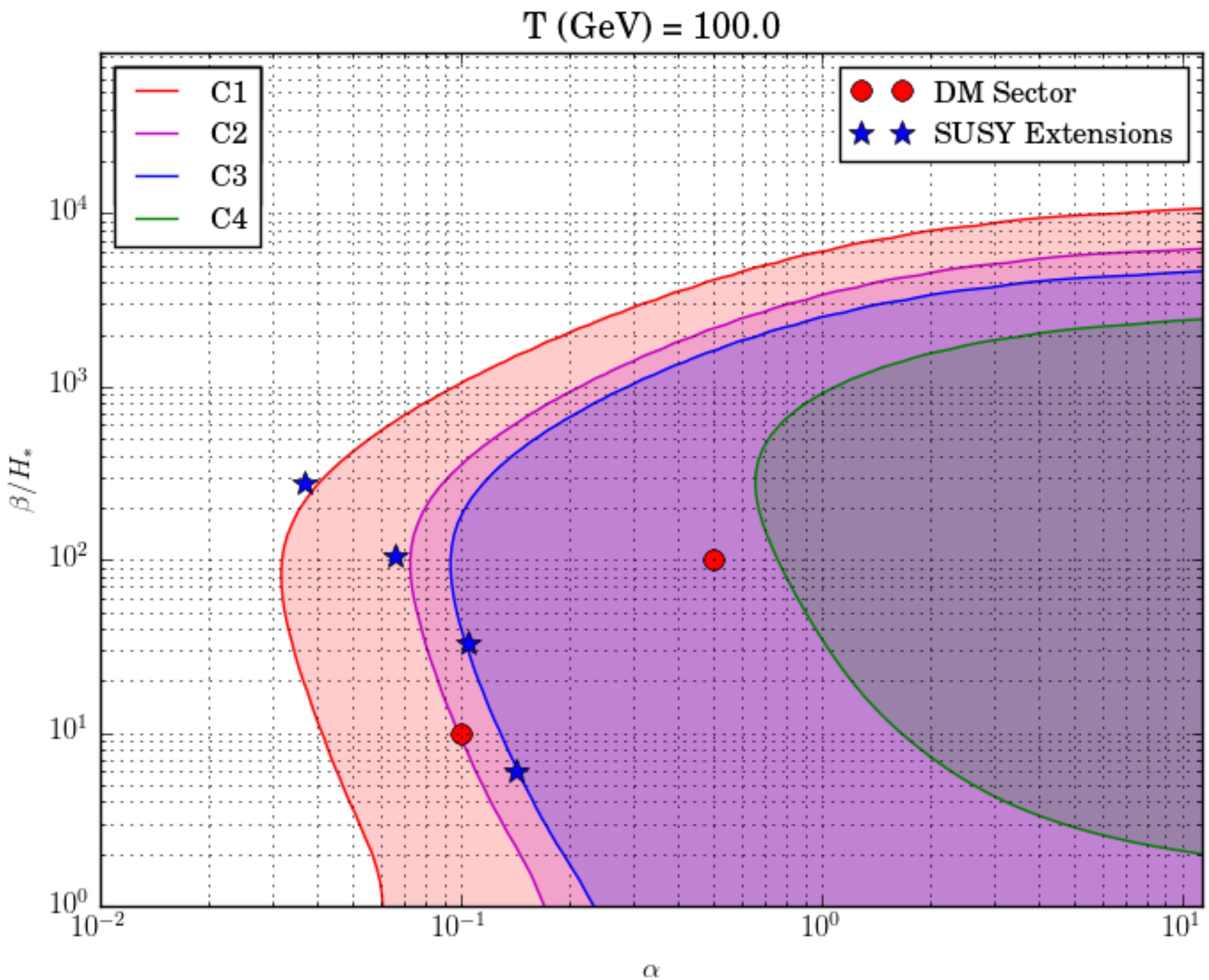


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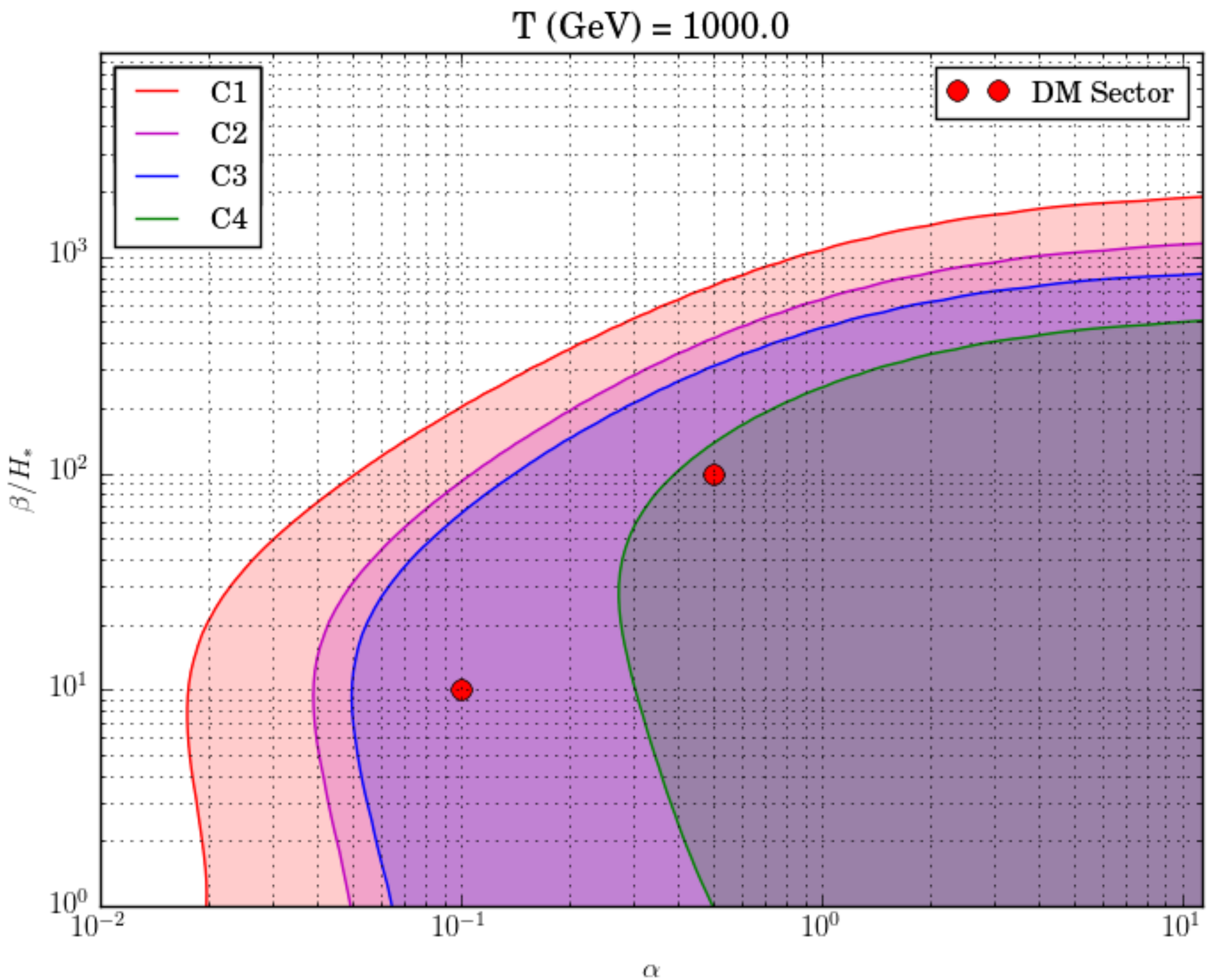


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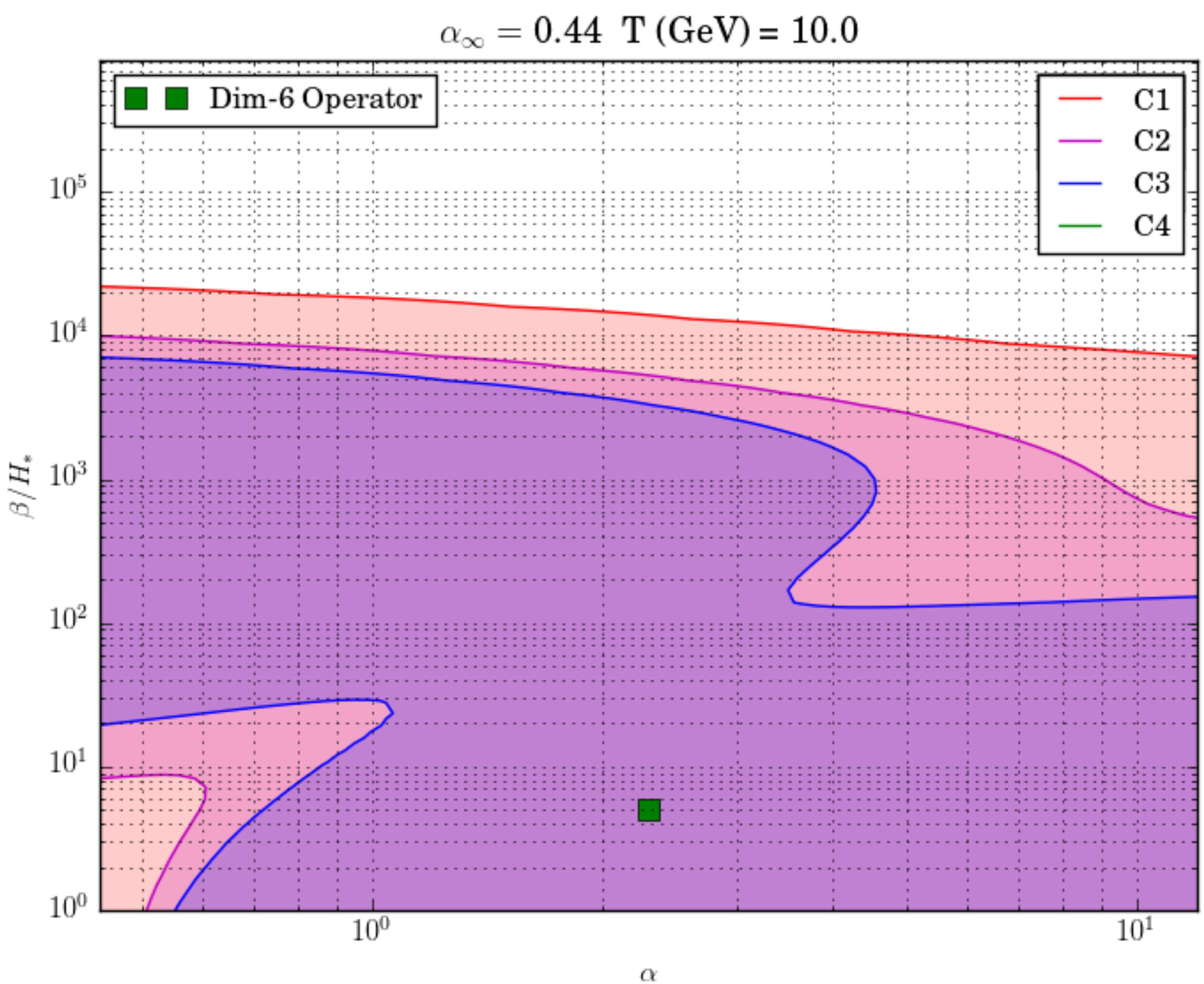


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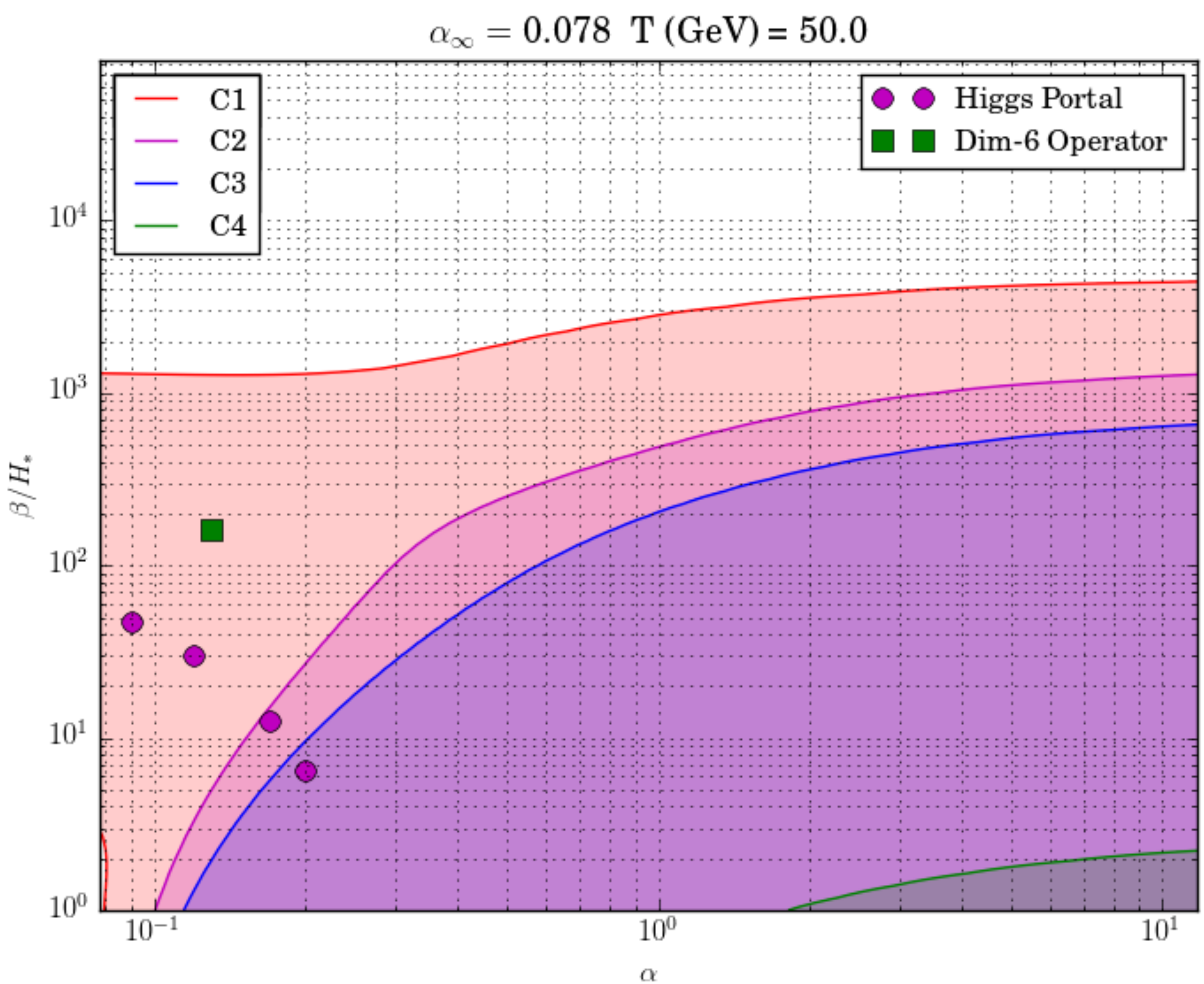
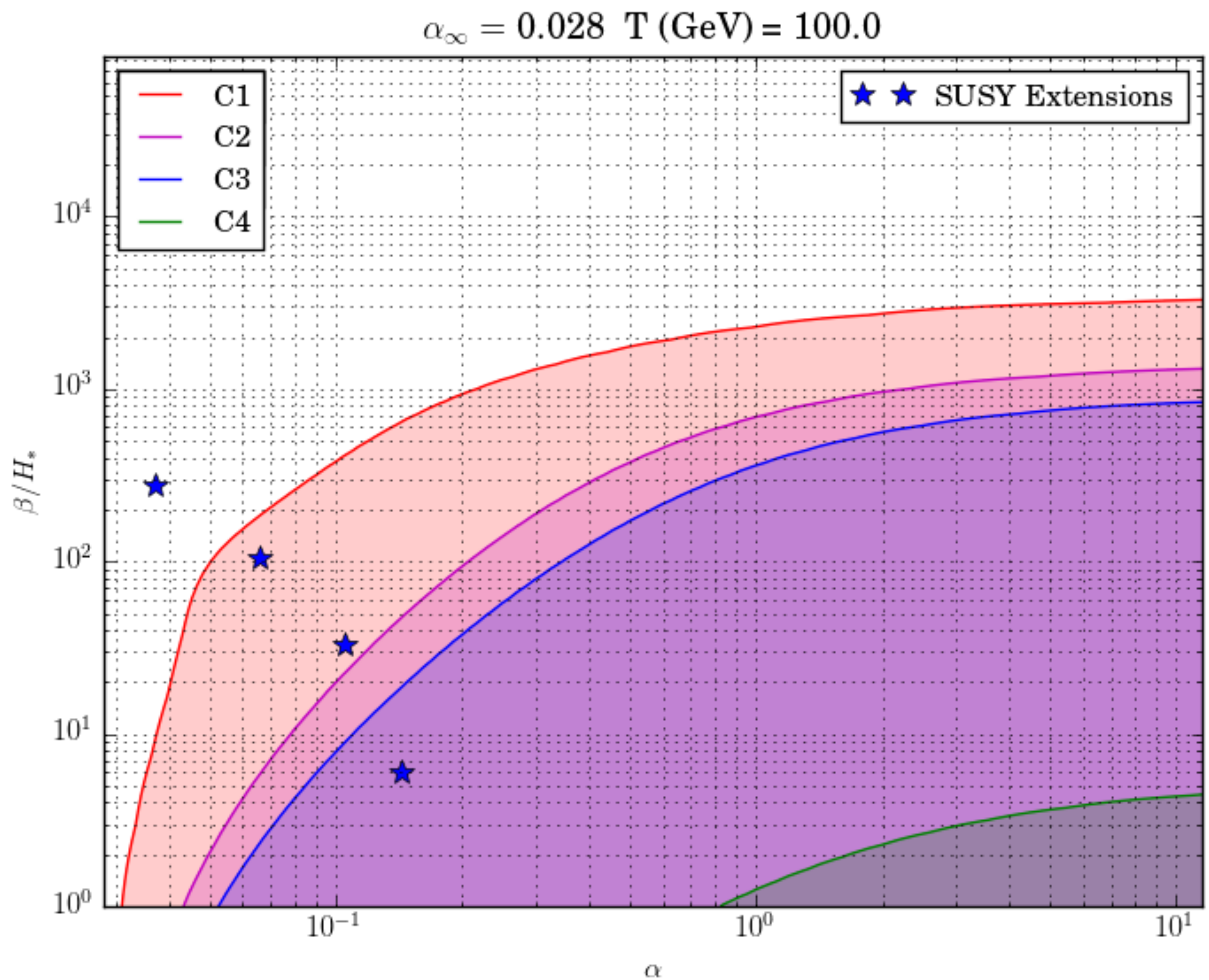


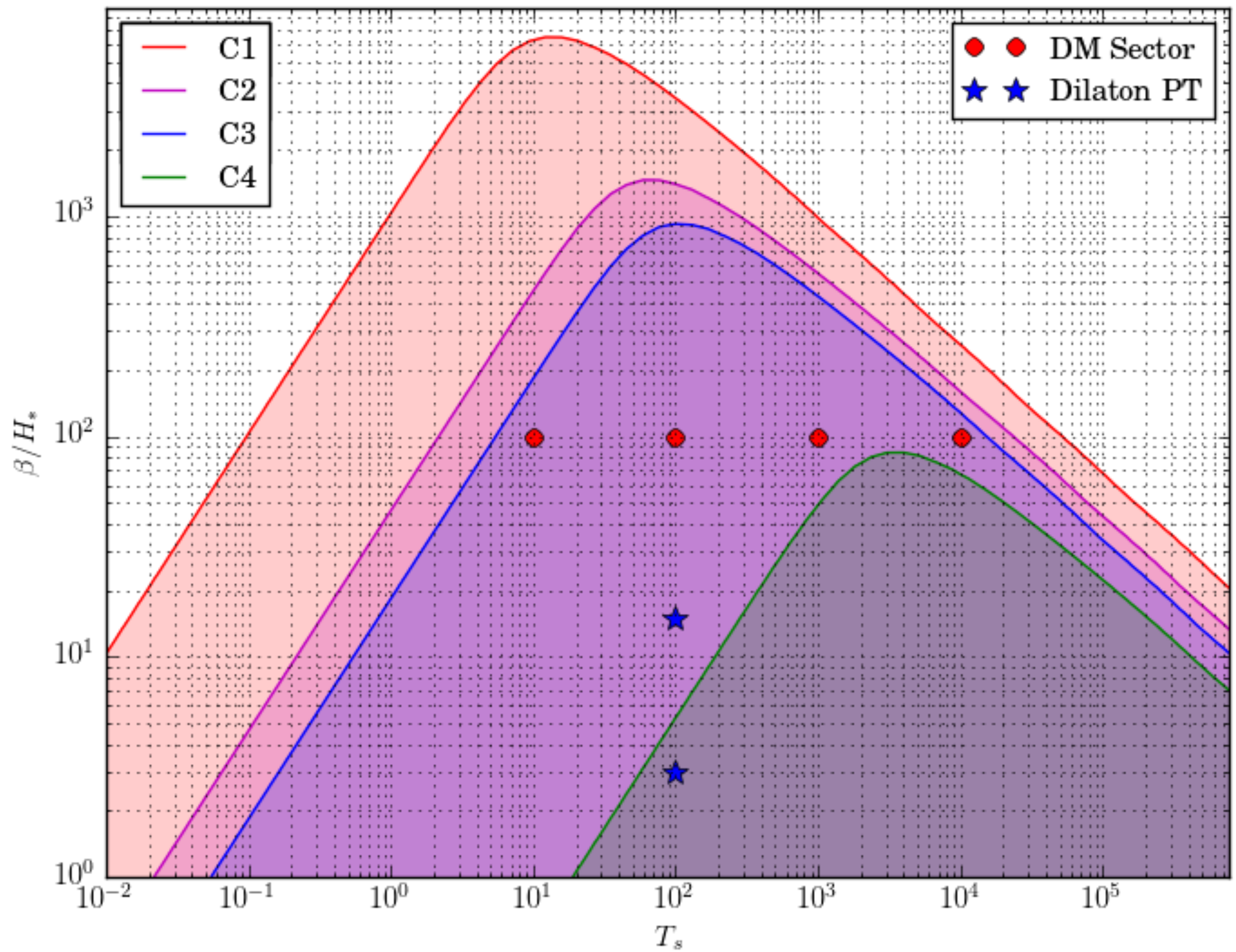

Caprini et al, 2015/2016 (LISA 1PhT working group)

# Detection prospects for LISA: runaway




Caprini et al, 2015/2016 (LISA 1PhT working group)

# Detection prospects for LISA: runaway in vacuum




Caprini et al, 2015/2016 (LISA 1PhT working group)

# What about
# Cosmic Defects ?

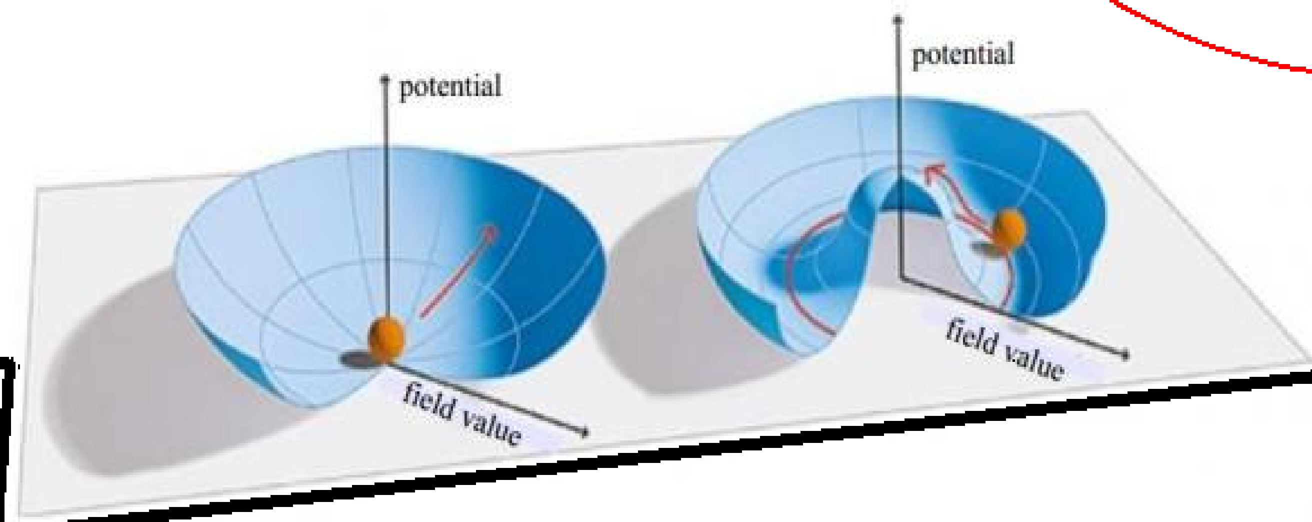
**(aftermath products of a PhT)**

## 0) Phase Transition ↔ Cosmic Defects (if conditions met)

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

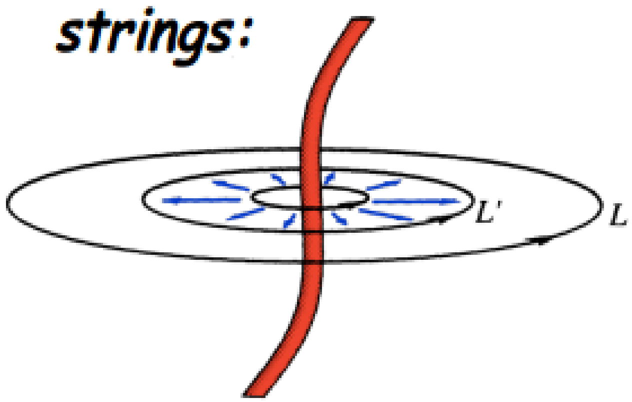
$$V = \frac{\lambda}{4}\left(|\Phi|^2 - v^2\right)^2 + V_{\rm int}(\Phi, \chi, T)$$

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

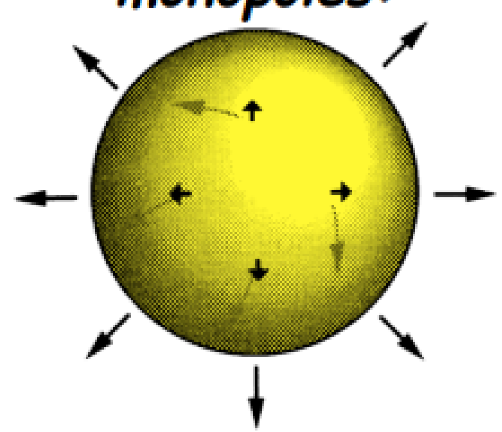



**ZOOLOGY:**

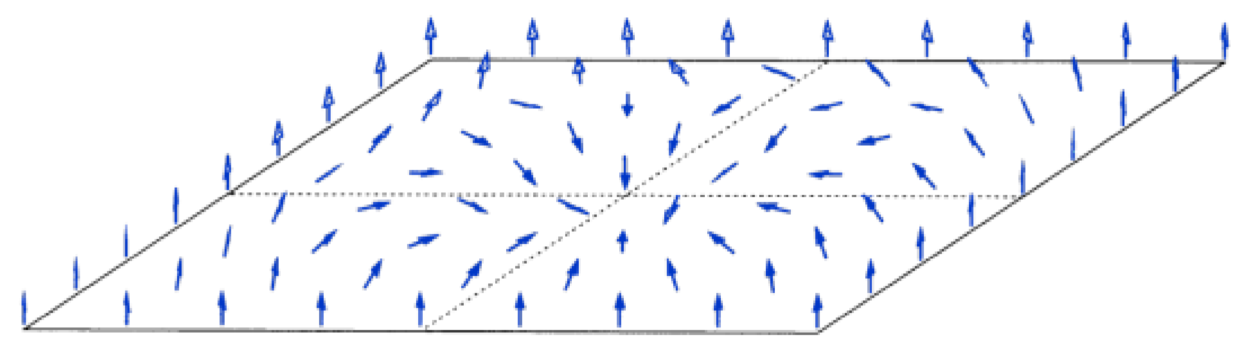
*strings:*




*monopoles:*



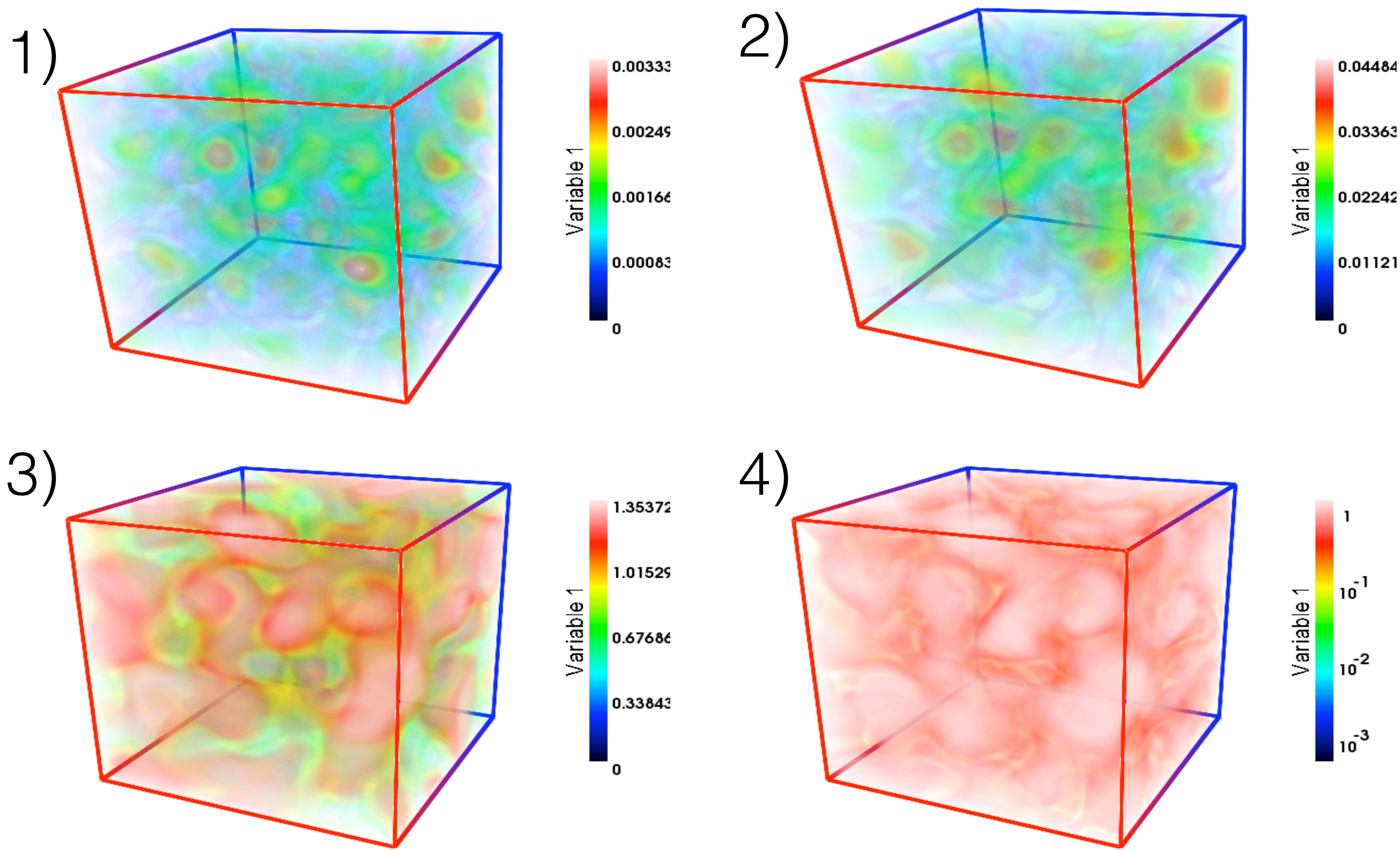
*texture:* (non-topological)



**MICRO-PHYSICS → COSMIC DEFECTS**

# 0) Phase Transition ↔ Cosmic Defects (if conditions met)

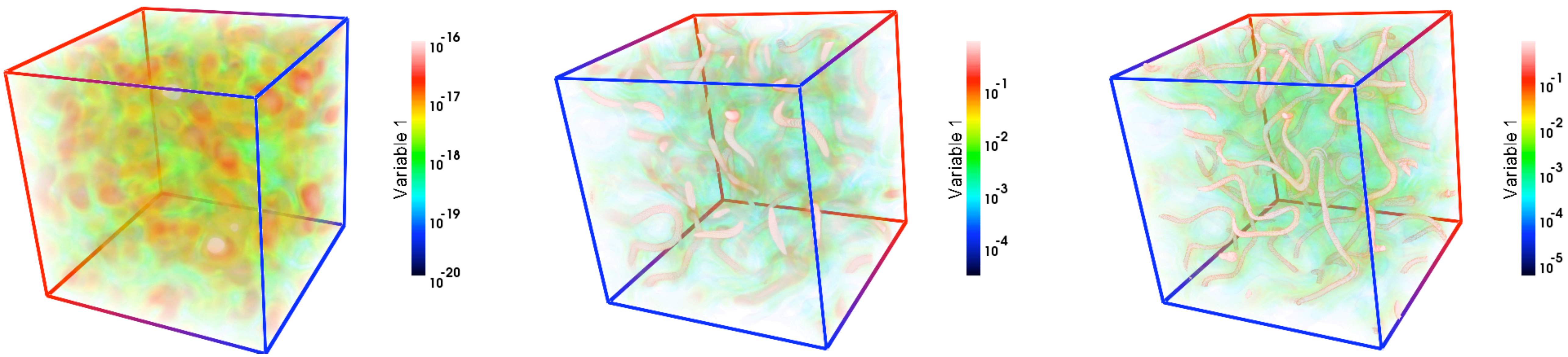
## U(1) Breaking (e.g. after Hybrid Inflation)




*Dufaux et al PRD 2010*

## 0) Phase Transition ↔ Cosmic Defects (if conditions met)

### U(1) Breaking (after Hybrid Inflation): Mag. Fields




*Dufaux et al PRD 2010*

# Theorem: GW from Evolution of Defect Networks

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

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

(Kibble' 76)

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

**Unequal Time Correlator (UTC)**

# Theorem: GW from Evolution of Defect Networks

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

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

**(Unequal Time Correlator)**

GW spectrum: Expansion UTC

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

**Comoving** **Conformal**

# Theorem: GW from Evolution of Defect Networks

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

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

**Rad. Dom**

**SCALING**

# Theorem: GW from Evolution of Defect Networks

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

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

Rad. Dom SCALING

# Theorem: GW from Evolution of Defect Networks

GW spectrum: $(x_i \equiv kt_i)$ R.D. and SCALING

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

# Theorem: GW from Evolution of Defect Networks

GW spectrum: $(x_i \equiv k t_i)$ R.D. and SCALING

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

$$\boxed{\frac{d\rho_{\rm GW}}{d\log k}(k,t) \propto \left(\frac{\rm V}{M_p}\right)^4 \frac{M_p^2}{a^4(t)}\, F_U}$$

$F_U \sim$ Const. (Dimensionless)

# Theorem: GW from Evolution of Defect Networks

VEV

Scaling @ RD

GW today:

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

Defect type

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

*(Figueroa et al, PRL 2013)*

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

*(Figueroa et al, PRL 2013)*

# More on GW from Defect Networks

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**What about Matt-Dom (MD) modes?**

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## What about Matt-Dom (MD) modes?

GW spectrum: Expansion UTC

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

**SCALING**

# More on GW from Defect Networks

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**Matt. Dom**

**SCALING**

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# What about Matt-Dom (MD) modes?

$$\boxed{(x_i \equiv k t_i)}$$

GW spectrum:

Expansion

UTC

$$\frac{d\rho_{\rm GW}}{d\log k}(k,t) \propto \left(\frac{v}{M_p}\right)^4 \frac{M_p}{k^2 a^4(t)}\left[\int_{x_{\rm eq}}^{x} dx_1 dx_2\ x_1^{\frac{3}{2}} x_2^{\frac{3}{2}}\ \cos(x_1 - x_2)\ U(x_1, x_2)\right]$$

**Matt. Dom**

**SCALING**

**Scale-Dependence !**

# More on GW from Defect Networks

Total GW Spectrum

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

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

RD

Scaling

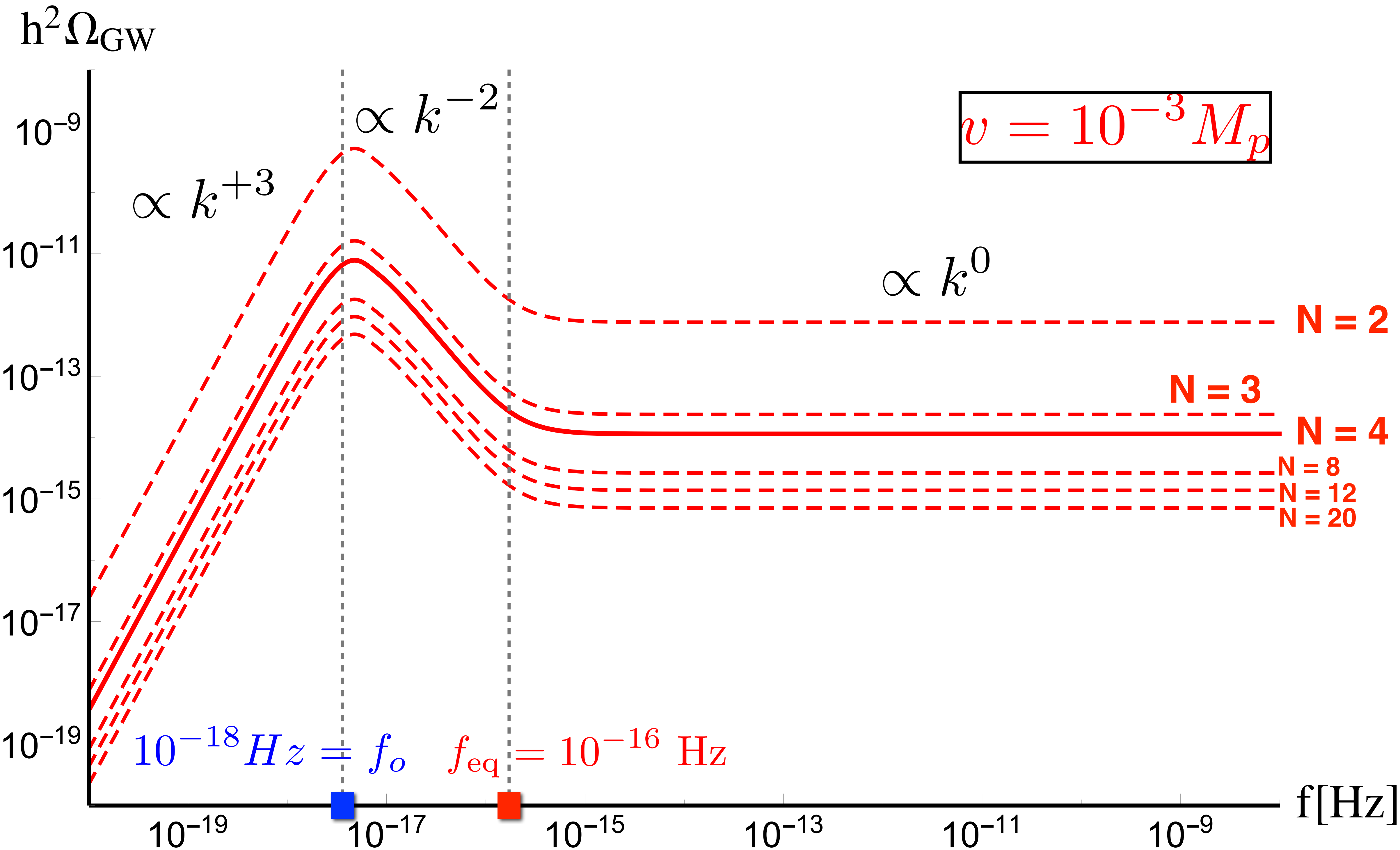
$$F_U^{(\rm M)} \equiv \frac{32}{3}\frac{(\sqrt{2}-1)^2}{2}\int_{x_{\rm eq}}^x dx_1 dx_2\,(x_1x_2)^{3/2}\cos(x_1-x_2)\,U_{\rm MD}(x_1,x_2)$$

MD

Scaling

# More on GW from Defect Networks

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



# More on GW from Defect Networks

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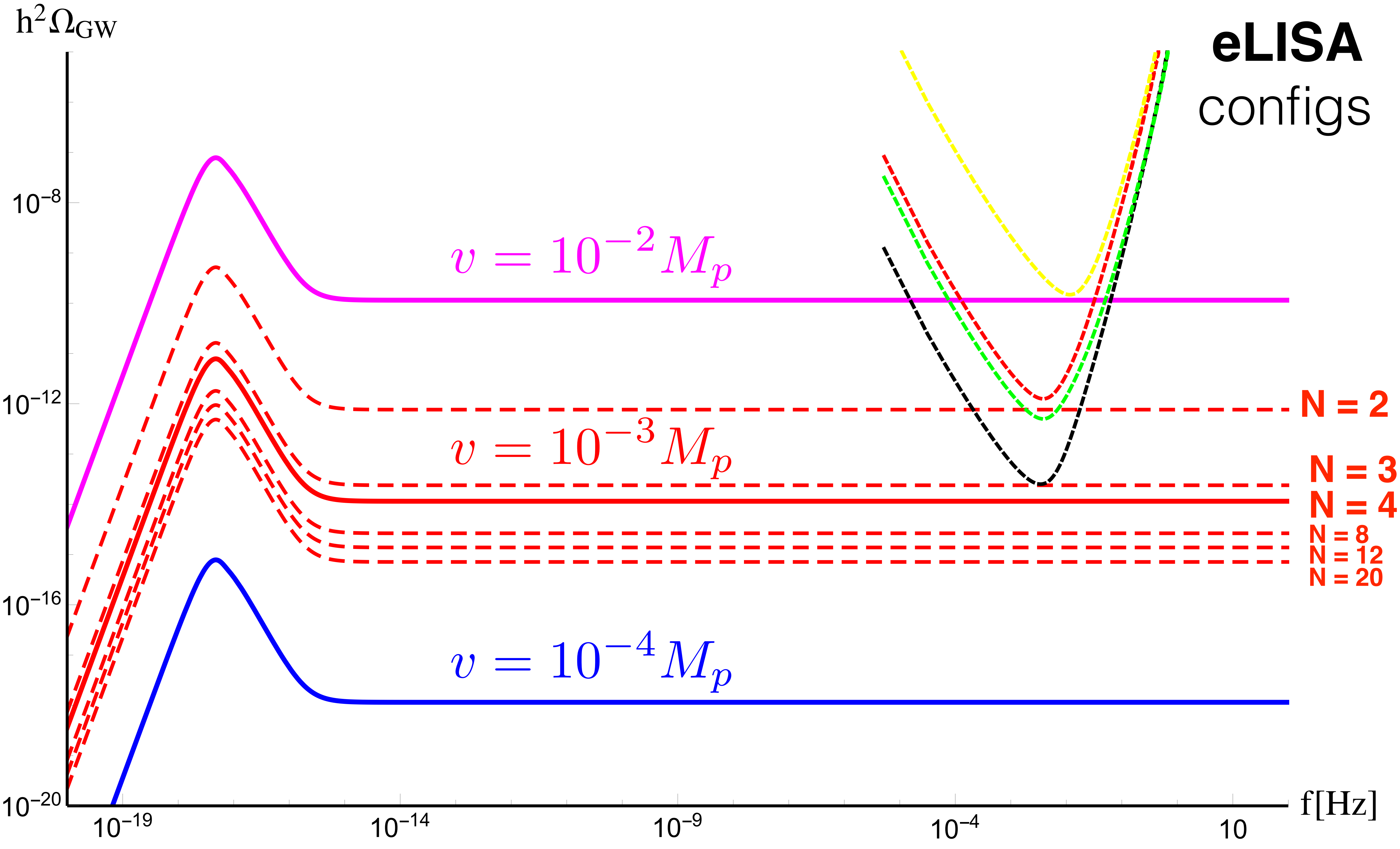
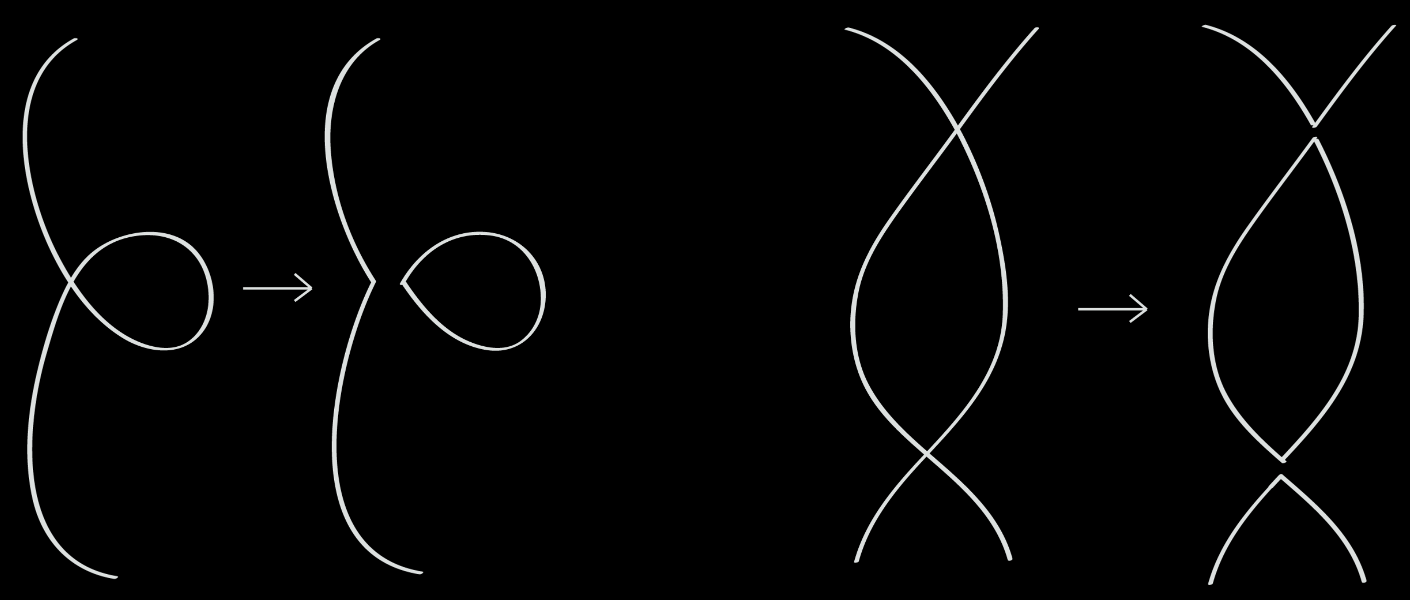


# What about if Defects are Cosmic Strings ?

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

A cosmic string network formed by:
1) 'Infinite' long cosmic strings
2) (subhorizon)Cosmic string loops

Intercommutation !



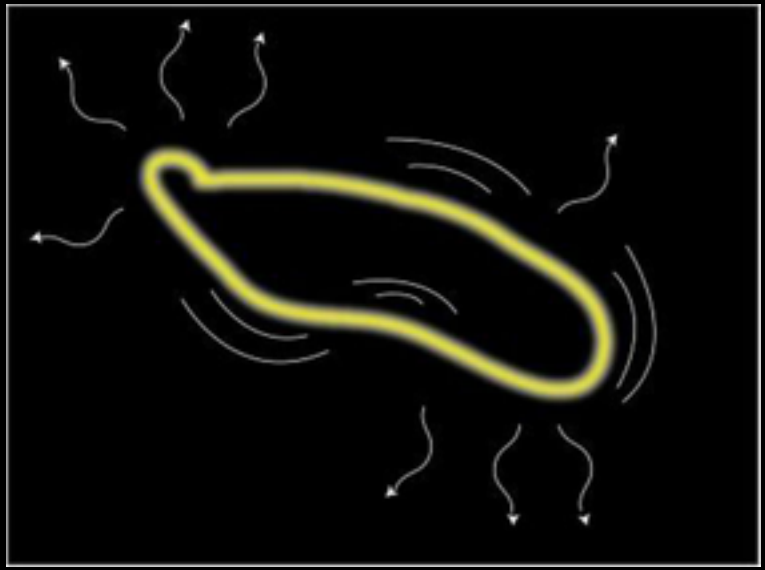
Cosmic strings: $p = 1$

Cosmic superstrings: $p \in [10^{-3}, 1]$

# What about if Defects are Cosmic Strings ?

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

Loops once formed, decay by radiation emission



$\longrightarrow$

* GW emission
* Boson emission
* UHCR
* …

*** Widely believed that GW represents dominant emission channel (Nambu-Goto)**

*** However… Abelian-Higgs field theory simulations show loops decay into bosons**

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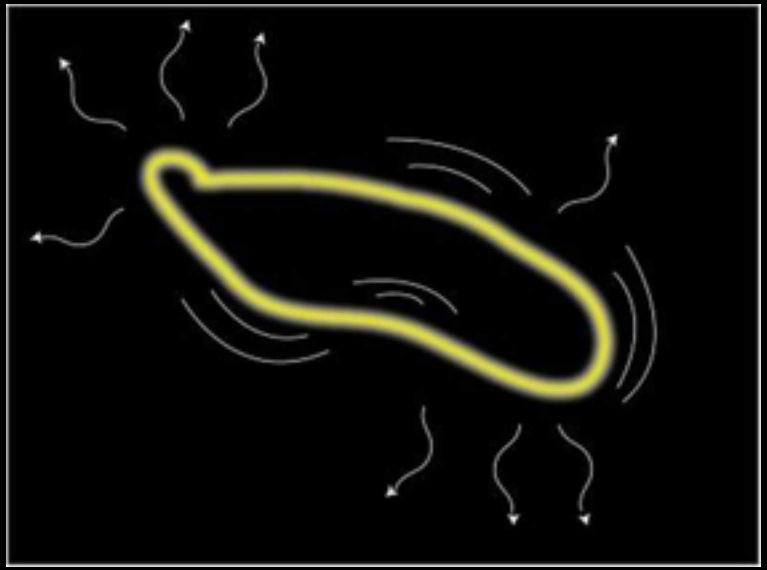
**Extra emission of GWs !** (Vilenkin '81)

Loops once formed, decay by radiation emission



$\longrightarrow$
* GW emission
* Boson emission
* UHCR
* …

**Assuming GW emission dominates …**

Given a loop number density $n(\ell, t)$

$$\Omega_{\rm gw}(f) = \frac{2G\mu^2 c^3}{\rho_{\rm crit} a^5(t_0) f} \sum_{j=1}^{\infty} j P_j \int_{t_{\rm f}}^{t_0} a^5(t') n_j(f, t') dt'$$

# What about if Defects are Cosmic Strings ?

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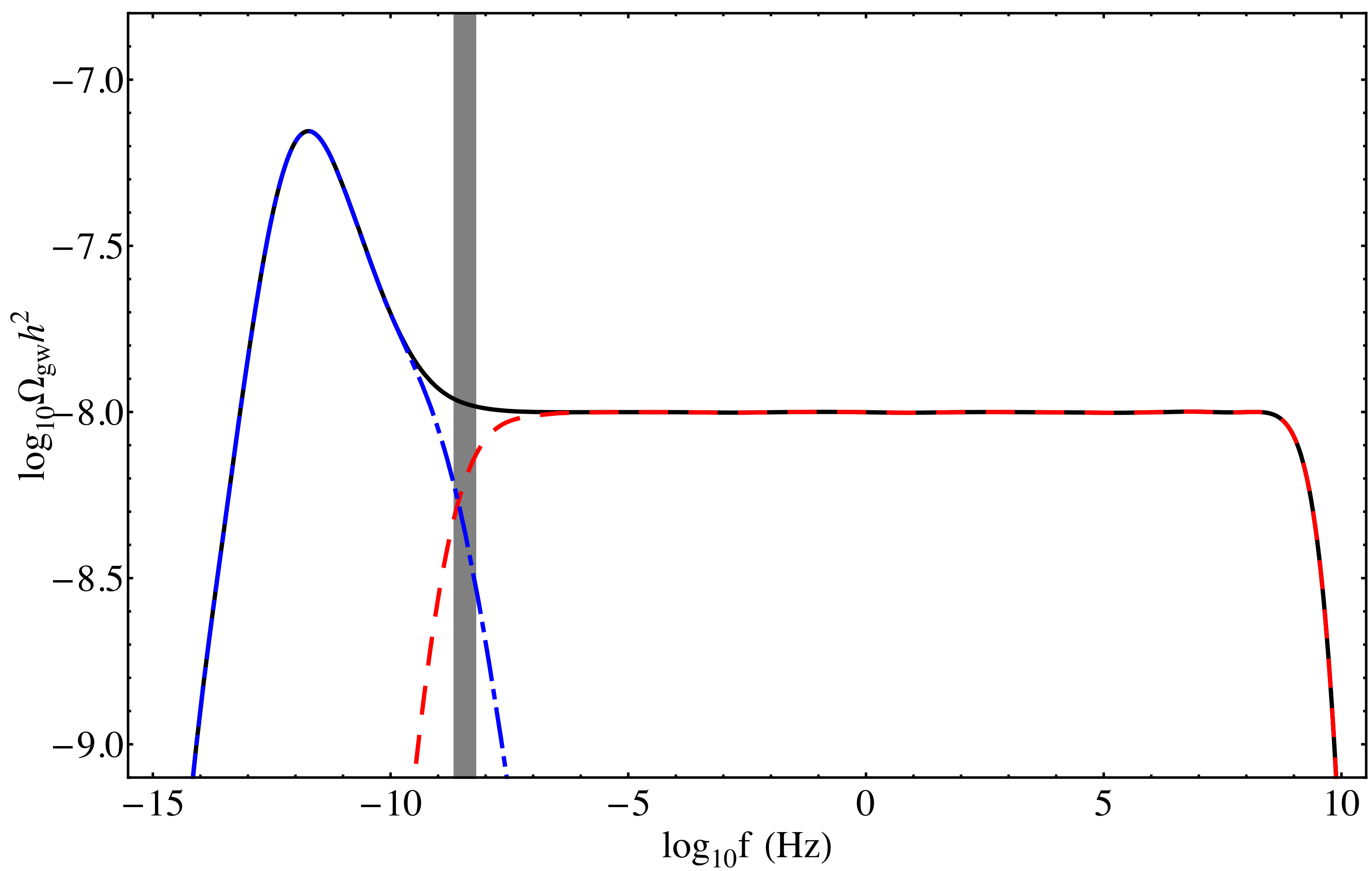


Sanidas et al 2012

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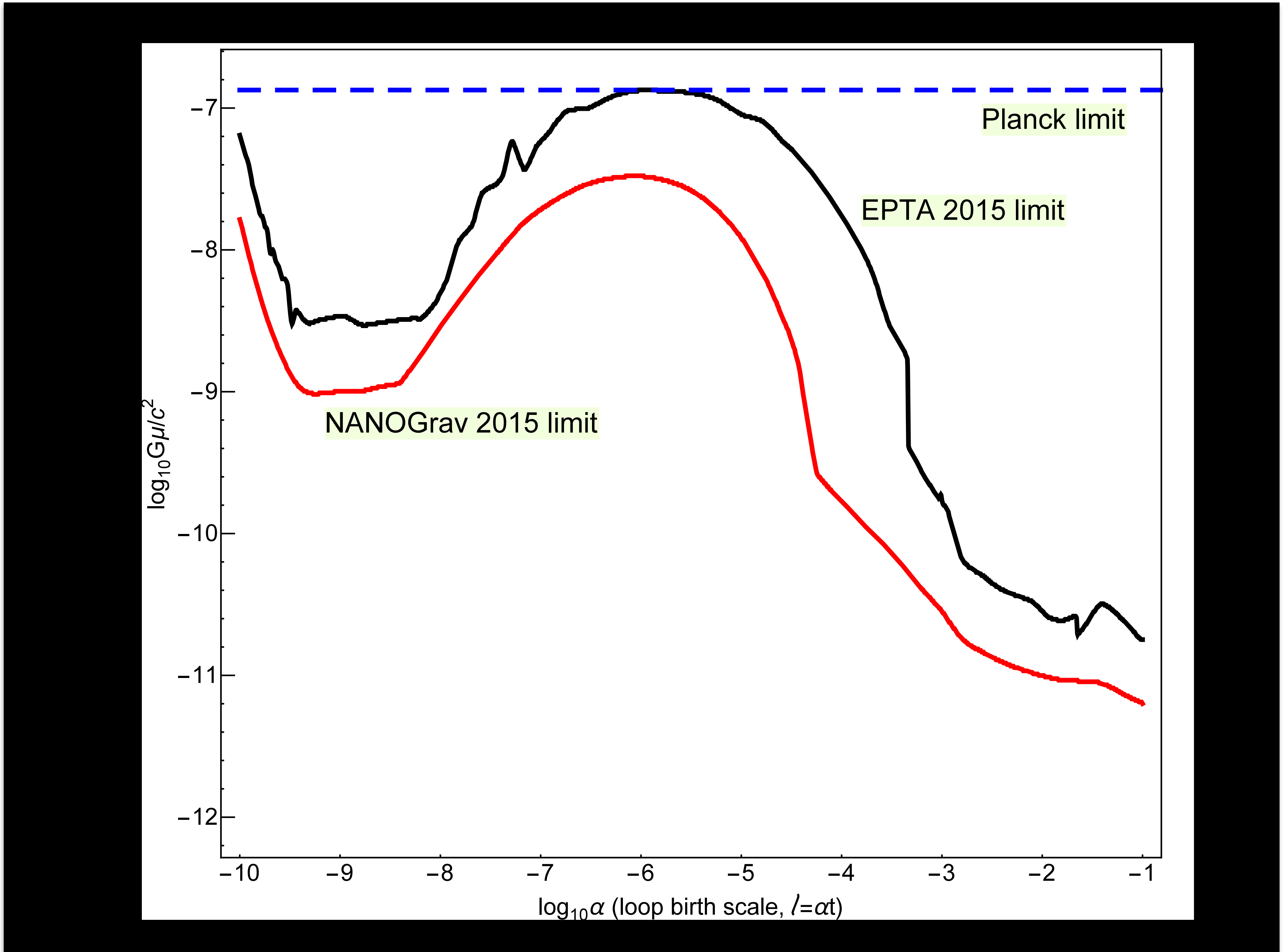


(From Sanidas et al,LISA GW cosmology 3rd encounter)

# What about if Defects are Cosmic Strings ?

## Extra emission of GWs !

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: $G\mu/c^2 < 4.4 \times 10^{-18}$ $\rightarrow$ $\boxed{v \lesssim 10^{10} GeV}$

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

# 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 ✓

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complicated, but robust

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Intensive search at the CMB

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High amplitude, unlike detection

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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, If large loops present]

# Coming Soon …

*** Caprini & Figueroa, REVIEW (**expected Feb 2017**)**

*** Benasque GW school (2 weeks): May 28 - June 10**

http://benasque.org/2017gw/

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# Thanks for your attention !