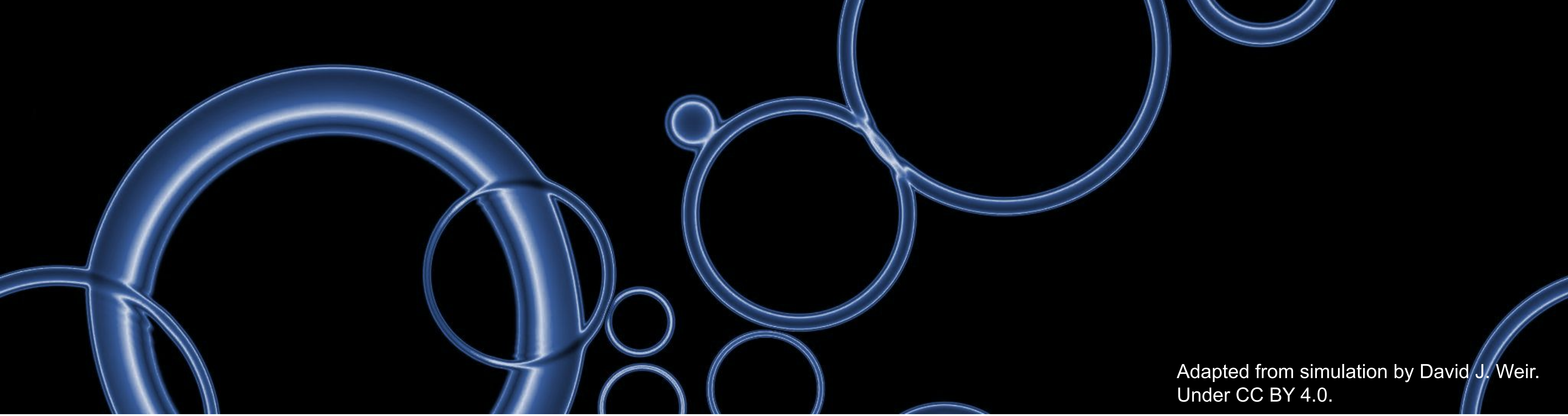


From bubbles to ripples: probing the Higgs phase structure through gravitational waves

14th Iberian Gravitational Waves Meeting · CIEMAT | June 23rd 2025

Luis Gil (Universidad de Granada)

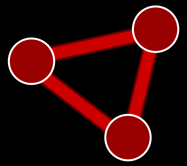
High Energy Theory

Junta de Andalucía

GOBIERNO DE ESPAÑA

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

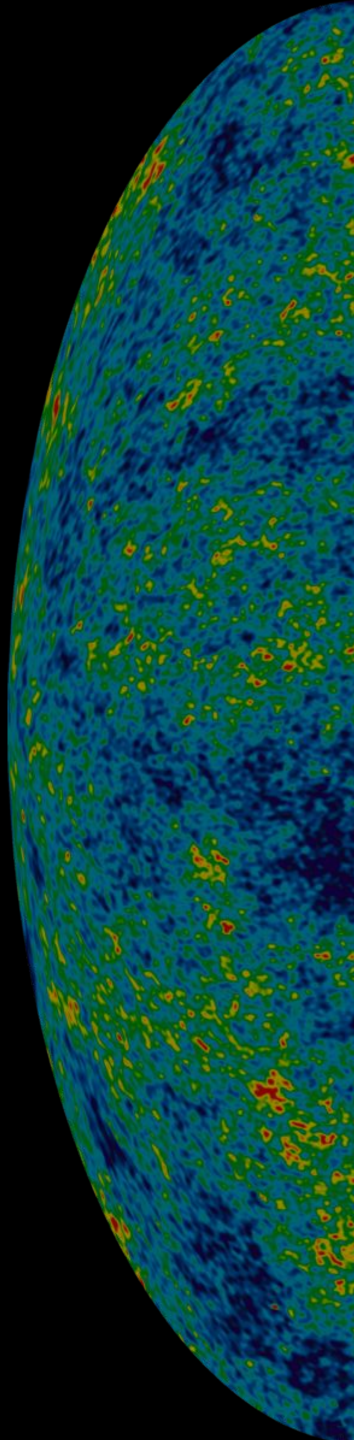
The search for *new physics* in the early universe

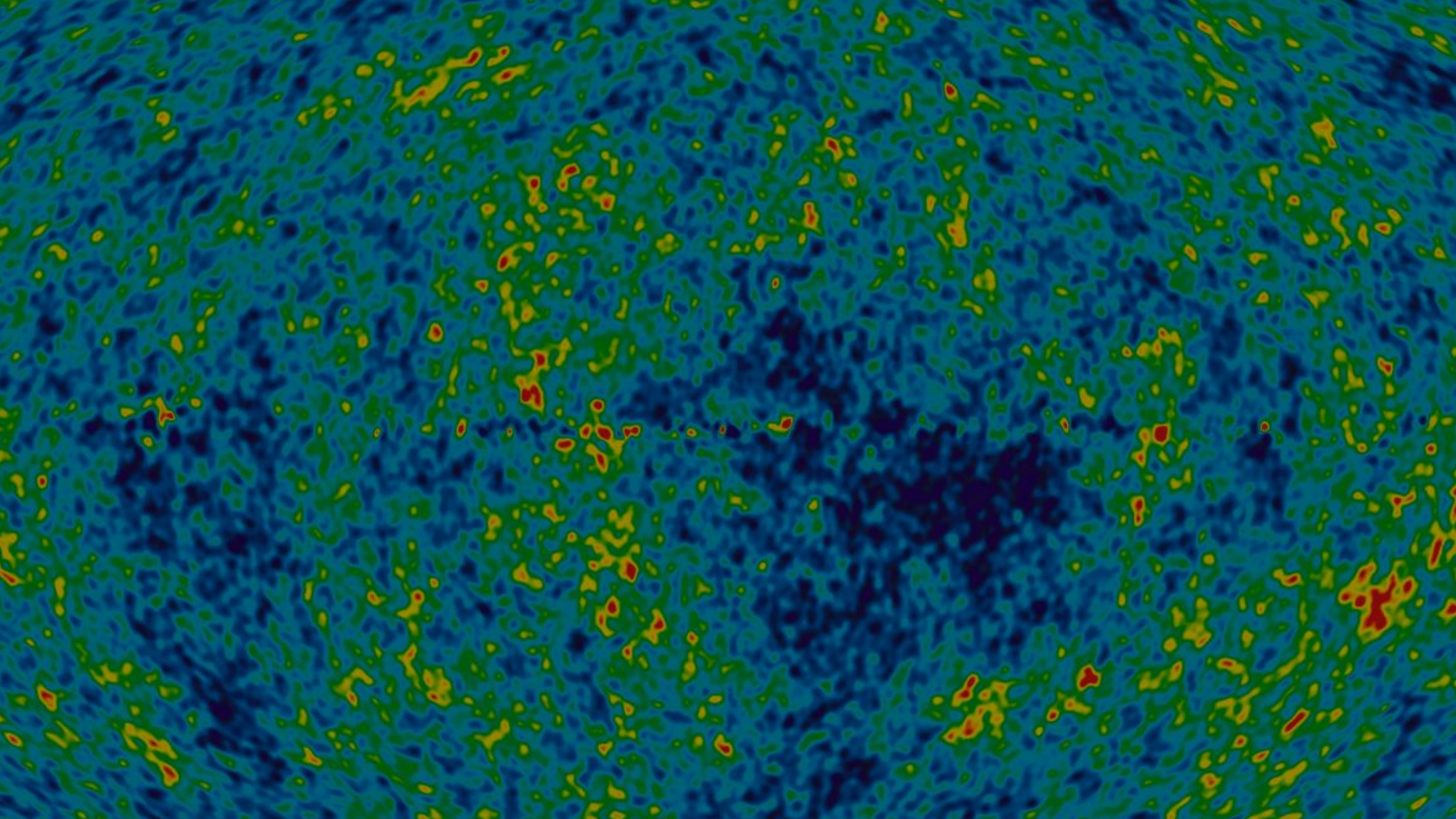


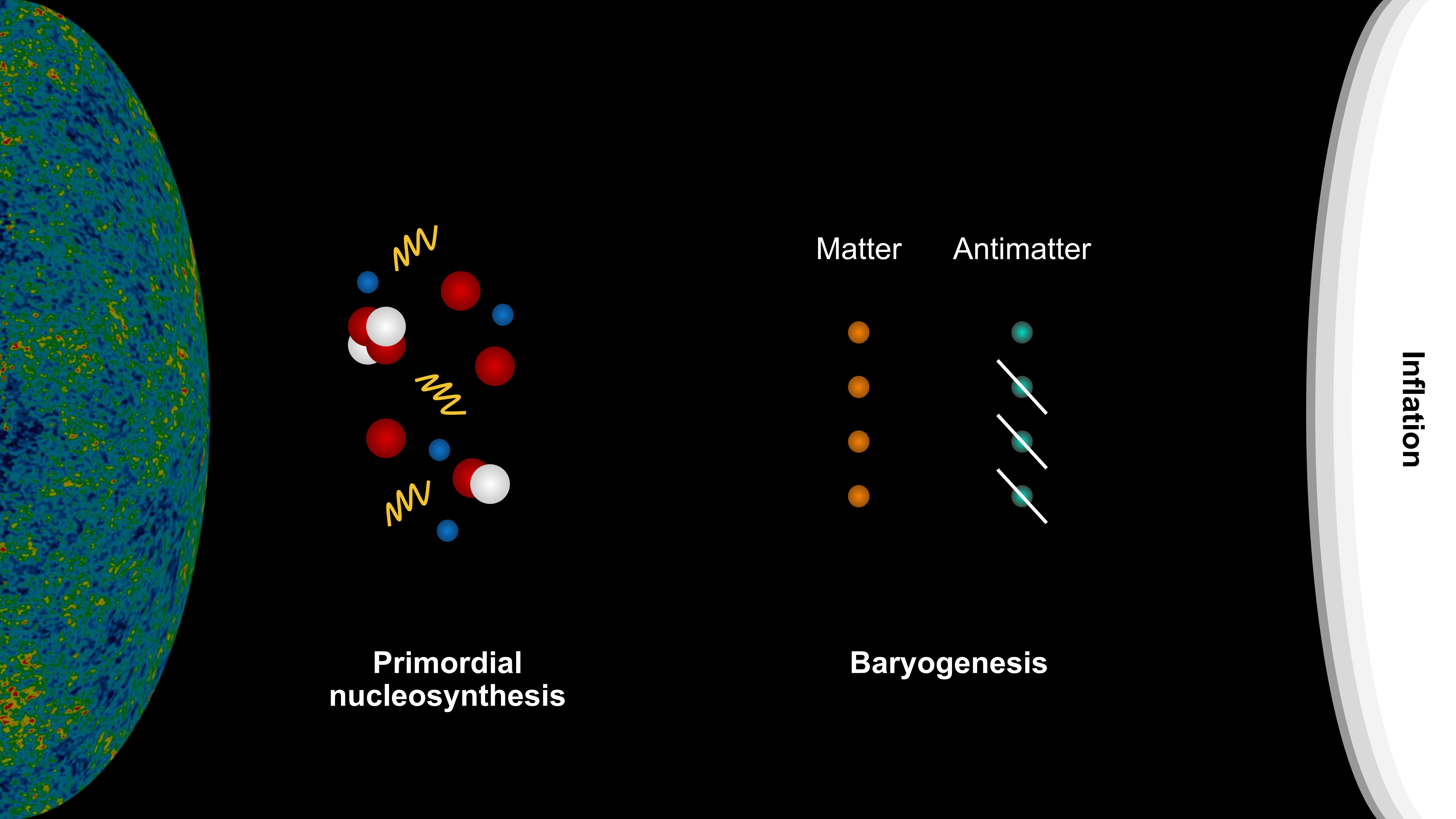
Colliders

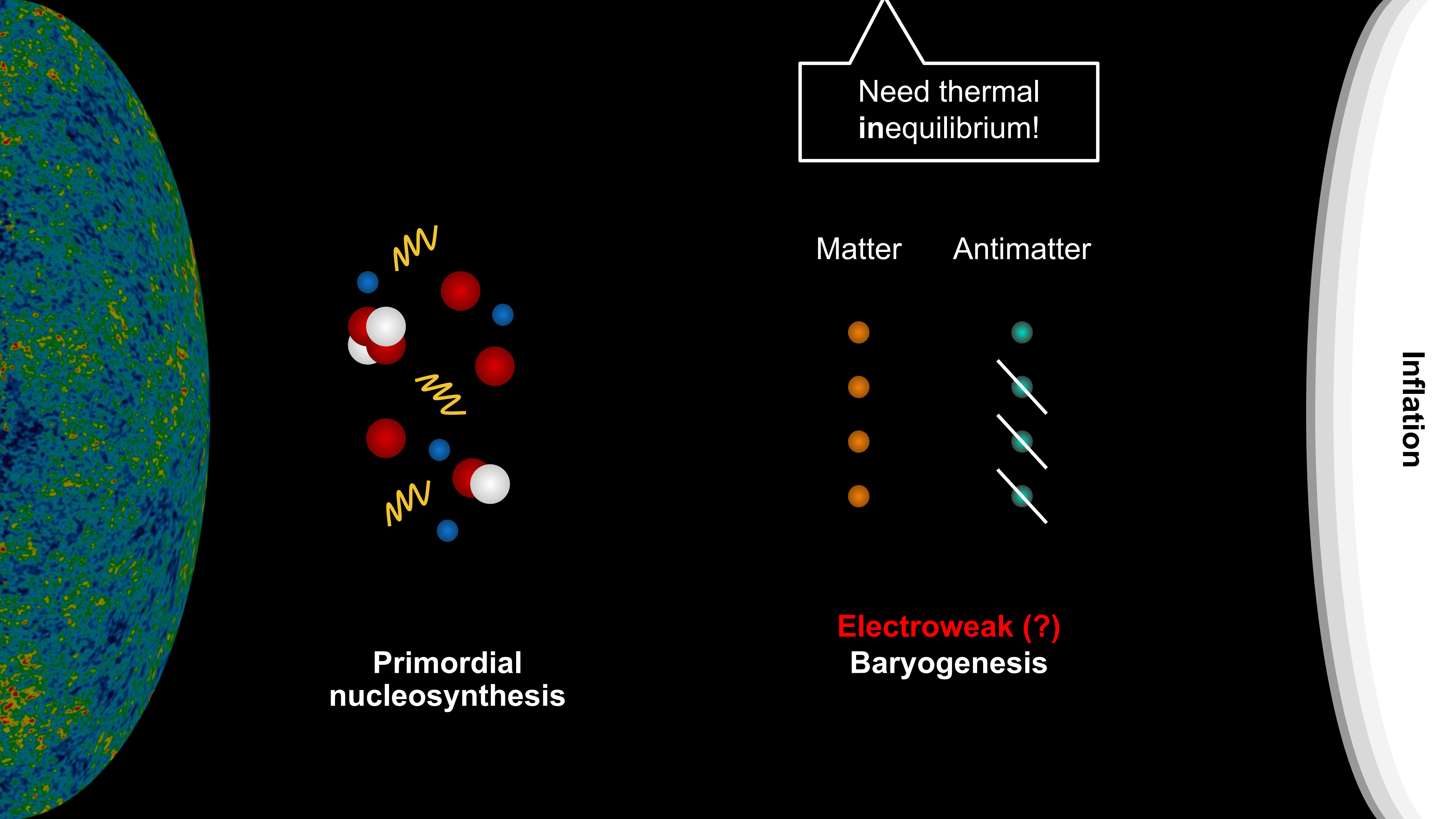
Cosmic rays

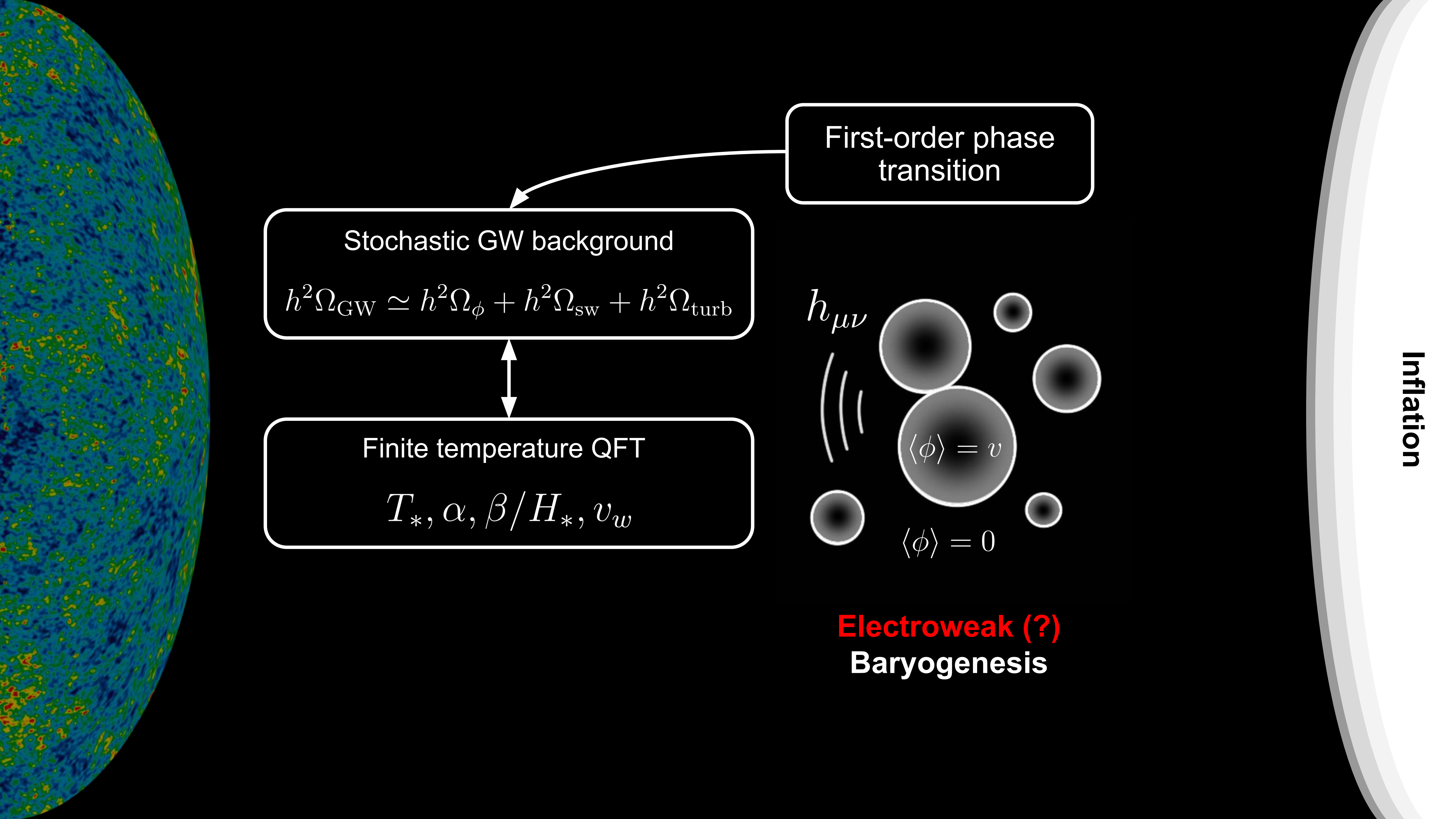
Cosmic Microwave Background



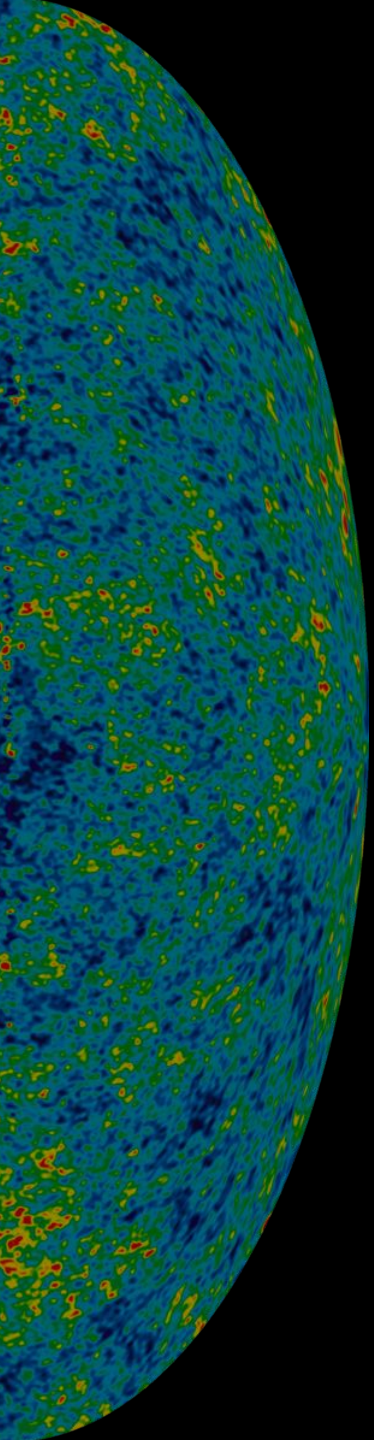



Matter
Antimatter
Primordial nucleosynthesis
Baryogenesis
Inflation


Need thermal
inequilibrium!
Matter
Antimatter
Inflation
Primordial
nucleosynthesis
Electroweak (?)
Baryogenesis



First-order phase transition
Stochastic GW background
$h^2\Omega_{\rm GW} \simeq h^2\Omega_\phi + h^2\Omega_{\rm sw} + h^2\Omega_{\rm turb}$
Finite temperature QFT
$T_*, \alpha, \beta/H_*, v_w$
$h_{\mu\nu}$
$\langle\phi\rangle = v$
$\langle\phi\rangle = 0$
Electroweak (?)
Baryogenesis
Inflation



In this talk, I will address **two** fundamental questions:

What is the electroweak phase transition?

What are the GW sources in a cosmological PT?

Inflation

What is the electroweak PT?

QFT at finite temperature

- In the very early universe, temperature effects were not negligible ($T \gg m_i$)

Temperature is a coarse-grained description of a background of many interactions

- In this context, we use **quantum field theory at finite temperature**. Physics of thermal equilibrium is described in the **imaginary time formalism:**

$$\mathcal{Z}_{\mathrm{th}} = \mathrm{Tr}\left(e^{-\beta\mathcal{H}}\right) = \sum_q \langle q\ 0|e^{-\beta\mathcal{H}}|q\ 0\rangle = \mathcal{N}\int_{q(0)=q(-i\beta)} \mathcal{D}q \exp\left(-S_E\right)$$

QFT at finite temperature $\longleftrightarrow$ Euclidean QFT with periodic time (radius = 1/T)

What is the electroweak PT?

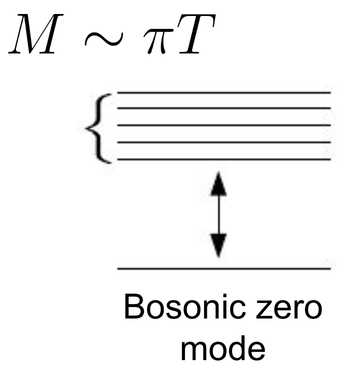
3D EFTs

- Fields decompose in towers of 3D **Matsubara modes** with thermal masses:

Bosons: $$\omega_n = 2\pi n T$$

Fermions: $$\omega'_n = 2\pi\left(n + \frac{1}{2}\right)T$$

$\Rightarrow$



$\Rightarrow$

3D Effective field theory
for bosonic zero modes

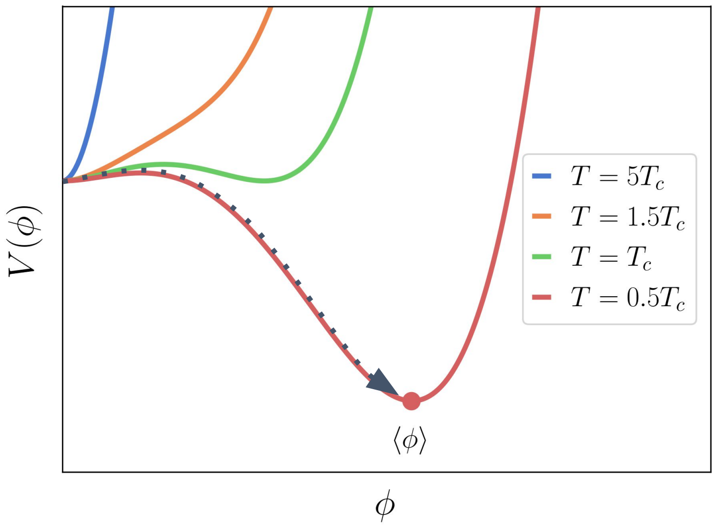
We can study the onset of cosmological phase transitions using a simple 3D theory where only bosons are present!

What is the electroweak PT?

Phase transitions

- The parameters in the effective Lagrangian **encode all temperature-dependence**:

$$V(\phi) = m^2\phi^2 + \kappa\phi^3 + \lambda\phi^4 \to V(\varphi;T) = (m^2 + \#\lambda T^2)\varphi^2 + \kappa\sqrt{T}\varphi^3 + \lambda T\varphi^4$$



Below the **critical temperature**, there exists a non-zero transition rate between vacua.

➔ A scalar can spontaneously acquire a new vacuum expectation value (phase transition)

➔ For the Higgs, it marked the **electroweak phase transition**, when SM fields acquired their masses

What is the electroweak PT?

Electroweak phase transition

- **What type** was the EWPT?

First-order	**Crossover**
• Jump in **free energy** and **Higgs condensate** between phases $\Delta\langle\phi^\dagger\phi\rangle$ • Latent heat is released	• Smooth transition between phases • No energy released

Studied combining:

a) perturbative (analytical)
b) lattice (numerical)

within the 3D EFT of the EW sector.

$$\mathscr{L}_3 = \frac{1}{4}F^a_{ij}F^a_{ij} + D_i\phi^\dagger D_i\phi + (m_3^2 + \delta m_3^2)\phi^\dagger\phi + \lambda_3(\phi^\dagger\phi)^2$$

What is the electroweak PT?

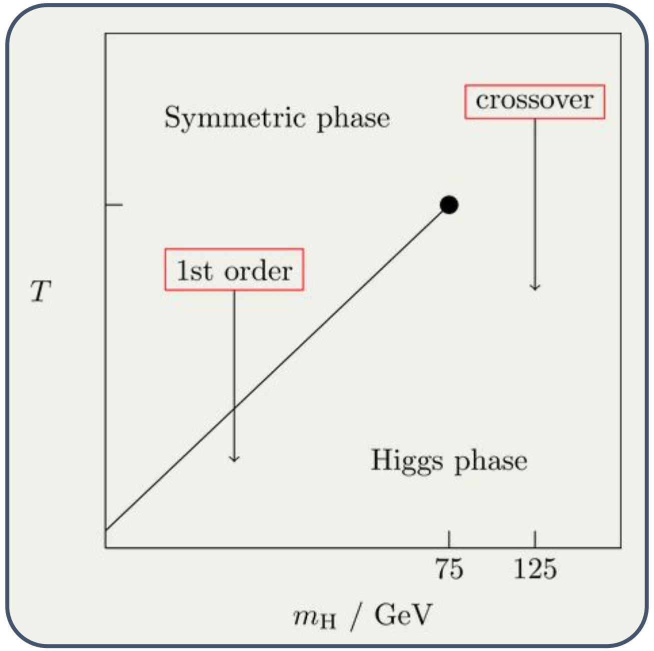
Electroweak phase transition

[Kajantie et al. - hep-ph/9605288]
[Gürtler et al. - hep-lat/9704013]
[Csikor et al. - hep-ph/9809291]

- **What type** was the EWPT?

First-order	Crossover
• Jump in **free energy** and **Higgs condensate** between phases $$\Delta\langle\phi^\dagger\phi\rangle$$ • Latent heat is released	• Smooth transition between phases • No energy released

SM predicts a **crossover :(**



What is the electroweak PT?

Electroweak phase transition

- **What type** was the EWPT?

First-order

- Jump in **free energy** and **Higgs condensate** between phases

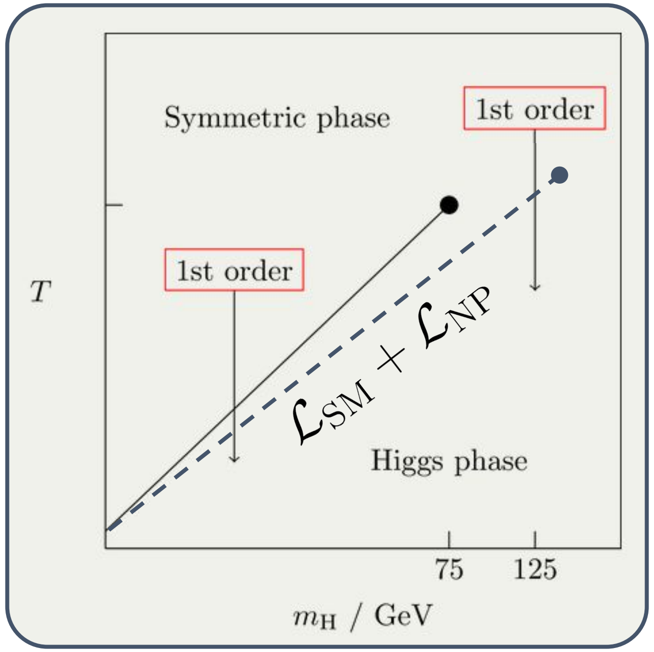
$$\Delta\langle\phi^\dagger\phi\rangle$$

- Latent heat is released

Crossover

- Smooth transition between phases
- No energy released

New physics allows for a **FOPT :)**



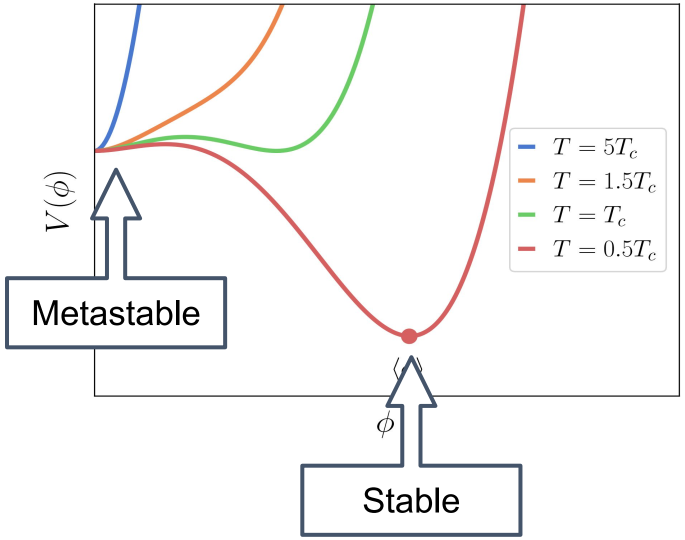
What are the GW sources in a PT?

Bubble nucleation

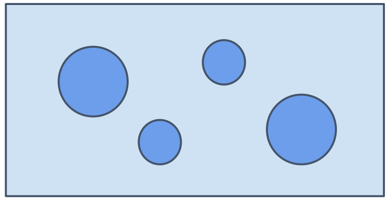
Microscopic scale

Key magnitude: Transition rate

How: QFT at finite T



- The PT proceeds through the nucleation of *bubbles* of true vacuum within the false vacuum (~ droplets in supercooled vapor)



- Equilibrium magnitudes can be computed at this stage:

Nucleation temperature	Strength parameter	Inverse duration
$\mathscr{P} \sim e^{-S_3[\varphi_c]}\Big\vert_{T=T_*} \sim 1$	$\alpha \sim \dfrac{V_3(\varphi_T)}{T_*^3}$	$\dfrac{\beta}{H_*} = T\dfrac{dS_3[\varphi_c]}{dT}\Big\vert_{T=T_*}$

What are the GW sources in a PT?

[Ekstedt et al. (WallGo) - 2411.04970]

Bubble expansion

Mesoscopic scale **Key magnitude:** Wall velocity **How:** Coupled differential equations

- To describe the expansion of bubbles (Higgs field configuration), one must solve the EoM for the **coupled scalar-plasma** system:

$$\partial_\mu \partial^\mu \phi \underbrace{- V'(\phi)}_{\text{driving force}} + \underbrace{\sum_i \frac{dm_i^2}{d\phi} \int \frac{d^3p}{(2\pi)^3 2E_i} f_i(p,x)}_{\text{friction force}} = 0 \quad \textbf{and} \quad \underbrace{\partial_\mu \left(T^{\mu\nu}_{\text{plasma}} + T^{\mu\nu}_{\phi} \right) = 0}_{\text{boundary conditions}}$$

where one accounts for:

i) Out-of-equil. Boltzmann equations

ii) Non-homogeneous scalar configuration

iii) Scalar field-dependent masses

iv) Reheating in wall front

What are the GW sources in a PT?

Bubble dynamics

Macroscopic scale

Key magnitude: GW spectrum

How: Rel. hydrodynamic simulations

Three processes are involved in the production of GWs during a FOPT:

1) **Collisions of bubble walls** and shocks in the plasma $\Longrightarrow$ **Negligible**
2) **Sound waves in the plasma** after bubble collision $\Longrightarrow$ **Most relevant**
3) **Magnetohydrodynamic turbulence** in the plasma $\Longrightarrow$ **Not very well understood**

$h^2\Omega_{\rm GW}$ and $f_{\rm peak}$ show different parametric dependencies in different simulated models

Relevant parameters: $T_*, \alpha, \beta/H_*, g_*, c_s, v_w, \ldots$

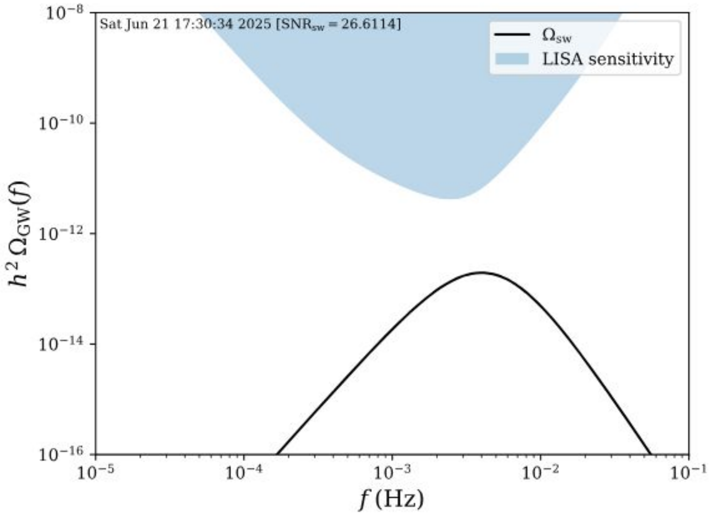
What are the GW sources in a PT?

Bubble dynamics

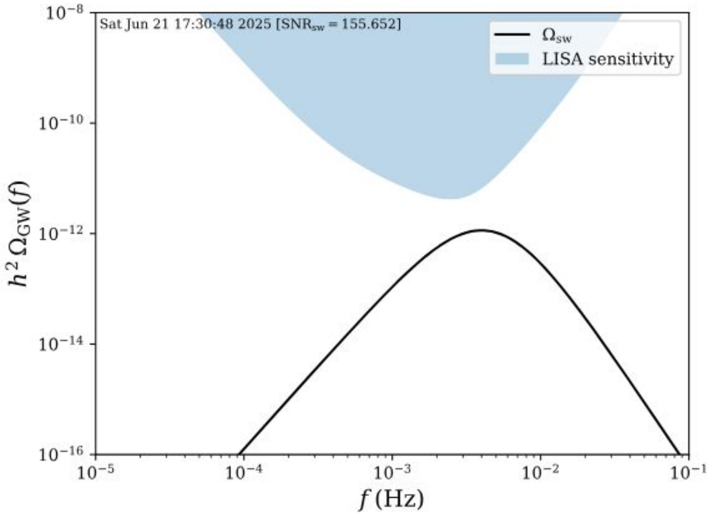
Macroscopic scale **Key magnitude:** GW spectrum **How:** Relativistic hydrodynamics

- GW production is **highly sensitive** to microscopic magnitudes. They must therefore be computed with high accuracy from QFT at finite temperature

$\alpha = 0.1$



$\alpha = 0.2$



NNLO corrections are instrumental in stronger transitions (most likely to be observed)

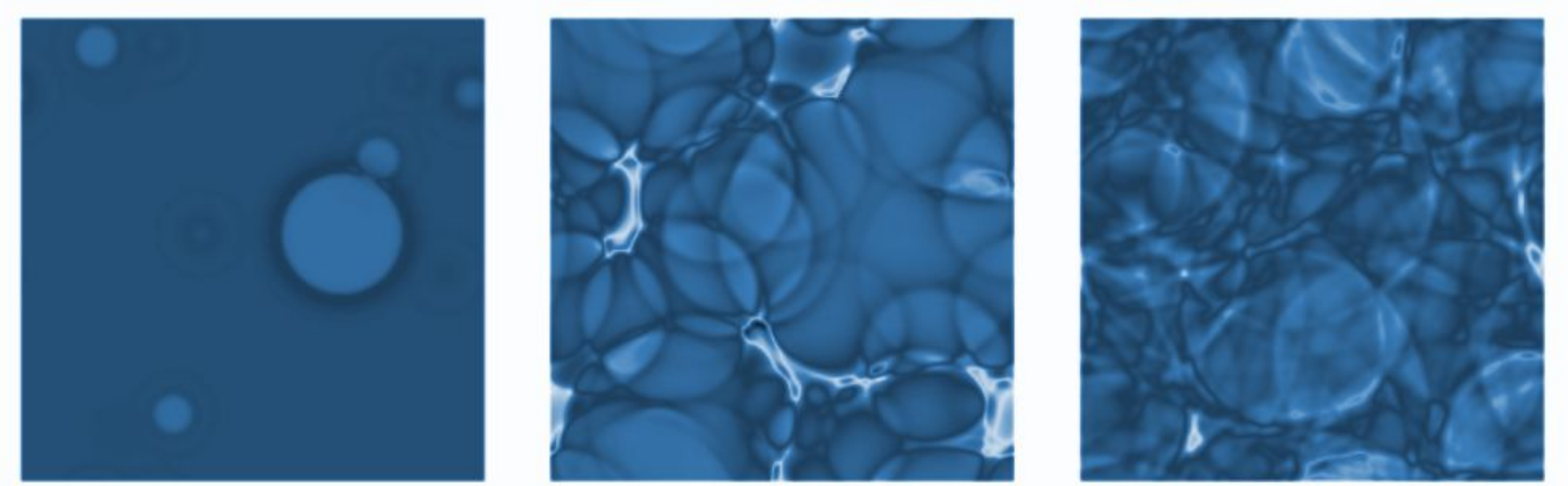
[M. Chala, LG, Z. Ren - 2505.14335]

[M. Chala, J. C. Criado, LG, J. López Miras - 2406.02667]

(*) Generated with **PTPlot** **[Caprini *et al.* - 1910.13125]**

What are the GW sources in a PT?

Summary

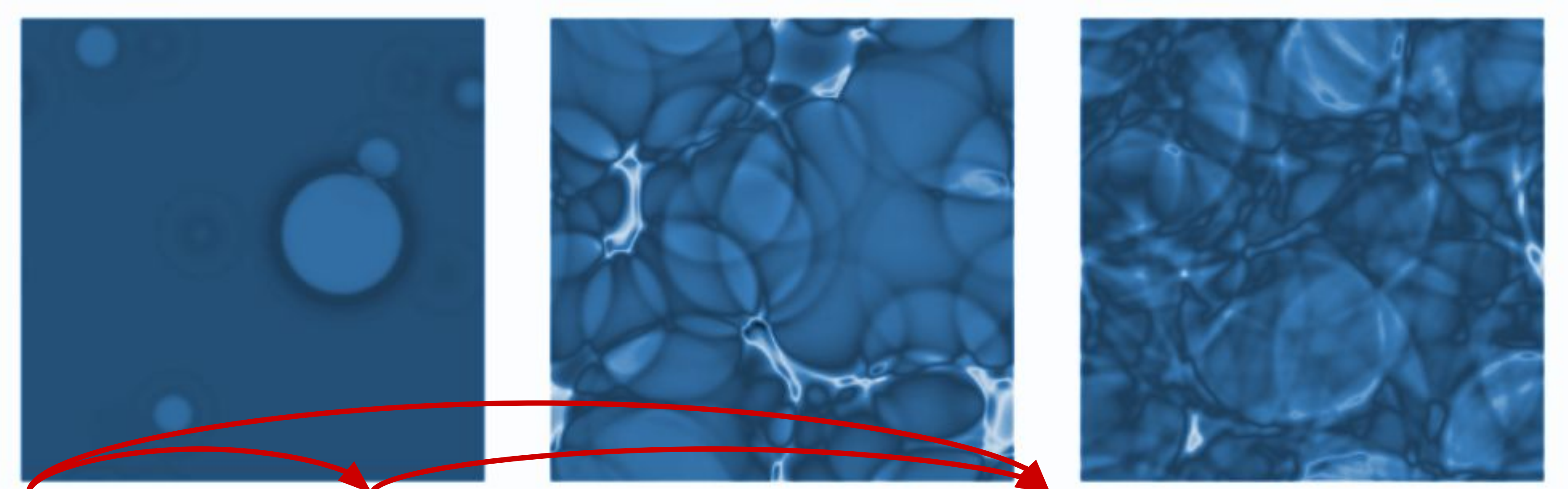


Adapted from: [1304.2433]

	Microscopic	Mesoscopic	Macroscopic
How:	QFT at finite T	Diff. eqs.	Relativistic hydrodynamic simulations
What:	Equilibrium parameters	Wall velocity	GW production

What are the GW sources in a PT?

Summary



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	Microscopic	**Mesoscopic**	**Macroscopic**
How:	QFT at finite T	Diff. eqs.	Relativistic hydrodynamic simulations
What:	Equilibrium parameters	Wall velocity	GW production

A probe of new physics complementary to colliders!

Thank you for your attention!

¡Gracias por vuestra atención!