Bubble wall dynamics at the electroweak phase transition

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based on S. De Curtis, LDR, A. Guiggiani, A. Gil Muyor, G. Panico, JHEP 03 (2022) 163

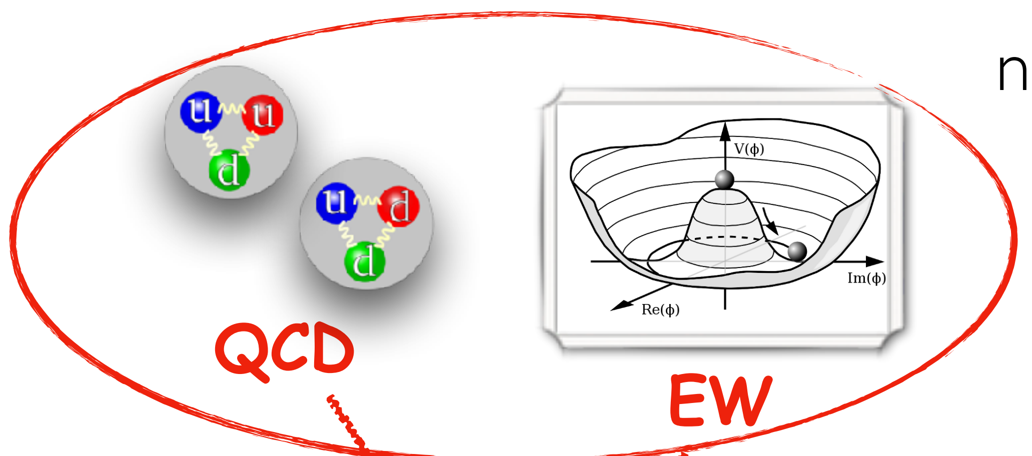
Thermal History of the Universe

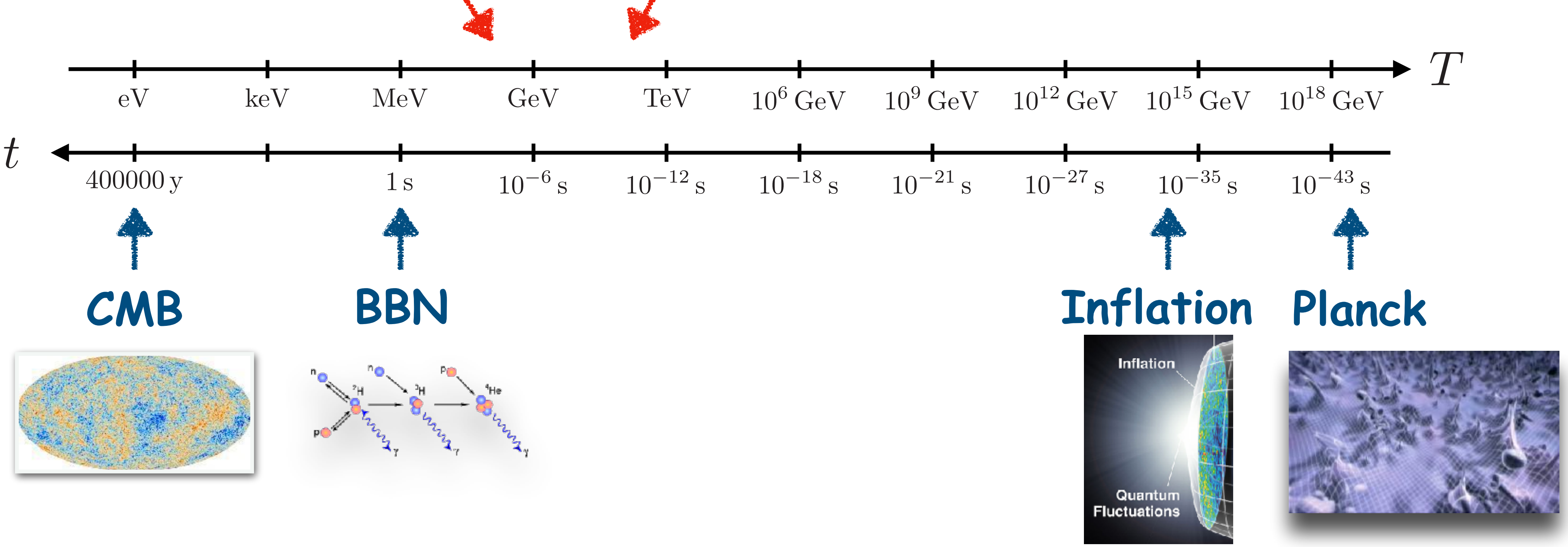
Phase transitions are important events in the evolution of the Universe

- the SM predicts two of them *(the two phases are smoothly connected (cross over))*

no strong breaking of thermal equilibrium

no distinctive experimental signatures





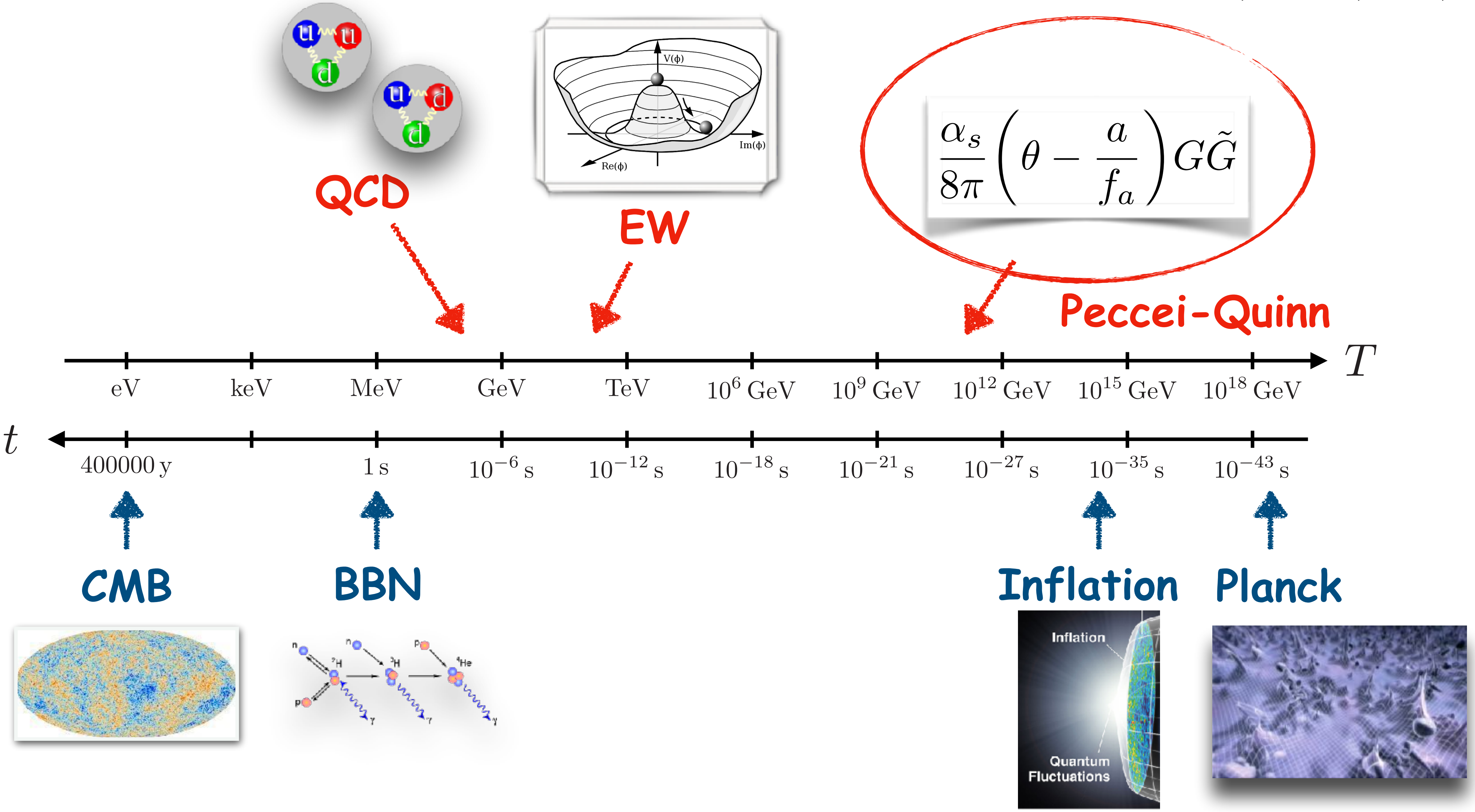
Thermal History of the Universe

Additional phase transitions could be present due to **new-physics**

well motivated example:

- Peccei-Quinn symmetry breaking connected to QCD axion

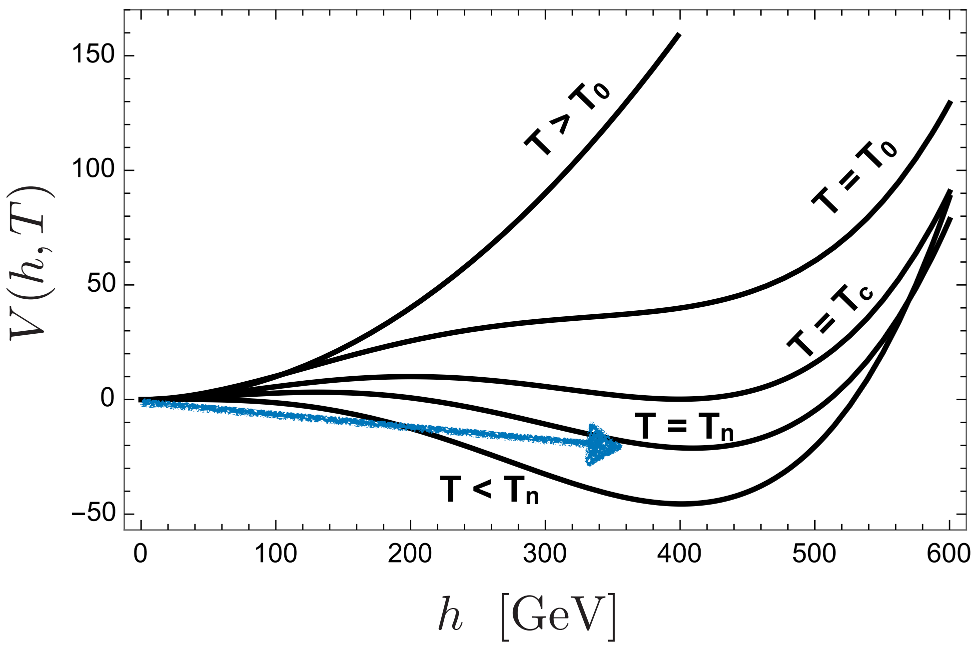
LDR, Panico, Redi, Tesi, 2020



first-order EWPhT

New physics may provide **first order** phase transitions

- a barrier in the potential may be generated from tree-level deformations, thermal or quantum effects

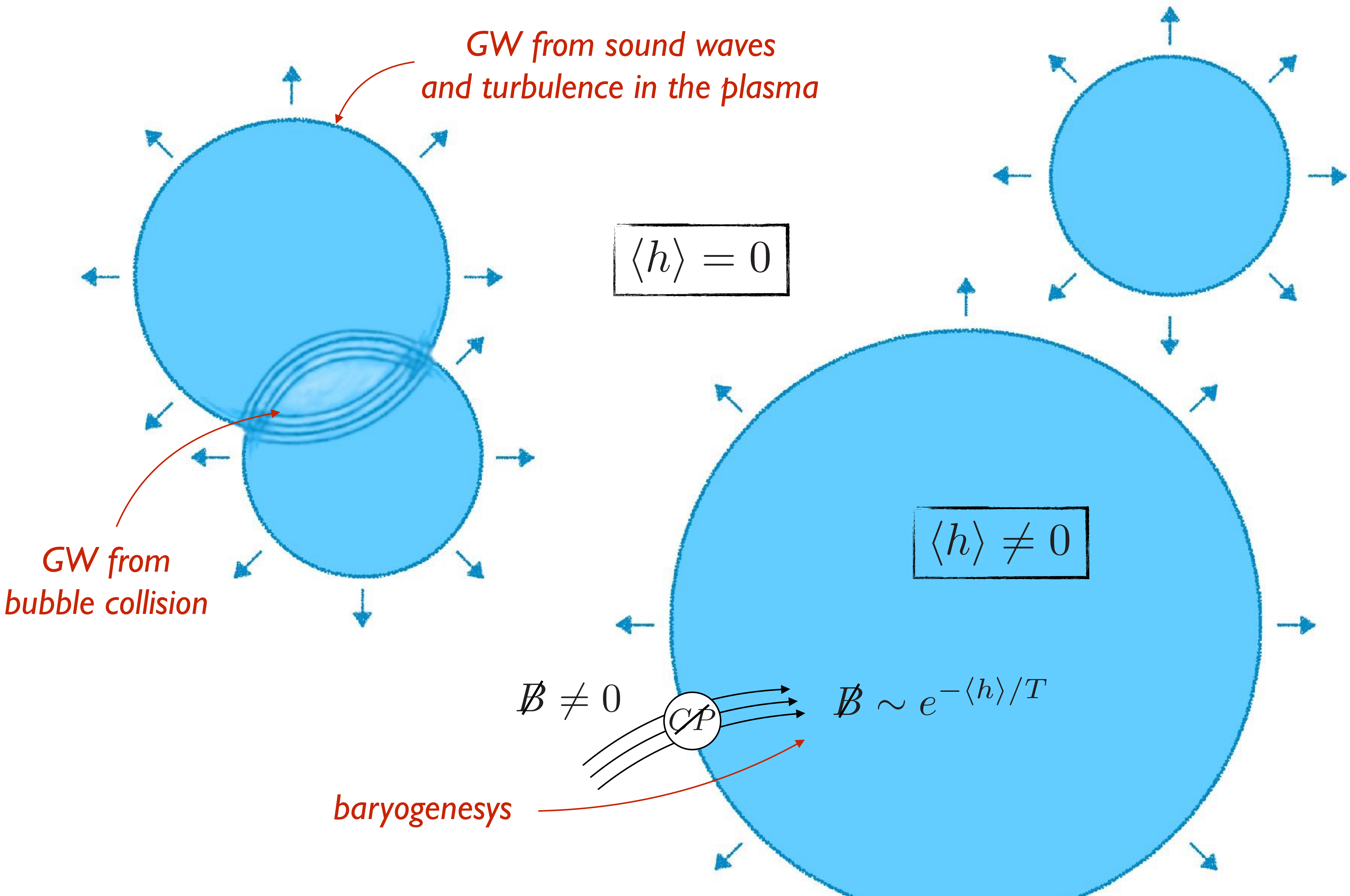


- the field tunnels from false to true minimum at $T = T_n < T_c$
- the transition proceeds through bubble nucleation

- significant breaking of thermal equilibrium (relevant for baryogenesis)
- interesting experimental signatures (eg. gravitational waves)

Bubble nucleation

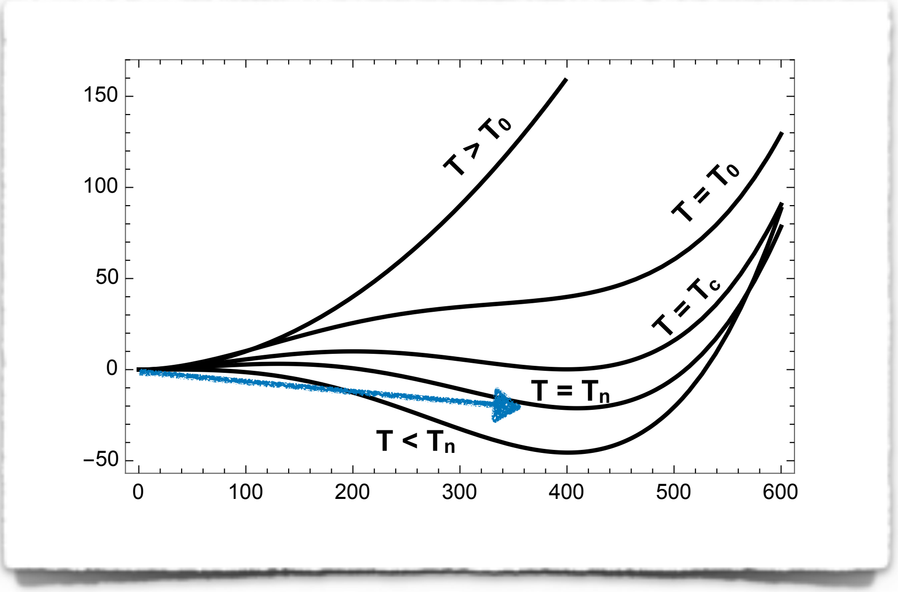
Bubble dynamics can produce **gravitational waves** and **baryogenesys**



How to get a first-order PhT

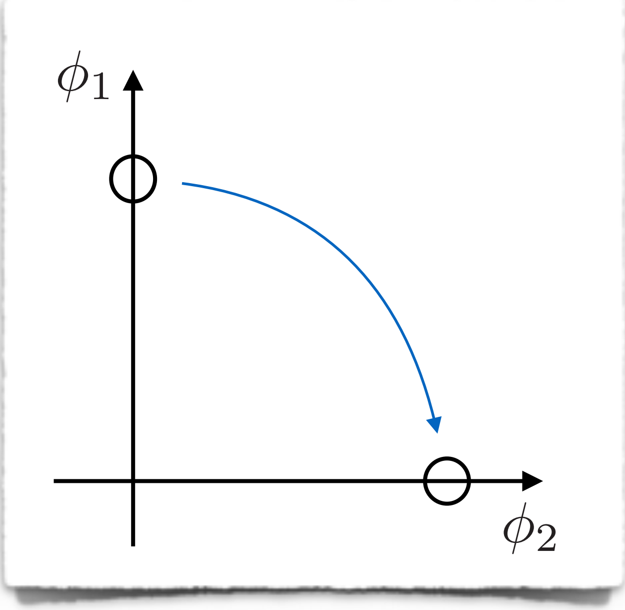
I. **"Single field"** transitions

- barrier coming from:
  - quantum corrections due to additional fields
  - thermal effects

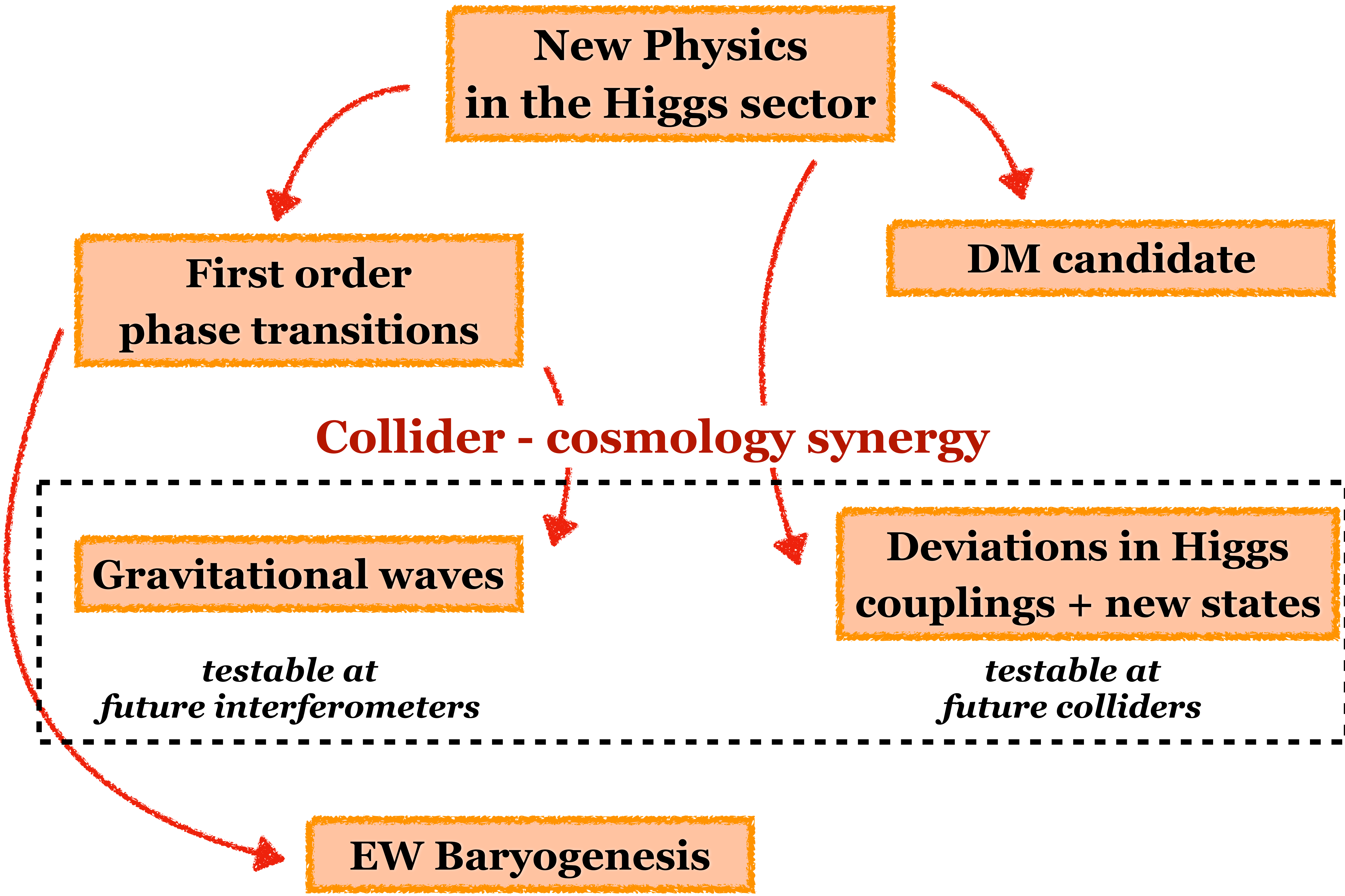


II. **"Multiple field"** transitions

- barrier can be present already at tree-level and T=0
- minima in different directions in field space



Extended Higgs sectors


New Physics
in the Higgs sector
First order
phase transitions
DM candidate
Collider - cosmology synergy
Gravitational waves
Deviations in Higgs
couplings + new states
testable at
future interferometers
testable at
future colliders
EW Baryogenesis

Key features of a first-order PhT

- the nucleation temperature T_n
- the strength α
- the (inverse) time duration of the transition β/H
- the speed of the bubble wall v_w
- the thickness of the bubble wall L_w

equilibrium quantities (first three)

non-equilibrium quantities (last two)

Gravitational waves and the efficiency of the EW-baryogenesis crucially depend on them

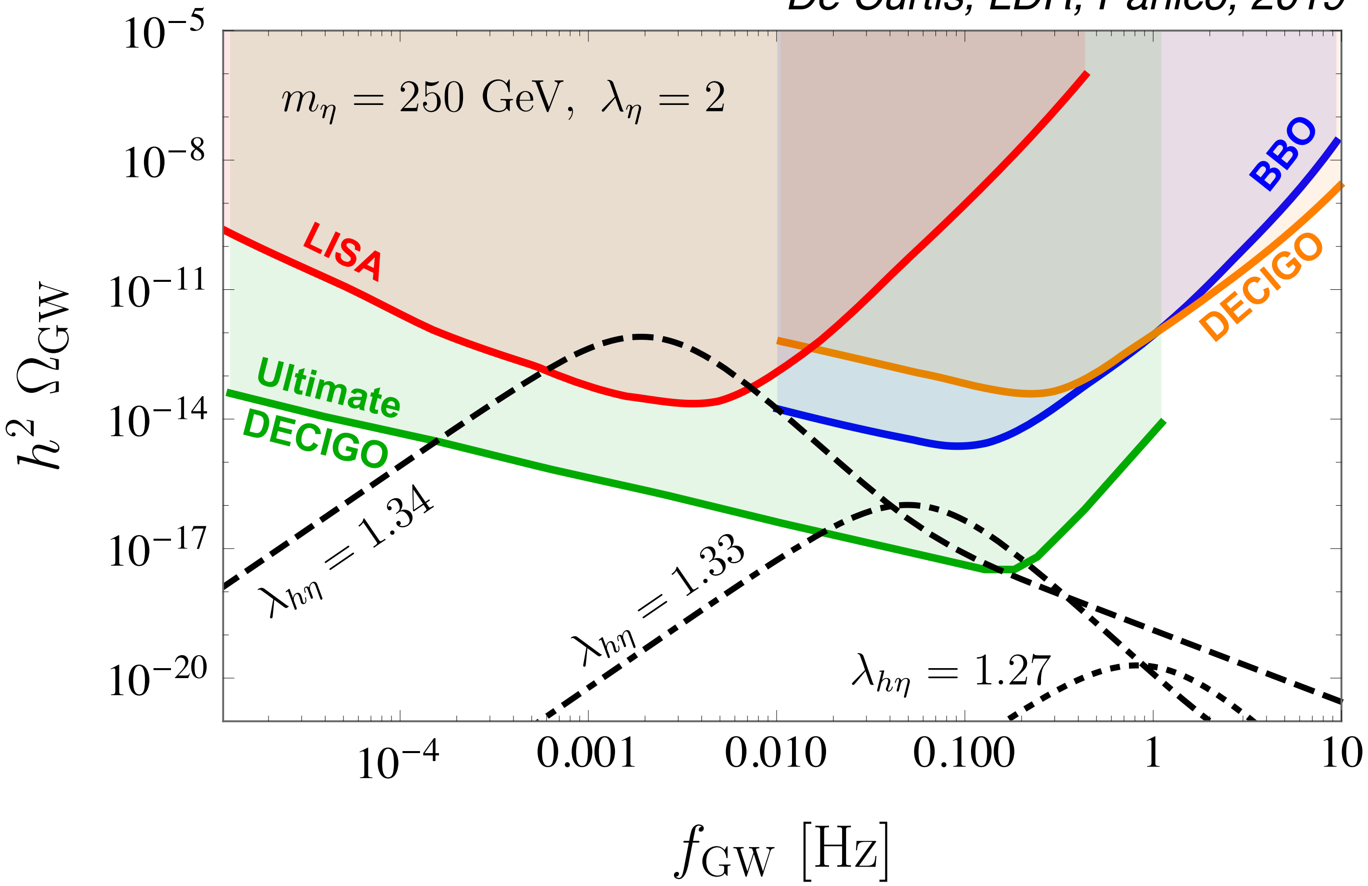
EWBG is typically efficient for slowly-moving walls. Recent results show efficiency also for fast-moving walls [Dorsch, Huber, Konstandin, 2021]

GWs are maximised for fast-moving walls

GW from a first-order PhT

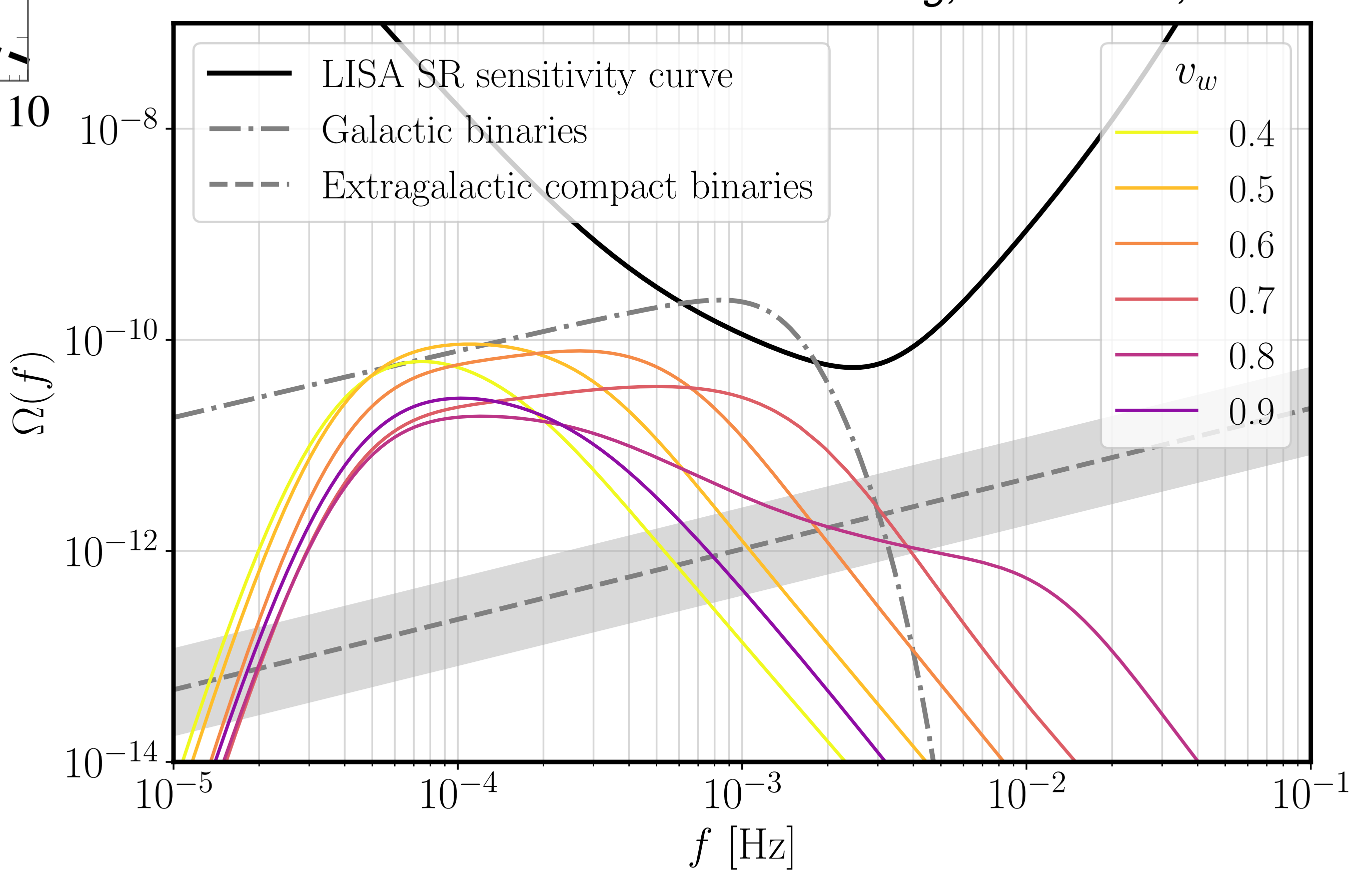
First-order PhTs produce stochastic background of gravitational waves

De Curtis, LDR, Panico, 2019



for the EWPhT the peak frequency is within the range of future experiments

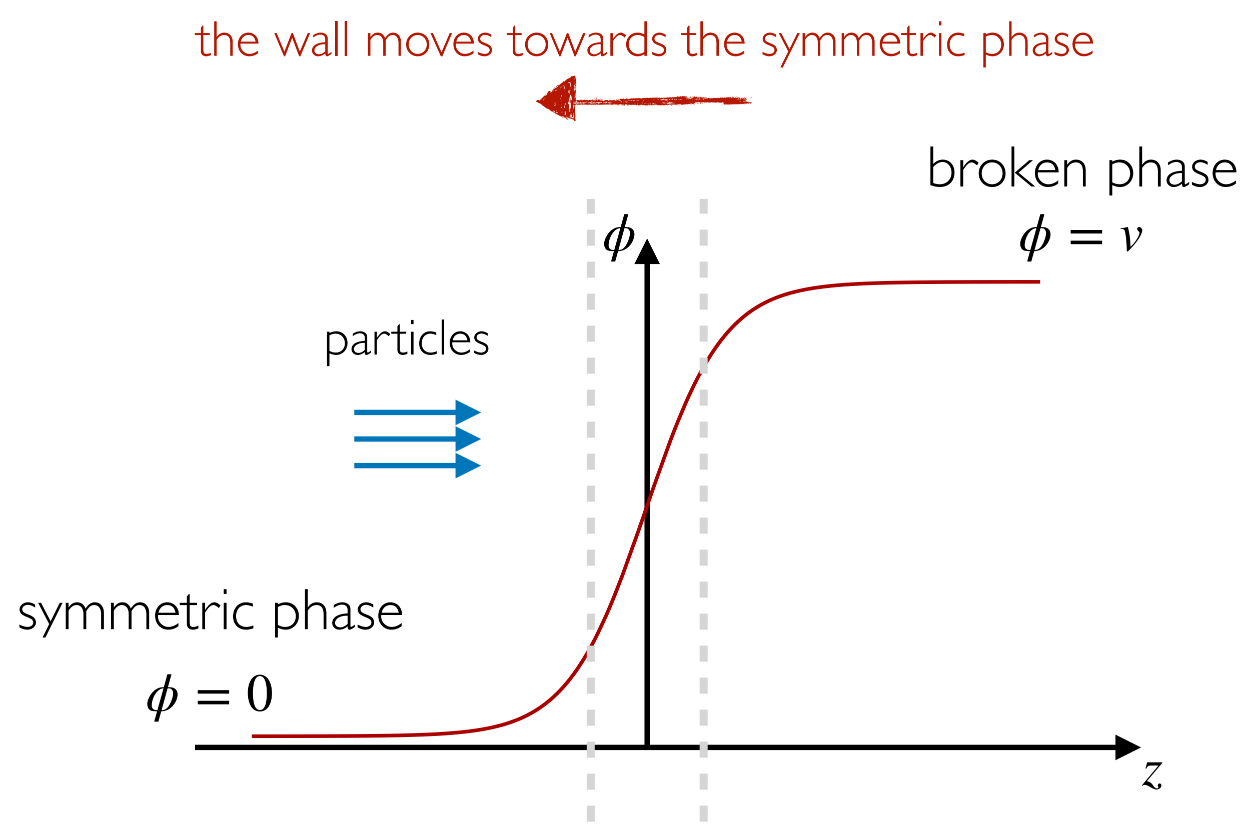
Gowling, Hindmarsh, 2019



- wall speed has a strong effect on the shape of the power spectrum
- wall speed will be the best determined parameter

Dynamics of the bubble wall

System setup:
scalar field + plasma



- The bubble wall drives plasma out of equilibrium
- Interactions between plasma and wall front produce a friction
- If the friction and pressure inside the bubble balance we can realise a steady state regime (terminal velocity reached)

in the following we assume a planar wall and a steady state regime

Dynamics of the bubble wall

Coupled system of equations. For each particle species $f(p,z) = f_v(p,z) + \delta f(p,z)$

- Scalar field equation

$$\phi' \Box \phi - V'_T = \sum N_i \frac{dm^2}{dz} \int \frac{d^3p}{(2\pi)^3 2E_p} \delta f(p)$$

- Boltzmann equation

$$\left(\frac{p_z}{E} \partial_z - \frac{(m^2)'}{2E} \partial_{p_z} \right) (f_v + \delta f) = -\mathcal{C}[f_v + \delta f]$$

  - External force from space dependent mass drives the plasma out of equilibrium

$$m(z) = \frac{m_0}{2} \left(1 + \tanh\left[\frac{z}{L_w} \right] \right)$$

  - Collisions between particles in the plasma tend to restore equilibrium

$$\mathcal{C}[f_v + \delta f]$$

The Boltzmann equation

$$\left(\frac{p_z}{E}\partial_z - \frac{(m^2)'}{2E}\partial_{p_z}\right)f \equiv \mathscr{L}\left[f\right] = -\mathscr{C}[f]$$

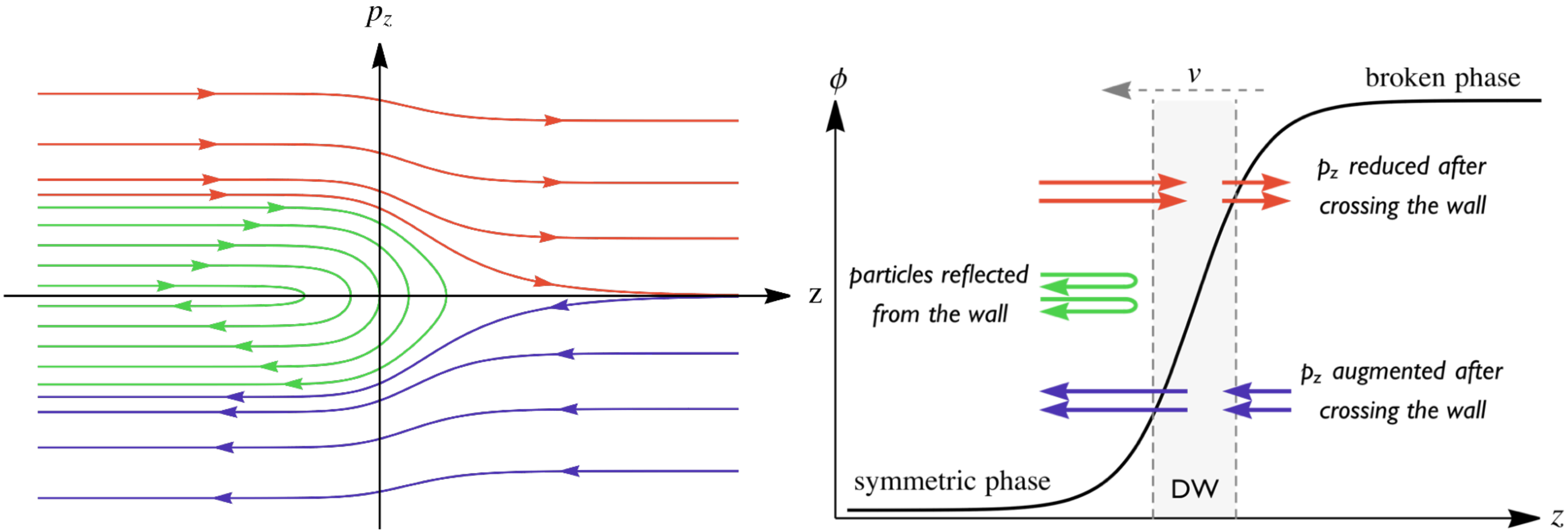
Assumptions on the plasma:

- High temperature, weakly coupled plasma
- Higgs varying scale $L_w \gg q^{-1}$ inverse of momentum transfer in the plasma
- Only $2 \to 2$ processes in the plasma are considered (*assumption valid for the computation of the collision integral*)
- Plasma made of two different kind of species
  - Top quark and W/Z bosons (main contributions)
  - All the other SM particles (background, assumed to be in equilibrium)

LHS - the Liouville operator

Liouville operator is a derivative along flow paths

$$\mathscr{L}[f] = \left(\frac{p_z}{E}\partial_z - \frac{\left(m^2(z)\right)'}{2E}\partial_{p_z} \right) f \longrightarrow \frac{p_z}{E}\frac{df}{dz}$$



$E,\ p_\perp$ and $c = \sqrt{p_z^2 + m^2(z)}$ are conserved along the flow paths

RHS - the collision term

The collision term is the hard part of the Boltzmann equation

$$\mathcal{C}[f_v+\delta f] = \frac{1}{4N_i E_i}\sum_j \int \frac{d^3k d^3p' d^3k'}{(2\pi)^5 2E_k 2E_{p'} 2E_{k'}} |\mathcal{M}_j|^2 \mathcal{P}[f_v+\delta f]\delta^4(p+k-p'-k')$$

for $2 \leftrightarrow 2$ *processes*

Boltzmann equation is an integro-differential equation

Typical setup:

- friction contributions only from the top quark
- background is not perturbed
- infrared divergences regularised by thermal masses
- only leading-log terms are considered

process	$\lvert\mathcal{M}\rvert^2$
$t\bar{t} \to gg$	$\frac{128}{3} g_s^4 \left[\frac{ut}{(t-m_q^2)^2} + \frac{ut}{(u-m_q^2)^2} \right]$
$tg \to tg$	$-\frac{128}{3} g_s^4 \frac{su}{(u-m_q^2)^2} + 96 g_s^4 \frac{s^2+u^2}{(t-m_g^2)^2}$
$tq \to tq$	$160 g_s^4 \frac{s^2+u^2}{(t-m_g^2)^2}$

Previous approaches to the Boltzmann equation

To deal with the collision term, previous approaches made assumptions on the *shape* of the perturbation in momentum space

- Fluid approximation [1]
- Extended fluid approximation [2]
- New formalism [3]

[1] Moore, Prokopec, 1995
[2] Dorsch, Huber, Konstandin, 2022
[3] Laurent, Cline, 2020

[1] and [2] dubbed "old formalism" (OF) in the following

1!!! the $\partial_{p_z}\delta f$ term neglected

2!!! Boltzmann equation integrated with a set of (*not unique*) weights

Alternative methods

- Expansion of δf in a polynomial basis [4]
- Holographic approach [5]

[4] Laurent, Cline, 2022
[5] Bigazzi, Caddeo, Canneti, Cotrone

Full solution to the Boltzmann equation

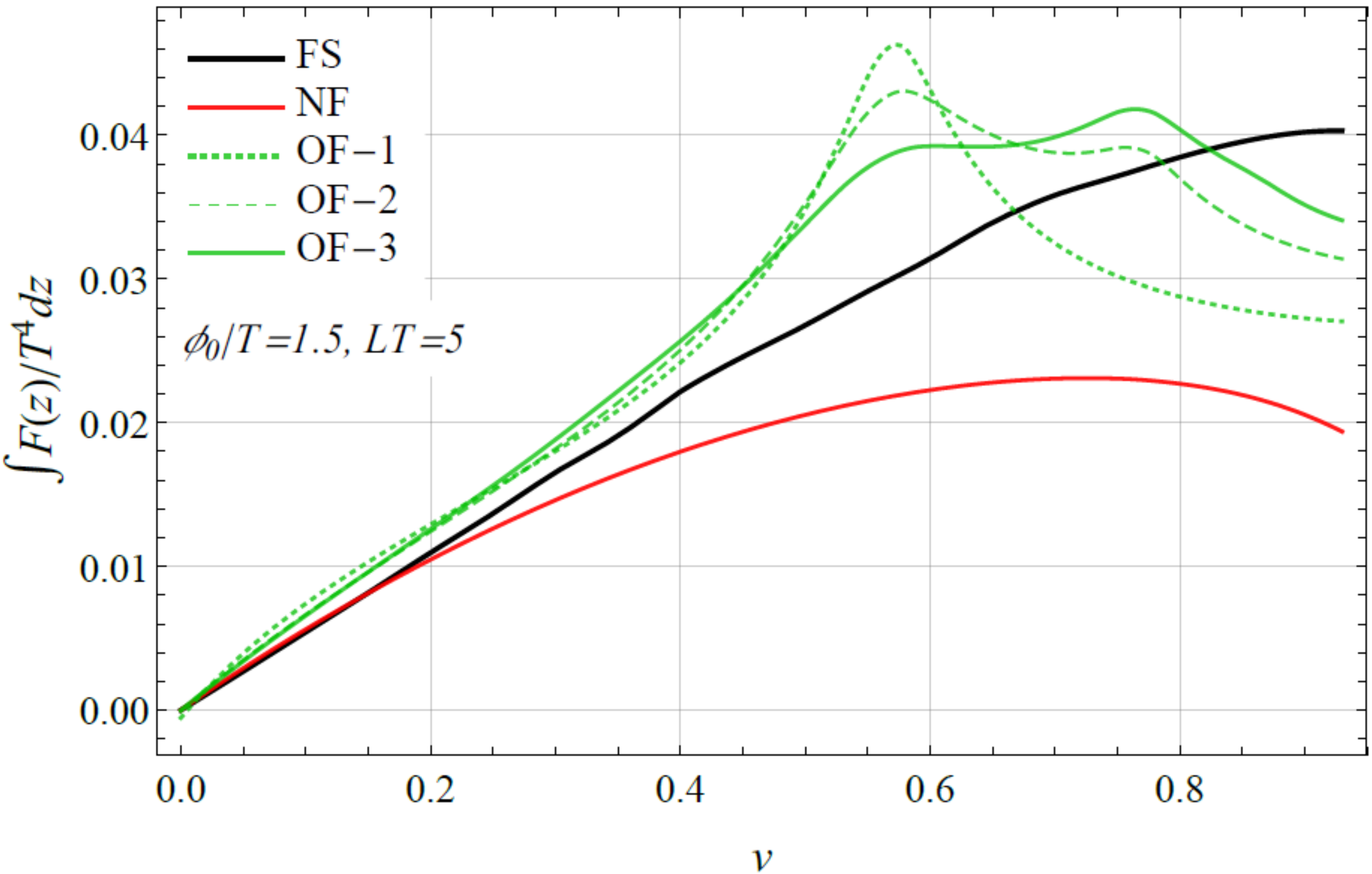
We propose a new method to solve the Boltzmann equation
without imposing any ansatz for δf

De Curtis, LDR, Guiggiani, Gil Muyor, Panico, 2022

Key features

- No term in the Boltzmann equation is neglected
- New approach to deal with collision integrals
- Iterative routine where convergence is achieved in few steps

Integrated friction



De Curtis, LDR, Guiggiani, Gil Muyor, Panico, 2022

Conclusions and outlook

Conclusions:

- Fully quantitative solution without any ansatz on δf
- Necessary for a reliable computation of v_w
- Quantitative and qualitative differences with previous approaches mainly for $v_w \gtrsim 0.2$

Future perspectives:

- Inclusion of the massive W/Z bosons and massless background species
- Inclusion of $1 \to 2$ and $2 \to 1$ plasma processes in the collision integrals
- going beyond leading-log
- determination of v_w *(by solving Boltzmann + scalar EOM)*