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Bubble dynamics of first order electroweak phase transitions

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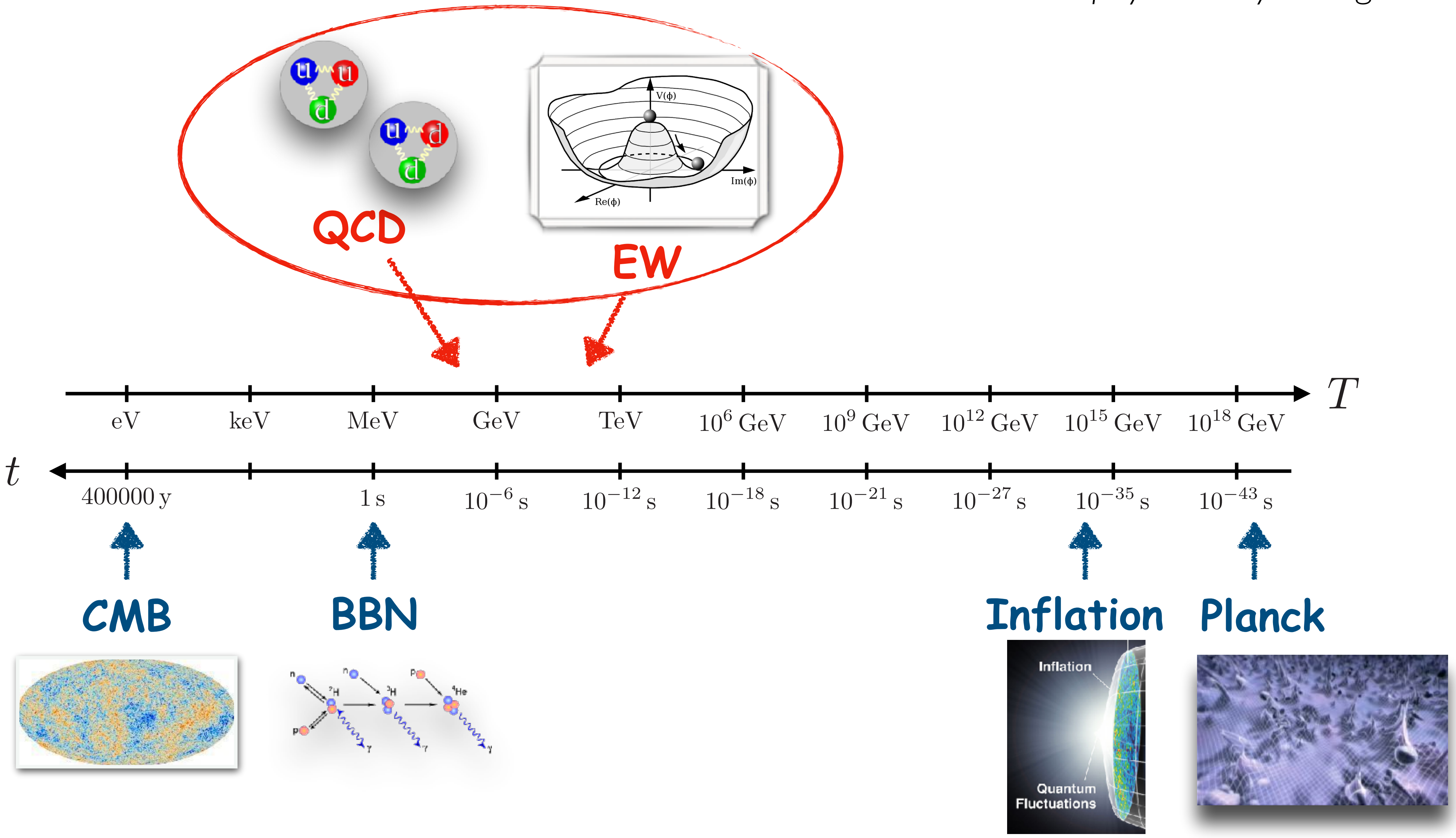
JHEP 03 (2022) 163, arXiv:2201:08220

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))*

new physics may change their nature



QCD

EW

T: eV, keV, MeV, GeV, TeV, 10^6 GeV, 10^9 GeV, 10^{12} GeV, 10^{15} GeV, 10^{18} GeV

t: 400000 y, 1 s, 10^{-6} s, 10^{-12} s, 10^{-18} s, 10^{-21} s, 10^{-27} s, 10^{-35} s, 10^{-43} s

CMB

BBN

Inflation

Planck

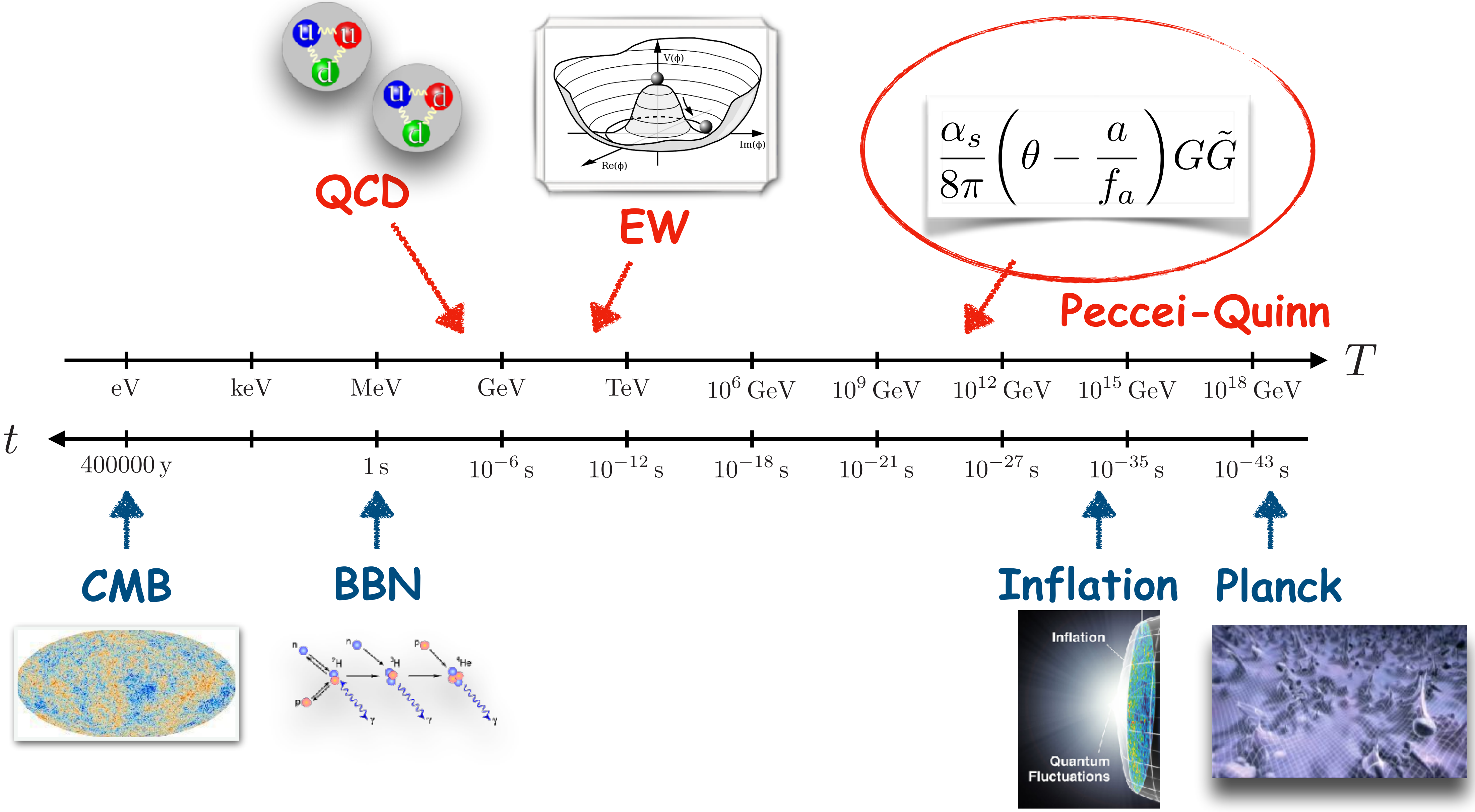
Thermal History of the Universe

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



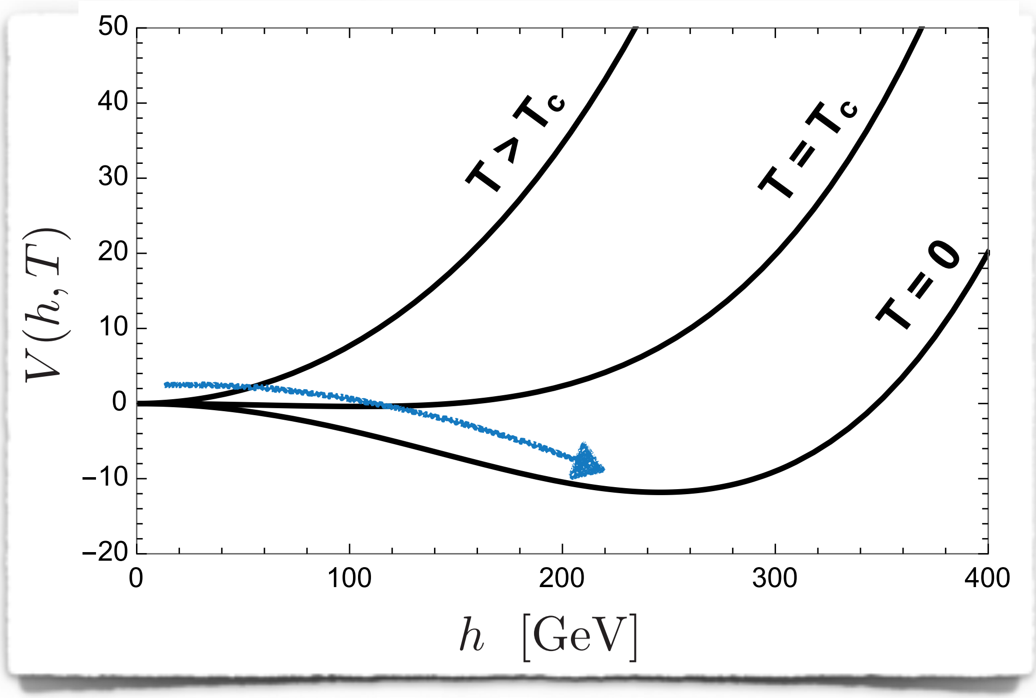
$$\frac{\alpha_s}{8\pi}\left(\theta - \frac{a}{f_a}\right)G\tilde{G}$$

Phase transitions in the SM

In the SM the QCD and EW PhTs are extremely weak

→ the two phases are smoothly connected (cross over)

- no barrier is present in the effective potential
- the field gently "rolls down" towards the global minimum when $T < T_c$

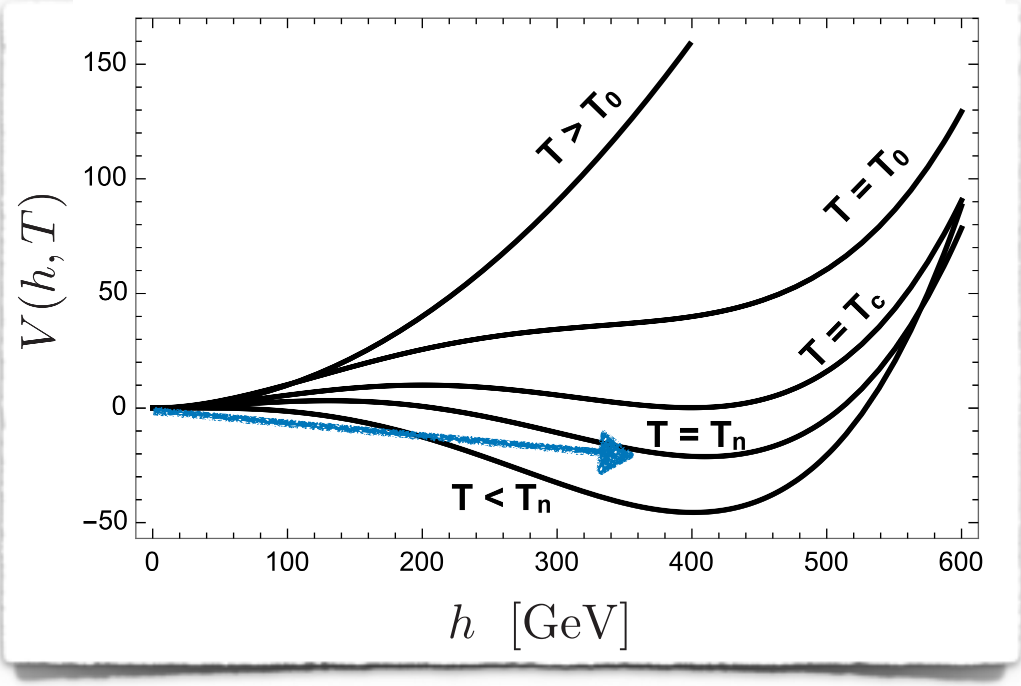


- no strong breaking of thermal equilibrium
- no distinctive experimental signatures

A 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

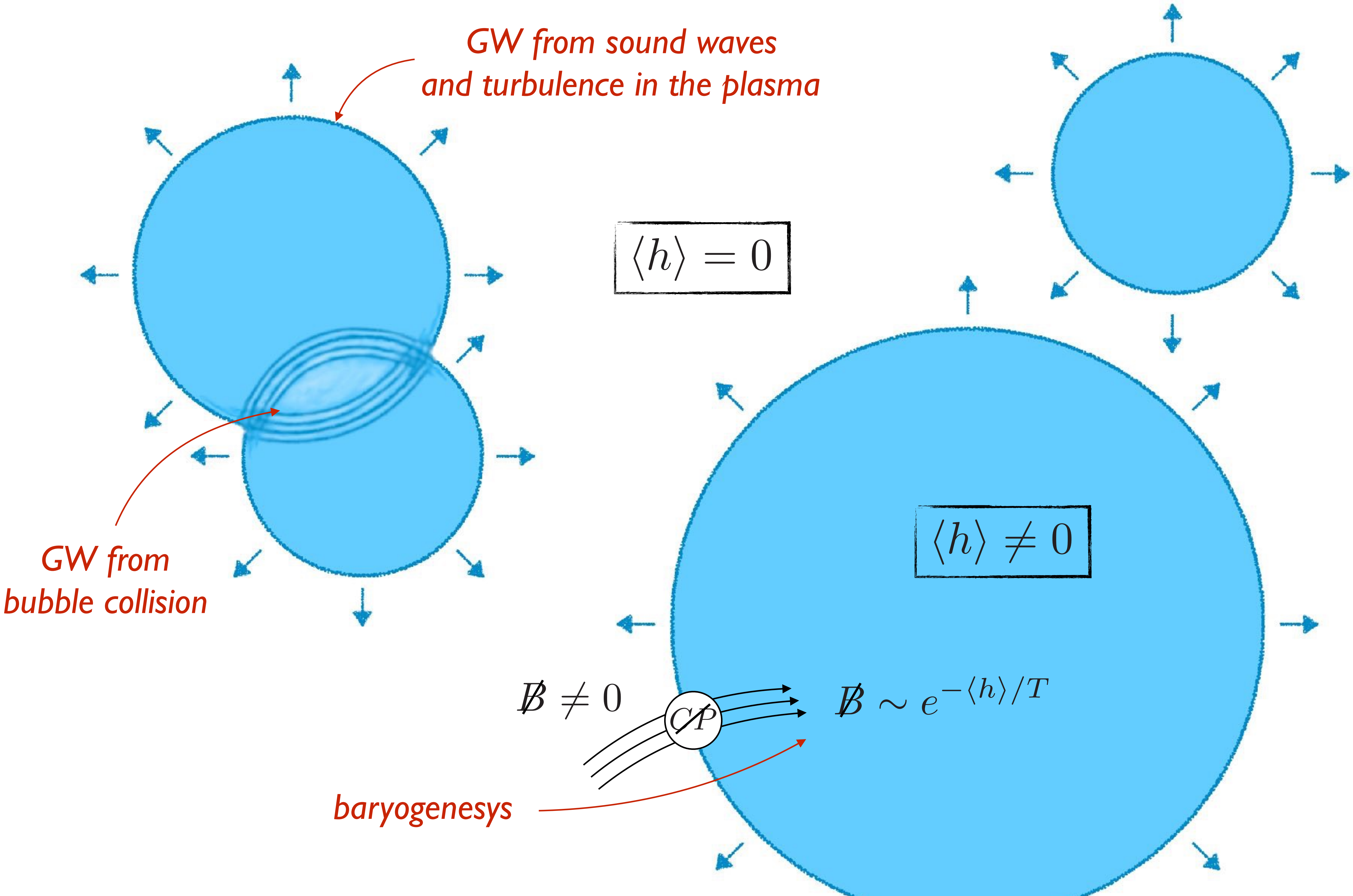


- the field tunnels from false to true minimum at $T = T_n < T_c$
- the transition proceeds through bubble nucleation

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

Bubble nucleation

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



GW from sound waves and turbulence in the plasma

$\boxed{\langle h \rangle = 0}$

GW from bubble collision

$\boxed{\langle h \rangle \neq 0}$

$\not{B} \neq 0$

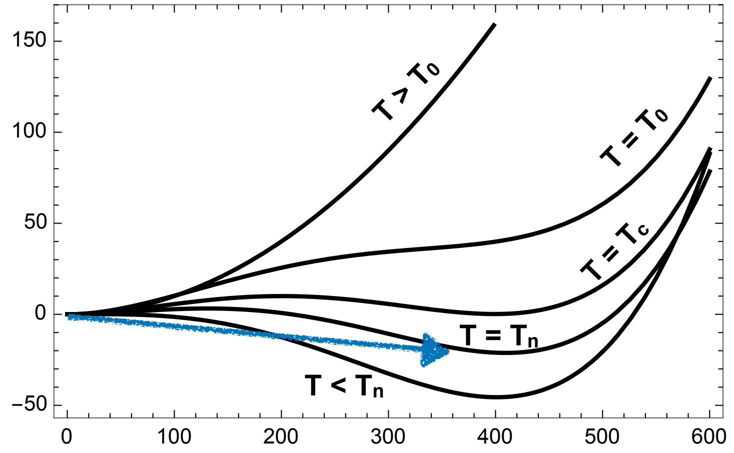
$\not{C}\not{P}$

$\not{B} \sim e^{-\langle h \rangle / T}$

baryogenesys

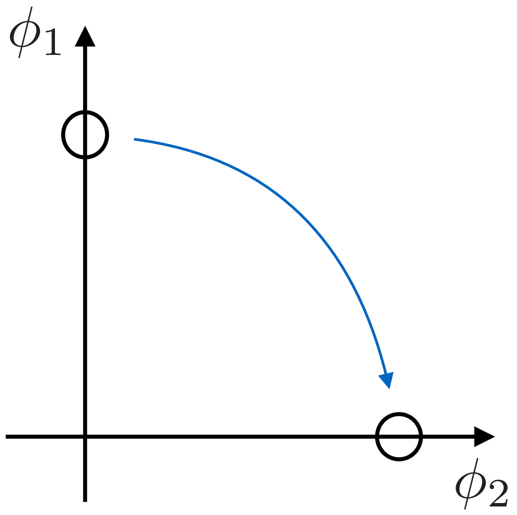
How to get a first-order PhT

I. **"Single field"** transitions



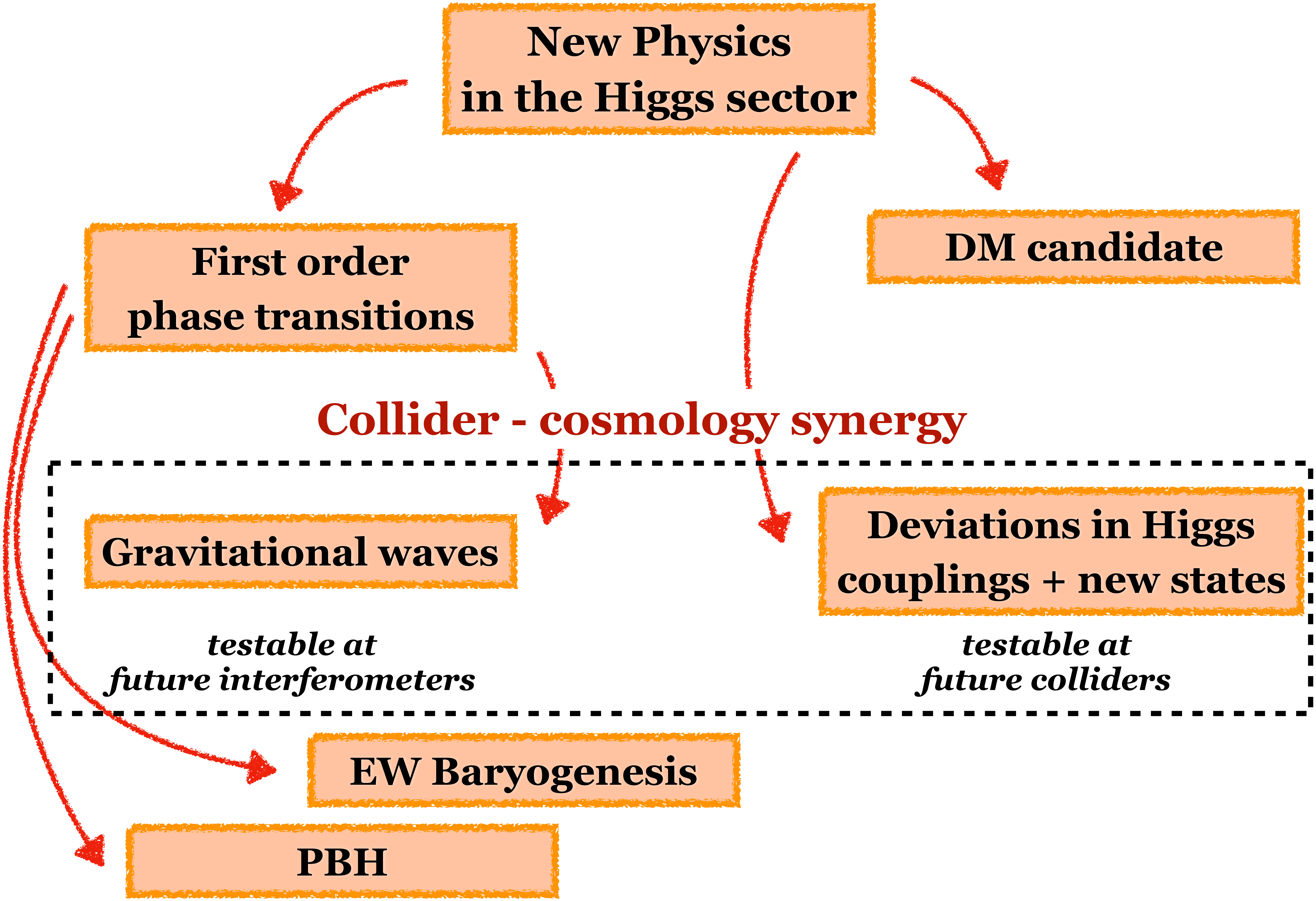
- barrier coming from:
  - quantum corrections due to additional fields
  - thermal effects

II. **"Multiple field"** transitions



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

New Physics in the Higgs sector



New Physics in the Higgs sector

First order phase transitions

DM candidate

Collider - cosmology synergy

Gravitational waves

testable at future interferometers

Deviations in Higgs couplings + new states

testable at future colliders

EW Baryogenesis

PBH

Key features of a first-order PhT

- the nucleation temperature T_n
- the strength α
- the (inverse) time duration of the transition β/H

equilibrium quantities

- the speed of the bubble wall v_w
- the thickness of the bubble wall L_w

non-equilibrium quantities

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

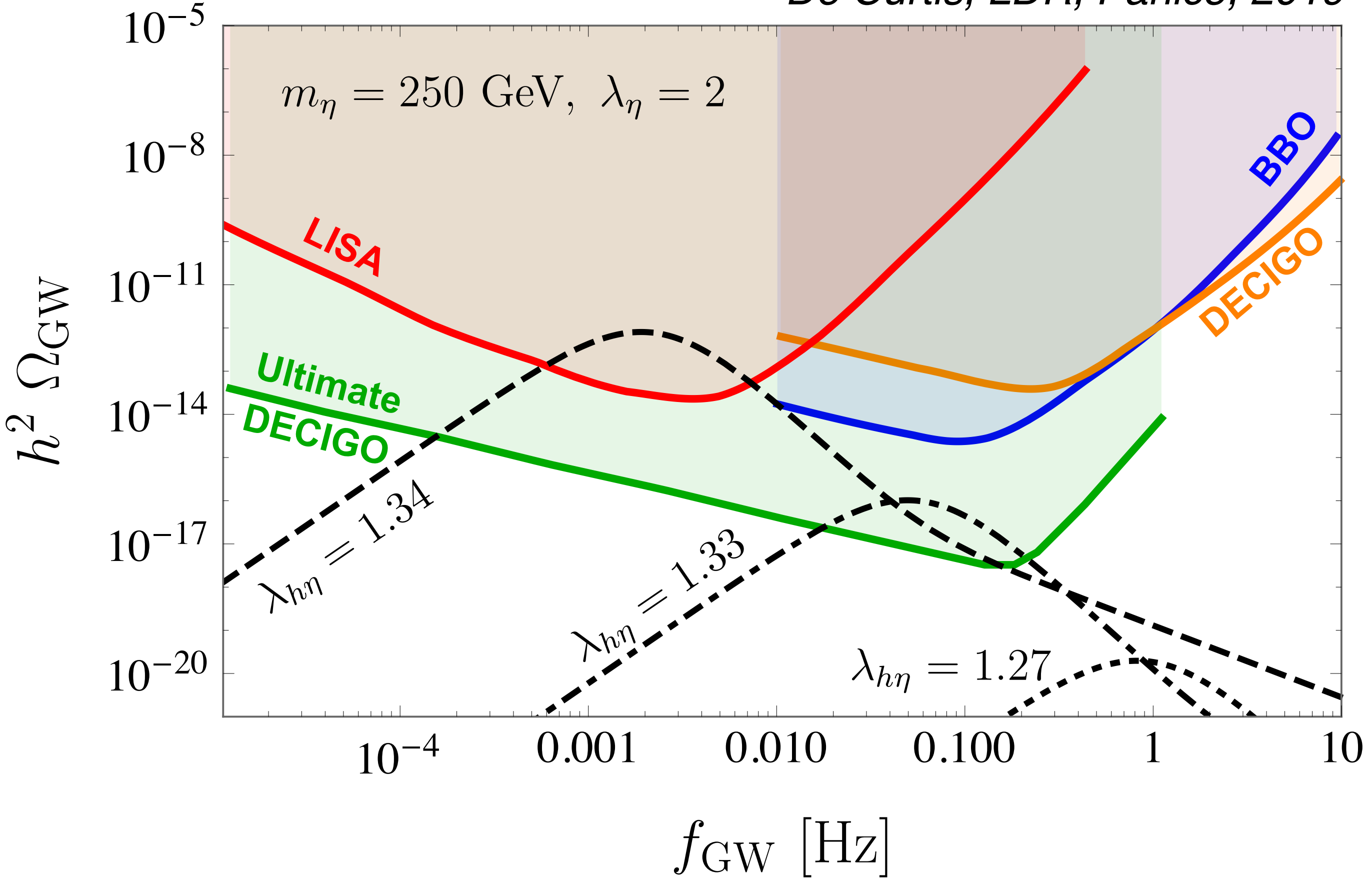
EWBG is typically efficient for slowly-moving walls. Recent results show efficiency also for fast-moving walls [Dorsch, Huber, Konstandin, 2021]

GWs are maximised for fast-moving walls

GW from a first-order PhT

First-order PhTs produce stochastic background of gravitational waves

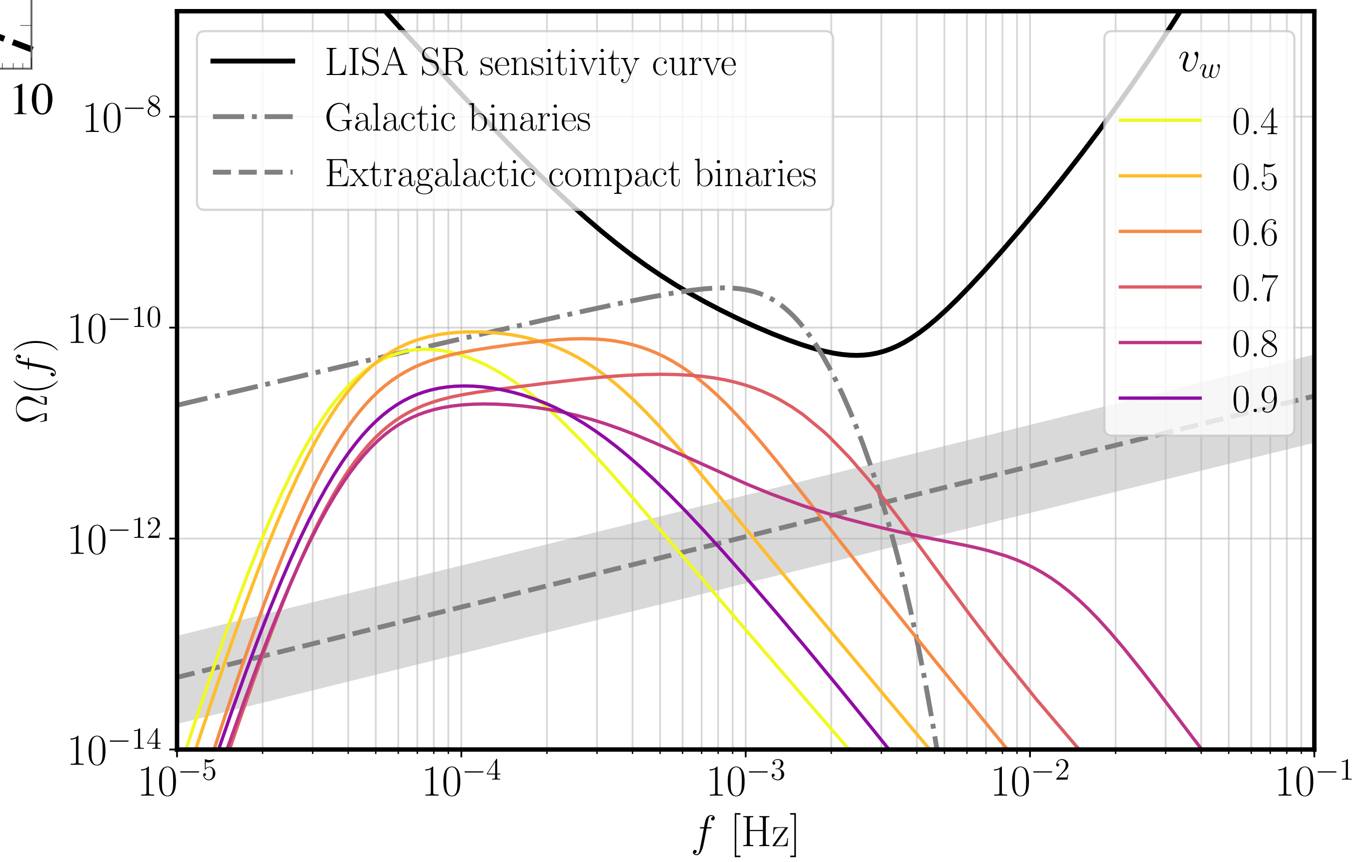
De Curtis, LDR, Panico, 2019



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

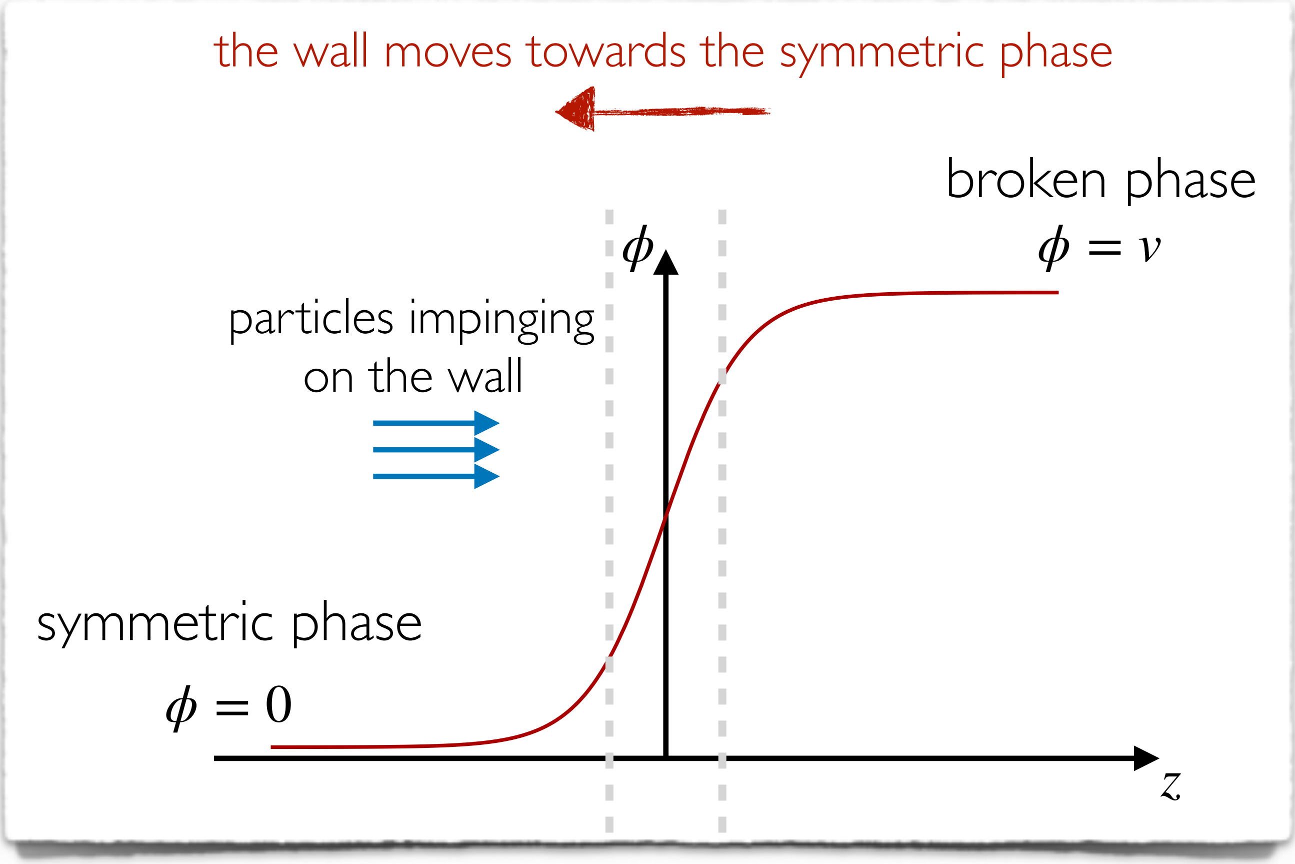
- wall speed has a strong effect on the shape of the power spectrum
- wall speed will be the best determined parameter

Gowling, Hindmarsh, 2019



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 for out-of-equilibrium fluids

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

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

- Energy-momentum conservation for background fluids

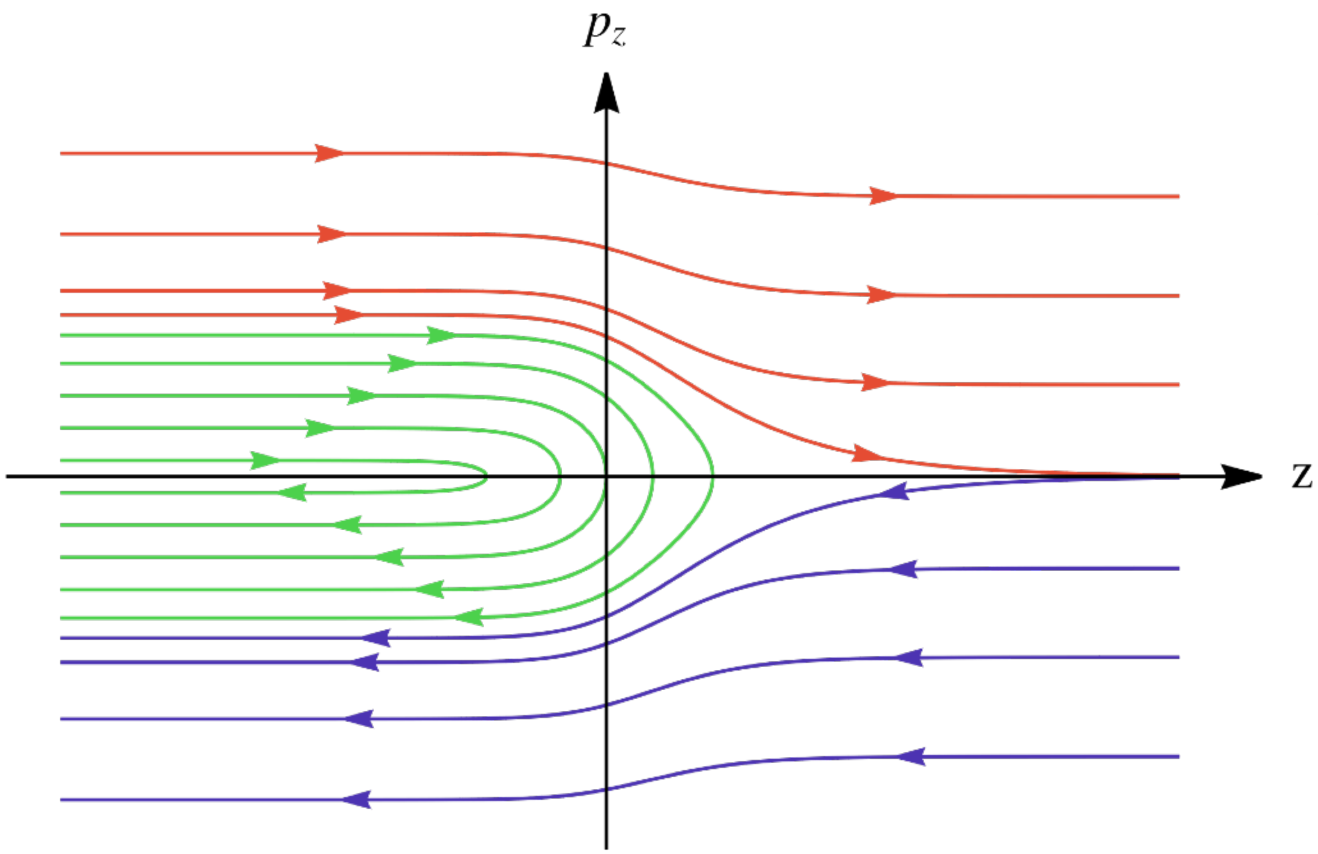
$$f_v = \frac{1}{e^{\beta(z)\gamma(z)(E - v_{pl}(z)p_z)} + 1}$$

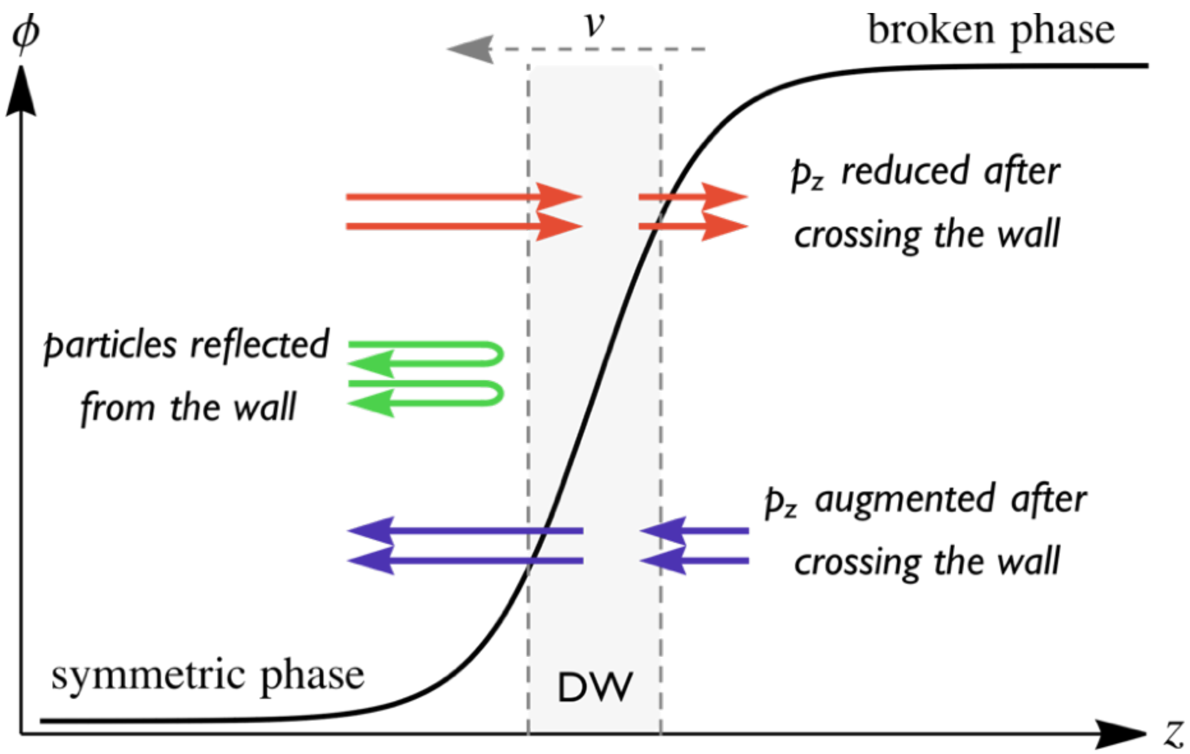
the effects of the background are encapsulated in the temp. and velocity profiles

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 challenging 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
- processes included: $t\bar{t} \leftrightarrow gg, \quad tg \leftrightarrow tg, \quad tq \leftrightarrow tq$
- background is not perturbed
- infrared divergences regularised by thermal masses
- only leading-log terms are considered

Structure of the collision integral

The linearised collision integral

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

the population factor

$$\bar{\mathcal{P}}[f] = f_v(p) f_v(k)(1 \pm f_v(p'))(1 \pm f_v(k')) \sum \mp \frac{\delta f}{f_v'}$$

the collision integral yields two classes of terms:

$$\overline{\mathcal{C}}[\delta f_i] = \mathcal{Q}\frac{\delta f}{f_v'(p)} + (\langle \delta f(k)\rangle - \langle \delta f(p')\rangle - \langle \delta f(k')\rangle)$$

- the perturbation does not appear inside the integral: easy to handle

- perturbation is integrated (*bracket*): very challenging

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

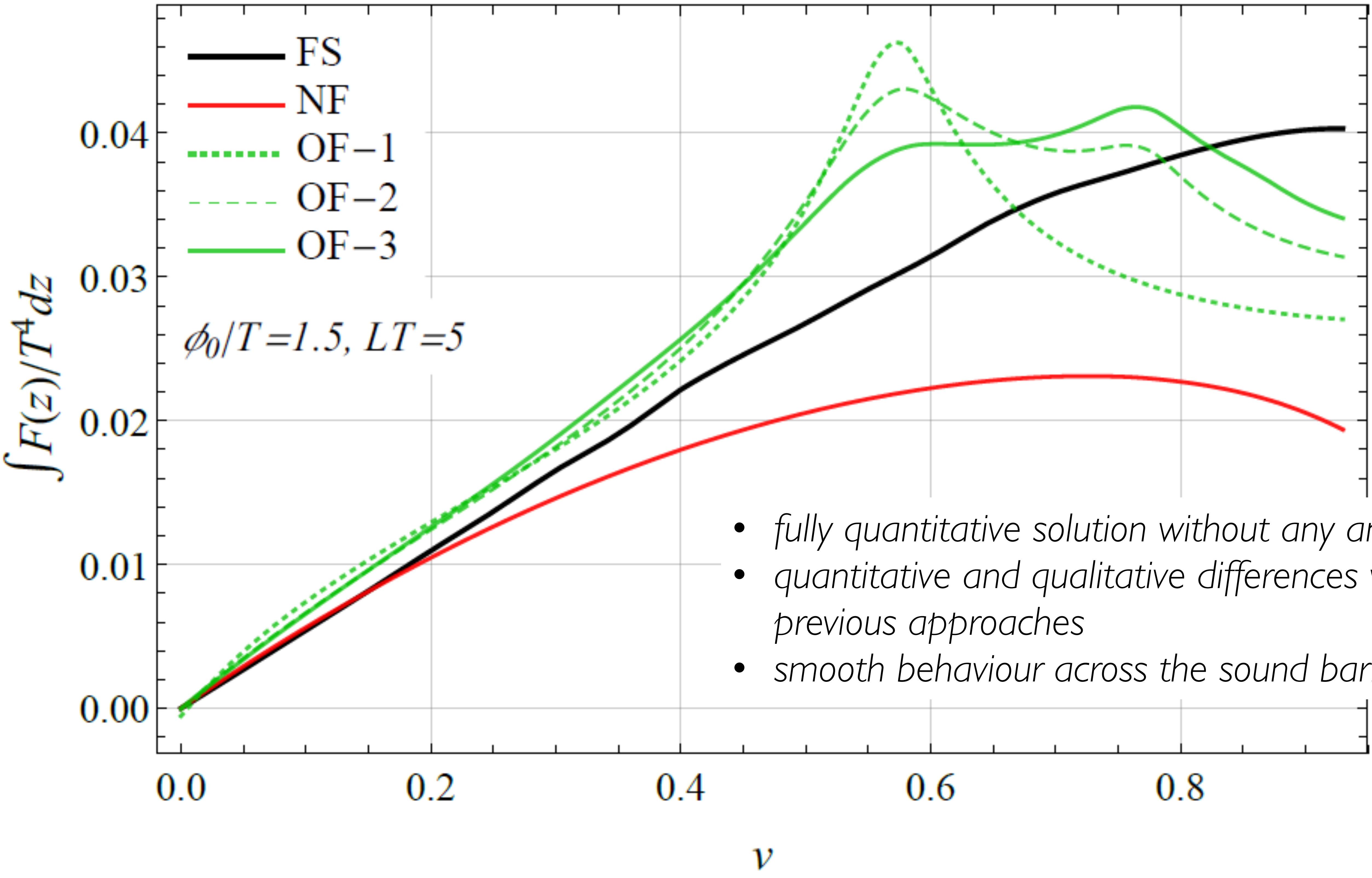
- ❖ We developed an algorithm to solve the coupled system of *bubble wall* and *Boltzmann* equations, thus getting v_w, L_w, etc.

De Curtis, LDR, Guiggiani, Gil Muyor, Panico, 2023

Key features

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

Integrated friction



- *fully quantitative solution without any ansatz*
- *quantitative and qualitative differences with previous approaches*
- *smooth behaviour across the sound barrier*

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

SM + singlet scalar

Higgs + singlet scalar potential (Z_2 symmetric)

in the high-temperature limit

$$V(h,s,T) = \frac{\mu_h^2}{2}h^2 + \frac{\lambda_h}{4}h^4 + \frac{\mu_s^2}{2}s^2 + \frac{\lambda_s}{4}s^4 + \frac{\lambda_{hs}}{4}h^2s^2 + \left(c_h\frac{h^2}{2} + c_s\frac{s^2}{2}\right)T^2$$

important to create a barrier in the potential

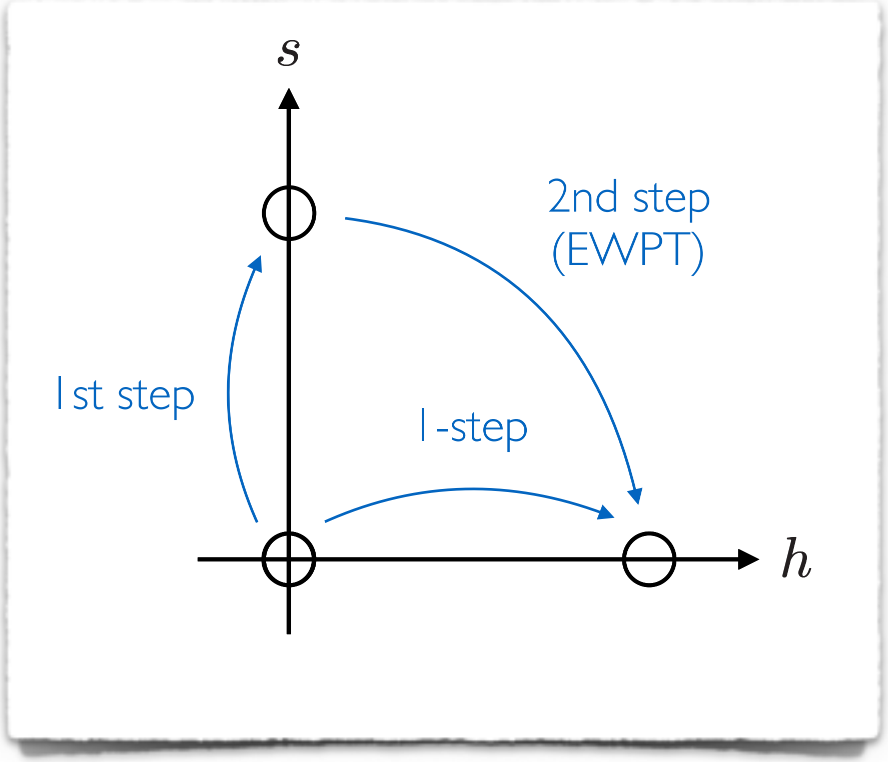
with thermal masses

$$c_h = \frac{1}{48}(9g^2 + 3g'^2 + 12y_t^2 + 24\lambda_h + \lambda_{hs}) \qquad c_s = \frac{1}{12}(2\lambda_{hs} + \lambda_h)$$

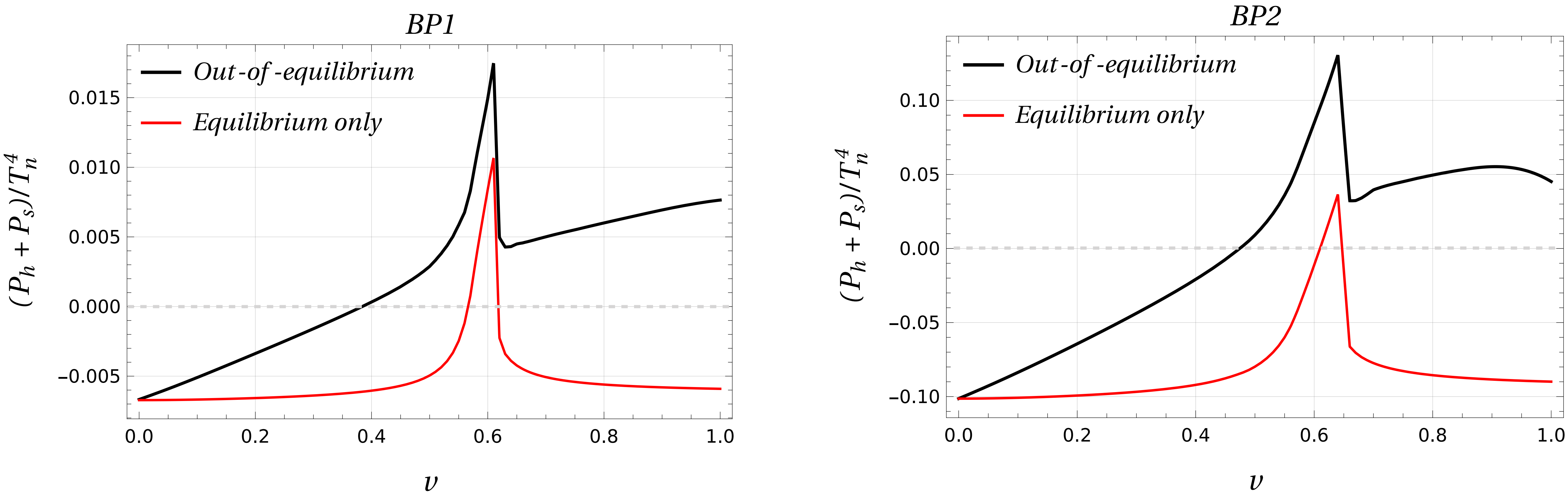
- ✦ EW symmetry is restored at very high T

$$\langle h, s\rangle = (0,0)$$

- ✦ Two interesting patterns of symmetry breaking (as the Universe cools down)
  - i. 1-step PhT $\quad (0,0) \to (v,0)$
  - ii. 2-step PhT $\quad (0,0) \to (0,w) \to (v,0)$
    - ‣ 2-step naturally realised since singlet is destabilised before the Higgs ($c_s < c_h$)



Results



	m_s (GeV)	λ_{hs}	λ_s	T_n (GeV)	T_c (GeV)	T_+ (GeV)	T_- (GeV)
BP1	103.8	0.72	1	129.9	132.5	130.3	129.9
BP2	80.0	0.76	1	95.5	102.8	97.5	95.5

	v_w	δ_s	$L_h T_n$	$L_s T_n$
BP1	0.388 (0.566)	0.789 (0.751)	9.69 (8.05)	7.66 (6.66)
BP2	0.473 (0.610)	0.808 (0.810)	5.15 (4.68)	4.26 (4.07)

De Curtis, LDR, Guiggiani, Gil Muyor, Panico, in prep.

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

Work in progress:

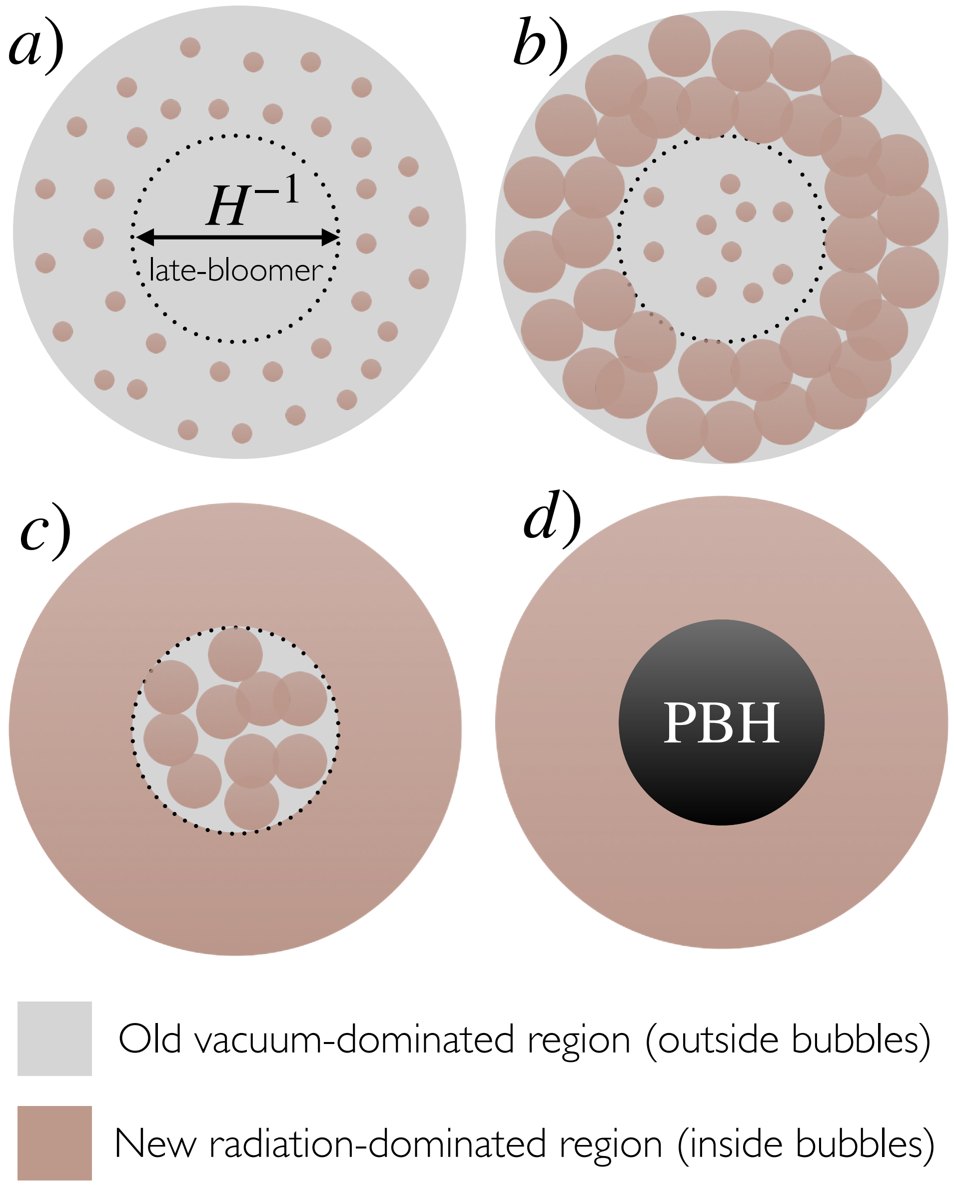
- inclusion of the massive W/Z bosons
- evaluation of the impact of the leading-log approximation
- code release

Supercool PhTs

Primordial Black Hole
productions in supercool PhT

$$M_{\rm PBH} \simeq 3.7 \times 10^{-8} M_\odot \left(\frac{106.75}{g_*(T_{\rm eq})}\right)^{1/2} \left(\frac{500\ {\rm GeV}}{T_{\rm eq}}\right)^2$$

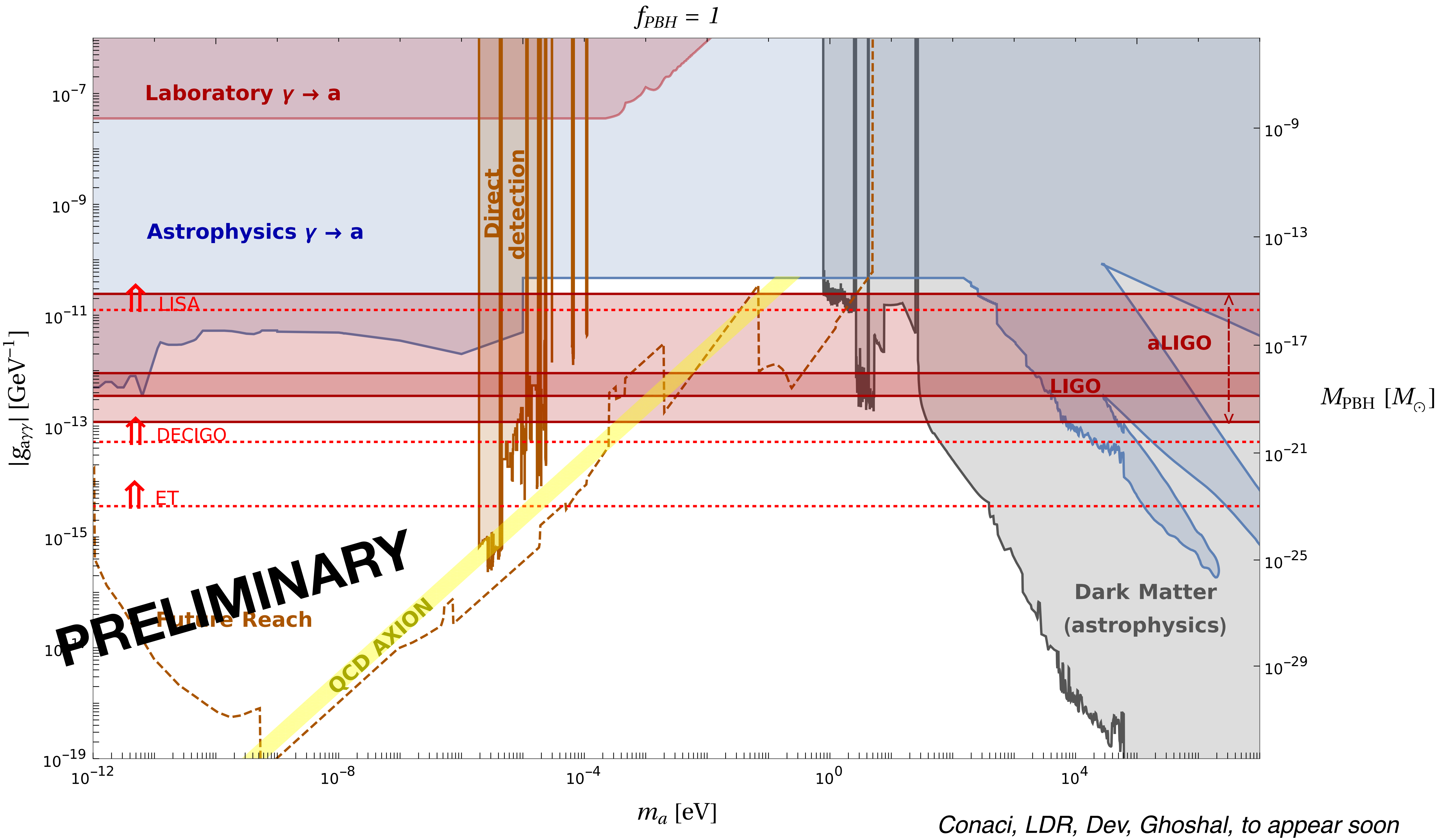
$$f_{\rm PBH} \simeq 0.32 \times 10^{12} \exp\left[-a\left(\frac{\beta}{H}\right)^b (1+\delta_c)^{c\frac{\beta}{H}}\right]\left(\frac{T_{\rm eq}}{1\ {\rm GeV}}\right)$$



Gouttenoir, Volansky, 2023

Supercool ALP

Another example of synergy between cosmology and lab. searches



Conaci, LDR, Dev, Ghoshal, to appear soon

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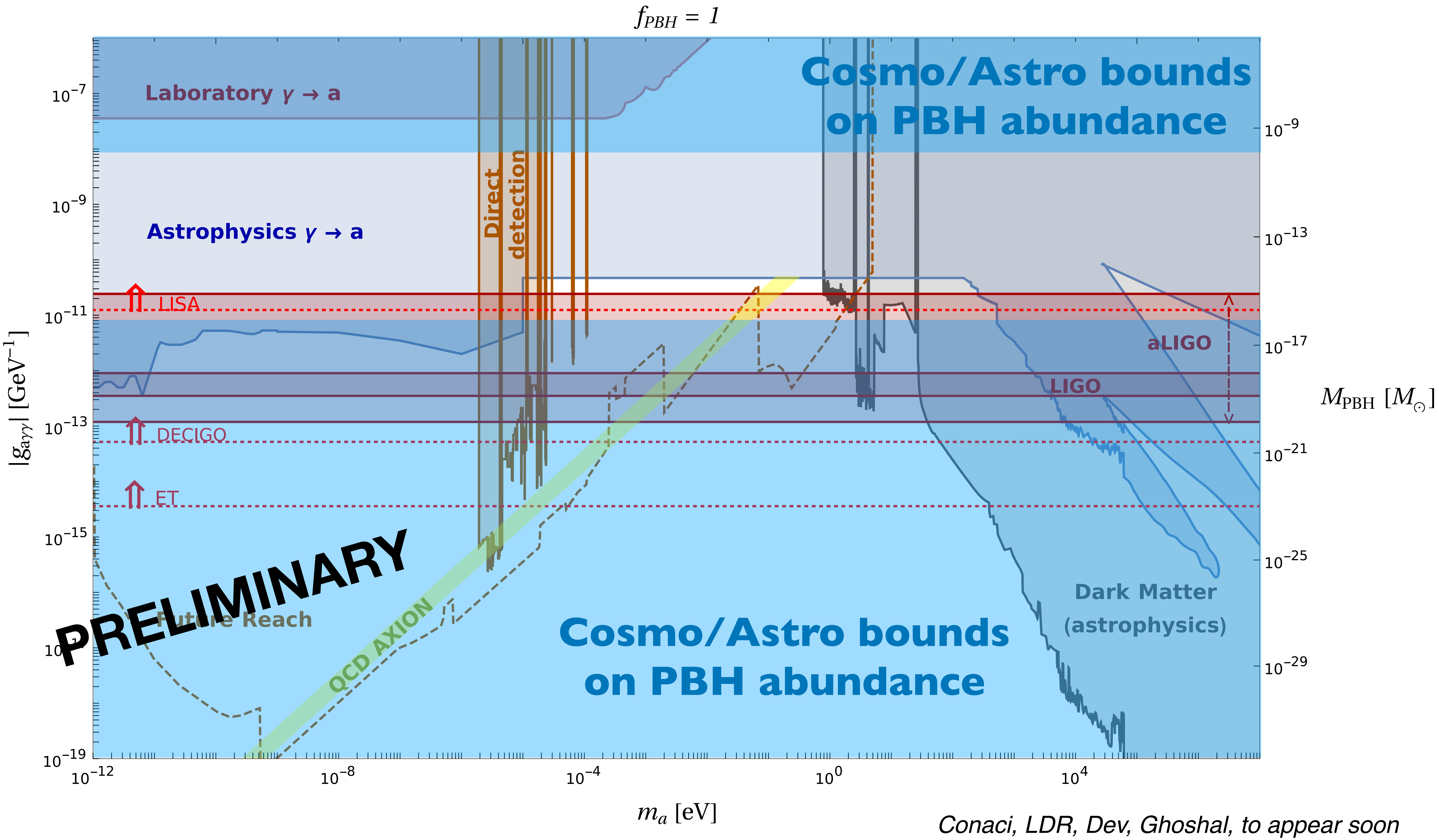

Conaci, LDR, Dev, Ghoshal, to appear soon

Backup slides

The Boltzmann equation

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

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 $2 \rightarrow 2$ 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 local equilibrium)