Bubble wall velocity in cosmological phase transitions

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New Physics Directions in the LHC era and beyond
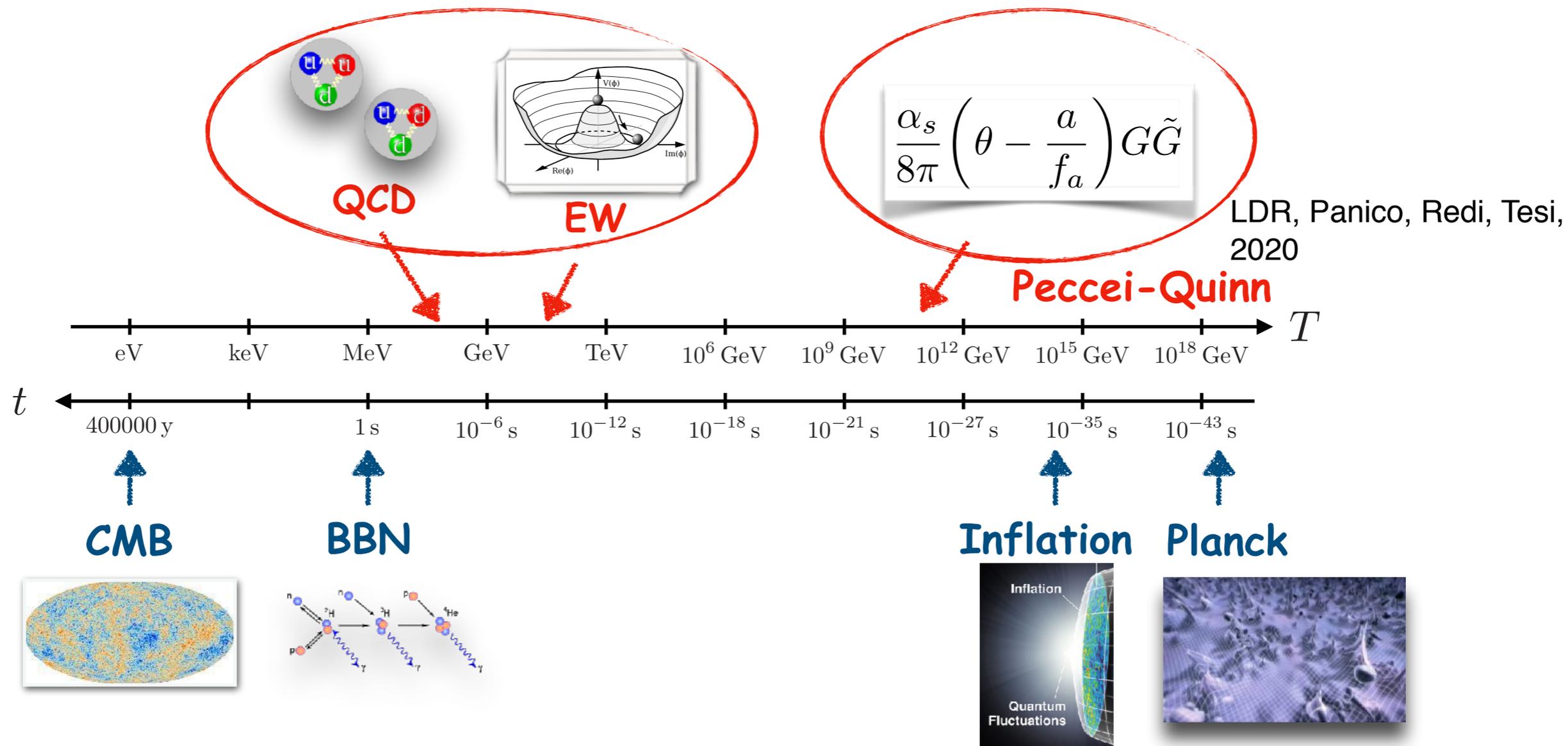
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Thermal History of the Universe

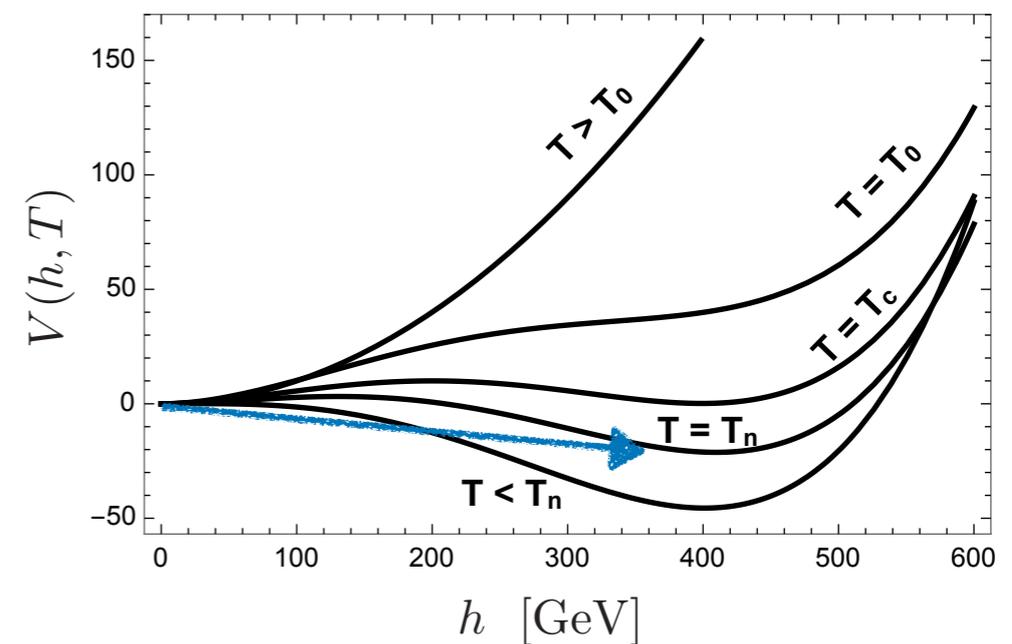**Phase transitions** are crucial events in the evolution of the Universe

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

  no strong breaking of thermal equilibrium

  no distinctive experimental signatures

- ▸ New physics may change the nature of these PhTs, or add new ones

QCD

$$V(\phi)$$
$$Re(\phi) \quad Im(\phi)$$

EW

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

LDR, Panico, Redi, Tesi,
2020

Peccei-Quinn

$$T$$

| 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

first-order EWPhT

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

New Physics at finite temperature

- 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

$\langle h \rangle = 0$

GW from
bubble collision

$\langle h \rangle \neq 0$

$\not{B} \neq 0$ $\not{B} \sim e^{-\langle h \rangle / T}$

CP

baryogenesys

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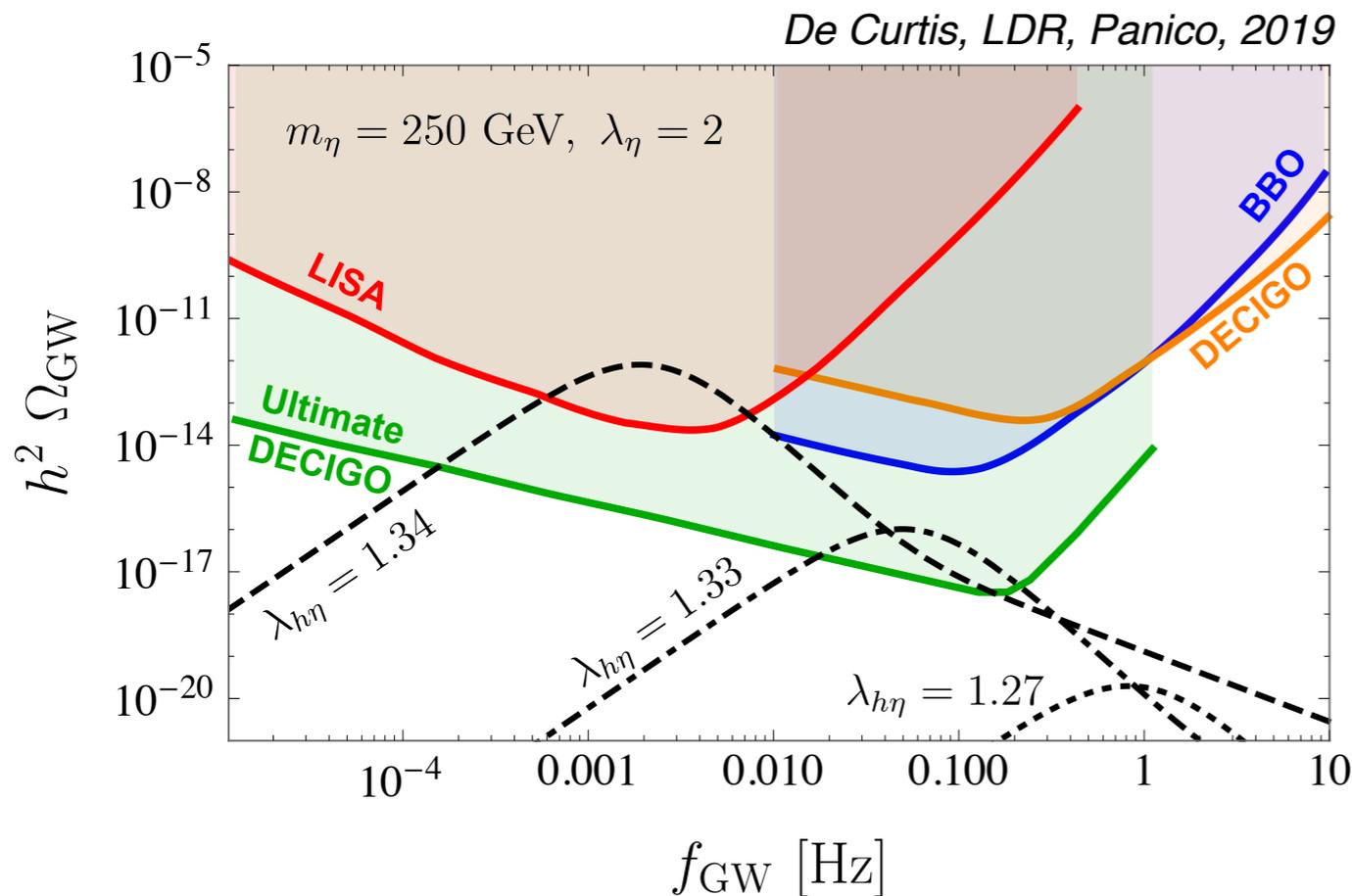
EWBG is typically efficient for slowly-moving walls. Recent results show efficiency also for fast-moving walls [Dorsch, Huber, Konstandin, 2021]

BG at the EW scale also possibile with $v_w \sim 1$ [Azatov, Vanvlasselaer, Yin, 2021]

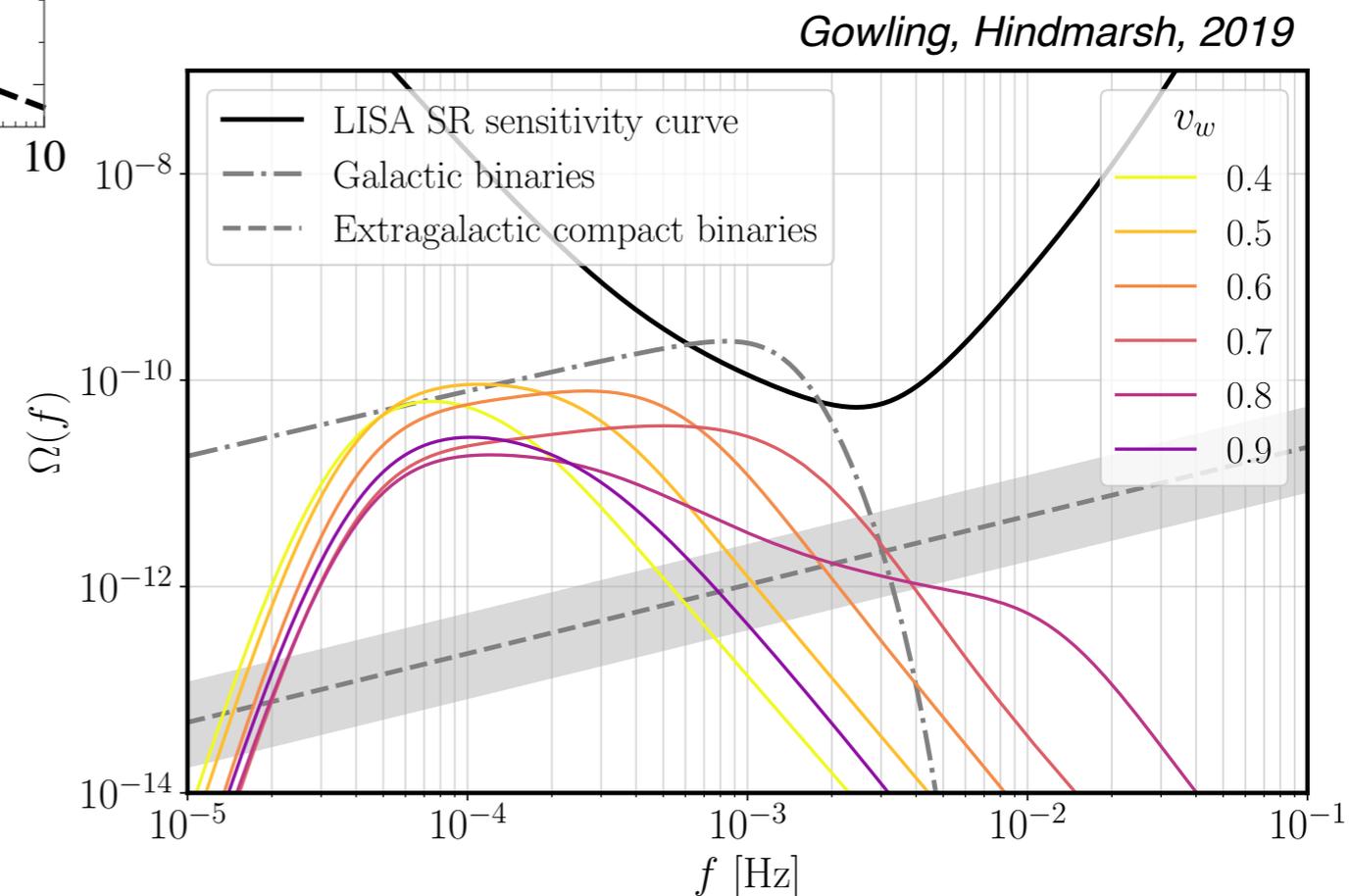GWs are maximised for fast-moving walls

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
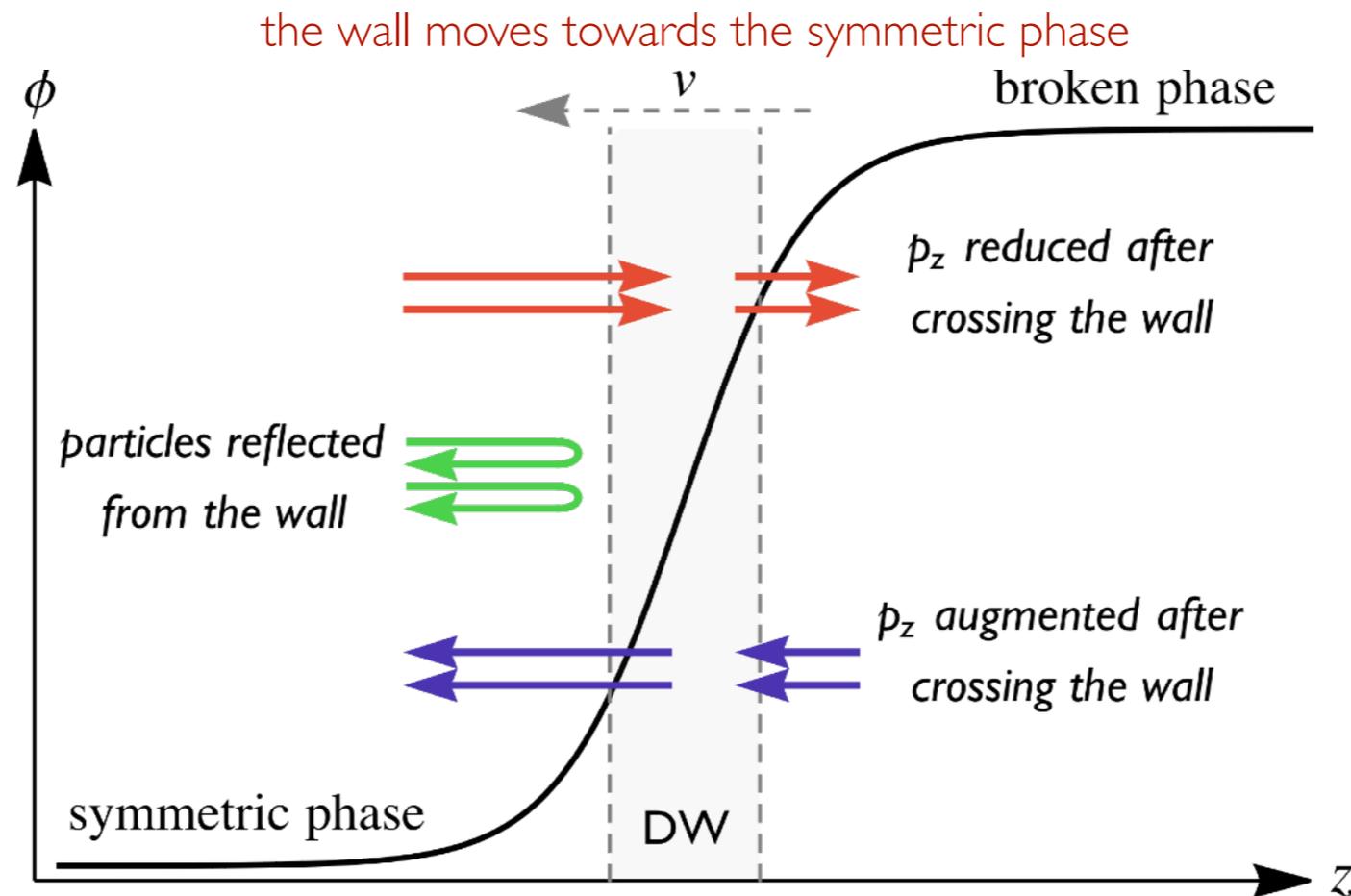
Gowling, Hindmarsh, 2019

- wall speed has a strong effect on the shape of the power spectrum

- wall speed will be the best determined parameter

for further motivations, see also A. Azatov talk on Monday

Dynamics of the bubble wall

System setup: scalar field + plasma

the wall moves towards the symmetric phase

broken phase

p_z reduced after crossing the wall

particles reflected from the wall

p_z augmented after crossing the wall

symmetric phase

DW

- 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)

- The bubble wall drives plasma out of equilibrium

Dynamics of the bubble wall

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

1. Scalar field equation
$$\phi' \Box \phi - V_T' = \sum N_i \frac{dm^2}{dz} \int \frac{d^3 p}{(2\pi)^3 2E_p} \delta f(p)$$

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

two competing effects: $(m^2)'$ and $\mathcal{C}$

we assume a planar wall and a steady state regime

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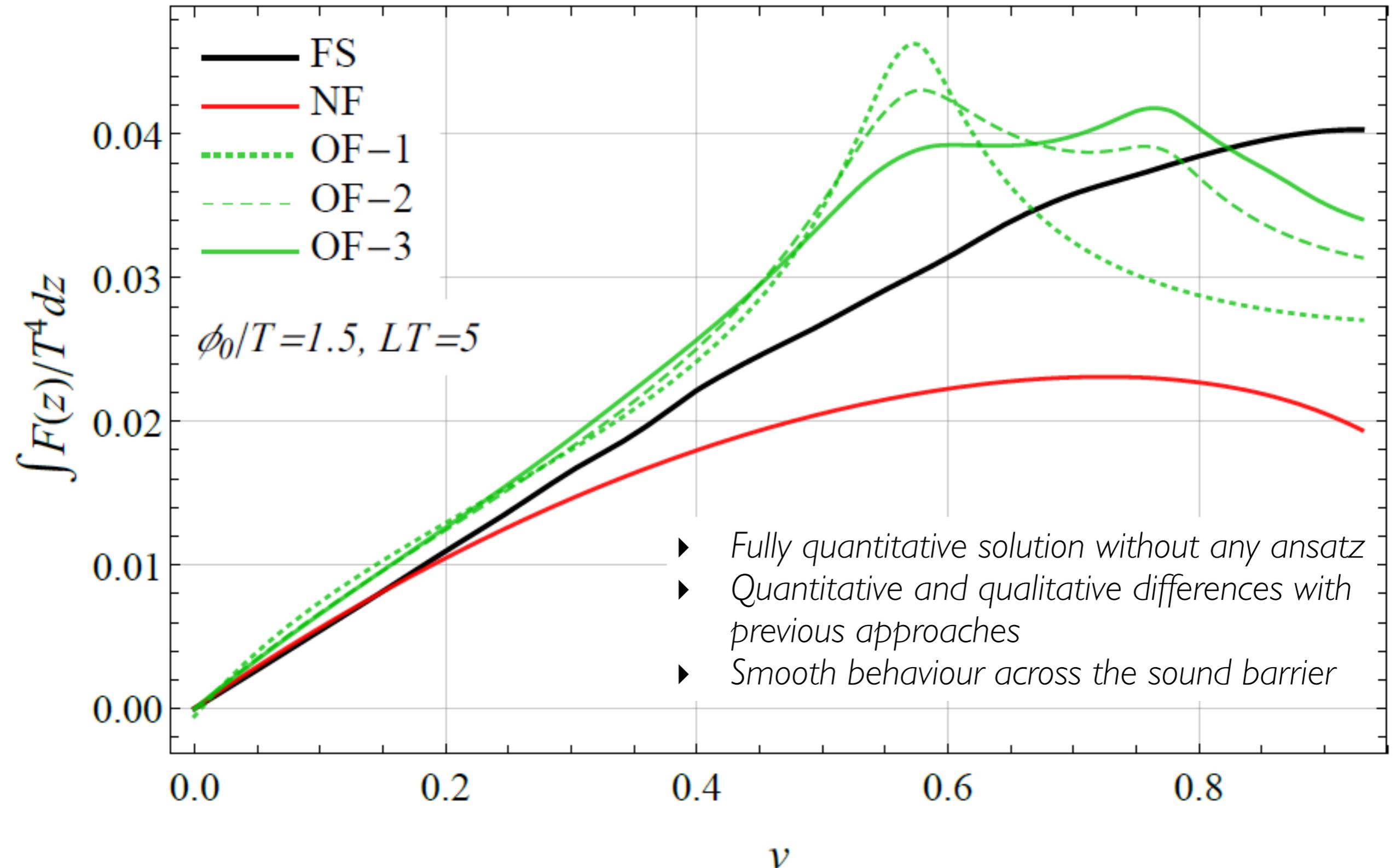
[4] Laurent, Cline, 2022
[5] Bigazzi, Caddeo, Canneti, Cotrone

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.

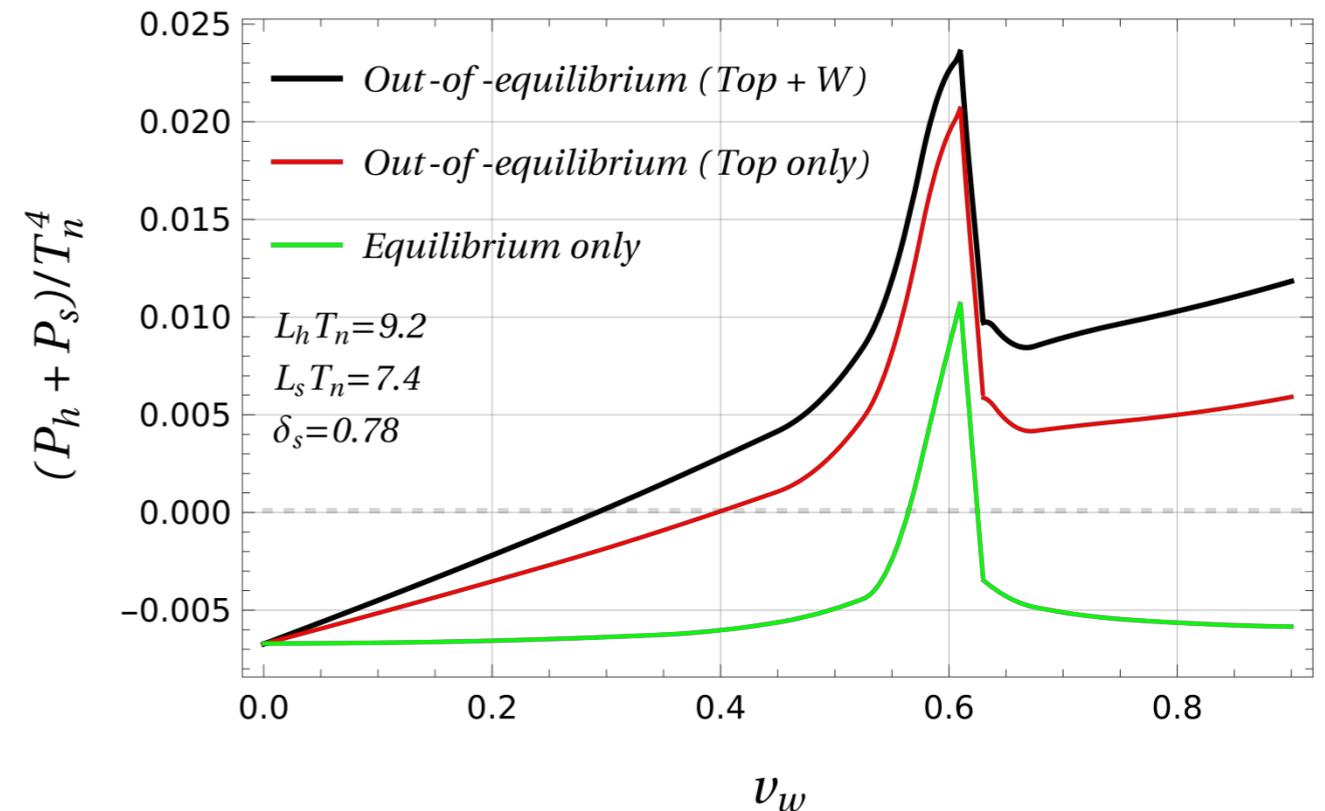*De Curtis, LDR, Guiggiani, Gil Muyor, Panico, 2023*
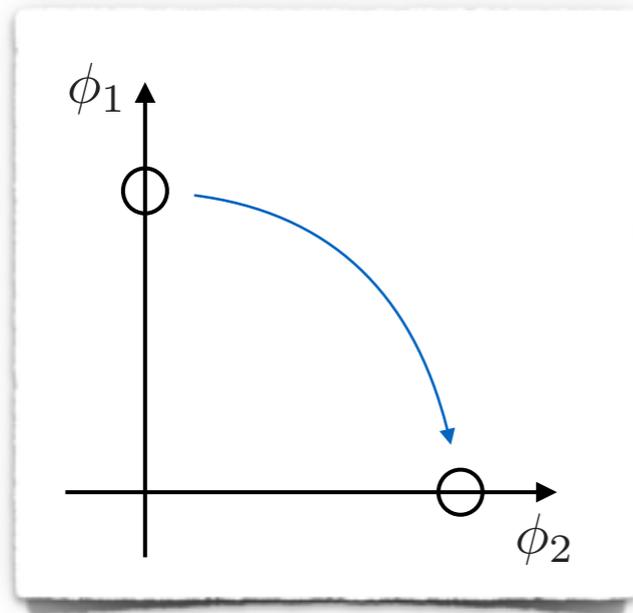
Key features

- 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

Determination of the wall speed

Benchmark scenario: SM + singlet

	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	130.1	129.9

	v_w	δ_s	$L_h T_n$	$L_s T_n$
BP1	0.28 [0.39] (0.57)	0.78 [0.79] (0.75)	9.2 [9.7] (8.1)	7.4 [7.7] (6.7)

▸ *Peak corresponding to the Jouguet velocity*
▸ *Important corrections from out-of-equilibrium perturbations*
▸ *Sizeable corrections given by the W bosons*

De Curtis, LDR, Guiggiani, Gil Muyor, Panico, 2024

Conclusions and outlook

Conclusions:

- ▶ Fully quantitative solution to the Boltzmann equation

- ▶ Computation of v_w

- ▶ New spectral method based on multipole decomposition

- ▶ Quantitative and qualitative differences with previous approaches

- ▶ Important impact of out-of-equilibrium friction

Work in progress:

- ▪ inclusion of $1 \to 2$ and $2 \to 1$ plasma processes in the collision integrals

- ▪ improving the description of W bosons in the ultra-soft regime

- ▪ Release of the code