DM Gravity Cosmology

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&
Danièle Steer

DMLab meeting, December 13, 2022

Gravitational waves from first-order phase transitions

• first-order phase transitions proceed by bubble nucleations

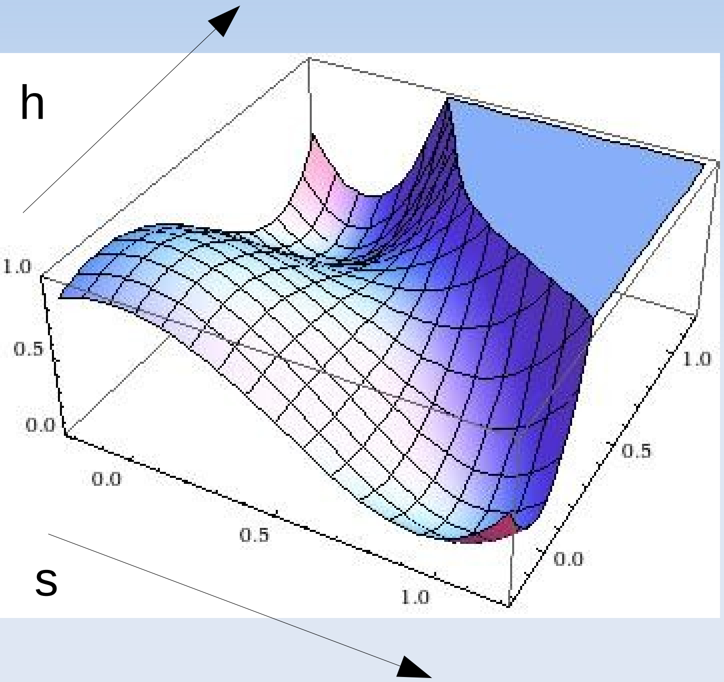
• in case of the electroweak phase transition, the ”Higgs bubble wall” separates the symmetric from the broken phase

• this is a violent process $(v_{wall} \simeq O(c))$ that drives the plasma out-of-equilibrium and sets the fluid into motion

Singlet extension

The Standard Model only features a electroweak crossover.

A potential barrier and hence first-order phase transitions are quite common in extended scalar sectors:



$$V(h,s) = \frac{\lambda}{4}\left(h^2 - v^2\right)^2 + m_s^2 s^2 + \lambda_s s^4 + \lambda_m s^2 h^2$$

The singlet field has an additional $\mathbb{Z}_2$ symmetry and is a viable DM candidate.

The phase transition proceeds via

$$(h,s) = (0,w) \to (h,s) = (v,0)$$

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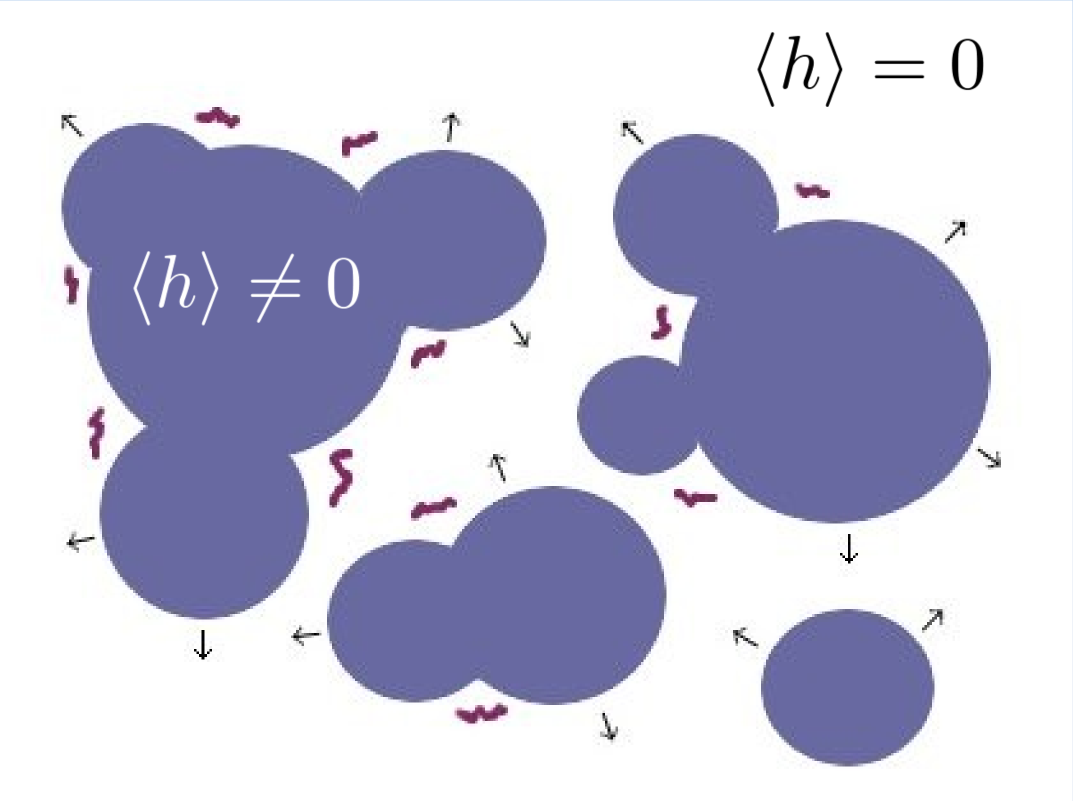
Gravitational waves

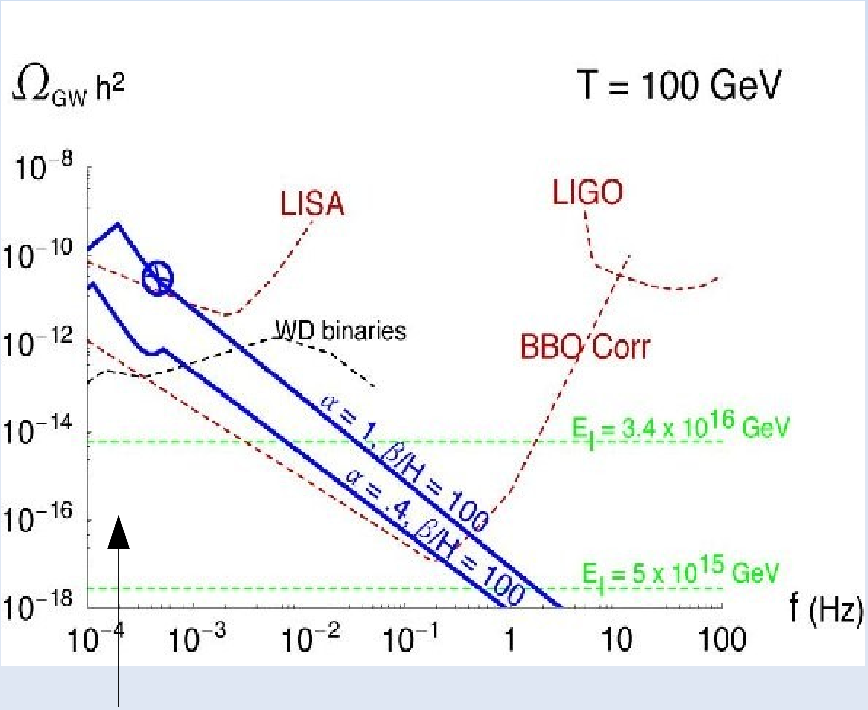


During the first-order phase transitions, the nucleated bubbles expand. Finally, the colliding bubbles break spherical symmetry and generate stochastic gravitational waves.

Observation

[Grojean&Servant '06]

The produced gravitational waves can be observed with laser interferometers in space ...

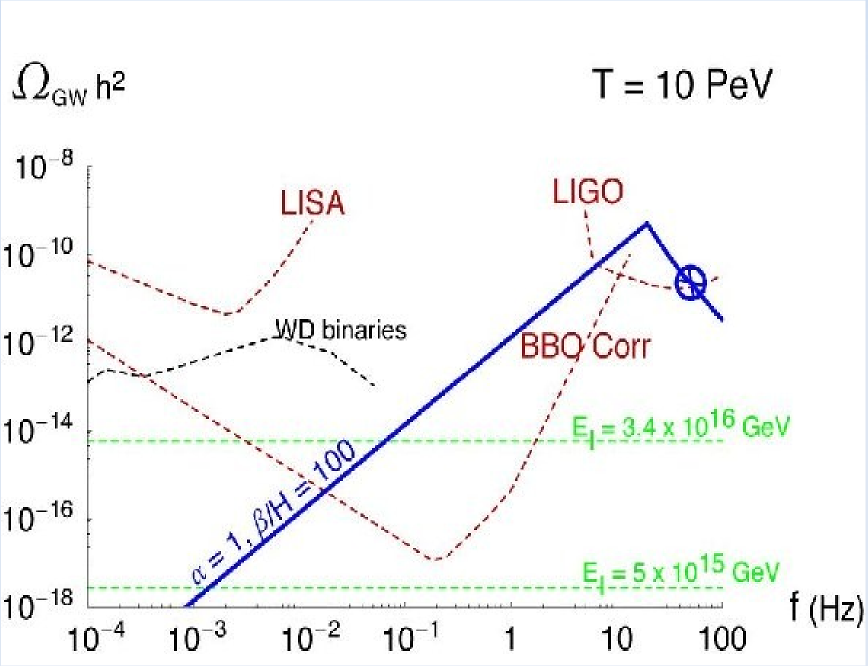


redshifted **Hubble horizon** during a phase transition at T ~ 100 GeV

Observation

[Grojean&Servant '06]

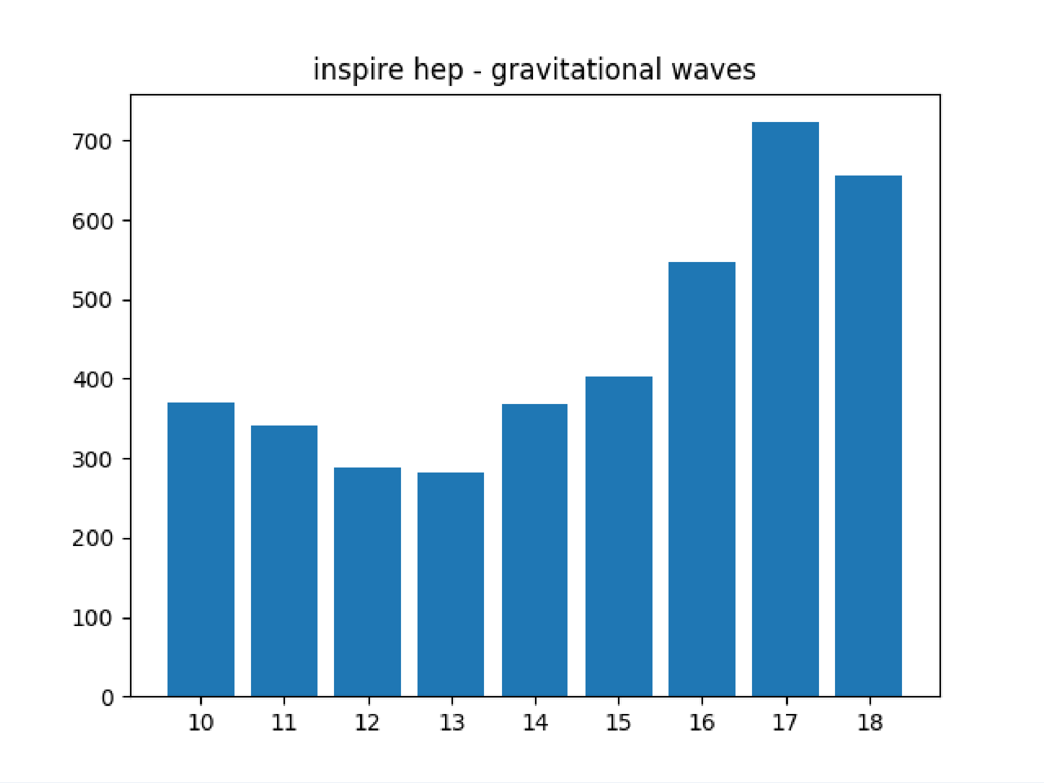
… or on the ground

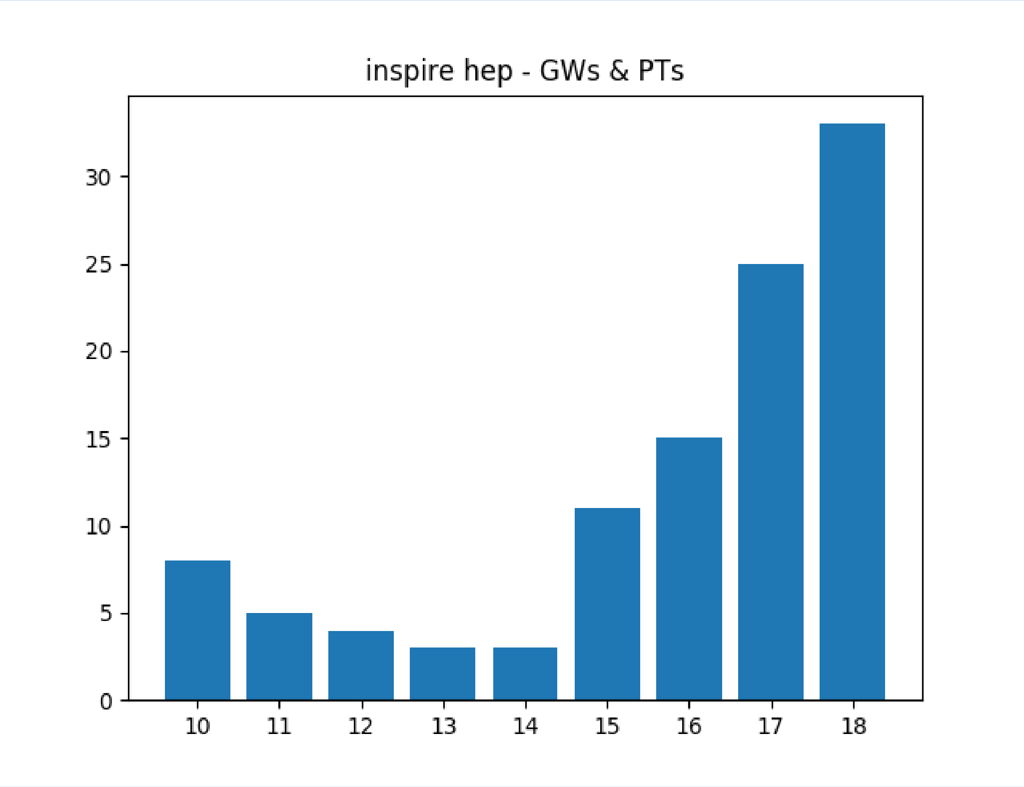


Strong phase transition at larger temperatures produce the same energy fraction of gravitational waves but at higher frequencies.

GWs from PTs

ArXiv activity:





GWs from PTs

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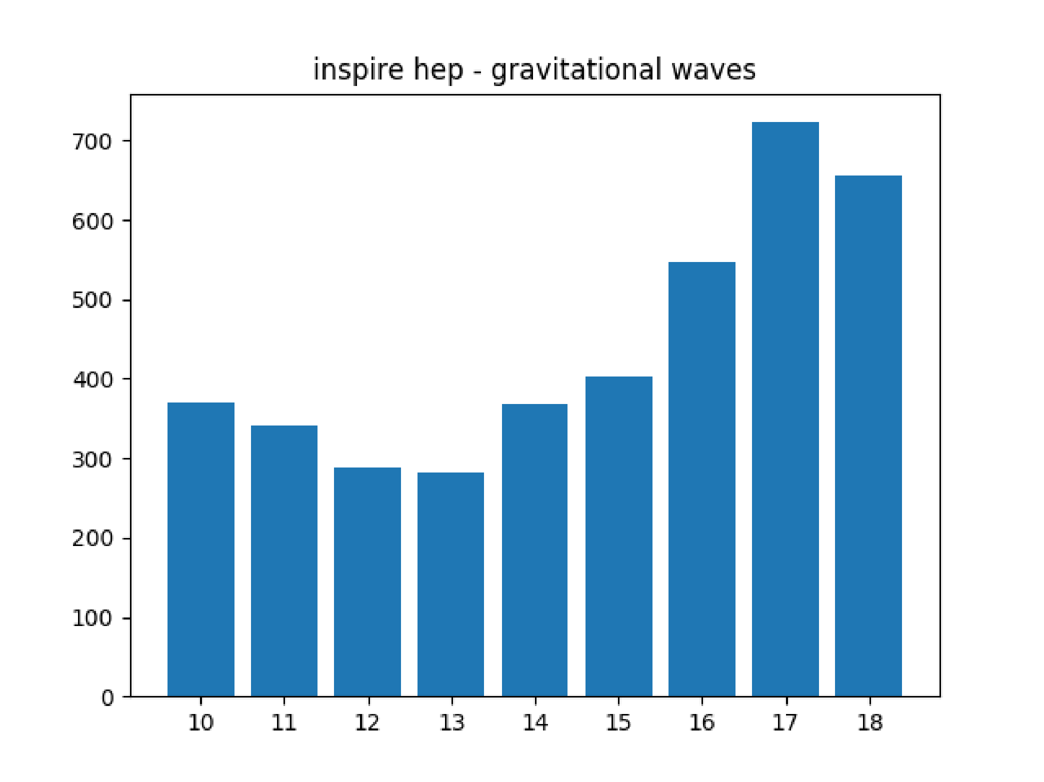
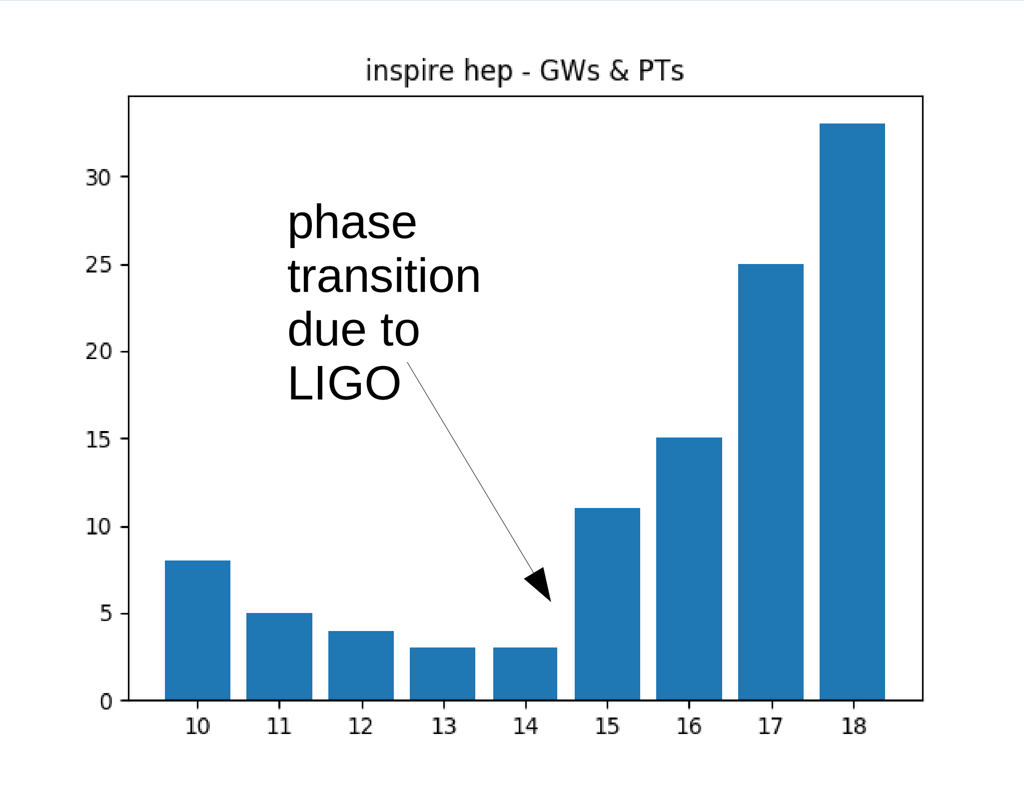




Back of the envelope

There are several quantities that can enter in the determination of the GW spectrum:

The temperature of the phase transition T.

The (inverse) duration of the phase transition

$P \propto \exp(\beta t)$ and typically

The wall velocity $v_w \sim 1$.

The amount of latent heat that is transformed into kinetic energy *K* in the plasma:

$$\Lambda \to K \, , \quad \alpha = \frac{\Lambda}{\rho_{\rm tot}}$$

Back of the envelope

There are several quantities that can enter in the determination of the GW spectrum:

The temperature of the phase transition T.

The (inverse) duration of the phase transition

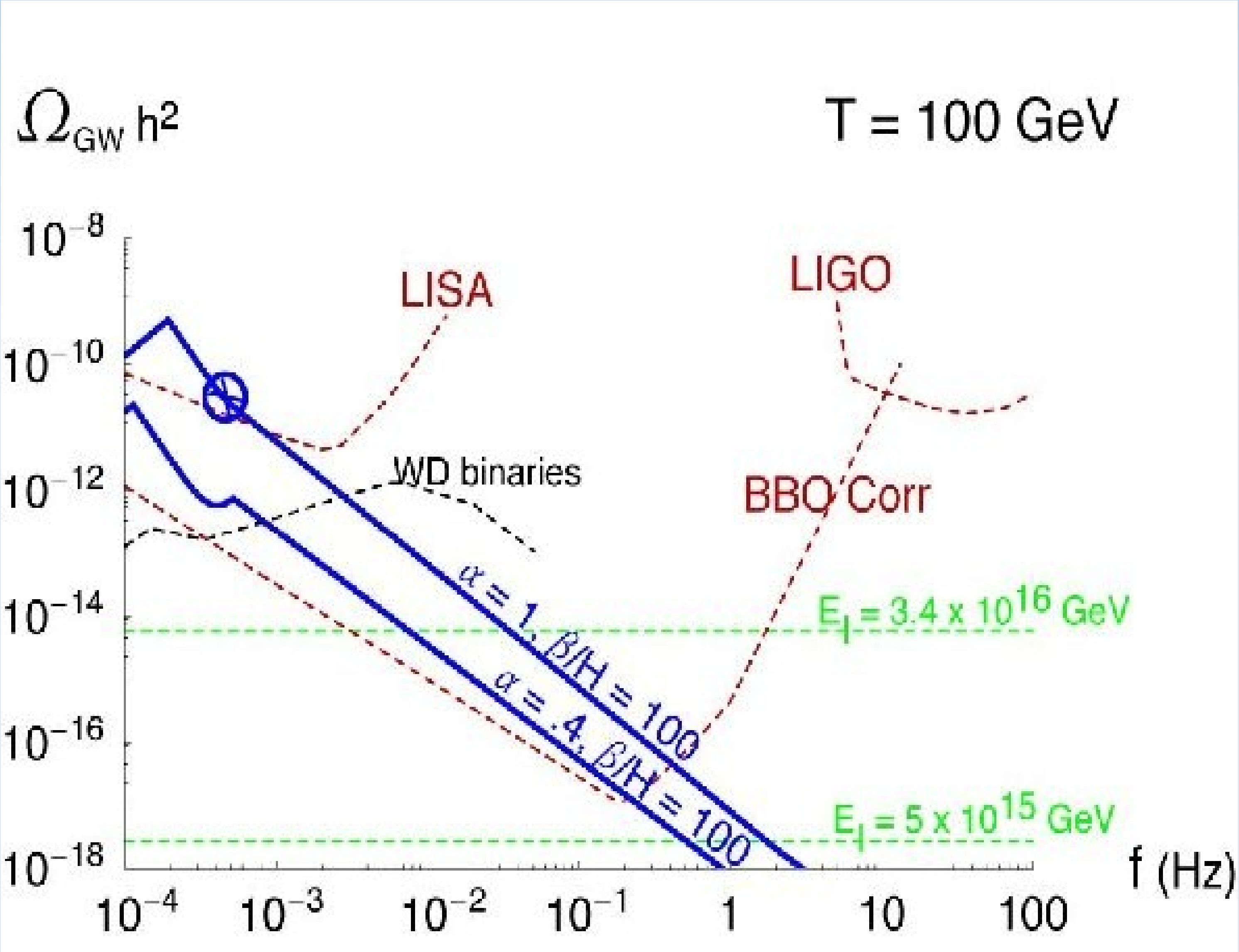
$P \propto \exp(\beta t)$ and typically $\beta/H \sim O(100)$

The wall velocity $v_w \sim 1$.

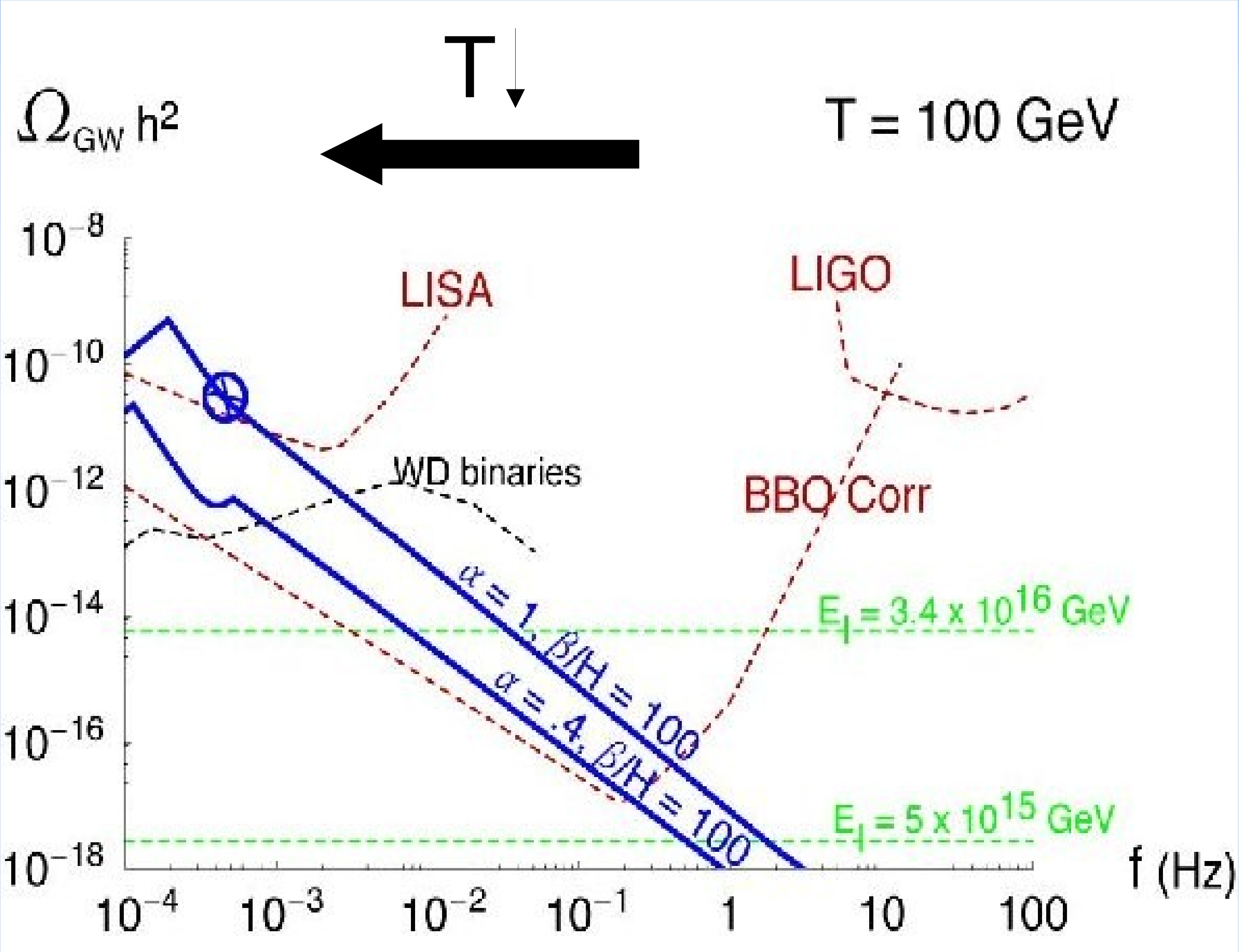
The amount of latent heat Λ that is transformed into kinetic energy *K* in the plasma:

$$\Lambda \to K \, , \quad \alpha = \frac{\Lambda}{\rho_{\rm tot}}$$

Observation



Observation



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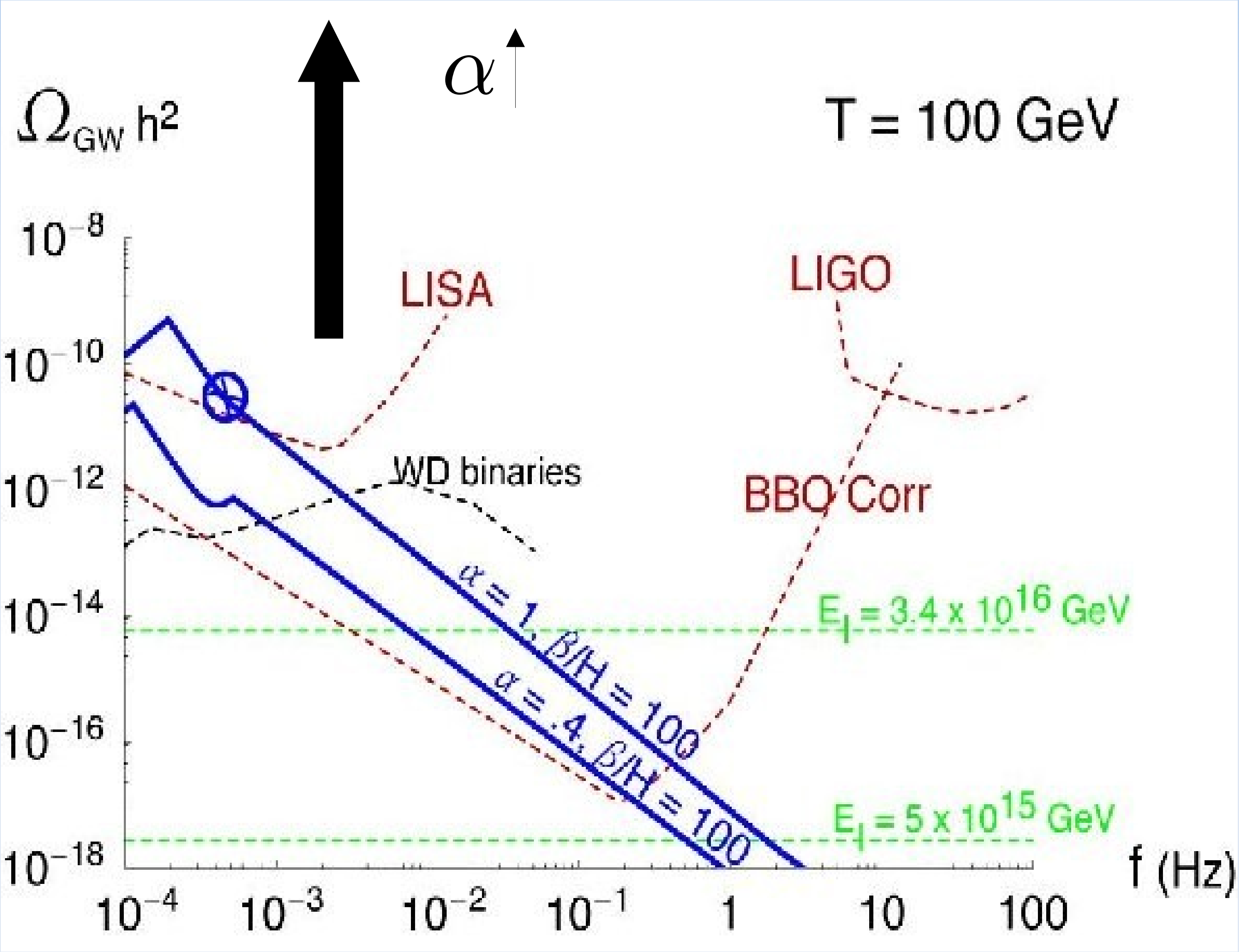

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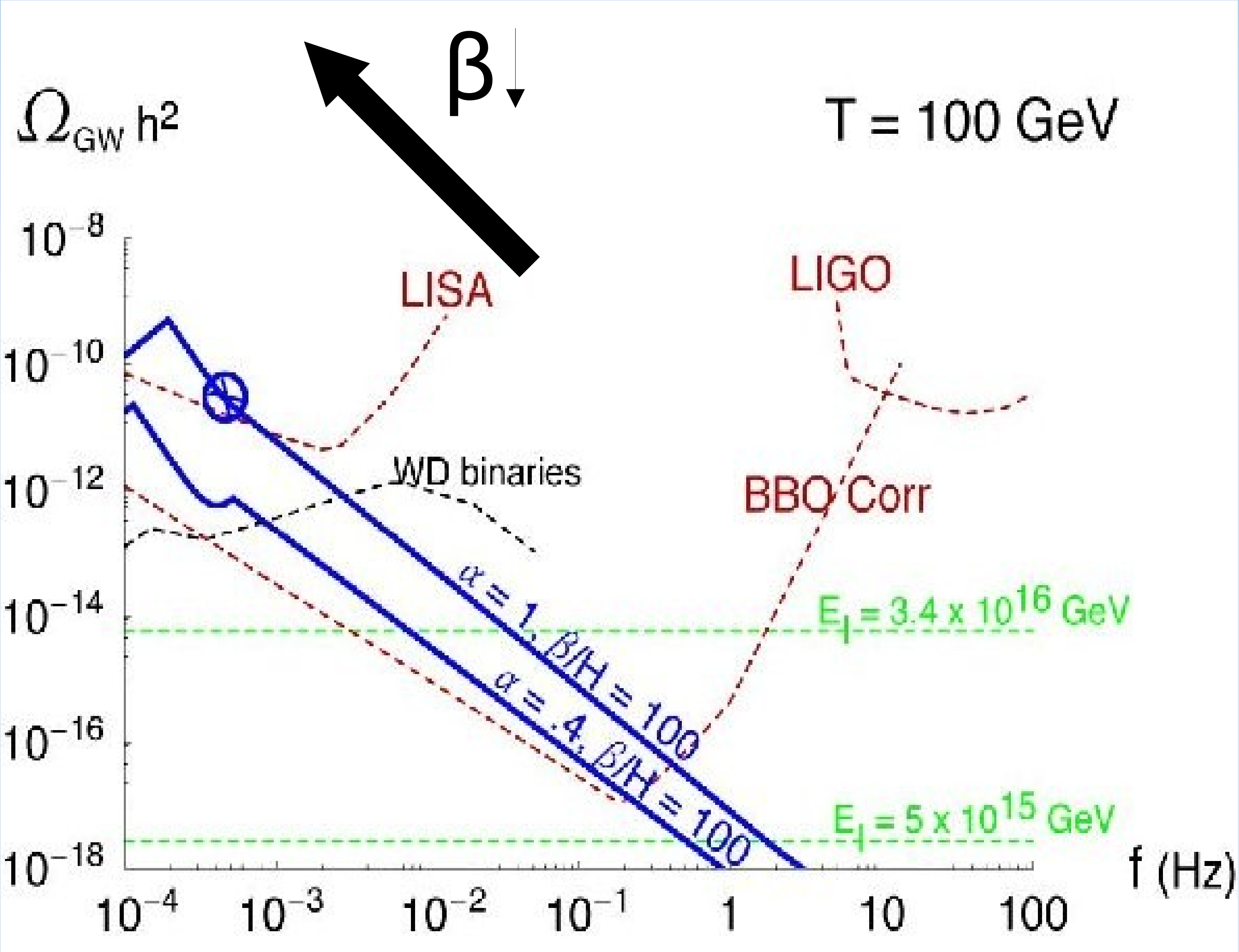

Sources of GWs from PTs

During and after the phase transition, several sources of GWs are active

- Collisions of the scalar field configurations / initial fluid shells
- Sound waves after the phase transition (long-lasting → dominant source)
- Turbulence
- Magnetic fields

In the last 10 years, simulations became the main tool to incorporate all these effects.

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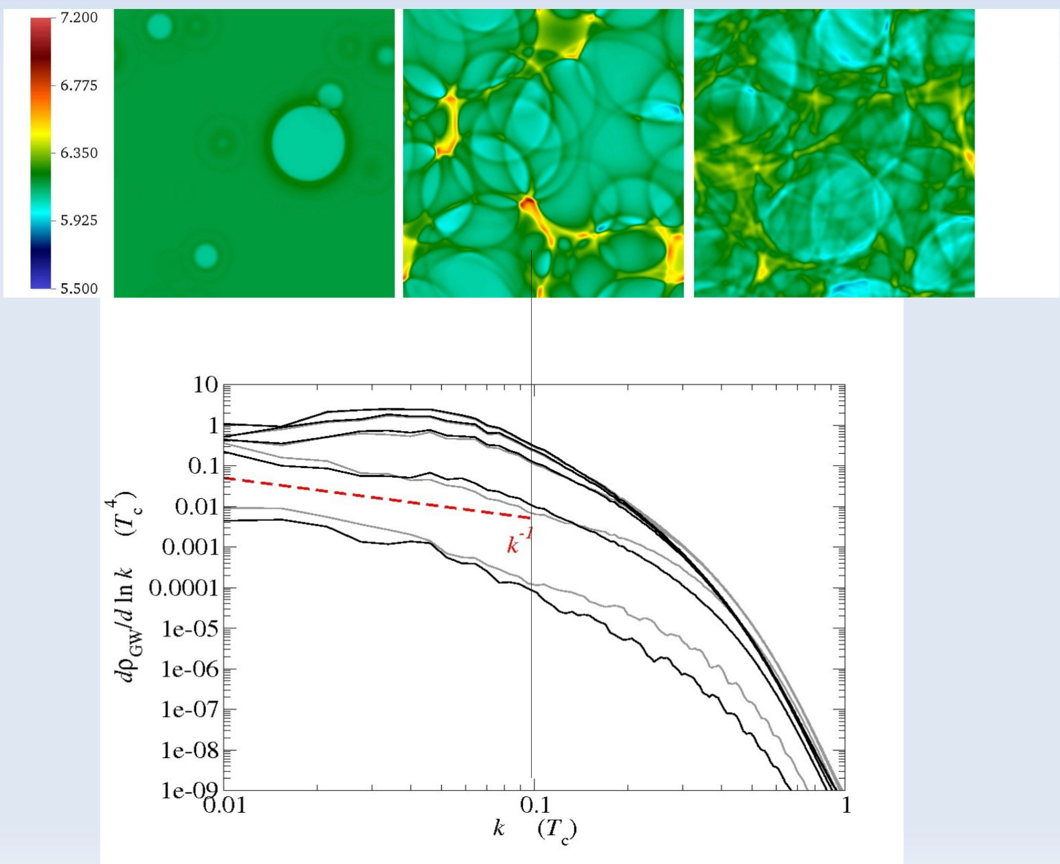
State-of-the-art: simulations

[Hindmarsh, Huber , Rummukainen, Weir '13, ’15, ’17]
[Weir ’16] [Gould, Sukuvaara,Weir ’21] [Cutting, Hindmarsh, Weir ’18&’19]
[Cutting, Escartin, Hindmarsh, Weir ’20]

Depending on the context, the system can be descibed using hydrodynamics (fluid + Higgs) or just a scalar field



The produced GW spectrum can be read off from the simulation.

Really robust results, not many a priori assumptions.
But very costly.
How to extrapolate to other models and parameters?

Bubble wall thickness

The main challenge in the hydrodynamic simulation is to cover very different length scales.

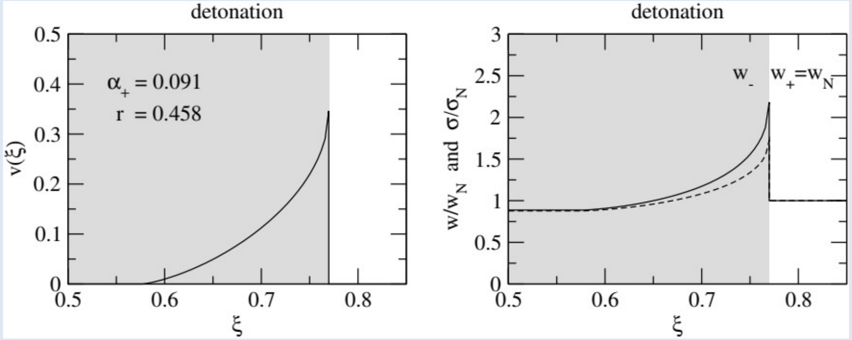
In the physical phase transition

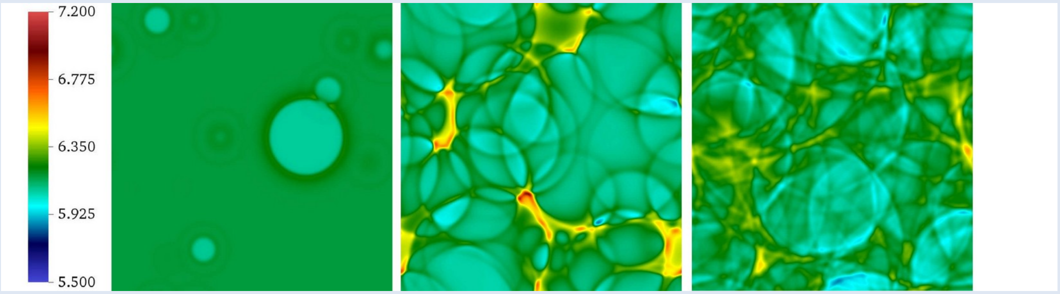
wall thickness   <<<<<<<   fluid shell thickness < bubble size

1/100GeV   % of Hubble radius

In simulations:

grid spacing < (wall thickness < fluid shell thickness < bubble size) < box size





Higgsless simulations

In order to avoid this issue, we want to perform simulations that are agnostic about the wall thickness. This would resemble an *EFT* where the Higgs field was integrated out.

However, this requires a hydrodynamic numerical framework that can deal with *shocks* and other discontinuities:

New High-Resolution Central Schemes for Nonlinear Conservation Laws and Convection–Diffusion Equations

Alexander Kurganov* and Eitan Tadmor†

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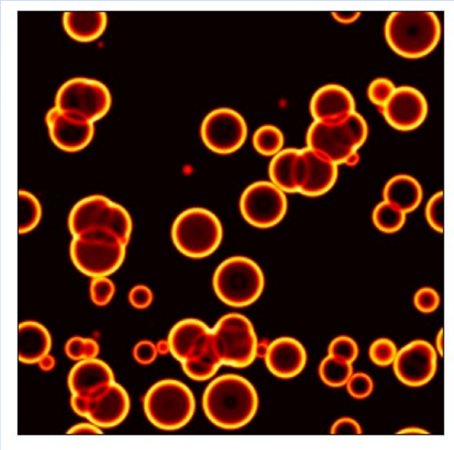
Received April 8, 1999; revised December 8, 1999

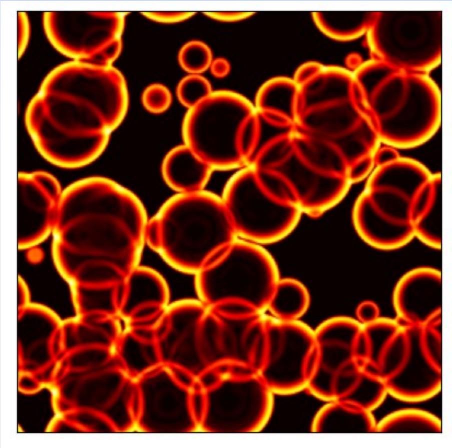
Central schemes may serve as universal finite-difference methods for solving nonlinear convection–diffusion equations in the sense that they are not tied to the specific eigenstructure of the problem, and hence can be implemented in a straightforward manner as black-box solvers for general conservation laws and related equations governing the spontaneous evolution of large gradient phenomena. The first-order Lax–Friedrichs scheme (P. D. Lax, 1954) is the forerunner for such central schemes. The central Nessyahu–Tadmor (NT) scheme (H. Nessyahu and E. Tadmor, 1990) offers higher resolution while retaining the simplicity of the Riemann-solver-free approach. The numerical viscosity present in these central schemes is of order $\mathcal{O}((\Delta x)^{2r}/\Delta t)$. In the convective regime where $\Delta t \sim \Delta x$, the improved resolution of the NT scheme and its generalizations is achieved by lowering the amount of numerical viscosity with increasing r. At the same time, this family of central schemes suffers from excessive numerical viscosity when a sufficiently small time step is enforced, e.g., due to the presence of degenerate diffusion terms.

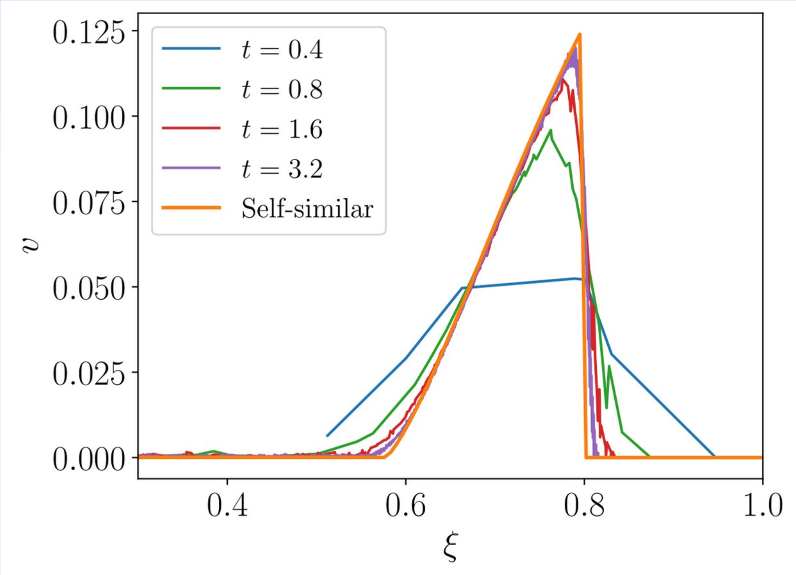
In this paper we introduce a new family of central schemes which retain the sim-

Simulation of cosmological phase transitions

We recently developed a highly efficient scheme to simulate relativistic hydrodynamics during cosmological first-order phase transitions.





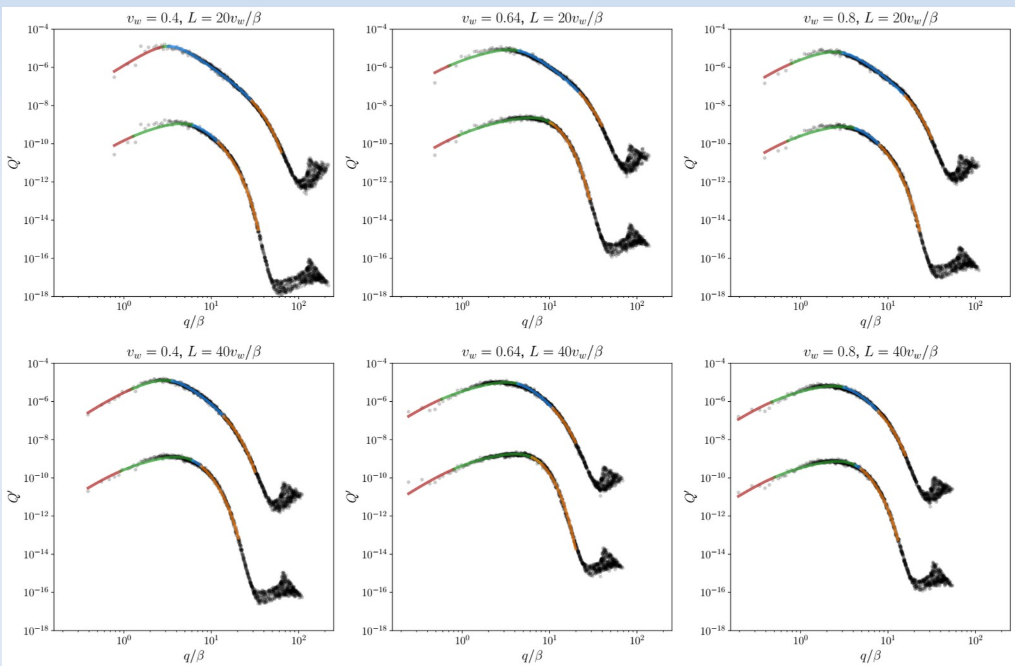


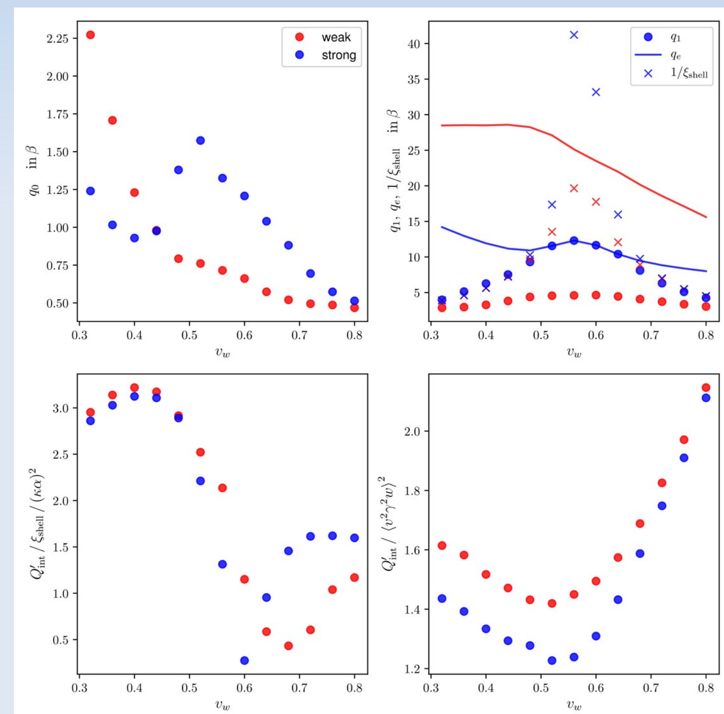
These simulations allow to extract GW spectra from the phase transition in a few hours instead of weeks

(factor 2000 speed improvement compared to former approaches)

Simulation of cosmological phase transitions

The setup allows to run many simulations a day and to extract the GW spectra as functions of the PT properties: wall velocity v_w, PT strength α





The spectra have two features due to the bubble size and the shell thickness.

[Jinno, TK, Rubira, Stomberg 2022]

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In the last 10 years, simulations became the main tool to incorporate all these effects.

Generation of gravitational waves from freely decaying turbulence

Pierre AUCLAIR, Chiara Caprini, Daniel Cutting, Mark Hindmarsh, Kari Rummukainen, Danièle A. Steer, David J. Weir
arXiv:2205.02588

June 7, 2022

Cosmology, Universe and Relativity at Louvain (CURL)
Institute of Mathematics and Physics
Louvain University, Louvain-la-Neuve, Belgium

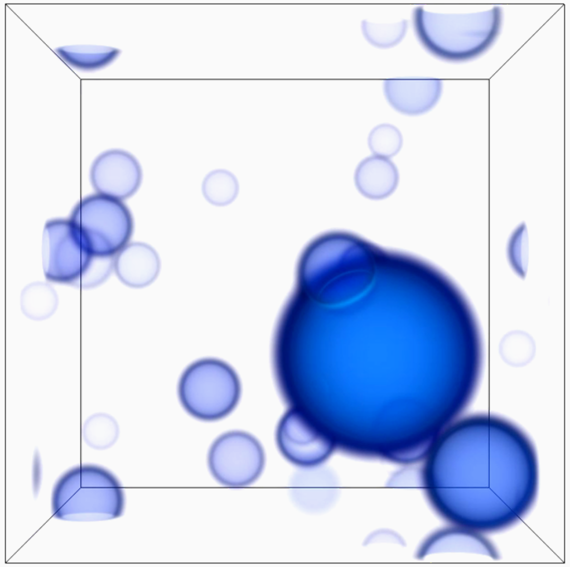
Physics of a thermal first order phase transition

Several processes during the phase transition may generate GW

- Bubble collisions Turner and Wilczek 1990
- Sound waves Hindmarsh et al. 2014
- In strong phase transitions, shocks may convert the acoustic phase into a turbulent one Pen and Turok 2016

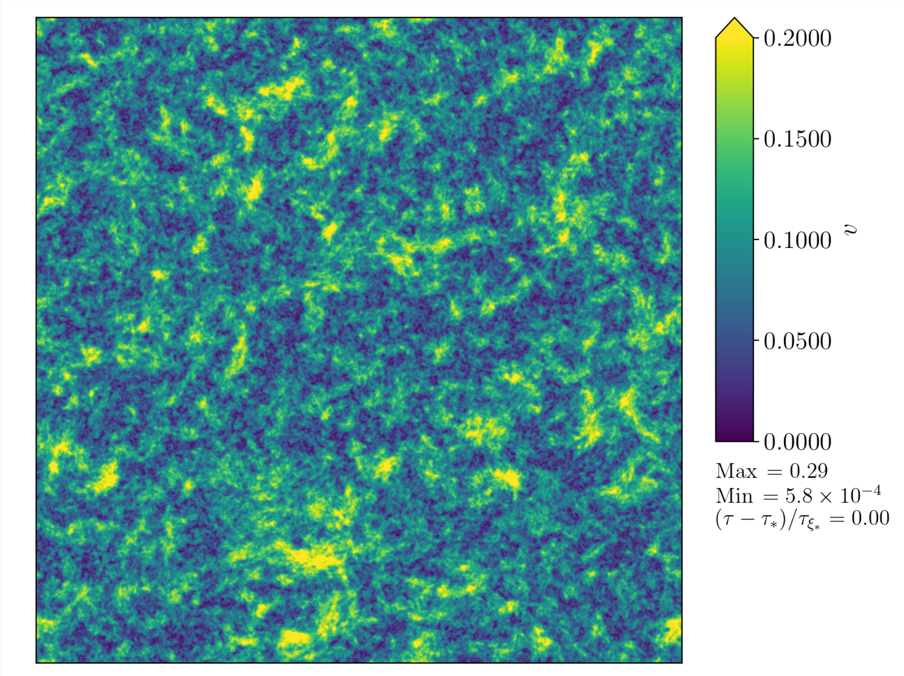
Purpose of the paper:

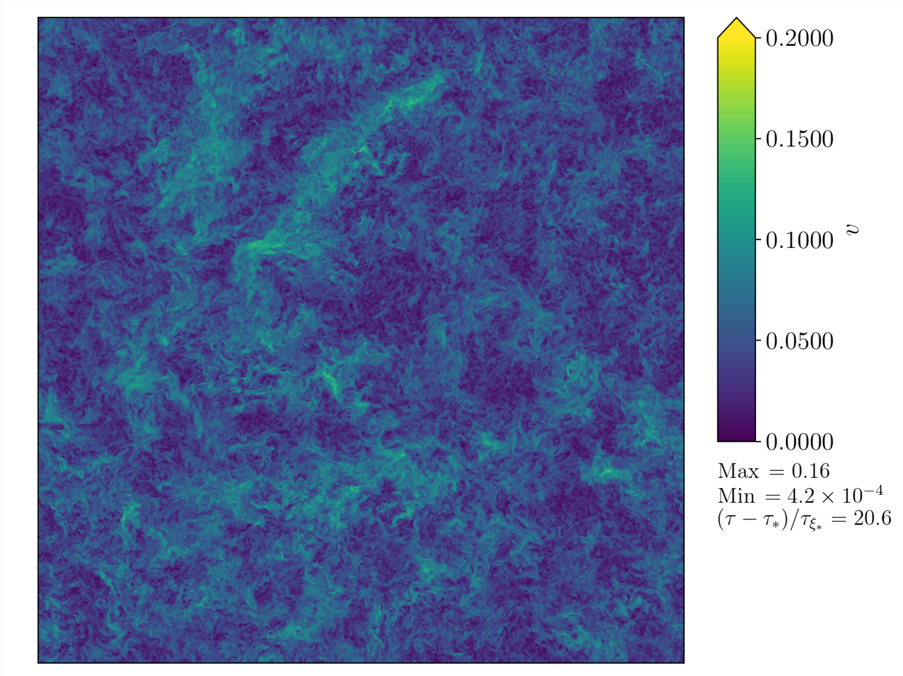
- provide templates for the future LISA GW detector.
- More specifically, we model decaying turbulence semi-analytically and validate with massively parallel numerical simulations



Credits: Hindmarsh et al. 2014

Snapshot of the simulations



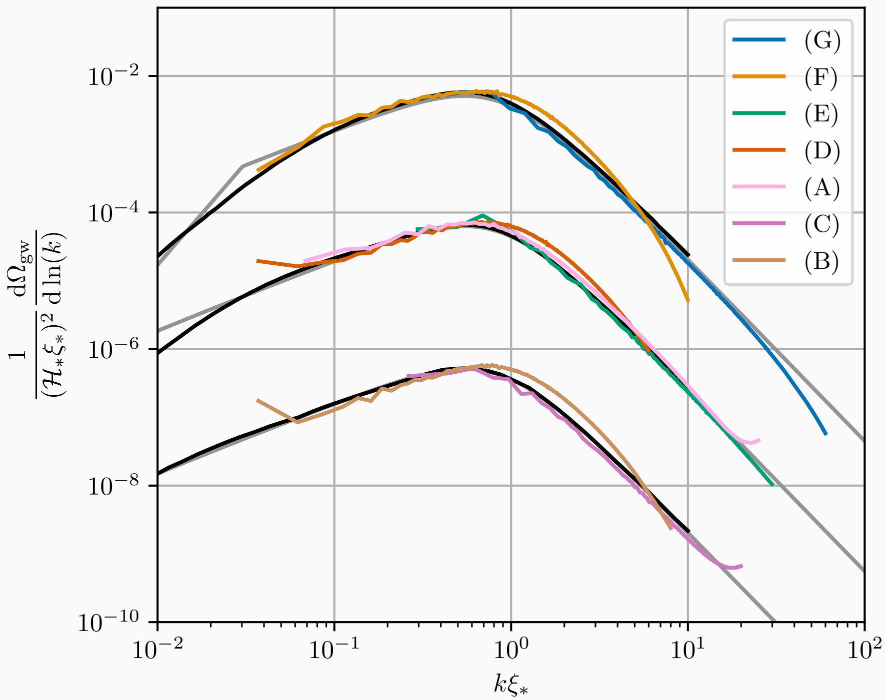


Left panel: Slice through simulation (A') showing the velocity initial conditions in real space. *Right panel*: Same slice as the left panel but after a time $\Delta\tau = 20.6\tau_{\xi_*}$ has elapsed.

GW power spectrum for instantaneous generation

- Gray lines: our analytical approximation based on a constant source lasting a few eddy turnover times
- Black lines: result of the 4d numerical integration
- Colored lines: From top to bottom $\overline{v}_* = 0.3$, $\overline{v}_* = 0.1$ and $\overline{v}_* = 0.03$ respectively for simulations (A)-(G)

Main result 1



eq 7.16

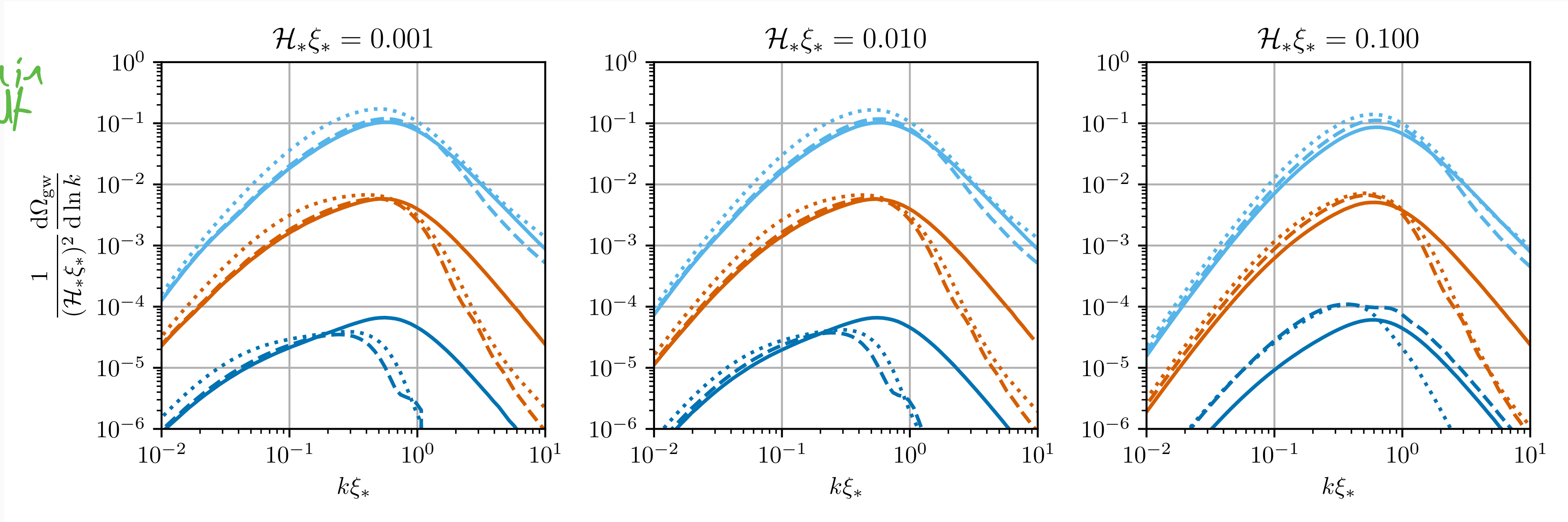
in the paper we have a neat formula for the grey line

Impact of a growth phase

We include a growth phase for the turbulence kinetic energy

Main result 2

Main result



In principle, one would have to model the onset of turbulence by simulating the complete system of scalar field and fluid

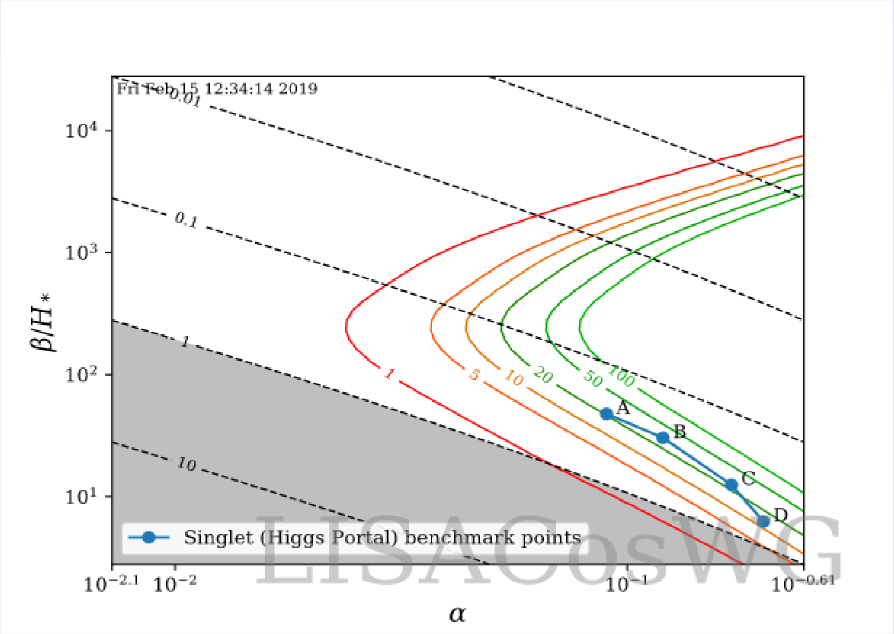
Putting it all together

The different sources and the relation to particlue physics model building is discussed in publications by the LISA cosmology working group on GWs from cosmological phase transitions:

Science with the space-based interferometer eLISA. II: Gravitational waves from cosmological phase transitions
Caprini et al.
arxiv/1512.06239

Detecting ravitational waves from cosmological phase transitions with LISA: an update
Caprini et al.
arxiv/1910.13125

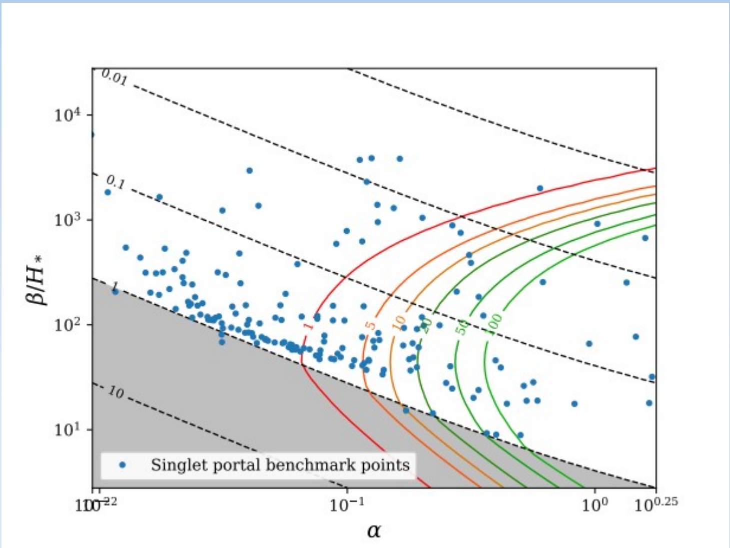
web-tool by *David Weir*
http://www.ptplot.org



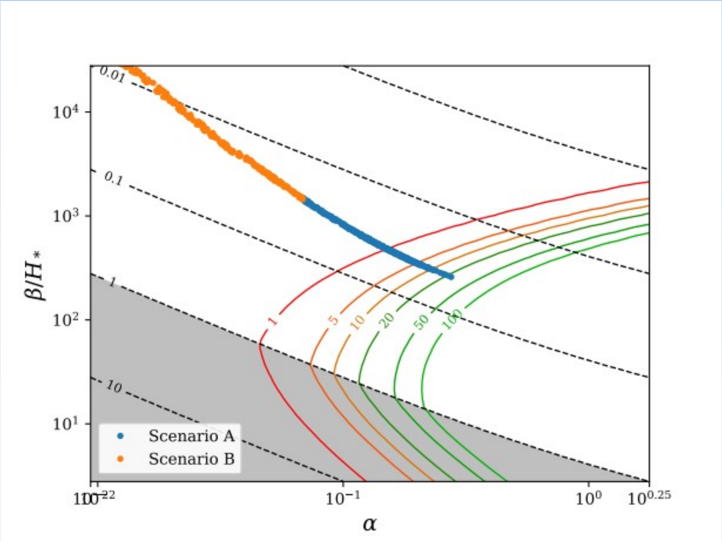
DMLab will help to intensify this collaboration!

Thank you!

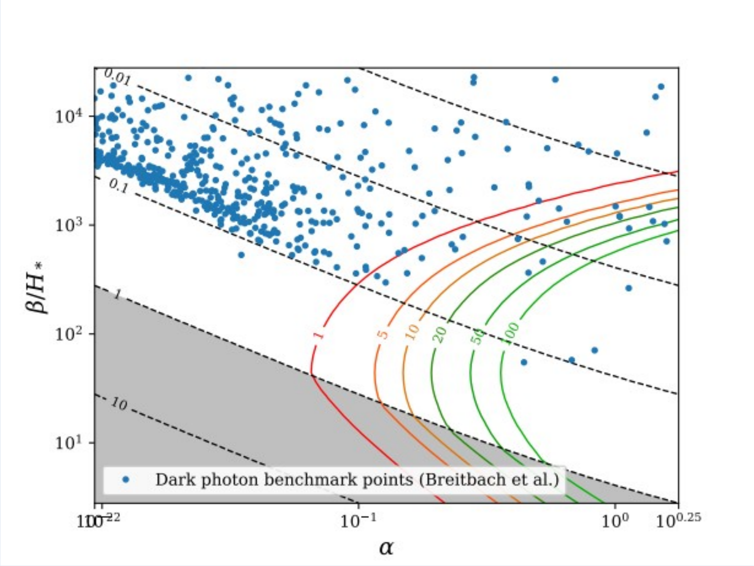
singlet portal model



SM EFT



dark photon



THD