IFAE, Nov 22

Higgsless simulations of gravitational wave in 1st-order phase transitions

(based on 2010.00971, 2108.11947, 2209.04369)

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In collaboration with: Ryusuke Jinno, Thomas Konstandin, Jorinde v.d. Vis, Isaac Stromberg, Valerie Domcke

Before anything else, cool things always come with videos

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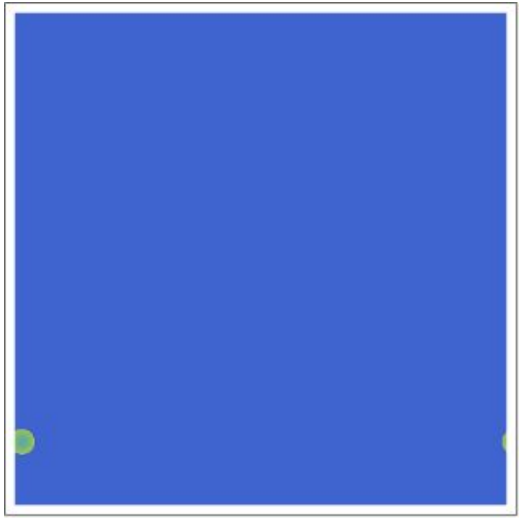

Notice two scales:

- Initially we see mainly the bubble size
- Later we see sound shells superposing

A message to take home...

New simulation scheme for sound-shell contribution in 1st order PT

Advantages:

1) fast (easier to explore parameter dependence);

2) Don't need to include scalar field (solve particle physics scale in a cosmo simulation);

3) Incorporate shock front easily.

4) We can go non-linear!!!

5) Exploring alternative scenarios

A message to take home...

A user-friendly parametrization...

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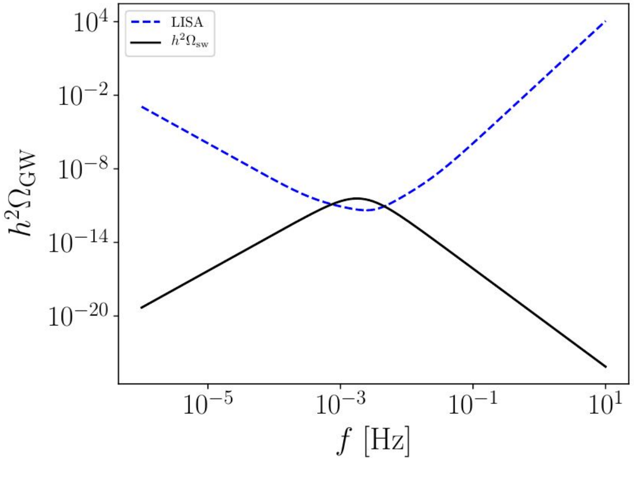
$$\Omega_{\mathrm{GW}} \propto \frac{(q/q_0)^3}{1+(q/q_0)^2[1+(q/q_1)^4]}$$

$$q_l \simeq 1, \qquad q_h \simeq 1/\xi_{\mathrm{shell}},$$

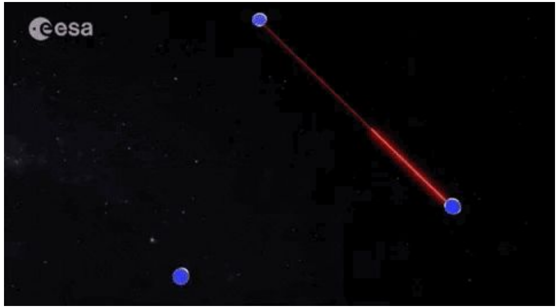


Outline of this talk

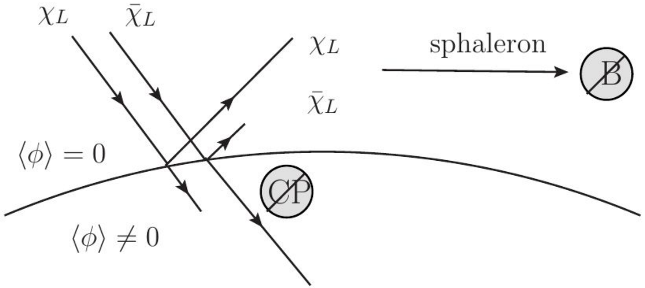
- **Prerequisites of 1st order PT**
- Gravitational waves
- Simulations
- Temperature fluctuations

Motivations for 1st Order PT

1) LISA is flying in the next decade

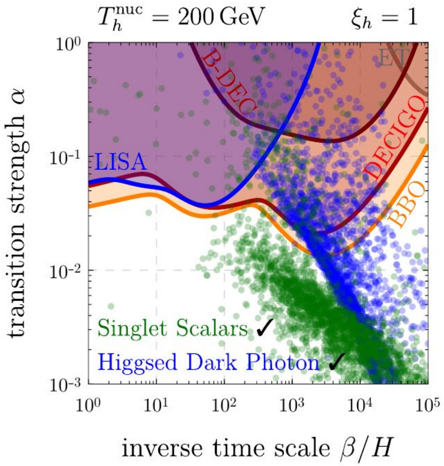


2) Electroweak Baryogenesis



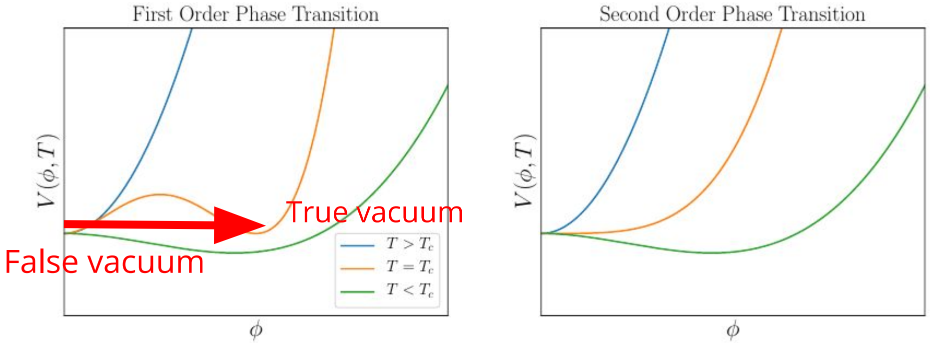
Konstandin (13)

3) BSM physics



Breitbach+ (18)

1st Order PT

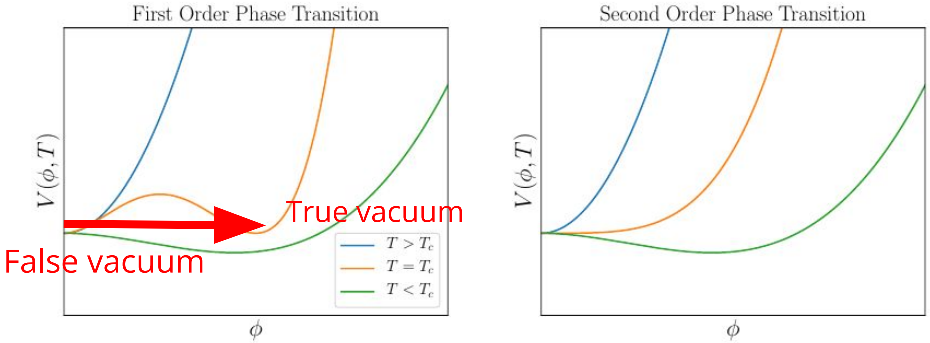


Scalar potential in thermal bath gets temperature corrections

$$V(\phi, T) = \frac{1}{2}M^2(T)\phi^2 - \frac{1}{3}\delta(T)\phi^3 + \frac{1}{4}\lambda\phi^4$$

At high temperatures we expect electroweak sym. to be restored. As temperature goes down higgs gets a vev and gives mass to particles

1st Order PT



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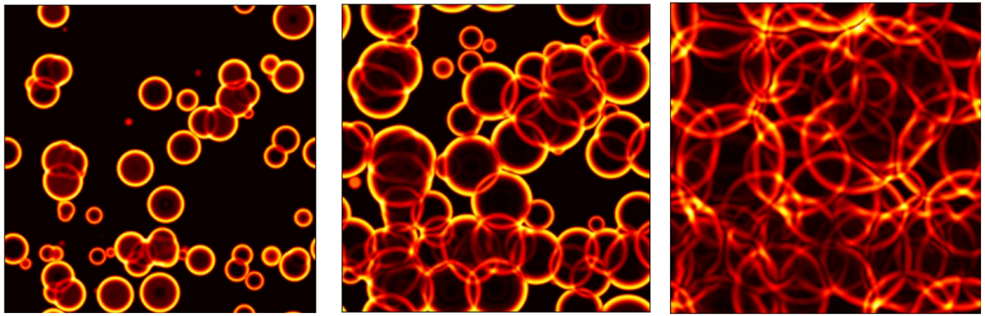
$$\Gamma(t) = \Gamma_* e^{\beta(t-t_*)}$$

Disjoint regions of space can make the transition, generating bubbles at different places



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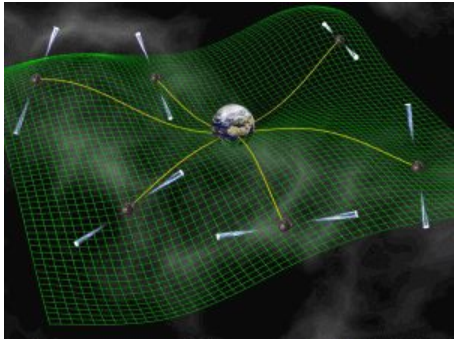
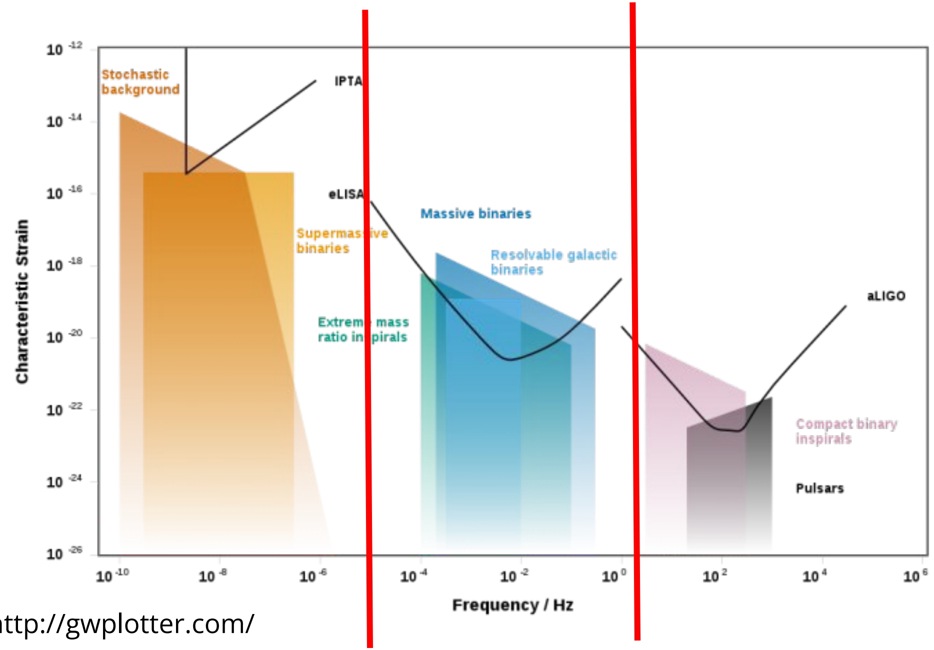
The (three) GW frequency ranges





http://gwplotter.com/

Low Intermediate High [...]

Low: We probe this region using Pulsar Timing Array (PTA). O(> 10^7 solar masses)

Intermediate: Supermassive BHs O(10^3-10^7 solar masses). One of the most interesting regions to probe the early Universe.

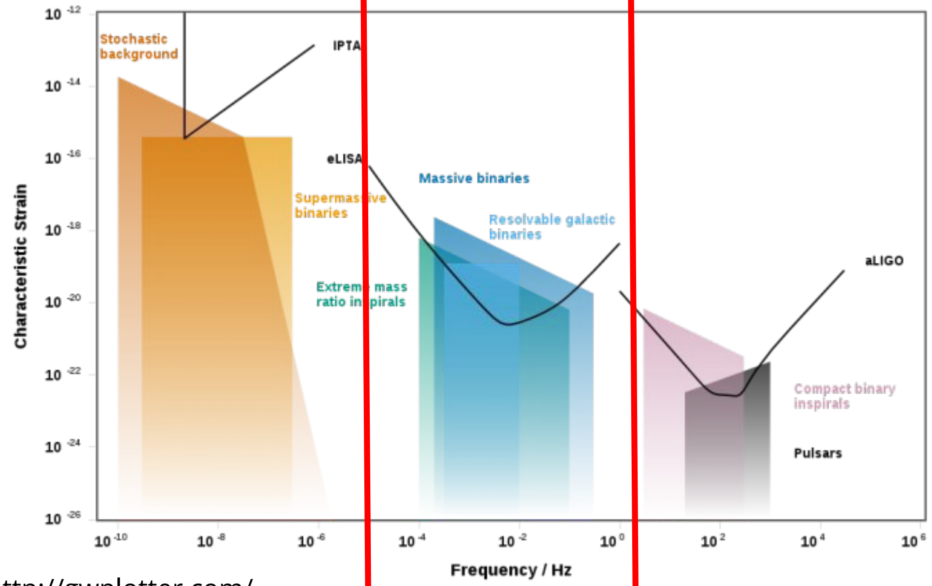
High: O(1-100) solar masses objects

The (three) GW frequency ranges

$$f_{\rm peak} \sim \text{a few} \times 10^{-6} \left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{100\,\text{GeV}}\right) \text{Hz}\,.$$

Nucleation rate O(100)

Close to EW scale



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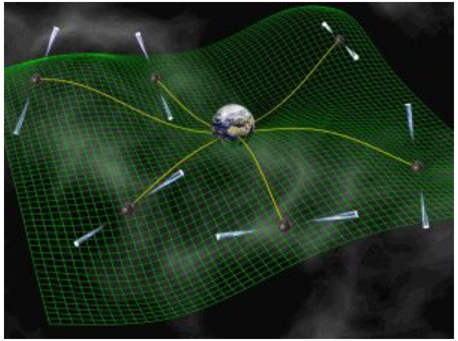

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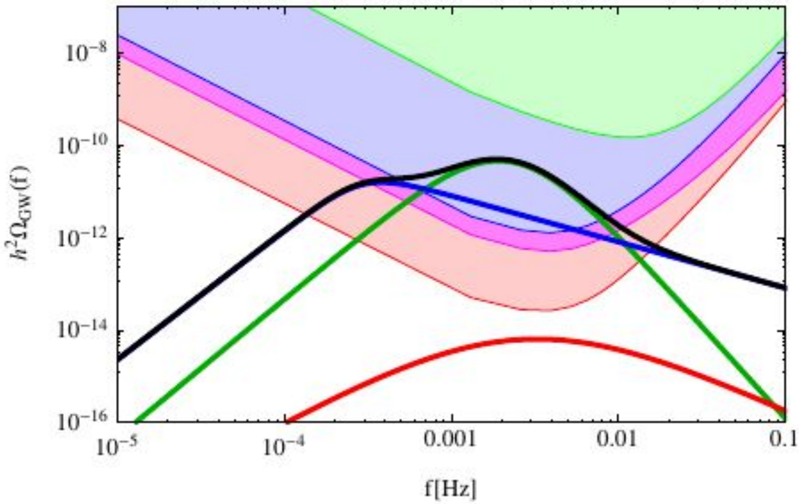
1st Order Phase Transition (PT)



(Caprini et al, 15)

3 sources:

Scalar field

Sound waves

Turbulence

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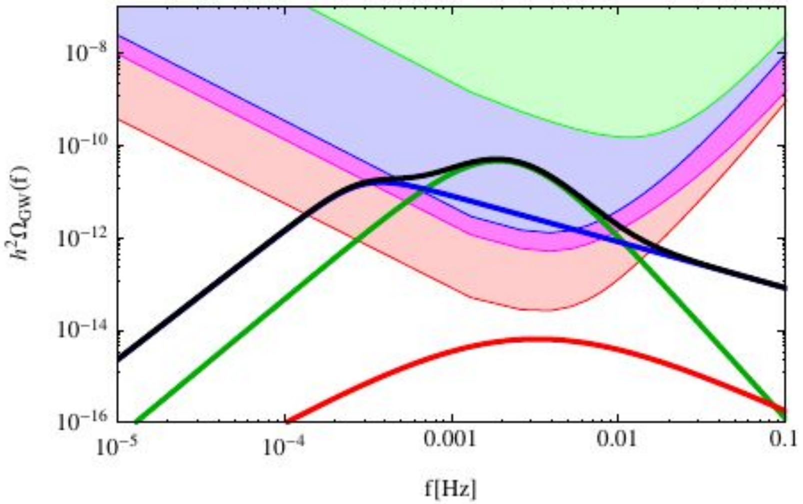

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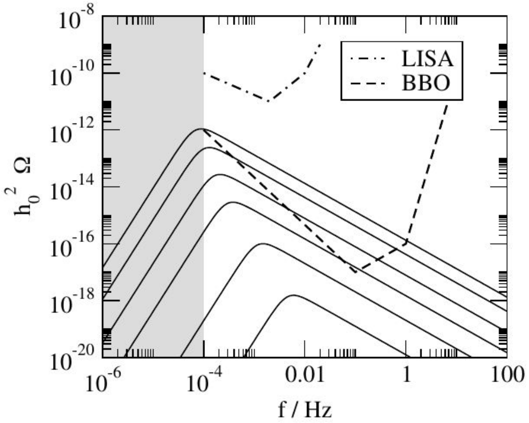
Relevant when bubbles runaway (e.g. supercooling)

GW from 1st Order PT -- State of the art

Envelope approximation



Konstandin, Huber (08)

Energy contained in a thin non-collided yet shell (fluid or scalar)

See also Kamionkowski, Kosowsky, Turner (94) and Jinno, Takimoto (17a)

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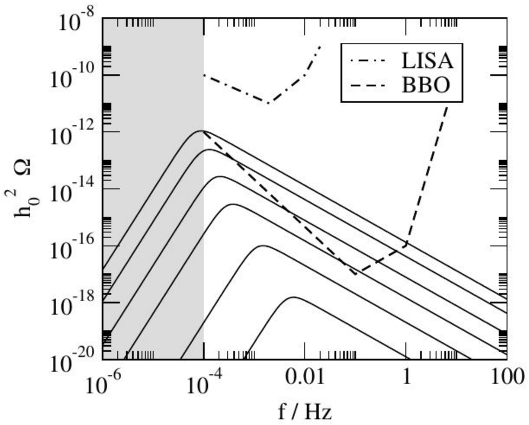

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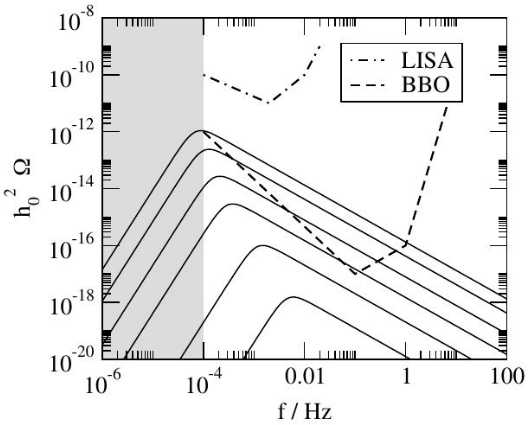

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Enhanced by $\left(\frac{\beta}{H_*}\right)$

since they propagate for long time
Hindmarsh, Huber, Rummukainen, Weir (13)

Difficult for bubbles to runaway, coupling to the plasma
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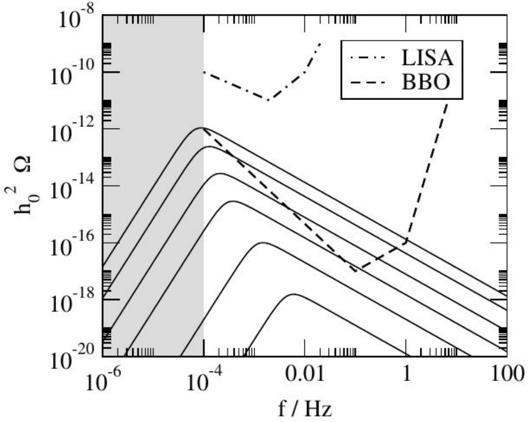

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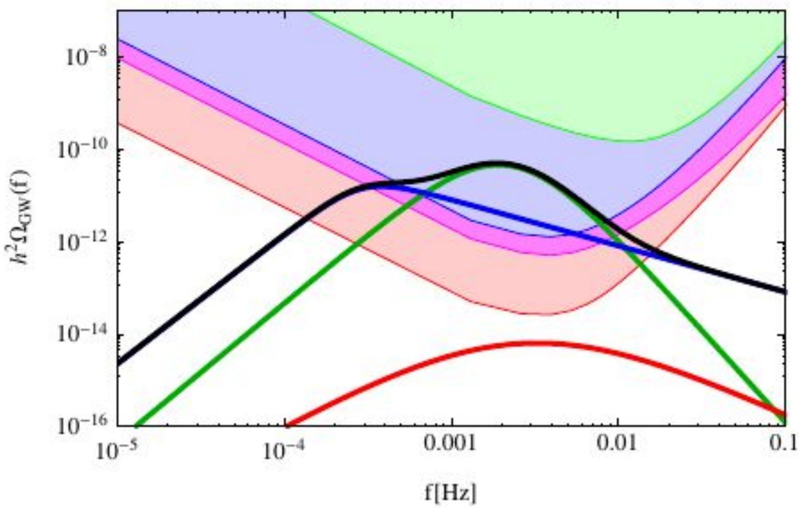
FLUID CONTRIBUTION IS RELEVANT!

1st Order Phase Transition (PT)



(Caprini et al, 15)

3 sources:

Scalar field

Sound waves

Turbulence

Relevant when we talk about PTs in a plasma

Working flow

Working flow

How we can connect a Lagrangian to macroscopic properties of plasma+wall

α PT strength

β Bubble nucleation time scale (and bubble size)

v_w Bubble wall velocity

T_* Temperature of PT

Working flow

Prediction of GW
(analytics, simulations)

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Noise

Sensitivity

Foregrounds

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Non-linear dynamics are ultra-relevant!
- **GW Templates**
- **Turbulence**
- **Strong PTs**

Analytical prediction

Sound shell model

Hindmarsh (16) +Hijazi (19)

$$\frac{d\Omega_{\rm GW}(k)}{d\ln(k)} \sim \begin{cases} (kR_*)^5, & k\Delta R_*, kR_* \ll 1, \\ (kR_*)^1, & k\Delta R_* \ll 1 \ll kR_*, \\ (kR_*)^{-3}, & 1 \ll k\Delta R_*, R_*. \end{cases}$$

Assumes:

- Gaussianity of velocities
- Linear superposition of sound shells
- Hard to extrapolate to stronger PTs

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Simulations (two schemes)

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Scalar field + Fluid, Hindmarsh, Huber, Rummukainen, Weir (13,15,17)

Phenomenological friction term between between scalar and fluid

Model-dependence when assuming free energy for the scalar and T-dependence of friction

No separation of scales (scalar shell and bubble size)

Higgsless, Jinno, Konstandin, **HR**, Stromberg

Constant wall velocity + Bag equation of state

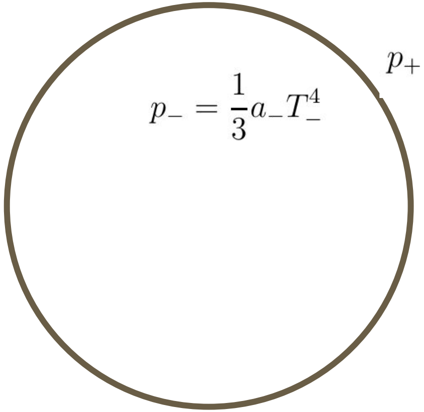
Model only the fluid part

Clear separation of scales

Lattice simulations: Higgsless

Bag Equation of State

Espinosa, Konstandin, No, Servant (10)



$$p_+ = \frac{1}{3}a_+T_+^4 - \epsilon$$

$$p_- = \frac{1}{3}a_-T_-^4$$

Lattice simulations: Higgsless

Bag Equation of State

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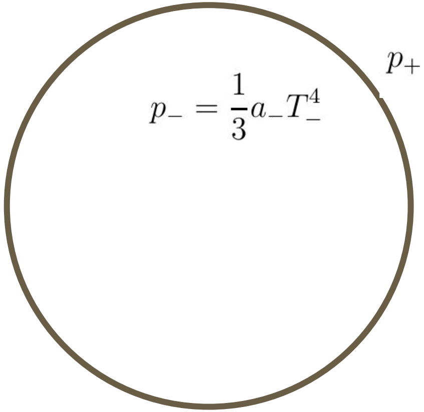

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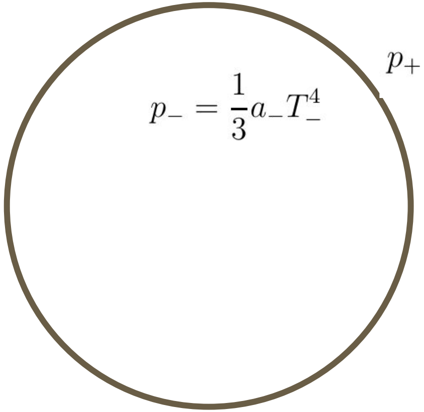

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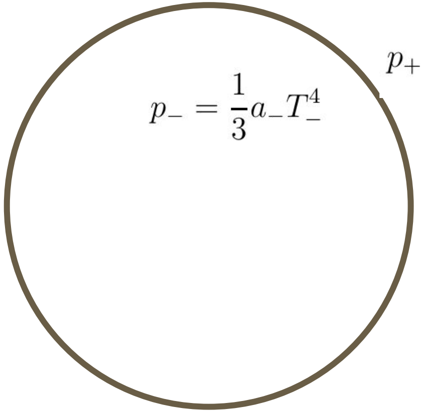

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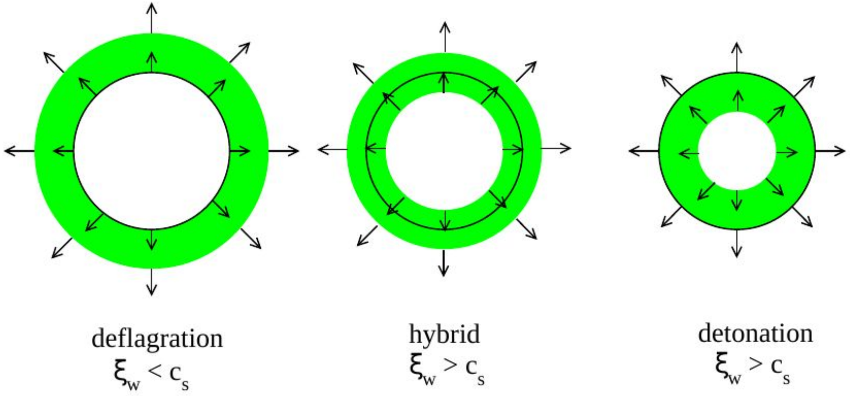

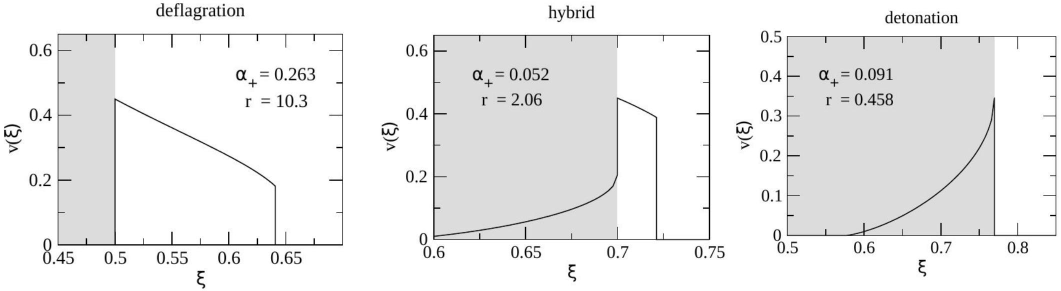

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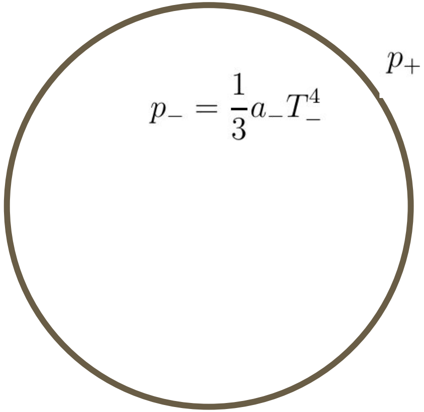
How our simulation works:

Lattice simulations: Higgsless

Bag Equation of State

Espinosa, Konstandin, No, Servant (10)



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$$\partial^\mu T_{\mu\nu} = \partial^\mu T^{\phi}_{\mu\nu} + \partial^\mu T^{\text{plasma}}_{\mu\nu} = 0$$

Enters via a time dependent energy background $\epsilon(\vec{x}, t)$

You can spend all your computer energy solving the fluid part!

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Lattice simulations: Higgsless

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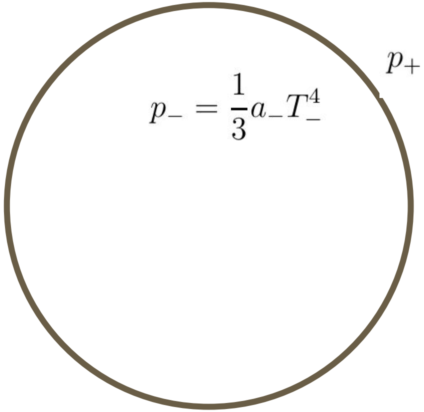

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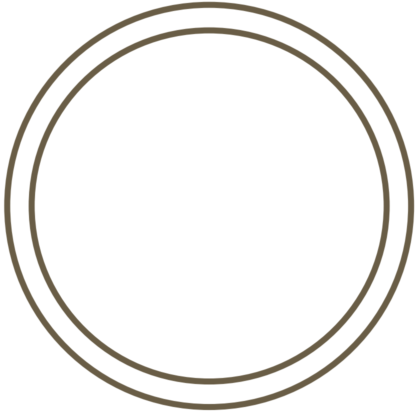

The scales of the problem:

How our simulation works:

Lattice simulations: Higgsless

Bag Equation of State

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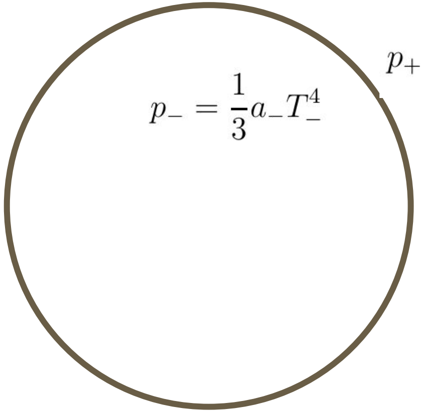

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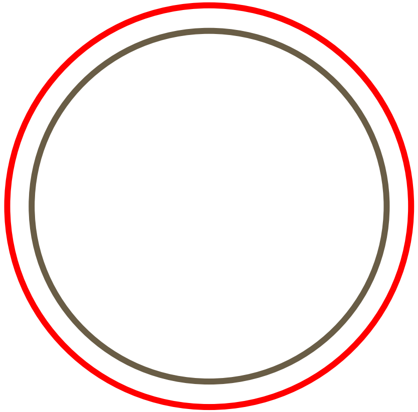

The scales of the problem:

- Bubble thickness: TeV

Lattice simulations: Higgsless

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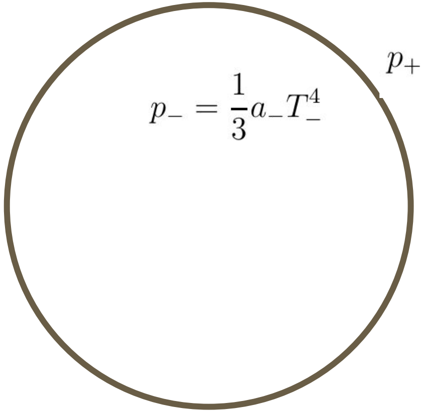

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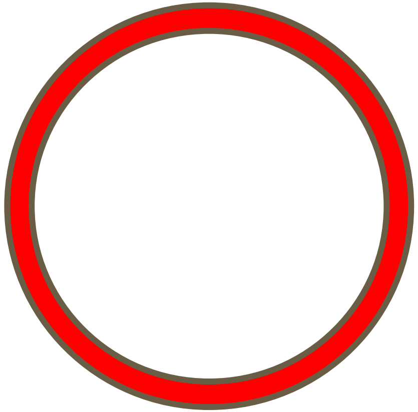

The scales of the problem:

- Bubble thickness: TeV
- Sound Shell

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How our simulation works:

Lattice simulations: Higgsless

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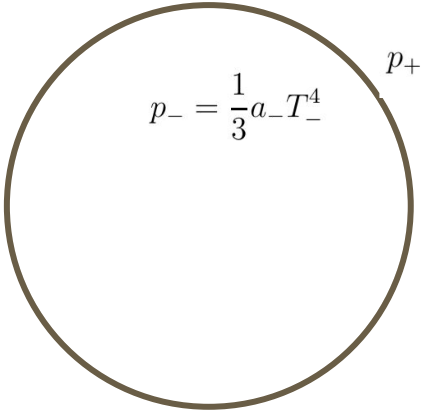

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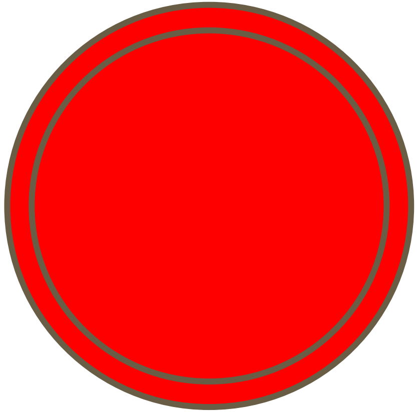

The scales of the problem:

- Bubble thickness: TeV
- Sound Shell
- Bubble size: Hubble size

Lattice simulations: Higgsless

Can we reproduce the correct result with one single bubble?

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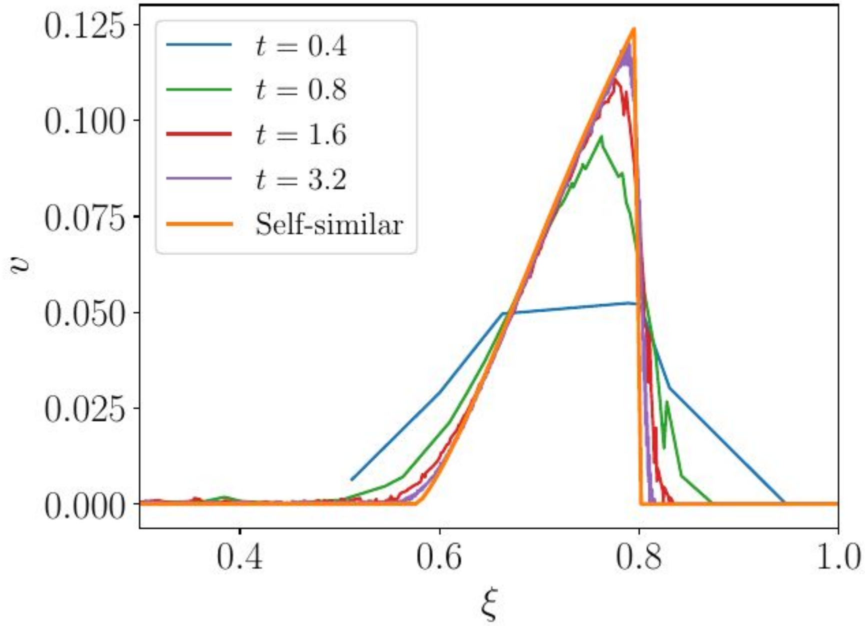

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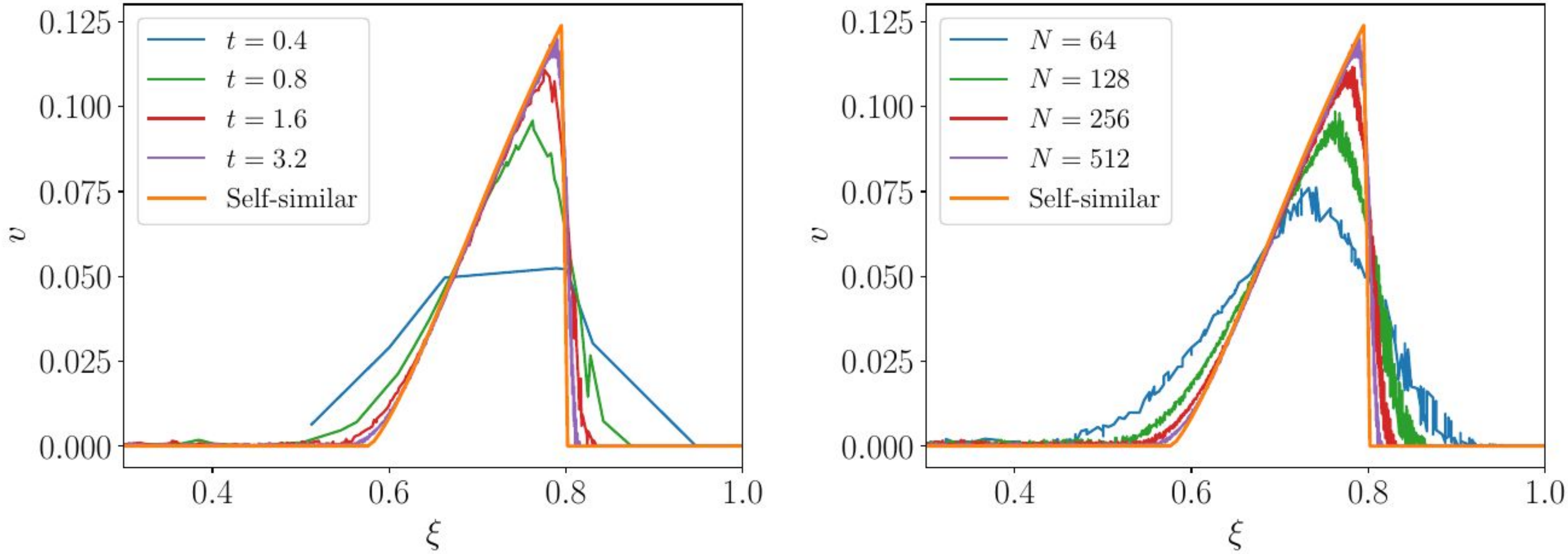


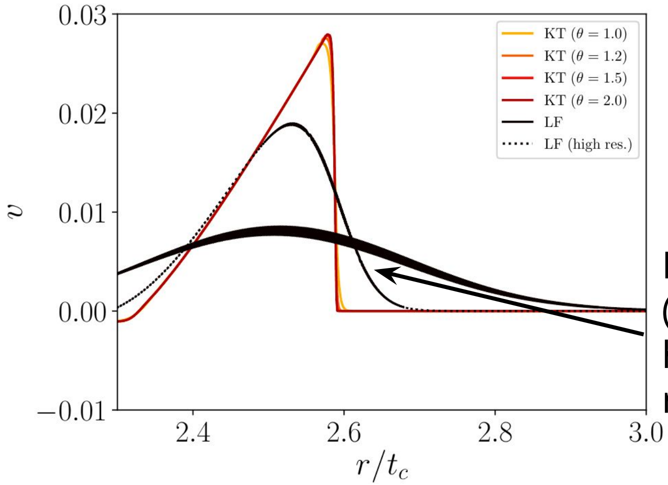
Solving shocks

Solving shocks

$$\partial_t u + \partial_x f(u) = 0$$

Simples scheme, Lax Friedrichs (LF)

$$u_j^{n+1} = \frac{u_{j+1}^n + u_{j-1}^n}{2} - \frac{\lambda}{2}\left[f(u_{j+1}^n) - f(u_{j-1}^n)\right] - g_j^n \Delta t$$



Large viscosity (refined mesh here would not help too)

Solving shocks

Gudunov's theorem: Linear scheme can only respect positivity at first order

$$\partial_t u + \partial_x f(u) = 0$$

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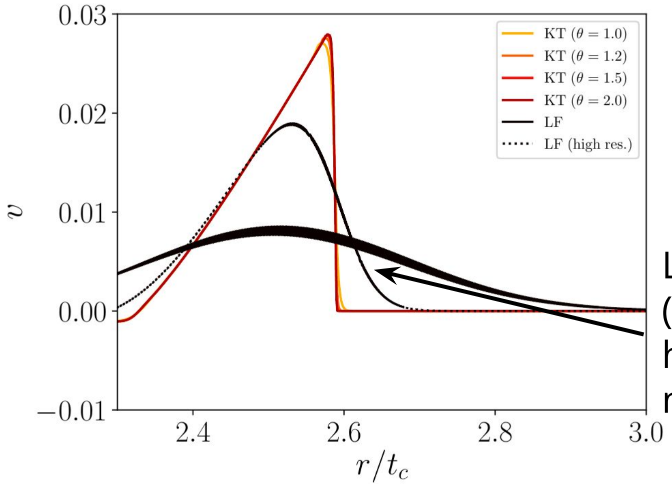

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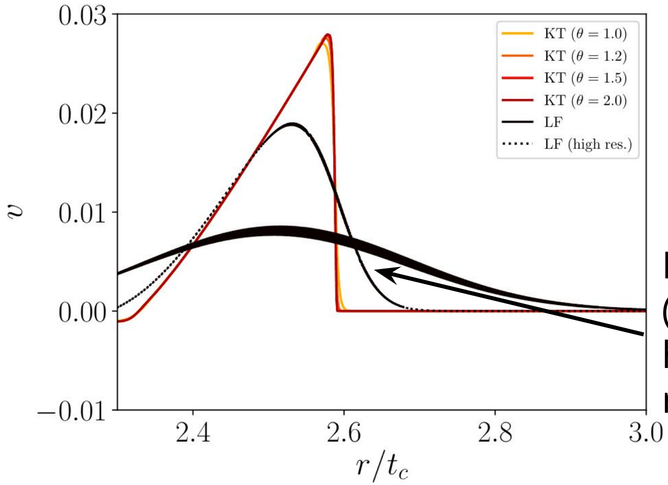

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Solution 1: Riemann solvers or Godunov schemes
Solve exact linearized scheme, diagonalize matrix locally

Solution 2: Hybridization
Introduce non-linear terms via 'flux limiters'

Henrique Rubira

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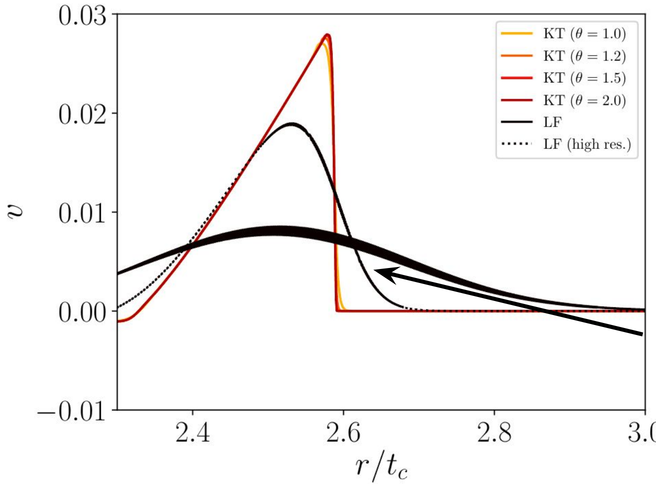

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Solve exact linearized scheme, diagonalize matrix locally

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Kurganov - Tadmor (KT) scheme for conservative schemes $\partial_\mu T^{\mu\nu} = 0$

Flux

$$u_j^{n+1} = u_j^n - \frac{\Delta t}{\Delta x}\left(H_{j+1/2}^n - H_{j-1/2}^n\right)$$

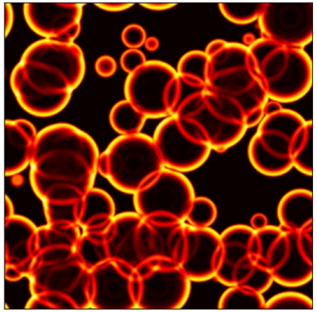
Viscosity

$$H_{j+1/2} = \frac{f(u_{j+1/2}^+) + f(u_{j+1/2}^-)}{2} - \frac{a_{j+1/2}}{2}\left[u_{j+1/2}^+ - u_{j+1/2}^-\right]$$

Local max velocity

Results

Now with many bubbles...



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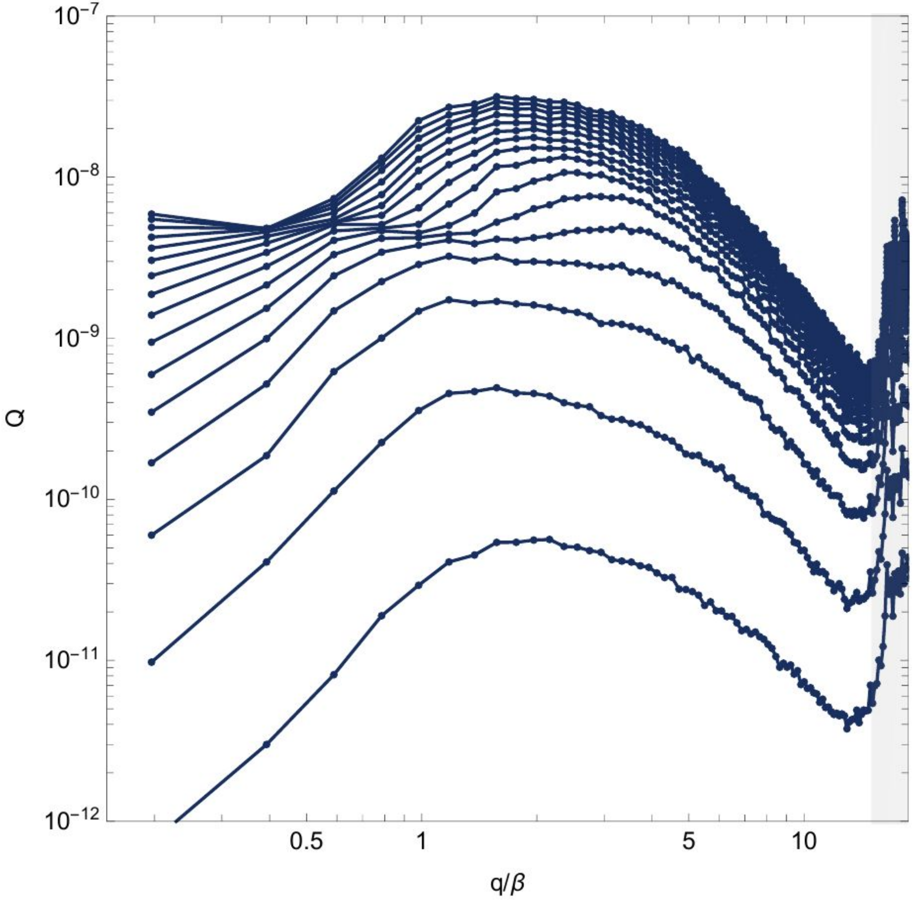

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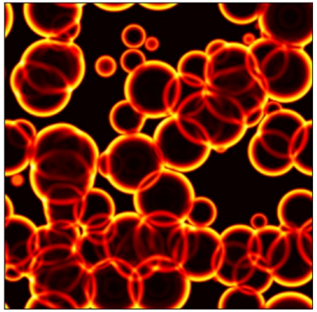

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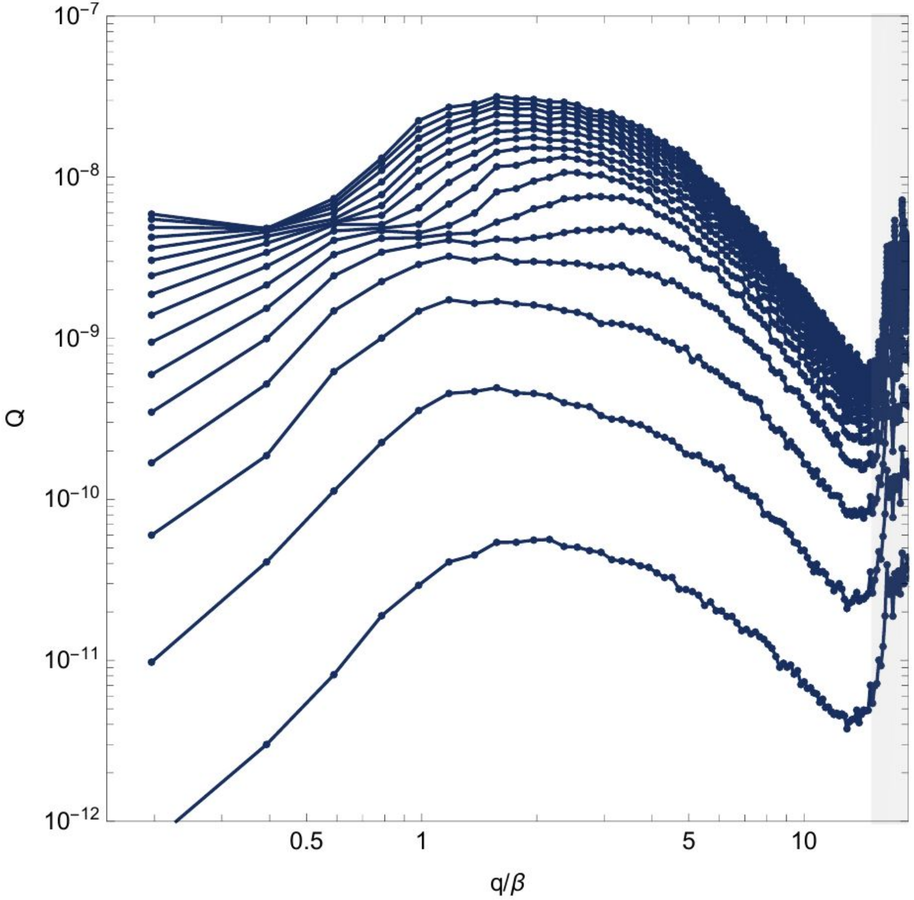
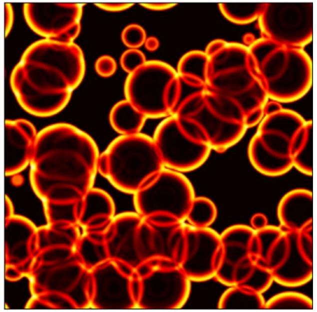


Simulation time

Results

Now with many bubbles...



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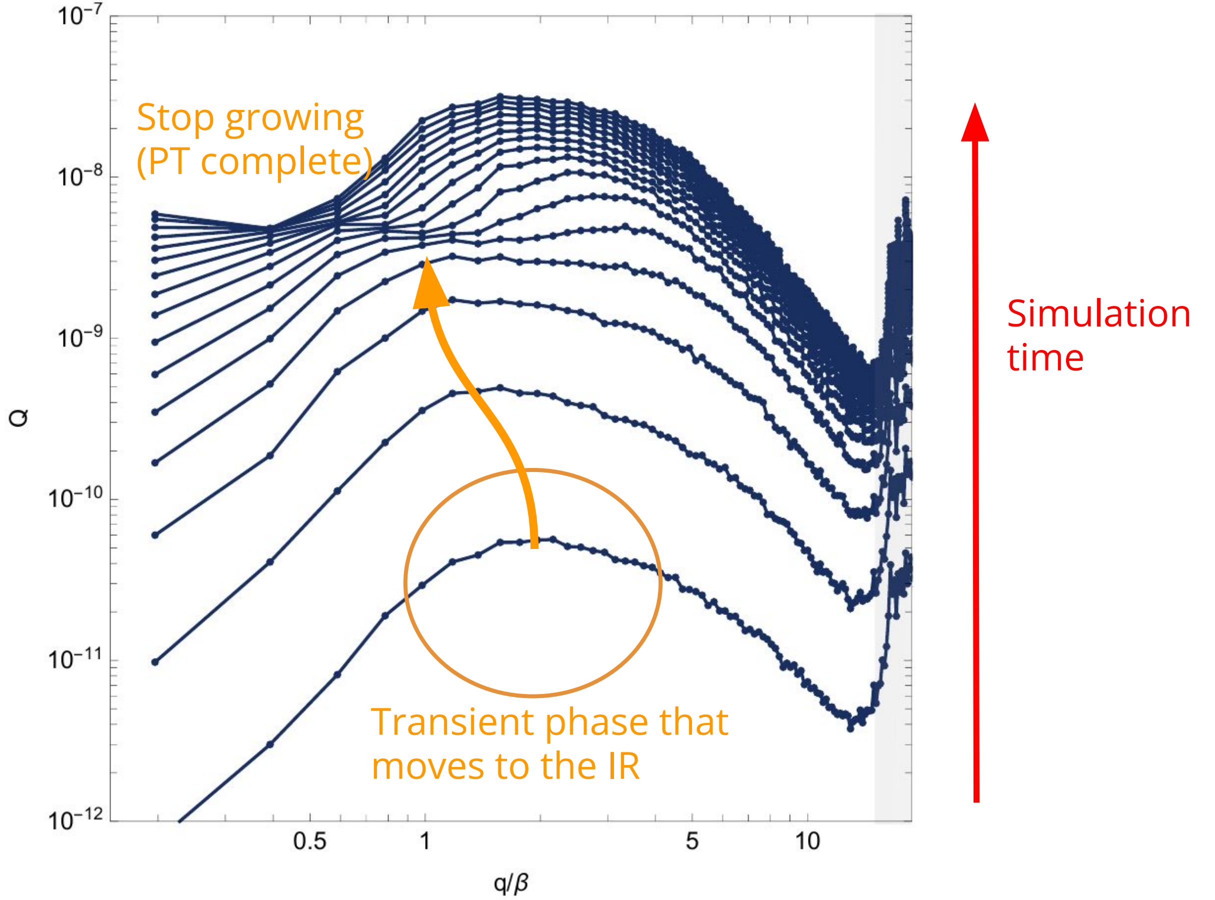

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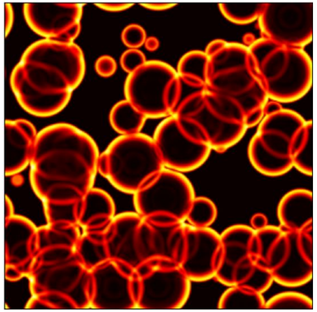

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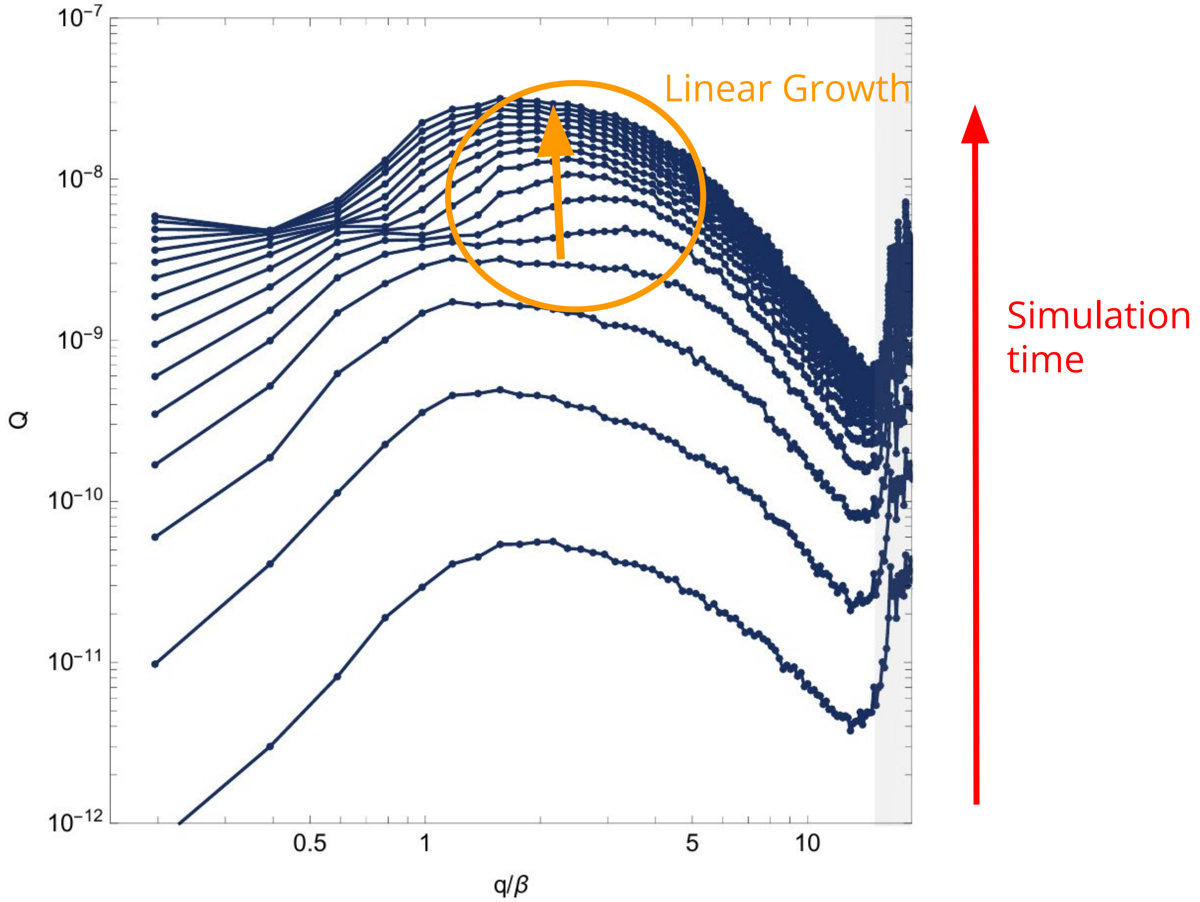


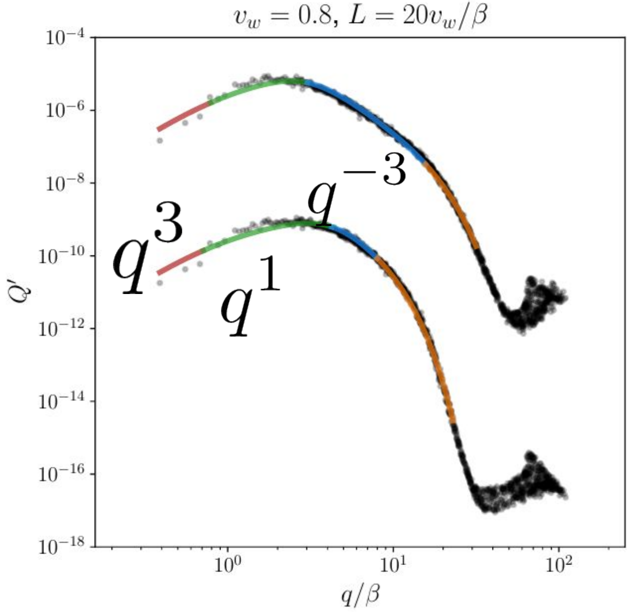
Results

Amplitude Shape

$$Q'(q) = Q'_{\rm int} \times S_f(q)$$

A double-broken power law

$$S_f(q) = S_0 \times \frac{(q/q_0)^3}{1+(q/q_0)^2[1+(q/q_1)^4]} \times e^{-(q/q_e)^2}$$



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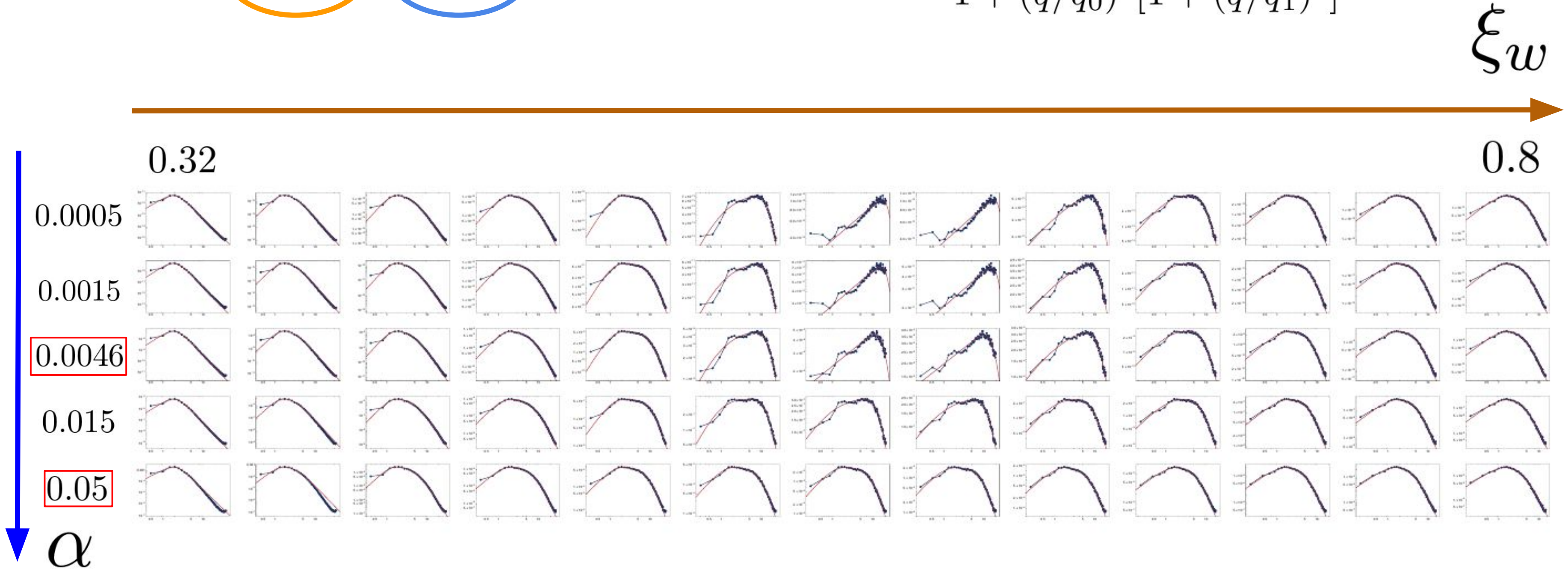

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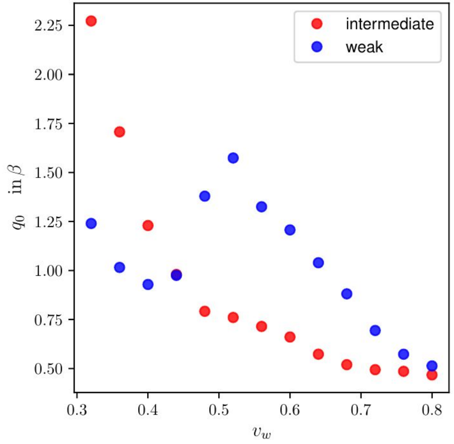
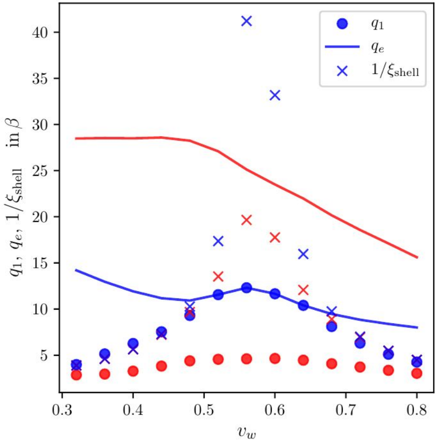
Position of the peaks

IR peak looks complex

UV peak scales as sound shell thickness





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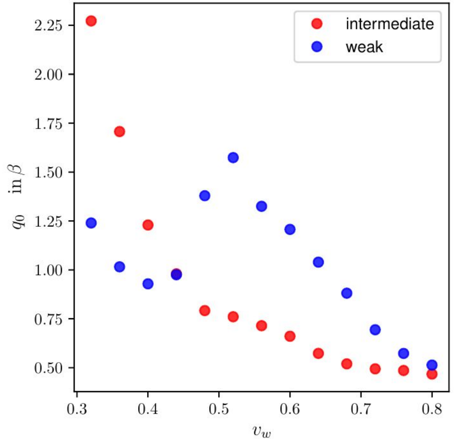
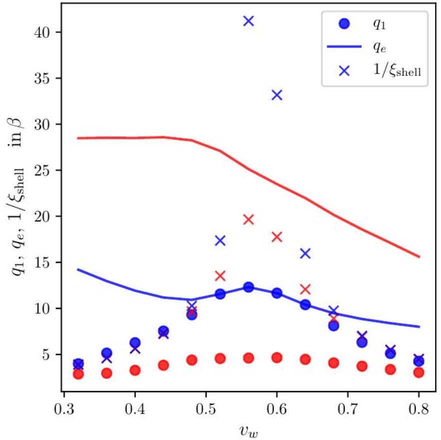
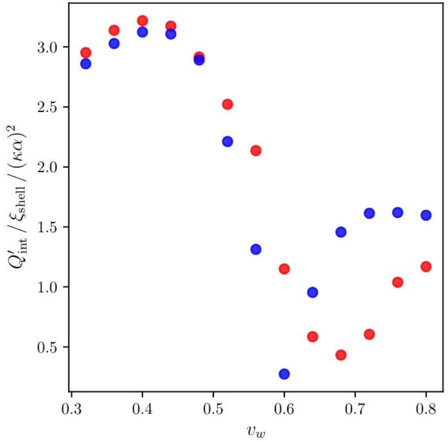


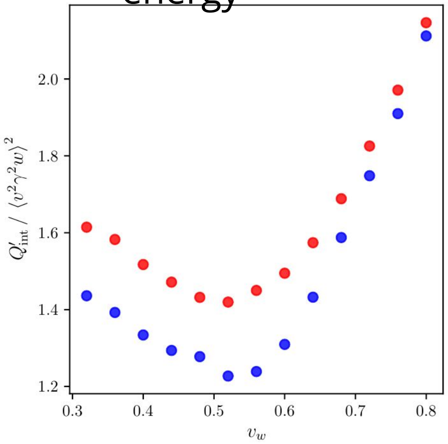


Amplitude of the spectrum

Normalized by kinetic energy

Normalized by 3d simulation kinetic energy





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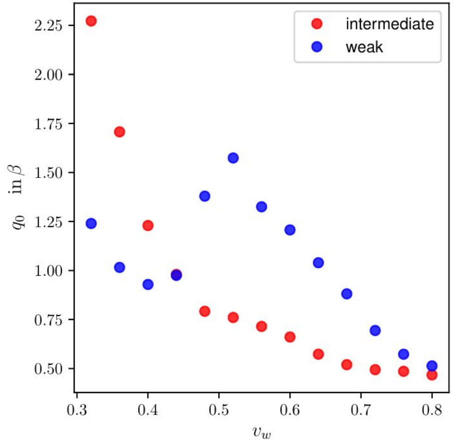

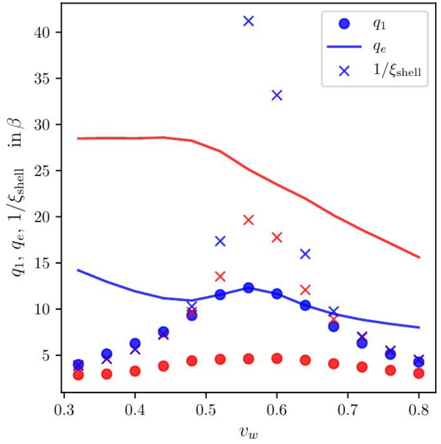

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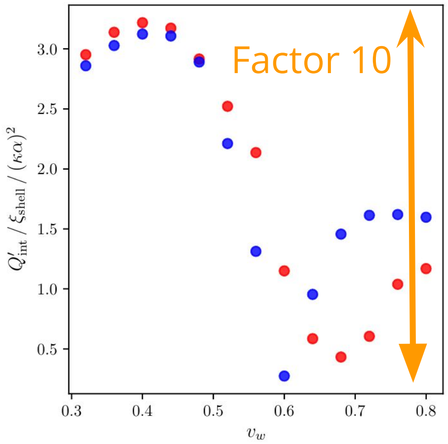

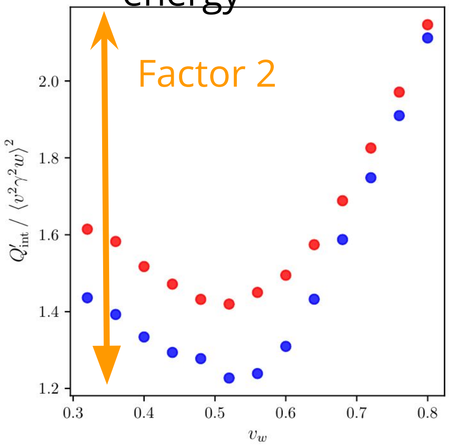

Comparison to other works

We find very similar GW spectra when comparing weak and intermediate transitions

1000x faster! (Fluid only + second-order discretization scheme)

More bubbles -- O(2500)

Realistic nucleation (not simultaneous)

Now we can move to non-linear fluid dynamics! Easy to go to strong PTs and to explore turbulence

Outline of this talk

- Prerequisites of 1st order PT
- Gravitational waves
- Simulations
- **Temperature fluctuations**

Is it the end of the story connecting observed spectra to sourced spectra?

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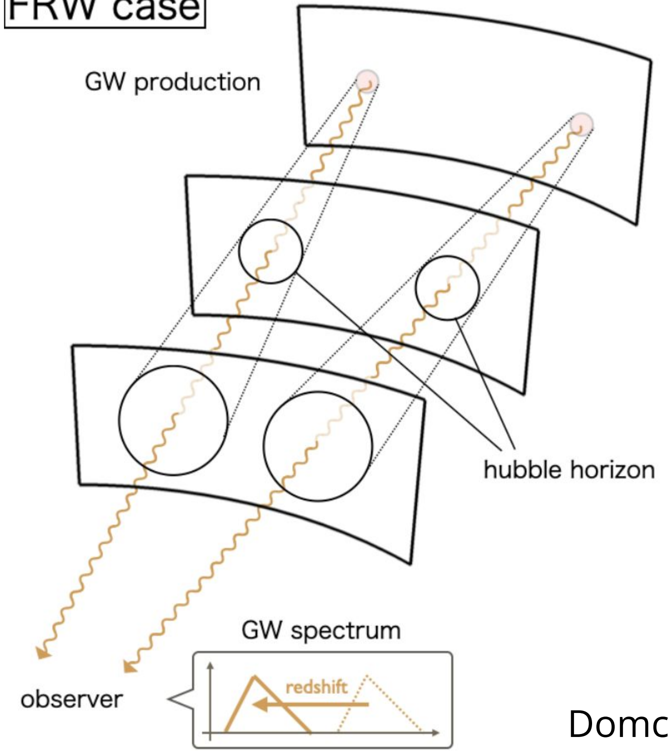
FRW case



Domcke, Jinno, HR; 19

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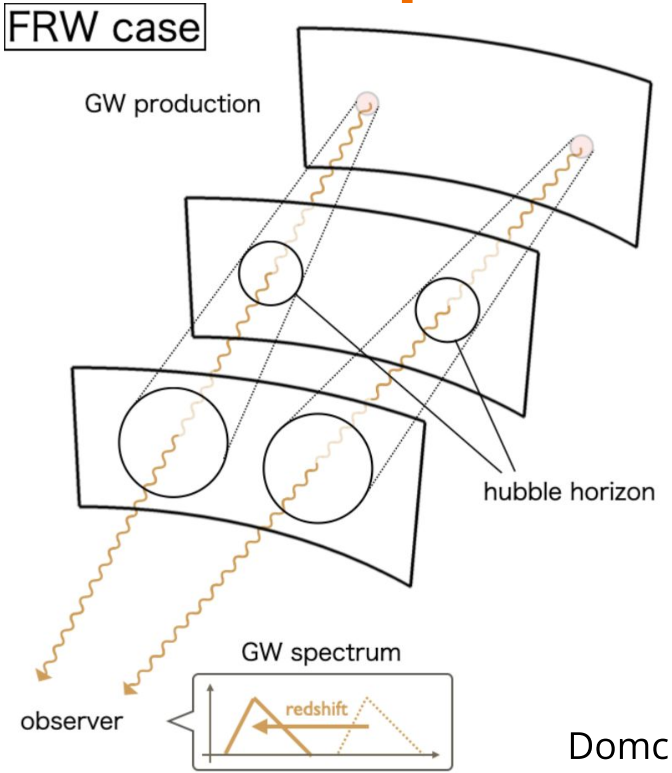
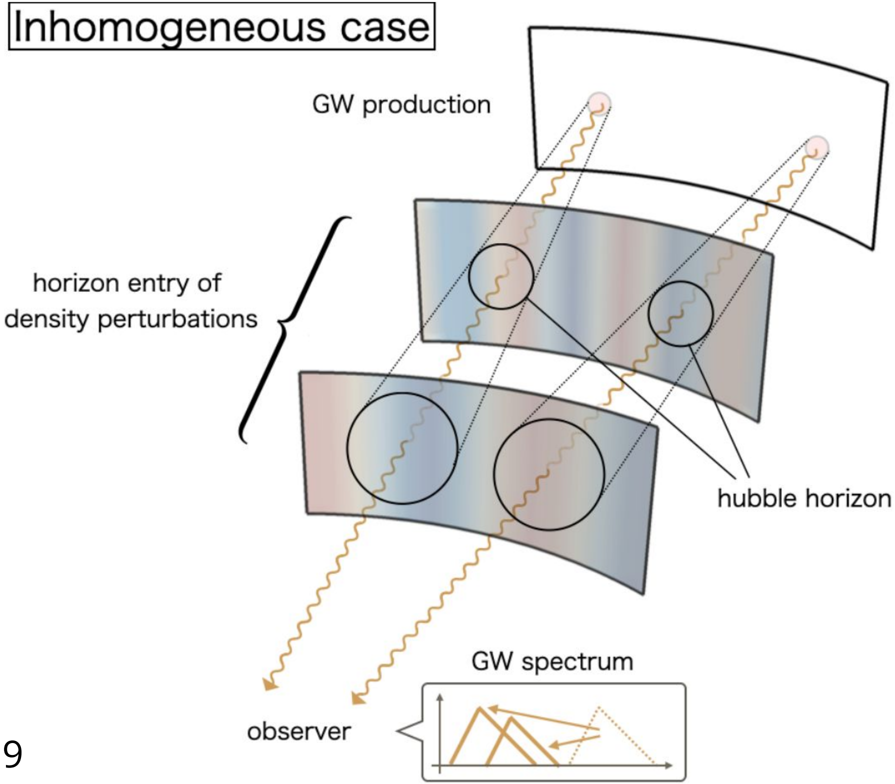


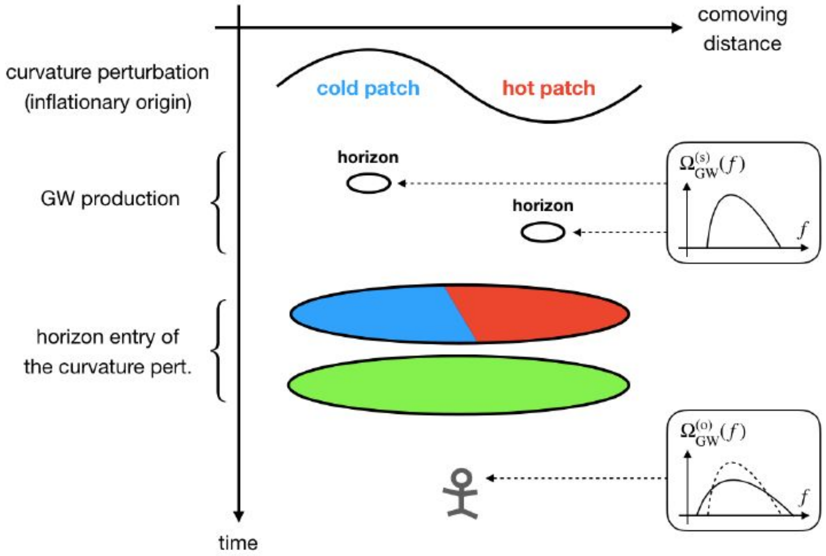


Domcke, Jinno, HR; 19

Is it the end of the story connecting observed spectra to sourced spectra?

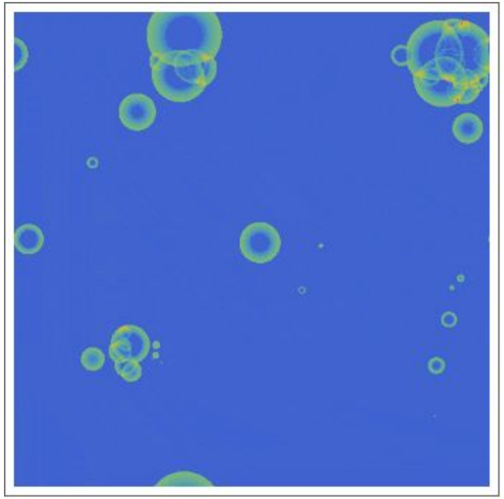
We know that temperature fluctuations in the line-of-sight can affect the GW spectrum

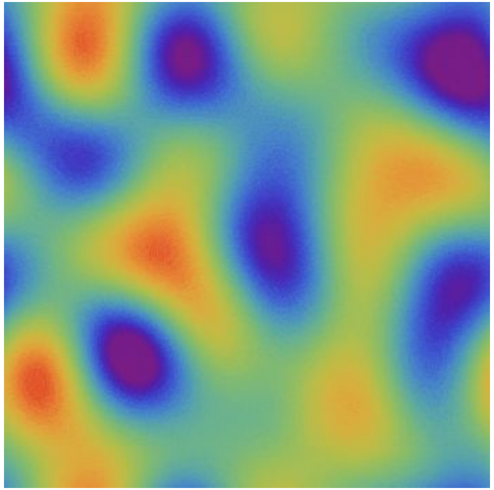
Domcke, Jinno and **Rubira** 2002.11083



Similar to (I)SW for CMB

More videos...





Can temperature fluctuations also affect the sourcing of GWs from 1st order PTs?

Henrique Rubira

Can temperature fluctuations also affect the sourcing of GWs from 1st order PTs?

Nucleation rate proportional to the 3d bounce action: $\Gamma \propto e^{-S_3/T}$

After expanding it around $t = t_*$

$$\Gamma = \Gamma_* \exp\left[\beta(t - t_*) - \frac{\beta}{H_*}\frac{\delta T}{\overline{T}}\right]$$

This next term in the expansion may be large if $\frac{\delta T}{T} \sim \left(\frac{\beta}{H_*}\right)^{-1}$

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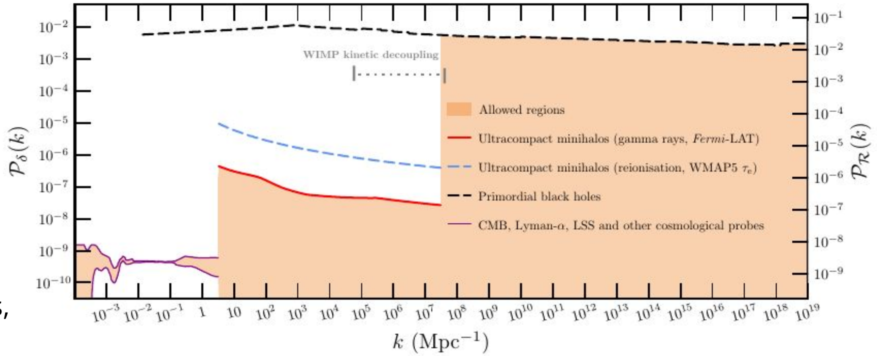
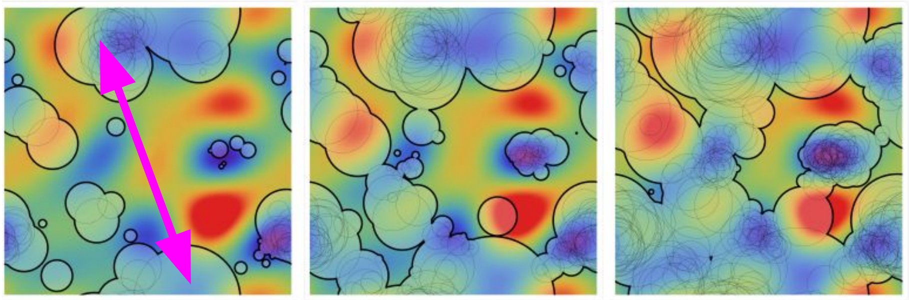
Since we are talking about T~Tev, it is pretty in the (unconstrained) UV



Bringmann, Scott, Akrami, 1110.2484. See also Byrnes, Cole, Patil

What is the effect in the GW spectra?

We simulate bubble nucleation under temperature fluctuations and plug it into the hybrid simulation



Result: increase the bubbles size and therefore enhance GW spectra

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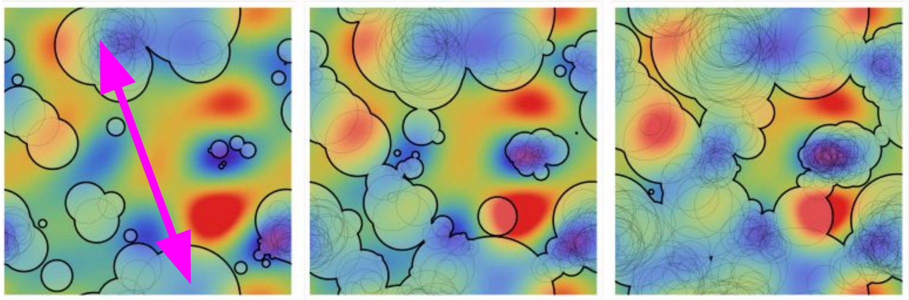

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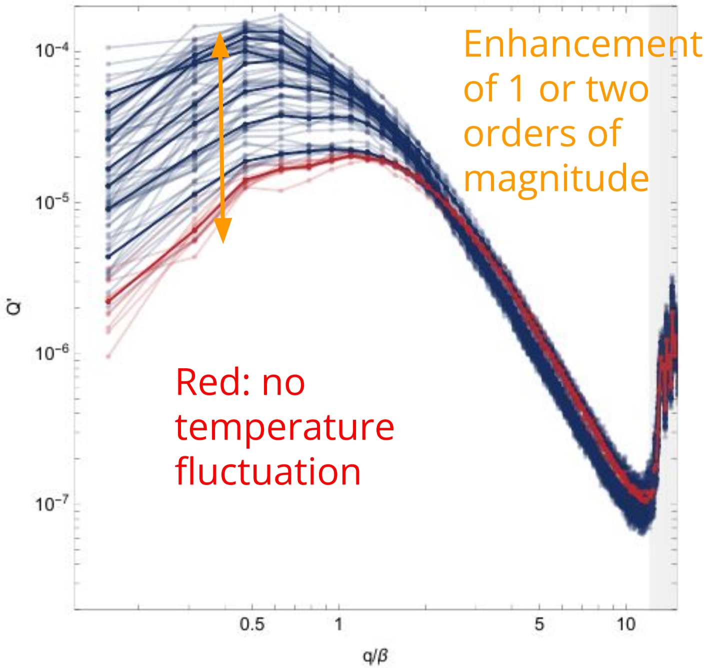


We also parametrized how spectra depends on temperature fluctuations

Conclusions

- We have a fast and precise scheme to calculate GWs from PT that can explore non-linear PTs also alternative scenarios (PBHs, topological defects, ...)

What comes next?

- Deep into non-linear PTs
- Topological defects
- Turbulence
- Parameter extraction
- Template building

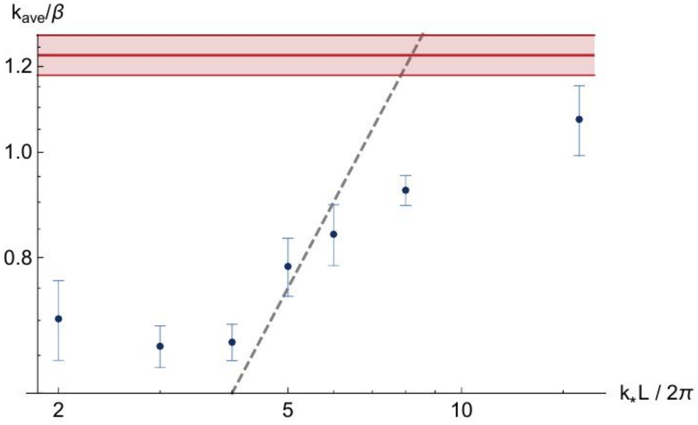
Thanks a lot!

Extra slide: parametrizing the spectra

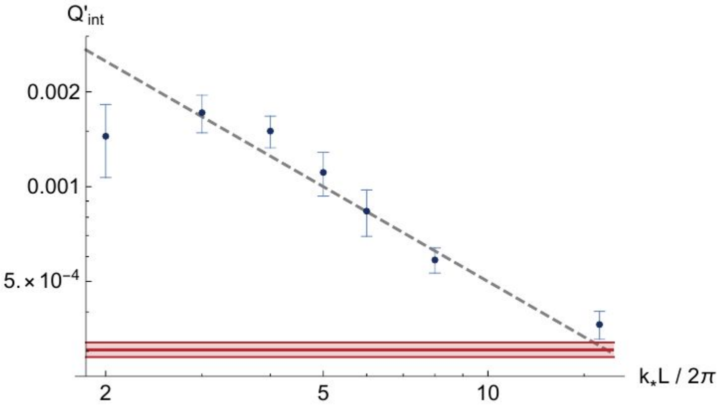
Henrique Rubira

$$k_{\rm ave} \equiv \int d\ln k \; k \; Q'(k) \Big/ \int d\ln k \; Q'(k),$$

$$Q'_{\rm int} \equiv \int d\ln k \; Q'(k).$$



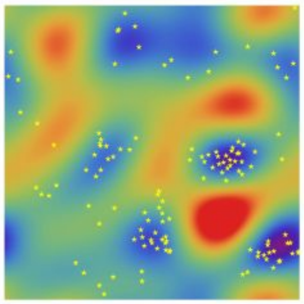
Red: no temperature fluctuation



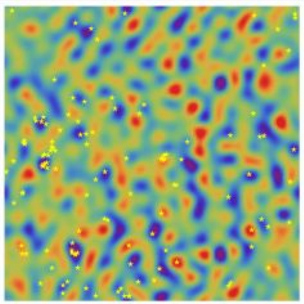
Extra slide: deep IR, IR and UV

Henrique Rubira

Deep IR: temperature is uniform, no difference



Only IR affects the spectra



In the limit in which $k_* \to \infty$, it does not affect the spectra since any volume has many hot and cold spots

Extra slide: the algorithm

Instead of letting bubbles nucleate linearly distributed in space and (exp) time, we consider the cumulative probability calculated from the Temperature grid