The Higgsless simulations (and PTs to address the H0 tension)

based on 2010.00971, 2108.11947, 2209.04369, 2302.06952, 2409.0365, 2404.07256, 2508.TODAY

Henrique Rubira

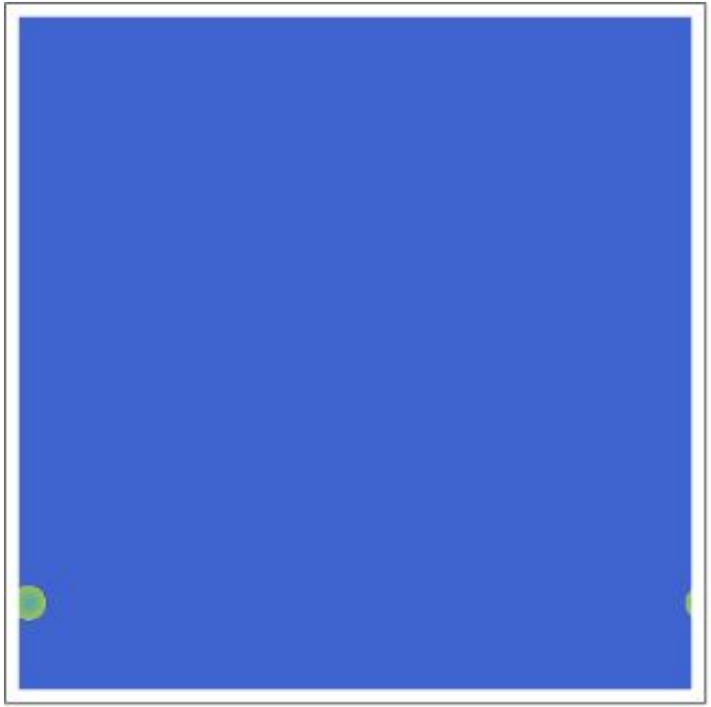
(LMU/Cambridge)

The Higgsless team: Ryusuke Jinno, Thomas Konstandin, Isaac Stromberg

\+ Chiara Caprini, Alberto Roper Pol, Jorinde v.d. Vis, Simone Blasi, Mathias Garny, Martin Sloth, Florian Niedermann

Nordita, Aug 25

Before anything else, cool things always come with videos



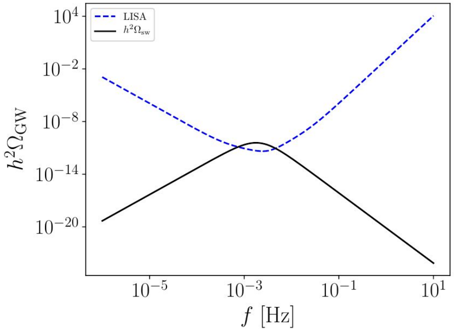
A message to take home...

New simulation scheme for GWs from PTs

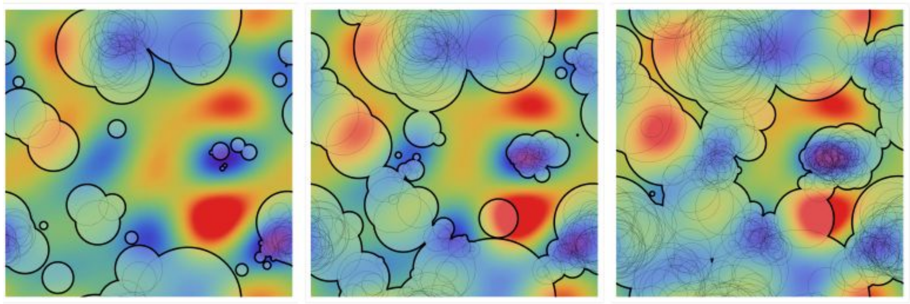
Advantages: fast, shocks, non-linear, Higgsless, different frequencies...

A user-friendly parametrization for ongoing and future data analysis...

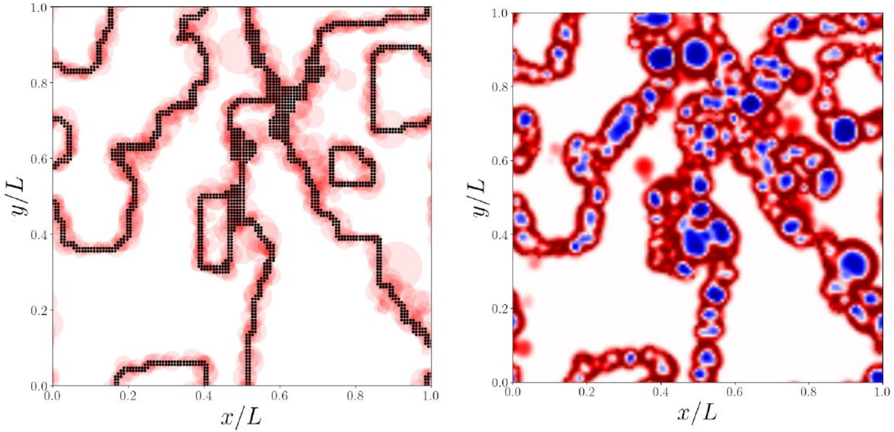
$$\Omega_{\rm GW} \propto \frac{(q/q_0)^3}{1+(q/q_0)^2[1+(q/q_1)^4]}$$



Temperature fluctuations sourcing PT



Domain walls sourcing PT



Outline of this talk

Part I: Higgsless

- **Simulations**
- Results
- Temperature fluctuations and Topological defects

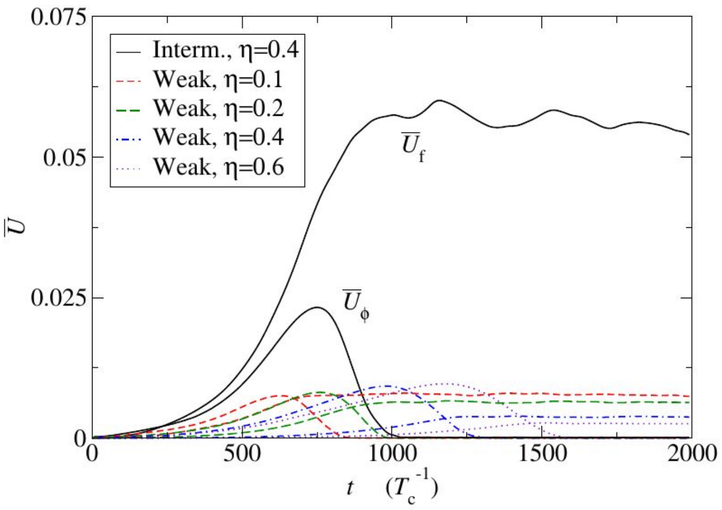
Part II: Phase transitions and H0 tension

Sounds waves are important

Gravitational waves from the sound of a first order phase transition

Mark Hindmarsh,[1, 2, *] Stephan J. Huber,[1, †] Kari Rummukainen,[2, ‡] and David J. Weir[2, §]
[1] *Department of Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9QH, U.K.*
[2] *Department of Physics and Helsinki Institute of Physics, PL 64, FI-00014 University of Helsinki, Finl*
(Dated: January 30, 2014)

We report on the first 3-dimensional numerical simulations of first-order phase transitions in the early universe to include the cosmic fluid as well as the scalar field order parameter. We calculate the gravitational wave (GW) spectrum resulting from the nucleation, expansion and collision of bubbles of the low-temperature phase, for phase transition strengths and bubble wall velocities covering many cases of interest. We find that the compression waves in the fluid continue to be a source of GWs long after the bubbles have merged, a new effect not taken properly into account in previous modelling of the GW source. For a wide range of models the main source of the GWs produced by a phase transition is therefore the sound the bubbles make.



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Working flow

Noise

Sensitivity

Foregrounds

Prediction of GW
(analytics, simulations)

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

For how long do sound waves propagate?

Turbulence

α PT strength

β Bubble nucleation time scale (and bubble size)

v_w Bubble wall velocity

T_* Temperature of PT

Non-linear dynamics are ultra-relevant!

- **GW Templates**
- **Turbulence**
- **Strong PTs**

Simulations (two schemes)

How can we simulate a scalar field that has TeV mass in the same lattice of a fluid with bubbles of Horizon size (10^{-20} eV)?

Simulations (two schemes)

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

Phenomenological friction term between between scalar and fluid

No separation of scales (scalar shell and bubble size)

Wall velocity is determined after stabilization and see plasma

(Hybrid+) Higgsless, Jinno, Konstandin, **HR**, Stromberg

Constant wall velocity (**input**) + Bag equation of state

Model **only the fluid** part

Clear **separation of scales**

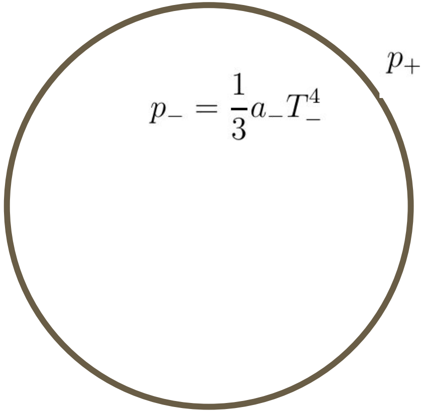
Important for the community:

Two very different schemes, different systematics, in relatively good agreement

Higgsless intuition

Bag Equation of State

Espinosa, Konstandin, No, Servant (10)



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

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

Higgs is incorporated as a boundary condition

Higgsless intuition

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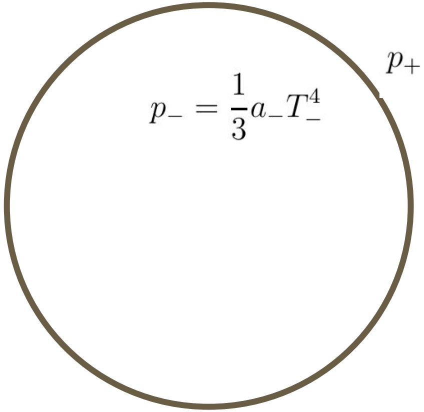

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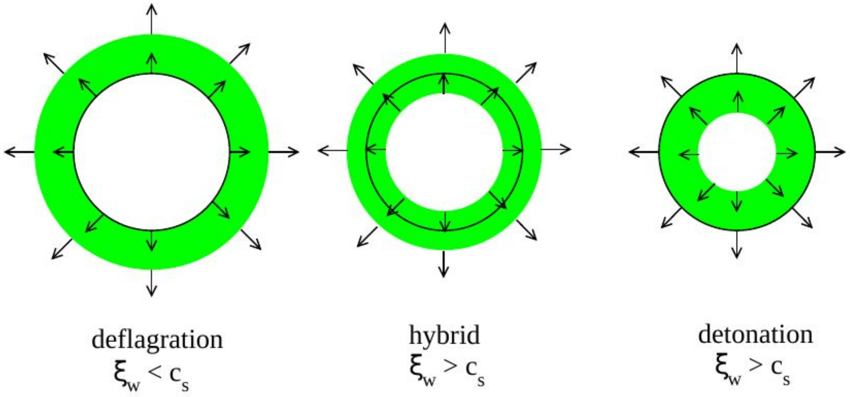
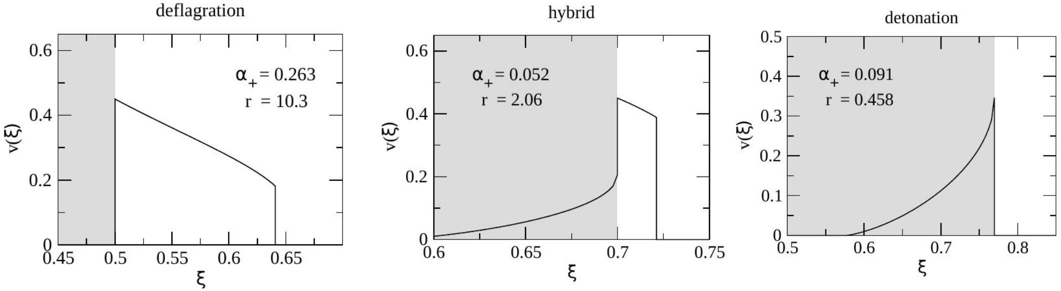
$$\xi = r/t$$





Higgsless intuition

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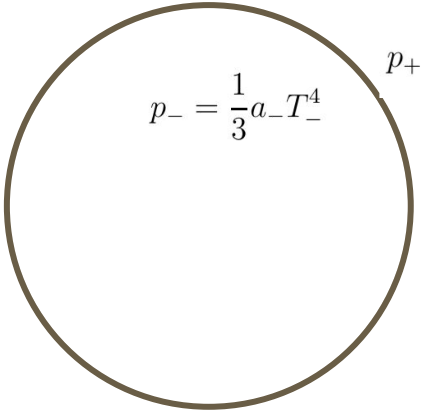

$$p_+ = \frac{1}{3} a_+ T_+^4 - \epsilon$$

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Higgs is incorporated as a boundary condition

How our simulation works:

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

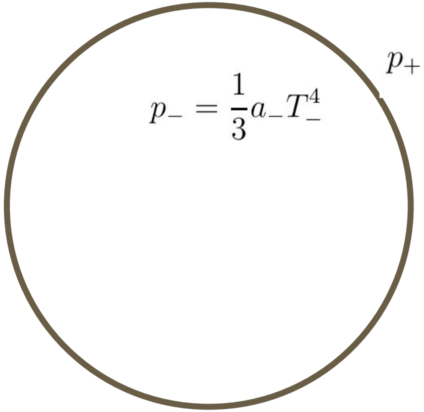
Enters via a time dependent energy background $\epsilon(\vec{x}, t)$

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

Higgsless intuition

Bag Equation of State

Espinosa, Konstandin, No, Servant (10)



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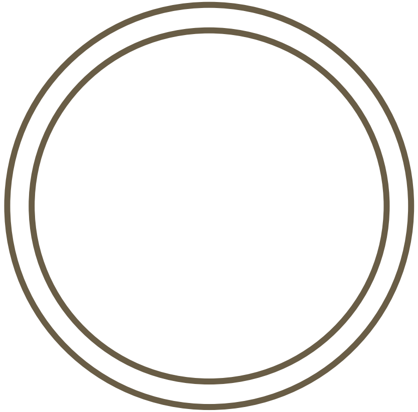

The scales of the problem:

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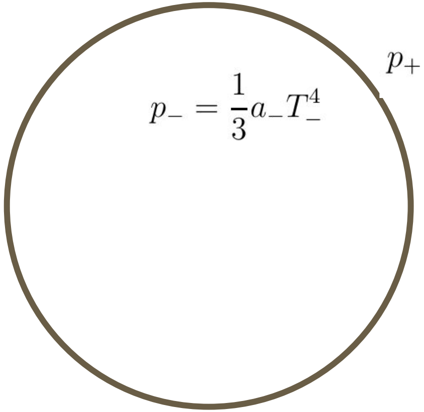
Higgsless intuition

How our simulation works:

Bag Equation of State

Espinosa, Konstandin, No, Servant (10)



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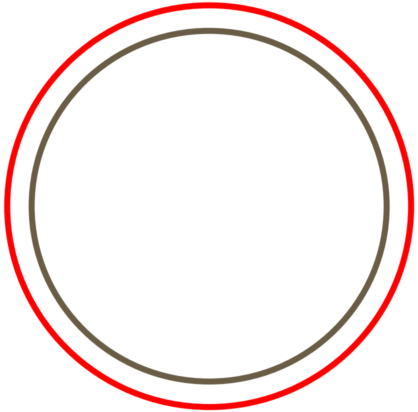

The scales of the problem:

- Bubble thickness: TeV

Higgsless intuition

How our simulation works:

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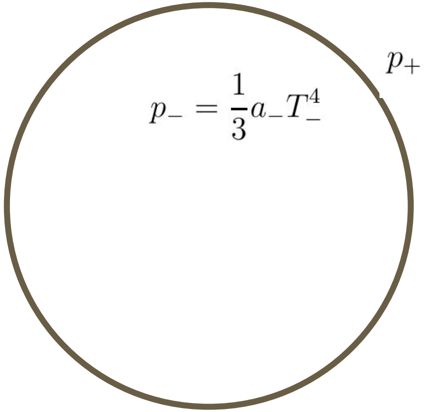

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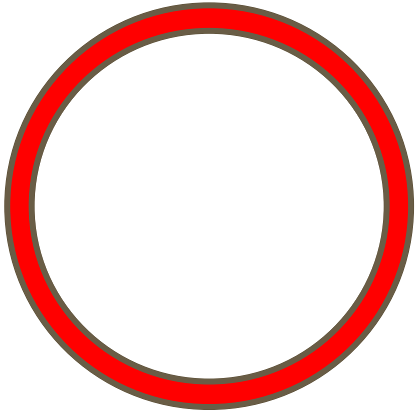

The scales of the problem:

- Bubble thickness: TeV
- Sound Shell

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Higgsless intuition

How our simulation works:

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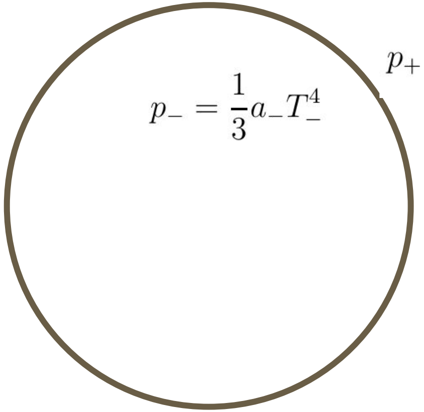
Enters via a time dependent energy background $\epsilon(\vec{x}, t)$

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

Bag Equation of State

Espinosa, Konstandin, No, Servant (10)



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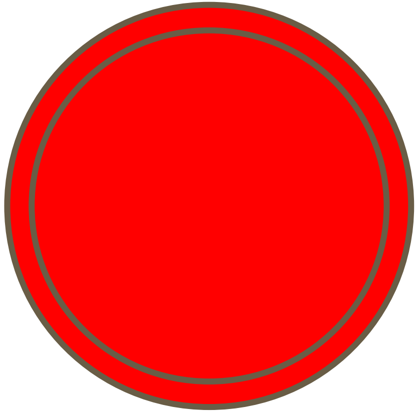

The scales of the problem:

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

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What exactly we solve in the lattice

Conservation Eq. $\partial_\mu T^{\mu\nu} = 0$ with $T^{\mu\nu} = u^\mu u^\nu w - \eta^{\mu\nu} p$

Enthalpy and pressure:

$$p = \frac{1}{3} a T^4 - \epsilon \,, \quad w = T\frac{dp}{dT} = \frac{4}{3} a T^4$$

Modelling of the vacua:

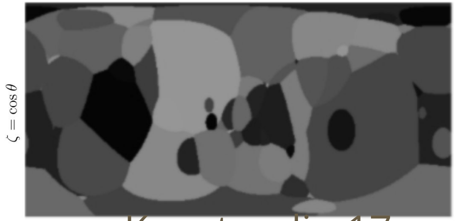
$$\epsilon(t, \vec{x}) = \begin{cases} 0 & \text{inside bubbles}\,, \\ \epsilon & \text{outside bubbles}\,, \end{cases}$$

Wall velocity enters here

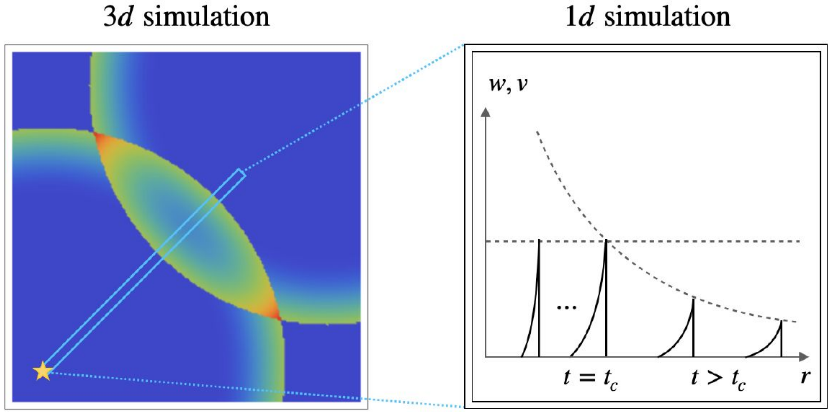
PT strength enters here

$$\alpha = \frac{4\epsilon}{3w}$$

Hybrid (1d embedded in 3d) Higgsless

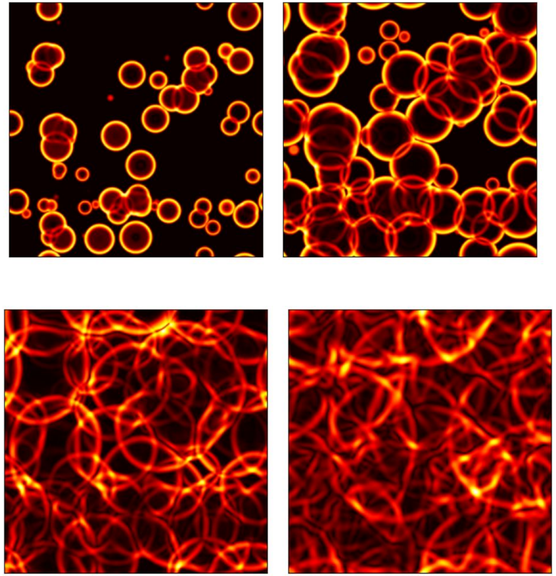


Konstandin 17



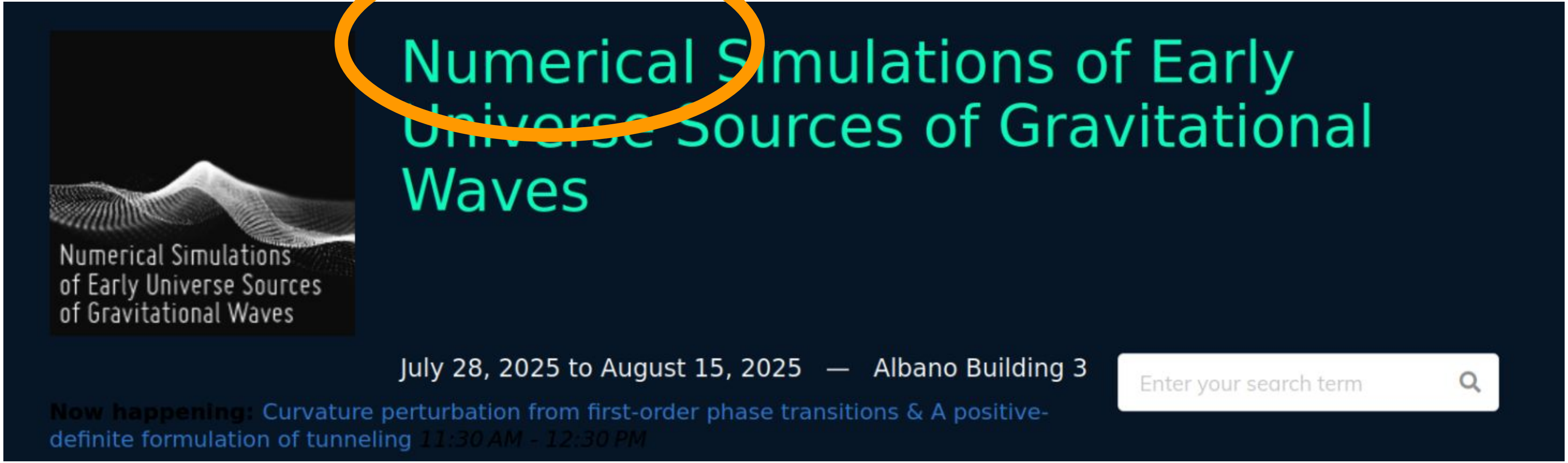
Jinno, Konstandin, **HR,** 2020

The full 3D Higgsless



Jinno, Konstandin, **HR,** Stomberg 2022

This is a part I always skip in my talks but always wanted to focus on



The numerics

- Higgs->0 leads to fluid discontinuities. How to deal with them?
- Dealing with shocks there is a tradeoff: numerical viscosity vs. unphysical oscil.

1d PDE example:

$$\partial_t u + \partial_r f + g = 0,$$

$$u = \begin{pmatrix} u_1 \\ u_2 \end{pmatrix} = \begin{pmatrix} w\gamma^2 - p \\ w\gamma^2 v \end{pmatrix}, \quad f = \begin{pmatrix} w\gamma^2 v \\ w\gamma^2 v^2 + p \end{pmatrix}, \quad g = \frac{d-1}{r} \begin{pmatrix} w\gamma^2 v \\ w\gamma^2 v^2 \end{pmatrix}.$$

Option 0
Lax-Friedrichs (LF)
Linear, first-order

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

$$\lambda = \Delta t / \Delta x$$

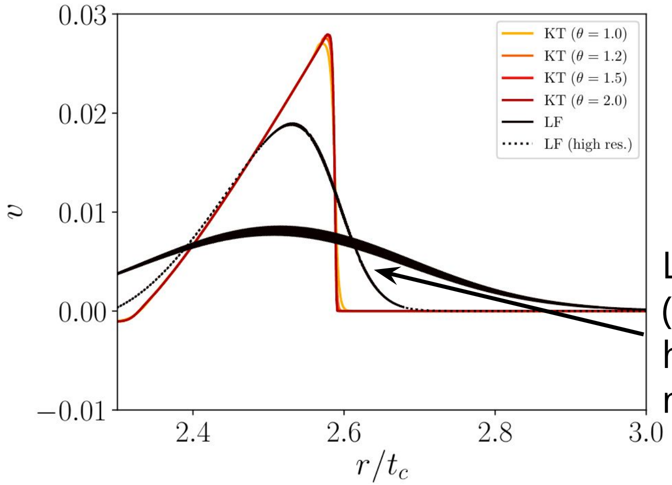
Solving shocks

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

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

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)

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

Solving shocks

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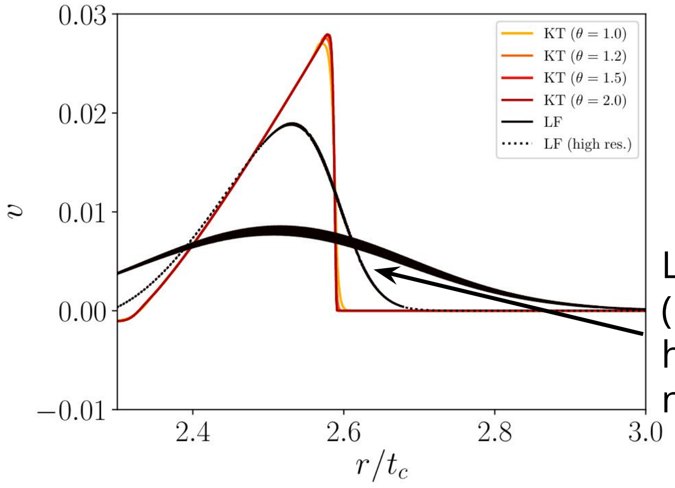
Simples scheme, Lax Friedrichs (LF)

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



Large viscosity (refined mesh here would not help too)

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

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

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

Kurganov - Tadmor (KT) for conservative schemes
Non-linear, second order

$$\partial_\mu T^{\mu\nu} = 0$$

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

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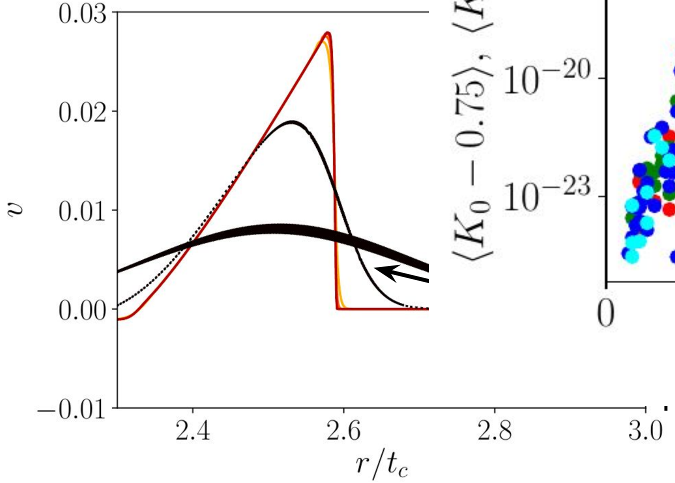
Solving shocks

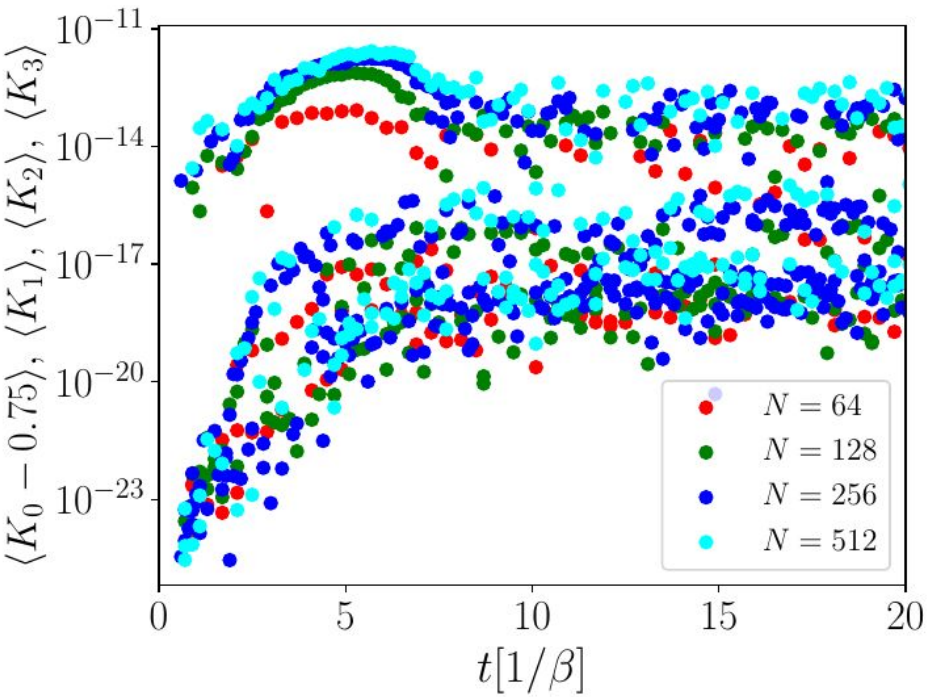
Gudunov's theorem: Linear scheme can only respect positivity at first order

$$\partial_t u + \partial_x f$$

Simples scheme, Lax

$$u_j^{n+1} = \frac{u_{j+1}^n + u_{j-1}^n}{2} - \frac{\lambda}{2}\,[f$$





not help too)

Solution 1: Riemann solvers or Godunov schemes

diagonalize matrix locally

'flux limiters'

$$\partial_\mu T^{\mu\nu} = 0$$

Flux

$$H^n_{j+1/2} - H^n_{j-1/2})$$

Viscosity

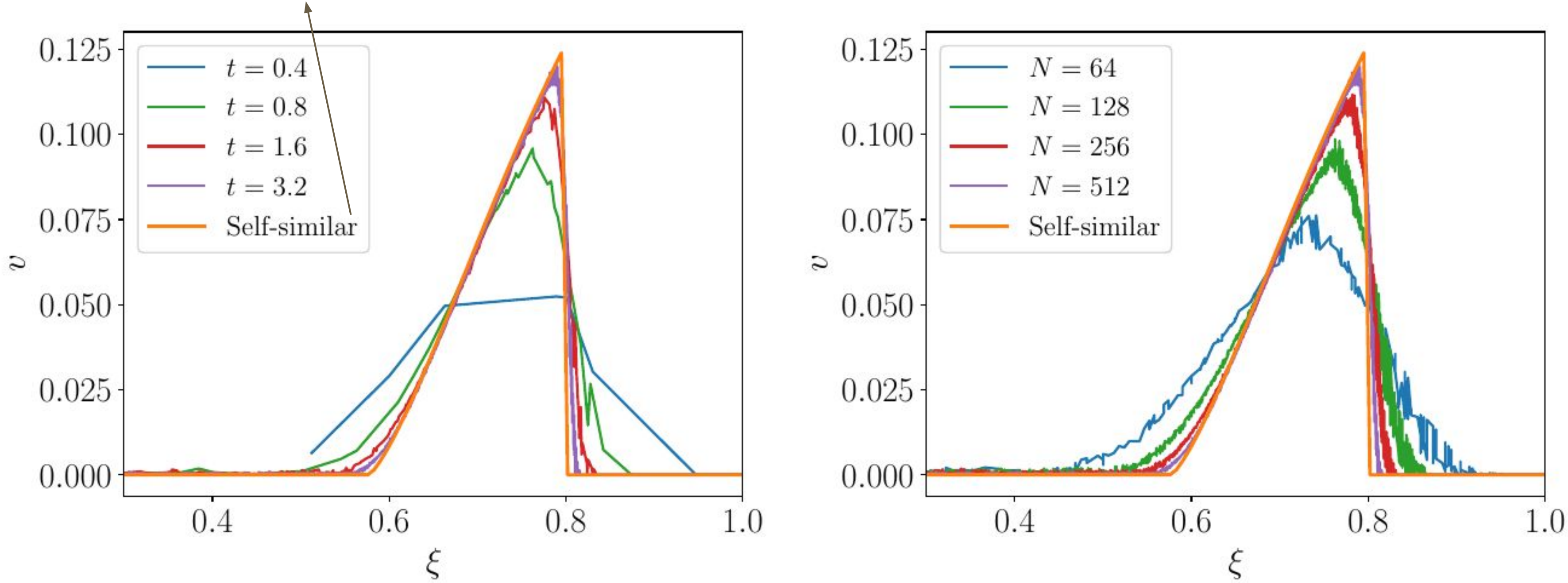
$$\frac{a_{j+1/2}}{2}\left[u^+_{j+1/2} - u^-_{j+1/2}\right]$$

Local max velocity

Can we reproduce bag EoS solution?

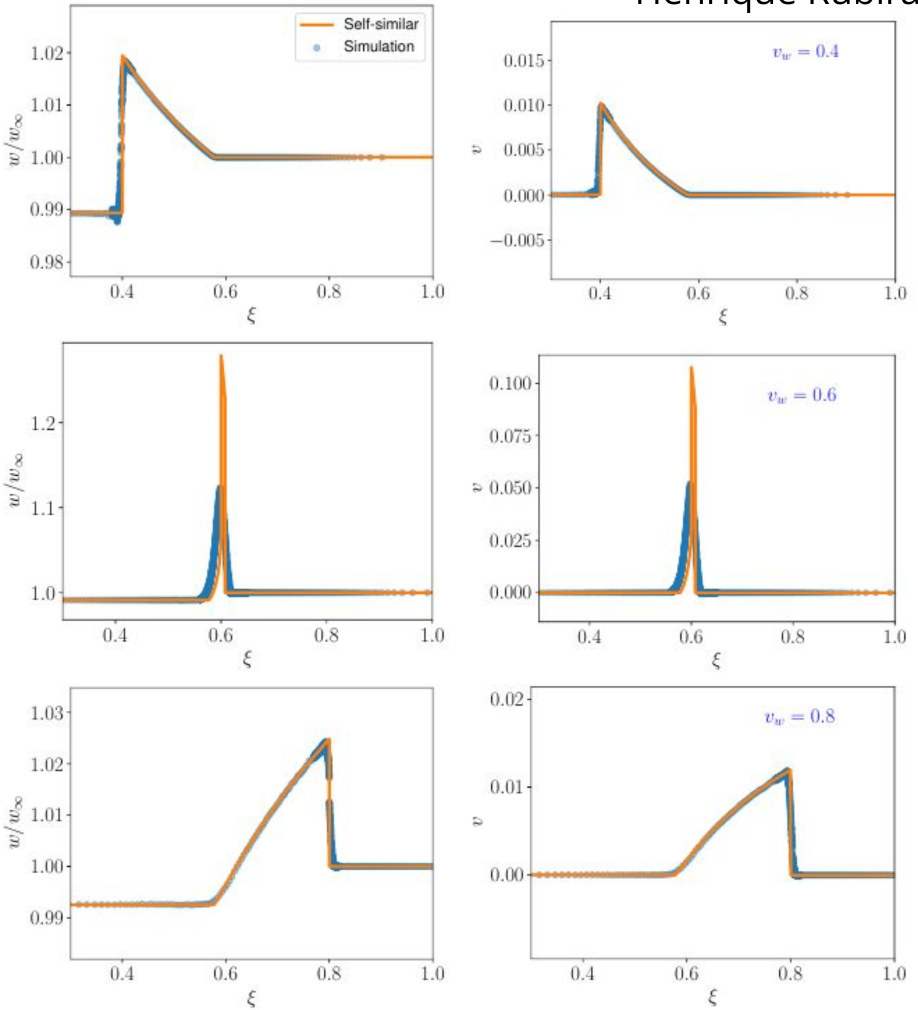
Comparing to the analytical solution

Can we reproduce the correct result with one single bubble?



Can we reproduce bag EoS solution?

Yes!
Struggling more for compact profiles



A short rest for your eyes… questions?

Outline of this talk

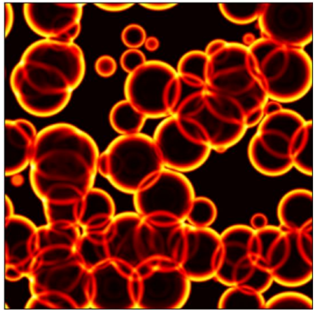
Part I: Higgsless

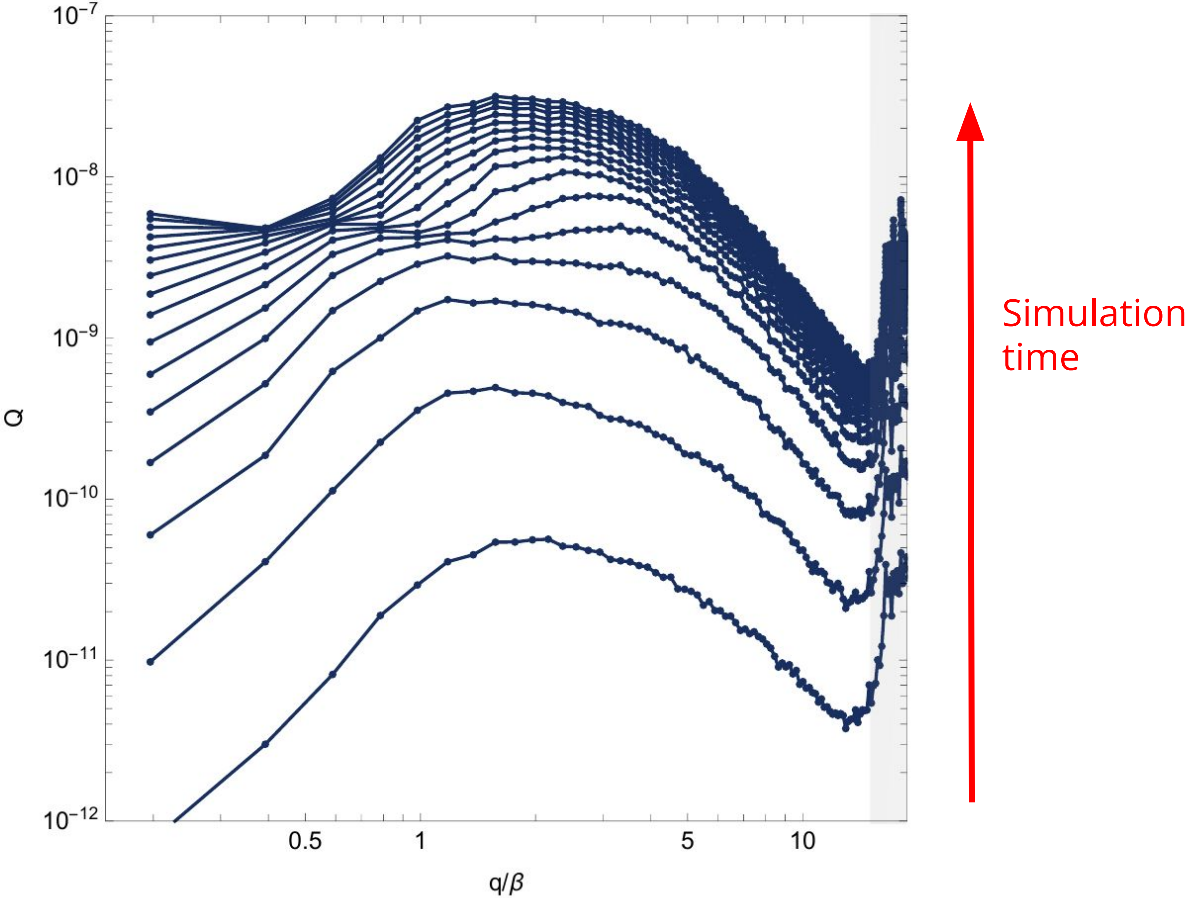
- Simulations
- **Results**
- Temperature fluctuations and Topological defects

Part II: Phase transitions and H0 tension

Results

Now with many bubbles...



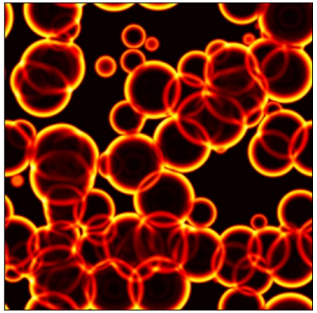


$$\Omega_{\rm GW} = \frac{w^2\,\tau}{4\pi^2 \rho_{\rm tot} M_P^2 \beta} \times Q',$$

Results

Amplitude   Shape

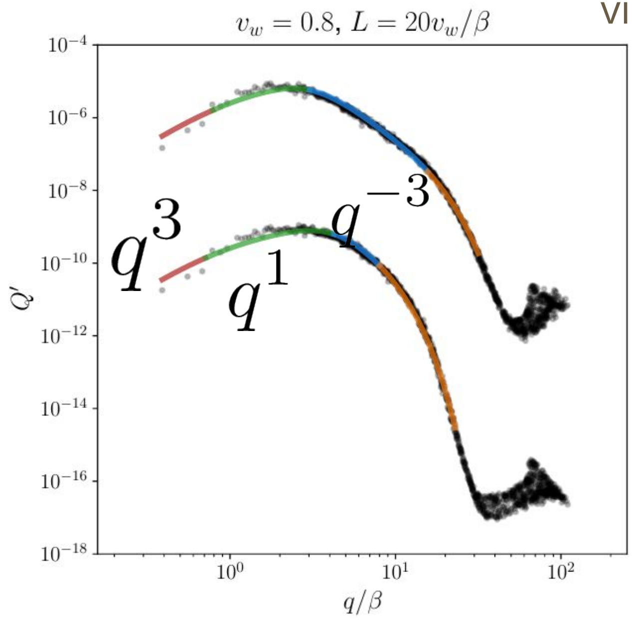
$$Q'(q) = Q'_{\rm int} \times S_f(q)$$



A double-broken power law

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

Exponential viscosity



Results

Amplitude Shape

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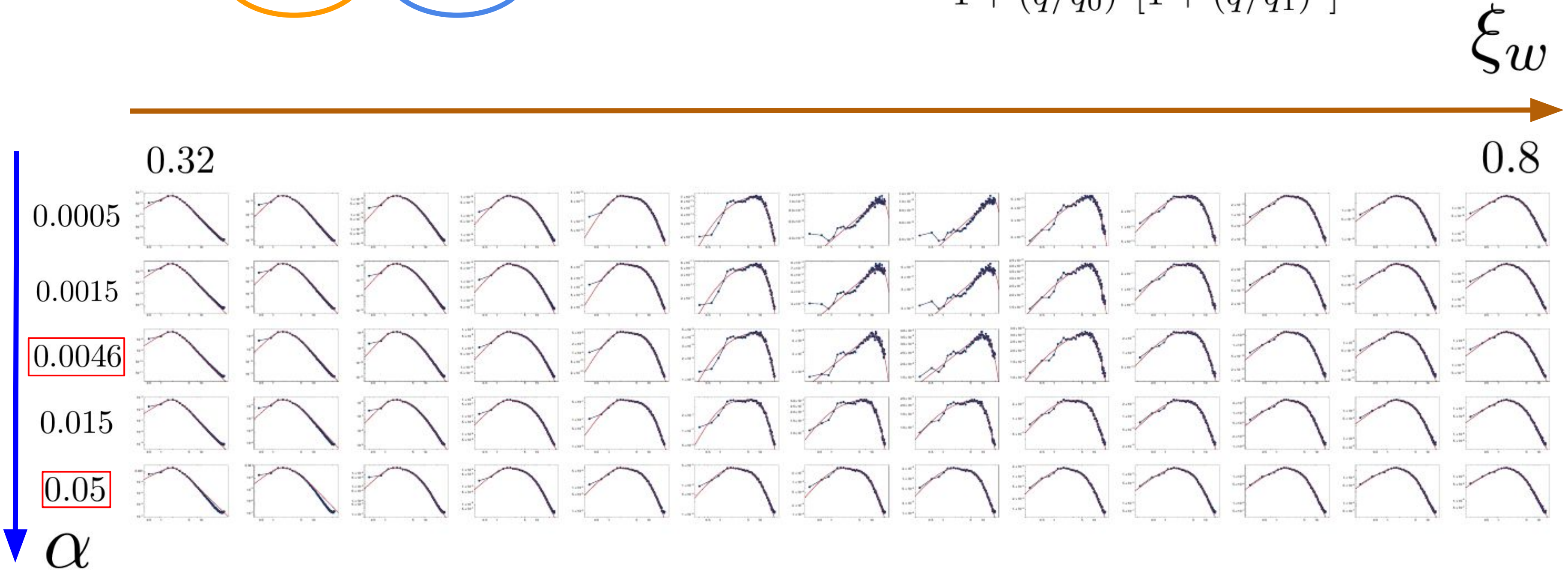

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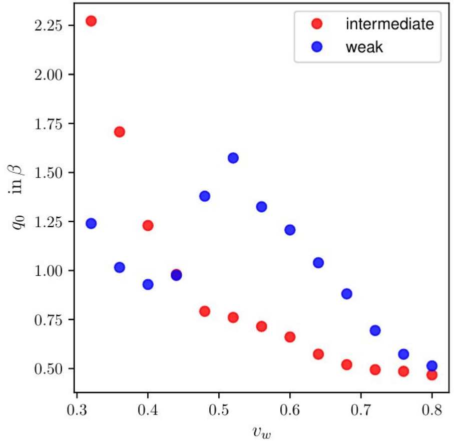
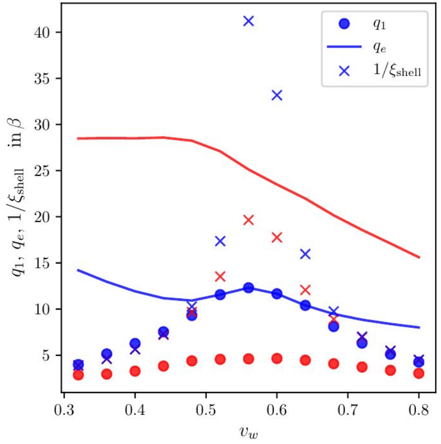
Position of the peaks

IR peak looks complex

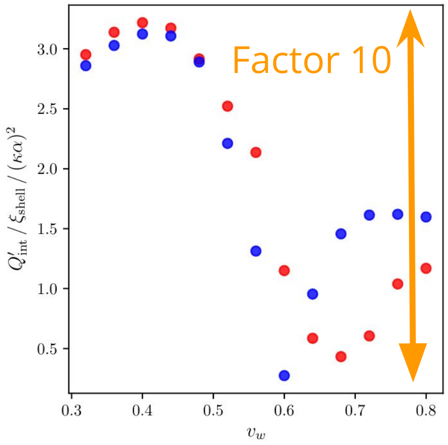


UV peak scales as sound shell thickness

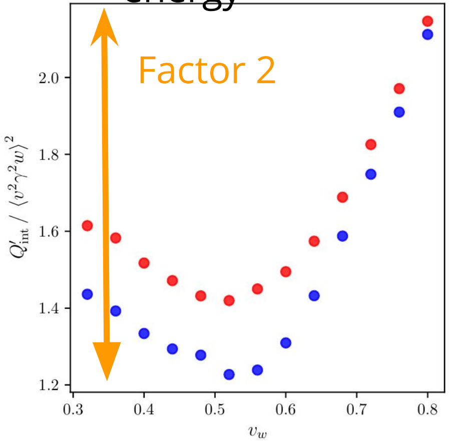


Amplitude of the spectrum

Normalized by kinetic energy



Normalized by 3d simulation kinetic energy



Comparison to other works

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

1000x faster! (Fluid only)

More bubbles -- O(2500)

	IR	Intermediate	UV
Sound shell	9	1	-3
Scalar + fluid lattice	-	1	-3
Hybrid	[2,4]	[-1,0]	[-4,-3]
Higgsless	3	1	-3

Pause for drinking water… questions?

Outline of this talk

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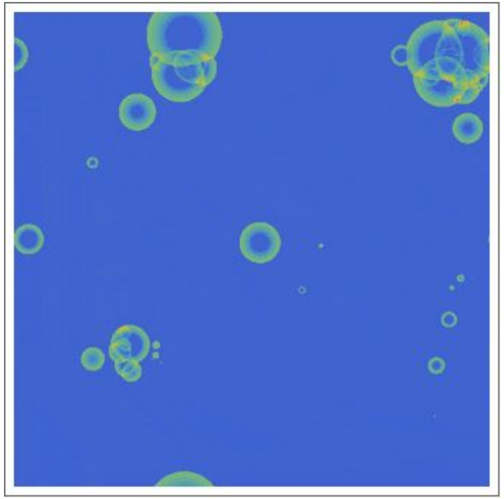
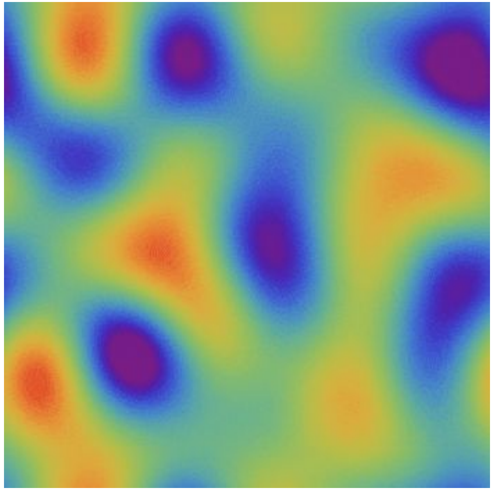
- Simulations
- Results
- **Temperature fluctuations and Topological defects**

Part II: Phase transitions and H0 tension

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





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

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

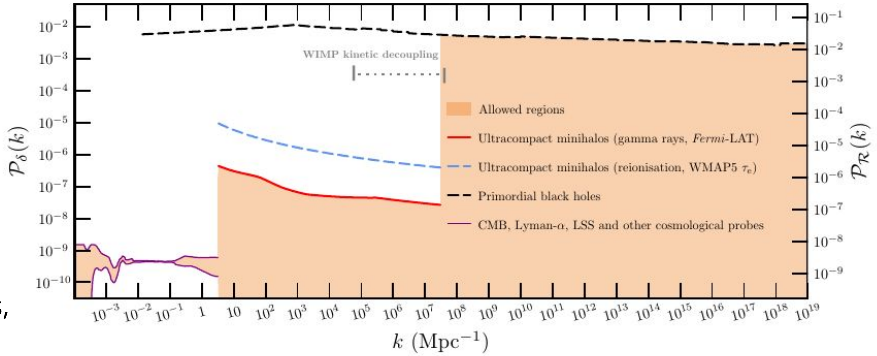
After expanding it around $t = t_*$

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

This next term in the expansion may be large if

$$\frac{\delta T}{T} \sim \left(\frac{\beta}{H_*}\right)^{-1}$$

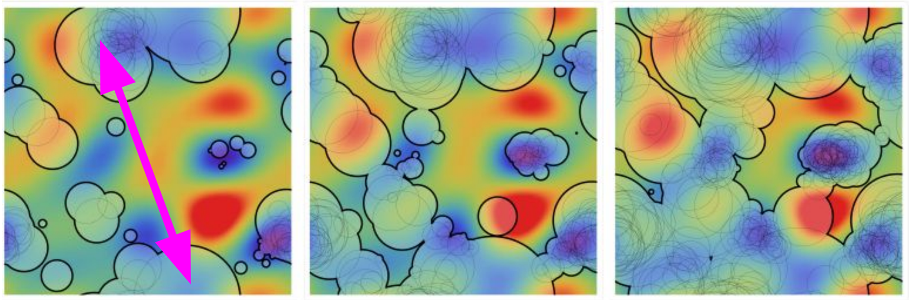
Since we are talking about T~Tev, it is pretty in the (unconstrained) UV



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

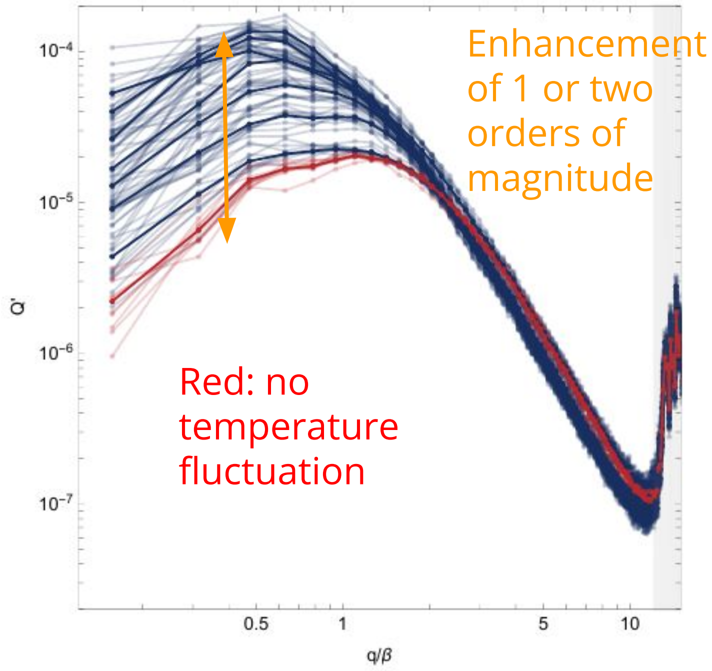
What is the effect in the GW spectra?

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



Result: increase the bubbles size and therefore enhance GW spectra

We also parametrized how spectra depends on temperature fluctuations



+ Jorinde v.d. Vis

Motivation

Domain walls appear in many **two-step PTs**
(e.g. singlet extension)

$$V = \frac{\lambda}{4}(\phi^2 - v^2)^2 + \frac{\lambda_m}{4} s^2 \phi^2 + \frac{\lambda_m}{4} s^4 - \frac{1}{2}\mu_S^2 s^2$$

s is a singlet with a Z2 sym

This Z2 is spontaneously broken producing DWs

At low Temperatures, this Z2 symmetry is restored when the other scalar ϕ gets a vev

Domain Walls stop to exist!
(they don't overclose the Universe but are relevant at transition time)

COSMIC STRINGS AND DOMAIN WALLS

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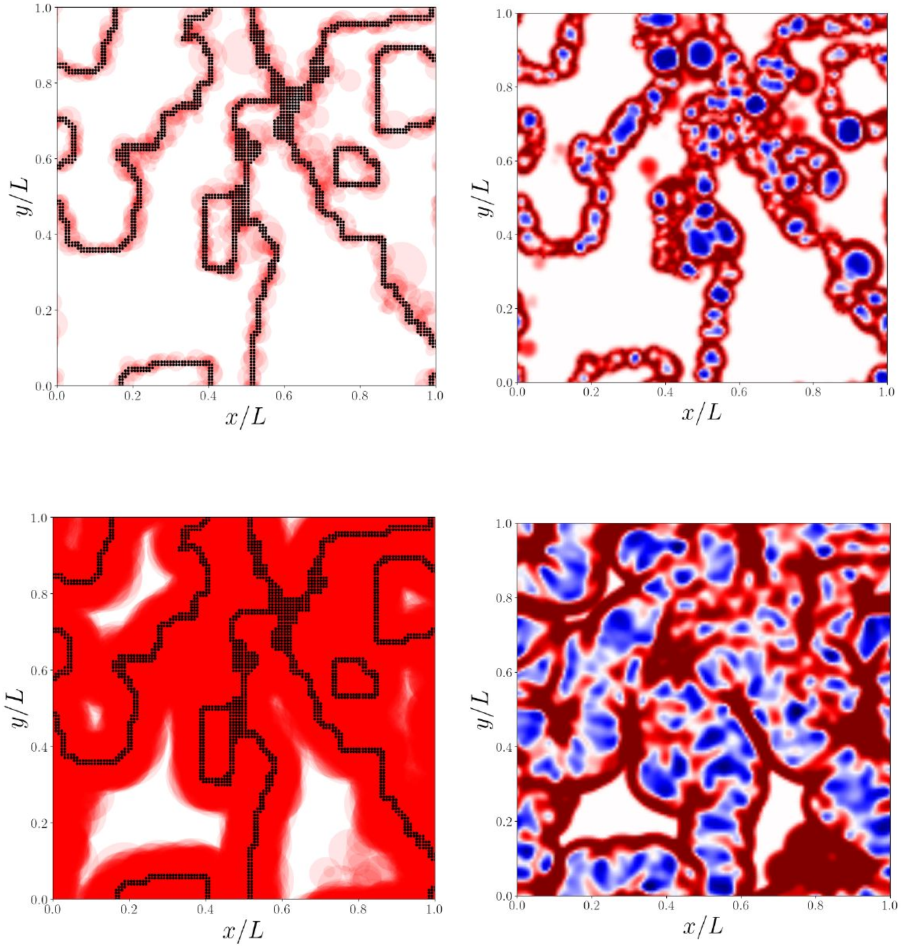
Received October 1984

To learn more about the system of walls at formation, one can use a Monte Carlo simulation [53, 54].

Using the Ising Model to mimic DWs! Both have a single scale

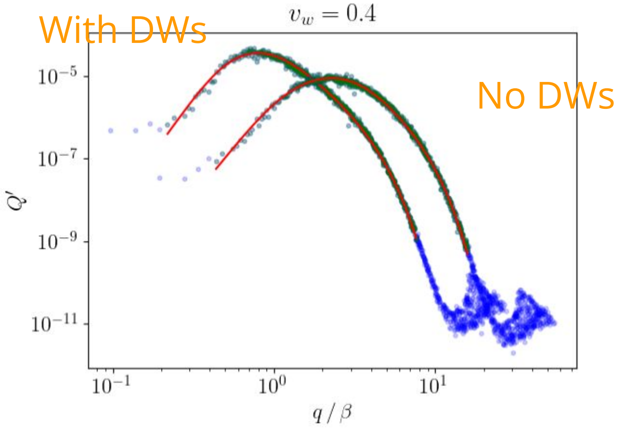
Henrique Rubira

The Ising Model and the fluid energy



Relevant whenever $\xi_{\rm DW} \gg 2\langle r\rangle \simeq 6v_w/\beta$

$$\beta \to 3/\xi_{\rm DW}$$



+ Simone Blasi

Conclusions I

We have a fast and precise scheme to calculate GWs from PT that can explore non-linear PTs also alternative scenarios

What comes next? (+ Chiara Caprini, Alberto Roper Pol)

- Deep into non-linear PTs
- Decaying sources

Another short rest for your eyes... questions?

Outline of this talk

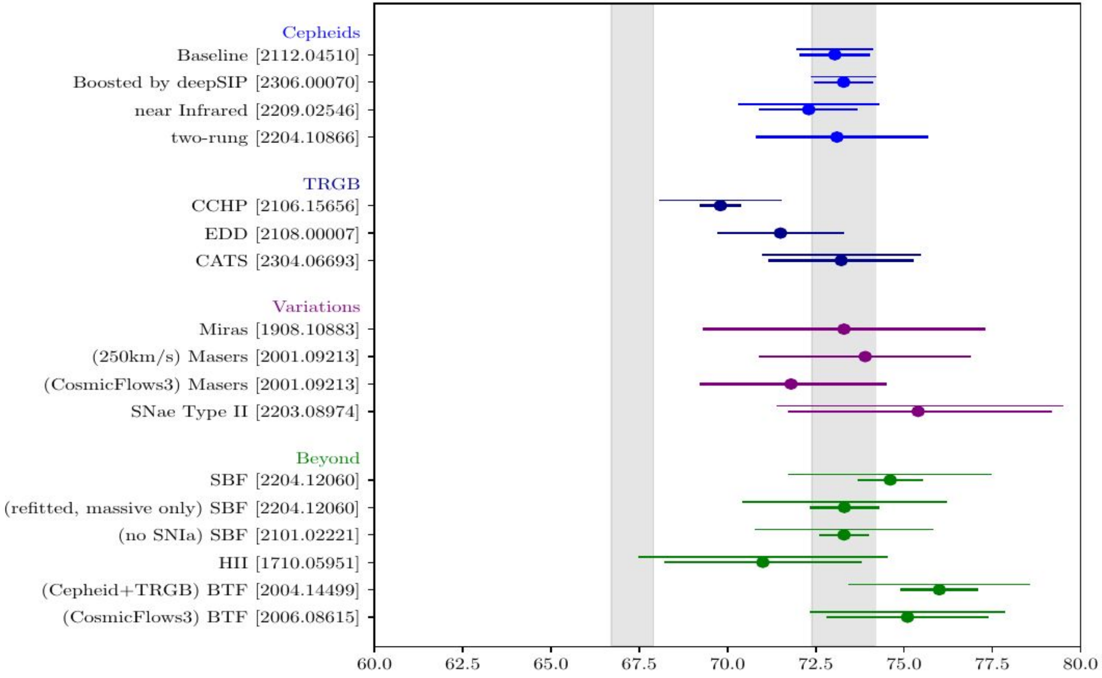
Part I: Higgsless

- Simulations
- Results
- Temperature fluctuations and Topological defects

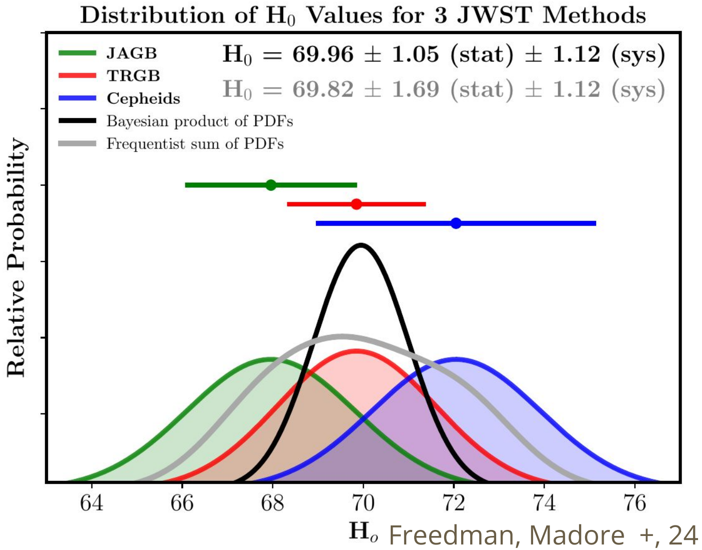
Part II: Phase transitions and H0 tension

The Hubble tension

Verde, Schoeneberg, Gil-Marin, 23



For now, JWST results are still inconclusive (see Riess+, 24)



Freedman, Madore +, 24

The theorist job

What is a simple model that can address the H0 tension?

The theorist job

What is a simple model that can address the H0 tension?

$$\mathcal{L} = \bar{\chi}(i\gamma^\mu D_\mu - m_\chi)\chi + |D\Psi|^2 - V_{\rm cl}(|\Psi|^2) - \frac{1}{4}F^a_{\mu\nu}F^{\mu\nu}_a$$

+ Symmetry breaking SU(N) -> SU(N-1)

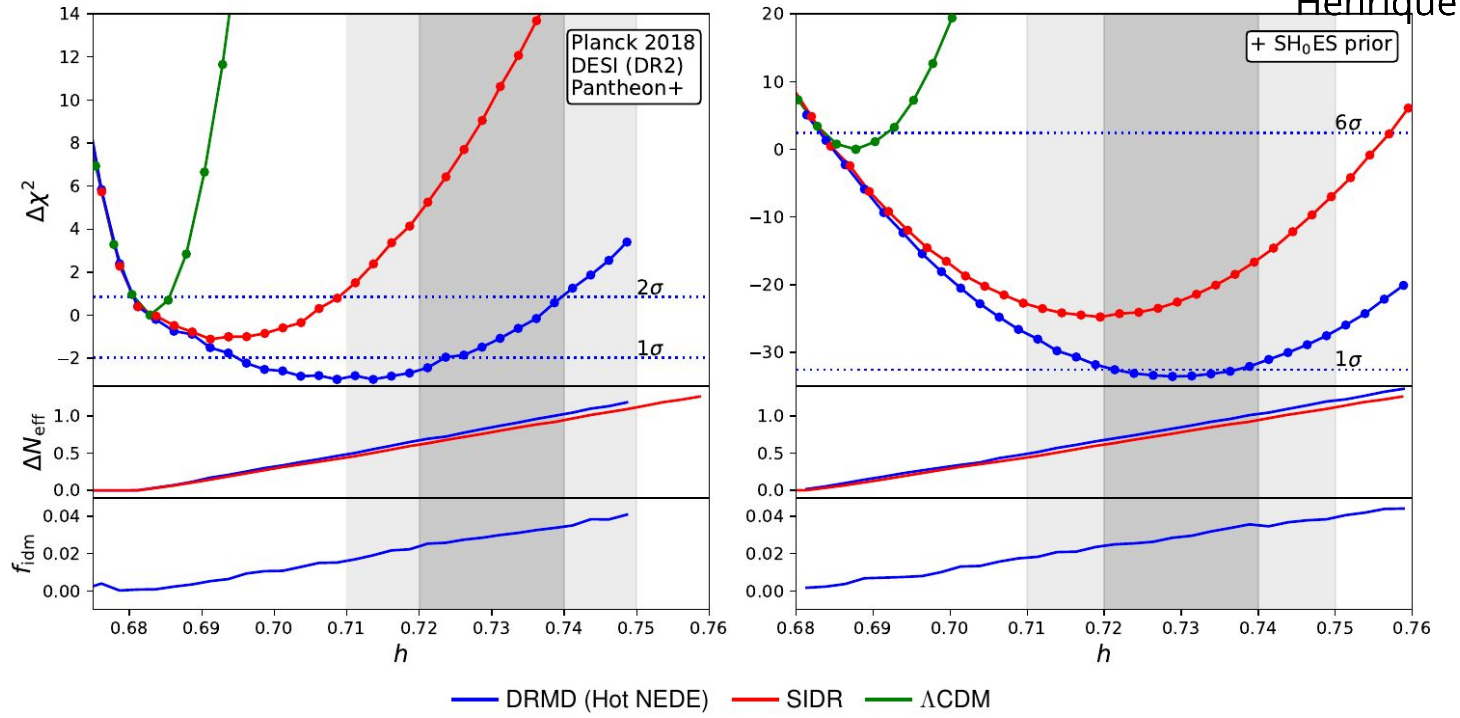
Produces a fraction of **EDE**
via supercooling
(Niedermann + Sloth)

$$f_{\rm NEDE} = \Delta V_* / \rho_{\rm tot}(T_d^*)$$

2404.07256, 2508.TODAY, Garny, Niedermann, **HR**, Sloth

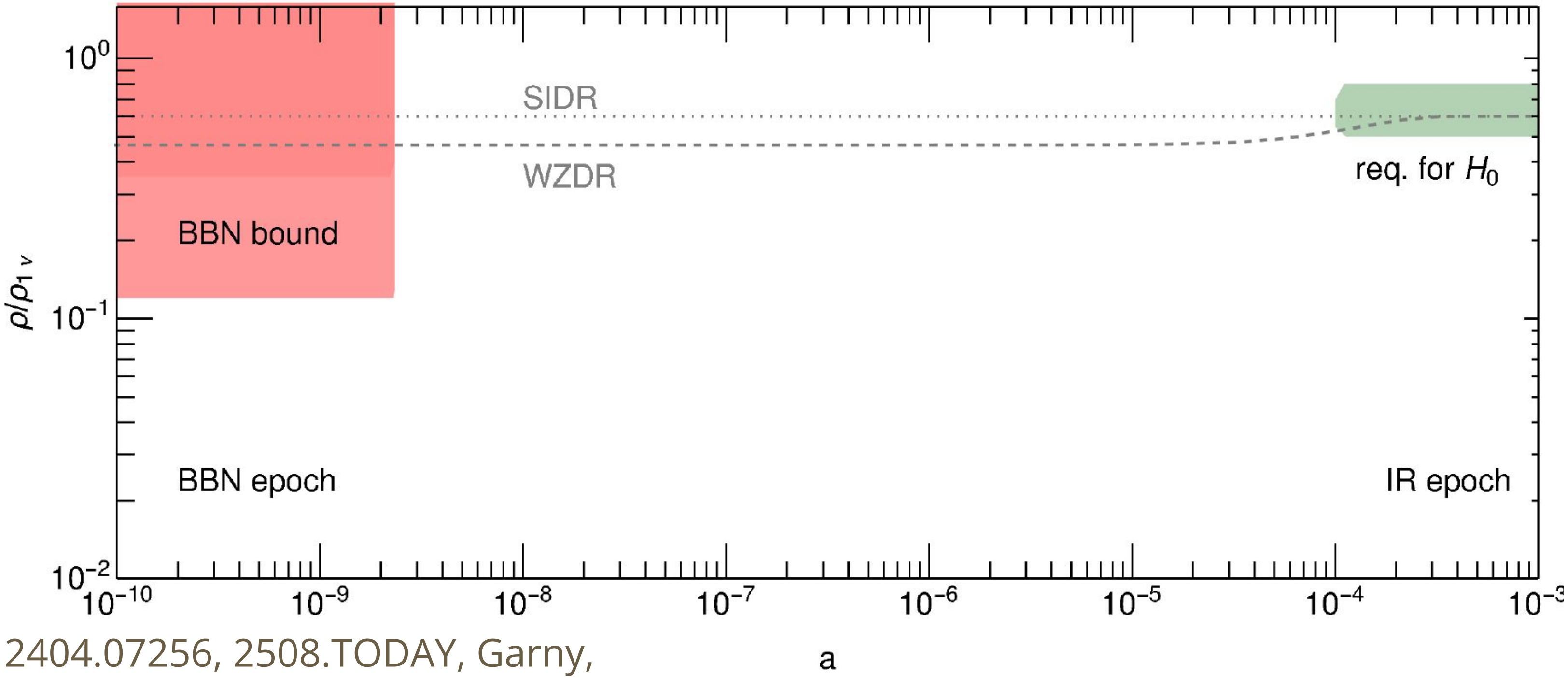
Results

Henrique Rubira



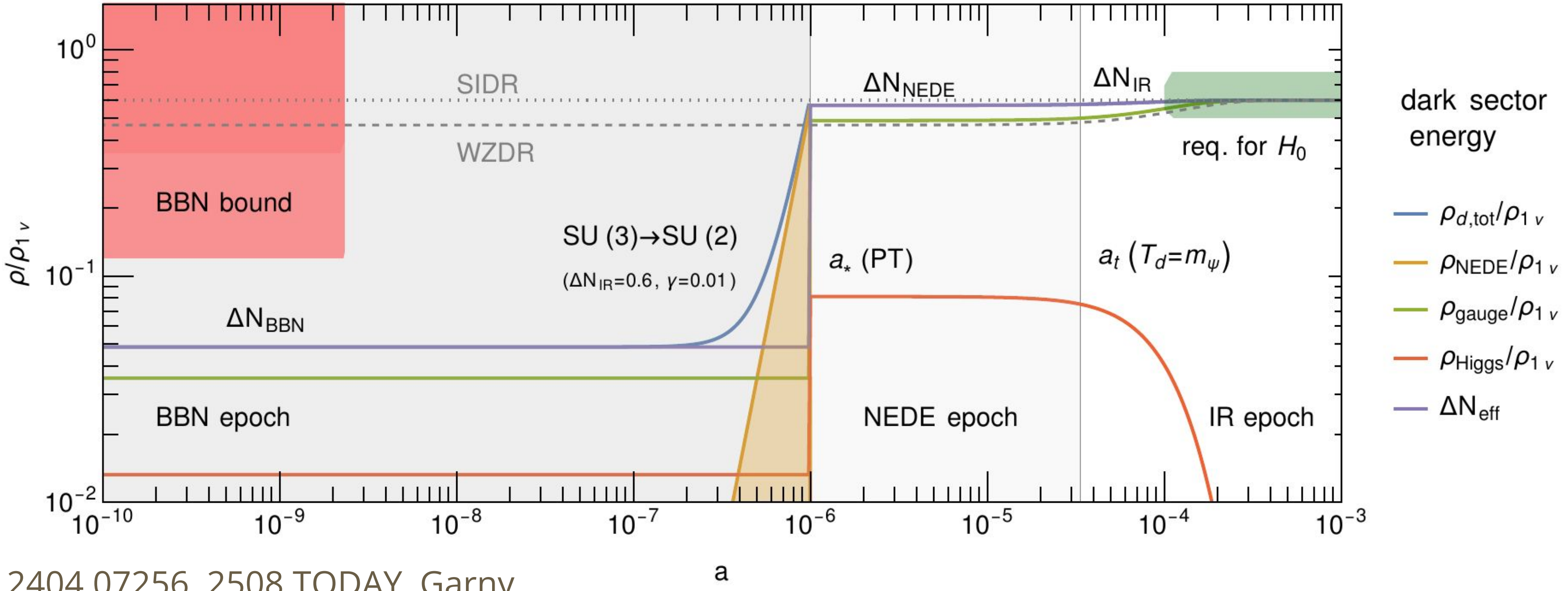
	Base				Base + SH_0ES prior				$Q^M_{\rm DMAP}$	$Q_{\rm Gauss}$
	H_0	$\Delta N_{\rm eff}$	$\Delta\chi^2$	ΔAIC	H_0	$\Delta N_{\rm eff}$	$\Delta\chi^2$	ΔAIC		
ΛCDM	68.30 ± 0.29	–	–	–	68.70 ± 0.29	–	–	–	5.7σ	4.4σ
SIDR	$69.8^{+0.8}_{-1.0}$ (69.4)	< 0.525 (0.188)	-1.2	0.8	71.9 ± 0.7 (72.0)	0.61 ± 0.13 (0.610)	-24.5	-22.5	3.0σ	2.5σ
DRMD	$70.5^{+1.0}_{-1.6}$ (70.9)	< 0.811 (0.462)	-3.0	5.0	72.8 ± 0.8 (72.9)	0.80 ± 0.16 (0.829)	-33.3	-25.3	1.4σ	1.7σ

Big picture of the model: evolution of energy density



2404.07256, 2508.TODAY, Garny, Niedermann, **HR**, Sloth

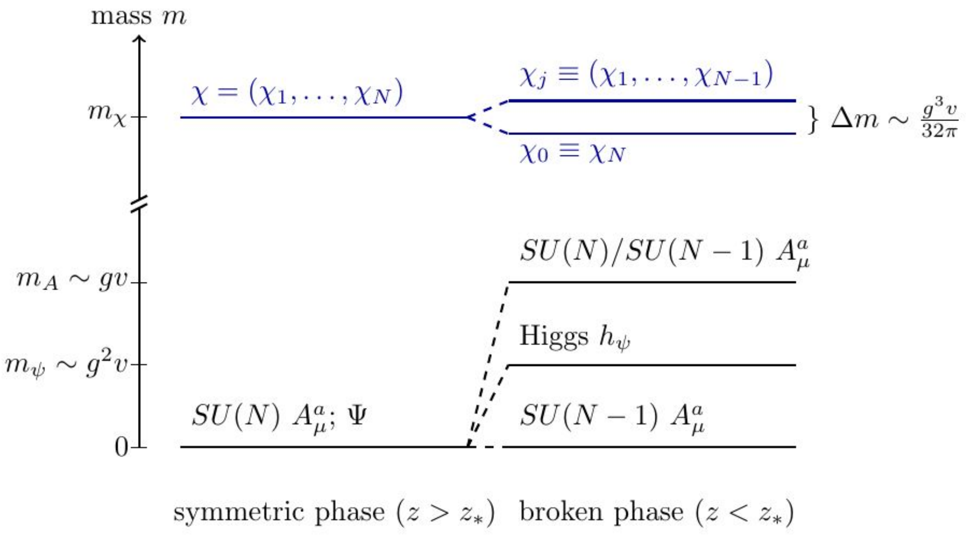
Big picture of the model: evolution of energy density

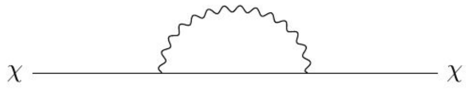


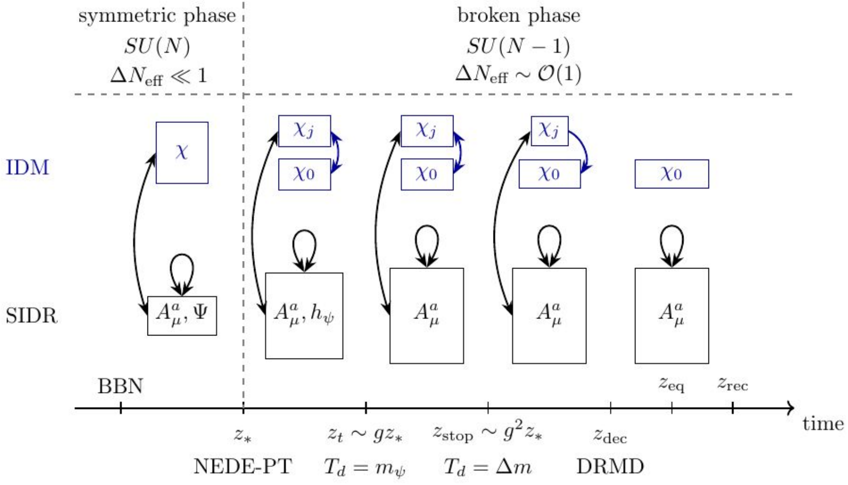
2404.07256, 2508.TODAY, Garny, Niedermann, **HR**, Sloth

Henrique Rubira

Phase transitions as a solution for H0

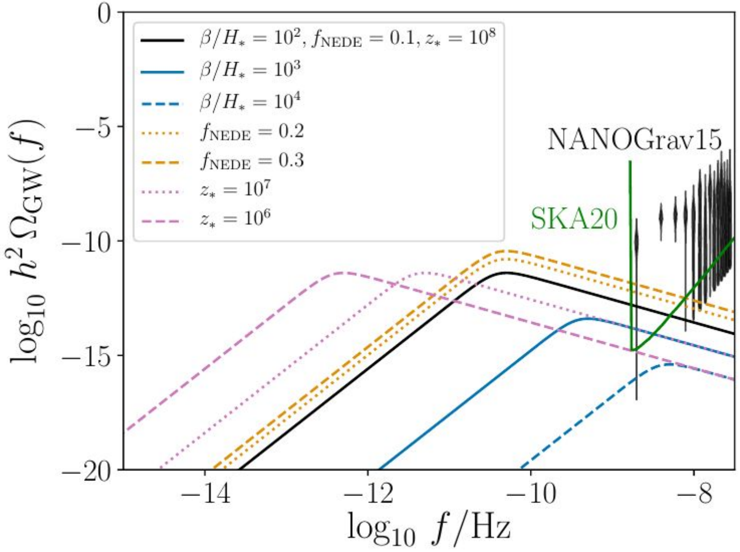






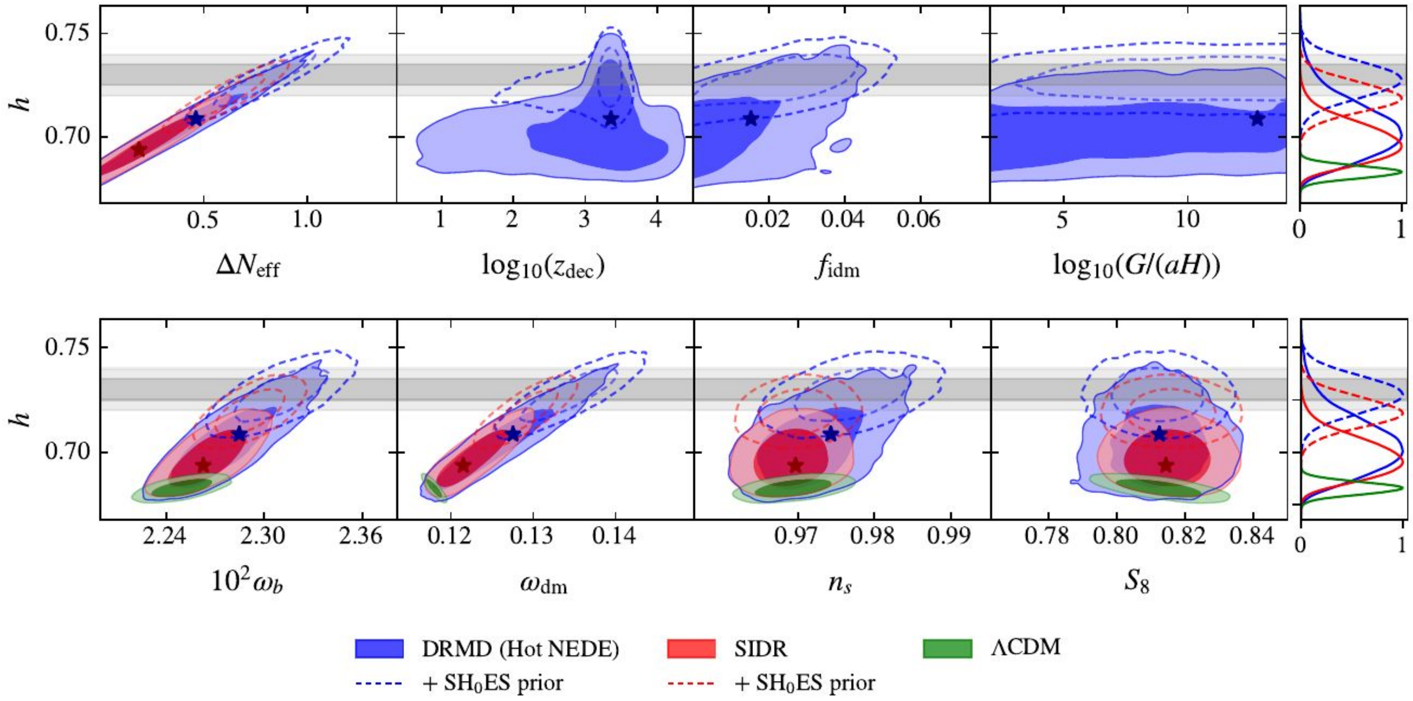
2404.07256, 2508.TODAY, Garny, Niedermann, **HR**, Sloth

Gravitational waves



2404.07256, 2508.TODAY, Garny, Niedermann, **HR**, Sloth

The posteriors



Conclusions II

Simple model for a complicated problem.

H0 Tension reduced from 5.7sigma to 1.4sigma

Complex pheno for us to have fun!

Thanks a lot!

Class of solutions to the tension

The three main quantities

1) Angular diameter distance

$$D_A(z) = \int_0^z \frac{1}{H(z')} dz'$$

2) The sound horizon

$$r_s(z_*) = \int_{z_*}^{\infty} \frac{c_s(z')}{H(z')} dz'$$

3) Angular-scale of the sound horizon

$$\theta_s(z) = \frac{r_s(z_*)}{D_A(z)}$$

Late Universe

- Raise H0 playing with the DE density;
- Challenge: Myriad of low-z measurements of $H(z')$ make it hard to keep $D_A(z)$ fixed

Early Universe: modifications of the sound horizon, adjusting $D_A(z)$ to keep $\theta_s(z)$ fixed across different scales. In general, perform better.

Supercooling

We work in the light Higgs mass limit (relative to gauge-bosons) $m_A \gg T_d^*, m_\psi$

Potential including loop gauge-boson loop-corrections (Coleman-Weinberg)

$$V(\psi; T_d) = V_0 - \frac{\mu_{\text{eff}}^2}{2}\psi^2\left(1 - \frac{\psi^2}{2v^2}\right) + B\psi^4\left(\ln\frac{\psi^2}{v^2} - \frac{1}{2}\right) + \Delta V_{\text{thermal}}(\psi; T_d)$$

with: $\Delta V_{\text{thermal}}(\psi; T_d) \to \frac{1}{24} c_0 n_A g^2 T^2 \psi^2$

The conformal limit is reached at $\mu_{\text{eff}} = 0$ (Witten, 1981)

Defining the supercooling parameter

Loop corrections

$$\gamma \equiv \frac{12\pi\mu_{\text{eff}}^2}{c_0 n_A v^2 g^4}$$

Thermal corrections

supercooling happens as long as $\gamma \lesssim \mathcal{O}(1)$

Reheating the Dark Sector

After the transition:

- kinetic/gradient energy of bubble walls;
- bubble collision leads to bubble fragments and condensate of small-scale anisotropic stress.

Decay of the scalar particles in bubble-wall condensate via $\psi \to AA$
(1-loop massless gauge bosons, similar to $h \to \gamma\gamma$)

$$\frac{\Gamma^{(\mathrm{cm})}_{\psi \to AA}}{H_*} = \mathcal{O}(1) \times \frac{g^9 f^{1/4}_{\mathrm{NEDE}}}{1+z_*} 10^{24}$$

imposes the condition $g \gtrsim 0.02$

Thermalization of the gauge bosons via $AA \to AA$

$$\frac{\Gamma_{\mathrm{therm}}}{H_*} \sim \frac{g^4}{1+z_*} 10^{31}$$

Coupling with the plasma can also reheat the plasma via other channels