UNIVERSITY OF HELSINKI
FACULTY OF SCIENCE

HELSINKI INSTITUTE OF PHYSICS

Primordial gravitational waves from first-order phase transitions

David J. Weir
University of Helsinki

This talk: saoghal.net/slides/cau2023

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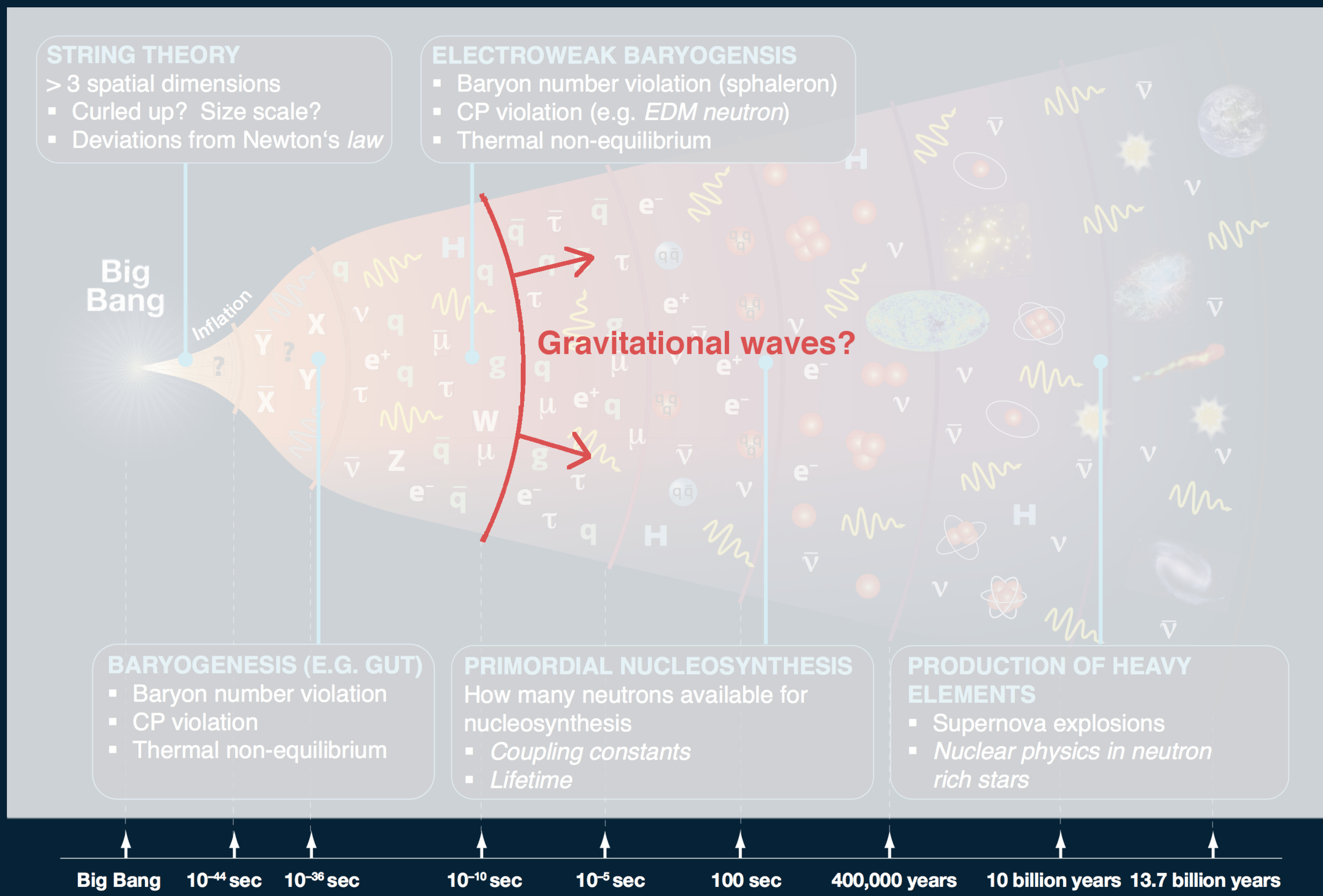
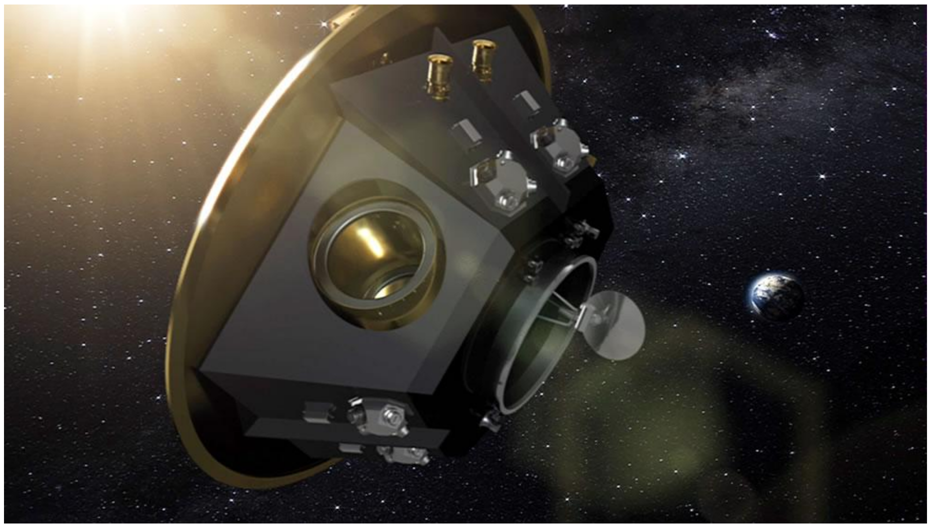
What happened in the early universe? when the universe was optically opaque? in dark sectors?

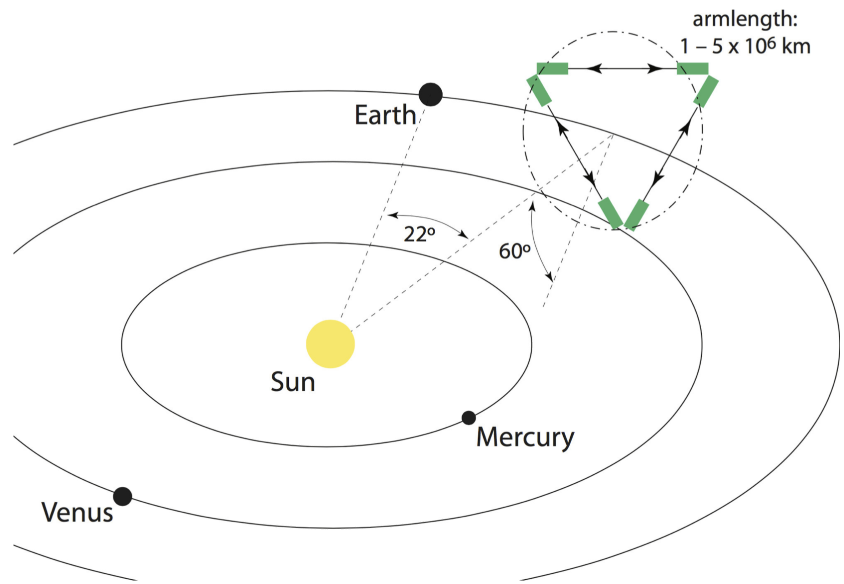


Credit: Stephan Paul, arXiv:1205.2451

How could gravitational waves help?

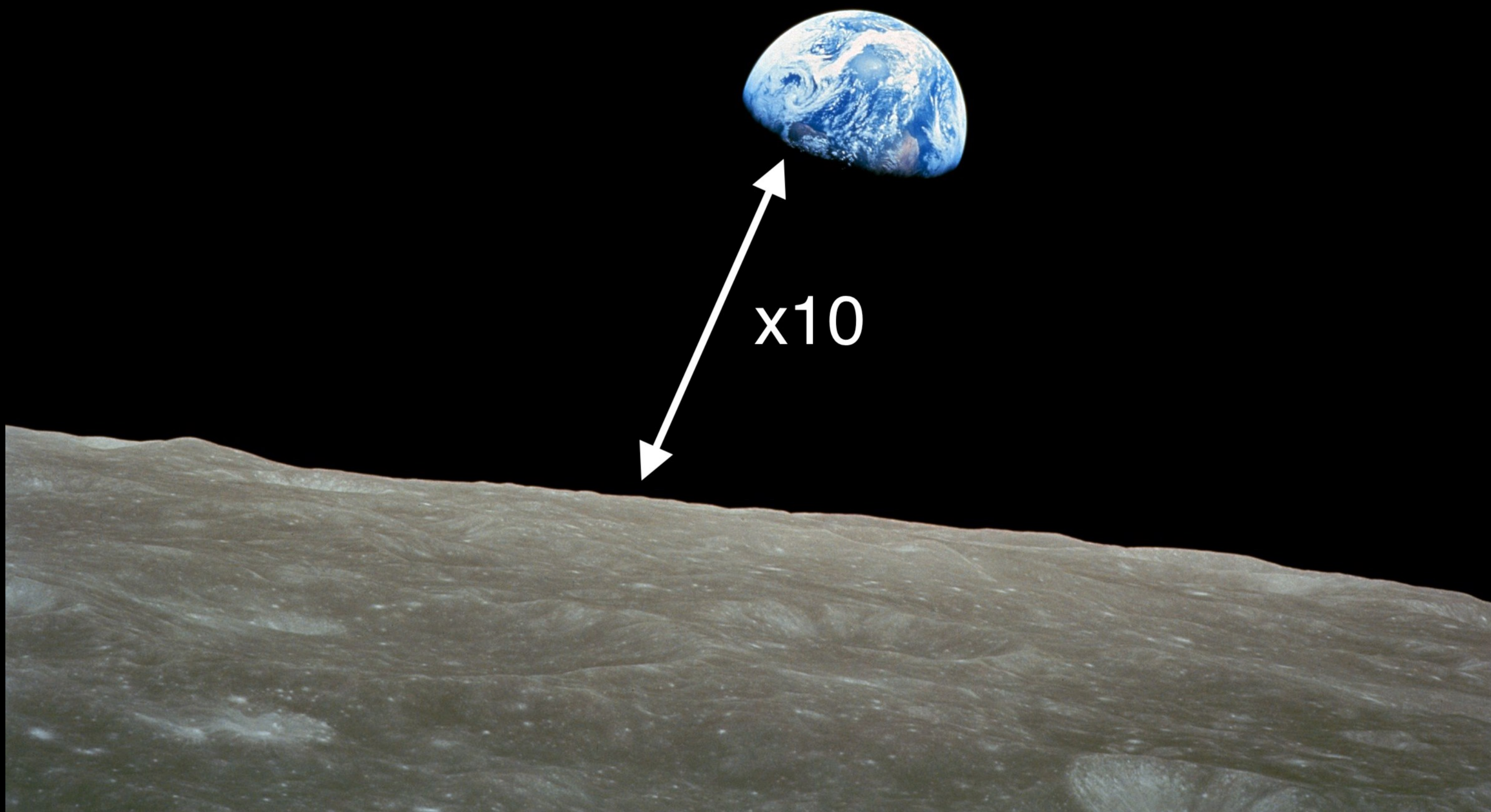
LISA is coming!





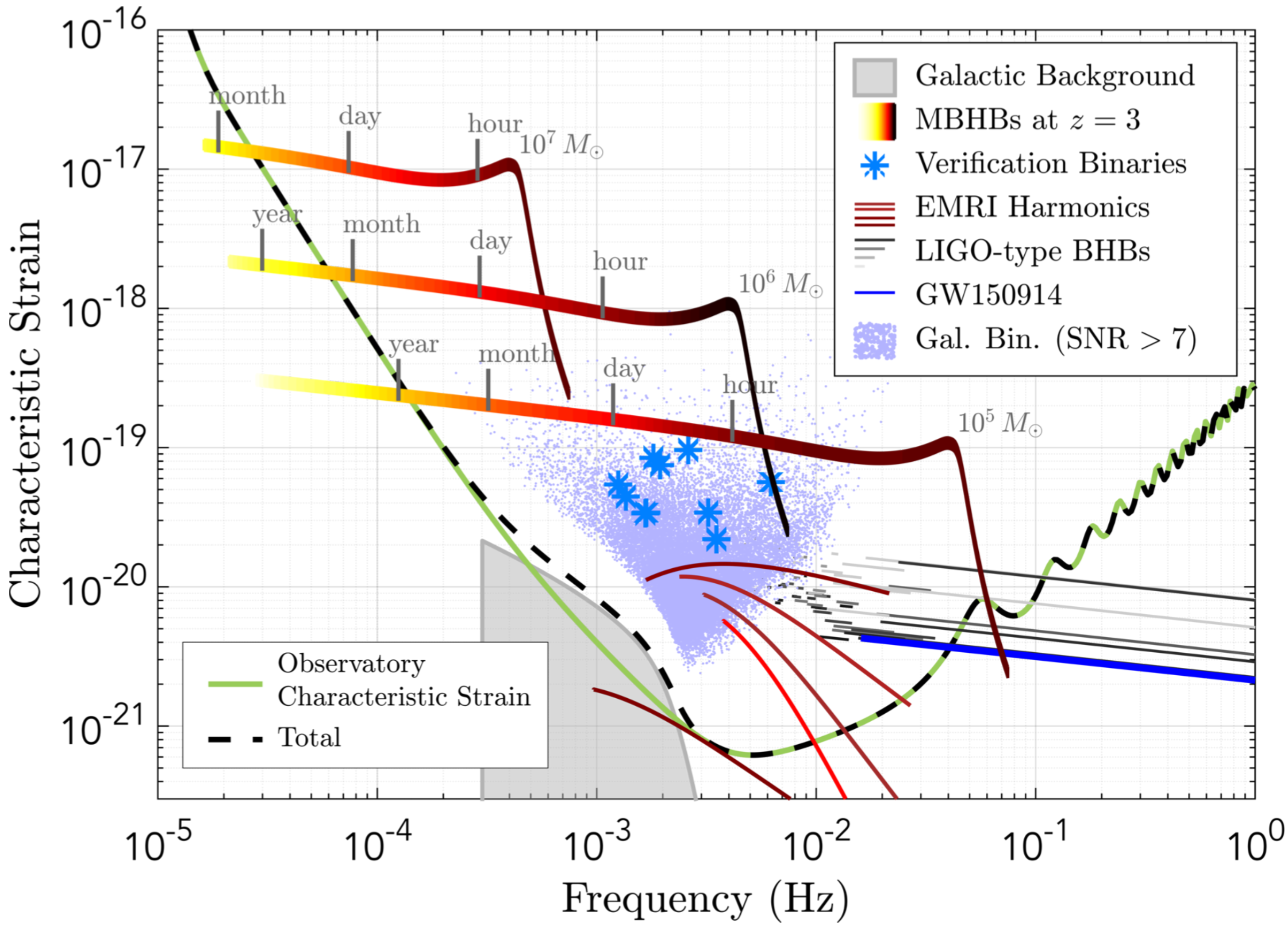
- Three laser arms, 2.5 M km separation
- ESA-NASA mission, launch 2030s
- Mission exited 'phase A' in December 2021

arXiv:1702.00786



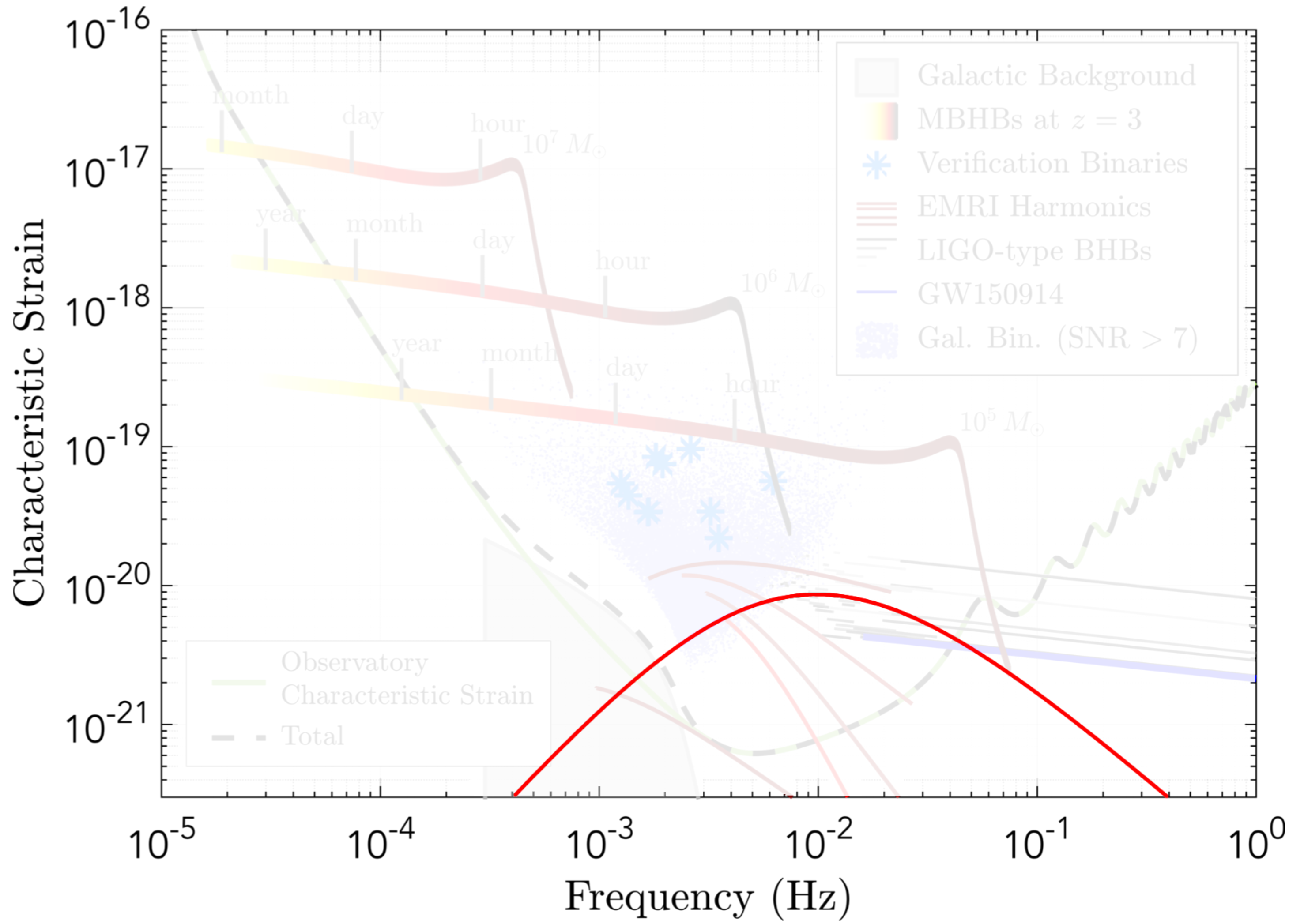
Source: [PD] NASA via Wikimedia Commons

LISA: "Astrophysics" signals



Source: arXiv:1702.00786

LISA: Stochastic background?



[qualitative curve, sketched on]

Scales and frequencies

By considering how GWs get redshifted on the way to us, and assuming they get produced at cosmological scales:

Event	**Time/s**	**Temp/GeV**	g_*	**Frequency/Hz**
QCD phase transition	10^{-3}	0.1	~ 10	10^{-8}
EW phase transition	10^{-11}	100	~ 100	10^{-5}
?	10^{-25}	10^{9}	$\gtrsim 100$	100
End of inflation	$\gtrsim 10^{-36}$	$\lesssim 10^{16}$	$\gtrsim 100$	$\gtrsim 10^{8}$

arXiv:2008.09136

Could BSM physics produce a stochastic background?

First-order phase transitions are a *complementary* probe of new physics that might be

- Out of sight of particle physics experiments, or
- At higher energy scales than colliders can reach

[what BSM physics might there be?]

Particle physics model

$\Downarrow \mathcal{L}_{\rm 4d}$

Dimensional reduction

$\Downarrow \mathcal{L}_{\rm 3d}$

Phase transition parameters
from lattice simulations

$\Downarrow \alpha, \beta, T_N, v_{\rm w}, \ldots$

Real time cosmological simulations

$\Downarrow \Omega_{\rm gw}(f)$

Cosmological GW background

[what would we see as a result?]

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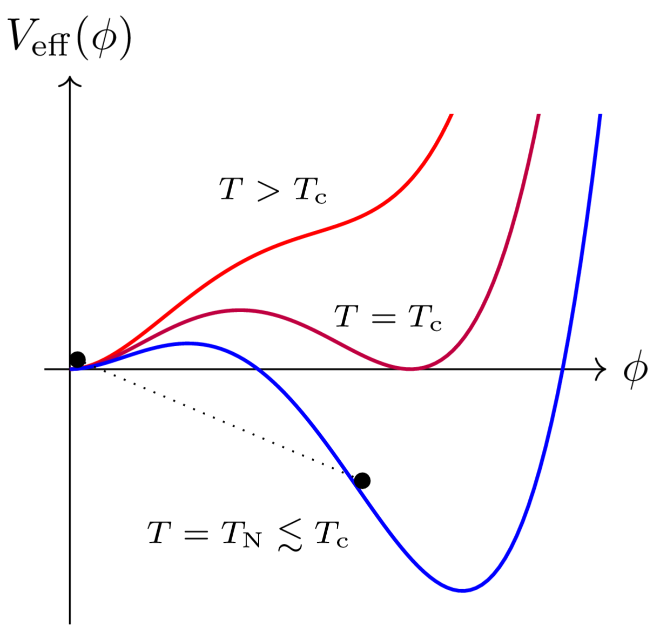
Cosmological GW background

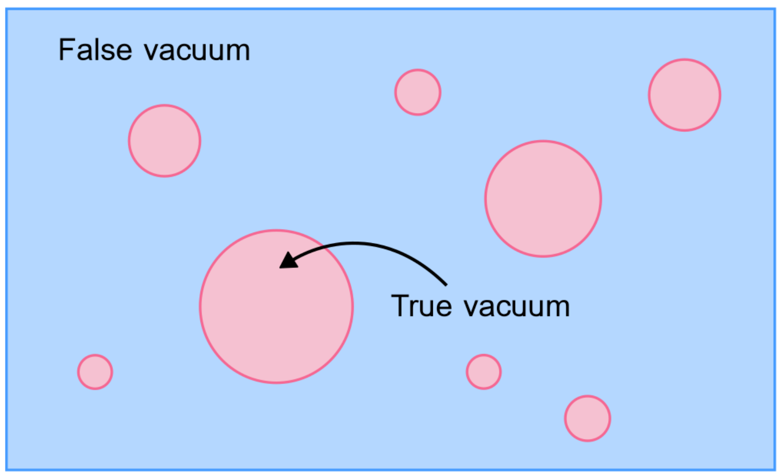
My focus: extensions of the Standard Model

$$\mathcal{L}_{\text{4d}} = \mathcal{L}_{\text{SM}}[\text{SM fields}] + \mathcal{L}_{\text{BSM}}[\text{SM fields}, \ldots ?]$$

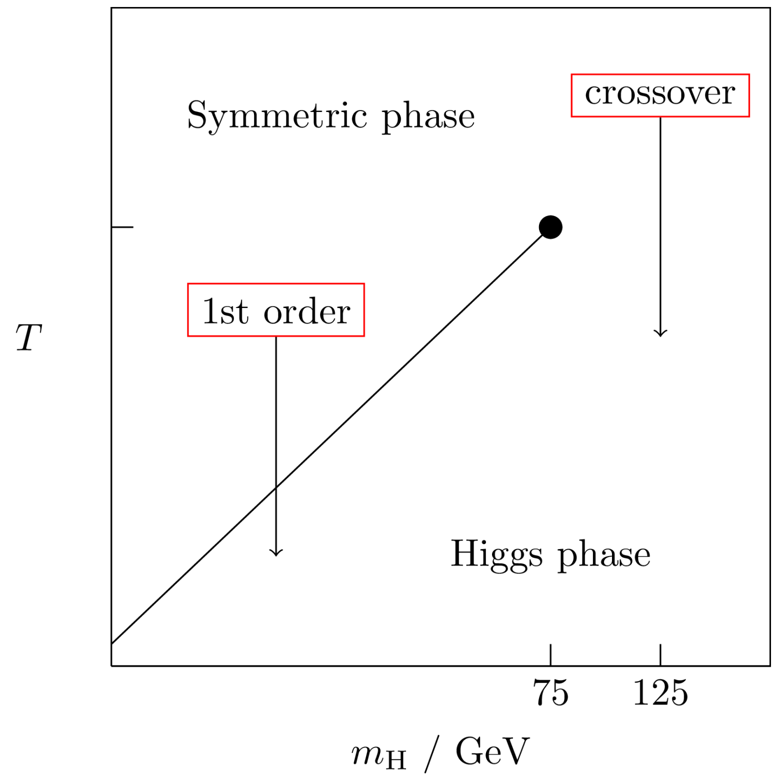
SM electroweak phase transition

- Process by which the Higgs 'switched on'
- In the Standard Model it is a crossover
- Possible in extensions that it would be first order
  ➥ colliding bubbles then make gravitational waves





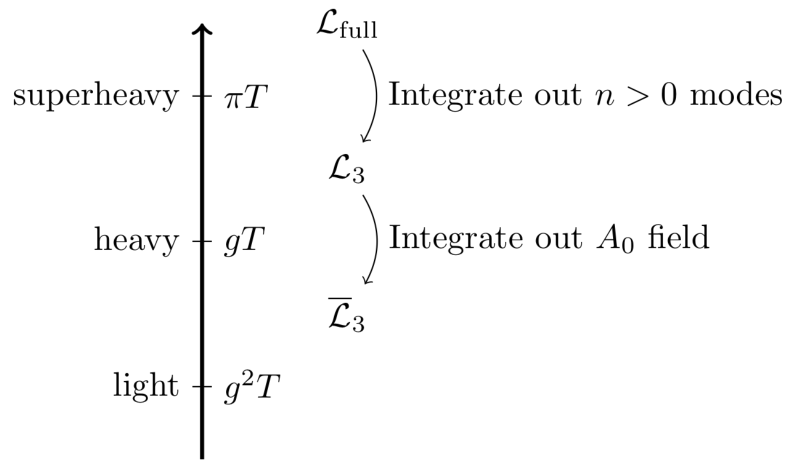
SM electroweak phase diagram



arXiv:hep-ph/9605288 ; arXiv:hep-lat/9704013; arXiv:hep-ph/9809291

Using dimensional reduction

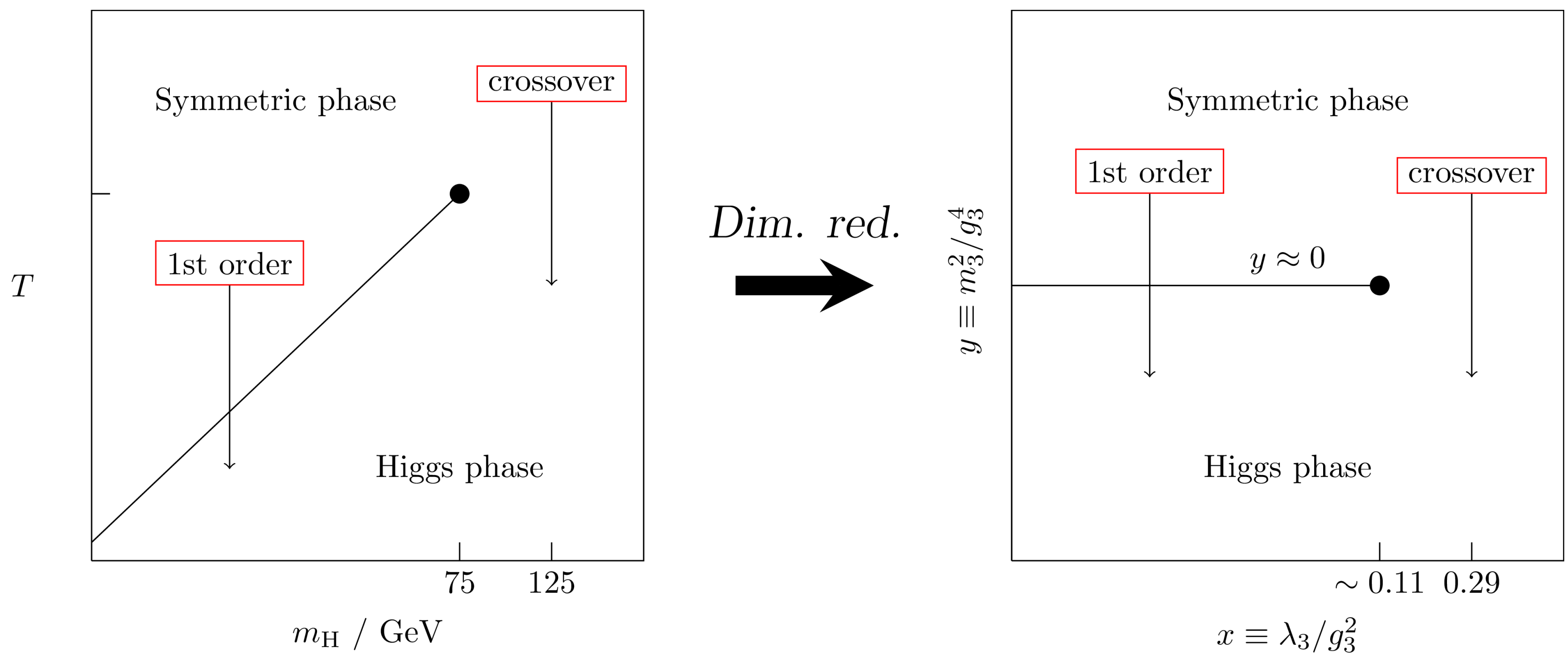
- At high T, system looks 3D at distances $\Delta x \gg 1/T$



- Match Green's functions at each step to desired order
- Handles the infrared problem, light fields can be studied on lattice arXiv:hep-ph/9508379

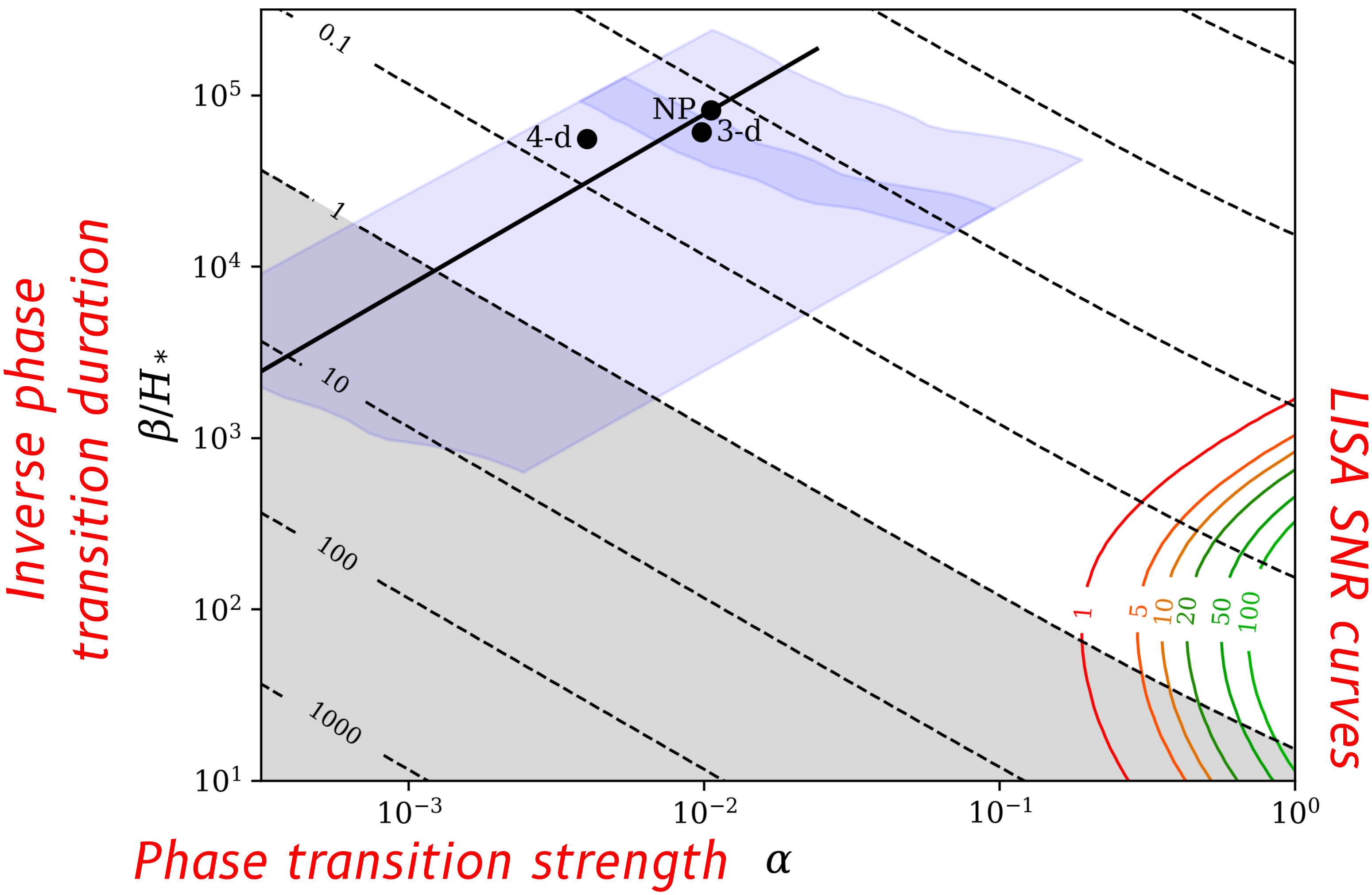
The electroweak phase transition

- Simulate DR'ed 3D theory on lattice arXiv:hep-let/9510020



- With DR, can integrate out heavy new physics and study simpler model

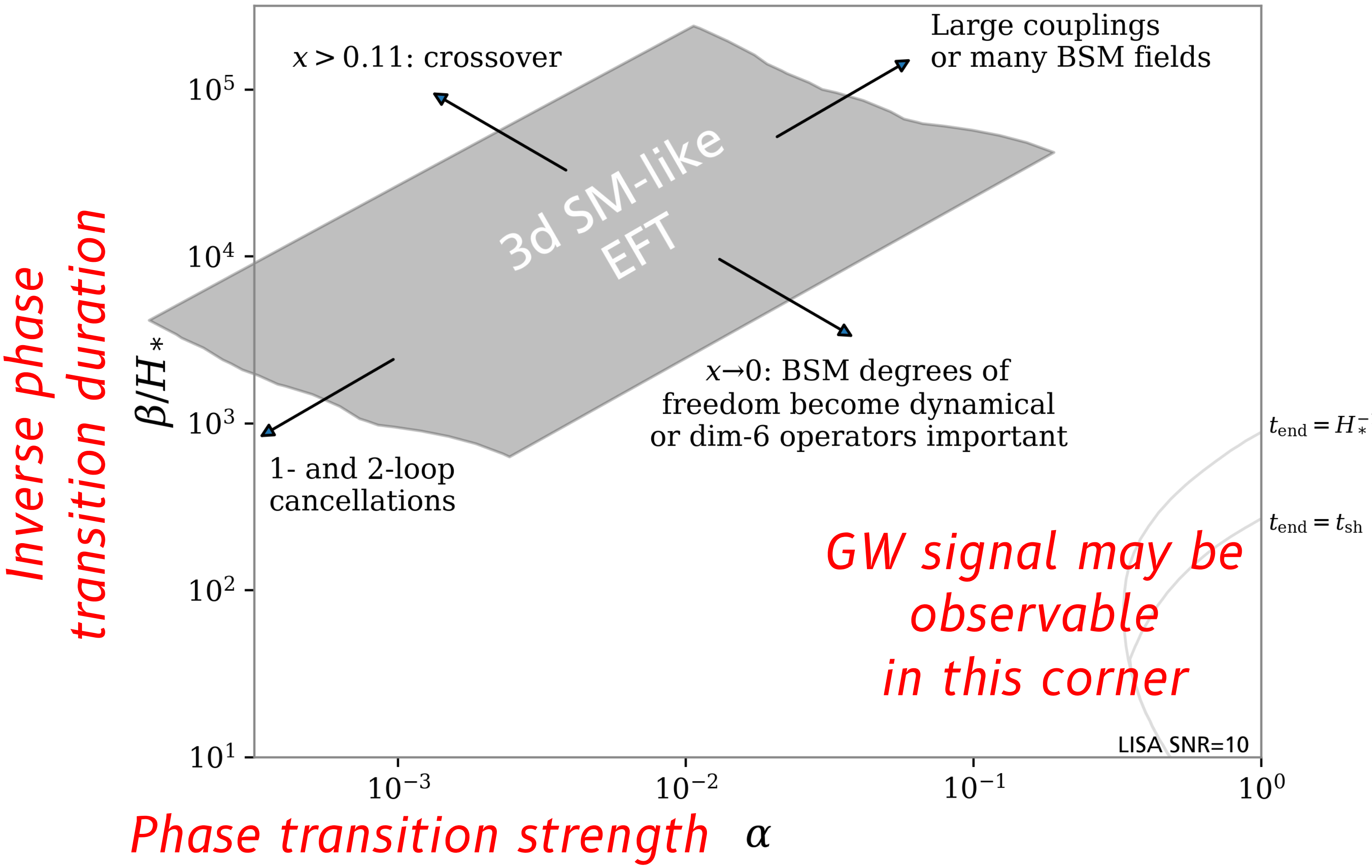
♲ When new physics is heavy



- Comparison at benchmark point in minimal SM
- Compare: • 4d PT vs • 3d PT vs • NP (= lattice)

arXiv:1903.11604

How to get strong transitions?

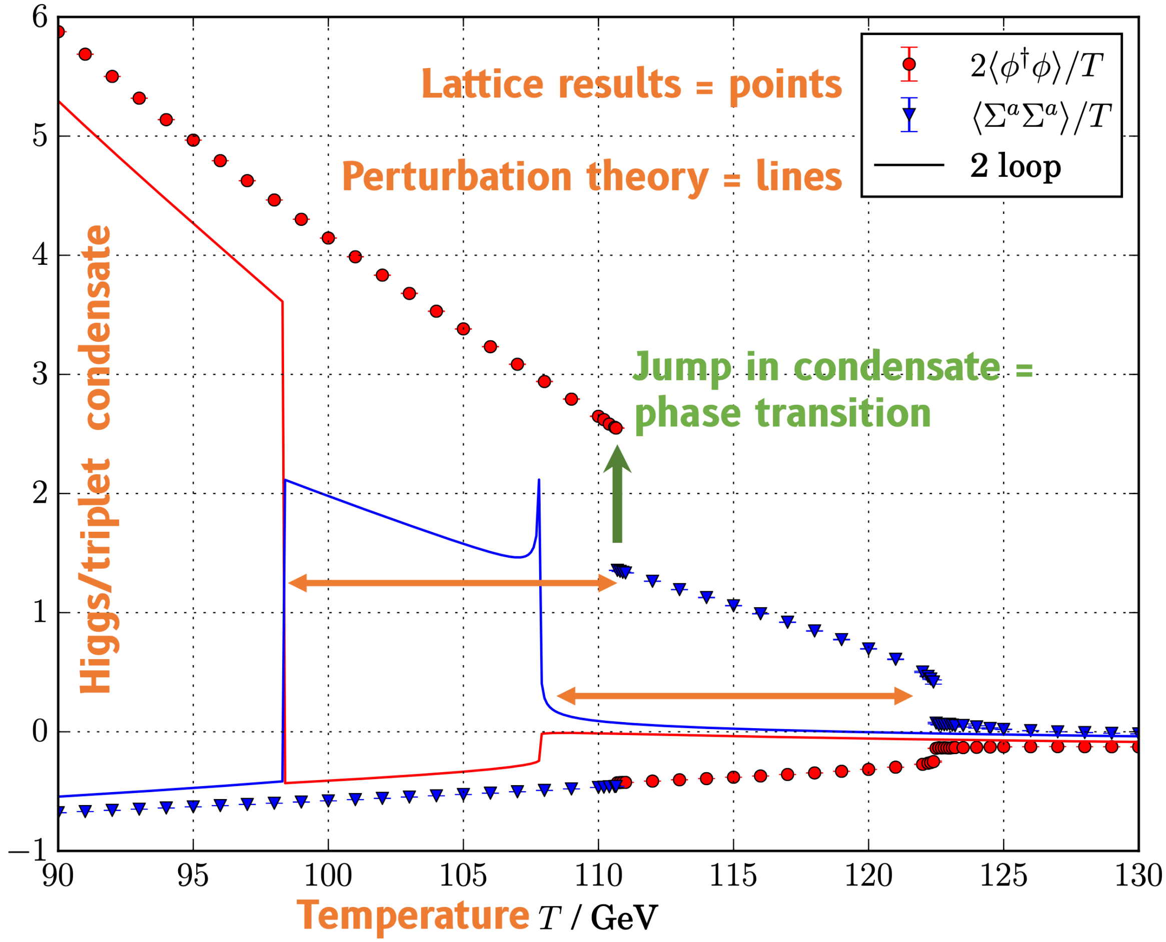


- Theories that look SM-like in the IR ⇒ not observable!
- But what happens with additional light fields?

arXiv:1903.11604

Lattice Monte Carlo benchmarks

Need for accuracy: ΣSM [triplet] example arXiv:2005.11332



Perturbation theory out by 10% or more!

Key points so far

- Dimensional reduction + lattice simulations a well-proven method for studying BSM theories
- Higher dimensional operators or **light** new physics needed for a strong phase transition
- Should benchmark perturbation theory with DR + lattice, particularly for strong transitions

Particle physics model ✅

$\Downarrow \mathcal{L}_{\rm 4d}$

Dimensional reduction ✅

$\Downarrow \mathcal{L}_{\rm 3d}$

Phase transition parameters from lattice simulations ✅

$\Downarrow \alpha, \beta, T_N, v_{\rm w}, \ldots$

Real time cosmological simulations

$\Downarrow \Omega_{\rm gw}(f)$

Cosmological GW background

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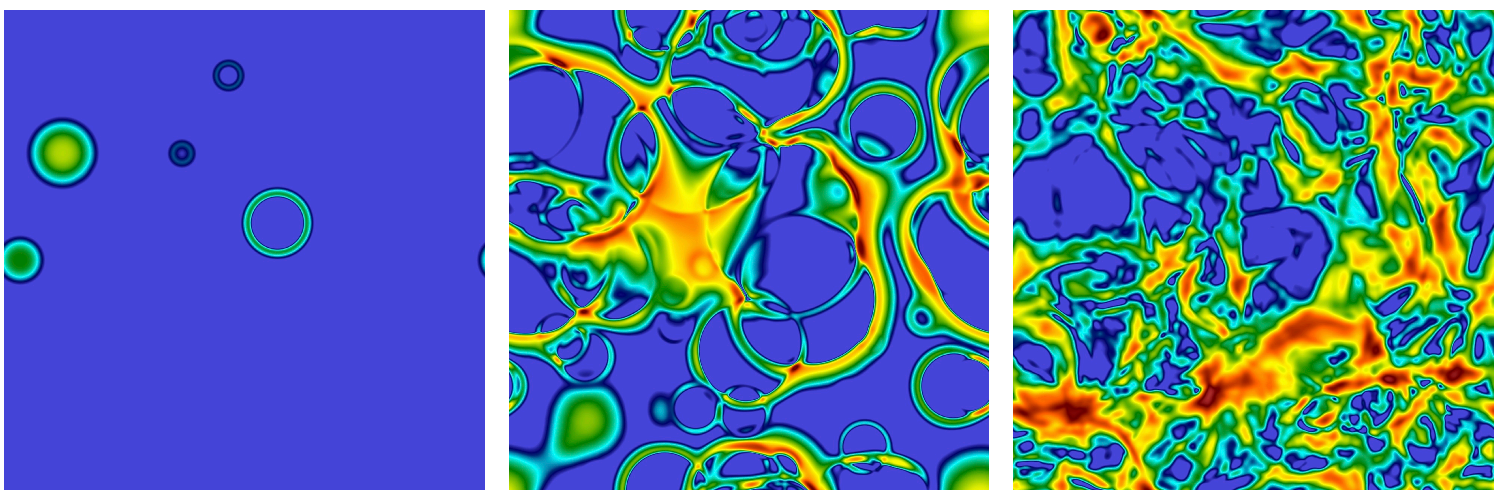
Model-independent parameters bridge the gap

Including:

- α, the phase transition strength
- β, the inverse phase transition duration
- T_N, the temperature at which bubbles nucleate
- v_w, the speed at which bubbles expand

Phase transition = out of equilibrium

1. Bubbles nucleate [temperature T_{N}, on timescale β^{-1}]
2. Bubble walls expand in a plasma [at velocity v_{w}]
3. Reaction fronts form around walls [with strength α]
4. Bubbles + fronts collide •)) GWs
5. **Sound waves** left behind in plasma •)) GWs
6. Shocks [$\rightarrow$ turbulence] $\rightarrow$ damping •)) GWs



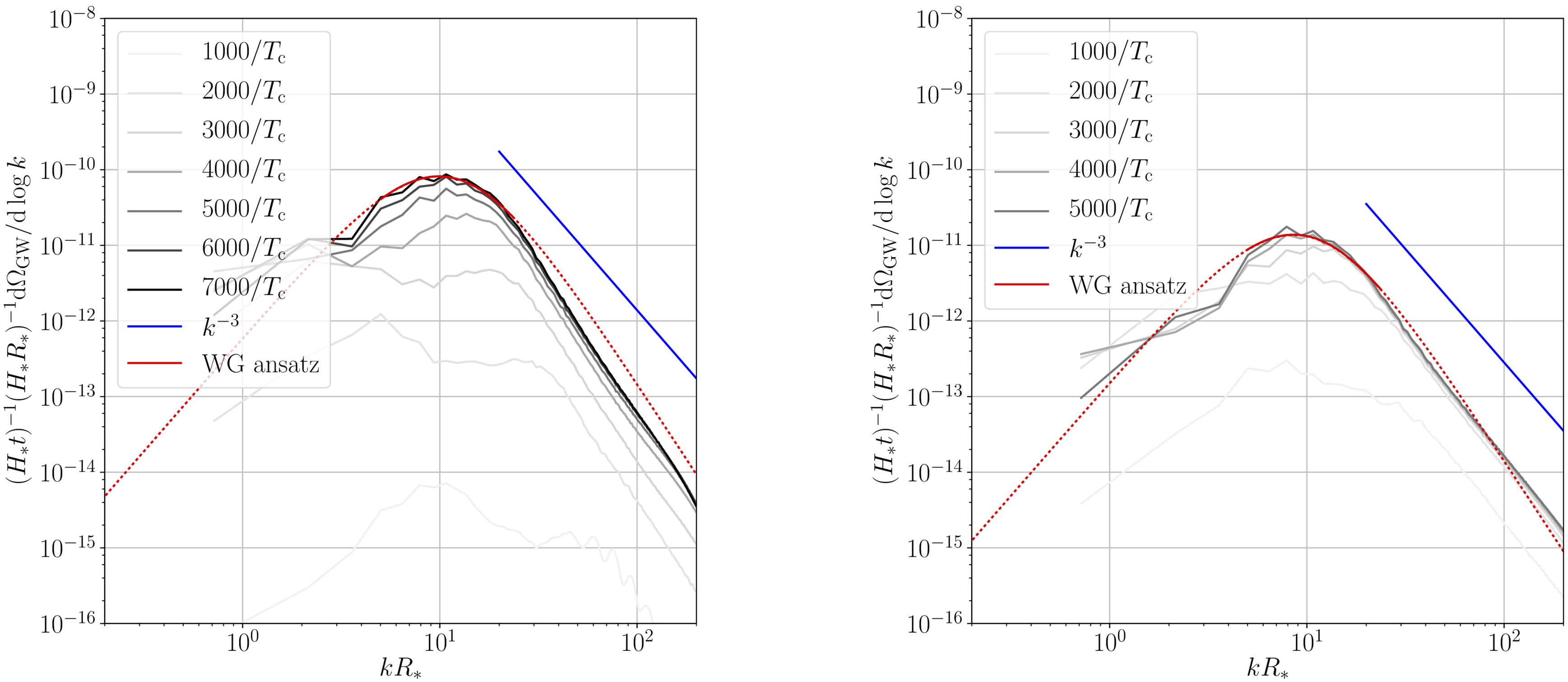
How are GWs produced at a first order phase transition?

- Not all phase transitions have $v_\mathrm{w} < c$ ...
  - 'Vacuum' transitions with no couplings/friction
  - 'Run away' transitions arXiv:1703.08215
- ... but if they do:
  - Plasma motion lasts a Hubble time $1/H_*$
  - Fluid motion becomes nonlinear on a time scale

$$\tau_\mathrm{sh} = \frac{R_*}{\overline{U}} = \frac{\text{Bubble radius (i.e. length scale)}}{\text{Typical fluid velocity}}$$

Using simulation results

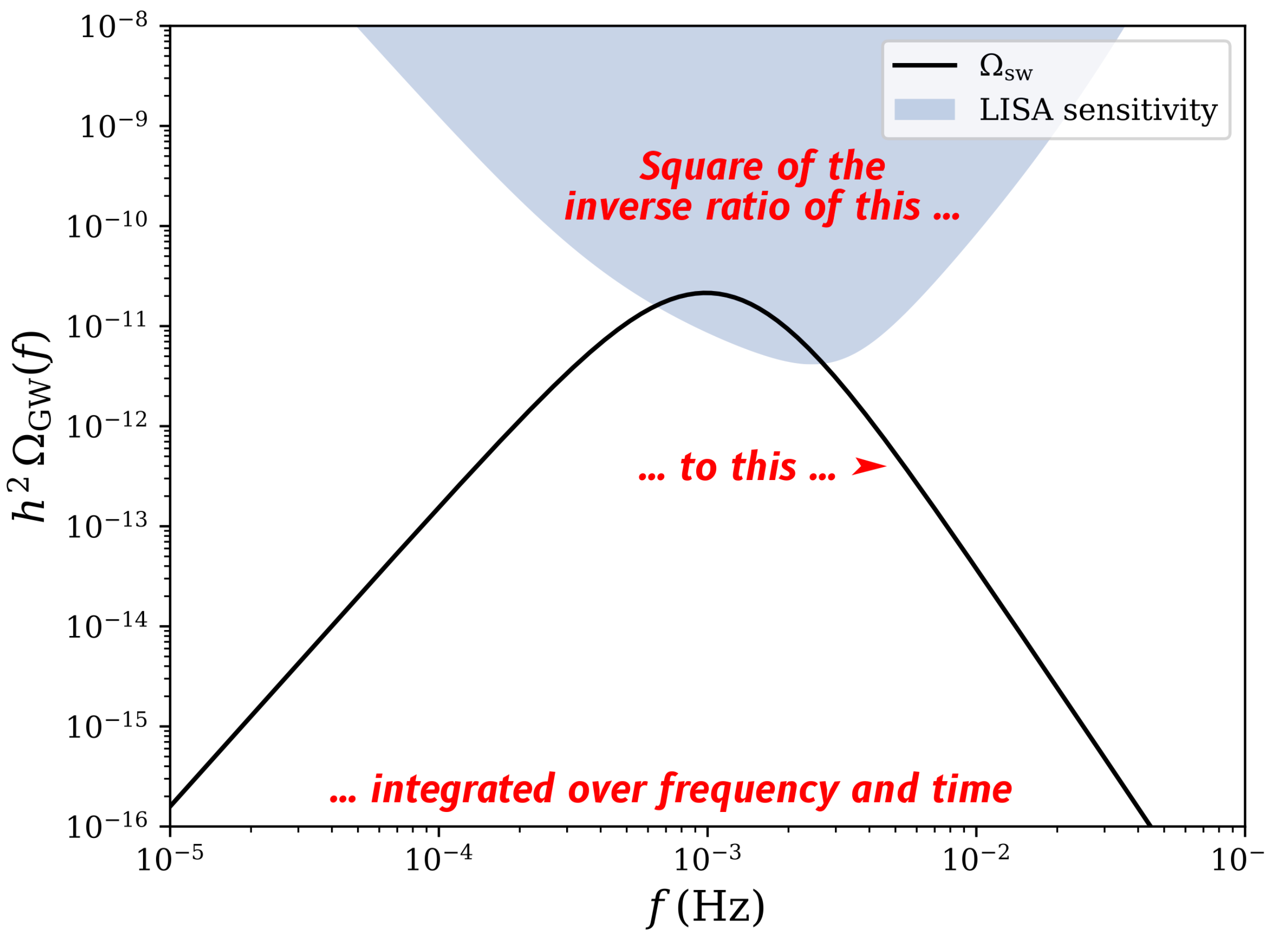
Those simulations yield GW spectra like [sound waves]:



[NB: curves scaled by t: collapse = constant emission]

What matters is the SNR

$$\mathrm{SNR} = \sqrt{\mathcal{T} \int_{f_{\rm min}}^{f_{\rm max}} \mathrm{d}f \left[\frac{h^2 \Omega_{\rm GW}(f)}{h^2 \Omega_{\rm Sens}(f)} \right]^2}$$



Still need to handle astrophysical foregrounds properly!

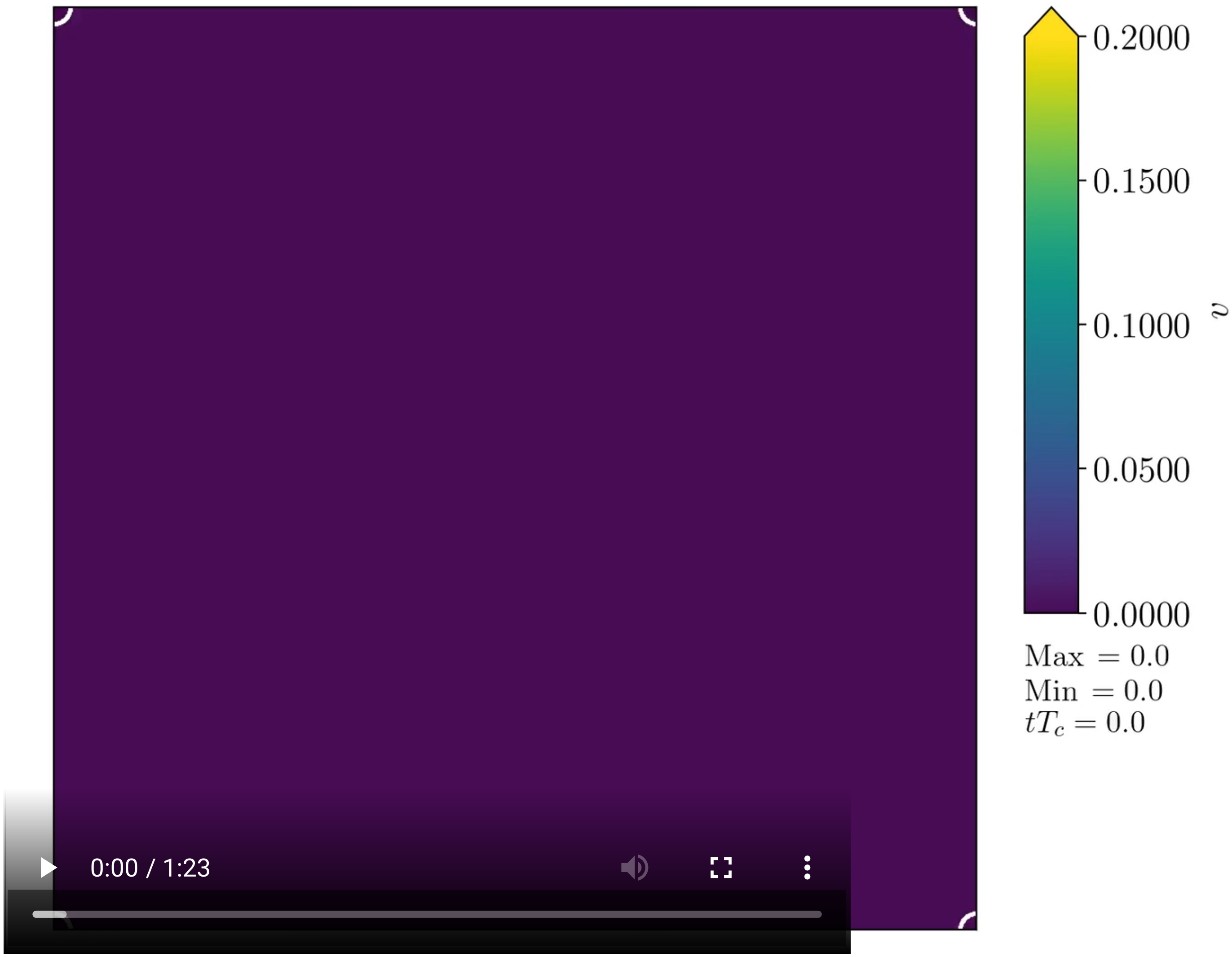
Nonlinearities?

- Nonlinearities during the transition:
  - Generation of vorticity
  - Droplets
- Nonlinearities after the transition:
  - Shocks
  - Turbulence (and acoustic turbulence)

Let's take a look at droplets and acoustic turbulence

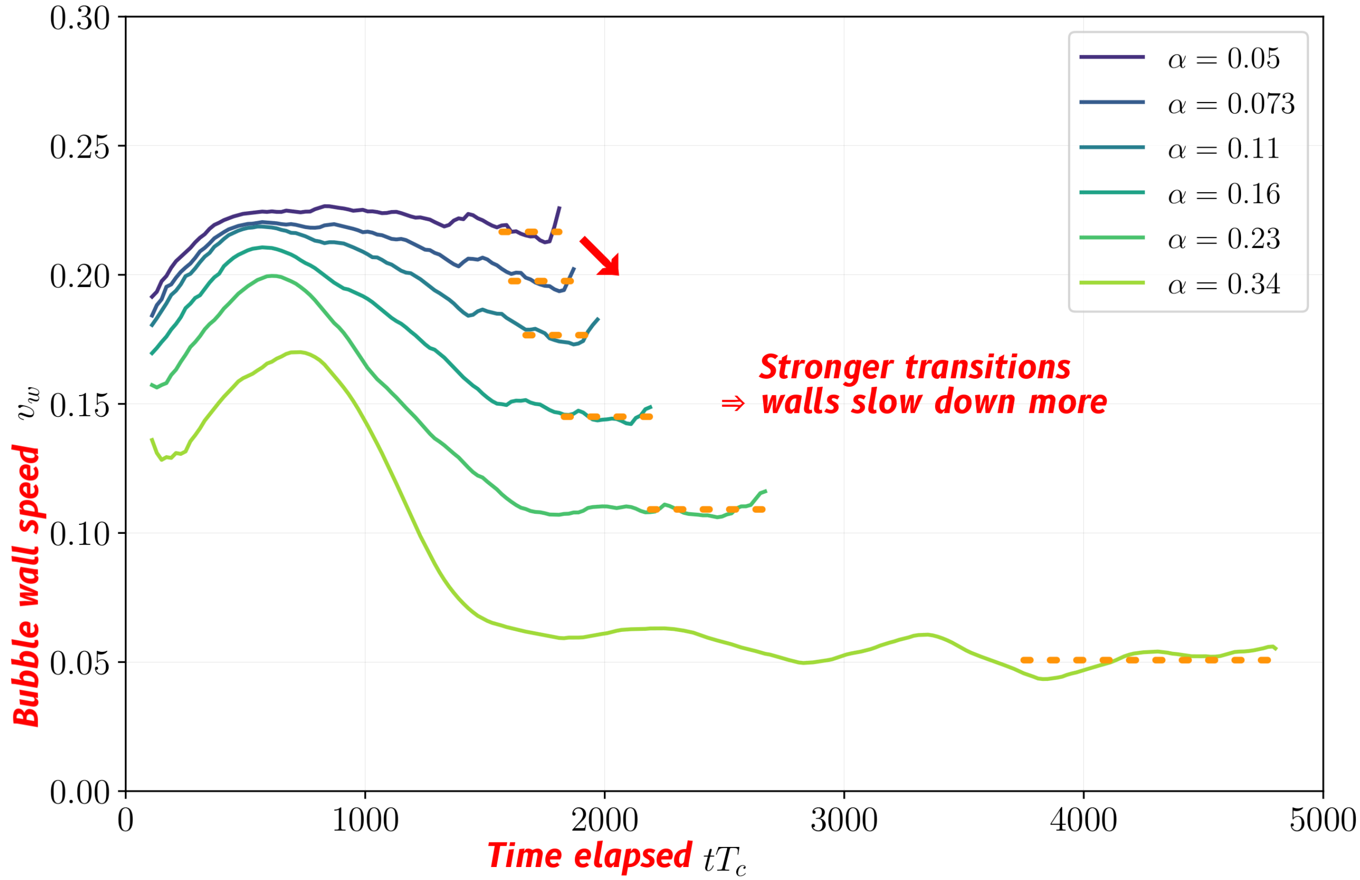
Strong deflagrations ⇒ droplets

[$\alpha_{T_*} = 0.34$, $v_\mathrm{w} = 0.24$ [deflag.]], velocity $\mathbf{v}$



Droplets form ➤ walls slow down

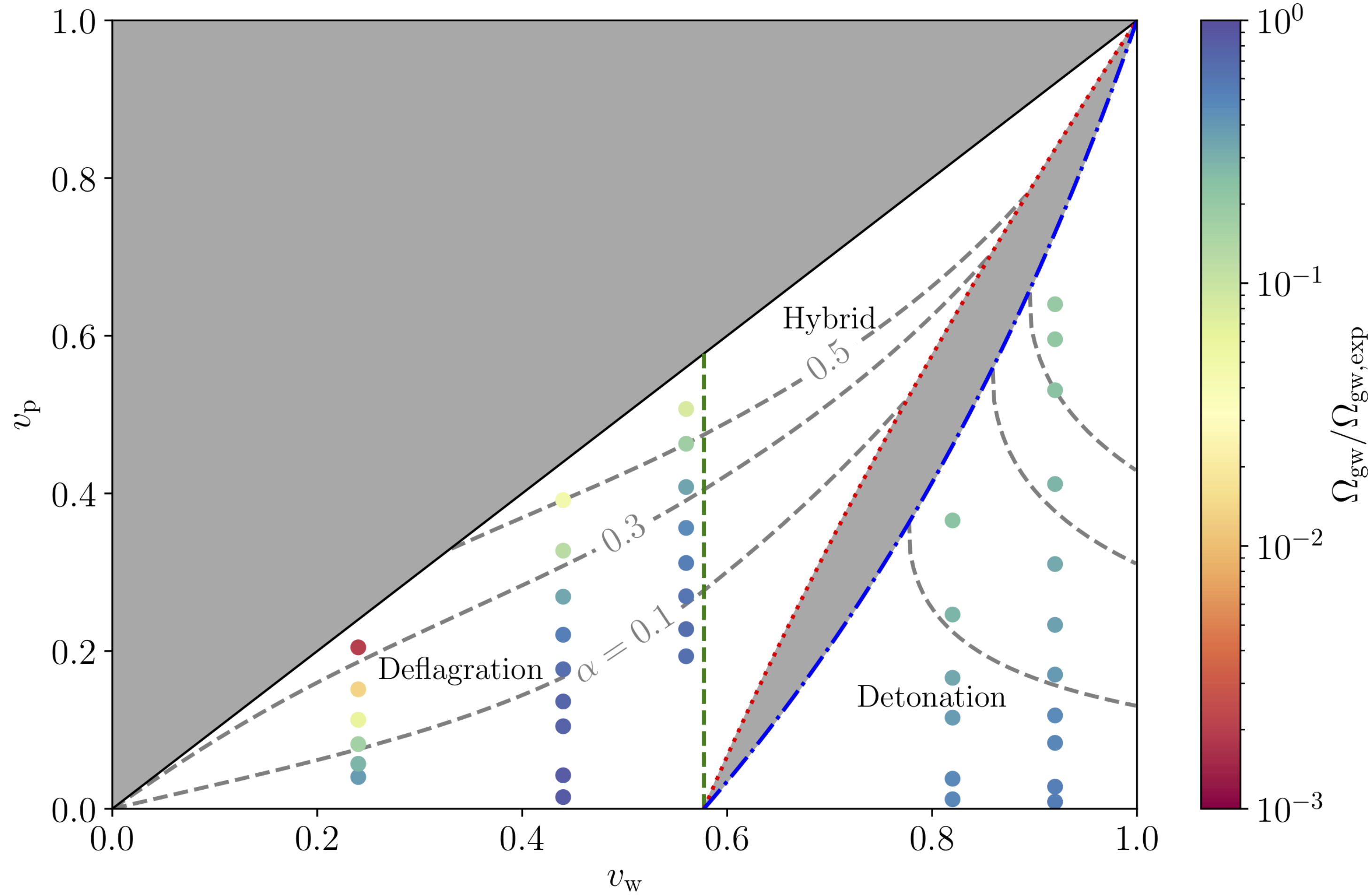
At large α_{T_*} reheated droplets form in front of the walls



arXiv:2204.03396

Droplets may suppress GWs

Suppression compared to sound waves [redder = worse]



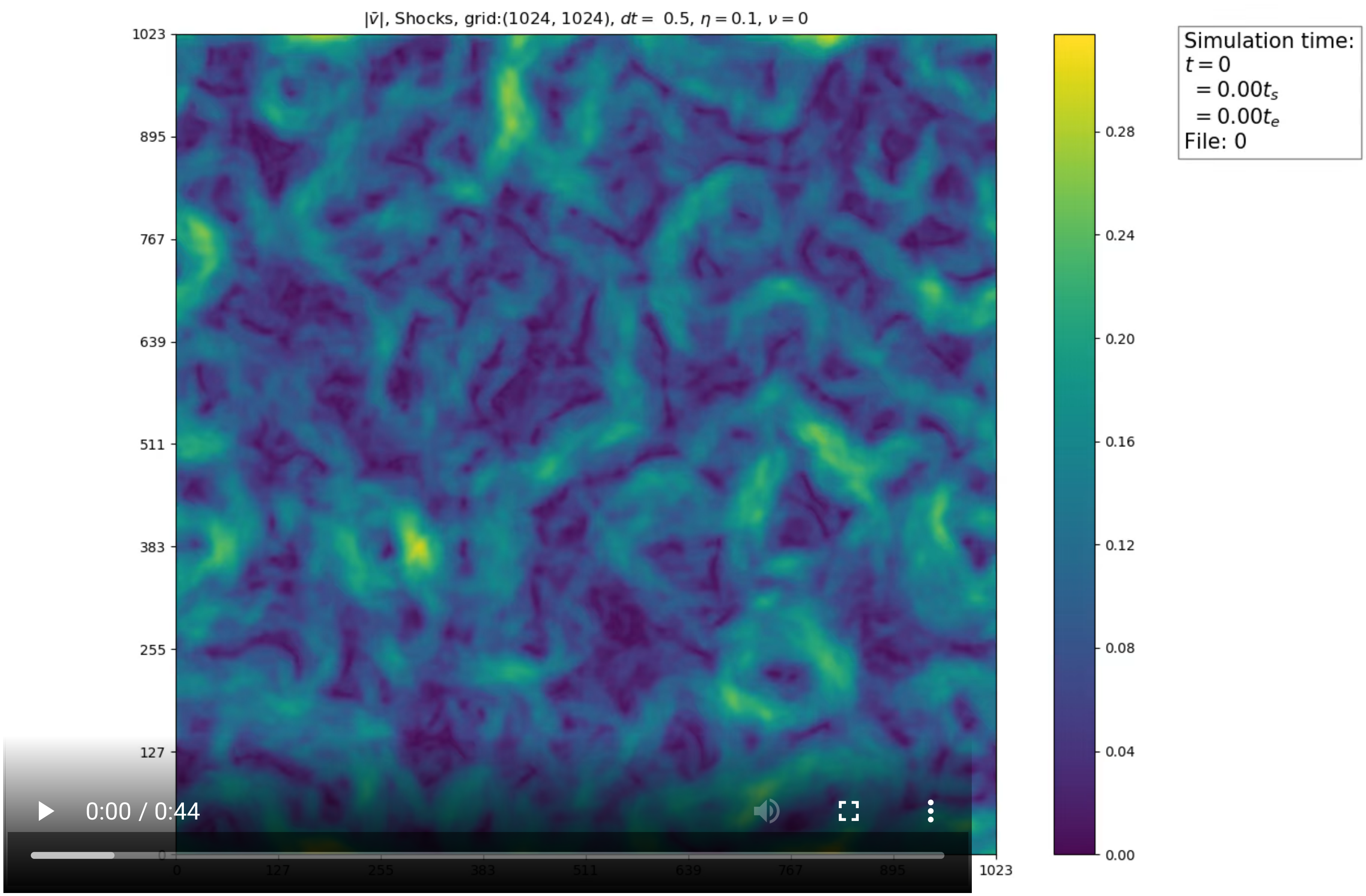
arXiv:1906.00480

Sound waves ➤ acoustic turbulence

- Thermal phase transitions produce sound waves
- Over time, sound waves steepen into shocks
- Overlapping field of shocks = 'acoustic turbulence'
- Distinct from, but related to Kolmogorov turbulence

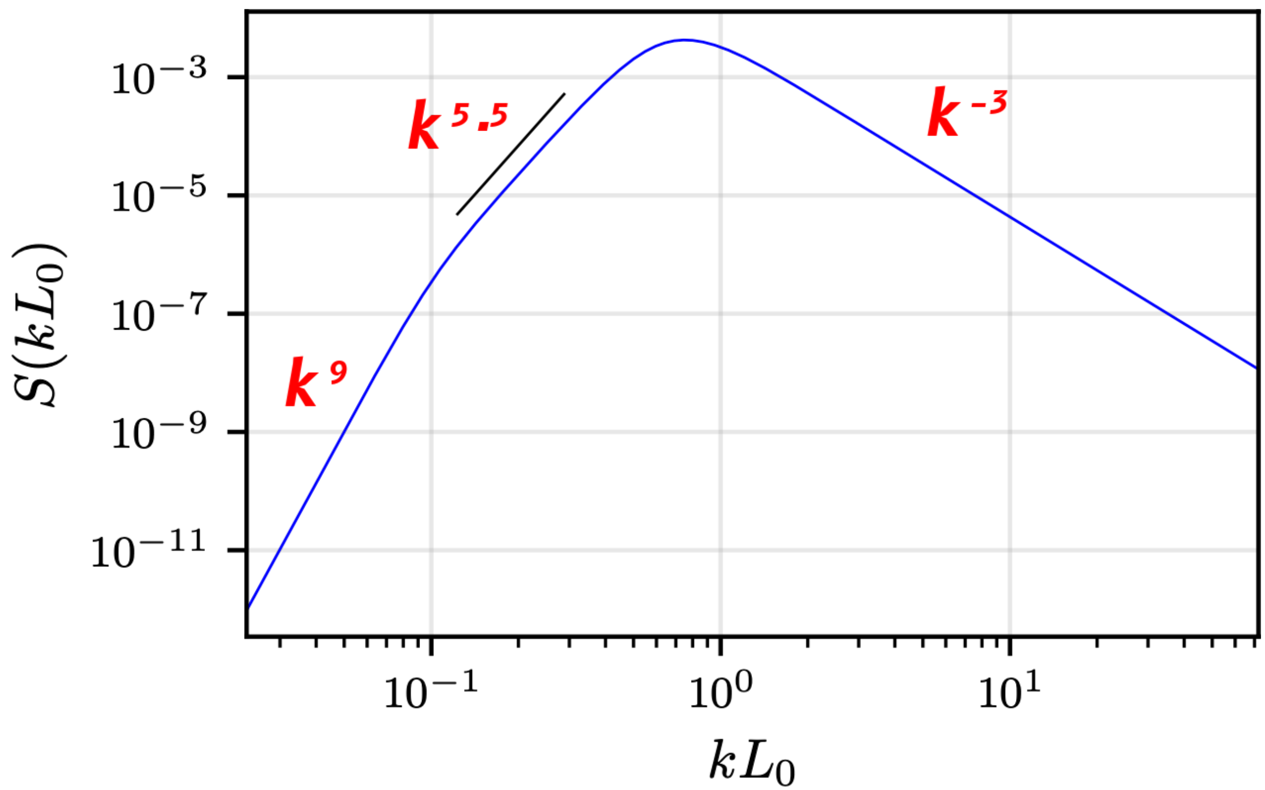
arXiv:2112.12013, arXiv:2205.02588

2d acoustic turbulence



Acoustic turbulence: GWs

Spectral shape S as function of k and integral scale L_0:



Different from sound waves and Kolmogorov turbulence!

⇒ all must be taken into consideration.

Thanks

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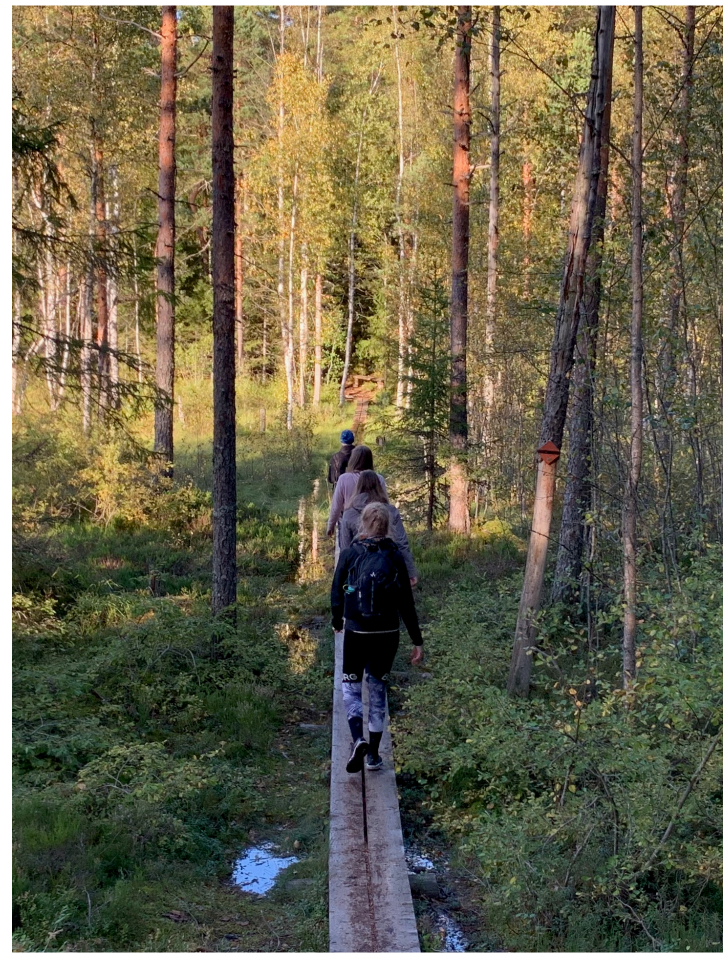
  Kari Rummukainen,
  Tuomas Tenkanen



What I want you to remember

- **Early universe processes** can probe BSM physics
  … but we need precise predictions of key parameters
  ⇒ lattice Monte Carlo simulations of phase transitions
- **Nonlinearities matter** when studying phase transitions
  ⇒ large-scale real-time cosmological simulations

More questions you can ask me

- How accurate are bubble nucleation calculations?
- What are the consequences of droplet formation?
- What about other types of turbulence?