[Strong] first order phase transitions and gravitational wave signatures

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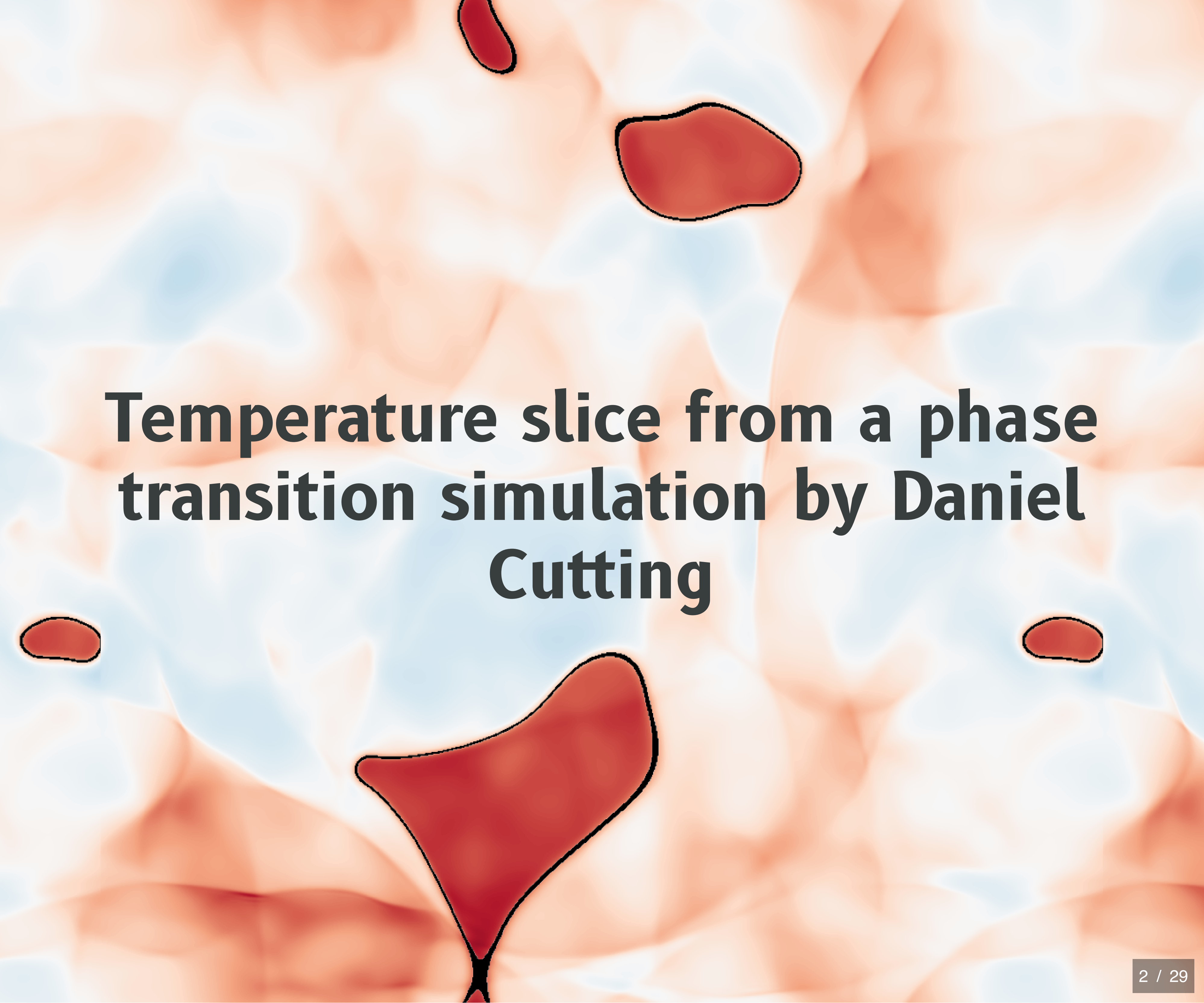
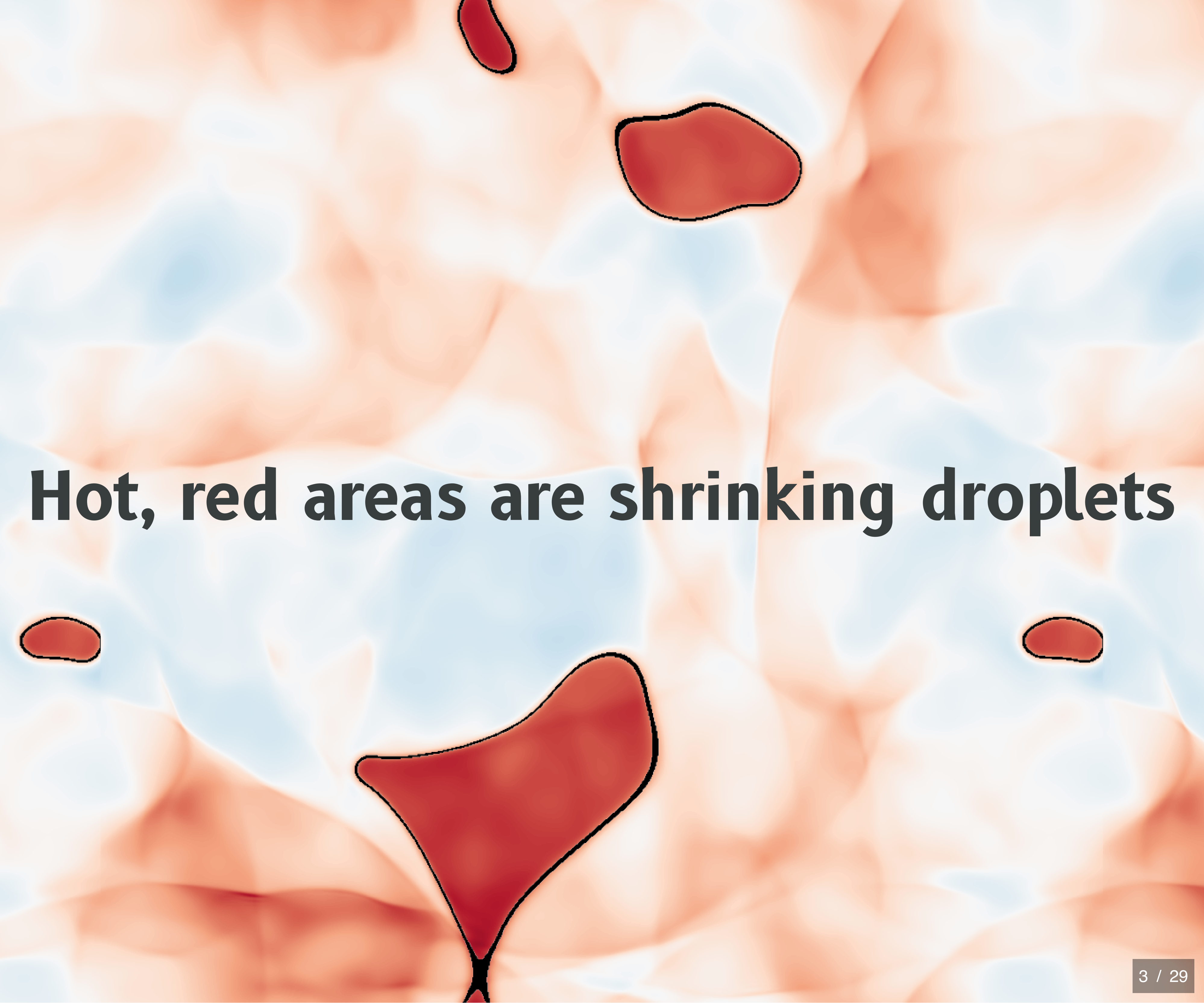
This talk: saoghal.net/slides/anomalies2021

Anomalies 2021, IIT Hyderabad



Temperature slice from a phase transition simulation by Daniel Cutting


Hot, red areas are shrinking droplets

- How do droplets form?
- What are the consequences for gravitational waves?

Particle physics model

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

Dimensional reduction

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

Phase transition parameters from lattice simulations

$\Downarrow \alpha, \beta, T_N, \ldots$

Real time cosmological simulations

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

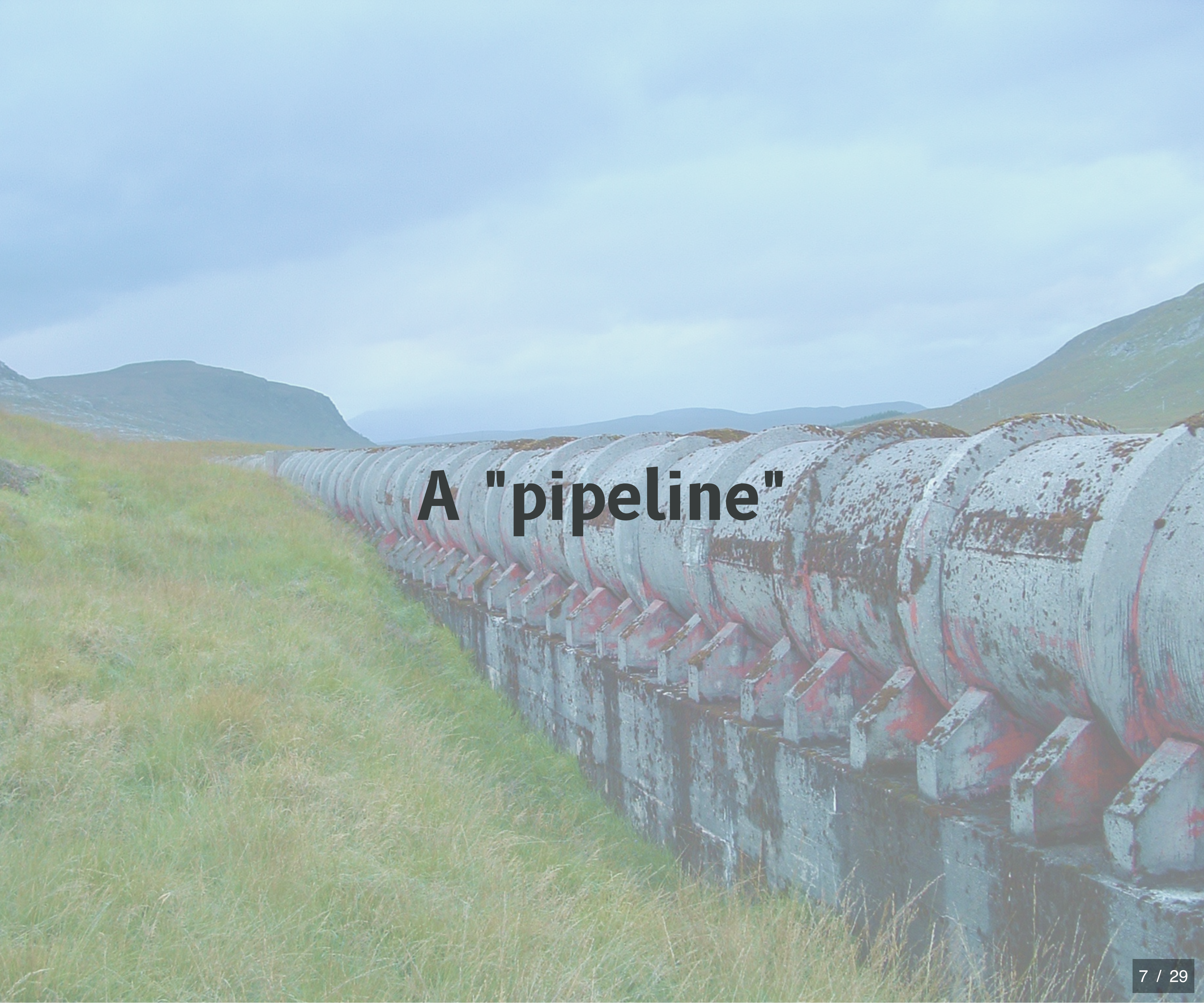
Cosmological GW background

Key parameters bridge the gap

Including:

- α, the phase transition strength
- β, the inverse phase transition duration
- T_N, the nucleation temperature

A "pipeline"



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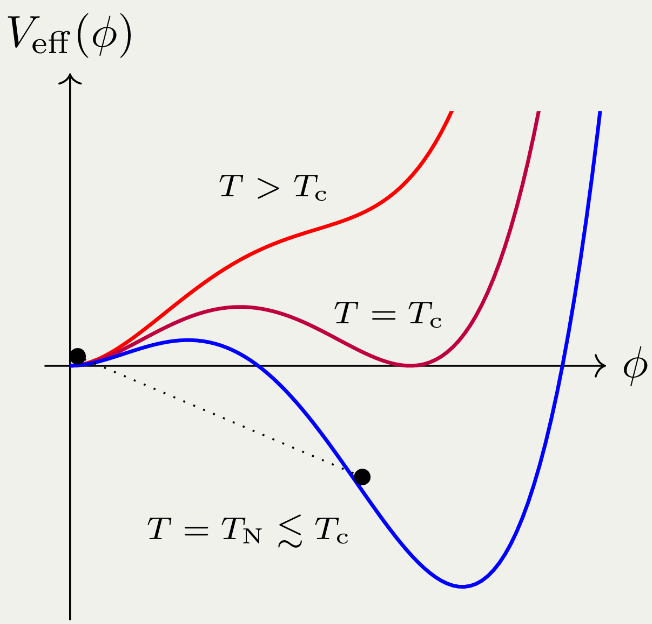
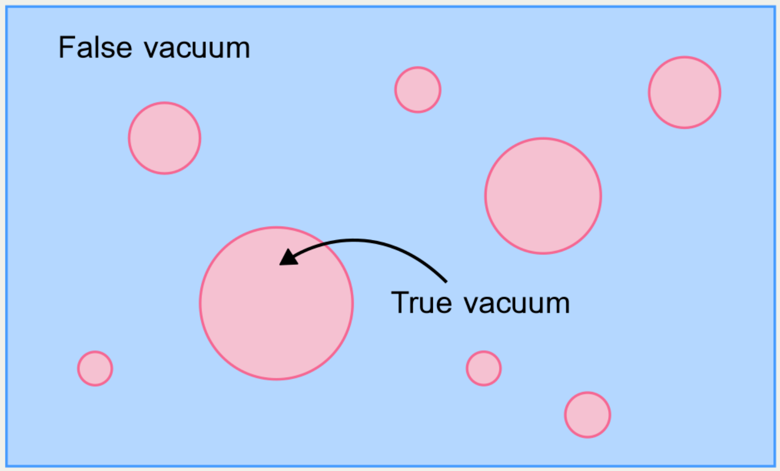
My focus: extensions of the Standard Model

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

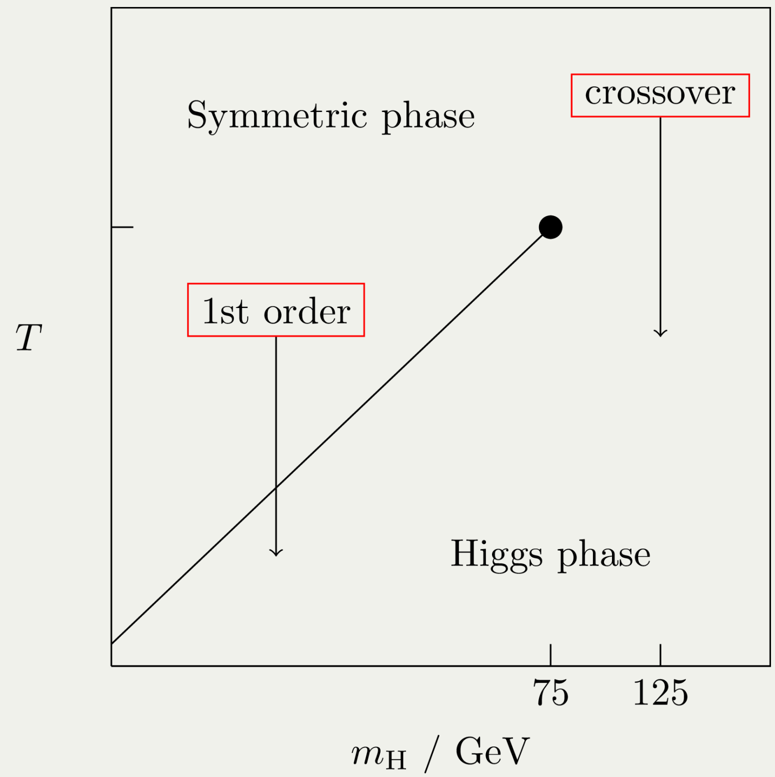
SM electroweak phase transition

- 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





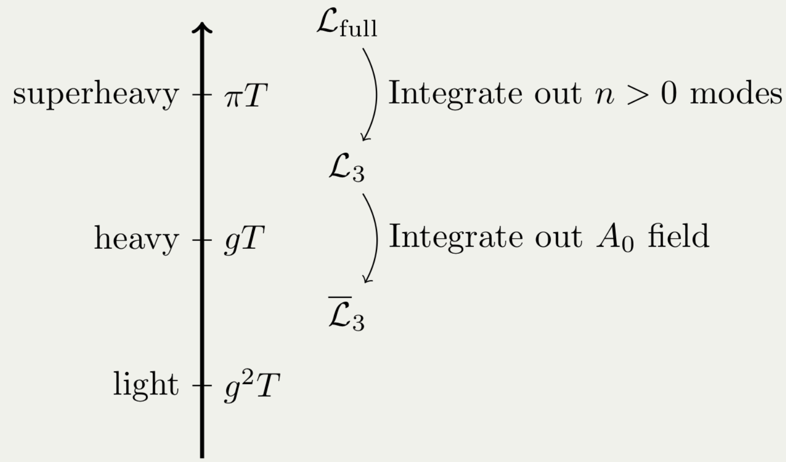
SM electroweak phase diagram



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

How? Dimensional reduction

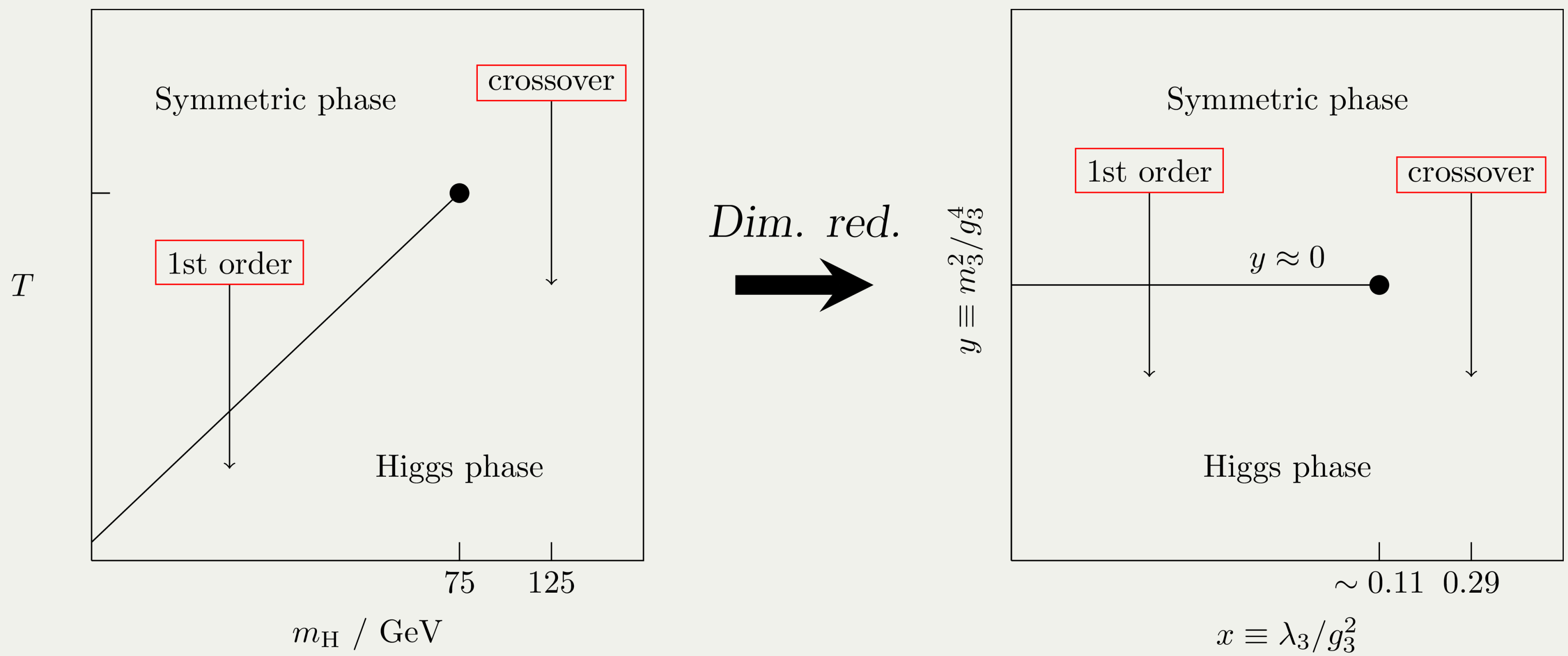
- At high T, system looks 3D at distances $\Delta x \gg 1/T$



- Each step involves matching Green's functions in the effective and full theories to the desired order.
- Handles the infrared problem, light fields can be studied on lattice. arXiv:hep-ph/9508379

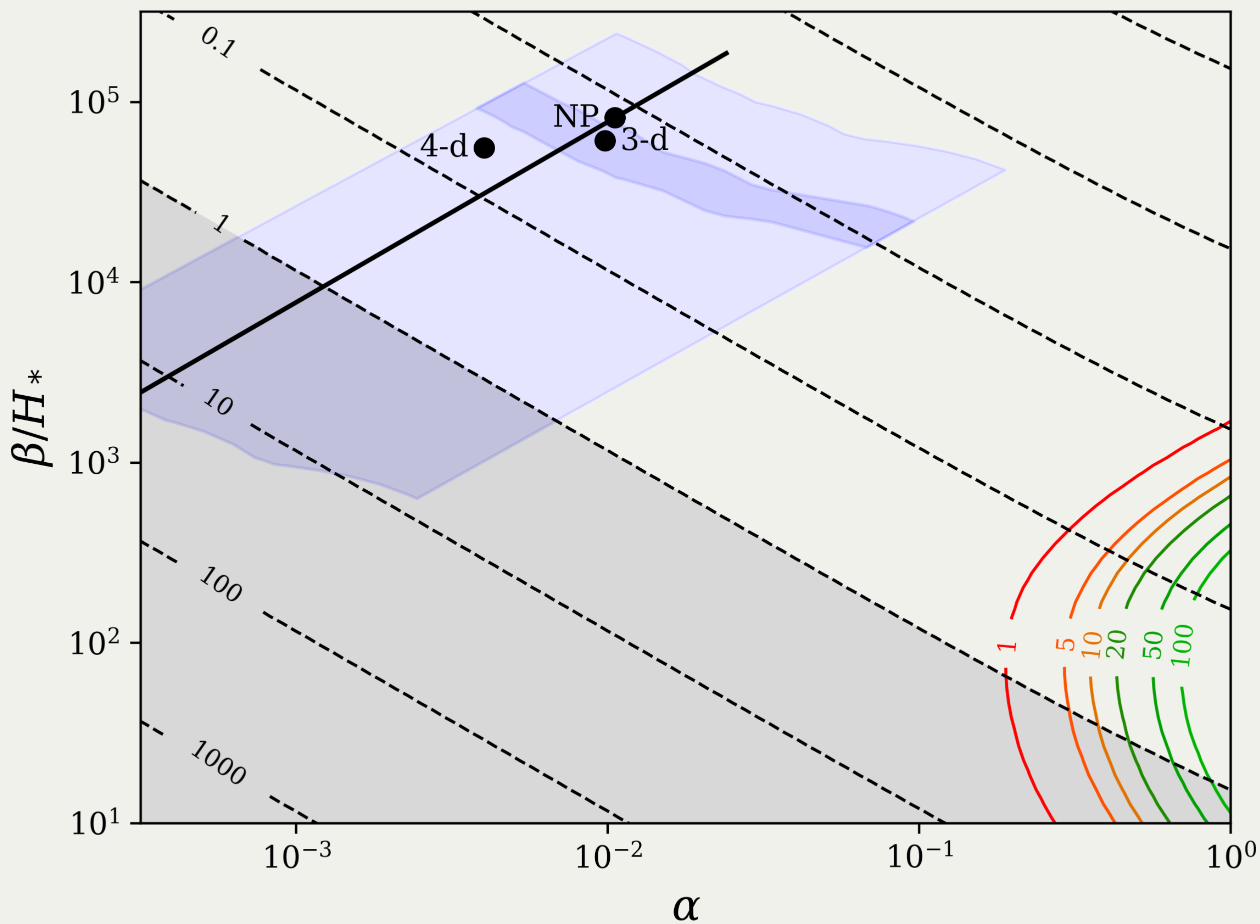
Using the dimensional reduction

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



- With DR, integrate out heavy new physics and recycle

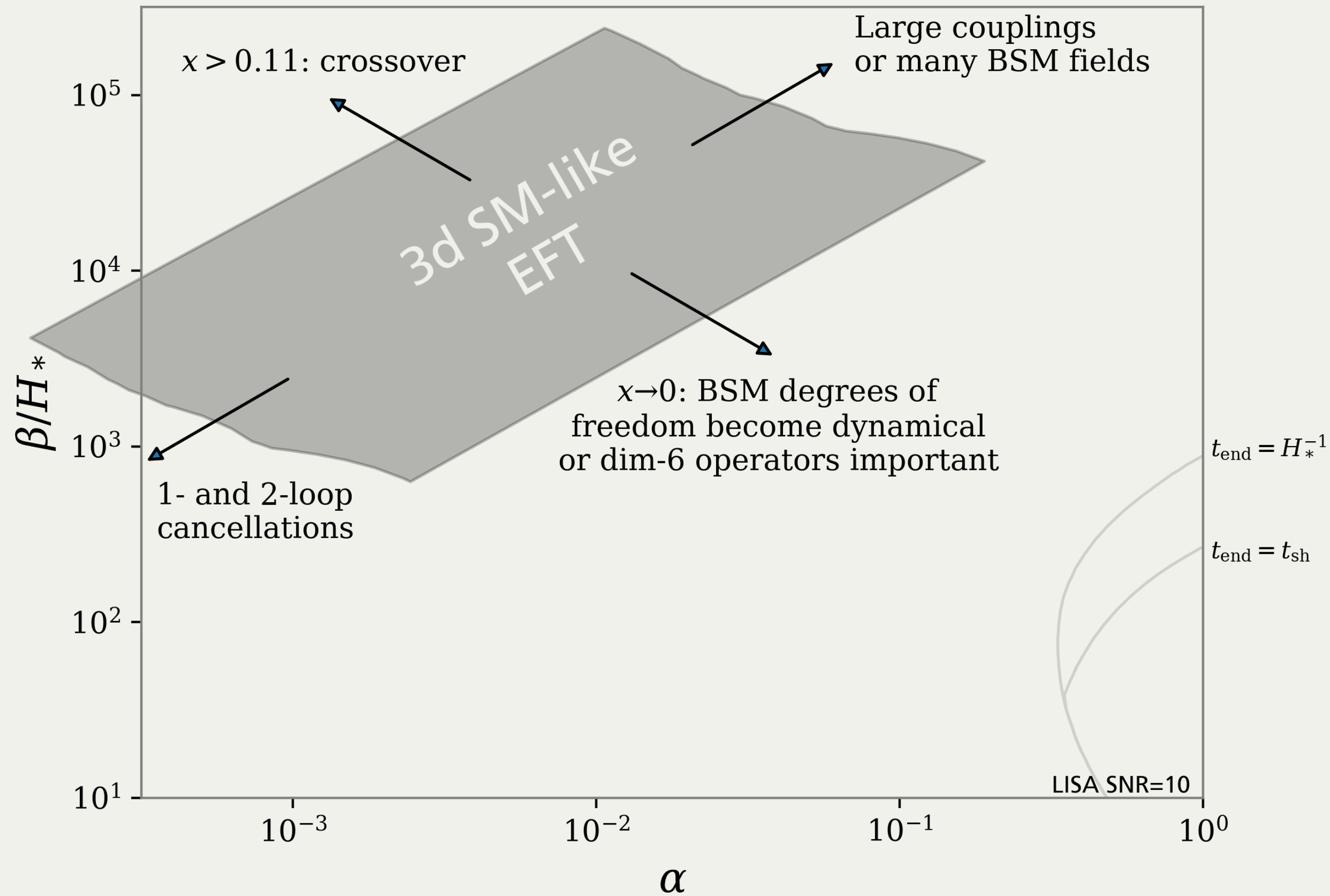
♻️ When new physics is heavy



Benchmark: • 4d PT vs • 3d PT vs • lattice

arXiv:1903.11604

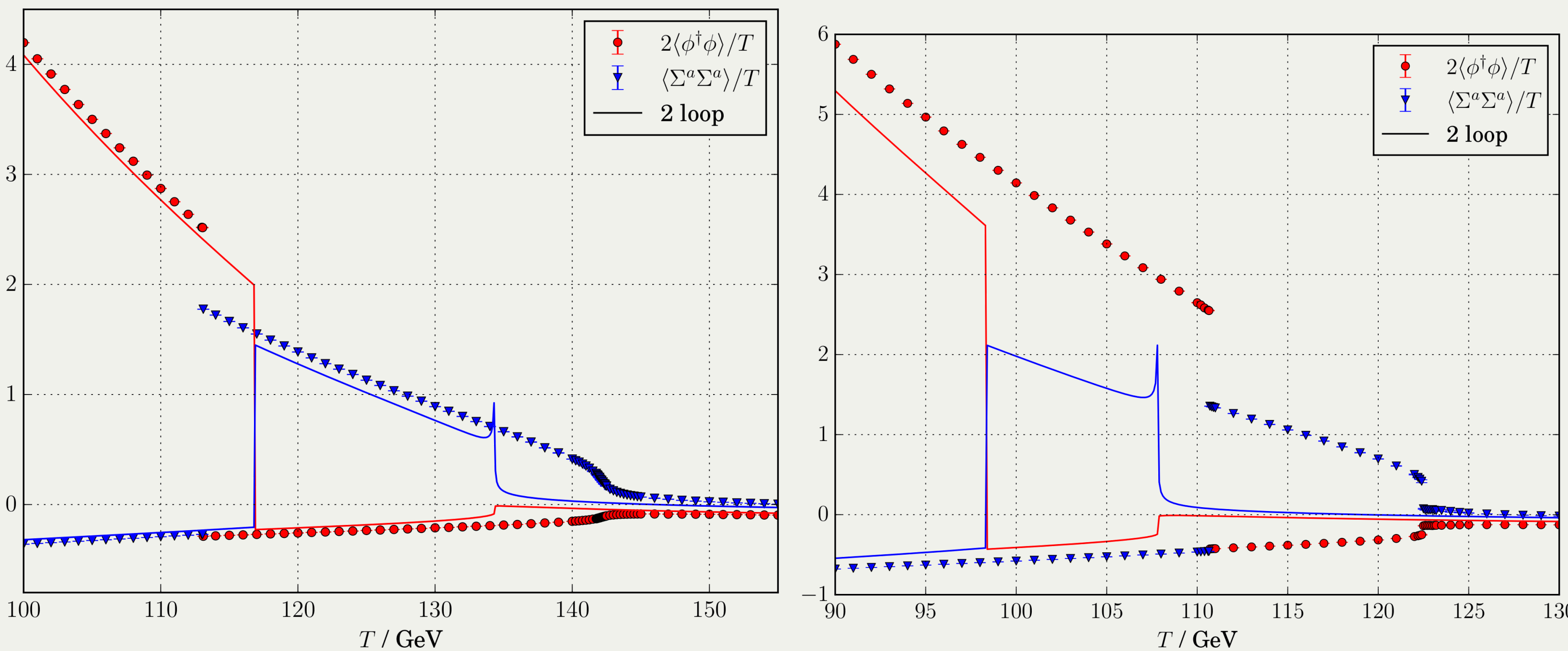
How to get strong transitions?



Need light physics or dim-6 operators

arXiv:1903.11604

DR: ΣSM (triplet) example



Perturbation theory doesn't see the phase transition!

arXiv:2005.11332

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 ✅

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Dimensional reduction ✅

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Cosmological GW background

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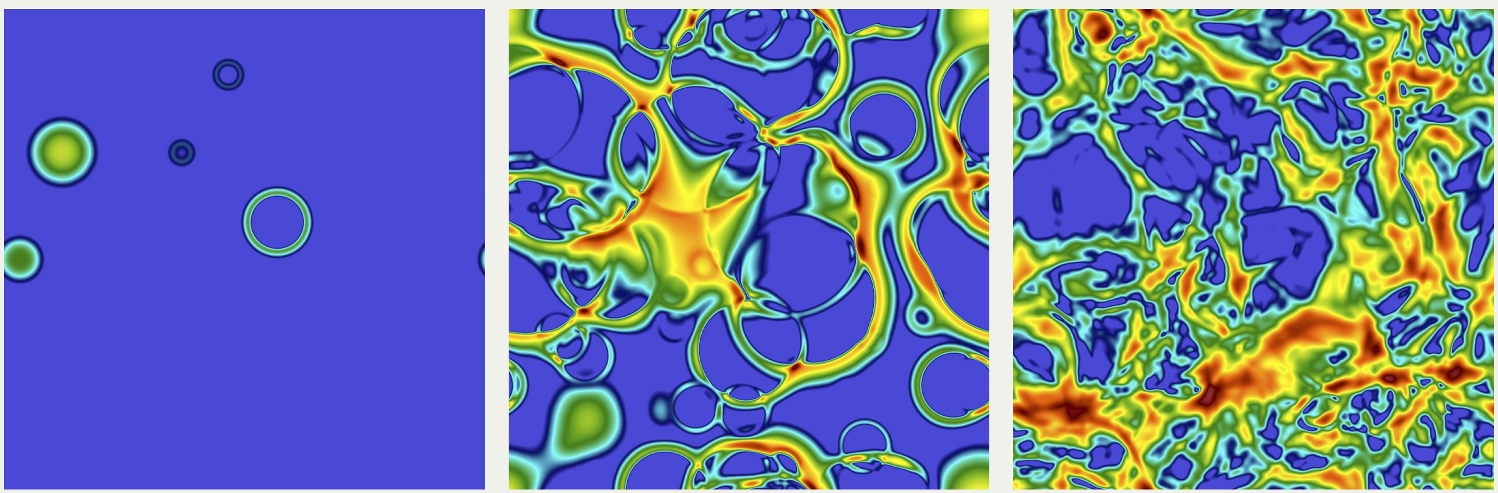
Cosmological GW background

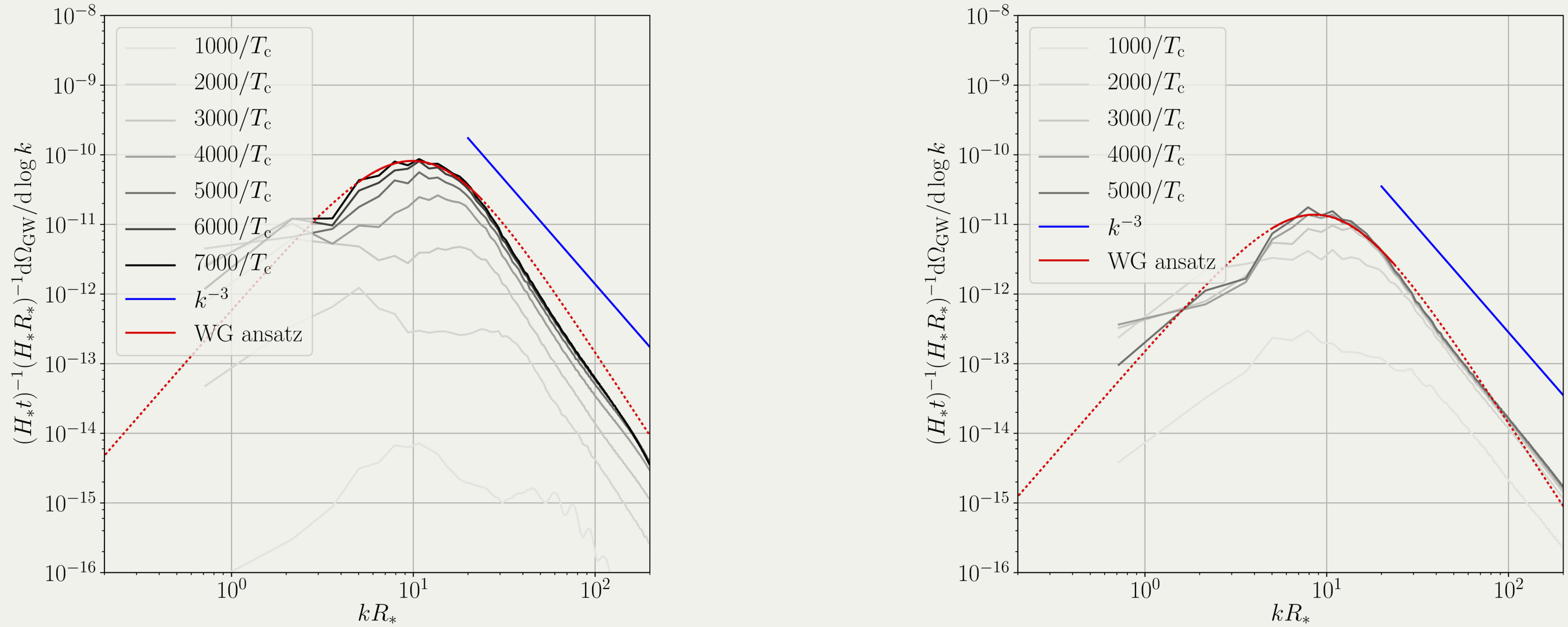
Out of equilibrium physics

1. Bubbles nucleate and grow
2. Expand in a plasma - create reaction fronts
3. Bubbles + fronts collide •)) $\Omega_{\rm col}(f)$
4. **Sound waves** left behind in plasma •)) $\Omega_{\rm sw}(f)$
5. Shocks [$\to$ turbulence] $\to$ damping •)) $\Omega_{\rm turb}(f)$



Simulating weak transitions: $\alpha \ll 1$

- Focusing on GWs from sound waves... arXiv:1704.05871

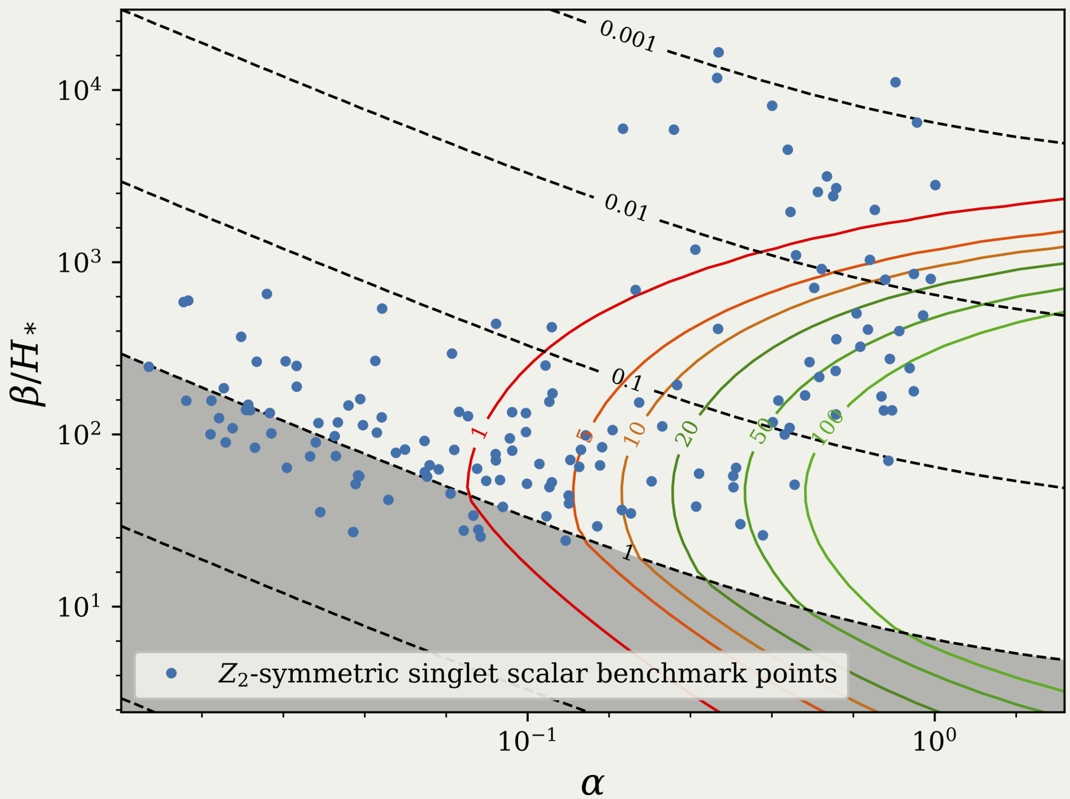


- ...$\Omega_{\mathrm{sw}}(f)$ fairly close to broken power law arXiv:1512.06239
- ...and the linear sound shell model arXiv:1608.04735

Explore $\Omega_{\rm sw}(f)$ with PTPlot.org

Model $\longrightarrow$ [T_*, α_{T_*}, $v_{\rm w}$, β] $\longrightarrow$ this plot

[Here: Z_2-symmetric xSM points from arXiv:1910.13125]



But what about strong transitions?

- Nonlinearities during the transition:
  - Generation of vorticity
  - Droplets
- Nonlinearities after the transition:
  - Shocks
  - turbulence

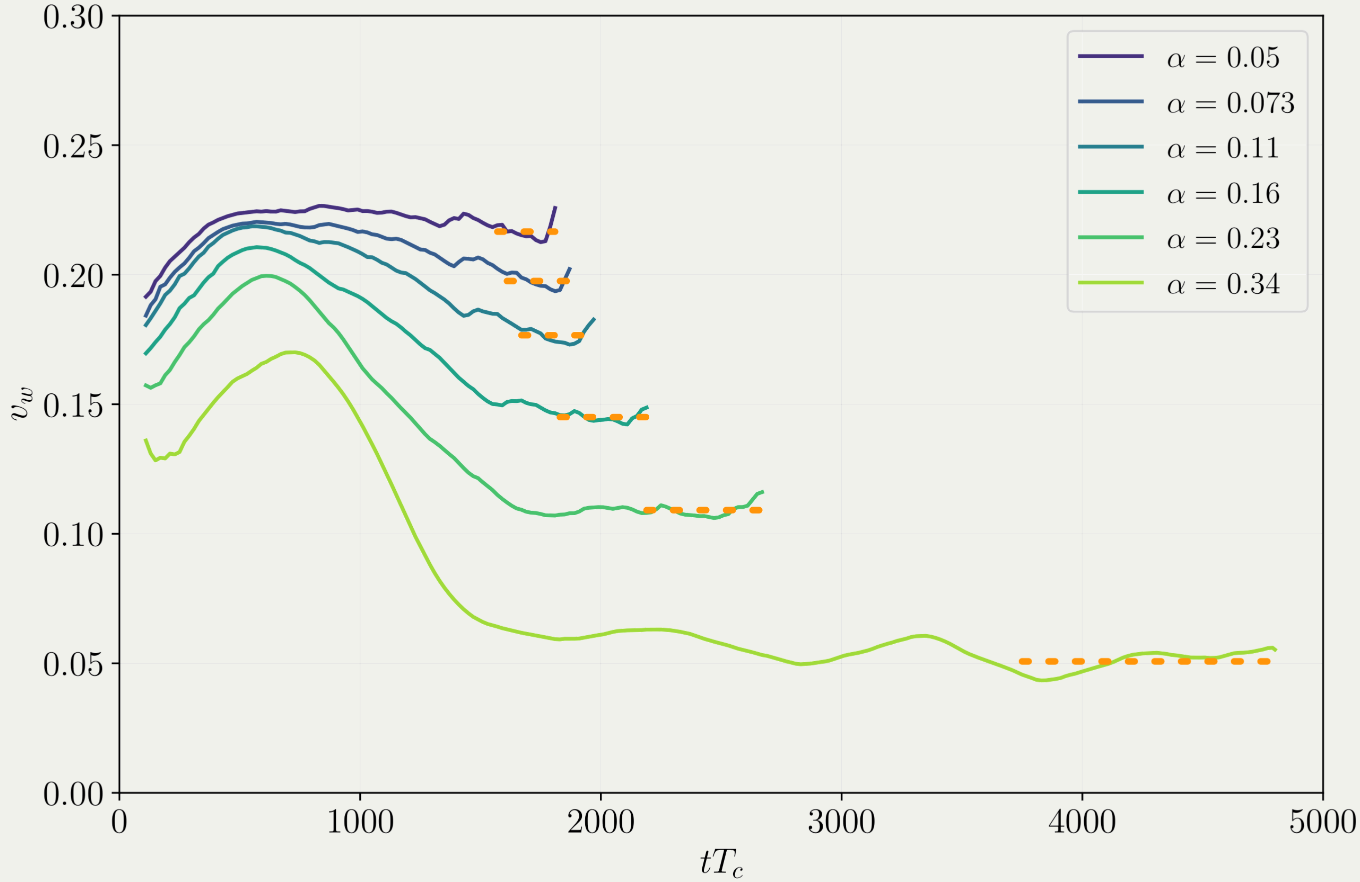
Let's take a look at droplets

Strong simulation velocity slice

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

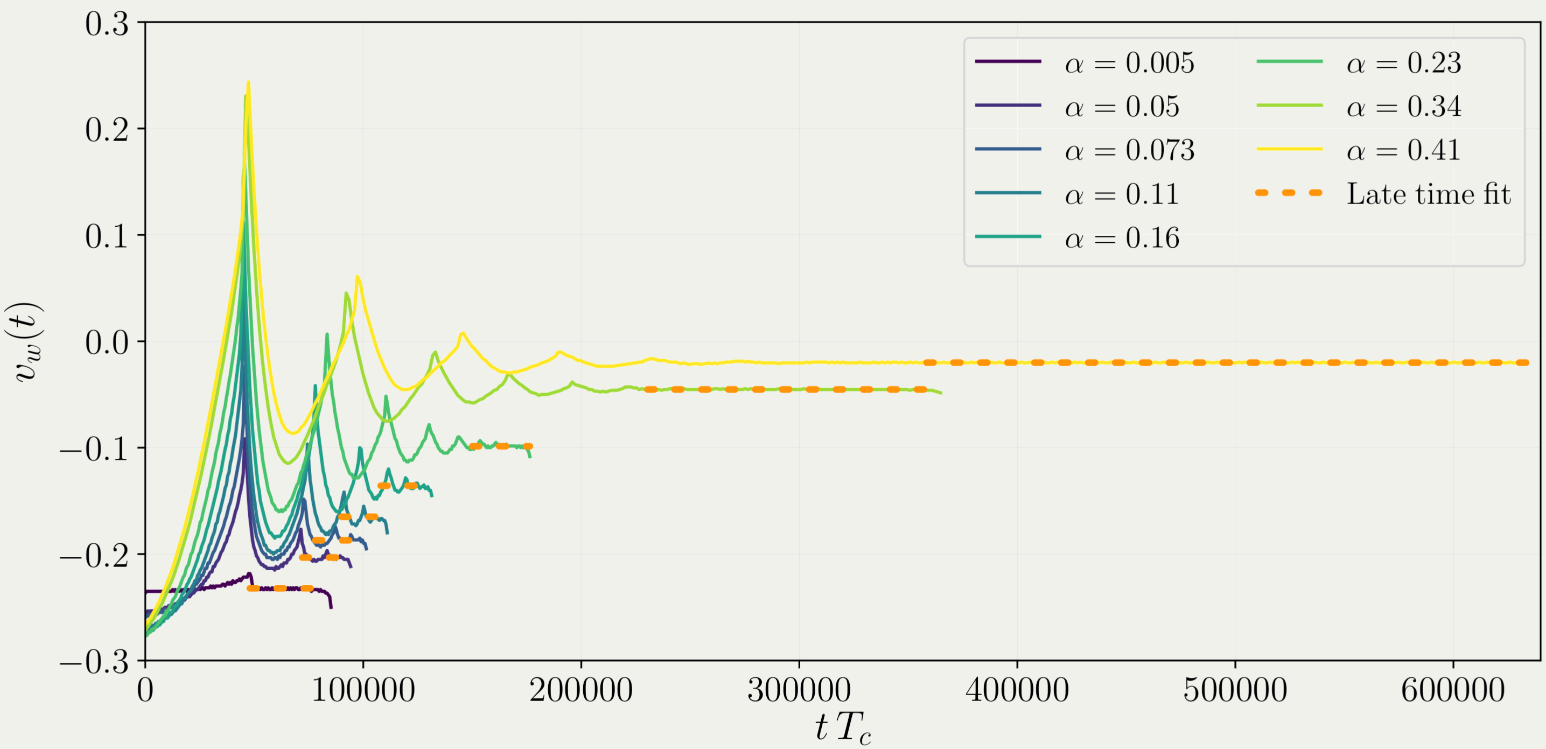
Walls slow, droplets form

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



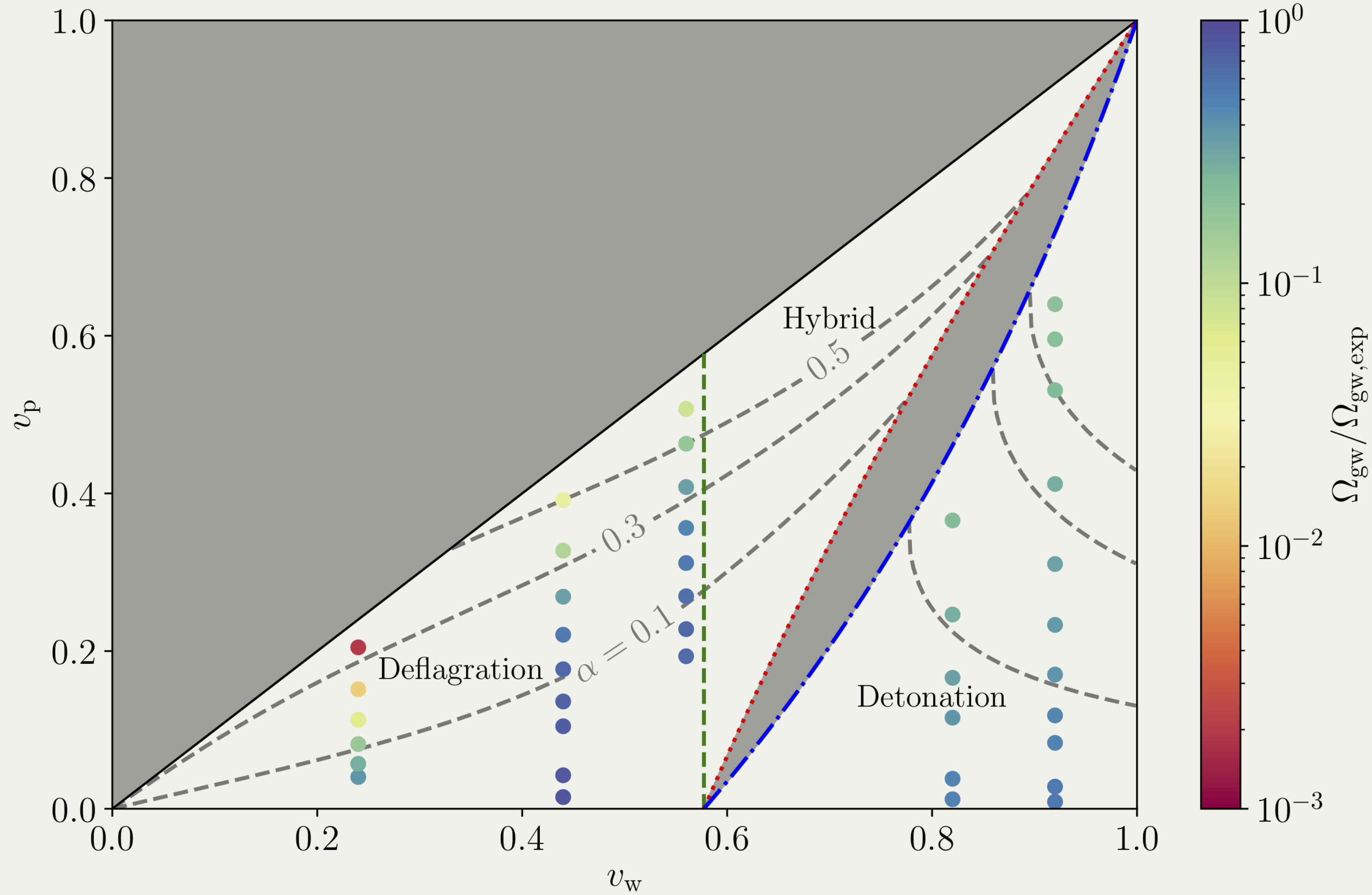
Isolated spherical droplets

In the spherical case, we can get a self-similar droplet.
We see the same wall velocity slowdown:



Droplets may suppress GWs

Suppression compared to sound waves [redder = worse]



arXiv:1906.00480

Thanks

- **Students**:
  Anna Kormu, Lauri Niemi,
  Satumaaria Sukuvaara,
  Essi Vilhonen
- **Postdocs**:
  Daniel Cutting, Oliver Gould
- **Collaborators**:
  Jonathan Kozaczuk,
  Mark Hindmarsh, Stephan Huber,
  Hiren Patel, Michael Ramsey-Musolf, Kari Rummukainen,
  Tuomas Tenkanen

What I want you to remember

- **Dimensional reduction**, a valuable field theory tool
  $\Rightarrow$ test perturbative studies of phase transitions
- Strong phase transitions: hot **droplets** slow completion
  $\Rightarrow$ also suppress GW production

Questions you can ask me

- How accurate are bubble nucleation calculations?
- What about the onset of shocks and turbulence?
- What other physics could explain the GW suppression seen in strong transitions?