GWs from the EWPT in the singlet model: [towards] a nonperturbative analysis

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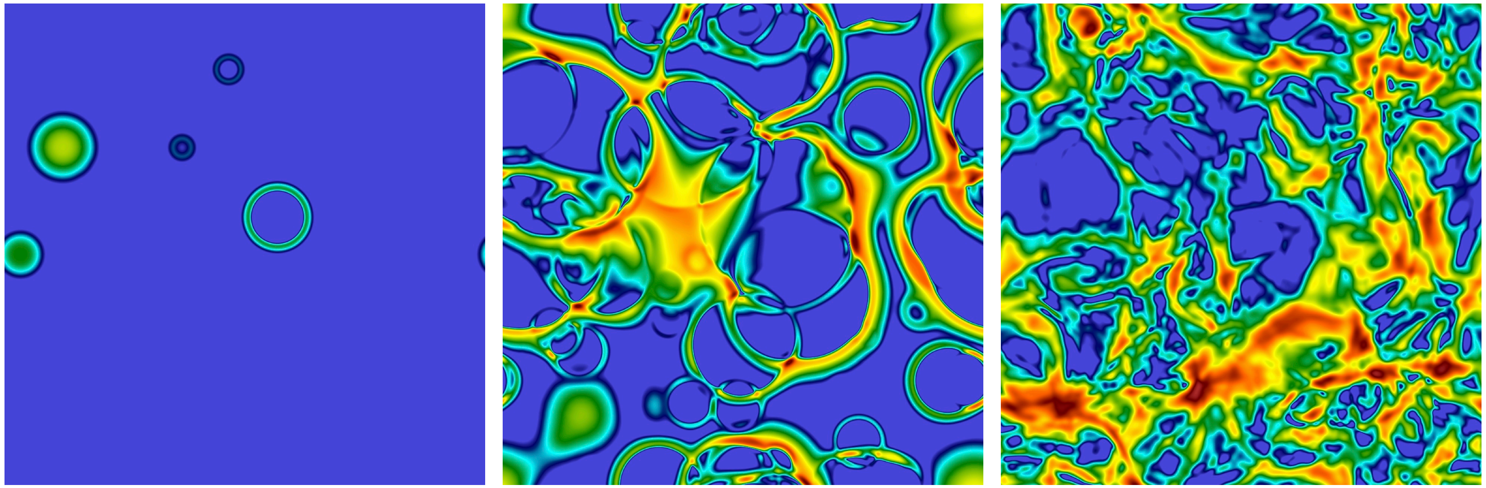
From the LISA proposal:

SI7.2 : Measure, or set upper limits on, the spectral shape of the cosmological stochastic GW background

OR7.2: Probe a broken power-law stochastic background from the early Universe as predicted, for example, by first order phase transitions [21] (other spectral shapes are expected, for example, for cosmic strings [22] and inflation [23]). Therefore, we need the ability to measure $\Omega = 1.3 \times 10^{-11} \left(f/10^{-4}\,\mathrm{Hz} \right)^{-1}$ in the frequency ranges $0.1\,\mathrm{mHz} < f < 2\,\mathrm{mHz}$ and $2\,\mathrm{mHz} < f < 20\,\mathrm{mHz}$, and $\Omega = 4.5 \times 10^{-12} \left(f/10^{-2}\,\mathrm{Hz} \right)^{3}$ in the frequency ranges $2\,\mathrm{mHz} < f < 20\,\mathrm{mHz}$ and $0.02 < f < 0.2\,\mathrm{Hz}$.

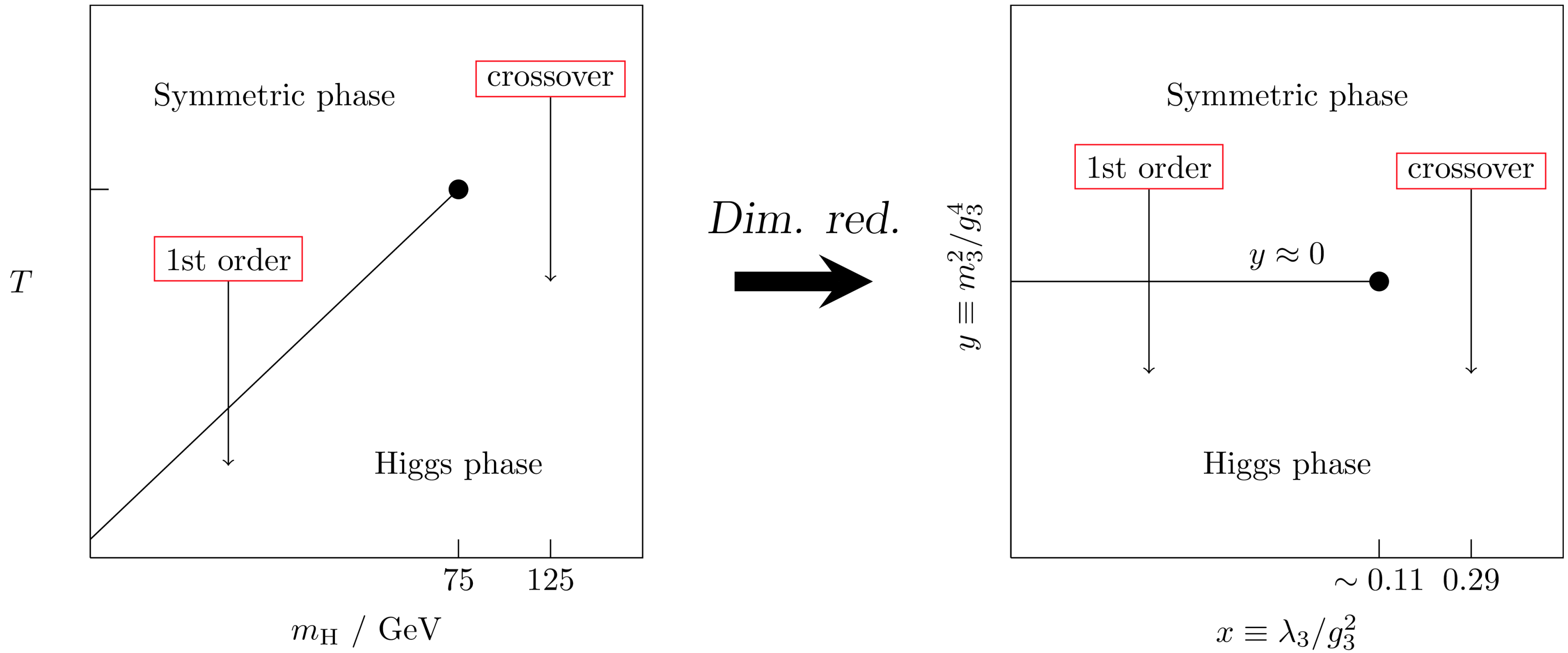
Thermal phase transitions:

1. Bubbles nucleate and grow
2. Expand in a plasma - create sound shells
   [+ baryon asymmetry forms?]
3. Bubbles + shells collide - violent process
4. Sound waves left behind in plasma
5. Shocks; turbulence; expansion



Electroweak phase transitions

- Standard Model is a crossover Kajantie *et al.*; Gurtler *et al.*; Csikor *et al.*; ...
- Dimensional reduction:
  high T, system three-dimensional for long-distance physics
- Then study nonperturbatively (on lattice)



- Can we map any other theories to the same 3D model?

Higgs singlet model

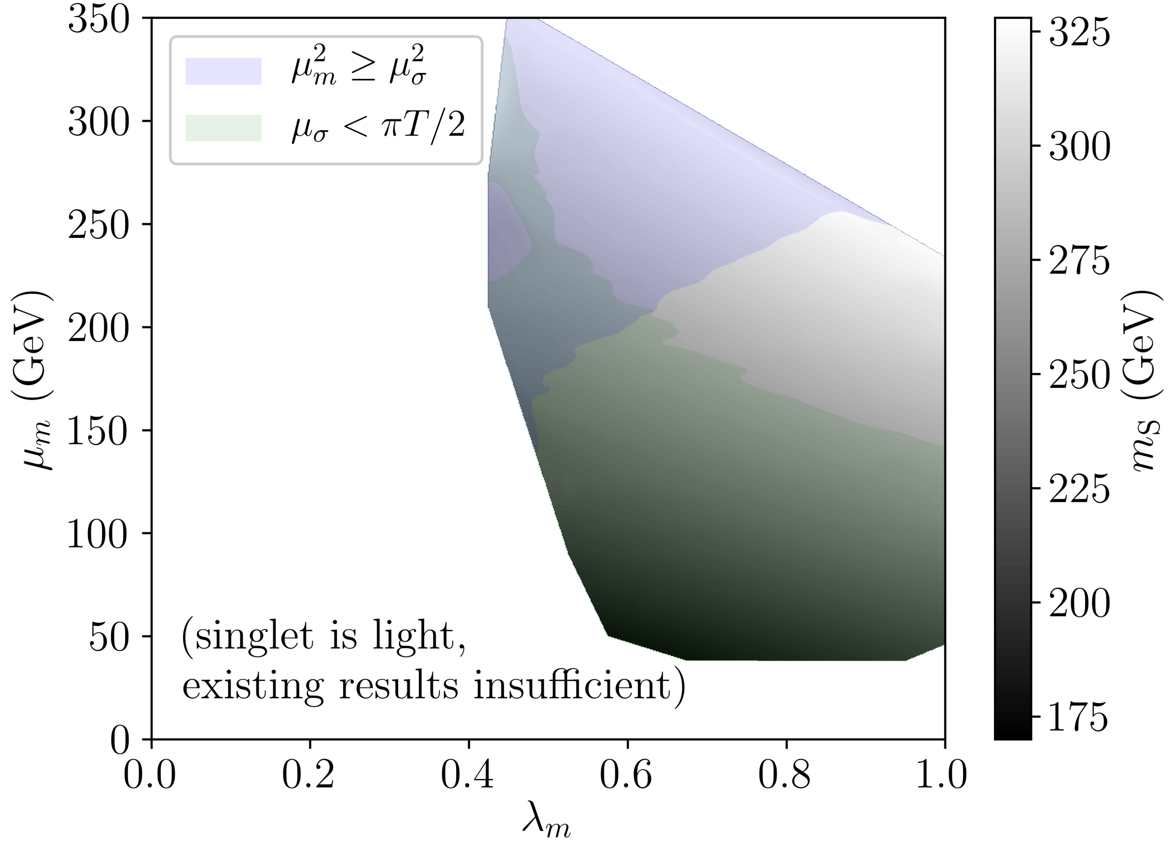
$$\mathcal{L}_{\Phi,\sigma} = D_\mu\phi^\dagger D_\mu\phi - \mu_h^2\phi^\dagger\phi + \lambda_h(\phi^\dagger\phi)^2 + \frac{1}{2}(\partial_\mu\sigma)^2 + \frac{1}{2}\mu_\sigma^2\sigma^2$$

$$+ \mu_1\sigma + \frac{1}{3}\mu_3\sigma^3 + \frac{1}{4}\lambda_\sigma\sigma^4 + \frac{1}{2}\mu_m\sigma\phi^\dagger\phi + \frac{1}{2}\lambda_m\sigma^2\phi^\dagger\phi$$

- More complicated symmetry breaking: σ, ϕ can get vevs...
- Singlet doesn't couple to gauge fields, harder to see at LHC
- If singlet is heavy, we can integrate it out during DR
- Then we rule out regions of parameter space where it plays an active role, but:
  - Some of that is at light singlet masses (and hence disfavoured) anyway
  - The system then maps onto the same 3D theory as the Standard Model! Two potential parameters: x, y

Reheated results:

Fix $x = 0.036$ in the 3D theory, use existing DR:



- Corresponds to a *somewhat* strong first order PT
- Wide choice of parameters!

GWs from thermal phase transitions

- Bubbles nucleate and expand, shocks form, then:
  1. $h^2\Omega_\phi$: Bubbles + shocks collide - 'envelope phase'
  2. $h^2\Omega_{\rm sw}$: Sound waves set up - 'acoustic phase'
  3. $h^2\Omega_{\rm turb}$: [MHD] turbulence - 'turbulent phase'

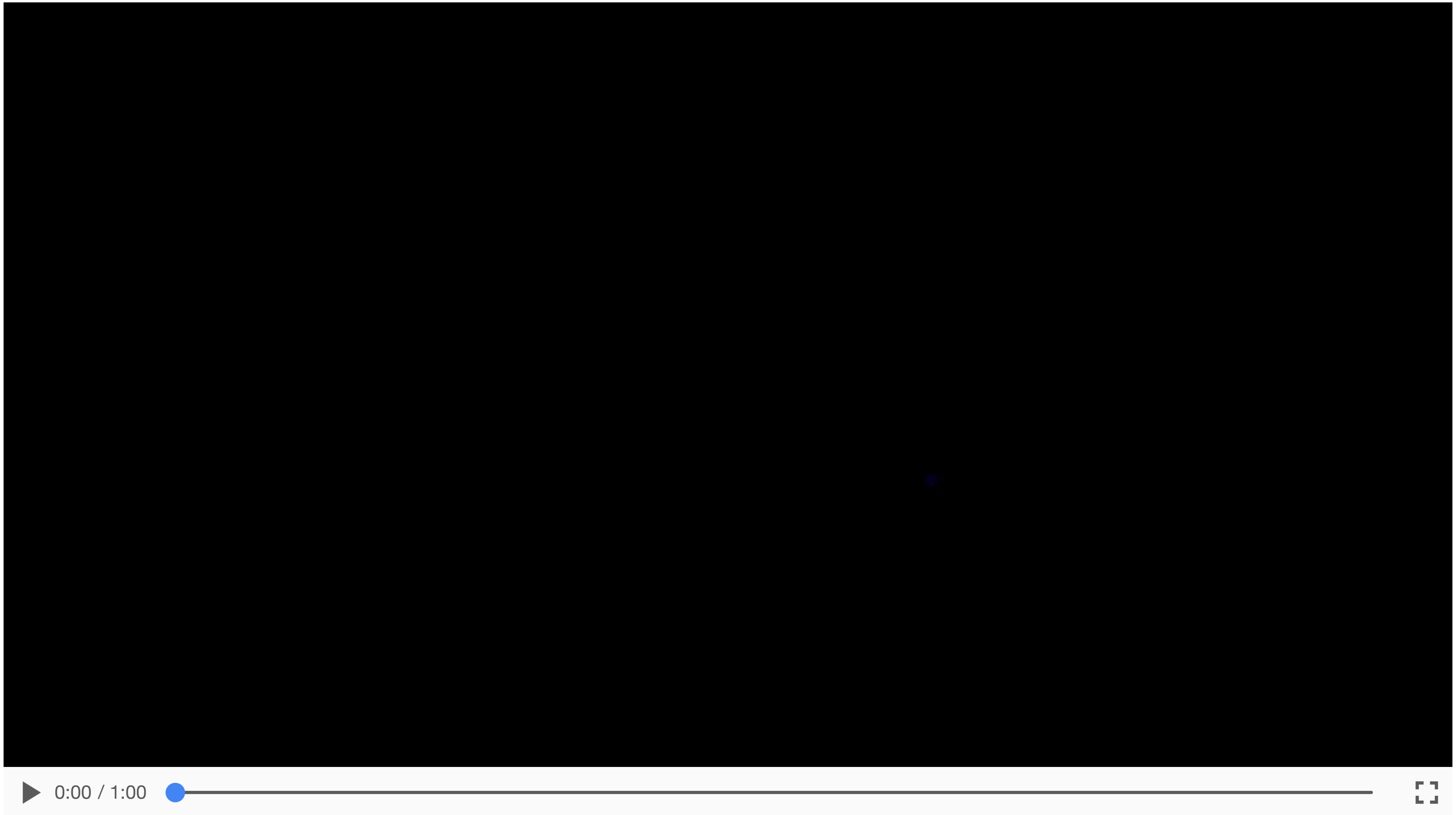
- Sources add together to give observed GW power:

$$h^2\Omega_{\rm GW} \approx h^2\Omega_\phi + h^2\Omega_{\rm sw} + h^2\Omega_{\rm turb}$$

- For a thermal phase transition, $h^2\Omega_\phi$ is very small:

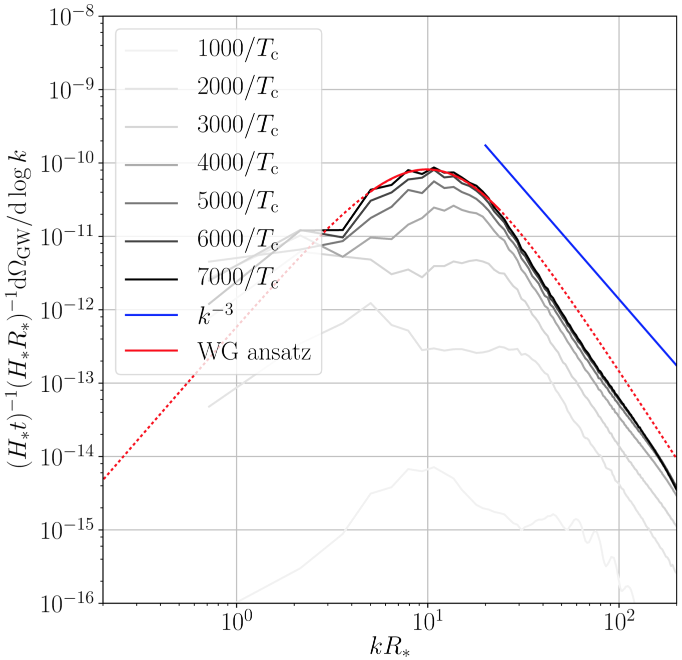
$$h^2\Omega_{\rm GW,\,thermal} \approx h^2\Omega_{\rm sw} + h^2\Omega_{\rm turb}$$

Simulation slice example

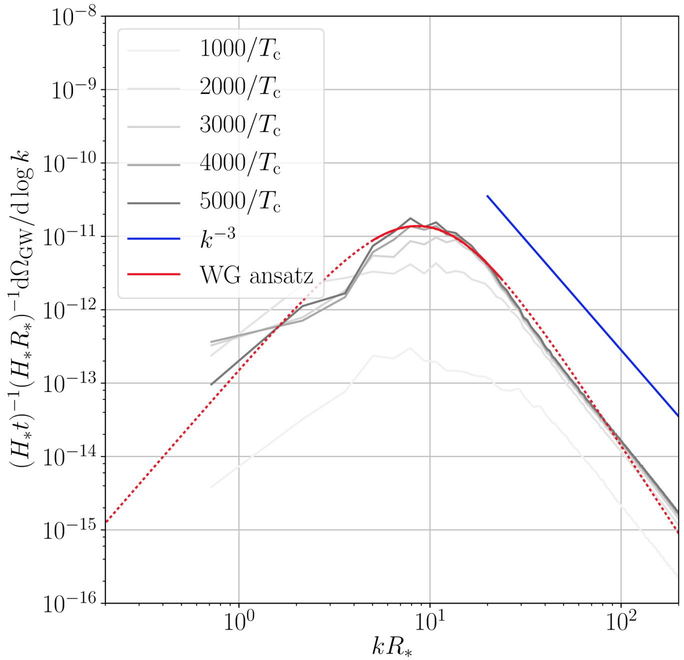


Acoustic GWs from simulations

$v_{\rm w} = 0.44$



$v_{\rm w} = 0.92$



- Causal f^3 at low f, approximate f^{-3} or f^{-4} at high k
- Curves scaled by t: stationary source for a Hubble time

→ power law ansatz for $h^2\Omega_{\rm sw}$

Reheated results:

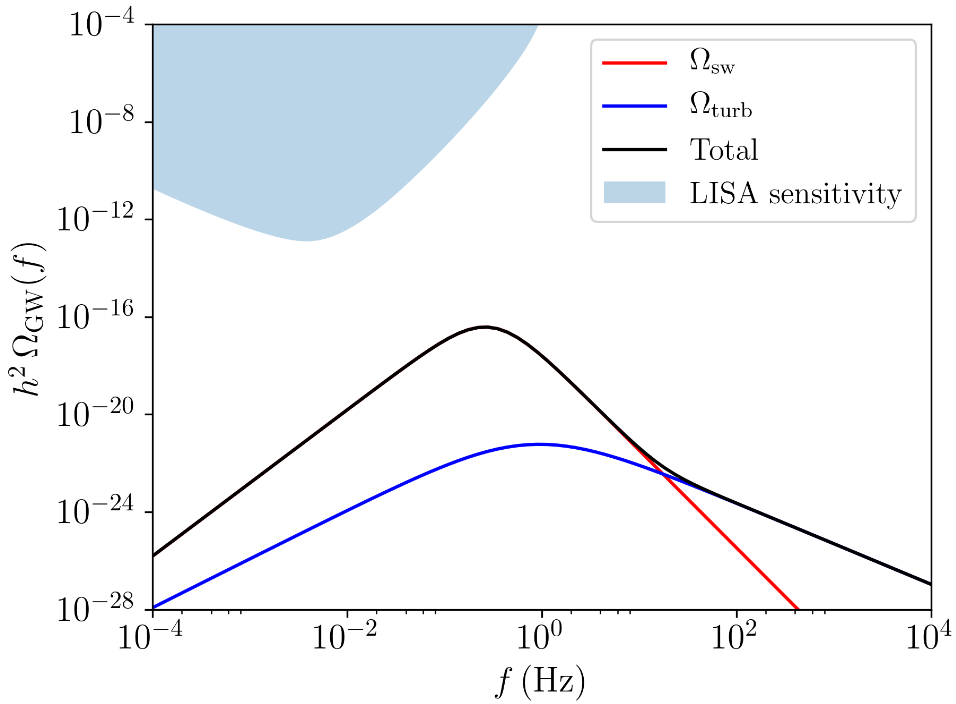
- Phase transition temperature T_* obtained from new DR: e.g. 200 GeV singlet, $\lambda_m = 0.8$, $T_* = 130\,\text{GeV}$
- Inverse phase transition duration: $\beta/H_* = 2 \times 10^4$ when $x = 0.036$ Moore and Rummukainen
- Phase transition strength: $\alpha_{T_*} = \mathcal{L}/\varepsilon_{\text{rad}} \approx 0.006$, extrapolating results of Kajantie *et al.*
- Wall velocity: *presume* $v_{\text{w}} = 0.55$, fast deflagration (no nonperturbative result possible... yet)

A caveat

- No Standard Model parameters would produce a strong GW signal - even if the Higgs were very light ($\sim$ 35 GeV)!
- This is also true of other systems having the same 3D theory, like the singlet model with heavy singlet.
- However, similar techniques will be needed for precision measurements in other theories.

Putting it all together - $h^2\Omega_{\rm gw}$

- Two sources, $\approx h^2\Omega_{\rm sw} + h^2\Omega_{\rm turb}$
- Use ansätze to predict the signal for our reheated results:



- Realistic, but low, result. Uses what we already have!

The pipeline

1. Choose your model (e.g. SM, xSM, 2HDM, ...)
2. Dim. red. model Kajantie et al.
3. Phase diagram (α_{T_*}, T_*); lattice: Kajantie et al.
4. Nucleation rate (β); lattice: Moore and Rummukainen
5. Wall velocities ($v_{\rm wall}$) Moore and Prokopec; Kozaczuk
6. GW power spectrum $\Omega_{\rm gw}$
7. Sphaleron rate

Very leaky, even for SM!

Conclusions

- Precision studies of GWs from thermal phase transitions are important for LISA and future colliders.
- Dimensional reduction allows us to:
  - Integrate out fermions...
  - ... and some bosons ...
  - ... and map onto previously studied theories, like SM
- Existing results were hard-won; remain thin on the ground.
- More simulations needed!