Stochastic gravitational waves from cosmological phase transitions

Third EuCAPT annual symposium, June 2nd 2023

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Gravitational wave experiments

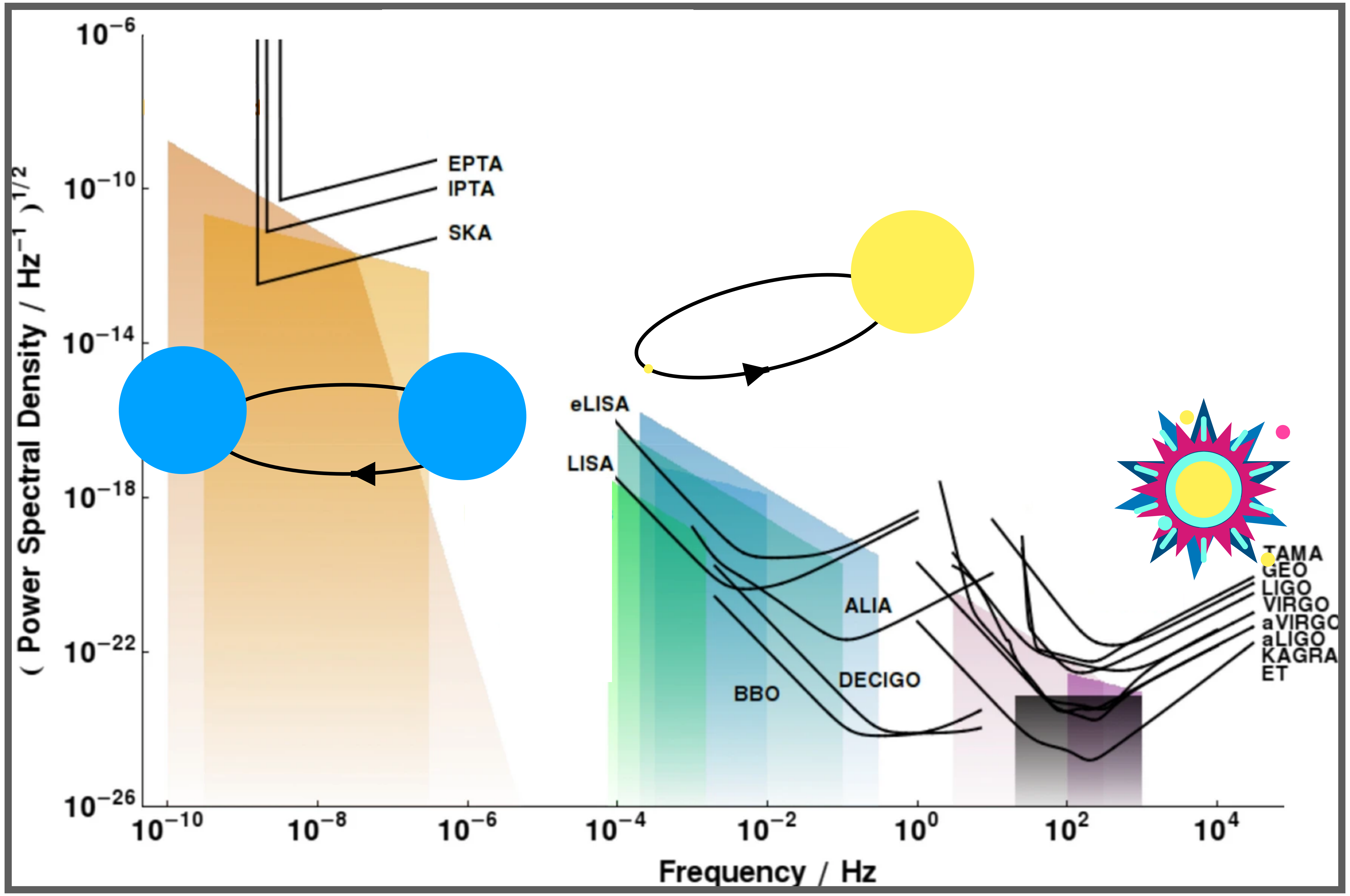


Figure: Park 2021

Gravitational wave experiments

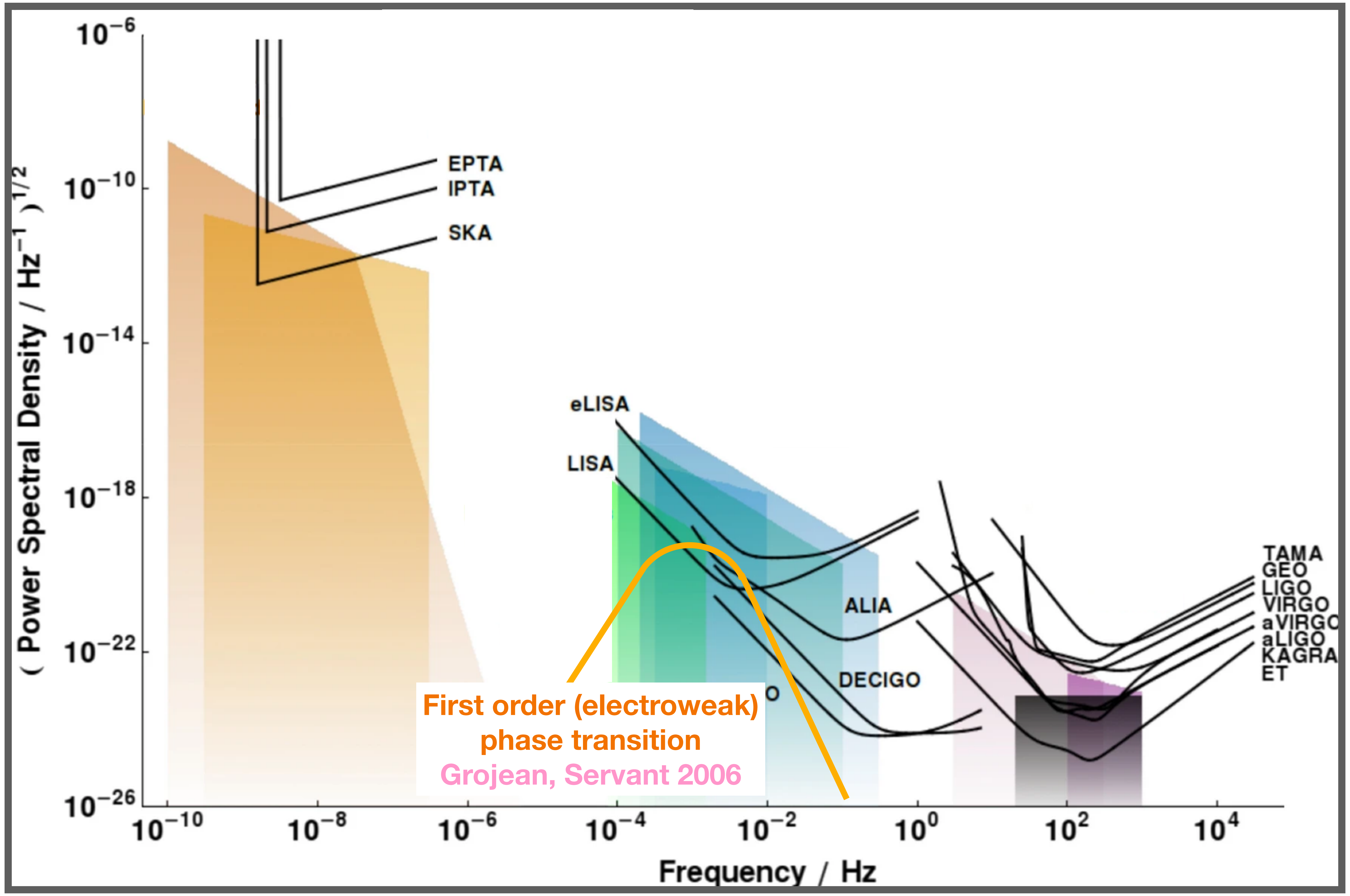


Figure: Park 2021

Stochastic signal

- Sum of many independent events
- Spectral parameters contain information about the source

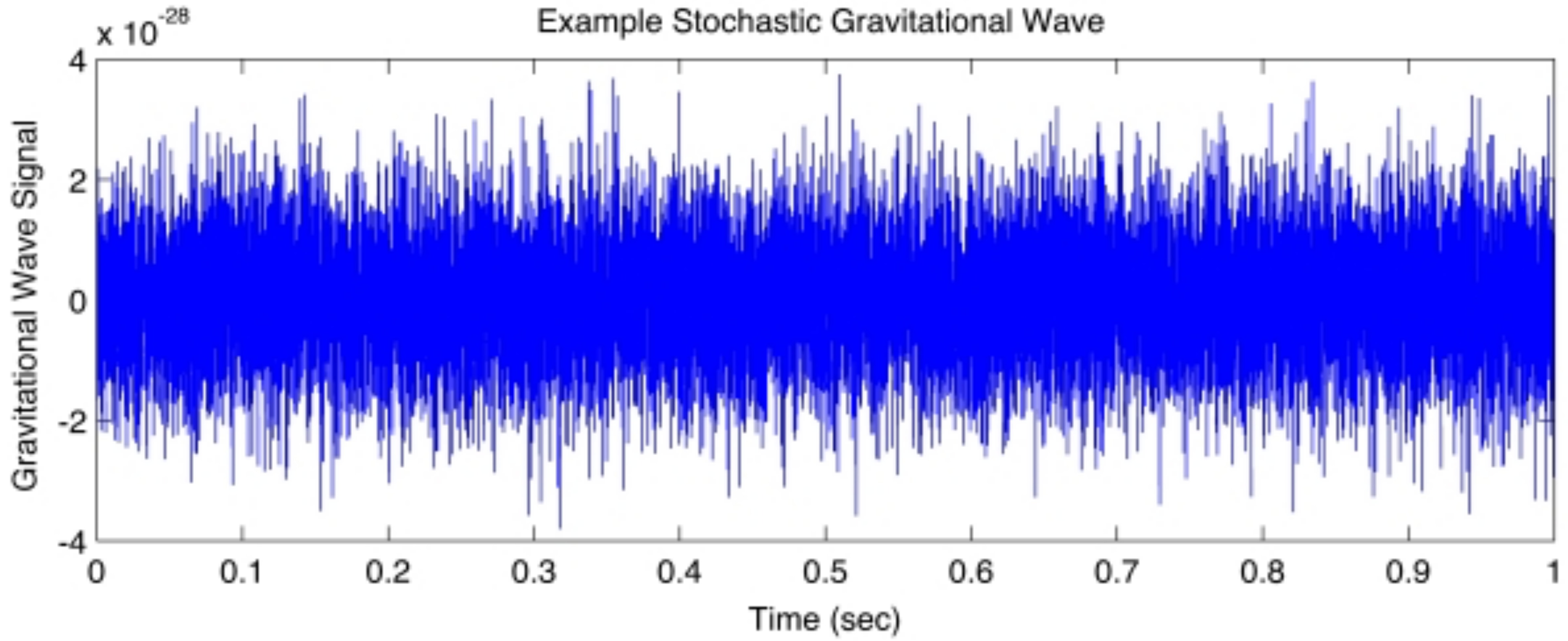


Figure: Stuver/LIGO

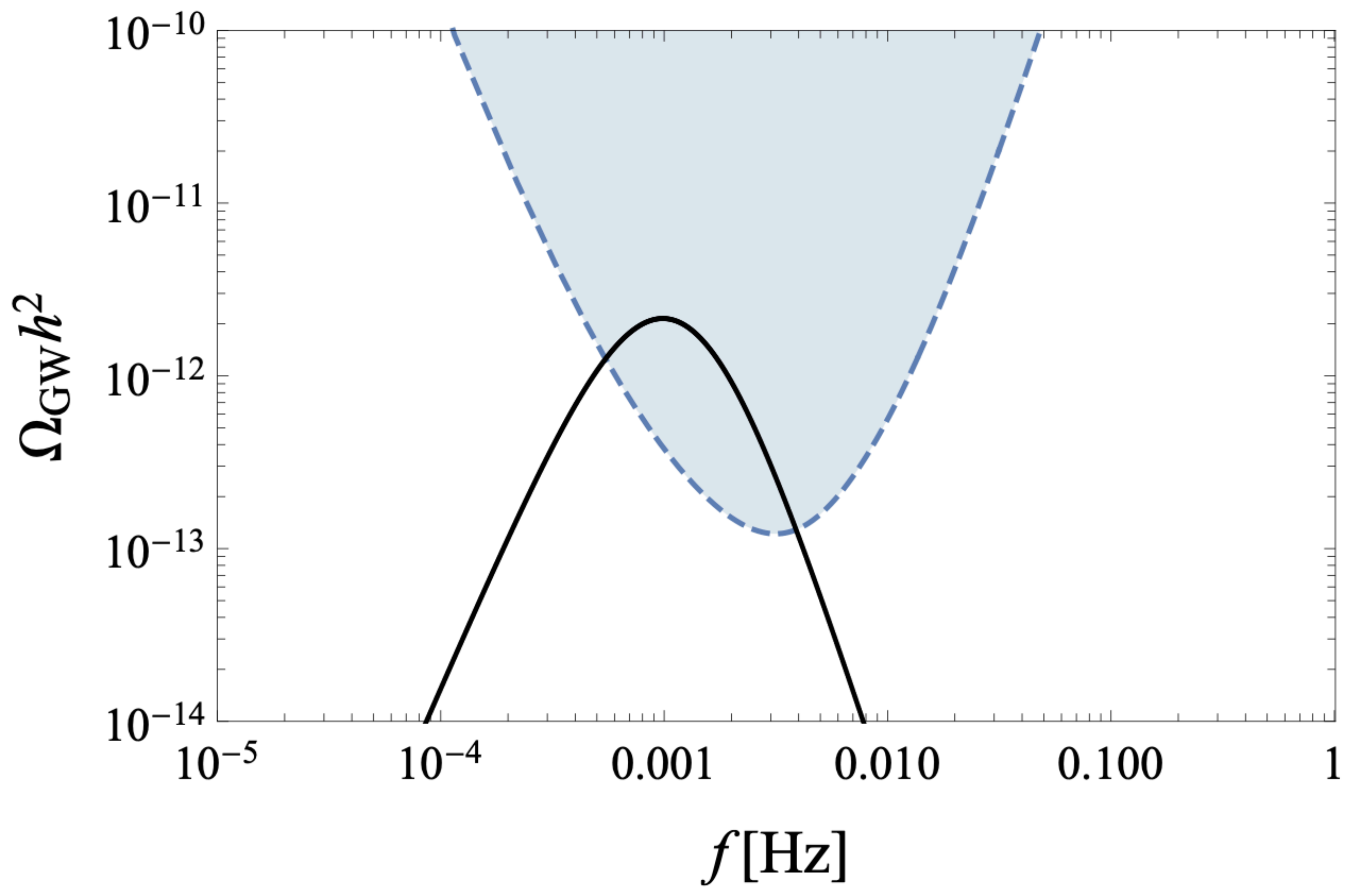
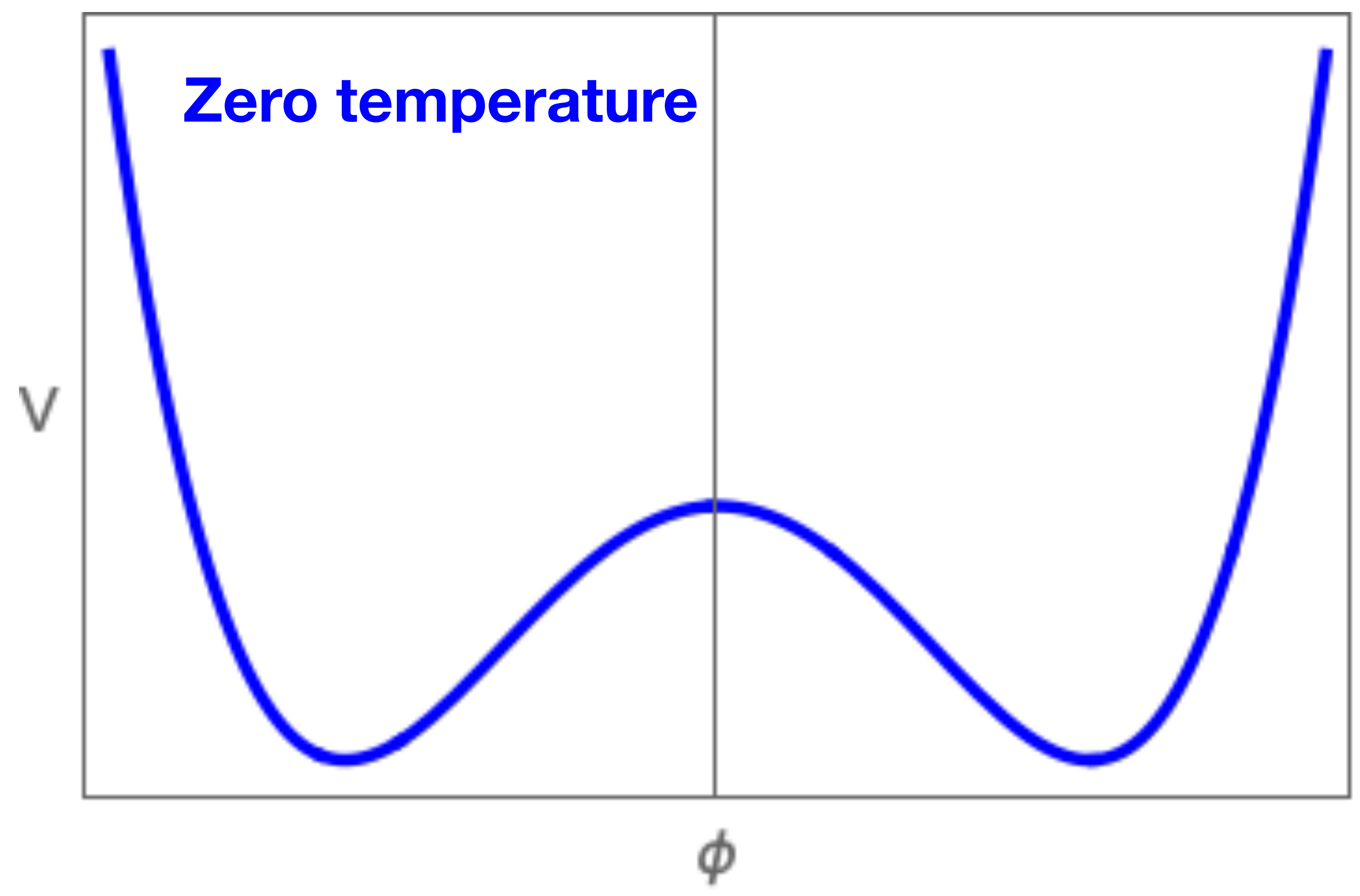


Figure: LISA Cosmology working group

Cosmological first order phase transitions

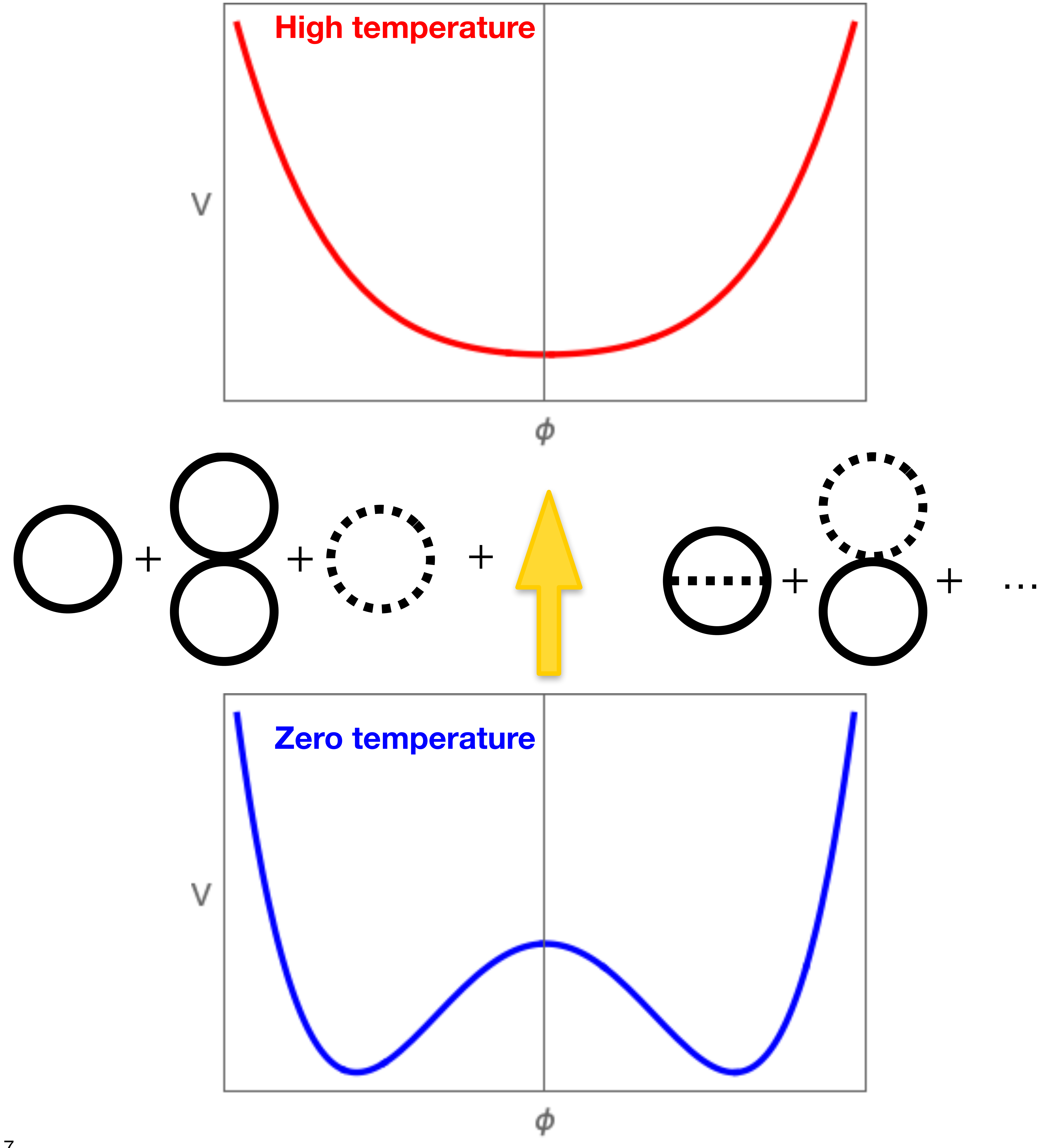
Temperature-dependent potential energy

- Broken symmetry at zero temperature



Temperature-dependent potential energy

- Broken symmetry at zero temperature
- Quantum corrections modify the shape and restore the symmetry



First order phase transition

- Barrier separating high- and low-temperature phase

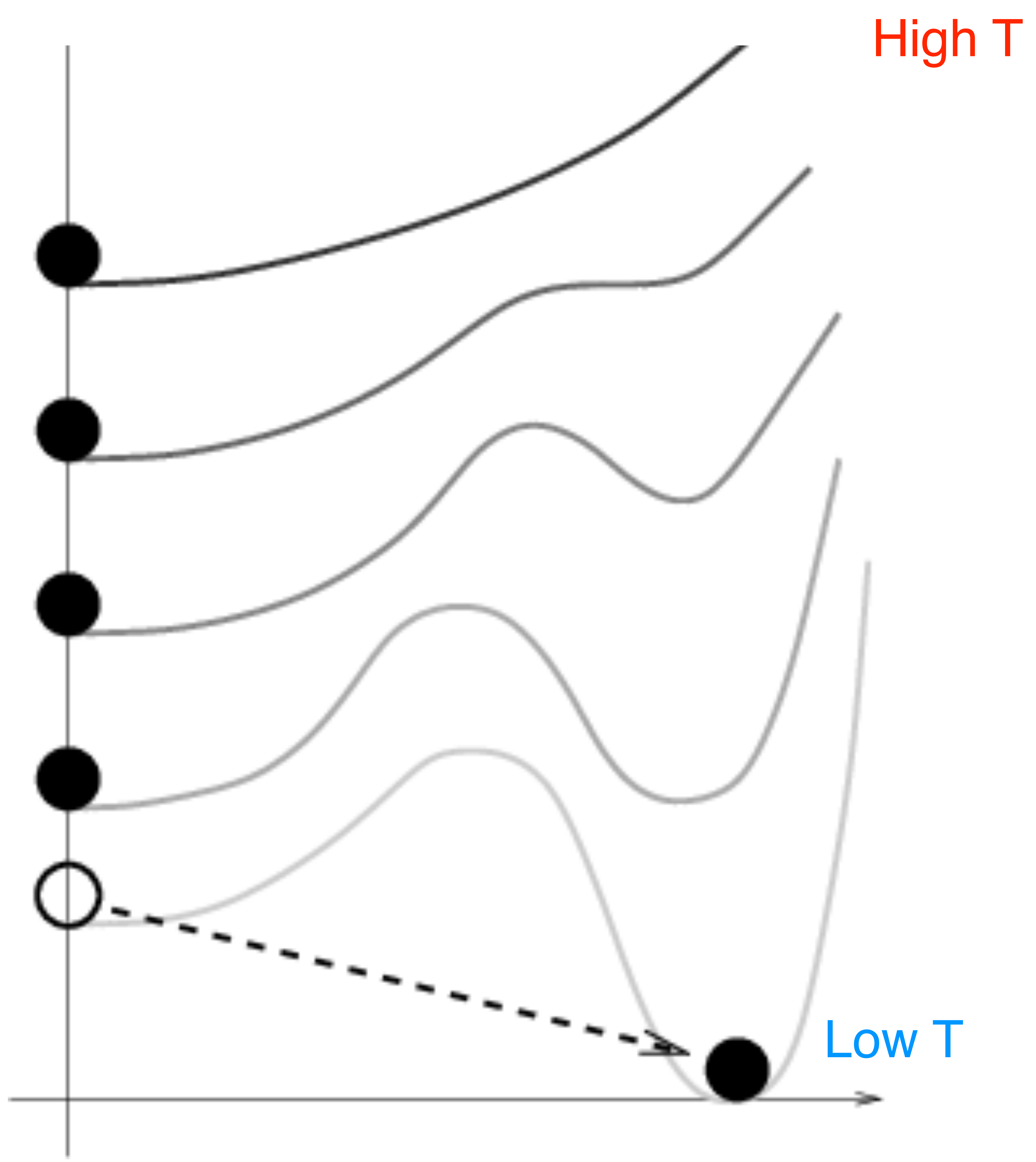
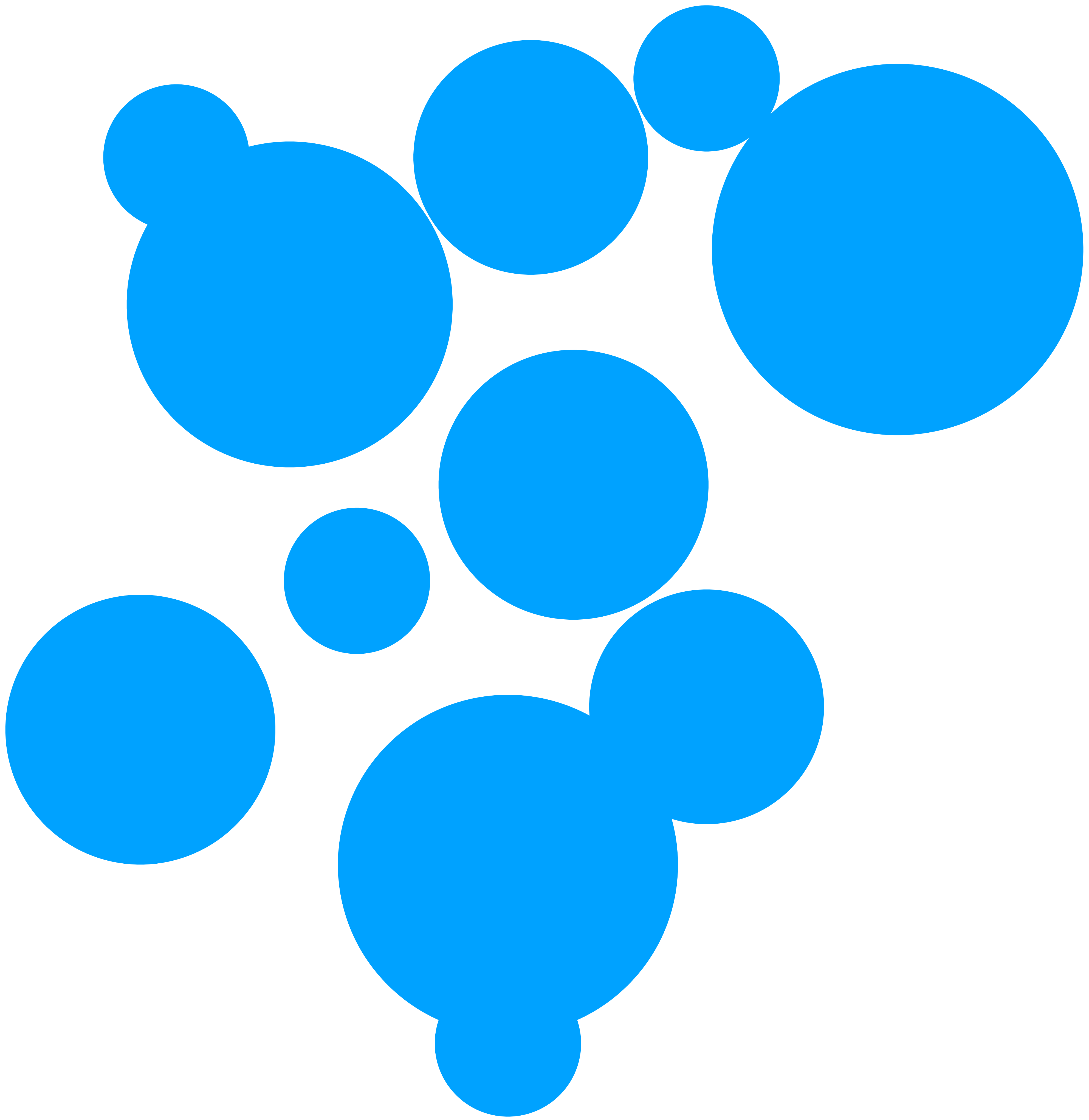


Figure: Rubakov, 2015

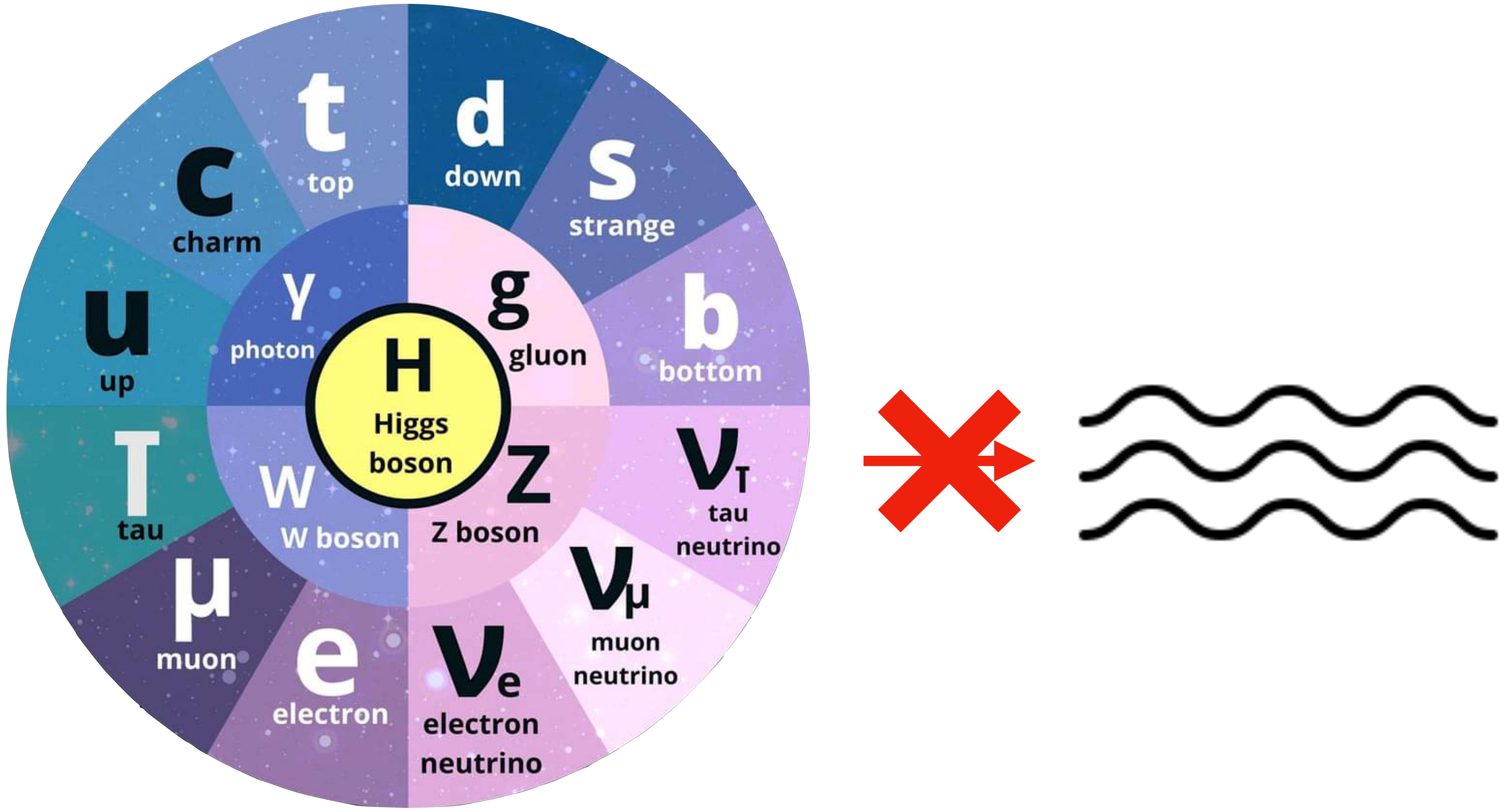
First order phase transition

- Barrier separating high- and low-temperature phase
- Nucleation of inhomogeneously distributed bubbles
- Released vacuum energy sources stochastic gravitational wave signal



GWs from a cosmological phase transition: sign of new physics

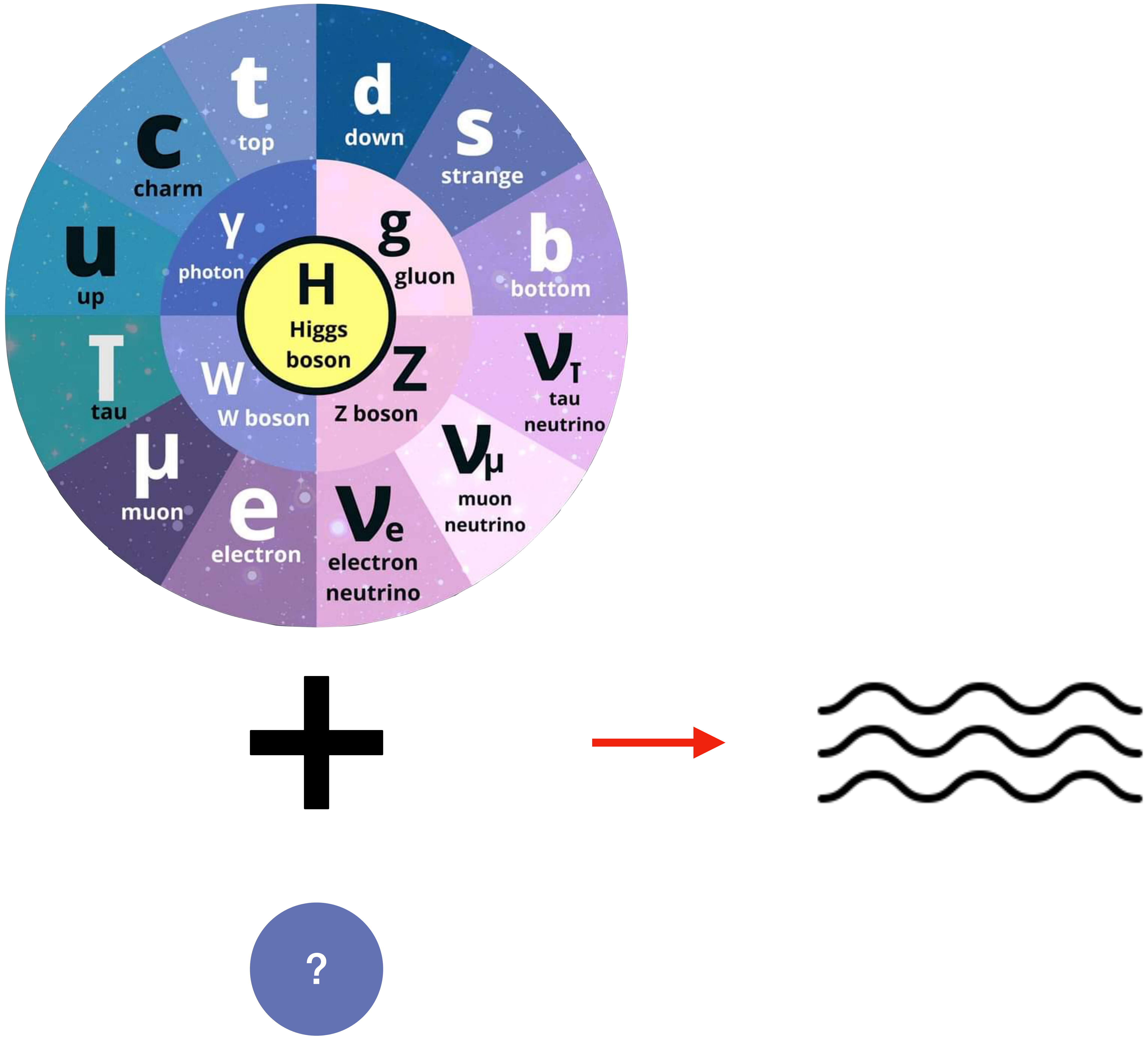
- Phase transitions in the Standard Model: electroweak and QCD
  Both cross-overs



GWs from a cosmological phase transition: sign of new physics

- Phase transitions in the Standard Model: electroweak and QCD
Both cross-overs

- New particles coupling to e.g. the Higgs can make the phase transition first order



GWs from a cosmological phase transition: sign of new physics

- Phase transitions in the Standard Model: electroweak and QCD
  Both cross-overs
- New particles coupling to e.g. the Higgs can make the phase transition first order
- Complementarity between GWs and collider searches

SM + real triplet phase structure

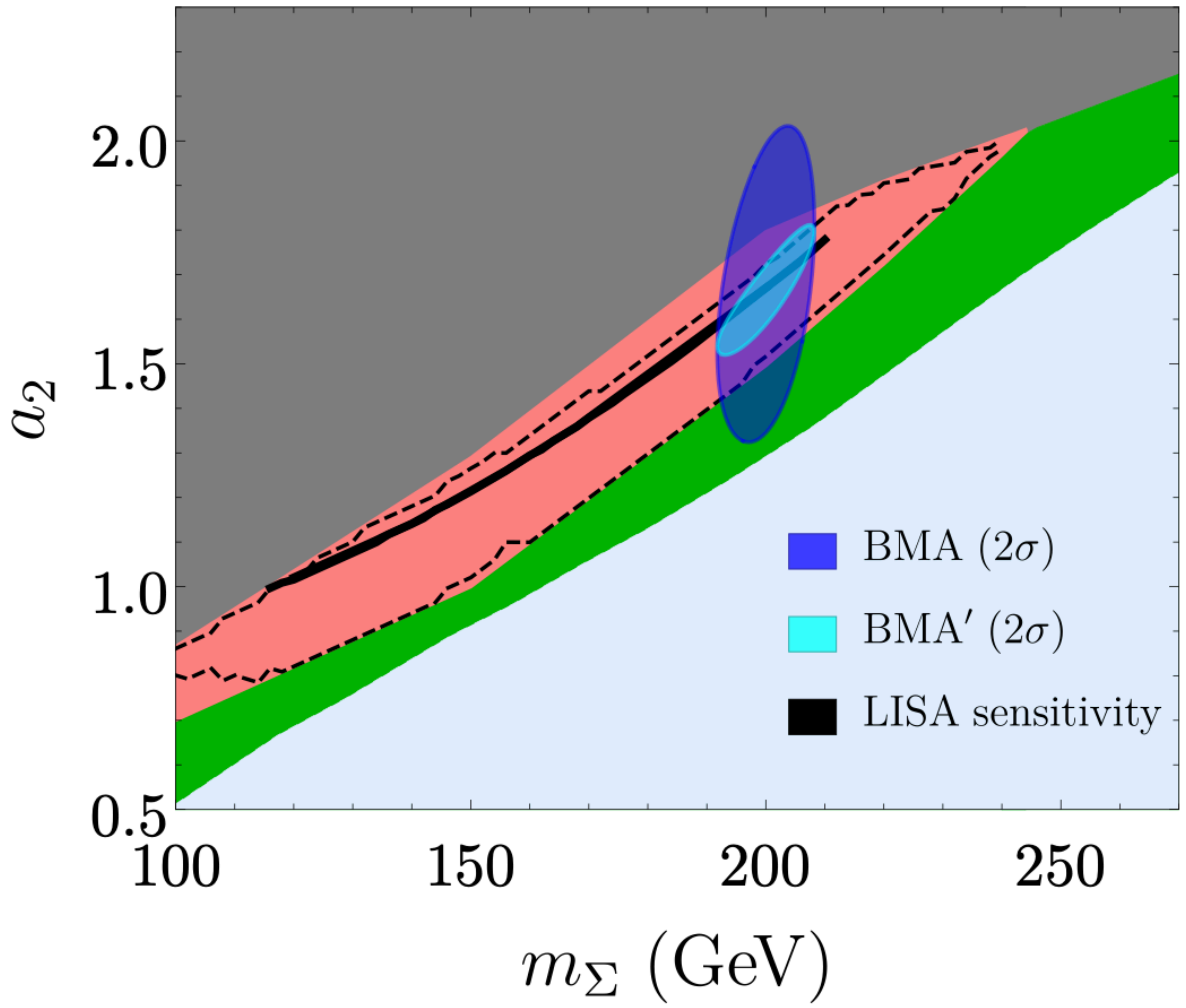


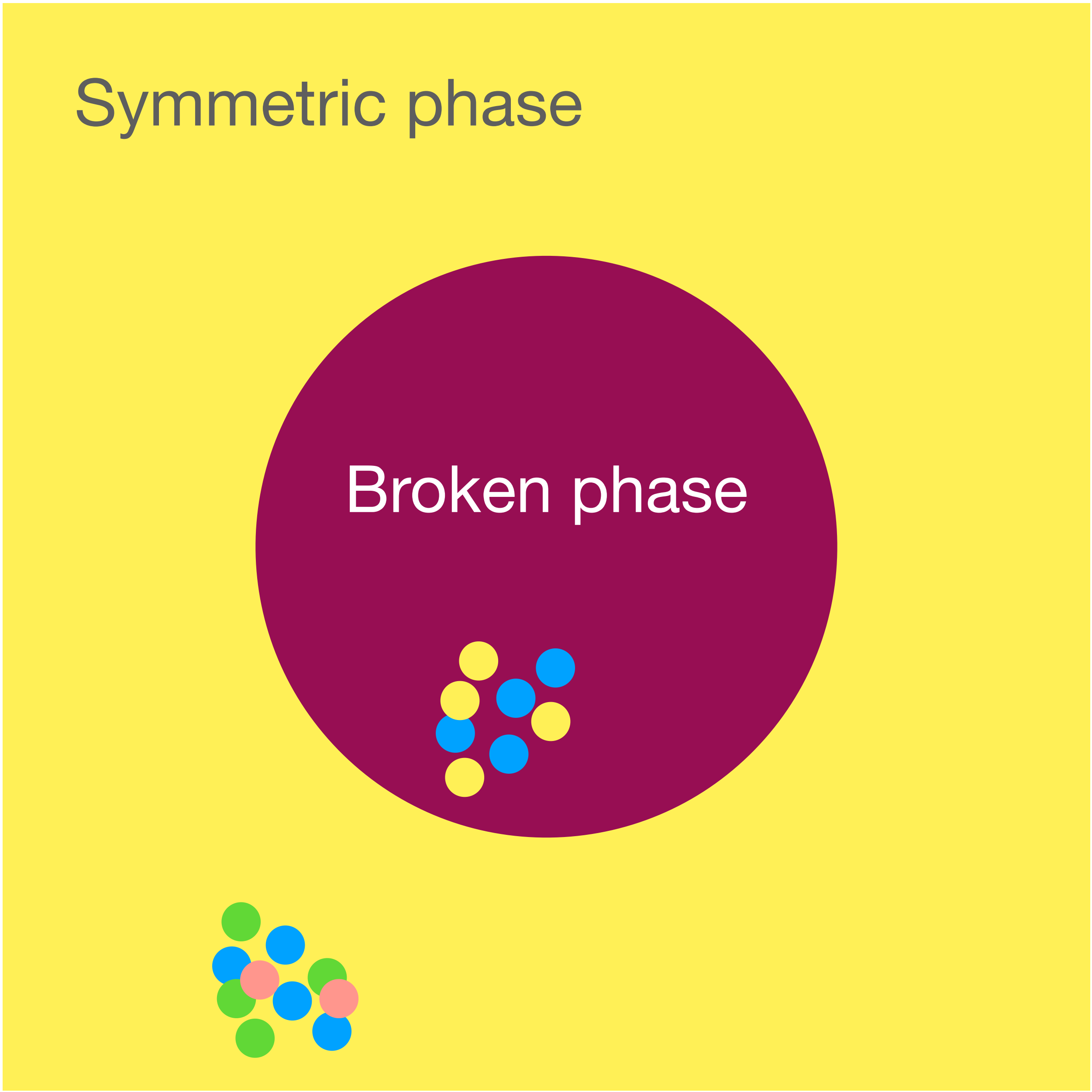
Figure: Friedrich, Ramsey-Musolf, Tenkanen, Tran, 2022

Predicting the GW spectrum

Thermodynamics of a bubble

Dependent on the particle physics model

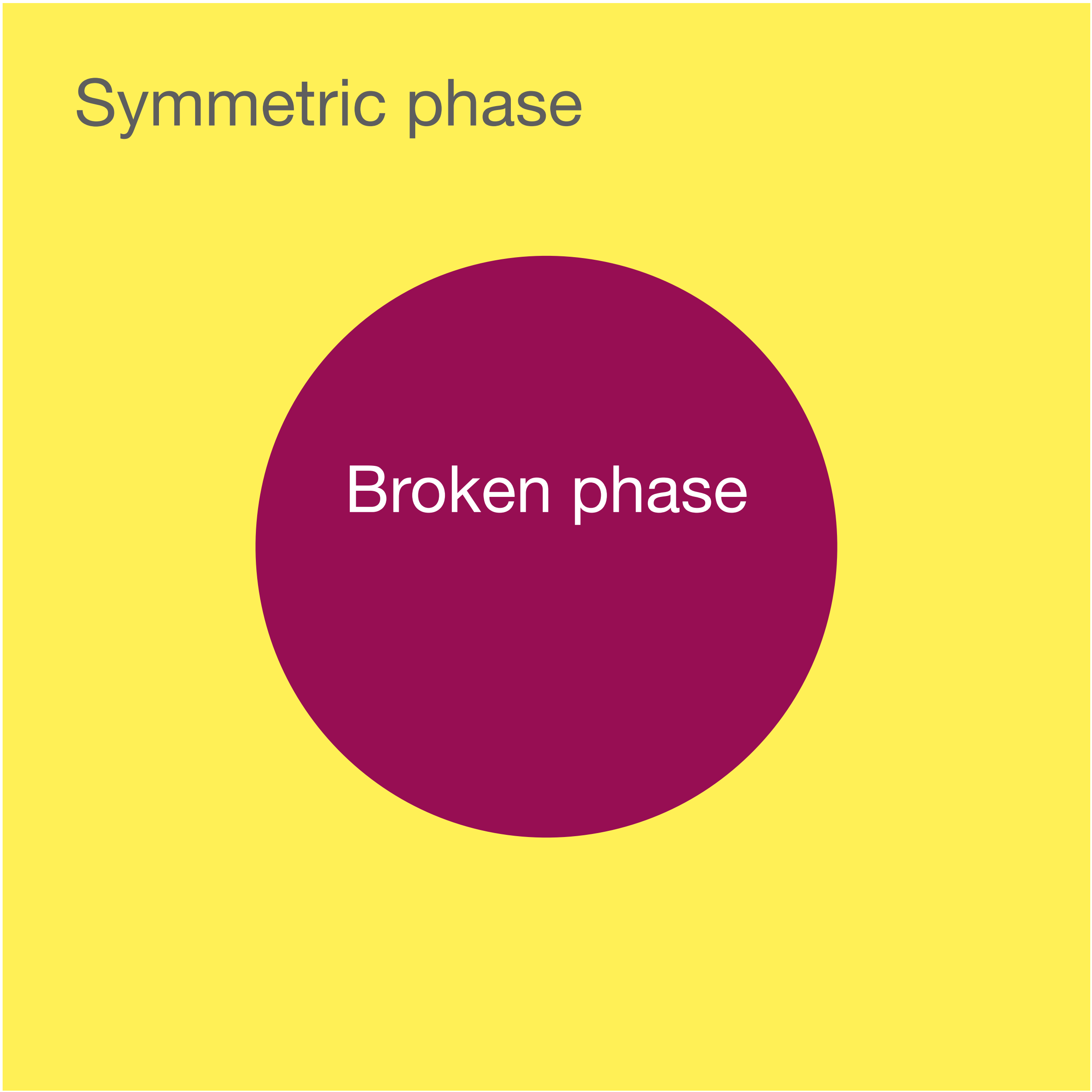
- Scalar field interacting with a plasma



Thermodynamics of a bubble

Bubble is characterised by

- Nucleation temperature T_n
- Phase transition strength α
- Phase transition rate β



Determining the thermodynamical quantities T_n, α, β

- Follow from the pressure: $p = -V_{\text{eff}}$

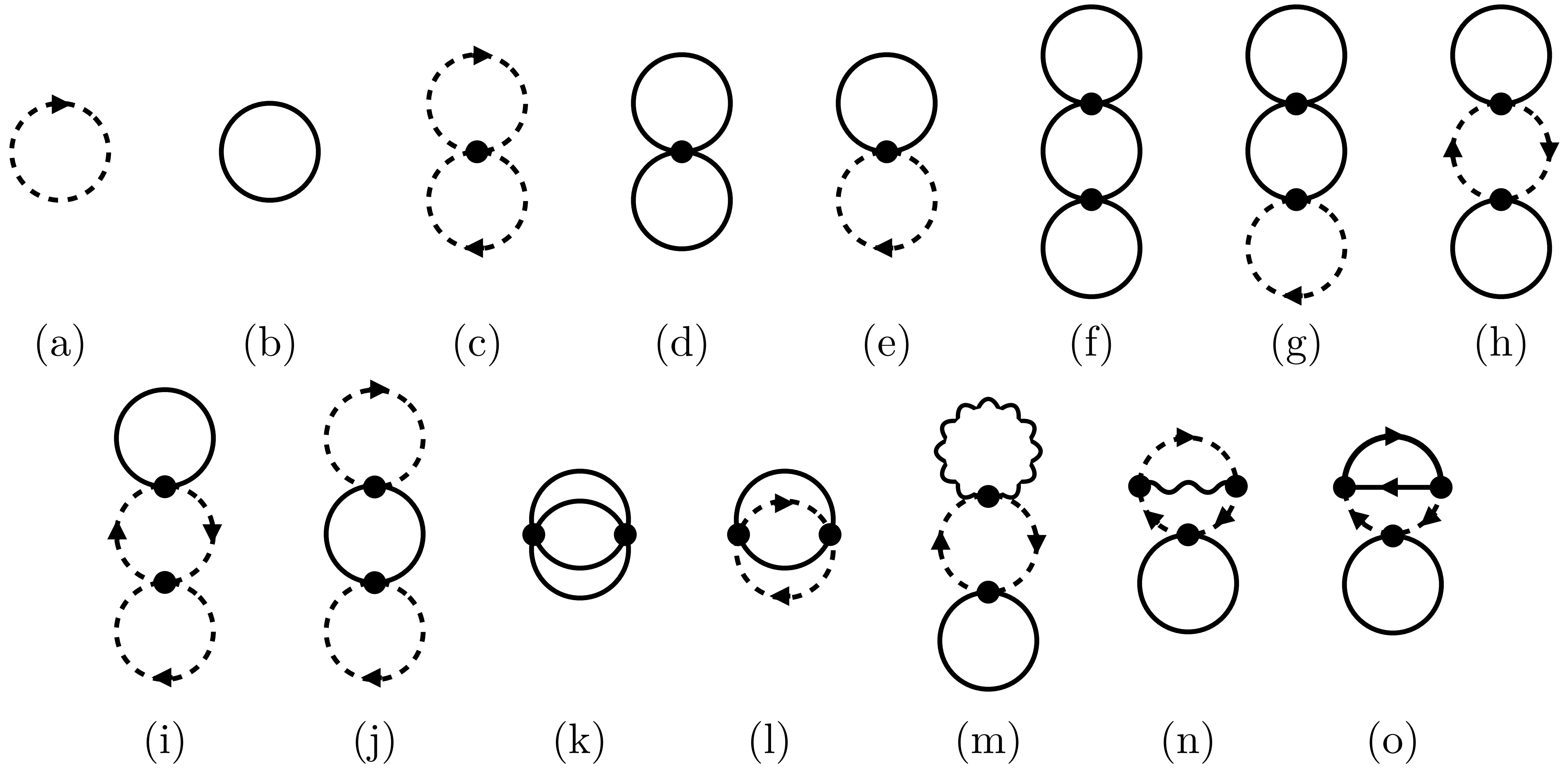


Figure: Tenkanen, JvdV 2022

Determining the thermodynamical quantities T_n, α, β

- Follow from the pressure:
  $p = -V_{\text{eff}}$
- Essential to go beyond standard 'daisy resummation'
  Croon, Gould, Schicho, Tenkanen, White 2020
  Gould, Tenkanen, 2021
  DRalgo: Ekstedt, Schicho, Tenkanen 2022

See talk by Anna Kormu

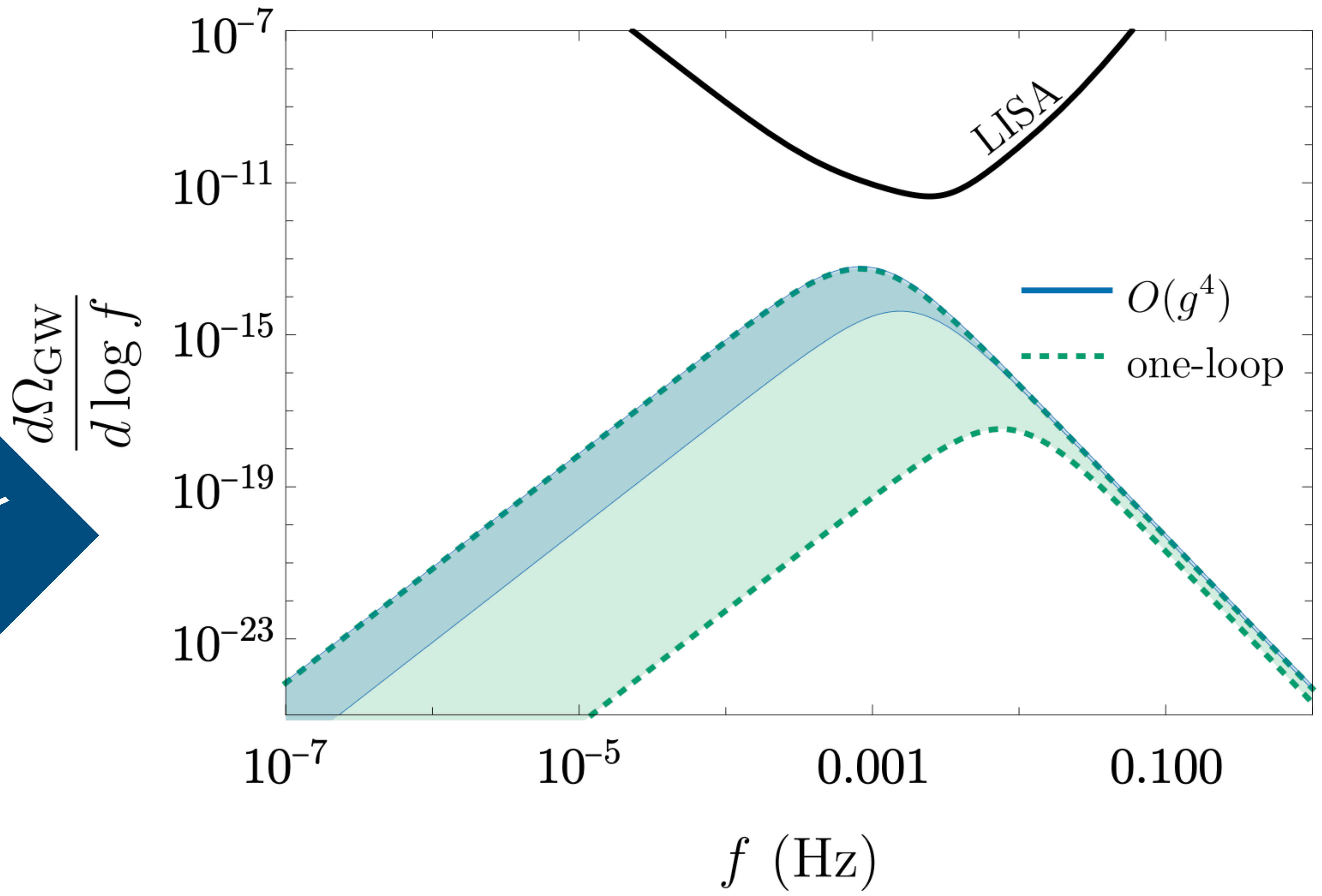
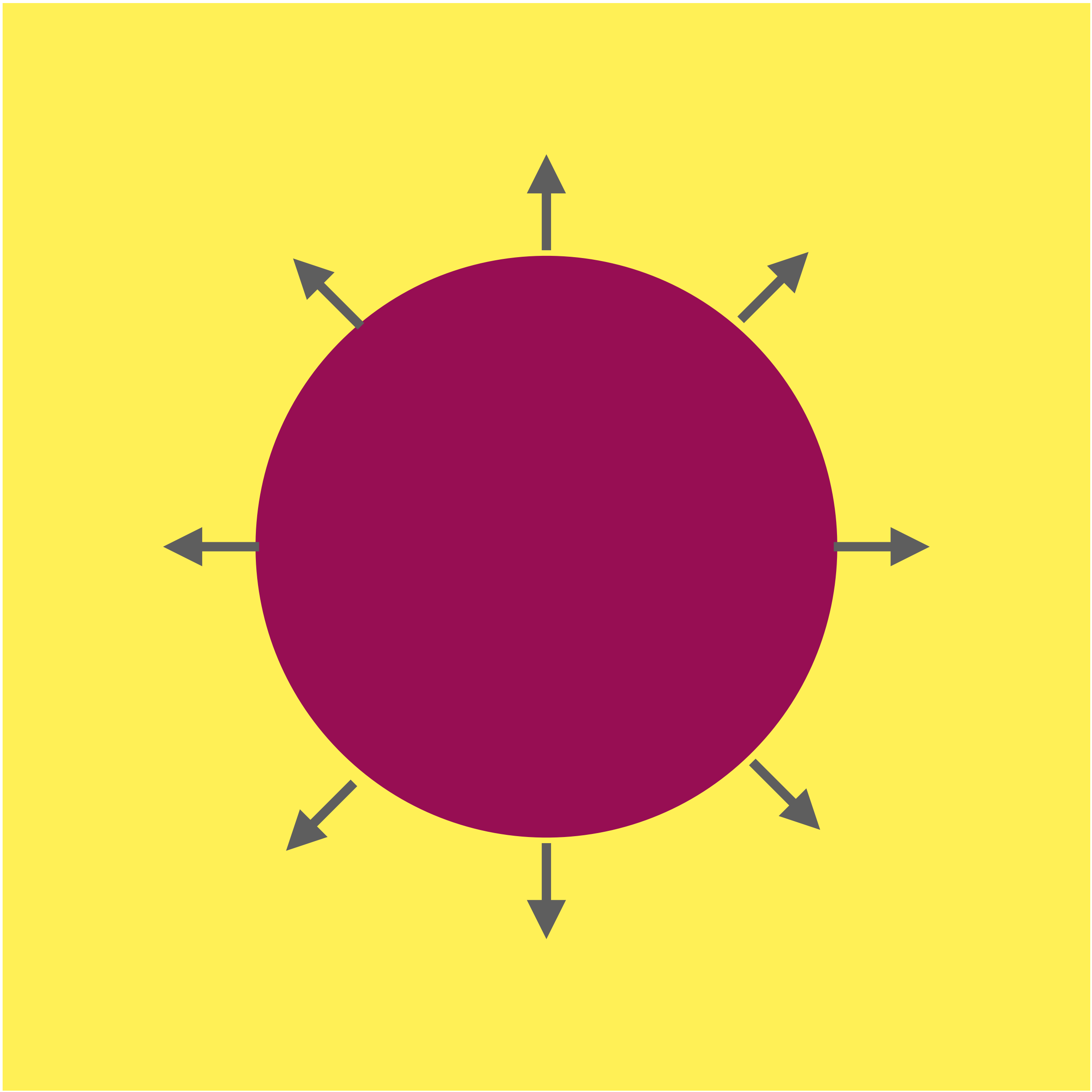


Figure: Gould, Tenkanen 2021

Thermodynamics of a bubble

Bubble is characterised by

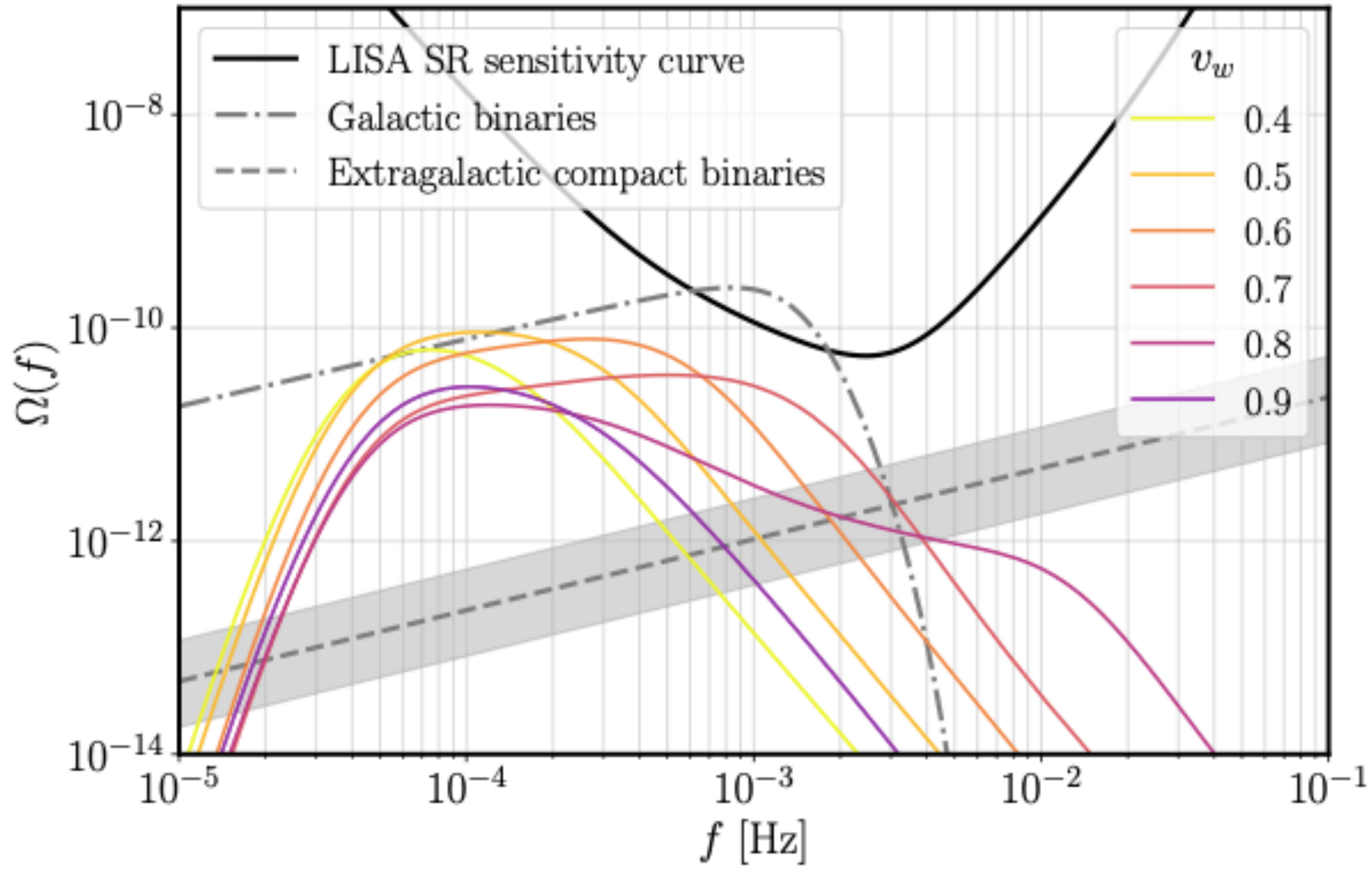
- Nucleation temperature T_n
- Phase transition strength α
- Phase transition rate β
- Expansion velocity v_w



Expansion velocity v_w

- Requires solution of coupled Higgs-plasma EOMs
  Moore, Prokopec 1995, Dorsch, Huber, Konstandin 2021, Laurent, Cline 2022

- In practice, wall velocity is often guessed



(a) Fixed: $\alpha = 0.2, \quad r_* = 0.1, \quad T_n = 100$ GeV.

Figure: Gowling, Hindmarsh 2021

Expansion velocity v_w

- Requires solution of coupled Higgs-plasma EOMs
  Moore, Prokopec 1995, Dorsch, Huber, Konstandin 2021, Laurent, Cline 2022
- Assuming local thermal equilibrium, wall velocity can be determined model-independently
  Ai, Garbrecht, Tamarit 2021
  Ai, Laurent, JvdV 2023
- Local Thermal Equilibrium is reasonable in SM+singlet, and at least an upper bound
  Laurent, Cline 2022

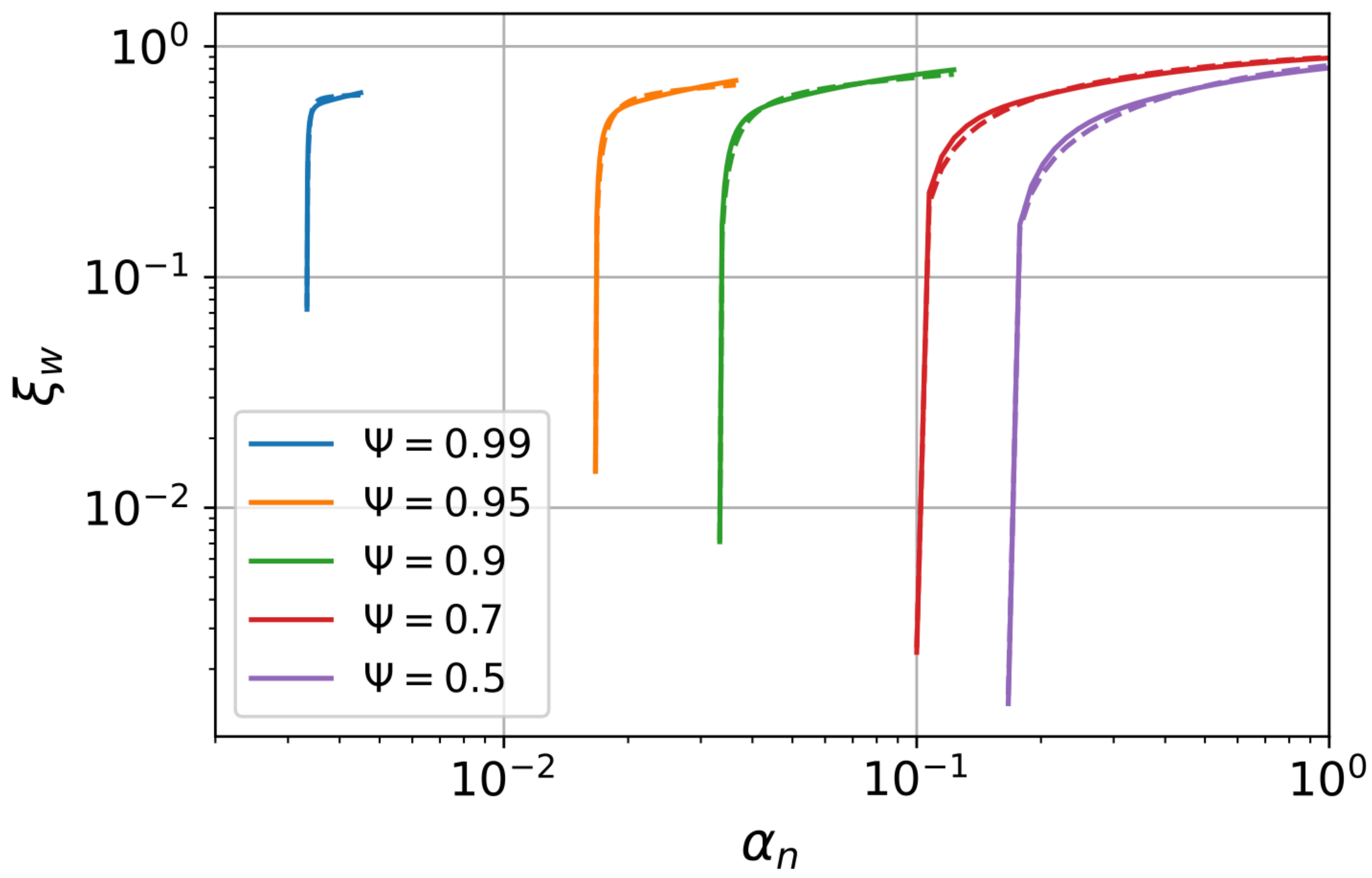
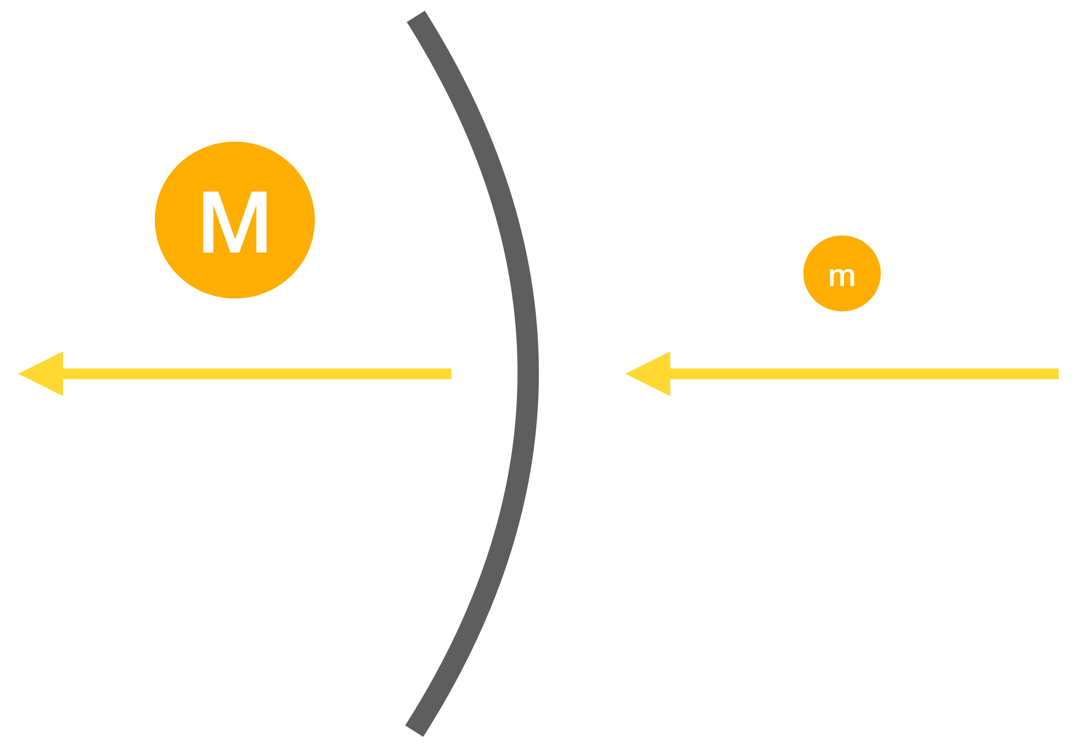


Figure: Ai, Laurent, JvdV 2023

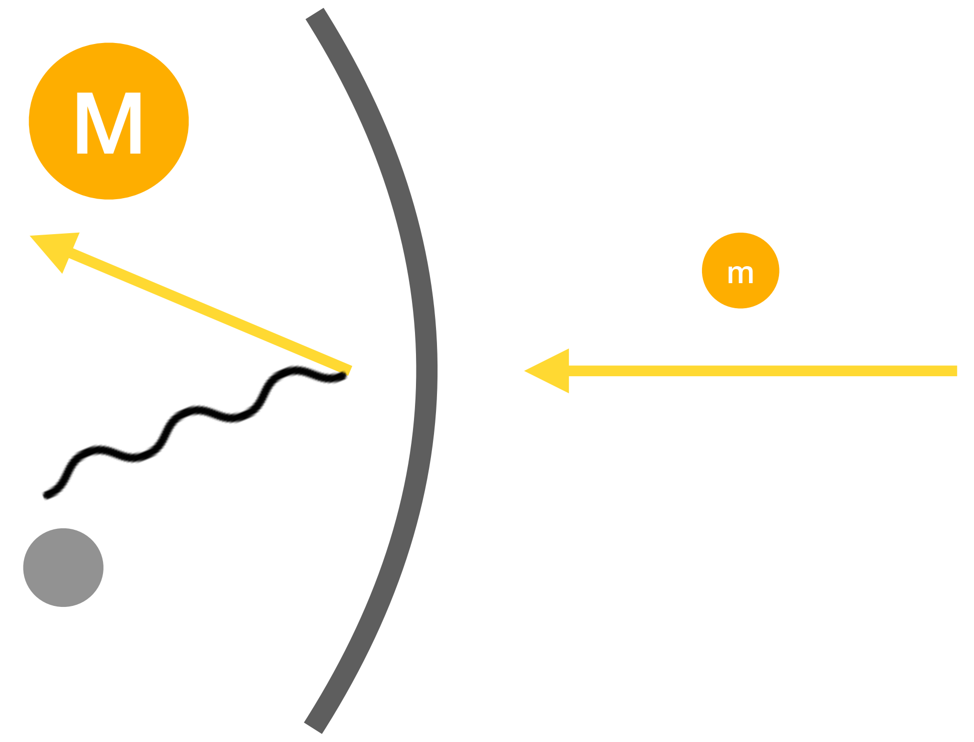
Runaway bubbles?

- If the energy release is large compared to the plasma pressure, bubbles might keep accelerating until they collide Bödeker, Moore 2009



Runaway bubbles?

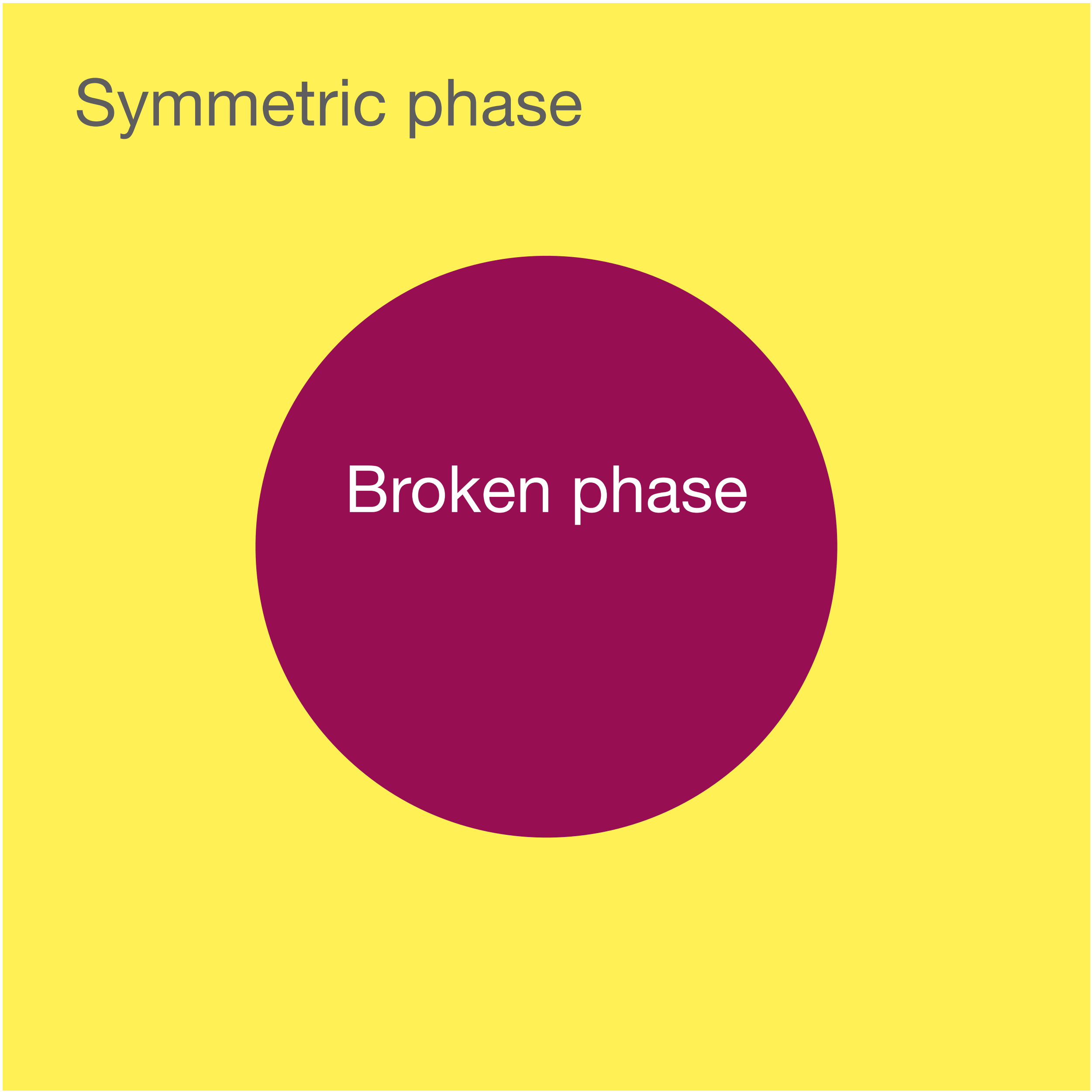
- If the energy release is large compared to the plasma pressure, bubbles might keep accelerating until they collide Bödeker, Moore 2009
- Transition radiation provides additional source of friction
Bödeker, Moore 2017, Höche, Kozaczuk, Long, Turner, Wang 2021, Jinno, Gouttenoire, Sala 2021
- Discrepancies between different results → uncertainty about dominant contribution to the GW signal



Thermodynamics of a bubble

Bubble is characterised by

- Nucleation temperature T_n
- Phase transition strength α
- Phase transition rate β
- Expansion velocity v_w
- Number of degrees of freedom in the plasma, adiabatic index, speed of sound…



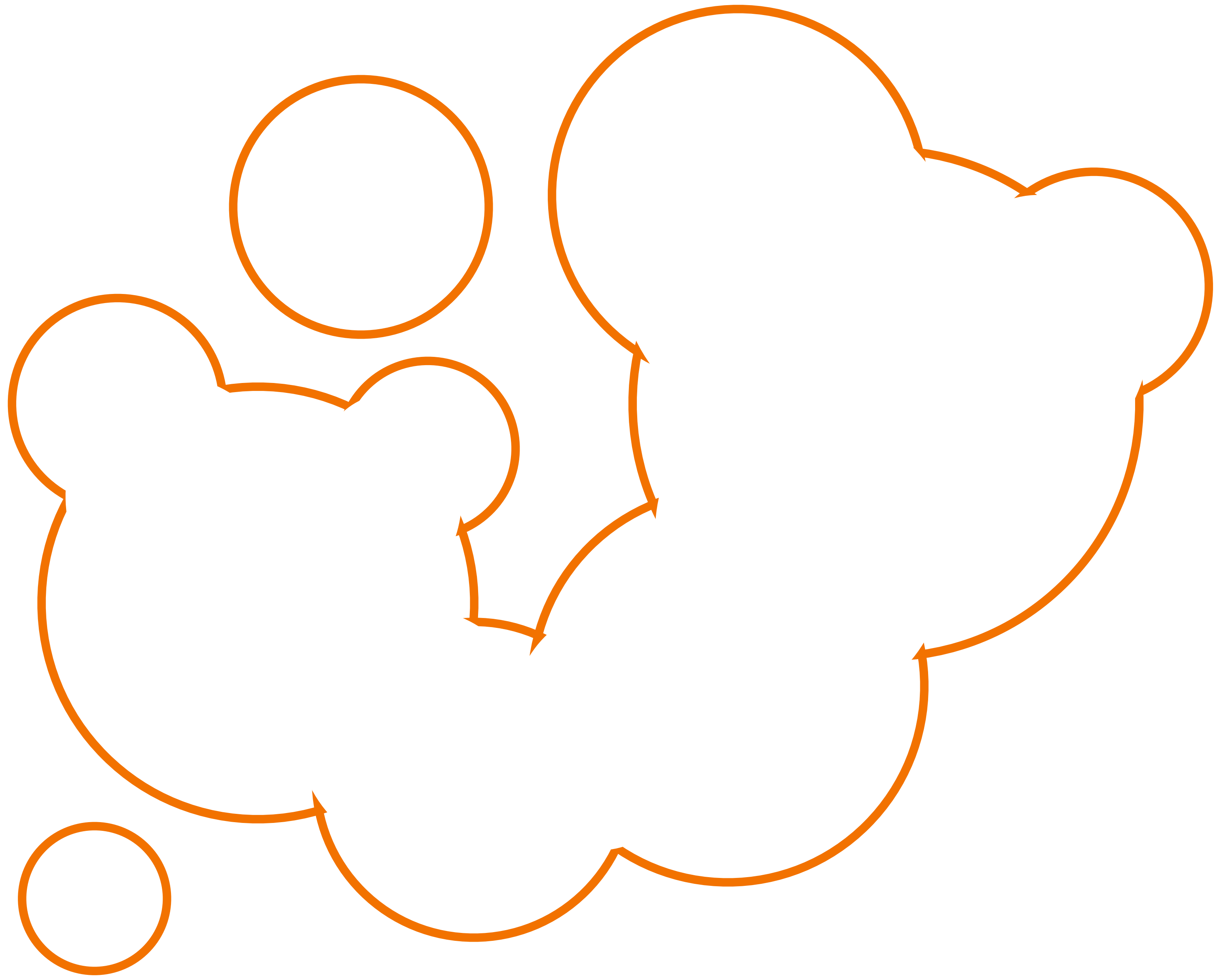
Gravitational wave signal from colliding bubbles

Contributions to the GW signal

- Gradient energy in the scalar field

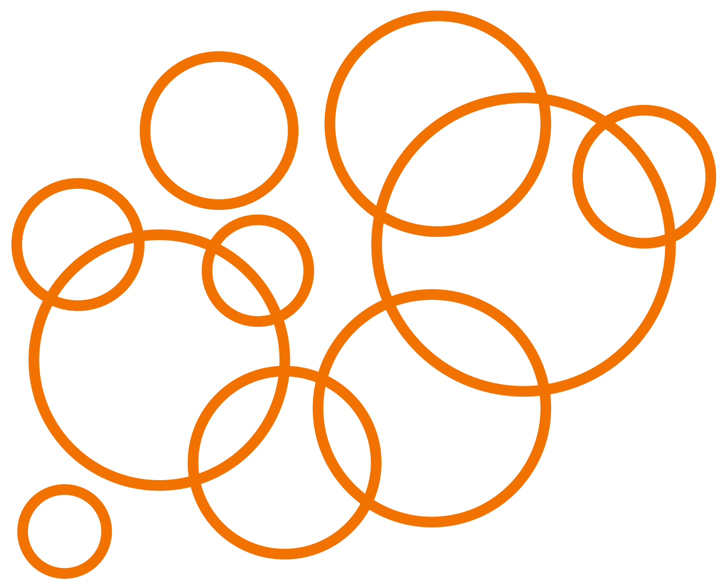
Gradient energy in the scalar field

- Dominant for ultra-relativistic walls
- Envelope approximation: thin walls, and only uncollided regions contribute
  Kosowsky, Turner, Watkins 1992, Kowowsky, Turner 1993



Gradient energy in the scalar field

- Dominant for ultra-relativistic walls
- Envelope approximation: thin walls, and only uncollided regions contribute
  Kosowsky, Turner, Watkins 1992, Kowowsky, Turner 1993
- Collided regions also contribute significantly Weir 2016, Cutting, Hindmarsh, Weir 2018, Jinno, Konstandin, Takimoto 2019 , Cutting, Escartin, Hindmarsh, Weir 2020
- Semi-analytic estimates Jinno, Takimoto 2017, Konstandin 2017
- Two-bubble simulations Lewicki, Vaskonen 2019 & 2020



Classically scale-invariant models

- Extensions of the Standard Model without tree-level mass term
- Significant supercooling $T_n \ll T_c \rightarrow \alpha \gg 1$

Gravitational waves from classically conformal SU(2)

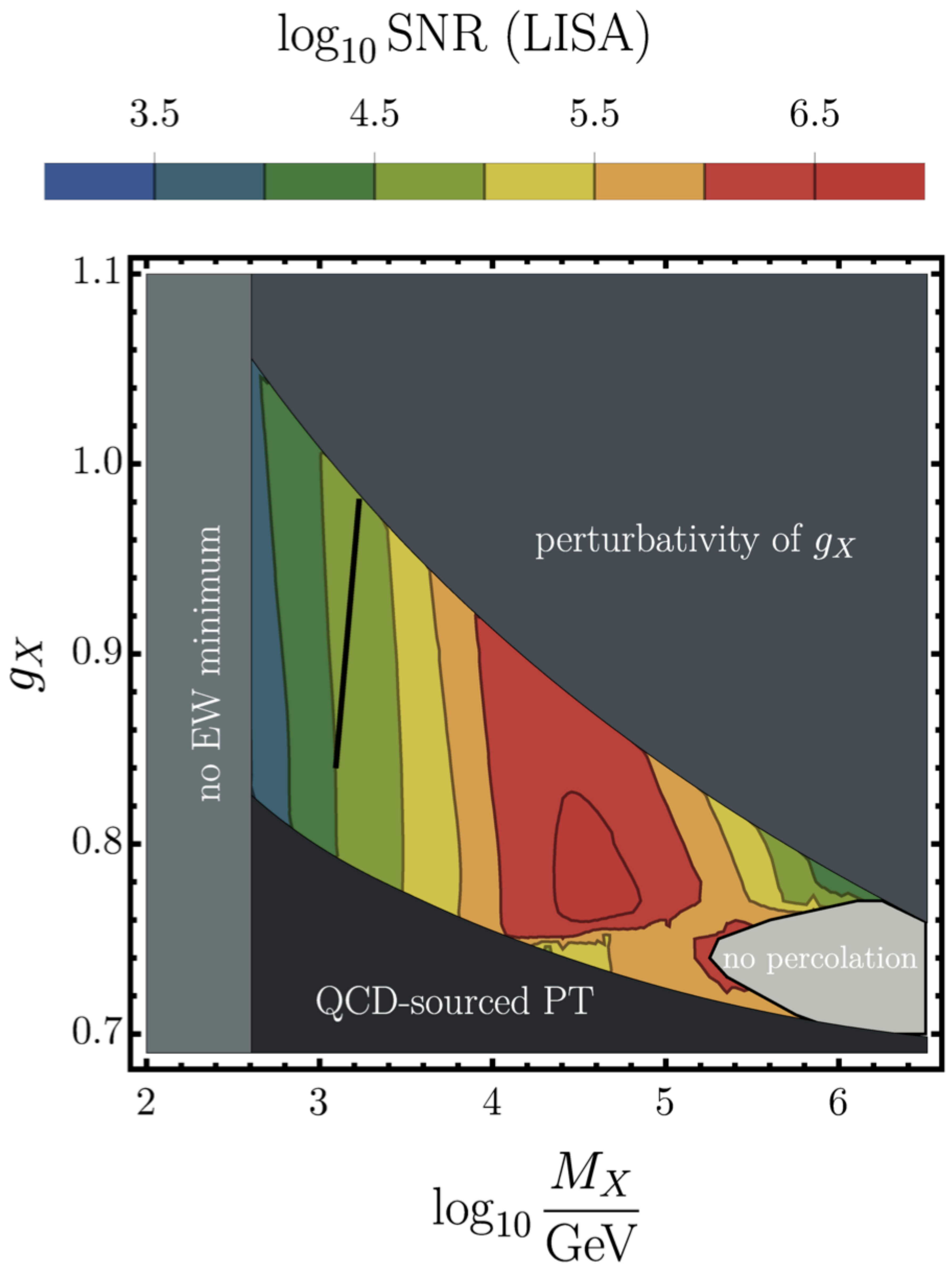


Figure: Kierkla, Karam, Swiezewska 2022

Contributions to the GW signal

- Gradient energy in the scalar field
- Sound waves

Sound waves

- Dominant source for $\alpha \lesssim 1$, e.g. scalar extensions of the SM

Scalar extensions of the Standard Model

- Standard Model + gauge singlet, 2HDM, real triplet extension…
- Phase transition can be radiatively generated or two-step

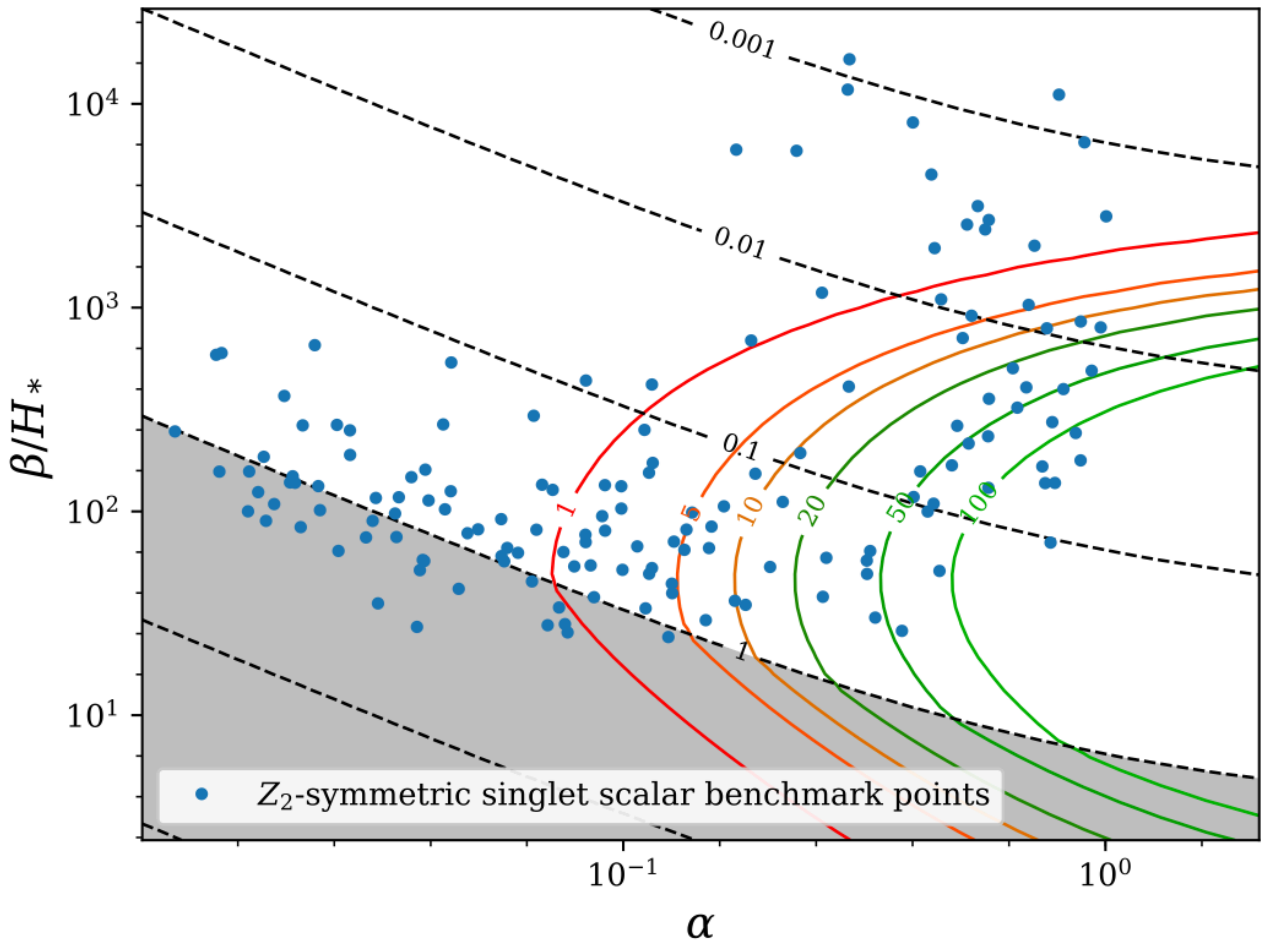
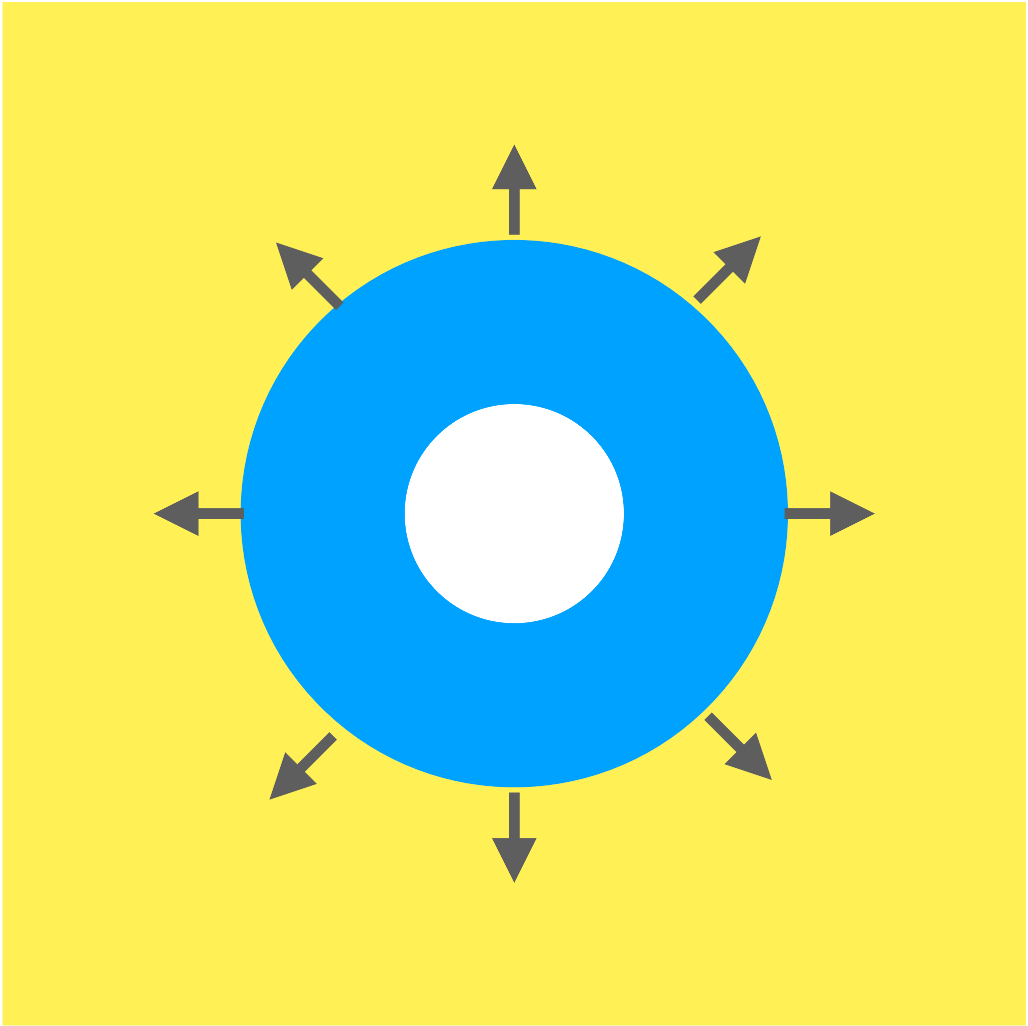


Figure: LiSA Cosmology WG 2019

Sound waves

- Dominant source for $\alpha \lesssim 1$, e.g. scalar extensions of the SM
- Interactions between the scalar field and plasma generate sound waves
- Sound waves persist after collisions, and effectively source GWs
  Hindmarsh, Huber, Rummukainen, Weir 2013



Hydrodynamic simulations

Scalar field + plasma system

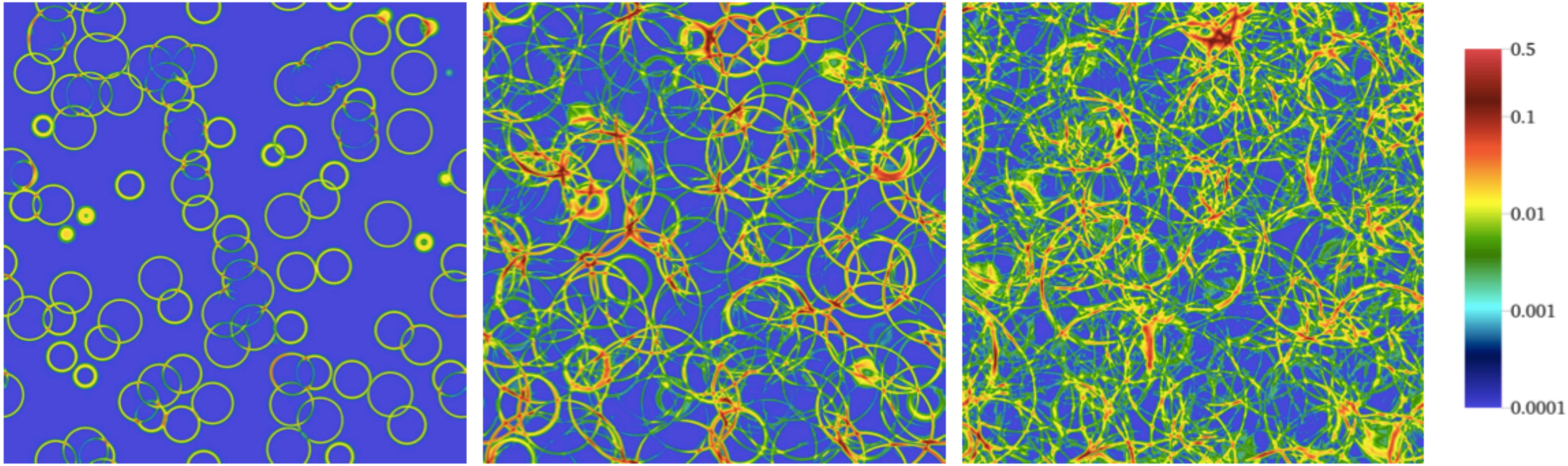


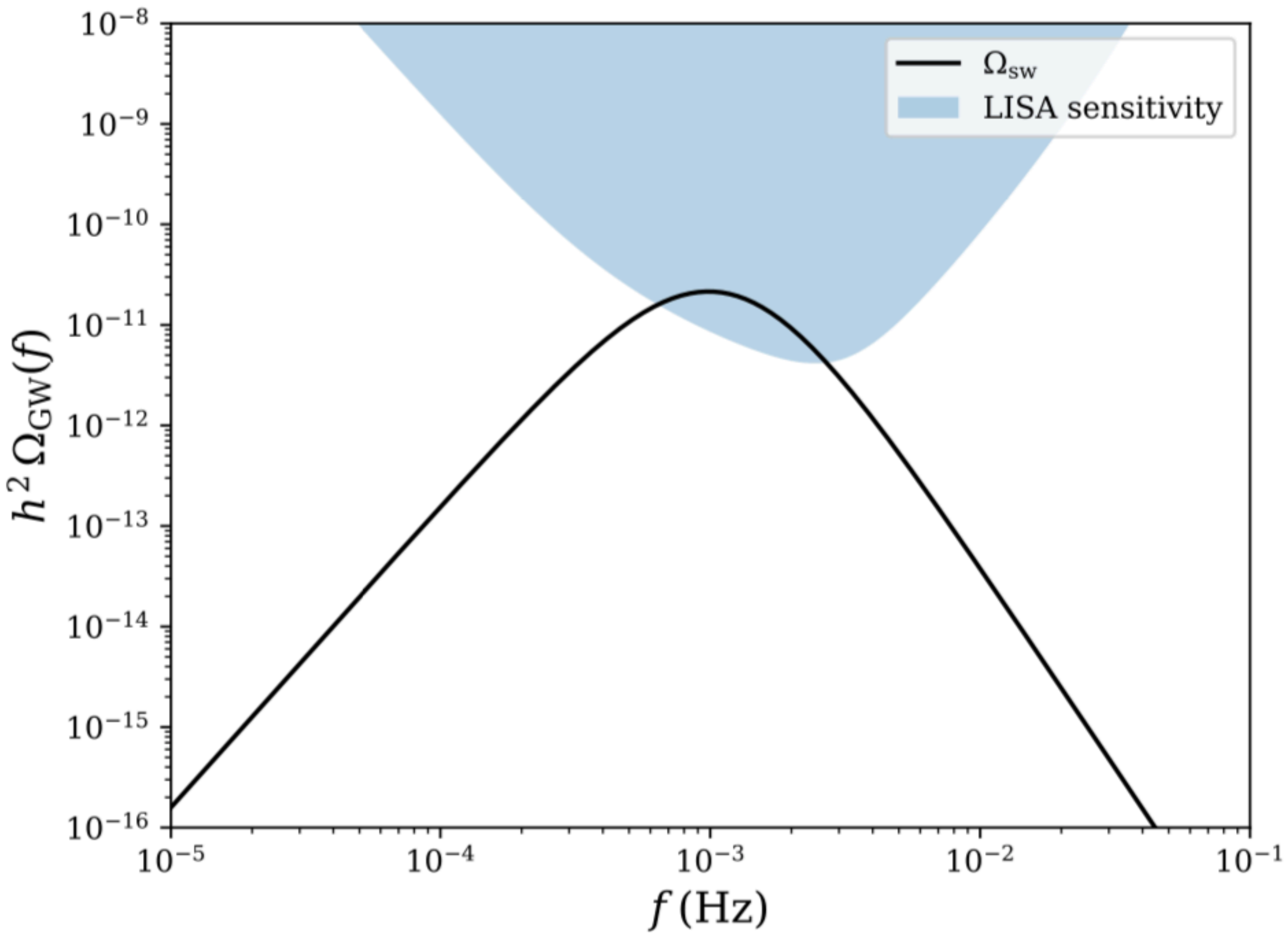
FIG. 4. Slices of fluid kinetic energy density E/T_c^4 at $t = 500\,T_c^{-1}$, $t = 1000\,T_c^{-1}$ and $t = 1500\,T_c^{-1}$ respectively, for the $\eta/T_c = 0.15$, $N_b = 988$ simulation.

Figure: Hindmarsh, Huber, Rummukainen, Weir 2015

Fit of the signal

LISA cosmo-wg, 2019 (based on Hindmarsh, Huber, Rummukainen, Weir 2015 & 2017)

- $$\frac{d\Omega_{\rm gw}}{d\ln(f)} = 0.687 F_{\rm gw,0} K^2 H_* R_* / c_s \tilde{\Omega}_{\rm gw} C\left(f/f_{p,0}\right)$$

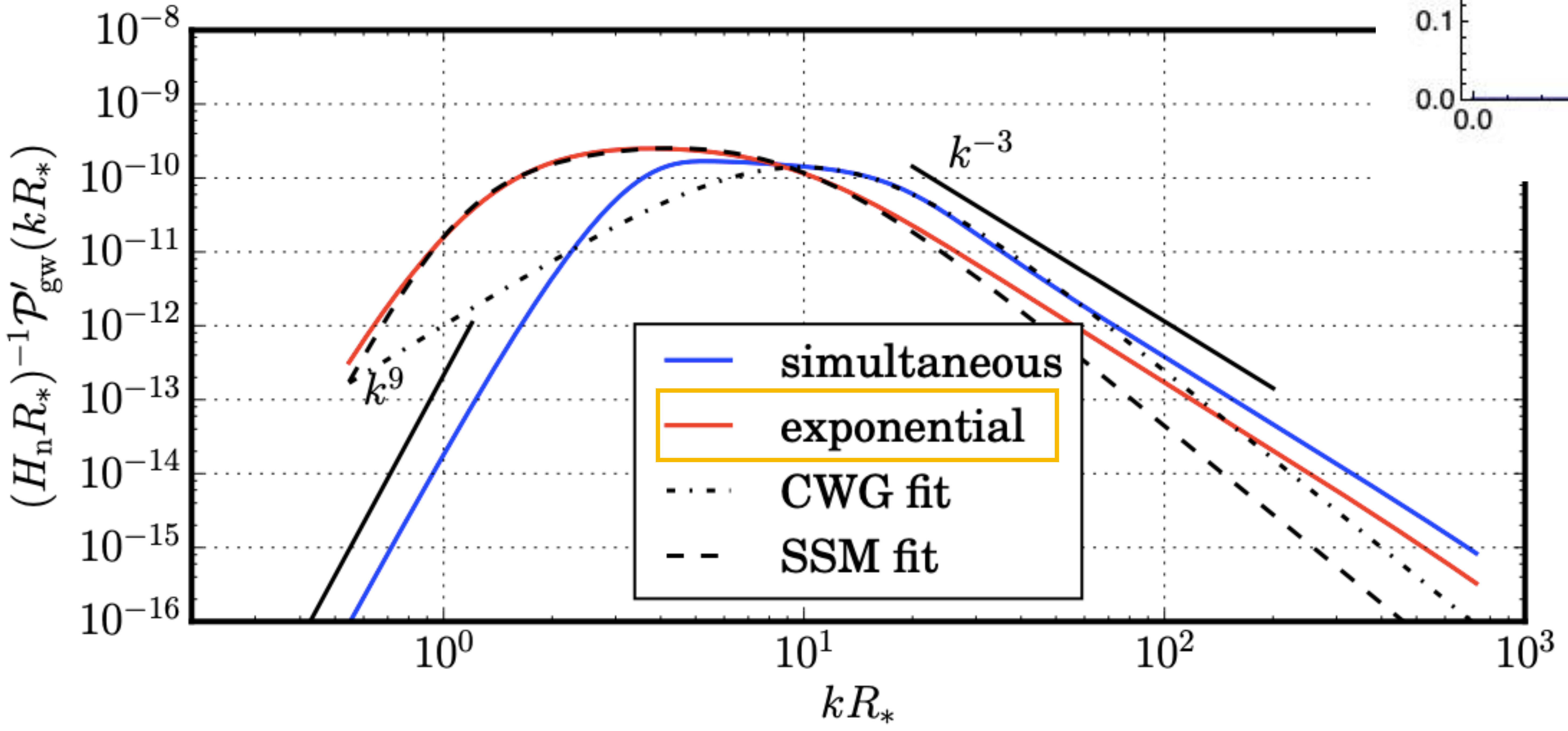


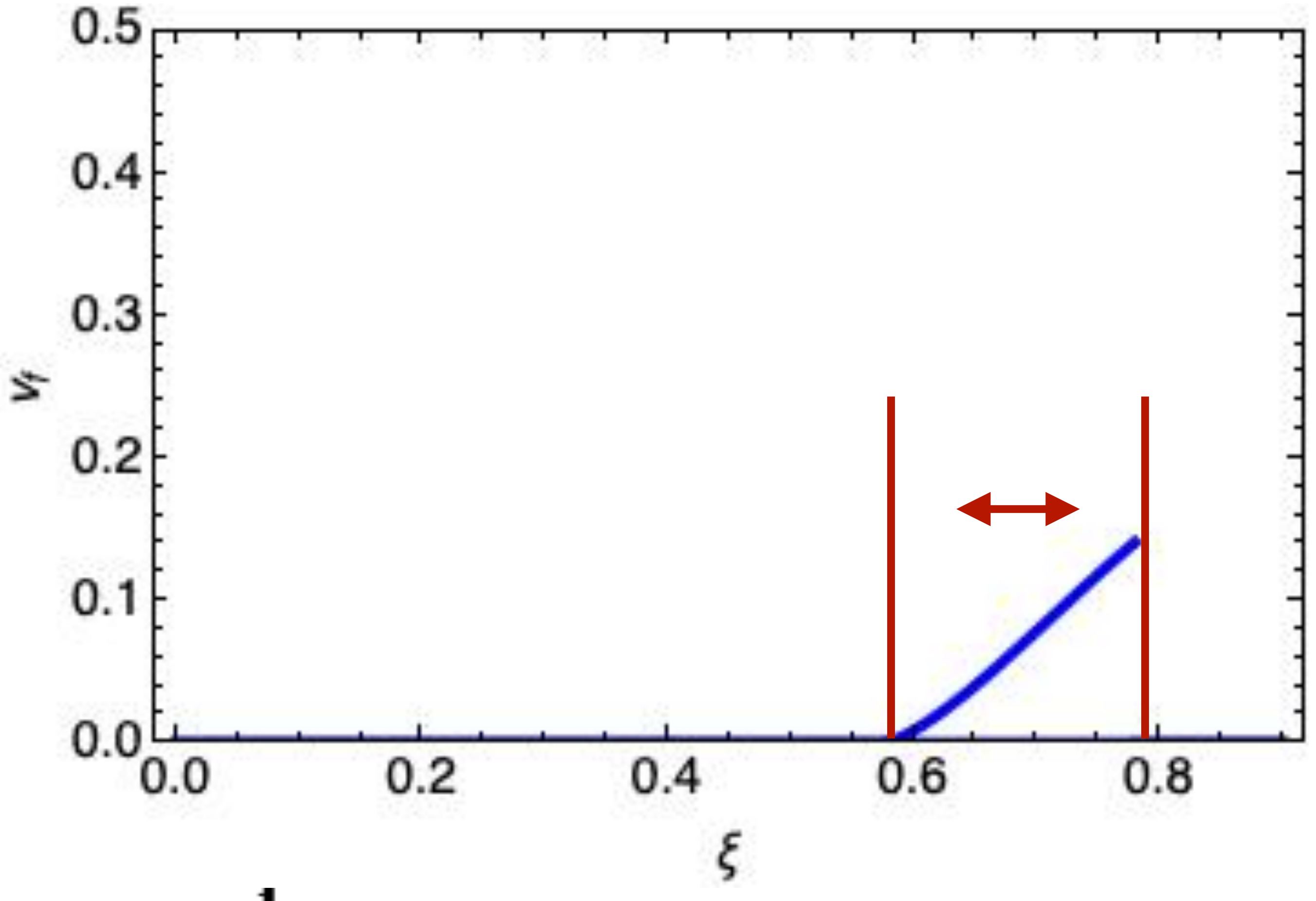
Limitation: finite lattice size

Can not capture all relevant length scales

~Gravitational wave spectrum in sound shell model

proportional to $h^2\Omega_{\rm gw}$ →





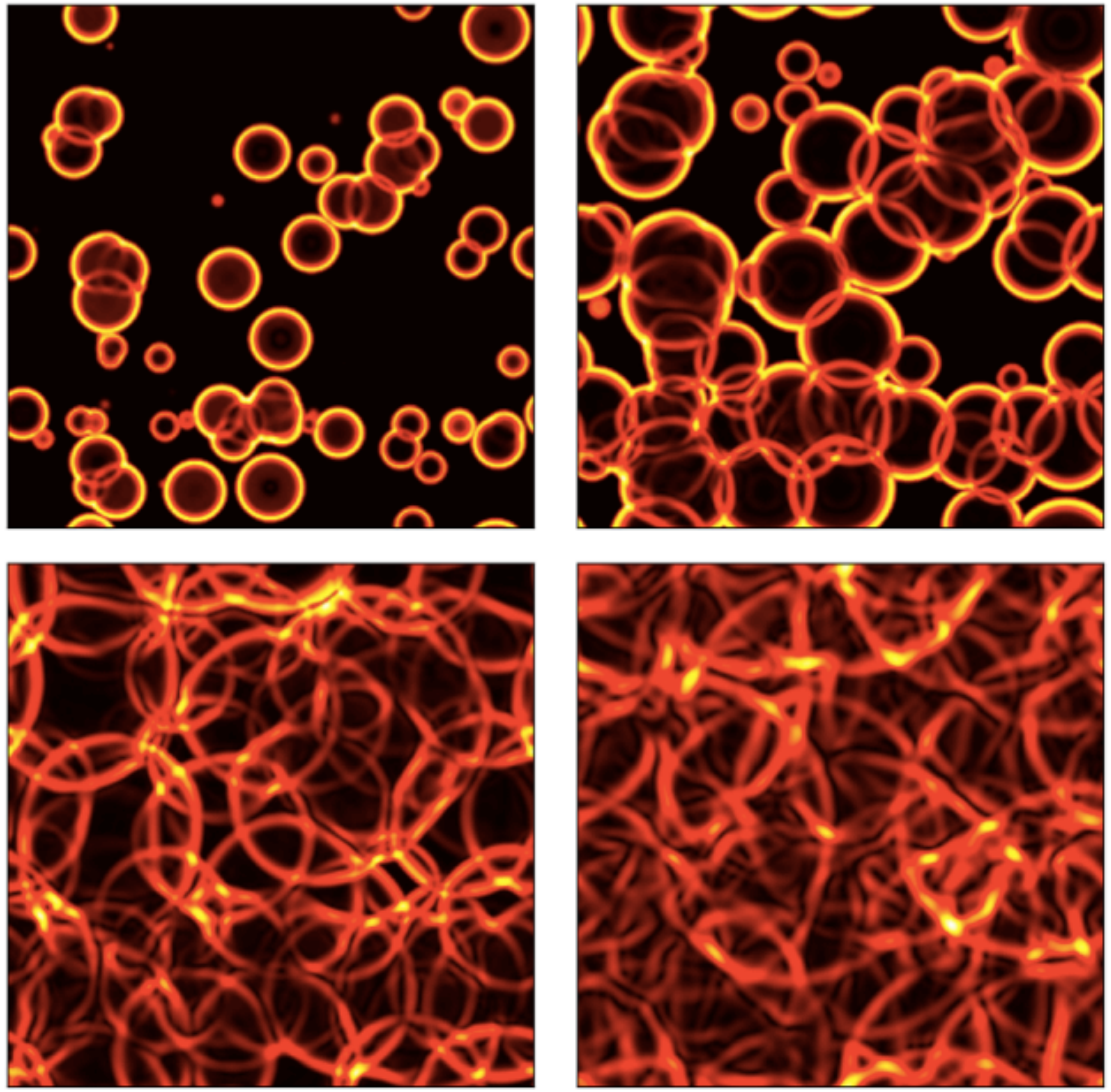
↑

proportional to f

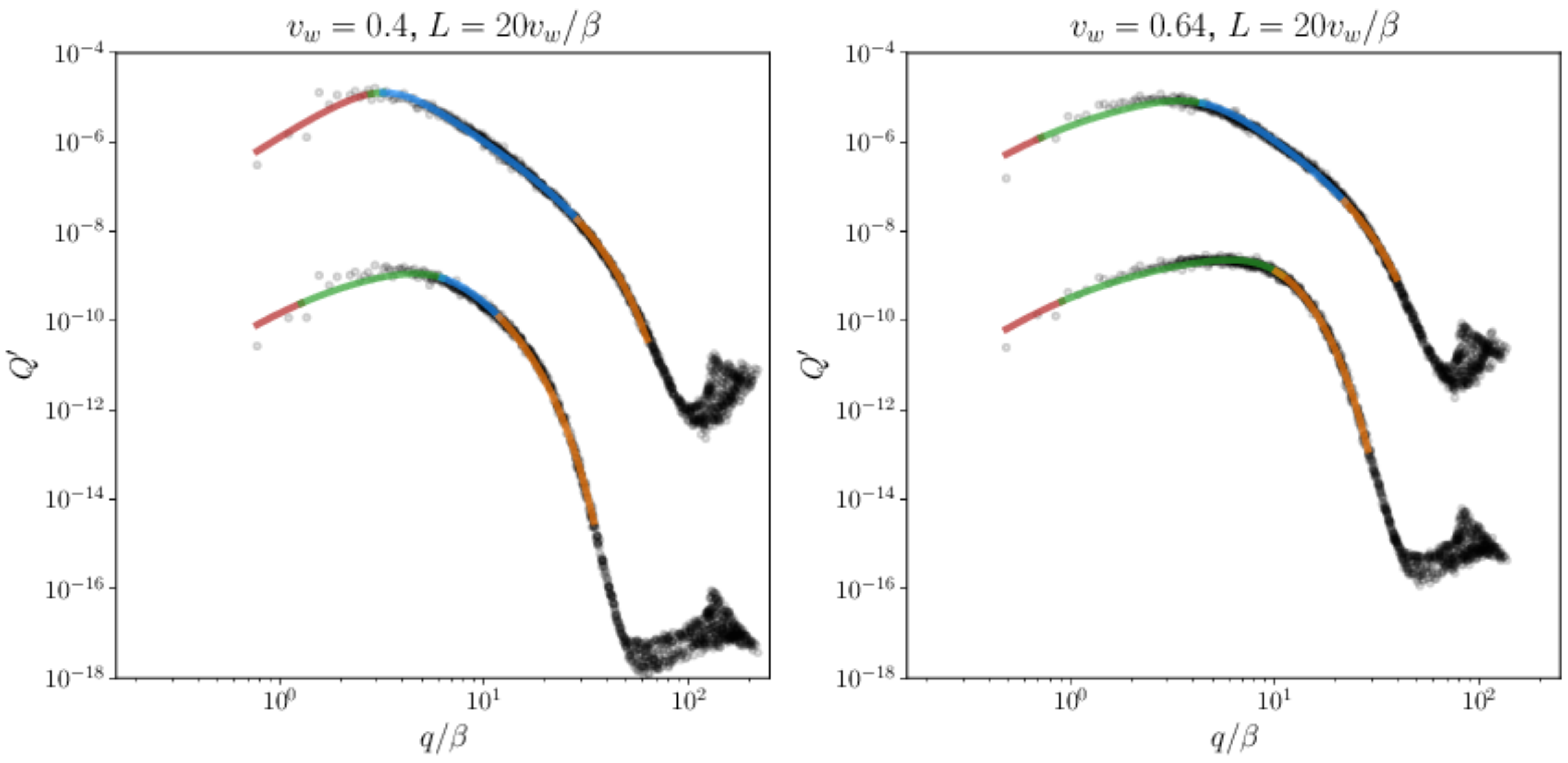
Figure: Hindmarsh, Hijazi 2019

Higgsless simulations

Simulation of the plasma only



~Gravitational wave spectrum



Figures: Jinno, Konstandin, Rubira, Stomberg 2022

Challenges

- No simulations for $\alpha \gtrsim 1$?
- Turbulence cuts off the signal - but moment of onset unknown

Contributions to the GW signal

- Gradient energy in the scalar field
- Sound waves
- Turbulence (vortical, acoustic, MHD)

Turbulence

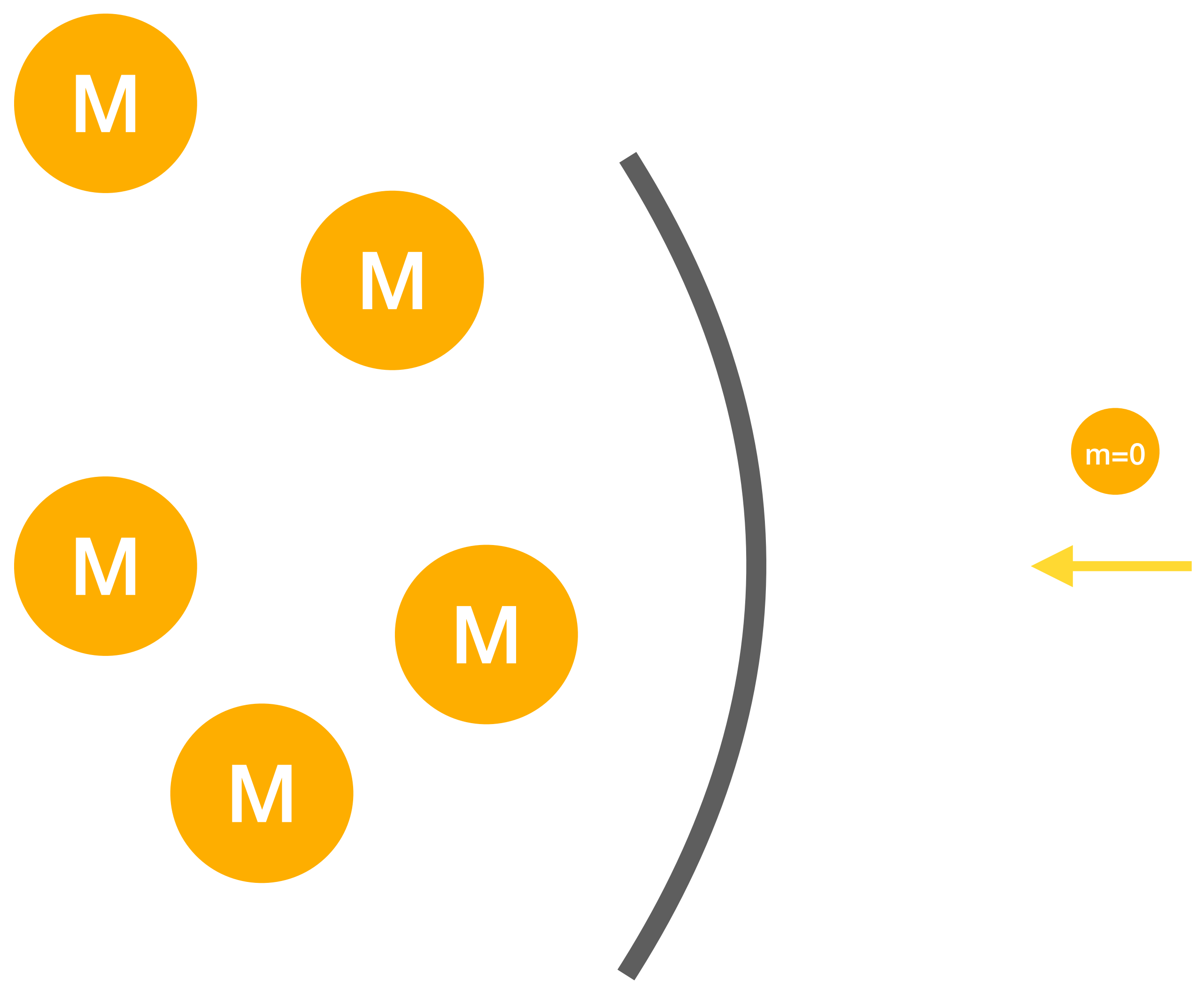
- Shock formation after a time $\tau_{\text{sh}} = R_* / \bar{v}_{\|}$
- More significant contribution for stronger phase transitions
- Onset of turbulence has not yet been simulated

Contributions to the GW signal

- Gradient energy in the scalar field
- Sound waves
- Turbulence (vortical, acoustic, MHD)
- Feebly interacting particles

Feebly interacting particles

- Relevant for phase transitions in dark sectors
- Particles obtain a mass by entering the bubble, but interact too feebly to generate a sound wave source



Feebly interacting particles

- Relevant for phase transitions in dark sectors
- Particles obtain a mass by entering the bubble, but interact too feebly to generate a sound wave source
- Possibly observable GW spectrum

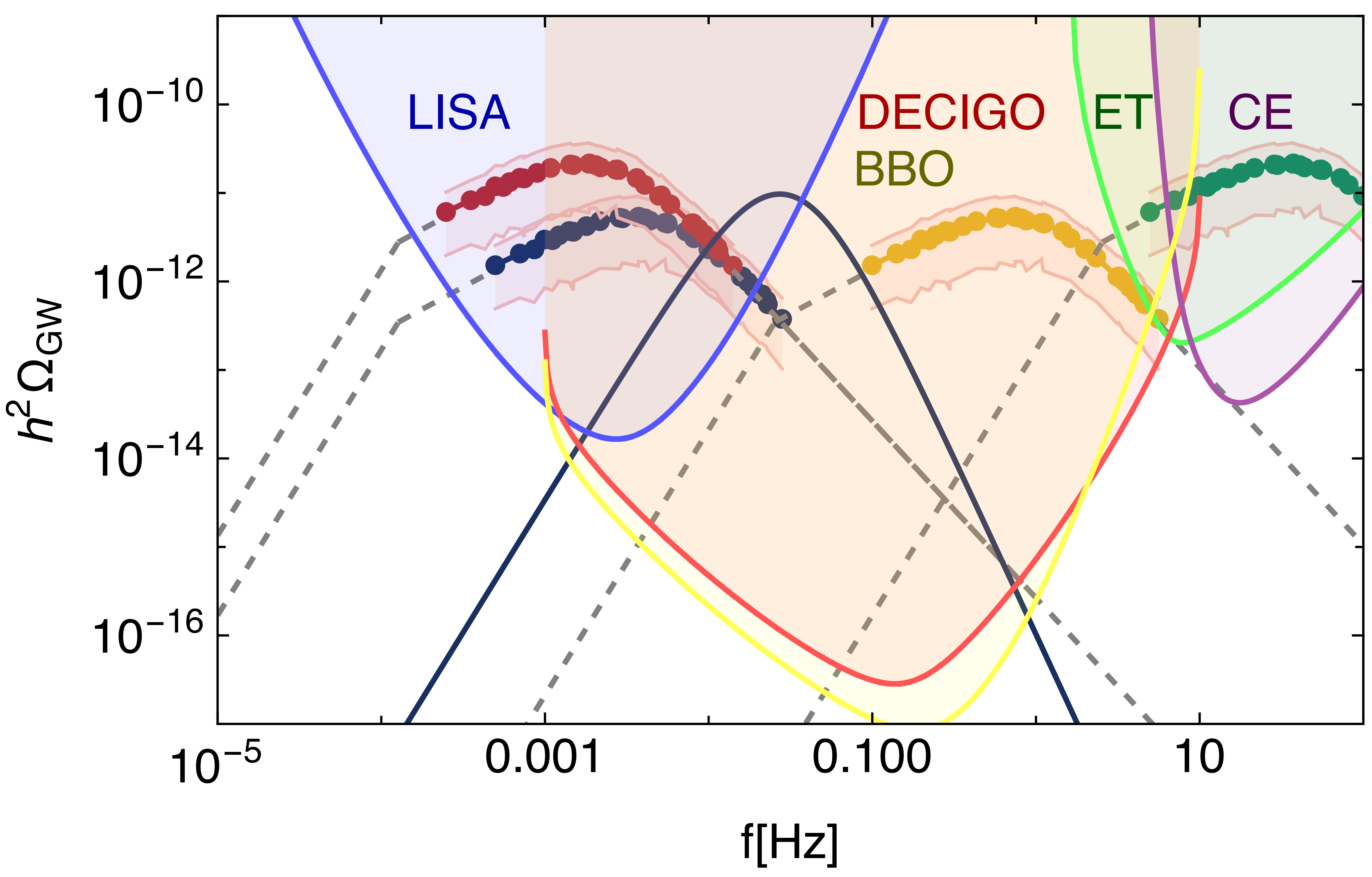
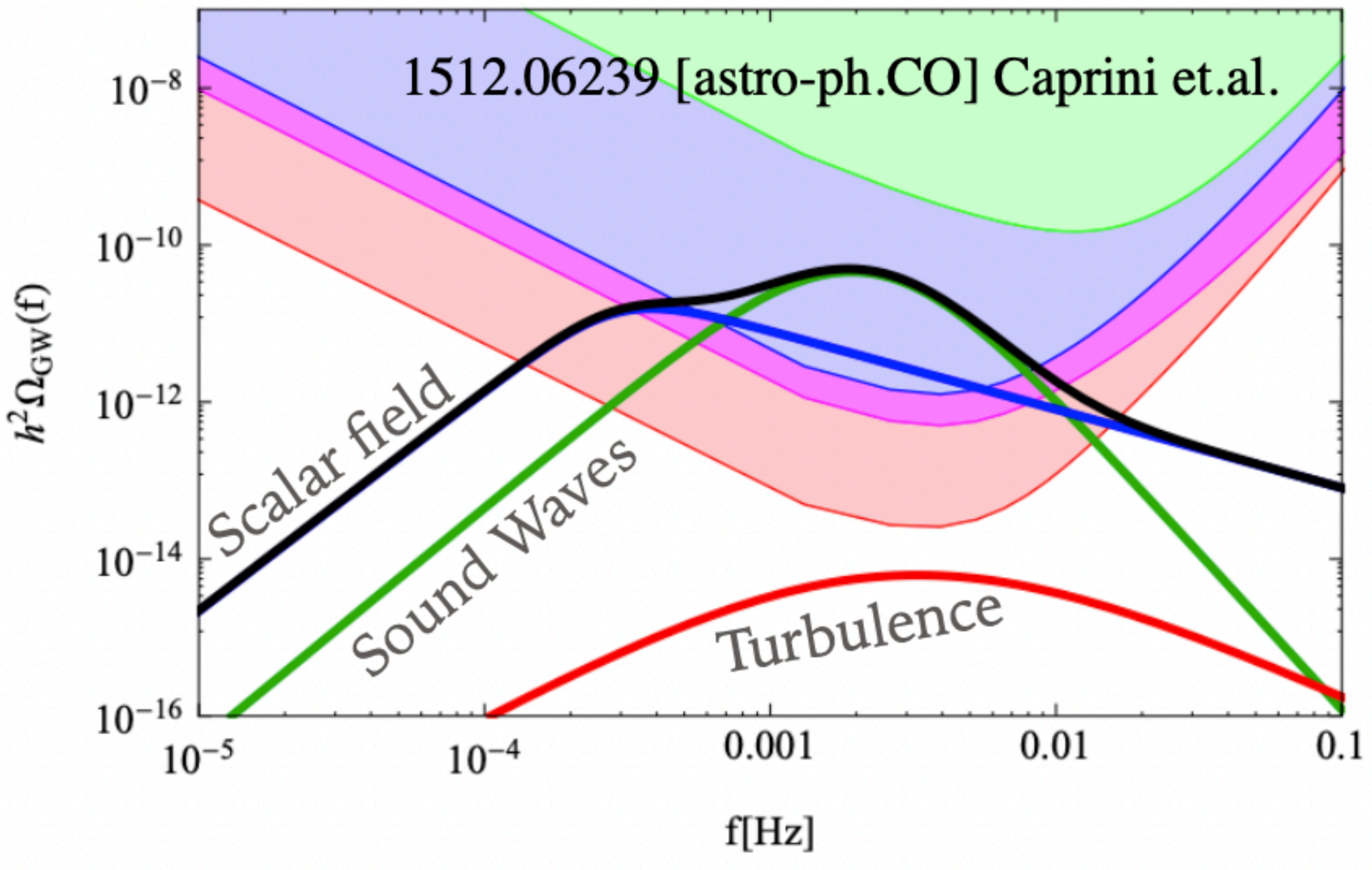


Figure: Jinno, Shakya, JvdV 2022

Conclusion

- Gravitational waves from cosmological phase transitions can teach us about new particle physics
- Particle physics gets captured by thermodynamic parameters $\alpha, \beta, T_n, v_w, \cdots$
- Spectrum is a sum of all four contributions



Challenges

- Improving the accuracy of the thermodynamics and wall velocity
- Improve and expand the simulations (large α, different equations of state)
- Obtain a better understanding of turbulence
- …