

From microphysics to Gravitational Waves for cosmological phase transitions

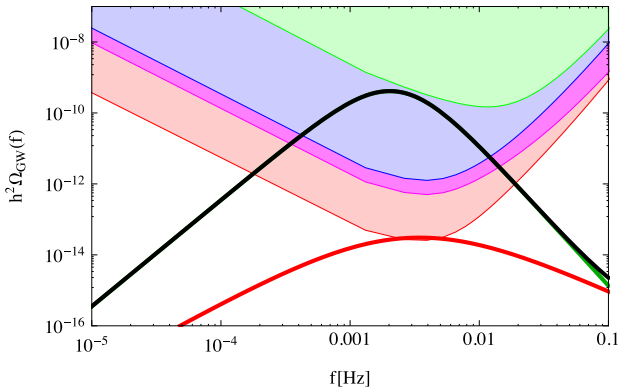
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Département de Physique Théorique, Université de Genève

Theory seminar
University of Oslo, 04/2026

10 years since ...

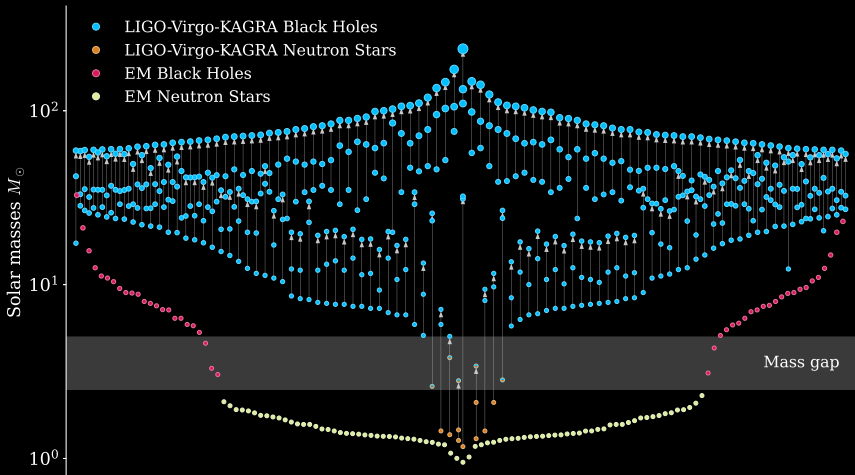
predictions for gravitational waves from cosmological phase transitions
in LISA Cosmology Working Group.¹



¹ $\alpha = 0.5$, $\beta/H_\star = 100$, $T_\star = 100$ GeV, $v_w = 0.95$; Caprini, Hindmarsh, Huber *et al.*, *Science with the space-based interferometer eLISA. II: Gravitational waves from cosmological phase transitions*, JCAP **04** (2016) 001 [1512.06239]

Observing the universe with gravitational waves

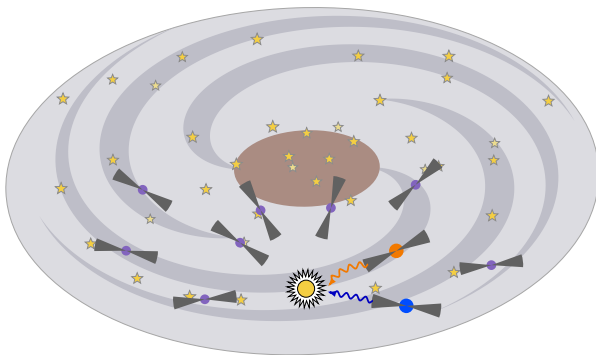
LIGO-Virgo-KAGRA observed $\mathcal{O}(10)M_{\odot}$ black holes and neutron stars



Observing the universe with gravitational waves

Pulsar timing arrays.² New physics: many models can fit the data.

Bayesian model comparison: **Supermassive black holes** or **new physics**?

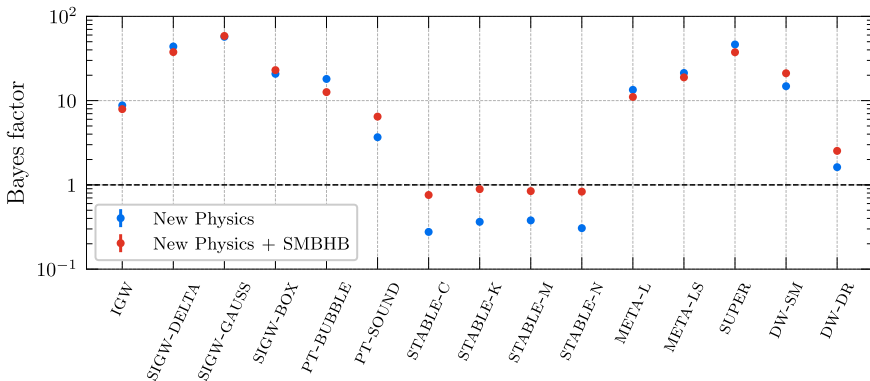


² **NANOGrav** Collaboration, Afzal et al., *The NANOGrav 15-year Data Set: Search for Signals from New Physics*, [2306.16219]

Observing the universe with gravitational waves

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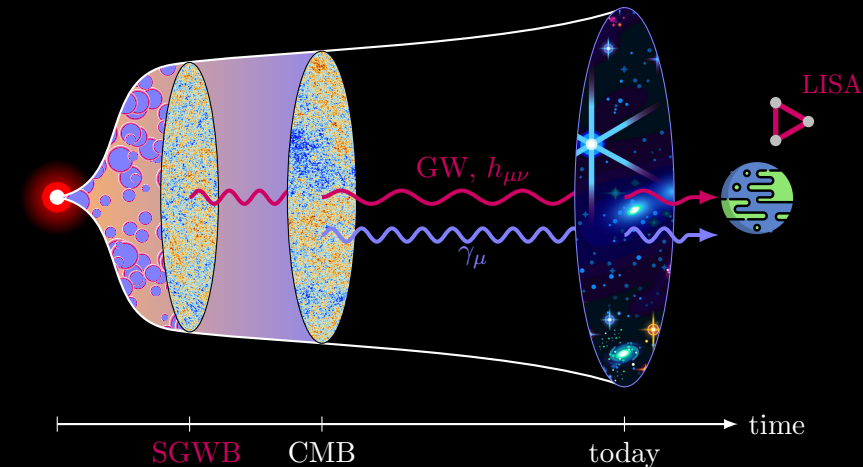
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Gravitational Waves (GWs) can be

sourced by early-universe phase transitions caused by new physics.

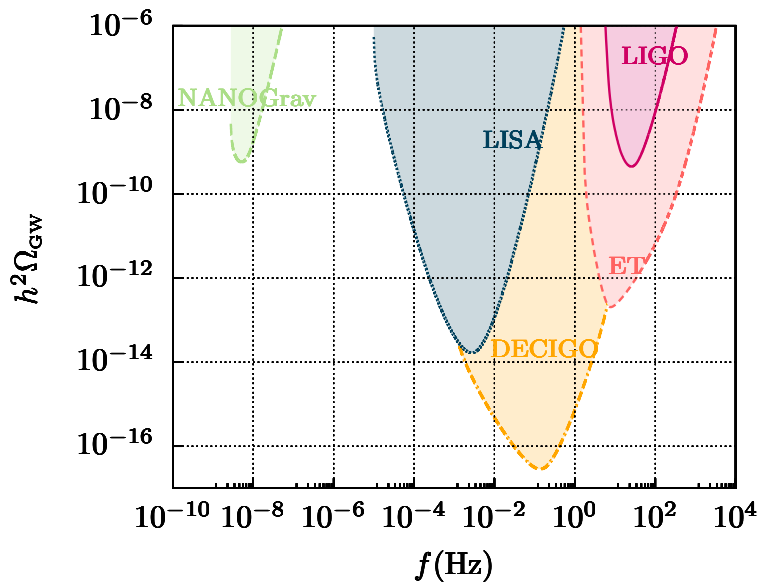


Cosmic Microwave Background (CMB)

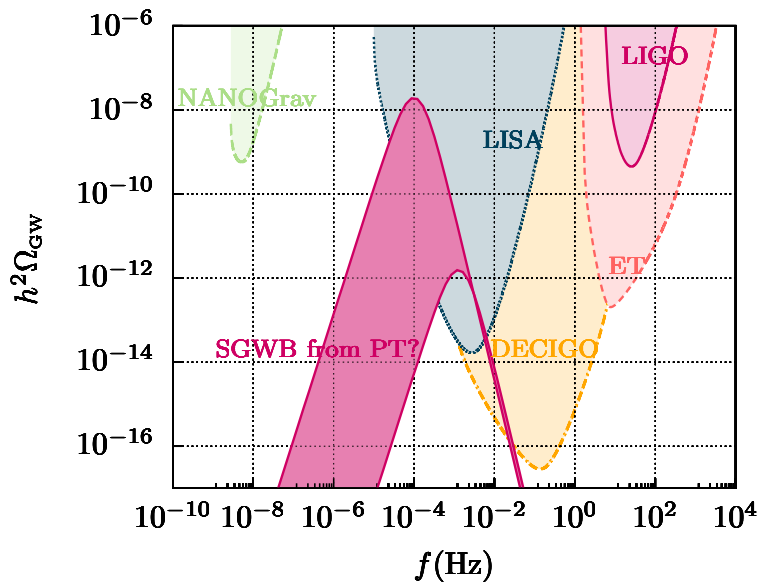
Stochastic GW Background (SGWB)

Laser Interferometer Space Antenna (LISA)

Some planned and ongoing experiments



Some planned and ongoing experiments



Lessons from the early universe

Does the universe contain a **network of cosmic strings**, remnant of breaking of a discrete symmetry?³

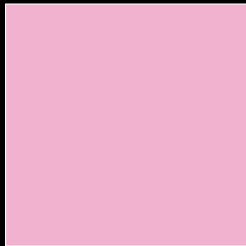
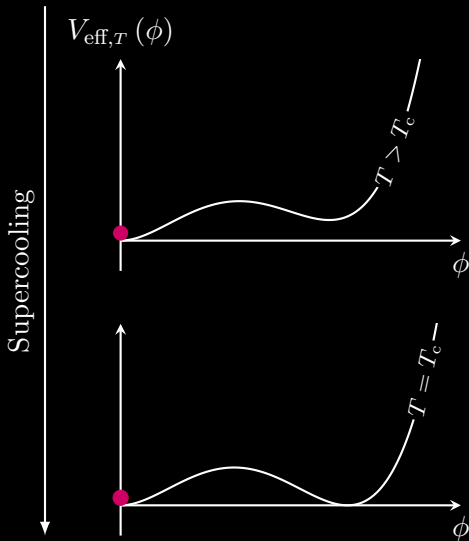
Did the early universe undergo a **first-order phase transition**?

If the **matter-antimatter asymmetry** was sourced in electroweak baryogenesis, can we observe traces of the generation in GWs?

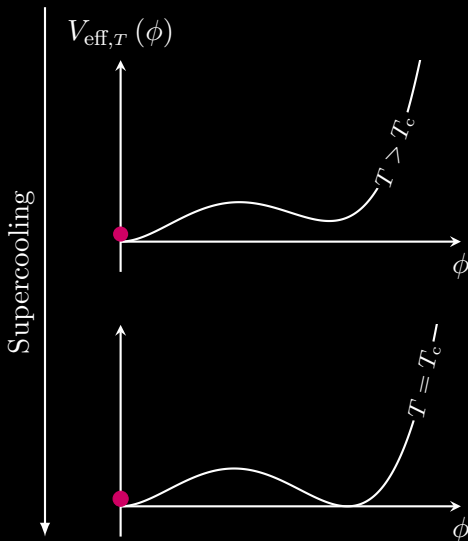
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Cosmological phase transitions

Cosmological first order phase transition

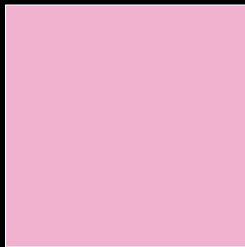


Cosmological first order phase transition

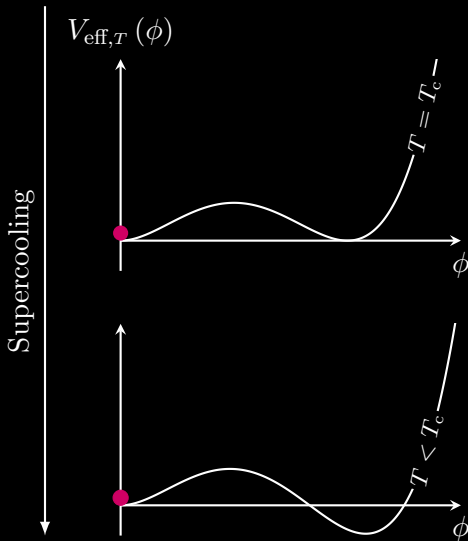


UV [thermal] corrections modify the zero- T potential and restore symmetry.

$$V_{\text{eff},T} \supset \text{[Feynman diagrams: tadpole, bubble, sunset, and higher-order terms]} \dots$$

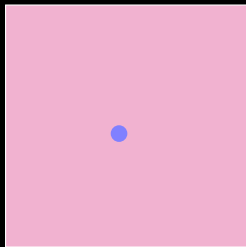


Cosmological first order phase transition

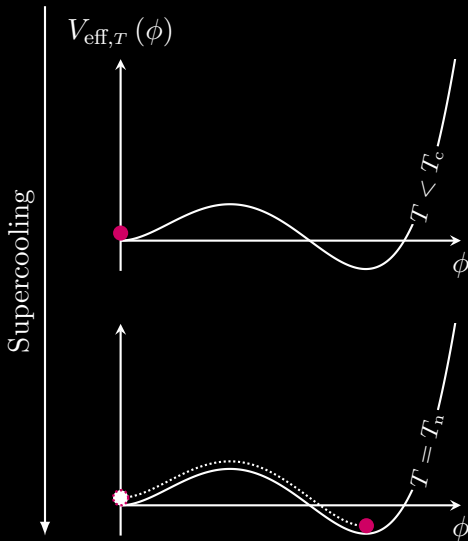


When the universe cools down, the field transitions.

If a barrier separates the phases, the transition is first order.

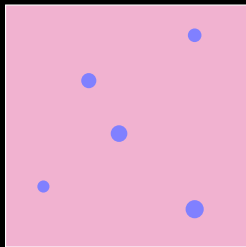


Cosmological first order phase transition



The phase transition proceeds via nucleation of bubbles.

Part of the released energy can be converted into gravitational waves: $\square h_{ij} = 4\pi G T_{ij}$



The gravitational wave signal is stochastic

and the sum of independent events (interactions between the bubbles).

The spectral parameters (amplitude, peak frequency, powers in the IR/UV) contain information about the source.

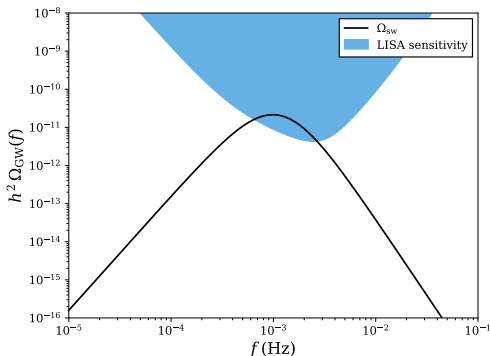
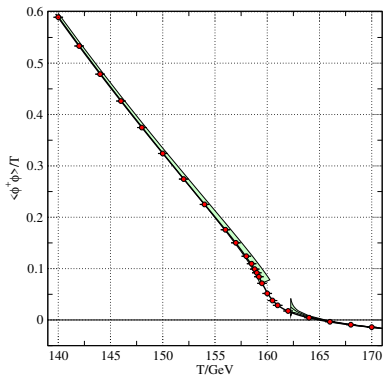
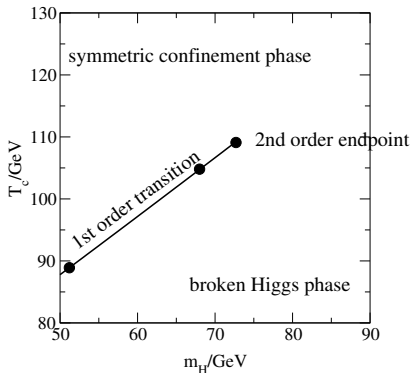


figure by Caprini, Chala, Dorsch et al., *Detecting gravitational waves from cosmological phase transitions with LISA: an update*, JCAP **03** (2020) 024 [1910.13125] at $v_w = 0.9$, $\alpha = 0.1$, $\beta/H_\star = 50$, $T_\star = 200$ GeV, $g_\star = 100$.

GWs from a cosmological phase transition: New physics?

In Standard Model, EWSB occurs via a smooth crossover⁴ but possible that it is first-order in Beyond the Standard Model (BSM) extensions.



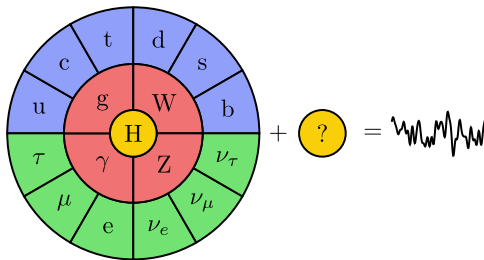
⁴ Kajantie, Laine, Rummukainen, Shaposhnikov, *Is there a hot electroweak phase transition at $m_H \gtrsim m_W$?*, Phys. Rev. Lett. **77** (1996) 2887 [hep-ph/9605288], D'Onofrio, Rummukainen, *Standard model cross-over on the lattice*, Phys. Rev. D **93** (2016) 025003 [1508.07161]

GWs from a cosmological phase transition: New physics?

In Standard Model, EWSB occurs via a smooth crossover⁴ but possible that it is first-order in Beyond the Standard Model (BSM) extensions.

Study **BSM physics** near EW scale in context of phase transitions:

- ▷ Light fields strongly coupled to Higgs
- ▷ Collider targets. BSM testing pipeline: Collider phenomenology

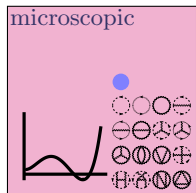


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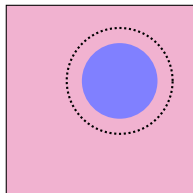
**Predicting the gravitational wave signal:
From micro- to macrophysics**

Connecting micro- and macrophysics

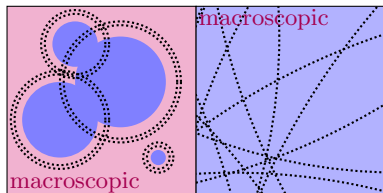
Large dynamic range to resolve Ω_{GW} at both low and high frequency.
Reliable GW predictions require control at **each** scale.



Bubble nucleation
thermodynamics



growth
wall-fluid system

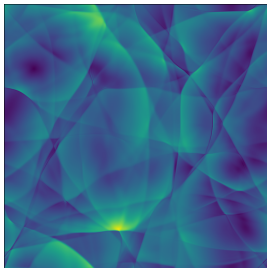
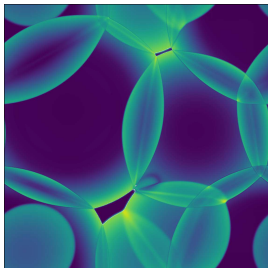
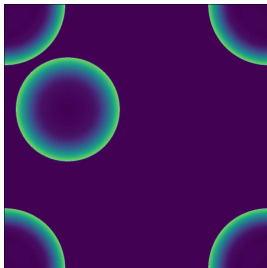


collisions

sound waves
shocks
turbulence

Connecting micro- and macrophysics

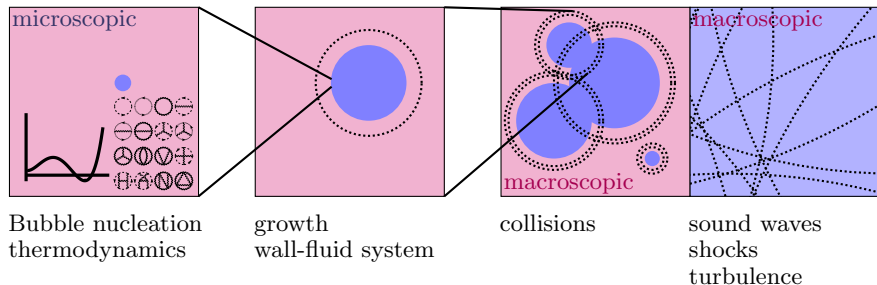
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figures by Cutting, Hindmarsh, Weir, *Vorticity, kinetic energy, and suppressed gravitational wave production in strong first order phase transitions*, Phys. Rev. Lett. **125** (2020) 021302 [1906.00480]

Connecting micro- and macrophysics

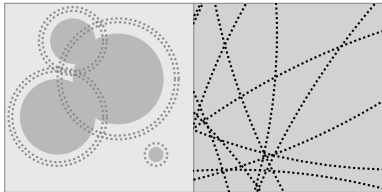
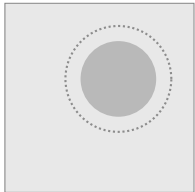
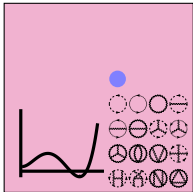
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Strategy:

Effective field theory (EFT) to connect **micro-** and **macrophysics**.

Microscopic scales



Fingerprinting the GW spectrum via microphysics

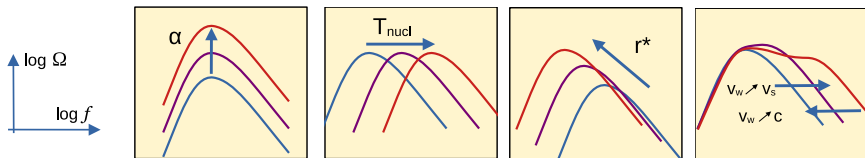
using a few equilibrium parameters:

$T_\star$ reference temperature of the transition ($T_\star = T_{\text{nucl}}, T_p$),

α phase transition strength,

β/H inverse duration of the transition (also $r_\star$),

c_s speed of sound in the plasma



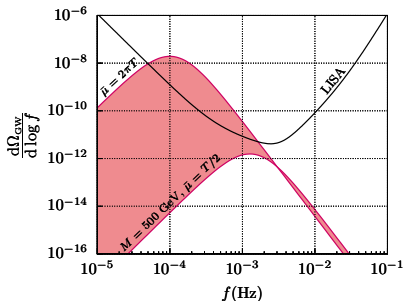
How robust are theoretical predictions?

$\mathcal{O}(10^4)$ uncertainty even for purely perturbative regimes⁵ as Ω_{GW} depends strongly on the transition temperature, T_* , in simulation fits:

$$\Omega_{\text{GW}} \propto \frac{(\Delta V_*)^2}{T_*^8}.$$

Vary RG scale $\bar{\mu}$ in SM extensions:

- ▷ SMEFT:⁶ $\text{SM} + \frac{1}{M^2}(\phi^\dagger\phi)^3$
- ▷ xSM:⁷ $\text{SM} + \text{singlet}$
- ▷ BSM models in general



⁵ Croon, Gould, Schicho, Tenkanen, White, *Theoretical uncertainties for cosmological first-order phase transitions*, JHEP **04** (2021) 055 [2009.10080]

⁶ Chala, Fiore, Gil, *Hot news on the phase-structure of the SMEFT*, [2507.16905]

⁷ Gould, Tenkanen, *On the perturbative expansion at high temperature and implications for cosmological phase transitions*, JHEP **06** (2021) 069 [2104.04399]

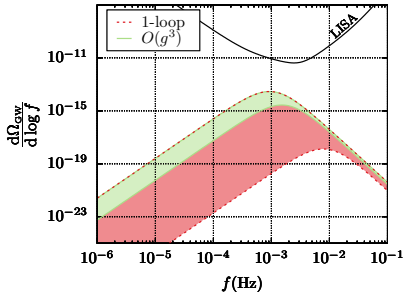
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Perturbative phase transitions need scale hierarchies

for quantum effects ΔV_{fluct} to influence the tree-level potential

$$V_{\text{eff}} = V_{\text{tree}} + \Delta V_{\text{fluct}} .$$

Relevant operators ($\sigma > 0$) in the IR get large **UV contributions**⁸ and

$$\frac{\Delta V_{\text{fluct}}}{V_{\text{tree}}} \sim g^2 \left[\frac{\Lambda_{\text{fluct}}}{\Lambda_{\text{tree}}} \right]^\sigma \stackrel{!}{\sim} 1 \quad \Rightarrow \quad \begin{cases} \text{strong coupling} & g^2 \gtrsim 1 \\ \text{scale hierarchy} & \frac{\Lambda_{\text{fluct}}}{\Lambda_{\text{tree}}} \sim \left[\frac{1}{g^2} \right]^{\frac{1}{\sigma}} \gg 1 \end{cases}$$

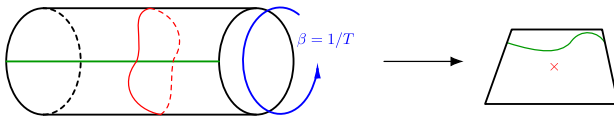
How to **reorganize perturbation** theory for large ΔV_{fluct} ?

⁸Consider e.g. hierarchy: $M_\chi \gg m_\Phi$, $(\Delta m_\Phi^2) \Phi^\dagger \Phi = \text{loop} \sim g^2 M_\chi^2 \Phi^\dagger \Phi$, $(\Delta m_\Phi^2)/m_\Phi^2 = g^2 [M_\chi/m_\Phi]^2$.

A robust EFT framework at high temperatures: 3d EFT⁹

Thermodynamics $\mathcal{Z} = \text{Tr} e^{-\beta \mathcal{H}}$ formulated in $\mathbb{R}^3 \times S^1_\beta$.

$$\underbrace{\int_{\mathbb{R}^3 \times S^1_\beta} \mathcal{L}}_{\text{bosons} + \text{fermions}} \rightarrow \underbrace{\int_{\mathbb{R}^3} \mathcal{L}_{\text{eff}}}_{\text{bosons only}} .$$



In 3d EFT, modified canonical mass dimensions render marginal operators relevant, $[A_0^a] = [g_{3,abc}] = 1/2$: **superrenormalizable** theory.

$$\int_{\mathbb{R}^3} \mathcal{L}_{\text{eff}} \supset \left[\frac{1}{2} \partial_i A_0^a \partial_i A_0^b - g_{3,abc} A_i^a A_0^b \partial_i A_0^c + \frac{m_{3,ab}^2}{2} A_0^a A_0^b \right] .$$

⁹ Braaten, Nieto, *Effective field theory approach to high temperature thermodynamics*, Phys. Rev. D **51** (1995) 6990 [hep-ph/9501375],

Powercounting the SM-like 3d EFT (SU(2)+Higgs)

Describes the thermodynamics¹⁰ of several parent 4d theories:

$$\mathcal{L}_{3d}^{\text{softer}} = \frac{1}{4} F_{ij}^a F_{ij}^a + (D_i \Phi)^\dagger (D_i \Phi) + V(\Phi) ,$$
$$V(\Phi) = m_3^2 \Phi^\dagger \Phi + \lambda_3 (\Phi^\dagger \Phi)^2 .$$

If $m_{A_i} \sim g_3 \phi \gg m_3$, integrating out vector boson introduces LO barrier

$$V_{\text{LO}}(\Phi) = \bullet + \text{blob} = m_3^2 \Phi^\dagger \Phi + \lambda_3 (\Phi^\dagger \Phi)^2 - \frac{g_3^3}{2\pi} \left(\frac{\Phi^\dagger \Phi}{2} \right)^{3/2} .$$

¹⁰ Kajantie, Laine, Rummukainen, Shaposhnikov, *Generic rules for high temperature dimensional reduction and their application to the standard model*, Nucl. Phys. B **458** (1996) 90 [[hep-ph/9508379](#)]

¹¹ Gould, Tenkanen, *Perturbative effective field theory expansions for cosmological phase transitions*, JHEP **01** (2024) 048 [[2309.01672](#)]

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If $m_{A_i} \sim g_3 \phi \gg m_3$, integrating out vector boson introduces LO barrier

$$V_{\text{LO}}(\Phi) \rightarrow y \Phi^\dagger \Phi + x (\Phi^\dagger \Phi)^2 - \frac{1}{2\pi} \left(\frac{\Phi^\dagger \Phi}{2} \right)^{3/2} .$$

Since $x \sim \frac{m_3^2}{m_{A_i}^2} \ll 1$, and at the phase transition $y \sim 1/x$, we strictly¹¹ x -pand the perturbative series using 3d EFT dimensionless couplings

$$x \equiv \frac{\lambda_3}{g_3^2} , \qquad y \equiv \frac{m_3^2}{g_3^4} .$$

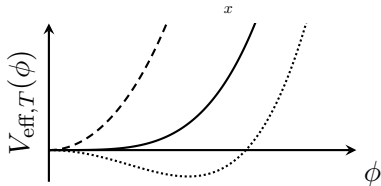
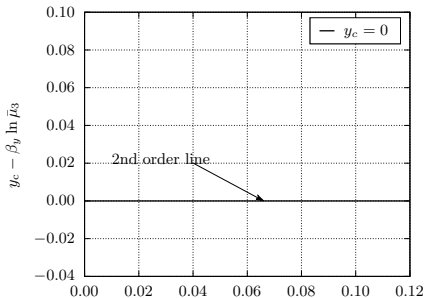
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The electroweak phase diagram

One-loop

$$V_{\text{eff},T} = V_0 + \text{---}\bigcirc\text{---}$$
$$= \frac{1}{2}m_3^2(T)\phi^2 + \frac{1}{4}\lambda_3(T)\phi^4$$



The electroweak phase diagram

One-loop

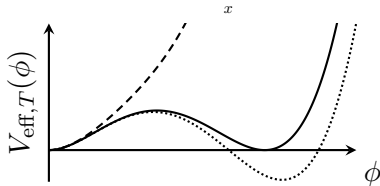
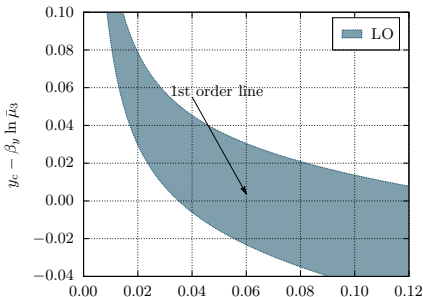
$$V_{\text{eff},T} = V_0 + \text{[one-loop diagram]} \\ = \frac{1}{2}m_3^2(T)\phi^2 + \frac{1}{4}\lambda_3(T)\phi^4$$

Leading-order resummations

$$V_{\text{eff},T} = V_0 + \text{[one-loop diagram]} + \text{[two-loop diagram]} \\ = \frac{1}{2}m_3^2\phi^2 + \frac{1}{4}\lambda_3\phi^4 - \frac{g_3^3}{16\pi}\phi^3$$

An EFT x -pansion¹² in

$$x = \lambda_3/g_3^2.$$



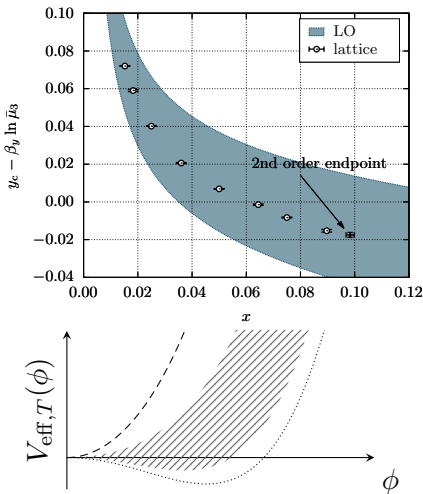
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The electroweak phase diagram

Infrared breakdown:

$$V_{\text{eff}} = ?$$

All higher loops $\subset$ N⁵LO. Resolve with lattice Monte-Carlo.¹³



¹³ Farakos, Kajantie, Rummukainen, Shaposhnikov, *3-d physics and the electroweak phase transition: A Framework for lattice Monte Carlo analysis*, Nucl. Phys. B **442** (1995) 317 [hep-lat/9412091], Kajantie, Laine, Rummukainen, Shaposhnikov, *The Electroweak phase transition: A Nonperturbative analysis*, Nucl. Phys. B **466** (1996) 189 [hep-lat/9510020], Gould, Güyer, Rummukainen, *First-order electroweak phase transitions: A nonperturbative update*, Phys. Rev. D **106** (2022) 114507 [2205.07238]

The electroweak phase diagram

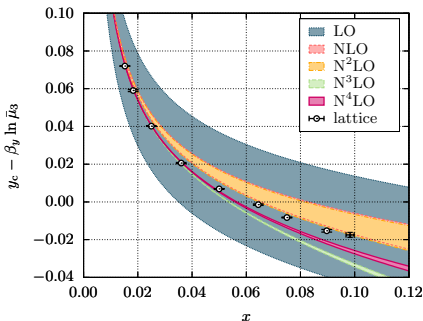
Infrared breakdown:

$$V_{\text{eff}} = ?$$

All higher loops $\subset$ $N^5\text{LO}$. Resolve with lattice Monte-Carlo.¹³

Resummations at

- ▷ $N\text{LO}^{14}$
- ▷ $N^2\text{LO}^{15}$
- ▷ $N^4\text{LO}^{16}$



¹⁴ Arnold, Espinosa, *Effective potential and first-order phase transitions: Beyond leading order*, Phys. Rev. D **47** (1993) 3546 [9212235]

¹⁵ Ekstedt, Gould, Löfgren, *Radiative first-order phase transitions to next-to-next-to-leading order*, Phys. Rev. D **106** (2022) 036012 [2205.07241]

¹⁶ Ekstedt, Schicho, Tenkanen, *Cosmological phase transitions at three loops: The final verdict on perturbation theory*, Phys. Rev. D **110** (2024) 096006 [2405.18349]

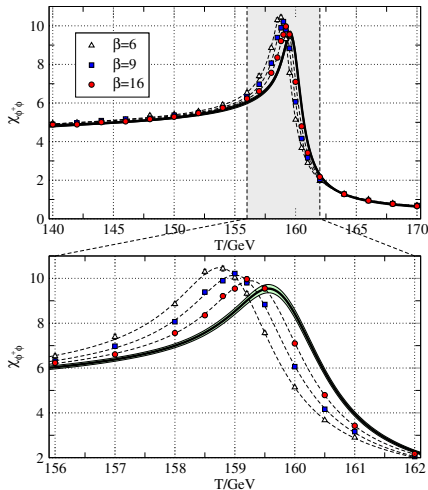
Order of the electroweak phase transition

Leading order (LO):¹⁷

$$1^{\text{st}} \text{ order, } V_{\text{eff},T} = V_0 + \text{---}\bigcirc\text{---}$$

Next-to-leading order (NLO):¹⁸

$$2^{\text{nd}} \text{ order, } V_{\text{eff},T} = V_0 + \text{---}\bigcirc\text{---}$$



¹⁷ Dolan, Jackiw, *Symmetry behavior at finite temperature*, Phys. Rev. D **9** (1974) 3320,

¹⁸ Arnold, Espinosa, *Effective potential and first-order phase transitions: Beyond leading order*, Phys. Rev. D **47** (1993) 3546 [9212235]

Order of the electroweak phase transition

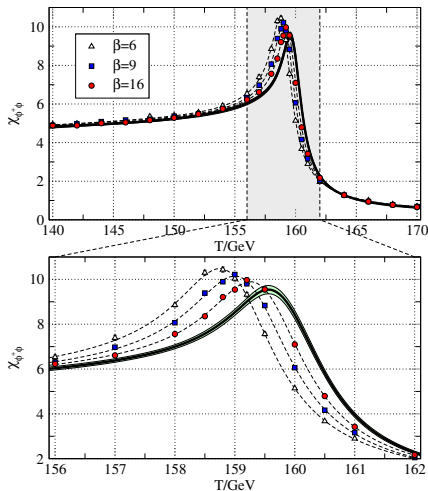
Higher-order infrared problems:¹⁹

(?) order

EFT + lattice resolves all issues:²⁰

crossover transition

Accurate SM thermodynamics²¹



¹⁹ Linde, *Infrared problem in the thermodynamics of the Yang-Mills gas*, Phys. Lett. B **96** (1980) 289

²⁰ Kajantie, Laine, Rummukainen, Shaposhnikov, *Is there a hot electroweak phase transition at $m_H \gtrsim m_W$?*, Phys. Rev. Lett. **77** (1996) 2887 [hep-ph/9605288]

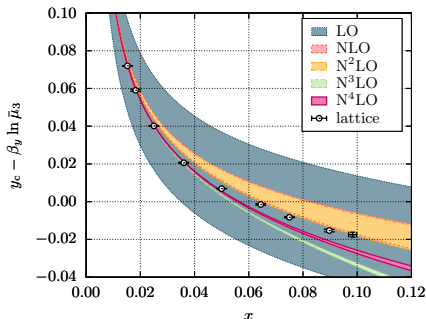
²¹ D'Onofrio, Rummukainen, *Standard model cross-over on the lattice*, Phys. Rev. D **93** (2016) 025003 [1508.07161]

Perturbation theory and lattice agree remarkably

at the last perturbative thermodynamic order (for $SU(2) + \text{Higgs}$).
By using $F \sim V_{\text{eff}}(\phi_{\min})$, determine the *critical mass* y_c (or T_c)

$$\Delta F(y_c(x), x) = [F_{\text{bro}} - F_{\text{sym}}](y_c(x), x) = 0,$$

and scalar *condensates*²² $\Delta\langle\Phi^\dagger\Phi\rangle \equiv \partial_y\Delta F$ and $\Delta\langle(\Phi^\dagger\Phi)^2\rangle \equiv \partial_x\Delta F$.



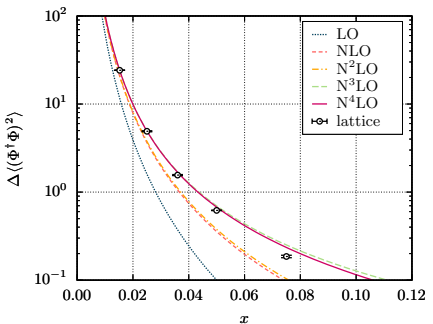
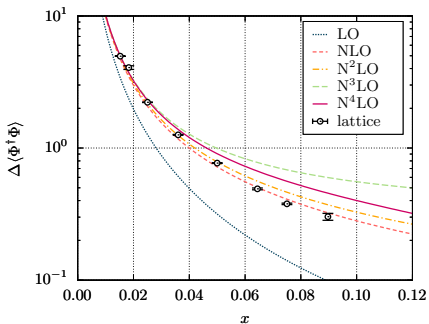
²²Lattice data: Kajantie, Laine, Rummukainen, Shaposhnikov, *The Electroweak phase transition: A Nonperturbative analysis*, Nucl. Phys. B **466** (1996) 189 [hep-lat/9510020], Gould, Güyer, Rummukainen, *First-order electroweak phase transitions: A nonperturbative update*, Phys. Rev. D **106** (2022) 114507 [2205.07238]

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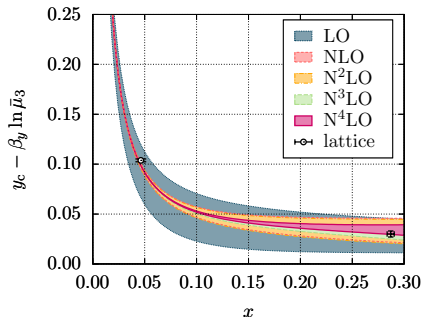
²²Lattice data: Kajantie, Laine, Rummukainen, Shaposhnikov, *The Electroweak phase transition: A Nonperturbative analysis*, Nucl. Phys. B **466** (1996) 189 [hep-lat/9510020], Gould, Güyer, Rummukainen, *First-order electroweak phase transitions: A nonperturbative update*, Phys. Rev. D **106** (2022) 114507 [2205.07238]

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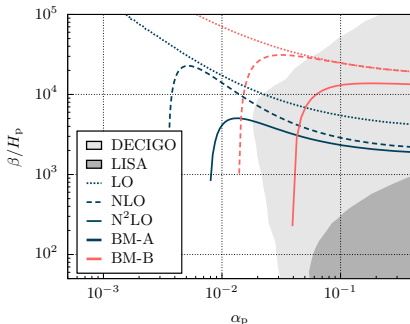
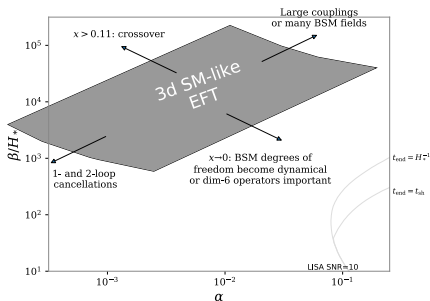
²²Lattice data: Kajantie, Karjalainen, Laine, Peisa, *Three-dimensional $U(1)$ gauge + Higgs theory as an effective theory for finite temperature phase transitions*, Nucl. Phys. B **520** (1998) 345 [hep-lat/9711048], Mo, Hove, Sudbo, *The Order of the metal to superconductor transition*, Phys. Rev. B **65** (2002) 104501 [cond-mat/0109260]

Beyond the SM and evading the rhombus of misery

$\alpha/(\beta/H)$ rhombus of SM-like EFT with no prospect for large SNR.²³
 Better access interesting LISA SNR by increasing loop order:

BM-A xSM with weakly portal-coupled singlet (decoupled)

BM-B xSM with strongly portal-coupled singlet

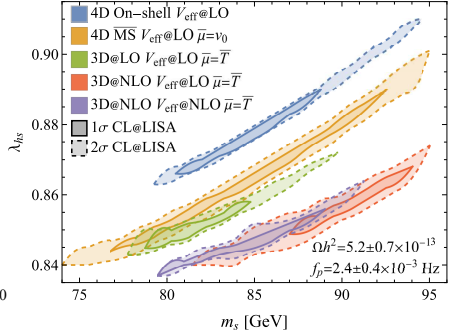
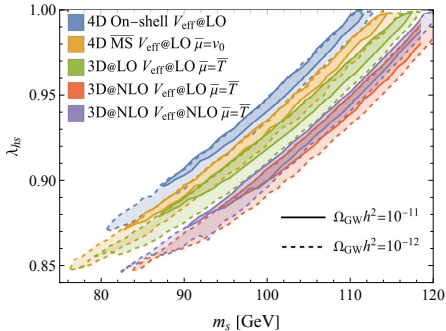


²³ Gould, Kozaczuk, Niemi, Ramsey-Musolf, Tenkanen, Weir, *Nonperturbative analysis of the gravitational waves from a first-order electroweak phase transition*, Phys. Rev. D **100** (2019) 115024 [1903.11604]

Computational diligence at $\mathcal{O}(g^4)$

Monitor Higgs (v) and **real singlet** (x) VEV after shift $s \rightarrow x + s$.
2-loop corrections **move “Bananas”**: significant effect on GW signal.²⁴

Parameters	m_s	λ_{hs}	$\lambda_s = 1$	$\alpha > 1$	$\text{SNR}_{\text{LISA}} > 10$
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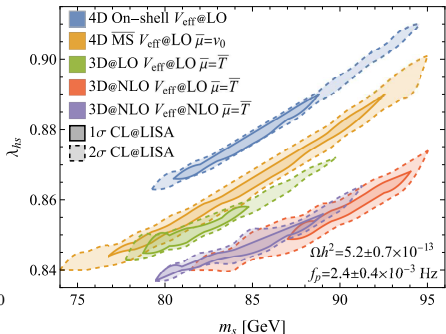
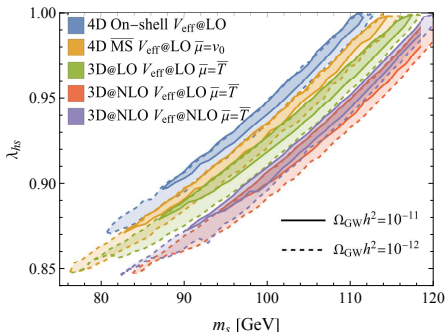


²⁴ Lewicki, Merchand, Sagunski, Schicho, Schmitt, *Impact of theoretical uncertainties on model parameter reconstruction from GW signals sourced by cosmological phase transitions*, Phys. Rev. D **110** (2024) 023538 [2403.03769], Niemi, Schicho, Tenkanen, *Singlet-assisted electroweak phase transition at two loops*, Phys. Rev. D **103** (2021) 115035 [2103.07467]

Does the **banana** move?

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Dimension-six operators in U(1) + Higgs²⁵

WHAT IF WE TRIED
MORE LOOPS ?



So far **truncated operators** at high T at dimension 4:

$$S_{\text{soft}}^{3\text{d}} = \frac{1}{T} \int_{\mathbf{x}} \left\{ \mathcal{L}_{\text{soft}}^{3\text{d}} + \sum_{n \geq 5} \frac{\mathcal{O}_n}{(\pi T)^n} \right\},$$

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²⁵ Bernardo, Klose, Schicho, Tenkanen, *Higher-dimensional operators at finite temperature affect gravitational-wave predictions*, JHEP **08** (2025) 109 [2503.18904], Bernardo, Chala, Gil, Schicho, *Hard thermal contributions to phase transition observables at NNLO*, [2602.06962]

Dimension-six operators in U(1) + Higgs²⁵

WHAT IF WE TRIED
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ORDER OF
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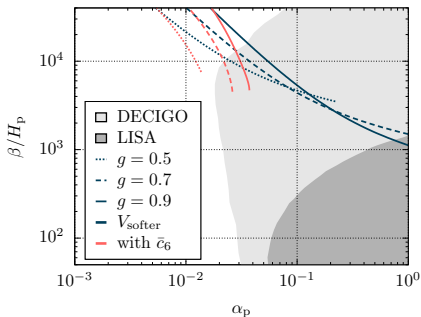
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Gravitational wave prospects

Soft scale **enhances** phase-transition strength, $\alpha(T)$.

High- T expansion is compromised for regime relevant for LISA:



Limitation: conventional lattice results of (dim-4) super-renormalizable 3d EFT do **not describe hard/soft-scale** driven transitions.²⁶

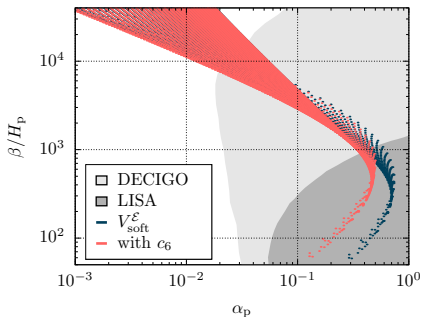
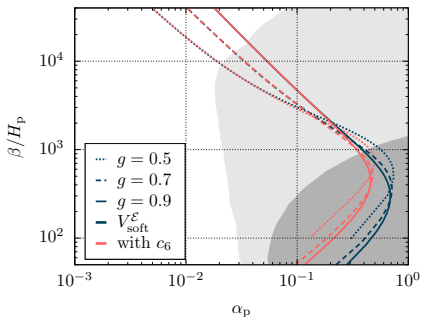
Need **4d full theory lattice** simulations for a reliable description?

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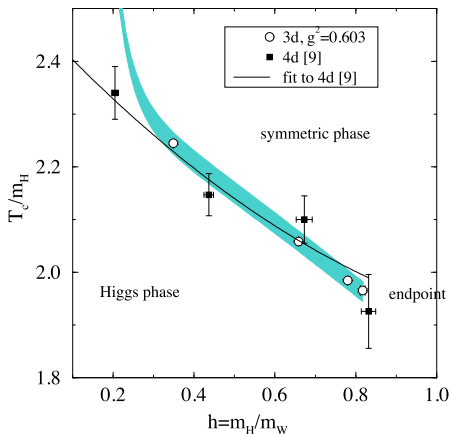
New lattice benchmarks²⁷ for strong transition tests

Breakdown is no surprise and was already known since 90s.²⁸

Need broad- T frameworks.

Not needed for weak SM-like transitions.

Relevant for:
strong **BSM** transitions.



²⁷ Annala, Hallfors, Rummukainen, Seppä, Schicho, Tenkanen, in progress

²⁸ Laine, *The Renormalized gauge coupling and nonperturbative tests of dimensional reduction*, JHEP **06** (1999) 020 [hep-ph/9903513], Csikor, Fodor, Heitger, *Endpoint of the hot electroweak phase transition*, Phys. Rev. Lett. **82** (1999) 21 [hep-ph/9809291]

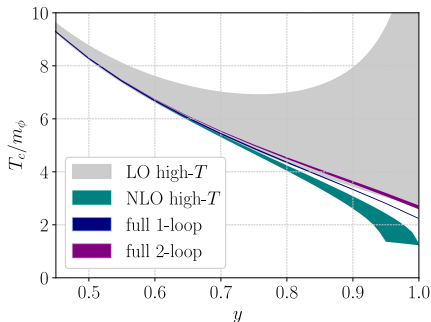
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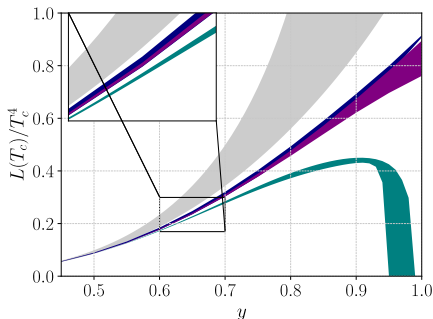
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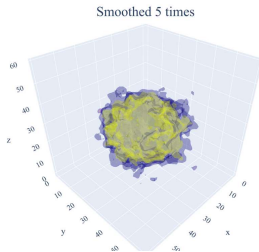
Beyond equilibrium: nucleation rate and temperature

Bubble nucleation rate determines the nucleation temperature and duration of the phase transition²⁹

$$\Gamma = \Gamma_{\text{dyn}} \times \Gamma_{\text{stat}} \sim A e^{-B},$$

B Internal energy of critical bubble. Solve one non-linear ODE

$$\frac{d^2\phi_b}{dr^2} + \frac{2}{r} \frac{d\phi_b}{dr} - V'(\phi_b) = 0$$



²⁹ Langer, Turski, *Hydrodynamic model of the condensation of a vapor near its critical point*, Physical Review A **8** (1973) 3230; figure for critical bubble in SU(2)-Higgs model by Gould, Güyer, Rummukainen, *First-order electroweak phase transitions: A nonperturbative update*, Phys. Rev. D **106** (2022) 114507 [2205.07238]

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$$\frac{d^2 \phi_b}{dr^2} + \frac{2}{r} \frac{d\phi_b}{dr} - V'(\phi_b) = 0$$

A log entropy of fluctuations about bubble. Infinite number of linear ODEs

$$\left[\frac{d^2}{dr^2} + \frac{2}{r} \frac{d}{dr} - \frac{l(l+1)}{r^2} + V''(\phi_b) \right] \psi_l^b(r) = 0$$

Need both *A* and *B* for **reliable** rate computation. EFT for Γ_{stat} ³⁰

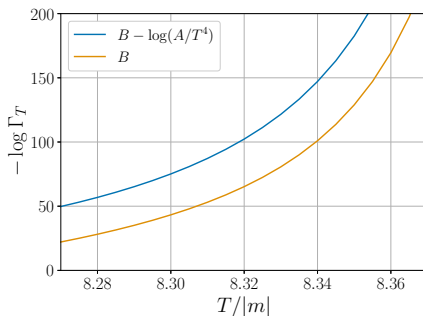
$$\Gamma_{\text{stat}} \sim [m_{\text{eff}}^4 e^S] \times e^{-E_b/T} \sim m_{\text{eff}}^4 e^{-(E_b - ST)/T}.$$

²⁹ Langer, Turski, *Hydrodynamic model of the condensation of a vapor near its critical point*, Physical Review A **8** (1973) 3230

³⁰ Gould, Hirvonen, *Effective field theory approach to thermal bubble nucleation*, Phys. Rev. D **104** (2021) 096015 [2108.04377]

Determining the Bubble determinant

BubbleDet³¹ computes term **A**. Here: Yukawa model.



Nucleation not just **energy** and **entropy** → out-of-equilibrium effects³²

$$\Gamma \sim \frac{\kappa_{\text{dyn}}}{2\pi} m^3 e^{-(E_b - ST)/T}.$$

³¹ Ekstedt, Gould, Hirvonen, *BubbleDet: a Python package to compute functional determinants for bubble nucleation*, JHEP **12** (2023) 056 [2308.15652]

³² Langer, *Statistical theory of the decay of metastable states*, Ann. Phys. (N. Y.) **54** (1969) 258, Hirvonen, *Real-time nucleation and off-equilibrium effects in high-temperature quantum field theories*, Phys. Rev. D **111** (2025) 116020 [2403.07987], Gould, Kormu, Weir, *Nonperturbative test of nucleation calculations for strong phase transitions*, Phys. Rev. D **111** (2025) L051901 [2404.01876]

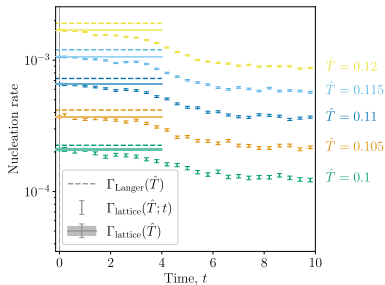
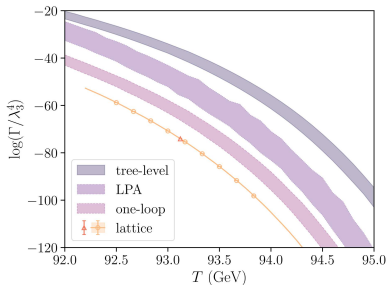
Agreement between perturbation theory and lattice?

Disagreement³³ because initial state is not thermalized on the lattice?

Recent $1+1D$ lattice simulations better match perturbation theory.³⁴

Agreement up to two-loop order for a thermalized initial state.³⁵

The rate is not constant, but **decays over time**.



³³ Gould, Kormu, Weir, *Nonperturbative test of nucleation calculations for strong phase transitions*, Phys. Rev. D **111** (2025) L051901 [2404.01876]

³⁴ Pîrvu, Shkerin, Sibiryakov, *Thermal false vacuum decay in (1+1) dimensions: Evidence for nonequilibrium dynamics*, Int. J. Mod. Phys. A **39** (2024) 2445007 [2408.06411]

³⁵ Hirvonen, Gould, *Langer's Nucleation Rate Reproduced on the Lattice*, Phys. Rev. Lett. **136** (2026) 081601 [2505.22732]

Supercooling in EFT: Classical scale-invariant models

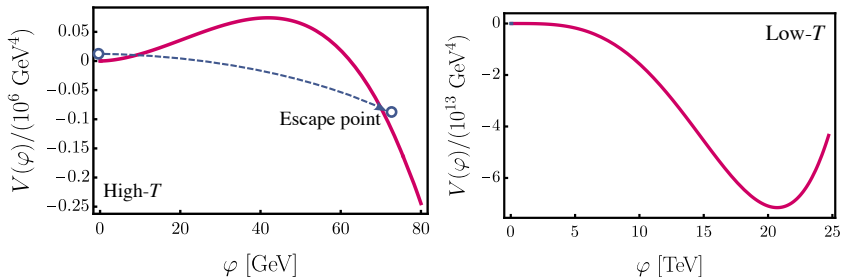
exhibit **strong supercooling** and phase transition. Barrier until low- T

$$m_\varphi^2(T) = [\mu_0^2] + m_T^2.$$

Trapped field φ in false vacuum φ_F until $T_p \ll T_c$. Split computation:³⁶

High- T : Small field regime $M(\varphi) < T$ use 3D EFT

Low- T : Large field regime $M(\varphi) > T$ use vacuum potential

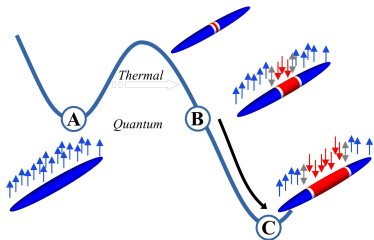
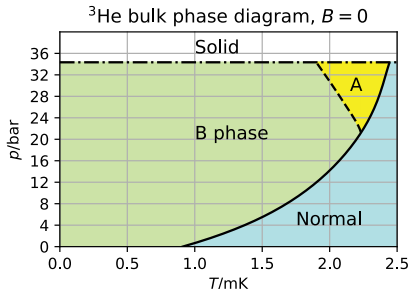


³⁶ Kierkla, Schicho, Swiezewska, Tenkanen, van de Vis, *Finite-temperature bubble nucleation with shifting scale hierarchies*, JHEP **07** (2025) 153 [2503.13597], Kierkla, Swiezewska, Tenkanen, van de Vis, *Gravitational waves from supercooled phase transitions: dimensional transmutation meets dimensional reduction*, JHEP **02** (2024) 234 [2312.12413]

How else can we study bubble nucleation?

Clear disagreement for A - B transition in superfluid ^3He .³⁷

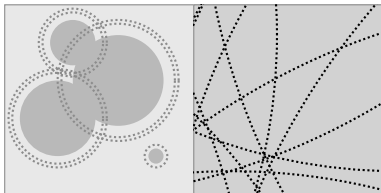
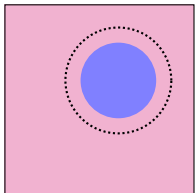
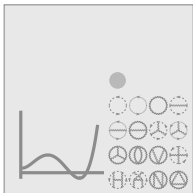
Good theoretical agreement for rate in $1+1d$ ferromagnetic superfluid, taking entropy (A) as a fit parameter.³⁸



³⁷ **QUEST-DMC** Collaboration, Hindmarsh *et al.*, *A-B Transition in Superfluid ^3He and Cosmological Phase Transitions*, J. Low Temp. Phys. **215** (2024) 495 [2401.07878]

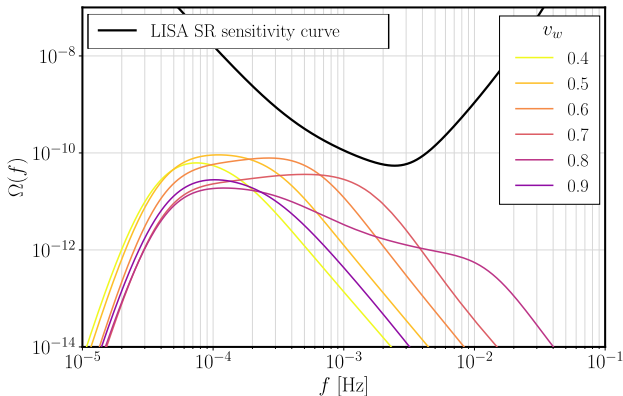
³⁸ Zenesini, Berti, Cominotti *et al.*, *False vacuum decay via bubble formation in ferromagnetic superfluids*, Nature Phys. **20** (2024) 558 [2305.05225], Cominotti, Baroni, Rogora *et al.*, *Observation of Temperature Effects on False Vacuum Decay in Atomic Quantum Gases*, Phys. Rev. Lett. **135** (2025) 183401 [2504.03528]

In between scales



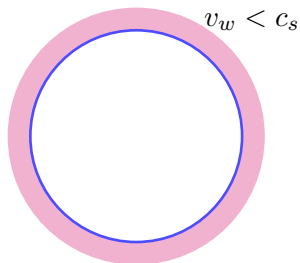
Fingerprinting the GW spectrum via bubble growth

Velocity of expanding bubbles determines the shape and strength of GW signal.³⁹

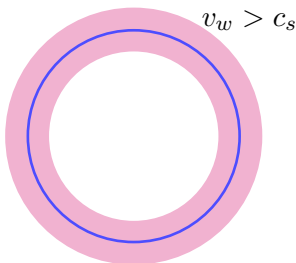


³⁹At fixed $\alpha = 0.2$, $r_* = 0.1$, $T_n = 100$ GeV from Gowling, Hindmarsh, *Observational prospects for phase transitions at LISA: Fisher matrix analysis*, JCAP **10** (2021) 039 [2106.05984]

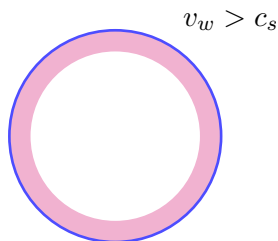
Bubble growth: relativistic combustion⁴⁰



Deflagration



Supersonic deflagration
“Hybrid”

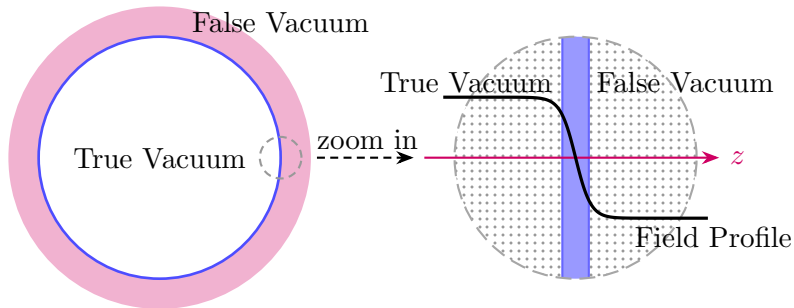


Detonation

⁴⁰ Landau, Lifshitz, *Fluid mechanics*, Pergamon, 1959, Steinhardt, *Relativistic Detonation Waves and Bubble Growth in False Vacuum Decay*, Phys. Rev. D **25** (1982) 2074, Ignatius, Kajantie, Kurki-Suonio, Laine, *The growth of bubbles in cosmological phase transitions*, Phys. Rev. D **49** (1994) 3854 [astro-ph/9309059], Espinosa, Konstandin, No, Servant, *Energy Budget of Cosmological First-order Phase Transitions*, JCAP **06** (2010) 028 [1004.4187]

Microscopic description of the bubble wall

The bubble wall is the region where the field(s) interpolate between the high- and low-temperature vacuum.



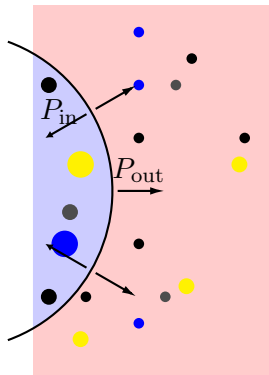
Bubbles typically reach terminal velocity before colliding if

$$|P_{\text{out}}| = |P_{\text{in}}|.$$

ΔP_{out} Vacuum energy release
(accelerating wall)

ΔP_{in} Particle friction on the wall
(decelerating wall)

ΔP_{in} Hydrodynamic backreaction
(decelerating wall)



Iteratively solve coupled **fluid**, **scalar field**, **Boltzmann** equations.⁴¹

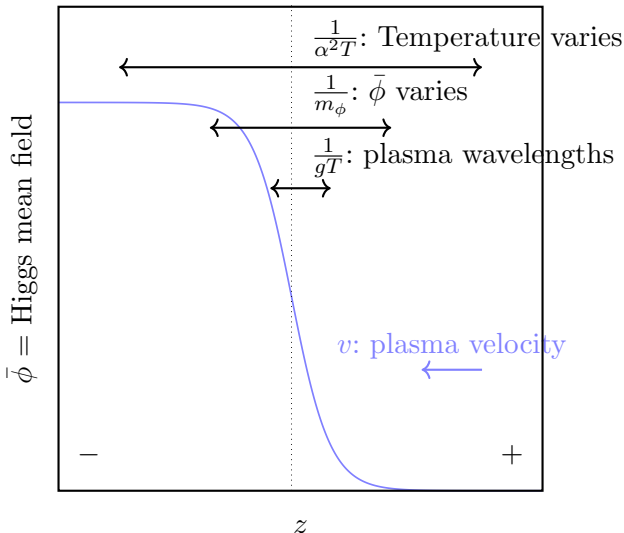
Public software for v_w :⁴² **WA(GO)**.

⁴¹ Moore, Prokopec, *How fast can the wall move? A Study of the electroweak phase transition dynamics*, Phys. Rev. D **52** (1995) 7182 [hep-ph/9506475], Laurent, Cline, *First principles determination of bubble wall velocity*, Phys. Rev. D **106** (2022) 023501 [2204.13120],

⁴²Schicho, Ekstedt, Gould, Hirvonen et al., *How fast does the WallGo? A package for computing wall velocities in first-order phase transitions*, JHEP **04** (2025) 101 [2411.04970].

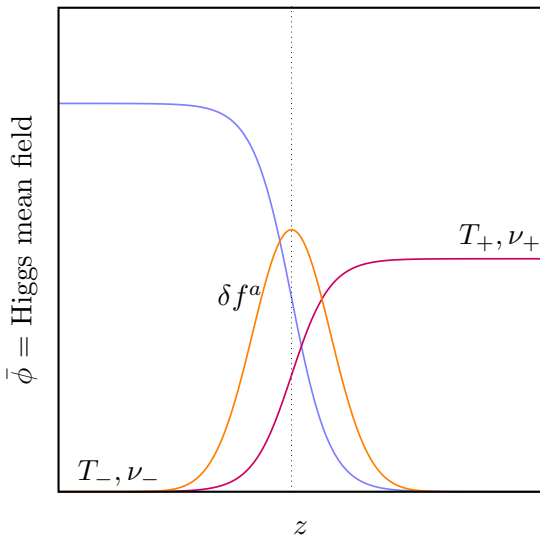
The relevant length scales during a phase transition

in the wall frame [plasma moves to the left; $\alpha = g^2/(4\pi)$].



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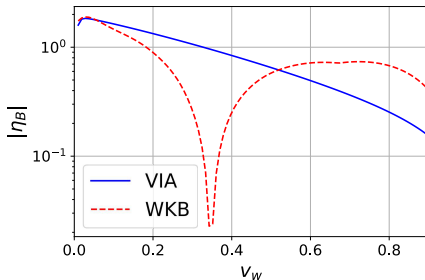
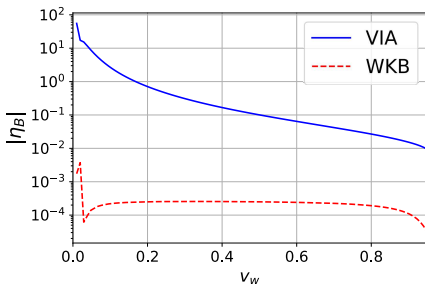
in the wall frame [plasma moves to the left; $\alpha = g^2/(4\pi)$].



Electroweak baryogenesis depends on the wall velocity⁴³

Baryogenesis from CP violation via lepton higher-dimensional Yukawa.

Baryogenesis by c - t or b - s flavor mixing.

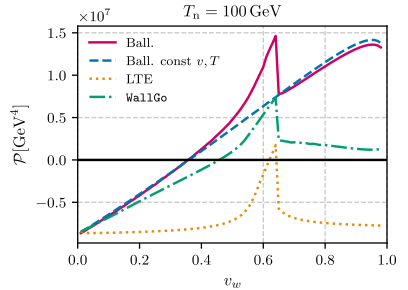
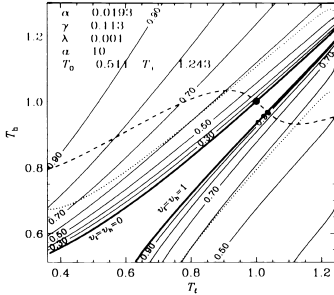


⁴³ Cline, Laurent, *Electroweak baryogenesis from light fermion sources: A critical study*, Phys. Rev. D **104** (2021) 083507 [2108.04249]

Pinching v_w with LTE and ballistic limit

Upper bound. Large collision term ($\mathcal{C}_a \rightarrow \infty$ and $\delta f^a \rightarrow 0$):
Local thermal equilibrium (LTE).^{44,45}

Lower bound. Small collision term ($\mathcal{C}_a \rightarrow 0$):
Ballistic limit.⁴⁶ Can solve Boltzmann equation analytically.



⁴⁴ Enqvist, Ignatius, Kajantie, Rummukainen, *Nucleation and bubble growth in a first order cosmological electroweak phase transition*, Phys. Rev. D **45** (1992) 3415

⁴⁵ Backreaction from hot fluid, and entropy production ($\Delta_{su} z \geq 0$) can still stop the wall c.f. Eriksson, Laine, *Entropy production at electroweak bubble walls from scalar field fluctuations*, JCAP **09** (2025) 027 [2507.07755]

⁴⁶ Ai, Laurent, van de Vis, *Bounds on the bubble wall velocity*, JHEP **02** (2025) 119 [2411.13641] at $m_s = 120$ GeV and $\lambda_{hs} = \lambda_s = 1$

Theoretical uncertainties in the wall velocity⁴⁷

from both the driving pressure ΔP and the wall velocity Δv_w ,

$$\Delta v_w \approx \Delta P \left(\frac{dP}{dv_w} \right)^{-1}.$$

Suggested largest uncertainties:

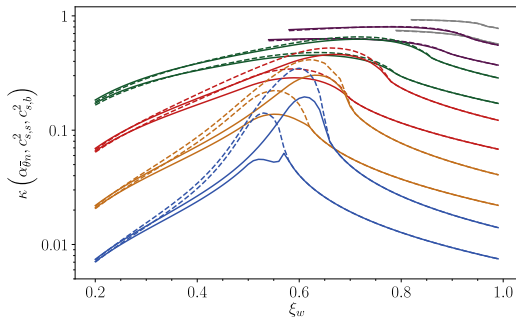
- 1) nucleation,
- 2) leading-log and power-enhancement in collisions,
- 3) out of equilibrium particles.

Source of uncertainty		$\Delta v_w/v_w$		
		xSM	IDM	$\mathcal{O}(\Delta P/P)$
Boltzmann	Linearization	0.1%	0.01%	$\mathcal{O}(\delta f_2/f_{\text{eq}})$
	Power enhanced	90%	300%	$\mathcal{O}(\delta f_1/f_{\text{eq}})$
	NLL collisions	—	20%	$\mathcal{O}(\delta f_1/(f_{\text{eq}} \ln(1/g)))$
	Out-of-eq. particles	30%	400%	$\mathcal{O}(\delta f_1/f_{\text{eq}})$
Scalar EOM	T_n	100%	—	$\mathcal{O}(g)$
	V_{eff}	—	20%	$\mathcal{O}(g)$

⁴⁷ van de Vis, Schicho, Niemi, Laurent, Hirvonen, Gould, *WallGo investigates: Theoretical uncertainties in the bubble wall velocity*, Accepted in JHEP (2025) [2510.27691]

The expanding bubble causes motion in the surrounding fluid.

The phase transition strength wall velocity and speed of sounds determine the amount of energy available for GWs.⁴⁸



$$\bar{\alpha}\theta_n = 0.01, \dots, 3$$

$$c_{s,b}^2 = 1/3 \text{ (upper)}$$

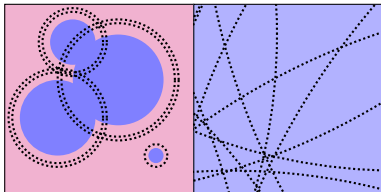
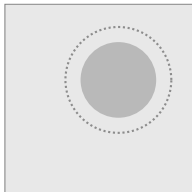
$$c_{s,b}^2 = 1/4 \text{ (lower)}$$

$$c_{s,s}^2 = 1/3 \text{ (solid)}$$

$$c_{s,s}^2 = 1/4 \text{ (dashed)}$$

⁴⁸ Giese, Konstandin, Schmitz, van de Vis, *Model-independent energy budget for LISA*, JCAP **01** (2021) 072 [2010.09744]

Macroscopic scales



Predicting the GW signal of colliding bubbles

Simulate numerically the scalar-fluid system consisting of

- ▷ Scalar field (gradient energy),
- ▷ Fluid motion.

For weak/intermediate phase transitions, the fluid motion is the dominant source of GWs.⁴⁹

Simulated using phenomenological fluid-scalar interaction

$$\partial_\mu T_\phi^{\mu\nu} = -\eta_T u^\mu \partial_\mu \phi \partial^\nu \phi.$$

Recent computations of $\eta_T(\phi)$ from first principles.⁵⁰

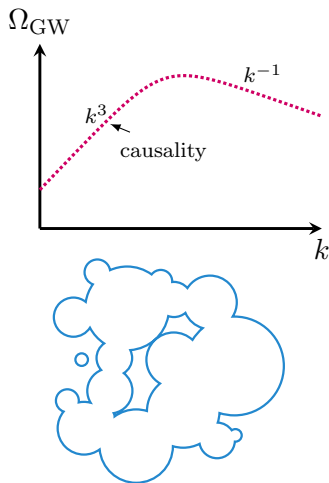
⁴⁹ Hindmarsh, Huber, Rummukainen, Weir, *Gravitational waves from the sound of a first order phase transition*, Phys. Rev. Lett. **112** (2014) 041301 [1304.2433]

⁵⁰ Ekstedt, Konstandin, van de Vis, *Scalar damping in cosmological phase transitions*, [2512.16663], Bhusal, Blasi, Konstandin, Perboni, van de Vis, *Slow-down of expanding bubbles in the early Universe*, [2603.22397]

A conspiracy of bubbles: From single bubbles to a GW signal

Gradient energy of scalar field:

▷ Envelope approximation⁵¹

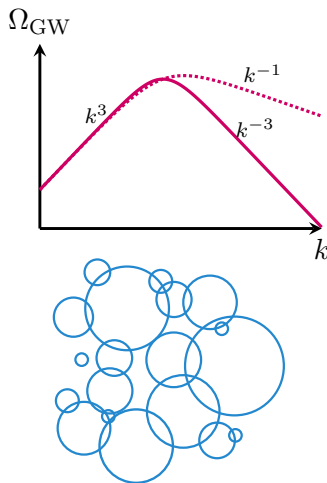


⁵¹ Kosowsky, Turner, *Gravitational radiation from colliding vacuum bubbles: envelope approximation to many bubble collisions*, Phys. Rev. D **47** (1993) 4372 [astro-ph/9211004], Weir, *Revisiting the envelope approximation: gravitational waves from bubble collisions*, Phys. Rev. D **93** (2016) 124037 [1604.08429]

A conspiracy of bubbles: From single bubbles to a GW signal

Gradient energy of scalar field:

- ▷ Envelope approximation⁵¹
- ▷ Contributions of collided walls can change UV power law⁵²



⁵² Cutting, Hindmarsh, Weir, *Gravitational waves from vacuum first-order phase transitions: from the envelope to the lattice*, Phys. Rev. D **97** (2018) 123513 [1802.05712], Konstandin, *Gravitational radiation from a bulk flow model*, JCAP **03** (2018) 047 [1712.06869], Jinno, Takimoto, *Gravitational waves from bubble dynamics: Beyond the Envelope*, JCAP **01** (2019) 060 [1707.03111], Lewicki, Vaskonen, *Gravitational waves from colliding vacuum bubbles in gauge theories*, Eur. Phys. J. C **81** (2021) 437 [2012.07826], Gould, Sukuvaara, Weir, *Vacuum bubble collisions: From microphysics to gravitational waves*, Phys. Rev. D **104** (2021) 075039 [2107.05657]

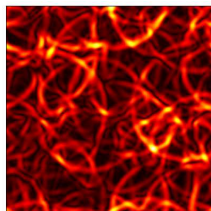
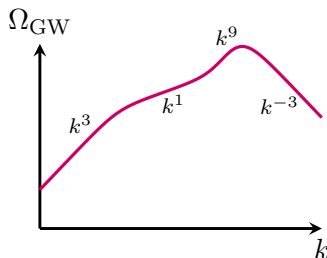
A conspiracy of bubbles: From single bubbles to a GW signal

Gradient energy of scalar field:

- ▷ Envelope approximation⁵¹
- ▷ Contributions of collided walls can change UV power law⁵²

Fluid motion:

Sound waves in fluid plasma⁵³



⁵³ Hindmarsh, Huber, Rummukainen, Weir, *Gravitational waves from the sound of a first order phase transition*, Phys. Rev. Lett. **112** (2014) 041301 [1304.2433], Hindmarsh, *Sound shell model for acoustic gravitational wave production at a first-order phase transition in the early Universe*, Phys. Rev. Lett. **120** (2018) 071301 [1608.04735], Sharma, Dahl, Brandenburg, Hindmarsh, *Shallow relic gravitational wave spectrum with acoustic peak*, [2308.12916], Jinno, Konstandin, Rubira, Stomberg, *Higgsless simulations of cosmological phase transitions and gravitational waves*, JCAP **02** (2023) 011 [2209.04369]

A conspiracy of bubbles: From single bubbles to a GW signal

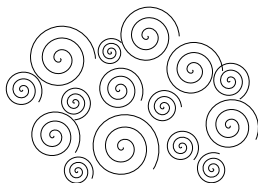
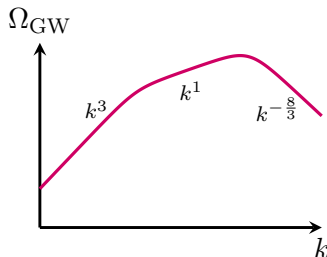
Gradient energy of scalar field:

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- ▷ Contributions of collided walls can change UV power law⁵²

Fluid motion:

Sound waves in fluid plasma⁵³

Vortical turbulence: Kolmogorov⁵⁴



⁵⁴ Caprini, Durrer, Servant, *The stochastic gravitational wave background from turbulence and magnetic fields generated by a first-order phase transition*, JCAP **12** (2009) 024 [0909.0622], Roper Pol, Mandal, Brandenburg, Kahniashvili, Kosowsky, *Numerical simulations of gravitational waves from early-universe turbulence*, Phys. Rev. D **102** (2020) 083512 [1903.08585], Auclair, Caprini, Cutting et al., *Generation of gravitational waves from freely decaying turbulence*, JCAP **09** (2022) 029 [2205.02588], Dahl, Hindmarsh, Rummukainen, Weir, *Primordial acoustic turbulence: Three-dimensional simulations and gravitational wave predictions*, Phys. Rev. D **110** (2024) 103512 [2407.05826]

A conspiracy of bubbles: From single bubbles to a GW signal

Gradient energy of scalar field:

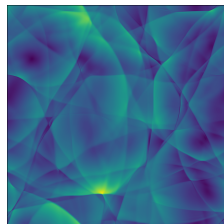
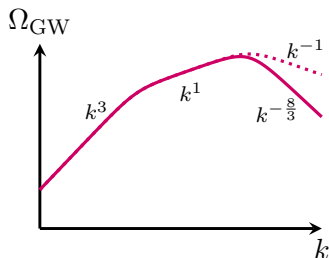
- ▷ Envelope approximation⁵¹
- ▷ Contributions of collided walls can change UV power law⁵²

Fluid motion:

Sound waves in fluid plasma⁵³

Vortical turbulence: Kolmogorov⁵⁴

Accoustic turbulence: fluid shocks⁵⁵



⁵⁵ Dahl, Hindmarsh, Rummukainen, Weir, *Decay of acoustic turbulence in two dimensions and implications for cosmological gravitational waves*, Phys. Rev. D **106** (2022) 063511 [2112.12013]

A conspiracy of bubbles: From single bubbles to a GW signal

Gradient energy of scalar field:

- ▷ Envelope approximation⁵¹
- ▷ Contributions of collided walls can change UV power law⁵²

Fluid motion:

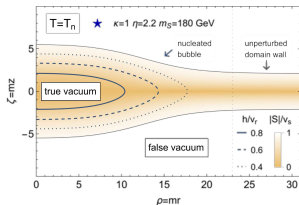
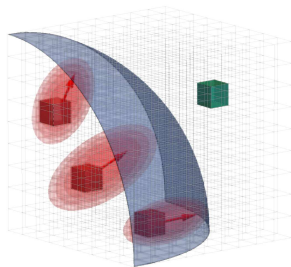
Sound waves in fluid plasma⁵³

Vortical turbulence: Kolmogorov⁵⁴

Acoustic turbulence: fluid shocks⁵⁵

Feebly interacting particles (FIP)⁵⁶

Domain walls⁵⁷



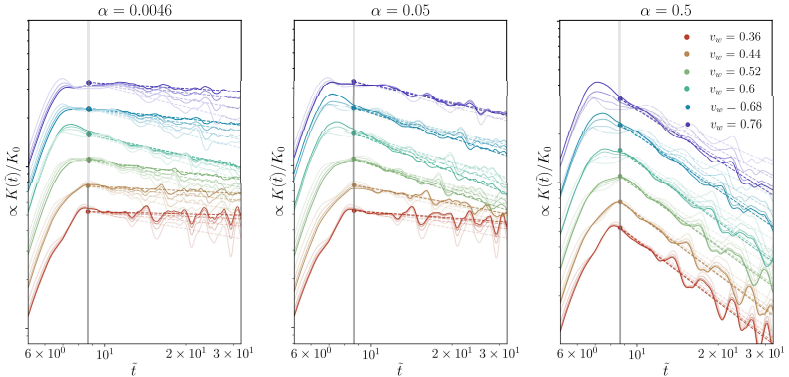
⁵⁶ Jinno, Shukya, van de Vis, *Gravitational Waves from Feebly Interacting Particles in a First Order Phase Transition*, Phys. Rev. Lett. **136** (2026) 131002 [2211.06405]

⁵⁷ Blasi, Mariotti, *Domain Walls Seeding the Electroweak Phase Transition*, Phys. Rev. Lett. **129** (2022) 261303 [2203.16450], Blasi, Jinno, Konstandin, Rubira, Stomberg, *Gravitational waves from defect-driven phase transitions: domain walls*, JCAP **10** (2023) 051 [2302.06952], Agrawal, Blasi, Mariotti, Nee, *Electroweak phase transition with a double well done doubly well*, JHEP **06** (2024) 089 [2312.06749]

Onset of non-linearities in simulations

Higgless scheme (the bubble motion is predetermined) to simulate the GWs from the fluid.⁵⁸

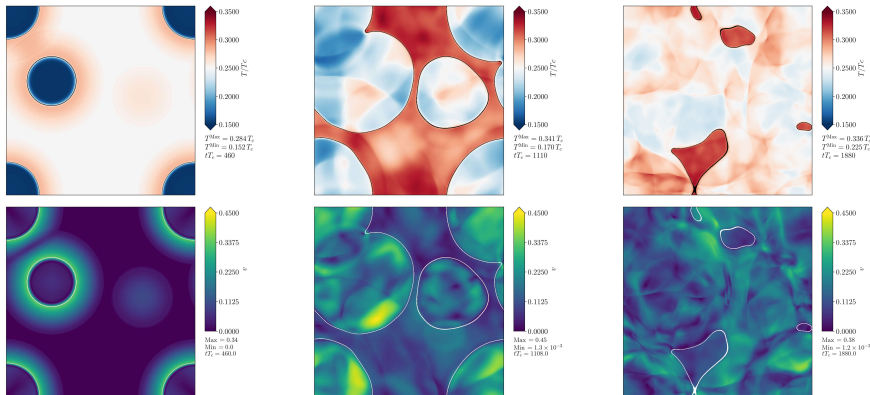
For stronger phase transitions, the GW source decays with time.



⁵⁸ Caprini, Jinno, Konstandin, Roper Pol, Rubira, Stomberg, *Gravitational waves from first-order phase transitions: from weak to strong*, JHEP **07** (2025) 217 [2409.03651]

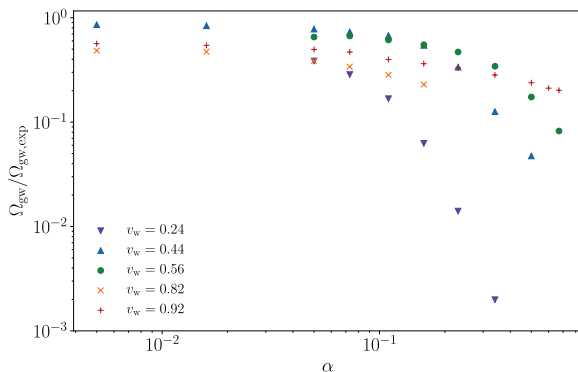
Slow-down of bubbles before collisions⁵⁹

challenges the picture that the signal is completely determined by the microscopic scales. More advanced modelling of the signal is necessary.



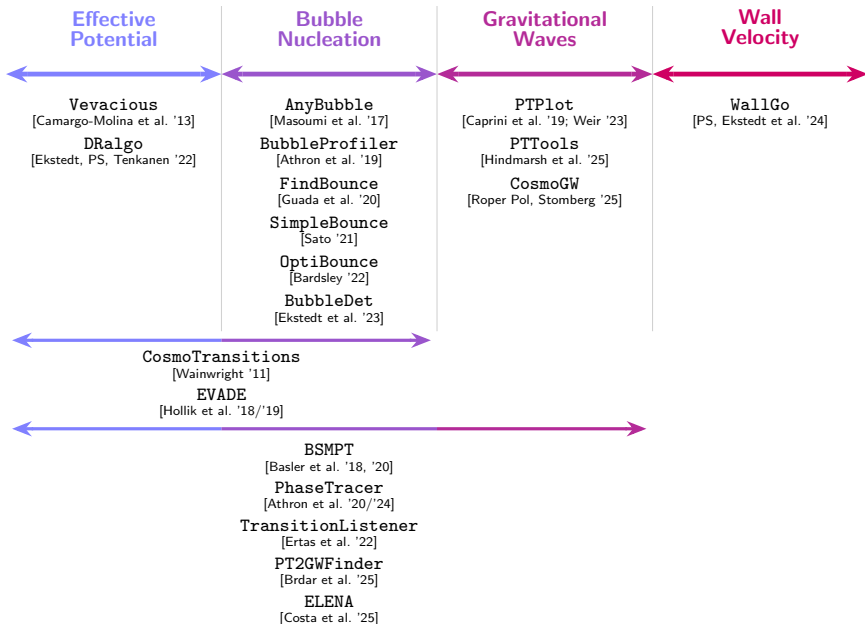
⁵⁹ Cutting, Hindmarsh, Weir, *Vorticity, kinetic energy, and suppressed gravitational wave production in strong first order phase transitions*, Phys. Rev. Lett. **125** (2020) 021302 [1906.00480]

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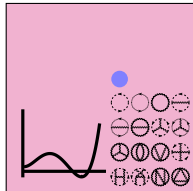


⁵⁹ Cutting, Hindmarsh, Weir, *Vorticity, kinetic energy, and suppressed gravitational wave production in strong first order phase transitions*, Phys. Rev. Lett. **125** (2020) 021302 [1906.00480]

The software landscape for PT induced GWs

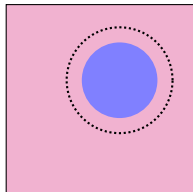


Conclusions: Progress and future challenges



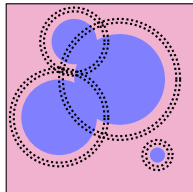
Precision thermodynamics of BSM theories:

- ▷ practical approach: **Effective Theories**
- ▷ Nucleation is hard. Discrepancy with lattice is becoming better.



Wall velocity and hydrodynamics of single bubbles:

- ▷ Can be predictive for the gravitational wave signal of colliding bubbles.



Collective effects:

- ▷ Fluid motion dominant source of GW signal,
- ▷ Simulations: decay of source and slow-down of bubbles, call for better modelling.

