ICCUB WINTER MEETING

Gravitational signals from symmetry breaking

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UNIVERSITAT DE BARCELONA

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Institut de Ciències del Cosmos
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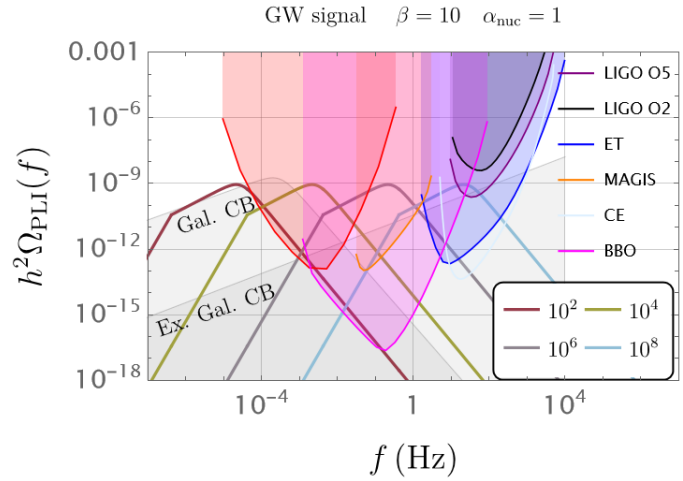
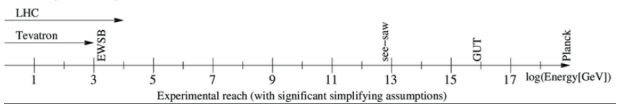
Gravitational wave detectors

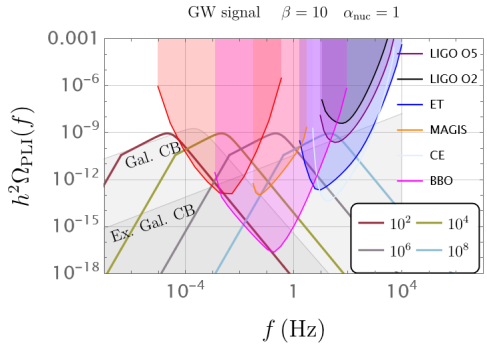


Search for a stochastic GW signal $\Rightarrow$ search for GW noise

Domain walls in the early universe



- Universe high-T: from $T \sim 10^{15}$ GeV



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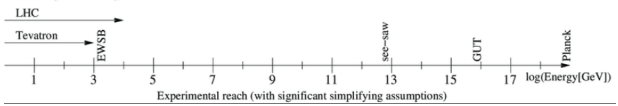

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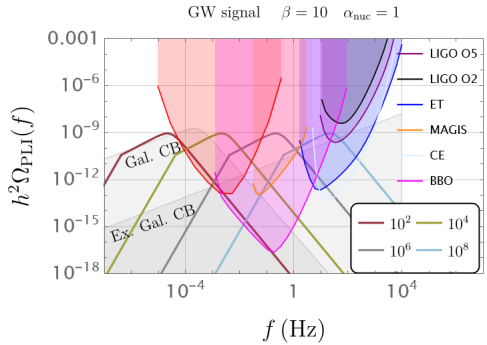
- Breaking of symmetry $\rightarrow$ GW stochastic background



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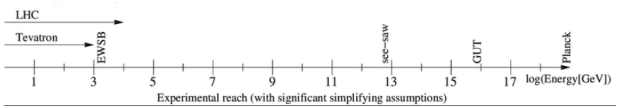

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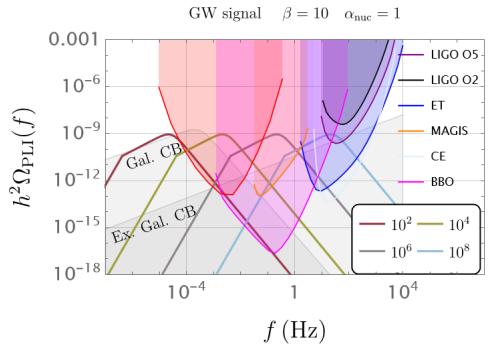
$$h^2\Omega_{GW}^{\text{today}} \sim \underbrace{h^2\Omega_{\text{rad}}}_{\sim 10^{-5}} \times \underbrace{\epsilon}_{\sim 0.01} \times \underbrace{S(??) \times f(k)}_{\text{source characteristics}}$$



Main question

How generic is it for symmetry breaking to induce detectable GW ?

GW from symmetry breaking remnants

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Topological Defects from Symmetry Breaking

- Symmetry breaking $\Rightarrow$ Topological defects form via Kibble-Zurek mechanism.

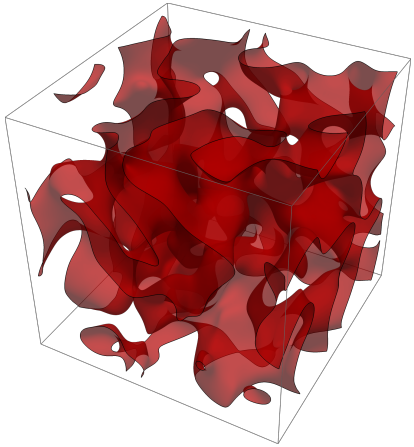
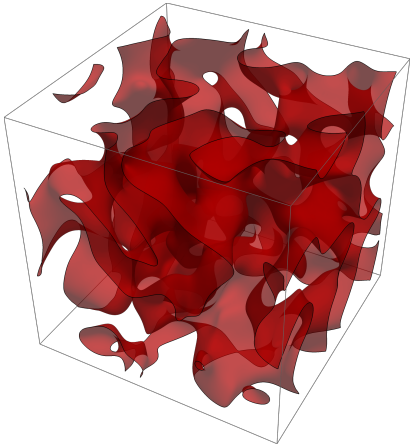


Figure:

Topological Defects from Symmetry Breaking

- Symmetry breaking $\Rightarrow$ Topological defects form via Kibble-Zurek mechanism.
- Defect type depends on the symmetry group and its breaking pattern:



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  1. Discrete symmetry ⇒ Domain Walls (DW)

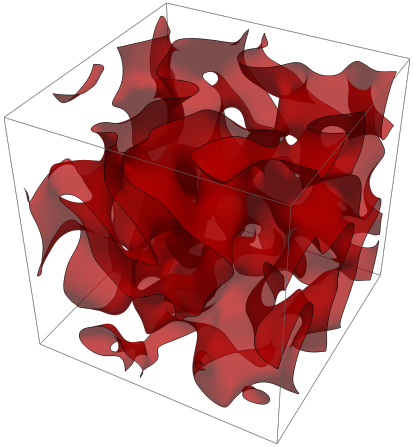

Figure: Domain Wall (2D defect)

Topological Defects from Symmetry Breaking

- Symmetry breaking ⇒ Topological defects form via Kibble-Zurek mechanism.
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  1. Discrete symmetry ⇒ Domain Walls (DW)
  2. U(1) symmetry ⇒ Cosmic Strings

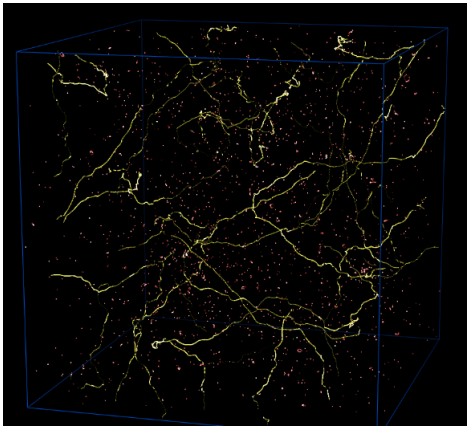

Figure: Cosmic String (1D defect)

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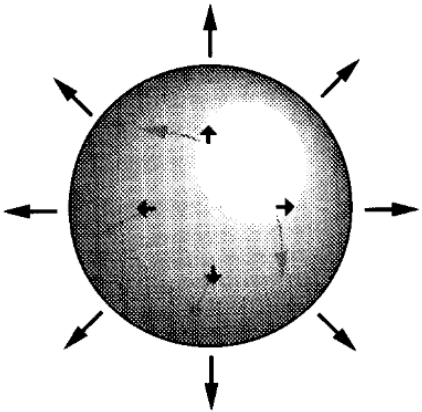

Figure: Magnetic Monopole (0D defect)

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  4. Non-Abelian groups ⇒ Textures

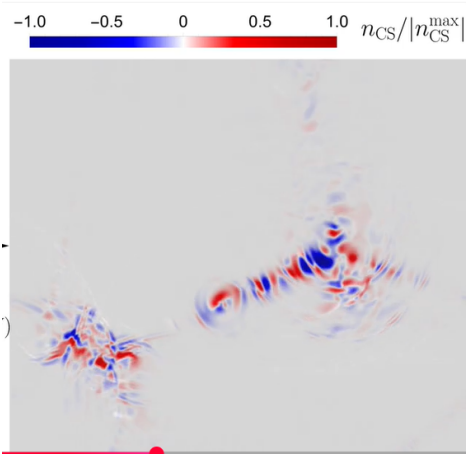

Figure: Texture (3D defect)

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  2. U(1) symmetry $\Rightarrow$ Cosmic Strings
  3. SU(2) or higher $\Rightarrow$ Magnetic Monopoles
  4. Non-Abelian groups $\Rightarrow$ Textures
- Defects are stable if topology forbids decay.

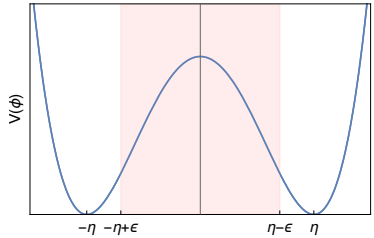
Figure:

Domain walls in the early universe

Universe high-T after inflation:cooling of primordial soup

- axion example

$$V_d(a) = m_a^2 f_a^2 \left(1 - \cos\left(\frac{a}{f_a}\right)\right)$$



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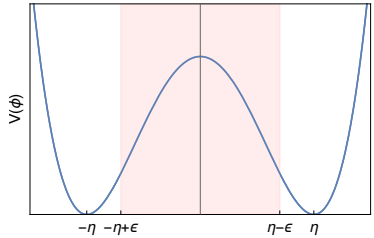

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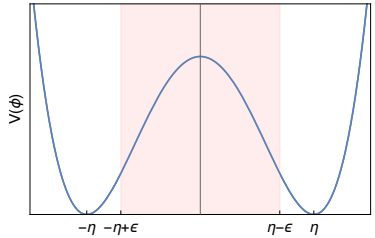

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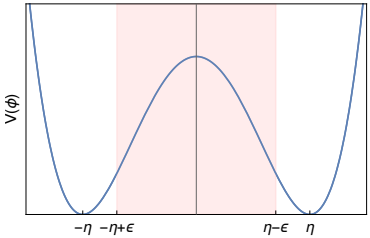

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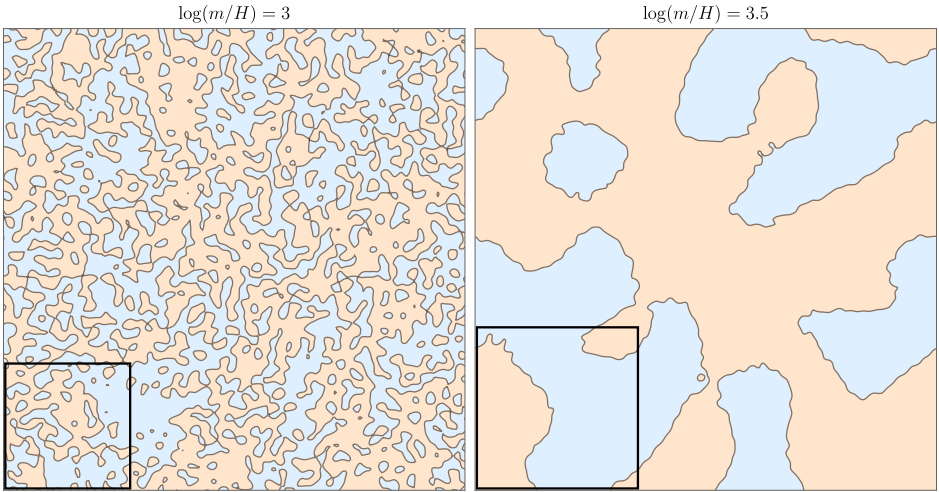
- Potential $V(T, a) = V_d(a) + V_{\text{thermal}}(T, a)$
- High T, potential melts: $V_d \sim$ const.
- Formation of DWs at $T \sim T_{\text{form}} \sim \sqrt{f_a m_a}$

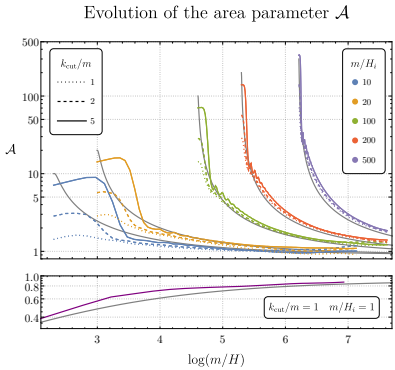
$$\sigma \sim m_a f_a^2$$

Formation of domain wall and Kibble Zurek mechanism



Attraction to scaling and GW signal

[2511.16649]: Blasi, Mariotti, Rase, MV



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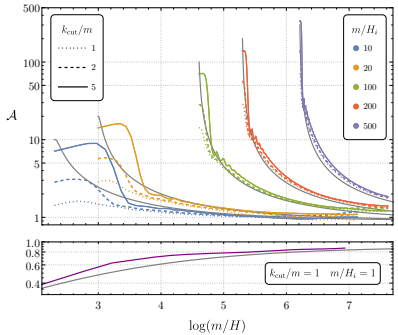
$$\mathcal{A}_{\rm initial} \sim \frac{m}{H(T\sim m)} \sim \frac{M_{\rm Pl}}{m} \gg 1$$

Evolution of the area parameter $\mathcal{A}$



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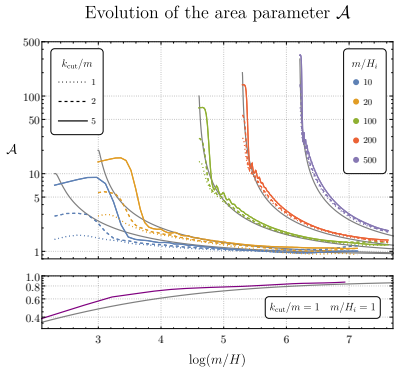

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Induced GW signal $P_{\rm gw} = \frac{G}{5}\left\langle \dddot{Q}_{ij}\, \dddot{Q}_{ij} \right\rangle$.

$$\rho_{\rm gw} \equiv \frac{1}{V}\int dt P_{\rm gw} \sim P_{\rm gw}\frac{t}{V}\,.$$

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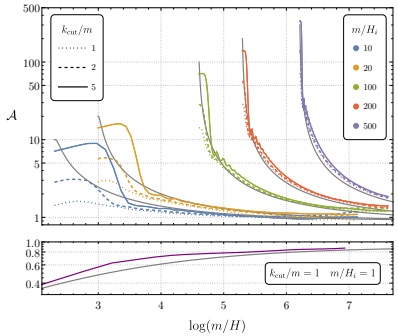

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$$Q_{ij}(t) = \int \rho_S(\mathbf{x},t)\left(x_i x_j - \frac{1}{3}\delta_{ij}\, r^2\right) d^3x \sim M_{dw}\ell^2$$

$$\rho_{\rm gw} \sim G\frac{M_{\rm dw}^2}{\ell^2}\times\frac{t}{V}\times\frac{V}{\ell^3} \sim \mathcal{A}^2\sigma^2/M_{\rm pl}^2 \qquad M_{\rm dw}\,, \sim \mathcal{A}\sigma\ell^2$$

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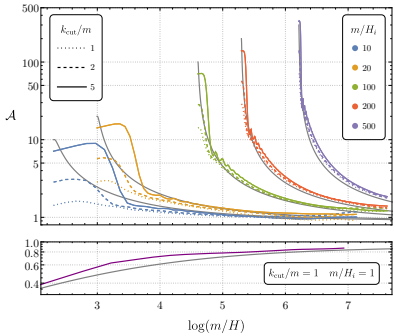

GW signal from domain wall

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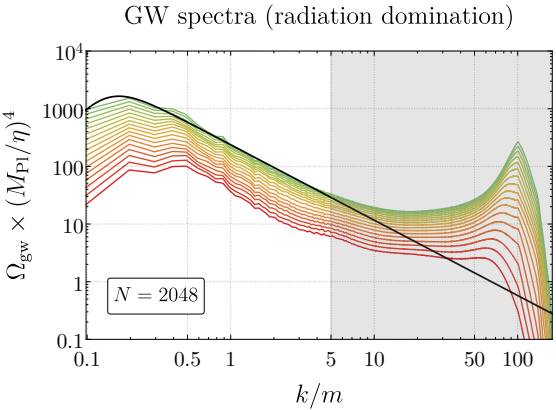

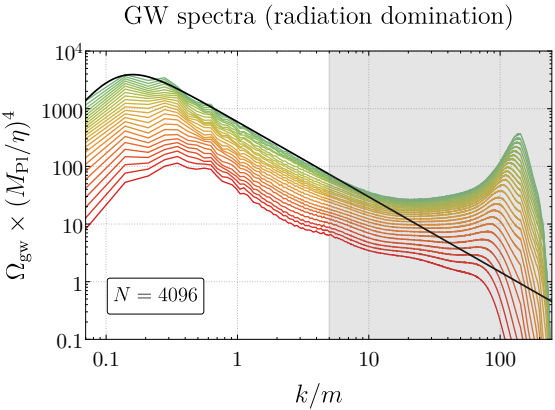

Domain wall and detectability

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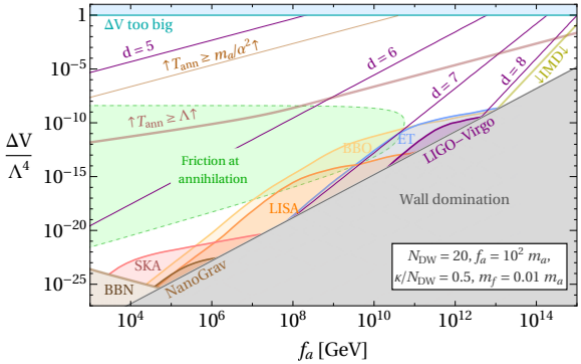

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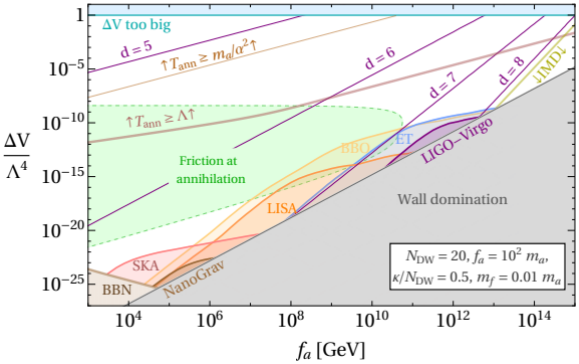

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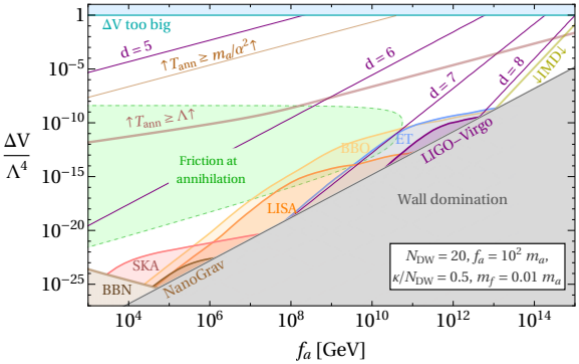

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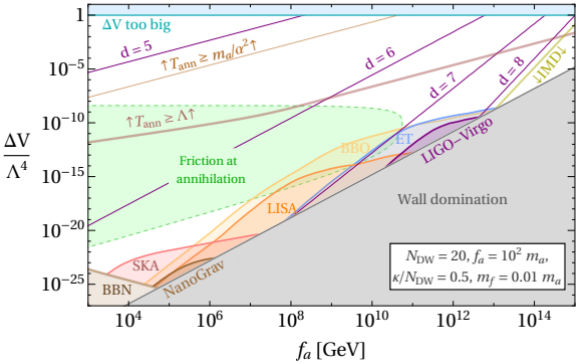

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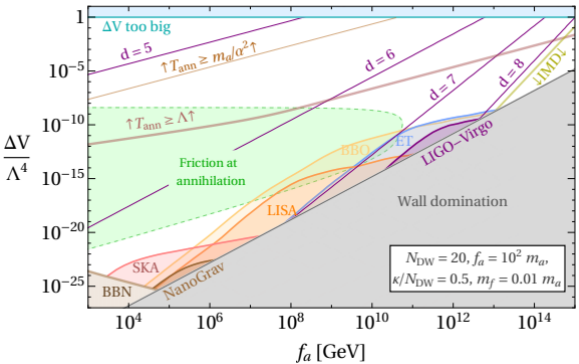
GW signal maximised if $T_{\rm ann} \to T_{\rm dom}$: Not related to special symmetry



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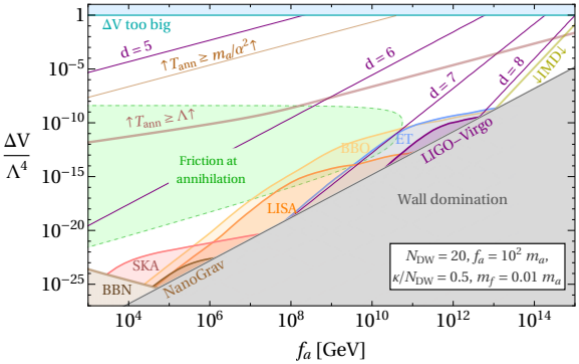
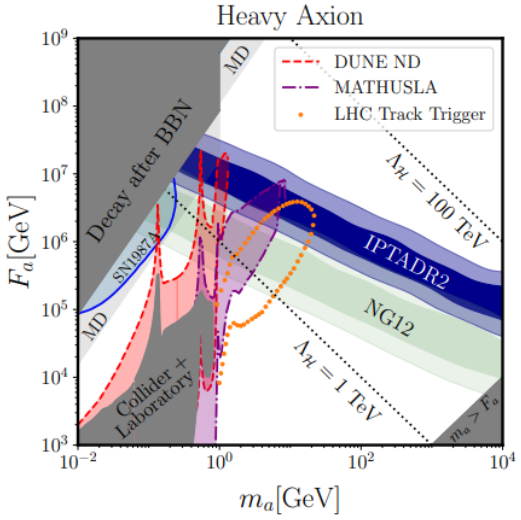


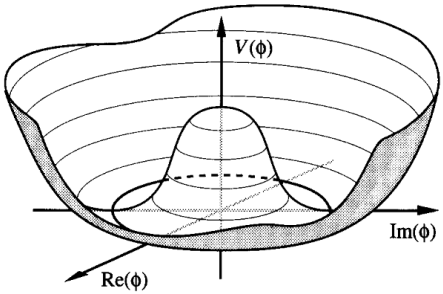
What is the physics of DW domination ? Z. Wang, M. Elley, MV with GRchombo

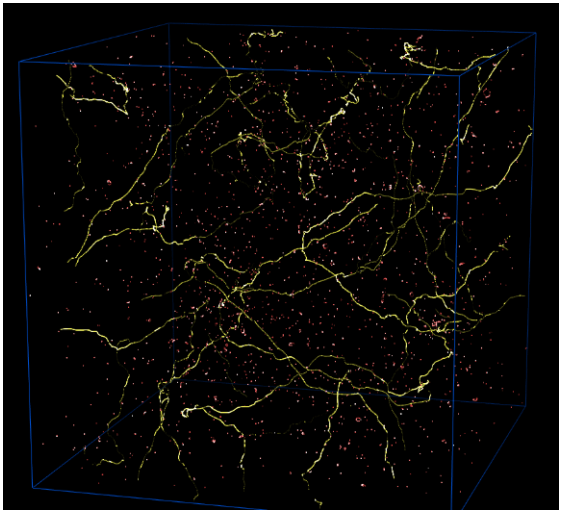
Domain wall at Nanograv

[arXiv:2204.04228]: Ferreira et al.



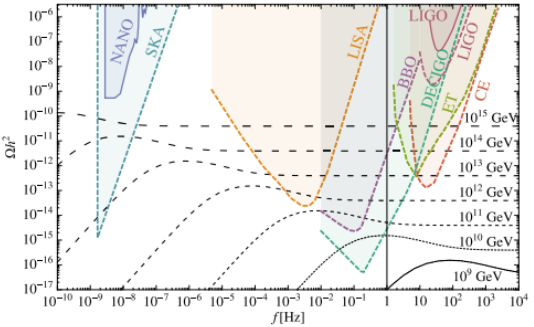
Cosmic strings





Cosmic strings and detectability

[arXiv:1908.03227]: Dror, et al.



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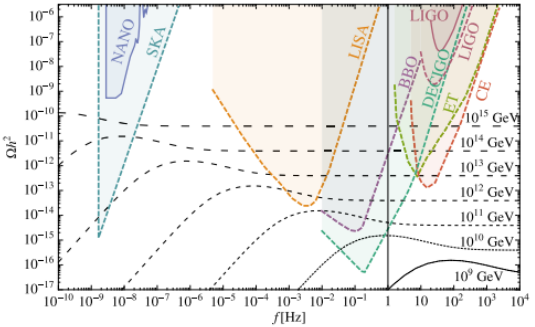

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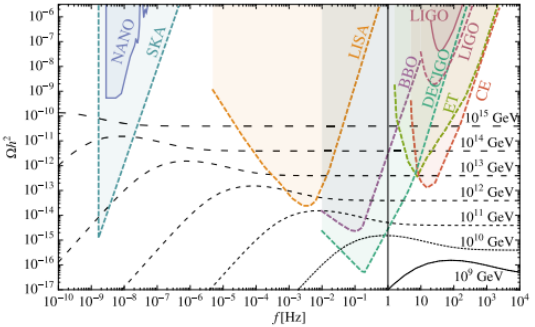
$\Rightarrow$ Scale invariant GW spectrum



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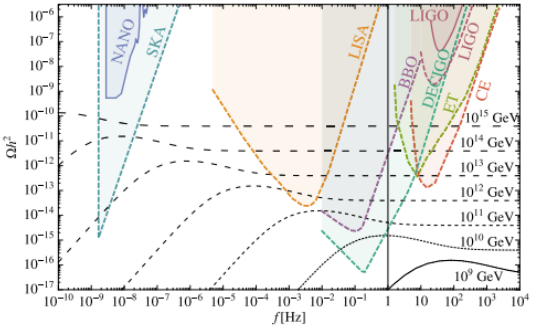
GW from NG strings ([arxiv:1909.00819]LISA)

$$\boxed{\Omega_{\rm GW} \sim \Omega_{\rm rad} \times (v/M_{\rm pl})}$$

(If particle production is subdominant)



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$$\rho_{cs} \propto v^2 H^2 \qquad \rho_{\rm rad} \propto H^2 : \frac{\rho_{cs}}{\rho_{\rm rad}} = \text{ const}$$

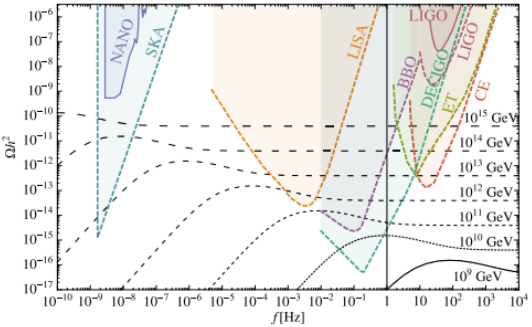
$\Rightarrow$ Scale invariant GW spectrum

GW from NG strings ([arxiv:1909.00819]LISA)

$$\boxed{\Omega_{\rm GW} \sim \Omega_{\rm rad} \times (v/M_{\rm pl})}$$

(If particle production is subdominant)

ET and LISA can detect $U(1)$ breaking for $v \gtrsim 10^{13-12}$ GeV.



Case of FOPTS

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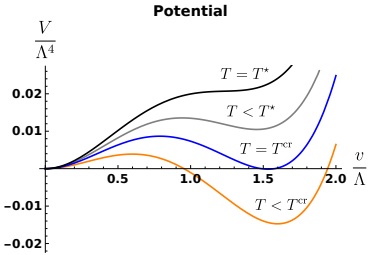
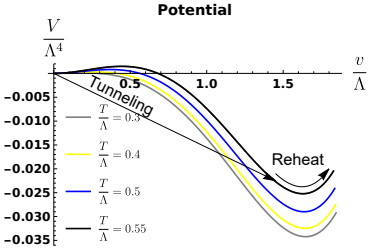
First order phase transition (FOPT) in the early universe

Universe high-T after inflation:cooling of primordial soup

- QFT = landscape of minima ⇒ PT





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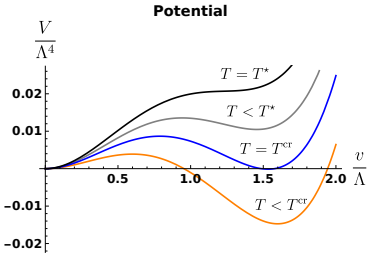

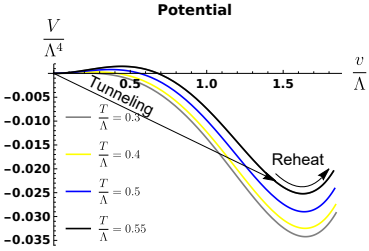

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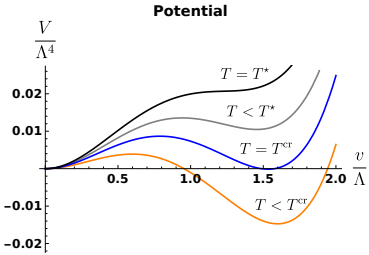

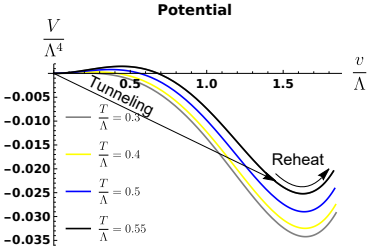

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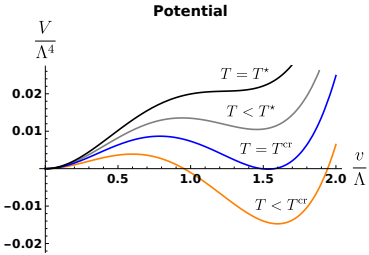

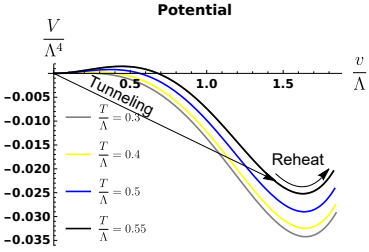

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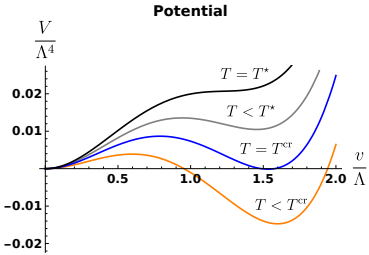
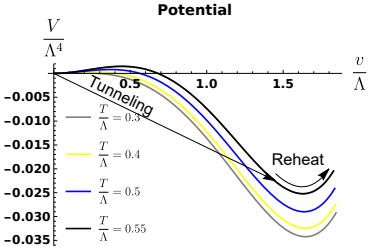
- Nucleation controlled by bounce solution

$$\Gamma \sim T^4 Exp\left[-\frac{S_3}{T}\right]$$



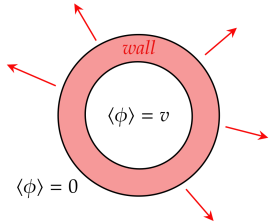


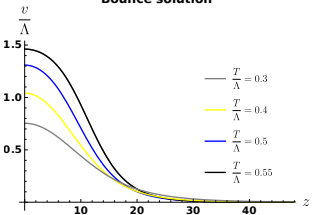
Nucleation and early expansion

- Energy released $\Delta V \Rightarrow$ Driving energy:

$$E_{\text{driving}} = -\frac{4}{3}\pi \Delta V R^3 \text{ VS } \Delta \mathcal{P}_{\text{tension}} = 4\pi\sigma R^2$$

Expansion when $R_{\text{initial}} > R_c \sim \sigma/\Delta V$





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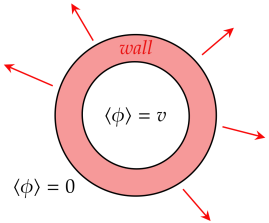

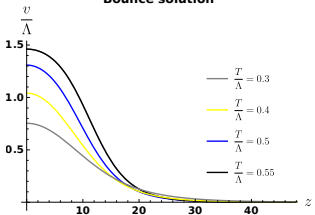

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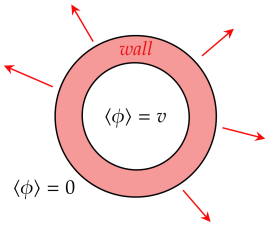

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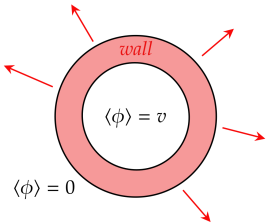
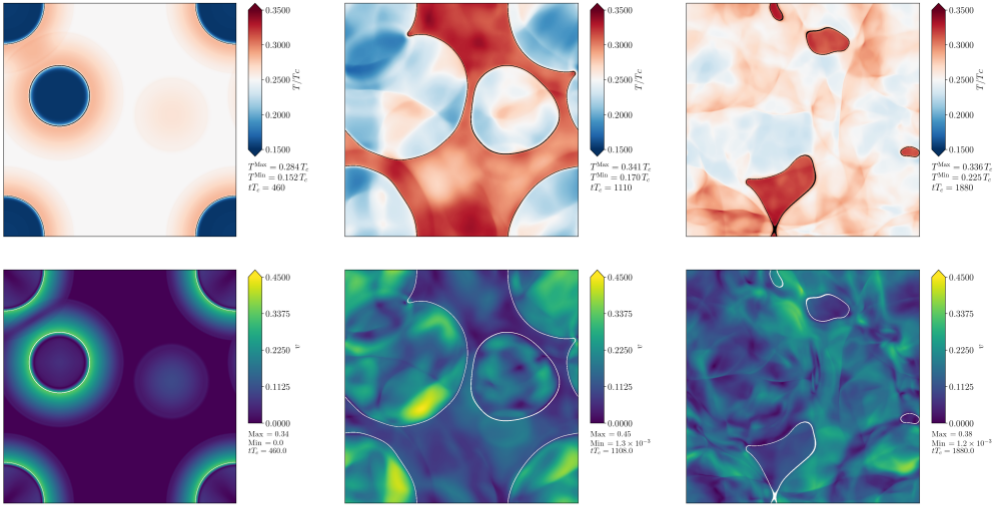
$$\beta \equiv \frac{t_{\text{exp}}}{t_{PT}} = \frac{1}{t_{PT} H} \propto R^{-1}_{\text{collision}}$$

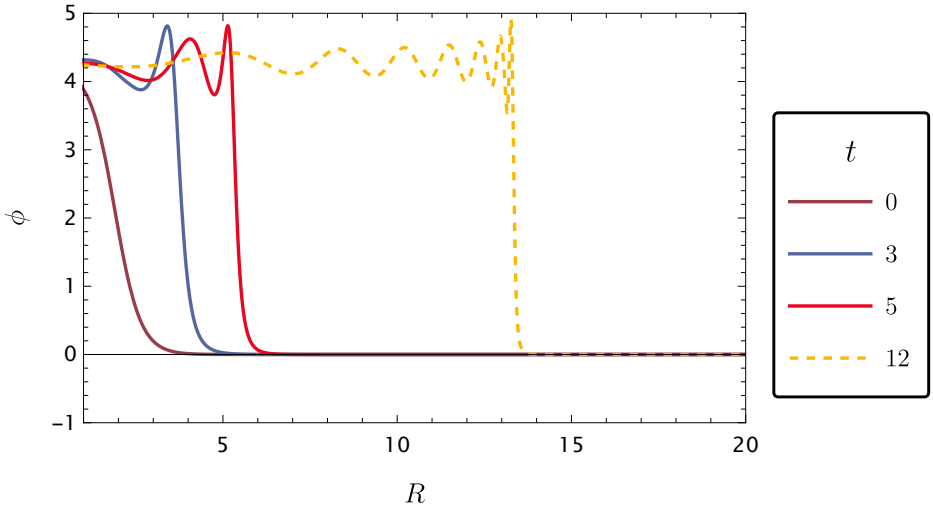


FOPT pictorially

Cutting, Hindmarsh and Weir:[1906.00480]: video in https://vimeo.com/showcase/5968055



The bubble wall in time



FOPT and Gravitational waves

1. Bubbles can produce a stochastic GW background from

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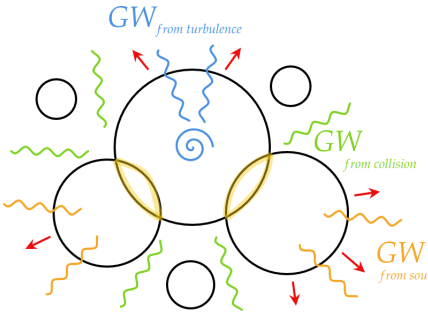
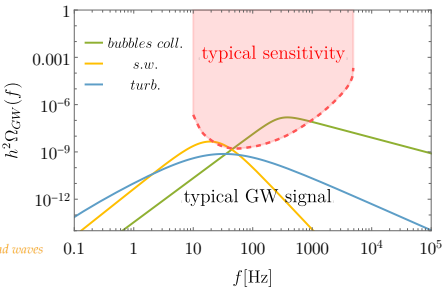
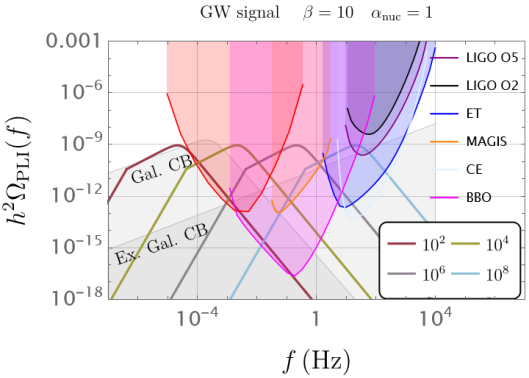
   - bubble collision
   - sound waves
   - turbulence

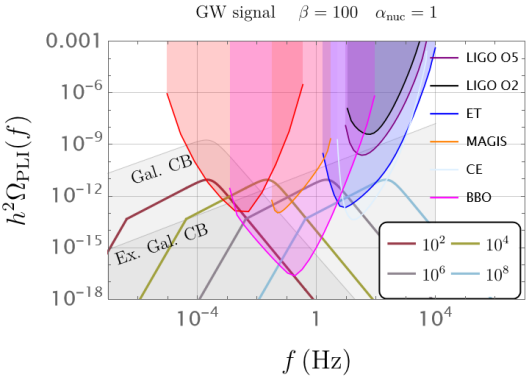




Primordial GWs could be observed soon: Frequency $\Rightarrow$ information about $T_{\rm reh}$: $f_{\rm peak} \propto T_{\rm reh}$

Observation prospects of GW





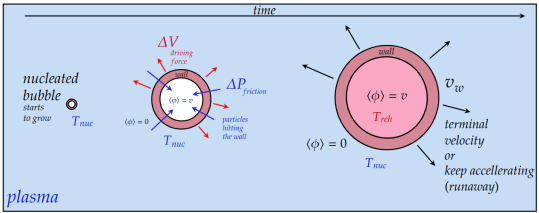
$$\Omega_{\rm GW} \propto v_w \left(\kappa_f \frac{\alpha_N}{1+\alpha_N} \right)^2 \frac{1}{\beta^2} \quad \Rightarrow \quad \text{Need } \textit{strong}, \textit{long} \text{ PT with } \textit{fast walls}$$

Good news: they *kinda* correlate

[2207.02230]: Azatov, Barni, Chakraborty,MV, Yin

v_w and α_N

- v_w: ΔV against $\Delta \mathcal{P}$



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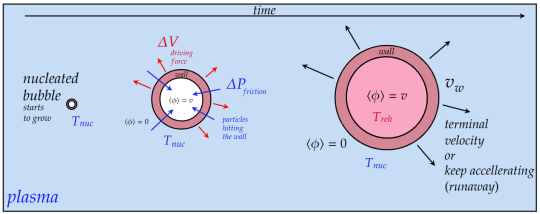

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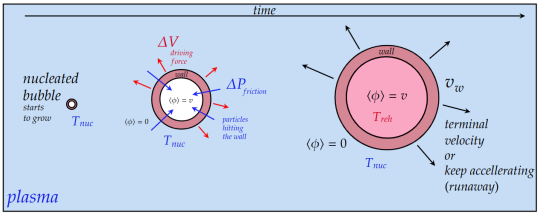

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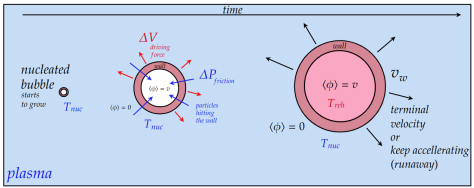

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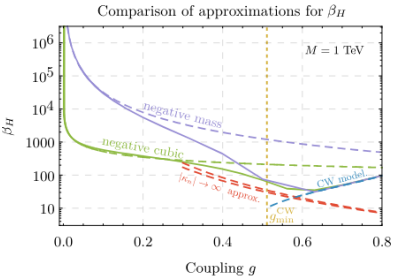

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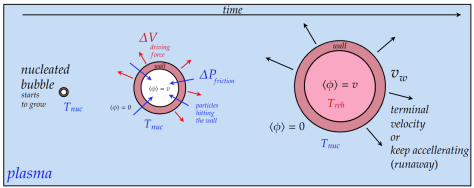

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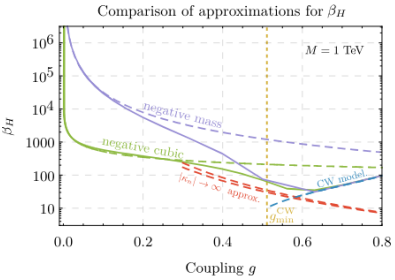

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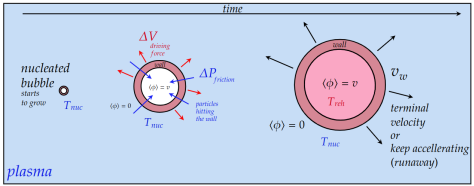

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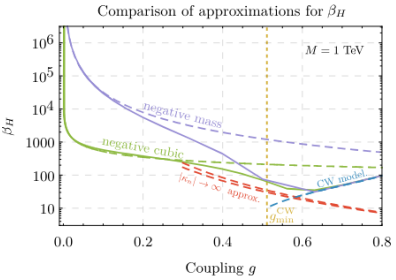

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For large GW signal $\Rightarrow$ cooling or supercooling: $\Rightarrow$ where is supercooling ??

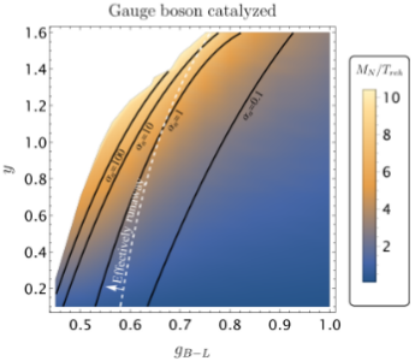
Conformal models

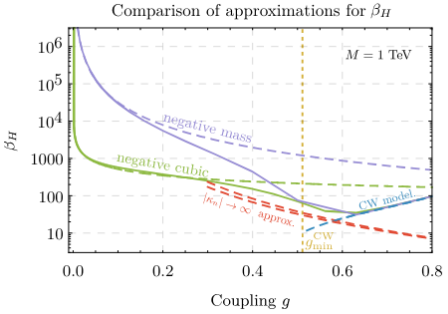
[2212.08085]: Noam Levi, Toby Opferkuch, Diego Redigolo,

[2003.10265]: Azatov, MV

Impose a scale symmetry: the CW potentials

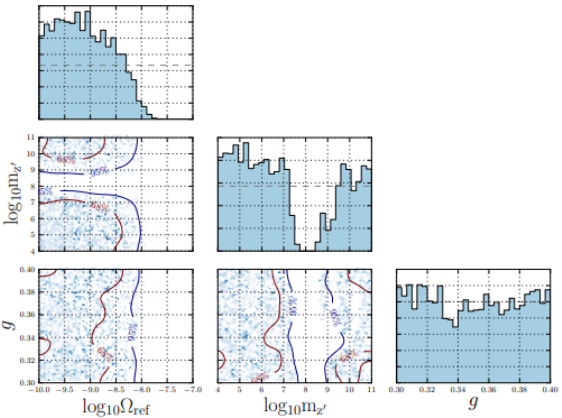
$$V_0(\phi) = \sum_i \frac{m_i^4(\phi)}{64\pi^2}\left(\log\frac{m_i^2(\phi)}{\mu^2} - c_i\right)$$





Constraining models with LVK

[2209.14707]: Badger, Fornal, Martinovic, Romero, Turbang, Guo, Mariotti, Sakellariadou, Sevrin,Yang,Zhao



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$$V_0(\phi) = \frac{m^4_{Z'}(\phi)}{64\pi^2}\left(\log\frac{m^2_{Z'}(\phi)}{\mu^2} - c_i\right)$$

$$m^2_{Z'}(\phi) = 4g^2\phi^2$$

Interferometers can help constraining particle physics for very strong FOPT (mostly conformal models)

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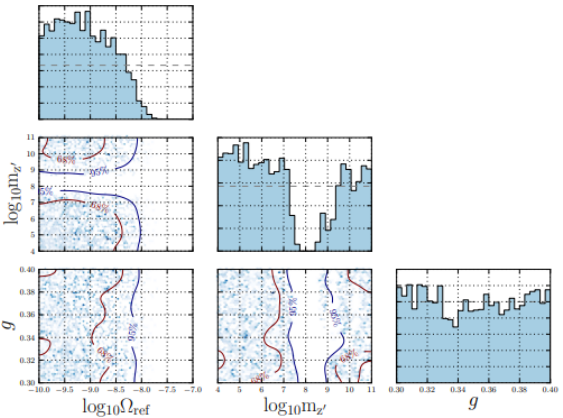

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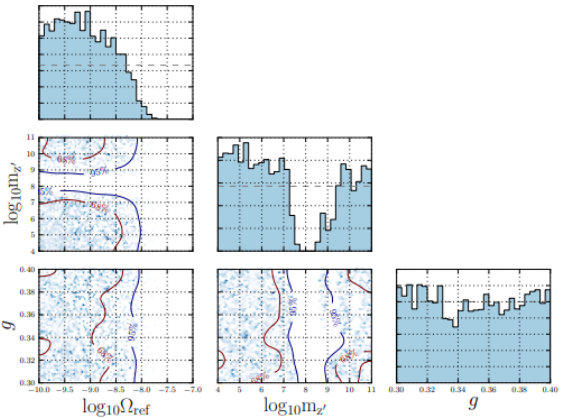

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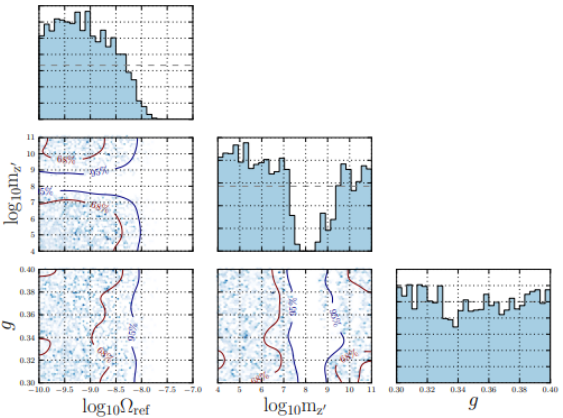

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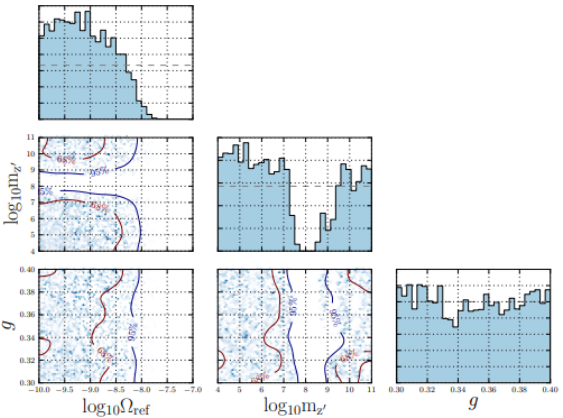
- Take into account CBC: $\Omega_{\rm ref}$.
- GW signal from sound waves
- Constraining $\quad (g, \quad m_{Z'} = 2gv_\phi, \quad \Omega_{\rm ref})$?

Interferometers can help constraining particle physics for very strong FOPT (mostly conformal models)

Constraining models with LVK

[2209.14707]: Badger, Fornal, Martinovic, Romero, Turbang, Guo, Mariotti, Sakellariadou, Sevrin,Yang,Zhao



- Consider the conformal model

$$V_0(\phi) = \frac{m^4_{Z'}(\phi)}{64\pi^2}\left(\log\frac{m^2_{Z'}(\phi)}{\mu^2} - c_i\right)$$

$$m^2_{Z'}(\phi) = 4g^2\phi^2$$

- Take into account CBC: Ω_{ref}.
- GW signal from sound waves
- Constraining $(g, \quad m_{Z'} = 2gv_\phi, \quad \Omega_{\mathrm{ref}})$?
- Disfavor $g \in [0.3, 0.4], \quad m_{Z'} \in [10^7, 10^9]$ GeV

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Case of the EWPT

Let us add a hard scale: m_h

- Problem of EWPT for supercooling:

$$V_{\rm tree} = -\frac{m_h^2}{2}h^2 + \frac{\lambda}{4}h^4, \qquad V_T(h) \propto \sum_i g_i^2 \frac{T^2 h^2}{24} - \frac{T h^3}{12\pi} \qquad \Rightarrow \boxed{T_{\rm min} \propto m_h}$$

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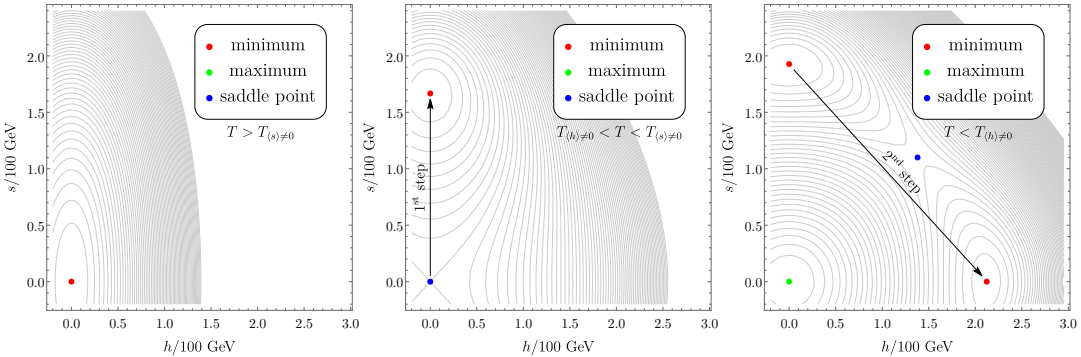
- **2-steps PT**: $\boxed{(0,0) \xrightarrow{SOPT} (0,v_s) \xrightarrow{FOPT} (v_{EW},0)}$

Relativistic EWPT: $2-$step PT

[2207.02230]: Azatov, Barni, Chakraborty,MV, Yin,

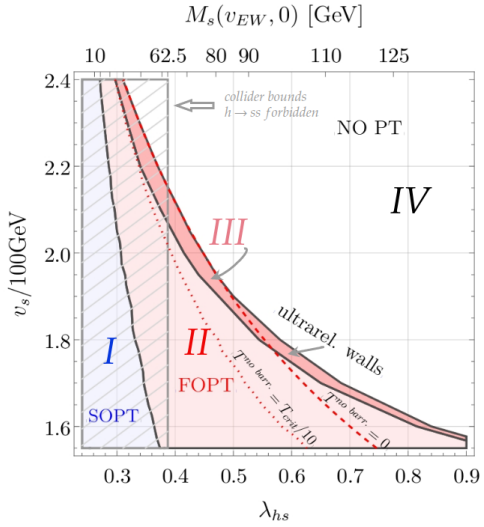
3. In the second PT:

$$m^2_{\rm eff}(T) = -\frac{m_h^2}{2} + \frac{\lambda_{hs}}{2} v_s^2 \to 0 \qquad \text{This is tuning!}$$



Singlet EWPT: Parameter scan

[2207.02230]: Azatov, Barni, Chakraborty, MV, Yin



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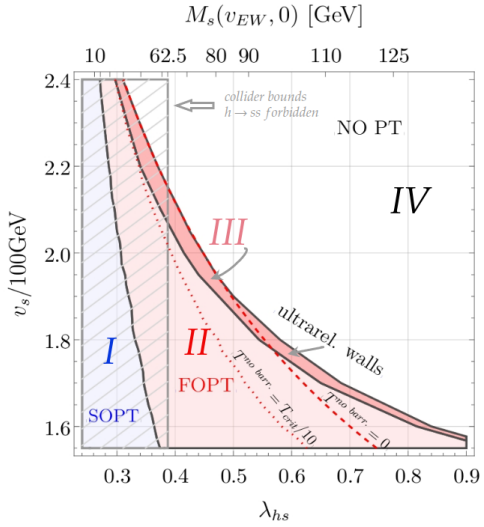
I. SOPT: there is **never a barrier** separating the two minima



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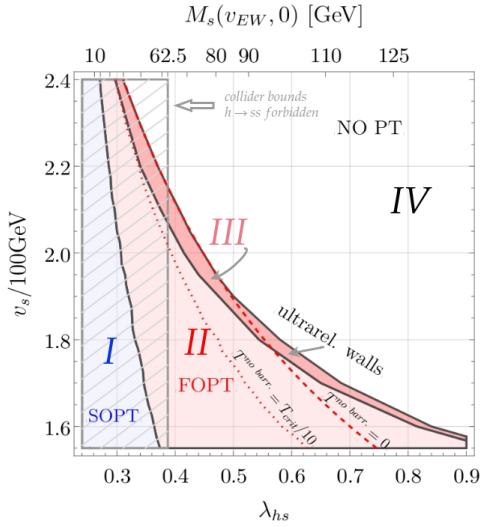

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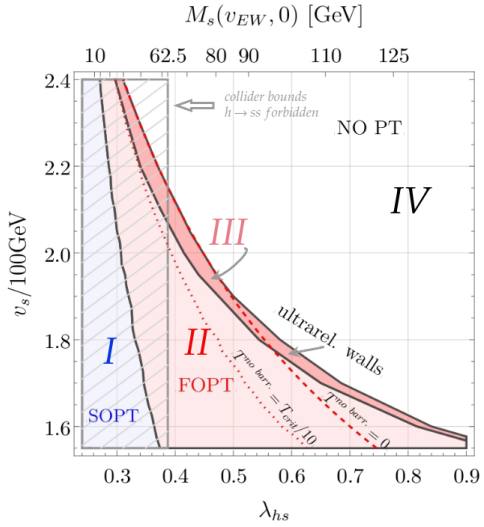

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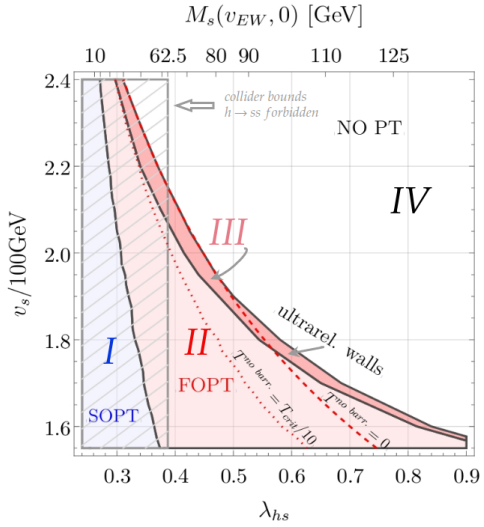
IV. No PT: the **system remains stuck** in the FV and never nucleates



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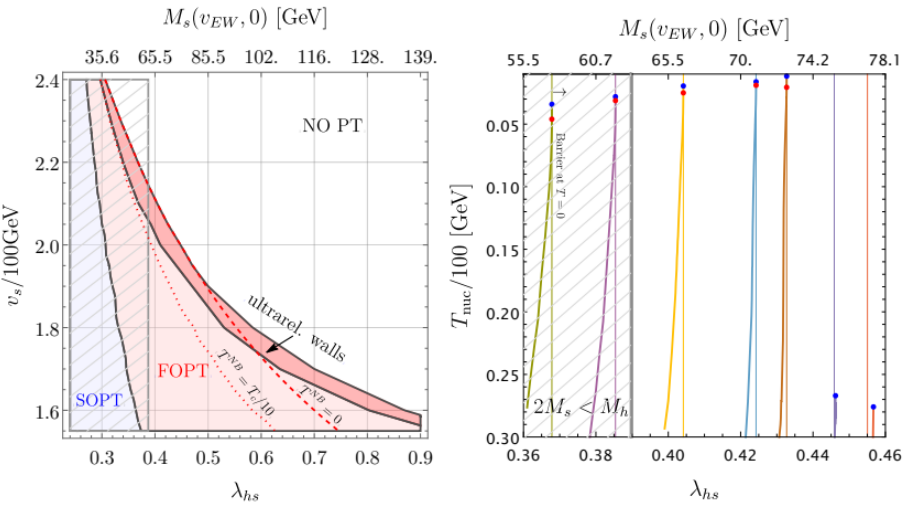

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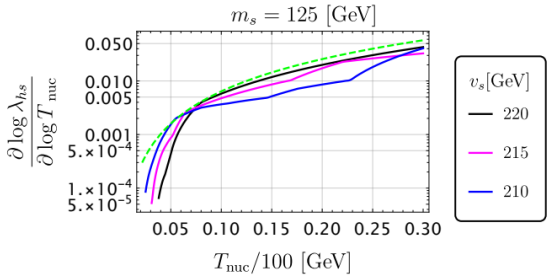

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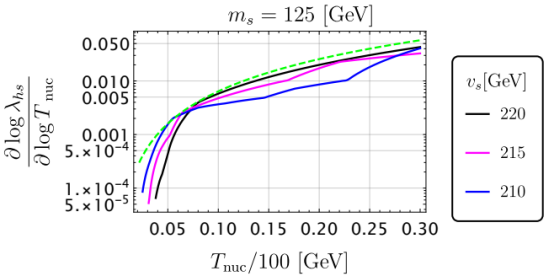
What fraction of the parameter space brings supercooling ?



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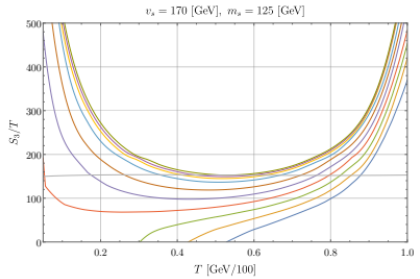

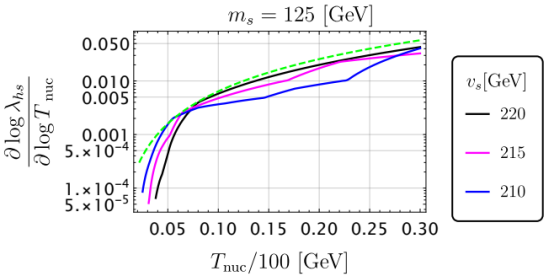

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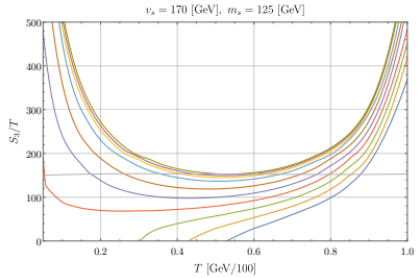

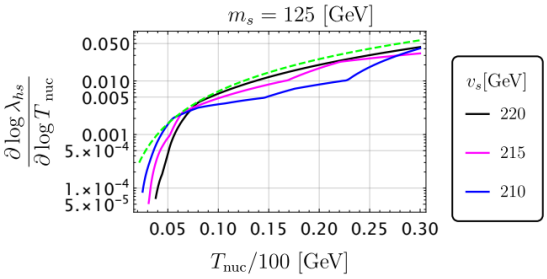

Supercooling requires tuning !!

Topological defect formation during FOPTs

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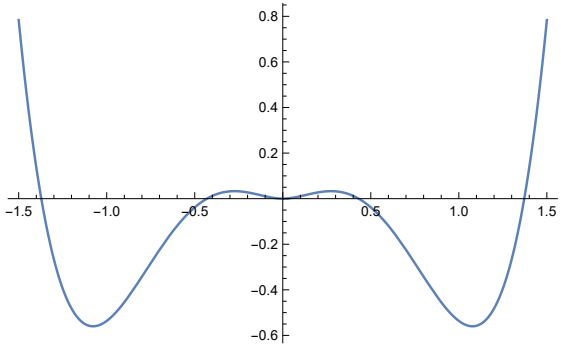
DW from bubbles

[26xx.xxxx]: Mariotti, Nagels, MV



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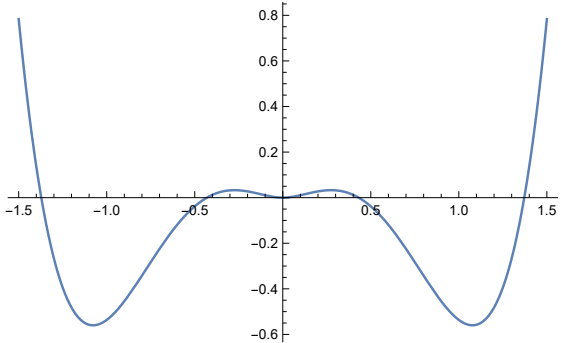

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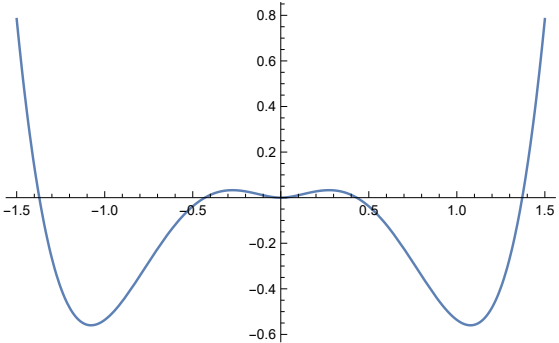

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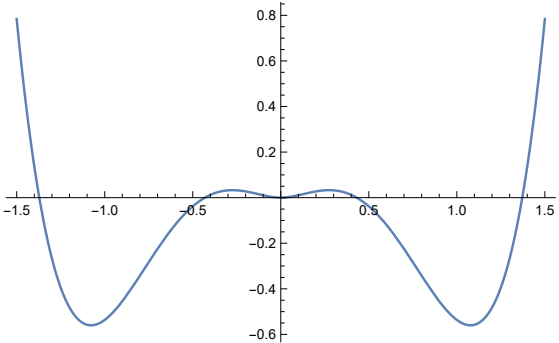

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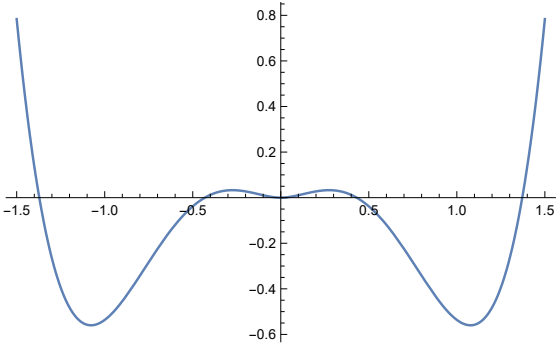
which one dominates ? Is the DW relativistic ?



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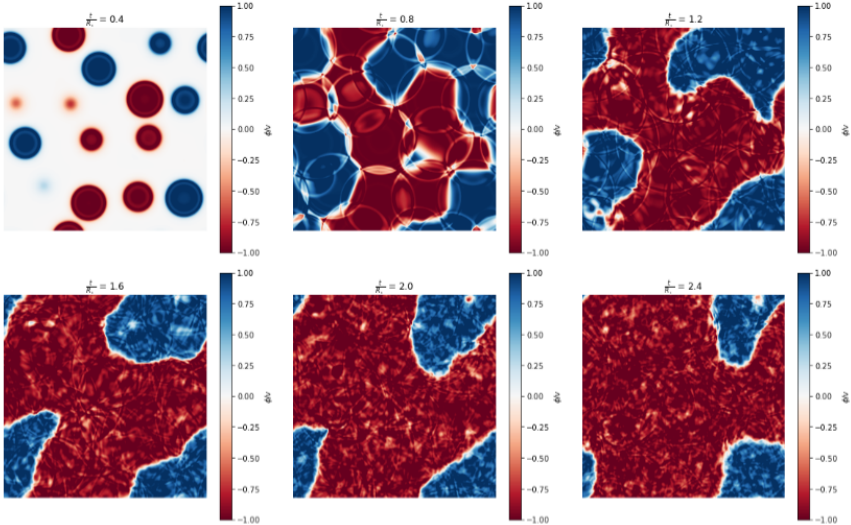
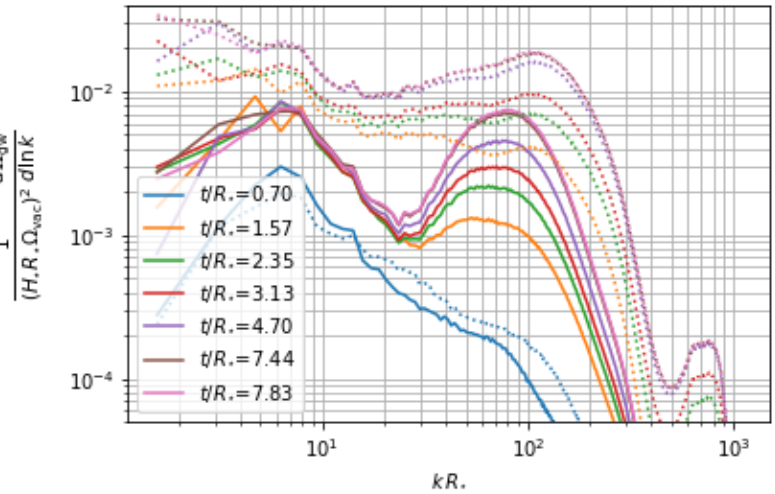


Enhanced GW signal ??

[26xx.xxxx]: Mariotti, Nagels, MV



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- From FOPTs: large signal if mild supercooling.
- Supercooling natural if underlying conformal symmetry
- Supercooling requires fine-tuning if hard mass scale in the theory

Where does the energy go ?

[1004.4187]: Espinosa,No,Konstandin, Servant,[2406.01596]:Barni,Blasi,MV

- Fluid motion $\Rightarrow$ GW !

$$\underbrace{\frac{\xi_w^3}{3}\epsilon}_{\text{vacuum}} + \underbrace{\frac{3}{4}\int \omega_N \xi^2 d\xi}_{\text{initial therm energy}} = \underbrace{\int \gamma^2 v^2 \omega \xi^2 d\xi}_{\text{fluid motion}} + \underbrace{\frac{3}{4}\int \omega \xi^2 d\xi}_{\text{final therm energy}}$$

-

$$\frac{\rho_{\rm kin}}{\rho_i} \equiv \frac{\kappa_f \alpha_N}{1+\alpha_N} \ ,$$

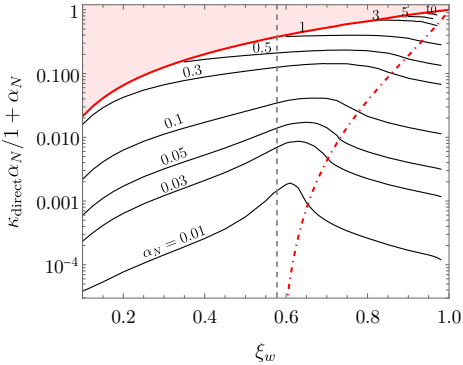

Figure: [2406.01596]:Barni,Blasi,MV