INVISIBLE TRACES OF CONFORMAL SYMMETRY BREAKING

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Yo, I'm
free


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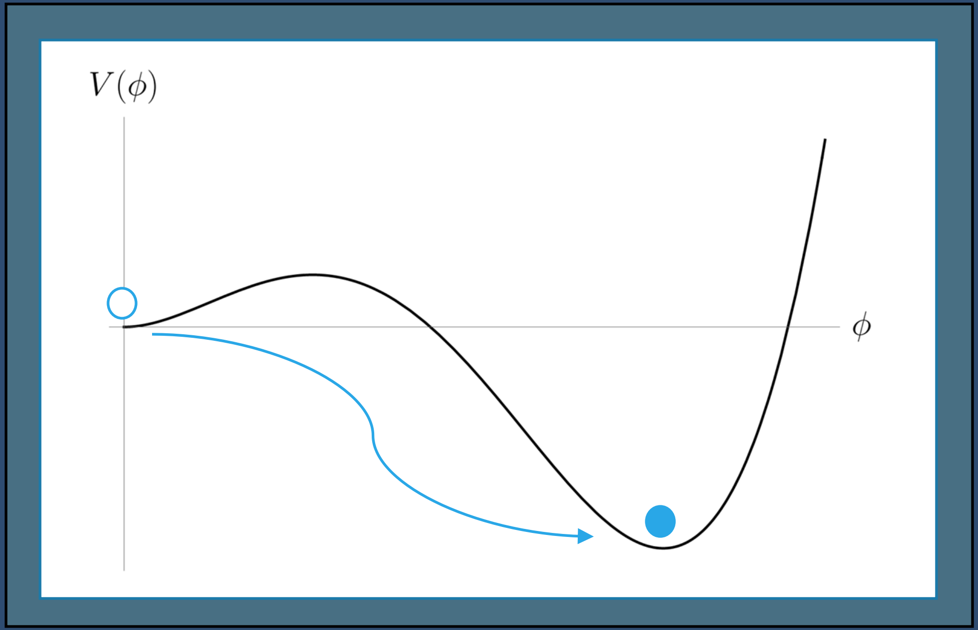
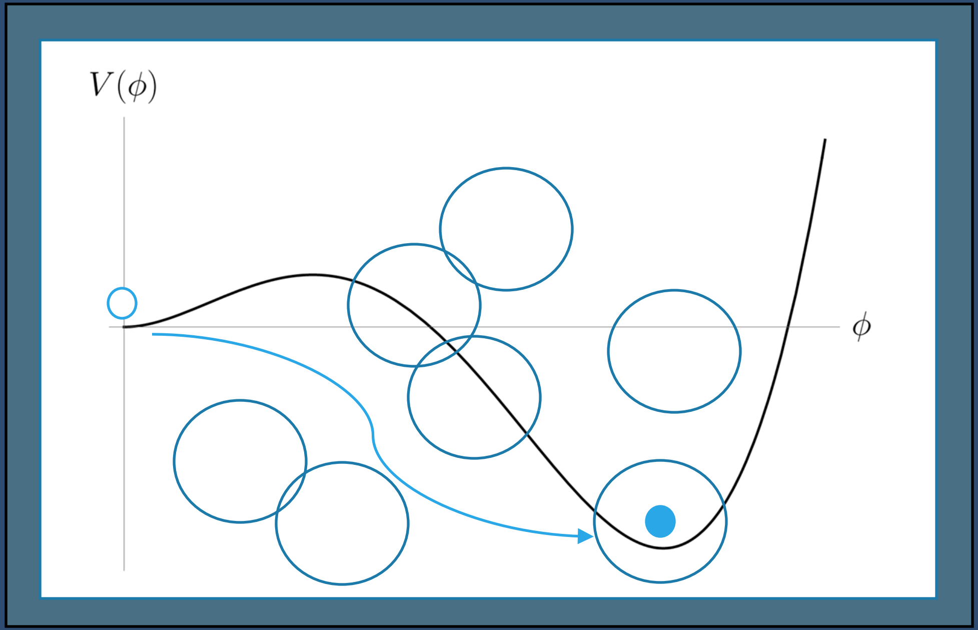
free

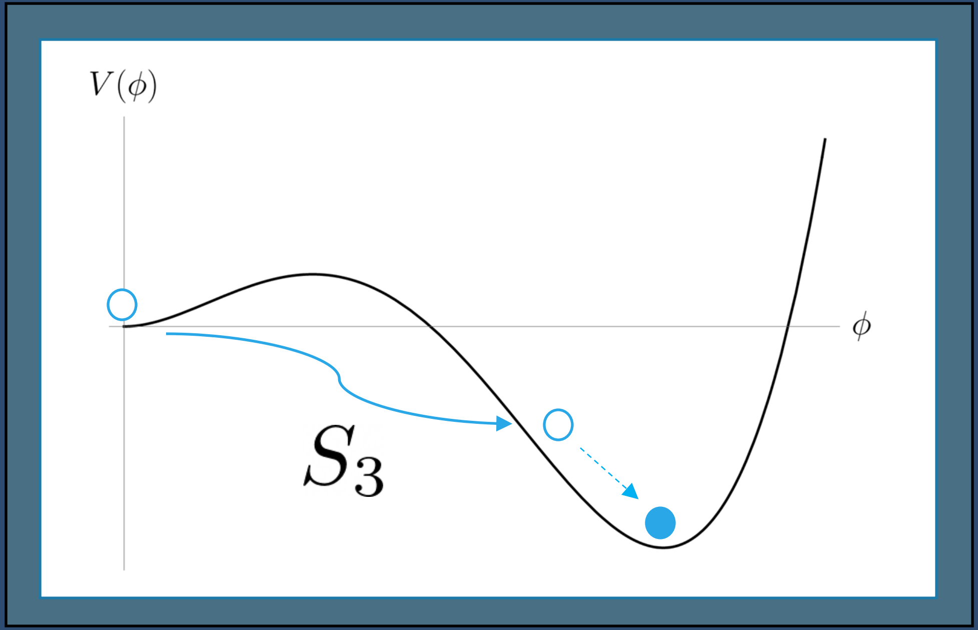

$V(\phi)$
ϕ


Yo, I'm
free


$V(\phi)$
ϕ

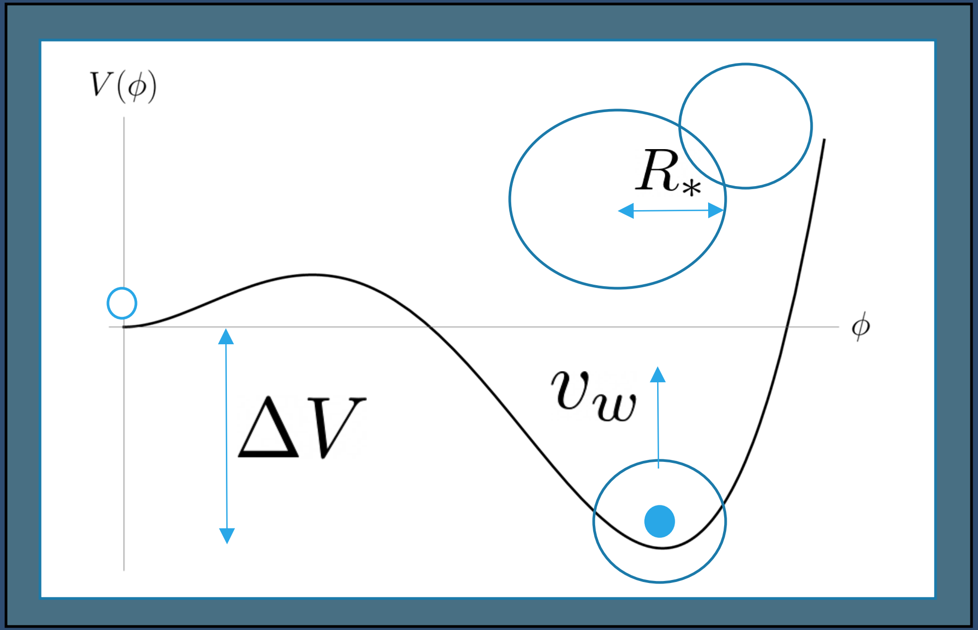
Thermal tunnelling

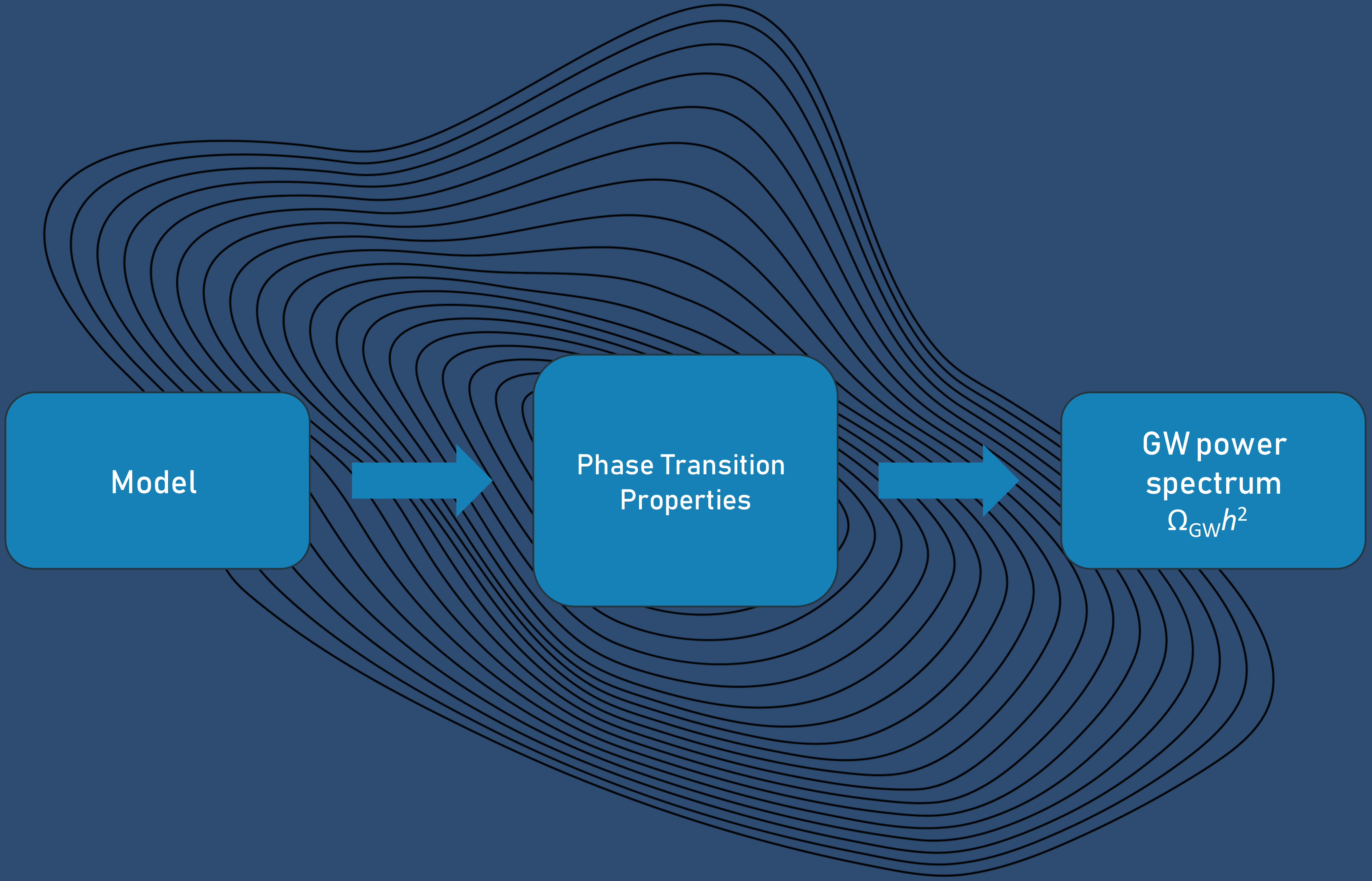
- Decay rate is given as: $$\Gamma(T) \simeq T^4 \left(\frac{S_3}{2\pi T}\right)^{\frac{3}{2}} e^{-S_3/T}$$
- The action of the field configuration $$S_3 = 4\pi \int r^2 \, \mathrm{d}r \left[\frac{1}{2}\left(\frac{\mathrm{d}\varphi}{\mathrm{d}r}\right)^2 + V_{\mathrm{eff}}(\varphi, T)\right]$$



Cosmological phase transitions

- Strength of the transition $\alpha \sim \frac{\Delta V}{\rho_{\text{rad}}(T_p)}$
- Average bubble radius R_* or inversed time scale $\beta \sim R_*^{-1}$
- Bubble wall velocity v_w




Model
Phase Transition Properties
GW power spectrum
$\Omega_{GW}h^2$

$$V_{\rm tree} = \frac{1}{4}\left(\lambda_1 h^4 + \lambda_2 h^2 \phi^2 + \lambda_3 \phi^4\right)$$

C. D. Carone, R. Ramos, *arXiv:1307.8428,* T. Hambye, A. Strumia, D. Teresi, arXiv:1306.2329

Classical conformal symmetry

All masses generated via Coleman-Weinberg mechanism

Only two free parameters

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Perturbative and stable up to the Planck scale

Vector DM candidate, gauge boson X

Exhibits supercooling

C. D. Carone, R. Ramos, *arXiv:1307.8428,* T. Hambye, A. Strumia, arXiv:1306.2329

Dark Matter

New gauge boson *X*, with mass $m_X^2 = \frac{1}{4} g_X^2 \phi^2$

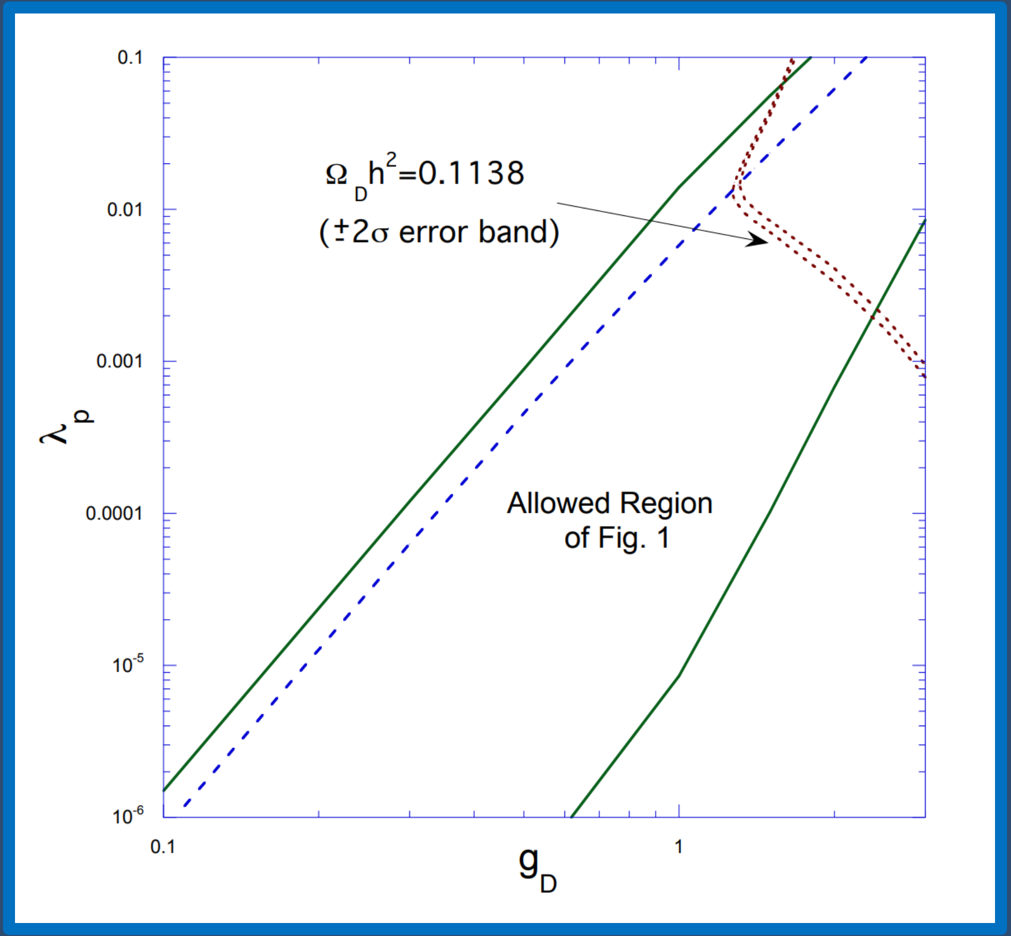
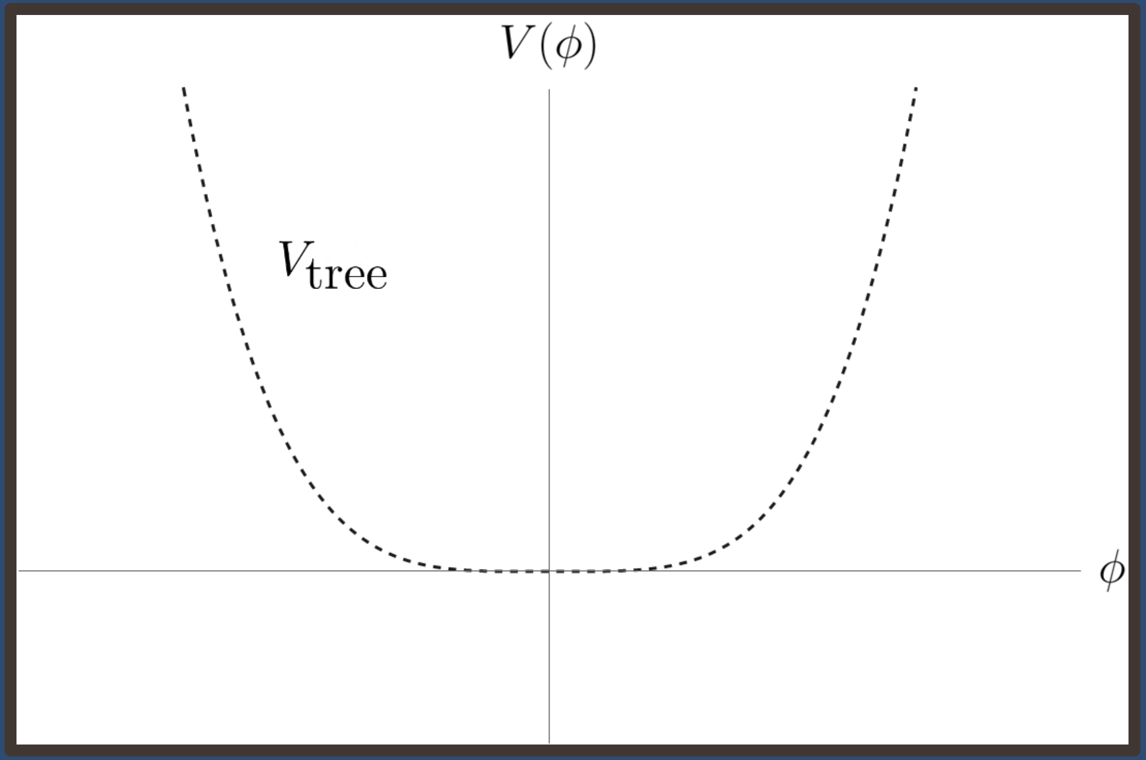


Figure from C. D. Carone, R. Ramos , arXiv:1307.8428

Coleman-Weinberg Mechanism

Example: massless scalar electrodynamics.



$$V_{CW} = \underbrace{\frac{\lambda}{4!}\phi^4}_{V_{\text{tree}}}$$

Coleman-Weinberg Mechanism

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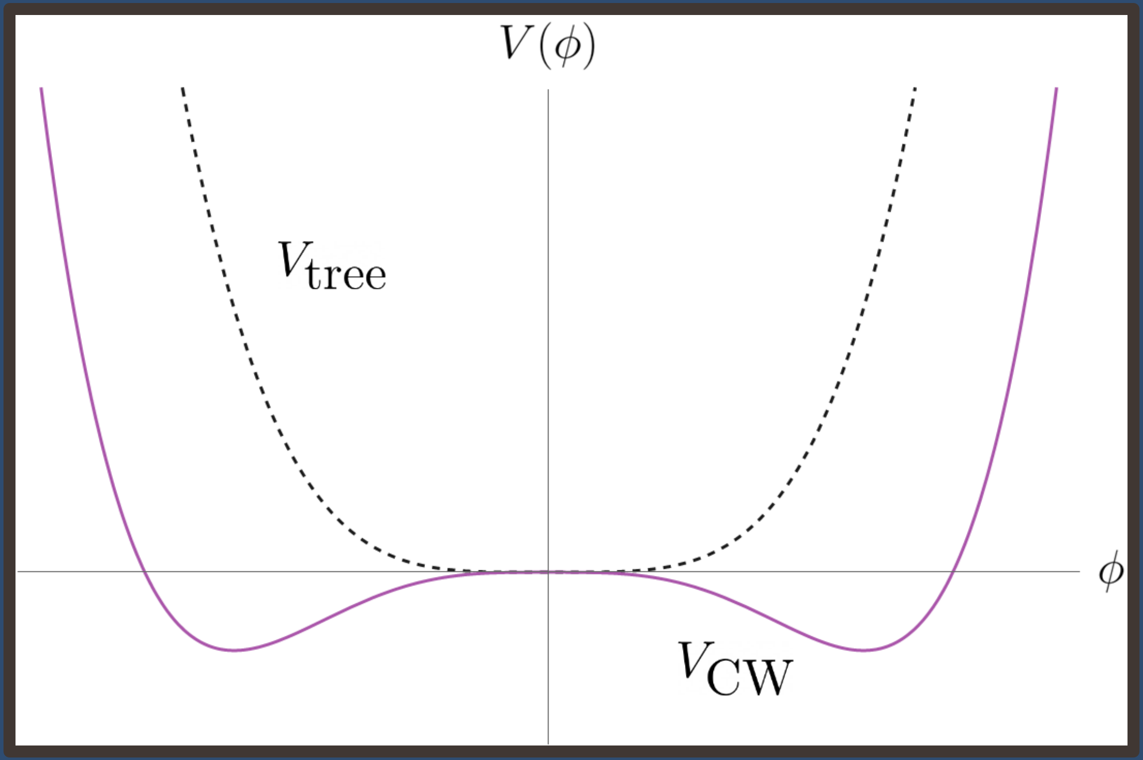
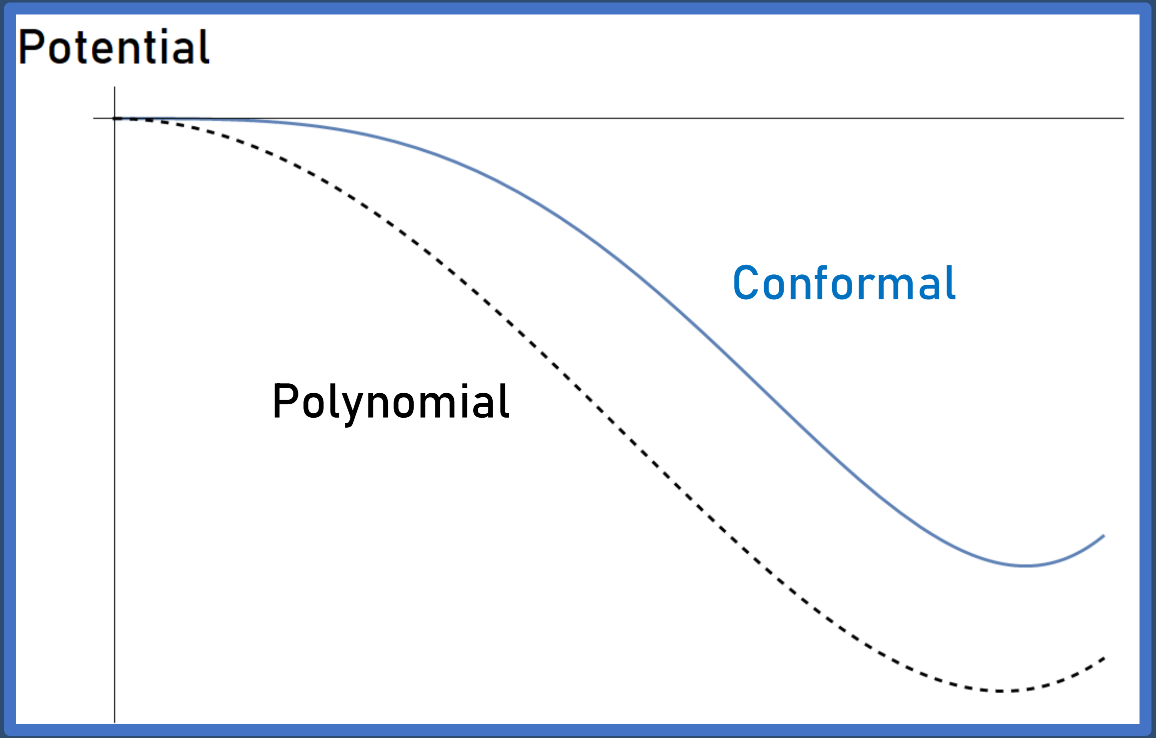


$$V_{CW} = \underbrace{\frac{\lambda}{4!}\phi^4}_{V_{\text{tree}}} + \underbrace{\frac{\lambda^4}{64\pi^2}\phi_c^4\left(\ln\frac{\phi_c^2}{\mu^2} - \frac{3}{2}\right)}_{\text{"scalar" correction}} + \underbrace{\frac{3e^4}{64\pi^2}\phi_c^4\left(\ln\frac{\phi_c^2}{\mu^2} - \frac{5}{6}\right)}_{\text{"boson" correction}}$$

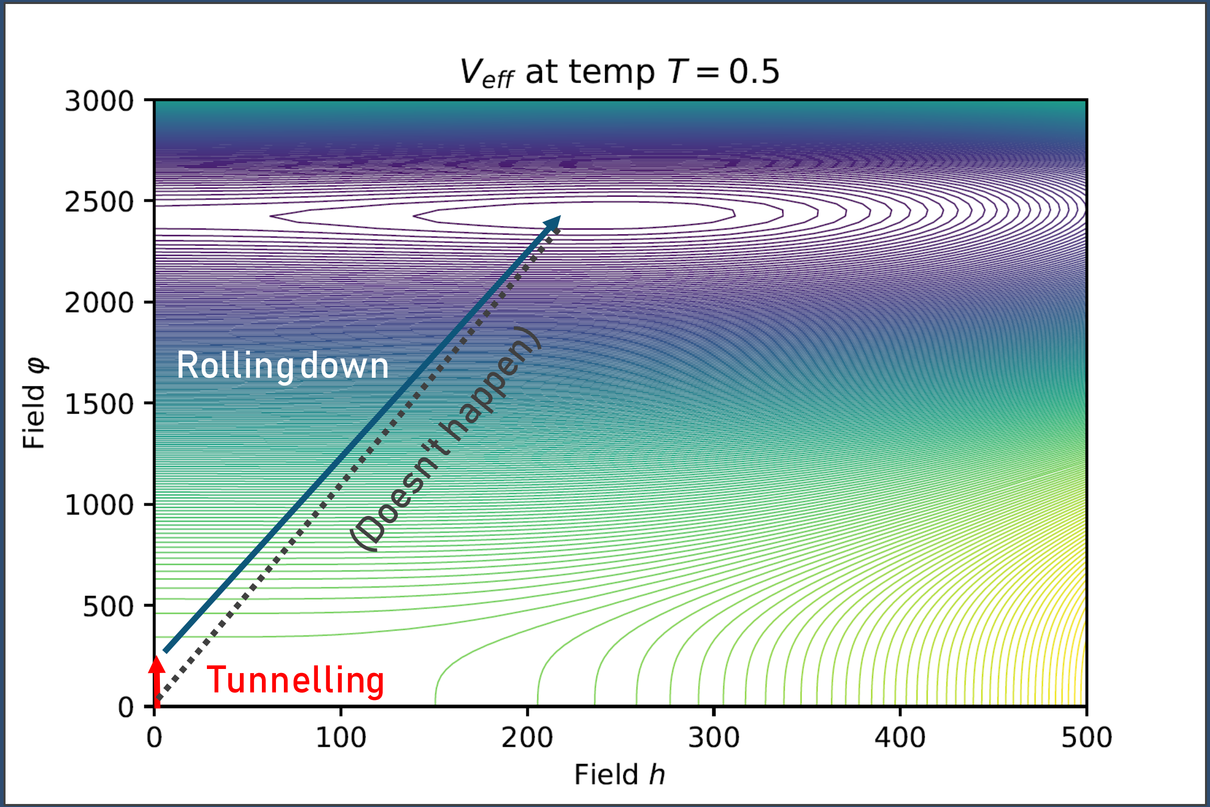
Introducing: supercooling



Features:

- phase transition happens at temperatures significantly below EW scale,
- thermally produced barrier lasts till $T = 0$,
- Induces strong Gravitational Wave signal.

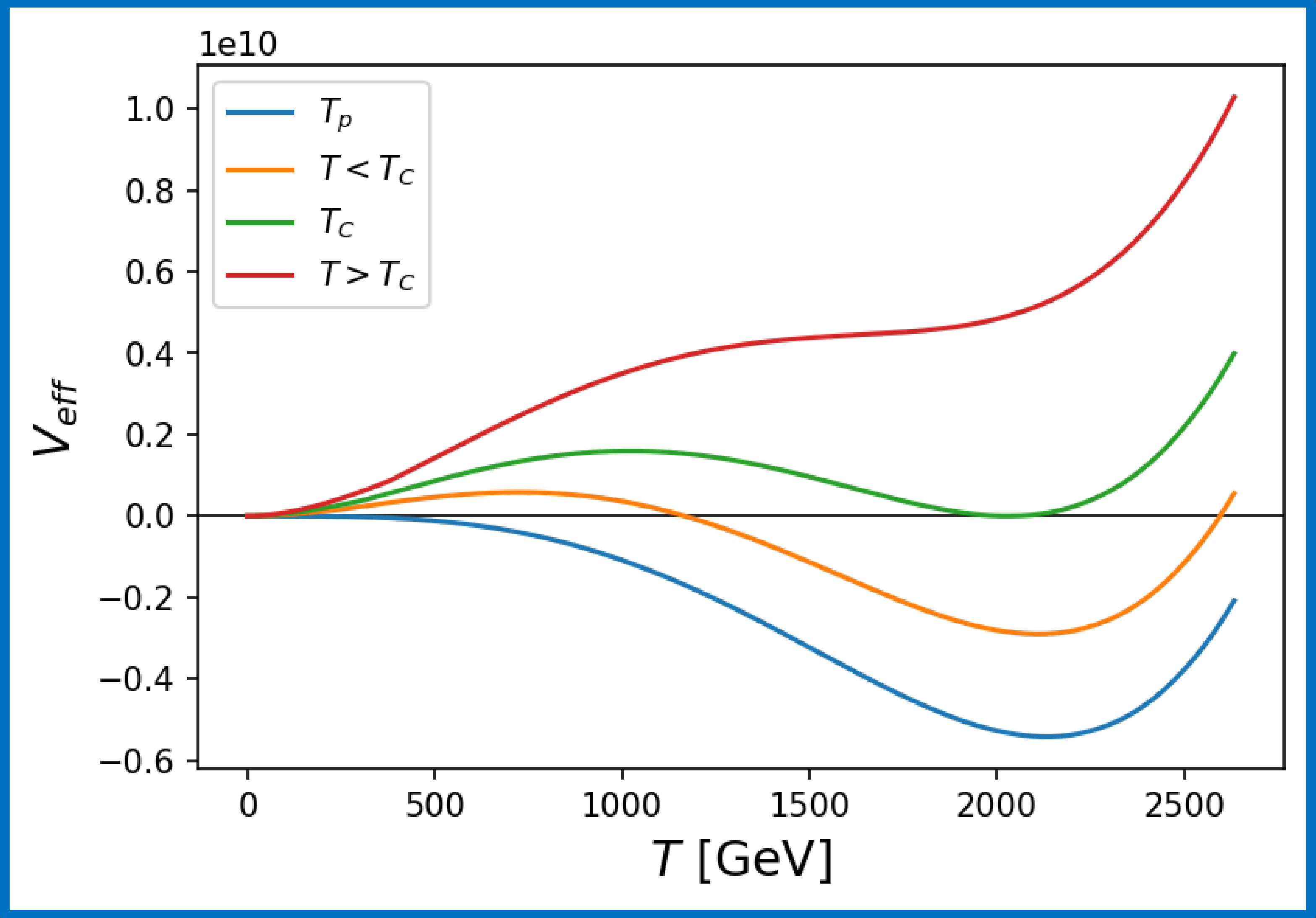
Tunneling scenario in SU(2)cSM



Tunnelling occurs only in the new scalar direction!

T. Prokopec, J. Rezacek, B. Świeżewska, *arXiv:1809.11129*

Thermal evolution of the effective potential



Thermal inflation

Hubble parameter is given as:

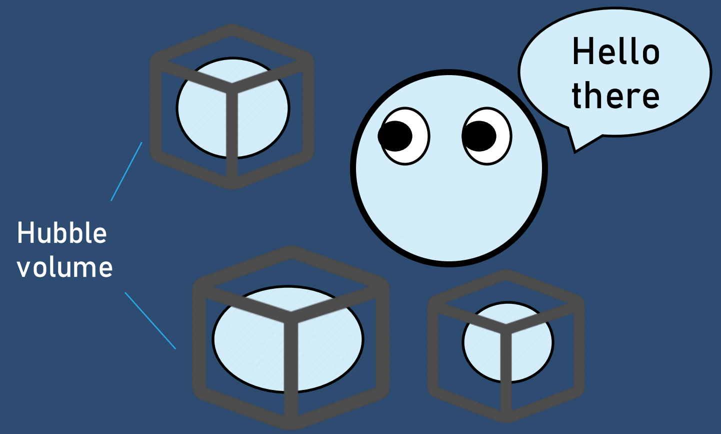
$$H^2 = \frac{1}{3M_{\rm pl}^2}\left(\rho_{\rm R} + \rho_{\rm V}\right) = \frac{1}{3M_{\rm pl}^2}\left(\frac{T^4}{\xi_g^2} + \Delta V\right)$$

We enter into the vacuum domination at the temperature $T_V = \sqrt[4]{\Delta V \xi_g^2}$

Due to non-zero vacuum energy there is a period of *thermal inflation*.
This affects the calculation of thermodynamical parameters.

J.Ellis et al. arXiv:1809.08242

- Nucleation temperature



We calculate: $$N(T_n) = \int_{T_n}^{T_c} \frac{dT}{T} \frac{\Gamma(T)}{H(T)^4} = 1$$

One can also use an approximation:

But not this one $$\frac{S_3}{T} \simeq 140$$

$$\frac{\Gamma(T_n)}{H(T_n)^4} \simeq 1 \Rightarrow \frac{S_3}{T_n} = 4 \log\left(\frac{T_n}{H(T_n)}\right)$$

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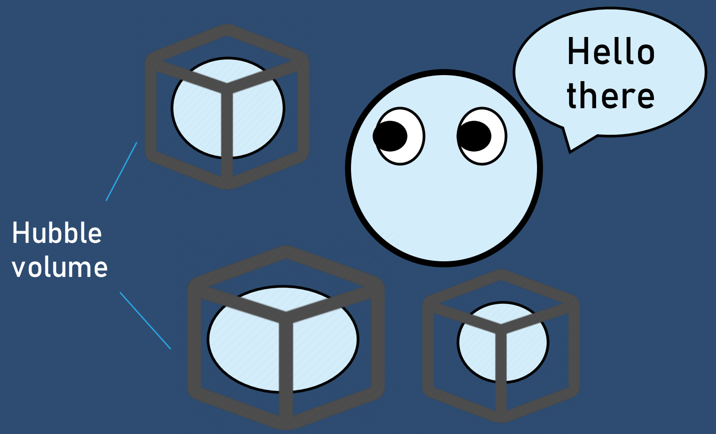

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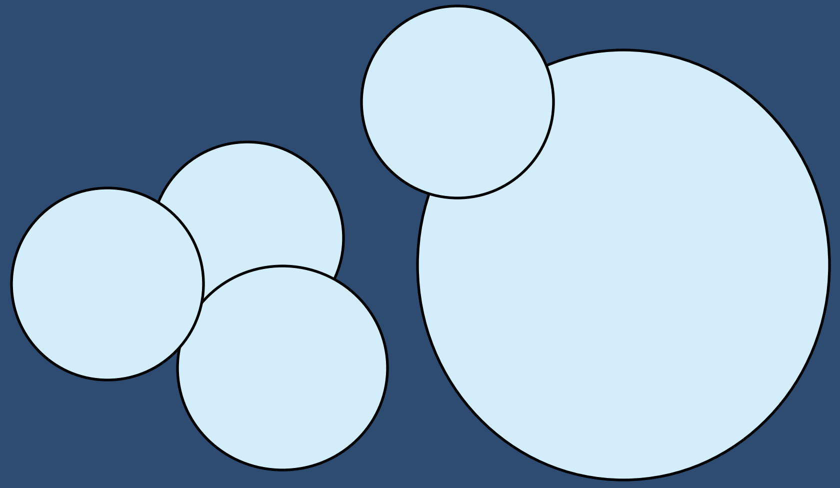
- Percolation temperature



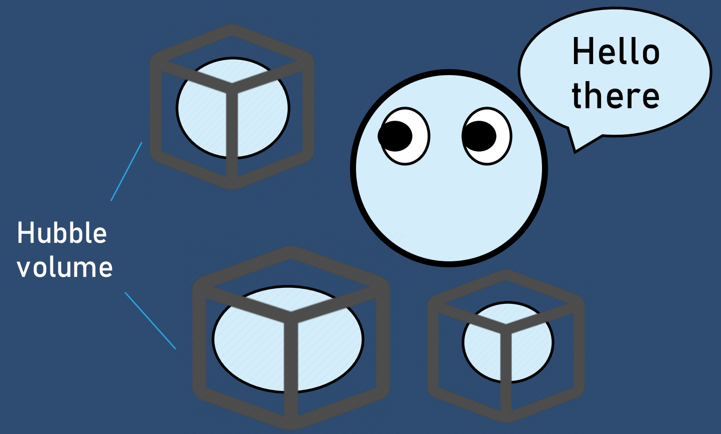
Probability of point still in false vacuum is $P = e^{-I(T)}$, where

$I(T)$ is the volume converted into true vacuum

Then we solve for condition:

$$I(T_p) \simeq 0.34$$

- Nucleation temperature



Are not equal in models with supercooling

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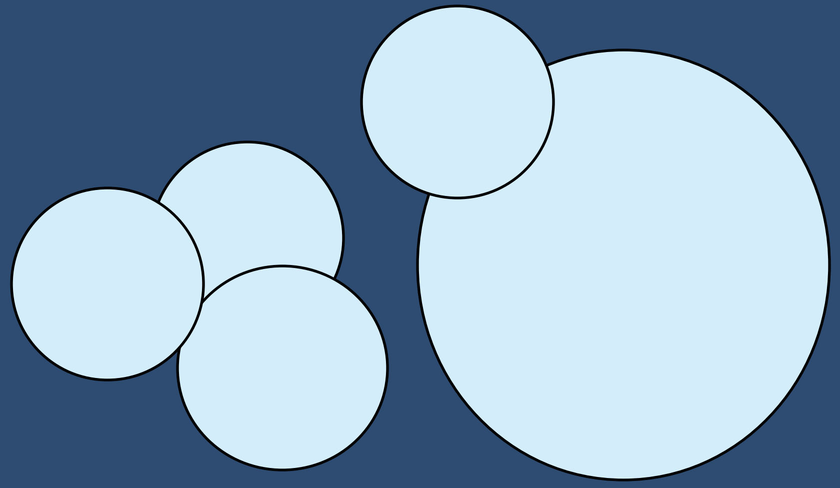

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J.Ellis et al. arXiv:1809.08242

Reheating temperature...

$$\Gamma_\varphi > H_*$$

- Reheating is instantenous
- Released energy transforms into radiation
- Universe reheats up to the temperature T_V

but if....

$$\Gamma_\varphi < H_*$$

- Energy will be stored in the scalar field oscillating about the true vacuum
- Matter domination until temperature at which decay rate is equal to Hubble parameter
- This matter domination period changes the shape of GW spectrum

arXiv:2007.15586

$$\Omega_{\mathrm{GW}} = \Omega_{\mathrm{collisions}} + \Omega_{\mathrm{sound\ waves}} + \Omega_{\mathrm{turbulence}}$$

How do we know which source dominates?

Efficiency factors:

$$\kappa_{col} = \frac{E_{\rm wall}}{E_V}$$

$$\kappa_{sw} \sim 1 - \kappa_{col}$$

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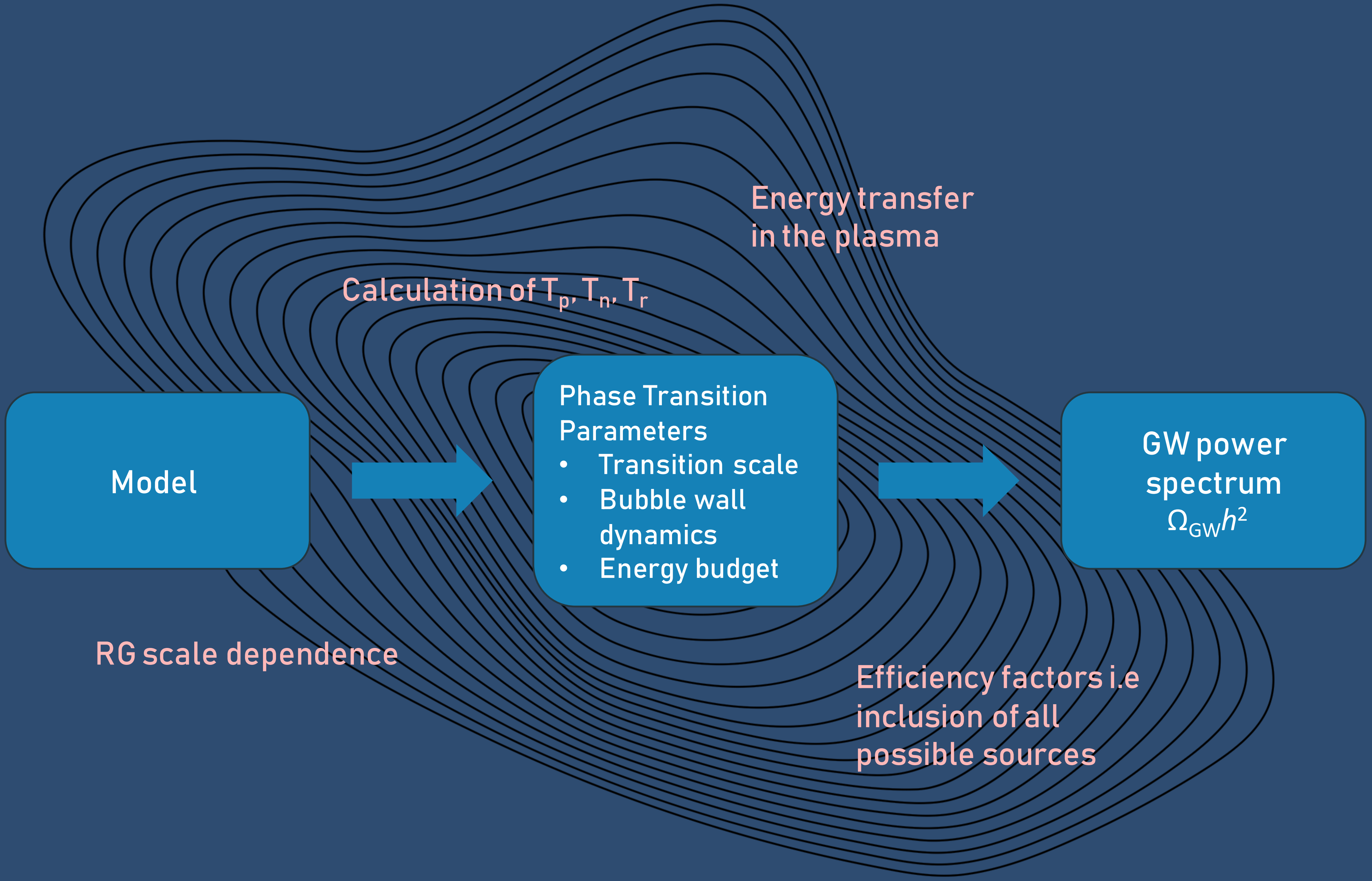
Where the energy goes?

There is a lot of friction → Energy is dissipated in the surrounding plasma → Sound waves + Turbulences

Bubble expansion accelerates → Energy goes to the bubble's wall → Bubble collisions

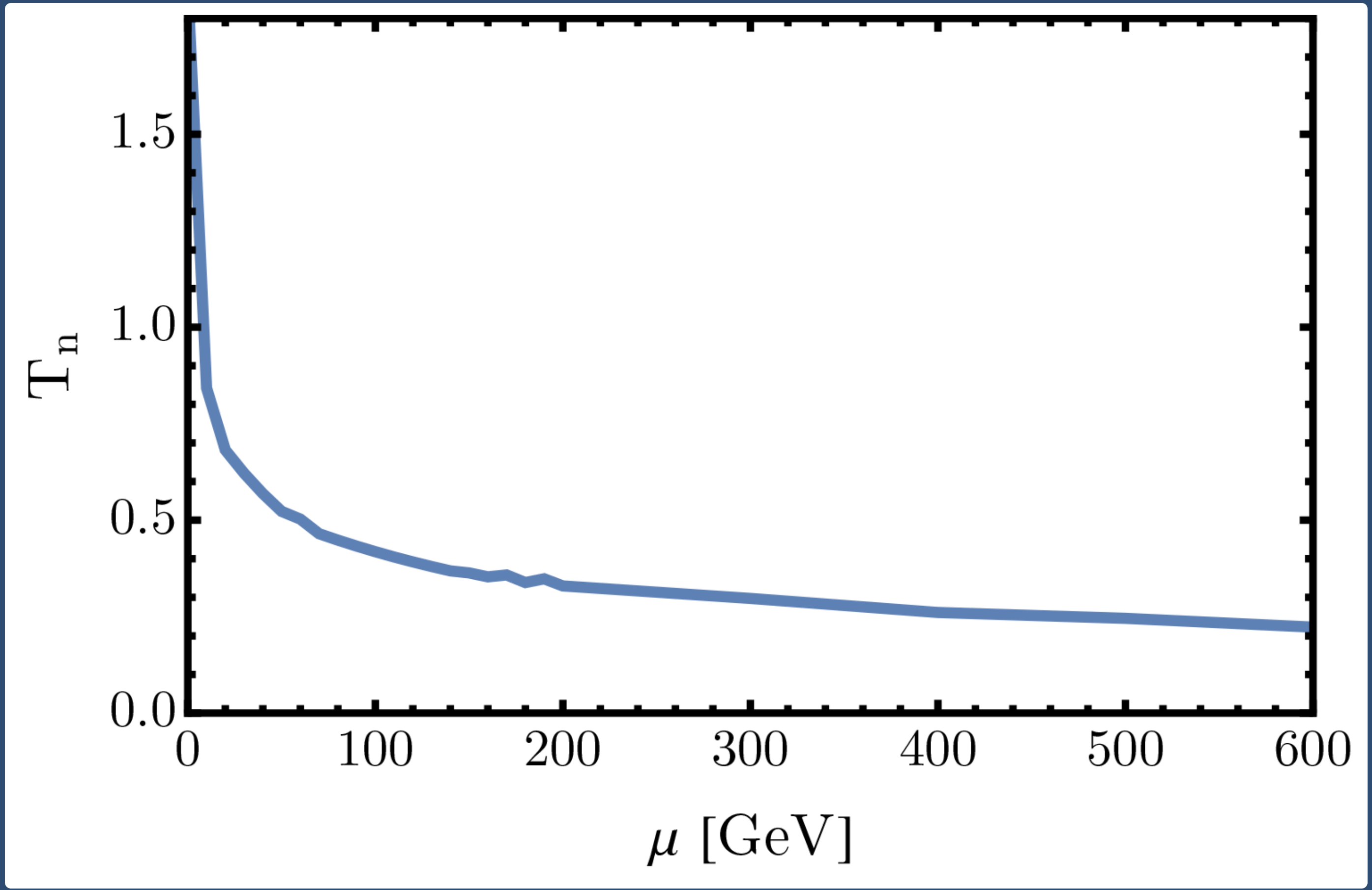
And the main GW source is...

J. Ellis, et al, arXiv:2007.15586



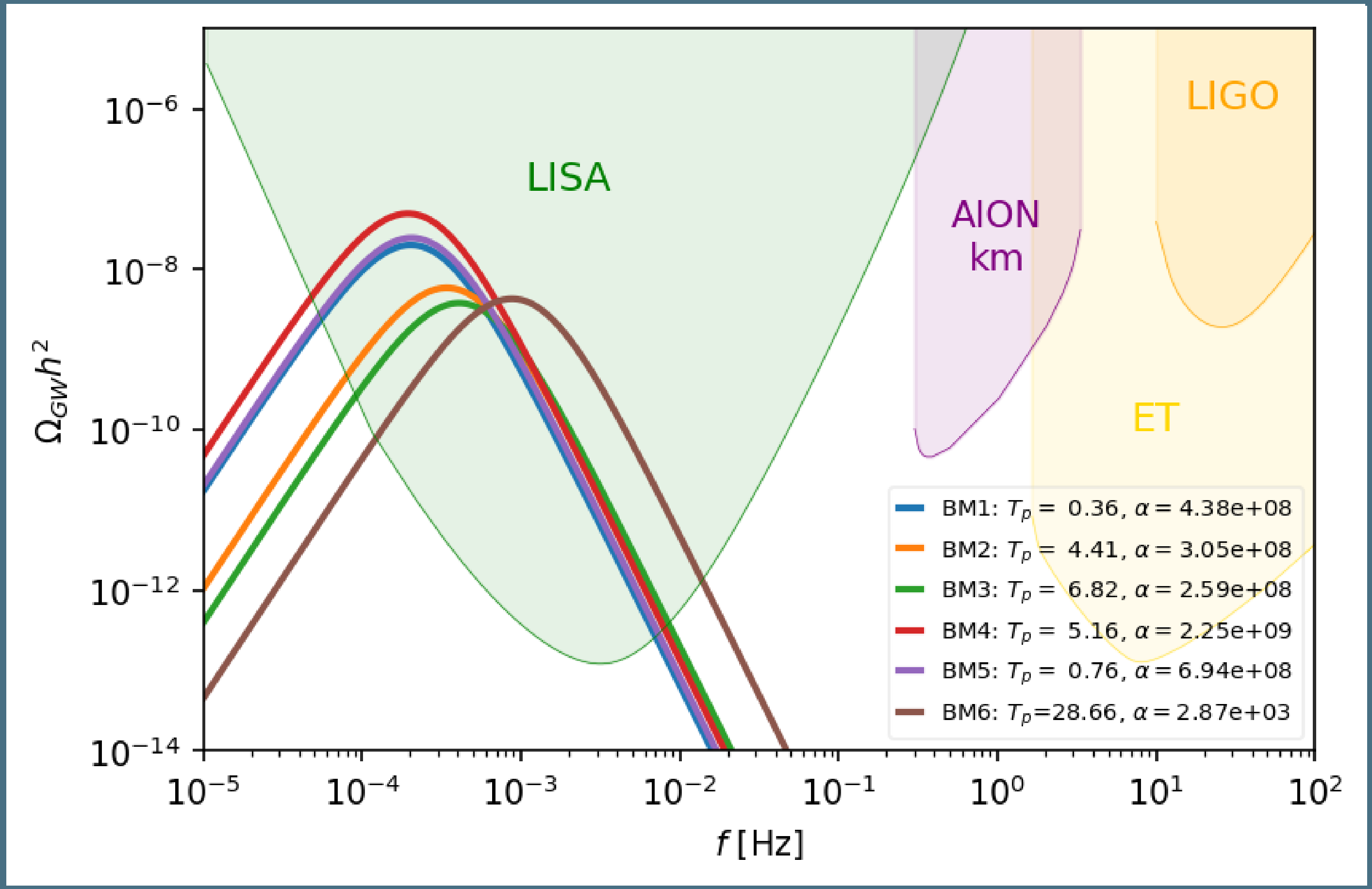
J. Ellis, M. Lewicki, V. Vaskonen, "*Updated predictions for gravitational waves produced in a strongly supercooled phase transition*", arXiv:2007.15586

- RG scale dependence



This affects other parameters and therefore the resulting spectrum.

Gravitational Waves spectra in SU(2)cSM



Goal: provide accurate predictions for LISA.

I. Baldes, C. Garcia-Cely, *arXiv:1809.01198,* T. Prokopec, J. Rezacek, B. Świeżewska, *arXiv:1809.11129*

Thank you