Gravitational waves from first order phase transition of the Higgs field at high energy scales

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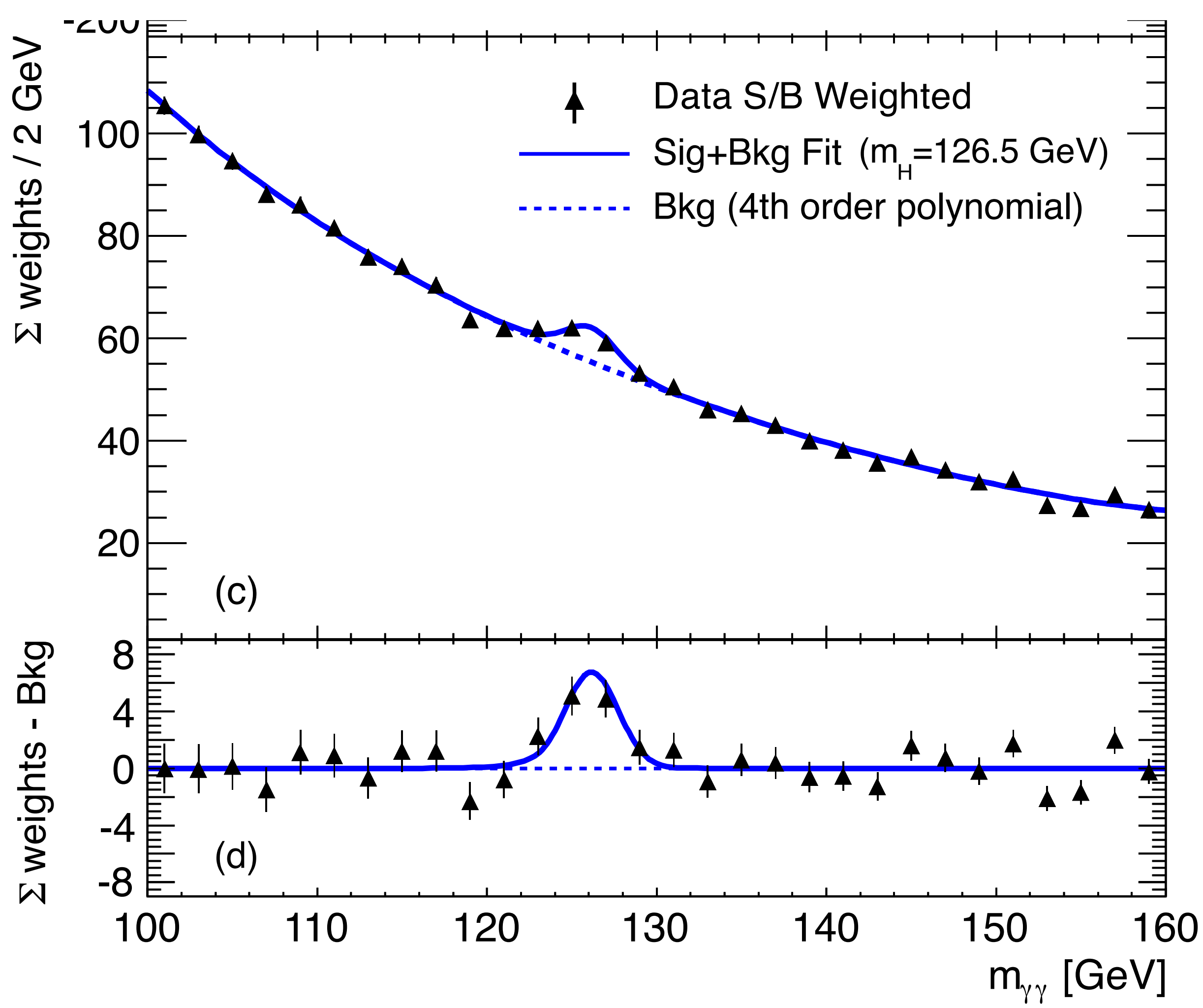
Introduction

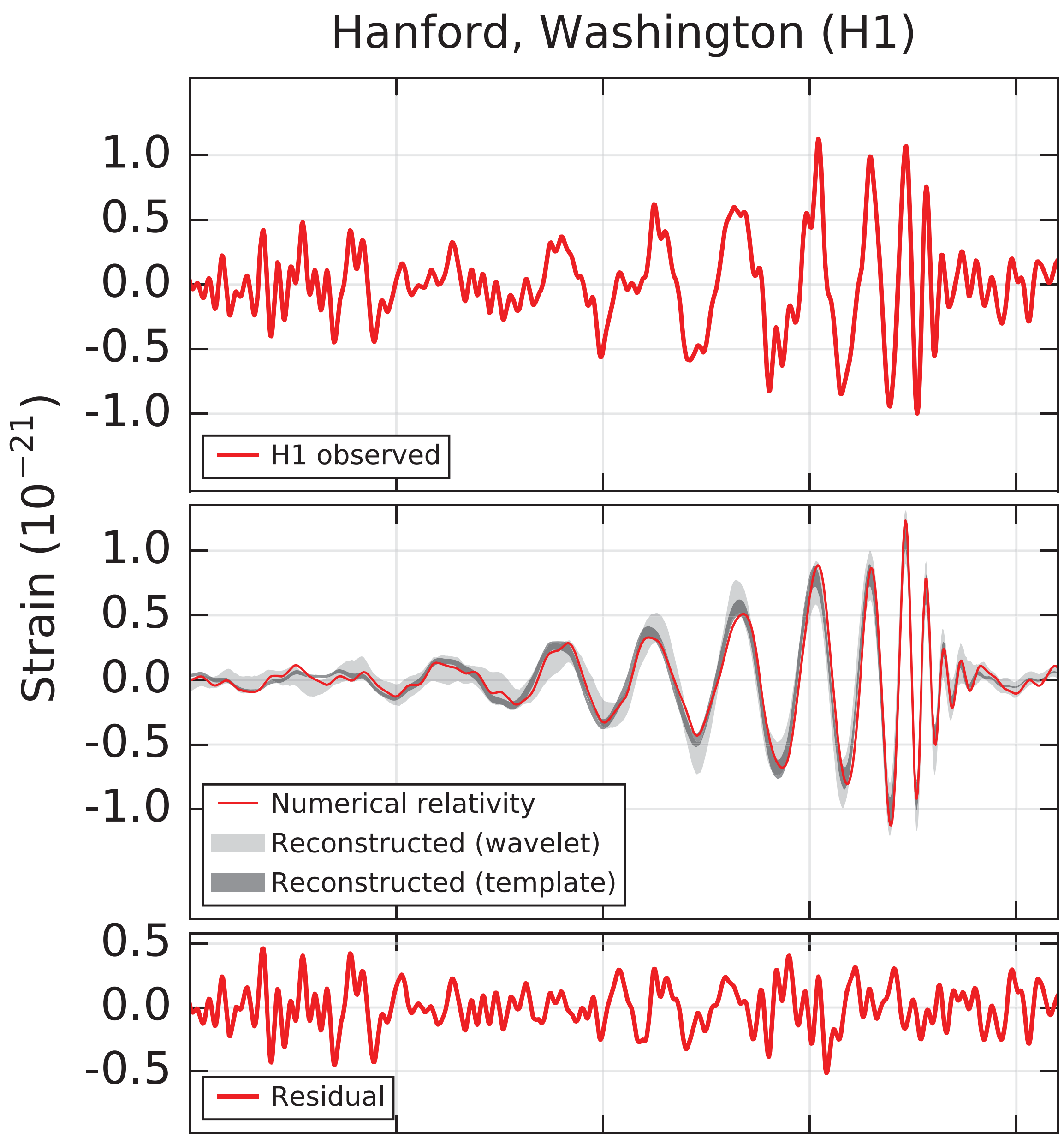
Recent discoveries

Higgs boson



ATLAS (2012)

Gravitational wave (GW)



LIGO (2016)

- Unfortunately (?), both are NOT new physics beyond SM

- However, both (Higgs & GWs) can be a new probe of physics beyond SM

- In some extension of SM, electroweak phase transition can be 1st order

$\longrightarrow$
  - Electroweak baryogenesis
  - GWs from bubble collisions

f~1mHz (LISA range)

- We show that Higgs phase transition can happen at much higher energy scale and resulting GWs may probe the nature of Higgs and physics beyond SM

GWs from 1st order phase transition

- Phase transition (toy model)

$$V(\phi) = V_0 - m_\phi^2 \phi^2 + \lambda \phi^4$$

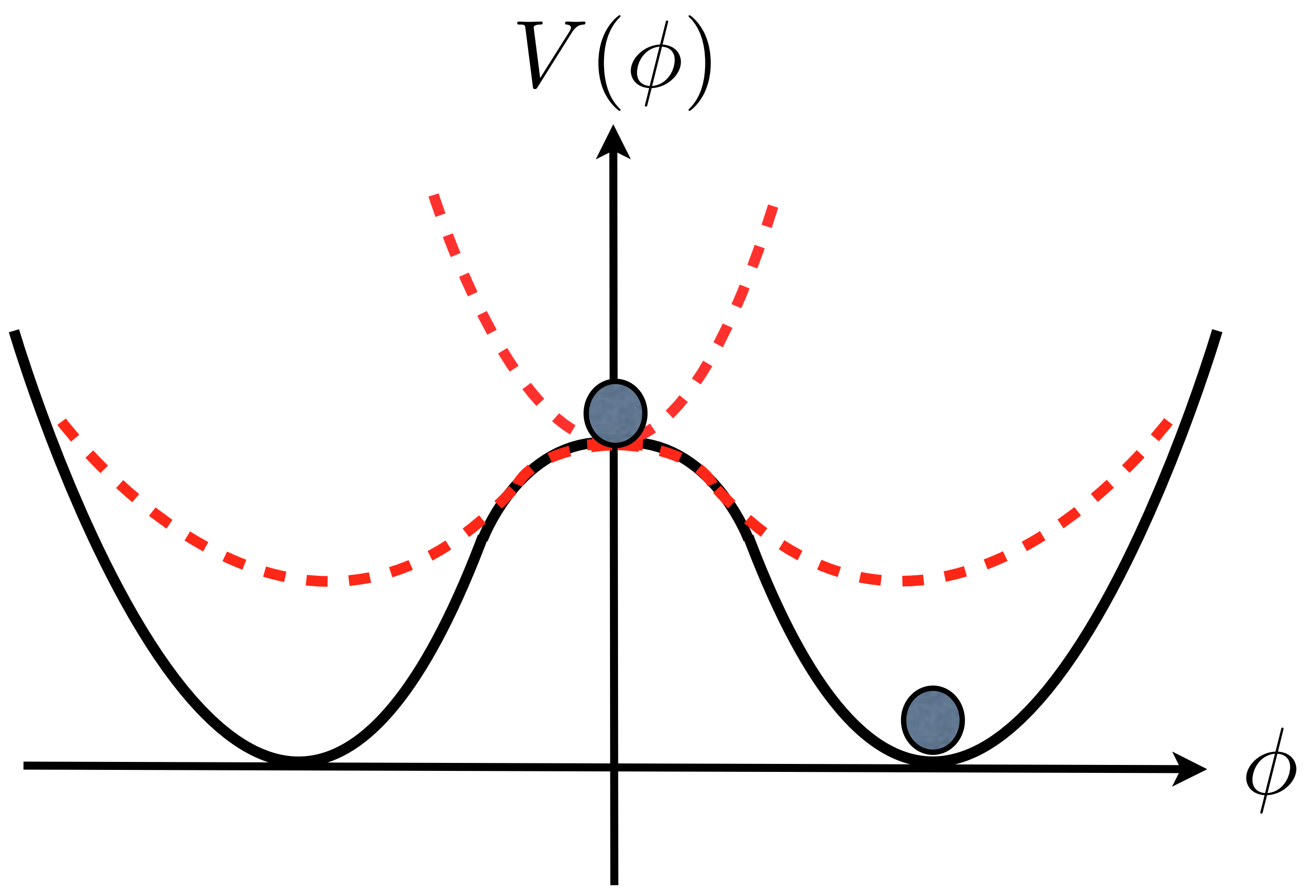
$$\mathcal{L} = -g^2 \phi^2 \chi^2$$

Suppose that χ is in thermal equilibrium

$$V_T(\phi) \simeq \frac{g^2}{12} T^2 \phi^2 \quad (\phi \ll T)$$

$T \gtrsim m_\phi / g$: Symmetric phase

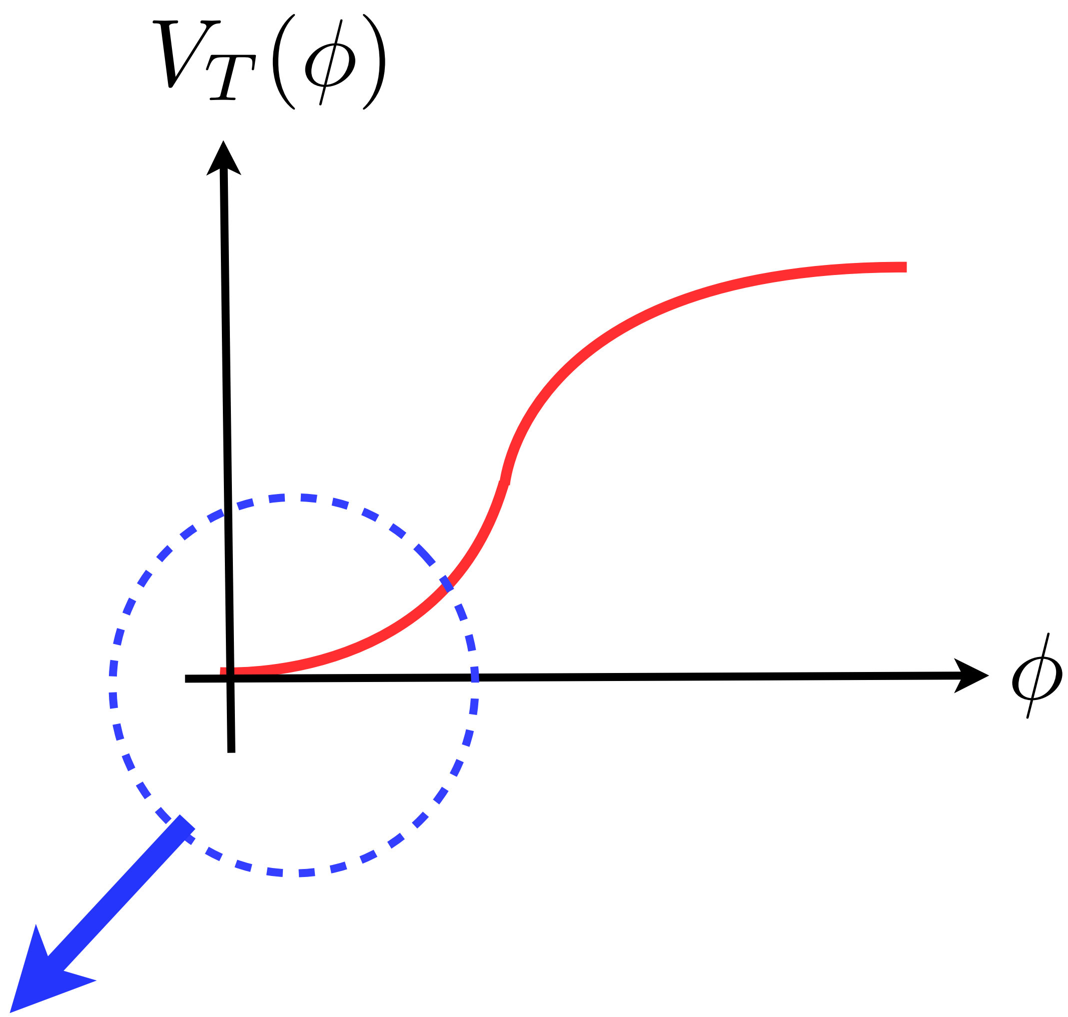
$T \lesssim m_\phi / g$: Broken phase



Phase transition (toy model)

- Finite-temperature effective potential

$$\boxed{V_T^{B/F}(\phi) = \frac{T^4}{2\pi^2} J_{B/F}\left(\frac{m^2}{T^2}\right)}$$



$$m(\phi) = g\phi$$

$$J_B[m^2\beta^2] = \int_0^\infty dx\; x^2 \log\left[1 - e^{-\sqrt{x^2+\beta^2 m^2}}\right]$$

- High-temperature expansion $(m \ll T)$

$$J_B(m^2/T^2) \quad = \quad -\frac{\pi^4}{45} + \frac{\pi^2}{12}\frac{m^2}{T^2} - \frac{\pi}{6}\left(\frac{m^2}{T^2}\right)^{3/2} - \frac{1}{32}\frac{m^4}{T^4}\log\frac{m^2}{a_b T^2}$$

Thermal mass term

$$V \sim g^2 T^2 \phi^2$$

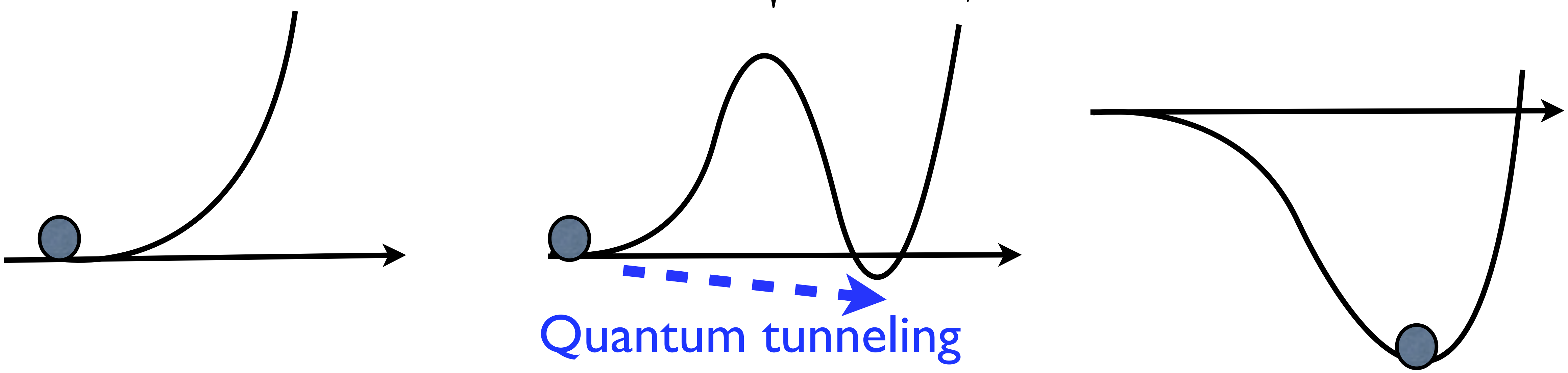
Cubic term

$$V \sim -g^3 T \phi^3$$

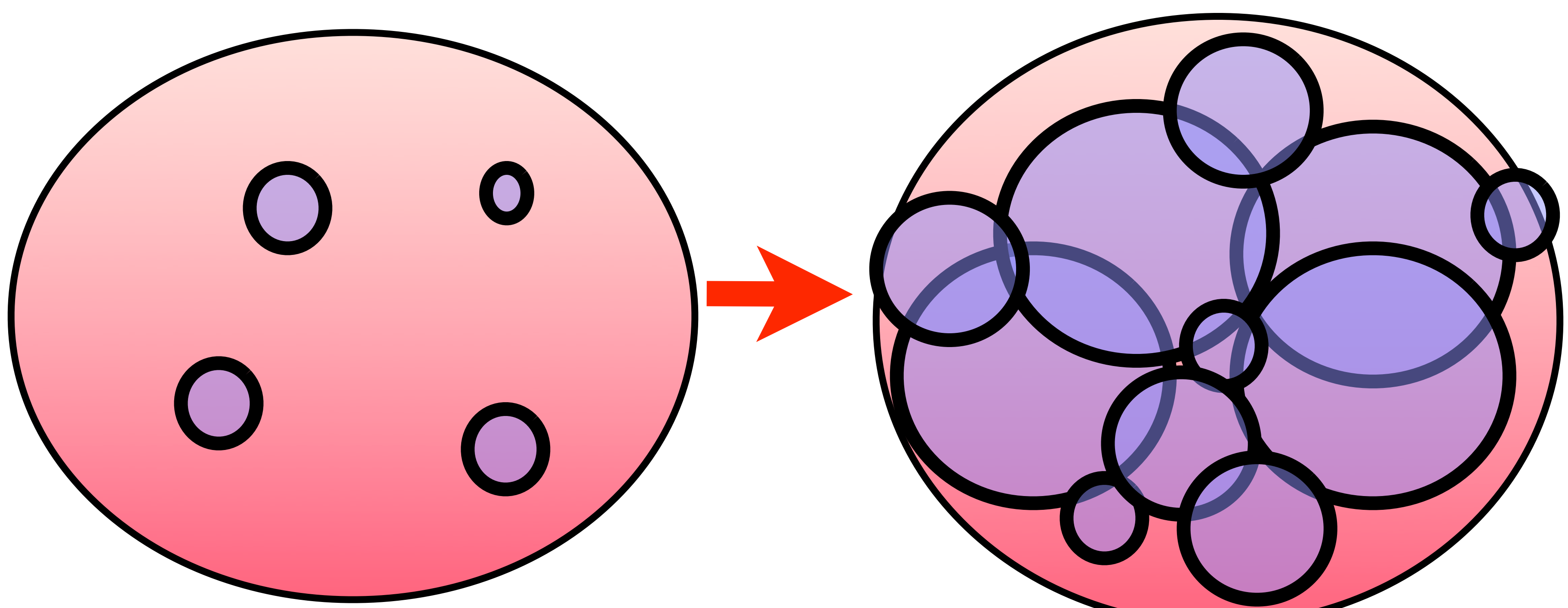
- Zero + Finite-T potential

$$V \sim (g^2T^2 - m_\phi^2)\phi^2 - AT\phi^3 + \lambda\phi^4$$

$T \gg m_\phi/g$ $T < T_c \equiv \sqrt{\dfrac{m_\phi^2}{g^2 - A^2/\lambda}}$ $T \ll m_\phi/g$



First order phase transition happens at $T \sim m_\phi/g$



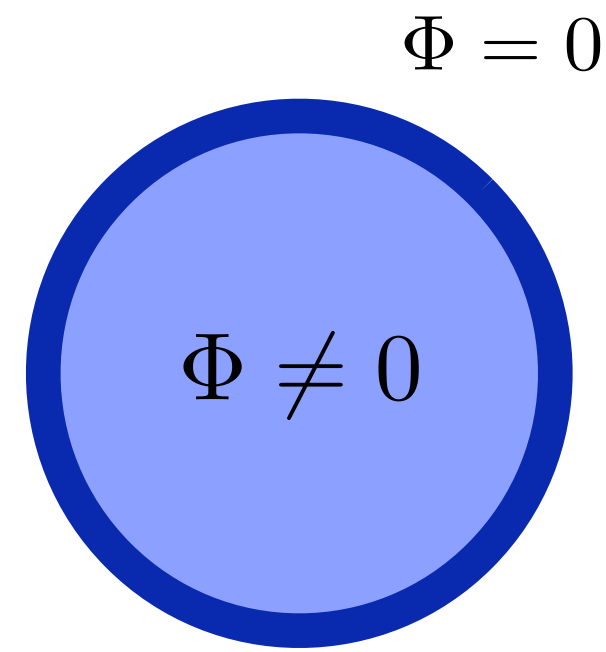
Bubble nucleation

Coleman (1977), Linde (1983)

- Vacuum decay rate

$$\boxed{\Gamma \sim T^4 e^{-S_3/T}}$$

- S_3 :Action of O(3) symmetric bounce solution

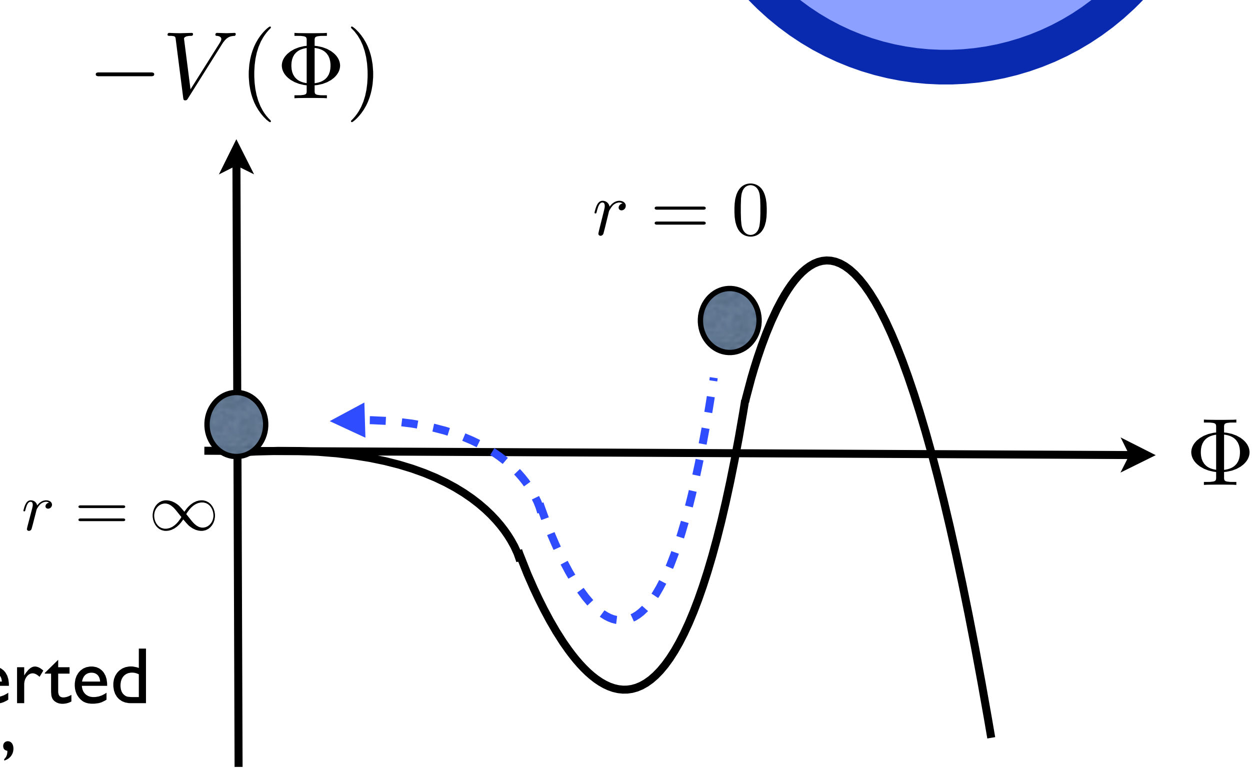


$$S_3(T) = \int d^3x \left[\frac{1}{2}(\nabla\Phi)^2 + V(\Phi, T)\right]$$

$$\frac{d^2\Phi}{dr^2} + \frac{2}{r}\frac{d\Phi}{dr} - \frac{\partial V}{\partial \Phi} = 0,$$

Boundary condition:

$$\Phi(r = \infty) = \Phi_{\text{false}},$$
$$\frac{d\Phi}{dr}(r = 0) = 0.$$



~ Dynamics of scalar field with inverted potential -V with r being “time”

$$V \sim (g^2T^2 - m_\phi^2)\phi^2 - AT\phi^3 + \lambda\phi^4 \qquad \left(\frac{m_\phi}{g} < T < T_c\right)$$

- Thick wall limit

Around temperature

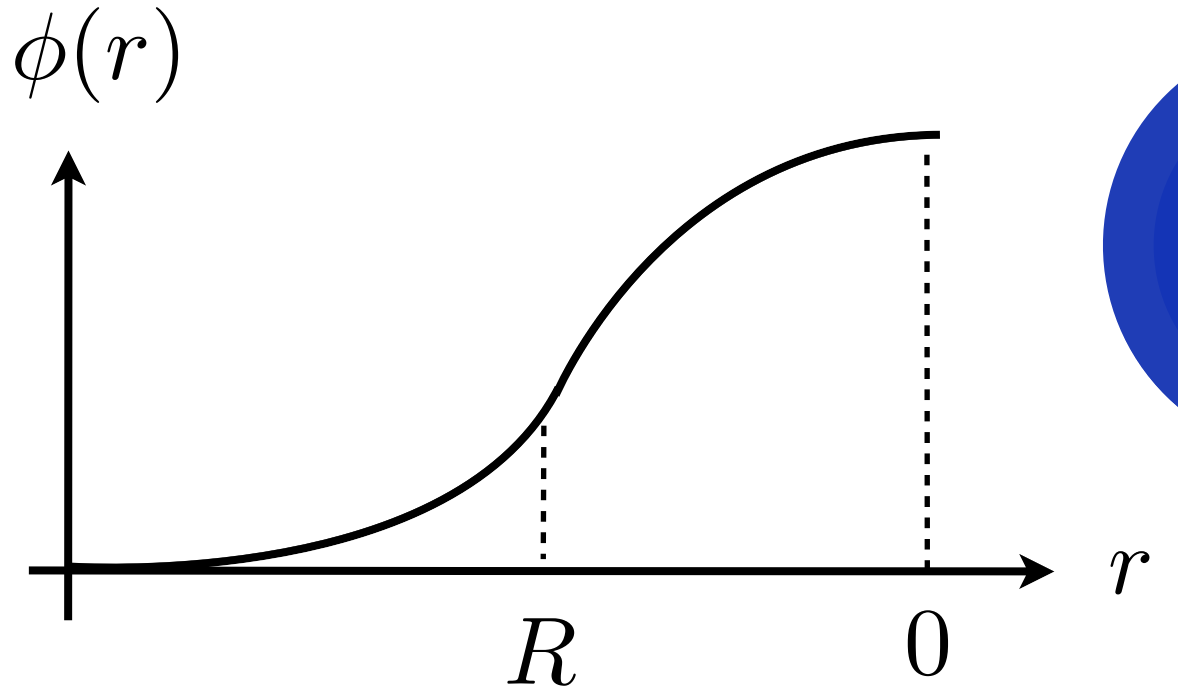
$$T \sim T_c$$

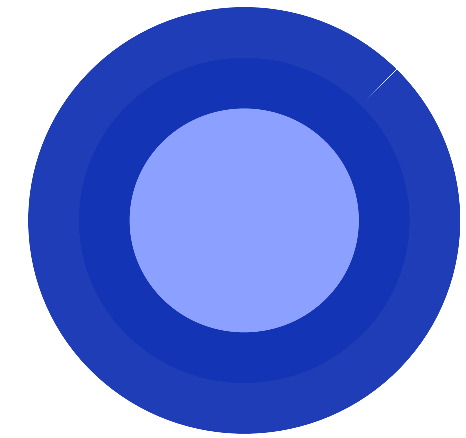
$$T_c \equiv \sqrt{\frac{m_\phi^2}{g^2 - A^2/\lambda}}$$

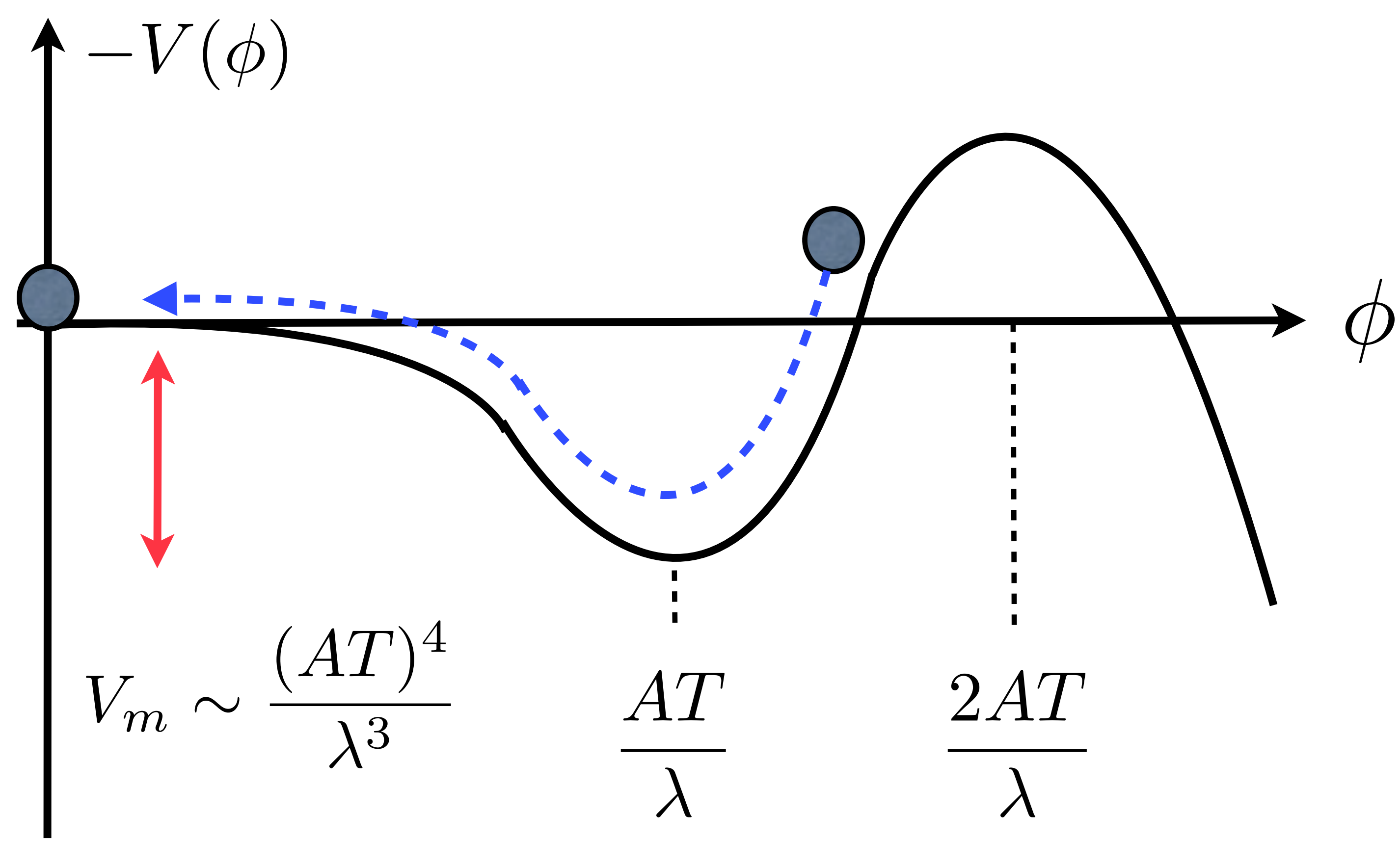
$$R^{-2} \sim g^2T^2 - m_\phi^2 \sim \frac{(AT)^2}{\lambda}$$

$$S_3 \sim \frac{4\pi}{3}R^3V_m$$

$$\longrightarrow \boxed{\frac{S_3}{T} \sim \frac{A}{\lambda^{3/2}}}$$







- Thin wall limit

$$T = T_c - \Delta T$$

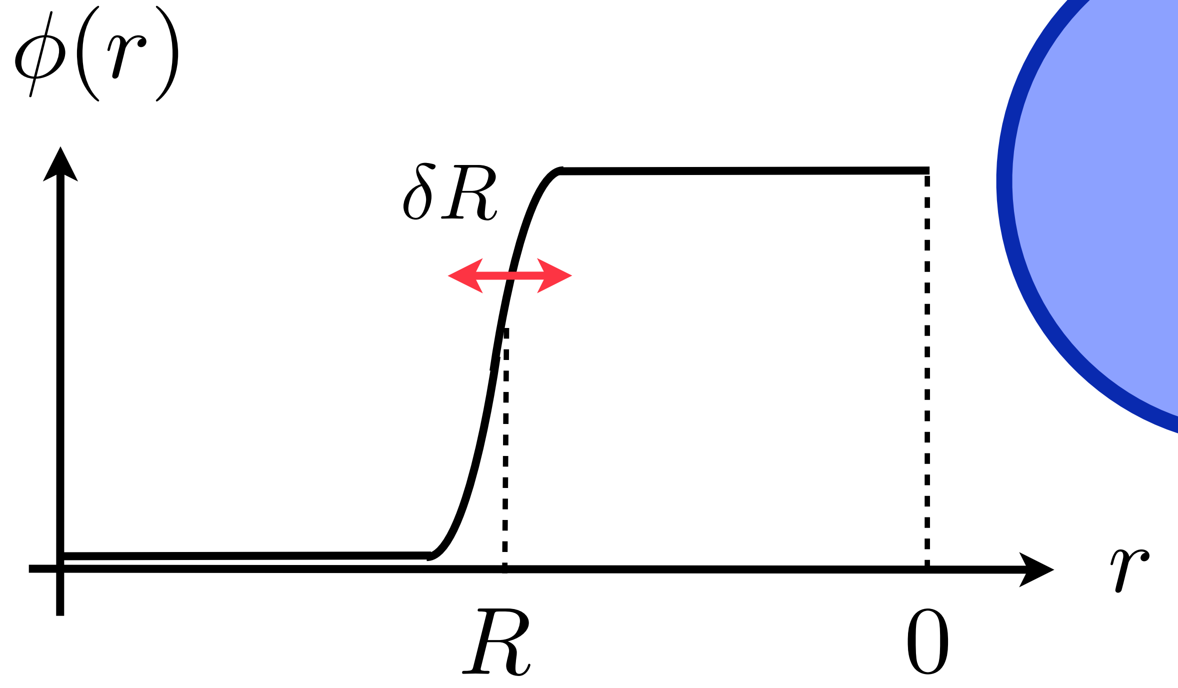
$$\Delta V \sim \frac{g^2 A^2 T_C^3 \Delta T}{\lambda^2}$$

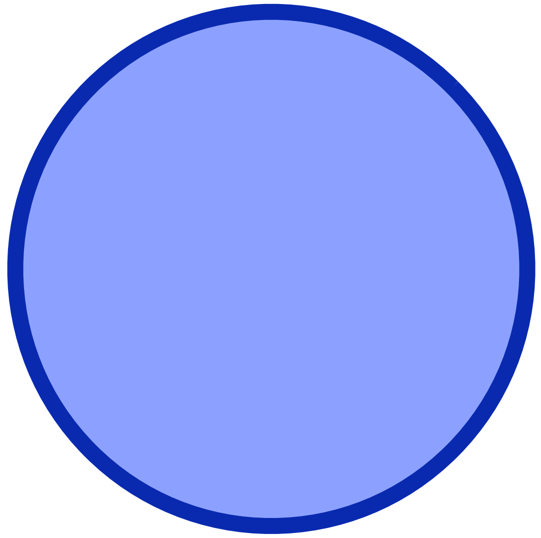
$$\delta R^{-2} \sim g^2 T^2 - m_\phi^2 \sim \frac{(AT)^2}{\lambda}$$

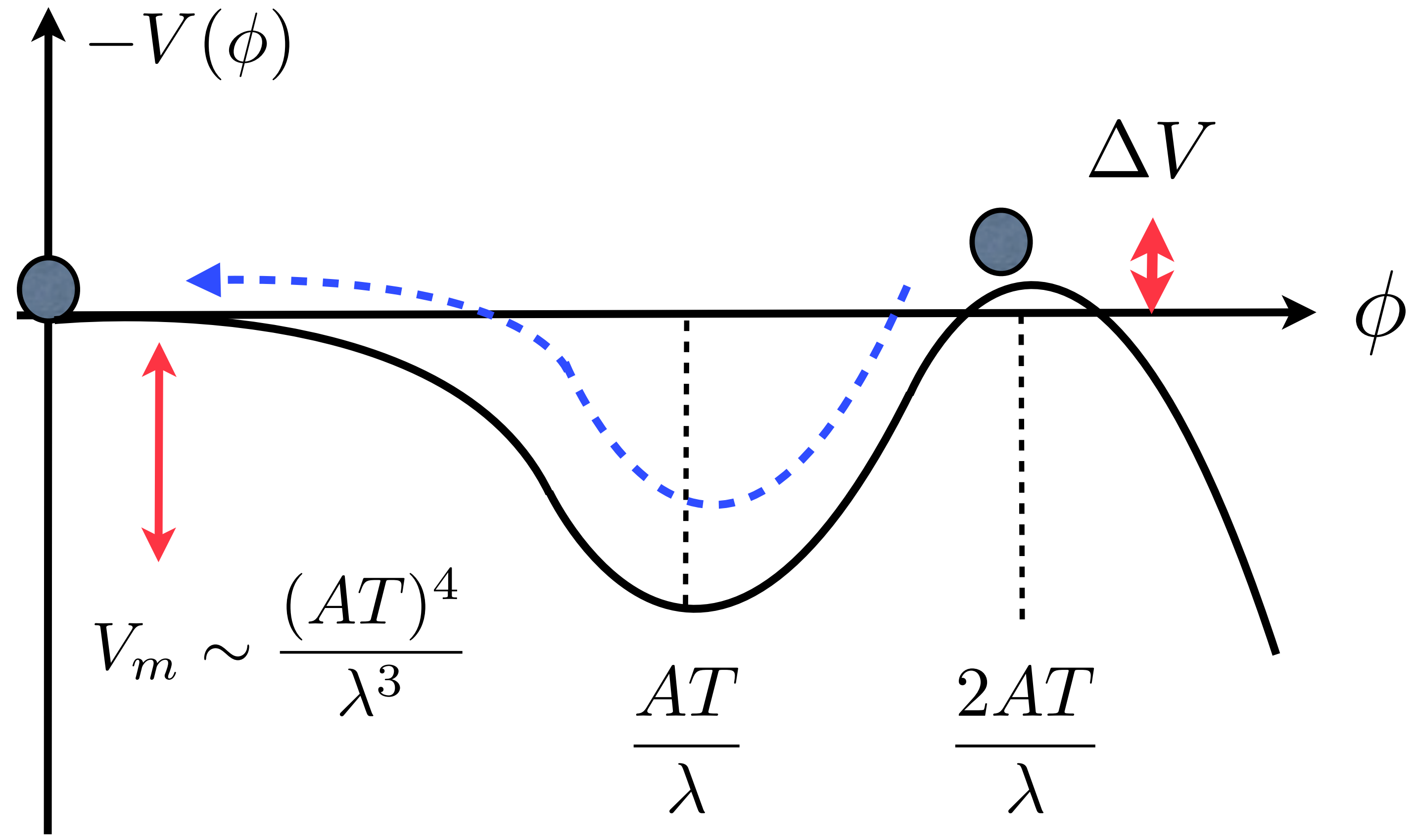
$$\frac{\delta R}{R} \sim \frac{\Delta V}{V_m} \sim \frac{g^2 \lambda \Delta T}{A^2 T_c}$$

$$S_3 \sim 4\pi R^2 \delta R V_m$$

$$\longrightarrow \boxed{\frac{S_3}{T} \sim \frac{A}{\lambda^{3/2}} \left(\frac{A^2 T_c}{\lambda g^2 \Delta T} \right)^2}$$





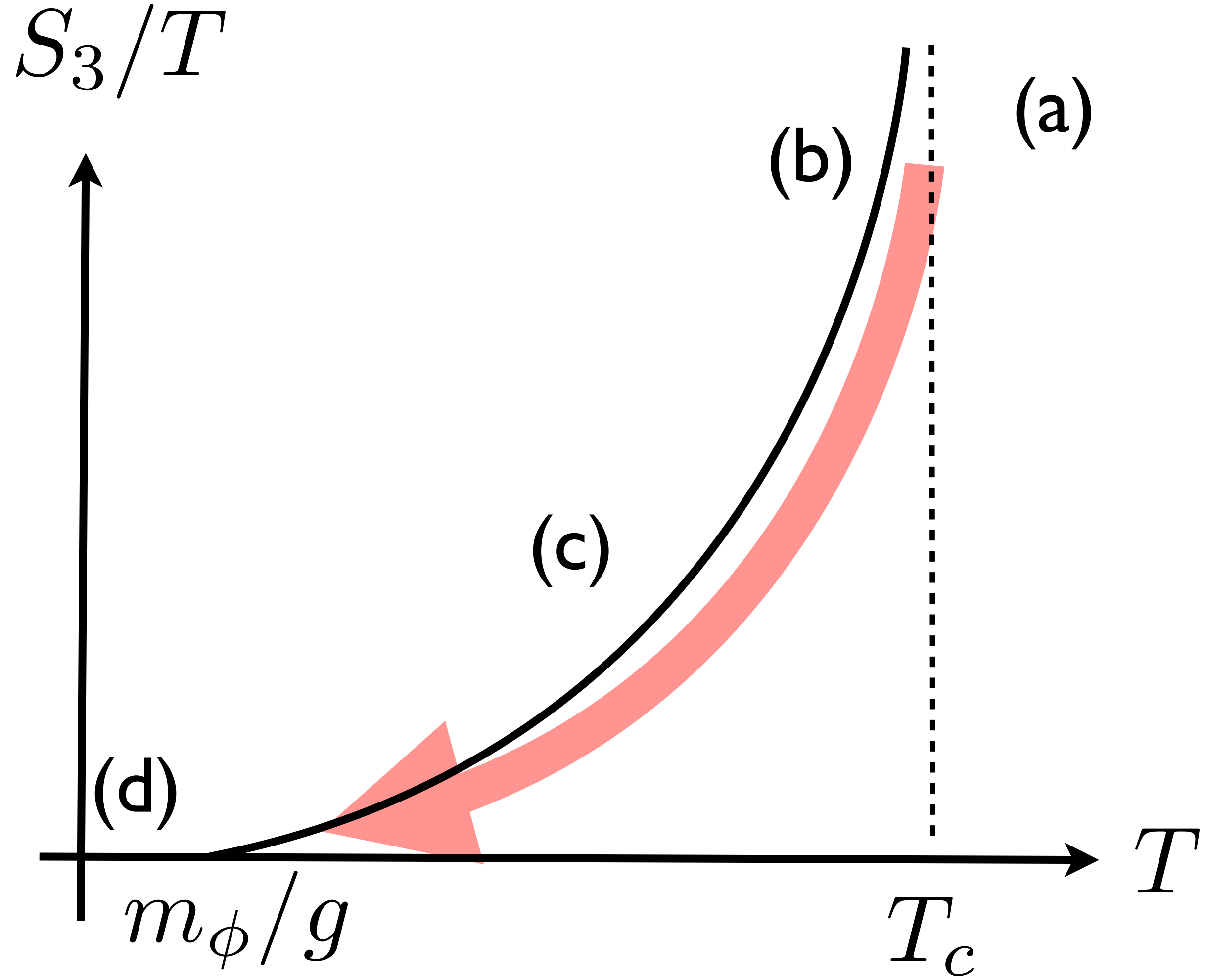


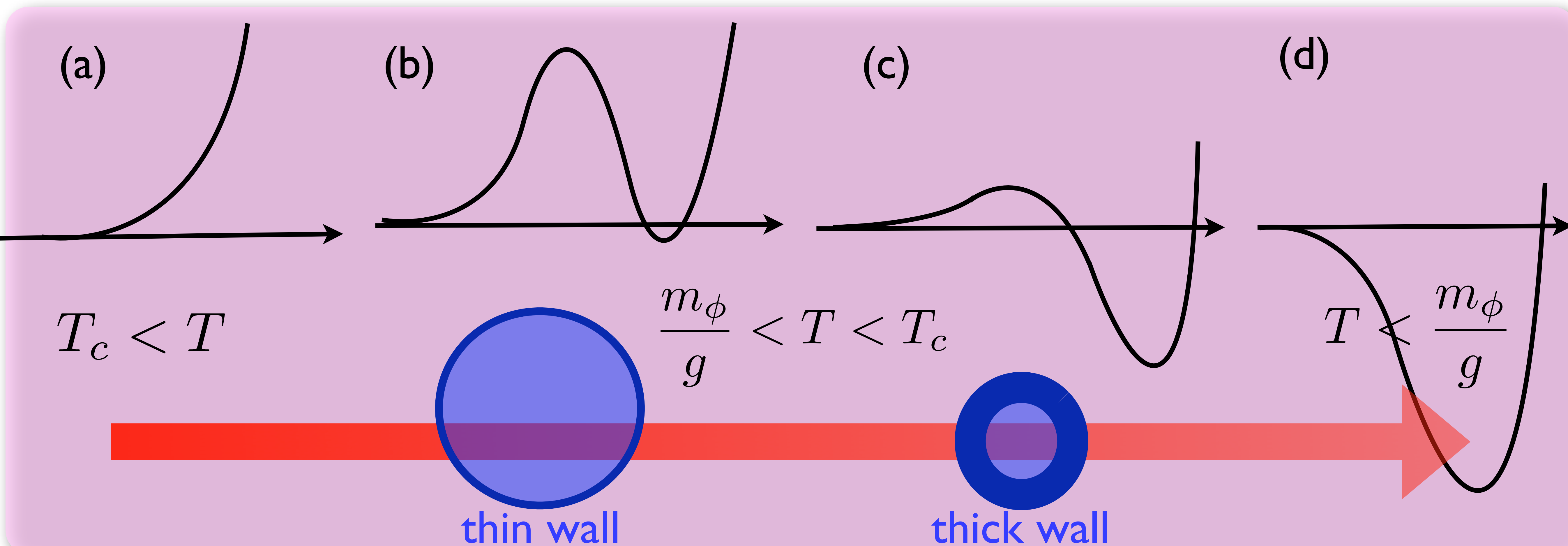
- Phase transition completes at

$$\Gamma \sim H^4 \sim \frac{T^8}{M_P^4} \longleftrightarrow$$

$$\boxed{\frac{S_3}{T} \sim 4 \ln \left(\frac{M_P}{T} \right) \sim 140}$$

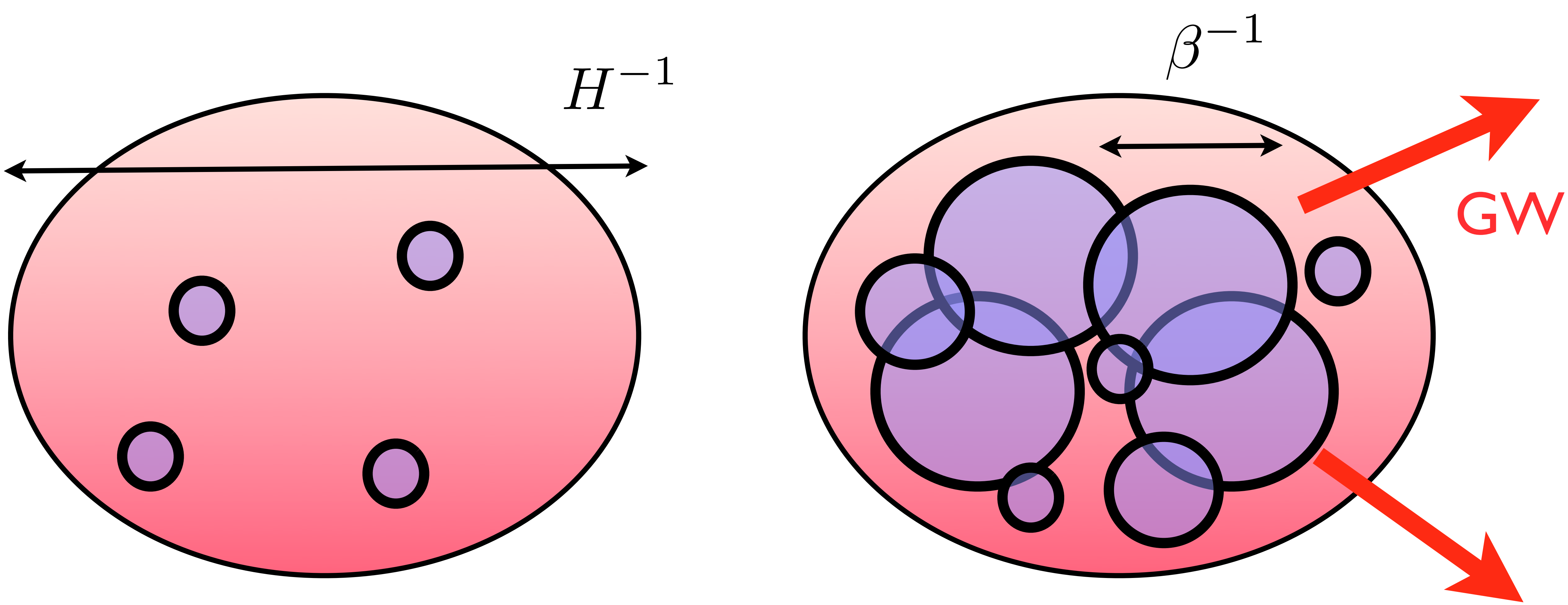
$$\text{if} \quad T \sim 100\,\text{GeV}$$





- GWs from bubble collision Kamionkowski, Kosowski, Turner (1994)
  - Collision of bubbles produce GWs
  - Important parameter is bubble size at collision: β^{-1}
  - Bubble size just after the production is $\sim T^{-1}$
  - β^{-1} is determined by duration of phase transition $\beta^{-1} \sim c\Delta t$

    Note that $T^{-1} \lll\lll\lll \beta^{-1} \ll H^{-1}$



- Duration of phase transition
  - Tunneling rate

$$\Gamma \sim T^4 e^{-S_3/T}$$

  - Phase transition happens at

$$\Gamma \sim H^4 \longrightarrow \left.\frac{S_3}{T}\right|_{T=T_*} = 137 + 4\log(100\,\mathrm{GeV}/T_*)$$

  - Duration of phase transition $(S_* \equiv S_3/T)$

Typical duration: $\dfrac{\Gamma}{H^4} = 1 \to 10$

$$\frac{dS_*}{dt}\Delta t \sim \mathcal{O}(1) \longrightarrow \Delta t \sim \frac{1}{\beta} \sim \left(\frac{dS_*}{dt}\right)^{-1} \sim \frac{1}{H_*}\left(T\frac{dS_*}{dT}\right)^{-1}$$

$$\boxed{\frac{\beta}{H_*} = T\left.\frac{d(S_3/T)}{dT}\right|_{T=T_*}}$$

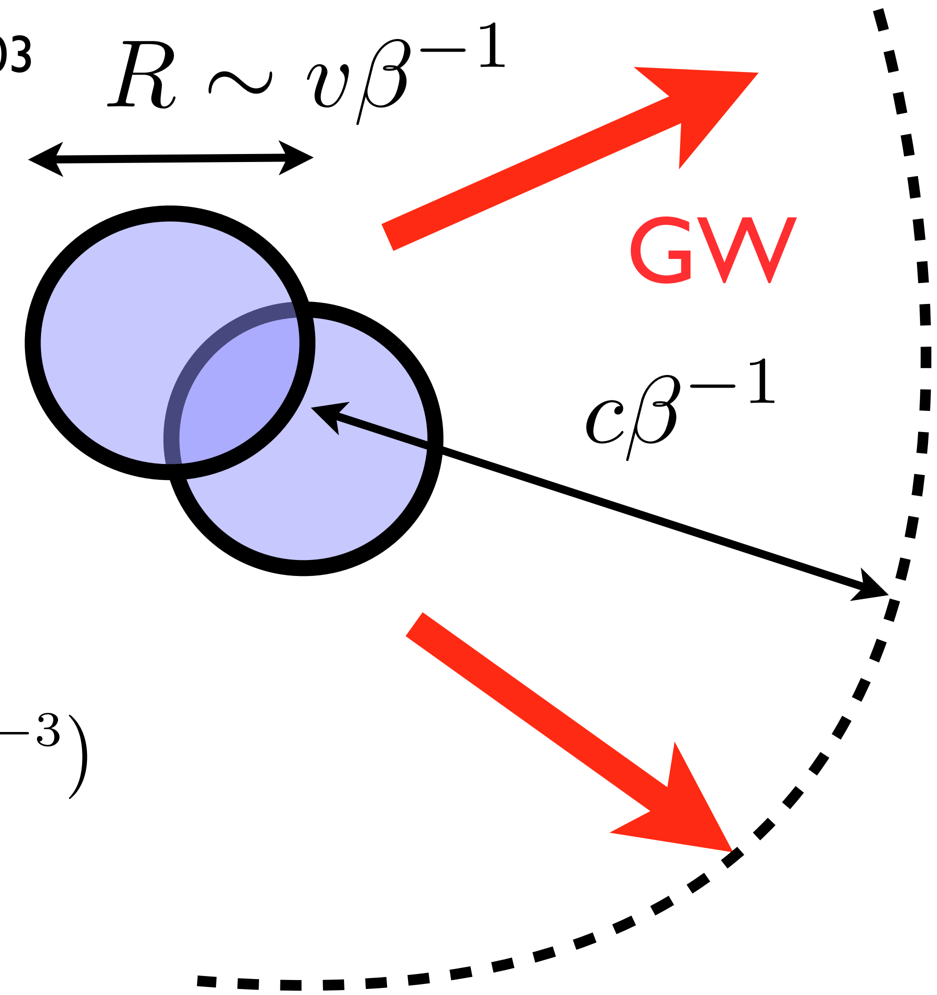
If $S_3 \sim T^4$, $\beta/H \sim 400$.

Actually the temperature dependence is complicated.

Typically, the duration of PT is much shorter than the Hubble scale at PT.

- # GWs from bubble collision

Kosowsky et al. (92), Caprini et al. (2007), Jinno, Takimoto 1605.01403



- **Frequency:** $f \sim \beta \dfrac{a_*}{a_0}$ redshift
- **Strength:** $\dot{E}_{\rm GW} \sim G(\dddot{I})^2$ Quadra-pole formula

$$I \sim MR^2 \sim \kappa\epsilon v^{-2} R^5$$

$$\rho_{\rm GW} \sim N \frac{\dot{E}_{\rm GW}\beta^{-1}}{(c\beta^{-1})^3} \sim G\kappa^2\epsilon^2 v^2\beta^{-2} \qquad (N \sim v^{-3})$$

$$\Omega_{\rm GW} \sim \Omega_{\rm rad}\frac{\rho_{\rm GW}}{\rho_{\rm tot}} \sim \Omega_{\rm rad}\kappa^2\alpha^2 v^3 H_*^2\beta^{-2}$$

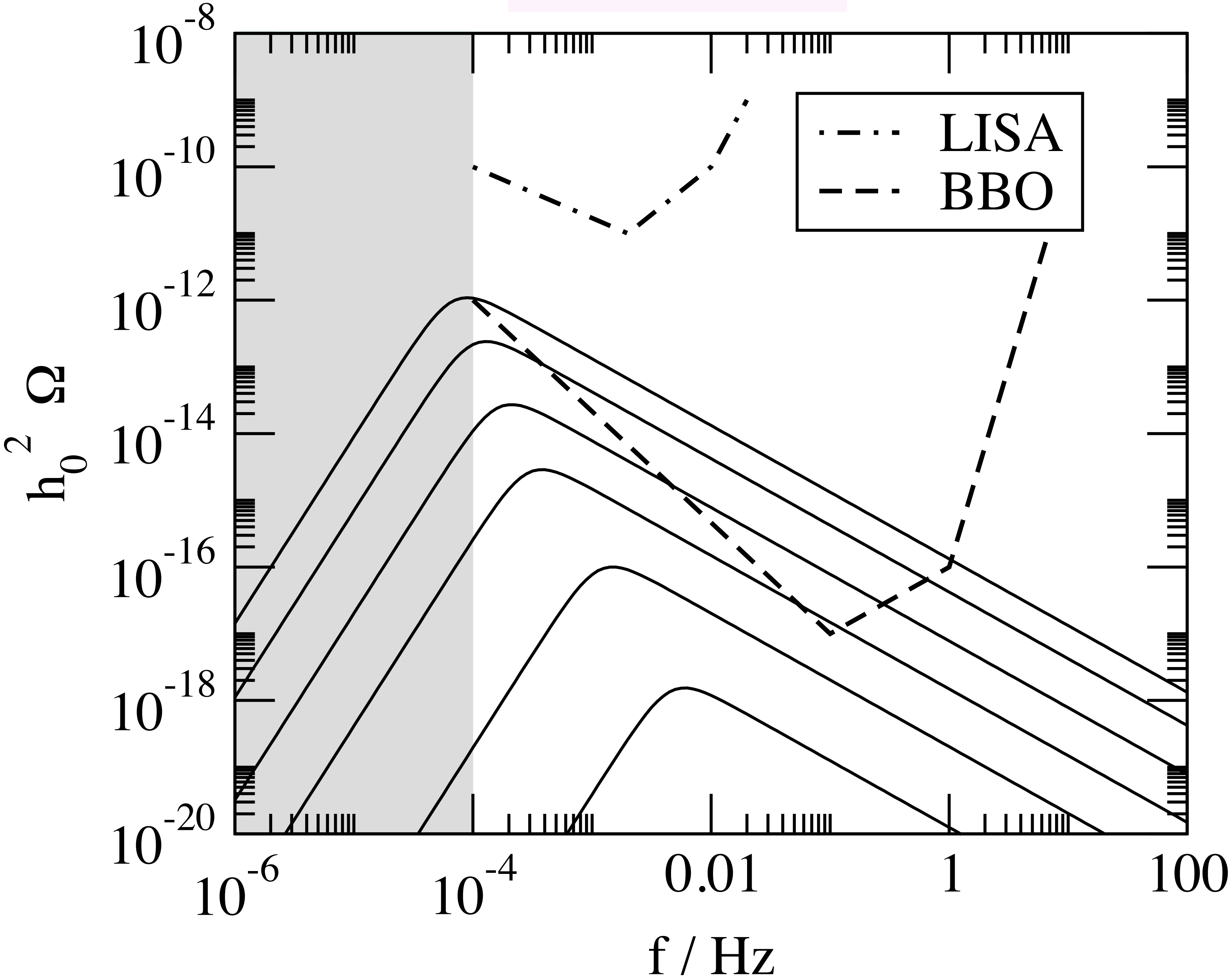
κ : fraction of bubble kinetic energy in latent heat $\kappa = \dfrac{(M/R^3)v^2}{\epsilon}$

α : energy fraction of latent heat $\alpha = \dfrac{\epsilon_*}{\frac{\pi^2}{30} g_* T_*^4}$

$$f_{\rm peak} \simeq 17 \left(\frac{f_*}{\beta}\right)\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{10^8\ {\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{\frac{1}{6}} \ [{\rm Hz}]$$

$$h_0^2\Omega_{\rm GW}(f_{\rm peak}) \simeq 1.7\times 10^{-5}\ \kappa^2\Delta\left(\frac{\beta}{H_*}\right)^{-2}\left(\frac{\alpha}{1+\alpha}\right)^2\left(\frac{g_*}{100}\right)^{-\frac{1}{3}}$$

Huber, Konstandin (2008)



set	α	β/H	T_* / GeV
1	0.03	1000	130
2	0.05	300	110
3	0.07	100	85
4	0.1	60	80
5	0.15	40	75
6	0.2	30	70

Phase transition of Higgs at high energy and GWs

- Unfortunately, the electroweak phase transition in SM is NOT first order for $m_h = 125\,\mathrm{GeV}$

- We need extension of SM to realize 1st order PT

  Singlet extension

  2HDM

  MSSM

  Many studies on 1st order electroweak PT and GWs.

- Once extended, the scale of PT is not limited to electroweak scale. Much higher scale PT is possible.

$\longrightarrow$ Much wider range of GW frequency.

Basic idea

- Suppose that there is a scalar field whose VEV is much higher than EW scale

  $\phi_{\rm NP}$ Peccei-Quinn field, B-L / GUT Higgs field etc.

- EW Higgs can have huge mass term: $V \sim |\phi_{\rm NP}|^2 |H|^2$
- EW scale is generated by tuning:

$$V \sim (|\phi_{\rm NP}|^2 - v^2)|H|^2 = -m_H^2 |H|^2 \qquad m_H \sim 100\,{\rm GeV}$$

- Before $\phi_{\rm NP}$ gets VEV, SM Higgs has huge mass term.

$$V \sim -v^2 |H|^2$$

- The scale of PT can be much different from EW scale!

- Model

$$V_0 = \lambda^2(|\phi_{\rm NP}|^2 - v_{\rm NP}^2 - \delta_{\rm EW}^2)|H|^2 + \frac{\lambda_H}{2}|H|^4 + \lambda_\phi^2(|\phi_{\rm NP}|^2 - v_{\rm NP}^2)^2 + V_S$$

$$V_S = \sum_i \frac{\lambda_{SH}^2}{2} S_i^2 |H|^2 + \sum_i \frac{\lambda_{S\phi}^2}{2} S_i^2 |\phi_{\rm NP}|^2$$

$\phi_{\rm NP}$: any scalar field having VEV of $v_{\rm NP}$ (Peccei-Quinn field, B-L Higgs, etc.)

S_i : singlet scalar having zero VEV

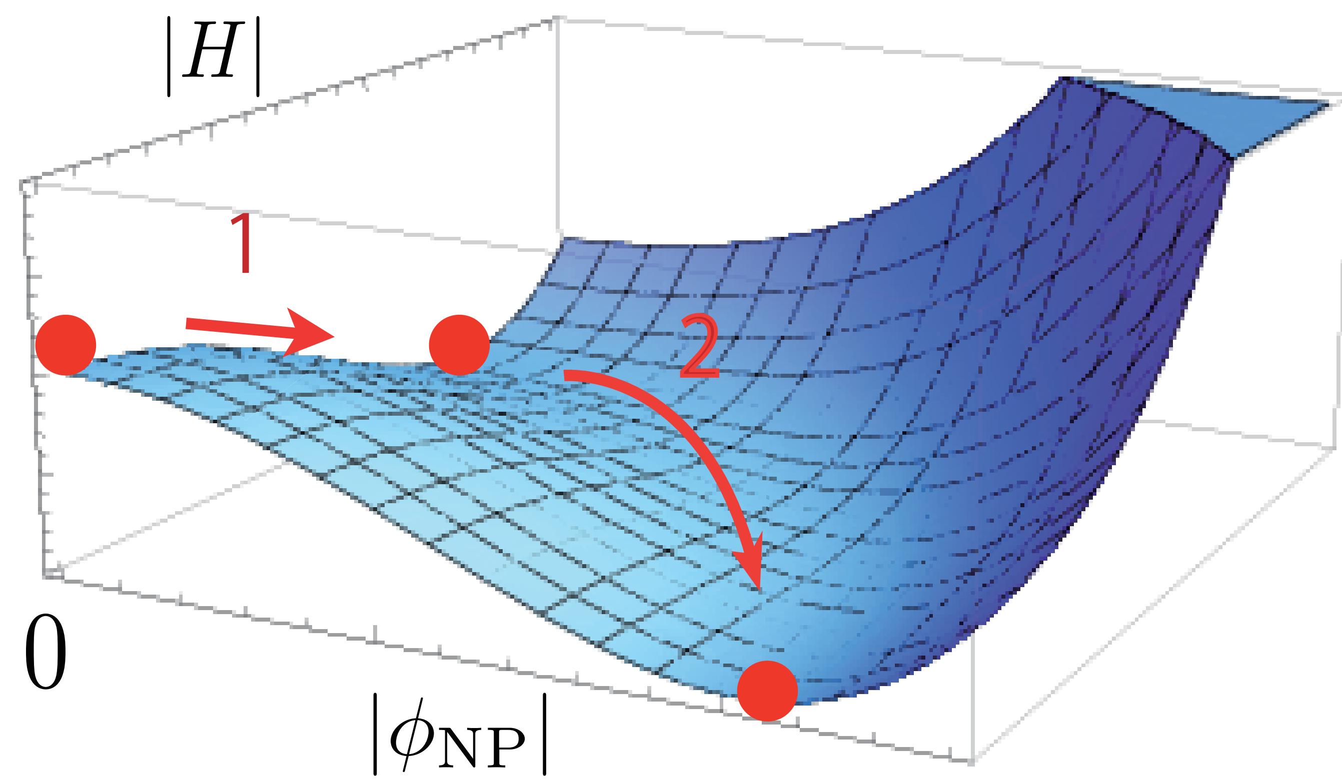
- At high temperature,

  $H = \phi_{\rm NP} = 0$

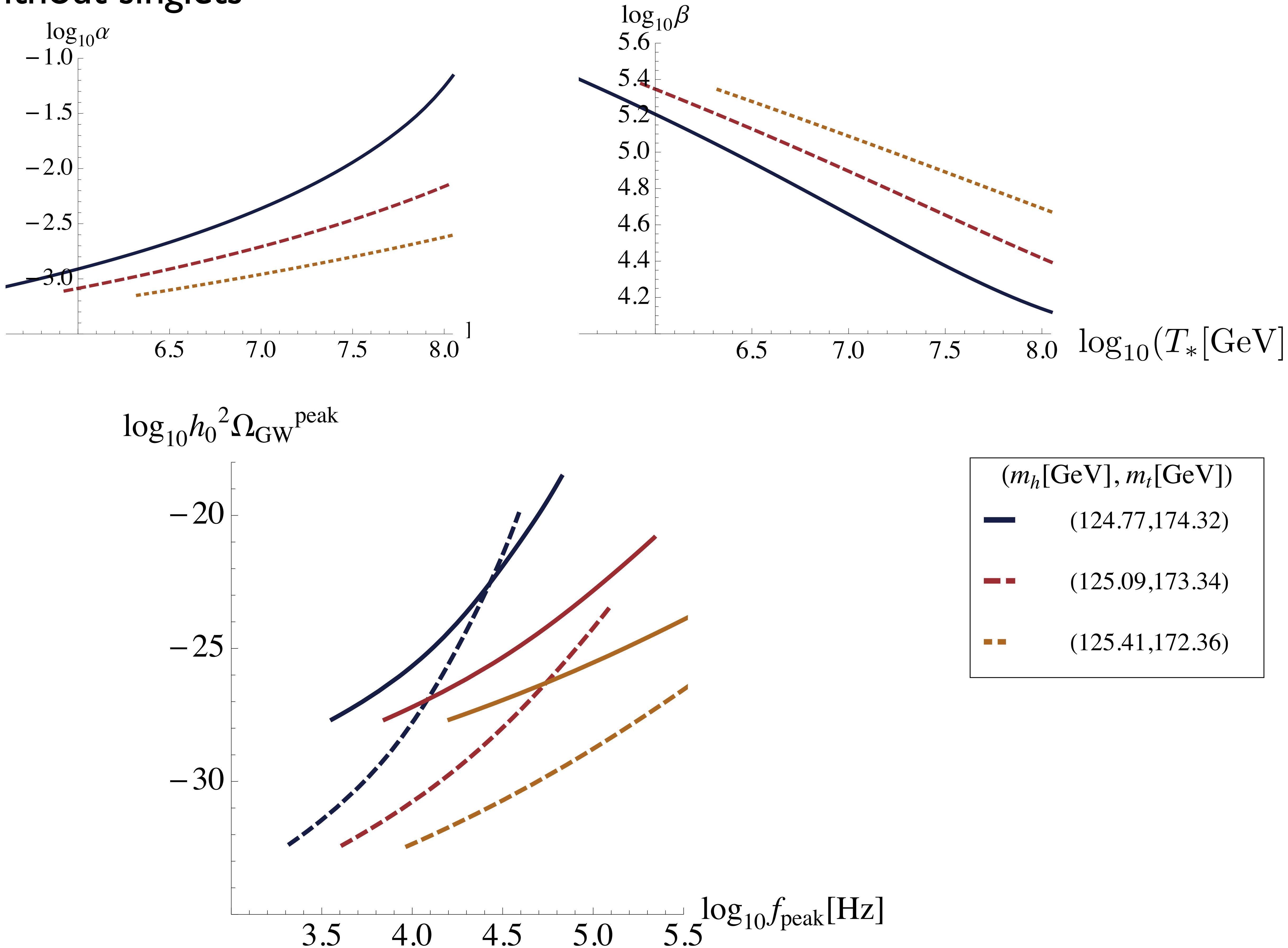
- Phase transition happens at

  $T \sim v_{\rm NP} \gg v_{\rm EW}$

- GW frequency can be much higher: e.g. f~1Hz (DECIGO)

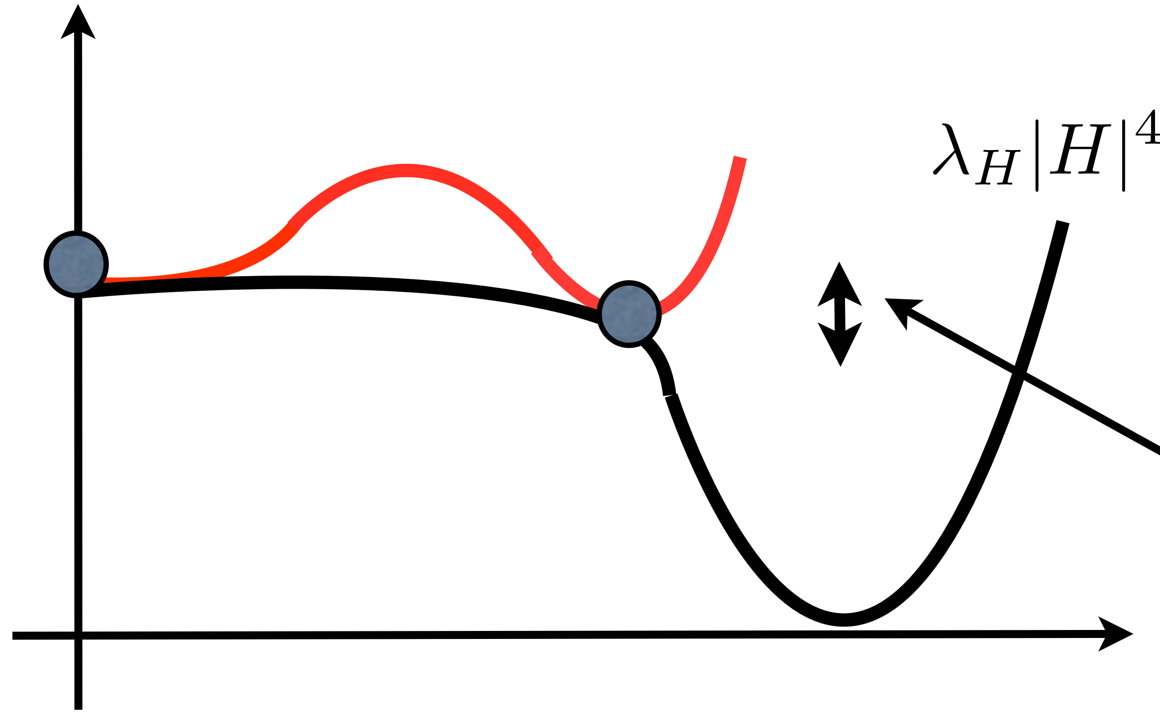


Without singlets



- Why is GW small ?

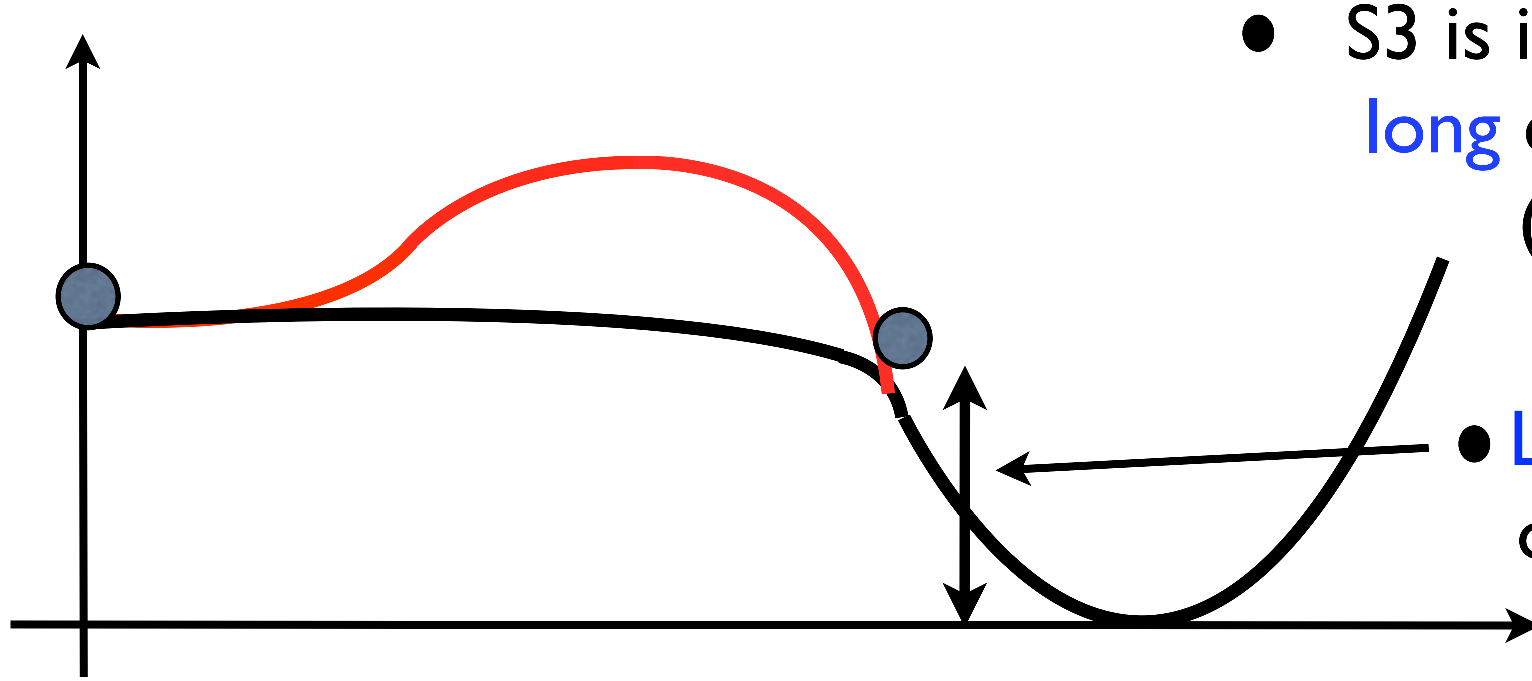
- Large λ_H



- S3 is sensitive to T: short duration of PT (large β)

- Small amount of latent heat α

- Small λ_H



- S3 is insensitive to T: long duration of PT (small β)

- Large amount of latent heat α

- Smaller λ_H $\longrightarrow$ Larger GW

- Singlet extension

$$V_S = \sum_i \frac{\lambda_{SH}^2}{2} S_i^2 |H|^2 + \sum_i \frac{\lambda_{S\phi}^2}{2} S_i^2 |\phi_{\rm NP}|^2$$

- Change Higgs quartic coupling through RGE:

$$\frac{d\lambda_H}{d\ln\mu} = \beta_H^{\rm SM} + \frac{N_S}{16\pi^2}\lambda_{SH}^4$$

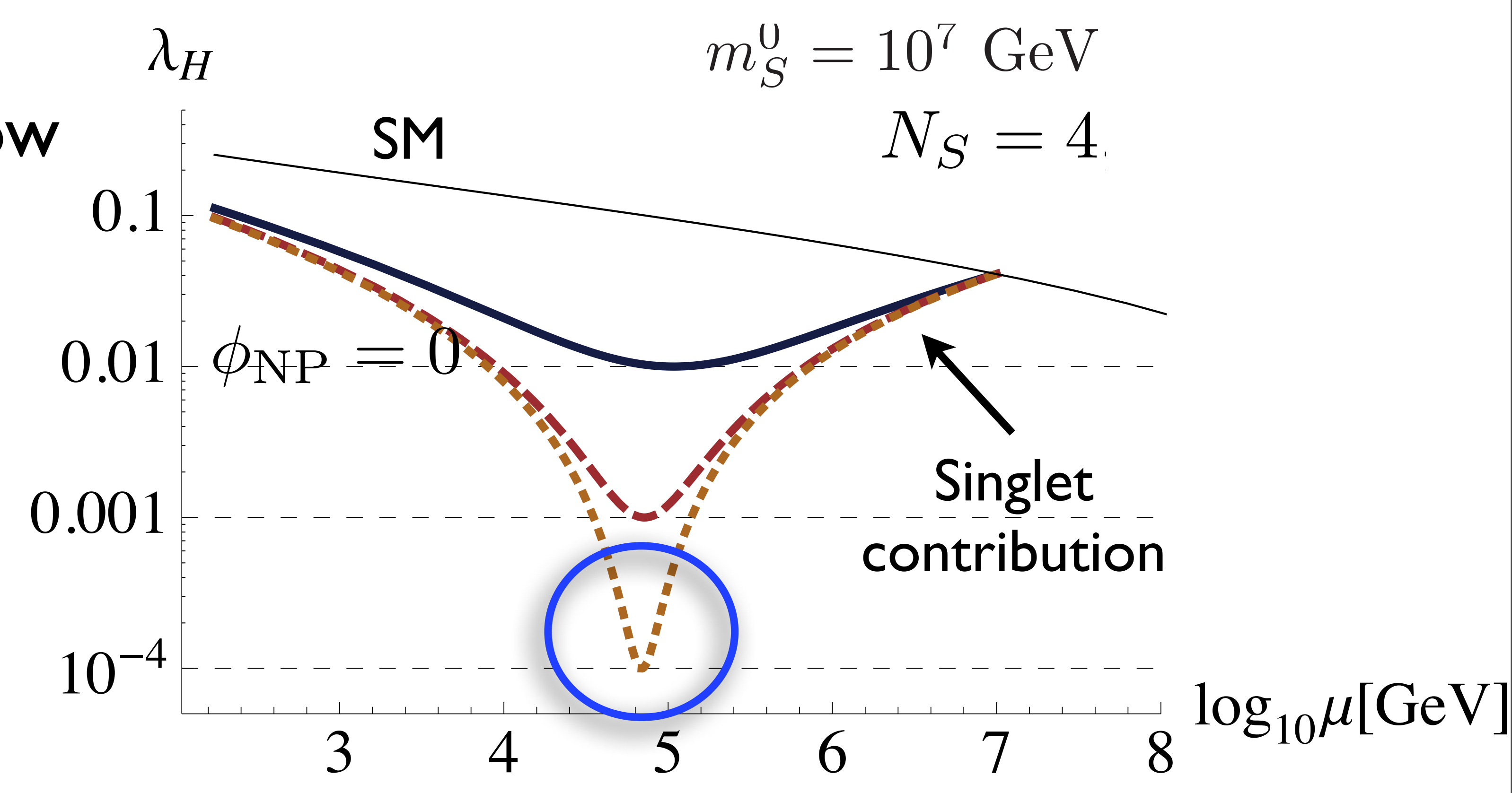
- At T=0, $m_S^0 = \lambda_{S\phi} v_{\rm NP}$

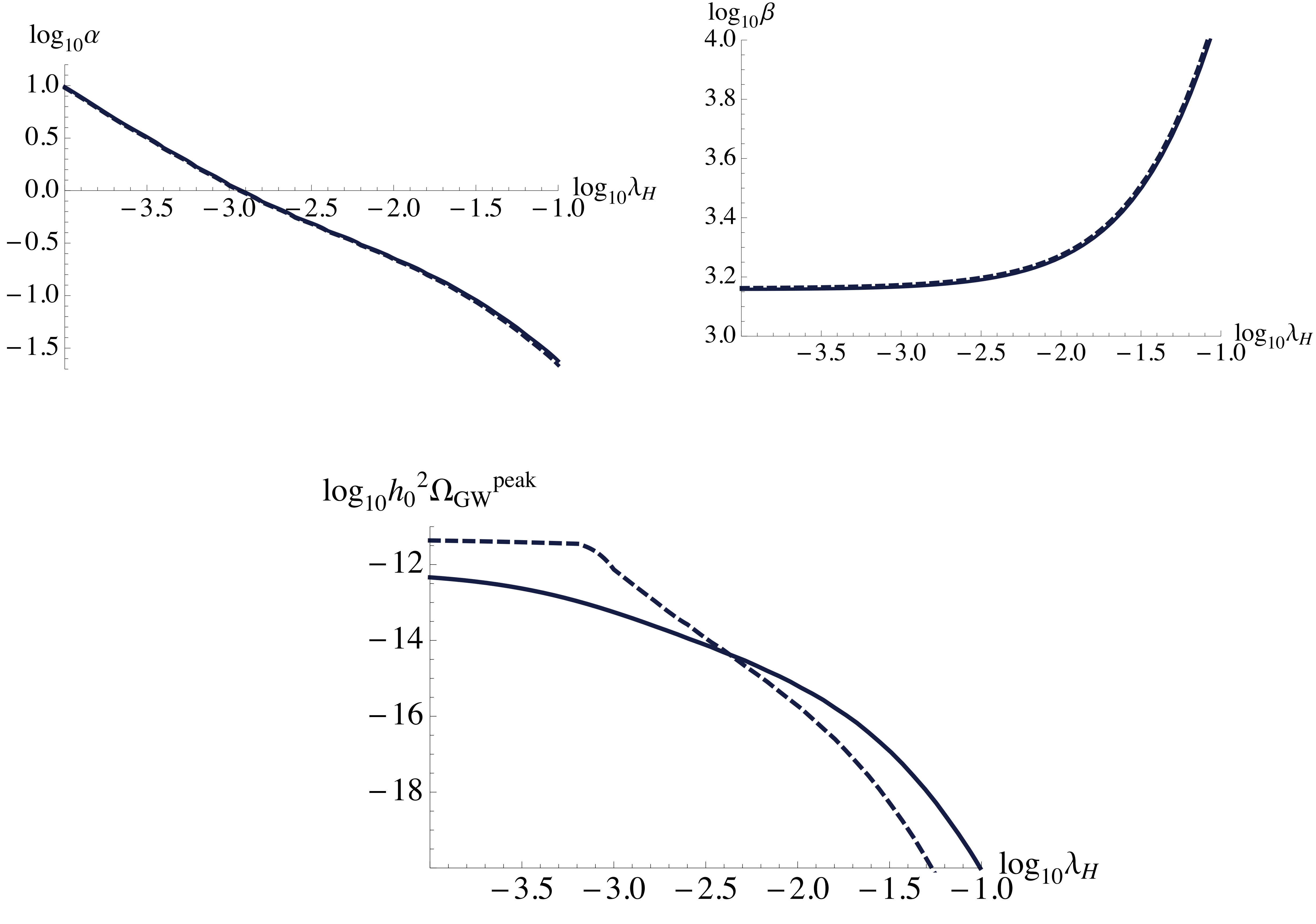
  RGE is not affected below this scale.

- At high T, $\phi_{\rm NP} = 0$

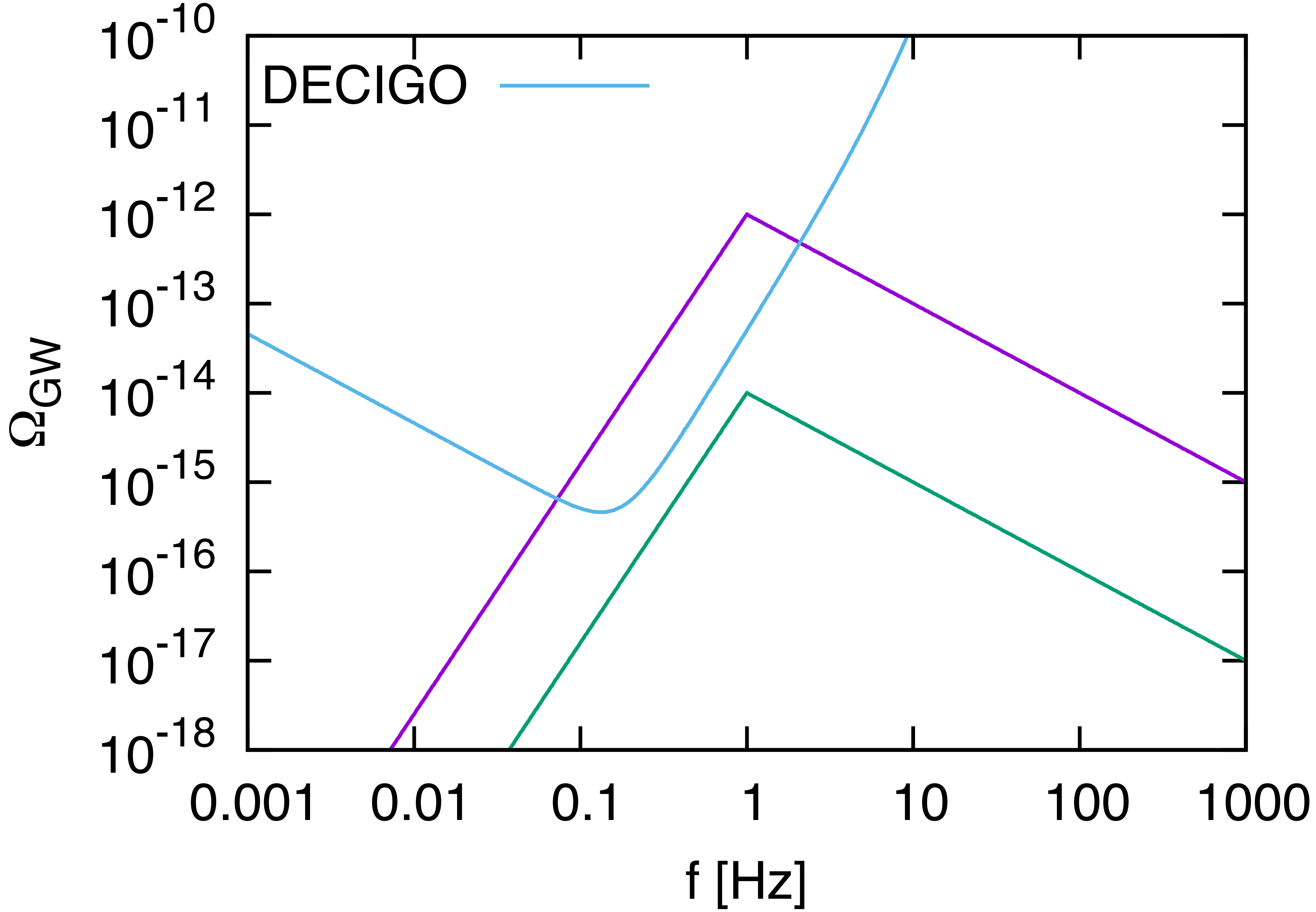
  hence $m_S = 0$

  RGE changes Higgs coupling at T=T*





$\log_{10}\alpha$
1.0
0.5
0.0
−0.5
−1.0
−1.5
−3.5
−3.0
−2.5
−2.0
−1.5
−1.0
$\log_{10}\lambda_H$
$\log_{10}\beta$
4.0
3.8
3.6
3.4
3.2
3.0
−3.5
−3.0
−2.5
−2.0
−1.5
−1.0
$\log_{10}\lambda_H$
$\log_{10}h_0{}^2\Omega_{\mathrm{GW}}{}^{\mathrm{peak}}$
−12
−14
−16
−18
−3.5
−3.0
−2.5
−2.0
−1.5
−1.0
$\log_{10}\lambda_H$



Maybe detectable at DECIGO

Summary

- 1st order phase transition can happen at much higher energy scale than electroweak scale (Peccei-Quinn, B-L, etc.)
- Frequency of GWs from bubble collisions can be significantly different from previously thought
- Typically GW amplitude is too small, but it is possible to enhance GW signal in singlet extended models.