Gravitational waves as probe of physics beyond standard model

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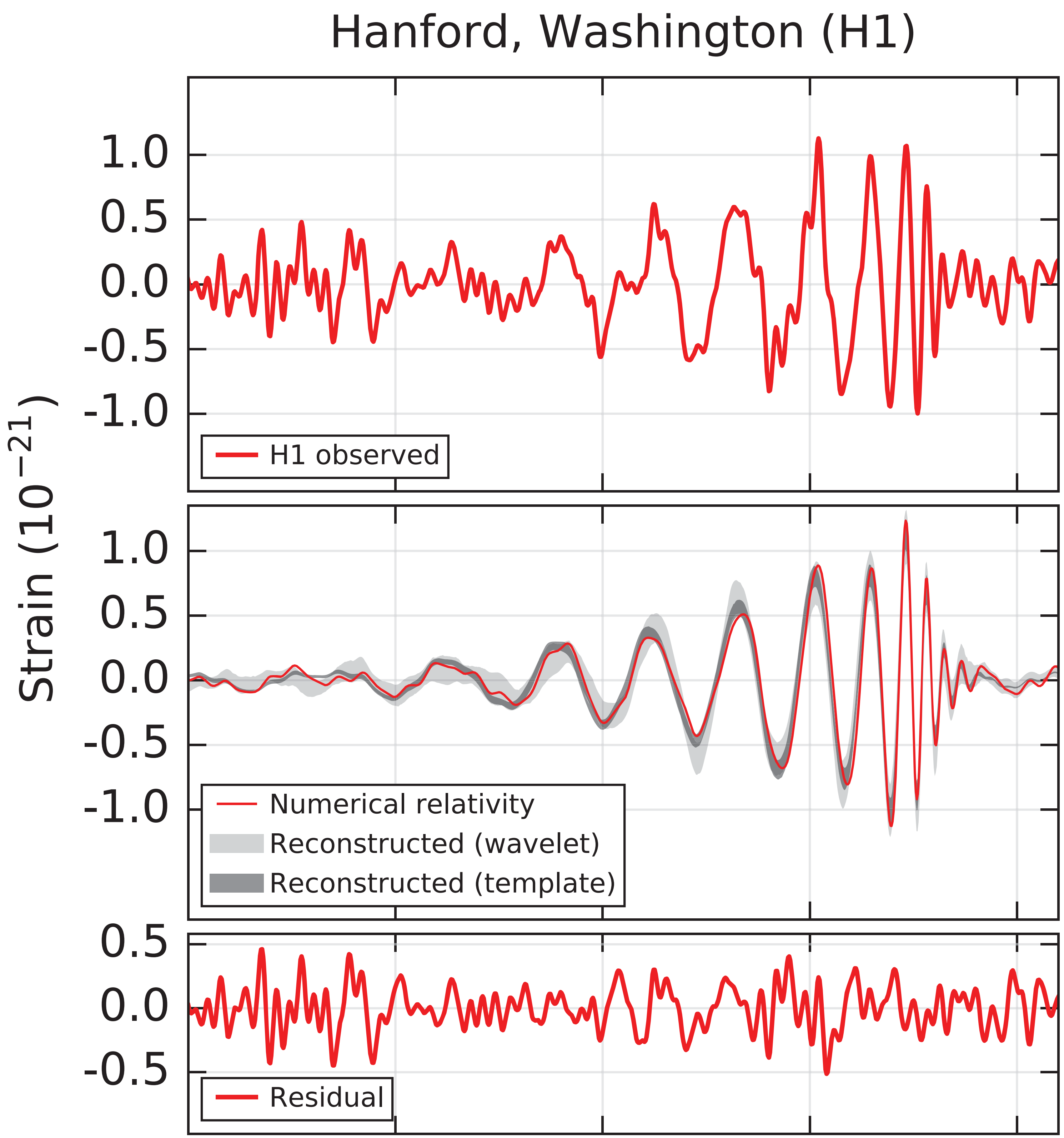
Contents

- Introduction
- 1st order phase transition and GWs
- GWs from domain walls

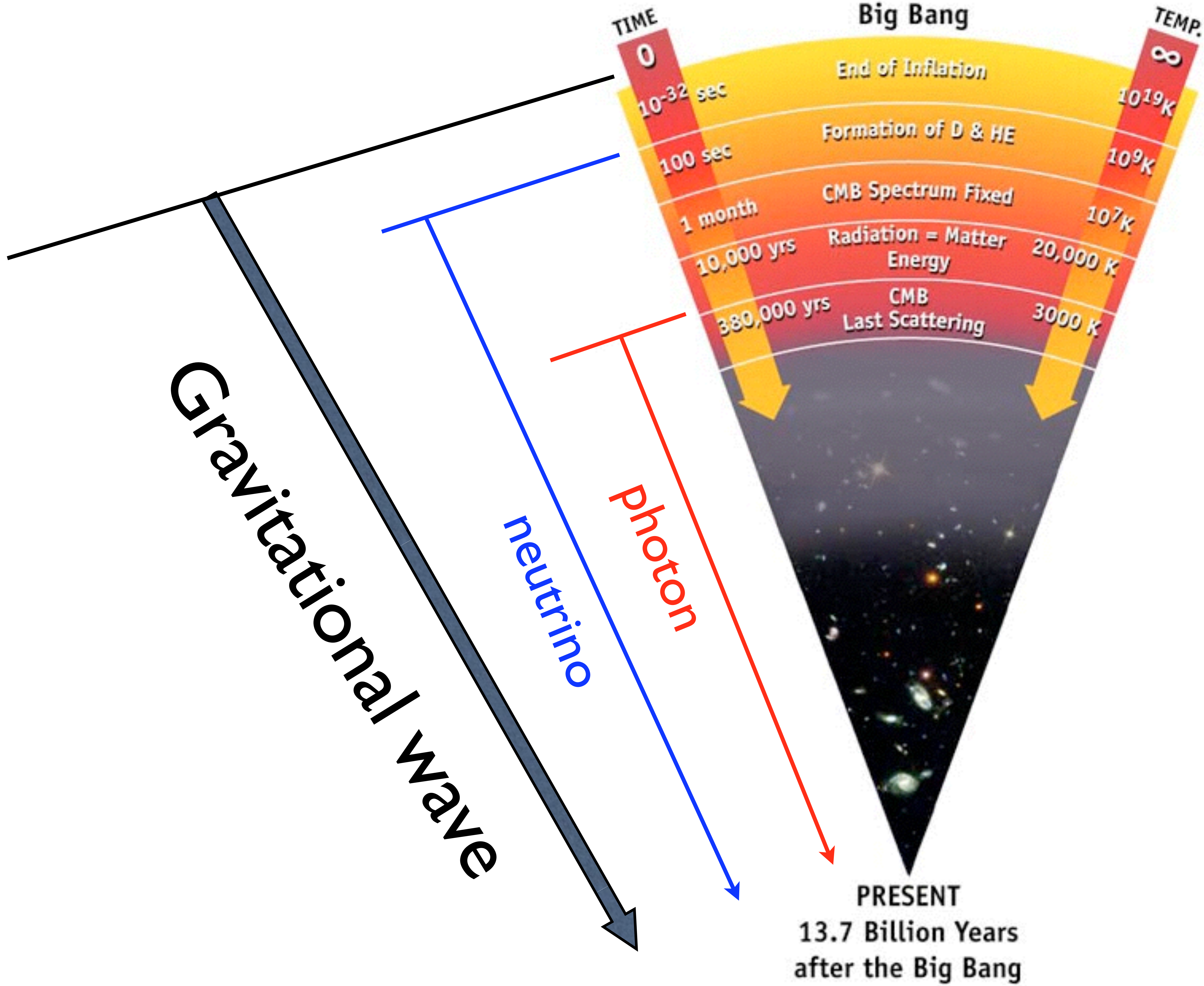
Gravitational wave (GW) is discovered!



LIGO (2016)

Can GW be a new probe of physics beyond standard model ?

Yes !!



Big Bang
TIME
TEMP.
0
∞
End of Inflation
10-32 sec
1019K
Formation of D & HE
100 sec
109K
CMB Spectrum Fixed
1 month
107K
Radiation = Matter Energy
10,000 yrs
20,000 K
CMB Last Scattering
380,000 yrs
3000 K
Gravitational wave
neutrino
photon
PRESENT
13.7 Billion Years after the Big Bang

GW and new physics

- Inflationary GW

  Inflation energy scale

  Thermal history after inflation

- Preheating after inflation

  Inflaton dynamics -- property of inflaton

- Topological defects

  Symmetry breaking (B-L, Peccei-Quinn, family symmetry, ...)

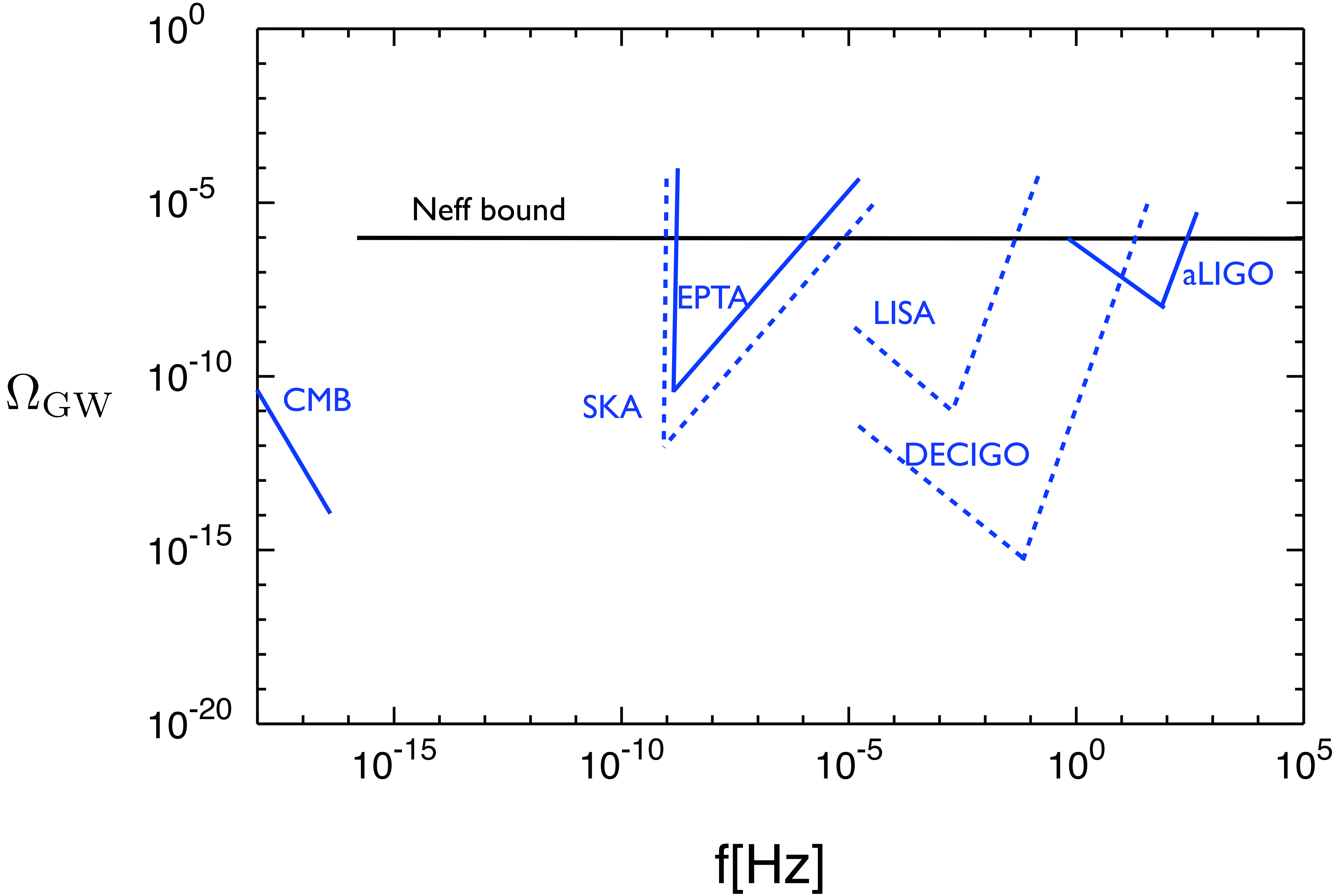
- Vacuum bubbles from 1st order phase transition

  Electroweak / other high energy phase transition

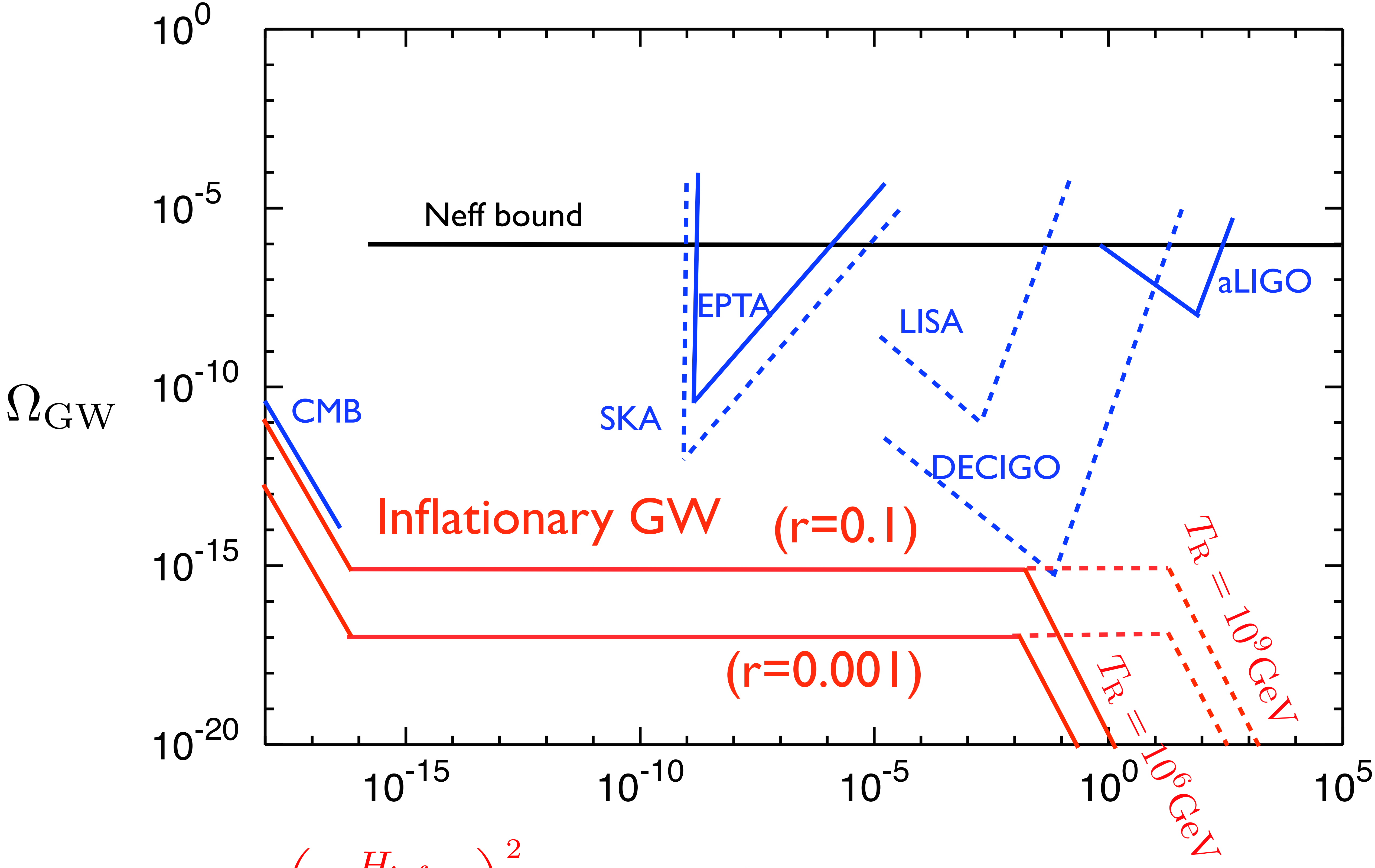
  Baryogenesis

- Others

Various sources of stochastic GW background

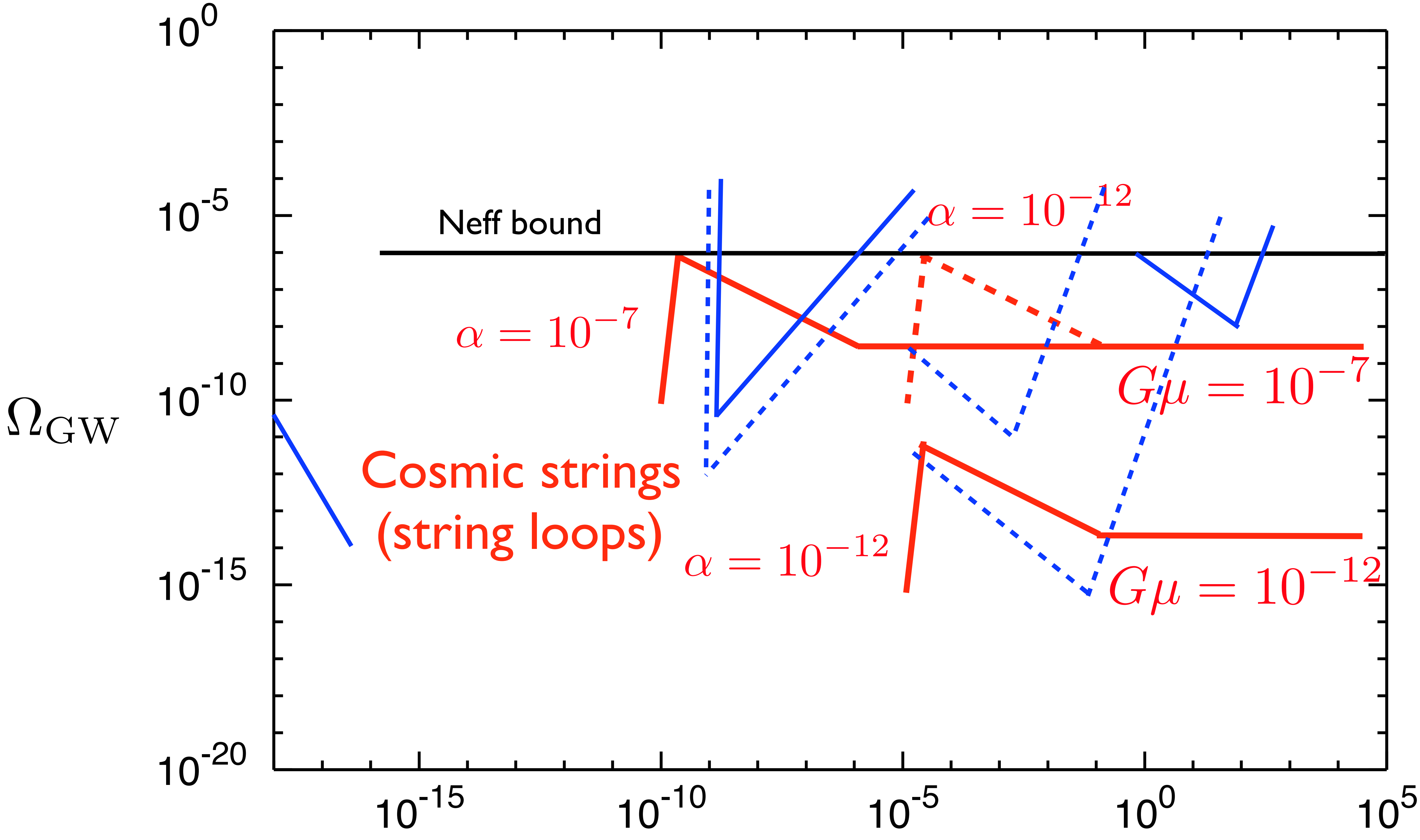


Various sources of stochastic GW background



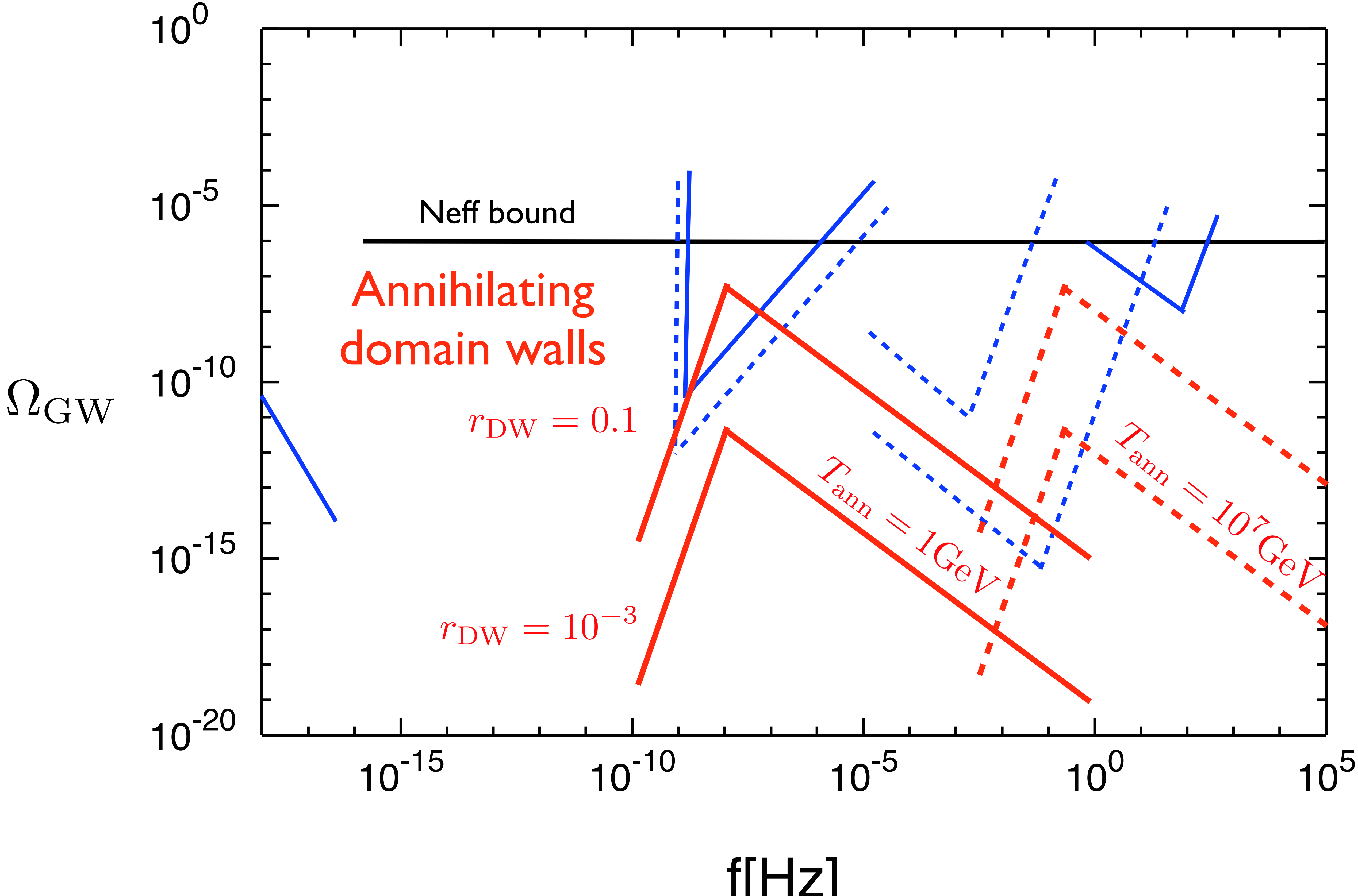
$$r \simeq 0.16 \left(\frac{H_{\rm inf}}{10^{14}{\rm GeV}}\right)^2$$

Various sources of stochastic GW background

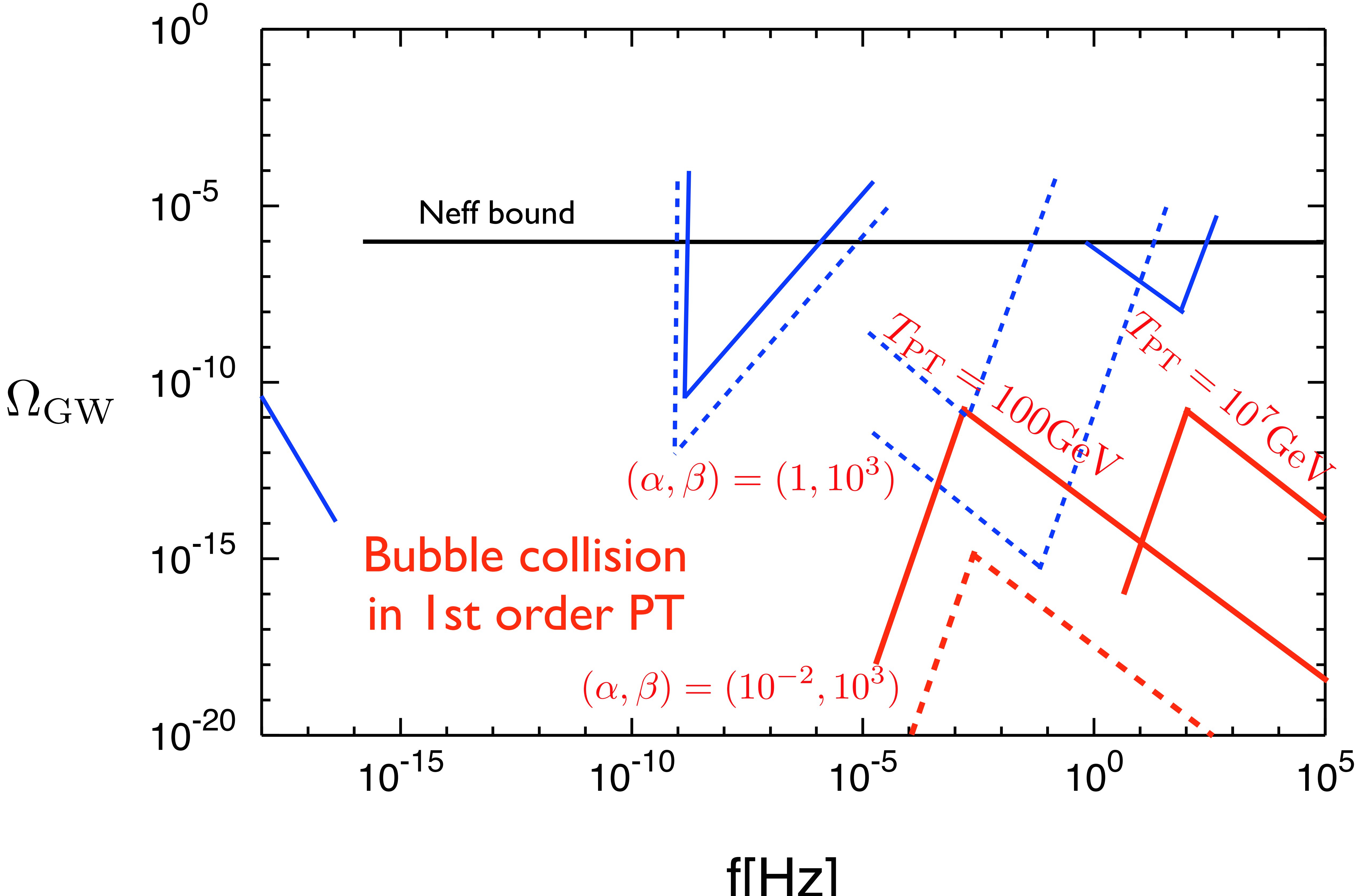


$$G\mu \sim 10^{-7}\left(\frac{\mu}{(10^{15}\mathrm{GeV})^2}\right)$$

Various sources of stochastic GW background



Various sources of stochastic GW background



GWs from 1st order phase transition

Thermal phase transition

- Toy model

$$\mathcal{L} = -g^2\phi^2\chi^2 - V(\phi) \qquad V(\phi) = V_0 - m_\phi^2\phi^2 + \lambda\phi^4$$

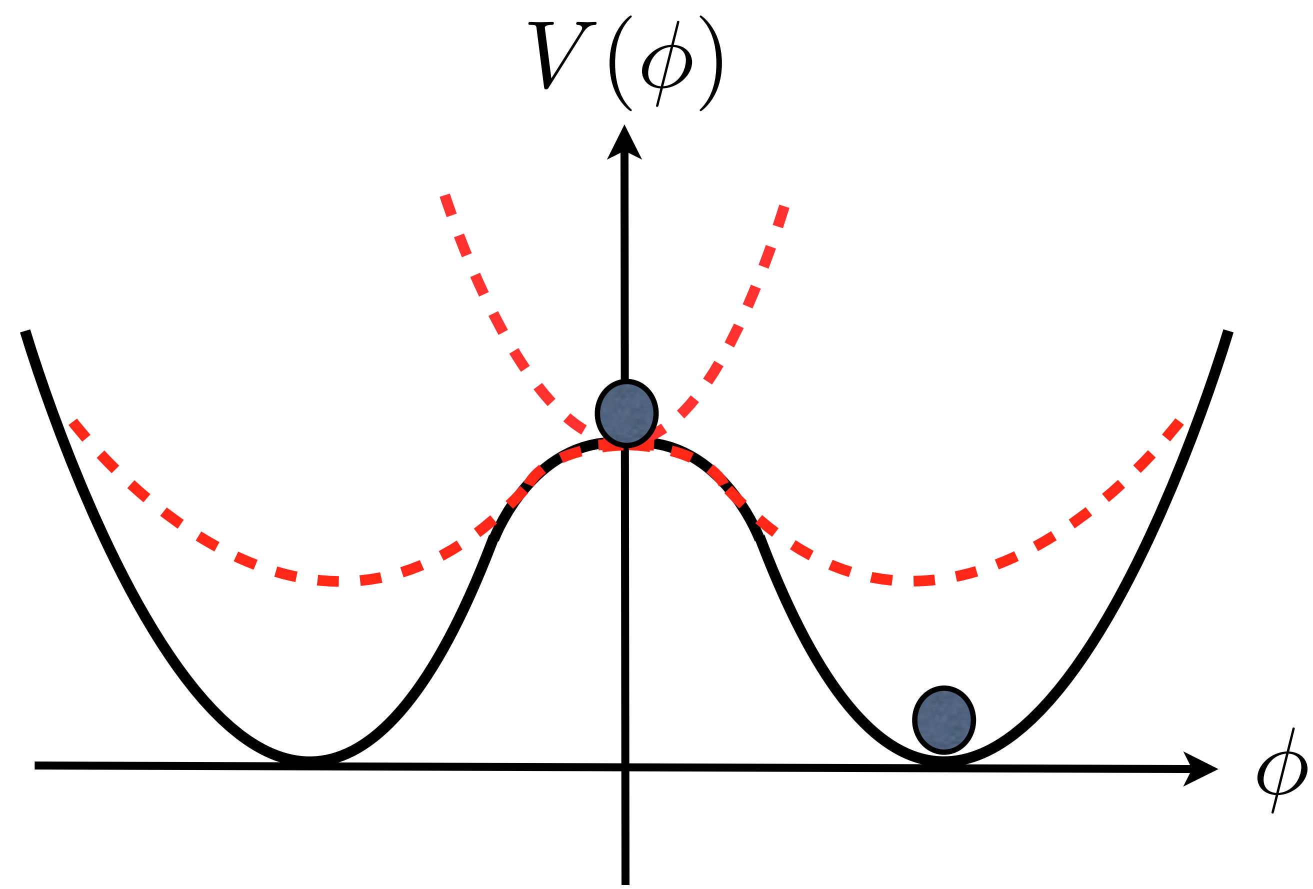
- Suppose that χ is in thermal equilibrium.

Thermal correction to the potential:

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

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

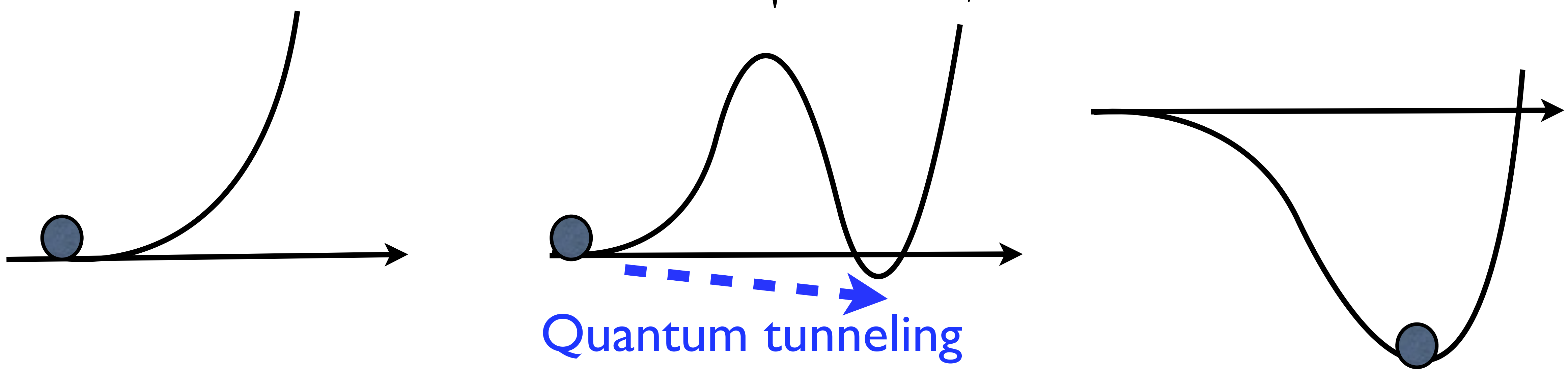
$T \lesssim m_\phi/g$: Broken phase



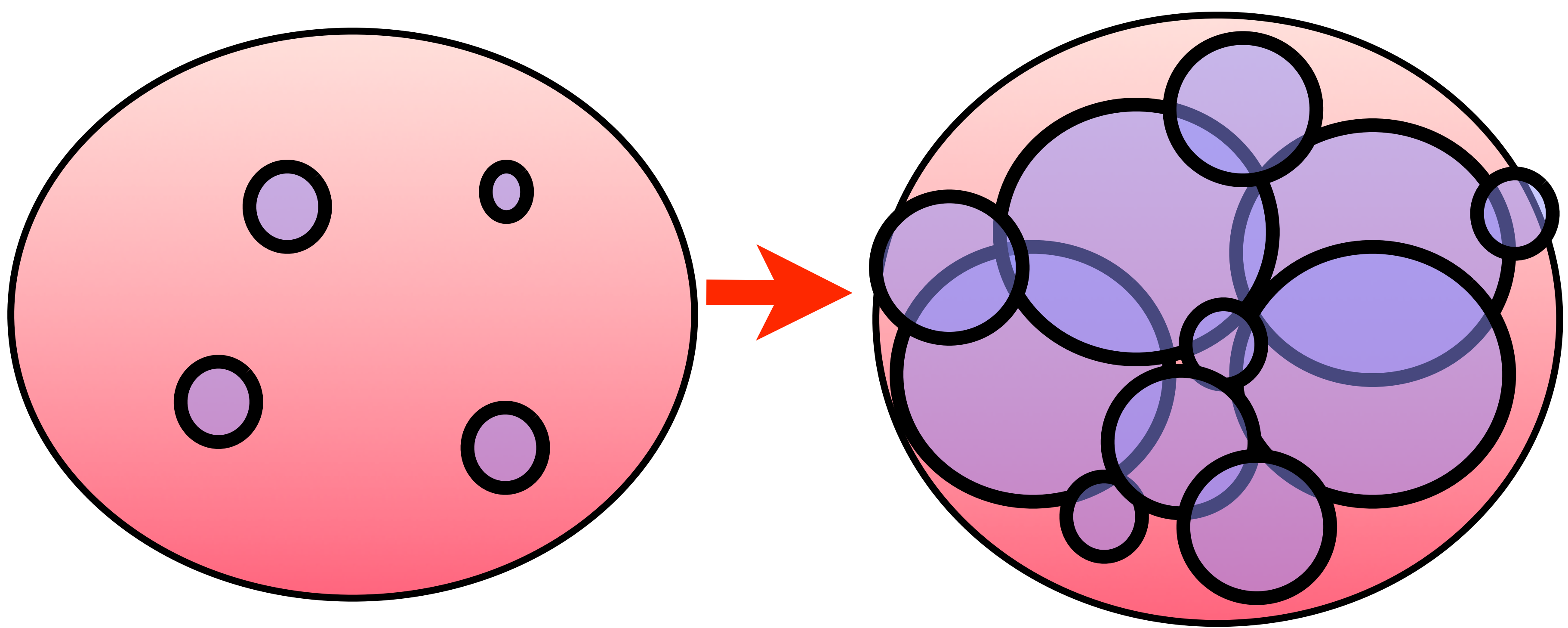
- Zero + Finite-T potential

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

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



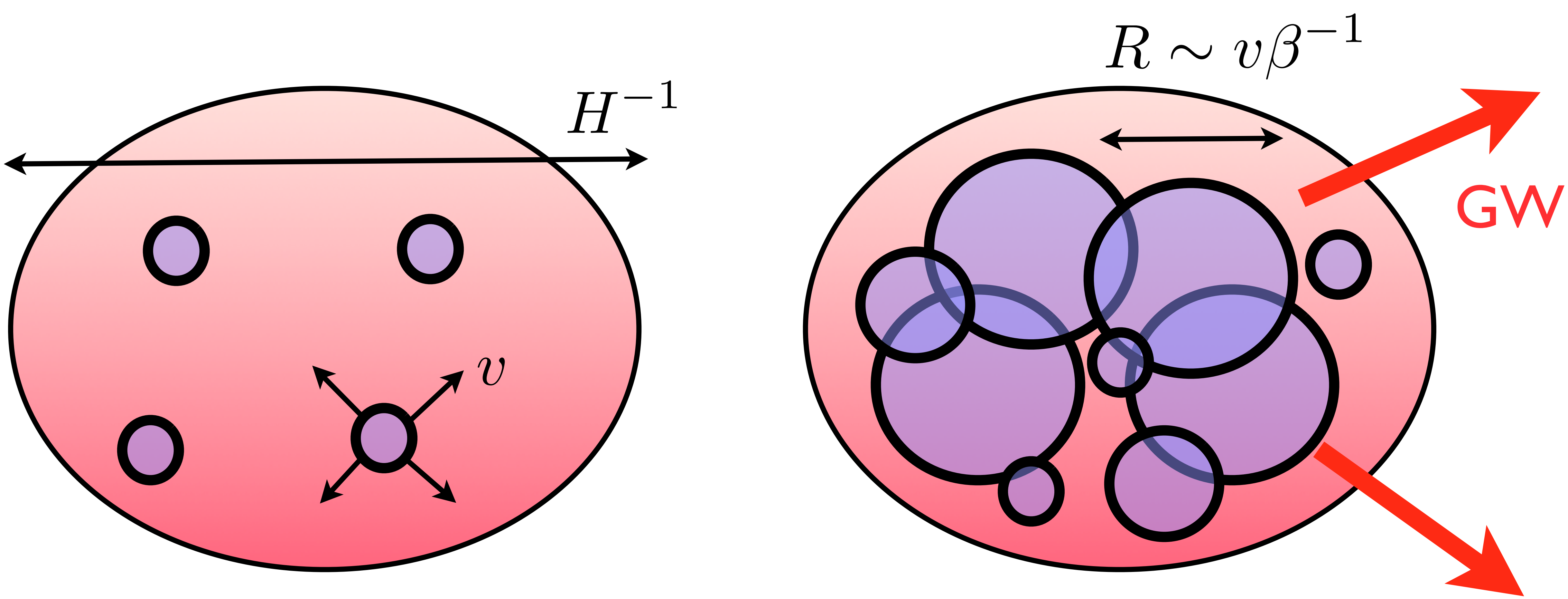
First order phase transition happens at $T \sim m_\phi/g$



GWs from bubble collision

Kamionkowski, Kosowski, Turner (1994)

- Important quantities are bubble size at collision R and latent heat α
- R is determined by duration of phase transition $\beta^{-1} \equiv \Delta t$ and wall velocity v : $R \sim v\beta^{-1}$
- Note that $T^{-1} \lll \ll \beta^{-1} \ll H^{-1}$



- Duration of phase transition

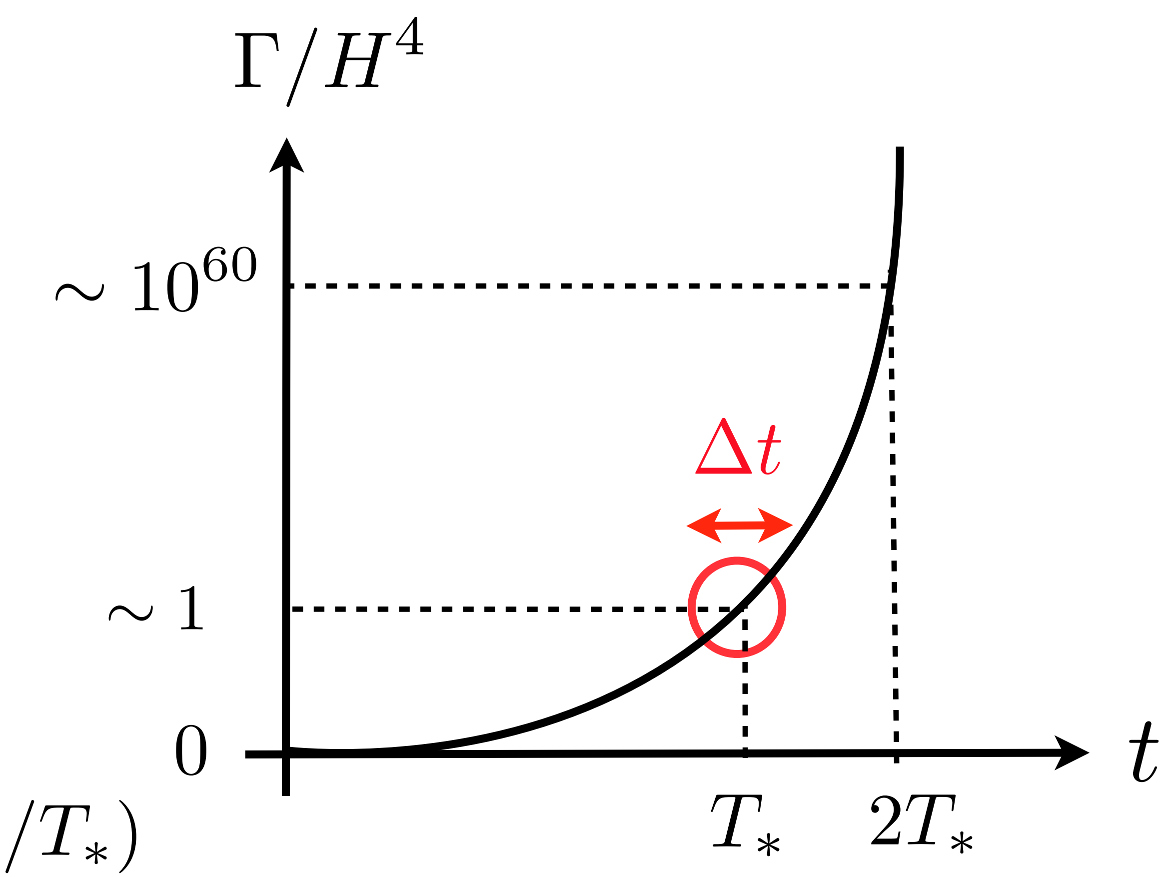
  - Tunneling rate

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

  - 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

$$\Delta\left(\frac{\Gamma}{H^4}\right) \sim \mathcal{O}(1) \longrightarrow \frac{dS_*}{dt}\Delta t \sim \mathcal{O}(1) \longrightarrow \Delta t \sim \frac{1}{\beta} \sim \left(\frac{dS_*}{dt}\right)^{-1} \sim \frac{1}{H_*}\left(T\frac{dS_*}{dT}\right)^{-1}$$

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

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

Actually the temperature dependence is more complicated.

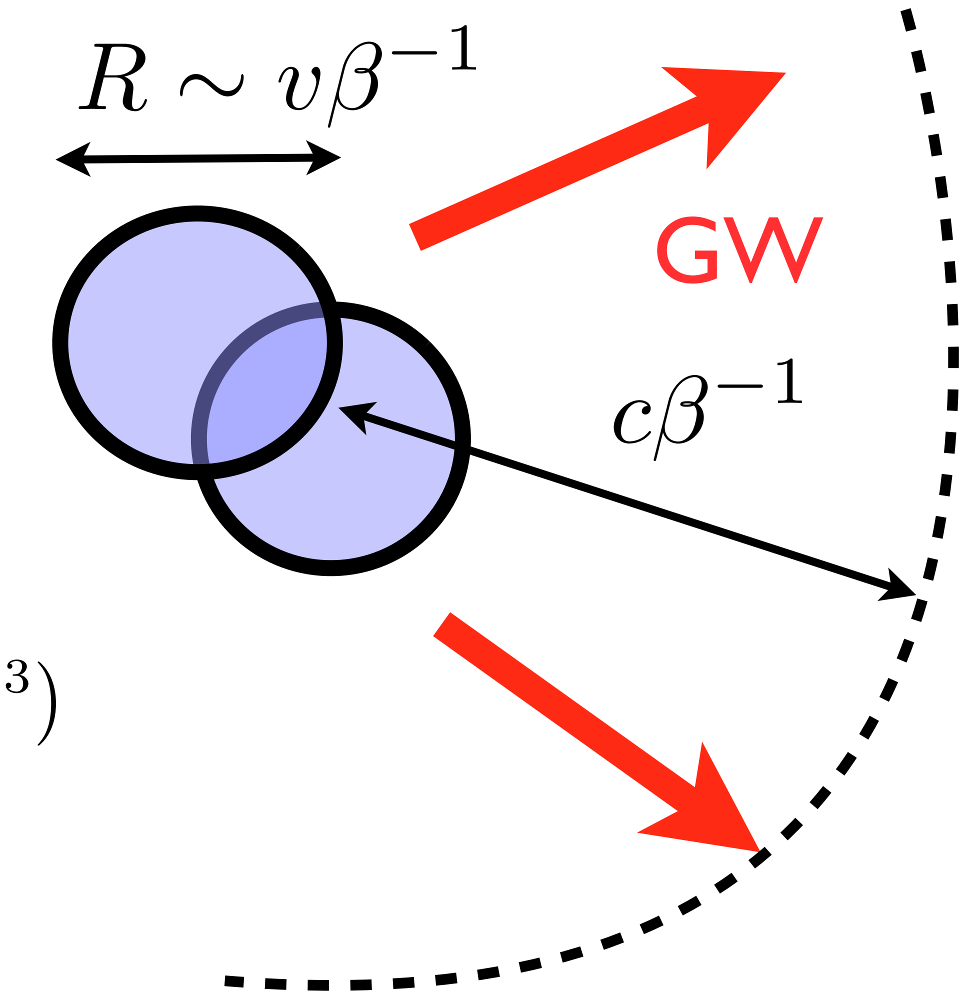
Typically, the duration of PT is much shorter than the Hubble scale at PT.

- Estimate of GWs   Kosowsky et al. (92), Caprini et al. (2007)

  - Frequency: $f \sim \beta \frac{a_*}{a_0}$ 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 $\kappa = \frac{(M/R^3)v^2}{\epsilon}$

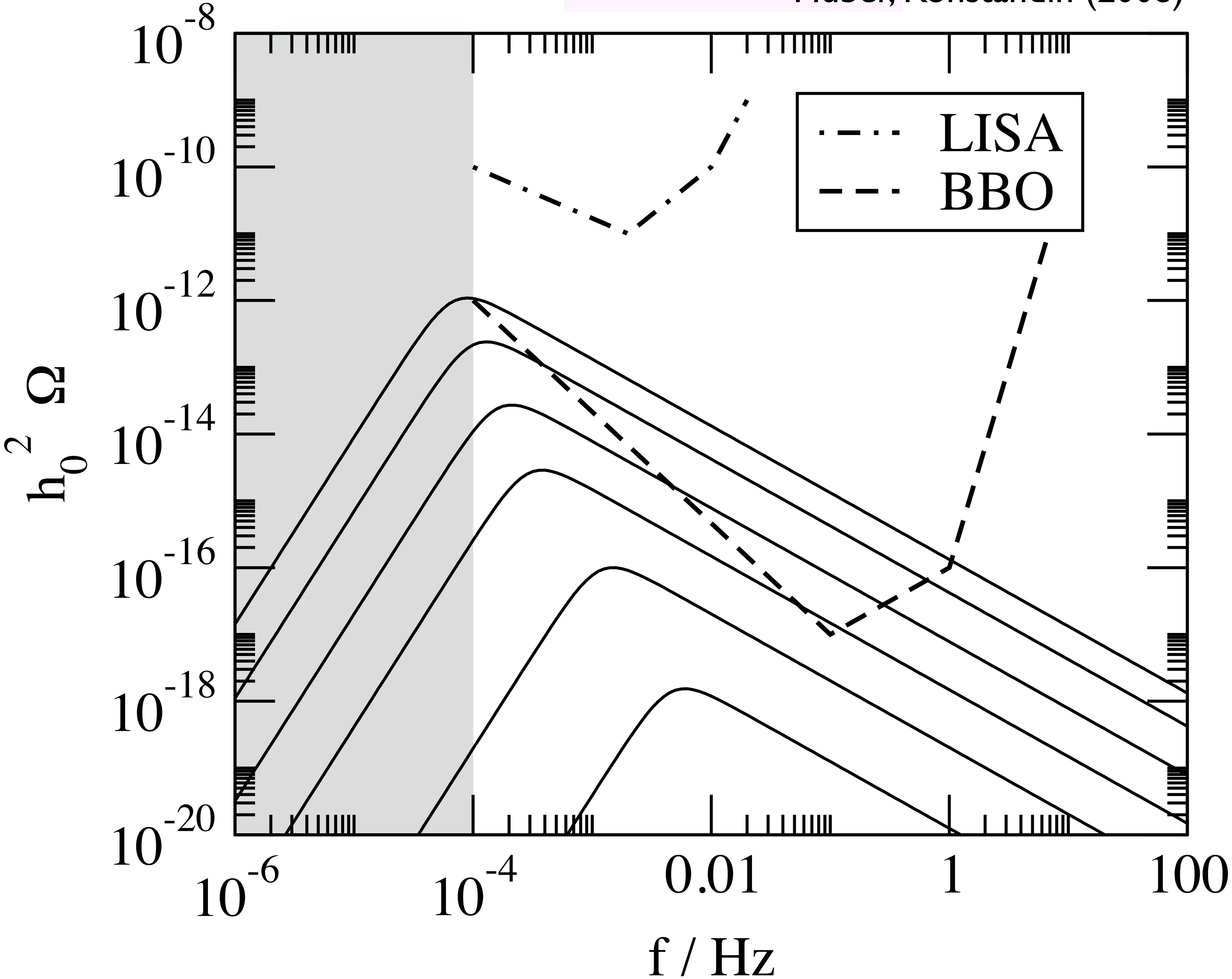
α : energy fraction of latent heat $\alpha = \frac{\epsilon_*}{\frac{\pi^2}{30} g_* T_*^4}$

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

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

- GW spectrum from bubble collision

Huber, Konstandin (2008)



$$\Omega_{\rm GW} \propto \beta^{-2}\alpha^2$$

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

- See Jinno, Takimoto (2016) for analytic derivation of the spectrum
- Another contribution to GW from turbulent fluid/acoustic waves [Hindmarsh et al.(2014)]

GWs from electroweak PT

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

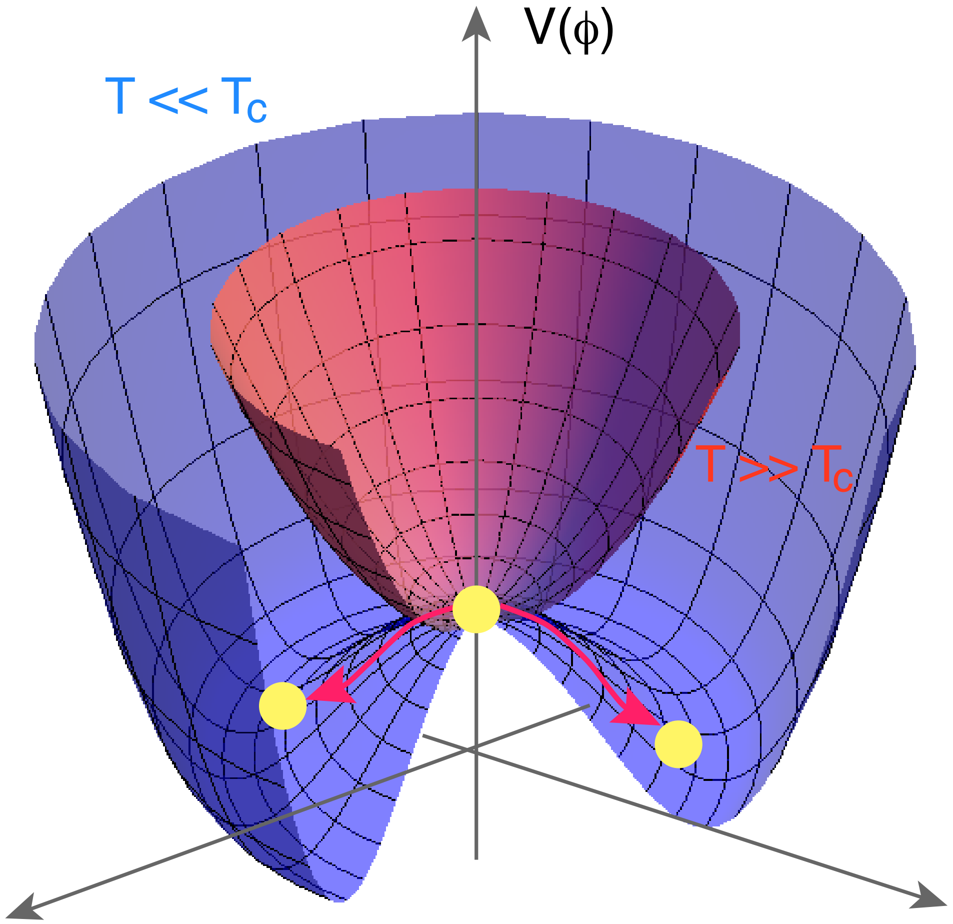
Kajantie et al. (1996)

- We need extension of SM to realize strong 1st order PT and large amount of GWs

Singlet extension, 2HDM, (N)MSSM,...

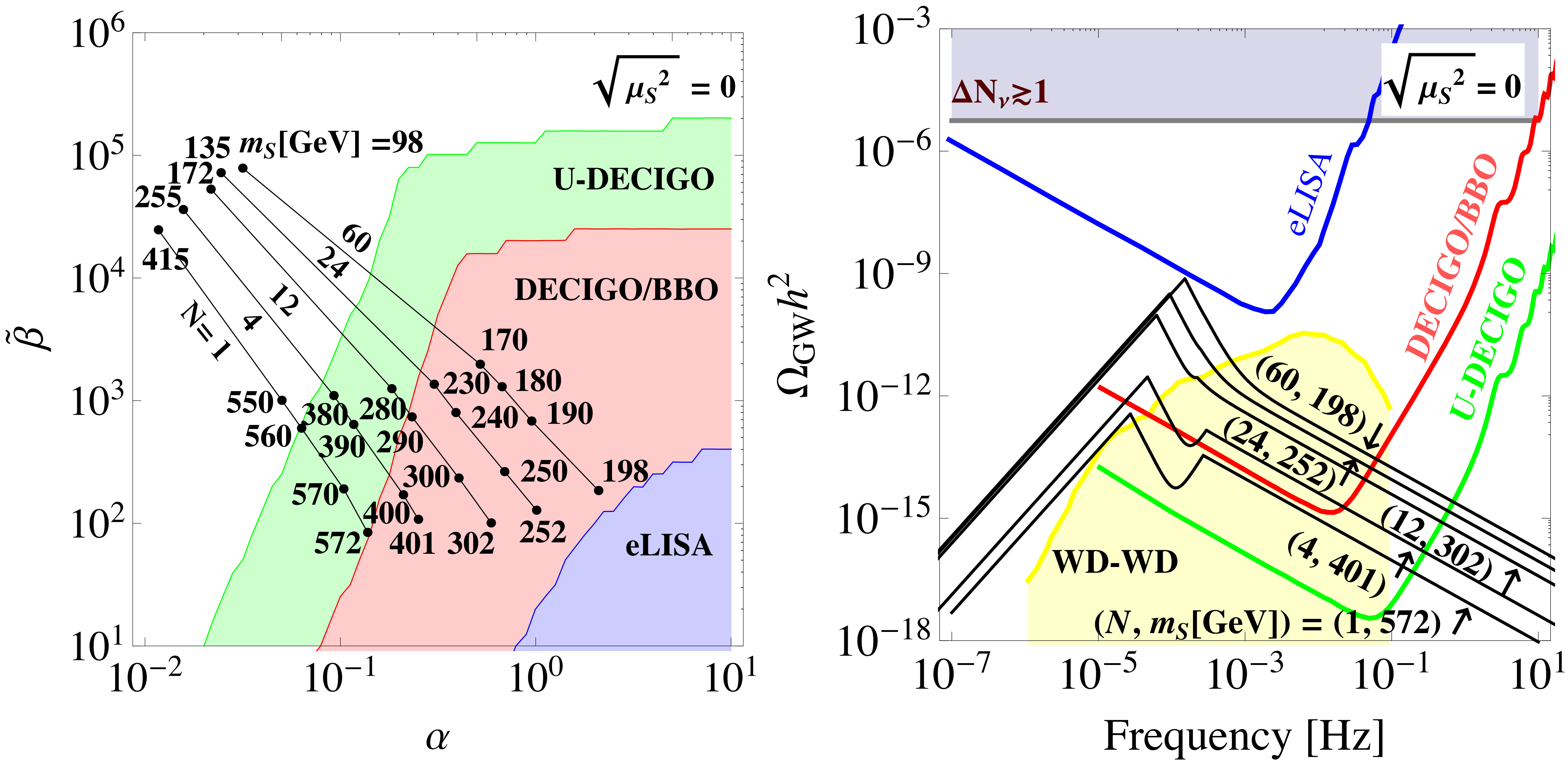
Apreda et al. (2002),
Grojean, Servant (2006),
Espinosa, Quiros (2007),
Huber, Konstandin (2007),...

- Discovery of GW may indicate new physics in the Higgs sector!



- **Singlet extension** $\vec{S} = (S_1, S_2, \cdots, S_N)^T$

$$V_0(\Phi, \vec{S}) = V_{\rm SM}(\Phi) + \frac{\mu_S^2}{2}|\vec{S}|^2 + \frac{\lambda_S}{4}|\vec{S}|^4 + \frac{\lambda_{\Phi S}}{2}|\Phi|^2|\vec{S}|^2,$$



Kakizaki, Kanemura, Matsui (2015)

High-scale EWPT & GW

R.Jinno, KN, M.Takimoto (2015)

- 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

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

$\phi_{\rm NP}$: any scalar field having VEV of $v_{\rm NP}$ $\delta_{\rm EW} \sim 100\mathrm{GeV}$

(Peccei-Quinn field, B-L Higgs, etc.)

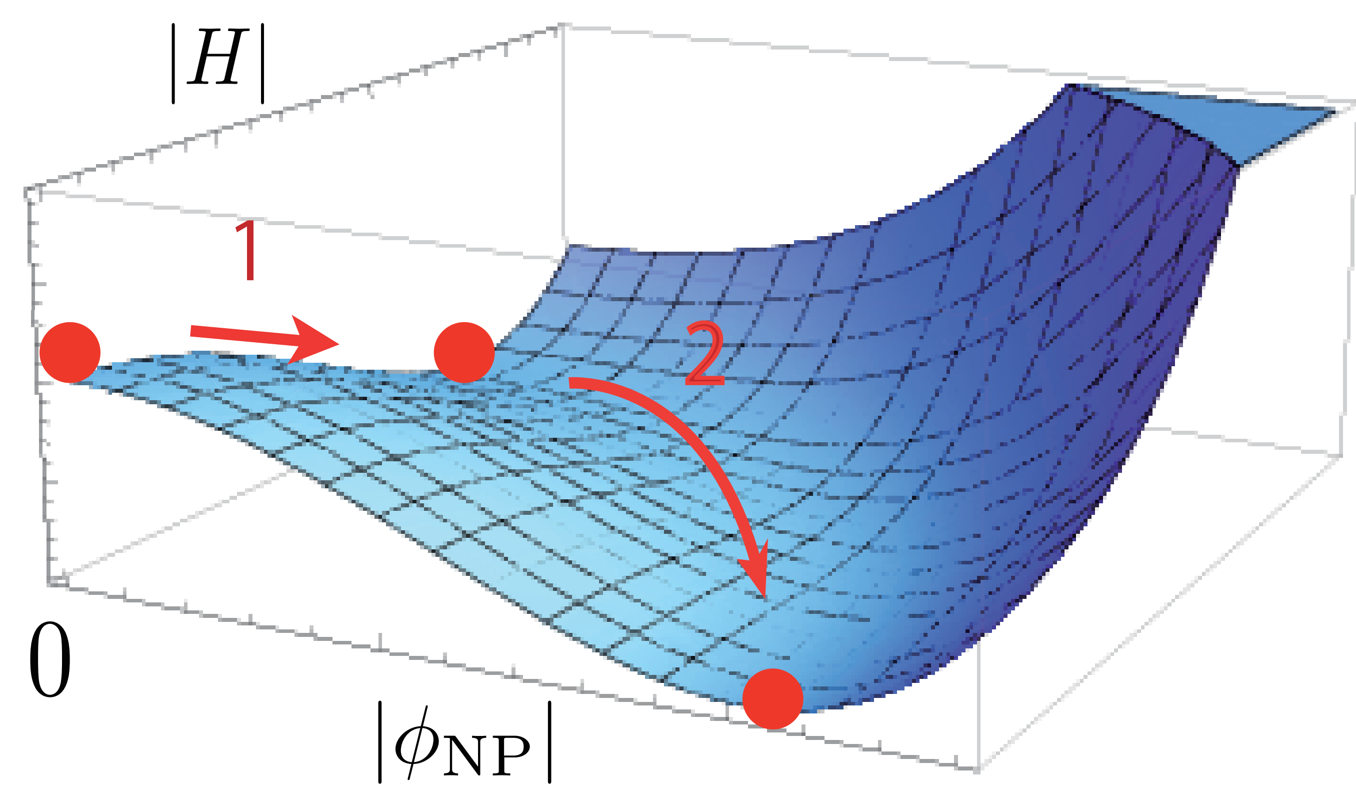
- At high temperature,

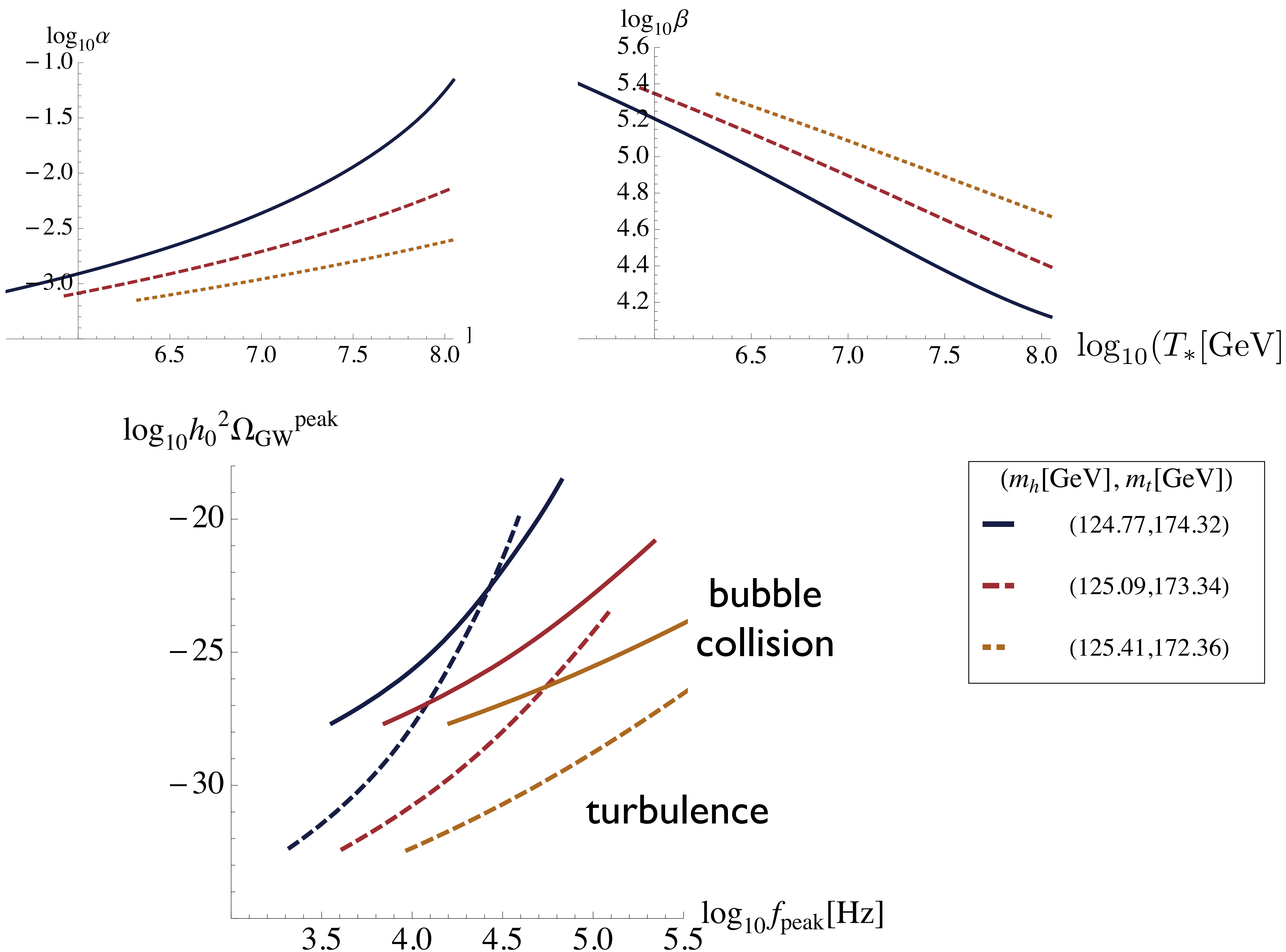
  $H = \phi_{\rm NP} = 0$

- Phase transition happens at

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

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





$\log_{10}\alpha$
$\log_{10}\beta$
$\log_{10}(T_*[\mathrm{GeV}])$
$\log_{10}h_0{}^2\Omega_{\mathrm{GW}}{}^{\mathrm{peak}}$
$\log_{10}f_{\mathrm{peak}}[\mathrm{Hz}]$
$(m_h[\mathrm{GeV}], m_t[\mathrm{GeV}])$
(124.77,174.32)
(125.09,173.34)
(125.41,172.36)
bubble collision
turbulence

- Singlet extension $V = V_0 + V_S$

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

S_i: singlet scalar without VEV

- Change Higgs quartic coupling through RGE:

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

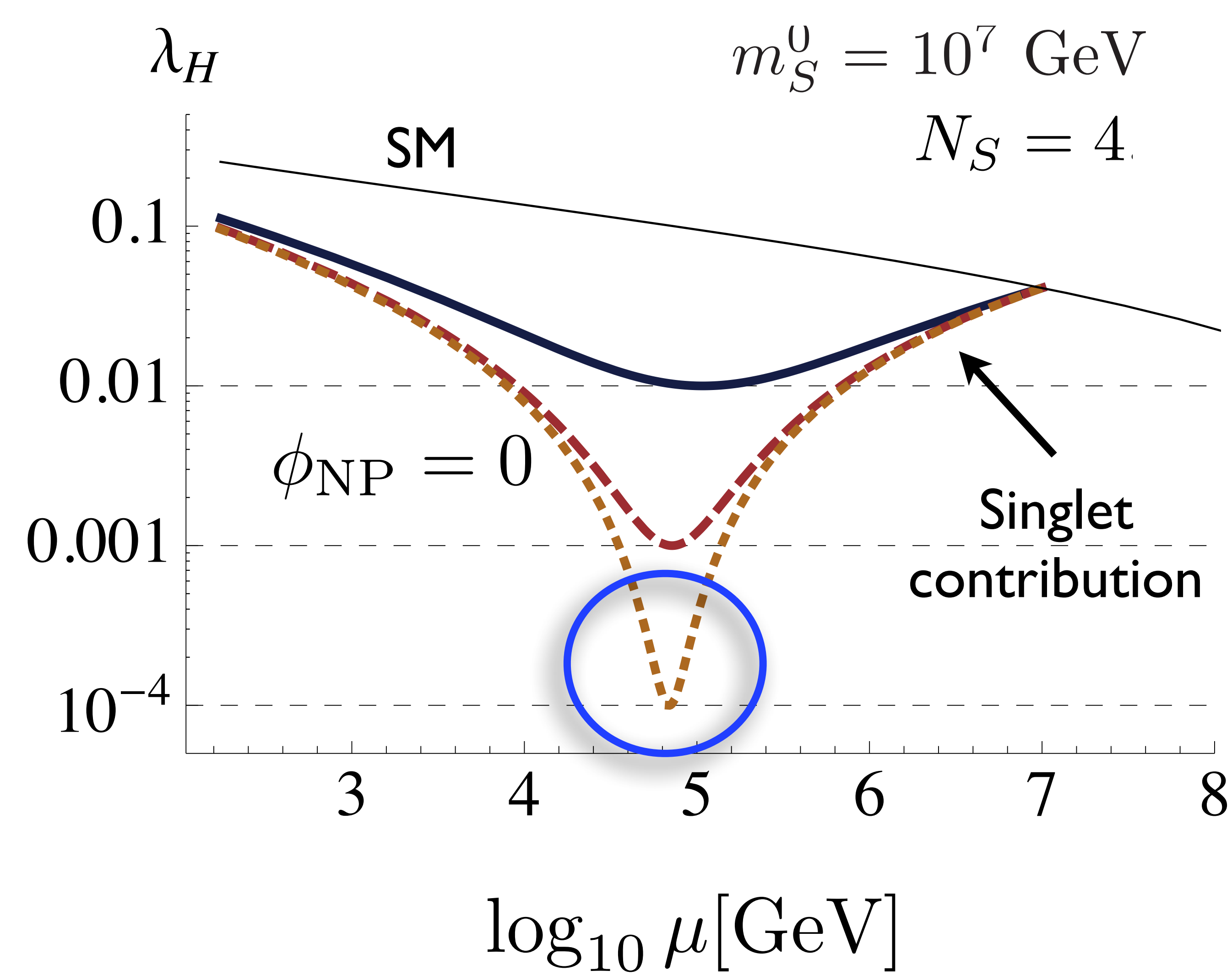
- At T=0, $m_S^0 = \lambda_{S\phi} v_{\rm NP}$

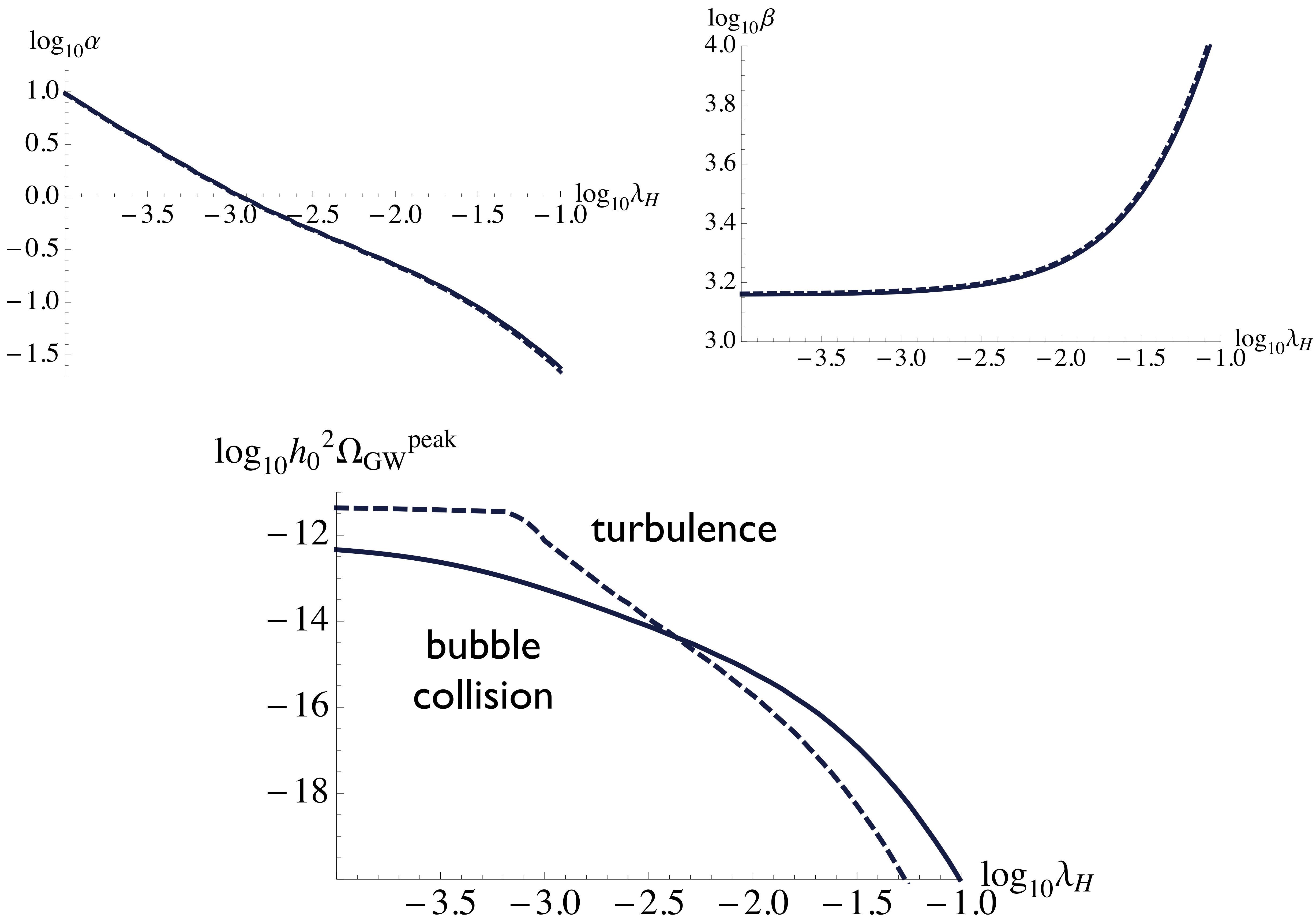
RGE is not affected below this scale.

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

hence $m_S = 0$

RGE changes Higgs coupling at T=T*

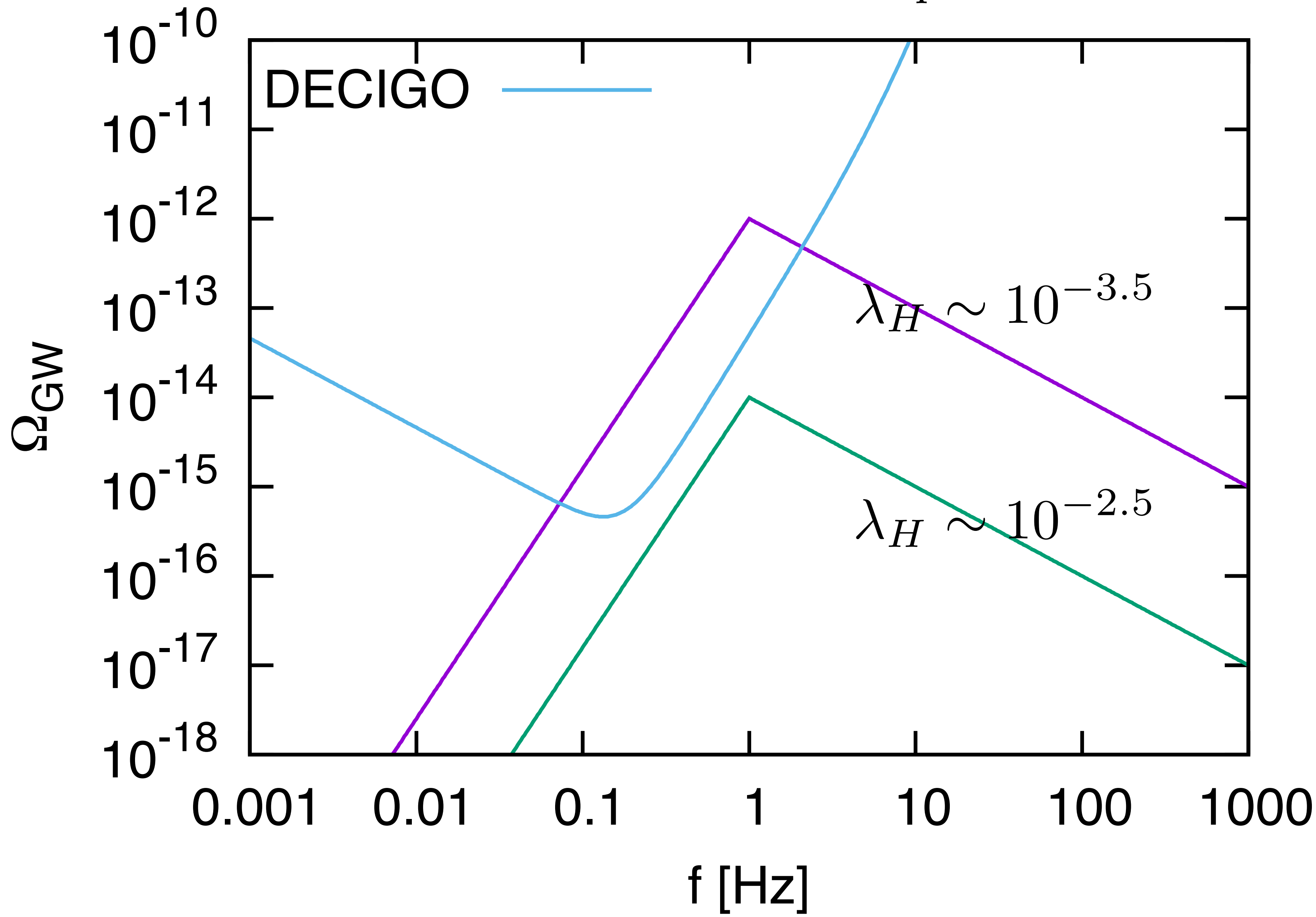




$\log_{10}\alpha$
1.0
0.5
0.0
−0.5
−1.0
−1.5
−3.5
−3.0
−2.5
−2.0
−1.5
−1.0
$\log_{10}\lambda_H$
$\log_{10}\beta$
4.0
3.8
3.6
3.4
3.2
3.0
−3.5
−3.0
−2.5
−2.0
−1.5
−1.0
$\log_{10}\lambda_H$
$\log_{10}h_0{}^2\Omega_{\mathrm{GW}}{}^{\mathrm{peak}}$
−12
−14
−16
−18
turbulence
bubble
collision
−3.5
−3.0
−2.5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

GW spectrum

$f_{\rm peak} \simeq 1\,{\rm Hz}$



R.Jinno, KN, M.Takimoto (2015)

More rich GW source

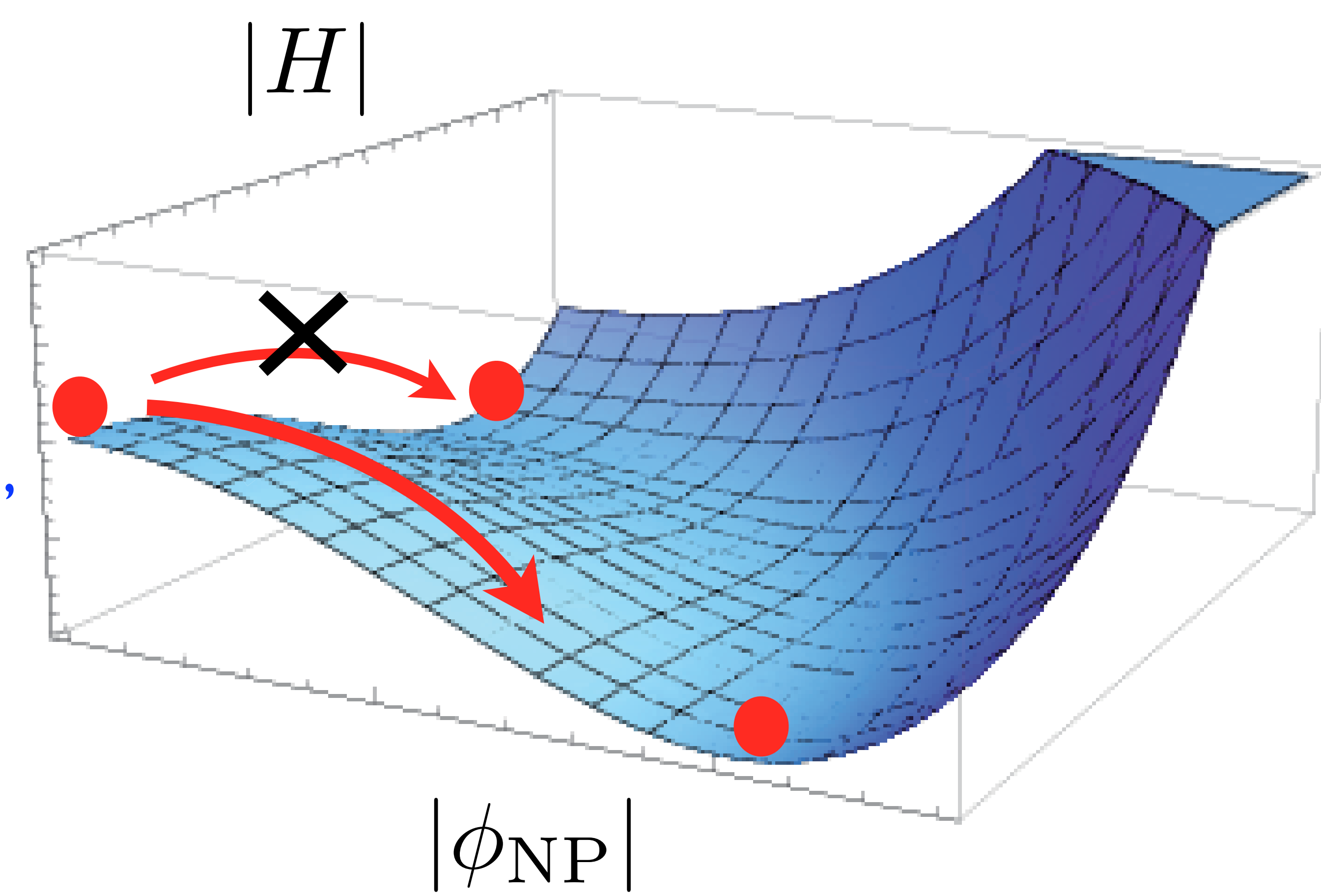
$$V_0 = \lambda^2(|\phi_{\rm NP}|^2 - v_{\rm NP}^2 - \delta_{\rm EW}^2)|H|^2 + \frac{\lambda_H}{2}|H|^4 + \lambda_\phi^2(|\phi_{\rm NP}|^2 - v_{\rm NP}^2)^2$$

- PT along the New Scalar can source GWs
  - Bubble collision from 1st order PT of $\phi_{\rm NP}$

    Jaeckel et al (2016), Dev, Mazumdar (2016), Jinno, Takimoto (2016), Balazs et al (2016)

  - Topological defects associated with $\phi_{\rm NP}$

    KN, Takahashi, Yokozaki (2016)



Domain walls

- Simplest case: real scalar $\phi_{\rm NP}$

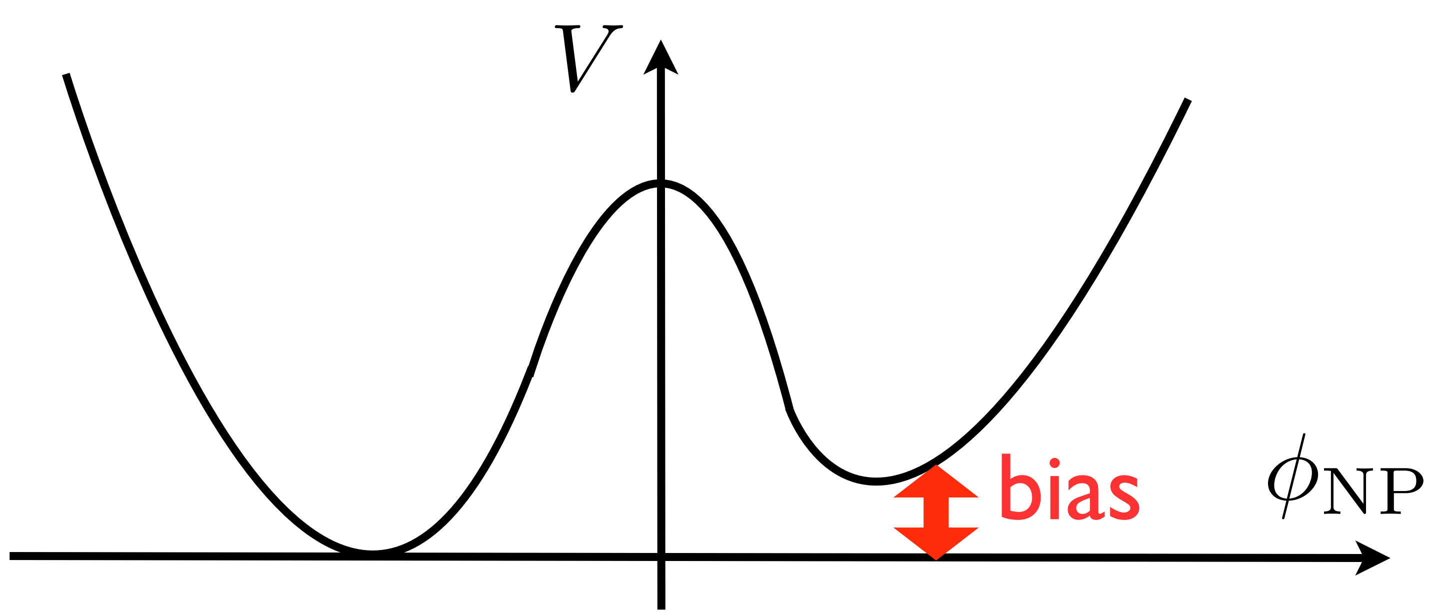
  $\longrightarrow$ Domain walls are formed after $\phi_{\rm NP}$ gets VEV

- This simple extension is motivated from the Higgs stability.

  Lebedev (2012), Elias-Miro et al (2012)

- We need small Z2 breaking ("bias") to avoid DW domination

- GWs are produced by the DW dynamics

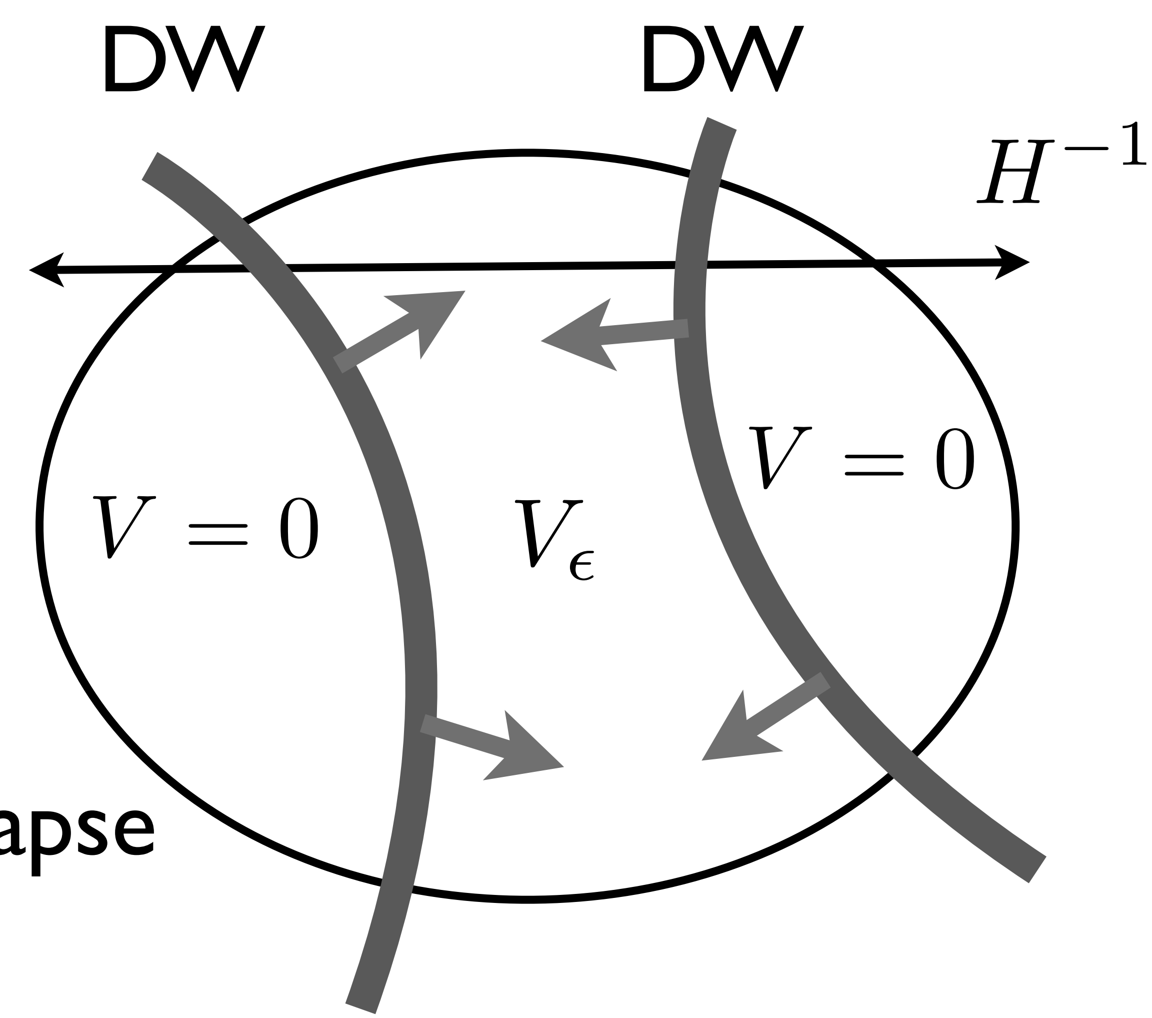


- Dynamics of biased DWs
  - DW energy density

$$\rho_{\rm DW} \sim \sigma H, \qquad (\sigma : \text{wall tension})$$

  - Bias becomes effective at

$$H \sim \frac{V_\epsilon}{\sigma} \longrightarrow$$ DWs collapse



  - DW energy fraction at the collapse

$$r_{\rm DW} \equiv \frac{\rho_{\rm DW}}{\rho_{\rm tot}} \sim \frac{\sigma^2}{V_\epsilon M_P^2}$$

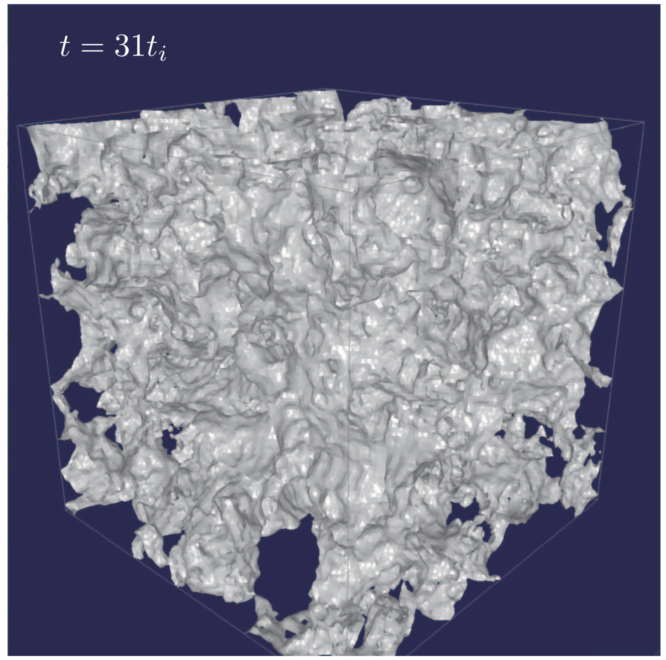
  - GWs emitted by annihilating DWs

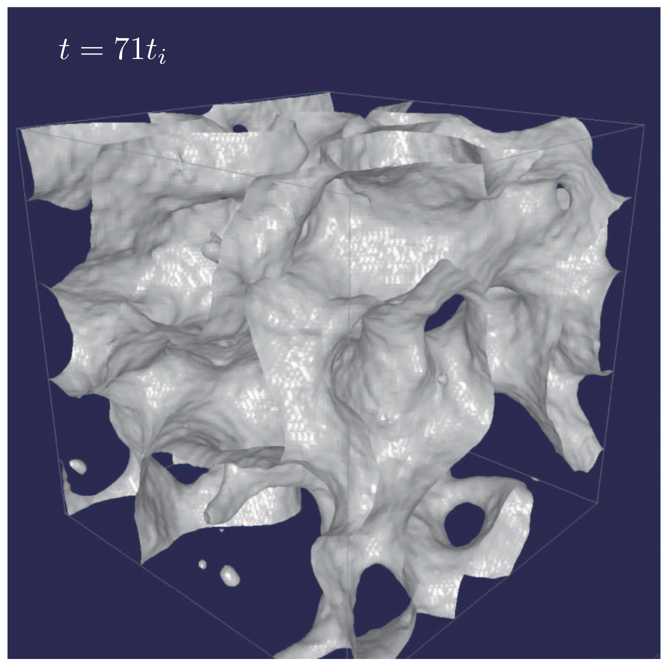
$$\Omega_{\rm GW} \sim \Omega_r (r_{\rm DW})^2$$

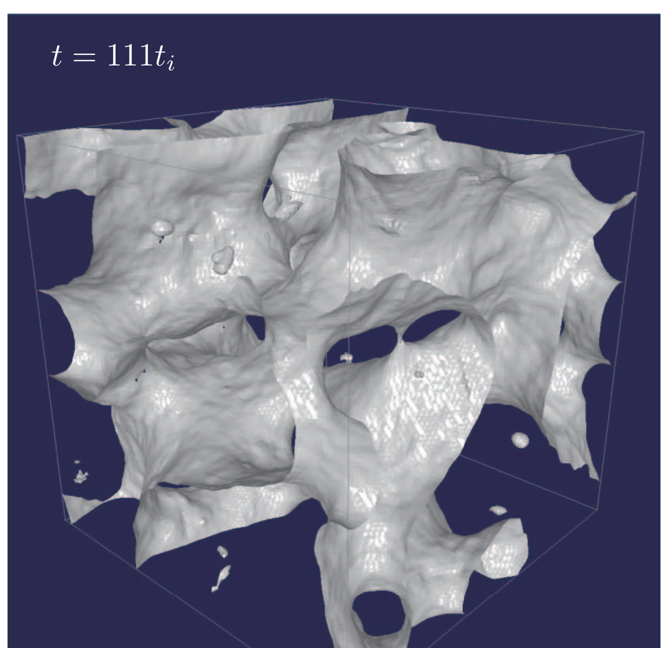
$$f_{\rm peak} \sim 3\,{\rm Hz} \left(\frac{T_{\rm ann}}{10^8\,{\rm GeV}}\right)$$

Numerical simulation of DW

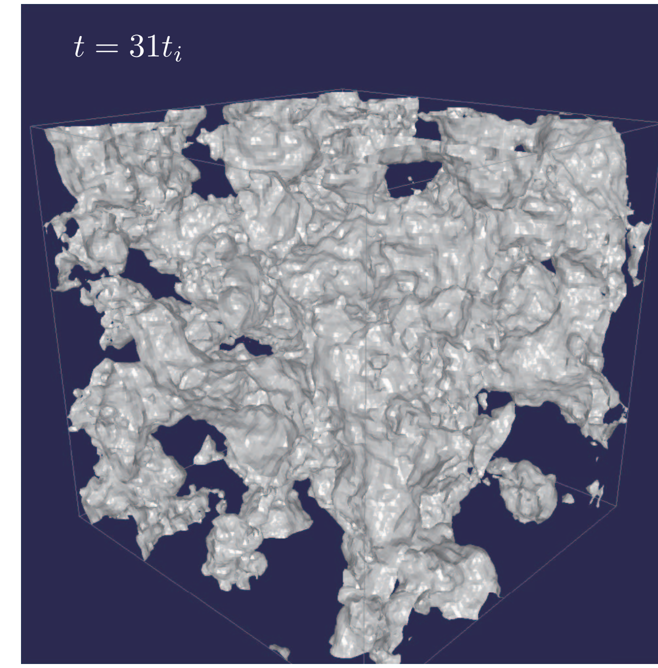
without bias

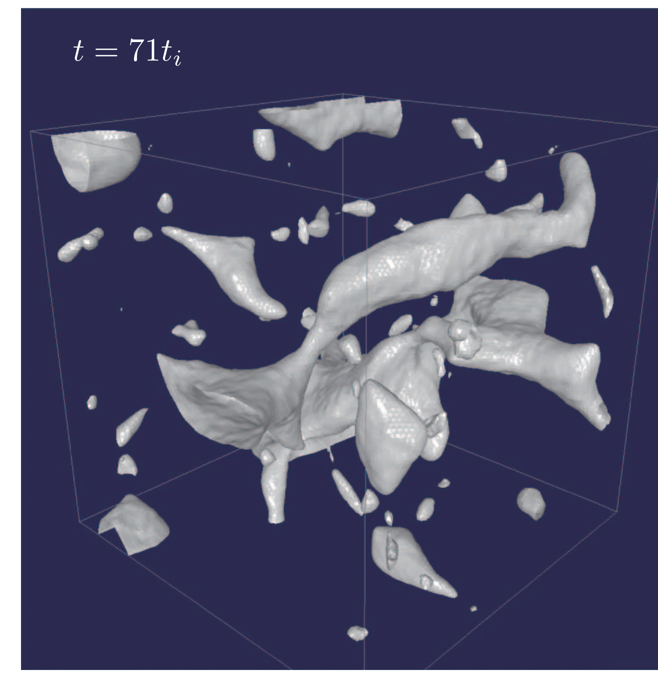


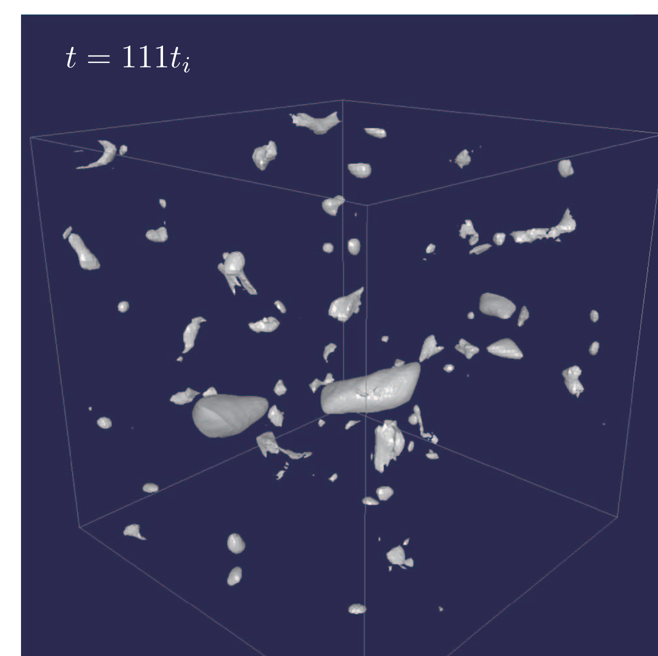




With bias

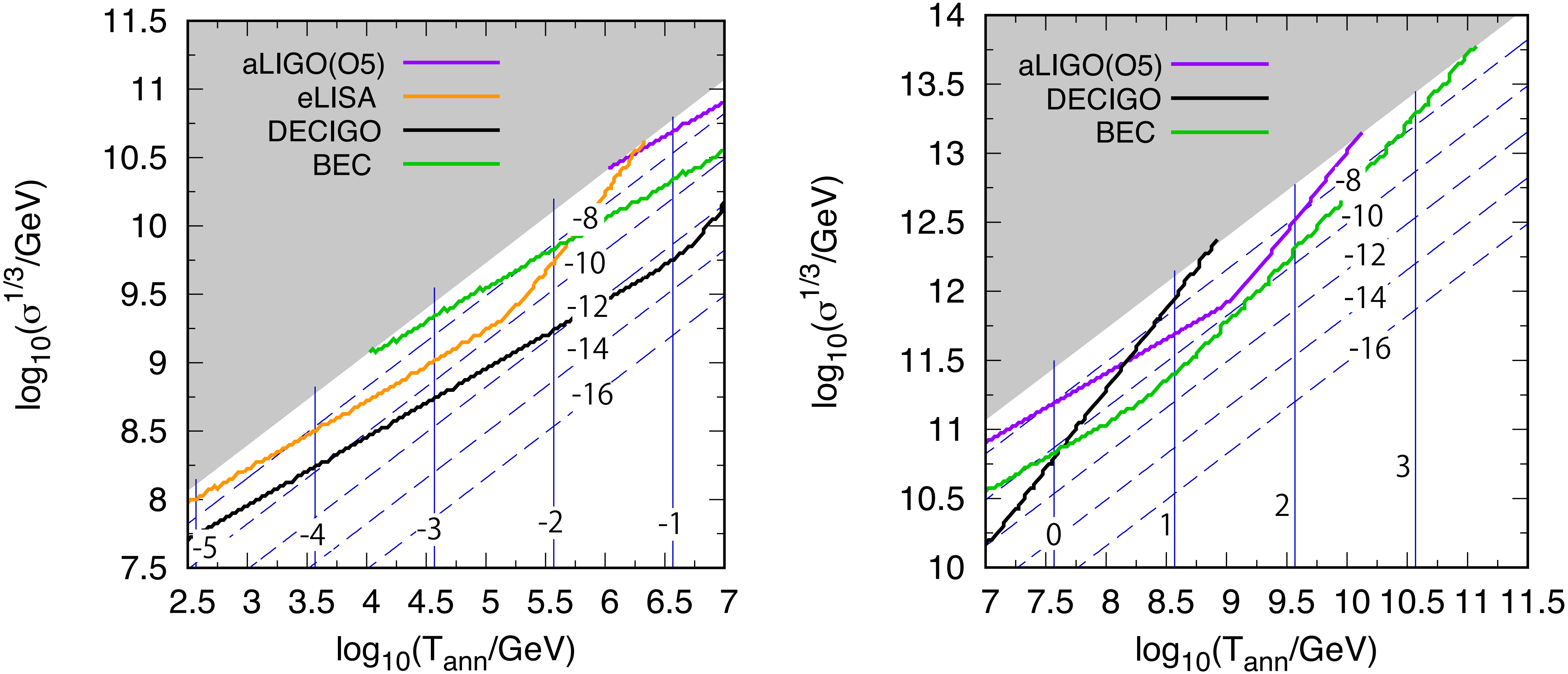






Hiramatsu, Kawasaki, Saikawa (2010)

KN, Takahashi, Yokozaki (2016)



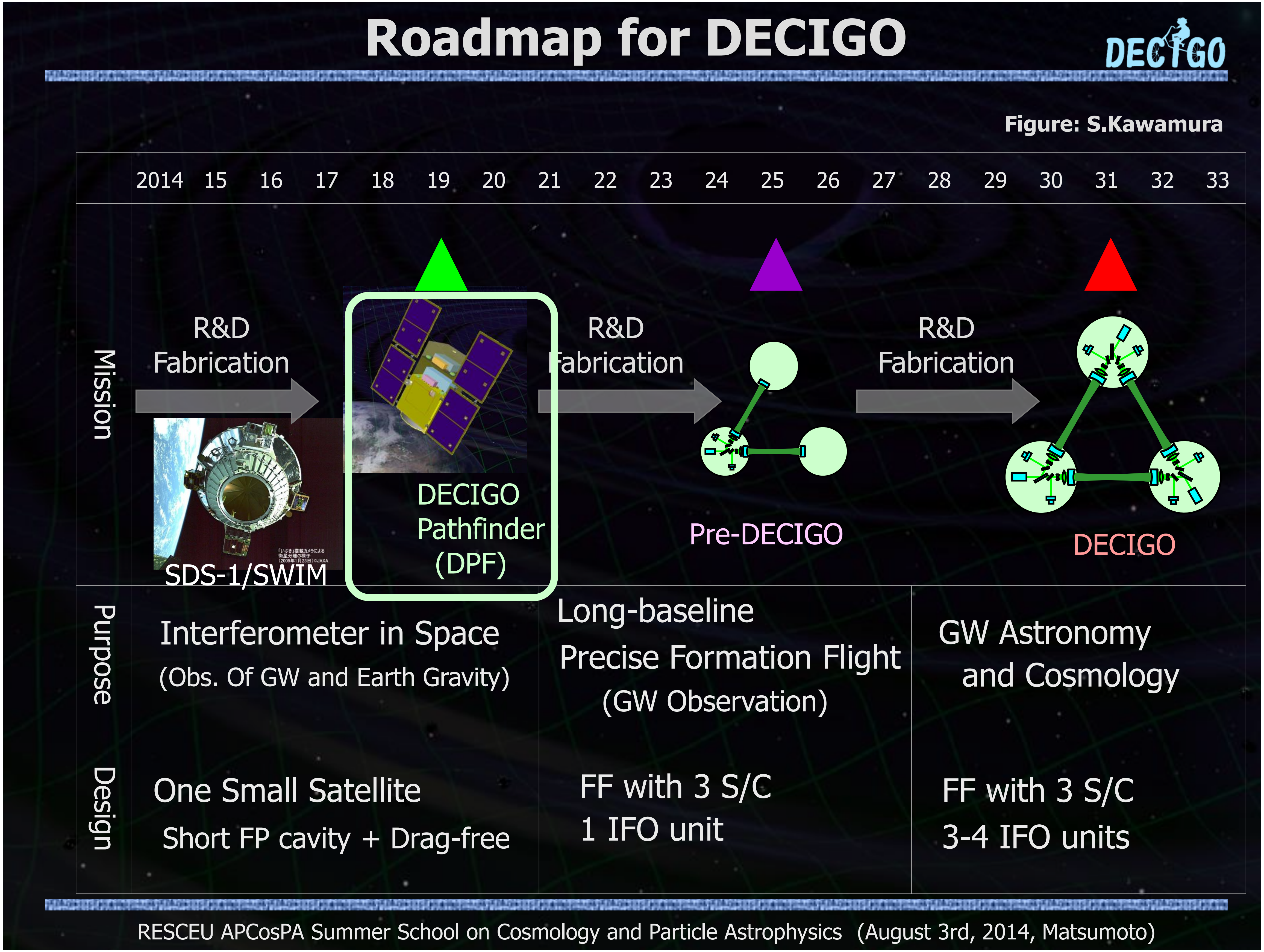
Wide parameter regions covered by current/future GW observations

Summary

- 1st order phase transition can happen at electroweak scale (or much higher scale) if there is physics beyond SM.
- Vacuum bubbles/topological defects can be good GW source in models with simply extended Higgs sector.
- Other GW source: inflation, reheating, etc.

GW as a probe of new physics!

Appendix



Slide by M.Ando

- Bubble nucleation   Coleman (1977), Linde (1983)

  - Vacuum decay rate

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

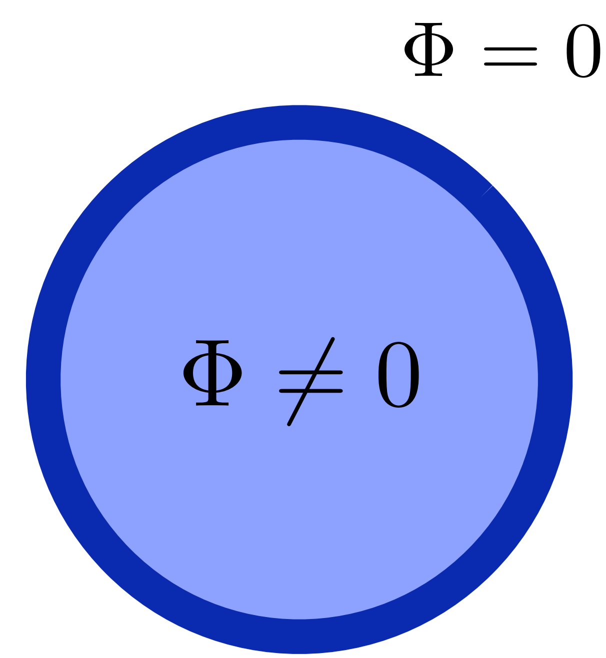
  - S_3 :Action of O(3) symmetric bounce solution

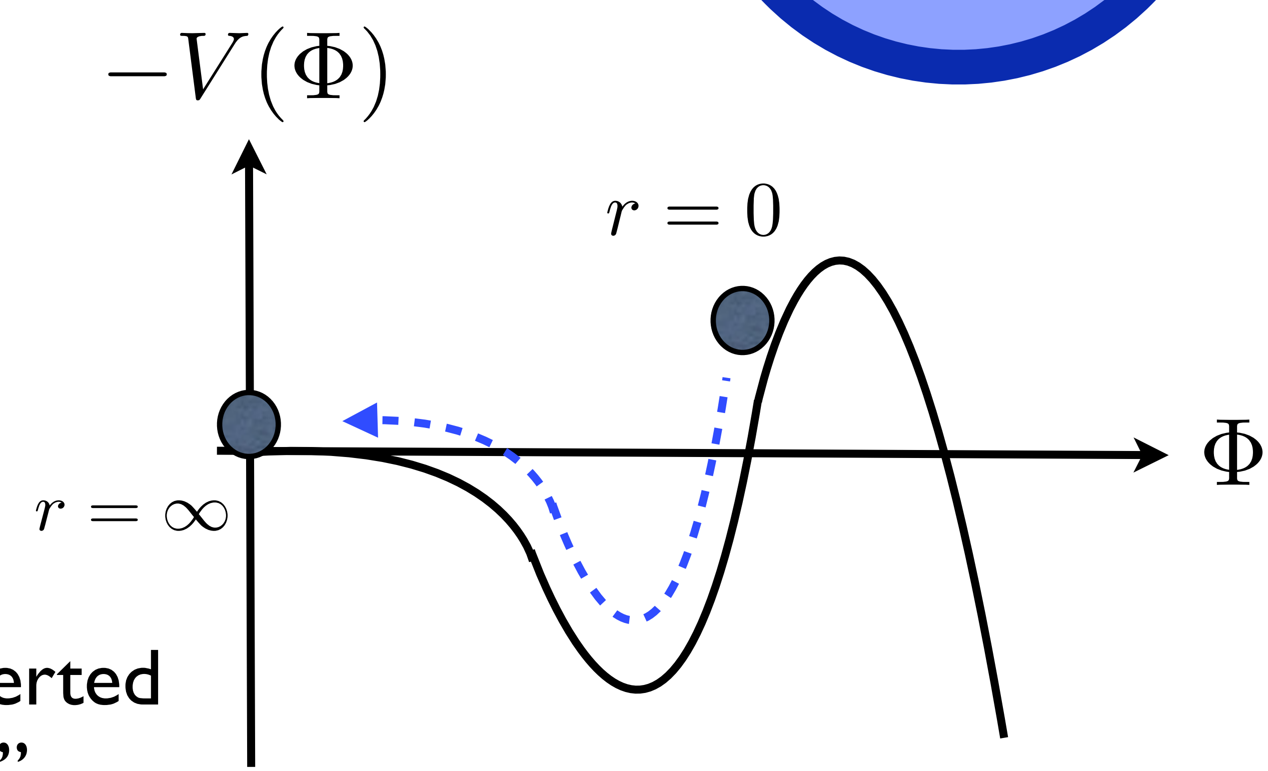
$$S_3(T) = \int d^3x \left[\frac{1}{2}(\nabla\Phi)^2 + V(\Phi, T)\right]$$

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

Boundary condition:

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





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

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

- <u>Thick wall limit</u>

Around temperature

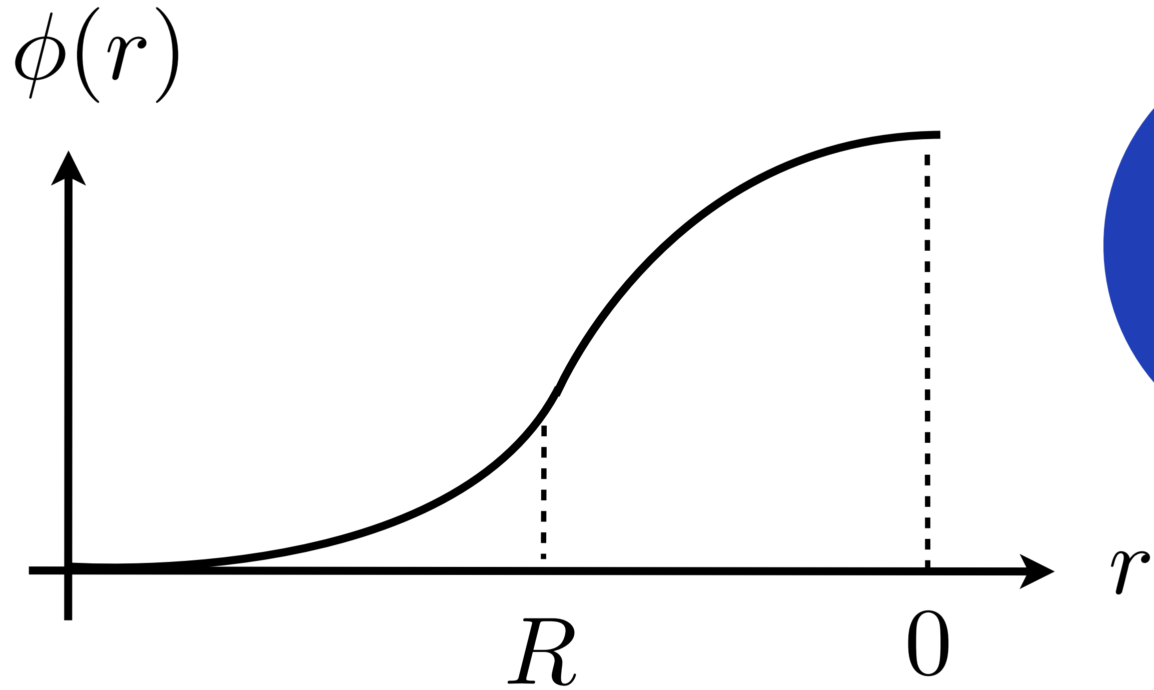
$$T \sim T_c$$

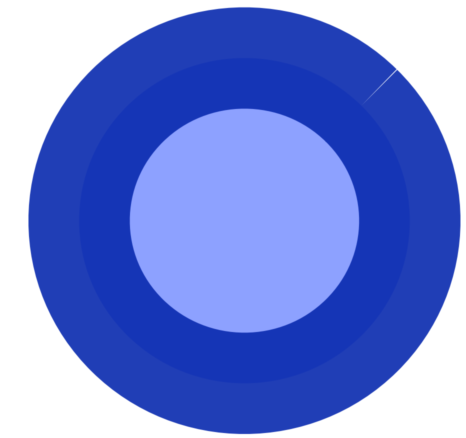
$$T_c \equiv \sqrt{\frac{m_\phi^2}{g^2 - A^2/\lambda}}$$

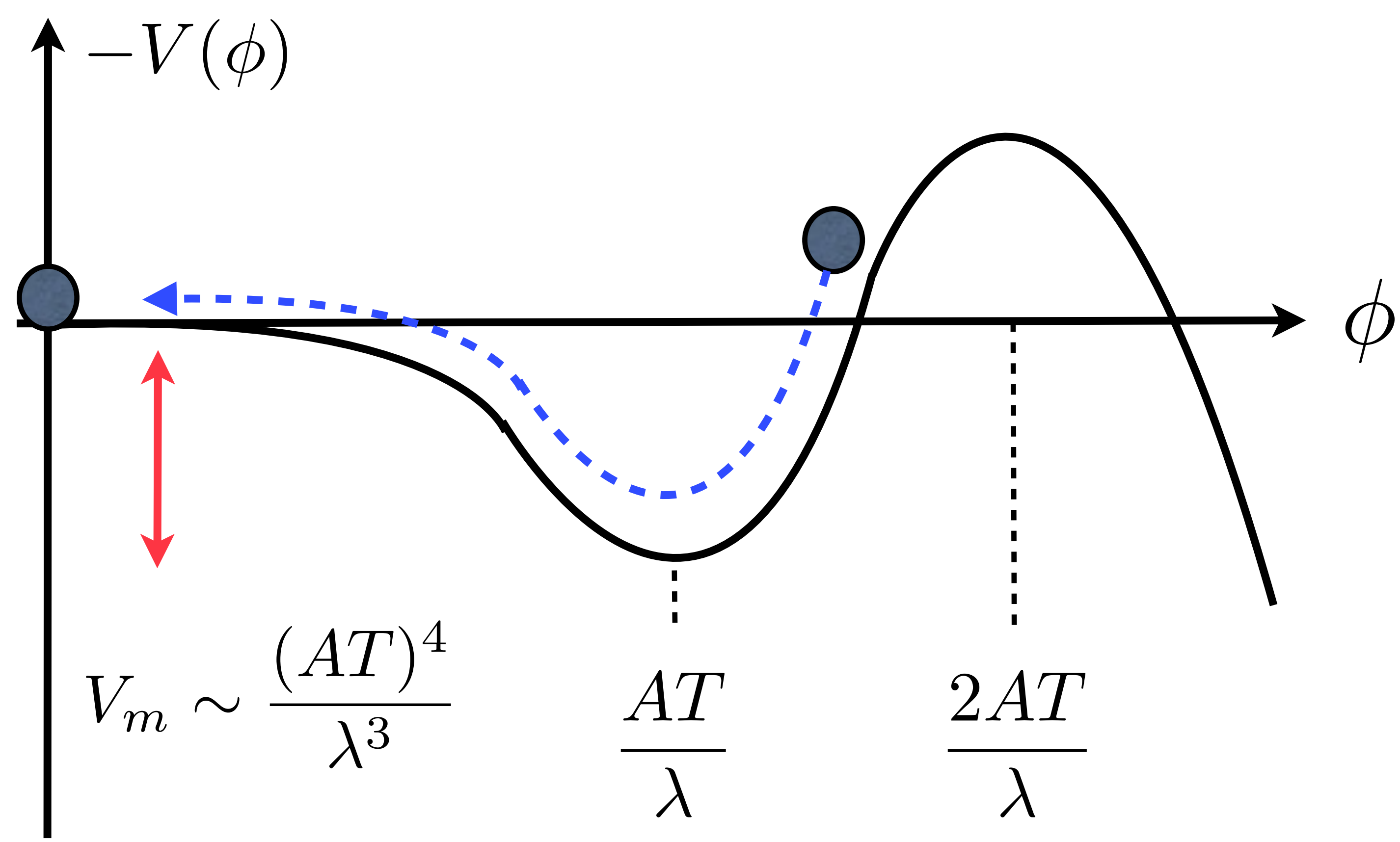
$$R^{-2} \sim g^2T^2 - m_\phi^2 \sim \frac{(AT)^2}{\lambda}$$

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

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







- Thin wall limit

$$T = T_c - \Delta T$$

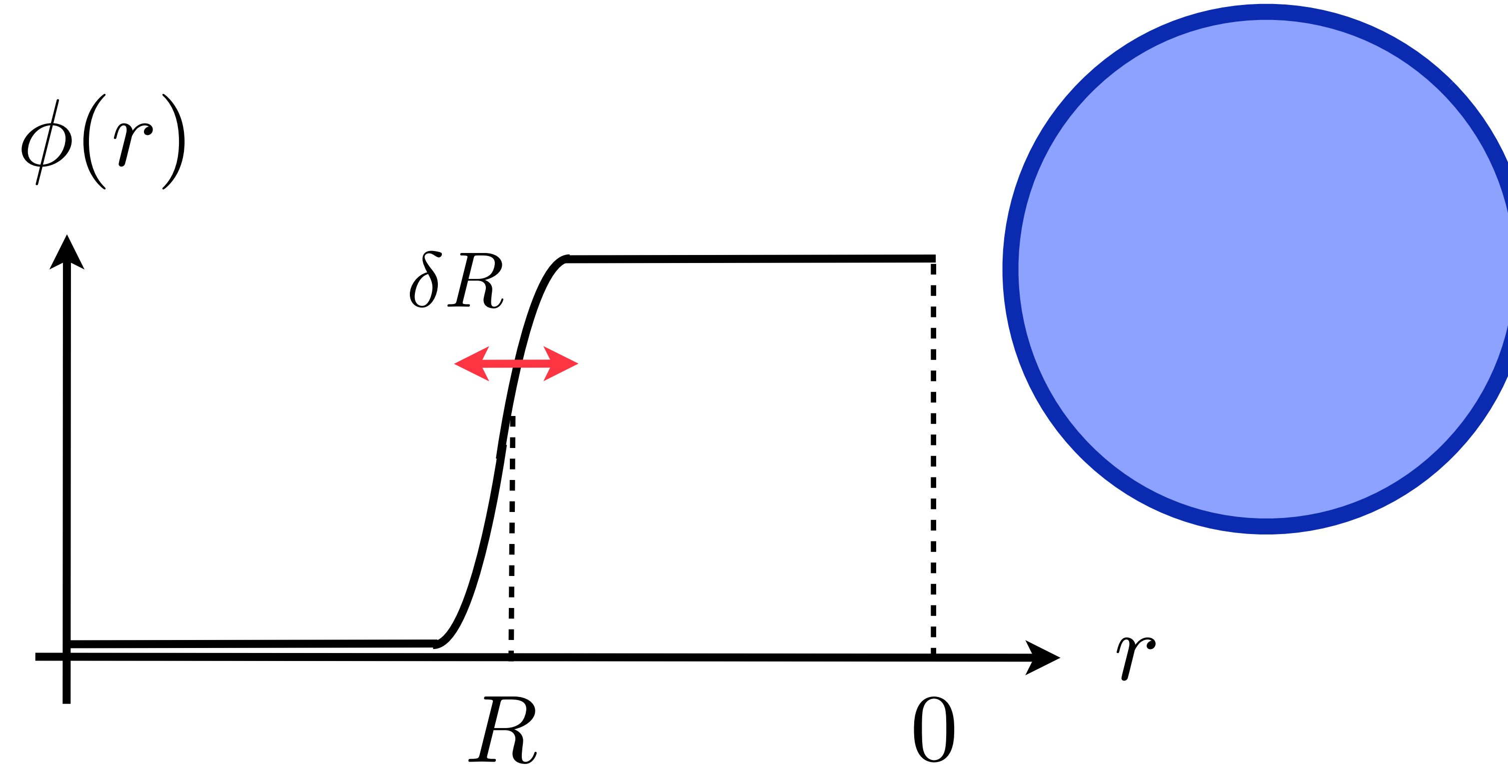
$$\Delta V \sim \frac{g^2 A^2 T_C^3 \Delta T}{\lambda^2}$$

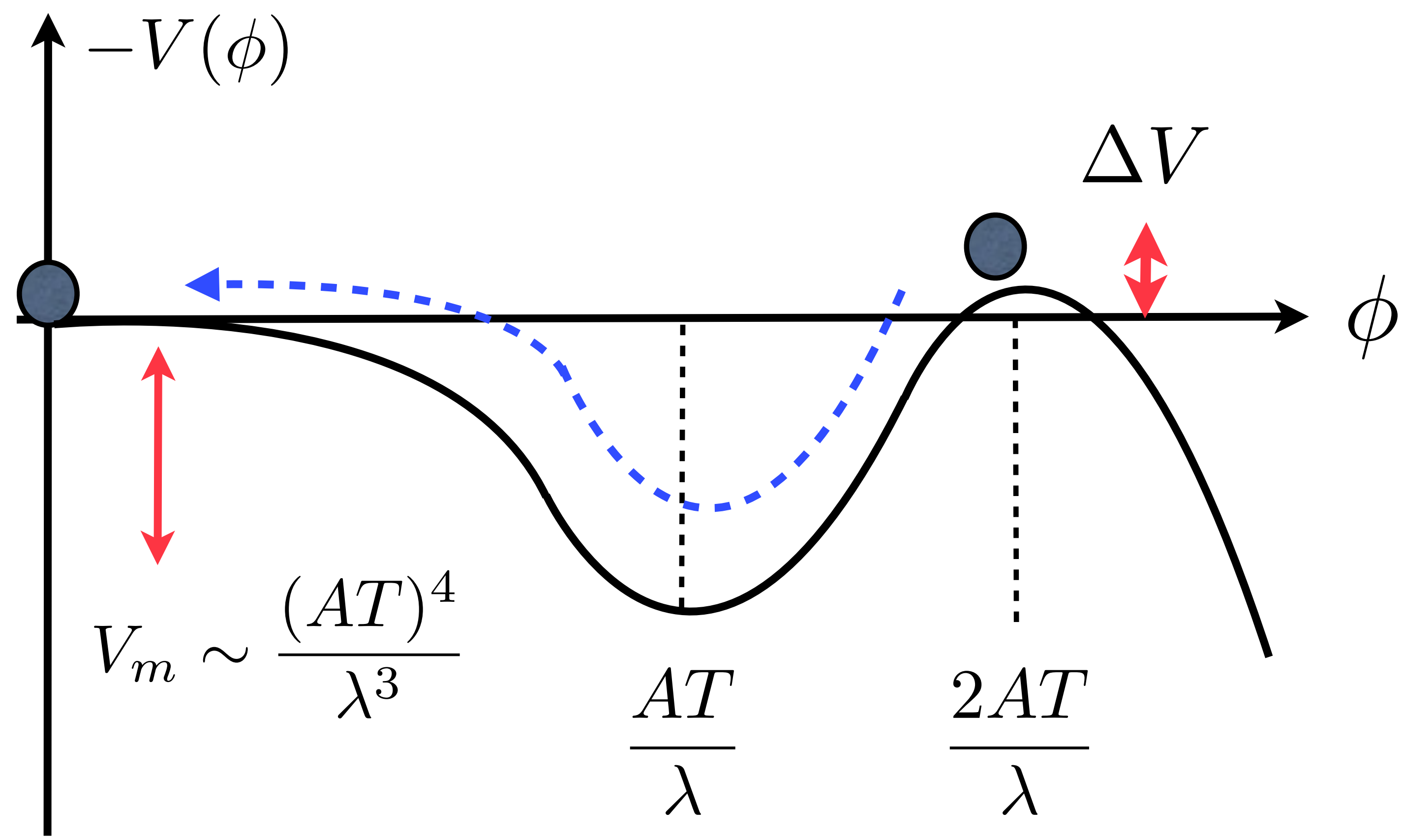
$$\delta R^{-2} \sim g^2 T^2 - m_\phi^2 \sim \frac{(AT)^2}{\lambda}$$

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

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

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



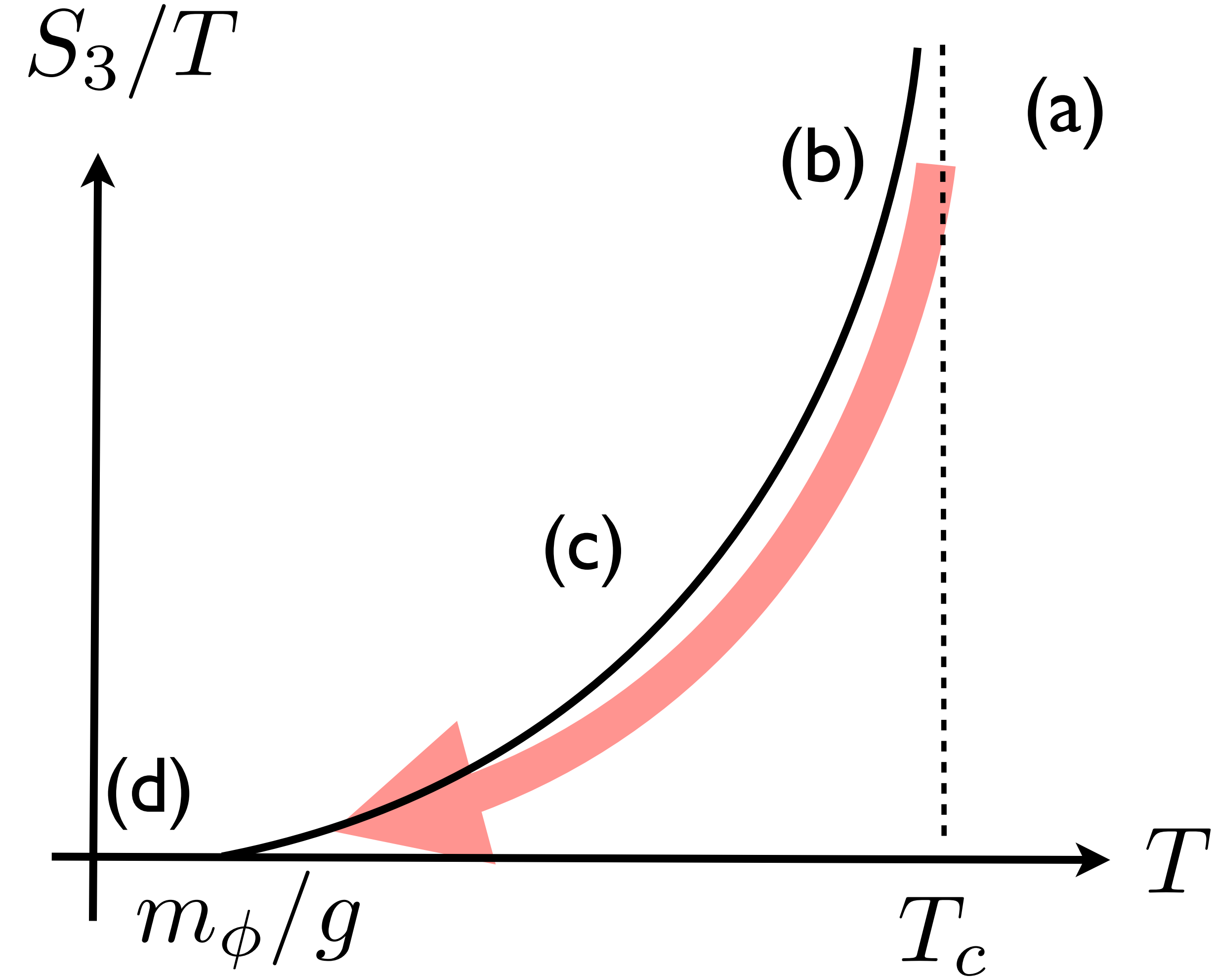


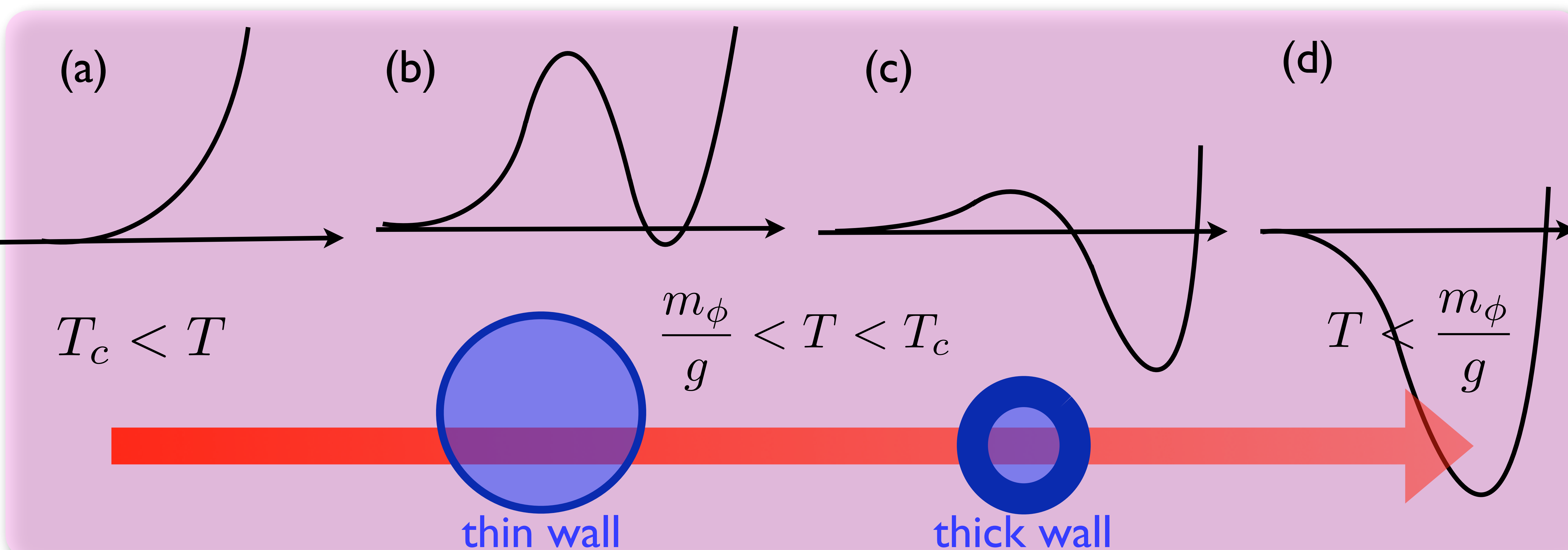
- Phase transition completes at

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

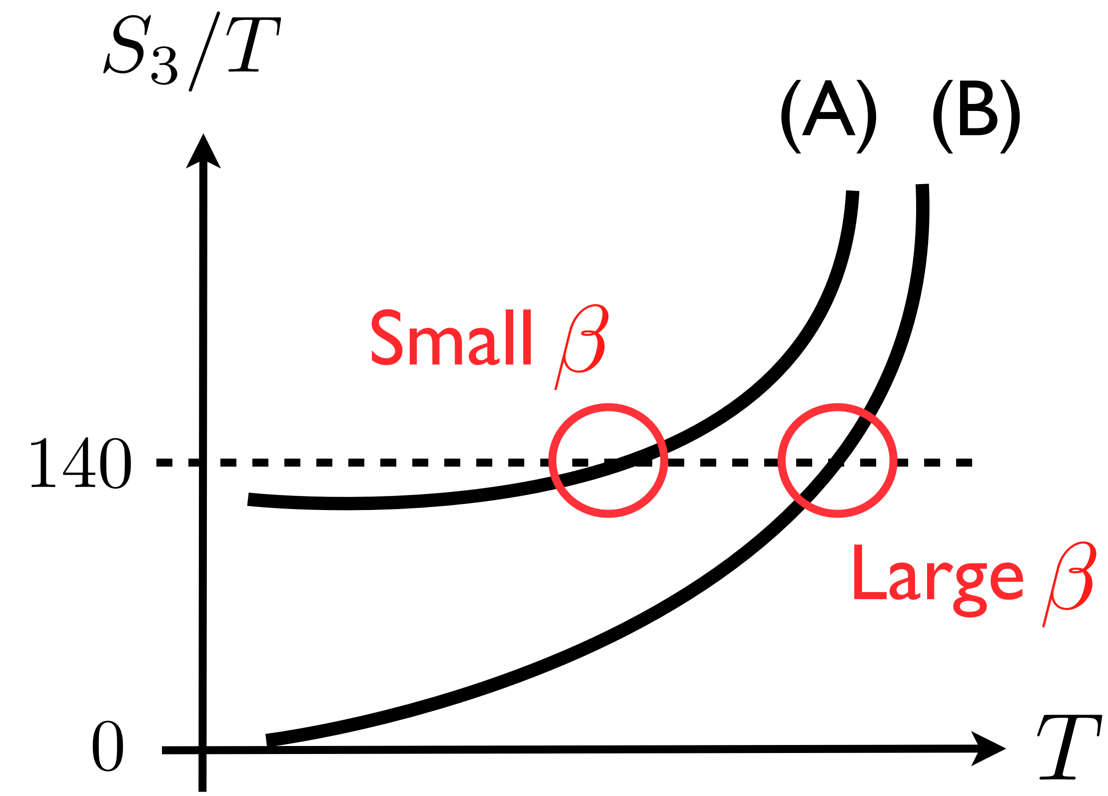
$$\frac{S_3}{T} \sim 4 \ln\left(\frac{M_P}{T}\right) \sim 140$$

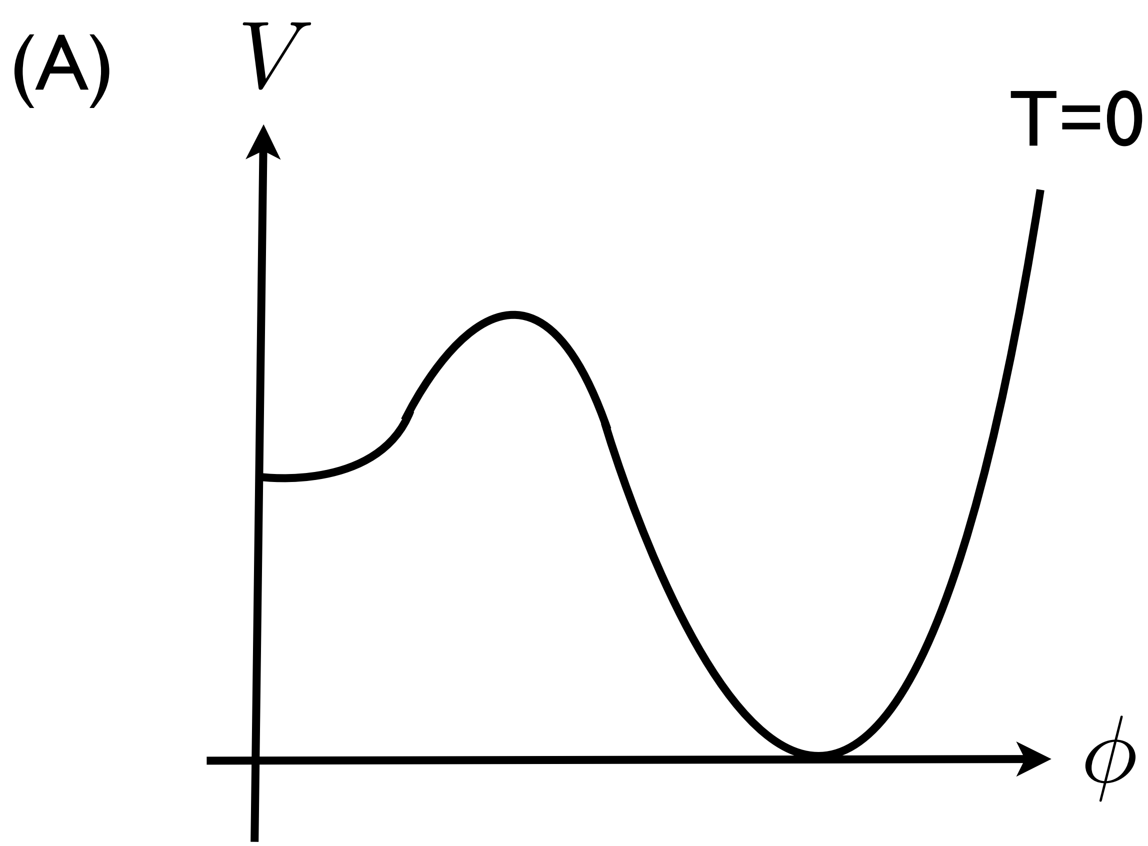
if $T \sim 100\,\text{GeV}$

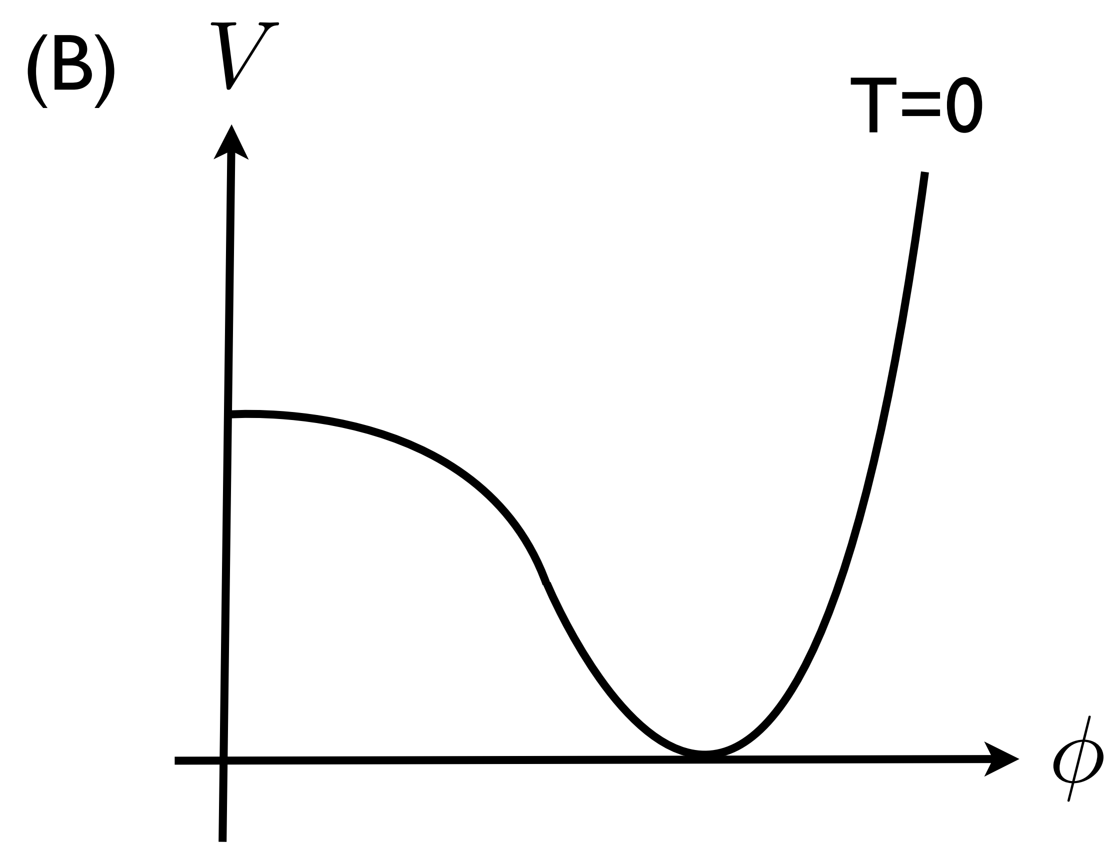




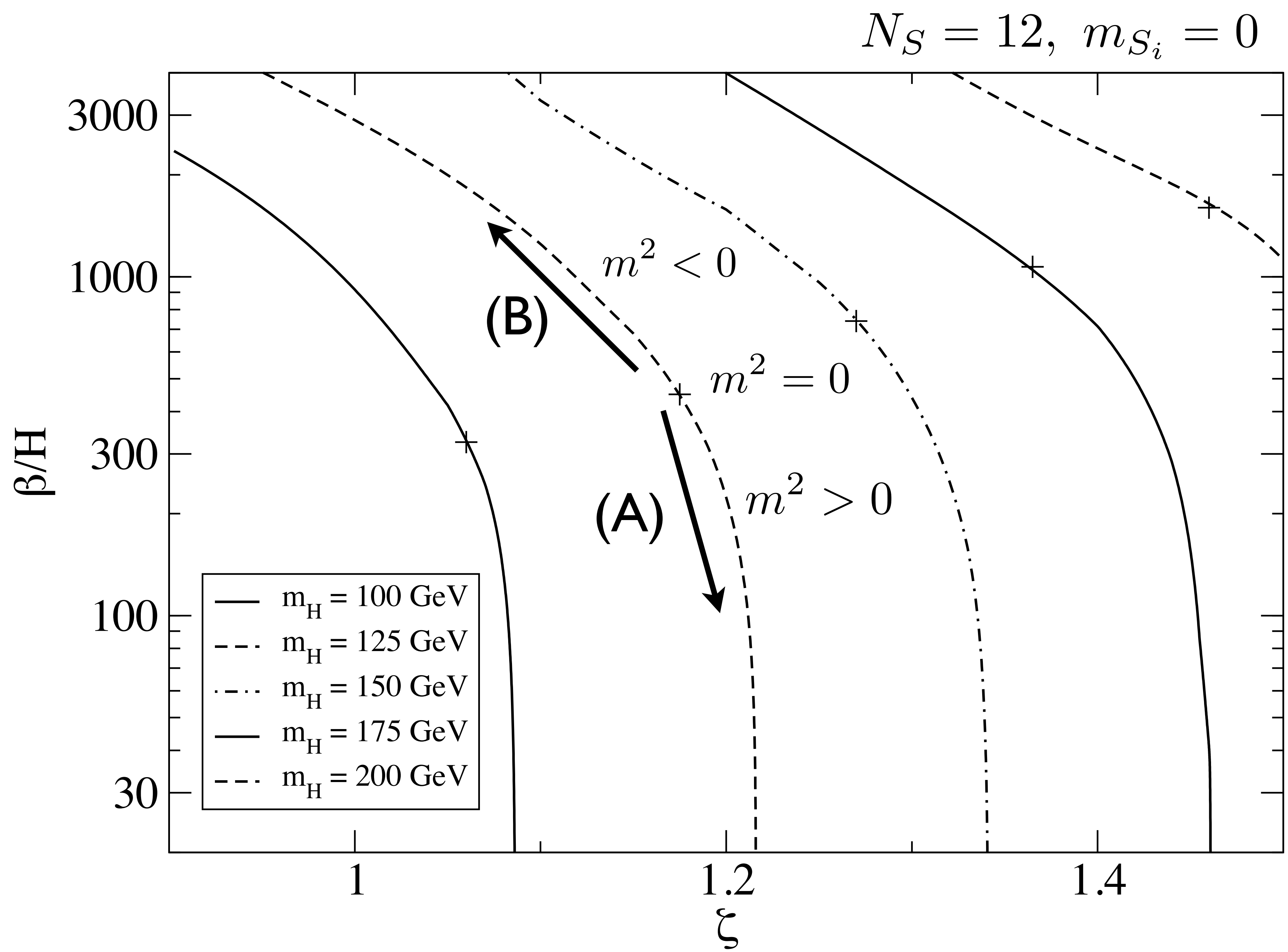
- Enhancing GW $(T_c \sim m/g)$
  - Large GW $\longrightarrow$
    Small β $\longrightarrow$ Small $\frac{d(S_3/T)}{dT}$
  - Schematically, zero-T potential of (A) can lead to strong PT and enhanced GW







$$V_0 = m^2 H^\dagger H + \lambda (H^\dagger H)^2 + \sum_i \left(\frac{1}{2} m_{S_i}^2 + \zeta_i^2 \, H^\dagger H \right) S_i^2$$



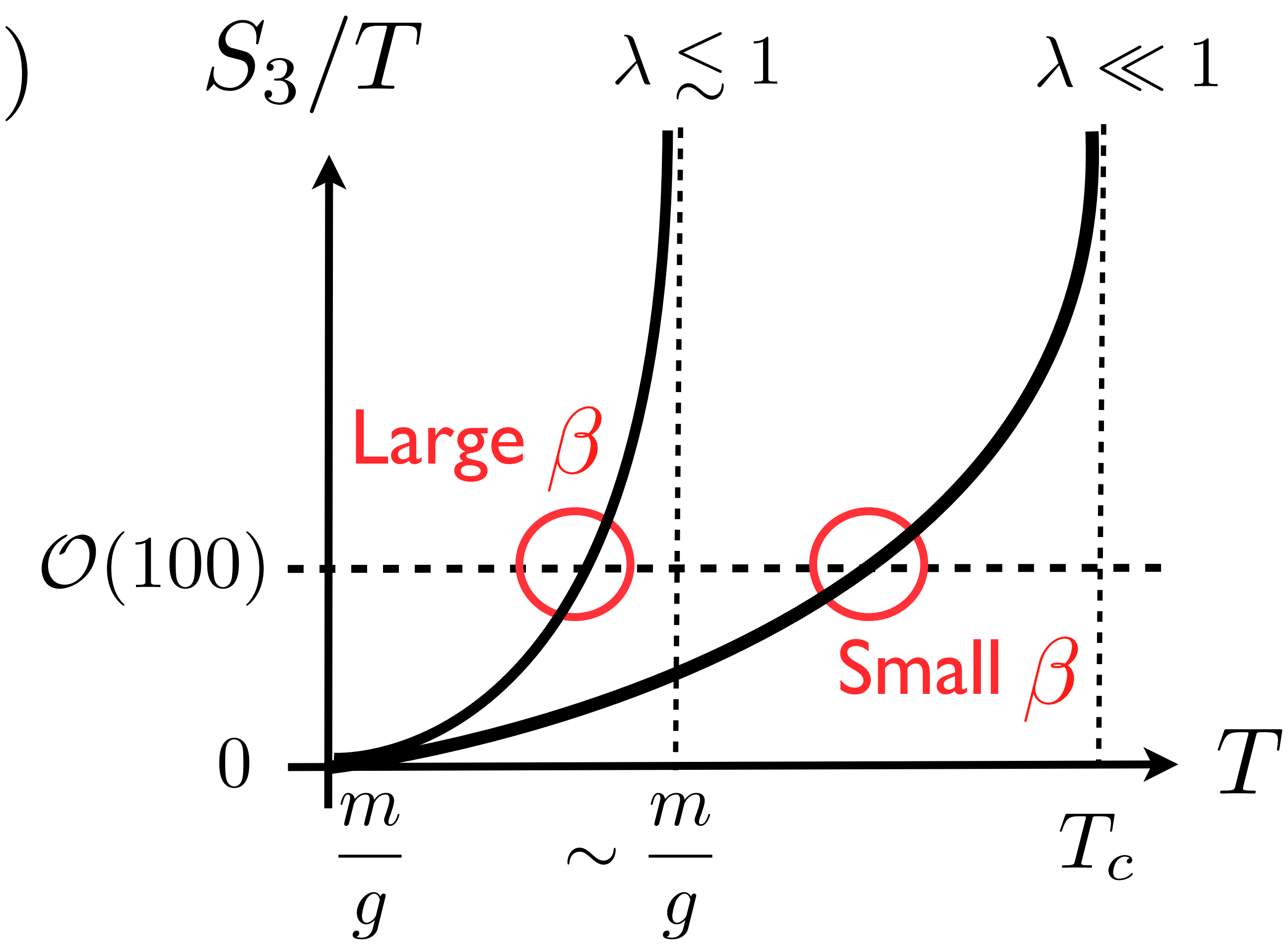
Espinosa, Konstandin, No, Quiros (2009)

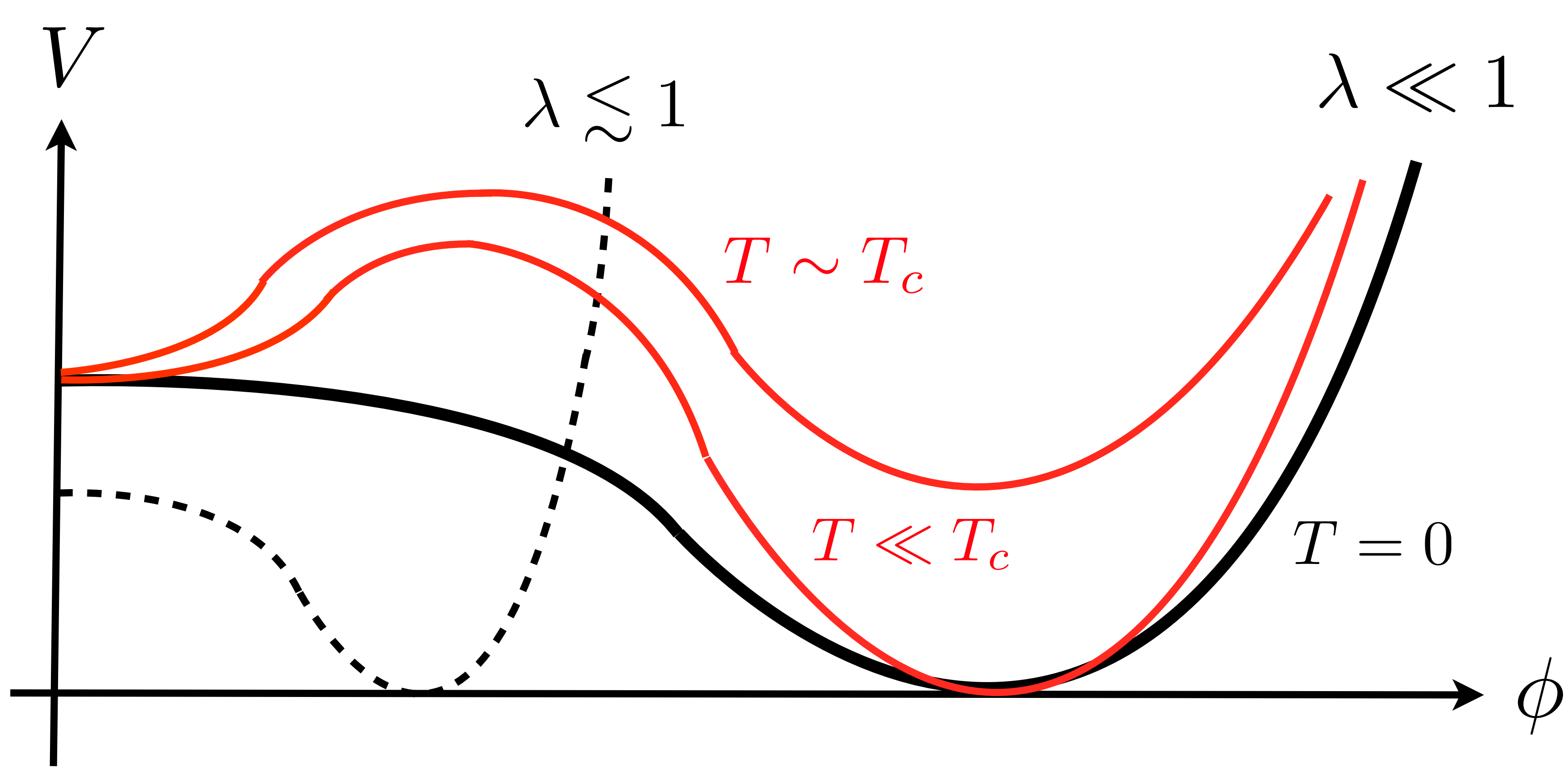
- Enhancing GW $(T_c \gg m/g)$

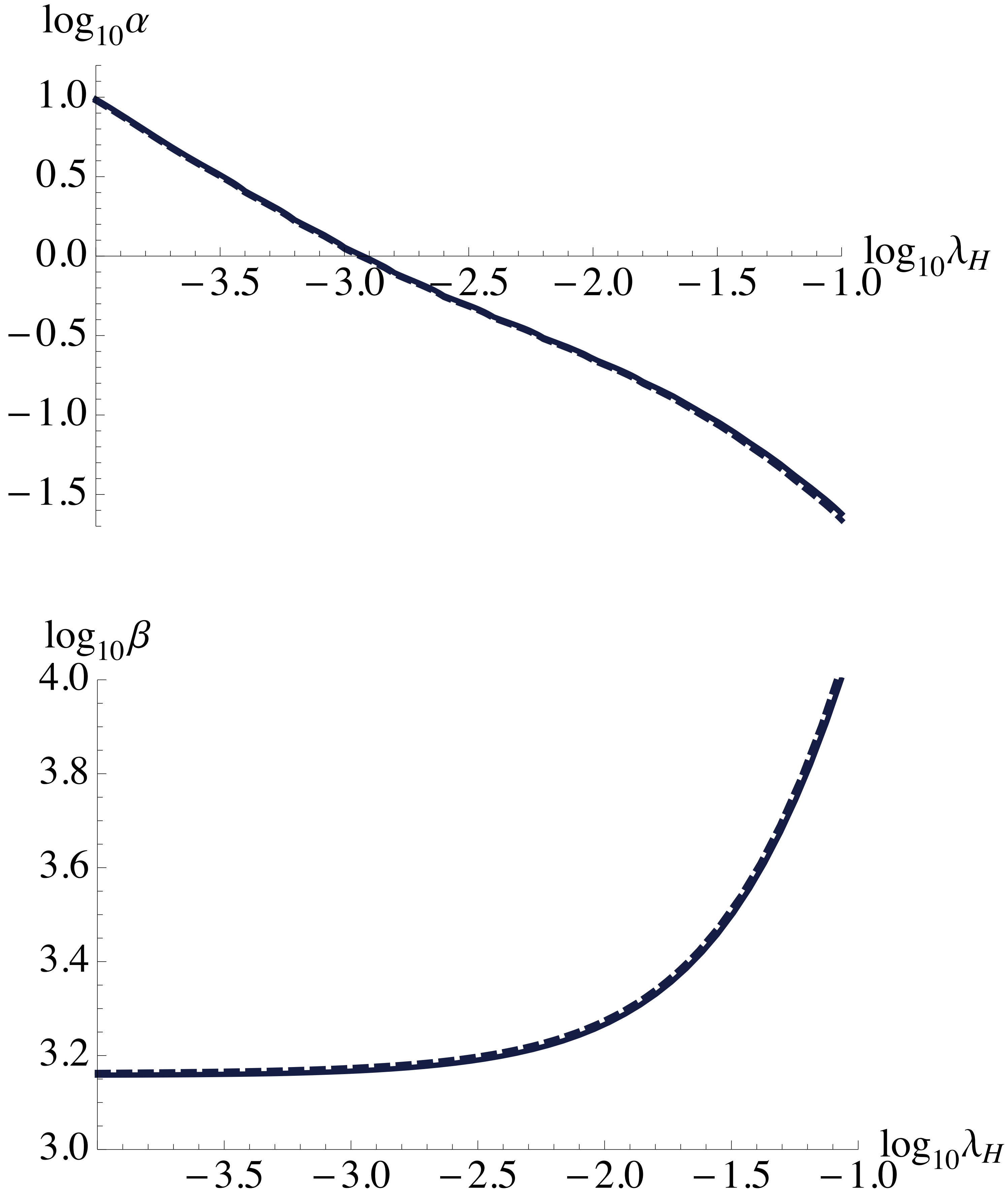
$$V \sim -m^2\phi^2 + \lambda\phi^4$$

$$T_c \sim m\lambda^{-1/4} \ (\gg m/g)$$

- Duration of PT becomes longer for small lambda (small beta), and enhances GWs







R.Jinno, KN, M.Takimoto (2015)