Observable Gravitational Waves in Minimal Scotogenic Model

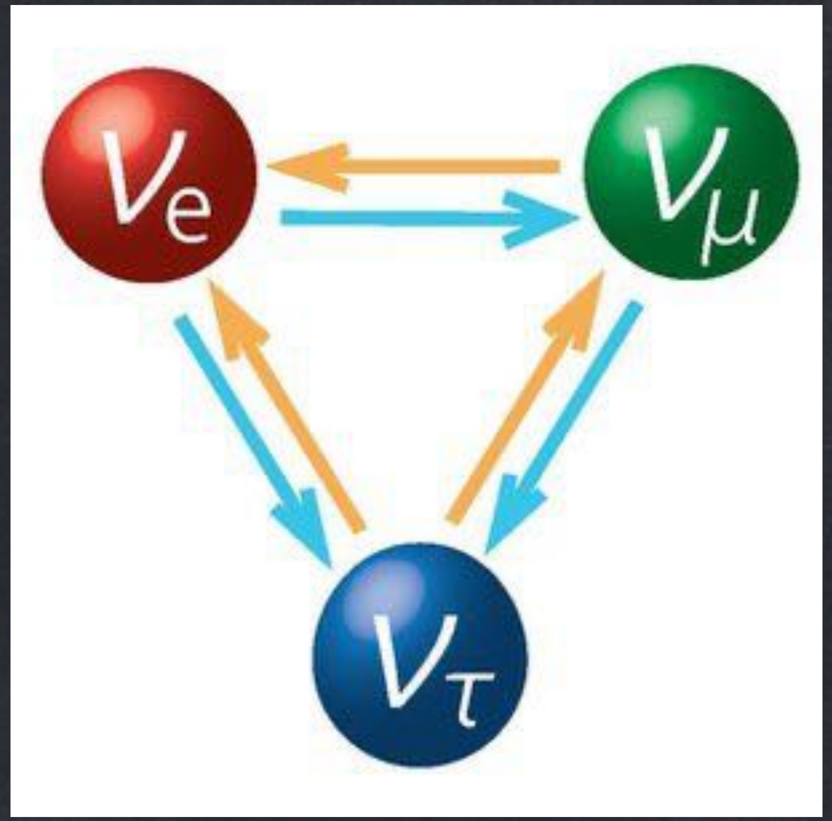
Arnab Dasgupta
In Collaboration with
Kohei Fujikura, Devabrat Mahanta, Debasish Borah and Sin Kyu Kang

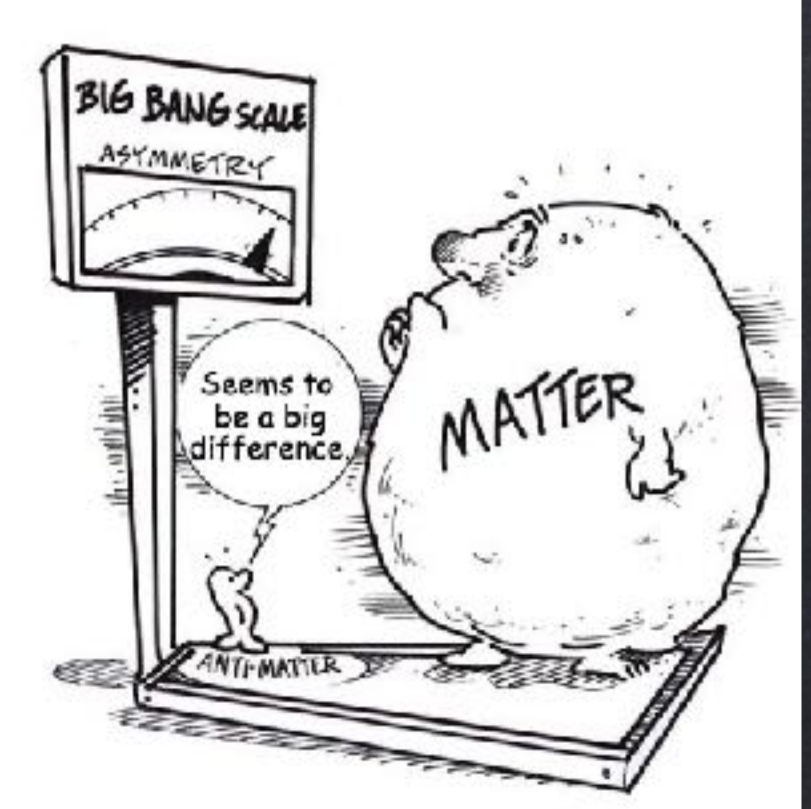
Content

- Problems in Standard Model
- Scotogenic Model
- First-order Phase transition
- Important parameters for GW
- GW Amplitude
- Results
- Conclusion

Problems in Standard Model

- Standard Model cannot explain the observed Neutrino Mass
- Standard Model does not have a darkmatter candidate
- Standard Model cannot explain the observed baryon asymmetry





Scotogenic Model

[E. Ma 2006]

- Extension of the SM by 3 RHN & 1 Scalar doublet
  - All of them are odd under Z_2 symmetry
- The lightest of the odd particles, if EM neutral, is a DM candidate
- Scalar DM resembles Inert Doublet DM (hep-ph/0603188, 0512090, 0612275)
- Lightest RHN DM (1710.0384)

→ ☑ Plausible explanation of DM candidate

- Neutrino Mass arises at one-loop level. → ☑ Plausible explanation of neutrino Mass

Scotogenic Model

[E. Ma 2006]

- Low-scale leptogenesis with hierarchical right handed neutrinos.
  [0903.4010, 1308.1840, 1505.05744
  1804.09660, 1810.03645, 1906.03577
  1912.09726, 2004.13762]

- While quasi-degenerate right handed neutrinos are discussed in earlier works (1207.2594, 1301.2087)

→ ☑ Explanation of baryonic asymmetry

Scotogenic Model

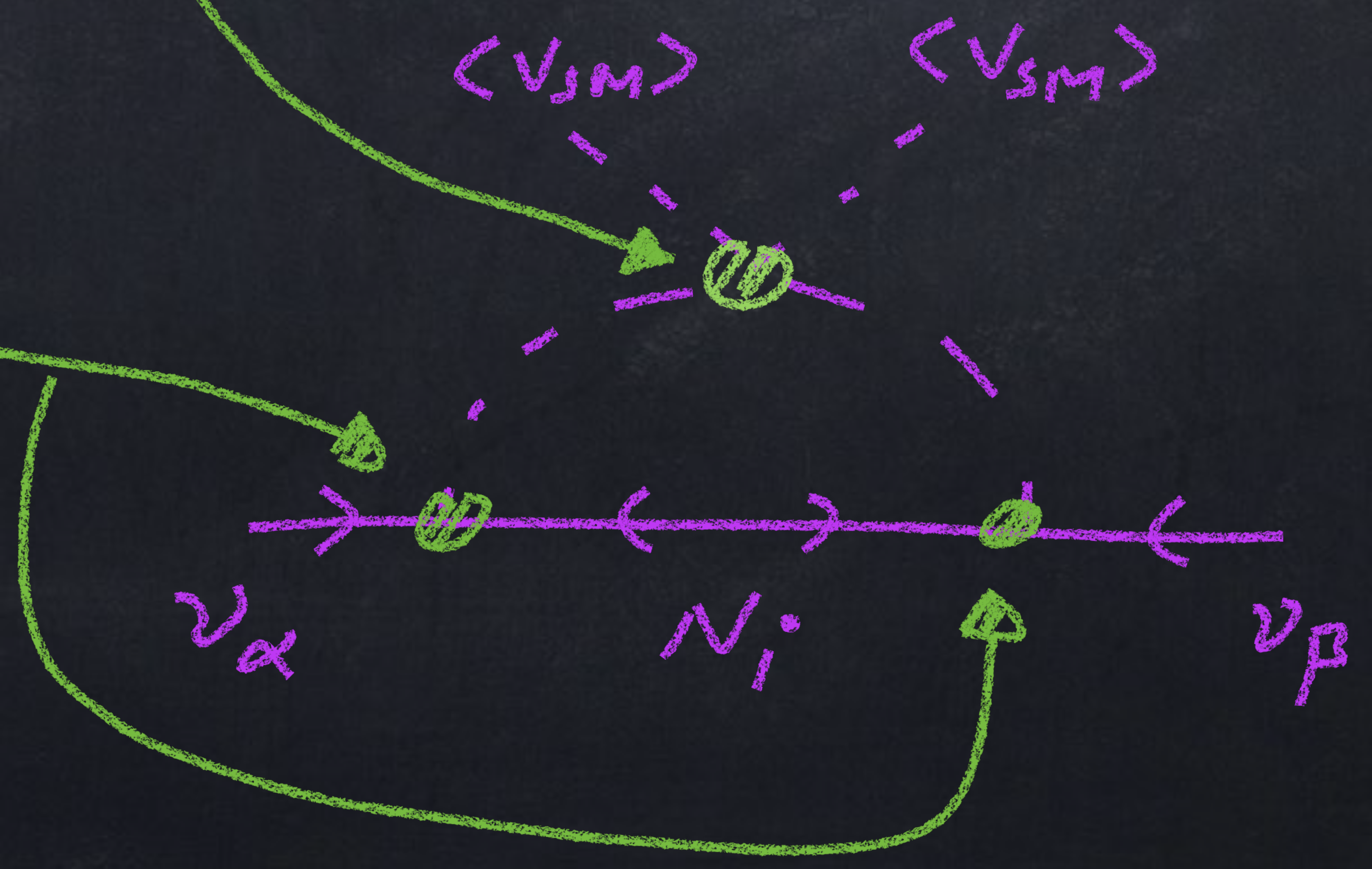
[E. Ma 2006]

$$V_{tree} = \lambda_{SM}\left(|H|^2 - \frac{v_{SM}^2}{2}\right) + m_1^2 |S|^2 + \lambda_1 |H|^2 |S|^2 + \lambda_2 |H^\dagger S|^2 + \left[\lambda_3 (H^\dagger S)^2 + h.c\right] + \lambda_S |S|^4$$

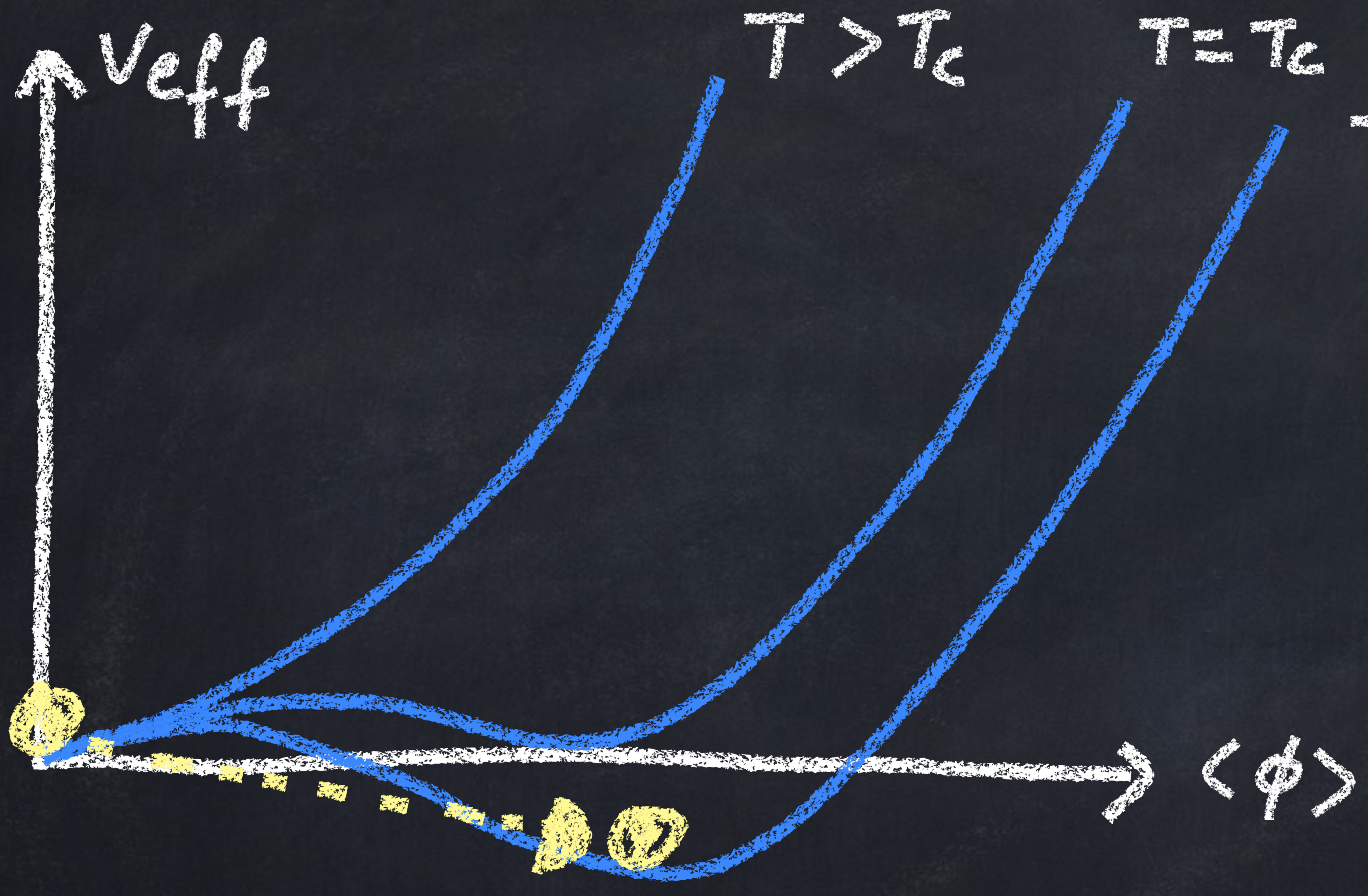
S: $SU(2)_W$ doublet

H: SM Higgs doublet

$$\mathcal{L}_{Yukawa} \supset \frac{1}{2}(M_N)_{ij} N_i N_j + \left(Y_{ij} \bar{L} \tilde{S} N_j + h.c\right)$$



First-Order Phase transition



- First-order phase transition proceeds through bubble nucleation

- One of the sources of Gravitional Wave is from Bubble Collision [Kosowski et.al. 1992]

- The other two sources are
  - Sound waves of the plasma [Hindmarsh et. al. 2004]
  - Turbulance of the plasma [Kamionkowski et. al. 1993]

First-Order Phase transition

Finite-temperature effective Potential

$$V_{tot} = V_{tree} + V_{CW} + V_{thermal}$$

degrees of freedom

$\overline{DR}$ regularisation

$$V_{CW} = \sum_i (-1)^{n_f} \frac{n_i}{64\pi^2} M_i^4(\phi)\left(\log\left(\frac{M_i^2(\phi)}{\mu^2}\right) - \frac{3}{2}\right)$$

$\mu = v_{SM}$ [as electroweak scale is the only relevant energy scale]

field dependent masses

+1 boson

-1 fermion

$$J_B{=}(x) = \int_0^\infty \partial z \; z^2 \log\left[1 - e^{-\sqrt{z^2+x^2}}\right]$$

$$V_{thermal} = \sum_i \left(\frac{n_{B_i}}{2\pi^2} T^4 J_B\left[\frac{M_{B_i}}{T}\right] - \frac{n_{F_i}}{2\pi^2} J_F\left[\frac{M_{F_i}}{T}\right]\right)$$

$$J_F{=}(x) = \int_0^\infty \partial z \; z^2 \log\left[1 + e^{-\sqrt{z^2+x^2}}\right]$$

First-Order Phase transition

Finite-temperature effective Potential

We have included a contribution from diasy diagram to improve the perturbative expansion during the phase transition

Parwani Method [hep-ph/9204216]

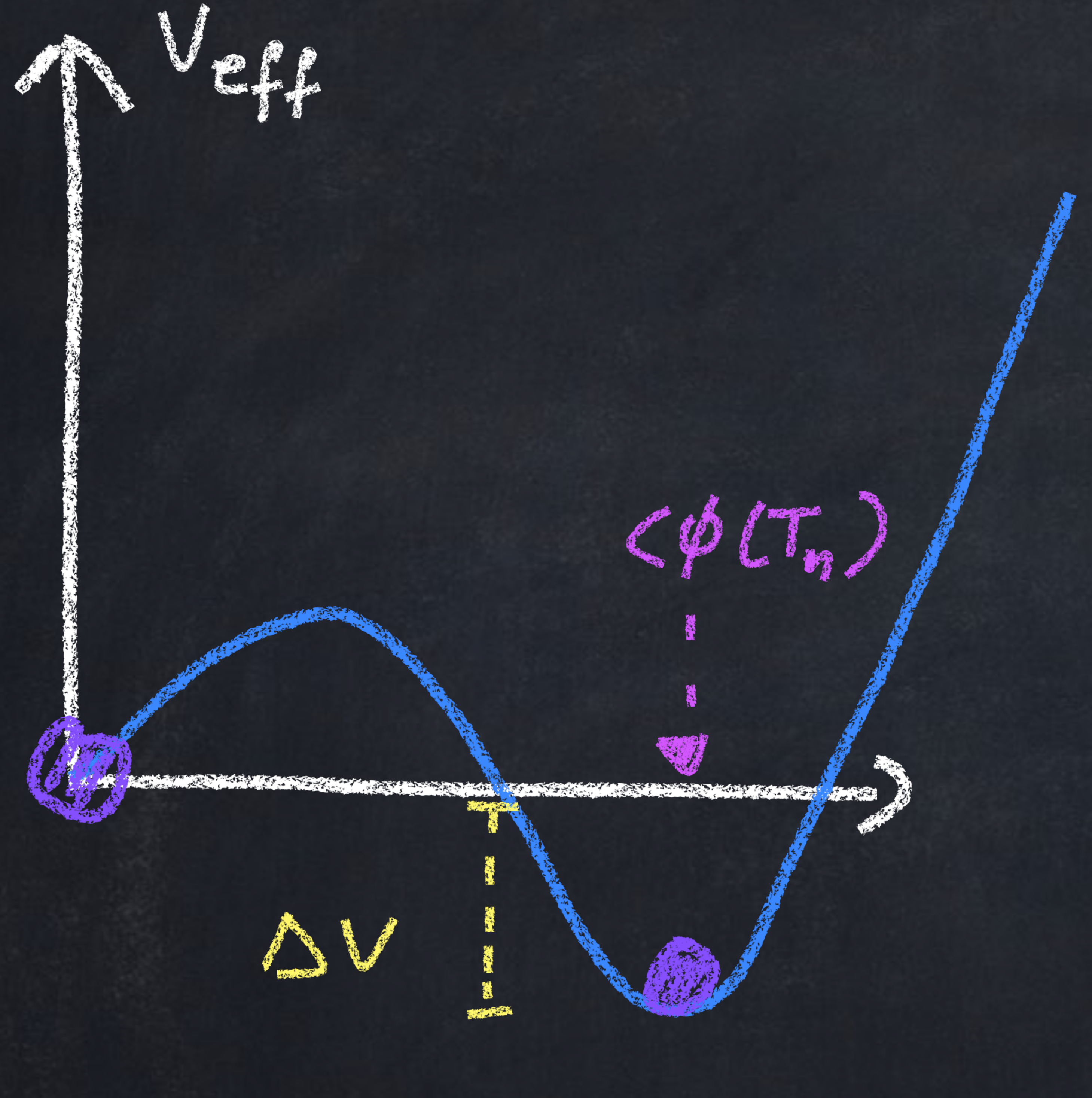
The thermal resummation prescription in which the thermal corrected field dependent are used for the calculation in V_{cw} and V_{th}

Arnold-Espiosa [hep-ph/9212235]

They include the effect of daisy diagram only for Matsubara zero-modes inside J_B function

- A qualitative difference between two prescription is in (1612.04086)

Important parameters for GW



- Tunneling occurs at $\Gamma(T_n)/H^4(T_n) \sim 1$

  $T_n :=$ Nucleation Temperature

- First-order phase transition: $\phi(T_n)/T_n \underline{>1}$

- GW amplitude is related to two important parameters
  - Latent Heat density: $\alpha = \epsilon/\rho_{rad}$
  - Duration of phase transition: $\beta \simeq H(T)T\frac{d}{dT}\left(\frac{S_3}{T}\right)\Big|_{T=T_n}$

$$\epsilon = \Delta V - \frac{T}{4}\frac{\partial \Delta V}{\partial T}\Big|_{T=T_n}$$

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

Linde (1983)

Γ: Bubble nucleation rate per unit time per unit volume

GW Amplitude

- **Sources of GWs:**
  - ▨ Bubble Collision
  - ▨ Sound Wave of the plasma
  - ▨ Turbulence of the plasma

$\therefore\ \Omega_{tot}h^2 \simeq \Omega_{sound}h^2 + \Omega_{tur}h^2$

⇒ Contribution from Bubble Collision is always subdominant for the case with supercooling, $\alpha < 1$, since the bubble kinetic energy is almost converted into the thermal plasma due to the process called "Transition radiation"

[1703.08215, 1903.09642]

GW Amplitude

- $\Omega_{sound} h^2$:

$$= 2.65\times10^{-6} \times HZ_{sound} \left(\frac{H(T_n)}{\beta}\right)\left(\frac{\overbrace{\kappa_{sound}\,\alpha}^{\text{Efficiency factor}}}{1+\alpha}\right)^{2} \left(\frac{100}{g_*}\right)^{1/3} \overbrace{v_w}^{\text{Bubble wall velocity}} \left(\frac{f}{f_{sound}}\right)^{3}$$

$$\times \left[\frac{7}{4+3\left(\frac{f}{\underbrace{f_{sound}}_{\text{Peak frequency of GW signals}}}\right)^{2}}\right]^{7/2}$$

$$HZ_{sound} = \min\left\{1,\ (8\pi)^{1/3}\left(\frac{\max\{c_s, v_w\}}{\beta/H(T_n)}\right)\left(\frac{4}{3}\,\frac{1+\alpha}{\kappa_{sound}\,\alpha}\right)^{1/2}\right\}$$

$$f_{sound} = 1.9\times10^{-2}\,\mathrm{mHz}\ \frac{1}{v_w}\left(\frac{\beta}{H(T_n)}\right)\left(\frac{T_n}{100\,\mathrm{GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6}$$

GW Amplitude

- $\Omega_{sound} h^2$:

$$v_w = \frac{1/\sqrt{3} + \sqrt{\alpha^2 + 2\alpha/3}}{1+\alpha}$$

⟹ In our we took Jouguet detonation

[Phys. Rev. D25 (1982) 2074]

$$K_{sound} = \frac{\sqrt{\alpha}}{0.135 + \sqrt{0.98 + \alpha}}$$

GW Amplitude

- $\Omega_{tur} h^2$:

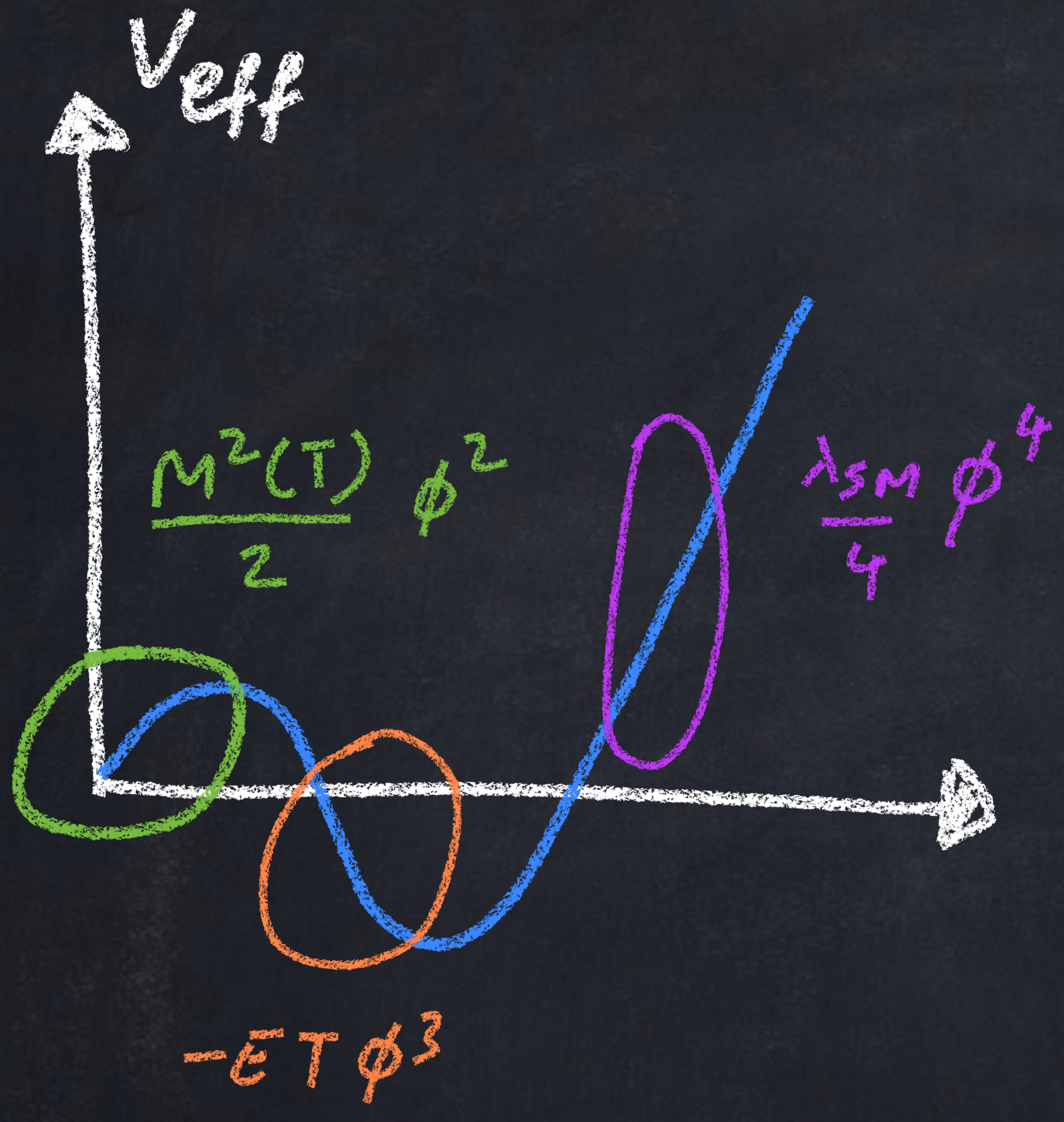
$$= 3.35 \times 10^{-4} \left(\frac{H(T_n)}{\beta} \right) \left(\frac{\kappa_{tur}\,\alpha}{1+\alpha} \right)^{3/2} \left(\frac{100}{g_*} \right)^{1/3} v_w \; \frac{(f/f_{tur})^3}{\left(1 + (f/f_{tur})\right)^{11/3} \left(1 + 8\pi f/H_0\right)}$$

$$\kappa_{tur} \simeq 0.1\, \kappa_{sound}$$

$$H_0 \simeq 1.65 \times 10^{-4}\, \mathrm{mHz} \times \left(\frac{T_n}{100\, \mathrm{GeV}} \right) \left(\frac{g_*}{100} \right)^{1/6}$$

$$f_{tur} = 2.7 \times 10^{-2}\, \mathrm{mHz} \left(\frac{1}{v_w} \right) \left(\frac{T_n}{100\, \mathrm{GeV}} \right) \left(\frac{\beta}{H(T_n)} \right) \left(\frac{g_*}{100} \right)^{1/6}$$

Effect of V_{eff} on GW



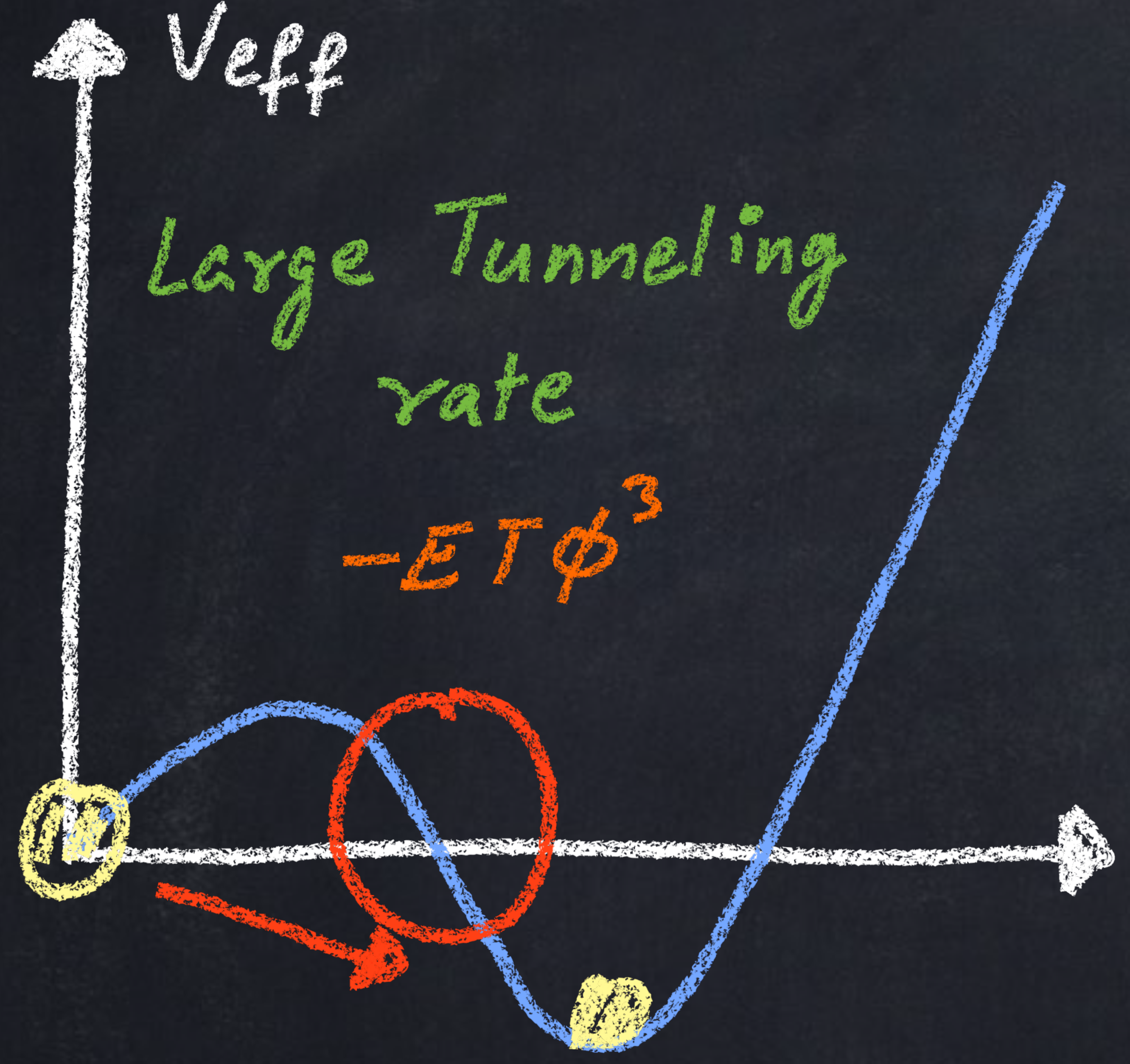
$$V_{eff} = \frac{M^2(T)}{2}\phi^2 - \underbrace{ET\phi^3}_{\text{Thermal fluctuation}} + \frac{\lambda_{SM}}{4}\phi^4$$

- Potential barrier comes from bosons!
  (Matsubara zero-modes)

- Standar Model : $SU(2)_W \times U(1)_Y$
- $SU(2)_W \times U(1)_Y$ + one scalar doublet

Effect of V_{eff} on GW

Standard Model (Small E)

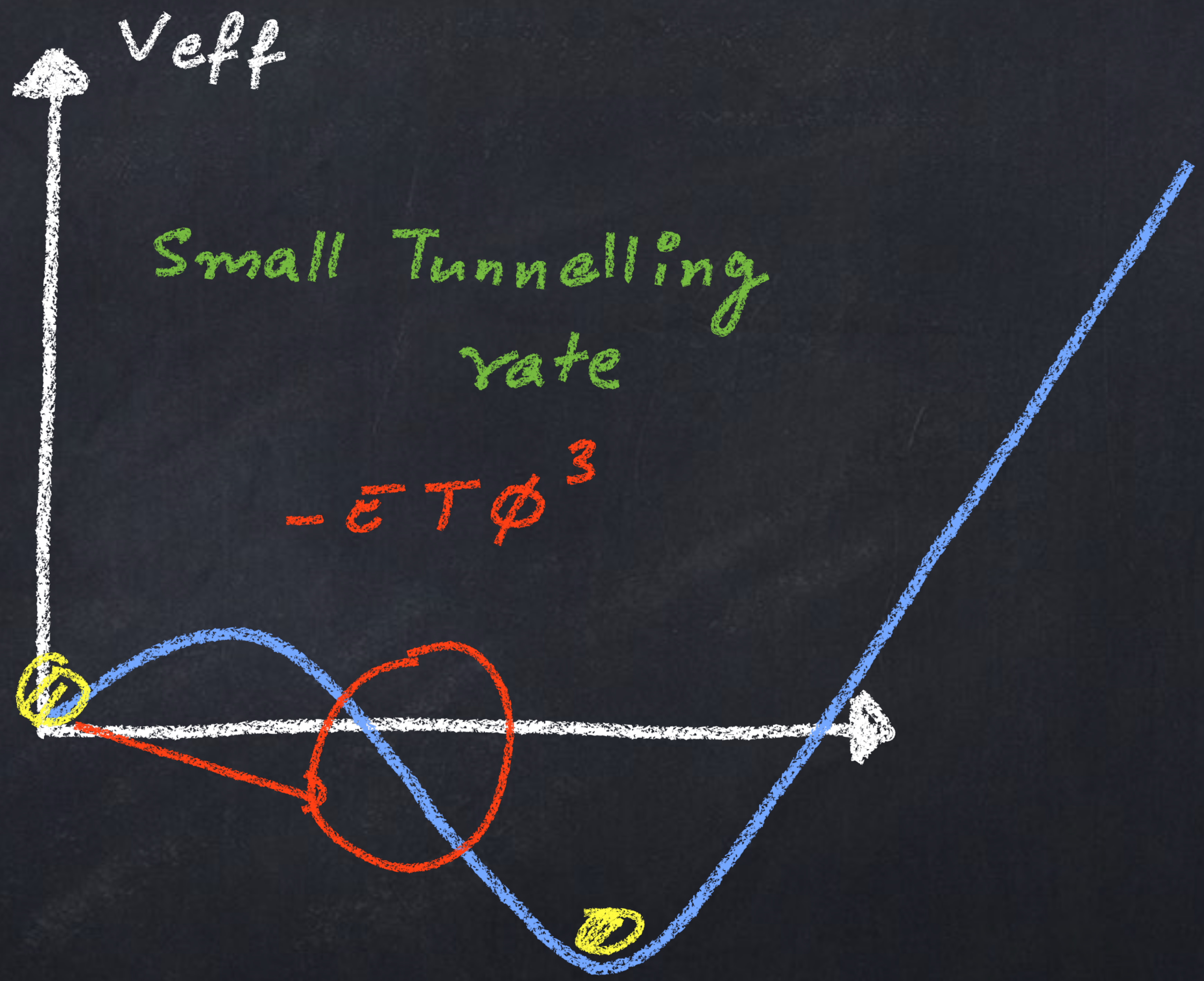


$\phi(T_n)/T_n \ll 1$

α : small β : large

Ω_{GW} : small

SM + one scalar doublet (Large E)



$\phi(T_n)/T_n \gtrsim 1$

α : Large β : small

Ω_{GW} : Large!!

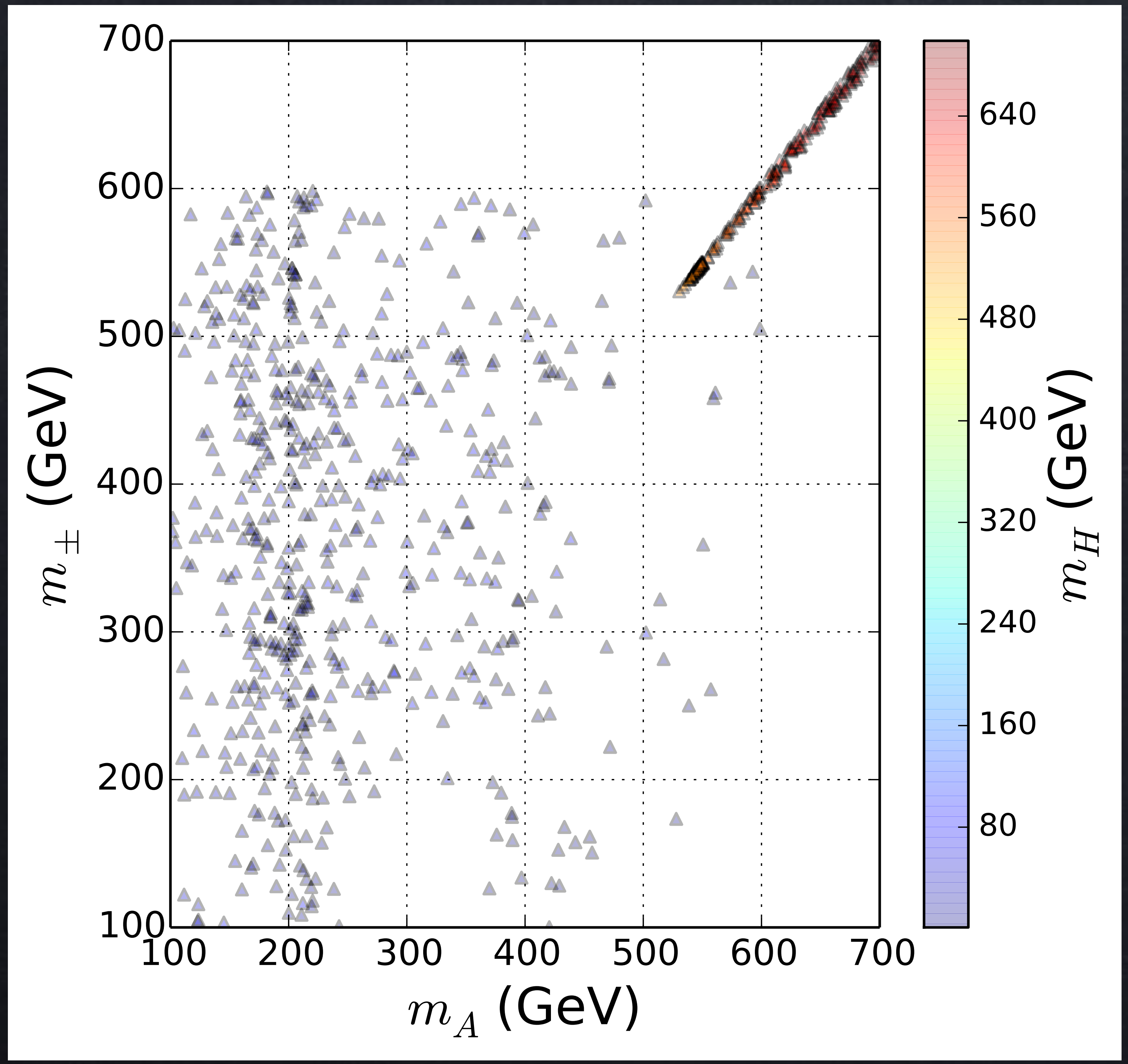
Results

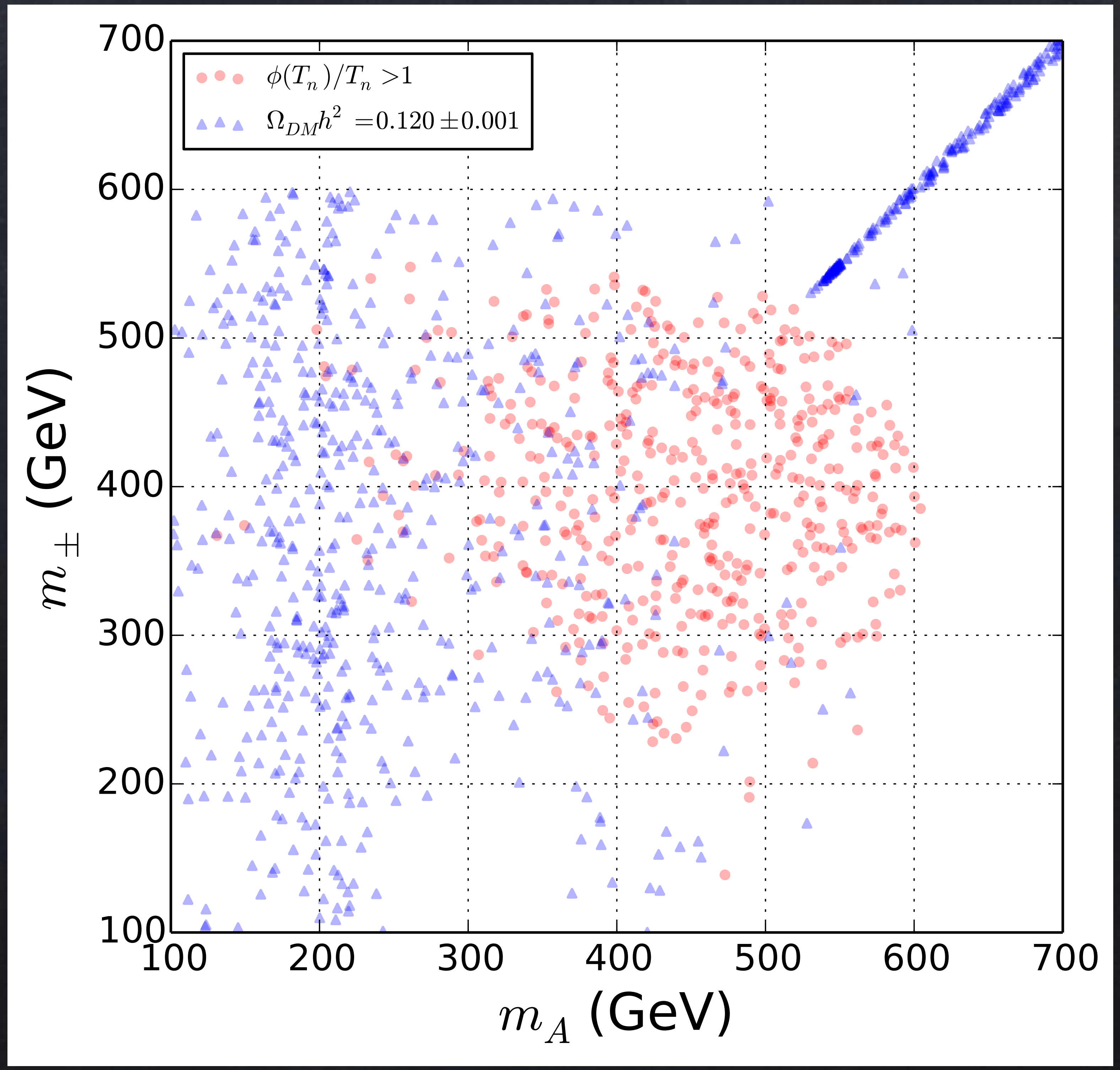
- Since the inert doublet couples to Higgs, and thus, larger λ_H, λ_A and λ_1 make the phase transition strength stronger.
  - Also, larger m_1 makes the phase transition strength weaker due to the screening effect.
  - For the same reason, larger λ_S corresponds to larger thermal mass making phase transition weaker.

Results

Scalar Dark Matter

- We impose conditions $\lambda_3 < 0$ and $\lambda_2 + 2\lambda_3 < 0$ in order to make CP even component of inert doublet H to be DM candidate.
- The two distinct regions of DM (H) mass : $m_H < 80$ GeV & $m_H > 550$ GeV

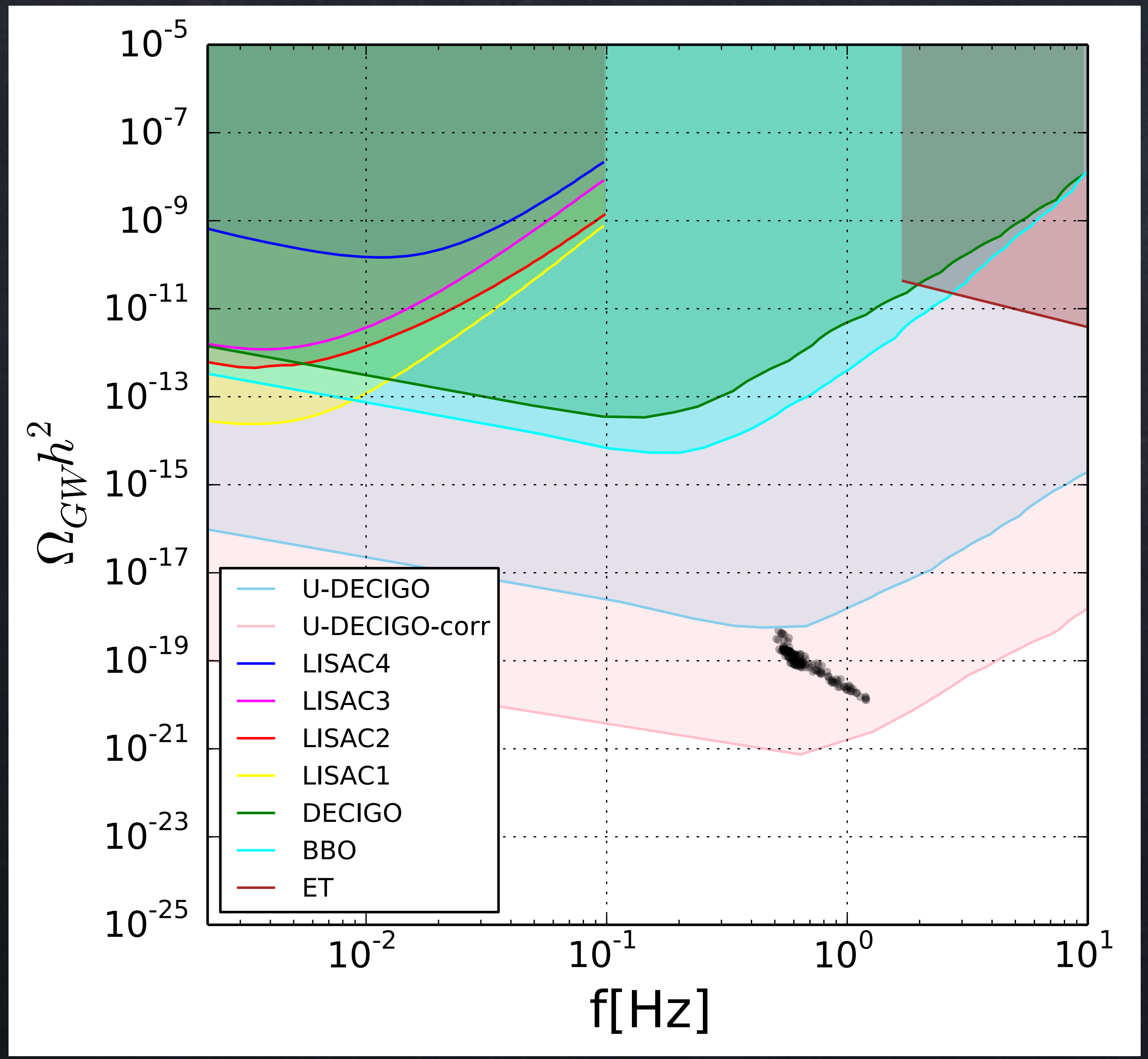


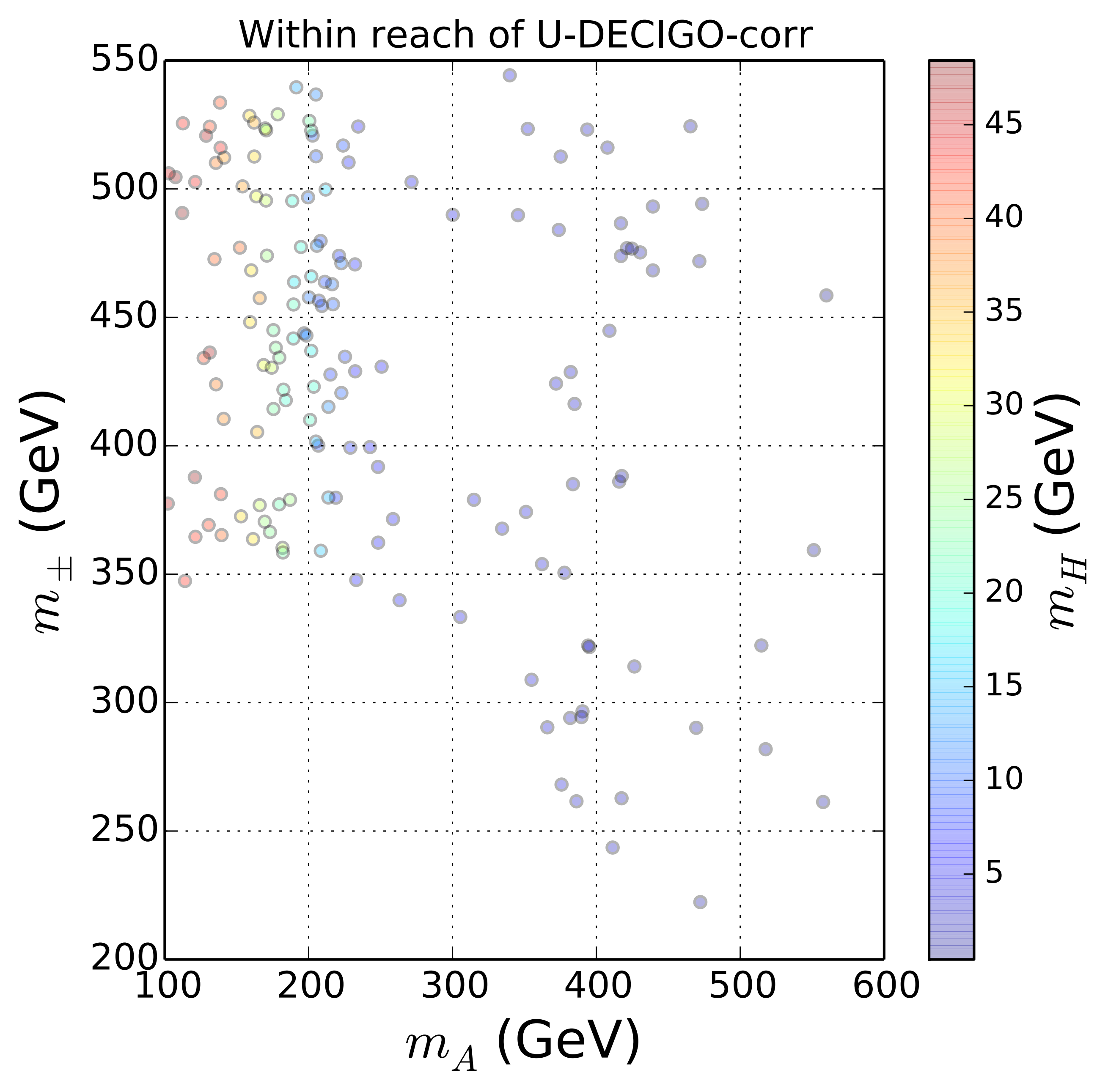


Results

Scalar Dark Matter

- It should be noted that the SFOPT requires fine-tuning between λ_1 & $\lambda_2+2\lambda_3$ to maintain small $\lambda_H=\lambda_1+\lambda_2+2\lambda_3$ for a low DM mass regime, $M_H<80$ GeV.
- The linear correlation in high mass regime beyond 550 GeV is in order to satisfy correct DM as the mass splitting is required to be small.





Results

Scalar Dark Matter

- The criteria for the SFOPT requires the bare mass parameter of inert doublet to be small $0 < m_1 < 50$ GeV.
- Although low mass DM is not completely ruled out yet by Xenon 1T, the region satisfying SFOPT criteria is ruled out.

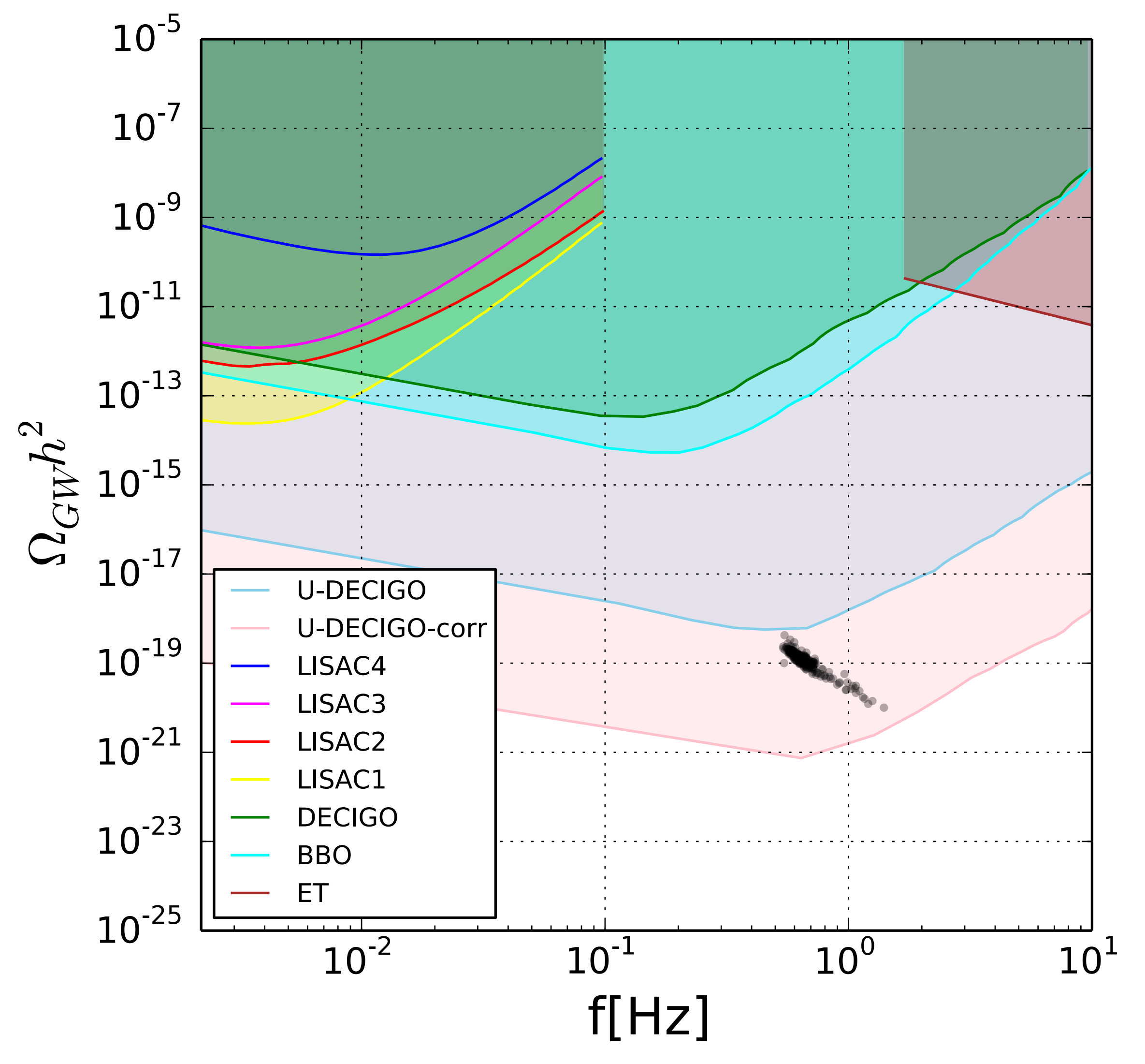
Results

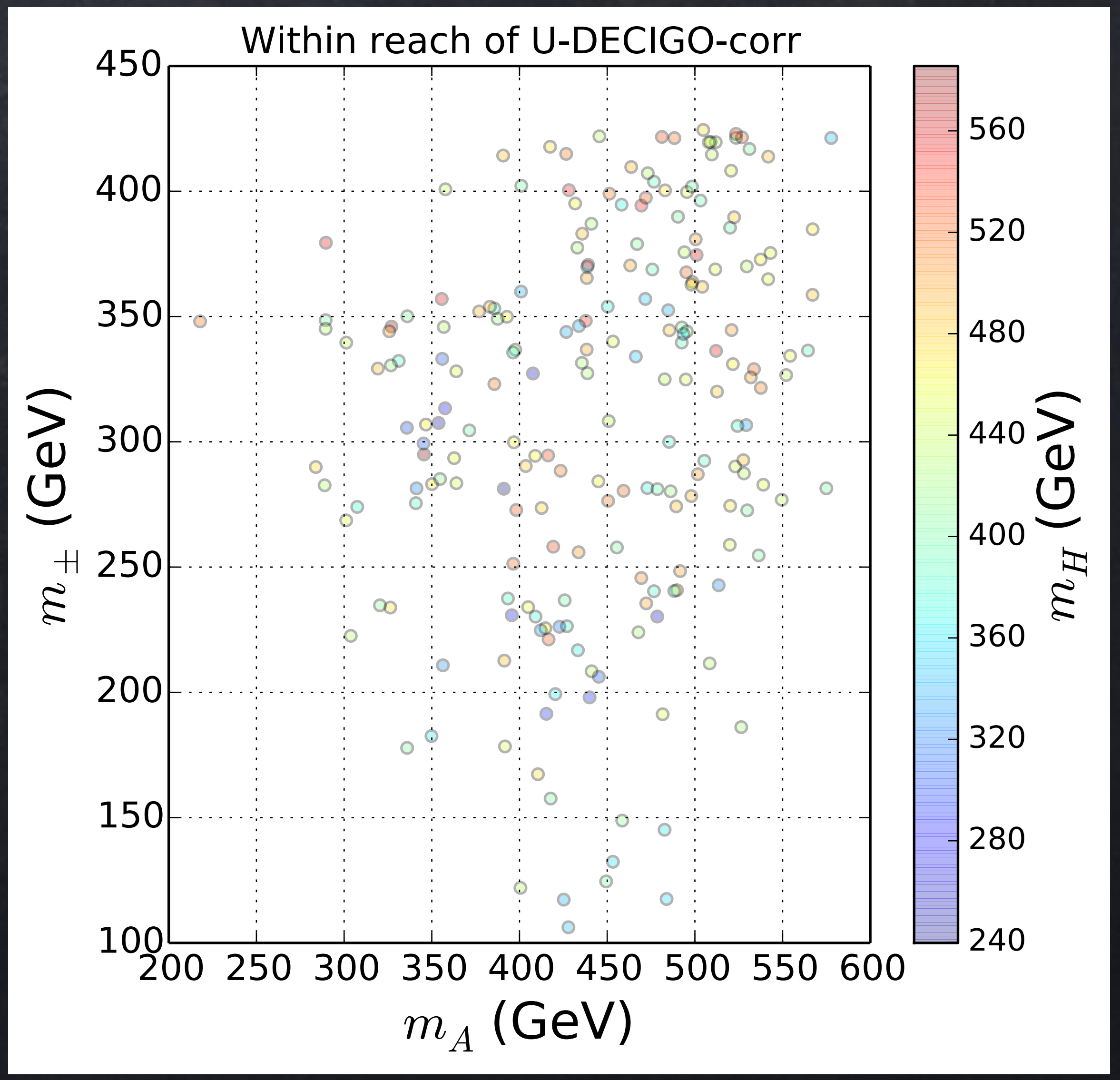
Fermion Dark Matter

- The conditions $\lambda_3<0$ and $\lambda_2+2\lambda_3<0$ is not imposed.
- Since $\phi(T_n)/T_n > 1$ can be realised for smaller λ_1 by making λ_H larger with fixed m_1

  Smaller m_1

  larger m_H
- It should be emphasised that we have no fine-tuning between λ_1, λ_2 and λ_3 in this scenario.





Conclusion

- we have studied the possibility of generating GWs from a strong first-order EWPT in minimal scotogenic model.
  - ⇨ Possibility of getting proded in future U-DECIGO.
- Our results for the Scalar Dark Matter case is in partial agreement with earlier works.
  - ⇨ However, the region favoured by SFOPT is disfavoured by direct detection bounds from Xenon 1T (2018).
- But for the Fermion Dark Matter scenario, favoured SFOPT parameter space is enlarged due to the mass ordering within scalar doublet components.