# On the fate of Electroweak Vacuum and Phase Transition in Beyond Standard Model Scenarios

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Based on: [1]JHEP 08 (2020) 154, [2]Eur.Phys.j.c 80 (2020) 8, 715, [3]JHEP 02 (2021) 075, [4]Eur.Phys.J.C 82 (2022) 516, [5]2111.03866

In collaboration with: Priyotosh Bandyopadhyay, Bhupal Dev, Arjun Kumar, Manimala Mitra, Anirban Karan

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భారతీయ సాంకేతిక విజ్ఞాన సంస్థ హైదరాబాద్
भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

# Outline of the talk

- The Standard Model (SM)
- Standard Model + Inert 2HDM/Triplet (IDM/ITM)
    - Dark Matter Constraint
    - Stability analysis
- Standard Model + IDM + Type-I
- Standard Model + IDM + Type-III
- Electroweak phase transition
- Gravitational Wave signatures

# Dominant top quark effect in SM

- The effective potential at high field values is written as

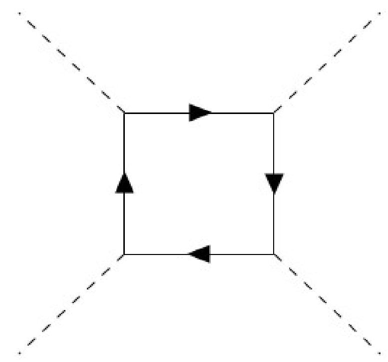
$$V_{\rm eff}(h,\mu) \simeq \lambda_{\rm eff}(h,\mu)\frac{h^4}{4}, \quad \text{with } h \gg v,$$

where $\lambda_{eff}$ is given by

$$\lambda_{\rm eff}(h,\mu) \simeq \underbrace{\lambda_h(\mu)}_{\text{tree-level}} + \underbrace{\frac{1}{16\pi^2}\Big[-12Y_t^4\Big[log\frac{Y_t^2}{\mu^2}-\frac{3}{2}\Big]\Big]}_{\text{Negative contribution from top quark}}.$$

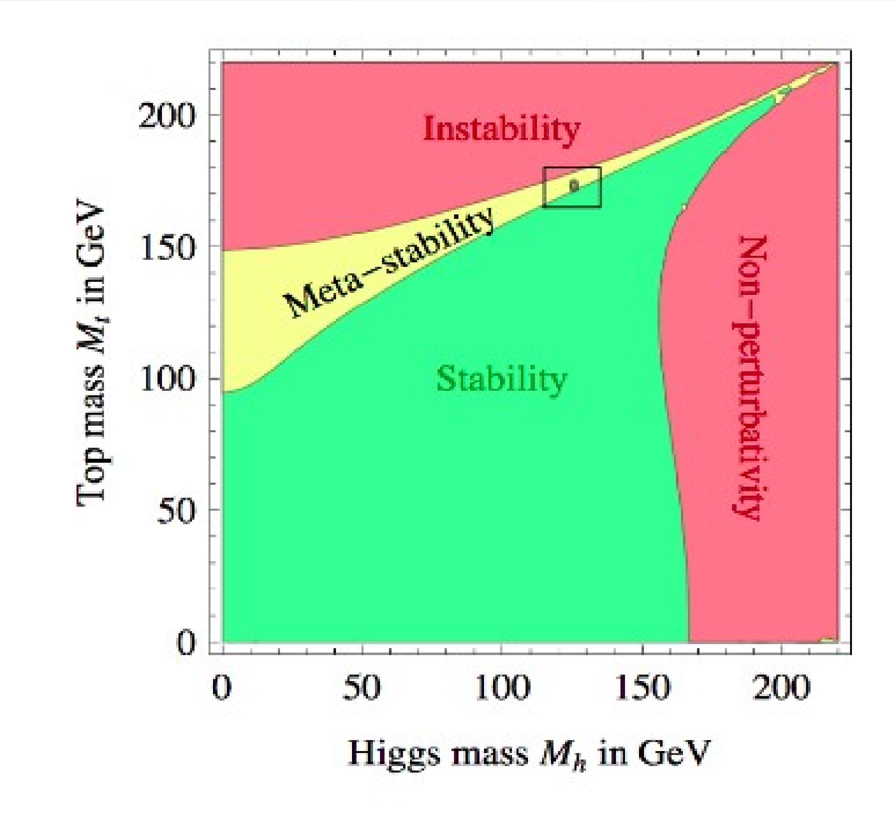
Condition of metastability

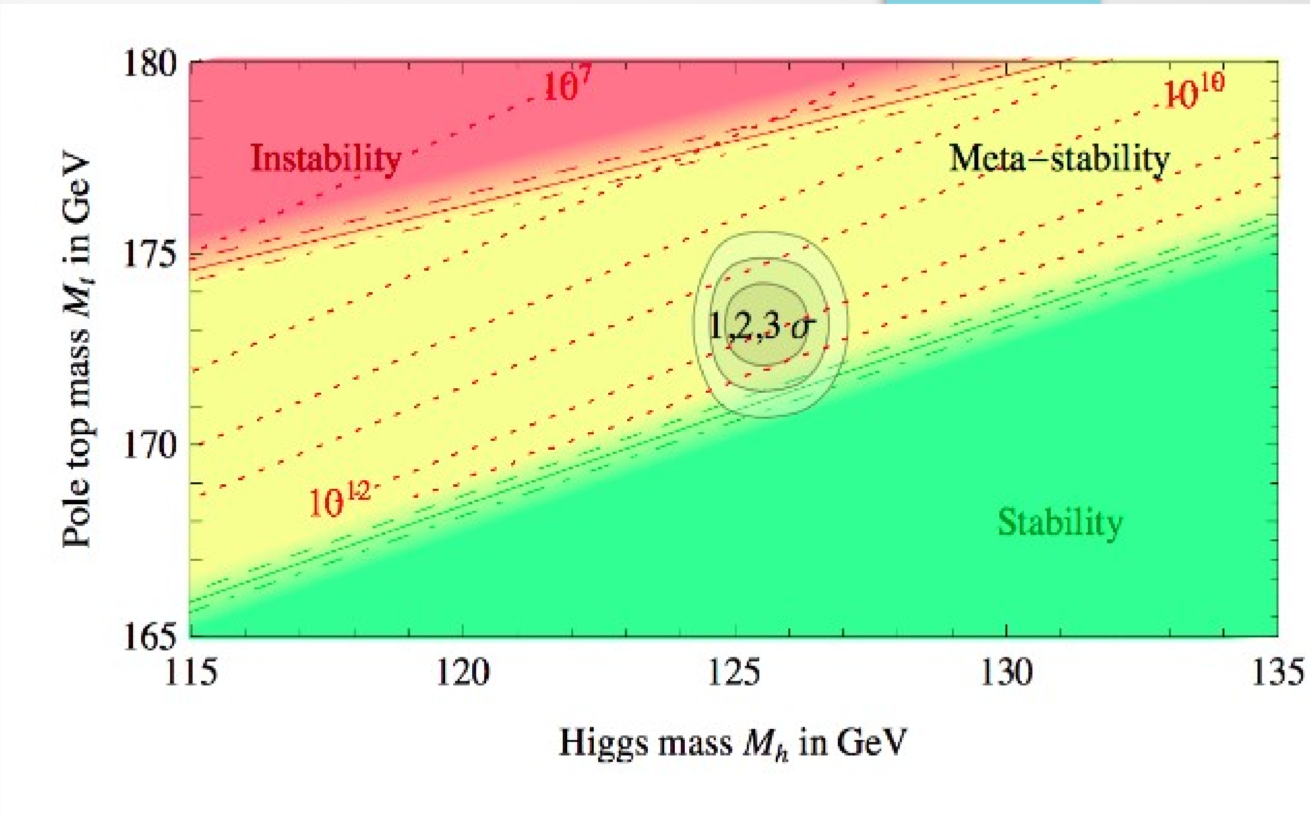
$$0 > \lambda_{eff}(\mu) \simeq \frac{-0.065}{1-0.01\,log\frac{v}{\mu}}$$



With the negative contribution from top-quark, the stability is compromised.

# Status of SM




Within the uncertainity of top mass we are in metastable vacuum

M.~Gogberashvili, Adv. High Energy Phys. (2018), 4653202

# Standard Model + Inert doublet

- We impose an additional discrete symmetry on 2HDM potential which is defined as $Z_2$ to have Dark matter candidate

$$Z_2 : \qquad \Phi_1 \to \Phi_1, \qquad \Phi_2 \to -\Phi_2$$

- The general Higgs potential for inert 2HDM is

$$\begin{aligned} V_{\text{scalar}} &= m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\ &+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + [\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \text{H.c}]. \end{aligned}$$

- Being odd under $Z_2$ , $\Phi_2$ does not contribute in EWSB

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ v_1 + h_1 + i\rho_1 \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ h_2 + i\rho_2 \end{pmatrix}$$

# Standard Model + Inert Triplet

- We introduce in addition to SM Higgs doublet i.e. Φ, another SU(2) triplet scalar with Y=0, i.e. T

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \; T = \frac{1}{2}\begin{pmatrix} T_0 & \sqrt{2}T^+ \\ \sqrt{2}T^- & -T_0 \end{pmatrix}.$$

- The general Higgs potential for Higgs triplet is

$$V = m_h^2 \Phi^\dagger \Phi + m_T^2 Tr(T^\dagger T) + \lambda_1 |\Phi^\dagger \Phi|^2 + \lambda_t (Tr|T^\dagger T|)^2 + \lambda_{ht} \Phi^\dagger \Phi Tr(T^\dagger T).$$

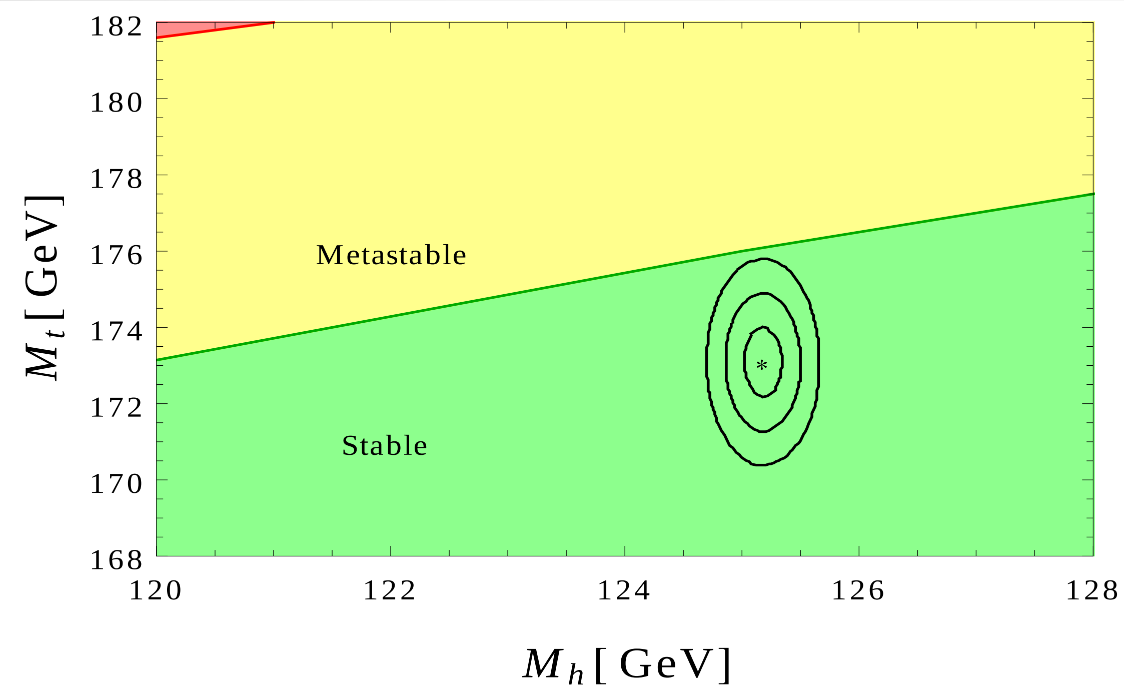
- Due to $Z_2$-odd nature, the triplet field does not take part in EWSB

$$\Phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v_h + h) + iG^0 \end{pmatrix}, \; T = \frac{1}{2}\begin{pmatrix} T_0 & \sqrt{2}T^+ \\ \sqrt{2}T^- & -T_0 \end{pmatrix}.$$

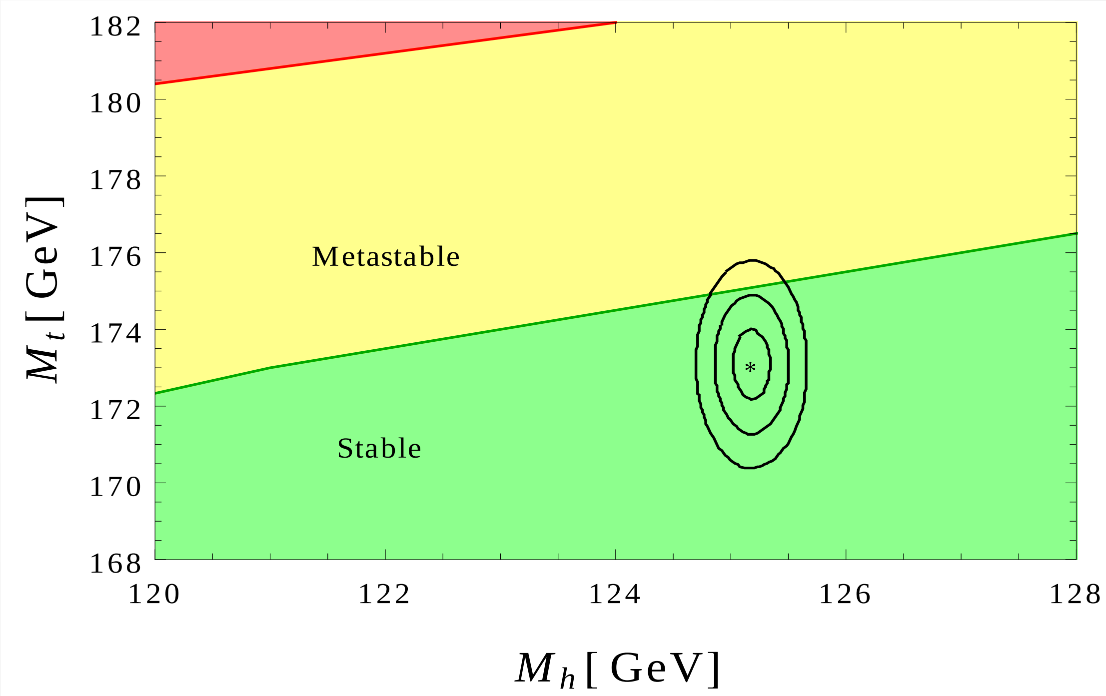
# Vacuum stability in IDM and ITM

More stable bacause of more degrees of freedom

SJ, Priyotosh Bandyopadhyay, Eur.Phys.J.C 80 (2020) 8, 715




(a) IDM

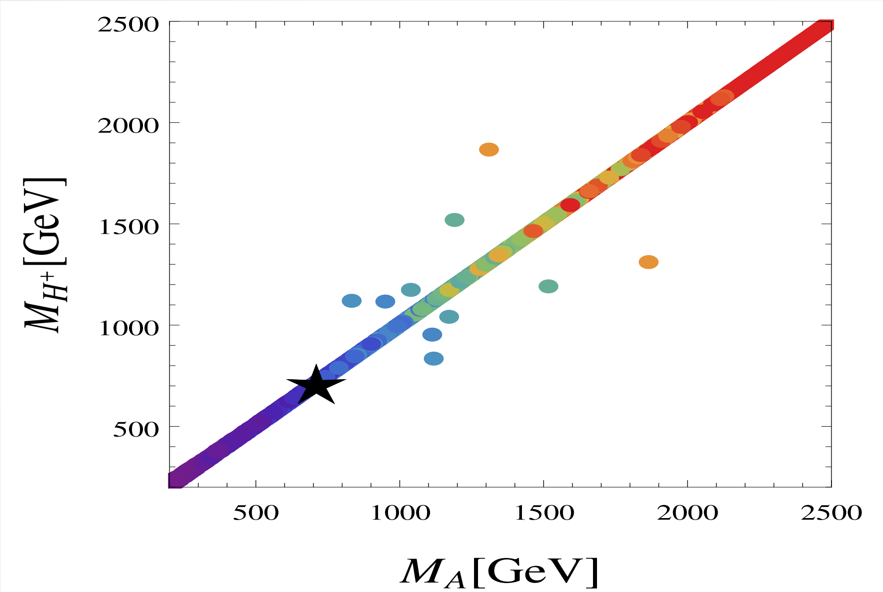



(b) ITM

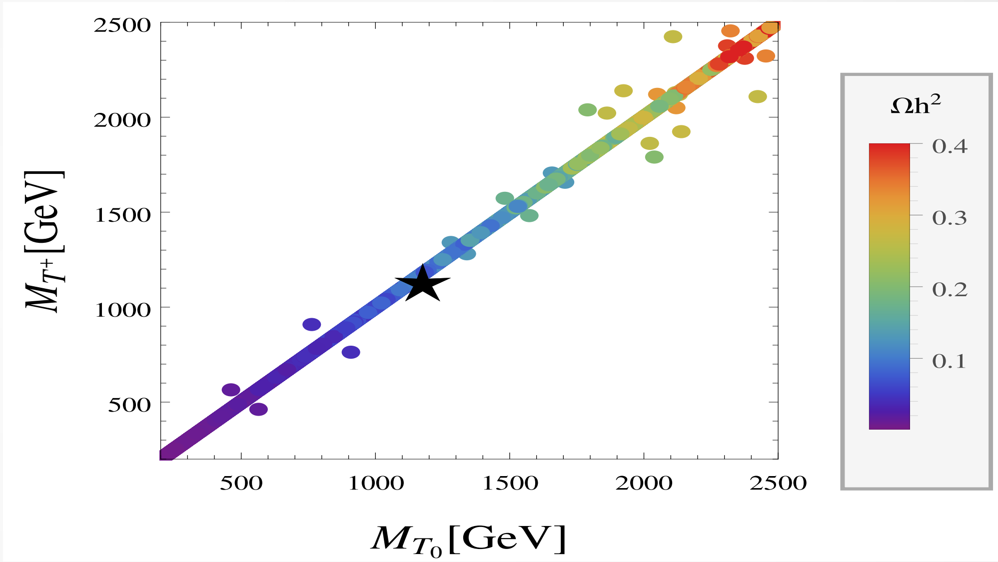
Planck scale stability is achieved in both the scenarios, unlike SM.

# Relic density bound in IDM and ITM

- For IDM, $M_A$> 700 GeV corresponds to correct DM relic value
- For ITM, $M_{T0}$> 1200 GeV corresponds to correct DM relic value




(a) IDM




(b) ITM

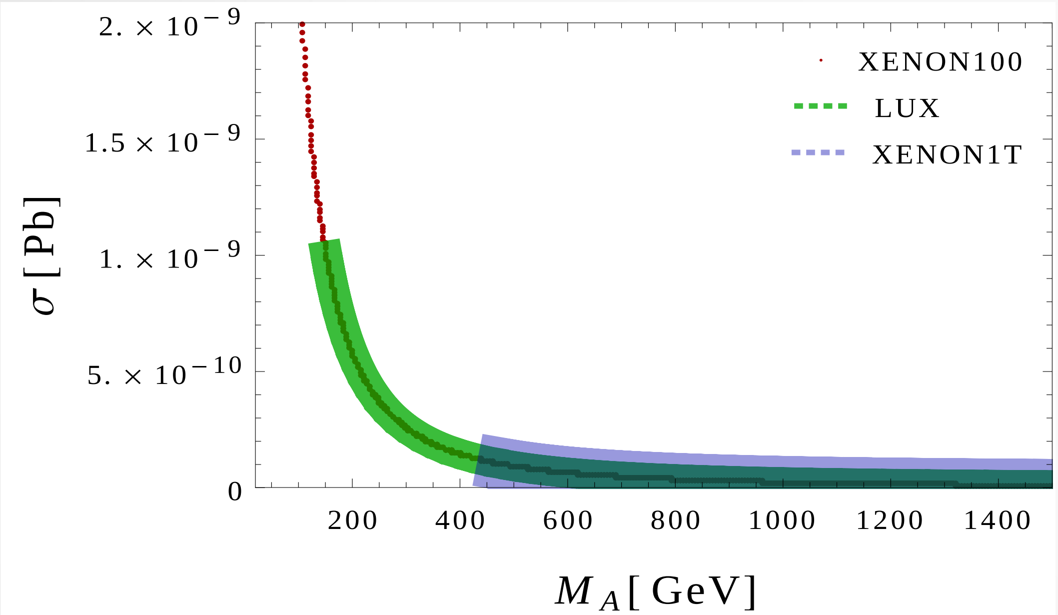
SJ, Priyotosh Bandyopadhyay, Eur.Phys.J.C 80 (2020) 8, 715

**The presence of one extra $Z_2$-odd scalar results into higher DM number density in IDM case, leading to lower mass bound on DM mass.**

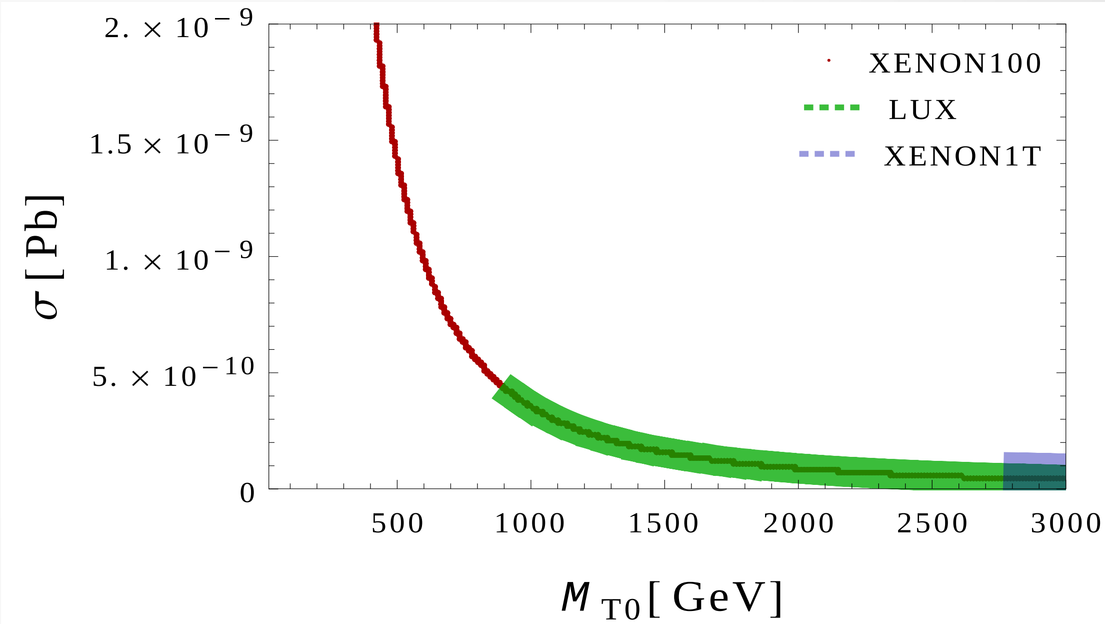
# SI cross section on DM mass

$$\text{XENON100}: \sigma_{\rm SI} \leq 2.0 \times 10^{-45}\ \text{cm}^2\,,$$
$$\text{LUX}: \sigma_{\rm SI} \leq 7.6 \times 10^{-46}\ \text{cm}^2\,,$$
$$\text{XENON1T}: \sigma_{\rm SI} \leq 1.6 \times 10^{-47}\ \text{cm}^2\,.$$

SJ, Priyotosh Bandyopadhyay,
Eur.Phys.J.C 80 (2020) 8, 715




(a) IDM




(b) ITM

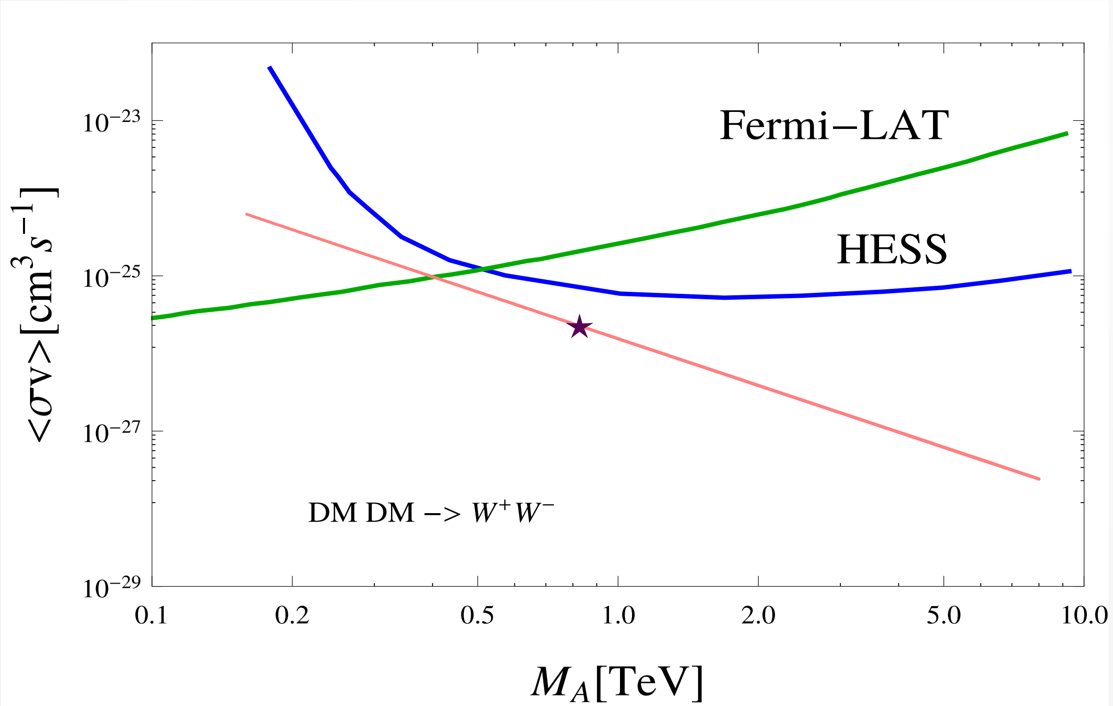
The cross-section varies with the DM mass and the Higgs quartic coupling $\lambda_{345}$ for IDM and $\lambda_{ht}$ for ITM. In IDM, Higgs quartic coupling $\lambda_{345} = (\lambda_3 + \lambda_4 - 2\lambda_5)$ can be fine-tuned to satisfy the cross-section bounds for much lower DM mass compared to ITM.

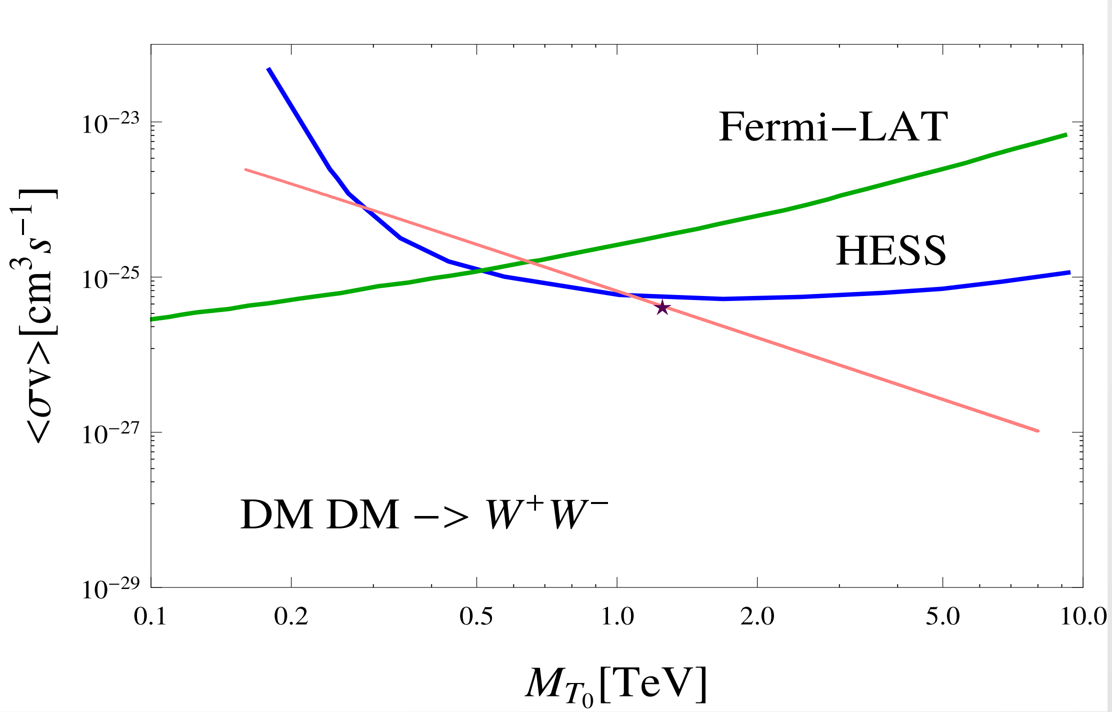
# Indirect detection: Constraints from H.E.S.S and Fermi-LAT experiments

- The expected gamm-ray flux coming from the dark matter annihilation for DM DM -> SM SM can be written as

$$\frac{d\phi_\gamma}{dE} = \frac{1}{8\pi m_{DM}^2} < \sigma v > \frac{dN_\gamma}{dE} J,$$

SJ, Priyotosh Bandyopadhyay, Eur.Phys.J.C 80 (2020) 8, 715




In both IDM and ITM, the DM annihilation to $W^+W^-$ is dominant which makes the H.E.S.S and Fermi-LAT bounds on <σv> very evident.

# Seesaw mechanism

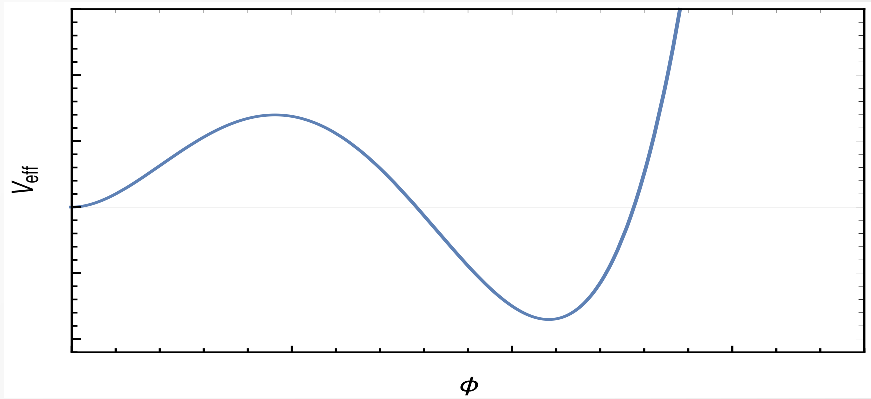
Smallness of neutrino mass can be explained by the existence of heavy neutrinos.

# Generation of neutrino mass

Type-I Seesaw
(Extension with fermionic singlet)

Type-III Seesaw
(Extension with fermionic triplet)

This will make me unstable




Further extension with inert 2HDM will compensate the negative effect and provide the DM candidate.

# Vacuum stability from RG-improved potential

- The effective potential for high field values is written as

$$V_{\text{eff}}(h,\mu) \simeq \lambda_{\text{eff}}(h,\mu)\frac{h^4}{4}, \quad \text{with } h \gg v\,,$$

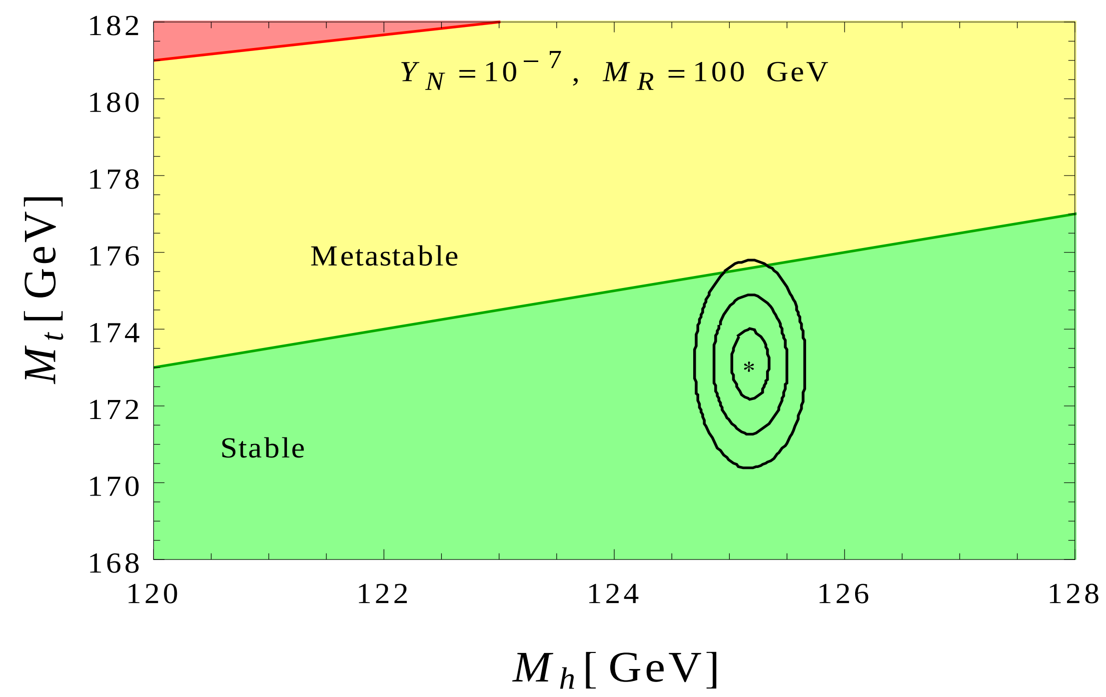
where $\lambda_{eff}$ is given by

$$\lambda_{\text{eff}}(h,\mu) \simeq \underbrace{\lambda_h(\mu)}_{\text{tree-level}} + \underbrace{\frac{1}{16\pi^2}\sum_{\substack{i=W^\pm,Z,t,\\ h,G^\pm,G^0}} n_i\kappa_i^2\left[\log\frac{\kappa_i h^2}{\mu^2} - c_i\right]}_{\text{Contribution from SM}} + \underbrace{\frac{1}{16\pi^2}\sum_{i=H,A,H^\pm} n_i\kappa_i^2\left[\log\frac{\kappa_i h^2}{\mu^2} - c_i\right]}_{\text{Contribution from inert doublet}}$$

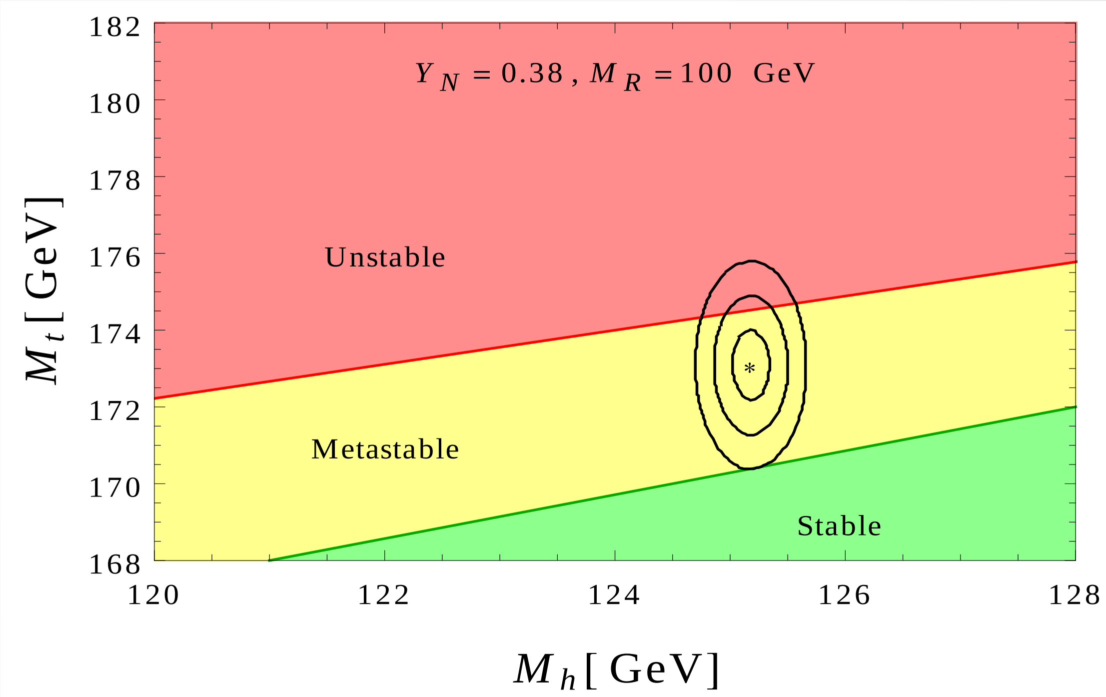
$$+ \underbrace{\frac{1}{8\pi^2}\sum_{i=1,2,3} n_i\kappa_i^2\left[\log\frac{\kappa_i h^2}{\mu^2} - c_i\right]}_{\text{Contribution from RHN}}.$$

# Metastability and instability

Higher $Y_N$ leads to higher unstable region




(a) ID + Type-I




(b) ID + Type-I

SJ, P Bandyopadhyay, Bhupal Dev, Arjun Kumar, JHEP 08 (2020) 154

# IDM with Type-III Inverse seesaw

- We have SU(2) doublets $\Phi_1$, $\Phi_2$ with same hypercharge 1/2 and three generations of fermionic triplets $\Sigma_1$, $\Sigma_2$ with zero hypercharge

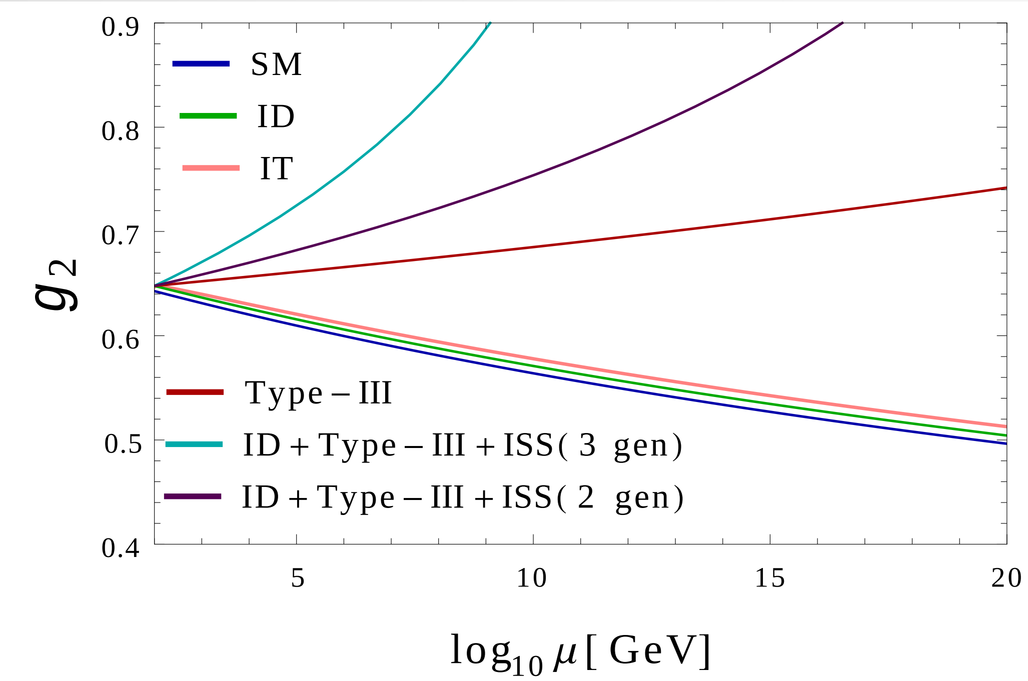
$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}$$

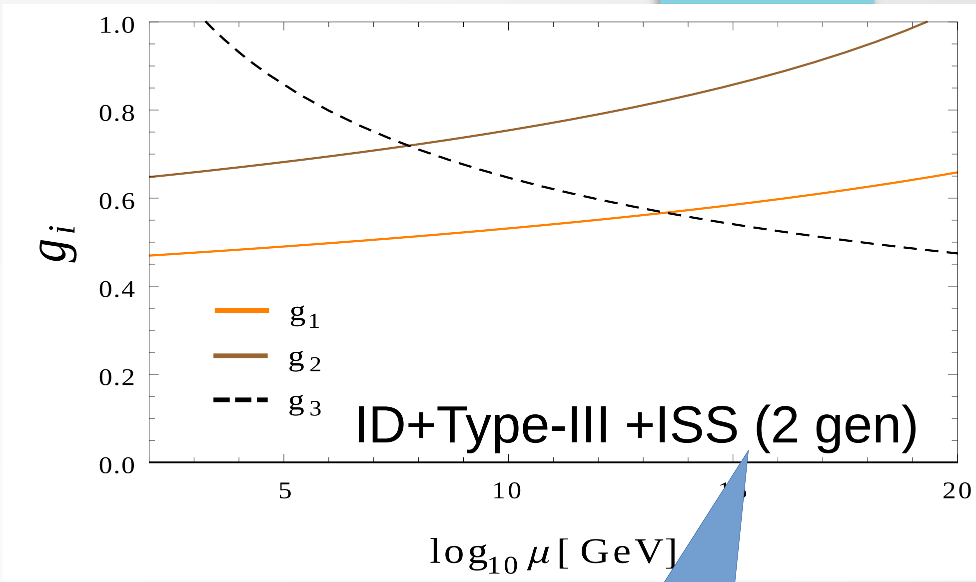
$$\Sigma_1 = \begin{pmatrix} \Sigma_1^0/\sqrt{2} & \Sigma_1^+ \\ \Sigma_1^- & -\Sigma_1^0/\sqrt{2} \end{pmatrix} \qquad \Sigma_2 = \begin{pmatrix} \Sigma_2^0/\sqrt{2} & \Sigma_2^+ \\ \Sigma_2^- & -\Sigma_2^0/\sqrt{2} \end{pmatrix}$$

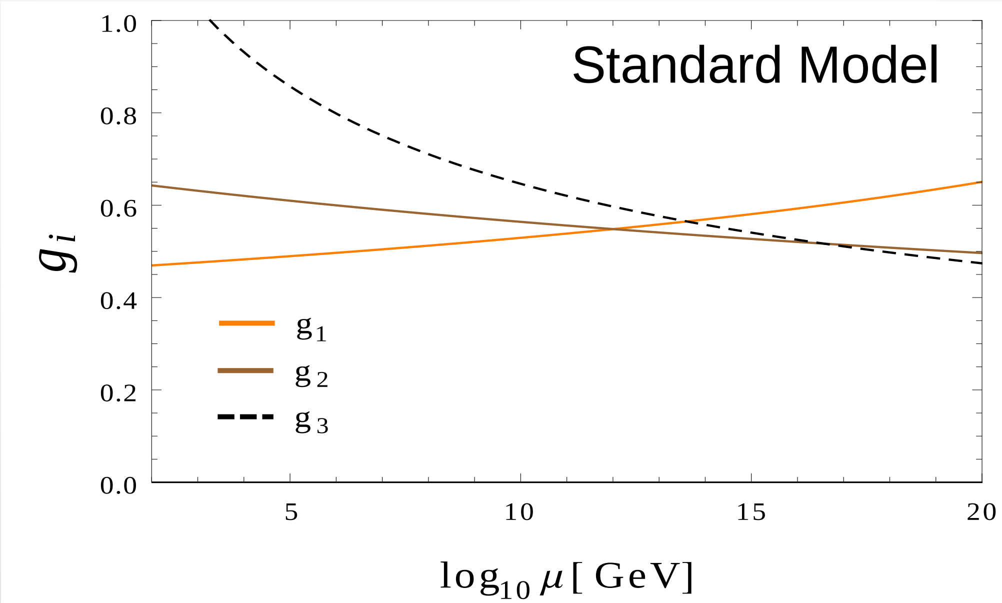
- The general Higgs potential for Type-III Inverse seesaw

$$\begin{aligned} \mathcal{L}_{\rm ISS} &= Tr[\overline{\Sigma_{1i}} D \Sigma_{1i}] + Tr[\overline{\Sigma_{2i}} D \Sigma_{2j}] - \frac{1}{2} Tr[\overline{\Sigma_{2i}} \mu_{\Sigma_{ij}} \Sigma_{2j}^c + \overline{\Sigma_{2i}^c} \mu_{\Sigma_{ij}}^* \Sigma_{2j}] \\ &- \left( \widetilde{\Phi}_1^\dagger \overline{\Sigma_{1i}} \sqrt{2} Y_{N_{ij}} L_j + Tr[\overline{\Sigma}_{1i} M_{N_{ij}} \Sigma_{2j}] + \text{H.c.} \right) \end{aligned}$$

# Running of gauge coupling $g_2$



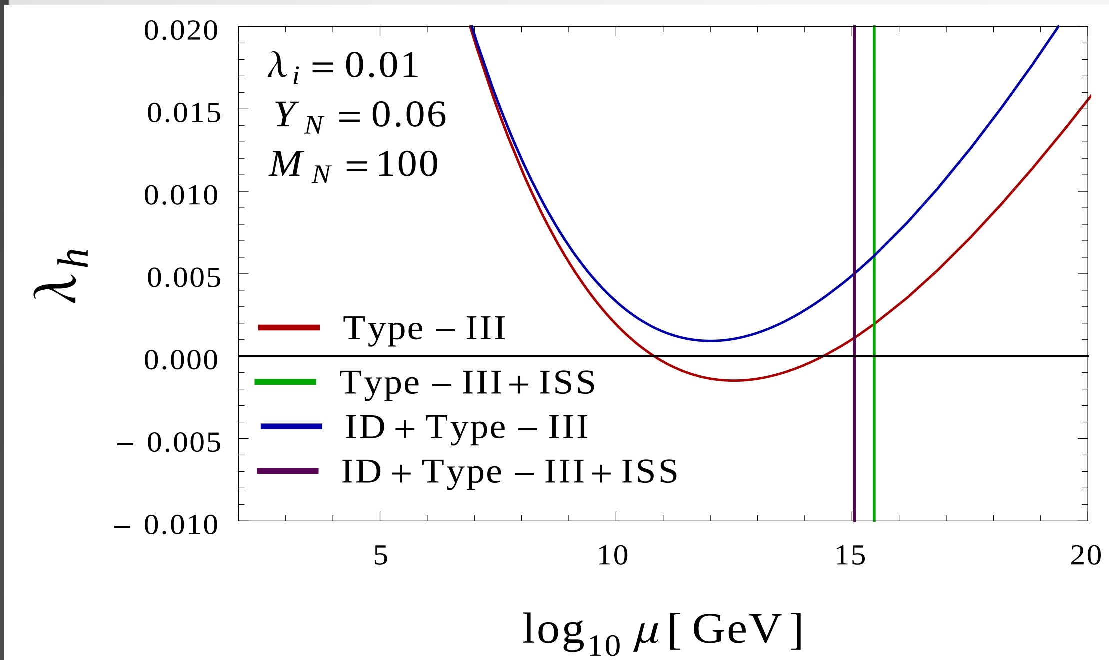



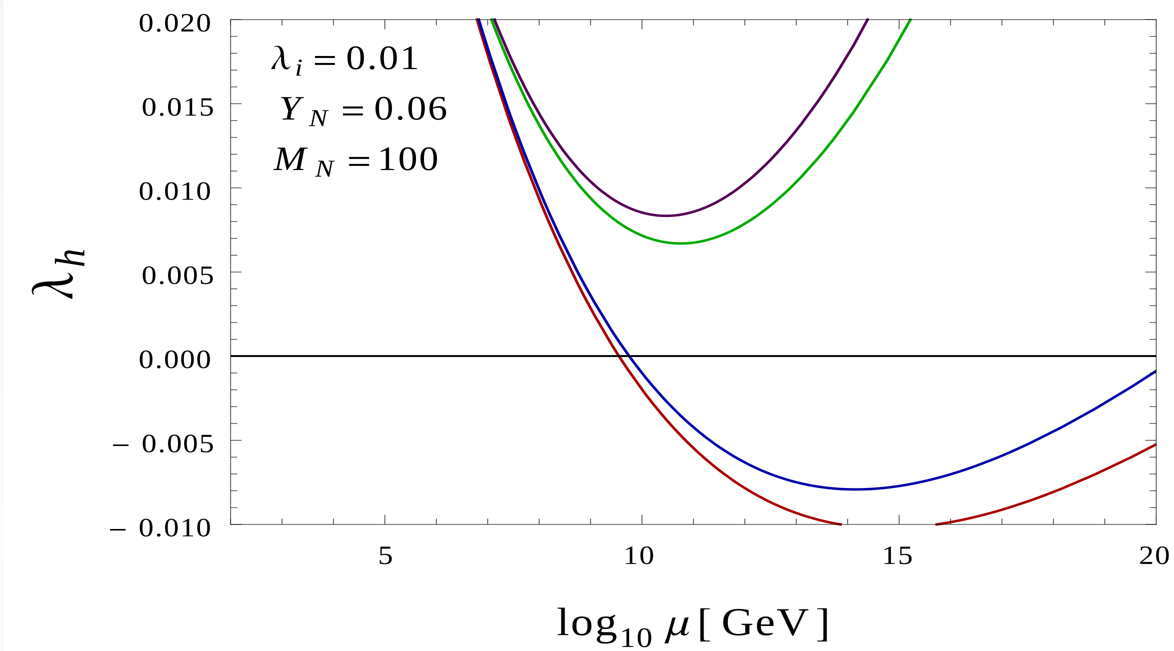

$g_2$ shows a contrasting behaviour to SM and asmyptotic freedom is lost

SJ, P Bandyopadhyay, Manimala Mitra, JHEP 02 (2021) 075

# Stability bound




(a) ID + Type-III +ISS (3 gen)

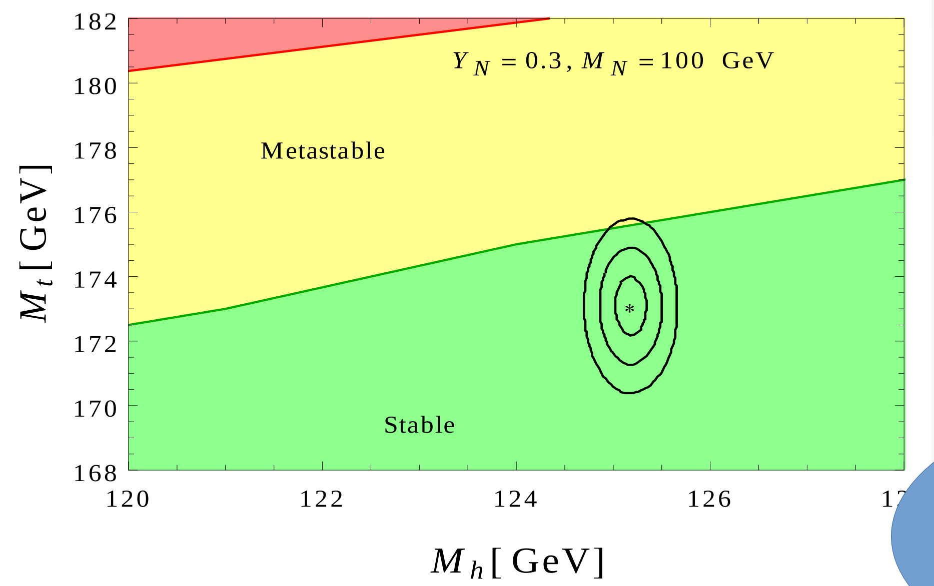



(b) ID+Type-III +ISS (2 gen)

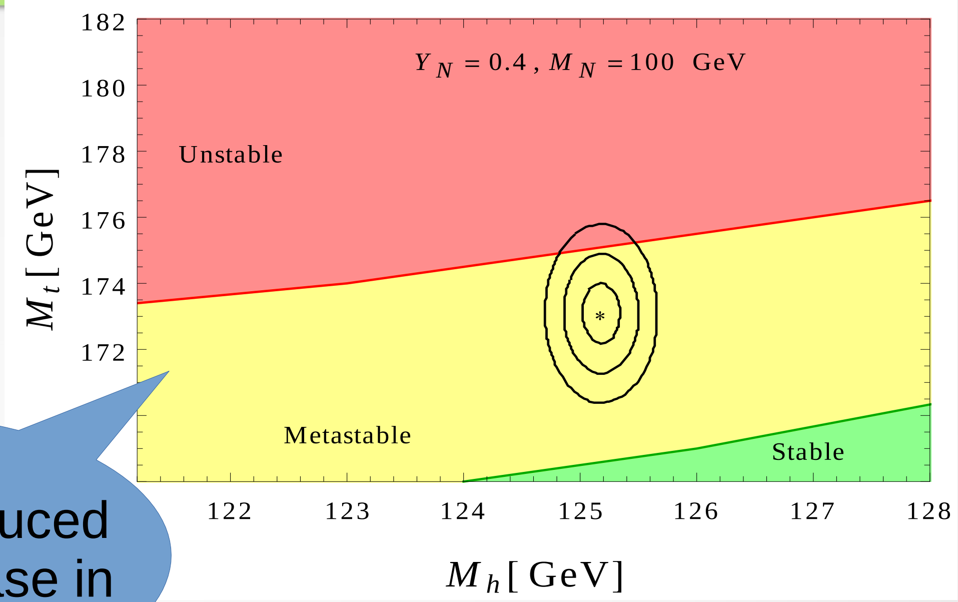
The number of generations of triplet fermions are restricted from Planck scale perturbativity.

SJ, P Bandyopadhyay, Manimala Mitra, JHEP 02 (2021) 075

# Stability analysis from effective potential approach

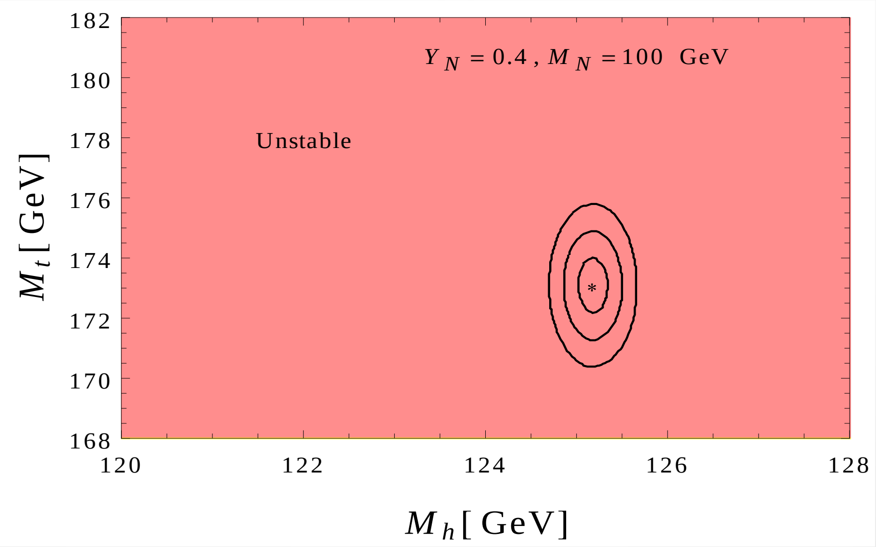



(a) ID+Type-III+ISS ($Y_N$=0.3)




(b) ID+Type-III+ISS ($Y_N$=0.4)

Stability is reduced with the increase in $Y_N$




(c) Type-III ($Y_N$=0.4)

I am completely unstable

# Electroweak phase transition at finite temperature

# EW phase transition

- The discovery of Higgs boson is the proof of the role of a scalar in electroweak symmetry breaking. However, the order of phase transition and the role of additional scalars or multiplets are yet to be discovered.
- This phenomena is known as symmetry restoration at high temperature, and gives rise to the phase transition from $\Phi(T)=0$ to $\Phi=\sigma$.

  The phase transition may be first or second order.

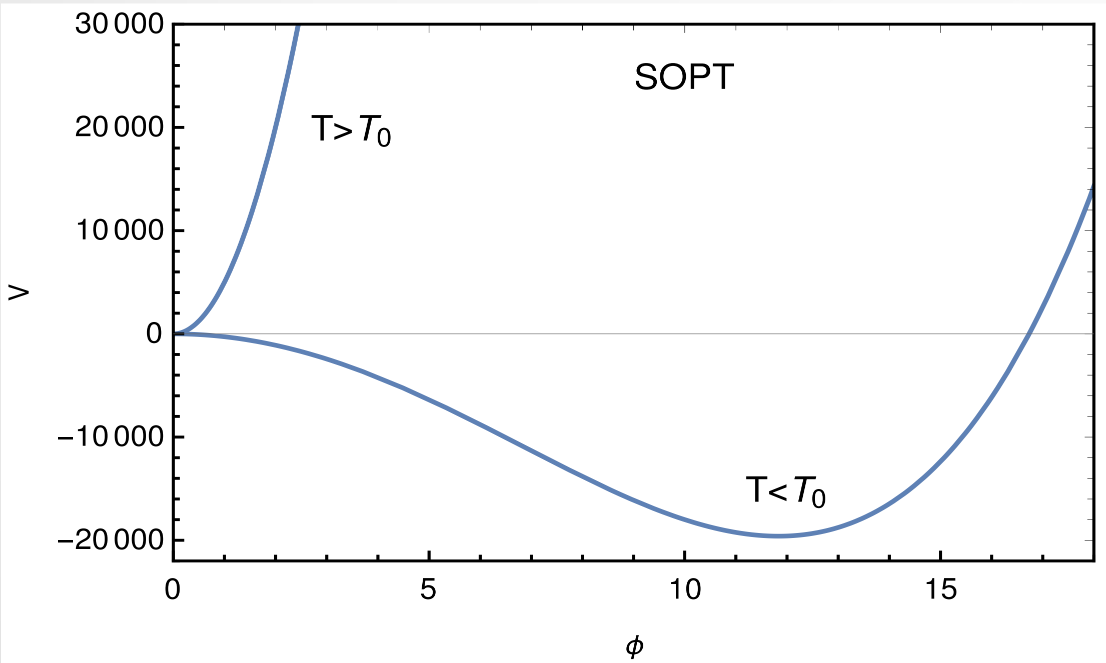
  First-order phase transitions (FOPT) have out of equilibrium symmetric states when the temperature decreases and are used for baryogenesis process.

# First and second order phase transitions

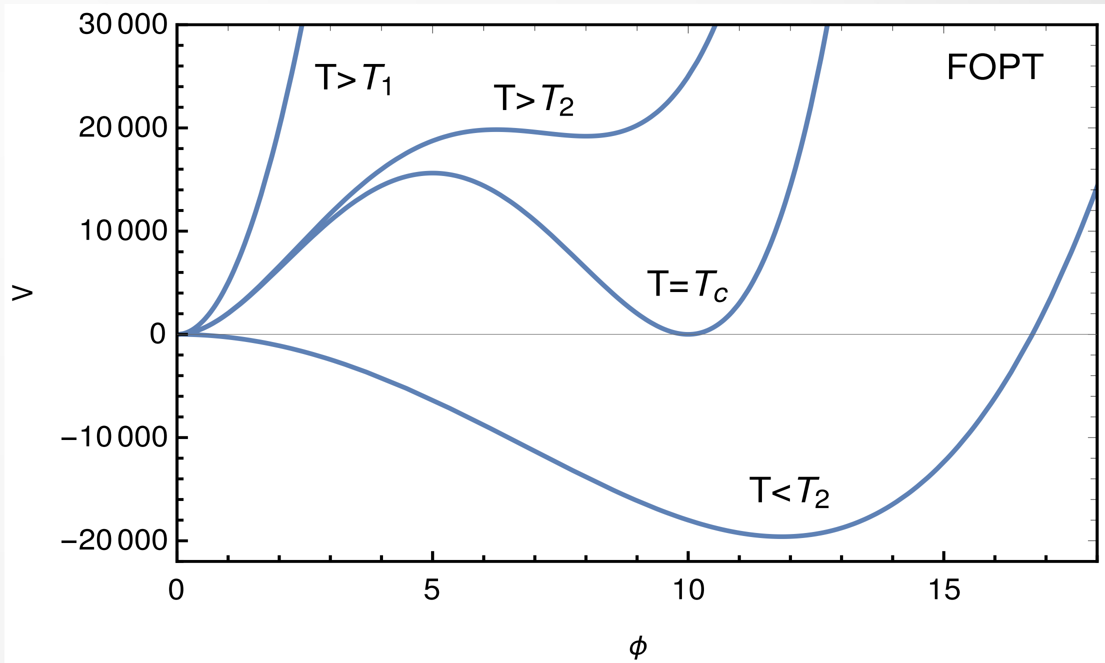
$$V(\Phi, T) = D(T^2 - T_0^2)\Phi^2 + \lambda(T)\Phi^4$$

$$V(\Phi, T) = D(T^2 - T_0^2)\Phi^2 + \lambda(T)\Phi^4 - ET(\Phi^3)$$

I am very crucial for first-order phase transition

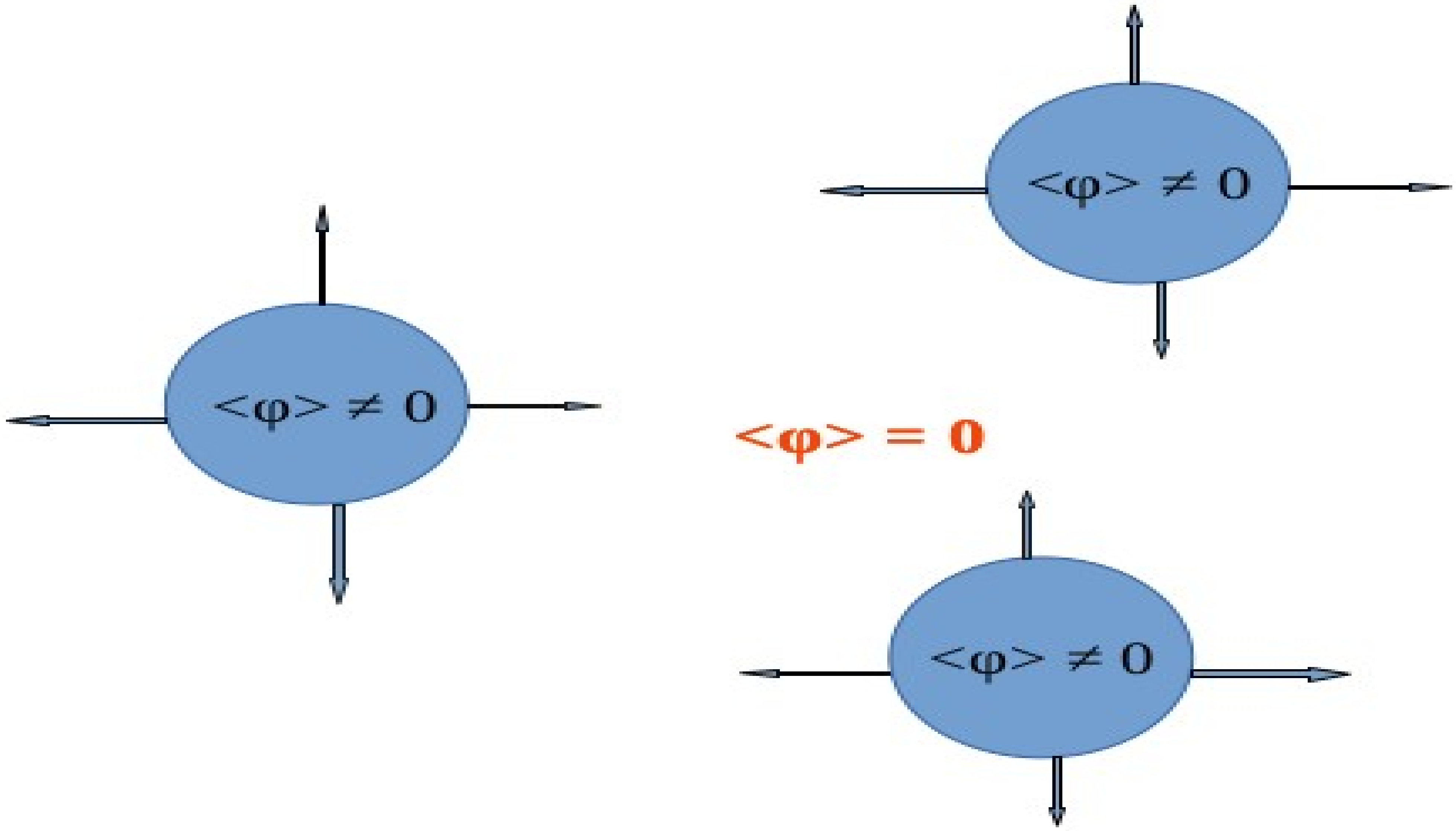



(a) SOPT




(b) FOPT

# Bubble nucleation



# Electroweak phase transition in Standard Model

- In Standard Model, this cubic term, E, gets contribution only by the electroweak gauge bosons.
- The paramter E is the cubic term of the effective potential of order of

$$E \sim \frac{2M_W^3 + M_Z^3}{4\pi v^3} \sim 0.01$$

- The Higgs self-coupling parameter has very small value

$$\lambda \sim 2E \sim 0.02 \to m_h = 49.2GeV.$$

- This is compatible with observed Higgs boson mass

$$M_h = \sqrt{2\lambda} v \sim 125.5GeV \to \lambda \sim 0.13$$

- In Standard Model the electroweak phase transition is a smooth crossover.

M.~Gogberashvili, Adv. High Energy Phys. (2018), 4653202

# Beyond Standard Model scenarios

In BSM scenarios, additional contribution from bosons to the cubic term in effective potential can trigger the first-order phase transition.

Why first order?

The first-order electroweak phase transition may solve some cosmological problems, like the generation of baryon asymmetry of the universe.

The 2017 Nobel Prize  was given for Gravitational waves detection by LIGO from black hole merging and similar GW signatures can be provided during First-order phase transition.

# Singlet extension

- The $Z_2$ symmetric tree-level potential for SM extended with singlet field is

$$\mathrm{H} \to \mathrm{H}, \qquad \mathrm{S} \to -\mathrm{S}.$$

$$\mathrm{V} = -\mu^2 \mathrm{H}^\dagger \mathrm{H} + \mathrm{m}_\mathrm{S}^2 \mathrm{S}^* \mathrm{S} + \lambda_1 |\mathrm{H}^\dagger \mathrm{H}|^2 + \lambda_\mathrm{s} |\mathrm{S}^* \mathrm{S}|^2 + \lambda_\mathrm{hs} (\mathrm{H}^\dagger \mathrm{H})(\mathrm{S}^* \mathrm{S}),$$

$$\mathrm{H} = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(\phi + h) + iG^0 \end{pmatrix}$$

- Being $Z_2$ odd, the Singlet field does not take part in EWSB and provides the DM candidate.

# Inert Higgs triplet

- The $Z_2$ symmetric tree-level potential for inert triplet model is

$$\mathrm{H} \to \mathrm{H}, \qquad \mathrm{T} \to -\mathrm{T}.$$

$$\mathrm{V} = -\mu^2 \mathrm{H}^\dagger \mathrm{H} + \mathrm{m}_\mathrm{T}^2 \mathrm{Tr}(\mathrm{T}^\dagger \mathrm{T}) + \lambda_1 |\mathrm{H}^\dagger \mathrm{H}|^2 + \lambda_\mathrm{t} (\mathrm{Tr}|\mathrm{T}^\dagger \mathrm{T}|)^2 + \lambda_\mathrm{ht} \mathrm{H}^\dagger \mathrm{H} \mathrm{Tr}(\mathrm{T}^\dagger \mathrm{T}),$$

$$\mathrm{H} = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(\phi + h) + iG^0 \end{pmatrix}, \; T = \frac{1}{2} \begin{pmatrix} T_0 & \sqrt{2} T^+ \\ \sqrt{2} T^- & -T_0 \end{pmatrix},$$

- Being $Z_2$ odd, the triplet field does not take part in EWSB and provides the DM candidate.

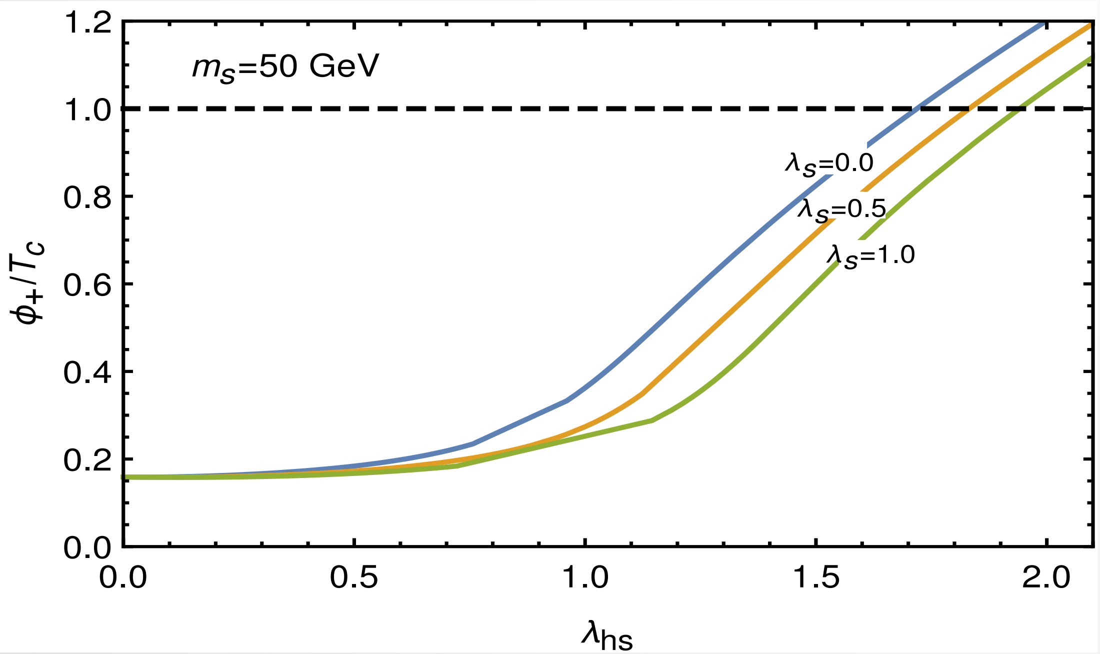
# Variation with quartic coupling

The condition for a strongly first-order phase transition has typically taken to be

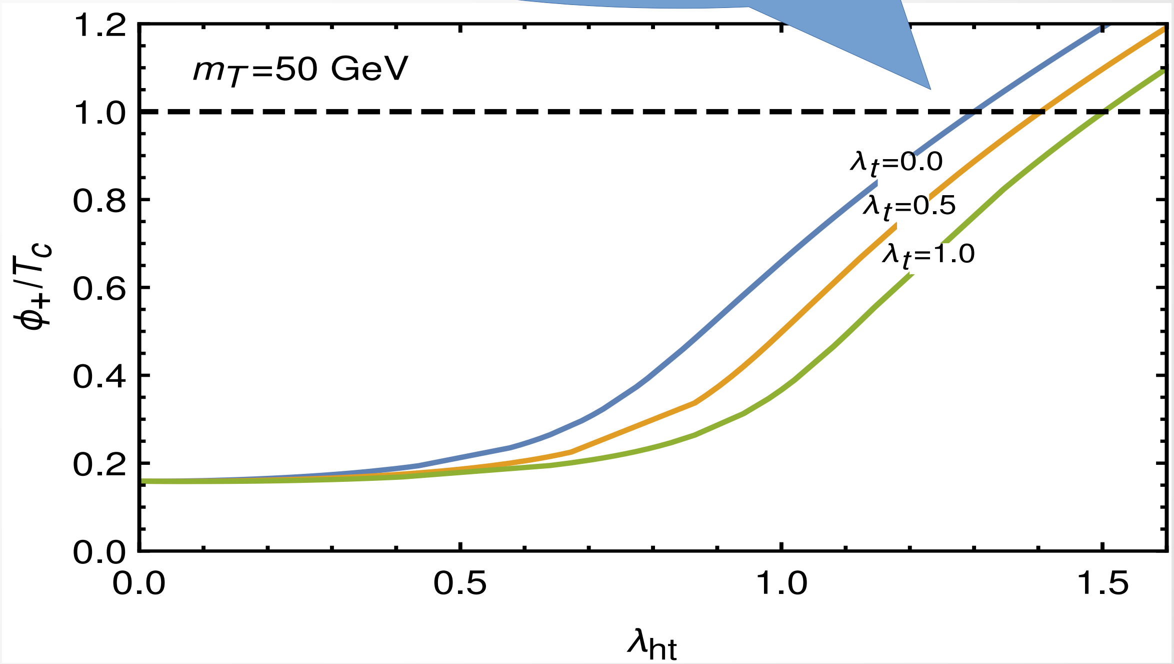
$$\frac{\Phi_+(T_C)}{T_C} \geq 1.$$

D.~E.~Morrissey, M.~J.~Ramsey-Musolf, New J. Phys. \textbf{14} (2012), 125003

The strength of phase transition is more for triplet because of more degrees of freedom




(a) Singlet

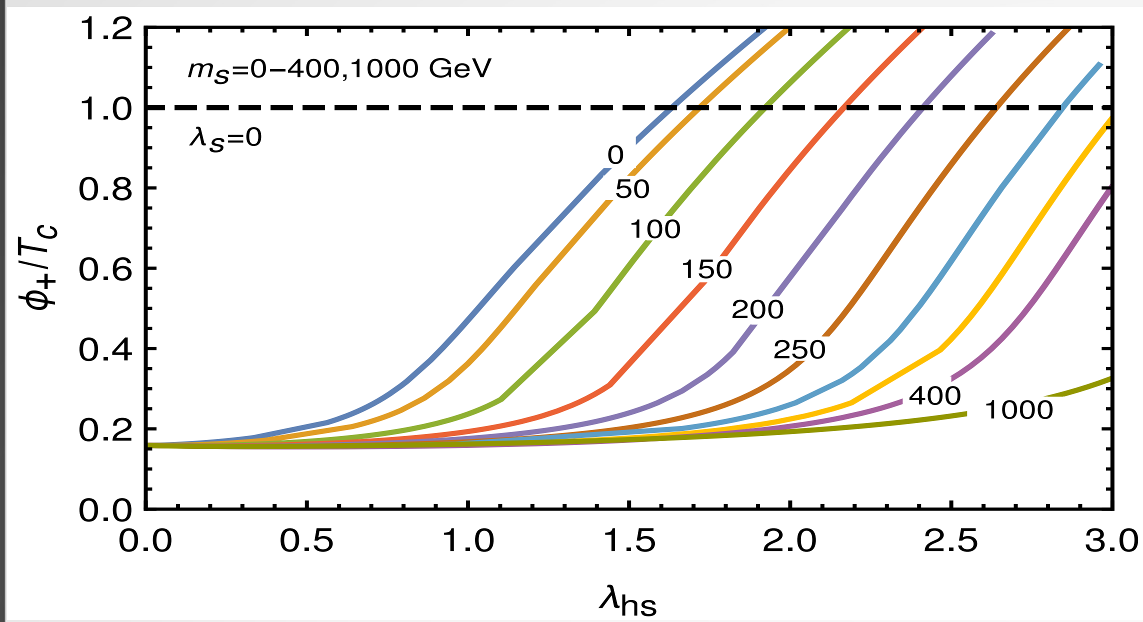



(b) Triplet

P. Bandyopadhyay, S. Jangid, arxiv:2111.03866 (Under review in PRD)

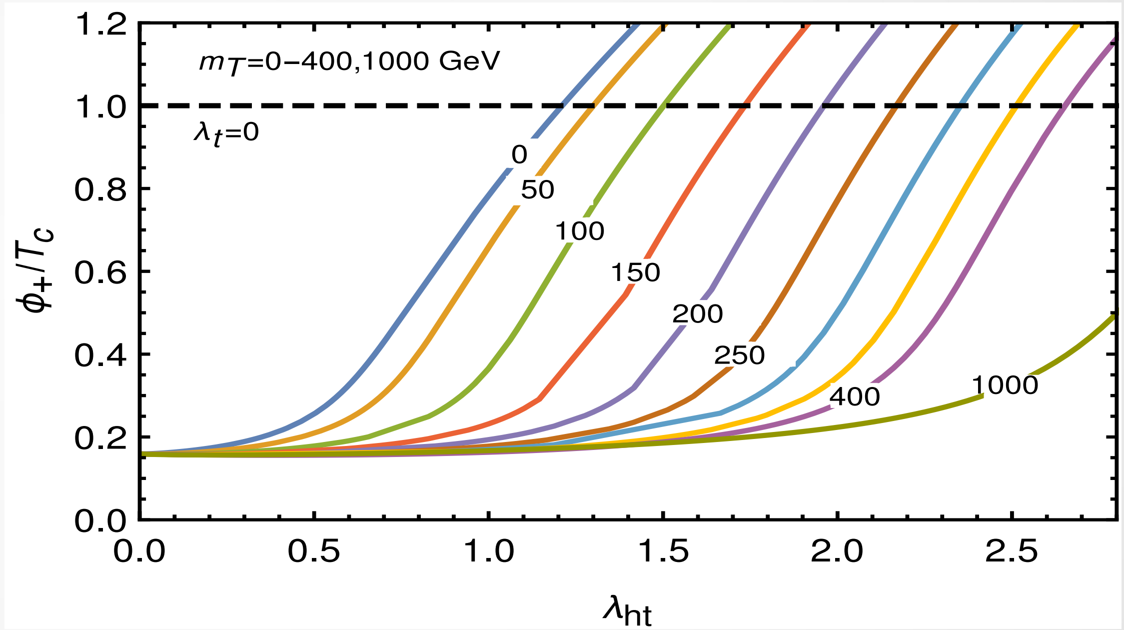
# Variation with soft mass parameter

The strength of phase transition is more for triplet because of more degrees of freedom




(a) Singlet

P. Bandyopadhyay, S. Jangid, arxiv:2111.03866
(Under review in PRD)

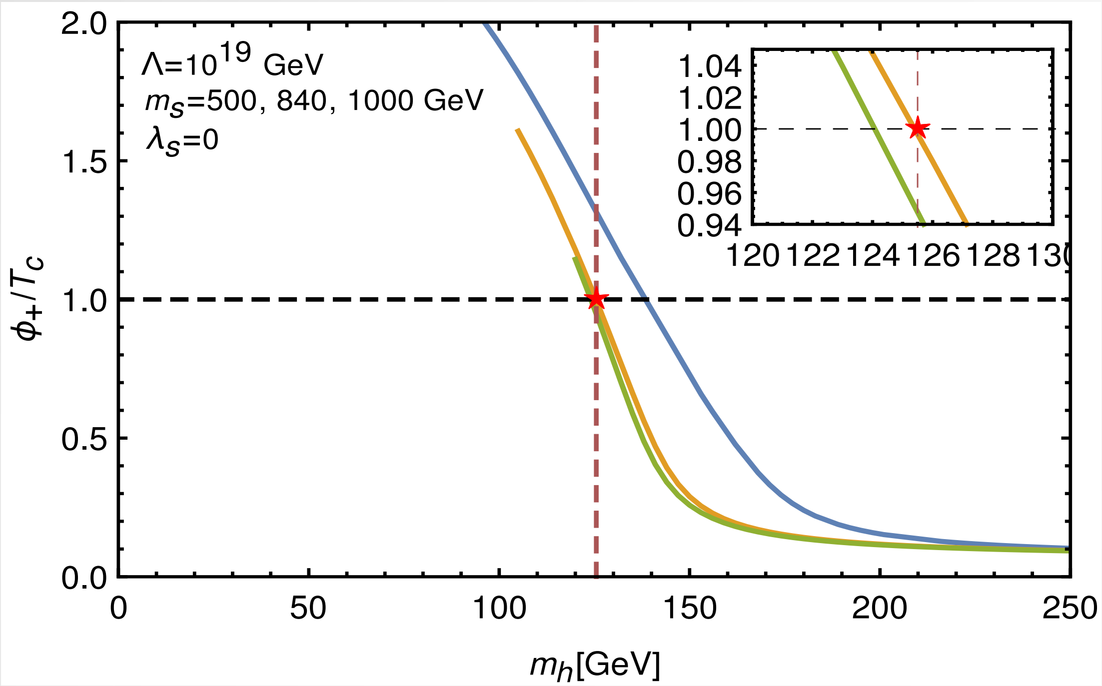



(b) Triplet

Soft mass paramter and self quartic coupling are considered to be zero to maximize

$$\frac{\Phi_+(T_C)}{T_C}.$$

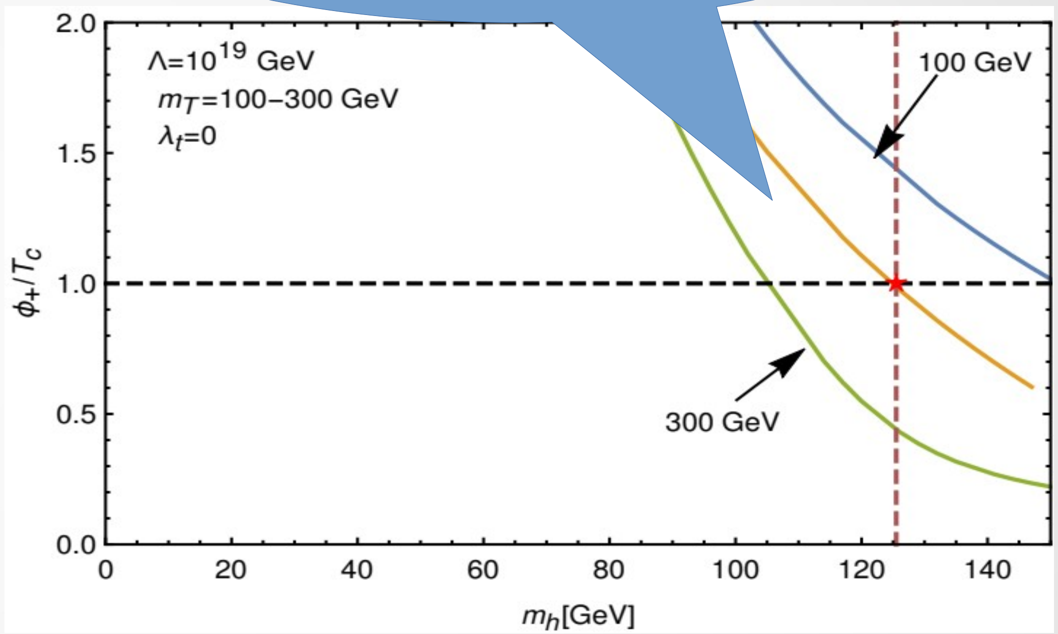
# Bounds on soft mass parameter




(a) Singlet

P. Bandyopadhyay, S. Jangid, arxiv:2111.03866
(Under review in PRD)

The mass bound is reduced to
193 Gev from 840 GeV for correct
Higgs mass bound and strongly first-order
phase transition



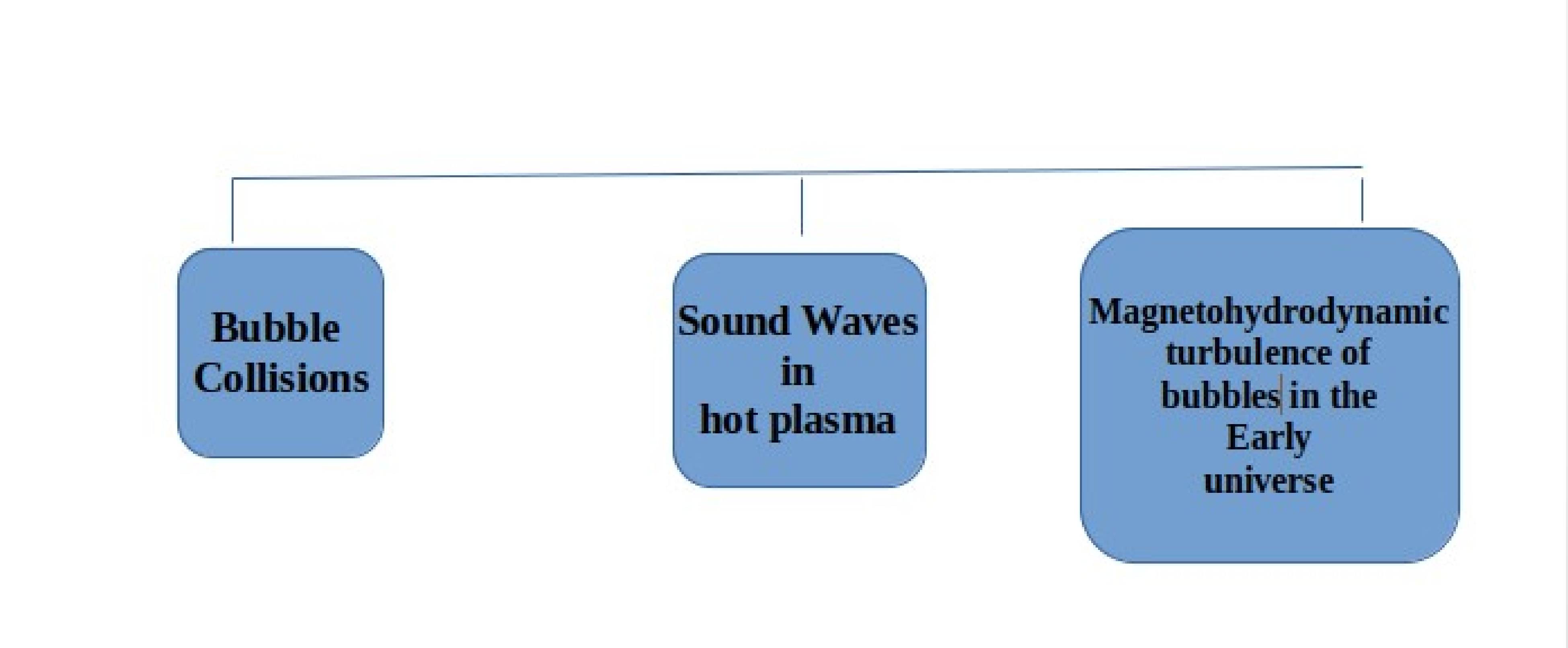

(b) Triplet

With the inclusion of two-loop finite temperature corrections, the mass bounds are relaxed a bit i.e. less than 5%.

# Gravitational Waves

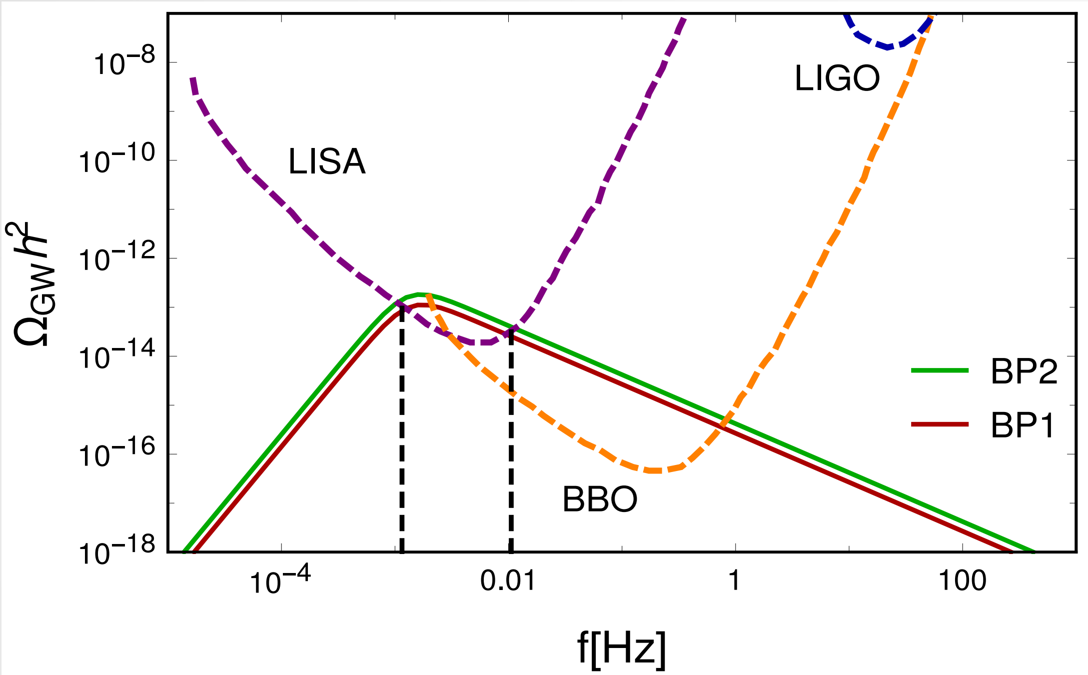
Gravitational Waves are a unique window to the early comos.

The GWs are produced from the strong first-order electroweak phase transition mainly by three mechanisms;

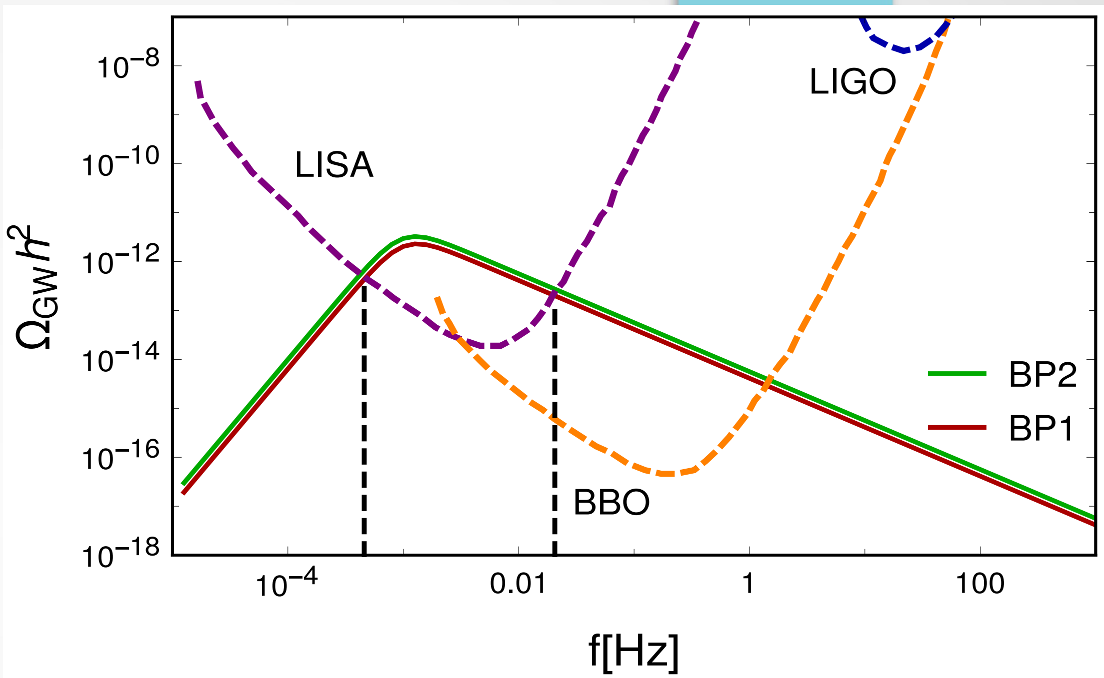



C.~Caprini, M.~Hindmarsh, S.~Huber, et al. JCAP (04) (2016), 001.

# Gravitational Wave intensity




(a) Singlet




(b) Triplet

The detectable frequencies for singlet lie between 1.15 x $10^{3}$-1.06 x $10^{-2}$ Hz, while for the triplet, the allowed ranges enhance to range 4.18 x $10^{-4}$-1.99 x $10^{-2}$ Hz, for the LISA experiment.

P. Bandyopadhyay, S. Jangid, arxiv:2111.03866
(Under review in PRD)

# Results

- Planck scale stability is achieved in both IDM and ITM unlike SM.
- IDM and ITM both are safe but in case of ITM we have LHC signatures of displaced vertex which are not so natural in IDM.
- The bound on DM mass from DM relic density is ≥ 700 GeV in IDM and ≥ 1176 GeV in ITM.
- In the case of IDM + Type-I, $Y_N$ =0.32 value is crucial from stability bound.
- The additional $Z_2$ ' symmetry in IDM and ITM also restricts their decay modes.
- The Planck scale stability/perturbativity demands only two generations of Type-III.
- No consistent solutions have been found at one-loop from Planck scale perturbativity consistent with first order phase transition, and current Higgs boson and top quark masses.
- For Planck scale perturbativity at two-loop, the maximum mass values for the singlet field and the triplet field as 909, 310 GeV respectively predicting first order phase transition, consistent with the current Higgs boson and top quark masses.
- The detectable frequency range by LISA is more for the triplet i.e. $\sim 4.18 \times 10^{-4} - 1.99 \times 10^{-2}$ Hz, in comparison to the singlet i.e. $\sim 1.15 \times 10^{-3} - 1.06 \times 10^{-2}$ Hz.

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Thank
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