Dark Matter Assisted Electroweak Phase Transition

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PLANCK 20th17

The Niels Bohr International Academy

Warsaw 05/25/2017

Outlines

- Why strong 1st electroweak phase transition?

- SM failed -> Our model
  (two Higgs doublets + one real singlet scalar DM)

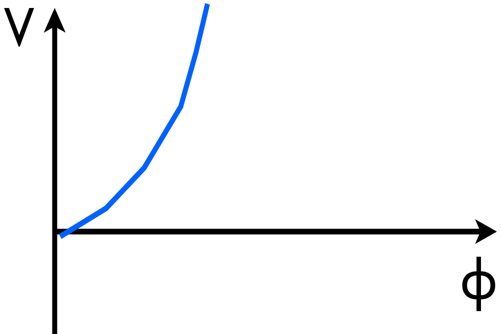
  - Tree level potential at T=0

    Dark matter phenomelogy

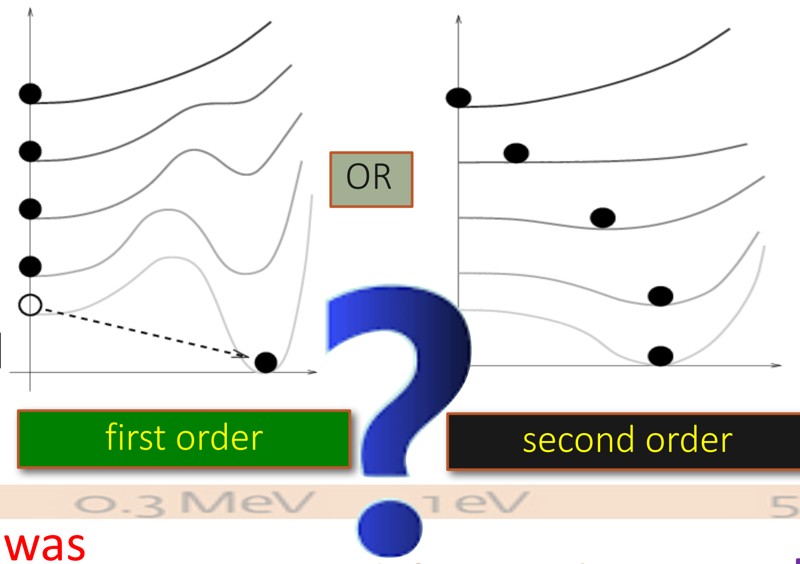
  - One-loop finite temperature effective potential

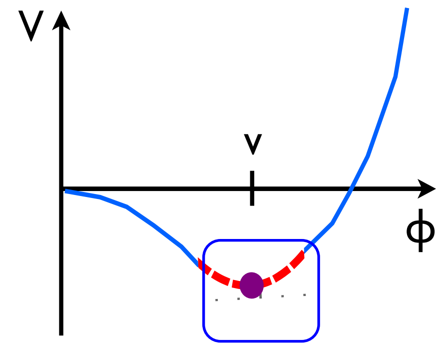
    EWPT

For “Higgs” itself, what we’ve learned is very little …



The Higgs is stabilized at the origin.





“vacuum expectation

We have known

small, quadratic oscillation

→ The early universe was SU(2) symmetric!

categorized if or not there is degenerate vacuum.

EWSB broken, the Higgs field acquires VEV.

✓ What is the dynamics of this transition? First-order (”boiling”) or second-order (”quasi- adiabatic”) transition? Cross-over?

This is a crucial question to be clarified as it is related to explain the baryon anti-baryon asymmetry originating from the early Universe.

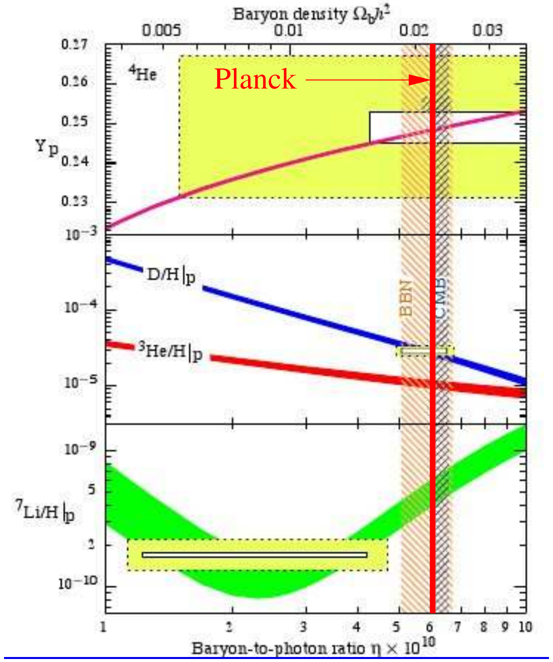
Conditions for Baryogenesis

$$\text{Observed BAU:} \quad \frac{n_B}{s} \sim 10^{-10}.$$

- **Baryogenesis**: dynamically generating baryon-antibaryon number asymmetry when three necessary conditions are satisfied

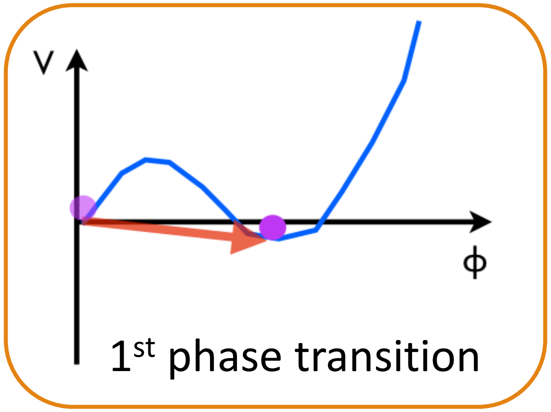
Sakharov's conditions

1) baryon number violation
   - ✓ Chiral anomaly and non-trivial SU(2) topology (sphaleron)
2) C and CP violation
   - ✓ Quark CKM matrix (but insufficient)
3) departure from thermal equilibrium
   fulfilled by a **1st order phase transition** involved with EWSB



Scenarios for baryogenesis: classical GUT baryogenesis, leptogenesis, electroweak baryogenesis, Affleck-Dine baryogenesis (scalar field dynamics).

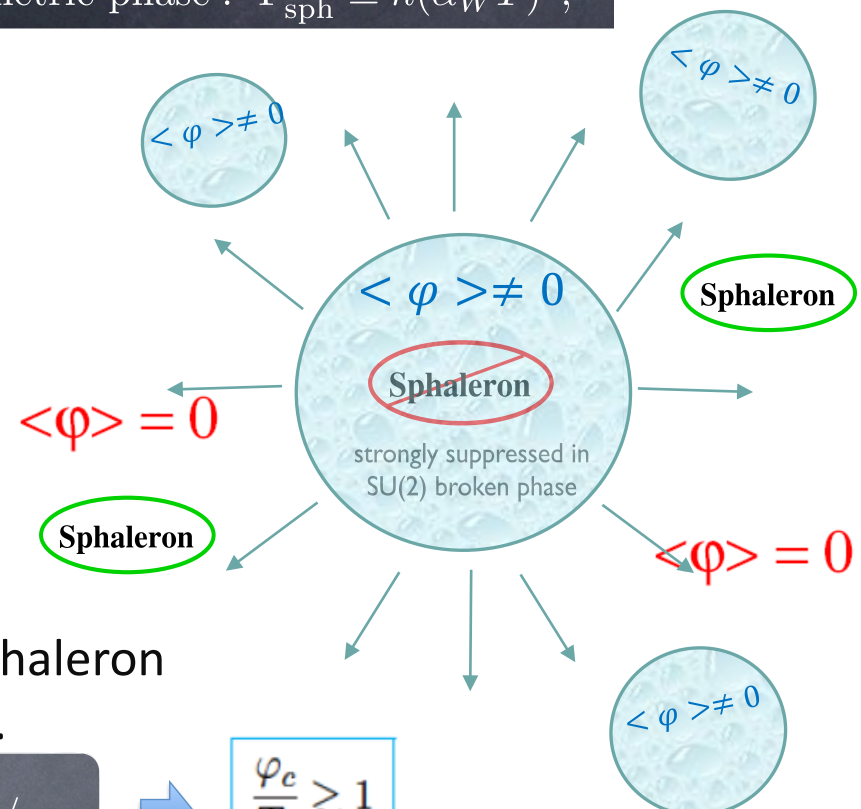
EWBG



sphaleron rates (/time/volume):

$$\text{broken phase}: \quad \Gamma^{(b)}_{\rm sph} \simeq T^4 e^{-E_{\rm sph}/T},$$

$$\text{symmetric phase}: \quad \Gamma^{(s)}_{\rm sph} \simeq \kappa(\alpha_W T)^4,$$



Sphaleron energy $E_{\rm sph} \propto < \varphi >$

Sphalerons produce net baryon number in the regions of unbroken phase

$$\Gamma^{(b)}_B(T) \simeq (\text{prefactor}) \frac{\Gamma^{(b)}_{\rm sph}}{T^3}$$

To avoid the B#asym be wahsed out, the sphaleron process must be decoupled after the EWPT.

$$\Gamma^{(b)}_B(T) \simeq (\text{prefactor}) e^{-E_{\rm sph}/T} < H(T) \simeq 1.66\sqrt{g_*}T^2/m_{\rm P}$$

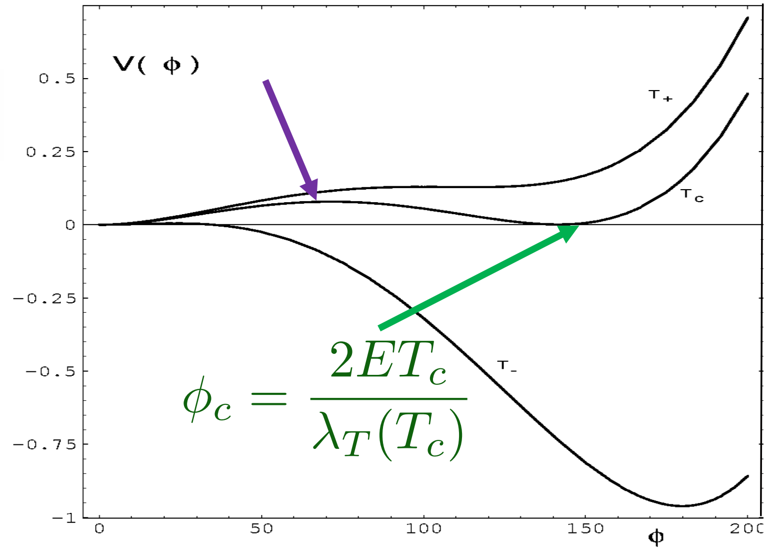
$$\Rightarrow \quad \frac{\varphi_c}{T_c} \gtrsim 1$$

EWPT in the SM

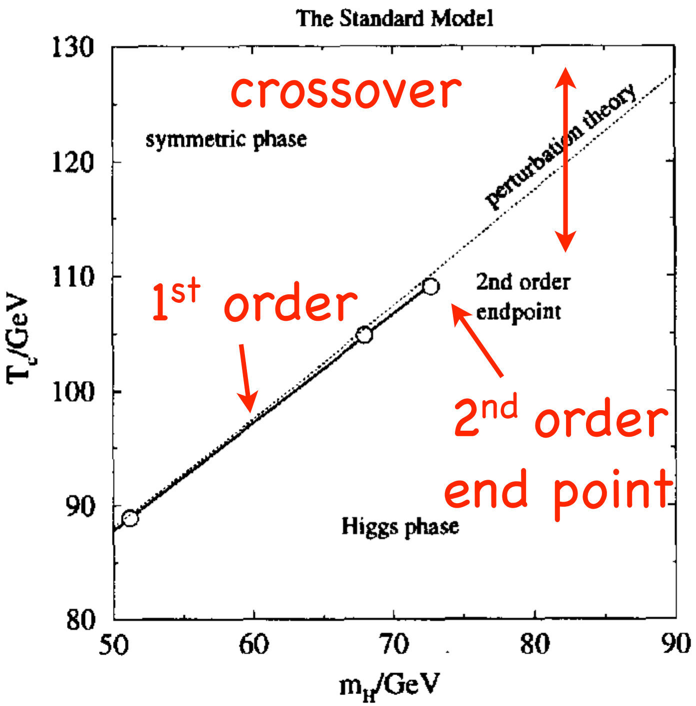
Finite Temperature Potential

$$V_T(\phi, T) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda_T}{4}\phi^4$$

$$E = \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3)$$



$$\phi_c = \frac{2ET_c}{\lambda_T(T_c)}$$



$$\frac{\phi_c}{T_c} \simeq \frac{1}{3\pi m_h^2}(6m_W^3 + 3m_Z^2 + \text{New Physics}$$

< 1 for m_h=125 GeV

In order to accomplish the strong 1st EWPT, the Higgs sector needs to be extended.

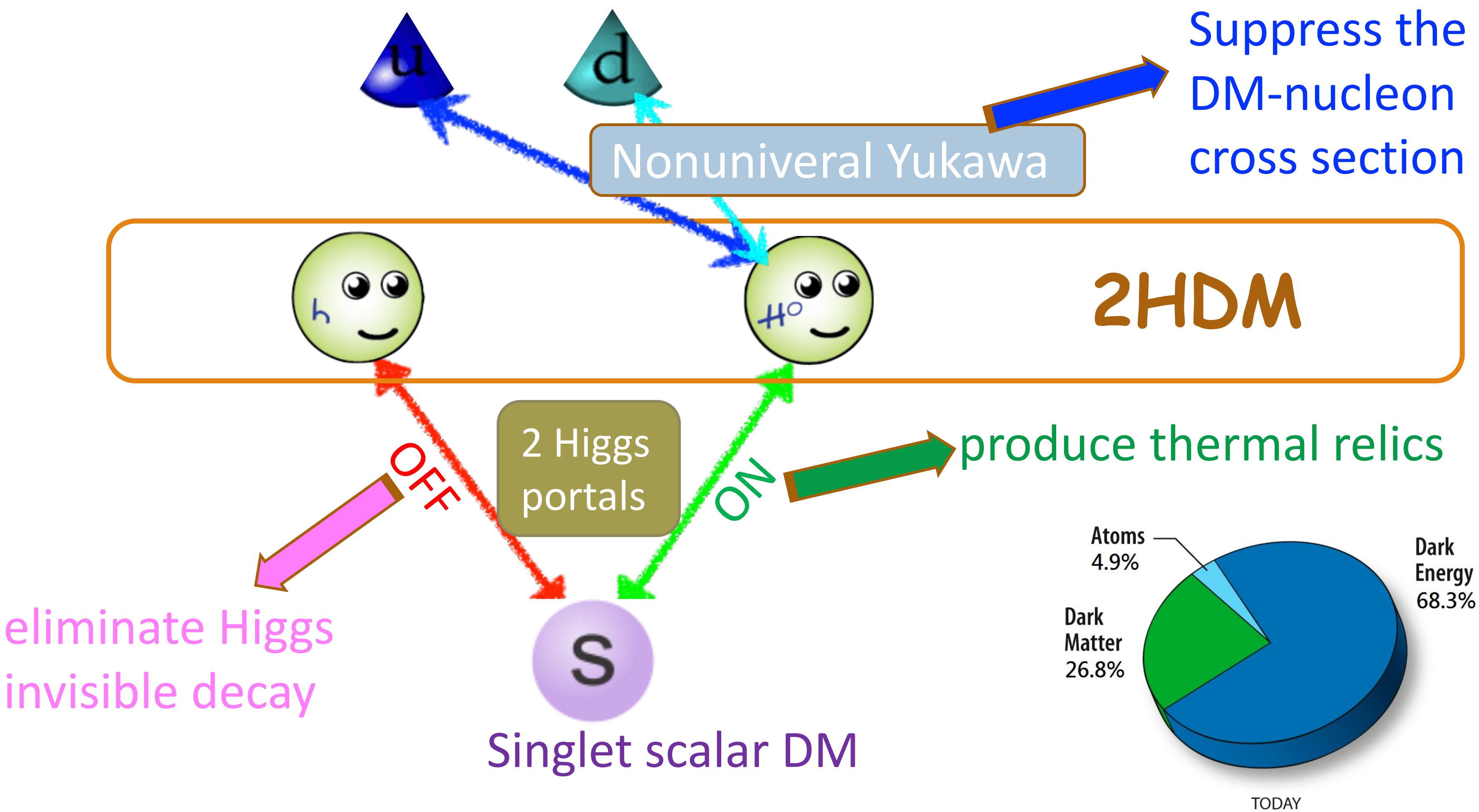
BSM considerations

Higgs (scalar) sector extended models can achieve the EWPT easily.

Model	References
SM + Scalar Singlet	Espinosa & Quiros, 1993; Benson, 1993; Choi & Volkas, 1993; McDonald, 1994; Vergara, 1996; Branco, Delepine, Emmanuel-Costa, & Gonzalez, 1998; Ham, Jeong, & Oh, 2004; Ahriche, 2007; Espinosa & Quiros, 2007; Profumo, Ramsey-Musolf, & Shaughnessy, 2007; Noble & Perelstein, 2007; Espinosa, Konstandin, No, & Quiros, 2008; Ashoorioon & Konstandin, 2009; Das, Fox, Kumar, & Weiner, 2009; Espinosa, Konstandin, & Riva, 2011; Chung & AL, 2011; Wainwright, Profumo, & Ramsey-Musolf, 2012; Barger, Chung, AL, & Wang, 2012; Huang, Shu, Zhang, 2012; Jiang, Bian, Huang, Shu, 2015; Huang & Li 2015
SM + Scalar Doublet	Davies, Froggatt, Jenkins, & Moorhouse, 1994; Huber, 2006; Fromme, Huber, & Seniuch, 2006; Cline, Kainulainen, & Trott, 2011; Kozhushko & Skalozub, 2011;
SM + Scalar Triplet	Patel, Ramsey-Musolf, 2012; Patel, Ramsey-Musolf, Wise, 2013; Huang, Gu, Yin, Yu, Zhang 2016
SM + Chiral Fermions	Carena, Megevand, Quiros, Wagner, 2005
MSSM	Carena, Quiros, & Wagner, 1996; Delepine, Gerard, Gonzales Felipe, & Weyers, 1996; Cline & Kainulainen, 1996; Laine & Rummukainen, 1998; Cohen, Morrissey, & Pierce,; Carena, Nardini, Quiros, & Wagner, 2012;
NMSSM / nMSSM / μνSSM	Pietroni, 1993; Davies, Froggatt, & Moorhouse, 1995; Huber & Schmidt, 2001; Ham, Oh, Kim, Yoo, & Son, 2004; Menon, Morrissey, & Wagner, 2004; Funakubo, Tao, & Toyoda, 2005; Huber, Kontandin, Prokopec, & Schmidt, 2006; Chung, AL, 2010, Huang, Kang, Shu, Wu, Yang, 2014
EFT-like Approach (H^6 operator)	Grojean, Servant, Wells, 2005; Huang, Gu, Yin, Yu, Zhang 2015; Huang, Joglekar, Li, Wagner, 2015; Huang, Wan, Wang, Cai, Zhang 2016; Huang, Gu, Yin, Yu, Zhang 2016

Working Model (including DM)

- To satisfy the existing constraints, the minimal model is NOT sufficient.



2HDMS model

(see more details for 2HDMS model in Jiang et.al., JHEP (2014) arXiv:1408.2106)

- Add a real scalar singlet S, together with two doublet Higgs fields

The full potential (defined in the general basis) in the scalar sector is

$$V(\Phi_1,\Phi_2,S) = m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - \left[m_{12}^2\Phi_1^\dagger\Phi_2 + h.c.\right]$$
$$+\frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4|\Phi_1^\dagger\Phi_2|^2$$
$$+\left[\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + h.c.\right]$$

Singlet sector
$$+\frac{1}{2}m_0^2S^2 + \frac{1}{4!}\lambda_S S^4 + \kappa_1 S^2(\Phi_1^\dagger\Phi_1) + \kappa_2 S^2(\Phi_2^\dagger\Phi_2) + S^2(\kappa_3\Phi_1^\dagger\Phi_2 + h.c.)$$

Higgs portal

Symmetry: $\mathbb{Z}_2 \times \mathbb{Z}_2'$

- $\mathbb{Z}_2 : \Phi_1 \to \Phi_1, \Phi_2 \to -\Phi_2$
- $\mathbb{Z}_2' : \Phi_1 \to \Phi_1, \Phi_2 \to \Phi_2, S \to -S$

S could be a dark matter candidate provide it does not acquire a VEV.

2HDMS model (after EWSB)

Electroweak symmetry breaking

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ (v\cos\beta + \rho_1 + i\eta_1)/\sqrt{2} \end{pmatrix}$$

$$\Phi_2 = \begin{pmatrix} \phi_2^+ \\ (e^{i\xi} v\sin\beta + \rho_2 + i\eta_2)/\sqrt{2} \end{pmatrix}$$

2 CP-even neutral scalars: $h = -\rho_1 \sin\alpha + \rho_2 \cos\alpha$
$H = \rho_1 \cos\alpha + \rho_2 \sin\alpha$

1 CP-odd neutral pseudoscalar: $A = -\eta_1 \sin\beta + \eta_2 \cos\beta$

2 charged scalars: $H^\pm$

the S-dependent part (after the EWSB)

2 portal couplings

$$V_S = \frac{1}{2} m_S^2 S^2 + \frac{1}{4!}\lambda_S S^4 + \lambda_h v h S^2 + \lambda_H v H S^2 + S^2(\lambda_{HH} HH + \lambda_{hH} hH + \lambda_{hh} hh + \lambda_{AA} AA + \lambda_{H^+H^-} H^+ H^-)$$

Remarks

- NO AS^2 interaction, so A cannot be a portal in this model.
- The set of independent inputs:
  $\{m_S, \lambda_h, \lambda_H, \lambda_S\}$ + $\{m_h, m_H, m_A, m_{H^\pm}, \sin(\beta-\alpha), \tan\beta, m_{12}^2\}$

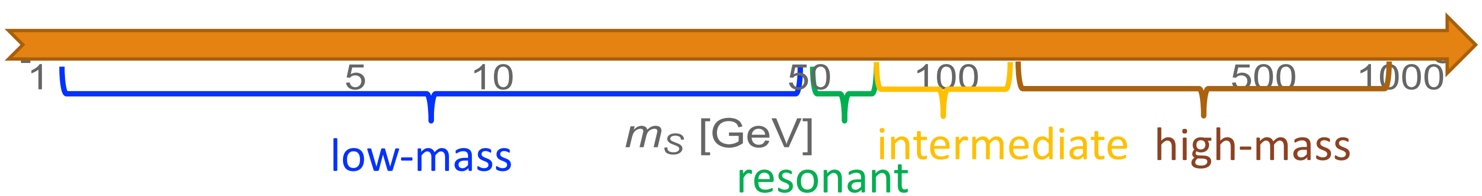
Phenomenology

what we consider ...

- preLHC: Stability, Unitarity, Perturbativity, STU, B-physics, $(g-2)_\mu$, LEP (applied for some scenarios)
- H/A limits:
  - $H \to ZZ^{(*)} \to 4\ell$
  - $gg \to H \to \tau\tau$ and $gg \to bbH$ with $H \to \tau\tau$
- postLHC: additionally, $\gamma\gamma$, ZZ, WW, bb, $\tau\tau$ signals for 125 GeV Higgs

- Fully suppressed the invisible decay for the SM-like Higgs.
- Produce proper relic abundance
- Direct detection
- Indirection detection

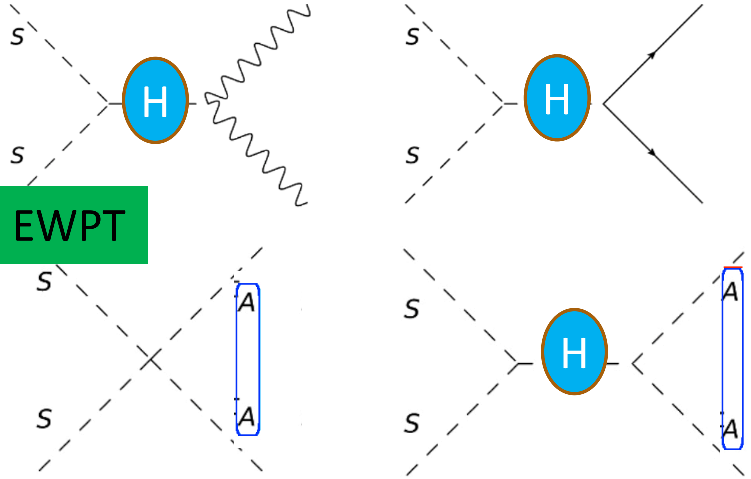
We mainly focus on the constraints on the strength of portal couplings in different DM mass range.



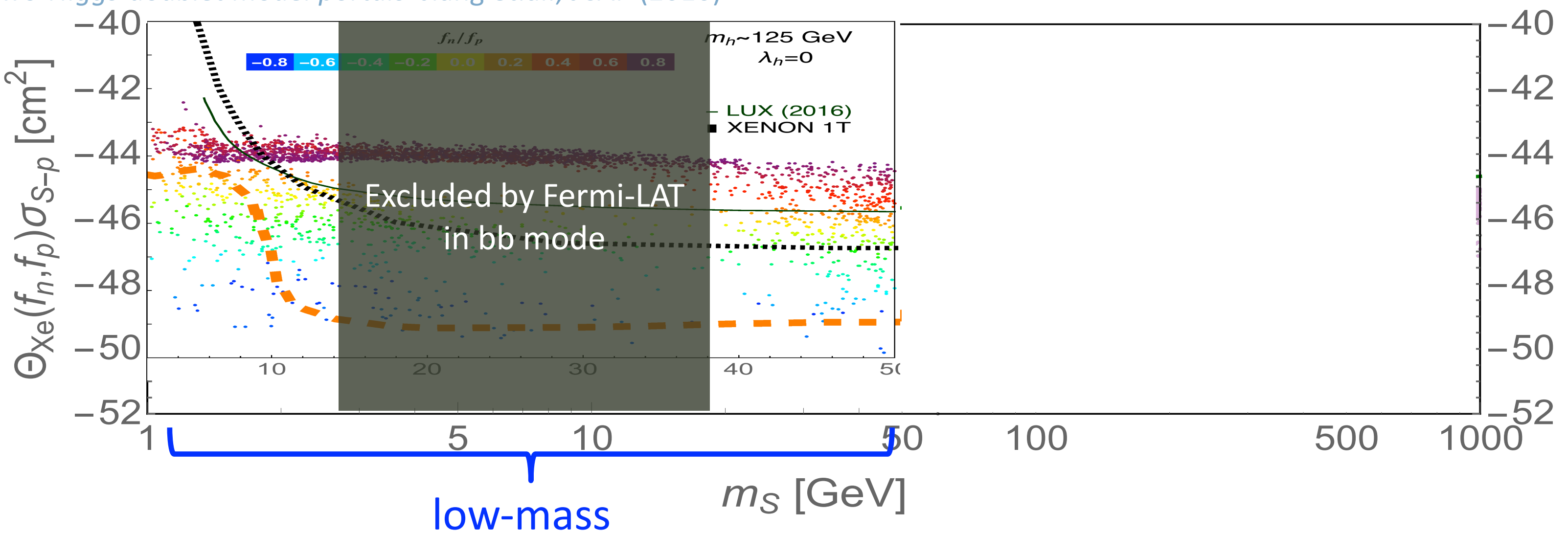
DM phenomenology

Low-mass region

- Suppress the *h*-*SS* coupling
- m_H range is definite → crucial in EWPT
- *S* is heavier than *A*
- Isospin-violating -> $\tan\beta$=1



IVDM via two-Higgs-doublet model portals Jiang et.al., JCAP (2016)

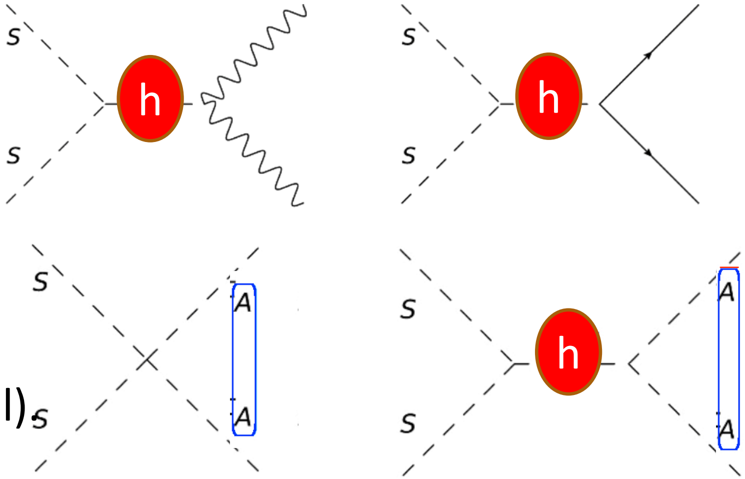


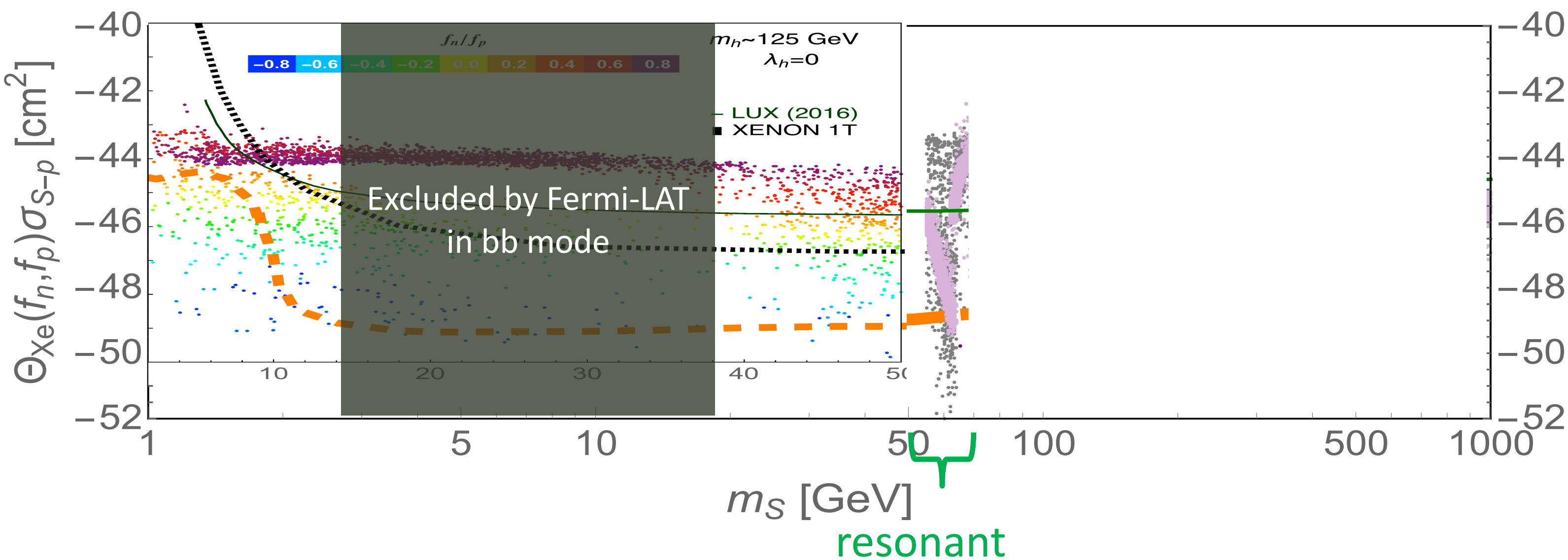
DM phenomenology

Resonance region

- No constraint on the h-SS coupling
- It is also small in order to compensate the pole effect.

$$\langle \sigma v_{rel} \rangle \sim \frac{\lambda_{\mathcal{H}SS}\, v}{4m_S^2 - m_{\mathcal{H}}^2 + i m_{\mathcal{H}} \Gamma_{\mathcal{H}}}$$ (s-channel)





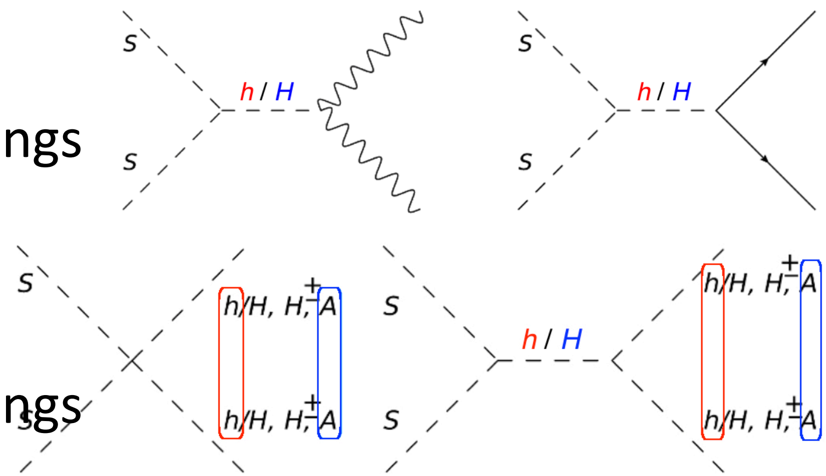
DM phenomenology

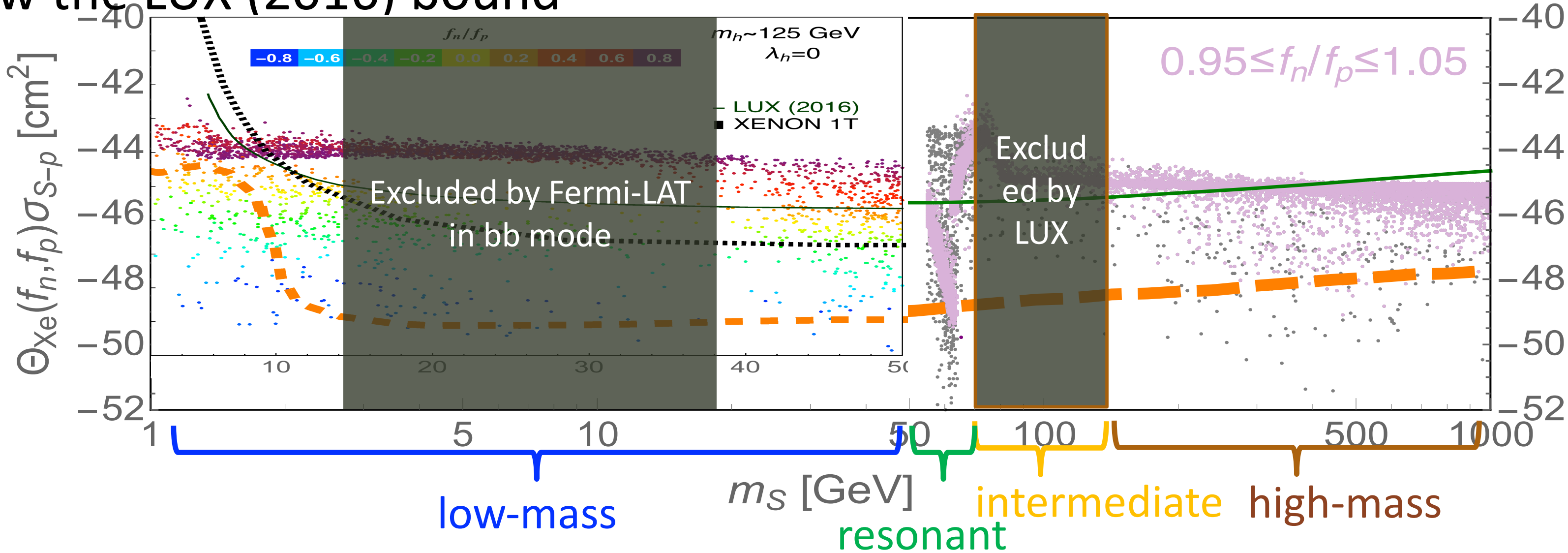
Intermediate-mass region

- No constraint on the portal couplings
- Excluded by LUX (2016)

High-mass region

- No constraint on the portal couplings
- Below the LUX (2016) bound





Finite temperature potential

$$V_{\rm eff}(\phi_i, T) = \underbrace{V_0(\phi_i) + V_{\rm CW}(\phi_i) + V_{\rm CT}(\phi_i)}_{} + V_{\rm th}(\phi_i, T)\ , \quad \phi_i = h_1, h_2, S$$

T=0 part

$$V_{\rm CW}(\phi_i) = \sum_i n_i \frac{m_i^4(\phi_i)}{64\pi^2}\left[\ln\left(\frac{m_i^2(\phi_i)}{Q^2}\right) - C_i\right]$$

Field-dependent mass

$$m^2_{h,H,S} = \text{eignevalues}(\mathcal{M}^2_{\rm P})$$
$$m^2_{G,A} = \text{eignevalues}(\mathcal{M}^2_{\rm A})$$
$$m^2_{G^\pm,H^\pm} = \text{eignevalues}(\mathcal{M}^2_{\pm})$$

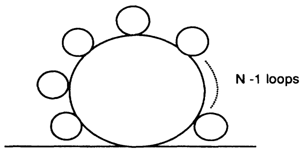
3x3 mass matrices in terms of
i. model parameters
ii. fields' classical values

$$V_{\rm th}(\phi_i, T) = \frac{T^4}{2\pi^2}\sum_i n_i J_{B,F}\left(\frac{M_i^2(v, v_S, T)}{T^2}\right)$$

$$M_i^2(v, v_S, T) = \text{eigenvalues}\left[\mathcal{M}_i^2(v, v_S) + \Pi_i\right]$$

Thermal mass correction

$$\Pi_P = \begin{pmatrix} \Pi^P_{11} & \Pi^P_{12} & \Pi^P_{1S} \\ \Pi^P_{12} & \Pi^P_{22} & \Pi^P_{2S} \\ \Pi^P_{1S} & \Pi^P_{2S} & \Pi^P_{SS} \end{pmatrix}\frac{T^2}{12}$$



$$\Pi_A = \begin{pmatrix} \Pi^A_{11} & \Pi^A_{12} \\ \Pi^A_{12} & \Pi^A_{22} \end{pmatrix}\frac{T^2}{12}$$

$$\Pi_{H^\pm} = \begin{pmatrix} \Pi^\pm_{11} & \Pi^\pm_{12} \\ \Pi^\pm_{12} & \Pi^\pm_{22} \end{pmatrix}\frac{T^2}{12}.$$

$$\Pi^P_{11} = \Pi^A_{11} = c_{\rm SM} + 6Z_1 + 2Z_3 + Z_4 + \frac{1}{2}\lambda_h\,,$$
$$\Pi^P_{22} = \Pi^A_{22} = c_{\rm SM} + 6Z_2 + 2Z_3 + Z_4 + \frac{1}{2}\lambda_H\,,$$
$$\Pi^P_{SS} = \frac{1}{2}\lambda_S + 2(\lambda_h + \lambda_H)\,,$$

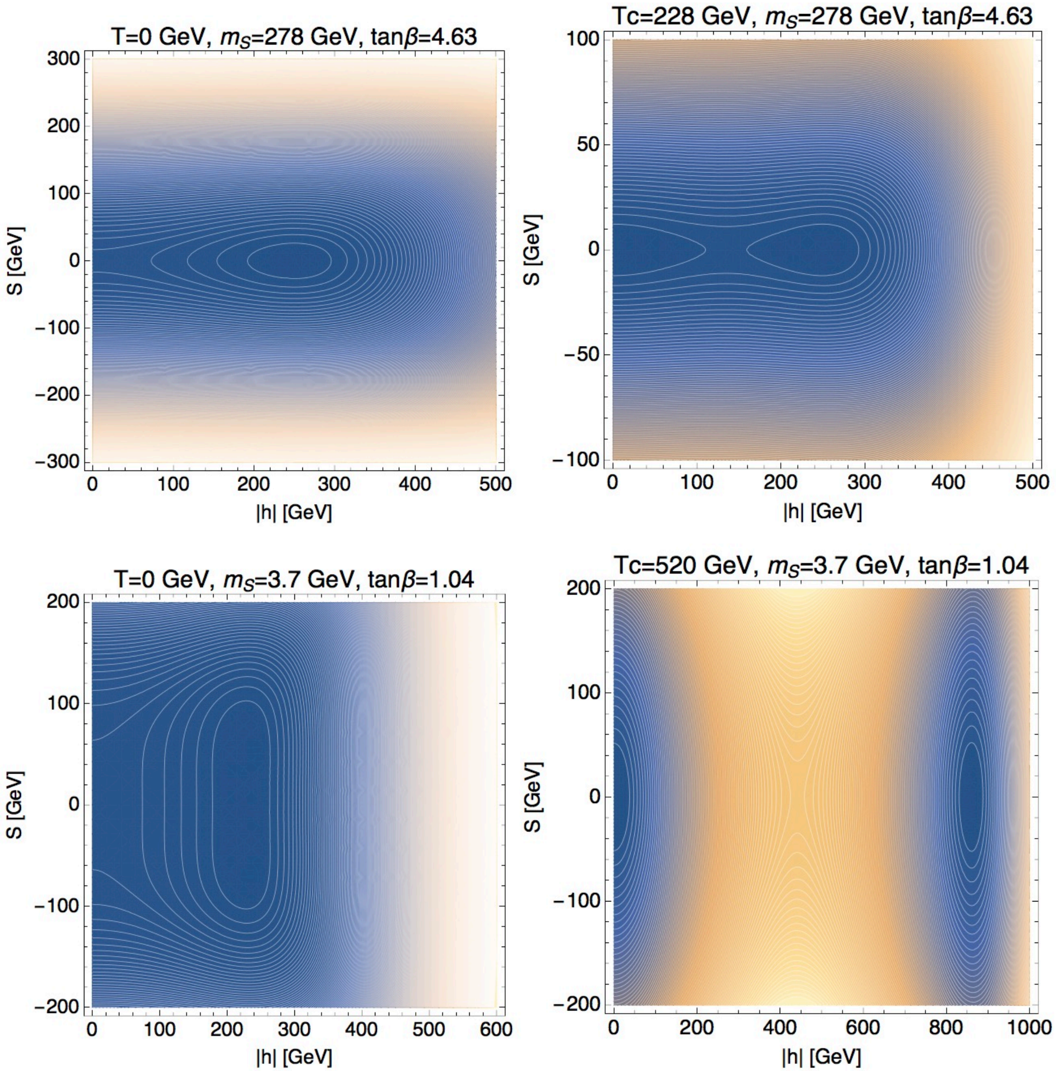
High-T expansion:

$$J_B(y) \overset{y\ll 1}{\simeq} -\frac{\pi^4}{45} + \frac{\pi^2}{12}y - \frac{\pi}{6}y^{3/2} - \frac{y^2}{32}\ln\frac{y}{a_B}$$

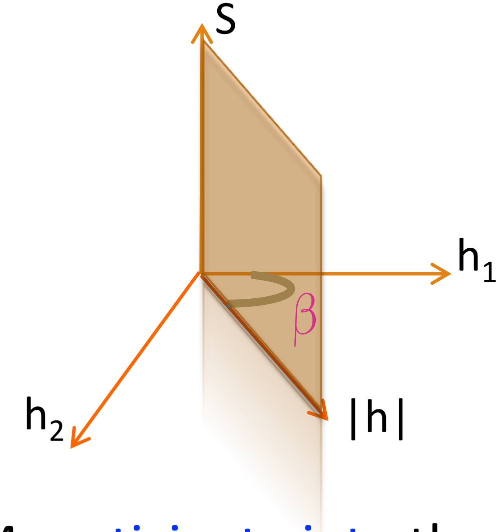
$$J_F(y) \overset{y\ll 1}{\simeq} \frac{7\pi^4}{360} - \frac{\pi^2}{24}y - \frac{y^2}{32}\ln\frac{y}{a_F},$$

$(M^2)^{3/2}$ cubic term enhance the barrier

Potential evolution

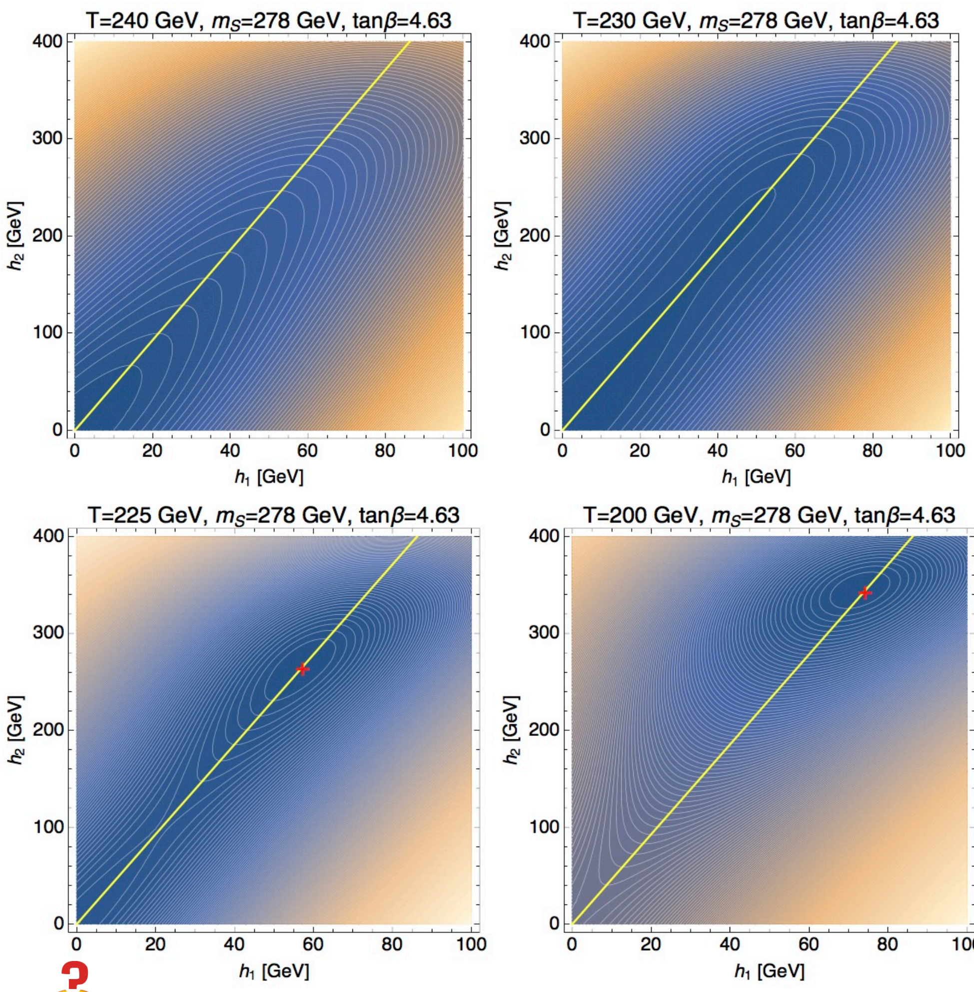


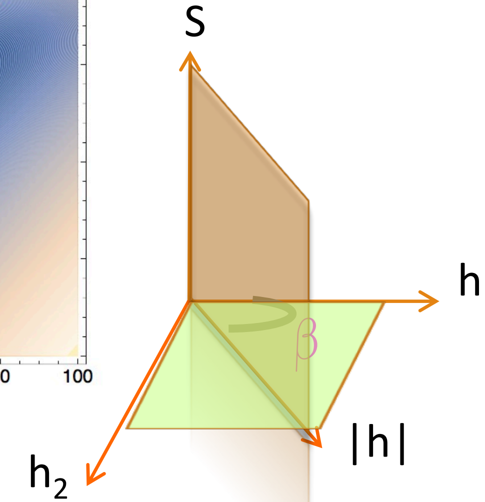
Three fields structure

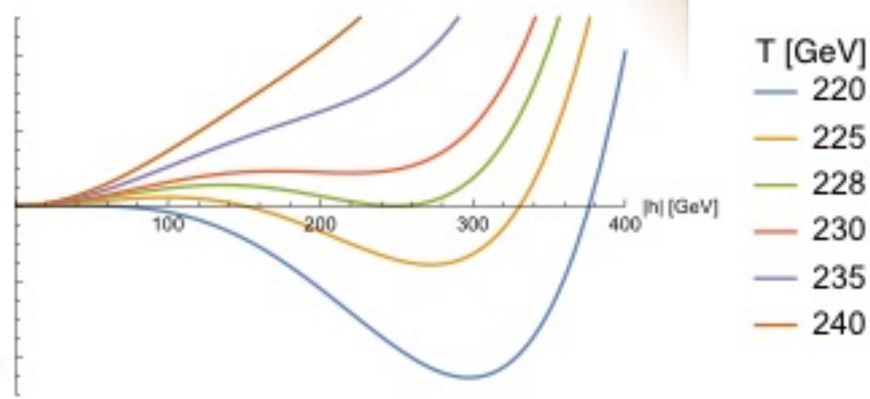


- DM participate into the EWPT, though the S=0 is a flat direction in the potential at any temperature.
- DM is produced before the EWPT.

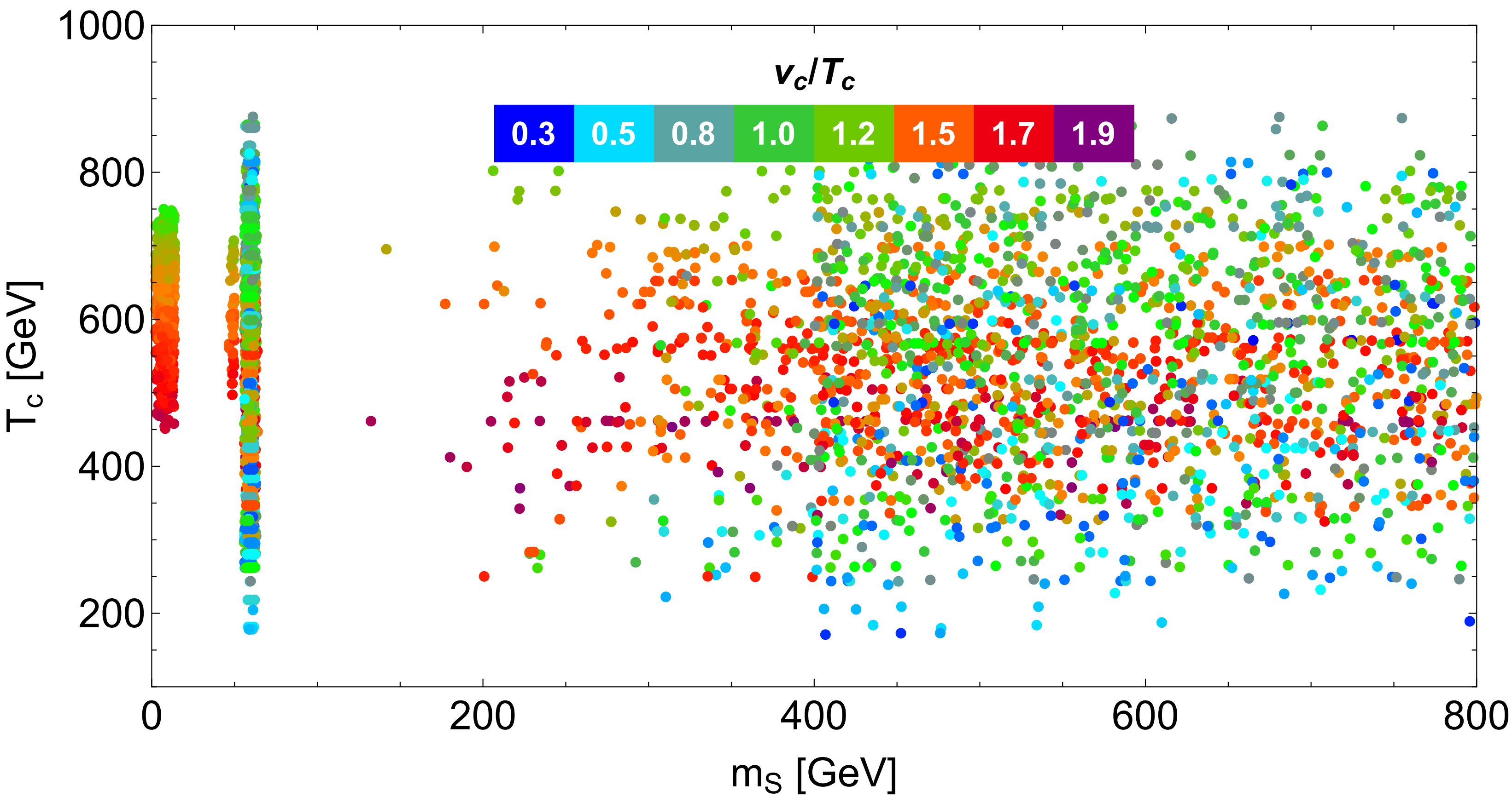
Potential evolution



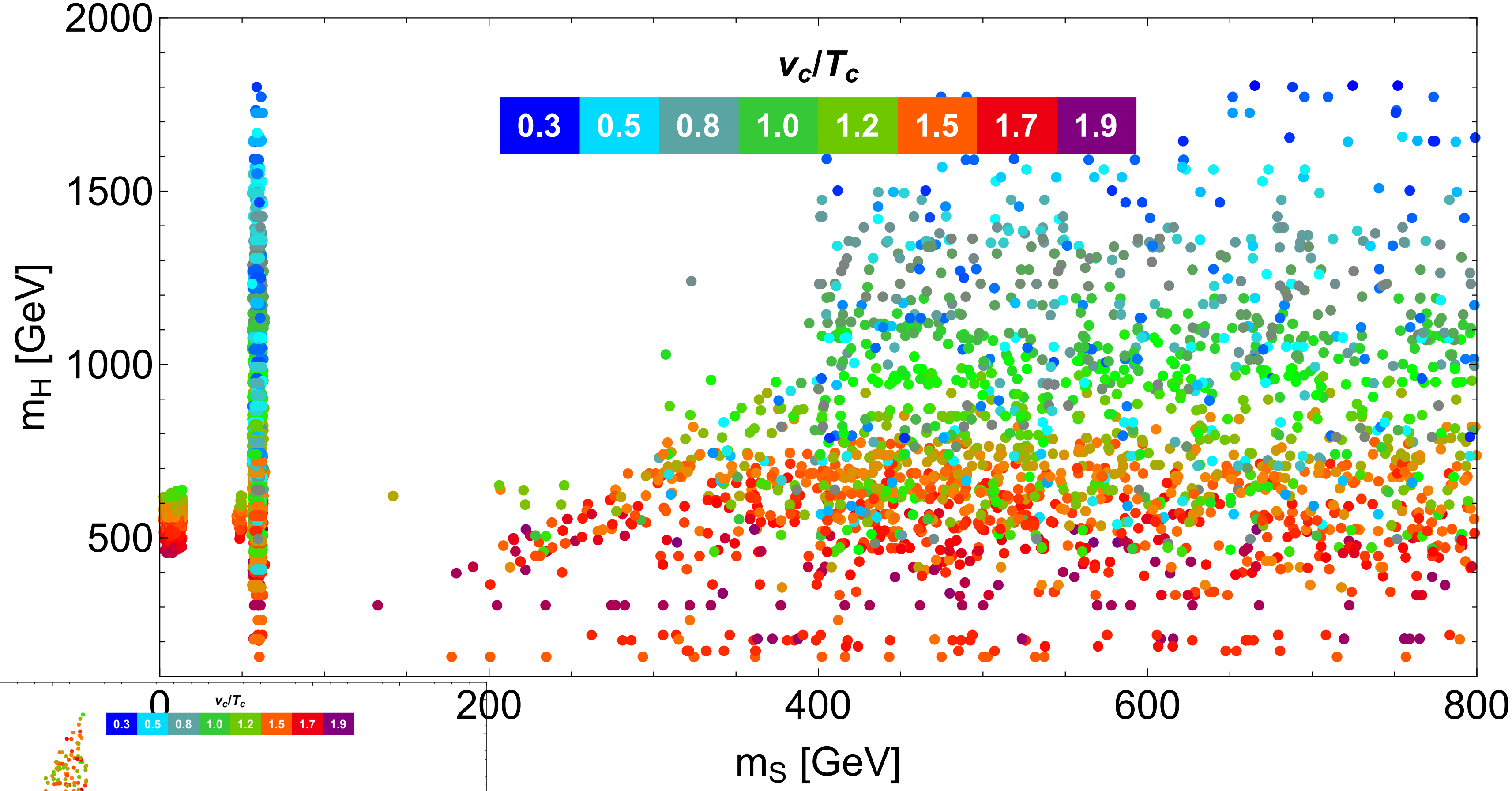


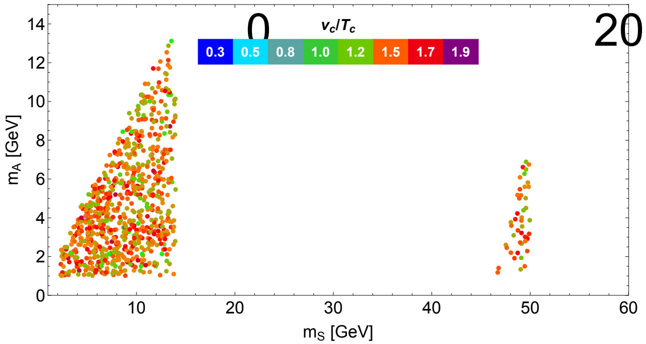


The ratio h2/h1, does not dramatically change, tanβ has NO running.

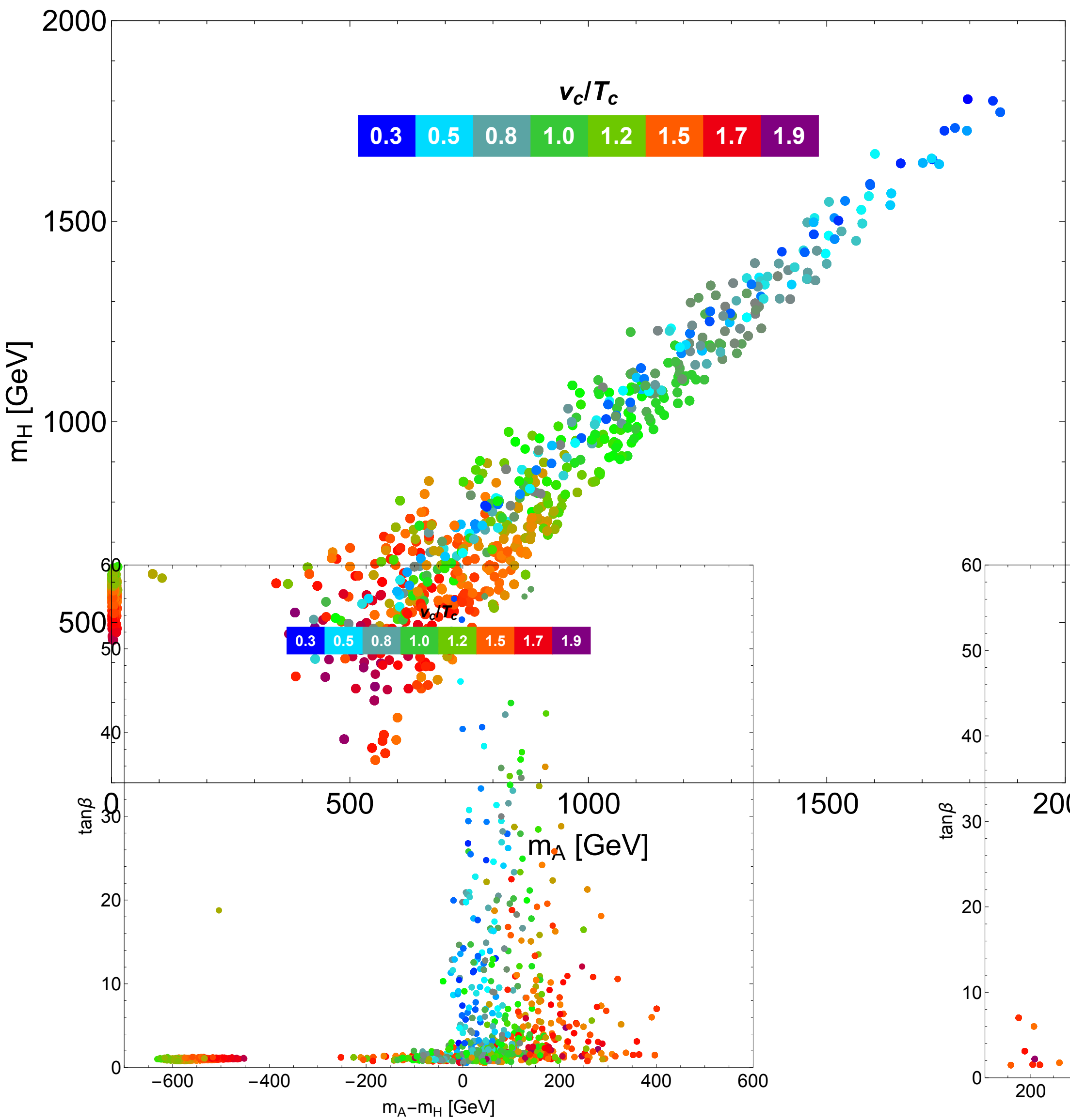


- Critical temperature is at the ~few x 10^2 GeV
- 450 < Tc < 750 GeV (DM has low–mass)

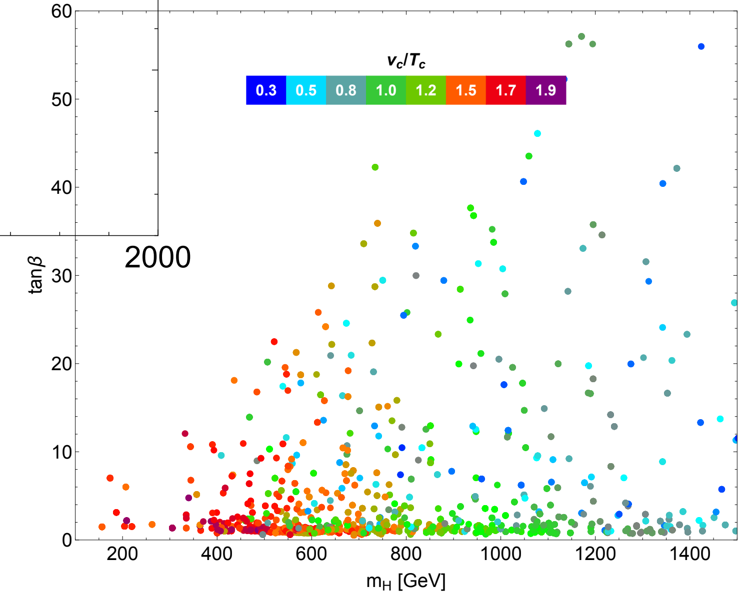




Additional scalars affect the thermal mass correction, enhancing the potential barrier.



Large mass splitting is favored to achieve a strong 1[st]-order EWPT, is nonetheless severely constrained by the EWPD.



Conclusions

- Introducing the additional scalars in the Higgs sector significantly affects the finite temperature potential, leading to the success of realizing the strong EWPT mainly through the effect of thermal mass correction.
- The extended model having **two Higgs portals** is phenomenologically viable, even for a very light DM.
- The critical temperature at which the EWPT occurs has dependence on the DM mass.
- The dynamical mechanism of producing DM before the EWPT is demanded.

Back up

Baryon Asymmetry of the Universe

Observed BAU:

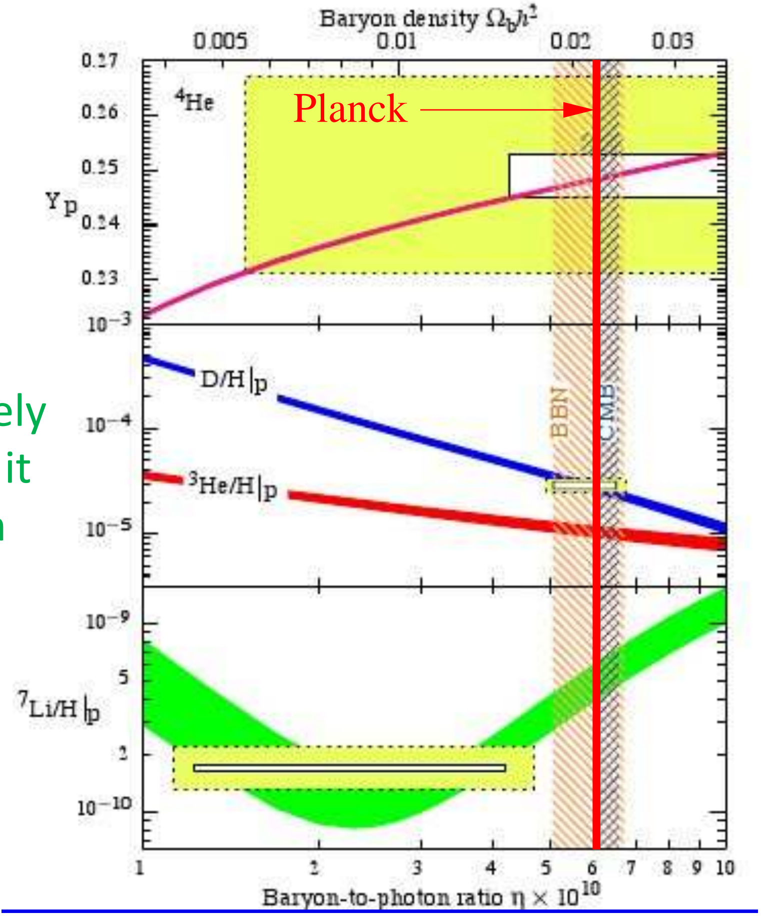
$$\frac{n_B}{s} \sim 10^{-10}.$$

an excellent agreement between the value obtained in two epochs (CMB/BBN) is striking

Even if the baryon number asymmetry were naively taken as one of the initial conditions of Universe, it would be washed out in the inflation & sphaleron processes the initial asymmetry.

What is the dynamical origin?

--- Baryogenesis



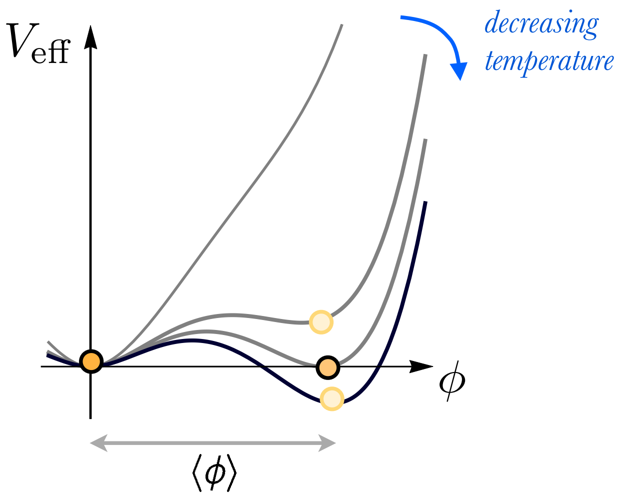
Observed value by Planck/WMAP is consistent with BBN

Computation of $\frac{\langle\phi\rangle}{T_c}$

1. Track evolution of minima in V_{eff} as function of temperature

2. Numerically solve minimization and degeneracy condition equations:

   1. $V'_{\text{eff}}(\phi_{\text{min}}, T_c) = 0$
   2. $V_{\text{eff}}(0, T_c) = V_{\text{eff}}(\phi_{\text{min}}, T_c)$



Bottom line

Gauge-invariant baryon number preservation criterion:

$$\frac{\langle\phi\rangle}{T_c} \longrightarrow \frac{\bar{v}(T_c^{\text{G.I.}})}{T_c^{\text{G.I.}}}$$

1. Use gauge invariant sphaleron scale

2. Determine Tc gauge-invariantly