From inflation to cosmological EWPT with a complex scalar singlet

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Based on latest work with Ligong Bian

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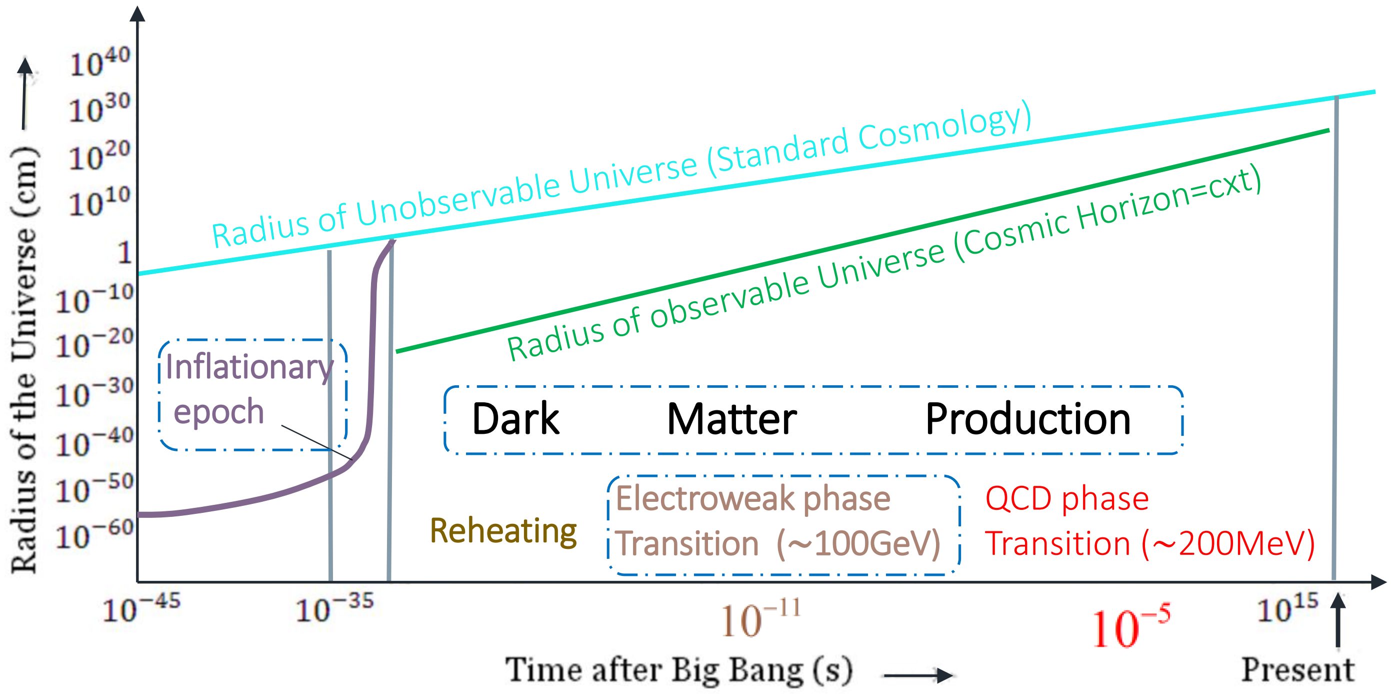
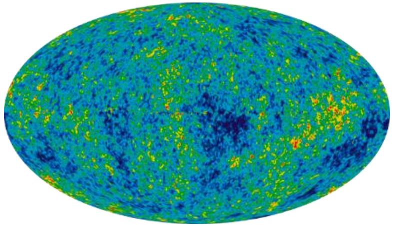
Expansion history of universe



Problem and Solving

Horizon and flatness



CMB

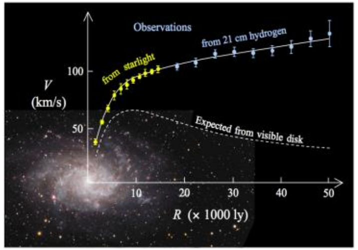
Inflation

Baryon asymmetry

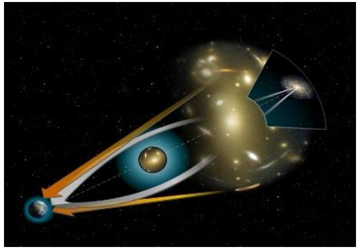
Both Big bang Nucleosynthesis and measurements of CMB gives:

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (8.61 \pm 0.09) \times 10^{-11}$$

EWPT



Rotation curve of a disc galaxy



Gravitational lens

Dark matter

The Standard Model should be extension for the three cases!!!

Tommi Tenkanen, Kimmo Tuominen, Ville Vaskonen
J. Cosmol.Astropart. Phys. 09 (2016) 037.

Real scalar singlet
+Fermion

Complex scalar singlet Model

The direct detection bounds from XENON1T yield null exclusions!!!

scalar potential

Standard model — Scalar partical Mass + self coupling — Higgs portal interaction

$$V_0(H,S) = -\mu_h^2|H|^2+\lambda_h|H|^4 - \mu_s^2|S|^2 - \left(\frac{1}{2}\mu_b^2 S^2 + h.c.\right) + \lambda_s|S|^4 + \lambda_{hs}|H|^2|S|^2$$

The global U(1) breaking to product the DM A

- vacuum stability confines: $\lambda_h > 0, \lambda_s > 0, \lambda_{sh} > 0$

$$H^T = (0,h)/\sqrt{2} \quad S = (s+IA)/\sqrt{2}$$

$$V_0(h,s,A) = \frac{\lambda_h h^4}{4} + \frac{1}{4}\lambda_{hs}h^2A^2 - \frac{\mu_h^2 h^2}{2} + \frac{1}{4}\lambda_{hs}h^2s^2 + \frac{\lambda_s A^4}{4} - \frac{\mu_s^2 A^2}{2} + \frac{\mu_b^2 A^2}{2} + \frac{\lambda_s s^4}{4} + \frac{1}{2}\lambda_s s^2 A^2 - \frac{\mu_s^2 s^2}{2} - \frac{\mu_b^2 s^2}{2}$$

$$DM: m_A = \sqrt{2}\,\mu_b$$

- minimization conditions:

$$\frac{dV_0(h,s,A)}{dh}|_{h=v} = 0, \qquad \frac{dV_0(h,s,A)}{ds}|_{s=v_s} = 0.$$

$$\Rightarrow \quad \mu_h^2 = \lambda_h v^2 + \lambda_{hs} v_s^2/2, \qquad \mu_s^2 = -\mu_b^2 + \lambda_{hs} v^2/2 + \lambda_s v_s^2.$$

Free parameters

$$\mathcal{M}^2 = \begin{pmatrix} 2v^2\lambda_h & v v_s \lambda_{hs} \\ v v_s \lambda_{hs} & 2v_s^2\lambda_s \end{pmatrix}$$

$$R = ((\cos\theta, \sin\theta), (-\sin\theta, \cos\theta))$$

$$\tan 2\theta = -\lambda_{hs} v v_s / (\lambda_h v^2 - \lambda_s v_s^2)$$

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

$$m^2_{h_1,h_2} = \lambda_h v^2 + \lambda_s v_s^2 \mp \frac{\lambda_s v_s^2 - \lambda_h v^2}{\cos 2\theta}$$

$$\lambda_h = \frac{\cos(2\theta)(m^2_{h_1} - m^2_{h_2}) + m^2_{h_1} + m^2_{h_2}}{4v^2}$$

$$\lambda_s = \frac{\cos(2\theta)(m^2_{h_2} - m^2_{h_1}) + m^2_{h_1} + m^2_{h_2}}{4v_s^2}$$

$$\lambda_{hs} = \frac{\tan(2\theta)\cos(2\theta)(m^2_{h_2} - m^2_{h_1})}{2 v v_s}$$

Parameters:

$v_s, m^2_{h_2}, \mu_b$

$\theta \approx 0.2$,

LHC Higgs data (Phys. Rev. D 91, 035018 (2015))

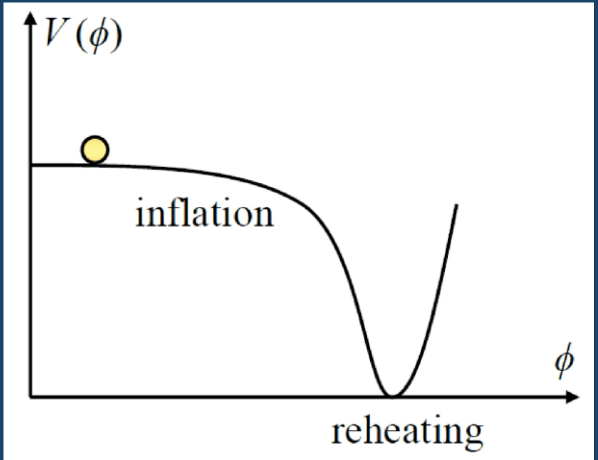
Electroweak precision observables (Phys. Rev. D 97,095032 (2018))

For real scalar singlet case: $A, \mu_b, v_s \rightarrow 0$;

$DM: m_s^2 = -\mu_s^2 + \lambda_{hs} v^2/2$

$Parameters: m_s^2$、λ_{hs}、λ_s

Inflations



Slow-roll inflation

$$\frac{1}{2}\dot{\phi}^2 \ll V(\phi) \qquad |\ddot{\phi}| \ll \mathcal{H}|\dot{\phi}|$$

The friedman Equation: $3M_P^2\mathcal{H}^2 = \frac{1}{2}\dot{\phi}^2 + V(\phi),$

$$\mathcal{H} \equiv \dot{a}/a$$

The motion equation of field: $\ddot{\phi} + 3\mathcal{H}\dot{\phi} + \frac{\partial V(\phi)}{\partial \phi} = 0.$

Slow-roll parameters:

$$\epsilon(\chi) = \frac{M_p^2}{2}\left(\frac{dU/d\chi}{U(\chi)}\right)^2 \ll 1 \quad \eta(\chi) = M_p^2\left(\frac{d^2U/d\chi^2}{U(\chi)}\right) \ll 1$$

e-folding number: $N_e = \int_{\chi_{end}}^{\chi_{in}} d\chi \frac{1}{M_p\sqrt{2\epsilon}}$ =60

Inflations

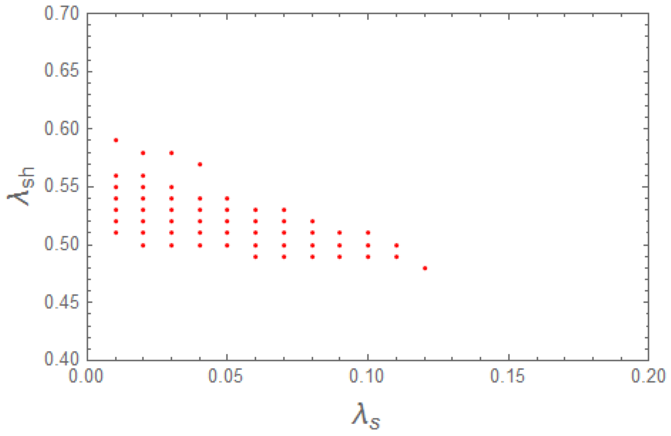
Inflationary observables: Spectrum index Tensor to scalar

$$n_s = 1 + 2\eta - 6\epsilon \qquad r = 16\epsilon$$

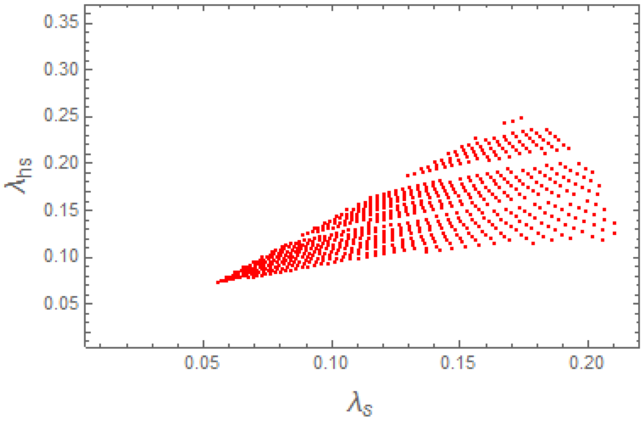
Plank bounds $n_s = 0.9677 \pm 0.0060$ $r < 0.11$ with N_e=60

Amplitude of scalar fluctuations: $$\Delta^2_{\mathcal{R}} = \frac{1}{24\pi^2 M_p^4}\frac{U(\chi)}{\epsilon} = 2.2 \times 10^{-9}$$

Real scalar singlet case

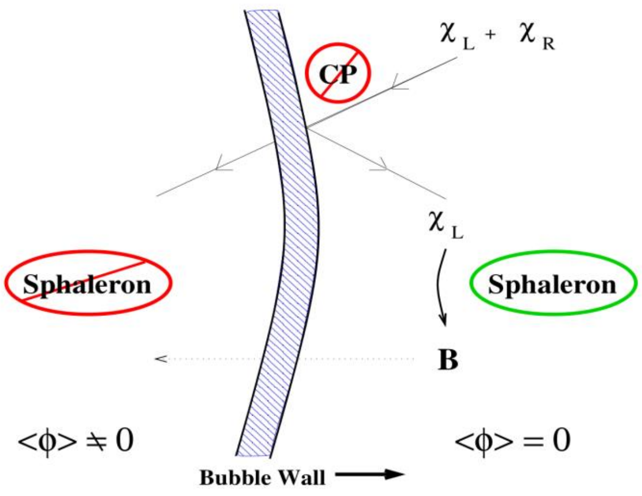


Complex scalar singlet case

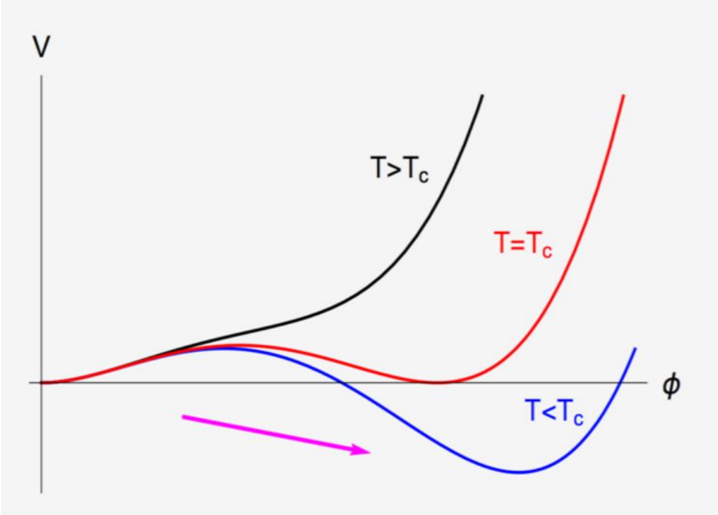


Phase transition

Baryon production



Phase transition



The finite temperature effective potential:

Tree level scalar potential

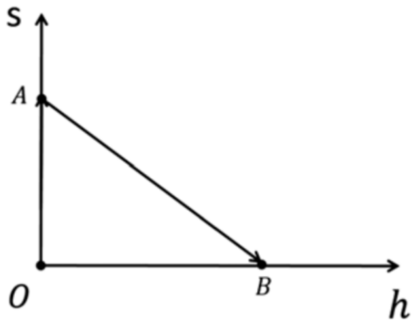
Coleman-Weinberg potential

Finite temperature corrections

$$V(h,s,A,T) = V_0(h,s,A) + V_{CW}(h,s,A) + V_{ct}(h,s,A) + V_1(h,s,A,T) + V_{\rm daisy}(h,s,A,T).$$

Phase transition

Real



$$(h = 0, \ \ s = \pm\sqrt{\mu_s^2/\lambda_s})$$

$$(h = v, \ \ s = 0)$$

$$\lambda_s > 2(m_s^2 - \lambda_{hs} v^2)^2/(m_h^2 v^2)$$

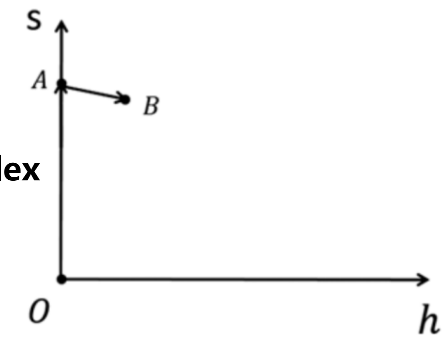
$$\mu_s^2 = -(m_s^2 - \lambda_{hs} v^2/2) > 0$$

$$V(0, s_C^A, T_C) = V(v_C^B, 0, T_C),$$

$$\left.\frac{dV(0, s, T_C)}{ds}\right|_{s=s_C^A} = 0,$$

$$\left.\frac{dV(h, 0, T_C)}{dh}\right|_{h=v_C^B} = 0.$$

Complex



$$(h = 0, \ \ s^A = \pm\sqrt{\mu_s^2/\lambda_s})$$

$$(v_h, v_s)$$

$$({\lambda_{hs}}^2 - 4\lambda_h\lambda_s) < 0$$

$$\mu_s^2 = -(m_s^2 - \lambda_{hs} v^2/2) > 0$$

$$V(0, s_C^A, \theta, 0, T_C) = V(v_C^B, s_C^B, \theta, 0, T_C),$$

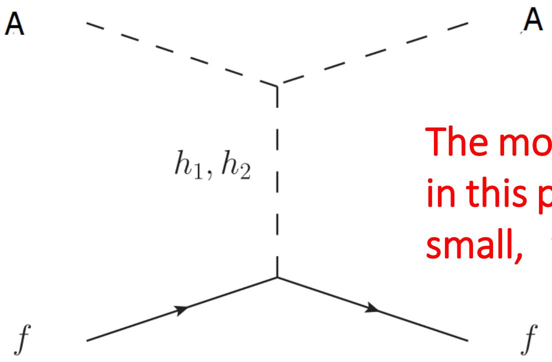
$$\left.\frac{dV(h, s, \theta, 0, T_C)}{ds}\right|_{h=v_C^B, s=s_C^B} = 0,$$

$$\left.\frac{dV(0, s, \theta, 0, T_C)}{ds}\right|_{s=s_C^A} = 0,$$

Dark matter

The tree-level direct detection scattering amplitude:

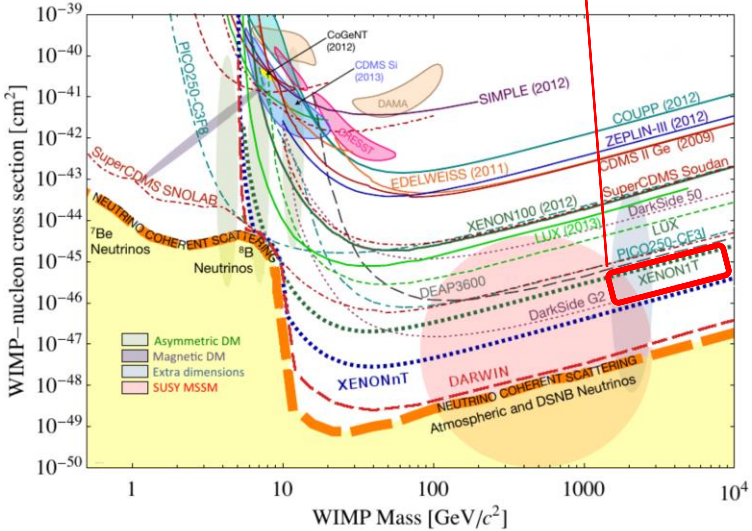
$$\propto \sin\theta\cos\theta\left(\frac{m_{h_2}^2}{t-m_{h_2}^2}-\frac{m_{h_1}^2}{t-m_{h_1}^2}\right)\simeq \sin\theta\cos\theta\,\frac{t\,(m_{h_2}^2-m_{h_1}^2)}{m_{h_1}^2\;m_{h_2}^2}\simeq 0$$



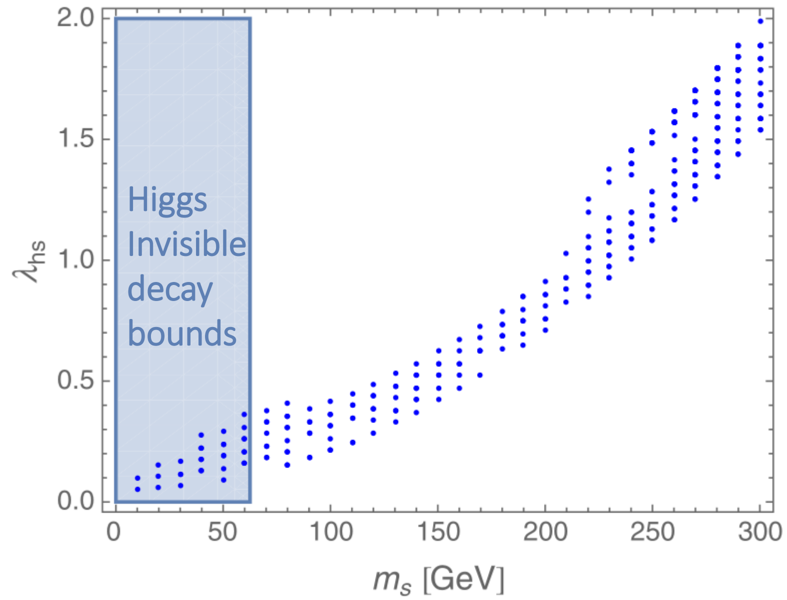
The momentum transfer in this process is negligibly small, t≃0

Tree–level dark matter scattering off SM matter

Most stringent direct DM detection

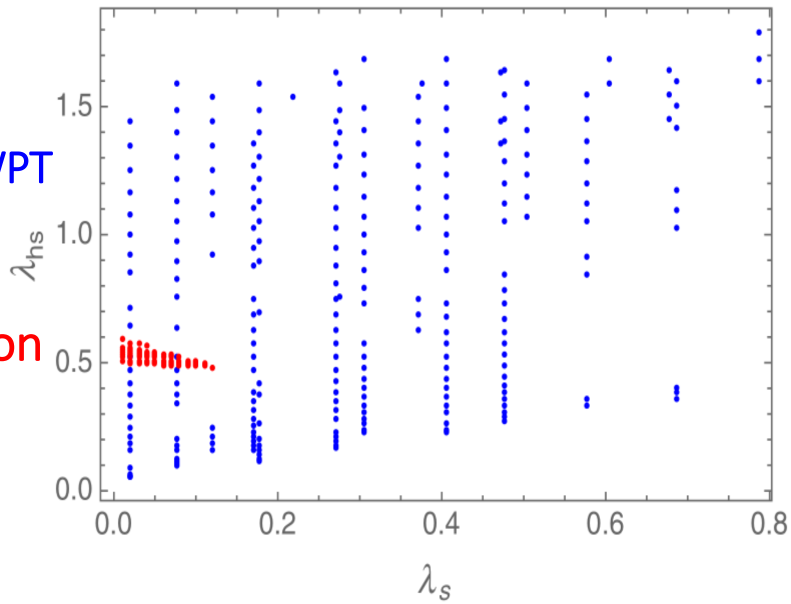


Results (Real scalar singlet case)



SFOEWPT

Inflation



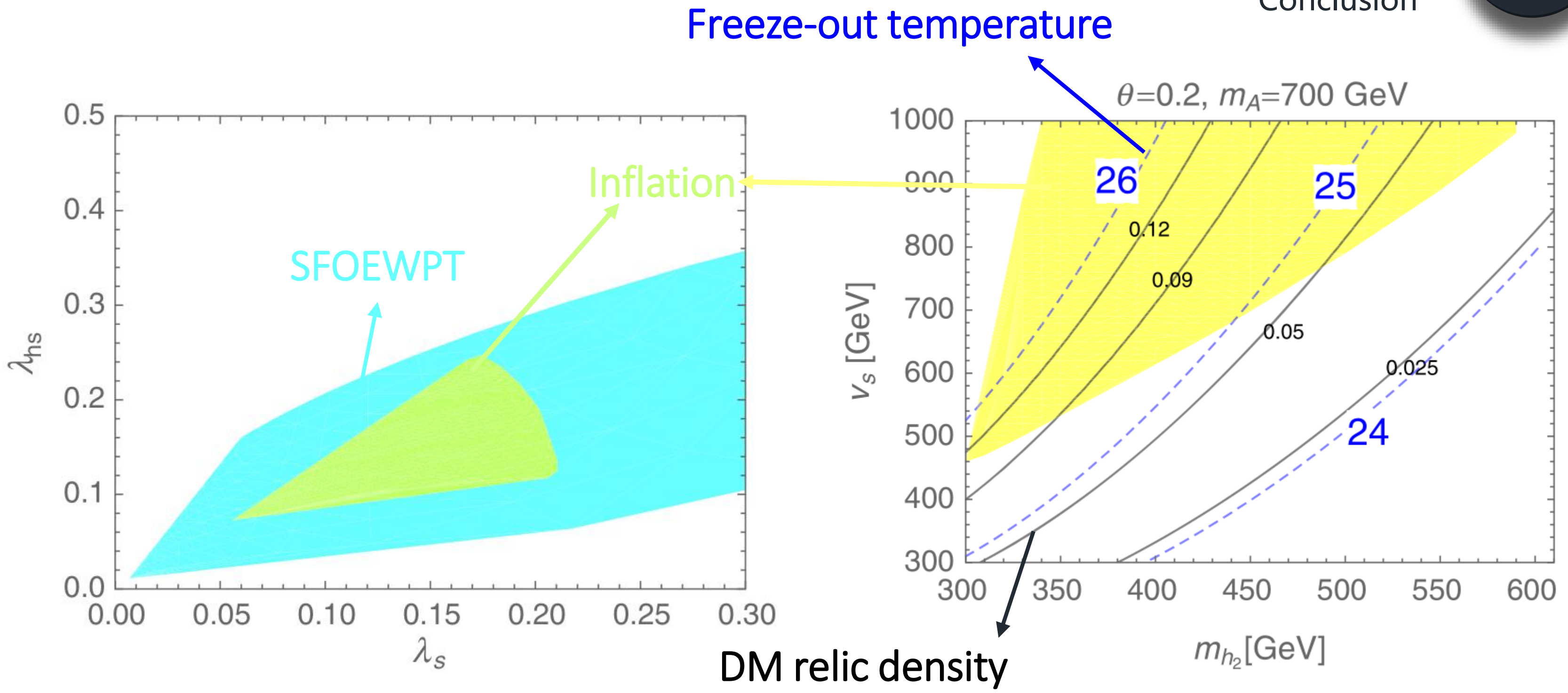
$$(h = 0,\ \ s = \pm\sqrt{\mu_s^2/\lambda_s})$$

$$(h = v,\ \ s = 0)$$

$$\lambda_s > 2(m_s^2 - \lambda_{hs} v^2)^2/(m_h^2 v^2)$$

$$\mu_s^2 = -(m_s^2 - \lambda_{hs} v^2/2) > 0$$

Results (Complex scalar singlet case)



The direct detection bounds from XENON1T yield null exclusions！！

Conclusion

<table>
<tr><th></th><th>Inflation</th><th>SFOEWPT</th><th>DM</th></tr>
<tr><td>The complex singlet scalar with the global U(1) being broken</td><td colspan="3">🙂</td></tr>
<tr><td rowspan="2">SM +Real singlet scalar</td><td colspan="2">🙂</td><td></td></tr>
<tr><td colspan="3">☹️</td></tr>
</table>