Phase transition and dark matter in the singlet extension of SM

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1. The model
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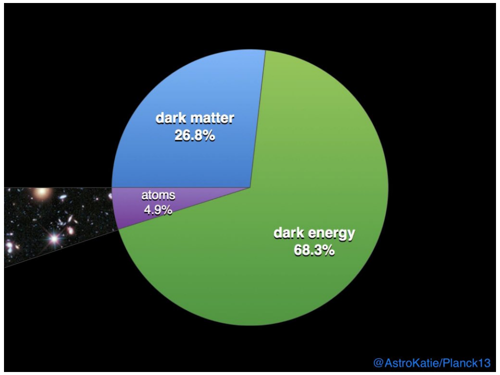
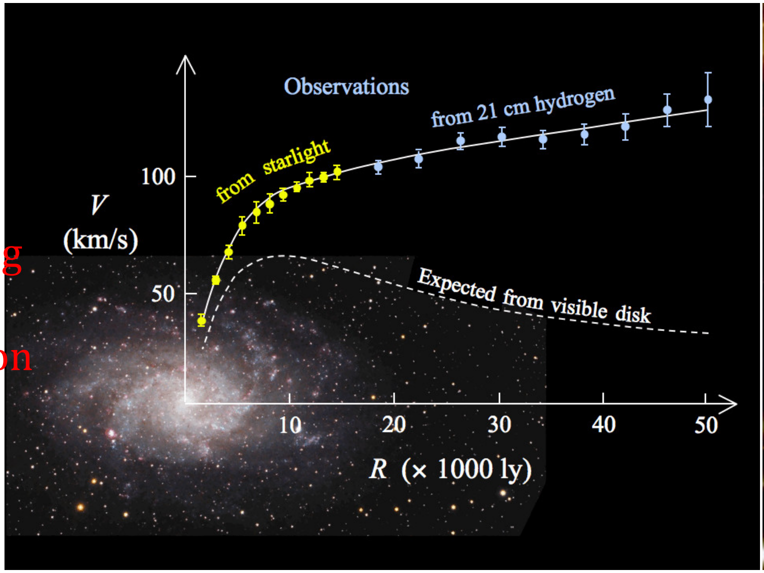
- Summary

What is the Universe made of?

- The Universe content:
  - -Luminous matter ~ 5%
  - -Dark matter ~ 27%
  - -Dark energy ~ 68%



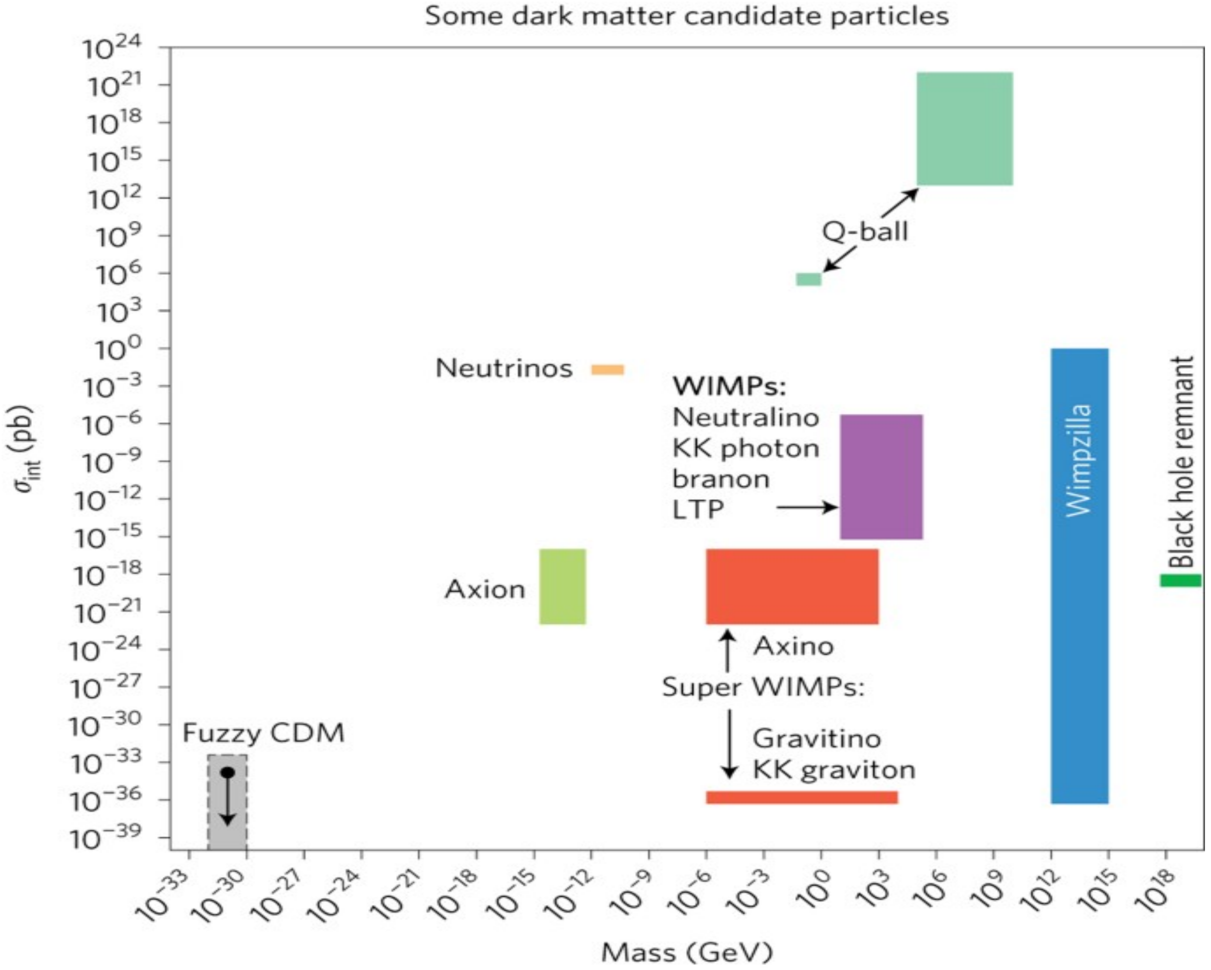
- Evidence is overwhelming :
  - -Rotation curve;
  - -Gravitational Lensing
  - -N-body simulations of structure formation
  - -CMB
  - -BBN
  - -...



The rotation curve of typical spiral galaxy M33

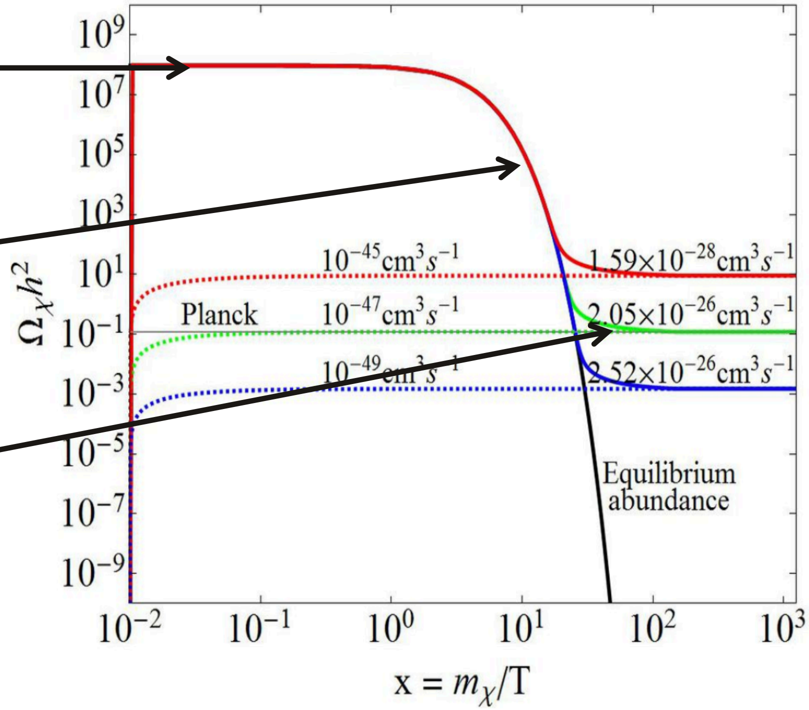
Composite image of X-ray (pink) and weak gravitational Lensing (blue) of the famous Bullet Cluster of galaxies.

Dark matter candidates



The WIMP miracle

1. In the early Universe, WIMPs are in thermal and chemical equilibrium with SM particles.
2. With the expanding and cooling of the Universe, WIMPs become nonrelativistic and their production drops exponentially.
3. The WIMPs decouple from the thermal bath when the mass-to-temperature is ~20.Then their abundance remains a constant.

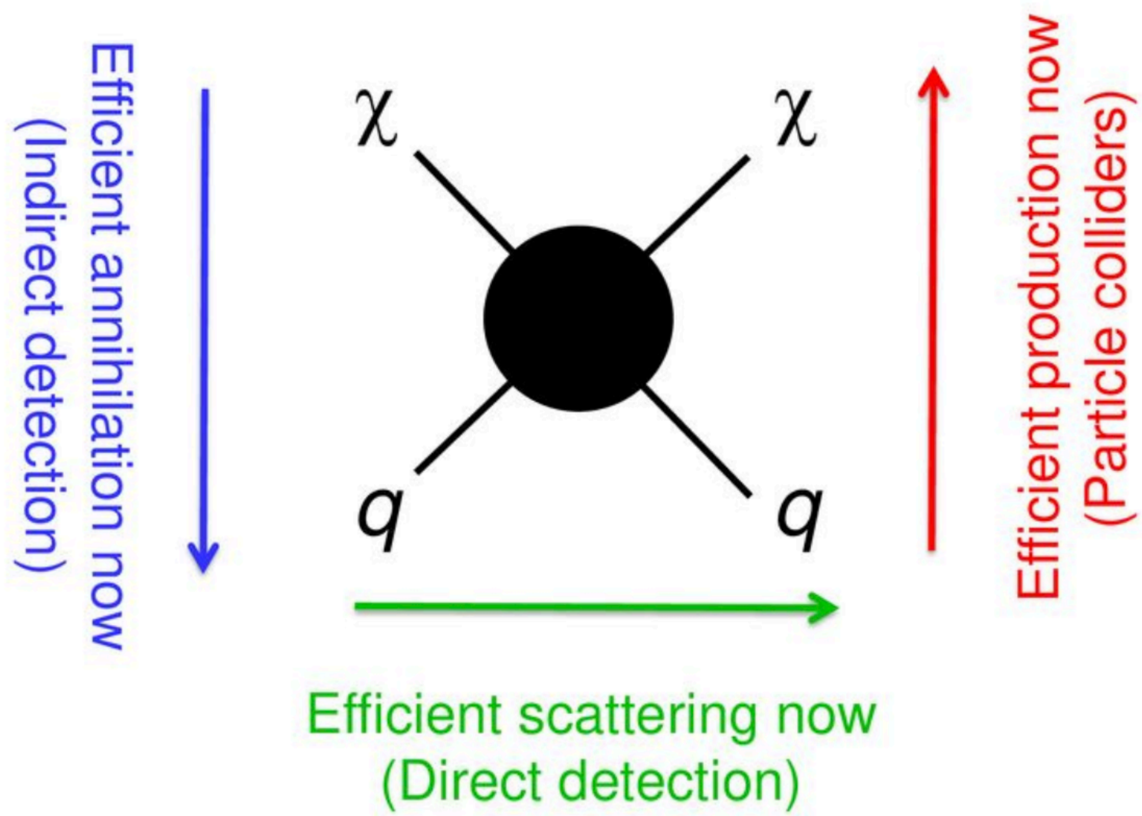


$$\Omega_\chi h^2 \simeq \frac{1.07\times10^9\ \mathrm{GeV}^{-1}}{M_{\mathrm{pl}}}\frac{x_F}{\sqrt{g_*}}\frac{1}{(a+3b/x_F)}$$

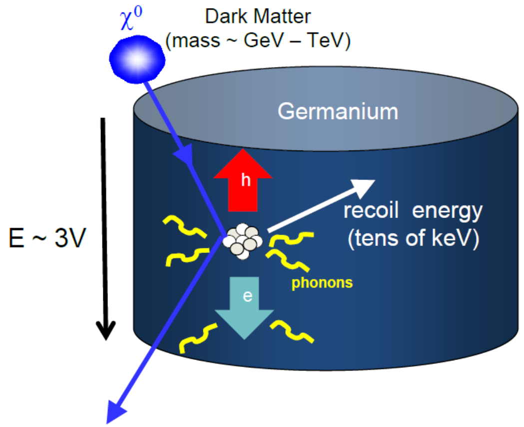
$$\simeq \frac{3\times10^{-27}\ \mathrm{cm}^3\ \mathrm{s}^{-1}}{\langle\sigma_{\mathrm{ann}}v\rangle}$$

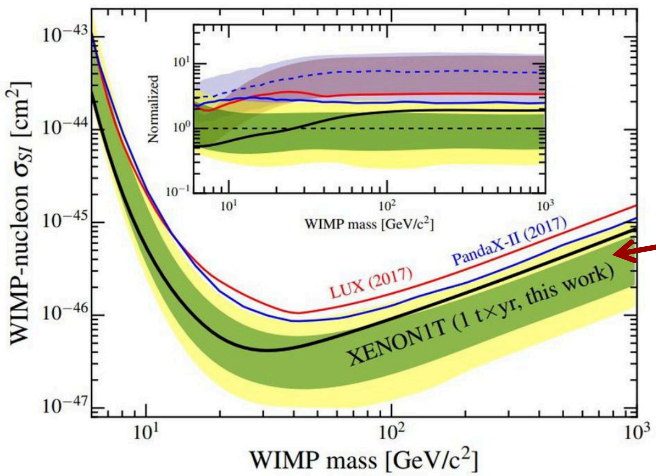
WIMP detection

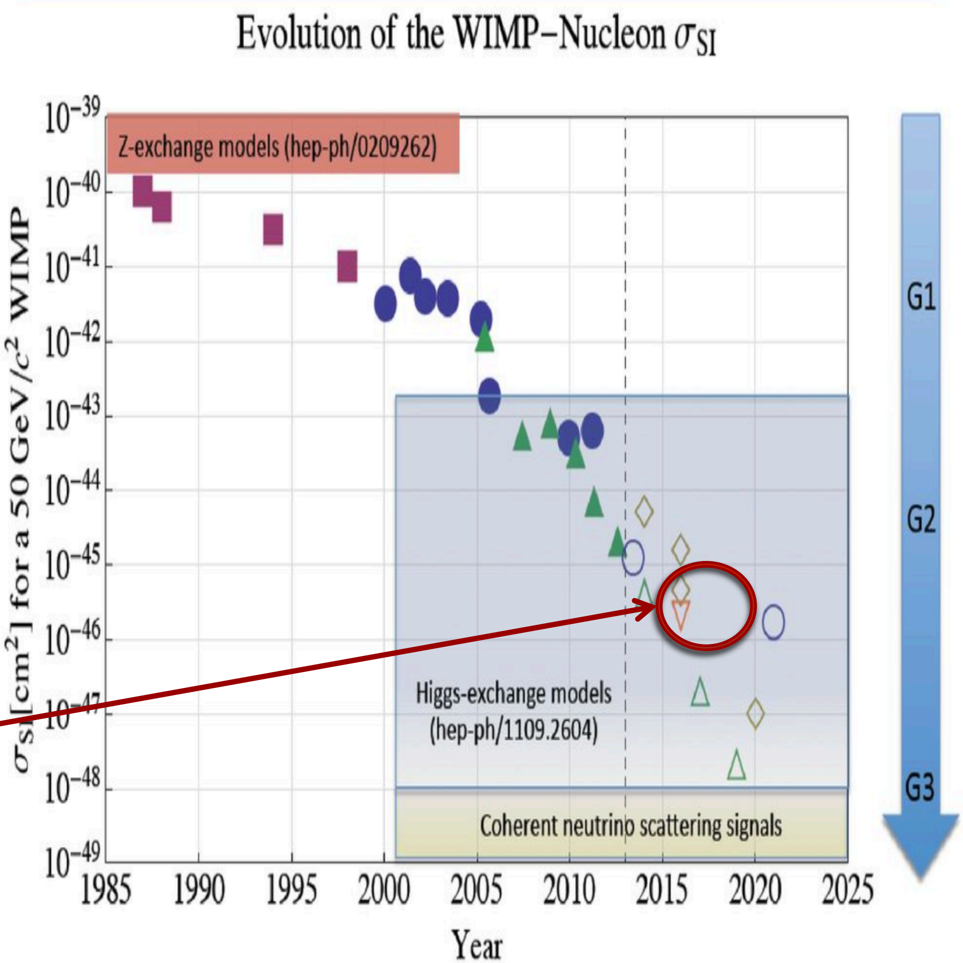
Correct relic density → Efficient annihilation then



Direct detection

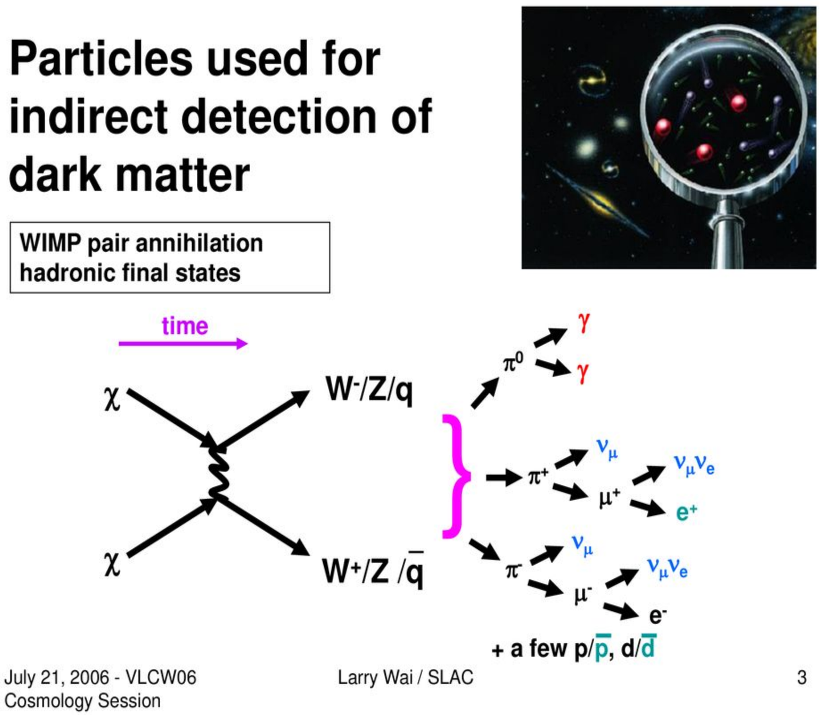


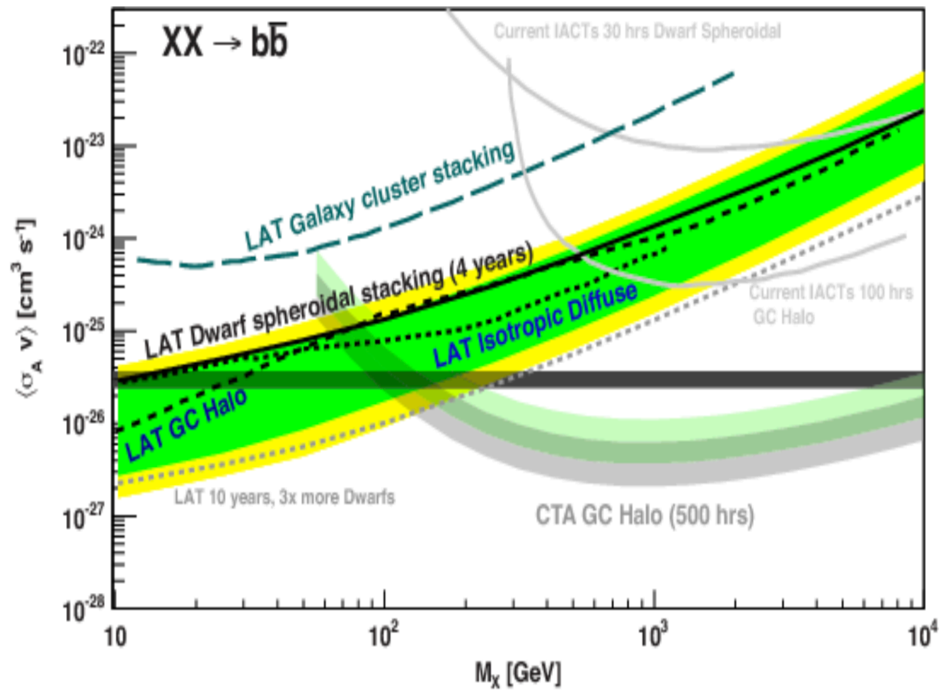




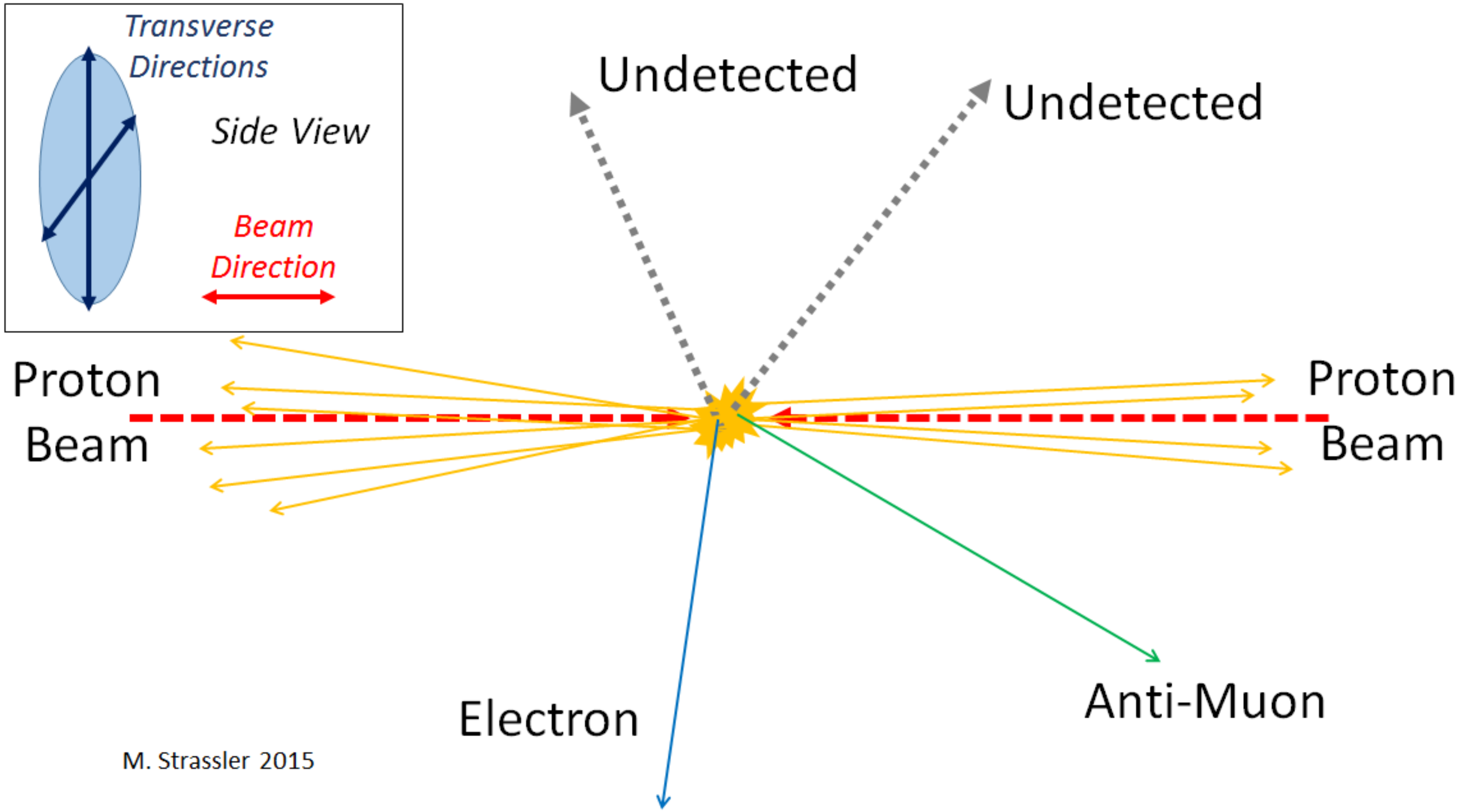
Moore's law for DM direct detection

Indirect detection





DM searches at the LHC

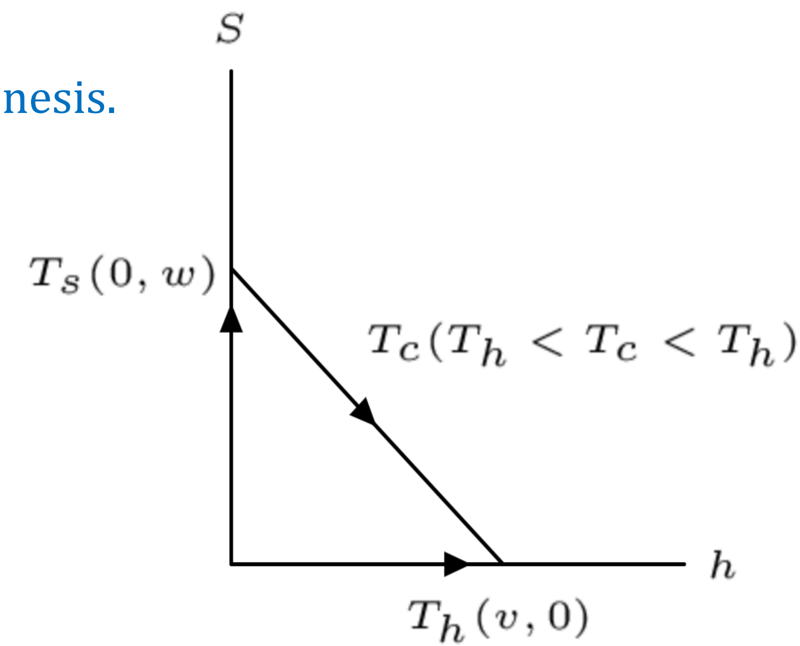


Phase transition (PT) in the singlet extension of SM

- Trigger a strong first-order PT for baryogenesis.
- Provide CP violation source,

$$\mathcal{O}_6 = \frac{S^2}{\Lambda^2}\bar{Q}_{3L}\tilde{H}t_R + \text{H.c.}$$

- Dark matter candidate.
- Generate gravitational-waves.



Type-II PT

Real singlet extension with a Z2 symmetry

The model:

$$V(H,S) = -\mu_h^2|H|^2 + \lambda_h|H|^4 + \frac{1}{2}\mu_s^2 S^2 + \frac{1}{4}\lambda_s S^4 + \frac{1}{2}\lambda_m |H|^2 S^2,$$

S becomes a dark matter candidate in the type-II PT since its VEV vanished in the present Universe.

Write the potential in terms of the background fields h and s:

$$V_0(h,s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2.$$

The tree-level potential exists a potential barrier for the type-II EWPT.

Real singlet extension with a Z2 symmetry

The finite temperature potential is given by

$$V(h,s,T) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2 - \frac{1}{2}(c_h h^2 + c_s s^2)(T_c^2 - T^2).$$

Temperature-dependent parameters

$$\mu_h^2(T) = \mu_h^2 - c_h(T^2 - T_c^2),$$
$$\mu_s^2(T) = \mu_s^2 + c_s(T^2 - T_c^2).$$

Real singlet extension with a Z2 symmetry

Local minimum in the type-II PT:

$$w^2 = -\frac{\mu_s^2}{\lambda_s}; \quad v^2 = \frac{\mu_h^2}{\lambda_h},$$

The critical temperature is given by

$$v_0^2 = v^2 + \frac{c_h}{\lambda_h} T_c^2.$$

The degeneracy of the two vacua at critical temperature requires

$$m_s^2 = \frac{1}{2}\left(\lambda_m - 2\sqrt{\lambda_h \lambda_s}\right) v_0^2 + \left(c_h \sqrt{\frac{\lambda_s}{\lambda_h}} - c_s\right) T_c^2.$$

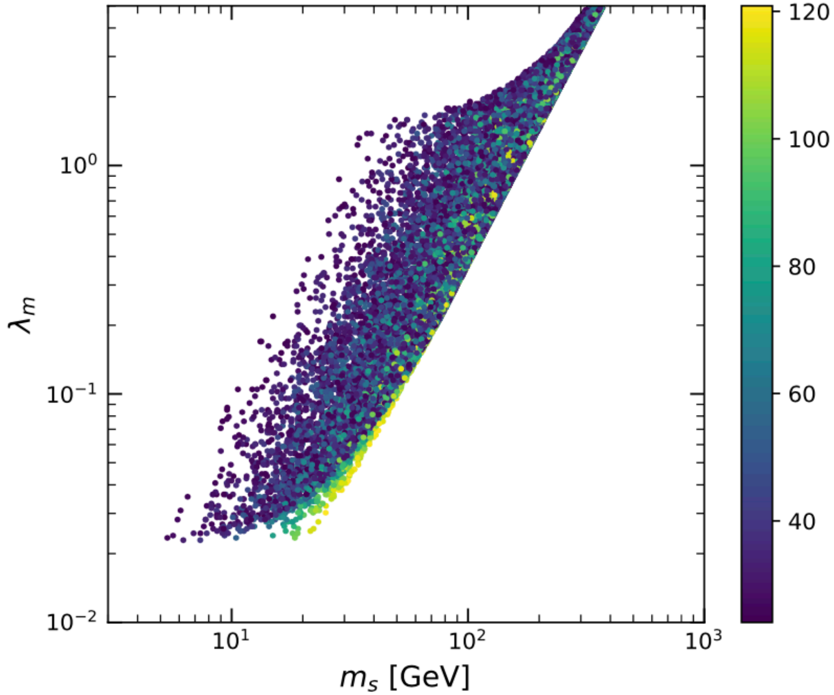
To ensure a correct EWPT, the broken minimum should decrease faster than the symmetry one as the temperature decreases, this requires:

$$\frac{c_h}{c_s} > \sqrt{\frac{\lambda_h}{\lambda_s}}.$$

Real singlet extension with a Z2 symmetry

To search for the parameter space for the type-II PT, we make a random scan of the parameters in the following ranges:

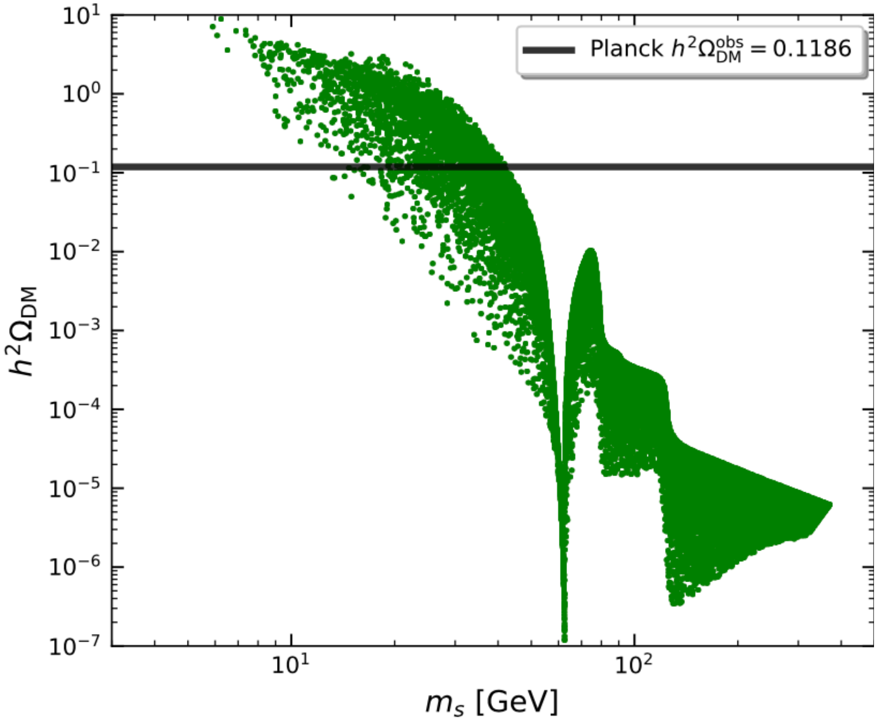
$$10^{-3} < \lambda_s < 5, \quad 10^{-3} < \lambda_m < 5, \quad \text{and} \quad 1 < \frac{v}{T_c} < 10.$$



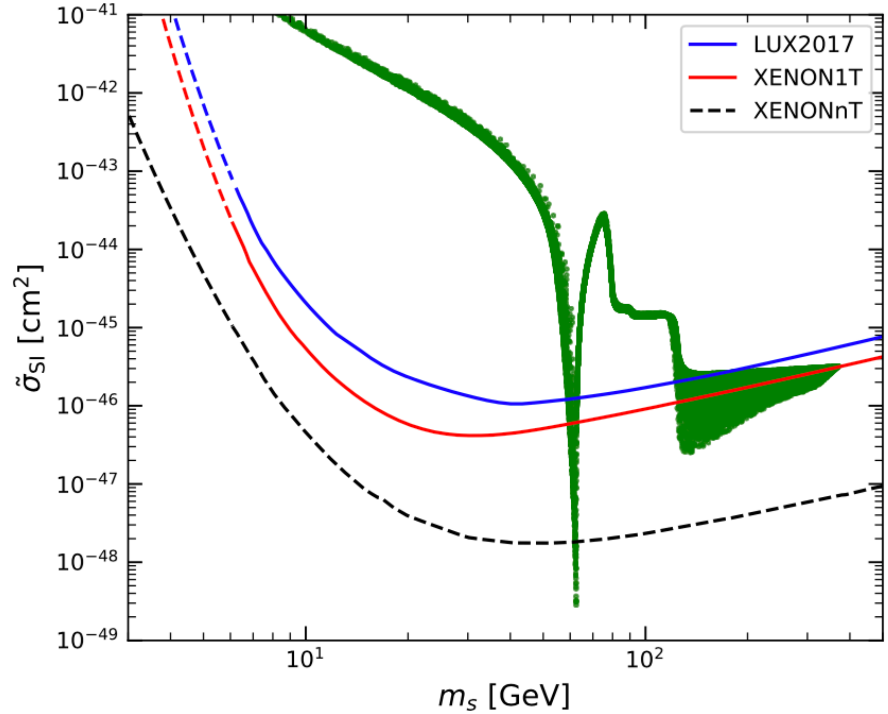
1. $30\ GeV \leq T_c \leq 120\ GeV$
2. $40\ GeV \leq m_s \leq 400\ GeV$
3. $\lambda_m \geq 10^{-2}$

Real singlet extension with a Z2 symmetry

Dark matter relic density



Direct detection



Complex singlet extension with a CP symmetry

Consider the model with a CP symmetry $S \rightarrow S^*$:

$$V(H,S) = -\mu_h^2|H|^2 + \lambda_h|H|^4 - \mu_1^2(S^*S) - \frac{1}{2}\mu_2^2(S^2+S^{*2}) + \lambda_1(S^*S)^2 + \frac{1}{4}\lambda_2(S^2+S^{*2})^2 + \frac{1}{2}\lambda_3(S^*S)(S^2+S^{*2}) + \kappa_1|H|^2(S^*S) + \frac{1}{2}\kappa_2|H|^2(S^2+S^{*2}) + \frac{1}{\sqrt{2}}a_1^3(S+S^*) + \frac{1}{2\sqrt{2}}b_m|H|^2(S+S^*) + \frac{\sqrt{2}}{3}c_1(S^*S)(S+S^*) + \frac{\sqrt{2}}{3}c_2(S^3+S^{*3}).$$

With $S=(s+i\chi)/\sqrt{2}$, we have

$$V(h,s,\chi) = -\frac{1}{2}\mu_h^2h^2 - \frac{1}{2}\mu_s^2s^2 - \frac{1}{2}\mu_\chi^2\chi^2 + \frac{1}{4}\lambda_hh^4 + \frac{1}{4}\lambda_ss^4 + \frac{1}{4}\lambda_\chi\chi^4 + \frac{1}{2}\lambda_as^2\chi^2 + \frac{1}{4}\kappa_sh^2s^2 + \frac{1}{4}\kappa_\chi h^2\chi^2 + a_1^3s + \frac{1}{4}b_mh^2s + \frac{1}{3}c_ss^3 + \frac{1}{3}c_\chi s\chi^2,$$

Complex singlet extension with a CP symmetry

with

$$\mu_1^2 = \frac{1}{2}(\mu_s^2 + \mu_\chi^2), \quad \mu_2^2 = \frac{1}{2}(\mu_s^2 - \mu_\chi^2),$$
$$\kappa_1 = \frac{1}{2}(\kappa_s + \kappa_\chi), \quad \kappa_2 = \frac{1}{2}(\kappa_s - \kappa_\chi),$$
$$c_1 = \frac{1}{4}(3c_s + c_\chi), \quad c_2 = \frac{1}{4}(c_s - c_\chi),$$

and

$$\lambda_1 = \frac{1}{2}\left[\frac{1}{2}(\lambda_s + \lambda_\chi) + \lambda_a\right], \ \lambda_2 = \frac{1}{2}\left[\frac{1}{2}(\lambda_s + \lambda_\chi) - \lambda_a\right], \ \lambda_3 = \frac{1}{2}(\lambda_s - \lambda_\chi).$$

Complex singlet extension with a CP symmetry

The potential at finite temperature is given by

$$V_{\rm eff}(h,s,\chi,T) = V(h,s,\chi) - \frac{1}{2}\left(g_h h^2 + g_s s^2 + g_\chi \chi^2 + 2m_3 s\right)(T_c^2 - T^2),$$

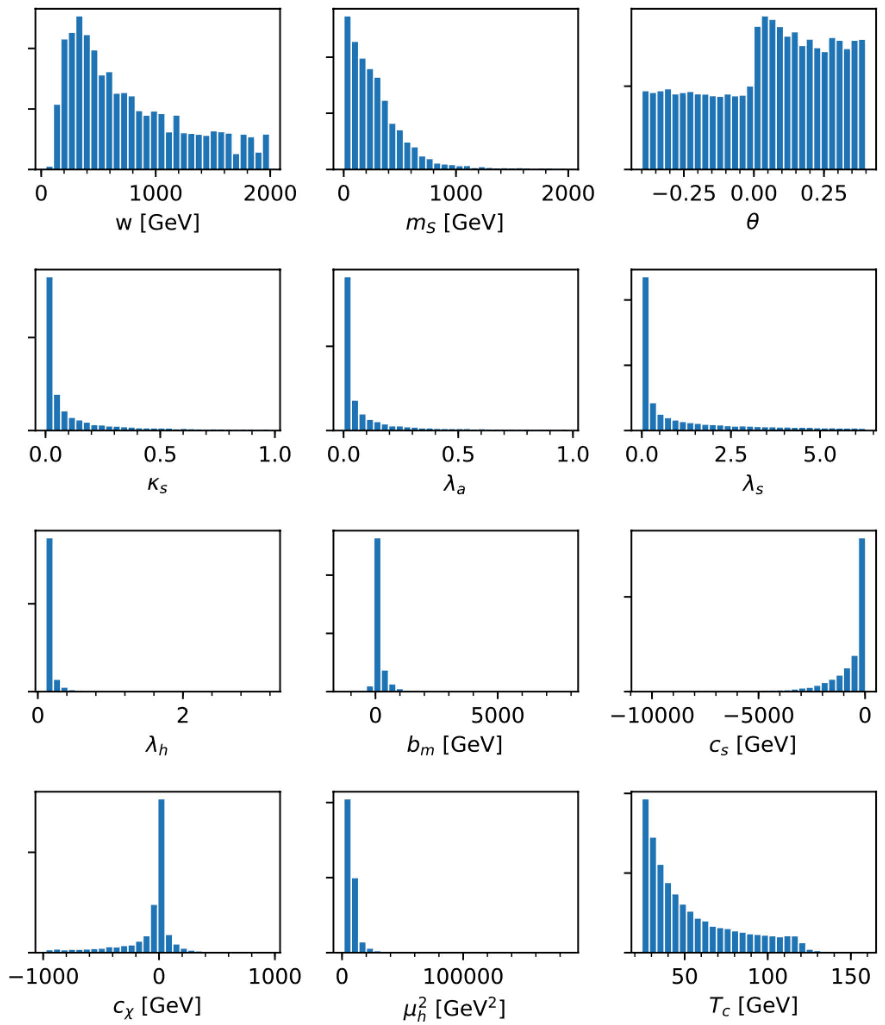
T-dependent parameters:

$$\mu_h^2(T) = \mu_h^2 - g_h(T^2 - T_c^2), \quad \mu_s^2(T) = \mu_s^2 - g_s(T^2 - T_c^2),$$
$$\mu_\chi^2(T) = \mu_\chi^2 - g_\chi(T^2 - T_c^2), \quad a_1^3(T) = a_1^3 + m_3(T^2 - T_c^2).$$

The following relations are required for generating the type-II PT

$$\lambda_h = \frac{M_{hh}^2}{2v_0^2}, \quad \mu_h^2 = \lambda_h v^2, \quad b_m = \frac{2M_{hs}^2}{v_0}, \quad a_1^3 = -\frac{b_m v^2}{4},$$
$$\lambda_s = \frac{36\lambda_h v^4 + w[96a_1^3 + (24M_{ss}^2 + 4\kappa_s T_c^2 + 4\lambda_a T_c^2 - \lambda_\chi T_c^2 - 12\kappa_s v_0^2)w]}{12w^4 - 5T_c^2 w^2},$$
$$\mu_s^2 = \frac{15\lambda_h T_c^2 v^4 + 40a_1^3 T_c^2 w + (24M_{ss}^2 + 4\kappa_s T_c^2 + 4\lambda_a T_c^2 - \lambda_\chi T_c^2 - 12\kappa_s v_0^2)w^4}{10T_c^2 w^2 - 24w^4},$$
$$c_s = -\frac{1}{w^2}(a_1^3 - \mu_s^2 w + \lambda_s w^3).$$

Complex singlet extension with a CP symmetry

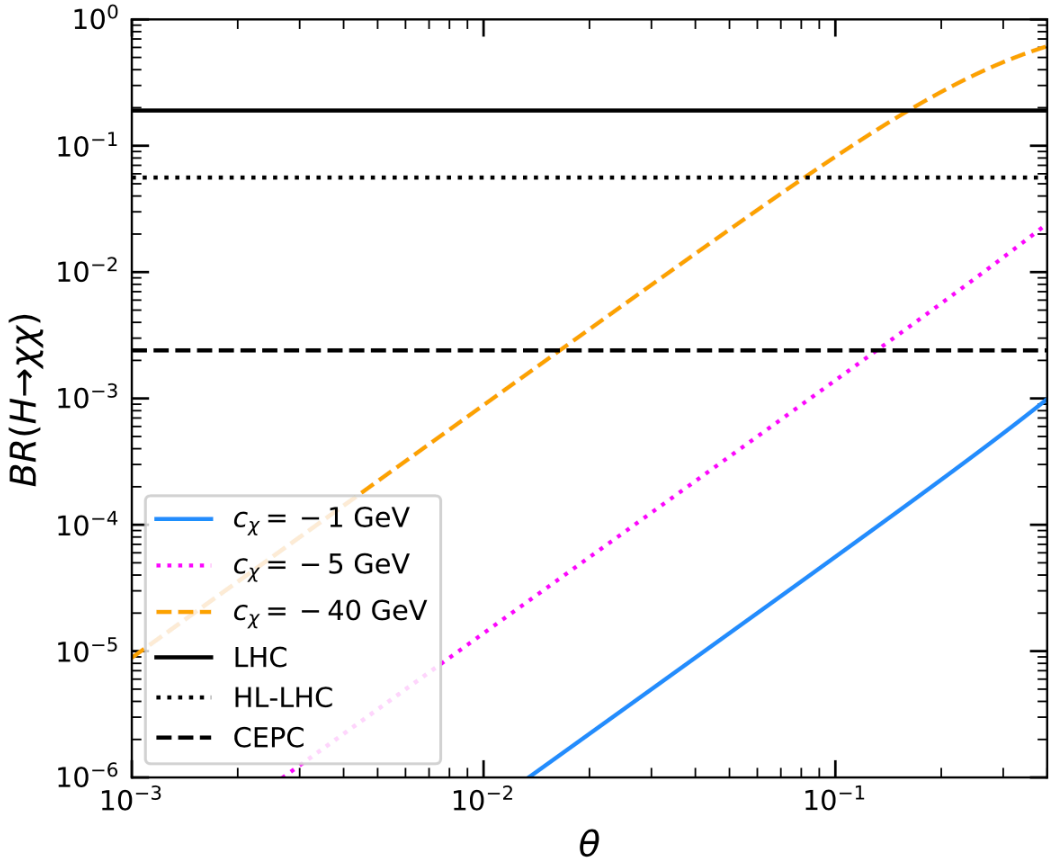


Complex singlet extension with a CP symmetry

Invisible Higgs decay

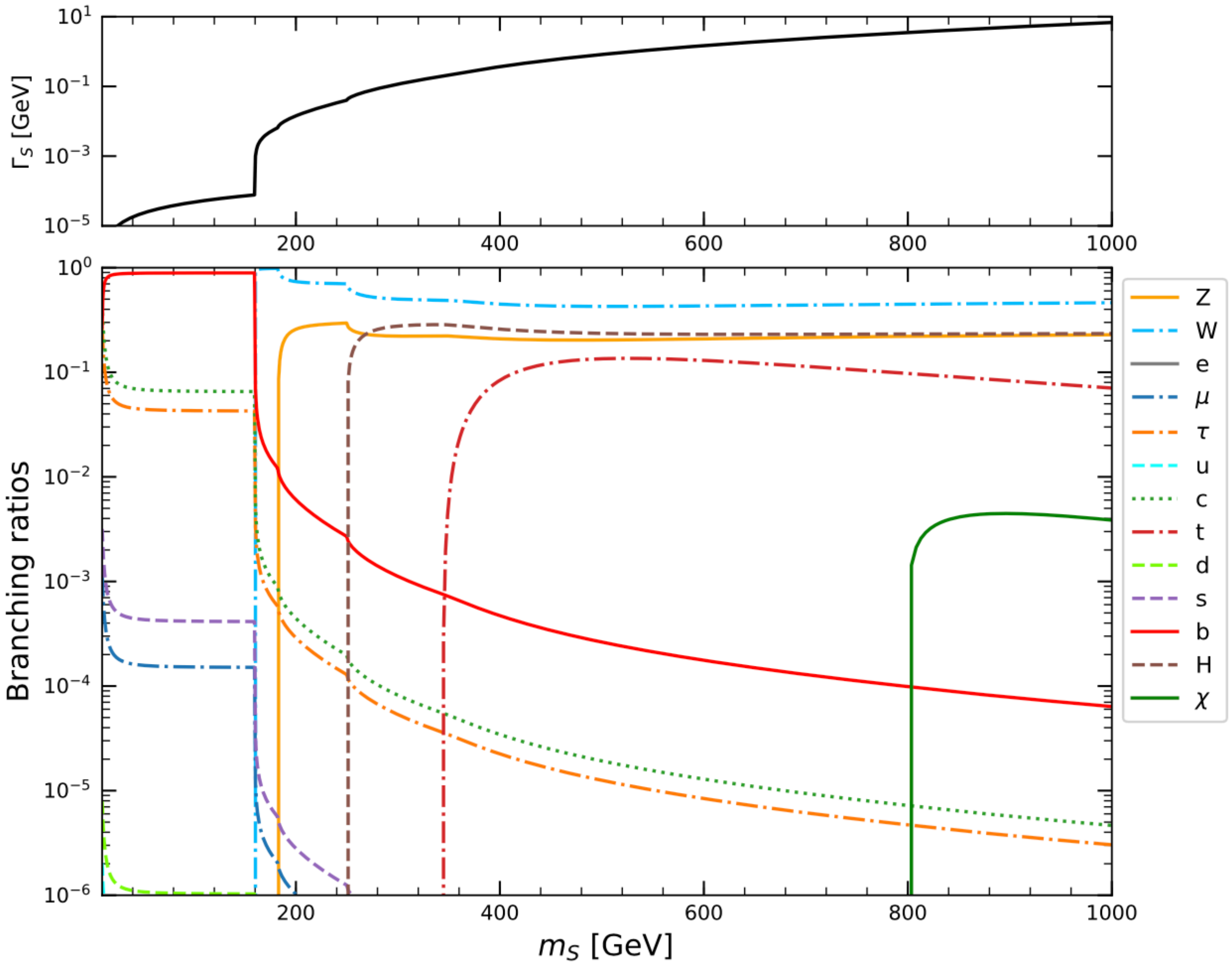
$$\Gamma_{\mathcal{H}\to\chi\chi} = \frac{\lambda_{H\chi\chi}^2}{32\pi m_{\mathcal{H}}}\sqrt{1-\frac{4m_\chi^2}{m_{\mathcal{H}}^2}},$$

$$\lambda_{\mathcal{H}\chi\chi} = -\kappa_\chi v_0 \cos\theta + \frac{2}{3}c_\chi \sin\theta.$$



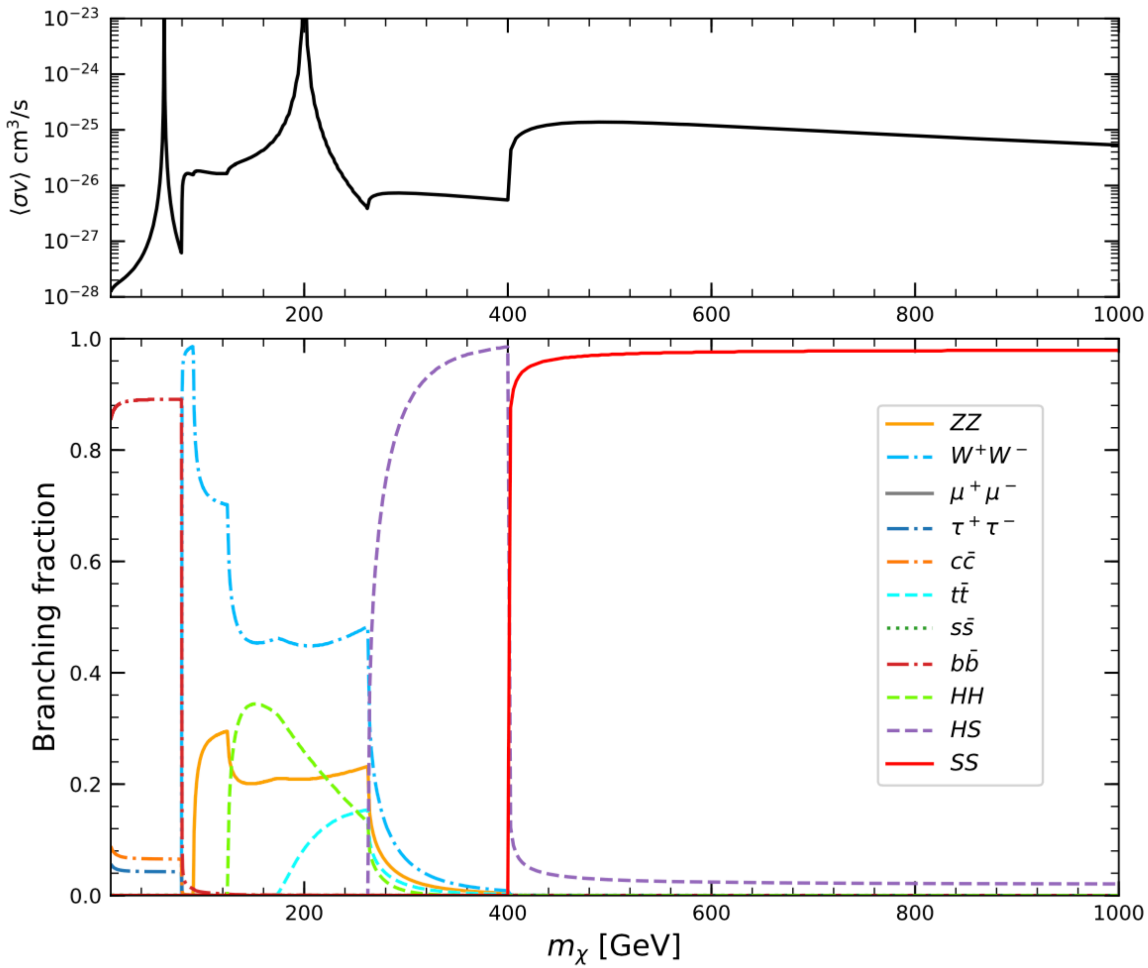
Complex singlet extension with a CP symmetry

s decay width $\Gamma_s \simeq sin^2\theta\Gamma_h$



Complex singlet extension with a CP symmetry

Annihilation cross section



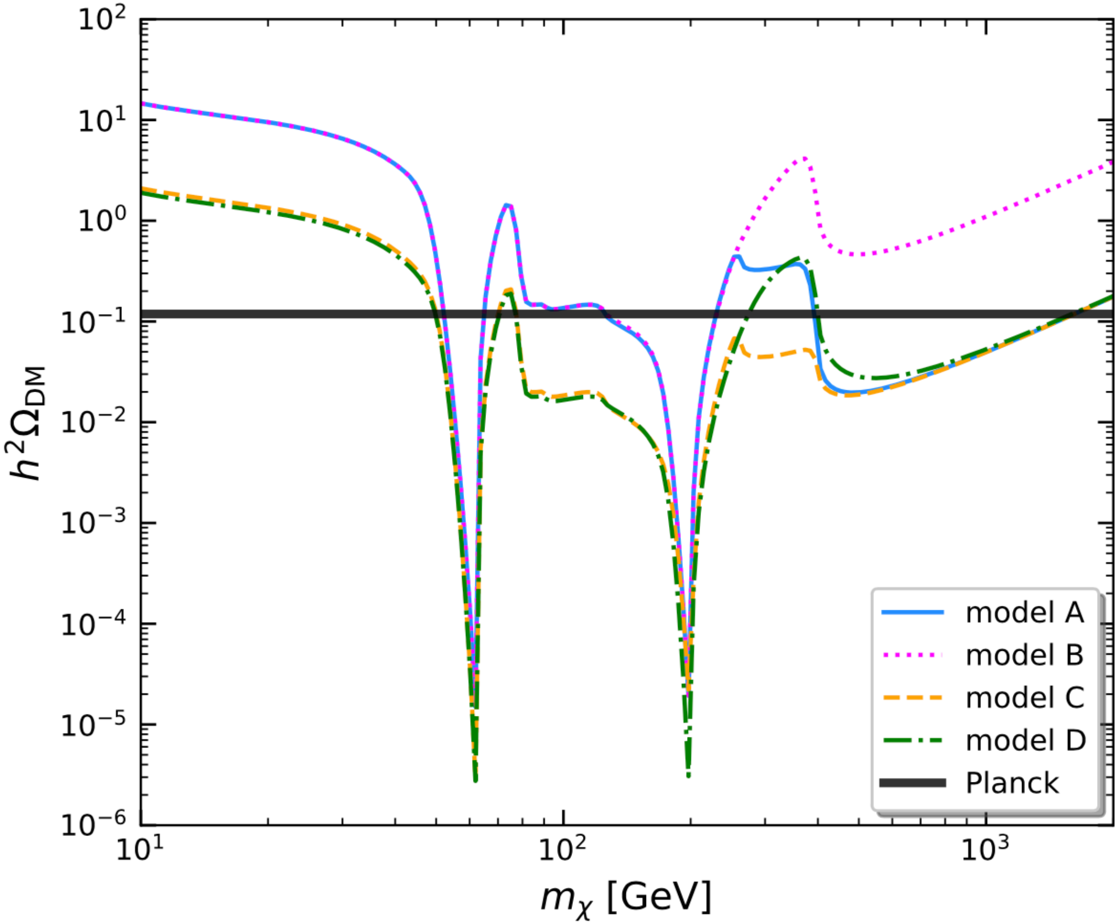
Complex singlet extension with a CP symmetry

Benchmark models

Model	θ	λ_a	c_χ [GeV]
A	0.1	0.5	-100
B	0.1	0.1	-100
C	0.3	0.5	-100
D	0.1	0.5	-300

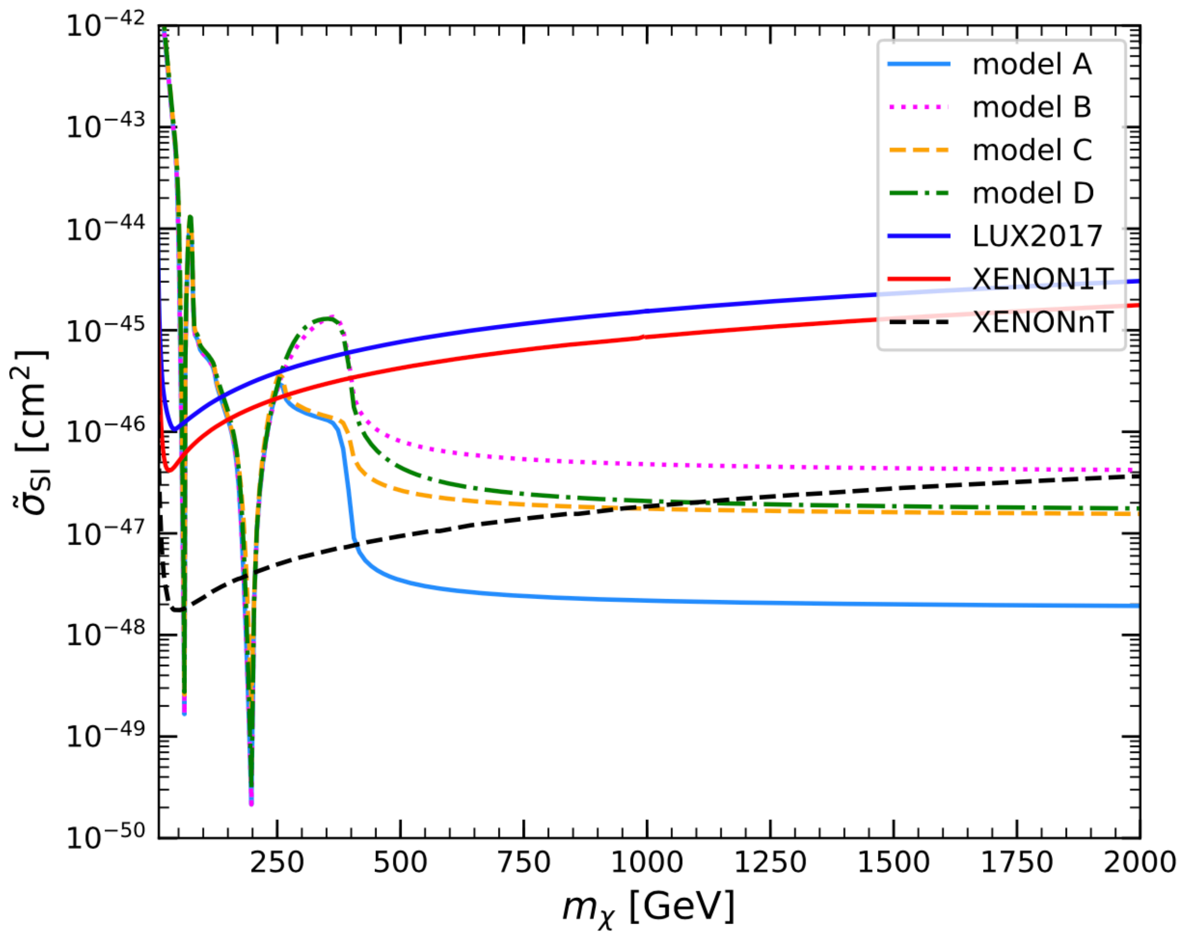
Complex singlet extension with a CP symmetry

Dark matter relic density

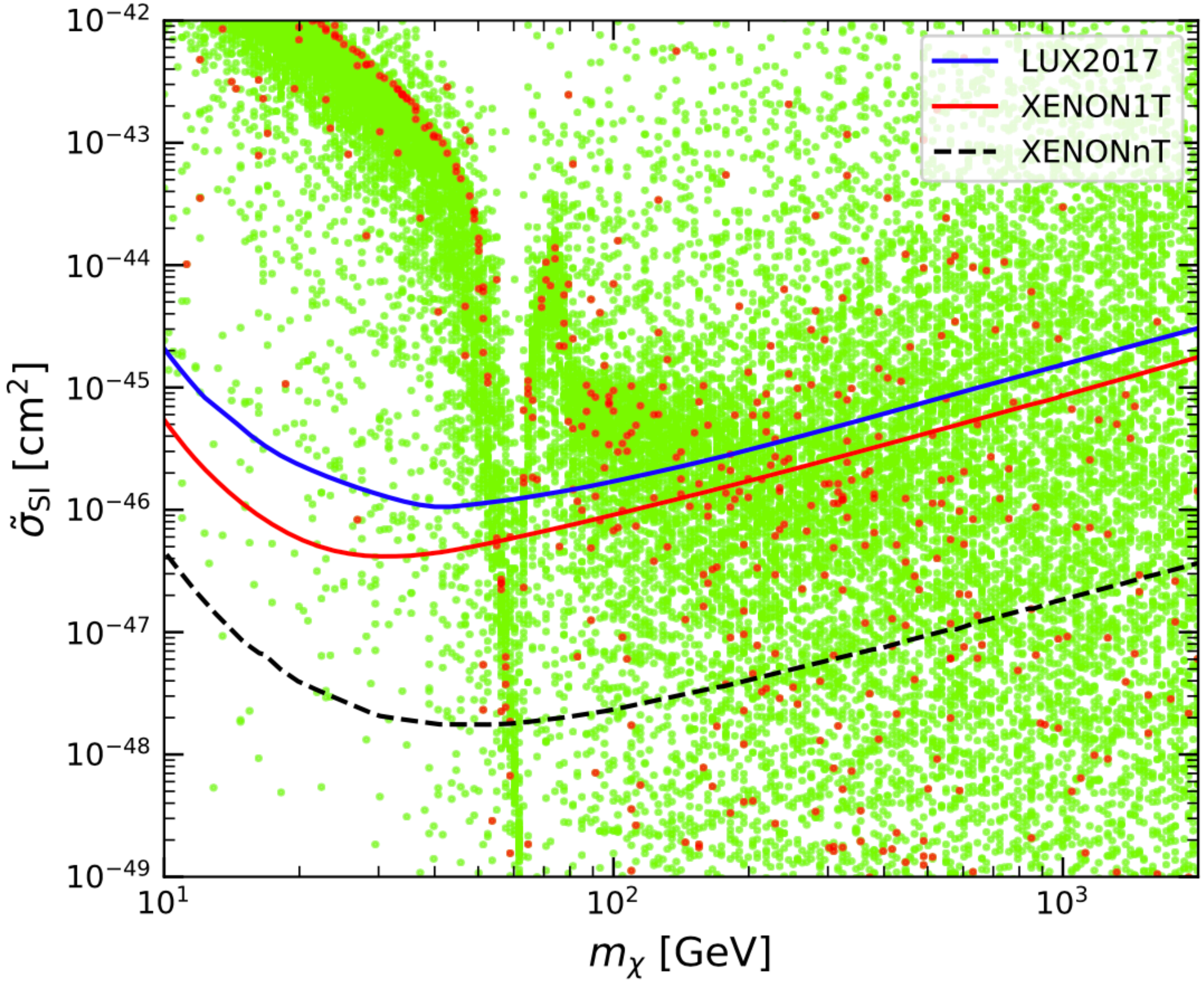


Complex singlet extension with a CP symmetry

Direct detection



Complex singlet extension with a CP symmetry



Summary

In this talk, we focus on the type-II EWPT in the singlet extension of SM and the related DM phenomenology. The main conclusions are as follows:

1. We show that the in the real singlet extension of SM with a Z2 symmetry, parameter regions for the type-II PT is constrained by the DM direct detection.
2. We then study the type-II EWPT in a complex singlet extension with a CP symmetry and find that plenty of parameter space is available for both generating the observed DM relic density while survive from various experimental constraints including Higgs signal strength measurements, DM relic density observations, and DM direct and indirect detections.
3. The future precious measurements of di-Higgs production at the colliders and DM direct detection experiments, such as XENONnT could further test the CP symmetry model.

The End.

Thank you!