Dark matter as the trigger of strong electroweak phase transition

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Talk at Pheno 2012

Based on: T. Chowdhury, M. Nemevsek, G. Senjanovic, YZ , JCAP **1202**, 029 [arXiv: 1110.5334]

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Baryon asymmetry & dark matter

- Two issues that particle physics SM cannot answer for cosmology:
  - Dark matter candidate.
  - Origin of baryon asymmetry of the universe.
- Connections between dark matter and baryon relic densities?
  - After/during baryogenesis, dark matter shares part of the asymmetry -- generally use B or L violating processes beyond SM.
  - Dark matter plays role in generating the baryon asymmetry.

Electroweak baryogenesis

- Baryon number in the SM is known able to be violated efficiently at high temperature.

‘t Hooft, 76’; Klinkhamer, Manton, 84’;
Kuzmin, Rubakov, Shaposhnikov, 85’

- SM fails for two reasons: no strong first-order phase transition & no enough CP violation -- mainly focus on phase transition in this talk.
- Strong first-order PhT calls for $v_c/T_c \gtrsim 1$ (suppress sphalerons inside the bubble). Thermal cubic from boson loops. SM: gauge bosons couple to Higgs too weakly.
- New scalars with sizable coupling to Higgs (like stop in MSSM).
- Can (one of) these scalars be dark matter candidate?

DM from an inert scalar doublet

- Two Higgs doublet (H, D) model with Z2 symmetry.

$$V = \mu_H^2 |H|^2 + \mu_D^2 |D|^2 + \lambda_1 |H|^4 + \lambda_2 |D|^4 + \lambda_3 |H|^2 |D|^2 + \lambda_4 |H^\dagger D|^2 + \frac{\lambda_5}{2}\left[(H^\dagger D)^2 + h.c. \right]$$

- Original motivations from little hierarchy problem, mirror fermions.

Deshpande, Ma, 78'; Barbieri, Hall, Rychkov hep-ph/0603188
Melfo, Nemevsek, Nesti, Senjanovic, YZ, 1105.4611

- Only one doublet H (Z2 even) gets VEV, breaks EW symmetry; The second doublet (Z2 odd) does not couple to fermions -- inert.

- Spectrum:

$$D = \begin{pmatrix} C^+ \\ (S + iA)/\sqrt{2} \end{pmatrix}$$

$$m_S^2 = \mu_D^2 + \frac{1}{2}\lambda_S v^2 \quad (\lambda_S = \lambda_3 + \lambda_4 + \lambda_5)$$

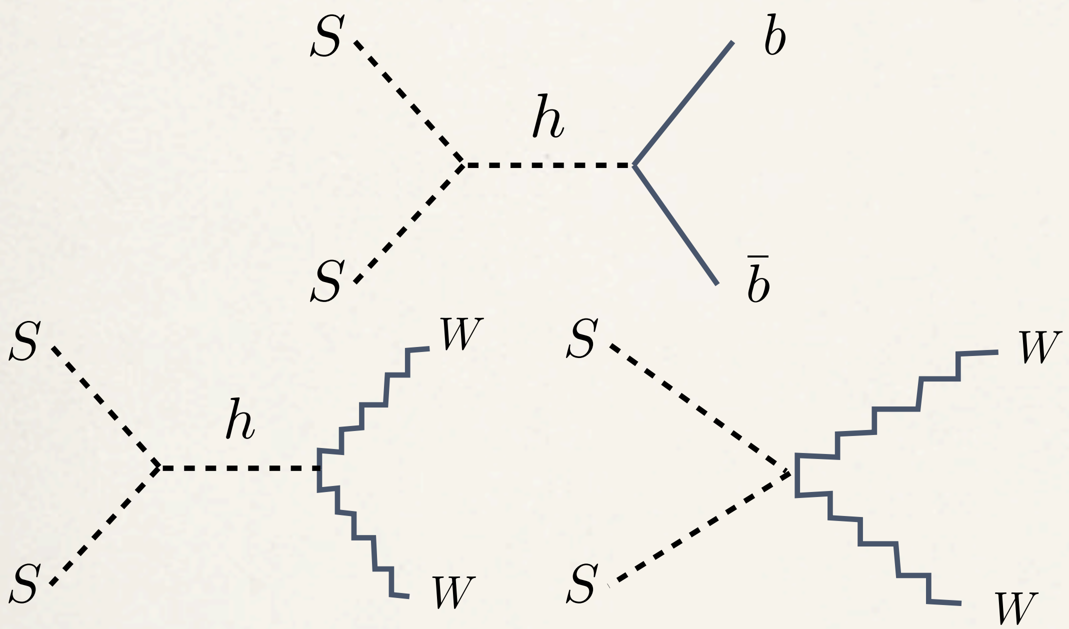
$$m_A^2 = \mu_D^2 + \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5) v^2$$

$$m_C^2 = \mu_D^2 + \frac{1}{2}\lambda_3 v^2$$

Dark matter candidate

- Precision test: $\Delta T \approx \frac{1}{24\pi^2 \alpha v^2}(m_C - m_A)(m_C - m_S)$ $\quad \Rightarrow m_A \approx m_C \gg m_S$

Relic density and direct detection

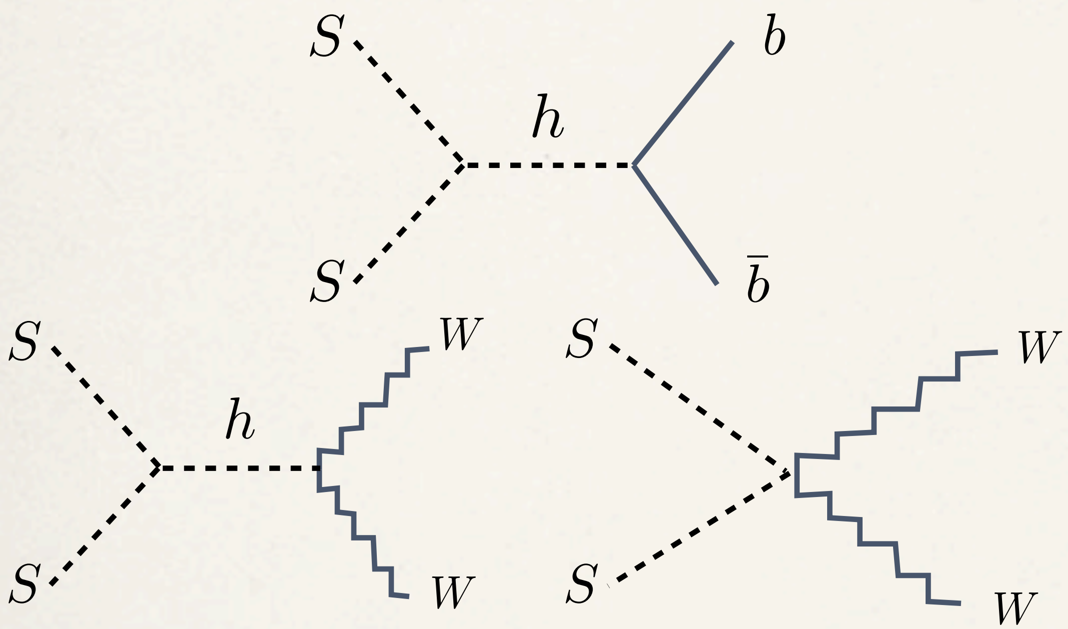


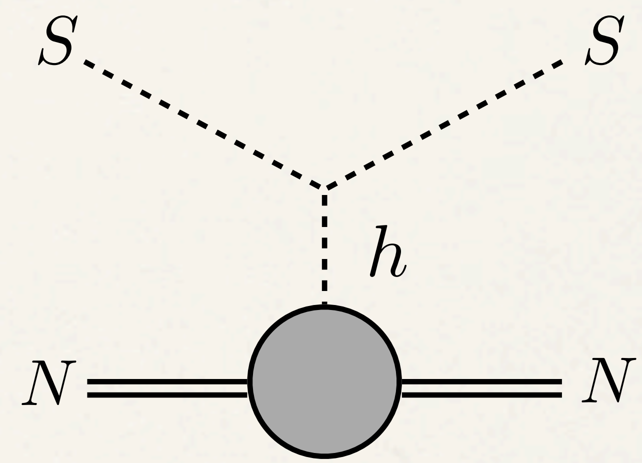
- Thermal freeze out

- Annihilate either through gauge interaction or via SM Higgs exchange.

- Destructive interference possible.

Relic density and direct detection





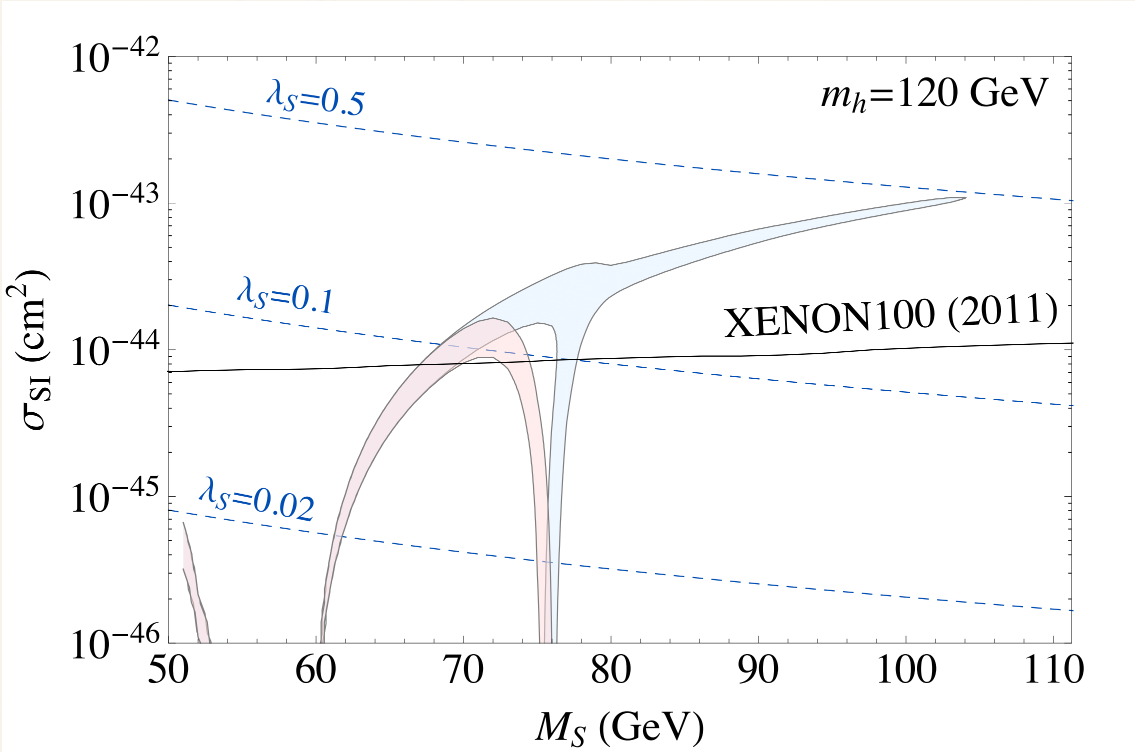
- Thermal freeze out
- Annihilate either through gauge interaction or via SM Higgs exchange.
- Destructive interference possible.

- Direct detection: Higgs mediated.
- Via interaction: $\lambda_S SS(h+v)^2$
- Cross section:

$$\sigma_{\mathrm{SI}} = \frac{\lambda_S^2 f^2}{4\pi} \frac{\mu_N^2 m_N^2}{m_h^2 m_S^2}$$

$$f = f_{T_u}^{(N)} + f_{T_d}^{(N)} + f_{T_s}^{(N)} + 2/9, \quad m_N f_{T_q}^{(N)} \equiv \langle N | m_q \bar{q} q | N \rangle$$

Constraints from Xenon 100



- DM mass: $m_h/2 - 76$ GeV, up to uncertainties in strange form factor and local dark matter density.

Melfo, Nemevsek, Nesti, Senjanovic, YZ, 1105.4611

- Lighter thermal singlet S (<~50 GeV) excluded by Xenon, and LEP (due to Z*SS production) and recently invisible Higgs decay.

- Indirect detection through gamma-ray line enhanced by W-loop.

M. Gustafsson, E. Lundstrom, L. Bergstrom, J. Edsjo, astro-ph/0703512

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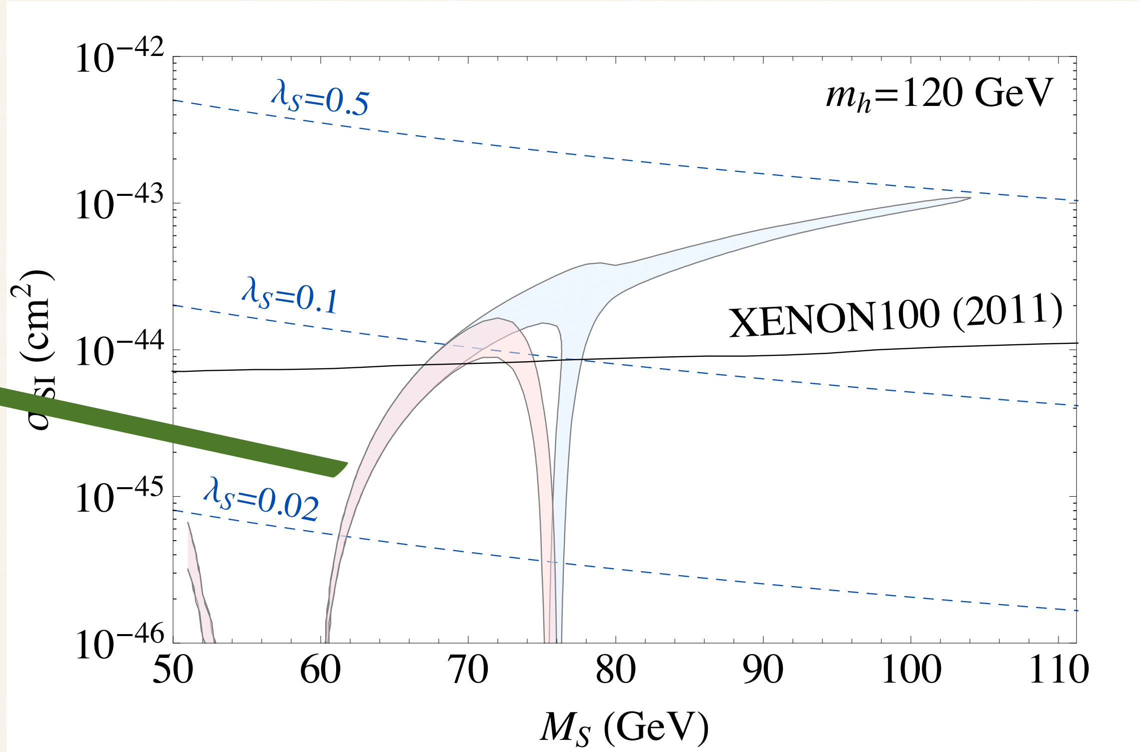
(on-shell Higgs)



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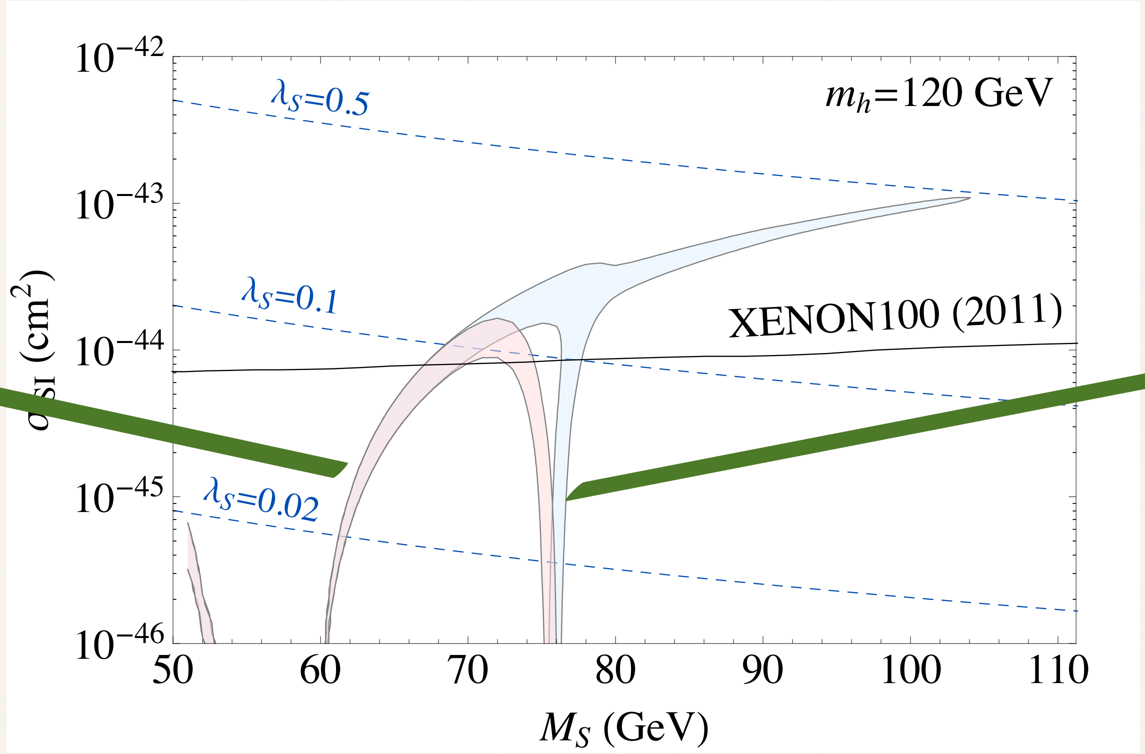

SS-->WW at threshold, via tail of Boltzmann distribution.

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EW phase transition

- Effective potential at high T: $V_{\text{eff}} = \frac{m^2(T)}{2}\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4$
- Strong first order phase transition, $\frac{v_c}{T_c} \gtrsim 1$ suppress sphaleron inside bubble.
- Cubic term is crucial. SM case: $\frac{v_c}{T_c} \approx \frac{3}{2\pi}\frac{2M_W^3 + M_Z^3}{m_h^2 v_0}$
- Require the Higgs be lighter than 50 GeV.
- Higgs potential at finite T

Only bosons contribute to thermal cubic

$$V_{\text{tot}} \approx \frac{1}{4}\lambda_1\phi^4 + \frac{1}{2}\left[-\mu_H^2 + a\frac{T^2}{12}\right]\phi^2 - \frac{T}{12\pi}\sum_{\text{bosons}} n_B m_B^3(\phi, T)$$

$$a = 6\lambda_1 + 2\lambda_3 + \lambda_4 + (9g^2 + 3g'^2)/4 + 3y_t^2$$

- List of bosons: $W^\pm, Z^0, h$; inert components $C^\pm, A, S$.

Phase transition w. inert doublet

- With an inert doublet, term proportional to T

$$-\frac{T}{12\pi}\left[m_S^3(T)+m_A^3(T)+2m_C^3(T)+4M_W^3(T)+2M_Z^3(T)\right]$$

- Thermal mass not purely from Higgs vev (like MSSM stop)

$$m_i^2(\phi,T)\approx\left(\mu_D^2+b\,\frac{T^2}{12}\right)+\frac{1}{2}\lambda_i\phi^2\ ,(i=S,A,C)$$

- Non-zero first term tends to weaken the strength of phase transition

$$\mu_D^2+\frac{T_c^2}{12}\left[6\lambda_D+\frac{m_S^2+m_A^2+2m_C^2-4\mu_D^2}{v_c^2}+\frac{9g^2+3g'^2}{4}\right]$$

- Need to minimize -- upper bound on μ_D^2 .

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Connection to direct detection

- More correlations:

  - S, A, C masses share the same μ_D^2, whose upper bound means lower bound on λ_S .

$$\text{Recall}: \quad V \sim \lambda_S SS(h+v)^2$$

  - DM mass: $m_S^2 = \mu_D^2 + \frac{1}{2}\lambda_S v^2 = m_h/2 - 76\,\mathrm{GeV}$ (relic density)

  - Direct detection: $\sigma_{\rm SI} = \frac{\lambda_S^2 f^2}{4\pi}\frac{\mu_N^2 m_N^2}{m_h^2 m_S^2}$

  - Thus strong phase transition implies a lower bound on direct detection cross section.

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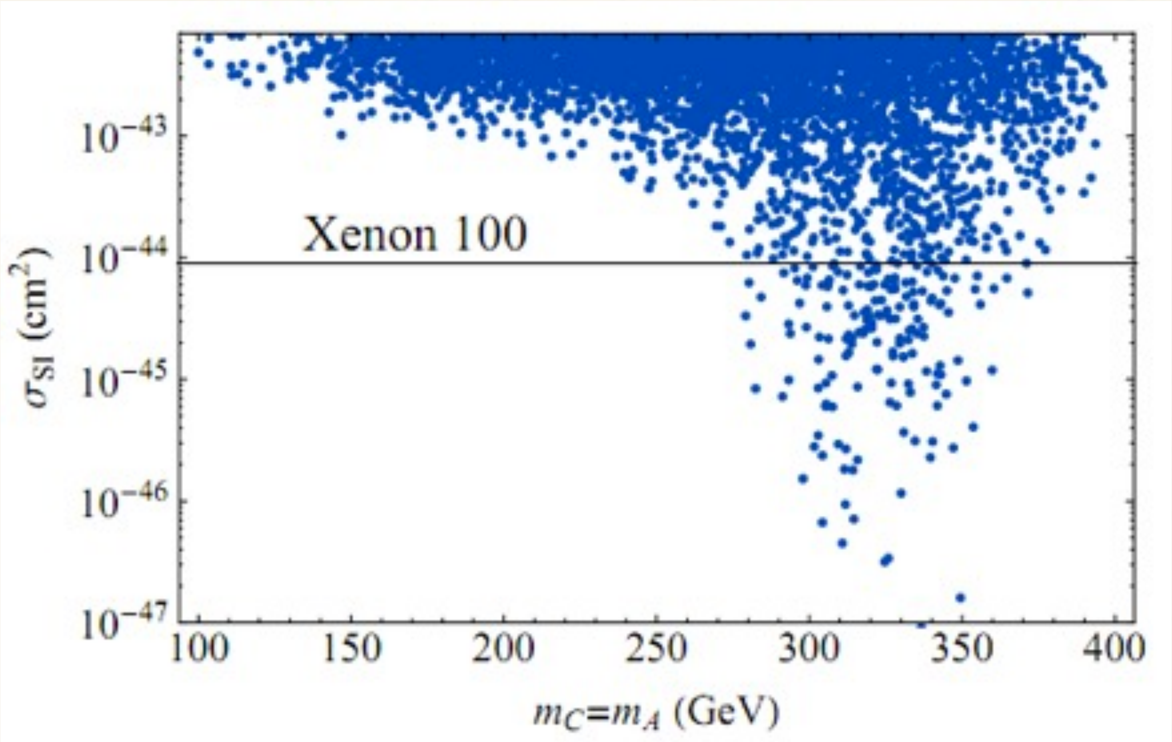
Constraints on the model



T. Chowdhury, M. Nemevsek, G. Senjanovic, YZ, JCAP, 1110.5334
D. Borah, J.M. Cline, 1204.4722

Constraints on the spectrum:

- A, C masses between 270-350 GeV (nearly degenerate);
- DM S mass mh/2-76 GeV, and small self interaction;
- SM Higgs mass must be <130 GeV.

Unique representation(s)

- Why not scalar singlet: direct detection wants its coupling to Higgs small, but phase transition wants it large.
- Can be done with a complex singlet -- essentially two real singlets -- less correlation between direct detection and phase transition?

  Barger, Langacker, McCaskey, Ramsey-Musolf, Shaughnessy, 0811.0393
- Higher representation?
- Integer weak-isospin: cannot accommodate light DM (end up >TeV).

  Cirelli, Fornengo, Strumia, hep-ph/0512090
- Half integer weak-isospin, allow light DM, but larger gauge contribution to thermal mass -- too weak phase transition (even for quadruplet).

Conclusions

- Dark matter could play important role in EW baryogenesis.
- We work with inert scalar doublet dark matter example -- a unique candidate.
- Strong phase transition implies a lower bound on direct detection cross section.
- Interplay with relic density - tightly constraint the spectrum - SM Higgs must be lighter than 130 GeV - new states testable at the LHC.
- Not a complete picture yet - new sources of CP violation needed, towards the symmetric dark matter - asymmetric baryon connection.

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Thank you!