Dark Matter and Electroweak Phase Transition

Leila Kalhor

Shahid Beheshti University, Tehran, Islamic Republic of Iran
l.kalhor@yahoo.com

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Light dark matter around 100 GeV from the inert doublet model

Shehu AbdusSalam, Leila Kalhor & Mohammad Mohammadidoust

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Abstract

We made global fits of the inert Higgs doublet model (IDM) in the light of collider and dark matter search limits and the requirement for a strongly first-order electroweak phase transition (EWPT). These show that there are still IDM parameter spaces compatible with the observational constraints considered. In particular, the data and theoretical requirements imposed favour the hypothesis for the existence of a scalar dark matter candidate around 100 GeV. This is mostly due to the pull towards lower masses by the EWPT constraint. The impact of electroweak precision measurements, the dark matter direct detection limits, and the condition for obtaining a strongly enough first-order EWPT, all have strong dependence, sometimes in opposing directions, on the mass splittings between the IDM scalars.

Outline

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- **Beyond Standard Model**

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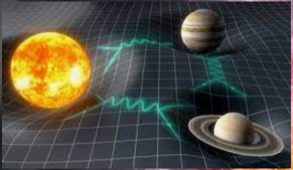
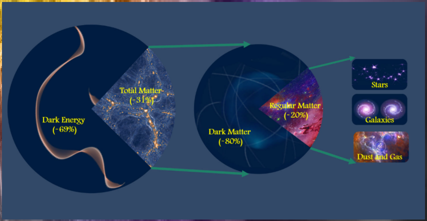
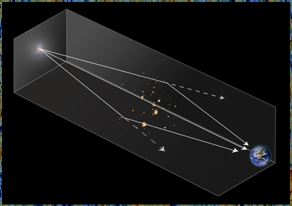
- **The IDM Global Fits**
- **Conclusion**

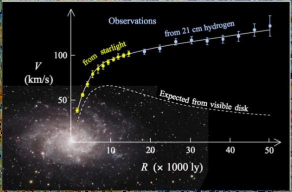
Can Standard Model describe All Phenomena in the nature ?





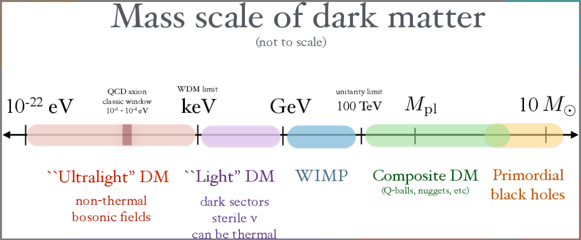
Evidence for Dark Matter

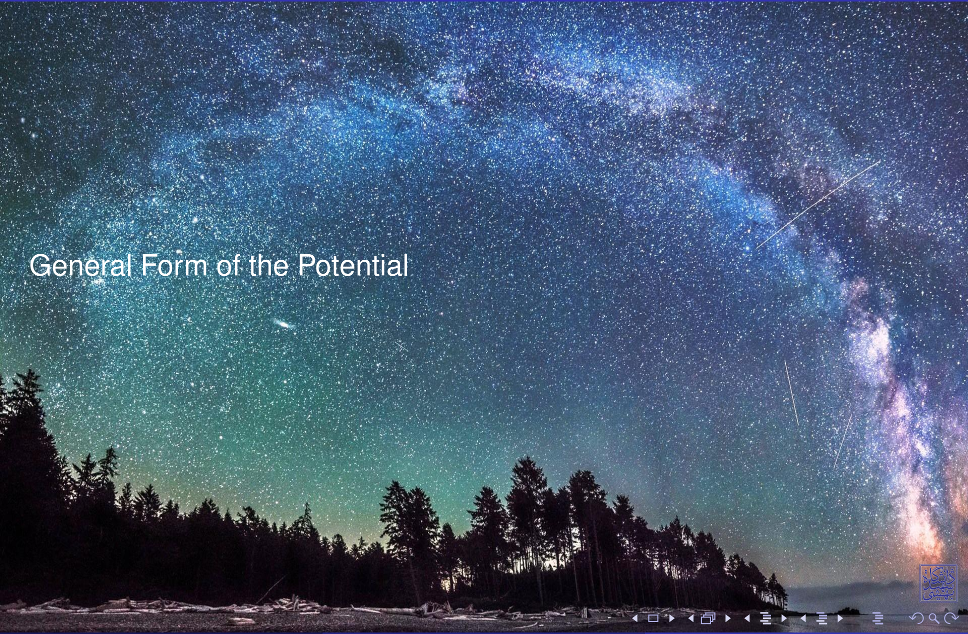




Candidate for Dark Matter

- Primordial Black Holes
- Axion
- Non-interacting or Sterile Neutrino
- WIMP





General Form of the Potential

Scalar Electroweak Multiplet Dark Matter

We use the most general, renormalizable scalar potential, assuming the presence of the Standard Model Higgs doublet, H, and an electroweak multiplet Q of arbitrary $SU(2)_L$ rank and hypercharge, Y .

For the structure of $V(H, Q)$ we consider Q to be a general representation of $SU(2)_L \times U(1)_Y$.

Shehu S. AbdusSalam and Talal Ahmed Chowdhury 1 , 2 , 3 , 4 , 5 doi = 10.1088/1475-7516/2014/05/026, title = Scalar representations in the light of electroweak phase transition and cold dark matter phenomenology,

W. Chao, G. J. Ding, X. G. He and M. Ramsey-Musolf, JHEP **08** (2019), 058 doi:10.1007/JHEP08(2019)058 [arXiv:1812.07829 [hep-ph]].

The usual Inert Doublet Model (IDM)

The Inert Doublet Model is a slightly extended version of the SM by an additional doublet which has the form

$$\text{with } H \equiv \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} x_1 + ix_2 \\ h + ix_3 \end{pmatrix} \quad \text{and} \quad Q = \frac{1}{\sqrt{2}} \begin{pmatrix} y_1 + iy_2 \\ S + iR \end{pmatrix} . \tag{1}$$

$$\begin{aligned} V = {} & \mu_h^2 \left|H\right|^2 + \mu_Q^2 \left|Q\right|^2 + \lambda_1 \left|H\right|^4 + \lambda_2 \left|Q\right|^4 \\ & + \lambda_3 \left|H\right|^2 \left|Q\right|^2 + \lambda_4 \left|H^\dagger Q\right|^2 + \frac{\lambda_5}{2} \left[\left(H^\dagger Q \right)^2 + \text{h.c.} \right] , \end{aligned} \tag{2}$$

The General IDM

The scalar potential is given by; [1]

$$V = \mu_h^2 |H|^2 + \lambda_h |H|^4 + \mu_Q^2 Q^\dagger Q + \lambda_1 [(QQ)_1 (\overline{Q}\,\overline{Q})_1]_0 + \alpha (H^\dagger H)(Q^\dagger Q) + \beta [(\overline{H}H)_1 (\overline{Q}Q)_1]_0 + \left\{ \kappa_1 [(HH)_1 (\overline{Q}\,\overline{Q})_1]_0 + H.c. \right\} \tag{3}$$

$$\text{with } H \equiv \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} x_1 + i x_2 \\ h + i x_3 \end{pmatrix} \quad \text{and} \quad Q = \frac{1}{\sqrt{2}} \begin{pmatrix} y_1 + i y_2 \\ S + i R \end{pmatrix}. \tag{4}$$

The transformation matrix V is equal to $\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$

$$\overline{H} = V H^* = \frac{1}{\sqrt{2}} \begin{pmatrix} h - i x_3 \\ -x_1 + i x_2 \end{pmatrix} \quad \text{and} \quad \overline{Q} = V Q^* = \frac{1}{\sqrt{2}} \begin{pmatrix} S - i R \\ -y_1 + i y_2 \end{pmatrix} \tag{5}$$

- In unitary gauge, the parameters used here map to the commonly used $\lambda_{1,2,\ldots,5}$ as follows:

$$\left(\lambda_h, \quad \frac{1}{\sqrt{3}} \lambda_1, \quad \alpha, \quad \frac{1}{2\sqrt{3}} \beta, \quad \frac{2}{\sqrt{3}} \kappa_1 \right) \to (\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5). \tag{6}$$

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IDM

The mass terms for the neutral scalar S, the pseudoscalar state, R, and for the charged scalar, $Y^{\pm}$, after electroweak symmetry breaking are

$$M_S^2 = \mu_Q^2 + (\frac{\alpha}{2} + \frac{\sqrt{3}}{3}K - \frac{\sqrt{3}}{12}\beta)v^2 \tag{7}$$

$$M_R^2 = \mu_Q^2 + (\frac{\alpha}{2} - \frac{\sqrt{3}}{3}K - \frac{\sqrt{3}}{12}\beta)v^2 \tag{8}$$

$$M_{Y^{\pm}}^2 = \mu_Q^2 + (\frac{\alpha}{2} + \frac{\sqrt{3}}{12}\beta)v^2. \tag{9}$$

For S to be the DM candidate particle, and stable, $M_S < M_R, M_{Y^{\pm}}$ must be satisfied. Accordingly, this choice will imply that $K < 0$ and $\frac{\sqrt{3}}{3}K + \frac{\sqrt{3}}{6}\beta < 0$.

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IDM

Table: The vertex factors for the IDM couplings.

vertex	factor	vertex	factor
$SSSS$	$2\sqrt{3}\lambda_1$	hhY^+Y^-	$\alpha + \frac{\sqrt{3}}{6}\beta$
$RRRR$	$2\sqrt{3}\lambda_1$	hY^+Y^-	$(\alpha + \frac{\sqrt{3}}{6}\beta)v$
$Y^+Y^-Y^+Y^-$	$4\frac{\sqrt{3}}{3}\lambda_1$	$hhRR$	$2\bar{\Lambda}_1$
$SSRR$	$\frac{2\sqrt{3}}{3}\lambda_1$	hSS	$2\Lambda_1 v$
SSY^+Y^-	$\frac{2\sqrt{3}}{3}\lambda_1$	$hhSS$	$2\Lambda_1$
RRY^+Y^-	$\frac{2\sqrt{3}}{3}\lambda_1$		

$$\Lambda_1 = \frac{\alpha}{2} + \frac{\sqrt{3}}{3}K - \frac{\sqrt{3}}{12}\beta, \quad \text{and} \quad \bar{\Lambda}_1 = \frac{\alpha}{2} - \frac{\sqrt{3}}{3}K - \frac{\sqrt{3}}{12}\beta \tag{10}$$

are respectively related to the triple and quartic couplings between the SM Higgs h and the DM candidate S or the pseudoscalar R. The parameters α and β, on the other hand, determines the mass term, and describe the h interaction with the charged scalars $Y^{\pm}$. The parameter λ_1 describes the quartic self- and non-self couplings of extended Higgs sector particles.

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The Constraints On The IDM

- Vacuum Stability
- Perturbativity
- Oblique parameters
- Limits from collider searches
- First order electroweak phase transition

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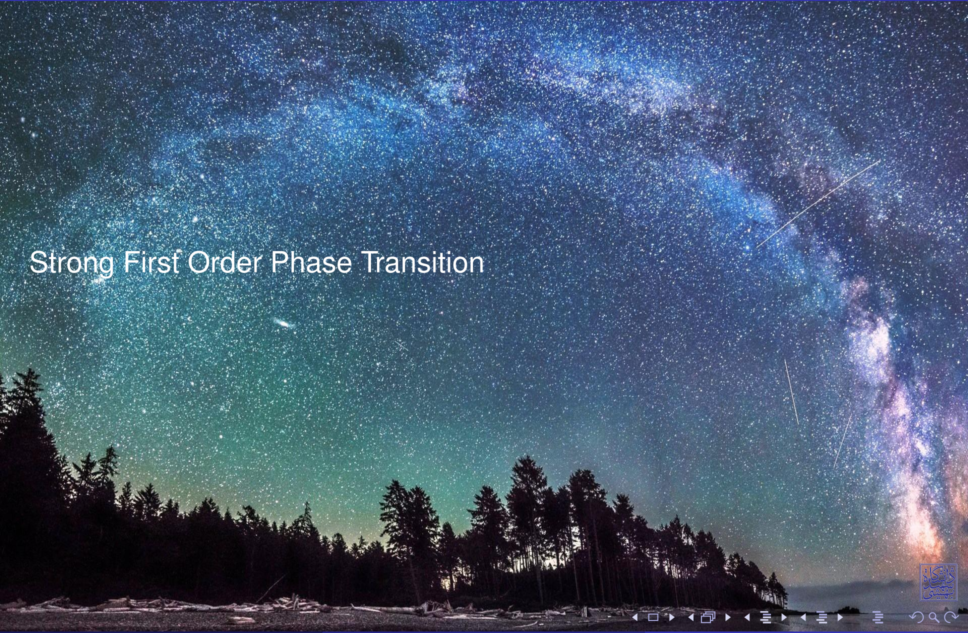
Electroweak Phase Transition



Strong First Order Phase Transition

First Order Phase Transition

In the SM, the EWPT is a crossover which means that there is no discontinuous change in any derivative of order parameter and there is no bubble nucleation during the transition.

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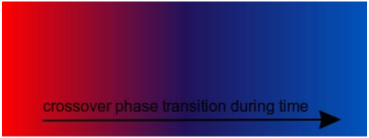

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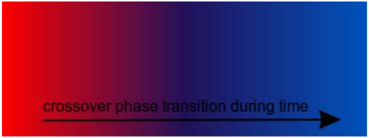

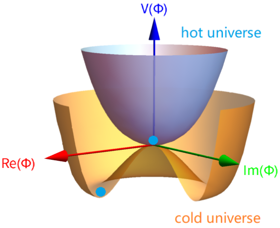

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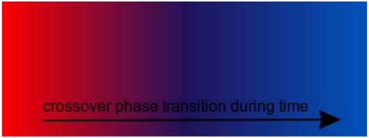

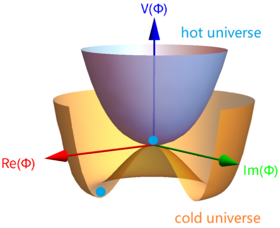

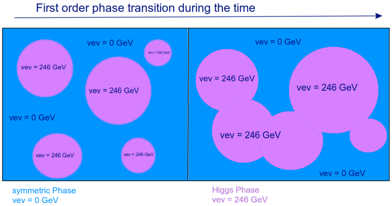

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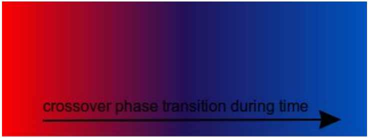
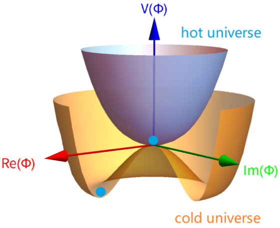
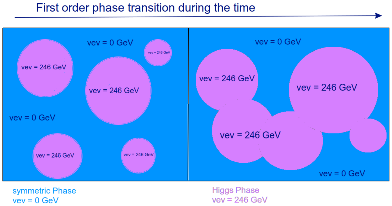


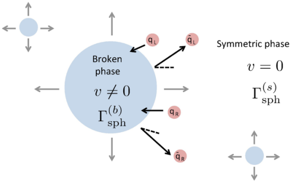




The most relevant equilibrium features of the EWPT are its strength and character whether the transition is of first or second order, or a crossover.

Strong First Order Thase Transition

Sphaleron transition rate that describe the rate of baryon number generation and washout.



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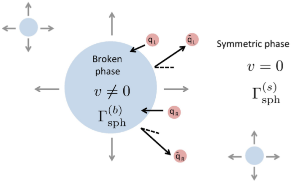

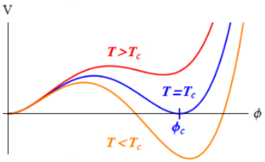

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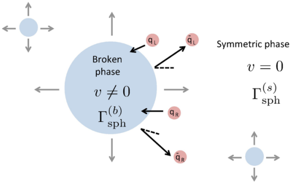

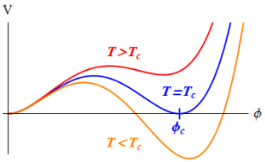

At T_c , there is another minimum at a non-zero value of the field that is degenerate with the minimum at the origin.

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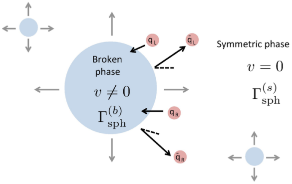

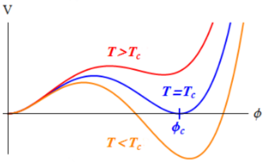

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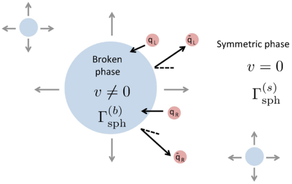

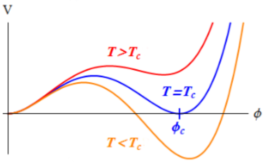

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Strong First Order Phase Transition

(sphaleron Rate)<(Expansion Rate) $\rightarrow \frac{\phi_c}{T_c} > 1$

$\theta = \{M_S^2, M_R^2, M_Y^2, \Lambda_1\}$

$d = \{M_H, \Omega h, \frac{V_c}{T_c}, other\ constraints\}$

Only model points that pass the set of theoretical and experimental constraints, d, described above and for which the lightest odd particle is the CP-even IDM Higgs boson, S, are passed for implementing the nested sampling algorithm. For these IDM parameter points, we model the likelihood $p(d|\theta)$ of the IDM predictions, O_i, corresponding to the ith constrain, with experimental central values μ_i and uncertainties σ_i, as

$$p(d|\theta) = \prod_i \frac{\exp\left[-(O_i - \mu_i)^2/2\sigma_i^2\right]}{\sqrt{2\pi\sigma_i^2}}. \quad (12)$$

F. Feroz, M. P. Hobson and M. Bridges, Mon. Not. Roy. Astron. Soc. **398** (2009), 1601-1614 doi:10.1111/j.1365-2966.2009.14548.x [arXiv:0809.3437 [astro-ph]].

Results from Global Fits

What is happening for Dark matter when
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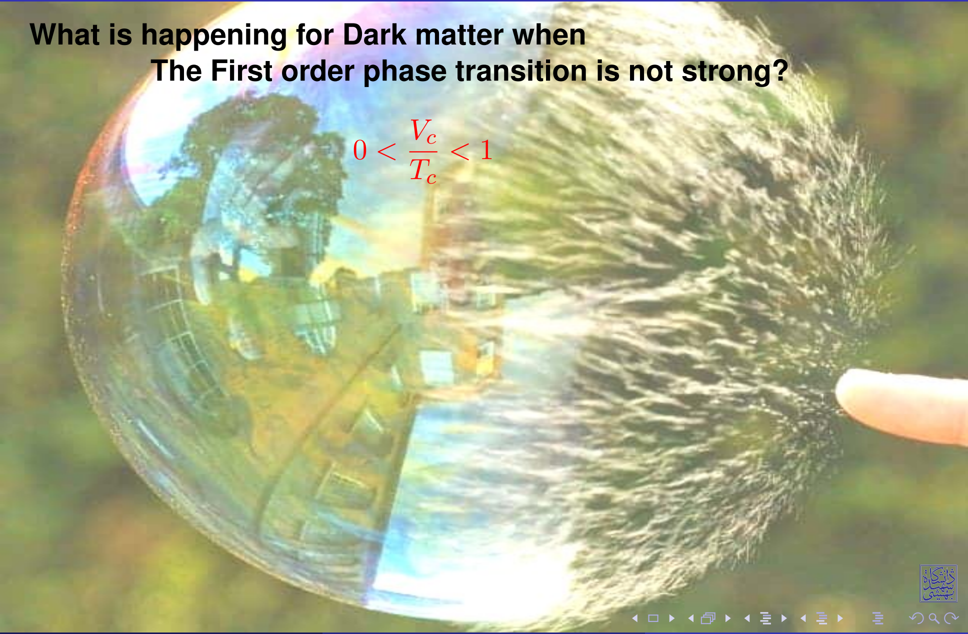

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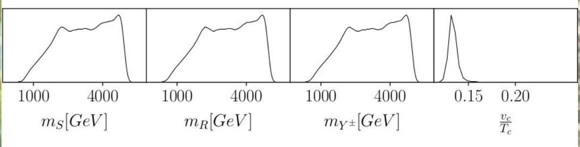

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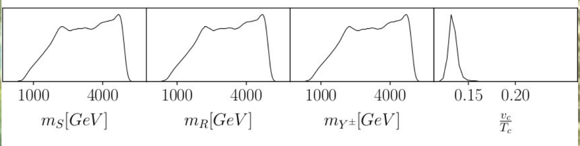

1-Dimensional posterior distributions from the global fit of the IDM parameters to data. The prior distributions for the mass parameters are flat in the range, [1, 5000] GeV. All model points pass the set of constraints.

Results from Global Fits

What is happening for Dark matter when
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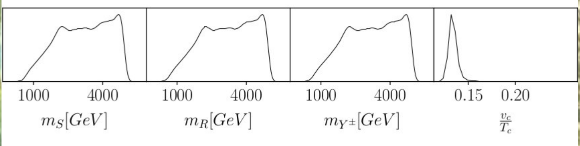

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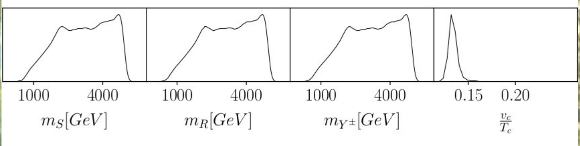

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S. AbdusSalam, L. Kalhor and M. Mohammadidoust, Eur. Phys. J. C **82** (2022) no.10, 892 doi:10.1140/epjc/s10052-022-10862-4 [arXiv:2208.13705 [hep-ph]].

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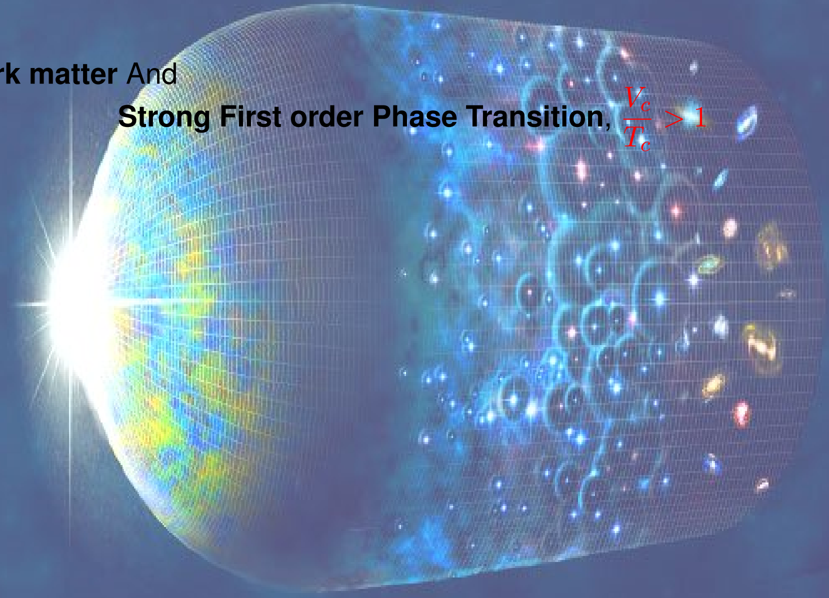

Dark matter And

Strong First order Phase Transition, $\frac{V_c}{T_c} > 1$

Results from Global Fits

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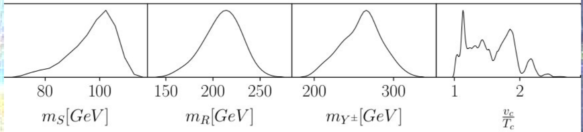

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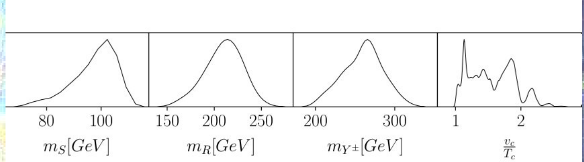

Light dark matter around 100 GeV from the inert doublet model

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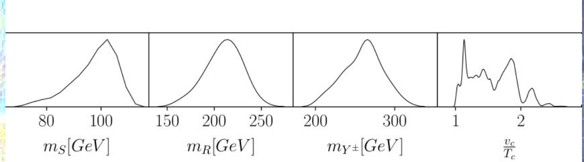

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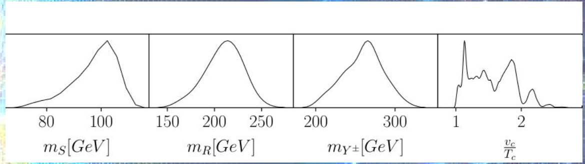

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Ali Ibn Abitaleb:

“You presume you are a small entity,
but within you is enfolded an entire universe.”

Diwan al-Imam Ali, Dar al-kutub al-ilmiyya, Beirut, P.86