Scalar Electroweak Multiplet DM

M.J. Ramsey-Musolf

U Mass Amherst / TDLI-SJTU

My pronouns: he/him/his

http://www.physics.umass.edu/acfi/

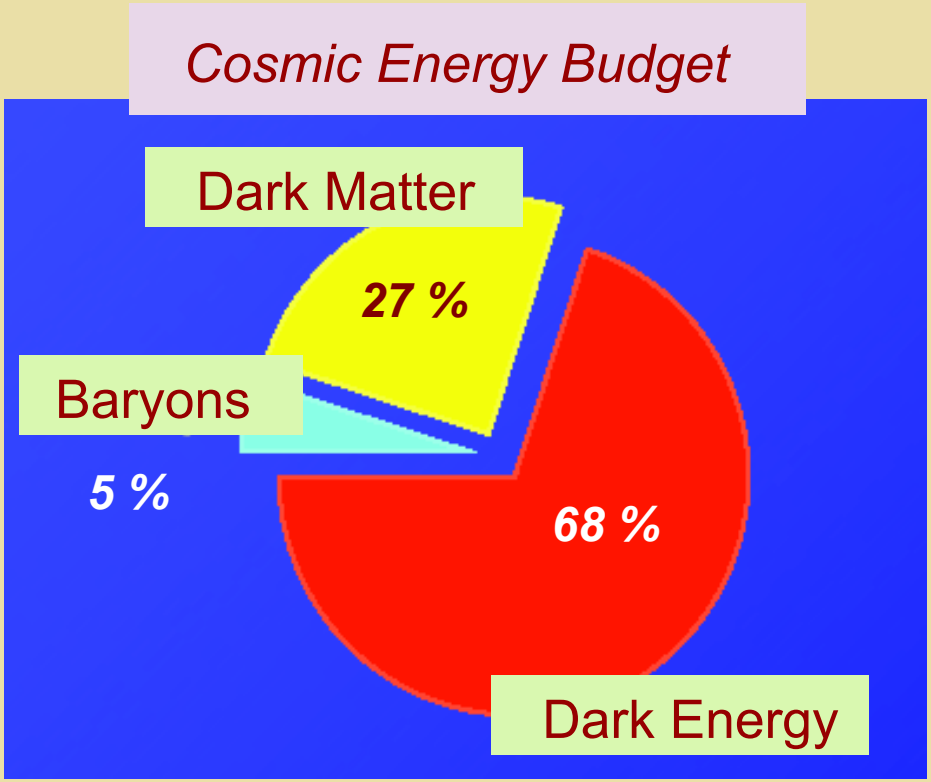
http://tdli.sjtu.edu.cn/web/yjxy/5130001.htm

***Collaborators:** W. Chao, G-J Ding, X-G He*

1812.07829/hep-ph (to appear in JHEP)

FLASY 2019
TDLI/SJTU, July 2019

Particle Physics-Cosmology Interface



Can extensions of the SM scalar sector with EW multiplets address open problems in cosmology ?

This talk: dark matter

Scalar EW Multiplets

- *For a suitable choice of parameters, extended scalar sectors with EW multiplets (colorless) can lead to a strong, first order EW phase transition as needed for EW baryogenesis*
- *To what extent can the neutral component(s) of these multiplets contribute to the DM relic density and what are the phenomenological signatures ?*

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Outline

I. Context

II. Models

III. DM Dynamics & Pheno

IV. Collider Probes ← *Time permitting*

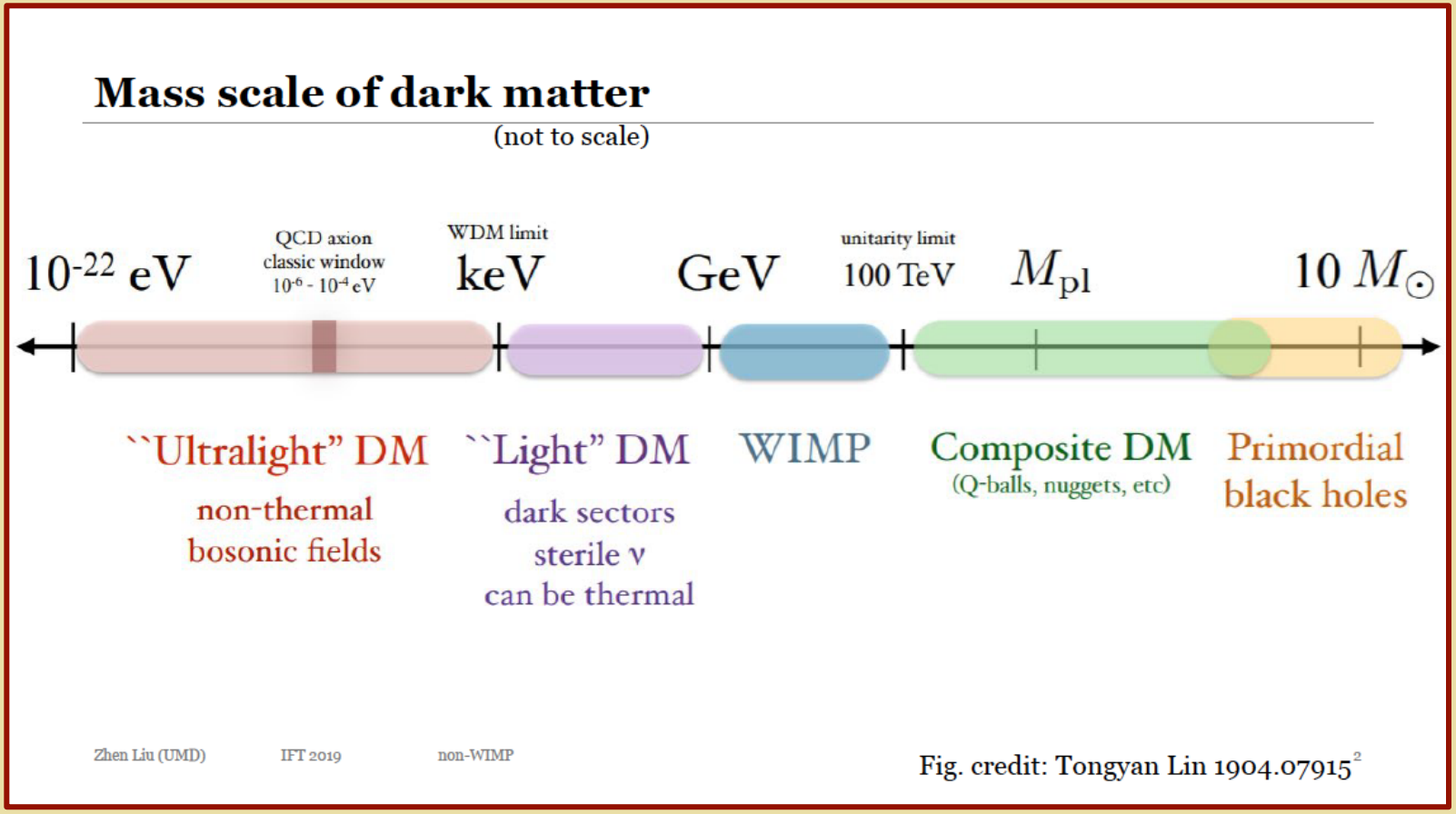
V. Outlook

I. Context

Dark Matter

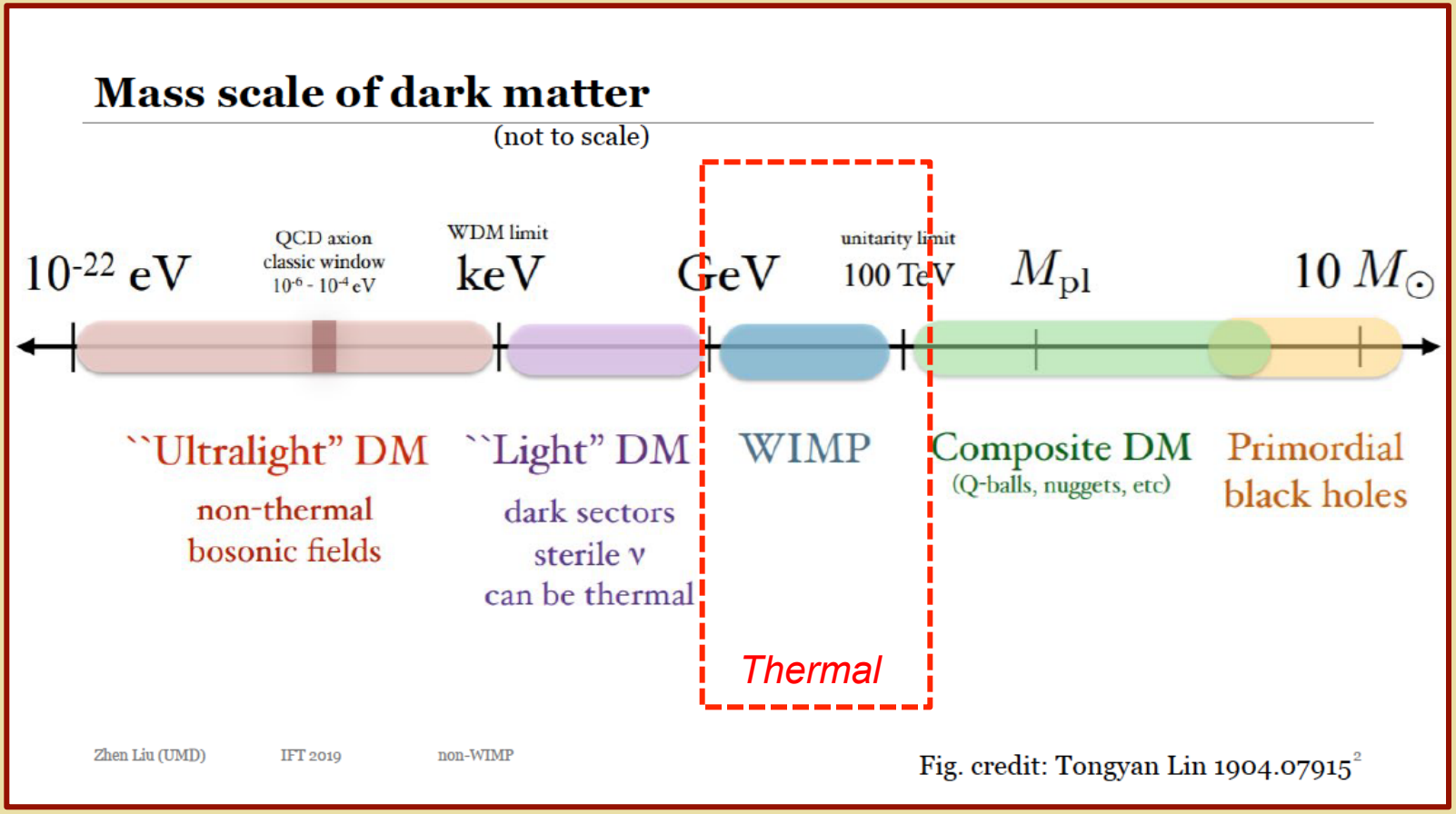
- *What is the dark matter ?*
- *What are its properties (thermal/non-thermal, density profiles,…) ?*
- *What are its interactions ?*

Dark Matter



Thanks: Z. Liu, T. Lin

Dark Matter



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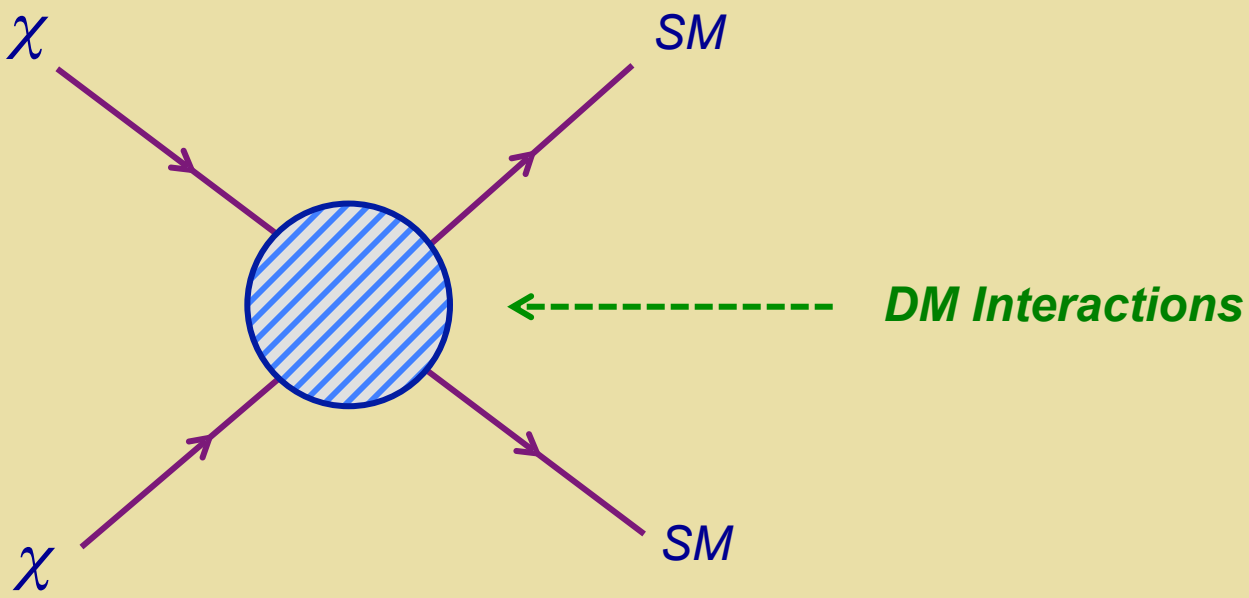
WIMP Dark Matter



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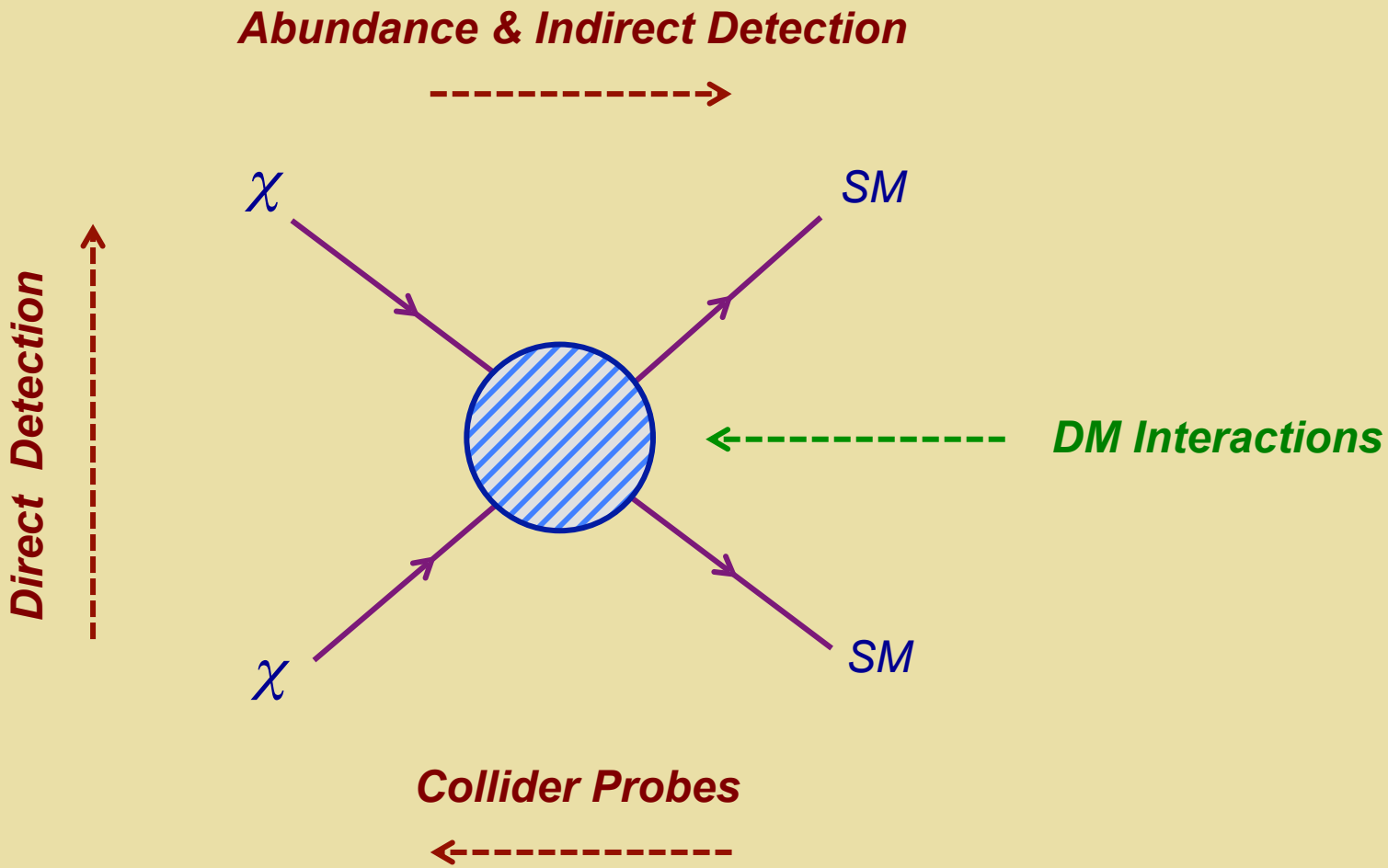

Dark Matter Portals

- *Gauge sector (SUSY neutralinos)*
- *Higgs portal (BSM scalars)* *This Talk*
- *QCD portal (Axion)*
- *Yukawa portal (neutrinos)*
- *Vector Portal*

Extended Higgs Sector: EW Multiplets

- ***To what extent can EW multiplets catalyze a strong 1st order EWPT and contribute to Ω_{DM} ?***
- ***What is interplay between DM mass, Higgs portal coupling, dimension of the representation, Ω_{DM} , and bounds on σ_{SI} ?***

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EWPT & Dark Sector: EW Multiplets

Cirelli & Strumia '05

Quantum numbers $SU(2)_L$	$U(1)_Y$	Spin	DM can decay into	DM mass in TeV	$m_{DM^\pm} - m_{DM}$ in MeV	Events at LHC $\int \mathcal{L}\, dt = 100/\text{fb}$	σ_{SI} in $10^{-45}\,\text{cm}^2$
2	1/2	0	EL	0.54 ± 0.01	350	$320 \div 510$	0.2
2	1/2	1/2	EH	1.1 ± 0.03	341	$160 \div 330$	0.2
3	0	0	HH^*	2.0 ± 0.05	166	$0.2 \div 1.0$	1.3
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Higgsino

Real Triplet

Wino Triplet

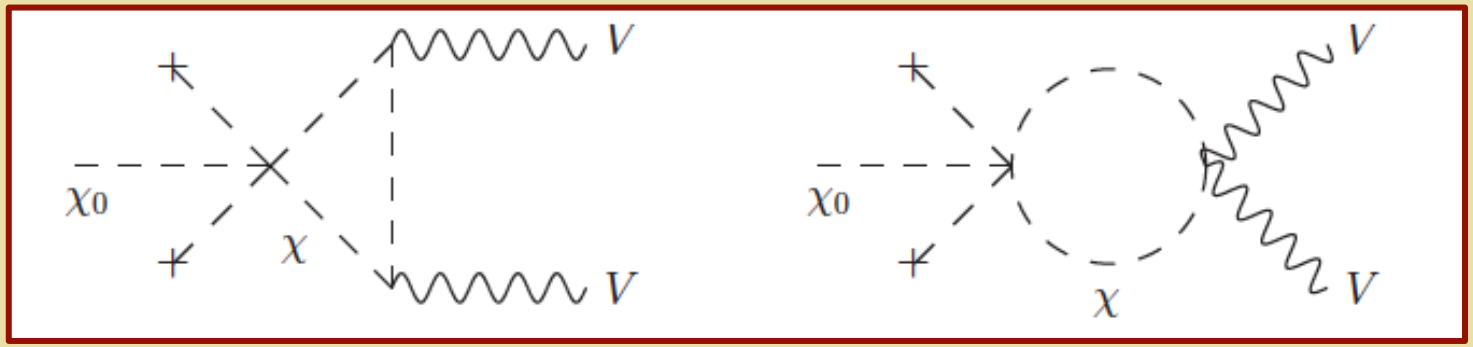
This study

This study

"Minimal Scalar DM"

EWPT & Dark Sector: EW Multiplets

***Caveat:* "minimality" is a tree-level identification**



Luzio et al '15; Nobile et al '15: Loops involving higher dim op's can lead to "fast" DM decay for $\Lambda < M_{Planck}$

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Gauge interactions only

"Minimal Scalar DM"

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Gauge interactions only

"Minimal Scalar DM"

Impact of Higgs portal ?

II. Models

W. Chao, G-J Ding, X-G He, MJRM 1812.07829/hep-ph (to appear in JHEP)

Previous work: Hambye et al '09, Abdus Salaam & Chowdhury '13

General Considerations

- *Renormalizable interactions*
- *$Y = 0$*
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General EW Multiplet Φ

$$\overline{\Phi}_{j,m} = (-1)^{j-m}\Phi^*_{j,-m}$$ *Conjugate Rep*

$$A = \frac{1}{\sqrt{2}}\left(\Phi + \overline{\Phi}\right), \qquad B = \frac{i}{\sqrt{2}}\left(\Phi - \overline{\Phi}\right)$$ *Contains 2 real reps:* $\Phi = \overline{\Phi}$.

General Considerations

Invariants

$\left((\Phi\Phi)_J\left(\overline{\Phi}\,\overline{\Phi}\right)_J\right)_0$, $J=0,1,\ldots,2j$ — *Self-interactions*

$\left(\left(\overline{H}H\right)_L\left(\overline{\Phi}\Phi\right)_L\right)_0$ *L=0,1* — *Higgs portal: real or complex Φ*

$\left(\overline{H}H\right)_0(\Phi\Phi)_0$ — *Higgs portal: complex Φ (distinct)*

Scalar Potential: Higgs Portal

Septuplet case (n=5 similar)

$$
\begin{aligned}
V = & +M_A^2(\Phi^\dagger\Phi) + \left\{M_B^2(\Phi\Phi)_0 + \text{h.c.}\right\} - \mu^2 H^\dagger H \\
& +\lambda(H^\dagger H)^2 + \lambda_1(H^\dagger H)(\Phi^\dagger\Phi) \\
& +\lambda_2[(\overline{H}H)_1(\overline{\Phi}\Phi)_1]_0 + [\lambda_3(\overline{H}H)_0(\Phi\Phi)_0 + \text{h.c.}]
\end{aligned}
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\end{aligned}
$$

Three portal couplings and three mass terms in general

N.B. Previous work did not include all possible renormalizable interactions

Spectrum

Septuplet case (n=5 similar)

$$\mathcal{L}_{\rm mass} = \begin{pmatrix} \phi_{3,k} & \phi^*_{3,-k} \end{pmatrix} \begin{pmatrix} M_A^2 + \frac{1}{2}\lambda_1 v^2 + \frac{1}{4\sqrt{42}} k\lambda_2 v^2 & \frac{\sqrt{7}}{7}(-1)^{k+1}\left\{2M_B^2 + \frac{1}{\sqrt{2}}\lambda_3 v^2\right\} \\ \frac{\sqrt{7}}{7}(-1)^{k+1}\left\{2M_B^{2*} + \frac{1}{\sqrt{2}}\lambda_3^* v^2\right\} & M_A^2 + \frac{1}{2}\lambda_1 v^2 - \frac{1}{4\sqrt{42}} k\lambda_2 v^2 \end{pmatrix} \begin{pmatrix} \phi^*_{3,k} \\ \phi_{3,-k} \end{pmatrix}$$

Eigenvalues:

$$M^2_{\hat{\phi}_{3;\pm k}} = M_A^2 + \frac{1}{2}\lambda_1 v^2 \pm \sqrt{\left|\frac{2M_B^2}{\sqrt{7}} + \frac{\lambda_3 v^2}{\sqrt{14}}\right|^2 + \frac{k^2\lambda_2^2 v^4}{672}}$$

$$M^2_{\hat{\phi}_{3;(0,\pm)}} = M_A^2 + \frac{1}{2}\lambda_1 v^2 \pm \left|\frac{2M_B^2}{\sqrt{7}} + \frac{\lambda_3 v^2}{\sqrt{14}}\right|$$

$M^+ - M^0$ = |EW loops|

+/- λ_2 contribution

Spectrum

Septuplet case (n=5 similar)

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- *Set $\lambda_2 = 0$: no stable charged scalars*
- *If set $M_B = 0$: two degenerate multiplets (can be real)*

Scalar Potential: Higgs Portal

Septuplet case (n=5 similar)

$$
\begin{aligned}
V = & +M_A^2(\Phi^\dagger\Phi) + \left\{M_B^2(\Phi\Phi)_0 + \text{h.c.}\right\} - \mu^2 H^\dagger H \\
& +\lambda(H^\dagger H)^2 + \lambda_1 (H^\dagger H)(\Phi^\dagger\Phi) \\
& +\lambda_2 (\overline{H}H)_1(\overline{\Phi}\Phi)_1]_0 + [\lambda_3 (\overline{H}H)_0(\Phi\Phi)_0 + \text{h.c.}]
\end{aligned}
$$

Three portal couplings and three mass terms in general

- *Set $\lambda_2 = 0$ for DM stability*
- *All dynamics affected by λ_{eff}*

$$
\lambda_{\text{eff}} = \begin{cases} \lambda_1 \pm \sqrt{\frac{2}{7}}\lambda_3 \ , & \text{septuplet} \\ \lambda_1 \mp \sqrt{\frac{2}{5}}\lambda_3 \ , & \text{quintuplet} \end{cases}
$$

Scalar Potential: DM Self Interactions

Septuplet case (n=5 similar)

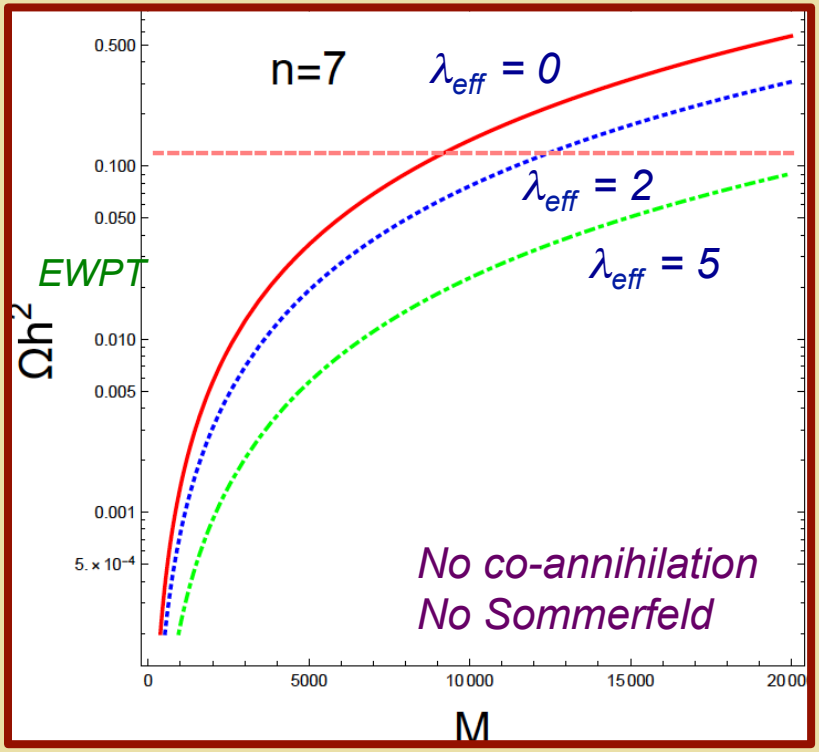
$$V_{quartic} = \sum_{J=0}^{2J} \kappa_k \left((\Phi\Phi)_k (\overline{\Phi}\,\overline{\Phi})_k \right)_0 + \sum_{k=0}^{2J} \Big\{ \kappa'_k \left((\Phi\Phi)_k (\Phi\Phi)_k \right)_0 + \kappa''_k \left((\overline{\Phi}\,\Phi)_k (\Phi\Phi)_k \right)_0 + \text{h.c.} \Big\}$$

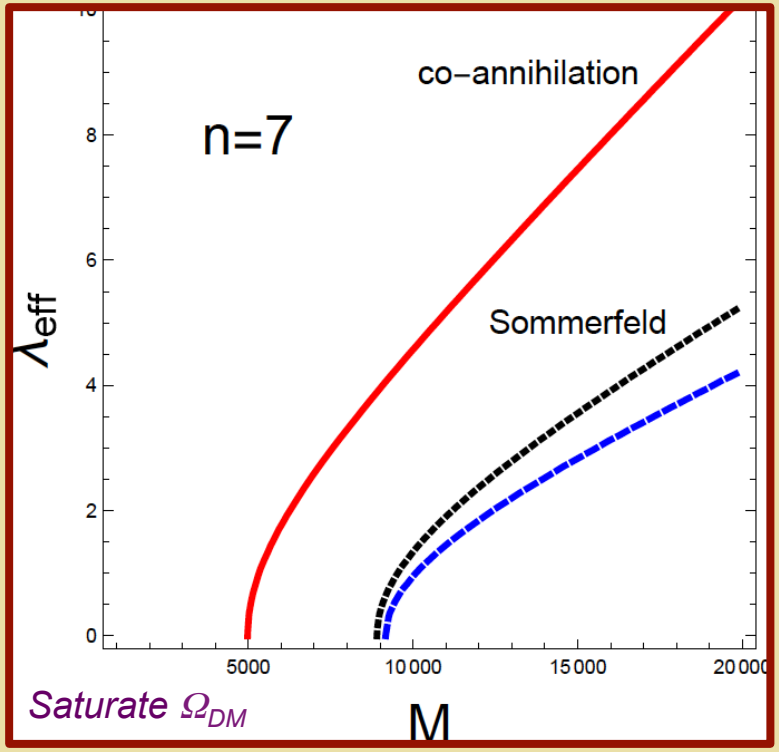
$$\mathcal{L}_\chi^{\text{self}} = -\tilde{\lambda}_{\text{self}}\, \chi^4$$

$$4\tilde{\lambda}_{\text{self}} = +\frac{1}{7}\left[\kappa_0 + 2\text{Re}(\kappa'_0) + 2\text{Re}(\kappa''_0)\right] + \frac{6}{77}\left[\kappa_4 + 2\text{Re}(\kappa'_4) + 2\text{Re}(\kappa''_4)\right] + \frac{4}{21\sqrt{5}}\left[\kappa_2 + 2\text{Re}(\kappa'_2) + 2\text{Re}(\kappa''_2)\right] + \frac{100}{231\sqrt{13}}\left[\kappa_6 + 2\text{Re}(\kappa'_6) + 2\text{Re}(\kappa''_6)\right]$$

III. DM Dynamics & Phenomenology

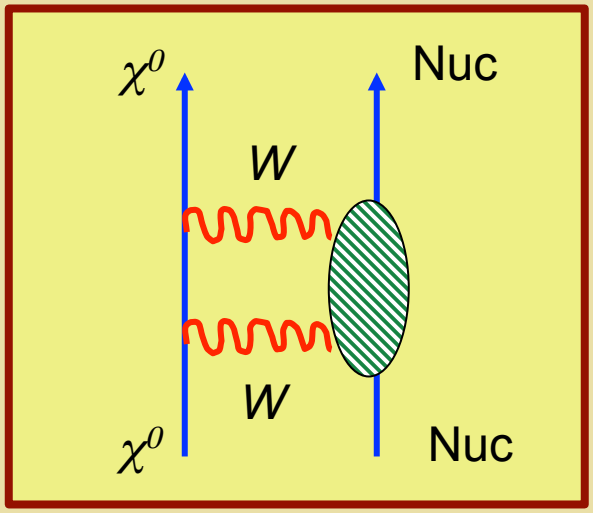
Relic Density & Higgs Portal Coupling



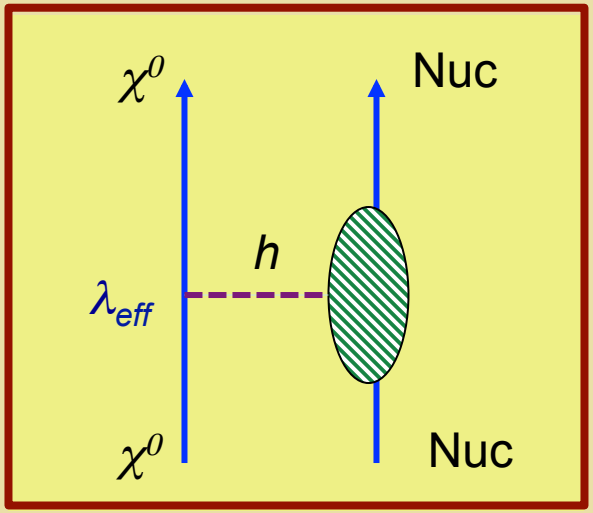


EW Multiplet DM: Direct Detection

Gauge interactions



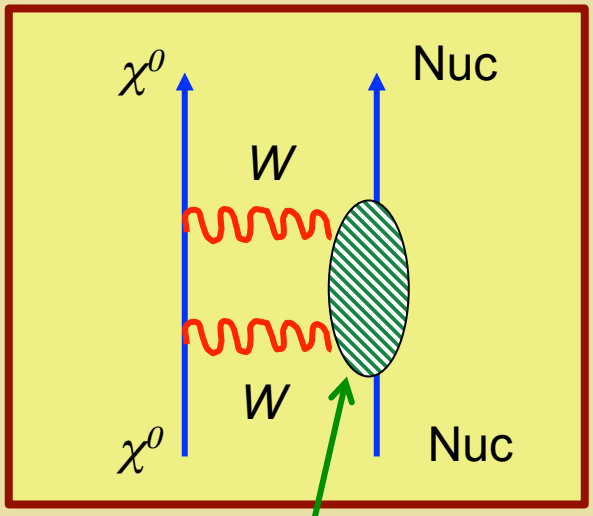
Higgs portal interactions



$$\mathcal{L}_{\rm eff} = \frac{1}{2}\lambda_{\rm eff}\frac{1}{m_h^2}\Phi_{n,0}^2\bar{q}m_q q + \frac{f_T}{M_\Phi^2}\Phi_{n,0}(i\partial^\mu)(i\partial^\nu)\Phi_{n,0}\mathcal{O}^q_{\mu\nu}$$

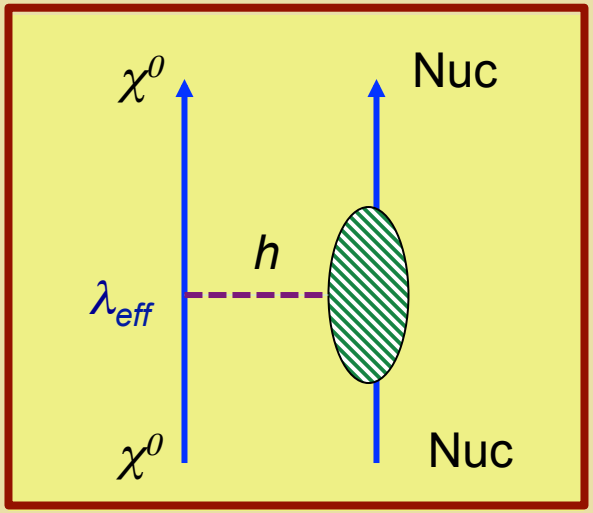
EW Multiplet DM: Direct Detection

Gauge interactions



Dominant: twist-two

Higgs portal interactions



$$\mathcal{O}^q_{\mu\nu} = \frac{1}{2}\bar{q}i\left(D_\mu\gamma_\nu + D_\nu\gamma_\mu - \frac{1}{2}g_{\mu\nu}\not{D}\right)q$$

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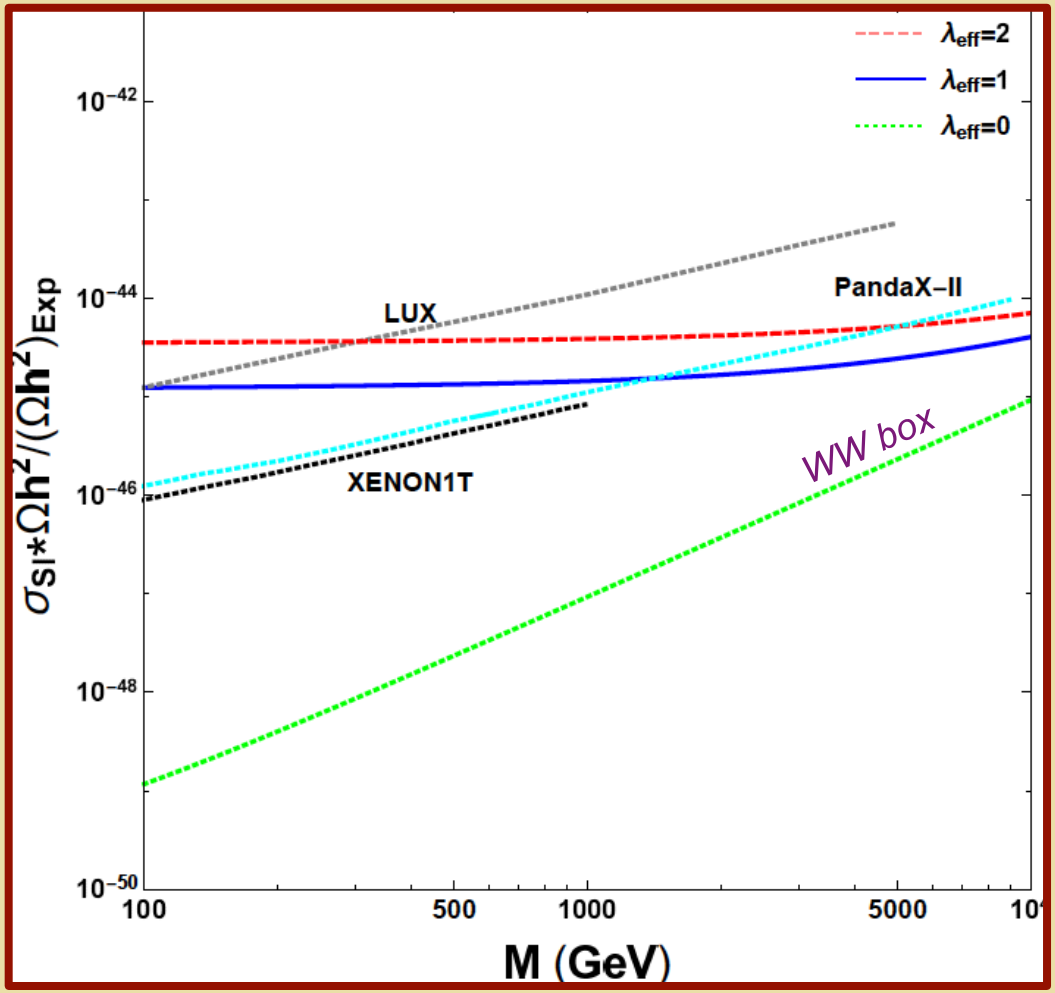

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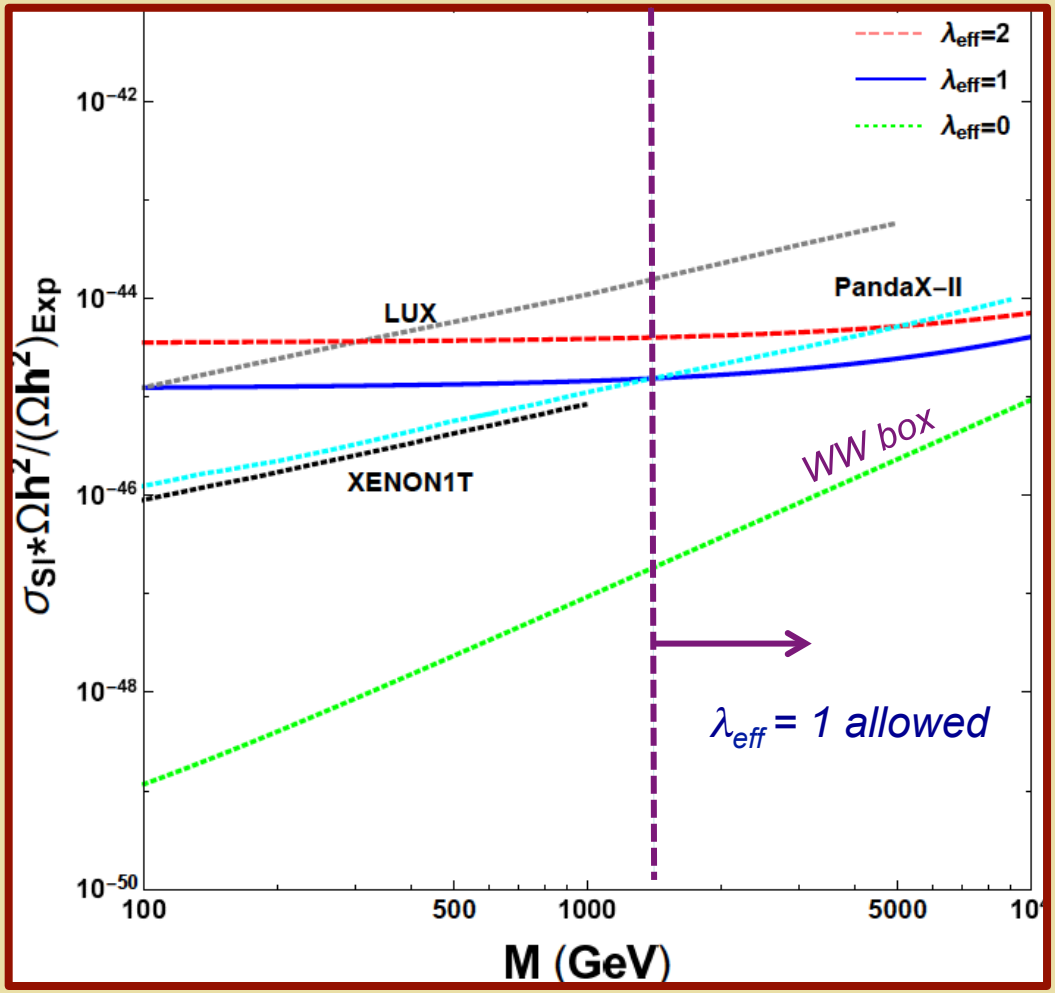

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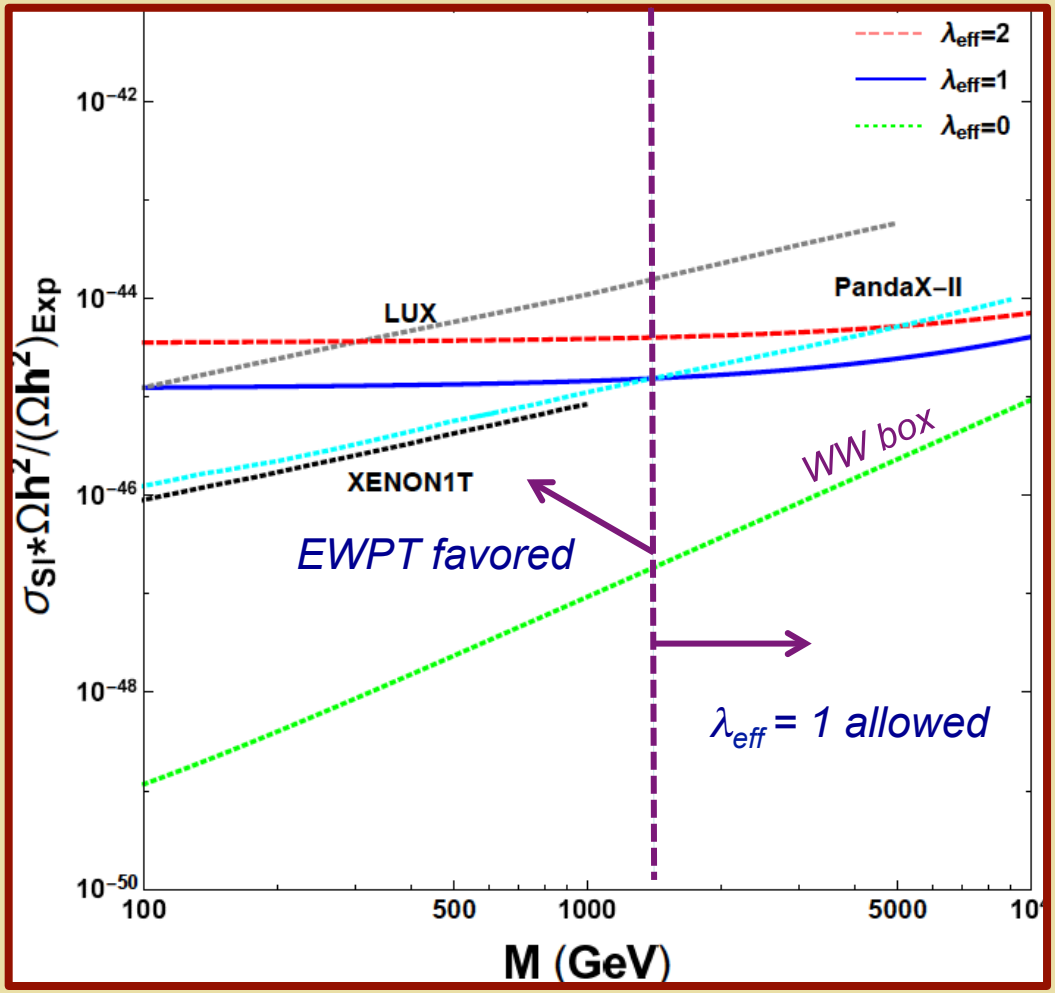

IV. Collider Probes

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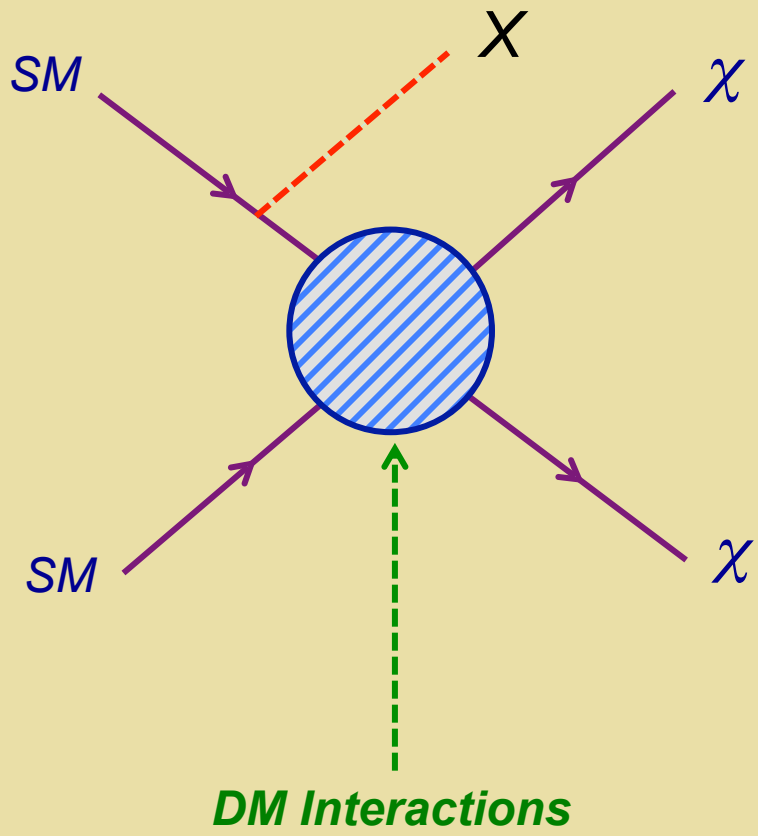
4	3/2	1/2	(LHH)	2.6 ± 0.07	712	$1.7 \div 9.5$	7.5	
5	0	0	(HHH^*H^*)	5.0 ± 0.1	166	$\ll 1$	12	*This study*
5	0	1/2	–	4.4 ± 0.1	166	$\ll 1$	12	
7	0	0	–	8.5 ± 0.2	166	$\ll 1$	46	*This study*

"Minimal Scalar DM"

Signature: Disappearing charge track $S^+ \to S_{DM} + \pi^+$ *(soft)*

WIMP Dark Matter Probes

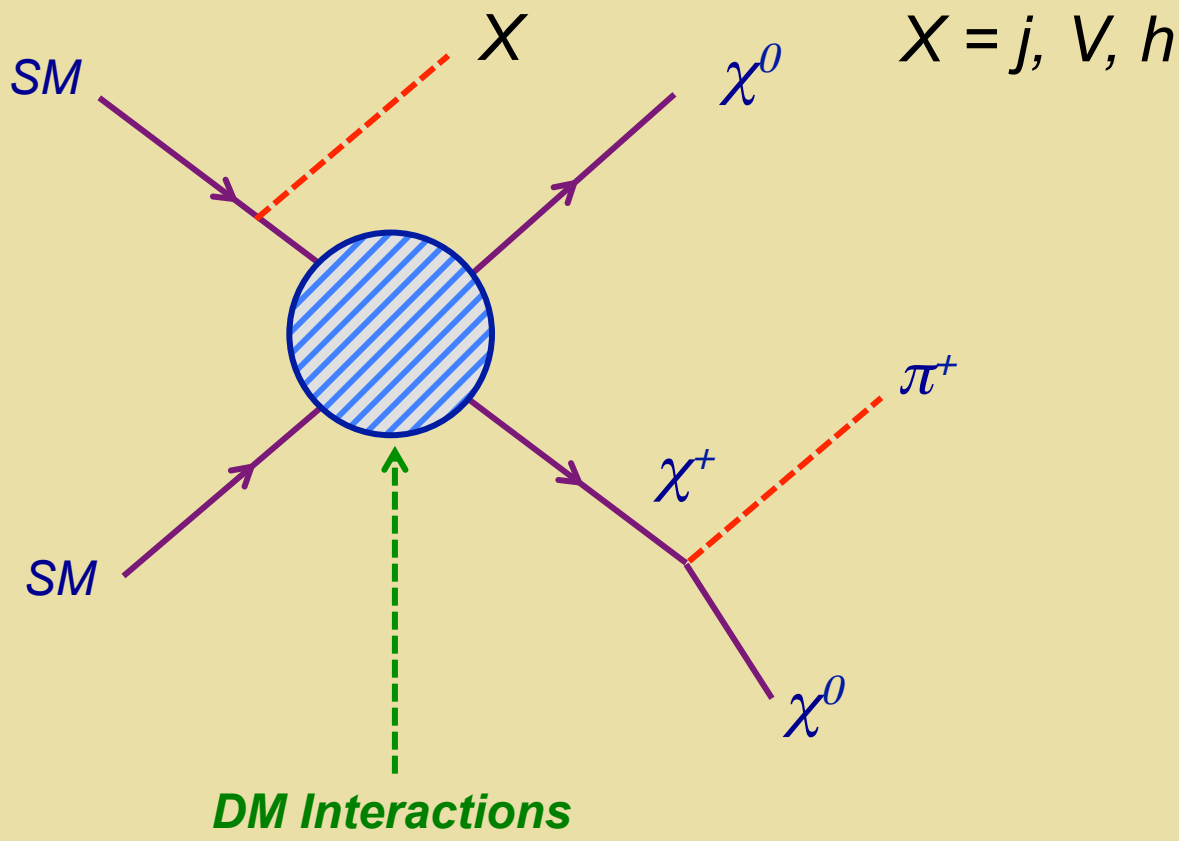
Mono-X + MET

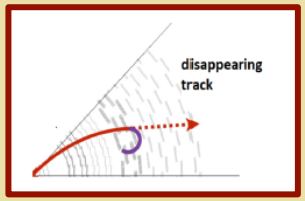


$X = j,\ V,\ h$

WIMP Dark Matter Probes

Disappearing Charged Track





Thanks: J.M. No

DCT: Real Triplet DM

Basic signature: ***Charged track disappearing after ~ 5 cm***

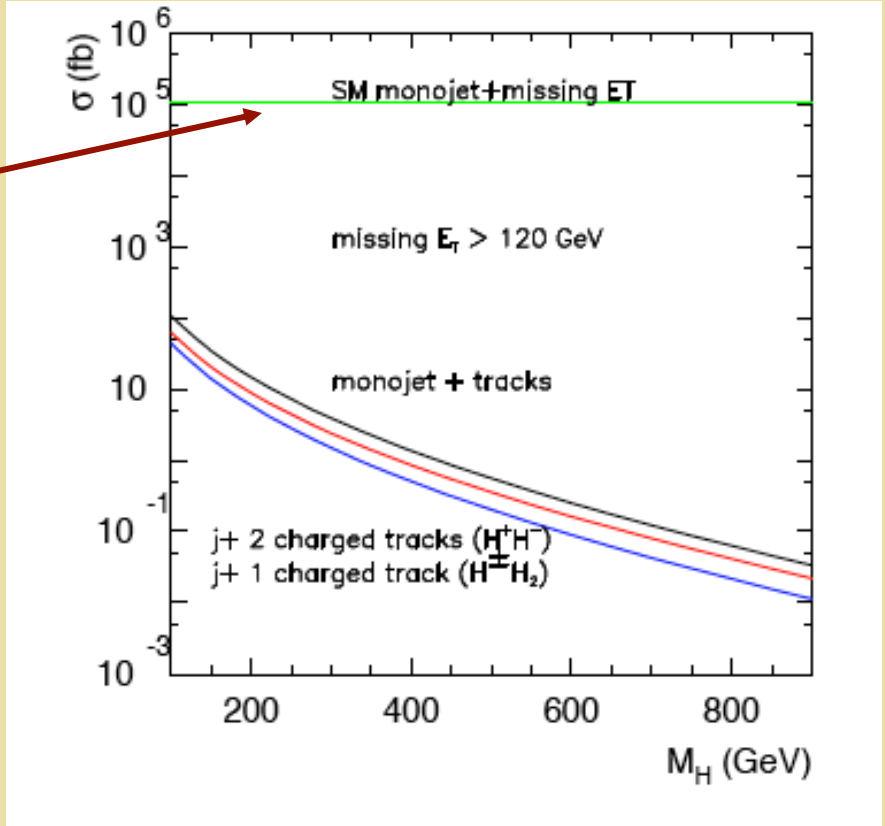
$$x_0 = 0 : H^{\pm} \to H_2 \, \pi^{\pm}$$

Fileviez Perez, Patel, MRM, Wang '08

Trigger: Monojet (ISR) + large $\not{E}_T$

SM Background:
QCD jZ and jW w/
$Z \to \nu\nu$ & $W \to l\nu$

Cuts: ***large $\not{E}_T$ hard***
jet ***One 5cm track***



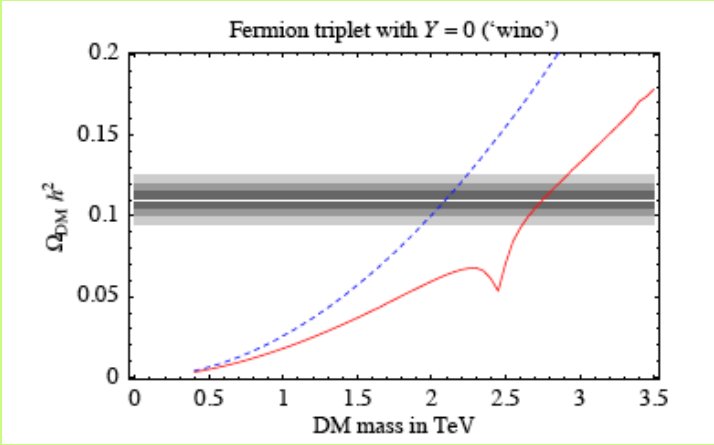
DCT: Real Triplet DM @ LHC

Basic signature: ***Charged track disappearing after ~ 5 cm***

$$x_0 = 0 : H^{\pm} \to H_2 \, \pi^{\pm}$$

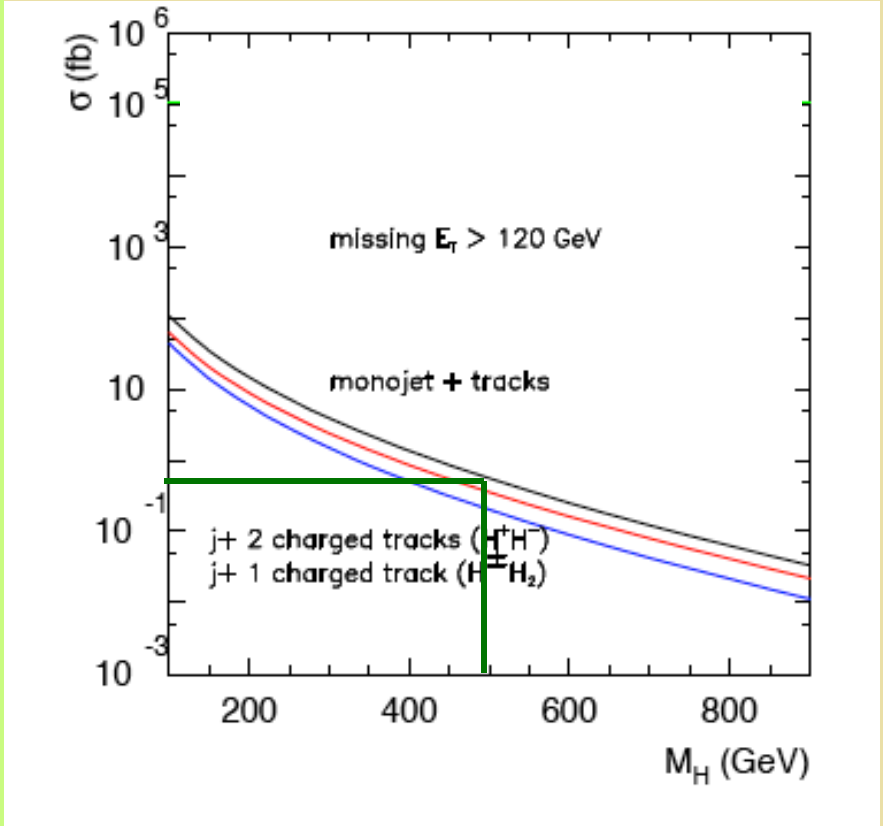
Fileviez Perez, Patel, MRM, Wang '08

Cirelli et al:



M_Σ = 500 GeV:

$\Omega_\Sigma / \Omega_{CDM}$ ~ 0.1

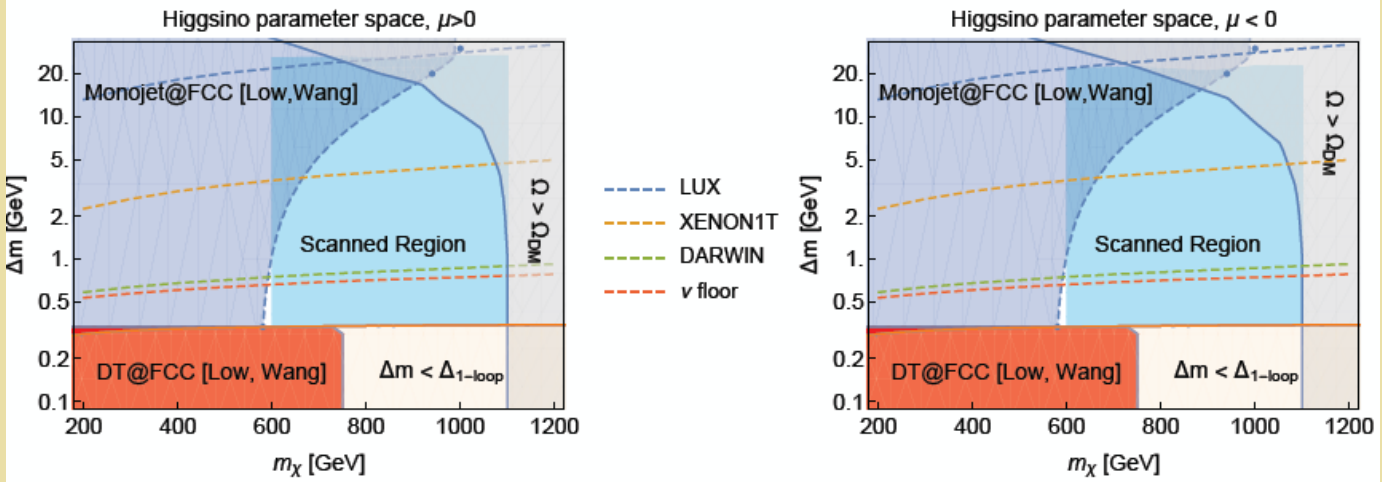


DCT: 100 TeV pp Collider

Mono-jet, DCT, Mono-Z

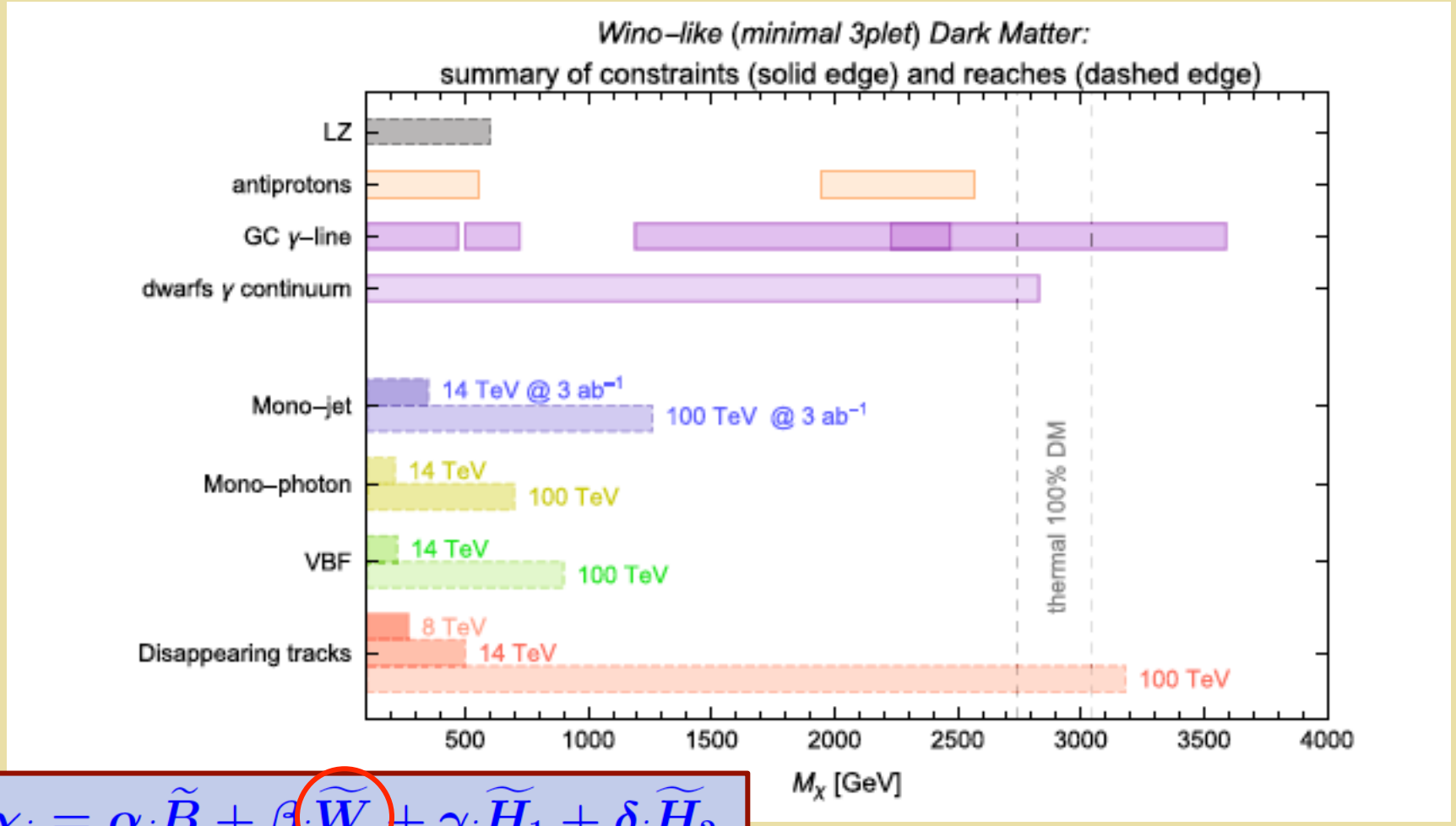
J.F. Zurita

The parameter space



- Xenon 1-T forces splittings below 2-5 GeV.
- LHC 95% C.L bounds give m_χ > 200 GeV.
- FCC monojet bounds: m_χ > 600 GeV for nominal splitting.
- Relic density forces m_χ < 1100 GeV.
- Scanned region: $|\mu|$ = 600, 750, 900, 1000, 1100 ; t_β = 15, M_1 scans Δ_{+-}.

Dark Sector EW Multiplets @ FCC-hh



$$\chi_i = \alpha_i \widetilde{B} + \beta_i \widetilde{W} + \gamma_i \widetilde{H}_1 + \delta_i \widetilde{H}_2$$

Dark Sector EW Multiplets @ FCC-hh

Work in progress: C-W Chiang, G. Cotton, Y. Du, MJRM

- *For a general EW multiplet, what is the DCT reach for a 100 TeV pp collider ?*
- *If a DCT signature observed, what fraction of the relic density would it correspond to ?*

Stay tuned !

IV. Outlook

- *Extended scalar sectors provide an interesting avenue for addressing open problems in cosmology*
- *Scalar EW multiplet DM ("minimal" or otherwise) can provide a viable DM scenario while potentially catalyzing a first order EW phase transition as needed for EW baryogenesis*
- *There exists a rich interplay involving the Higgs portal coupling, gauge interactions, and the EW multiplet mass − and the phenomenological consequences for the DM relic density, direct detection, collider probes, and the possibility of a first order EWPT*
- *A definitive test of this scenario may await the next generation of experiments*