Pseudoscalar Portal to Dark Matter: Beyond Simplified Models

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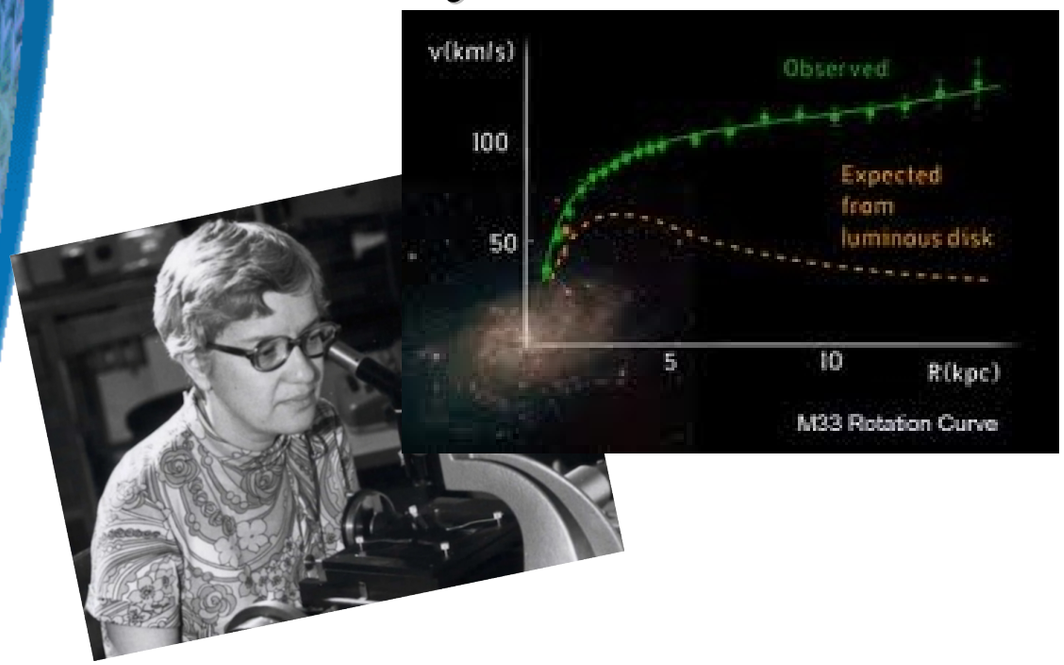
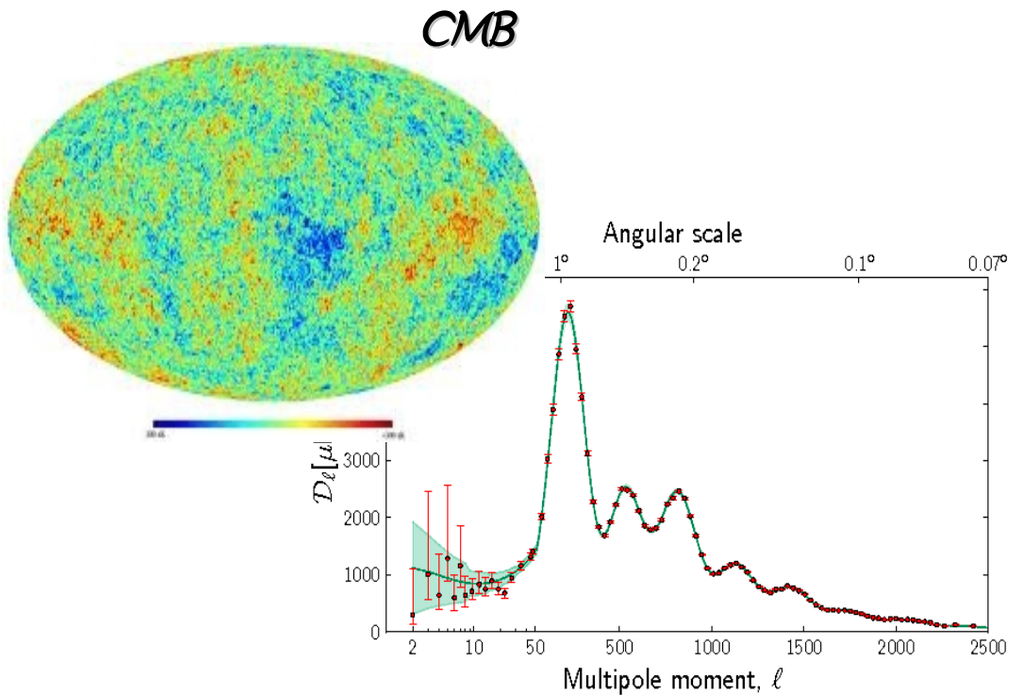
A Dark Matter Motivational Slide

Abundant & Robust Evidence of Dark Matter!

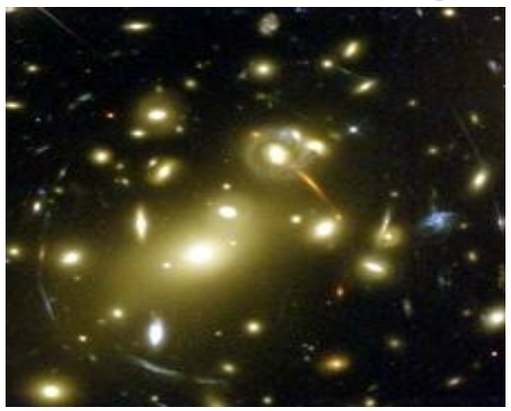
Galaxy Rotation Curves



CMB



Gravitational Lensing



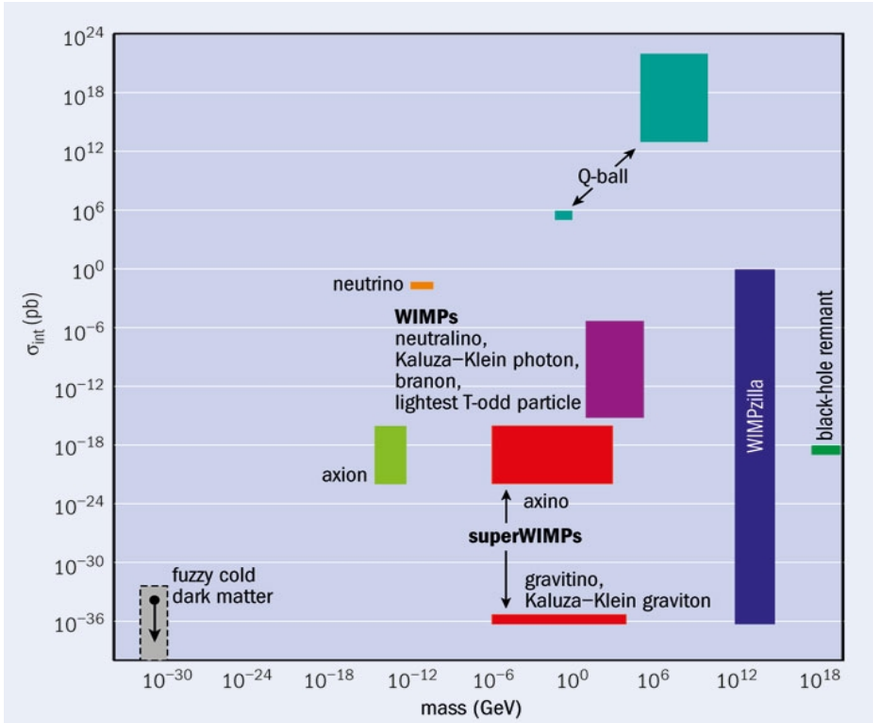
Bullet Cluster

A Dark Matter Motivational Slide

Abundant & Robust Evidence of Dark Matter!

What is it?

No idea...



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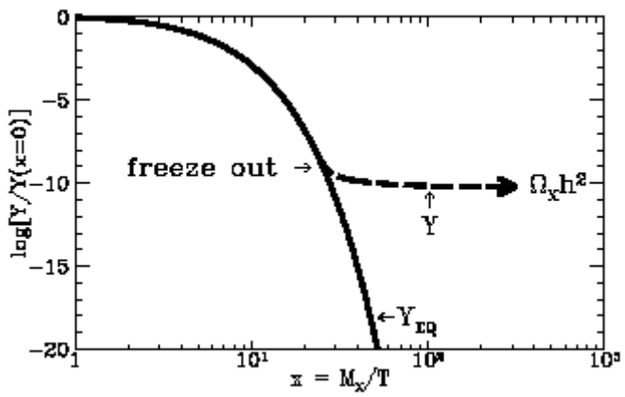
Abundant & Robust Evidence of Dark Matter!

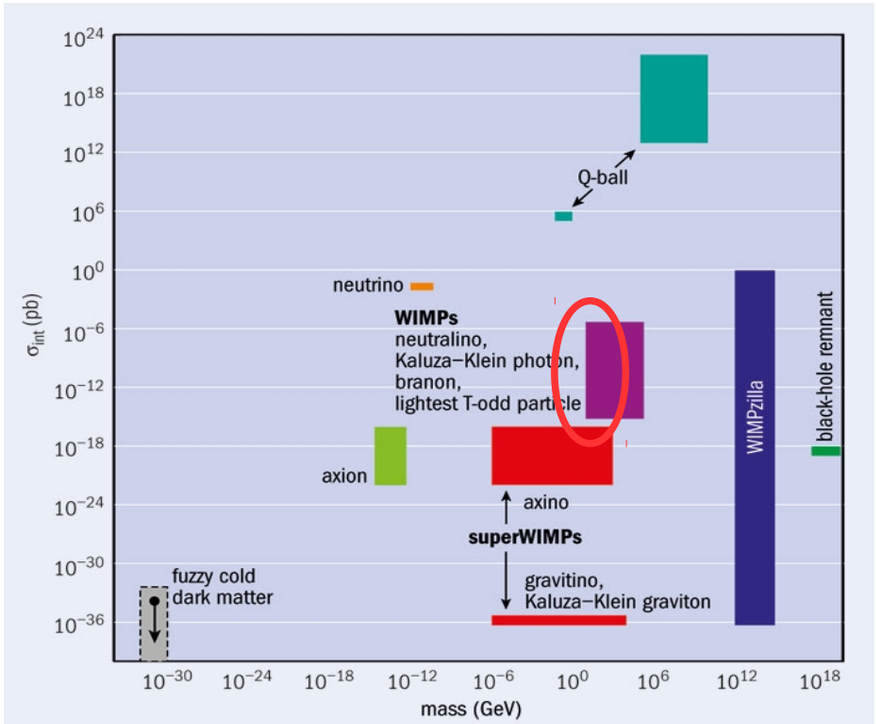
Traditional DM Poster Child:

The **WIMP**

(Weakly Interacting Massive Particle)

Thermal Relic





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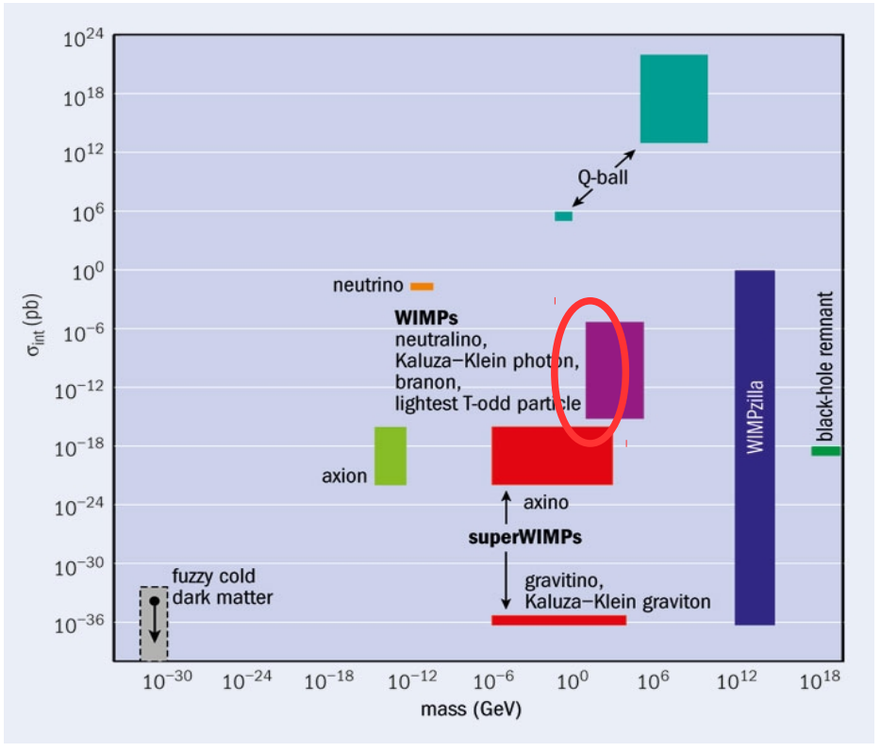

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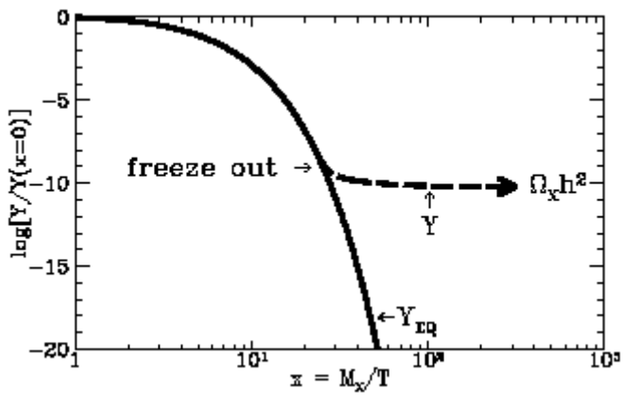
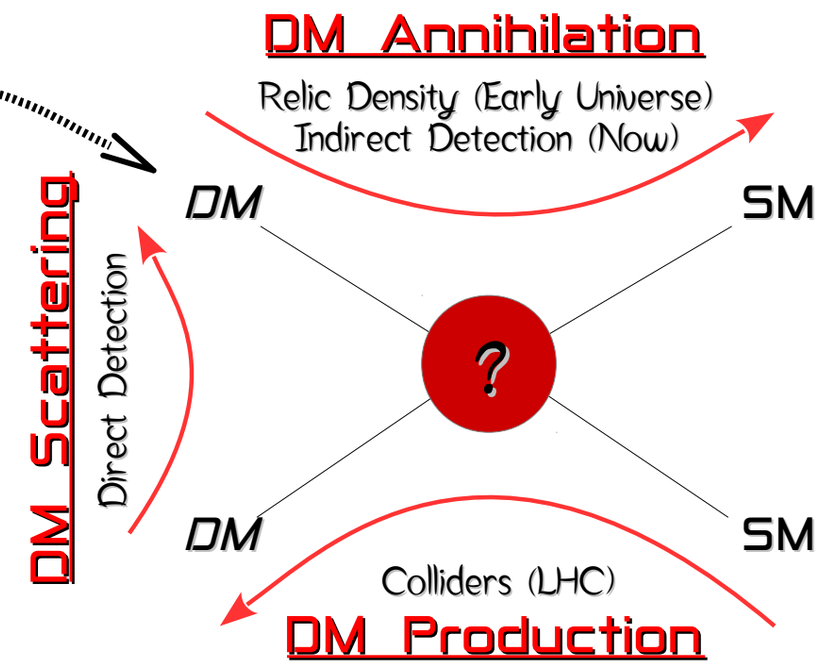


Probes of **WIMP** DM Interactions with the SM



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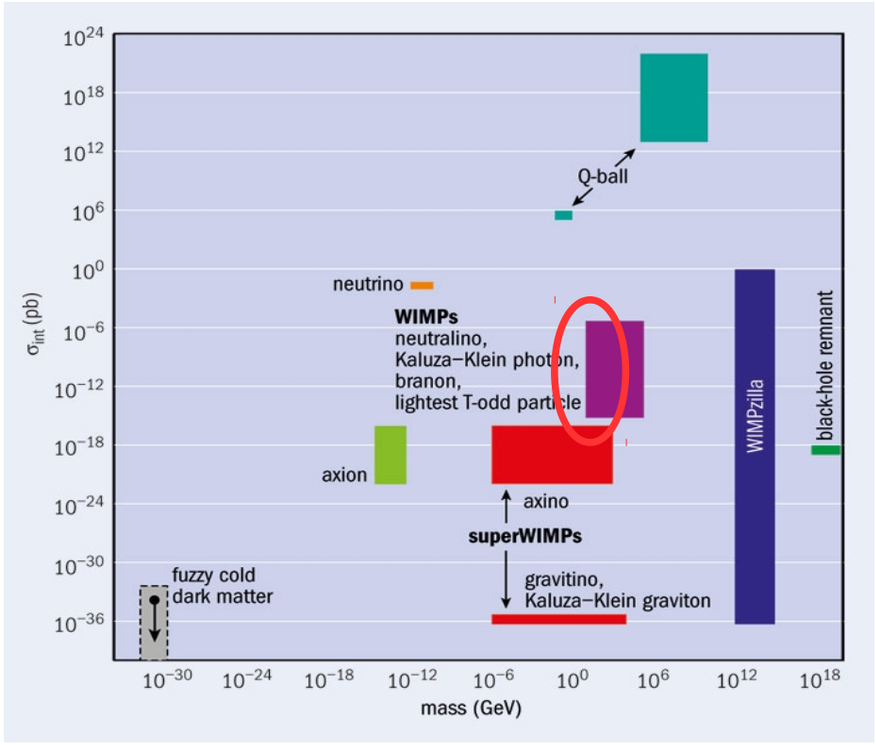

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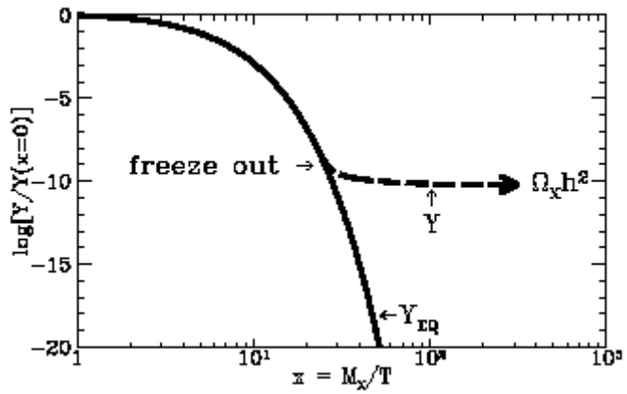
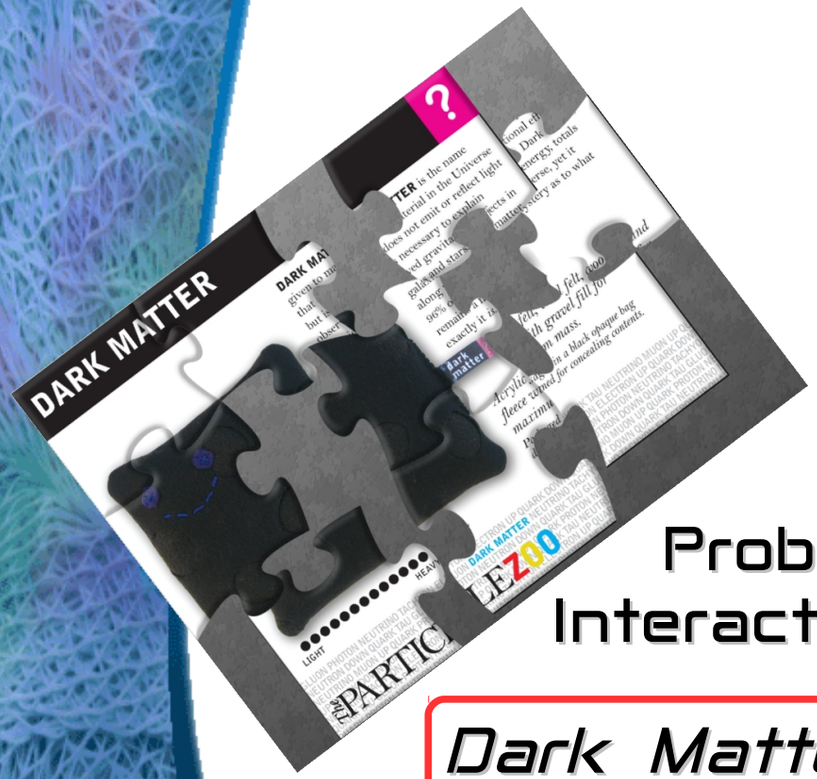
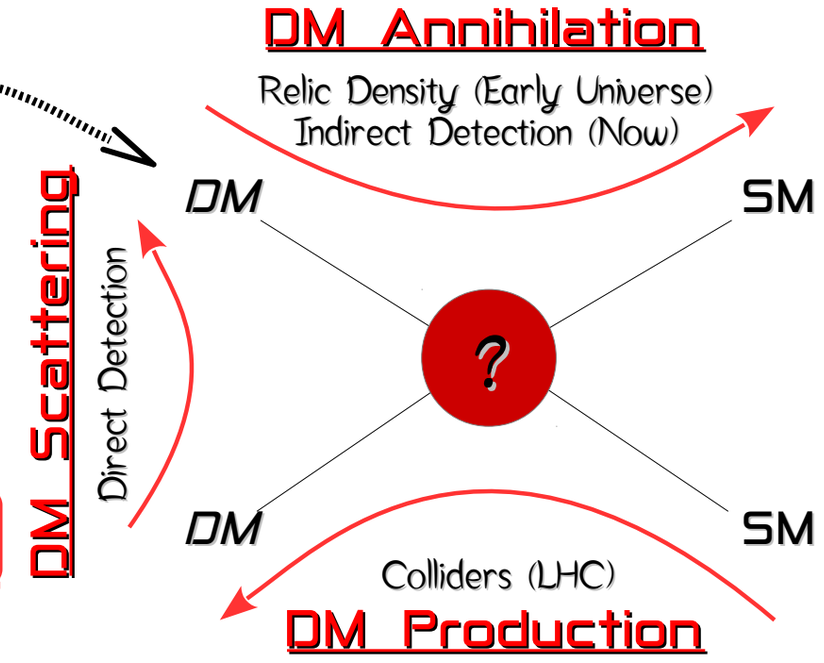


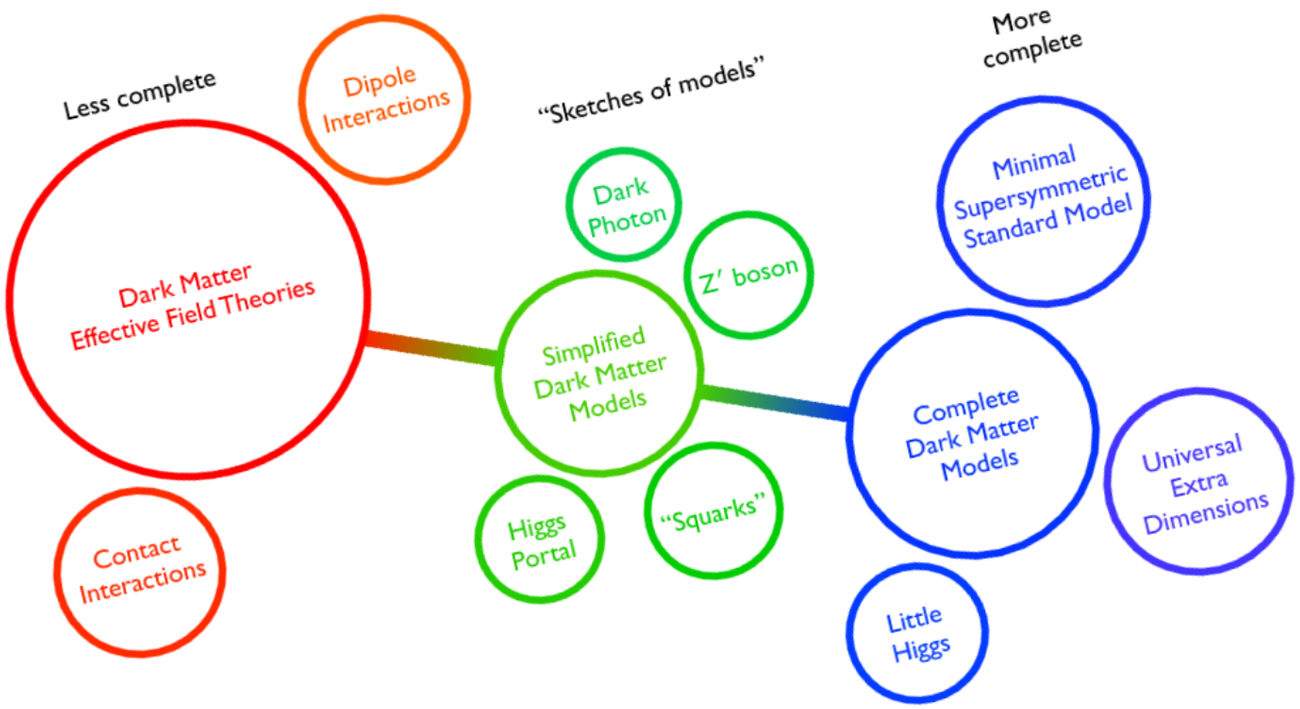


Probes of **WIMP** DM Interactions with the SM

Dark Matter Complementarity



Dark Matter Complementarity for the **WIMP** Landscape



Courtesy of Tim Tait

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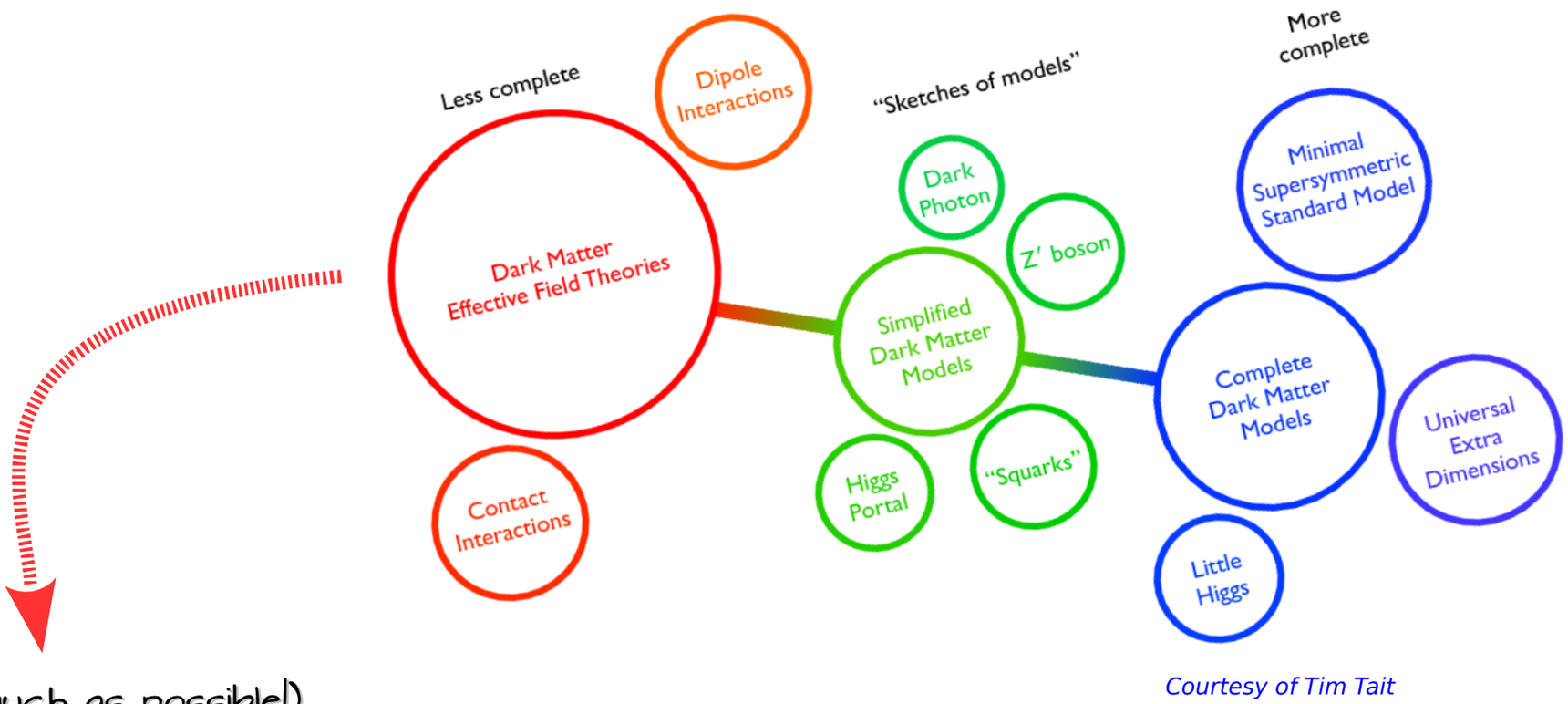

Courtesy of Tim Tait

(as much as possible!)

MODEL INDEPENDENT APPROACH(es) TO DM SEARCHES

EFT

- Add Only DM as new particle → ***simple!***
- Interactions between DM & SM via non-renormalizable operators
- Valid when $M_* \gg E$
  - E → Relevant (experimental) Energy Scale
  - M_* → Effective Scale of New Physics Connecting DM & SM

Dark Matter Complementarity for the **WIMP** Landscape

EFT

⇨ Consider DM in a HIDDEN SECTOR

Singlet under SM Gauge Interactions

Table 1 Operators for Dirac DM

Label	Operator	Usual coefficient	Dimension
$\mathcal{O}_{\mathrm{D1}}$	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3	6
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*De Simone, Jacques, Eur. Phys. J. C**76** (2016) 7, 367*

Dark Matter Complementarity for the WIMP Landscape

EFT

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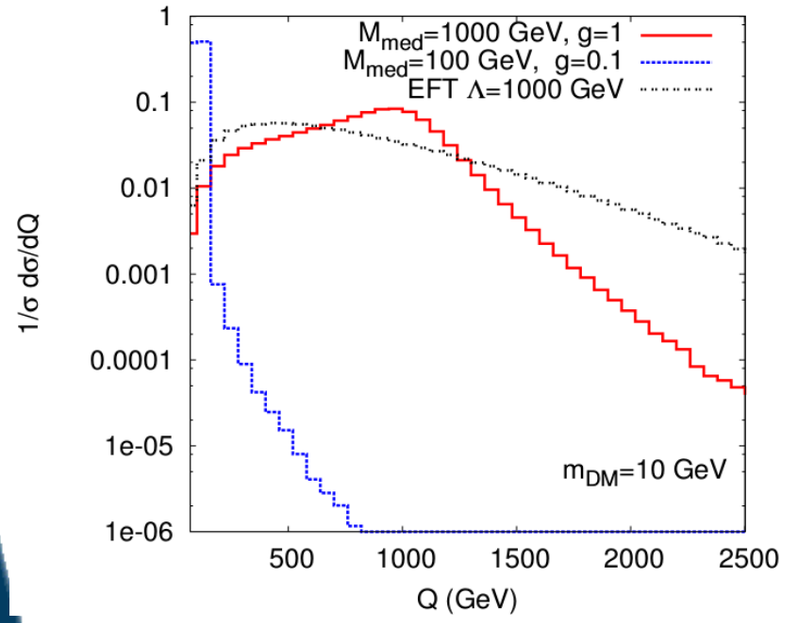
Singlet under SM Gauge Interactions

- Valid when $M_* \gg E$

DM DIRECT DETECTION E ~ MeV ✓

DM LHC SEARCHES E ~ TeV ✗



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*De Simone, Jacques, Eur. Phys. J. C **76** (2016) 7, 367*

EFT fails when DM - SM Mediator Accessible

*Busoni, De Simone, Morgante, Riotto, Phys. Lett. B **728** (2014) 412*
*Buchmueller, Dolan, McCabe, JHEP **01** (2014) 025*

Dark Matter Complementarity for the **WIMP** Landscape

⇨ Consider DM in a HIDDEN SECTOR
Singlet under SM Gauge Interactions

SOLUTION :

- "Open up" effective interaction

$$\mathcal{L} \supset Z'_\mu \left(g_{\rm SM}\, \bar{q}\gamma^\mu q + g_\chi\, \bar{\chi}\gamma^\mu \chi \right)$$

- Add DM & Mediator as new particles

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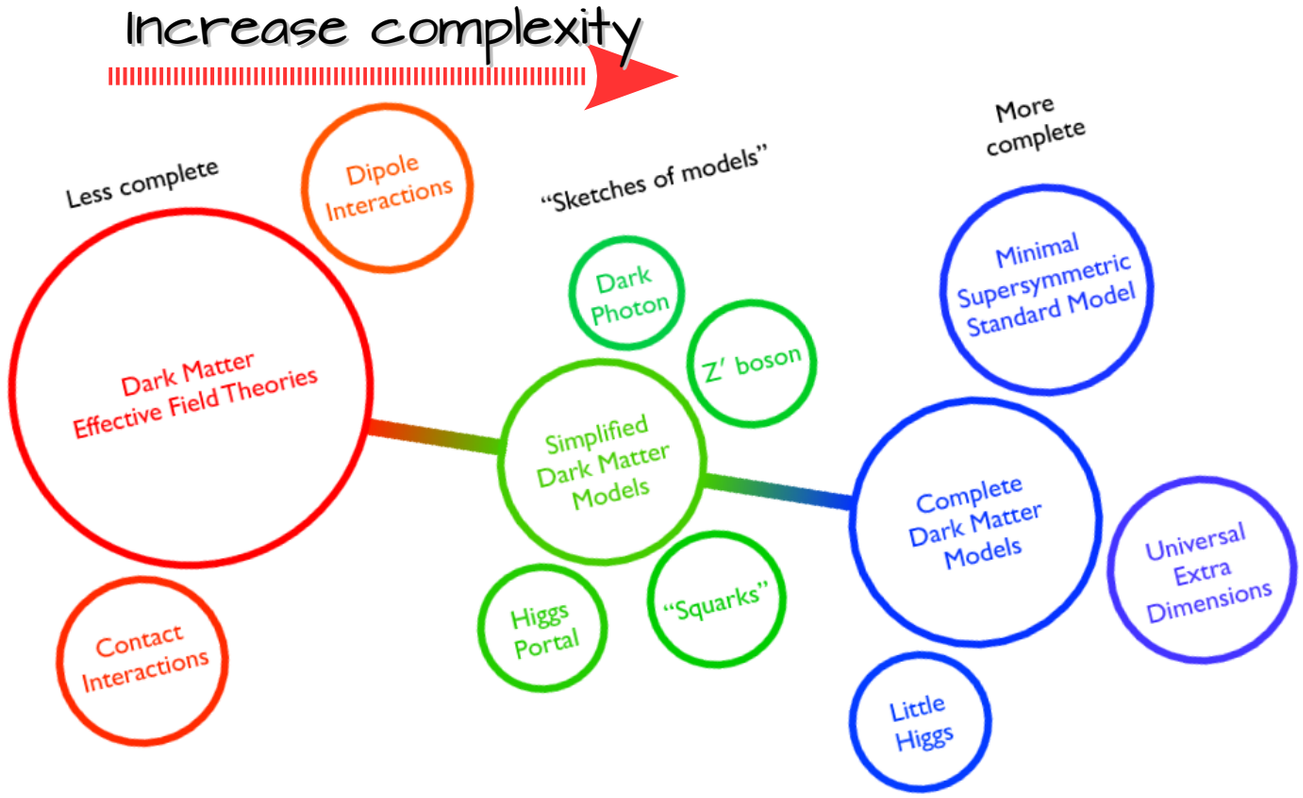
Let's add it!

Rationale of Simplified Models for Dark Matter Phenomenology



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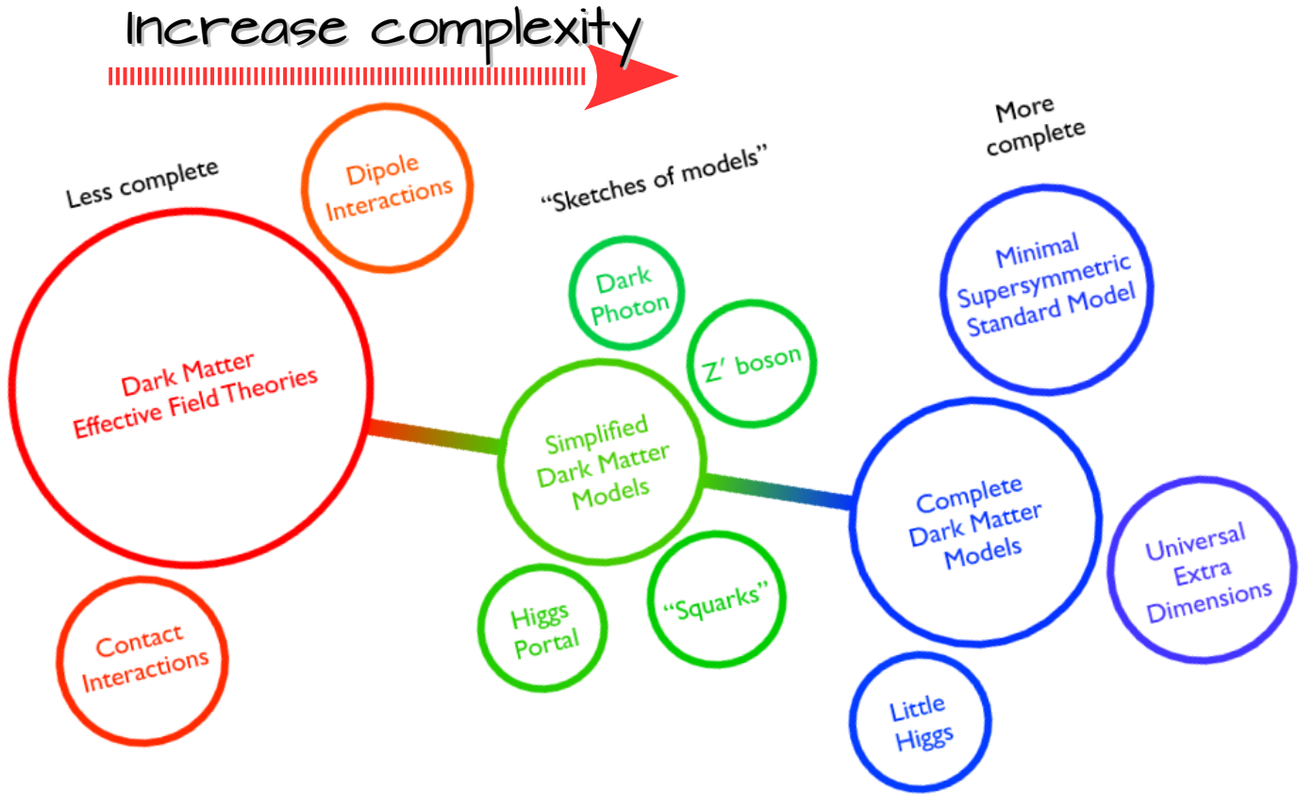
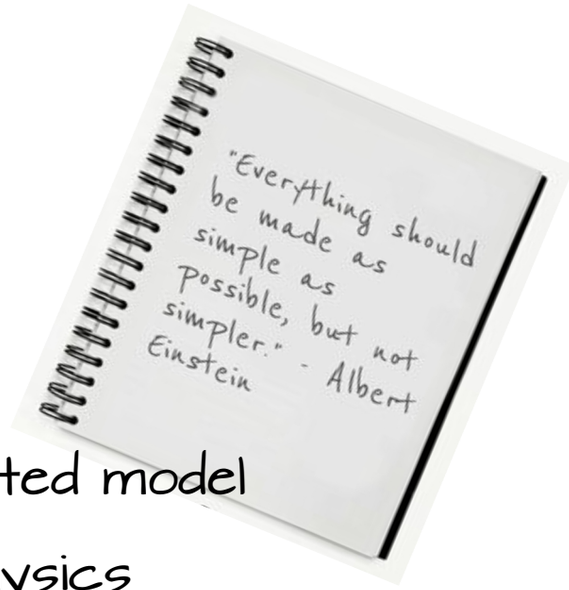


wish list

Dark Matter Pheno. Models



- **Simple enough** as sensible unit within (more) complicated model
- **Complete enough** to accurately capture relevant physics

Simplified Models for DM Searches

I focus on **Dirac Fermion DM**

*Shoemaker, Vecchi, Phys. Rev. D**86** (2012) 015023*
*Frandsen, Kahlhoefer, Preston, Sarkar, Schmidt-Hoberg, JHEP**1207** (2012) 123*
*Buckley, Feld, Goncalves, Phys. Rev. D**91** (2015) 015017*

Vector/Axial-Vector Mediator

$$\mathcal{L}_V \supset V_\mu \left(\sum_q \bar{q}\gamma^\mu (g^V_{\rm SM} + g^A_{\rm SM}\gamma^5) q + \bar{\chi}\gamma^\mu (g^V_\chi + g^A_\chi \gamma^5)\chi \right)$$

Scalar Mediator

$$\begin{aligned} \mathcal{L}_s &= \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial_\mu s)^2 - \frac{m_s^2}{2}s^2 \\ &- g_\chi\, s\, \bar{\chi}\chi - g_{\rm SM}\, s \sum_q \frac{y_q}{\sqrt{2}}\, \bar{q}q \end{aligned}$$

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Models defined after EWSB

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KEY QUESTION

Complete enough to accurately describe DM phenomenology?

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The Issue is $SU(2)_{\rm L} \times U(1)_{\rm Y}$ Gauge Invariance

Simplified Models for DM Searches

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DM is SM GAUGE SINGLET

MEDIATOR NEEDS $SU(2)_{\rm L} \times U(1)_{\rm Y}$ CHARGE to couple to SM fermions

Scalar Case: Restoring Gauge Invariance is Direct → S mixes with SM Higgs boson

$$V = -\frac{1}{2}M_{SS}^2 S^2 + \mu_{HS}\Phi^\dagger\Phi S + \frac{1}{2}\lambda_{HS}\Phi^\dagger\Phi S^2 + \frac{1}{3!}\mu_S S^3 + \frac{1}{4!}\lambda_S S^4$$

Simplified Models for DM Searches

Scalar Mediator

$$\begin{aligned}\mathcal{L}_s &= \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial_\mu s)^2 - \frac{m_s^2}{2}s^2 \\ &- g_\chi\, s\,\bar{\chi}\chi - g_{\rm SM}\, s \sum_q \frac{y_q}{\sqrt{2}}\,\bar{q}q\end{aligned}$$

Pseudoscalar Mediator

$$\begin{aligned}\mathcal{L}_a &= \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 \\ &- i g_\chi\, a\,\bar{\chi}\gamma^5\chi - i g_{\rm SM}\, a \sum_q \frac{y_q}{\sqrt{2}}\,\bar{q}\gamma^5 q\end{aligned}$$

The Issue is $SU(2)_{\rm L} \times U(1)_{\rm Y}$ Gauge Invariance

$$\begin{aligned}\mathcal{L}_s &= \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial_\mu s)^2 - \frac{m_s^2}{2}s^2 \\ &- g_\chi\, s\,\bar{\chi}\chi - g_{\rm SM}\, s \sum_q \frac{y_q}{\sqrt{2}}\,\bar{q}q\end{aligned}$$

DM is SM GAUGE SINGLET

MEDIATOR NEEDS $SU(2)_{\rm L} \times U(1)_{\rm Y}$ CHARGE to couple to SM fermions

Scalar Case: Restoring Gauge Invariance is Direct → S mixes with SM Higgs boson

$$V = -\frac{1}{2}M_{SS}^2 S^2 + \mu_{HS}\Phi^\dagger\Phi S + \frac{1}{2}\lambda_{HS}\Phi^\dagger\Phi S^2 + \frac{1}{3!}\mu_S S^3 + \frac{1}{4!}\lambda_S S^4$$

SM Higgs Boson is also a Mediator! (two mediators)

*Kahlhoefer, Schmidt-Hoberg, Schwetz, Vogl, JHEP**1602** (2016) 016*

*Bell, Busoni, Sanderson, JCAP**1703** (2017) 015*

Simplified Models for DM Searches

Scalar Mediator

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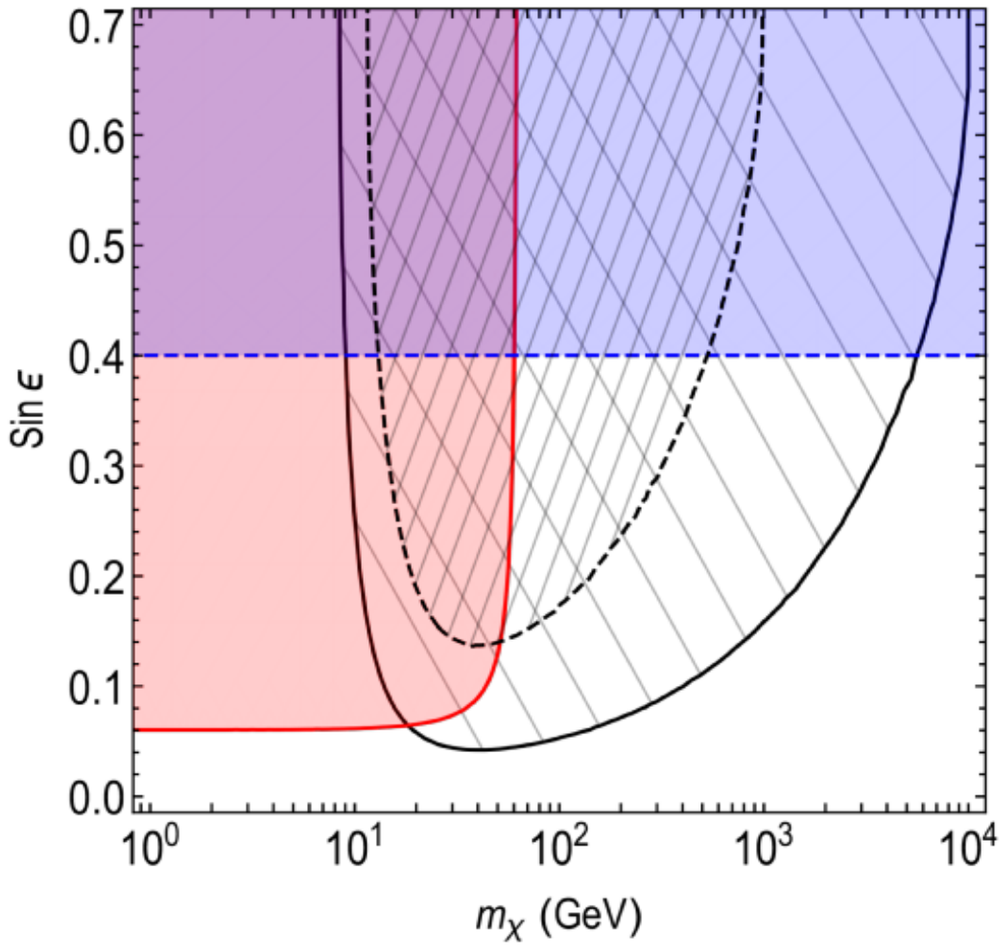
Need two-mediator interplay for correct DM Direct Detection bounds



*Bell, Busoni, Sanderson, JCAP**1703** (2017) 015*

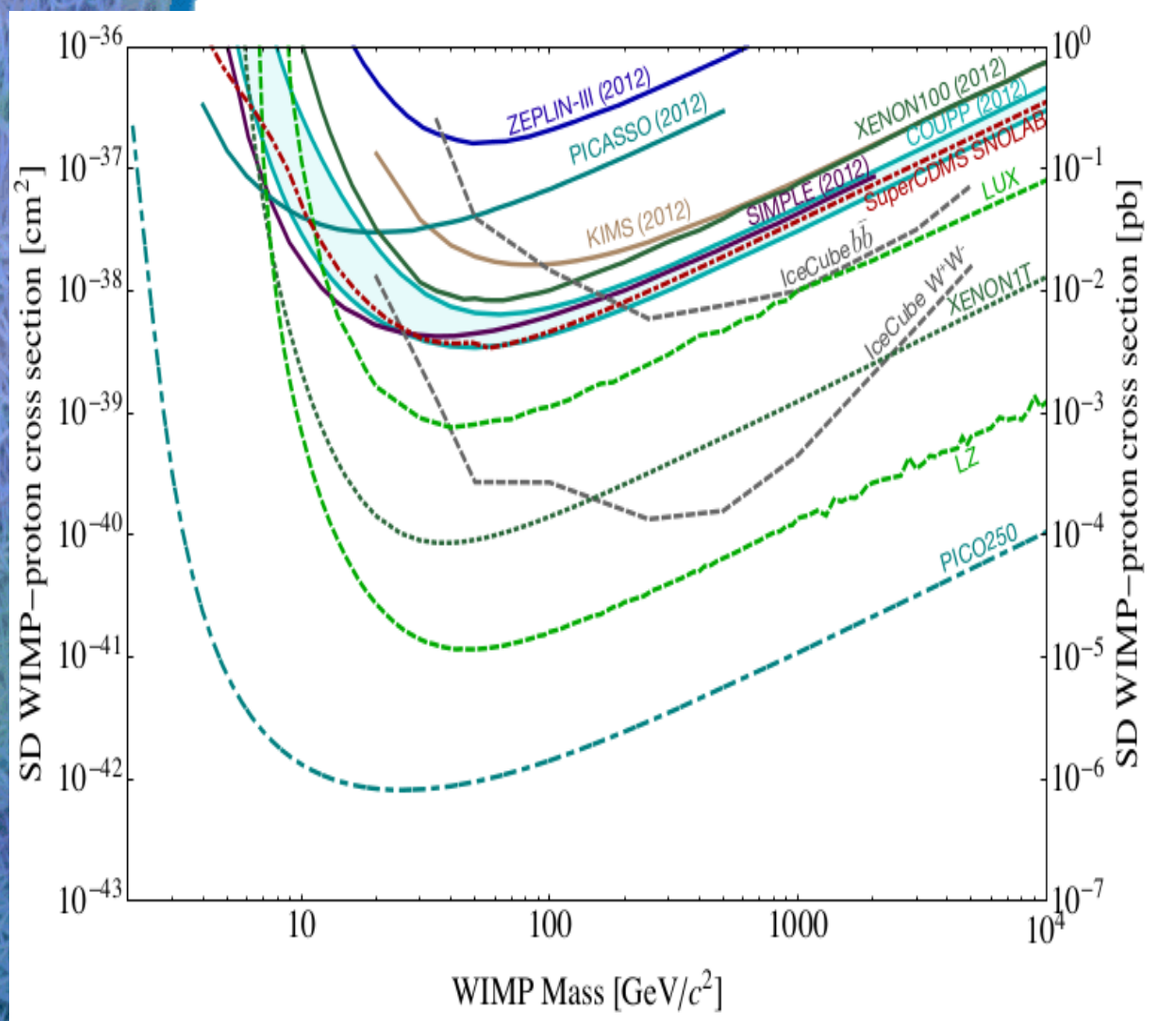
Simplified Models for DM Searches

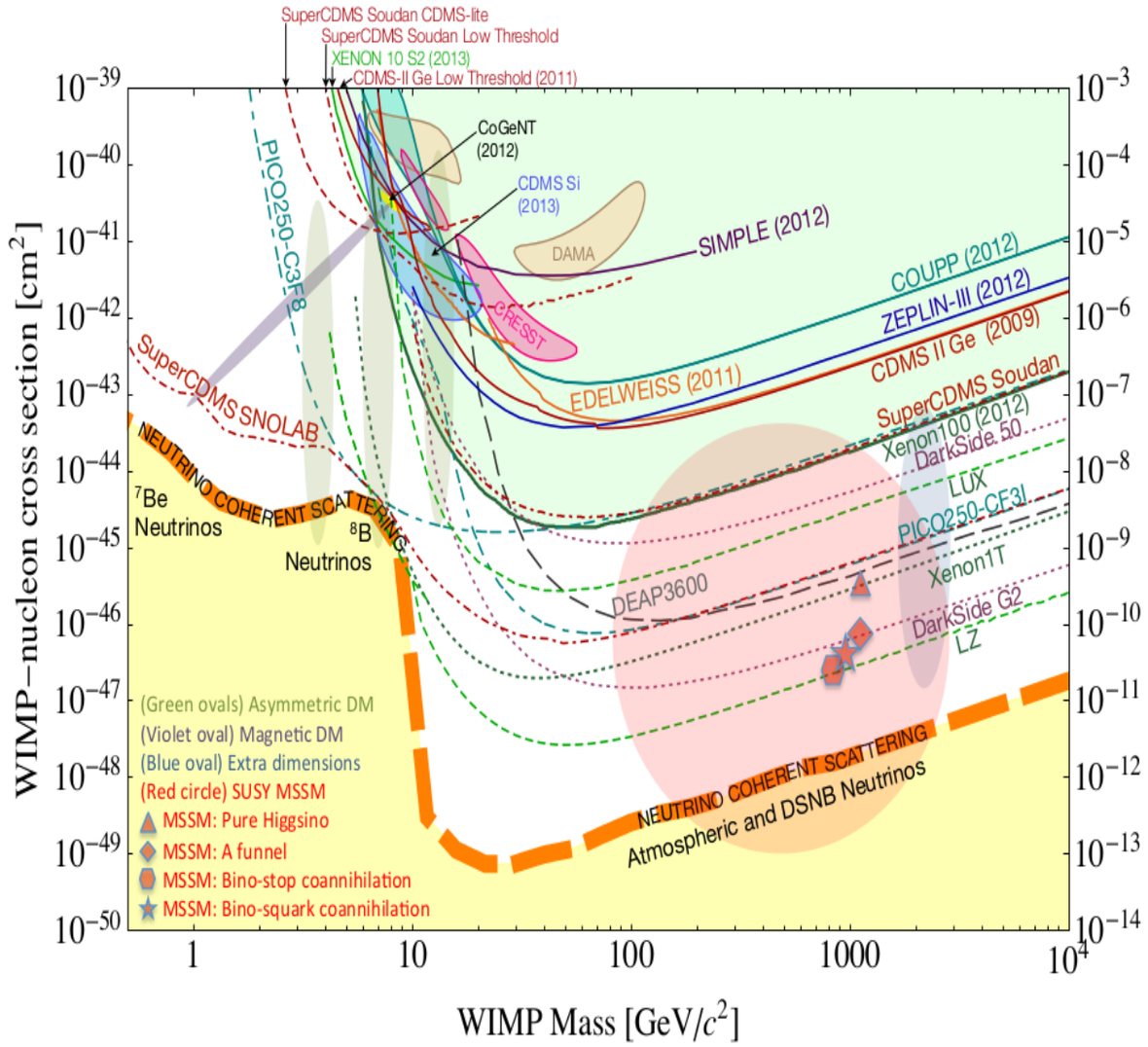
Pseudoscalar Case

- DM Direct Detection signatures strongly suppressed w.r.t. Scalar Case

$\bar{\chi} i\gamma_5 \chi \bar{q} i\gamma_5 q$ yields Spin-Dependent DM-Nucleon cross section @ Tree-level

yields Spin-Independent DM-Nucleon cross section @ One-loop





Pseudoscalar Case not constrained by DM DD

Simplified Models for DM Searches

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LHC Searches are Key for Pseudoscalar Scenario

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No pseudoscalar in SM for a to mix with.

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Mixing requires Higgs sector with two Doublets (2HDM)

$$V_{\rm portal} = i\,\kappa\, a_0\, H_1^\dagger H_2 + {\rm h.c.}$$

*Nomura, Thaler, Phys. Rev **D79** (2009) 075008*

⇒ 2HDM + a (+ DM) ⇨ $a,\ A,\ H_0,\ H^\pm$ (New Scalars)

*Ipek, McKeen, Nelson, Phys. Rev **D90** (2014) 055021*

*JMN, Phys. Rev **D93** (2016) 031701*

Goncalves, Machado, JMN, ArXiv:1611.04593

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⇨ $a,\ A,\ H_0,\ H^\pm$ (New Scalars)

⇒ 2HDM (+ DM)

*Berlin, Gori, Lin, Wang, Phys. Rev **D92** (2015) 015005*

⇨ $a,\ H_0,\ H^\pm$ (New Scalars) $\quad m_{H_0,H^\pm} - m_a \leq \mathcal{O}(\text{few}) \times v$

⇨ Rich(er) DM Sector (+ DM feels SM Gauge Interactions)

$$V_{\rm 2HDM}(H_1, H_2) + g_\chi \bar{D}_{\chi_i} H_{1,2} \chi + h.c.$$

SU(2) doublet(s)

Simplified Models for DM Searches

Pseudoscalar Case

- DM Direct Detection signatures strongly suppressed w.r.t. Scalar Case

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LHC Searches are Key for Pseudoscalar Scenario

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No pseudoscalar in SM for a to mix with.

Mixing requires Higgs sector with two Doublets (2HDM)

$$V_{\rm portal} = i\,\kappa\, a_0\, H_1^\dagger H_2 + {\rm h.c.}$$

*Nomura, Thaler, Phys. Rev **D79** (2009) 075008*

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*Ipek, McKeen, Nelson, Phys. Rev **D90** (2014) 055021*
*JMN, Phys. Rev **D93** (2016) 031701*
Goncalves, Machado, JMN, ArXiv:1611.04593

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*Berlin, Gori, Lin, Wang, Phys. Rev **D92** (2015) 015005*

⇒ a, A, H_0, $H^\pm$ (New Scalars)

⇒ a, H_0, $H^\pm$ (New Scalars) $\quad m_{H_0,H^\pm} - m_a \leq \mathcal{O}(\text{few}) \times v$

New States

⇒ Rich(er) DM Sector (+ DM feels SM Gauge Interactions)

$$V_{\rm 2HDM}(H_1, H_2) + g_\chi \bar{D}_{\chi_i} H_{1,2} \chi + h.c.$$

SU(2) doublet(s)

Simplified Models for DM Searches

$$\begin{aligned}\mathcal{L}_a &= \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 \\ &- ig_\chi\, a\,\bar{\chi}\gamma^5\chi - ig_{\rm SM}\, a \sum_q \frac{y_q}{\sqrt{2}}\,\bar{q}\gamma^5 q\end{aligned}$$

QUESTION

Complete enough to accurately describe DM phenomenology?

Simplified Models for DM Searches

$$\begin{aligned}\mathcal{L}_a &= \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 \\ &- ig_\chi\, a\,\bar{\chi}\gamma^5\chi - ig_{\rm SM}\, a \sum_q \frac{y_q}{\sqrt{2}}\,\bar{q}\gamma^5 q\end{aligned}$$

QUESTION

Can the New States A, H_0, $H^\pm$ be pushed beyond LHC reach?

Simplified Models for DM Searches

$$\begin{aligned}\mathcal{L}_a &= \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 \\ &- ig_\chi\, a\,\bar{\chi}\gamma^5\chi - ig_{\rm SM}\, a \sum_q \frac{y_q}{\sqrt{2}}\,\bar{q}\gamma^5 q\end{aligned}$$

QUESTION

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Generally...

Simplified Models for DM Searches

$$\begin{aligned}\mathcal{L}_a &= \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 \\ &- ig_\chi\, a\,\bar{\chi}\gamma^5\chi - ig_{\rm SM}\, a \sum_q \frac{y_q}{\sqrt{2}}\,\bar{q}\gamma^5 q\end{aligned}$$

QUESTION

Can the New States A, H_0, $H^\pm$ be pushed beyond LHC reach?

Mixing between a and Scalar EW Multiplet

$\sin\theta$

New States
(Mediator EW Partners)

New States Only Decouple by Closing DM Portal: $\sin\theta \sim \dfrac{\lambda\, v^2}{M^2 - m_a^2}$

2HDM + *a* Portal to Dark Matter

Visible Sector

$$
\begin{aligned}
V_{\text{2HDM}} &= \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 - \mu^2 \left[H_1^\dagger H_2 + \text{h.c.} \right] \\
&+ \frac{\lambda_1}{2} |H_1|^4 + \frac{\lambda_2}{2} |H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 \\
&+ \lambda_4 \left| H_1^\dagger H_2 \right|^2 + \frac{\lambda_5}{2} \left[\left(H_1^\dagger H_2 \right)^2 + \text{h.c.} \right]
\end{aligned}
$$

$$
-\mathcal{L}_{\text{Yuk}} = Y^u_{1,2} \bar{Q}_L q^u_R \tilde{H}_{1,2} + Y^d_{1,2} \bar{Q}_L q^d_R H_{1,2} + Y^\ell_{1,2} \bar{L}_L \ell_R H_{1,2} + h.c.
$$

Dark Sector

$$
V_{\text{Dark}} = m_\chi \bar{\chi}\chi + \frac{1}{2}(\partial_\mu a_0)^2 + \frac{m_{a_0}^2}{2} a_0^2 + i g_\chi \, a_0 \, \bar{\chi}\gamma^5\chi
$$

Portal

$$
V_{\text{portal}} = i \, \kappa \, a_0 \, H_1^\dagger H_2 + \text{h.c.}
$$

$$
H_j = \begin{pmatrix} \phi_j^+ \\ \frac{v_j + h_j + i\,\eta_j}{\sqrt{2}} \end{pmatrix} \qquad
\begin{aligned}
H^\pm &= -s_\beta \phi_1^\pm + c_\beta \phi_2^\pm \qquad & A_0 &= -s_\beta \eta_1 + c_\beta \eta_2 \\
h &= -s_\alpha h_1 + c_\alpha h_2 \qquad & H_0 &= -c_\alpha h_1 - s_\alpha h_2
\end{aligned}
$$

$h \rightarrow$ 125 GeV Higgs

Assume Natural Flavour Conservation in $\mathcal{L}_{\text{Yuk}}$

2HDM + *a* Portal to Dark Matter

Visible Sector

$$
\begin{aligned}
V_{\rm 2HDM} &= \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 - \mu^2 \left[H_1^\dagger H_2 + \text{h.c.} \right] \\
&+ \frac{\lambda_1}{2} |H_1|^4 + \frac{\lambda_2}{2} |H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 \\
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$$

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-\mathcal{L}_{\rm Yuk} = Y^u_{1,2} \bar{Q}_L q^u_R \tilde{H}_{1,2} + Y^d_{1,2} \bar{Q}_L q^d_R H_{1,2} + Y^\ell_{1,2} \bar{L}_L \ell_R H_{1,2} + h.c.
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$$

Portal

$$
V_{\rm portal} = i\,\kappa\, a_0\, H_1^\dagger H_2 + \text{h.c.}
$$

Mixing

Physical States

$$
A = c_\theta \, A_0 + s_\theta \, a_0 \quad , \quad a = c_\theta \, a_0 - s_\theta \, A_0
$$

$$
V_{\rm Dark} \supset i g_\chi \, (c_\theta a + s_\theta A) \, \bar{\chi}\gamma^5\chi
$$

$$
\begin{aligned}
V_{\rm portal} &= \frac{\left(m_A^2 - m_a^2\right) s_{2\theta}}{2\,v} \left(c_{\beta-\alpha} \, H_0 - s_{\beta-\alpha} \, h \right) \\
&\times \left[aA \left(s_\theta^2 - c_\theta^2 \right) + \left(a^2 - A^2 \right) s_\theta c_\theta \right]
\end{aligned}
$$

2HDM + *a* Portal to Dark Matter

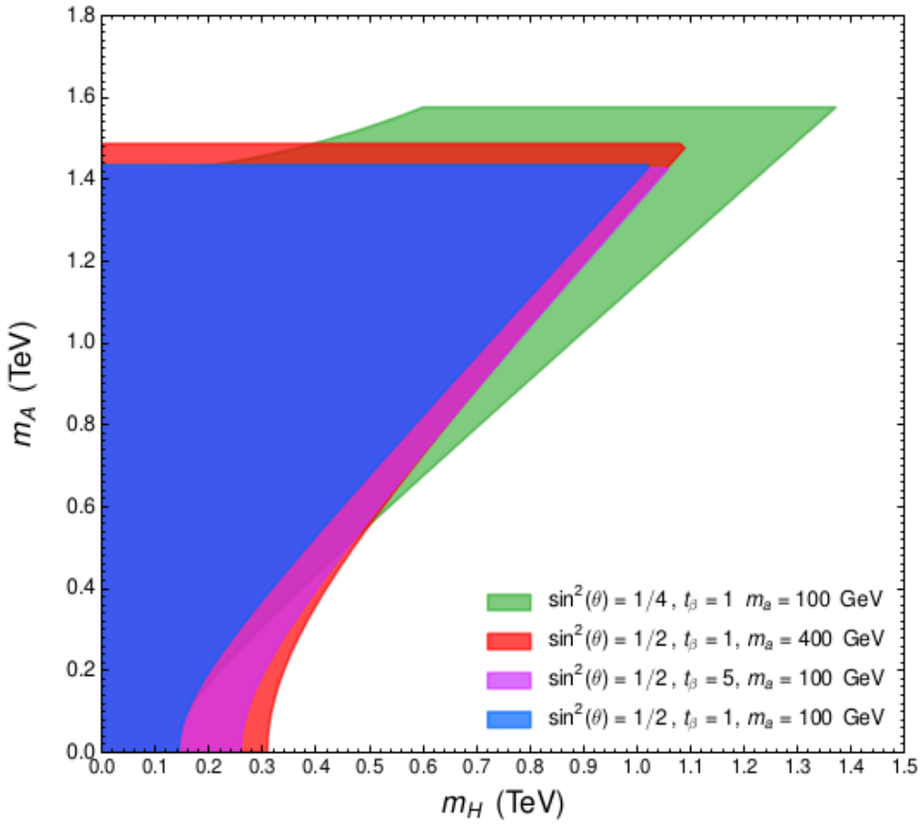
ALLOWED MASS RANGE FOR NEW STATES $A \quad H^{\pm} \; H_0$

- Mass Splittings among $A \quad H^{\pm} \; H_0$ bounded by 2HDM Unitarity

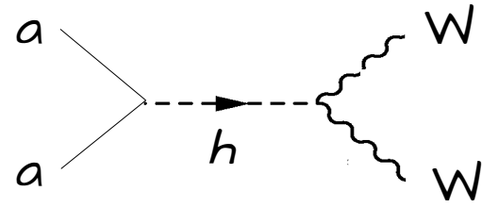
  *Ginzburg, Ivanov, Phys. Rev **D72** (2005) 115010*

$$m_i - m_j \leq \mathcal{O}(\text{few}) \times v$$

- Mass Splittings $m_{A,H_0,H^{\pm}} \gg m_a$ also bounded by Unitarity (if $\sin\theta$ is kept fixed)



Goncalves, Machado, JMN, ArXiv:1611.04593



$$M^2 = \mu^2/(s_\beta c_\beta)$$

$$\Delta_a^2 \equiv m_A^2 - m_a^2 \qquad \Delta_H^2 = M^2 - m_{H^{\pm}}^2 + 2m_W^2 - m_h^2/2$$

$$\Lambda_{\pm} = \left[\frac{\Delta_H^2}{v^2} - \frac{\Delta_a^2 (1 - c_{4\theta})}{8\, v^2} \pm \sqrt{\frac{\Delta_H^4}{v^4} + \frac{\Delta_a^4 (1 - c_{4\theta})}{8\, v^4}} \right]$$

Pert. Unitarity ➔ $|\Lambda_{\pm}| \leq 8\pi$

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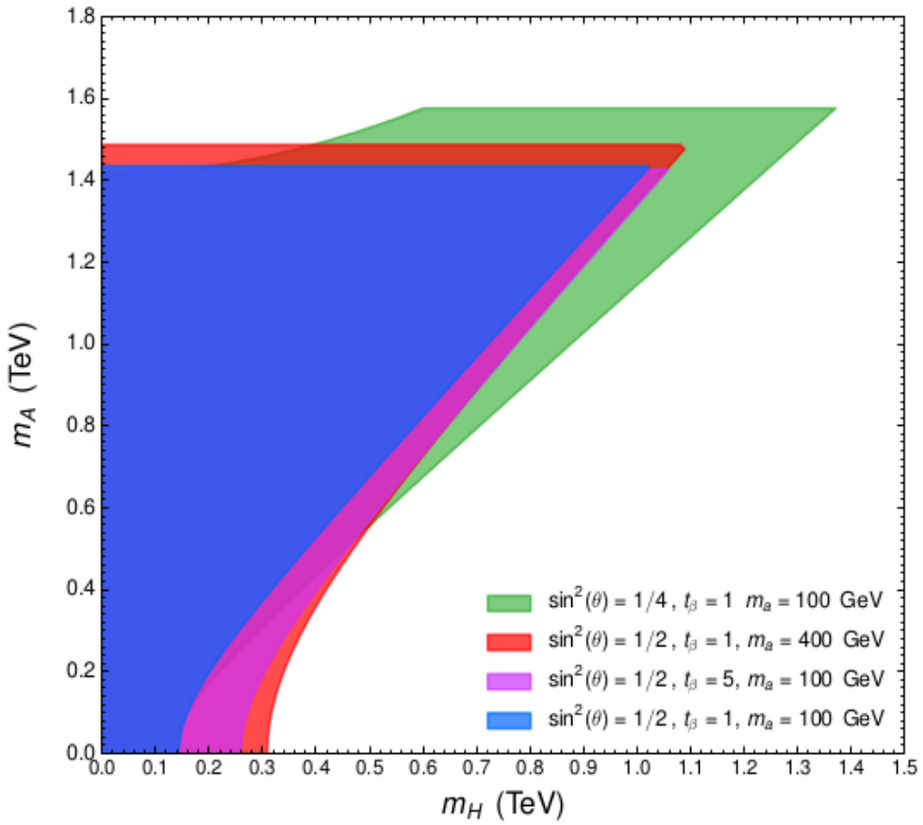

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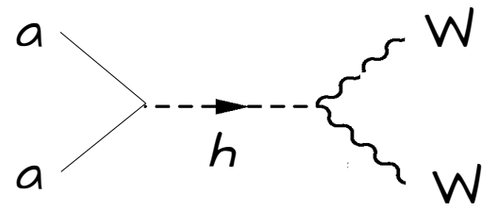

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Generally within LHC Reach

2HDM + *a* Portal to Dark Matter

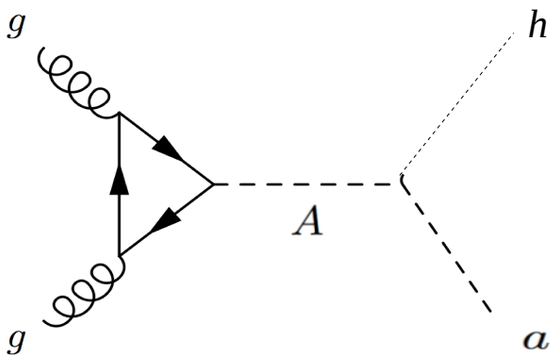
LHC SIGNATURES $m_{A,H_0,H^\pm} \gg m_a$

*JMN, Phys. Rev **D93** (2016) 031701*

Goncalves, Machado, JMN, ArXiv:1611.04593

Bauer, Haisch, Kahlhoefer, ArXiv:1701.07427

$m_A > m_a + m_h$

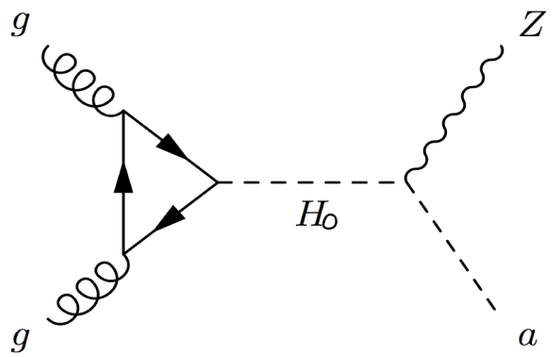


(Resonant) mono-*h* / mono-Z

(mono-W)

(Assume *a* Decays invisibly)

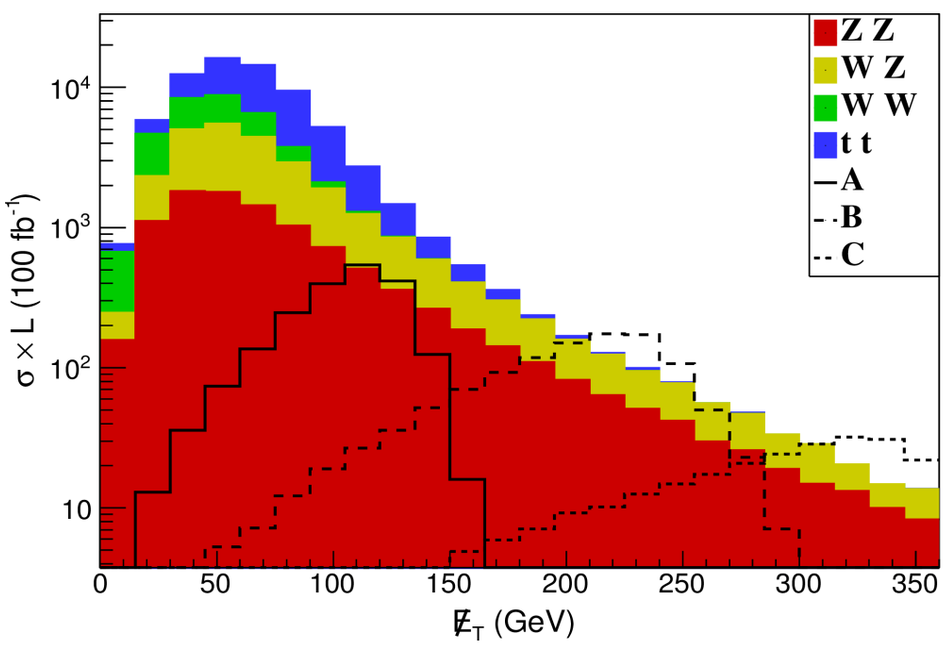
$m_{H_0} > m_a + m_Z$



$$\not{E}_T^{\max} \sim \frac{1}{2\,m_A}\sqrt{(m_A^2 - m_h^2 - m_a^2)^2 - 4\,m_h^2\,m_a^2}$$

$$\not{E}_T^{\max} \sim \frac{1}{2\,m_{H_0}}\sqrt{(m_{H_0}^2 - m_Z^2 - m_a^2)^2 - 4\,m_Z^2\,m_a^2}$$

mono-Z



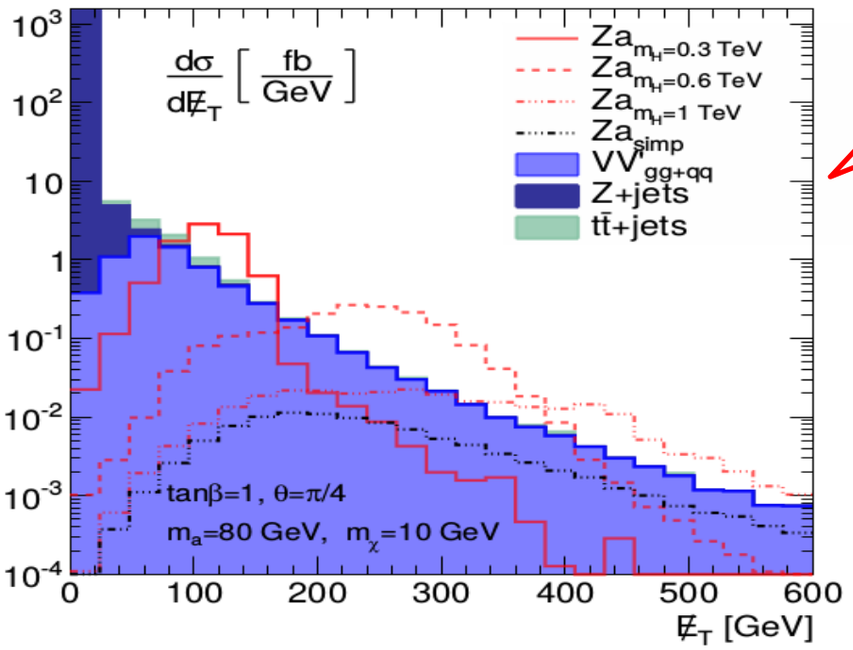
A	B	C
300 GeV	500 GeV	700 GeV

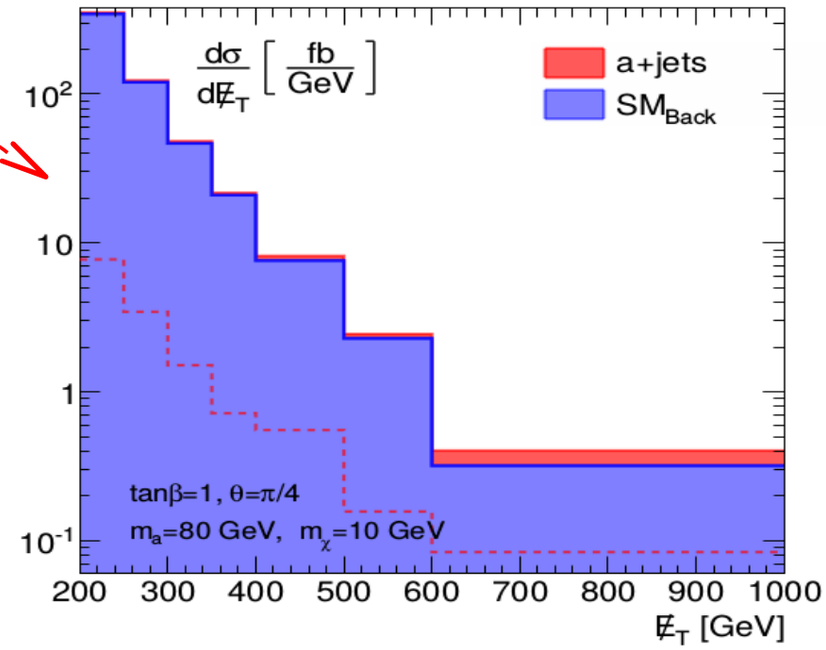
m_a = 80 GeV

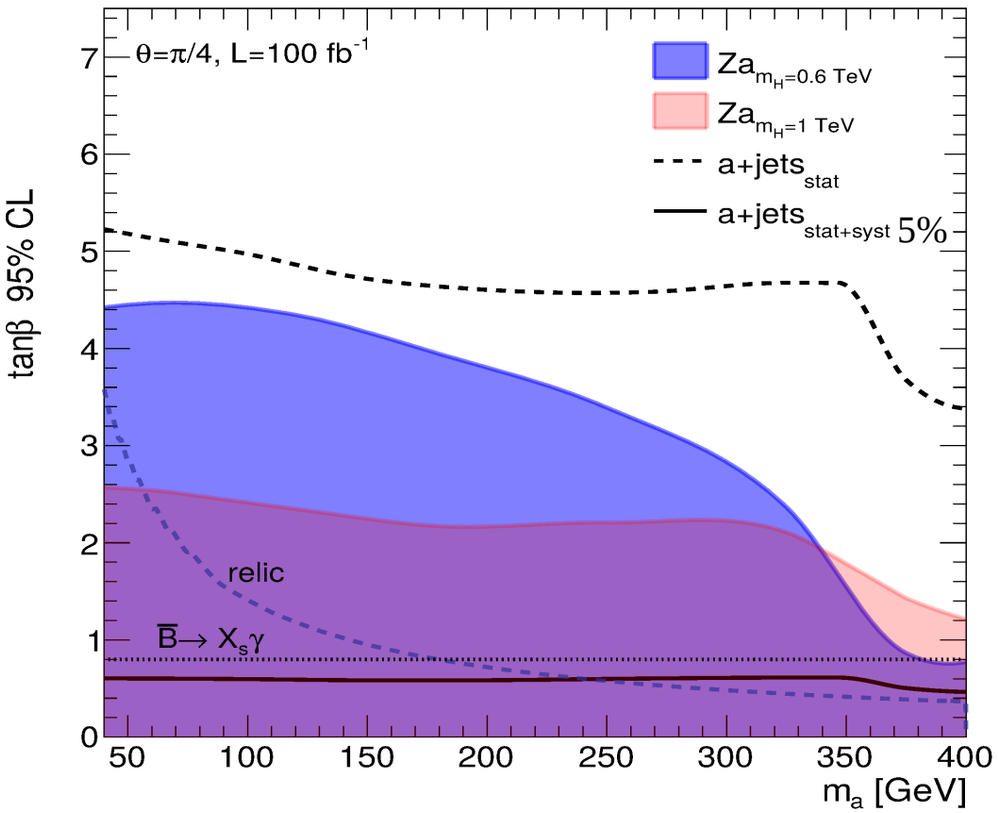
m_χ = 30 GeV

2HDM + *a* Portal to Dark Matter

Compare $Z + \not{E}_T$ to Jets $+ \not{E}_T$ @ LHC



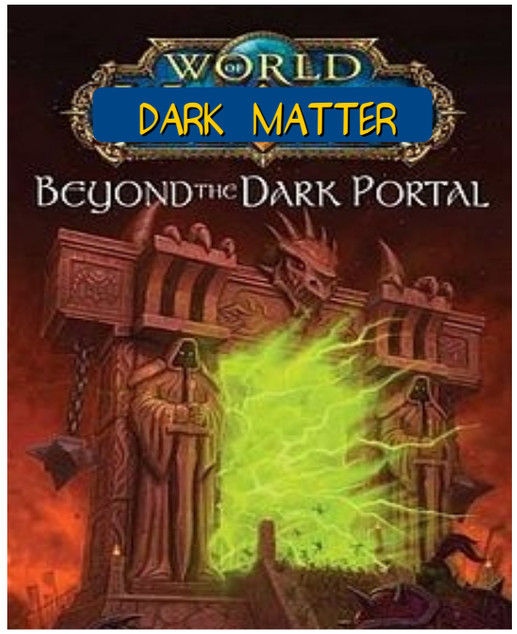




XS for signal scales as $\tan\beta^{-2}$

Mono-Z significantly more sensitive than **mono-jet** (w. syst)

Summary & Thoughts



- Strong Case to go beyond "traditional" simplified models for Dark Matter searches @ LHC

Simple Argument

⇒ DM from EW Multiplet → DM Phenomenology neglecting rest of Multiplet misses relevant physics

⇒ Mediator from EW Multiplet → Neglecting States in Mediator Multiplet Misses Relevant DM Physics

- Pseudoscalar Mediator scenario: New LHC signatures

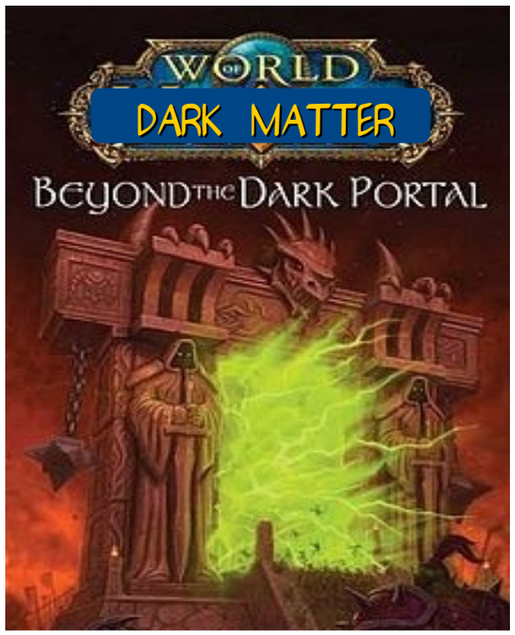
  2HDM + a (+ DM)

  Resonant mono-Z

  Resonant mono-h

  ⇒ LHC could probe DM interpretation of Galactic Center gamma ray excess

- In general, identifying minimal consistent "model unit" for Dark Matter phenomenology in each scenario is important


WORLD
DARK MATTER
BEYOND THE DARK PORTAL


Thanks!