The WIMP Next Door: Simplified Models for Hidden Sector Dark Matter

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JAE, Gori, Shelton – 170[5-6].xxxxx

Dark Matter

What we know

The cynic's response: **NOTHING**

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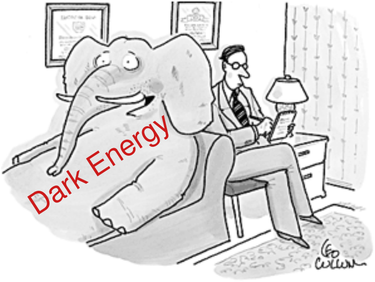

"I'm right there in the room, and no one even acknowledges me."

Dark Matter

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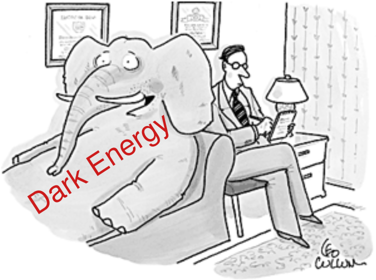
DATA



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Dark Matter

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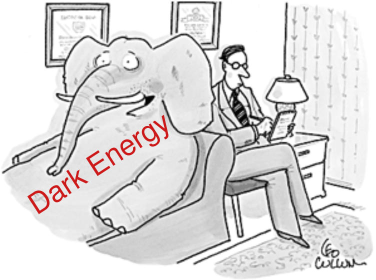
DATA

→

Theory
Interpretation



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Dark Matter

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DATA

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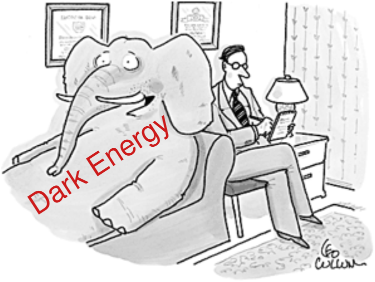
Theory Interpretation



"I'm right there in the room, and no one even acknowledges me."

<u>Three possibilities:</u>

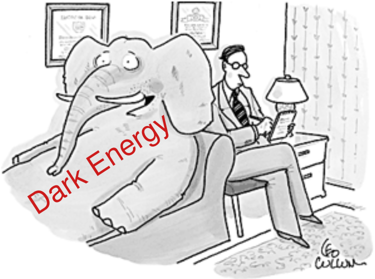
Explain the elephant | Find flaw(s) in data | Fix our fun factory

The cynic's response: **NOTHING**

DATA

→

Theory Interpretation



"I'm right there in the room, and no one even acknowledges me."

FOUR ~~Three~~ possibilities:

Could change DM properties

- Explain the elephant
- Find flaw(s) in data
- Fix our fun factory

COMPLETELY IGNORE THE ELEPHANT

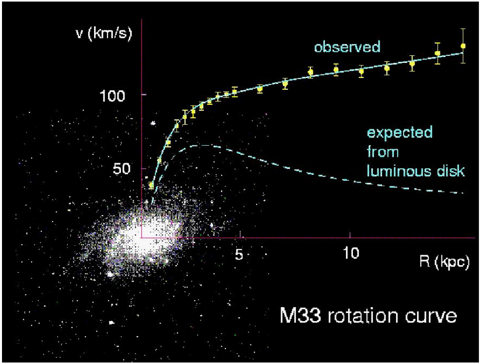
Dark Matter

What we know (what elephant?)

Dark Matter

What we know (what elephant?)

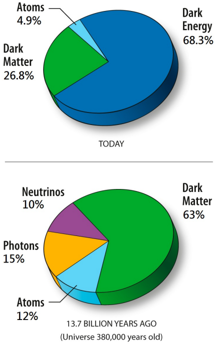
1. It exists – LOTS of evidence

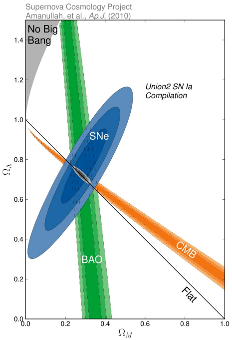


Dark Matter

What we know (what elephant?)

1. It exists – LOTS of evidence
2. There is a lot of it

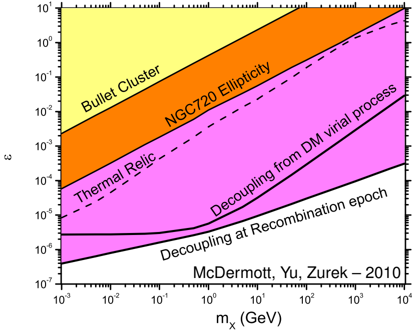




Dark Matter

What we know (what elephant?)

1. It exists – LOTS of evidence
2. There is a lot of it
3. It is dark



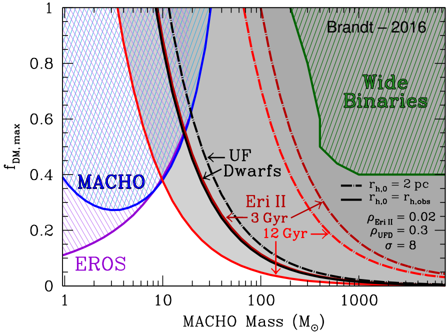
$$\frac{d\sigma_{\chi\chi}}{d\Omega_*} = \frac{\alpha_{EM}^2 \epsilon^4}{m_\chi^2 v_{rel}^4 \sin^4(\theta_*/2)}$$

$$\frac{d\sigma_{\chi B}}{d\Omega_*} = \frac{\alpha_{EM}^2 \epsilon^2}{4\mu_B^2 v_{rel}^4 \sin^4(\theta_*/2)}$$

Dark Matter

What we know (what elephant?)

1. It exists – LOTS of evidence
2. There is a lot of it
3. It is dark
4. It isn't MACHOs (baryons)



Dark Matter

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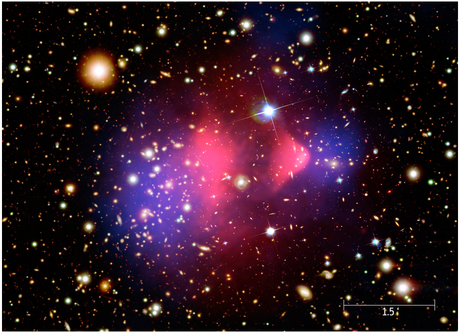
5. Self-interactions aren't huge



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5. Self-interactions aren't huge
6. It isn't too light

Boson: deBroglie wavelength

$$\lambda_{dB} = \frac{2\pi}{mv} \lesssim 1 \text{ kpc}$$

$$m_{DM} \geq 1 \times 10^{-22} \text{ eV}$$

Hu, Barkana, Gruzinov – 2000

Hui, Ostriker, Tremaine, Witten – 2016

Fermion: Pauli exclusion principle

$\Rightarrow$ can't fit enough DM in dwarfs

$$m_{DM} \geq 410 \text{ eV}$$

Tremaine, Gunn – 1979

Boyarsky, Ruchayskiy, Iakubovsky – 2008

Dark Matter

What we know (what elephant?)

1. It exists – LOTS of evidence
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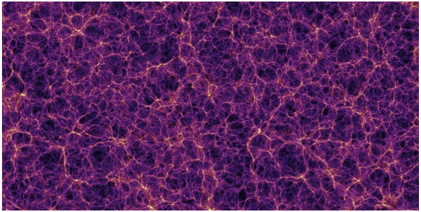
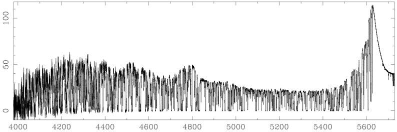
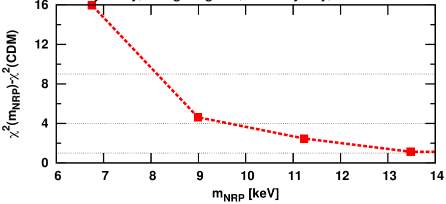
6. It isn't too light
7. It isn't hot





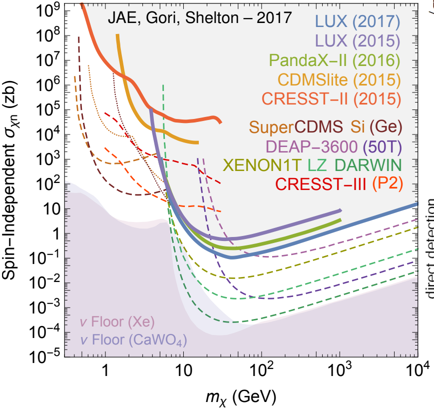
Boyarsky, Lesgourgues, Ruchayskiy, Viel – 2008

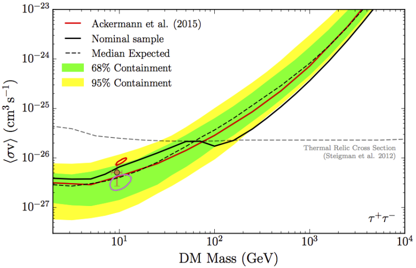


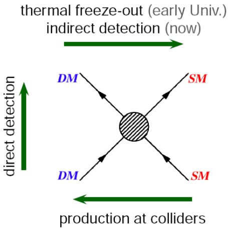
Dark Matter

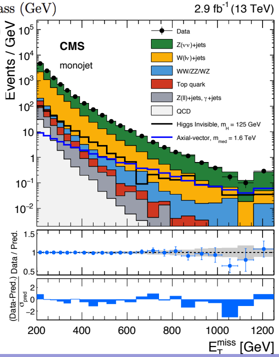
What we know

8. It is quite elusive!



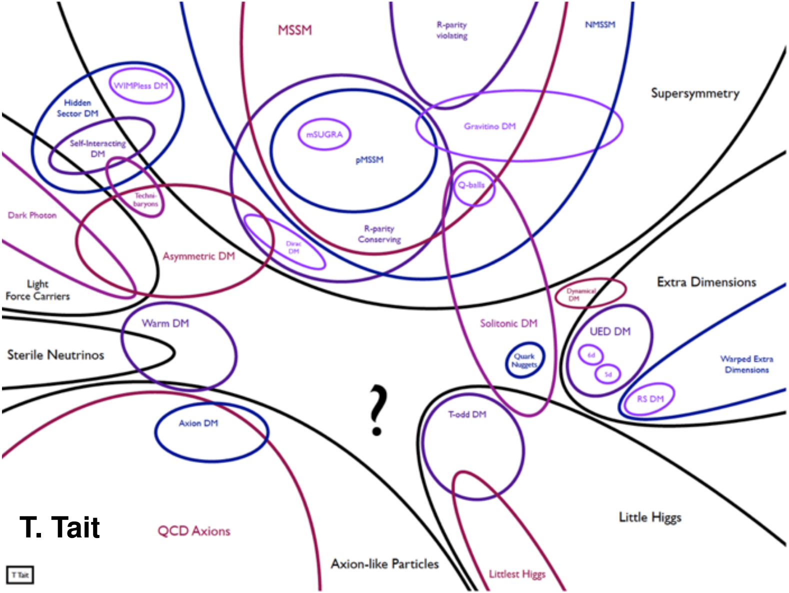






Dark Matter

What it could be



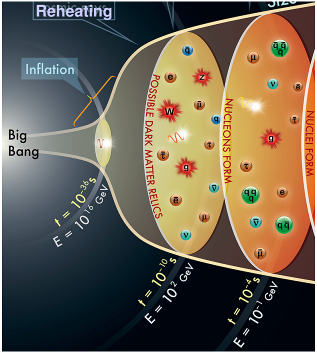
- WIMP Freezeout
- Hidden Sector Freezeout
- Sommerfeld Enhancement
- Vector Simplified Model
- Scalar Simplified Model
- Future Direction & Conclusions

Everything is preliminary!

Thermal Freezeout in the Early Universe

- After reheating, universe expands and cools adiabatically,

$$\text{Expansion rate: } H \propto \frac{T^2}{M_{pl}}$$



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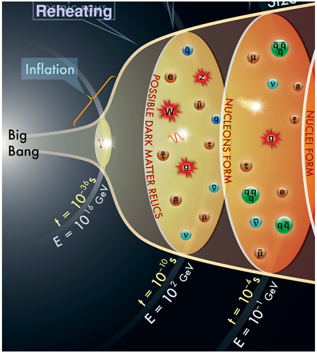
- Rapid collisions keep SM in equilibrium
- Thermodynamics dictates properties,

$$n_{relativistic} \propto T^3, \; n_{massive} \propto (mT)^{\frac{3}{2}} e^{-\frac{m}{T}}$$



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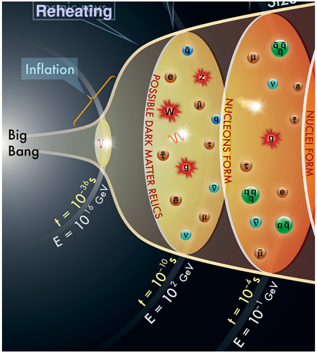


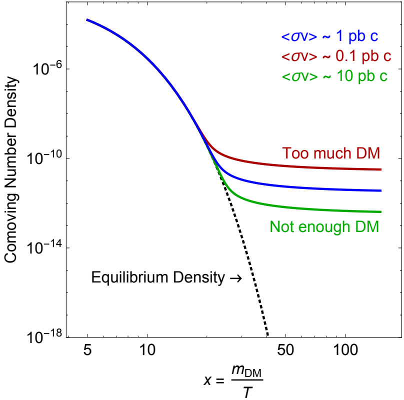
For Dark Matter, χ (any state with approximate $\mathbf{Z}_2$):

- Falling $n_\chi \Rightarrow \Gamma_{\Delta\#} = n_\chi \langle \sigma v \rangle_{\chi\bar{\chi}\to SM} < H$
- Number changing ceases, and χ departs *chemical equilibrium*

WIMP Miracle

Dark matter freezeout gives observed relic dark matter abundance for

$$\langle \sigma v \rangle_{\chi\bar{\chi}\to SM} \approx 1\ \text{pb}\cdot\text{c}$$



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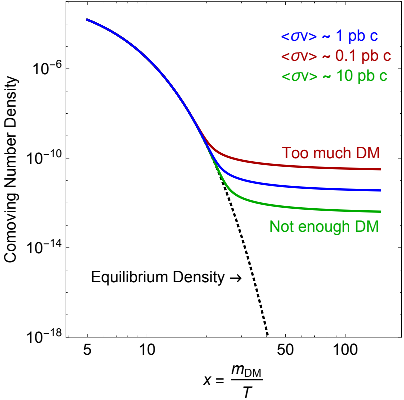

WIMP miracle:

$$\langle \sigma v \rangle_{\chi\bar{\chi}\to SM} \approx \frac{\alpha_{weak}^2}{\Lambda_{weak}^2} \approx 1\ \text{pb}\cdot\text{c}$$

TeV scale mass and $SU(2)_L$ interaction can provide our dark matter!

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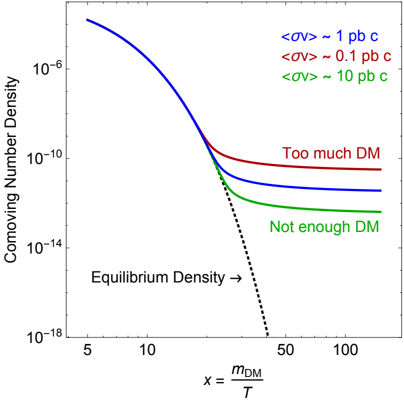

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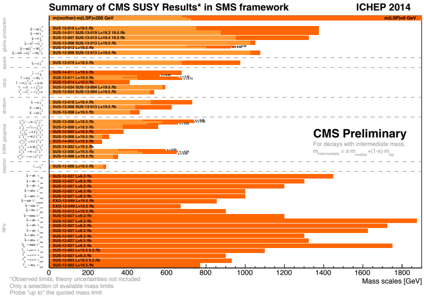
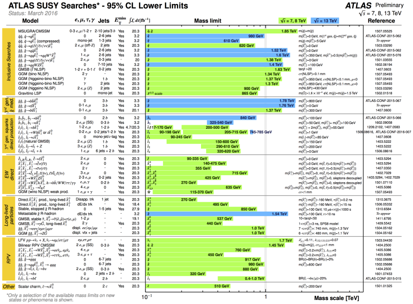
Natural models like SUSY have perfect candidates (neutralino)!

WIMP Schmiracle





No evidence of SUSY (or top partners or anything else)

SUSY WIMP parameter space remains, but outlook not great

WIMP Schmiracle

Dark Matter	Z, Higgs Coupling	Direct	Status	XENON1T	Indirect (10^{-26} cm^3/s)
Majorana Fermion	$\bar{\chi}\gamma^\mu\gamma^5\chi Z_\mu$	$\sigma_{SD} \sim 1$	$m_\chi \sim m_Z/2$ or $m_\chi \gtrsim 190$ GeV	Yes Up to 440 GeV	$\sigma v \simeq$ small $\sigma v \simeq 2.1 - 2.3$
Dirac Fermion	$\bar{\chi}\gamma^\mu\chi Z_\mu$	$\sigma_{SI} \sim 1$	$m_\chi \gtrsim 6$ TeV	Yes	$\sigma v \simeq 2.1 - 2.3$
Dirac Fermion	$\bar{\chi}\gamma^\mu\gamma^5\chi Z_\mu$	$\sigma_{SD} \sim 1$	$m_\chi \sim m_Z/2$ or $m_\chi \gtrsim 240$ GeV	Yes Up to 570 GeV	$\sigma v \simeq$ small $\sigma v \simeq 2.1 - 2.3$
Complex Scalar	$\phi^\dagger \overleftrightarrow{\partial_\mu}\phi Z^\mu$, $\phi^2 Z^\mu Z_\mu$	$\sigma_{SI} \sim 1$	Excluded	–	–
Complex Vector	$(X_\nu^\dagger \partial_\mu X^\nu + \text{h.c.})Z^\mu$	$\sigma_{SI} \sim 1$	Excluded	–	–
Real Scalar	$\phi^2 H^2$	$\sigma_{SI} \sim 1$	$m_\chi \sim m_H/2$ or $m_\chi \gtrsim 400$ GeV	Maybe Up to 5 TeV	$\sigma v \simeq 0.0012 - 0.019$ $\sigma v \simeq 2.1 - 2.3$
Complex Scalar	$\phi^2 H^2$	$\sigma_{SI} \sim 1$	$m_\chi \sim m_H/2$ or $m_\chi \gtrsim 840$ GeV	Maybe Up to 10 TeV	$\sigma v \simeq 0.0019 - 0.017$ $\sigma v \simeq 2.1 - 2.3$

Escudero, Berlin, Hooper, Lin – 2016

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Renormalizable minimal models are heavily constrained

Some territory remains, but not much for long

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Perhaps the WIMP miracle is a red herring?

WIMPless Freezeout

Minimal idea – keep thermal freezeout, lose the weak scale

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Consider new, electrically neutral dark particle:

- Scalar, ϕ
- Fermion, χ
- Vector, V

Couple to standard model – allowable dim $\leq$4 couplings:

$$\chi H L$$
$$\phi H^\dagger H$$
$$B^{\mu\nu} V_{\mu\nu}$$
$$|\phi|^2 H^\dagger H$$

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χHL
$\phi H^\dagger H$
$B^{\mu\nu} V_{\mu\nu}$

} No $\mathbf{Z}_2$, will decay if froze out

$|\phi|^2 H^\dagger H$ Viable model, but constrained

Real Scalar	$\phi^2 H^2$	$\sigma_{SI} \sim 1$	$m_\chi \sim m_H/2$ or $m_\chi \gtrsim 400$ GeV	Maybe Up to 5 TeV	$\sigma v \simeq 0.0012 - 0.019$ $\sigma v \simeq 2.1 - 2.3$
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One-step more complicated than a standard WIMP:

Hidden sector freezeout $\chi\bar{\chi} \to VV/\phi\phi$

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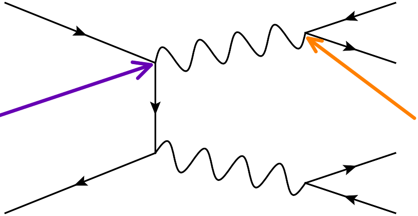
Dark Matter	Mediator	Interaction	Portal
Dirac χ	Vector V	$g_D V_\mu \bar{\chi}\gamma_\mu\chi$	$\epsilon B^{\mu\nu} V_{\mu\nu}$
Majorana χ	Scalar ϕ	$y_D \phi\chi\chi$	$\epsilon \lvert\phi\rvert^2 H^\dagger H$

$m_\chi > m_V, m_\phi$



g_D, y_D sets relic abundance

ϵ thermalizes with SM & dumps entropy back to SM

Pospelov, Ritz, Voloshin – 07; Feng, Kumar – 08; Feng, Tu, Yu – 08; ...

The Models

Minimal Hidden Sector Vector Model ($\epsilon \ll 1$):

$$\mathcal{L}_{Z_D} = g_D Z_{D,\mu} \bar{\chi} \gamma^\mu \chi + \frac{1}{2} m_{Z_D}^2 Z_D^\mu Z_{D\mu} + m_\chi \bar{\chi} \chi + \frac{\epsilon}{2 \cos \theta} Z_{D\mu\nu} B^{\mu\nu}$$

Free parameters: m_χ, m_{Z_D}, ϵ, $g_D \leftarrow$ fixed by relic abundance

The Models

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Free parameters: m_χ, m_{Z_D}, ϵ, $g_D \leftarrow$ fixed by relic abundance

Minimal Hidden Sector Scalar Model ($\epsilon \ll 1$):

$$\mathcal{L}_S = -\frac{1}{2} (y_D S) (\chi\chi + \text{h.c.}) + \frac{\mu_s^2}{2} S^2 - \frac{\lambda_s}{4!} S^4 - \frac{\epsilon}{2} S^2 |H|^2$$

Free parameters: m_χ, m_s, $\sin\theta \propto \epsilon$, $y_D \leftarrow$ fixed by relic abundance

The Models

Minimal Hidden Sector Vector Model ($\epsilon \ll 1$):

$$\mathcal{L}_{Z_D} = g_D Z_{D,\mu}\bar{\chi}\gamma^{\mu}\chi + \frac{1}{2}m_{Z_D}^2 Z_D^{\mu} Z_{D\mu} + m_{\chi}\bar{\chi}\chi + \frac{\epsilon}{2\cos\theta} Z_{D\mu\nu}B^{\mu\nu}$$

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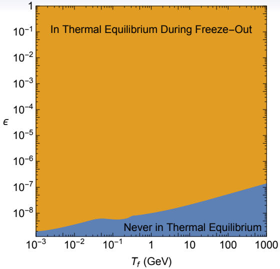
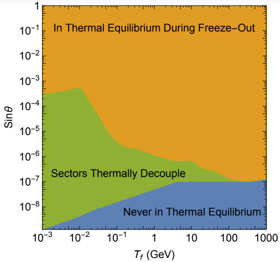
Free parameters: m_{χ}, m_s, $\sin\theta \propto \epsilon$, $y_D \leftarrow$ fixed by relic abundance

Probe	Constraints (examples)	Suppression
Relic abundance	Planck, Supernova, BAO	None
Indirect detection	Fermi, AMS-02, Planck	None
Direct detection	LUX, CDMSlite, CRESST-II	ϵ^2
Colliders	Atlas, CMS	ϵ^2
Precision	LHCb, Belle, CHARM, (SHiP)	ϵ^2 (mediator)

The Models

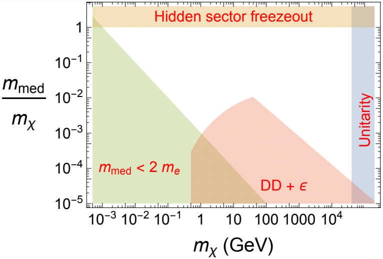




In both models, $(m_{DM}, m_{med}, \epsilon)$ parameter space is bounded:

Bound	Reason
$\epsilon \gtrsim 10^{-7} - 10^{-9}$	SM and hidden sector thermalize

The Models



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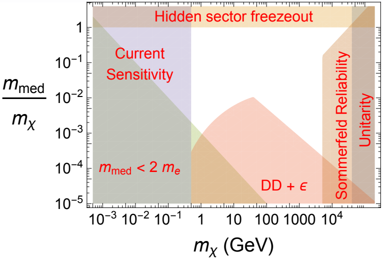
$\epsilon \gtrsim 10^{-7} - 10^{-9}$	SM and hidden sector thermalize
$m_{DM} > m_{med}$	hidden sector freezeout
$m_{DM} \lesssim 50\,TeV$	unitarity
$m_{med} > 2m_e$	do not disrupt BBN (and other constraints)
$m_{med}/m_{DM} > ?$	Direct Detection + ϵ bound

The Models



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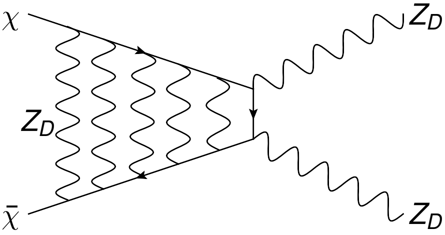
$m_{DM} > m_{med}$	hidden sector freezeout
$m_{DM} \lesssim 50\, TeV$	unitarity
$m_{med} > 2m_e$	do not disrupt BBN (and other constraints)
$m_{med}/m_{DM} > ?$	Direct Detection + ϵ bound
$m_{DM} > 500$ MeV	Current experimental sensitivity
$m_{DM} \lesssim 5$ TeV	Reliable freezeout with Sommerfeld Enhancement

Sommerfeld Enhancement

Light mediators & Low velocities $\Rightarrow \langle \sigma v \rangle$ is Sommerfeld enhanced

SE: Non-relativistic QM effect from particles feeling each other's potential



Largest for:

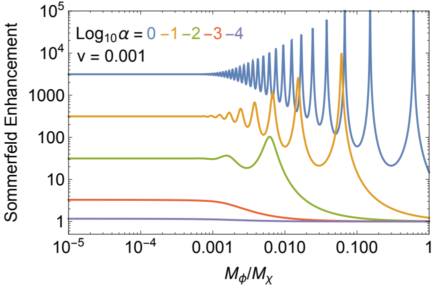
- small velocity, v
- small mass ratio, $R = \frac{m_{med}}{m_{DM}}$
- large coupling strength, α

$$\sigma v|_{s-wave} \approx S_0(\alpha, R, v)\sigma_0 + \mathcal{O}\left(v^2\right)$$

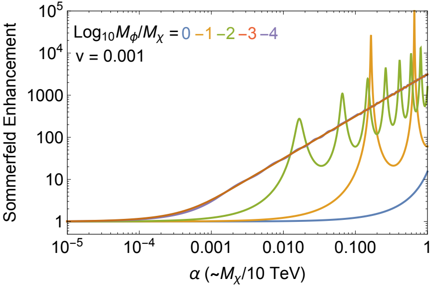
$$\sigma v|_{p-wave} \approx S_1(\alpha, R, v)\sigma_1 v^2 + \mathcal{O}\left(v^4\right)$$

Sommerfeld Enhancement

$\langle \sigma v \rangle_s \approx S_0(v_c)\sigma_0$



$\langle \sigma v \rangle_p \approx S_1(v_c)\sigma_1 v_c^2$



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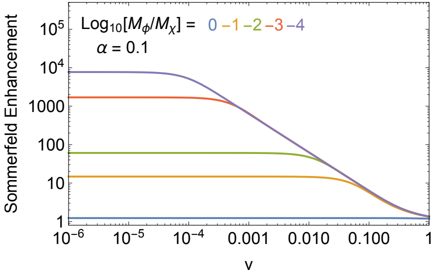

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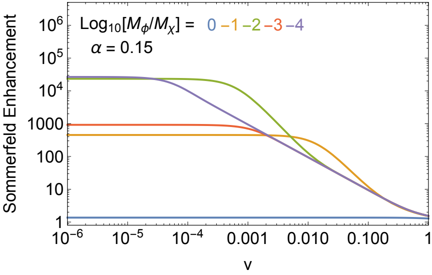

Affects:

- Annihilation at CMB – $v_c \lesssim 10^{-7}$
- The Milky Way – $v_c \sim 1.7 \times 10^{-3}$
- Dwarfs – $v_c \sim 10^{-4}$
- Freezeout – $v_c \sim \sqrt{\frac{6T}{m_\chi}}$

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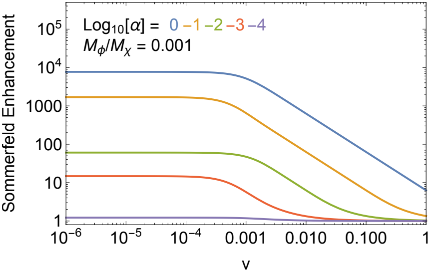

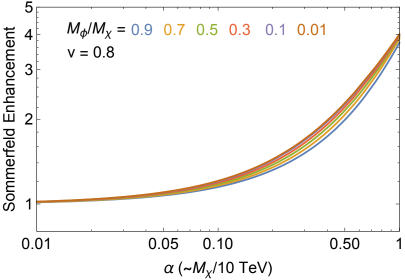

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Freezeout is greatly perturbed, reliability condition: $\alpha|_{\text{w/o SE}} / \alpha|_{\text{w/ SE}} > 2$

Vector Model

$$\mathcal{L}_{Z_D} = g_D Z_{D,\mu} \bar{\chi} \gamma^\mu \chi + \frac{1}{2} m_{Z_D}^2 Z_D^\mu Z_{D\mu} + m_\chi \bar{\chi} \chi + \frac{\epsilon}{2\cos\theta} Z_{D\mu\nu} B^{\mu\nu}$$

Free parameters: m_χ, m_{Z_D}, $\epsilon \ll 1$, $g_D \leftarrow$ fixed by relic abundance

Vector Model: Indirect Detection

Teaching us about pulsars since 1998

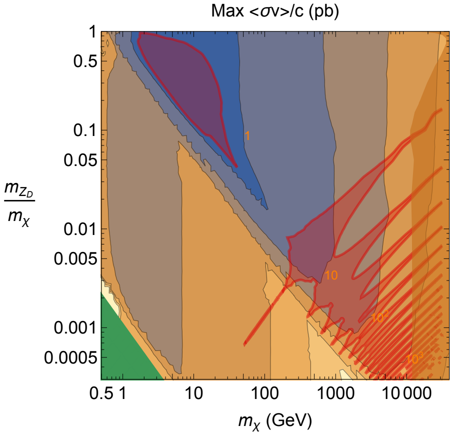
Several sources for indirect detection of annihilating dark matter:

- Photons at Fermi-LAT (dwarfs most sensitive!)

Fermi : use 41 dwarfs $\times$ 24 E bins (dwarf $\langle \sigma v \rangle$ constraint shown)

$m_{med} > 2m_e$

Sommerfeld Condition



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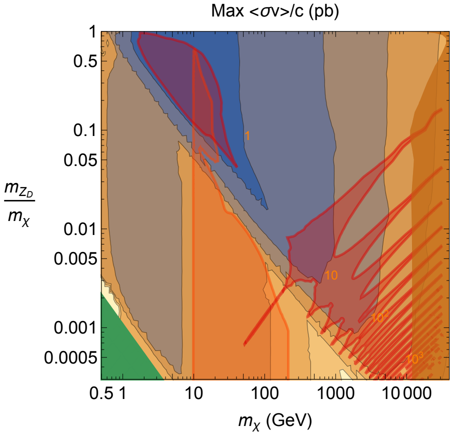

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- CMB spectral distortions at PLANCK, SPT, etc Slatyer – 2015

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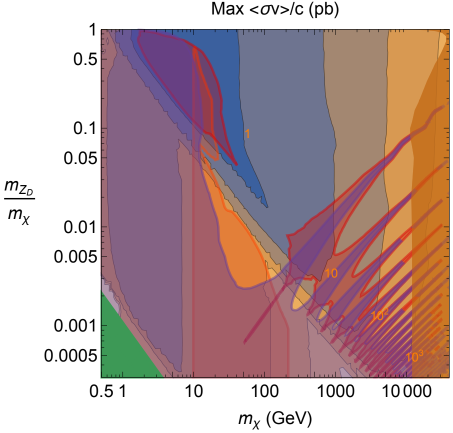


Vector Model: Direct Detection

$$\sigma_{\chi n} = \frac{\epsilon^2 g_D^2 \mu_{\chi n}^2}{\pi} \left| \frac{f_n^{(Z_D)}}{m_{Z_D}^2} + \frac{f_n^{(Z)} \sin\theta_W}{m_Z^2 - m_{Z_D}^2} \right|^2 \propto m_{Z_D}^{-4}$$

DM-nucleon cross-section

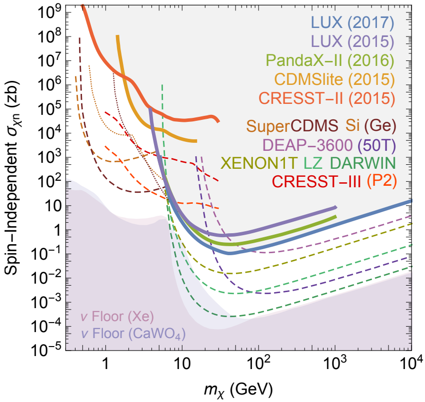
Effective Z_D-nucleon coupling

Reduced DM-nucleon mass

Set by relic abundance

Vector Model: Direct Detection

$$\epsilon < \frac{\sqrt{\pi \sigma_{\chi n}^{DD\,bound}}}{g_D \mu_{\chi n}} \left| \frac{f_n^{(Z_D)}}{m_{Z_D}^2} + \frac{f_n^{(Z)} \sin\theta_W}{m_Z^2 - m_{Z_D}^2} \right|^{-1}$$



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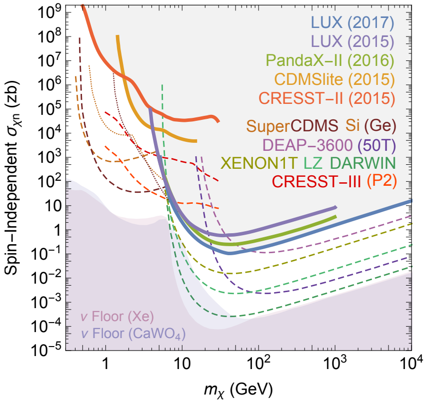
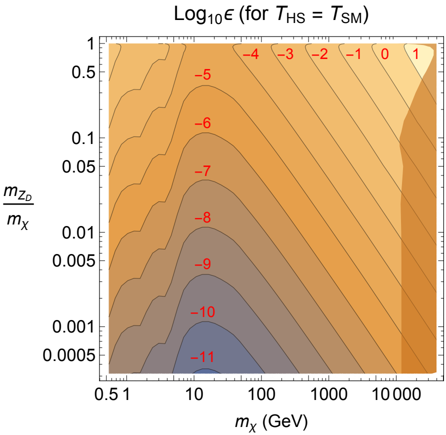
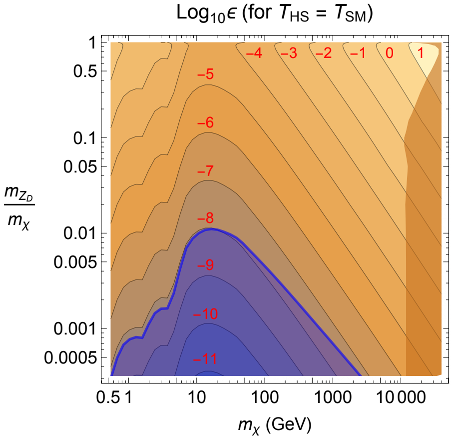


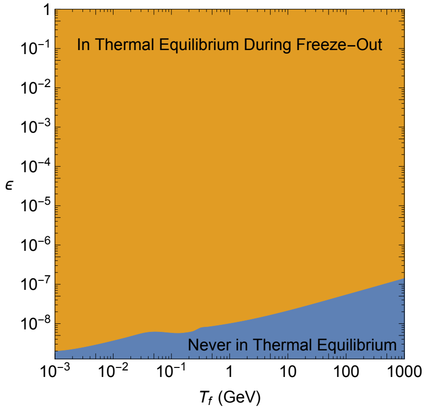


Vector Model: Direct Detection

Thermal Coupling

$$\Gamma_{int,Z_d}(T) = \sum_{X,Y,Z} \langle \sigma_{Z_d X \to YZ} v \rangle_T \, n_X^{eq} \quad \text{for} \begin{cases} Z_D f \to fg/\gamma \\ Z_D g/\gamma \to f\bar{f} \\ Z_D t \to th \\ Z_D h \to t\bar{t} \end{cases} \quad \left(T_f \sim \frac{m_\chi}{20}\right)$$





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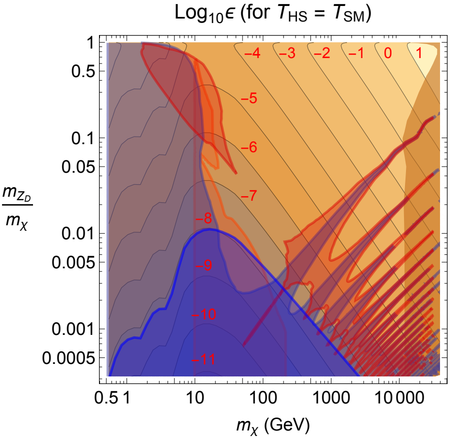

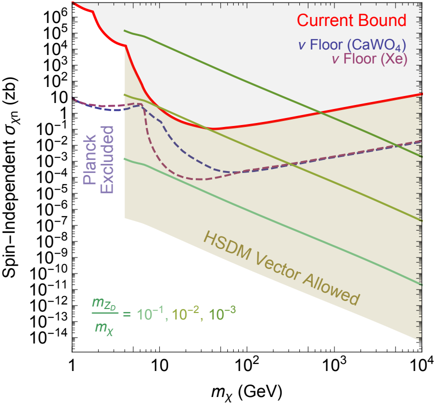

Vector Model: Collider & Precision Constraints

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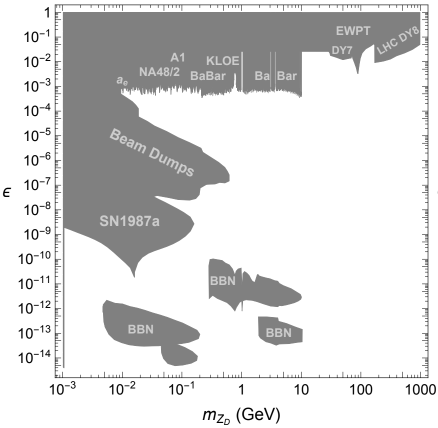

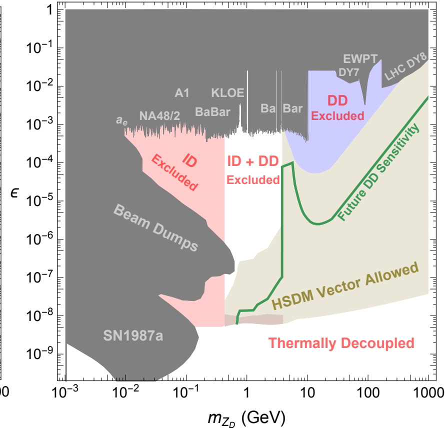

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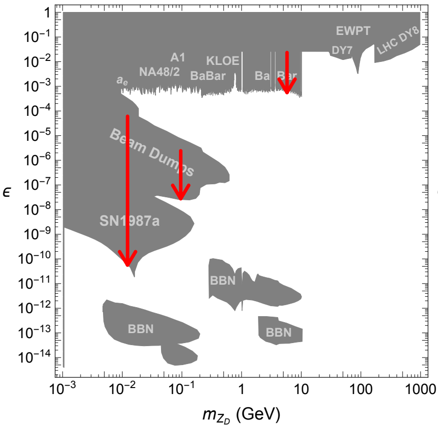

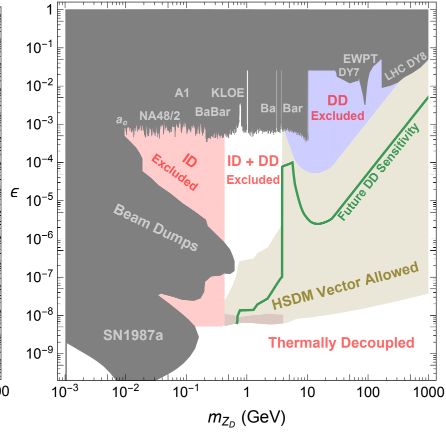

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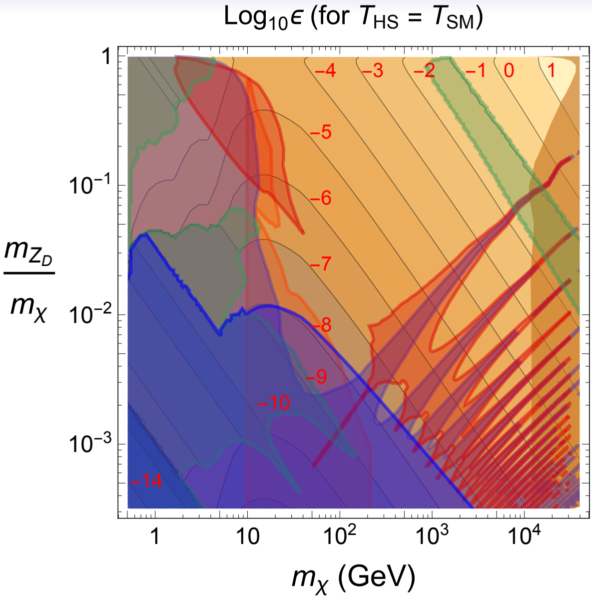

EXCLUDED:

Fermi (γ)

AMS-02 (e^+)

Planck (CMB)

Other:

Thermal Decoupling

Constraint: Z_D > DD

Sommerfeld

How generic are the features of the simplified model?

A simplified model is only as interesting as it is general

Modification	Effect	Comments
Additional Heavy States	No effect	Can thermalize, if connected to SM
Additional DM (global sym)	Increased FO coupling	$g_D \to g_D\sqrt{N} \Rightarrow$ stronger DD
Vector$\to$V-A	$\mathcal{O}(1)$ corrections	Qualitatively identical
Dark Higgs	Can be irrelevant	Could also dominate the story
Pseudo-Dirac	Reduced DD	Inelastic dark matter
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Need dark vector and dark matter as the lightest states of the sector

Scalar Model

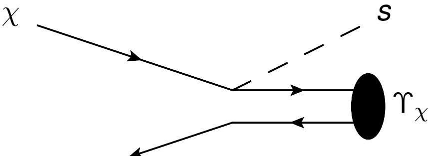
$$\mathcal{L}_S = -\frac{1}{2}(y_D S)(\chi\chi + \text{h.c.}) + \frac{\mu_s^2}{2} S^2 - \frac{\lambda_s}{4!} S^4 - \frac{\epsilon}{2} S^2 |H|^2$$

Free parameters: m_χ, m_s, $\sin\theta \propto \epsilon$, $y_D \leftarrow$ fixed by relic abundance

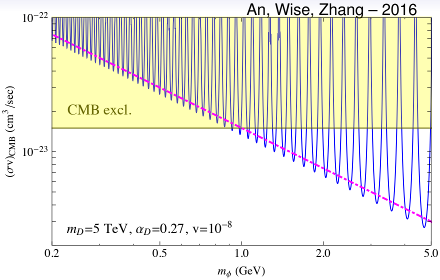
Scalar Model: Indirect Detection

Fermionic dark matter annihilating to scalars is *p*-wave: $\langle \sigma v \rangle \propto v^2$

Scalar Model: Indirect Detection



$m_s < \frac{1}{4}\alpha_D^2 m_\chi$



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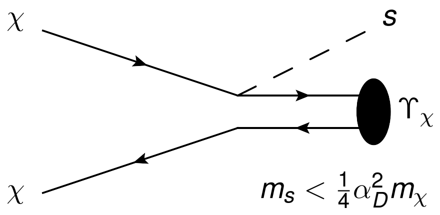

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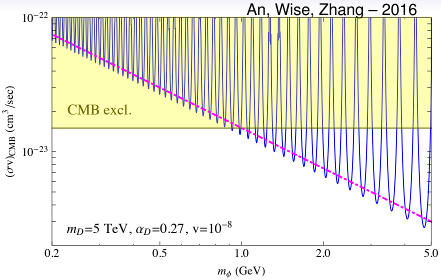

CMB: combine all decay paths

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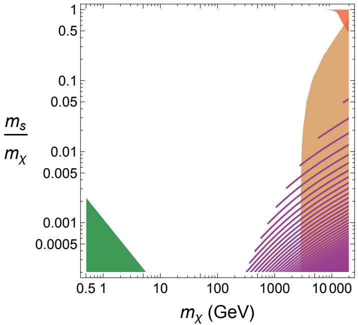
Sommerfeld Condition

$\alpha > 1$



Scalar Model: Direct Detection

$$\sigma_{\chi n} = \frac{2 y_D^2 \sin^2\theta \mu_{n\chi}^2 f_n^{(s)2} m_n^2}{\pi m_s^4 v_h^2}\left(1 - \frac{m_s^2}{m_h^2}\right)^2$$

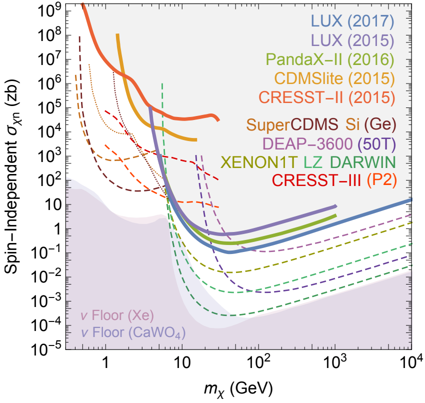
DM-nucleon cross-section

Effective higgs-nucleon coupling

Set by relic abundance

Scalar Model: Direct Detection

$$\sin\theta < \sqrt{\frac{\pi}{2}} \frac{\sqrt{\sigma_{\chi n}^{DD\,bound}}\, m_s^2 v_h}{y_D f_n^{(s)} \mu_{\chi n} m_n} \left| 1 - \frac{m_s^2}{m_h^2} \right|^{-1}$$



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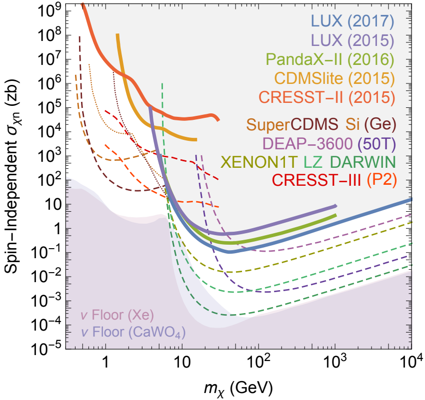
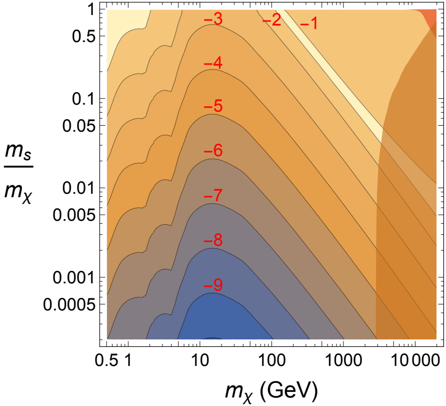


Log$_{10}$[Sin θ] (for T_{HS} = T_{SM})



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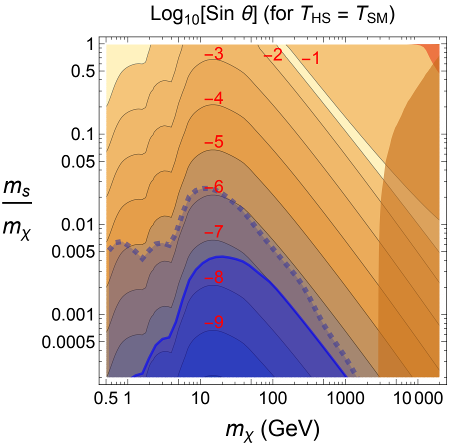

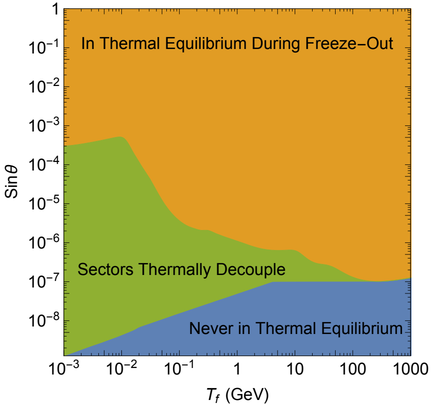

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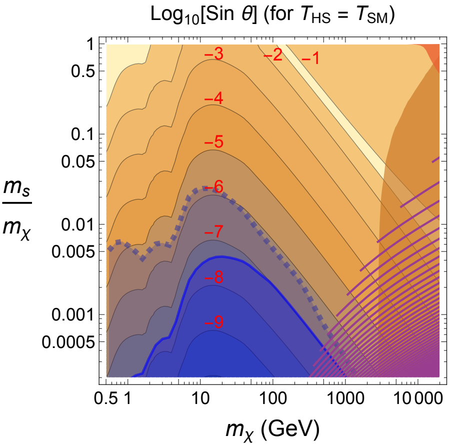

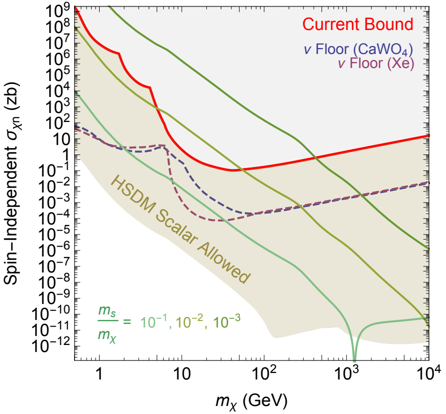

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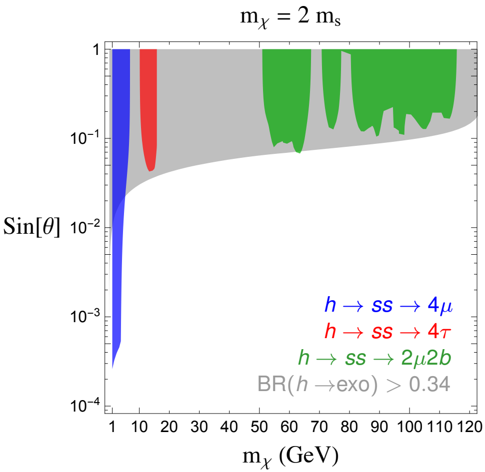
From exotic Higgs decays

Curtin, et al – 2013



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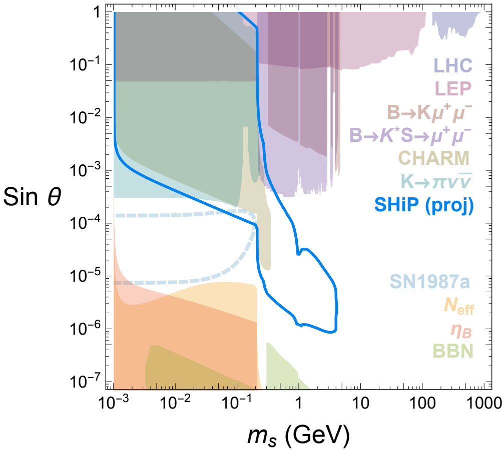
and direct searches for the mediator!

Krnjaic – 2015

Flacke, Frugiuele, Fuchs, Gupta, Perez – 2016



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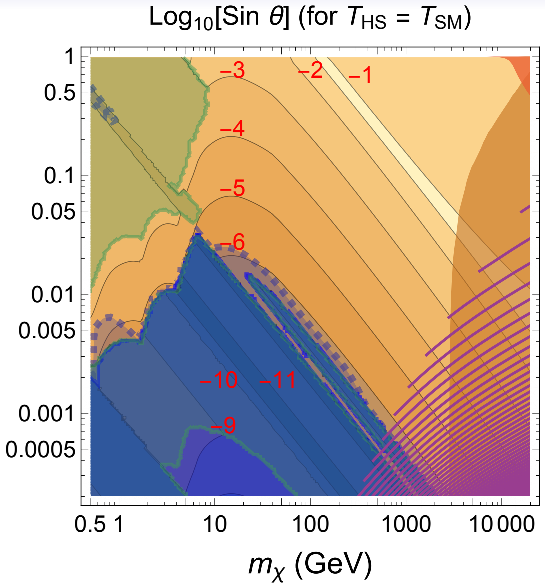

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The Future

Tons of interesting future directions!

- Construct simplified models for HS scalar DM
- Phenomenology of thermally decoupled sectors
- Cosmology of light dark matter
- New bounds on light, Higgs-mixed scalars
- Proper thermal field theory treatment of thermal (de)coupling
- Direct detection under the influence of bound states
- And many more!

Summary

- The WIMP next door is a simple, plausible story for dark matter
- These simplified models are:
  - Minimal
  - Bounded
  - Constrained
  - General
  - Simple
  - Complete
- Thermal coupling mandates sufficient connection to the SM
- Direct detection can access cosmological lower bound on portal
- A lot of opportunities for future experiments to access this sector