Dark Matter Searches

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McMaster University

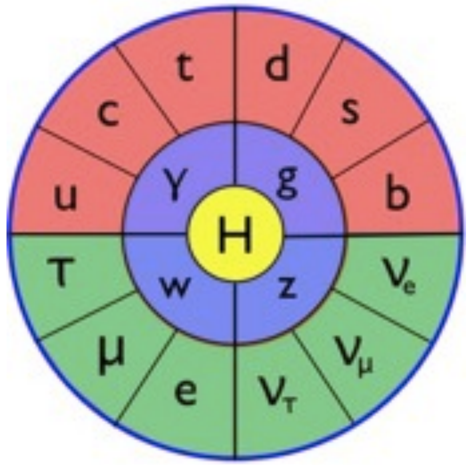
Perimeter Institute

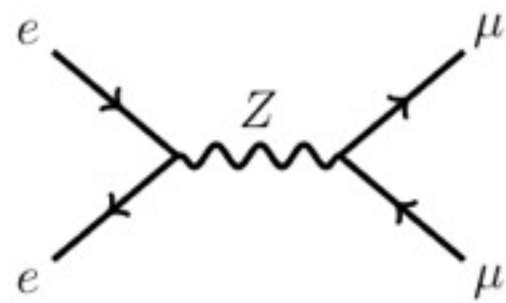
CLIC Workshop

28 Jan 2015

Big Lessons

The material world is made of tiny particles interacting through four basic forces.





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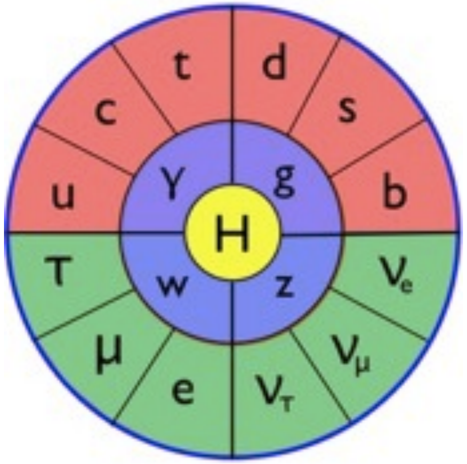

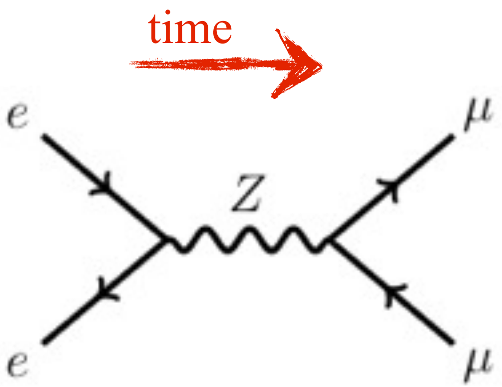

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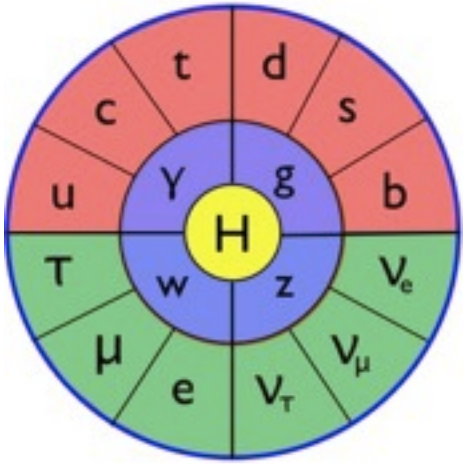

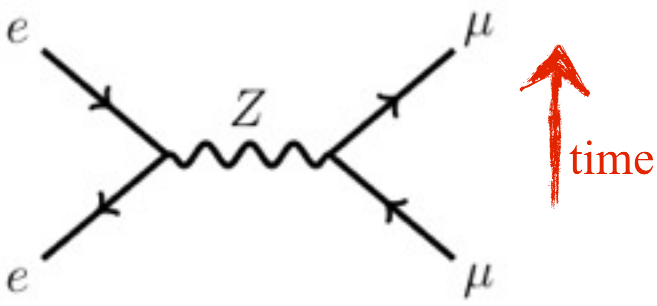

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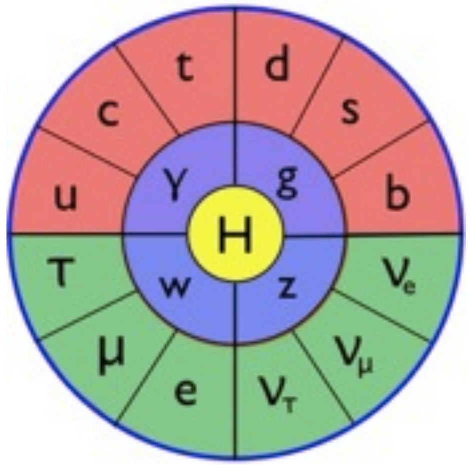

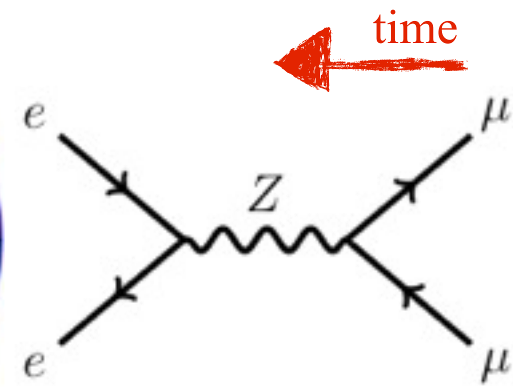

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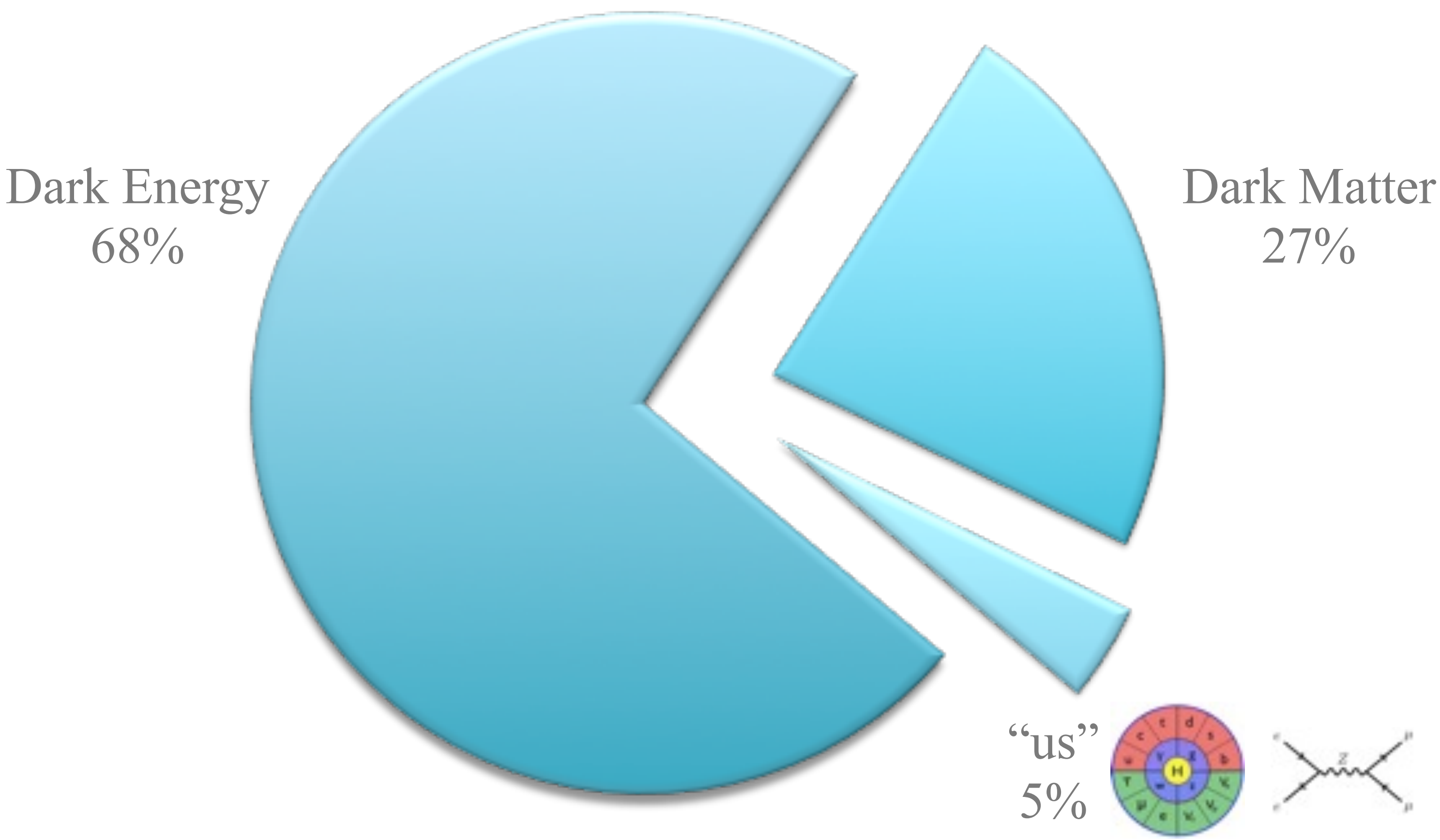

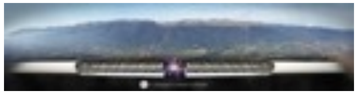

Dark Matter in Space-Time

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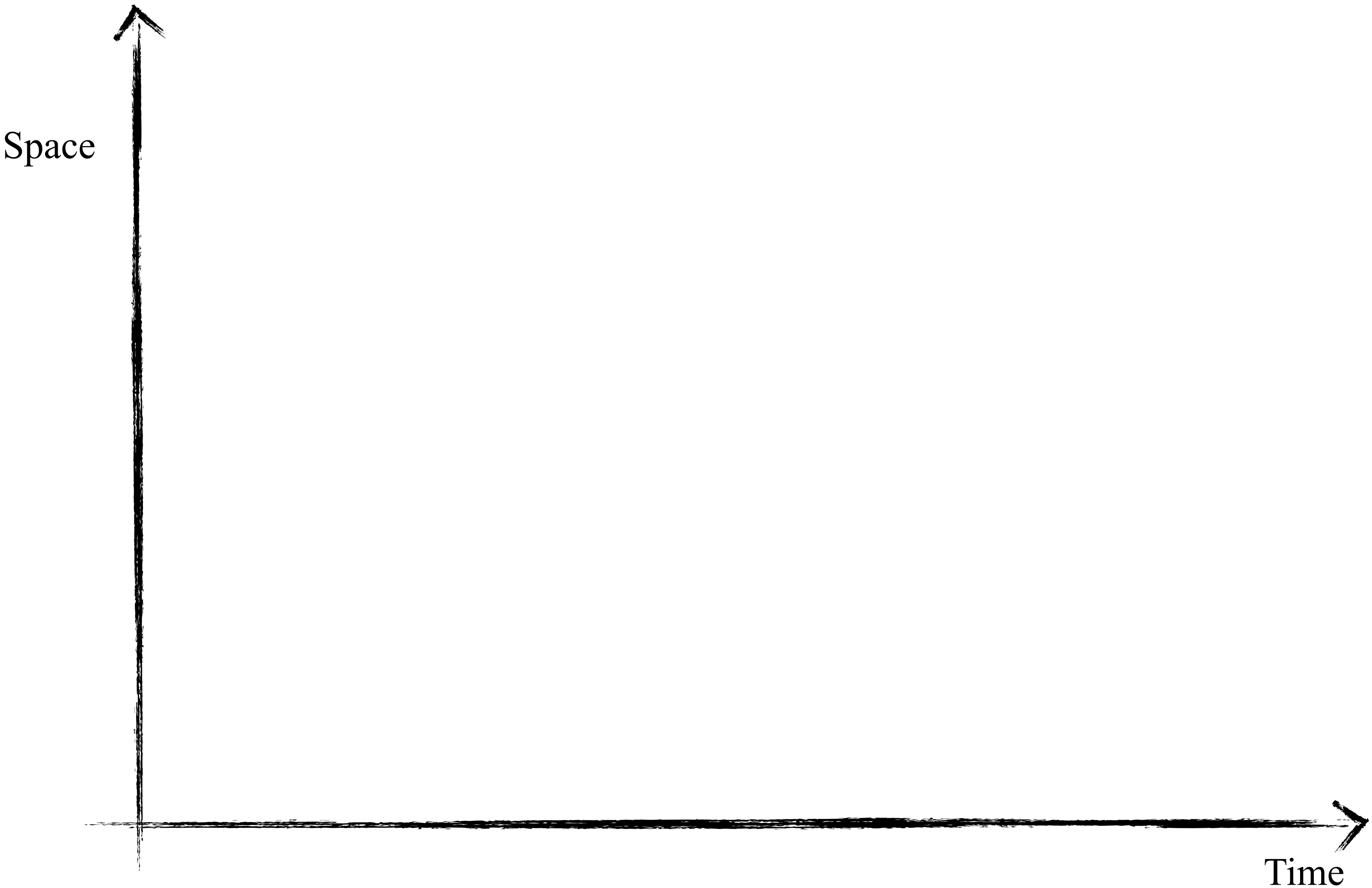

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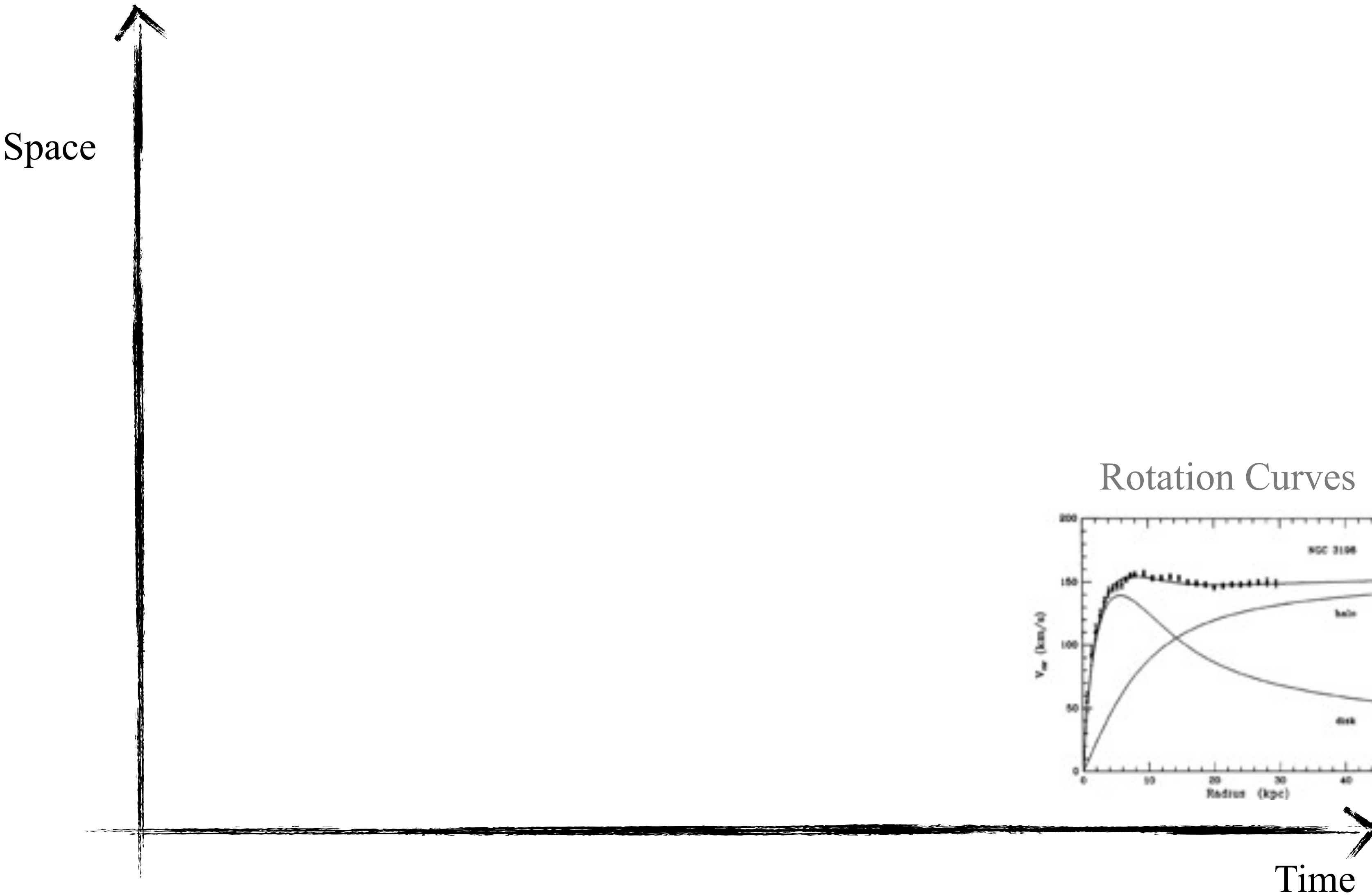
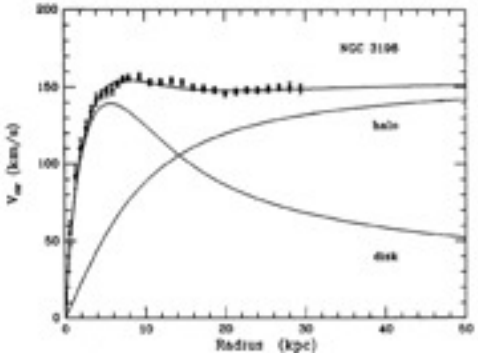


Dark Matter in Space-Time

Space

Lensing

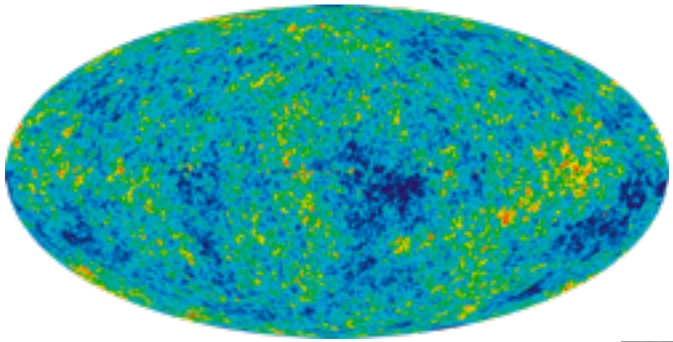
Rotation Curves



Time

Dark Matter in Space-Time

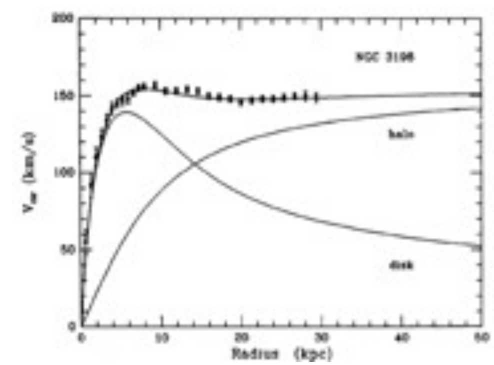
Space



Cosmic Microwave
Background

Lensing

Rotation Curves



Time

What is it?

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The Parameter Space

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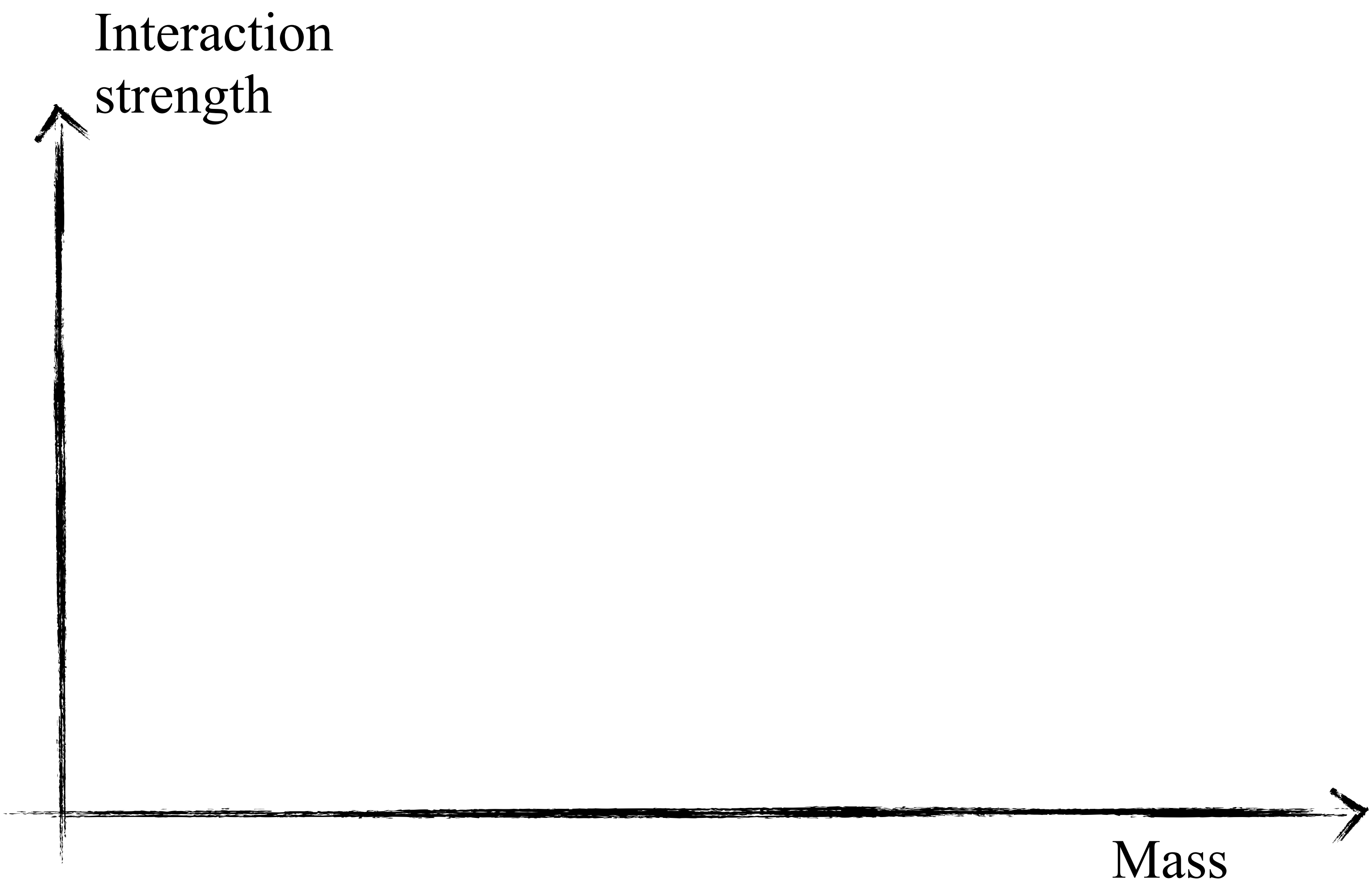

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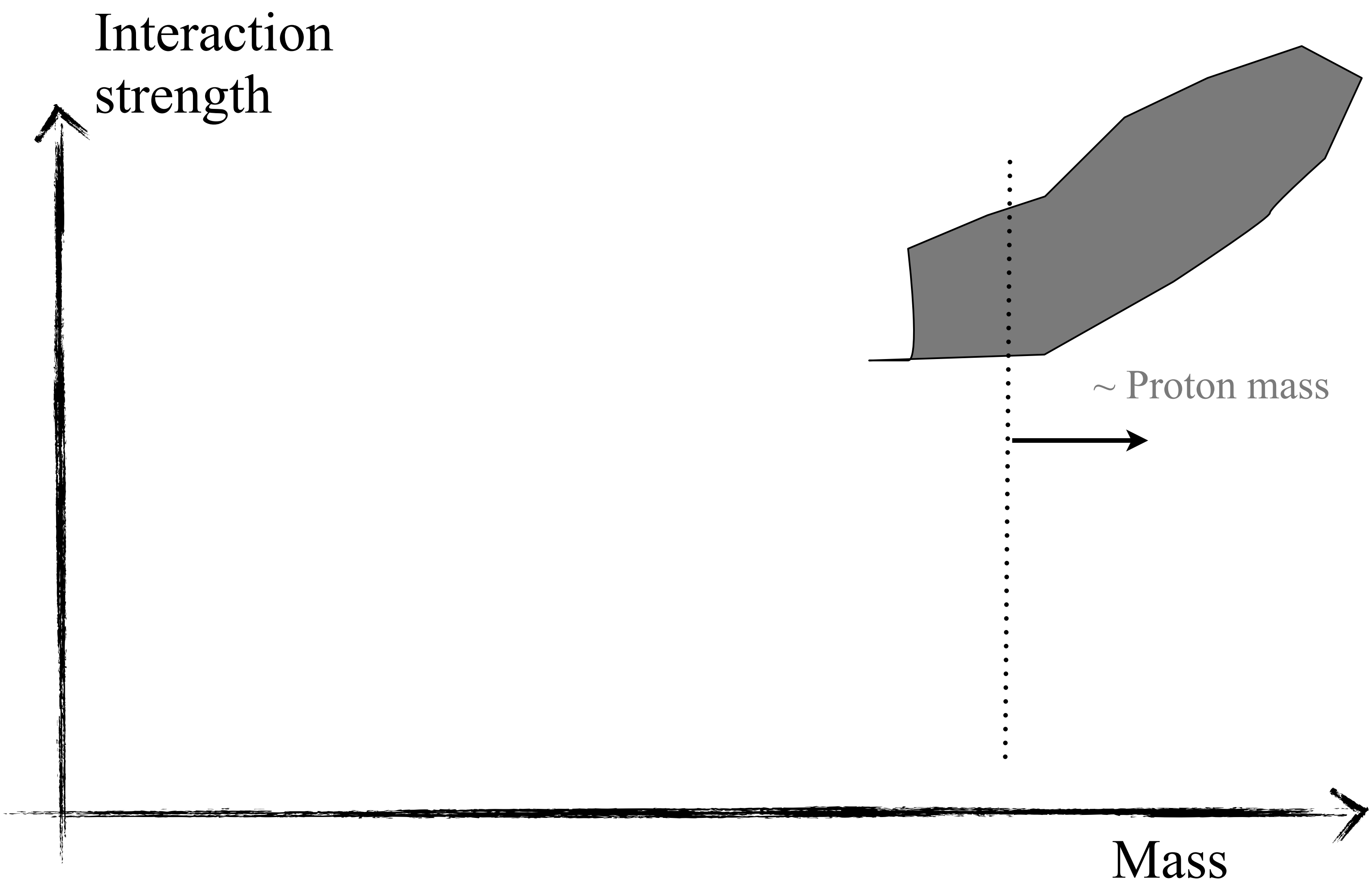

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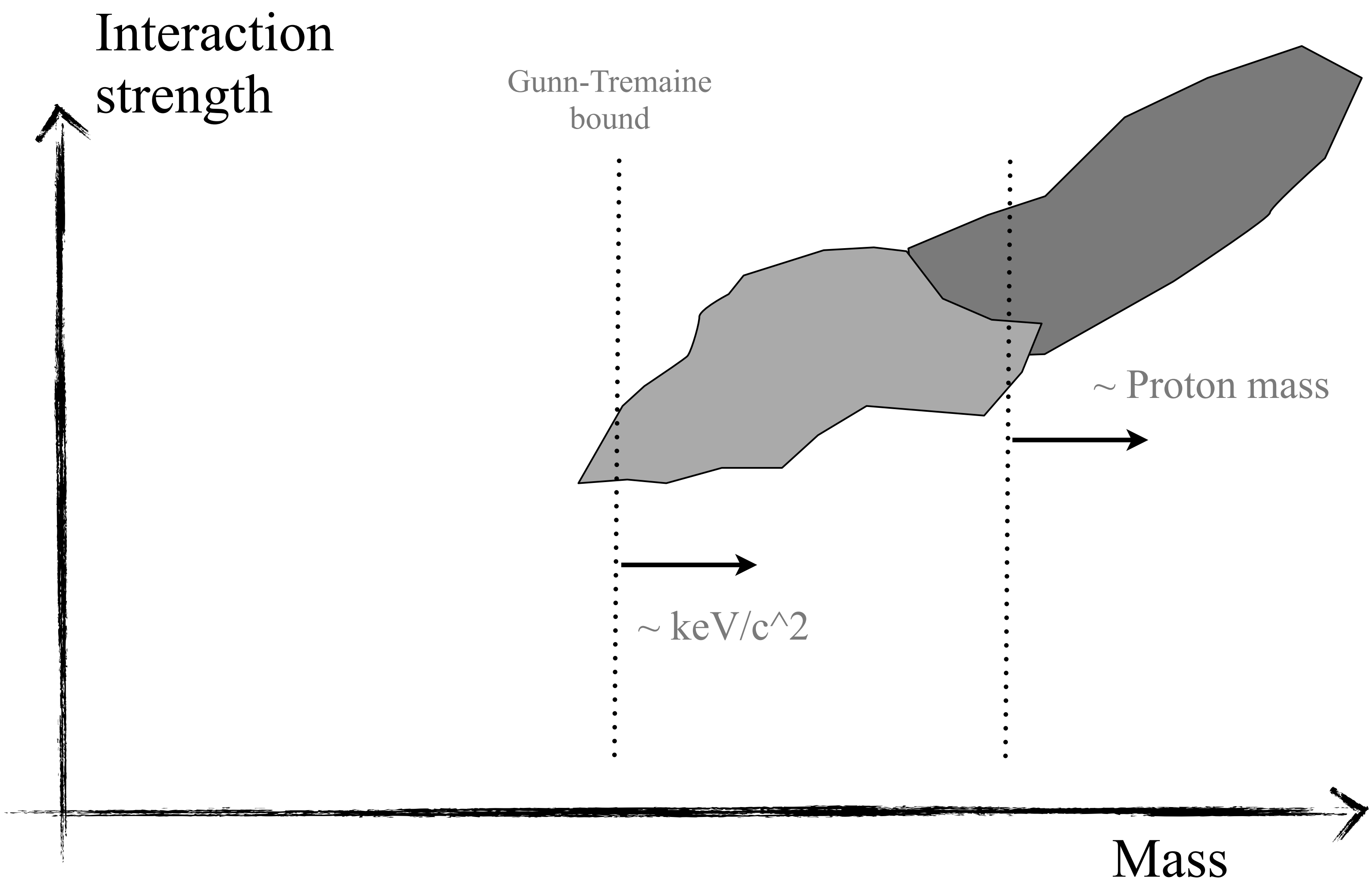

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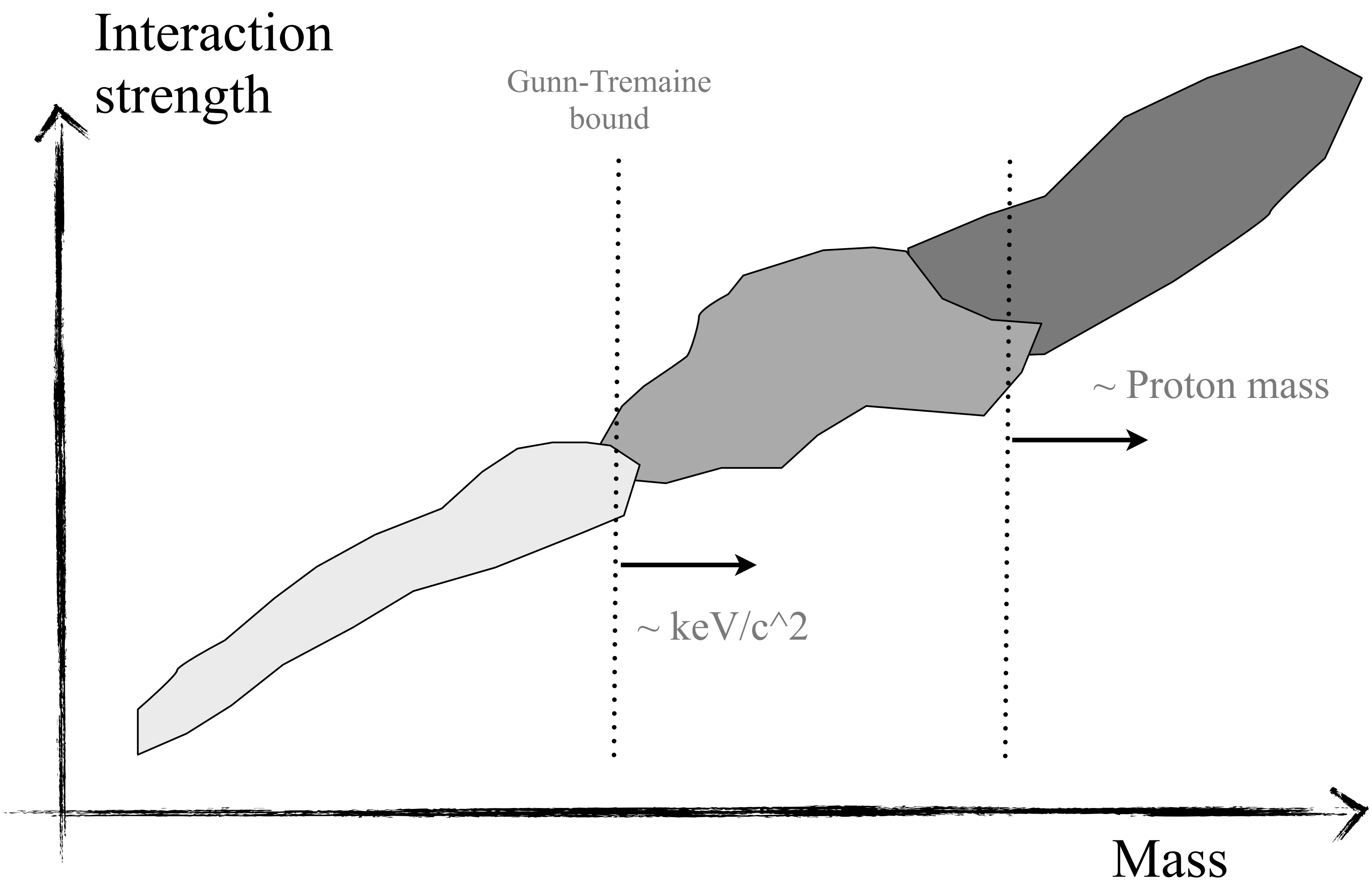

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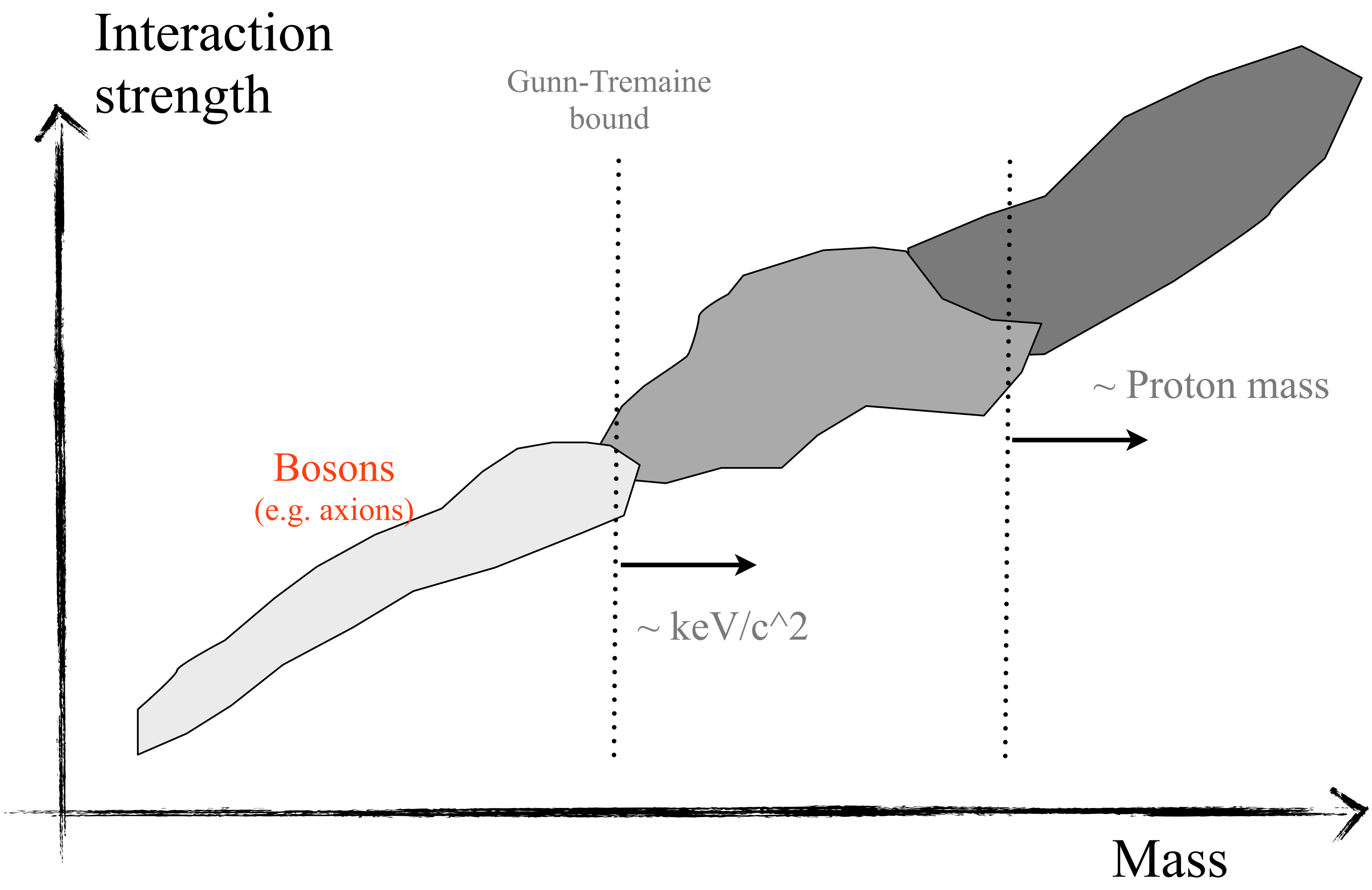

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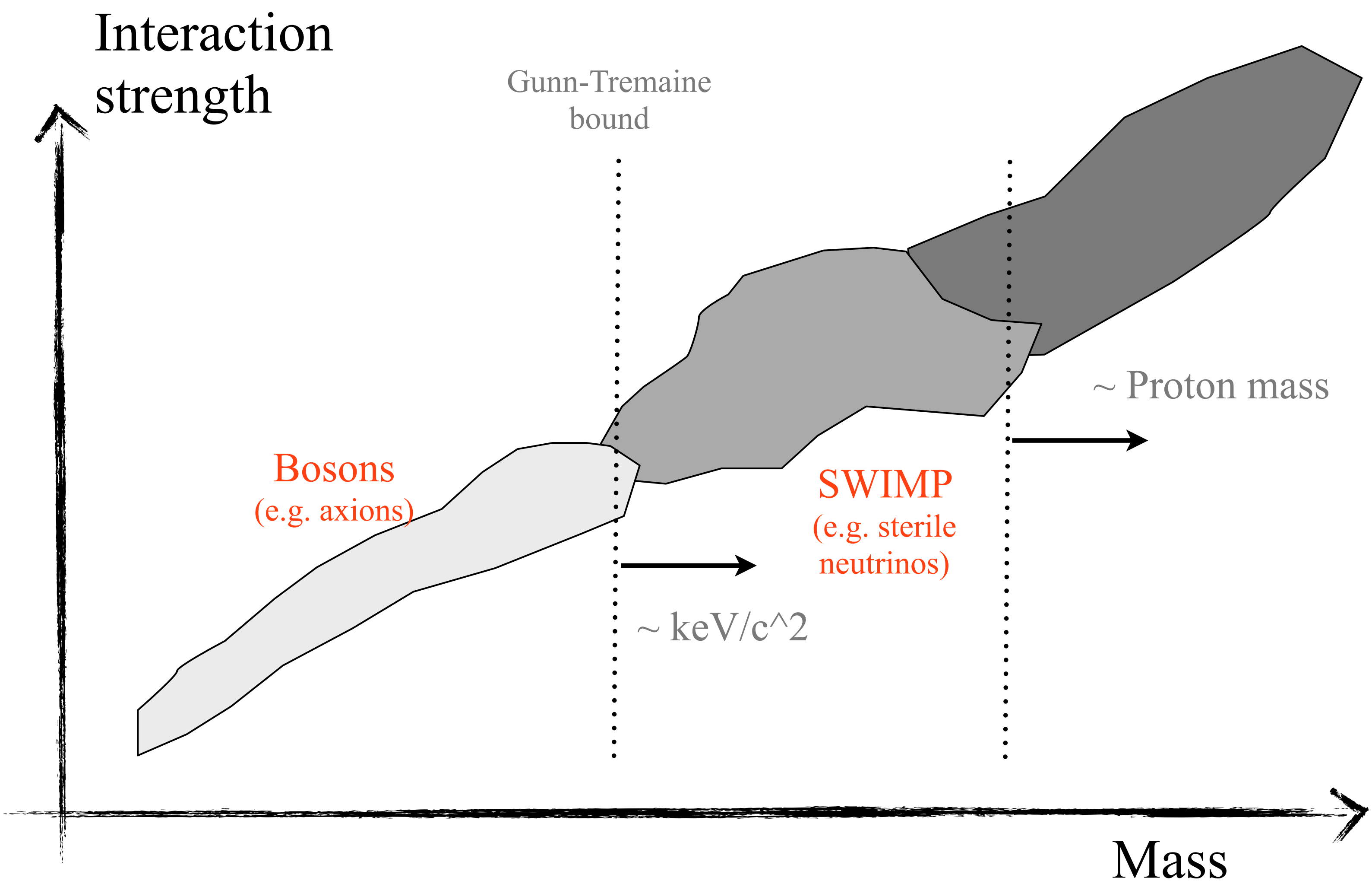

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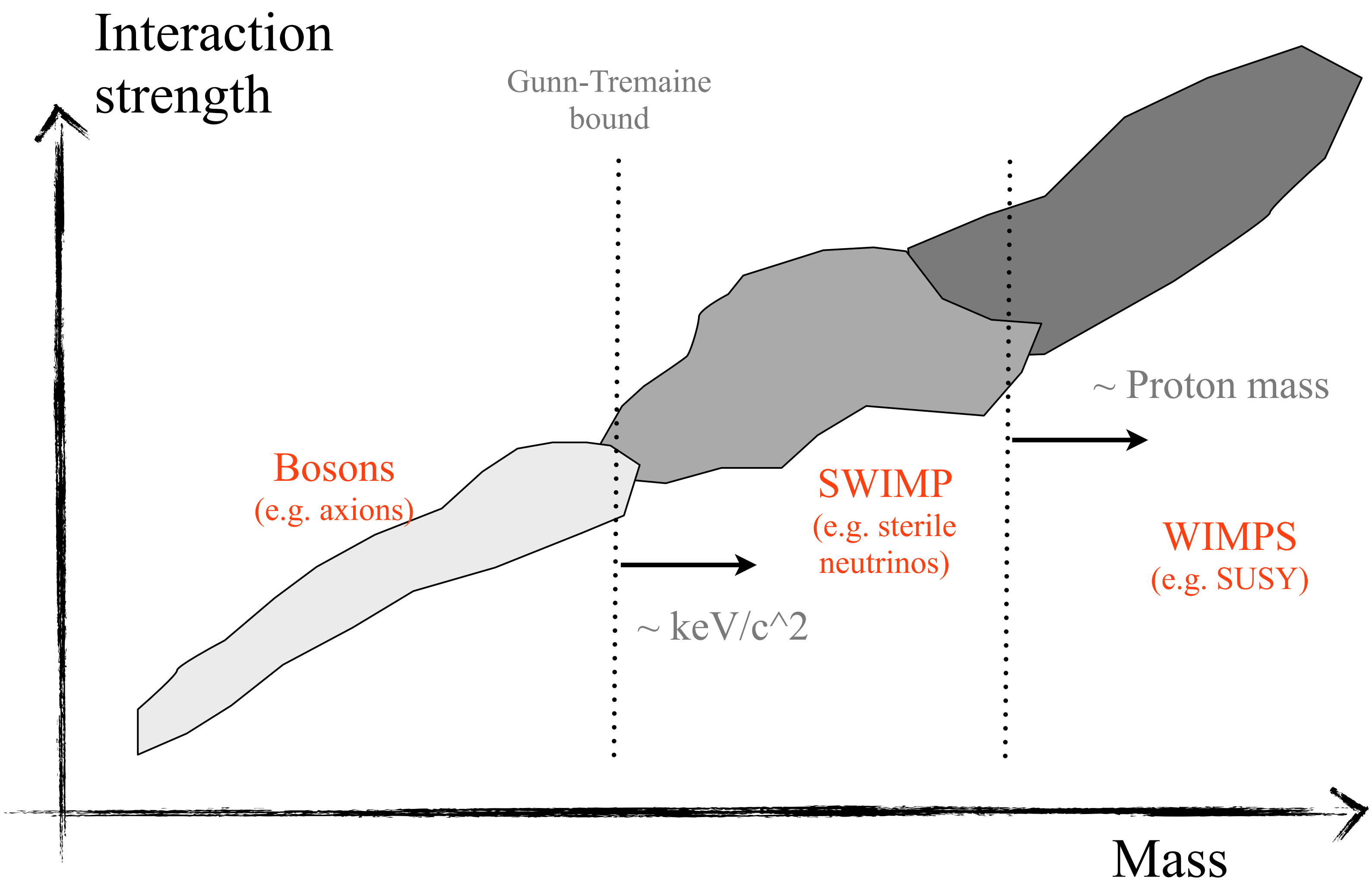

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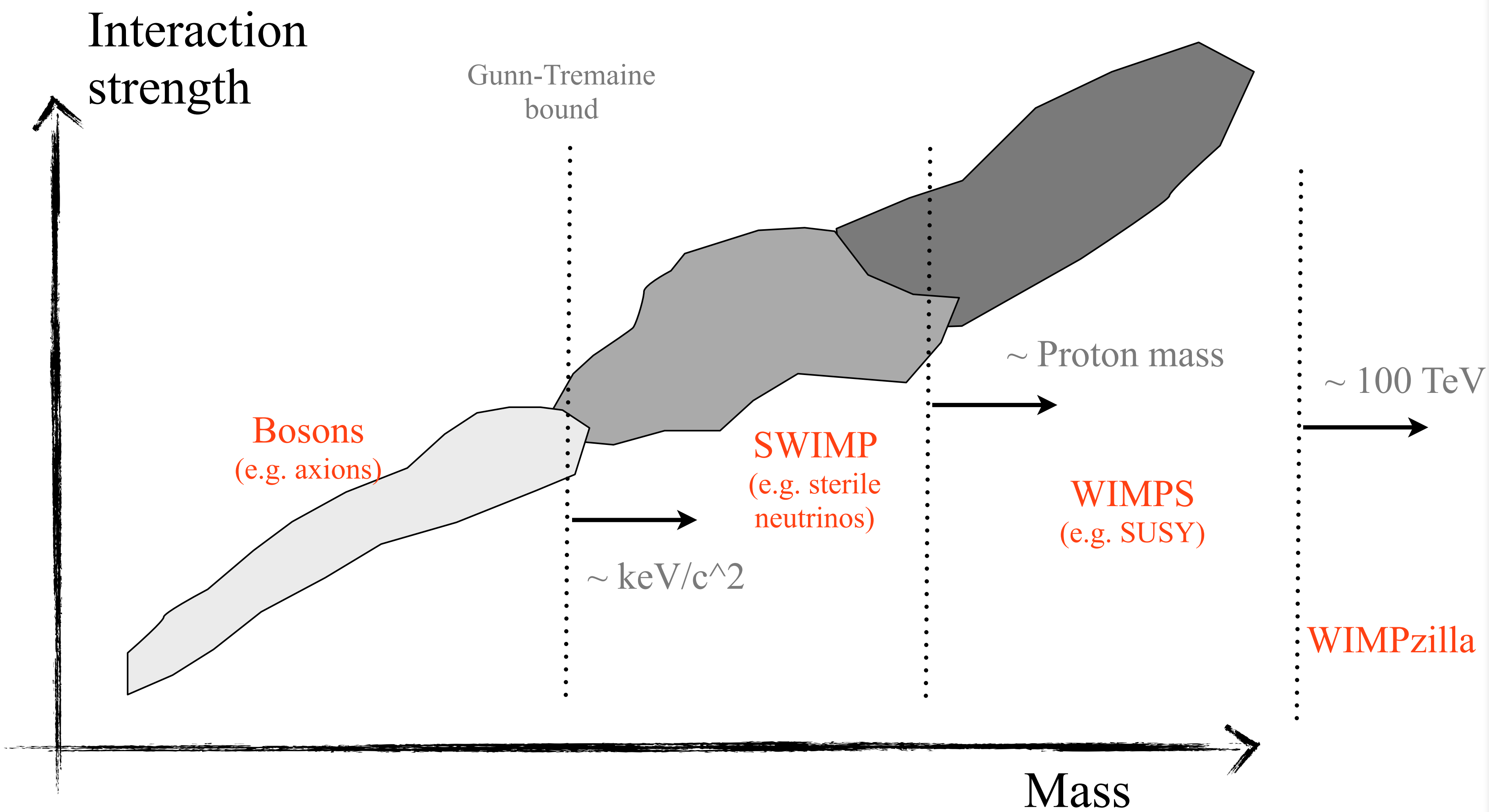

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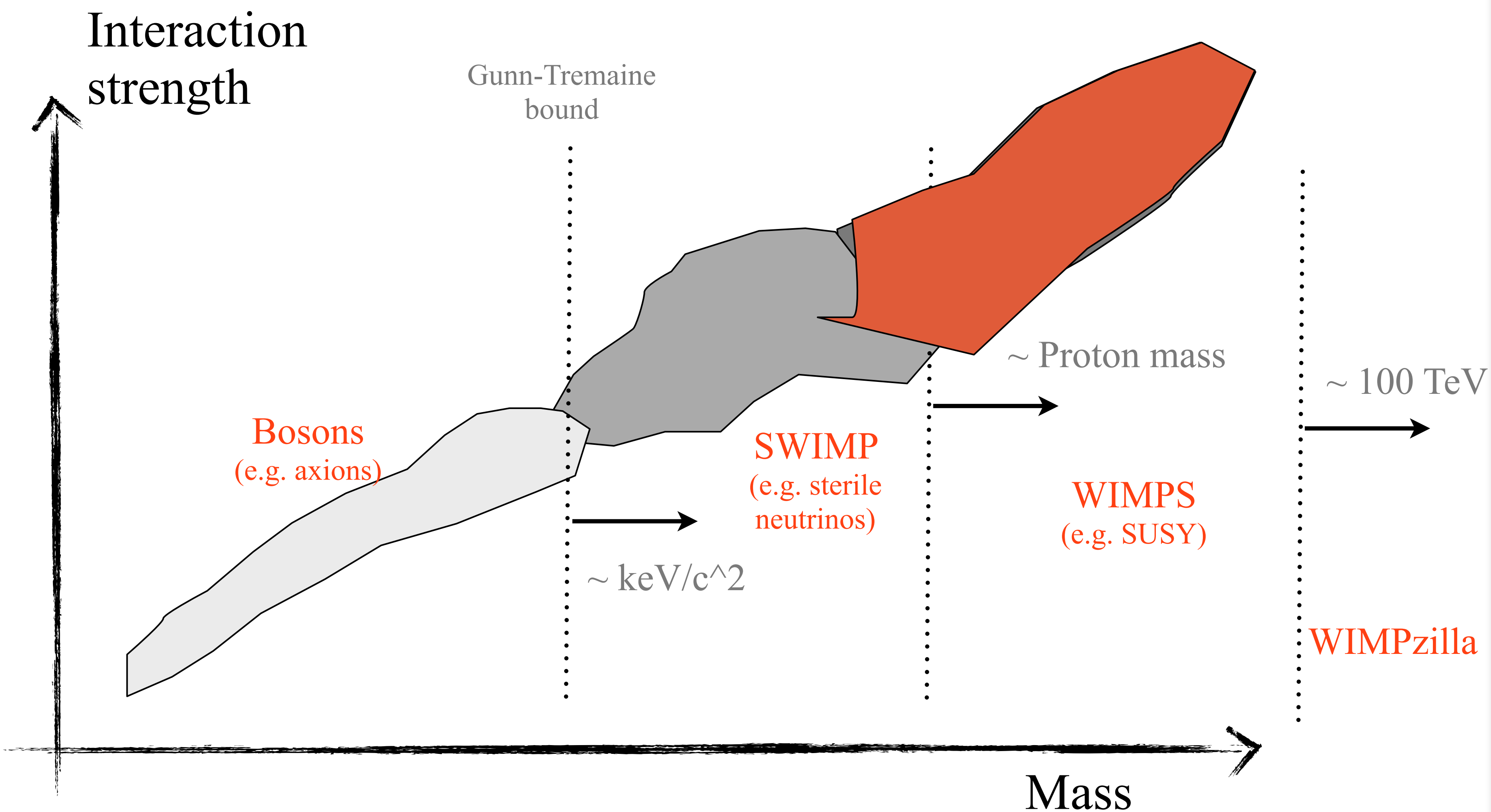

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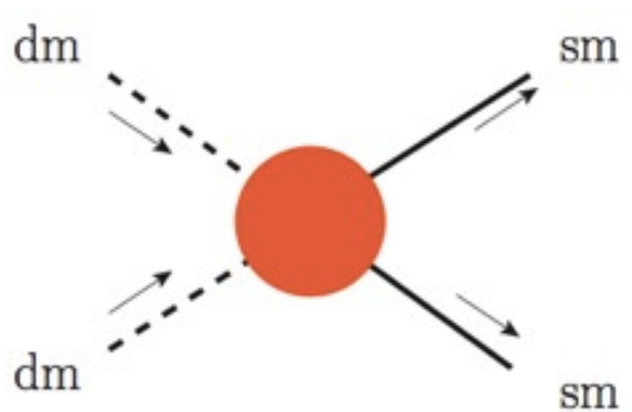
The WIMP "miracle"

WIMPs freeze-out in the early universe leads to the correct relic abundance for electroweak-like cross sections.



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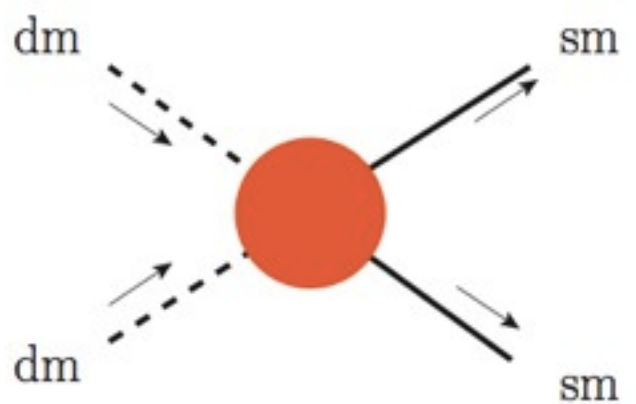

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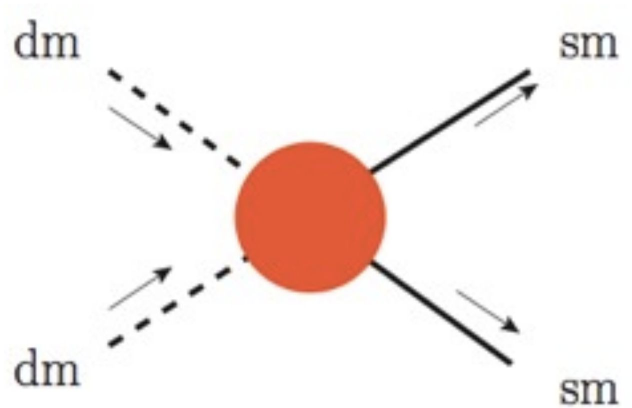


The hierarchy problem

The hierarchy problem points to new physics and new particles that could also give a dark matter candidate.

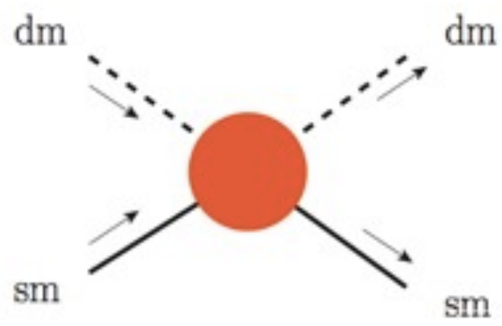
$$\frac{m_{\rm H}}{M_{\rm Pl}} \sim 10^{-17}$$

New Physics

Dark Matter

The Frontiers

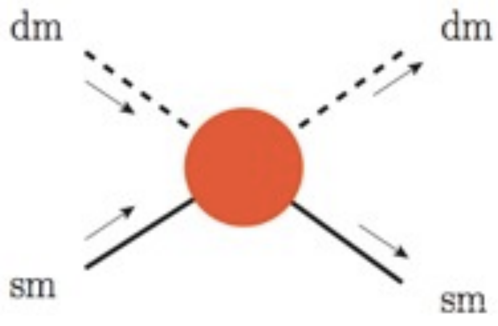
The Frontiers



--- Direct detection

LUX
XENON
CDMS
CoGeNT
CRESST

The Frontiers



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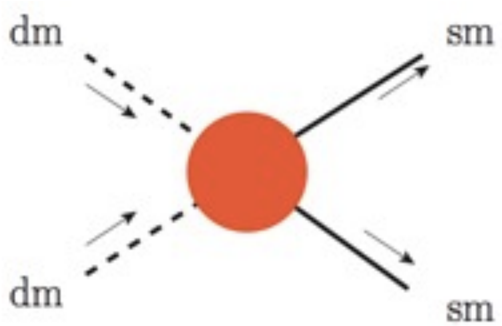

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FERMI/LAT
PAMELA
AMS-II
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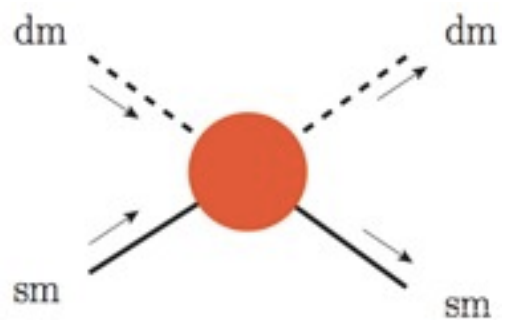
IceCube

The Frontiers



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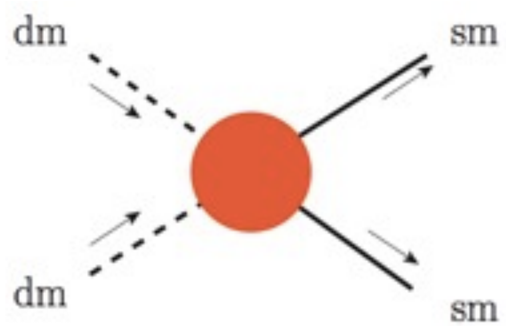

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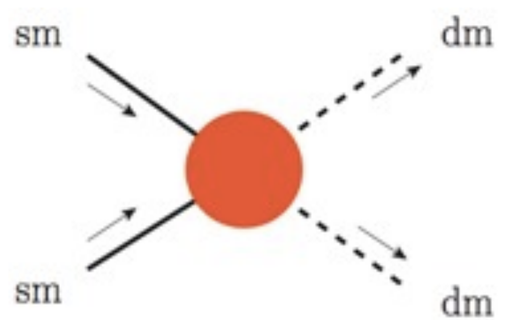
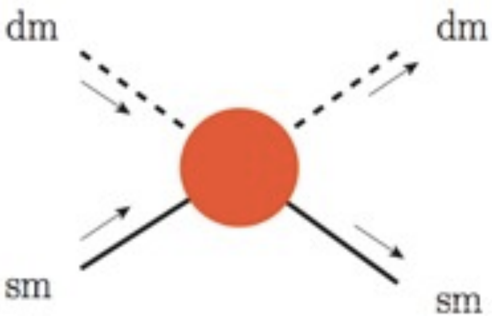


--- Collider searches

LHC
Tevatron
LEP
Babar/Belle
CLIC

The Frontiers



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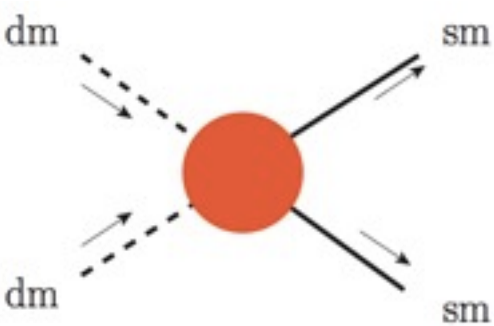

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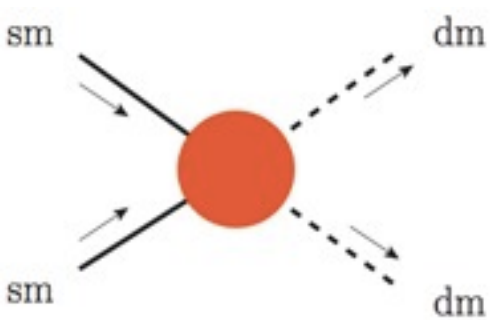

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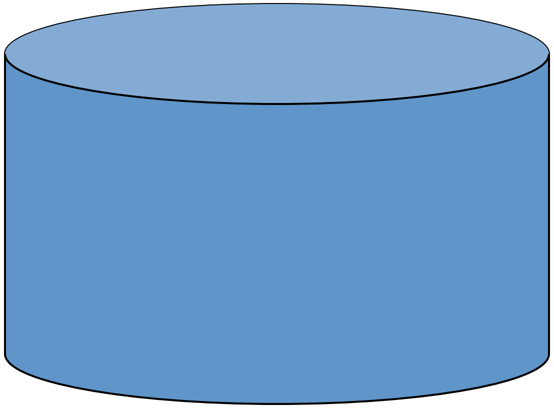

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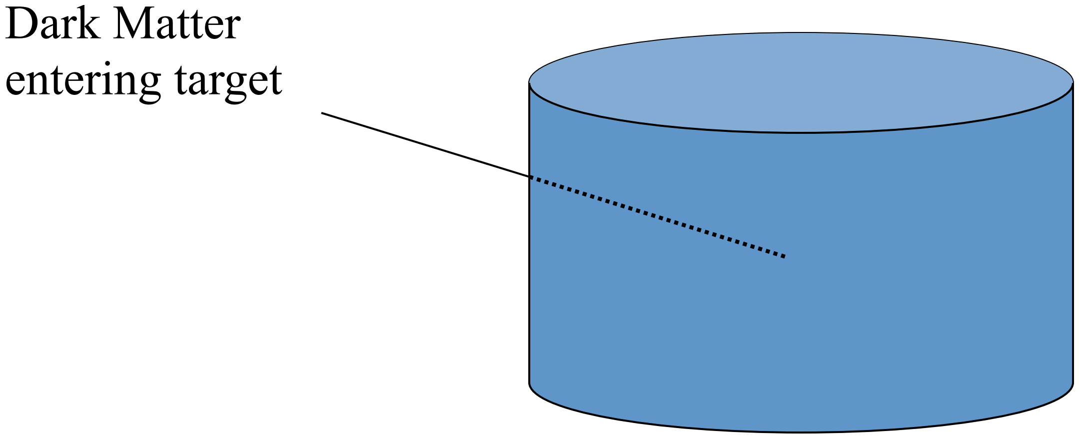

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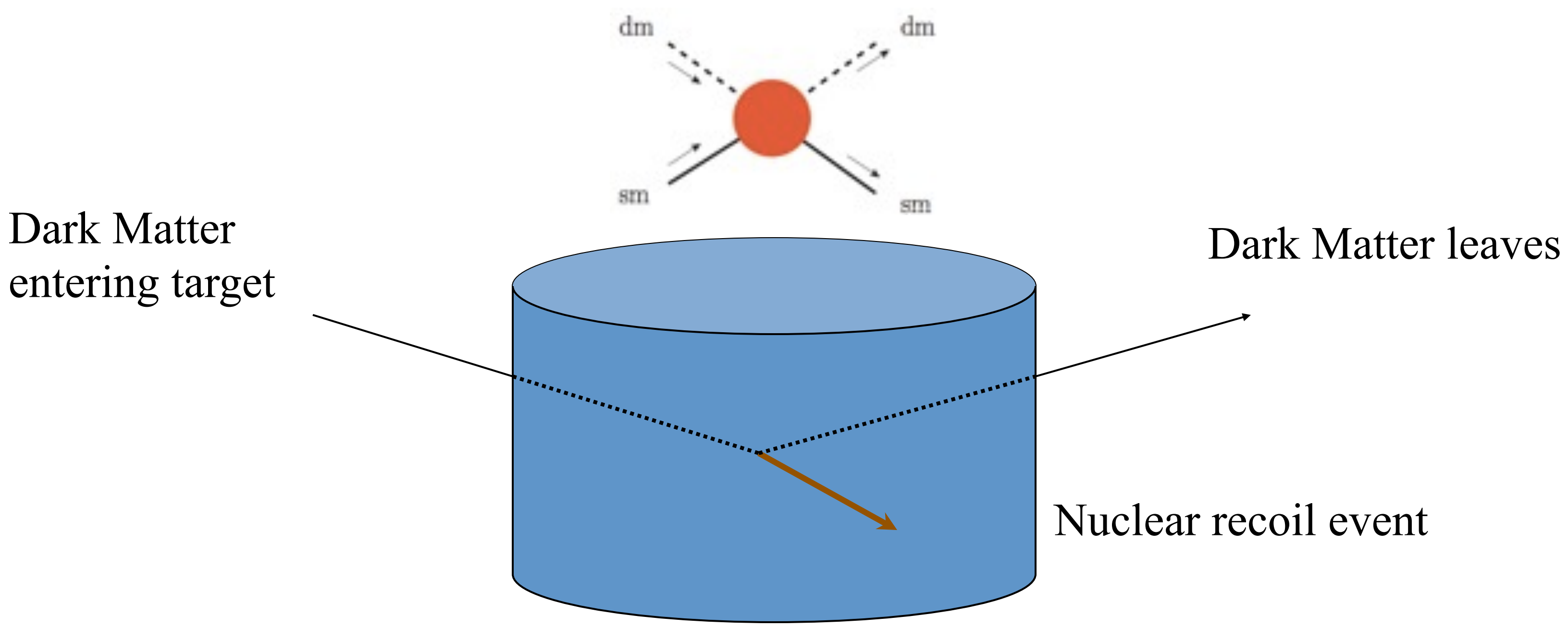

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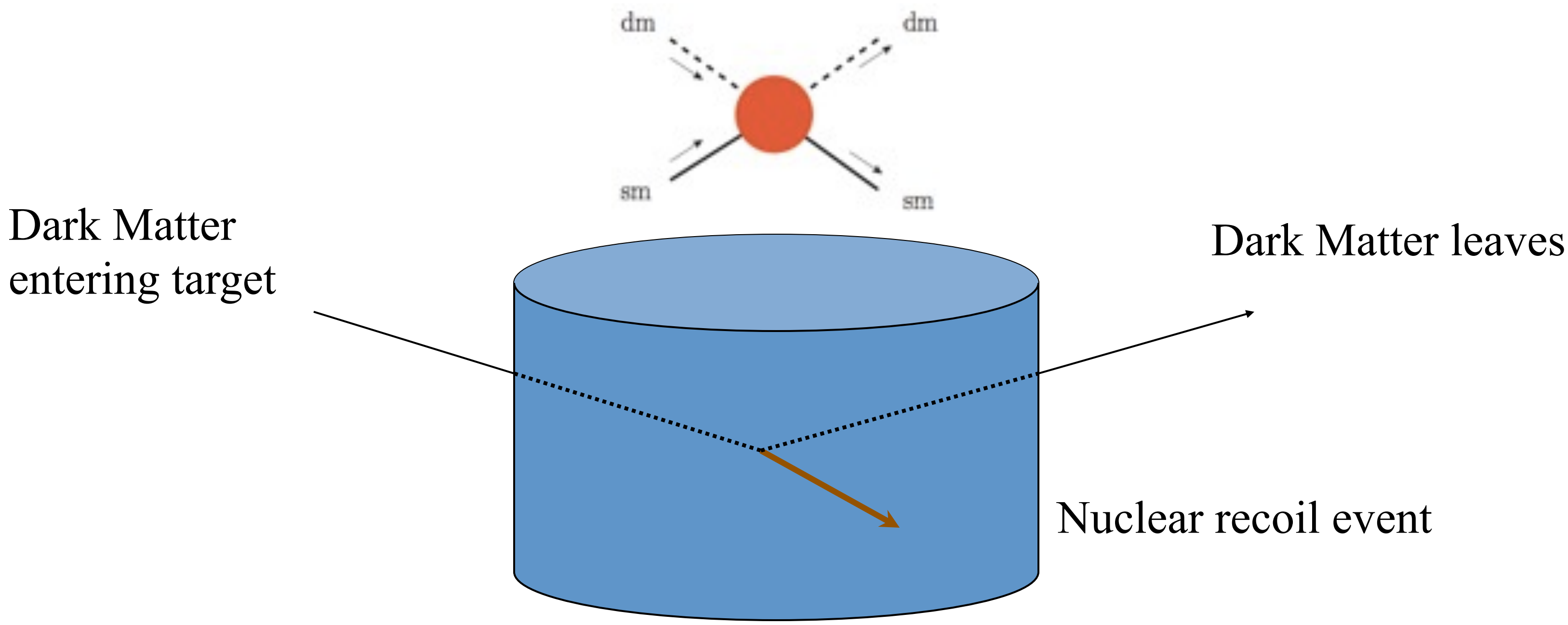
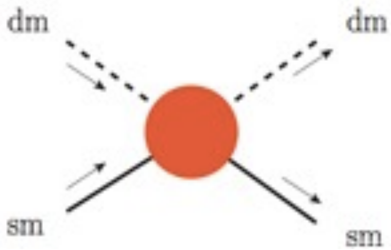
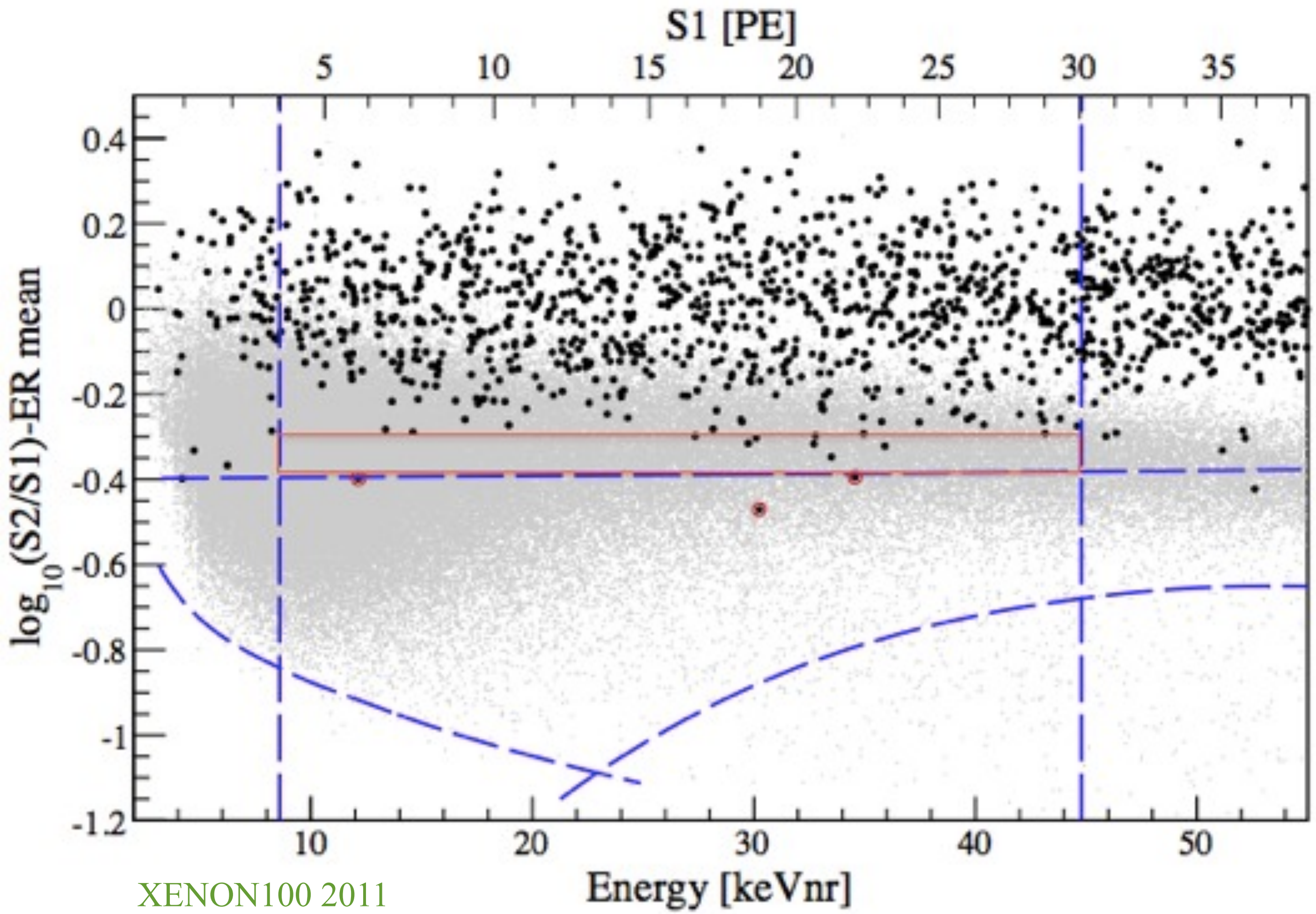


The only thing we can really measure is the energy deposition. That's a violent event whereby a nucleus gets kicked. The energy is released in the form of heat, light, and electrons.

Observable

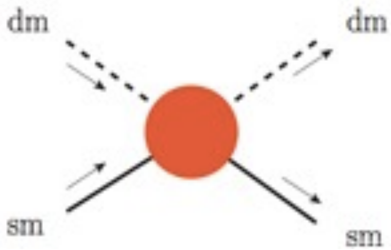


DM collision with target



XENON100 2011

Observable



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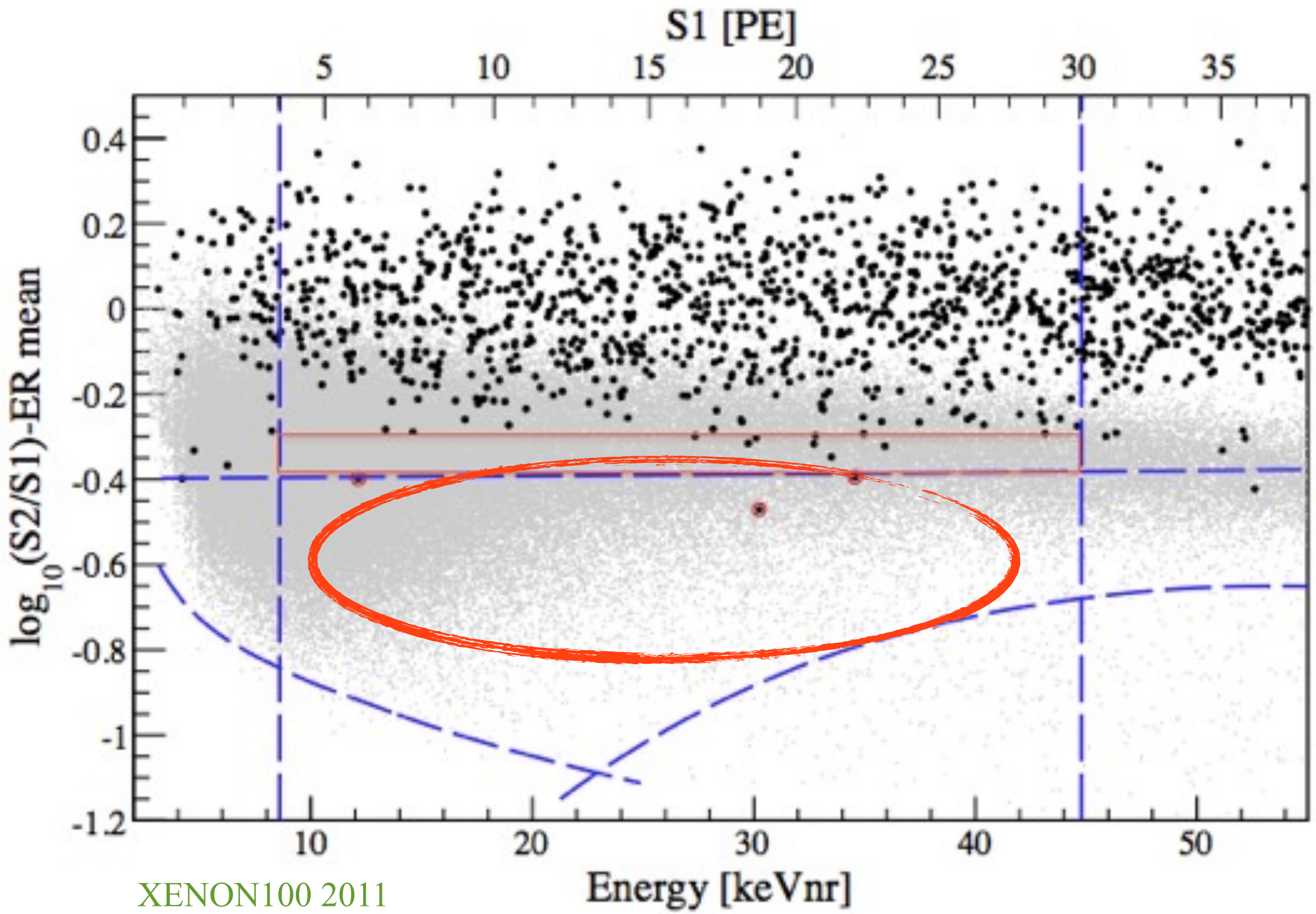

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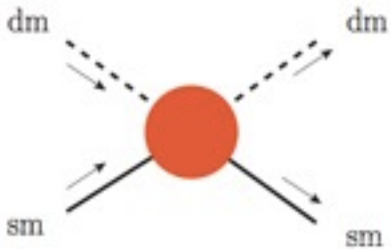

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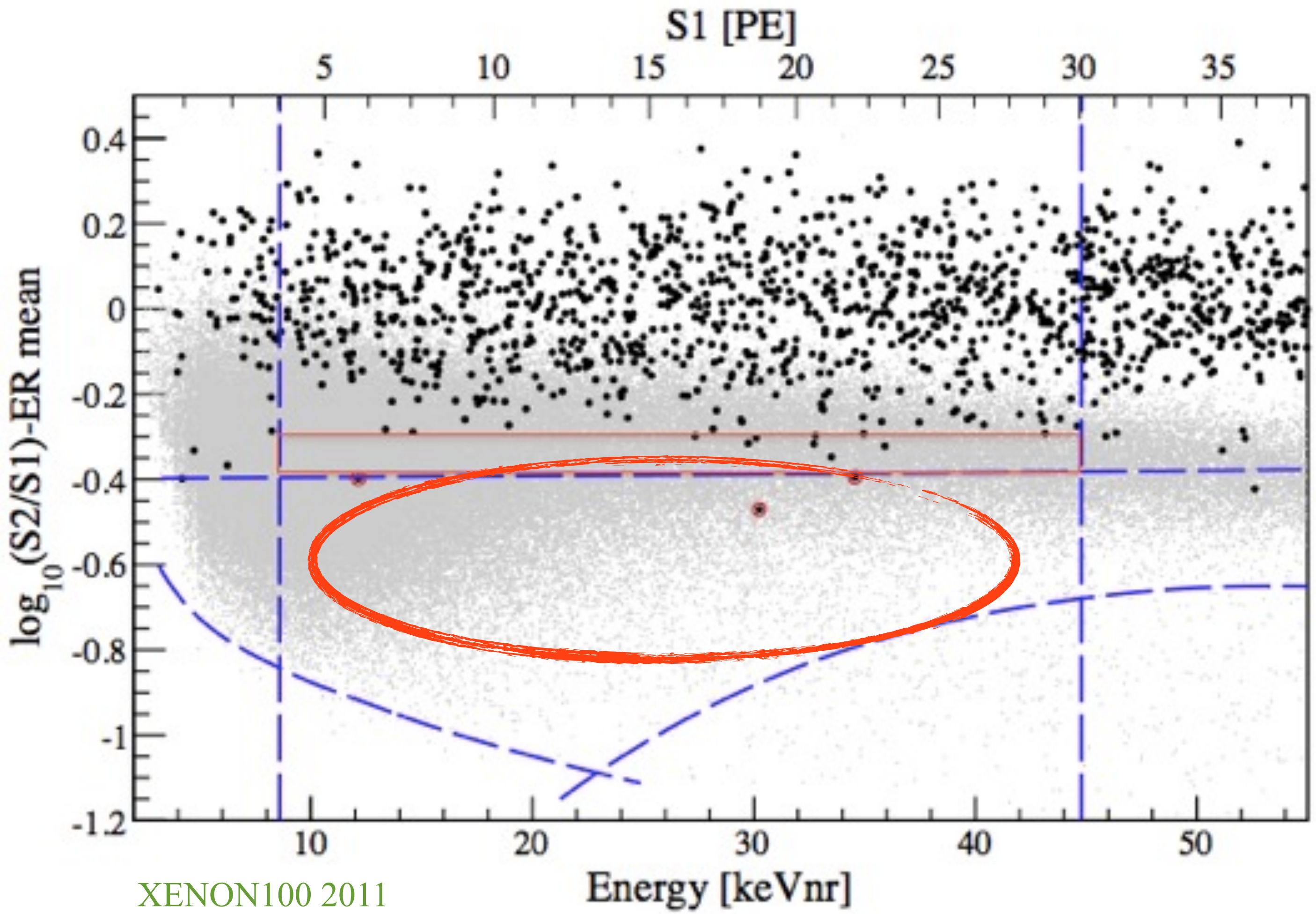

XENON100 2011

Direct detection experiments are no longer "cheap". What else can we do with them? What else can be probed?

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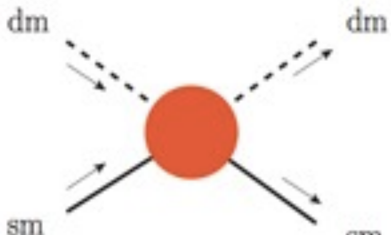

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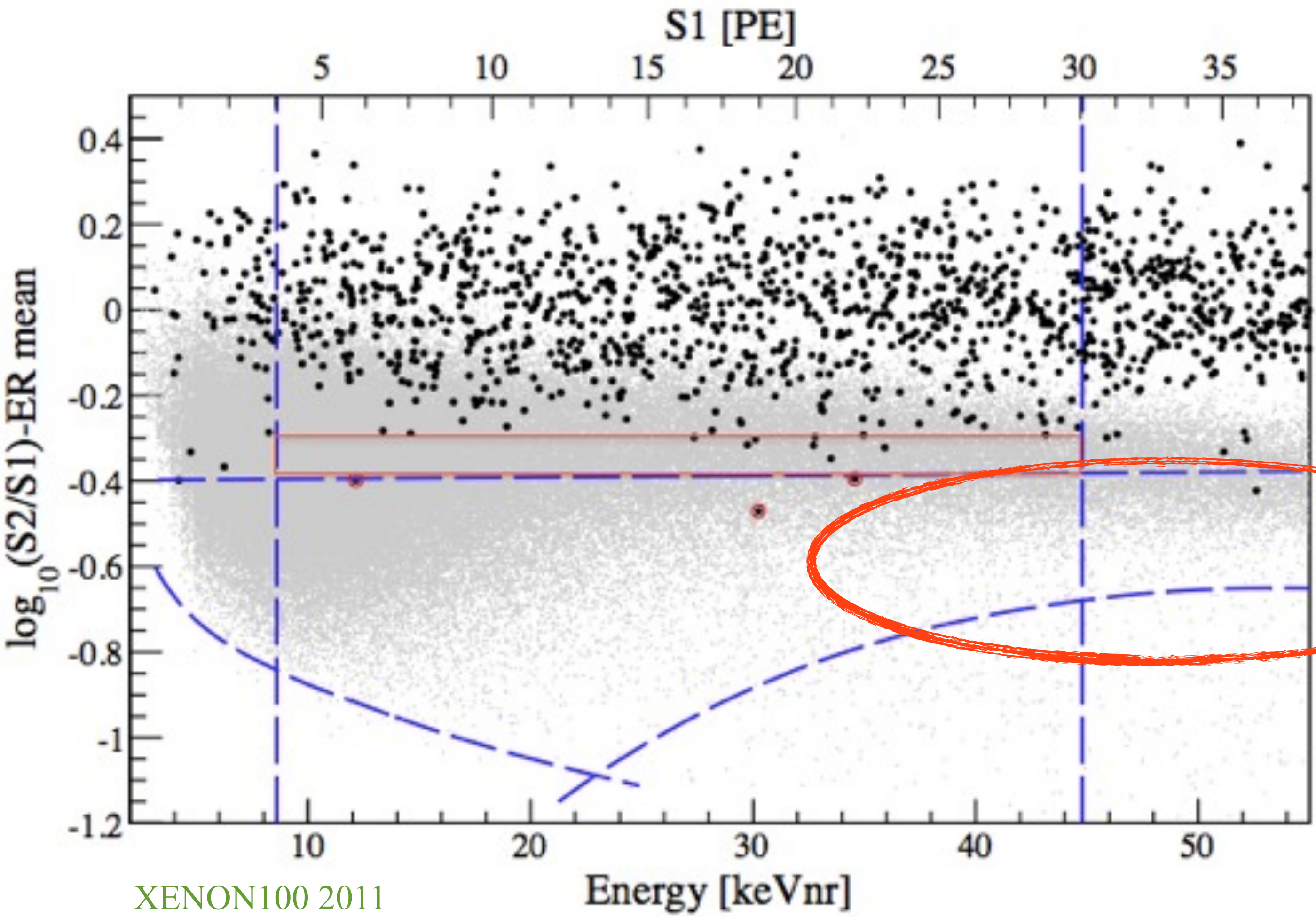

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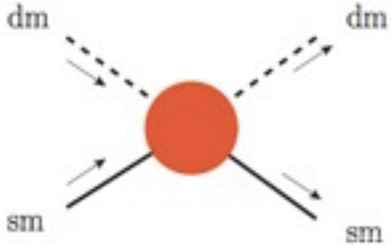

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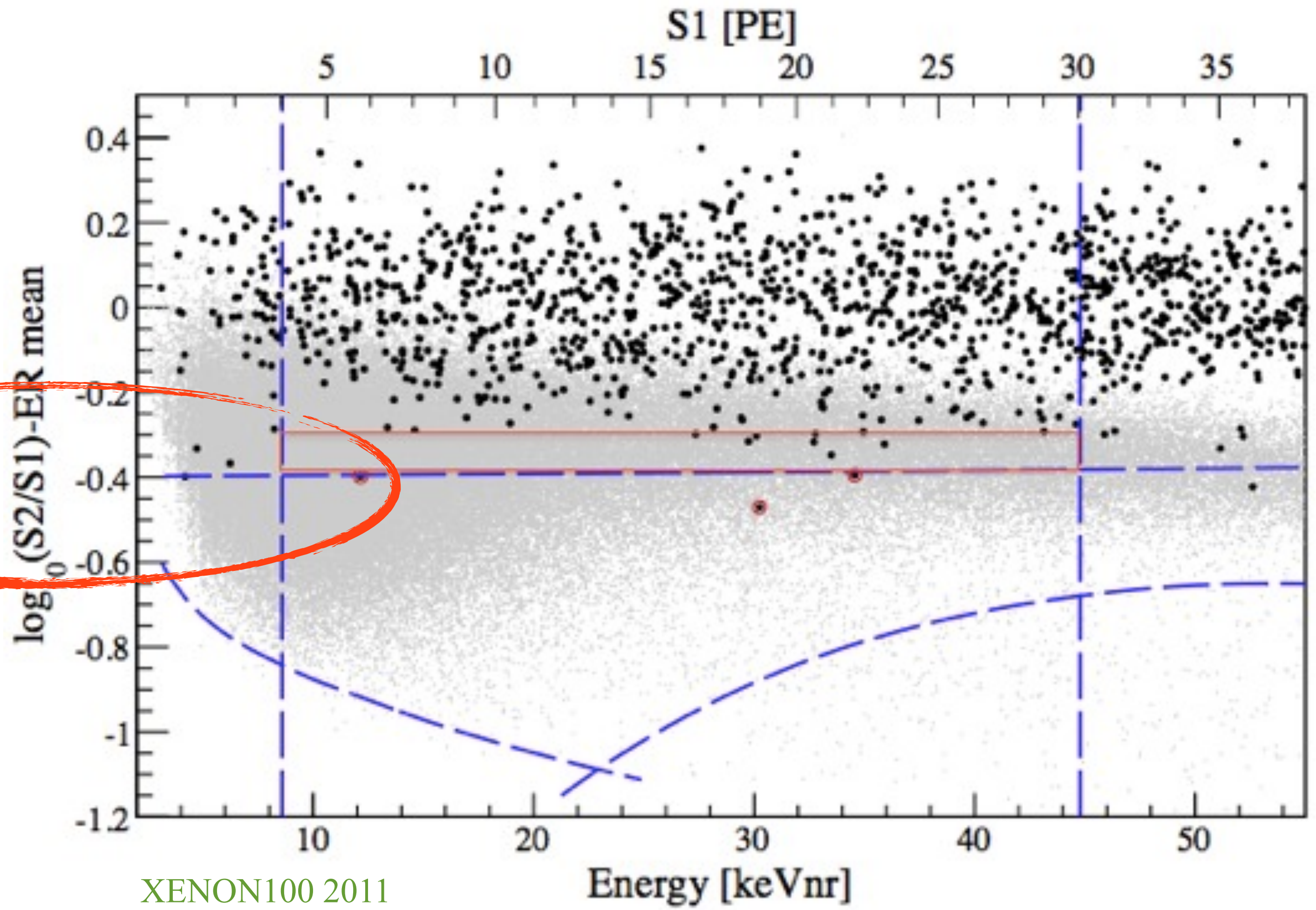

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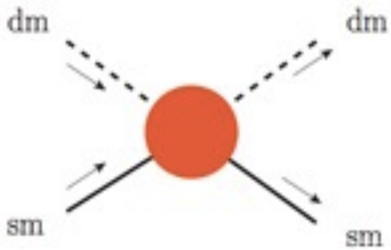

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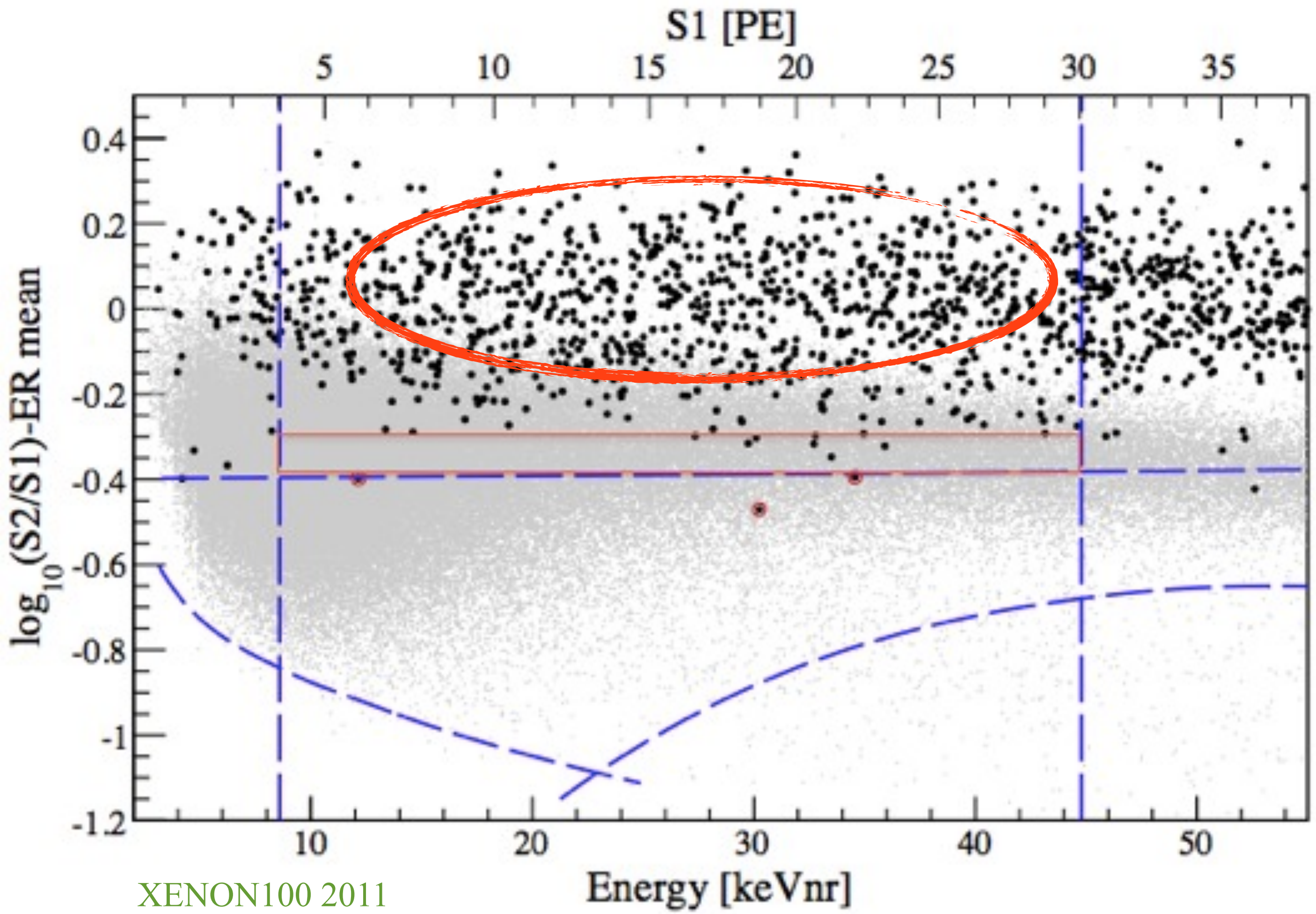

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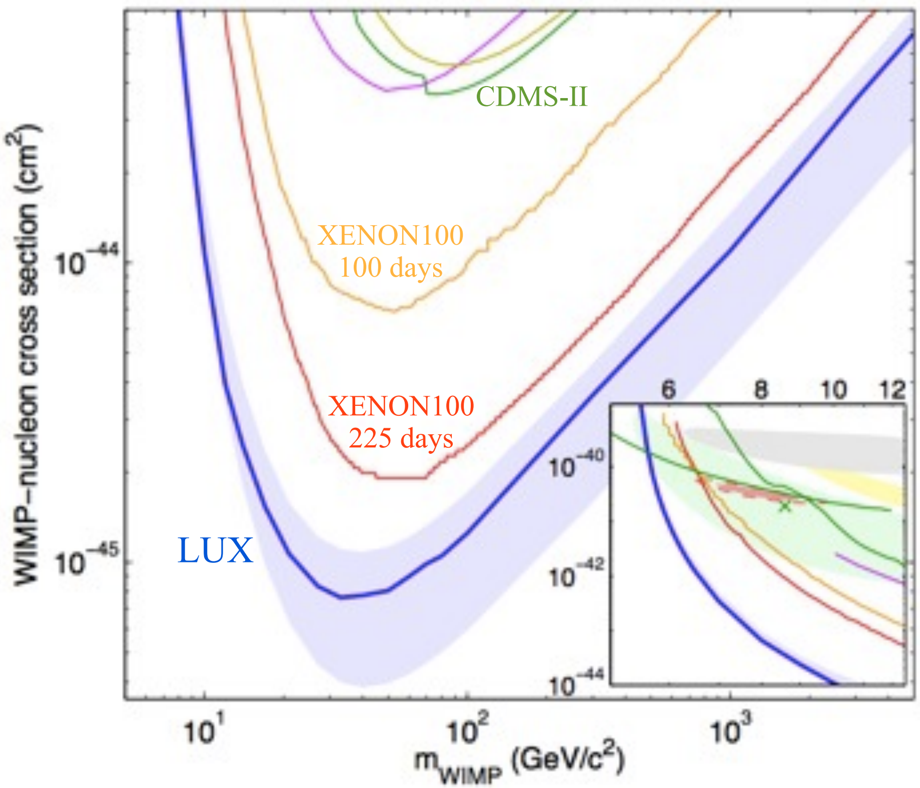
LUX - PRL 112 (2014) 9, 091303



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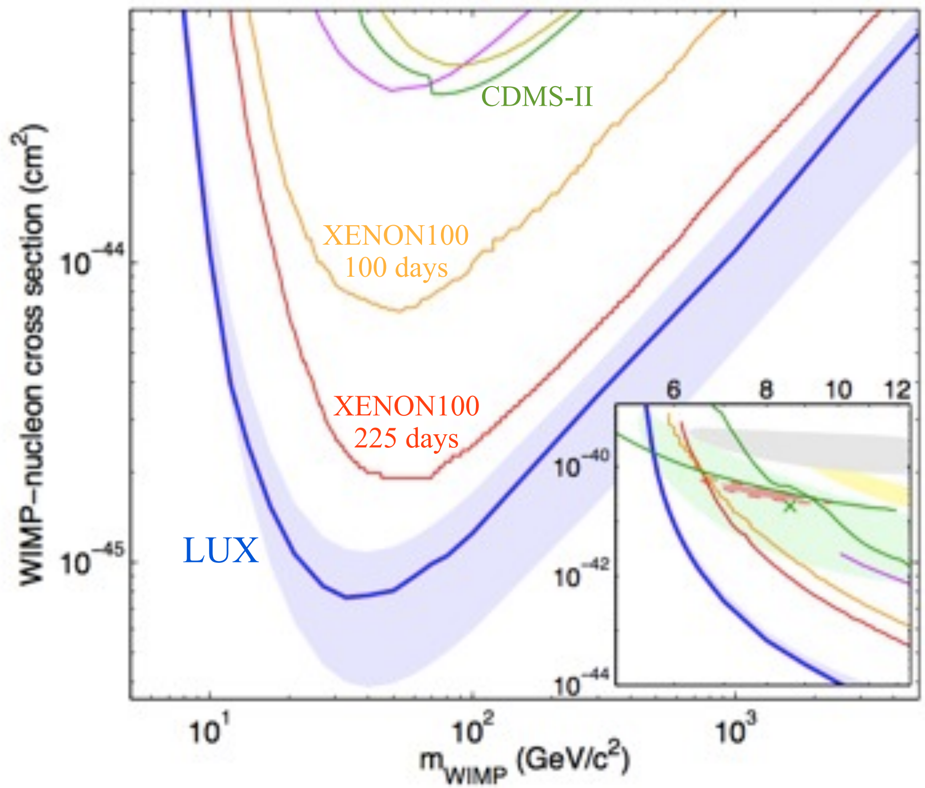
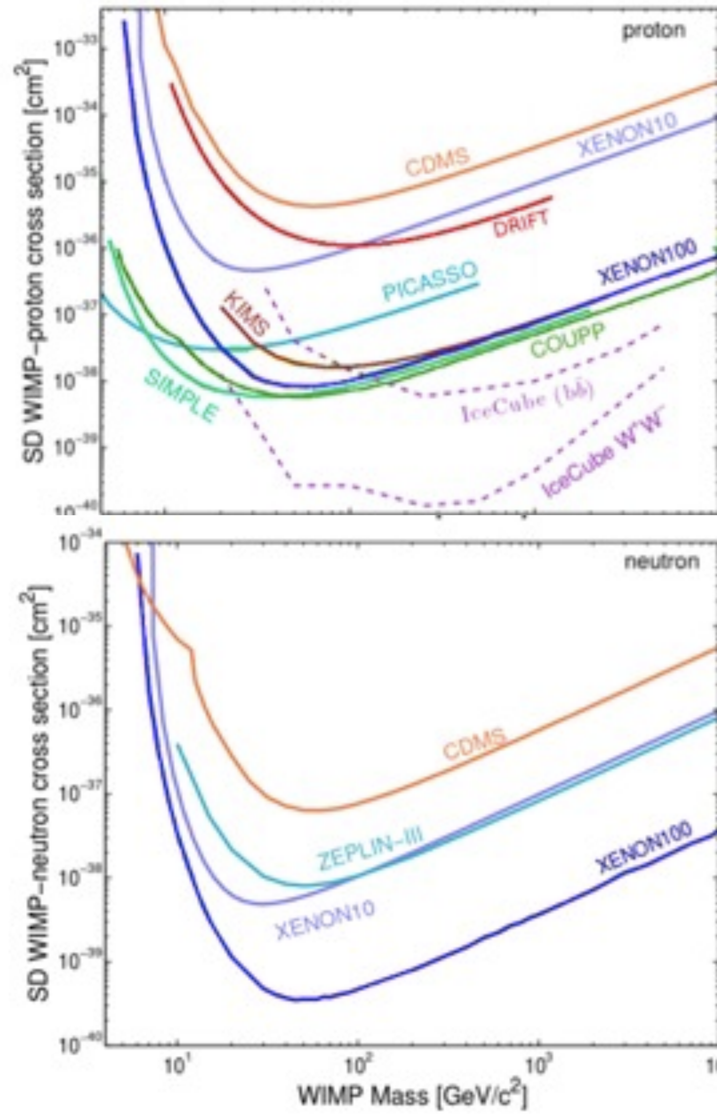


Schumann - 1501.01200



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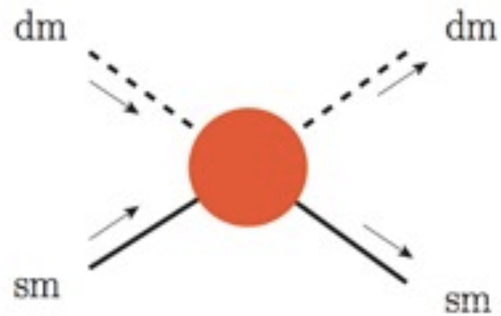
The Frontiers



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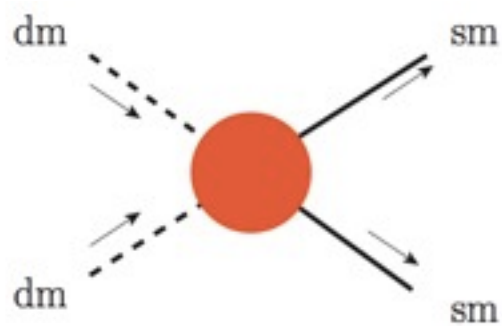

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FERMI/LAT
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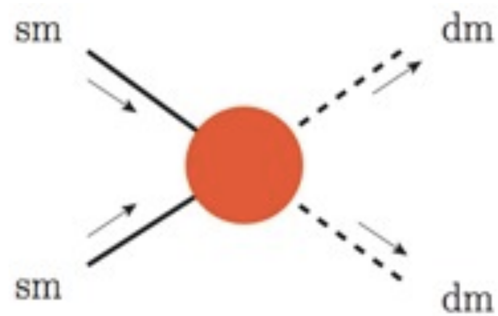

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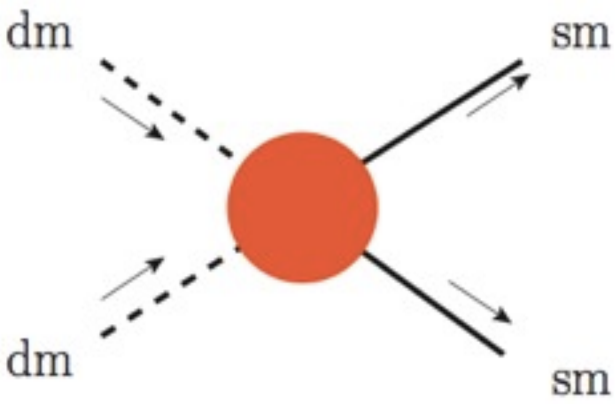
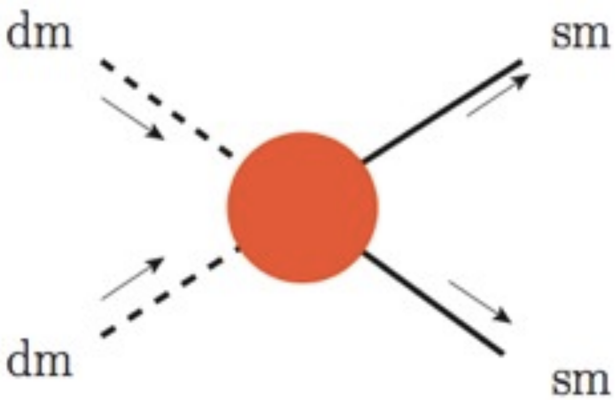


Annihilation somewhere
in the galaxy

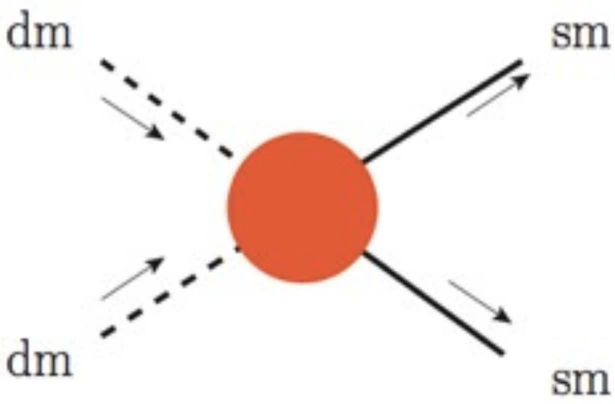
Indirect Detection



Annihilation somewhere
in the galaxy

propagation in
interstellar medium

Indirect Detection



Annihilation somewhere
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propagation in
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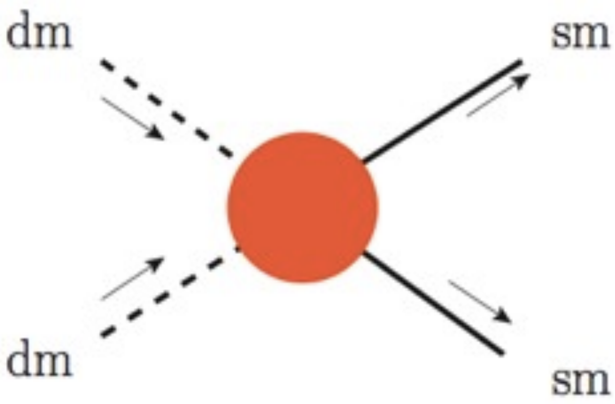
Detection on Earth

Indirect Detection



Annihilation somewhere in the galaxy

propagation in interstellar medium

Detection on Earth

FERMI/LAT
PAMELA
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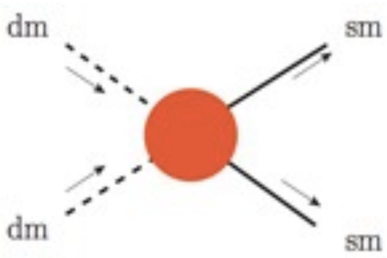
HESS
...

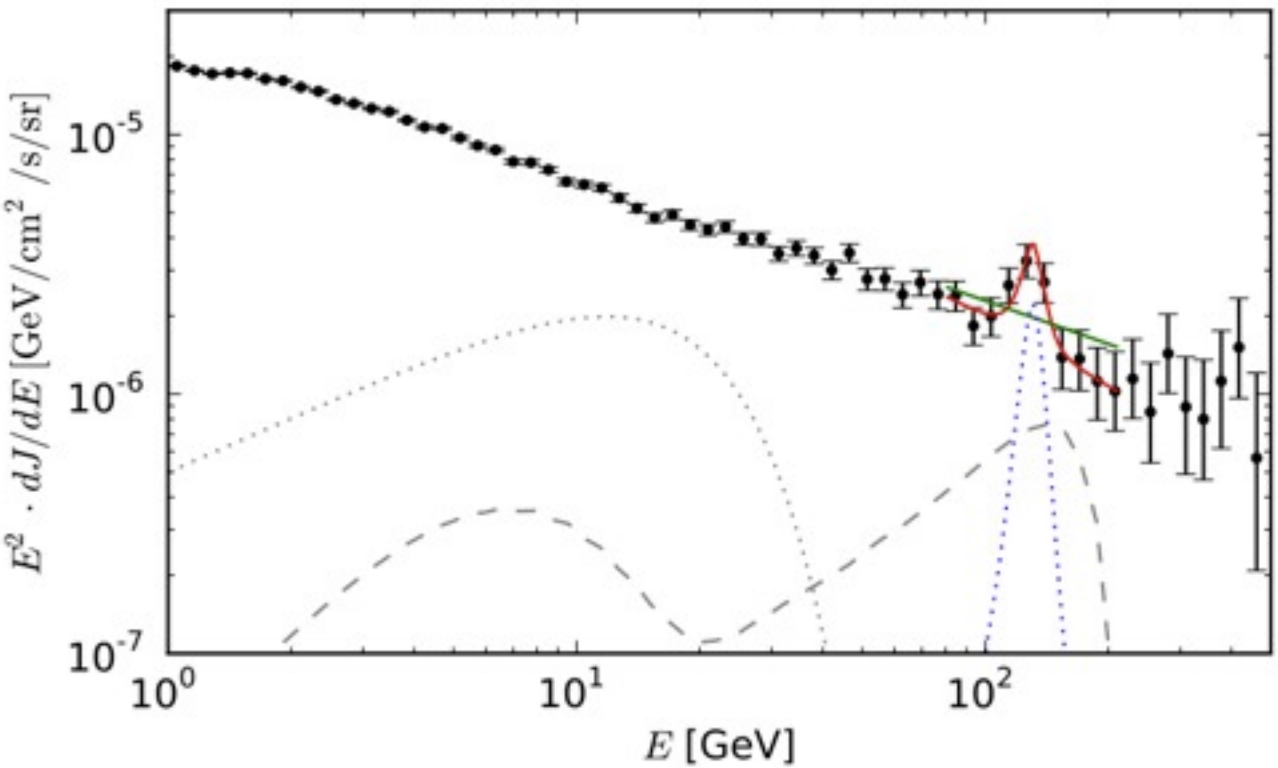
Can measure flux of different particles (electrons, protons, positrons, gammas) and their direction. Then compare to expectations . . .

Observable

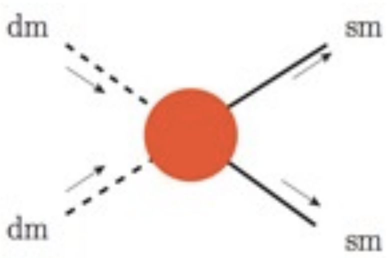


Annihilation somewhere in the galaxy

Weniger, arXiv:1303.1798 on Fermi/LAT data



Observable



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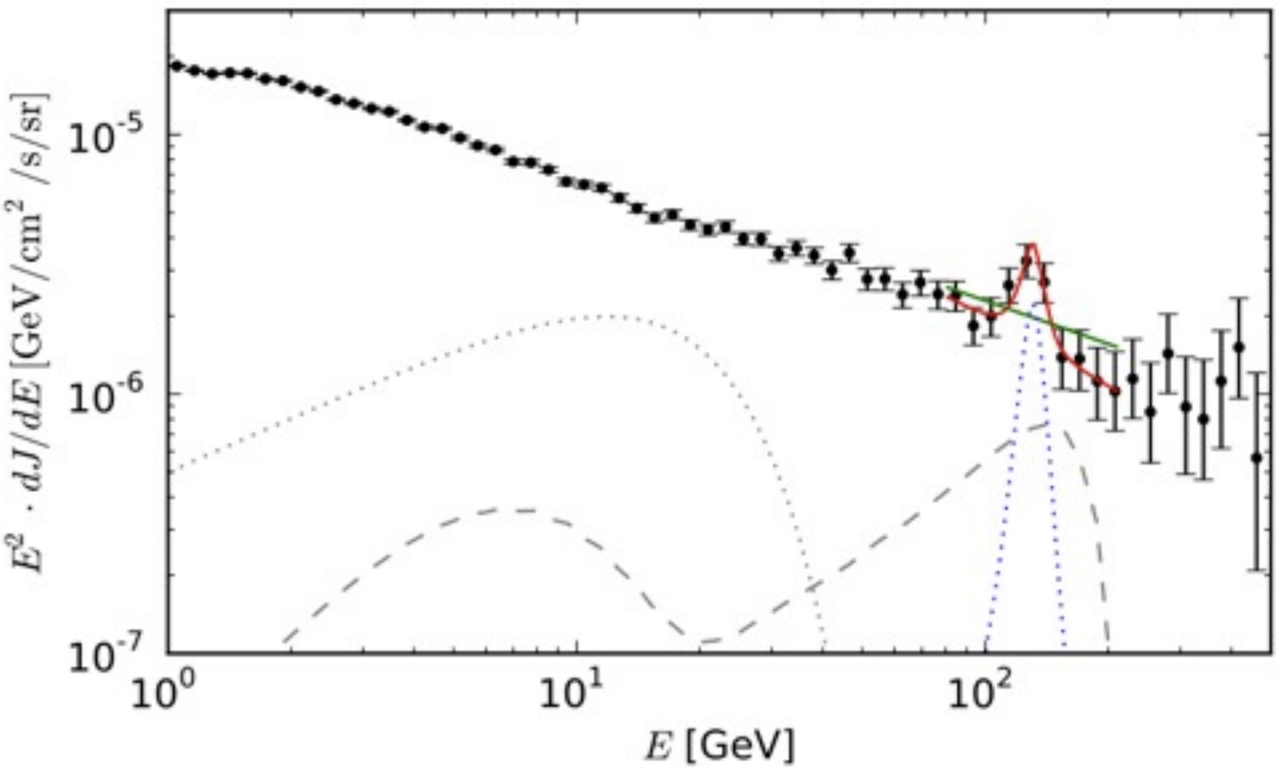
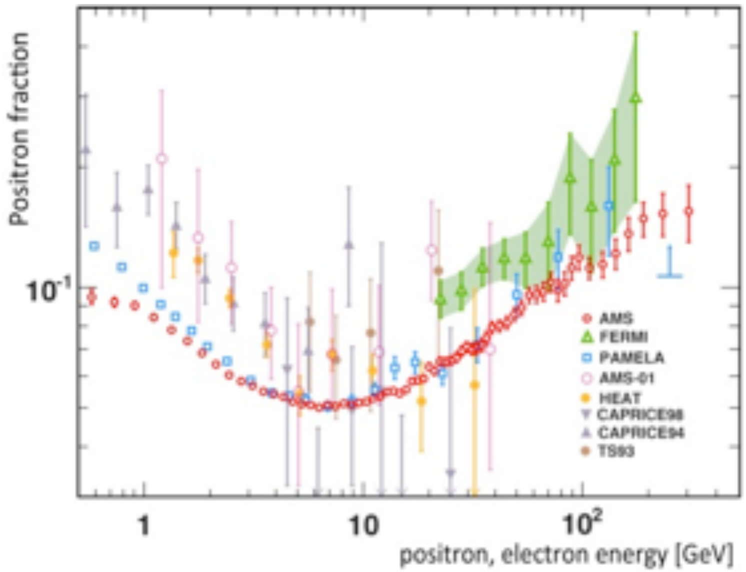


Large uncertainties, "mundane" astrophysical processes can mimic signal, how can we be certain?

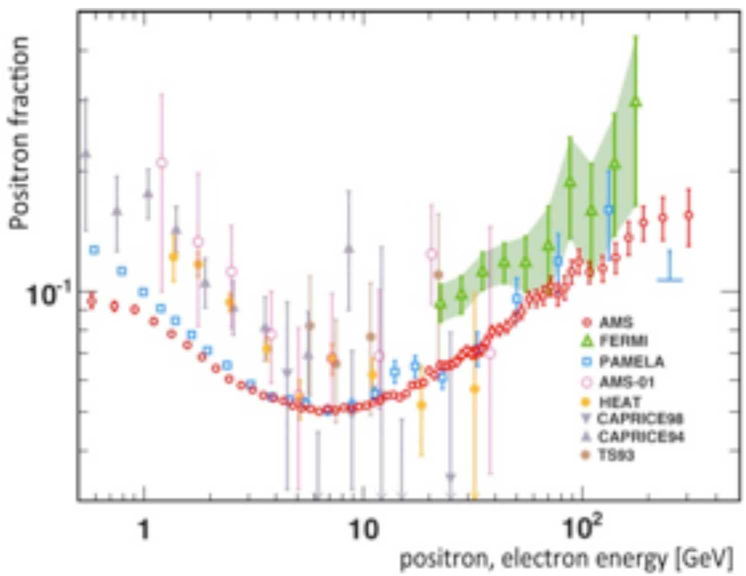
Many Discoveries

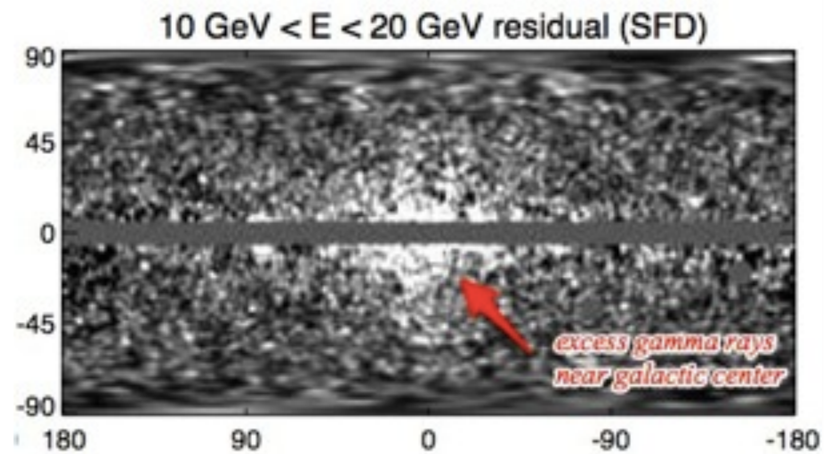
PRL110 (2013) 141102



Many Discoveries

PRL110 (2013) 141102

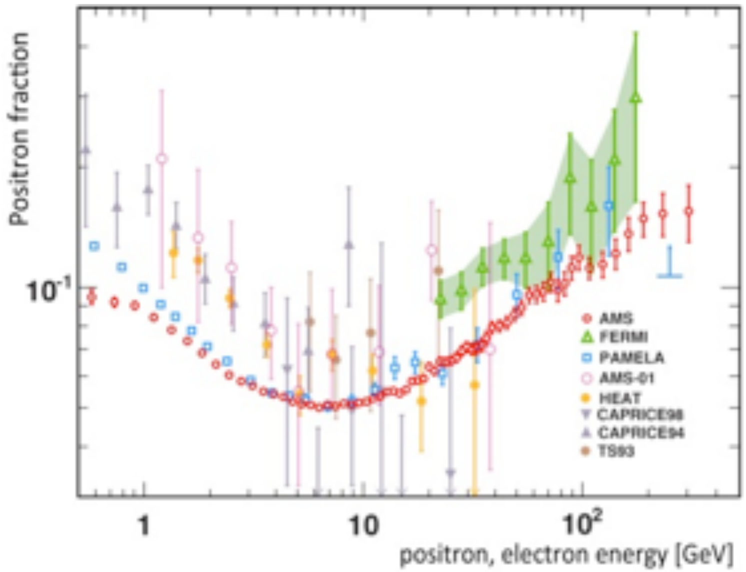


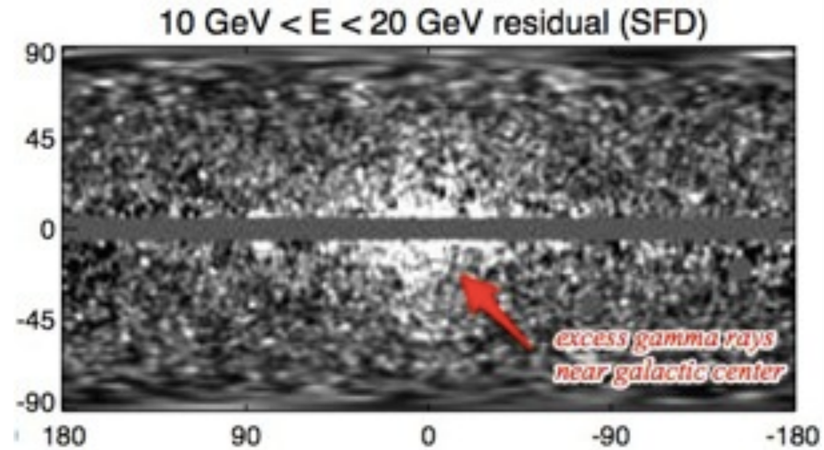


Finkbeiner, WMAP haze

Many Discoveries

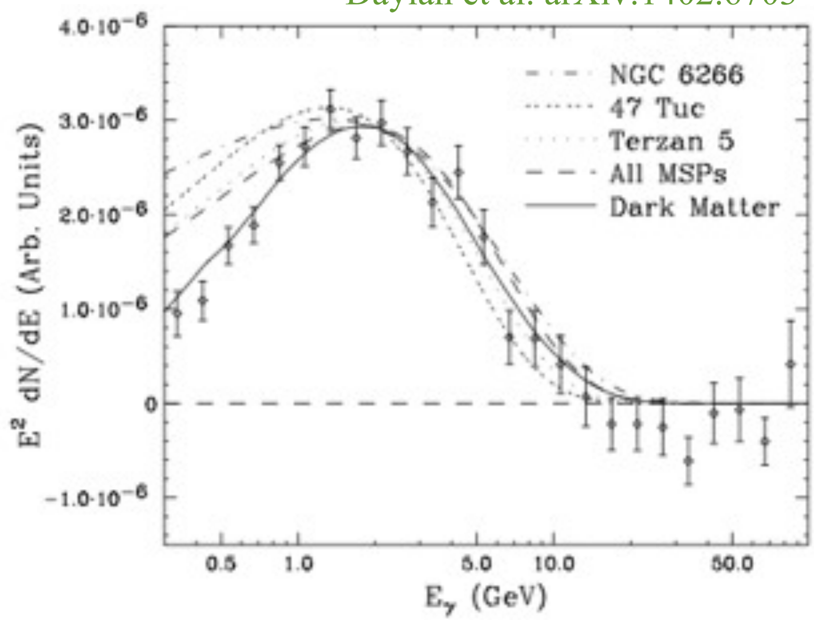
PRL110 (2013) 141102





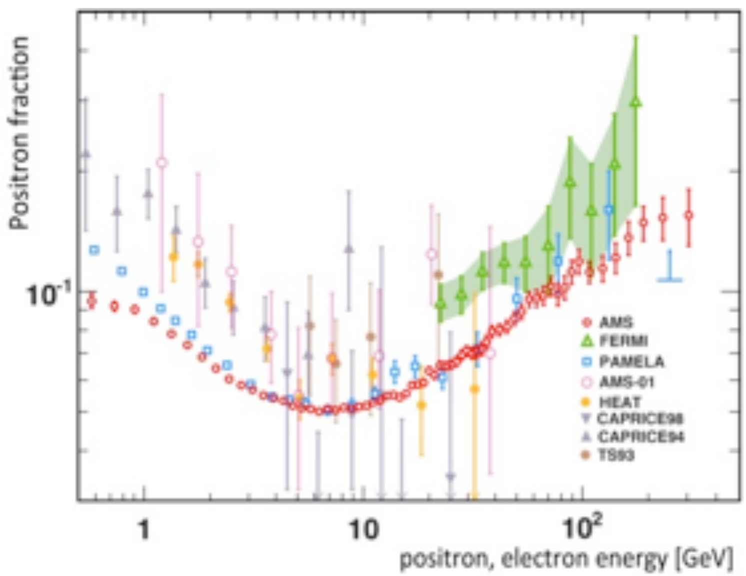
Finkbeiner, WMAP haze

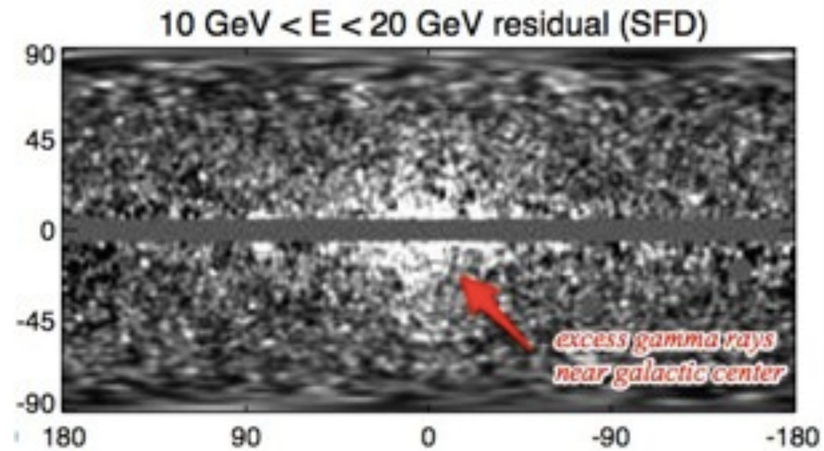
Daylan et al. arXiv:1402.6703



Many Discoveries

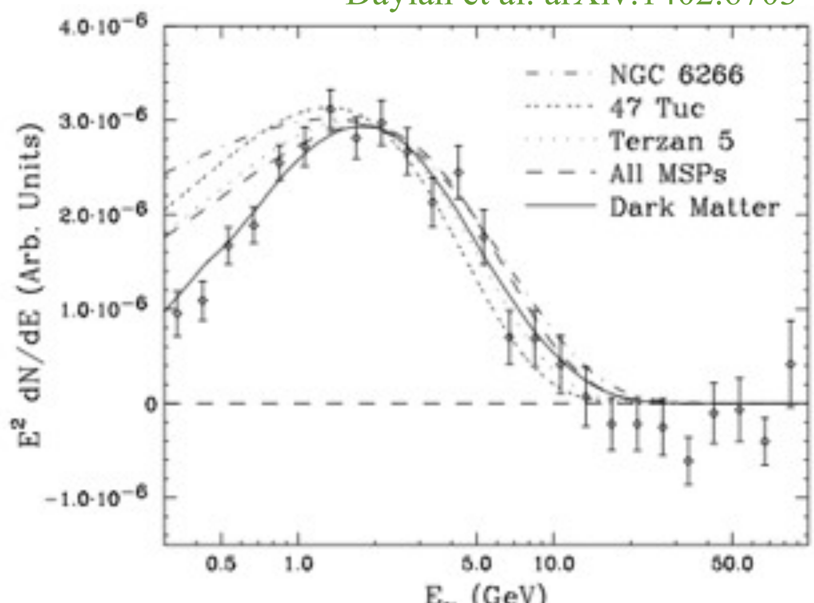
PRL110 (2013) 141102





Finkbeiner, WMAP haze

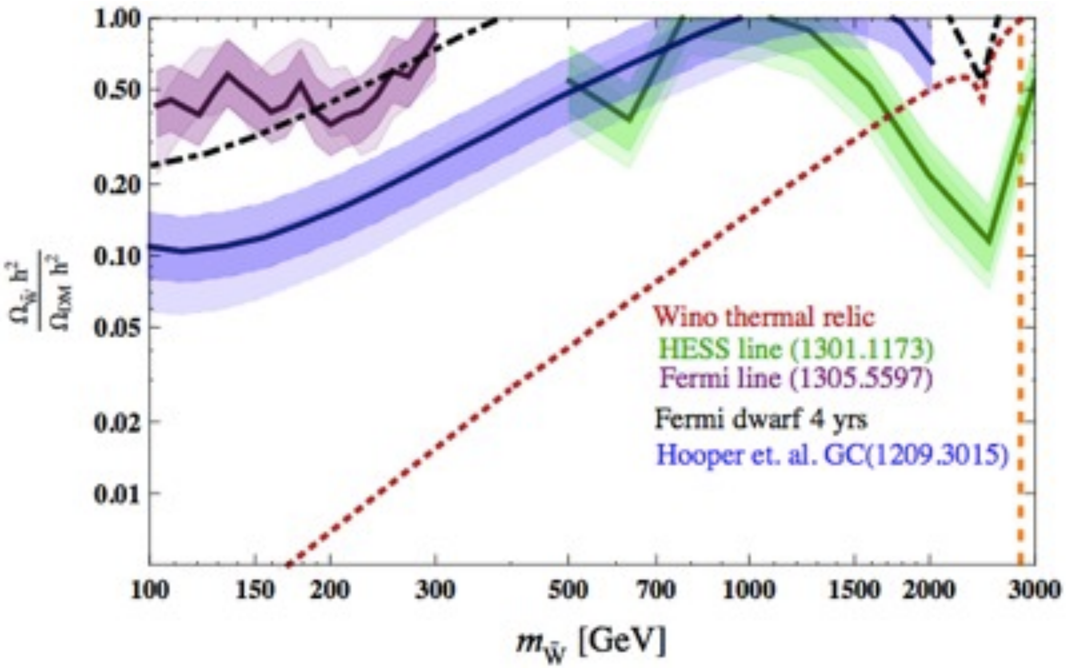
Daylan et al. arXiv:1402.6703



These are most likely discoveries about astrophysical processes unrelated to dark matter.

Constraints

Fan and Reece, arXiv:1307.4400



Constraints

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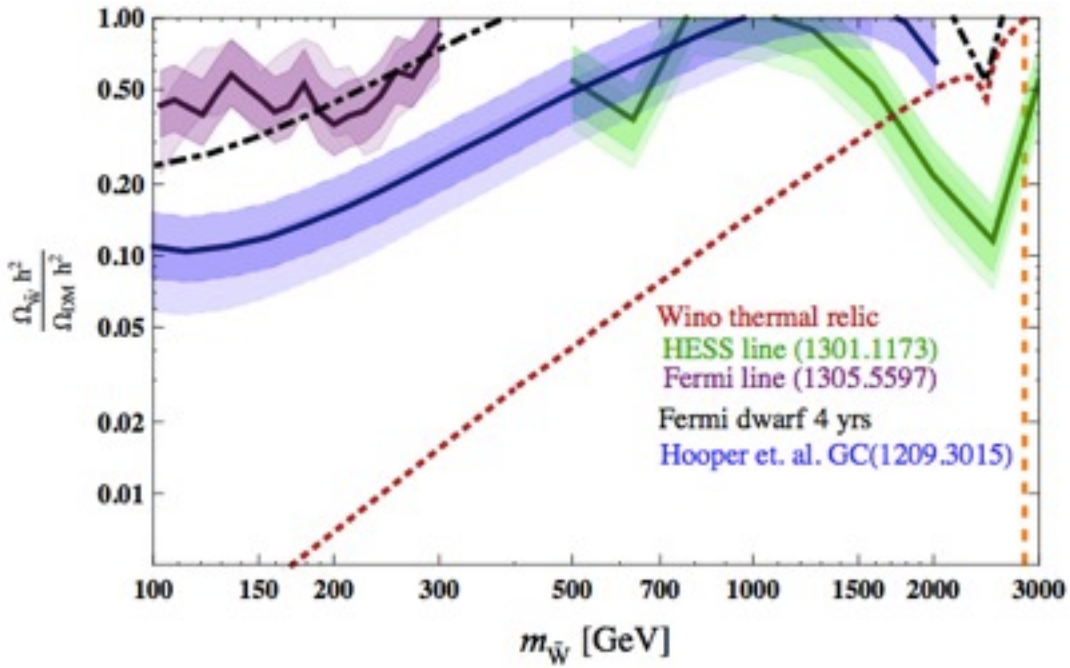
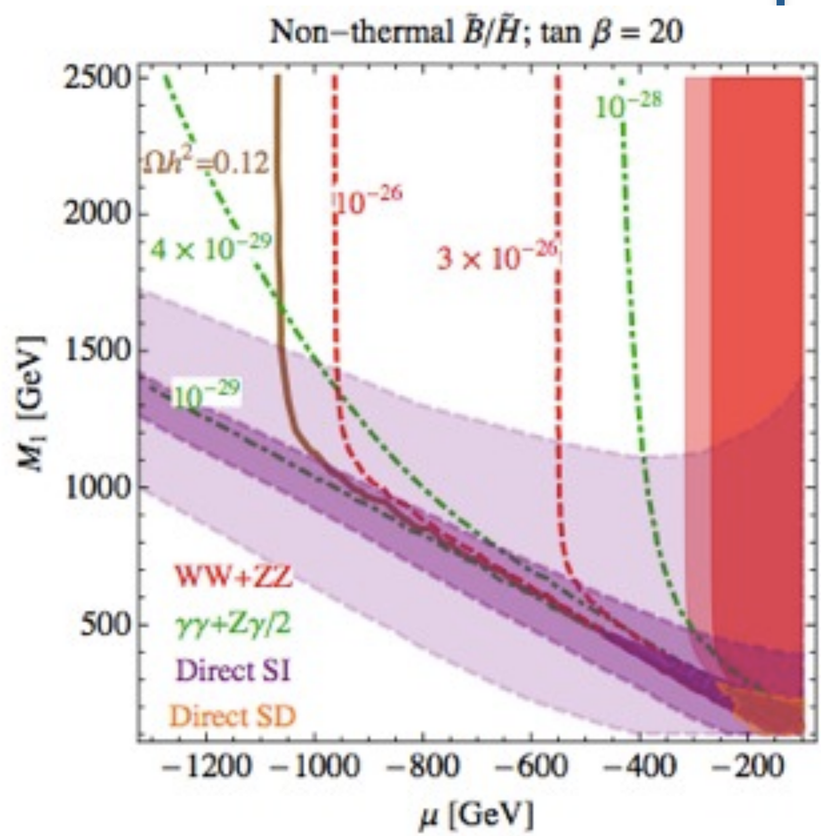
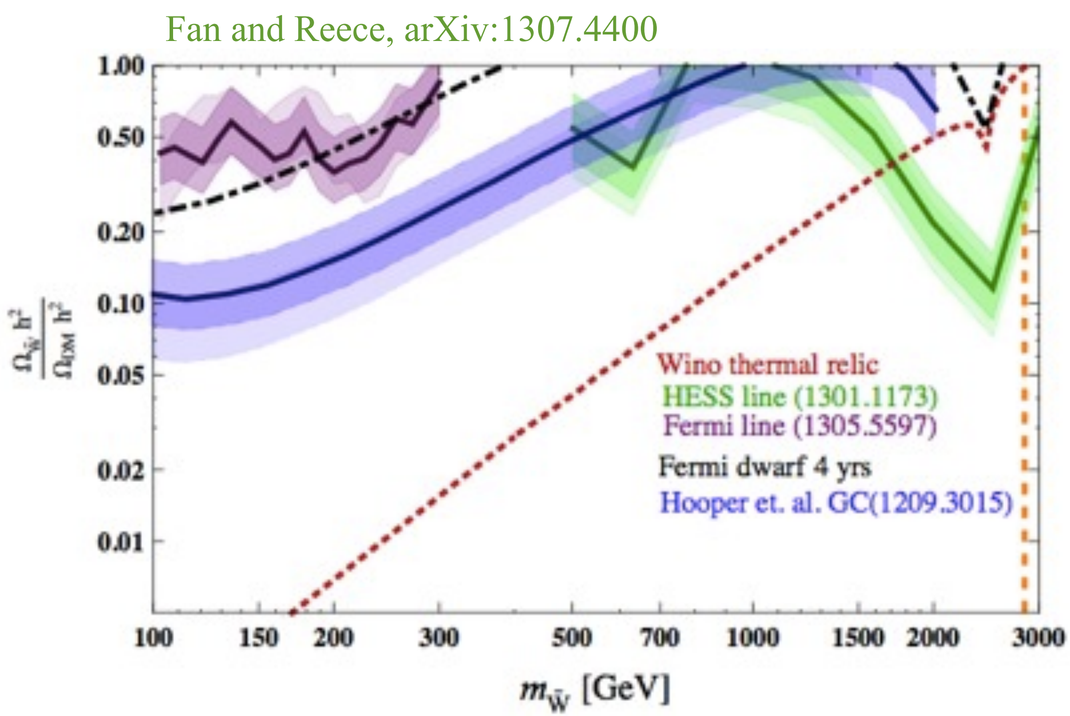
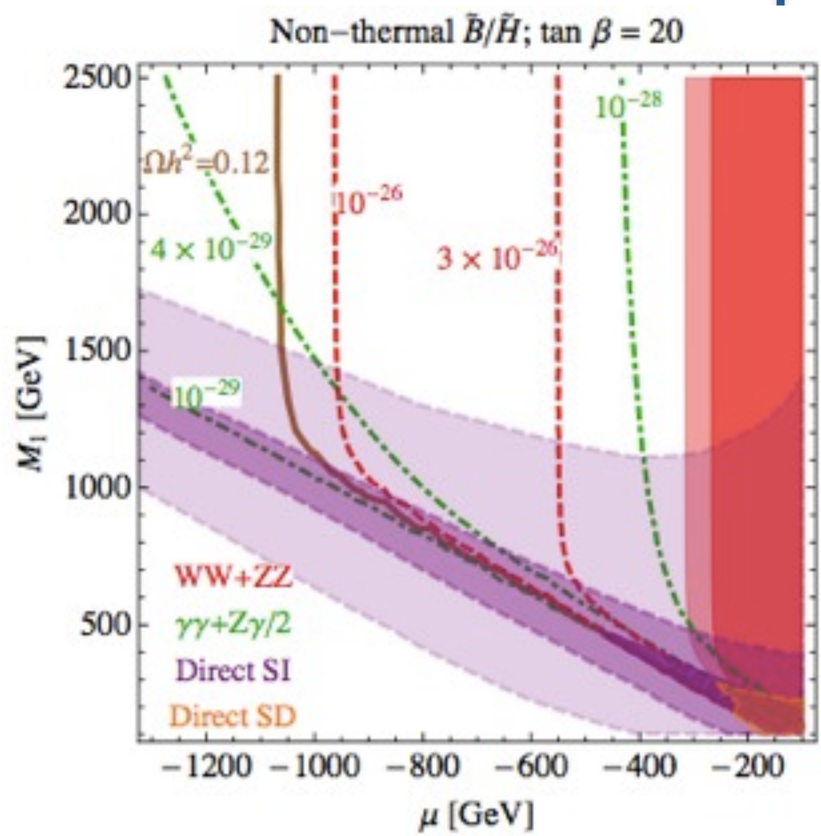




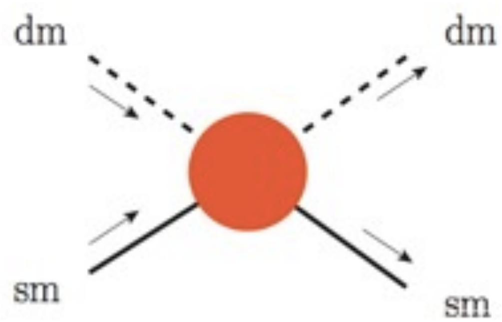
Constraints





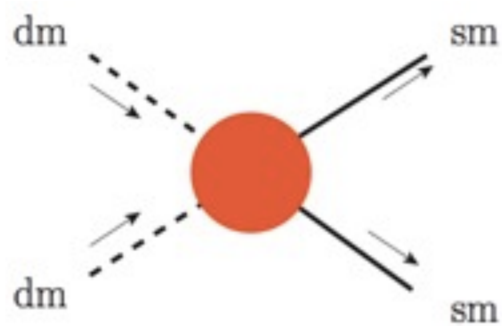
The minimal supersymmetric Standard Model and its dark matter candidate, is not in good shape . . .

The Frontiers



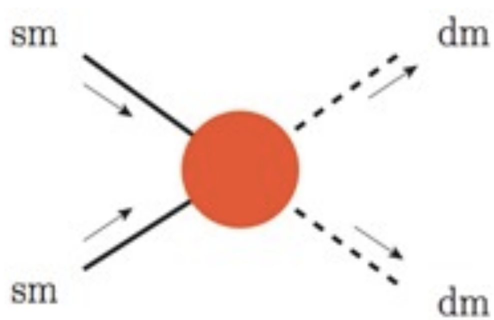
--- Direct detection

LUX
XENON
CDMS
CoGeNT
CRESST



--- Indirect detection

FERMI/LAT
PAMELA
AMS-II
HESS
IceCube

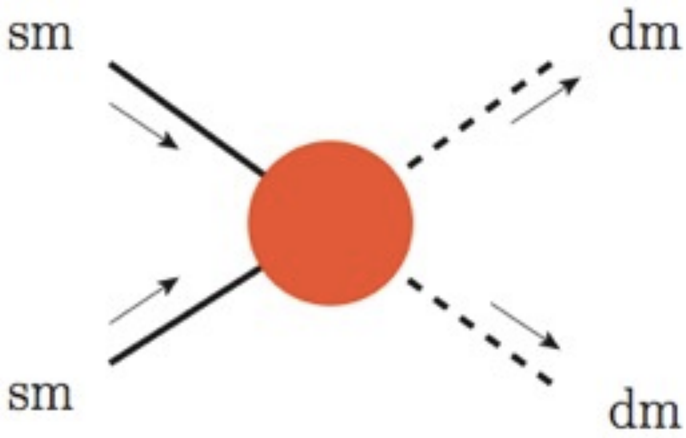


--- Collider searches

LHC
Tevatron
LEP
Babar/Belle
CLIC

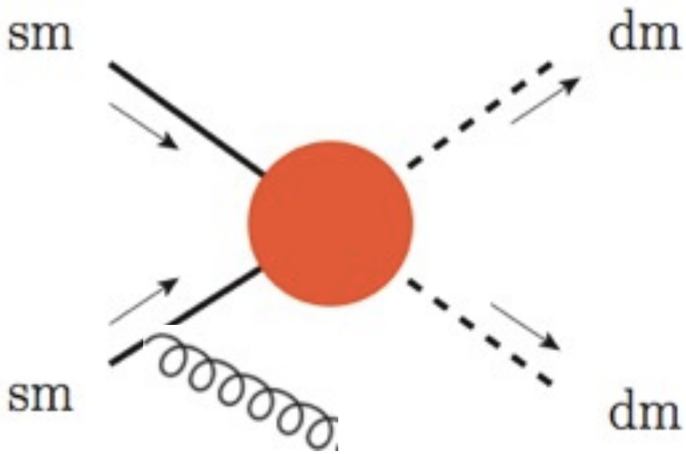
Collider searches

If the dark matter mass is not too heavy, and its production cross-section is not too small, we can have



Collider searches

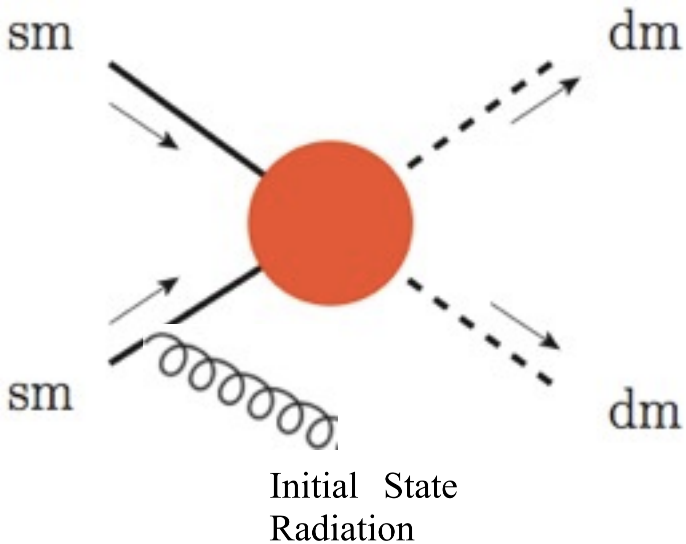
If the dark matter mass is not too heavy, and its production cross-section is not too small, we can have



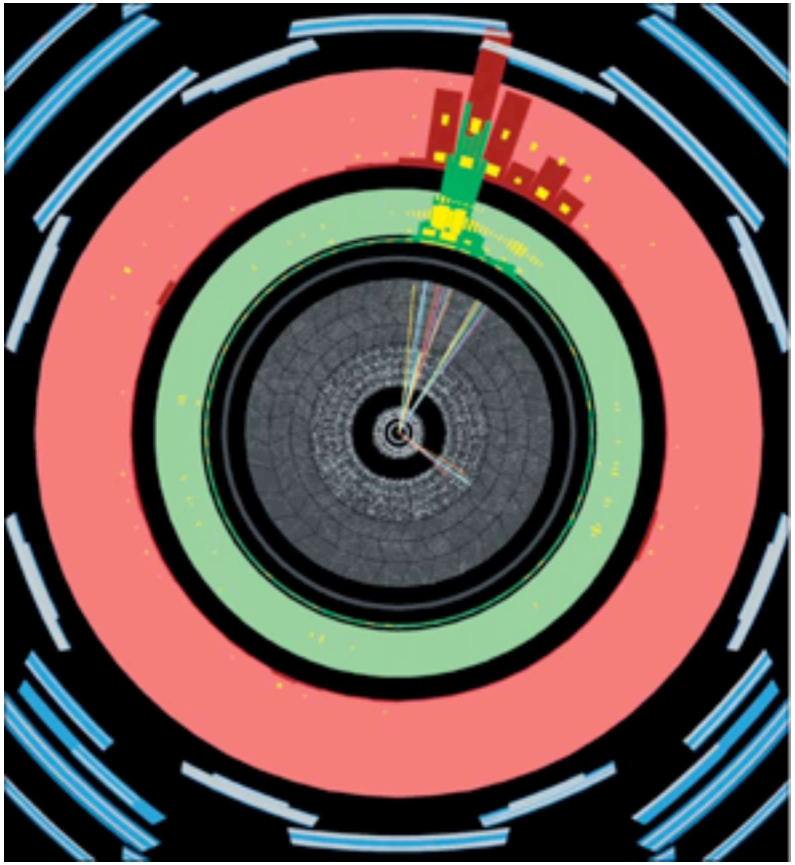
Initial State Radiation

Collider searches

If the dark matter mass is not too heavy, and its production cross-section is not too small, we can have

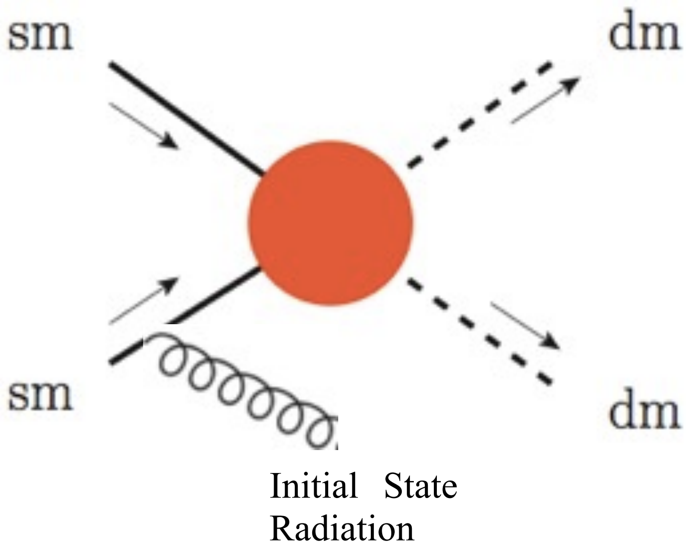


ATLAS coll. event display

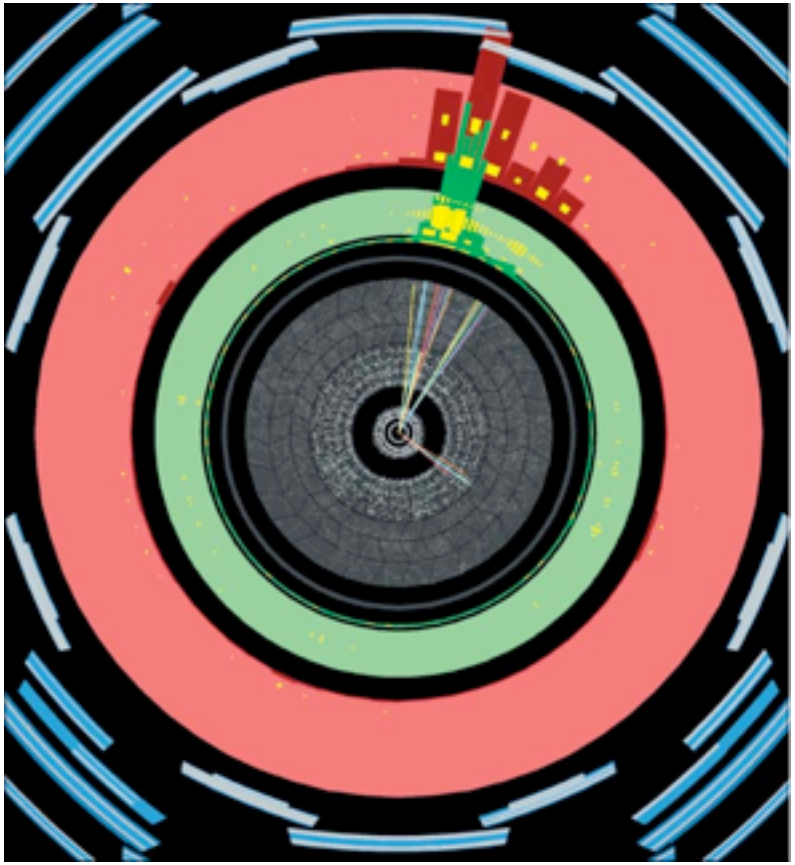


Collider searches

If the dark matter mass is not too heavy, and its production cross-section is not too small, we can have



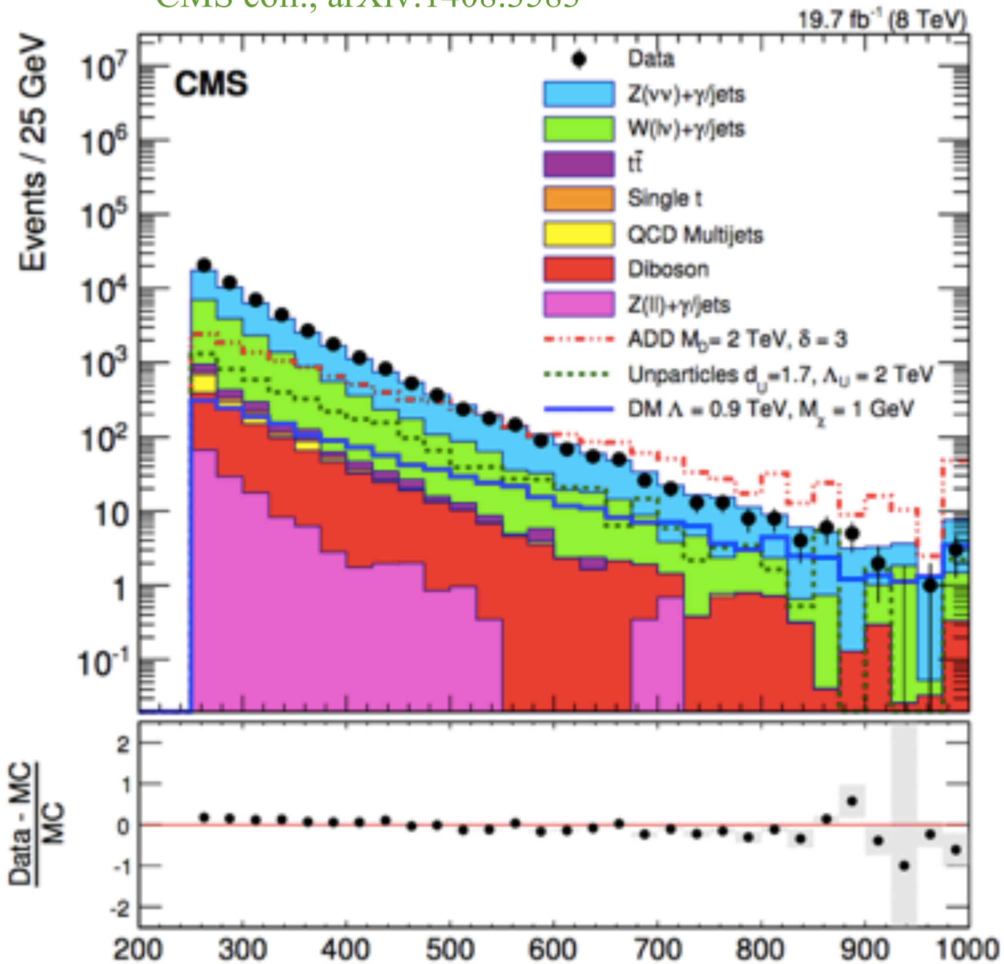
ATLAS coll. event display



We search for missing energy and/or missing momentum.

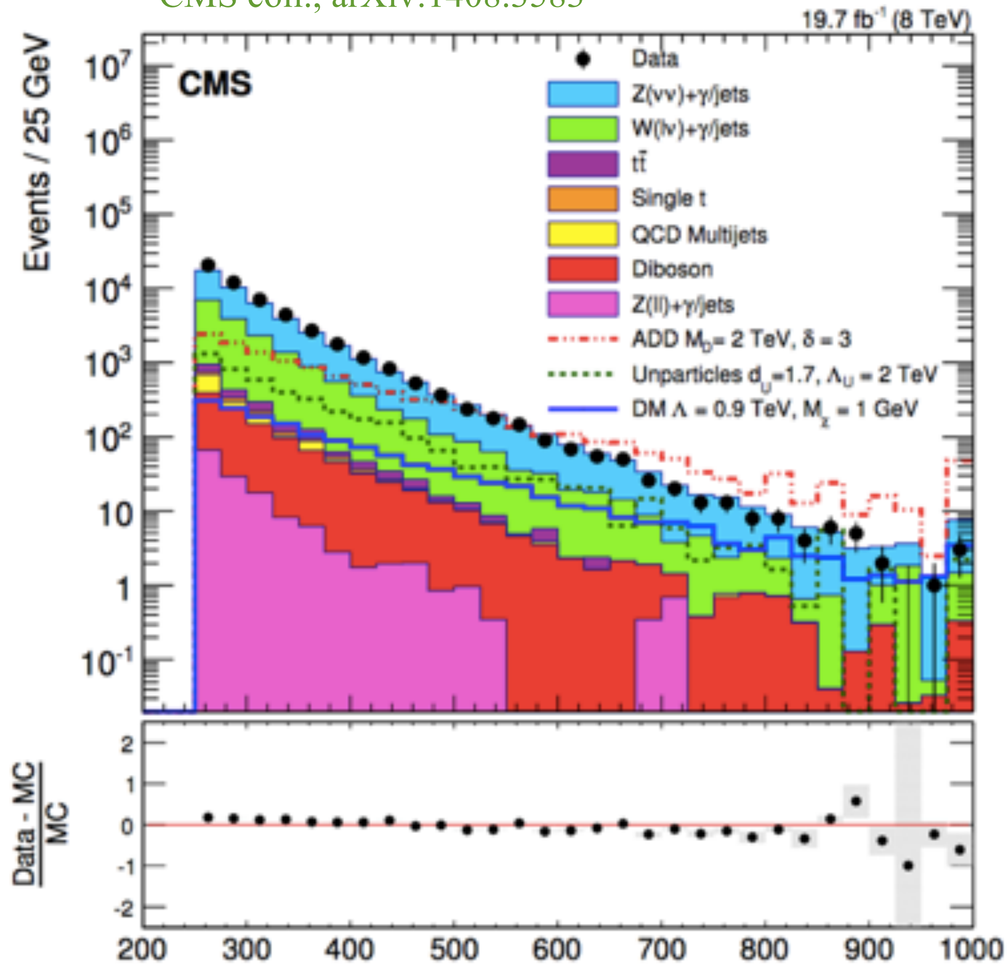
Observable

CMS coll., arXiv:1408.3583



Observable

CMS coll., arXiv:1408.3583



How to interpret these (null) results? What else can be done? Are there any blind spots?

Parametrize our failures . . .

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu} q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$
D15	$\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$	M
D16	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi F_{\mu\nu}$	D
M1	$\bar{\chi}\chi\bar{q}q$	$m_q/2M_*^3$
M2	$\bar{\chi}\gamma^5\chi\bar{q}q$	$im_q/2M_*^3$

Name	Operator	Coefficient
M3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	$im_q/2M_*^3$
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M5	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/2M_*^2$
M6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/2M_*^2$
M7	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^3$
M8	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/8M_*^3$
M9	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^3$
M10	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/8M_*^3$
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
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See e.g. Goodman et al arXiv:1009.0008

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D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$	i/M_*^2
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D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$
D15	$\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$	M
D16	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi F_{\mu\nu}$	D
M1	$\bar{\chi}\chi\bar{q}q$	$m_q/2M_*^3$
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M5	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/2M_*^2$
M6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/2M_*^2$
M7	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^3$
M8	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/8M_*^3$
M9	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^3$
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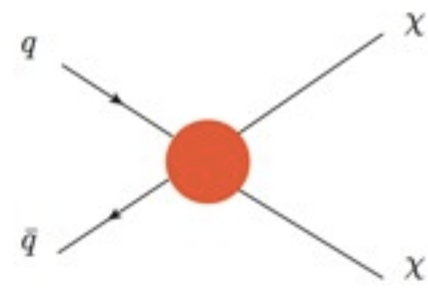
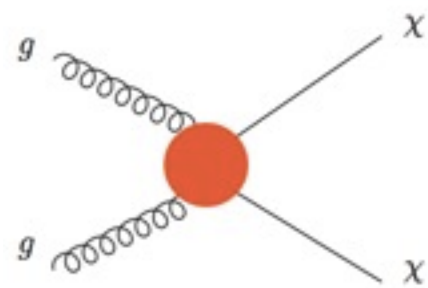
Non-renormalizable operators, come with a scale M_*, above which new particles must be present.





See e.g. Goodman et al arXiv:1009.0008

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D4	$\bar\chi\gamma^5\chi\bar q\gamma^5 q$	m_q/M_*^3
D5	$\bar\chi\gamma^\mu\chi\bar q\gamma_\mu q$	$1/M_*^2$
D6	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu q$	$1/M_*^2$
D7	$\bar\chi\gamma^\mu\chi\bar q\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar\chi\sigma^{\mu\nu}\chi\bar q\sigma_{\mu\nu} q$	$1/M_*^2$
D10	$\bar\chi\sigma_{\mu\nu}\gamma^5\chi\bar q\sigma_{\mu\nu} q$	i/M_*^2
D11	$\bar\chi\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar\chi\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar\chi\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar\chi\gamma^5\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$\alpha_s/4M_*^3$
D15	$\bar\chi\sigma^{\mu\nu}\chi F_{\mu\nu}$	M
D16	$\bar\chi\sigma_{\mu\nu}\gamma^5\chi F_{\mu\nu}$	D
M1	$\bar\chi\chi\bar q q$	$m_q/2M_*^3$
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M5	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu q$	$1/2M_*^2$
M6	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu\gamma^5 q$	$1/2M_*^2$
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M8	$\bar\chi\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/8M_*^3$
M9	$\bar\chi\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$i\alpha_s/8M_*^3$
M10	$\bar\chi\gamma^5\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$\alpha_s/8M_*^3$
C1	$\chi^\dagger\chi\bar q q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar q\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar q\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar q\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar q q$	$m_q/2M_*^2$
R2	$\chi^2\bar q\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
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See e.g. Goodman et al arXiv:1009.0008

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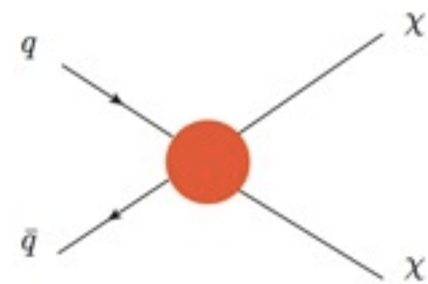
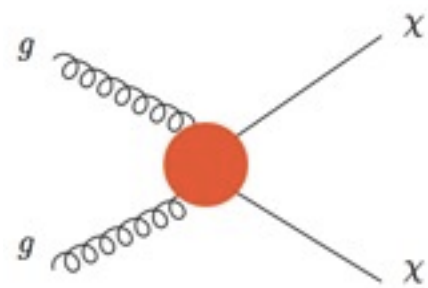


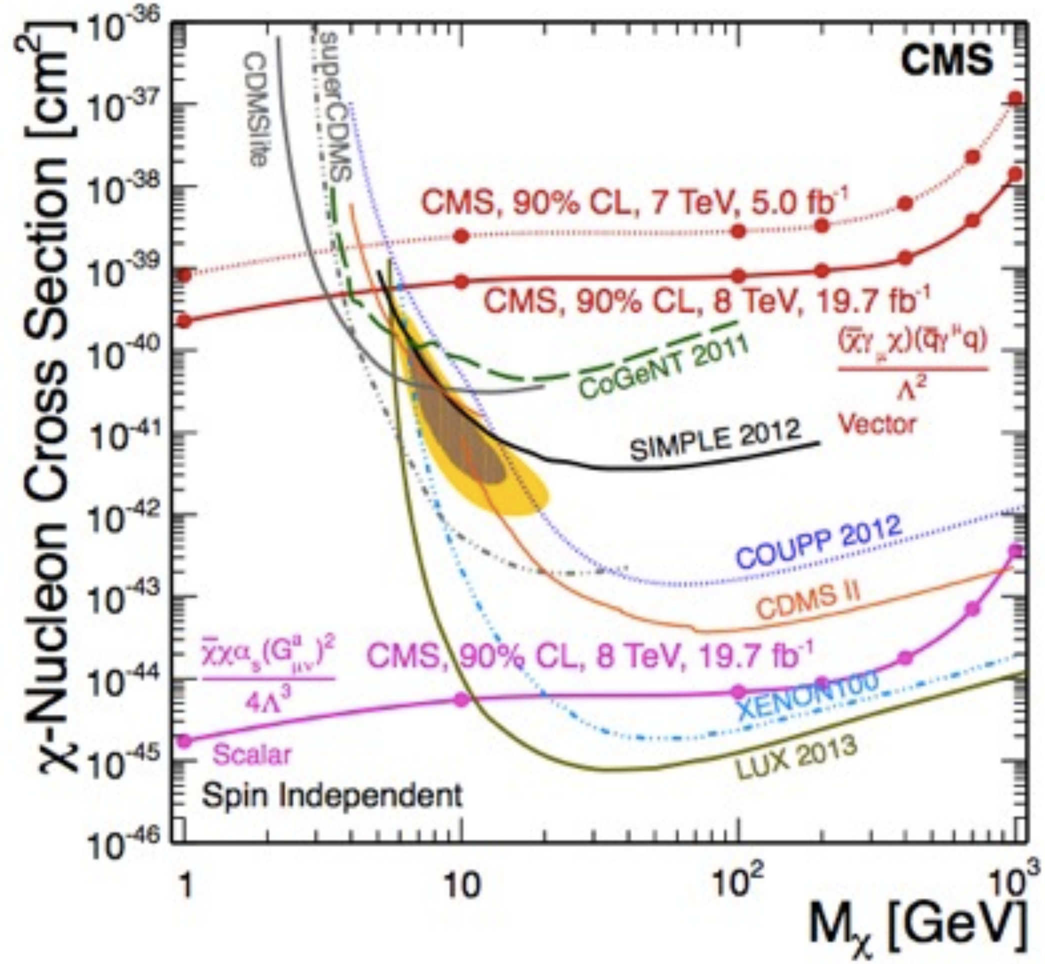


Also useful for comparison with other experiments looking for Dark Matter.

Connection with other frontiers

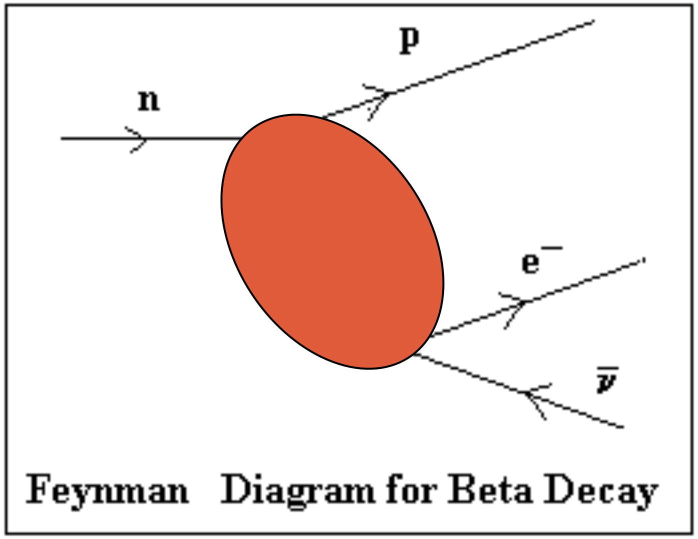
Constraints from colliders can also inform our efforts in direct detection experiments.

CMS arXiv:1408.3583



"Effective Field Theory" approach

Parametrizing the interactions of the WIMPs with normal matter is akin to Fermi's four-fermion theory of weak decays.



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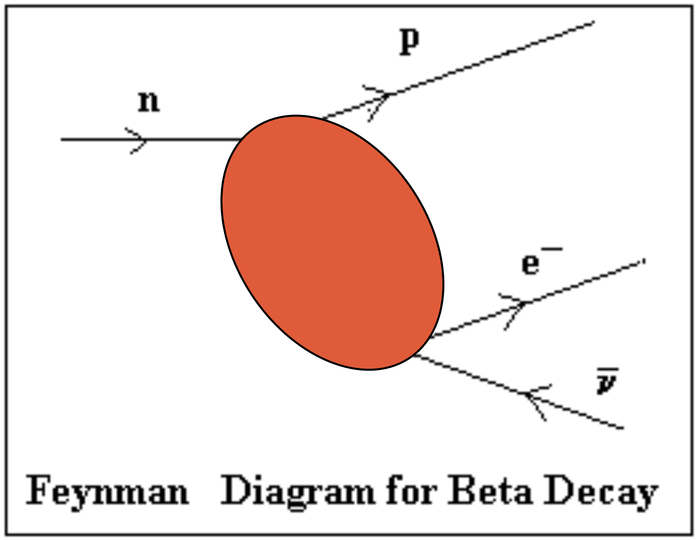

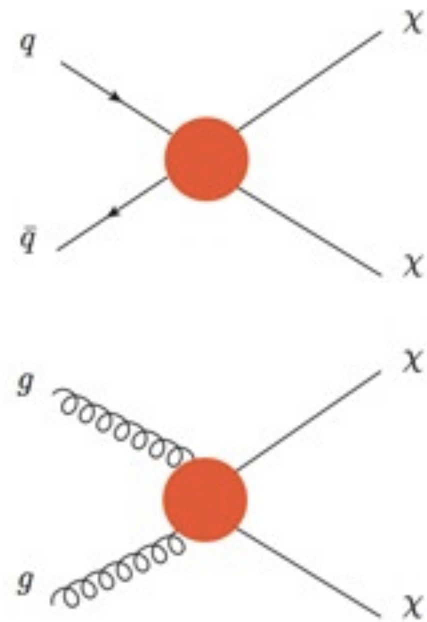

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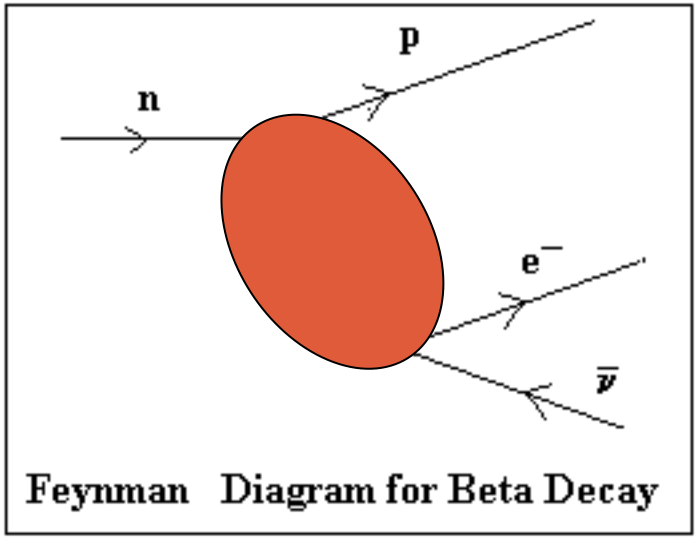

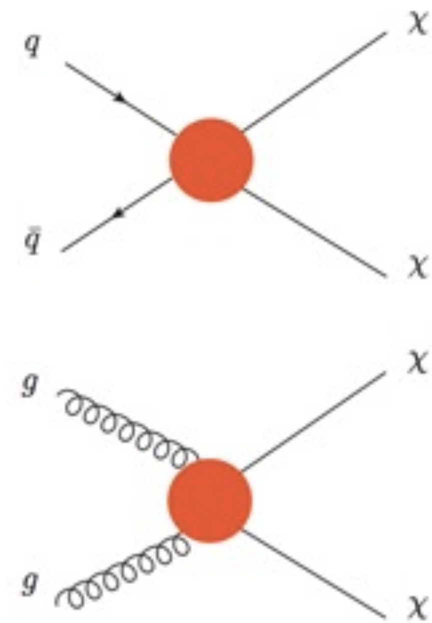

But, at sufficiently high energies this description is inadequate.

See e.g. Busoni et al arXiv:1402.1275

Simplified Models

We want to maintain the generality of the EFT while staying away from unphysical cross-sections. “Integrate-in” the heavy physics. . .

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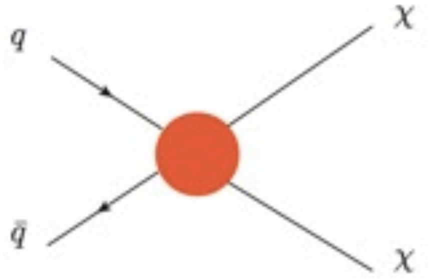

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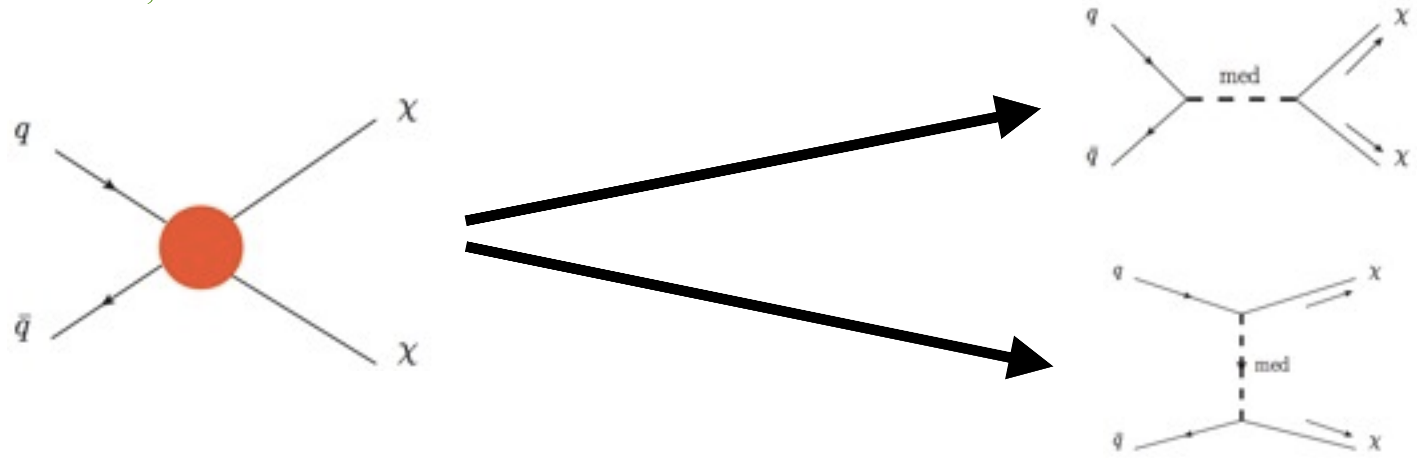

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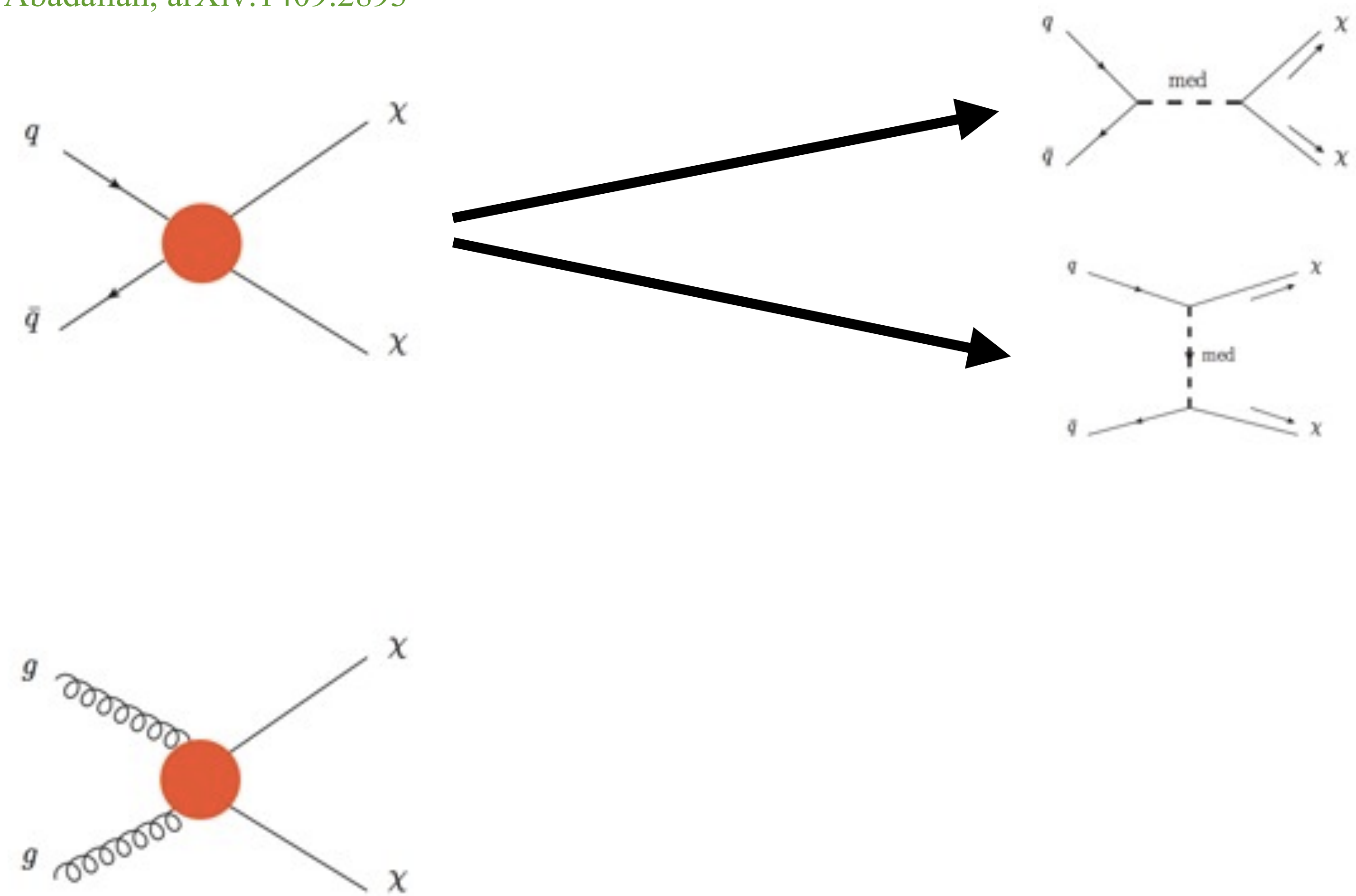

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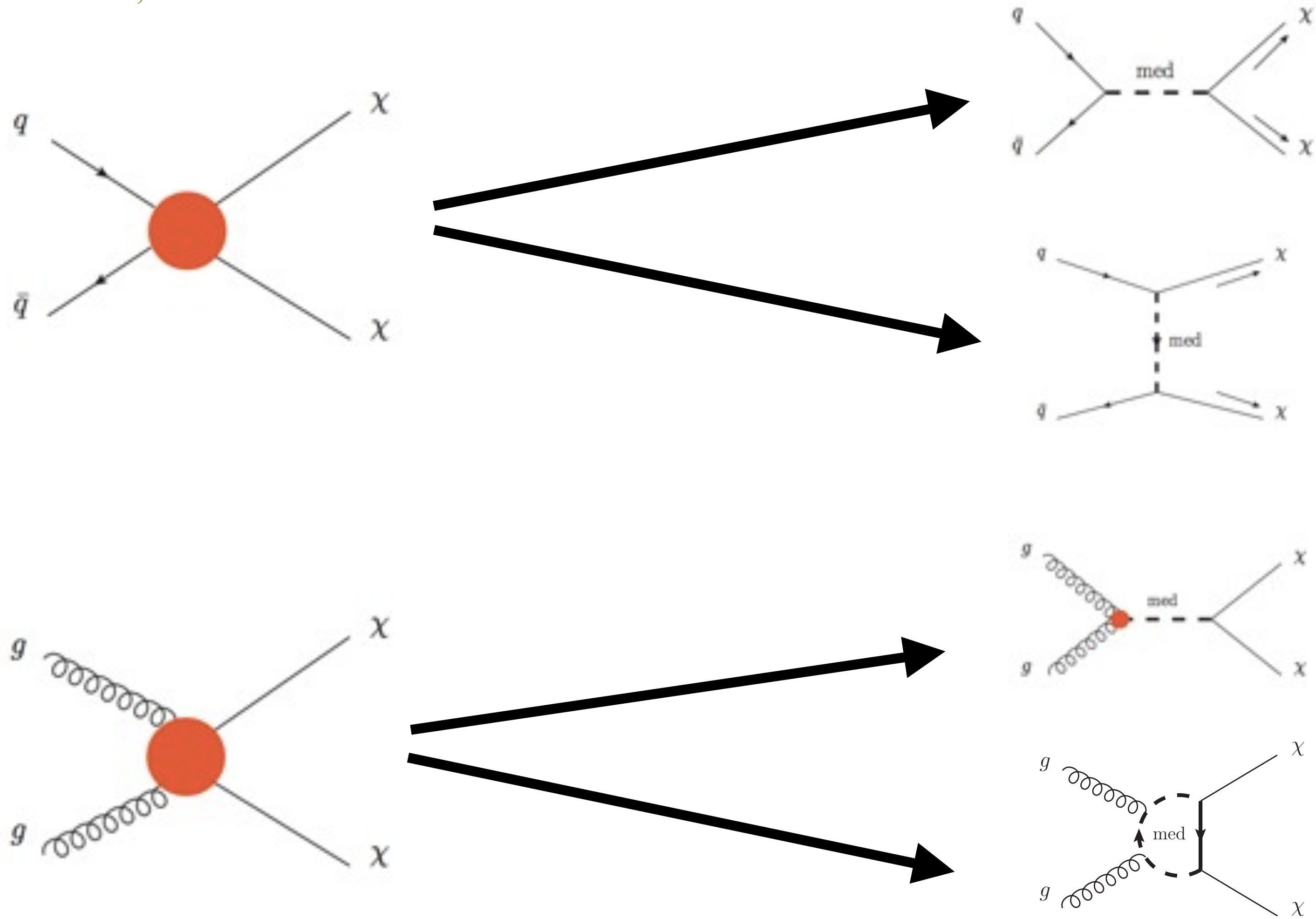

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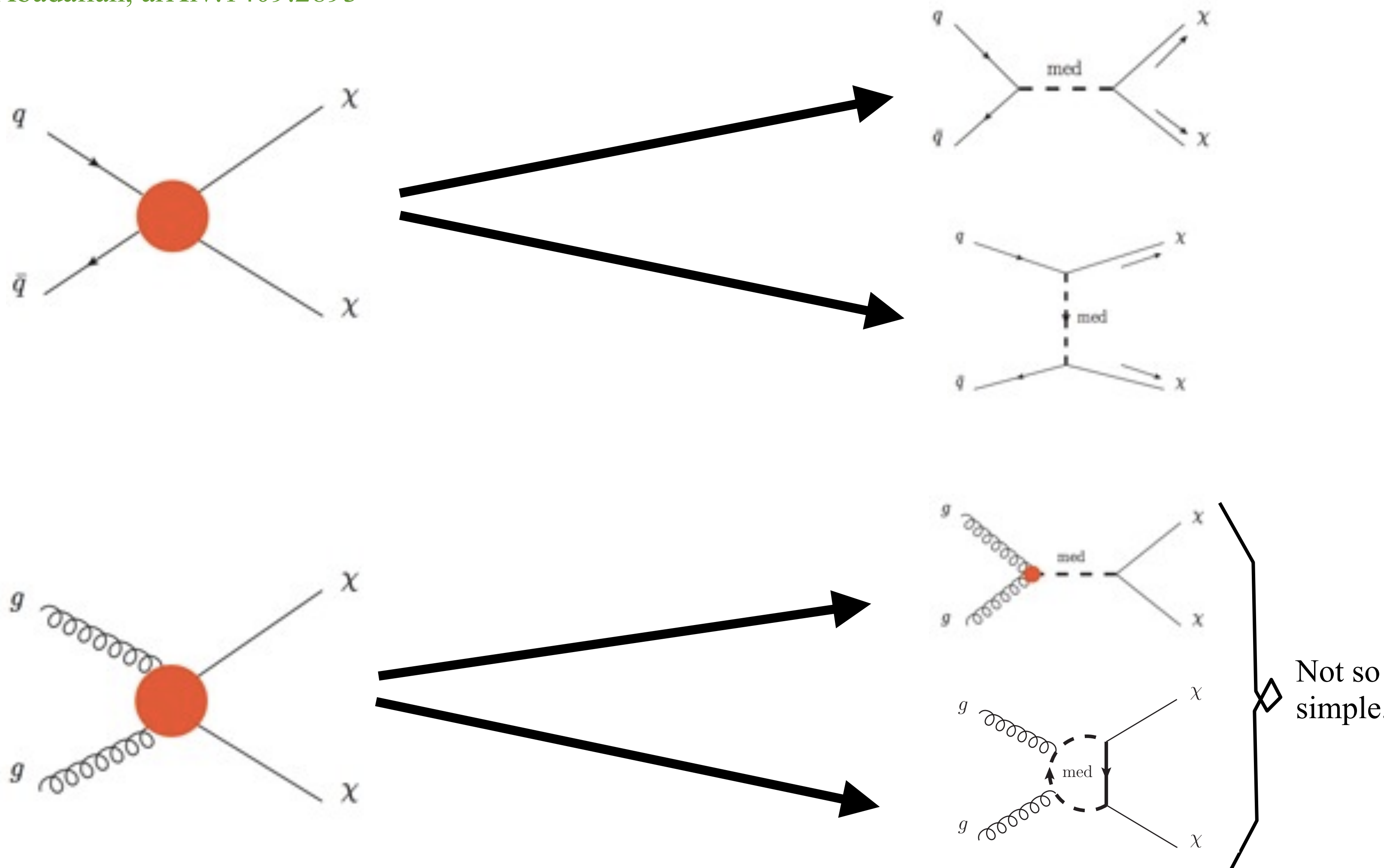

What can CLIC do?

CLIC can yield the strongest bounds on WIMPs interactions with electrons and other leptons!
Here is what was done with LEP data:

Fox et al, arXiv:1103.0240

$$\frac{1}{\Lambda^2}\,\bar{\chi}\chi\,\bar{e}e$$

$$\frac{1}{\Lambda^2}\,\bar{\chi}\gamma^\mu\chi\,\bar{e}\gamma_\mu e$$

$$\frac{1}{\Lambda^2}\,\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{e}\gamma_\mu\gamma^5 e$$

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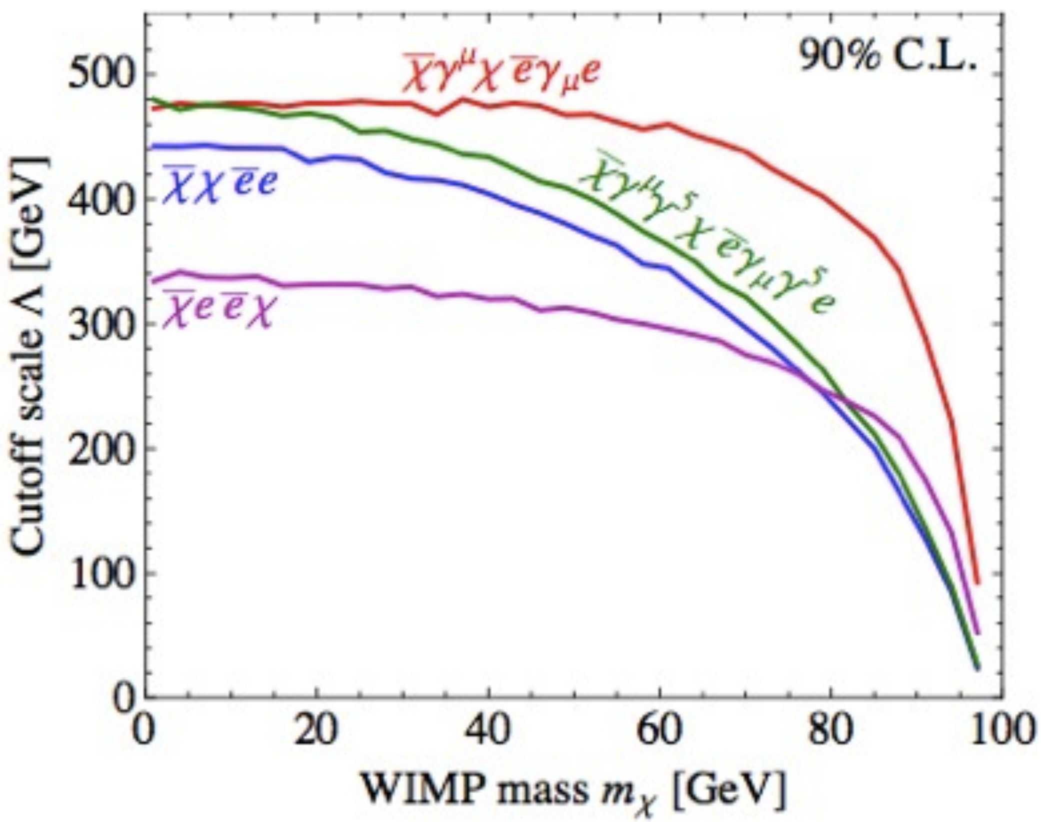

Dim-7 op with electroweak could also be probed,

Weiner & Yavin, arXiv:1206.2910

CLIC on other frontiers

CLIC would also strongly inform other frontiers, direct and indirect detection efforts.

Here it is for LEP:

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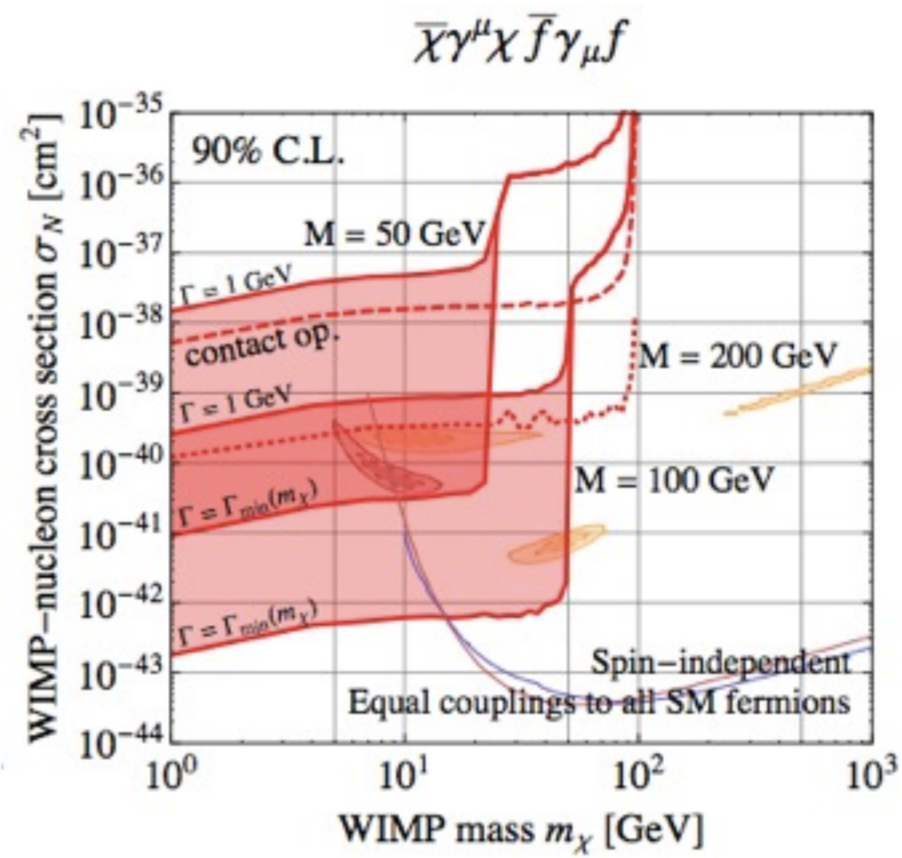

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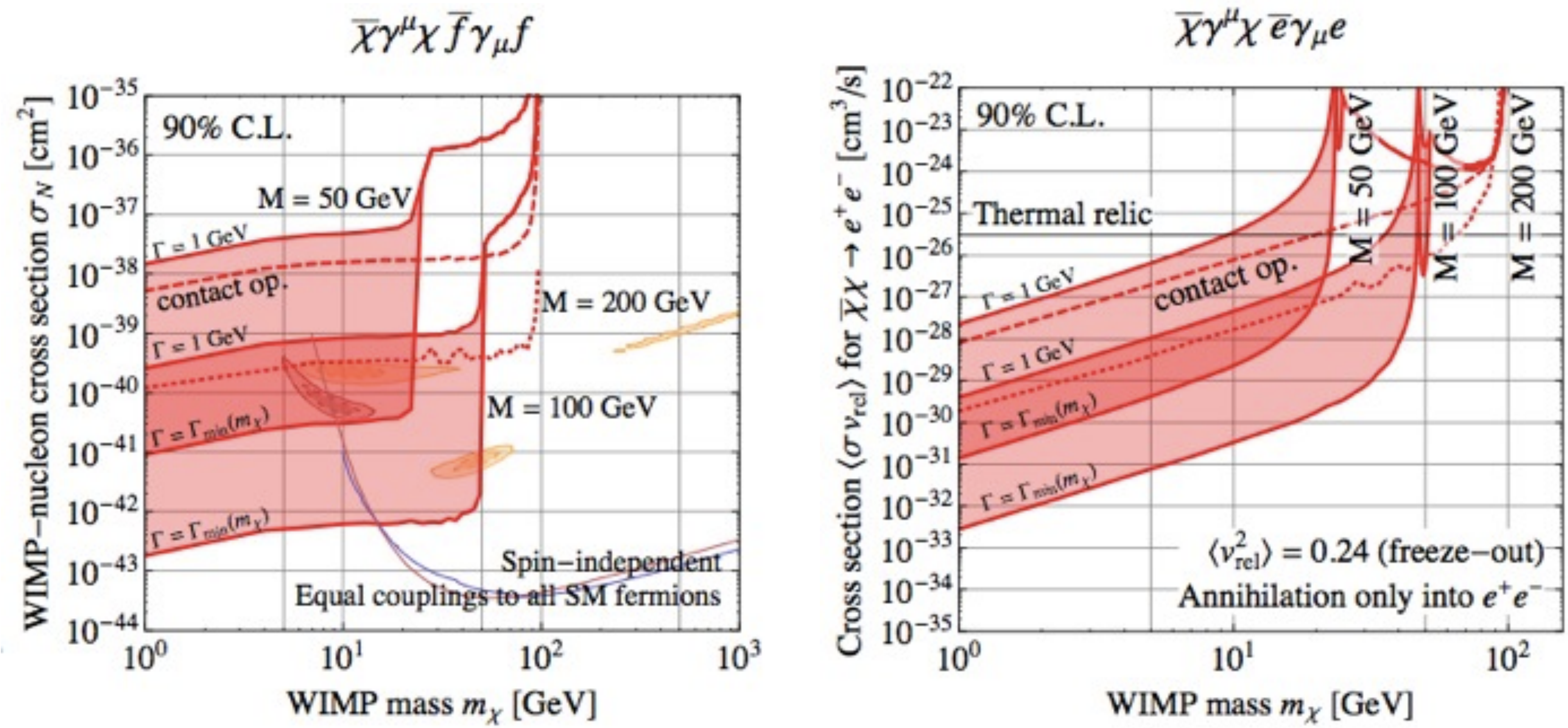
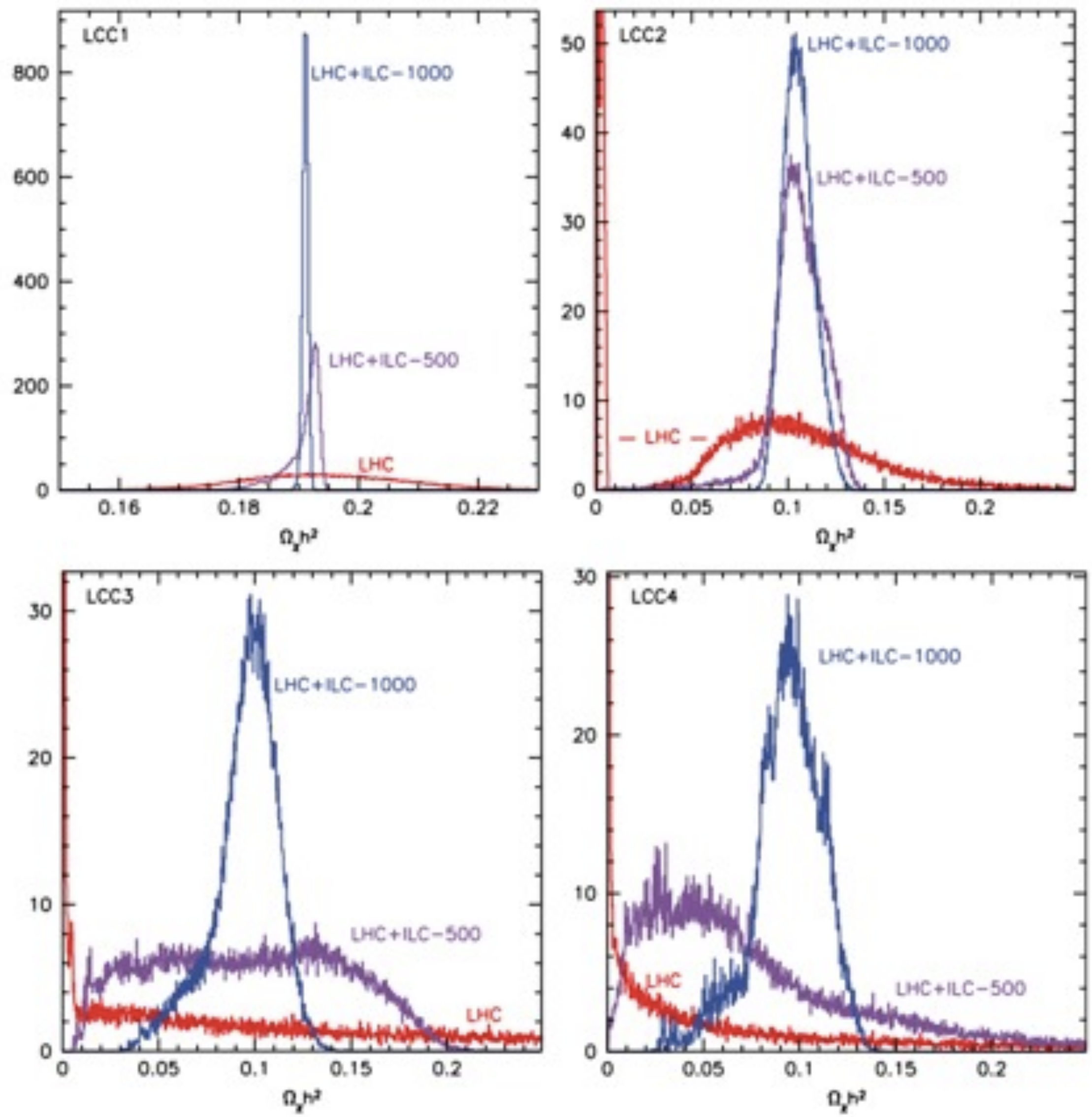


Fox et al, arXiv:1103.0240

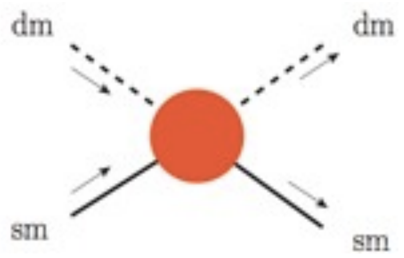
Precision measurements of DM

Baltz et al, arXiv:hep-ph/0602187)



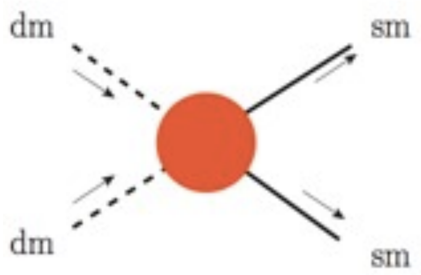
The Frontiers

Direct detection



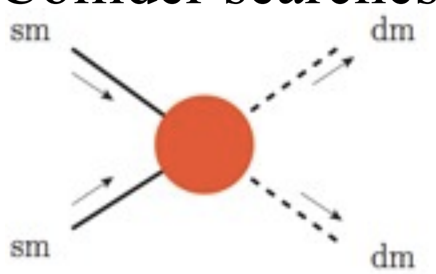
LUX
XENON
CDMS
CoGeNT
CRESST

Indirect detection



FERMI/LAT
PAMELA
AMS-II
HESS
IceCube

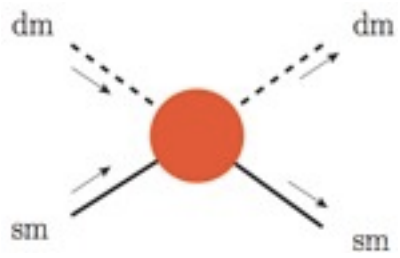
Collider searches



LHC
Tevatron
LEP
Babar/Belle
CLIC

The Frontiers

Direct detection



• Probing directly the idea of galactic DM

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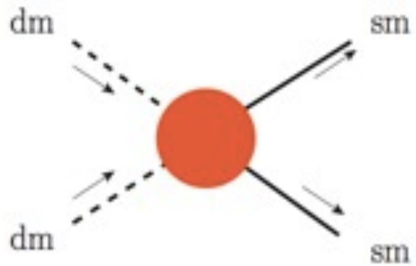

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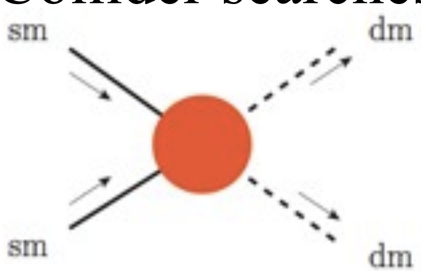

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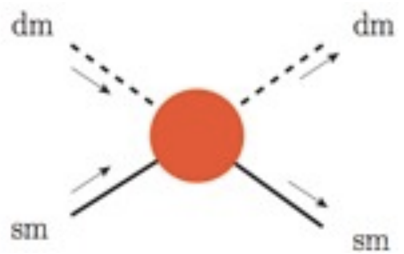

- Probing directly the idea of galactic DM
- Still relatively small scale experiments

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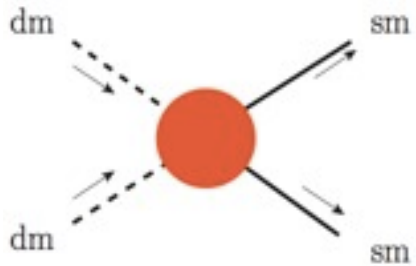

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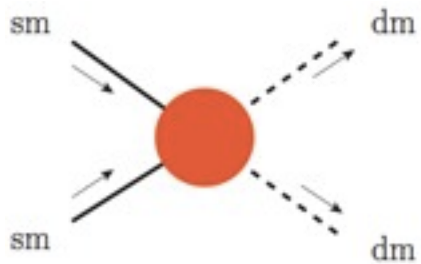

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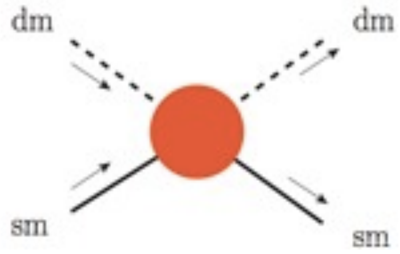

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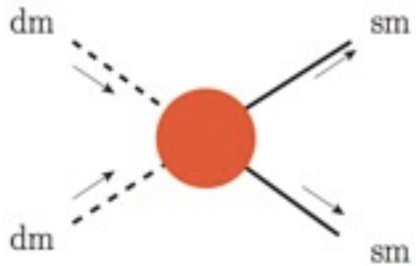

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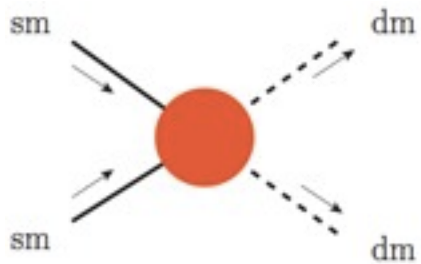

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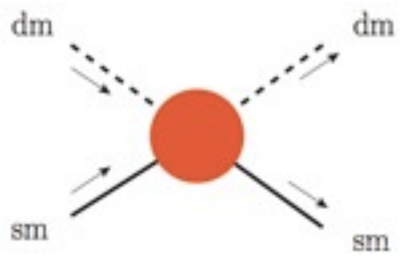

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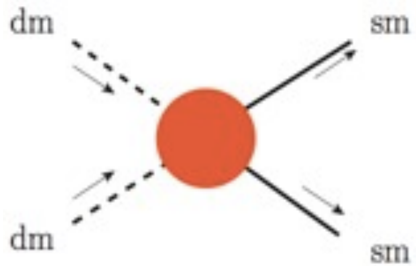

- Part of strong general astrophysics research

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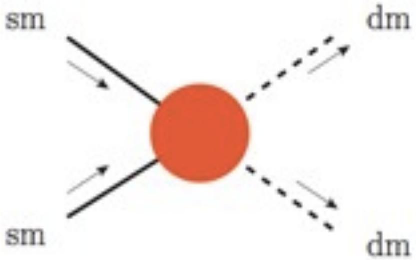

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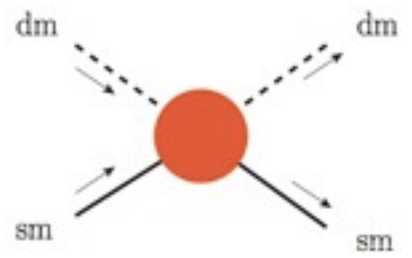

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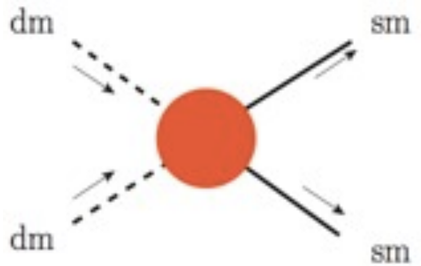

- Part of strong general astrophysics research
- Strong and important constraints on SUSY

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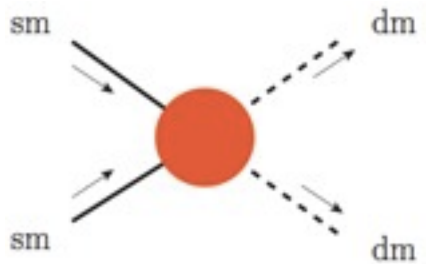

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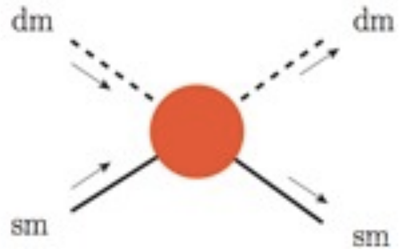

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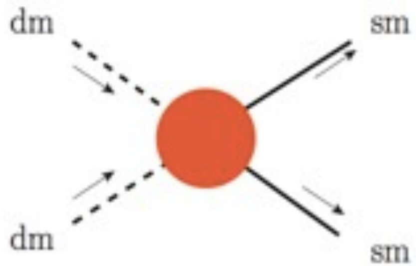

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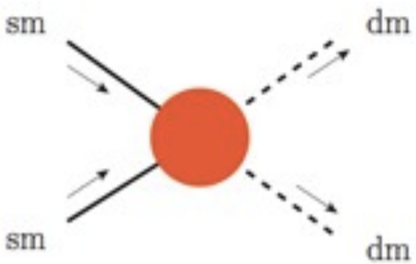

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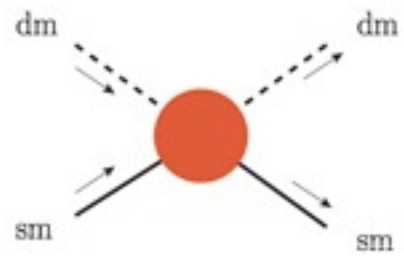

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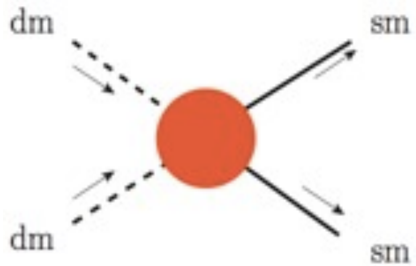

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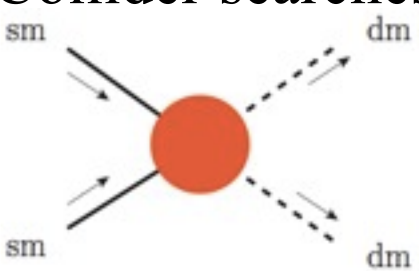

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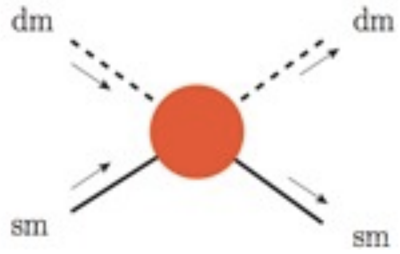

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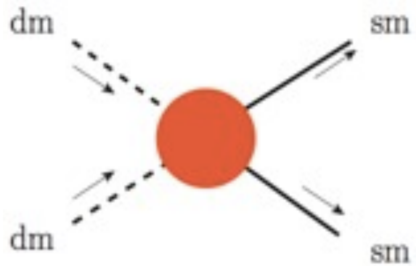

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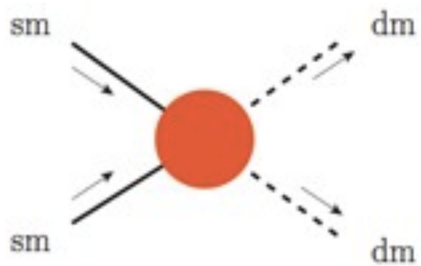

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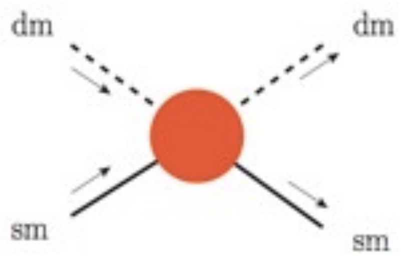

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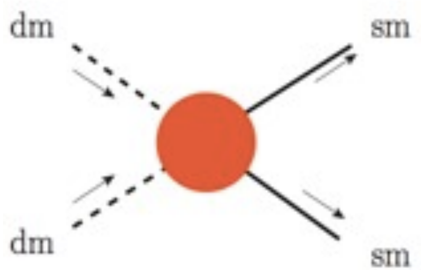

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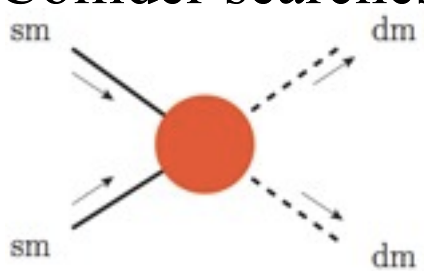

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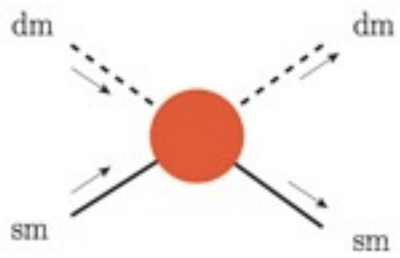

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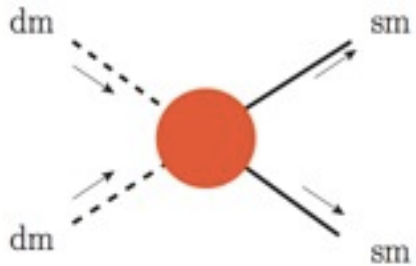

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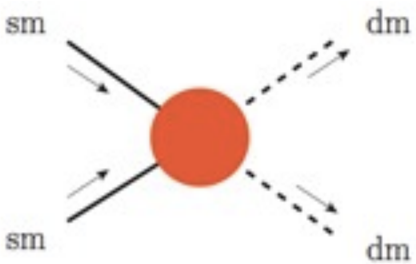

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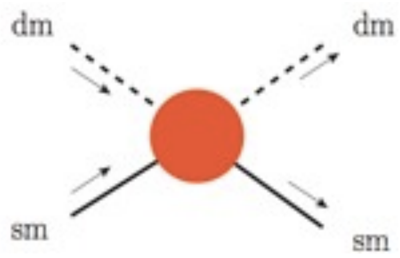

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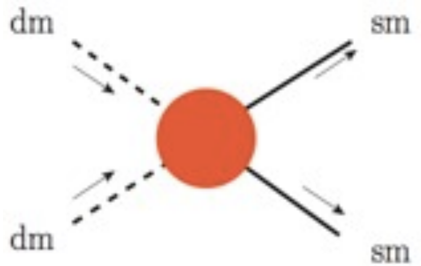

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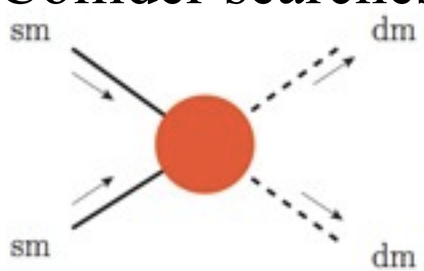

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