The Hunt for Dark Matter
WIMPs and Beyond

Sep 2016

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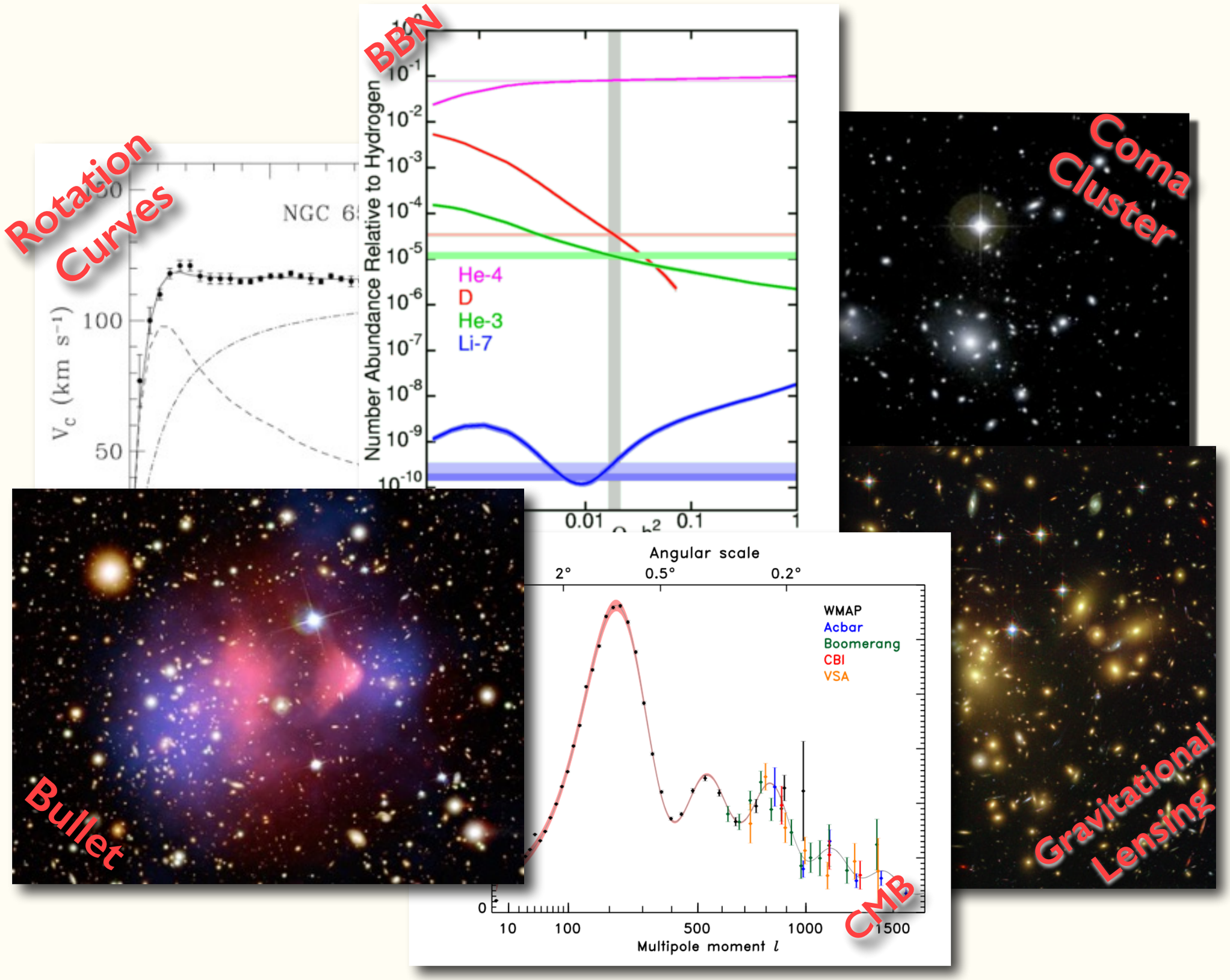
Outline

- WIMPs: Status Report
- Beyond WIMPs: Light Dark Matter
  - The Dark Sector: Self-interactions
  - Production Mechanisms
- Searching for Light Dark Matter
  - Collider and Beam-dump experiments
  - Direct Detection
  - Astrophysical Probes: Searching for Structure

(Gravitational) Evidence for Dark Matter



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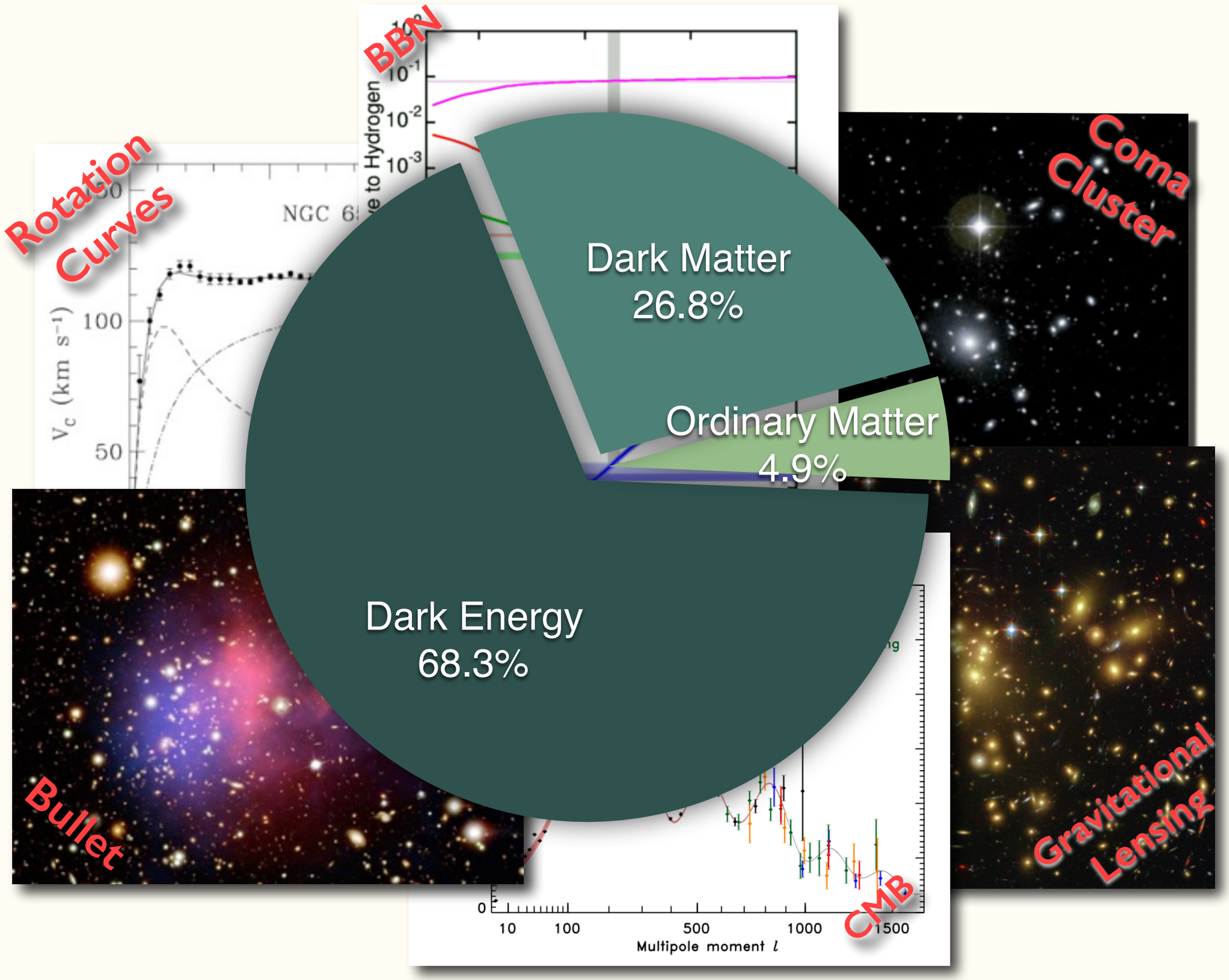
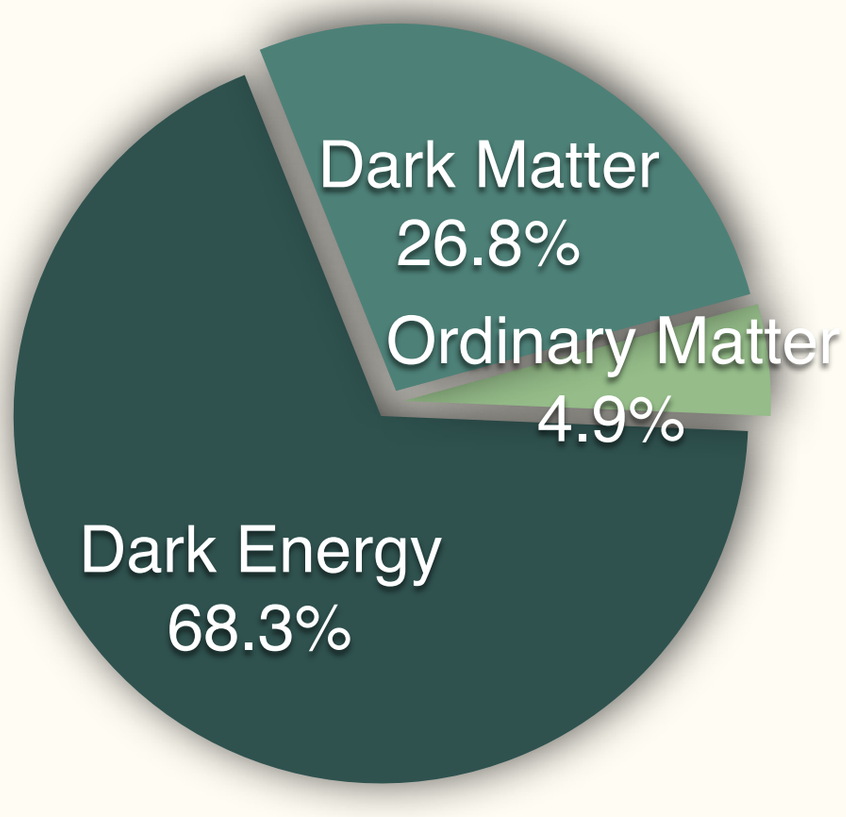


Will We Find Dark Matter?

All experimental signatures of dark matter are *gravitational*.



Q: Why should we see dark matter anywhere else?

A: Because it was produced in the early universe!

How do we usually explain the 85% DM abundance?

Thermal WIMP
(Weakly Interacting Massive Particle).

The Thermal WIMP

- Independent of initial conditions.
- Requirement:
  - DM was in thermal equilibrium in early universe.
  - DM stable on cosmological timescales.

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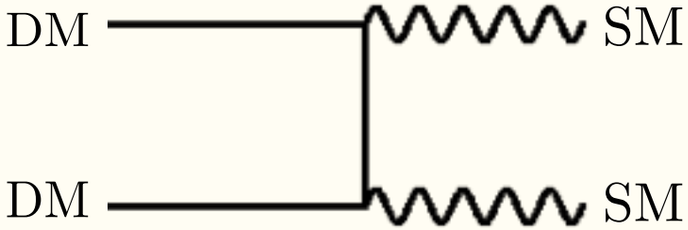

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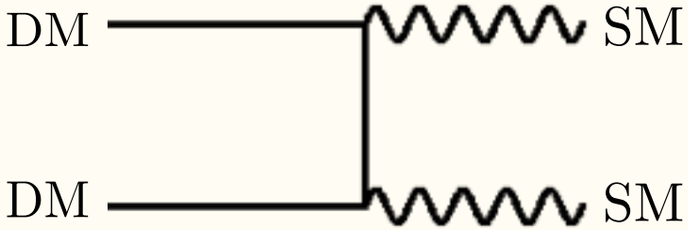

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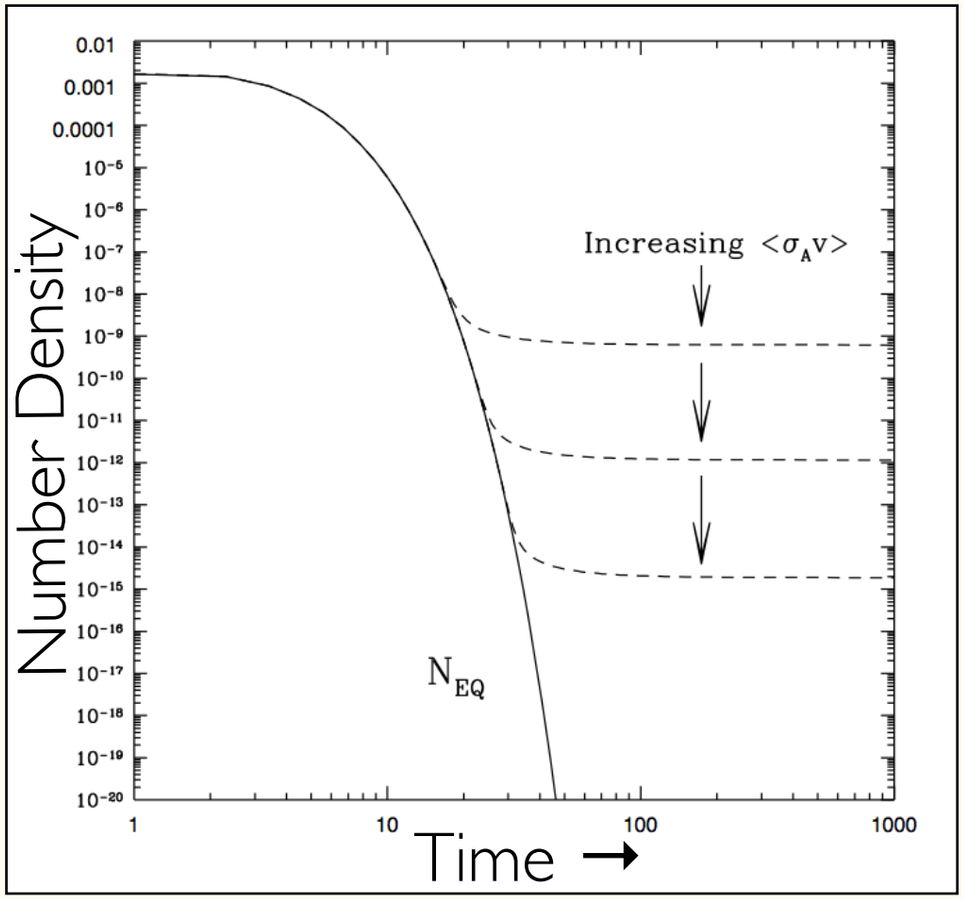

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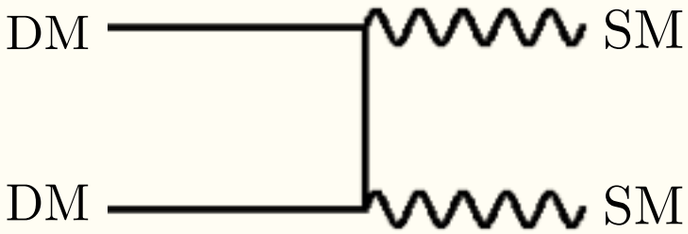

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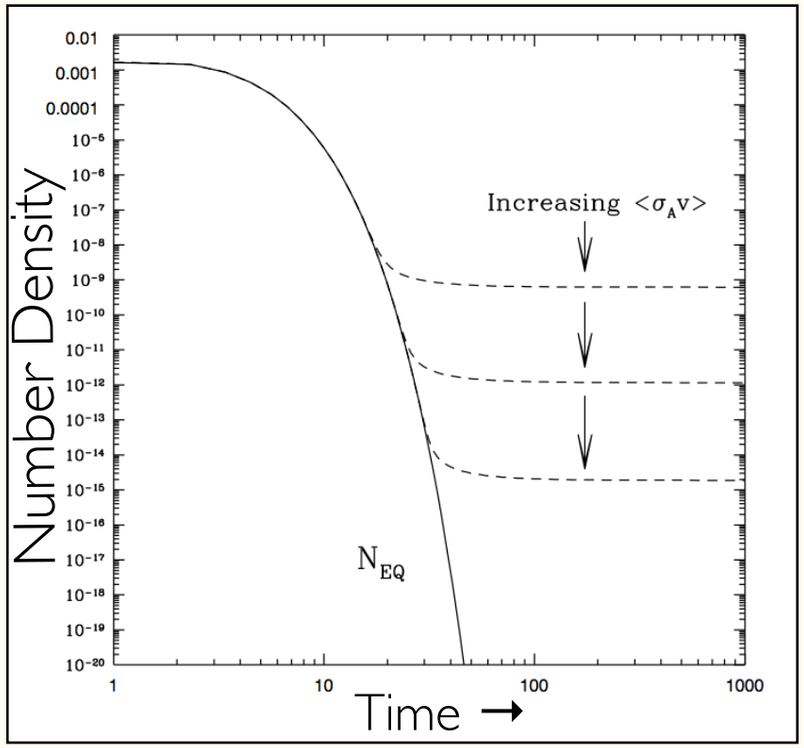
- Single parameter: $\langle \sigma v \rangle$
- A simple analysis shows,

$$\langle \sigma v \rangle \sim 2 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{sec}$$



- For standard annihilation cross-section:

$$\langle \sigma v \rangle \simeq \frac{g^4}{m_{\mathrm{DM}}^2} \Longrightarrow m_{\mathrm{DM}} \simeq 100\,\mathrm{GeV} - 1\,\mathrm{TeV}$$

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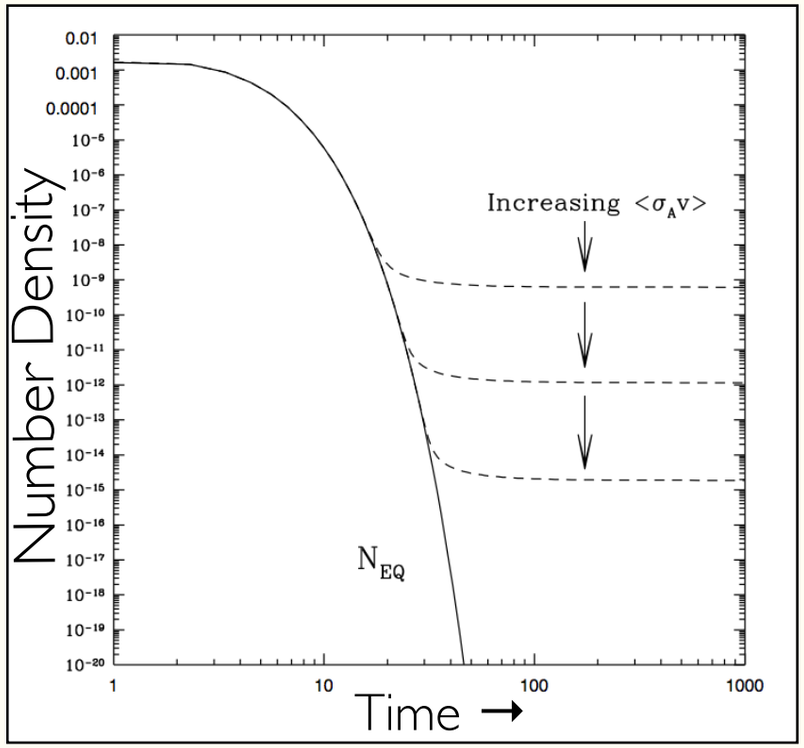

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Same mass-scale we are now probing at the LHC

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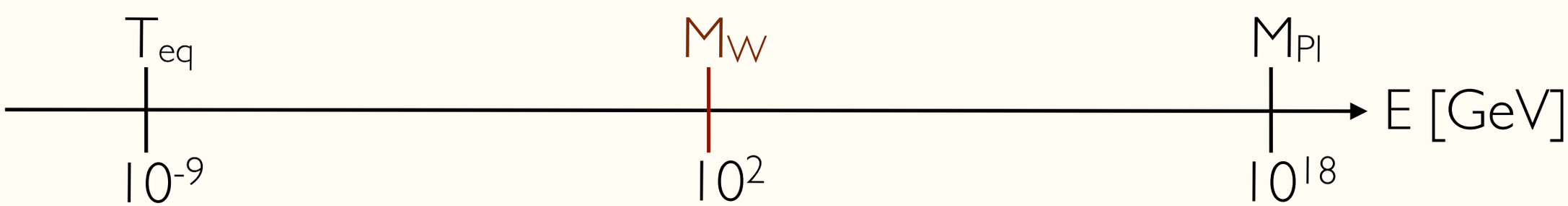


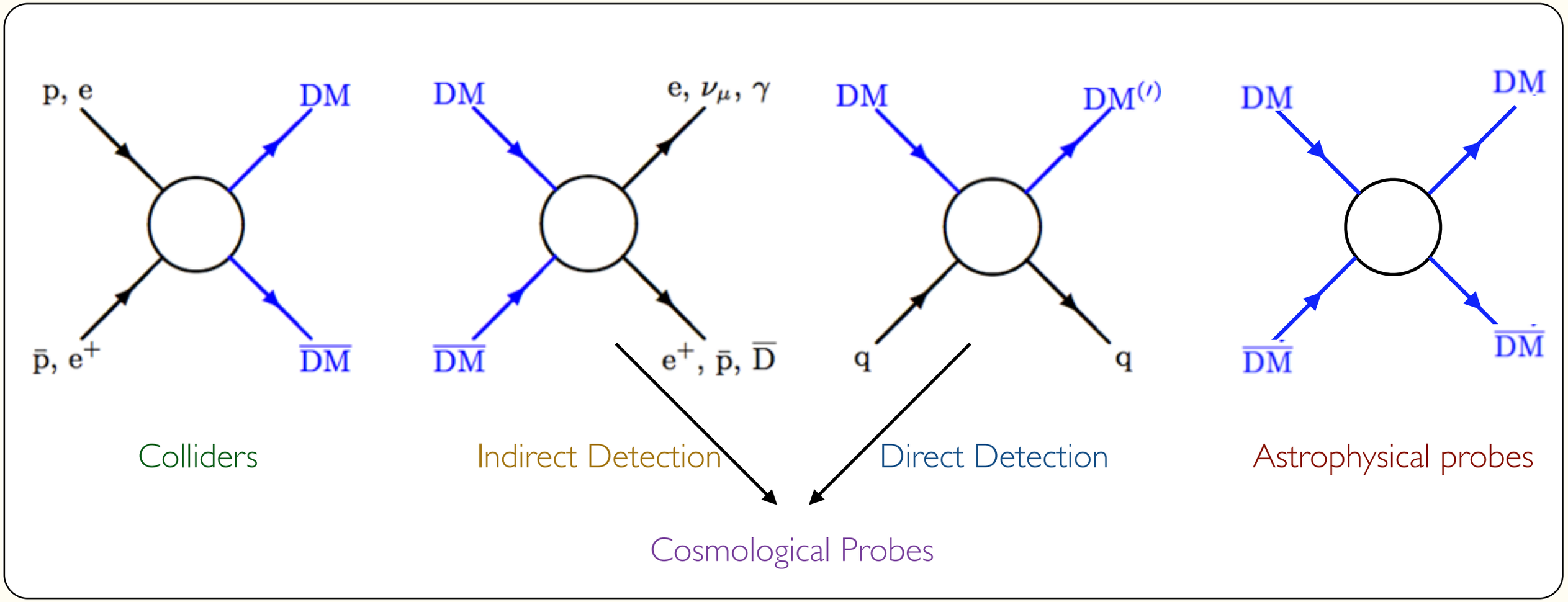
This is the WIMP Miracle

WIMPs

So where do we stand?

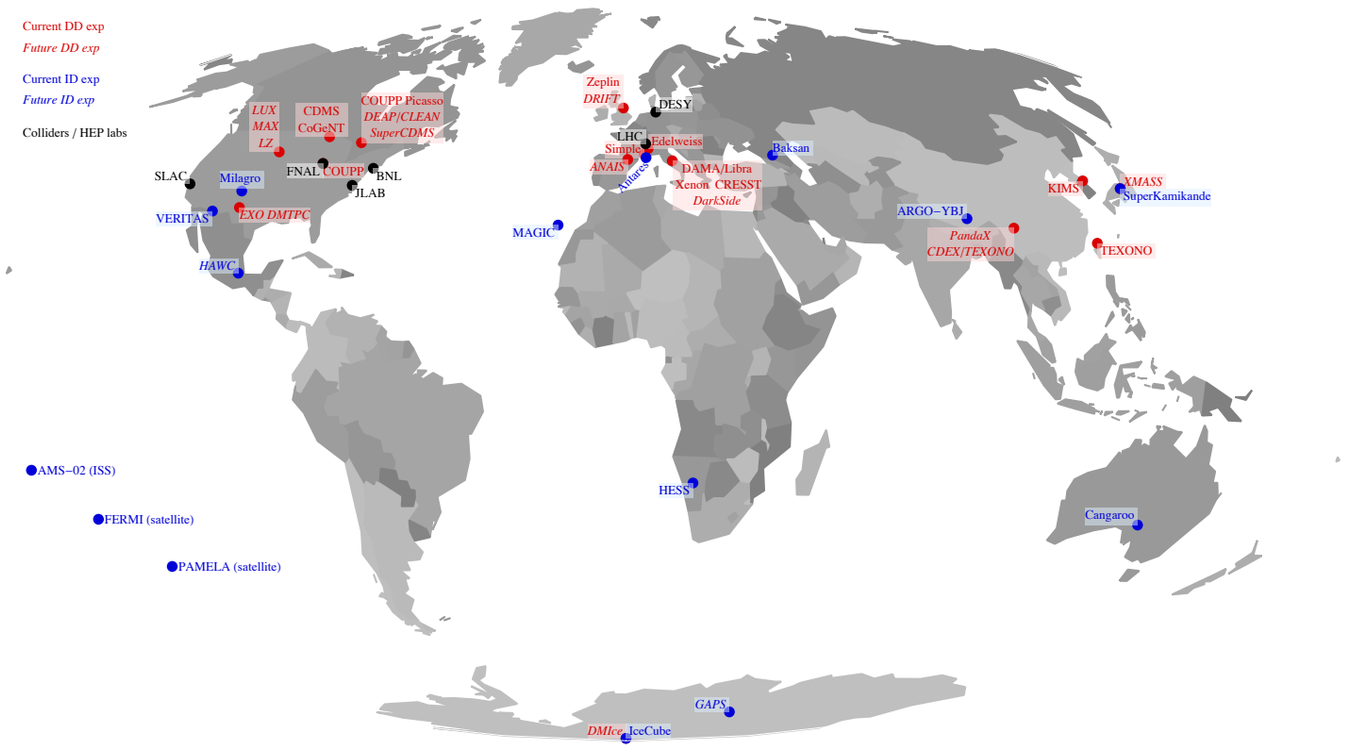
Several ways to search for DM

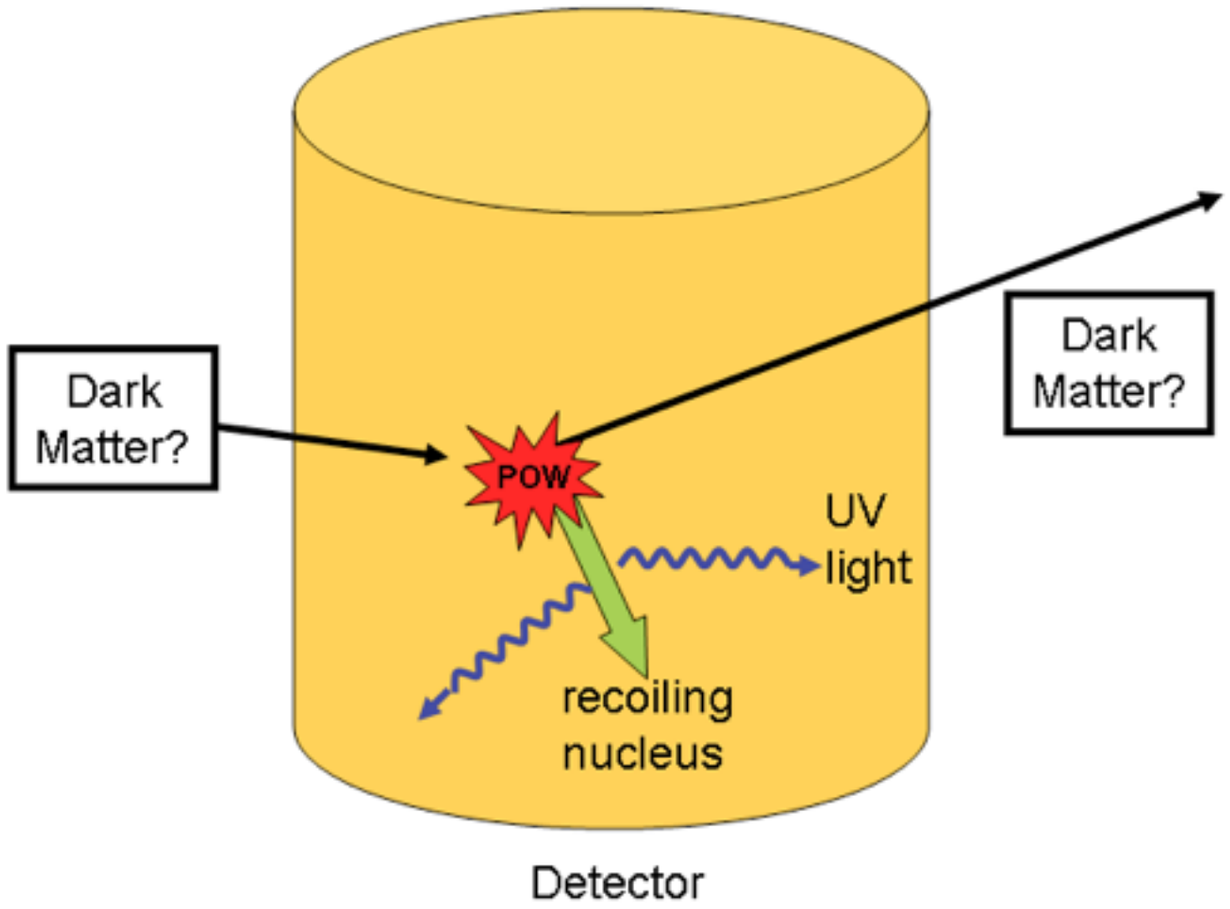
Several ways to detect DM:



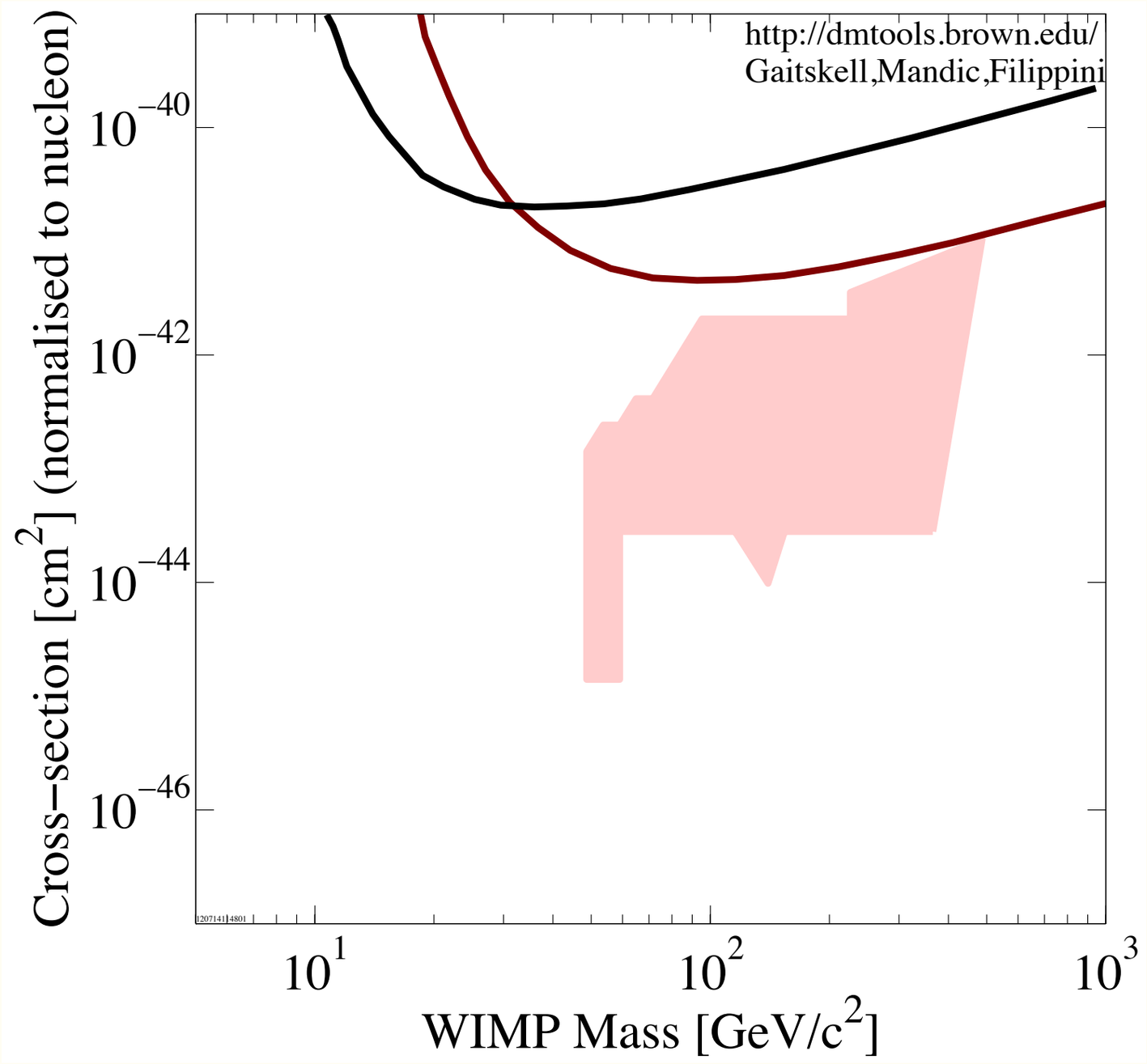
Direct Detection

Direct Detection: Basics

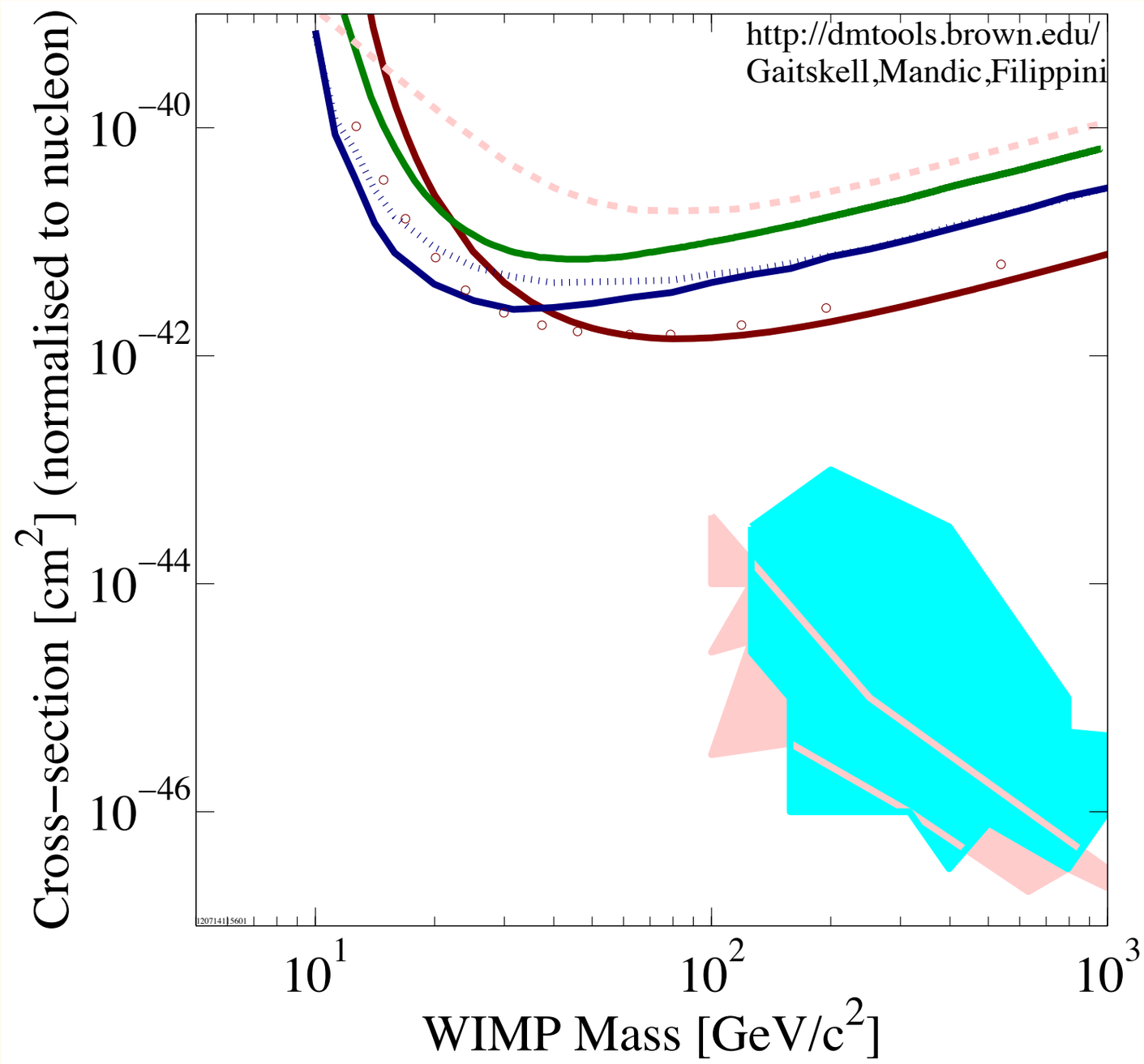




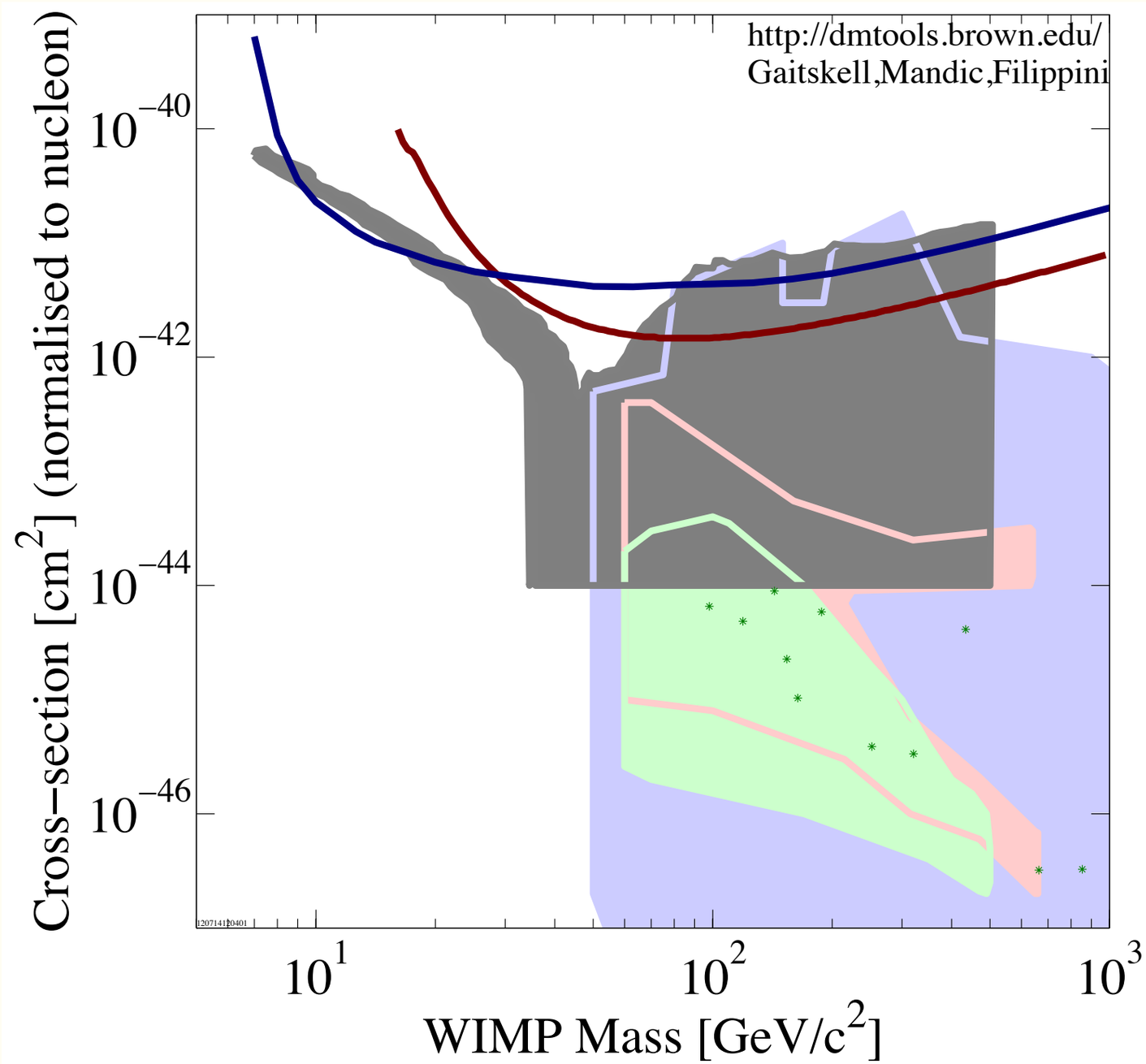
Direct Detection Limits: 2001



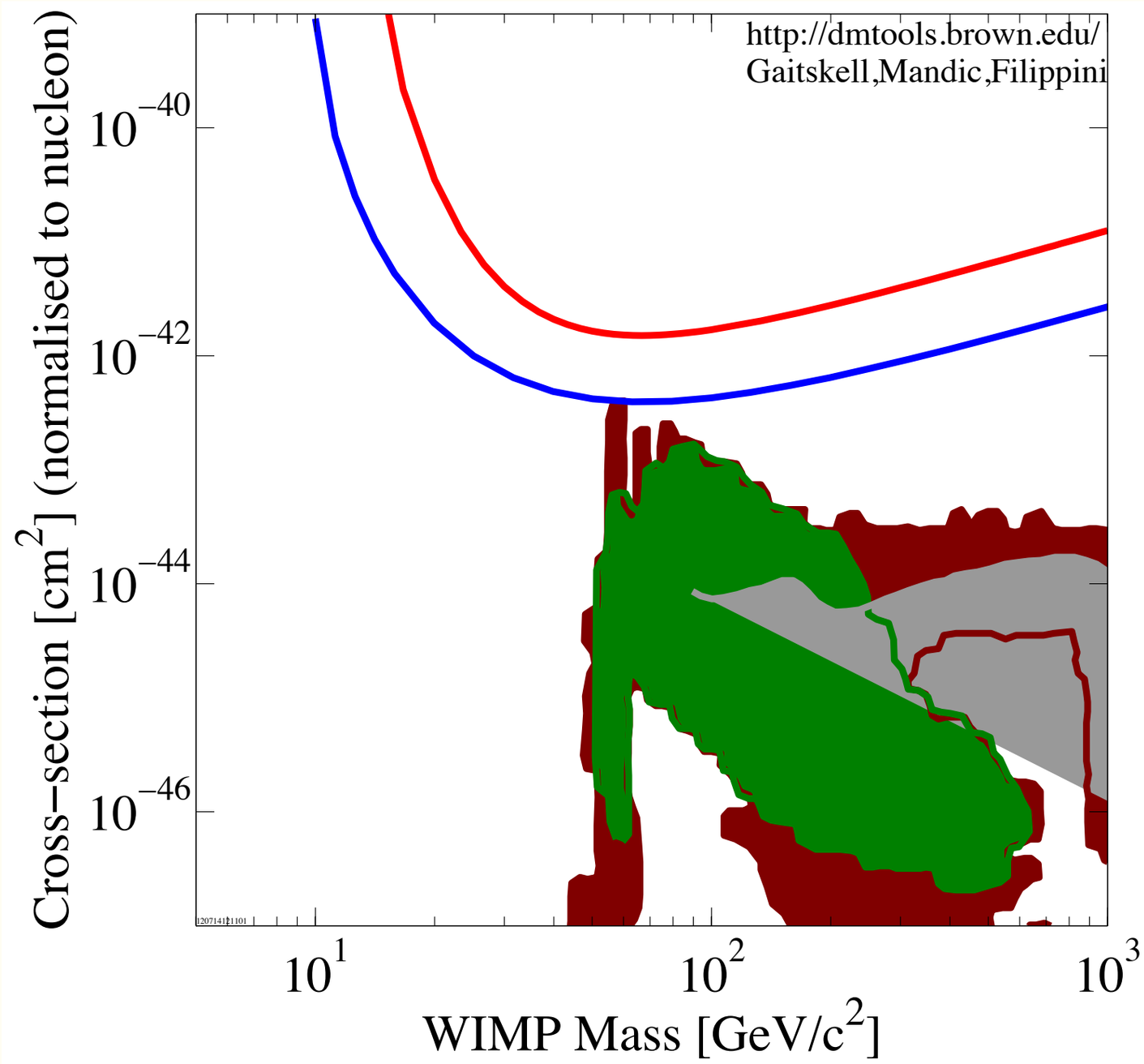
Direct Detection Limits: 2002



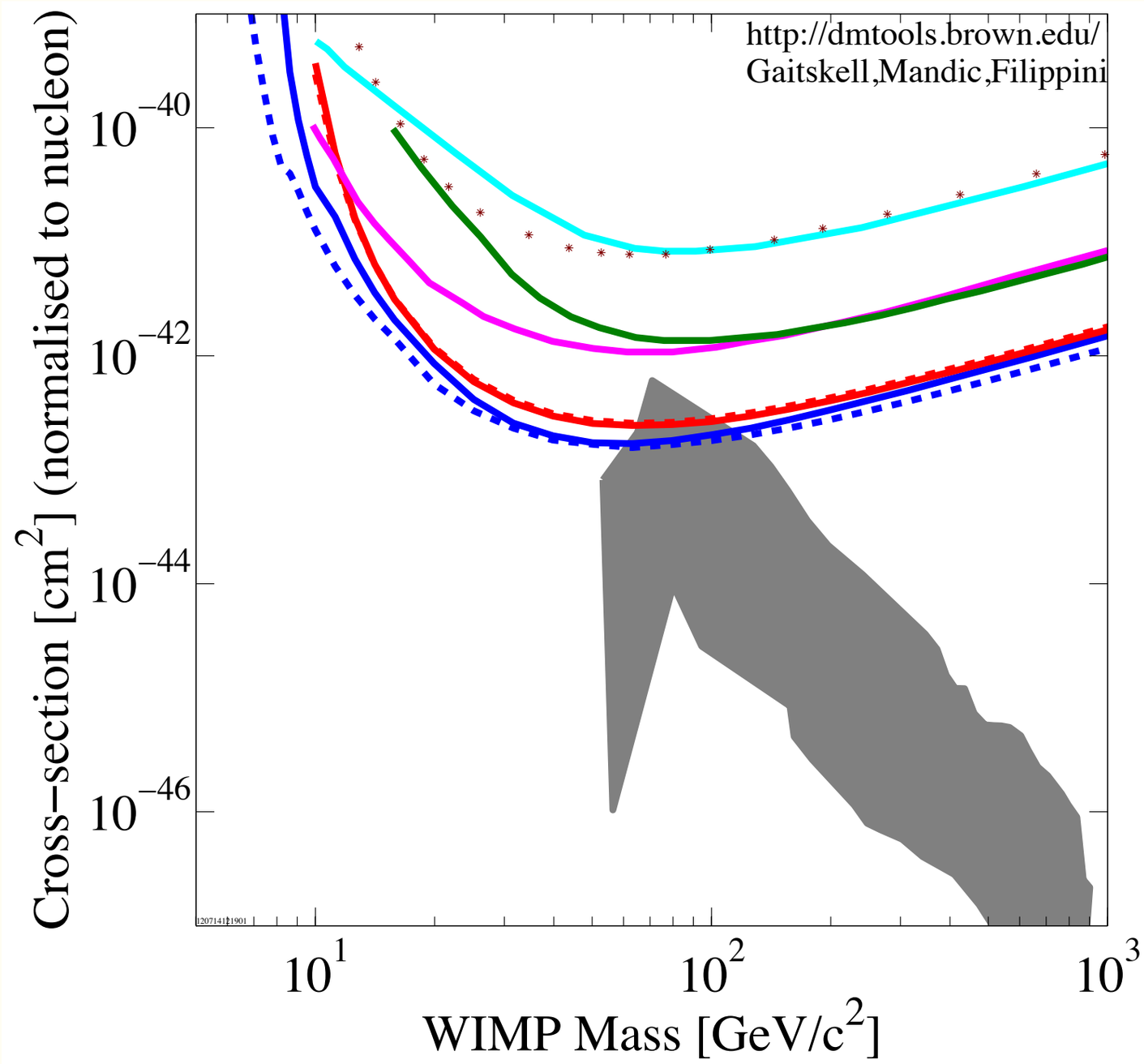
Direct Detection Limits: 2003



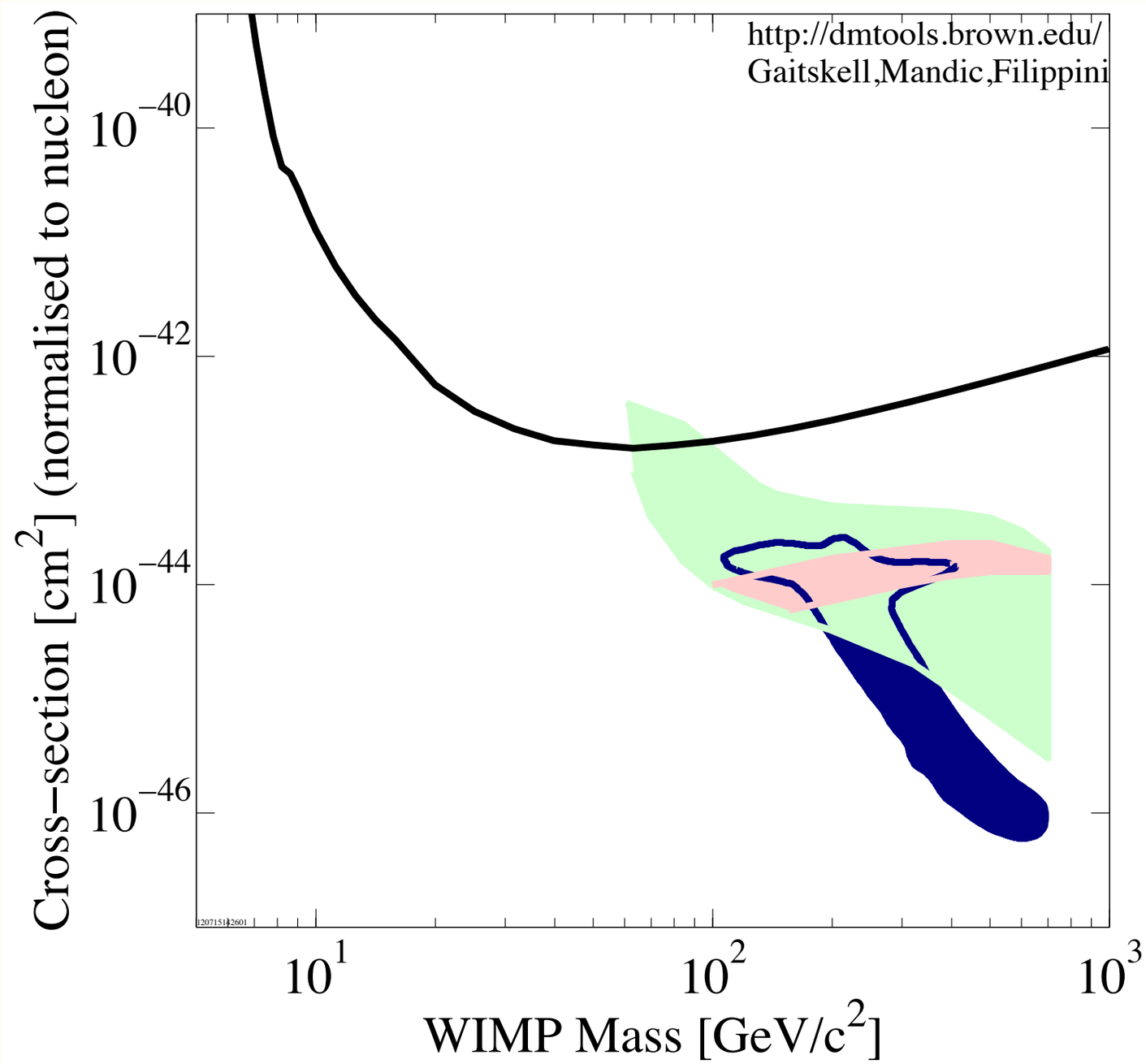
Direct Detection Limits: 2004



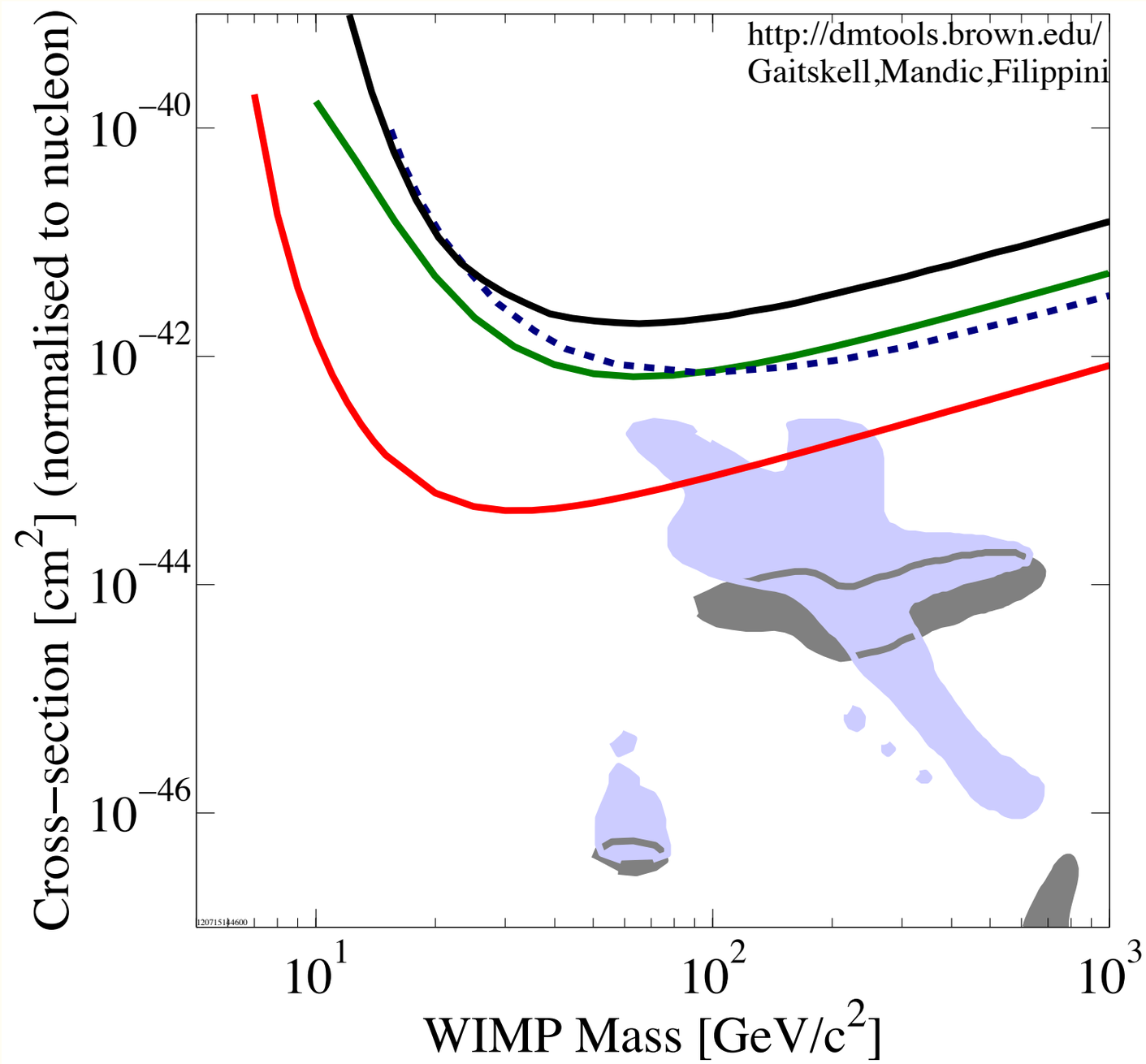
Direct Detection Limits: 2005



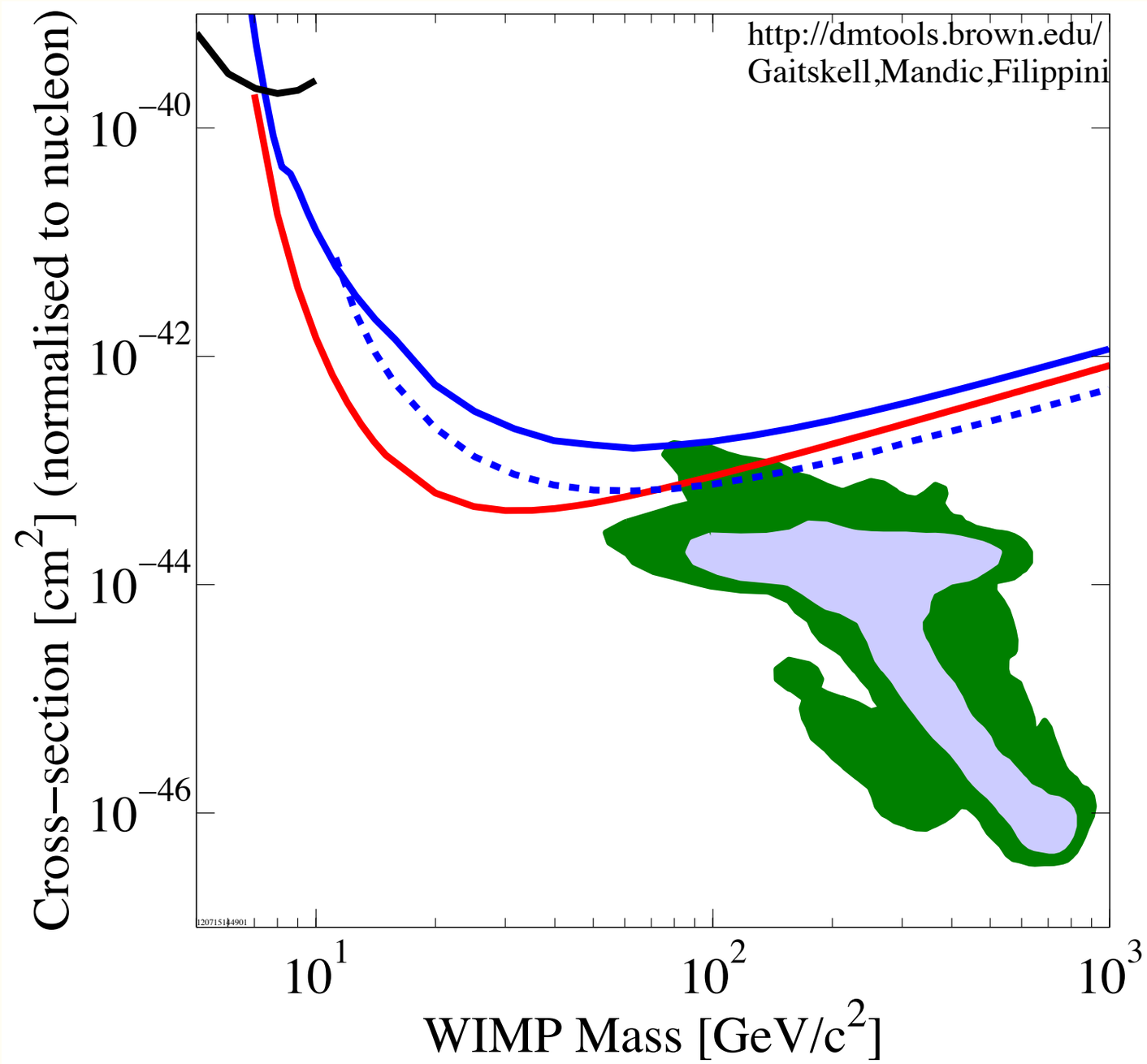
Direct Detection Limits: 2006



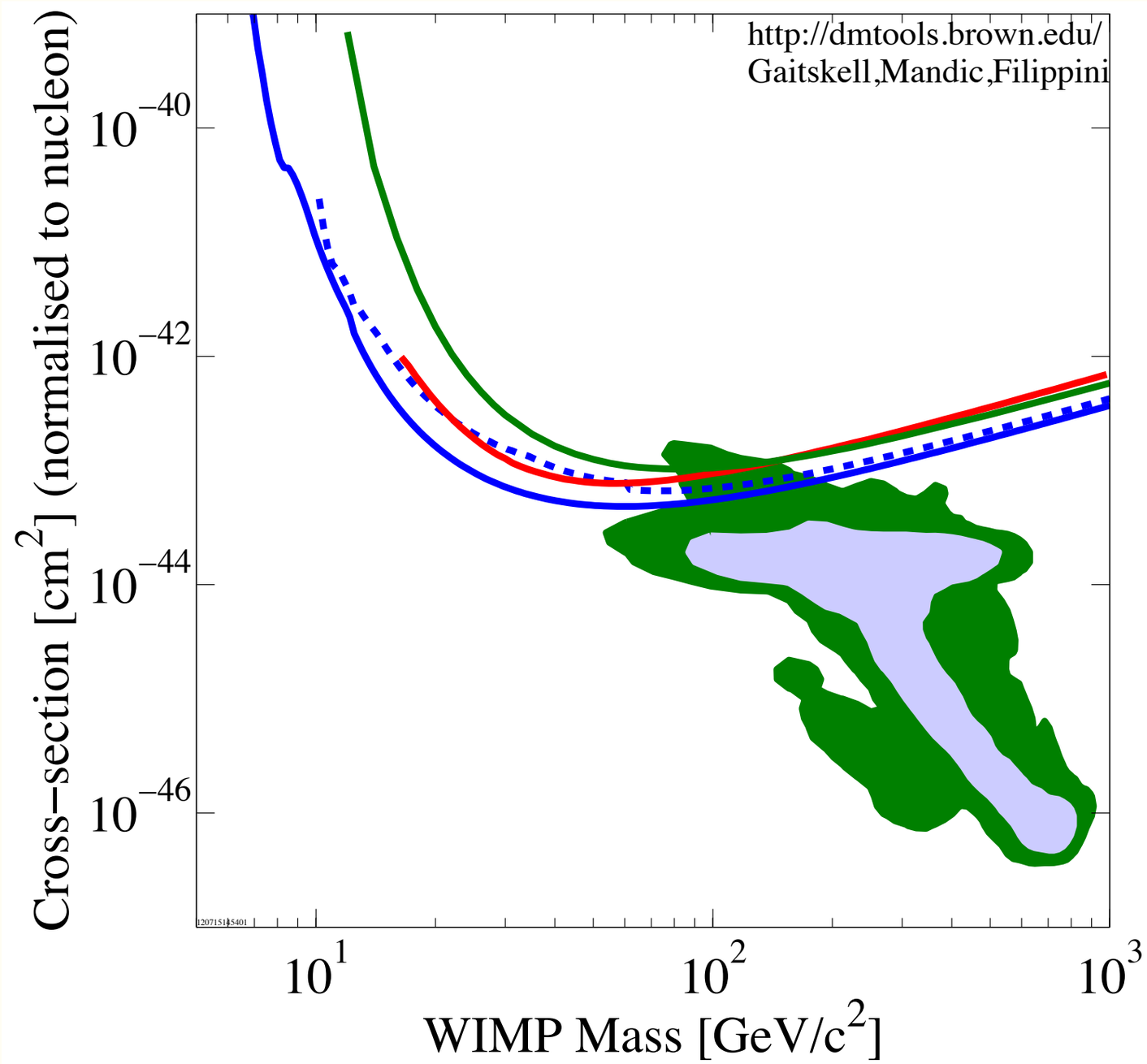
Direct Detection Limits: 2007



Direct Detection Limits: 2008



Direct Detection Limits: 2009



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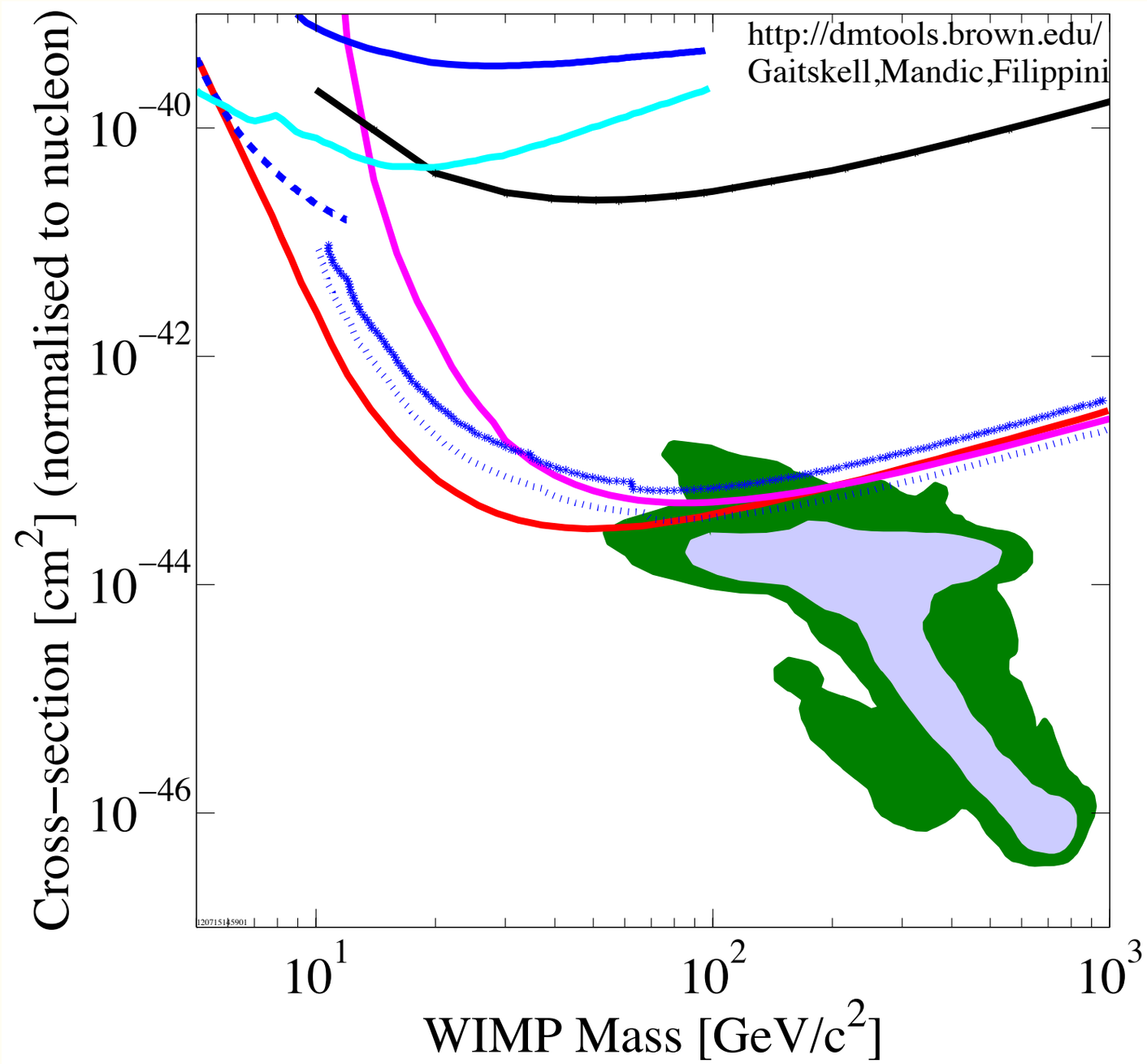
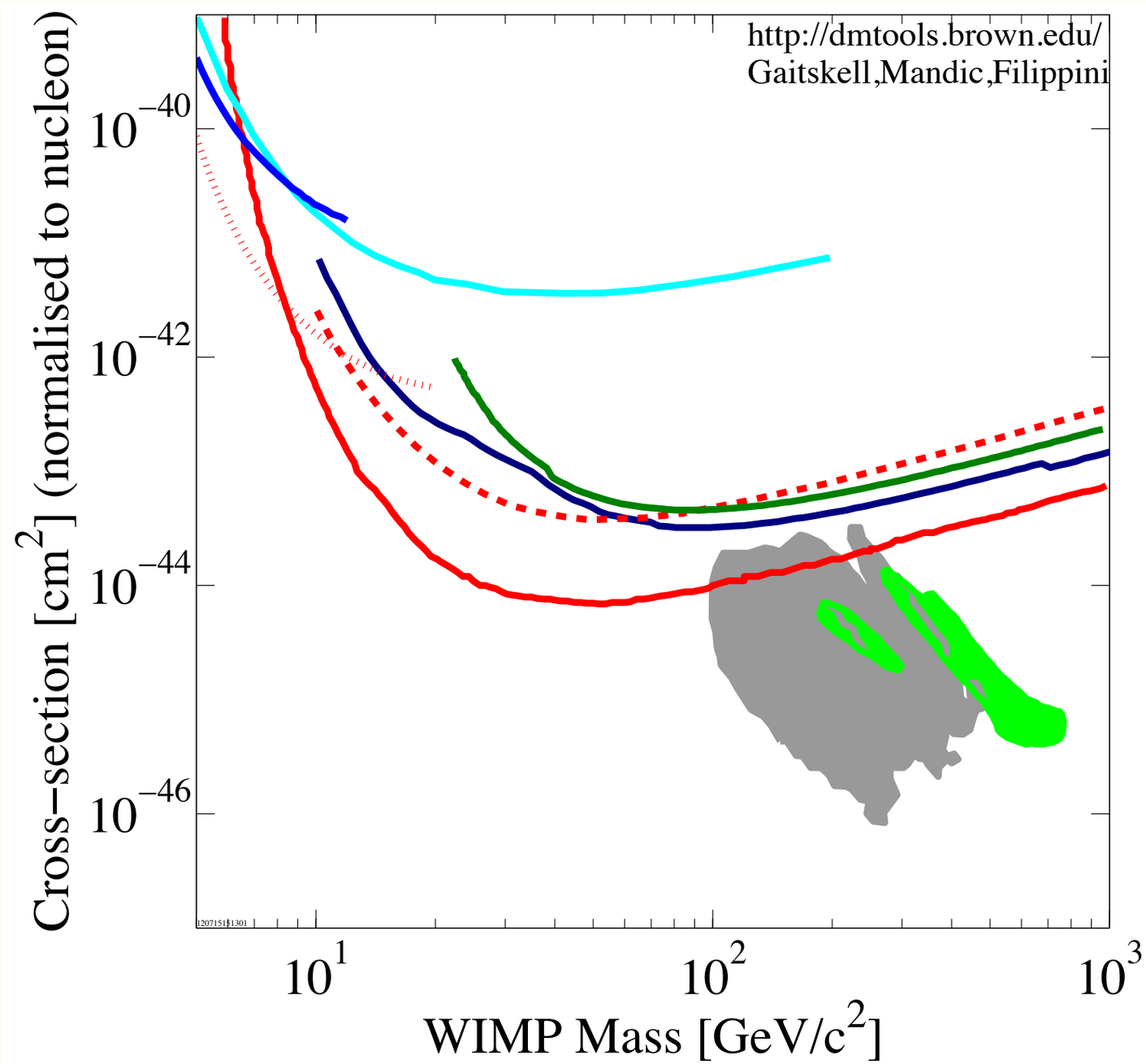


Direct Detection Limits: 2011



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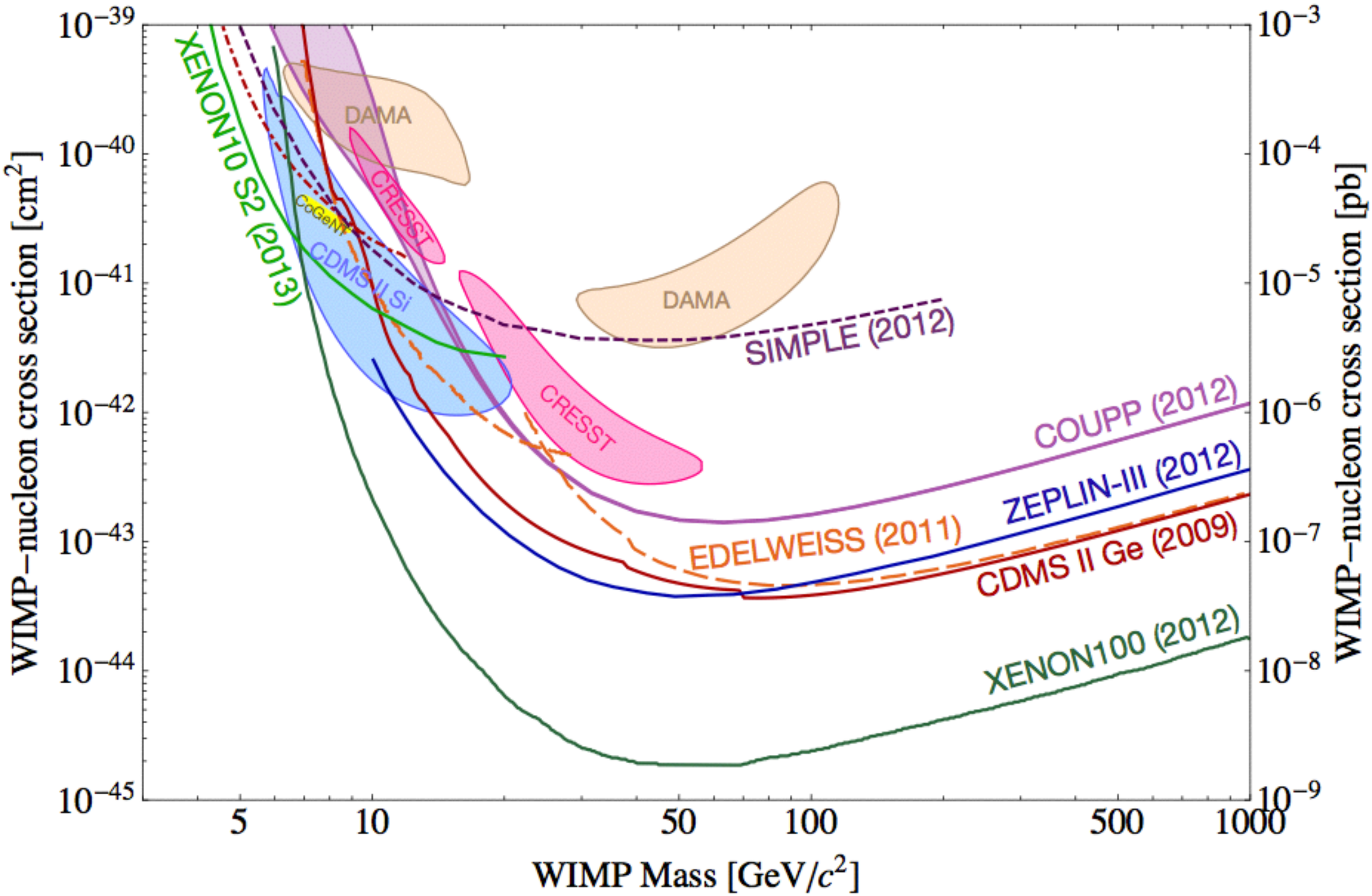

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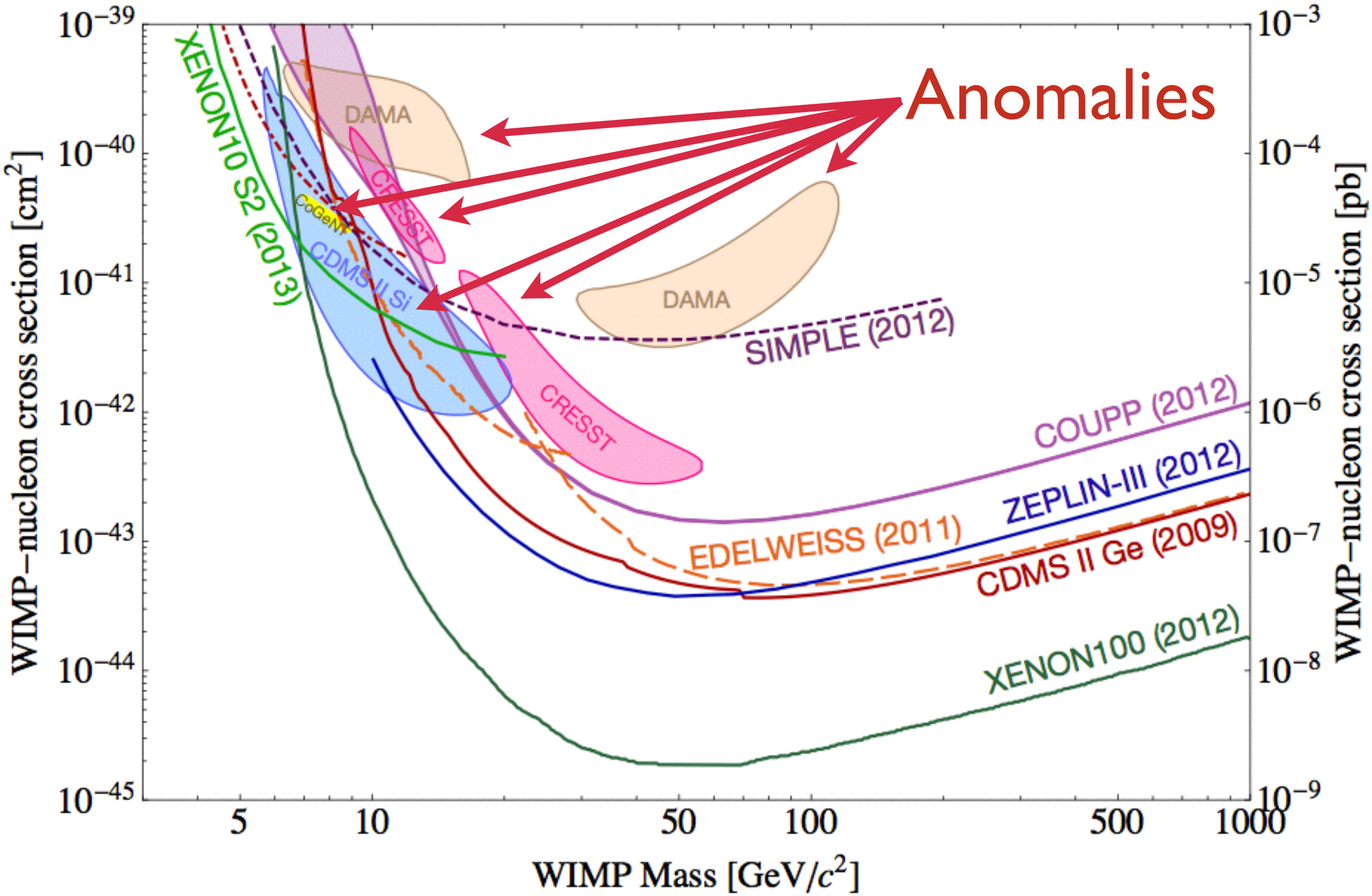

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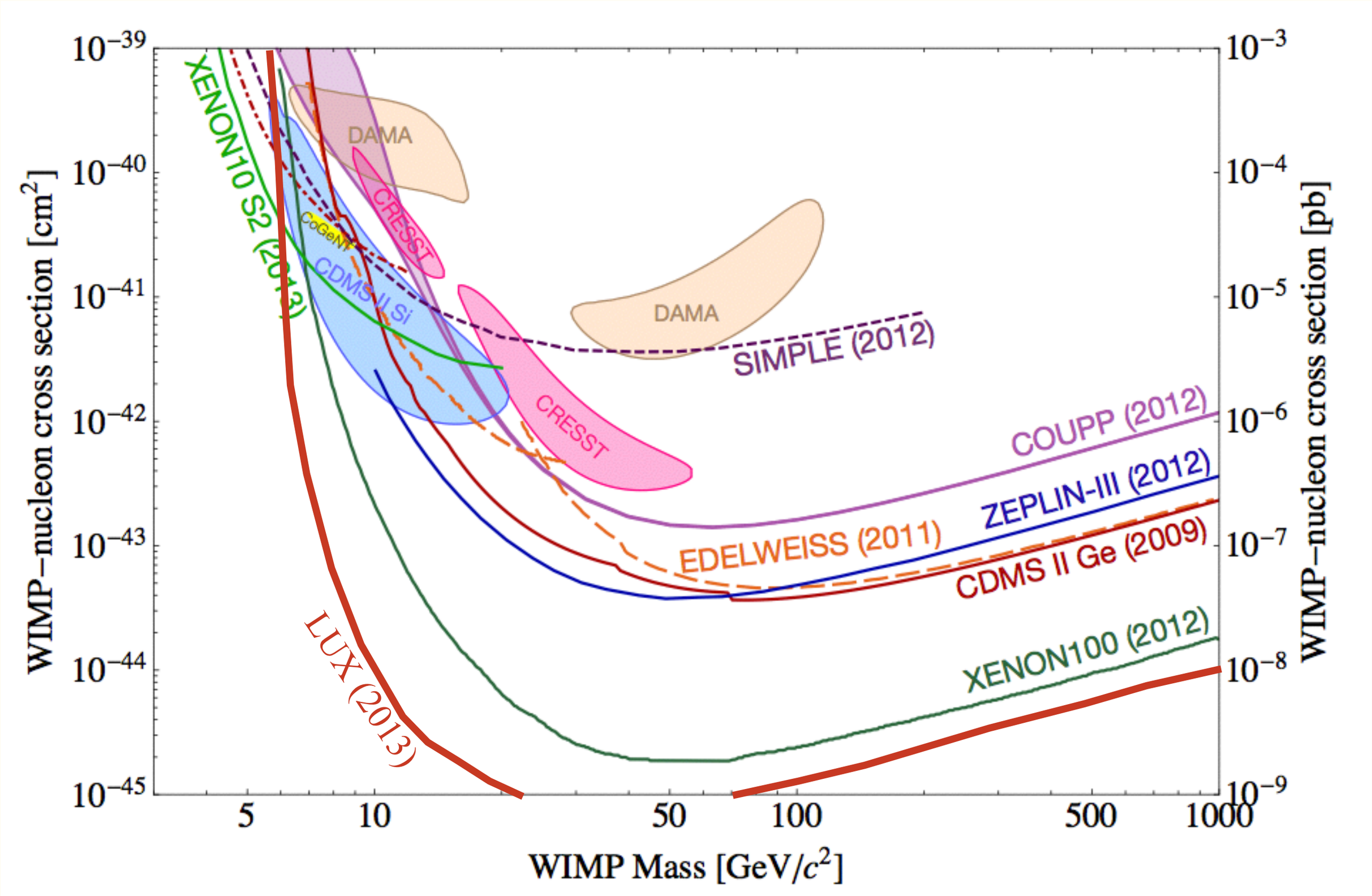
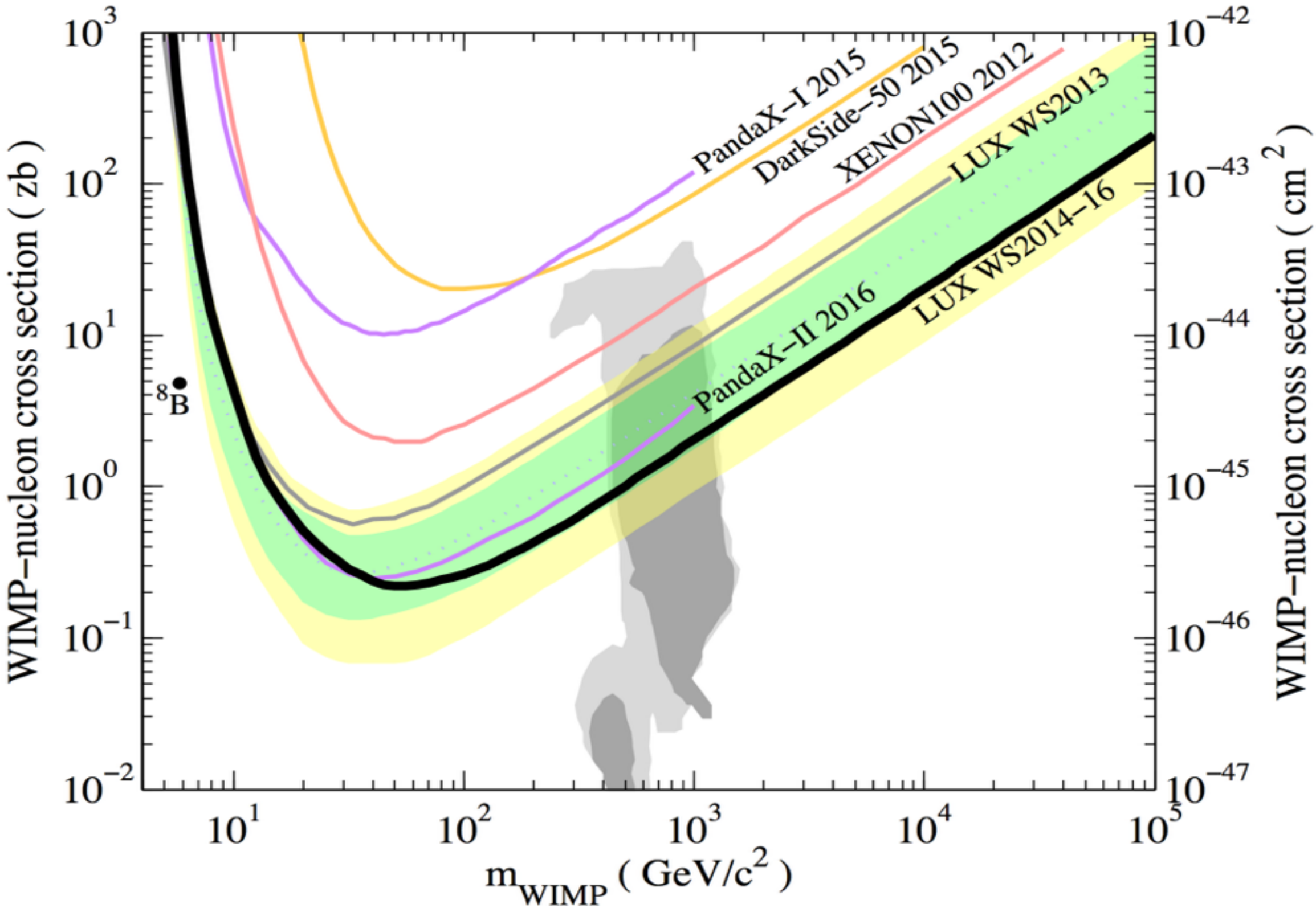
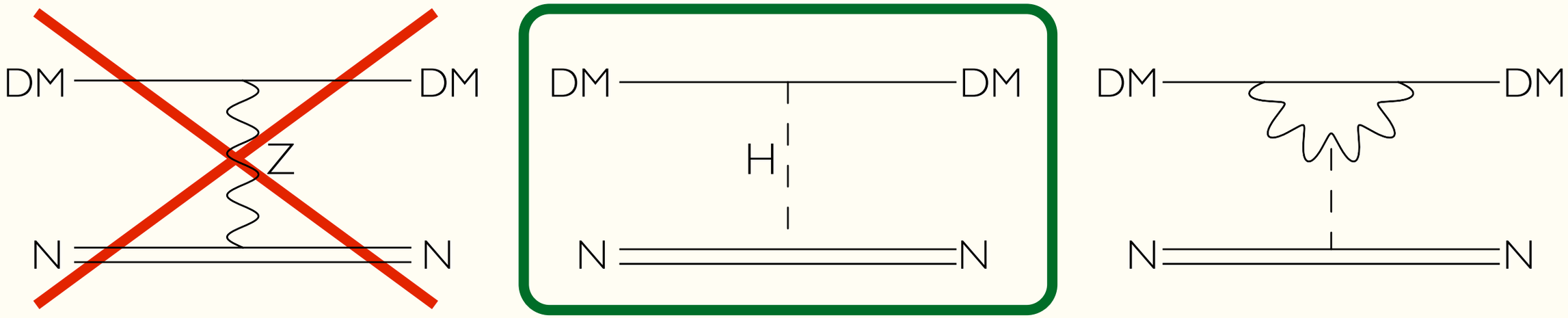


Direct Detection Limits: Today



Direct Detection: Implications



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XENON100
LUX
CDMS
...

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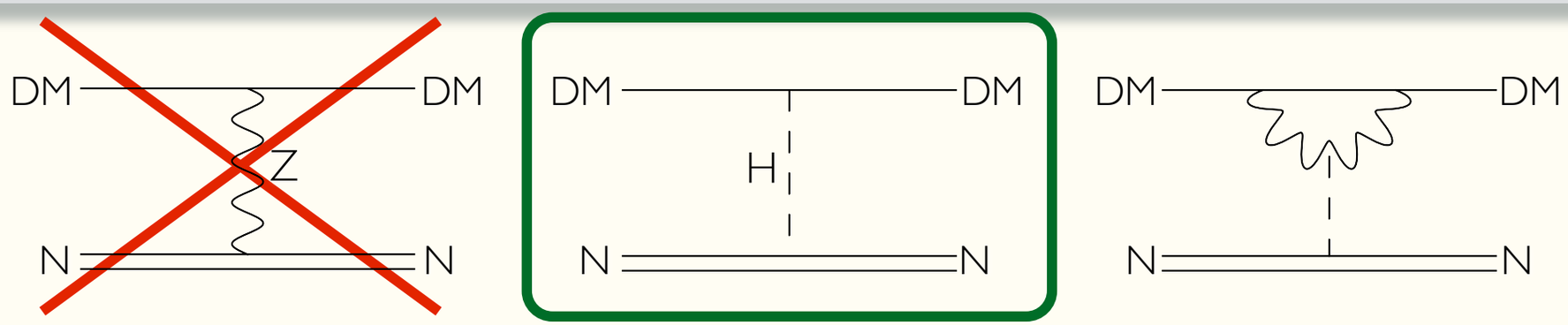

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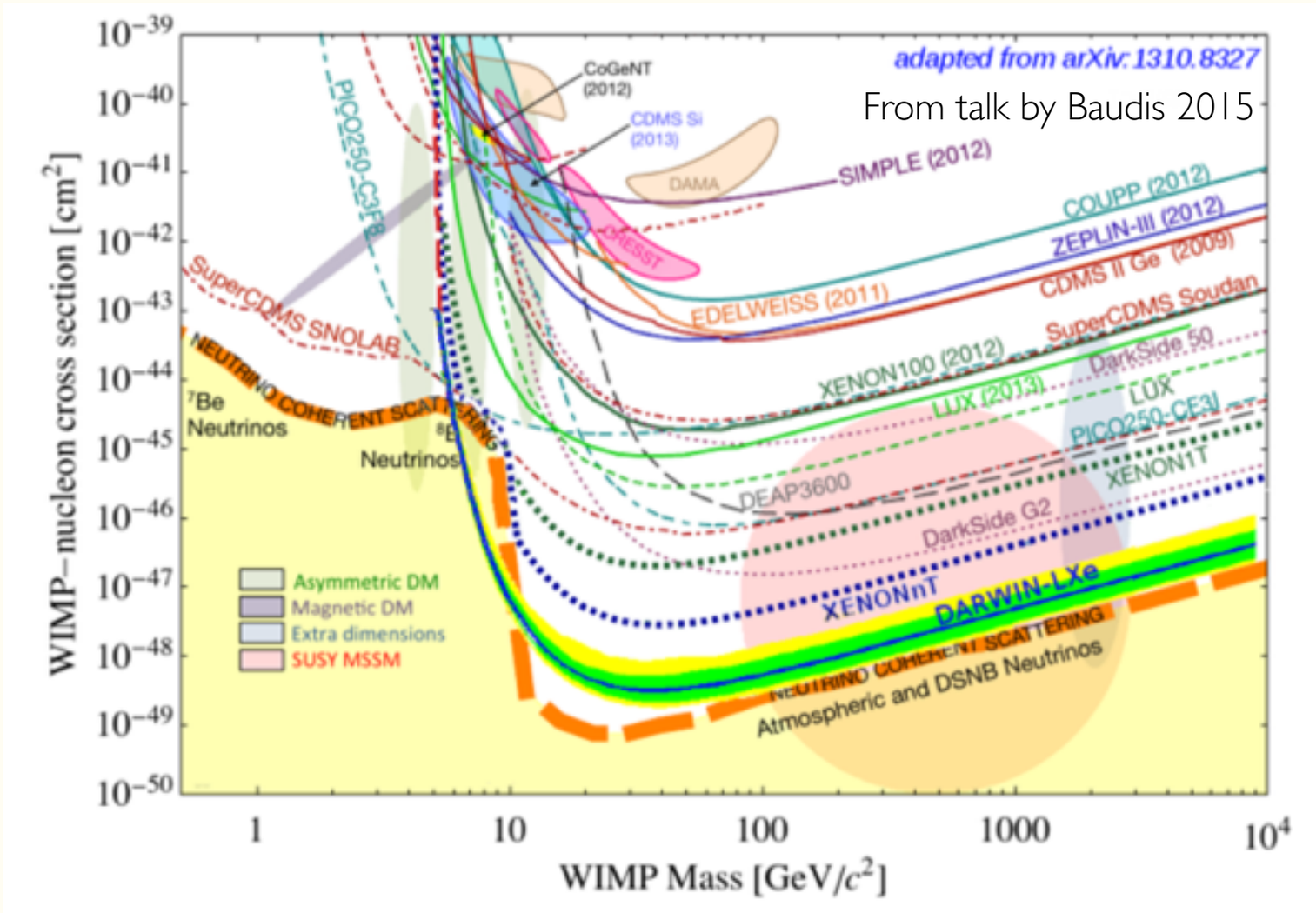
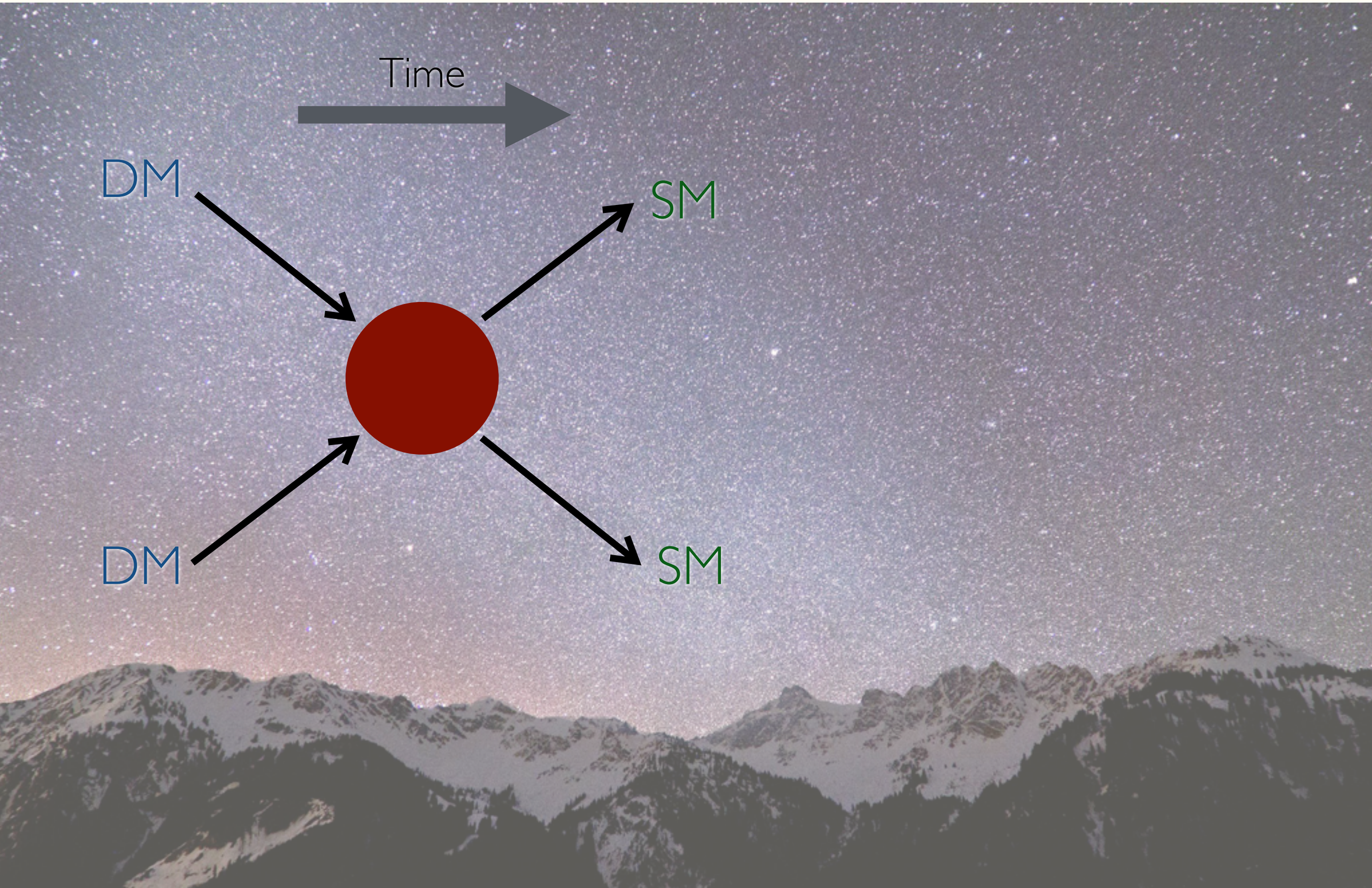


Current technologies will only be able to reach $\sim 10^{-48}\ \mathrm{cm}^2$ due to irreducible backgrounds

Indirect Detection

Indirect Detection: Basics



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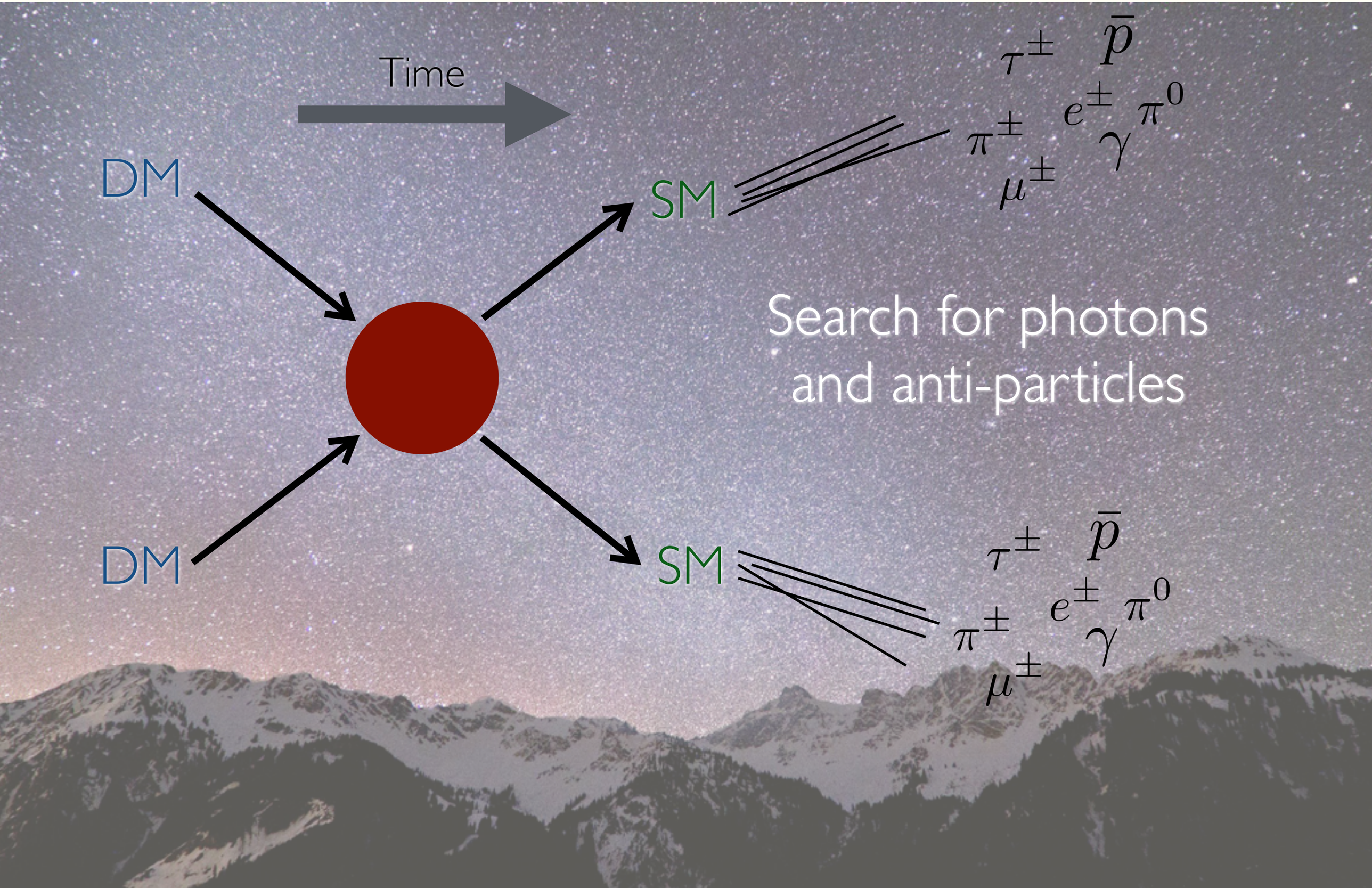

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Numerous measurements which place strong constraints on theory.

Few anomalies. Most notable:

- Galactic-center excess
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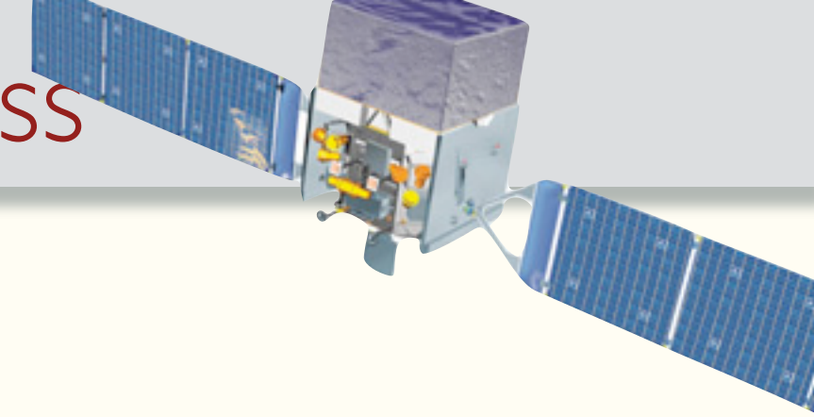
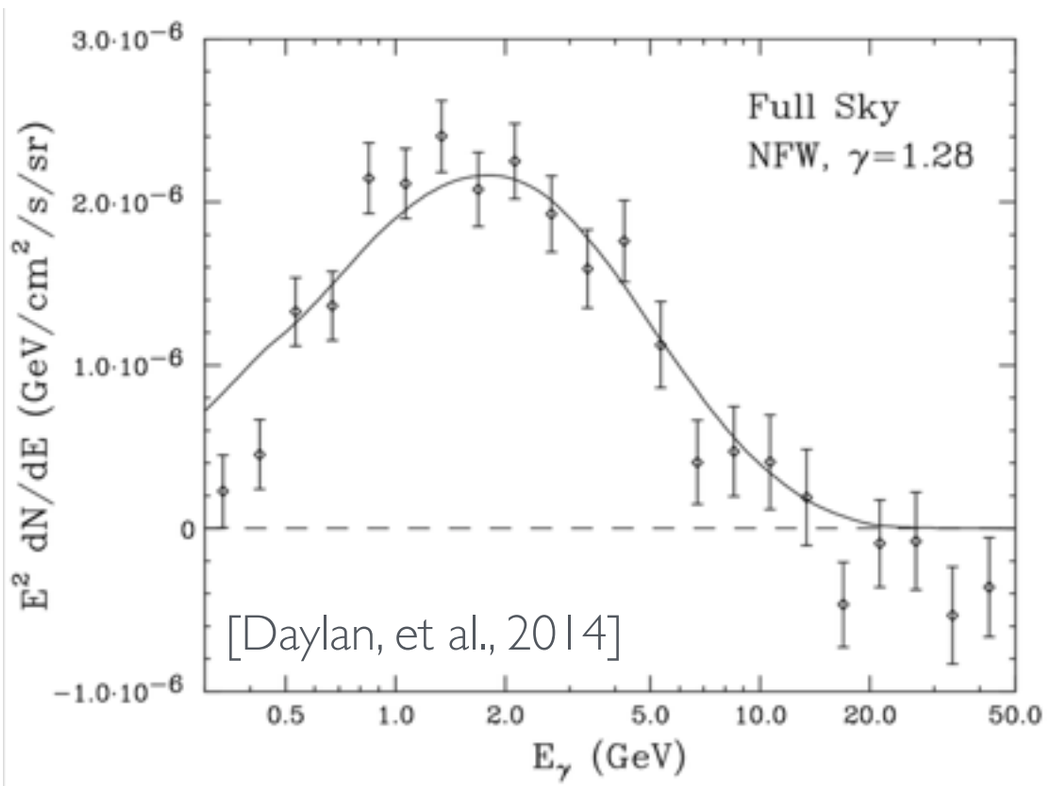
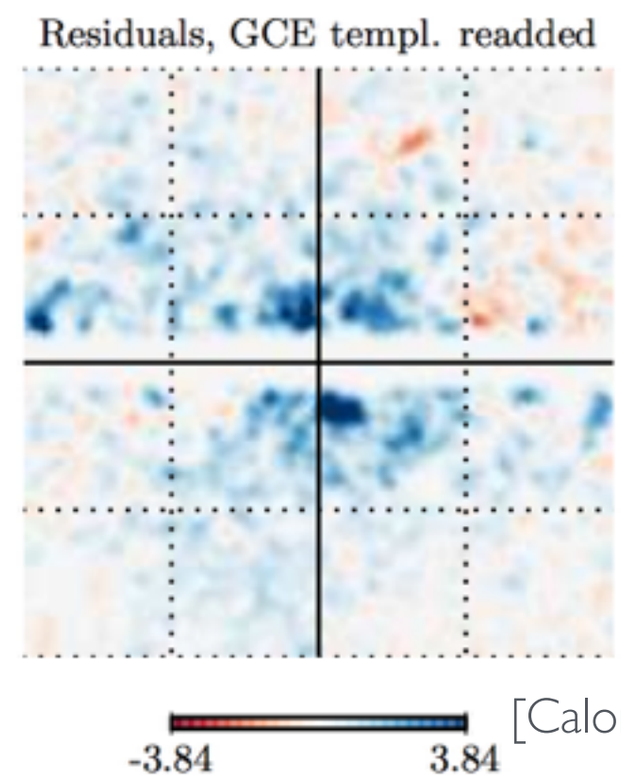


- Discovered with Fermi data.
- First found in Galactic Center, later at higher altitudes.

[Goodenough,Hooper, 2009,2010; Hooper, Linden 2011; Abazajian,Kaplinghat, 2012; Macias, Gordon, 2013; Hooper, Slatyer, 2013; Huang,Urbano,Xue, 2013; Abazajian et al. 2014; Daylan, et al., 2014; Zhou, et al. 2014; Calore, et al. 2014]

- Confirmed by Fermi collaboration.





[Calore, et al. 2015]

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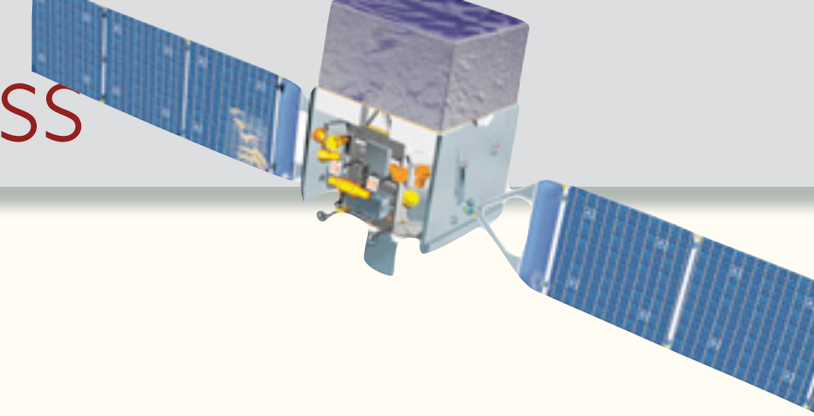
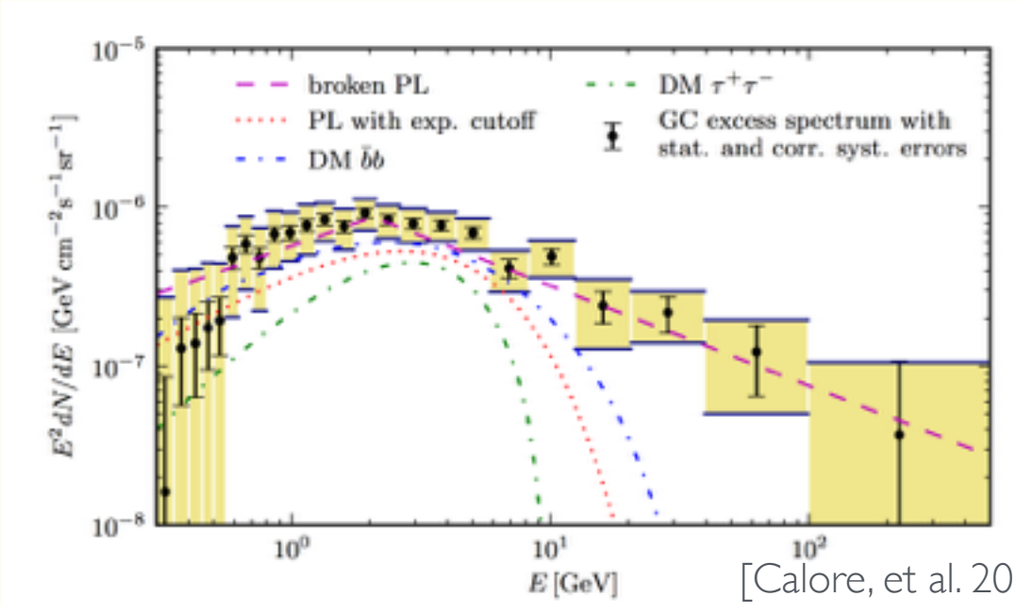


What can it be?

- Excess is highly statistically significant and robust under systematic uncertainties.
- However, modeling of the Galactic diffuse emission is very uncertain in center.



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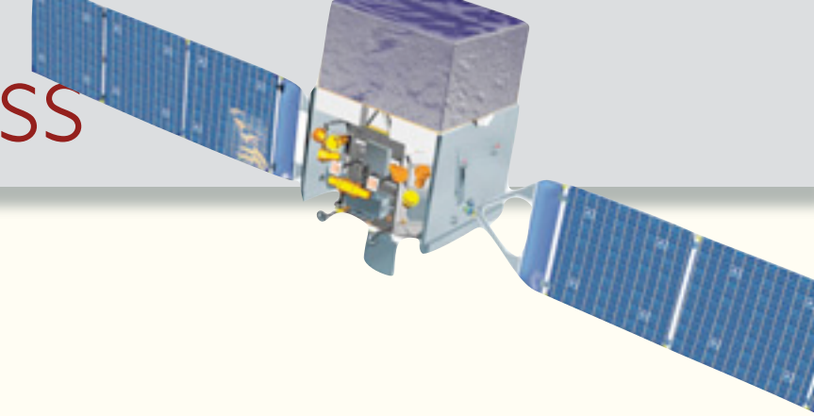

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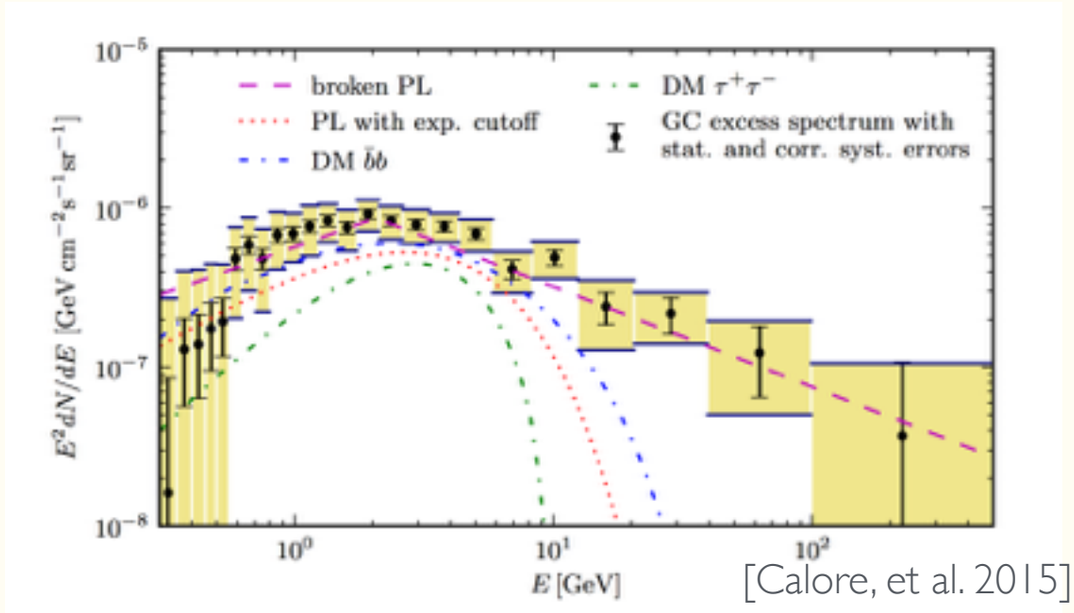

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  - Unresolved millisecond pulsars or other point sources.

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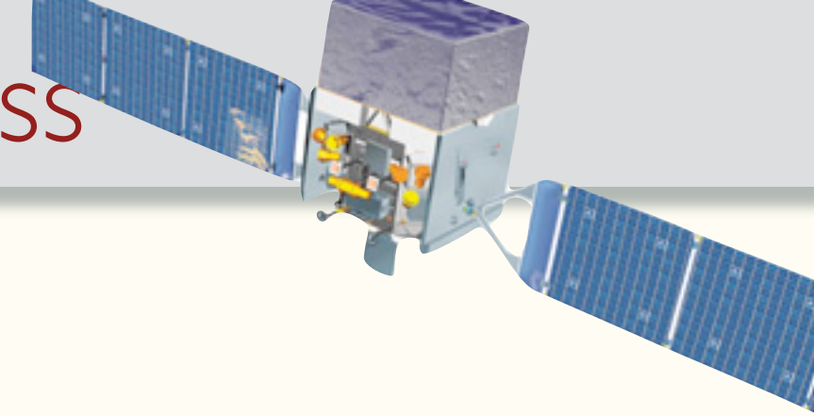

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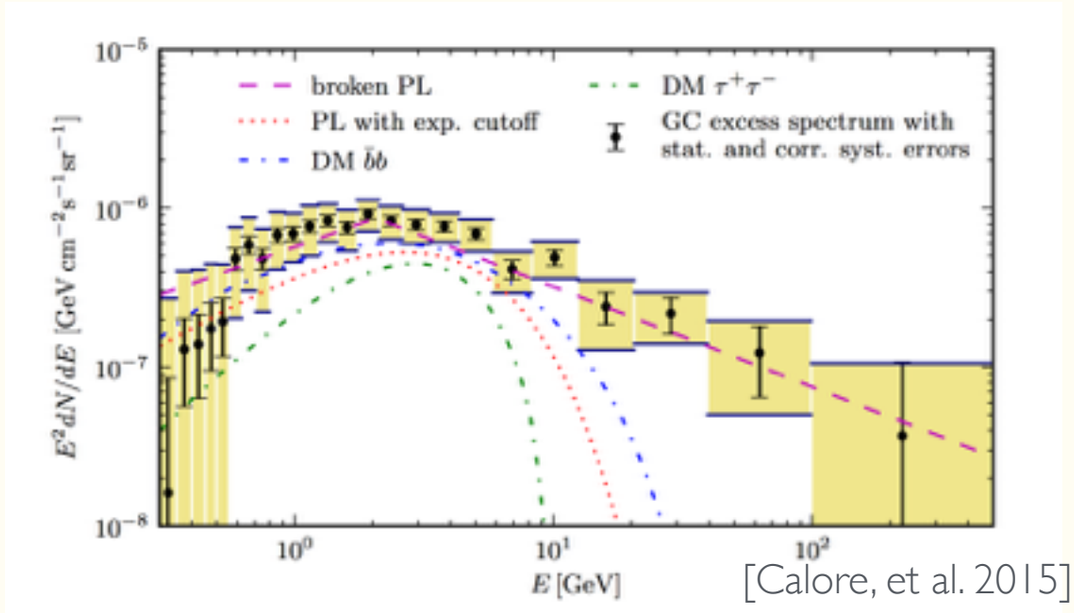

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  - Cosmic-ray interaction with gas from galactic center or burst-like events from supernova remnant or AGN.
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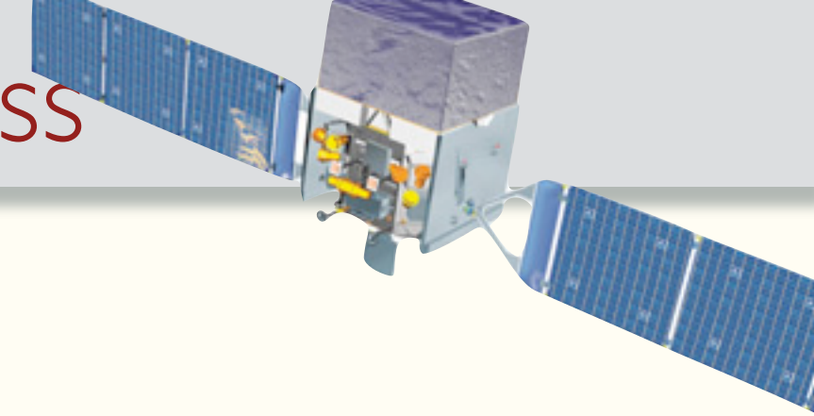

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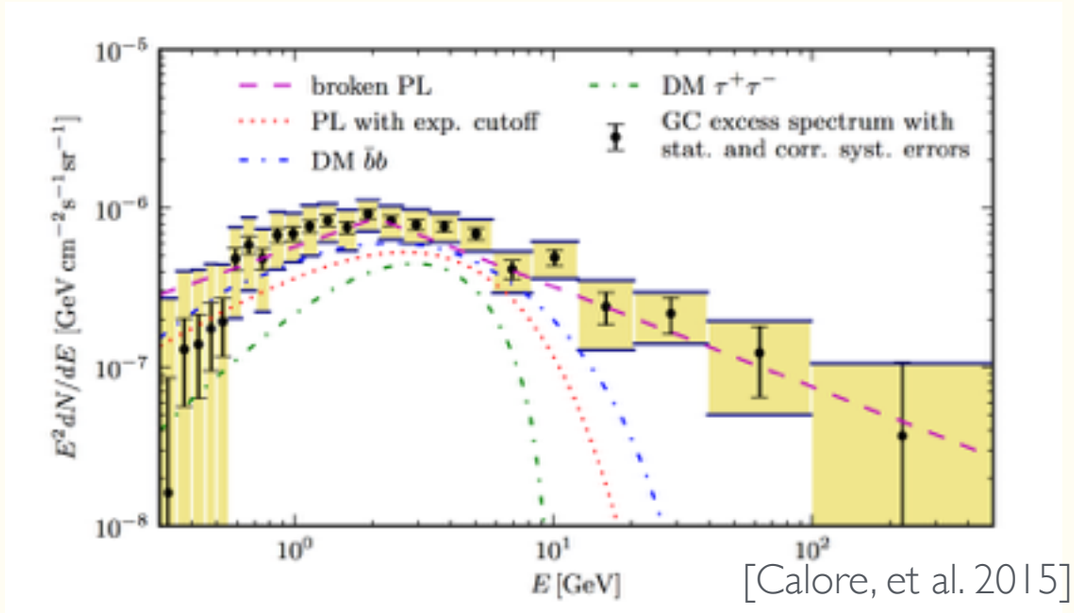

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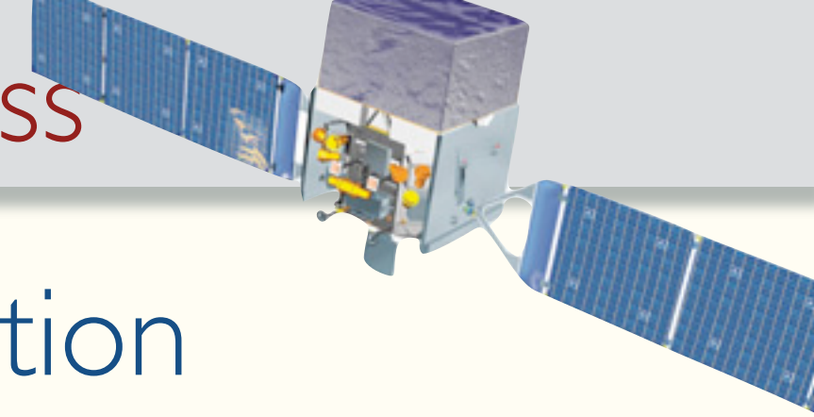
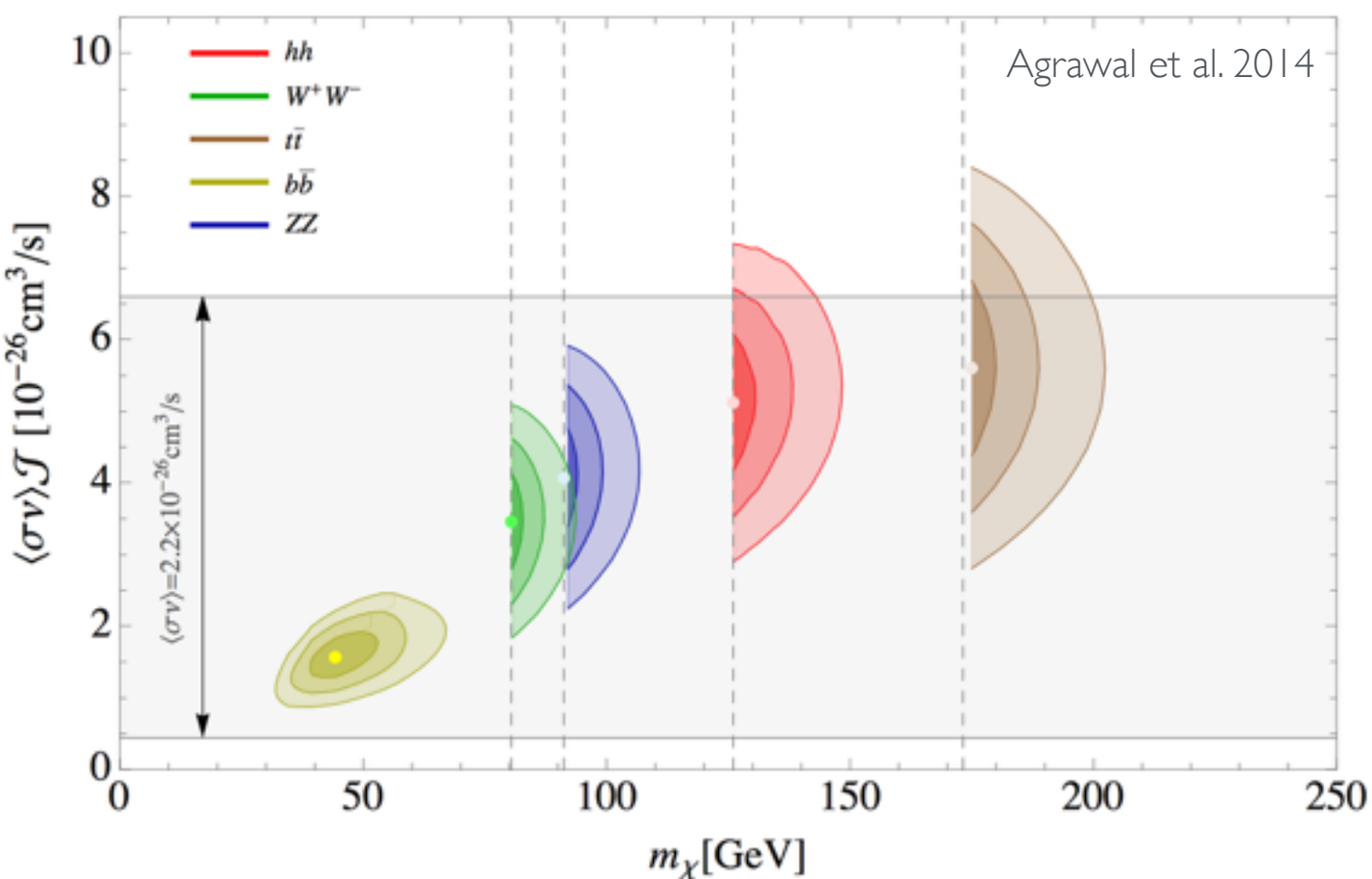
  - Annihilating dark matter.
    [Hooper, Goodenough, 2011; Abazajian,Kaplinghat, 2012; Abazajian et al. 2014; Daylan et al. 2014; Berlin et al. 2014; Agrawal et al. 2014; Alves et al. 2014; Martin et al. 2014; Majumdar et al. 2014; Han et al. 2014; Huang et al. 2014; Ko et al. 2014; Cahill-Rowley et al. 2014; Okada et al. 2014; …PLUS MANY MORE…]

Anomaly I: GeV Gamma-ray Excess



Dark Matter Interpretation

- Fits the WIMP thermal cross-section: $\langle \sigma_{\rm ann} v \rangle \sim 2 \times 10^{-26}\ {\rm cm}^3/{\rm sec}$
- The extended morphology is a highly non-trivial test for the dark matter interpretation.
- Uncertainties allow for several annihilation channels and variety of DM masses.



Anomaly I: GeV Gamma-ray Excess

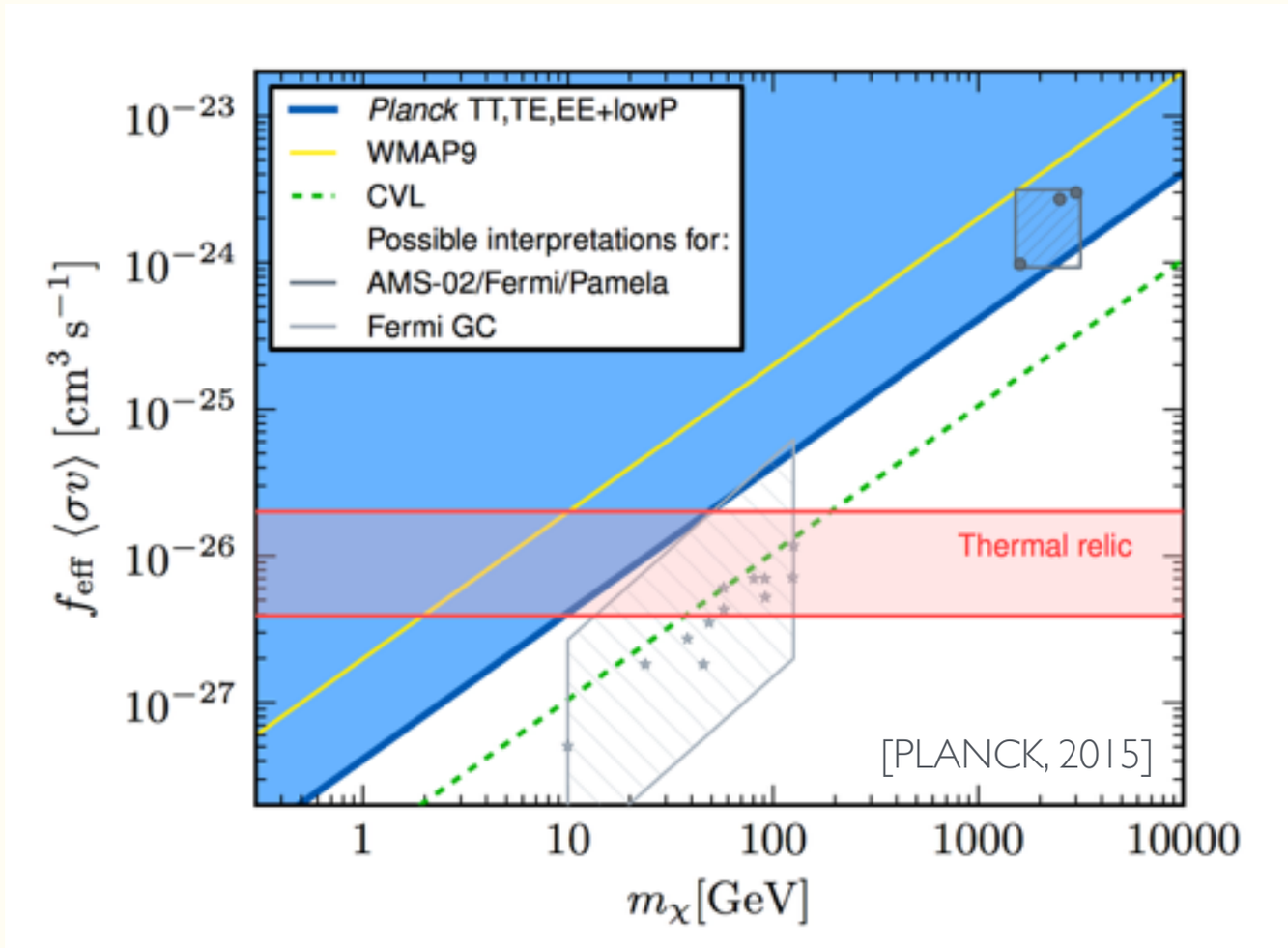
Is it Dark Matter?

Too early to tell!

- Looks intriguing but too many systematic uncertainties (morphology, background modeling, point sources, etc.).
- Many models exist, but are constrained by non-observations in indirect- and direct-detection. Will become more so (unless discovered) with more data.
- Other explanations are certainly still viable.

Cosmological Probes: Planck

- Injection of ionizing particles from DM annihilations changes reionization history, broadening the last scattering surface and modifying the CMB spectrum. [Adams et al. 1998; Chen et al. 2003; Padmanabhan et al. 2005; Finkbeiner et al. 2011]



- Places strong constraints on annihilating light dark matter.

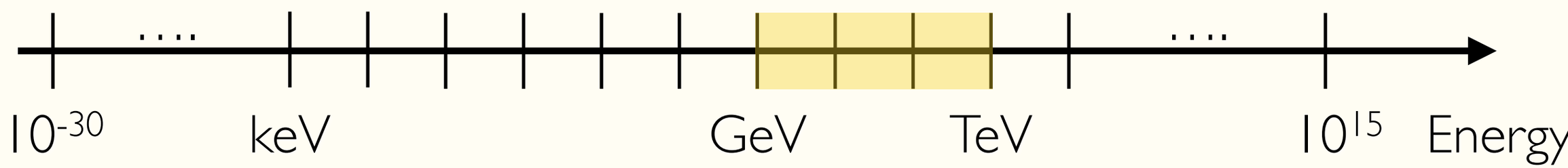
- Can be evaded in several ways. [e.g.: Essig et al. 2013; D'Agnolo, Ruderman, 2015]

Obsessed with the WIMP...

For the last ~30 years we have been focusing on the WIMP scenario

WIMP ⟷ Weak Scale Physics (~100 GeV)

Our experimental effort is strongly focused on the WIMP!



Obsessed with the WIMP...

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WIMP ⟷ Weak Scale Physics (~100 GeV)

Our experimental effort is strongly focused on the WIMP!

Lots more to do!
(repeat everything we did for the WIMP…)

Going Beyond the WIMP

Classifying Theories of Light Dark Matter

Classifying Theories of DM

Dark Sector

- Spin
- Mass
- Self-Interactions
- Light States
- Gauge symmetries
- …

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Production Mech.

- Freeze-out
- Freeze-in
- Freeze-out and decay
- Non-thermal
- Asymmetric
- Misalignment
- …

Classifying Theories of DM

Dark Sector	Production Mech.	Mediation Scheme
• Spin	• Freeze-out	• Gravity
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	• …	

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Mediation Scheme

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- Light Hidden photon
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- …

Couplings

- Quarks
- Gluons
- Charged Leptons
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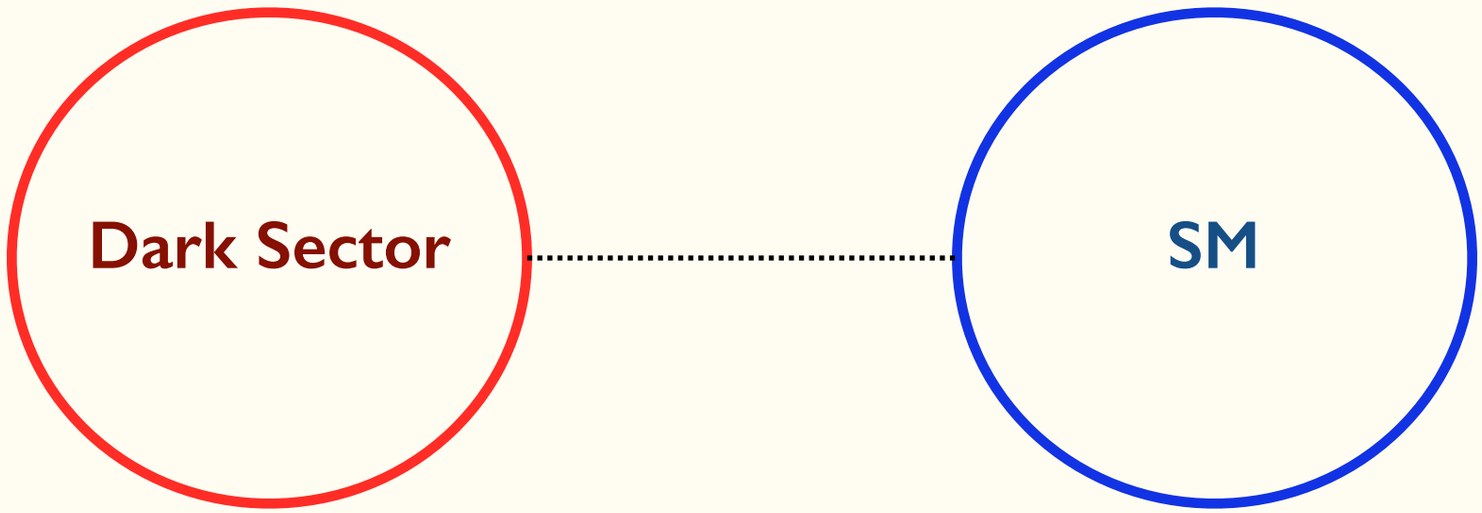
- Photons
- …

Direct

Indirect Colliders

Only a small fraction is probed for the WIMP

New production mechanisms and mediation schemes often imply a hidden dark sector. Possibly with complex dynamics.



Such hidden sectors often include low scale particles, below the GeV scale.

Very different from the WIMP paradigm!!

Classifying Theories of DM

Dark Sector	Production Mech.	Mediation Scheme	Couplings
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Self-Interacting Dark Matter?

Problems with Cold Dark Matter?

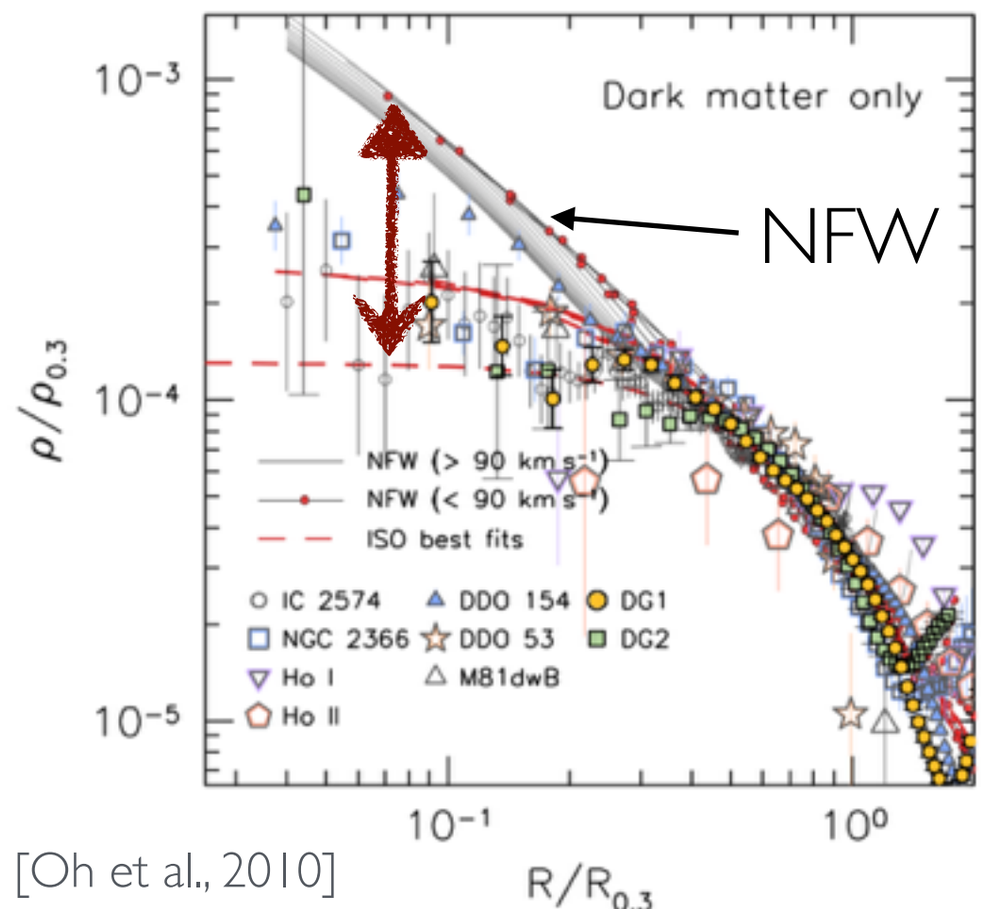
- Several discrepancies between N-body simulations and astrophysical observations:

1. Core vs. Cusp

[Moore 1994; Flores,Primack 1994]

- N-body simulations typically predict: $\rho(r) \xrightarrow{r\to 0} \frac{1}{r^\alpha}$
- Measurements suggest a core: $\rho(r) \xrightarrow{r\to 0} \text{const}$
- Problem exists in:
  (field and satellite) dwarfs,
  LSBs, Clusters

[Walker, Penarrubia, 2011; de Blok, Bosma, 2002; Kuzio de Naray et al., 2007; Kuzio de Naray, Spekkens, 2011; Newman et al. 2012; Oh et al. 2015;…]



[Oh et al., 2010]

Problems with Cold Dark Matter?

- Several discrepancies between N-body simulations and astrophysical observations:

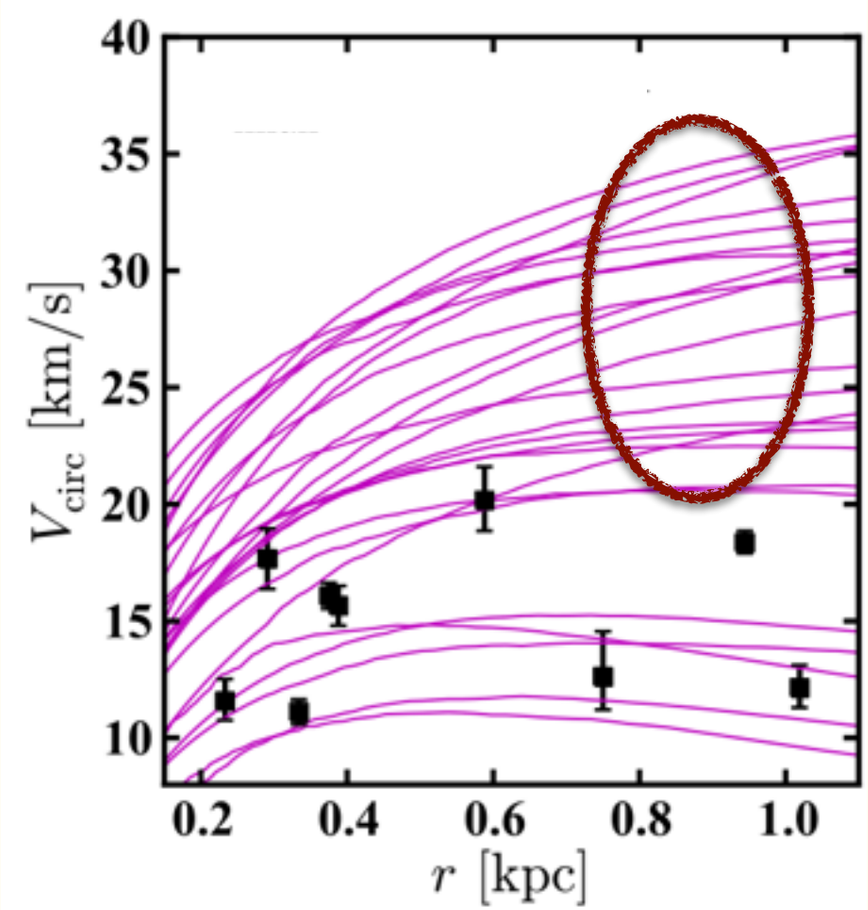
1. Core vs. Cusp [Moore 1994; Flores,Primack 1994]

2. "Too-big-to-fail" problem [Boylan-Kolchin,Bullock,Kaplinghat 2011,2012]

- N-body simulations typically predict: MW should have O(10) satellite galaxies that are more massive than the observed most massive dwarf.

- Problem recently shown to exist also in dSph in Andromeda and around the local group.

[Boylan-Kolchin,Bullock,Tollerud 2014; Garrison-Kimmel et al. 2014; Kirby et al. 2014; Papastergis et al. 2014;…]



[Boylan-Kolchin et al. '11]

Problems with Cold Dark Matter?

- Several discrepancies between N-body simulations and astrophysical observations:

1. Core vs. Cusp [Moore 1994; Flores,Primack 1994]
2. "Too-big-to-fail" problem [Boylan-Kolchin,Bullock,Kaplinghat 2011,2012]
3. Missing satellite problem [Kauffmann et al. 1993; Klypin et al. 1999; Moore et al. 1999]

- N-body simulations typically predict:
  More MW dSPhs than observed.

Problems with Cold Dark Matter?

Discrepancies above strongly rely on N-body simulations, typically without baryons.

- Statistically significant once M31 and field dwarfs are included.
  [Purcell, Zentner 2012; Rodríguez-Puebla et al., 2013]
- It is still possible that the missing dwarf galaxies will be discovered.

Can one explain these with CDM?

Problems with Cold Dark Matter?

Discrepancies above strongly rely on N-body simulations, typically without baryons.

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Definitely maybe!

But highly non-trivial…

Problems with Cold Dark Matter?

Discrepancies above strongly rely on N-body simulations, typically without baryons.

Can one explain these with CDM?

Definitely maybe!

But highly non-trivial…

Baryonic effects such as supernova feedback may explain (some) these discrepancies (significant ongoing study). Harder to explain (some) discrepancies in field dwarfs.

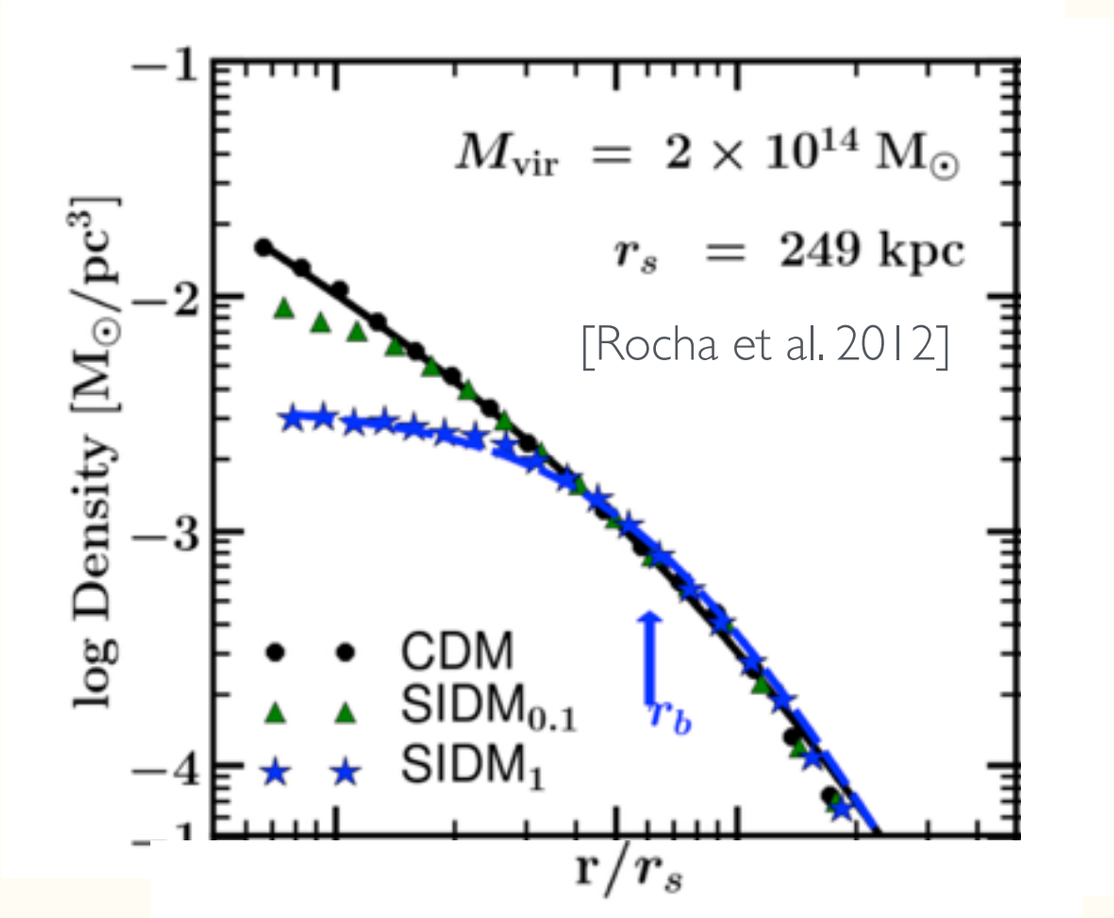
To answer, must understand baryonic feedback much better!

Self-Interacting Dark Matter?

- DM self-interactions may solve many of the above problems.

[Spergel, Steinhardt, 2000]

- Idea:
  - DM interacts with itself allowing for the transfer of heat from outer to inner regions, thereby producing a core.



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[Spergel, Steinhardt, 2000]

- Idea:
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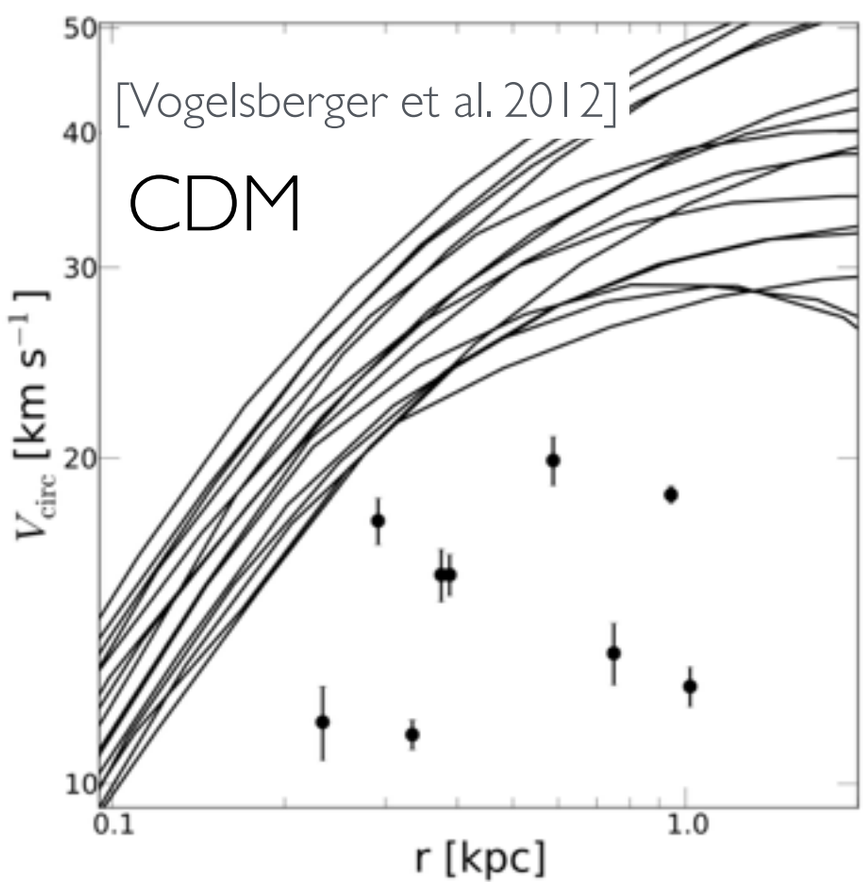
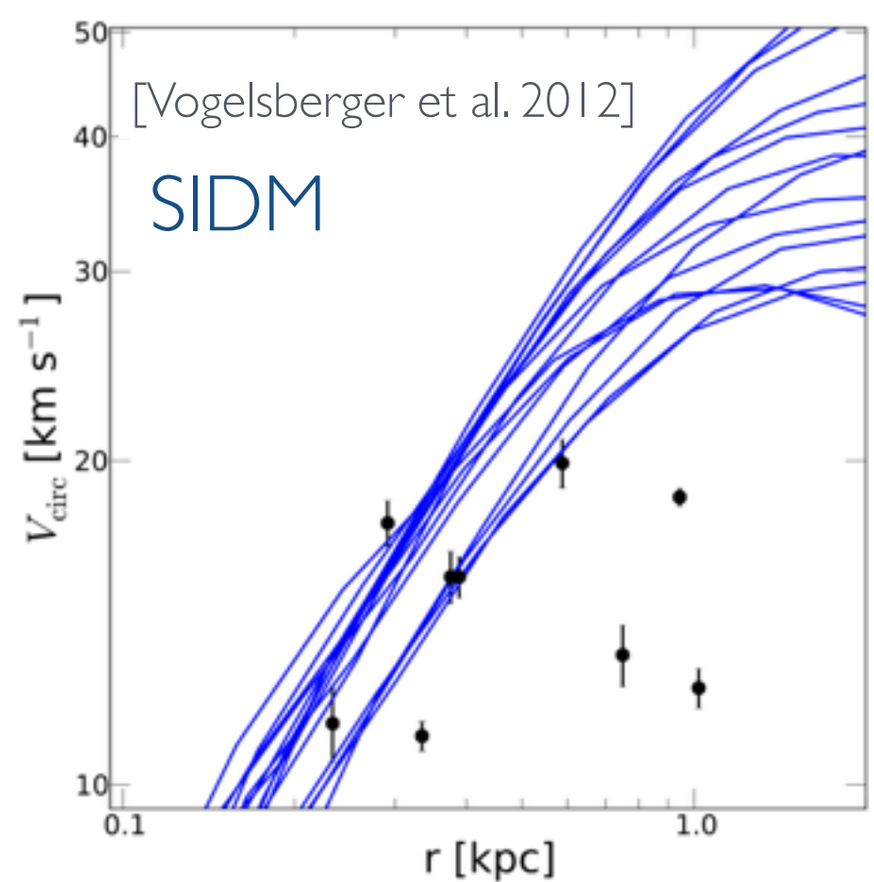
  - Collisions strip sub-halos and reduce number of satellites.





Self-Interacting Dark Matter?

Dark Matter Interpretation

- Numerous models of self-interactions.
- Several implications:
  - Typical self-interacting cross-section (for small-scale structure such as dwarfs):

$$\frac{\sigma_{\rm self}}{m_{\rm DM}} \simeq 0.1 - 10\,{\rm cm}^2/{\rm g}$$

  - Requires light states or strong dynamics.
  - Numerous additional constraints (on large-scale structure) imply

$$\frac{\sigma_{\rm self}}{m_{\rm DM}} \lesssim 0.5\,{\rm cm}^2/{\rm g}$$

A Non-trivial dark sector!

Self-Interacting Dark Matter?

Dark Matter Interpretation

- Numerous models of self-interactions.
- Several imp
  - Typical s ture such as dwarfs):
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Constraints should be taken with a grain of salt!

$$\frac{\sigma_{\rm self}}{m_{\rm DM}} \lesssim 0.5\,{\rm cm}^2/{\rm g}$$

A Non-trivial dark sector!

Dissipative Dark Matter?

- If light states exist for self-interactions, dark matter may dissipate. Consequently small-scale structure can be formed.

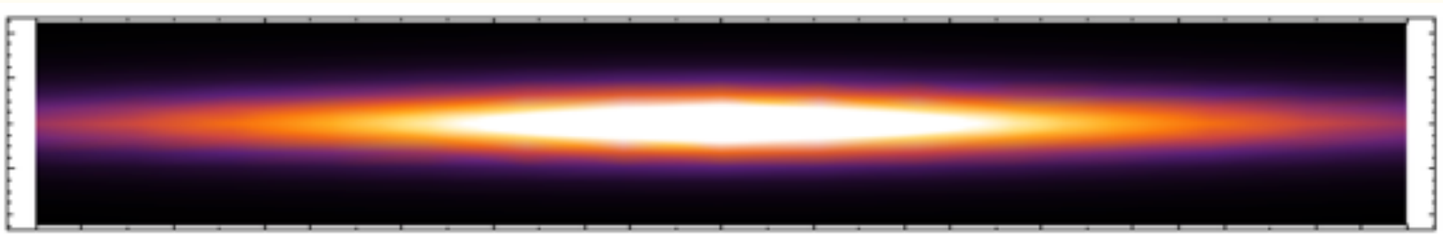
- One interesting example: Double Disk Dark Matter. [Katz, Fan, Randall,Reece,Shelton, 2013]

- Simple model: 2 charged states (heavy + light) under $U(1)_{hid}$.

X	———	~1-100 GeV
C	———	~1MeV
$A_{\mu,hid}$	———	≪ MeV

- Light states allow for dissipation through cooling.

- Consequently, DM may form a disk (instead of a halo).



Dissipative Dark Matter?

- Structure cannot be more than 5-10% of the total DM density! (quite model-dependent..)

- Once a disk is formed, can smaller structure be formed?

Dark Stars? Dark Planets? Accretion disks?

- What are the implications? (more on this later..)

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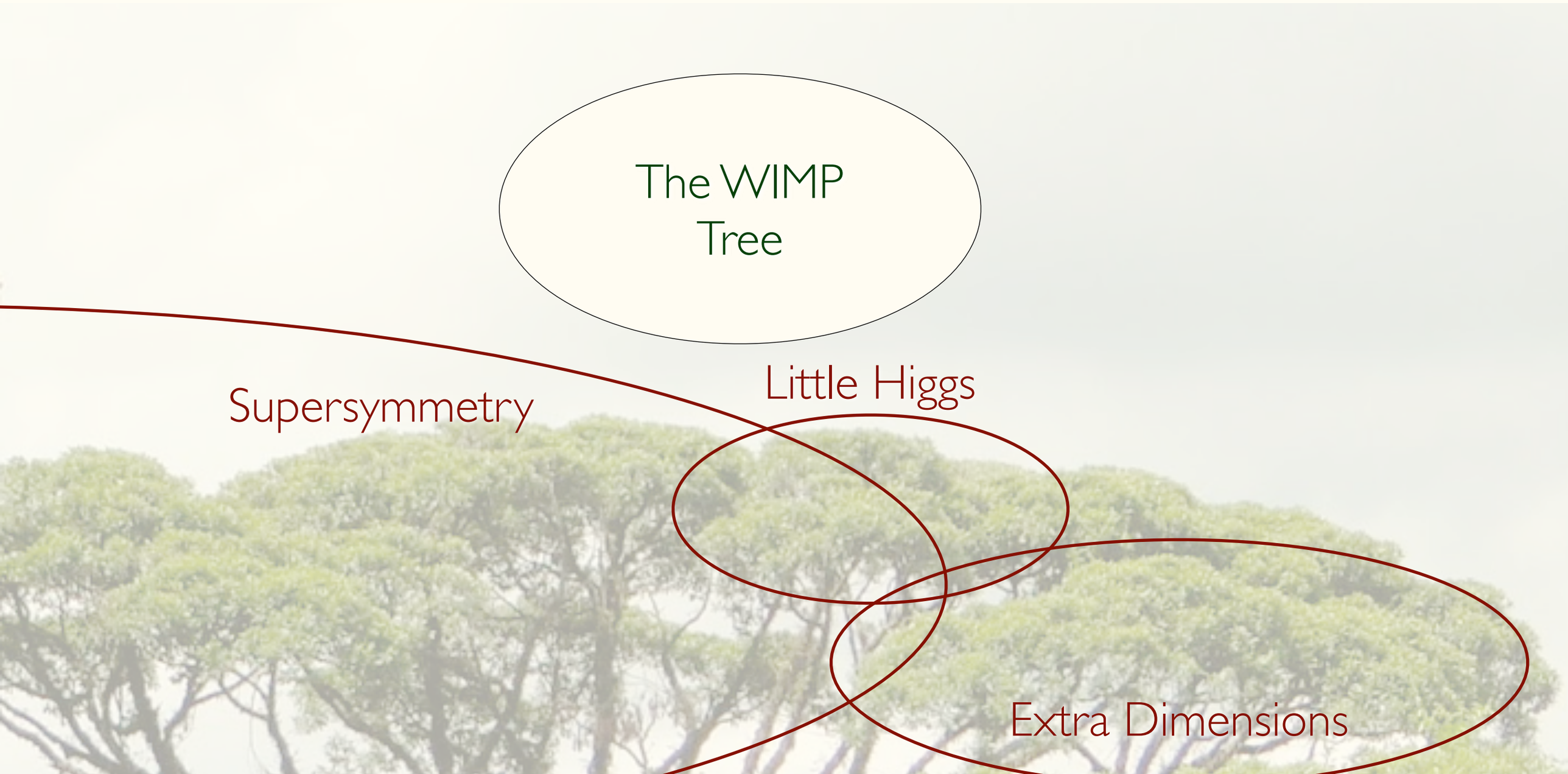
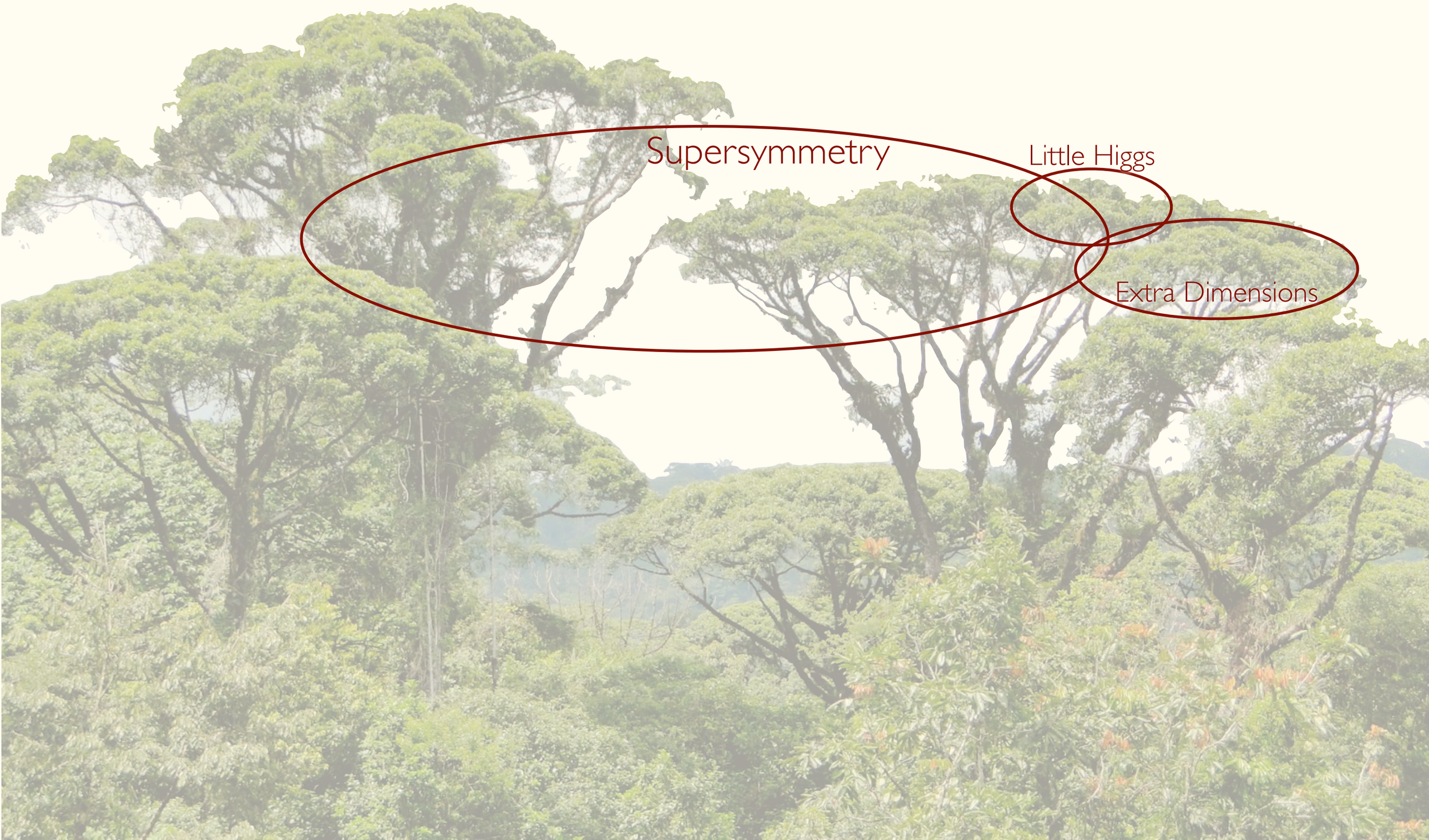
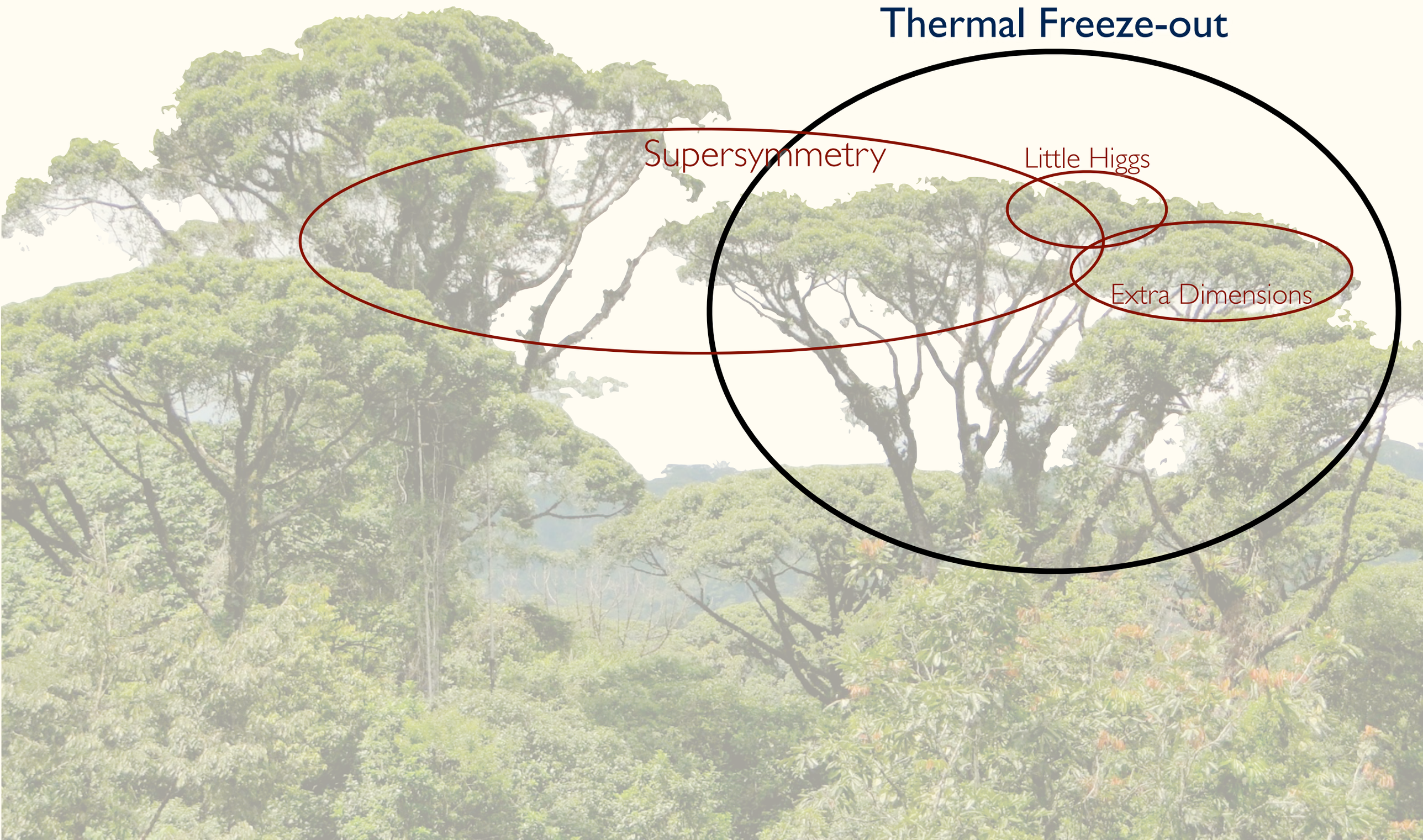
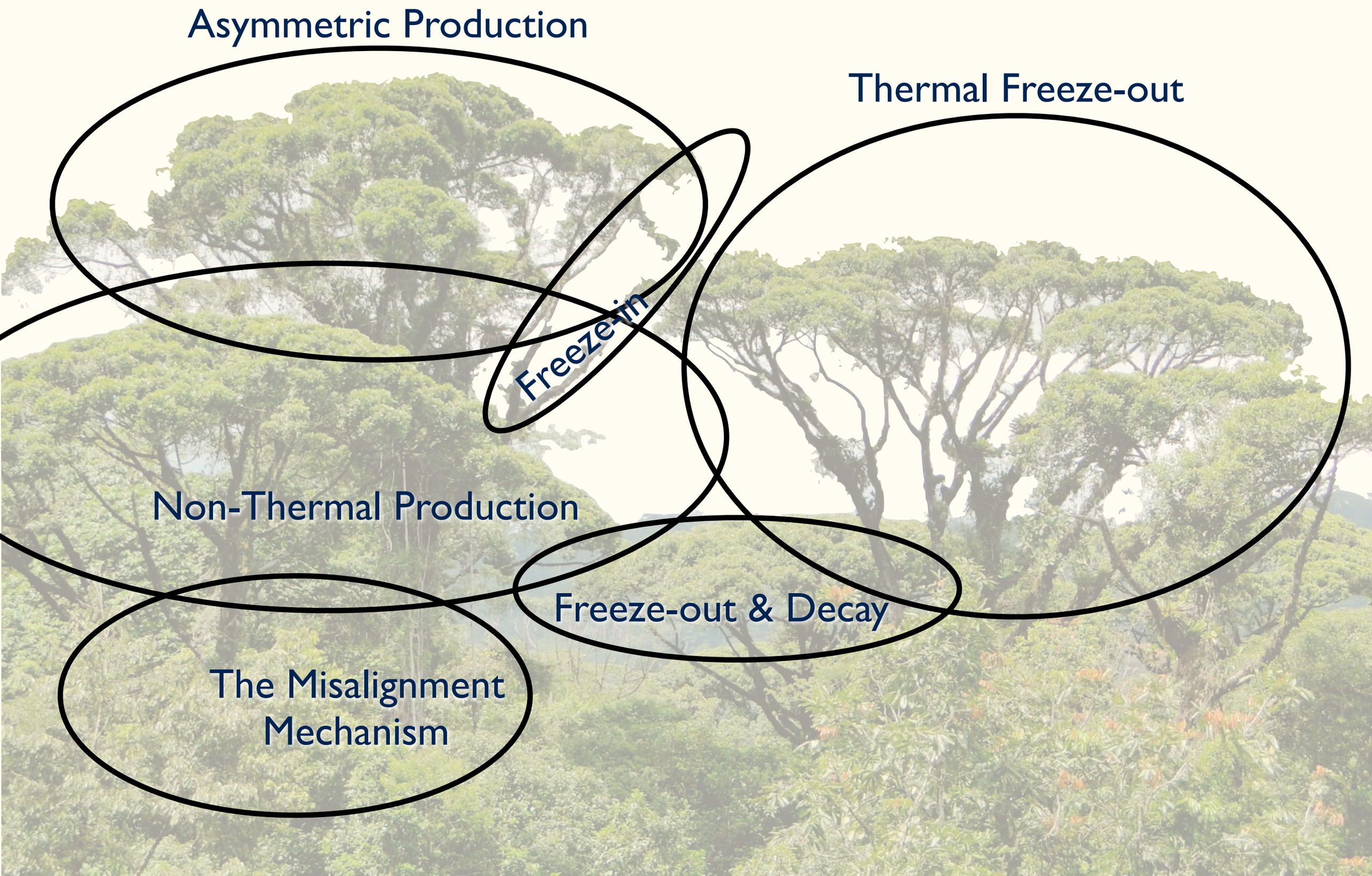
Skip

The Dark Matter Tree




Supersymmetry
Little Higgs
Extra Dimensions


Thermal Freeze-out
Supersymmetry
Little Higgs
Extra Dimensions


Asymmetric Production
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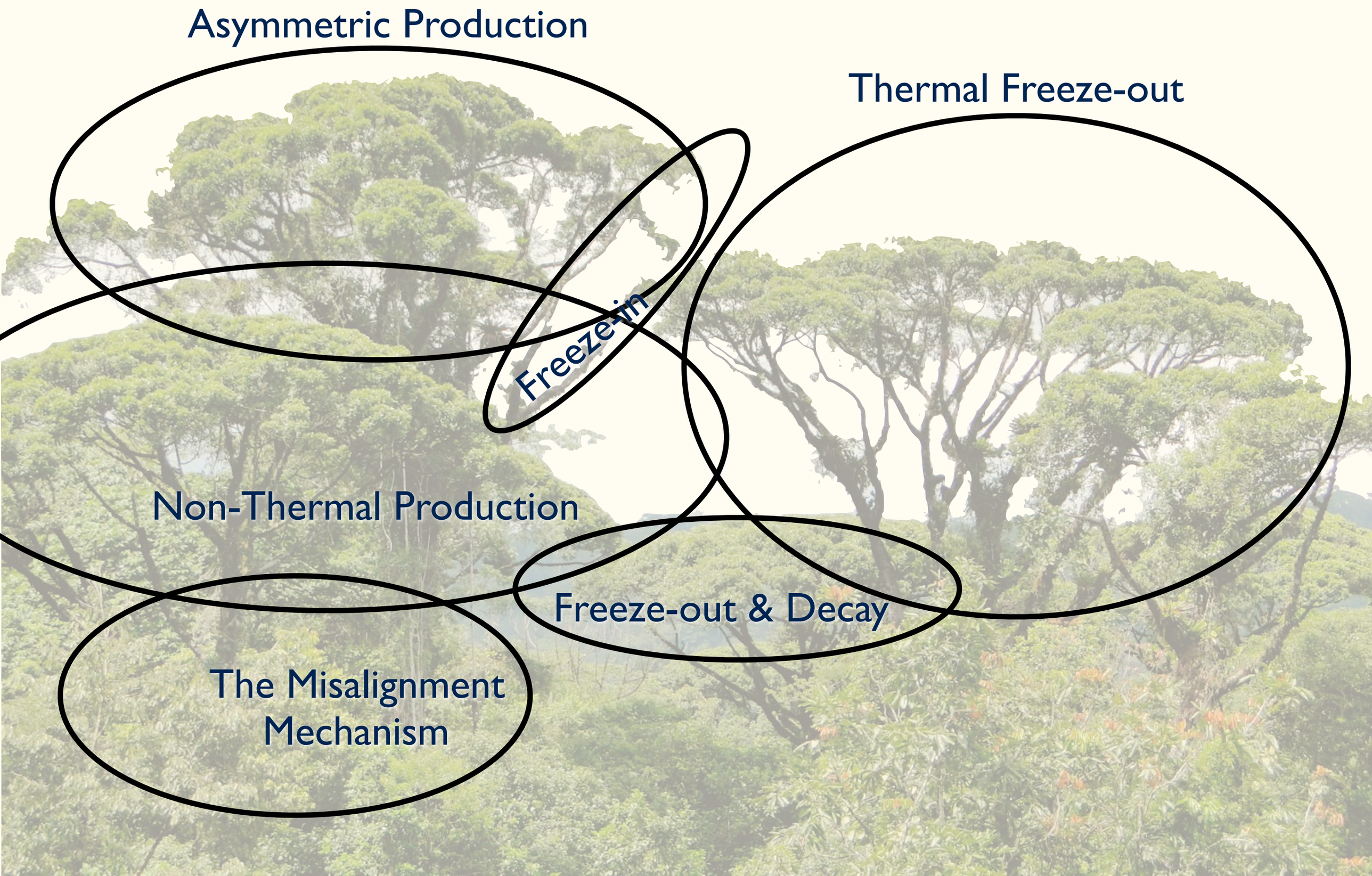
Freeze-in
Non-Thermal Production
Freeze-out & Decay
The Misalignment Mechanism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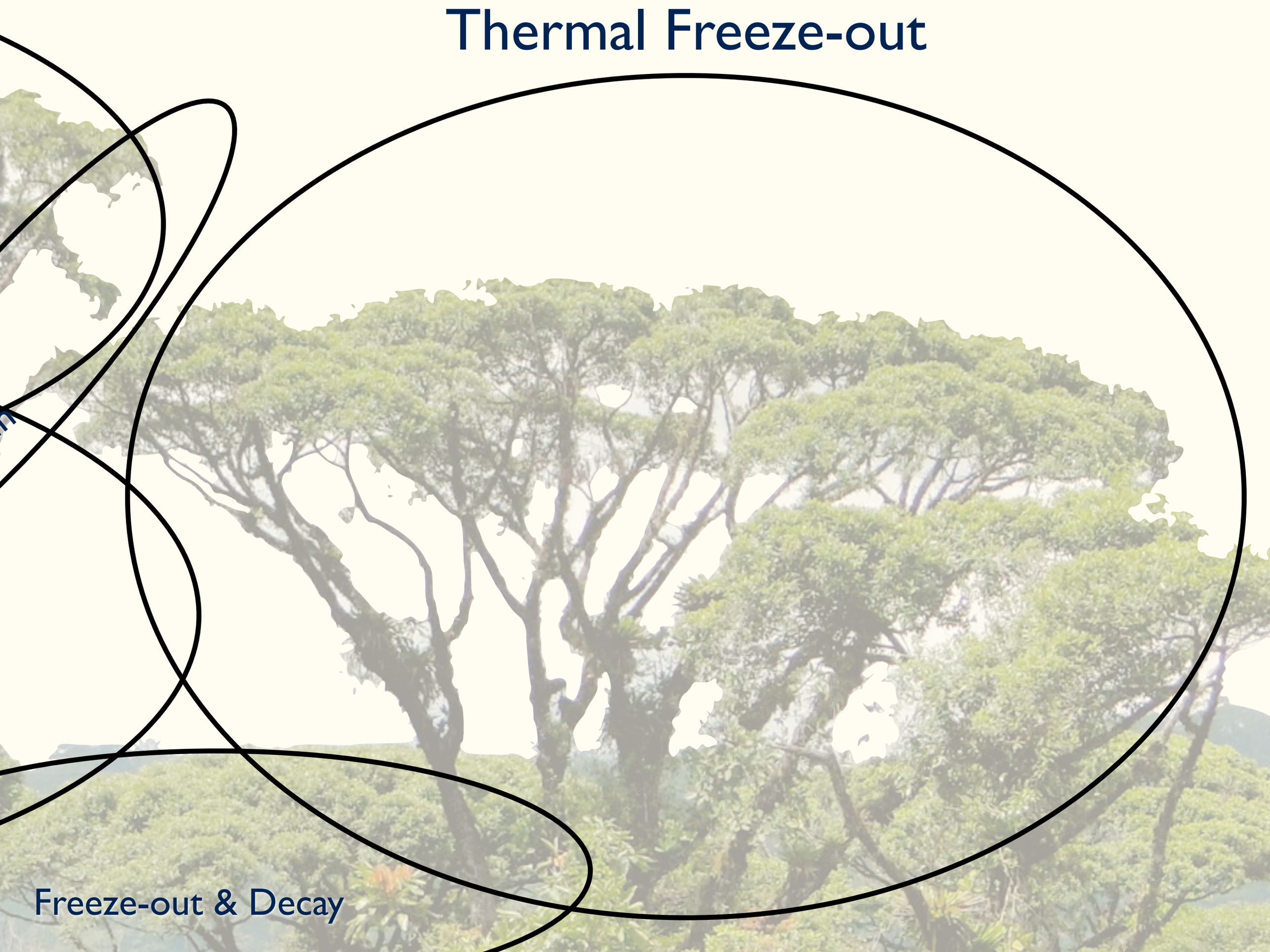
Thermal Freeze-out



Freeze-out & Decay

Thermal Freeze-out

Thermal Freeze-out

Strongly Interacting Massive Particles

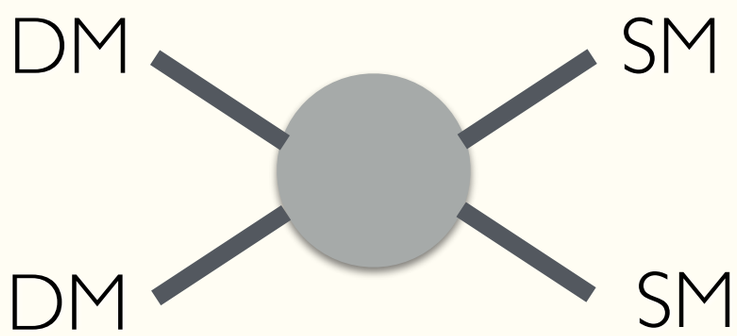
A New Perspective on Freeze Out

[Kuflik, Hochberg, TV, Wacker, 2014]

[Kuflik, Hochberg, Murayama, TV, Wacker, 2014]

No 2-2 Annihilations..

- The WIMP paradigm assumes significant 2-2 annihilations (typically to SM) that suppresses the number density.



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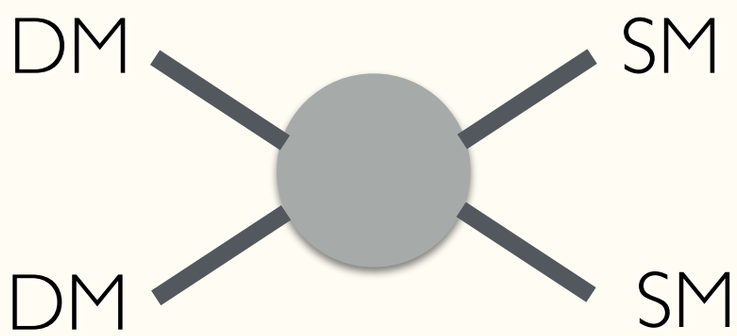
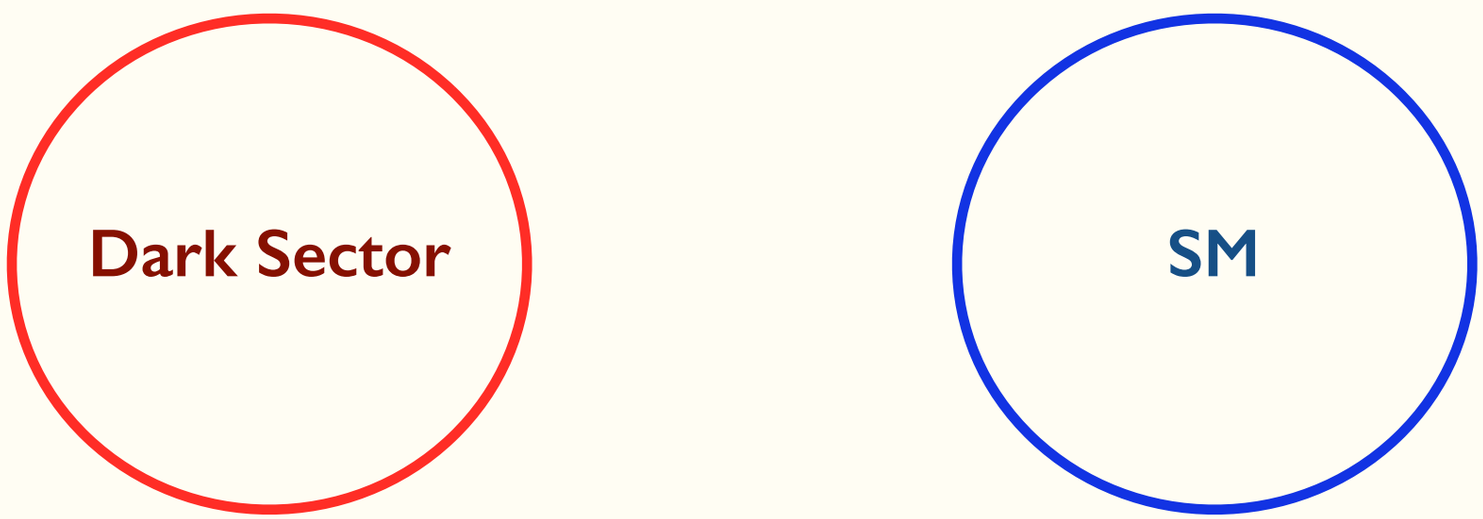


- But what if DM is the lightest state in a hidden (sequestered) sector?



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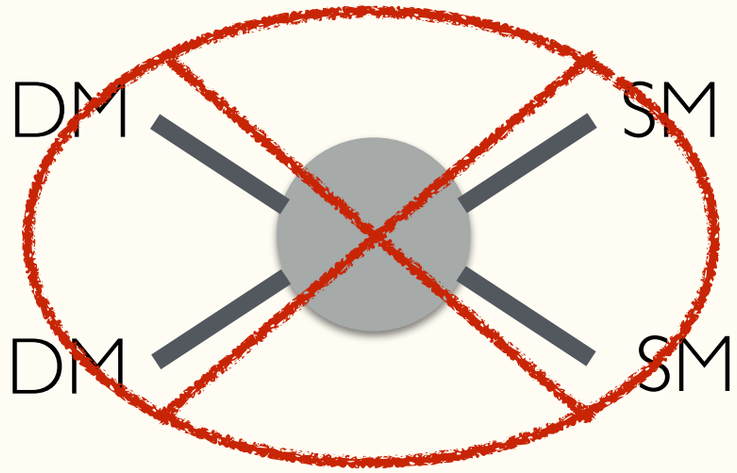

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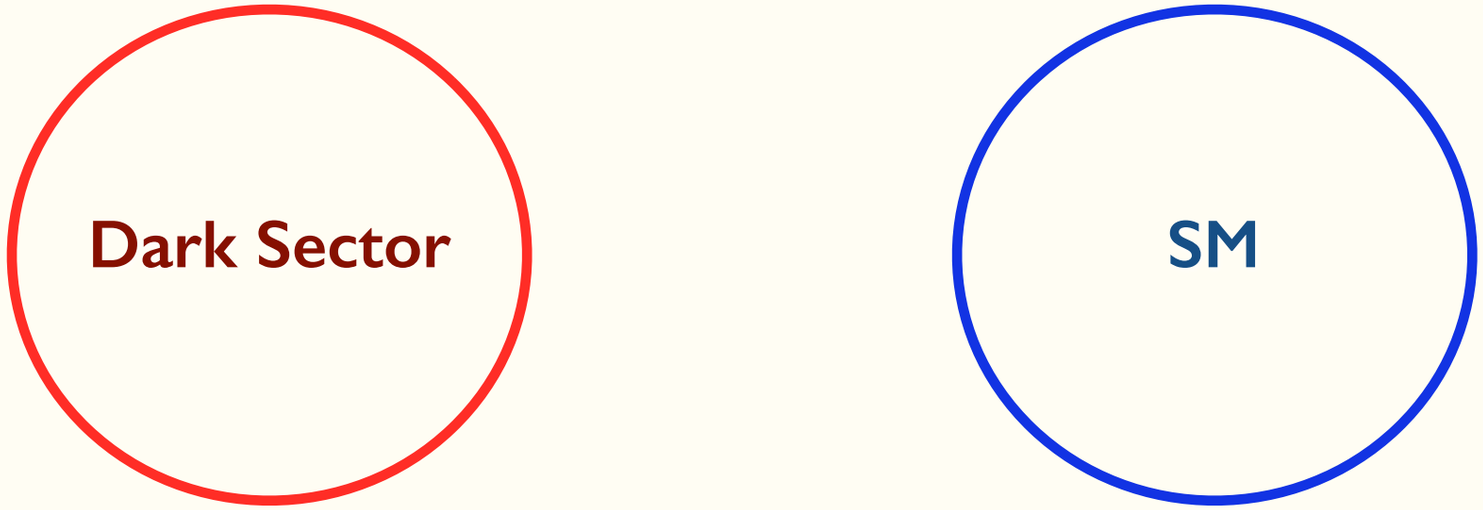
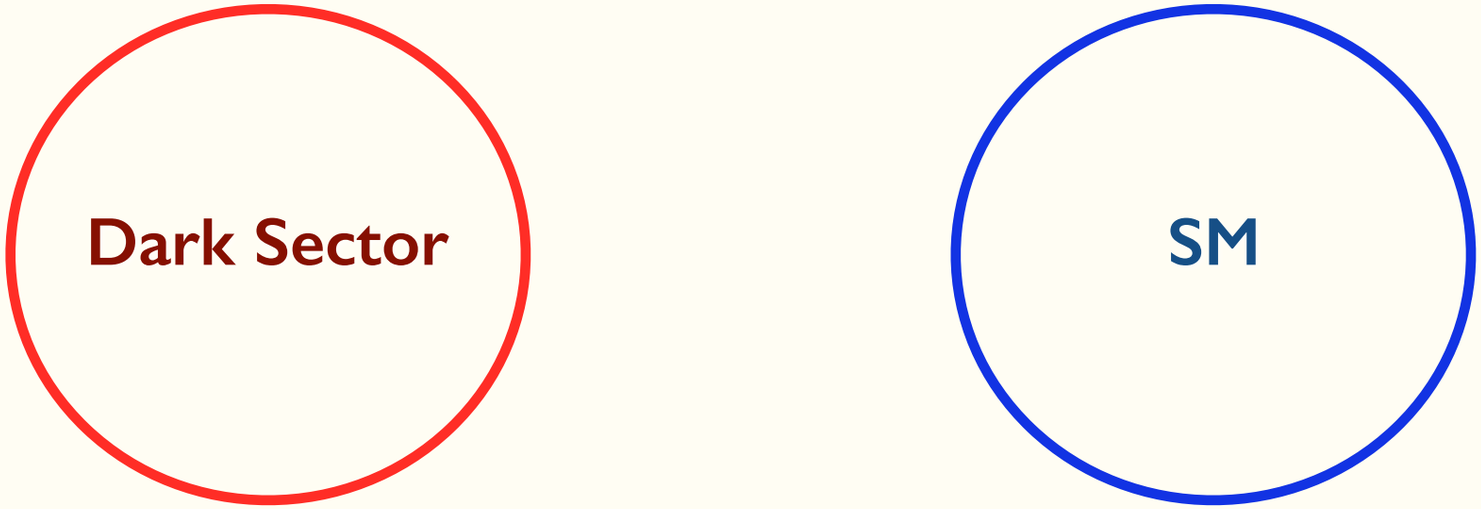


- Then 2-2 annihilations may be highly suppressed

No 2-2 Annihilations..



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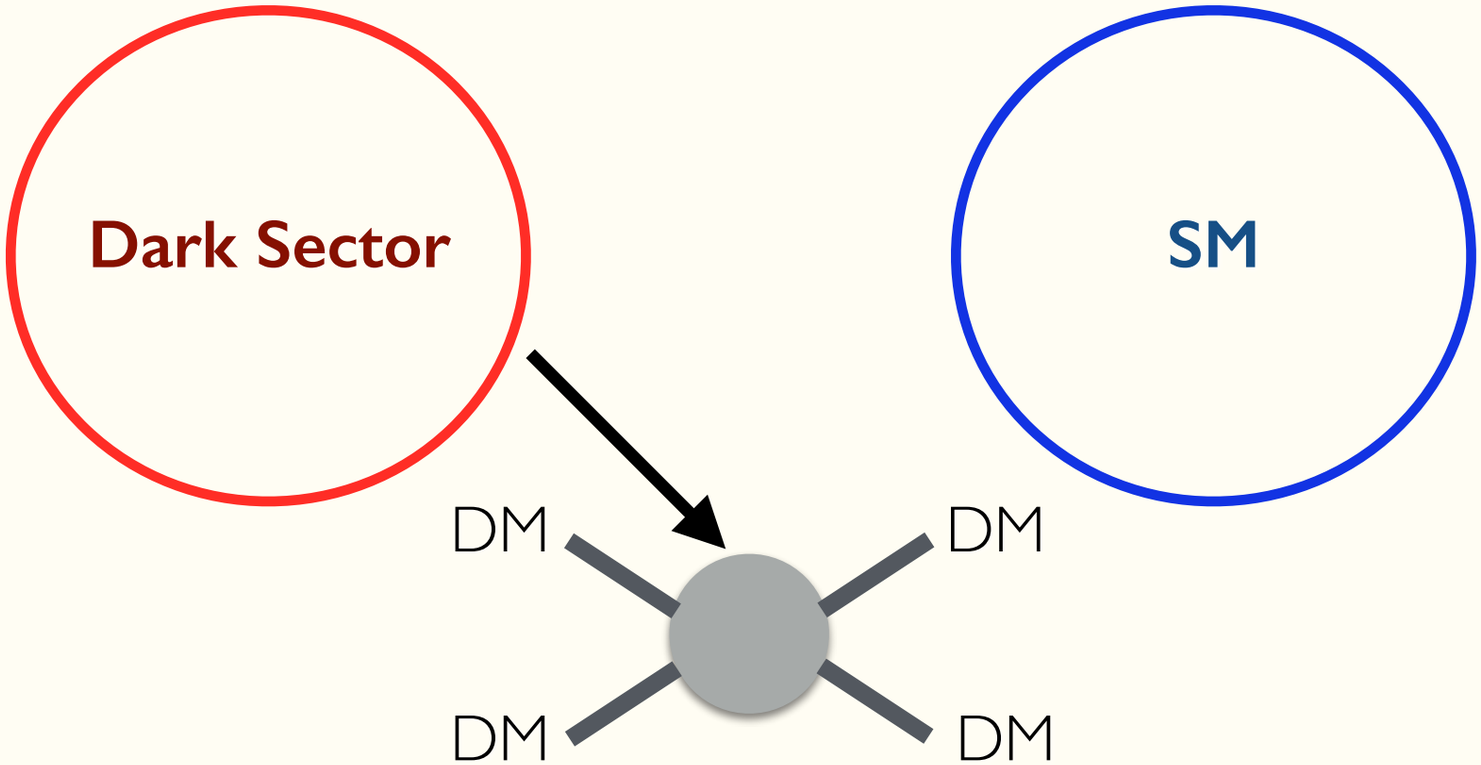
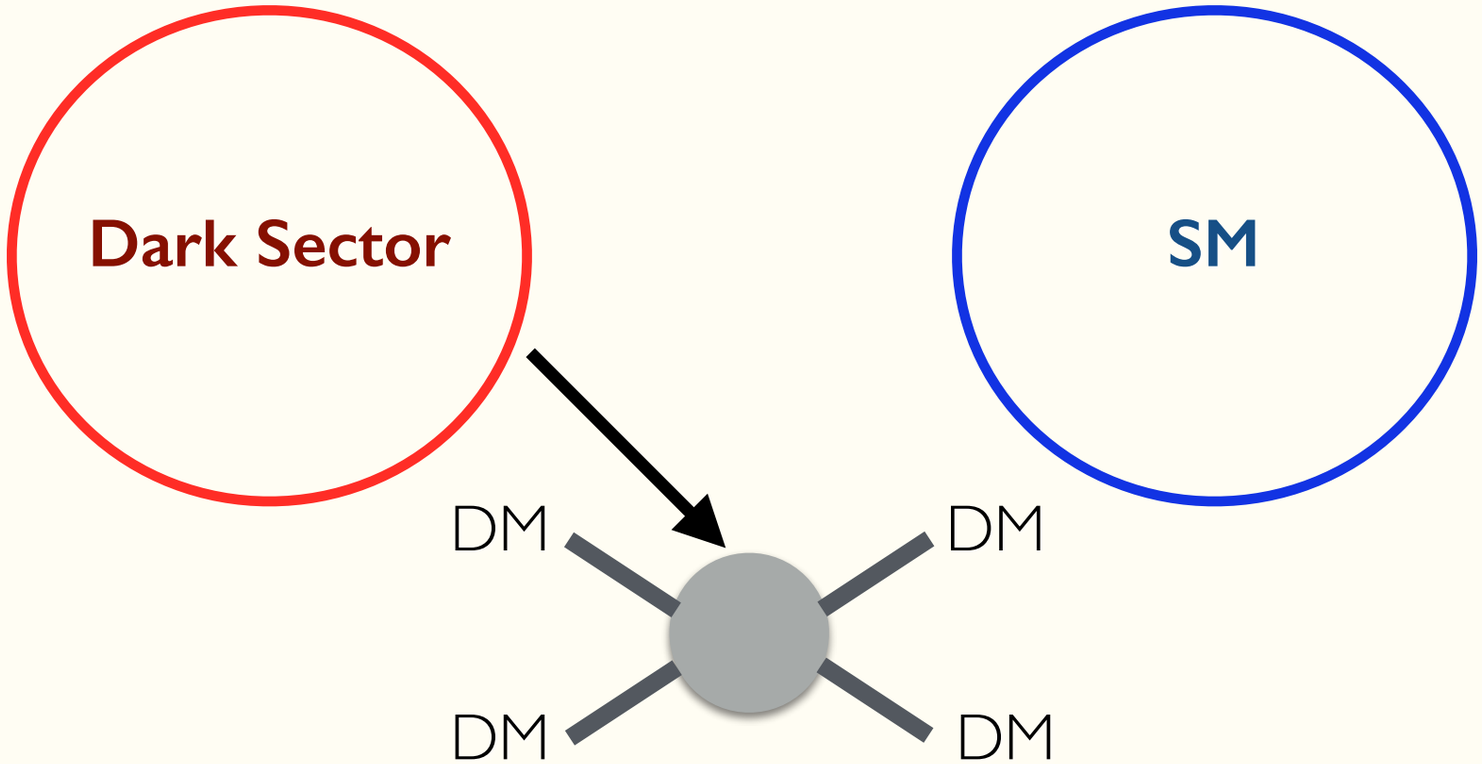


- However, DM can still interact in the hidden sector.
- But this is number-conserving, which implies,

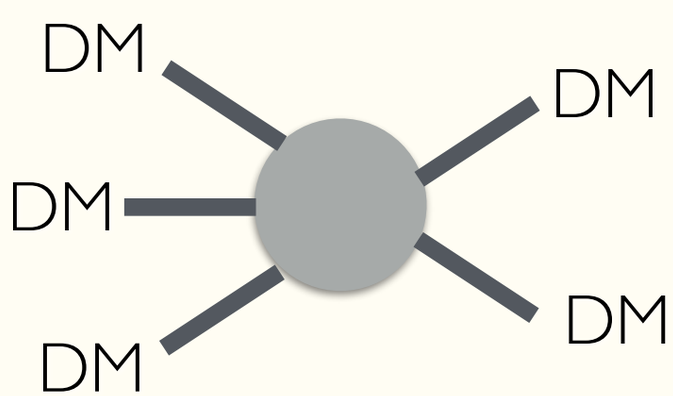
$$\frac{n_{\rm DM}}{s} \sim 1$$

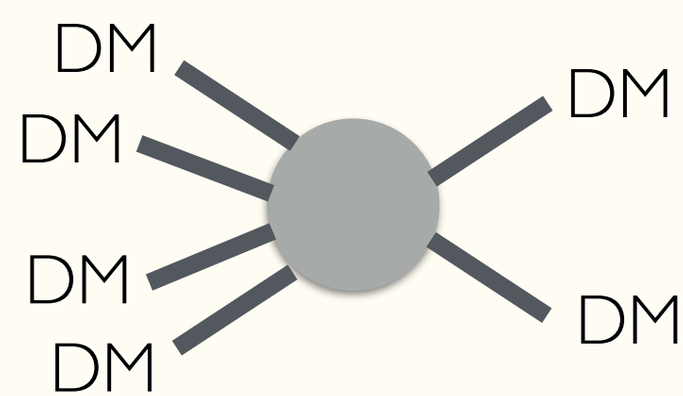
A way out?

No 2-2 Annihilations..



- More generally, the hidden sector will have additional interactions (especially in a strongly coupled case).





3-2 Freeze Out

WIMP DM

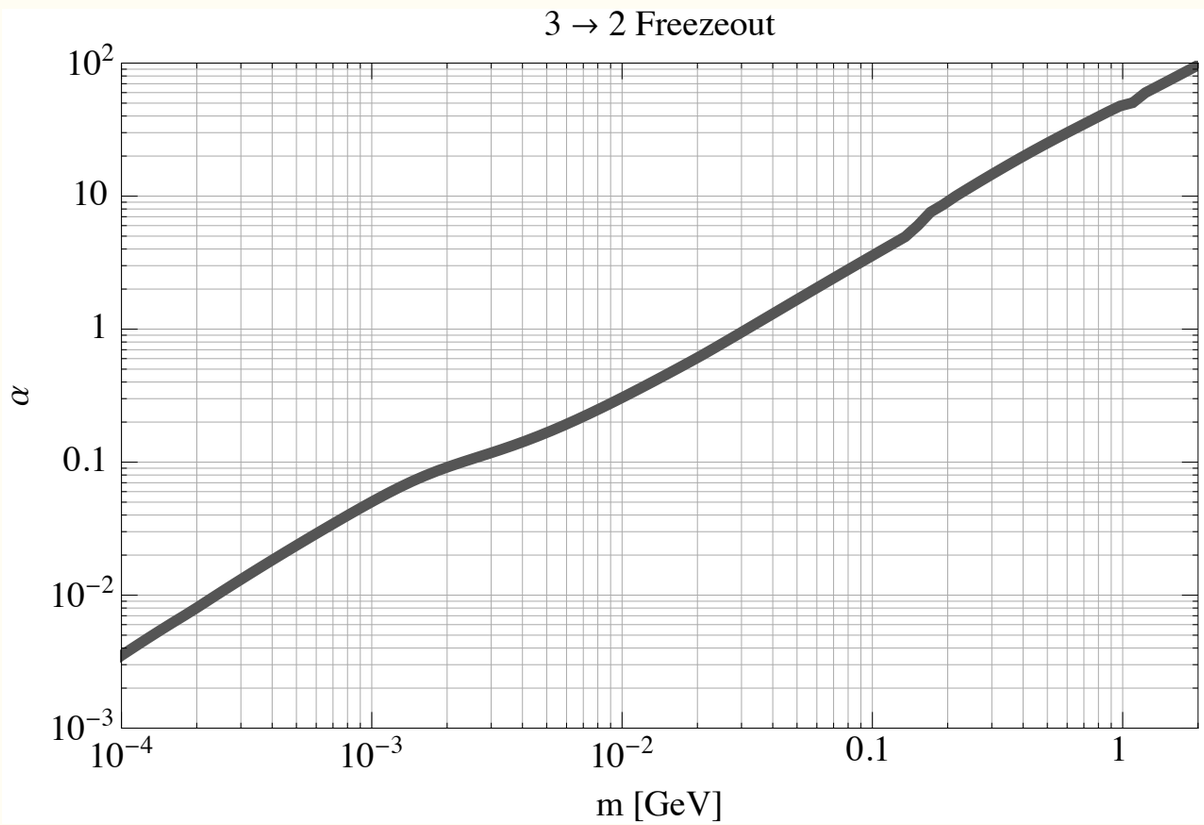
Weak scale emerges for a weak-strength interactions

$$m_{\rm DM} \simeq \alpha_{\rm eff} \left(T_{\rm eq} M_{\rm Pl}\right)^{1/2} \sim {\rm TeV}$$

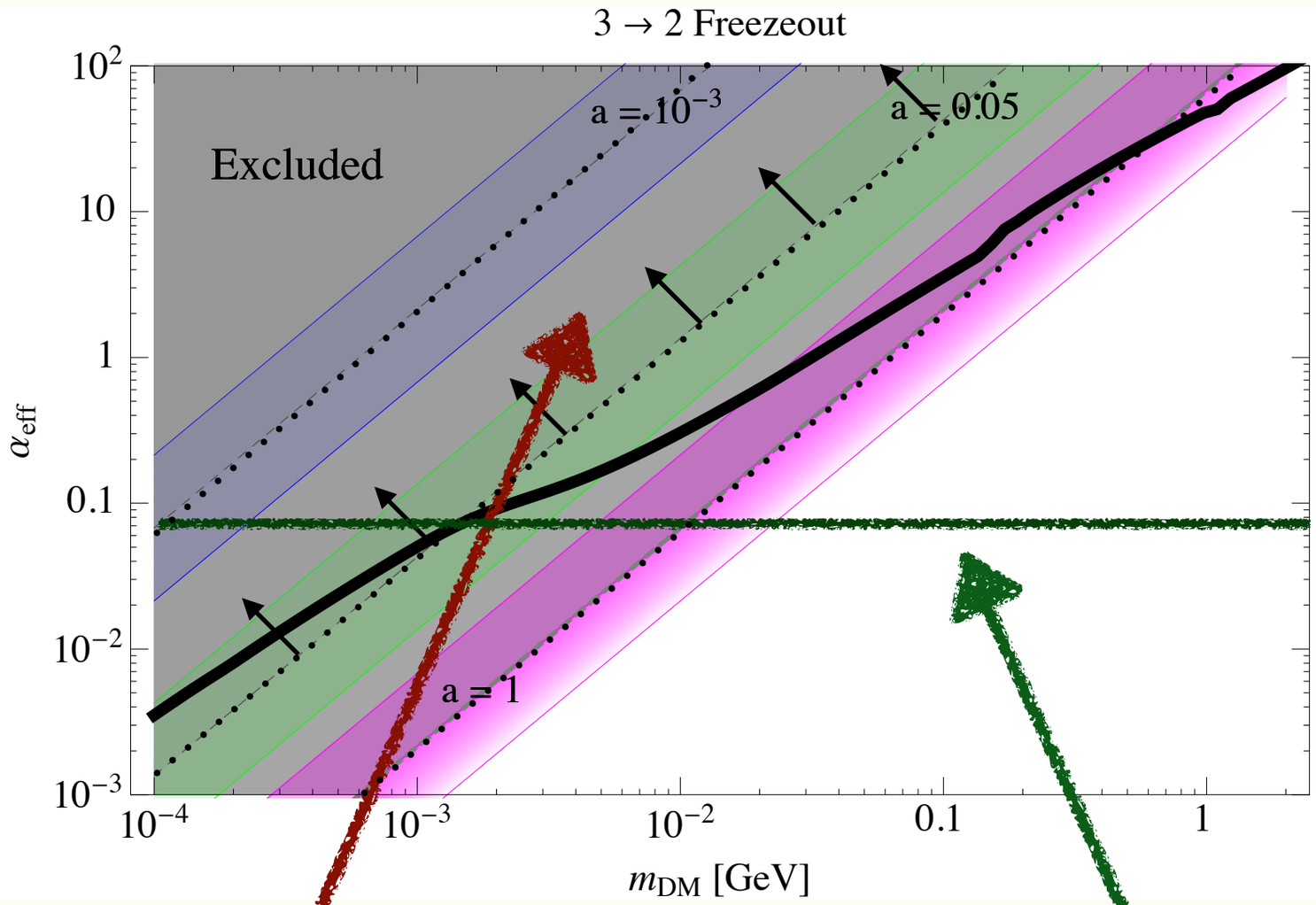
SIMP DM

QCD scale emerges for a strongly-interacting sector.

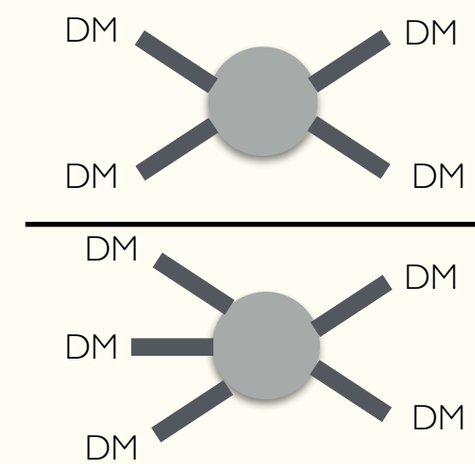
$$m_{\rm DM} \simeq \alpha_{\rm eff} \left(T_{\rm eq}^2 M_{\rm Pl}\right)^{1/3} \sim 100\ {\rm MeV}$$



2-2 Good or Bad?



$$a \equiv \frac{\alpha_{2-2}}{\alpha_{\rm eff}} =$$



Excluded by Bullet-cluster and halo-shape constraints

Constraints push to strong regime → **SIMP**

3-2 Freeze Out

Problem

We implicitly assumed that $\mathbf{T_{dark} = T_{SM}}$. Otherwise DM is hot and excluded.

Solution

To evade limits on hot DM, the dark sector needs to be in thermal equilibrium with SM.

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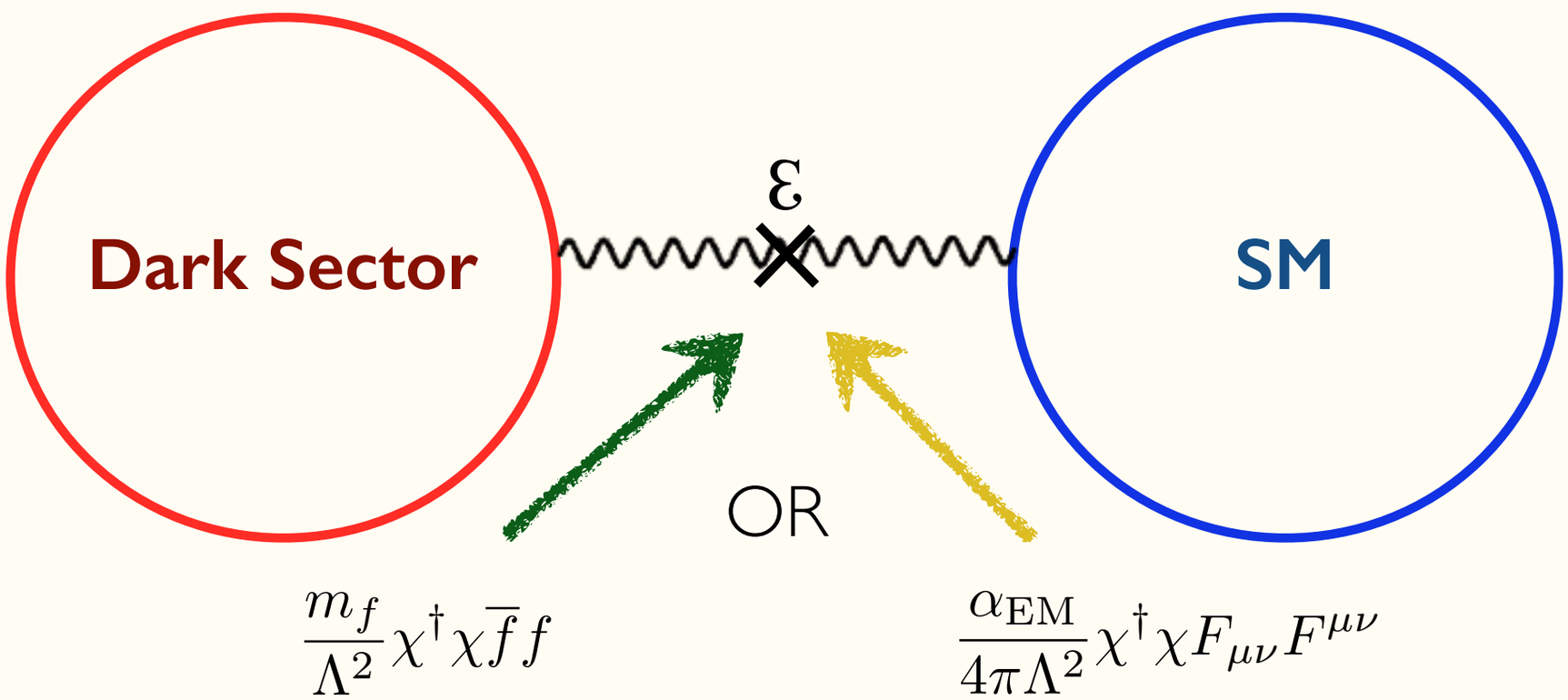
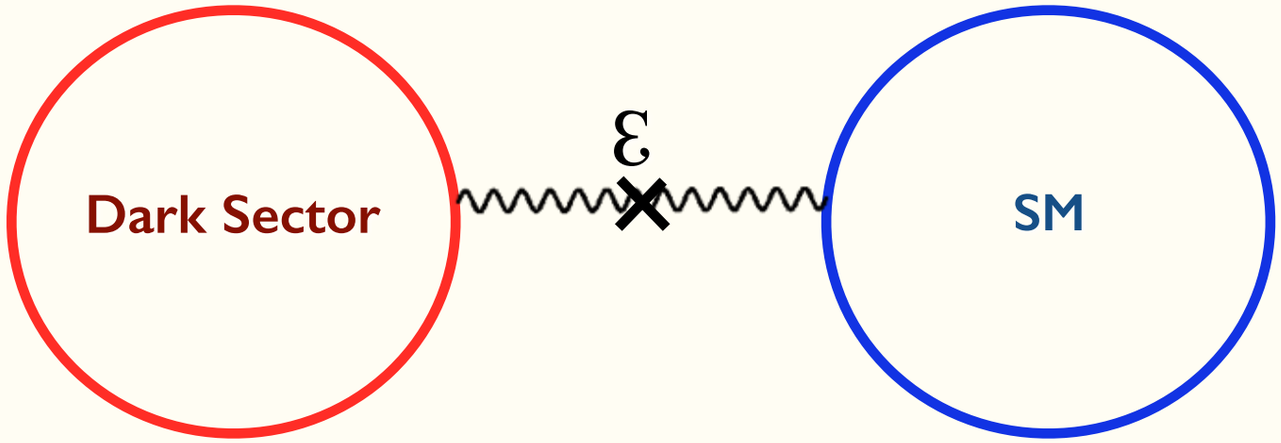
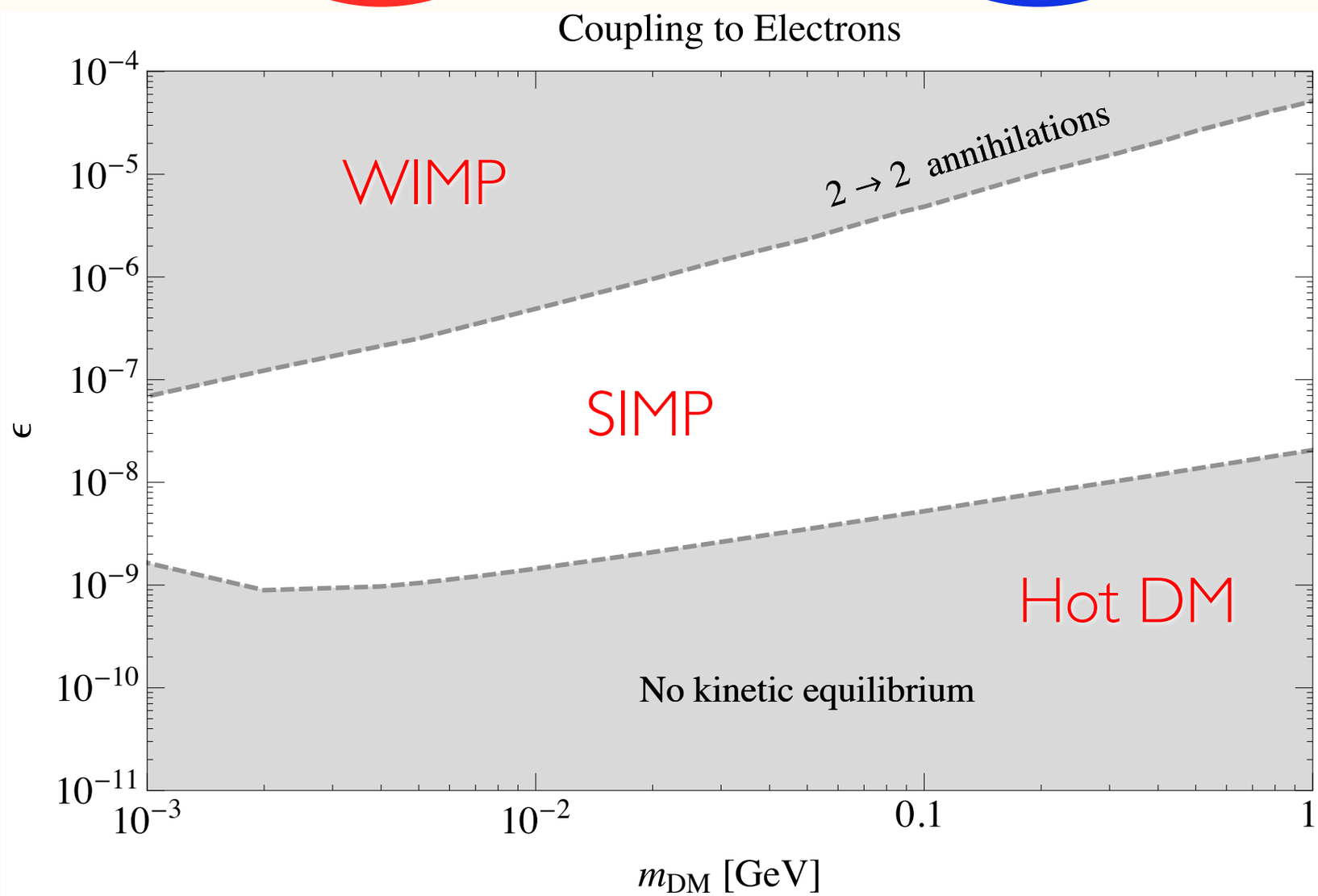


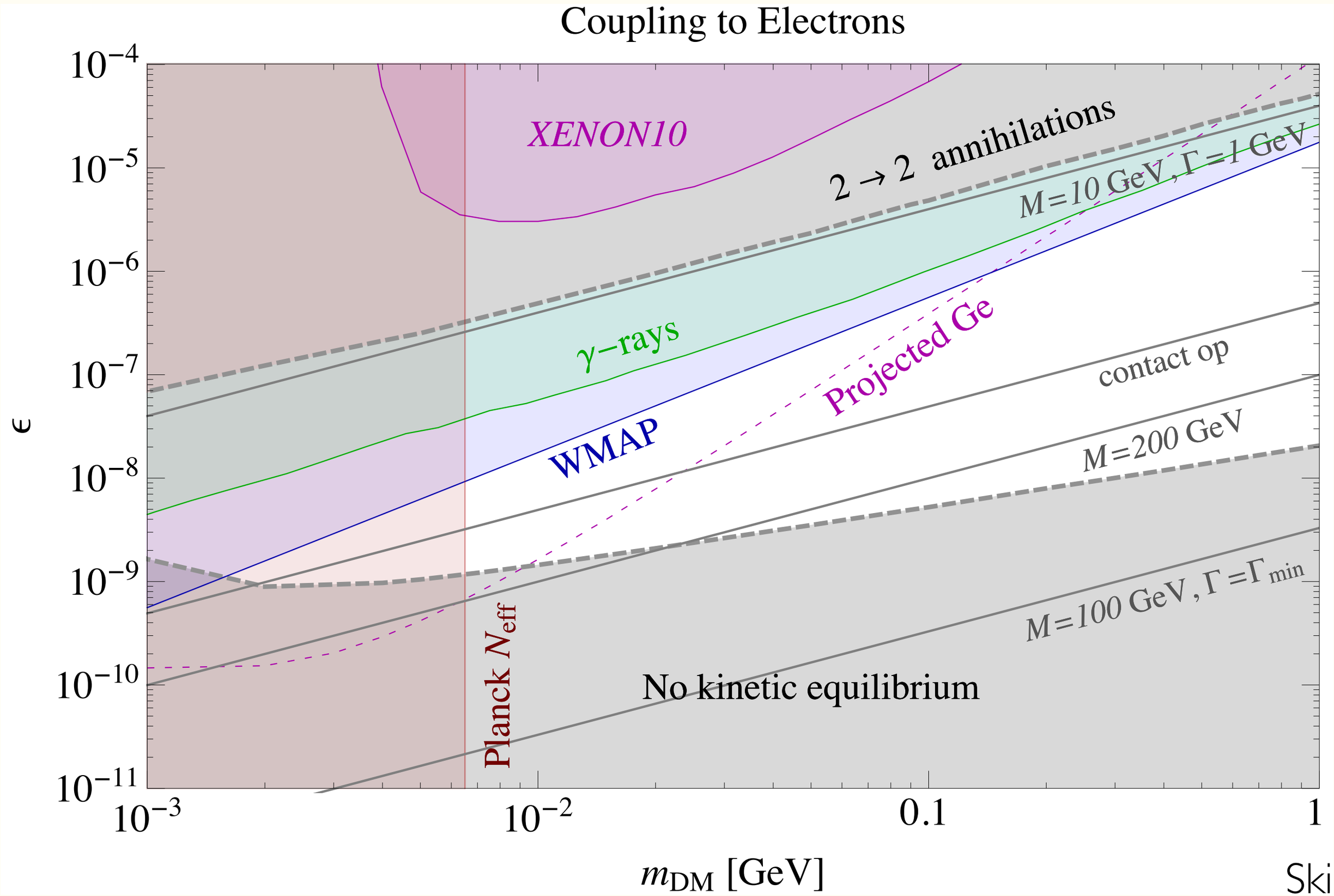
3-2 Freeze Out

Thus, much like the WIMP, the SIMP scenario predicts couplings to SM.





SIMP DM: Experimental Status



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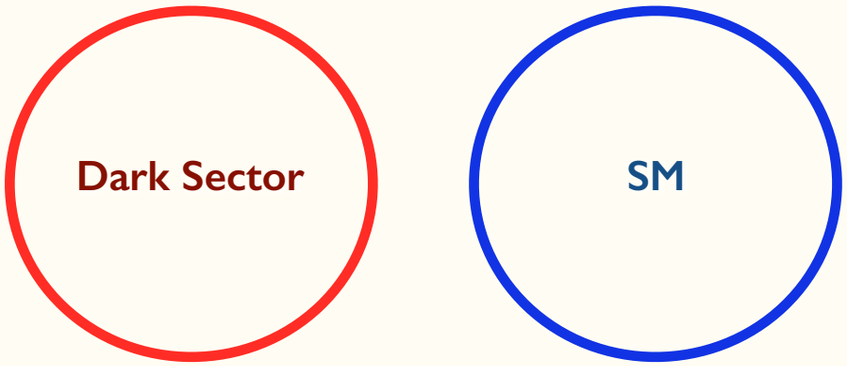
Self-Interacting Dark Matter?

E.g.: The SIMP

[Carlson, Hall, Machacek, 1992; Kuflik, Hochberg, TV, Wacker, 2014; Kuflik, Hochberg, Murayama, TV, Wacker, 2014; Kuflik, Hochberg, Murayama, TV, Wacker, in progress]

2 sectors weakly coupled



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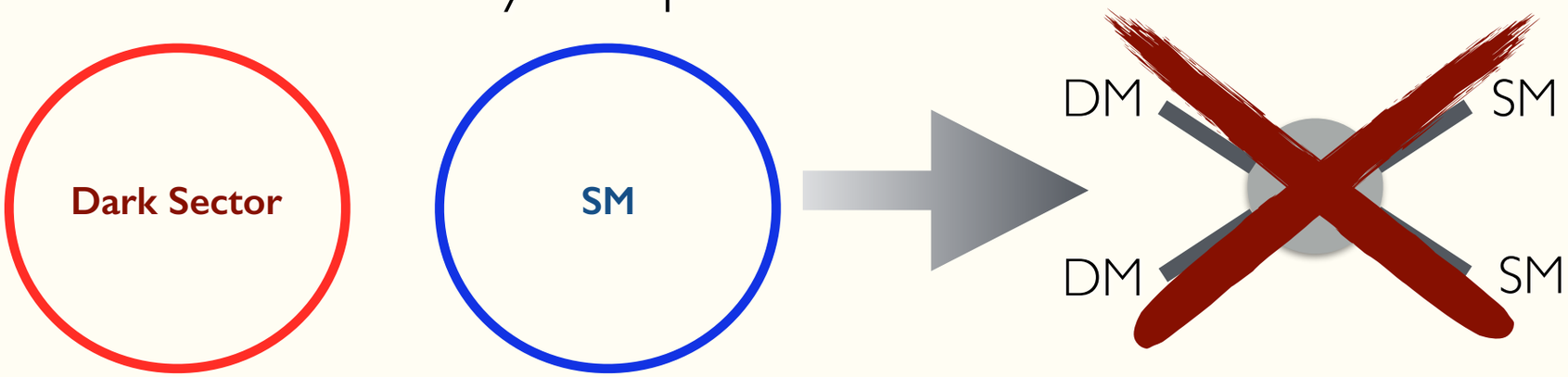

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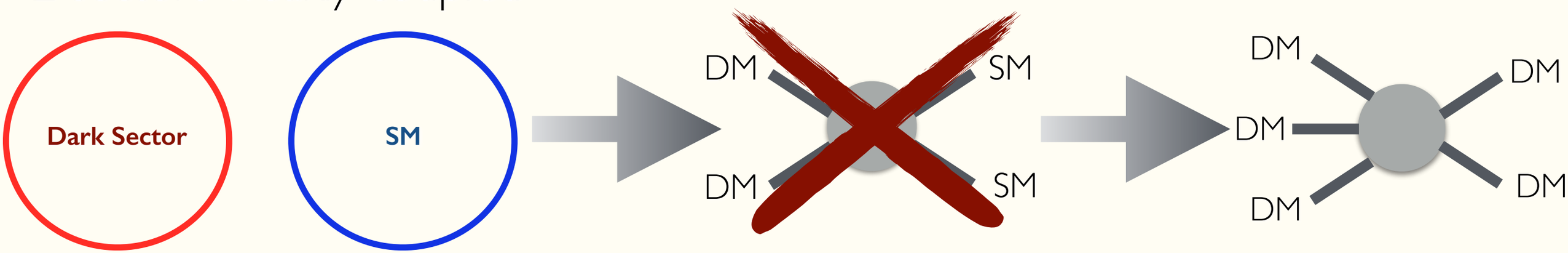

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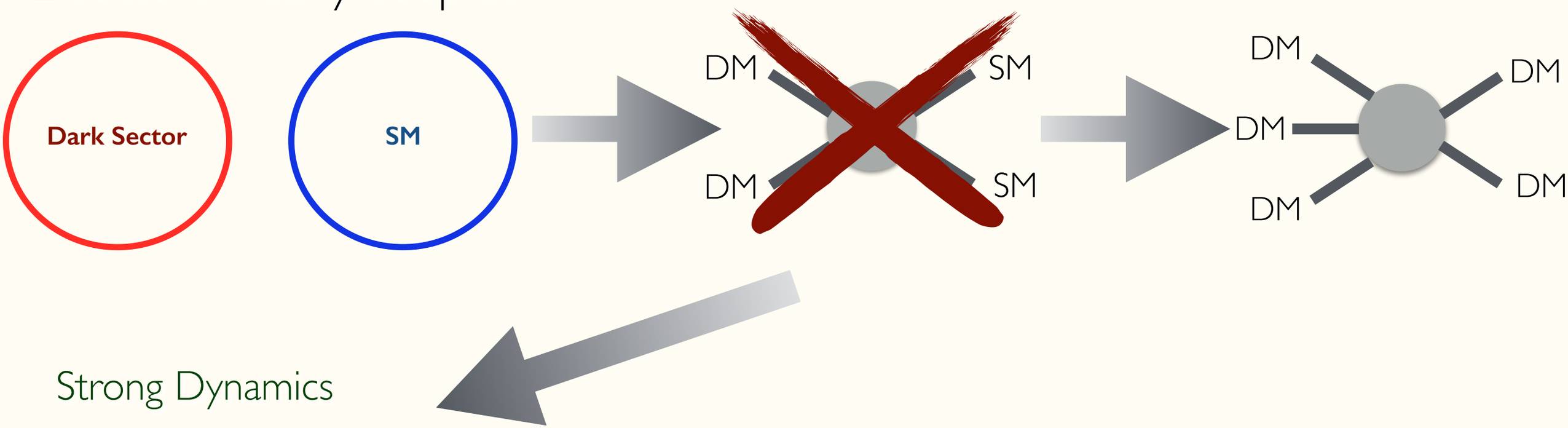

Strong Dynamics

$\alpha_{\rm eff} \simeq \mathcal{O}(1)$

Self-Interacting Dark Matter?

E.g.: The SIMP

[Carlson, Hall, Machacek, 1992; Kuflik, Hochberg, TV, Wacker, 2014; Kuflik, Hochberg, Murayama, TV, Wacker, 2014; Kuflik, Hochberg, Murayama, TV, Wacker, in progress]

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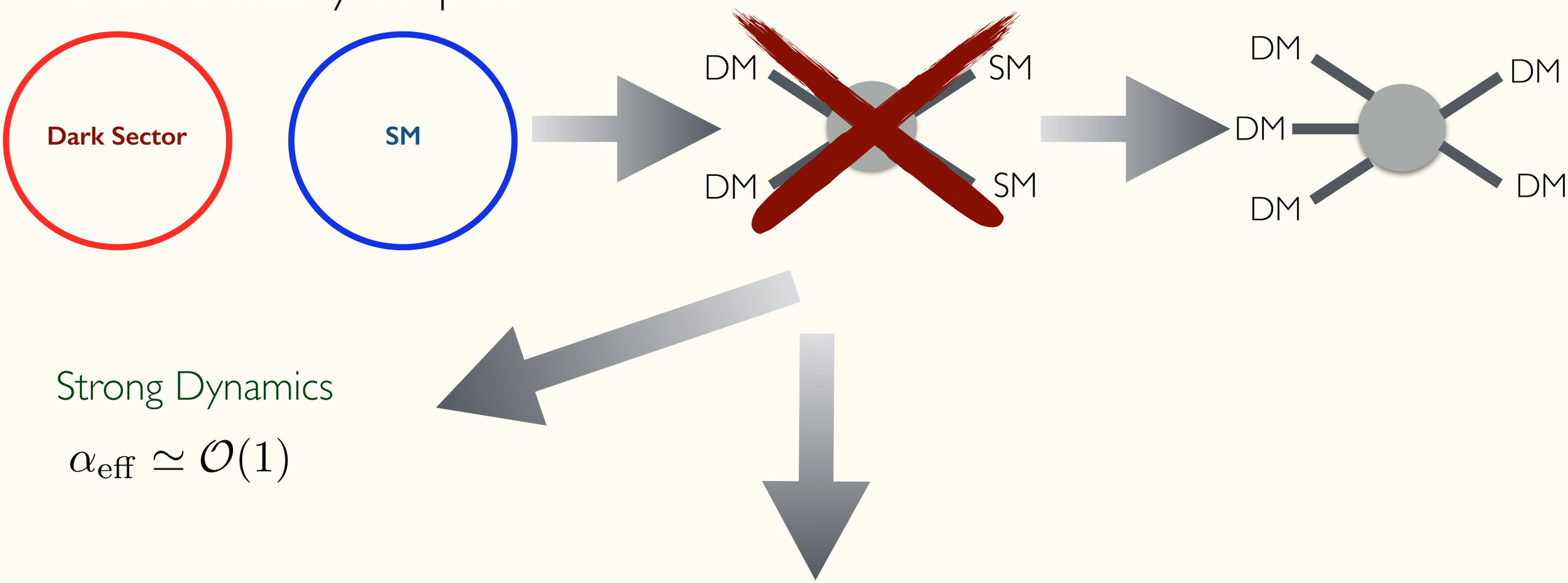

QCD (low!) scale emerges for a strongly-interacting sector.

$$m_{\rm DM} \simeq \alpha_{\rm eff} \left(T_{\rm eq}^2 M_{\rm Pl}\right)^{1/3} \sim 100 \text{ MeV}$$

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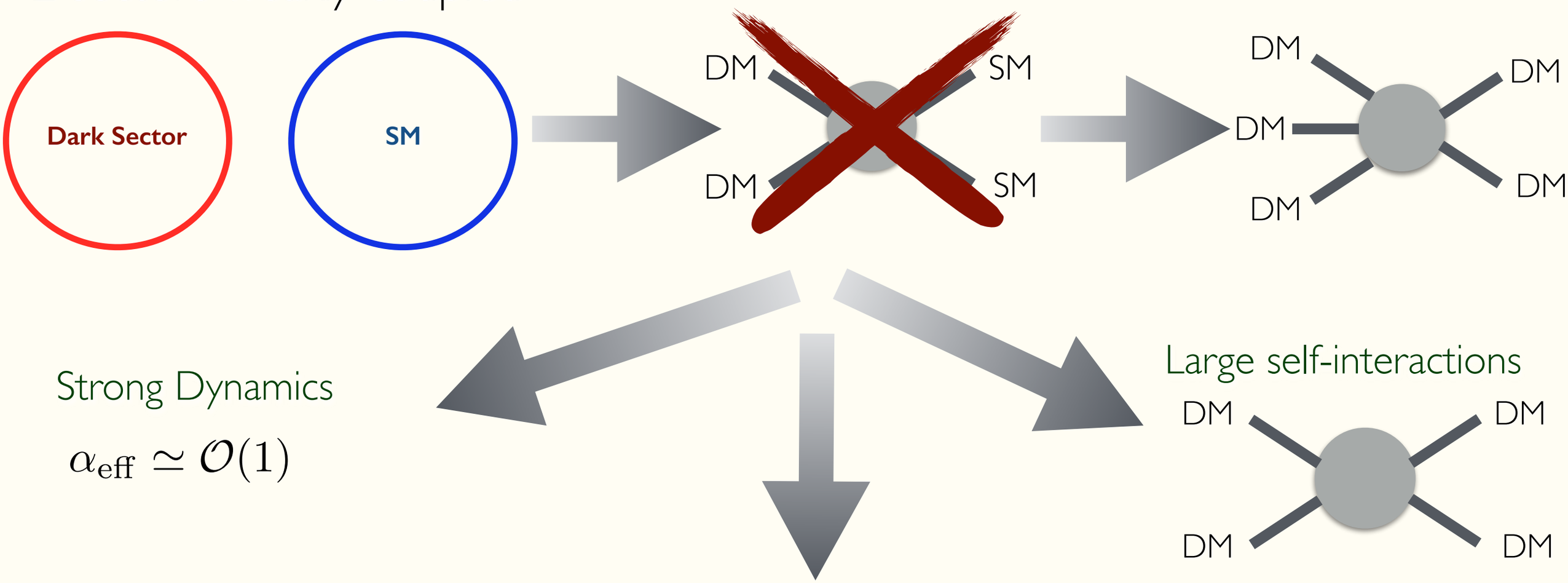

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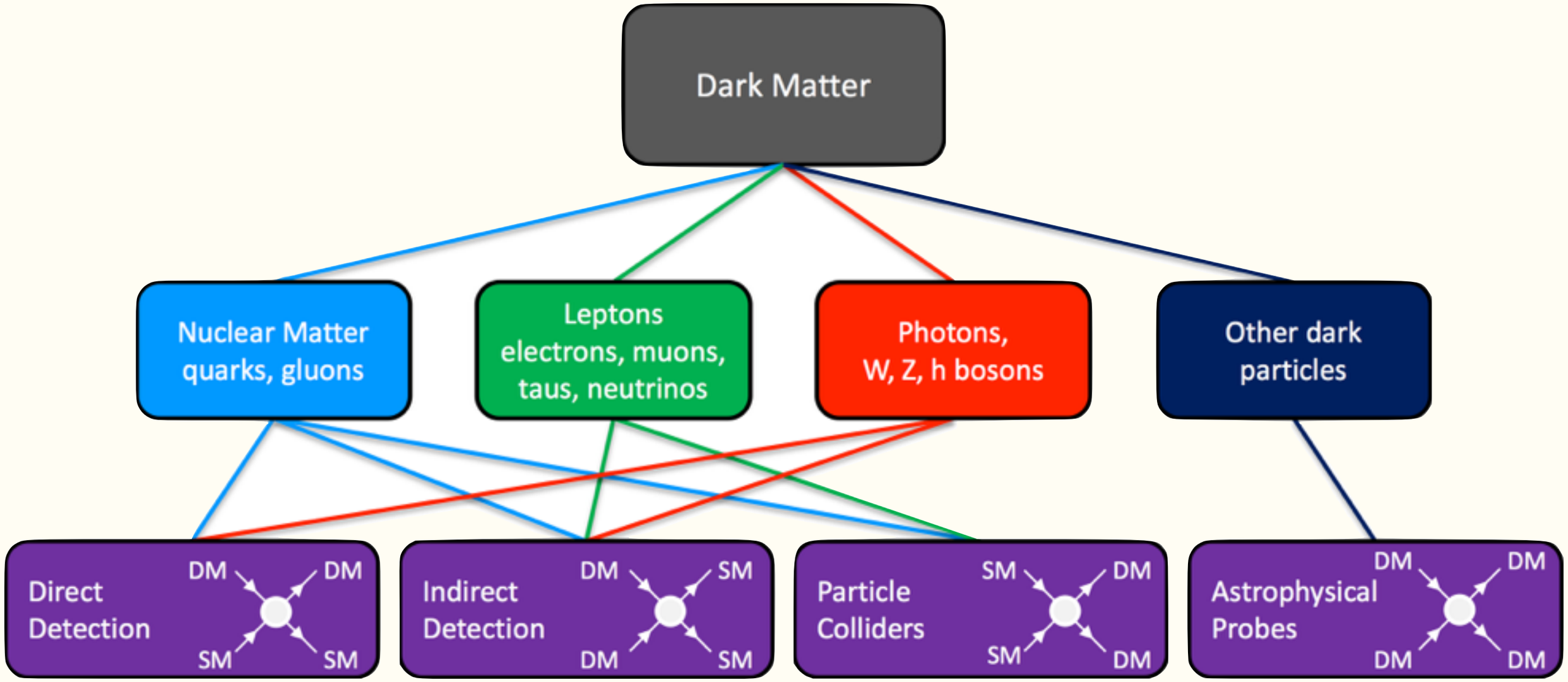
Searching for a Dark Sector

Searching for a Dark Sector

Searching for DM



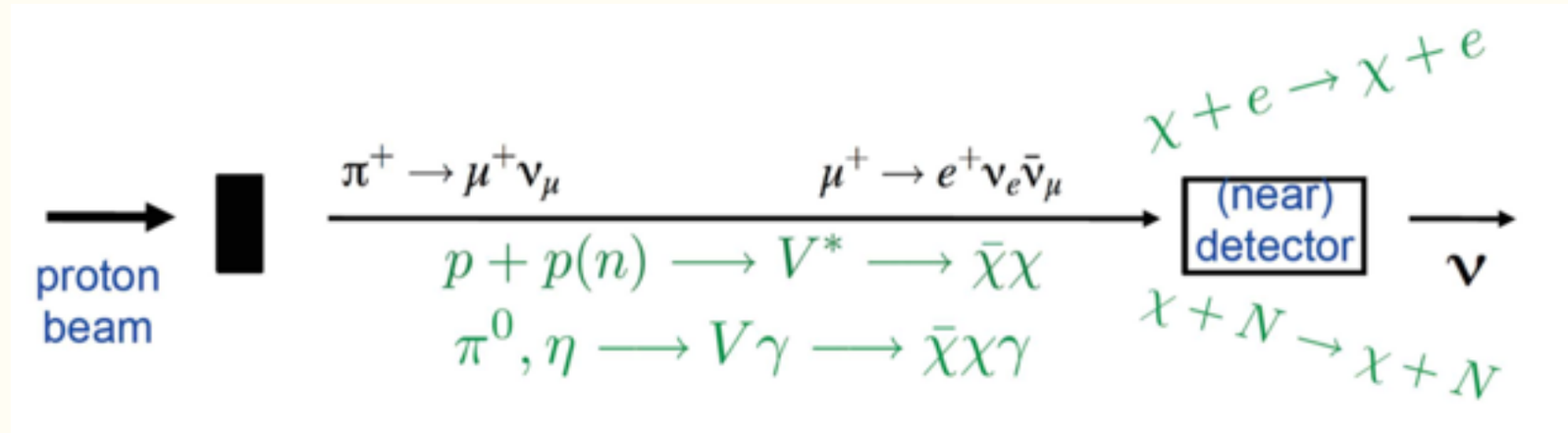
[Snowmass report, 2013]

Everything we've done for the WIMP should be repeated!

Which method is applicable depends strongly on the *production* and *mediation* scheme

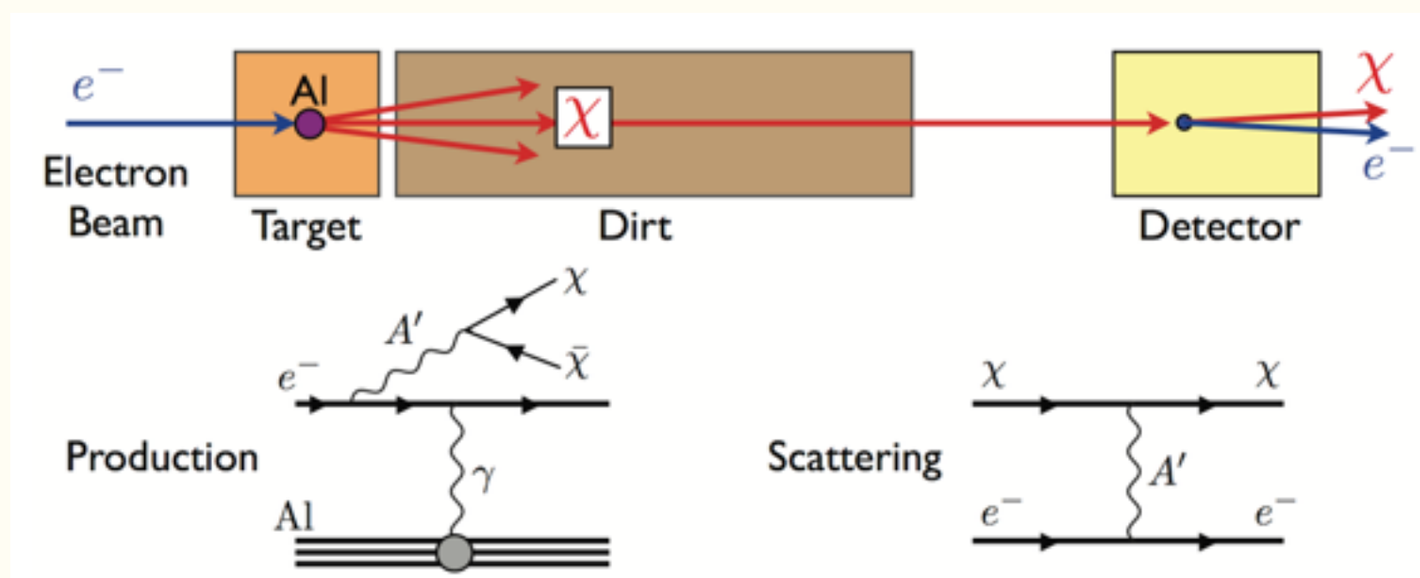
Beam-dump Experiments: A Dark Matter Beam

Neutrino Experiments



[MiniBooNE + Batell, deNiverville, McKeen, Pospelov, Ritz 2012]

Electron Beam-dumps

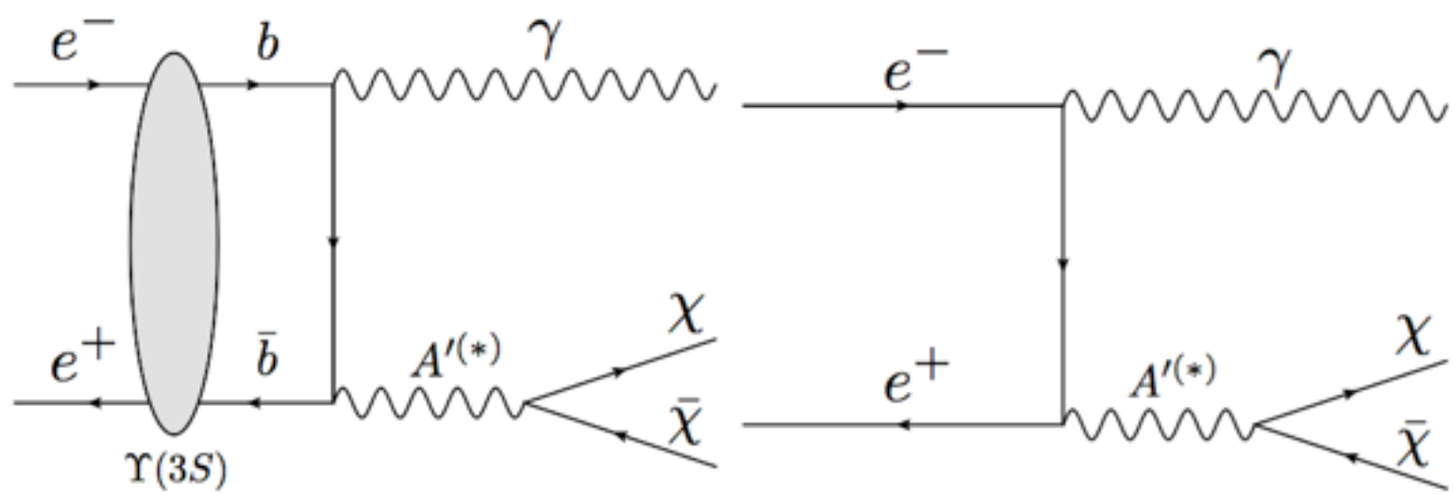


[Batell, Essig, Surujon 2014]

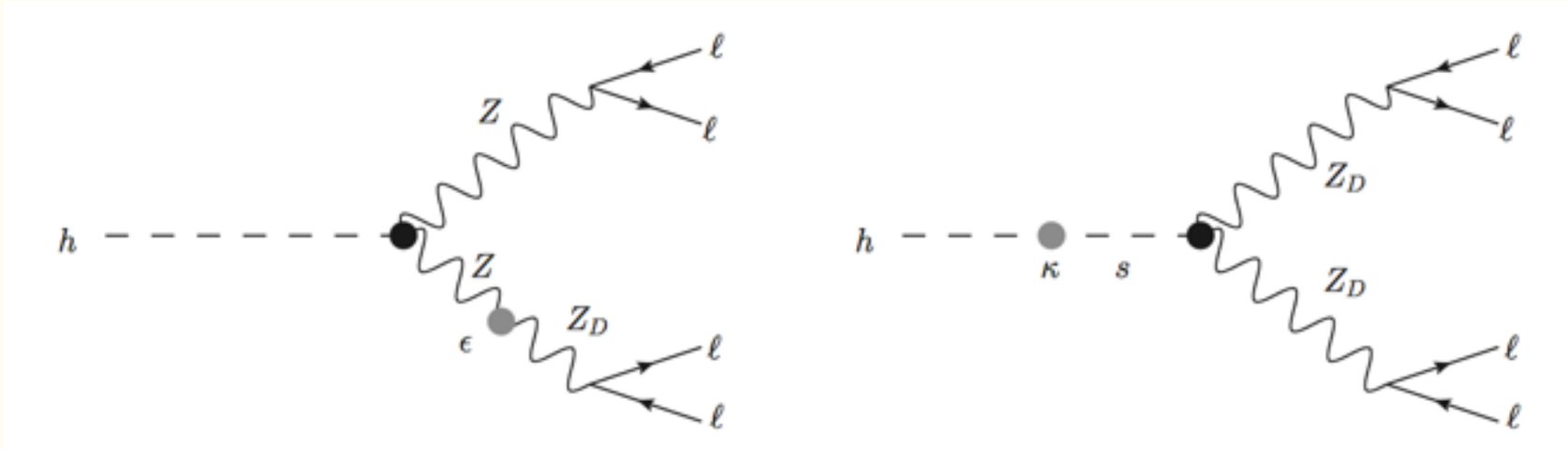
Colliders: Searching for the Mediator

[Bird et al. 2004; McElrath 2005; Fayel 20105; Dreiner et al. 2009;
Borodatchenkova et al. 2006; Reece, Wang 2009; Essig., Mardon, Papucci, TV, Zhong, 2013]

Low-E Colliders



High-E Colliders



[Curtin, Essig, Gori, Shelton, 2014]

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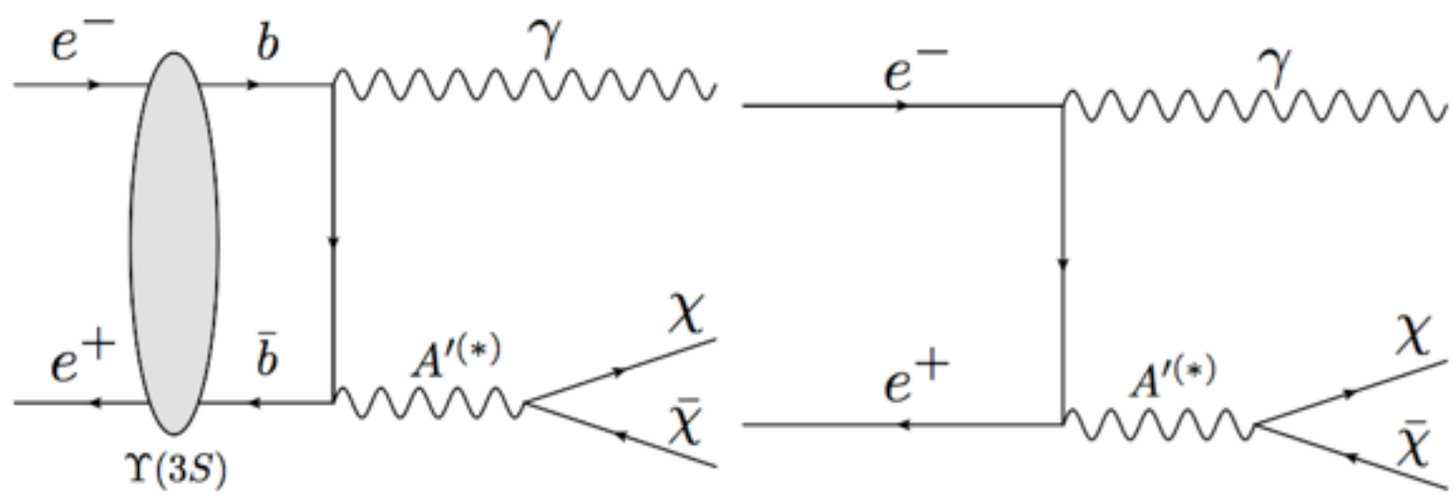
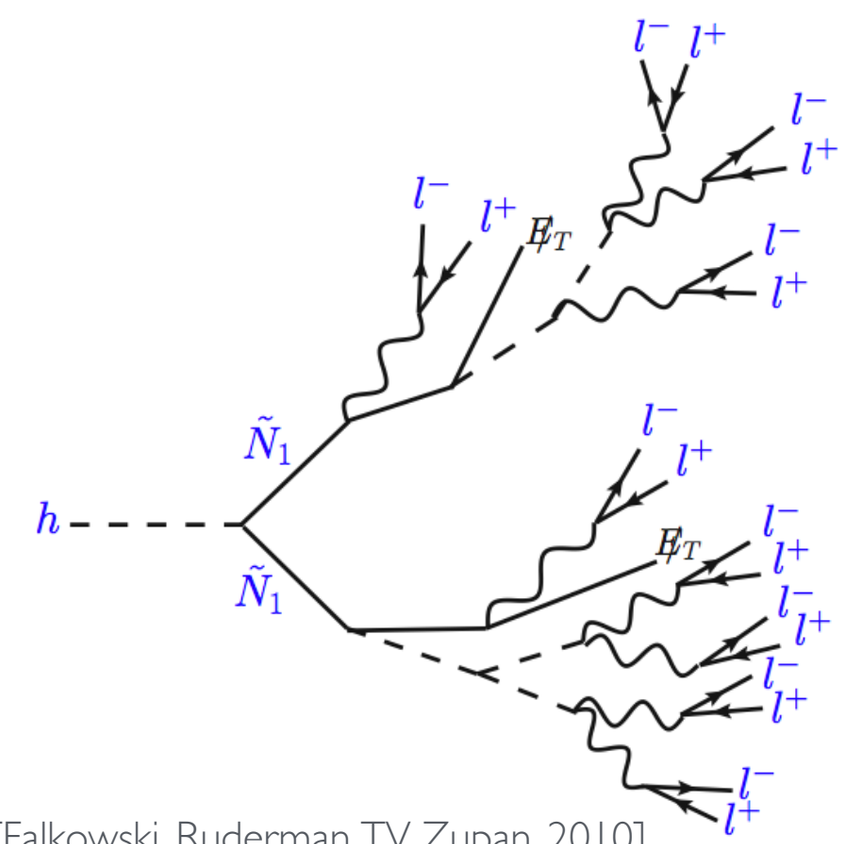
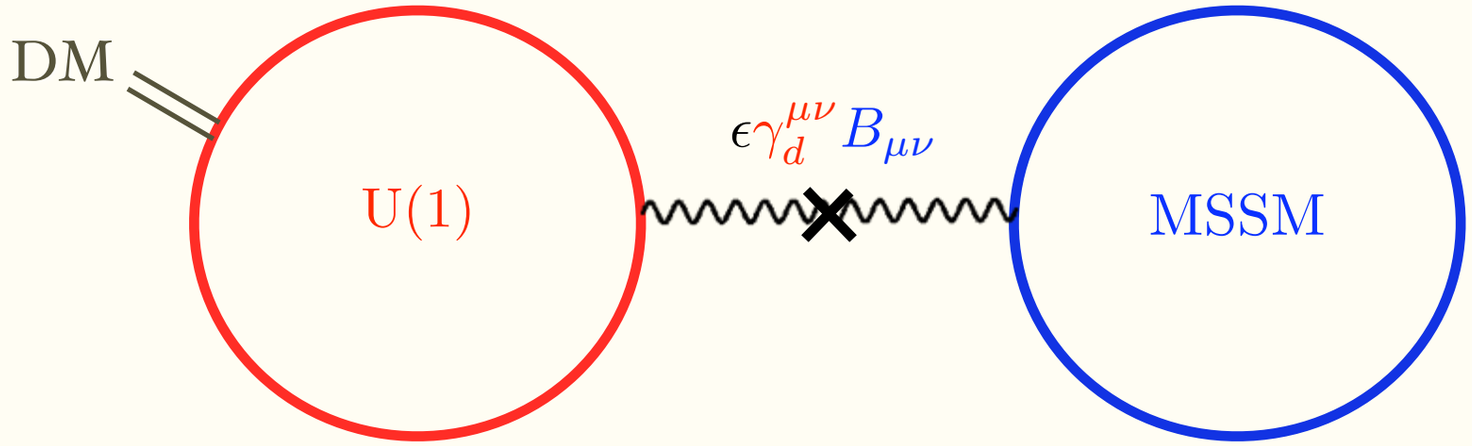


High-E Colliders

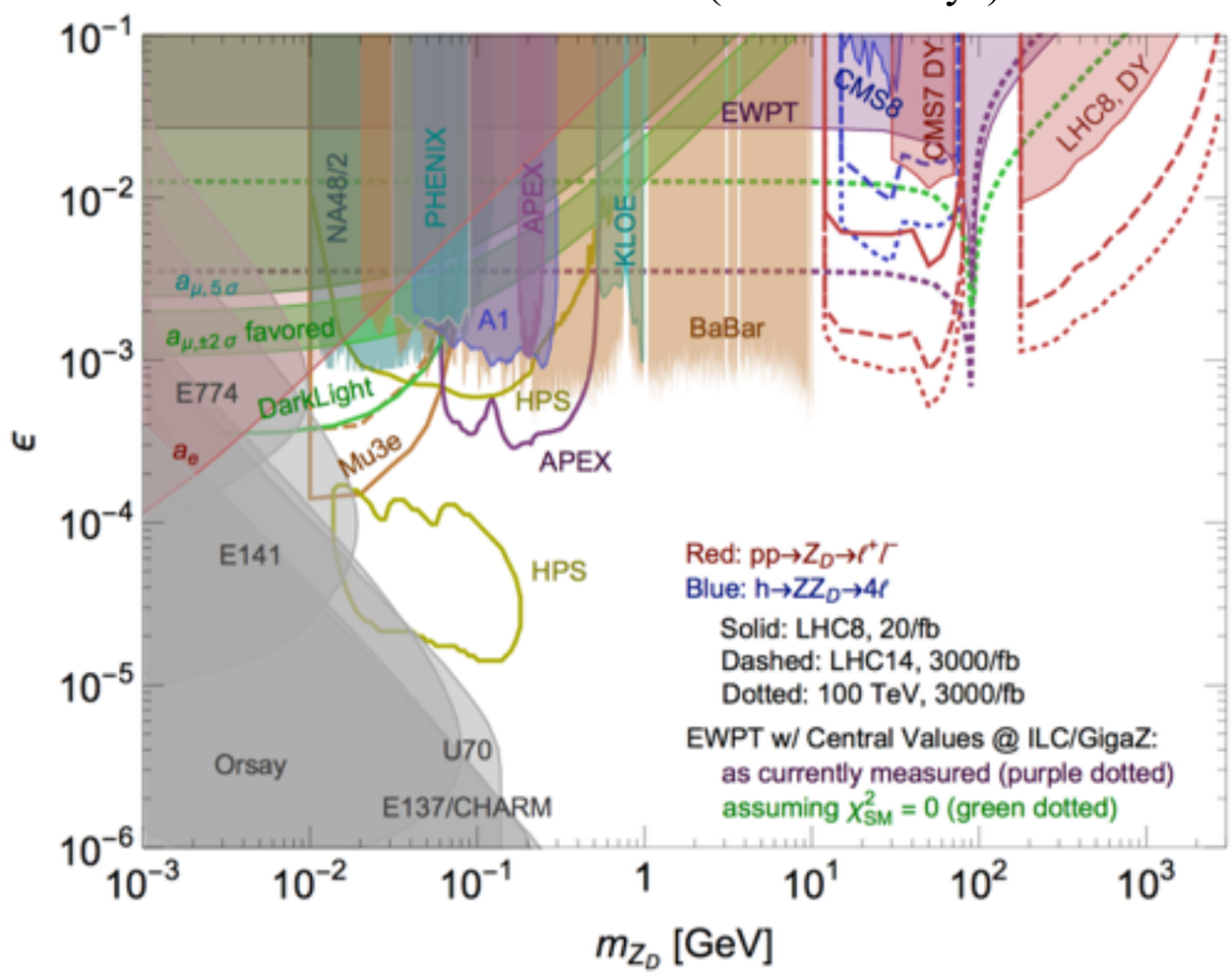


[Falkowski, Ruderman, TV, Zupan, 2010]

Collider and Beam-dumps: Selected Results

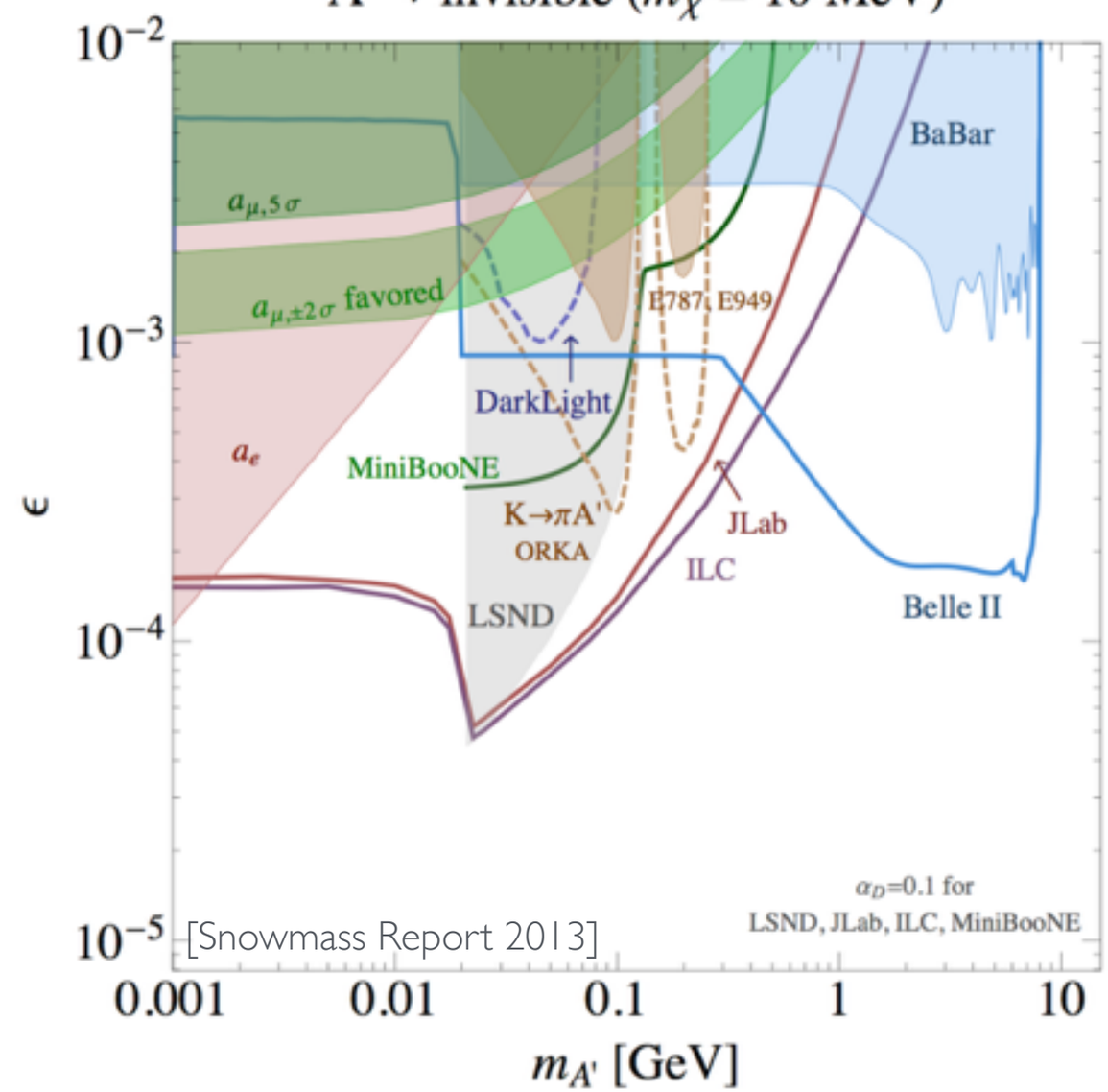


Hidden Photons (visible decays)



[Curtin, Essig, Gori, Shelton, 2014]

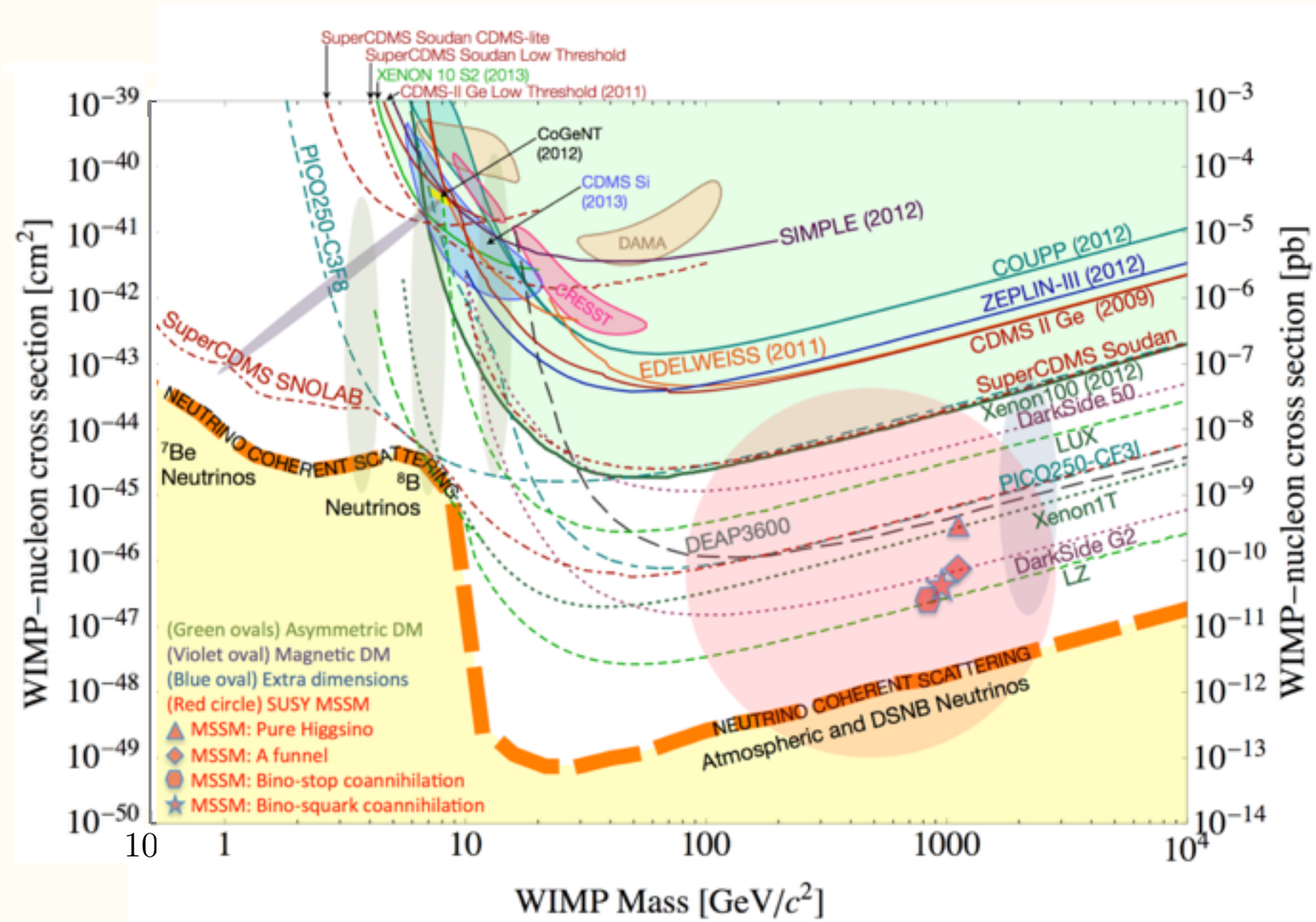
A' → invisible (m_χ = 10 MeV)



[Snowmass Report 2013]

Prospects for Direct Detection

Current experiments: Search for elastic nuclear recoils.
Extremely inefficient for light DM!



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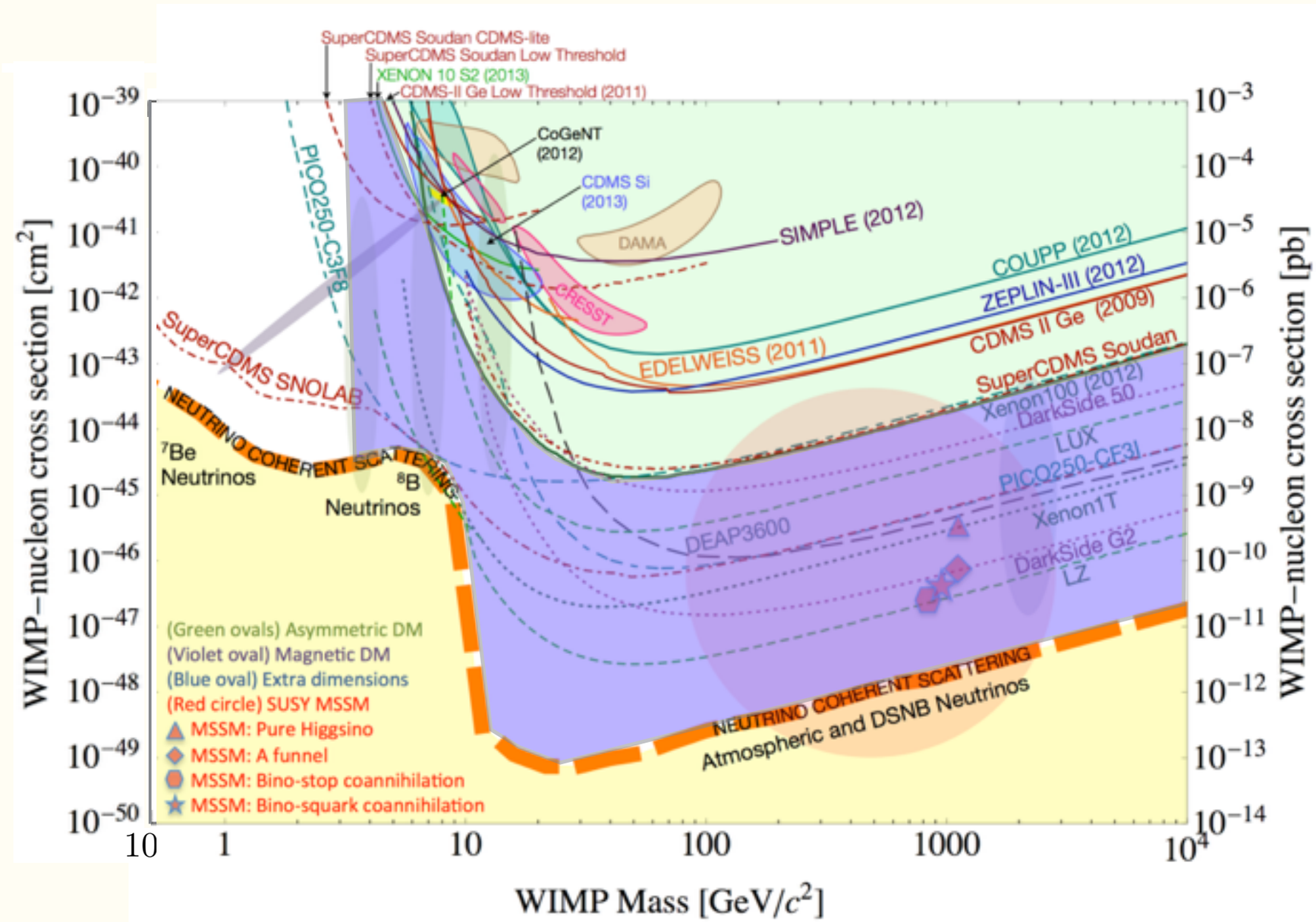

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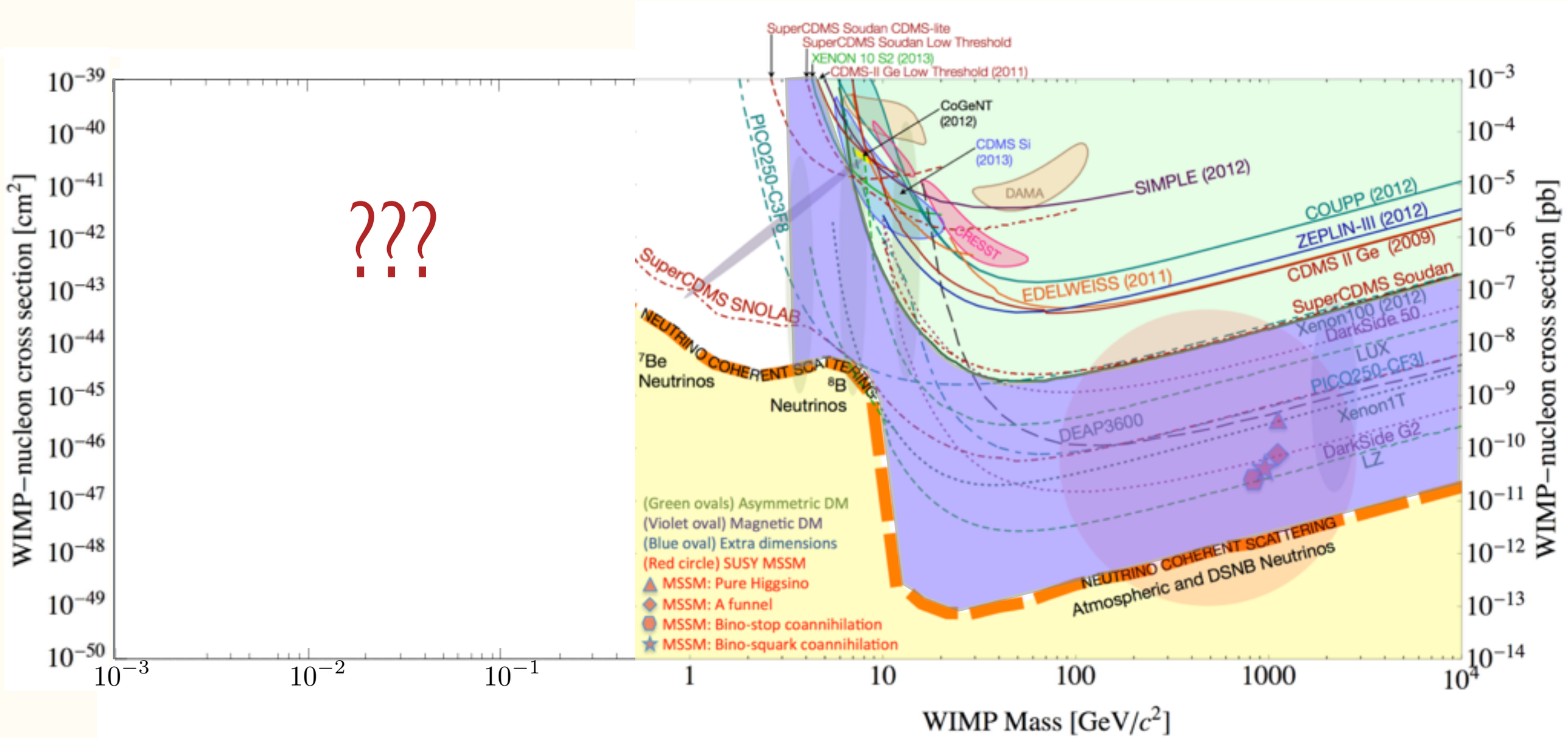
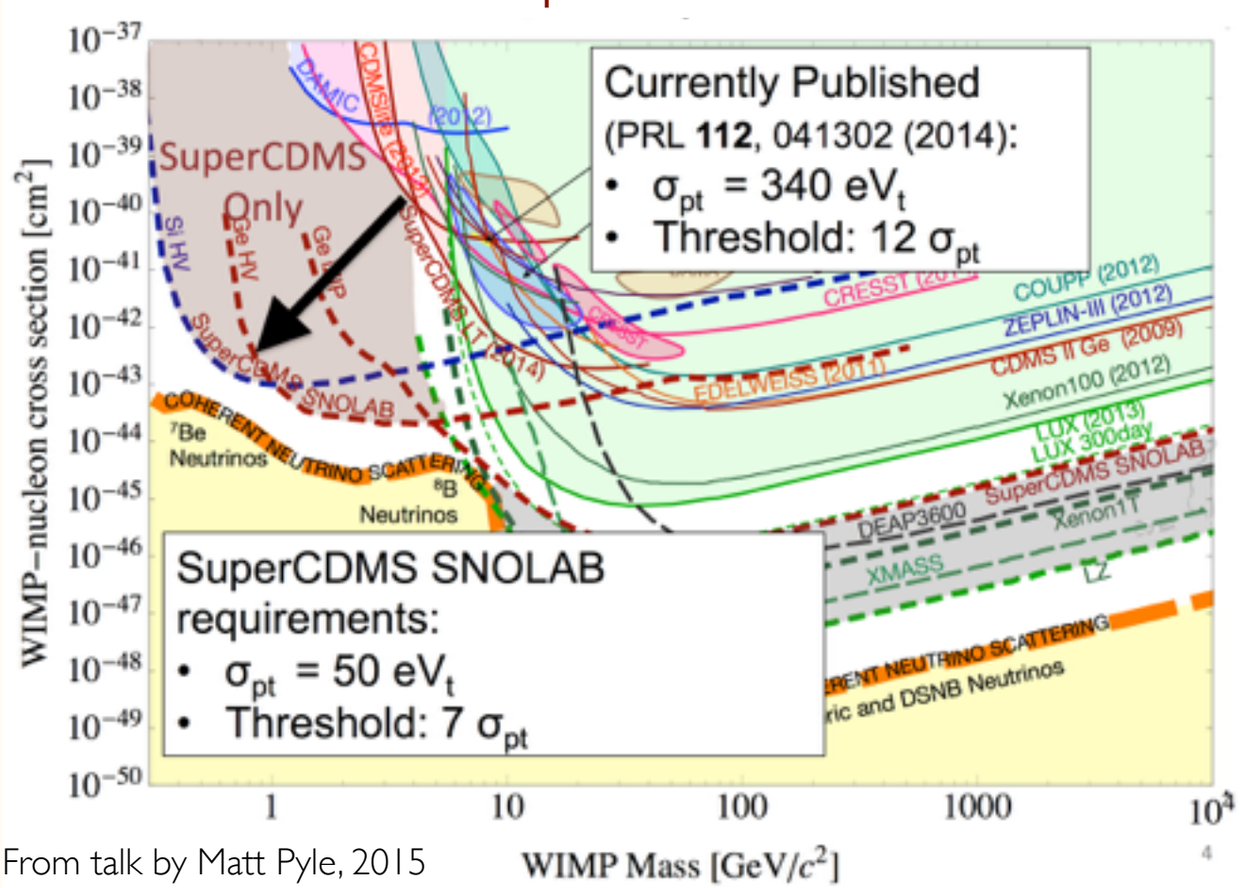


Direct Detection of Light and Exotic DM

- Two basic efforts:
  - Lower threshold of existing techniques (DM-nucleon elastic scattering)

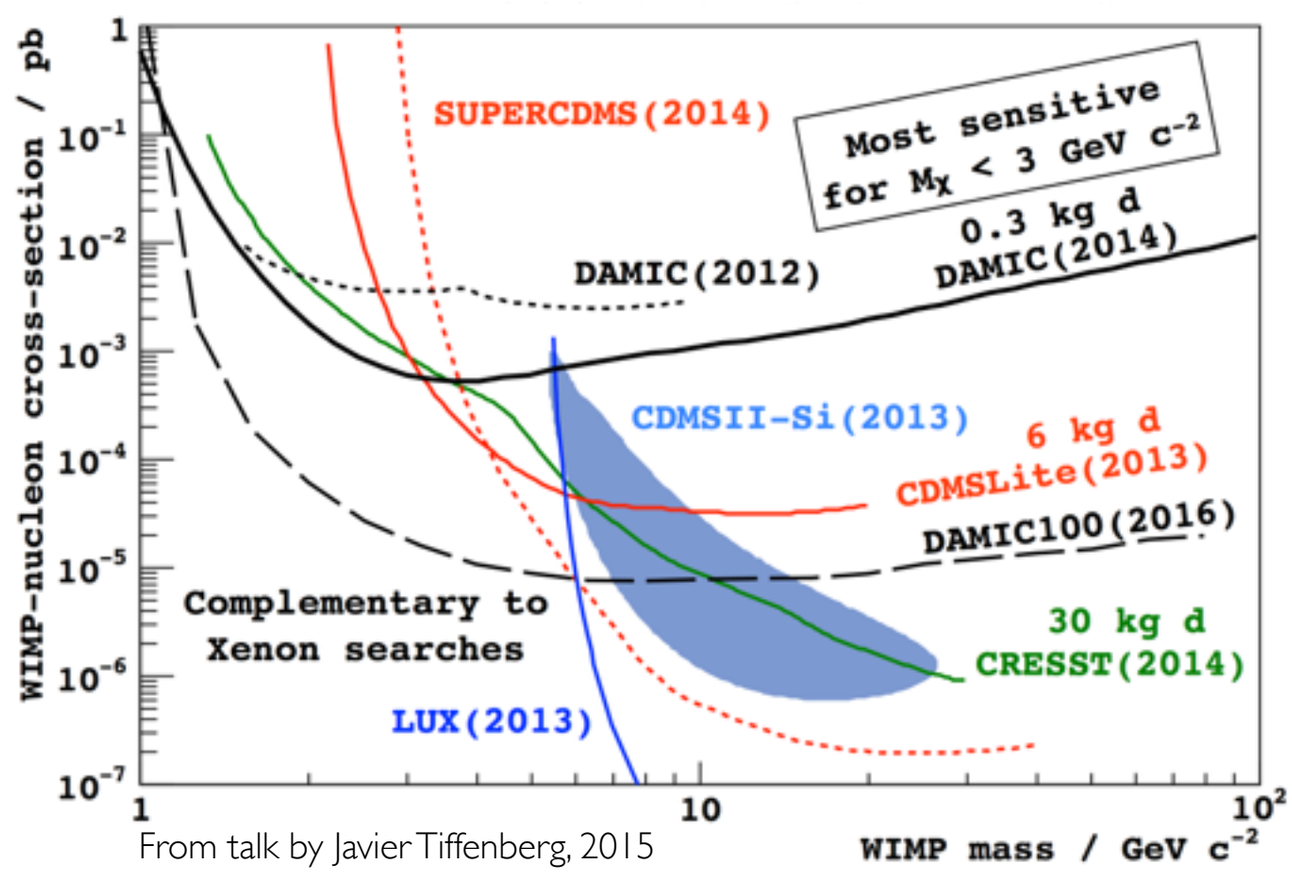
Threshold ≳ 10-50 eV

SuperCDMS



From talk by Matt Pyle, 2015

DAMIC



From talk by Javier Tiffenberg, 2015

Direct Detection of Light and Exotic DM

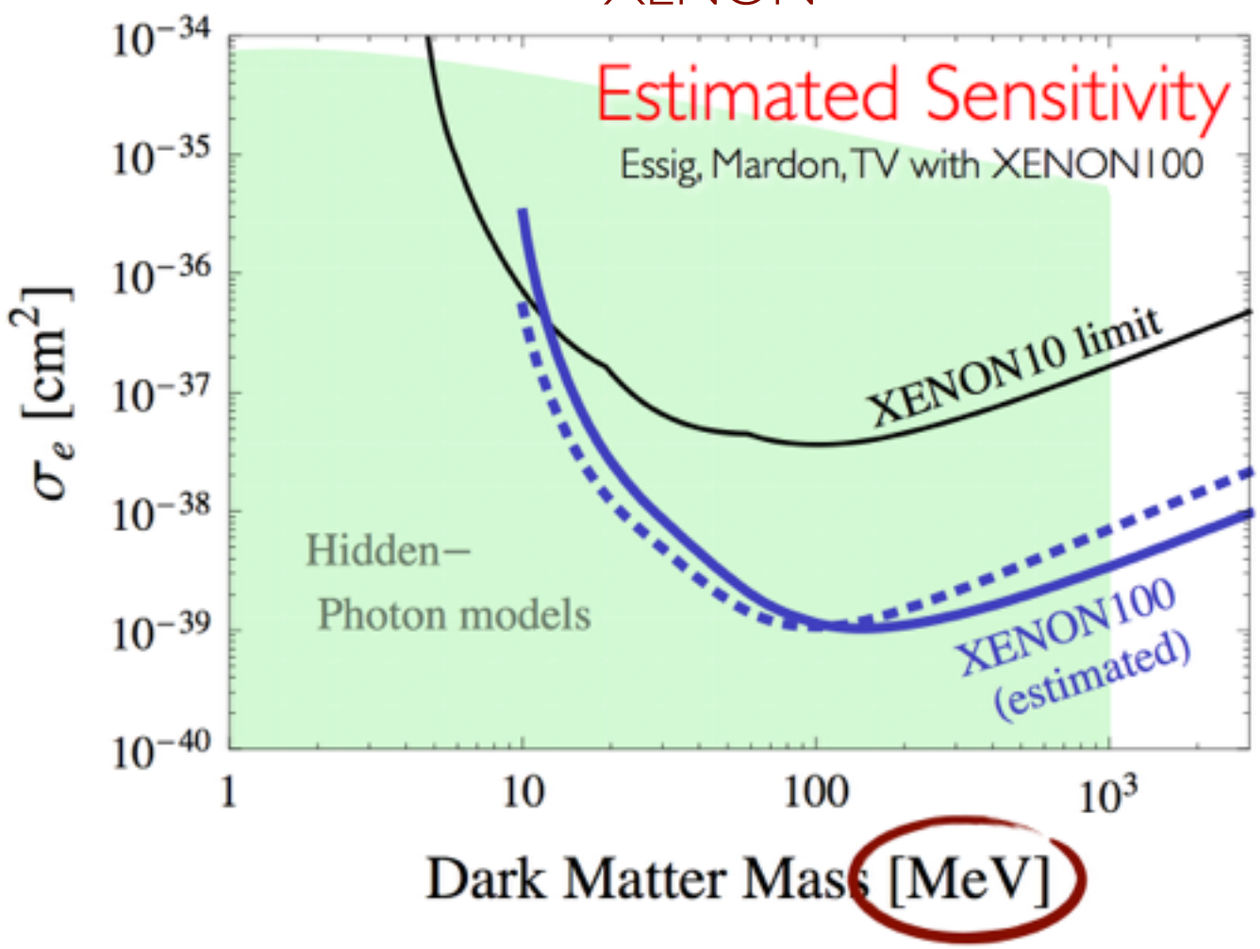
- Two basic efforts:
  - Lower threshold of existing techniques (DM-nucleon elastic scattering)
  - Search for inelastic processes (DM-electron and DM-nucleon scattering)

[Essig, Mardon, TV, 2011]

Threshold $\gtrsim$ 0.1 eV

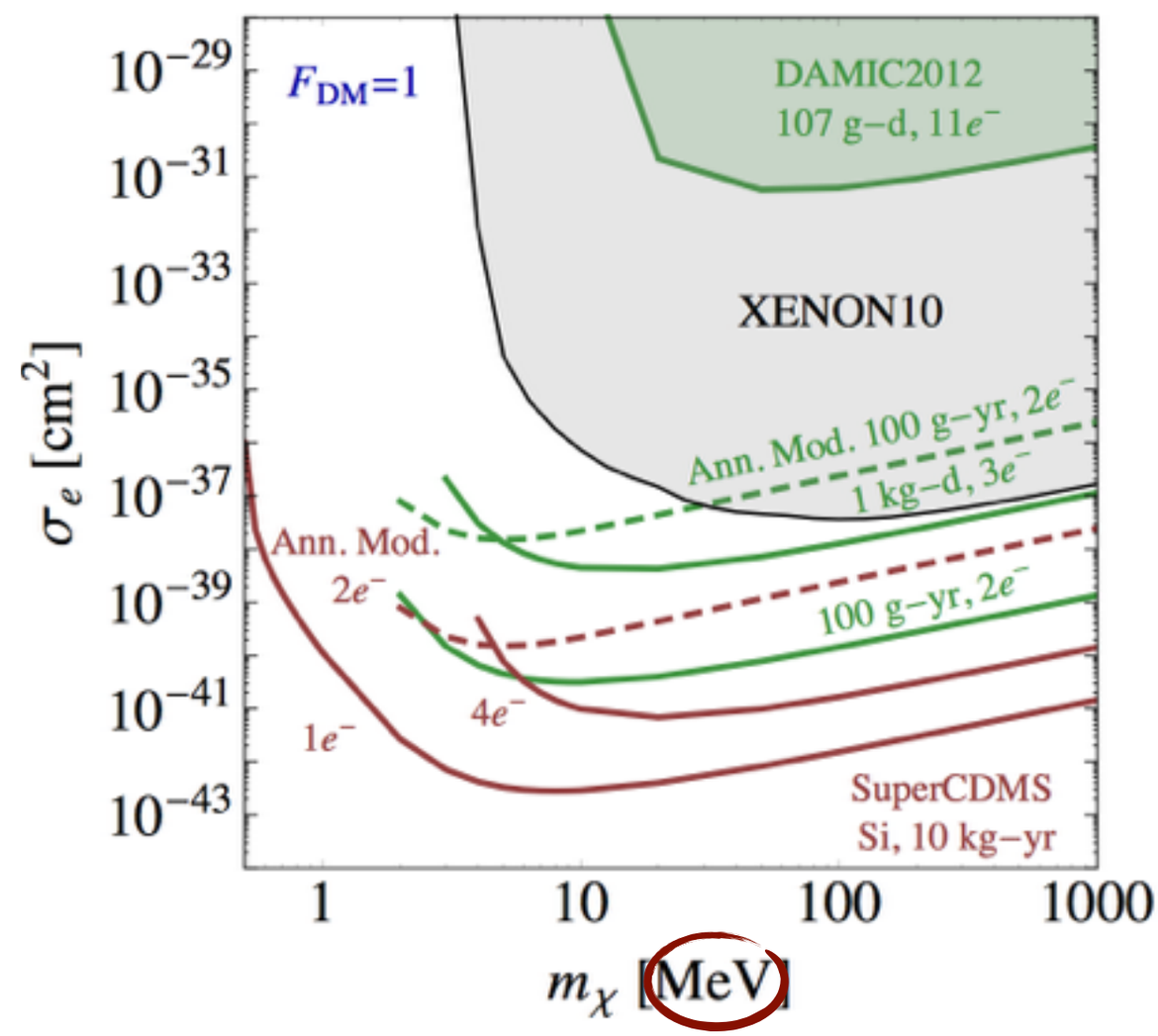
Direct Detection of Light and Exotic DM

XENON



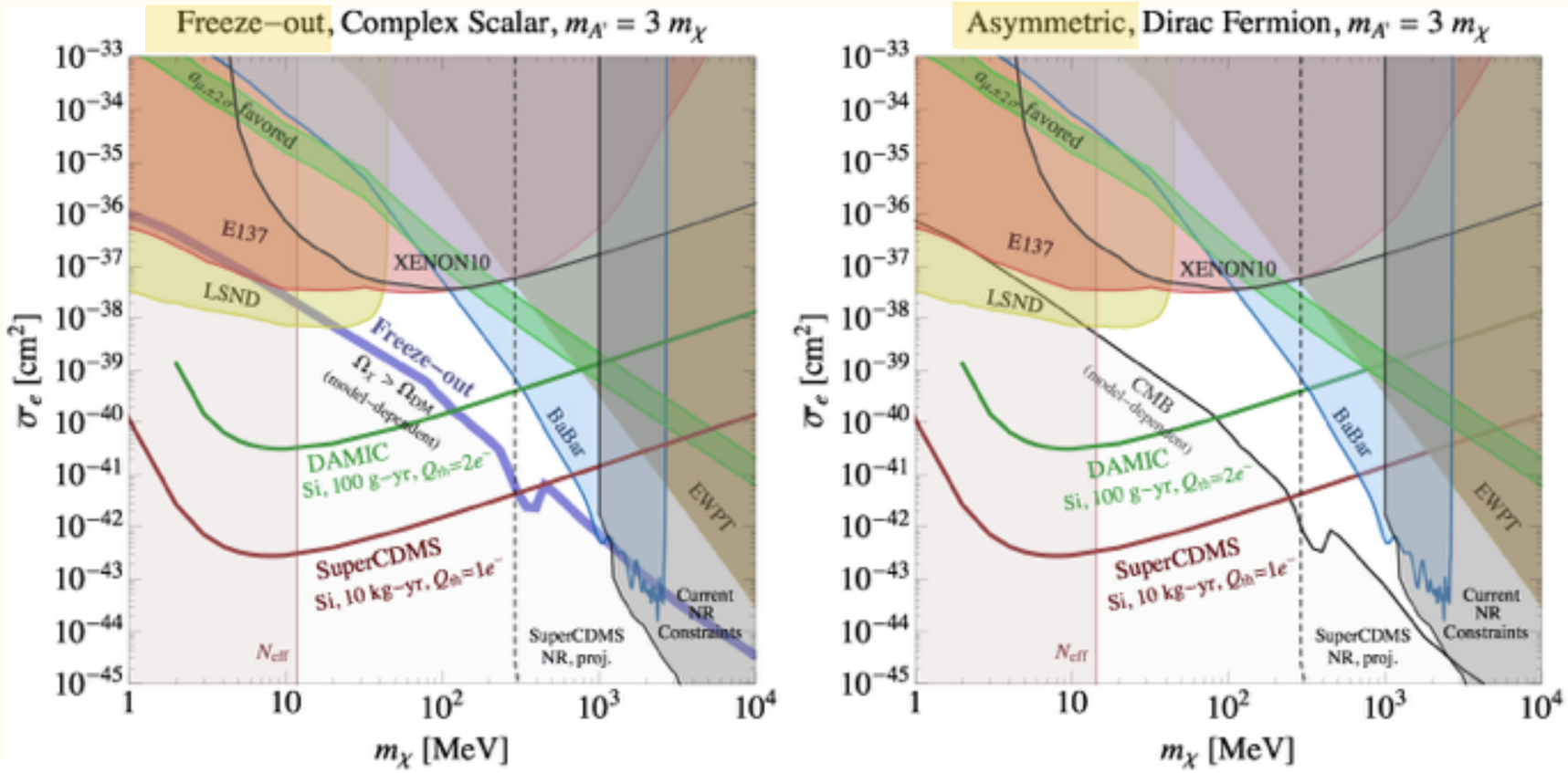
[Essig, Manalaysay, Mardon, Sorensen, TV, 2012;
Essig, Mardon, TV, XENON100 (upcoming)]

SuperCDMS and DAMIC



[Essig, Fernandez-Serra, Mardon, Soto, TV, Yu, 2015]

Direct Detection of Light and Exotic DM

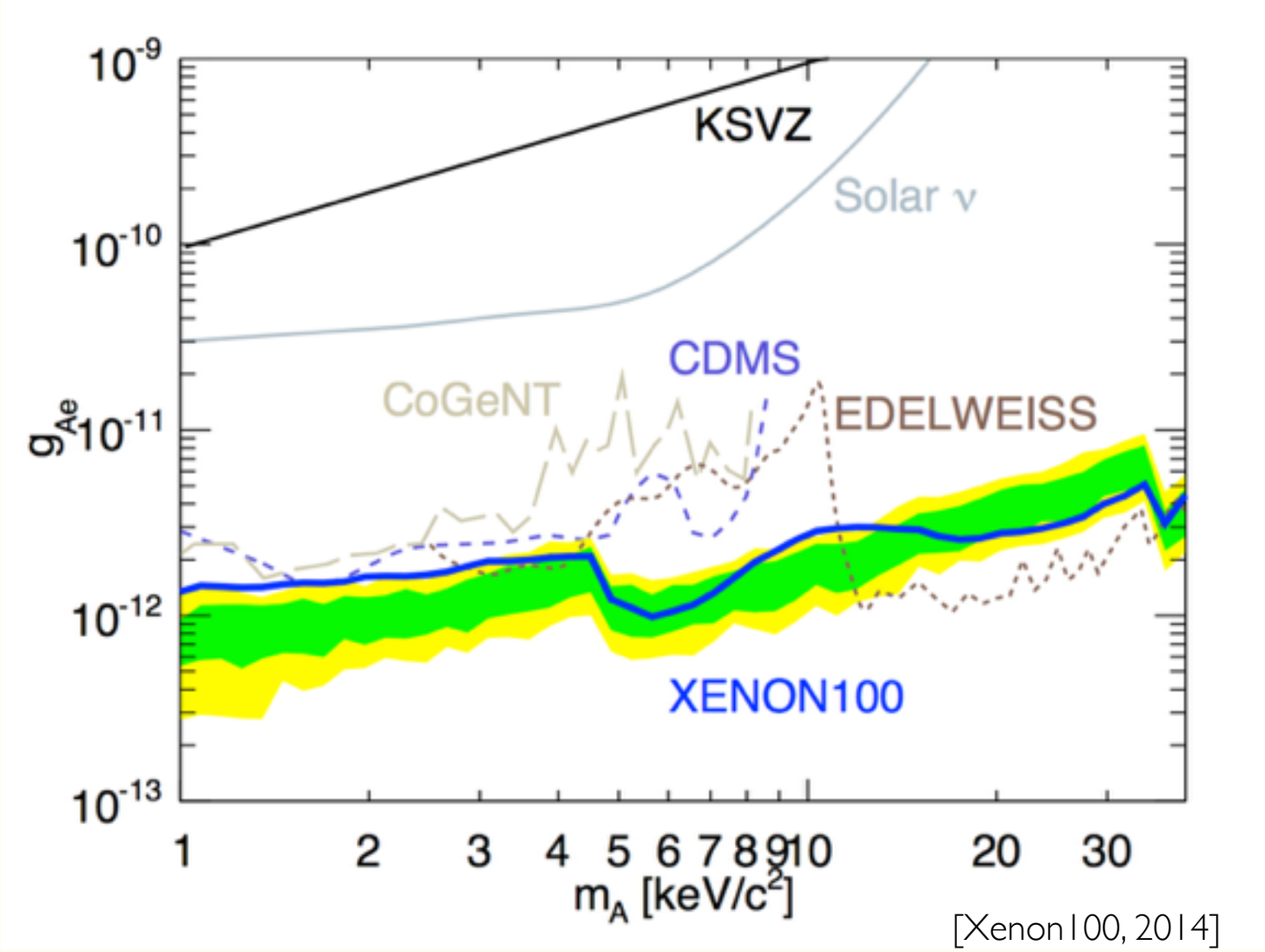


[Essig, Fernandez-Serra, Mardon, Soto, TV, Yu, 2015]

Upcoming and existing direct detection constraints from DM-electron recoil are sensitive to many interesting theories

Direct Detection of Light and Exotic DM

Electron Ionization is also sensitive to Axions!



[Xenon100, 2014]

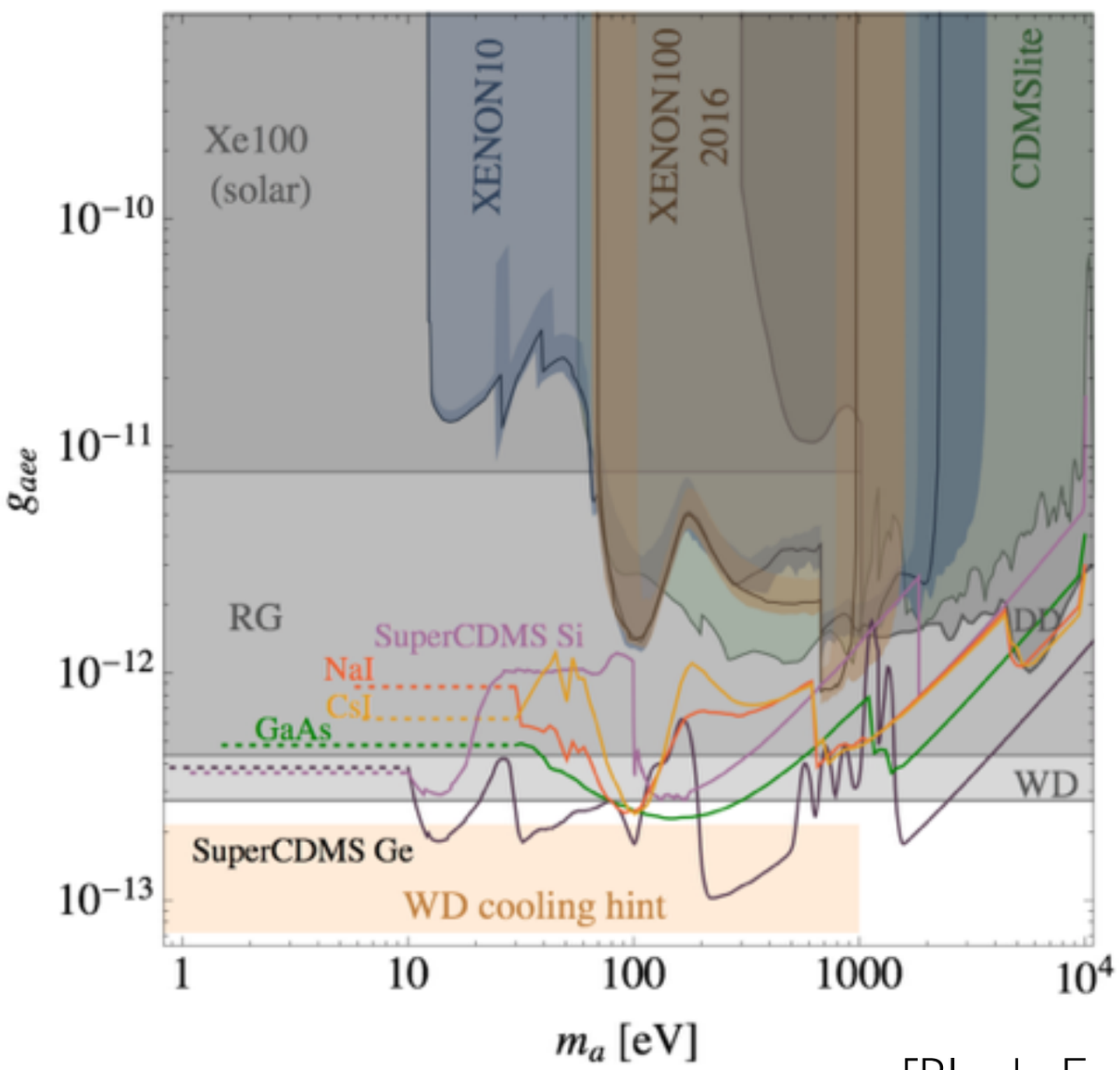
S2-only analysis can significantly lower the threshold and demonstrate sensitivity to lighter axions.

[Bloch, TV, in progress]

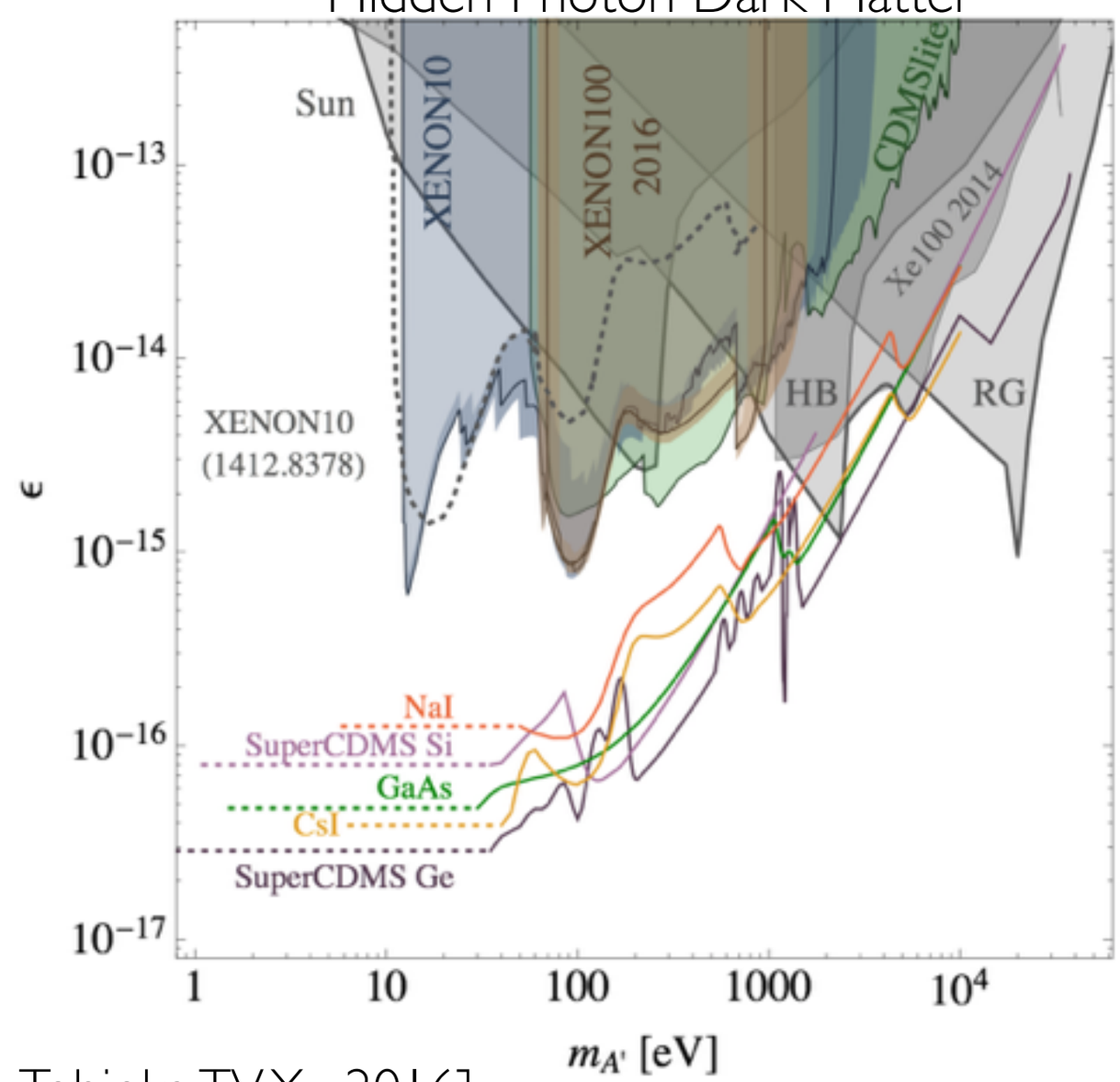
Direct Detection of Light and Exotic DM

S2-only analysis can significantly lower the threshold and demonstrate sensitivity to lighter axions and hidden photons.

Axion-Like Particles



Hidden Photon Dark Matter



[Bloch, Essig, Tobioka, TV, Yu, 2016]

Direct Detection of Light and Exotic DM

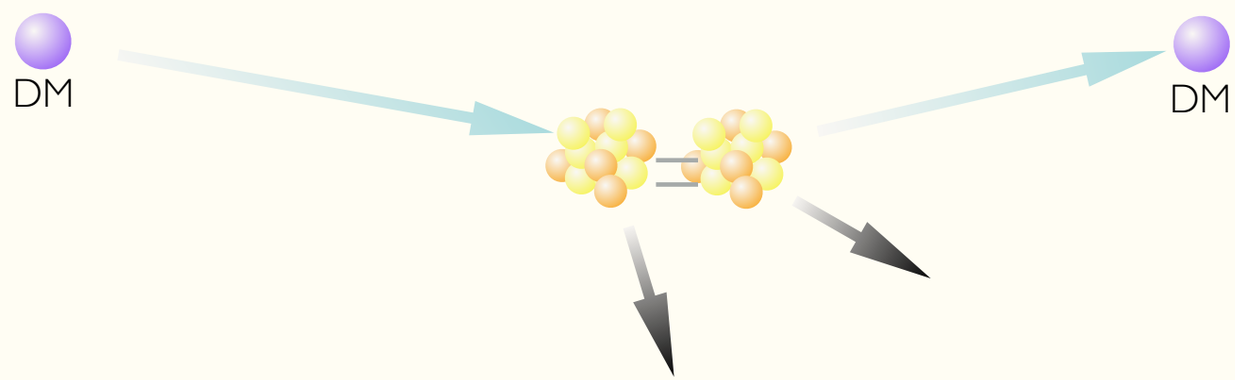
- Several new technologies have been suggested in recent years.

[Essig, Mardon, TV, 2011; Anderson, Figueroa-Feliciano, Formaggio, 2011; Drukier, Nussinov, 2013; Agnes et al. 2014; Hochberg, Zhao, Zurek, 2015; Essig, Mardon, Slone, TV, 2015 (upcoming)]

- One effort:

Concept

[Essig, Mardon, Slone, TV, 1605.xxxxx]



Ultra-low threshold (1eV - 10's of eV)

2-3 orders of magnitude below existing technologies

In crystals: search for color-center defects produced due to interaction with dark matter.

[Budnik, Chechnovsky, Slone, TV, 1605/6.xxxxx]

Direct Detection of Light and Exotic DM

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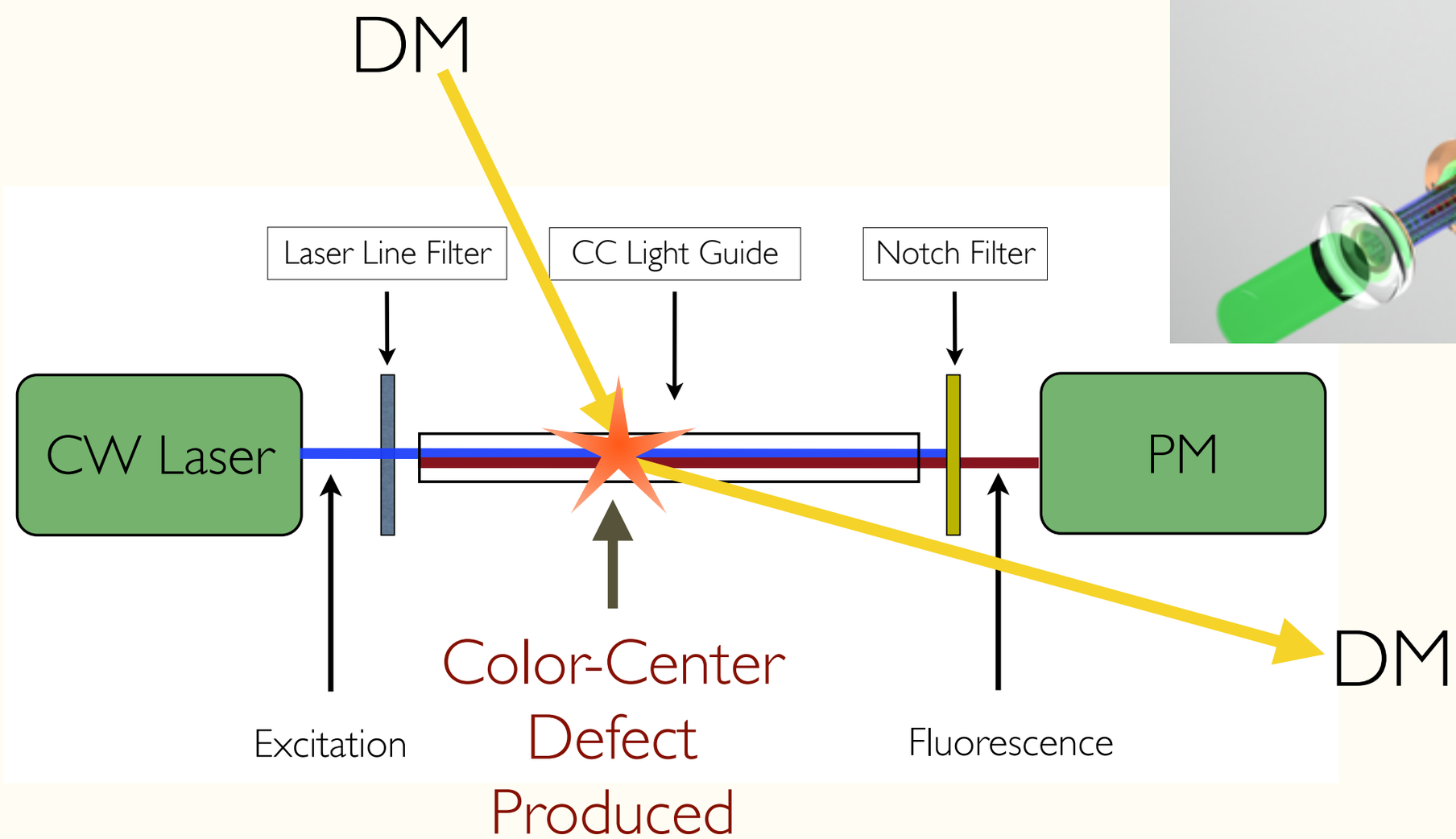
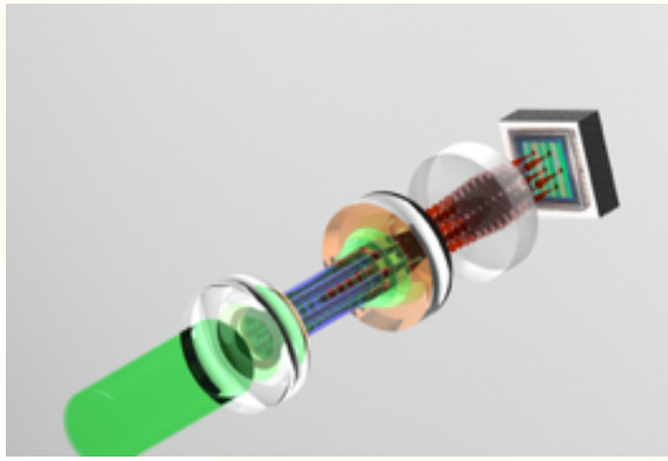
- One effort:

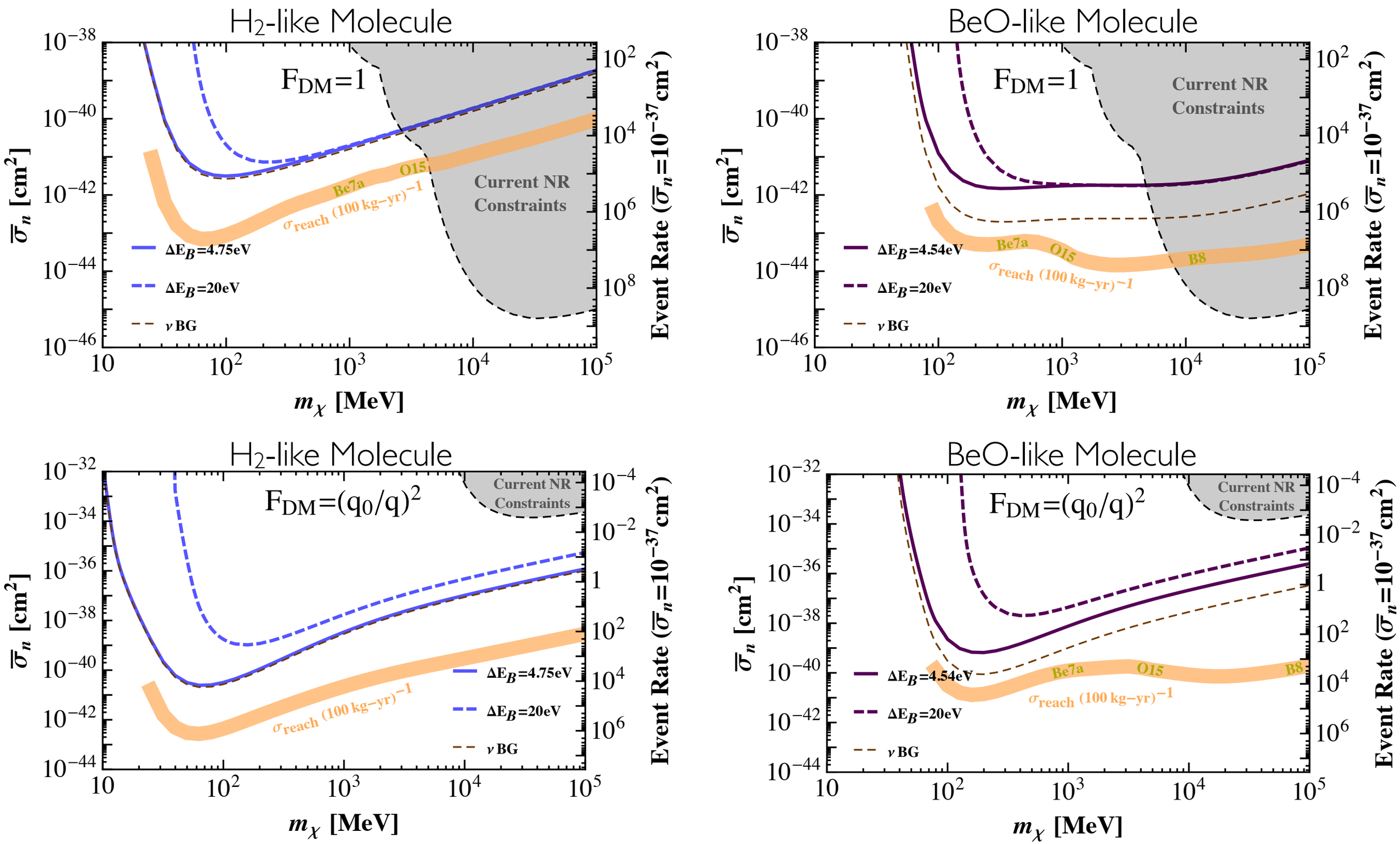




New theory-experimental collaboration. New lab opened.

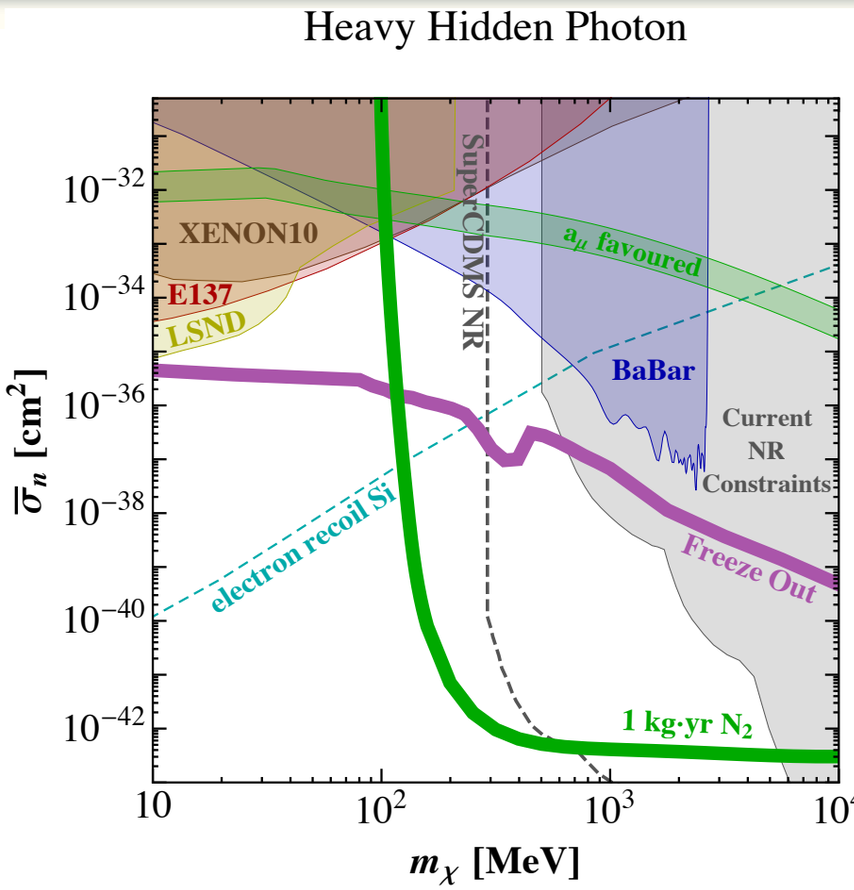
Bloch, Essig, Mardon, Slone, TV, Budnik, Chechnovsky, Kreisel, Soffer, Landsman, Mosbacher, Priel

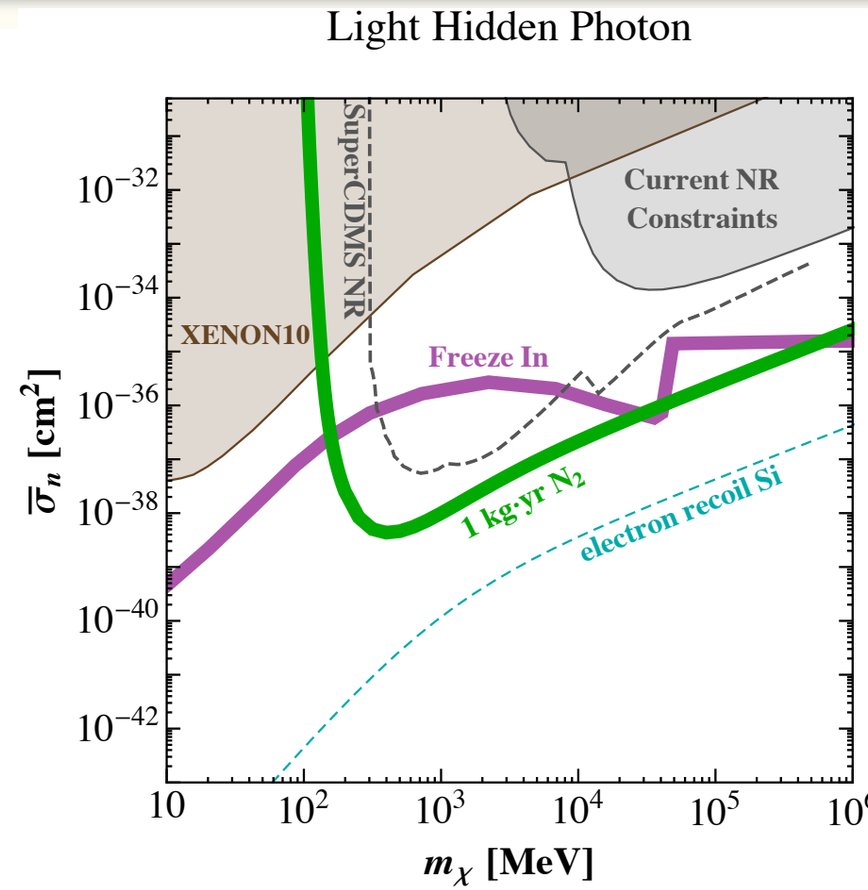
Direct Detection of Light and Exotic DM

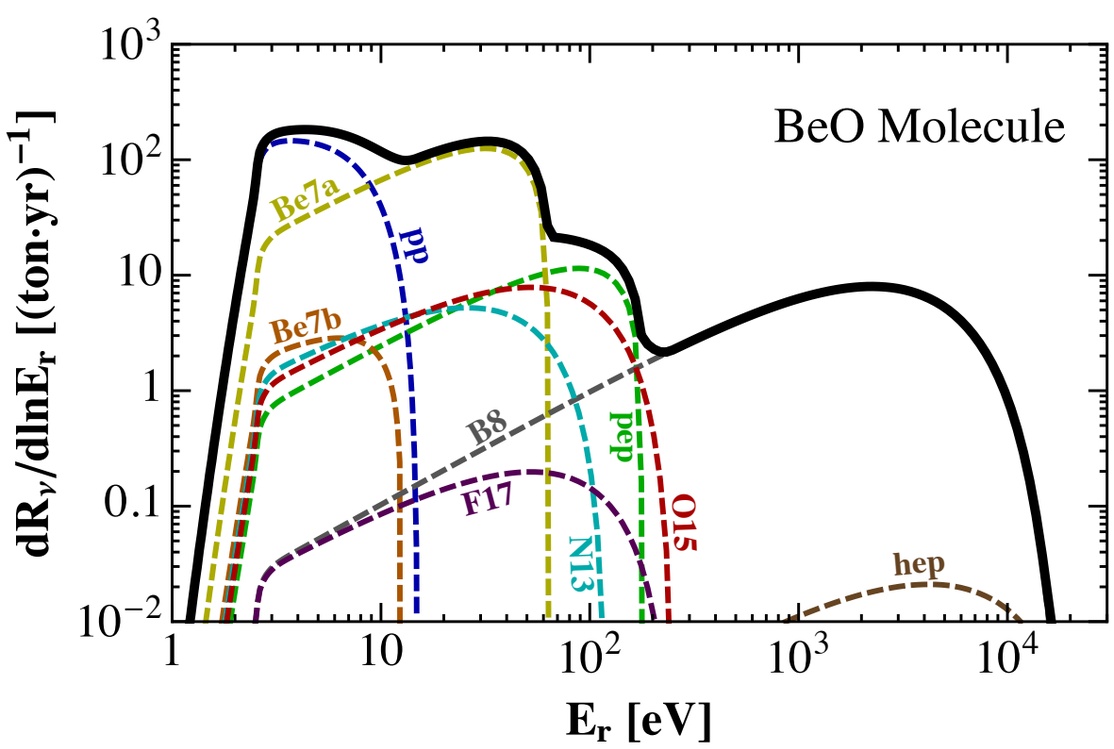


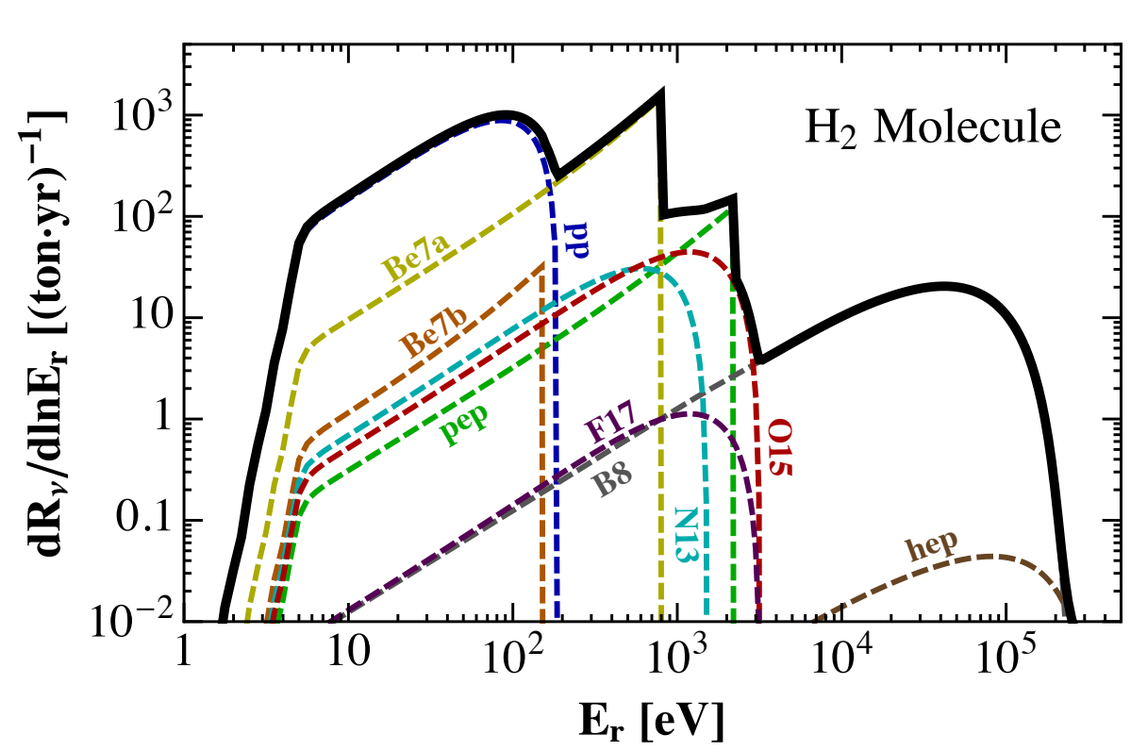
[Essig, Mardon, Slone, TV, 1608.02940]

Direct Detection of Light and Exotic DM





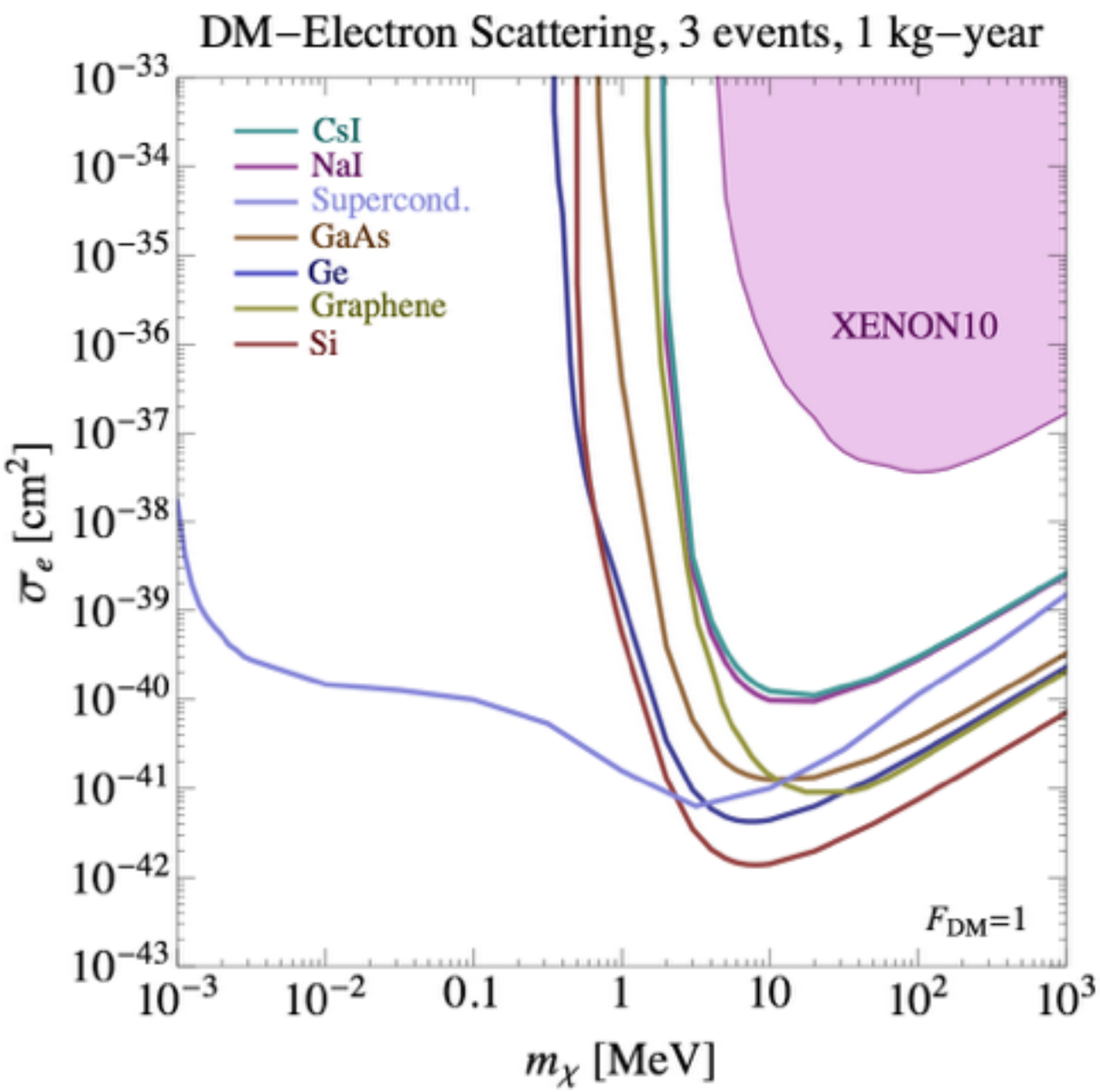


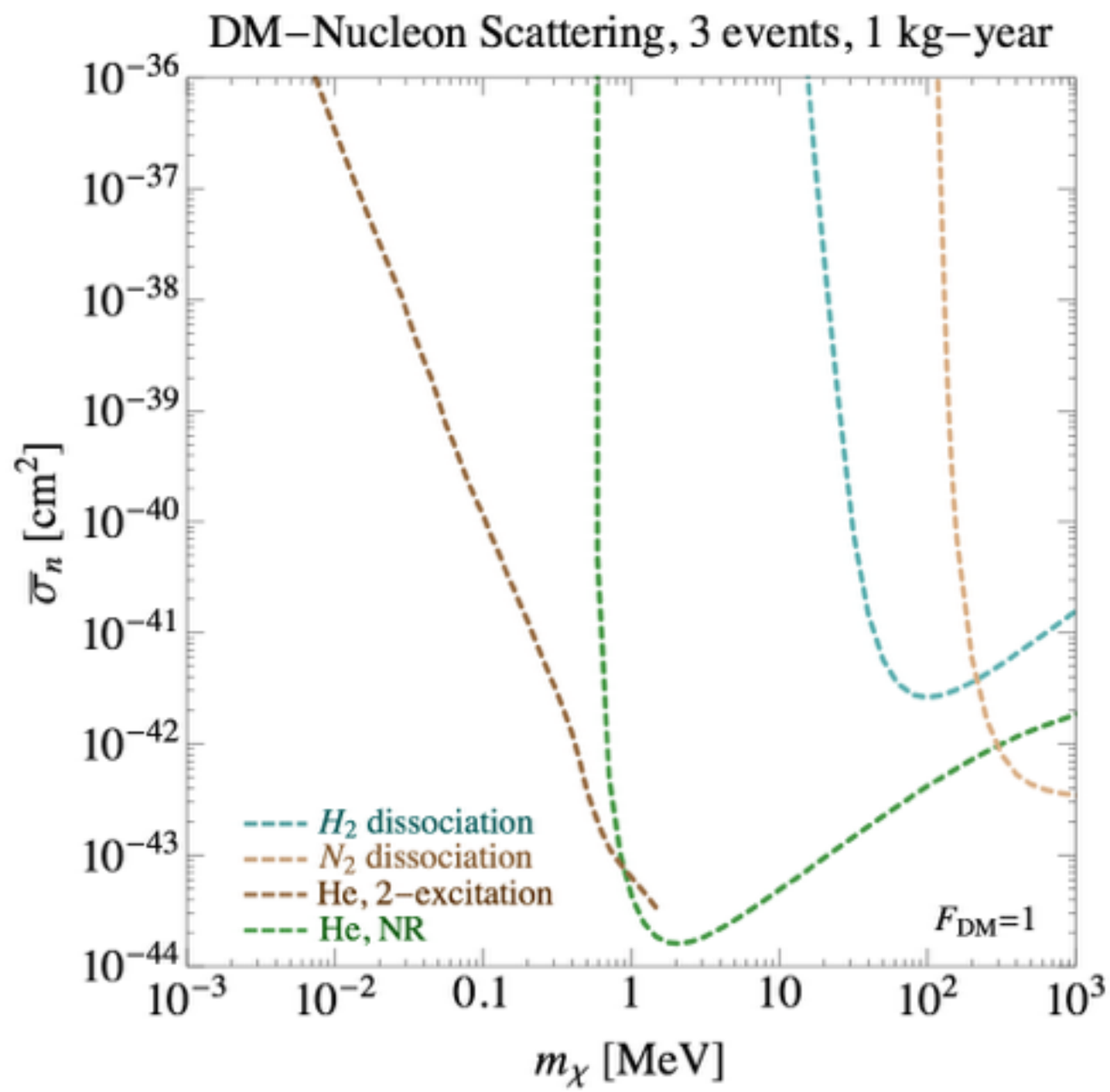


[Essig, Mardon, Slone, TV, 1608.02940]

Direct Detection of Light and Exotic DM

Future Experiments

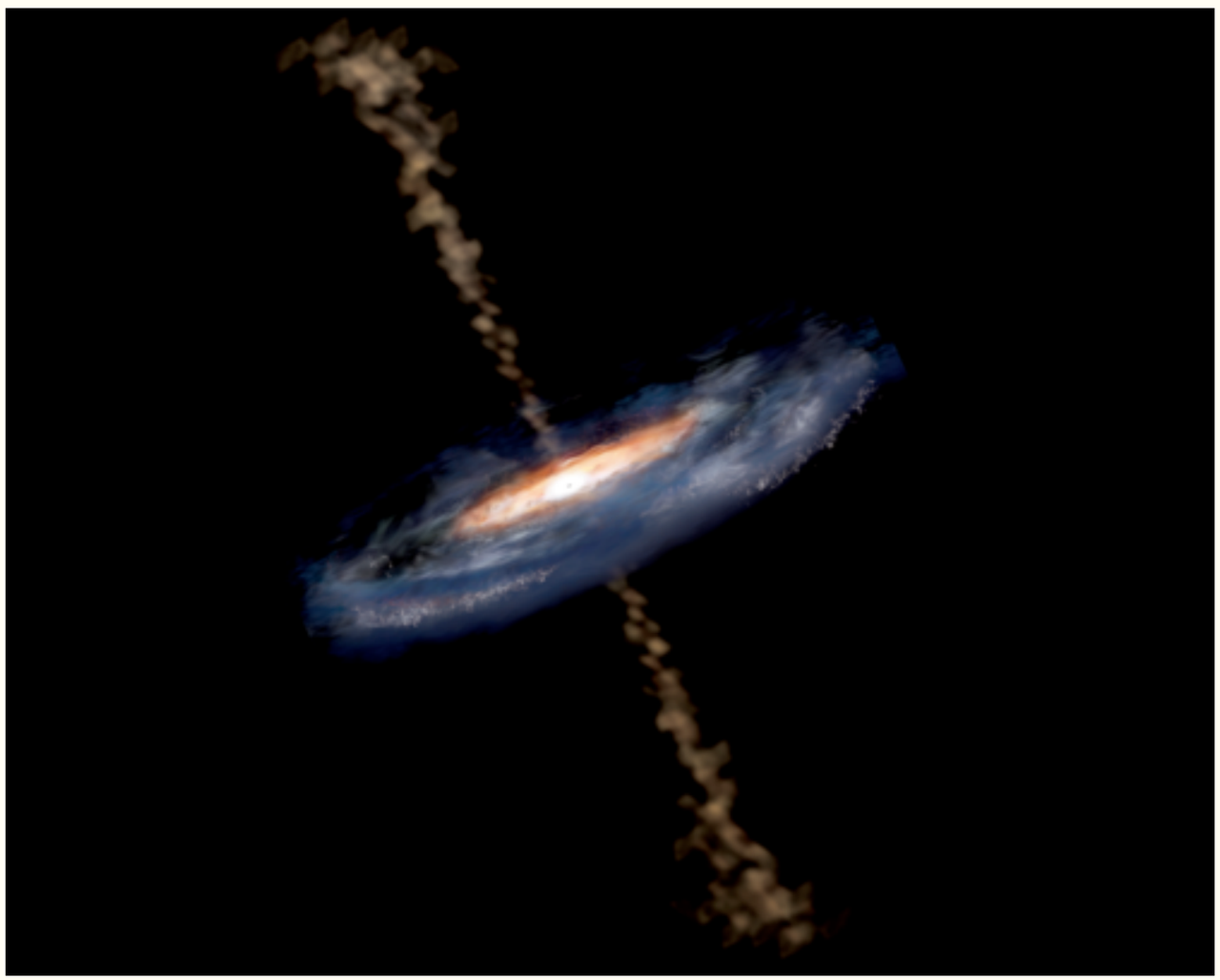


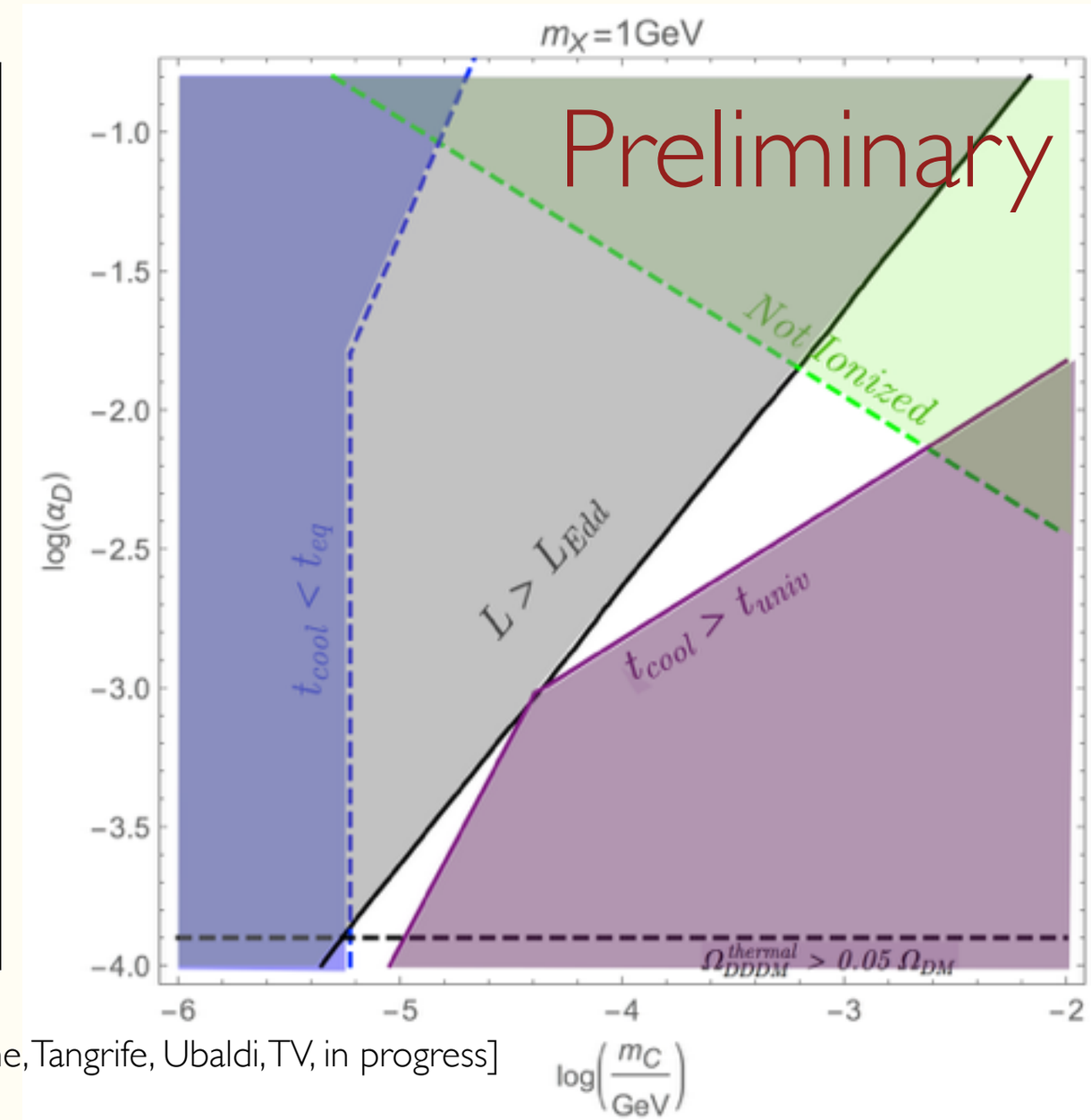


[Akerib et al., 1608.08632]

Active Galactic Nuclei (AGN)

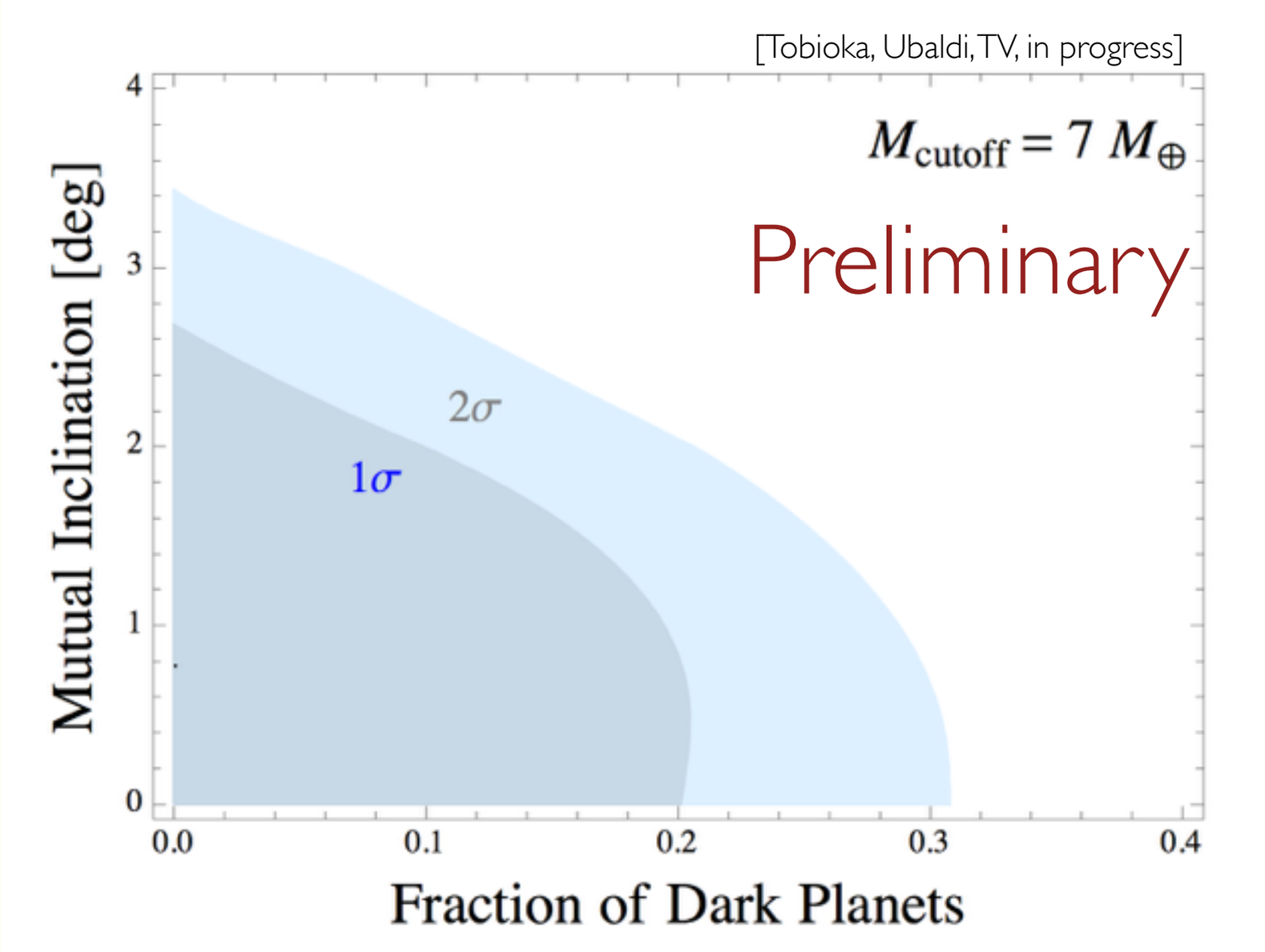
Black hole growth rate can significantly change in the presence of a dark disc!





[Outmezgine, Slone, Tangrife, Ubaldi, TV, in progress]

Astrophysical Probes II: Dark Planets



- If dark matter resides in a low-scale hidden sector, it may for structure!
- Searching for dark planets can be similar to searching regular planets.
- Key difference: no transits in dark planets.
- Idea: Statistically compare planet discovery using transits (Kepler) to those discovered with radial velocity methods (HARPS).

Conclusions

The WIMP paradigm is reaching its climax!

Either will be found soon or become less motivated.

Trends are changing!

Significant recent activity in understanding and searching for DM theories beyond the WIMP.

There are organising principles to help classify DM theories.

Many efforts in developing new technologies to expand the search for dark matter

Testing DM may not necessarily involve non-gravitational interactions!

Improved understanding of structure formation may play crucial role in upcoming years.

Far too many mysteries to solve. Can't stop now!

To be continued...