# Theories of Dark Matter

Lepton-Photon, Ljubljana

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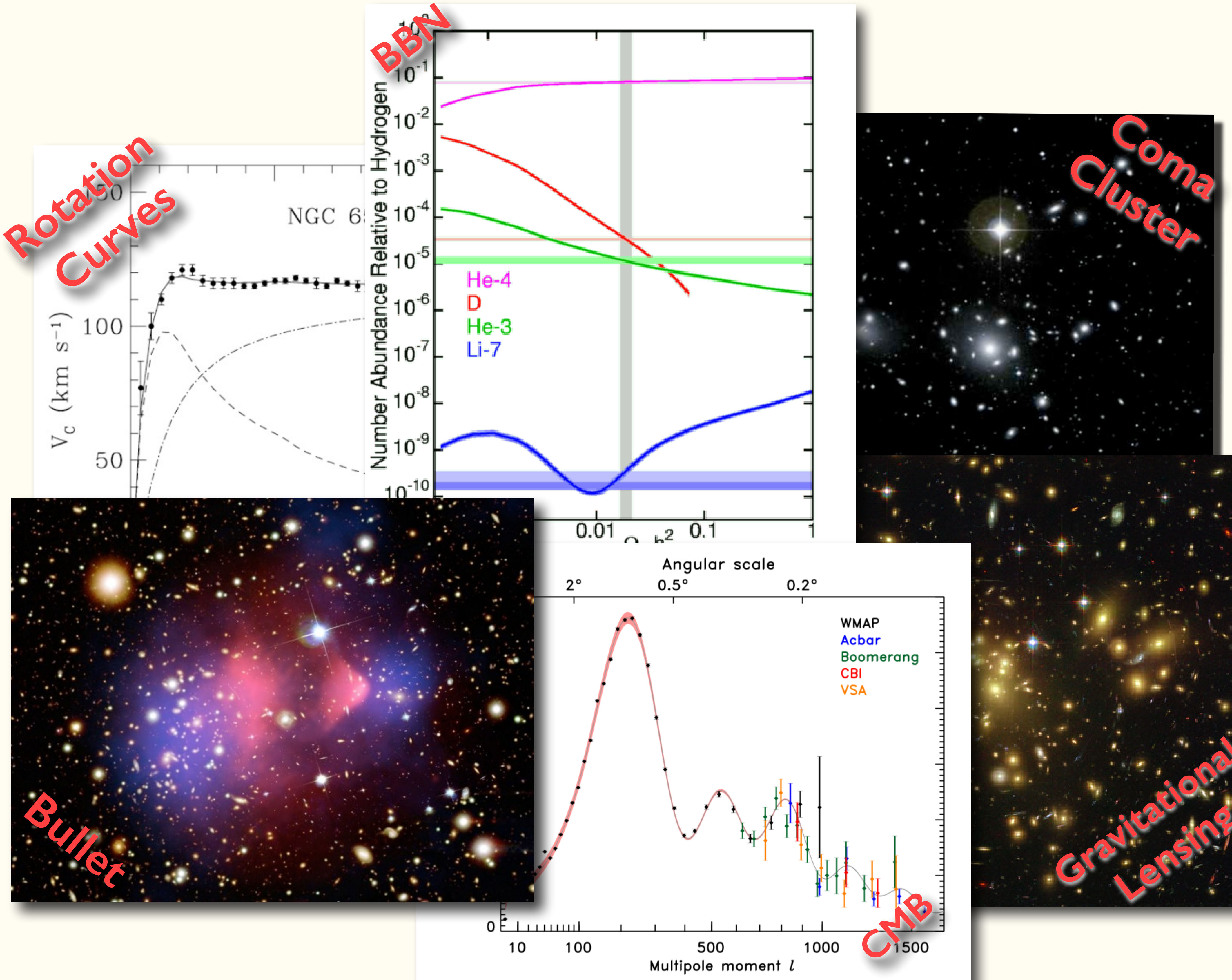
# Outline

- The Thermal WIMP
  - The mechanism
  - Experimental status and recent news
- Beyond WIMP
  - Classifying theories of dark matter
  - Self-interacting dark matter
- Direct Detection of Sub-GeV Dark Matter

# (Gravitational) Evidence for Dark Matter



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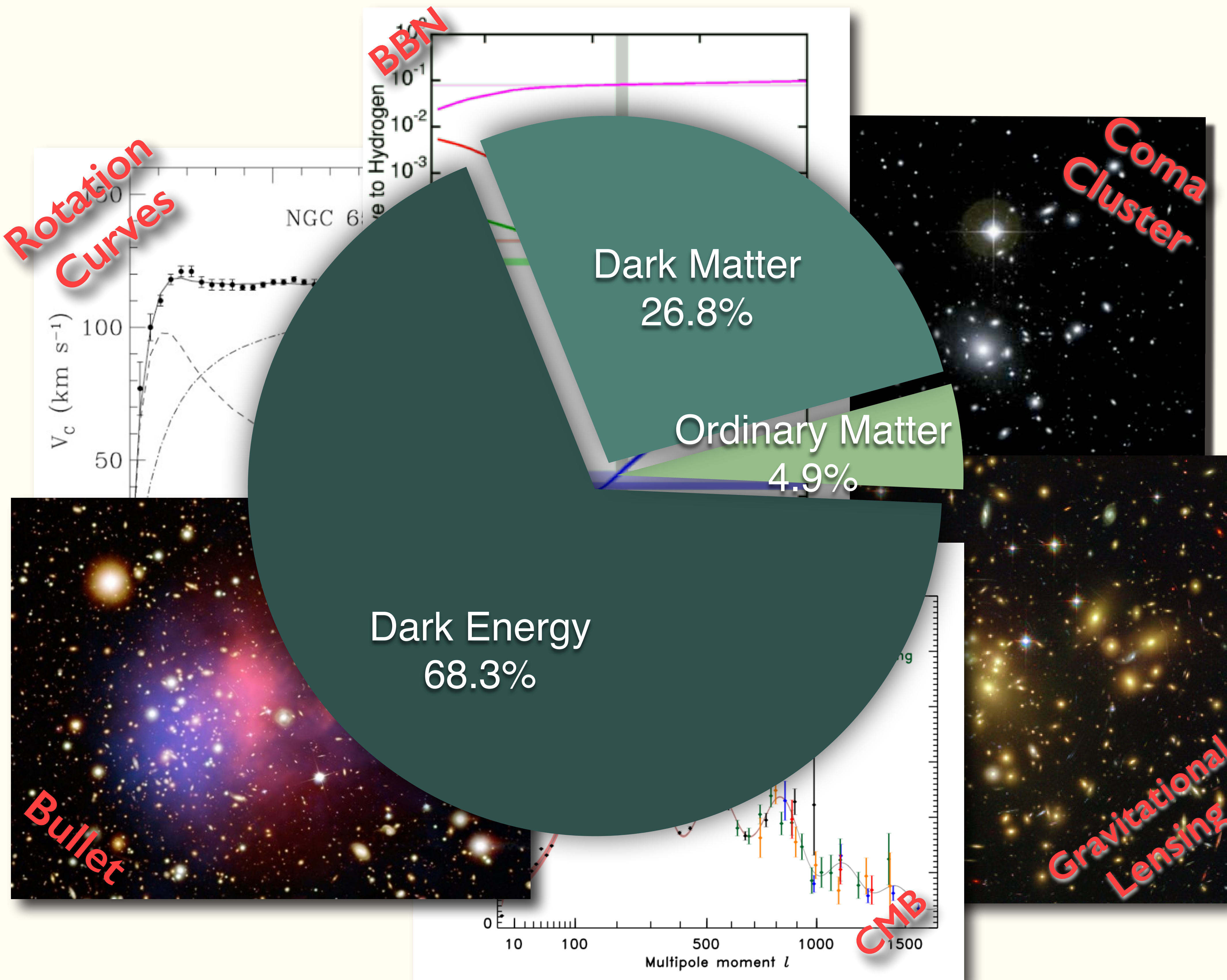


# Will We Find Dark Matter?

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 explain the 85% DM abundance?

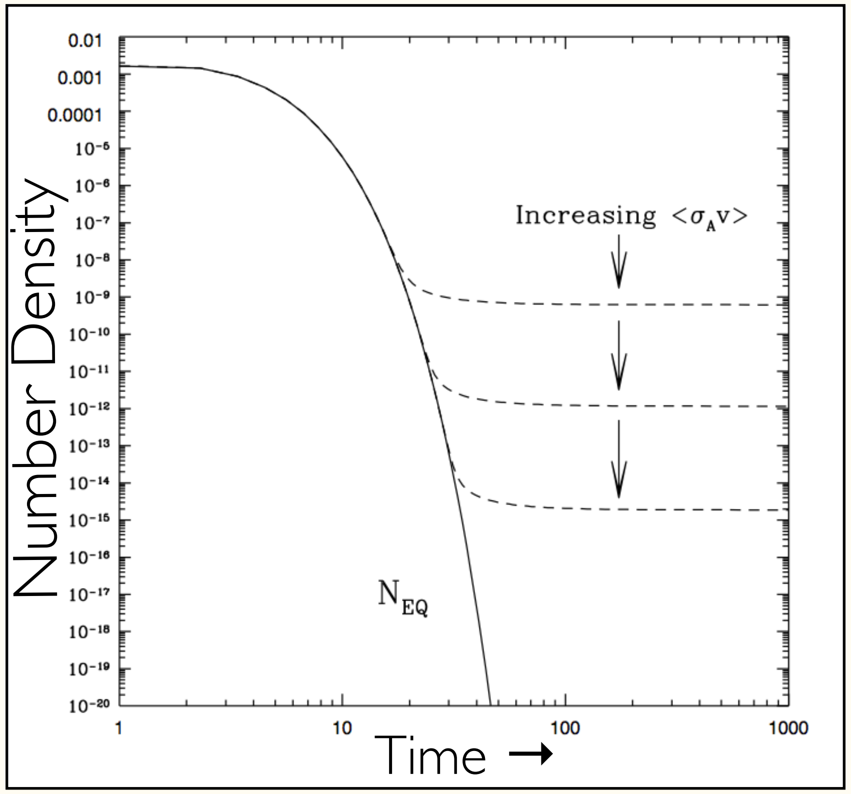
Thermal WIMP
(Weakly Interacting Massive Particle).

# The Thermal WIMP

- Single parameter: $\langle \sigma v \rangle$

- A simple analysis shows,

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

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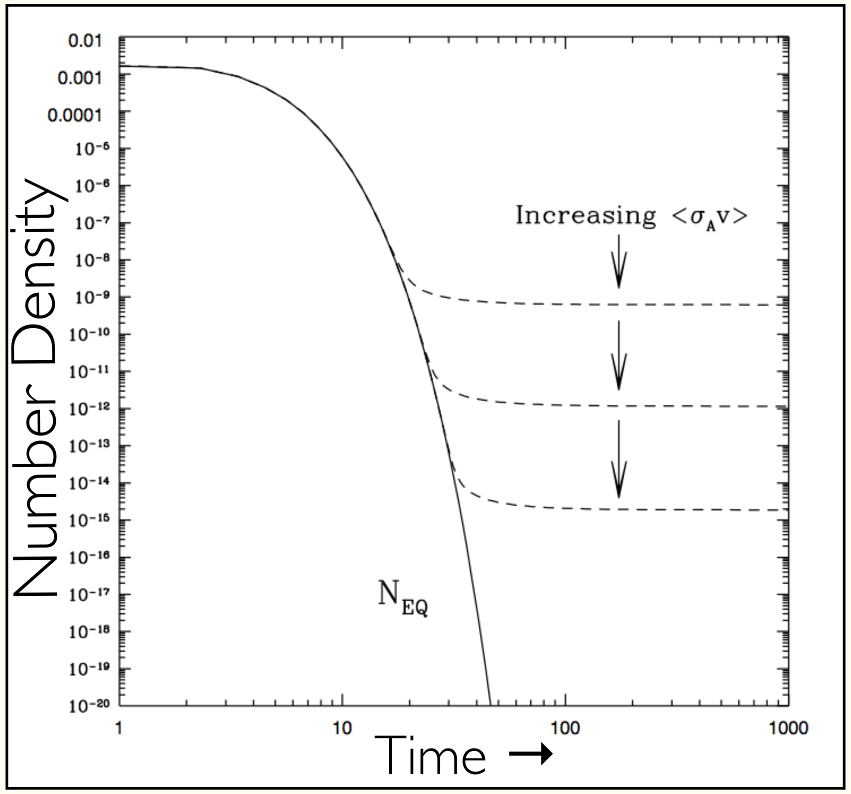


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Same mass-scale we are now probing at the LHC

# The Thermal WIMP

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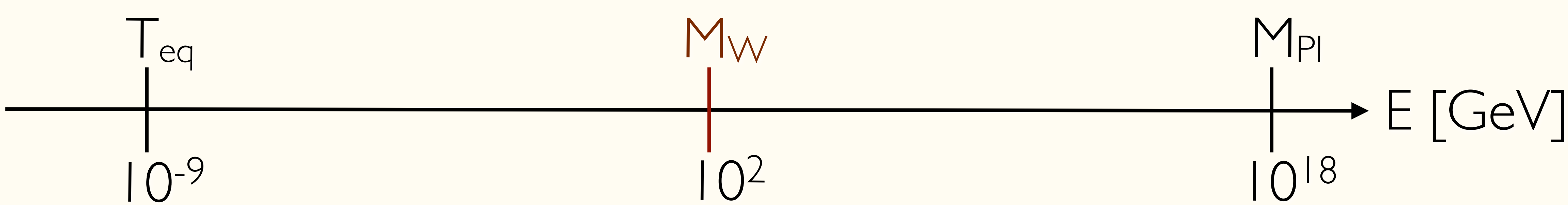
$$m_{\rm DM} \simeq \alpha \sqrt{T_{\rm eq} M_{\rm Pl}}$$

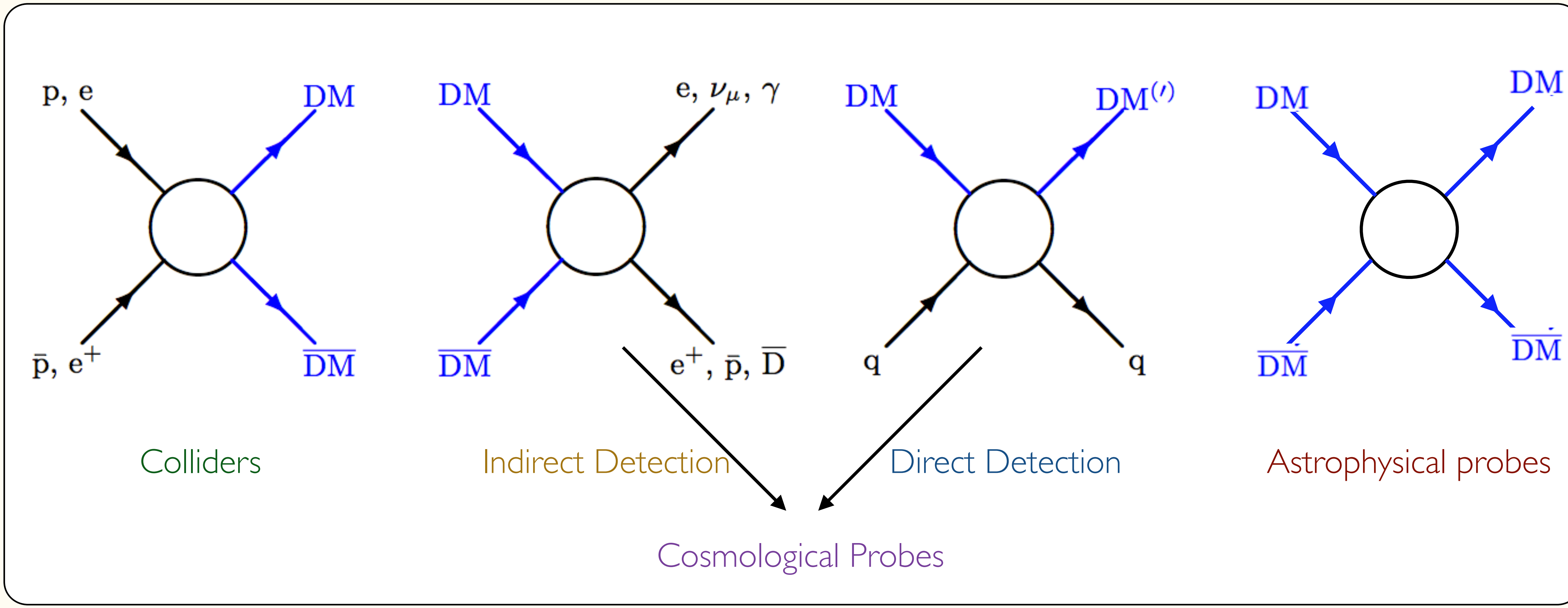



This is the WIMP Miracle

# WIMPs

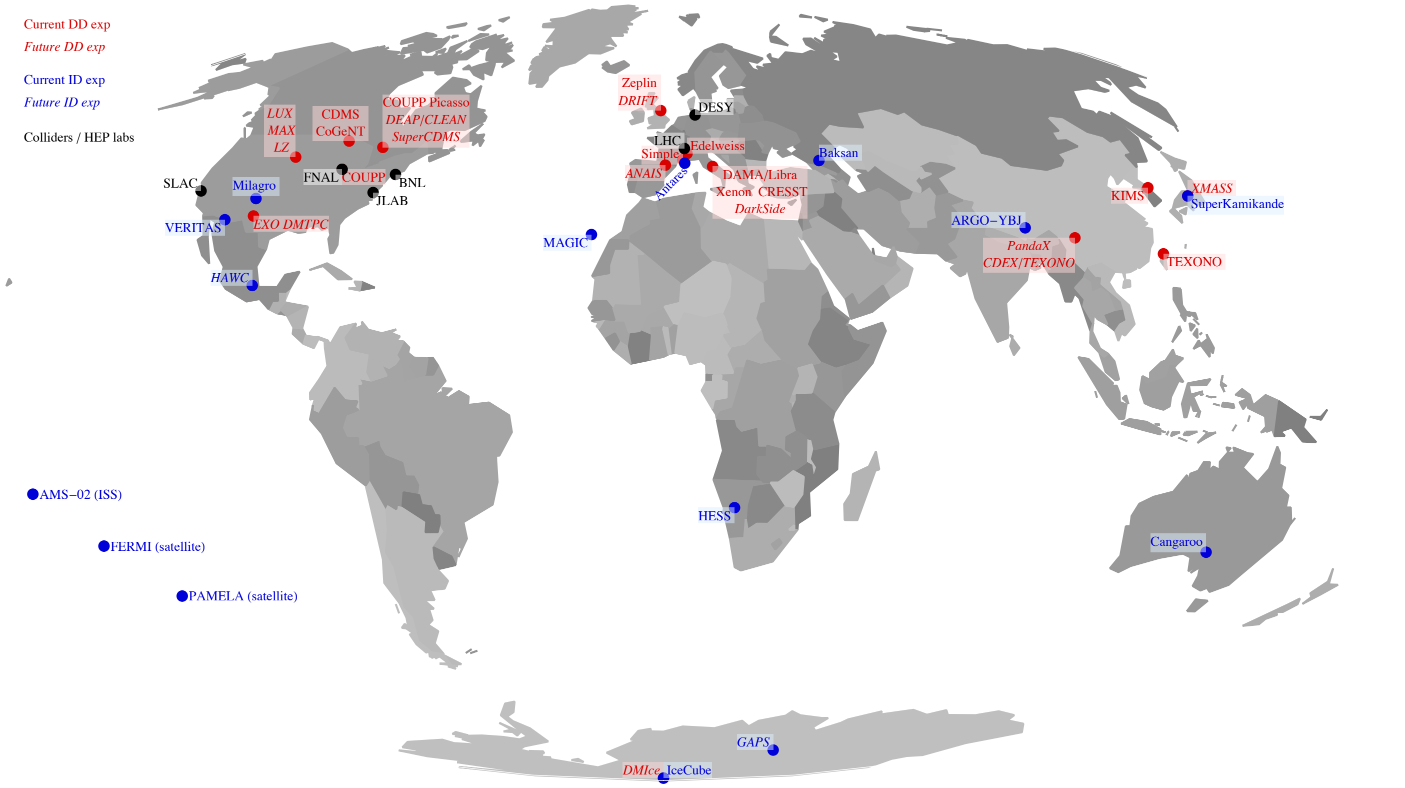
So where do we stand?

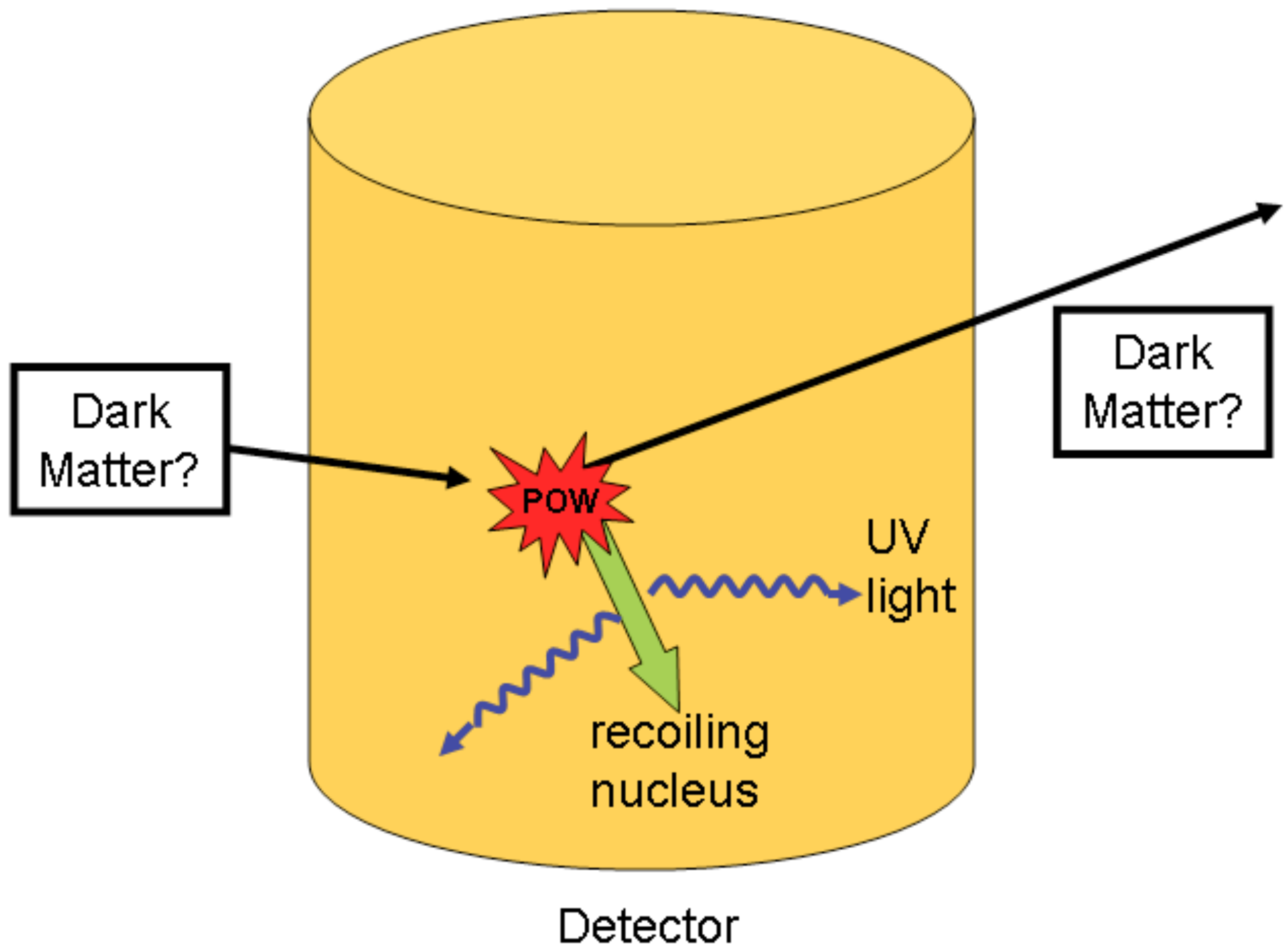
# Several ways to search for DM



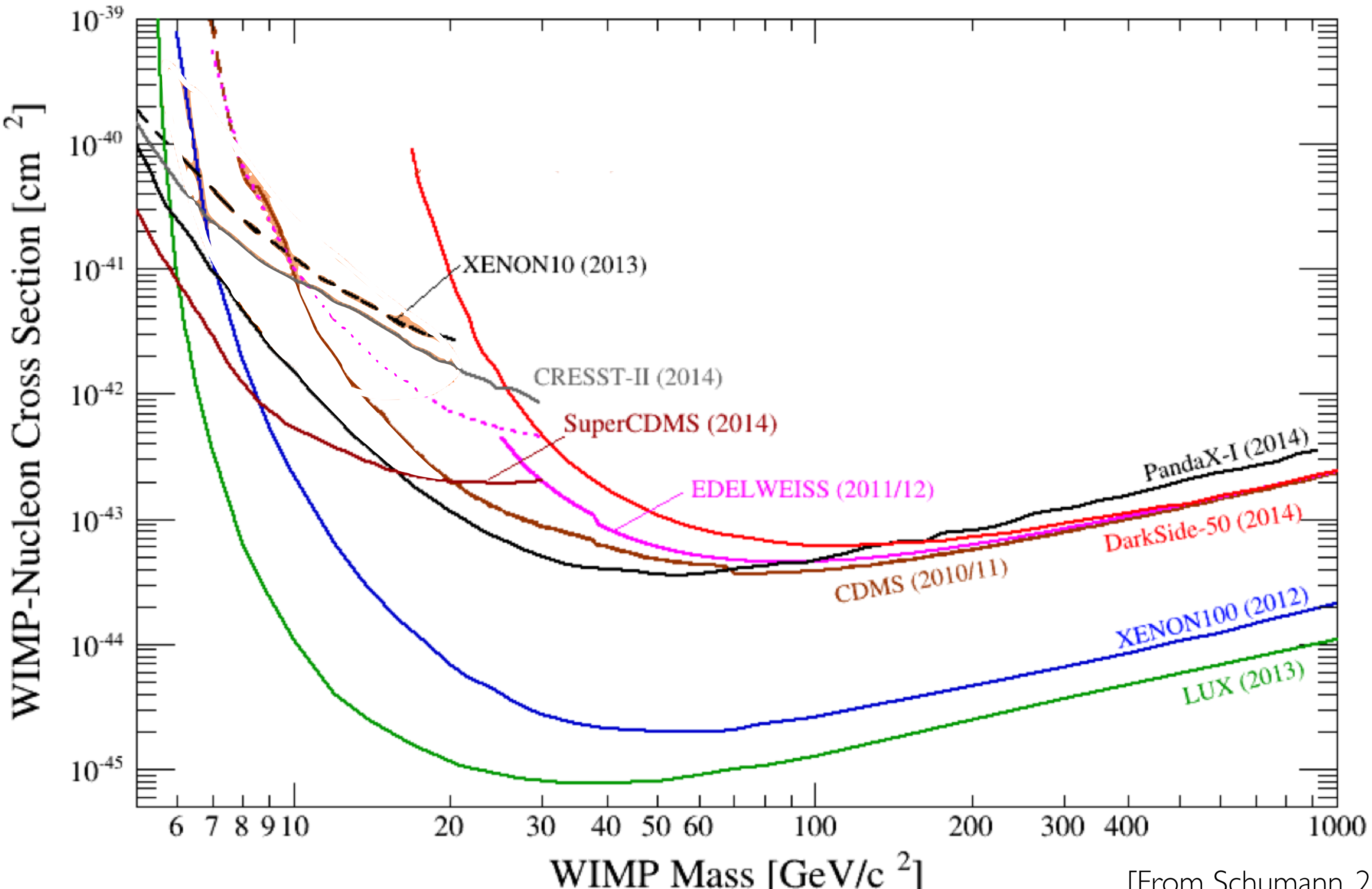
# Direct Detection

# Direct Detection: Basics



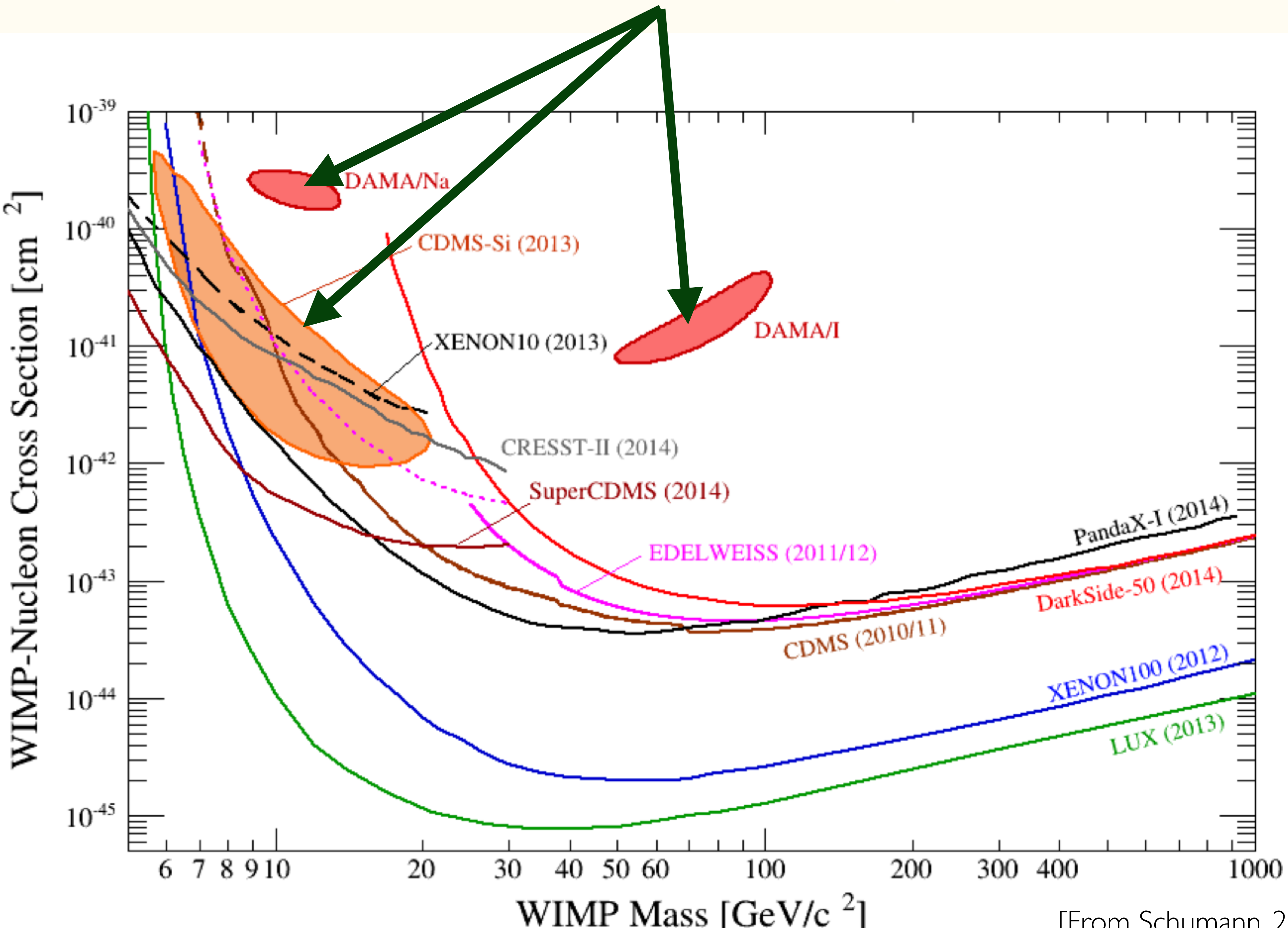
# Direct Detection: Status




[From Schumann, 2015]

# Direct Detection: Status

Two anomalies remain unexplained..

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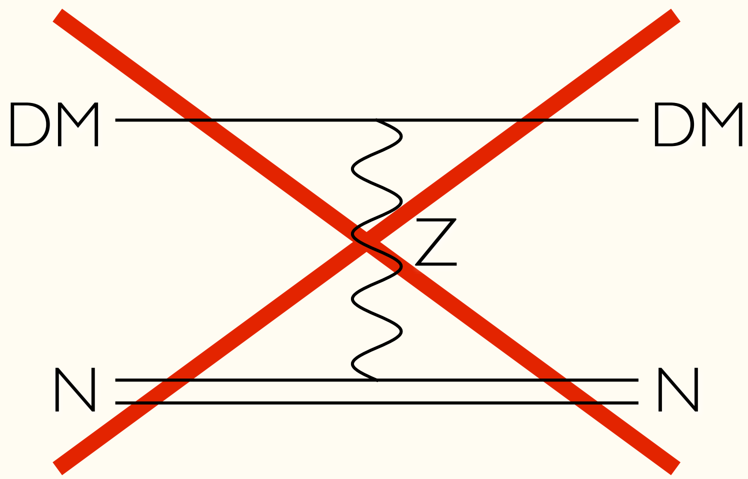
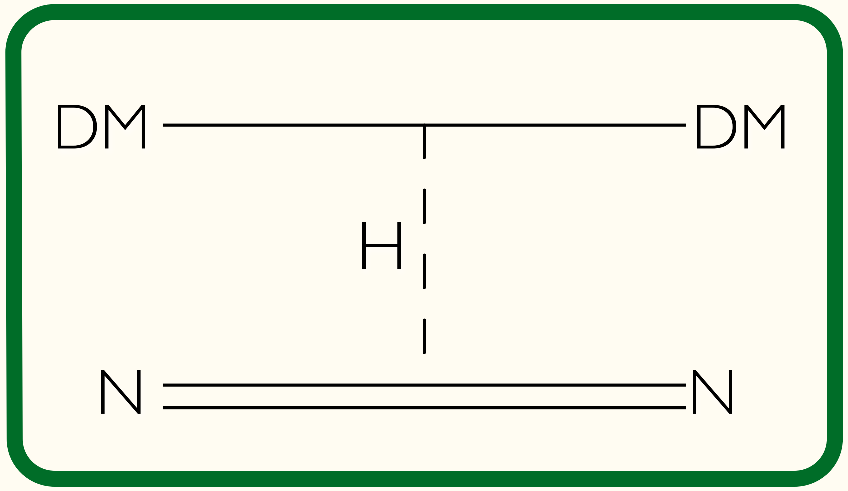
# Direct Detection: Implications




$\sigma_{\chi N} \sim 10^{-39}\ \mathrm{cm}^2$

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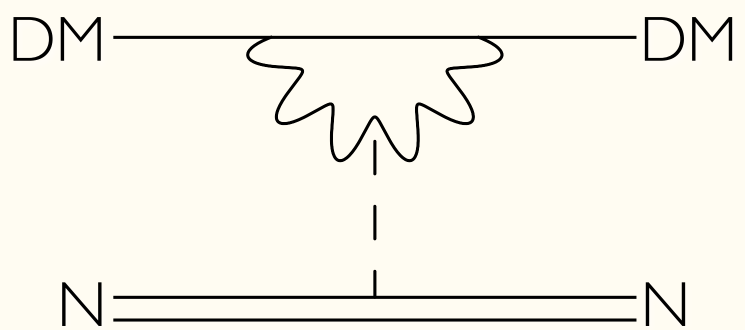


$\sigma_{\chi N} \lesssim 10^{-46}\ \mathrm{cm}^2$

XENON100
LUX
CDMS
...

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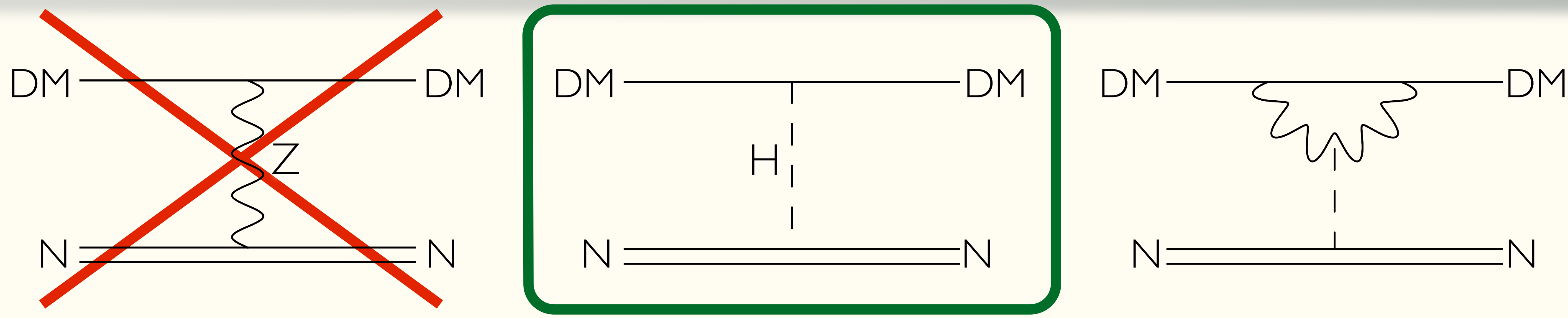


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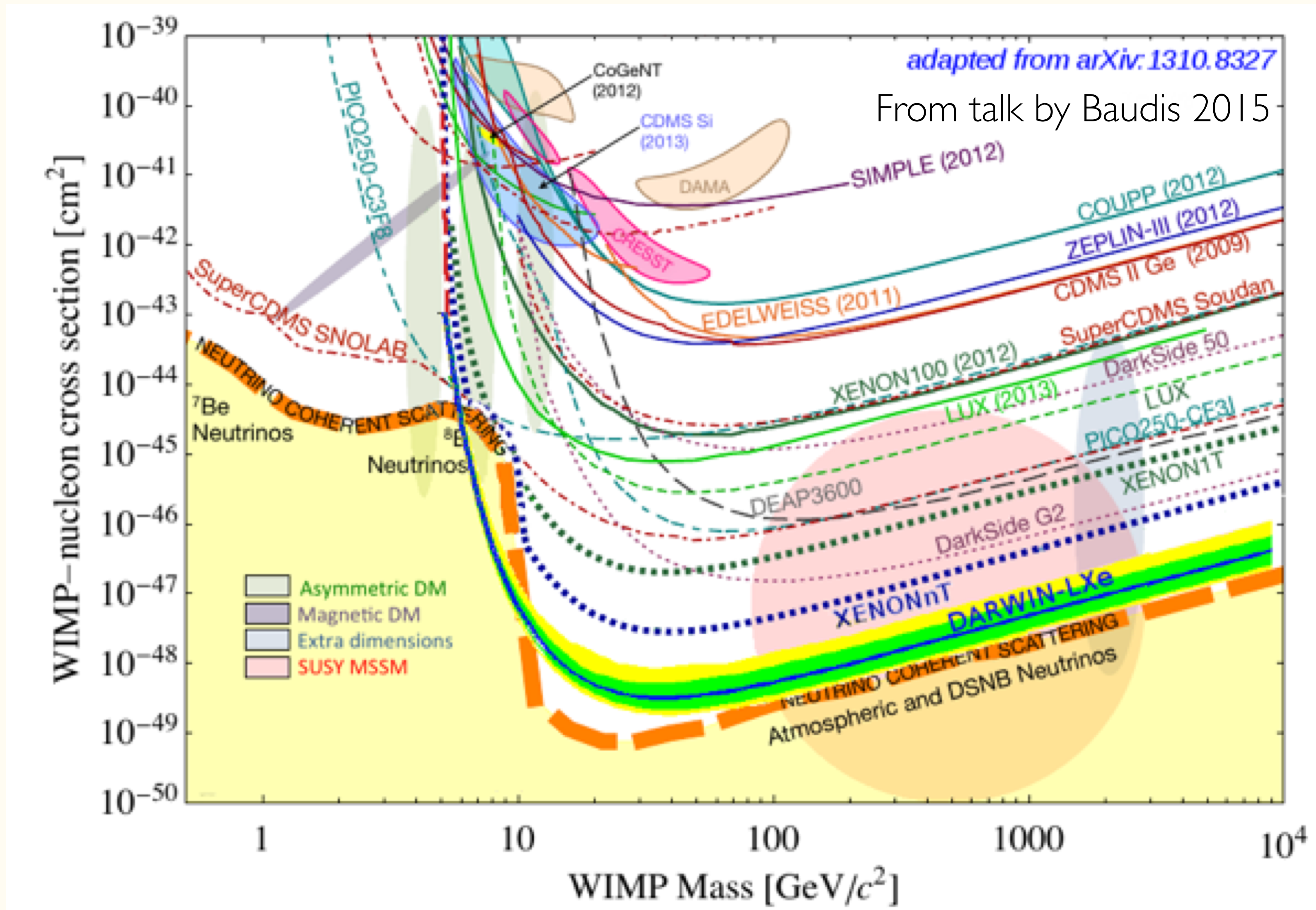
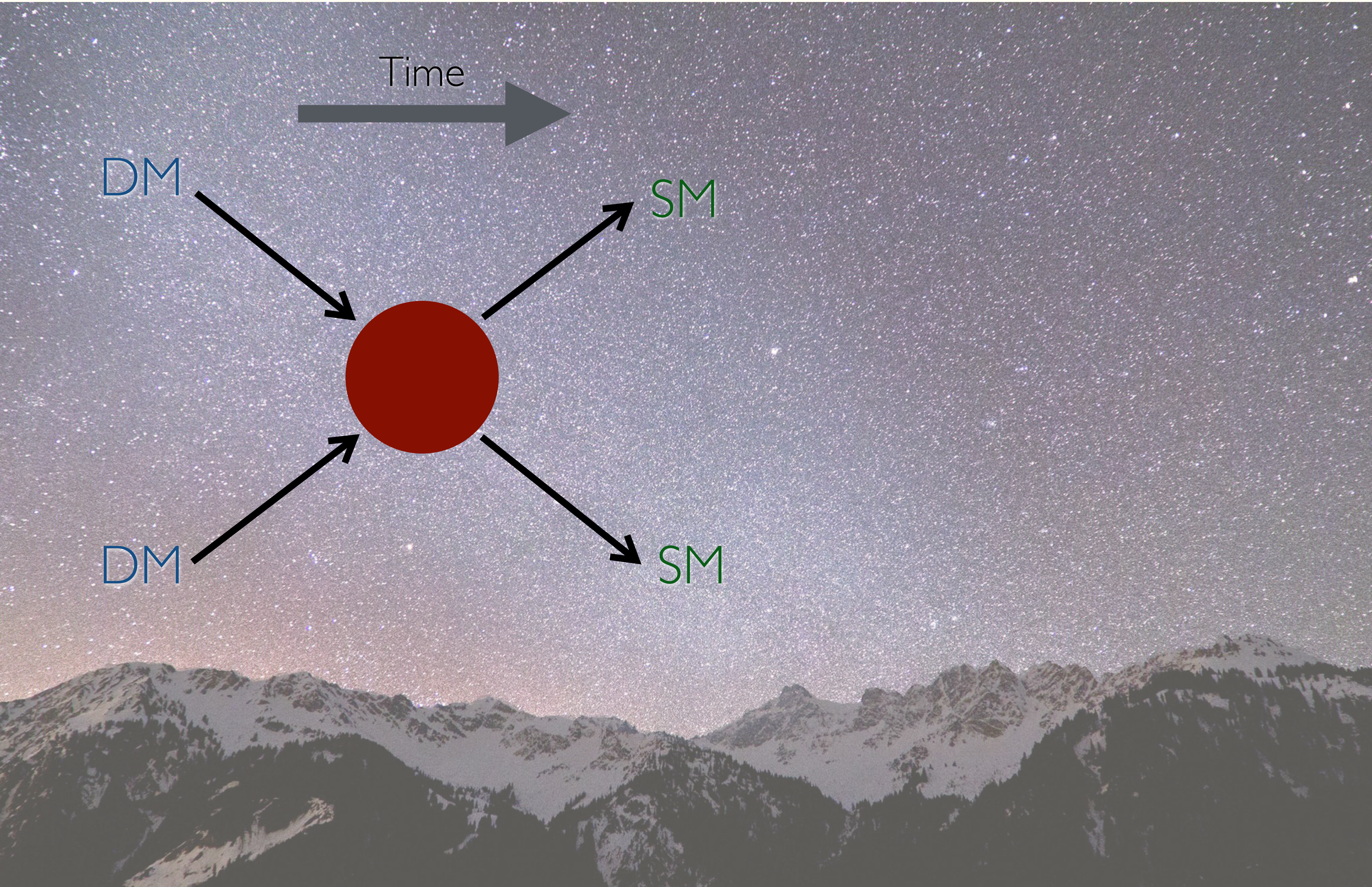



Current technologies will only be able to reach $\sim 10^{-48}\ \mathrm{cm}^2$ due to irreducible backgrounds

# Indirect Detection

# Indirect Detection: Basics



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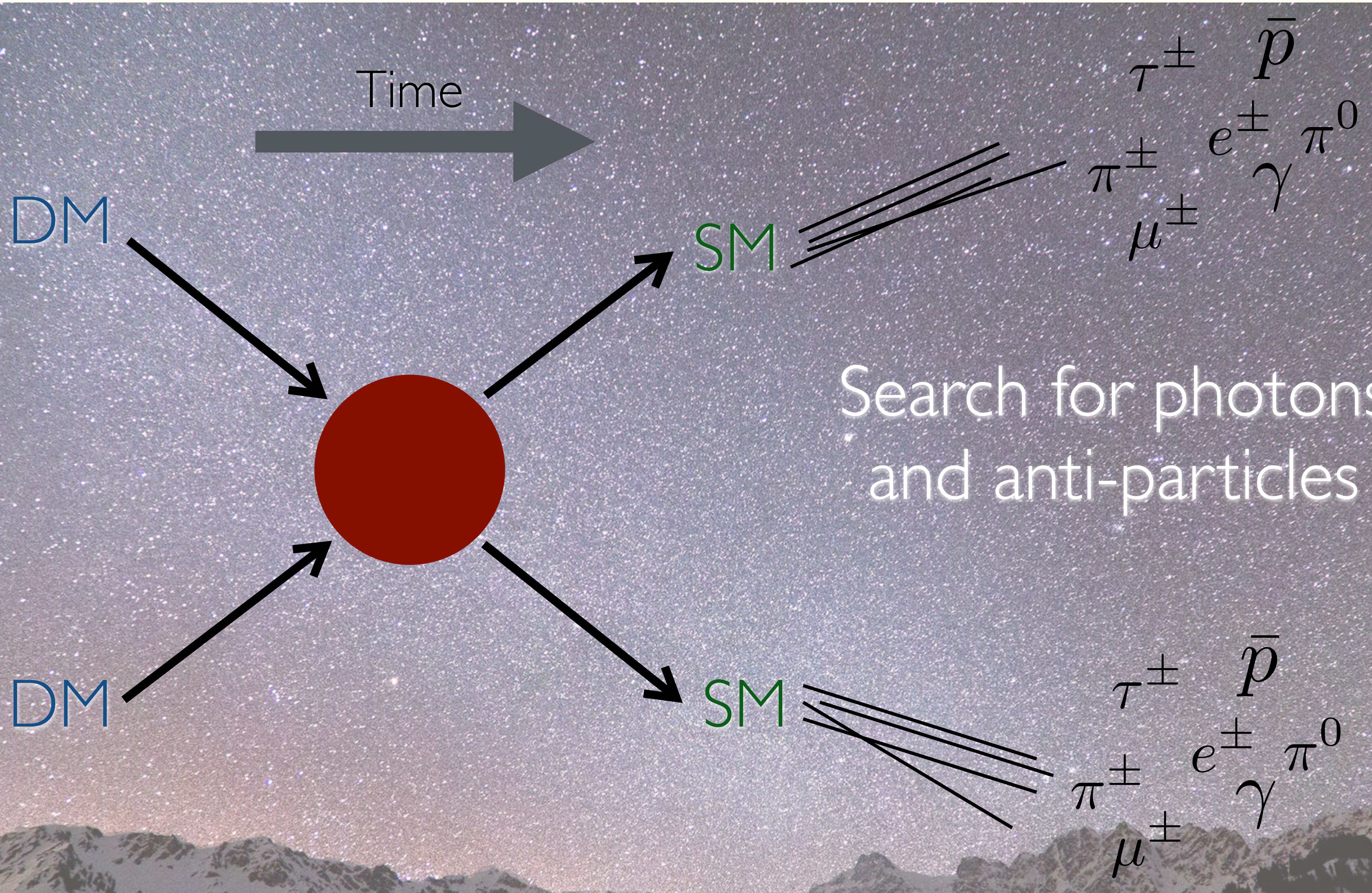


Search for photons and anti-particles

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In the past few years we've had:

Numerous measurements which place strong constraints on theory.

Few anomalies.  Most notable:

- Galactic-center excess
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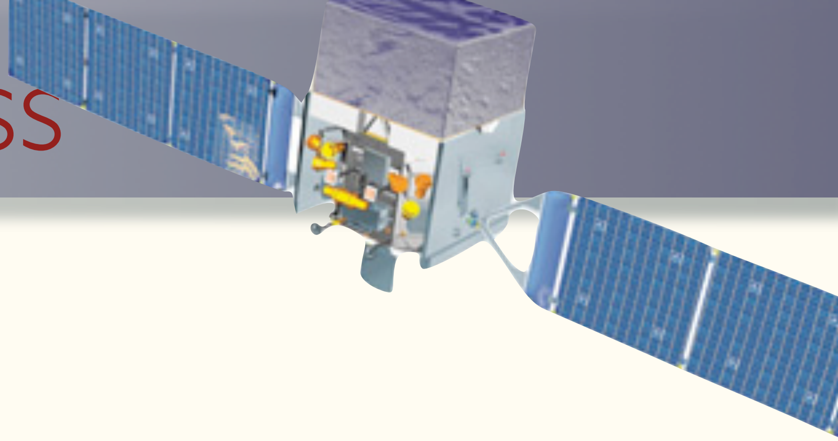
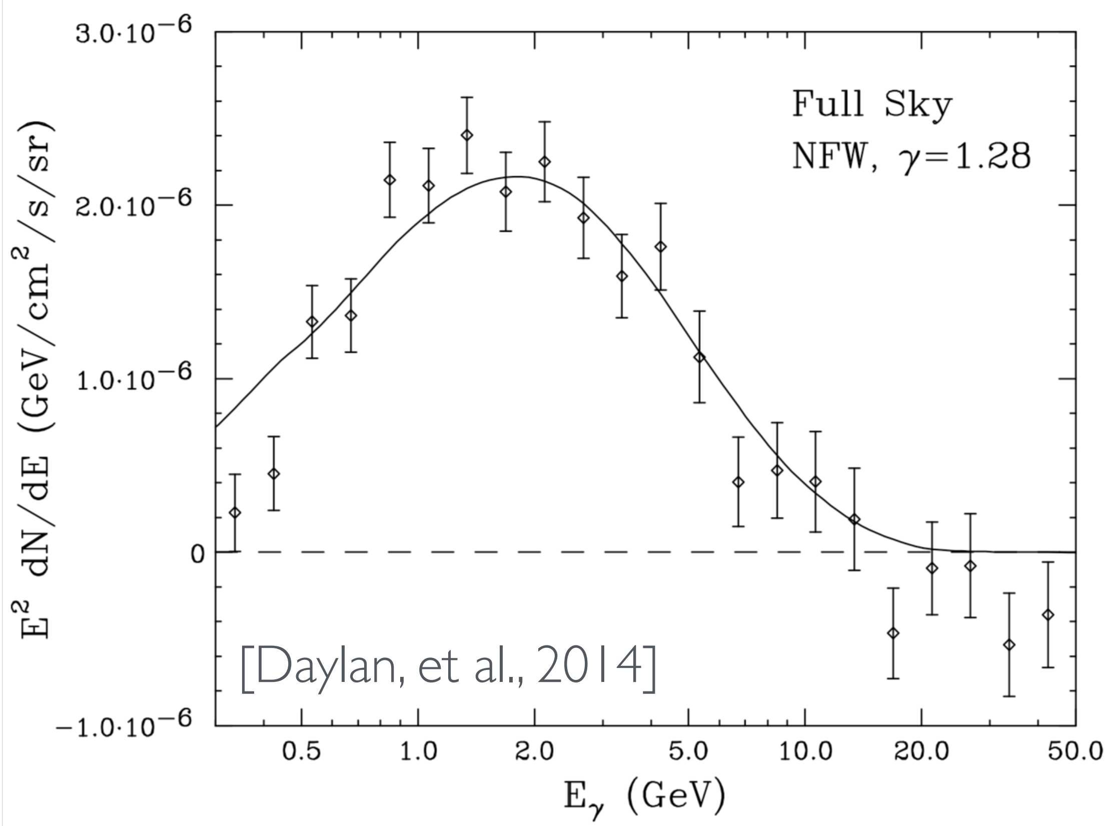


- Discovered with Fermi data.
- First found in Galactic Center, later at higher altitudes.

[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.

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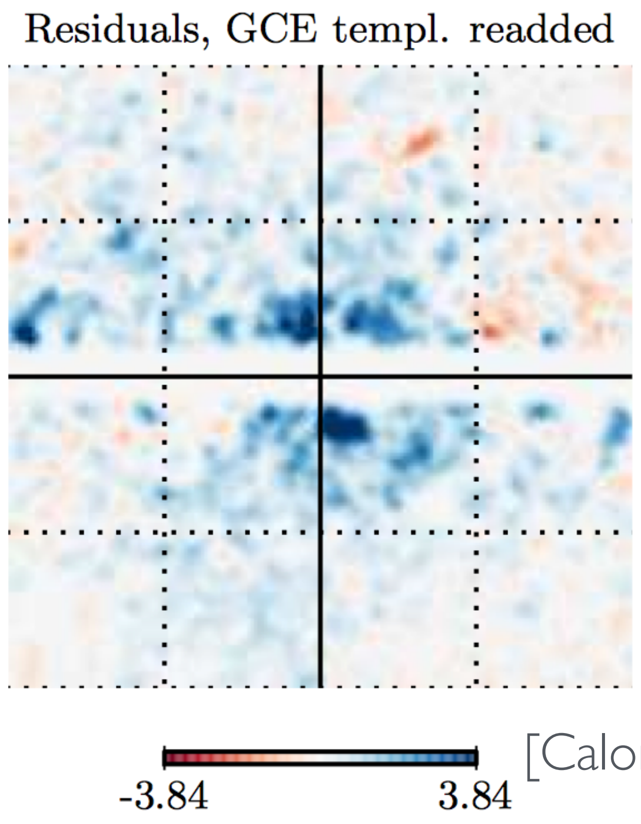


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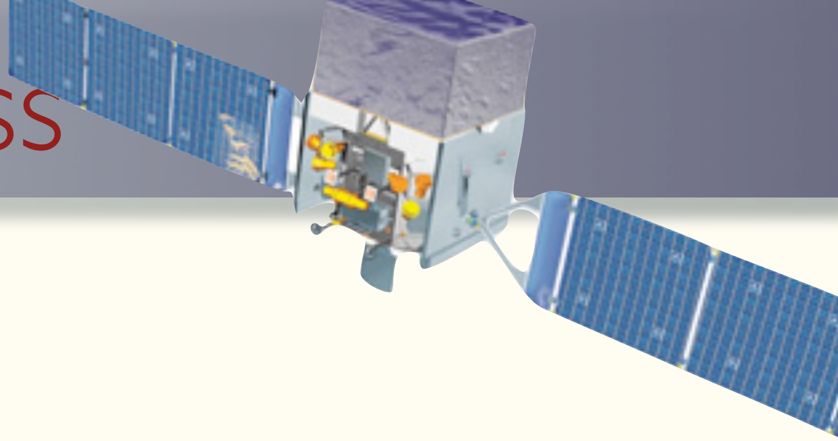
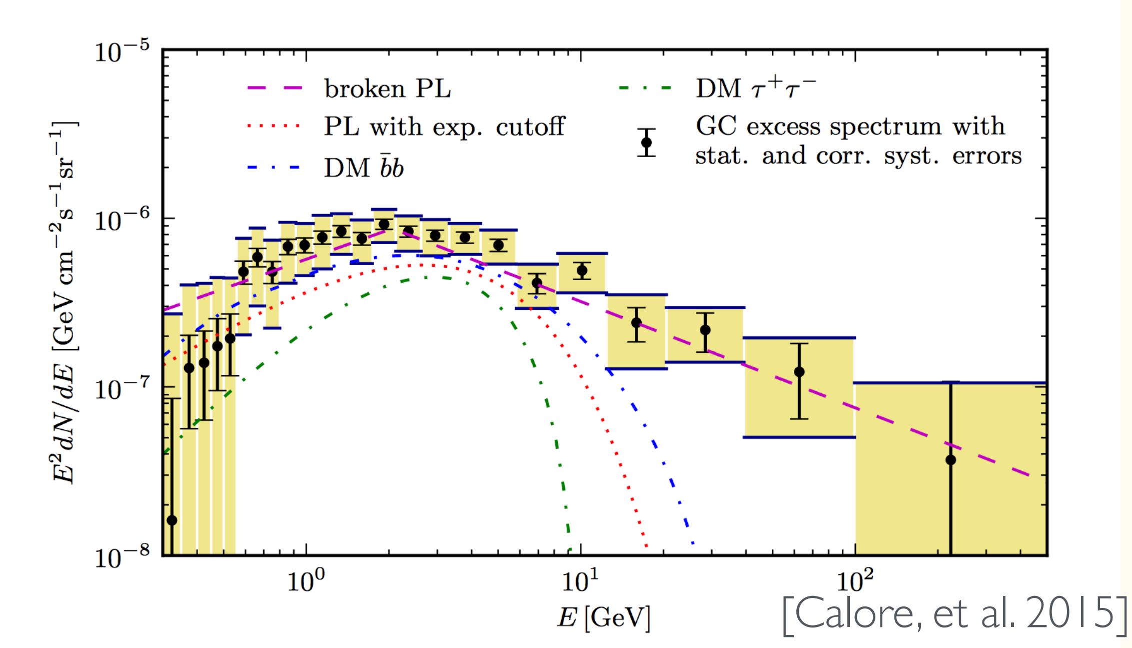


## What can it be?



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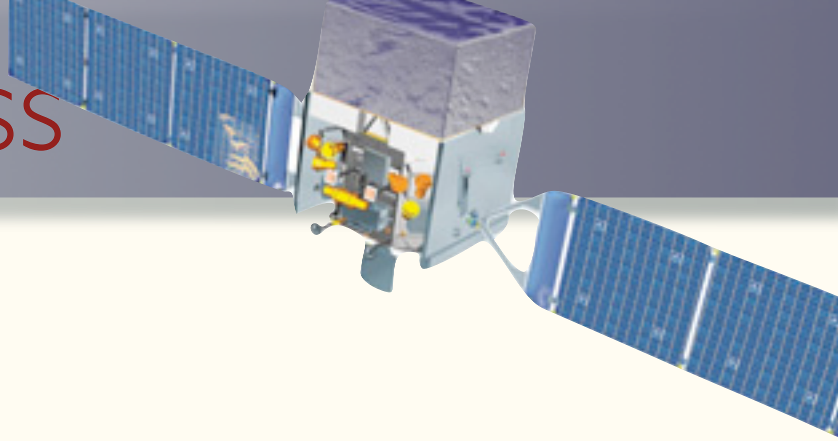
- Excess is highly statistically significant and robust under systematic uncertainties.
- However, modeling of the Galactic diffuse emission is very uncertain in center.
- Several possibilities have been suggested, e.g.:



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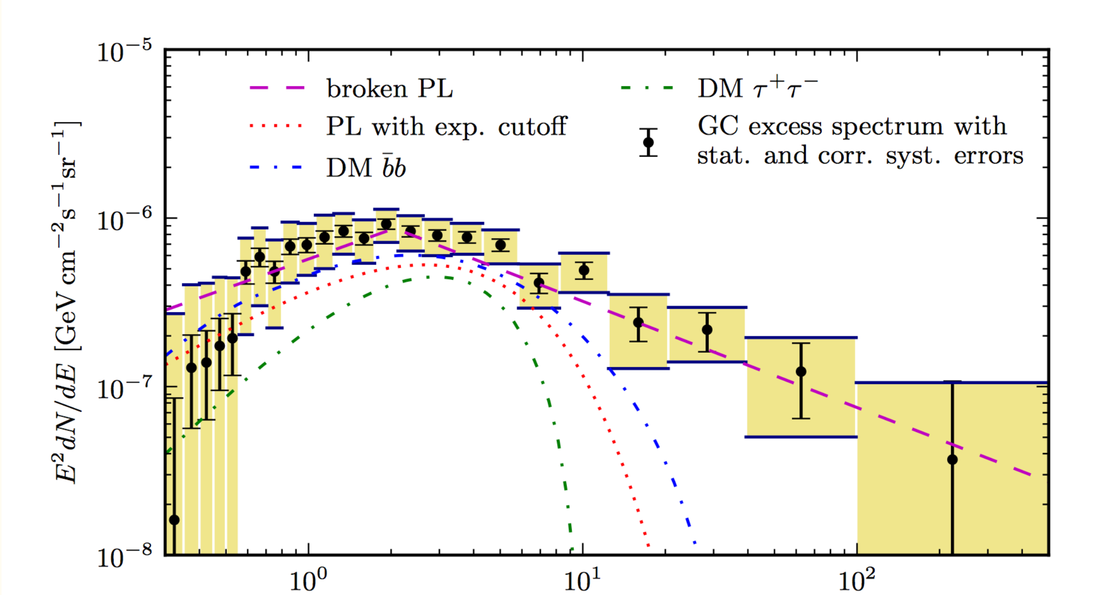


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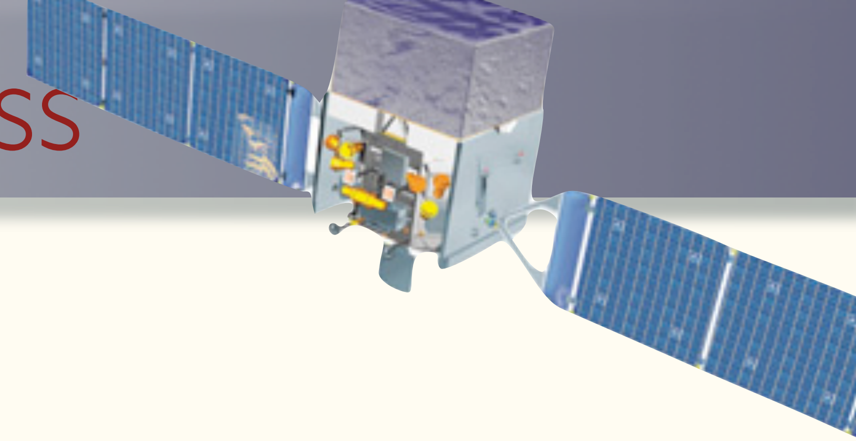

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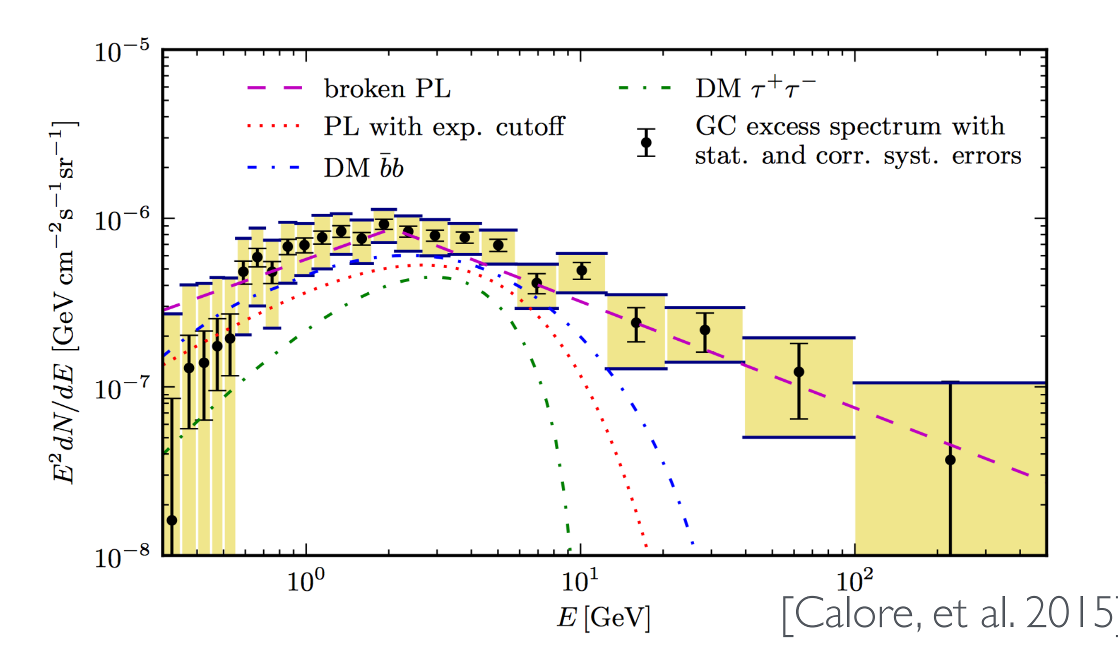

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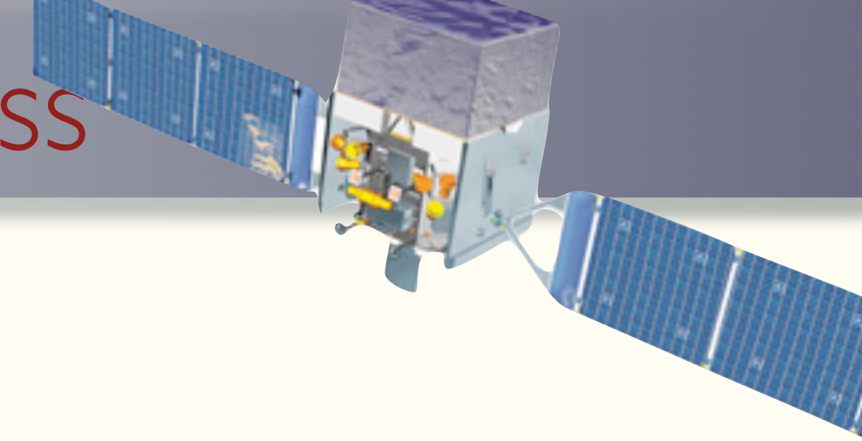

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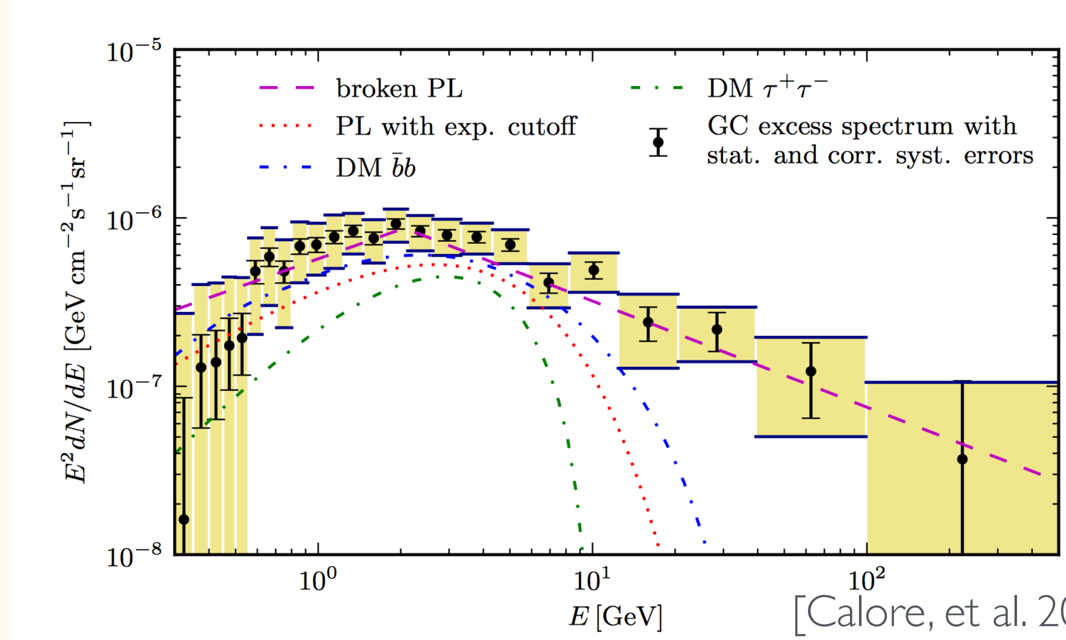


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  - Annihilating dark matter.
    [Hooper, Goodenough, 2011; Abazajian,Kaplinghat, 2012; Abazajian et al. 2014; Daylan et al. 2014; Berlin et al. 2014; Agrawal et al. 2014; Alves et al. 2014; Martin et al. 2014; Majumdar et al. 2014; Han et al. 2014;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

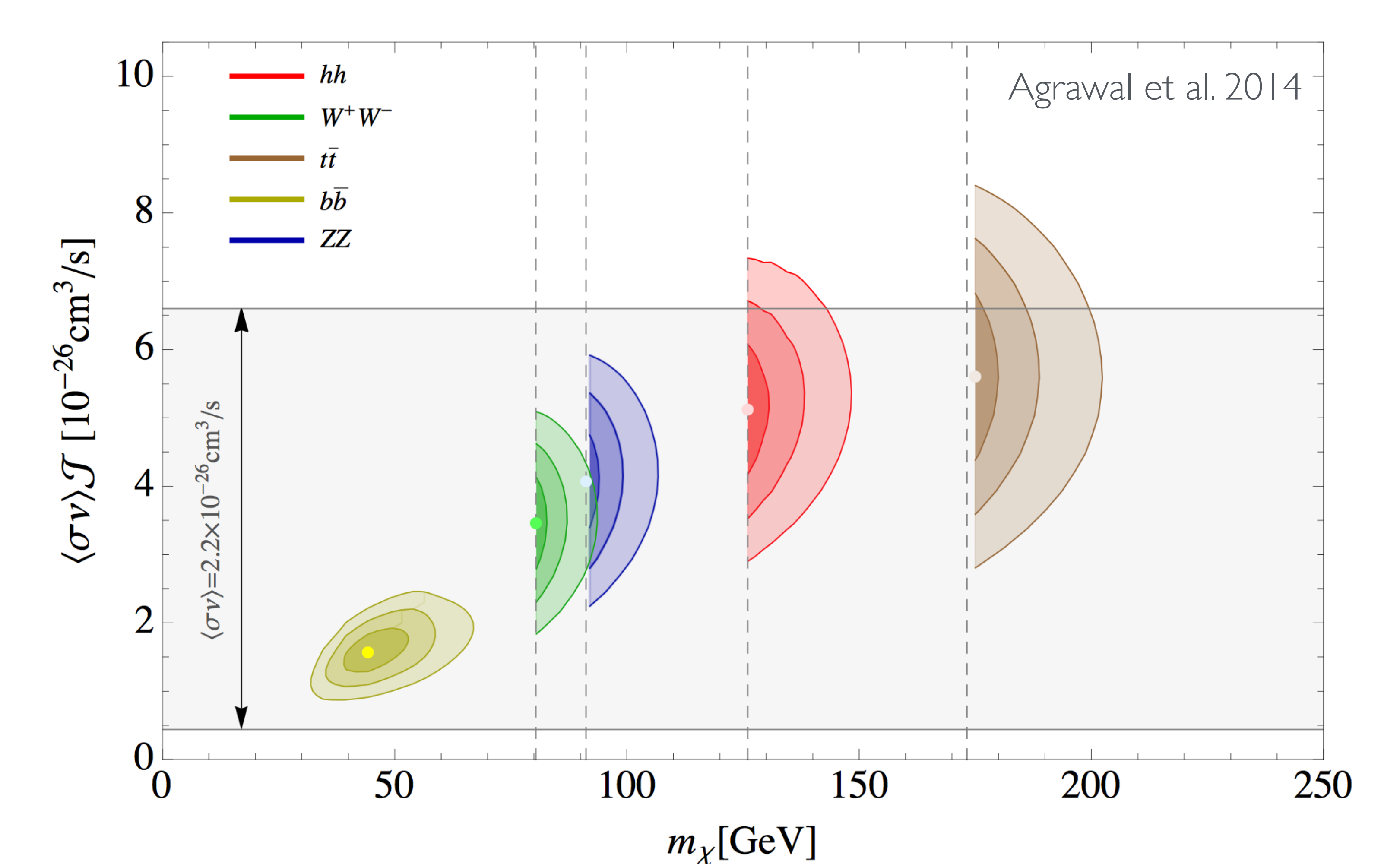
# Anomaly I: GeV Gamma-ray Excess

## 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?

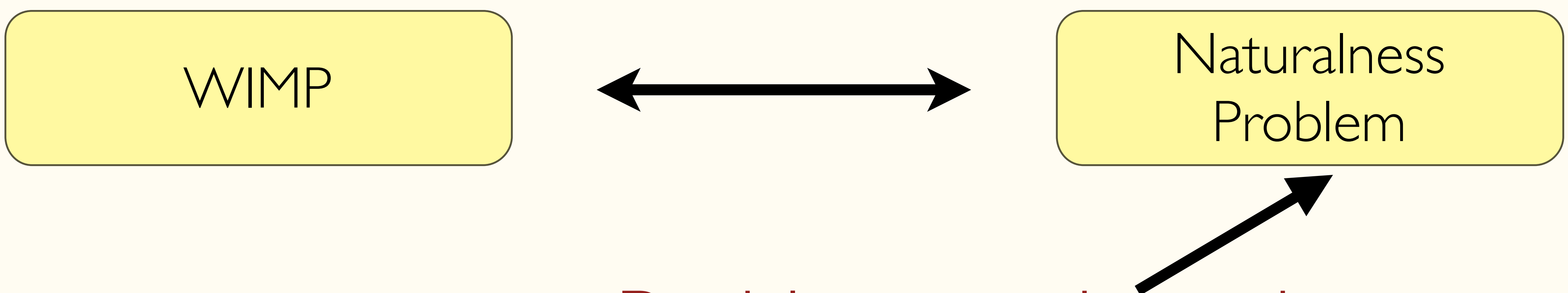
## Too early to tell!

- 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.

# Going Beyond WIMPs?

# Obsessed with the WIMP...

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




Problem made up by theorists..

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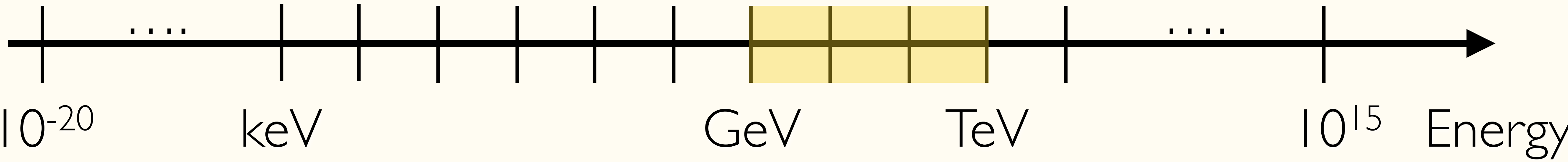

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WIMP ⟷ Naturalness Problem

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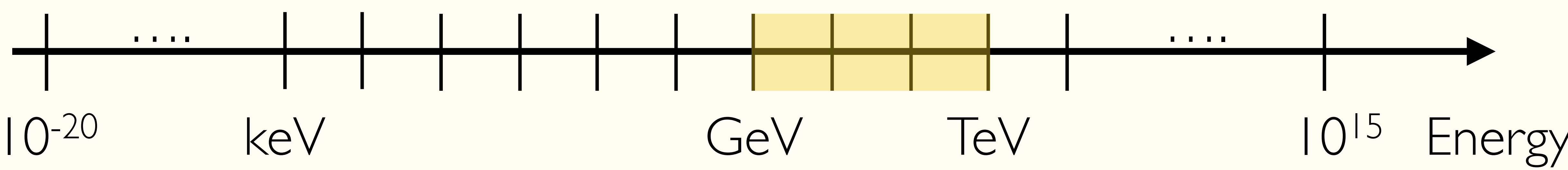


Lots more to do!

(repeat everything we did for the WIMP...)

# Beyond WIMP:
# Theories of Dark Matter

# Classifying Theories of DM

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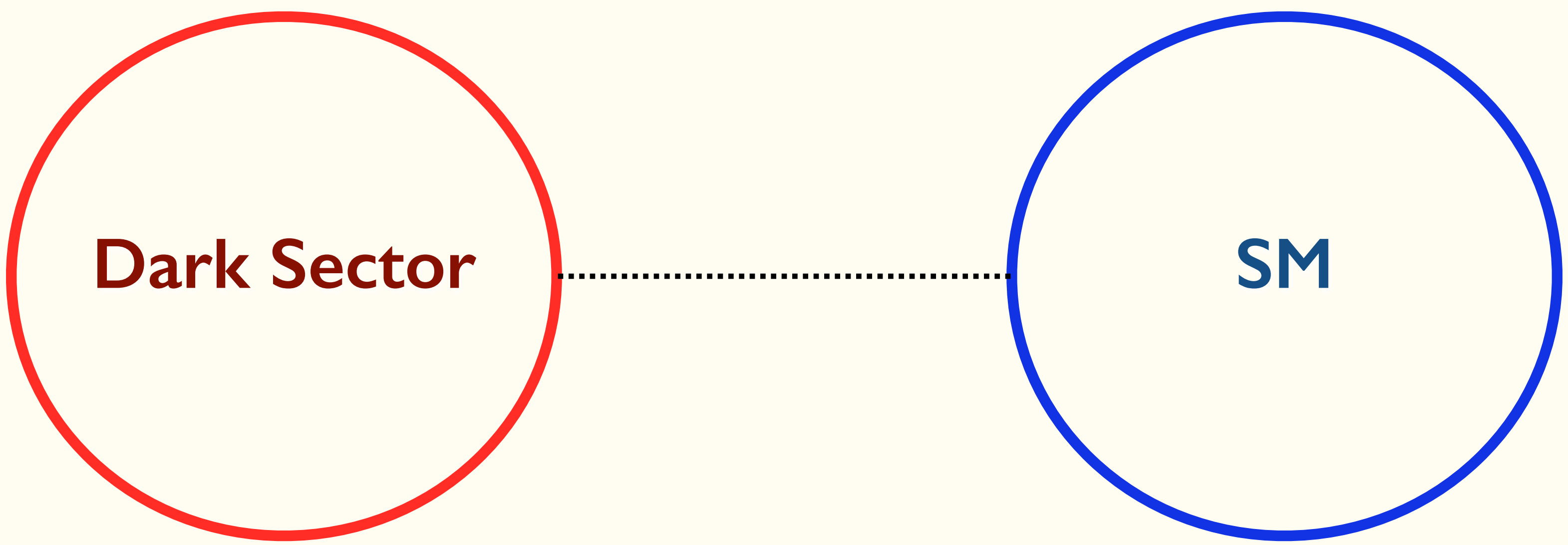
Direct

Colliders

Indirect

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!!

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# Self-Interacting Dark Matter?

# Problems with Cold Dark Matter?

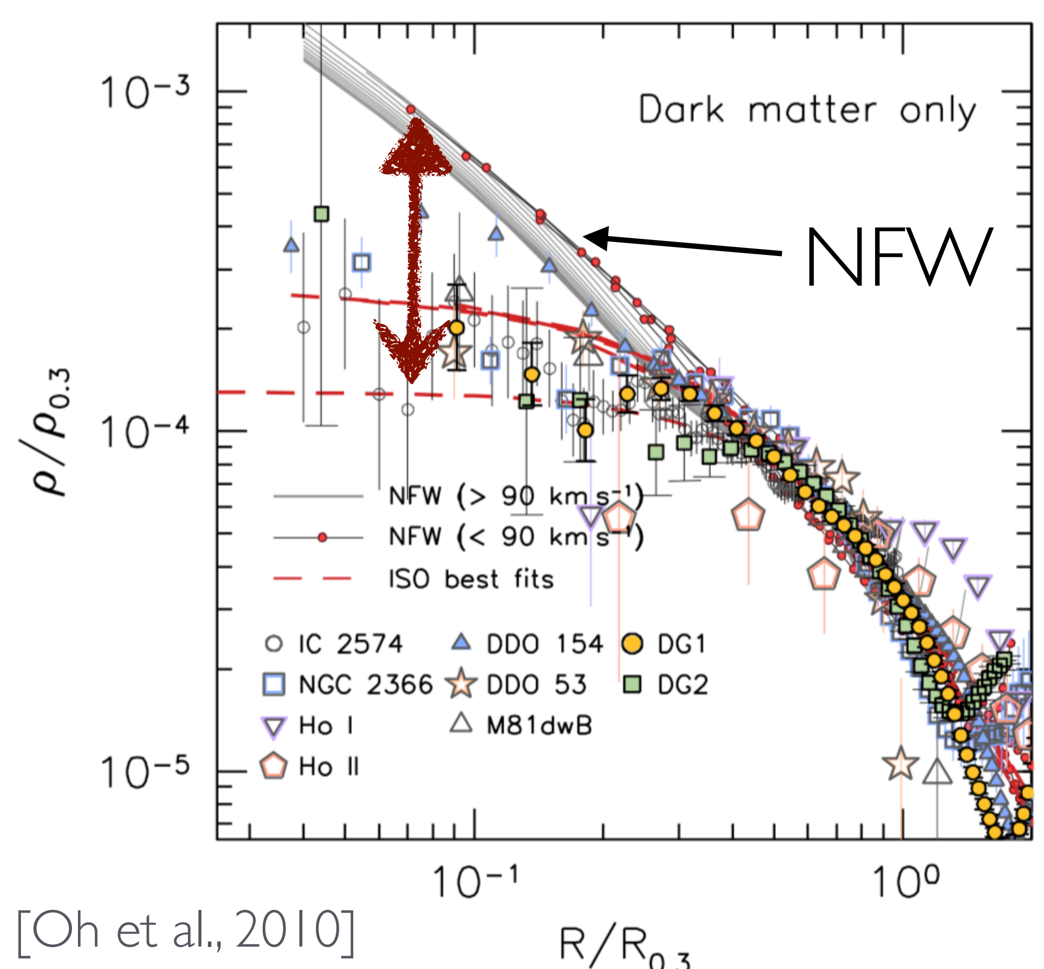
- Several discrepancies between N-body simulations and astrophysical observations:

  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: $\rho(r) \xrightarrow{r\to 0} \mathrm{const}$
- 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]

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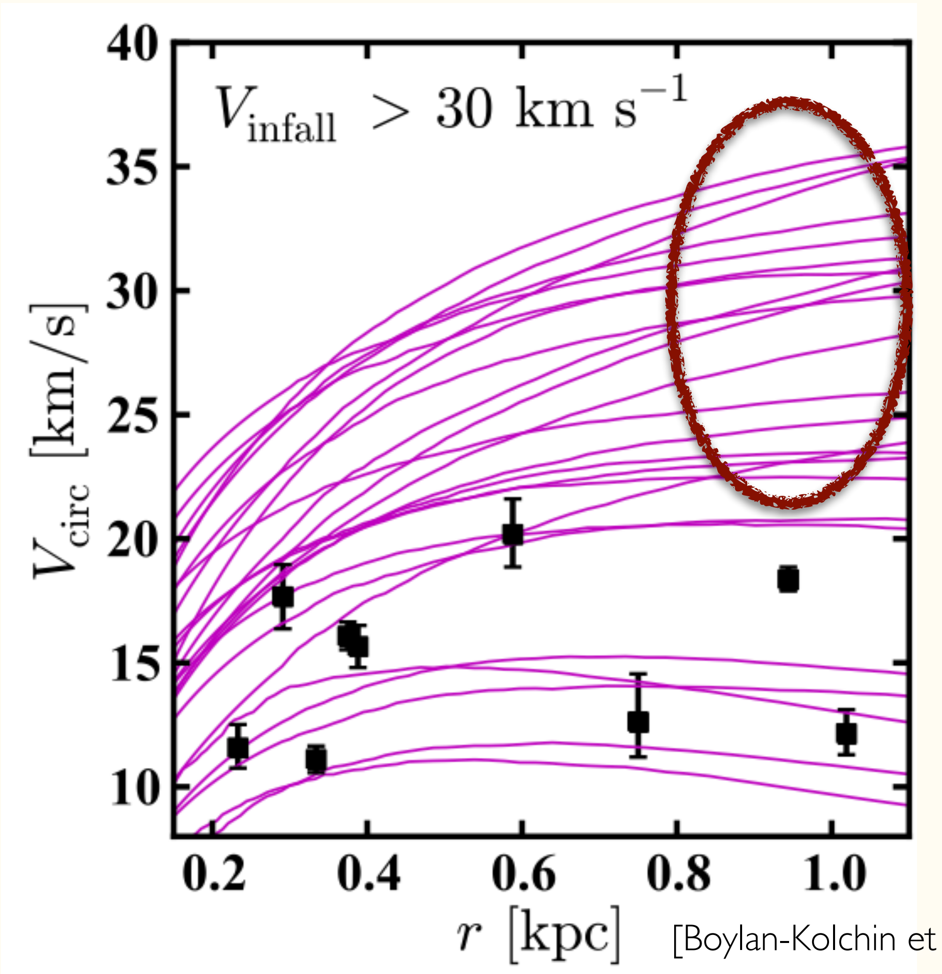
  2. "Too-big-to-fail" problem — [Boylan-Kolchin,Bullock,Kaplinghat 2011,2012]

     - 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]

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  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.

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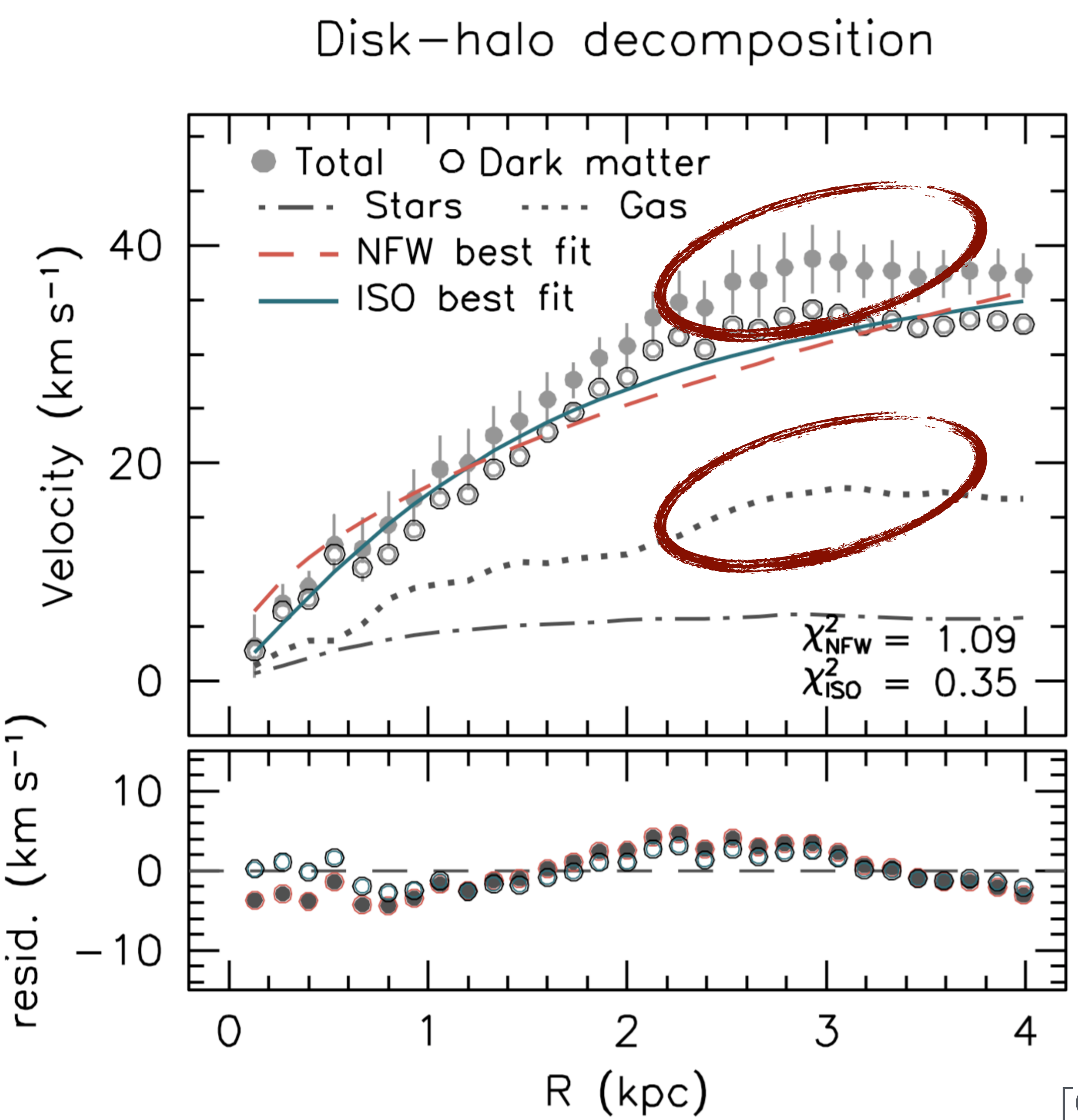
But highly non-trivial…

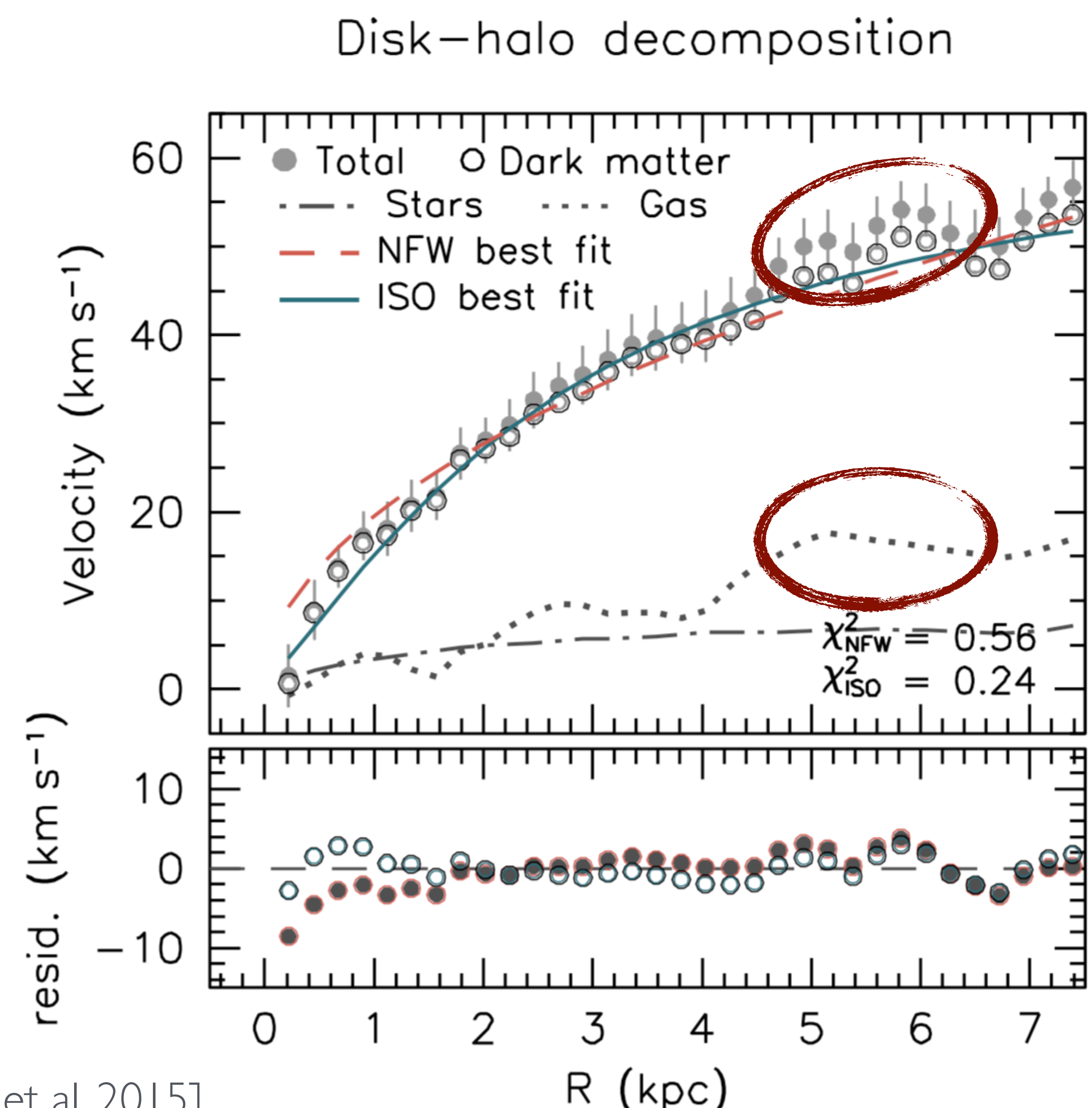
Baryonic effects such as supernova feedback may explain (some) these discrepancies (significant ongoing study). Harder to explain (some) discrepancies in field dwarfs.

To answer, must understand baryonic feedback much better!

# One more problem to note…

## Features in Rotation Curves




[Oh et al. 2015]

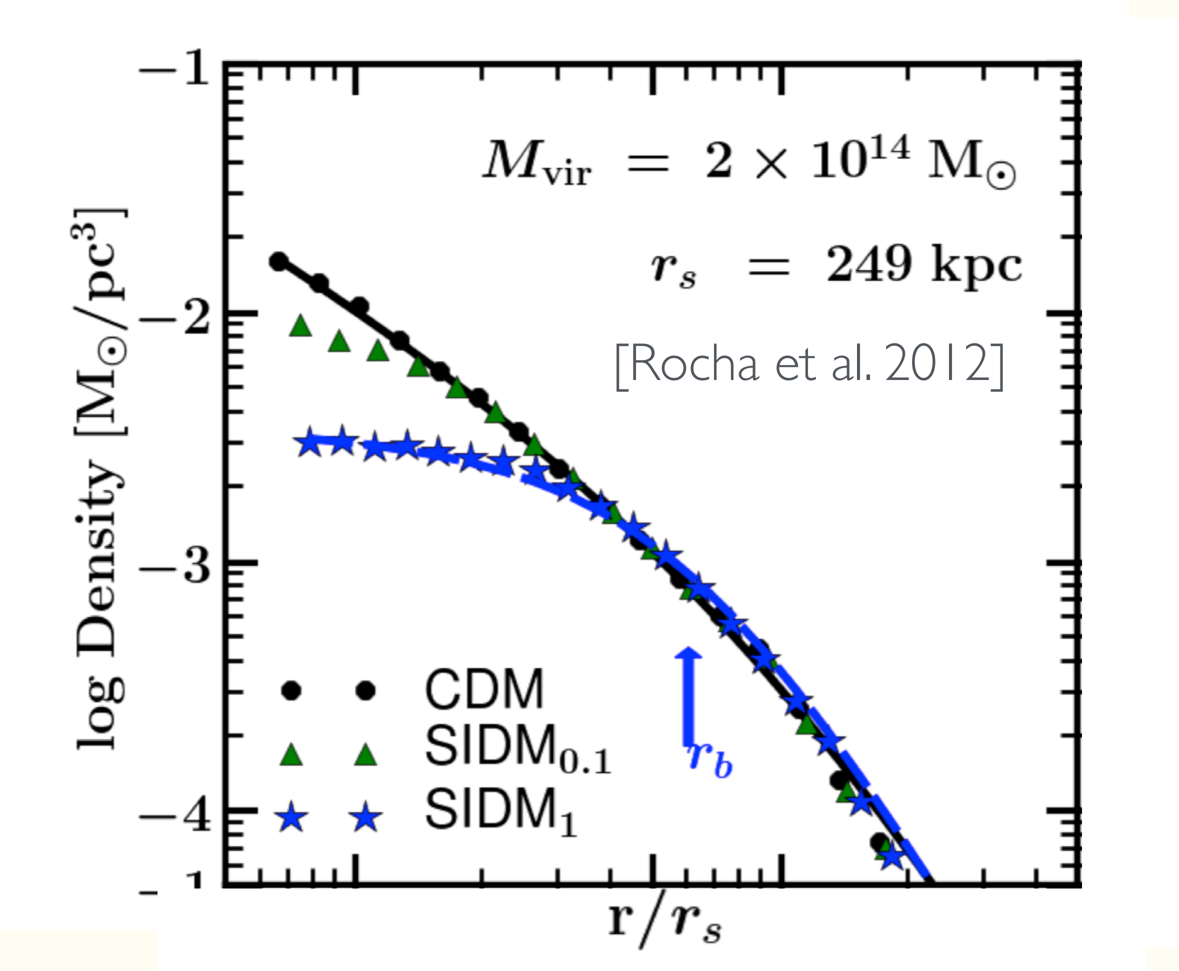
Features in rotation curves are intriguing. Mergers may provide a clue?

# 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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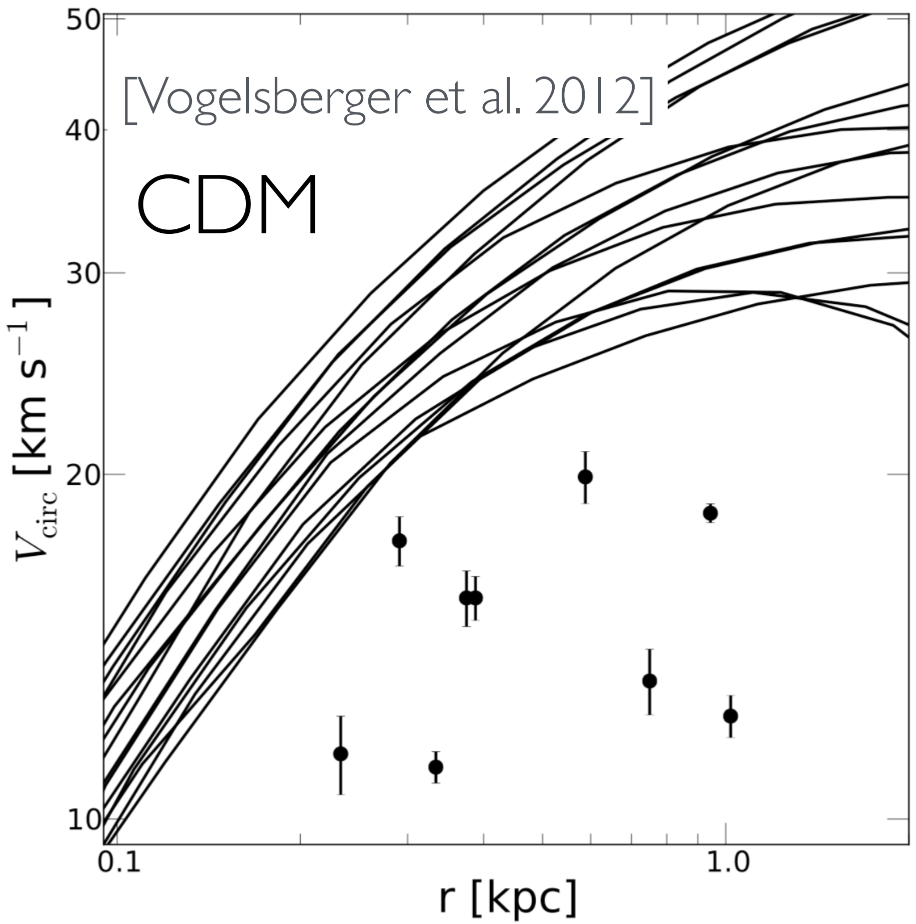
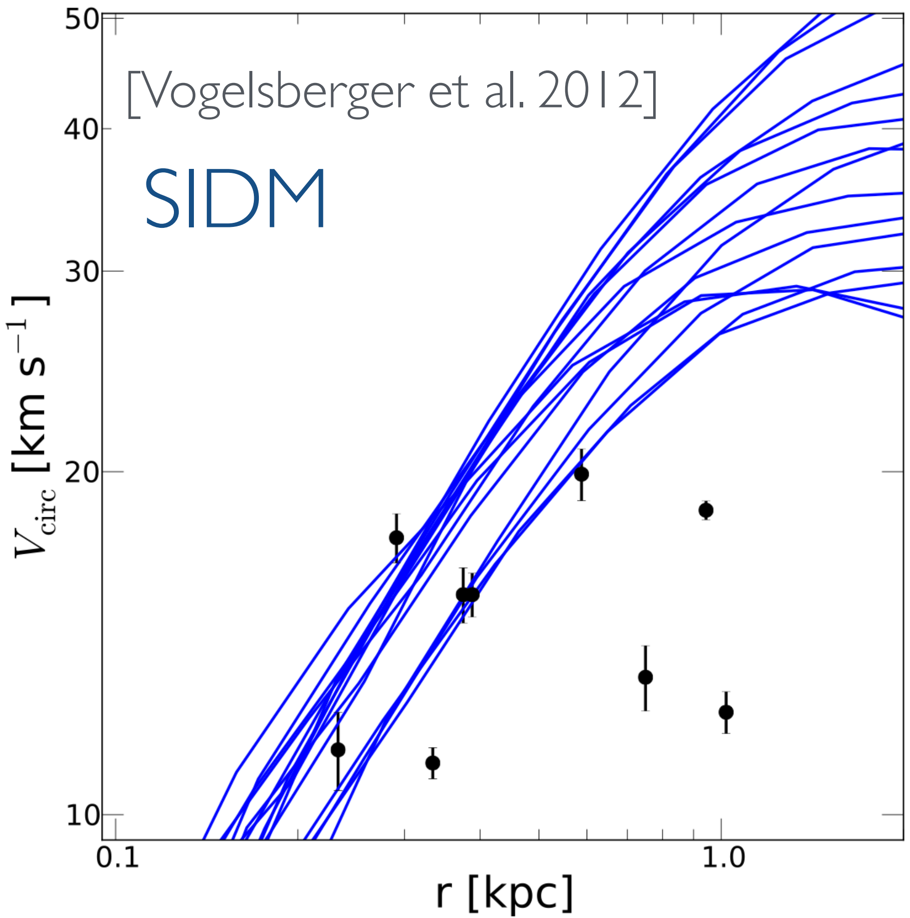
  - Collisions strip sub-halos and reduce number of satellites.



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

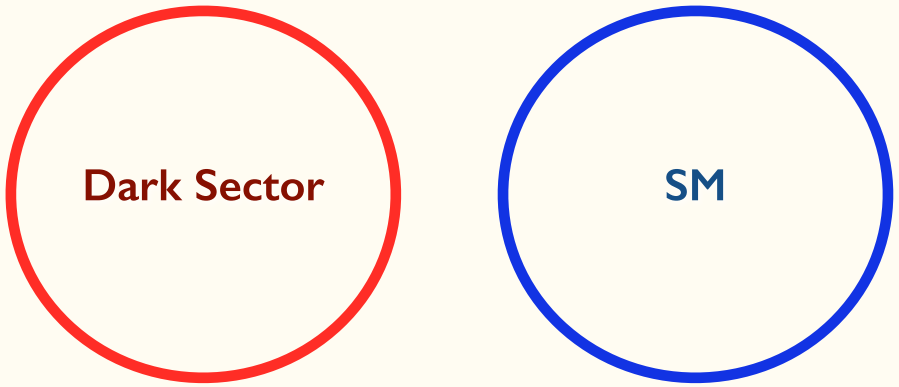
## A Non-trivial dark sector!

# Self-Interacting Dark Matter?

## 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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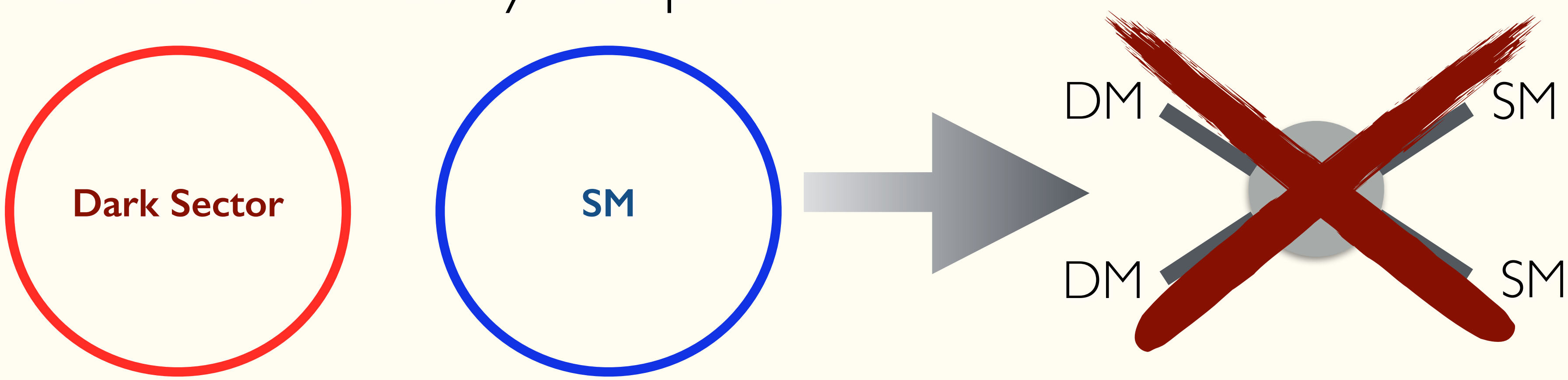

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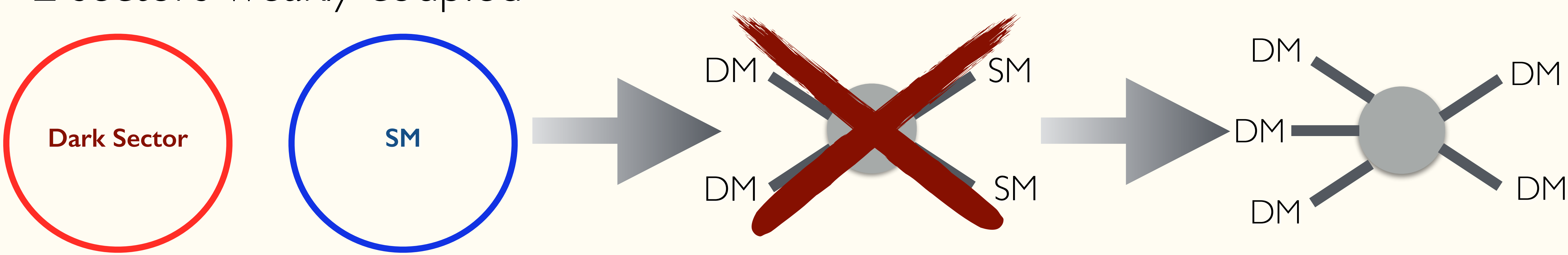

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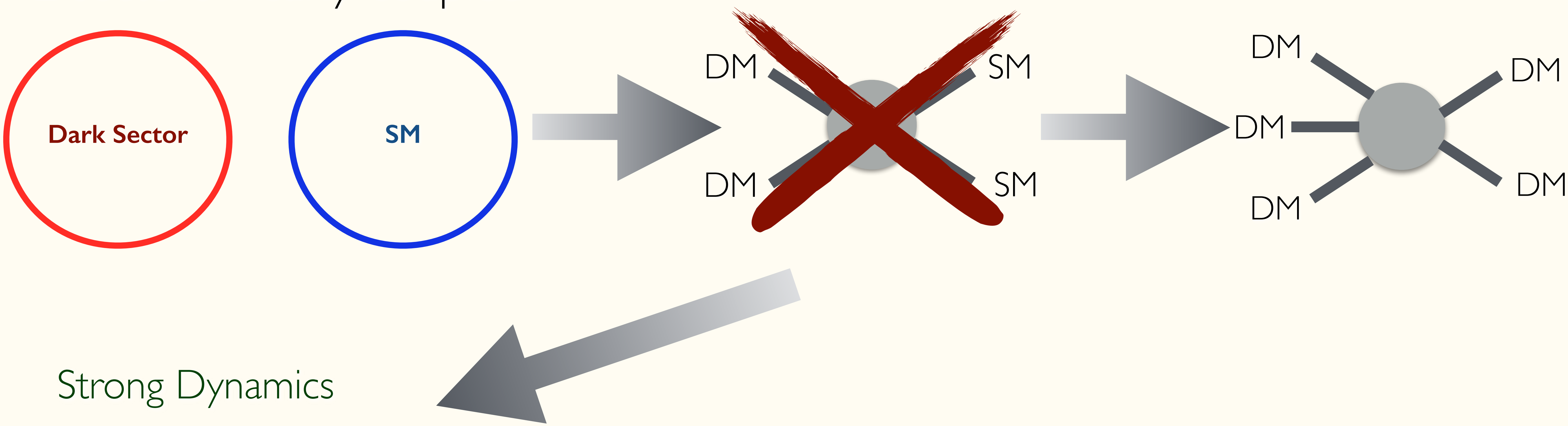


Strong Dynamics

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

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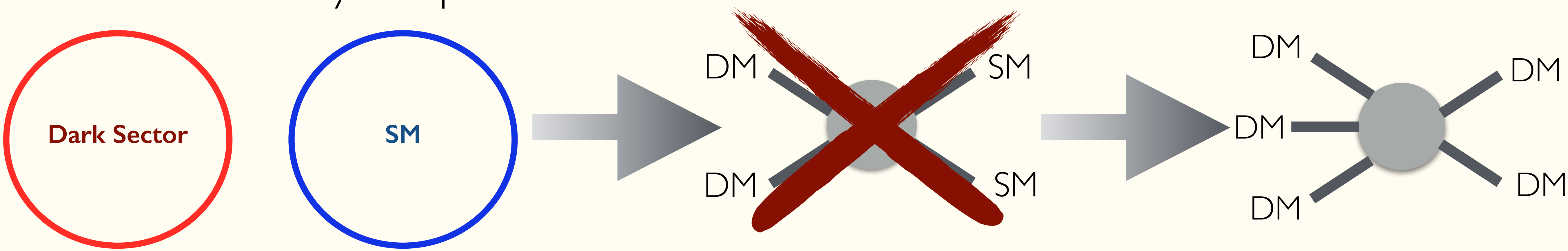


Strong Dynamics

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

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

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

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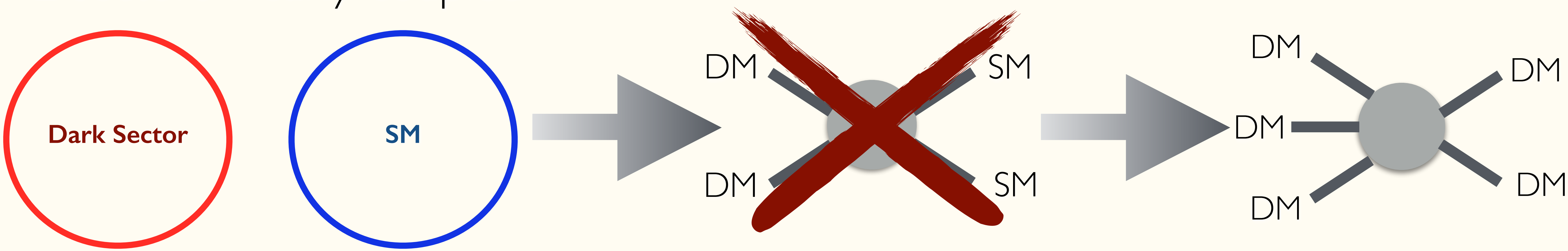


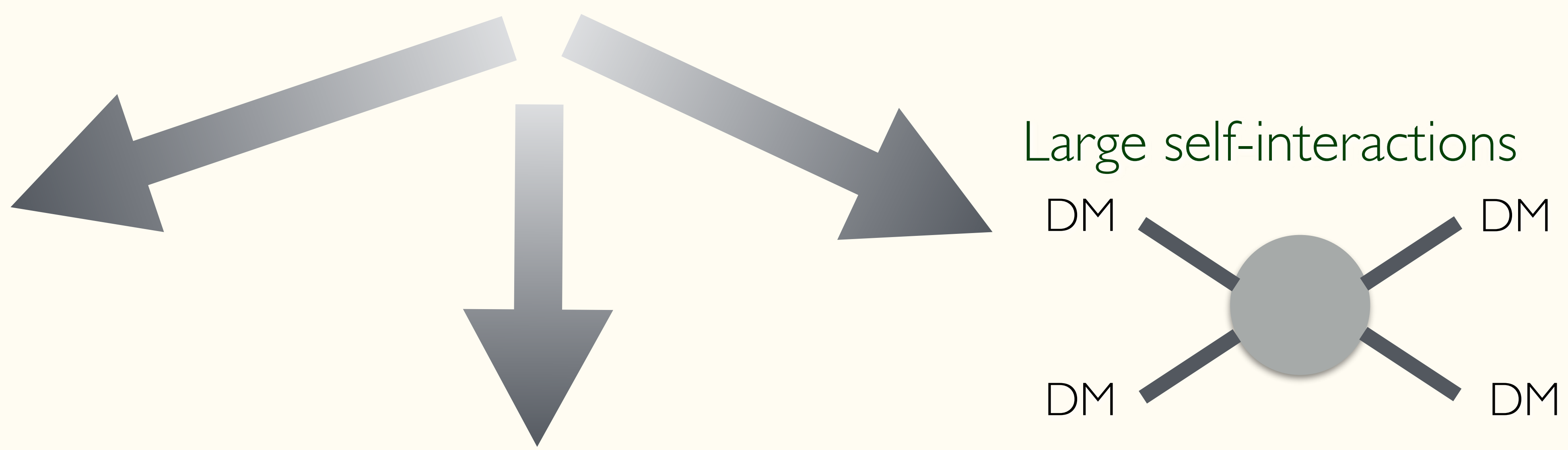


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QCD (low!) scale emerges for a strongly-interacting sector.

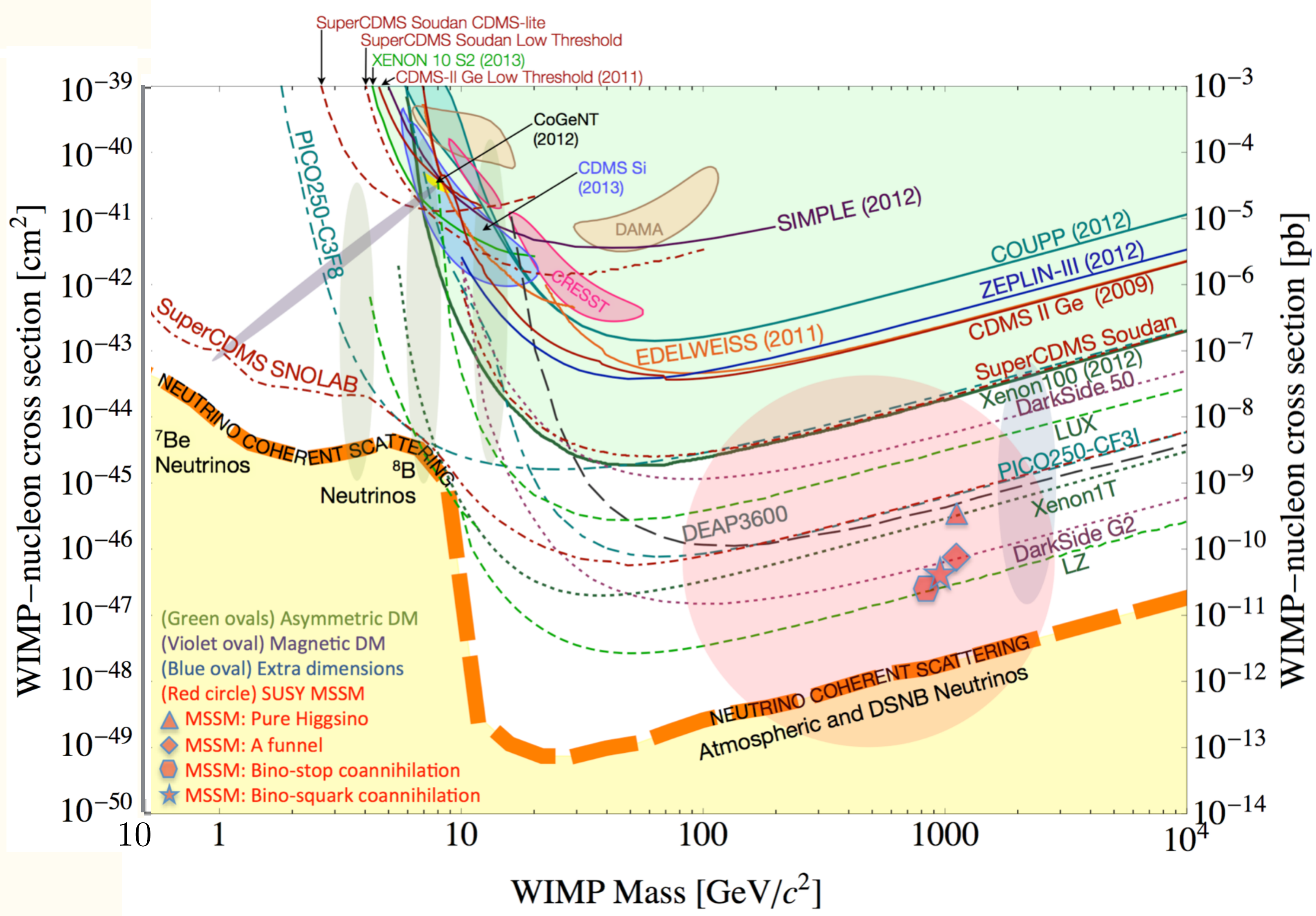
$$m_{\rm DM} \simeq \alpha_{\rm eff} \left(T_{\rm eq}^2 M_{\rm Pl}\right)^{1/3} \sim 100\ {\rm MeV}$$

Many theoretical and experimental considerations hint towards DM beyond the WIMP,
with low mass scales.

How do we search for it?

# Significant experimental efforts in recent years to search for a dark matter or dark sector

## Focus briefly on direct detection



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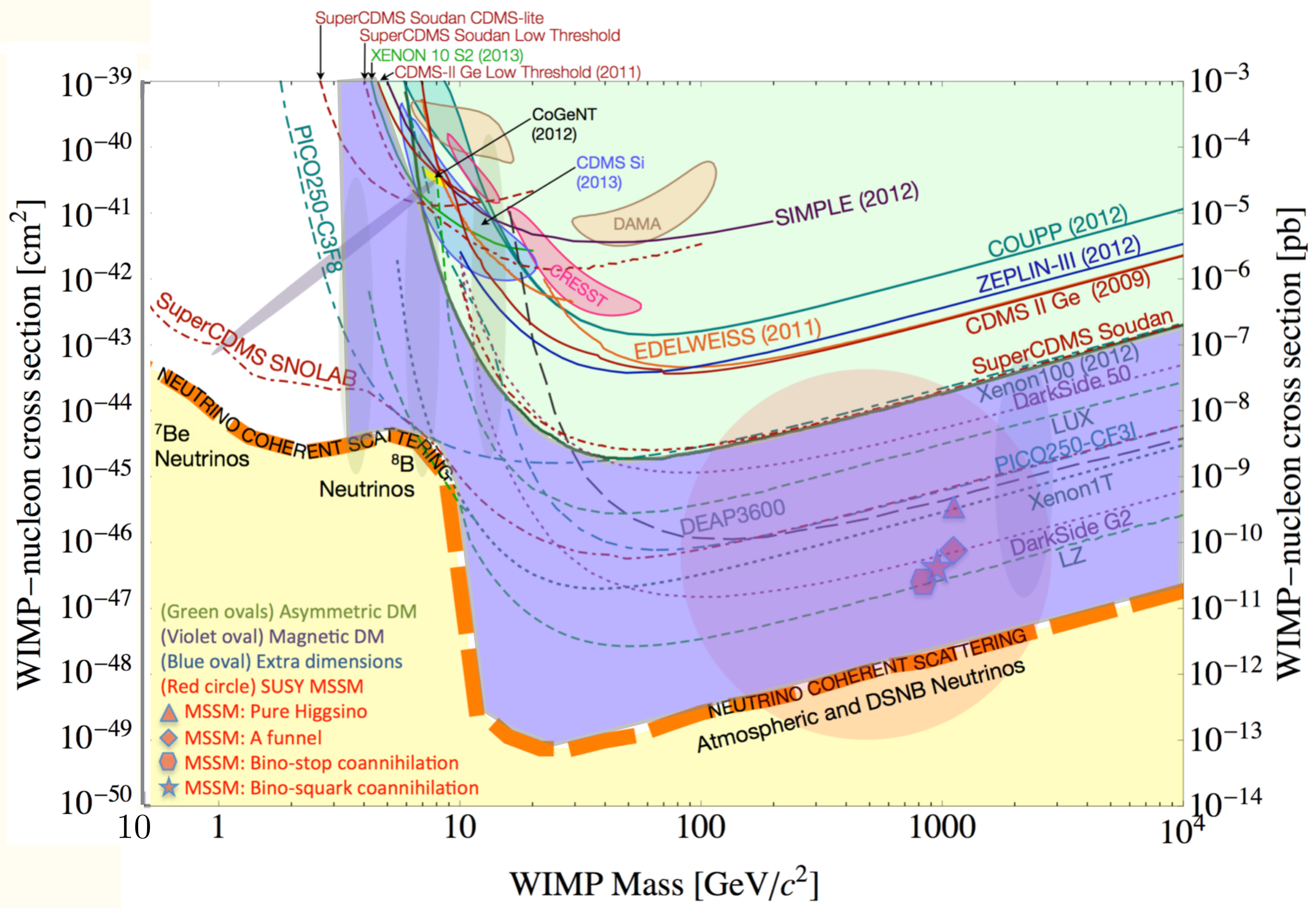

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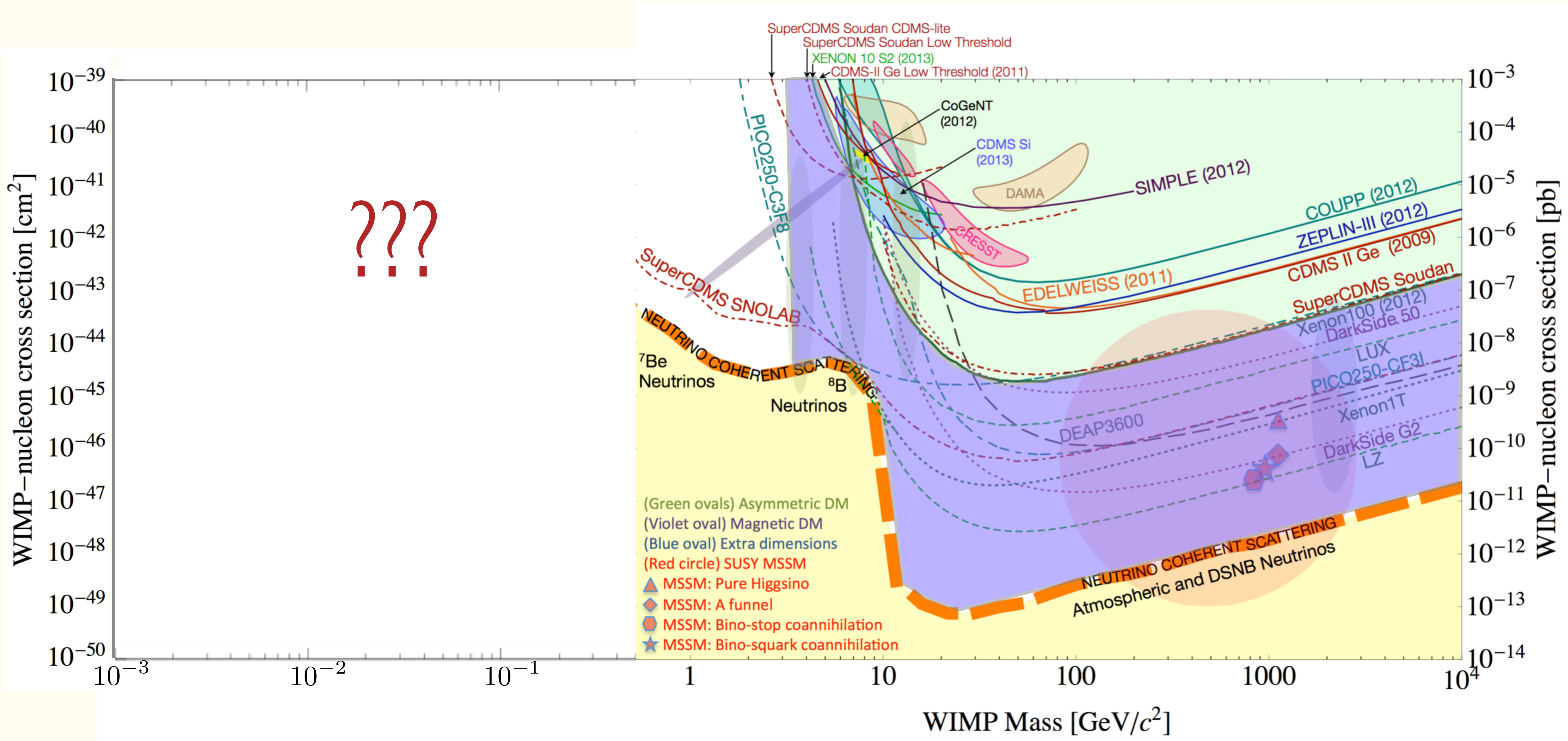
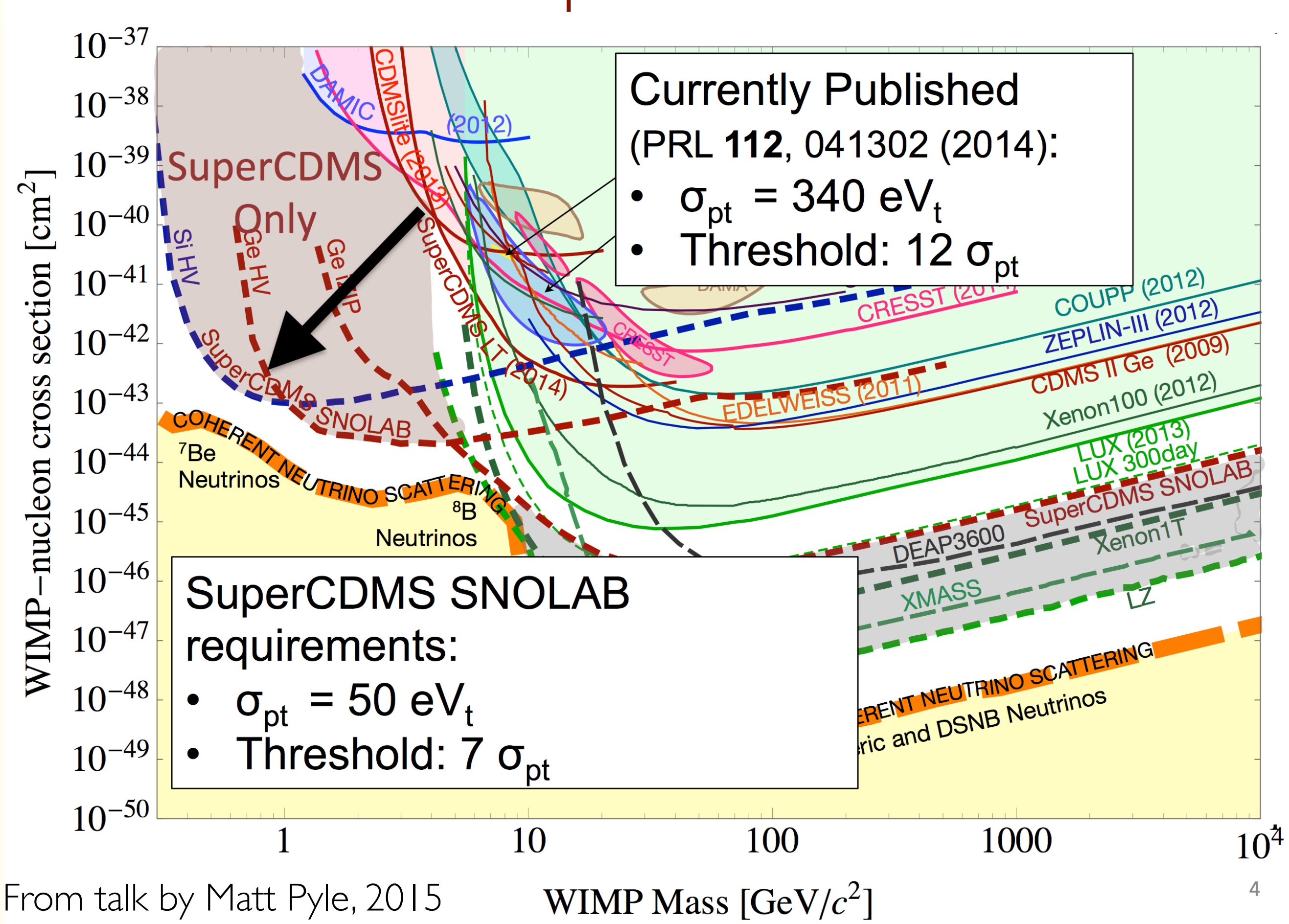


# Direct Detection of Light and Exotic DM

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

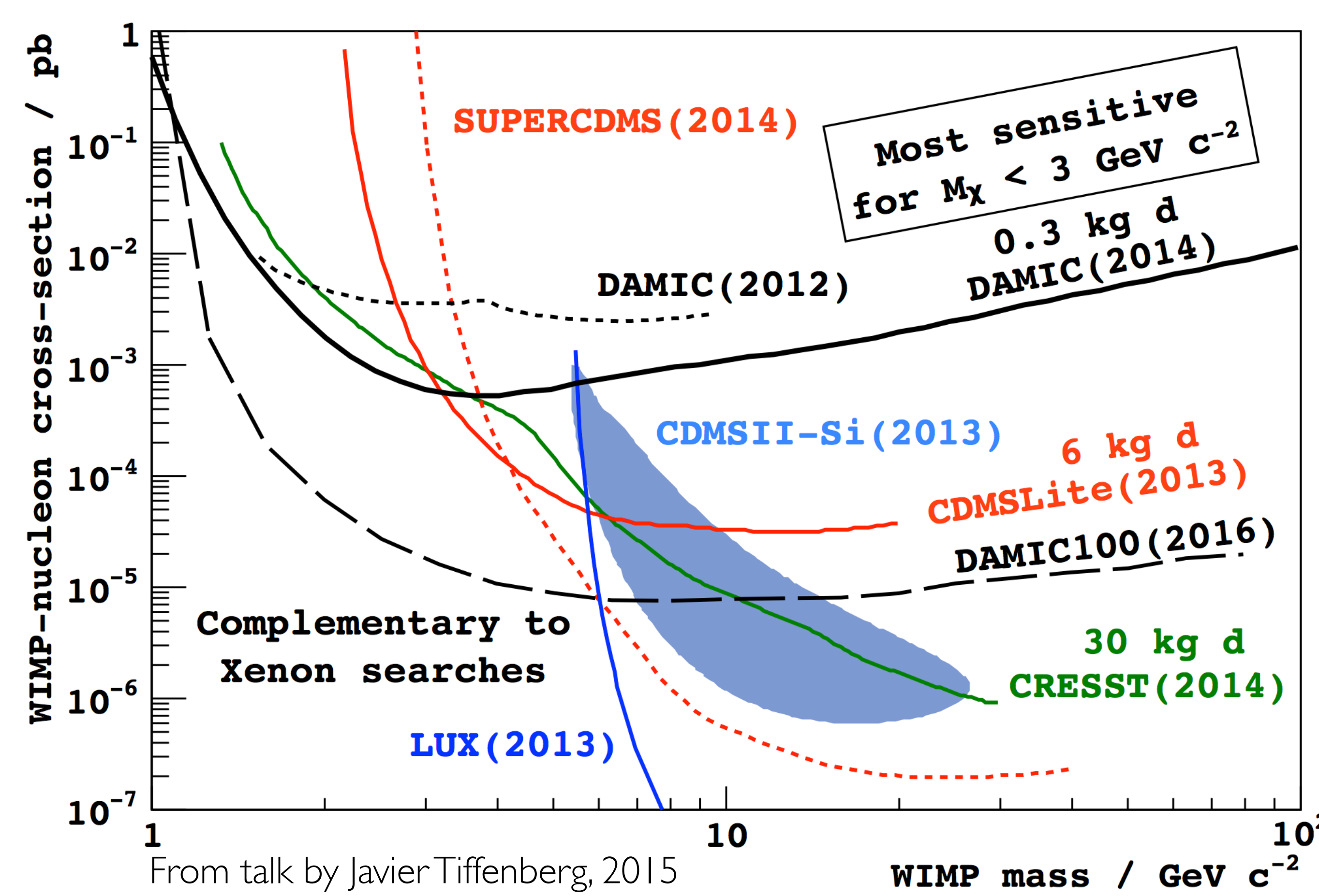
Threshold ≳ 50 eV

## SuperCDMS




From talk by Matt Pyle, 2015

## DAMIC




From talk by Javier Tiffenberg, 2015

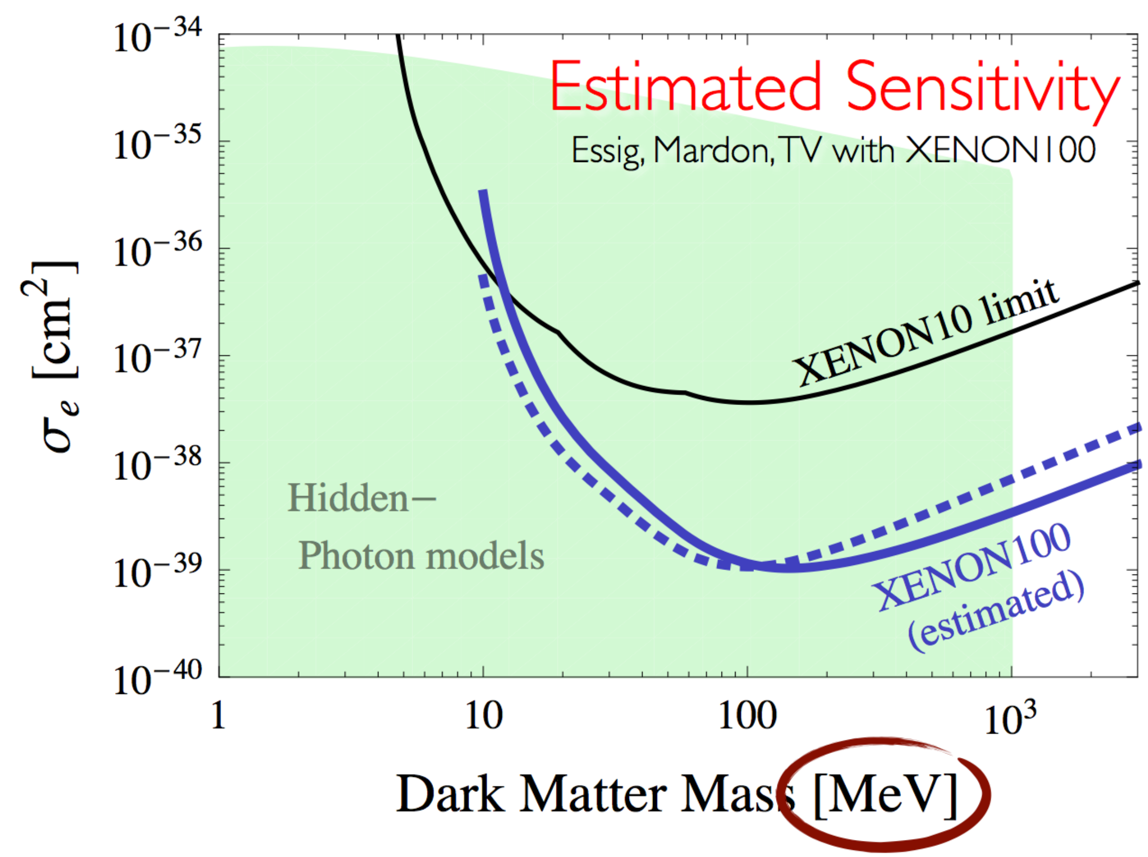
# Direct Detection of Light and Exotic DM

- 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]

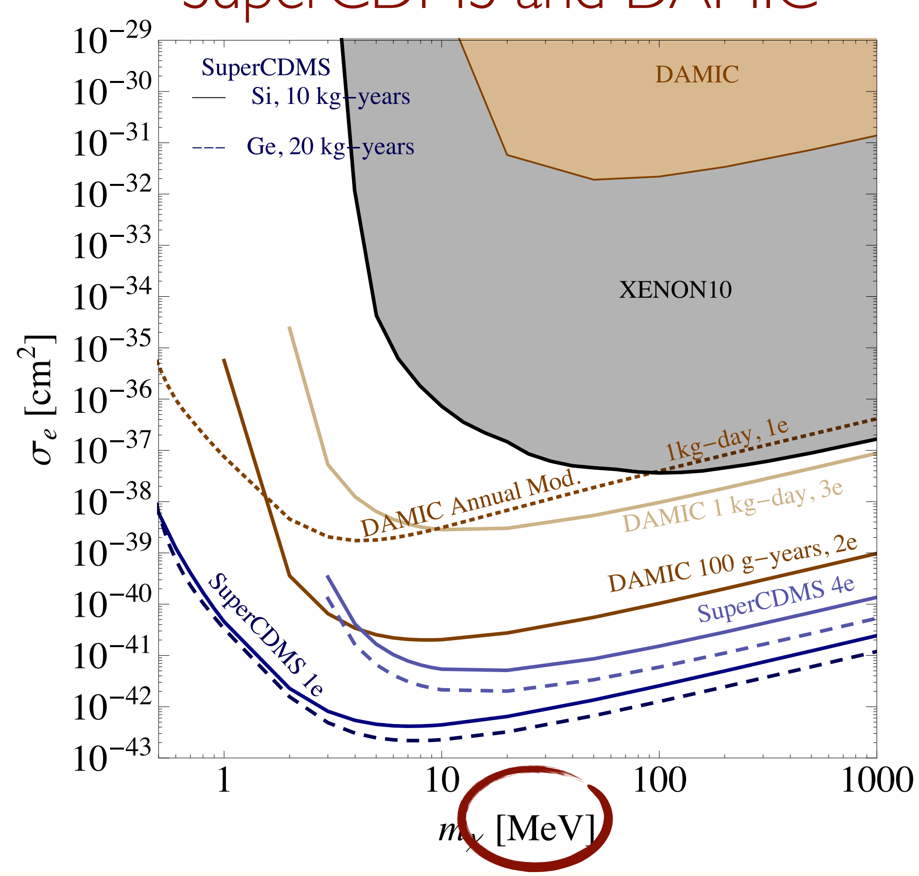
Threshold ≳ 0.1 eV

XENON



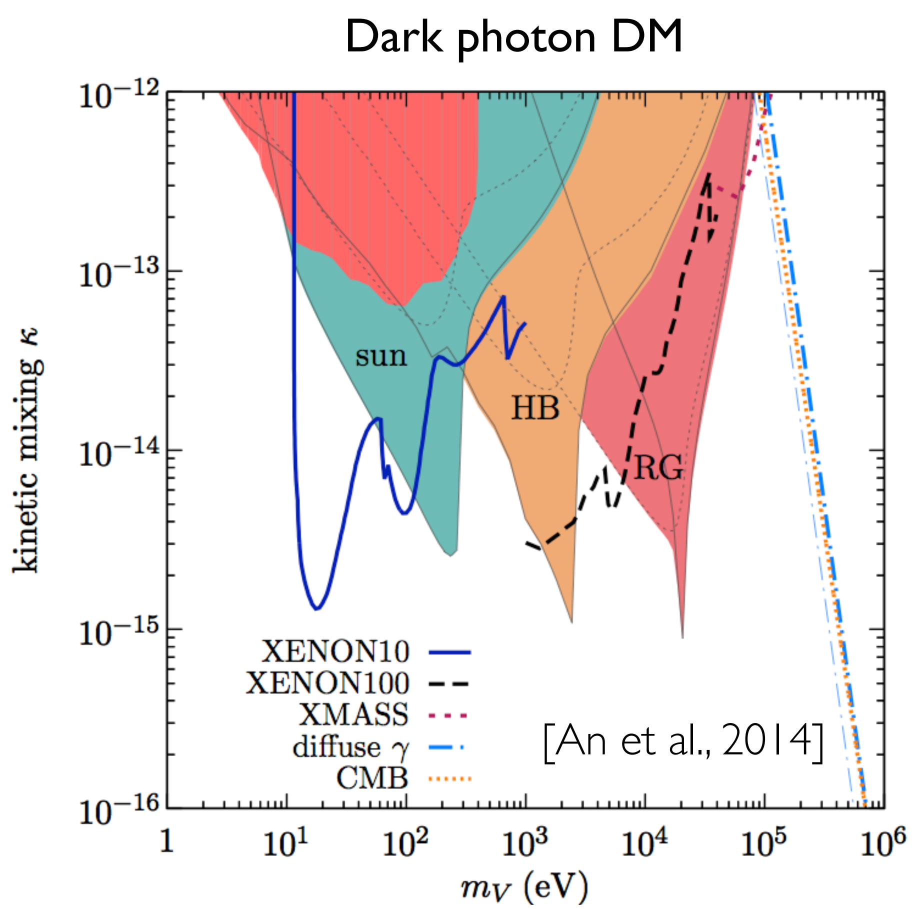

[Essig, Manalaysay, Mardon, Sorensen, TV, 2012;
Essig, Mardon, TV, XENON100 (upcoming)]

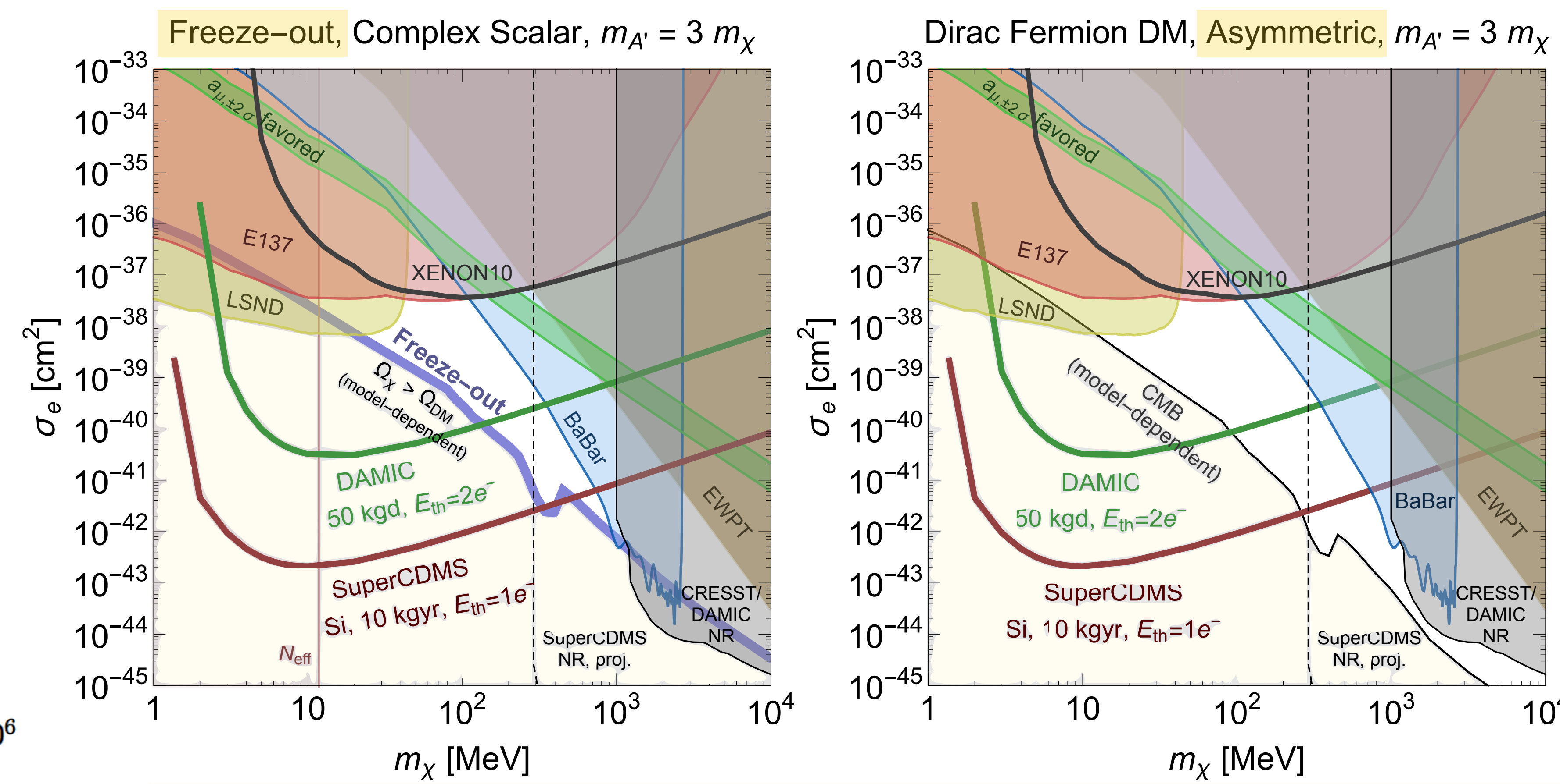
SuperCDMS and DAMIC




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

# Direct Detection of Light and Exotic DM




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

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

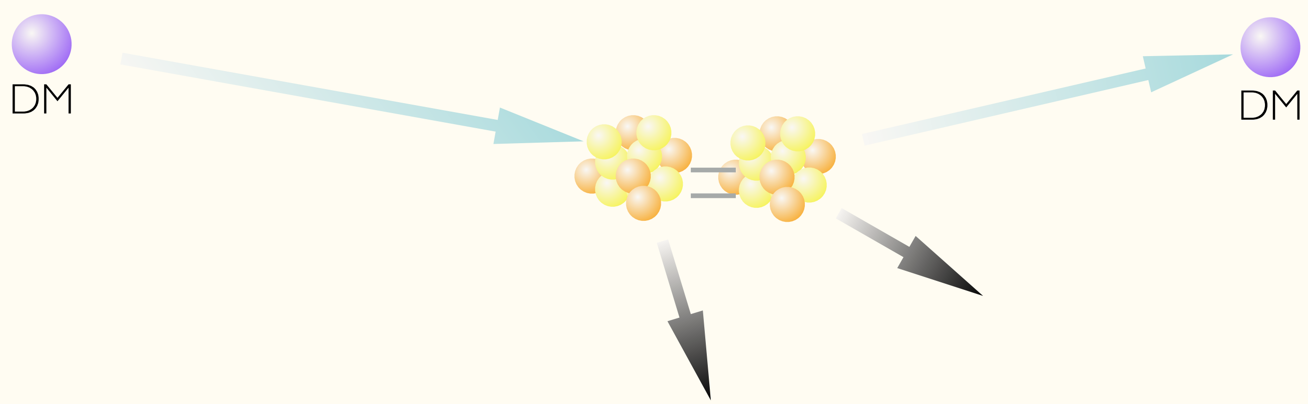
# Direct Detection of Light and Exotic DM

- 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




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.

# Direct Detection of Light and Exotic DM

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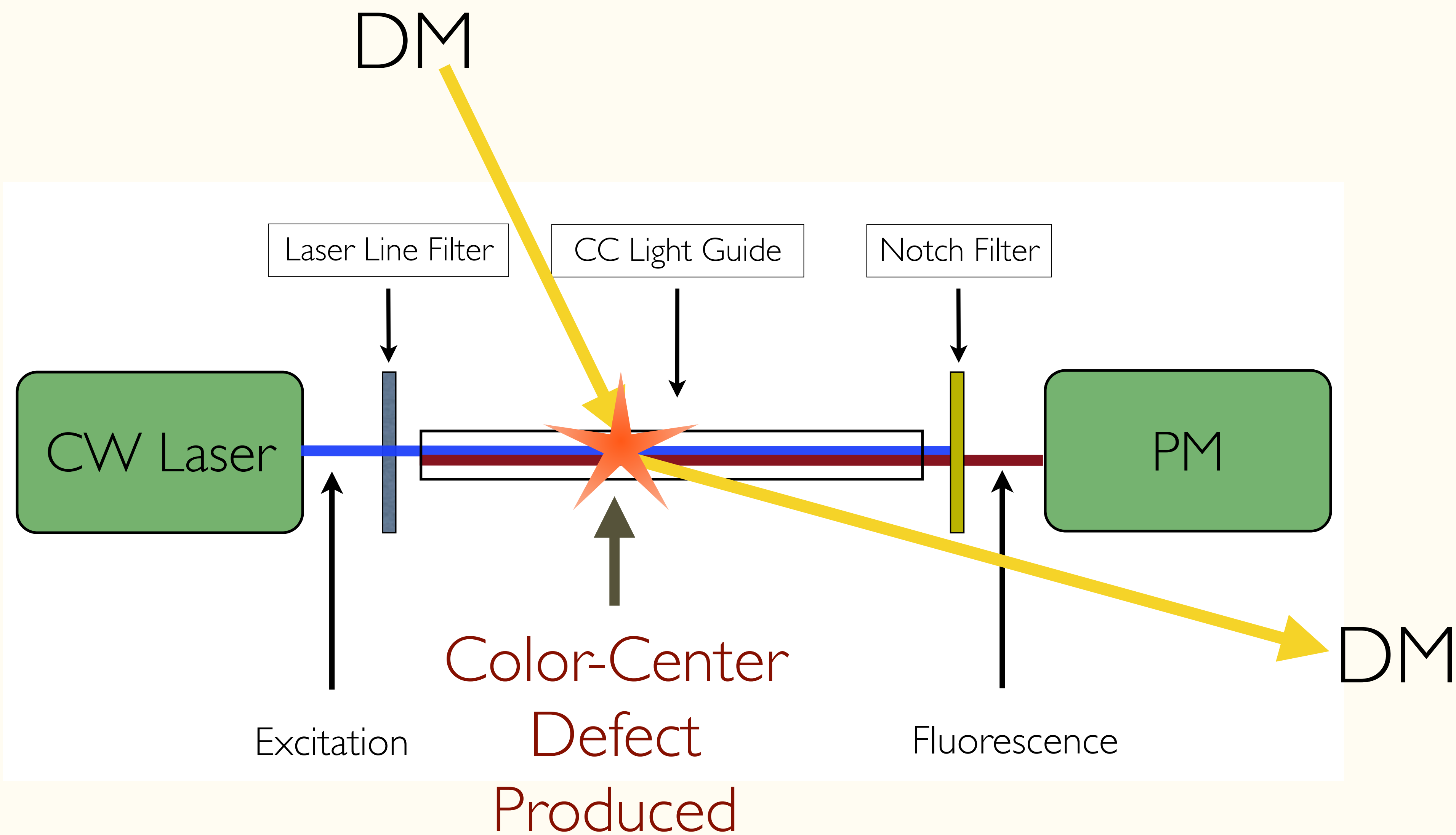
[Essig, Mardon, TV, 2011; Anderson, Figueroa-Feliciano, Formaggio, 2011; Drukier, Nussinov, 2013; Agnes et al. 2014; Hochberg, Zhao, Zurek, 2015; Essig, Mardon, Slone, TV, 2015 (upcoming)]

- One effort:




New theory-experimental collaboration.   New lab opened.

Abir, Bloch, Essig, Mardon, Slone, TV, Budnik, Chechnovsky, Kreisel, Soffer, Sagiv, Landsman, Ashkenazi, Priel

# 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.

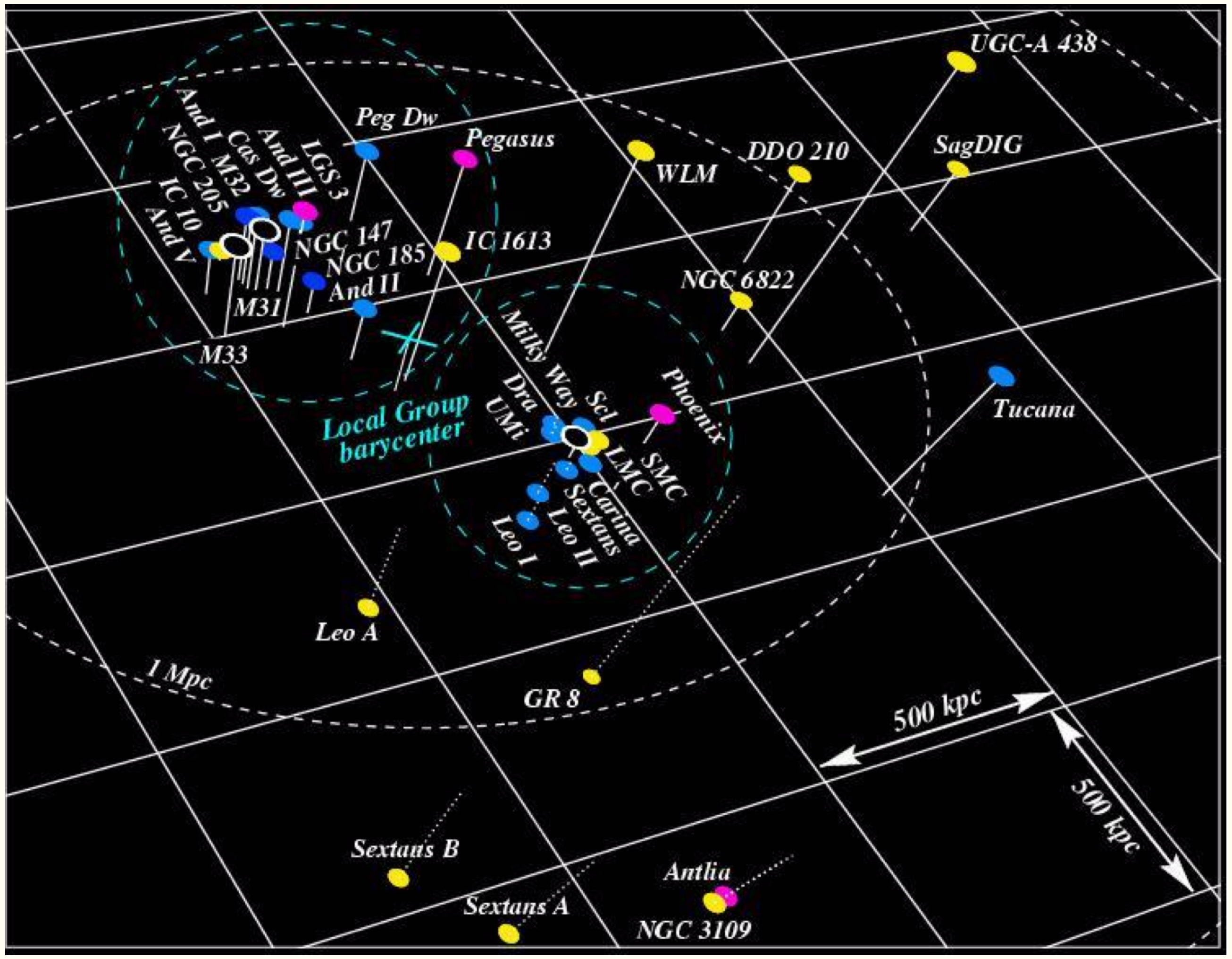
# Backup Slides

# Problems with Cold Dark Matter?

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

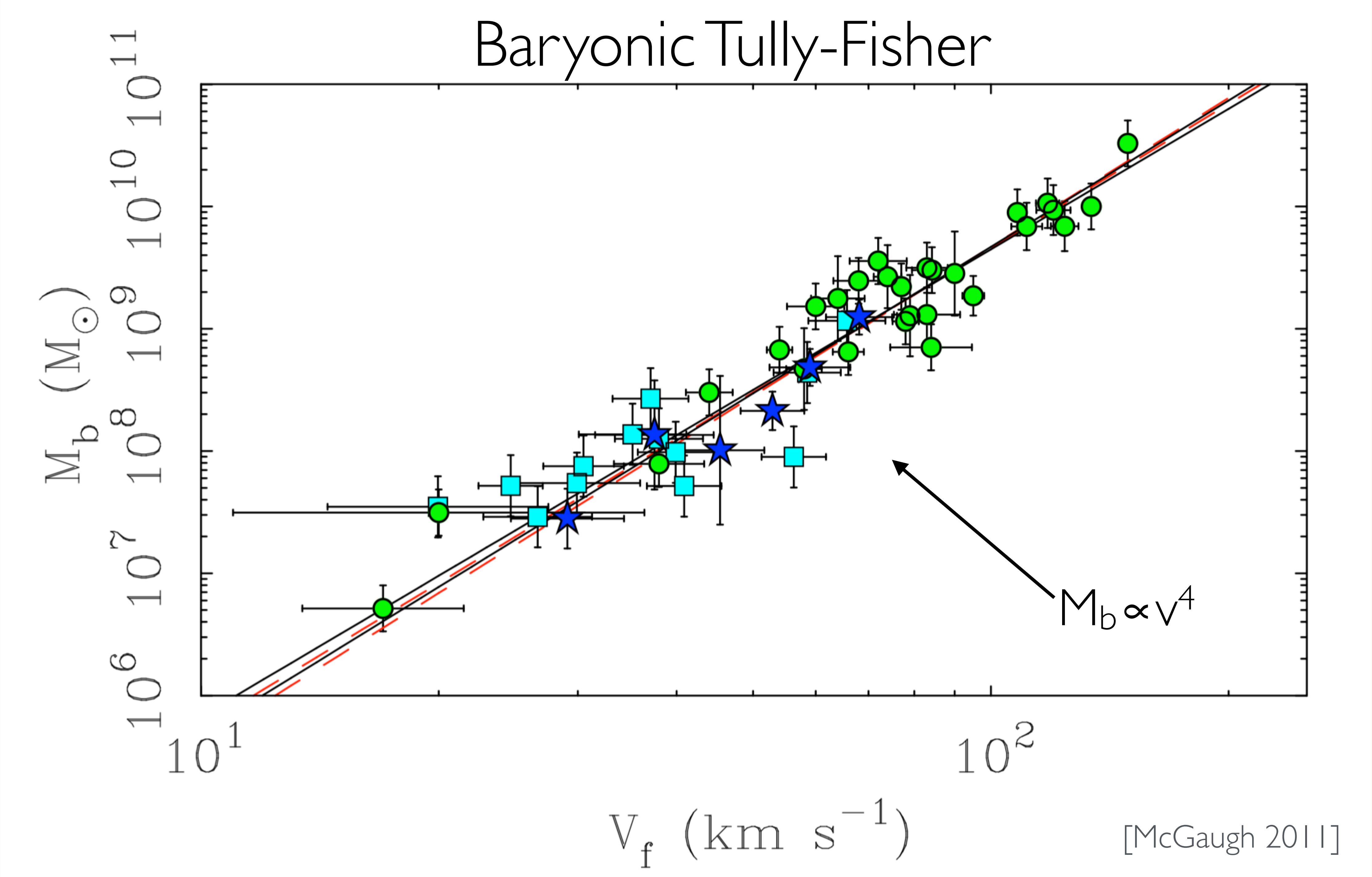
## Can one explain these with CDM?

- Baryonic effects (such as Supernova feedback) are important, and can explain core vs. cusp (may require late time star formation).
  [Governato et al. 2012;  Onorbe et al. 2015]
- Supernovae cannot explain too-big-to-fail but baryons from MW can.
- However harder to explain discrepancies in field dwarfs.




[Papastergis et al. 2014]

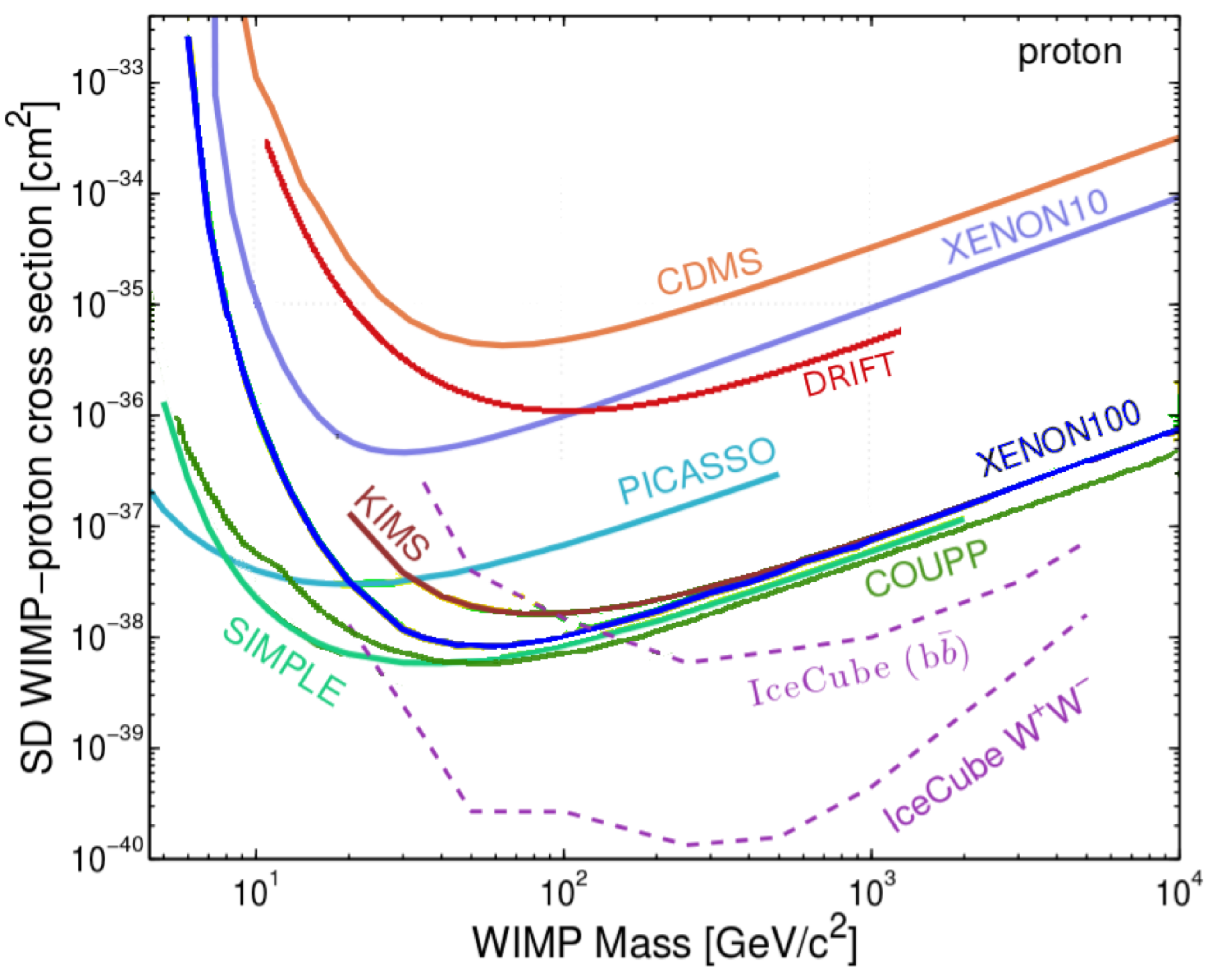
# Two more problems to note…

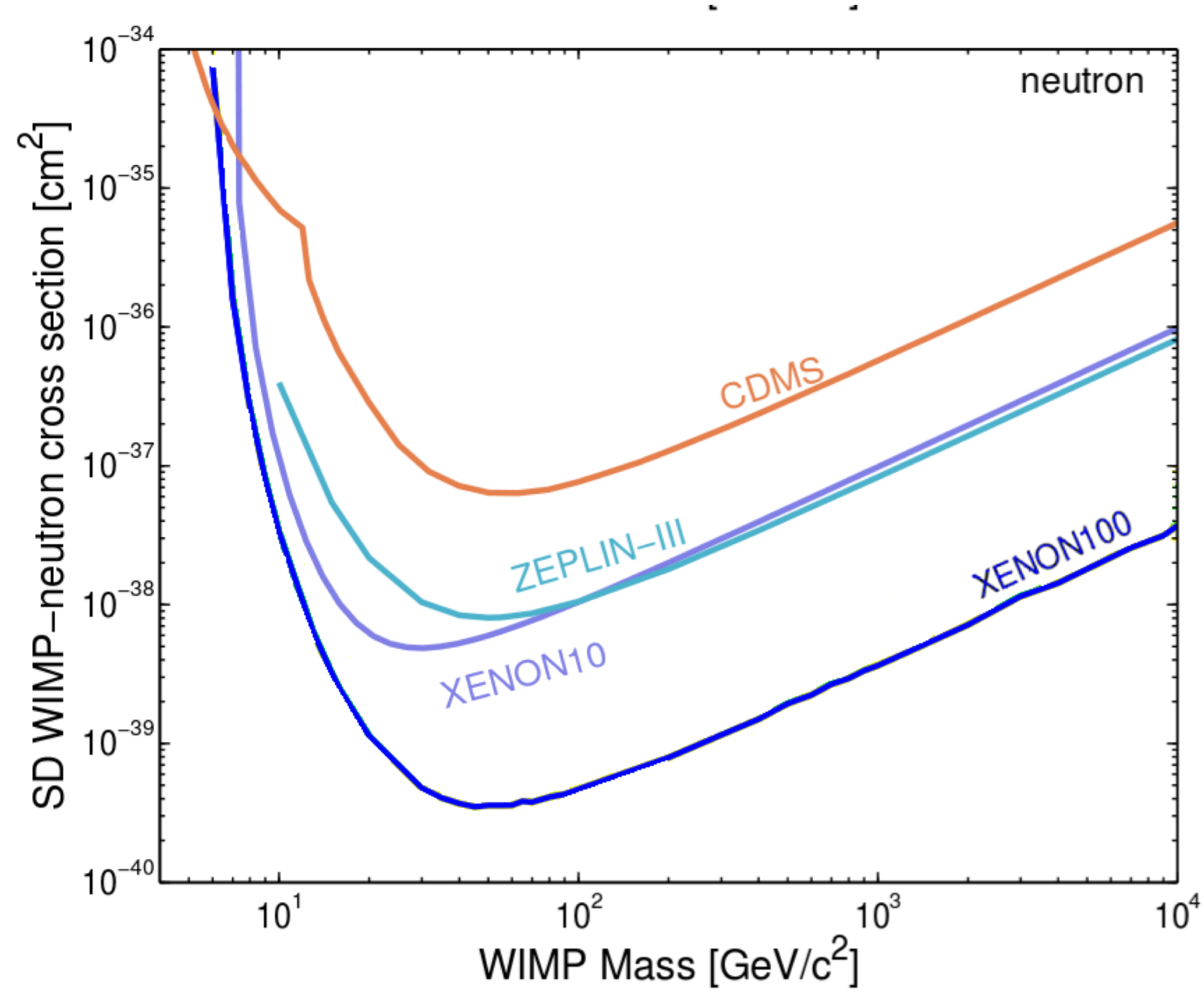



$\Lambda$CDM can explain, but requires baryonic feedback.

Non-trivial to explain jointly: slope, scatter, luminosity function..

# Direct Detection: Status (Spin-Independent)

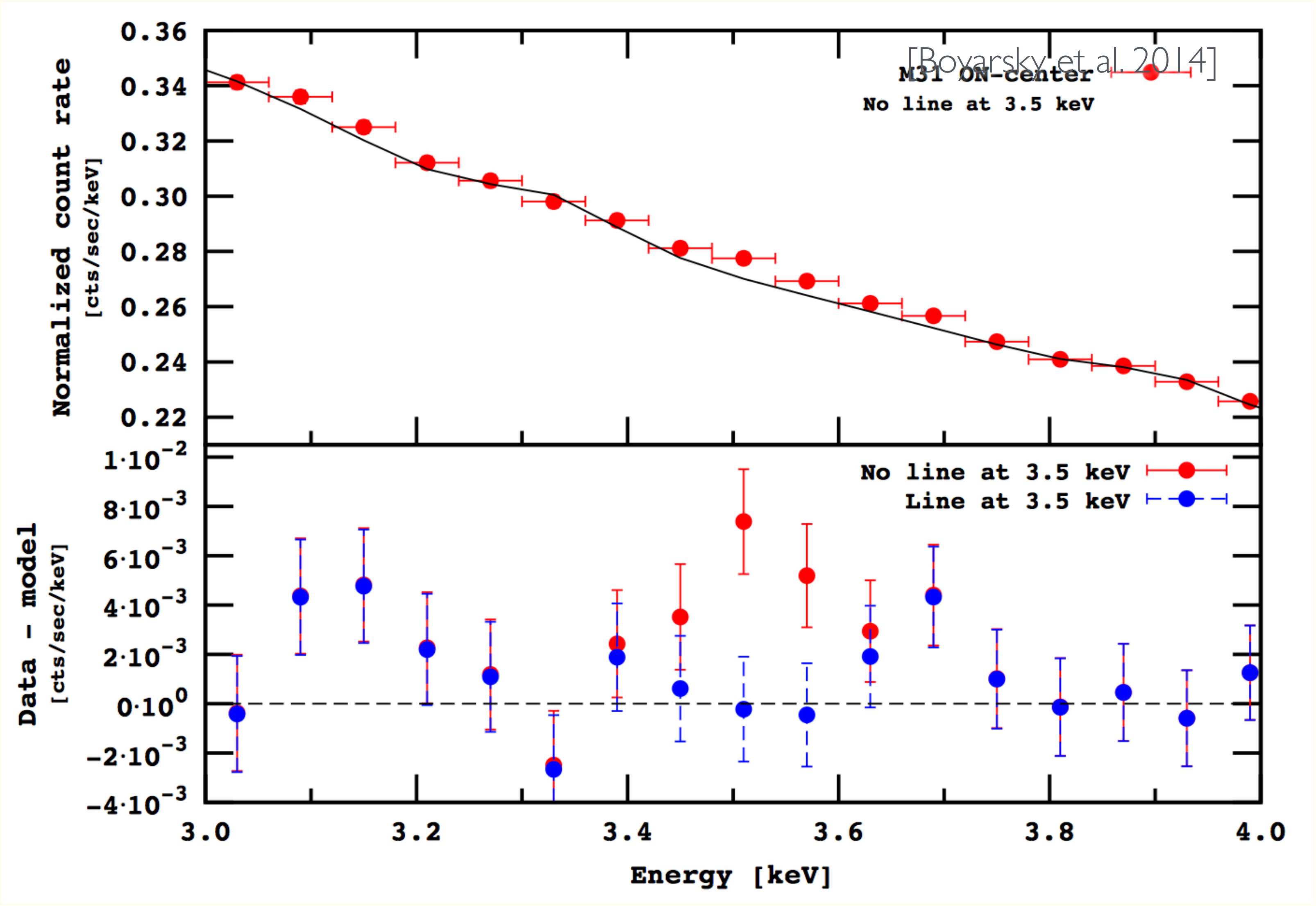


# Anomaly II: The 3.5 keV Line

- Initially discovered with XMM-Newton data in Perseus cluster, Andromeda galaxy, and several other clusters.

[Bulbul, et al. 2014; Boyarsky et al. 2014]



# Anomaly II: The 3.5 keV Line

- But not everyone agrees…
- There are several nearby atomic lines:
  - K-XVIII (3.47+3.51 keV)
  - Ar-XVII (3.68 keV)
- Need to know plasma model and atomic abundances.
- Jeltema and Profumo reanalyze and find no need for an excess.

[Jetelma, Profumo, 2014]

- They also find the same line in the Tycho supernova remnant which hosts no dark matter.
- Additional study argues the morphology is inconsistent with dark matter and line correlates strongly with nearby atomic transition lines.

[Carlson, Jetelma, Profumo. 2014]

- Original groups disagree with criticism: Required abundance of K or Ar to explain data must be O(10-20) above expectation.

# Anomaly II: The 3.5 keV Line

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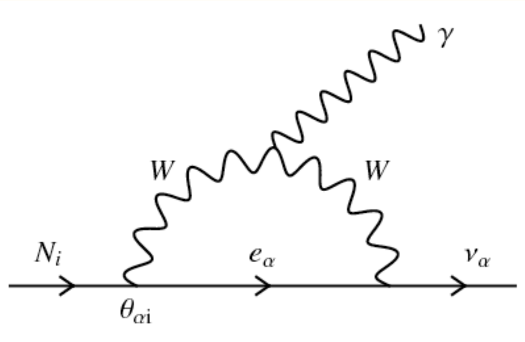
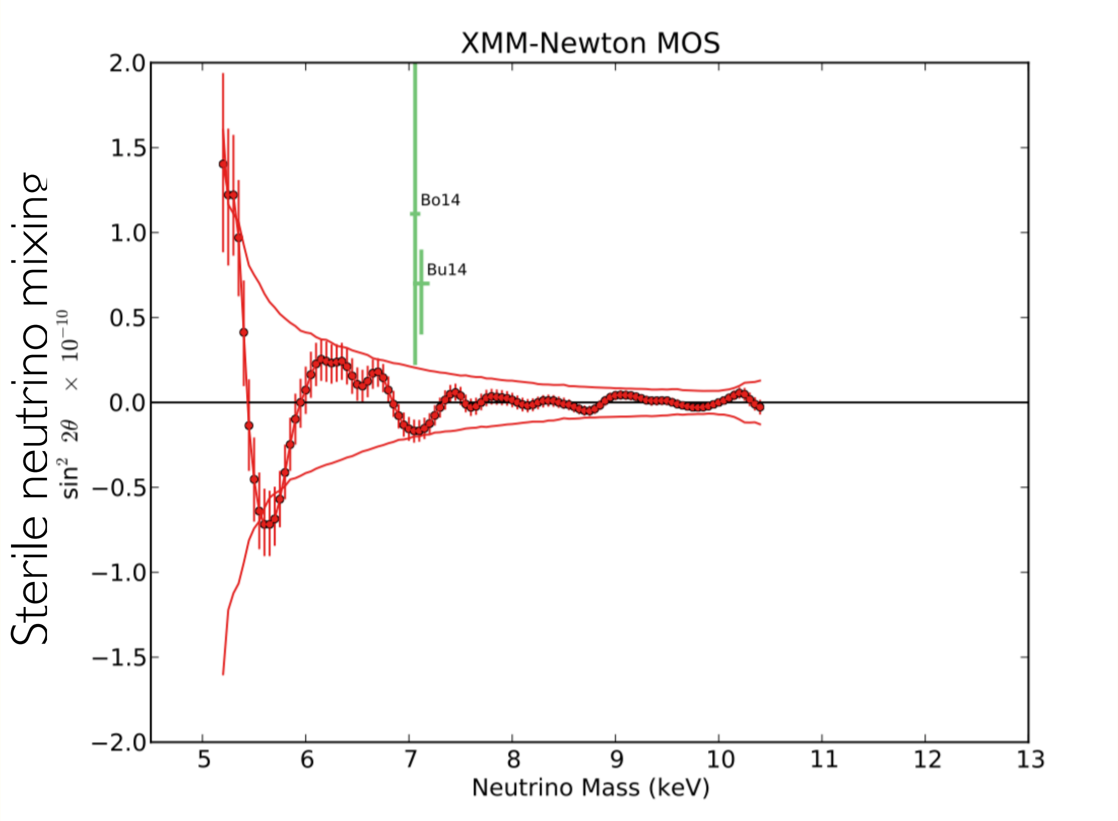
# Anomaly II: The 3.5 keV Line

## Dark Matter Interpretation




- Morphology requires decaying dark matter.
- Most attractive candidate: 7 keV sterile neutrinos.
- Sterile neutrinos ruled out (at ~12σ) by several null observations (in dwarfs, clusters, GC, Andromeda).

[Anderson, et al. 2014; Sekia et al. 2014; Riemer-Sorensen 2014; Malyshev et al. 2014]




- Other DM models that can ameliorate the tension between positive and null results exist.

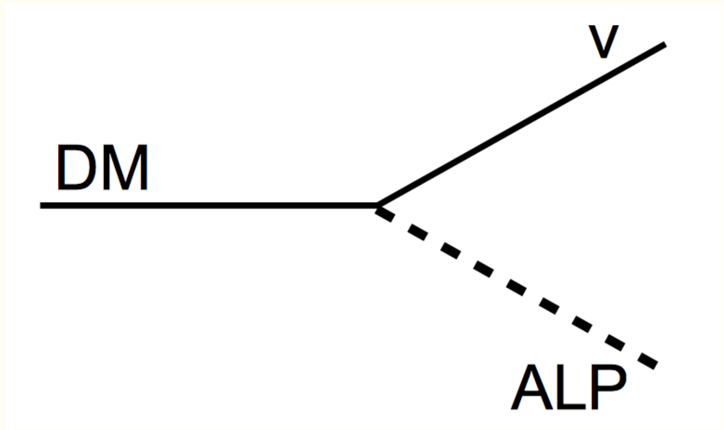
[e.g.: Cicoli et al. 2014; Conlon et al. 2014; Alvarez et al. 2014]

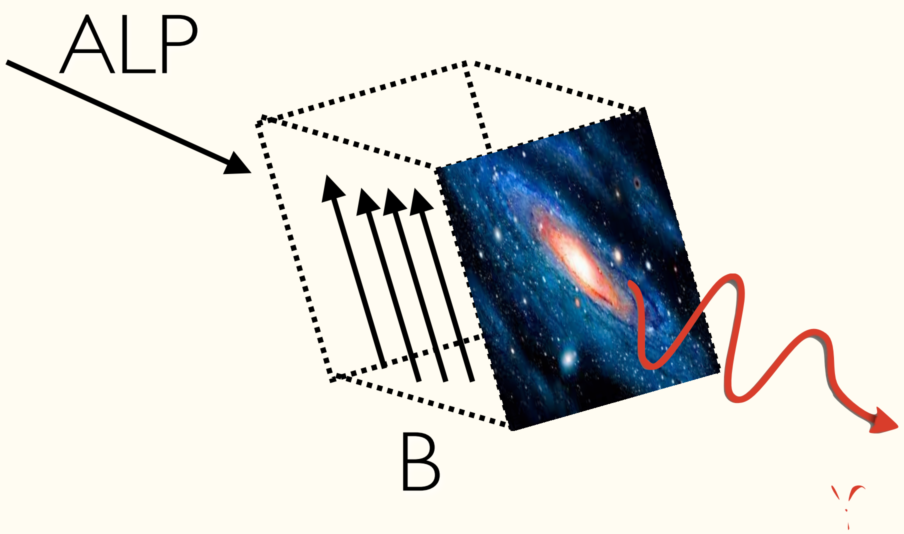
# Anomaly II: The 3.5 keV Line

## Dark Matter Interpretation

- Alternative exotic DM interpretations which are less constrained exist.  E.g.:

### DM decaying to axion-like particle



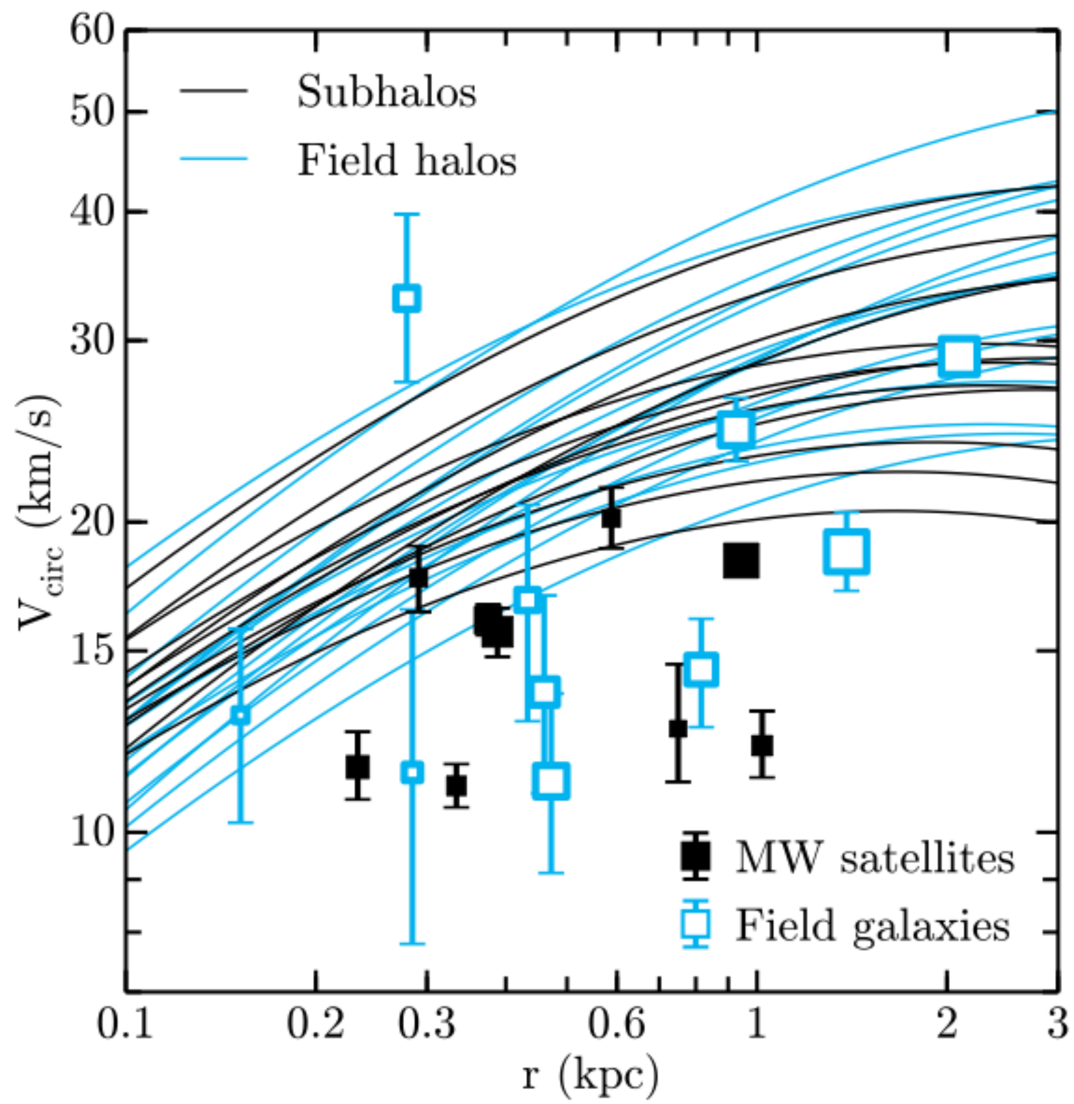




- Rate depends on magnetic fields.
- Can ameliorate tension between positive and null results.

[Cicoli et al. 2014; Conlon et al. 2014; Alvarez et al. 2014]

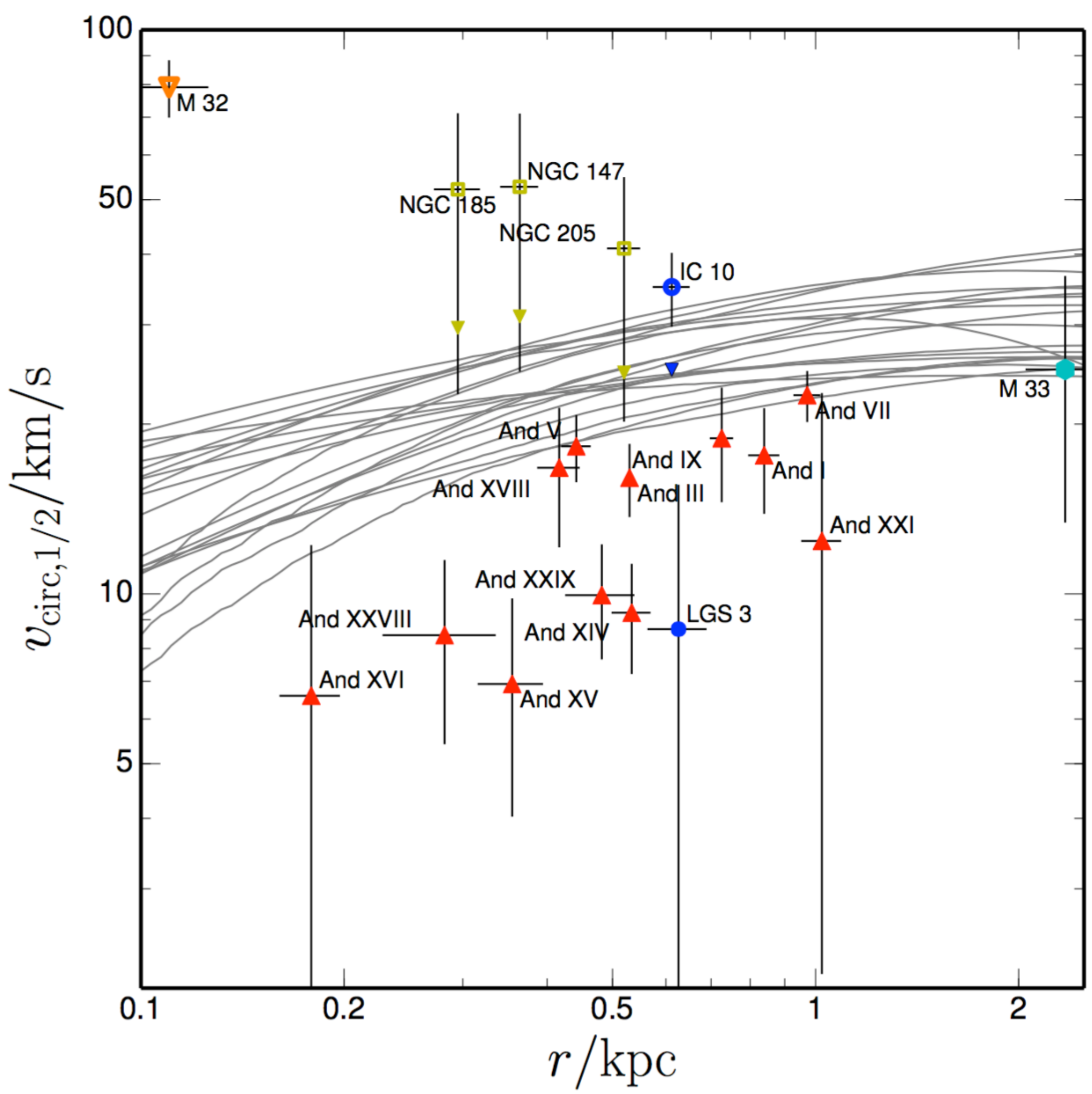
# Too-big-to-fail Outside the MW

## Field Dwarfs in the Local Group




[Garrison-Kimmel et al. 2014]

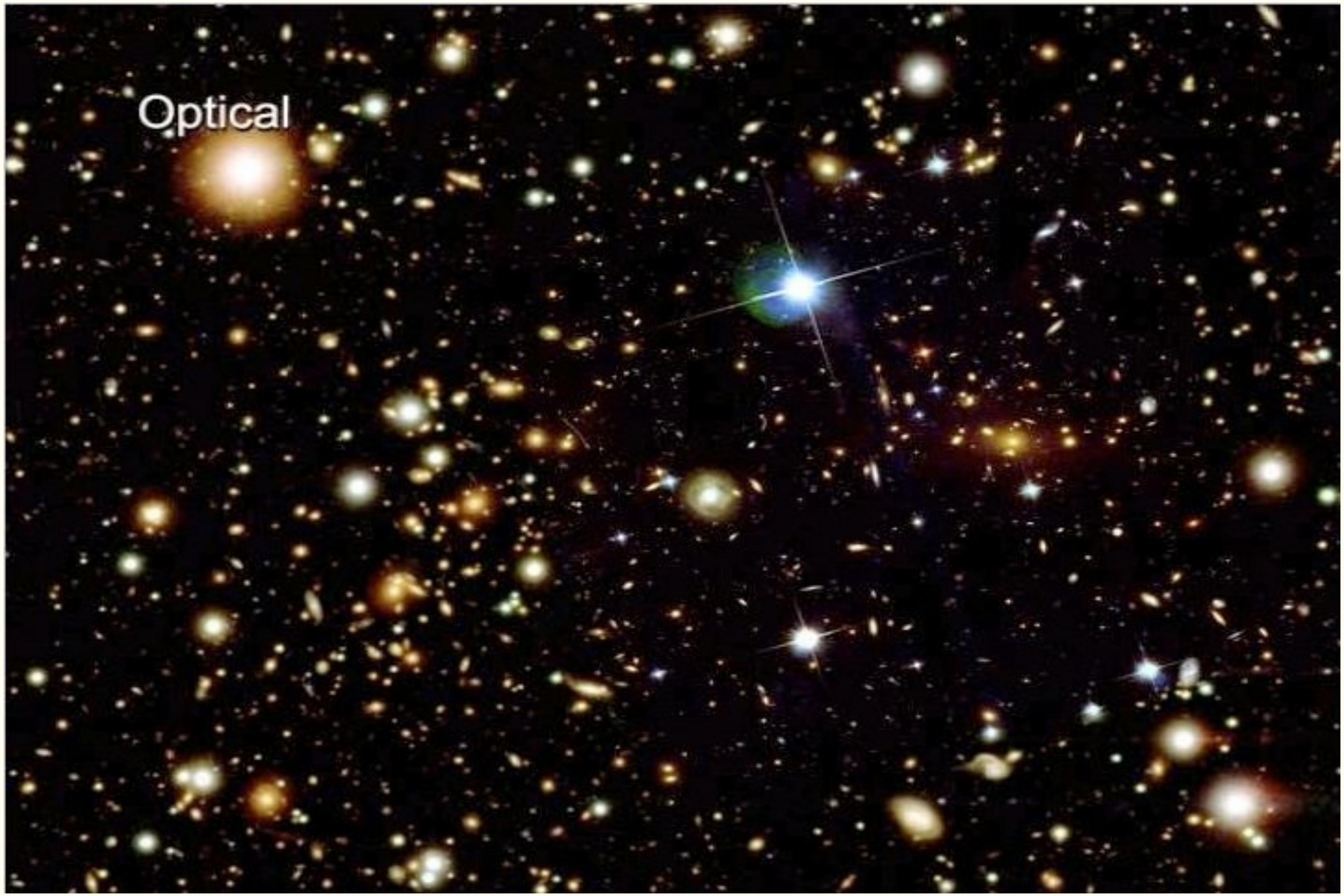
## dSph around Andromeda




[Boylan-Kolchin,Bullock,Tollerud 2014]

# Self-Interactions: Constraints

90% of ordinary matter is in gas, not in galaxies



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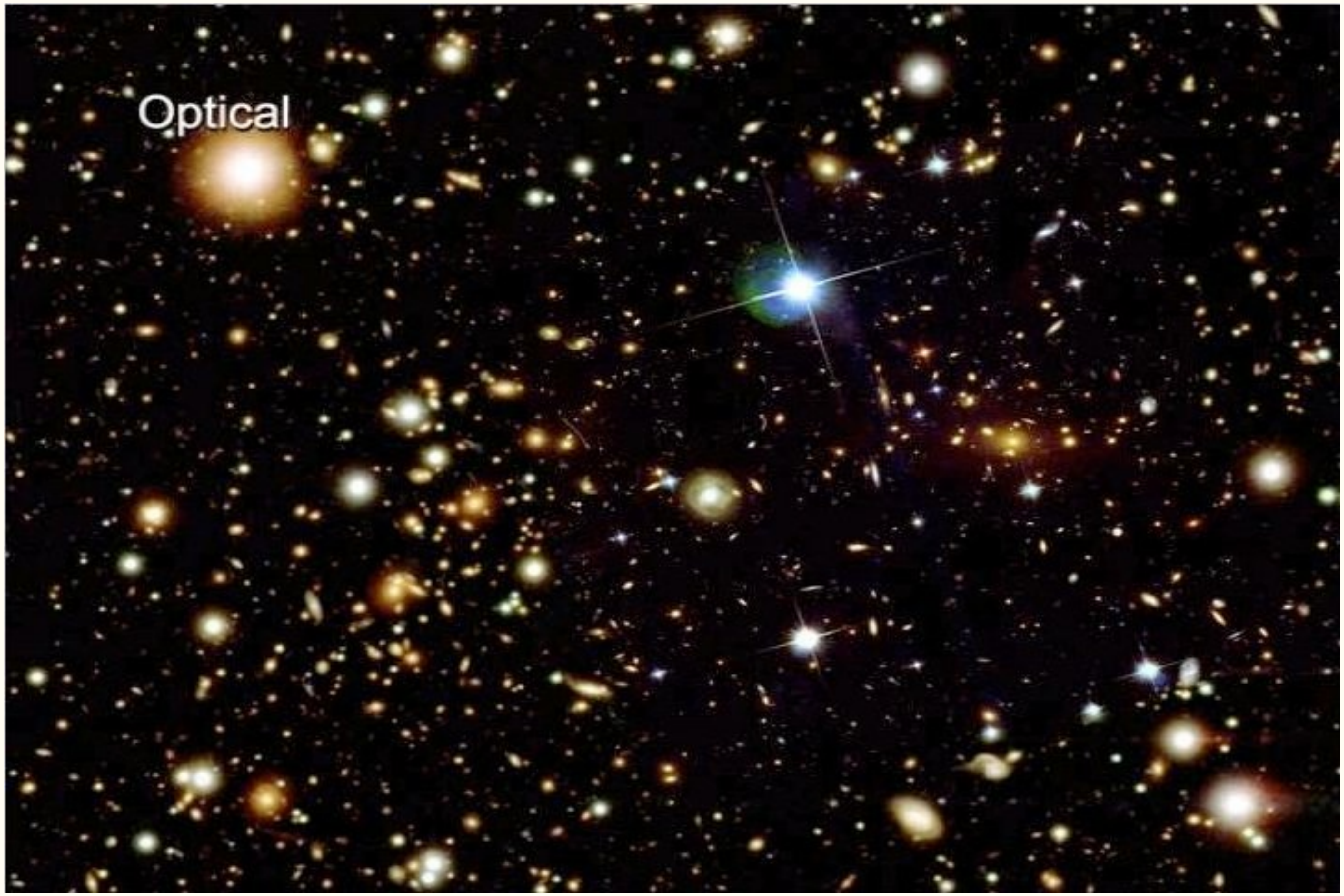

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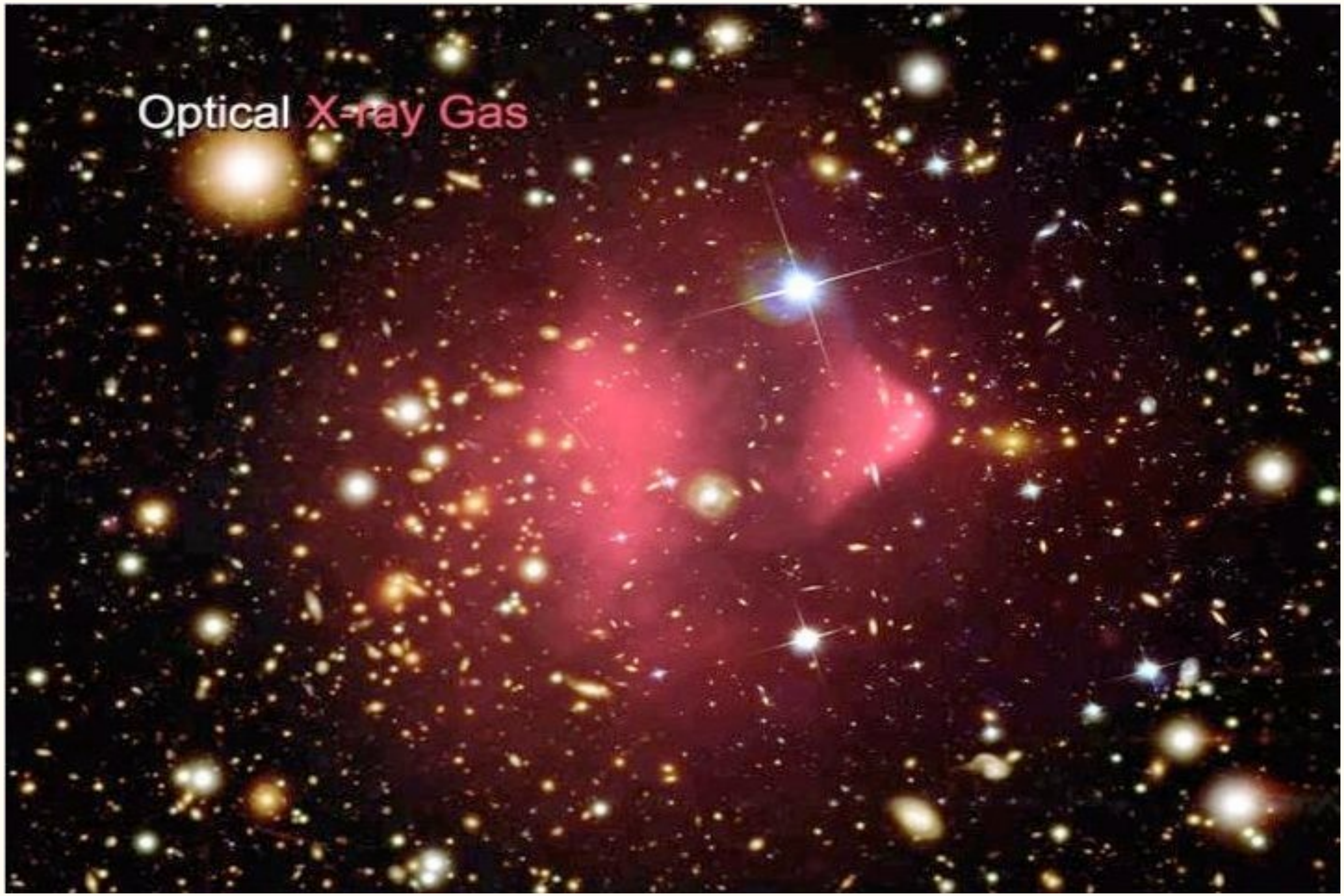
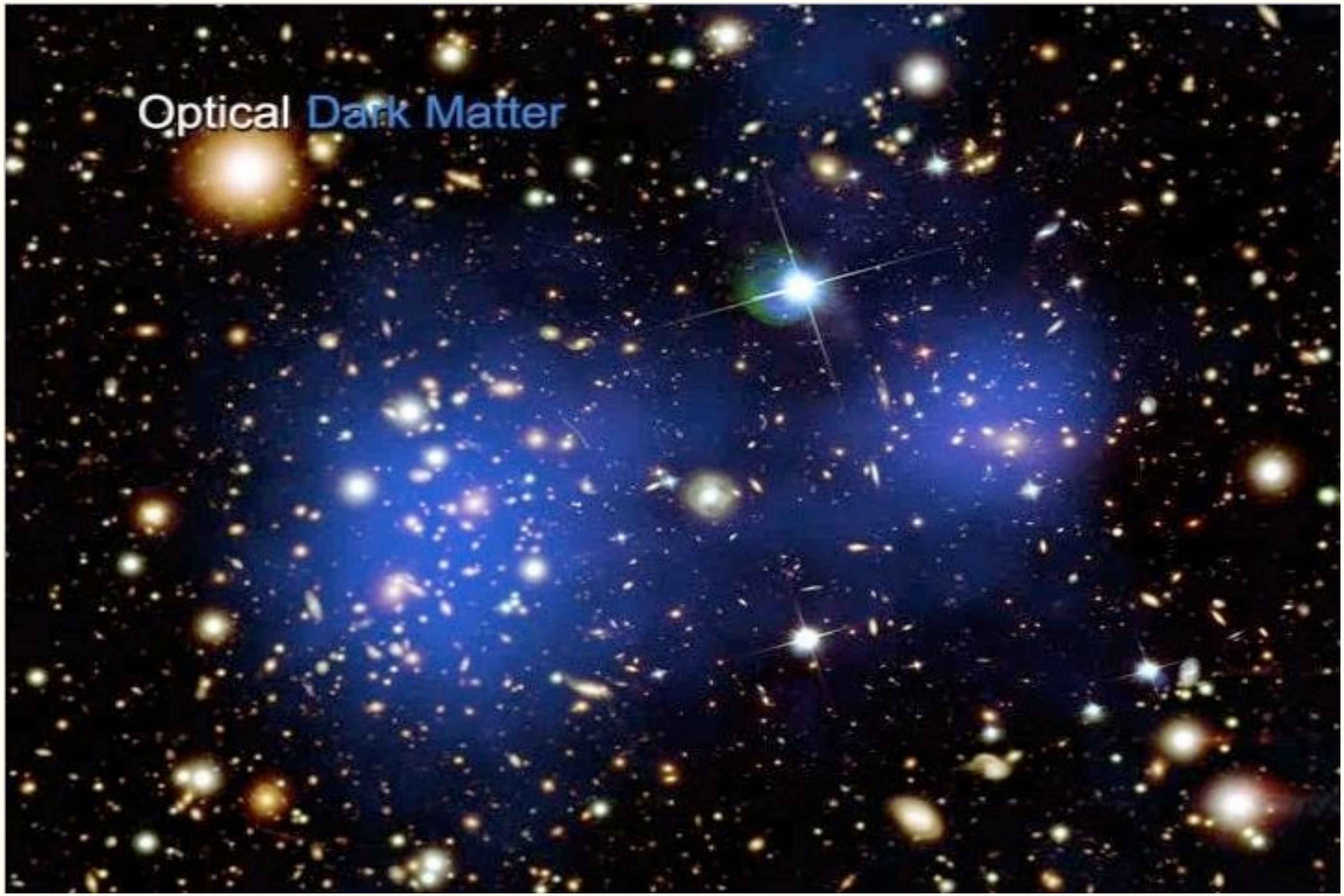


# Self-Interactions: Constraints

Determine location of mass with weak-lensing



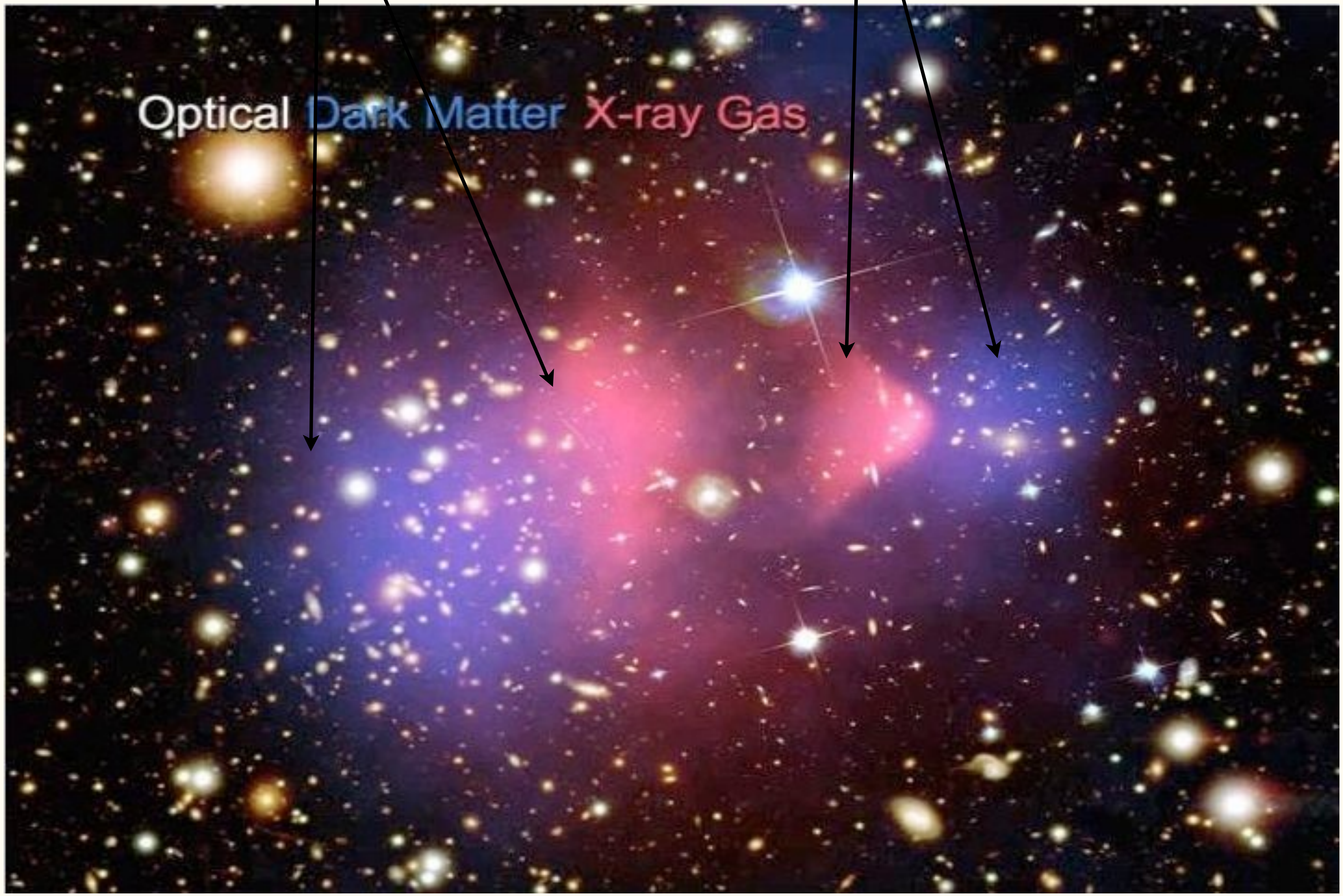
# Self-Interactions: Constraints

Composite image: ordinary + dark matter

# Self-Interactions: Constraints

Composite image: ordinary + dark matter

clear separation of gas/mass peaks



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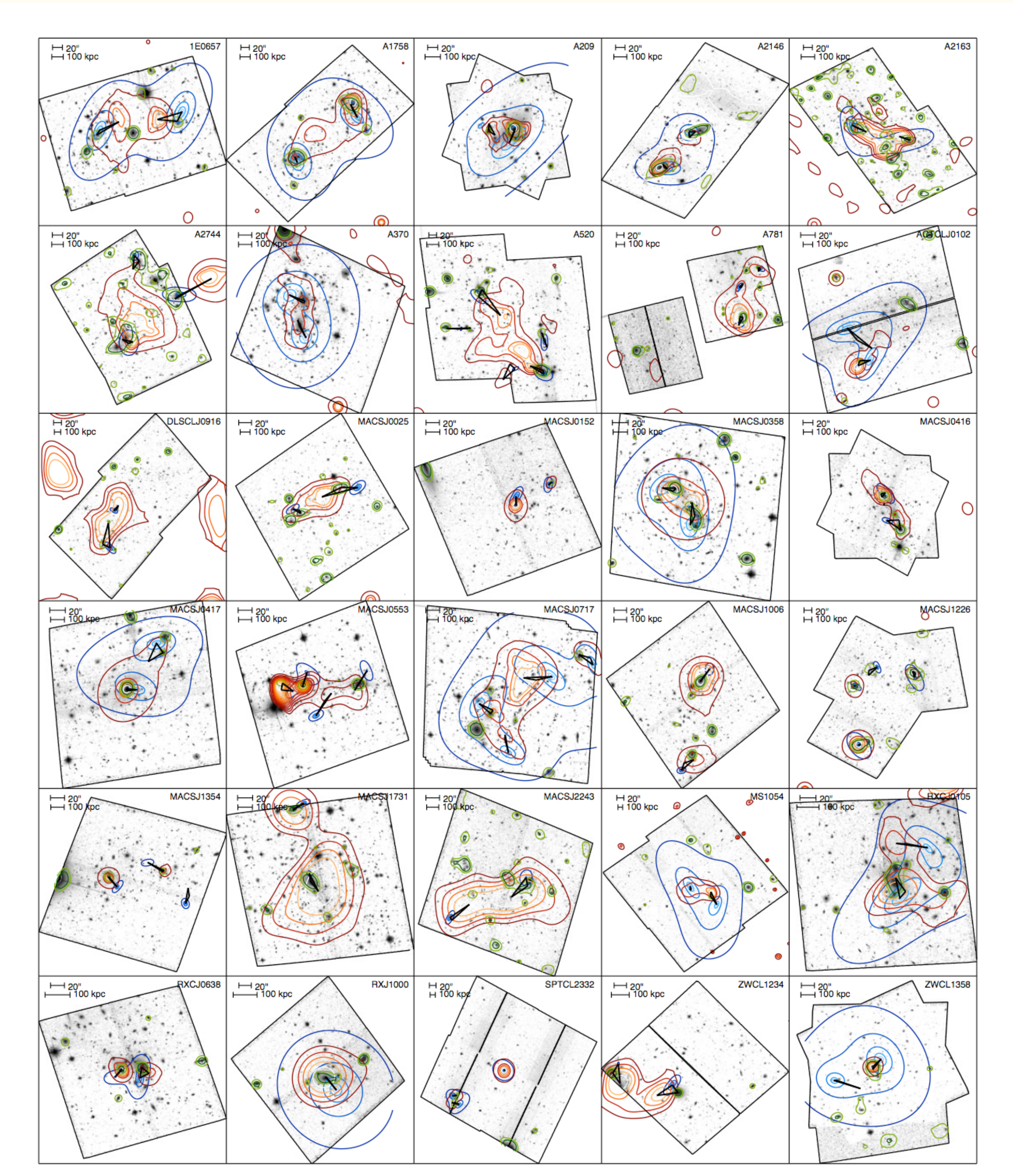



[Harvey et al. 2015]

- Bottom line: at cluster scale,

Cluster scale: $\dfrac{\sigma_{\rm self}}{m_{\rm DM}} \lesssim 0.5\,{\rm cm}^2/{\rm g}$

# Classifying Theories of DM

**Dark Sector**

- Spin
- Mass
- Self-Interactions
- Light States
- . . .

**Production Mech.**

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

**Mediation Scheme**

- Gravity
- Weak-scale Mediator
- Light Hidden photon
- Axion portal
- Higgs portal
- . . .

**Couplings**

- Quarks
- Gluons
- Charged Leptons
- Neutrinos
- Photons
- . . .

# Strongly Interacting Massive Particles

# A New Perspective on Freeze Out

[Kuflik, Hochberg, TV, Wacker, 2014]

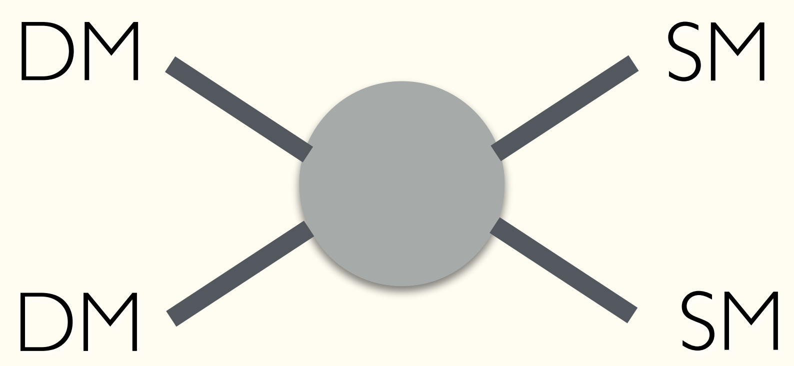
[Kuflik, Hochberg, Murayama, TV, Wacker, 2014]

[Kuflik, Hochberg, Murayama, TV, Wacker, in progress]

Skip

# No 2-2 Annihilations..

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



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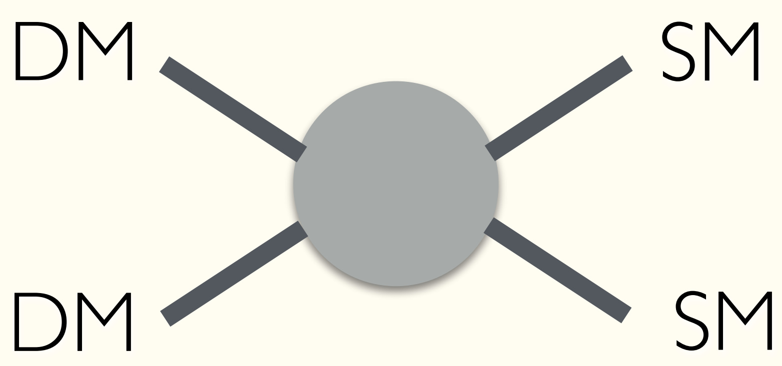
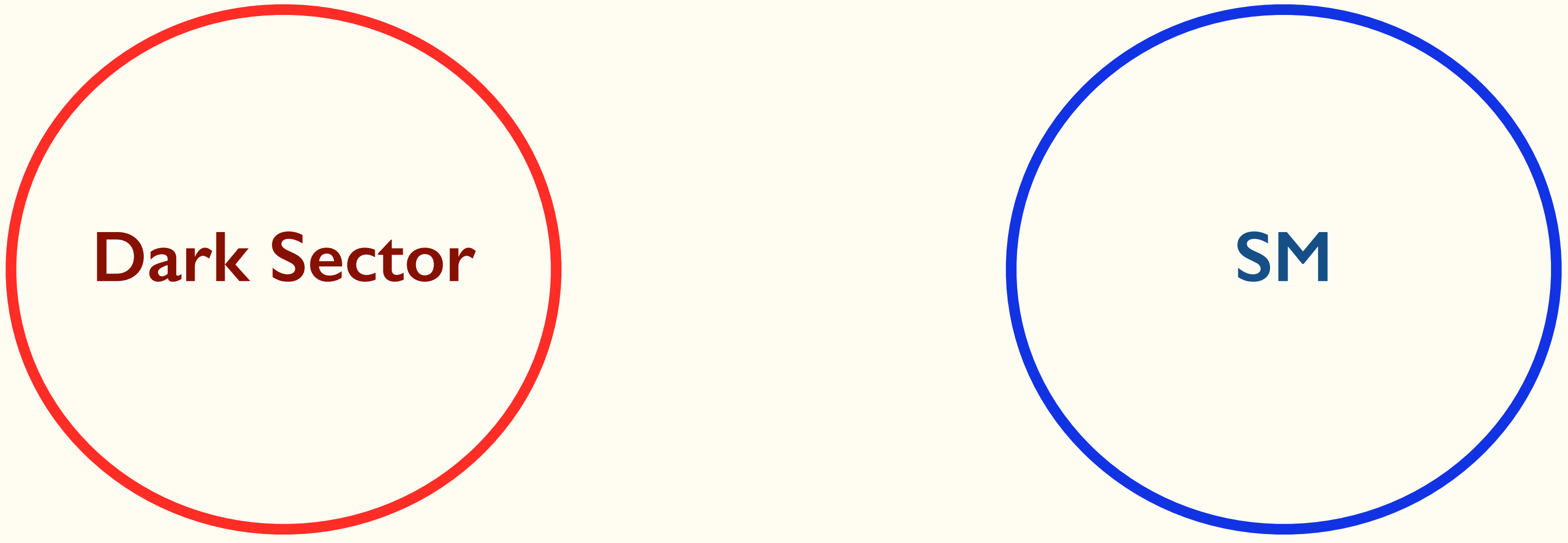



- But what if DM is the lightest state in a hidden (sequestered) sector?



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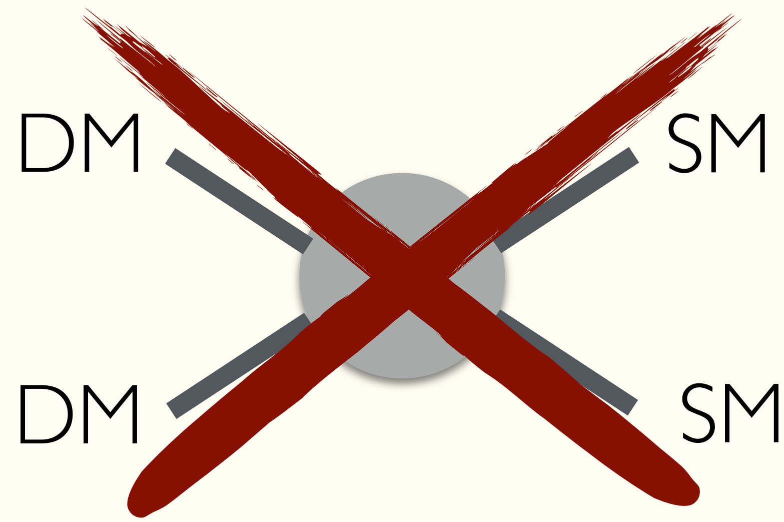


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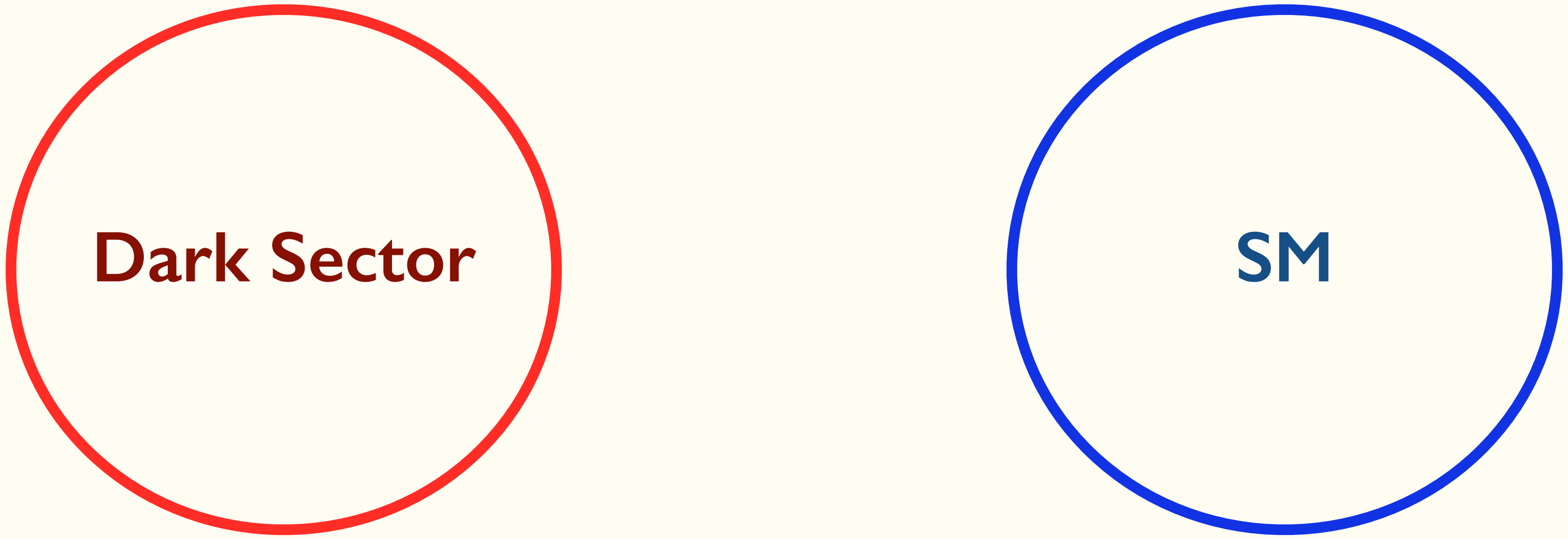
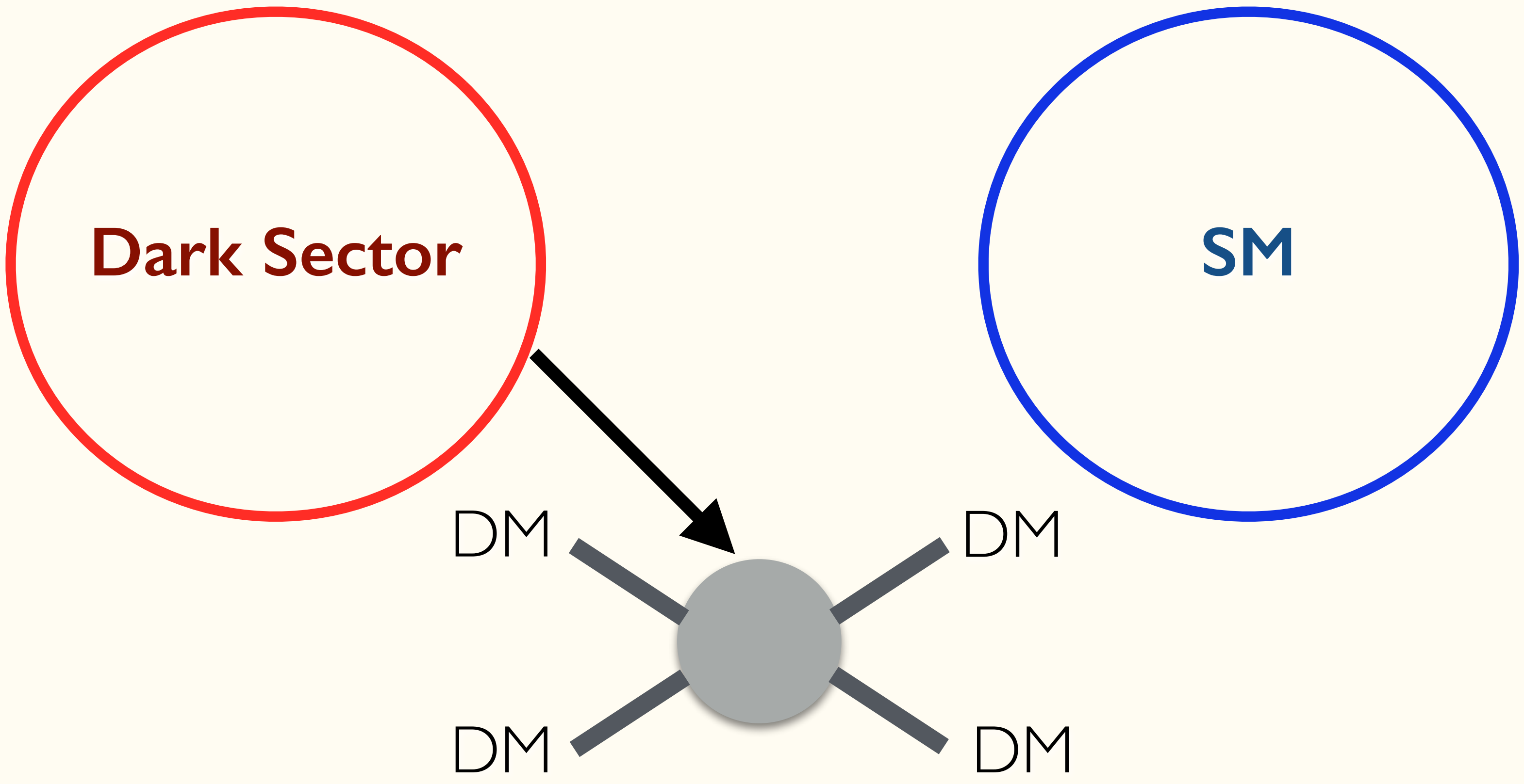
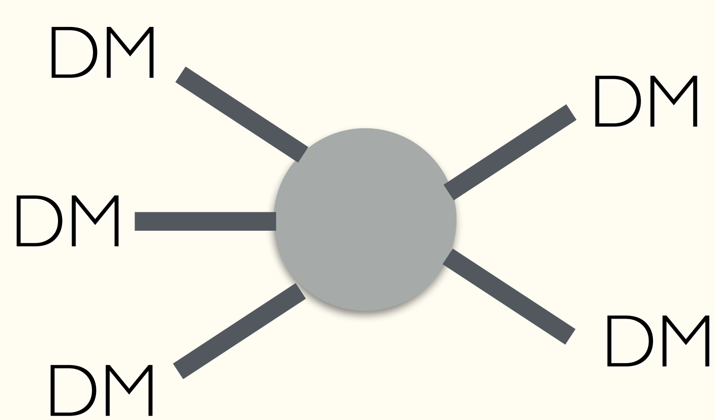


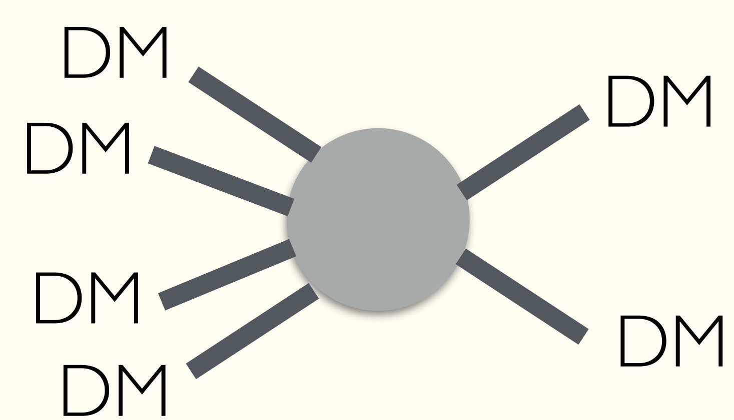

- Then 2-2 annihilations may be highly suppressed

# No 2-2 Annihilations..




- 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

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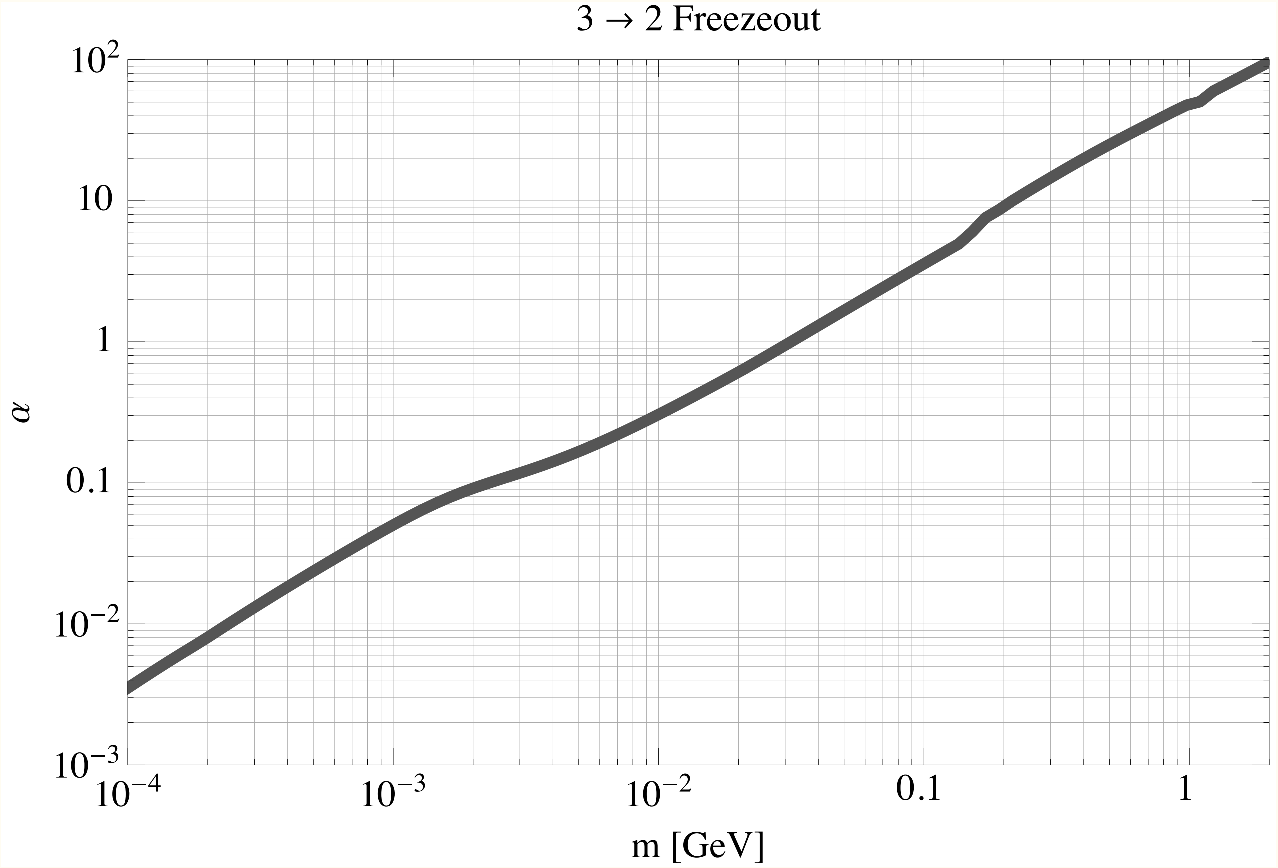
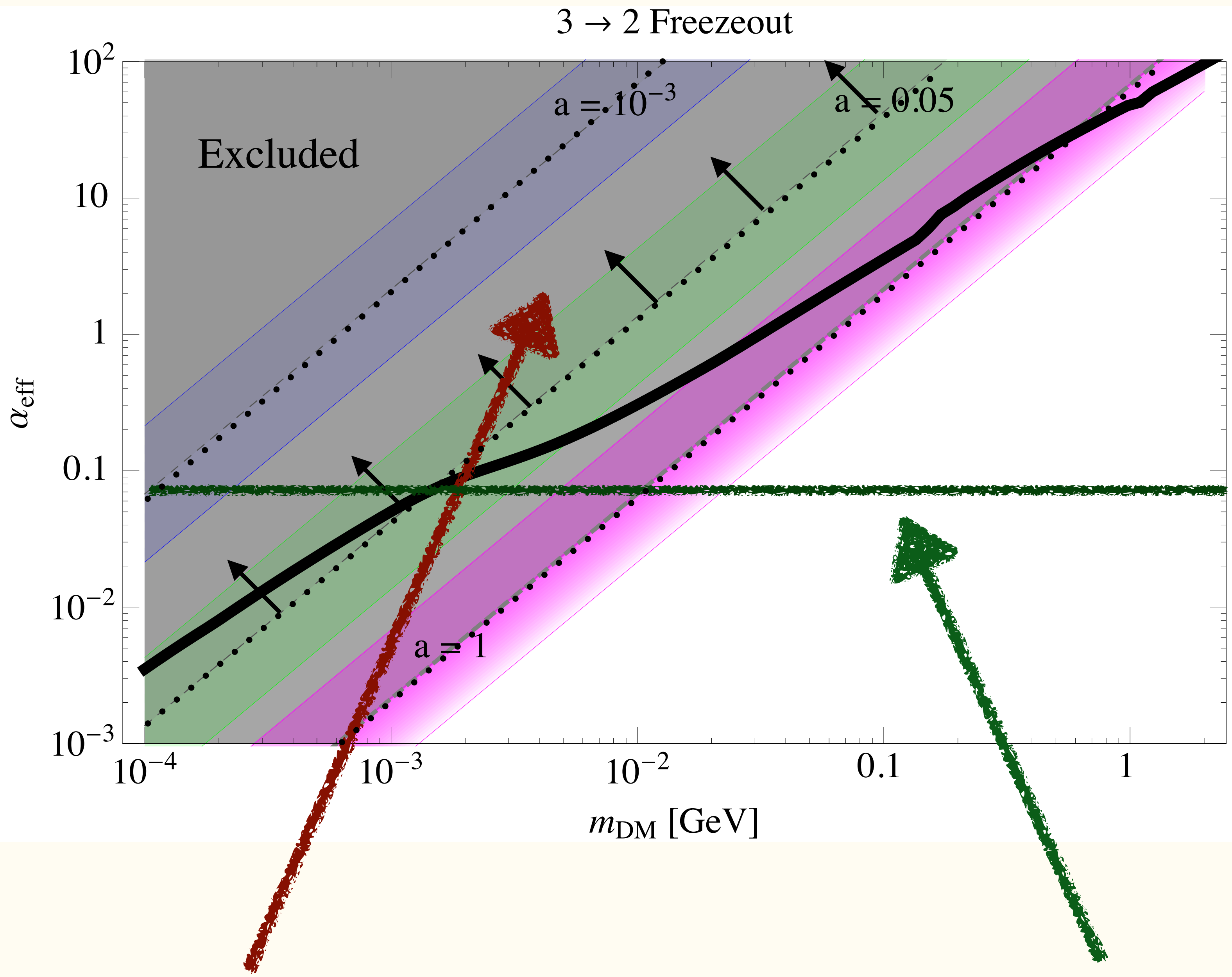
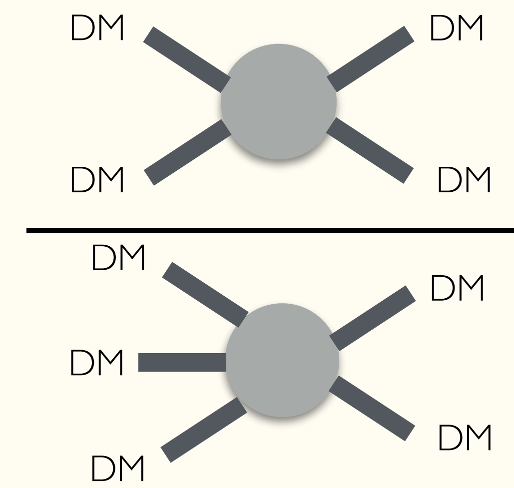


# 2-2 Good or Bad?

Weak scale emerges for a weak-strength interactions




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




Excluded by
Bullet-cluster and
halo-shape constraints

Constraints
push to strong
regime
→ **SIMP**

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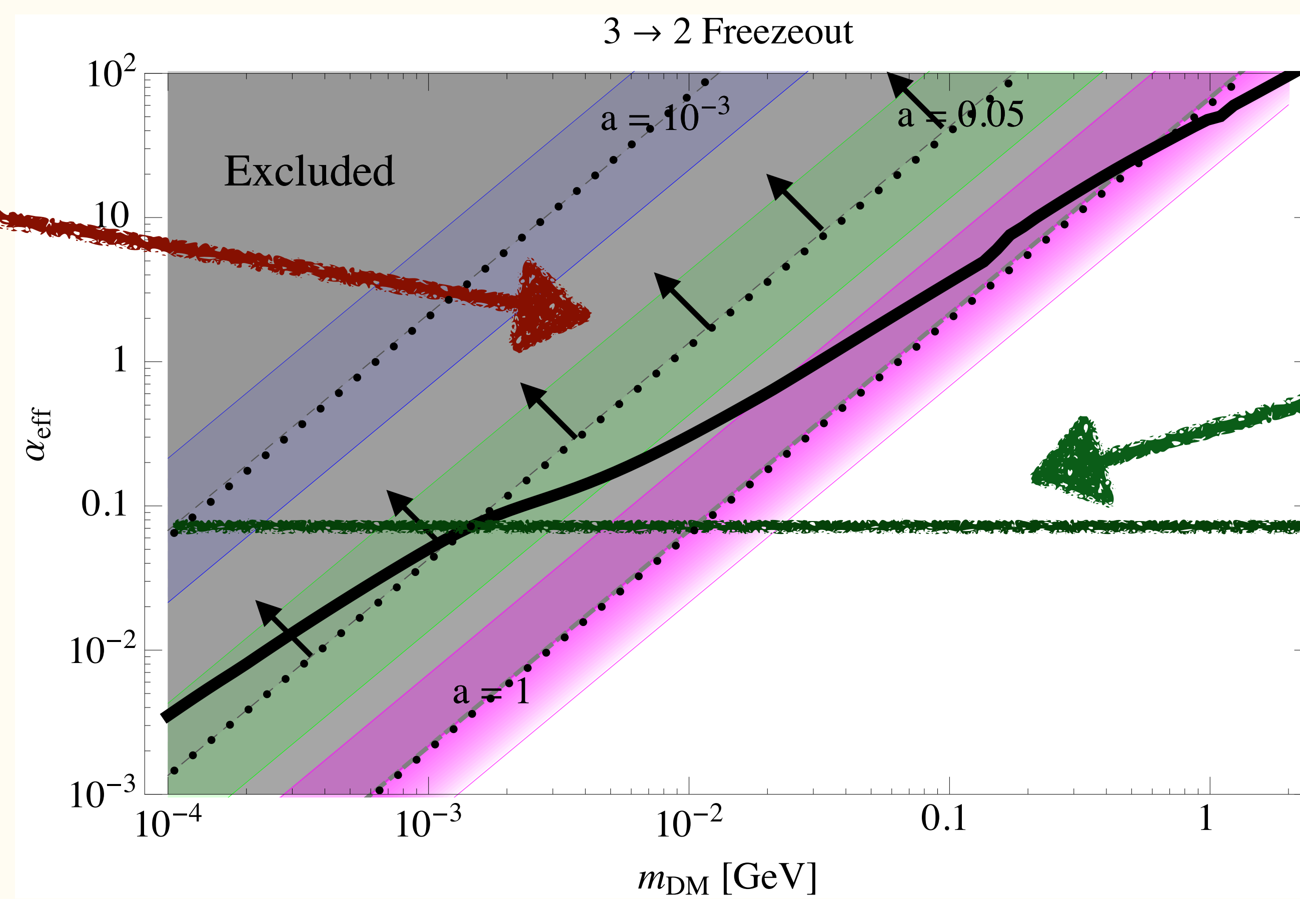



Constraints push to strong regime

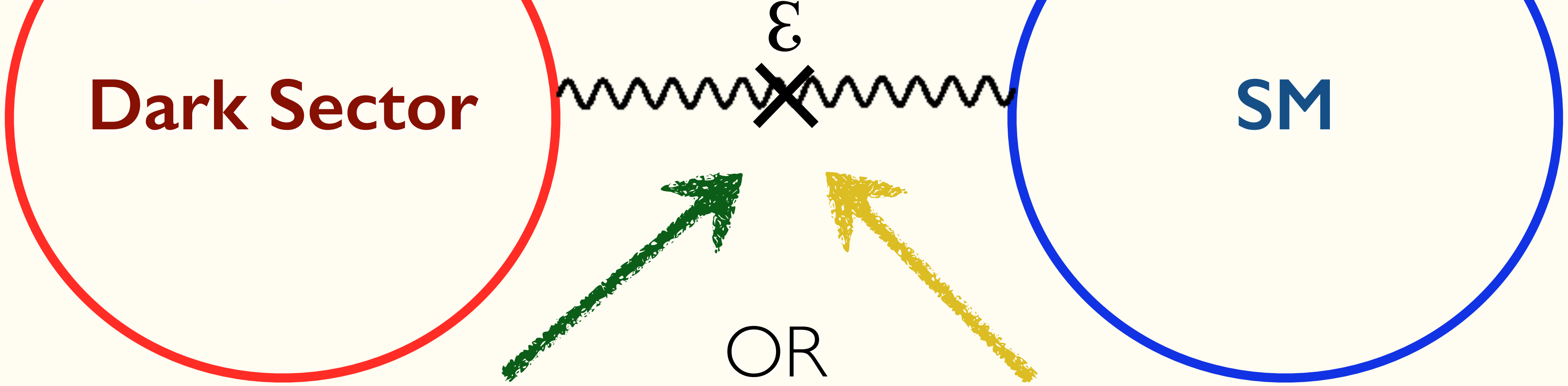
⇓

**SIMP**

# 3-2 Freeze Out

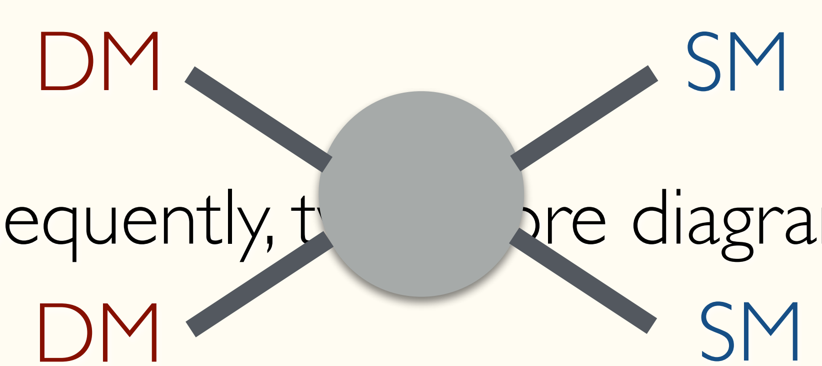
- Problem: We implicitly assumed that $\mathbf{T_{dark} = T_{SM}}$. Otherwise DM is hot and excluded.

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

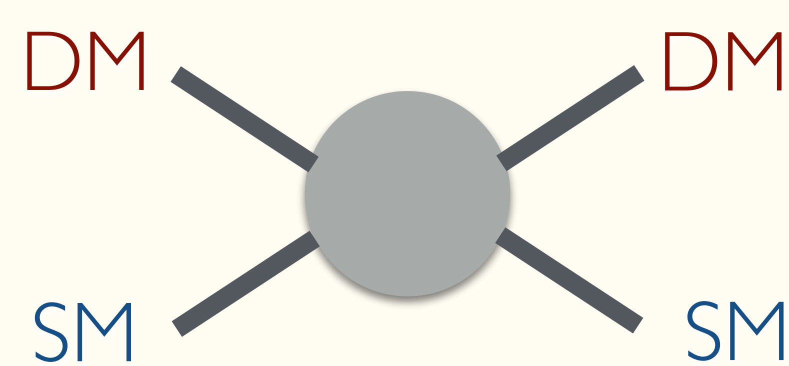



$$\frac{m_f}{\Lambda^2}\chi^\dagger\chi\bar{f}f \qquad \frac{\alpha_{\rm EM}}{4\pi\Lambda^2}\chi^\dagger\chi F_{\mu\nu}F^{\mu\nu}$$

- Consequently, t ore diagrams:




2-2 Annihilations




Thermal Equilibrium

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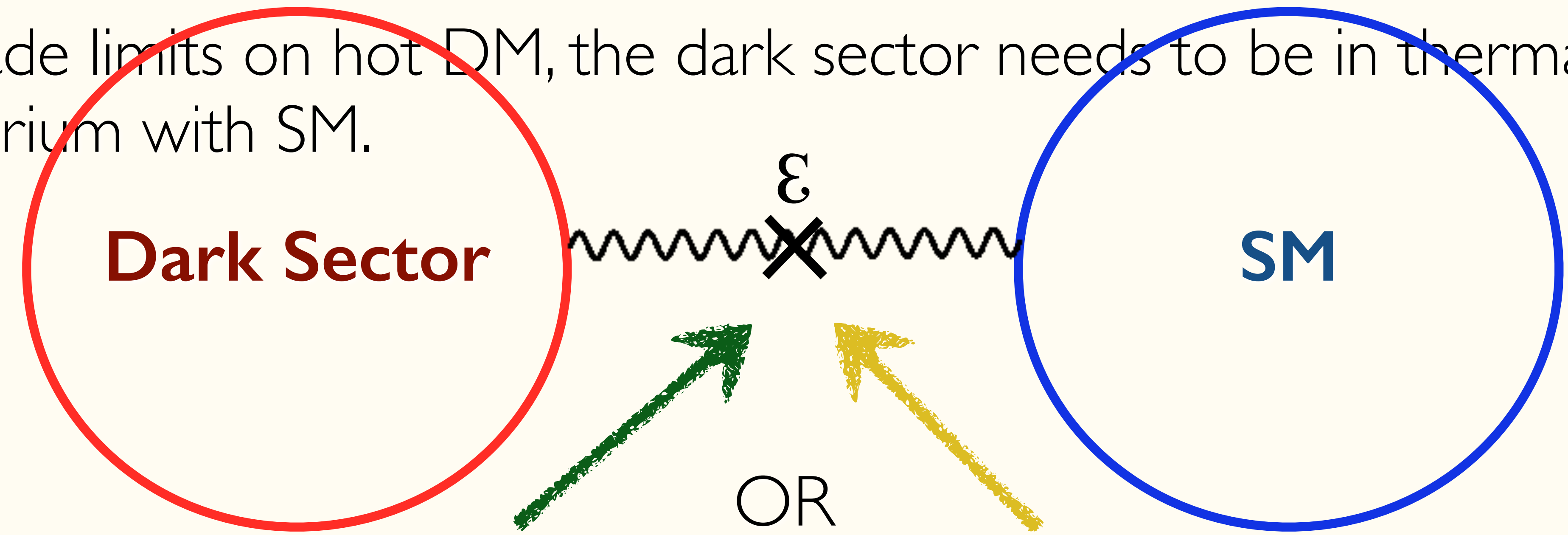


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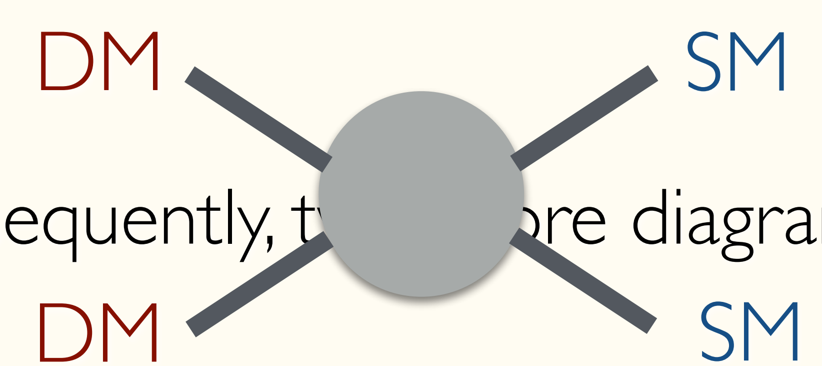


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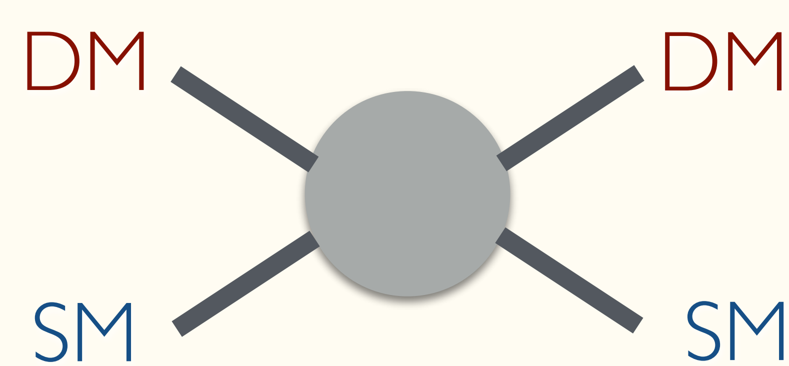


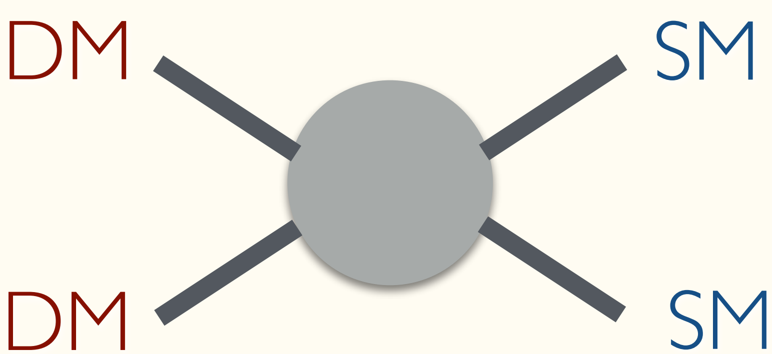

Thermal Equilibrium

# 3-2 Freeze Out

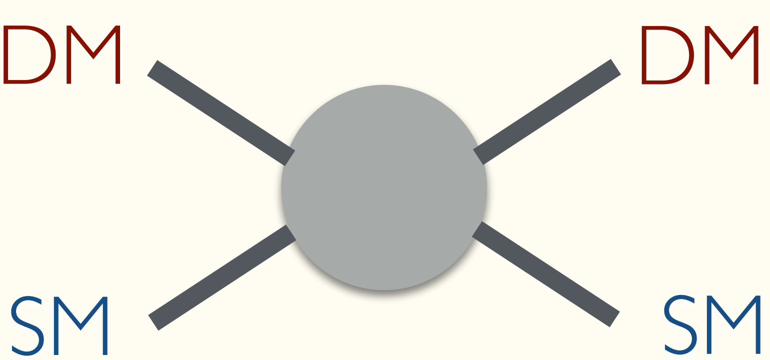
Taking:

$$\langle\sigma v\rangle_{\rm kin} \sim \langle\sigma v\rangle_{\rm ann} \equiv \frac{\epsilon^2}{m_{\rm DM}^2}$$

$$\Longrightarrow \quad \frac{\Gamma_{\rm ann}}{\Gamma_{\rm kin}} \sim \frac{n_{\rm DM}}{n_{\rm SM}} \sim e^{-m_{\rm DM}/T} \sim 2\times 10^{-7}$$



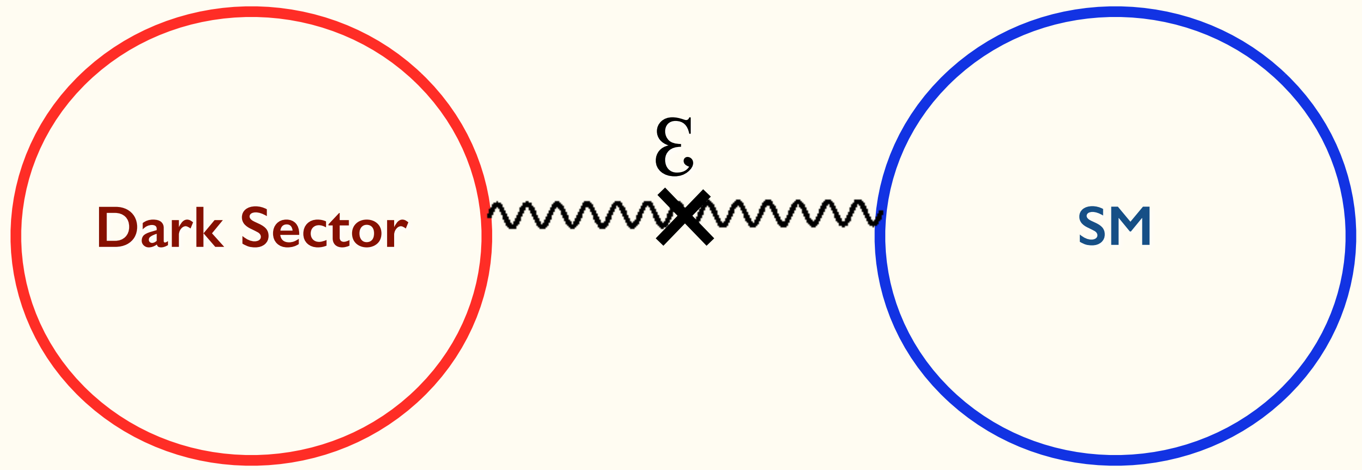

$$\left.\frac{\Gamma_{\rm ann}}{\Gamma_{3\to 2}}\right|_{T=T_F} \lesssim 1 \Longrightarrow \epsilon \lesssim \epsilon_{\rm max} \equiv 0.1\;\alpha_{\rm eff}\left(\frac{T_{\rm eq}}{M_{\rm Pl}}\right)^{1/6} \simeq 3\times 10^{-6}$$

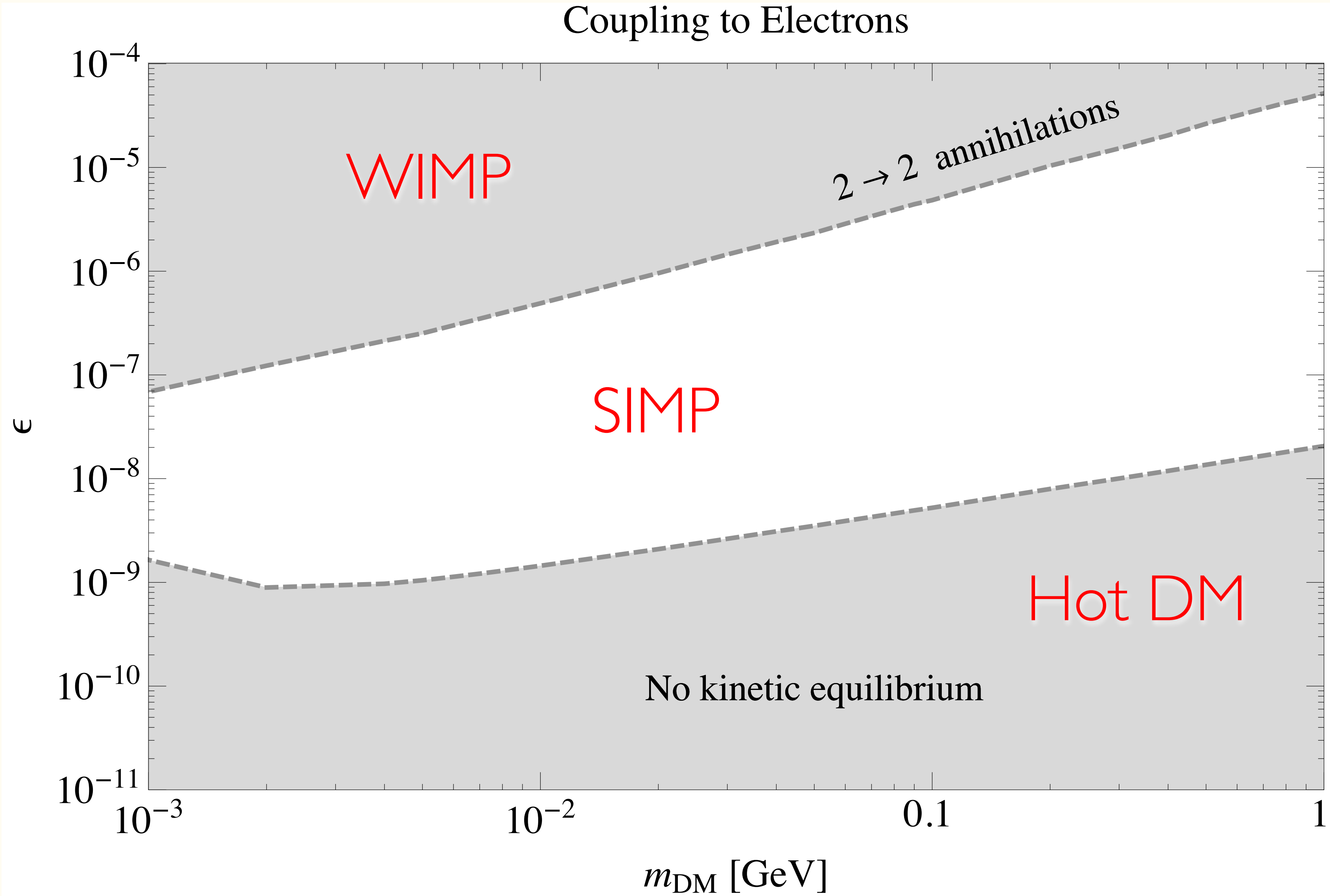



$$\left.\frac{\Gamma_{\rm kin}}{\Gamma_{3\to 2}}\right|_{T=T_F} \gtrsim 1 \Longrightarrow \epsilon \gtrsim \epsilon_{\rm min} \equiv 2\;\alpha_{\rm eff}^{1/2}\left(\frac{T_{\rm eq}}{M_{\rm Pl}}\right)^{1/3} \simeq 1\times 10^{-9}$$

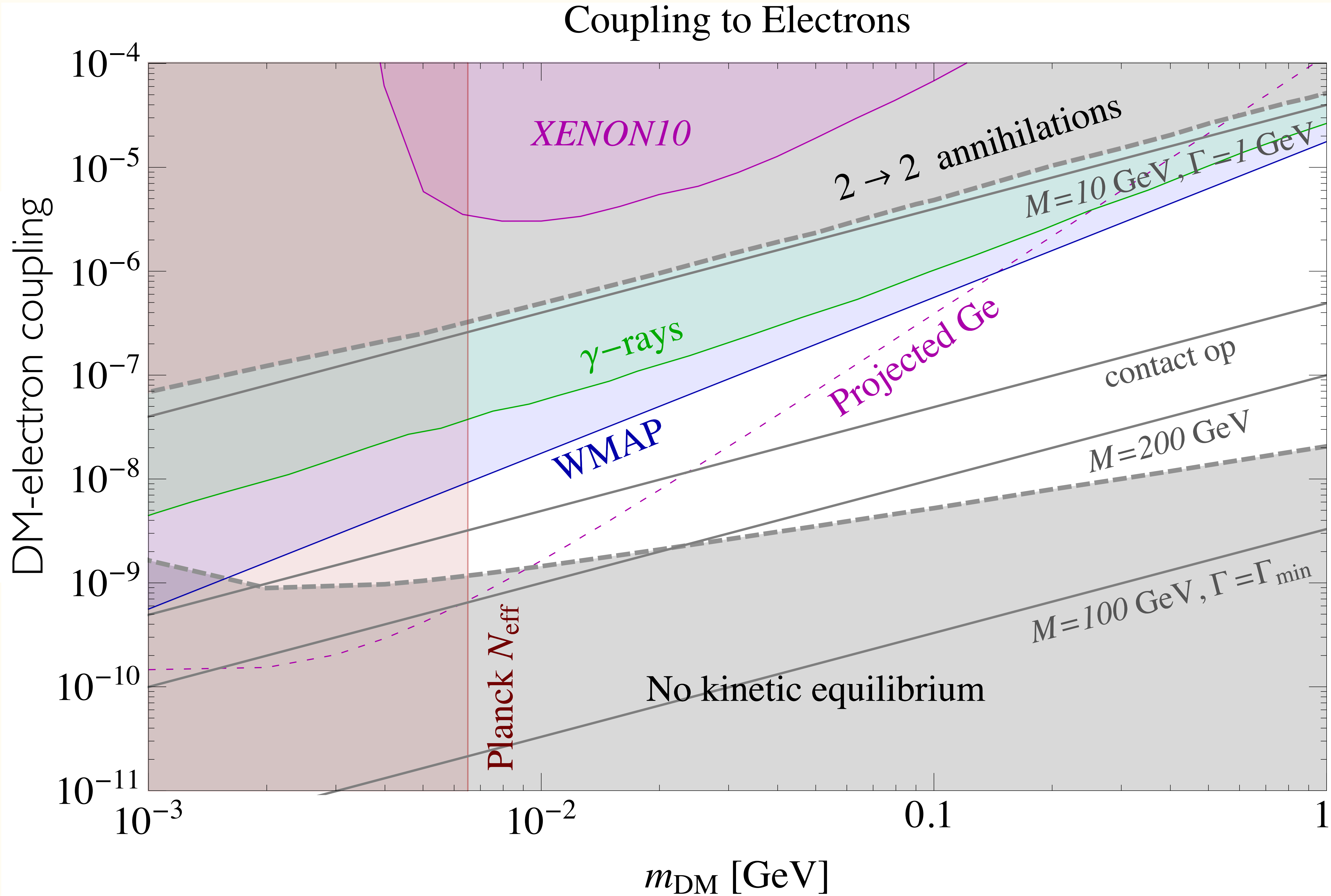
# 3-2 Freeze Out

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

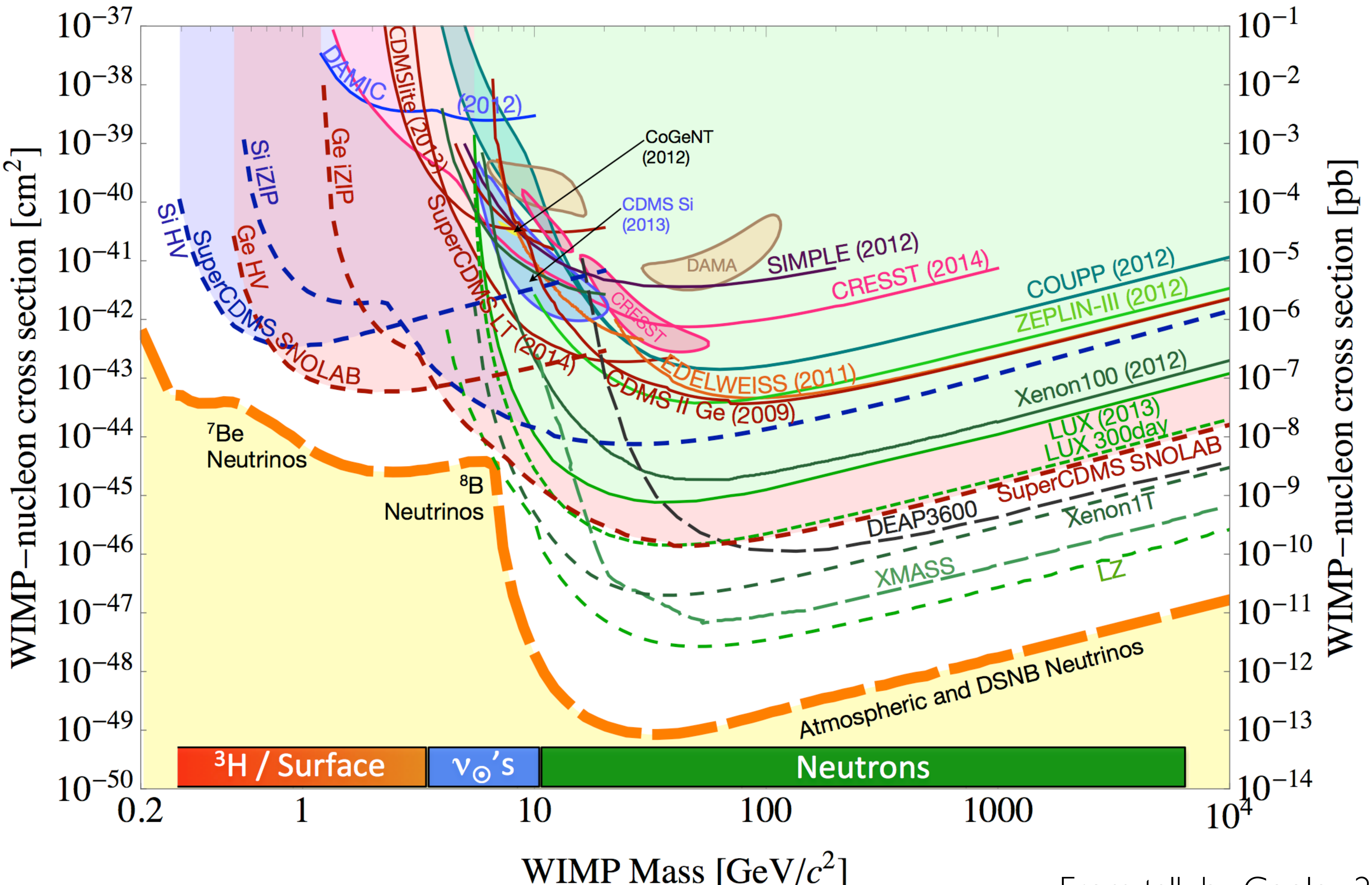


# SIMP DM: Experimental Status



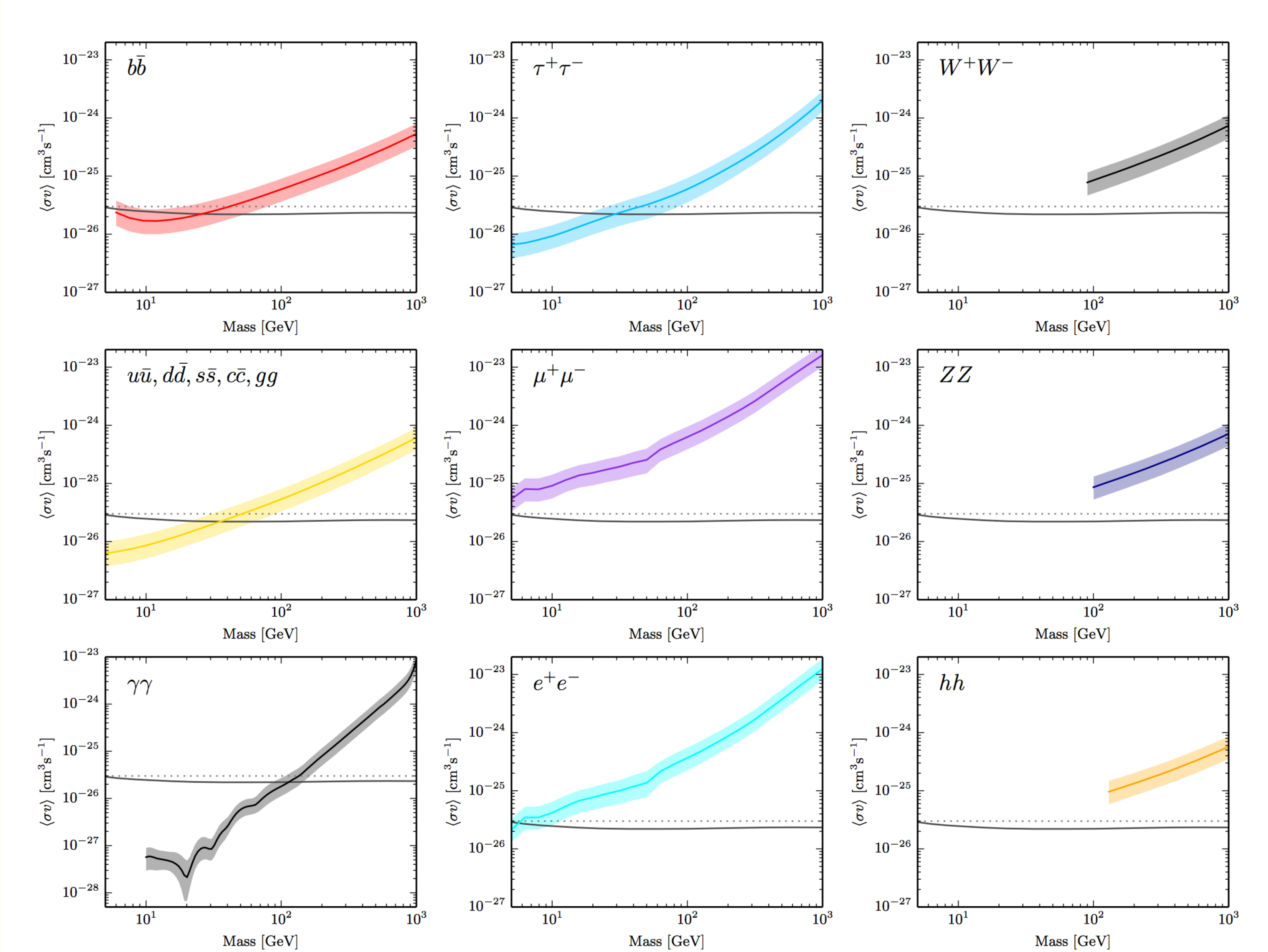
# CDMS: SNOLAB Projected Reach




From talk by Cooley, 2015

# Indirect Detection: Constraints

## Fermi Dwarf Galaxies




[Geringer-Sameth, Koushiappas, Walker, 2014]

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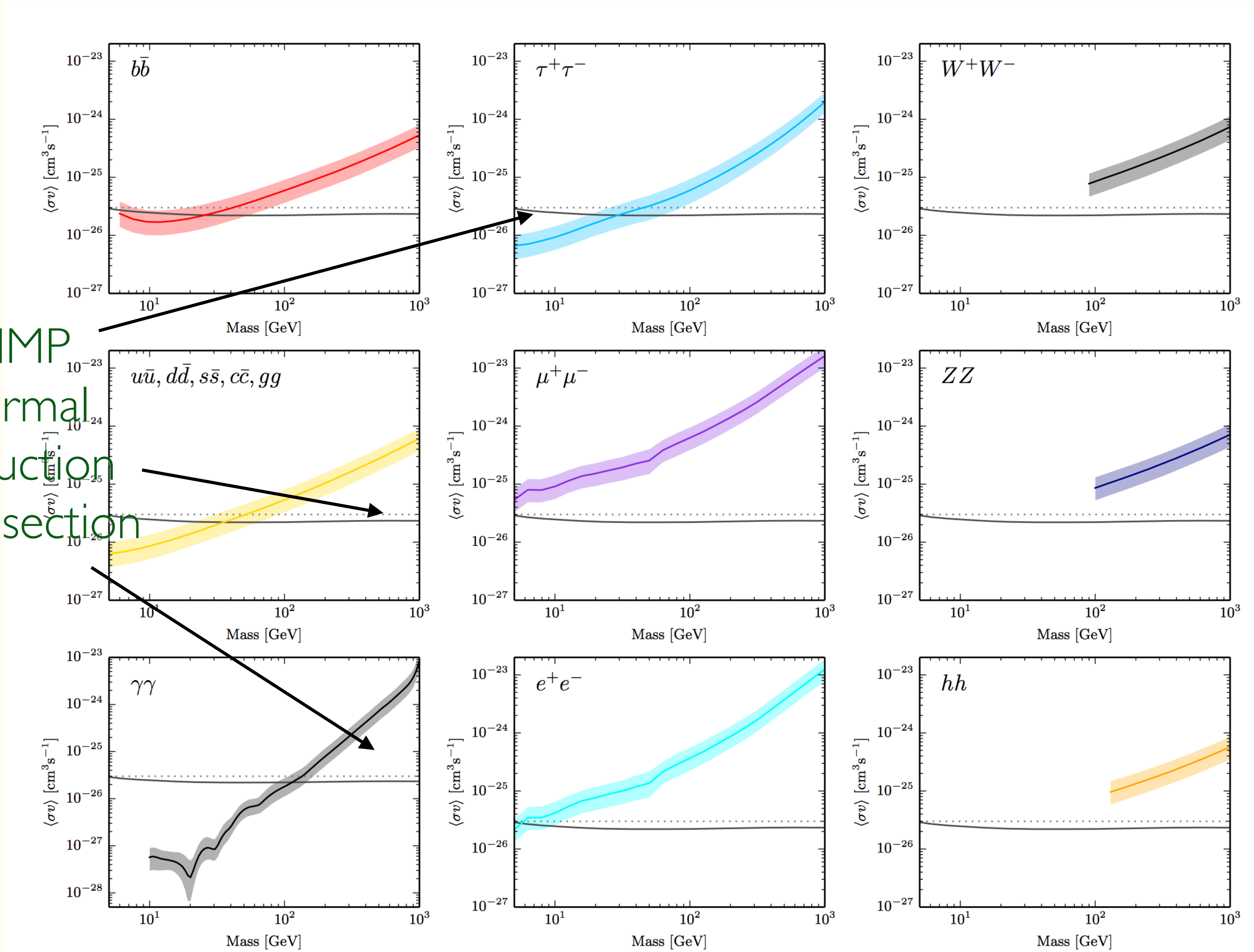


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