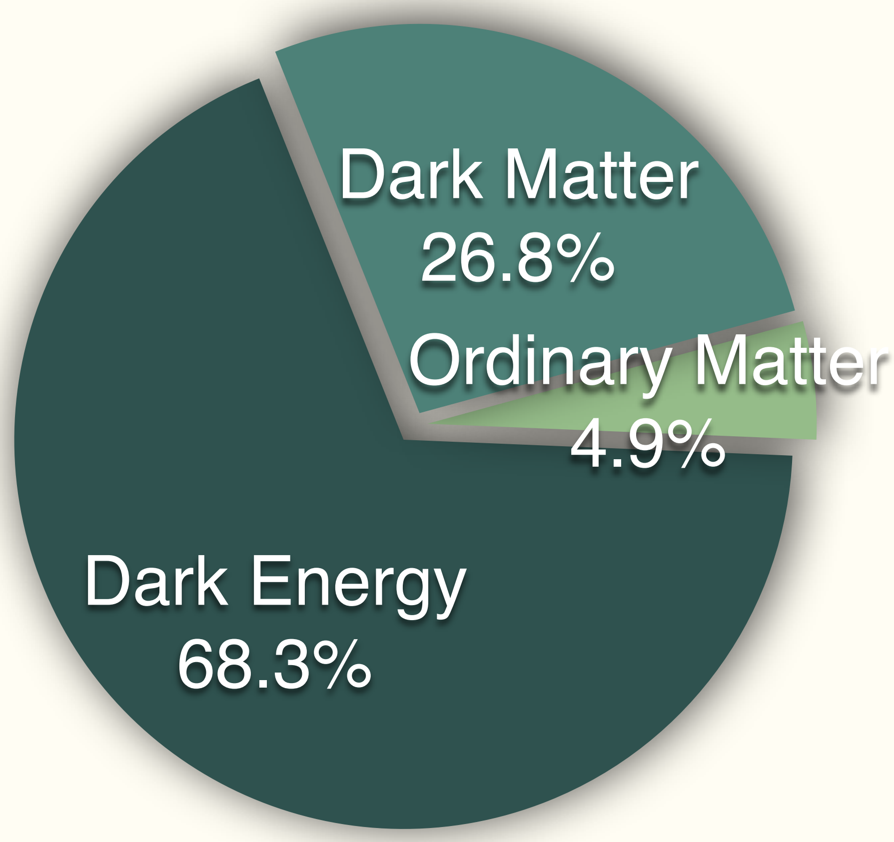
Going Beyond WIMPs:
Exploring Light Dark Matter

November 2015

Tomer Volansky
Tel-Aviv University

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!

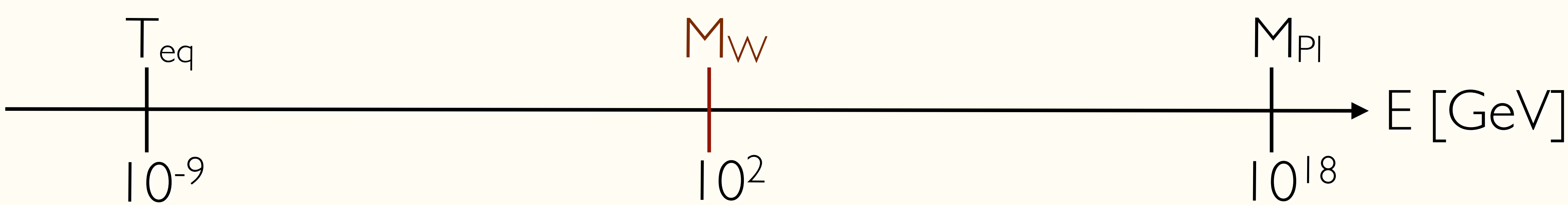
How do we usually explain the 85% DM abundance?

Thermal WIMP
(Weakly Interacting Massive Particle).

The Thermal WIMP

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

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



This is the WIMP Miracle

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!

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

Outline

- Classifying Theories of Light Dark Matter
  - The Dark Sector: Self-interactions
  - Production Mechanisms
- Searching for Light Dark Matter
  - Collider and Beam-dump experiments
  - Cosmological limits
  - Indirect Detection
  - Direct Detection
  - Astrophysical Probes: Searching for Structure

Going Beyond the WIMP
Classifying Theories of Light Dark Matter

Classifying Theories of DM

Dark Sector

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

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
- …

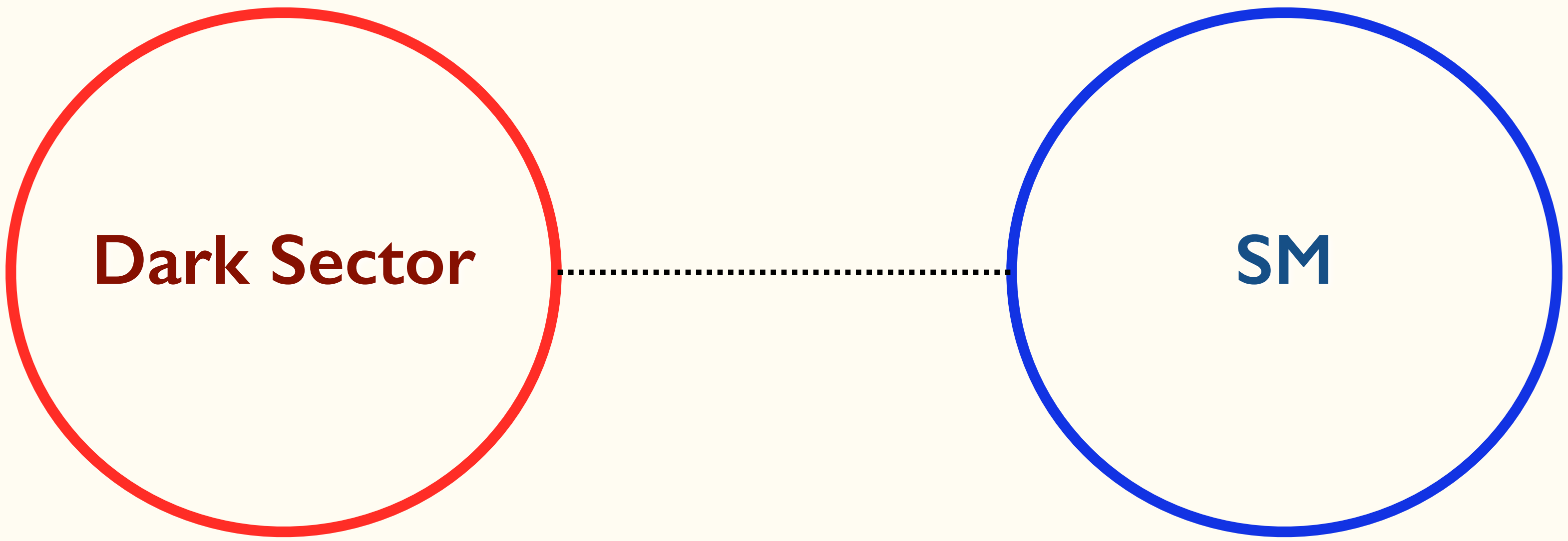
Direct

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!!

Classifying Theories of DM

Dark Sector	Production Mech.	Mediation Scheme	Couplings
• Spin	• Freeze-out	• Gravity	• Quarks
• Mass	• Freeze-in	• Weak-scale Mediator	• Gluons
• Self-Interactions	• Freeze-out and decay	• Light Hidden photon	• Charged Leptons
• Light States	• Non-thermal	• Axion portal	• Neutrinos
• Gauge symmetries	• Asymmetric	• Higgs portal	• Photons
• …	• Misalignment	• …	• …
	• …		

Self-Interacting Dark Matter?

Problems with Cold Dark Matter?

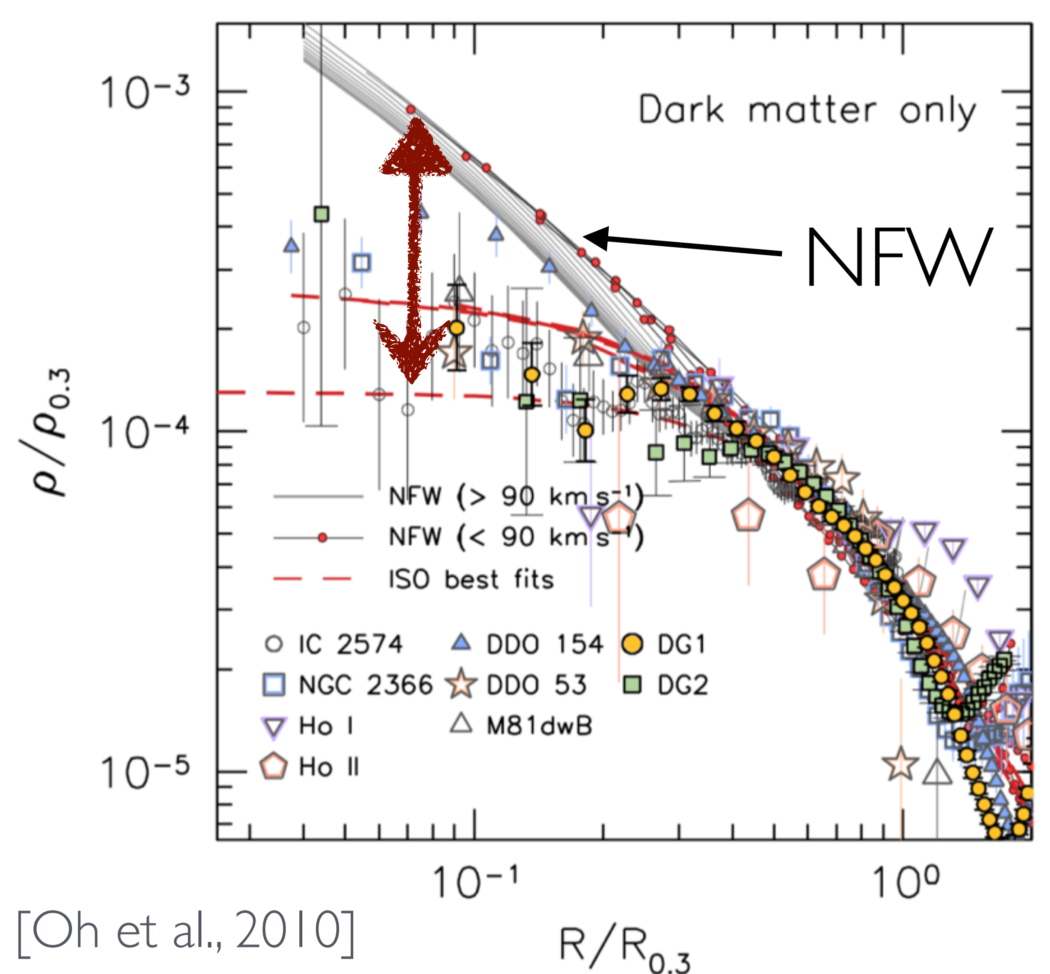
- Several discrepancies between N-body simulations and astrophysical observations:

  I. 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:

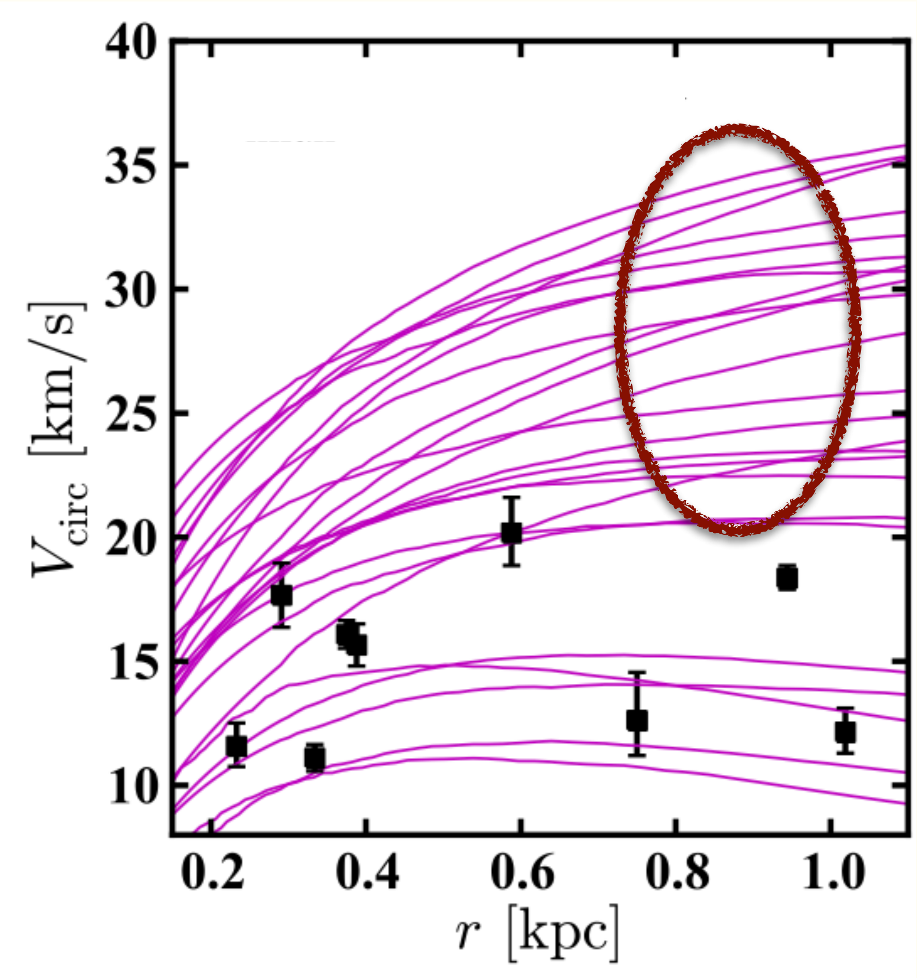
  1. Core vs. Cusp [Moore 1994; Flores,Primack 1994]

  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]

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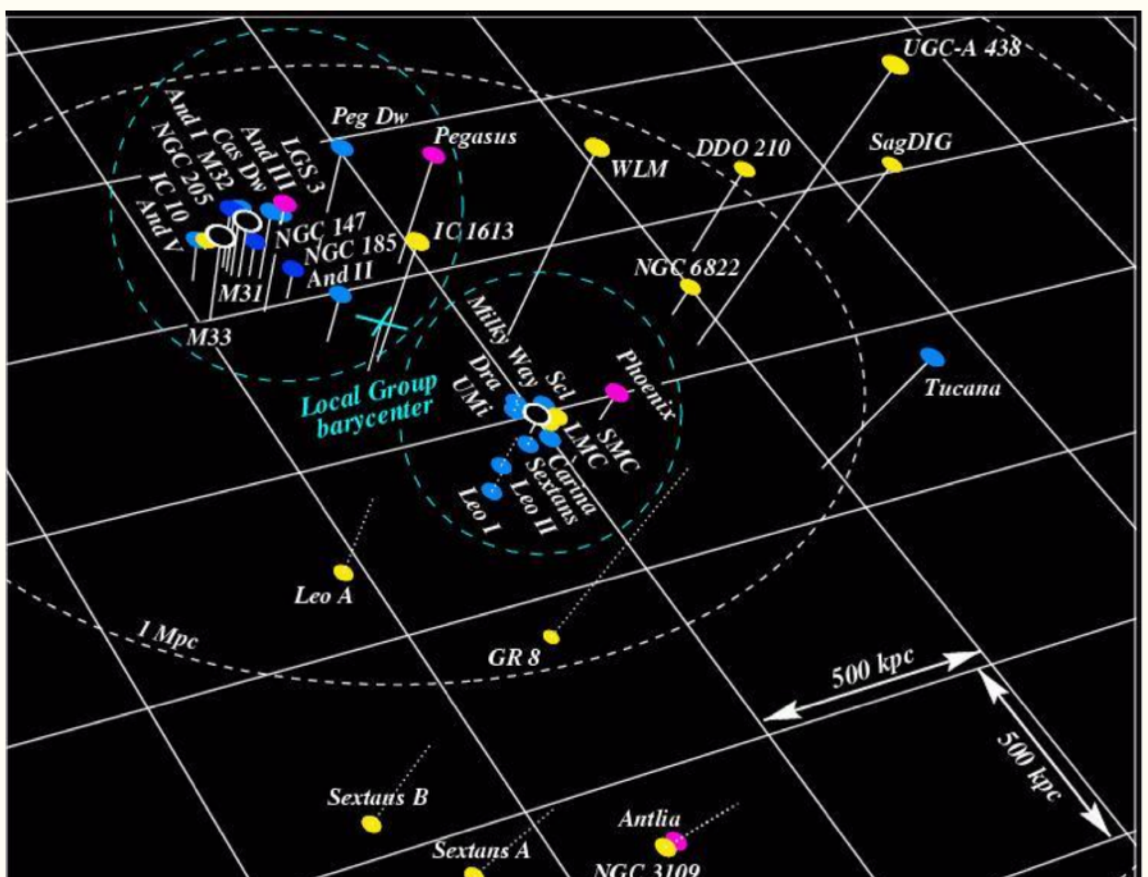
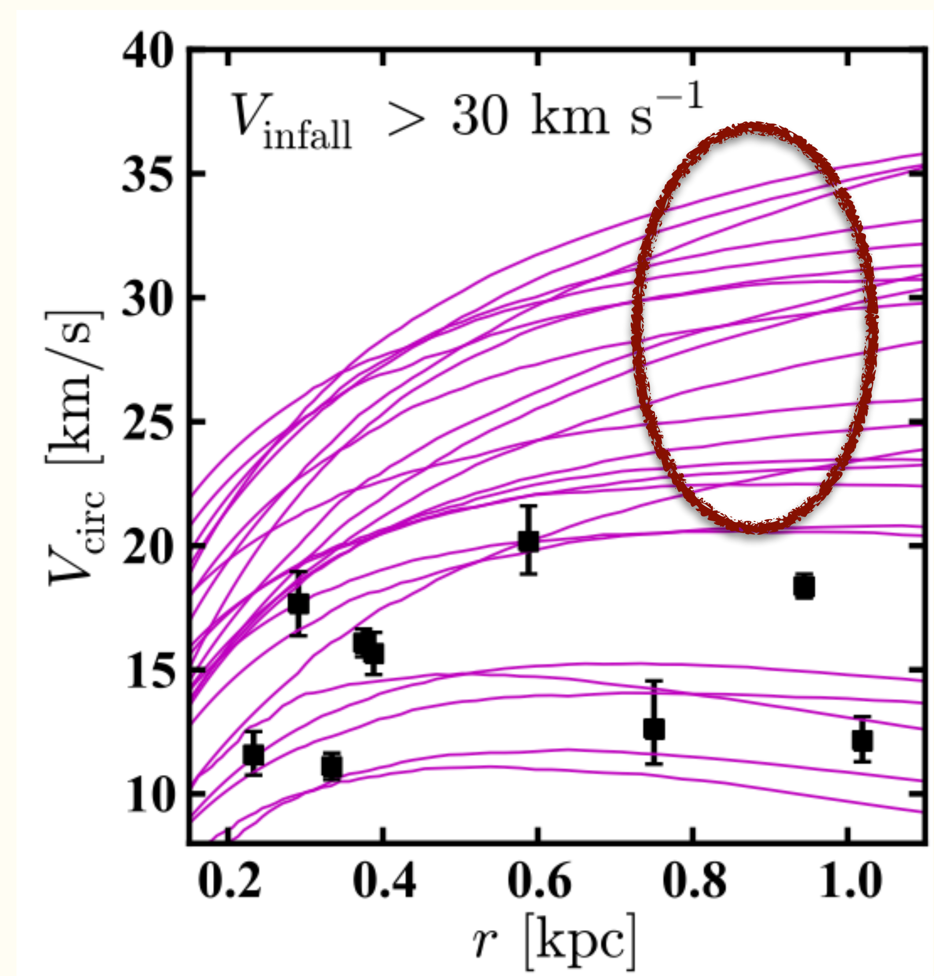


[Boylan-Kolchin,Bullock,Tollerud 2014; Garrison-Kimmel et al. 2014; Kirby et al. 2014; Papastergis et al. 2014;…]



[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.

Definitely maybe!

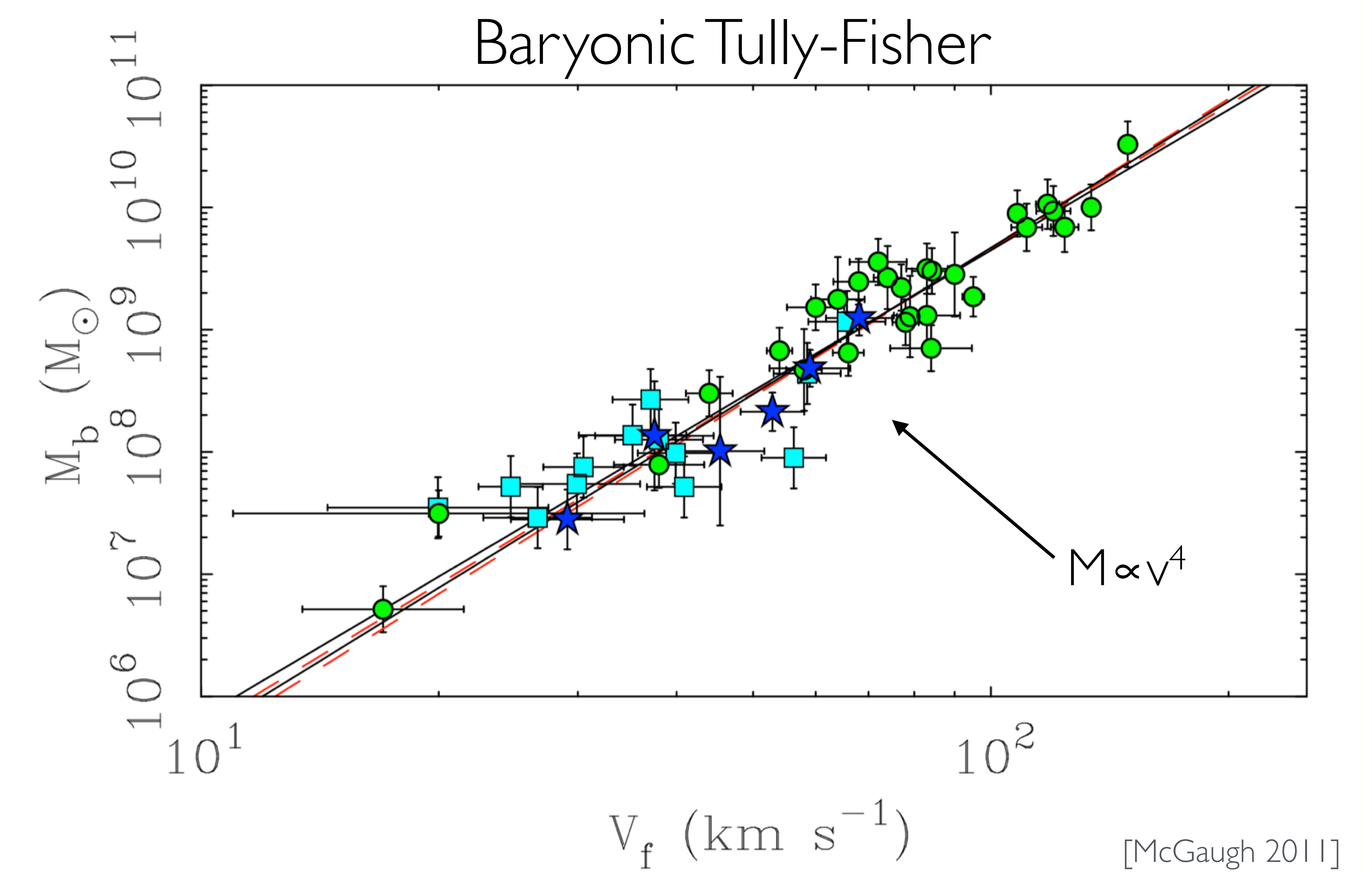
But highly non-trivial…

Can one explain these with CDM?

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!

Two more problems to note…



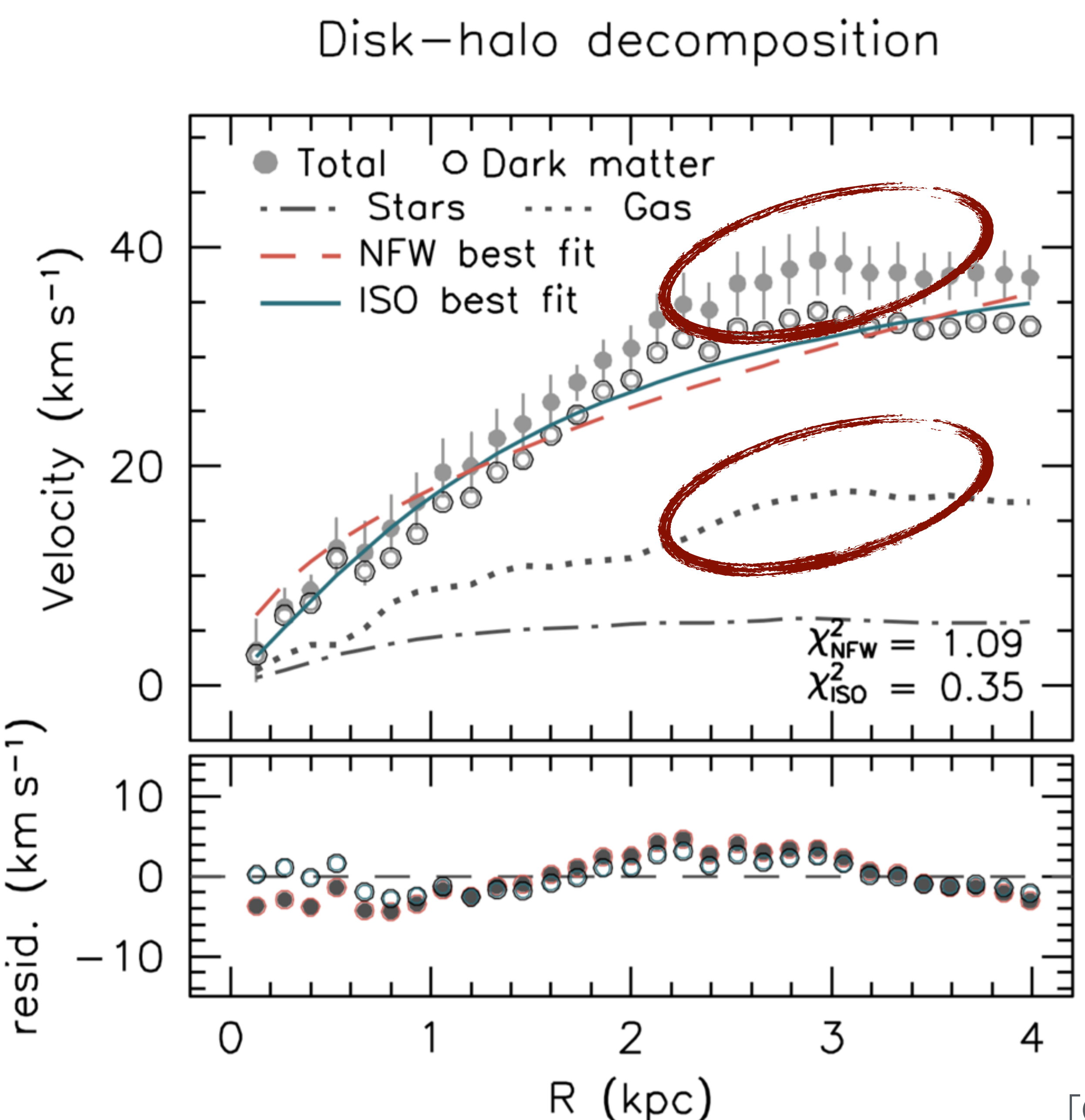
[McGaugh 2011]

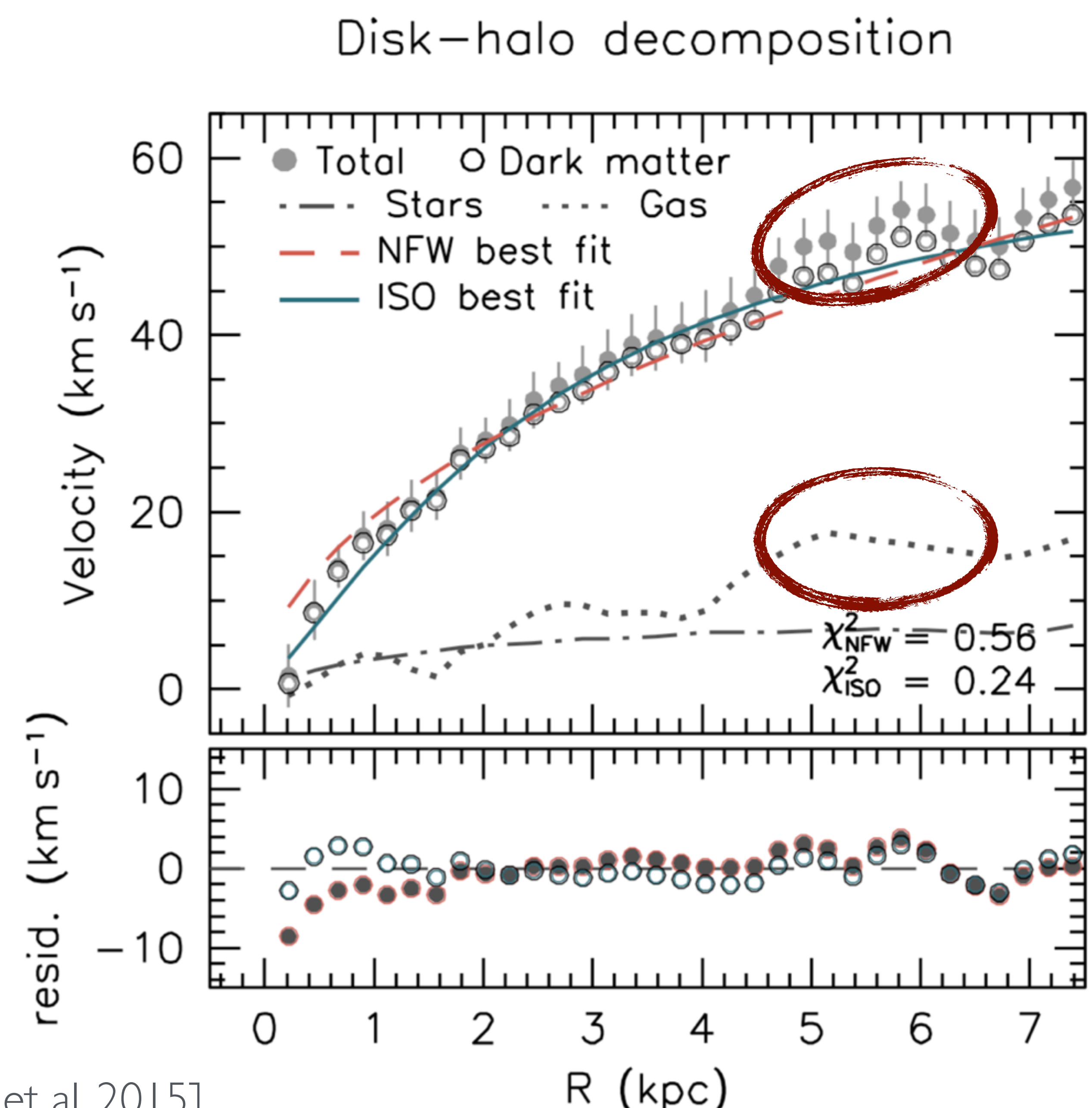
ΛCDM can explain, but requires baryonic feedback.

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

Two more problems to note…

Features in Rotation Curves





[Oh et al. 2015]

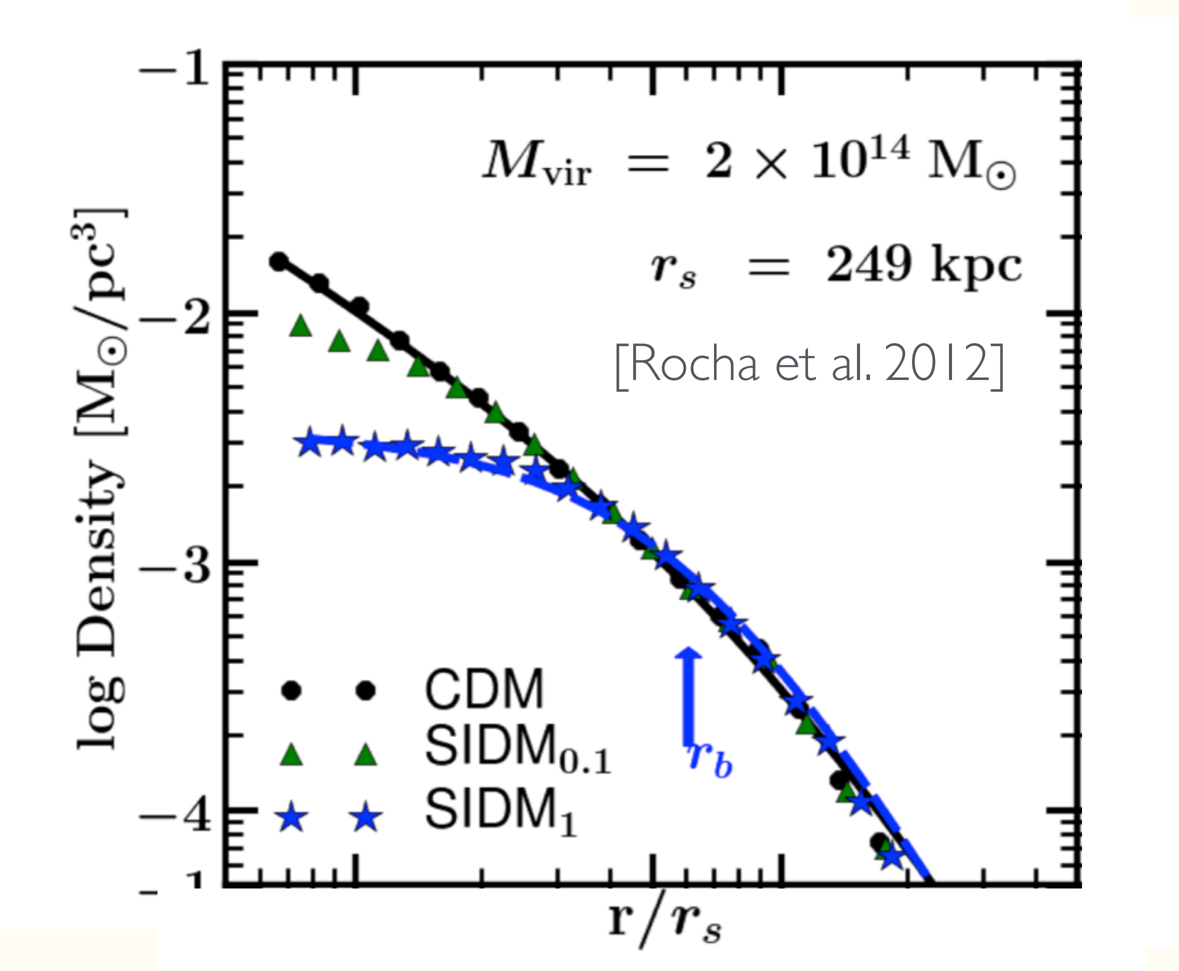
Features in rotation curves are intriguing. Mergers may provide a clue?

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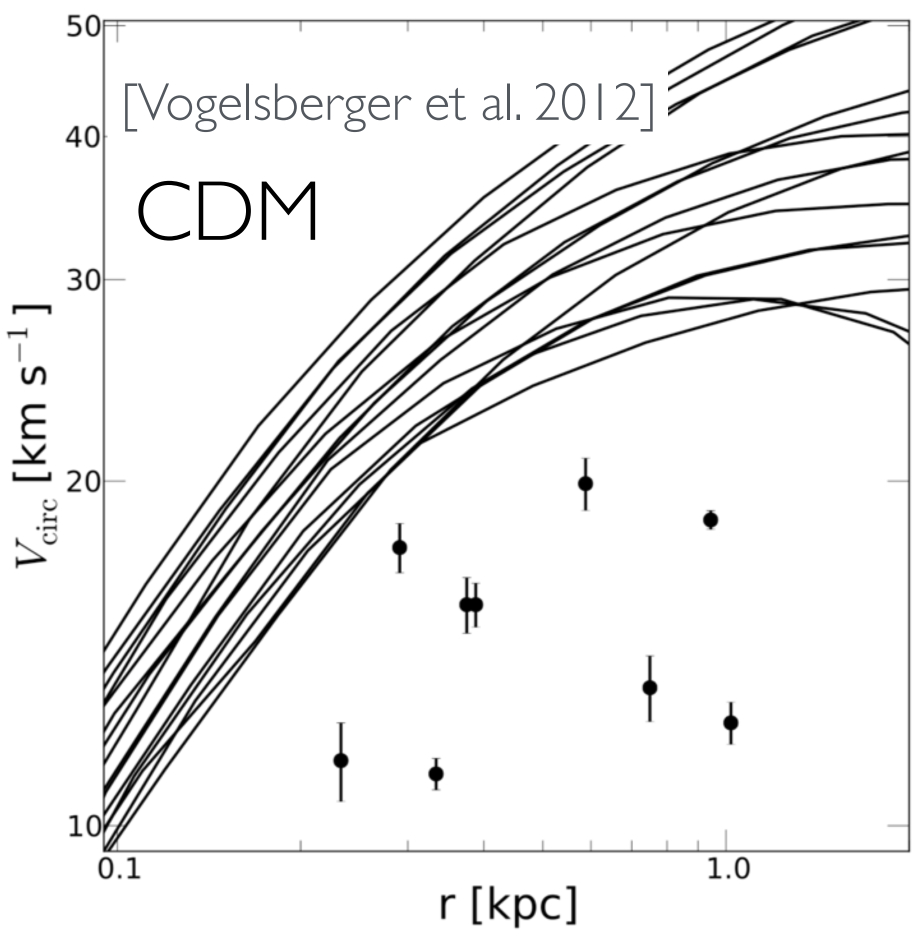
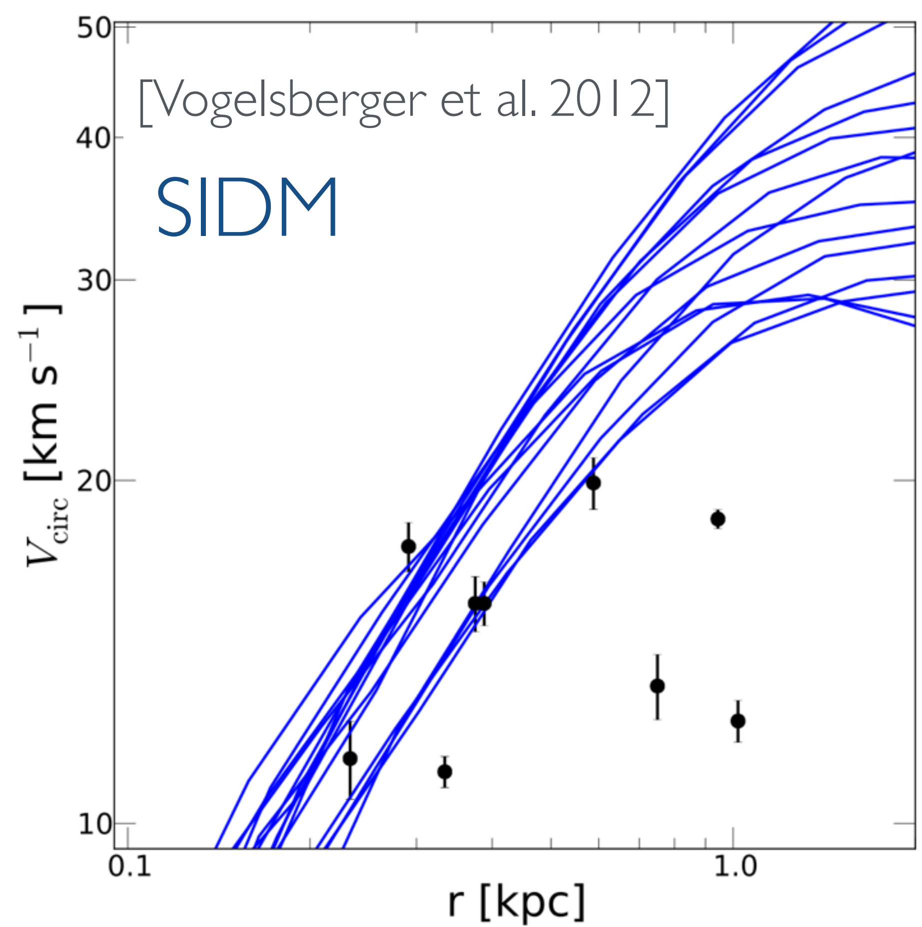
  - Collisions strip sub-halos and reduce number of satellites.





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

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

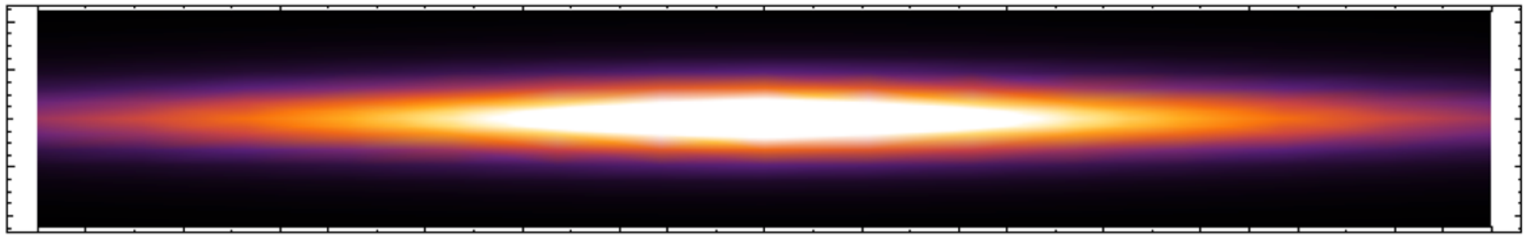
A Non-trivial dark sector!

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 $U(1)_{hid}$.

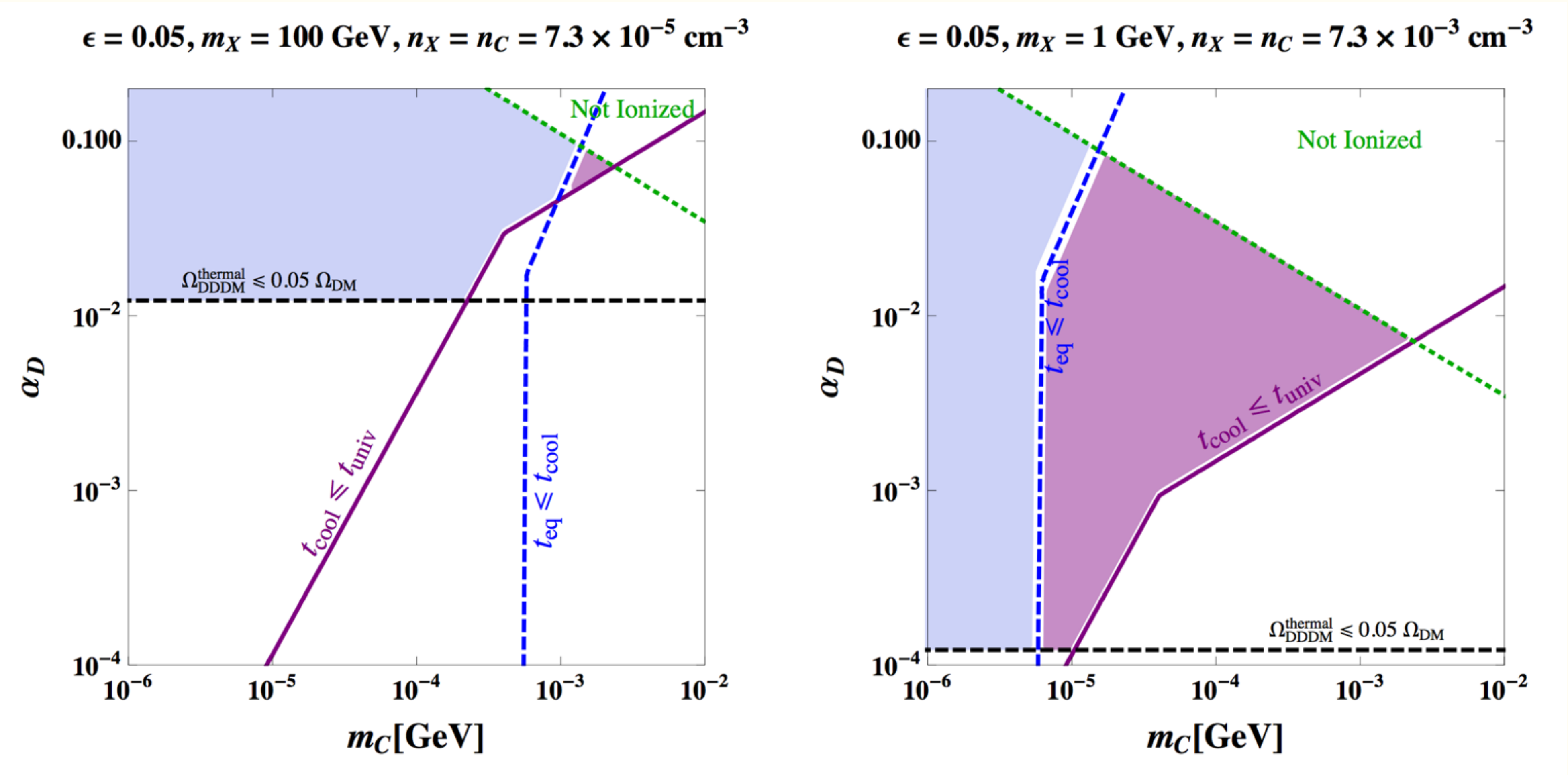
X	———	~1-100 GeV
C	———	~1MeV
$A_{\mu,hid}$	———	« MeV

- Light states allow for dissipation through cooling.
- Consequently, DM may form a disk (instead of a halo).



Dissipative Dark Matter?

- Three processes are important in the formation of a disk:
  - Cooling: Occurs via bremsstrahlung and Compton (C looses energy)
  - Equipartition of energy: Rutherford scattering ensures X energy loss.
- If cooling occurs within the age of the universe, a disk will form.



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..)

Classifying Theories of DM

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- 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
- …

Mediation Scheme

- Gravity
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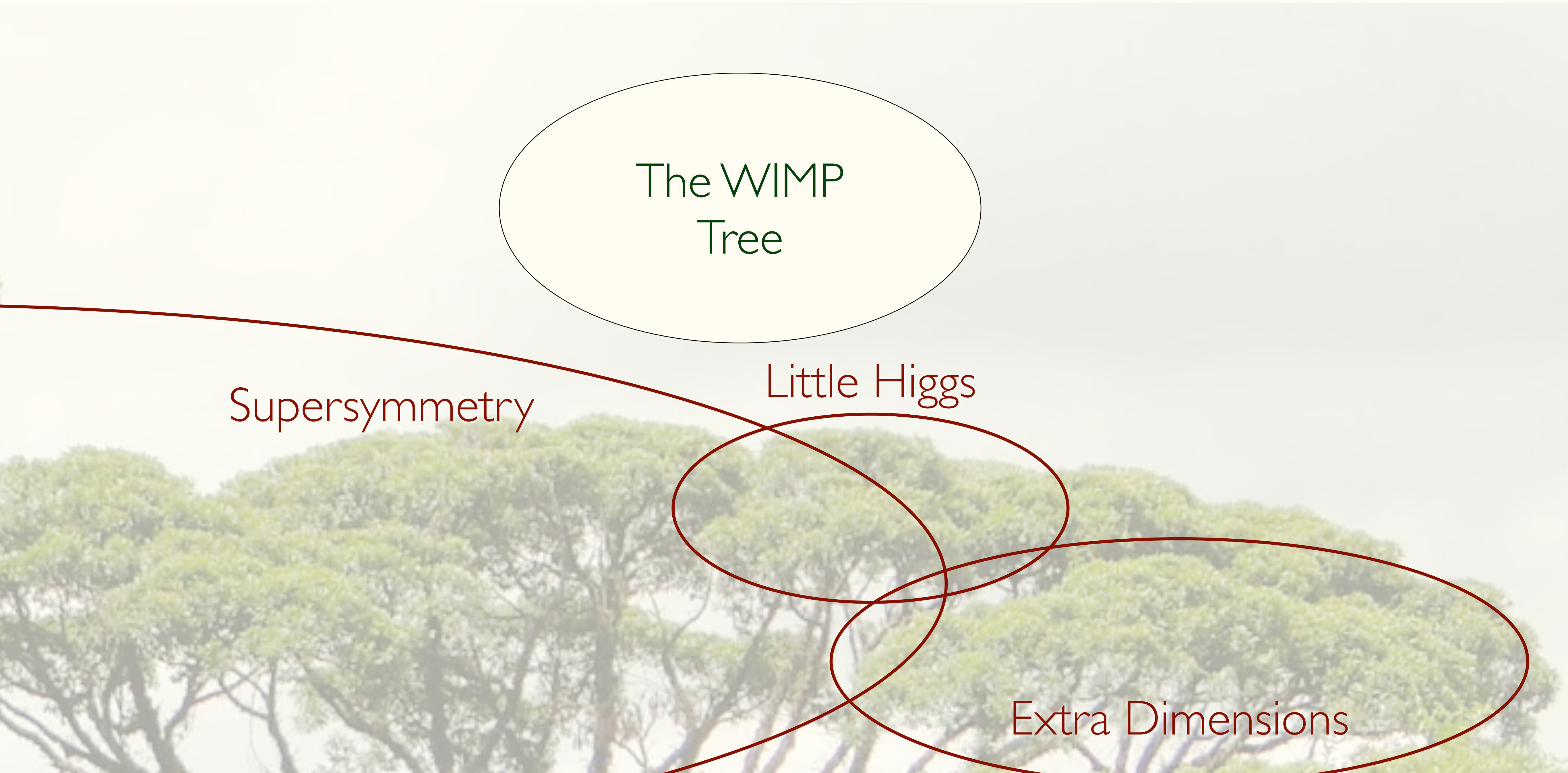
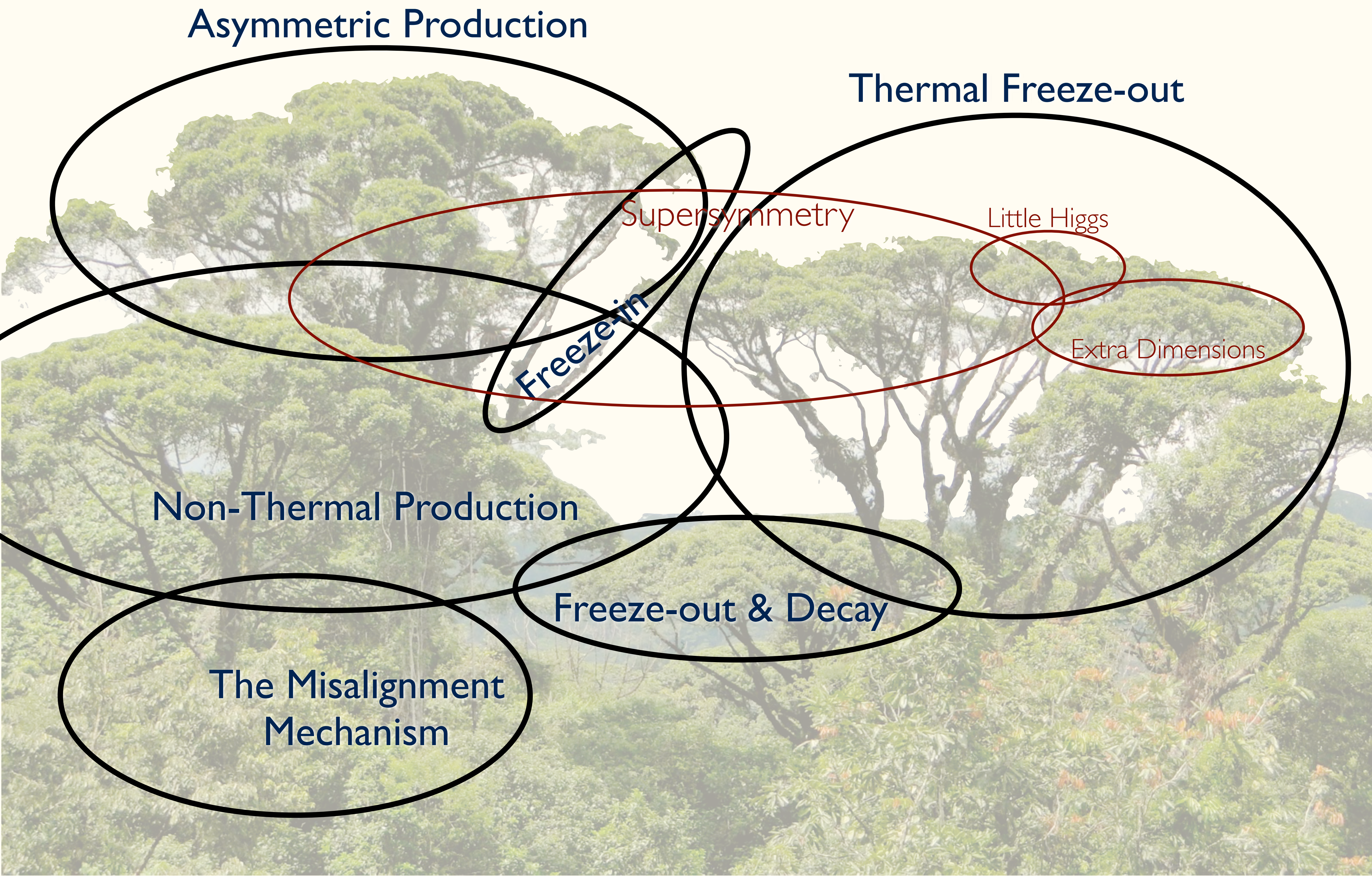
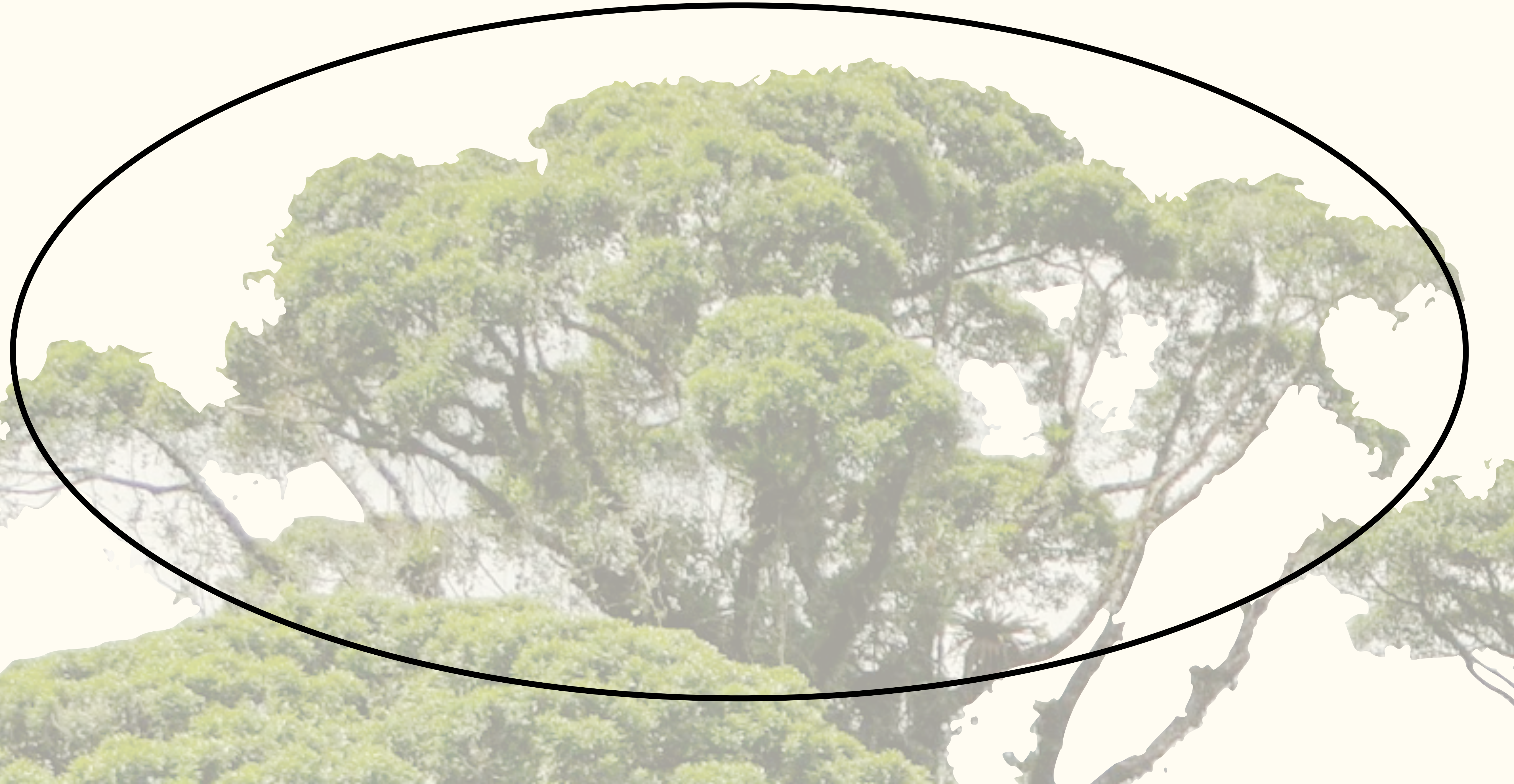
The Dark Matter Tree




Asymmetric Production
Thermal Freeze-out
Supersymmetry
Little Higgs
Freeze-in
Extra Dimensions
Non-Thermal Production
Freeze-out & Decay
The Misalignment Mechanism

Asymmetric Production



Asymmetric DM

[Nussinov, 1985; , Kaplan, 1992]

Experimental fact:

$$\Omega_{\mathrm{DM}} \simeq 5\Omega_b$$

Main idea:

Relate the DM abundance to the baryon abundance.

But:

Baryon density is asymmetric (no anti-baryons), so DM may also be asymmetric.

Asymmetric DM

- If we take this as a hint, both densities are related through some joint dynamics.

[Nussinov, `85; Gelmini, Hall, Lin, `87'; Barr, Chivukula, Farhi, `90'; Kaplan, Luty, Zurek, `09;…

- Typical models of Asymmetric DM work as follows:

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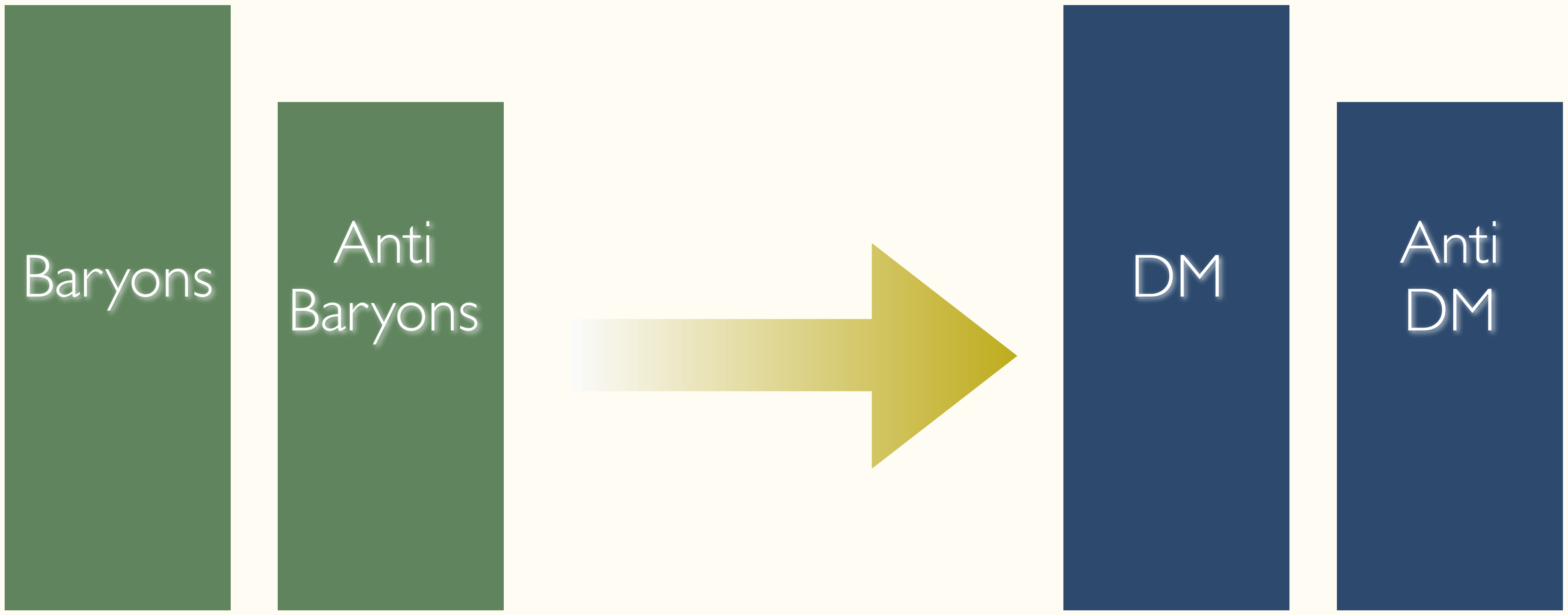
1. Asymmetry is **created** in one or both sectors. Couplings between the two sectors ensure an asymmetry in both.



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- Whether or not the symmetric component dominates, depends on the the DM annihilation cross-section

Asymmetric DM

- Example:
  - B-L asymmetry is generated at high scale in visible sector.
  - DM carries a B-L charge.
  - Asymmetry is transferred to DM through an operator, e.g. $\chi^2 HL$
  - Depending on when the operator decouples,

$$n_\chi = n_b \qquad \text{OR} \qquad n_\chi = n_b e^{-m_\chi/T_d}$$
$$m_\chi \sim \mathrm{GeV} \qquad\qquad m_\chi \sim \mathrm{TeV}$$

  - Meanwhile, the symmetric component is annihilated away.
  - DM density is controlled by the asymmetric component.

Asymmetric DM

ADM is experimentally distinguishable from Thermal WIMP (in principle...)

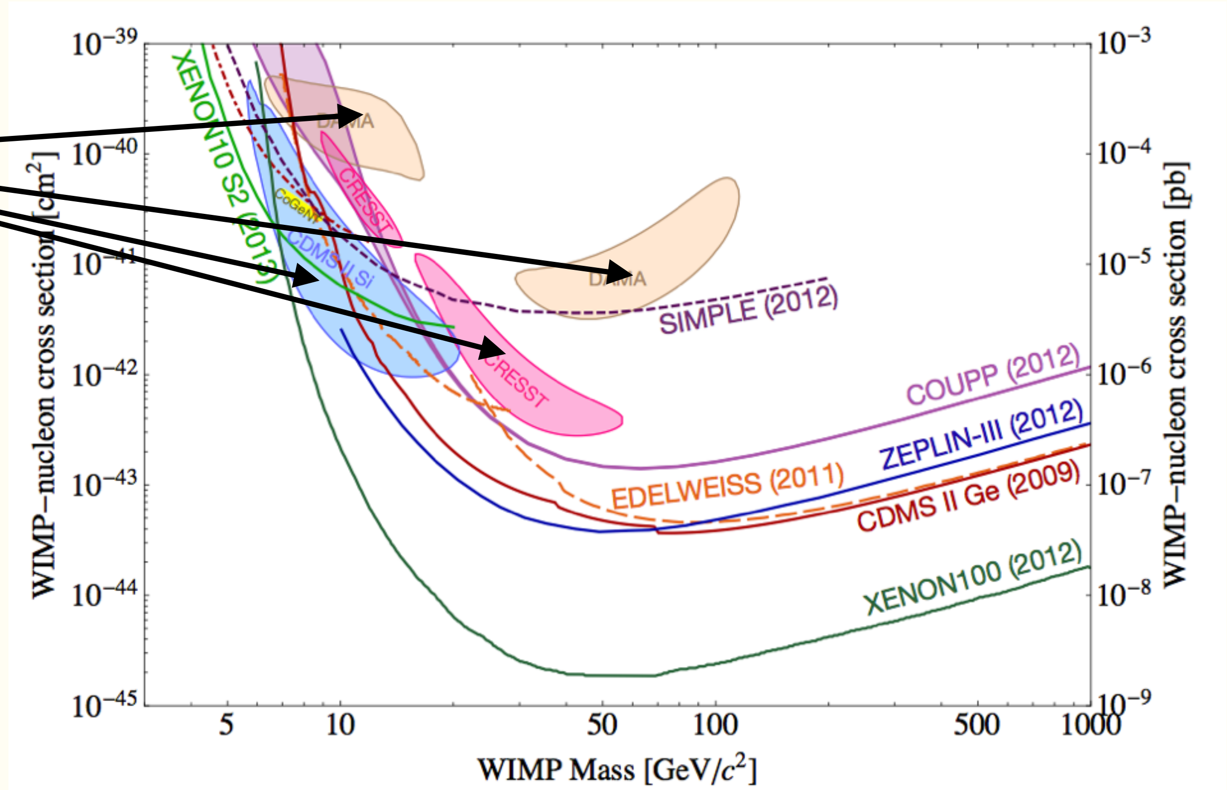
- There are many variations of the ADM story:

[Buckley, Cohen, Kaplan, Kitano, Hooper, Low, Luty, March-Russell, Murayama, Nardi, Phalen, Pierce, Randall, Ratz, Sannino, Shelton, Strumia, West, Zurek,Servant,Tulin,…..]

Aidogenesis, Darkogenesis, Xogenesis, Hylogenesis, Baryomorphosis, Higgsogenesis…

- DM is often predicted to be in the GeV mass range.

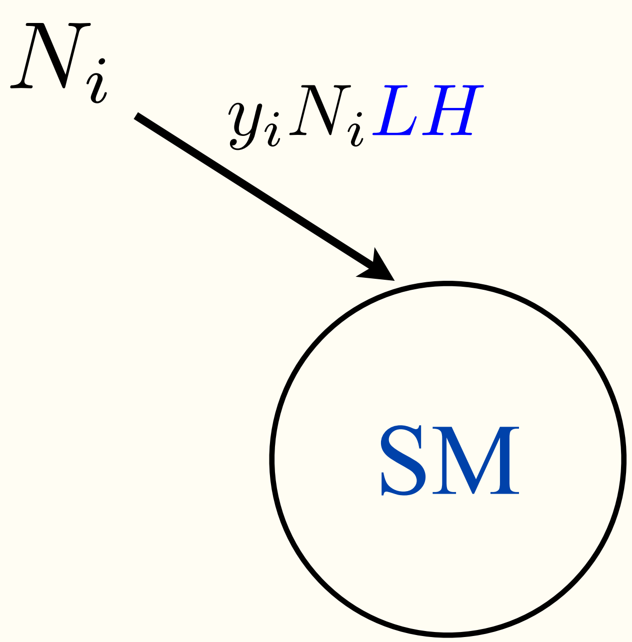
Lots of excitement
(probably for the wrong reason)

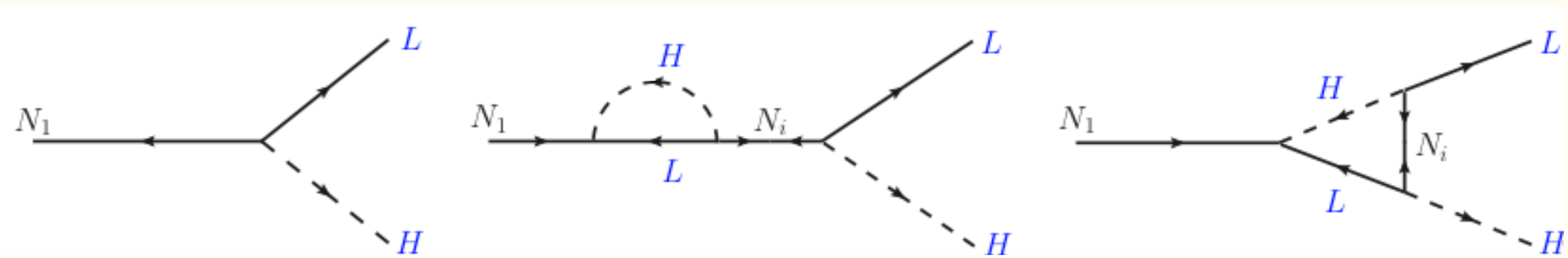


Asymmetric DM: GeV is NOT a Prediction!

- Thermal Leptogenesis:

[Fukugita,Yanagida,1986;
Review:Davidson,Nardi,Nir,2008]





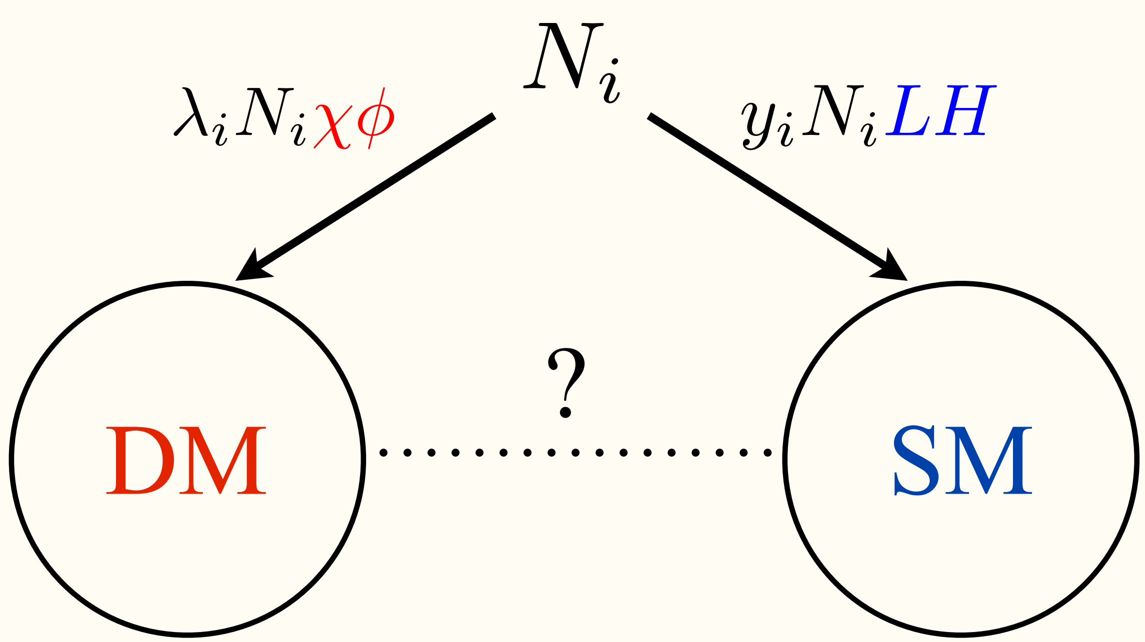
Sakharov's conditions:

1. **CP Violation**: Complex y_i. Requires at least two N_i's.
2. **Lepton Number Violation**: N_i are majorana.
3. **Departure from T.E.**: Decay out of equilibrium, $\Gamma_{N_1} < H(T = M_1)$.

Asymmetric DM: GeV is NOT a Prediction!

- Simple scenario: 2-sector leptogenesis.

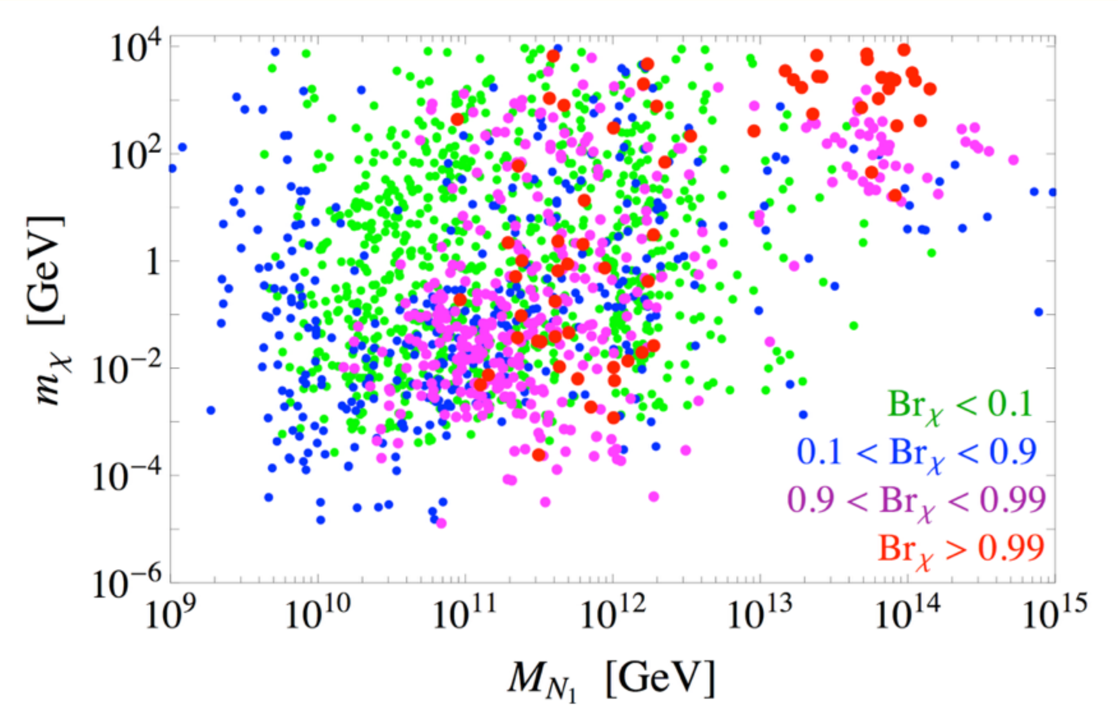
[Falkowski,Ruderman,TV, 2011]



- The number densities in the two sectors depend on the ratio of branching fractions and washout effects.

Wide range of DM masses:

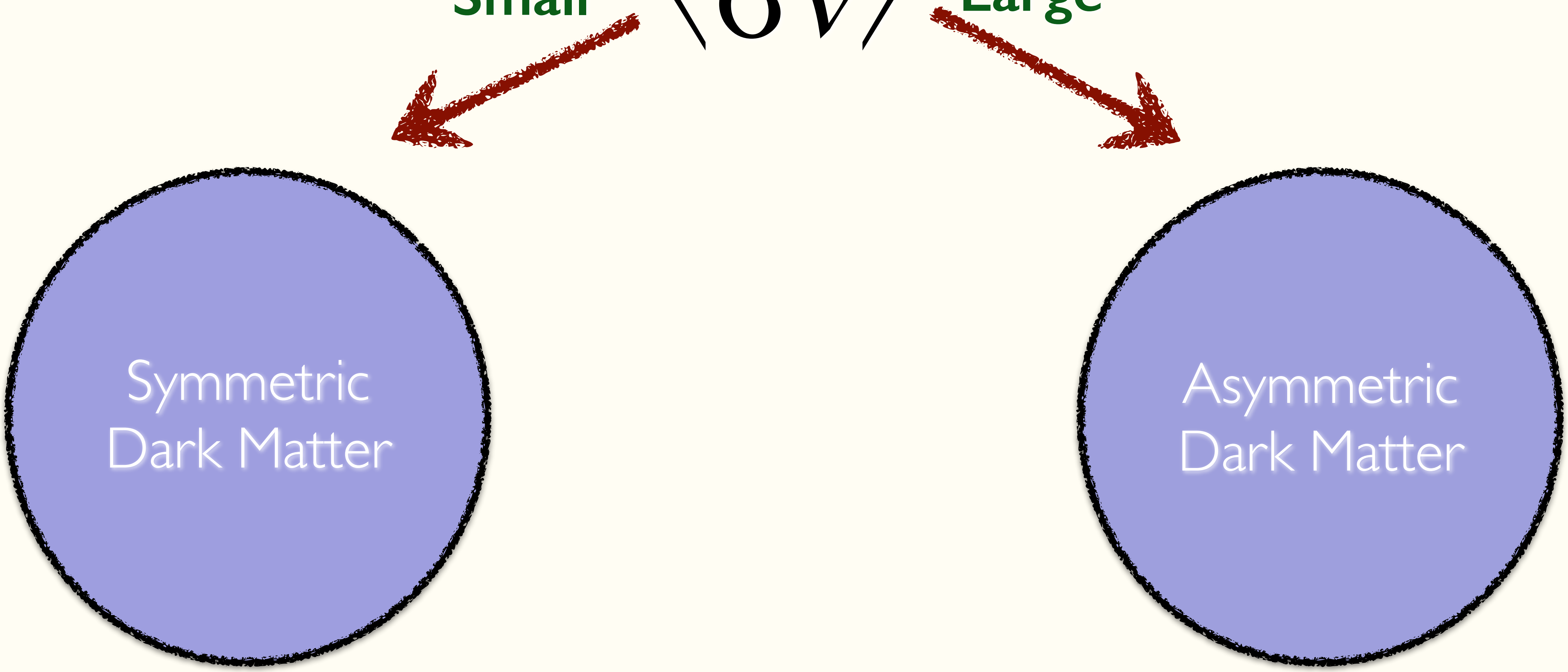
keV - 100 TeV



Asymmetric / Non-thermal

$$\Omega_{\rm DM} \simeq 5\Omega_b$$

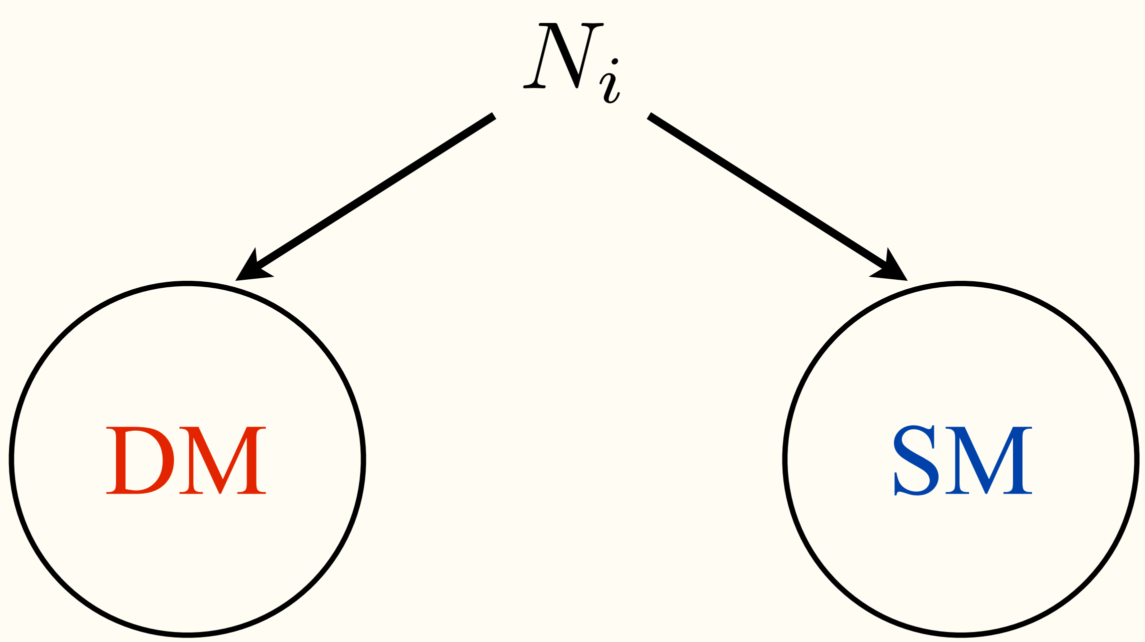
Small $\langle \sigma v \rangle$ **Large**



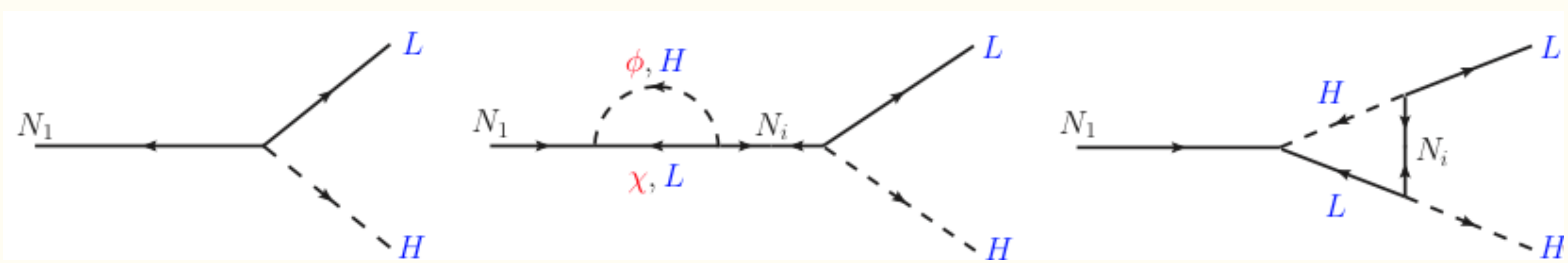
What should we expect here??

Asymmetric / Non-thermal

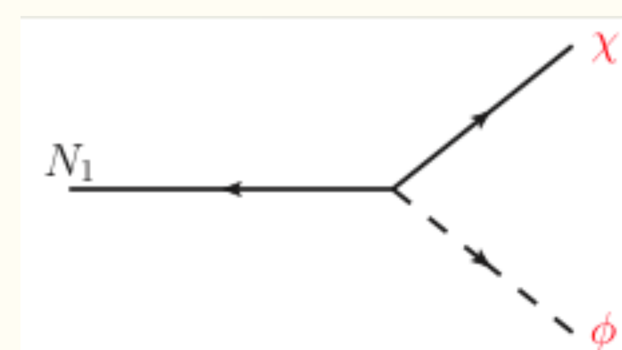
- Simple scenario: 2-sector leptogenesis.



- When N decays it produces the baryon asymmetry through CP violation (loops):

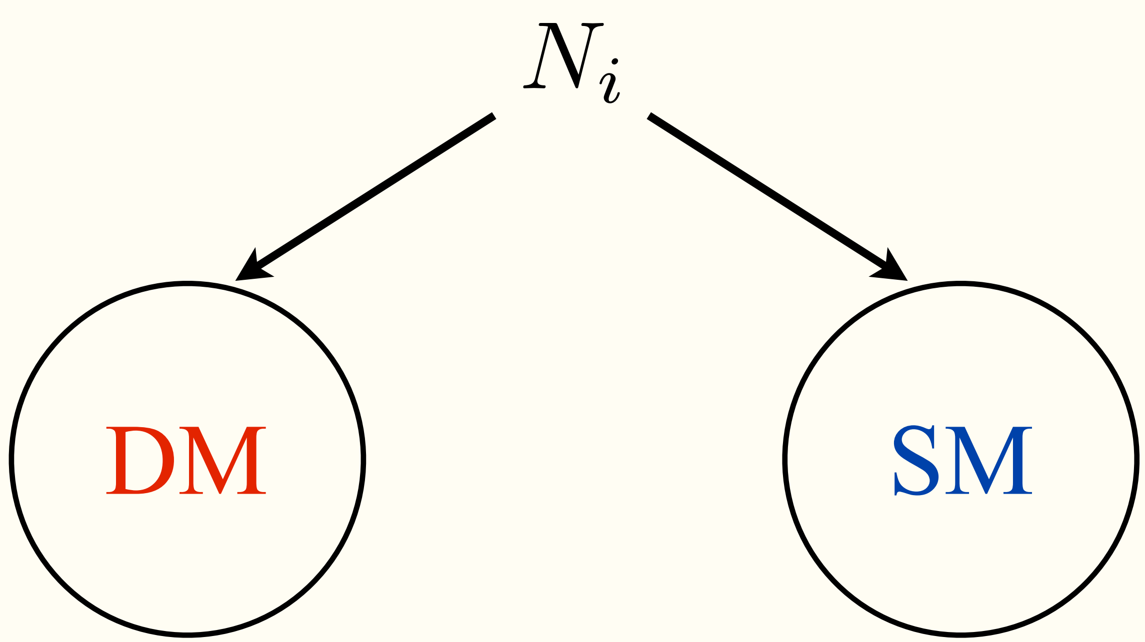


- Symmetric DM produced through tree level:



Asymmetric / Non-thermal

- Simple scenario: 2-sector leptogenesis.



- Consequently, DM number density is generically larger than number baryon density.

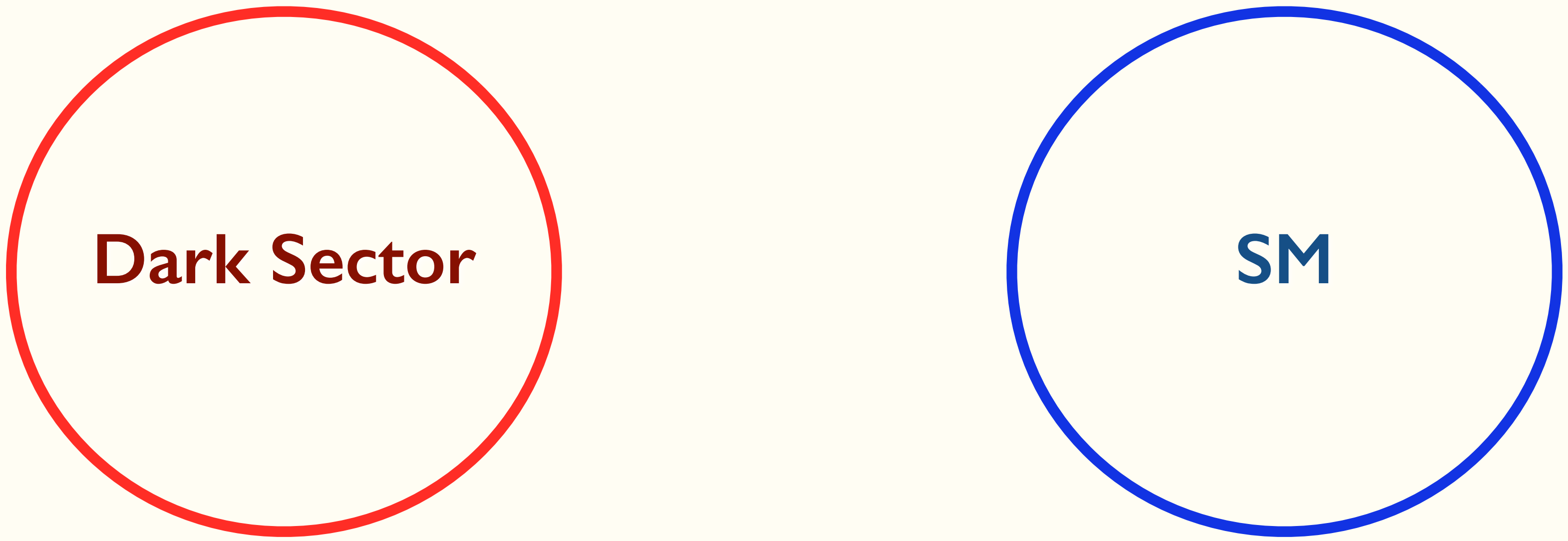
- To have the same mass density, $\Omega_i \propto m_i n_i$, this requires $m_{DM} < m_{proton}$

Light DM.

[Falkowski,Kuflik,Levi,TV, work in progress]

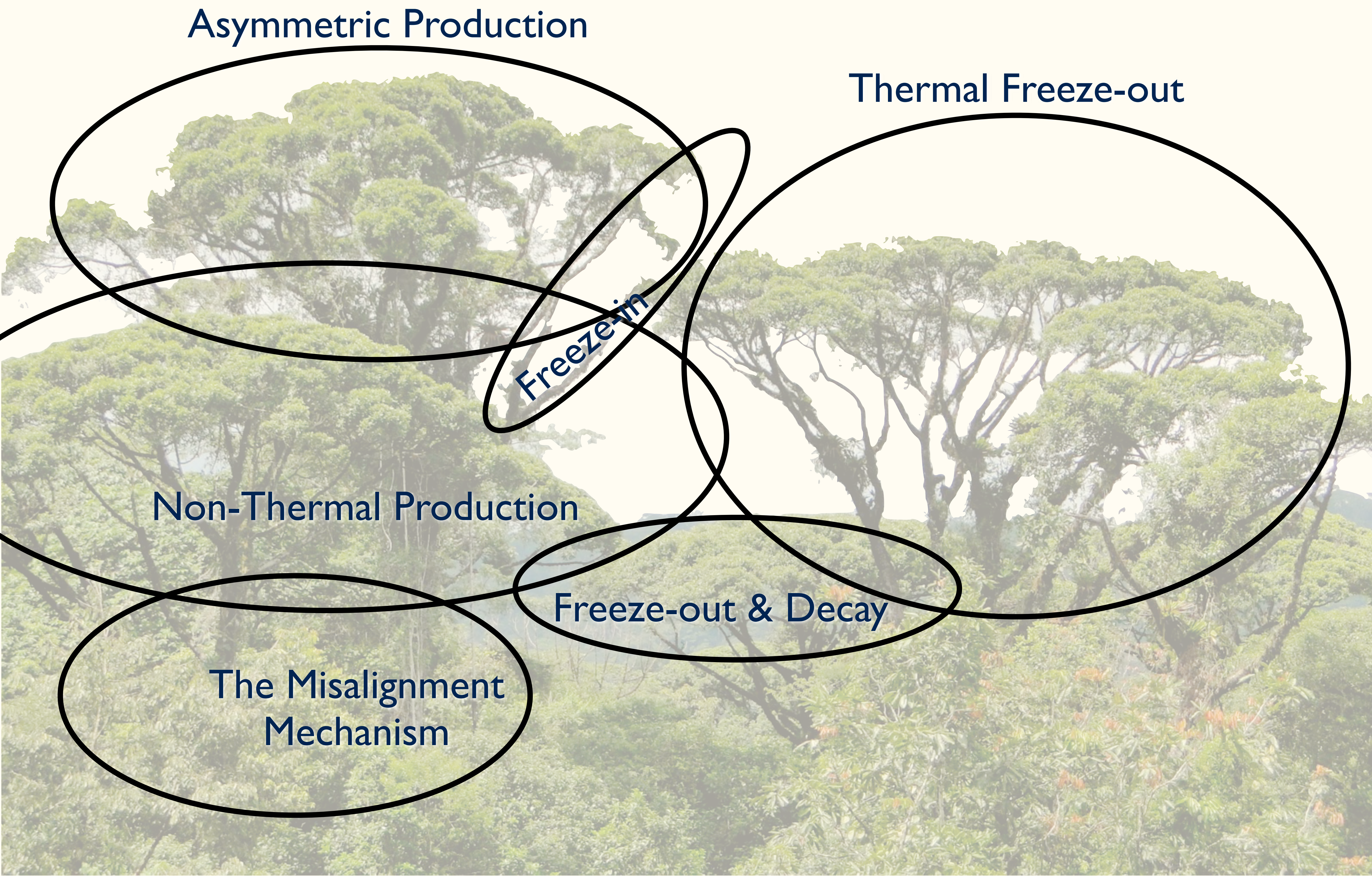
A Hidden Dark Sector

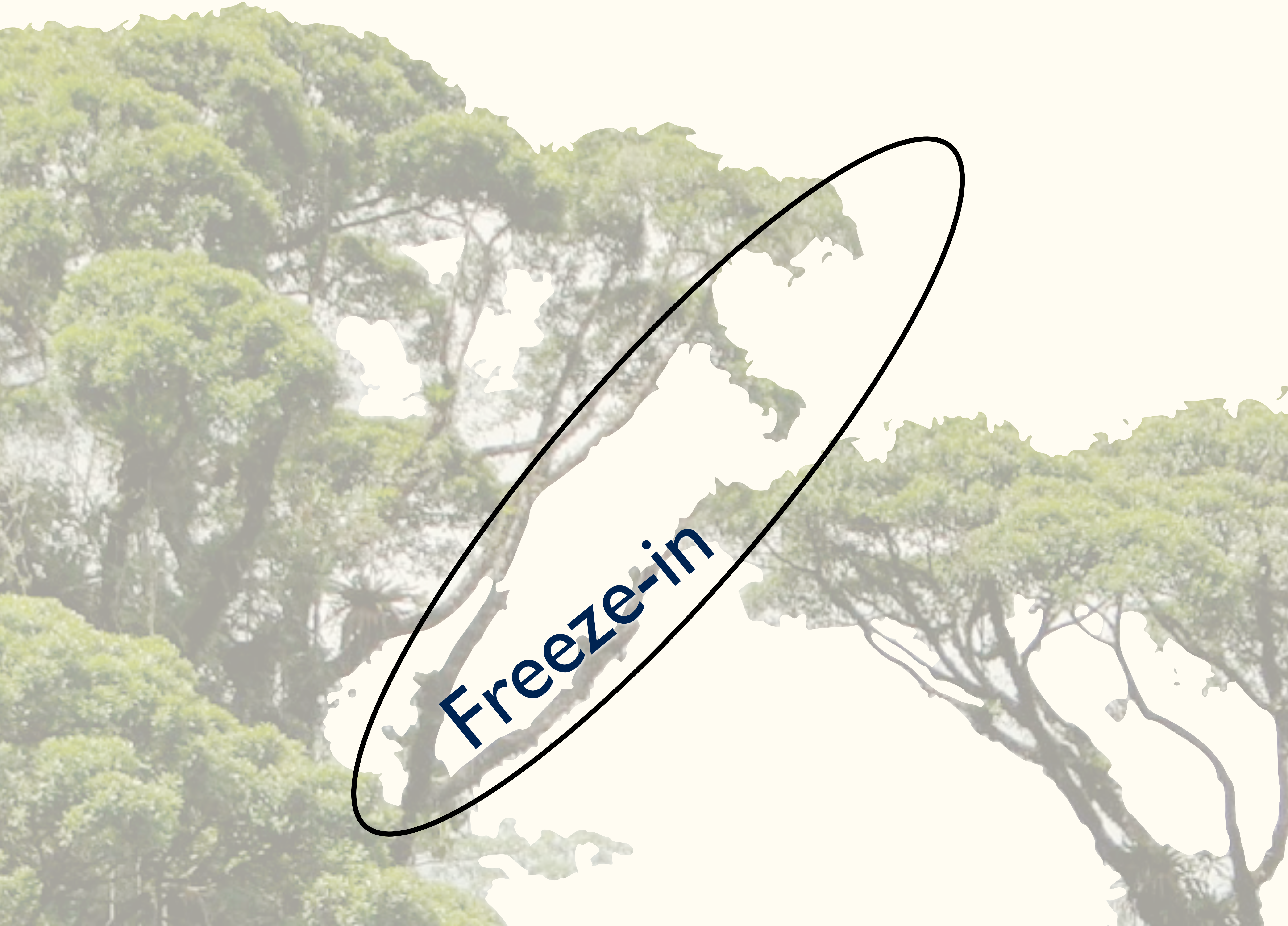
- The Leptogenesis scenario, much like many asymmetric DM models, imply a hidden sector in which the DM resides.



- This is often the case for other production mechanisms.

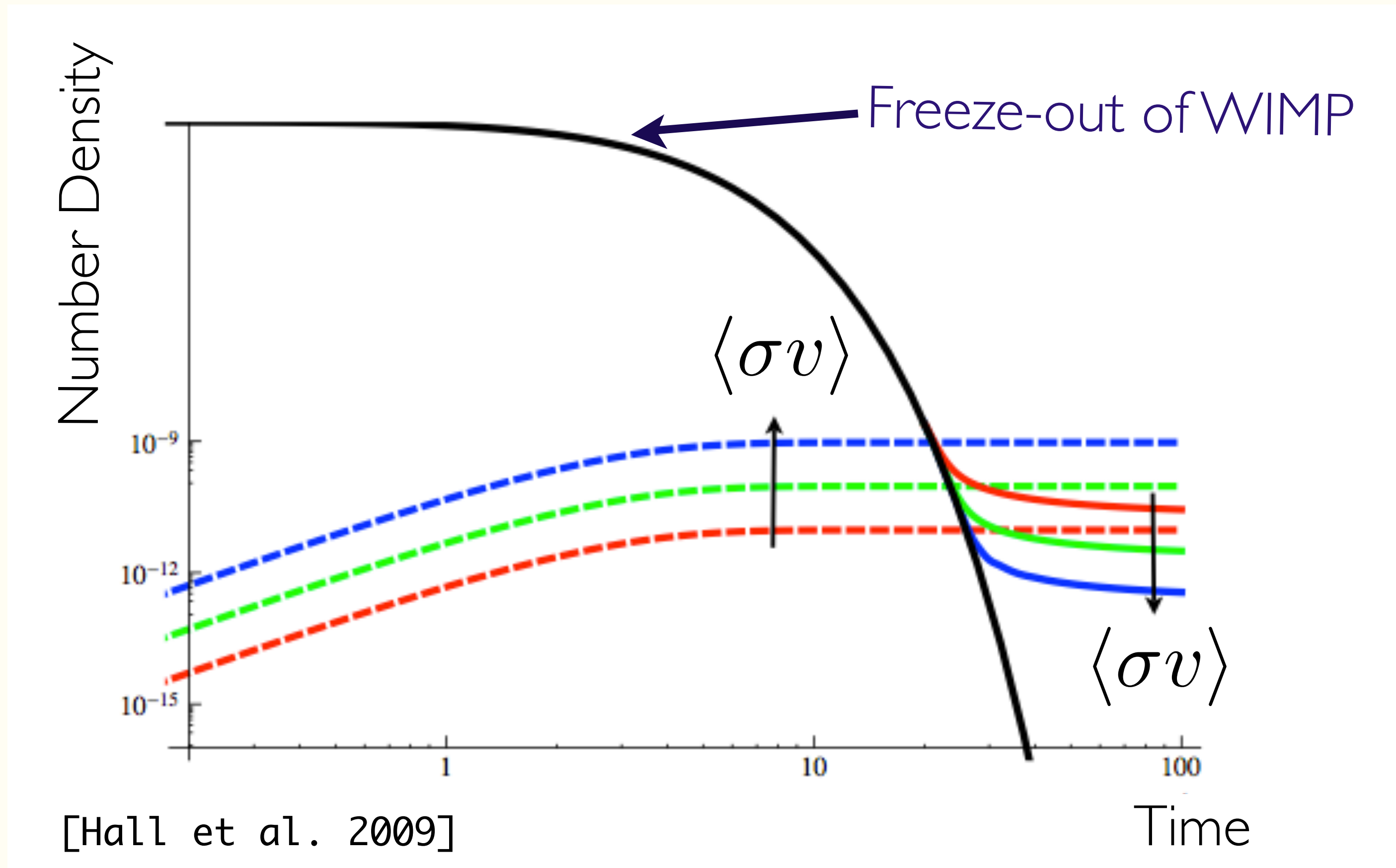
Is there an irreducible source of DM production?

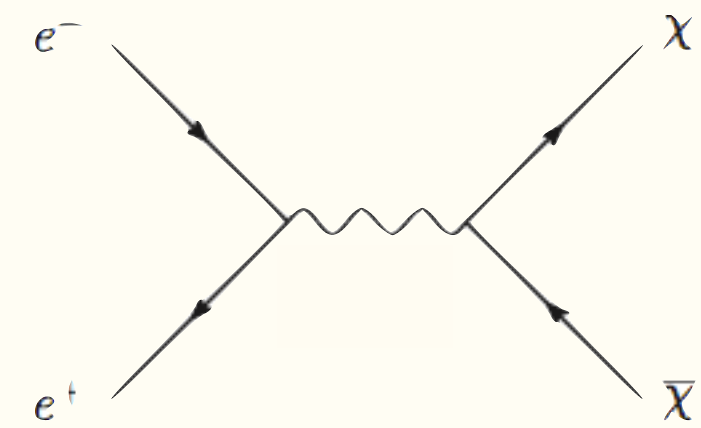

Asymmetric Production
Thermal Freeze-out
Freeze-in
Non-Thermal Production
Freeze-out & Decay
The Misalignment
Mechanism


Freeze-in

Freeze-In

- DM may couple very weakly to thermal bath, in which case it never reaches thermal equilibrium.

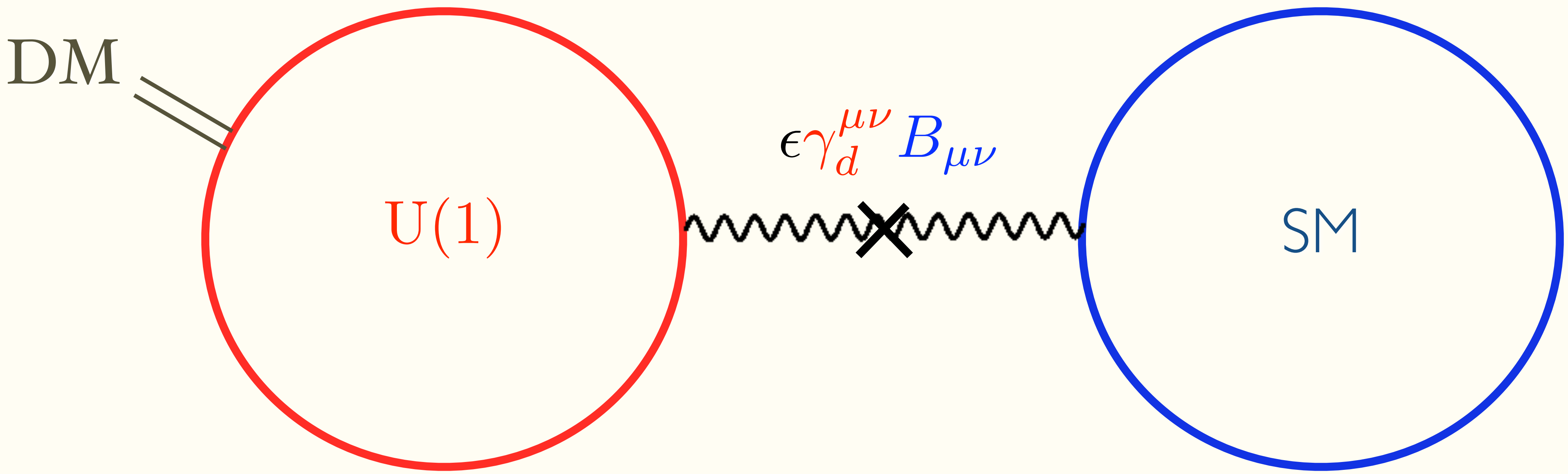




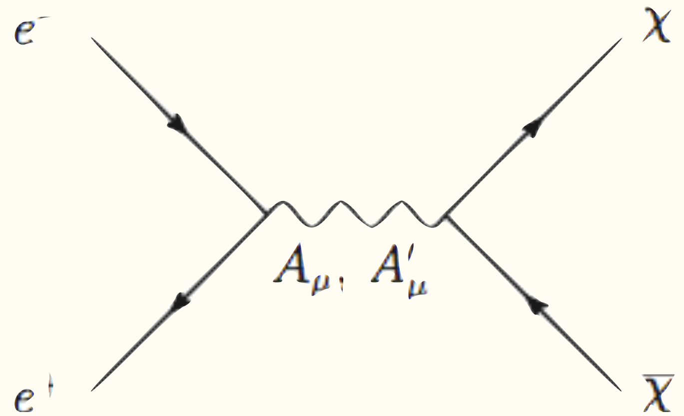
- Production is IR dominated. Independent of initial conditions (and UV quantities) much like in freeze-out.

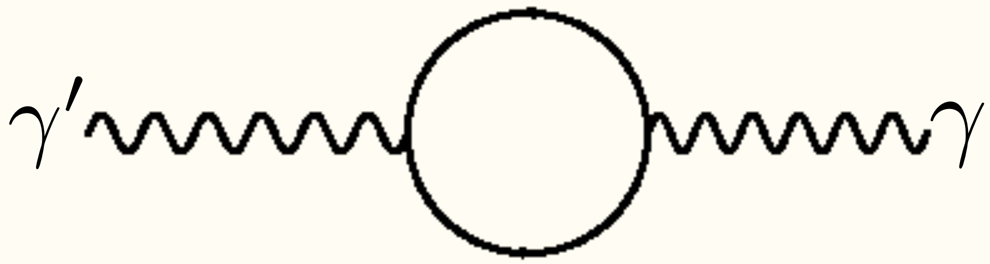
- Freeze-in could be responsible for DM density in hidden sector.

Freeze-In: Hidden Photon



- DM is charged under a new massive U(1) (hidden photon).
- Hidden photon mixes with the SM hypercharge.
- Thermal history of the hidden sector depends on **ε** and mass of hidden photon.



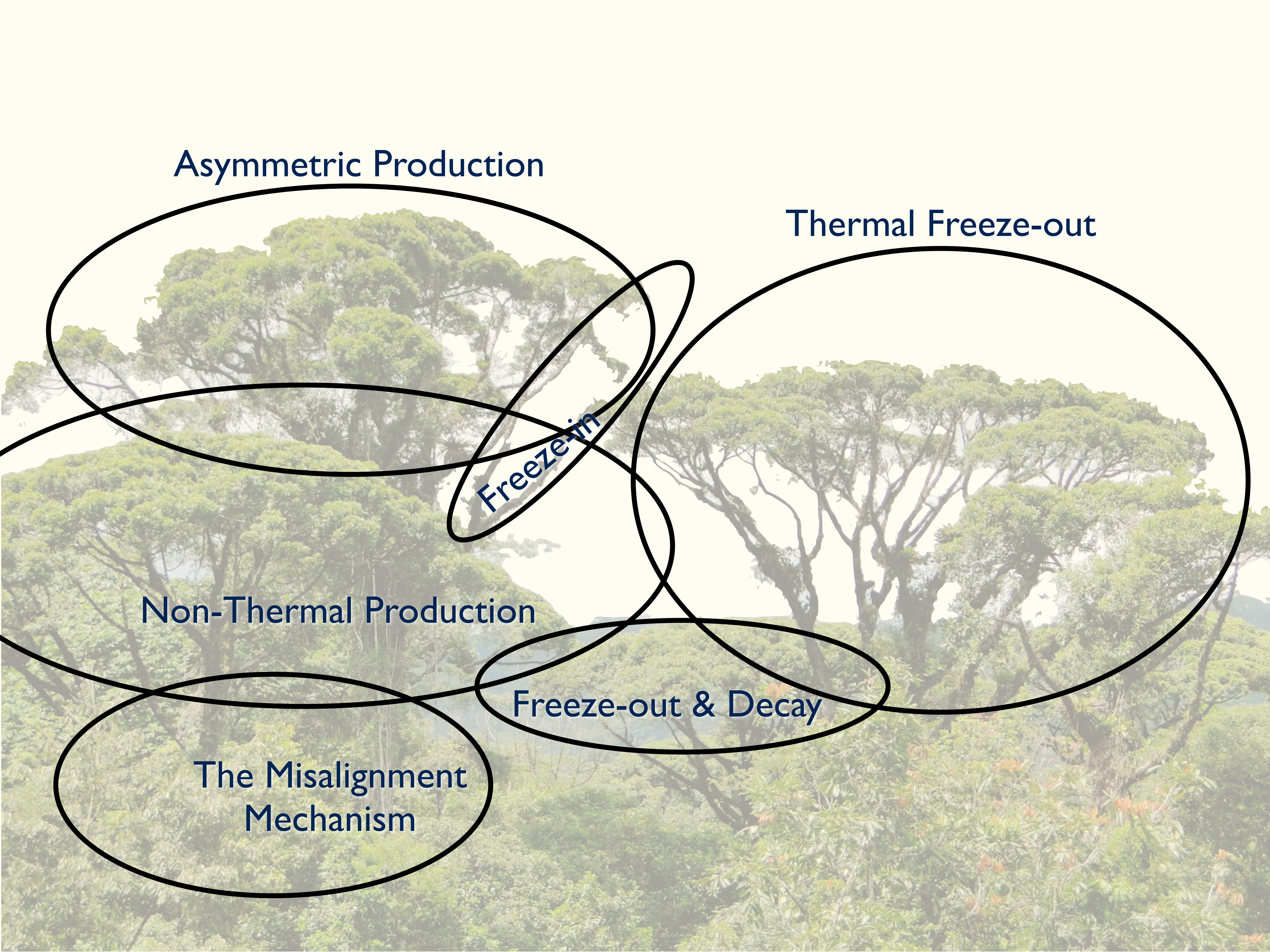


Freeze-In: Hidden Photon

[Essig,Manalaysay,Mardon,Sorensen,TV, 2012]

$$\sigma = \frac{16\,\pi\,m_e^2\,\alpha\,\alpha'\,\epsilon^2}{(m_{A'}^2 + q^2)^2}$$

For $m_A \ll$ keV hidden photon and $\varepsilon = 3\times10^{-6}$


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

Thermal Freeze-out

Strongly Interacting Massive Particles

A New Perspective on Freeze Out

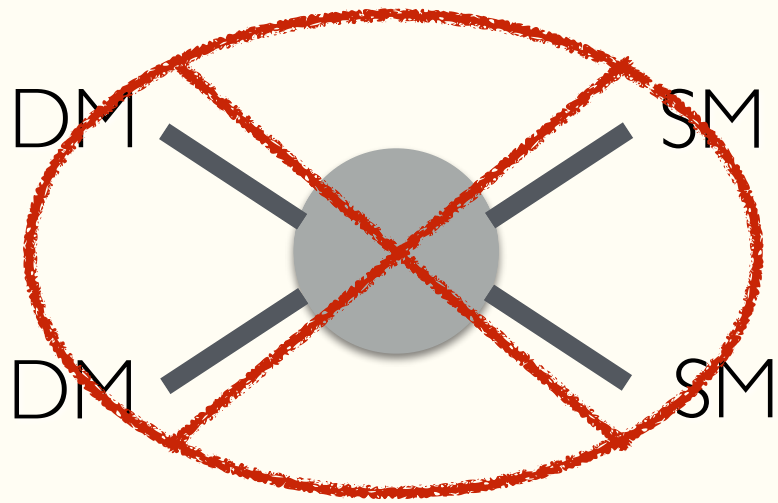
[Kuflik, Hochberg, TV, Wacker, 2014]

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

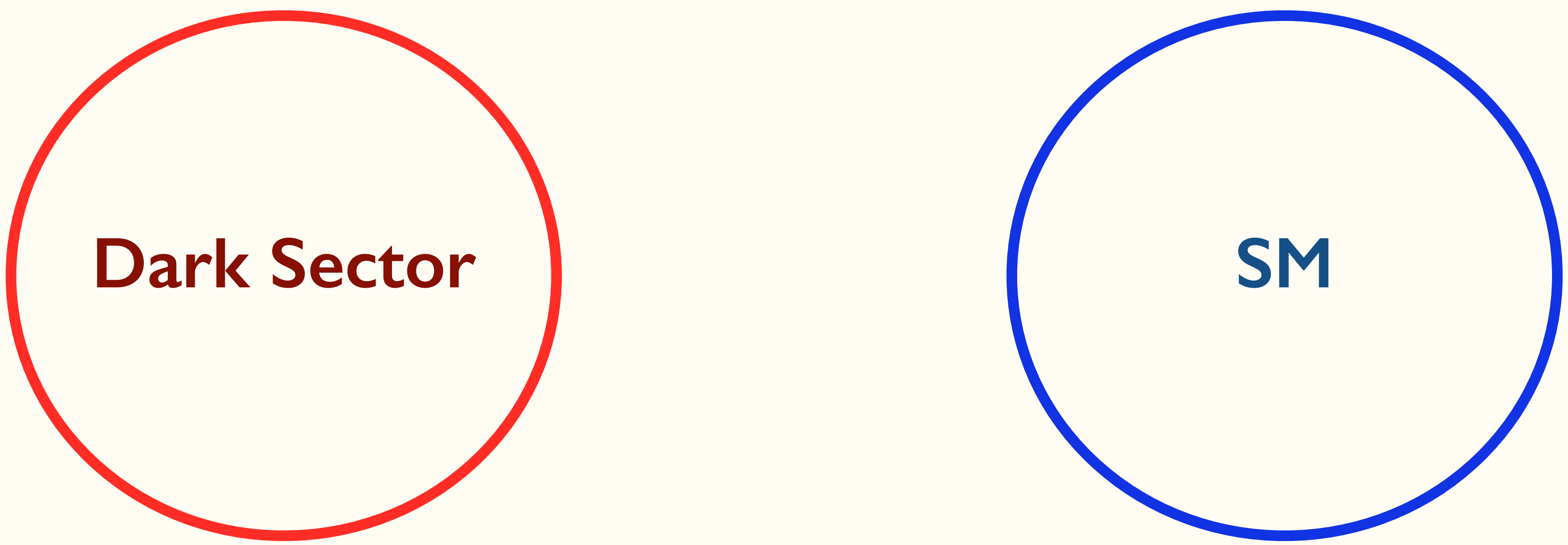
Skip

No 2-2 Annihilations..

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

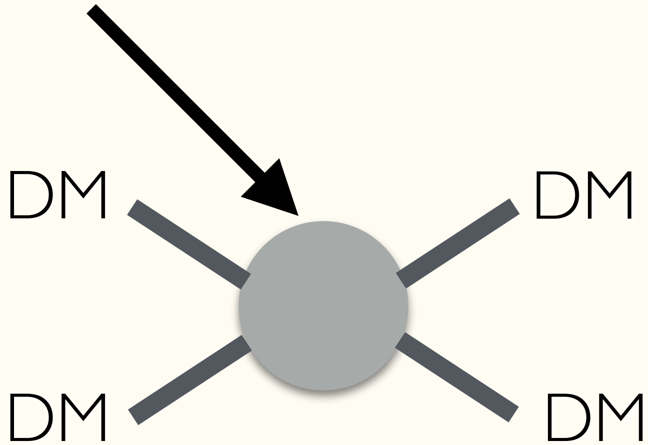


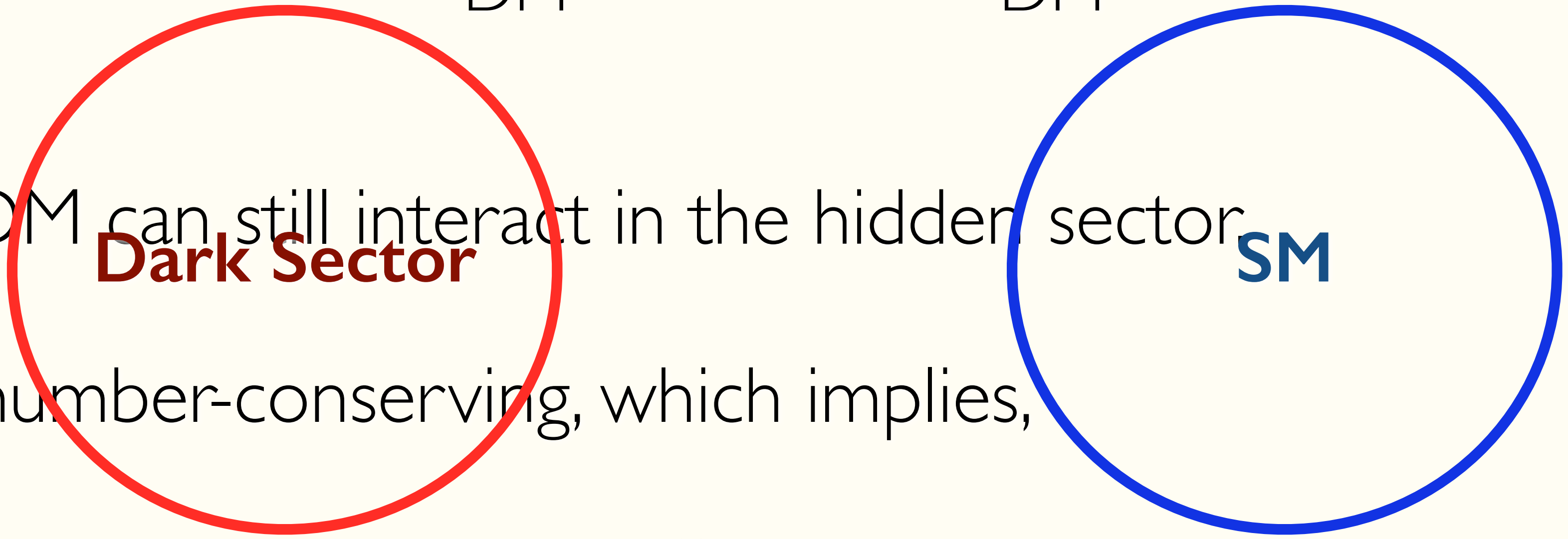
- But what if DM is the lightest state in a hidden (sequestered) sector?



- Then 2-2 annihilations may be highly suppressed

No 2-2 Annihilations..



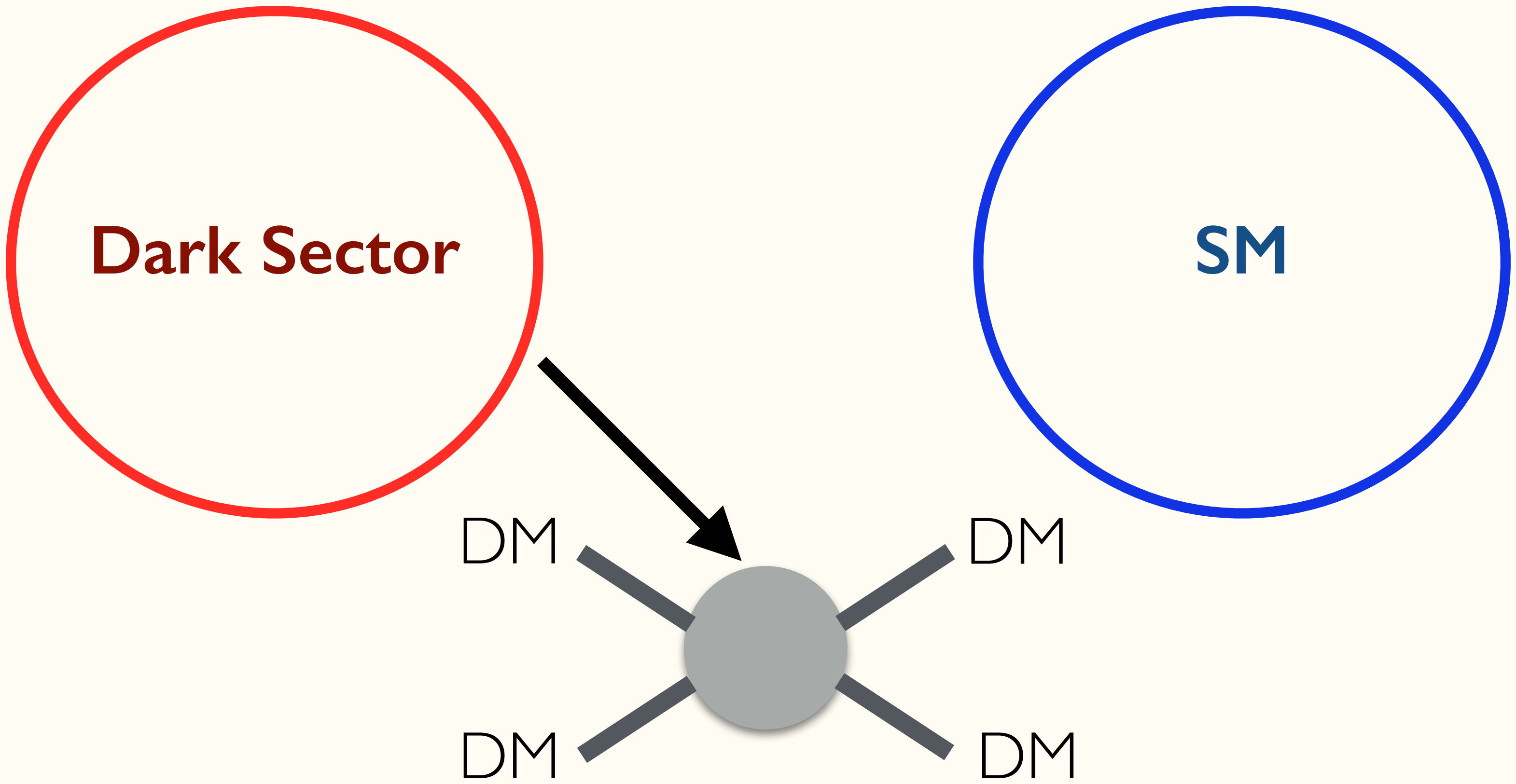


- However, DM can still interact in the hidden sector
- But this is number-conserving, which implies,

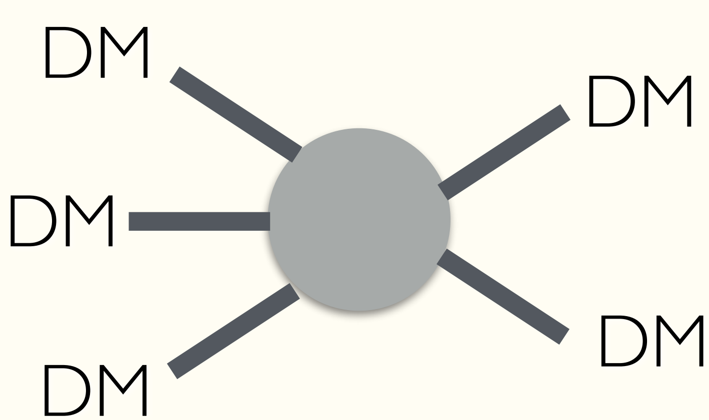
$$\frac{n_{\rm DM}}{s} \sim 1$$

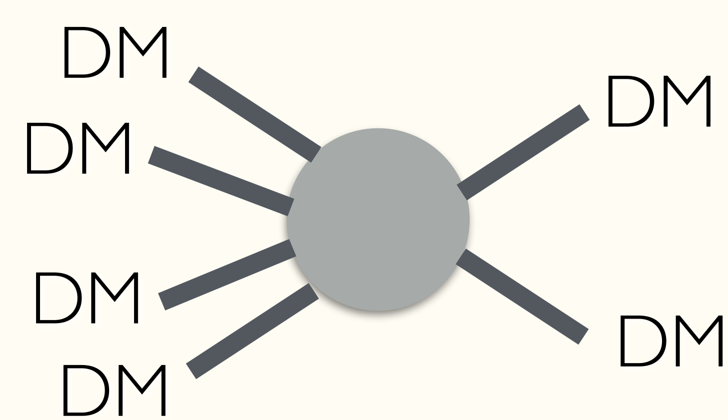
A way out?

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

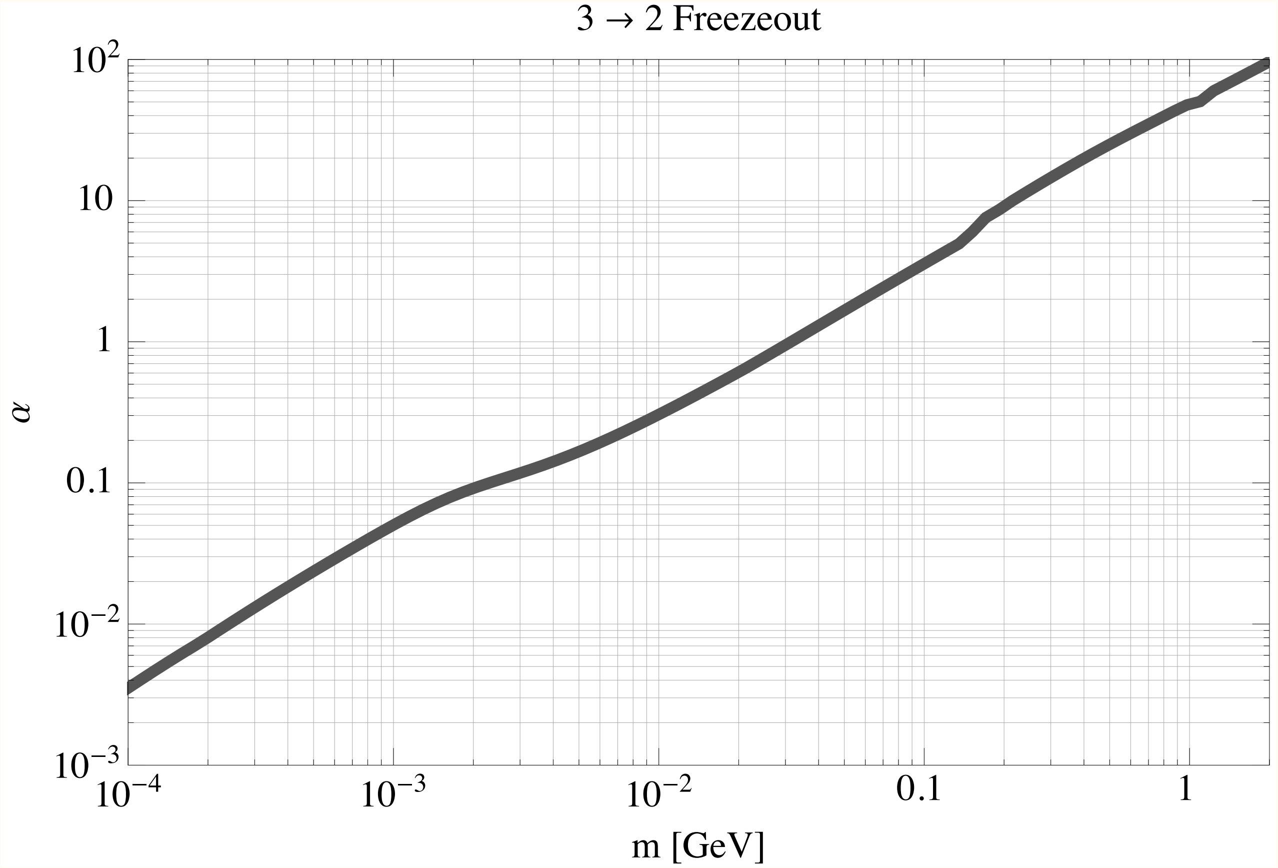
Weak scale emerges for a weak-strength interactions

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

SIMP DM

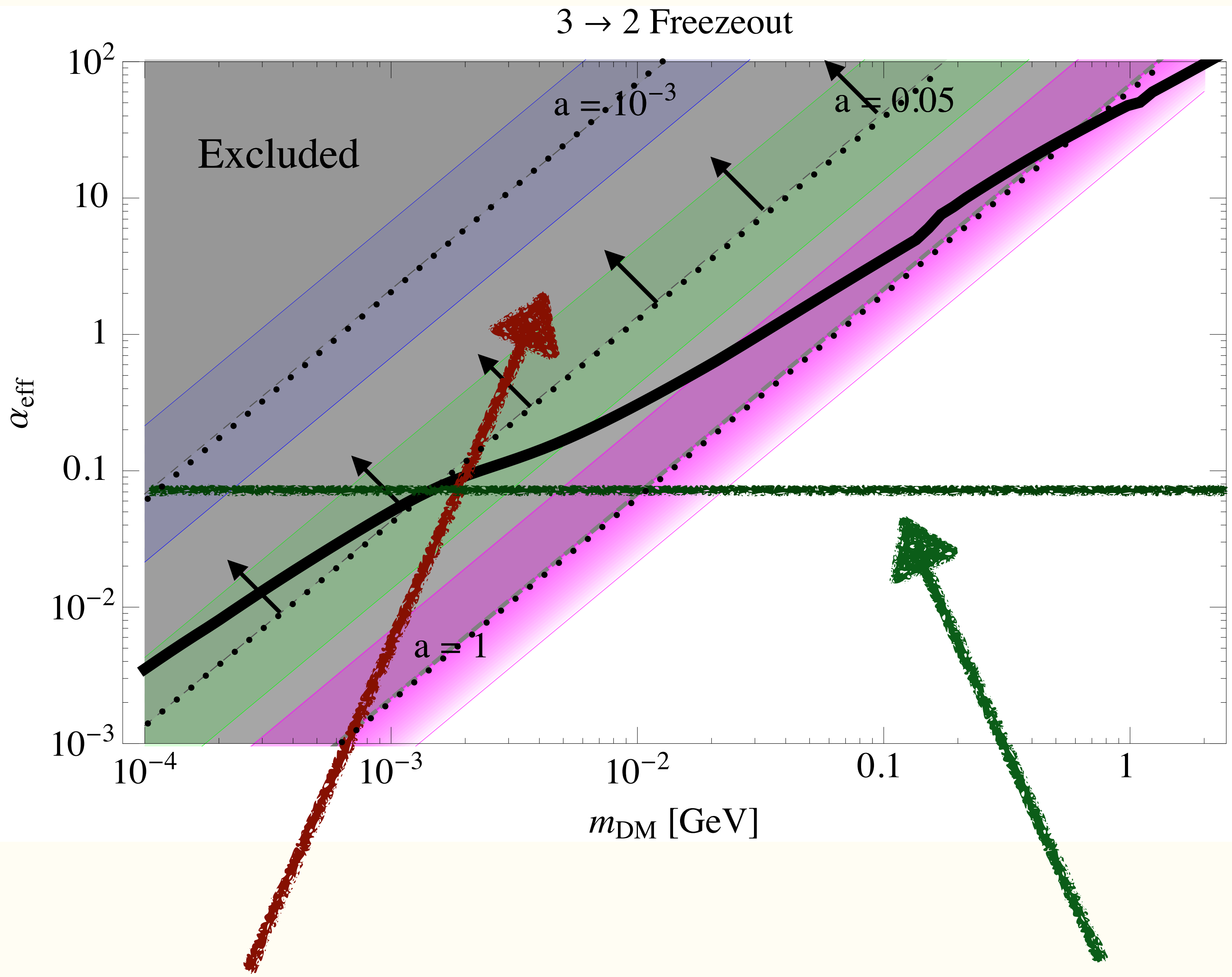
QCD scale emerges for a strongly-interacting sector.

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

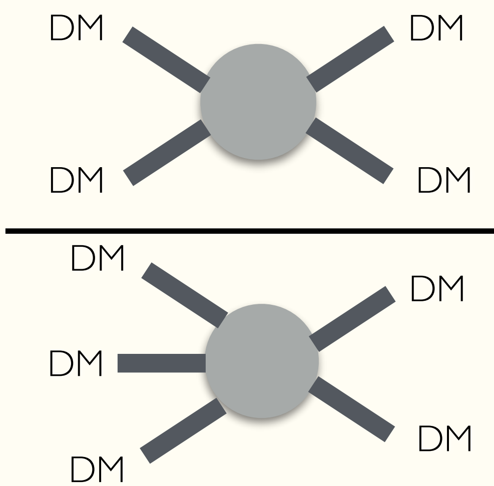


2-2 Good or Bad?

Weak scale emerges for a weak-strength interactions



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

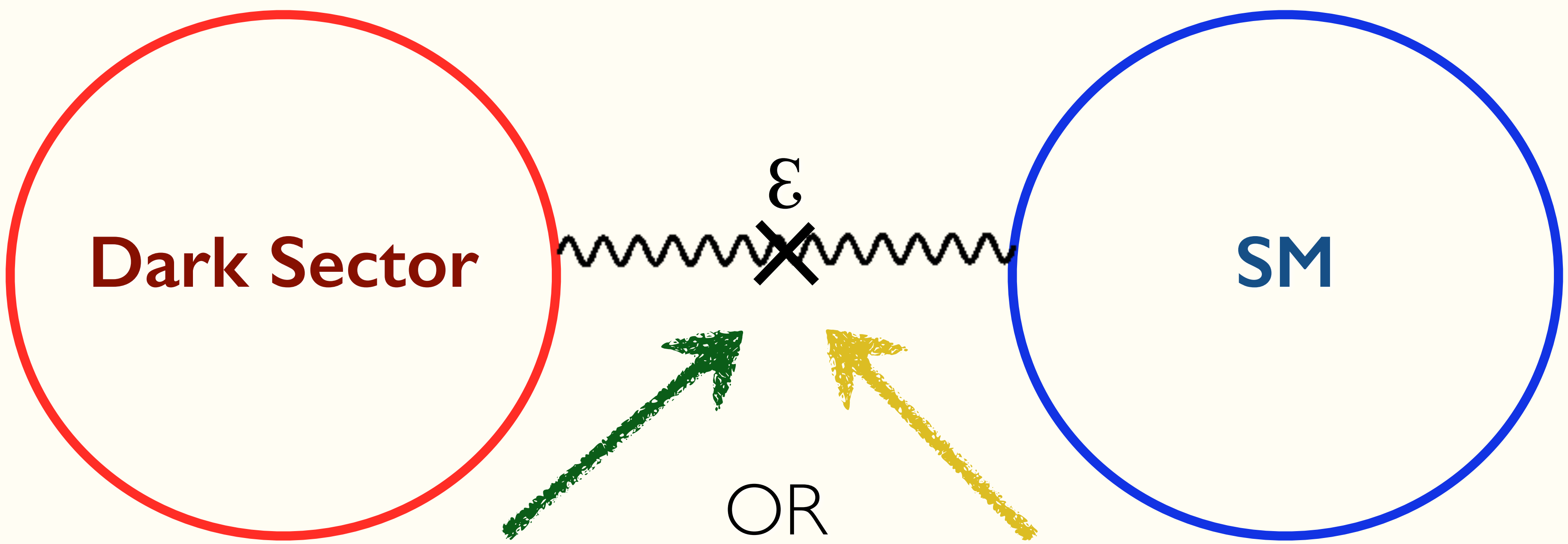


Excluded by Bullet-cluster and halo-shape constraints

Constraints push to strong regime → **SIMP**

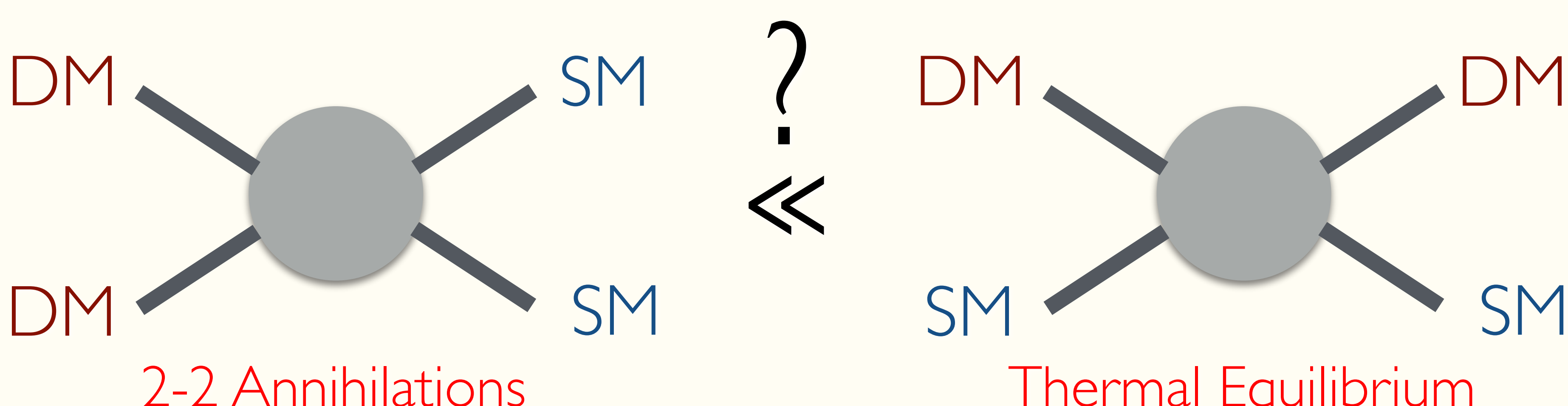
3-2 Freeze Out

- 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.



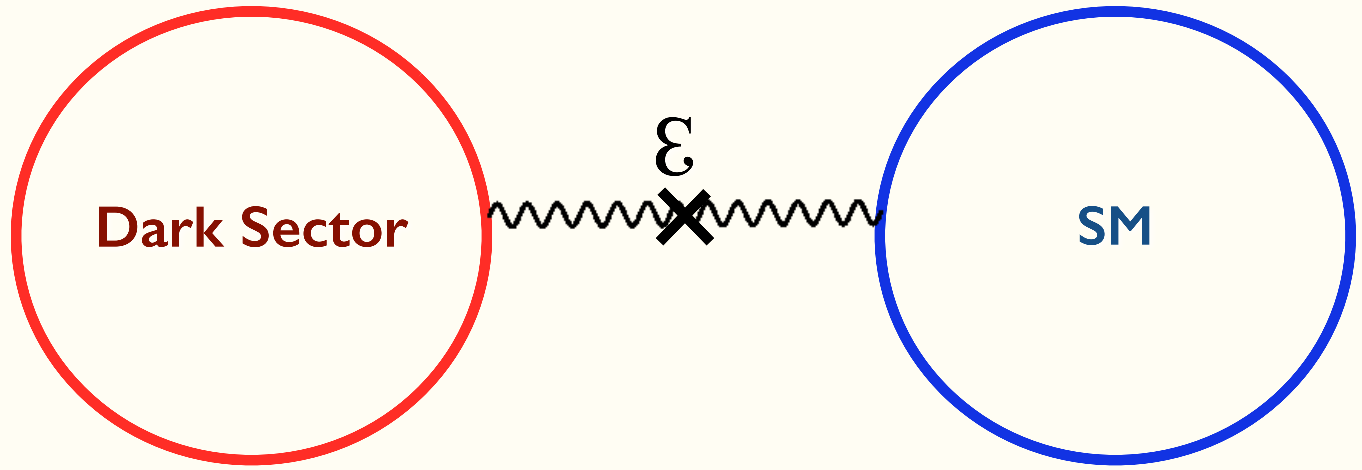
$$\frac{m_f}{\Lambda^2}\chi^\dagger\chi\bar{f}f \qquad \frac{\alpha_{\rm EM}}{4\pi\Lambda^2}\chi^\dagger\chi F_{\mu\nu}F^{\mu\nu}$$

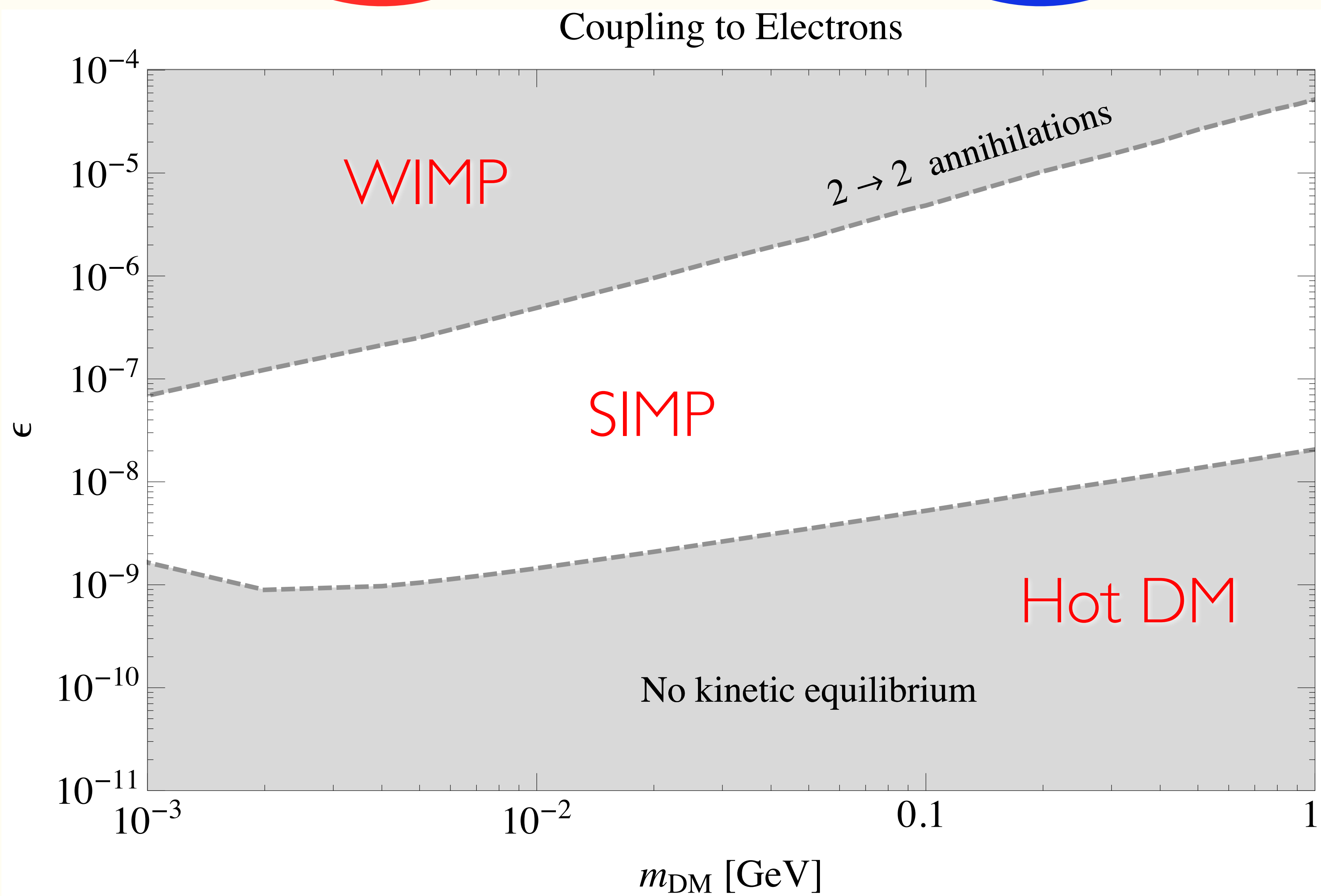
- Consequently, two more diagrams:



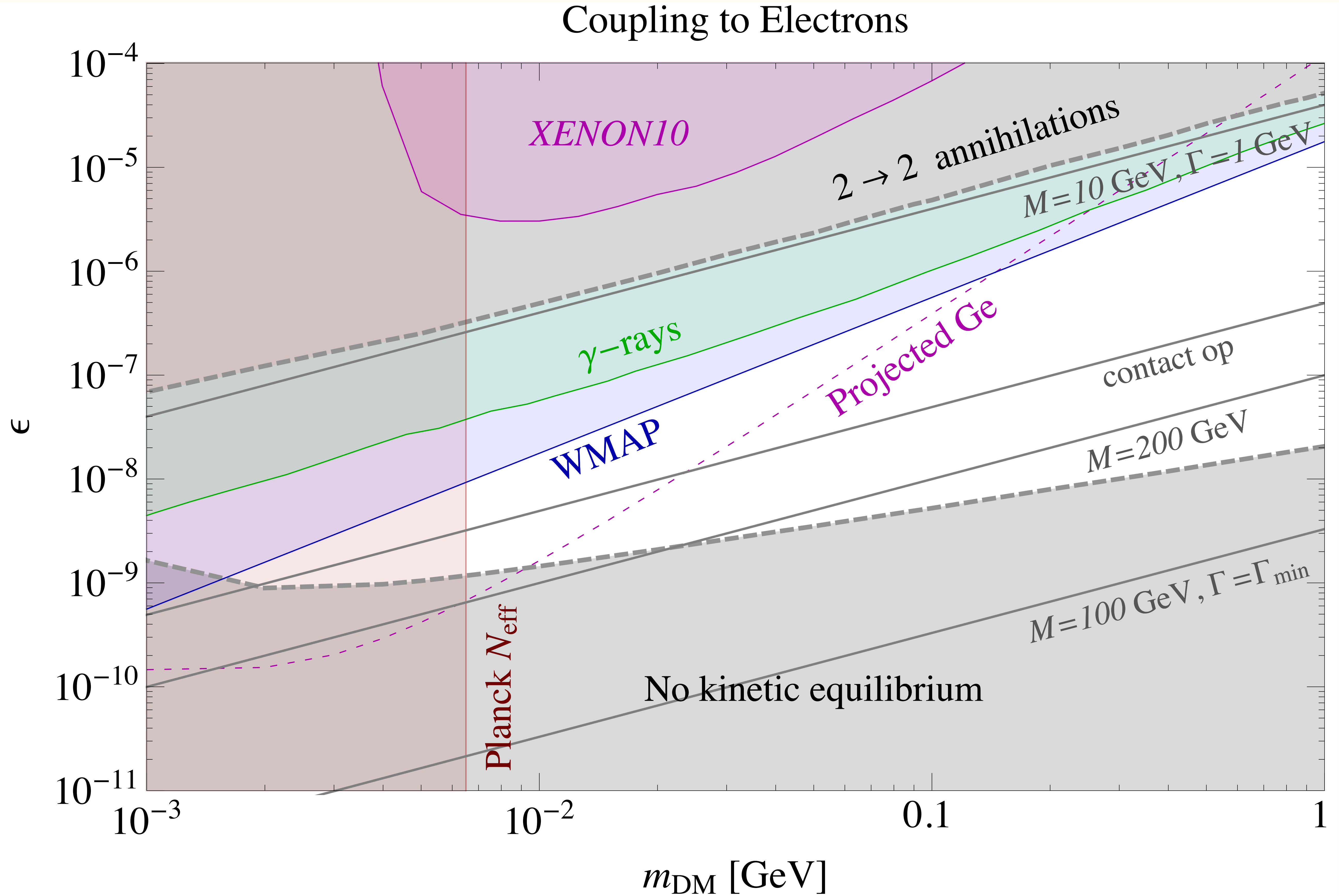
3-2 Freeze Out

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





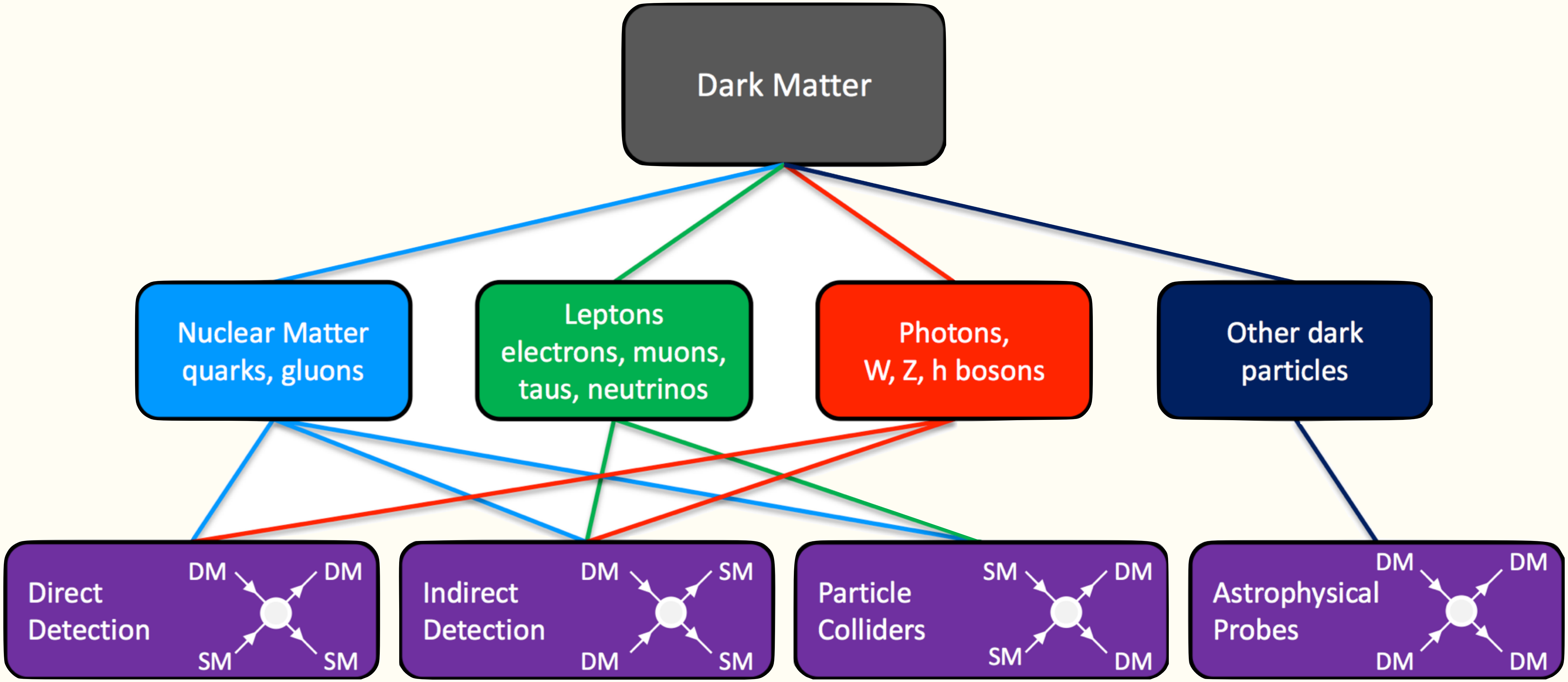
SIMP DM: Experimental Status



Searching for a Dark Sector

Searching for a Dark Sector

Searching for DM



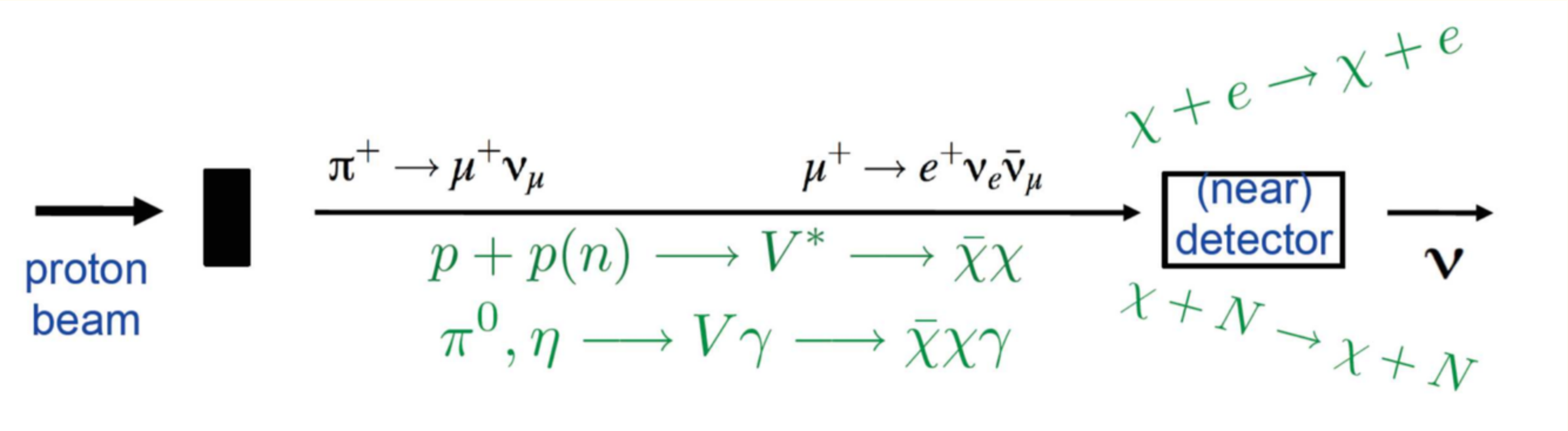
[Snowmass report, 2013]

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

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

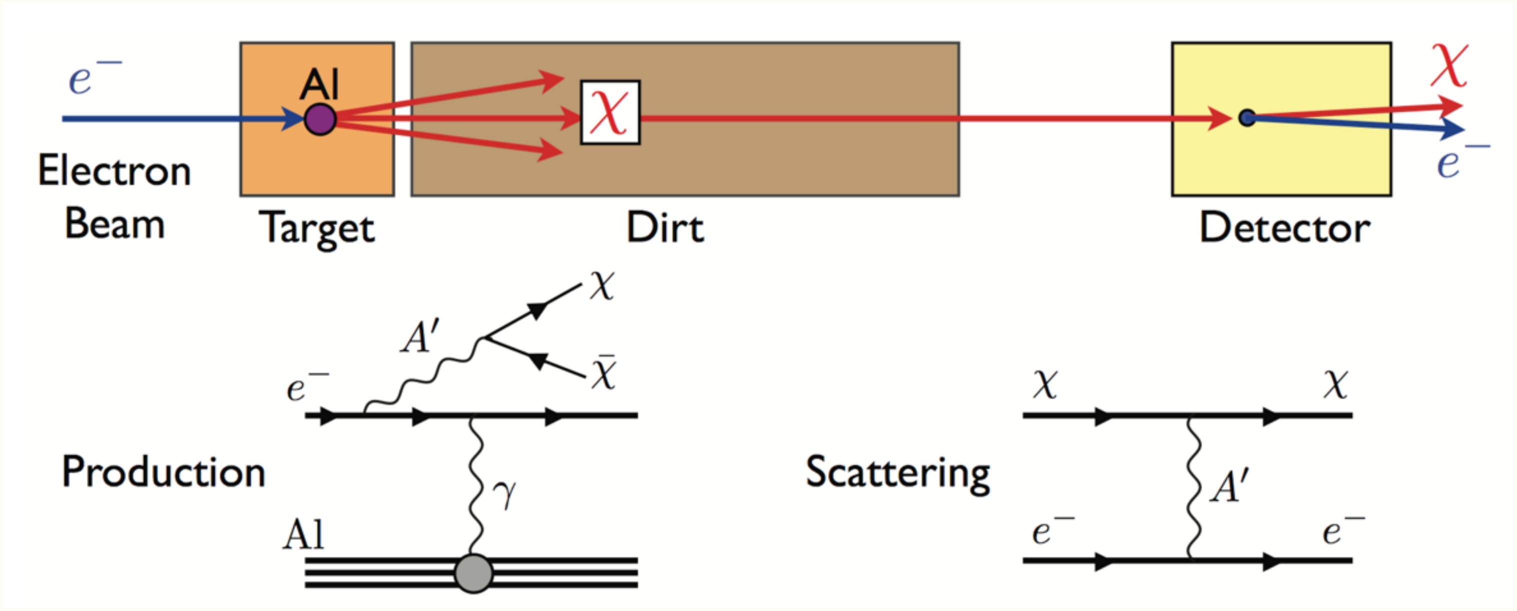
Beam-dump Experiments: A Dark Matter Beam

Neutrino Experiments



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

Electron Beam-dumps

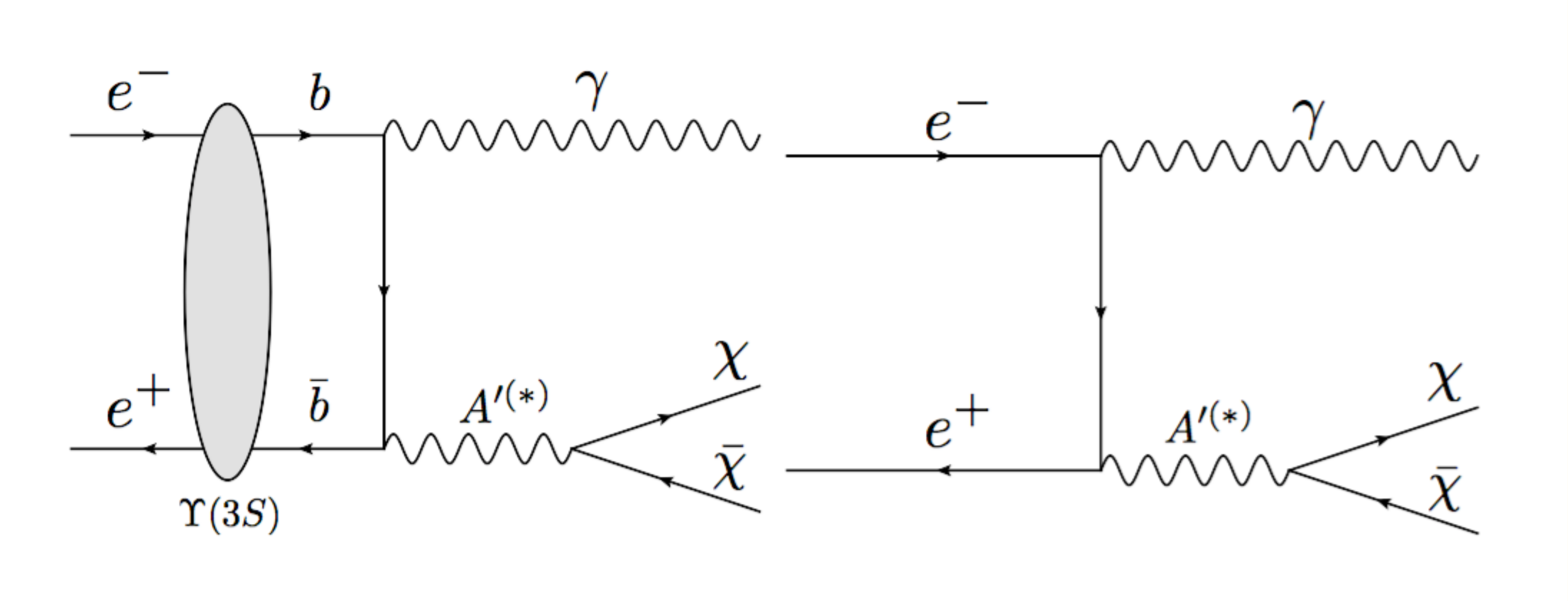


[Batell, Essig, Surujon 2014]

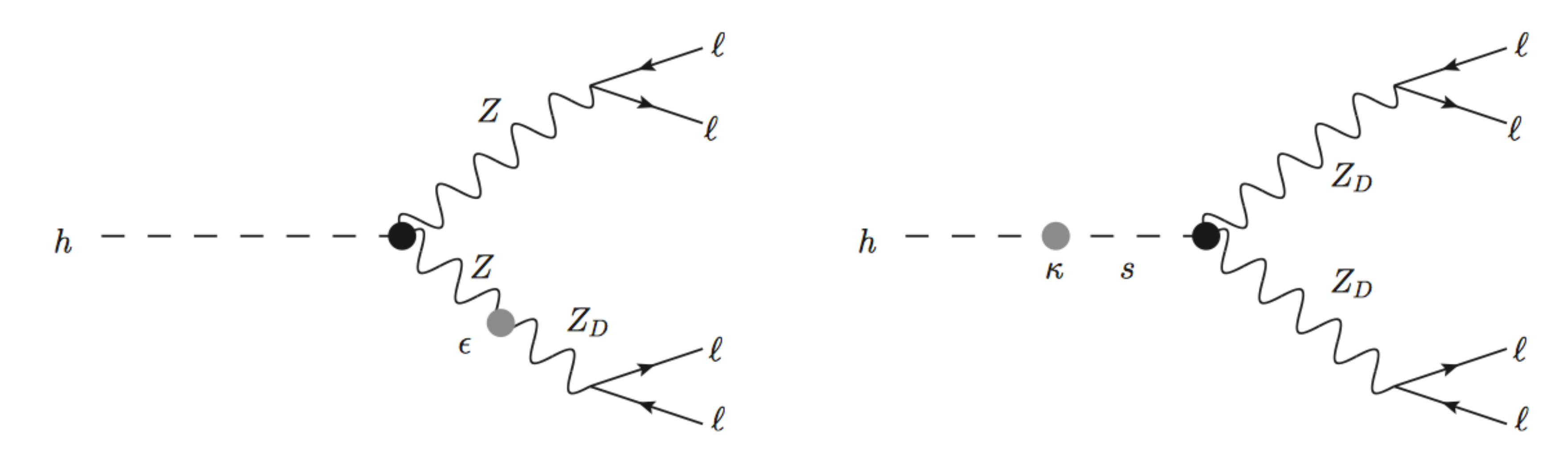
Colliders: Searching for the Mediator

[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

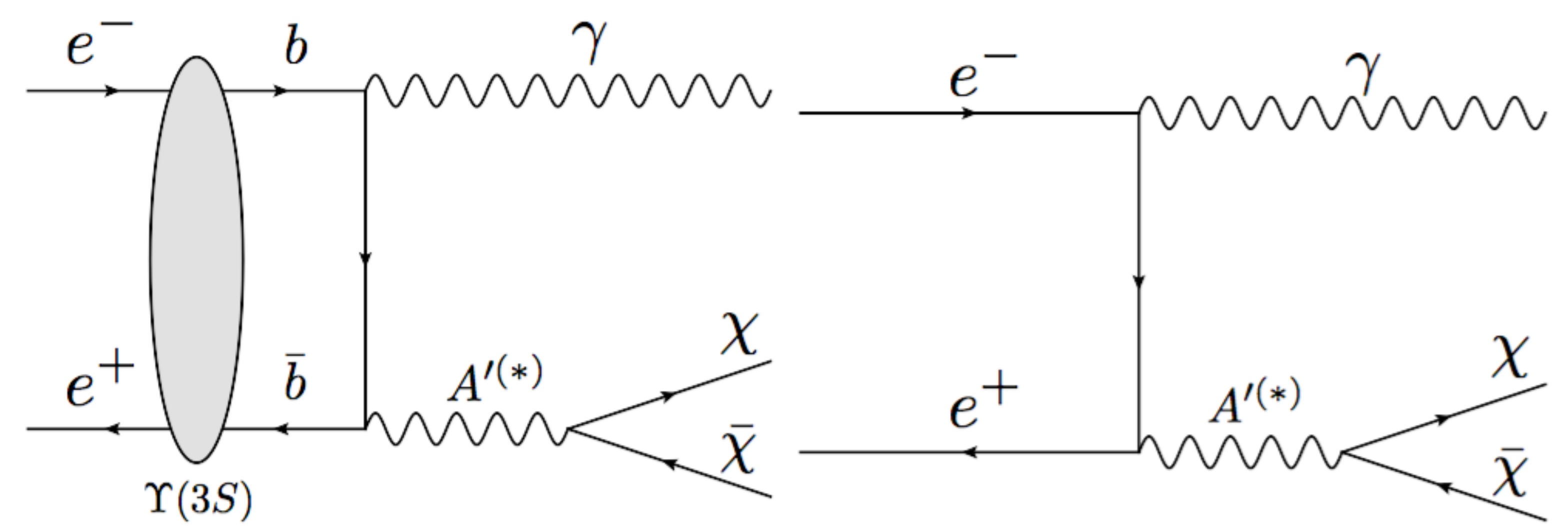


[Curtin, Essig, Gori, Shelton, 2014]

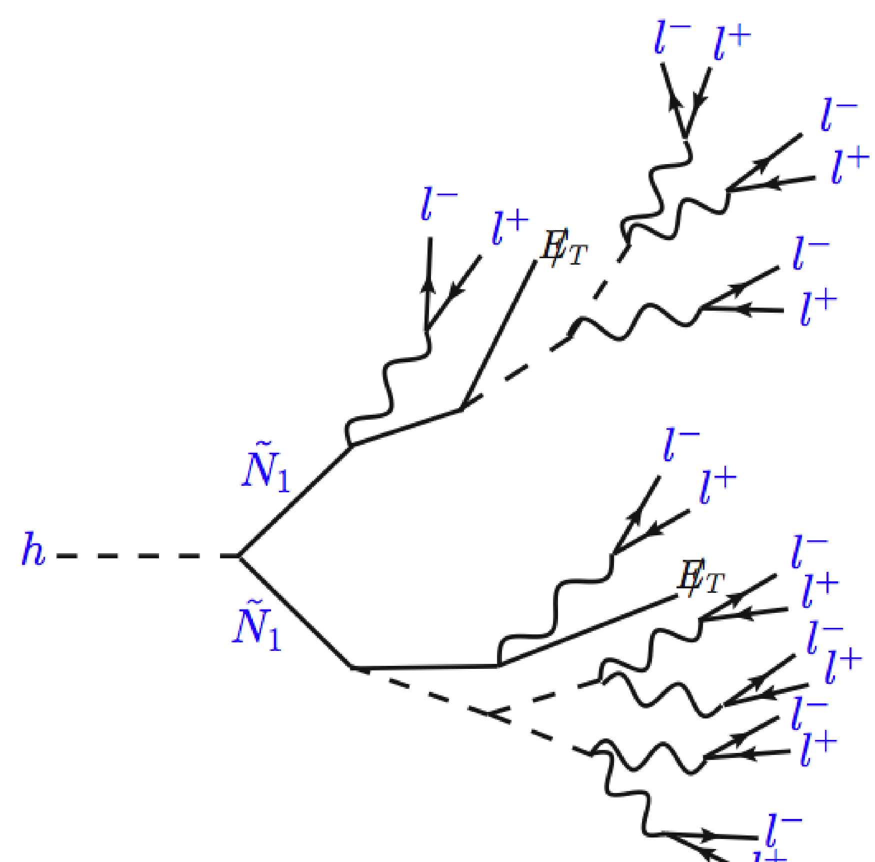
Colliders: Searching for the Mediator

[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

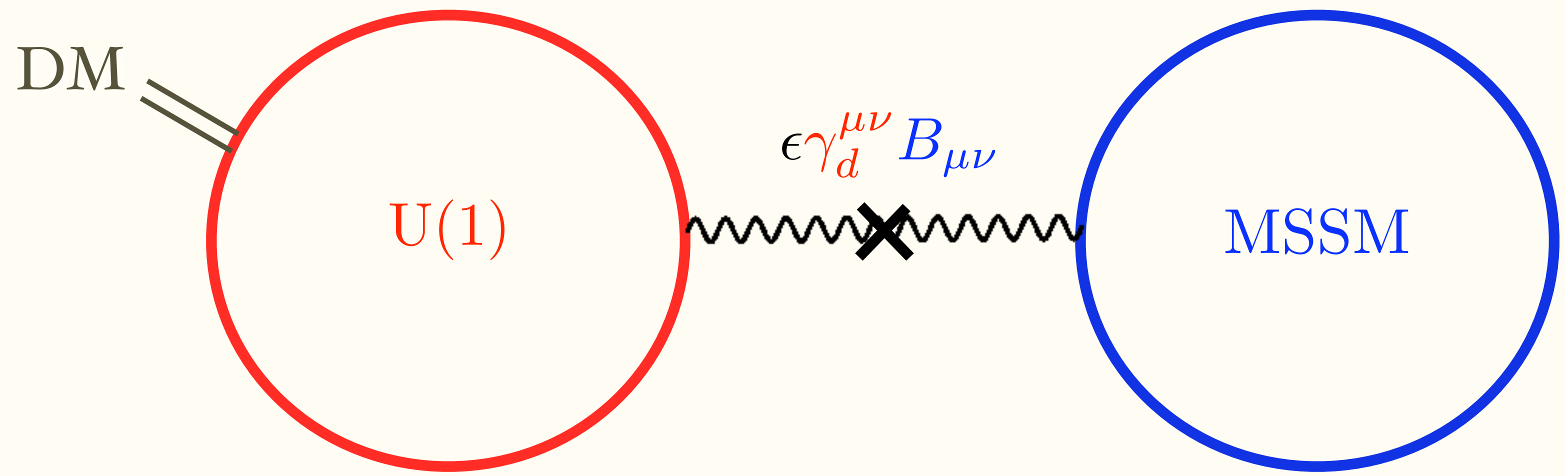


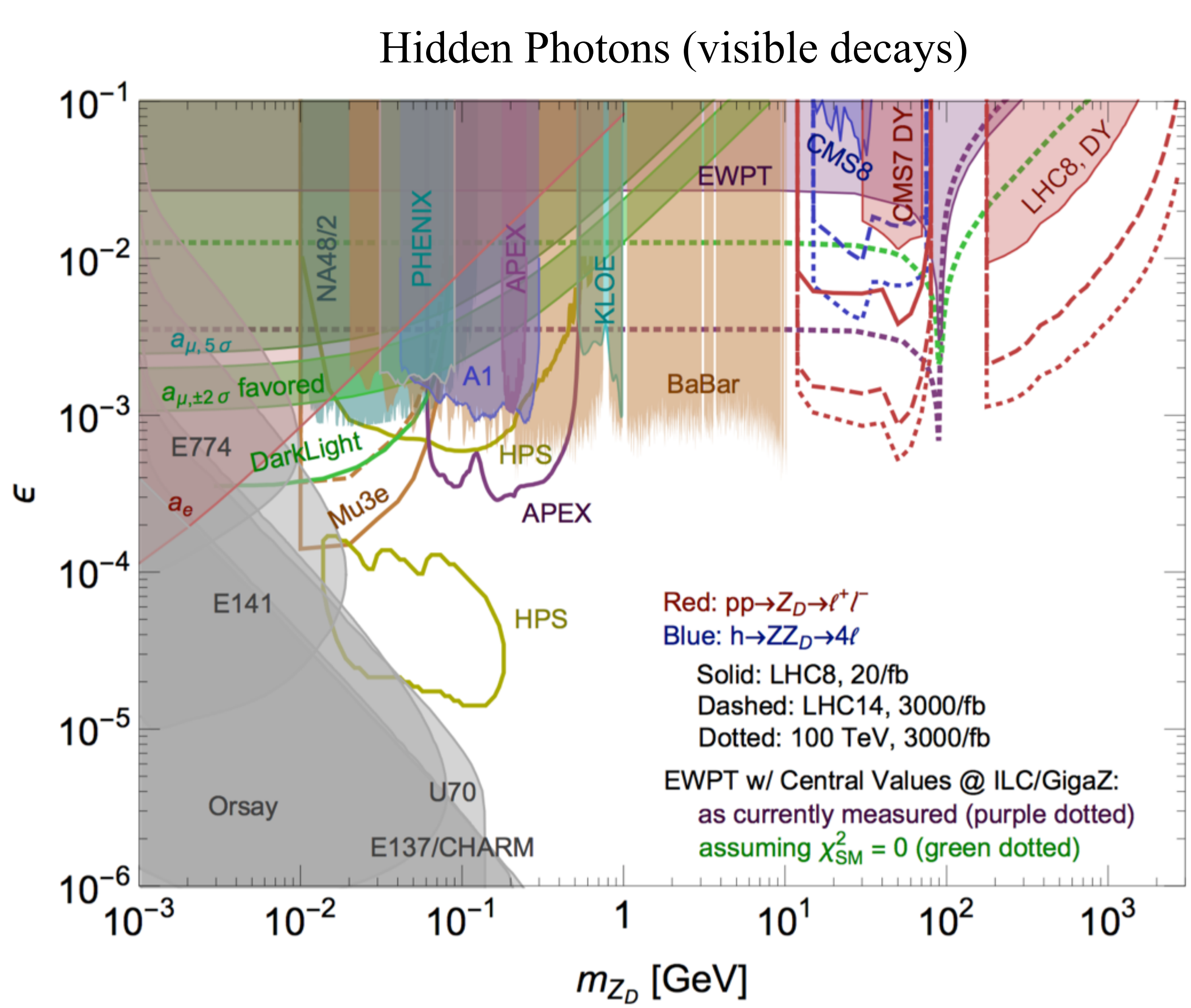
High-E Colliders



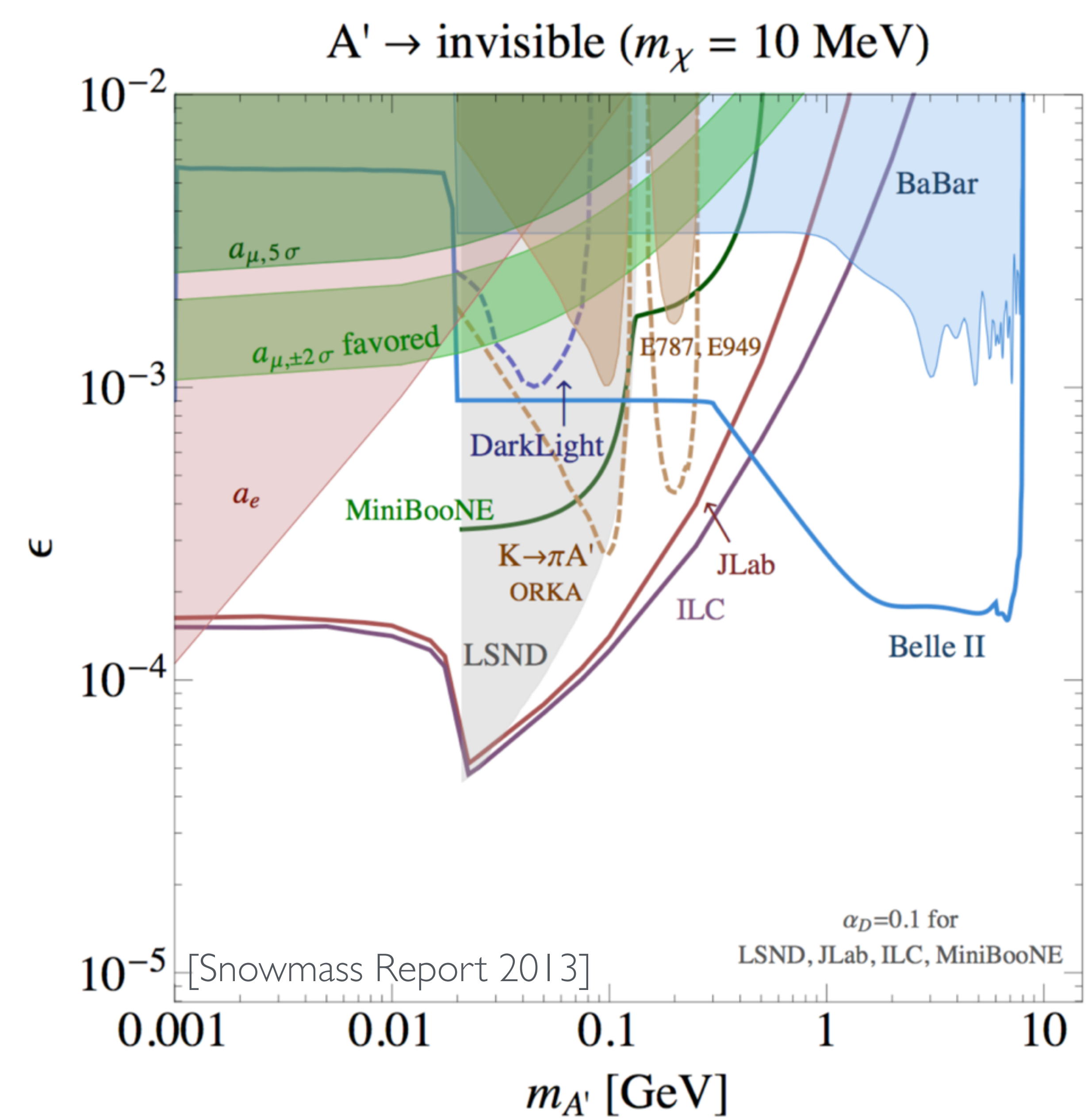
[Falkowski, Ruderman, TV, Zupan, 2010]

Collider and Beam-dumps: Selected Results





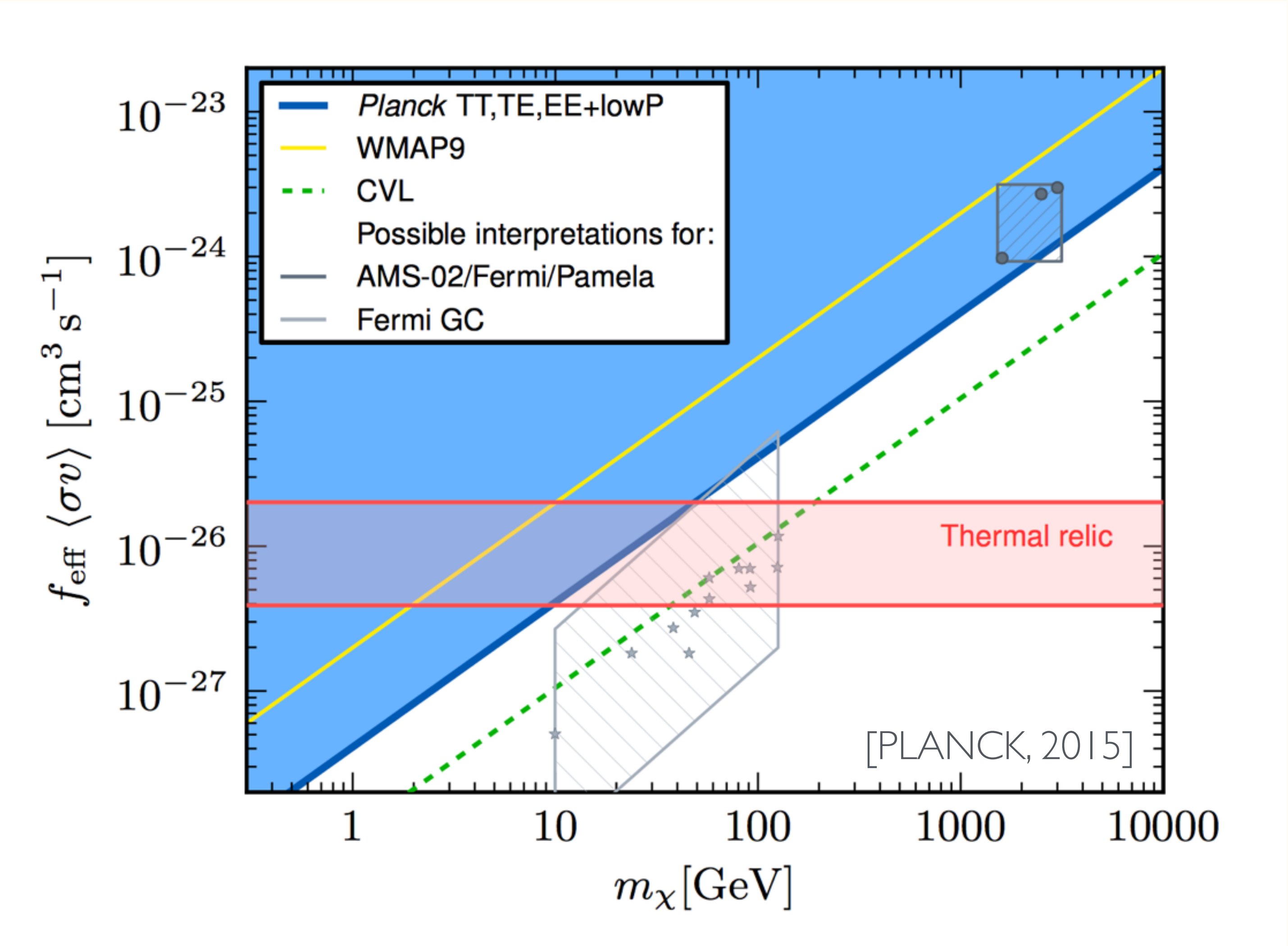
[Curtin, Essig, Gori, Shelton, 2014]



[Snowmass Report 2013]

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]



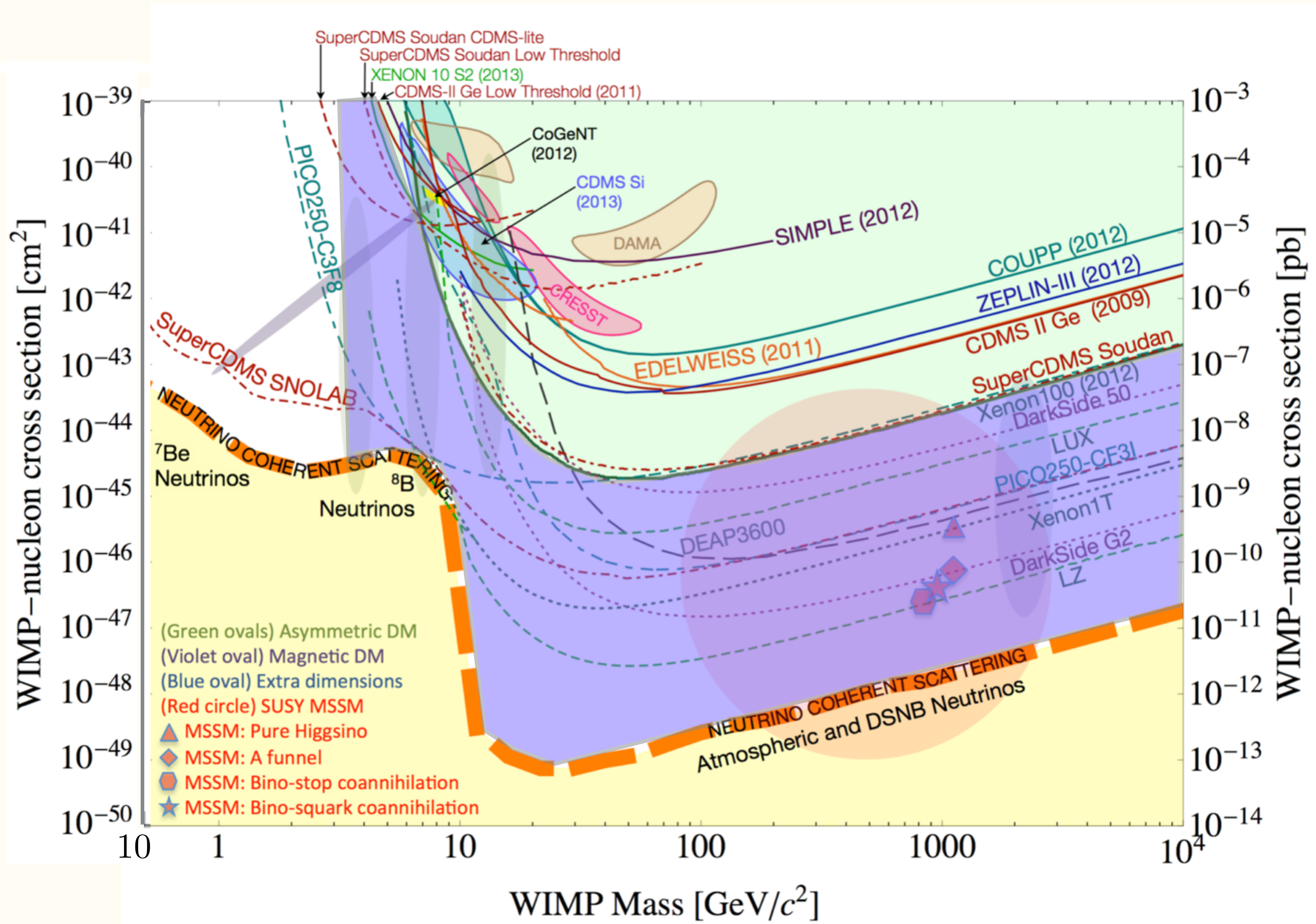
- Places strong constraints on annihilating light dark matter.

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

Prospects for Direct Detection

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

???

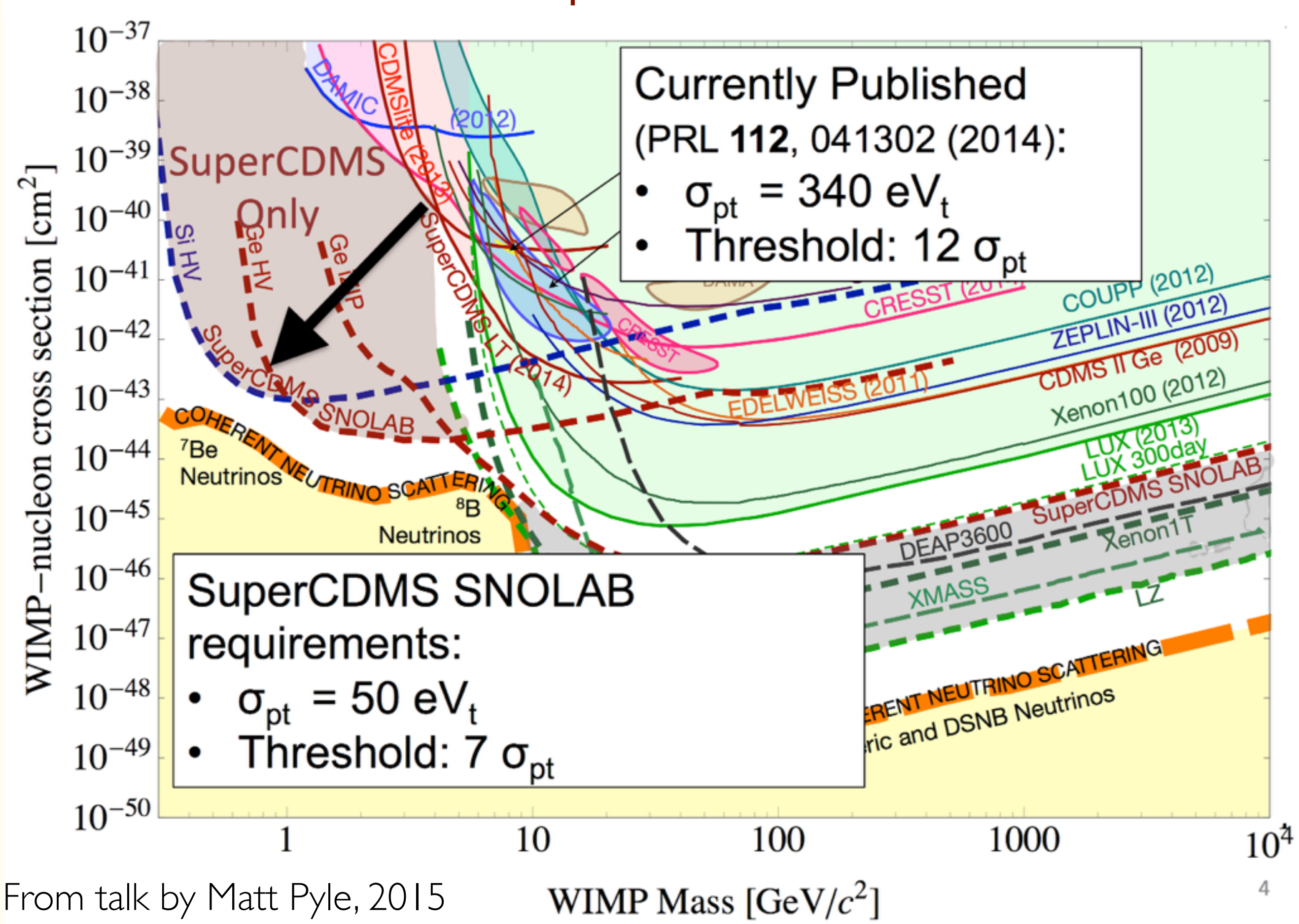


Direct Detection of Light and Exotic DM

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

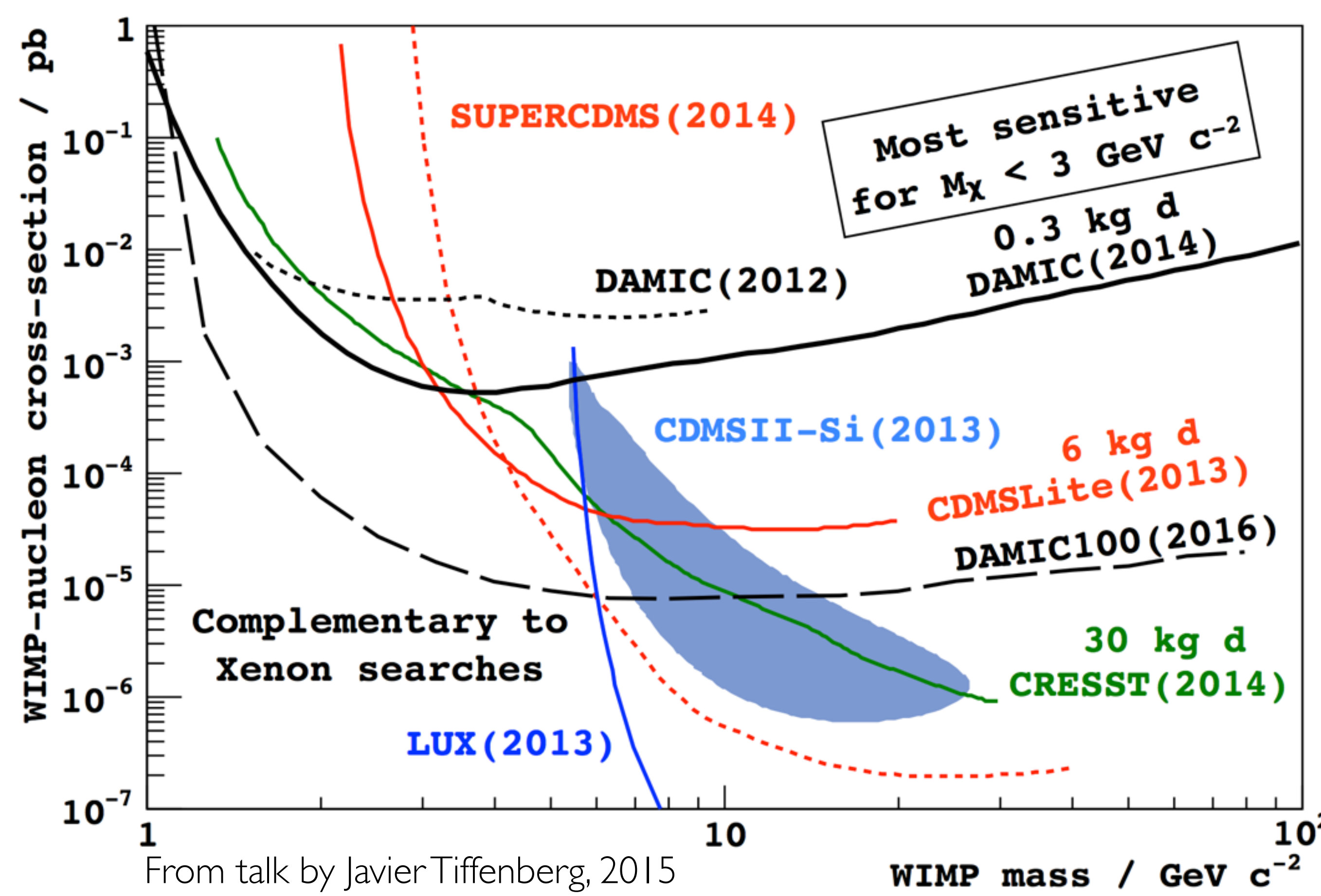
Threshold ≳ 10-50 eV

SuperCDMS



From talk by Matt Pyle, 2015

DAMIC



From talk by Javier Tiffenberg, 2015

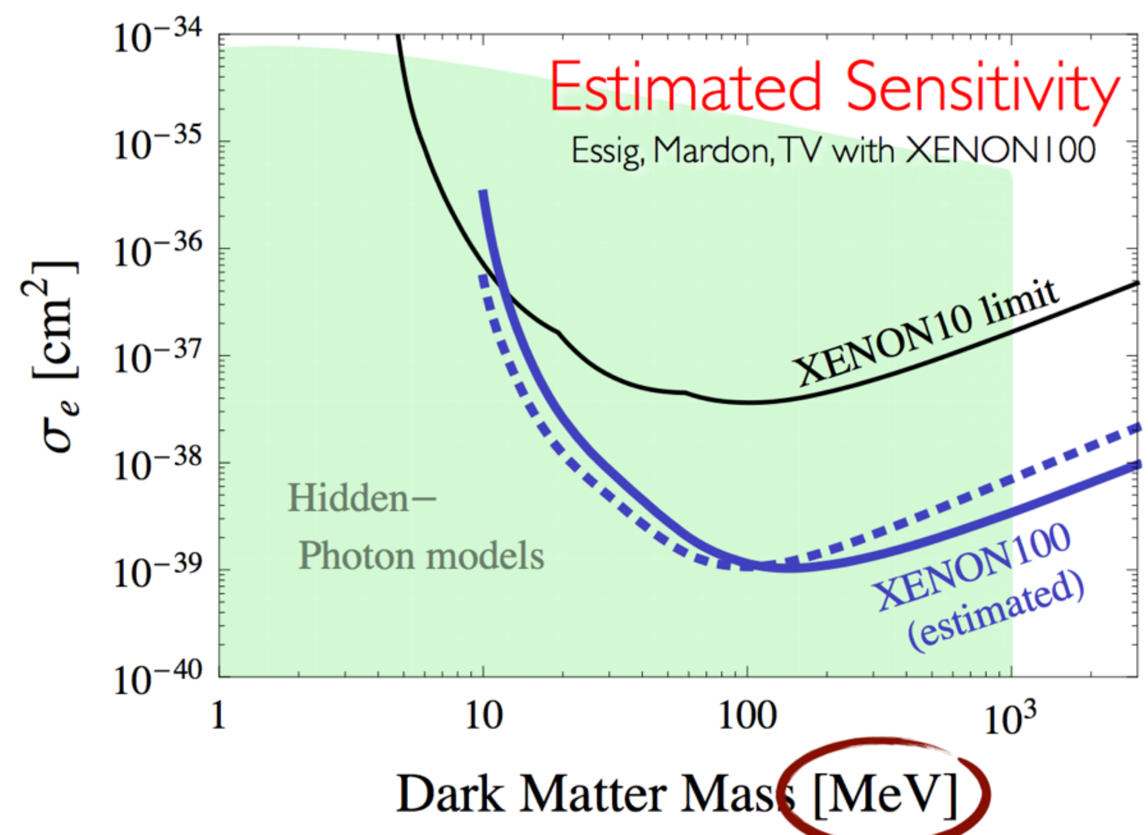
Direct Detection of Light and Exotic DM

- 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]

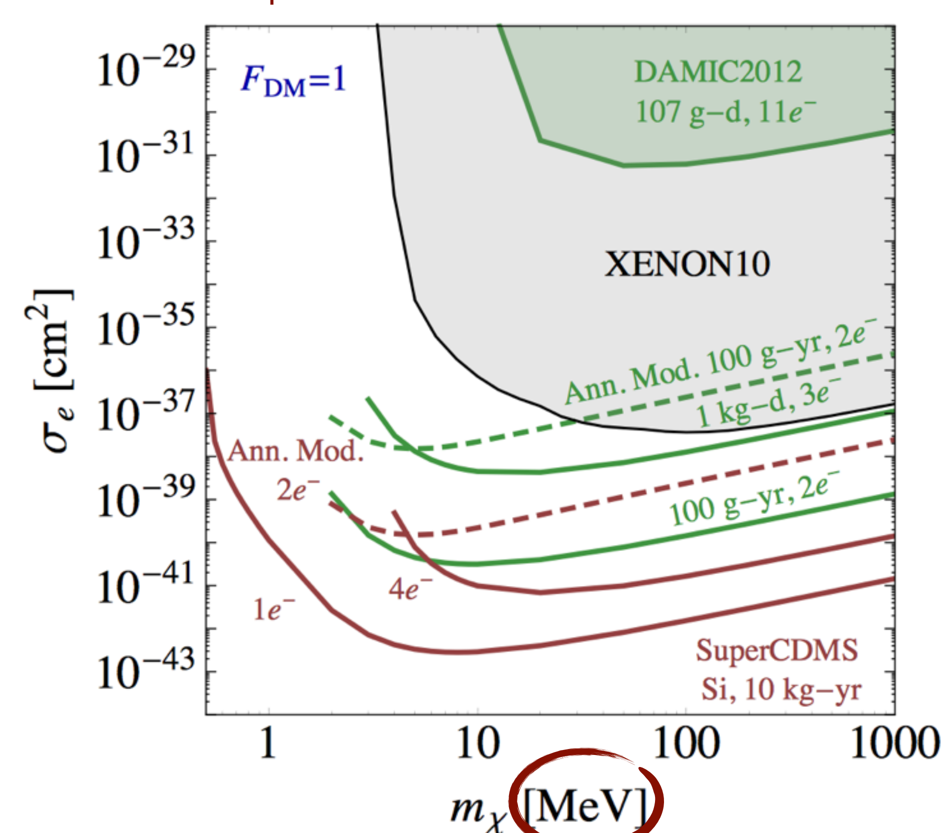
Threshold ≳ 0.1 eV

XENON



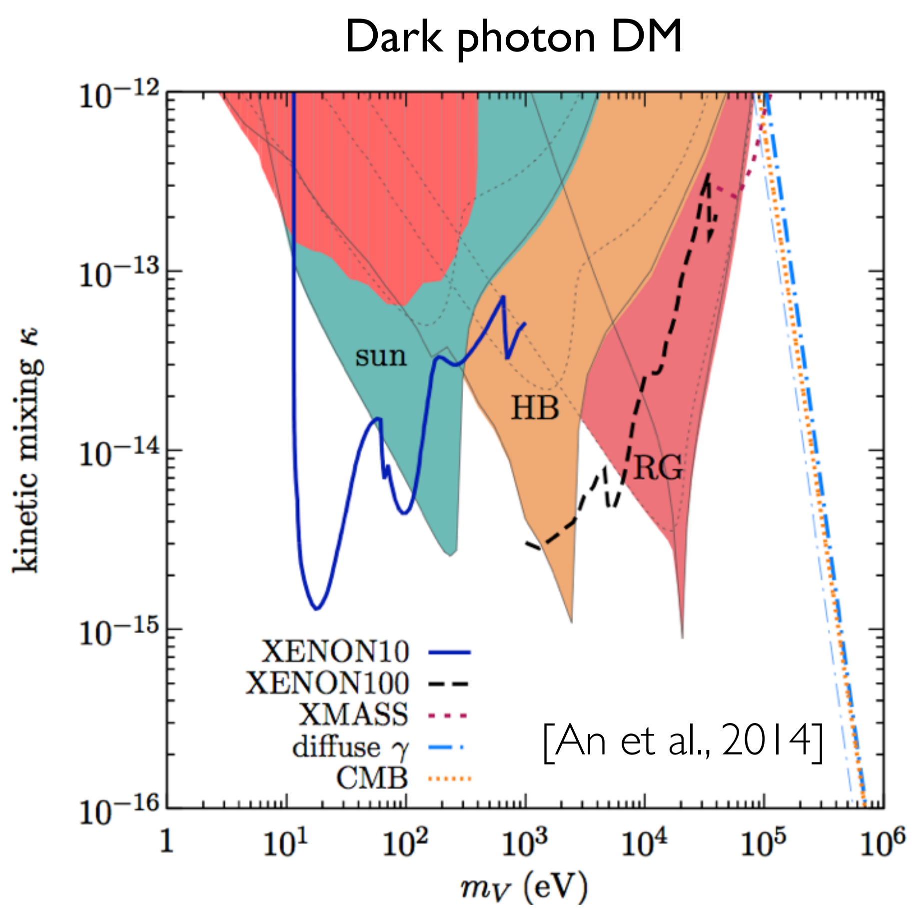
[Essig, Manalaysay, Mardon, Sorensen, TV, 2012; Essig, Mardon, TV, XENON100 (upcoming)]

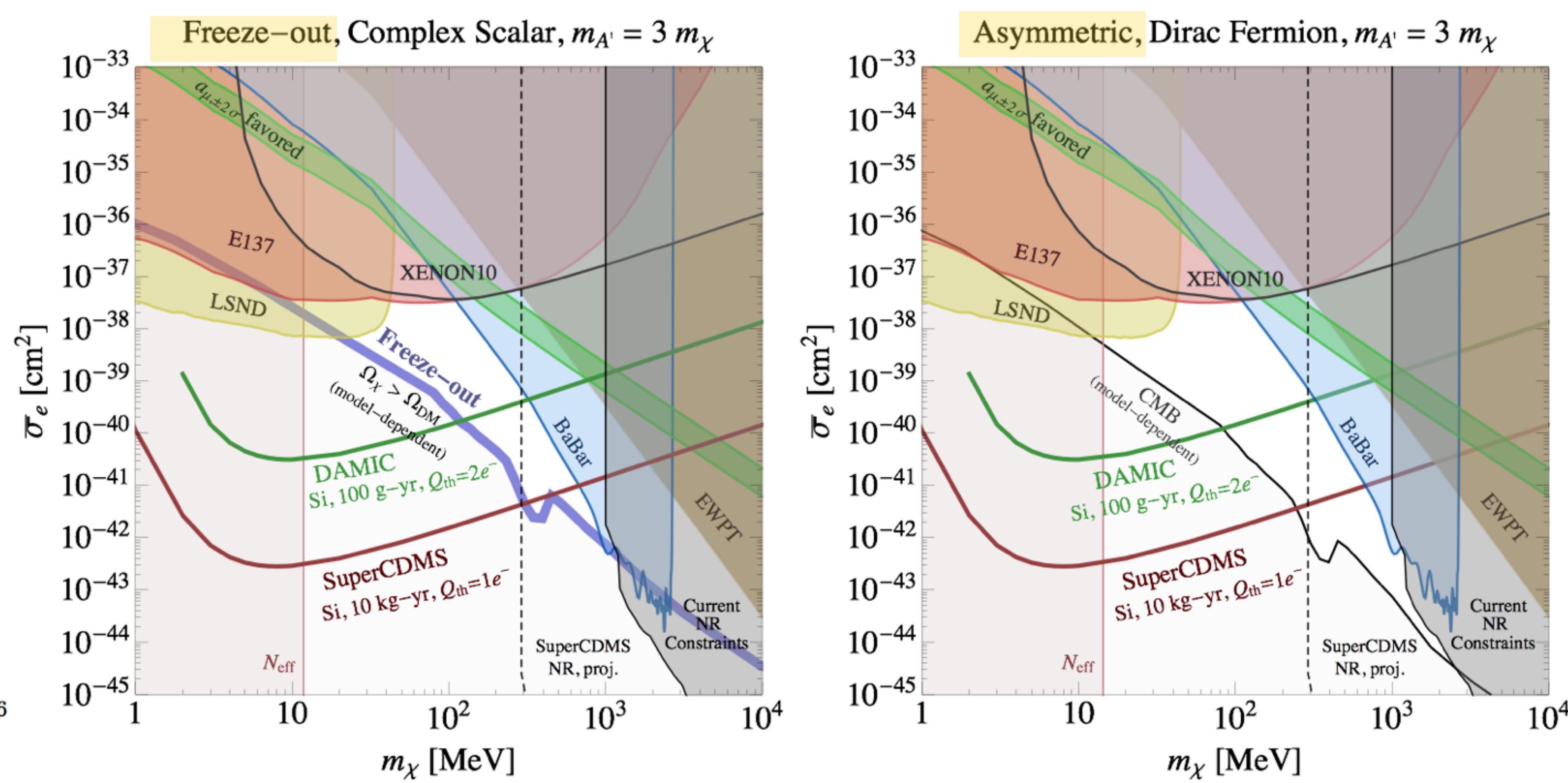
SuperCDMS and DAMIC



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

Direct Detection of Light and Exotic DM



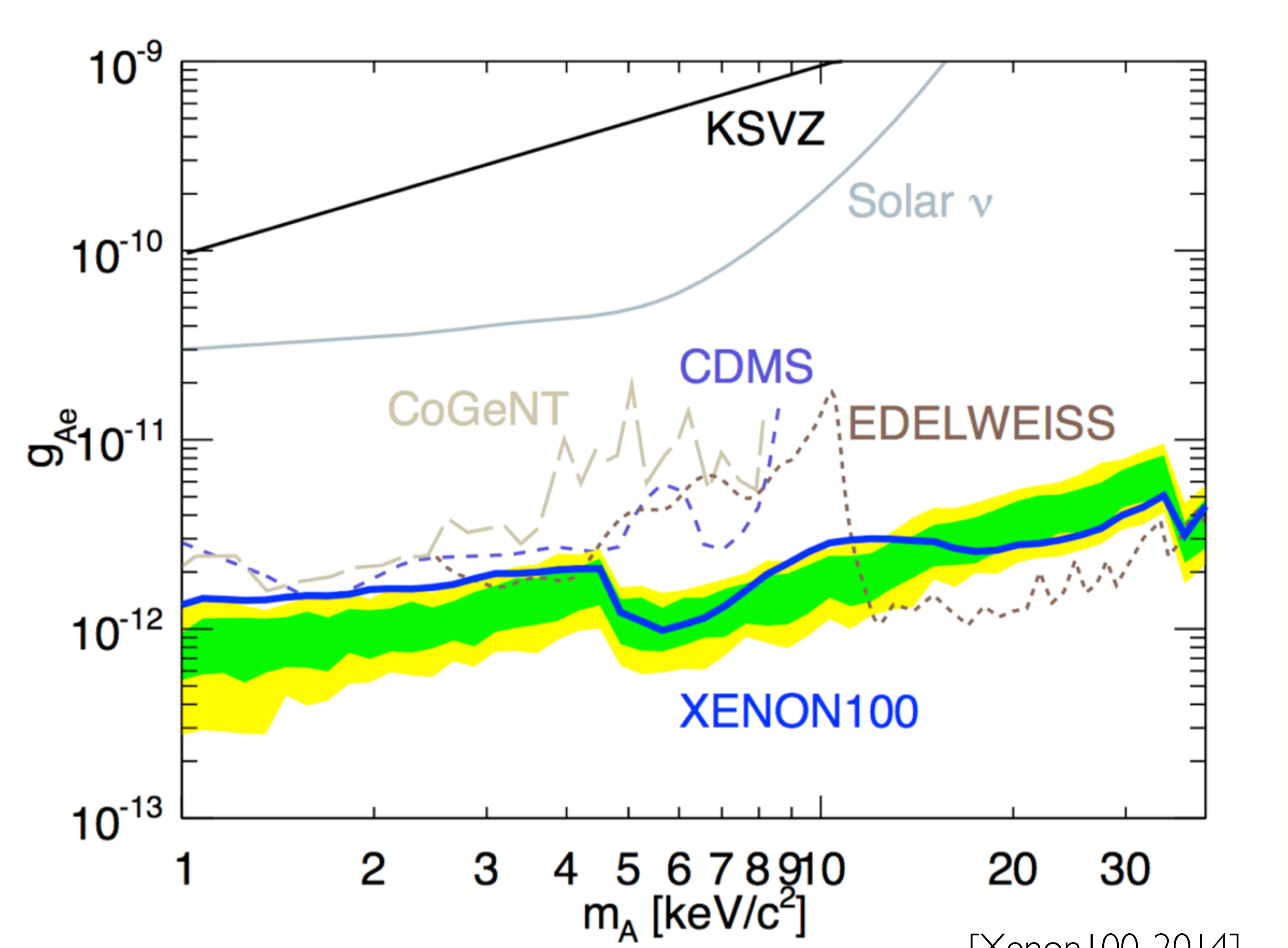


[Essig, Fernandez-Serra, Mardon, Soto, TV, Yu, 2015]

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]

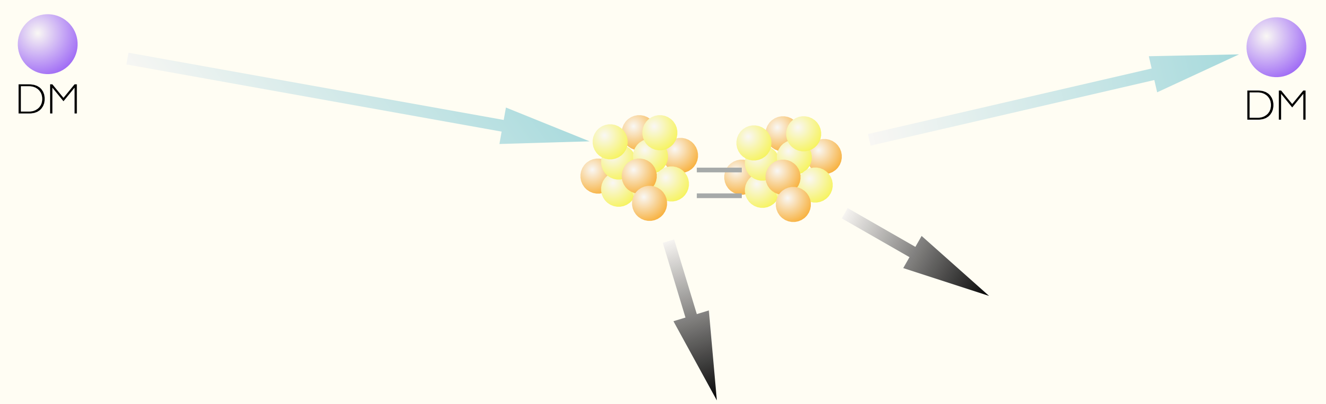
Direct Detection of Light and Exotic DM

- 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

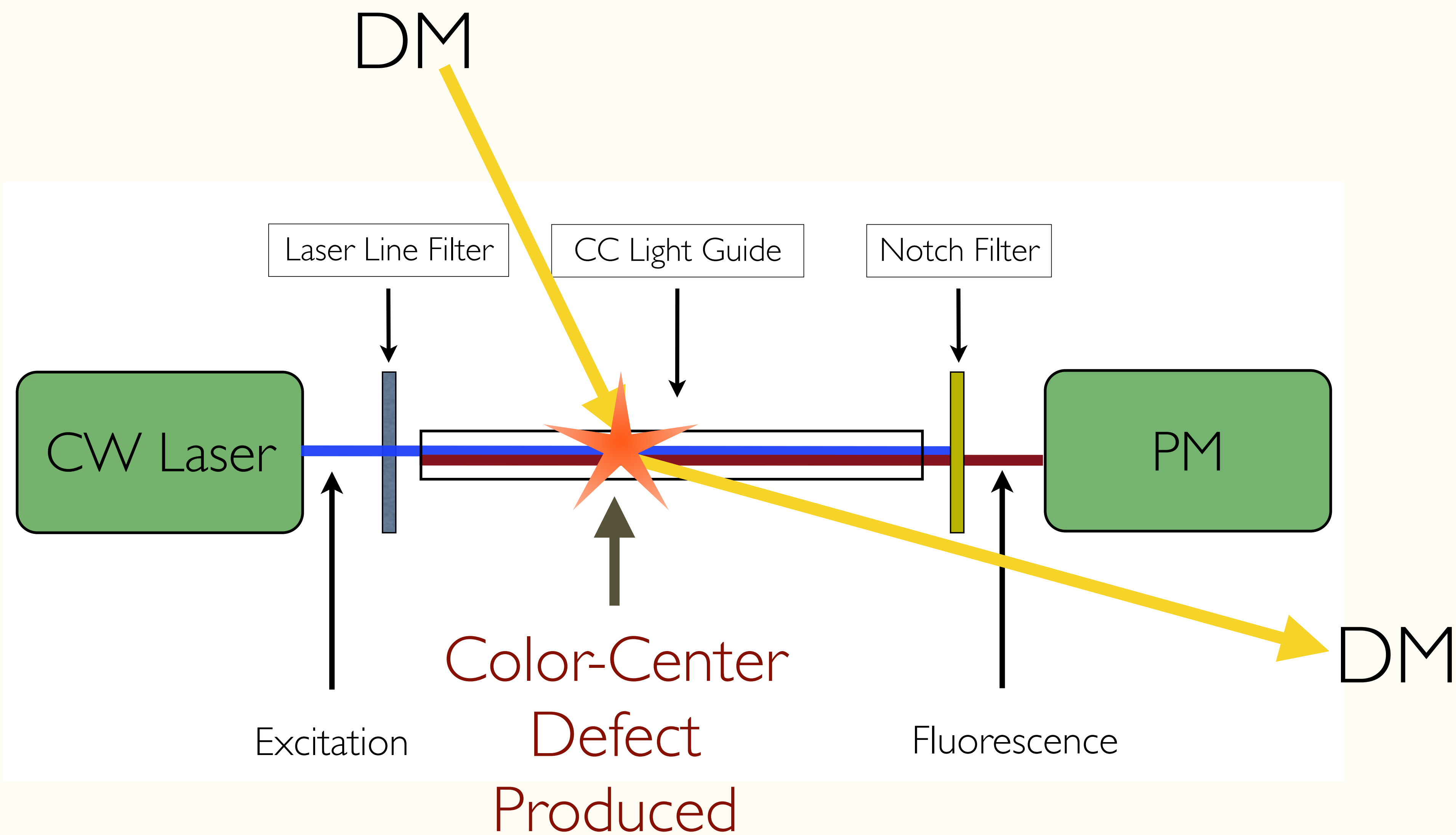
In crystals: search for color-center defects produced due to interaction with dark matter.

Direct Detection of Light and Exotic DM

- 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:

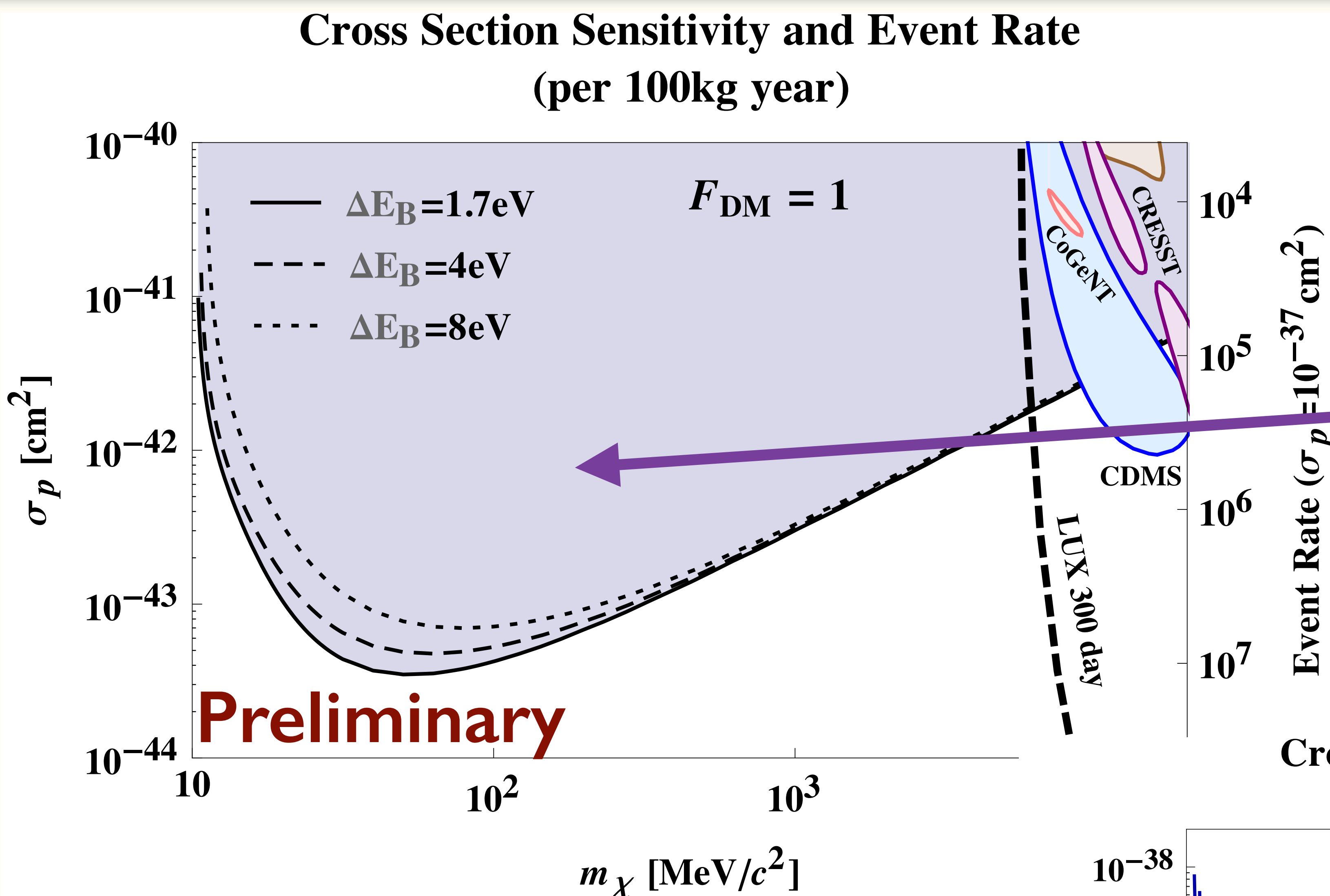


New theory-experimental collaboration. New lab opened.

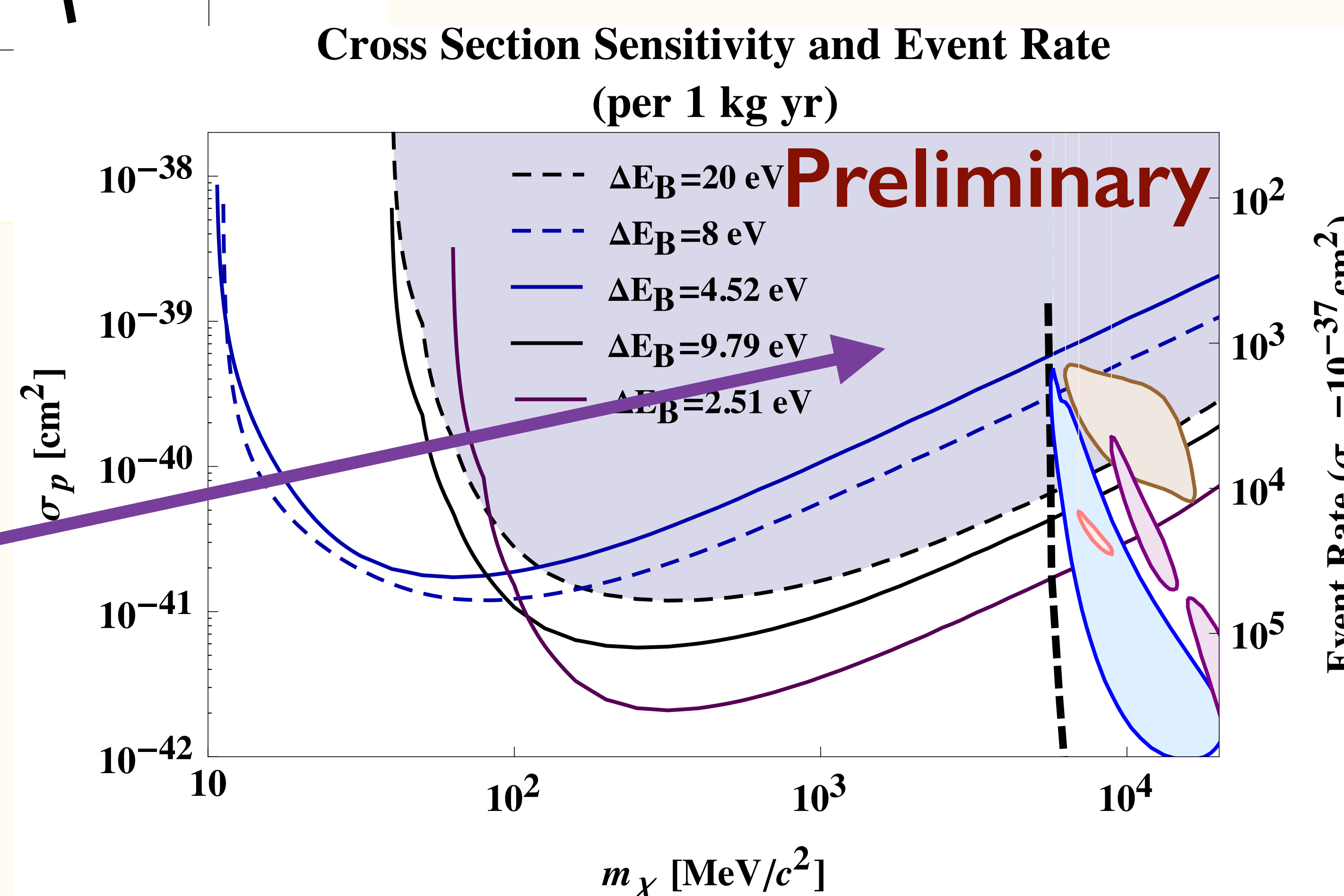
Abir, Bloch, Essig, Mardon, Slone, TV, Budnik, Chechnovsky, Kreisel, Soffer, Sagiv, Landsman, Ashkenazi, Priel

Direct Detection of Light and Exotic DM

[Essig, Mardon, Slone, TV, in writing]



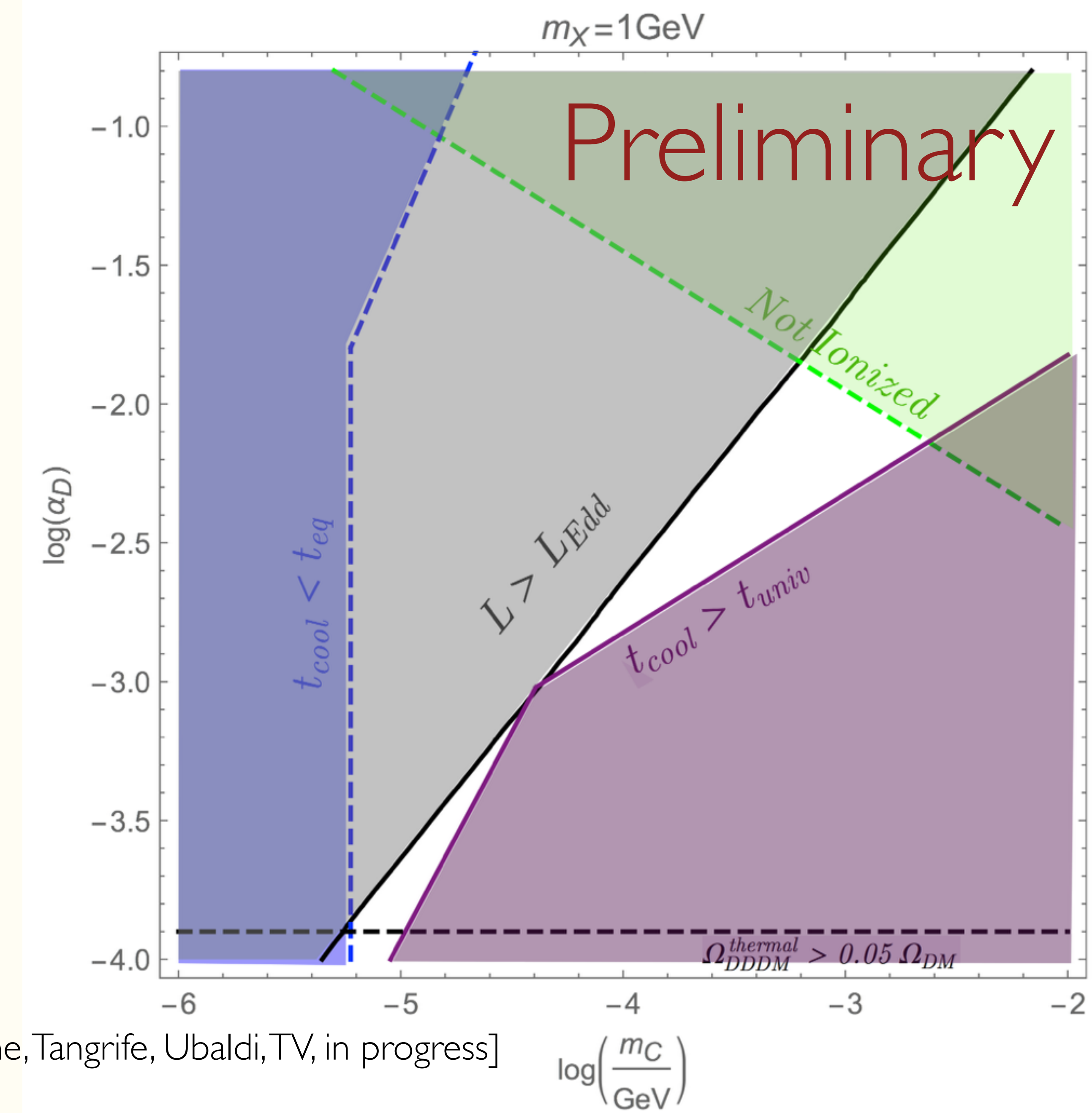
Exclusion region from molecules



Exclusion region from Color-center

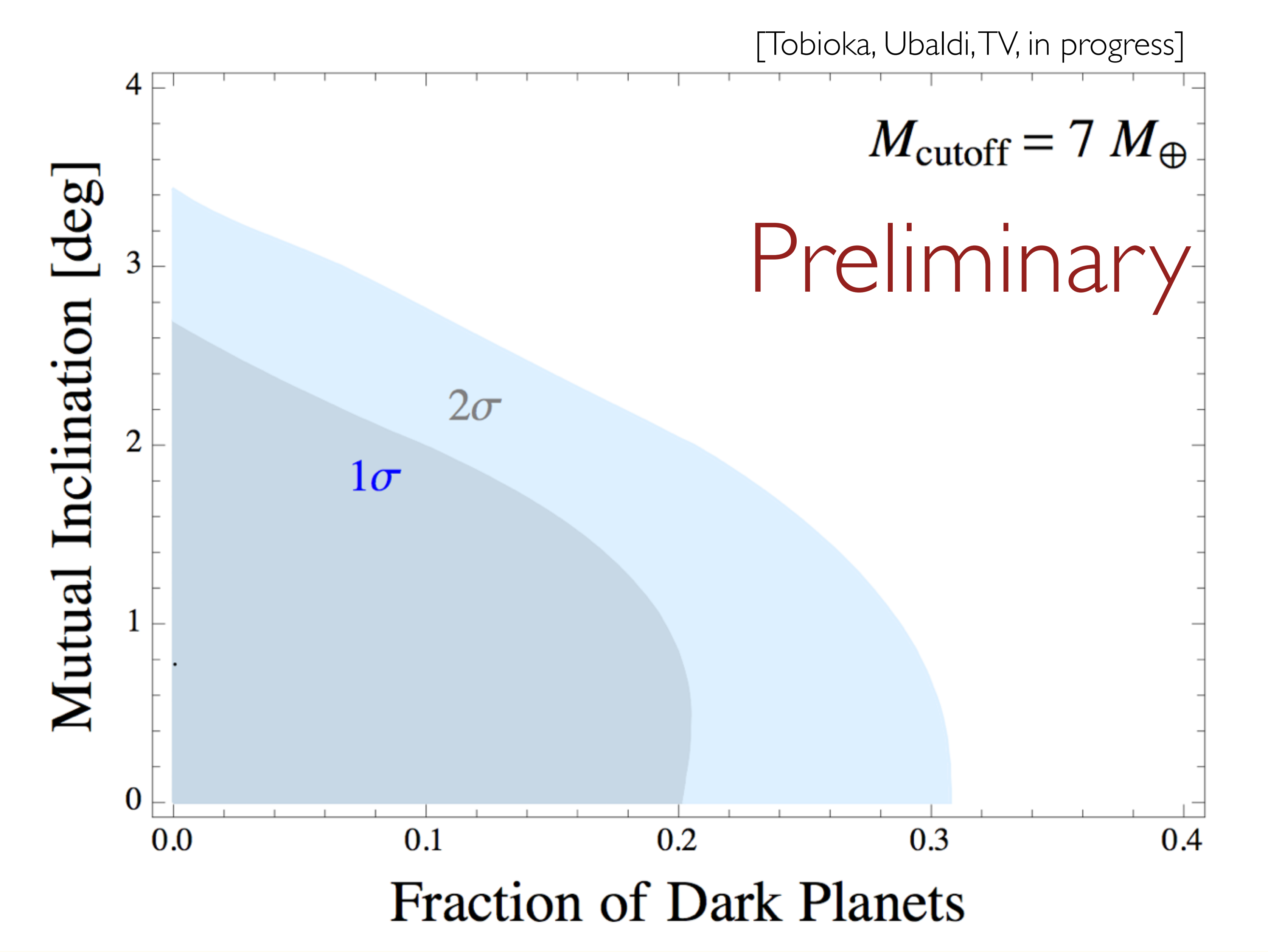
Active Galactic Nuclei (AGN)

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...

Hope for indirect detection of Sub-GeV DM?

YES

Velocity dependent annihilations

- DM may have velocity suppressed annihilations: $\langle \sigma v \rangle \simeq \sigma_0 v^{2(n-1)}$
- DM velocity depends on when it kinetically decoupled from thermal bath:

$$T_{\rm DM} = T_{\rm kd} \left(\frac{z}{z_{\rm kd}} \right)^2$$

- So DM velocity at CMB is:

$$v_{\rm DM} = \sqrt{3T_{\rm DM}/m_{\rm DM}} = \sqrt{3} x_\gamma \, x_{\rm kd}^{-1/2}$$
$$\simeq 2 \times 10^{-4} \left(\frac{T_\gamma}{1 \text{ eV}} \right) \left(\frac{1 \text{ MeV}}{m_{\rm DM}} \right) \left(\frac{10^{-4}}{x_{\rm kd}} \right)^{1/2}, \quad x_i \equiv \frac{T_i}{m_{\rm DM}}$$

vs. today: $v_{\rm DM,0} \simeq 10^{-3}$

Hope for indirect detection of Sub-GeV DM?

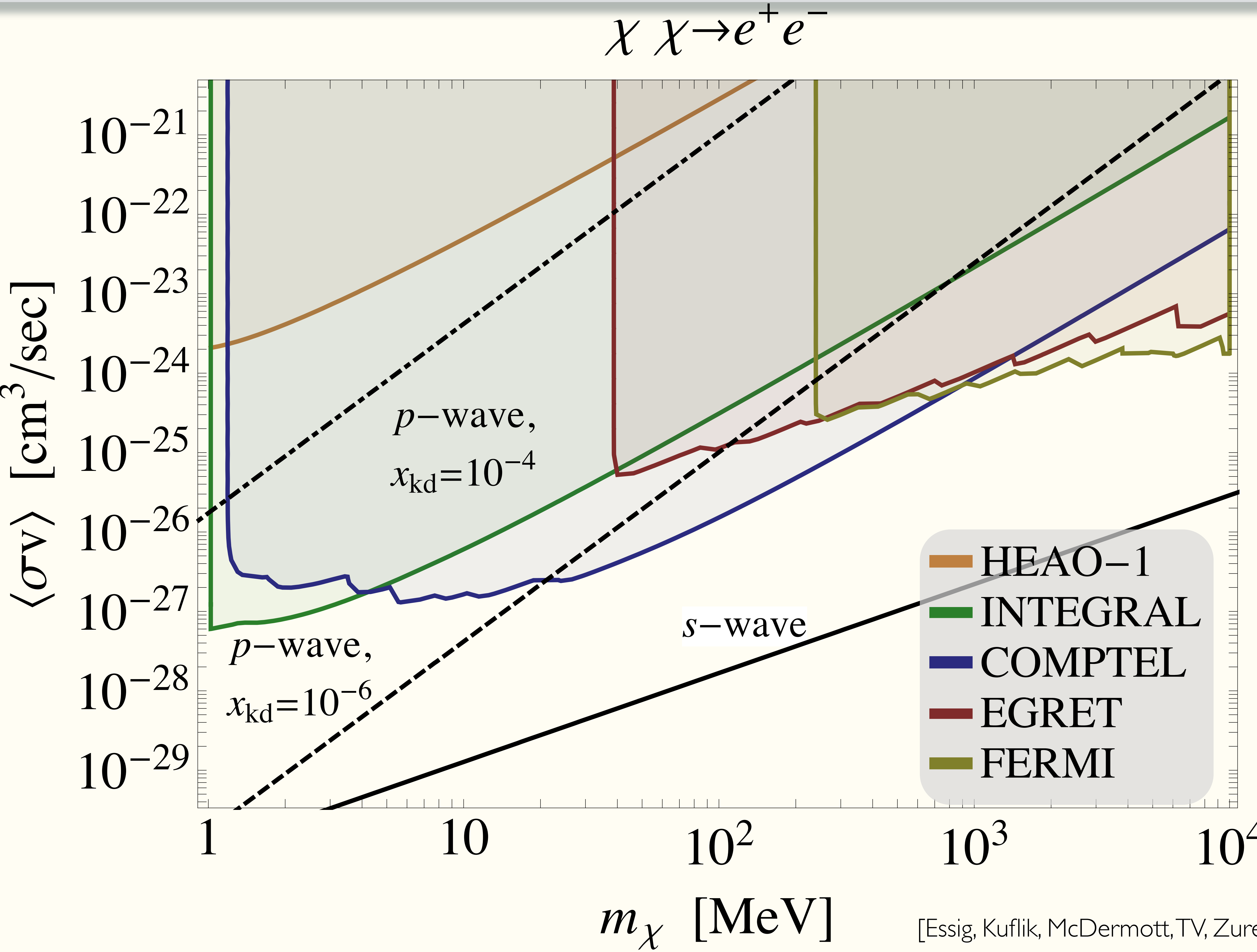
YES

Velocity dependent annihilations

Decaying DM

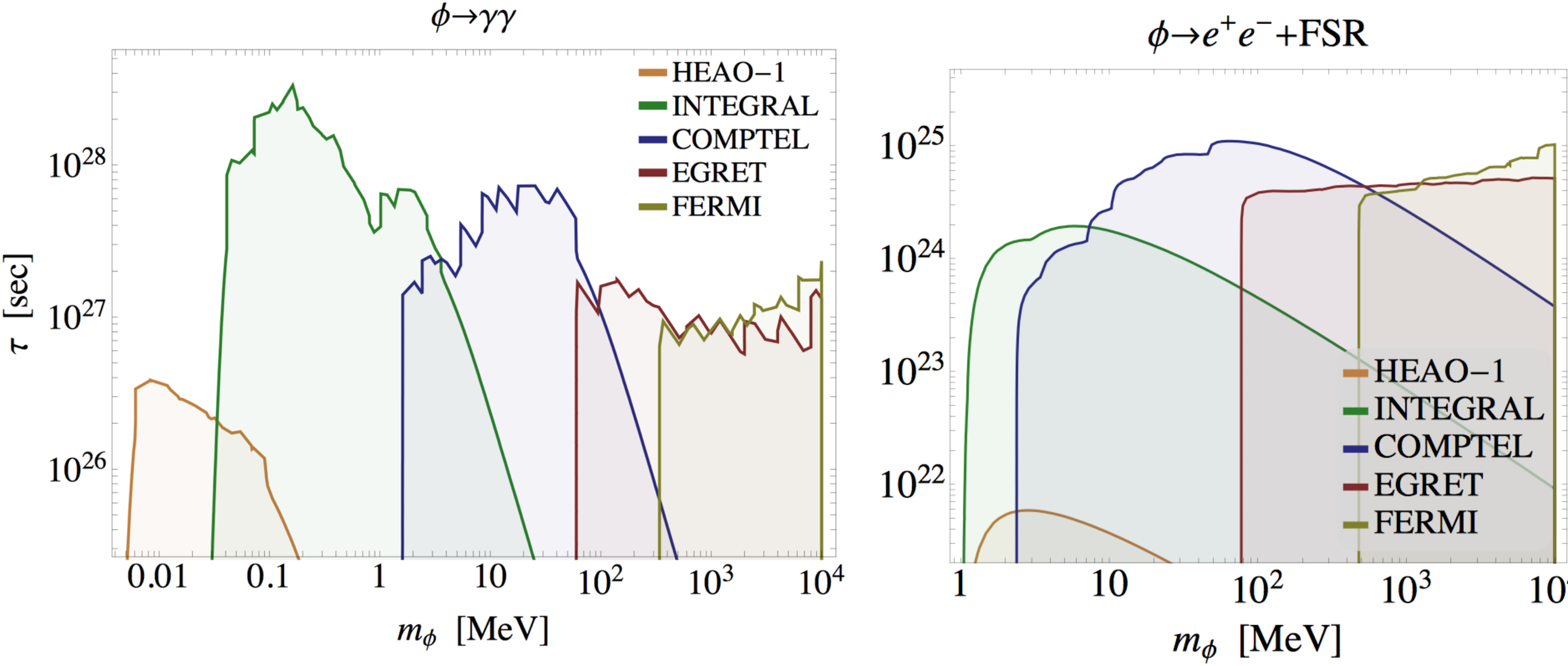
- Annihilation rate $\propto \rho^2$
- Decay rate $\propto \rho$
- Evades limits from CMB

Annihilating Light DM



[Essig, Kuflik, McDermott, TV, Zurek, 2013]

Decaying Light DM



[Essig, Kuflik, McDermott, TV, Zurek, 2013]

SIMP Realization: QCD-like Theories

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

- A simple realization: QCD-like theories with a Wess-Zumino-Witten term.

- Sp(Nc) gauge symmetry with 2Nf Weyl fermions and SU(2Nf) global symmetry.

$$\mathcal{L}_{\rm SIMP} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu a} + \bar{q}_i i \not{D} q_i \,, \quad i = 1, \ldots 2N_f$$

$$\mathcal{L}_{\rm mass} = -\frac{1}{2} M^{ij} q_i q_j + c.c., \quad M^{ij} = m_Q \, J^{ij}$$

- In the asymptotically-free range, theory breaks chiral symmetry, SU(2Nf) ⟶ Sp(Nf):

$$\langle q_i q_j \rangle = \mu^3 J_{ij}$$

- At low energy, theory described by the chiral Lagrangian. Pions parametrize the coset space SU(2Nf)/Sp(Nf). Play the role of DM.

- WZW produce 3-2 annihilations:

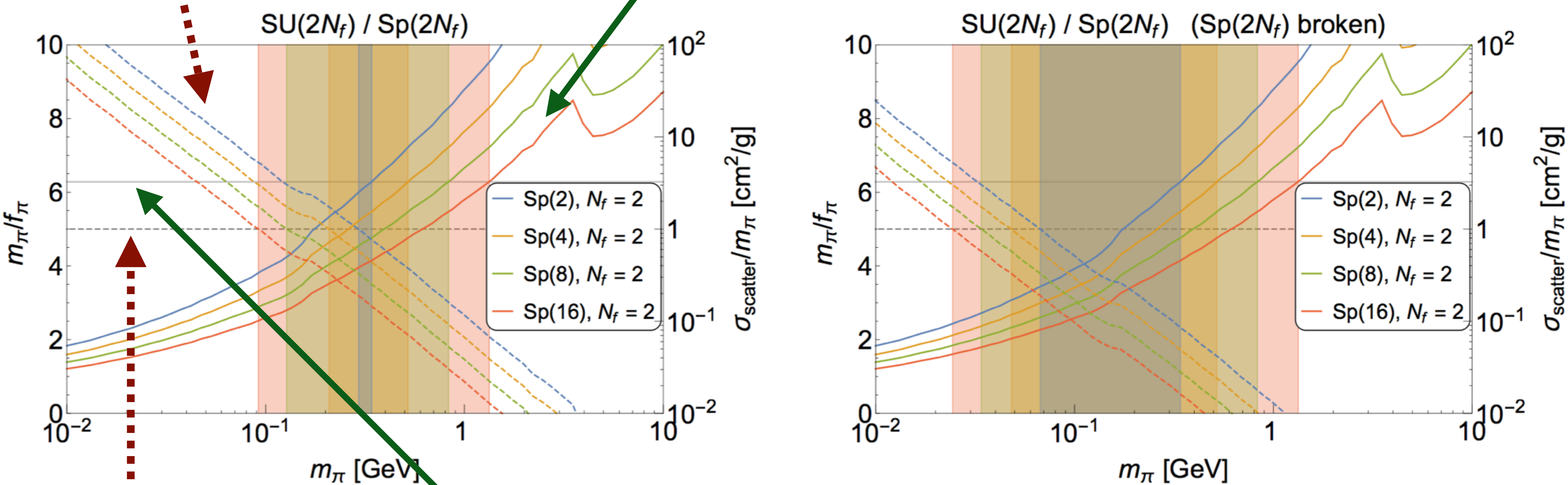
$$\mathcal{L}_{\rm WZW} = \frac{2N_c}{15\pi^2 f_\pi^5} \epsilon^{\mu\nu\rho\sigma} {\rm Tr}\left[\pi \partial_\mu \pi \partial_\nu \pi \partial_\rho \pi \partial_\sigma \pi\right]$$

SIMP Realization: QCD-like Theories

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

Predicted Self-Interaction

Solution to BE

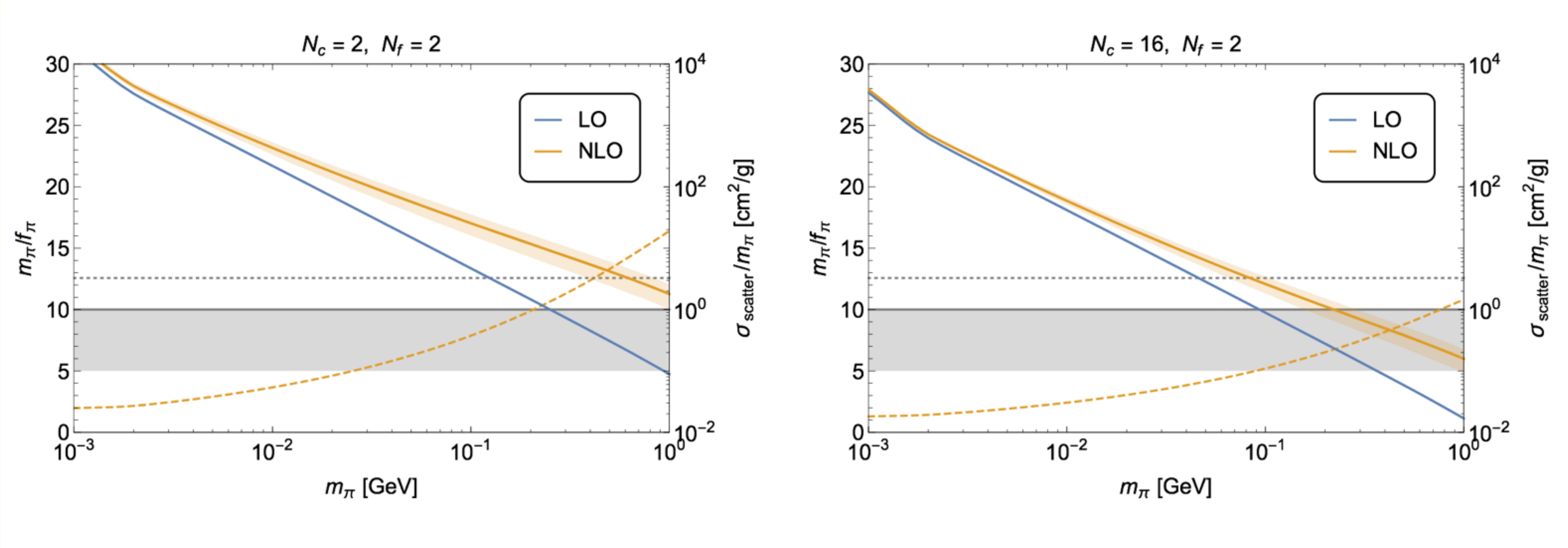


Self-interaction bound

Perturbativity limit

SIMP @ NLO and NNLO

- In the QCD-like realization of the SIMP mechanism, the 3-2 and 2-2 scatterings were calculated at leading order.
- Study by Hansen, Langaeble, Sannino, (2015) calculates the rates at NLO and NNLO.
- Paper shows that tension with self-interacting bounds are more significant and may exclude the simplest case of Nf=2, Nc≈2.



- Not all models are excluded. In particular, Nf>2 was not studied.
- Other SIMP realizations exist and should be studied.