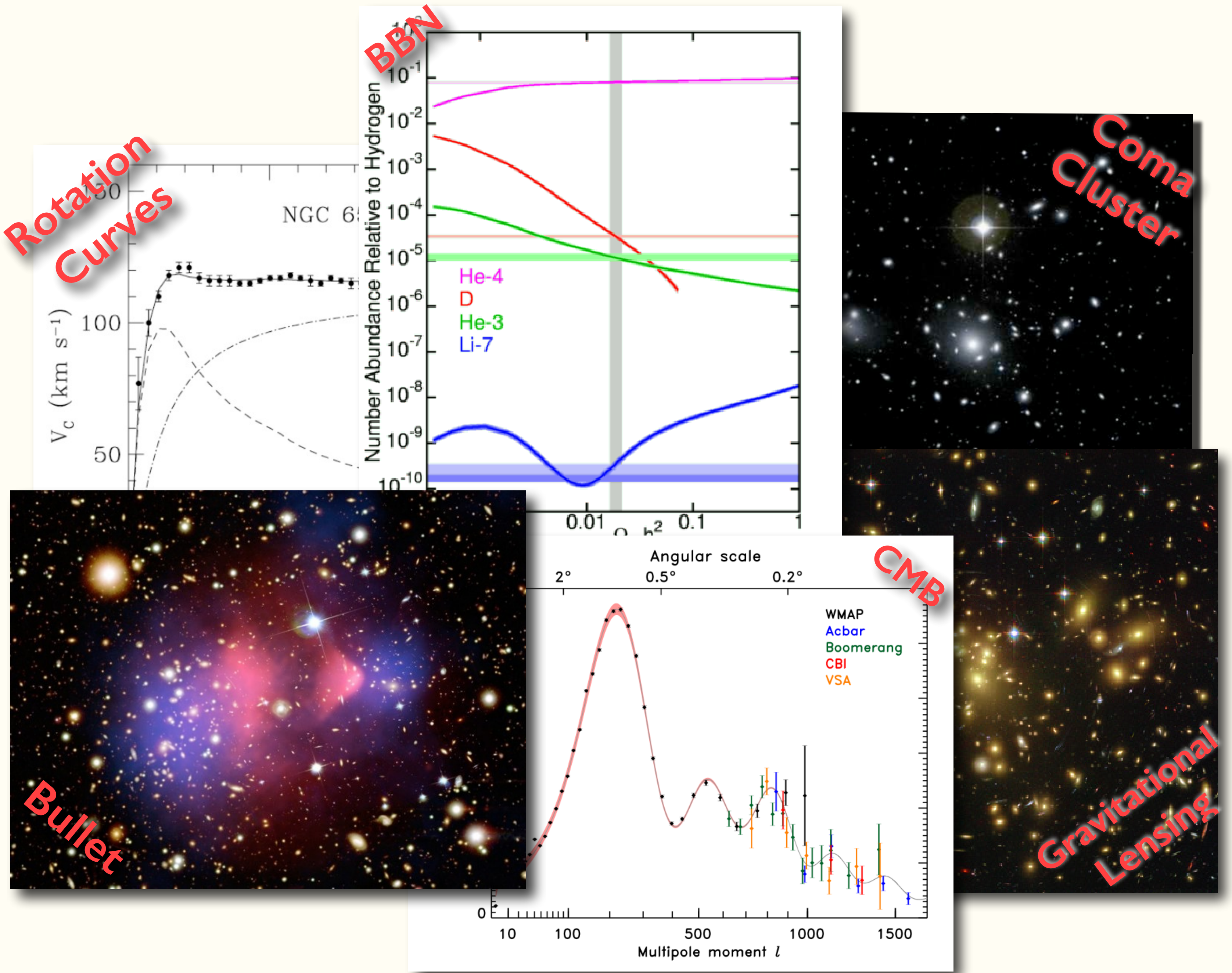
New Avenues in the Search for Dark Matter

June 2017

Tomer Volansky
Tel-Aviv University

Gravitational Evidence for Dark Matter



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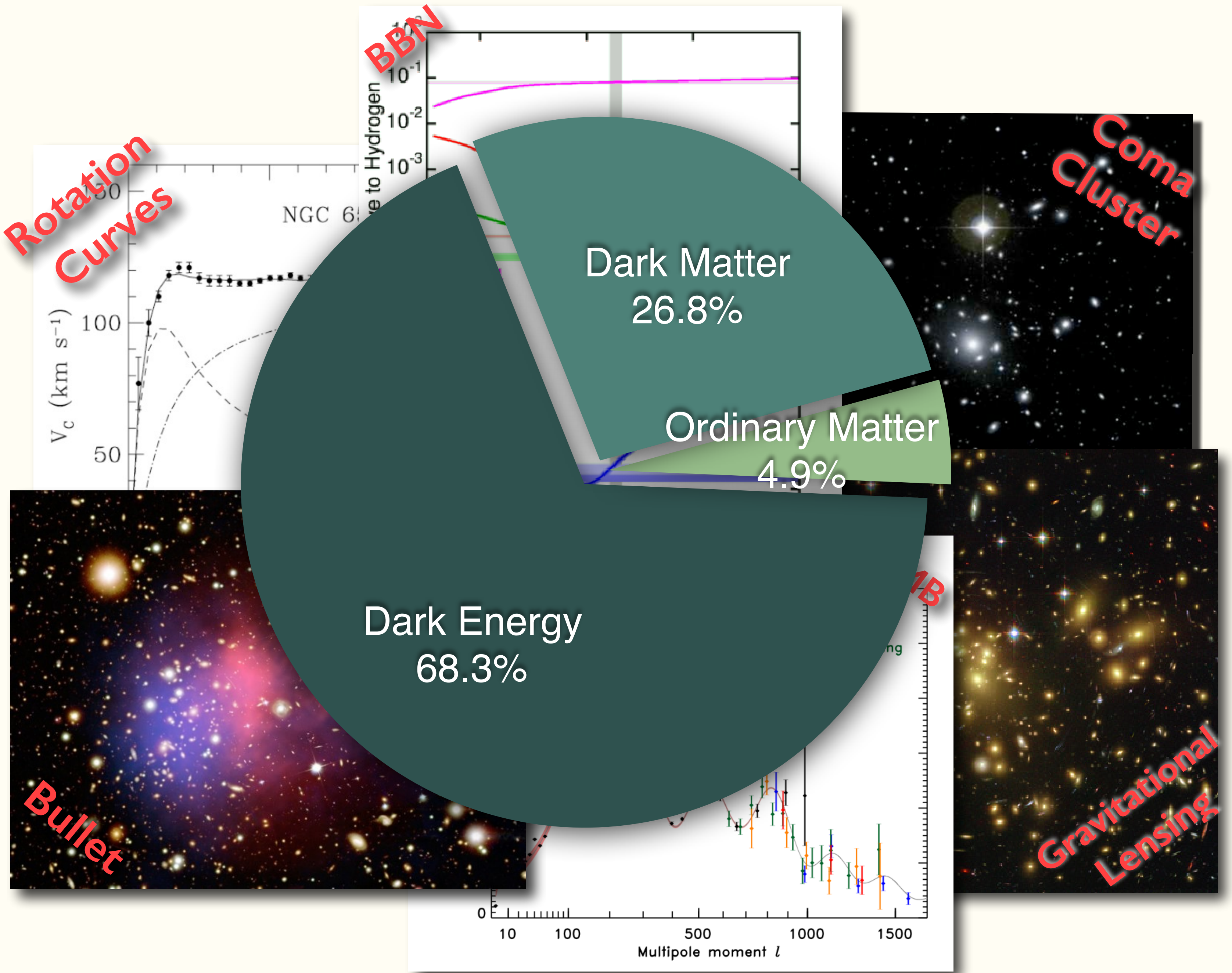


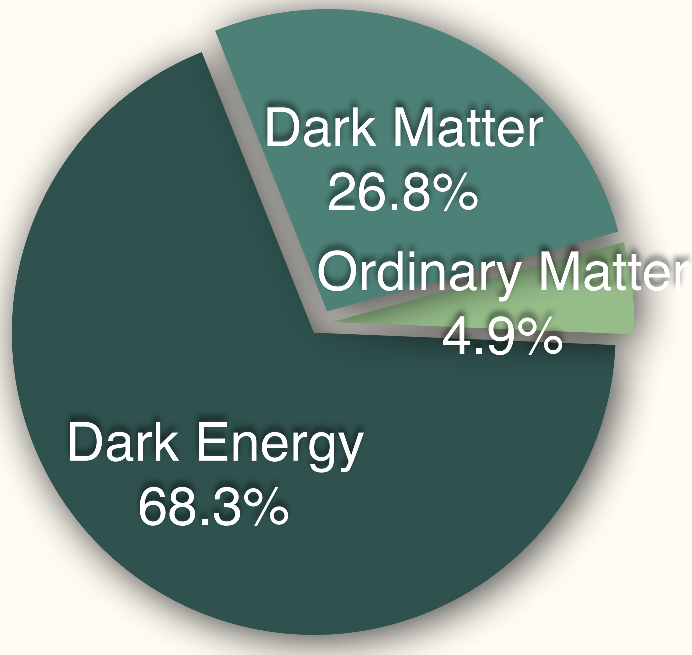
What is Dark Matter?

Have many ideas…

…but we simply don't know!

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!

Will We Find Dark Matter?

A moment of honesty….

Finding DM is far from guaranteed!

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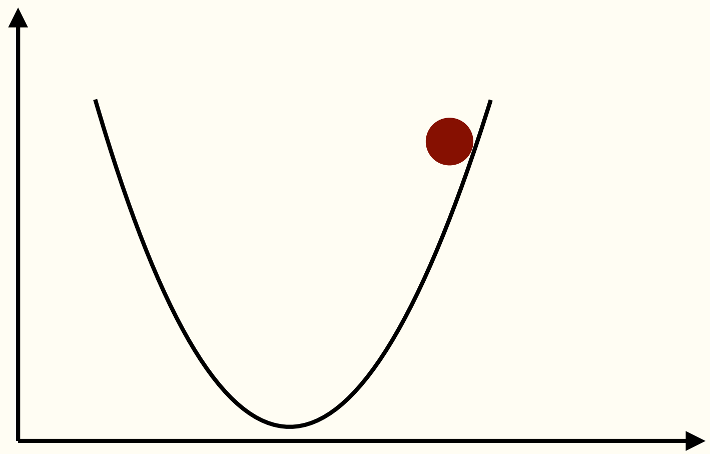
- Consider a light scalar during inflation: $\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m^2\phi^2$
- Equation of motion: $\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$



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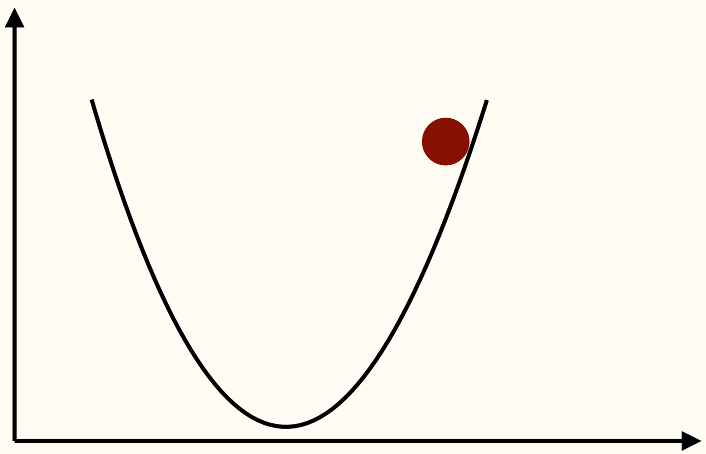

$H \gg m \Longrightarrow$ Over-dumped oscillator

Φ frozen

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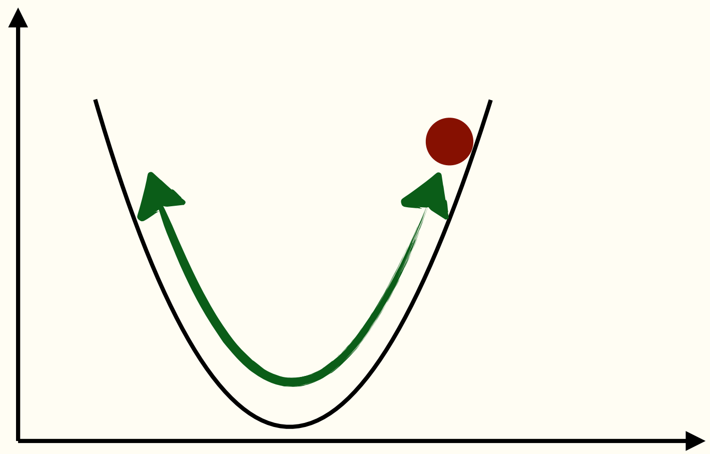

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$H < m \Longrightarrow$ Φ oscillates

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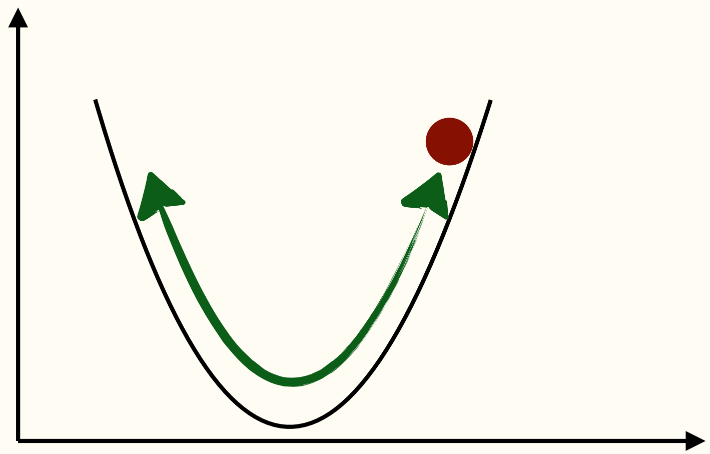

$$\rho_\phi \propto a^{-3}$$

Energy density today depends on initial condition set by inflation

Will We Find Dark Matter?

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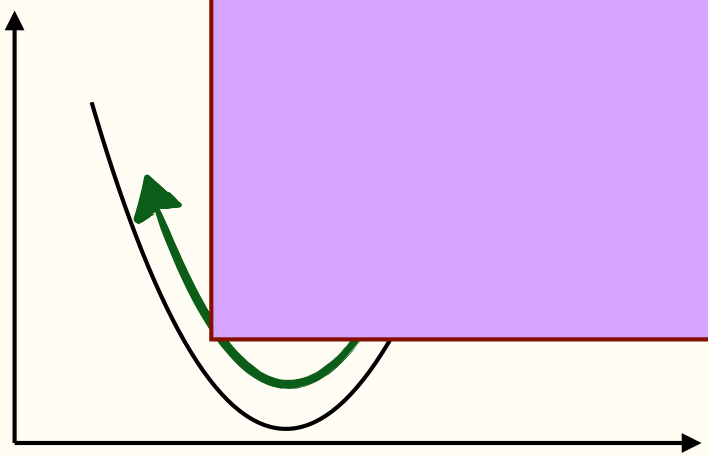
- Cons … ϕ^2
- Equa

This DM only interacts gravitationally.
We will never see it…



… s on initial condition set by inflation

Relax…

Fortunately, many motivated models predict some kind of detectable signals

Explore what you can!

How do we usually explain the 85% DM abundance?

Thermal WIMP
(Weakly Interacting Massive Particle).

The Thermal WIMP

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

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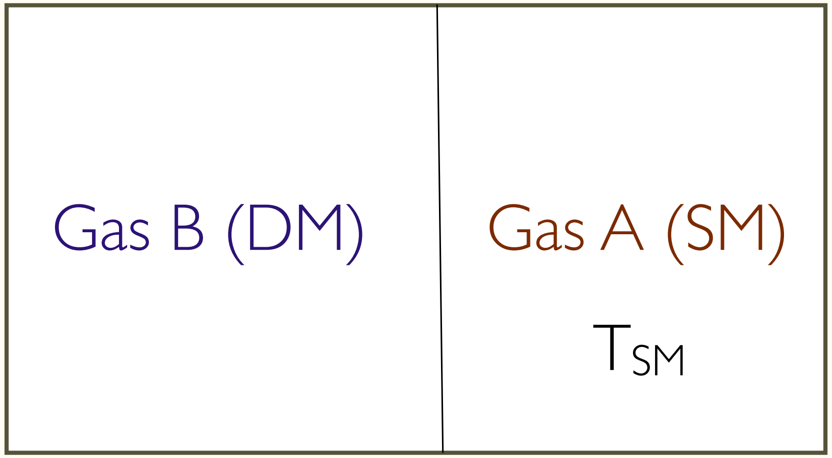
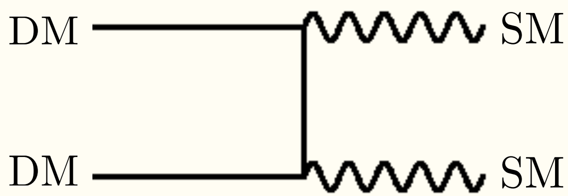


- Annihilations reduce DM density in our Universe:

$$\chi\chi \rightarrow \bar{f}f$$



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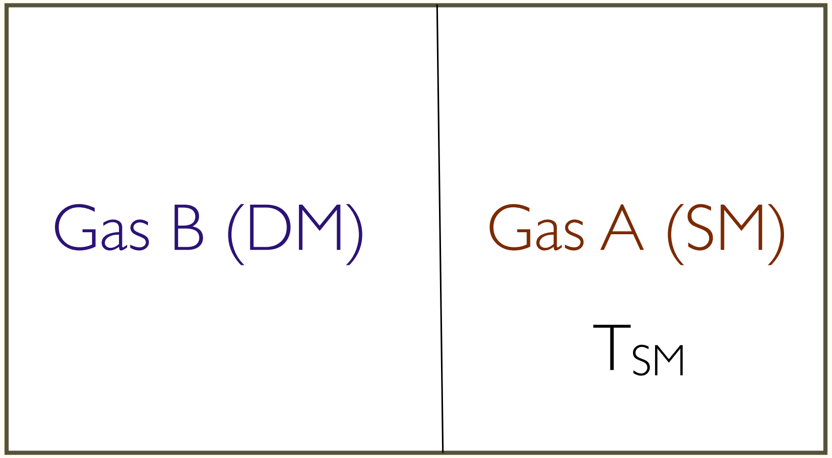

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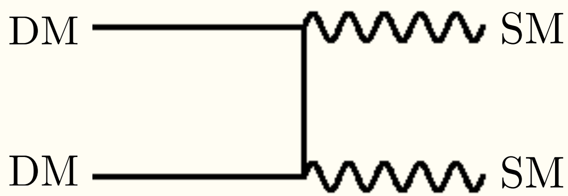

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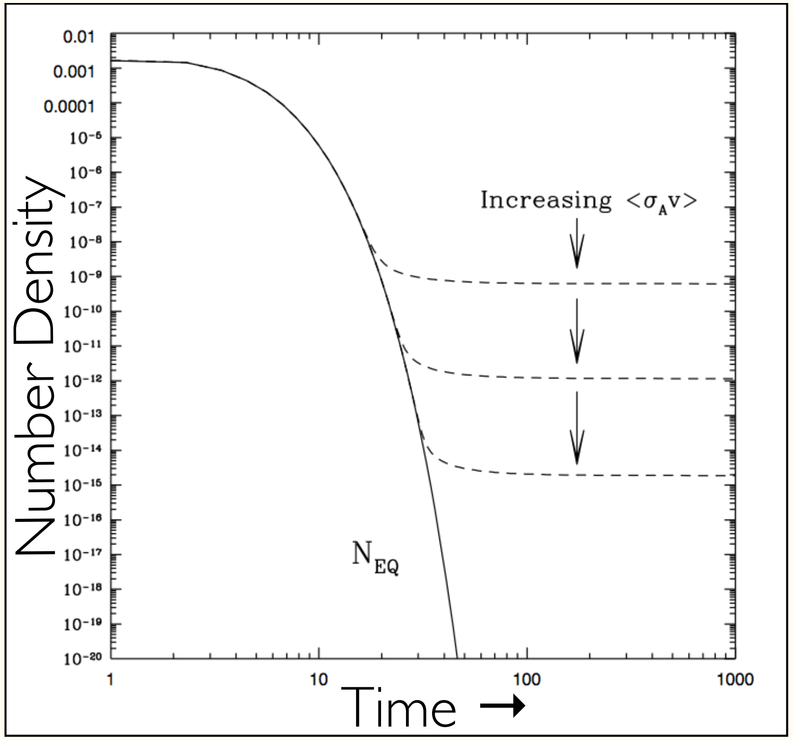

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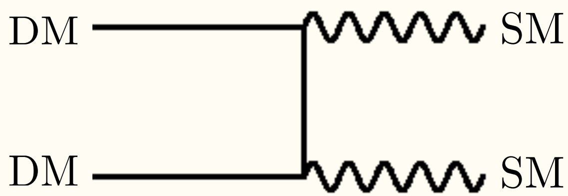

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- Evolution described by the Boltzamann eq.: $\frac{dn_\chi}{dt} = -3Hn_\chi - \langle\sigma v\rangle(n_\chi^2 - n_{\chi,\mathrm{eq}}^2)$
- Solution can be approximated by solving:

$$\Gamma = n_\chi\langle\sigma v\rangle = H$$

- As expected, solution depends (strongly) on a single parameter: $\langle\sigma v\rangle$.
- One finds:

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

- 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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Same mass-scale we are now probing at the LHC

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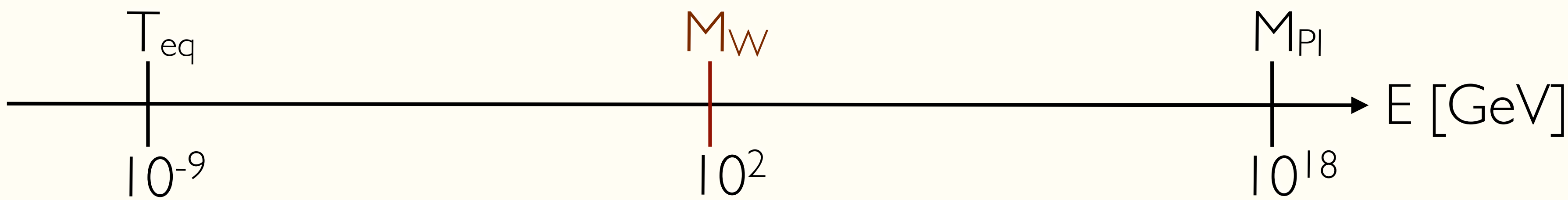
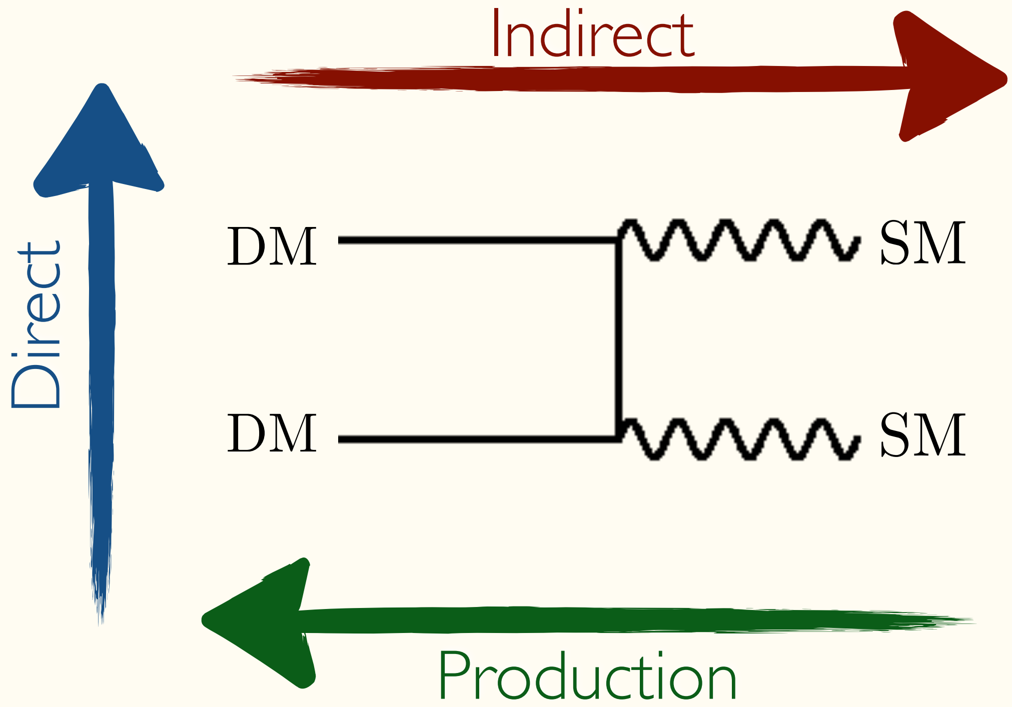
$$m_{\rm DM} \simeq \alpha \sqrt{T_{\rm eq} M_{\rm Pl}}$$

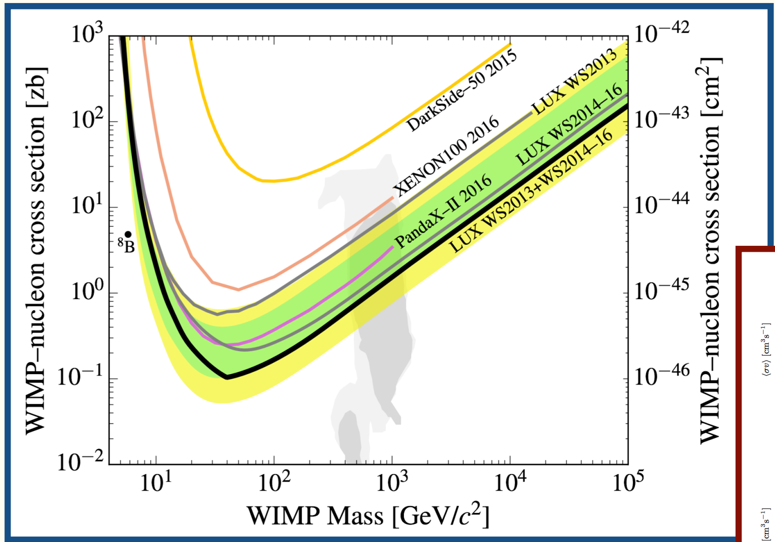


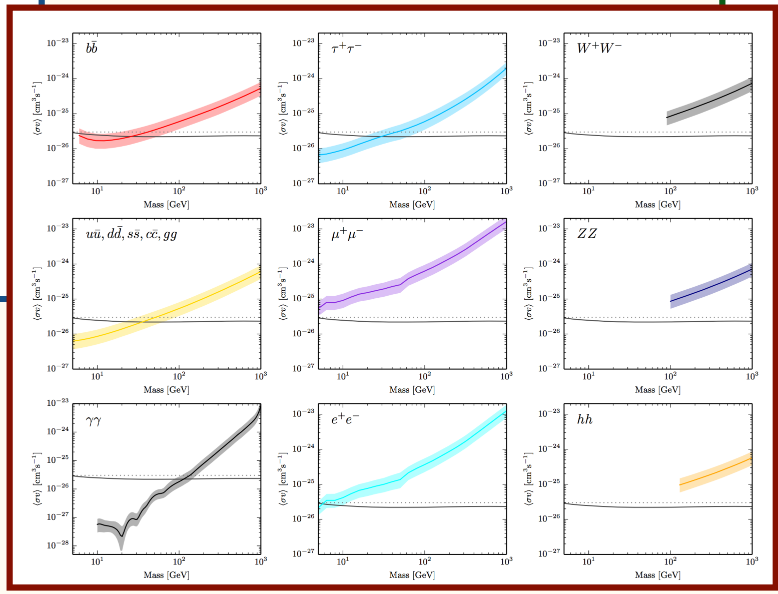
This is the WIMP Miracle

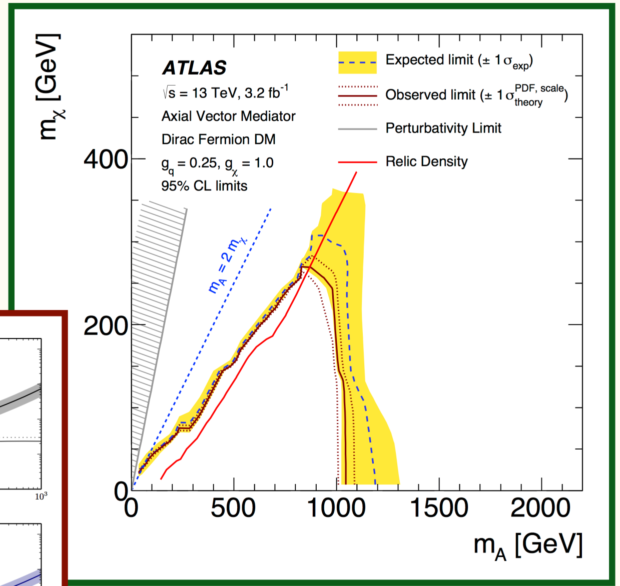
So where do we stand with WIMPs?



So where do we stand with WIMPs?







Tension is building up!

A Word of Caution…

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All constraints are *always* model-dependent

Direct detection:	Depends on mediator, couplings, inelasticity, etc.
Indirect detection:	Depends on annihilation channels, p-wave suppression, etc.
Collider:	Depends on mediator, couplings, etc.

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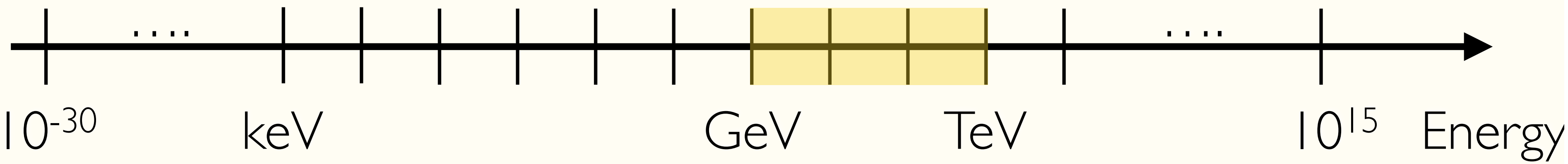
So no need to give up on WIMPS

BUT…

Obsessed with the WIMP...

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

Our experimental effort is strongly focused on the WIMP!



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Lots more to do!

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

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WIMPs are predicted by theories beyond the SM that address the **Naturalness Problem**.

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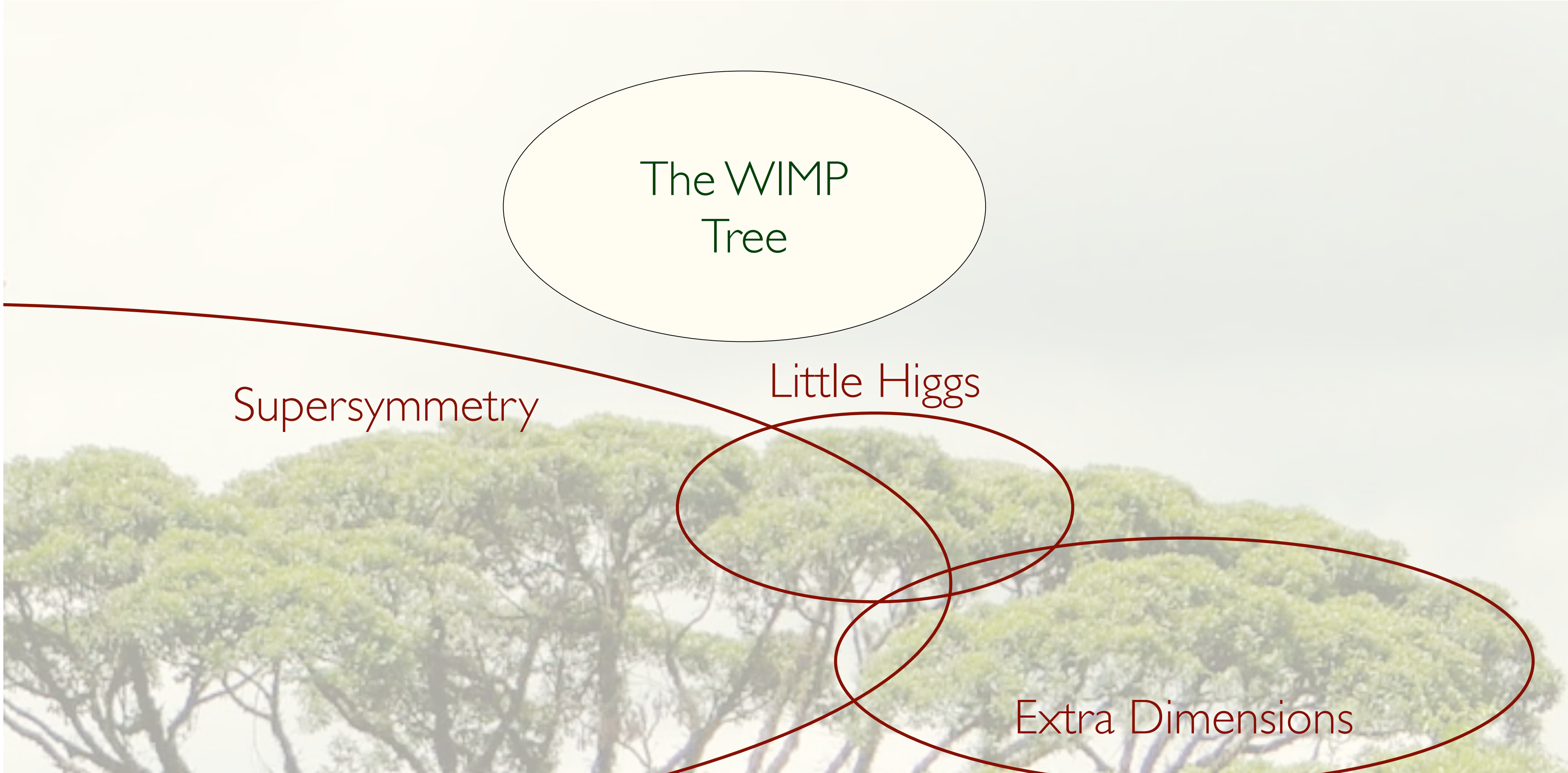

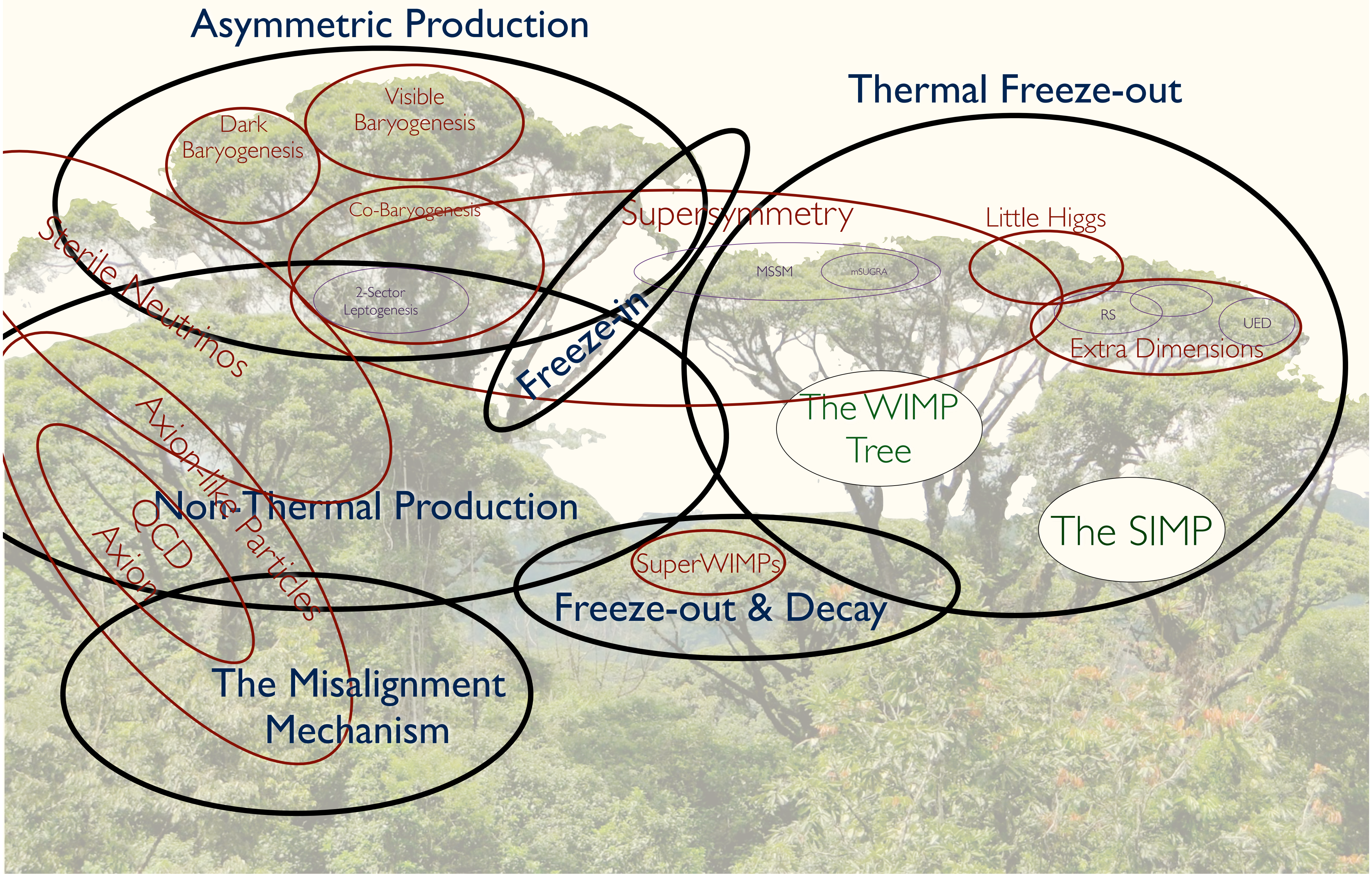
Asymmetric Production
Visible Baryogenesis
Dark Baryogenesis
Co-Baryogenesis
2-Sector Leptogenesis
Thermal Freeze-out
Supersymmetry
MSSM
mSUGRA
Little Higgs
RS
UED
Extra Dimensions
Freeze-in
Sterile Neutrinos
Axion-like Particles
QCD Axion
Non-Thermal Production
The WIMP Tree
The SIMP
SuperWIMPs
Freeze-out & Decay
The Misalignment Mechanism

Take-home Messages…

Significant theoretical and experimental activities in recent years to go beyond the WIMP paradigm

Experimentally, it is possible to search for DM much lighter than previously thought and it is possible to search for more complex DM sectors.

Outline

- Classifying Theories of 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

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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Mediation Scheme

- Gravity
- Weak-scale Mediator
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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	• ...	• ...
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Couplings

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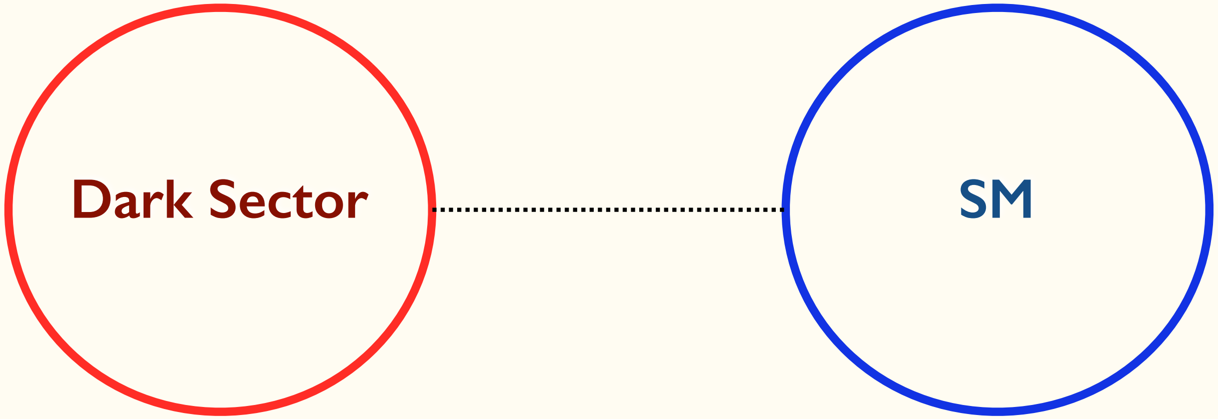
Direct (Quarks, Gluons)
Colliders (Quarks, Gluons, Charged Leptons)
Indirect (Charged Leptons, Neutrinos, Photons)

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?

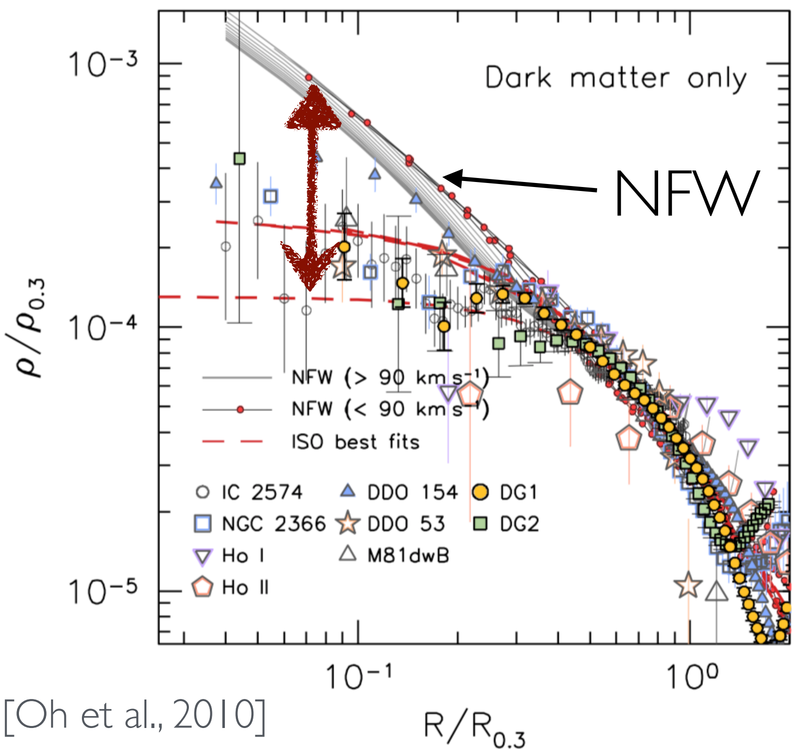
- Several discrepancies between N-body simulations and astrophysical observations:

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]

Problems with Cold Dark Matter?

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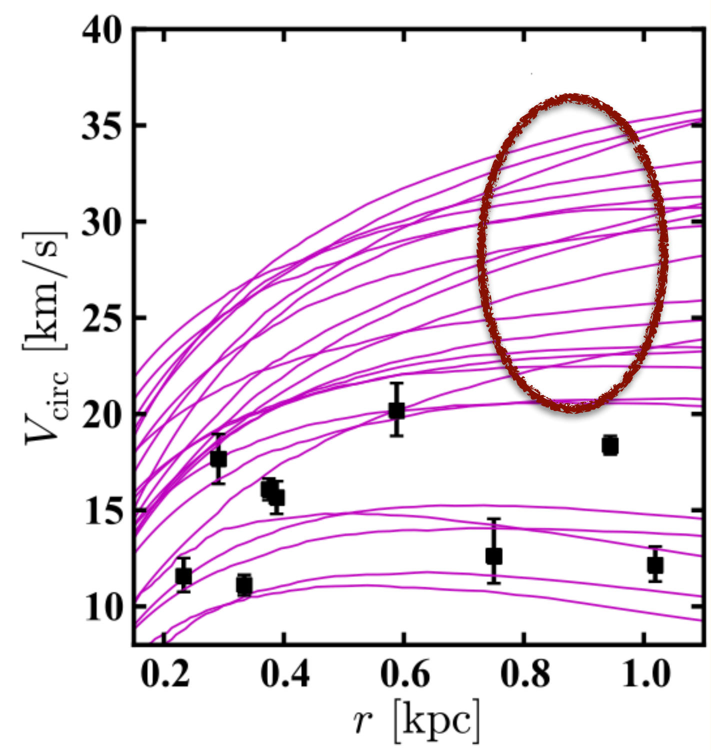
    1. Core vs. Cusp [Moore 1994; Flores,Primack 1994]

    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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  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?

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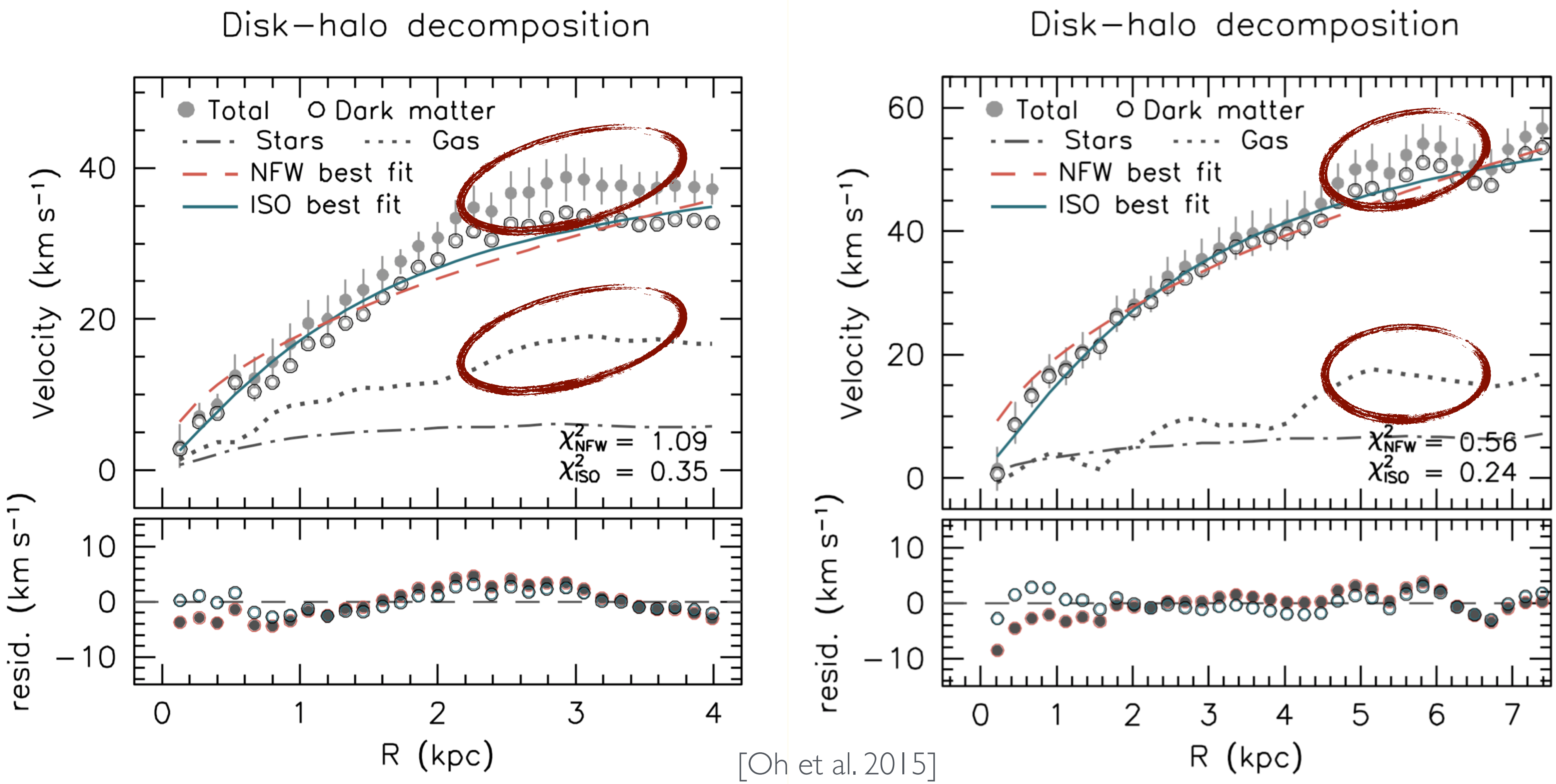
Baryonic effects such as supernova feedback may explain (some) these discrepancies (significant ongoing study). Harder to explain (some) discrepancies in field dwarfs.

To answer, must understand baryonic feedback much better!

One more problem to note…

Features in Rotation Curves



[Oh et al. 2015]

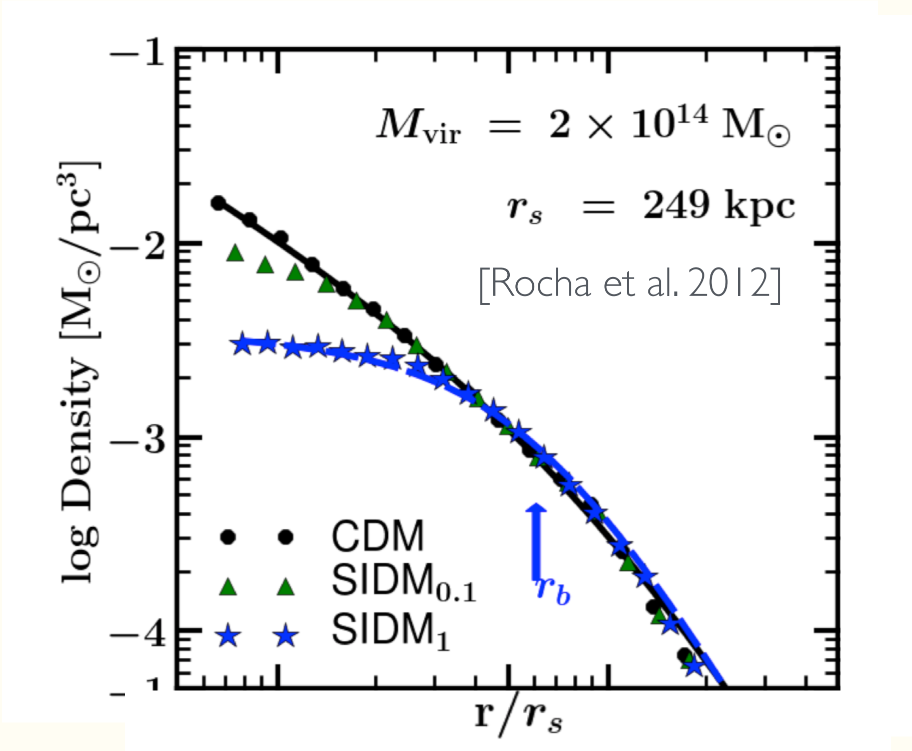
Features in rotation curves are intriguing. Mergers may provide a clue?

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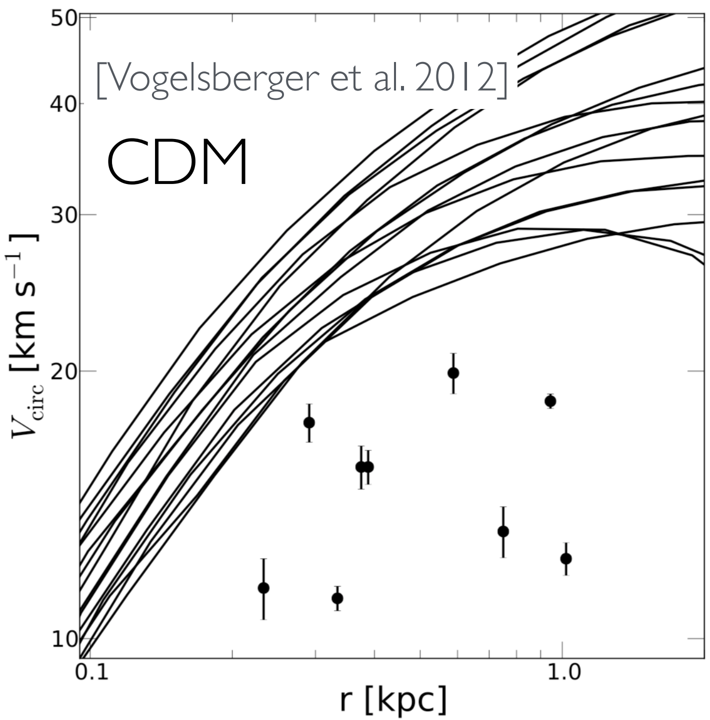
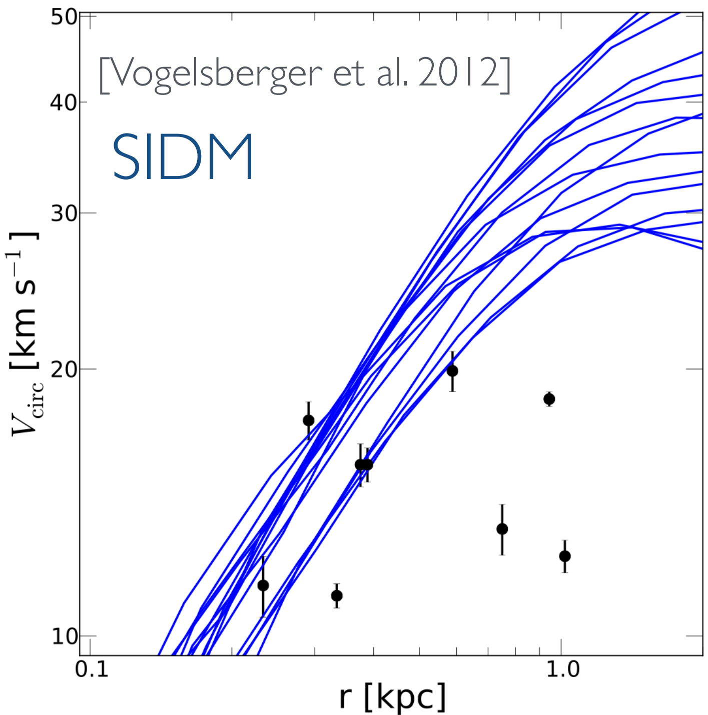
  - Collisions strip sub-halos and reduce number of satellites.





Self-Interacting Dark Matter?

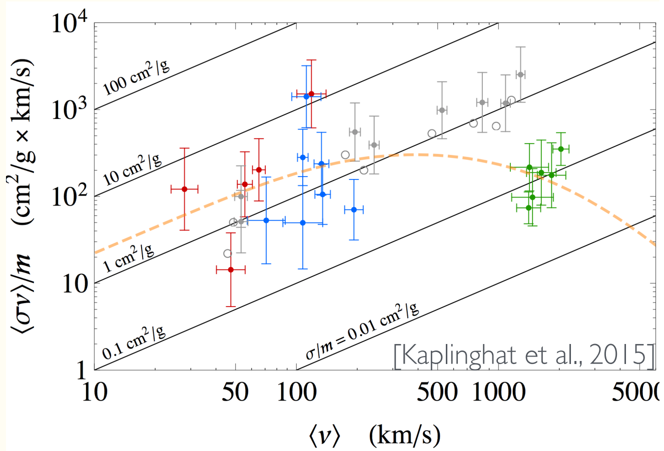
Dark Matter Interpretation

- 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.
      Prefers mild velocity-dependent Xsec.

    - 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.

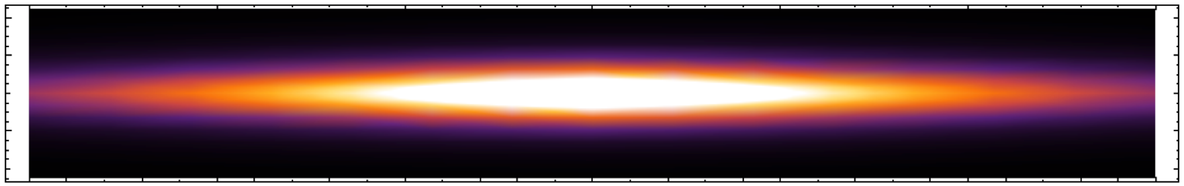
[Katz, Fan, Randall,Reece,Shelton, 2013]

- 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?

- 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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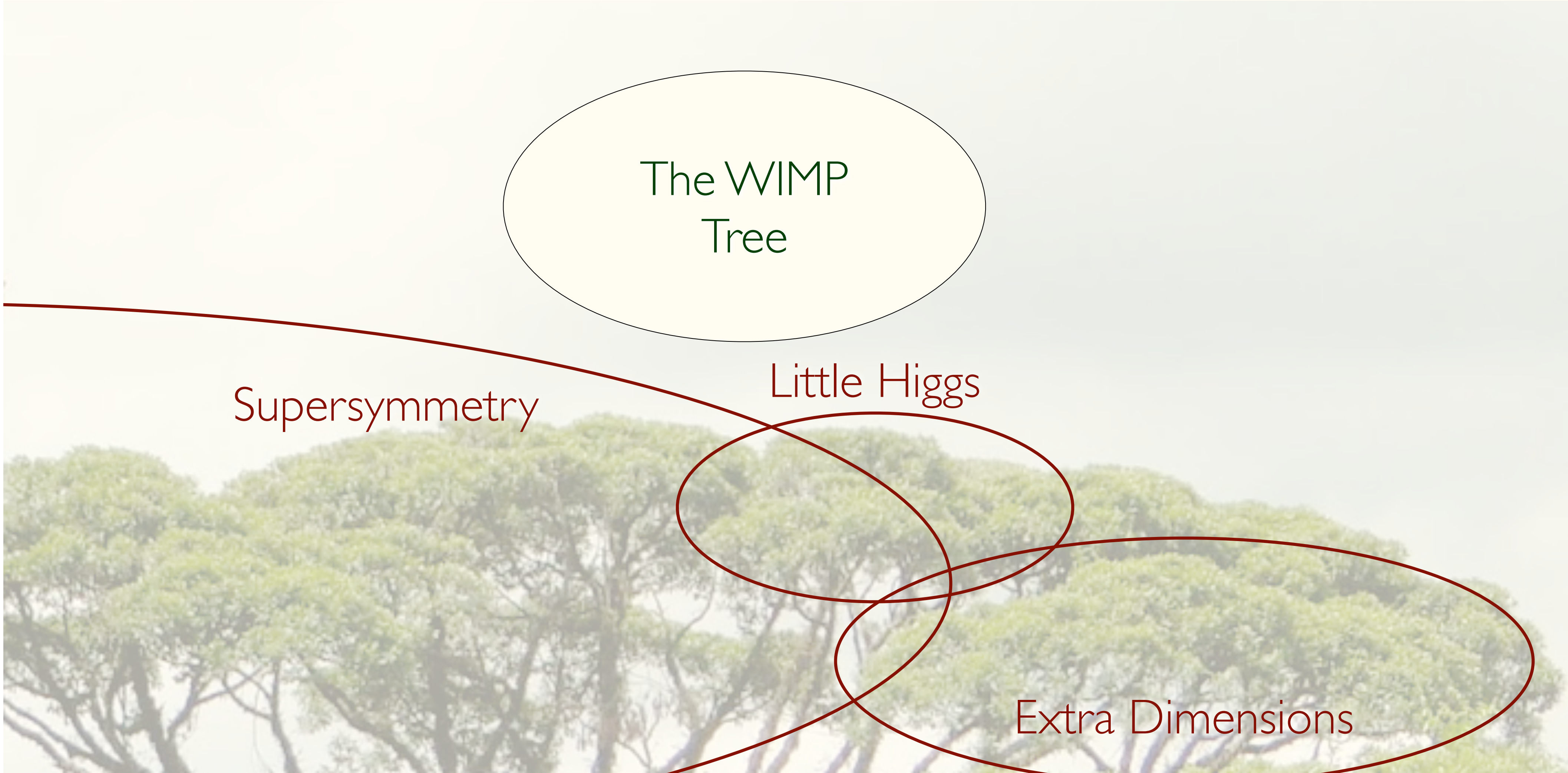
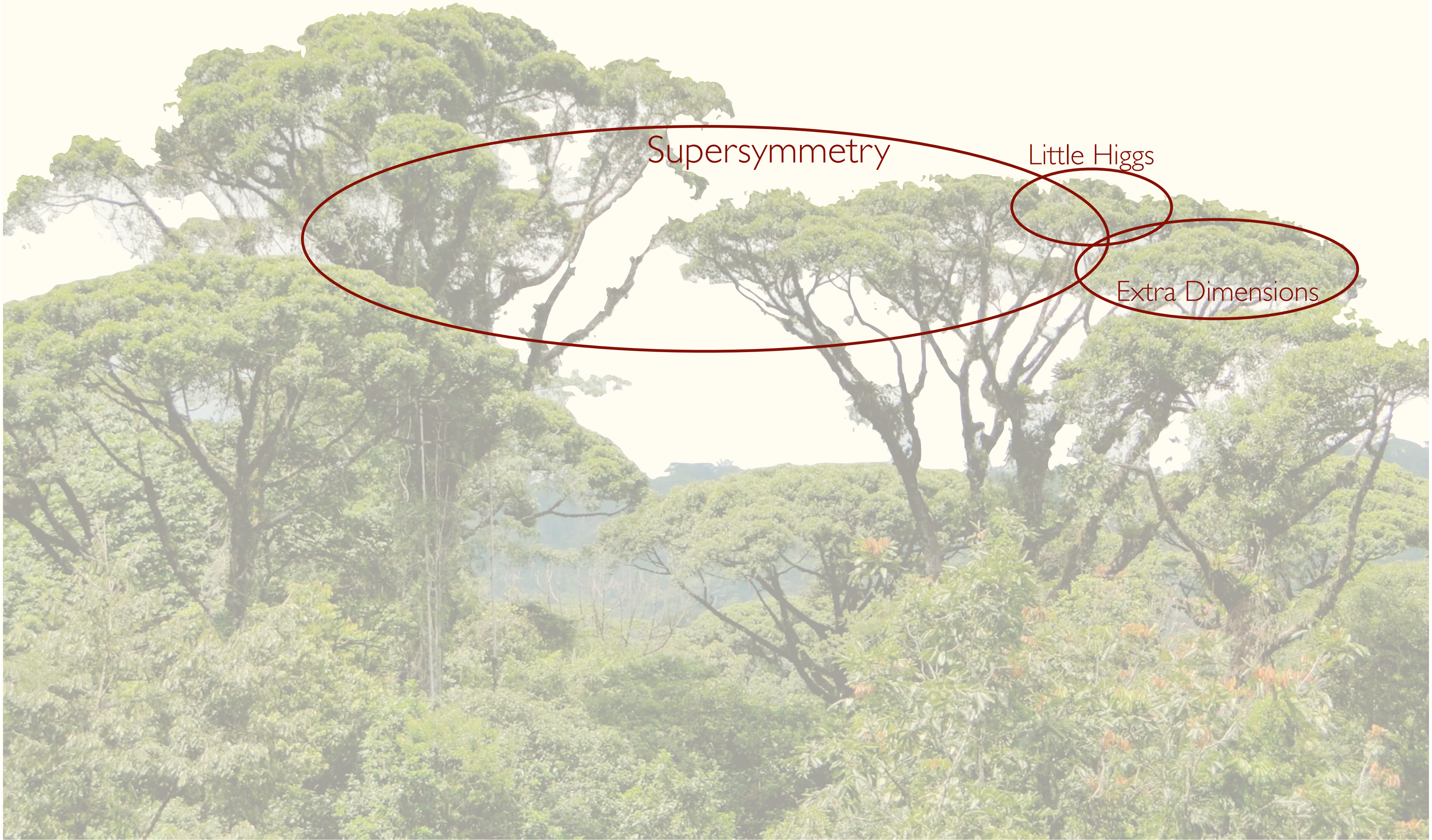
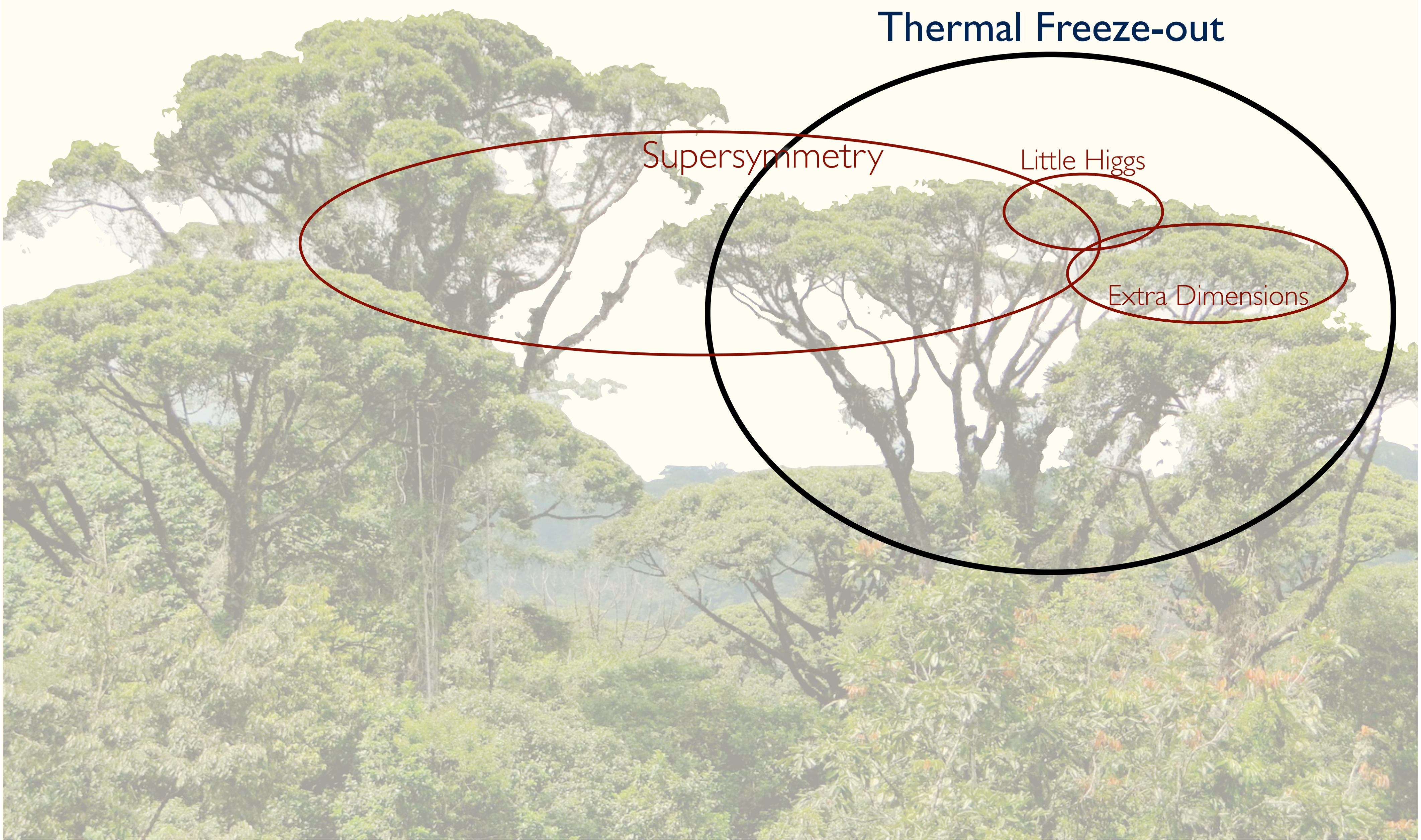
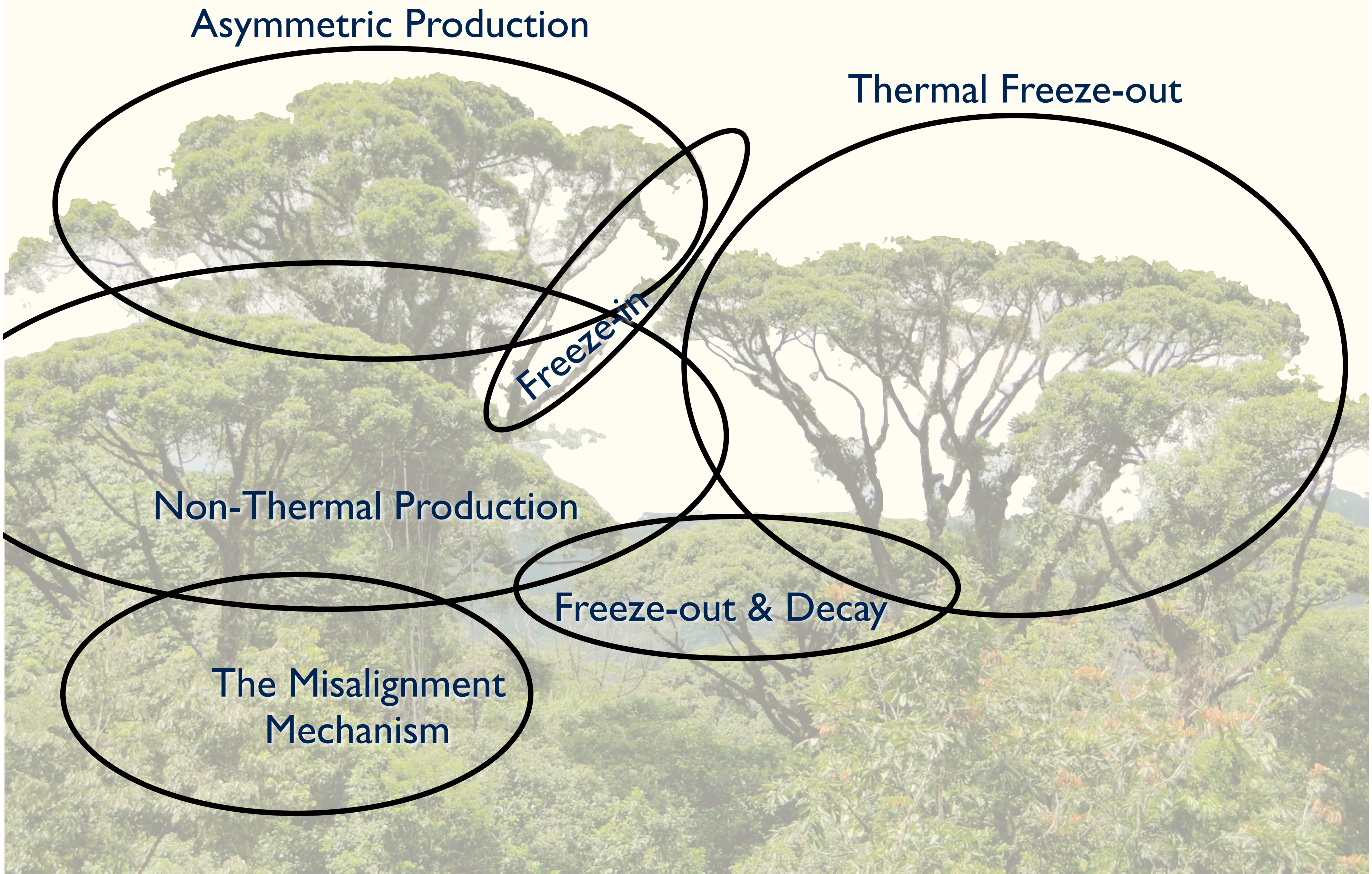
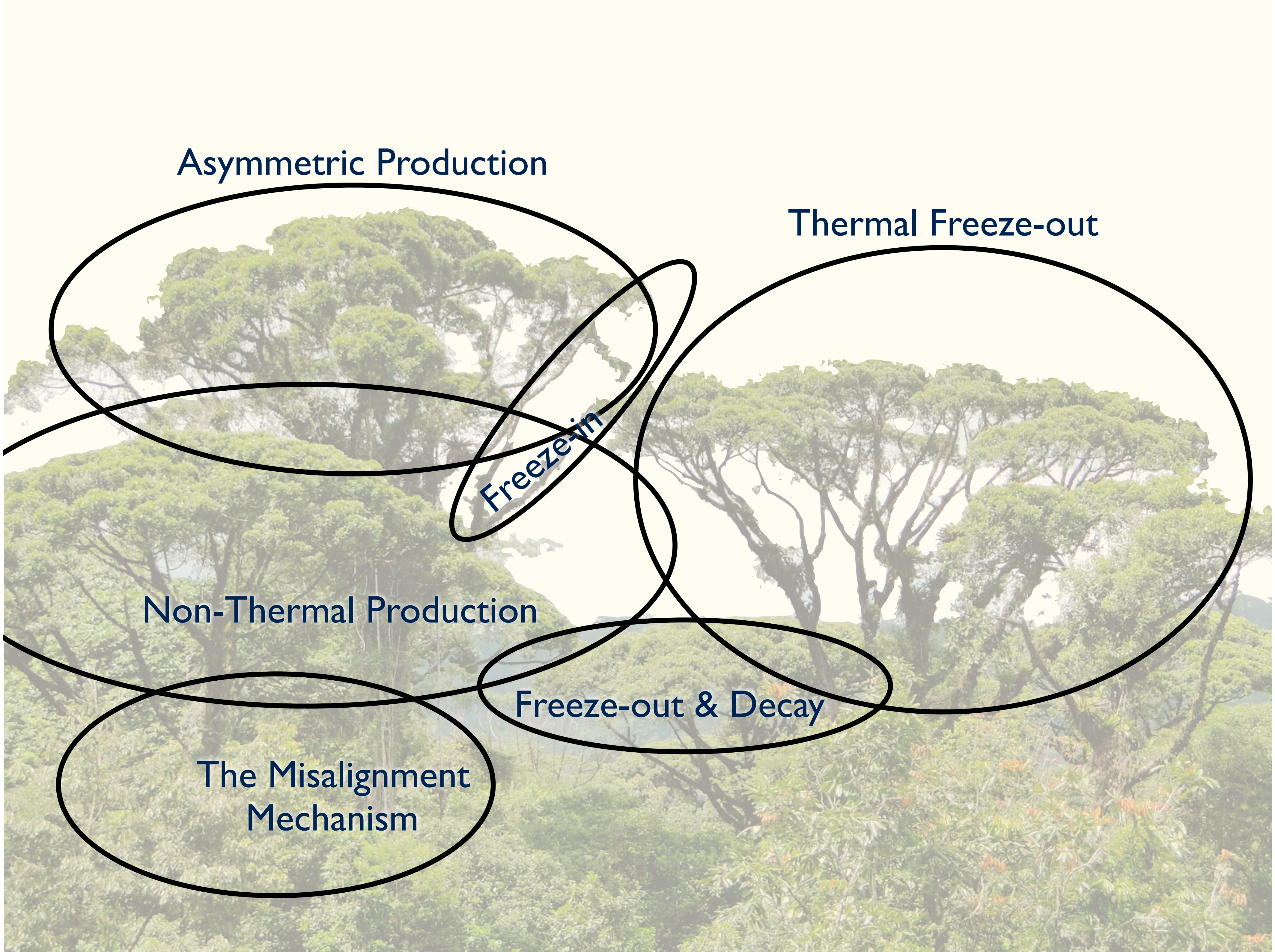
The Dark Matter Tree




Supersymmetry
Little Higgs
Extra Dimensions


Thermal Freeze-out
Supersymmetry
Little Higgs
Extra Dimensions


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



Asymmetric Production
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Thermal Freeze-out

Freeze-out & Decay

Thermal Freeze-out

Thermal Freeze-out

Strongly Interacting Massive Particles

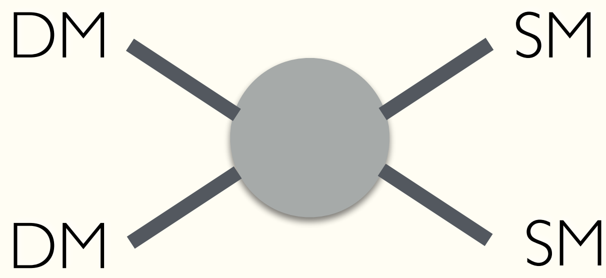
A New Perspective on Freeze Out

[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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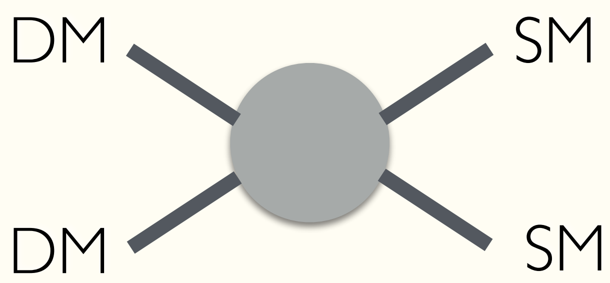
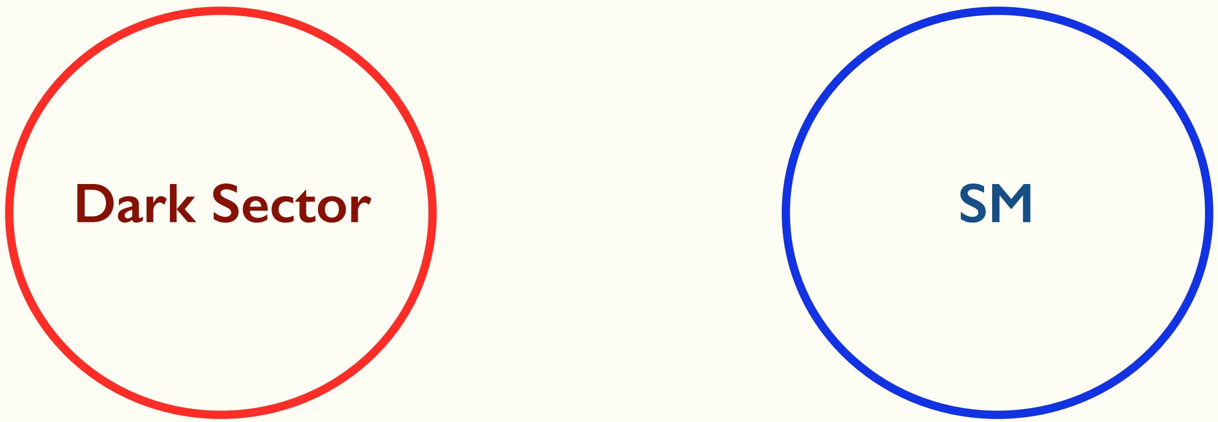


- But what if DM is the lightest state in a hidden (sequestered) sector?



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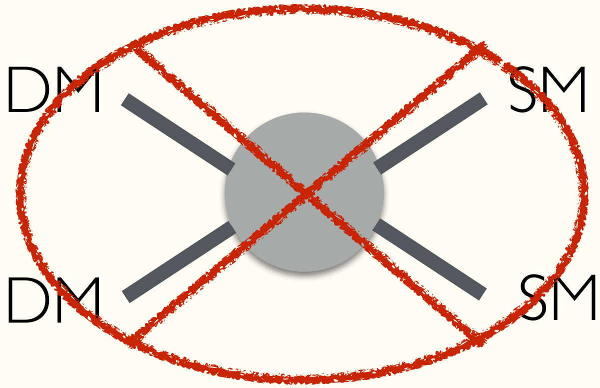

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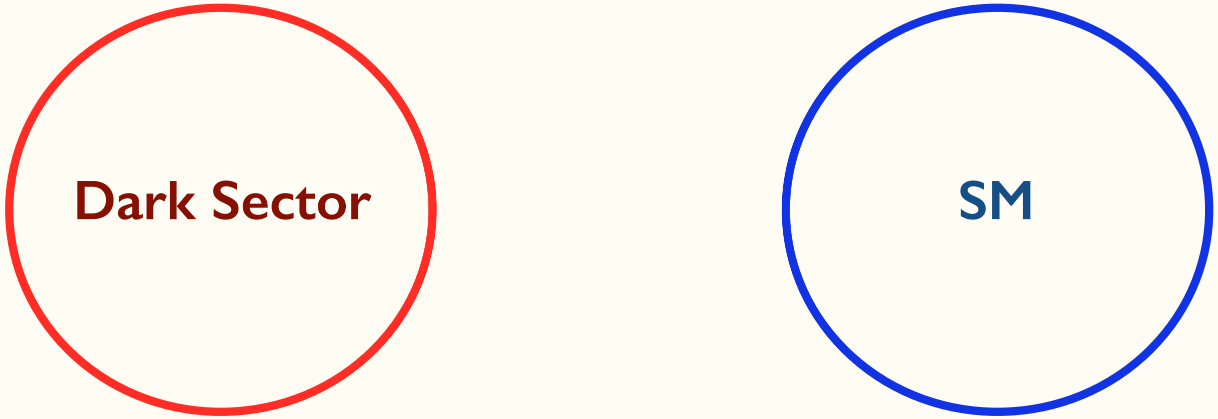
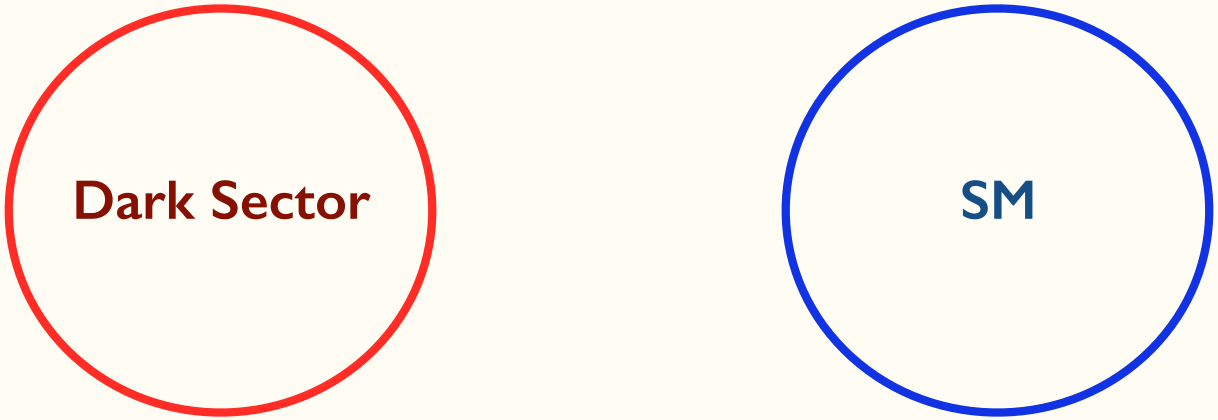


- Then 2-2 annihilations may be highly suppressed

No 2-2 Annihilations..



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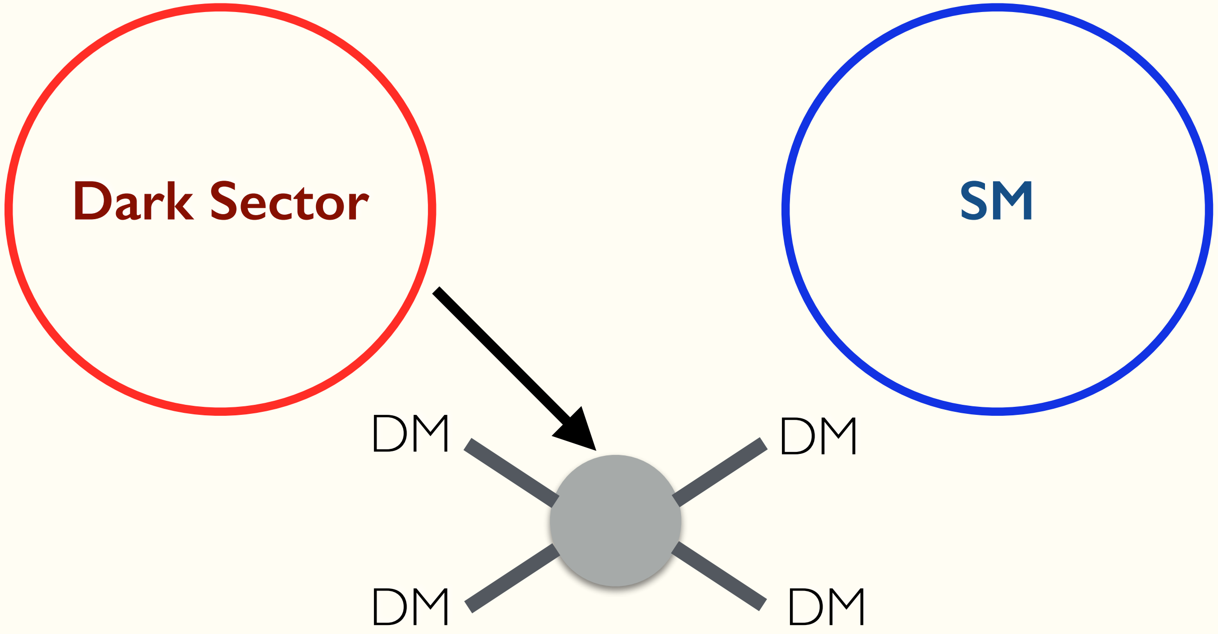
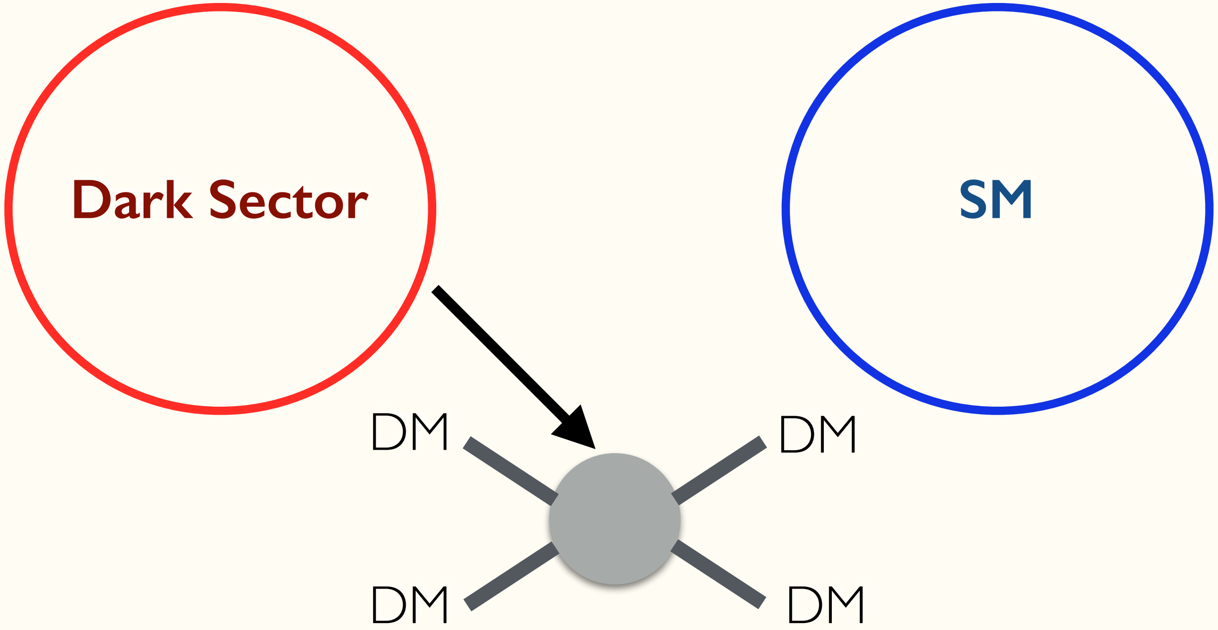


- However, DM can still interact in the hidden sector.
- But this is number-conserving, which implies,

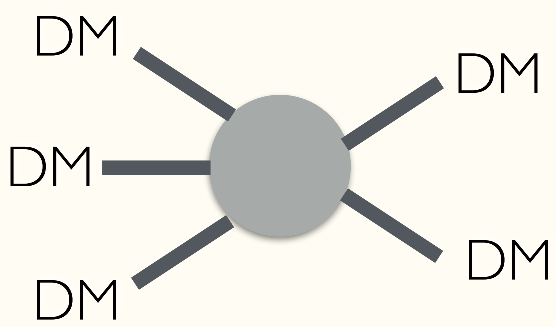
$$\frac{n_{\rm DM}}{s} \sim 1$$

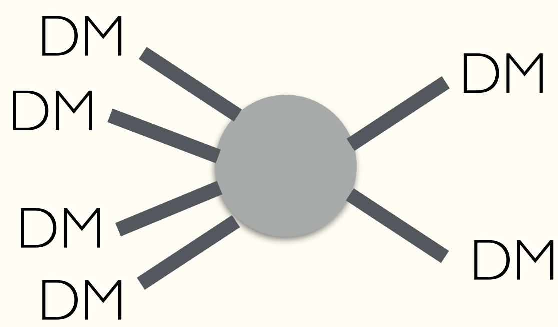
A way out?

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

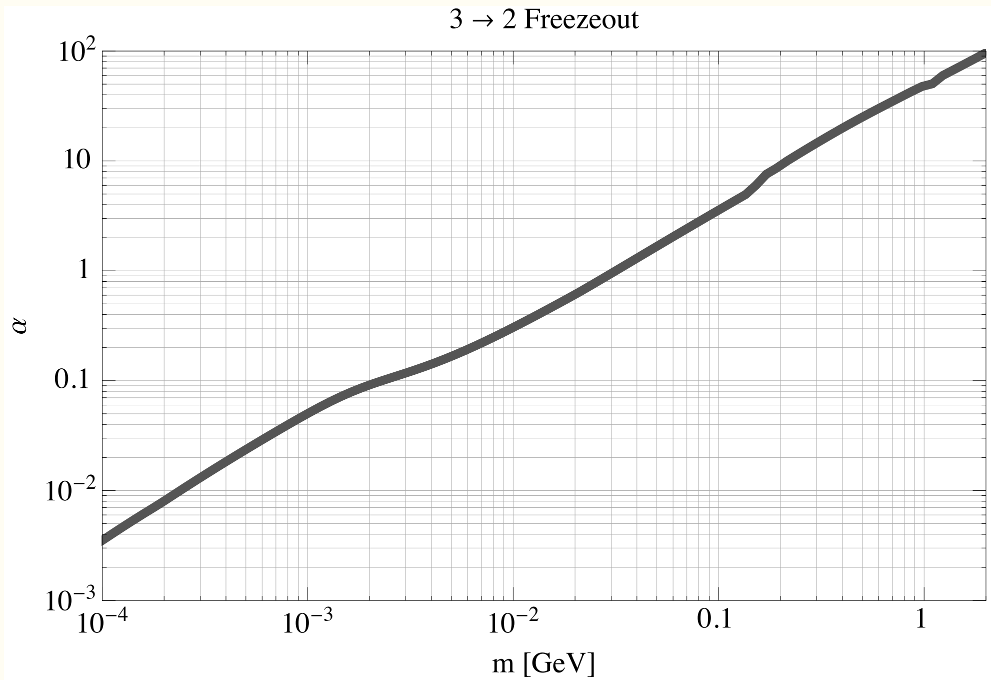
Weak scale emerges for a weak-strength interactions

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

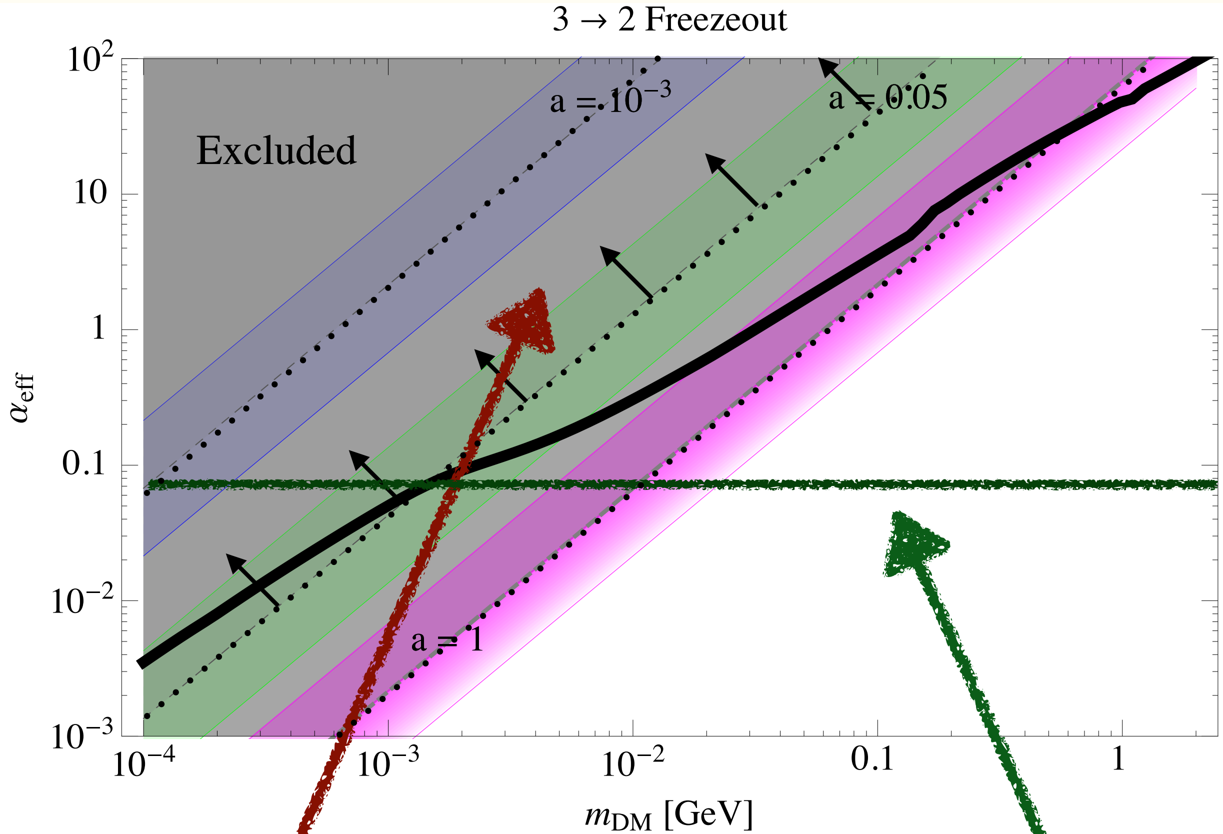
SIMP DM

QCD scale emerges for a strongly-interacting sector.

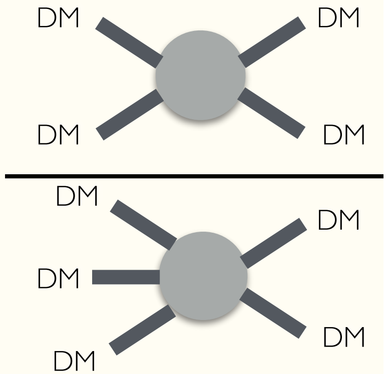
$$m_{\rm DM} \simeq \alpha_{\rm eff} \left(T_{\rm eq}^2 M_{\rm Pl}\right)^{1/3} \sim 100~{\rm MeV}$$



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.

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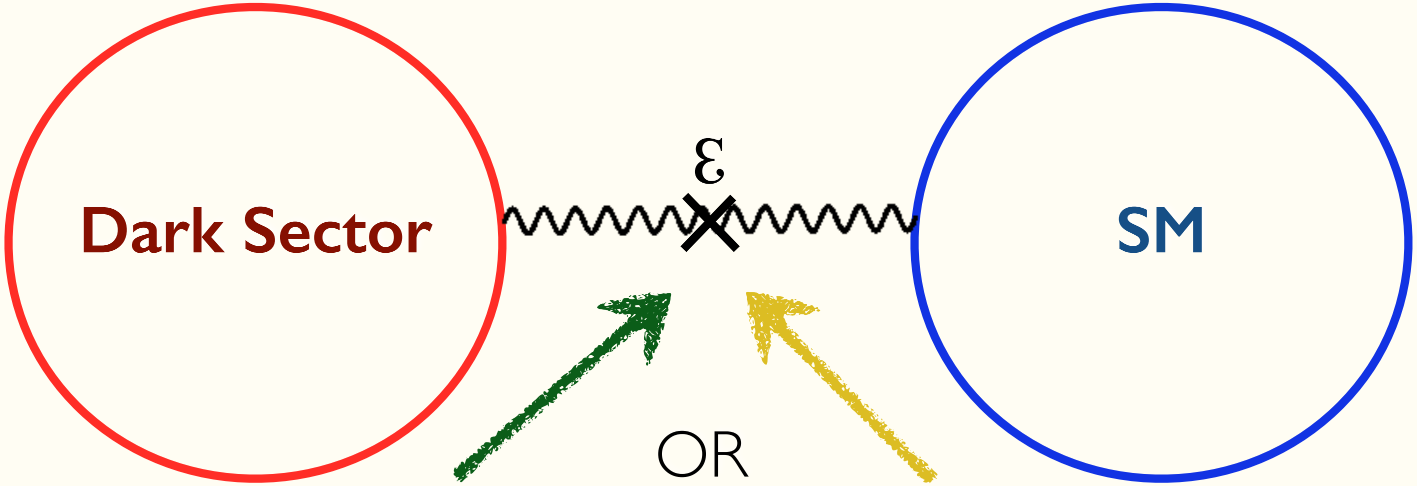

$$\frac{m_f}{\Lambda^2}\chi^\dagger\chi\bar{f}f \qquad \frac{\alpha_{\rm EM}}{4\pi\Lambda^2}\chi^\dagger\chi F_{\mu\nu}F^{\mu\nu}$$

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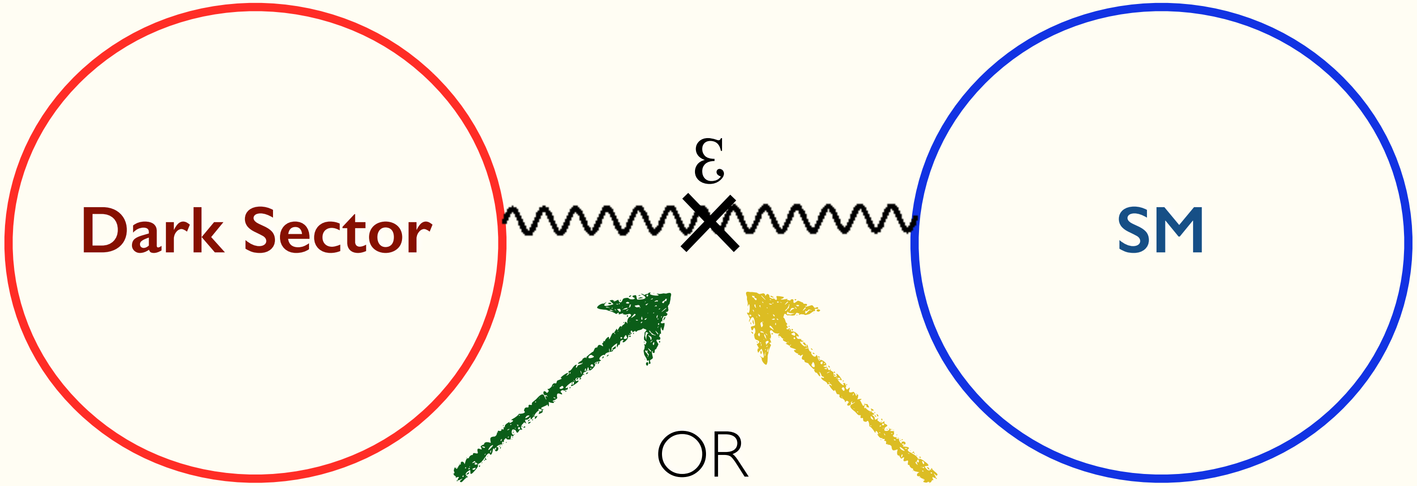

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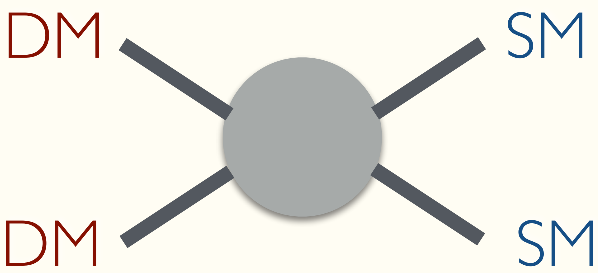
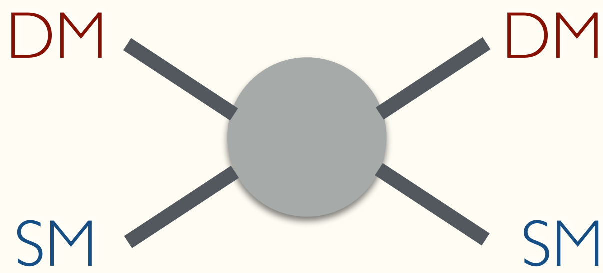
- Consequently, two more diagrams:



2-2 Annihilations



Thermal Equilibrium

3-2 Freeze Out

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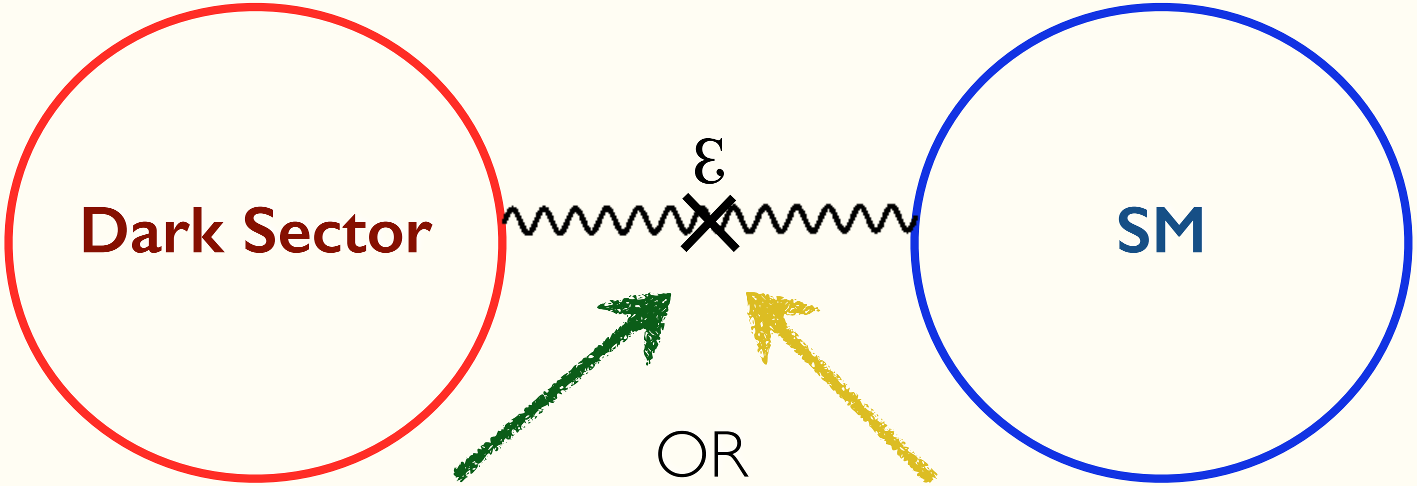

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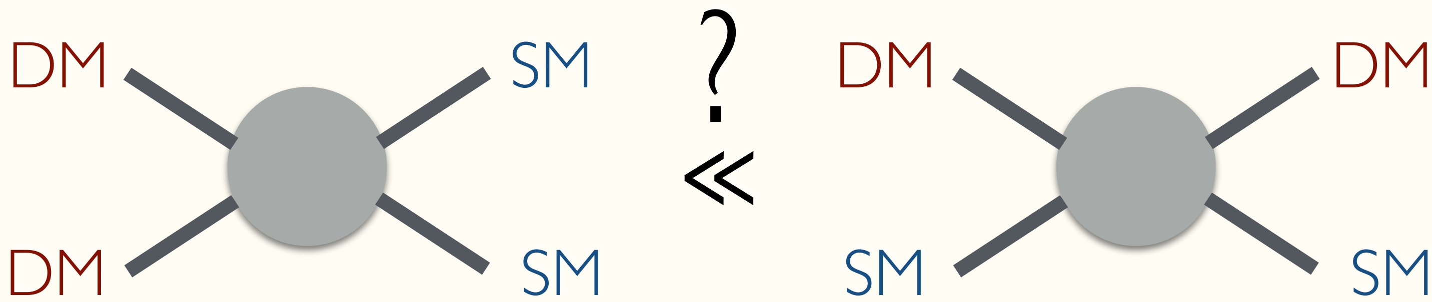
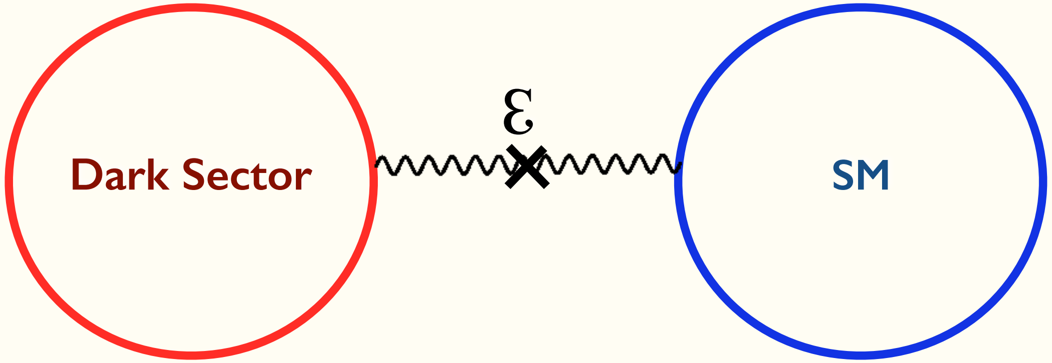


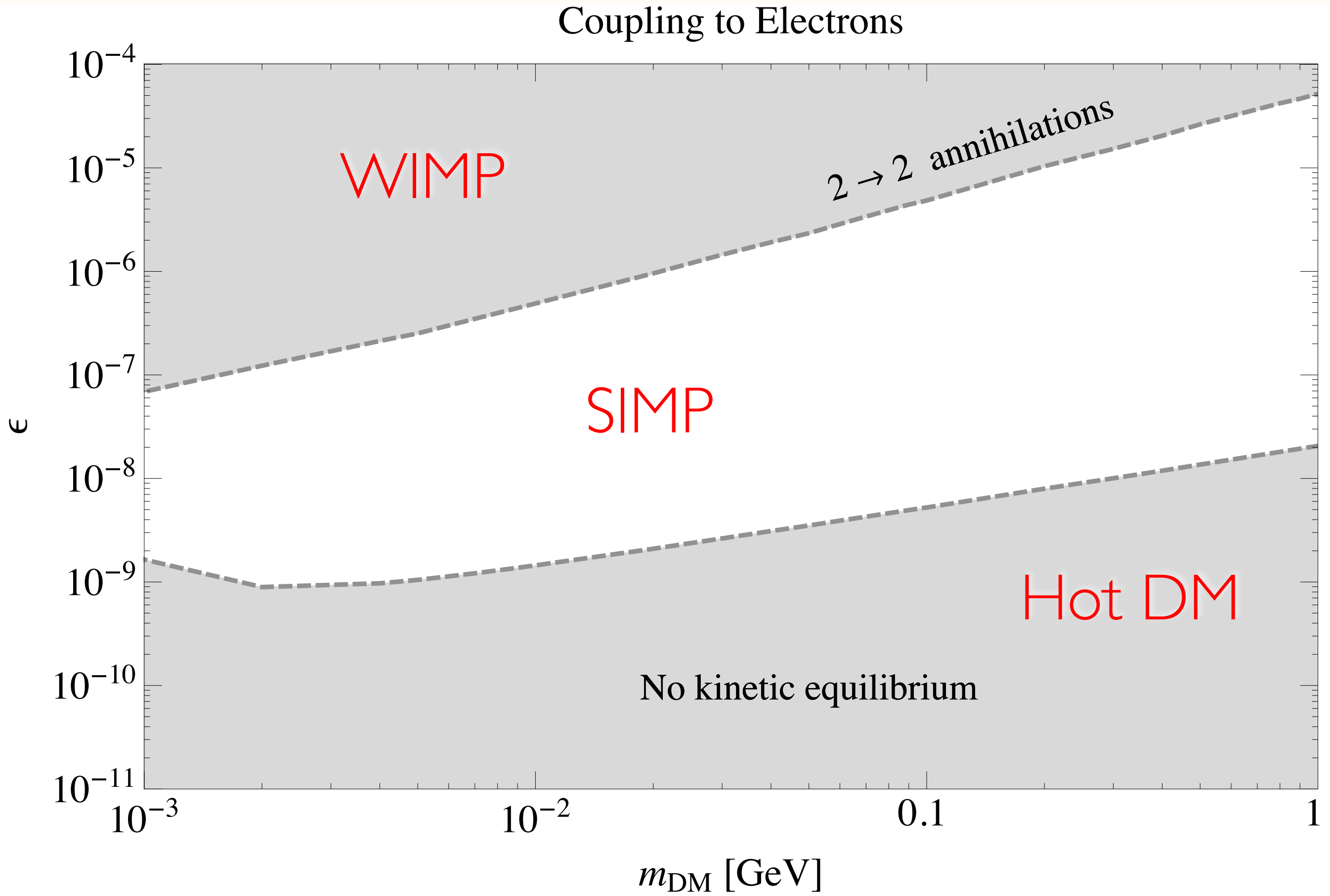
2-2 Annihilations

Thermal Equilibrium

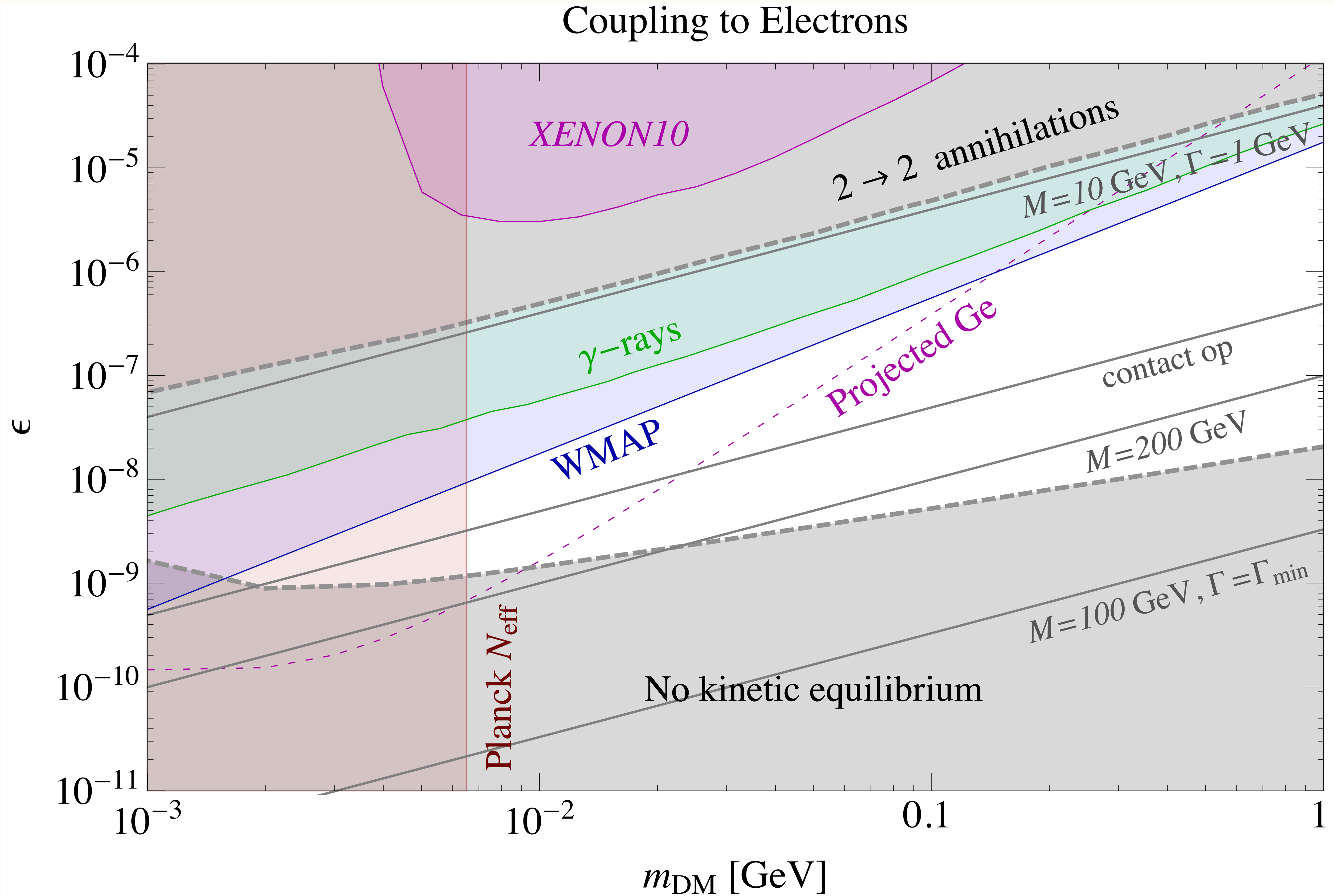
3-2 Freeze Out

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





SIMP DM: Experimental Status



SIMP Realization: QCD-like Theories

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

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

[Wess,Zumino 1971; Witten, 1983]

- 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) $\longrightarrow$ 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

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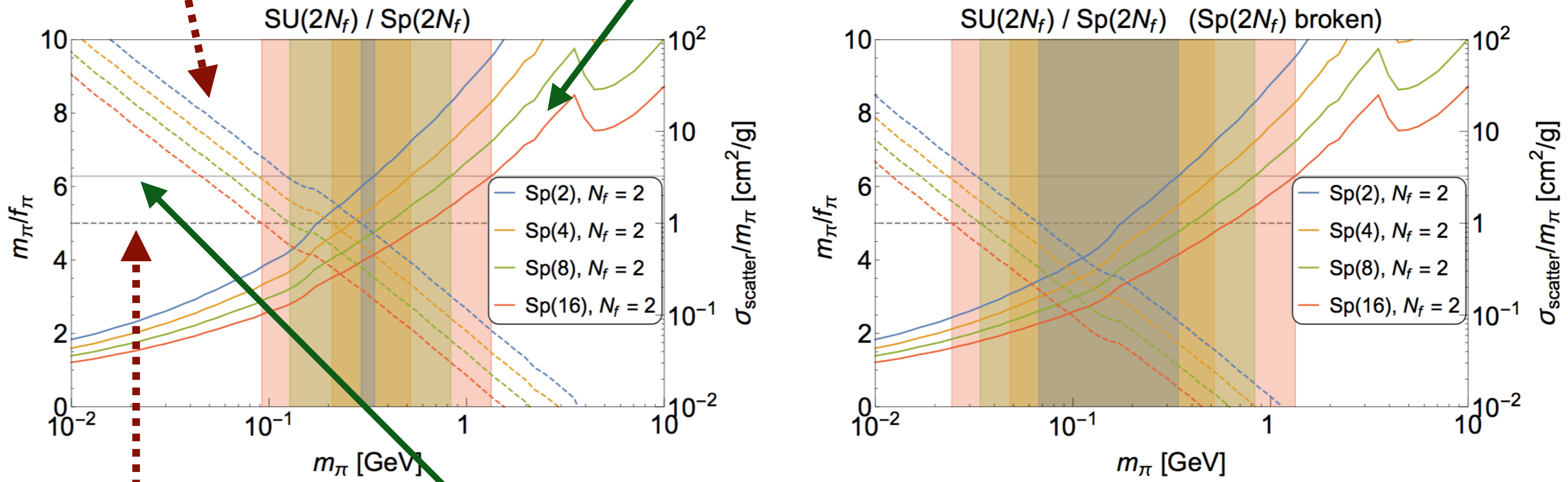
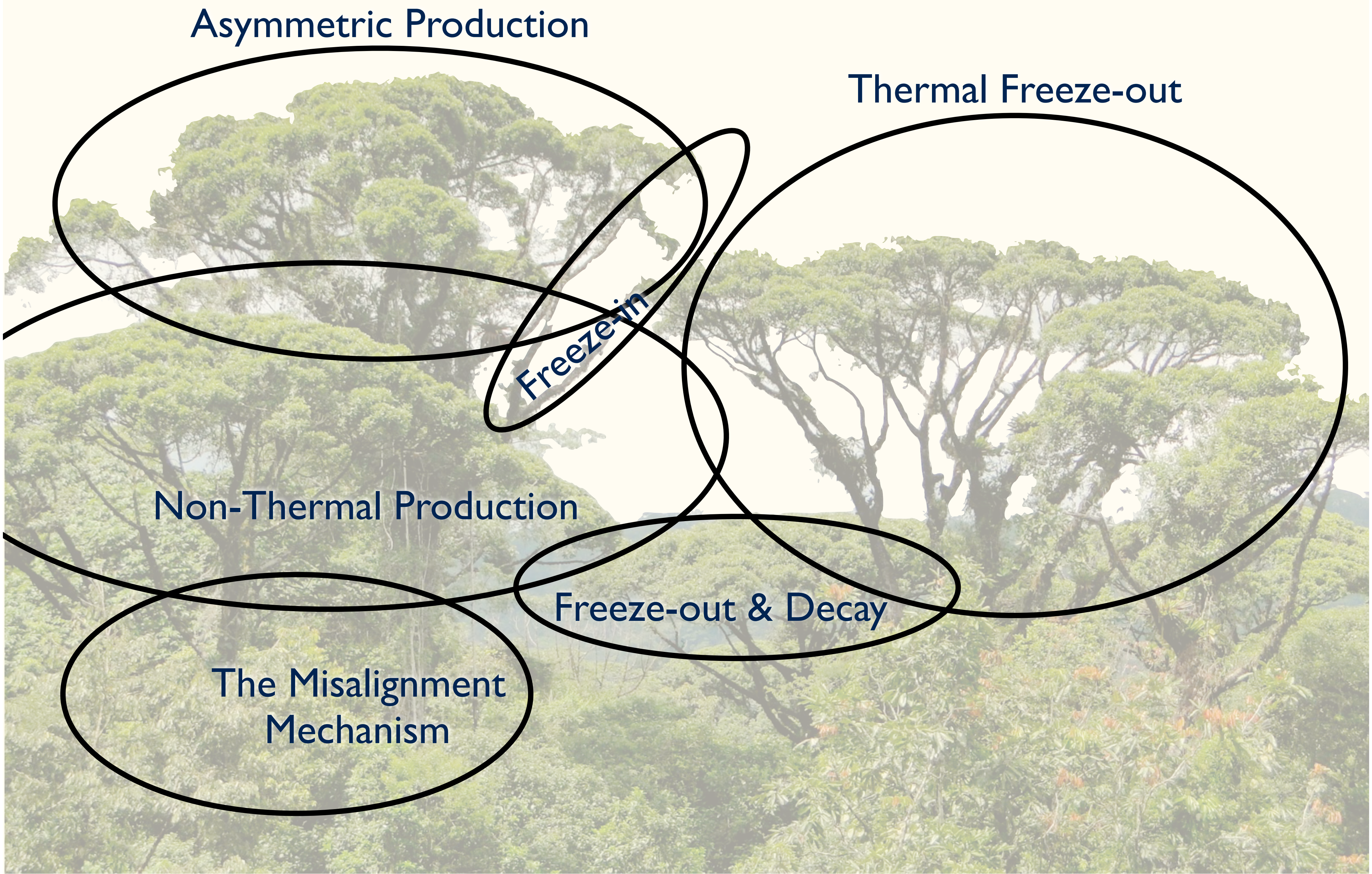
Predicted Self-Interaction

Solution to BE



Self-interaction bound

Perturbativity limit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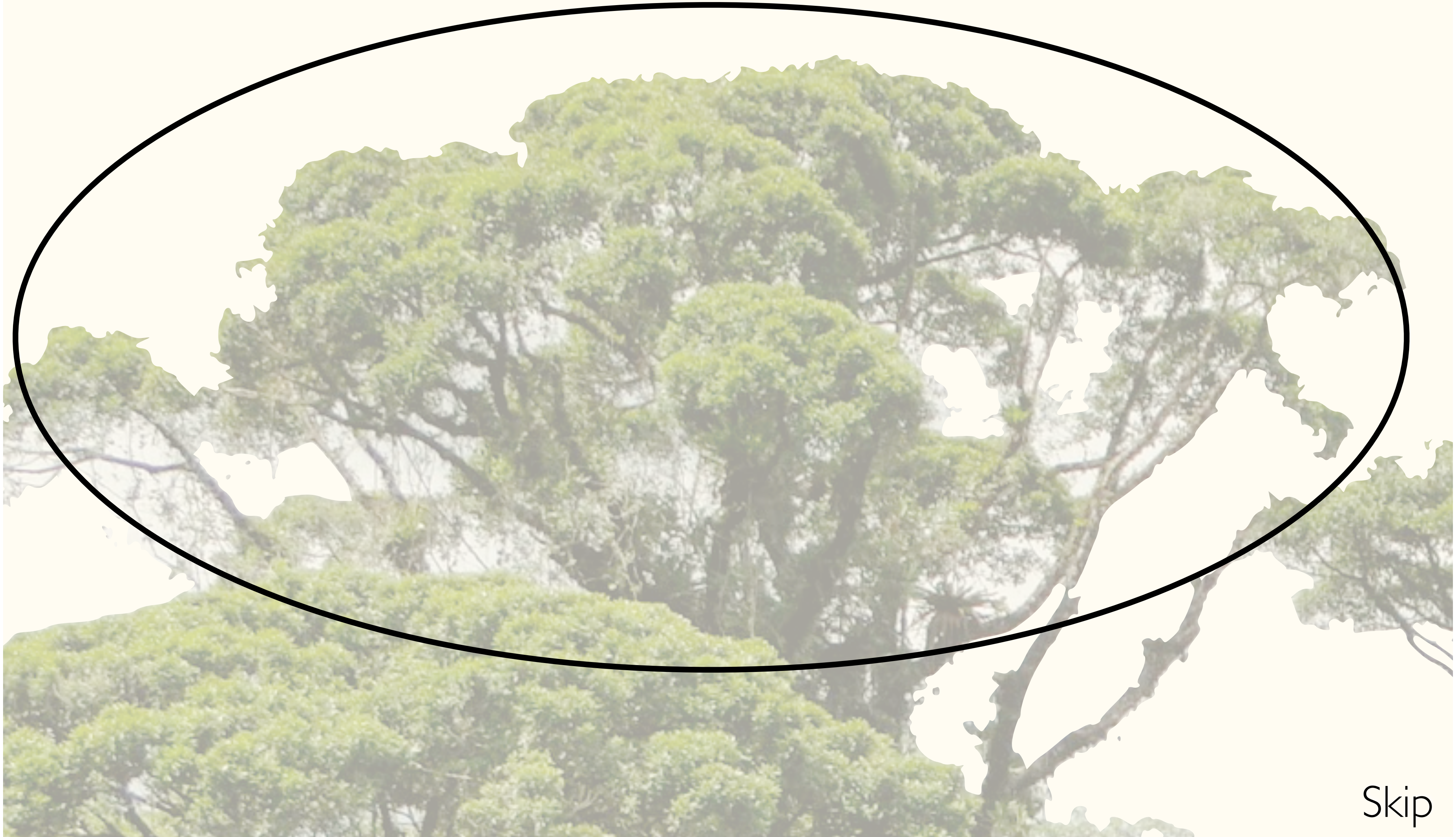
Asymmetric Production



Skip

Asymmetric DM

[Nussinov, 1985; , Kaplan, 1992]

Experimental fact:

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

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;...

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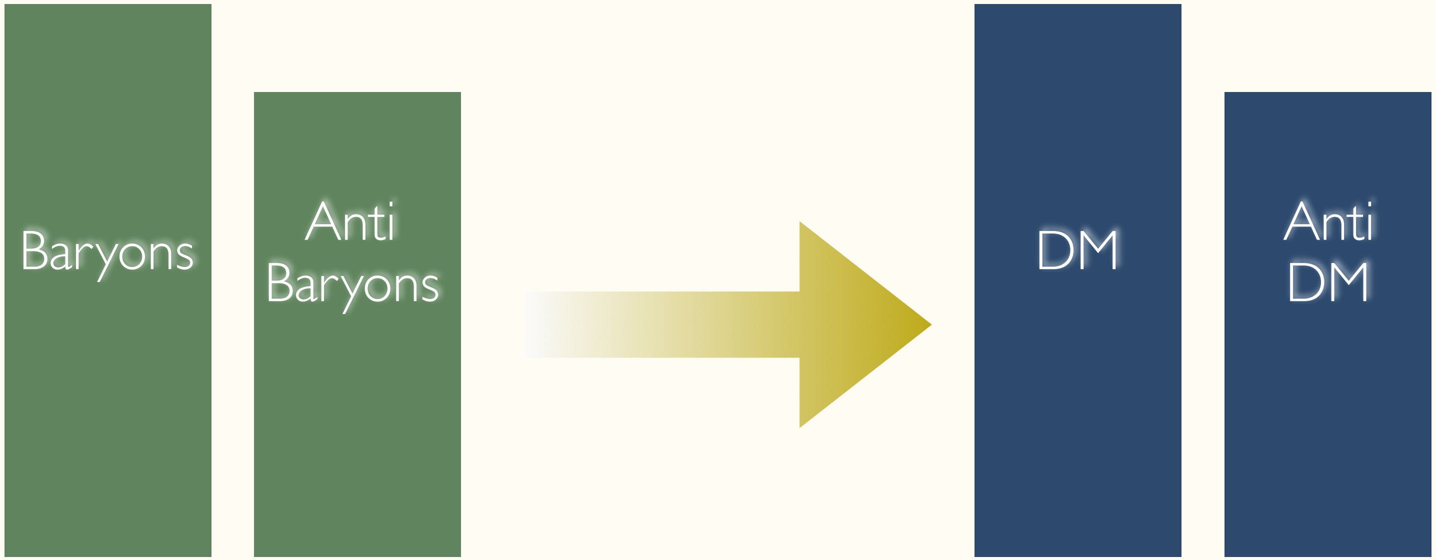

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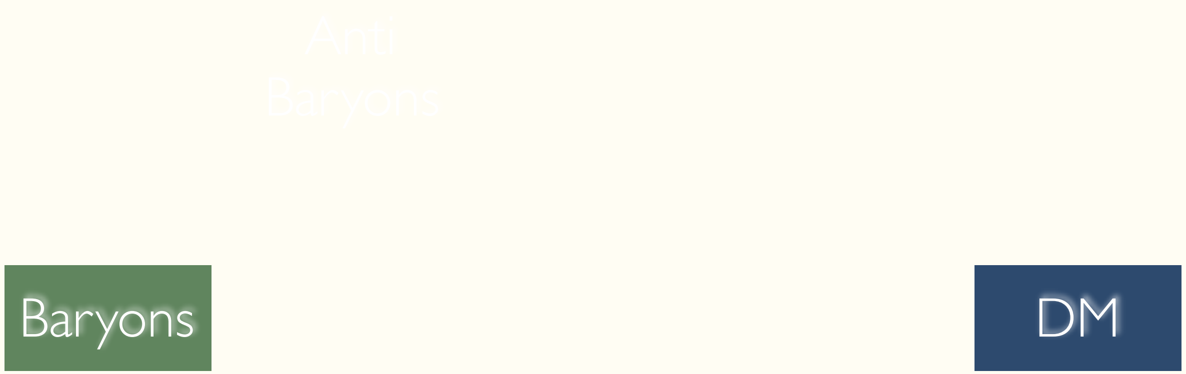

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- Whether or not the symmetric component dominates, depends on the DM annihilation cross-section

Asymmetric / Non-thermal

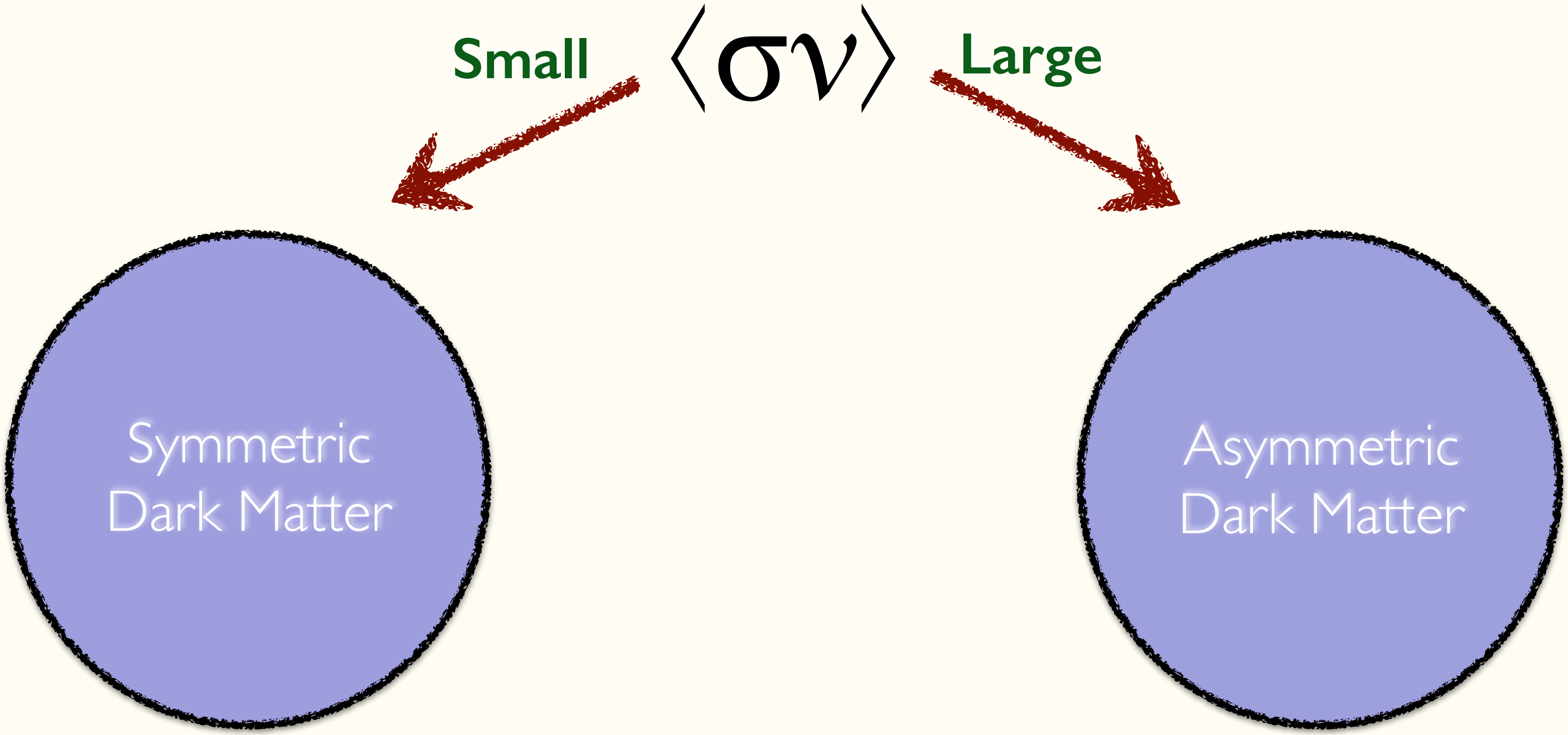
$$\Omega_{\rm DM} \simeq 5\Omega_b$$

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

Asymmetric Dark Matter

Asymmetric / Non-thermal

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

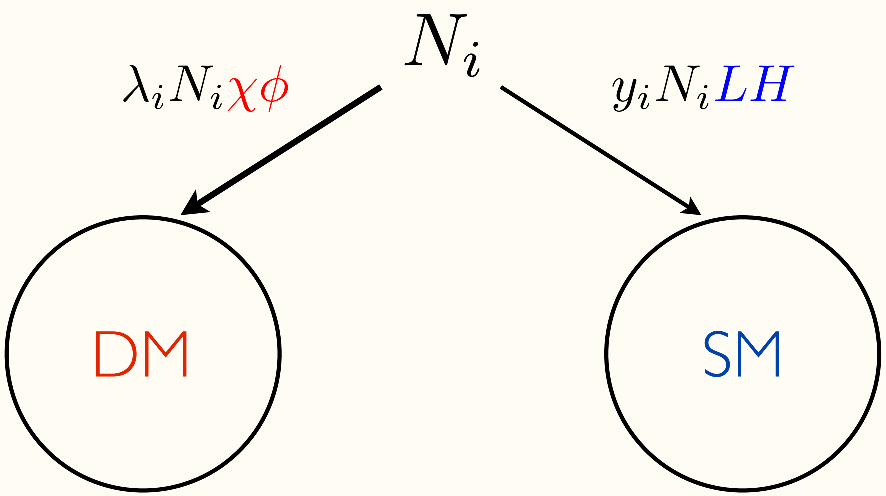


What should we expect here??

Sub-GeV?

- Simple scenario: 2-sector leptogenesis.

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



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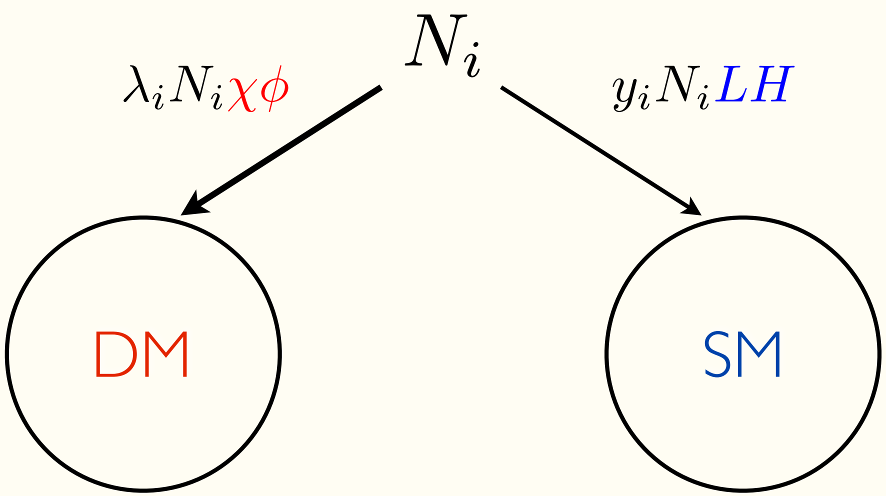
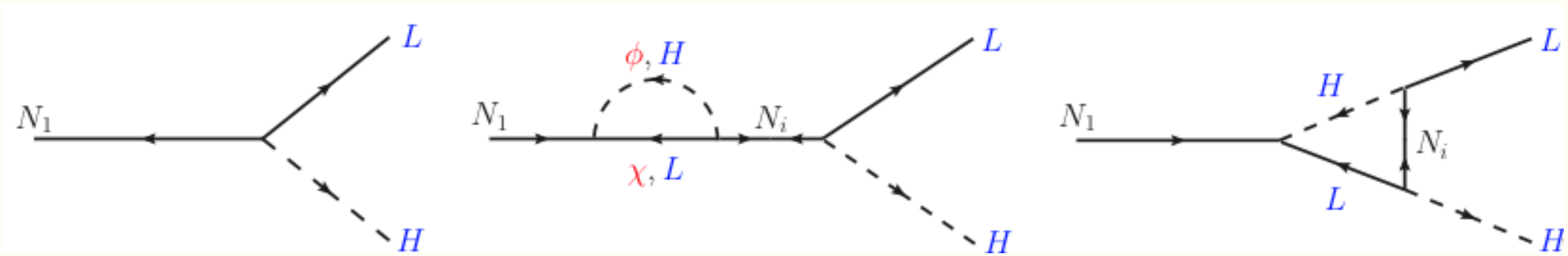


- When N decays it produces the baryon asymmetry through CP violation (loops):



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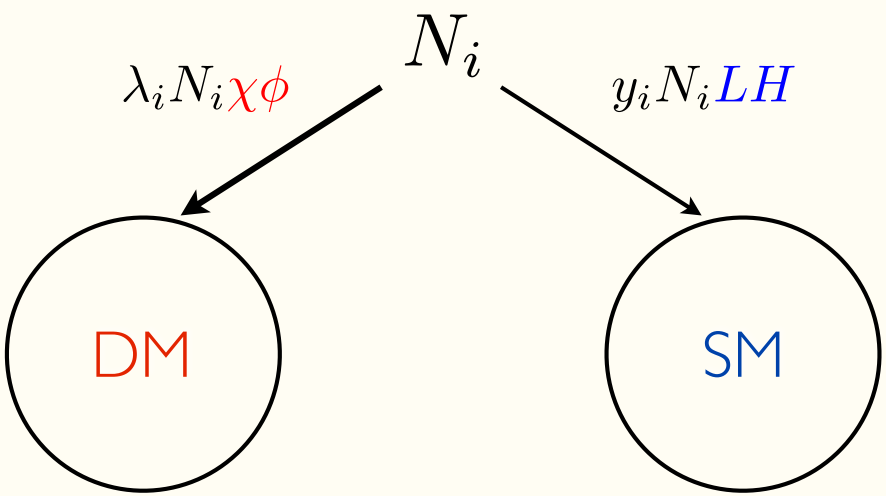

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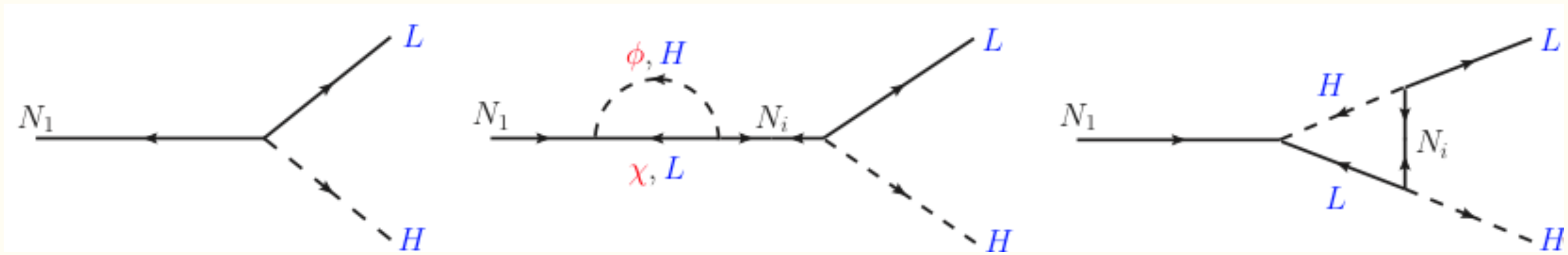
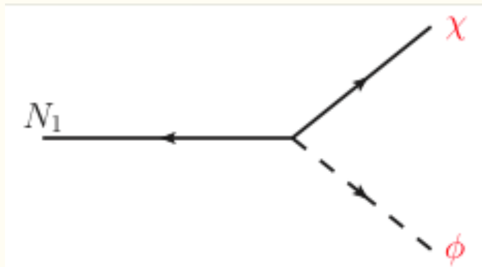


- Symmetric DM produced through tree level:



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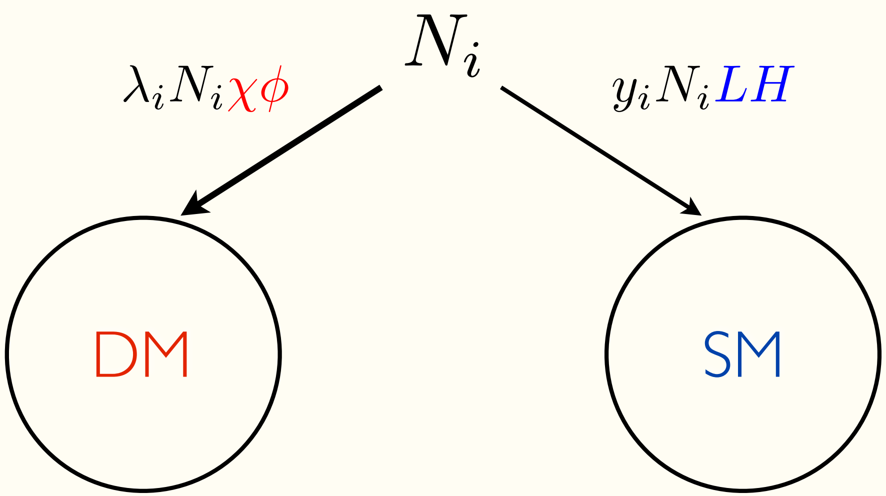


- Consequently, DM number density is generically larger than baryon number density:

$$n_{\rm DM} > n_b$$

$$m_{\rm DM} n_{\rm DM} = \Omega_{\rm DM} \simeq 5\Omega_b = m_{\rm p} n_b$$

- To have the same mass density:

$$m_{\rm DM} < m_p \simeq \ \text{GeV}$$

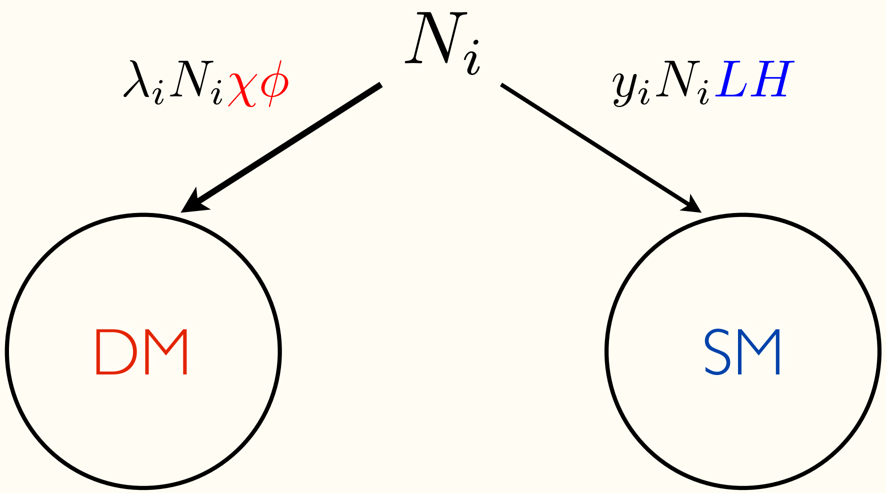
- And hence:

Light DM

Sub-GeV?

- Simple scenario: 2-sector leptogenesis.

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



- One typically finds (preliminary): $m_{DM} \sim O(\text{keV})$

$$\mathcal{L}_{\text{eff}} \sim \frac{\chi \phi L H}{M}$$

$$\langle \phi \rangle \neq 0$$

New
Production Mechanism

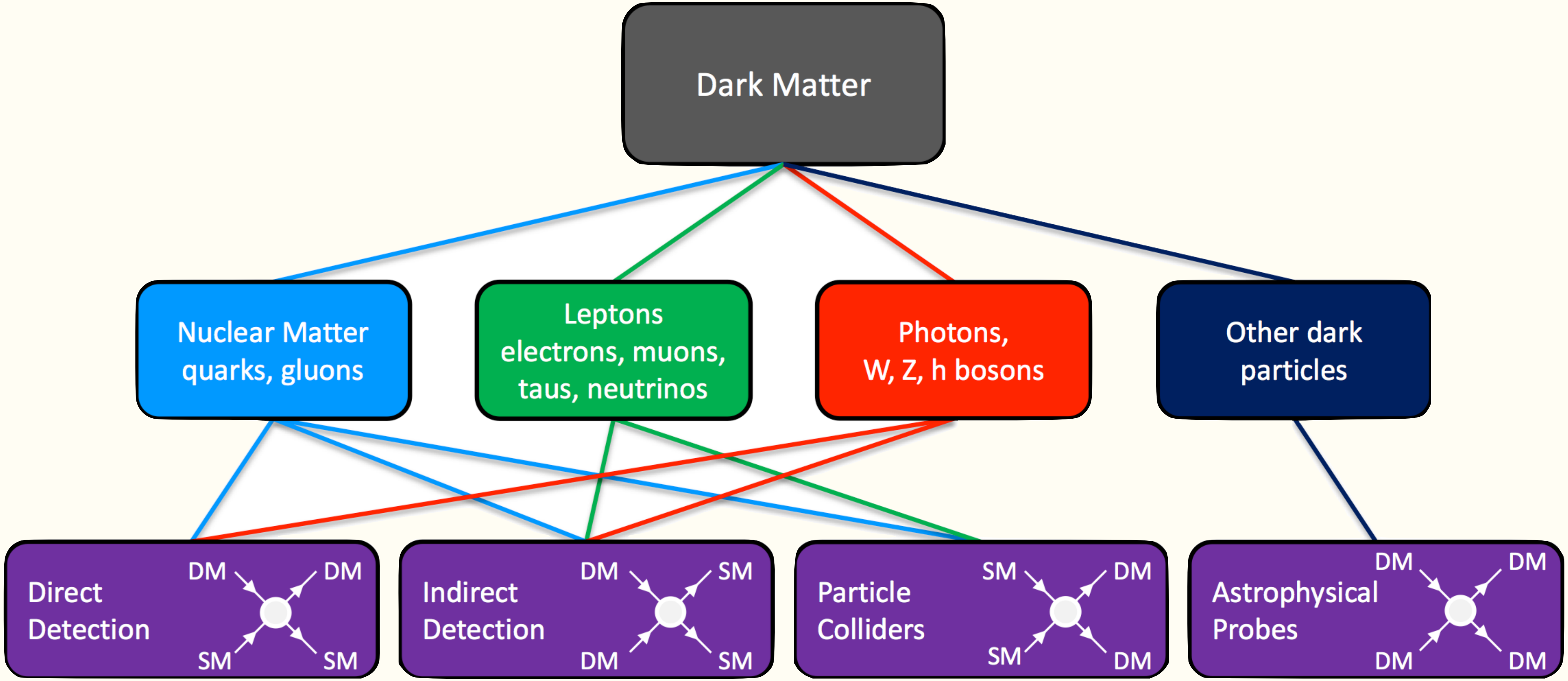
χ

Sterile neutrino
with possible self-interactions

Searching for a Dark Sector

Searching for a Dark Sector

Searching for DM



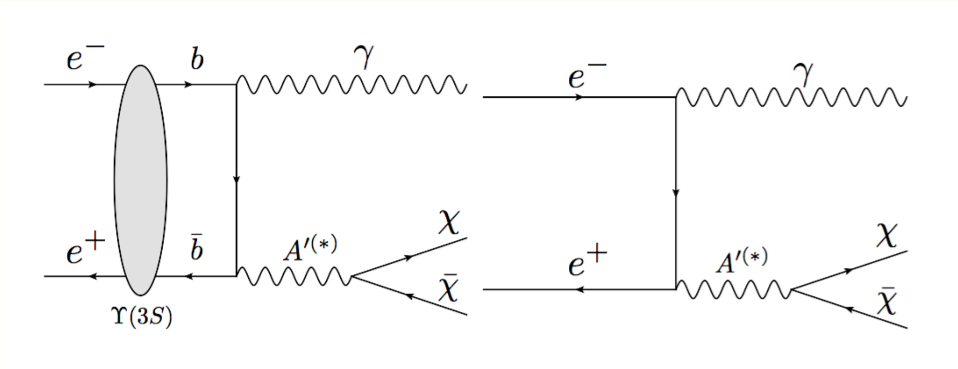
[Snowmass report, 2013]

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

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

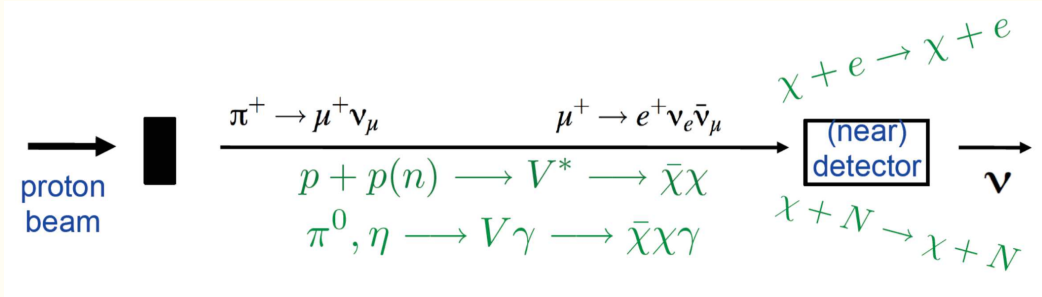
Collider Experiments

Low-E Colliders



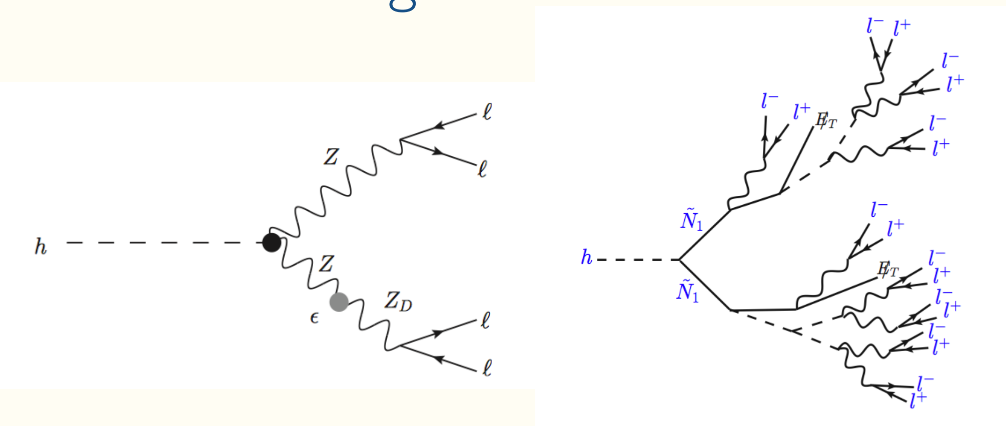
[Bird et al. 2004; McElrath 2005; Fayel 20105; Dreiner et al. 2009; Freytsis et al. 2009; Borodatchenkova et al. 2006; Reece, Wang 2009; Essig., Mardon, Papucci, TV, Zhong, 2013]

Neutrino Experiments



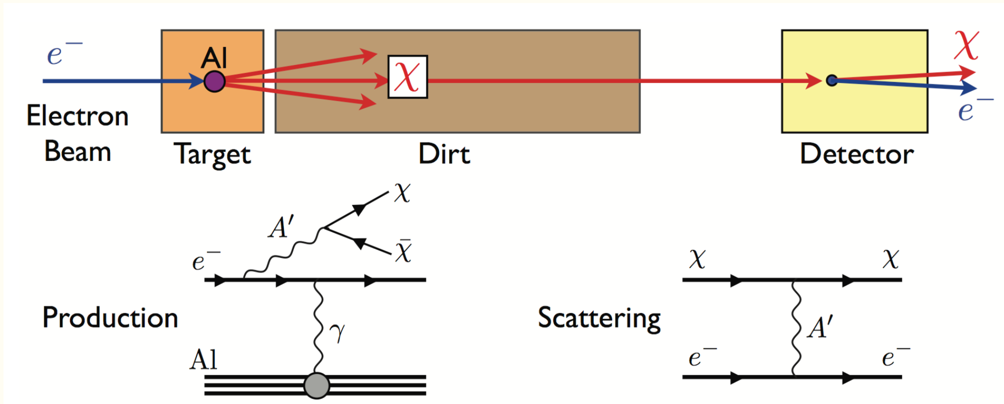
[MiniBooNE + Batell, deNiverville, McKeen, Pospelov, Ritz 2012]

High-E Colliders



[Falkowski, Ruderman, TV, Zupan, 2010; Curtin, Essig, Gori, Shelton, 2014; Ilten et al. 2015; Ilten et al. 2016]

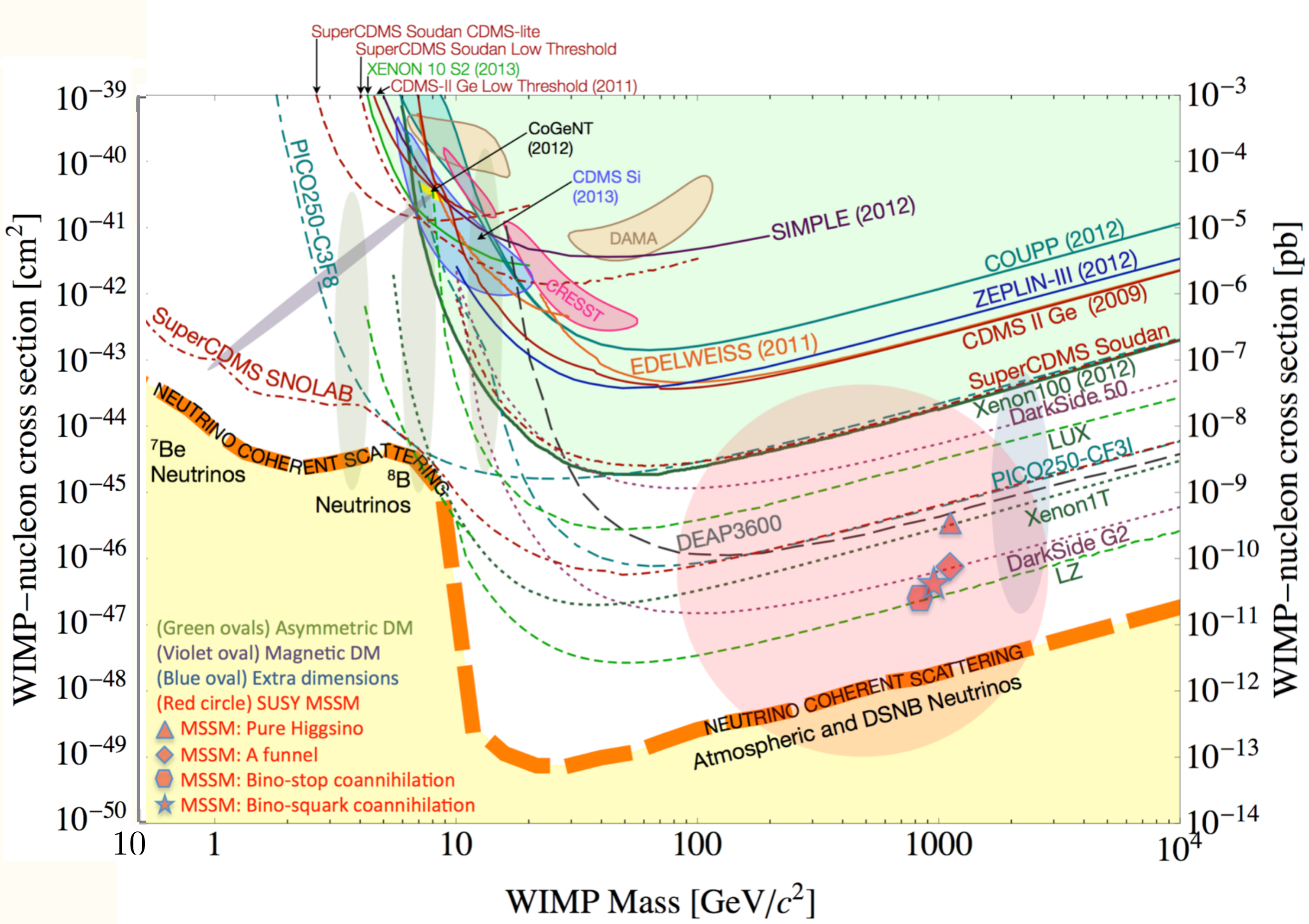
Electron Beam-dumps



[Batell, Essig, Surujon 2014]

Prospects for Direct Detection

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



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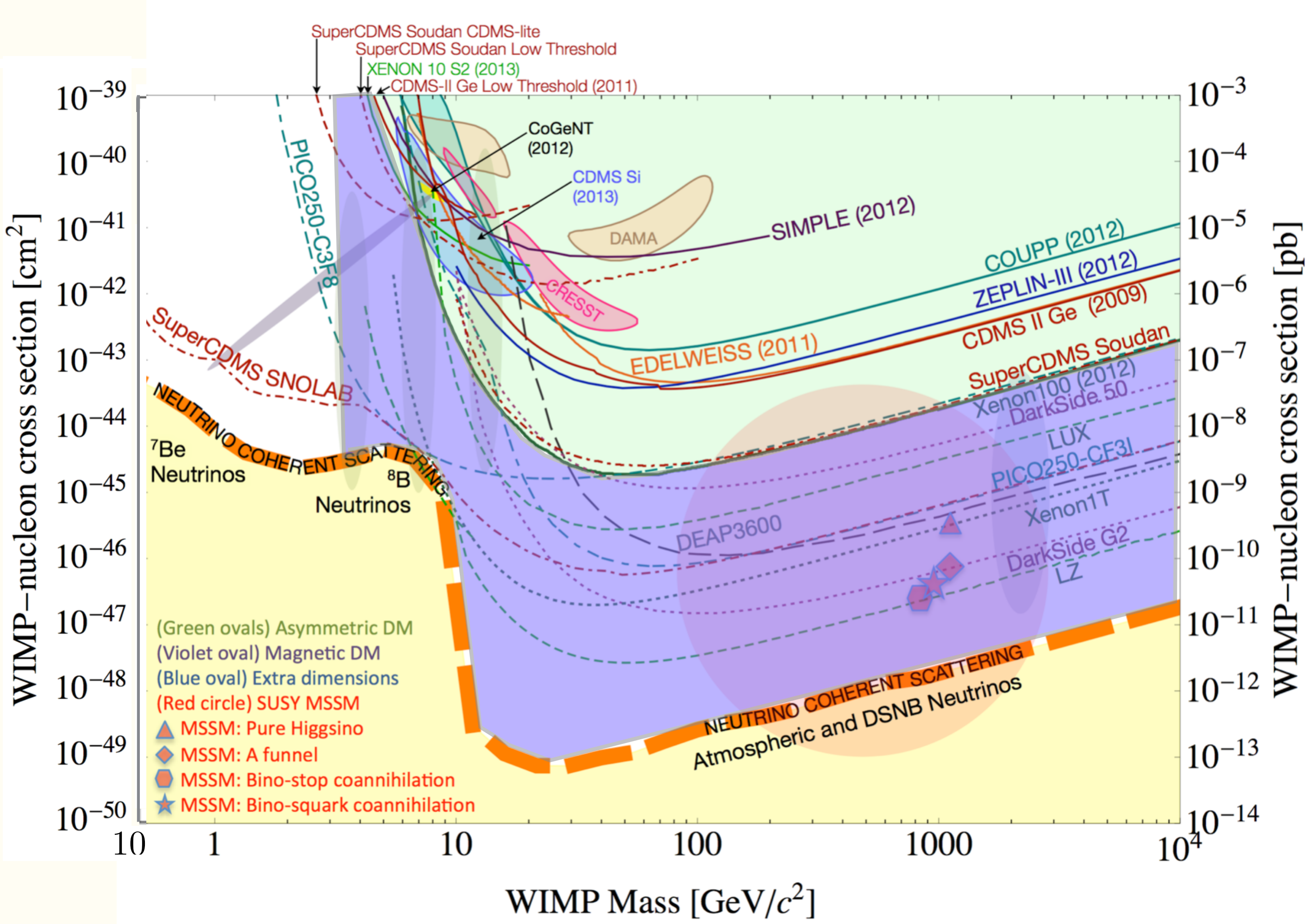
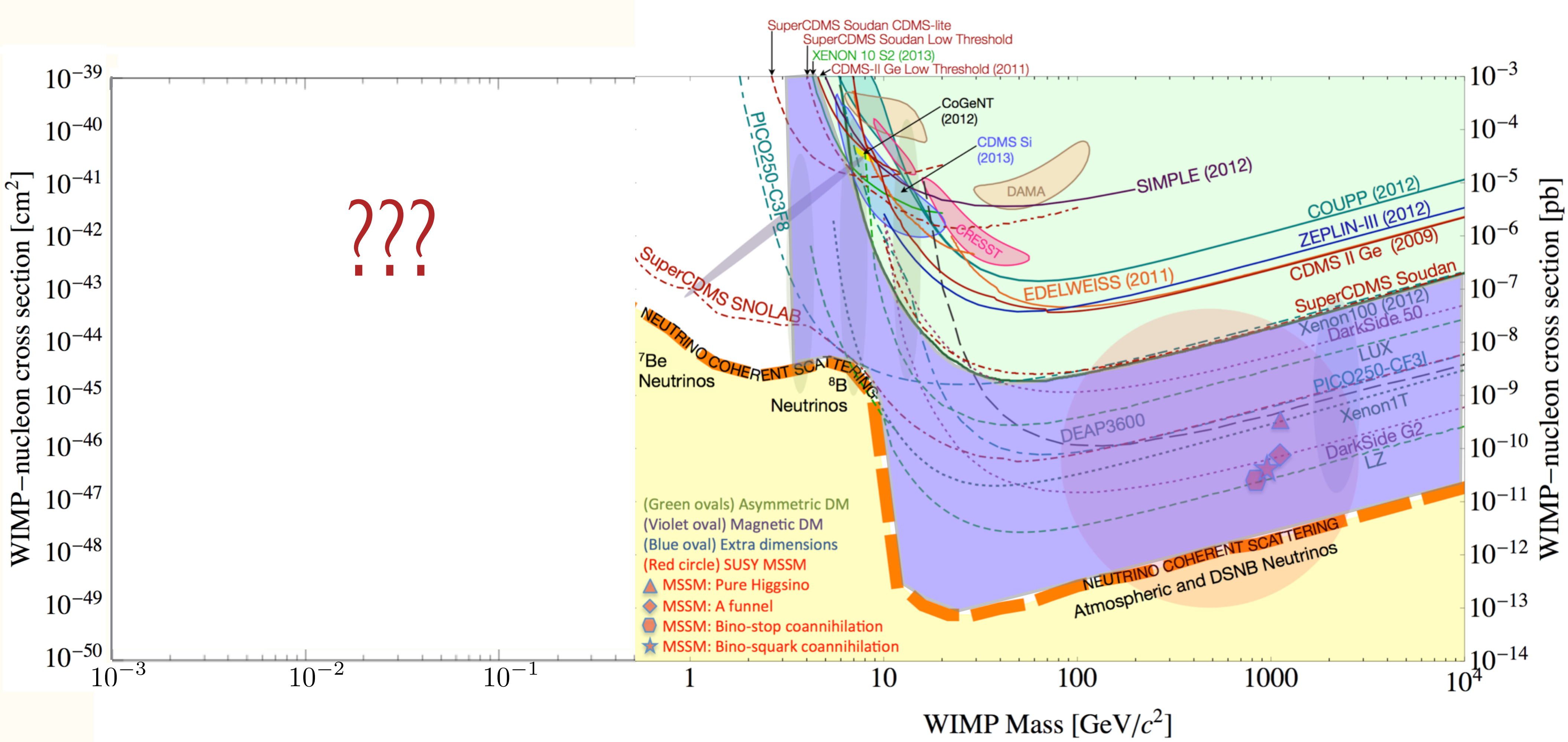


Prospects for Direct Detection

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

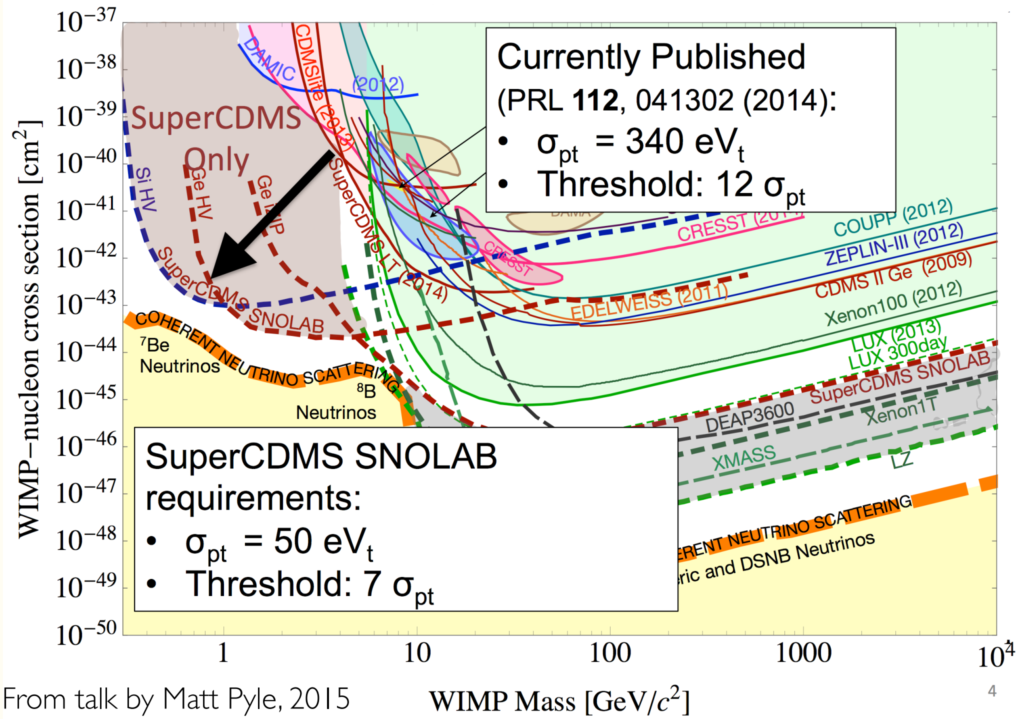


Direct Detection of Light and Exotic DM

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

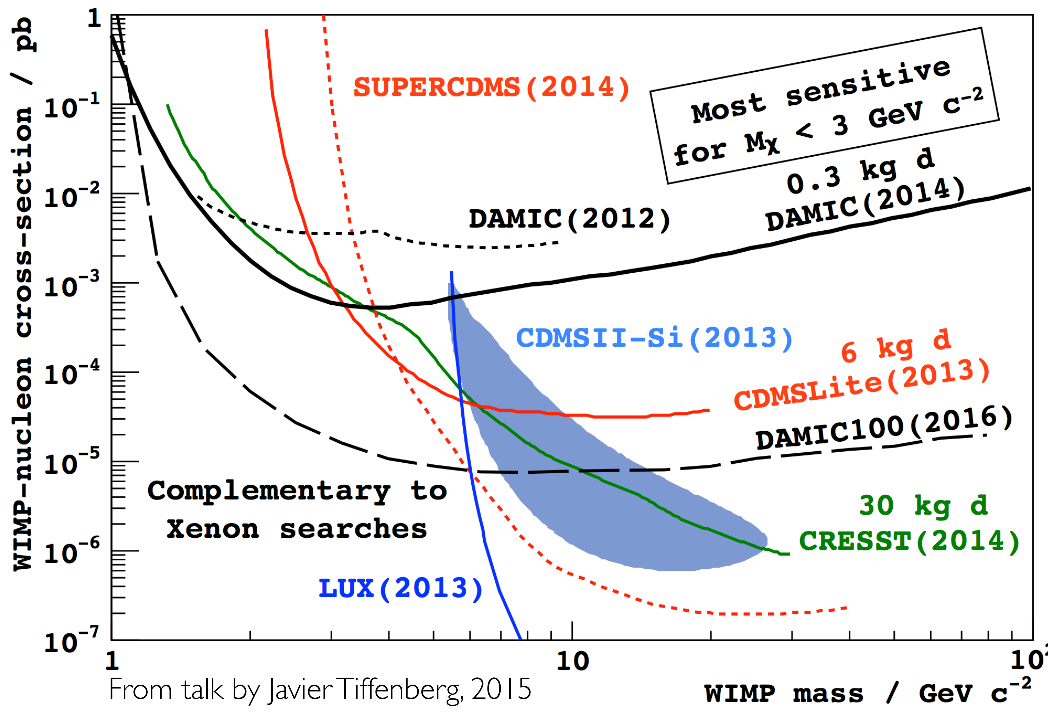
Threshold ≳ 10-50 eV

SuperCDMS



From talk by Matt Pyle, 2015

DAMIC



From talk by Javier Tiffenberg, 2015

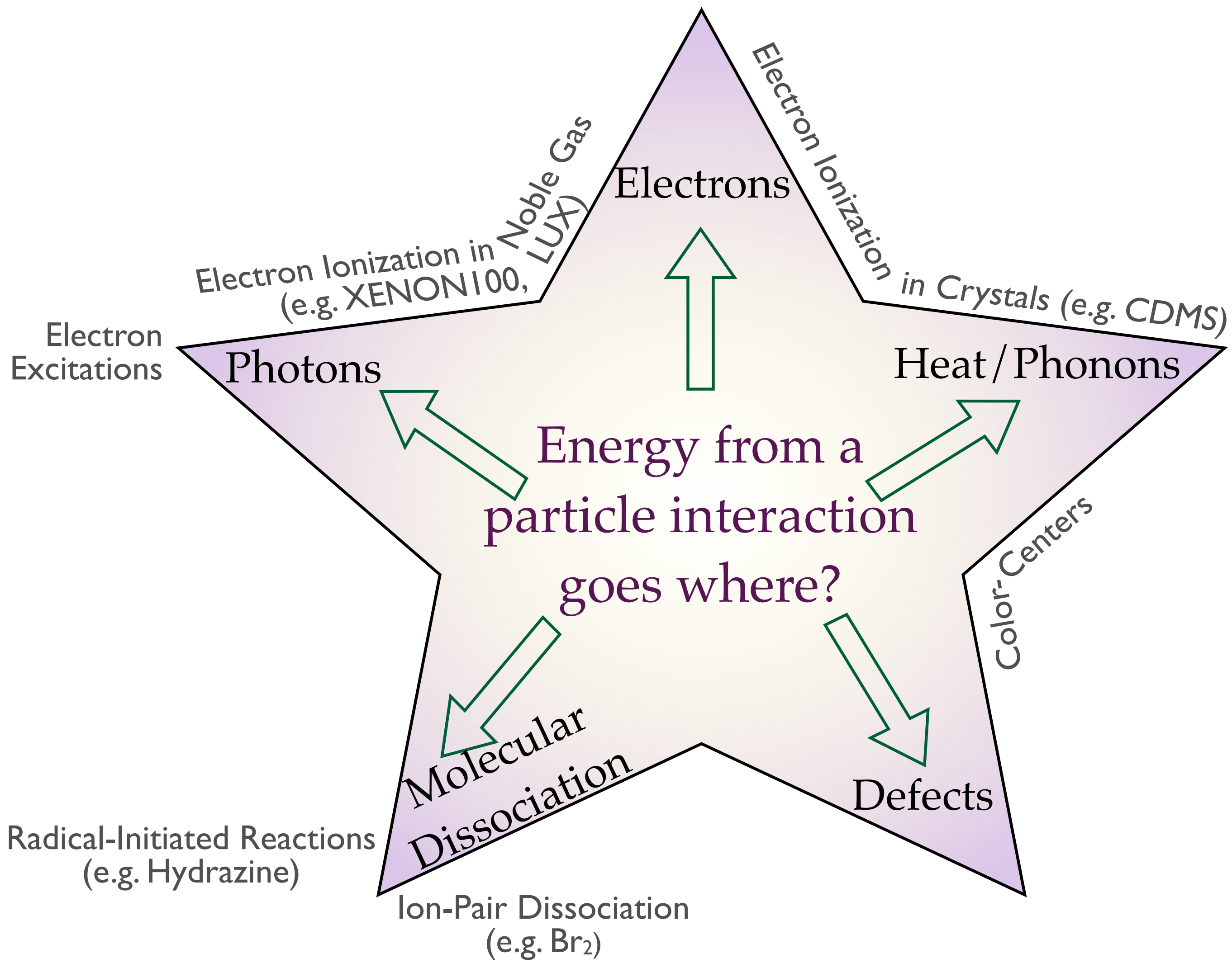
Direct Detection of Light and Exotic DM

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

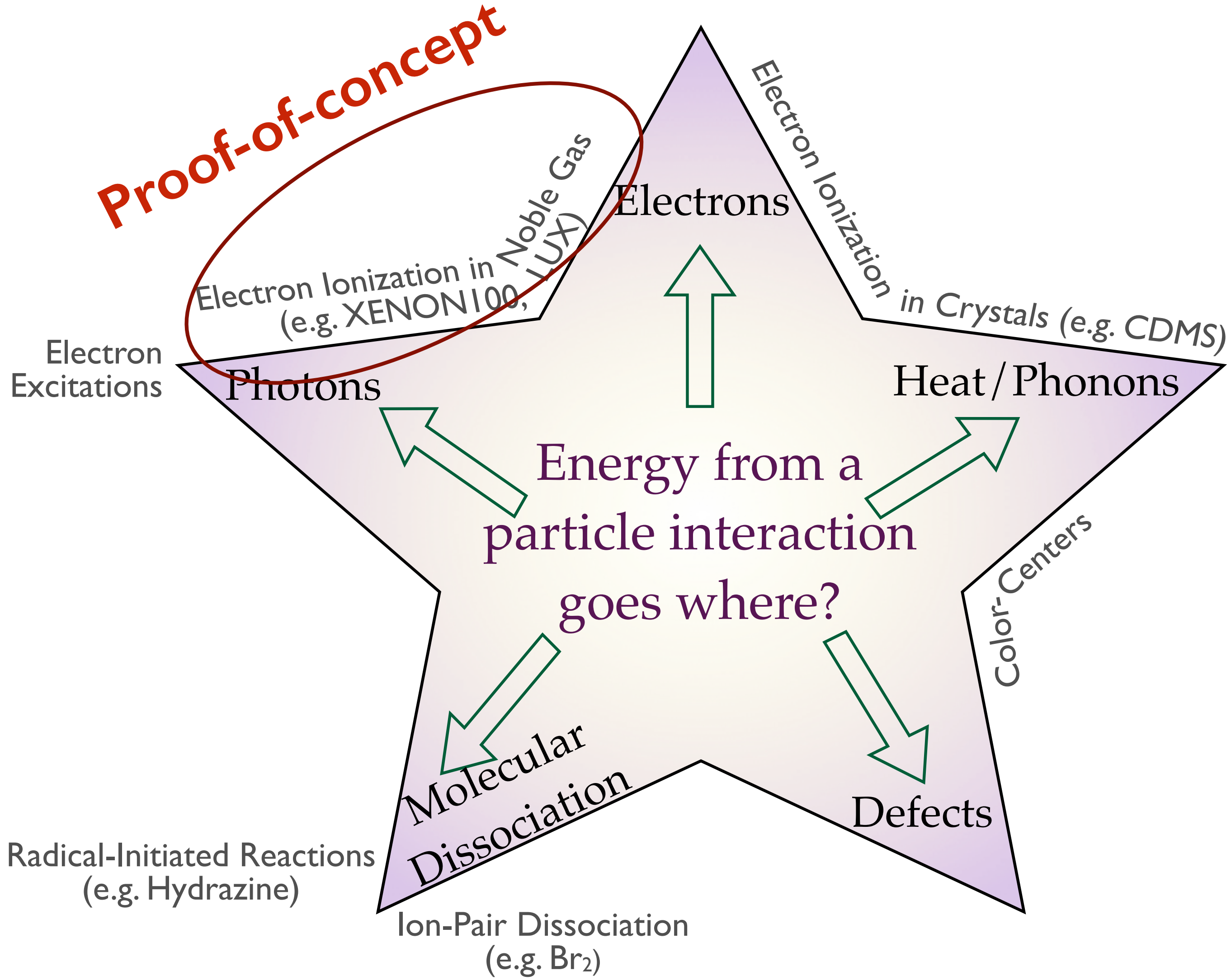
[Essig, Mardon, TV, 2011]

Threshold $\gtrsim 0.1$ eV

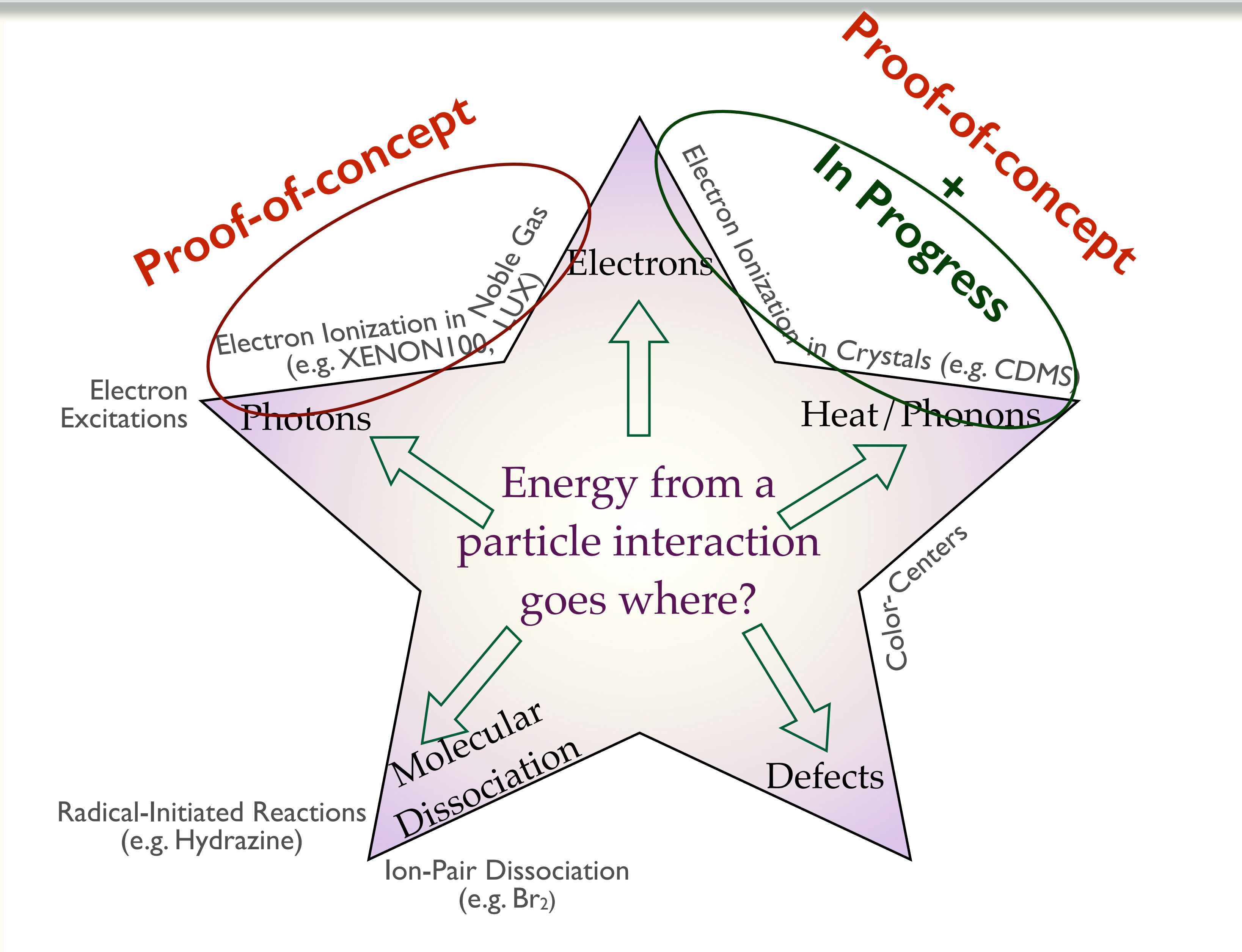
Detectable Signals



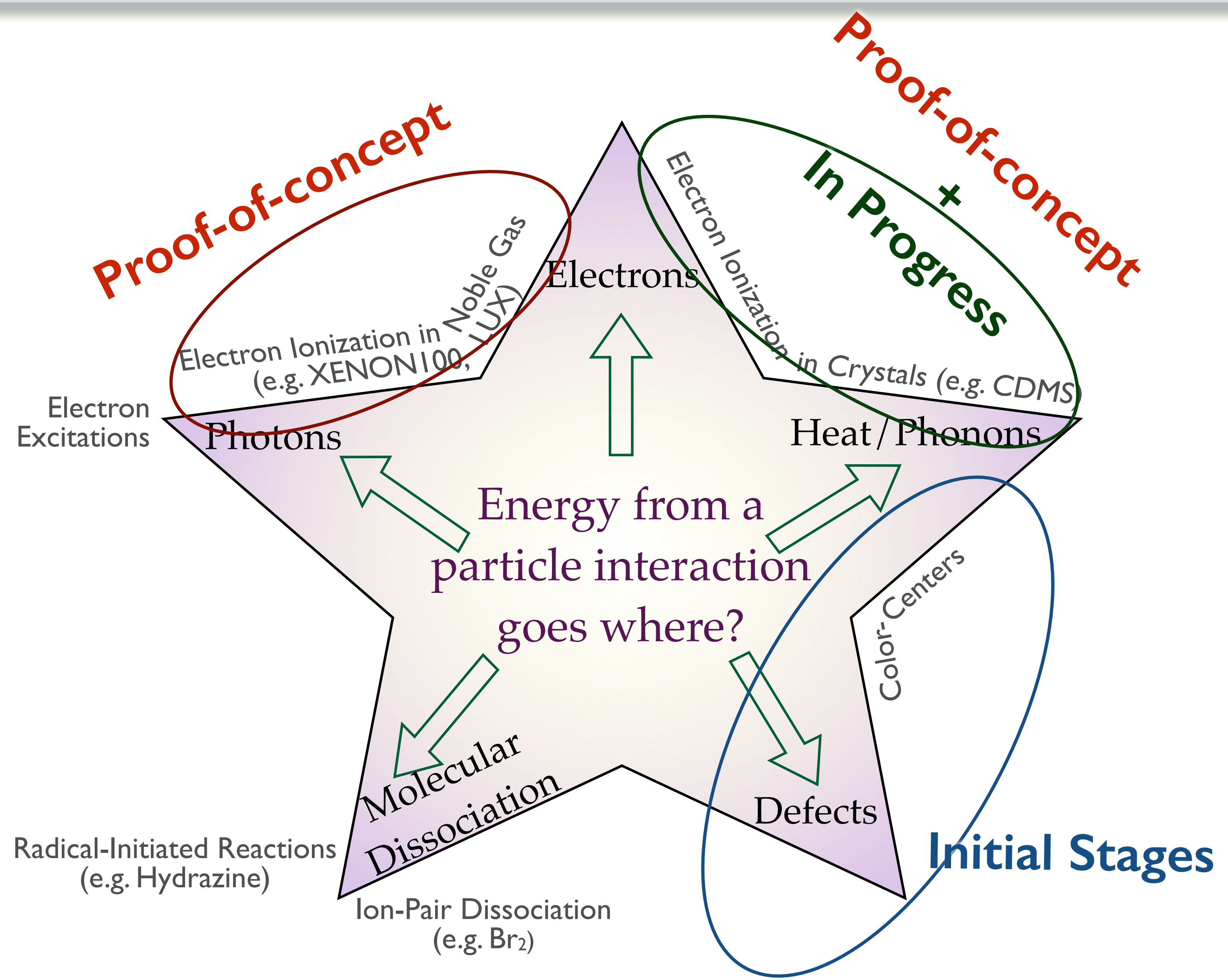
Detectable Signals



Detectable Signals



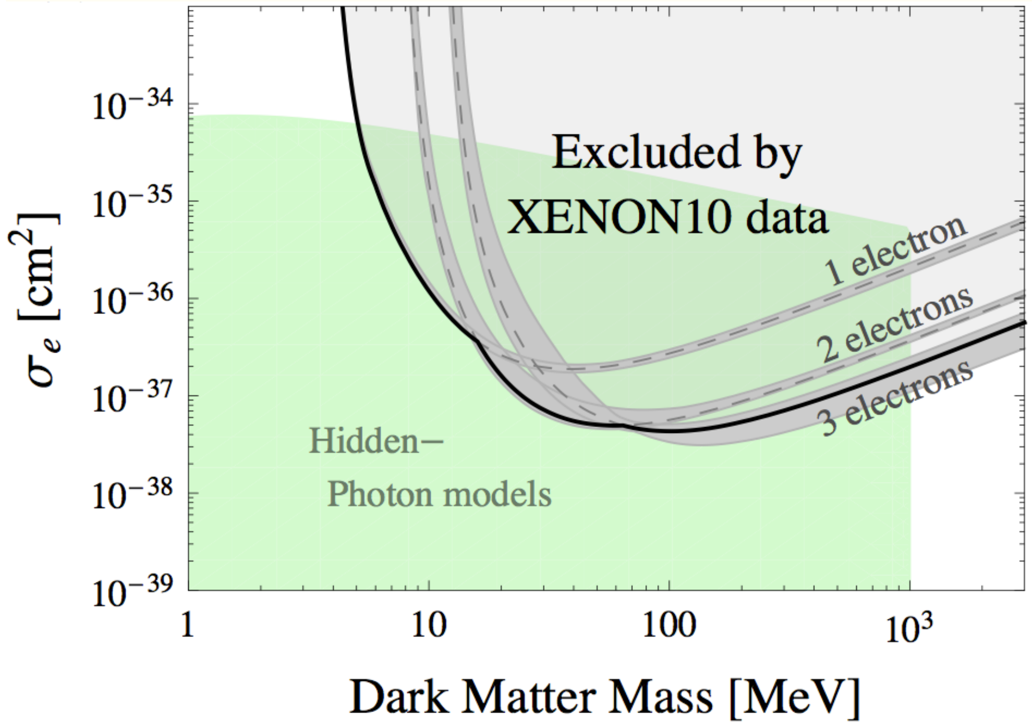
Detectable Signals



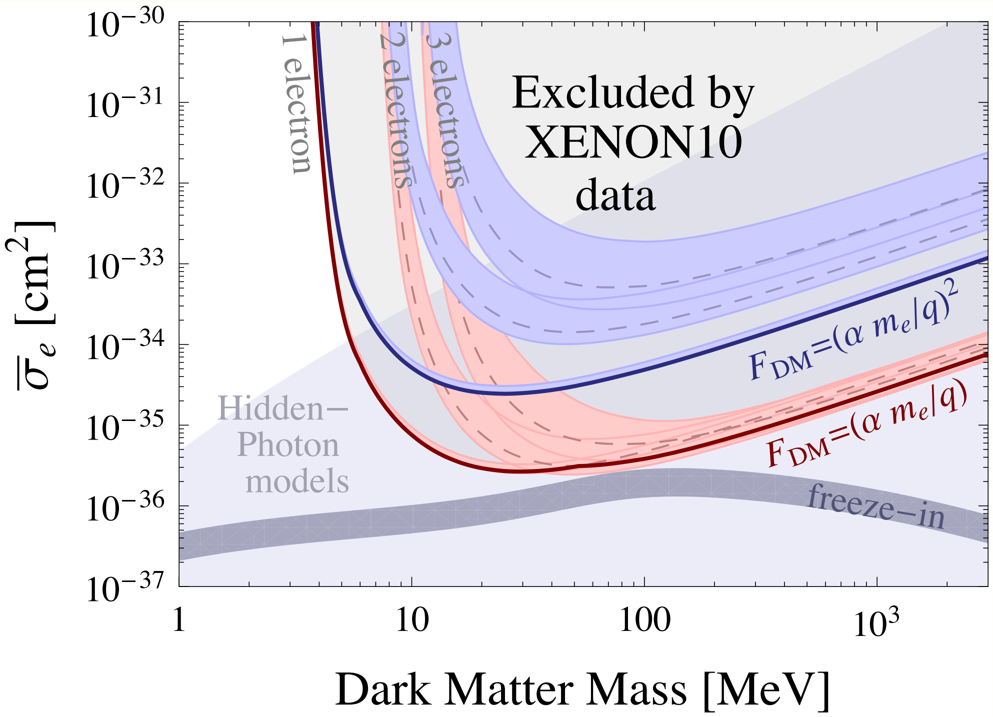
Electron Ionisation in Noble Gas

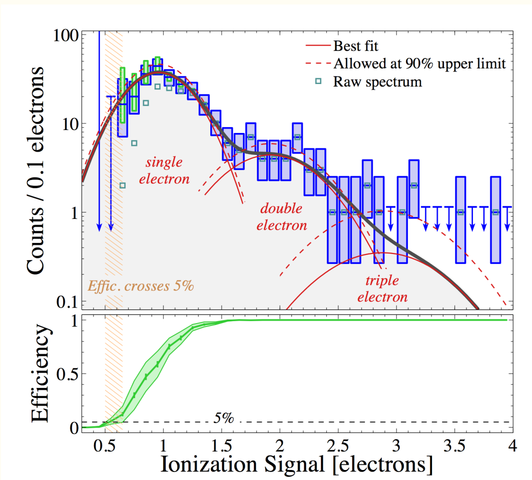
XENON10

$F_{DM}=1$



$F_{DM}=1/q,\ 1/q^2$



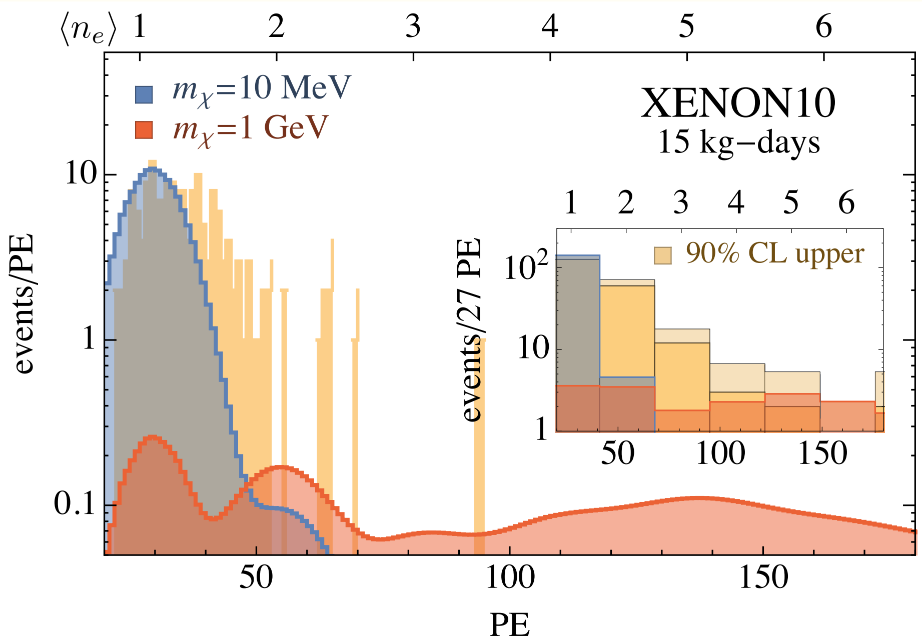


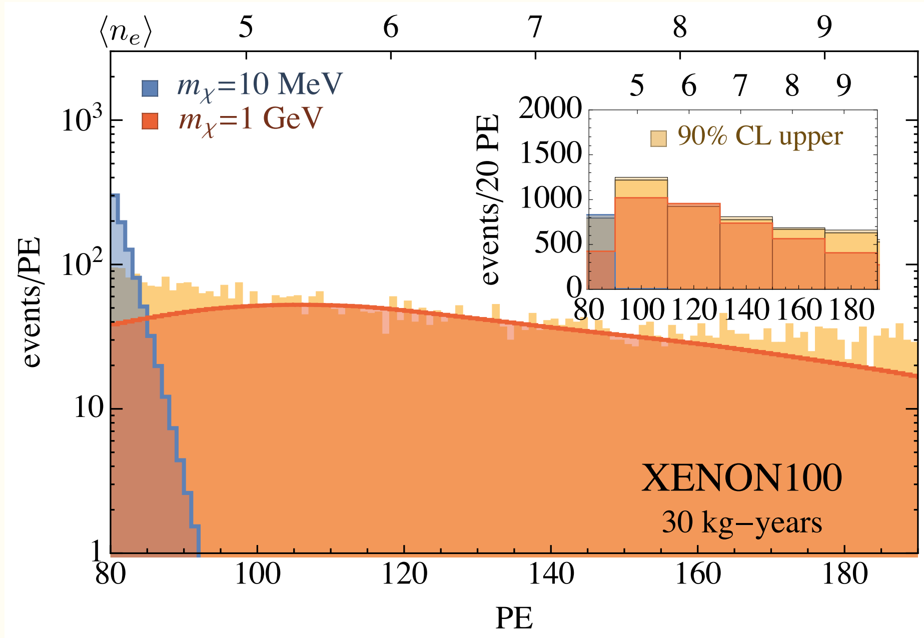
[Essig,Manalaysay,Mardon,Sorensen,TV, 2012]

Electron Ionisation in Noble Gas

XENON10 & XENON100
(Reanalysis)

[Essig,,TV,Yu, 2017]



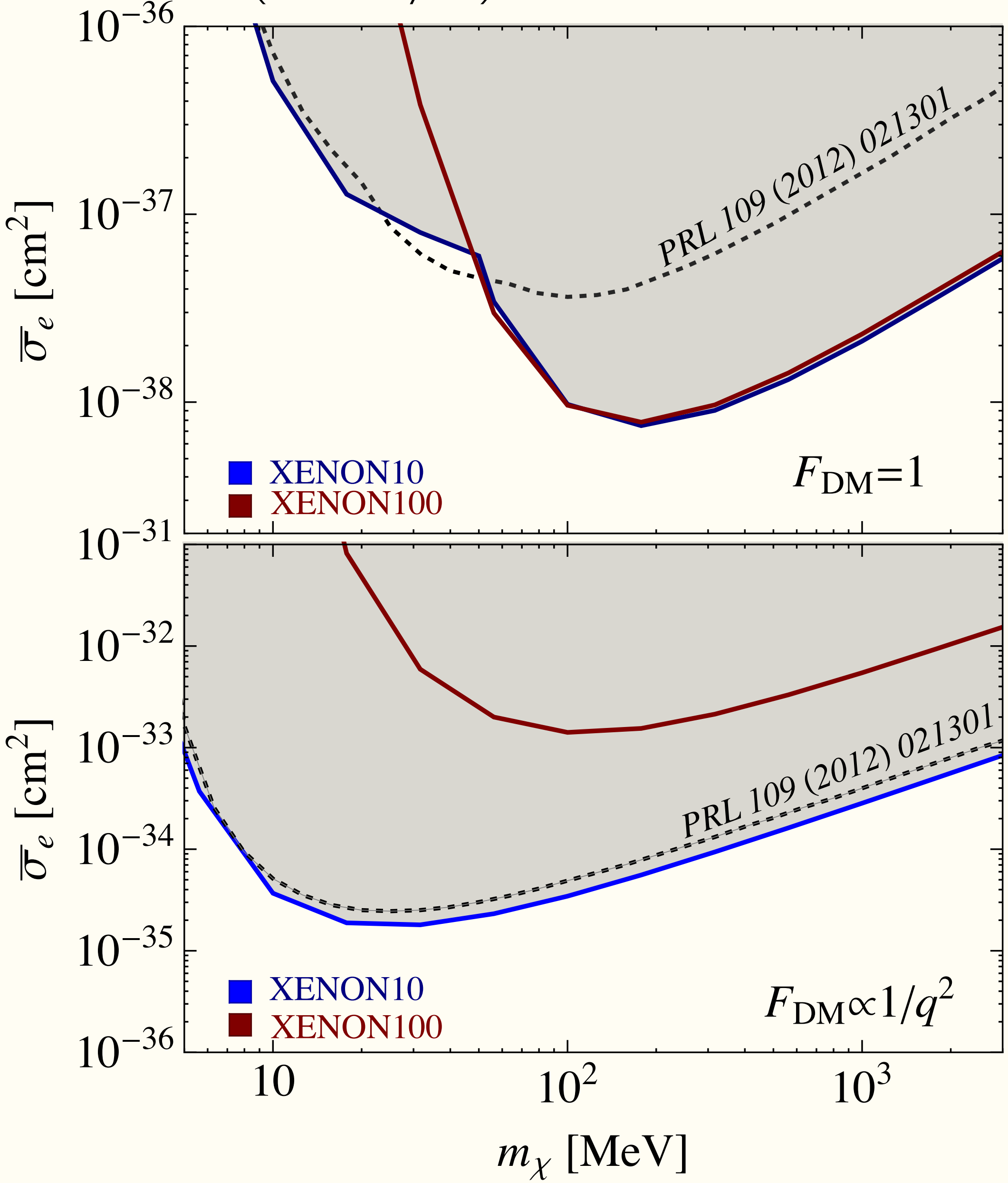


XENON100 has much more data, but a higher threshold

Electron Ionisation in Noble Gas

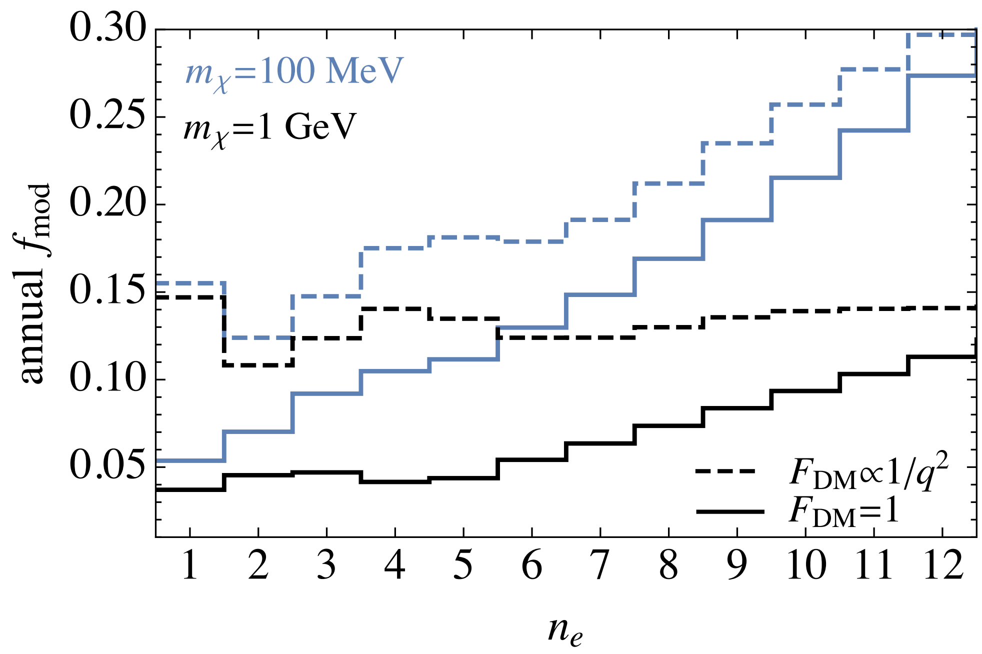
[Essig,,TV,Yu, 2017]

XENON10 & XENON100
(Reanalysis)



Electron Ionisation in Noble Gas

- Event rate in these experiments can be very high (event/minute in Xenon100, event/sec in LZ).
- Some idea for the origin (e.g. photo-dissociation of negatively charged impurities, electrons trapped in the liquid-gas interface, field emission from the cathode).
- Could it be DM? Probably not, but who knows…
- Study modulation!

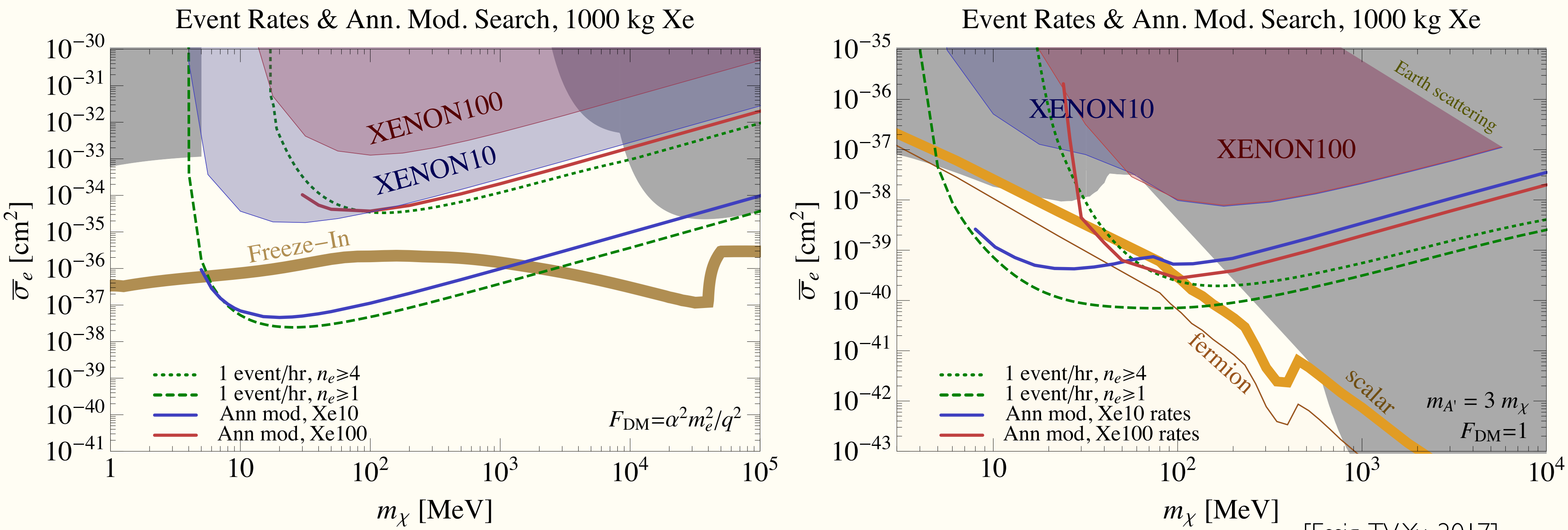


[Essig,,TV,Yu, 2017]

Electron Ionisation in Noble Gas

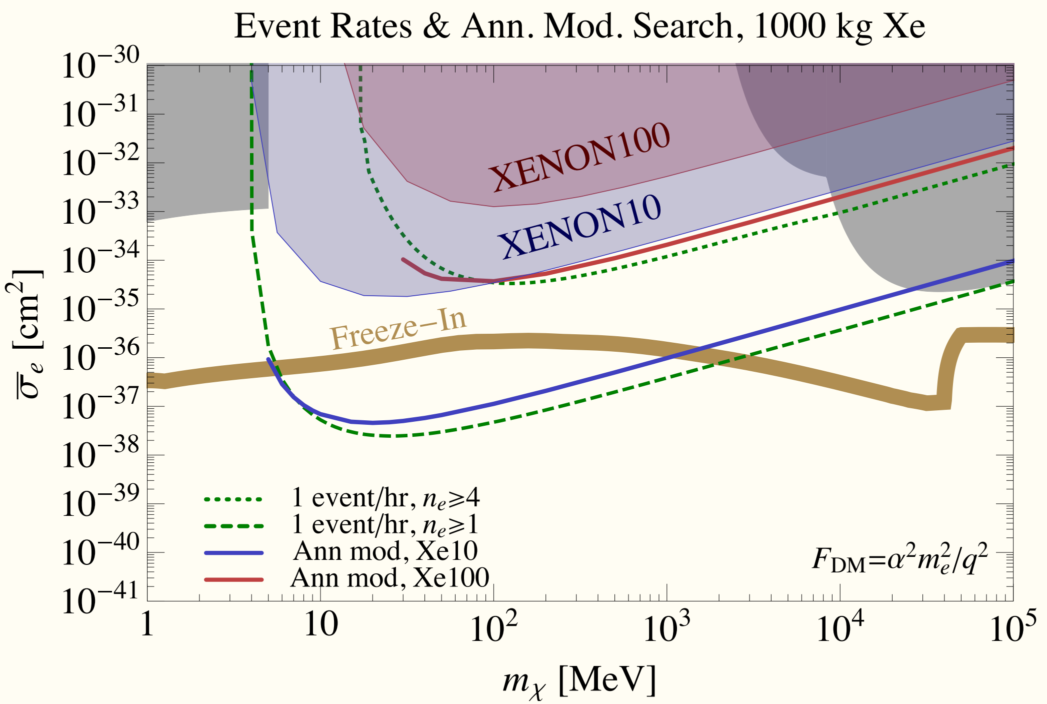
Potential Sensitivity for Annual Modulation

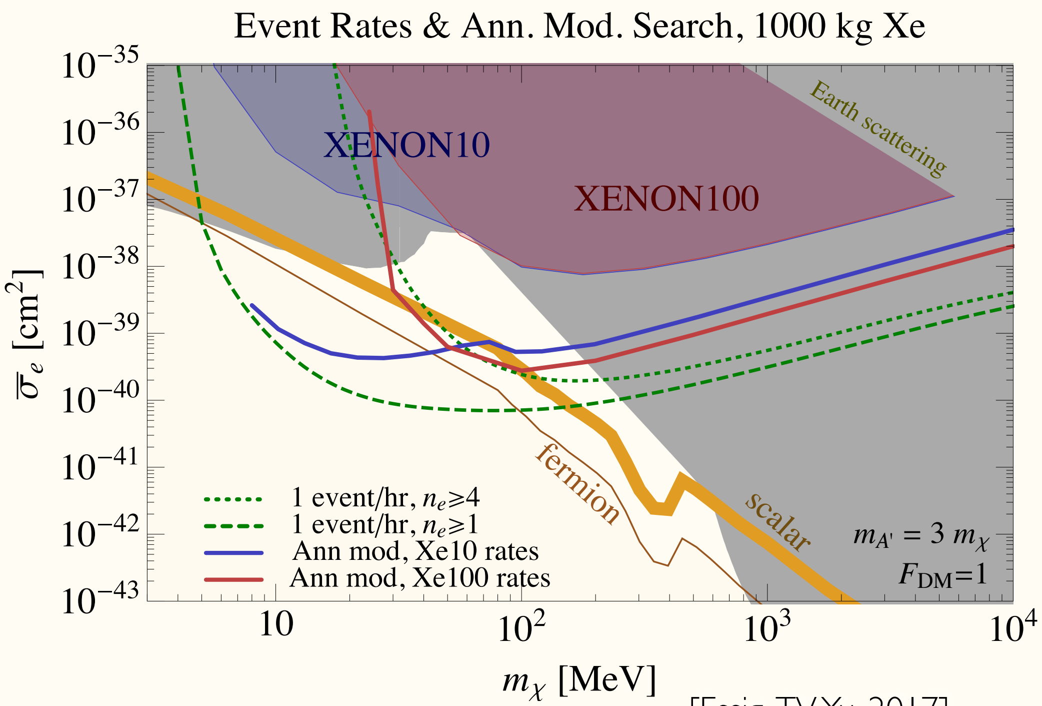
- Assume ton-year data with similar event rate as observed in XENON10/100.
- Assume no modulation is observed, and extract a limit.
- Modulation can significantly improve limits.



[Essig,,TV,Yu, 2017]

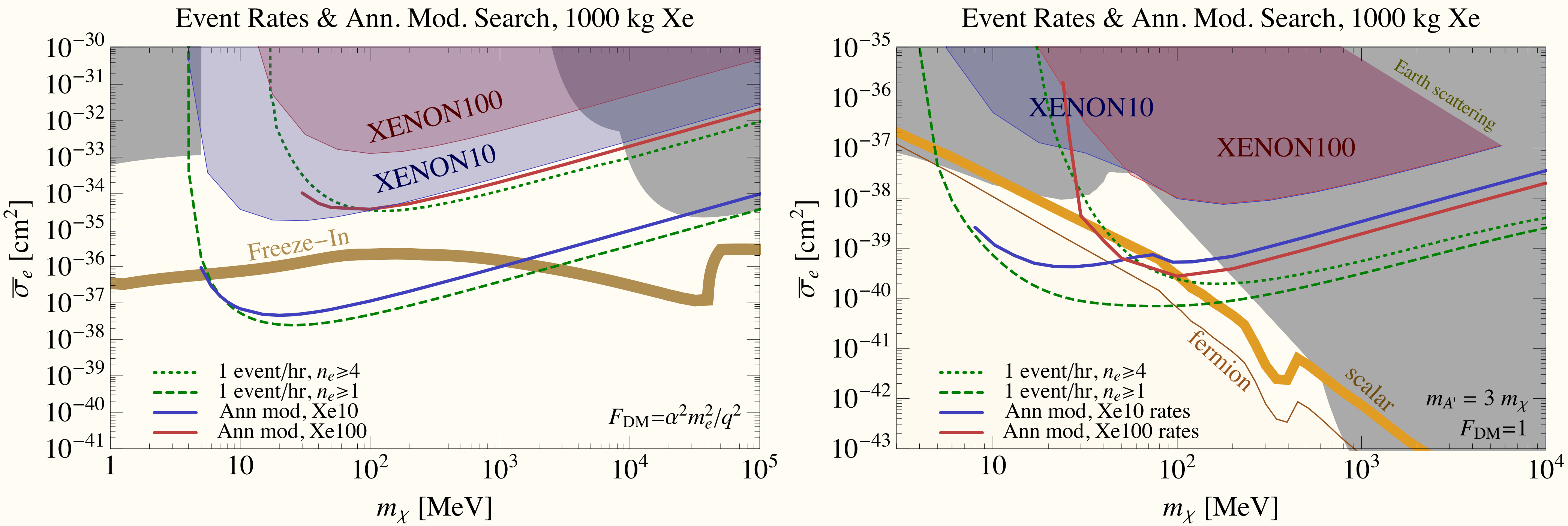
Electron Ionisation in Noble Gas





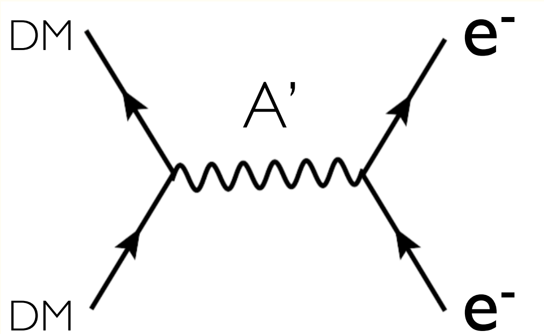
[Essig,,TV,Yu, 2017]

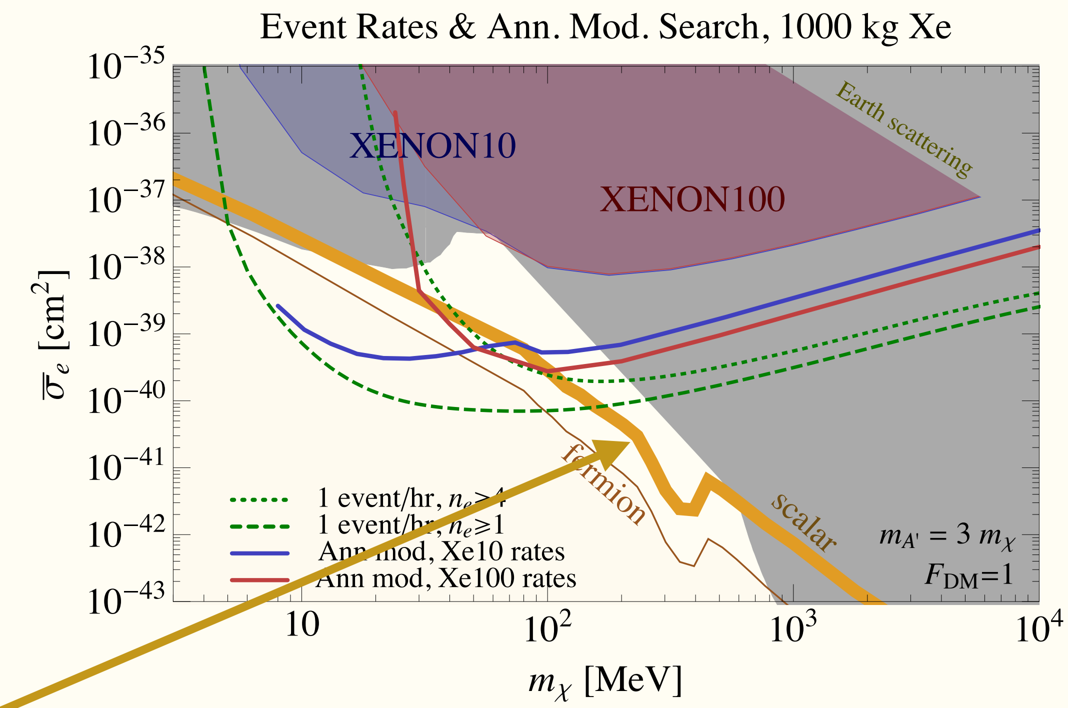
Electron Ionisation in Noble Gas



[Essig,,TV,Yu, 2017]

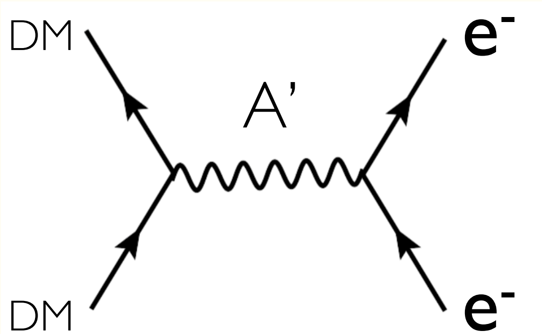
Target Models

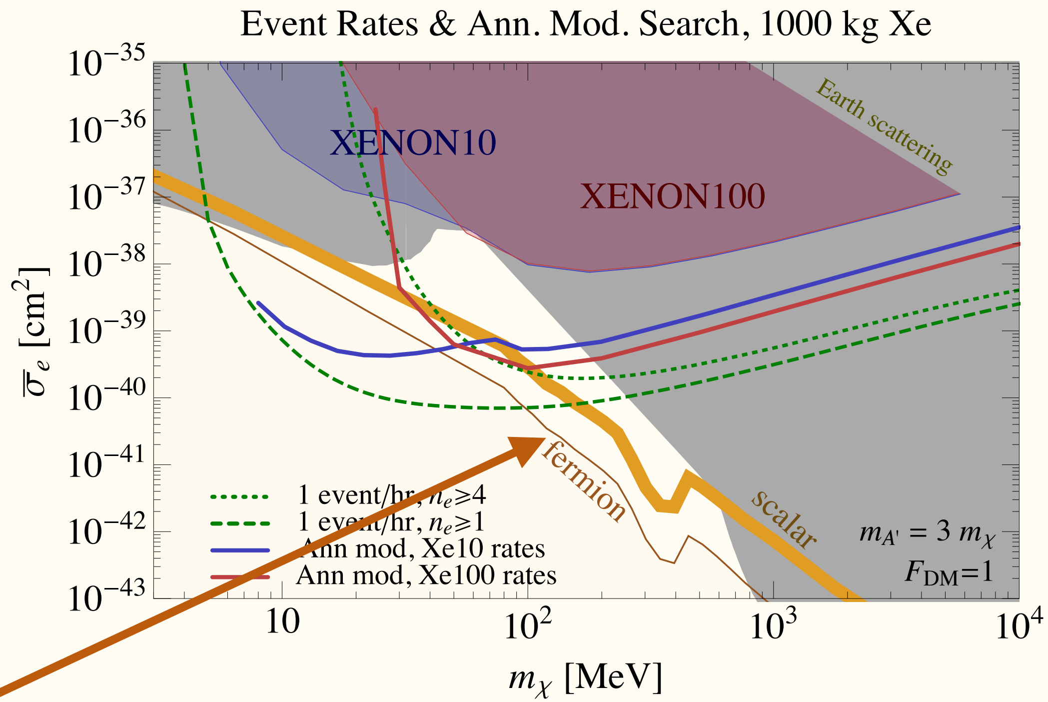




- Thermal freeze out for a **scalar** DM
- Annihilation is **p-wave** suppressed (so no CMB and gamma-ray constraints)
- Heavy mediator, $m_{A'}=3m_{DM}$.
- Below the line, too little DM. Can be easily fixed with additional annihilation channels.

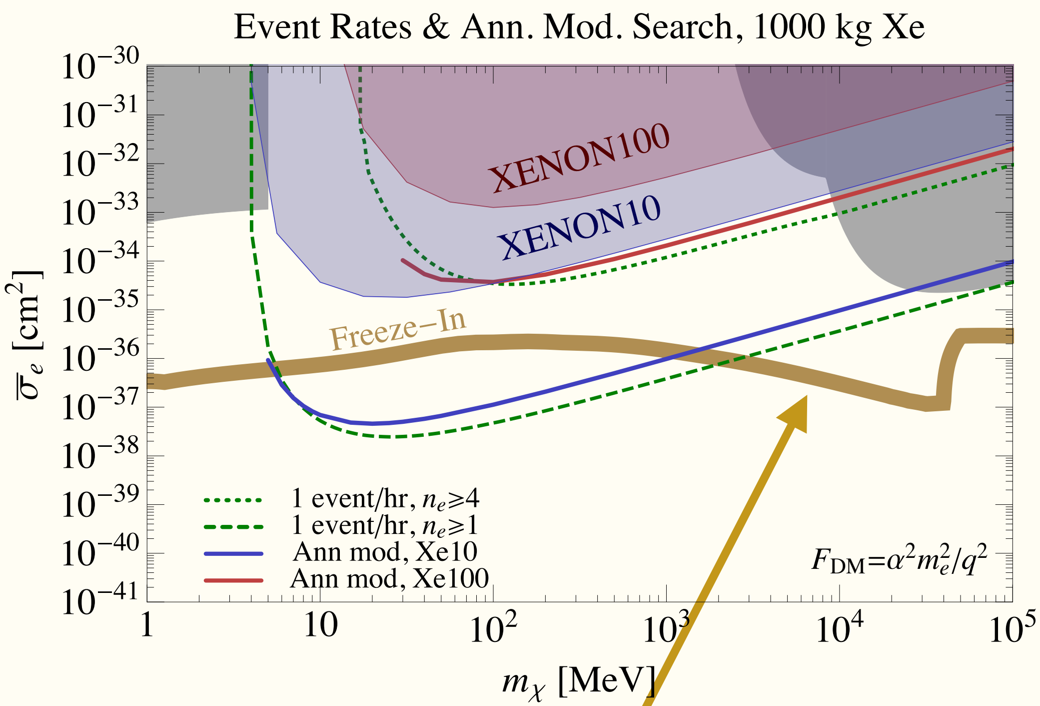
Target Models

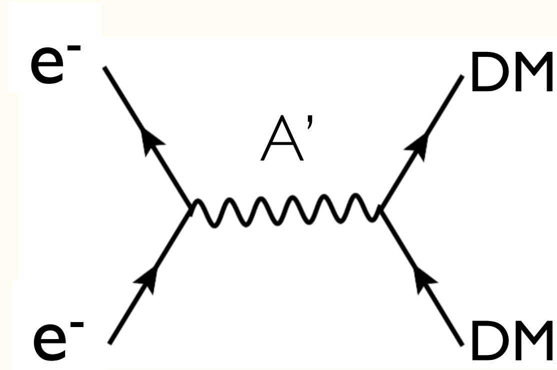




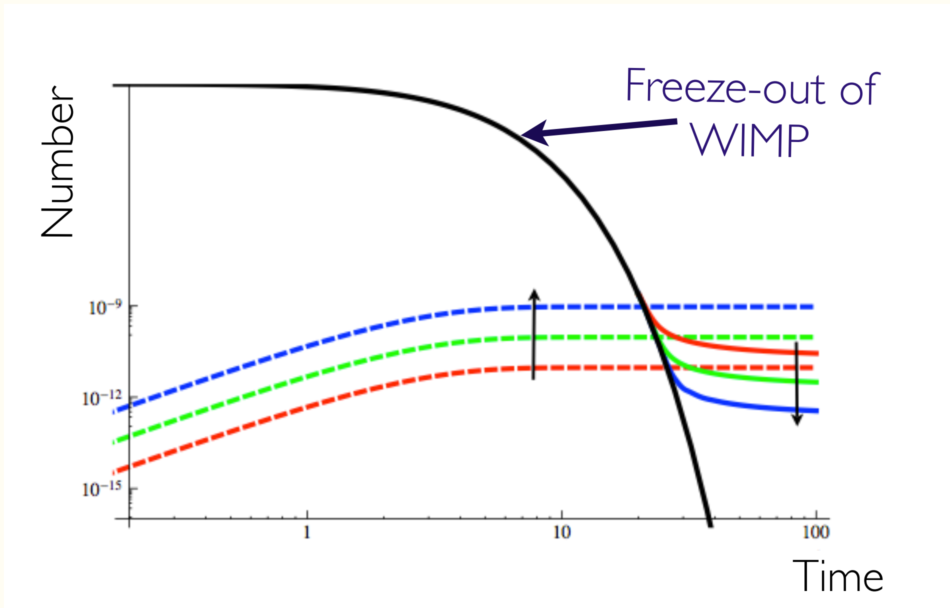
- Thermal freeze out for a **fermion** DM
- Annihilation is **s-wave** (so strong CMB and gamma-ray constraints).
- Instead, density must come asymmetric production to evade bounds.
- Heavy mediator, $m_{A'}=3m_{DM}$.
- Below the line, too much symmetric component. Can be easily fixed with additional annihilation channels.

Target Models



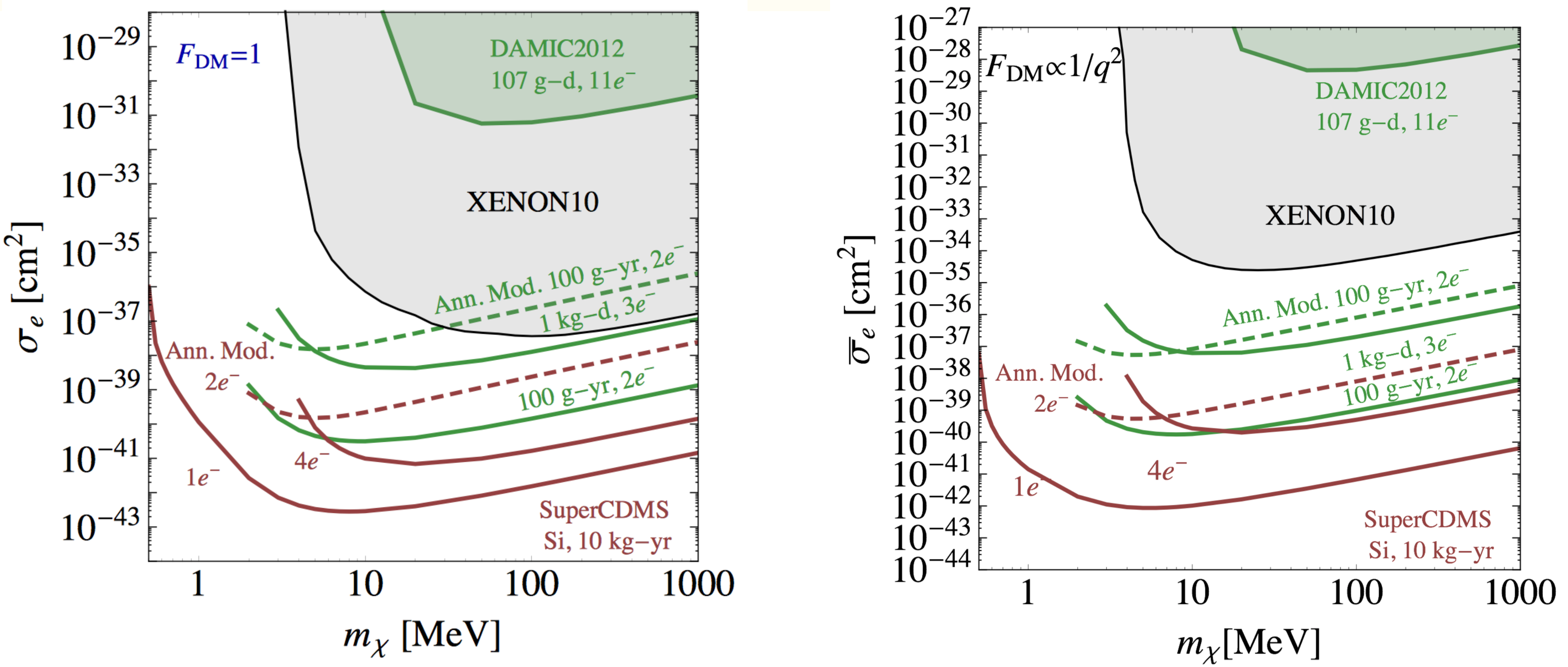


- Very light mediator.
- Couplings must be very small, so DM never thermalizes.
- Instead, it is constantly produced (freeze-in).



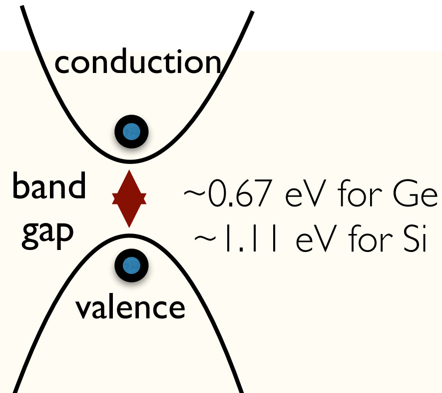
Electron Ionisation in Crystals

SuperCDMS and DAMIC

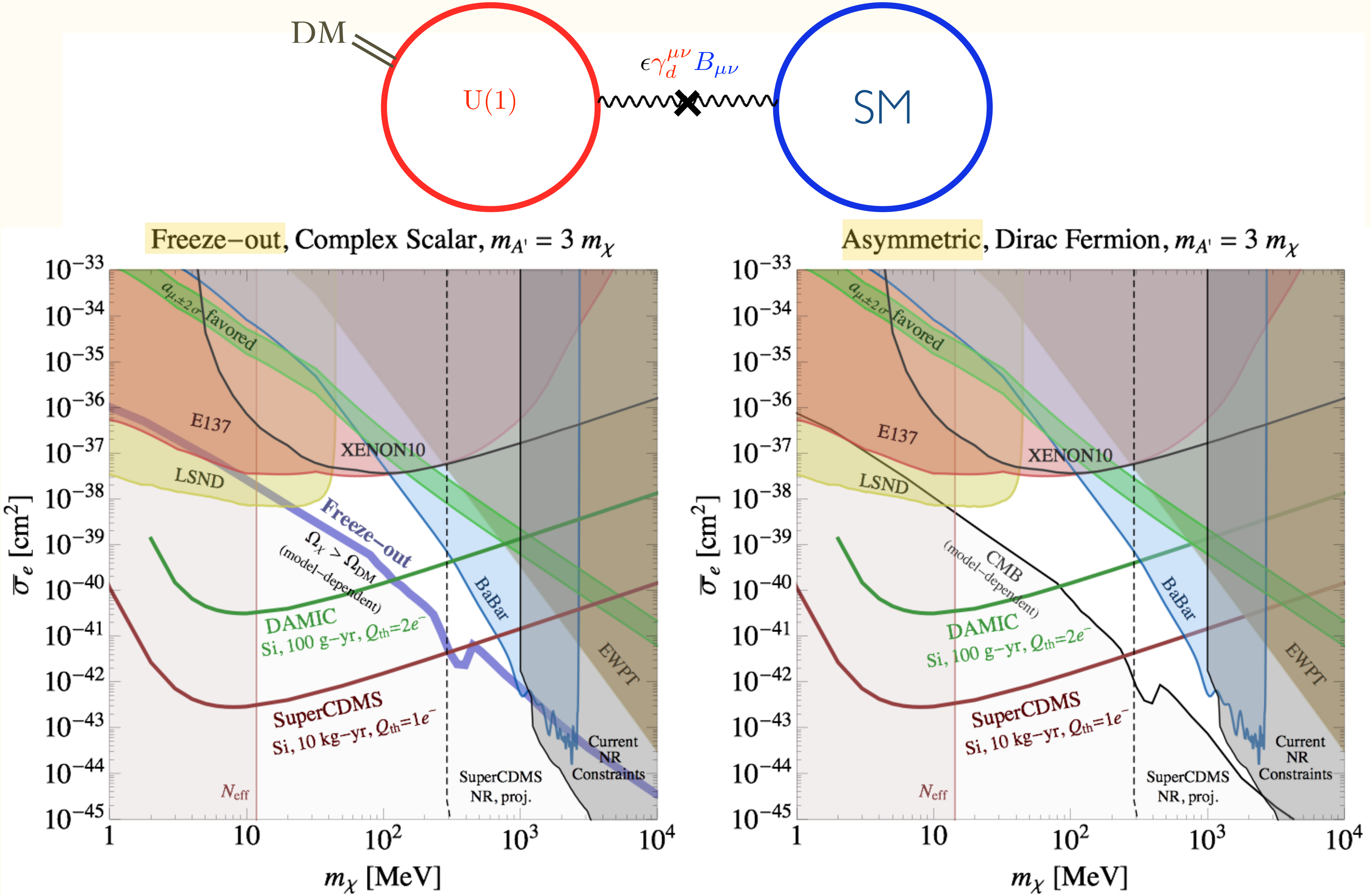


[Essig, Fernandez-Serra, Mardon, Soto, TV, Yu, 2015]

band gap (~1 eV) < atomic ionization energy (~10 eV)



Direct Detection of Light and Exotic DM



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

New Crystal Detector: SENSEI

Sub-Electron-Noise Skipper CCD Experimental Instrument

Tiffenberg (PI), Safo-Haro, Drlica-Wagner, Guardincerri, Holland, Essig, Mardon, TV, Yu

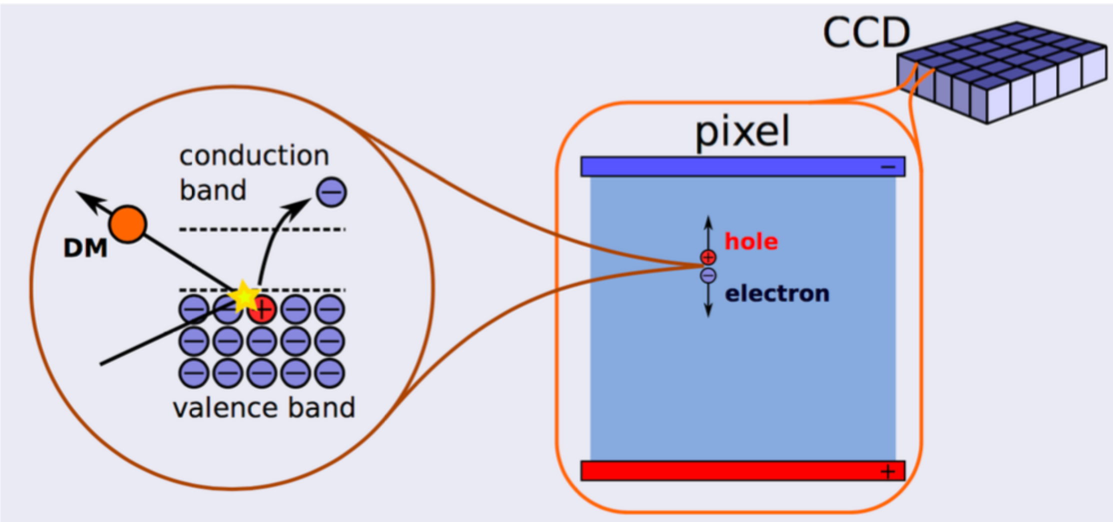
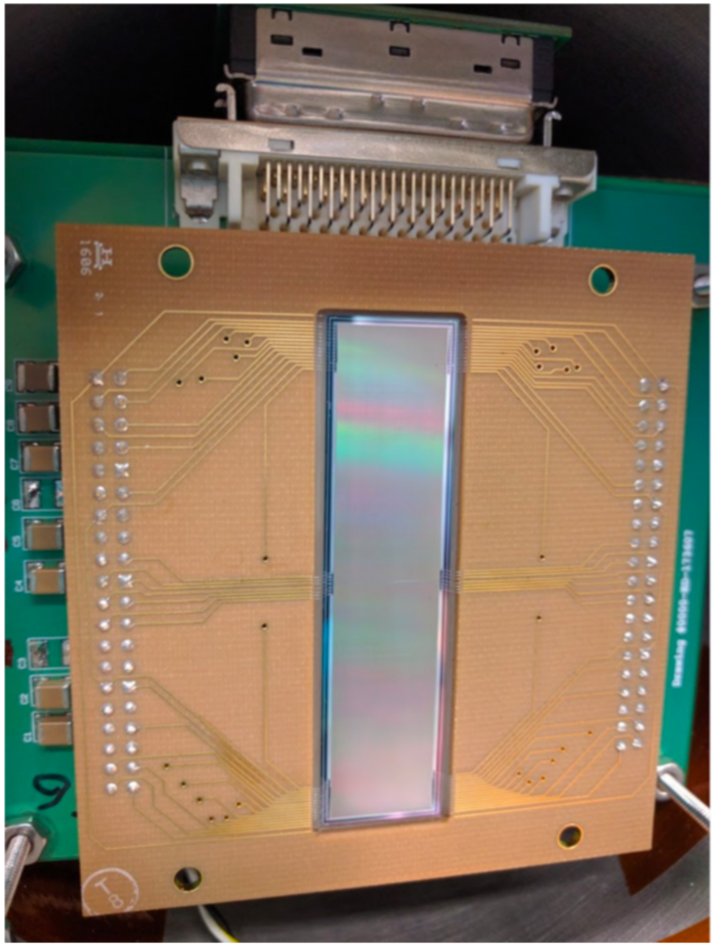


Figure credit: J. Tiffenberg

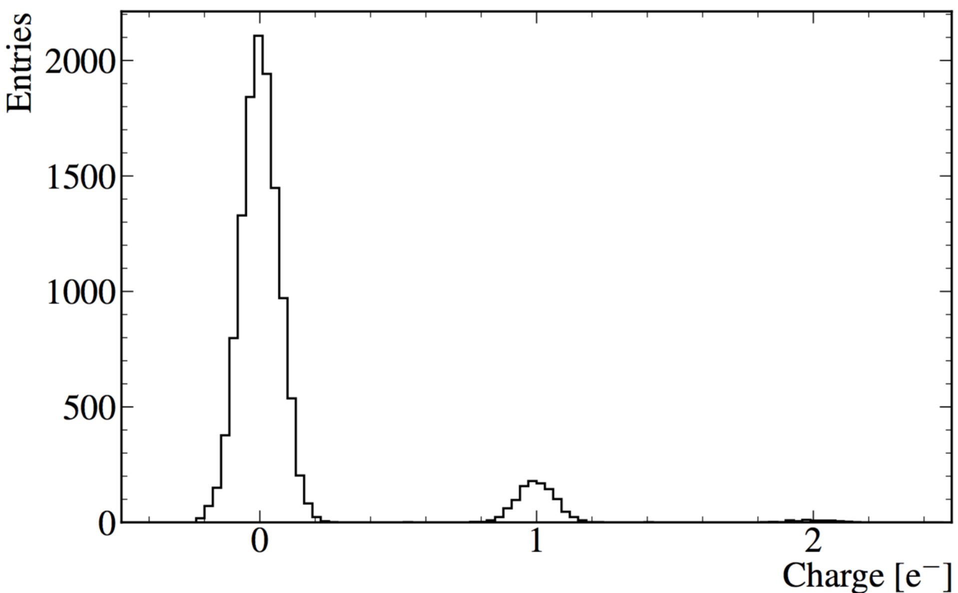


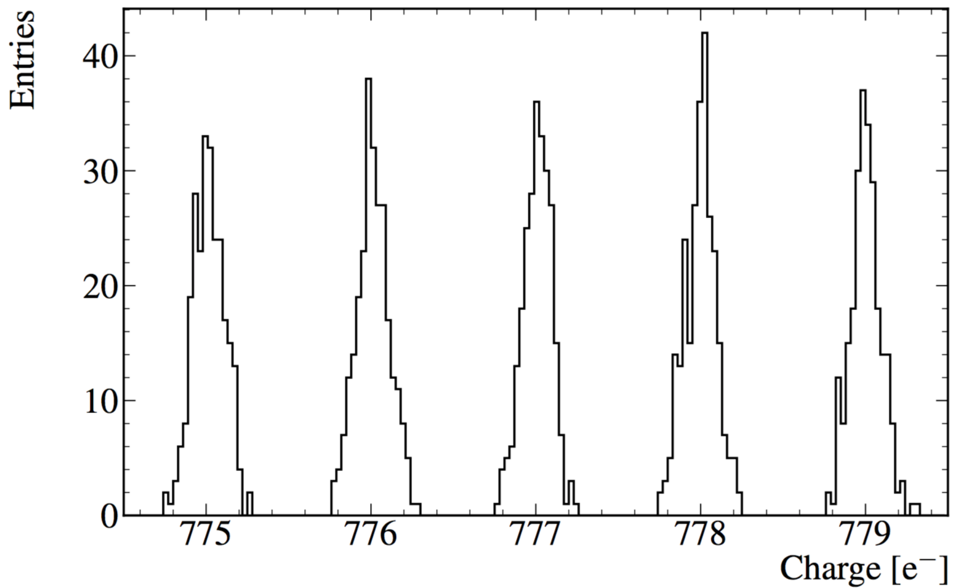
New Crystal Detector: SENSEI

Sub-Electron-Noise Skipper CCD Experimental Instrument

Tiffenberg (PI), Safo-Haro, Drlica-Wagner, Guardincerri, Holland, Essig, Mardon, TV, Yu

- Use "skipper CCDs" - Highly reduced readout noise (~0.06 e^-/pixel).
- Threshold of order few eV ($2e^-$).
- 1g detector is being installed in MINOS.
- Writing a proposal for 100g. Cost: $1.2M





New Crystal Detector: SENSEI

Sub-Electron-Noise Skipper CCD Experimental Instrument

Tiffenberg (PI), Safo-Haro, Drlica-Wagner, Guardincerri, Holland, Essig, Mardon, TV, Yu

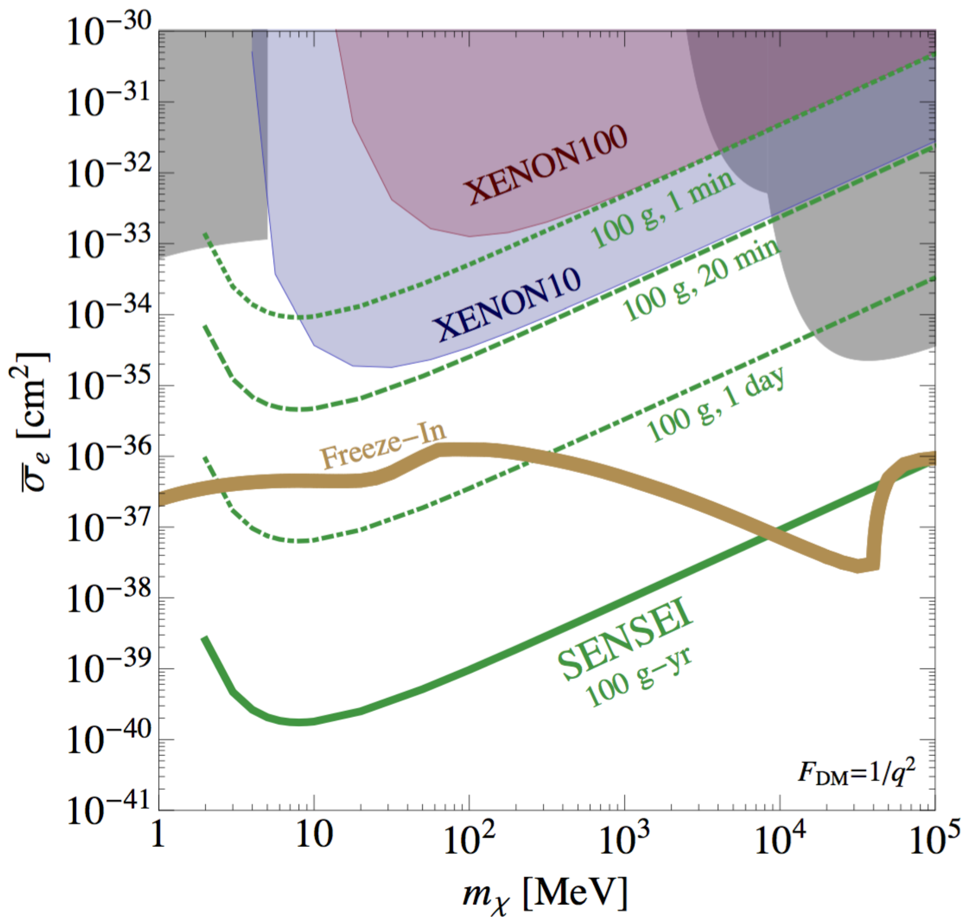
Background is expected to be very low and limited by dark current.

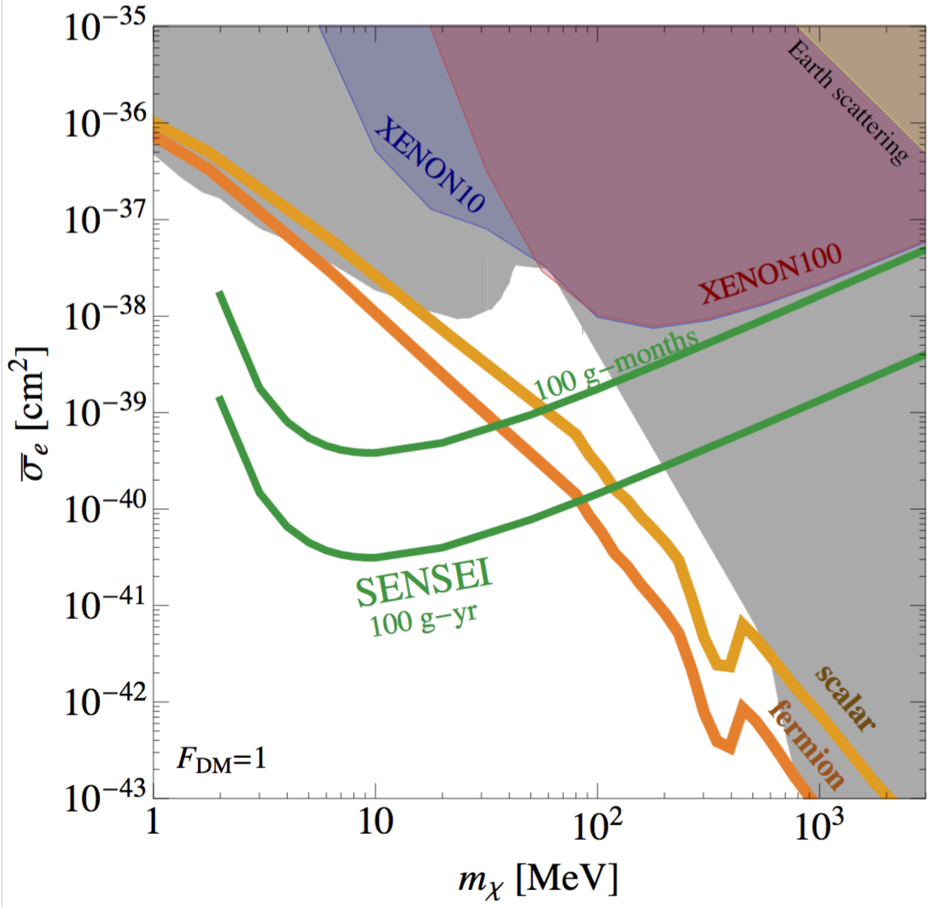
	Dark Current (e^- pix^{-1} day^{-1})	$\geq 1\,e^-$ (pix)	$\geq 2\,e^-$ (pix)	$\geq 3\,e^-$ (pix)
Measured upper limit →	10^{-3}	1×10^8	3×10^3	7×10^{-2}
	10^{-5}	1×10^6	3×10^{-1}	7×10^{-8}
Theoretical expectation →	10^{-7}	1×10^4	3×10^{-5}	7×10^{-14}

New Crystal Detector: SENSEI

Sub-Electron-Noise Skipper CCD Experimental Instrument

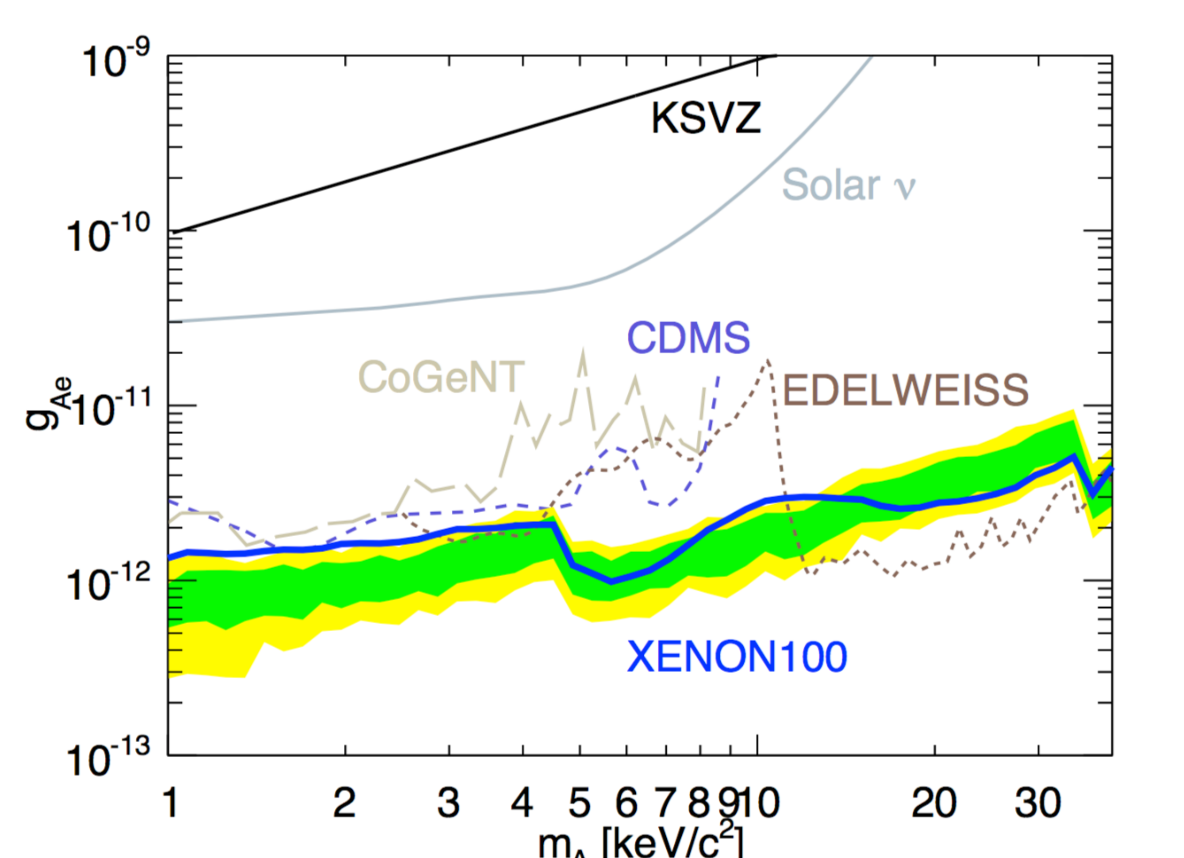
Tiffenberg (PI), Safo-Haro, Drlica-Wagner, Guardincerri, Holland, Essig, Mardon, TV, Yu





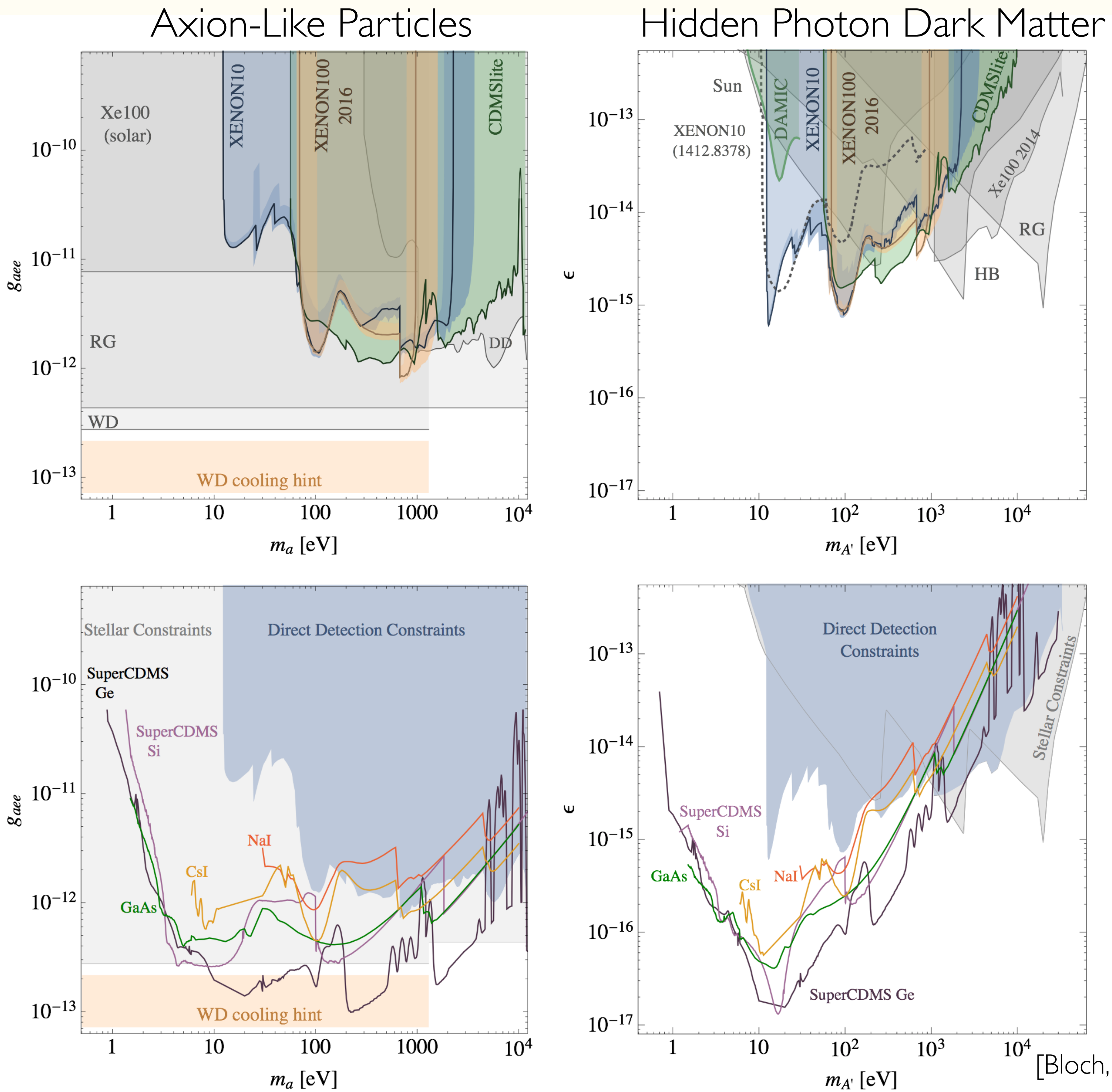
Direct Detection of Light and Exotic DM

Electron Ionization is also sensitive to Axions!



[Xenon100, 2014]

Direct Detection of Light and Exotic DM

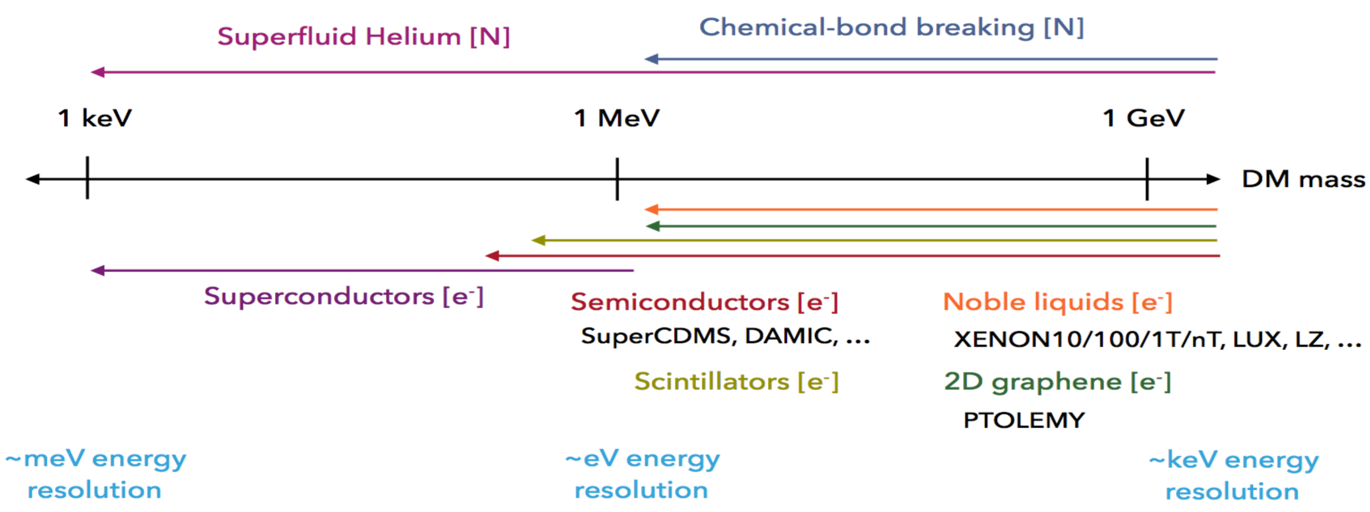


[Bloch, Essig, Tobioka, TV, Yu, 2016]

Direct Detection: New Concepts

- 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, 2016; Schutz, Zurek, 2016; Budnik, Cheshnovsky, Slone, TV, upcoming; ...]



Material	$m_{\rm DM,th}$ (theoretical)	Technology	Challenges	(Optimistic) Timescale
Noble liquids (Xe, Ar)	few MeV	two-phase TPC	dark counts	existing
Semiconductors (Si, Ge)	$\sim 0.1-1$ MeV	CCDs & Calorimeter	dark counts (?)	$\sim 1-2$ years
Scintillators (GaAs, NaI, CsI)	$\sim 0.5-1$ MeV	Calorimeter: $\sigma_E \sim 0.2$ eV	sensitivity & afterglow (?)	$\lesssim 5$ years
Superconductors (Al)	~ 1 keV	Calorimeter: $\sigma_E \sim 1$ meV	sensitivity & unknown backgrounds	$\sim 10-15$ years
Superfluid He (NR)	~ 1 MeV	Calorimeter: $\sigma_E \sim 1$ eV	sensitivity & unknown backgrounds	$\lesssim 5$ years
Bond Breaking	$\sim$few MeV	color centers	sensitivity & unknown backgrounds	$\lesssim 5$ years
Superfluid He (2-excitation)	~ 1 keV	Calorimeter $\sigma_E \sim 10$ meV	sensitivity & unknown backgrounds	$\sim 5-10$ years
2D-targets (graphene)	few MeV	based on PTOLEMY	low exposure, unknown backgrounds	$\sim 5-10$ years

[Dark Sectors 2016 Report]

Direct Detection: New Concepts

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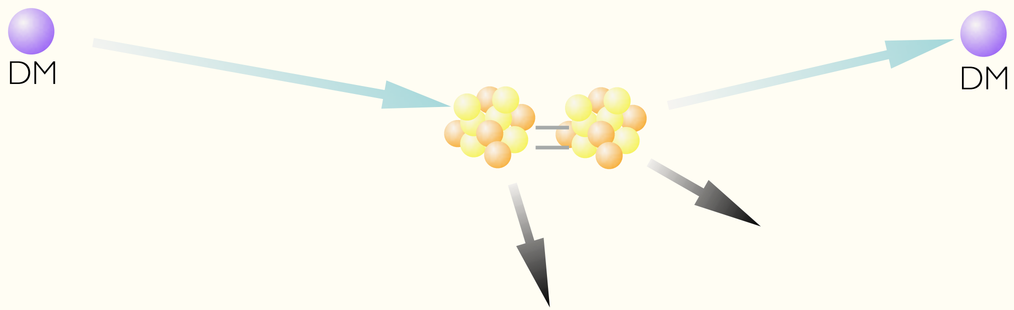
[Essig, Mardon, TV, 2011; Anderson, Figueroa-Feliciano, Formaggio, 2011; Drukier, Nussinov, 2013; Agnes et al. 2014; Hochberg, Zhao, Zurek, 2015; Essig, Mardon, Slone, TV, 2016; Schutz, Zurek, 2016; Budnik, Cheshnovsky, Slone, TV, …]

- One effort:

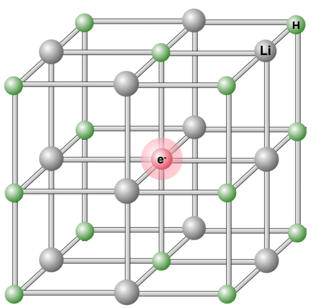
Concept

[Essig, Mardon, Slone, TV, 2016]



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, Cheshnovsky, Slone, TV, 2017]

Direct Detection: New Concepts

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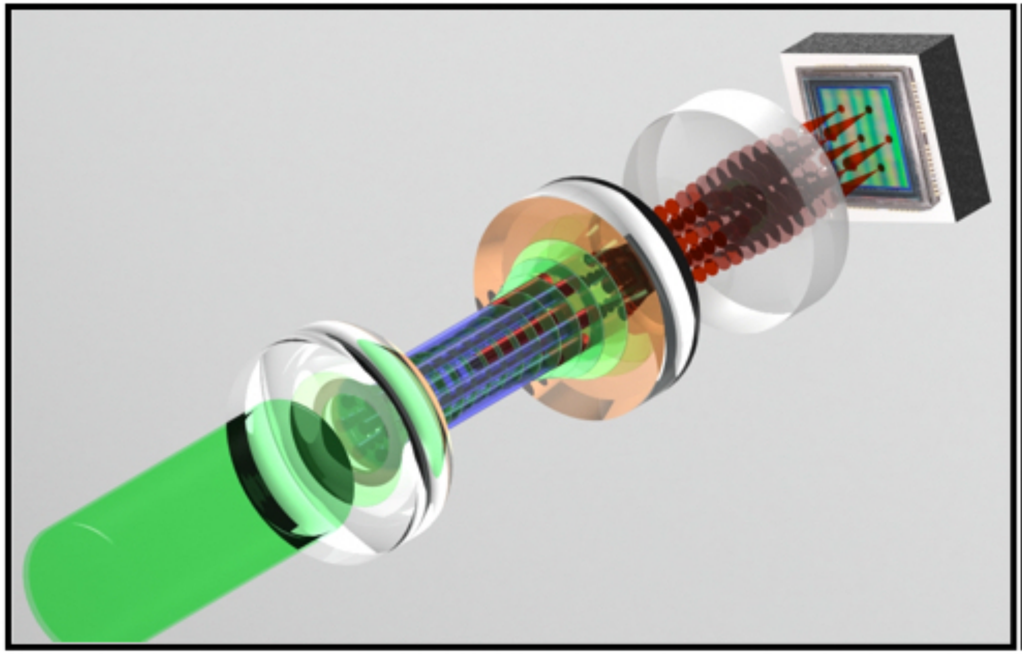
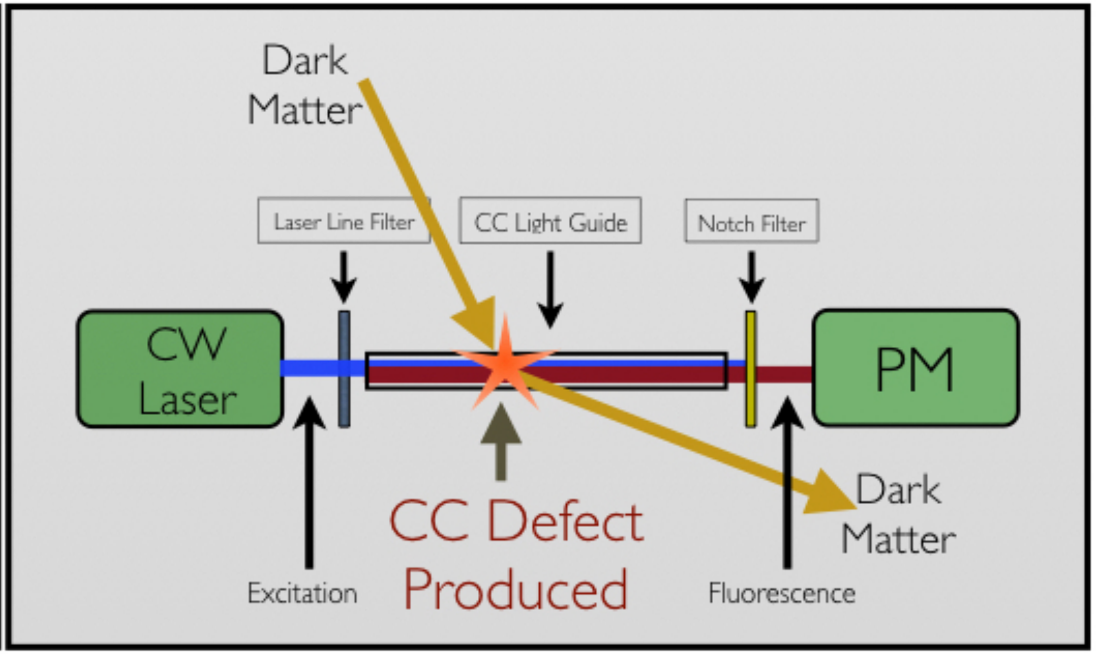
[Essig, Mardon, TV, 2011; Anderson, Figueroa-Feliciano, Formaggio, 2011; Drukier, Nussinov, 2013; Agnes et al. 2014; Hochberg, Zhao, Zurek, 2015; Essig, Mardon, Slone, TV, 2016; Schutz, Zurek, 2016; Budnik, Cheshnovsky, Slone, TV, …]

- One effort:

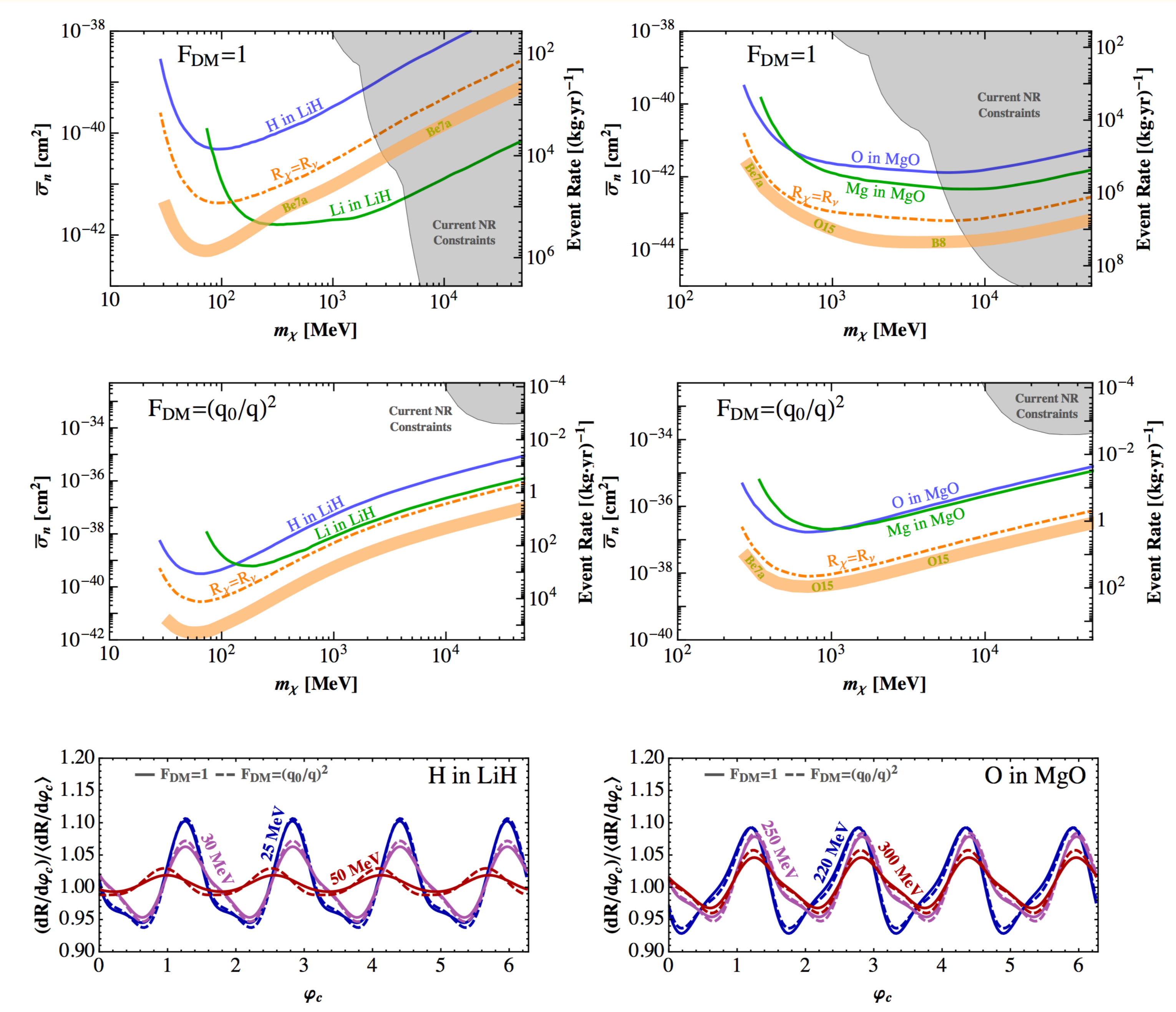




New theory-experimental collaboration. New lab opened.

Essig, Slone, TV, Budnik, Cheshnovsky, Kreisel, Soffer, Priel, Weiss, Mosbacher

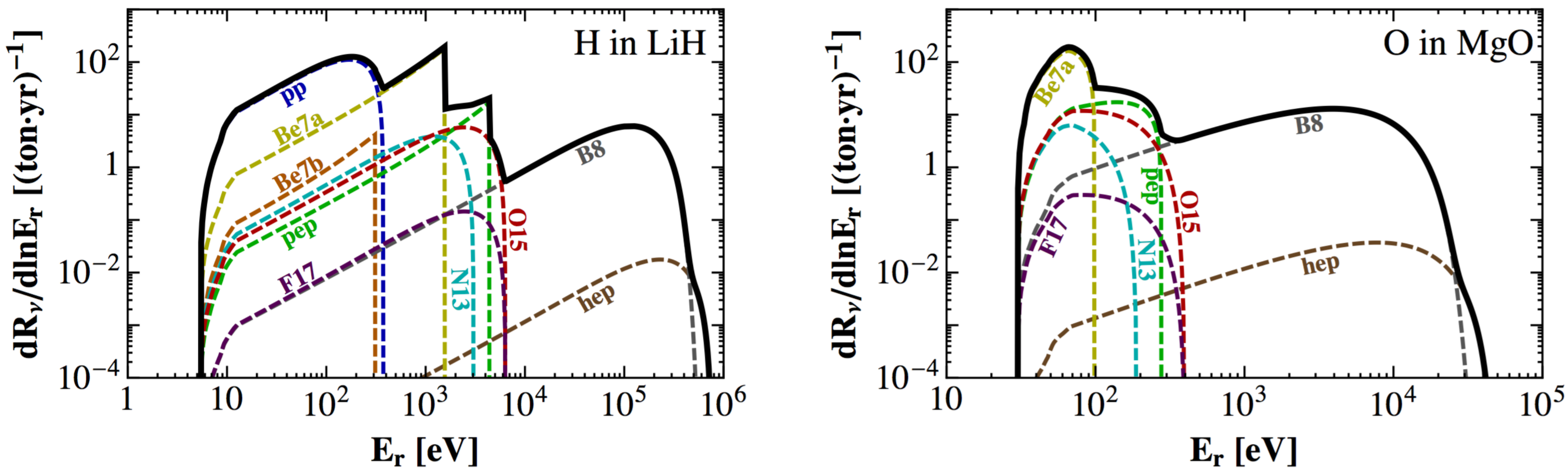
Direct Detection: New Concepts



[Budnik, Cheshnovsky, Slone, TV, 2017]

Direct Detection: New Concepts

[Budnik, Cheshnovsky, Slone, TV, 2017]

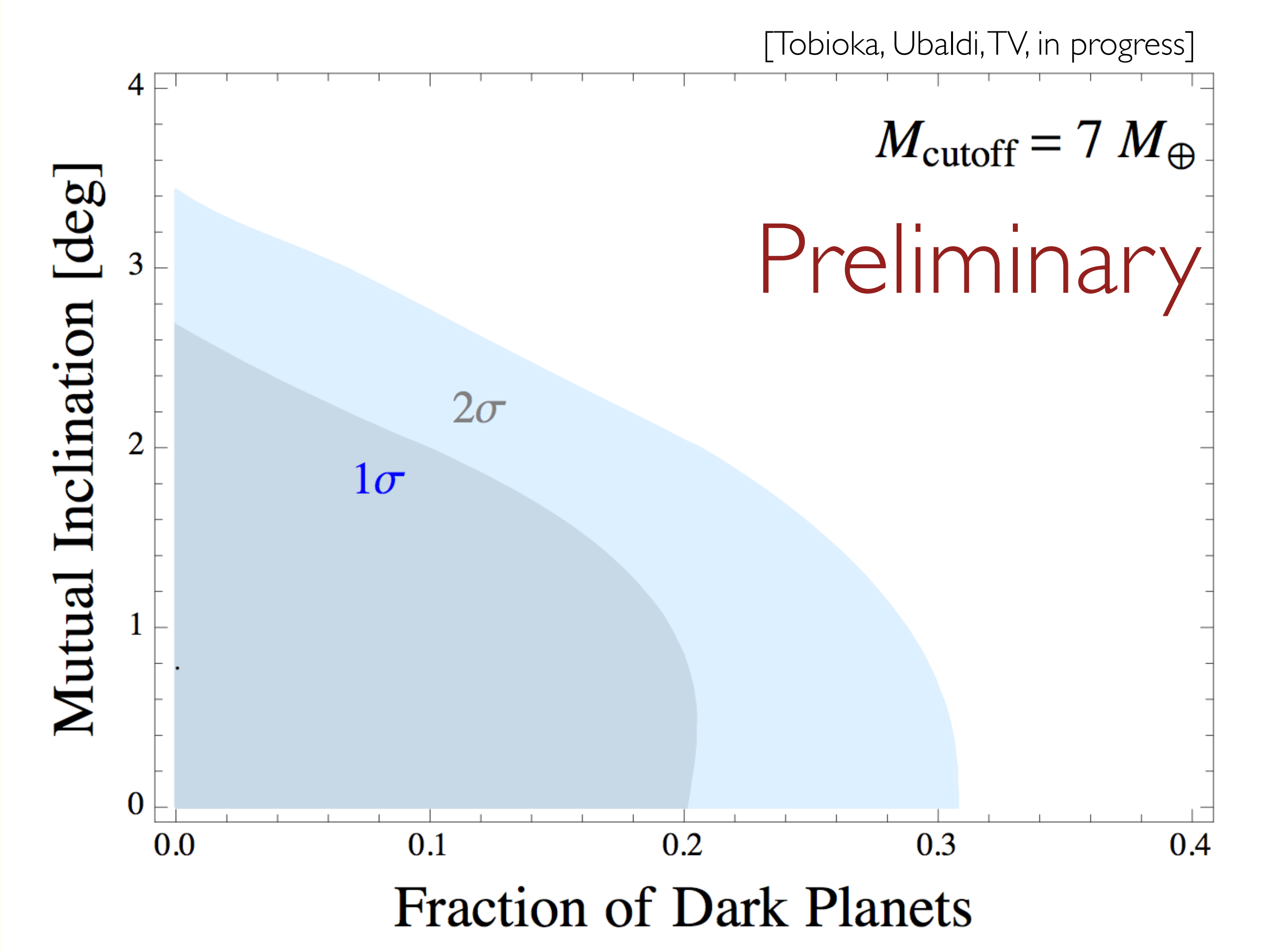


Active Galactic Nuclei (AGN)

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

[Outmezgine, Slone, Tangarife, 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.