WHEPP XIV, Indian Institute of Technology, Kanpur
4 December 2015

A Fresh Look at Dark Matter

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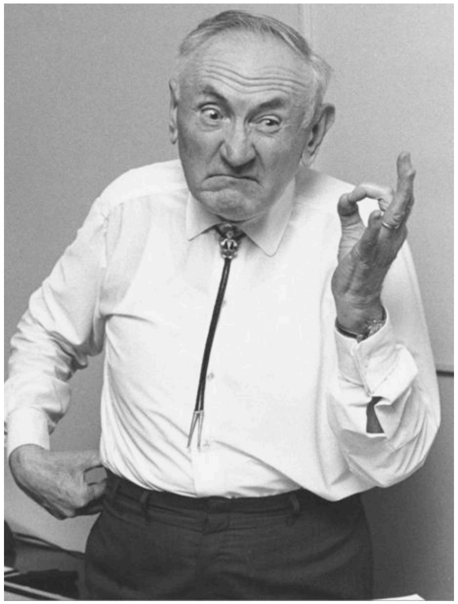
TIFR, Mumbai

Early Evidence : Coma Cluster

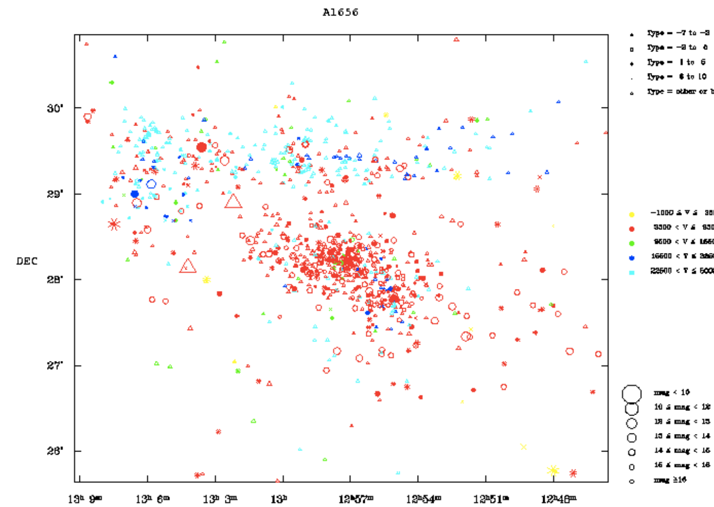


Fritz Zwicky, 1930s

$$\langle K.E.\rangle = -\frac{1}{2}P.E.$$

$$\frac{1}{2}m\langle v^2\rangle = \frac{-GMm}{2R}$$

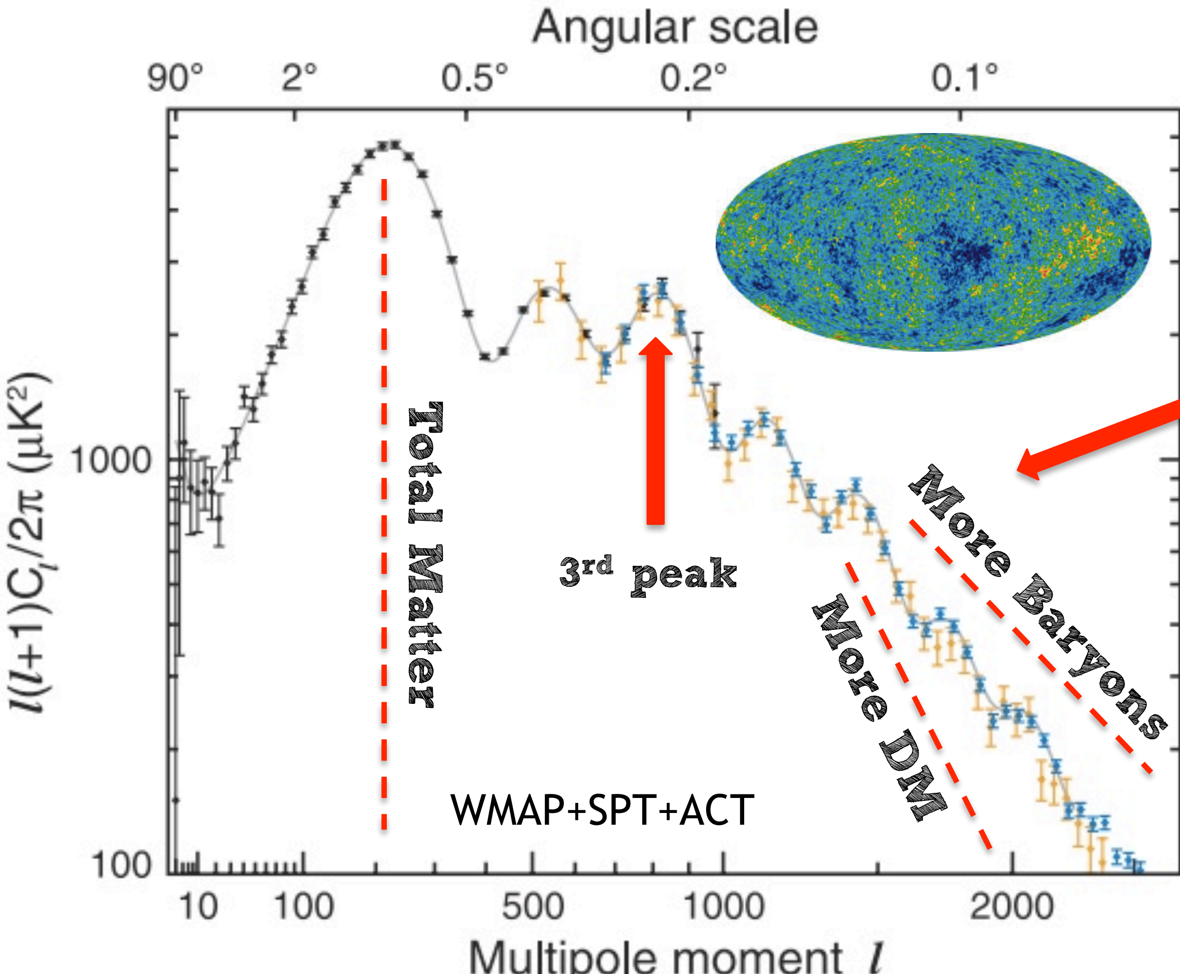
$$M = \frac{R\langle v^2\rangle}{2G}$$



Red : 1000 km/s
Blue : 10000 km/s

Mass inferred >> Mass seen

Evidence from CMB



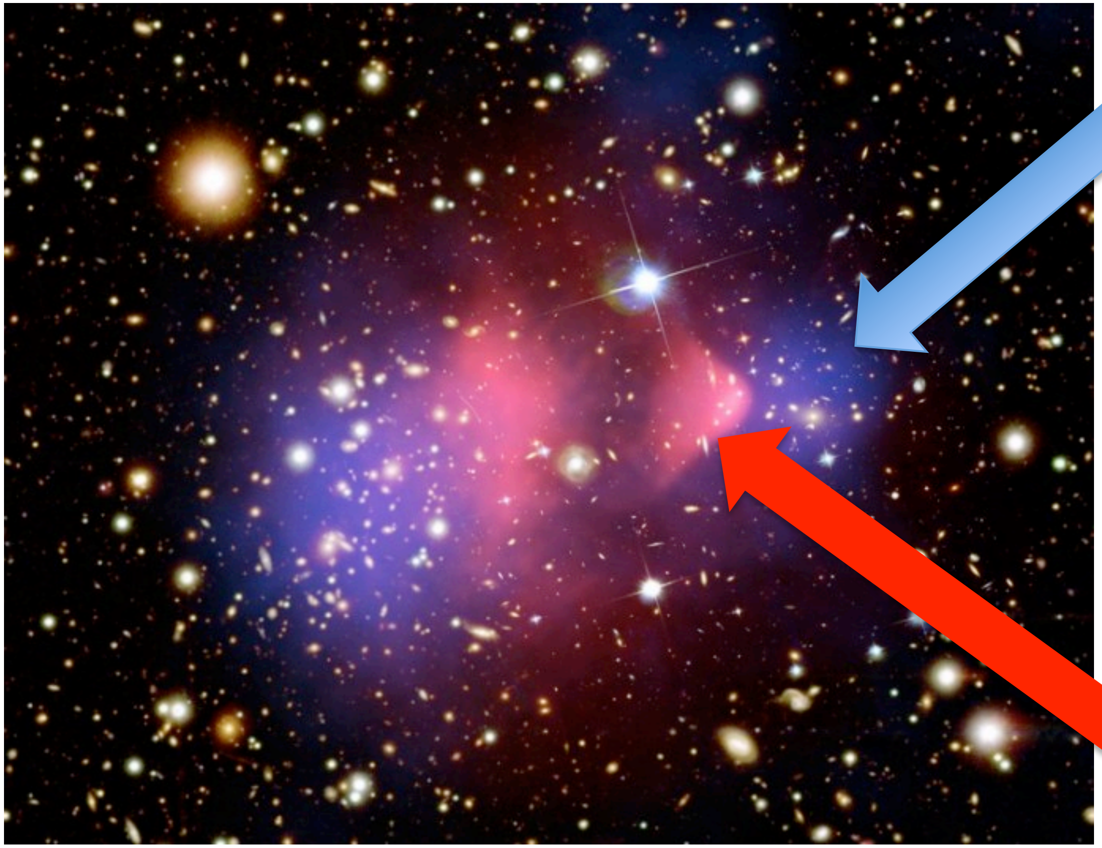
Silk damping, from diffusion of photons out of density wells

Baryons = less damping

DM = more damping

Approx. 80% matter is DM

Bulletproof Evidence

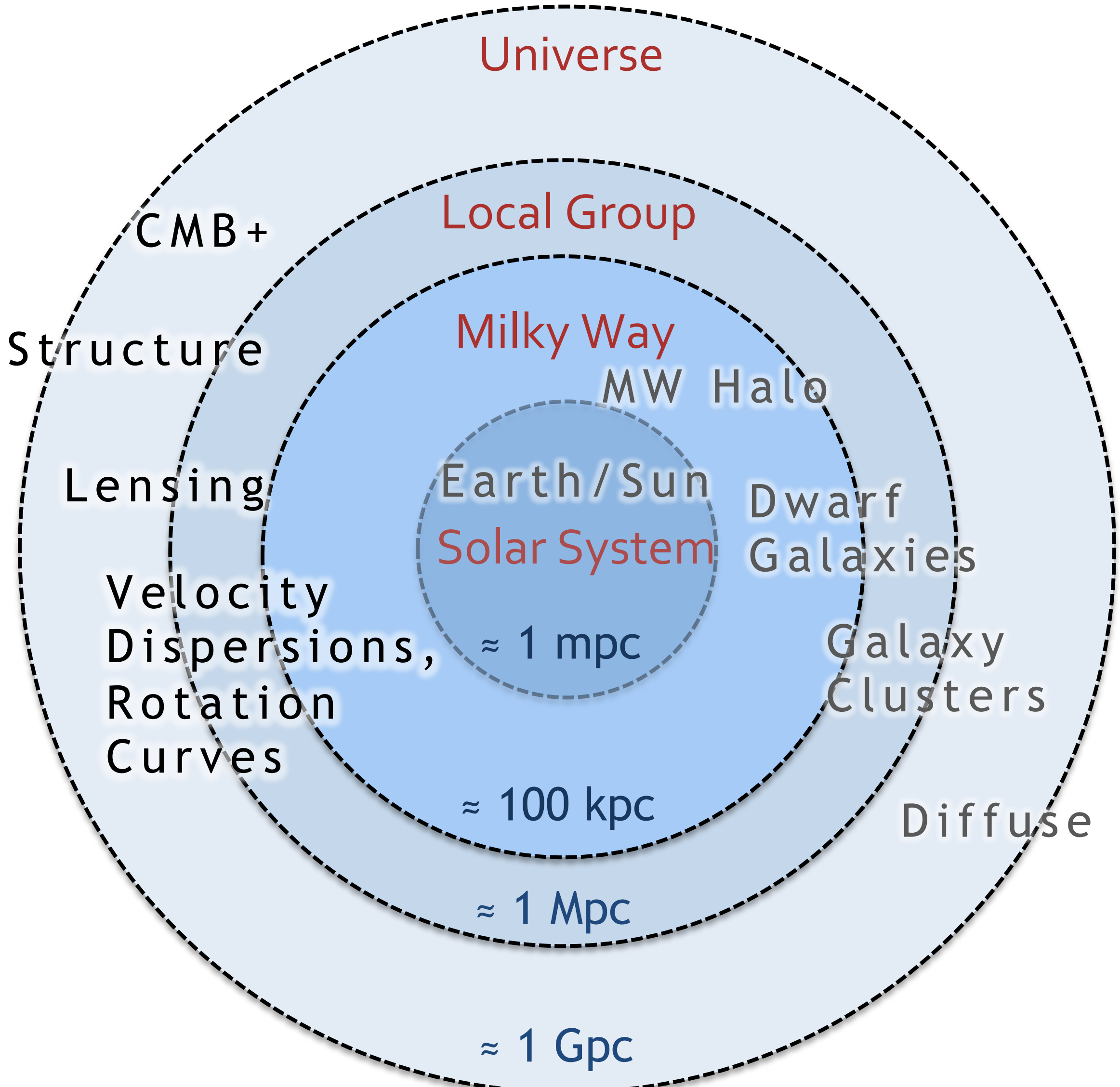


Gravitational Lensing Signal (DM + Baryons)

X-Ray Signal (Baryons)

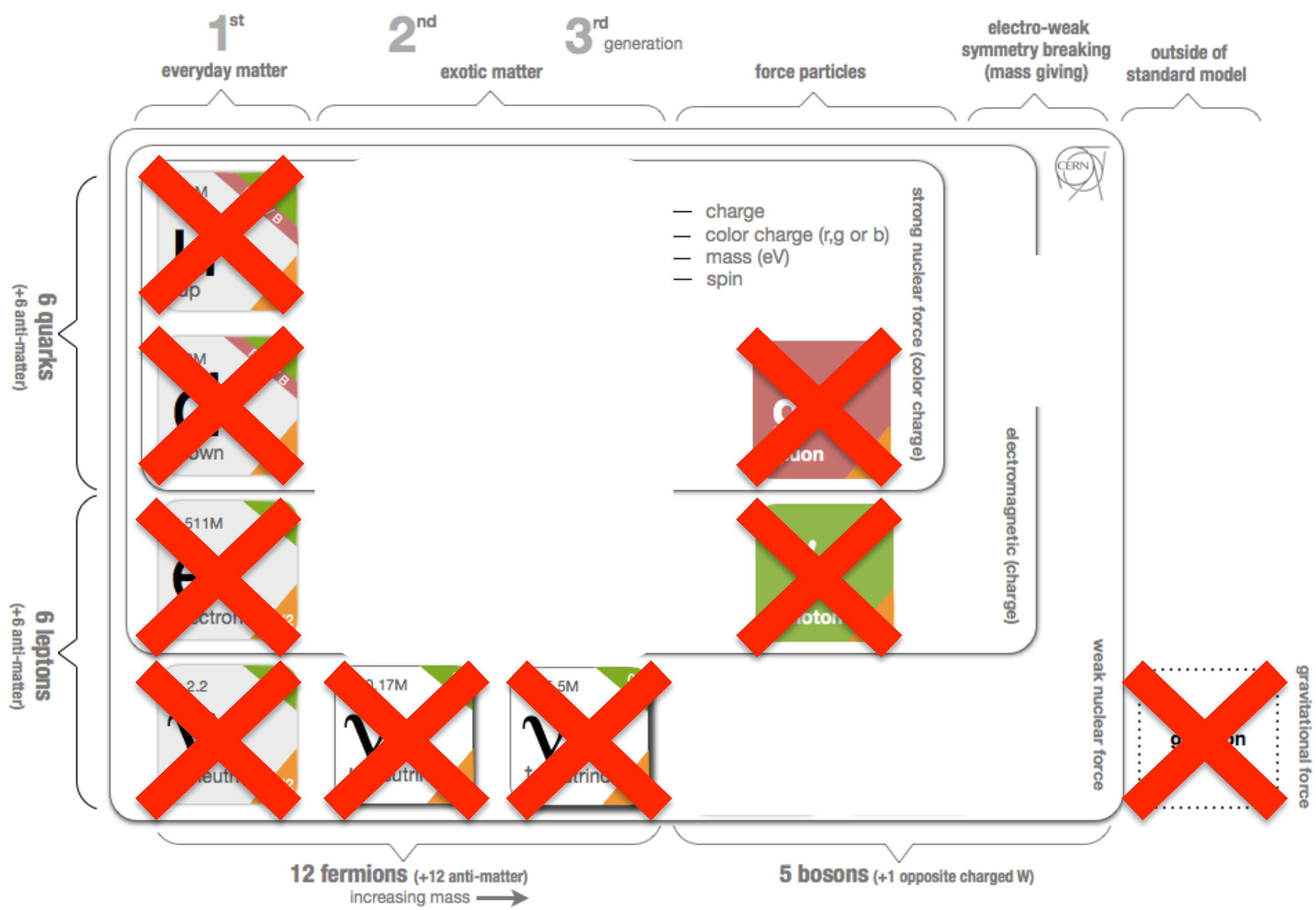
1E 0657-56 (Bullet Cluster), APOD

Dark Matter


Universe
Local Group
Milky Way
MW Halo
Earth/Sun
Solar System
≈ 1 mpc
Dwarf Galaxies
Galaxy Clusters
≈ 100 kpc
≈ 1 Mpc
≈ 1 Gpc
Diffuse
CMB+
Structure
Lensing
Velocity Dispersions,
Rotation Curves

But what is Dark Matter?

Not a Standard Particle



Mirror, mirror on the wall …

Idea	Motivation
WIMPs	Weak-scale
Axions	Strong CP
Asymmetric DM	Baryon/DM Ratio
Self-Interacting DM	Small-Scale Structure
Sterile Nu DM	Minimality
…	…

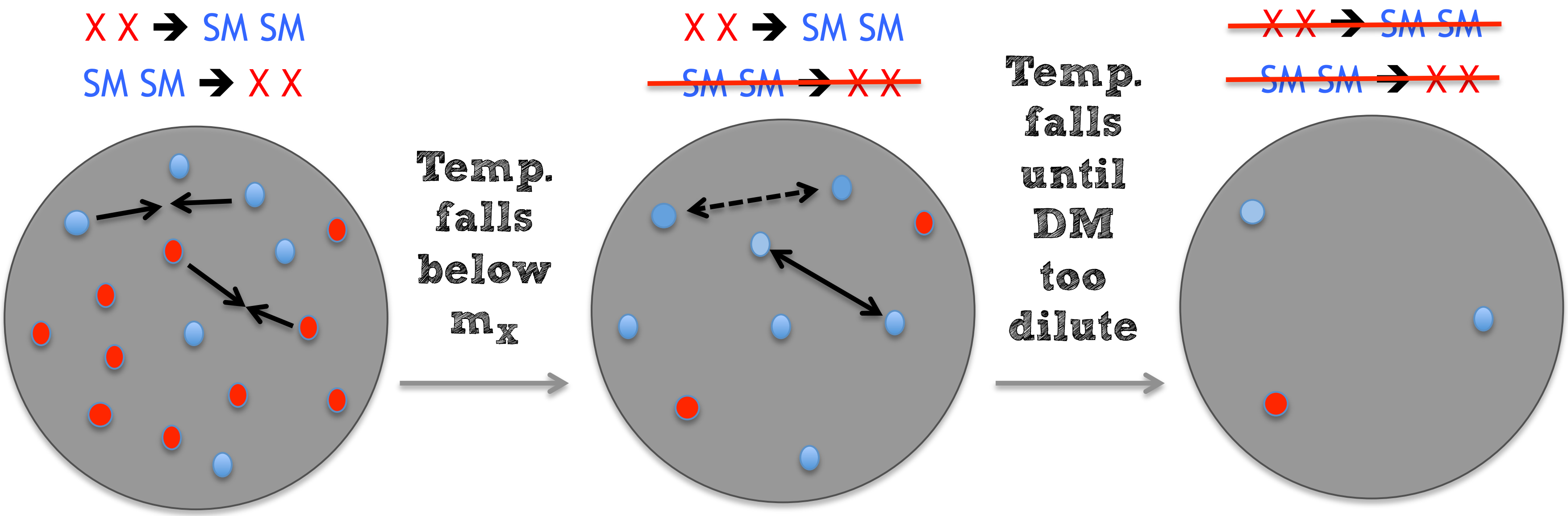
Ideas and Searches

WIMPs
Axions
Asymmetric DM
Self-Interacting DM
Sterile Nu DM
...

↔

Indirect Detection
Direct Detection
Colliders
Cosmology
Stellar Physics
...

Idea : WIMP DM



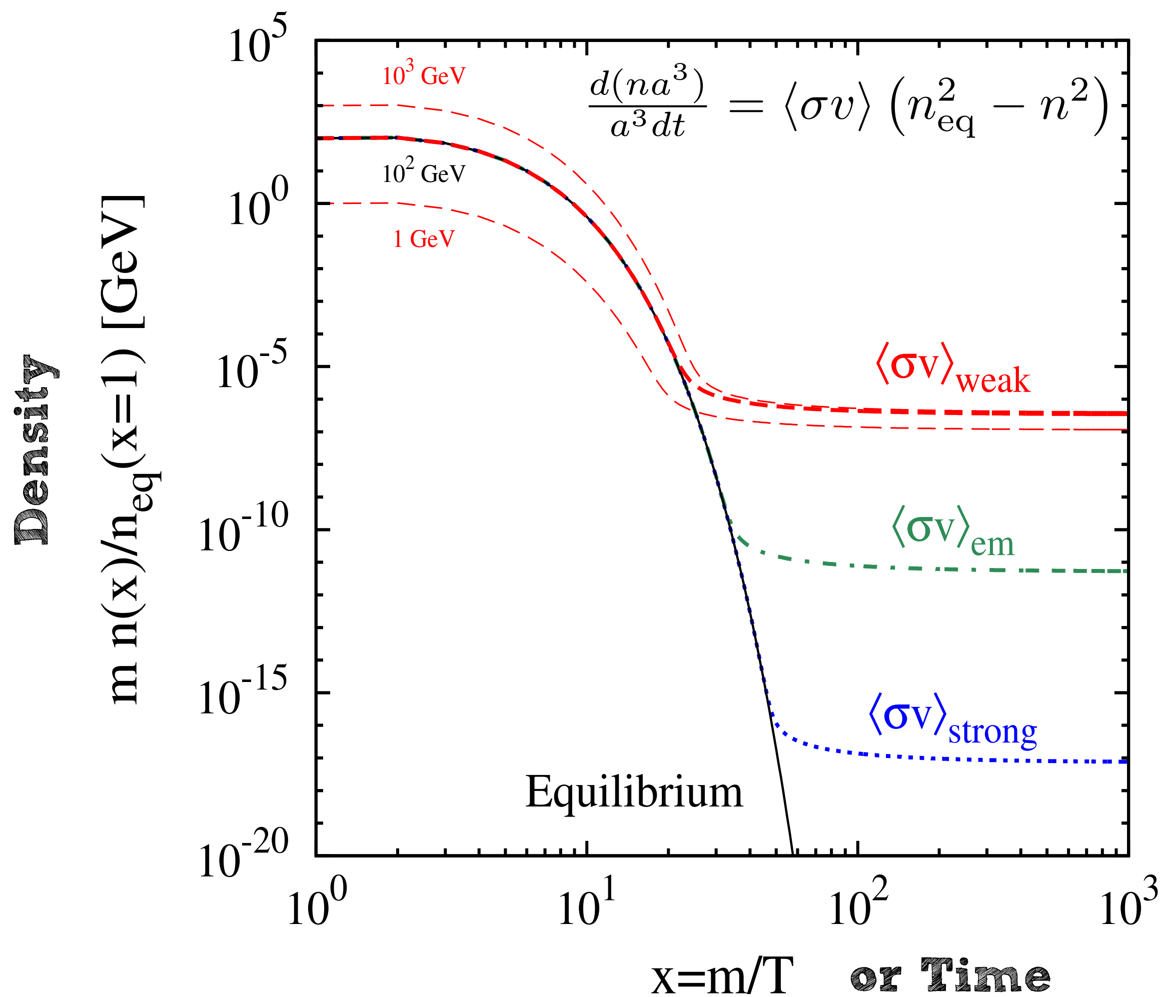
Equilibrium at high T

No more production,
but annihilations continue

No more annihilations,
as no partners available

Chemical Freeze-out sets DM Density

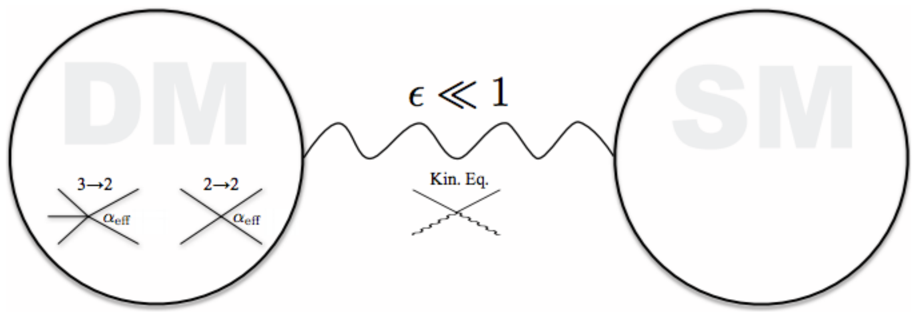
WIMP "Miracle"



$\Omega_{CDM}h^2 \approx 0.11$
i.e., observed density for weak scale annihilation

Zeldovich (1965); Chiu (1966); Lee and Weinberg (1977); Hut (1977); Wolfram (1979); Steigman (1979).

Thermal Relics Reloaded



Hochberg, Kuflik, Volansky, Wacker (2014)

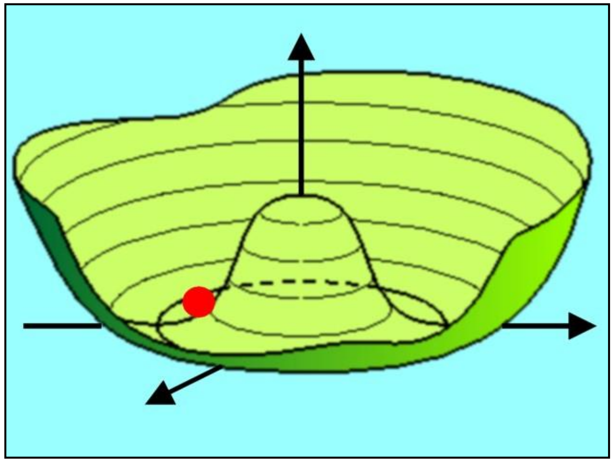
SIMP
FIMP
...

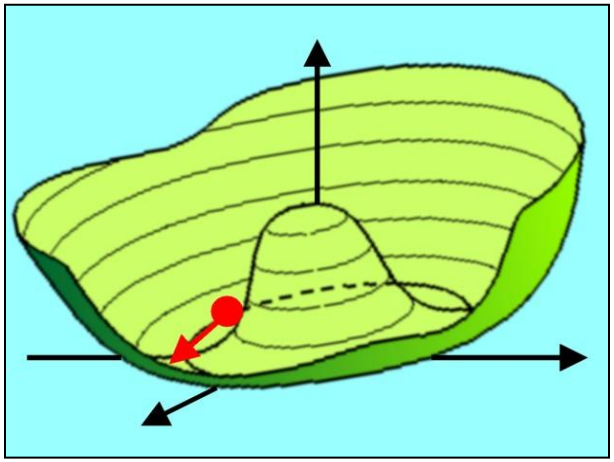
Many variations on a theme

Interplay of Production and Annihilation decides the final density

Idea : Axion DM

$$\mathcal{L}_{\rm QCD} \supset (\theta - \arg\det M)\frac{\alpha_s}{8\pi}G\tilde{G}$$





Gives too large CP violation in general.

Make θ dynamical, and get a vev via spontaneous symmetry breaking

Goldstone mode = axion

Gets mass from QCD, and can be DM

Peccei and Quinn (1977); Weinberg (1978); Wilczek (1978)

Is Axion DM a BEC?

Bose-Einstein Condensation of Dark Matter Axions

P. Sikivie and Q. Yang

Department of Physics, University of Florida, Gainesville, FL 32611, USA

Evolution and thermalization of dark matter axions in the condensed regime

Ken'ichi Saikawa[1,*] and Masahide Yamaguchi[2,†]

Axions: Bose Einstein Condensate or Classical Field?

Sacha Davidson *

IPNL, CNRS/IN2P3, 4 rue E. Fermi, 69622 Villeurbanne cedex, France; Université Lyon 1, Villeurbanne; Université de Lyon, F-69622, Lyon, France

Do Dark Matter Axions Form a Condensate with Long-Range Correlation?

Alan H. Guth,[1,*] Mark P. Hertzberg,[1,2,†] and C. Prescod-Weinstein[3,‡]

+ **more**

Axions + WIMPs

A U(1) global symmetry for a complex scalar with charge = 2

$$\mathcal{L}_{\rm scal.} = \partial_\mu \phi^* \partial^\mu \phi + \mu^2 |\phi|^2 - \lambda |\phi|^4$$

Coupled to "quarks" in order to solve the strong-CP problem

$$\mathcal{L}_{\rm KSVZ.} = \{ f_Q \phi \bar{Q}_L Q_R + \ h.c. \}$$

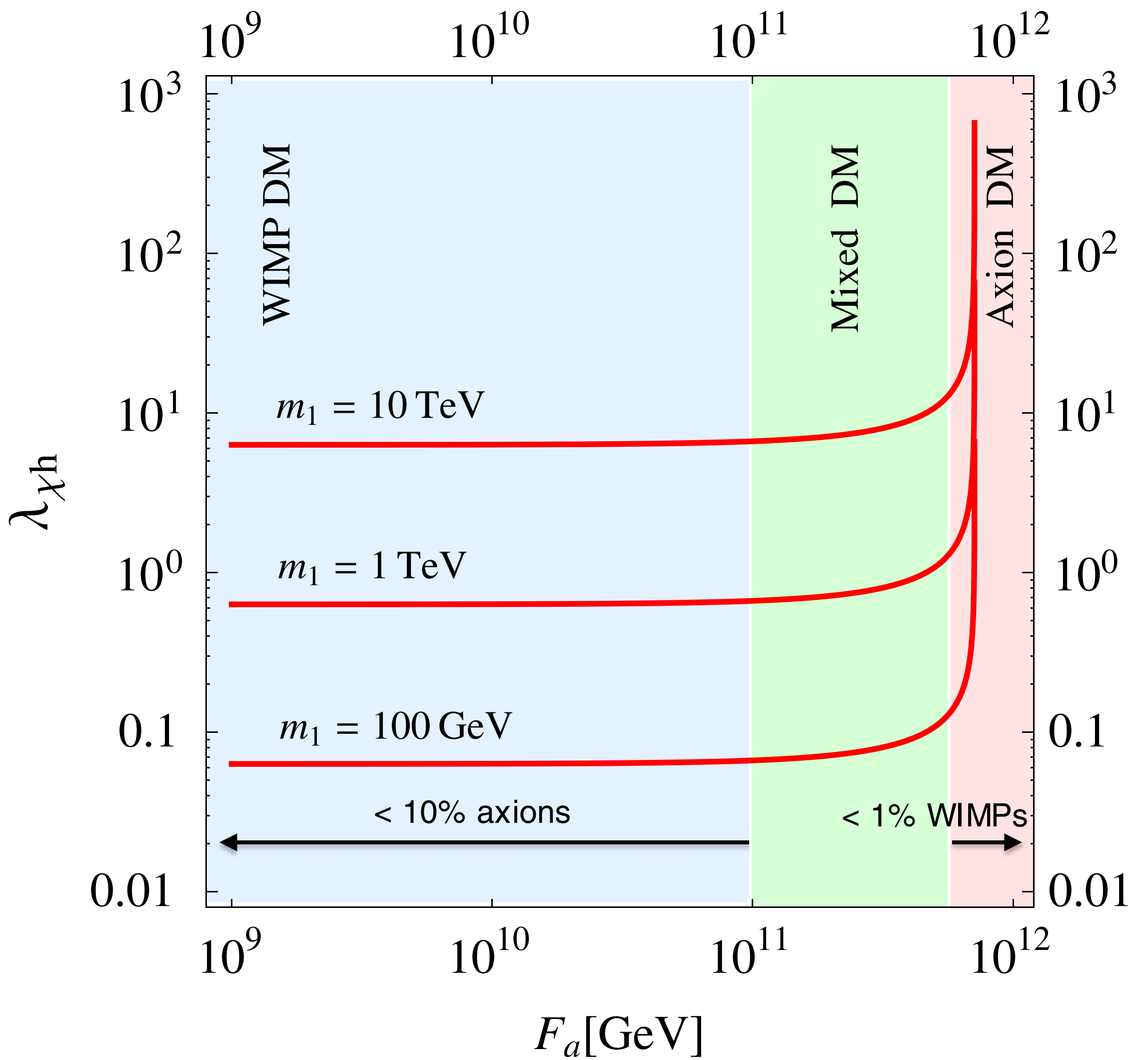
This is the KSVZ axion model. Note that after symmetry breaking the Q is odd under a Z2 symmetry.

Adding a new scalar with charge = 1 makes it *automatically* stable, if lighter than Q

$$\mathcal{L}_{\rm WIMP} = \{ f_d \chi \bar{Q}_L d_R + \epsilon \phi^* \chi \chi + \ h.c. \} + \lambda' |\phi|^2 |\chi|^2$$

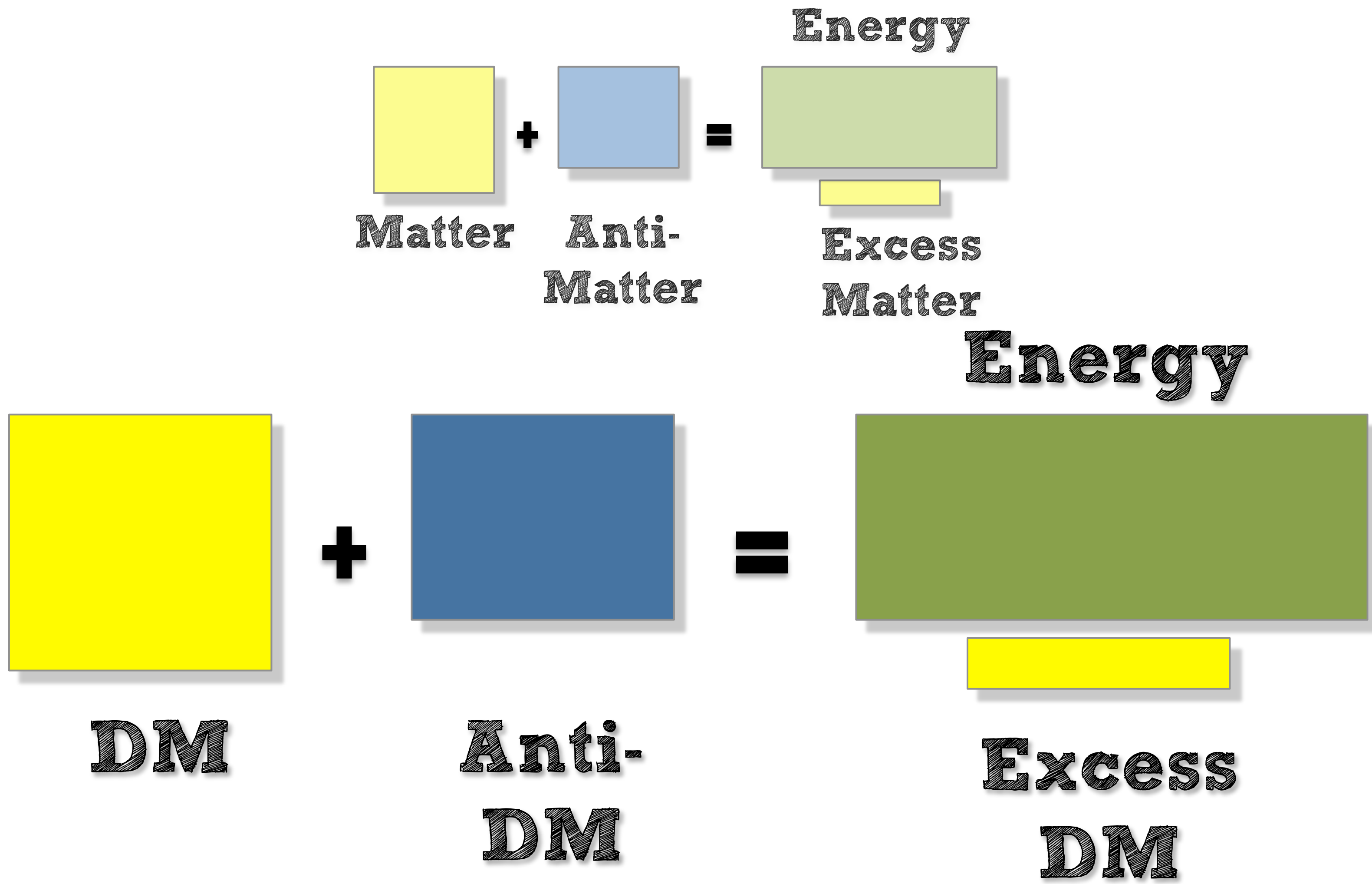
Dasgupta, Ma, and Tsumura (2014)

Axion + WIMPs



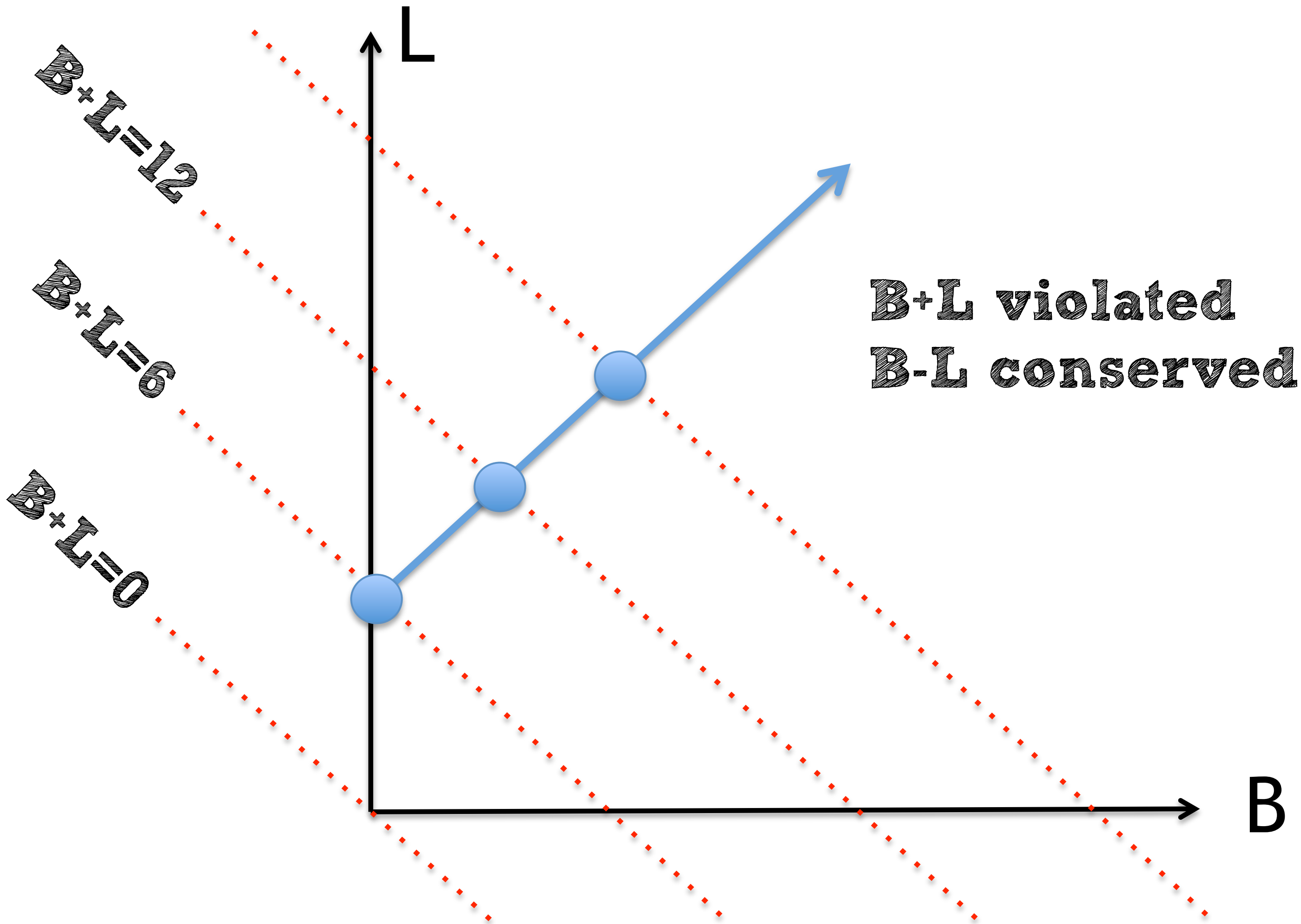
Dasgupta, Ma, and Tsumura (2014)

Idea : Asymmetric DM



Nussinov, ..., Kaplan, Luty, Zurek (2009)

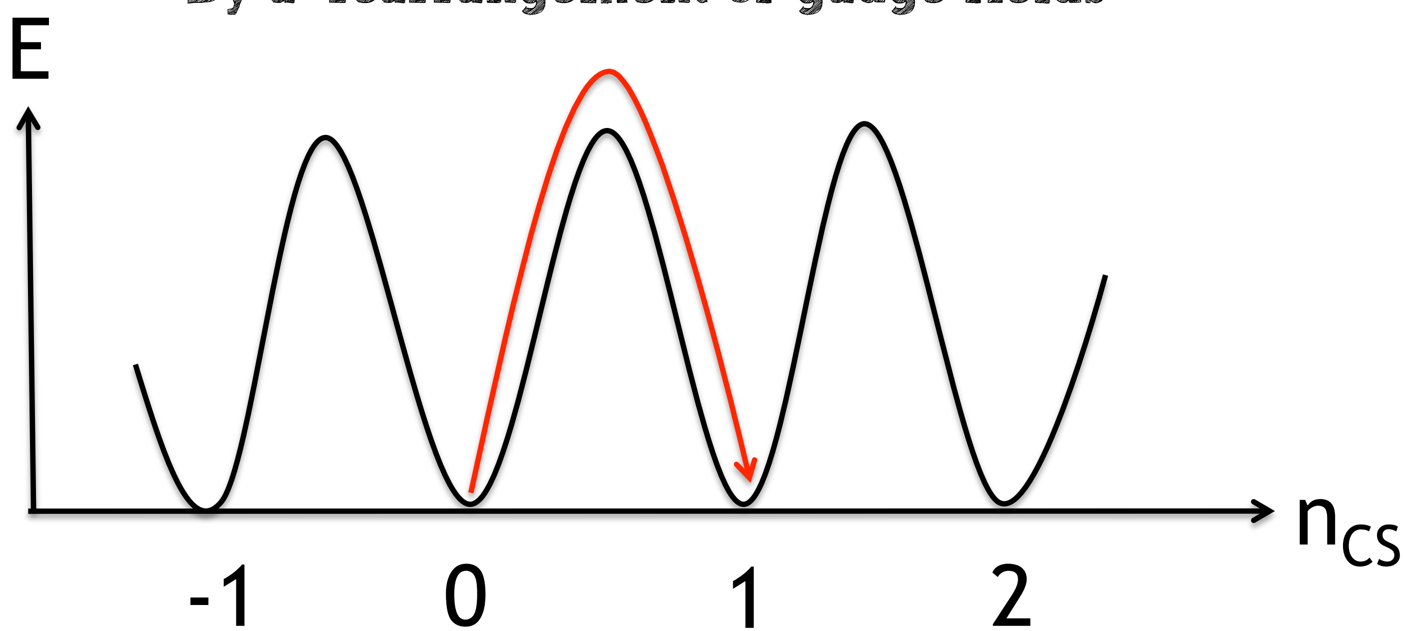
Usual Matter-genesis



Fukugita and Yanagida (1986)

Sphalerons

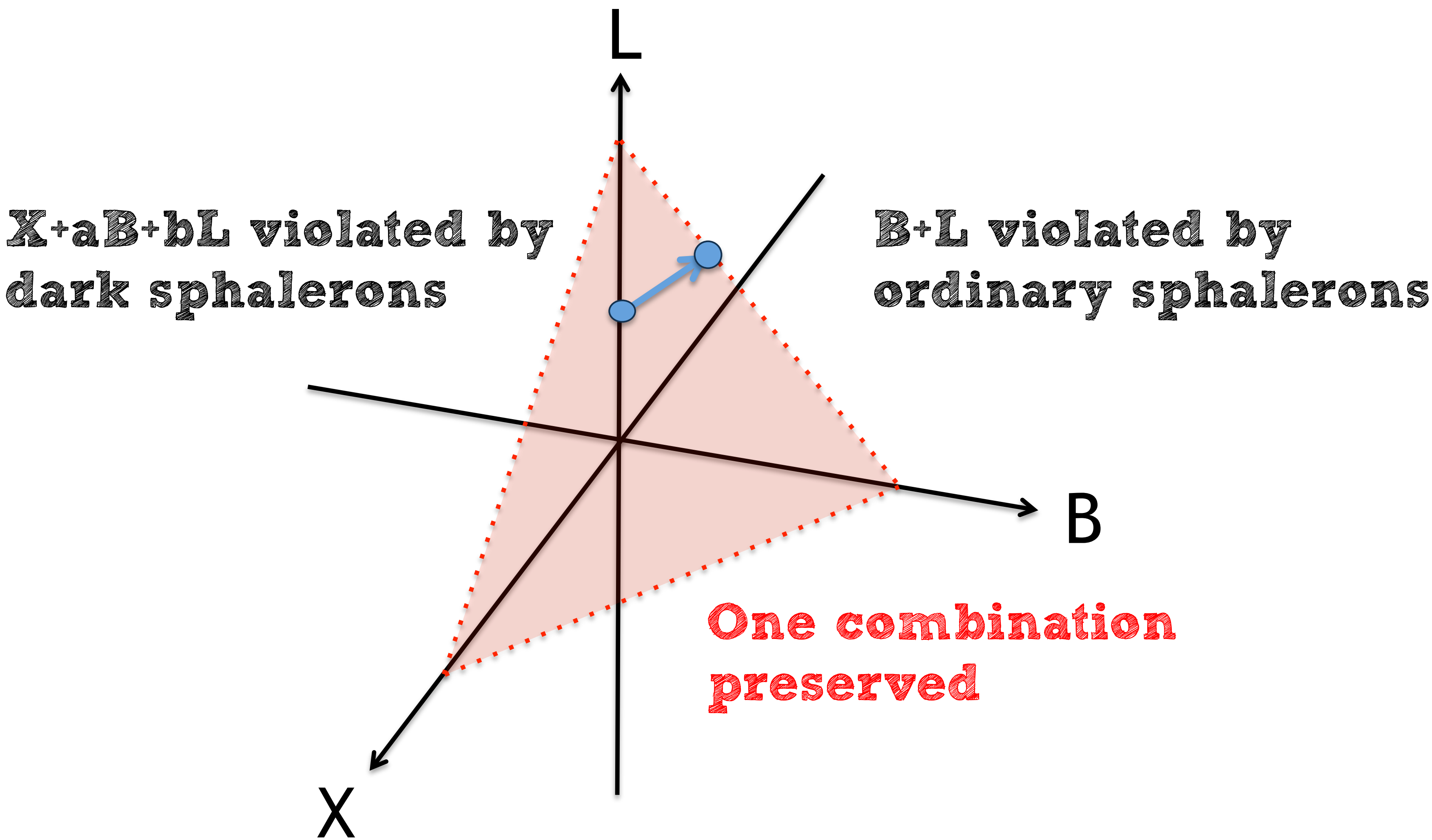
Nonperturbative process at high-T
Changes B+L by 1 unit per generation
By a "rearrangement of gauge fields"



$$n_{CS} = \int dx\, \epsilon_{ijk}\, Tr[F_{ij}A_k - \frac{2}{3}A_i A_j A_k]$$

Kuzmin, Rubakov, and Shaposhnikov (1985)

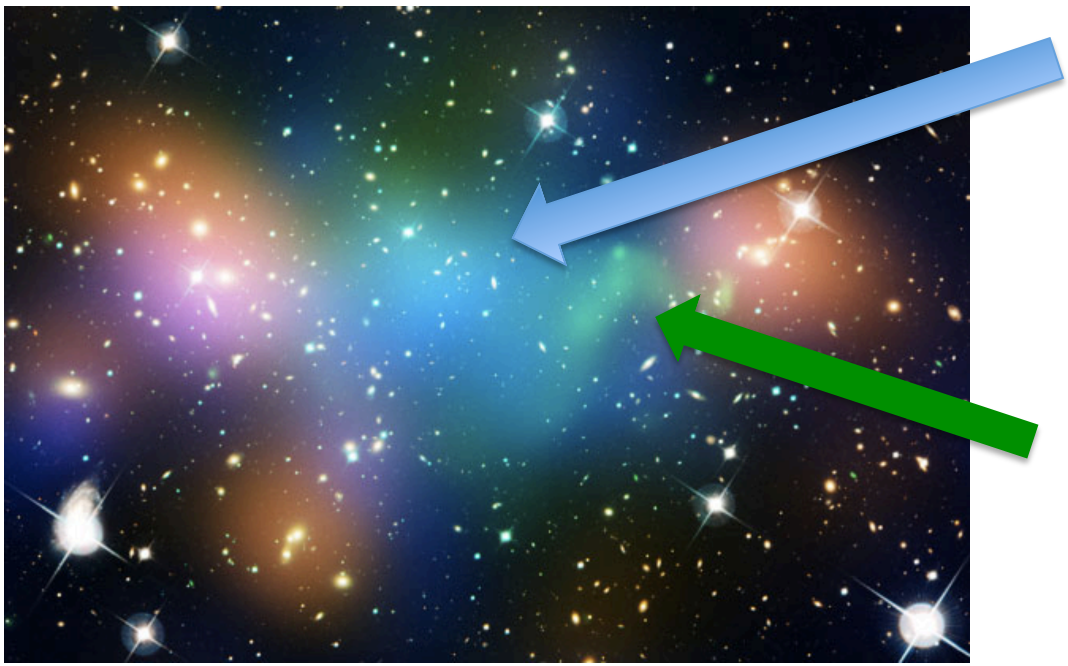
Aidnogenesis



Blennow, Dasgupta, Fernandez-Martinez, and Rius (2010)

Idea : Self-Interacting DM

Dark matter self-interacts a bit?



Gravitational
Lensing Signal
(all matter)

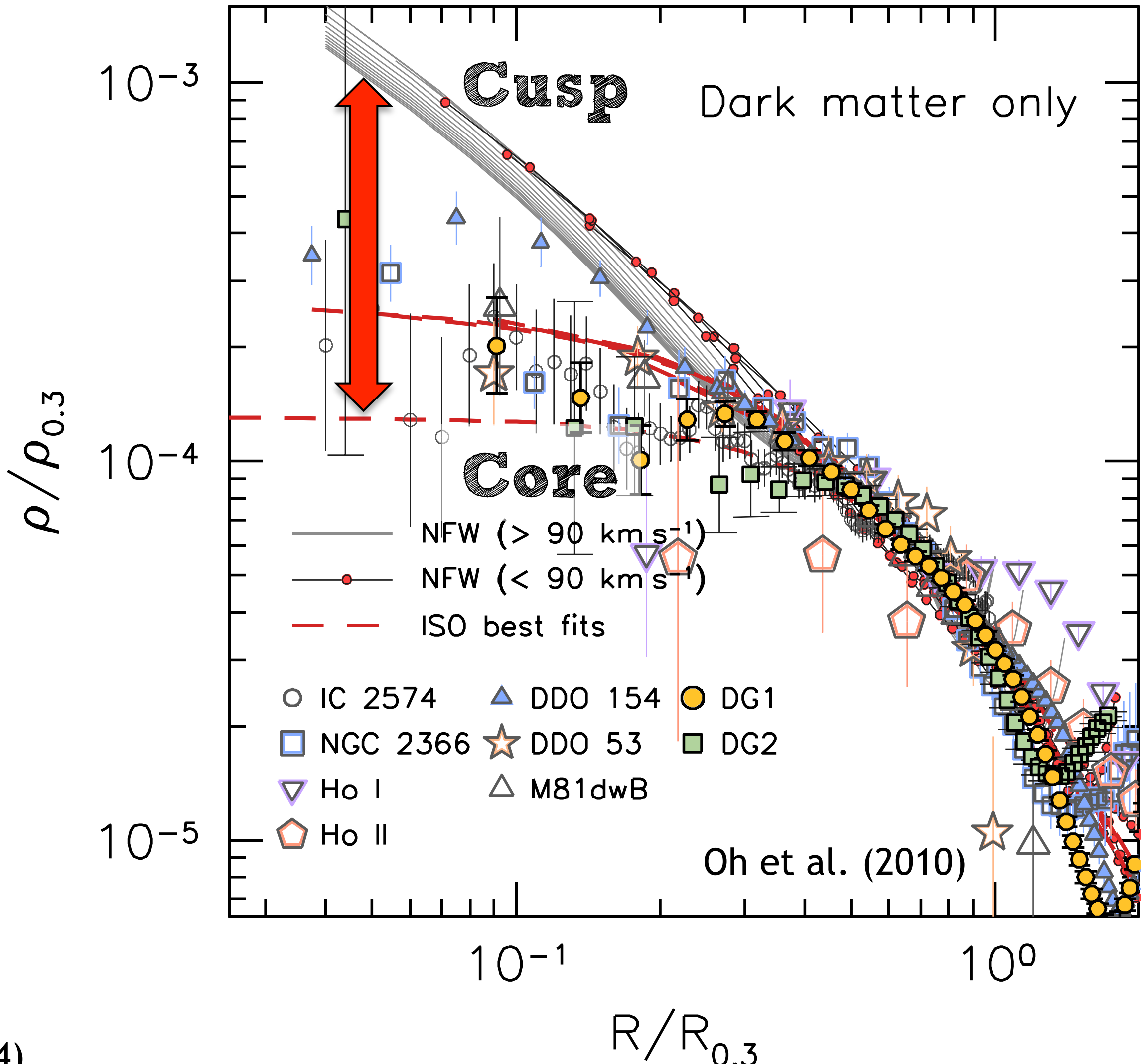
X-Ray Signal
(mostly gas)

Abel 502 Cluster

Most likely a complicated astrophysical system, but ...

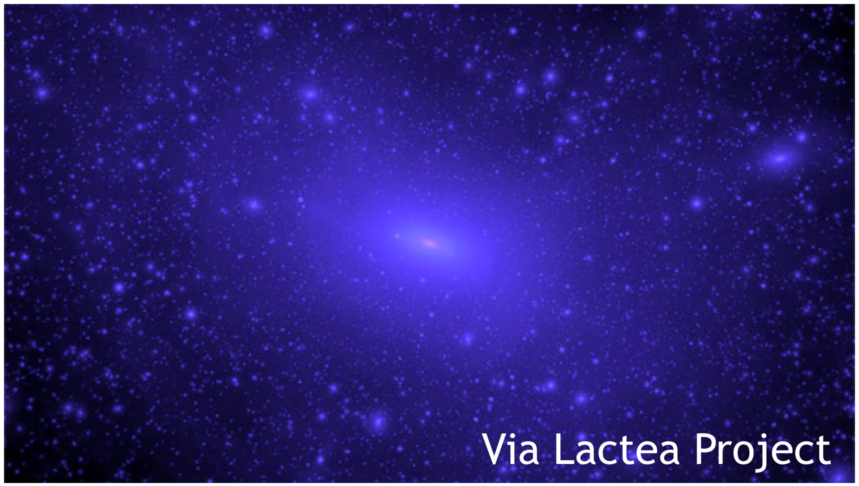
Core-vs.-Cusp Problem

Cold collisionless DM predicts too cuspy inner structure of dwarf galaxies

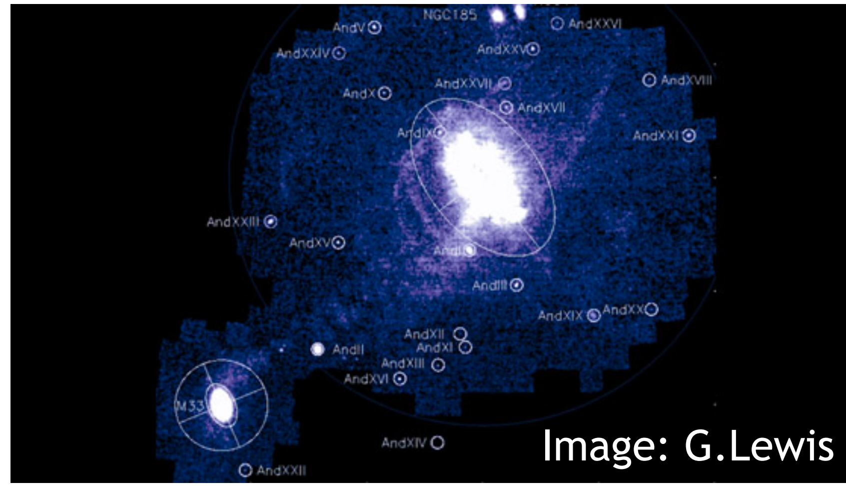


Moore (1994); Flores and Primack (1994)

Missing Satellites Problem



"WIMP" Simulations



PAndAS Survey

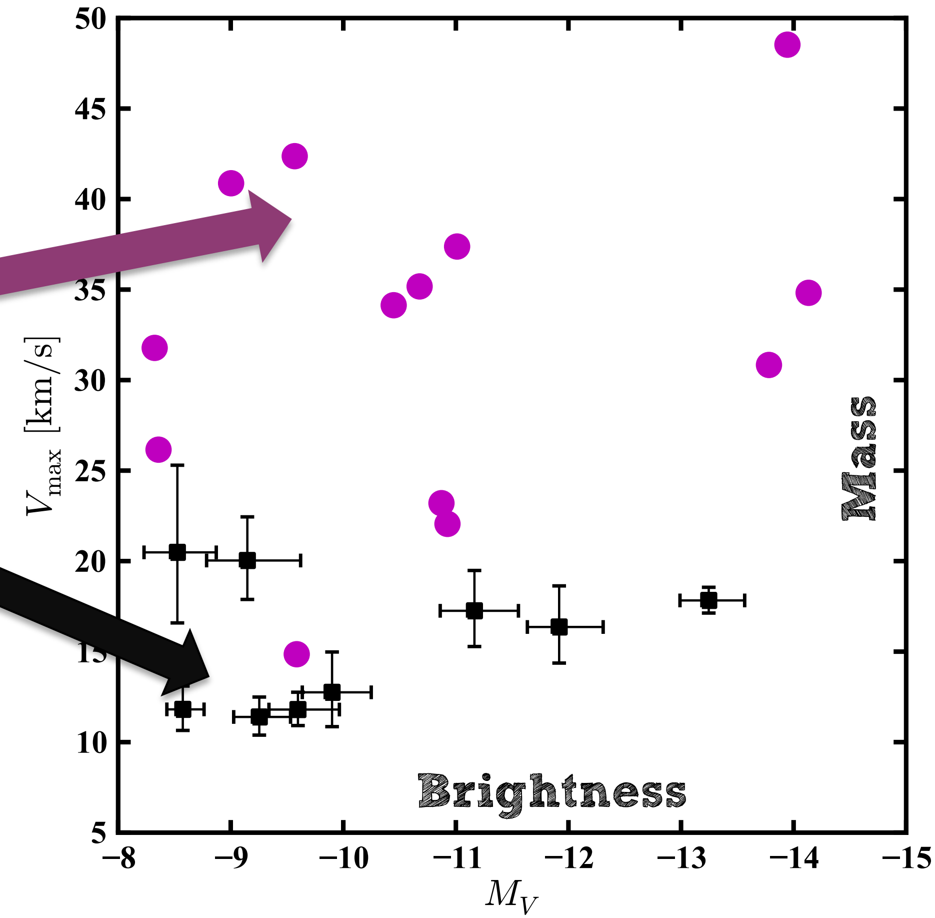
Where are all the satellites of Milky Way?

Klypin, Kravstov, Valenzuela, and Prada (1999)

Too-Big-to-Fail Problem

Predicted Halos

Seen Dwarfs

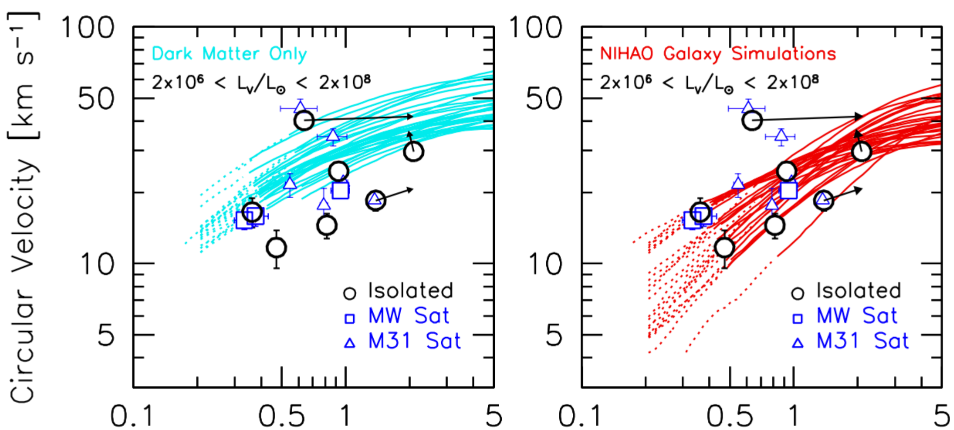


Why did the predicted massive dwarf-sized halos fail to host stars?

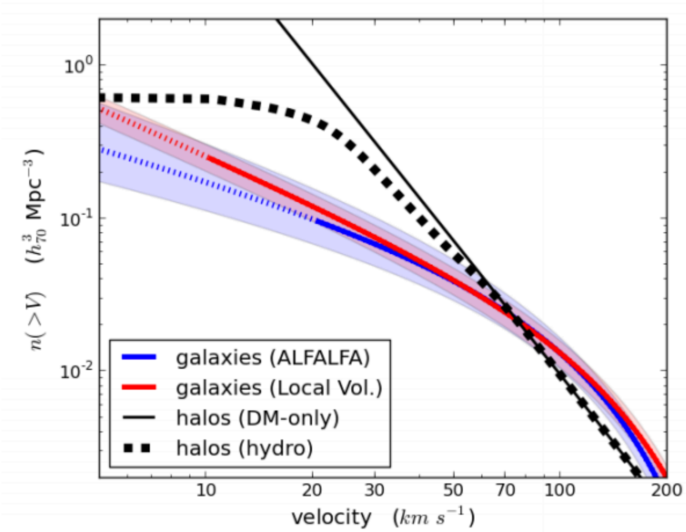
Boylan-Kolchin, Kaplinghat, and Bullock (2010)

How to improve structures ?

- Supernova feedback (blows out gas, no stars)
- Tidal effects (strips out small halos)
- Low star-formation (small halos have less stars)
- … several astrophysical solutions,



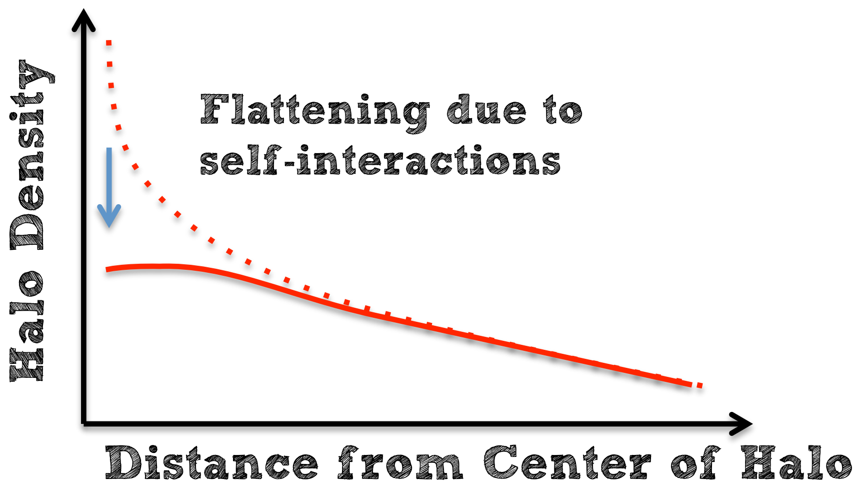
Dutton et al (2015)

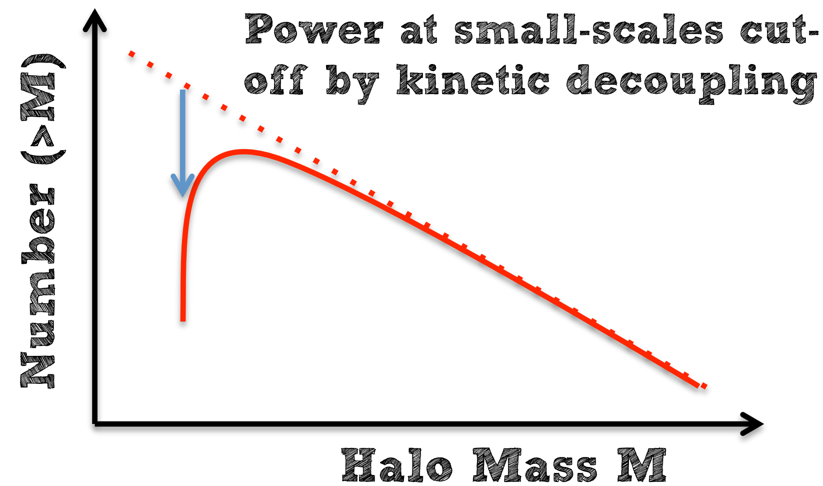


Papastergis and Shankar (2015)

- May be a particle physics solution?

A two-step solution





Core-Cusp problem and Too Big to Fail problem solved by halo flattening

Missing Satellites problem solved using late kinetic decoupling

Self-Interactions

DM – DM scattering before they fall into the cusp redistributes DM in phase space so that in they are very isotropic in velocity.

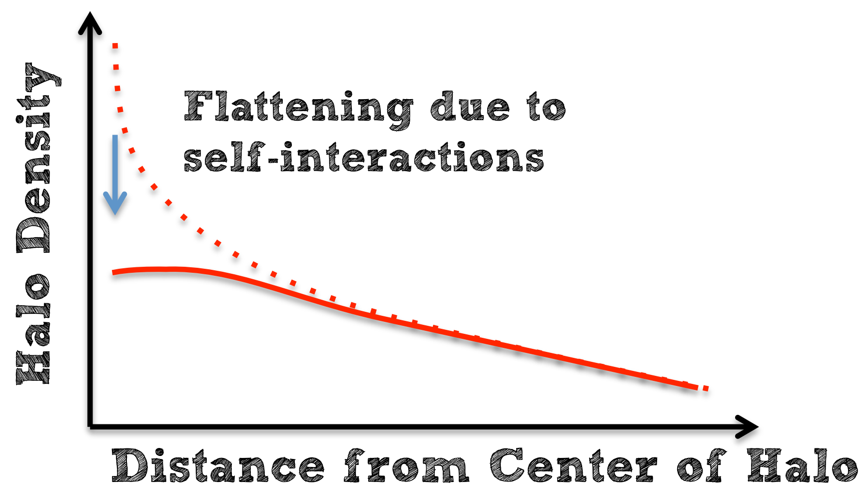
This leads to shallower density profiles.

The size of the core is where optical depth becomes order 1.

$$\frac{\rho}{m_\chi}\sigma_T L = 1$$

Put values of ρ and L

$$\frac{\sigma_T}{m_\chi} \approx (0.1 - 1)\mathrm{cm}^2\mathrm{g}^{-1}$$



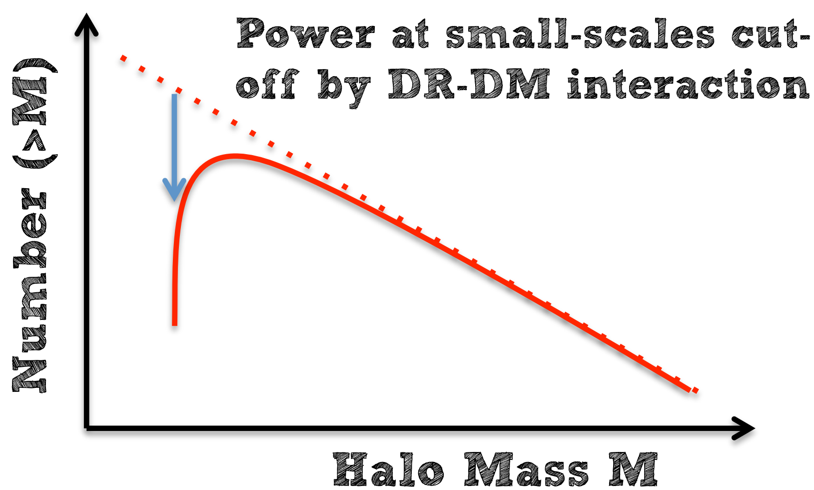
Spergel and Steinhardt (1999) Loeb and Weiner (2010)

Late Decoupling

The DM "freestreaming" length determines the size of the smallest halo that can exist. DM scattering on relativistic particles keeps them in kinetic equilibrium and can delay decoupling when freestreaming length is large. This happens as some temperature called kinetic decoupling temperature.

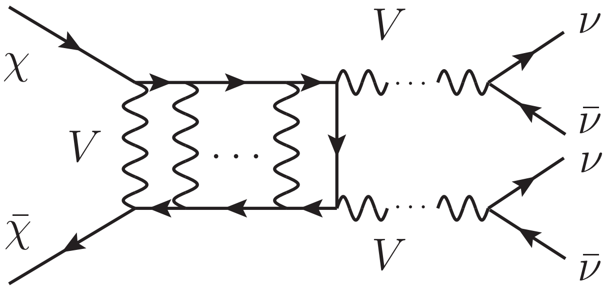
$$\frac{T}{m_\chi} n_{\rm rel.} \sigma \simeq H$$

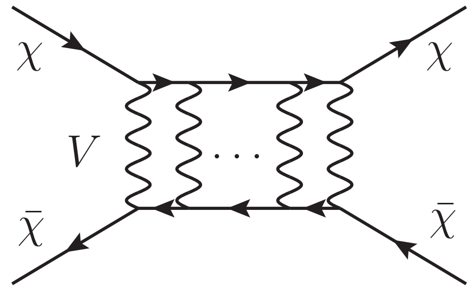
$$M_{\rm cut} \simeq 10^9 M_\odot \left(\frac{T_{kd}}{0.5\,{\rm keV}}\right)^{-3}$$

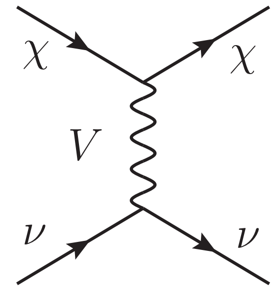


Boehm, Fayet, and Schaeffer (2001); Loeb and Zaldarriaga (2005)

Models with DM interactions







Relic Annihilation **Self-Scattering** **Late-Decoupling**

DM and Neutrinos share a common new gauge interaction

vanDen Aarssen, Bringmann, Pfrommer (2012); Dasgupta and Kopp (2014, PRL, Editors Sugg.)

Weinberg's DM + DR Model

$$\mathcal{L}_{\rm dark} \ni \partial_\mu \phi^* \partial^\mu \phi + \mu_\phi^2 |\phi|^2 - \lambda_\phi |\phi|^4$$ **Complex Scalar**

$$+ i\bar{\chi}\gamma^\mu \partial_\mu \chi - M\bar{\chi}\chi - (\frac{f_{\rm d}}{\sqrt{2}}\phi\chi^T C\chi + h.c.)$$ **Fermion**

On spontaneous symmetry breaking

$$\phi \equiv (v_\phi + \rho + i\eta)/\sqrt{2}$$

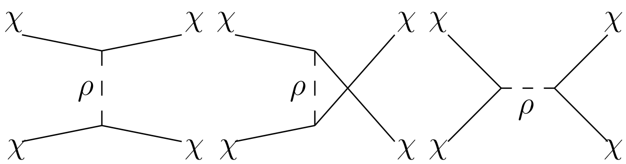
$$\chi_\pm \to -\chi_\pm \text{ and } (\rho, \eta) \to (\rho, \eta)$$

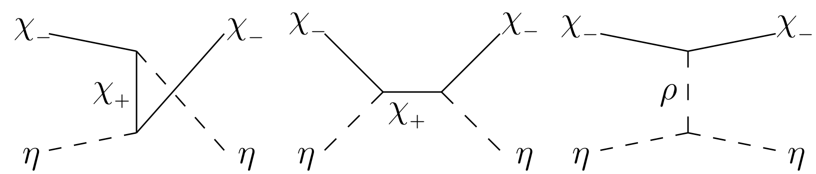
Residual Z2 symmetry ensures χ_- = DM is stable

Also η = DR

Weinberg (2013)

Solving the Small-Scale Issues



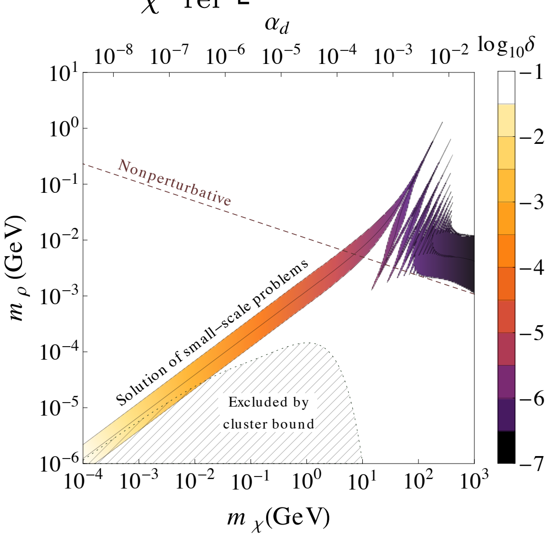


DM-DM Scattering

DM-DR Scattering

$$\sigma_T \simeq \frac{8\pi\alpha_{\rm d}^2}{m_\chi^2 v_{\rm rel}^4}\left[\log(1+R^2) - \frac{R^2}{1+R^2}\right]$$

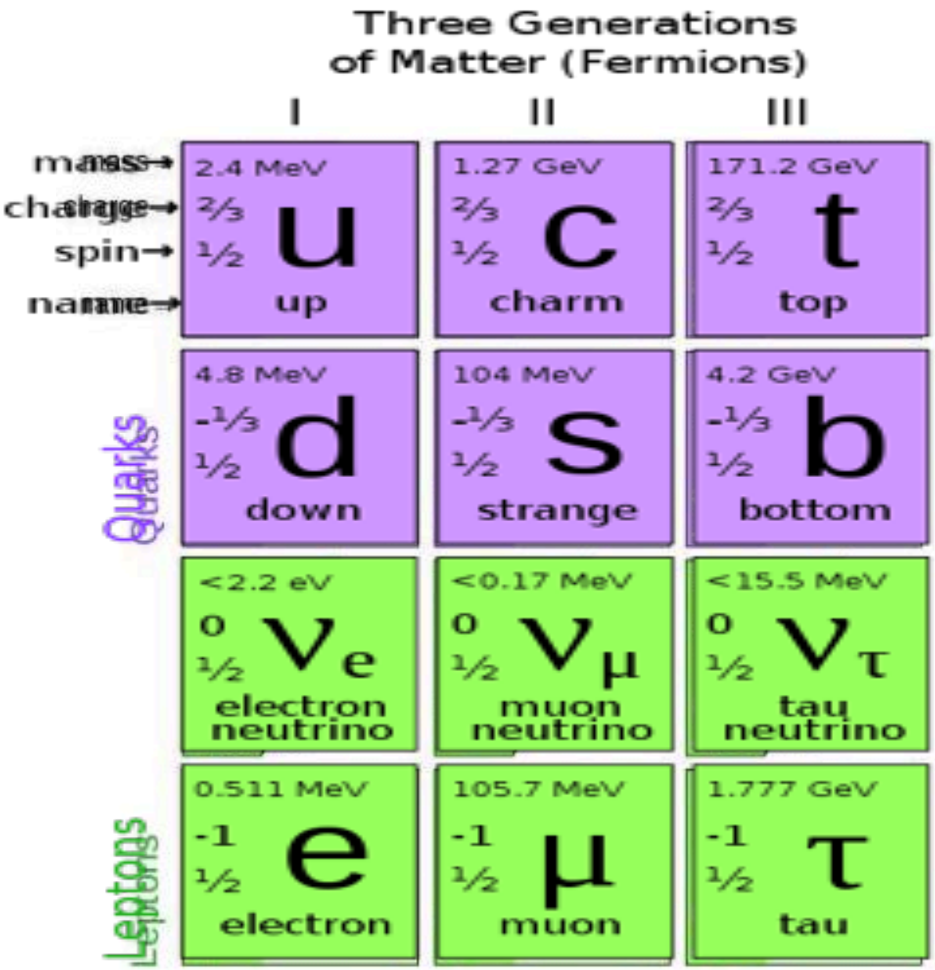
$$\sigma_{\eta\chi_-} = \frac{8\pi\alpha_{\rm d}^2\omega^4}{\Delta m_\chi^6}\left(1+\frac{16\Delta m_\chi^2}{3m_\rho^2}+\frac{8\Delta m_\chi^4}{m_\rho^4}\right)$$



$$T_{\rm kd} \simeq 0.5\,{\rm keV}\frac{\delta}{10^{-4.5}}\left(\frac{m_\chi}{\rm GeV}\right)^{7/6}\left(\frac{10^{-4}}{\alpha_{\rm d}}\right)^{1/3}\xi_{\rm kd}^{-4/3}$$

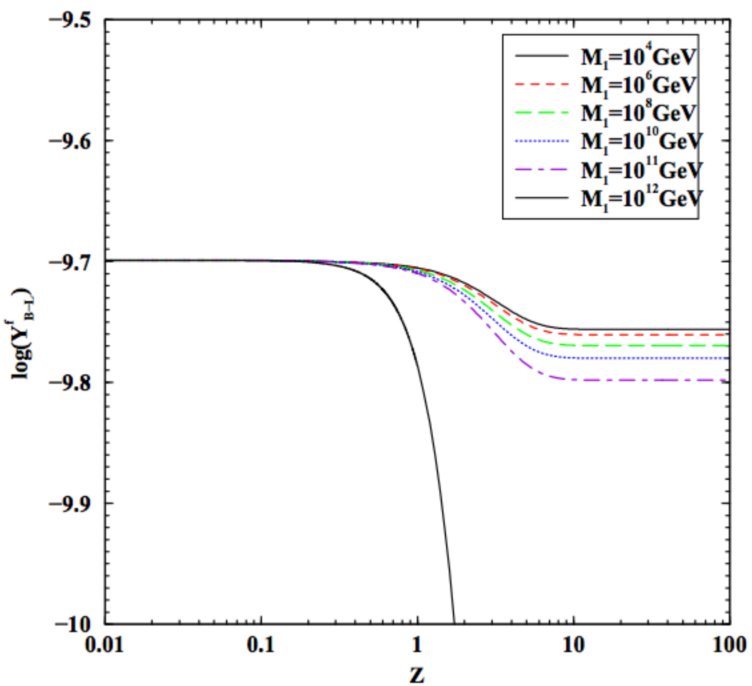
Chu and Dasgupta (2014, PRL)

Idea: Sterile Neutrino DM

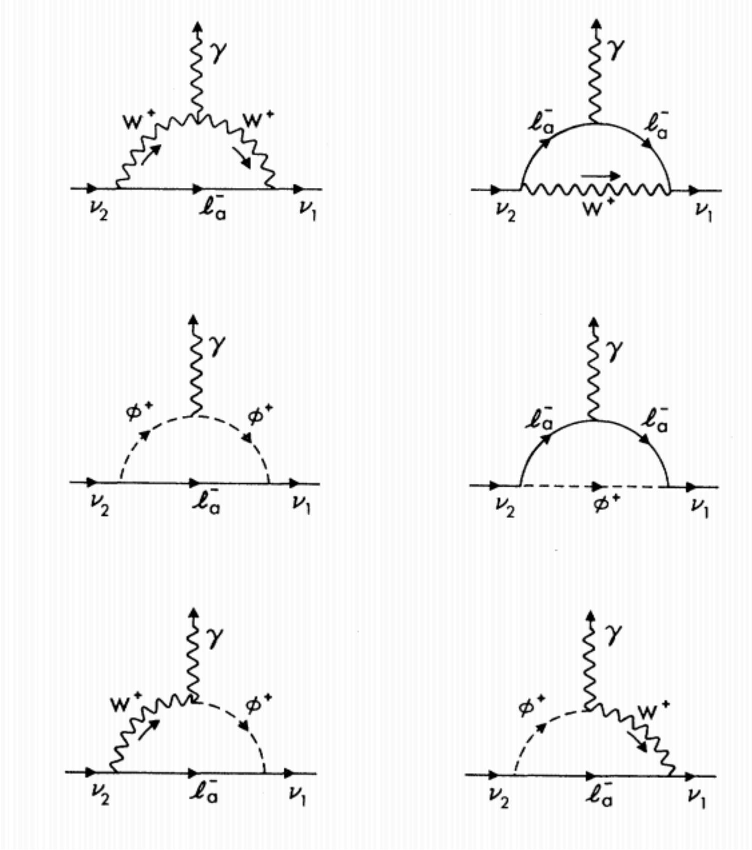


Shaposhnikov ++

Nu-MSM Phenomenology



Sahu and Yajnik (2005)



Pal and Wolfenstein (1981)

Leptogenesis + DM

DM decays to photon + neutrino

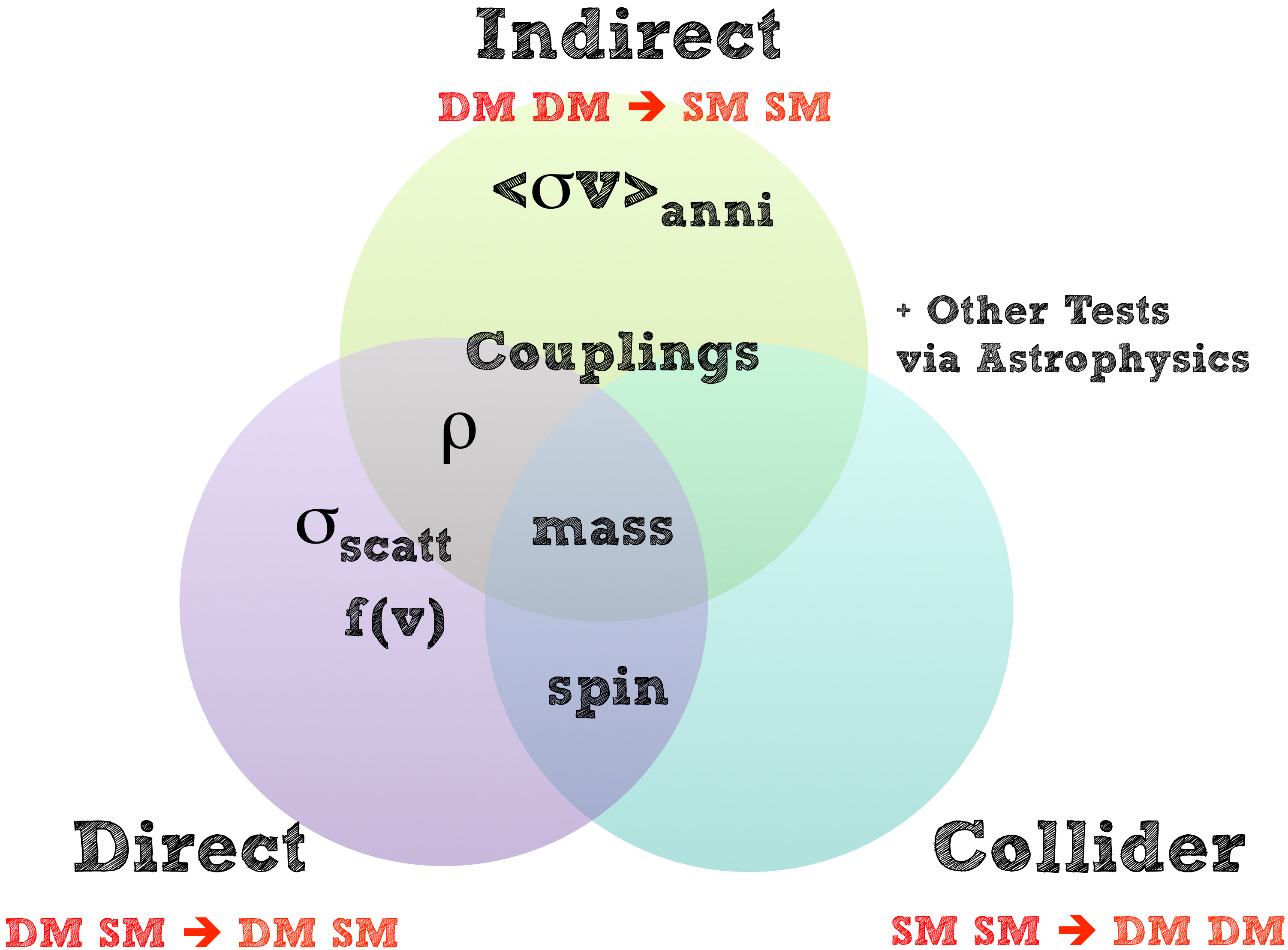
Ideas and Searches

WIMPs
Axions
Asymmetric DM
Self-Interacting DM
Sterile Nu DM
...

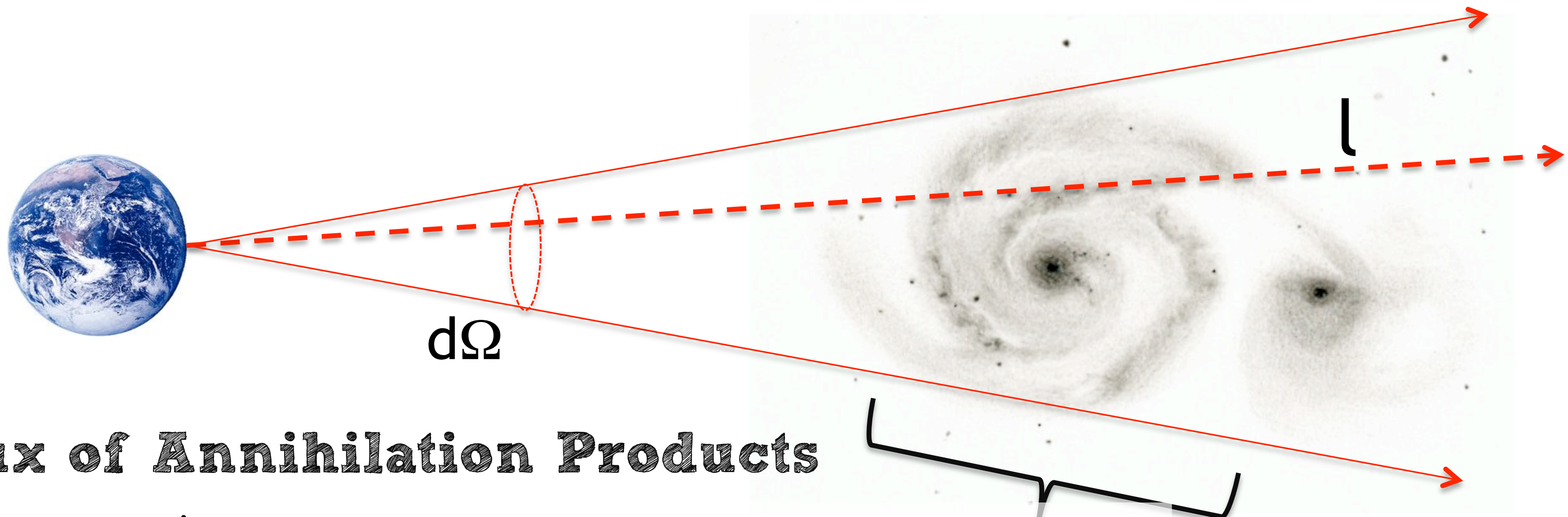
↔

Indirect Detection
Direct Detection
Colliders
Cosmology
Stellar Physics
...

Testing the Ideas



Indirect Detection



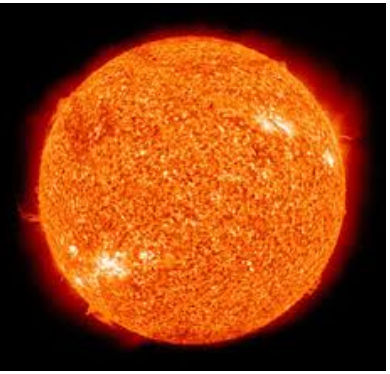
Flux of Annihilation Products

Astrophysics

$$\frac{d\Phi}{dE} = \int d\Omega \int dl\, \rho^2(l,\Omega) \times \frac{\langle \sigma v \rangle}{8\pi m^2} \sum \left(\frac{dN}{dE} B_f \right)$$

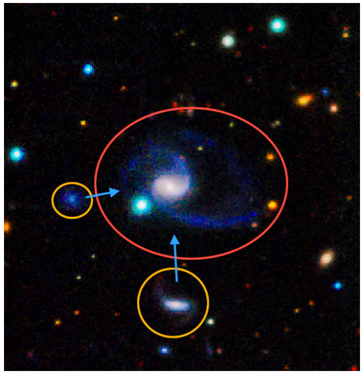
Particle Physics

Origin and Identity



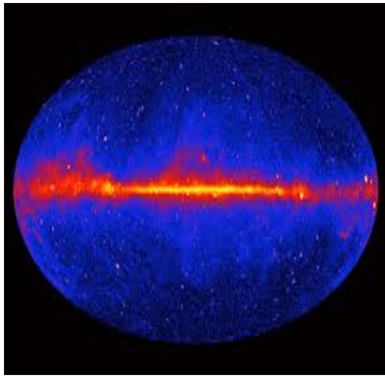
Sun

Milky Way



Nearby Dwarfs

Galaxy Clusters



Diffuse

Cosmic Rays

Pamela, AMS-02, GAPs

Neutrinos

IceCube, Super-K

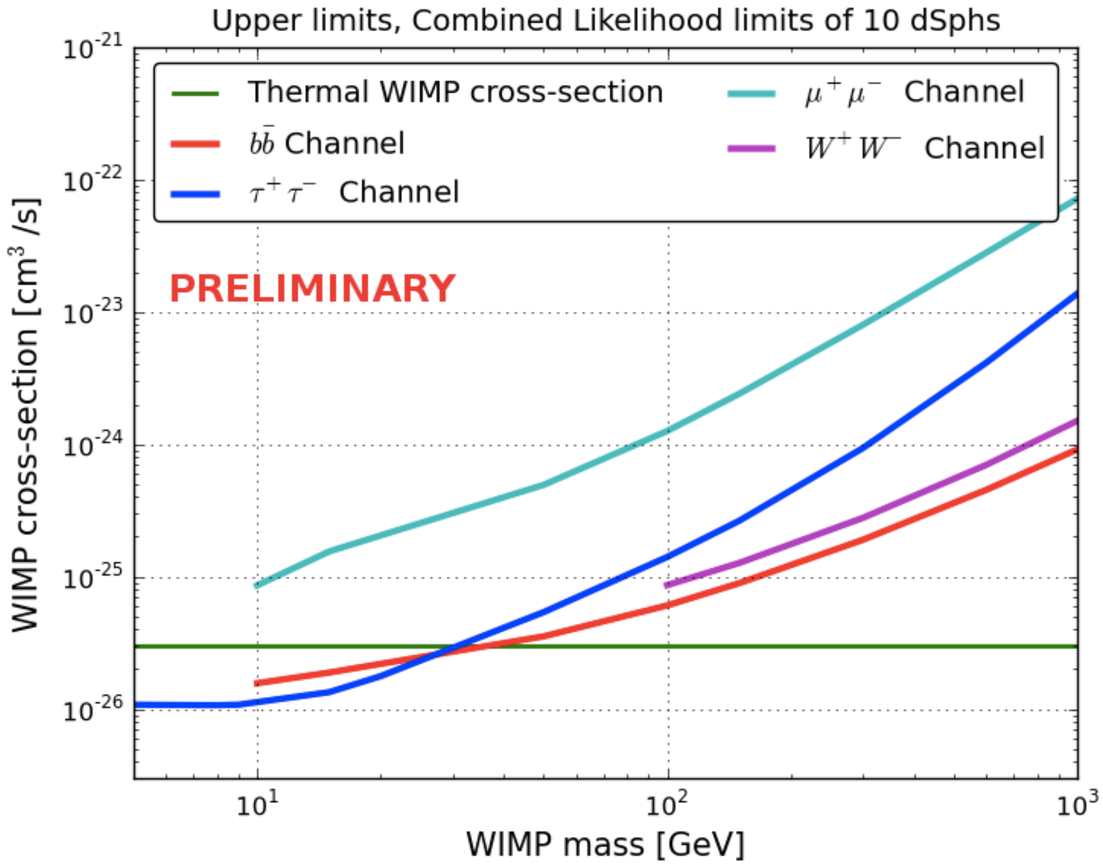
Photons

Fermi, MAGIC, HESS,...

What to really look for ?

- Clean (High signal to bckgrnd.)
- Distinctive
  - Spectral feature
  - Morphological signature
- Cross-checkable
  - Multi-messenger
  - Multi-source

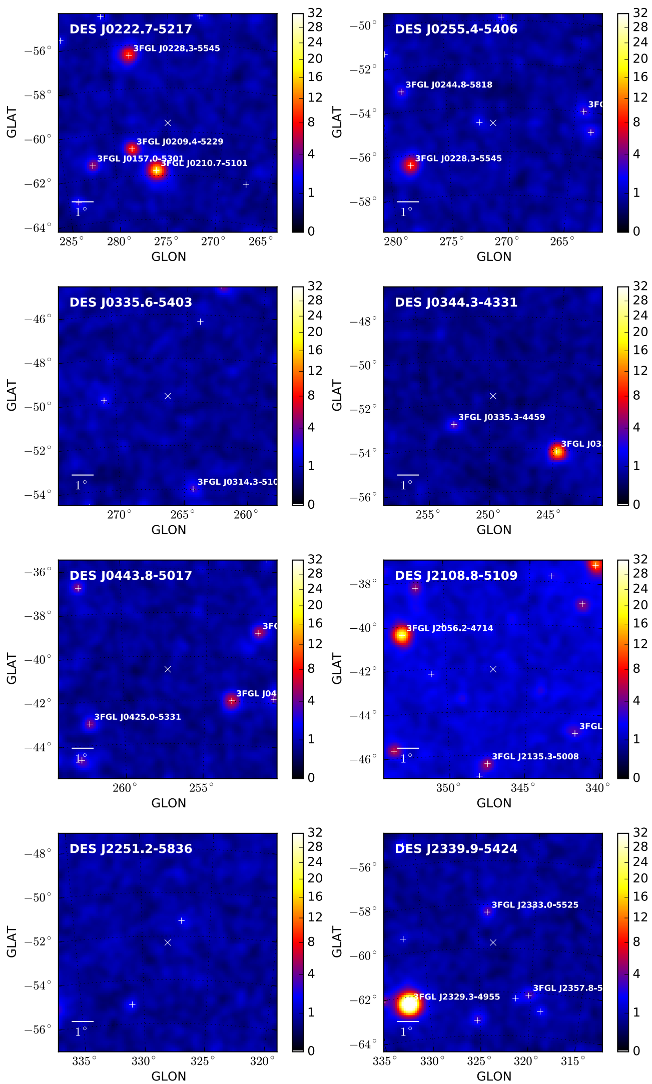
Clean Sources: Dwarf Galaxies



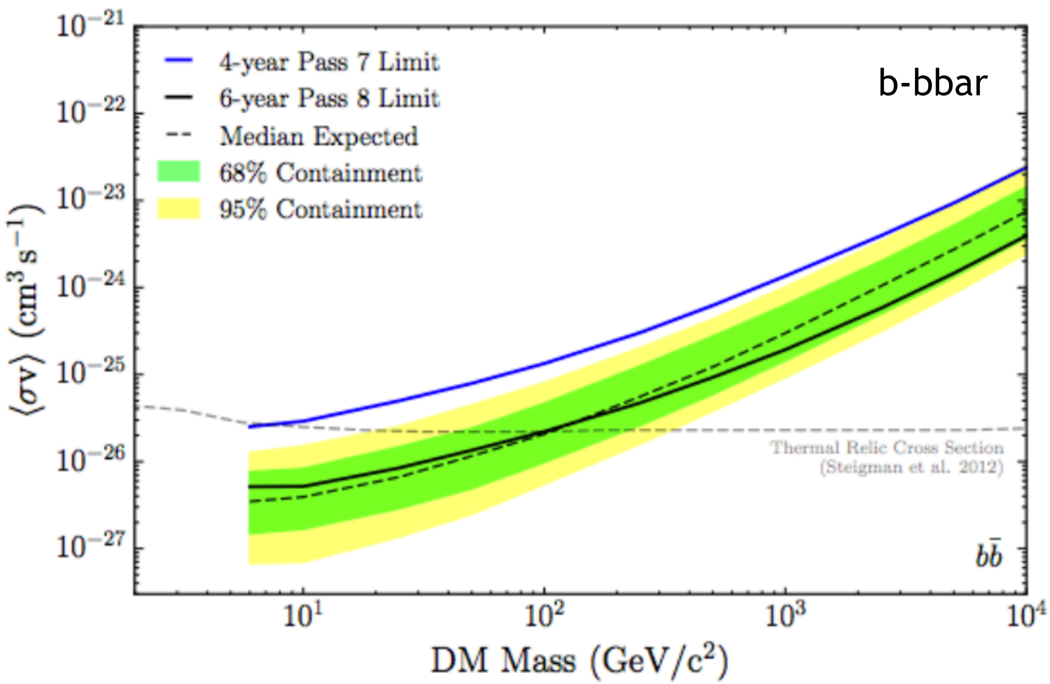
Already probing the interesting cross sections and ruling out models

Fermi Collaboration (2013)

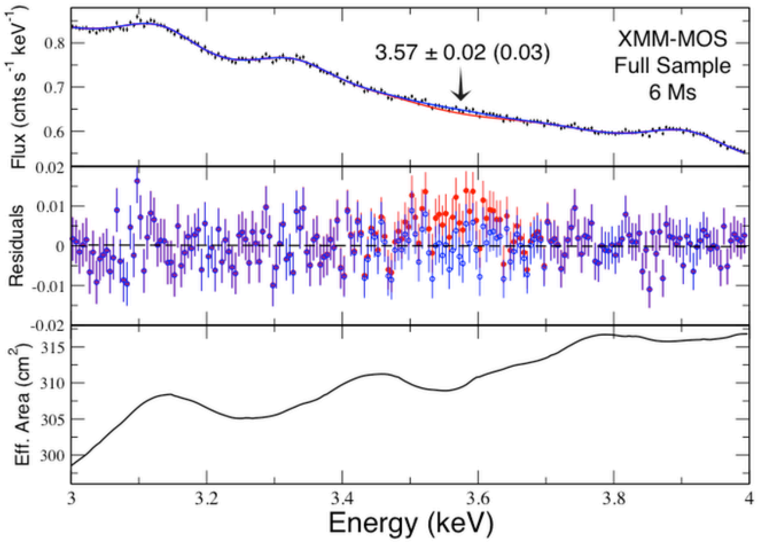
New Dwarf Galaxies



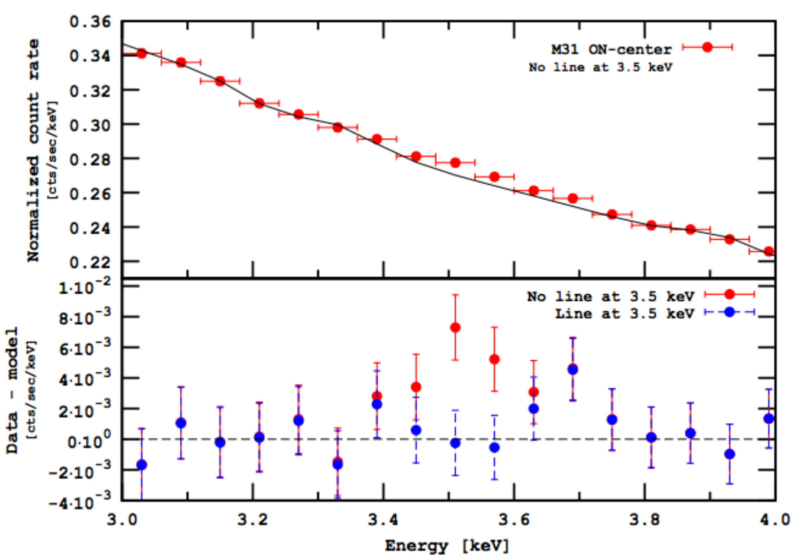
Fermi Coll. (2015)



3.5 keV Line



Bulbul et al (2014)



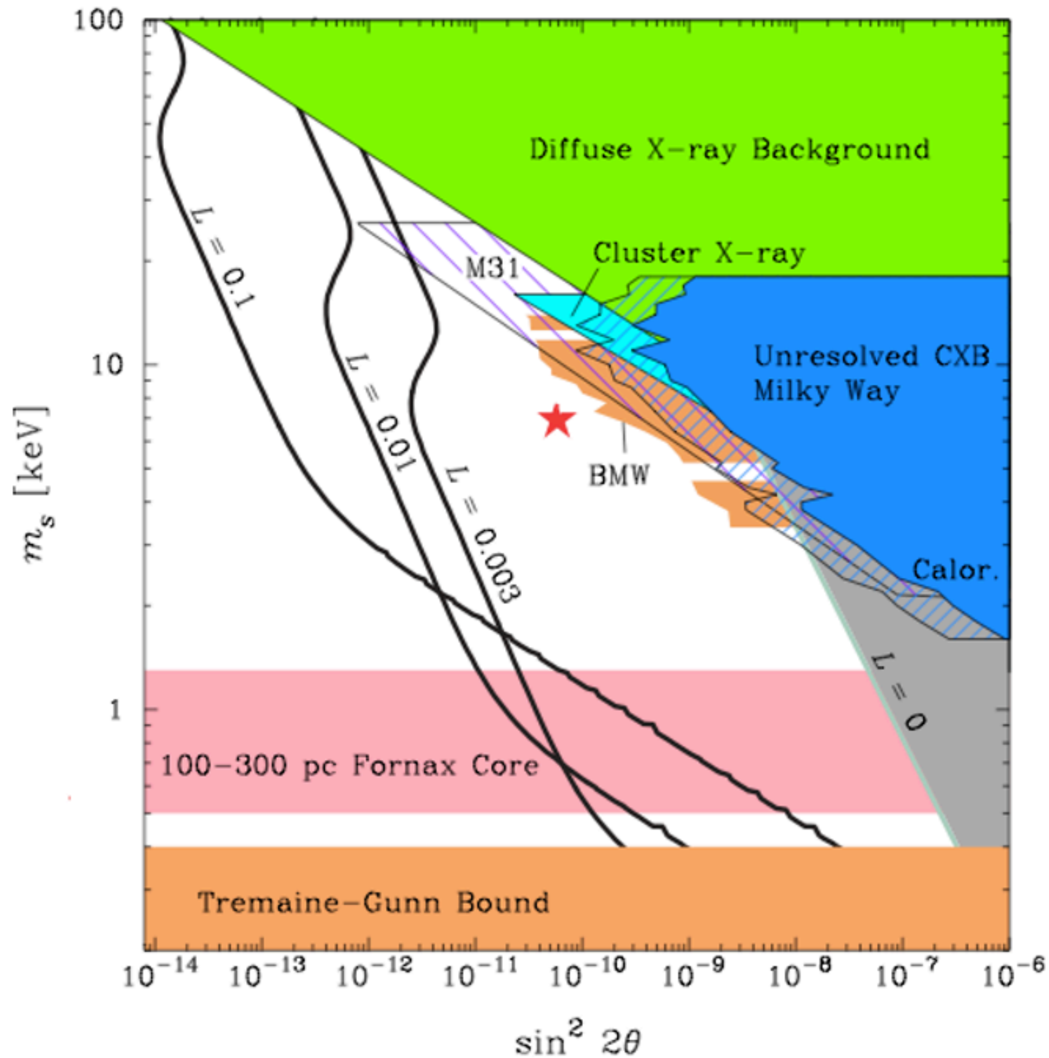
Boyarsky et al (2014)

Offered explanations:

1. **Astrophysics**
2. **Sterile Neutrino DM**
3. **Axion-like particle**

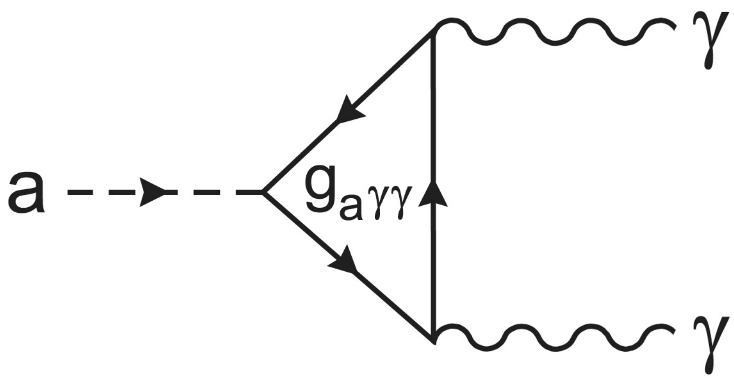
Similar "new" lines have been observed before

Sterile Nu DM decay?

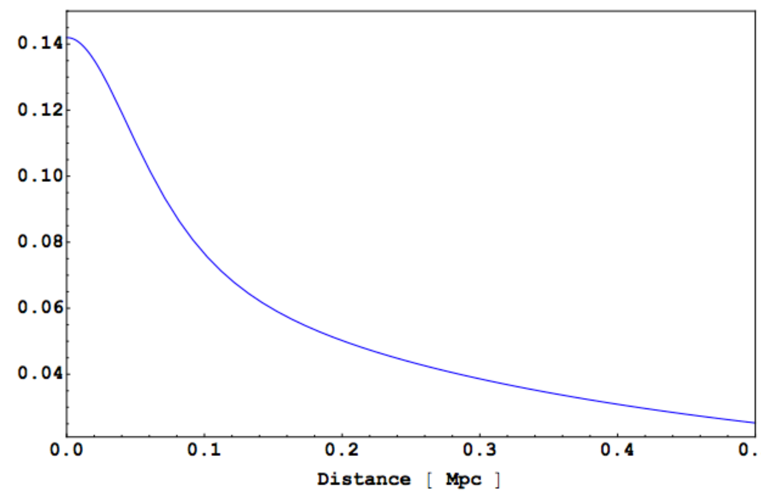


Bulbul et al (2014)

ALPs?



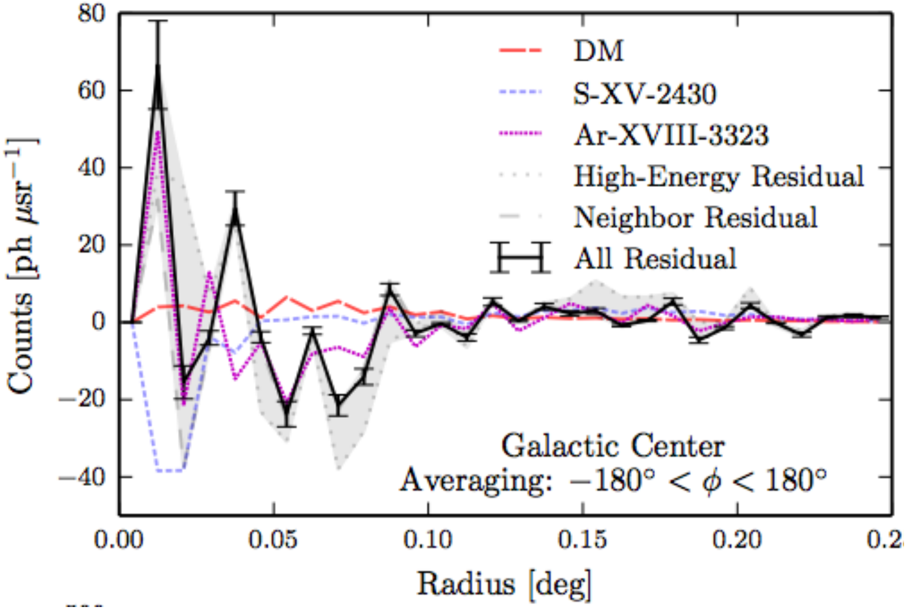
External B field

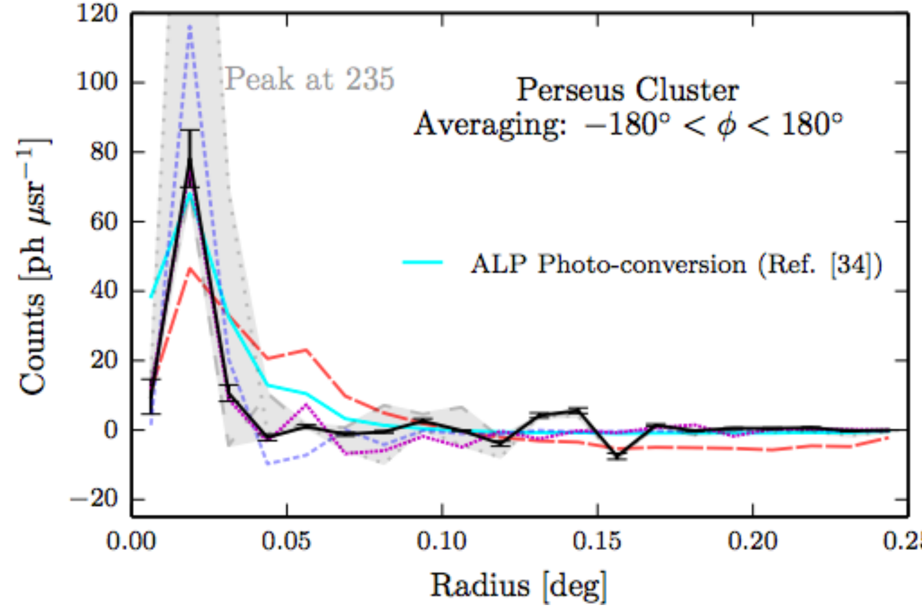


Cicoli et al (2014)

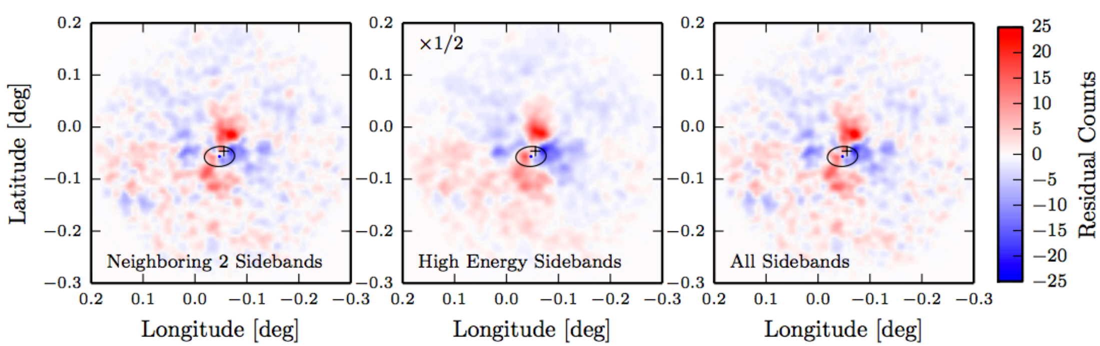
DM axions can be converted to photons in the astrophysical B-fields

Morphology

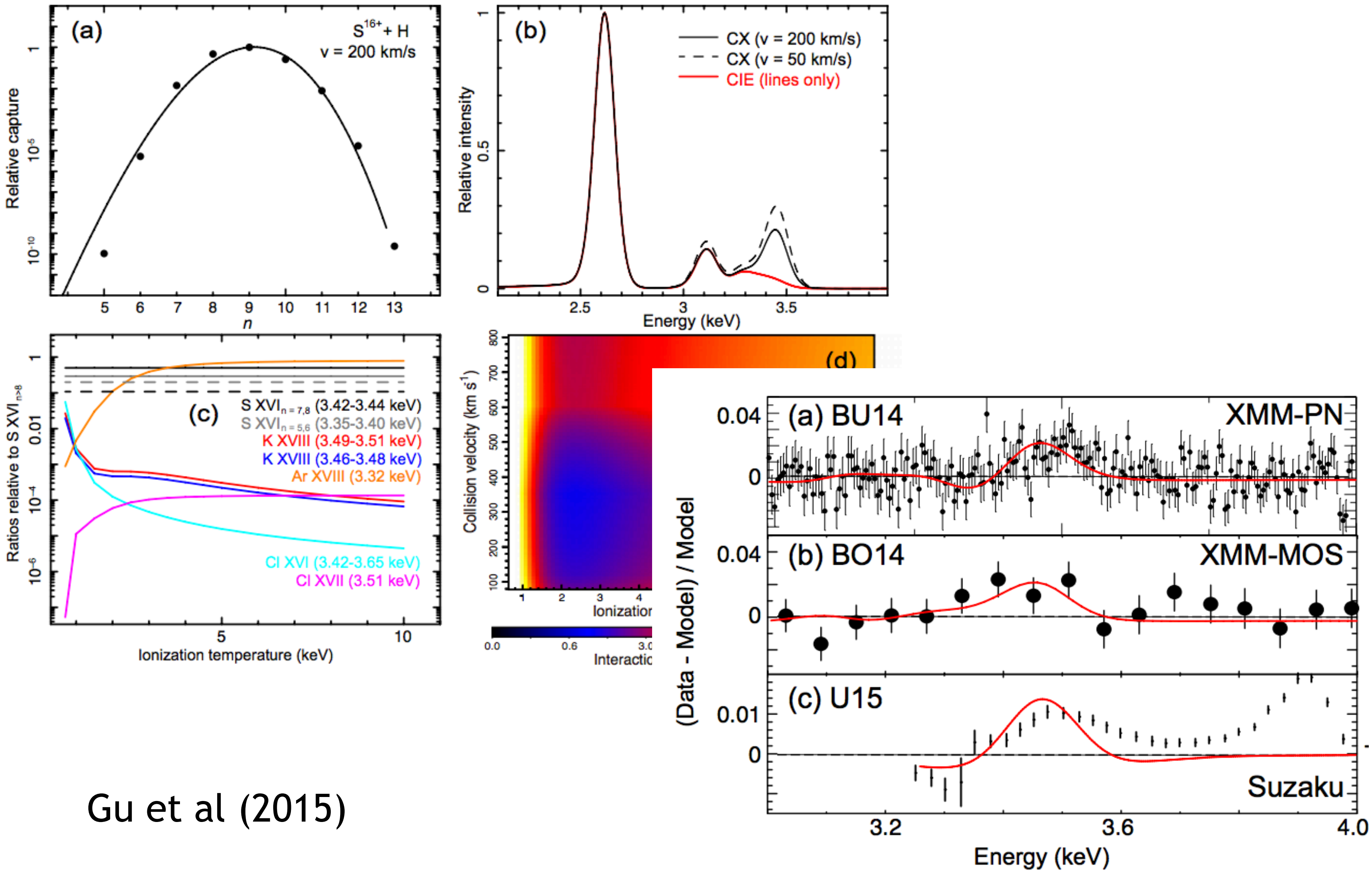




Carlson, Profumo, Jeltema (2014)

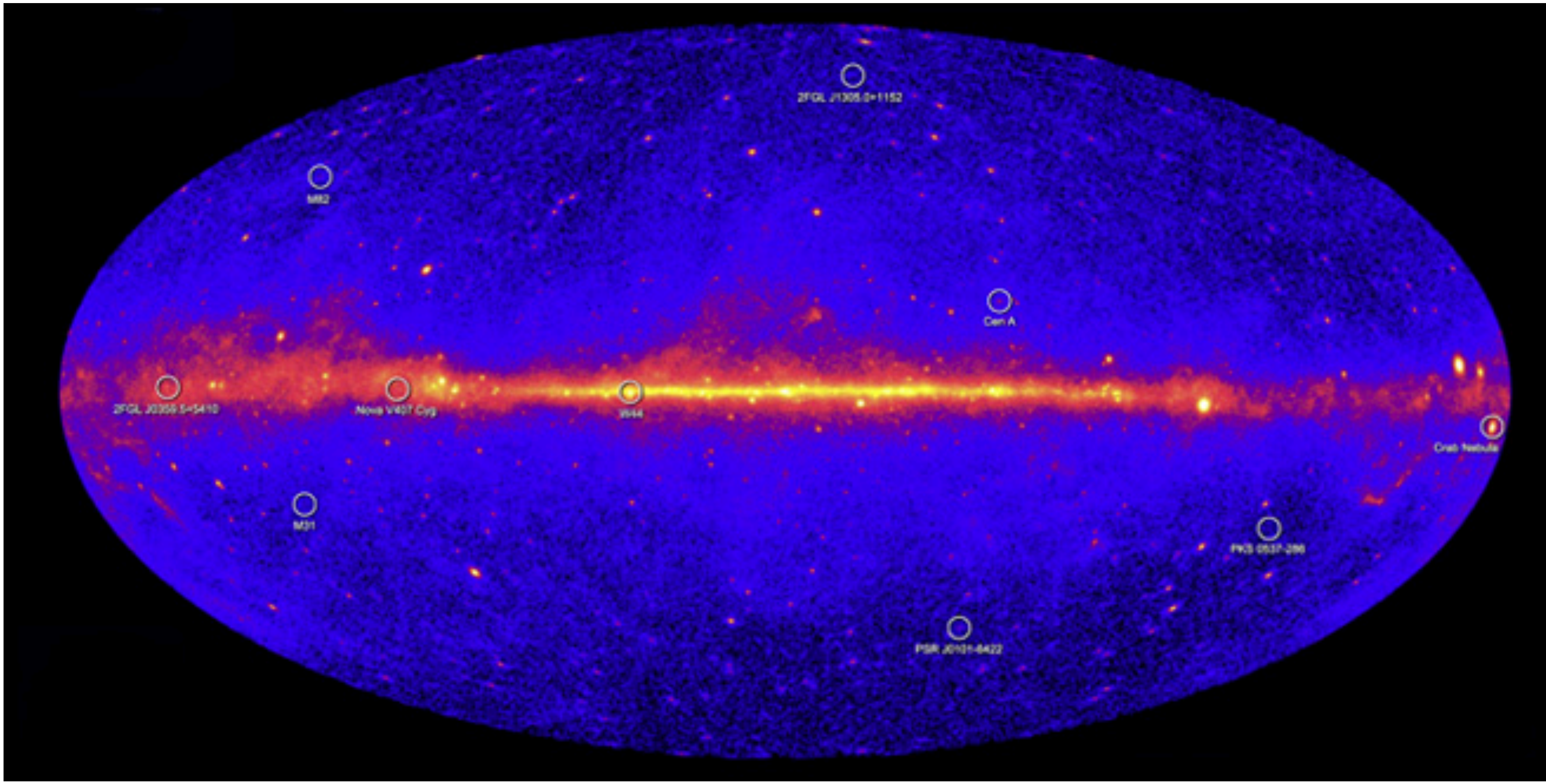


Astrophysical Origin?



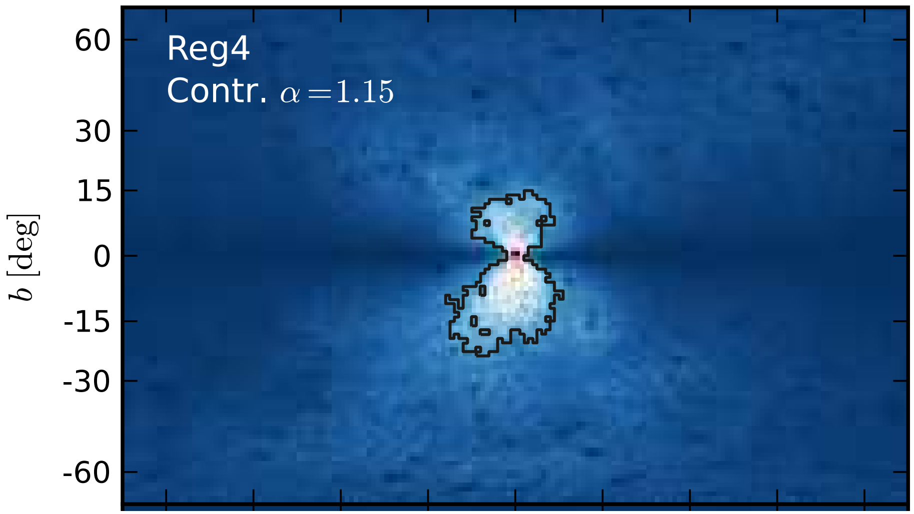
Gu et al (2015)

Galactic Center

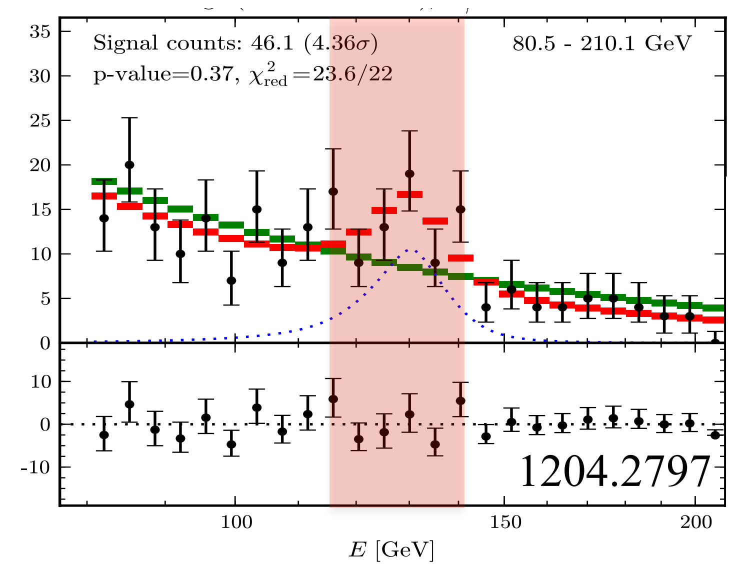


NASA/Fermi Coll.

Galactic Center Line

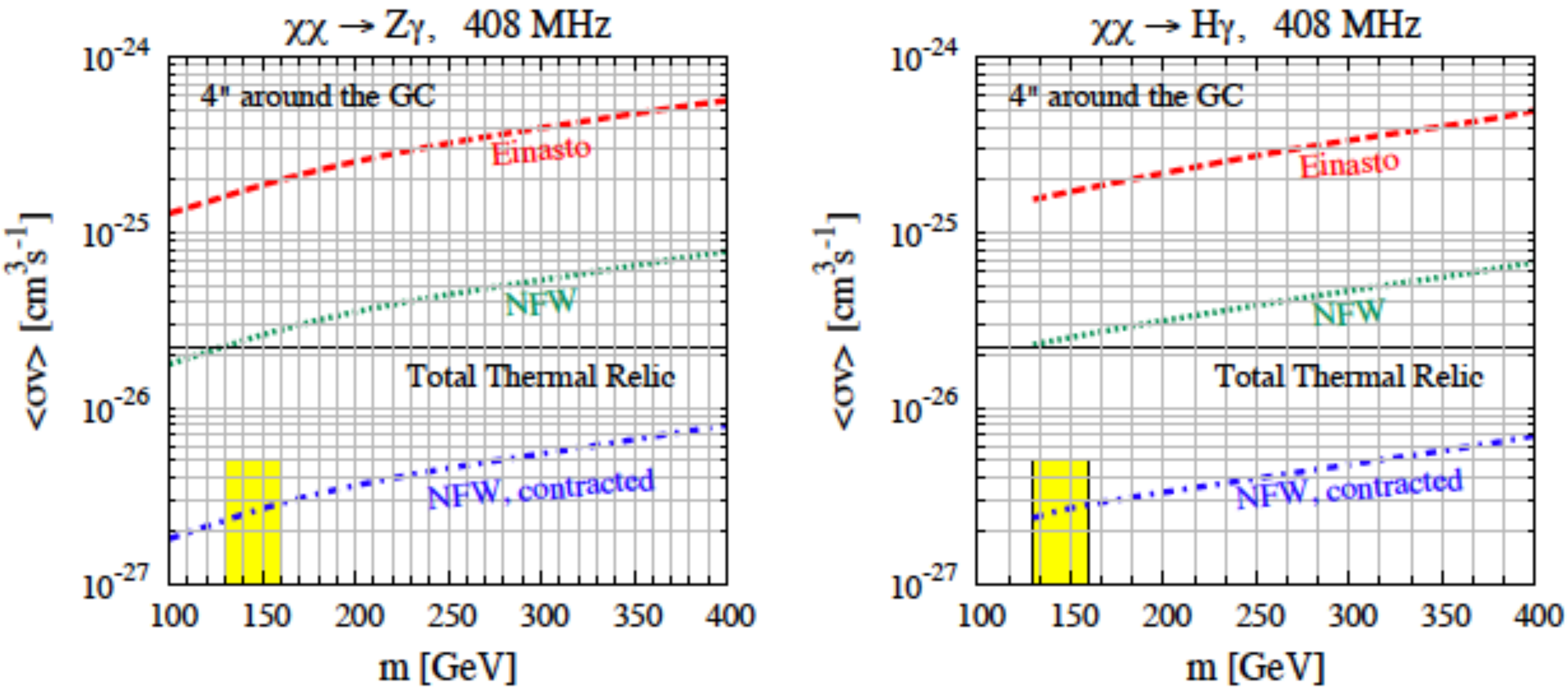


Weniger (2012)



If one has 2 photons by SU(2) symmetry one often gets also Z bosons
Z bosons decay to standard light particles (electron pairs), ...
which can be tested

Multimessenger : Radio

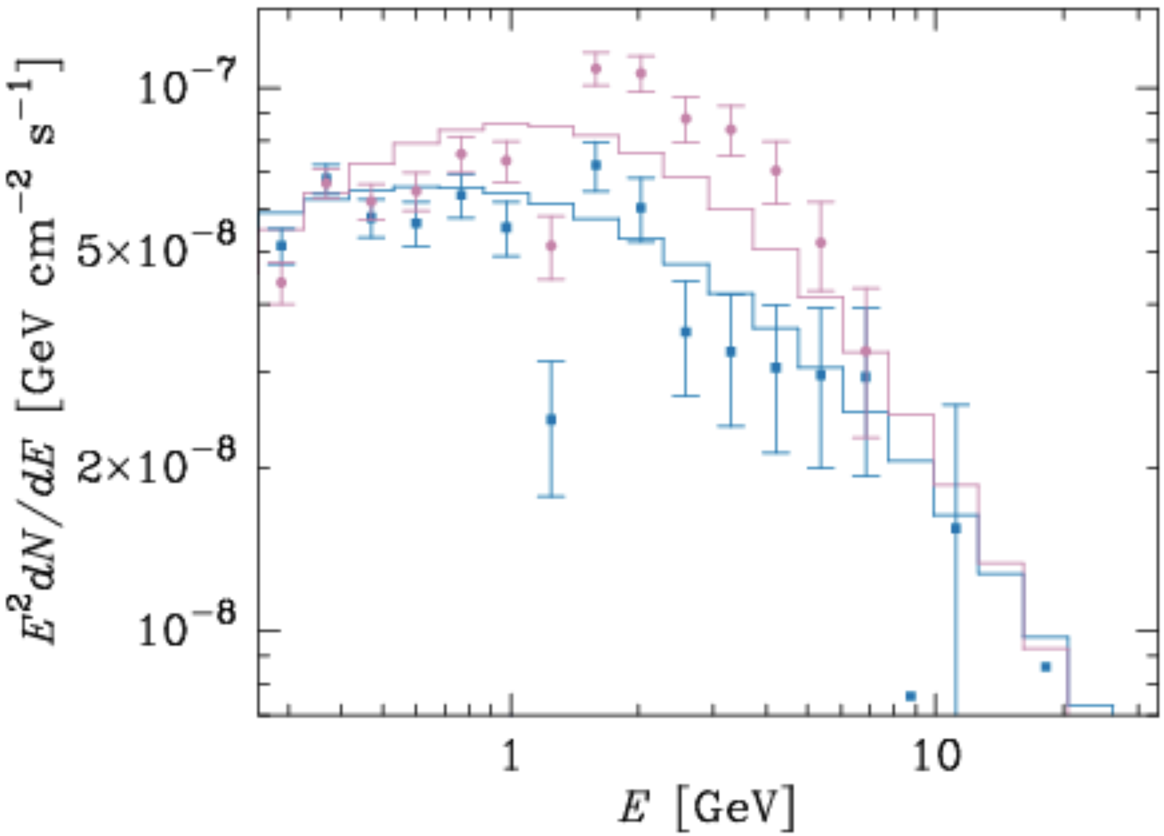


Calculated synchrotron flux from secondary electrons, and the constraints from archival radio data (Green Bank, Jodrell Bank,...)

Mild tension with the claim already. LOFAR can easily test this.

Laha (+Dasgupta) et al.

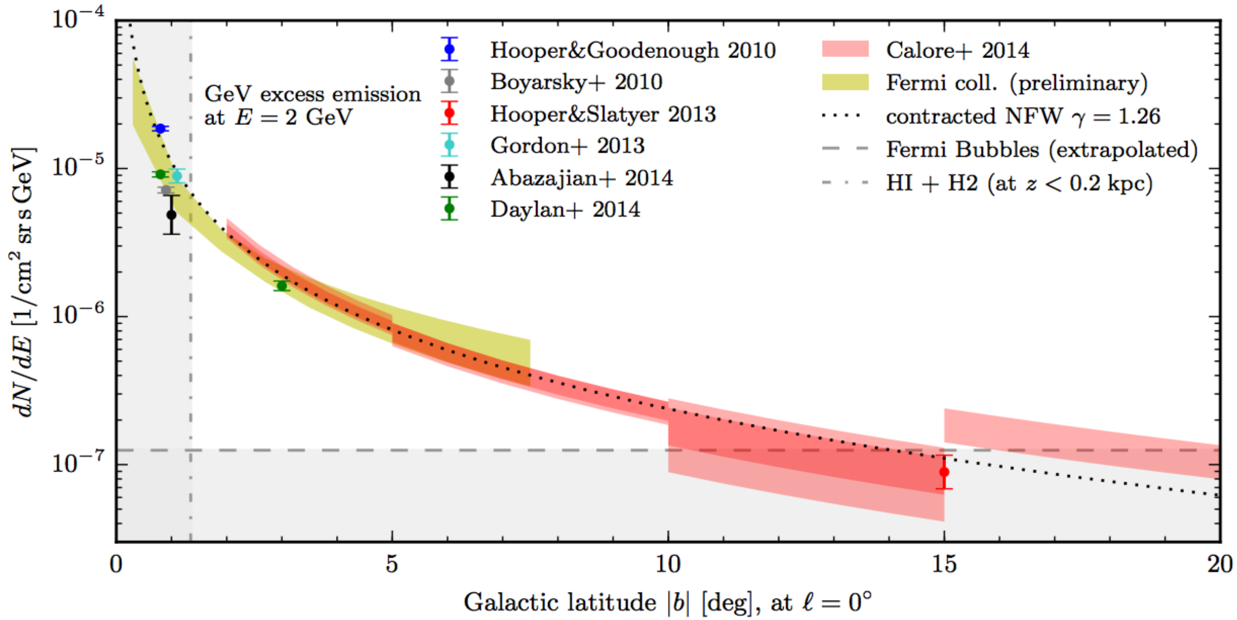
DM at the Galactic Center



A 40 GeV WIMP ?

Daylan et al, Abazajian,Canac, Horiuchi, Kaplinghat (2014), etc.

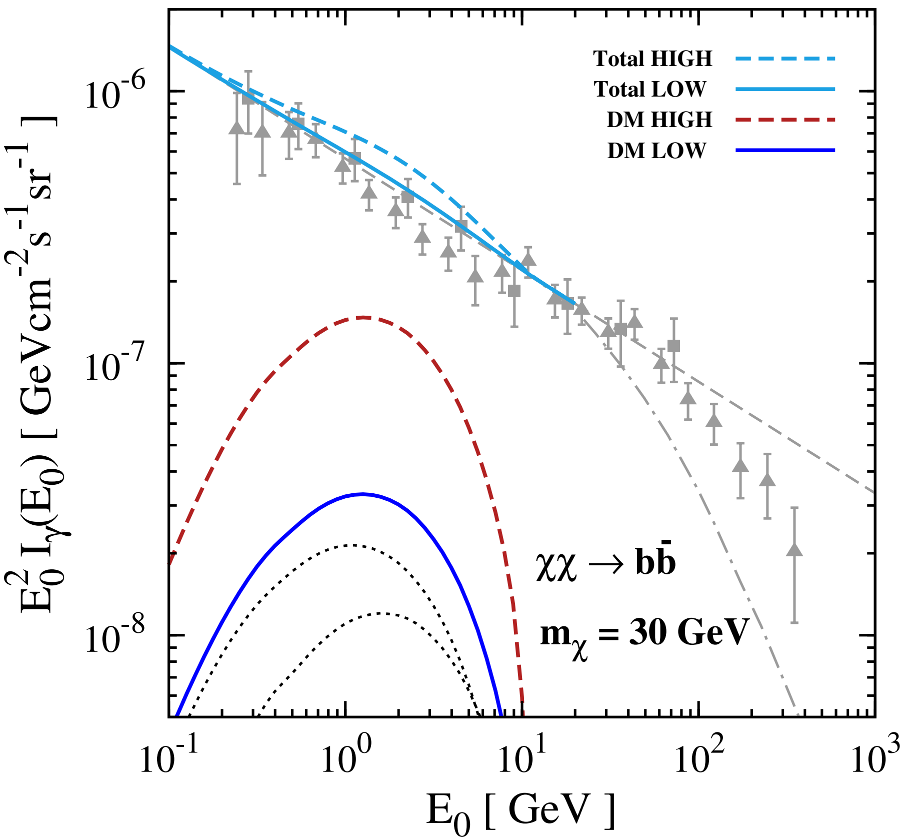
Systematics etc.



Calore, Cholis, McCabe, Weniger (2014)

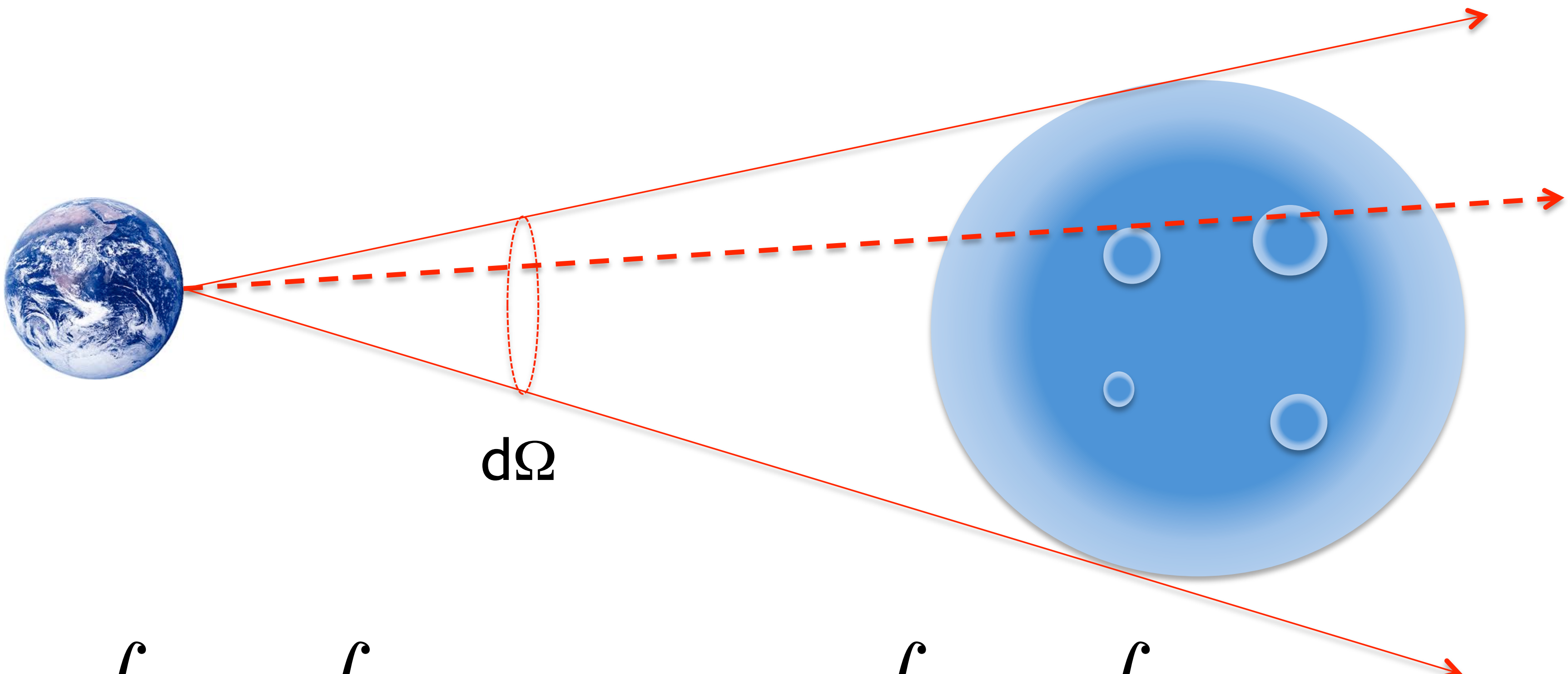
GeV excess is robust
Background model systemetics allow large uncertainties in tails
Much larger variety of DM models fit the data
Dwarfs can constrain by improving sensitivity by 3x

Isotropic Diffuse Flux



Extra-Galactic flux has density boosted by a clumping factor due to smaller subhalos inside bigger halos. There is a clumping vs. cross section degeneracy there.

Halo Substructure



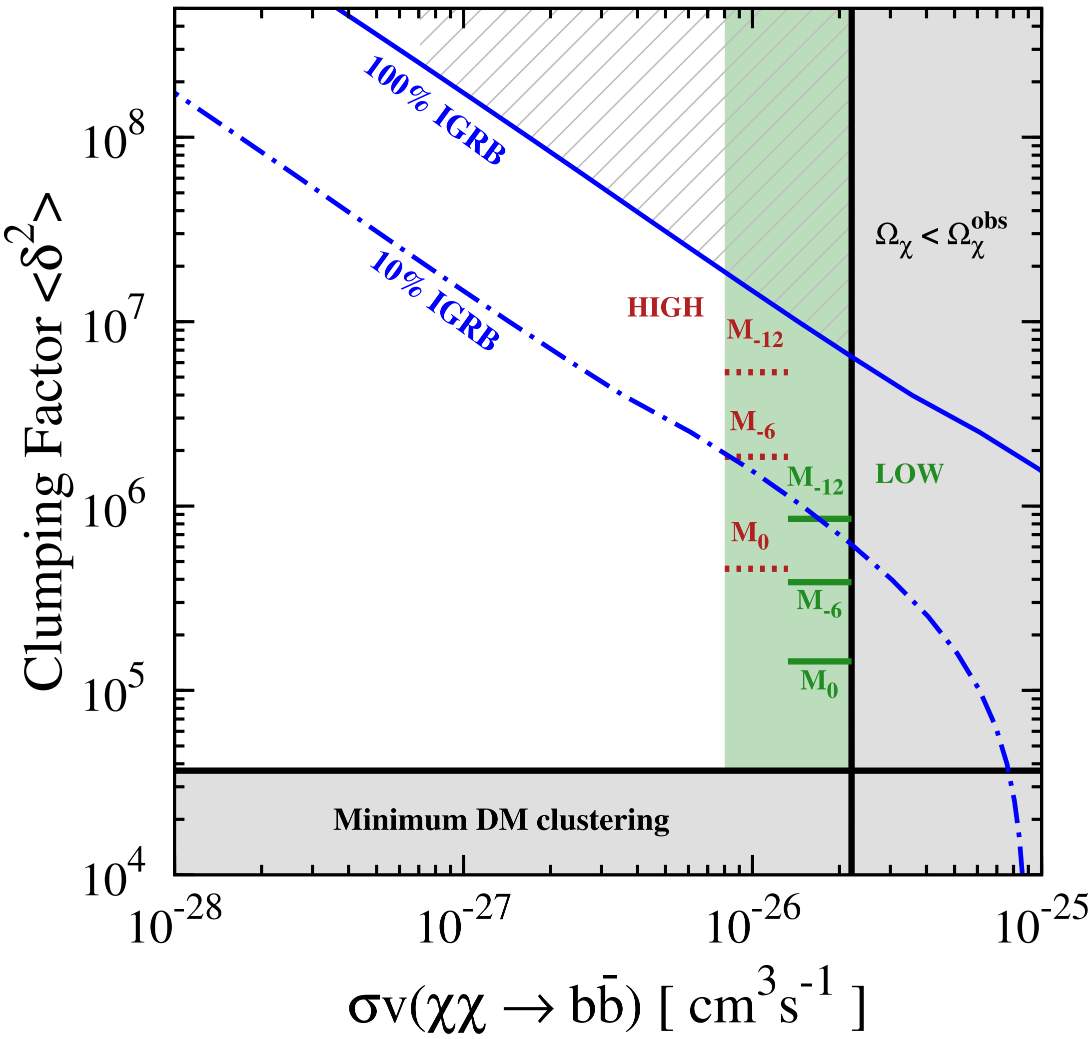
$$\int d\Omega \int dl\, \rho^2 \rightarrow \langle \delta^2 \rangle \int d\Omega \int dl\, \rho^2$$

Sub-halos inside halos "boost" the flux due to "clumpiness"
This depends on integrating over the halo-mass function

Kamionkowski, Koushiappas (2009)

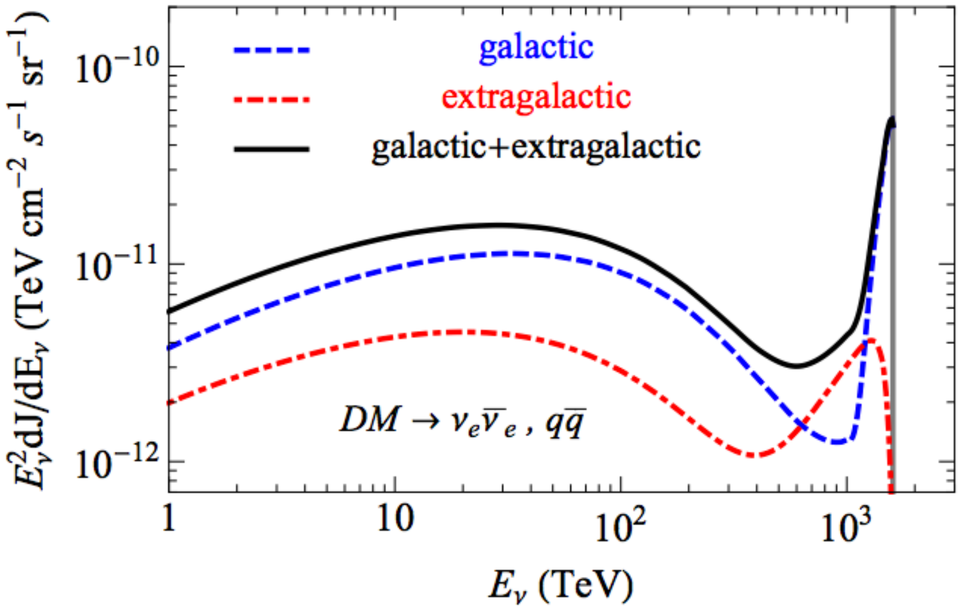
Multisource : GC + IGRB

Comparing Galactic Center signals with Isotropic Diffuse signals constrains the substructure models

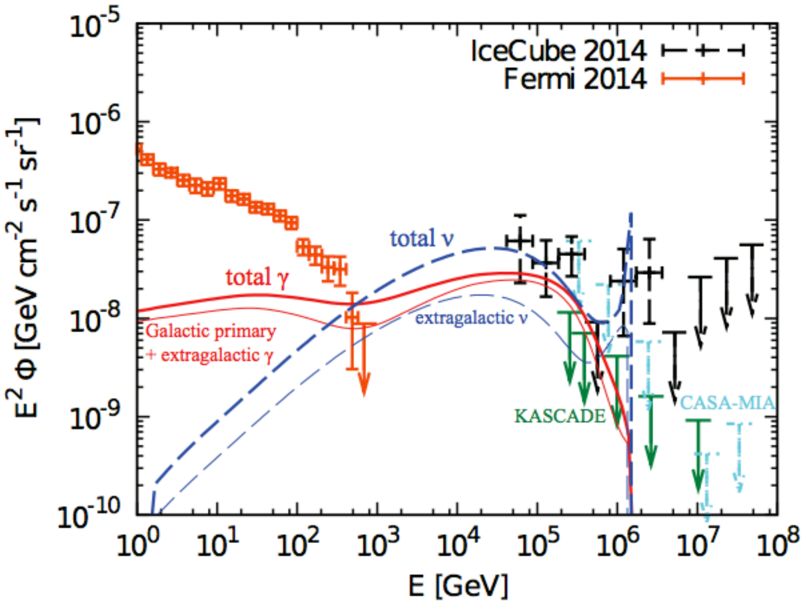


Ng et al. (+ Dasgupta) (2014)

PeV DM



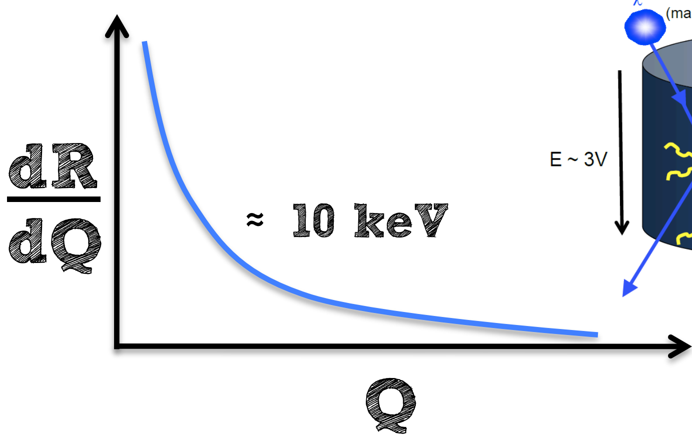
Esmaili and Serpico (2013)

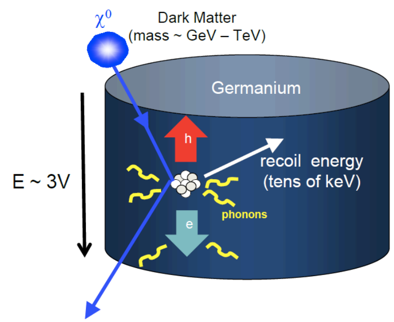


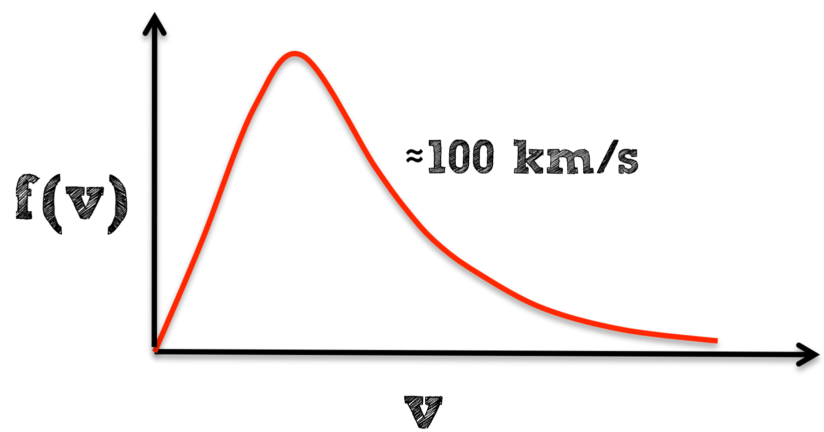
Murase et al (2015)

… various tensions with energy distribution

Direct Detection

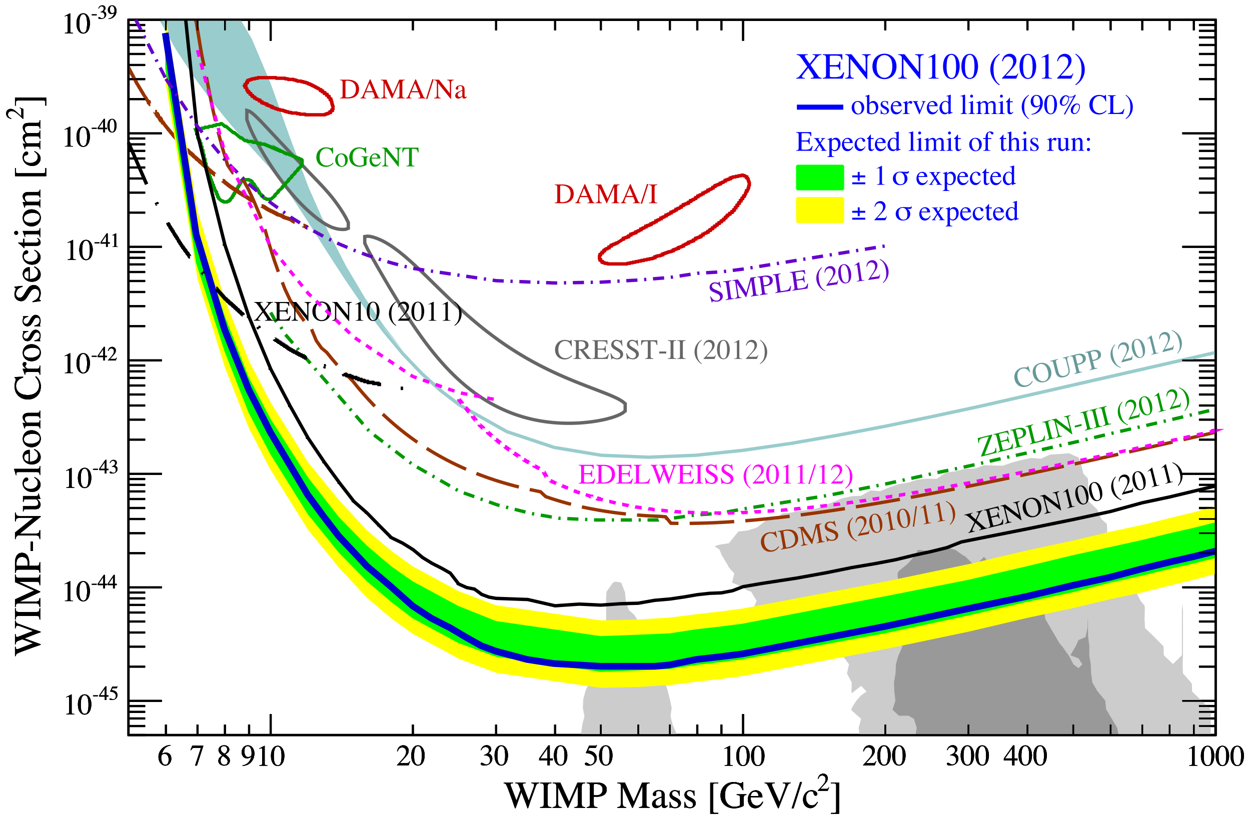






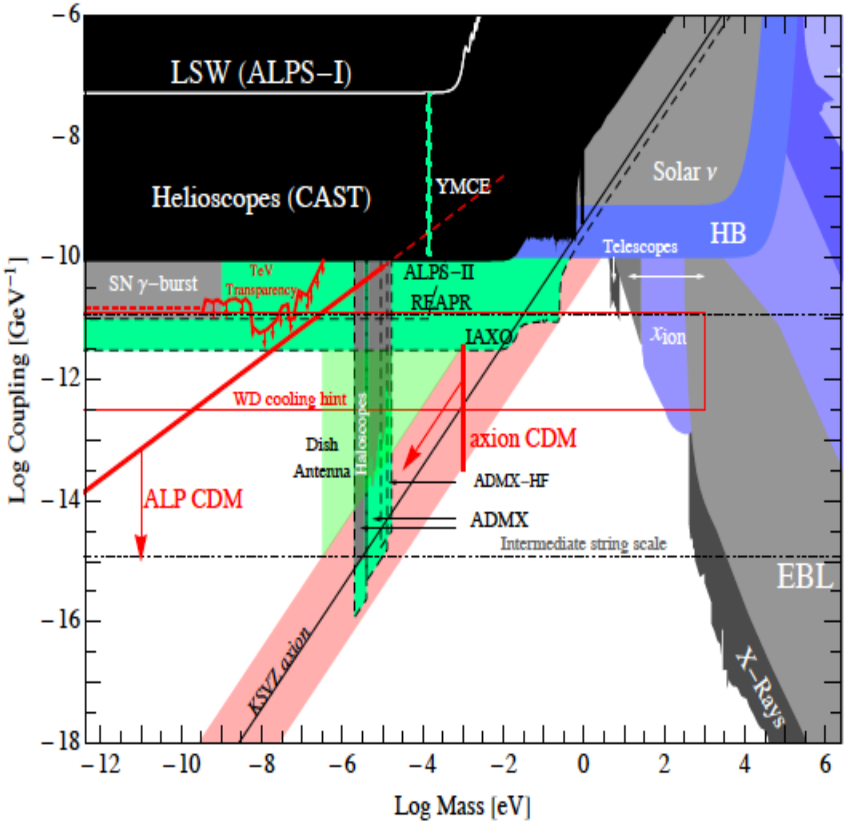
$$\frac{dR}{dQ} = \frac{\rho_0 \sigma_n}{2\mu^2 m} A^2 F(Q)^2 \int_{\sqrt{\frac{mQ}{2\mu^2}}}^{\infty} dv \frac{f_1(v)}{v}$$

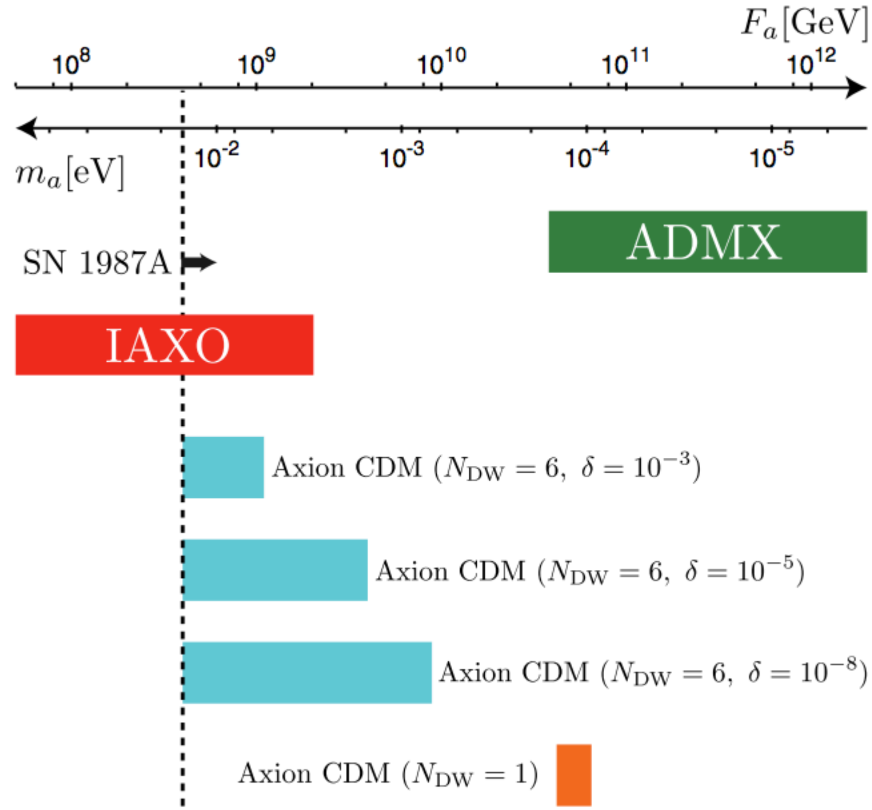
No clean detections yet



... but interesting hints/controversies in the low-mass range from DAMA, etc.

Axion Searches





Promising time for axion searches

Collider Searches

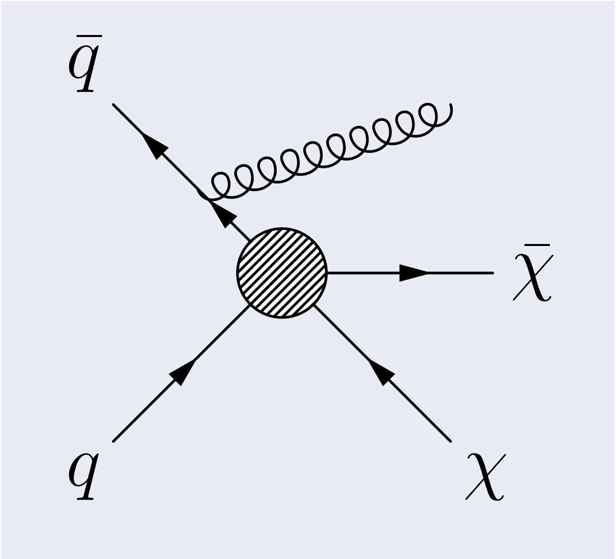
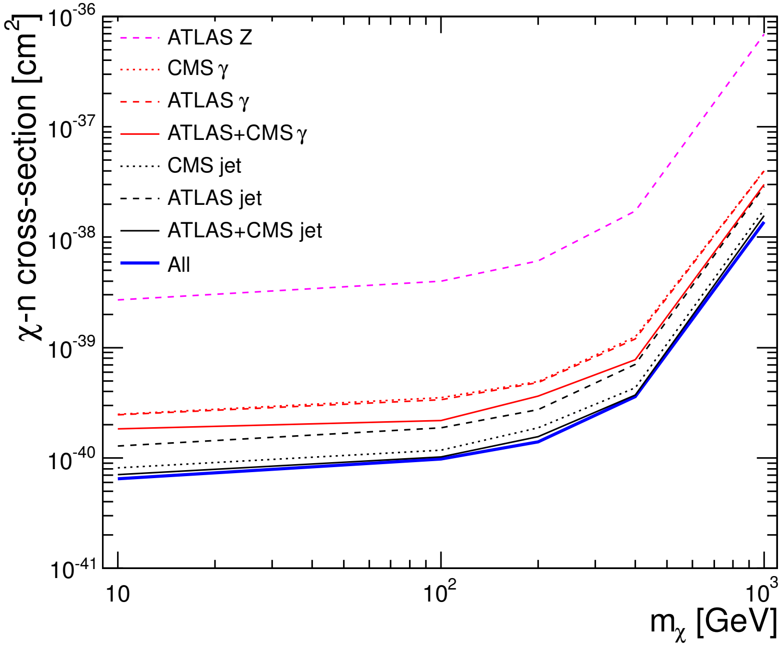


Image Credit: Joachim Kopp

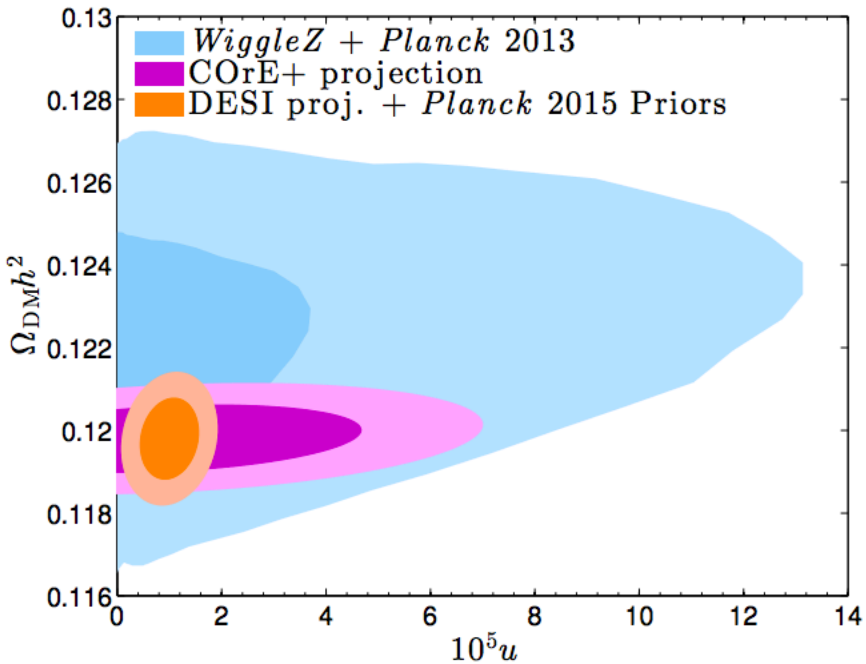


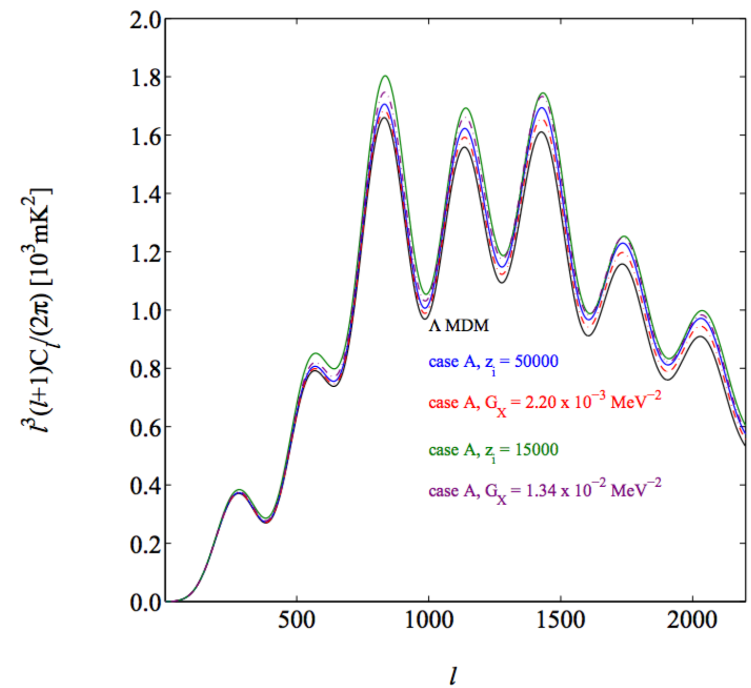
Zhou, Berge, Whiteson (2013)

No detections yet.

Limits are model-dependent, or based on an EFT / simplified model for the DM-SM coupling.

Cosmological Constraints





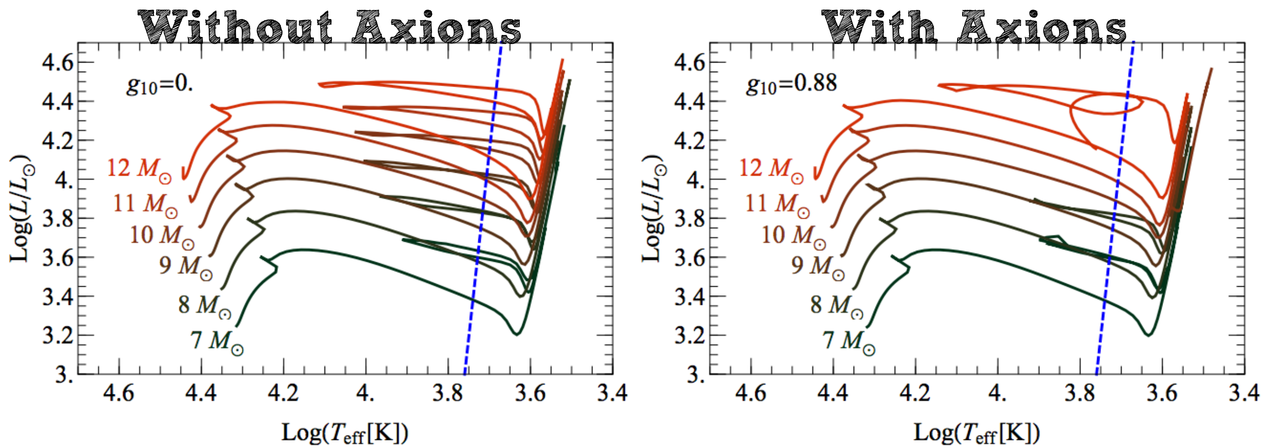
DM-Neutrino Coupling / DM mass

Escudero et al (2015)

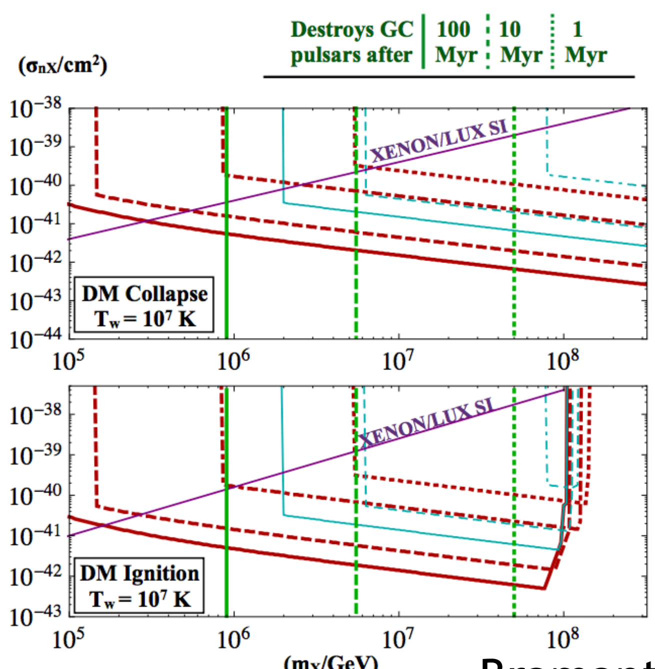
Archidiacono and Hannestad (2013)

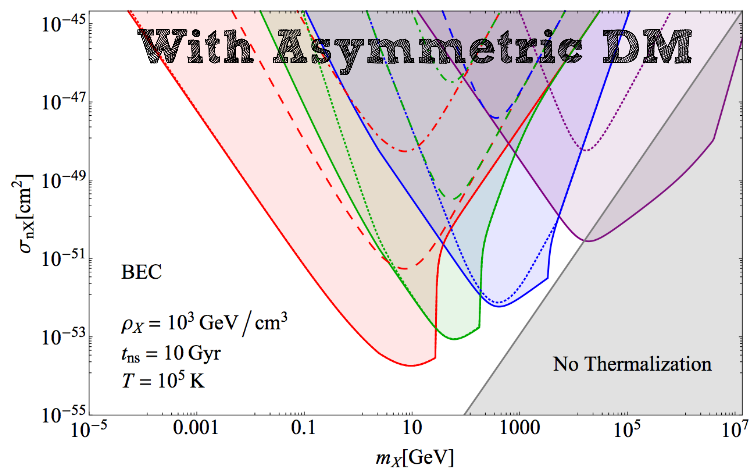
Limits on DM-neutrino interactions using Galaxies and CMB

Stellar Evolution Constraints



Friedland, Giannotti, Wise (2012)





Kumar (2013)

Bramante (2015)

Summary

Evidence for DM is overwhelming, but ...
... particle identity a mystery

Ideas old and new

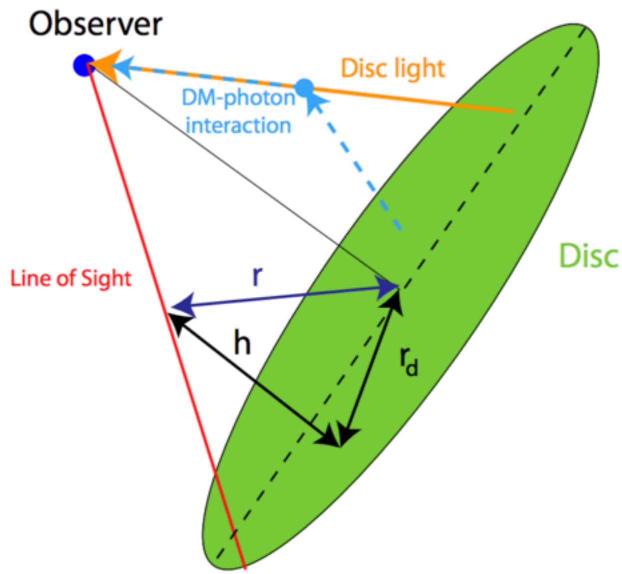
- WIMPs, and other variations
- Axions
- Asymmetric DM
- Self-Interactions
- Sterile Nus

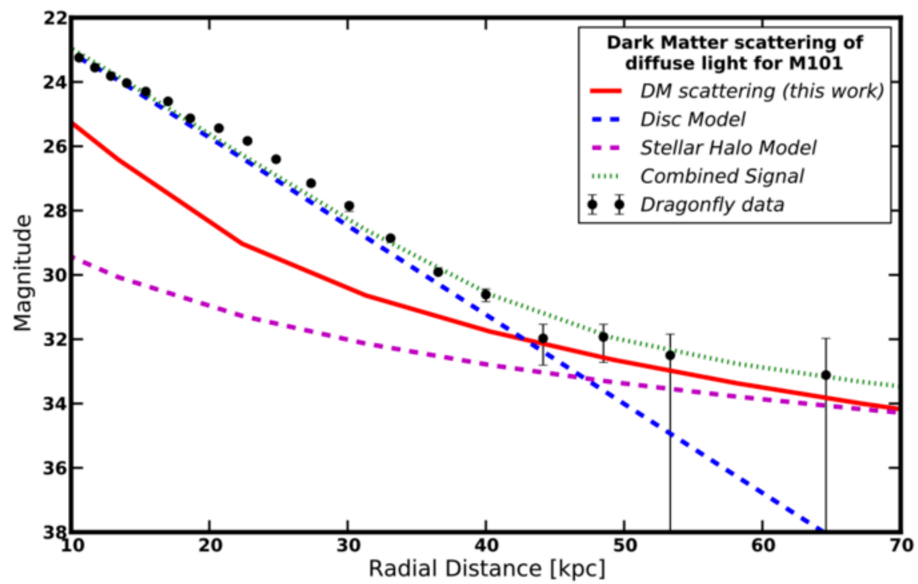
Searches for the particle ongoing

- Mostly no detections
- 3.5 keV, GeV, and PeV(?) anomalies
- Many new searches coming up

Uncertain and challenging, but we are on an exciting hunting expedition!

Not-Dark Dark Matter





Limits on DM-photon interactions using galaxy brightness profile

Davis and Silk (2015)