Dark Matter Theory

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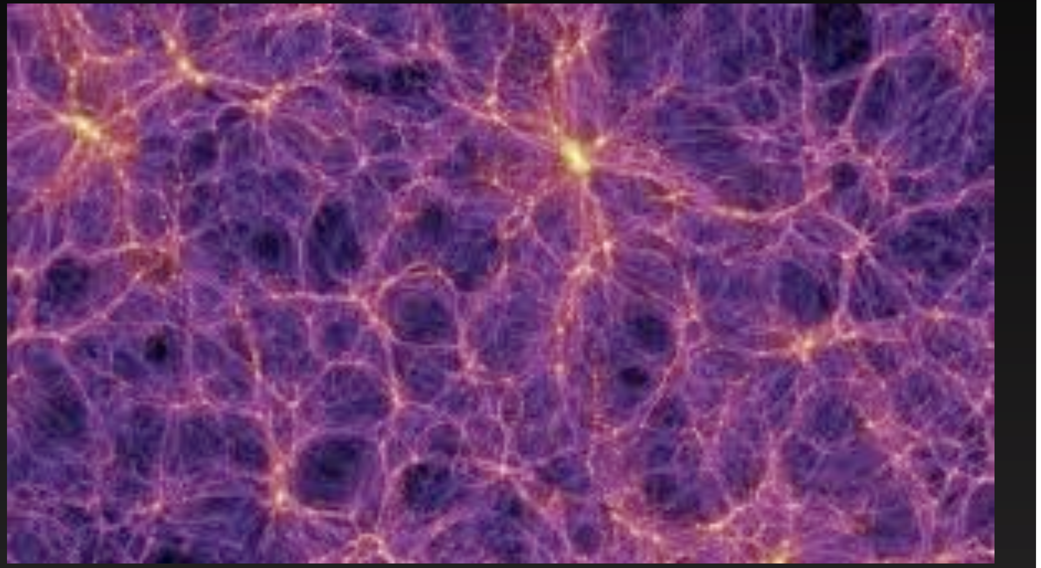
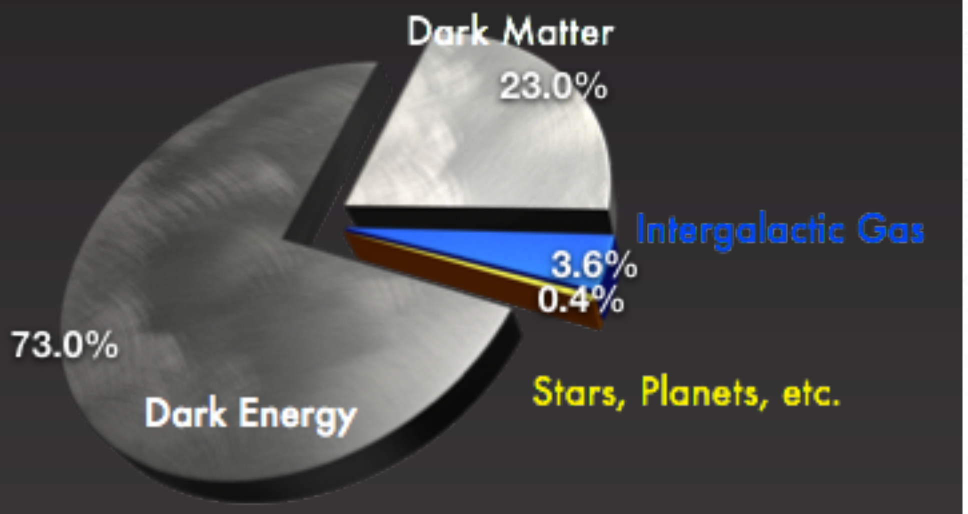
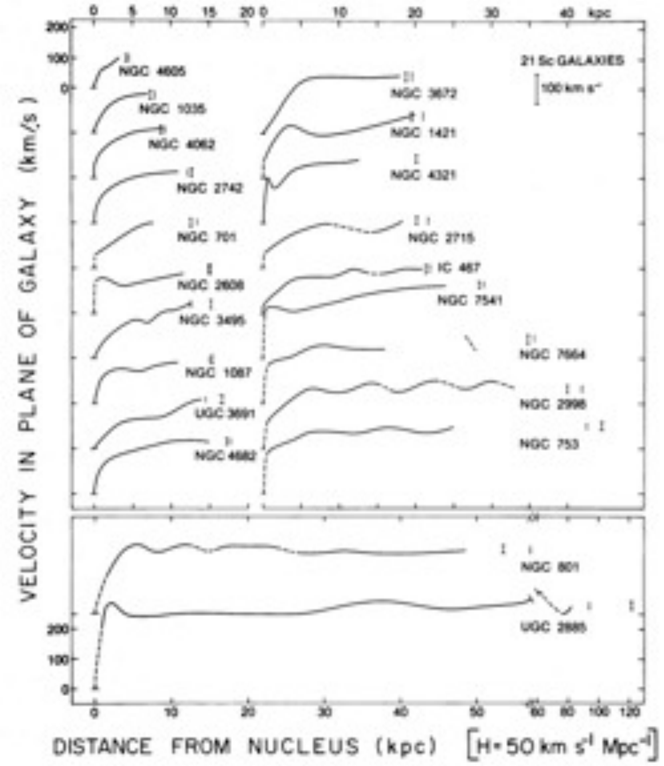
Fermilab

What do we know about Dark Matter?

- There's a lot of it $\Omega_{\rm DM}h^2 \sim 0.1$
- it interacts gravitationally
- does not interact with itself
    - or baryons
- It's cold
- it's (meta-)stable



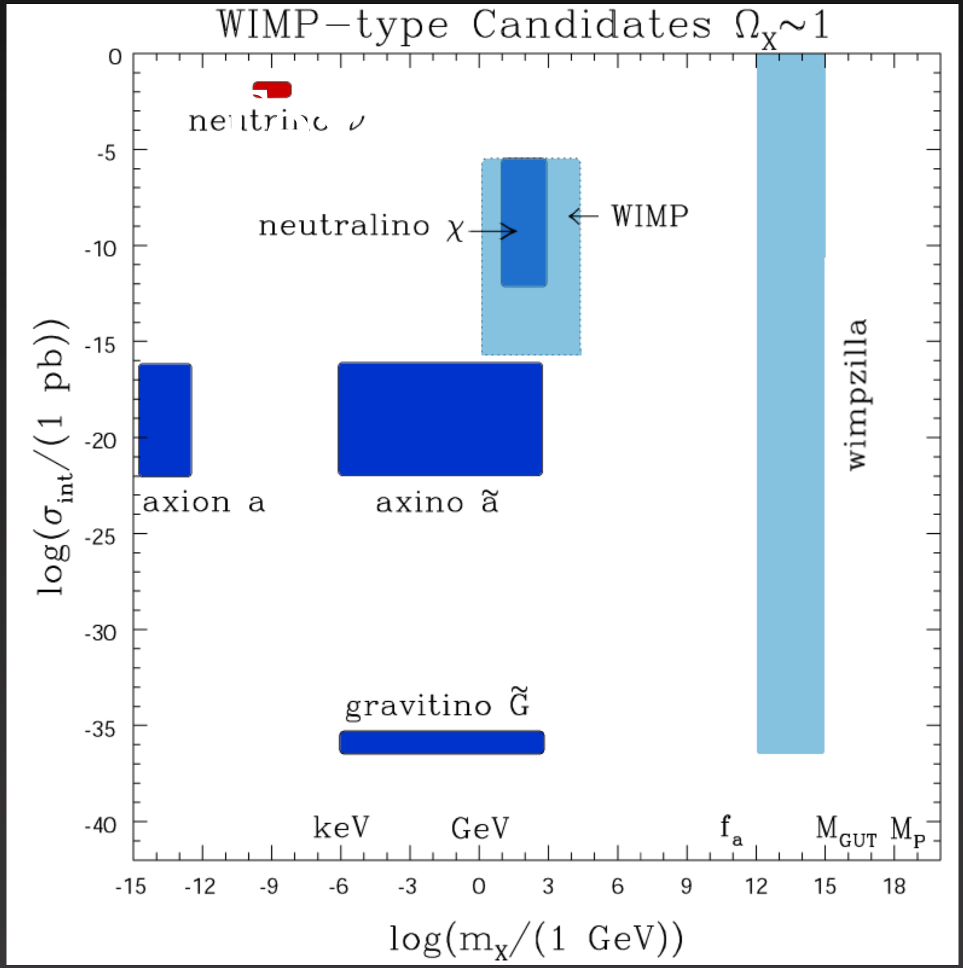




Bullet Cluster

What do we know about Dark Matter?

- Nothing in the Standard Model has these properties
  - Thus Dark Matter is a signal of new physics
- So what is it?

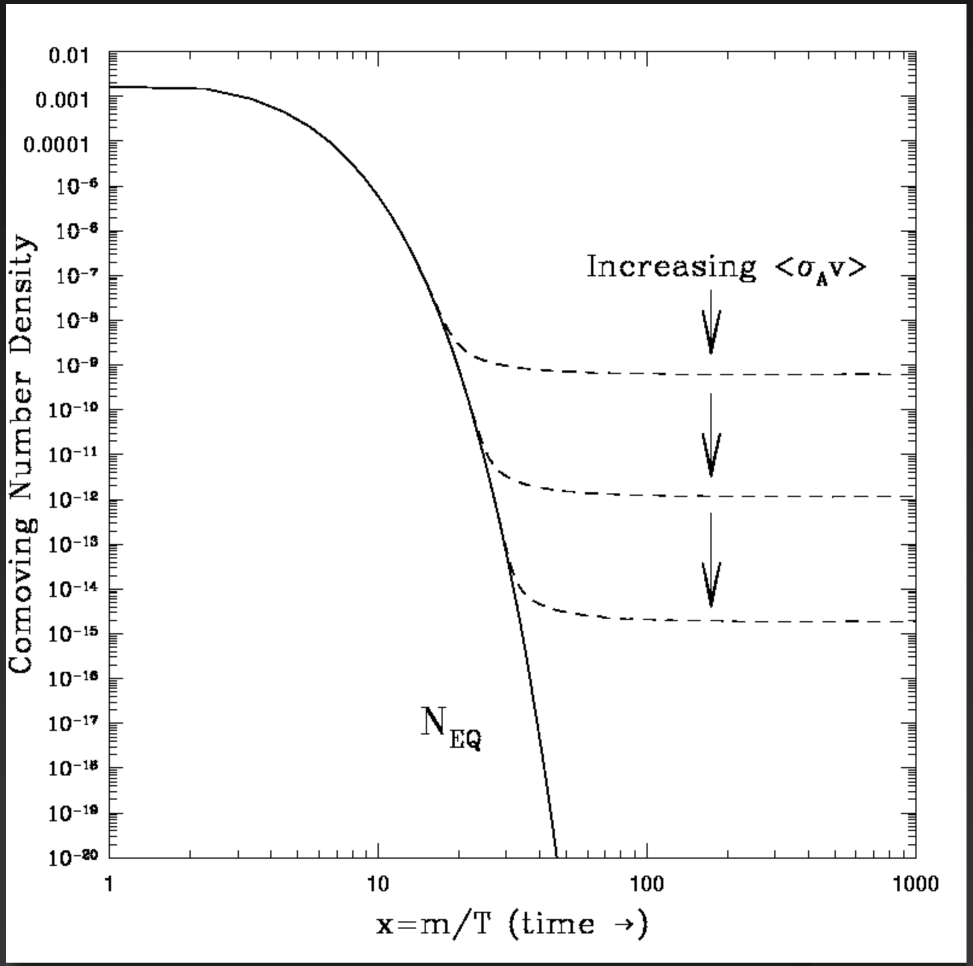


Roszkowski hep-ph/0404052

WIMP Dark Matter

- The best motivated solution (not necessarily the right one)

$$\frac{dn_X}{dt} + 3Hn_X = -\langle\sigma_{X\bar{X}}v\rangle(n_X^2 - n_{X,\mathrm{eq}}^2)$$



Jungman *et al* hep-ph/9506380

$$\Omega_X h^2 \sim 0.1 \left(\frac{x_{\mathrm{FO}}}{20}\right)\left(\frac{g_*}{80}\right)^{-1/2}\left(\frac{\langle\sigma_{X\bar{X}}v\rangle}{3\times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}}\right)^{-1}$$

very roughly:

$$\frac{\alpha^2}{m_W^2} \sim 3\times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

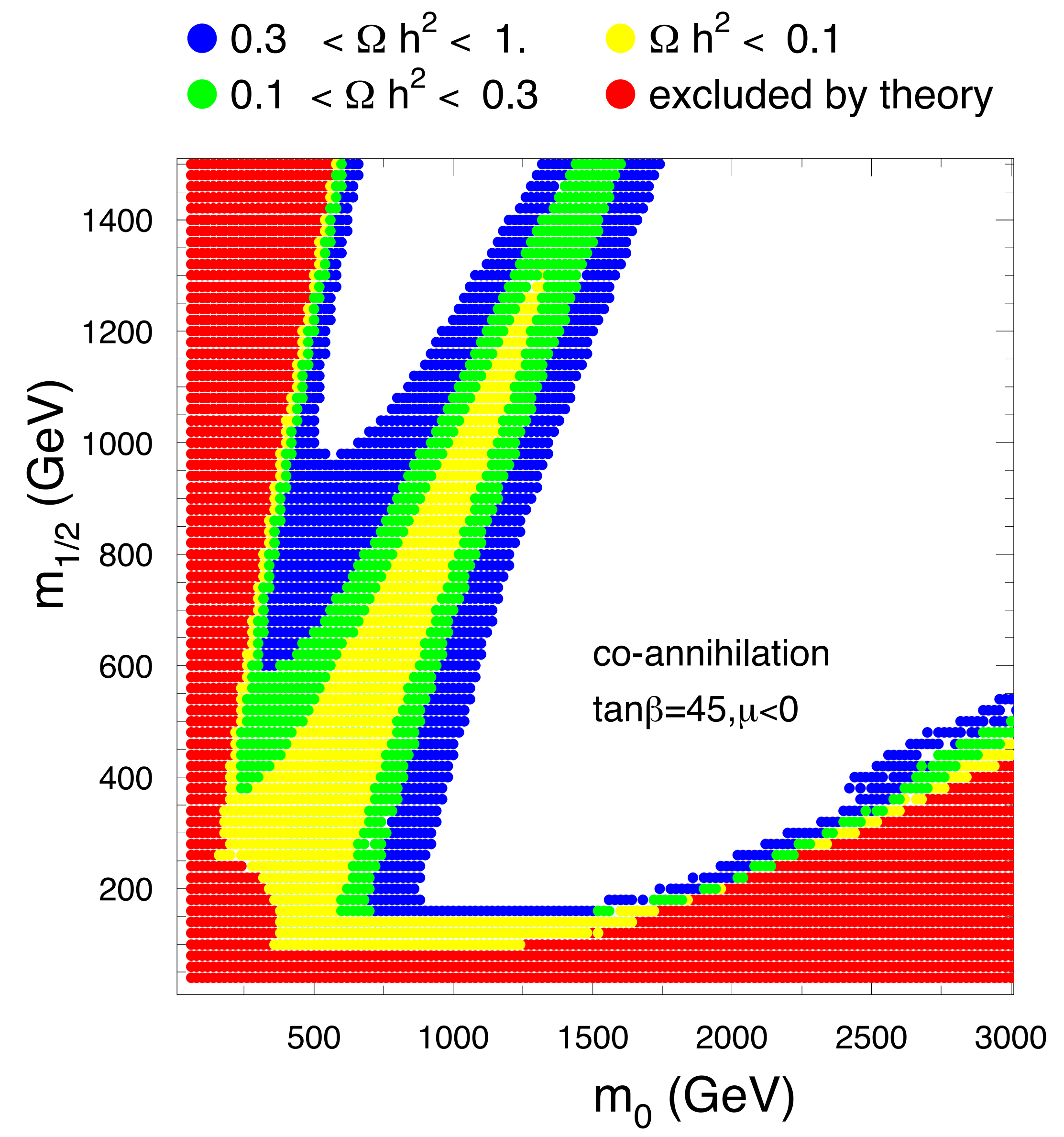
so reasonable to guess that weak scale physics and dark matter are related

Supersymmetric Solution

- The best known solution to weak-scale hierarchy and naturalness problems (Supersymmetry) has great DM candidate:
  - Neutralinos weakly interacting with mass expected to be $\Lambda_{\mathrm{SUSY}} \sim 100~\mathrm{GeV}$ (?)
  - *R*-parity makes them stable

Neutralino Dark Matter

- Should be noted: this is not the *only* solution for DM, and it is not known to be the *correct* solution.
- Neutralinos don't always satisfy the "WIMP miracle."
- Theorists need to keep an open mind; is there DM phenomenology that we miss in the MSSM?

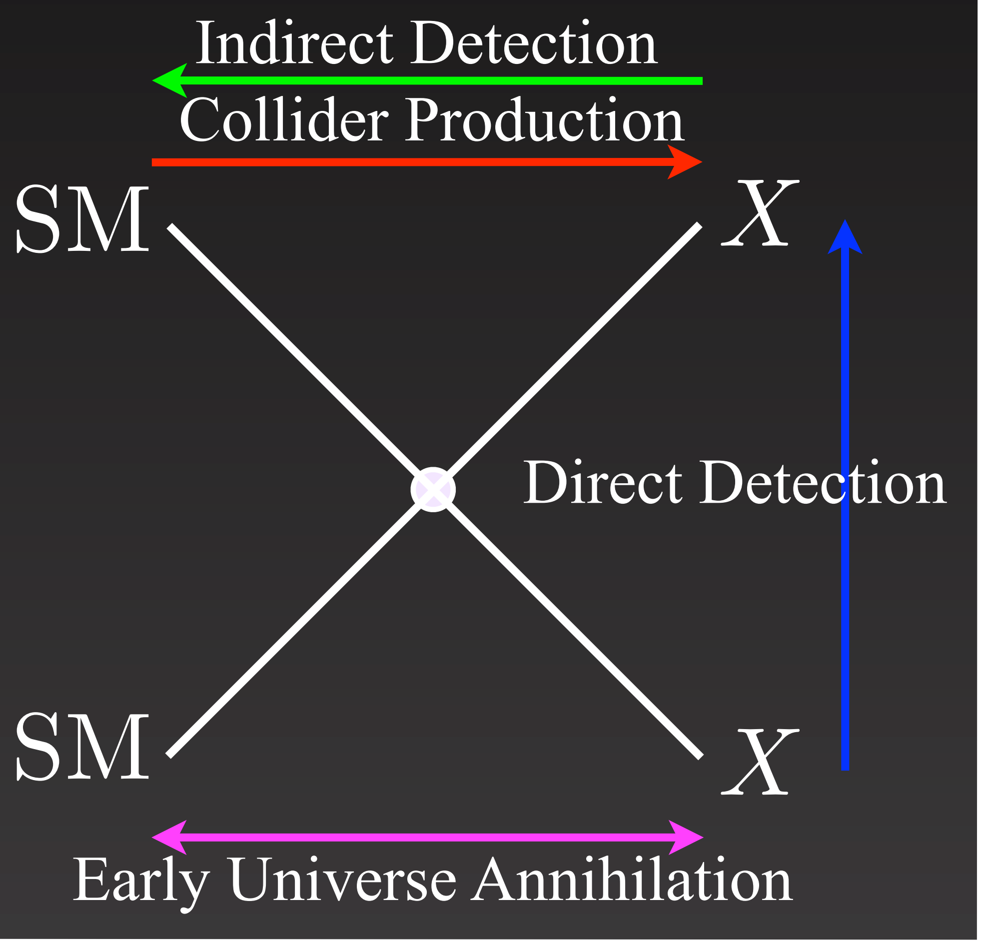


Baer *et al* hep-ph/0211213

What’s New from Experiment?

- Theorists can always run amok. Probably best to take our motivation from experiments.
- So, what’s new, and how do these results push the theory space?

- Indirect Detection
- Direct Detection
- Collider bounds
- *N*-body Simulation



Indirect Detection

Collider Production

SM

X

Direct Detection

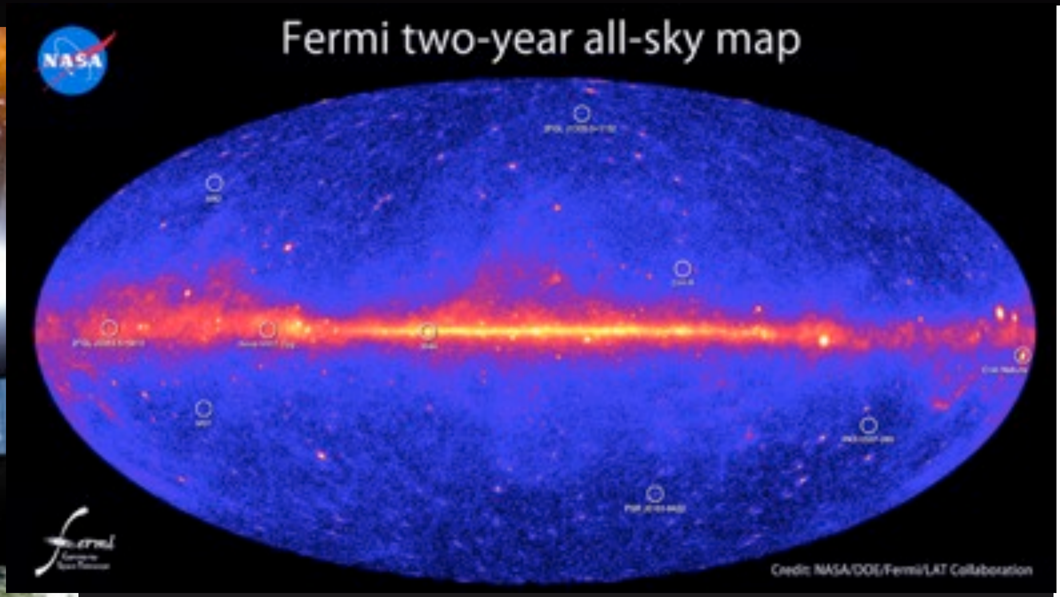
SM

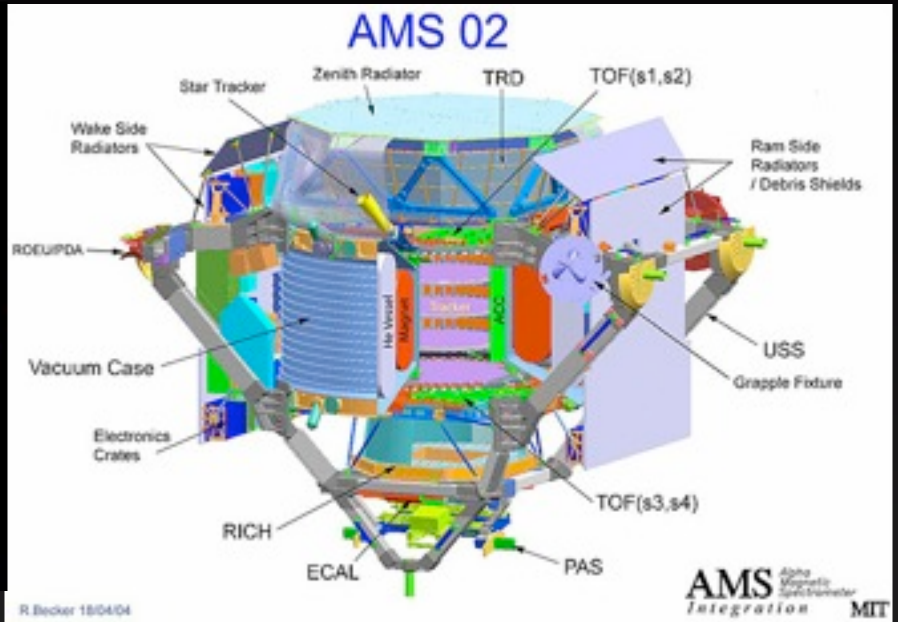
X

Early Universe Annihilation

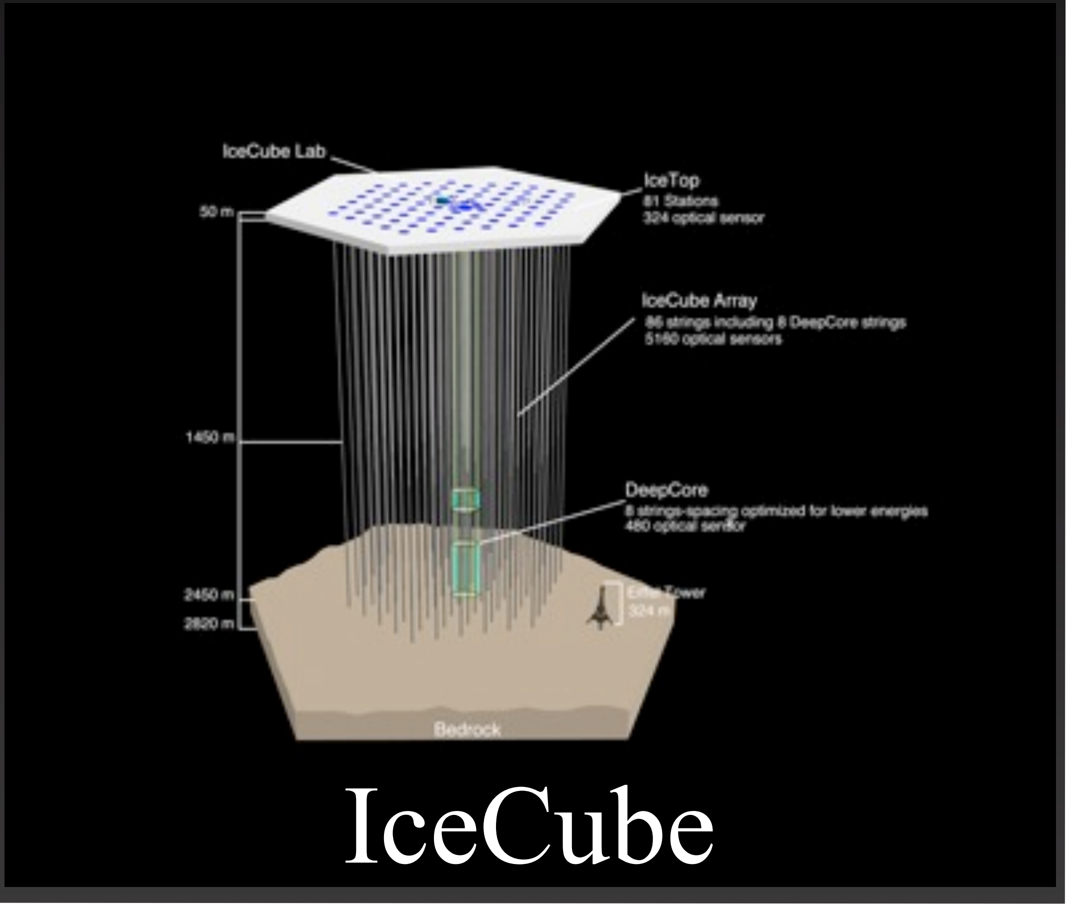
Indirect Detection

Fermi





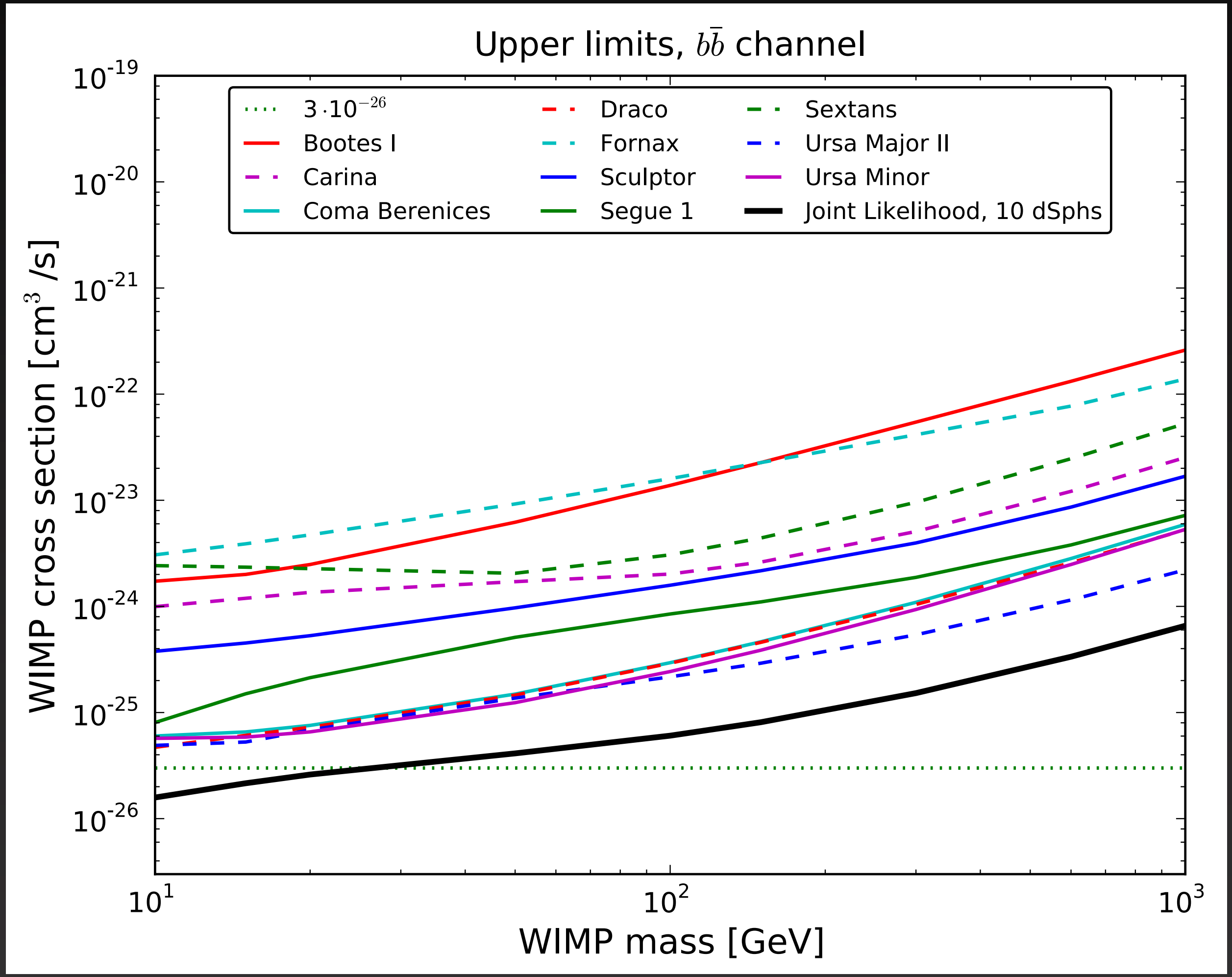
ACTs: MAGIC, HESS VERITAS, *etc*



IceCube

Dwarf Galaxy Bounds

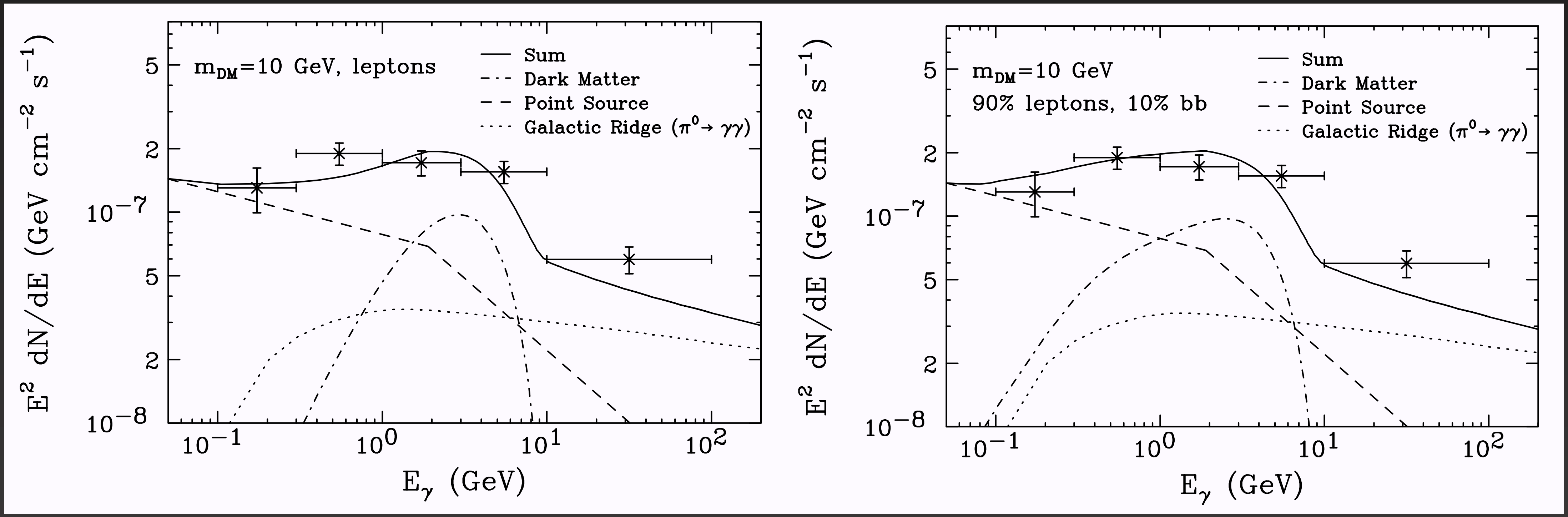
- Best bounds come from locations with high DM densities, low background (regular astrophysics)
  - *i.e.* dwarf galaxies
  - Considerable uncertainties on DM profile



Fermi 1108.3546 see also Geringer-Sameth *et al* 1108.2914

Galactic Center

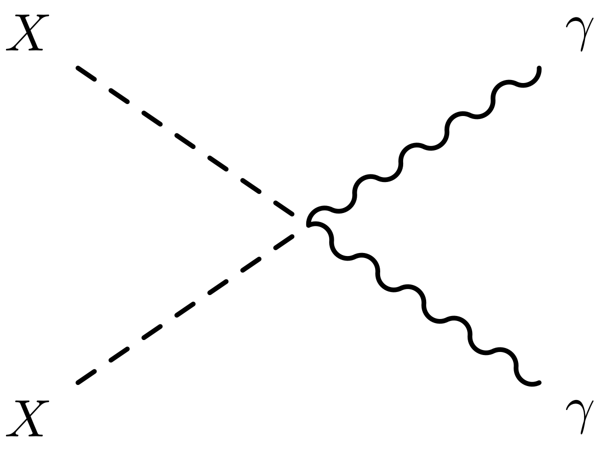
- Galactic center has lots of DM, and is very close.
  - But large astrophysical backgrounds
- One claim of 10 GeV DM annihilating to leptons with $\sigma v \sim 10^{-26/-27}\ \mathrm{cm}^3/\mathrm{s}$



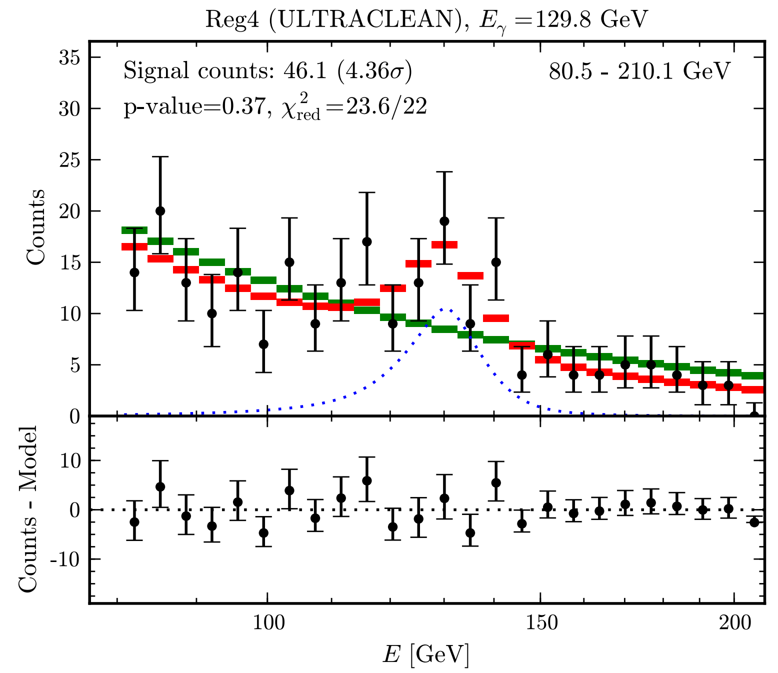
Hooper 1201.1303

Fermi 130 GeV Line

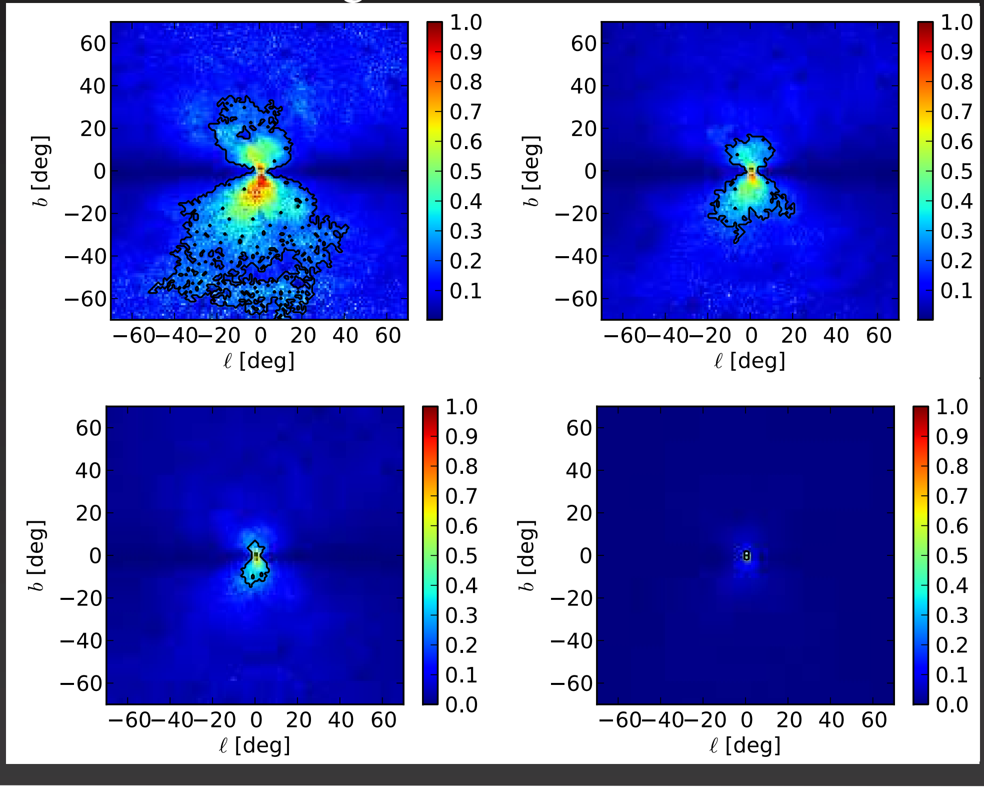
- Gamma-ray lines long held to be the smoking gun for DM annihilation
    - After all, what background in nature gives a line?
- Two papers, not from Fermi, but analyzing Fermi data from the Galactic center, claim a 130 GeV line



C. Weniger 1204.2797

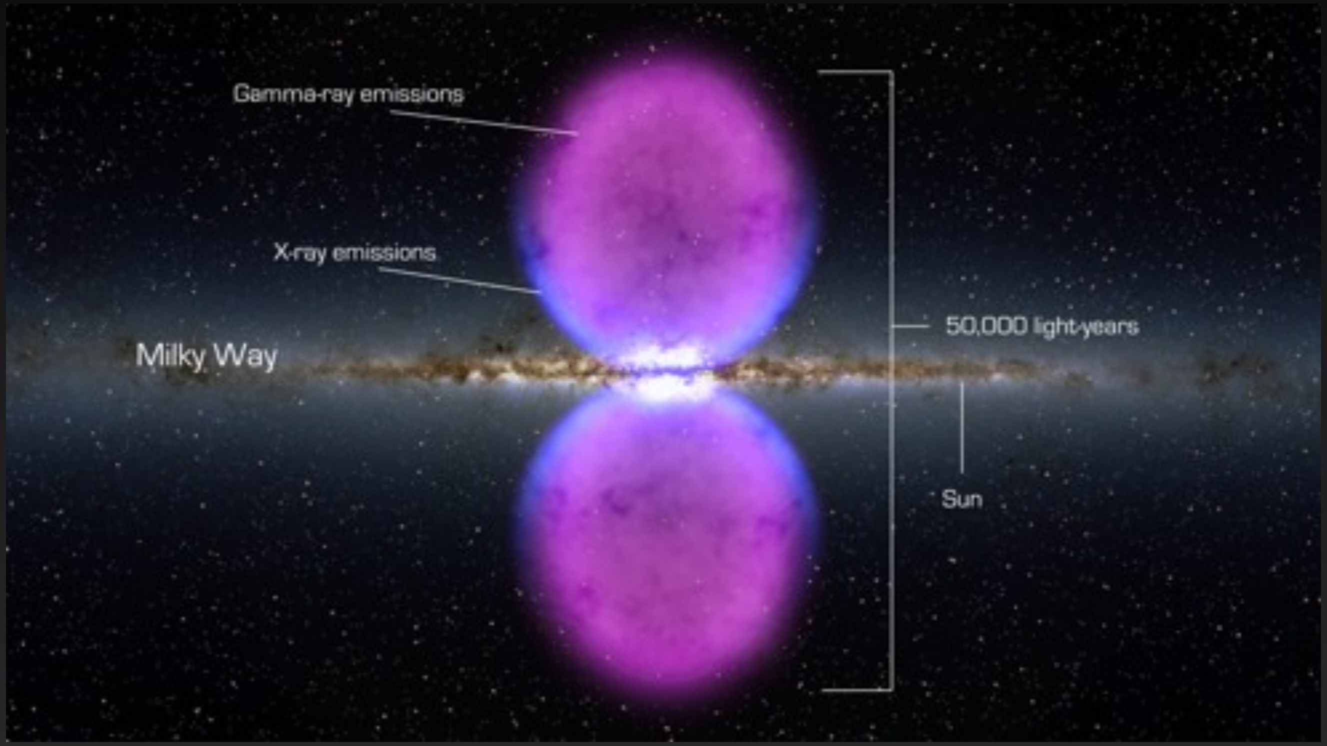


T. Bringmann *et al* 1203.1312

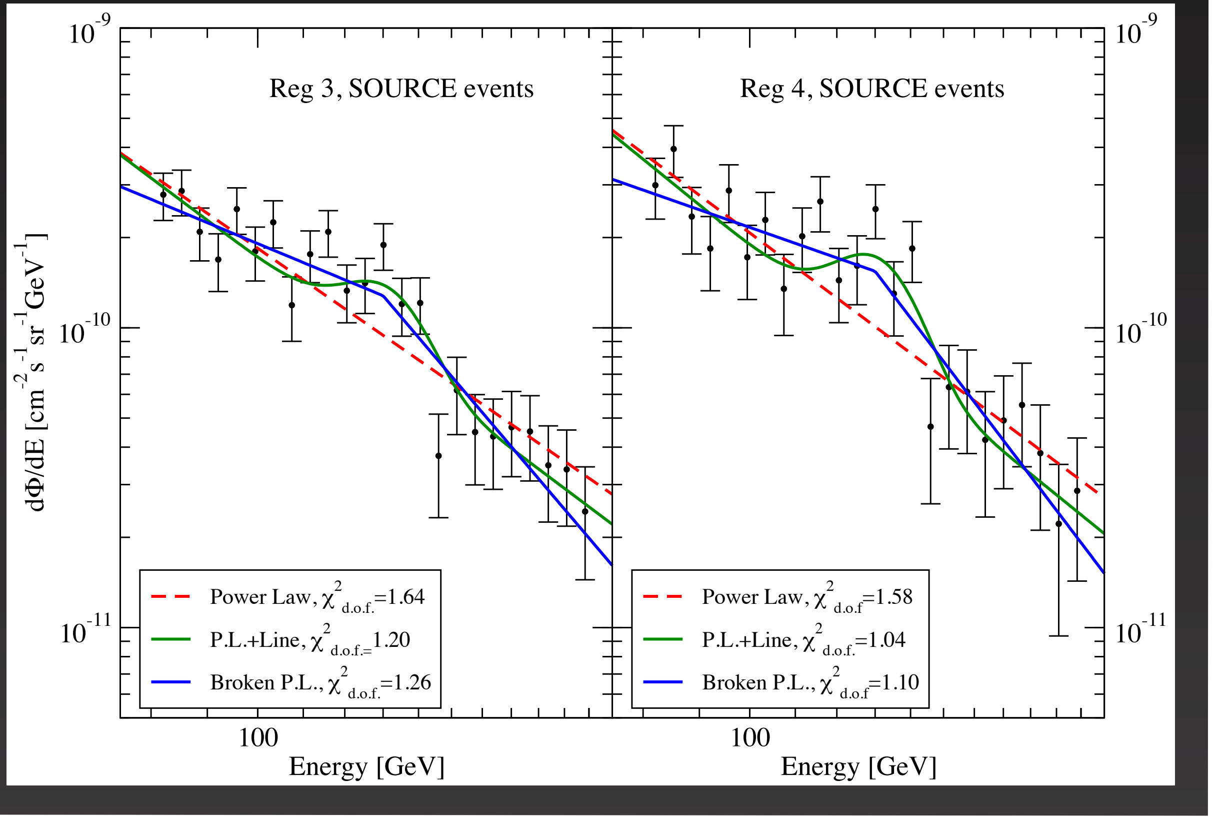


Fermi 130 GeV Line

- A possible background from bubbles?

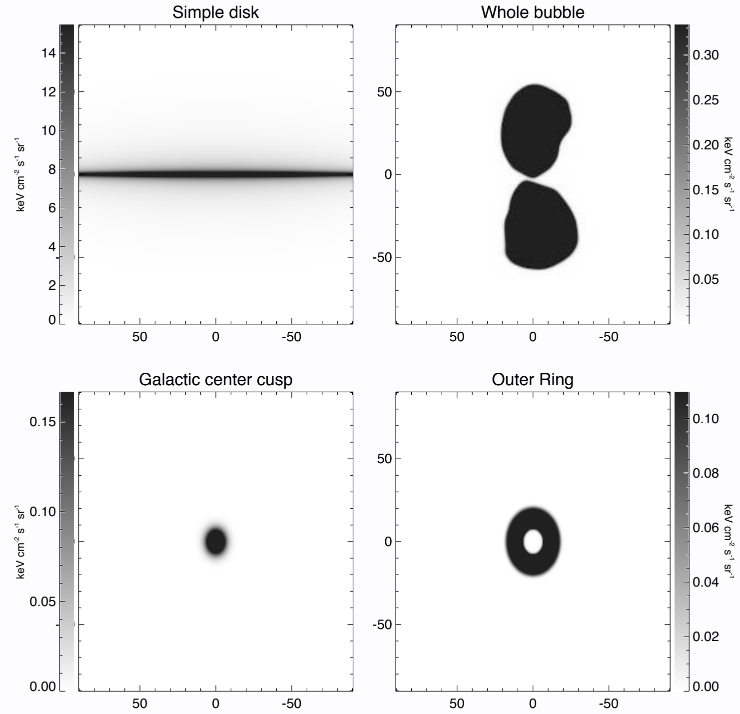


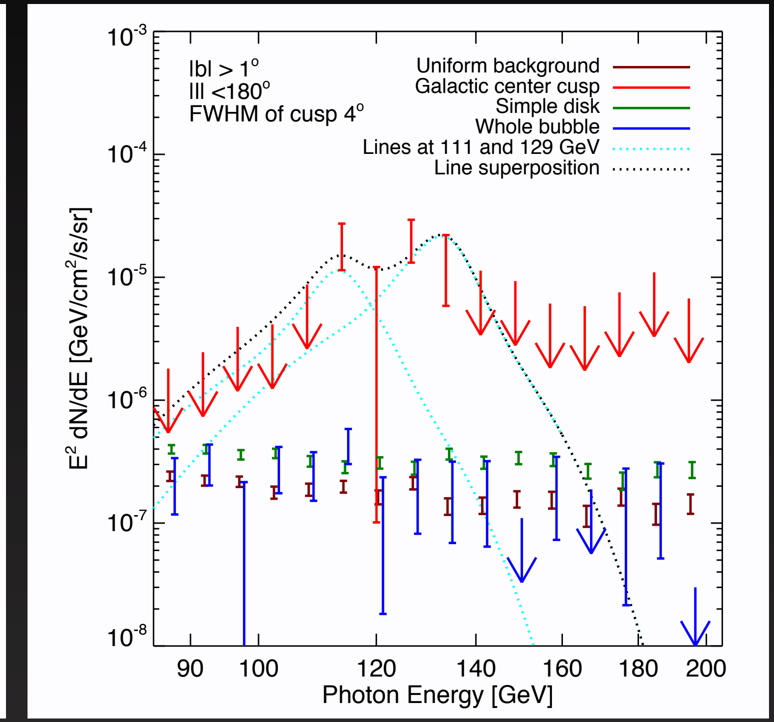
Profumo and Linden 1204.6047



Fermi 130 GeV Line

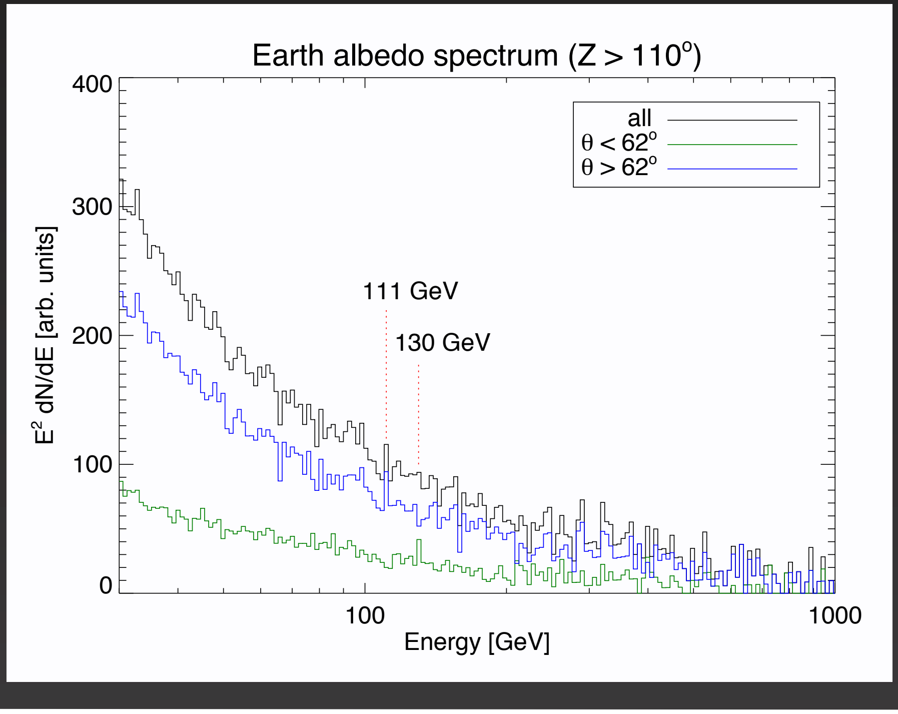
- Bubble morphology doesn't match that of the line





- Instrumentation effect?

Su and Finkbeiner 1206.1616

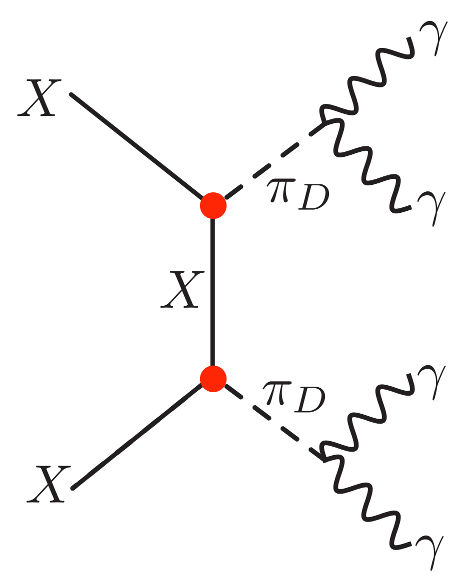


Theory Implications

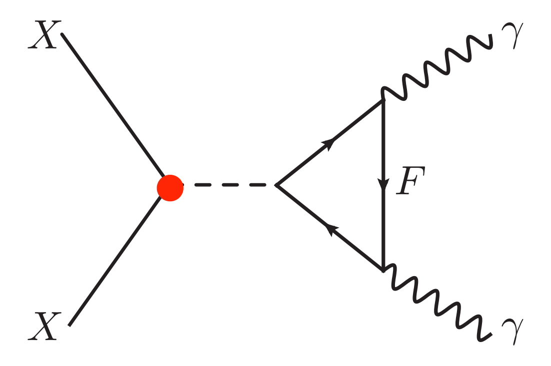
- If it is a line, what does the theory need to be?
- Large cross section:

$$\sigma_{XX\to\gamma\gamma}v \sim 2-5\times10^{-27}\ \mathrm{cm}^3/\mathrm{s}$$

- Either loops or decays into “dark pions”



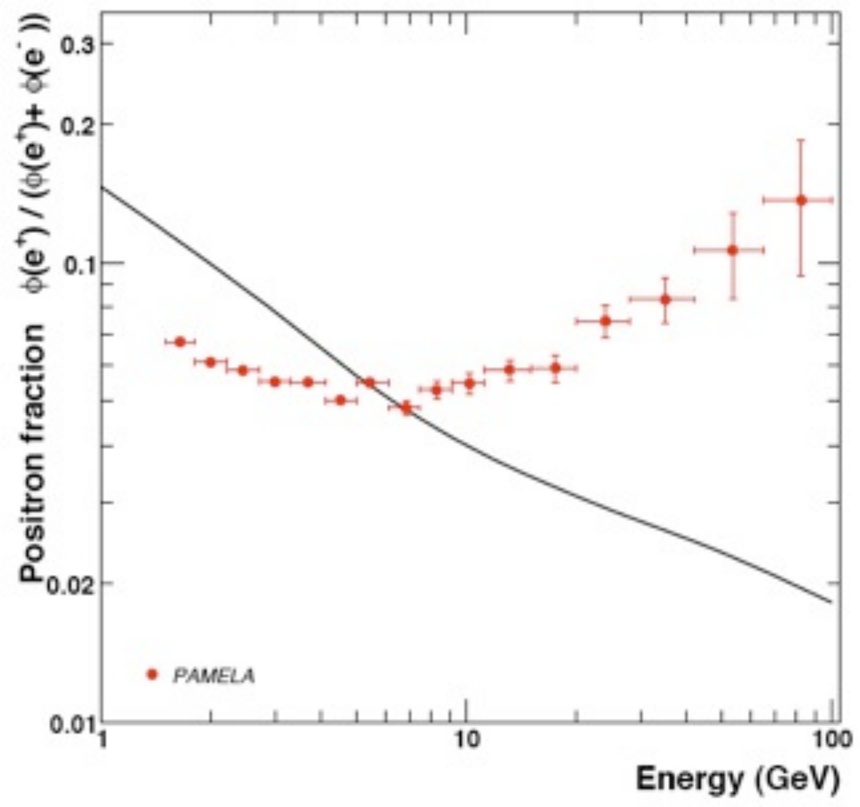
MRB and Hooper 1205.6811



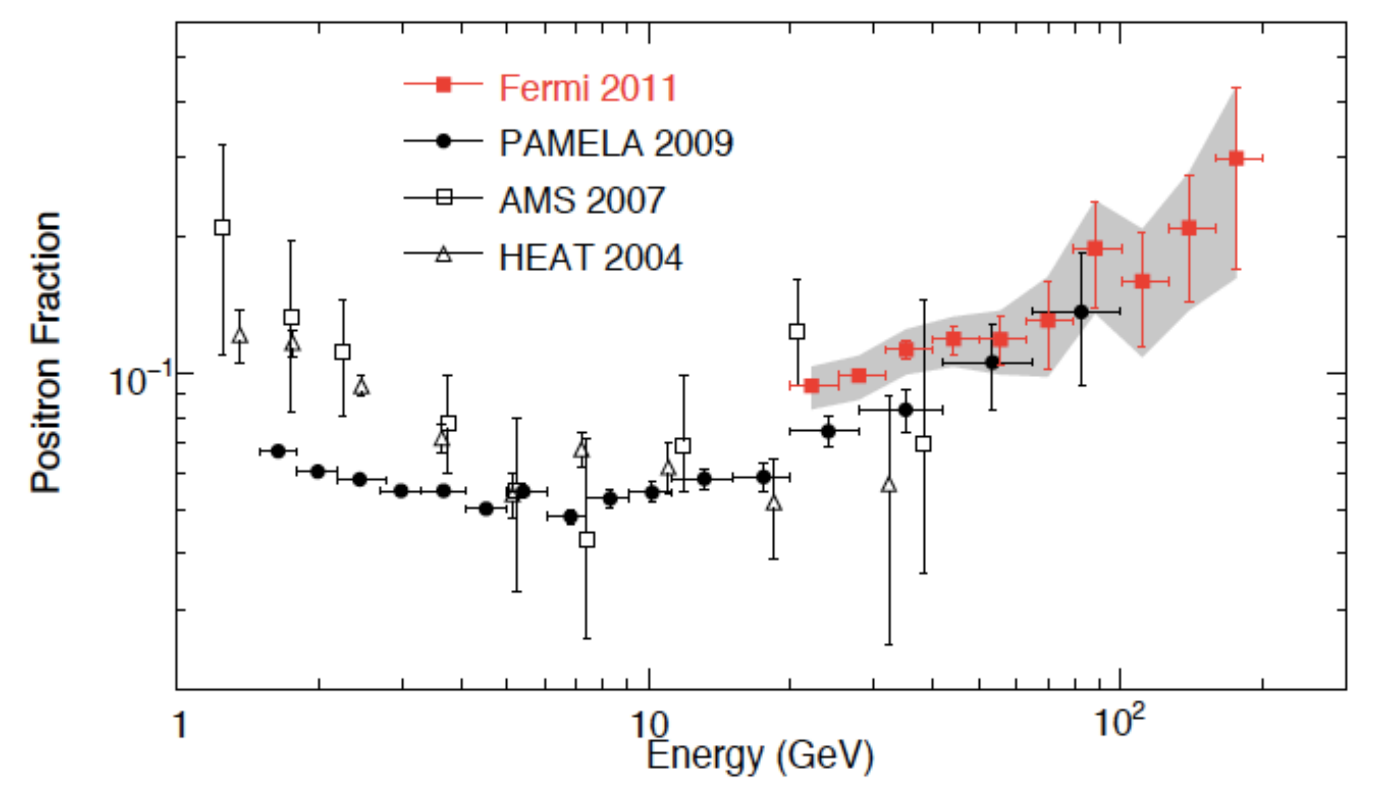
- Implies new light (130-150 GeV) charged particles or new scalars with very large couplings to DM
- Also: if true, we now know Galactic DM profile!

PAMELA & Fermi

- Excess of positrons at high energies, no associated excess in anti-protons



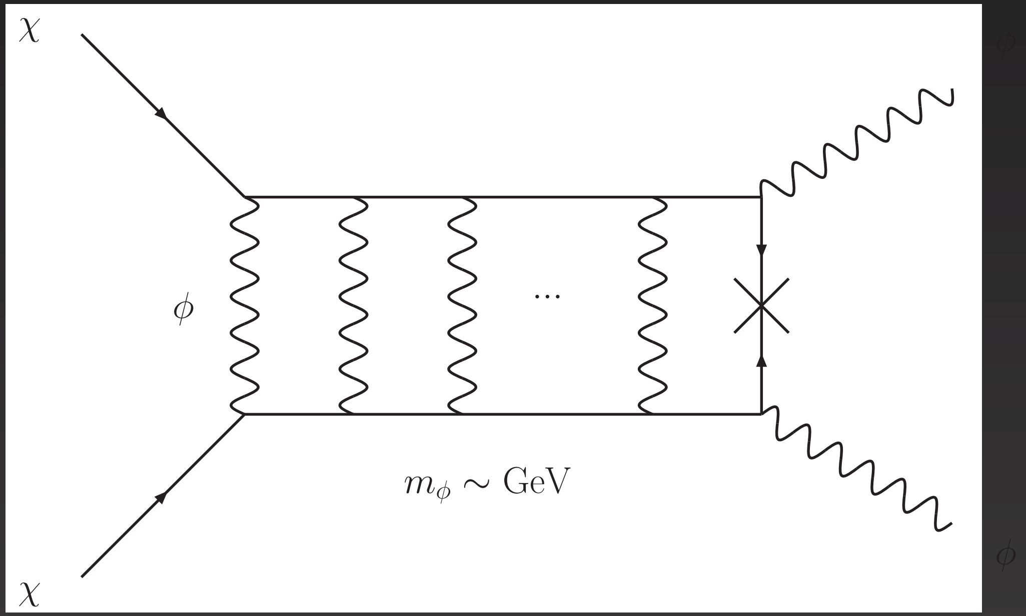
PAMELA 0810.4995



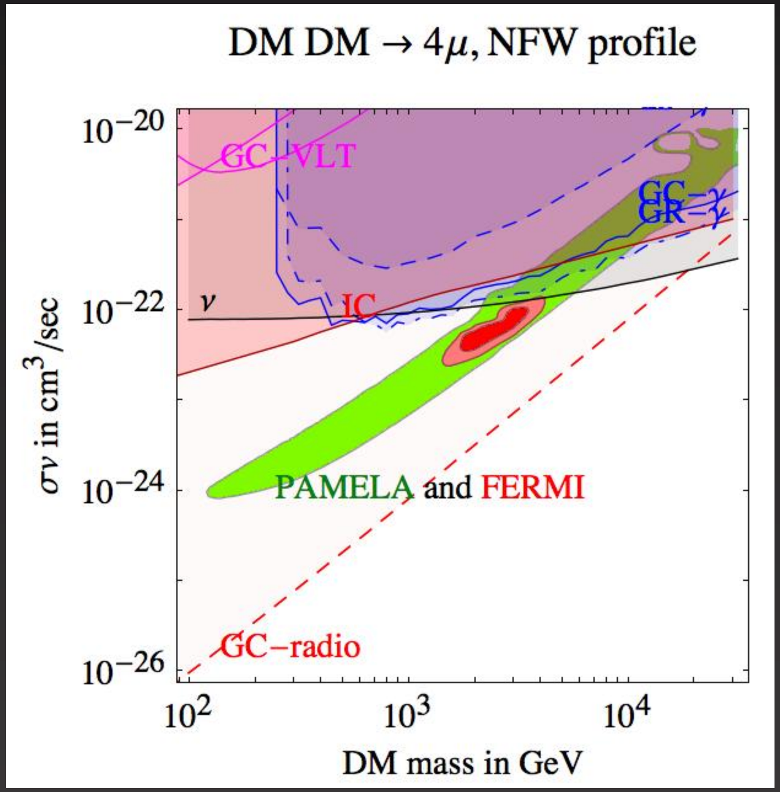
Fermi 2011

Theory Implications

- If due to Dark Matter annihilation, requires large cross section ($\sim 10^4\times$thermal), lepton final states but no hadrons.
- One solution: Sommerfeld enhancement via a light boson, $m_\phi < 2m_p$



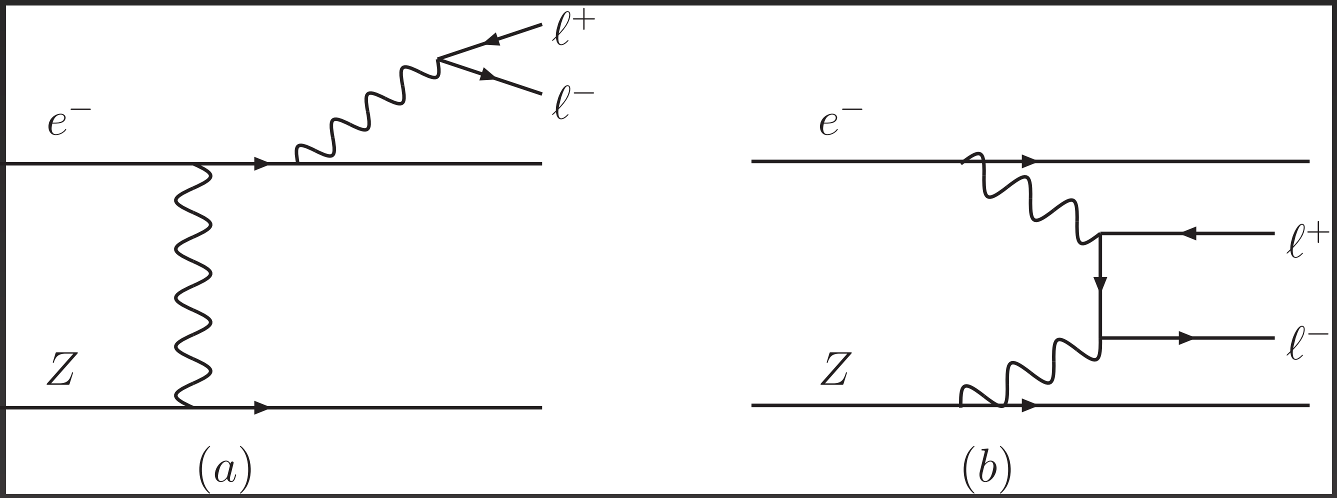
Arkani-Hamed *et al* 0810.0713

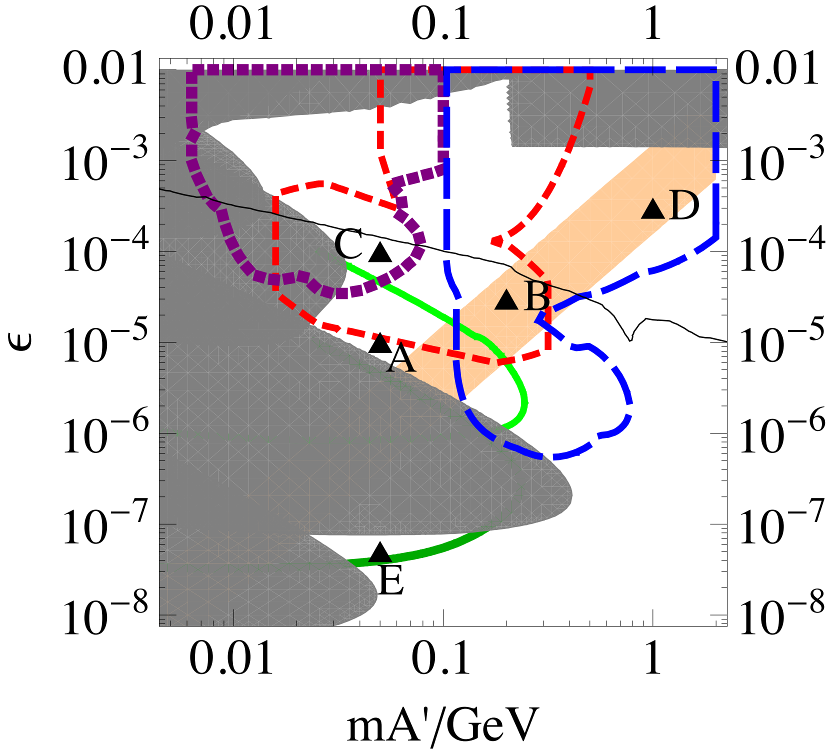


Meade *et al* 0905.0480

Dark Photons

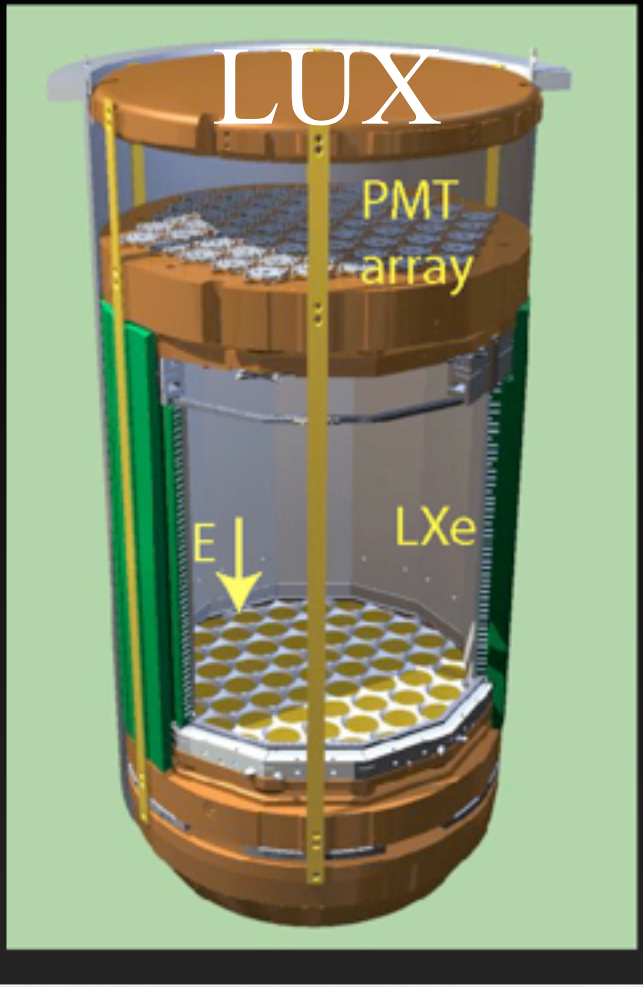
- PAMELA anomaly *possibly* pulsars, so why is this interesting?
- Revealed a theoretically interesting possibility:
  - Dark $U(1)$ kinetically mixed with the photon
  - Can be searched for at low energy e-beams (JLAB)
  - Or at b-factories



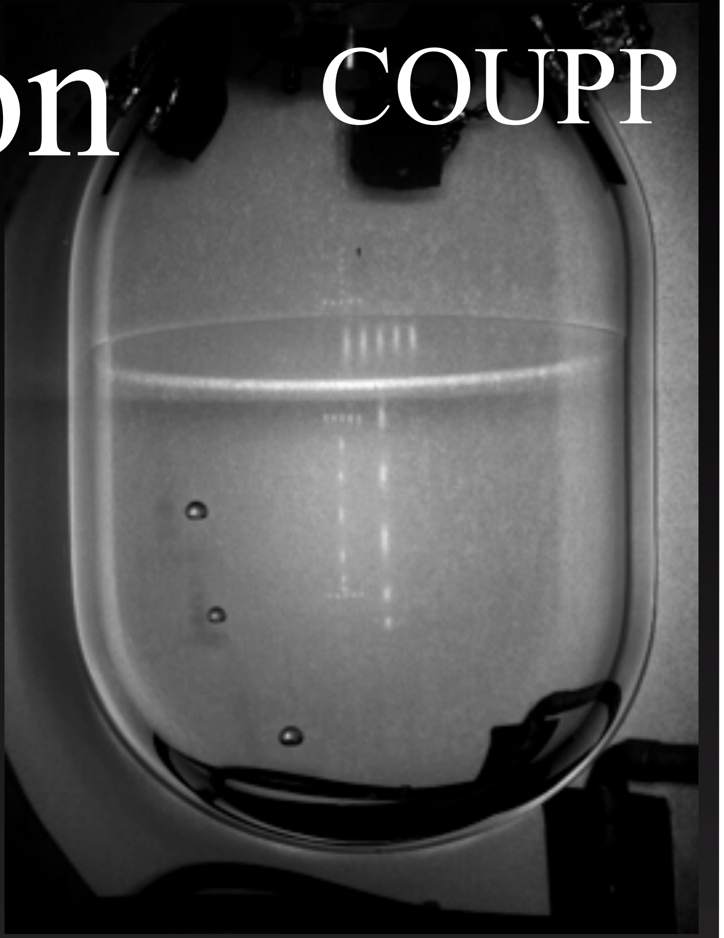


Bjorken *et al* 0906.0580

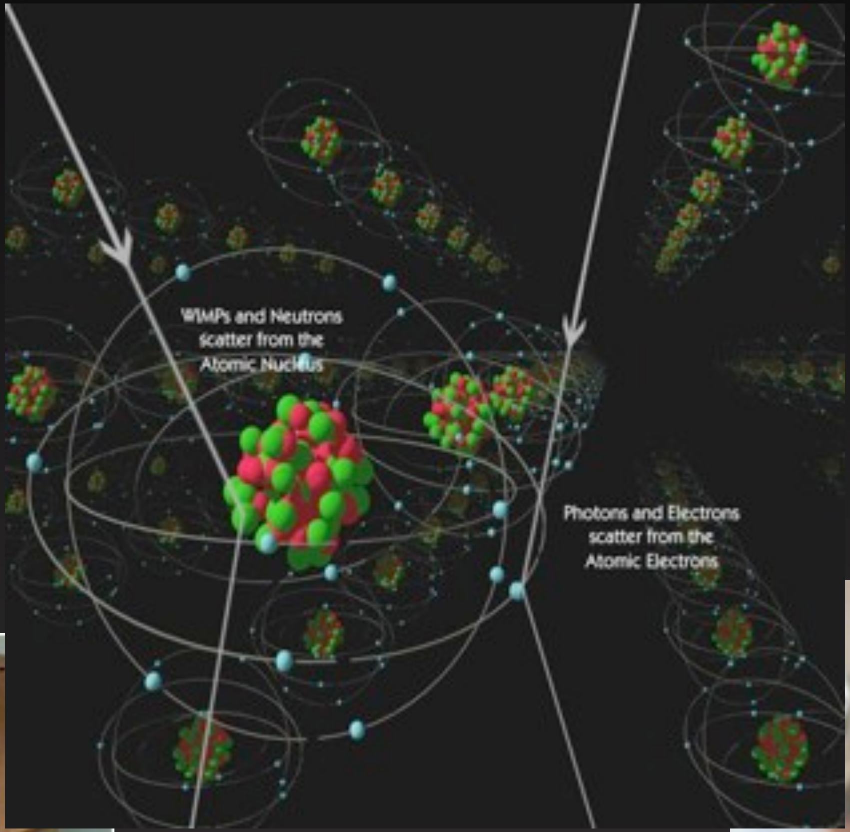
Direct Detection

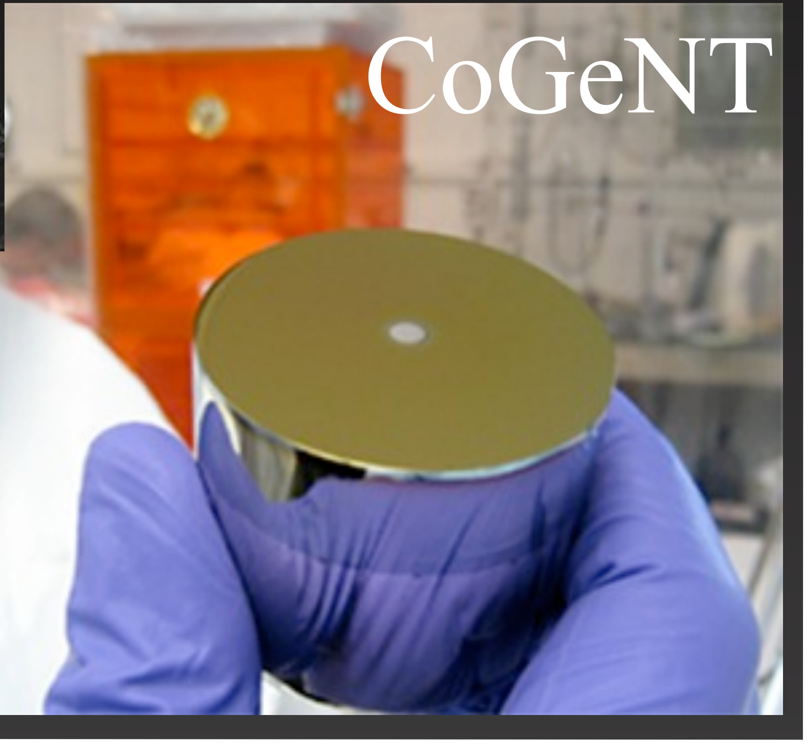


LUX

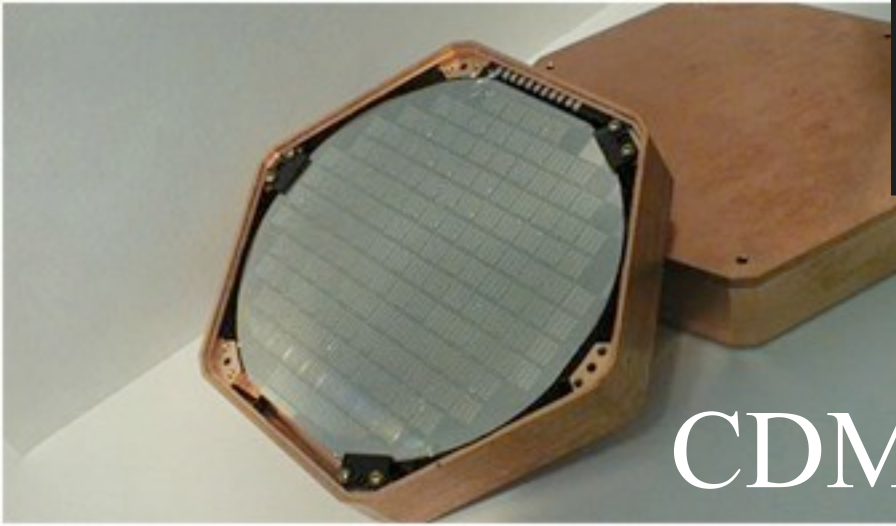


COUPP





CoGeNT



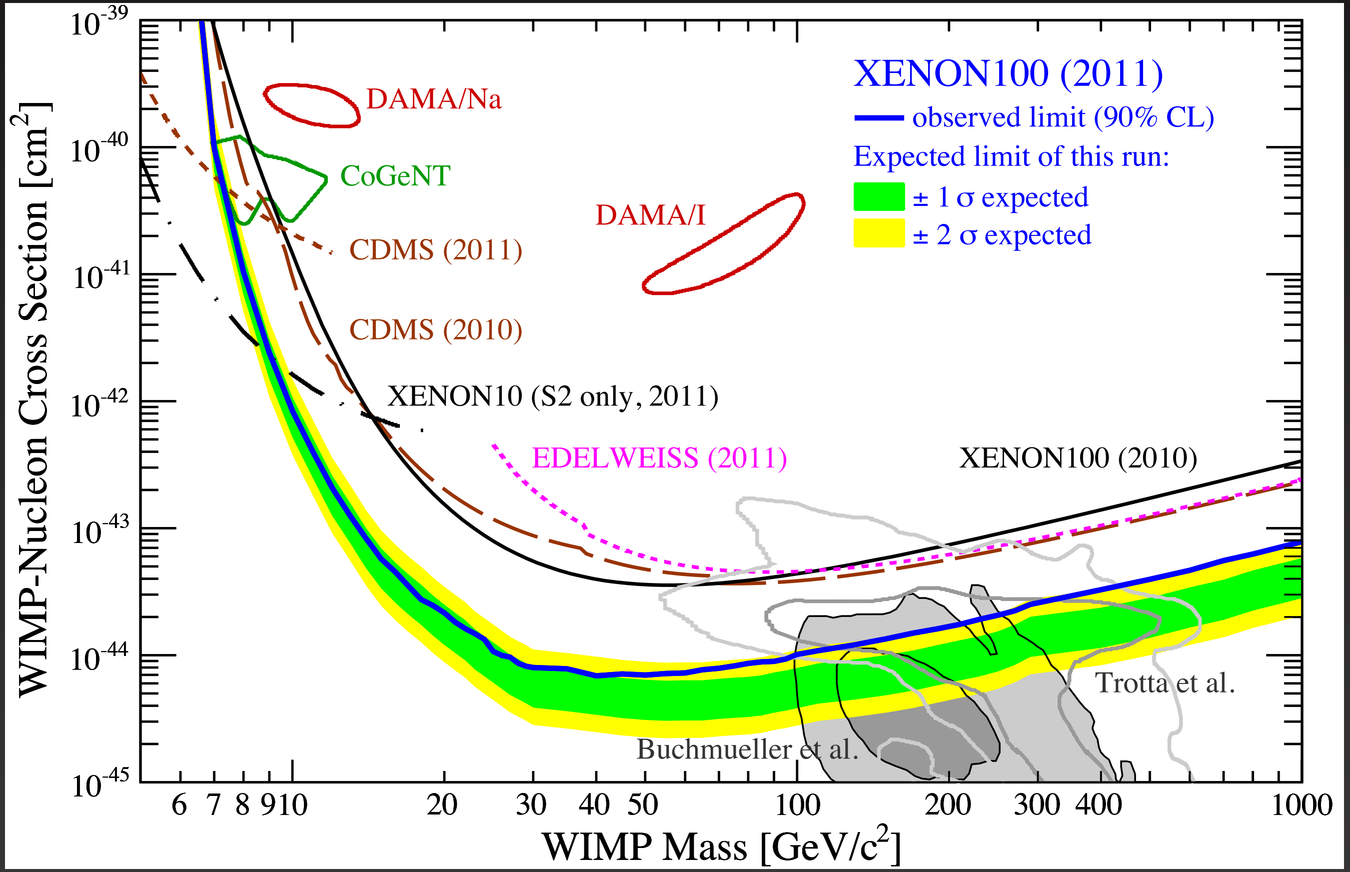
CDMS

plus XENON, DAMA/Libra, CRESST....

Exclusion Overview

- GeV-TeV dark matter from halo ($v \sim 300\ \mathrm{m/s}$) imparts $1 - 100\ \mathrm{keV}$ to nuclear targets
- Multiple technologies with multiple target elements (Ge, Xe) sensitive to a range of m_X

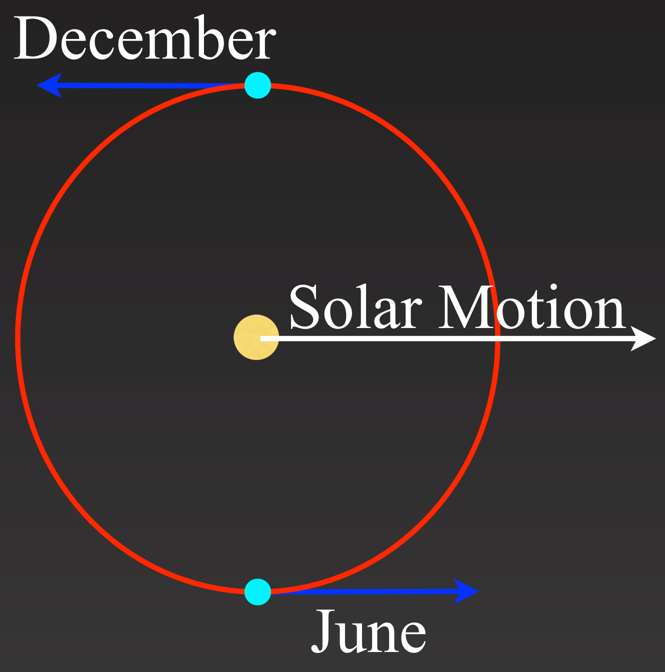
- Such plots are a great way to say how well you *didn't* see dark matter.

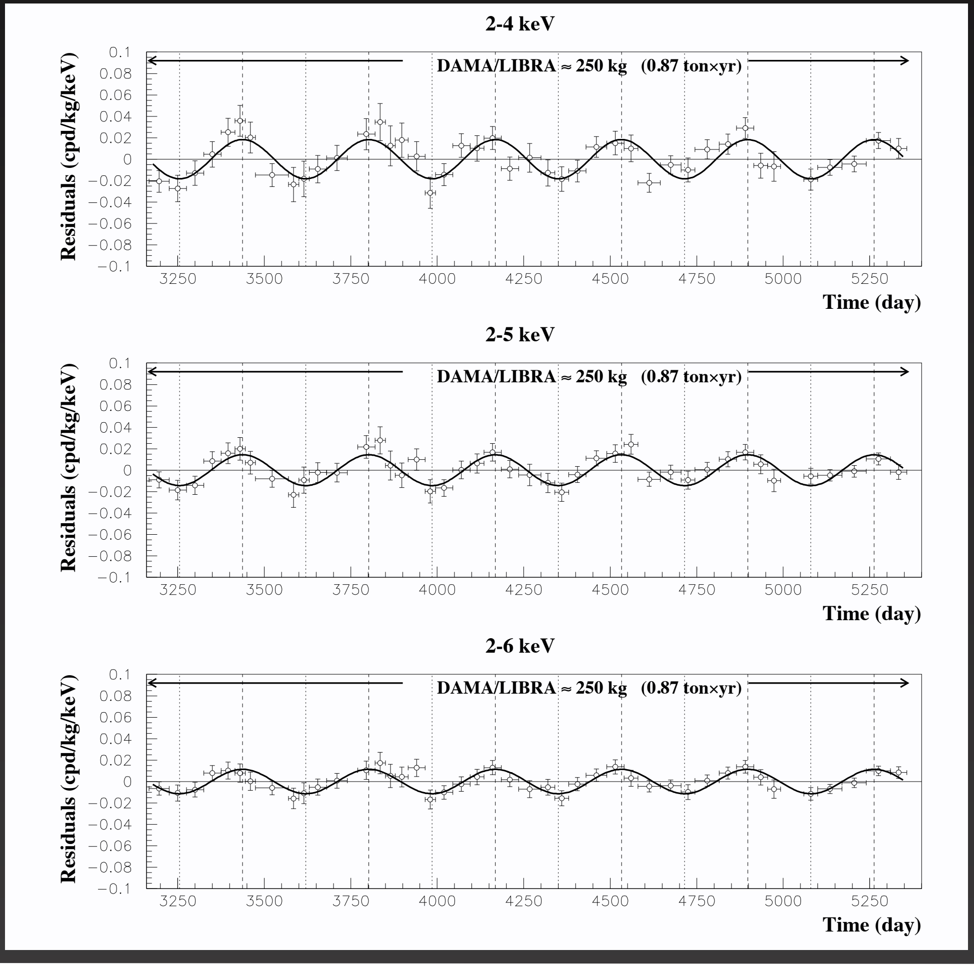


Xenon100 1104.2549

Direct Detection Anomalies

- DAMA/Libra: Na-I crystal in Gran Sasso
  - Don’t reject background. Look for DM in modulation of overall rate due to Earth’s motion around the Sun and through the Galactic halo



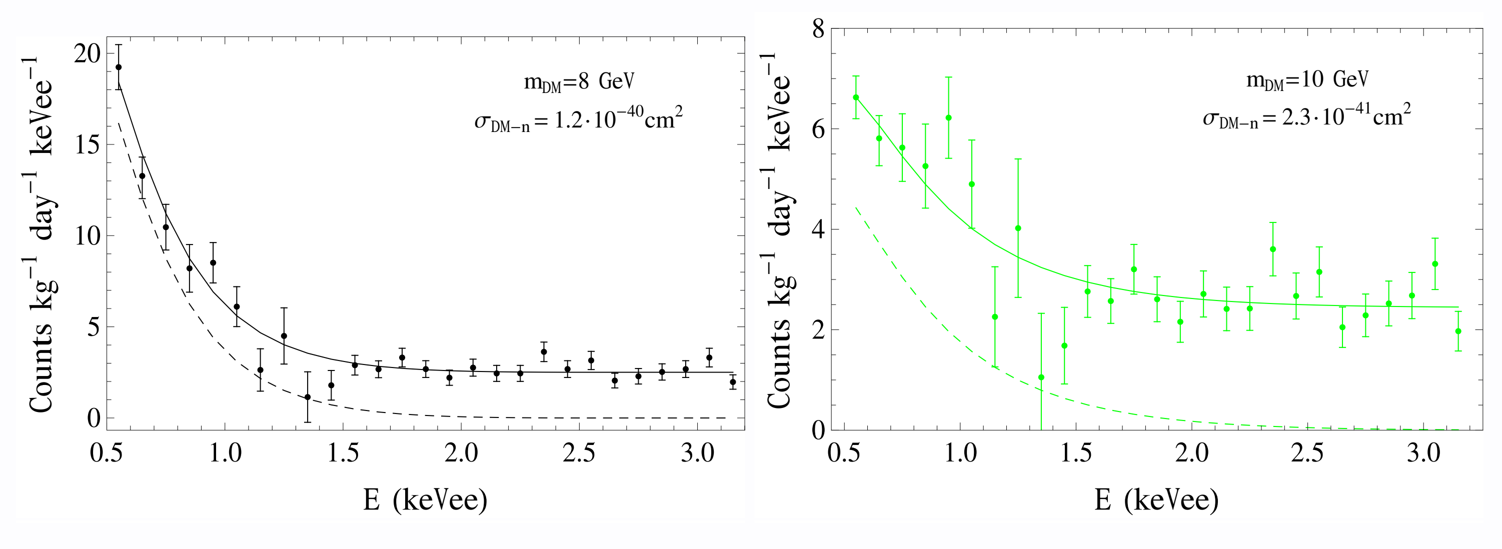


DAMA/Libra 1002.1028

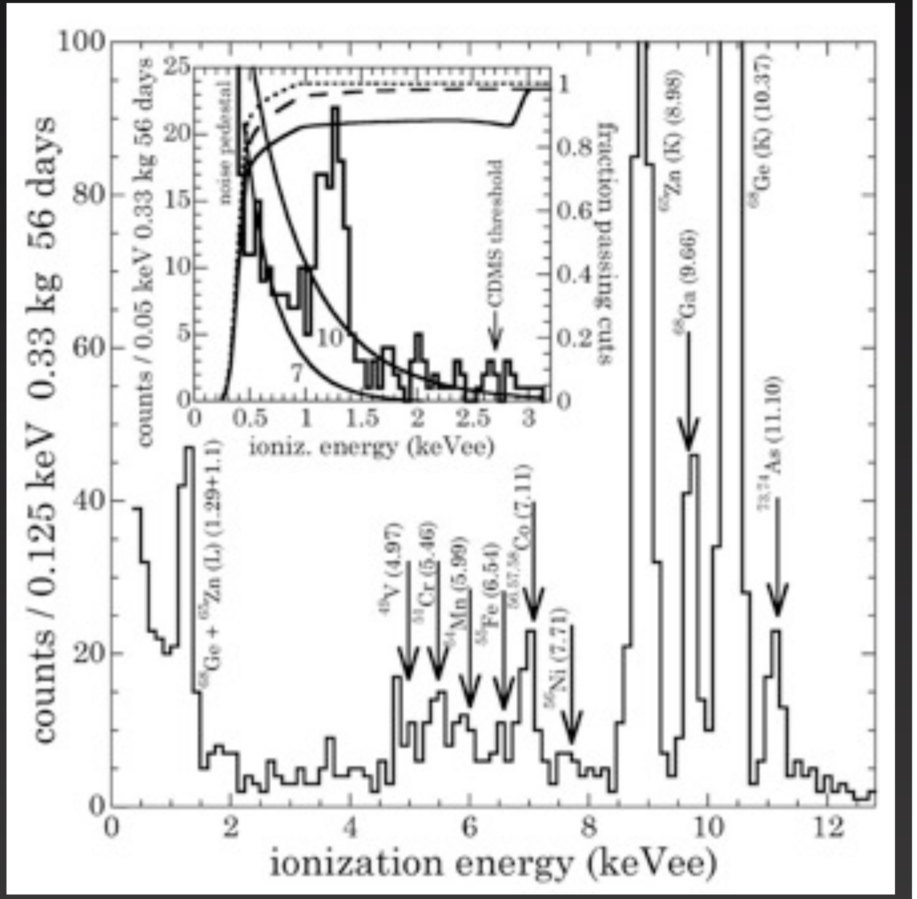
Direct Detection Anomalies

- CoGeNT: Ge crystal detector
- Attempts to be very low background, very low energy threshold.
- Claims an excess of events

- In tension with CDMS claims



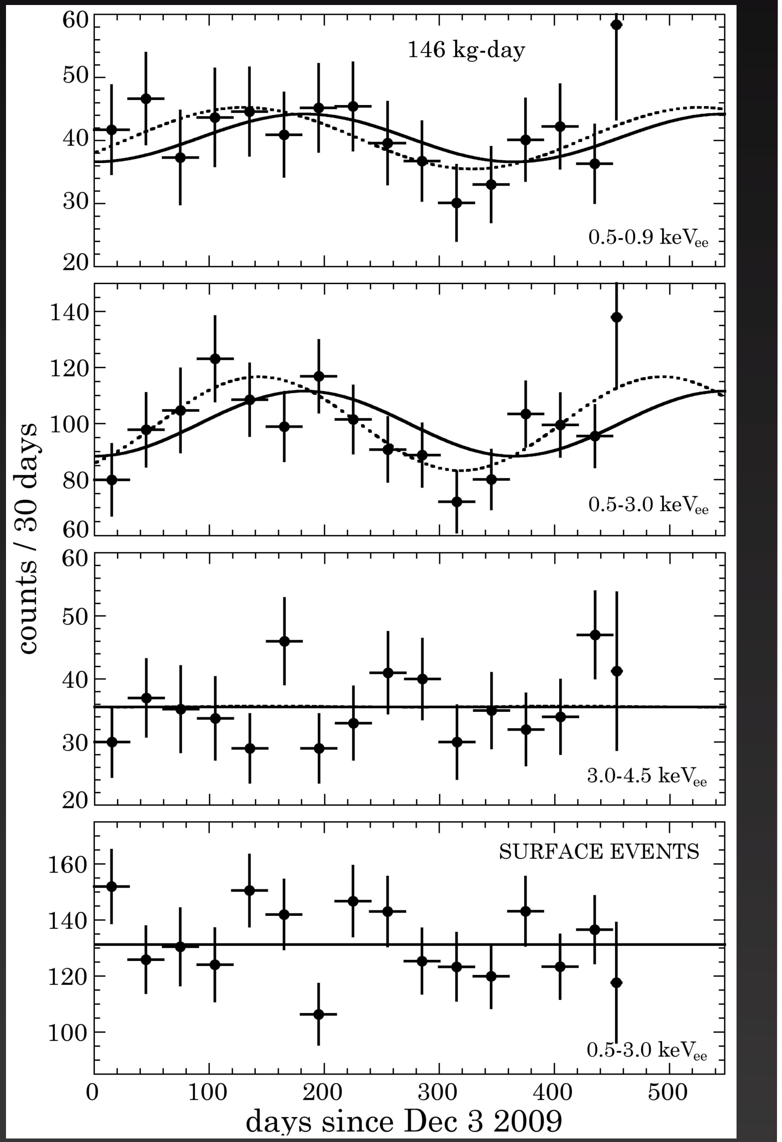
Kelso *et al* 1110.5338

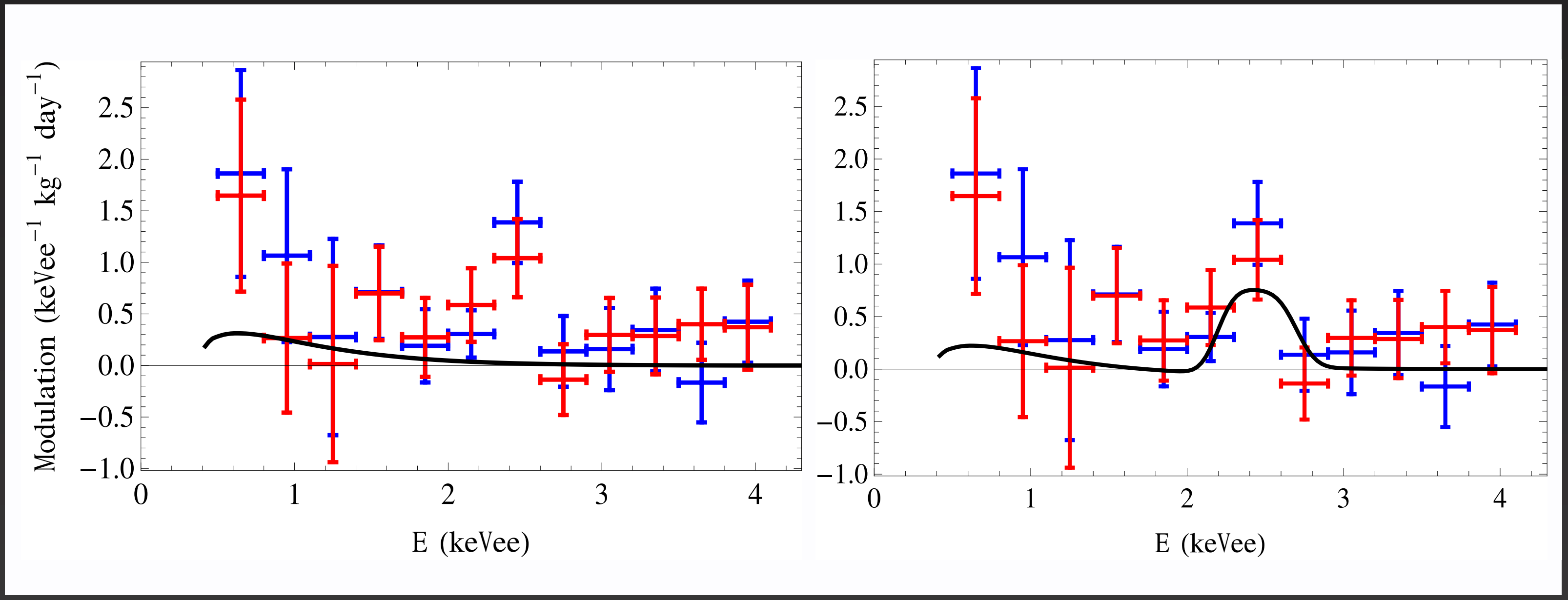


CoGeNT 1002.4703

Direct Detection Anomalies

- CoGeNT also claims modulation at low energies
  - Somewhat inconsistent with simple DM velocity profiles
- Not seen by CDMS, but analysis does not include lowest energies



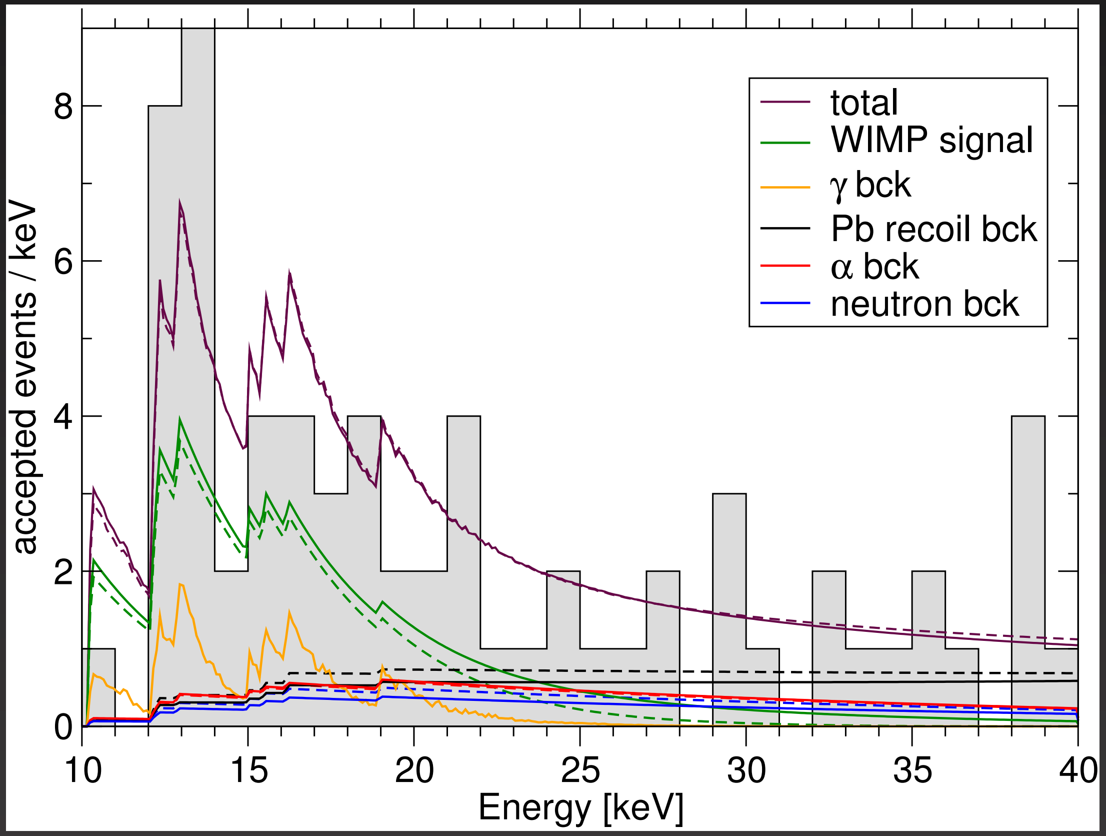


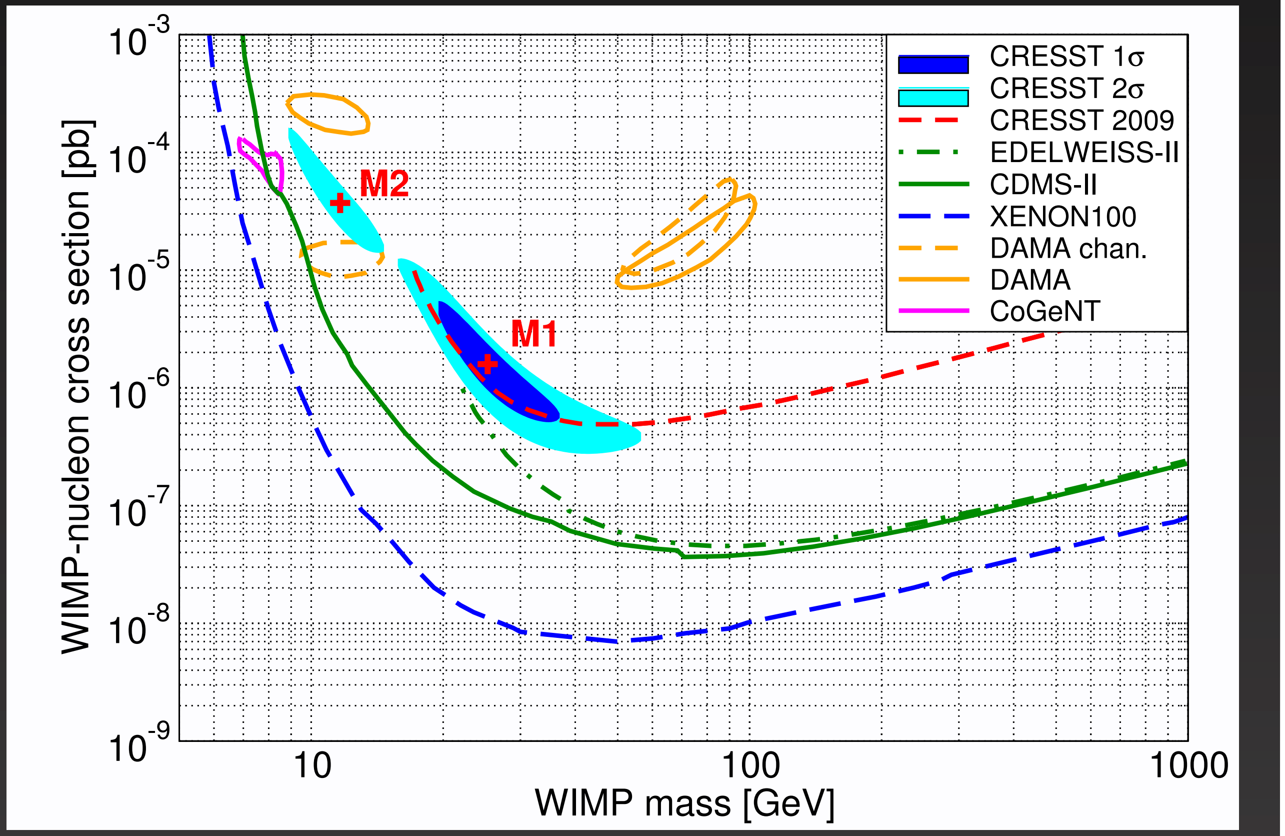
Kelso *et al* 1110.5338

CoGeNT 1106.0650

Direct Detection Anomalies

- CRESST-II: Ca-O-W crystal, measure light yield and phonon energy to discriminate background
  - Also sees excess at low energies



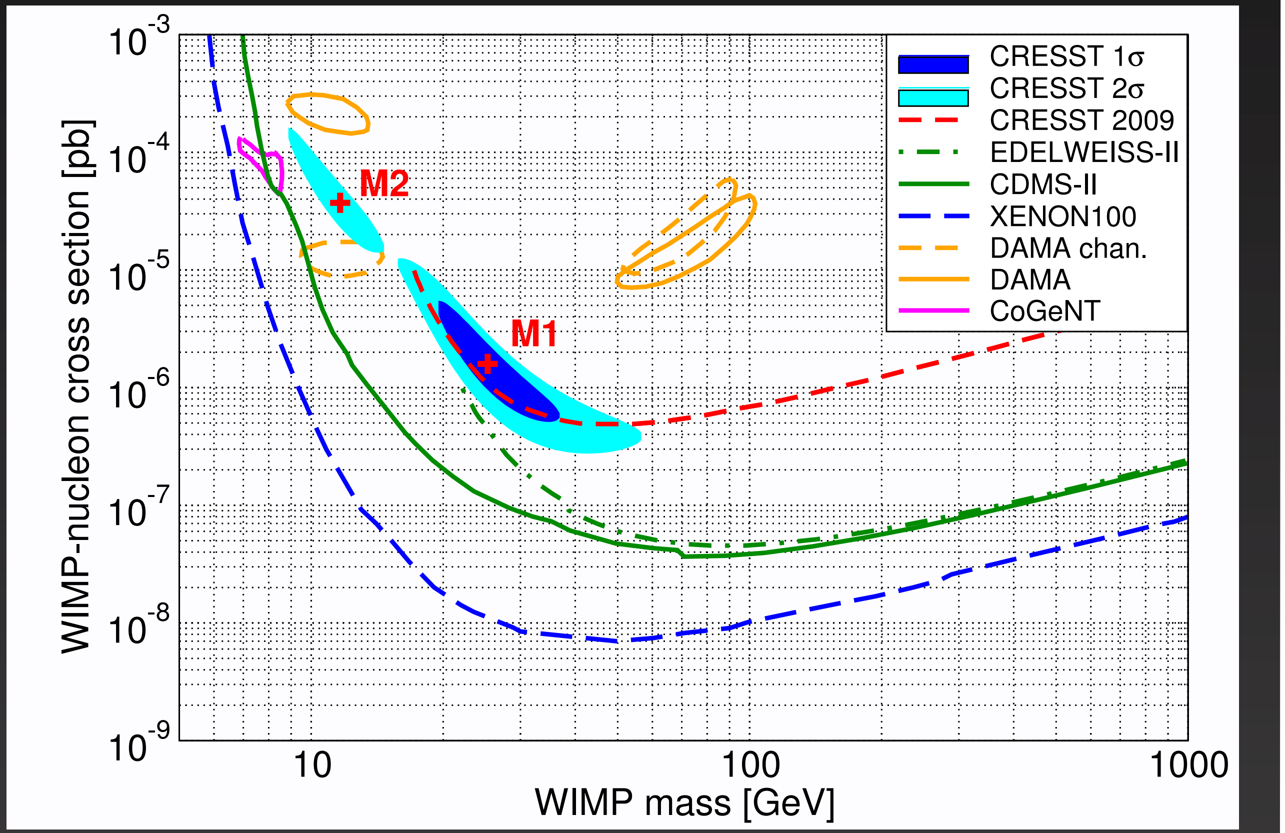


CRESST 1109.0702

Light Dark Matter

- Anomalies in conflict with XENON results
- 10 GeV not quite the weak scale, but thermal relic motivation can work for it as well
- But can't be the MSSM

- Heavy nuclear targets not ideal for light DM

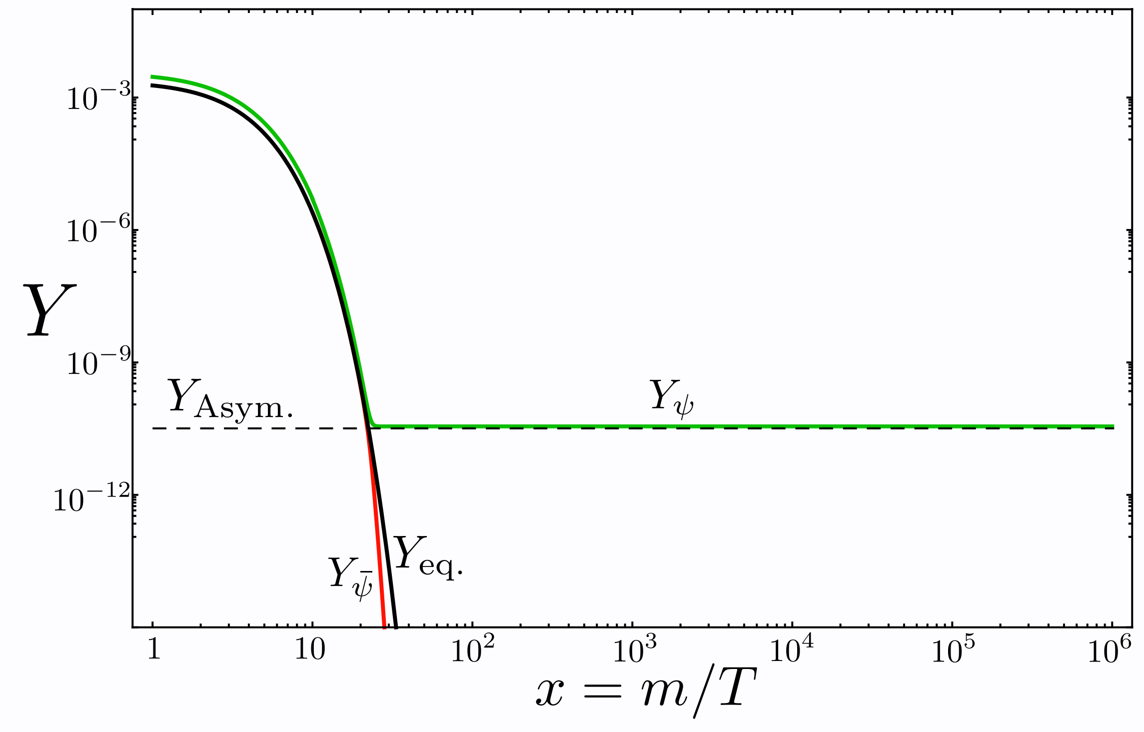


CRESST 1109.0702

Asymmetric Dark Matter

- Light dark matter not what's expected of a WIMP
- The one matter component we know of (baryons), not a thermal relic.
    - Maybe DM is asymmetric (X not $\bar{X}$) as well.
- Especially interesting for ~10 GeV DM

$$\begin{aligned} m_X &\sim \Omega_{\rm DM}/\Omega_{\rm B} m_p \\ &\sim 5\ \mathrm{GeV} \times \mathcal{O}(1) \end{aligned}$$



Asymmetric Dark Matter

- Lots of recent literature on this:

D.E. Kaplan *et al* 0901.4117
Cohen & Zurek 0909.2035
MRB & Randall 1009.0270
.... (see Refs. [1-2] of 1109.2164)

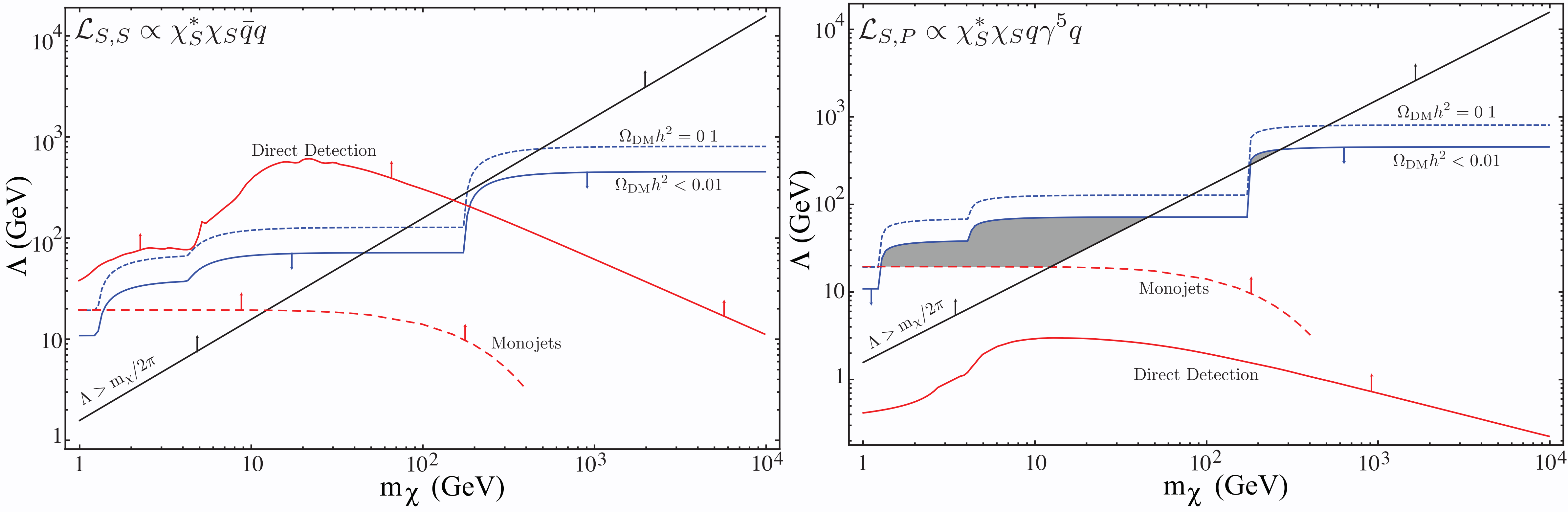
- Many possible DM masses, interactions, asymmetry generating mechanisms...
- But ADM must be asymmetric
  - So large interactions with *something:* $\sigma_{\rm ADM} \gtrsim \sigma_{\rm thermal}$
  - Assume effective operators formalism, and annihilation into quarks:

$$\begin{aligned}
\mathcal{L}_{S,S} &= \frac{m_q}{\Lambda^2}\chi_S^*\chi_S\bar{q}q \\
\mathcal{L}_{S,P} &= \frac{m_q}{\Lambda^2}\chi_S^*\chi_S\bar{q}\gamma^5 q \\
\mathcal{L}_{S,V} &= \frac{1}{\Lambda^2}\chi_S^*\partial_\mu\chi_S\bar{q}\gamma^\mu q
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{F,S} &= \frac{m_q}{\Lambda^3}\bar{\chi}_F\chi_F\bar{q}q \\
\mathcal{L}_{F,P} &= \frac{m_q}{\Lambda^3}\bar{\chi}_F\gamma^5\chi_F\bar{q}\gamma^5 q \\
\mathcal{L}_{F,V} &= \frac{1}{\Lambda^2}\bar{\chi}^F\gamma_\mu\chi_F\bar{q}\gamma^\mu q \\
\mathcal{L}_{F,A} &= \frac{1}{\Lambda^2}\bar{\chi}^F\gamma^5\gamma_\mu\chi_F\bar{q}\gamma^5\gamma^\mu q \\
\mathcal{L}_{F,T} &= \frac{1}{\Lambda^2}\bar{\chi}^F\sigma_{\mu\nu}\chi_F\bar{q}\sigma^{\mu\nu} q
\end{aligned}$$

Asymmetric Dark Matter

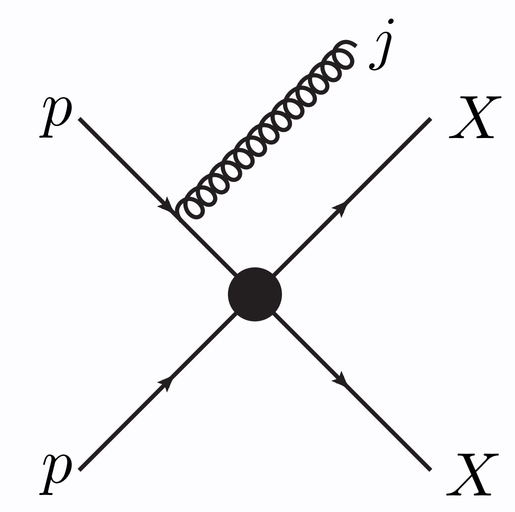
- Lower limits on Λ from direct detection, collider searches, applicability of formalism ($m_\chi < 2\pi\Lambda$)
- Upper limits from over-annihilation of ADM



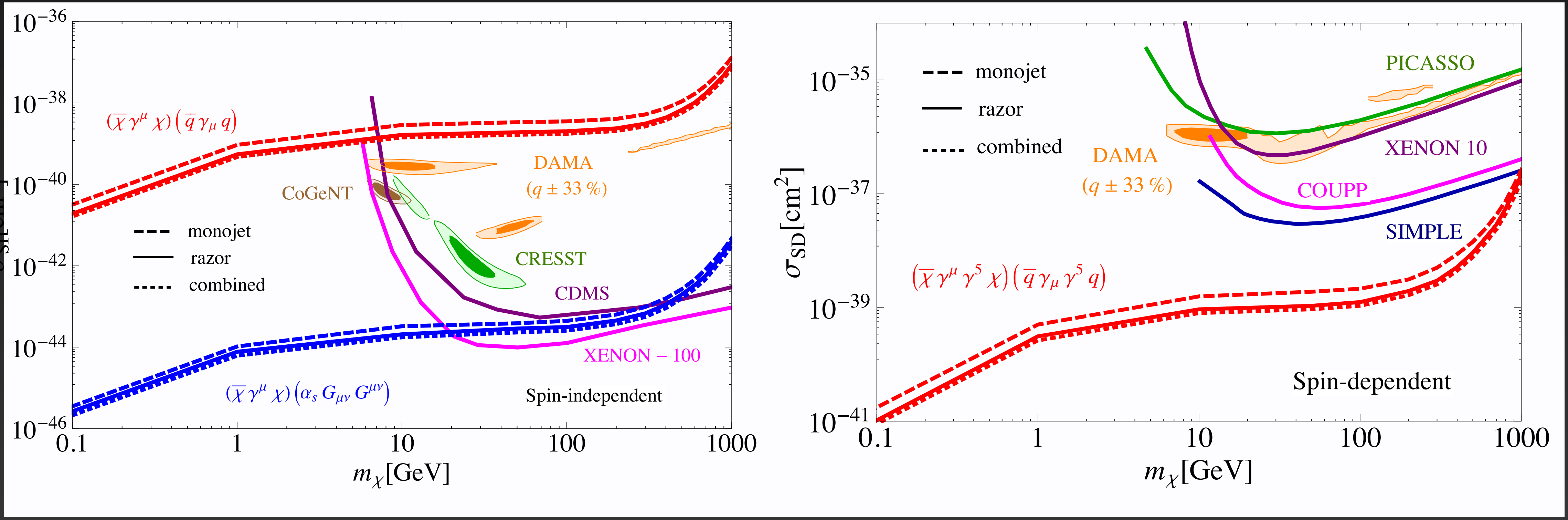
MRB 1104.1429

Collider Experiments

- Dark matter invisible at LHC, Tevatron
- Look for associate monojet/monophoton



- Recent Theory work using razor variable:

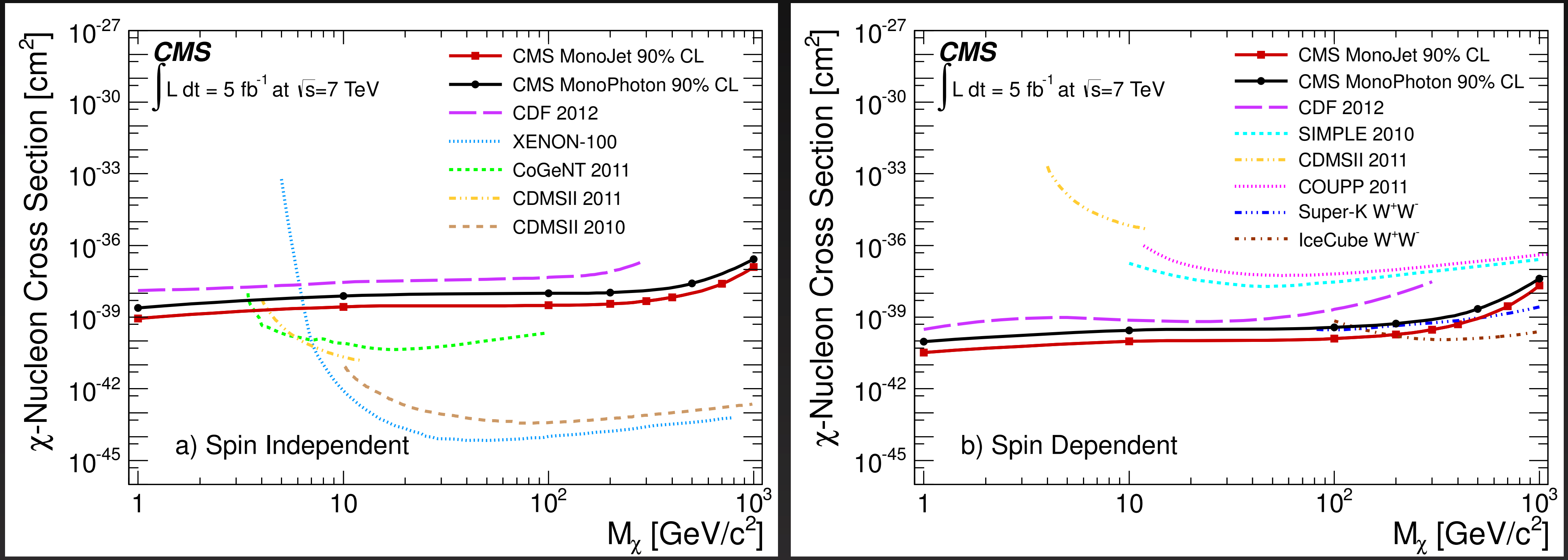


Fox *et al* 1203.1662

$$\mathcal{L} = 800\ \mathrm{pb}^{-1}$$

Collider Experiments

- Actual monojet results from CMS ($\bar{\chi}\gamma^{\mu}\chi\ \bar{q}\gamma_{\mu}q$):



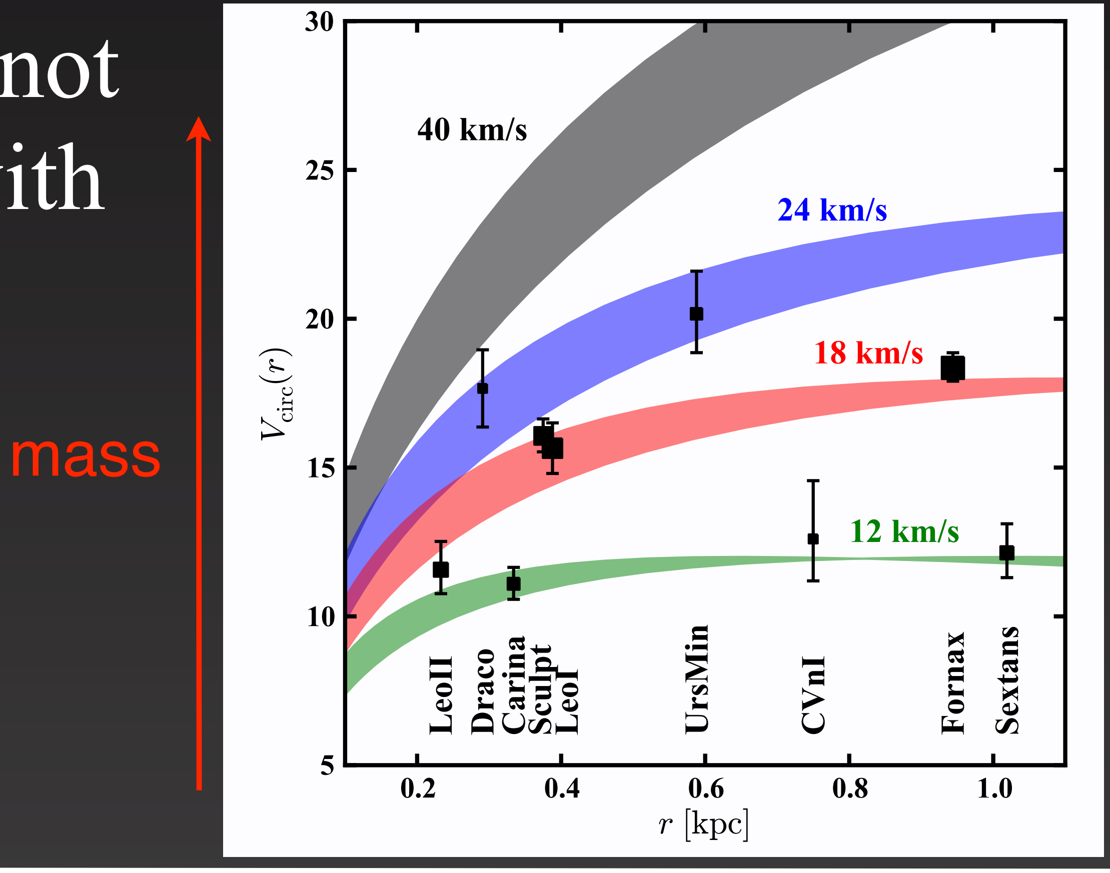
Malik on behalf of CMS 1206.0753

- Bounds get weaker if there is a light mediator (effective theory inapplicable)

N-body Simulations

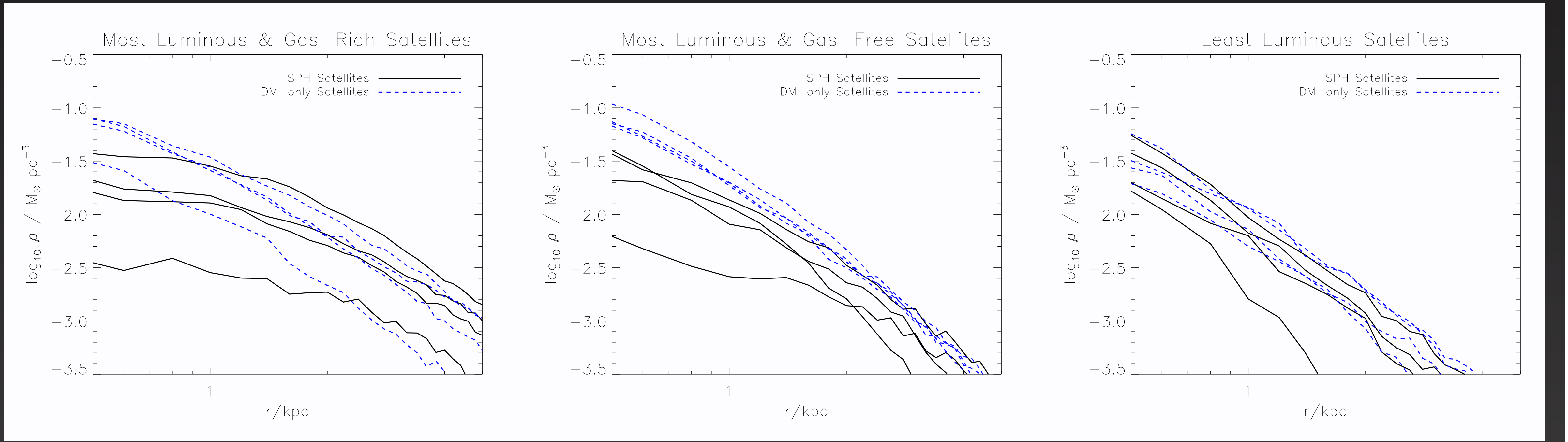
- Simulations getting to the point where we can begin to ask detailed questions about galactic structure.
- Example: Missing Satellite Problem
  - ΛCDM simulations do not have dwarf galaxies with the luminosities and masses observed.
  - Evidence for some warm dark matter?

Boylan-Kolchin *et al* 1111.2048



N-body Simulations

- But such simulations use only dark matter
- Luminous dwarfs have high baryon/DM ratio
  - Baryon+DM simulations see a reduction in central DM density today



Zolotov *et al* in preparation

Conclusions

- The WIMP model is very successful and well motivated solution to Dark Matter.
  - Not the only solution

- Recent years have shown us tantalizing *hints* from experiments that are difficult to explain by vanilla WIMP scenarios

Conclusions

- Many interesting theoretical models have resulted, revealing the breadth of what’s possible in the Dark Sector:
  - Sommerfeld enhancements, iDM, leptophilic DM, asymmetric DM, dark photons...
- Some of these have since been ruled out (or their motivating hint has disappeared), but in some cases, have opened new experimental arenas
- The take away: The Dark Sector doesn’t have to be simple, and we need to keep an open mind as results come in.