Astrophysical constraints on dark matter II

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Problems with the standard *Cold Dark Matter* model

1. *Density of dark matter halos*:
Faint, dark matter-dominated galaxies *appear* less dense that predicted in simulations

2. '*Missing satellites problem*':
Simulations have more dark matter subhalos than there are observed dwarf satellite galaxies

Solutions to the issues in *Cold Dark Matter*

3 possible directions from here:

1. Discuss how to construct and simulate non-CDM models [e.g. K. Zurek talk, Feng, et al. 2010; Loeb & Weiner 2011; van den Aarssen 2012; Tulin, Yu, Zurek 2013, Fan et al. 2013]

2. Talk about how baryons may alter dark matter distributions [Wadepuhl & Springel MNRAS 2011; Parry et al. MRNAS 2011; Pontzen & Governato MRNAS 2012; Brooks et al. ApJ 2012]

3. Understand how to measure macroscopic dark matter distributions [This talk]

Low Surface Brightness (LSB) Galaxies

- LSBs are late-type, gas-rich, dark matter-dominated disk galaxies
[see review by de Blok et al. 2010]

- First comparisons of HI rotation curves with CDM simulations
[Moore 1994; Flores & Primack 1994]

- HI and Halpha results hinted at cored (non NFW) profiles. But 2 systematics:

    1. Pointing problems

    2. Non-circular motions

Low Surface Brightness Galaxies

- Most systematics mitigated with 2D rotation curves from Integral Field Unit (IFU) spectrographs

- THINGS survey observes HI gas in LSBs and obtain a mean slope of 0.29 \pm 0.07 for (Oh et al. ApJ 2011)

- Kinematics as measured from Gas and Stars can give different slopes. Stars: 0.67 \pm 0.10; Gas: 0.58 \pm 0.24 (Adams et al. 2014)

Galaxy clusters

- Several observational tools: Strong and weak gravitational lensing, X-ray emission, stellar kinematics

- Measurement of clusters at $z = 0.2$-0.3 find that the total density profile (stars + dark matter) is consistent with NFW model

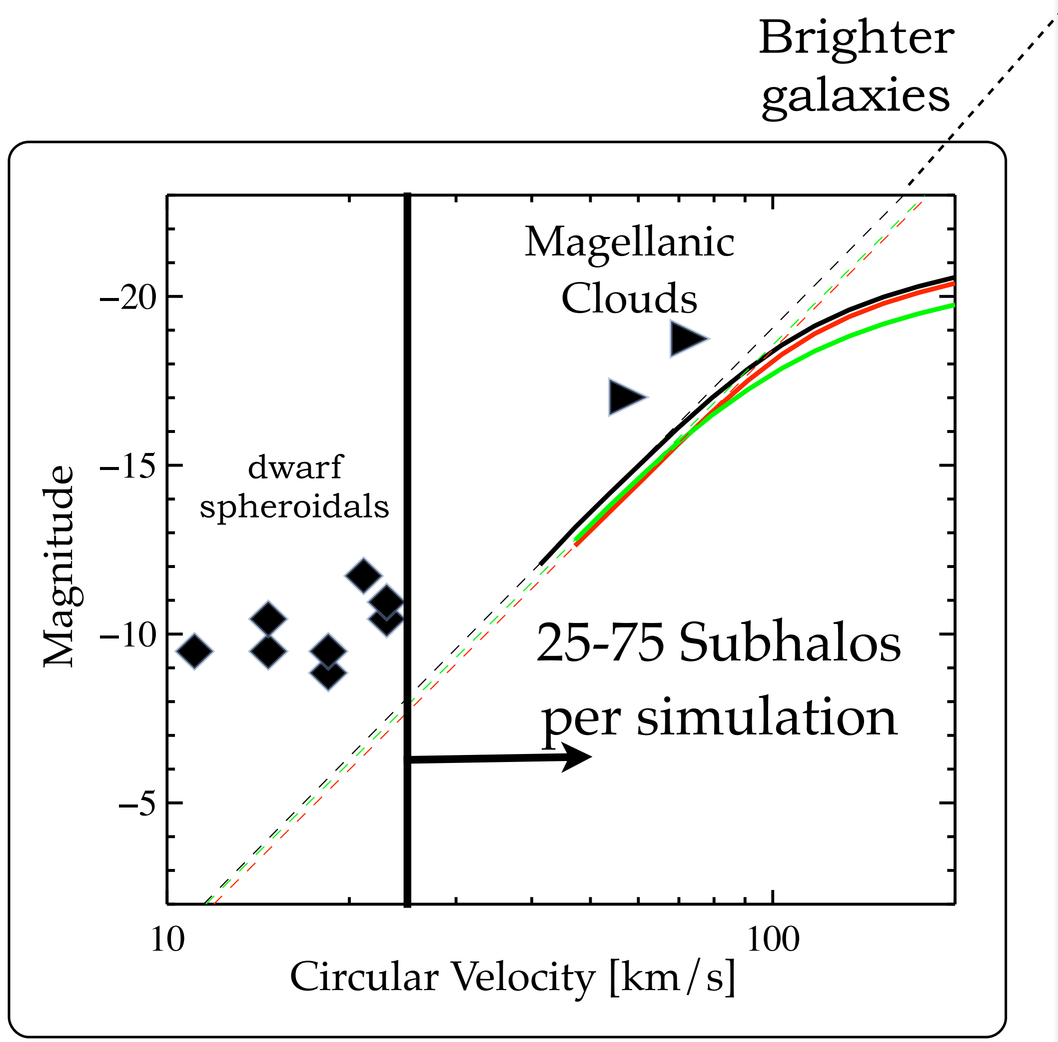
- However dark matter profiles are shallower than NFW: average inner slope is about 0.5 \pm 0.2 (Newman, Treu, Ellis, Sand et al. 2013)

A population of missing massive satellites?

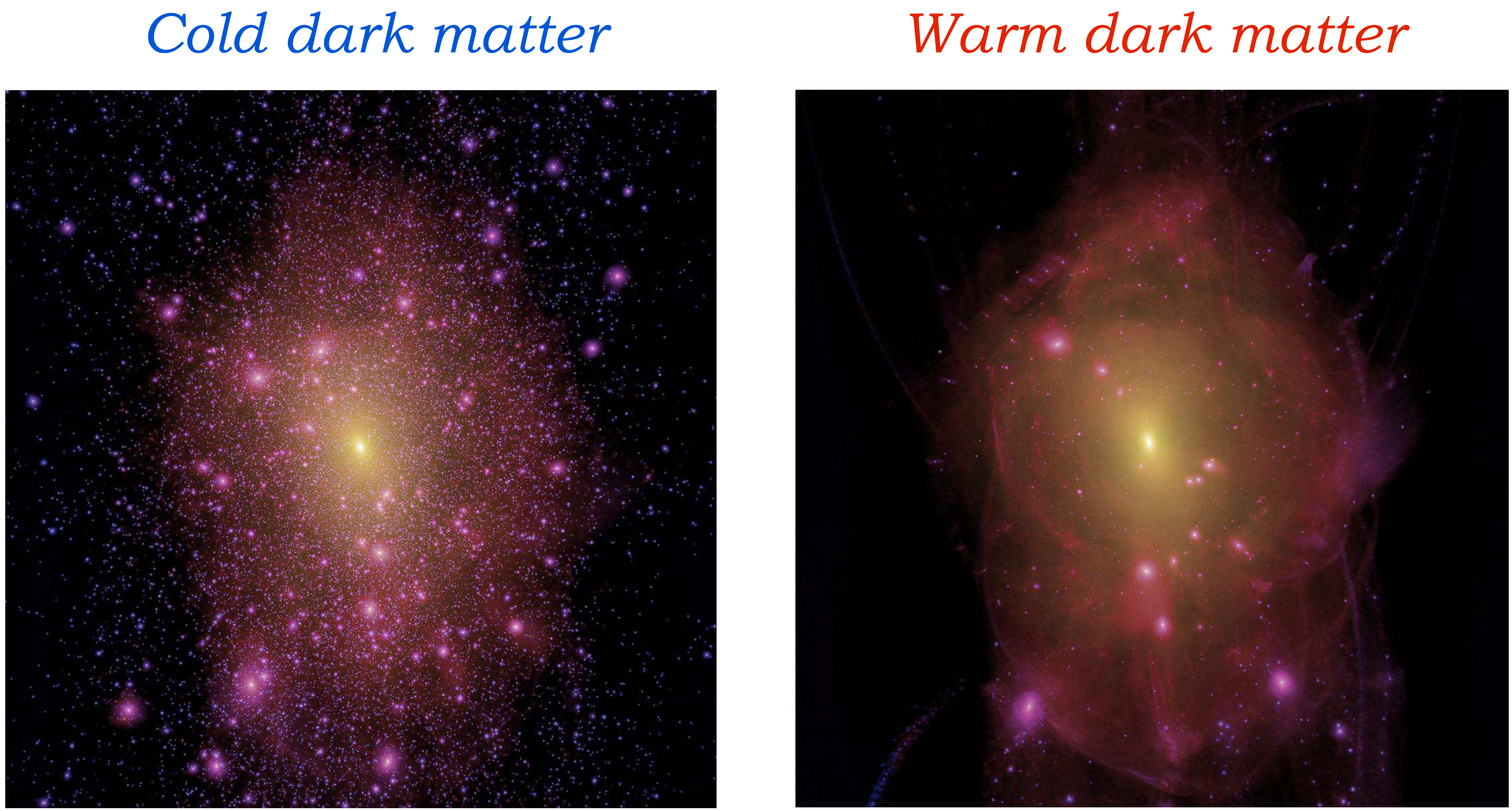
Strigari et al. Nature 2008;
Boylan-Kolchin et al. MNRAS 2011

- *Cold dark matter* predicts dozens of 'dark' satellites more massive than the dwarf spheroidals ('*Too big to fail problem*')

- Possible solutions:
  1) New dark matter physics
  2) 'Pesky' baryons
  3) Observational systematics



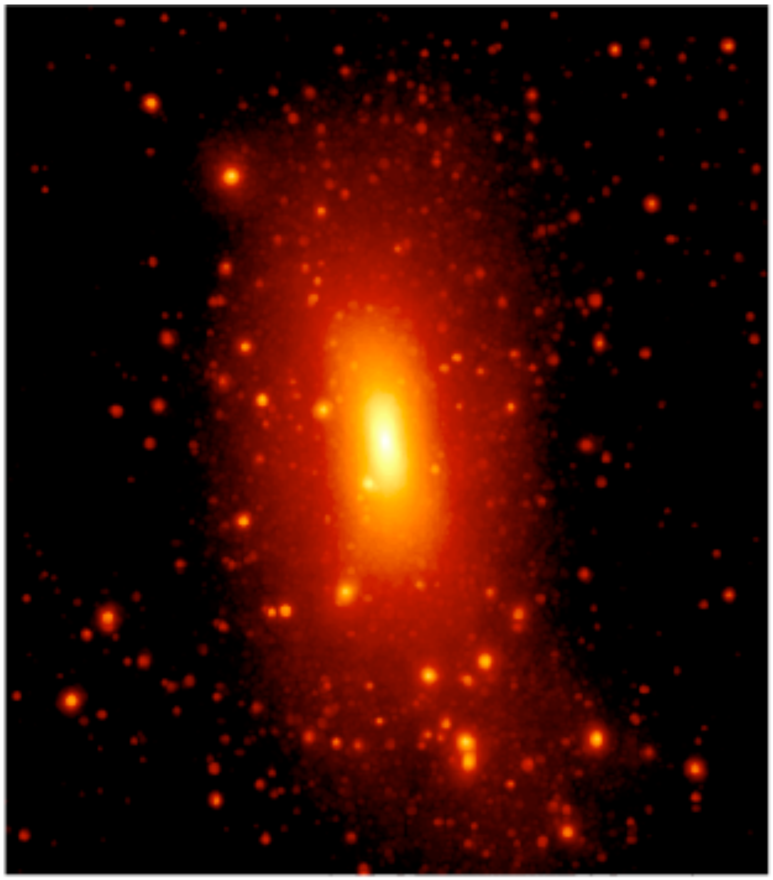
Warm dark matter simulations



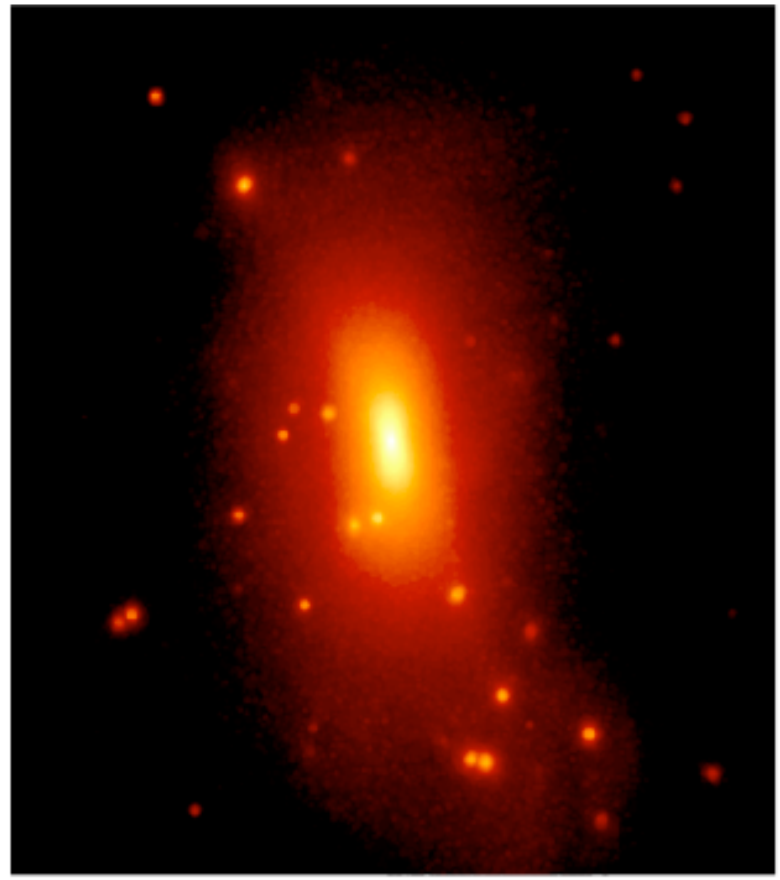
Lovell et al 2011

Decaying dark matter simulations

Cold dark matter



Decaying dark matter



Mei-Yu Wang et al 2014

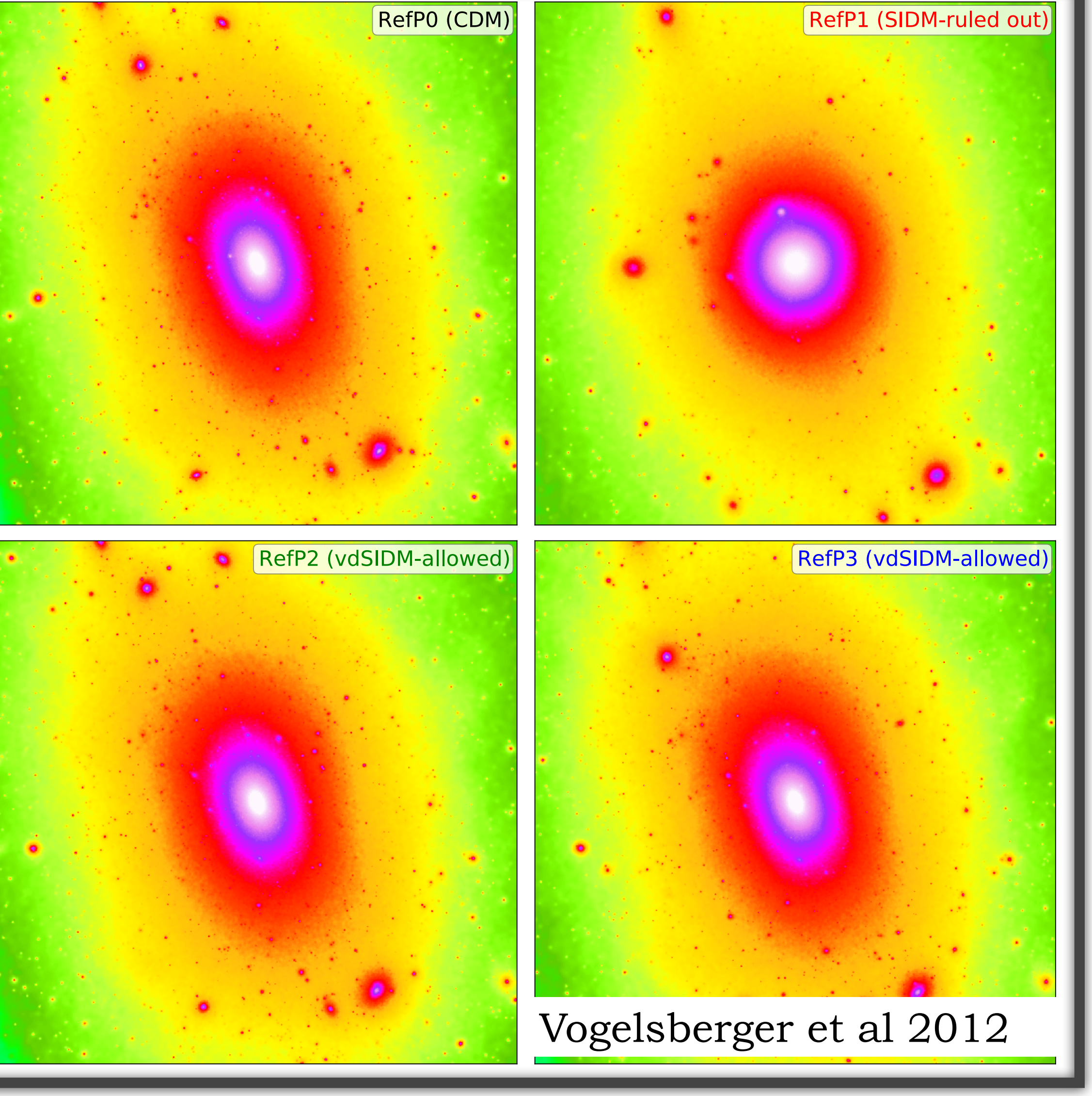
Self-interacting dark matter simulations

- **Canonical WIMP model:**
  Interaction rate in Milky Way 10^{13} times greater than age of Universe!

- Upper bounds 20 orders of magnitude greater than corresponding WIMP cross section

- Models with `dark' photons

- Simulations show halos, subhalos less dense, more spherical than cold dark matter



Vogelsberger et al 2012

Solutions to satellites issues: Redux

Non-dark matter ways out

- Cosmological model is correct. It's just the baryons! [e.g Wadepuhl & Springel MNRAS 2011; Parry et al. MRNAS 2011; Pontzen & Governato MRNAS 2012; Brooks et al. ApJ 2012]

- Maybe we don't know circular velocities of dSph dark matter halos after all (e.g. Stoehr et al. 2002)

- Is our estimate of Milky Way-mass wrong? [e.g. Wang et al. 2013]

- Is Milky Way galaxy an odd ball? [e.g. Liu et al. 2010, Tollerud et al. 2011, Guo et al. 2011, Strigari & Wechsler ApJ 2012, Nierenberg et al. 2013]

Too big to Fail in large scale context

- At the moment we are comparing a handful of theories (simulations) to one, maybe two, data points (MW and M31).

- We don't have any idea on a large scale of how representative the Milky Way galaxies is in terms of its populations of satellites

- It's difficult to count satellites around other ``Milky Ways", because the satellites are faint and systematic issues

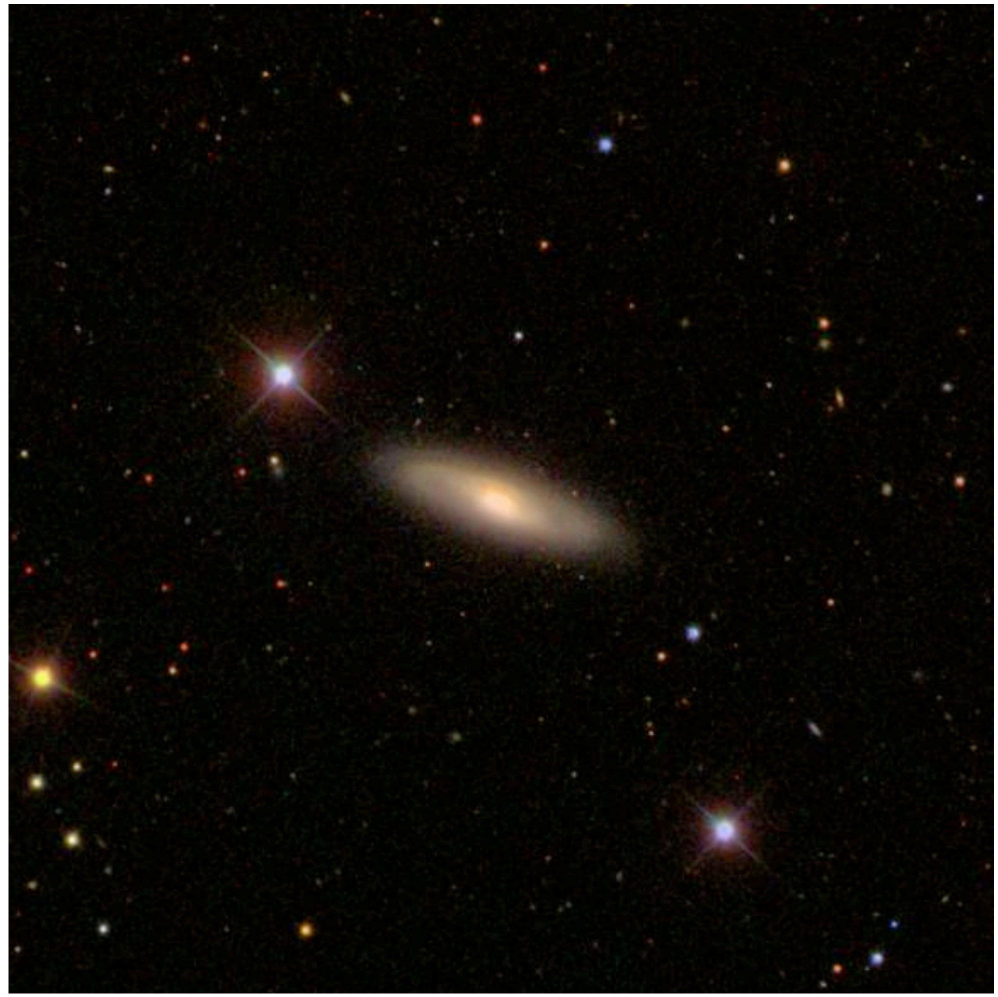
Dwarf spheroidals around other 'Milky Ways'

- About 5% of 'Milky Ways' have 'Magellanic Clouds' [Liu et al. 2010, Lares et al. 2011; James & Ivory 2011; Tollerud et al. 2011; Guo et al. 2011; Robotham et al. 2012]

✦ Going fainter difficult because unreliable distances to satellites

✦ Can only use bright, nearby 'Milky Ways'

- Down to limits of modern surveys, <u>Milky Way is 'normal'</u> [Guo et al. MNRAS 2012; Strigari & Wechsler ApJ 2012; Speller & Taylor ApJ 2014]



Program redux

1. Day I (Yesterday, some today): Macroscopic astronomical measurements and their implications for the nature of dark matter
   - Small-scale dark matter structure: density profiles, missing satellites
   - Cold, warm, self-interacting dark matter

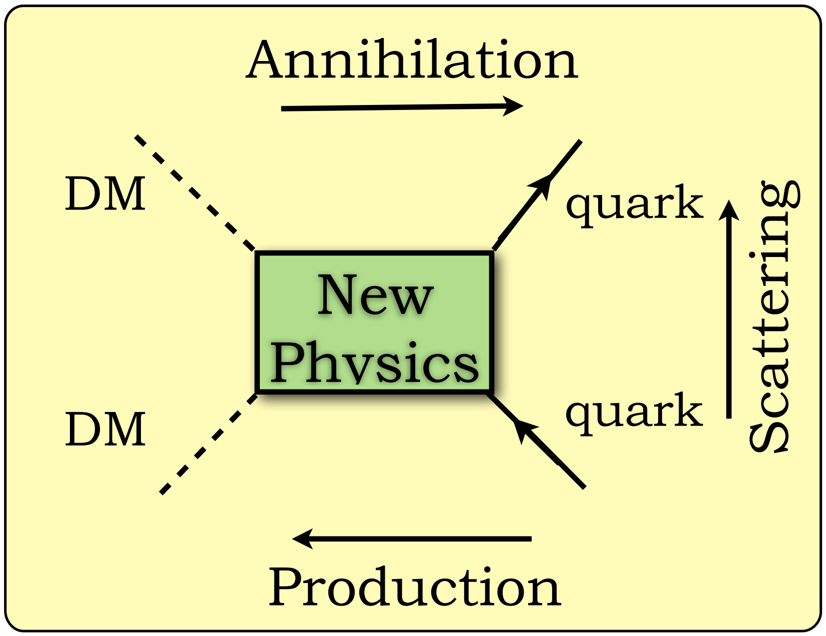
2. Day II (Rest of today): Astrophysical interplay in `classical' dark matter searches
   - Indirect and direct dark matter detection
   - Neutrino Floor

Astrophysical interplay with

Indirect dark matter detection

Indirect dark matter detection with gamma rays

Siegal-Gaskins, next week



$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\mathrm{DM}}^2}\int_{E_{\min}}^{E_{\max}}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}\mathrm{d}E_\gamma}_{\Phi_{\mathrm{PP}}} \times \underbrace{\int_{\Delta\Omega}\left\{\int_{\mathrm{l.o.s.}}\rho^2(r)\mathrm{d}l\right\}\mathrm{d}\Omega'}_{\text{J-factor}}$$

- Tens to hundreds of photons produced per WIMP annihilation
- 100 GeV mass WIMPs gives photons in the gamma-ray band, ~ 10 MeV - 10 GeV

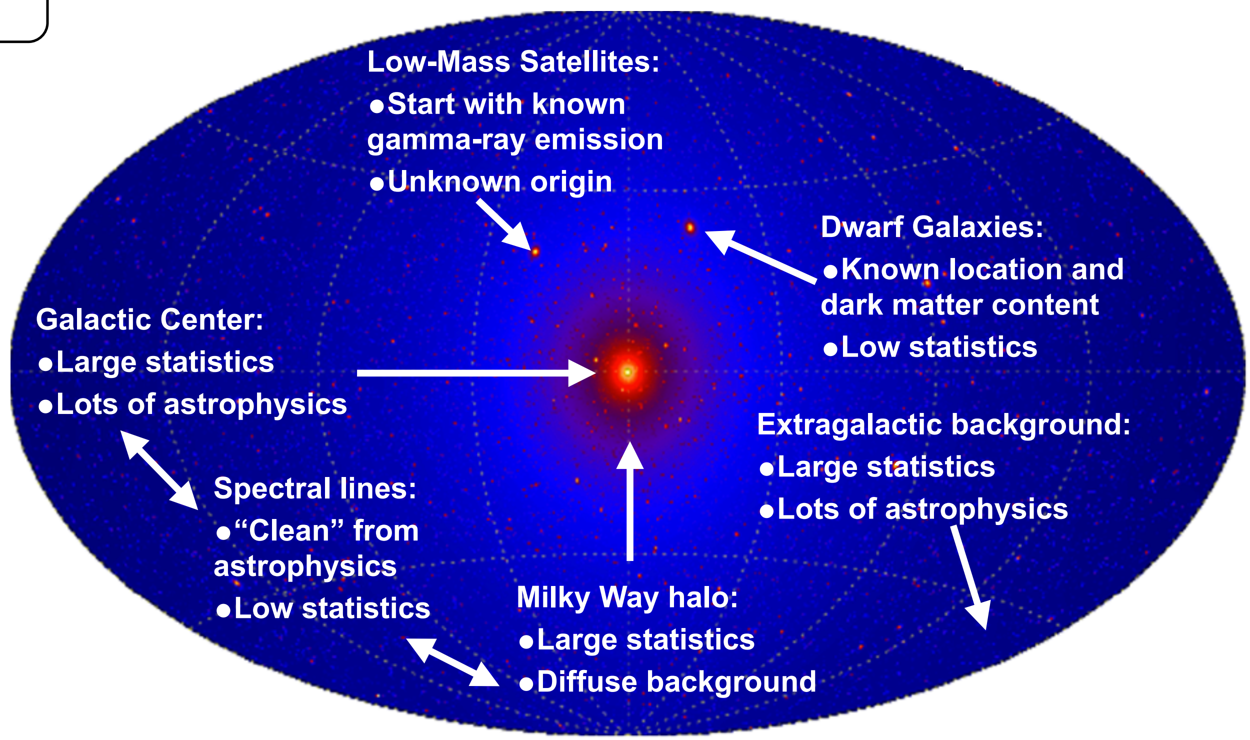
Fermi All-sky search strategies

Particle Dark Matter detectable from all astrophysical sources!

<u>Interesting dark matter sources</u>

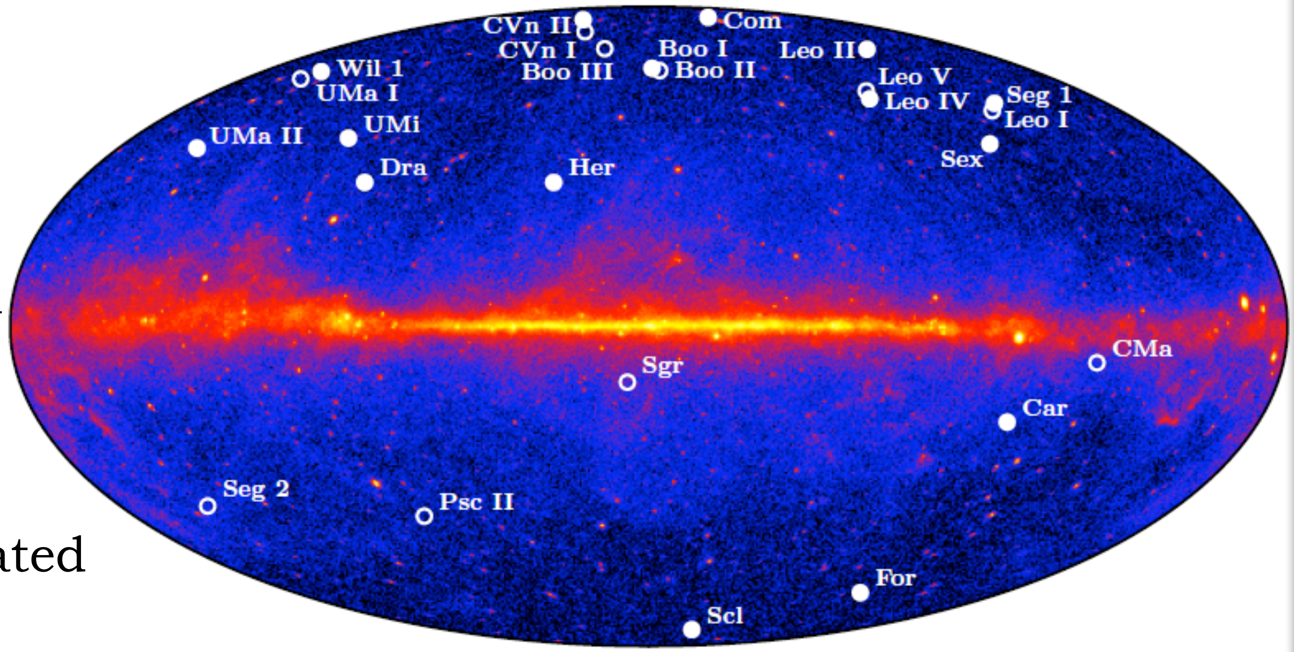
- **<u>Galactic center</u>**
- **<u>Satellite galaxies</u>**
- **<u>Galaxy clusters</u>**

Dark matter/gamma-ray map



Milky Way satellite galaxies (dwarf spheroidals)

- Interesting astrophysical systems!
- Dark matter masses from motions of individual stars
- Most dark matter-dominated galaxies known

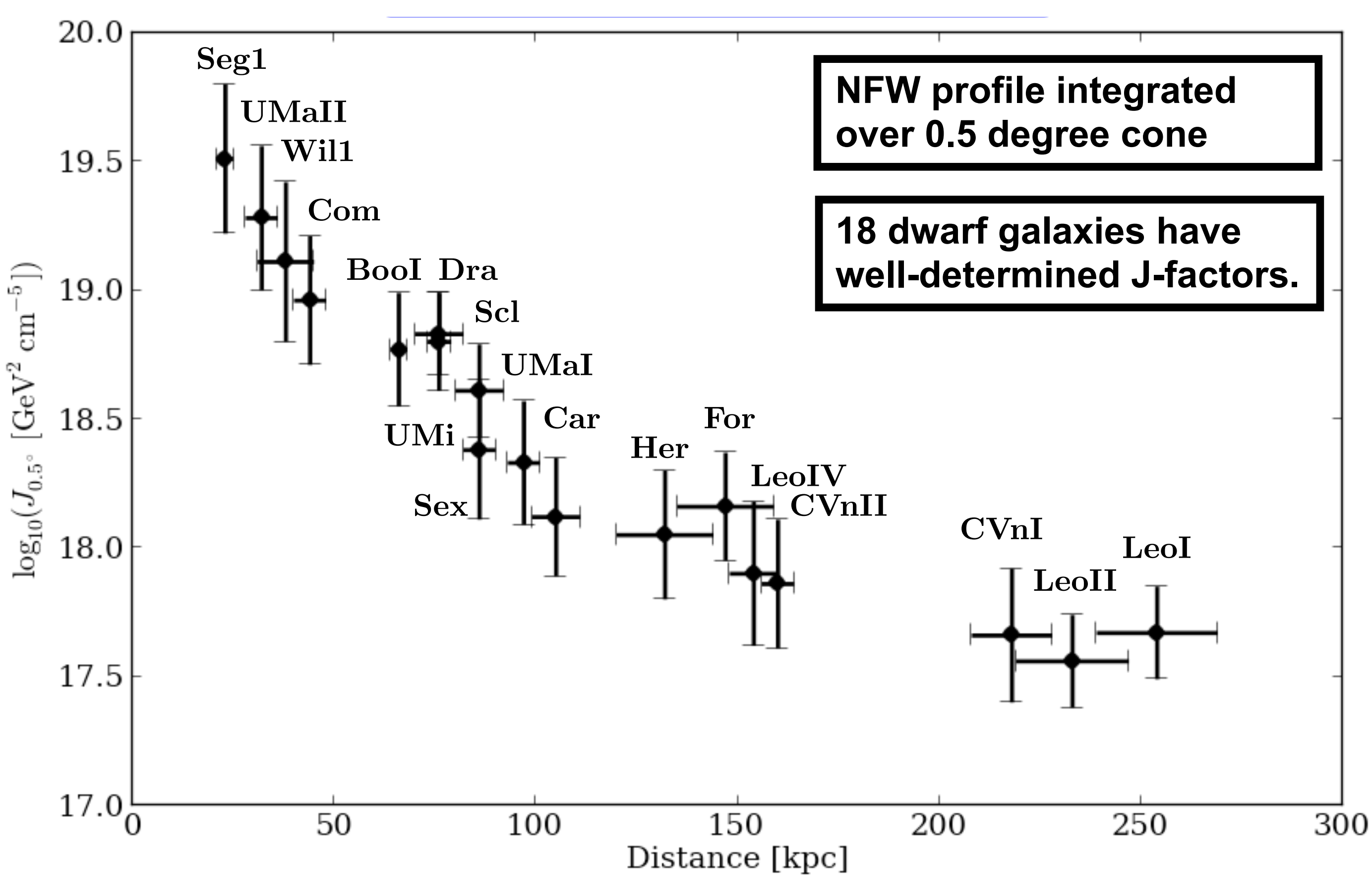


- Luminosities from hundreds to millions Solar luminosities
- No high energy gamma-rays from astrophysical sources

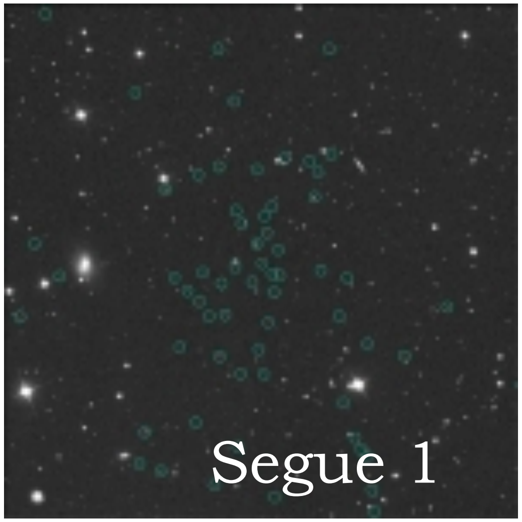
Measured dark matter distributions

$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\int_{E_{\rm min}}^{E_{\rm max}}\frac{dN_\gamma}{dE_\gamma}dE_\gamma}_{\Phi_{\rm PP}} \times \underbrace{\int_{\Delta\Omega}\left\{\int_{\rm l.o.s.}\rho^2(\boldsymbol{r})dl\right\}d\Omega'}_{\text{J-factor}}$$

Methodology from Strigari et al. 2007, 2008; Martinez 2013; Geringer-Sameth et al. 2014

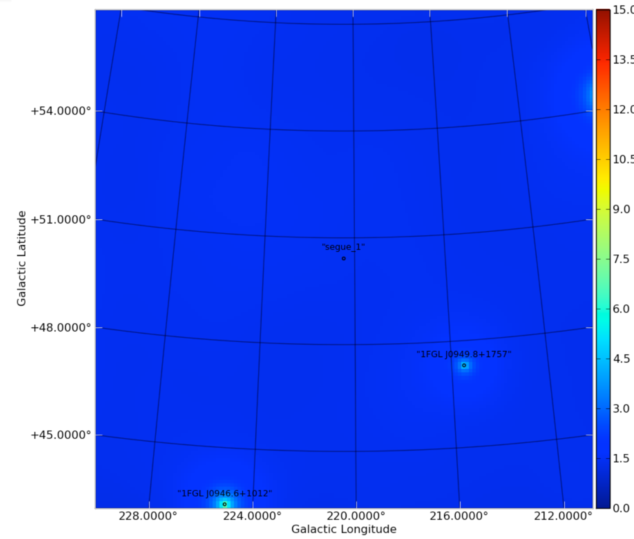


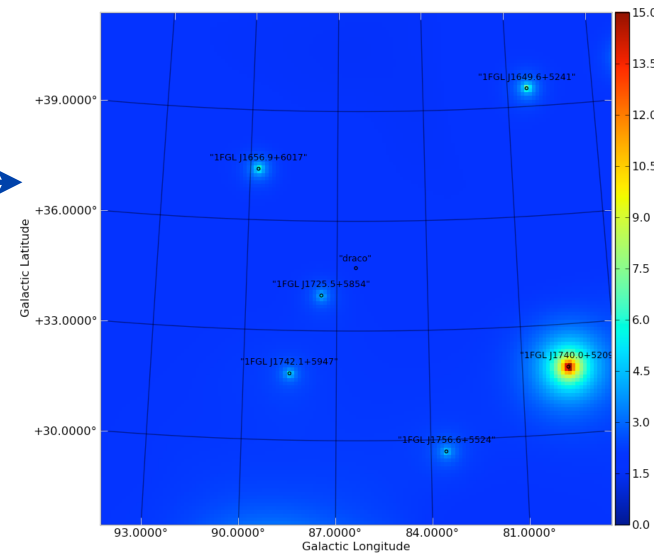
Satellite galaxies in visible light and gamma-rays



Visible Light

Gamma-rays

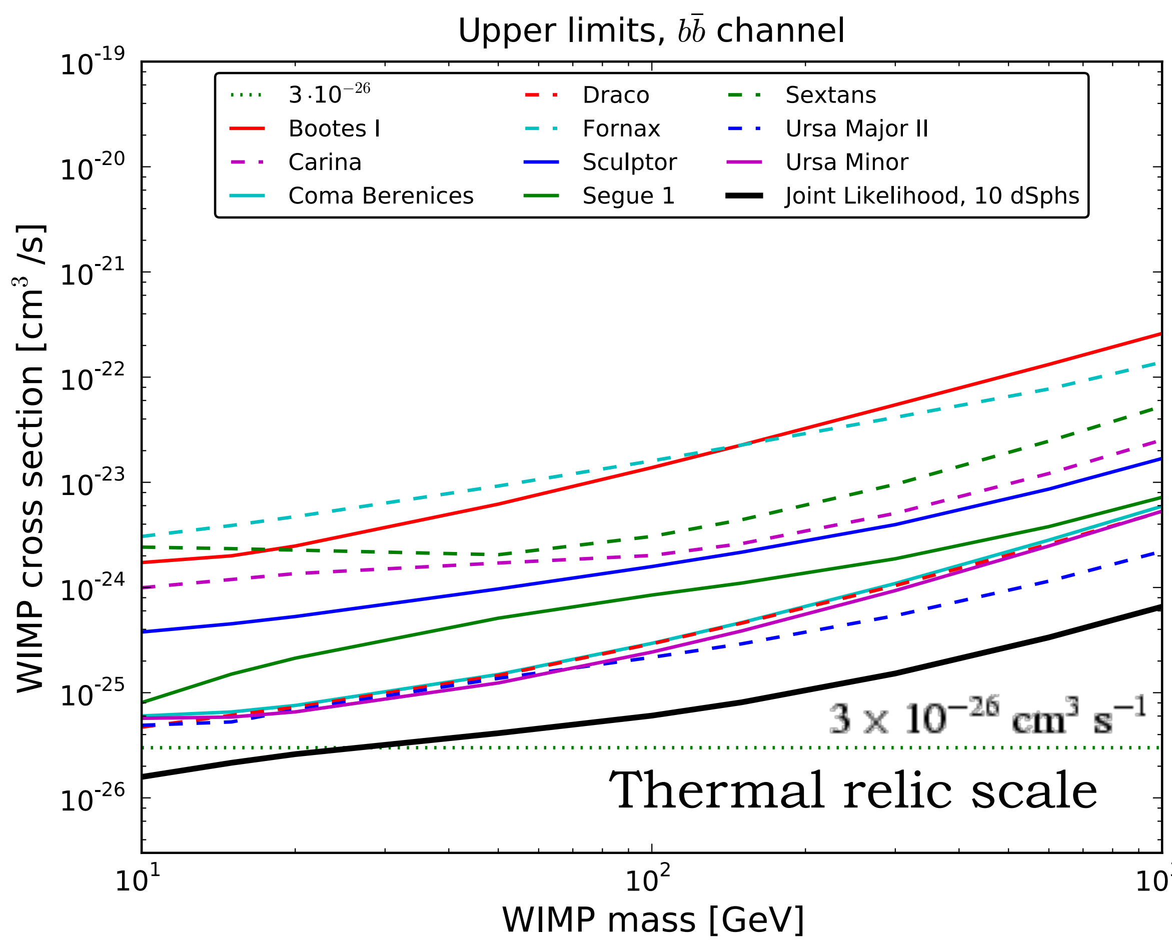




Dark matter bounds from Fermi-LAT

- ✦ Determine the total mass of dark matter from velocities of stars in each satellite

- ✦ Combine measured gamma-ray flux upper bound with total dark matter mass in each satellite to get upper bound on annihilation cross section



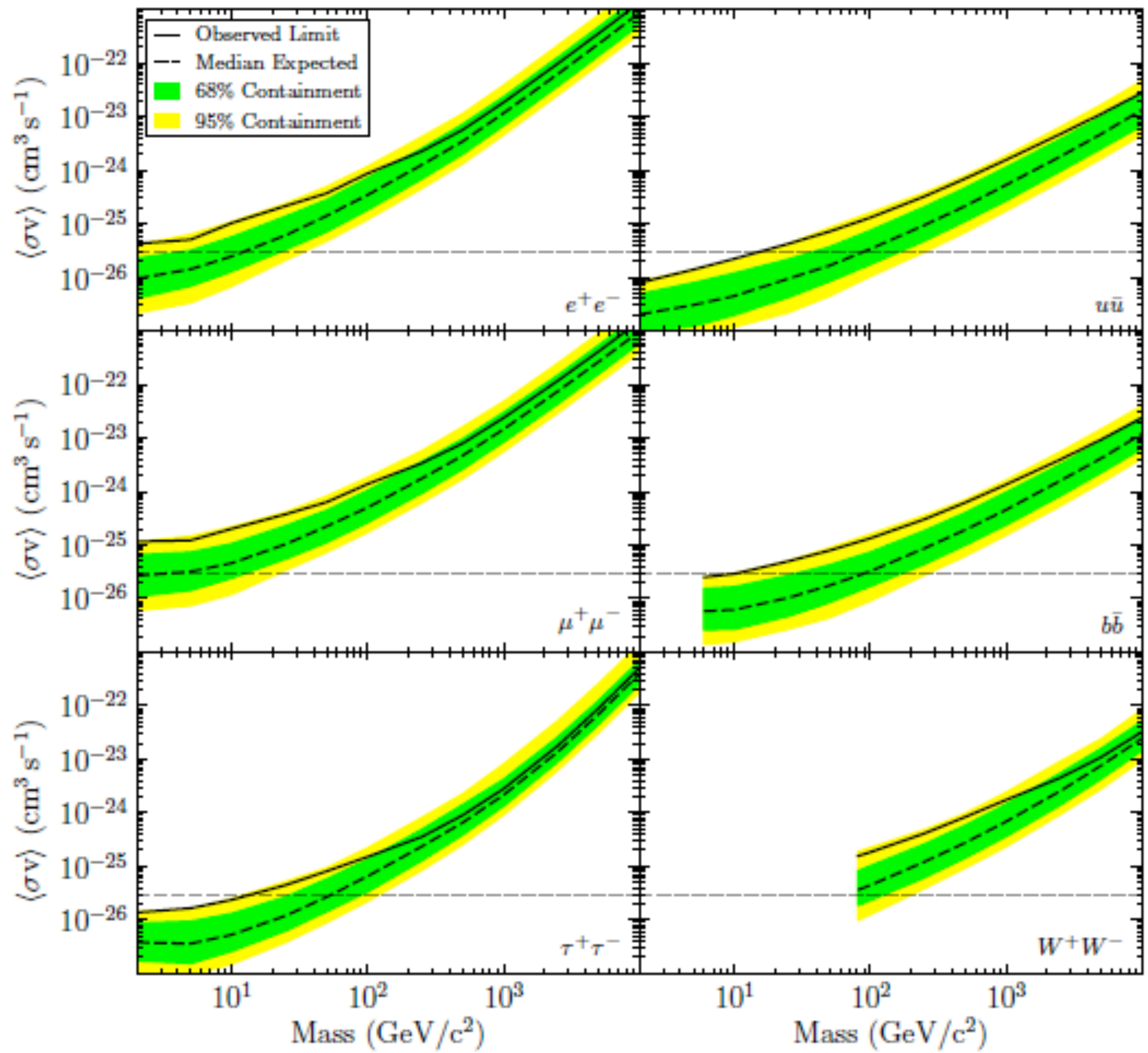
Fermi-LAT collaboration
PRL, arXiv:1108.3546

Dark matter bounds from Fermi-LAT: New results

- Determine the total mass of dark matter from velocities of stars in each satellite

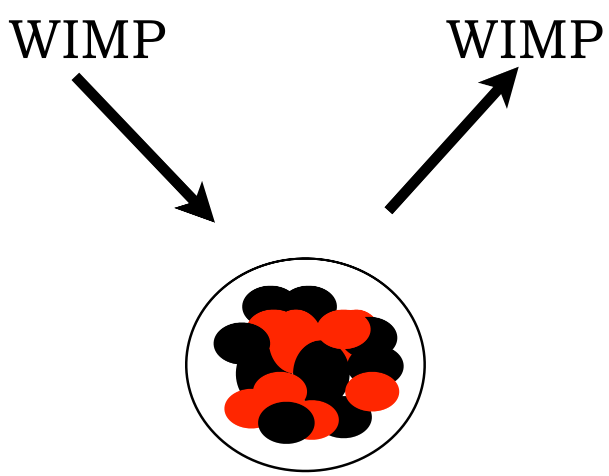
- Combine measured gamma-ray flux upper bound with total dark matter mass in each satellite to get upper bound on annihilation cross section

Fermi-LAT collaboration
arXiv:1310.0828 (PRD 2014)



Astrophysical interplay with
Direct dark matter detection

Direct dark matter searches: Basics



Goodman & Witten 1984, Ellis & Flores 1988, Engel 1991

$$\left.\frac{dR}{dQ}\right|_{Q} = \frac{\rho_0 \sigma_0}{2\mu^2 m_{\rm dm}} A^2 \, |F(Q)|^2 \int_{v_{\rm min}(Q)} d^3 v \, \frac{f(\mathbf{v}+\mathbf{v}_e)}{v}$$

- *Spin-Independent:* Cross section scales as the mass number of nucleus.

- *Spin-dependent:* Cross section depends on angular momentum

Two key `astrophysical' questions:

- How much DM in your coffee cup?
- How fast is it moving in there?

Standard Halo Model

- Of course we can only measure the velocities of stars
- Traditional to assume ``Standard Halo Model" (e.g. Lewin & Smith)

$$f(\vec{v}) = \begin{cases} \frac{1}{N_{\rm esc}(2\pi\sigma_v^2)^{3/2}} \exp\left[-\frac{(\vec{v}+\vec{V}_{\rm lab})^2}{2\sigma_v^2}\right] & \text{if } |\vec{v}+\vec{V}_{\rm lab}| < \mathrm{V_{esc}} \\ 0 & \text{if } |\vec{v}+\vec{V}_{\rm lab}| \geq \mathrm{V_{esc}} \end{cases}$$

- Two issues with this assumption:

1. Does not analytically correspond to an NFW/Einasto profile
2. Several dark matter-only simulations find different distributions

- Differences are very significant for interpretation of low mass WIMP results

Alternative phenomenological parameterizations

- General issues: Analytically difficult to connect velocity distribution to density profile.

- Typically have to make simplifying assumptions (velocity distribution is isotropic and spherically-symmetric)

- Tsallis model (Hansen & Moore New Astronomy 2004, arXiv:0411473):

$$f(\boldsymbol{v}) = \begin{cases} \frac{1}{N}\left[1-(1-q)\,\frac{\boldsymbol{v}^2}{v_0^2}\right]^{1/(1-q)}, & |\boldsymbol{v}| < v_{\rm esc} \\ 0, & |\boldsymbol{v}| \geq v_{\rm esc} \end{cases}$$

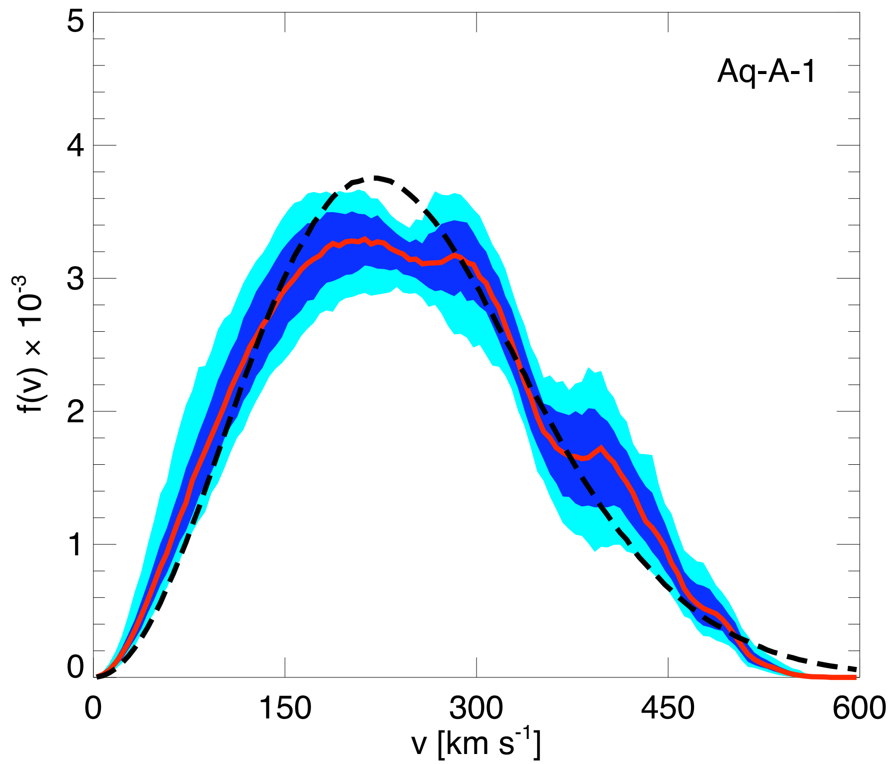
- Anisotropic model (Fairbairn & Schwetz JCAP2009, arXiv:0808.0704):

$$f(\boldsymbol{v}) = \begin{cases} \frac{1}{N}\left[\exp\left(-(v_r^2/\overline{v}_r^2)^{\alpha_r}\right)\exp\left(-(v_t^2/\overline{v}_t^2)^{\alpha_t}\right)\right], & |\boldsymbol{v}| < v_{\rm esc} \\ 0, & |\boldsymbol{v}| \geq v_{\rm esc} \end{cases}$$

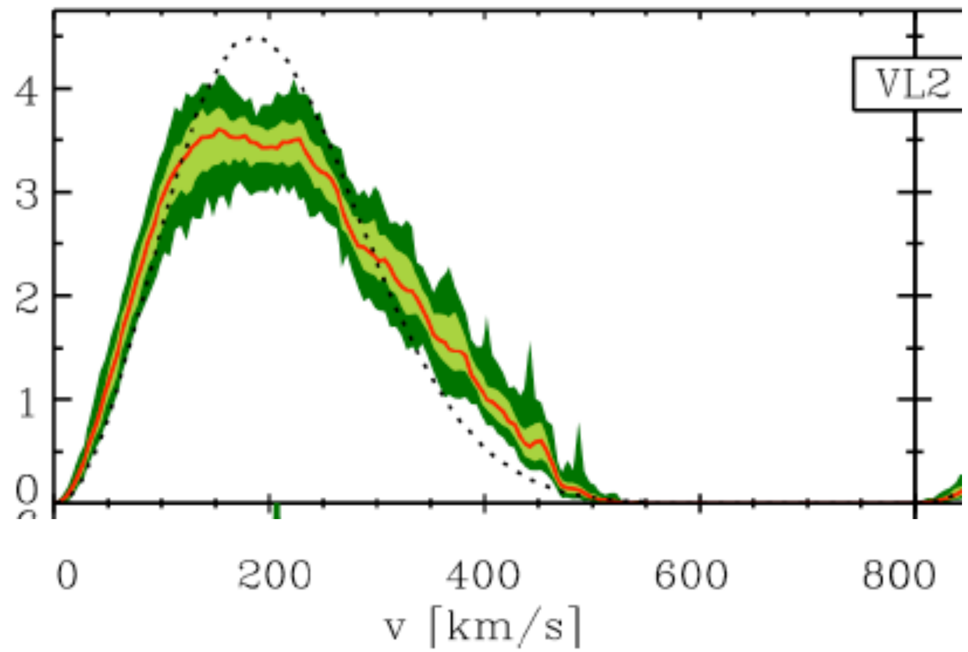
- Double power law model (Listanti, LS et al. PRD 2011, arXiv:1010.4300):

$$f(\boldsymbol{v}) = \begin{cases} \frac{1}{N}\left[\exp\left(\frac{v_{\rm esc}^2-v^2}{kv_0^2}\right)-1\right]^k, & |\boldsymbol{v}| < v_{\rm esc} \\ 0, & |\boldsymbol{v}| \geq v_{\rm esc} \end{cases}$$

Results from simulations. I

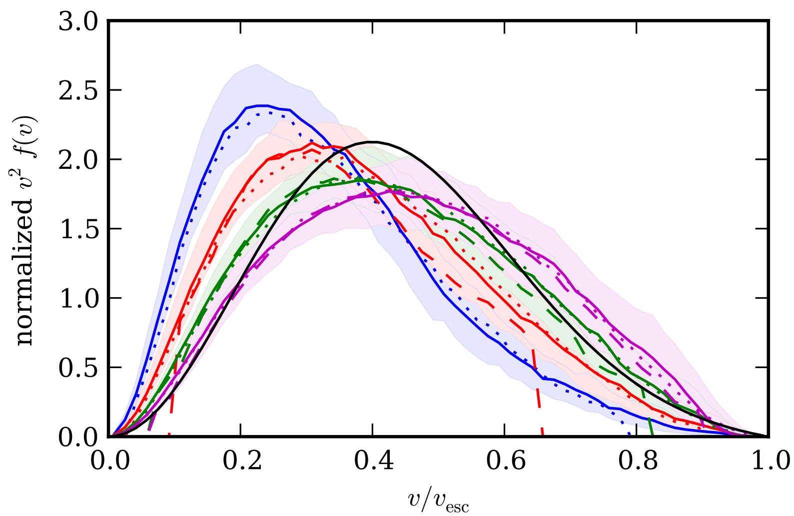


Vogelsberger et al., MNRAS 2009,
arXiv:0812.0362

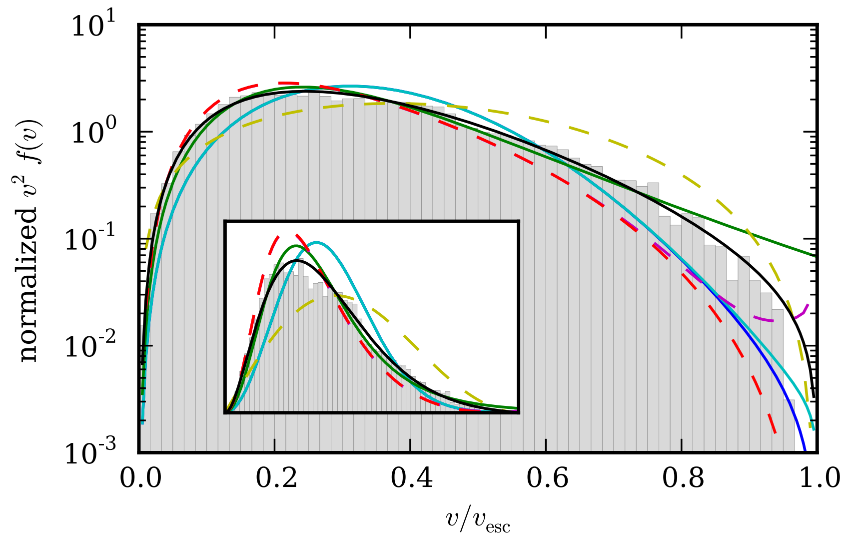


Kuhlen et al., JCAP 2009,
arXiv:0912.2358

Results from simulations. II



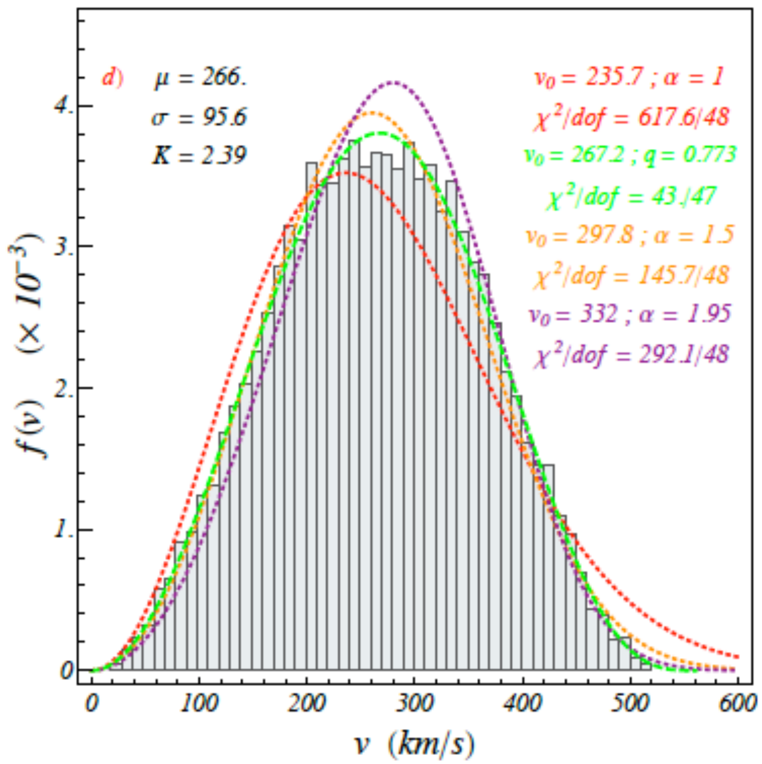
colored curves for different r/rs



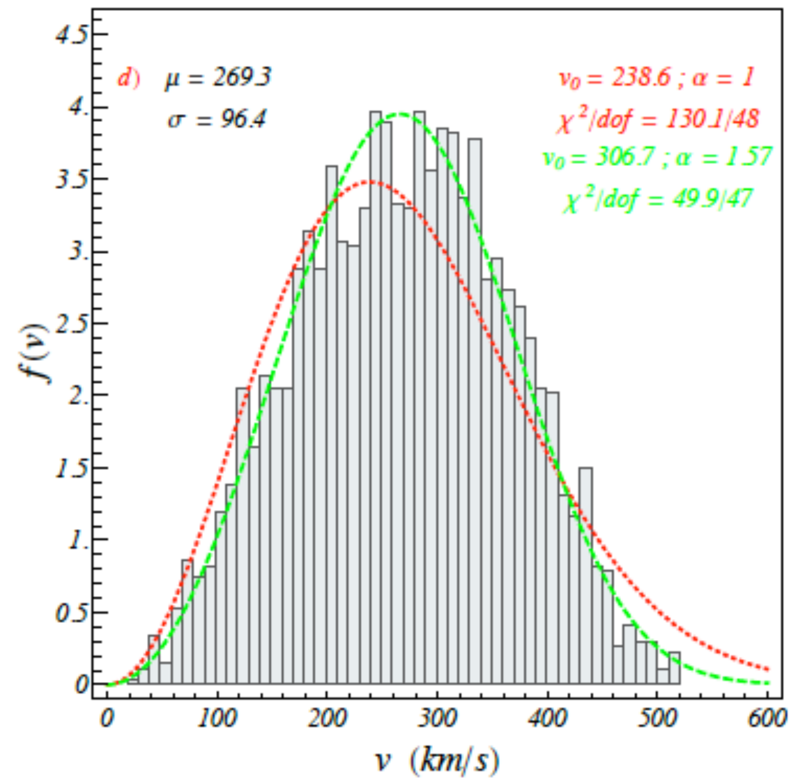
Mao et al., ApJ 2013, arXiv:1210.2721

- ``Cosmological” VDF: fewer particles in the tail of the distribution, smooth fall-off to the escape velocity (e.g. Vogelsberger et al. 2009; Ling et al. 2009; Kuhlen et al. 2010; Lisanti, LS, Wacker, Wechsler 2011; Mao et al ApJ 2013; Mao et al 2013)

Results from simulations: Baryons



thin shell, 7-9 kpc (16k particles)



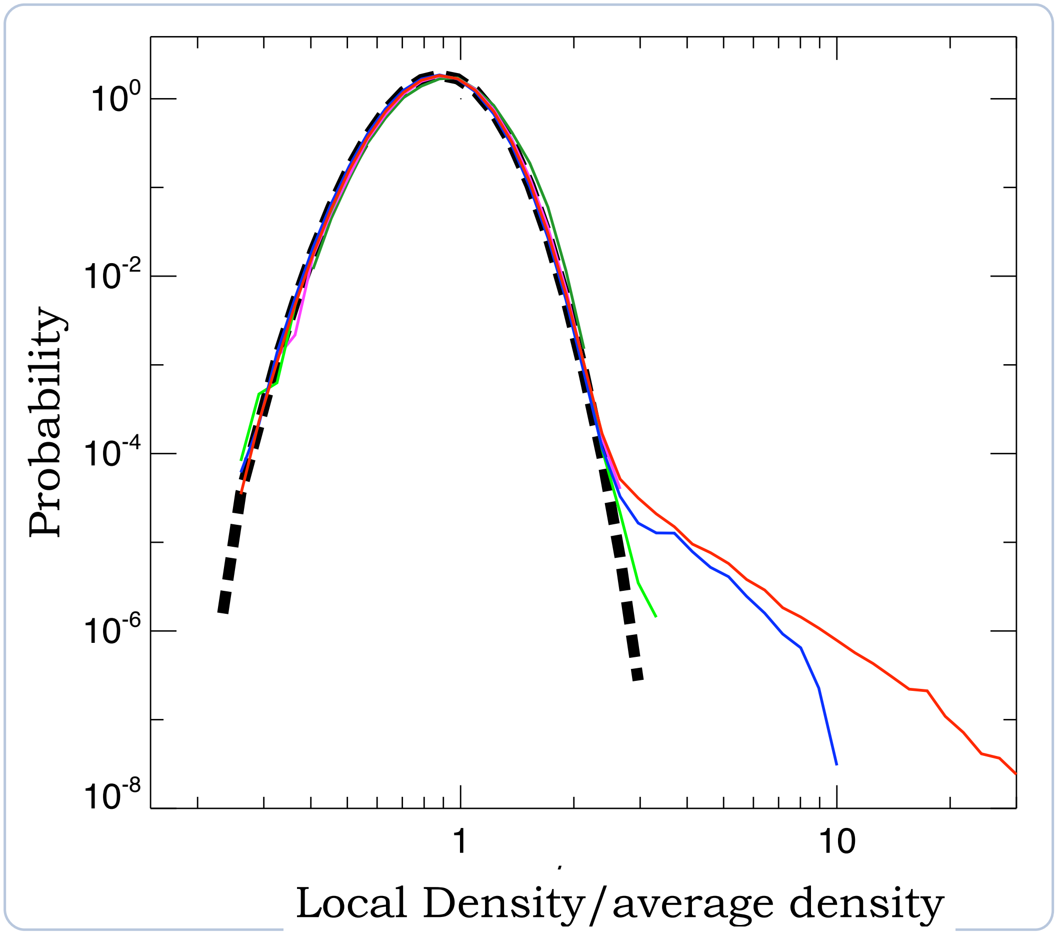
thin ring, 7-9 kpc (2k particles)

dark matter, stars, and gas components

Ling et al., JCAP 2010, arXiv:0909.2028

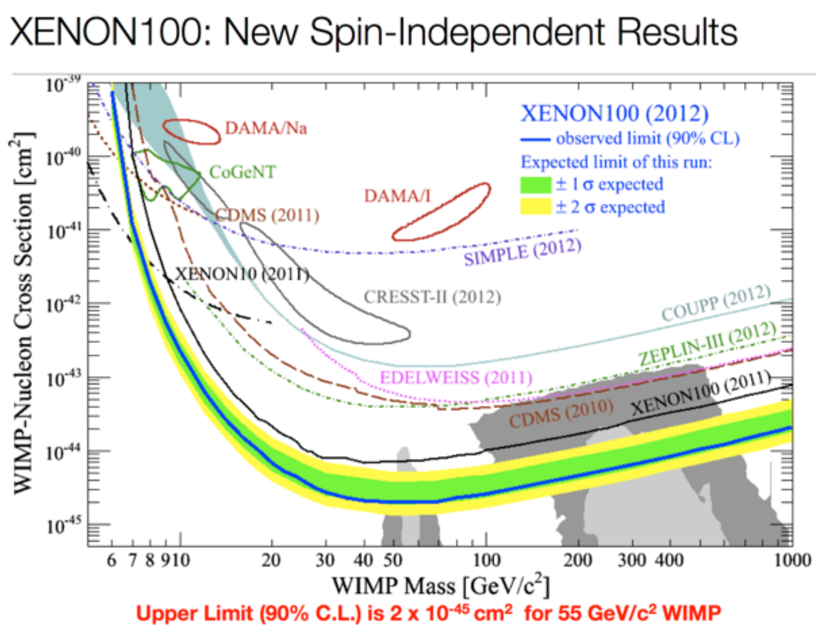
Clumps in the local DM distribution?

- Neutralino WIMP: Minimum mass sub-halo about the Earth mass
- Are we sitting in a local overdensity (or a local bubble)?
- Probably direct detection experiments sensitive to the ‘smooth’ distribution of dark matter

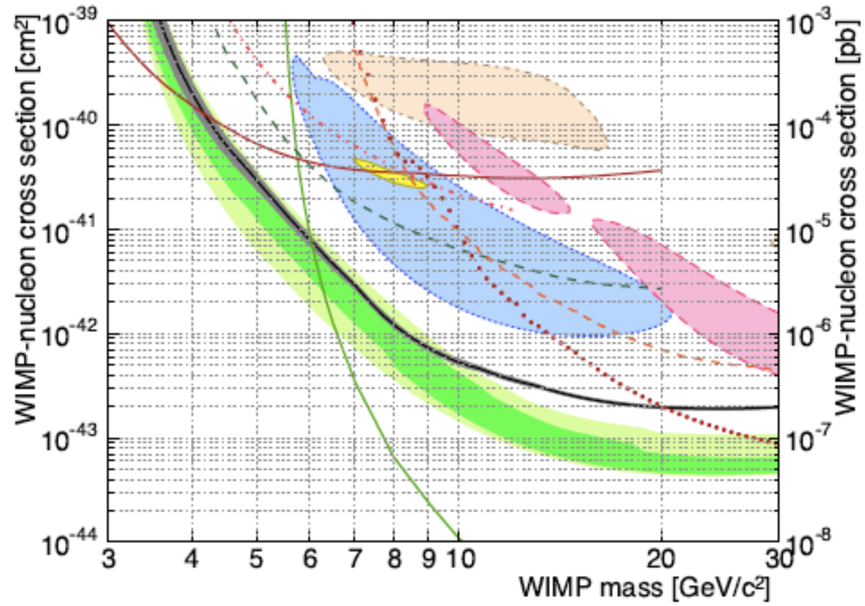


Koushiappas & Kamionkowski 2008; Vogelsberger et al 2009

Plethora of experimental results



SuperCDMS



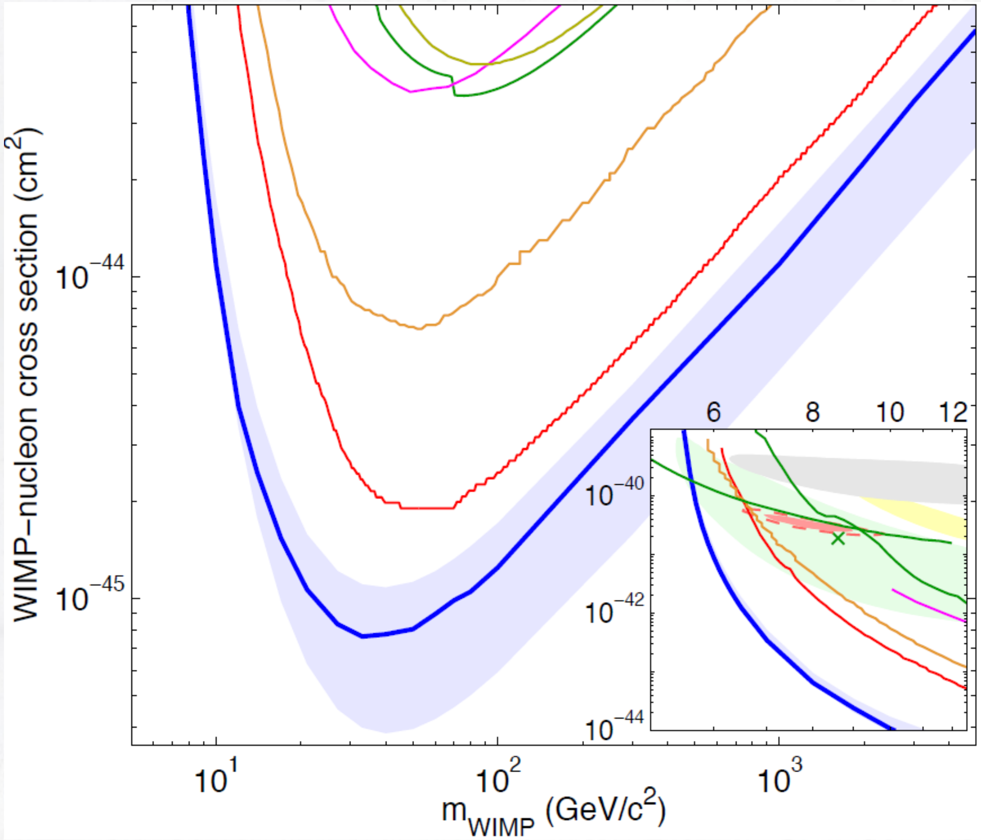
- DAMA, CoGENT, and CDMS-II report events not accounted for by known backgrounds

- Possible ways to make results consistent:
  1) Experimental issues
  2) Particle model (e.g. Isospin-violating DM, e.g. Feng & Kumar 2008)
  3) Galactic halo model

LUX results

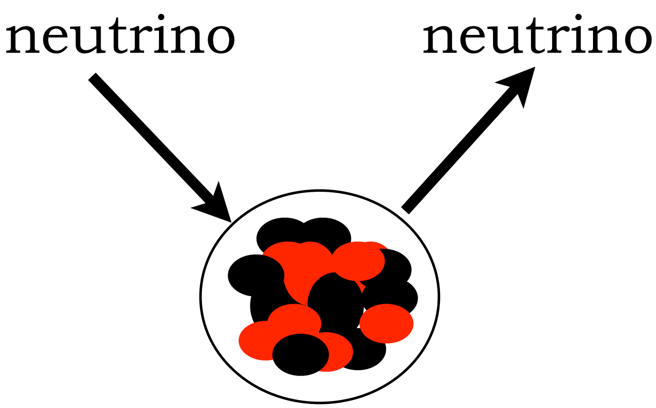
- LUX results compatible with background only
  - Appears to be no ``non-standard" particle or astrophysics

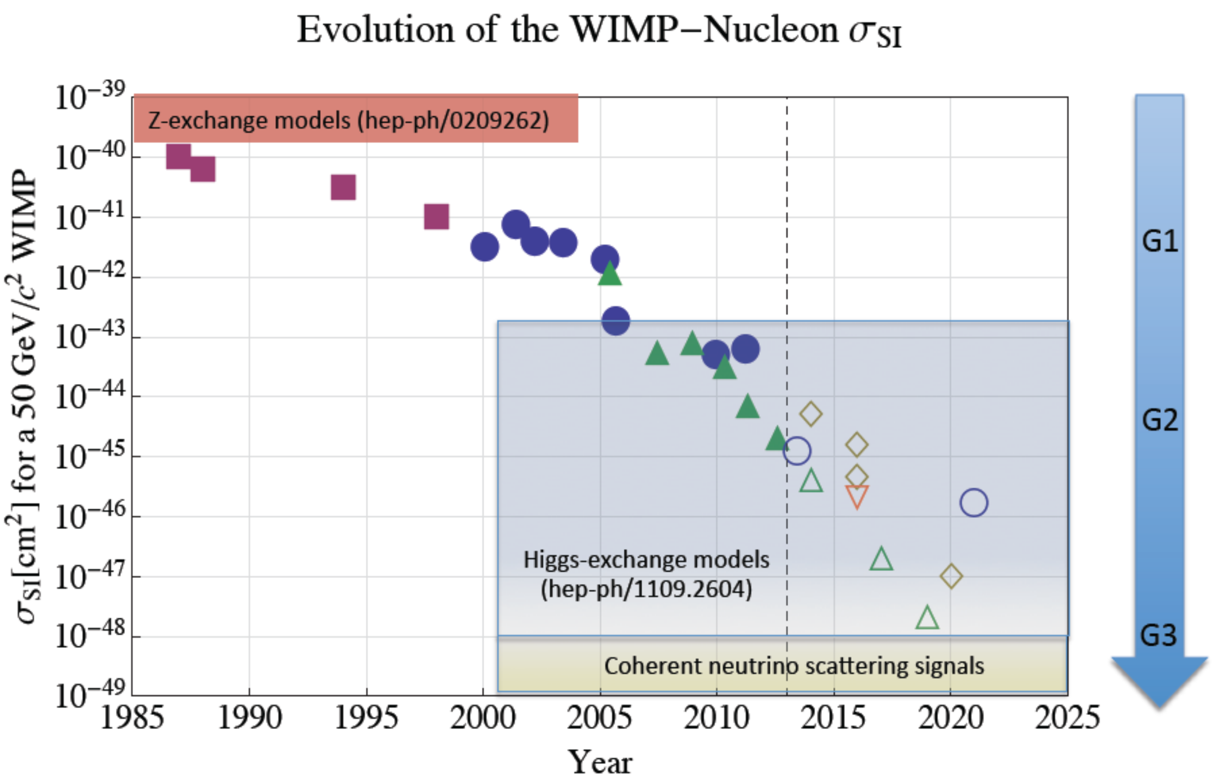
- As cross section limits improve, will become more difficult to disentangle particle physics from astrophysics.



Astrophysical backgrounds for direct dark matter searches

Zero background experiments?

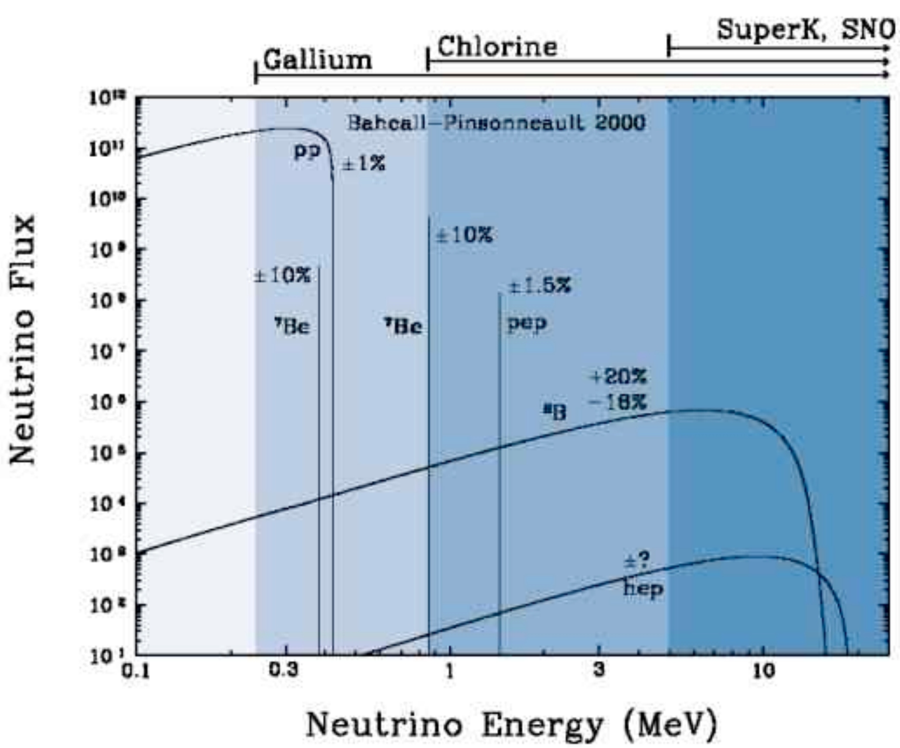




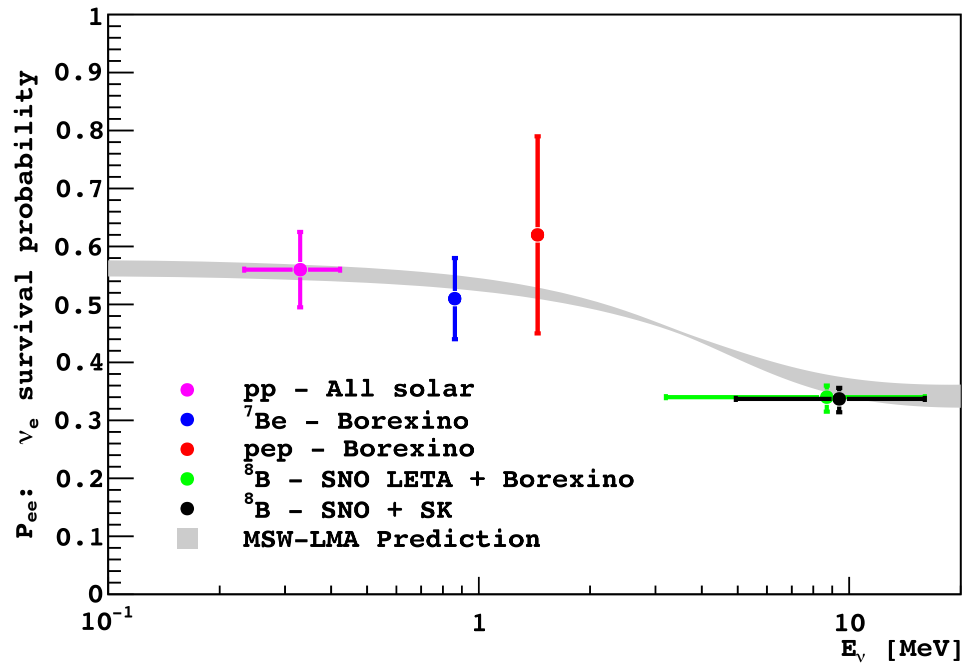
- *Coherent neutrino scattering will produce a signal similar to a WIMP*

Friedman 1974; Tubbs & Schramm 1977

Solar neutrinos



Electron neutrino survival probability



Atmospheric and supernova neutrinos

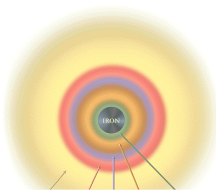
$$\pi^\pm \rightarrow \quad \mu^\pm \quad + \nu_\mu(\overline{\nu}_\mu)$$

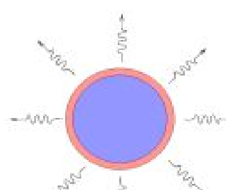
$$\searrow$$

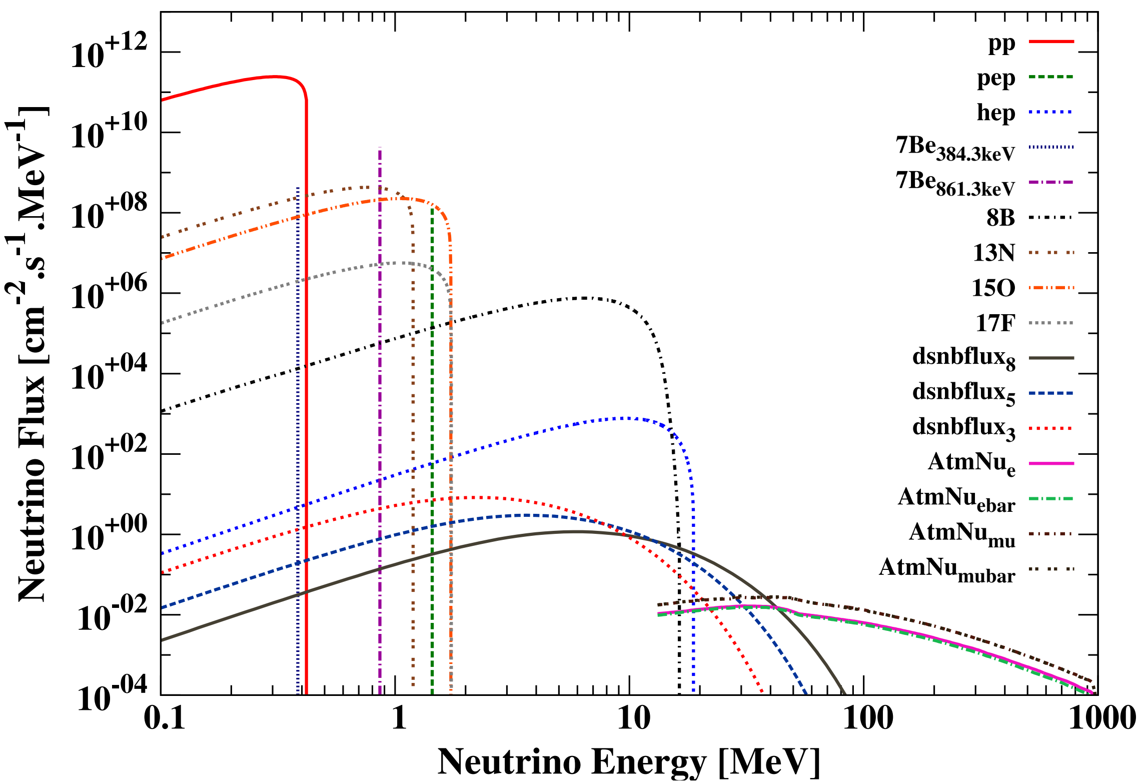
ATM Neutrinos

$$e^\pm + \nu_e(\overline{\nu}_e) + \overline{\nu}_\mu(\nu_\mu)$$

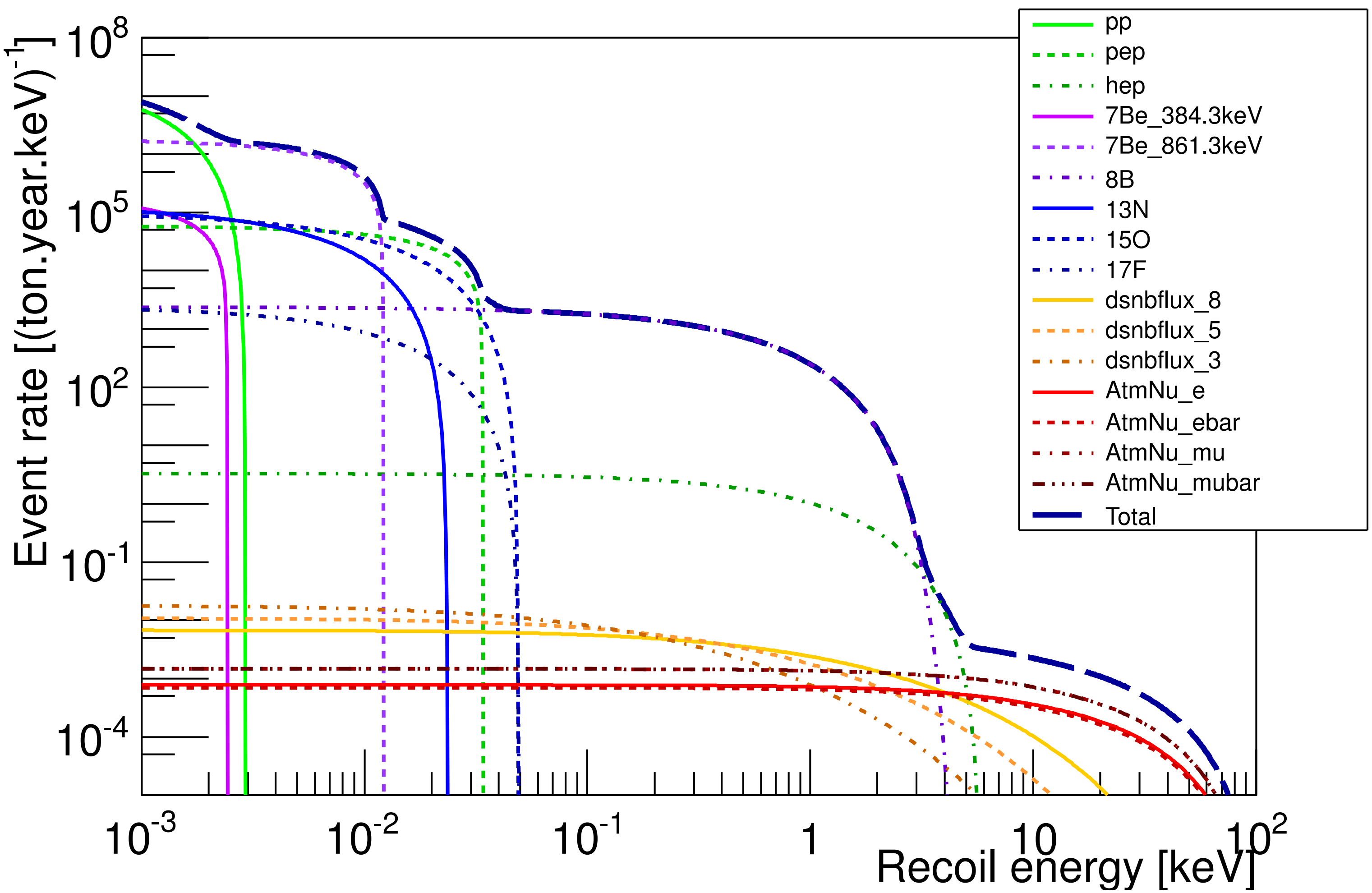
SN Neutrinos



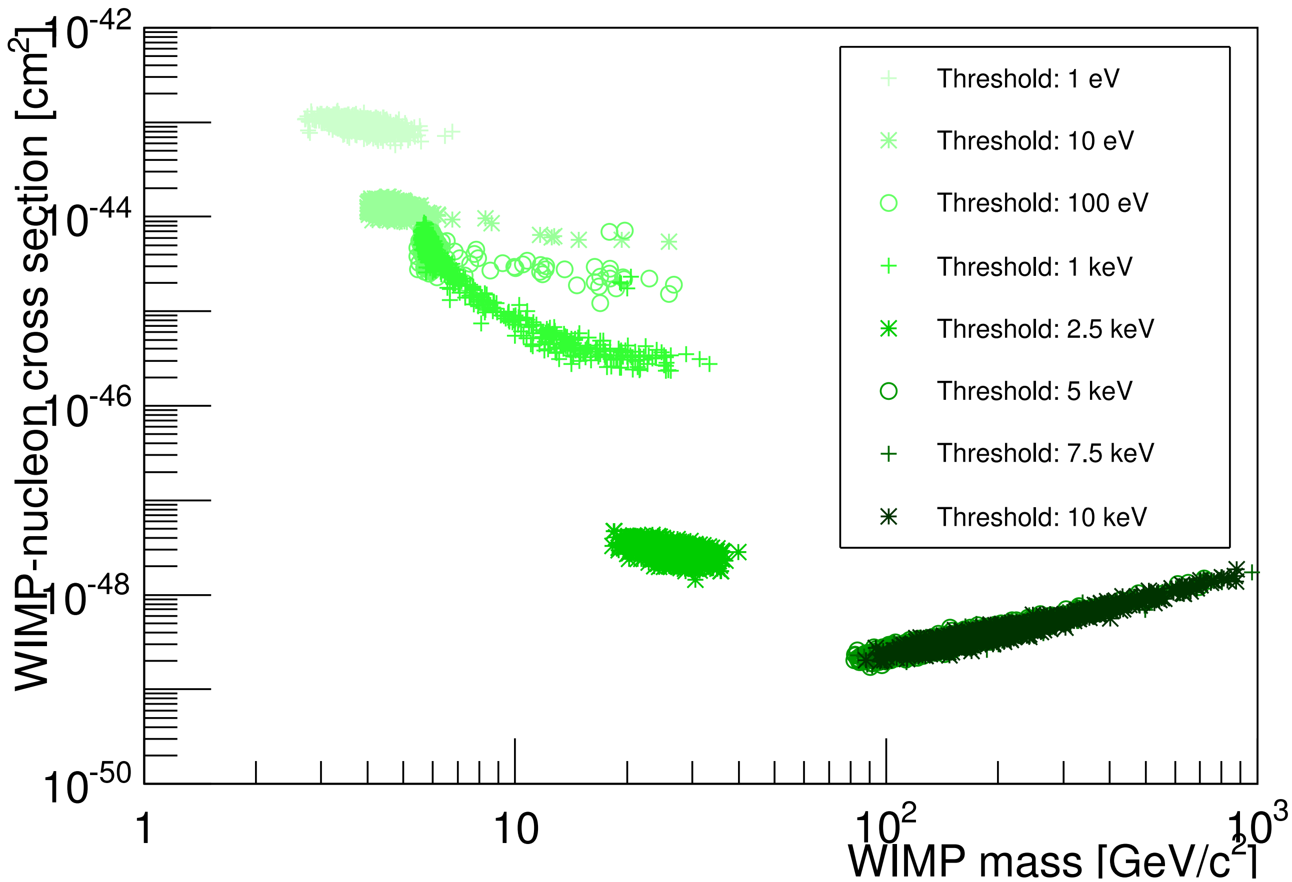




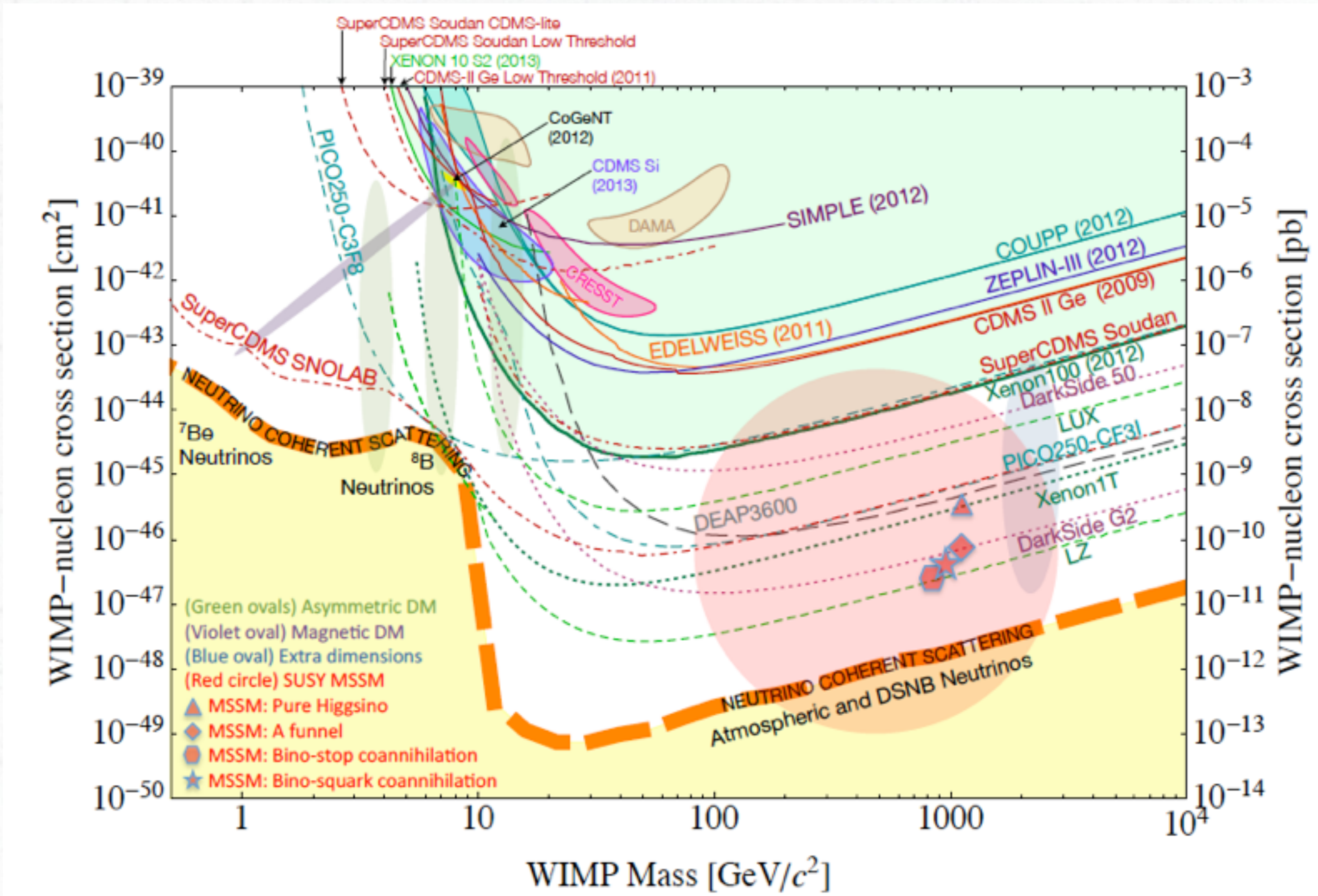
Event rates at high, low recoil energy



Fitting neutrino background to `WIMP only' hypothesis



End of (non directional) direct detection?



Billard, Strigari, Figueroa-Feliciano PRD 2014

Reducing background

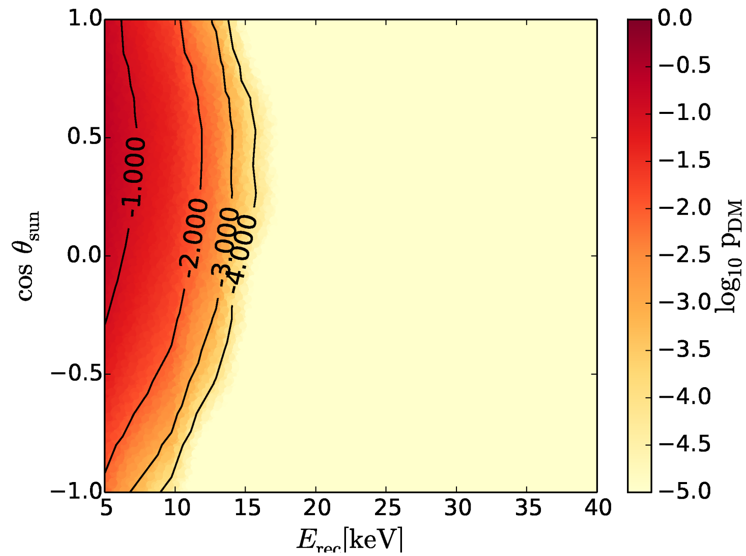
WIMP-nucleus scattering is isotropic in cos (theta)

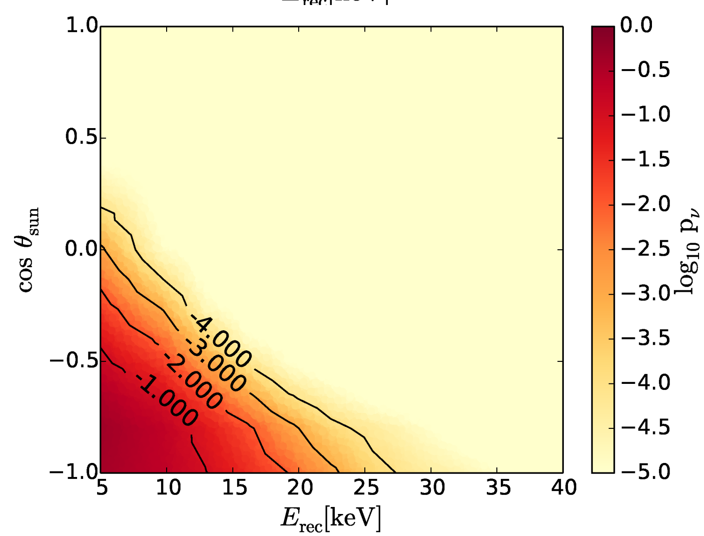
The angular dependence of the neutrino coherence cross section is:

$$\frac{d\sigma}{d(\cos\theta)} = \frac{G_F^2}{8\pi}\ Q_W^2\ E_\nu^2\ (1+\cos\theta)\ F(Q^2)^2$$

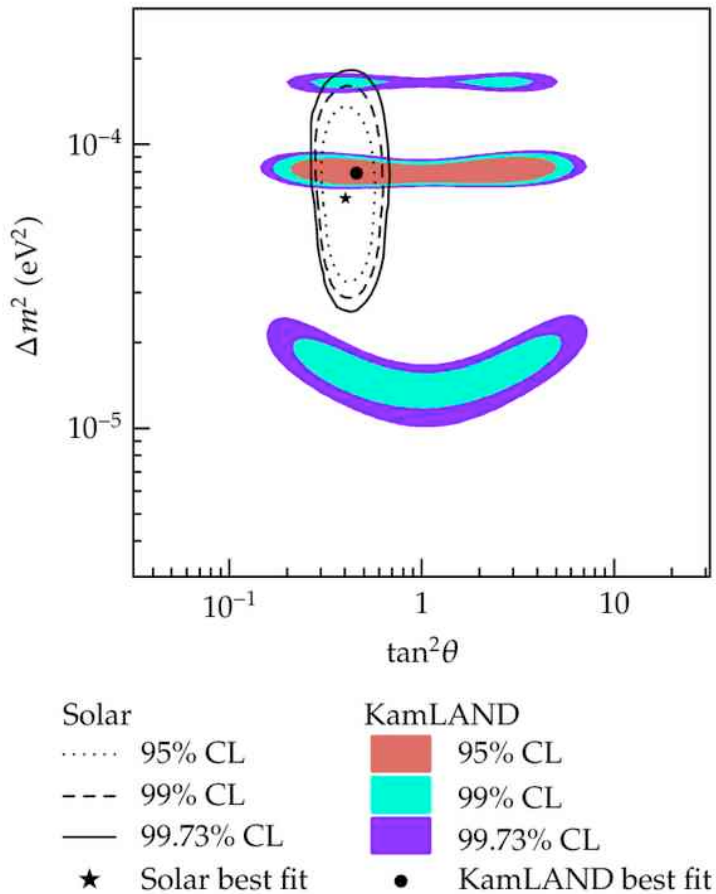
Solar neutrino events point back to the Sun

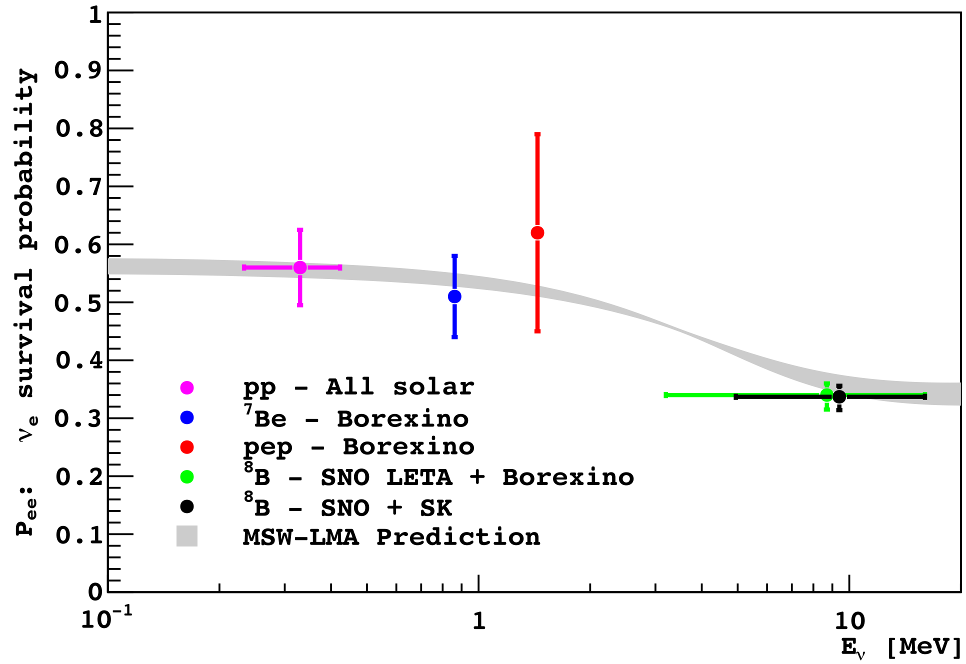
Grothaus et al. 2014





Solar neutrinos: Redux





Solar neutrinos: Outstanding issues

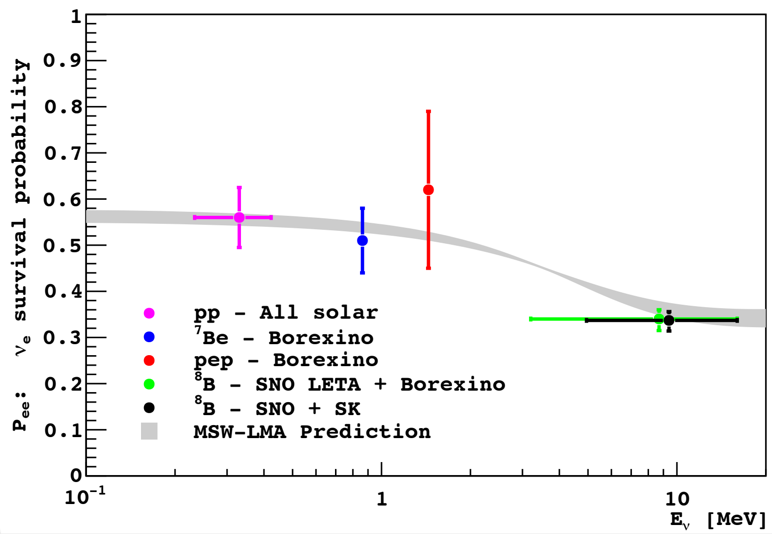
1. Solar Metallicity problem

New 3D rotational hydrodynamical simulations suggest lower metallicity in Solar core [Asplund et al. 2009]

However the low metallicity appears in conflict with both helioseismology data (aslo possible Solar neutrino data)

2. Intermediate energy survival probability

SK, Borexino, SNO CC data seem to not indicate an 'upturn' in the electron neutrino survival probability



Standard Solar Model predictions

ν flux	E_ν^{max} (MeV)	GS98-SFII	AGSS09-SFII	Solar	units
$p+p \to {}^2H+e^+ + \nu$	0.42	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.006)$	$6.05(1^{+0.003}_{-0.011})$	$10^{10}/cm^2s$
$p+e^- + p \to {}^2H+\nu$	1.44	$1.44(1 \pm 0.012)$	$1.47(1 \pm 0.012)$	$1.46(1^{+0.010}_{-0.014})$	$10^8/cm^2s$
${}^7Be+e^- \to {}^7Li+\nu$	0.86 (90%)	$5.00(1 \pm 0.07)$	$4.56(1 \pm 0.07)$	$4.82(1^{+0.05}_{-0.04})$	$10^9/cm^2s$
	0.38 (10%)				
${}^8B \to {}^8Be+e^+ + \nu$	~ 15	$5.58(1 \pm 0.14)$	$4.59(1 \pm 0.14)$	$5.00(1 \pm 0.03)$	$10^6/cm^2s$
${}^3He+p \to {}^4He+e^+ + \nu$	18.77	$8.04(1 \pm 0.30)$	$8.31(1 \pm 0.30)$	—	$10^3/cm^2s$
${}^{13}N \to {}^{13}C+e^+ + \nu$	1.20	$2.96(1 \pm 0.14)$	$2.17(1 \pm 0.14)$	≤ 6.7	$10^8/cm^2s$
${}^{15}O \to {}^{15}N+e^+ + \nu$	1.73	$2.23(1 \pm 0.15)$	$1.56(1 \pm 0.15)$	≤ 3.2	$10^8/cm^2s$
${}^{17}F \to {}^{17}0+e^+ + \nu$	1.74	$5.52(1 \pm 0.17)$	$3.40(1 \pm 0.16)$	$\leq 59.$	$10^6/cm^2s$
χ^2/P^{agr}		3.5/90%	3.4/90%		

Haxton et al Solar neutrino review, 2013

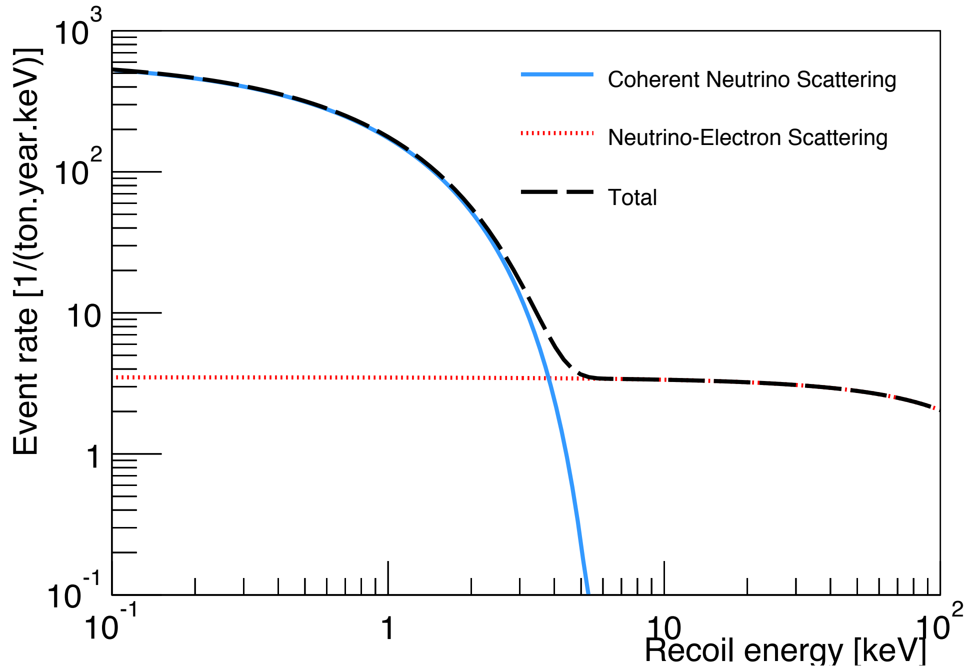
SNO NC measurement (5.25 x 10^6) right in between predictions of low and high metallicity SSMs

Appealing to dark matter detectors

- Coherent neutrino scattering substantially improves the measurement on the 8B flux, to a few percent or less

- Substantial improvement from 1 to 10 ton for Ge and Xe detectors

- Elastic scattering data from pp neutrinos an important contribution

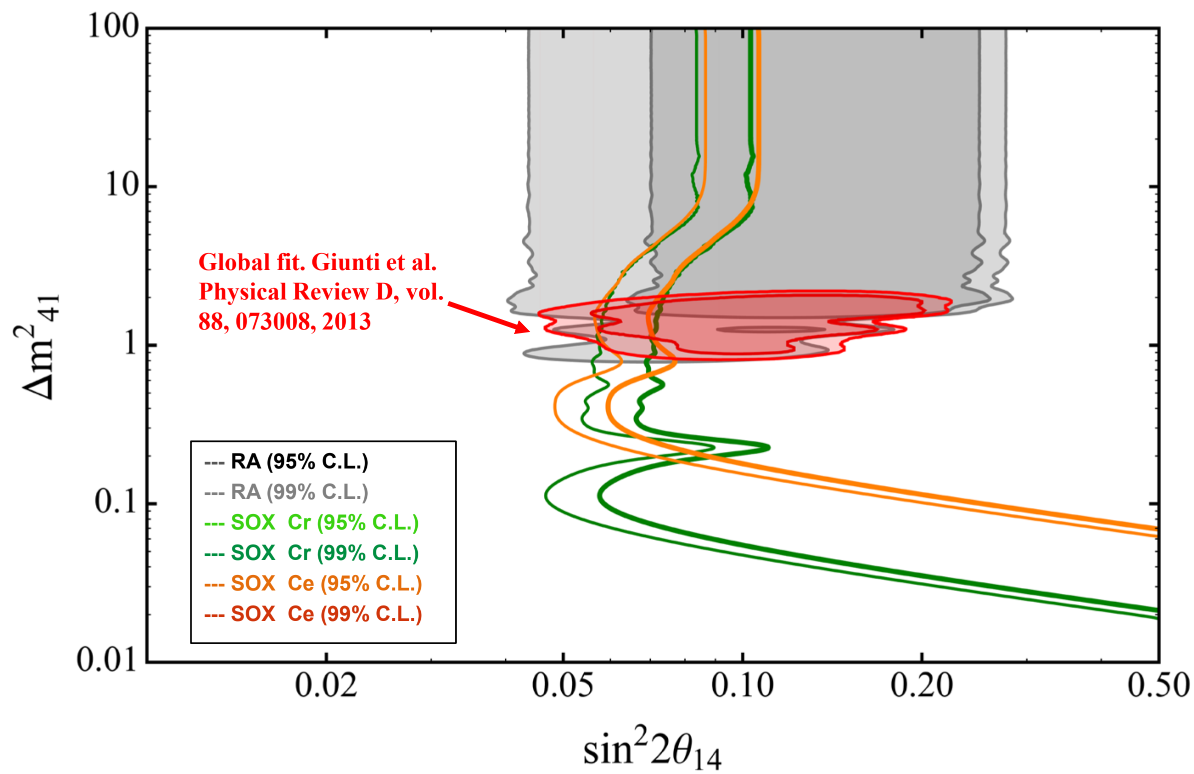


Appealing to dark matter detectors

- Hints at ~ eV mass sterile neutrinos from several terrestrial experiments: Gallium, reactor anomaly.

- Also, possible evidence from cosmology

- DM direct detection experiments that combine nuclear recoils through coherent scattering and electron recoils through elastic scattering will better probe sterile neutrino parameter space



Final remarks

- What if anything are astronomical measurements telling us about the nature of dark matter?
  - A multi-faceted question
- Can rule out extreme, simplified assumptions
  - Hot and some warm dark matter
- For many interesting candidates, we are in grey areas
  - Progress requires embrace of astronomical issues