Small Scales Redux

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PRIMORDIAL NUCLEOSYNTHESIS REDUX

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Received 1990 December 17; accepted 1991 January 17

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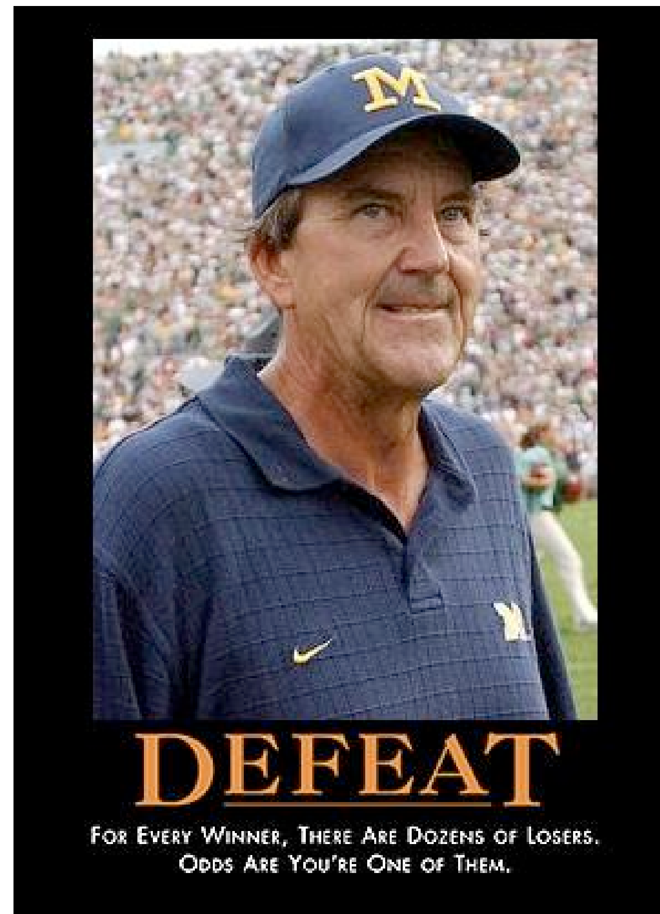
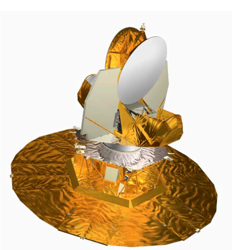


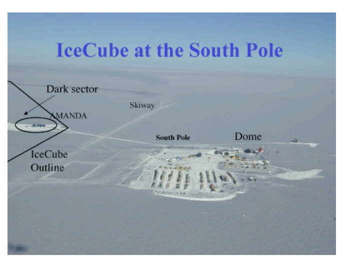
Our job: Understanding what the Universe is made up of

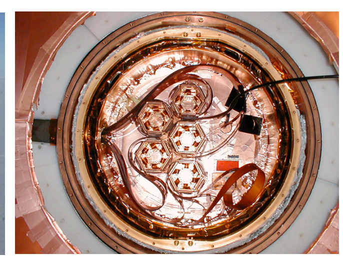
1. Data from different experimental techniques
2. Sophisticated theory and modelling
3. High-performance computing simulations
4. New and existing statistical and analysis tools

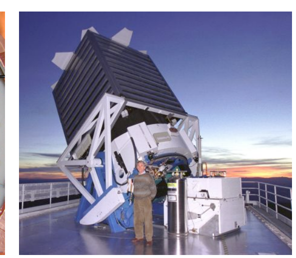
Particle colliders cannot discover the dark matter

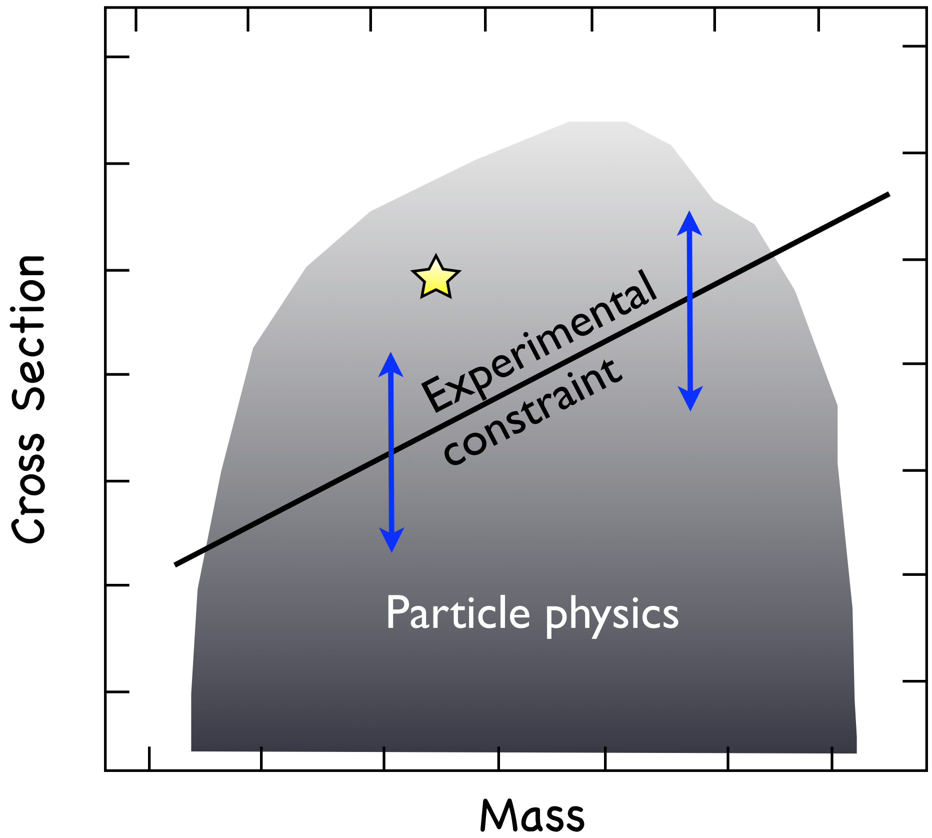
Astro experiments cannot discover new physics







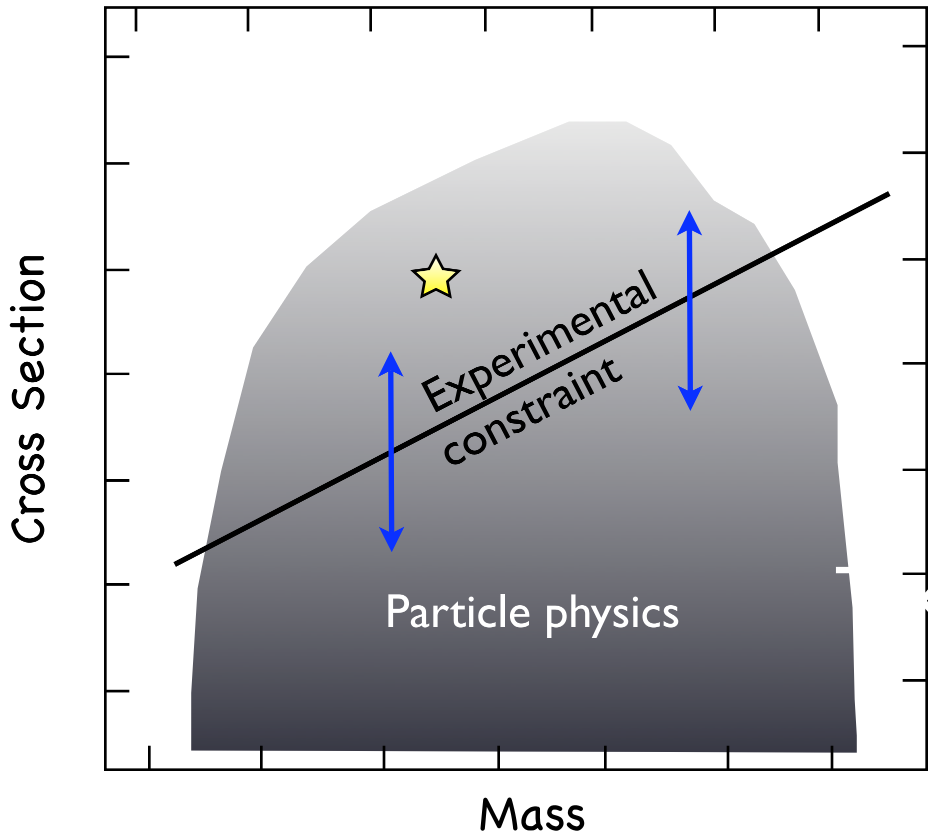




- Cold, Warm or Hot?
- Thermal or non-thermal?
- Easy or hard to detect?
- Expected or unexpected?

$$\text{Rate} = \text{Particle Physics} \times \text{Cosmology}$$

$$\text{Particle Physics} = \frac{\text{Rate}}{\text{Cosmology}}$$



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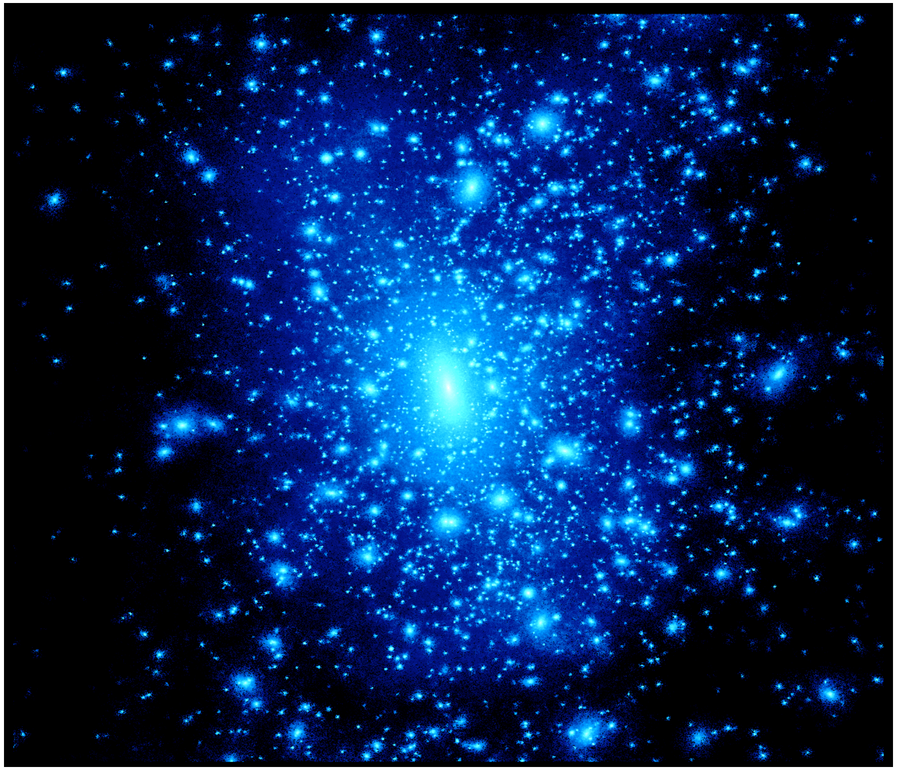
Joakim Edsjo's excellent talk from yesterday

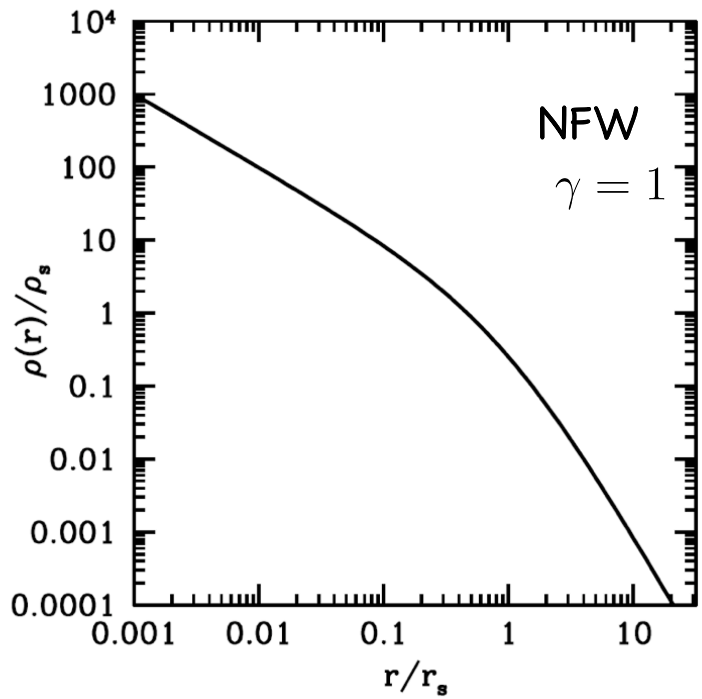
Rate = Particle Physics × Cosmology

$$\text{Particle Physics} = \frac{\text{Rate}}{\text{Cosmology}}$$

Substructure in dark matter halos and detection experiments



1. Visible substructure
2. Dark substructure
3. Ridiculously small-mass substructure

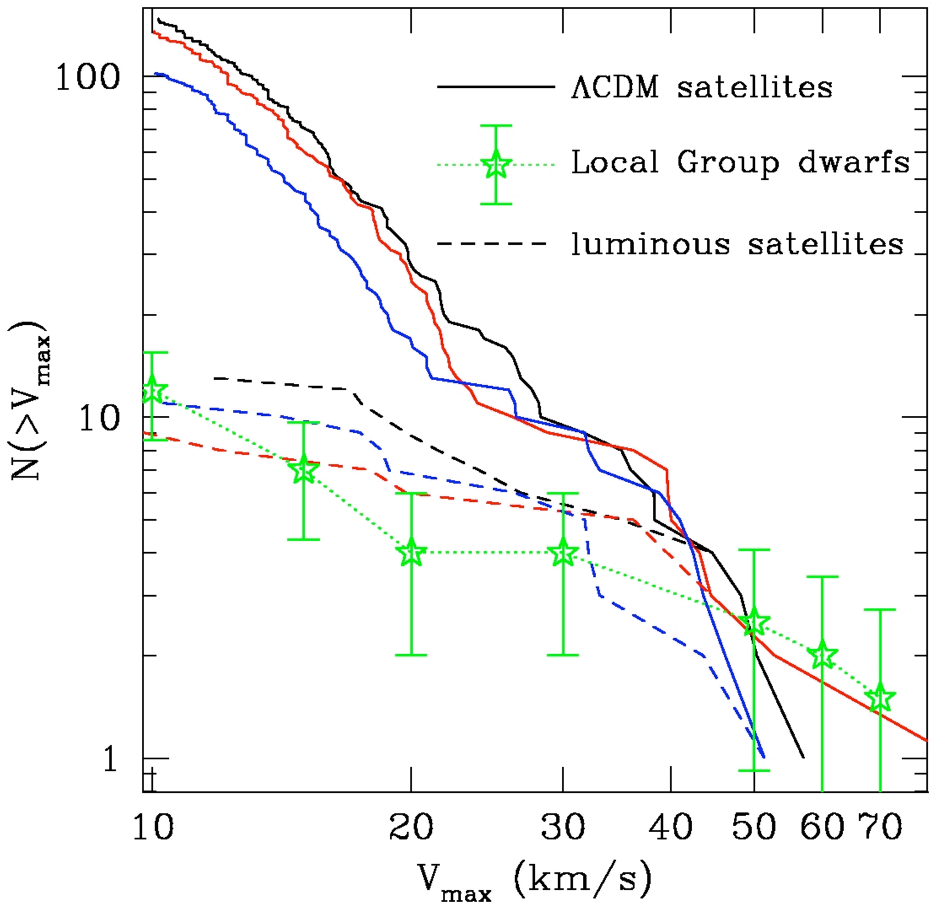


$$\chi\chi \rightarrow f\bar{f} \rightarrow \gamma' s$$

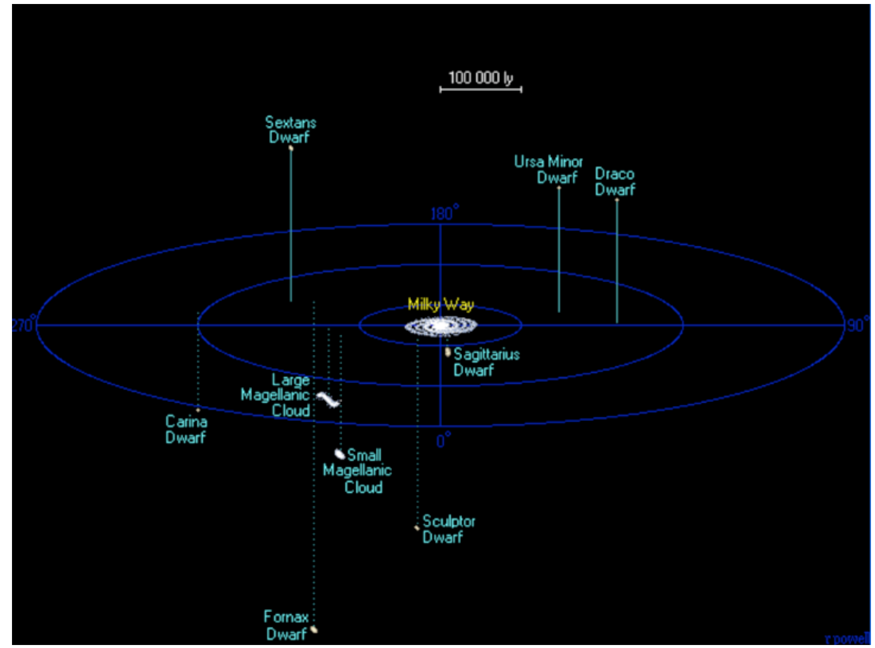
$$\chi\chi \rightarrow \gamma\gamma \,(\mathrm{or}\; Z^0)$$

$$\mathcal{L} \sim \int \rho^2(r) d^3 r \sim \rho_s^2 r_s^3$$

The dwarf satellite "problem" and its disputable existance



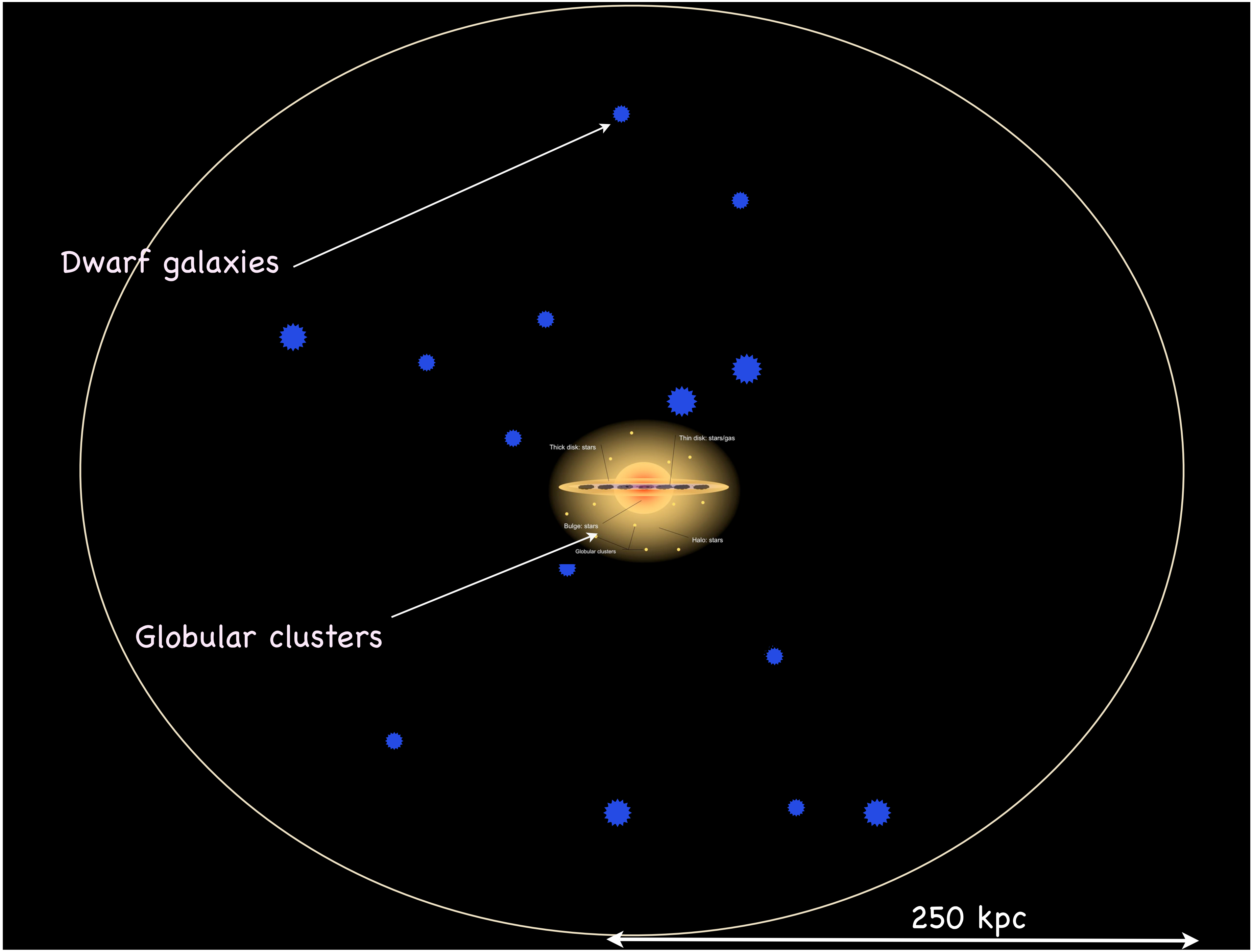
More massive



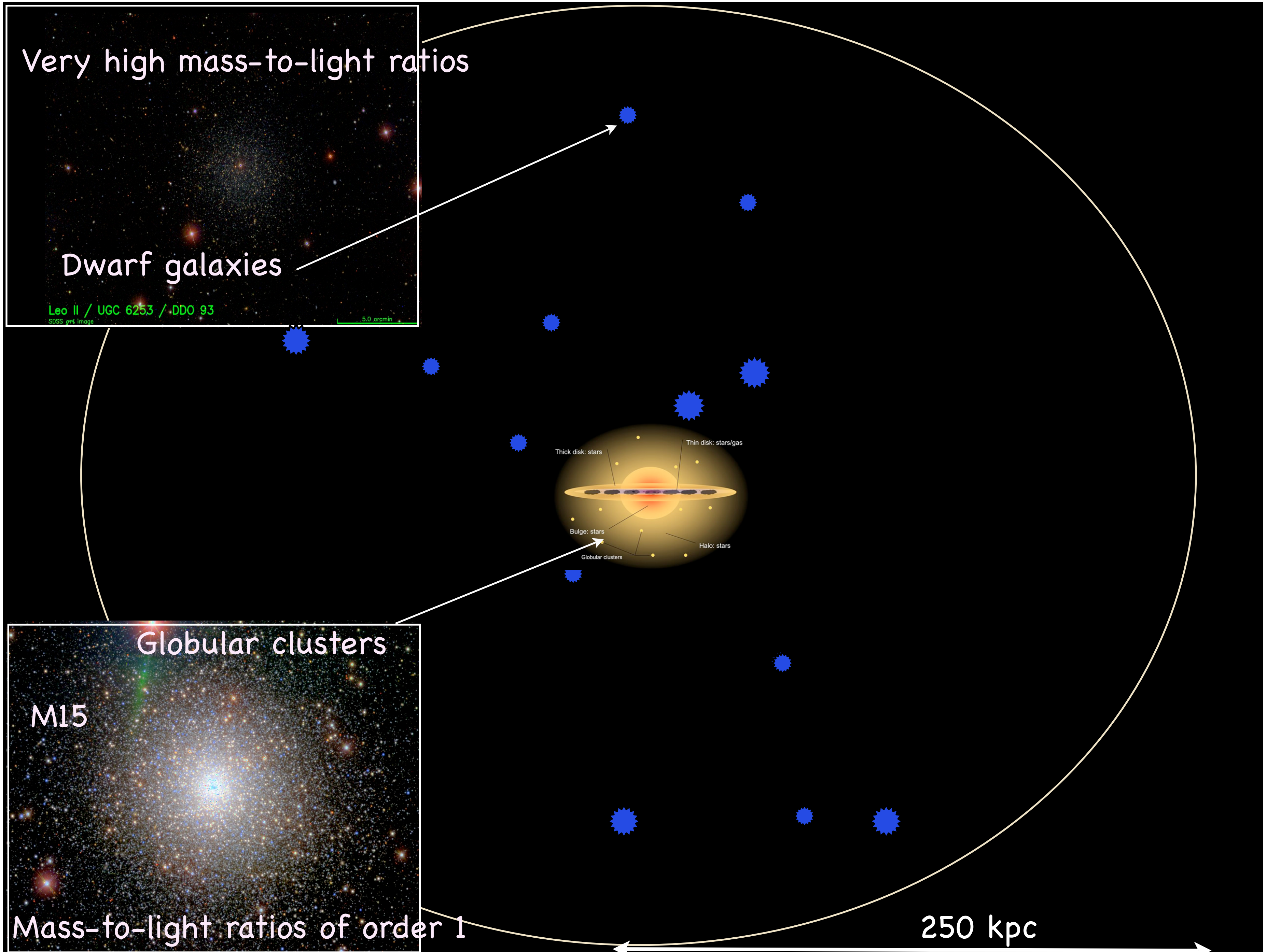
From Kravtsov, Gnedin & Klypin, ApJ, 609, 482 (2004), but see also **Reed et al. (2004)** and prior work by Klypin et al. (1991), Bullock, Kravtsov & Weinberg (2000), Benson et al.(2001), Somerville (2001)

Solutions:

- Changing the nature of the dark matter particle
- Modifying the spectrum of primordial density fluctuations
- Feedback mechanisms

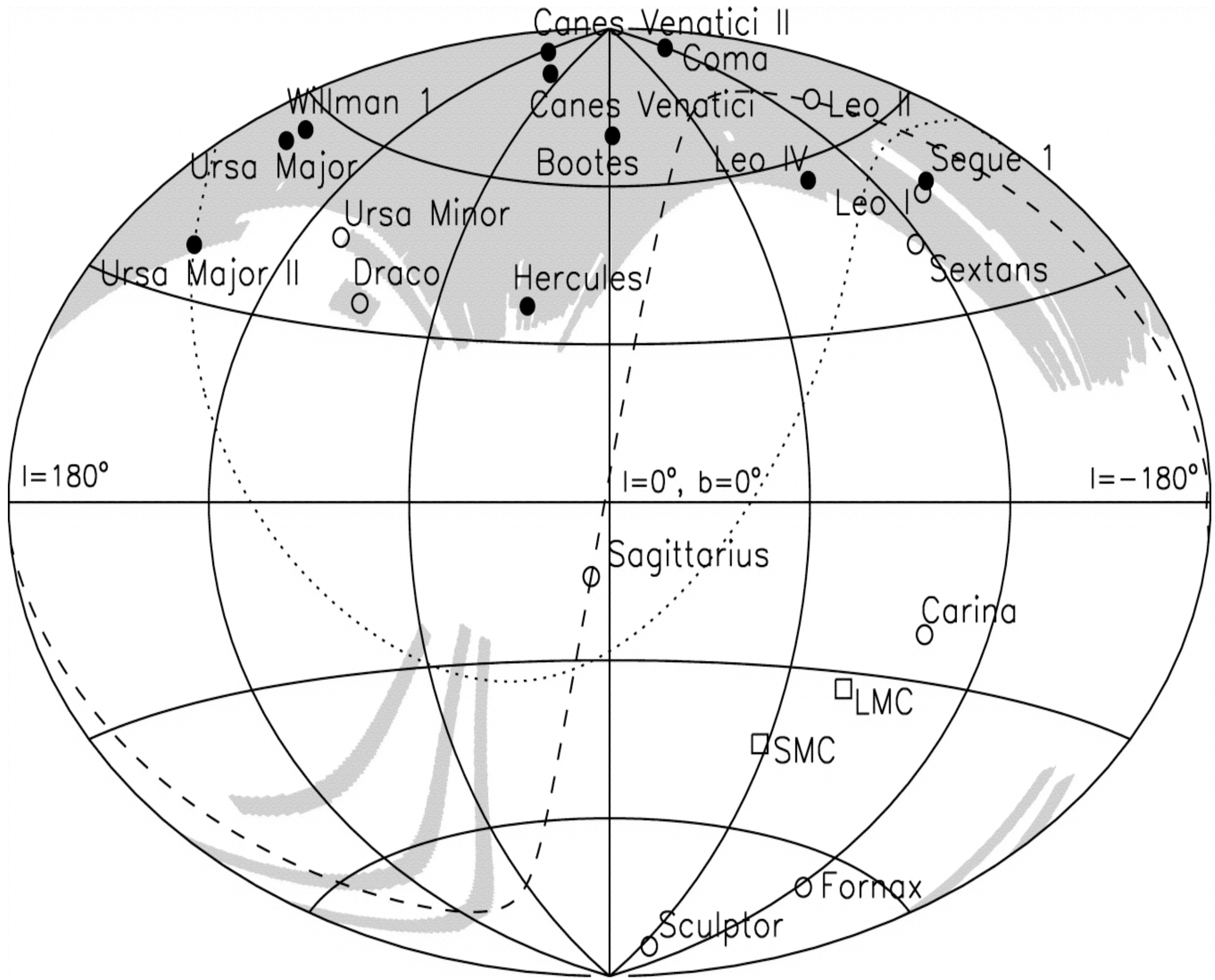


Dwarf galaxies
Thick disk: stars
Thin disk: stars/gas
Bulge: stars
Halo: stars
Globular clusters
Globular clusters
250 kpc

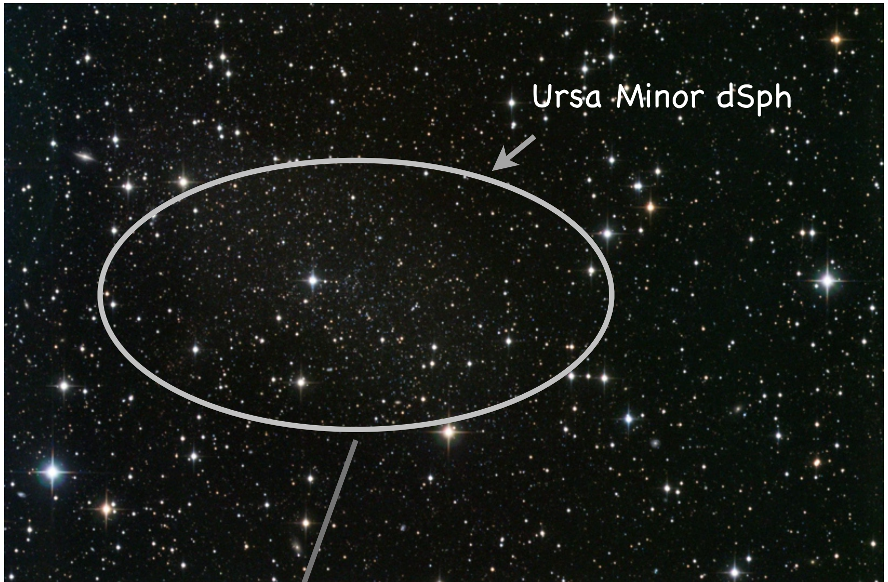

Very high mass-to-light ratios
Dwarf galaxies
Leo II / UGC 6253 / DDO 93
SDSS gri image
5.0 arcmin
Thick disk: stars
Thin disk: stars/gas
Bulge: stars
Halo: stars
Globular clusters
Globular clusters
M15
Mass-to-light ratios of order 1
250 kpc

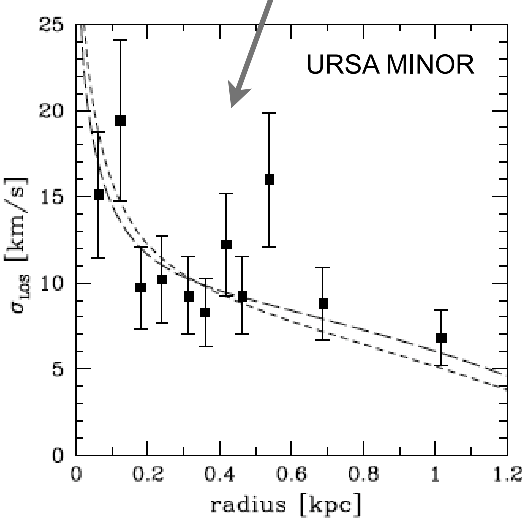
Dwarf satellites of the local group

dSph	Year
● LMC	1519
● SCM	1519
● Sculptor	1937
● Fornax	1938
● Leo I	1950
● Leo II	1950
● Ursa Minor	1954
● Draco	1954
● Carina	1977
● Sextans	1990
● Sagittarius	1994
● Canis Major	2003
● Ursa Major I	2005
● Willman 1	2005
● Ursa Major II	2006
● Bootes	2006
● Canes Venatici I	2006
● Canes Venatici II	2006
● Coma Berenices	2006
● Bootes	2006
● Hercules	2006
● Leo T	2007
● Leo IV	2007



Dwarf satellites of the local group





They are ideal laboratories for studying the distribution of dark matter:

- High mass-to-light ratios
- Astrophysical backgrounds relatively not present
- High galactic latitude - better prospects for detection

Baltz et al., Phys. Rev. D 61, 023514 (2000), Stoehr et al., MNRAS 345, 1313 (2003), Tyler, Phys. Rev. D 66, 023509 (2002), Evans, Ferrer & Sarkar, Phys. Rev. D 69, 123501 (2004), Bergstrom & Hooper, Phys. Rev. D 73, 063510, Strigari, Koushiappas, Bullock & Kaplinghat, Phys. Rev. D 75, 083506 (2007)

$$\sigma_t^2(R) = \frac{2}{I(R)} \int_R^\infty \left(1 - \beta \frac{R^2}{r^2}\right) \frac{\rho_\star \sigma_r^2 r}{\sqrt{r^2 - R^2}} dr$$

$$r \frac{d(\rho_\star \sigma_r^2)}{dr} = -\rho_\star(r) V_c^2(r) - 2\beta(r)\rho_\star \sigma_r^2$$

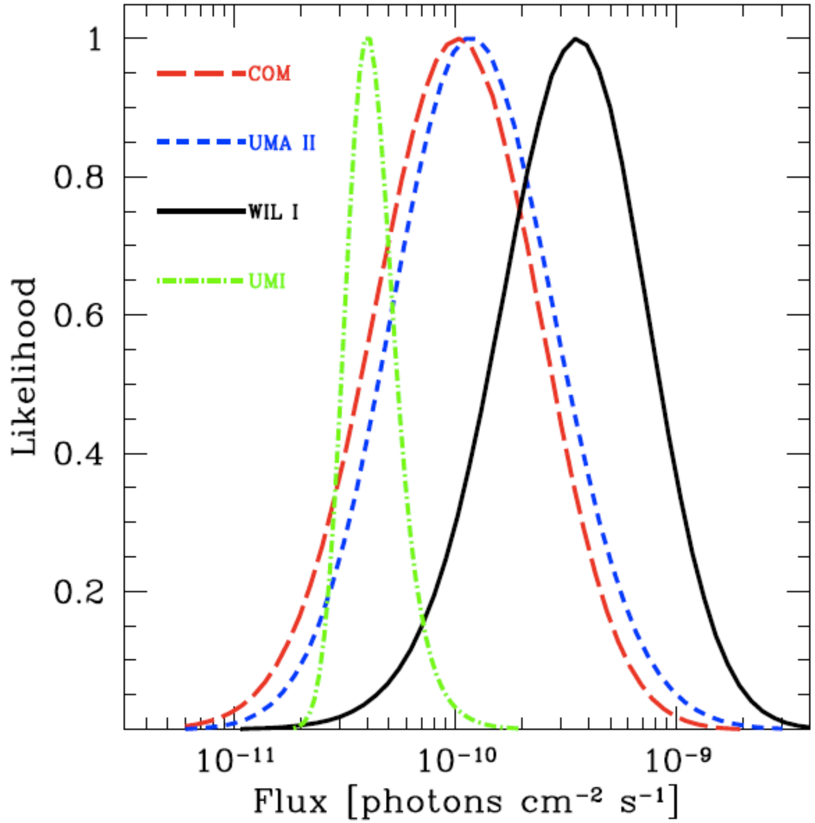
$$\rho(r) = \frac{\rho_s}{(r/r_s)^\gamma [1 + r/r_s]^{3-\gamma}}$$

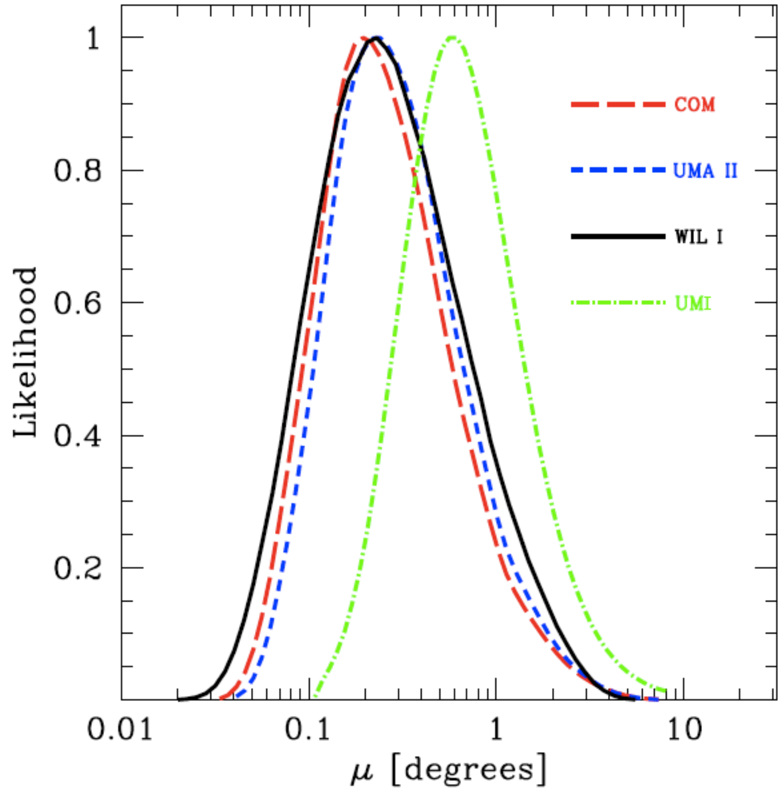
Strigari, Koushiappas, Bullock & Kaplinghat, Phys. Rev. D 75, 083506 (2007)

Strigari, Koushiappas, Kaplinghat, Bullock, Simon, Geha & Willman, ApJ 678, 614 (2008)

Dwarf satellites of the local group

dSph	Distance (kpc)	Luminosity (10^3 $L_\odot$)	Core Radius (kpc)	Cut-off Radius (kpc)	Number of stars
Ursa Major II	32	2.8	0.127 (P)	—	20
Coma Berenices	44	2.6	0.064 (P)	—	59
Willman 1	38	0.9	0.02 (K)	0.80 (K)	47
Ursa Minor	66	290	0.30 (K)	1.50 (K)	187





Strigari, Koushiappas, Bullock & Kaplinghat, Phys. Rev. D 75, 083506 (2007)
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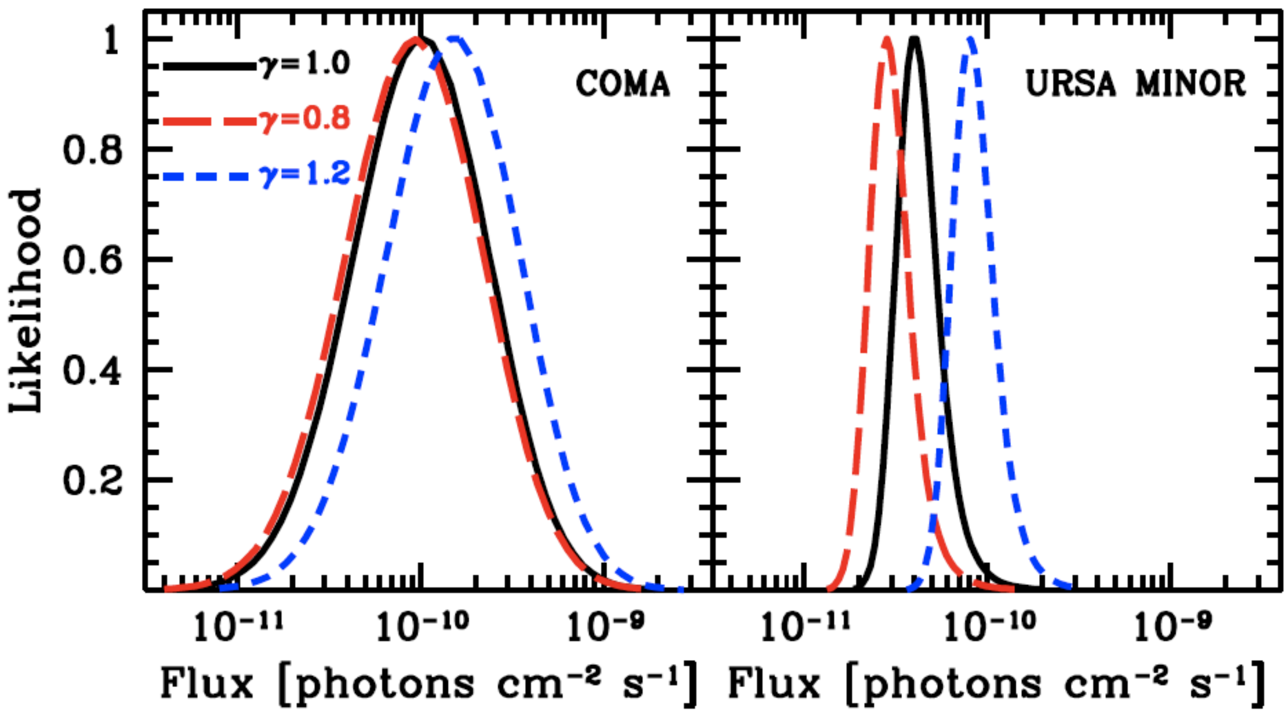
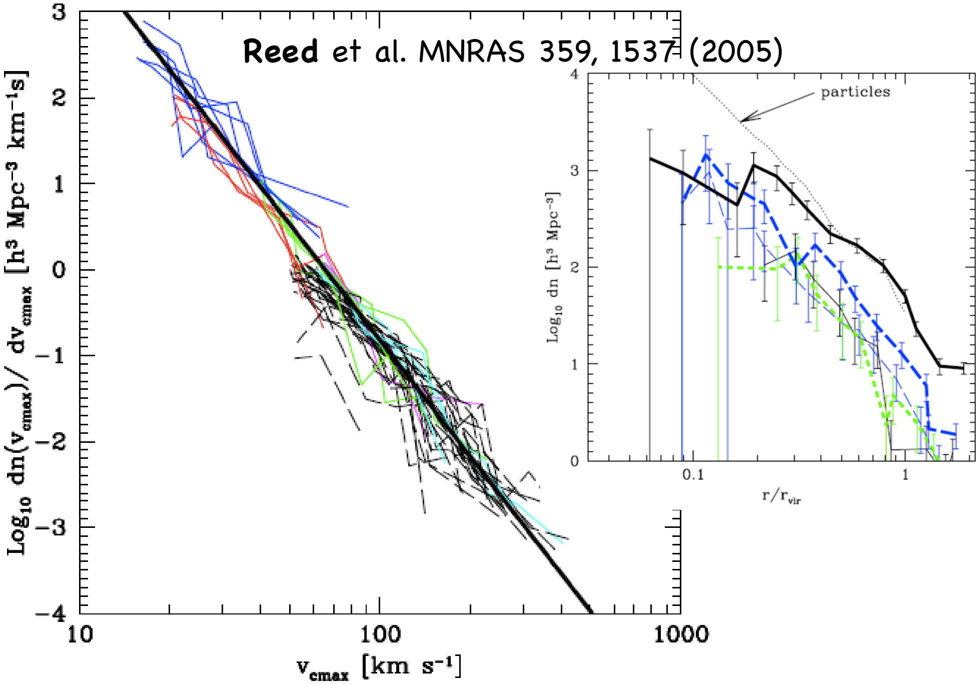
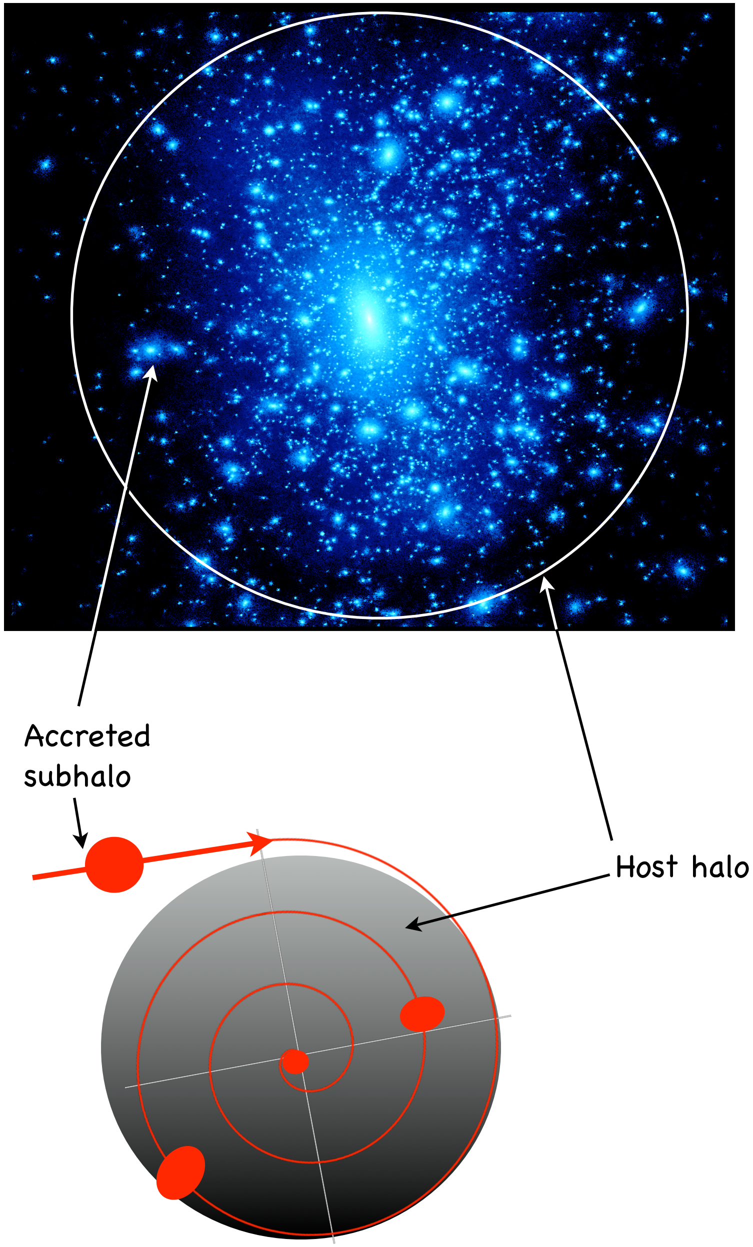


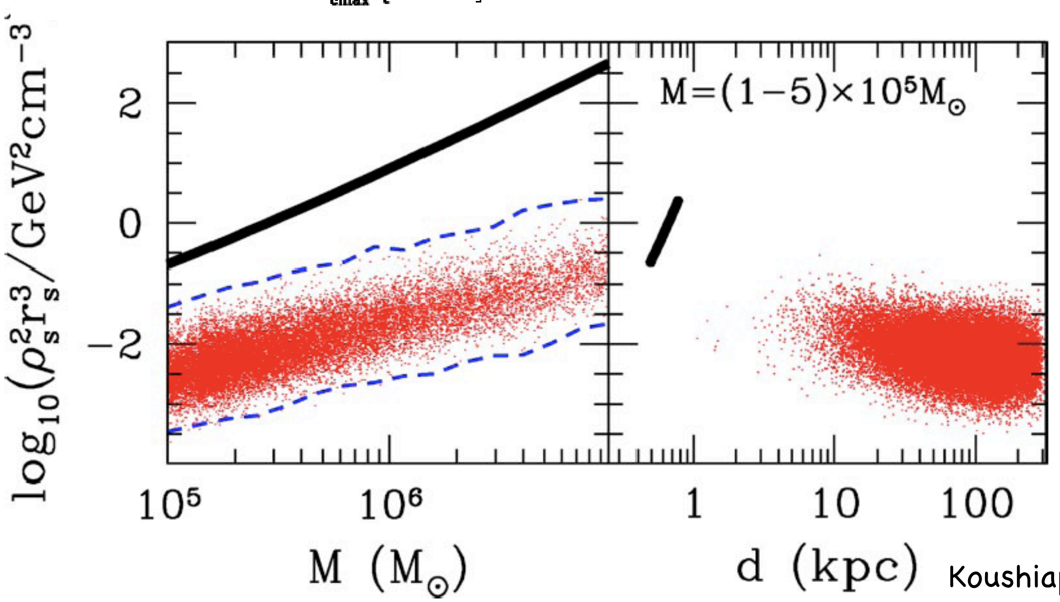
Strigari, Koushiappas, Bullock & Kaplinghat, Phys. Rev. D 75, 083506 (2007)

Strigari, Koushiappas, Kaplinghat, Bullock, Simon, Geha & Willman, ApJ 678, 614 (2008)

Dark Milky Way substructure



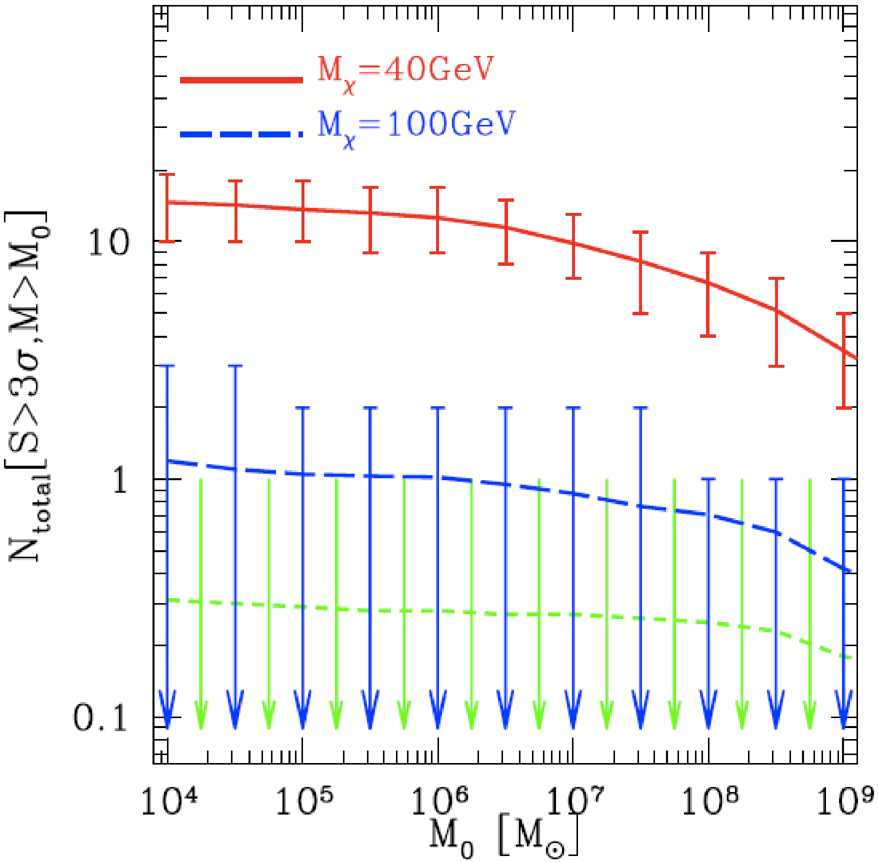


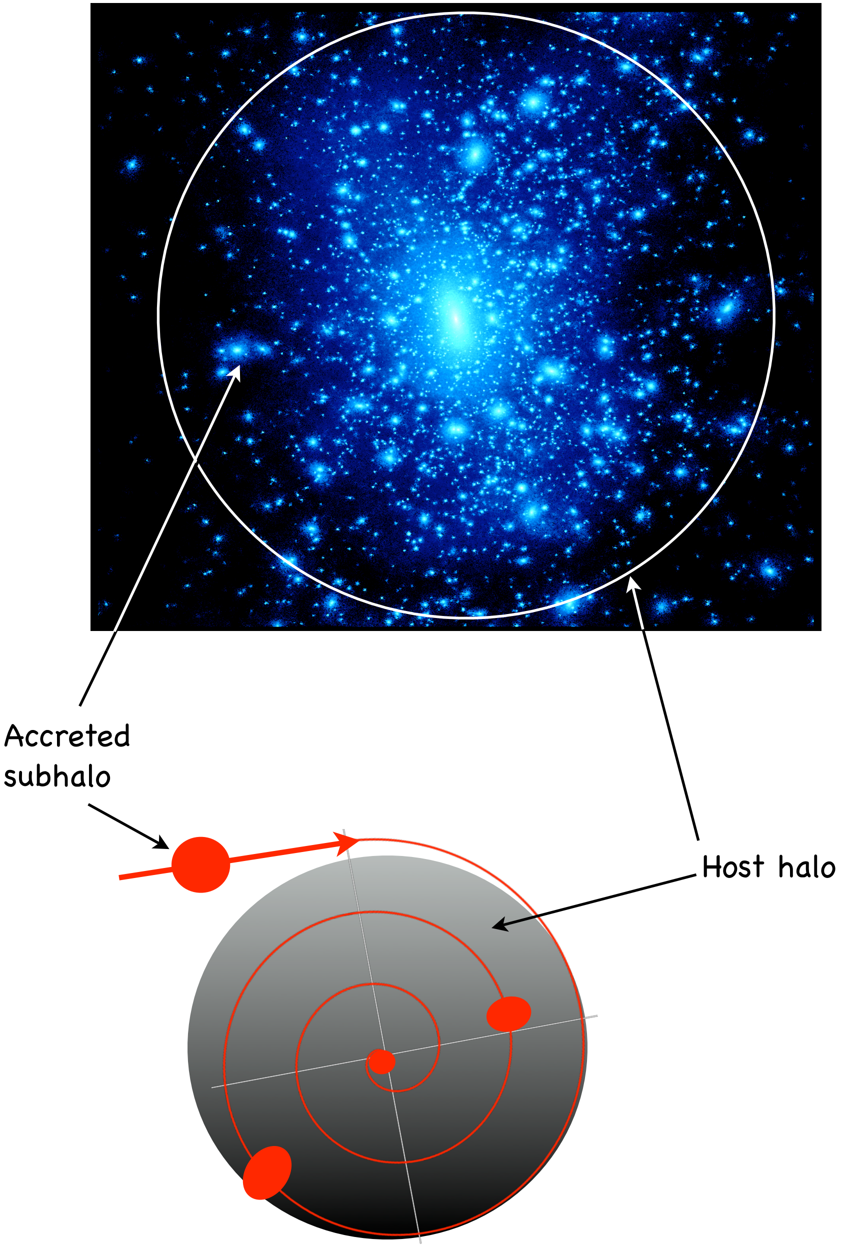


Koushiappas, Zentner & Walker, Phys. Rev. D 69, 043501 (2004)

Dark Milky Way substructure

Subhalo abundance and properties depend on cosmology (see Zentner & Bullock 2002 & 2003)





Koushiappas, Zentner & Walker, Phys. Rev. D 69, 043501 (2004)

Microhalos present in the solar neighborhood

$$M_m \geq 10^{-13} M_\odot$$

1. A possible detection can provide information about the particle physics properties of the dark matter particle.
2. A measured abundance in the Milky Way halo contains information on the hierarchical assembly of dark matter halos at very early times (survival/disruption), a task unattainable by any other method.

Theory:

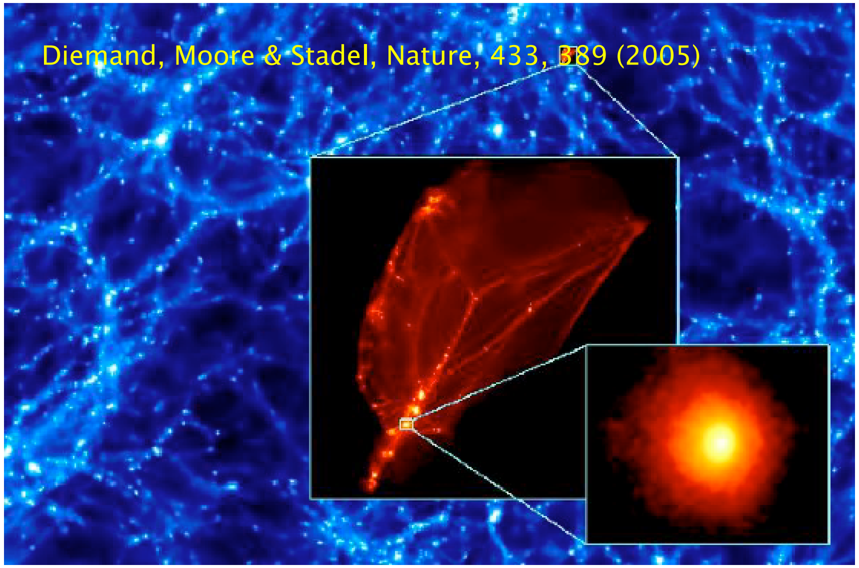
- Schmid et al., Phys Rev. D 59, 043517 (1999)
- Hofmann et al., Phys. Rev. D 64, 083507 (2001)
- Chen et al., Phys Rev. D 64, 021302 (2001)
- Berezinsky et al, Phys. Rev. D 68, 103003 (2003)
- Green, Hoffmann and Schwarz, MNRAS 353, L23 (2004)
- Green et al., JCAP 08, 003 (2005)
- Loeb & Zaldarriaga , Phys. Rev. D, 71, 103520 (2005)
- Profumo et al., Phys. Rev. Lett., 97, 031301 (2006)

Simulation:

- Diemand, Moore & Stadel, Nature 433, 389 (2005)
- Diemand, Kuhlen & Madau , ApJ 649, 1 (2006)

Debate:

- Zhao et al. astro-ph/0502049, astro-ph/0508215
- Moore et al. astro-ph/0502213
- Green & Goodwin, MNRAS 375, 1111 (2007)
- Goerdt et al, MNRAS 375, 191 (2007)



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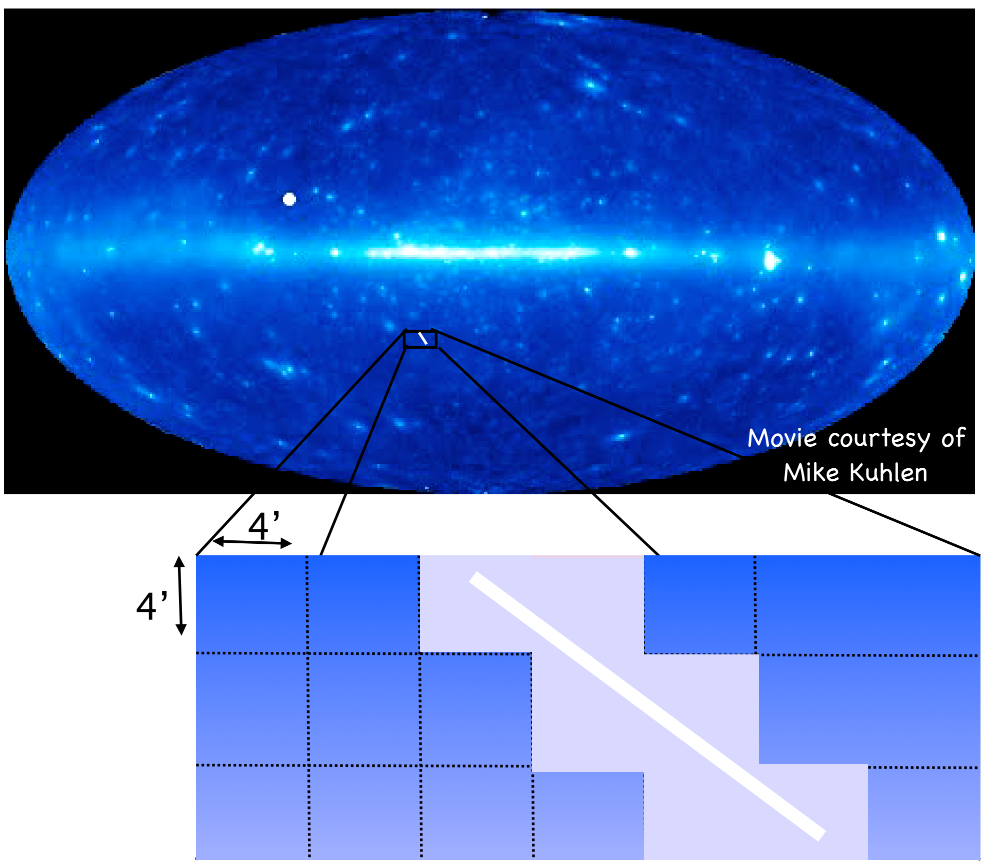
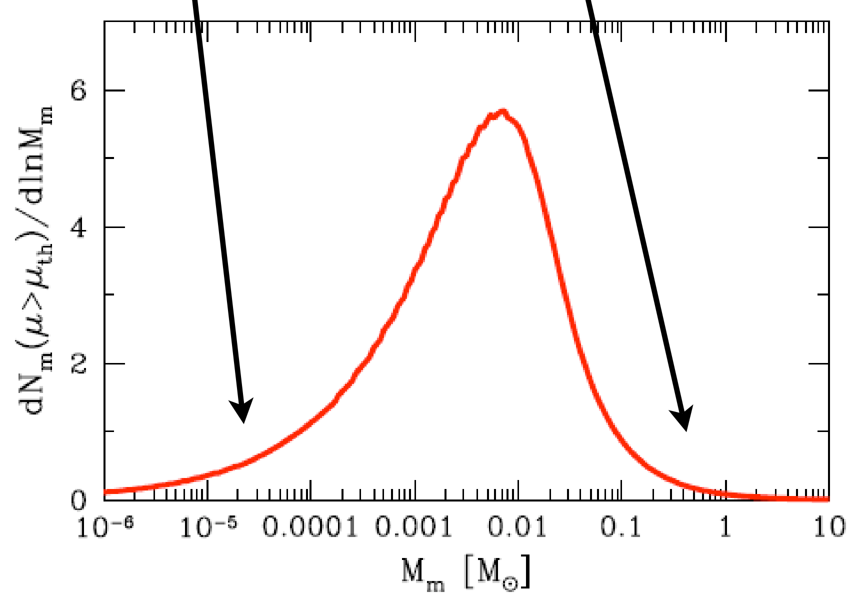


Limited by the **abundance** of detectable microhalos

Limited by the amount of **proper motion** exhibited



Koushiappas, Phys. Rev. Lett. 97, 191301 (2006)

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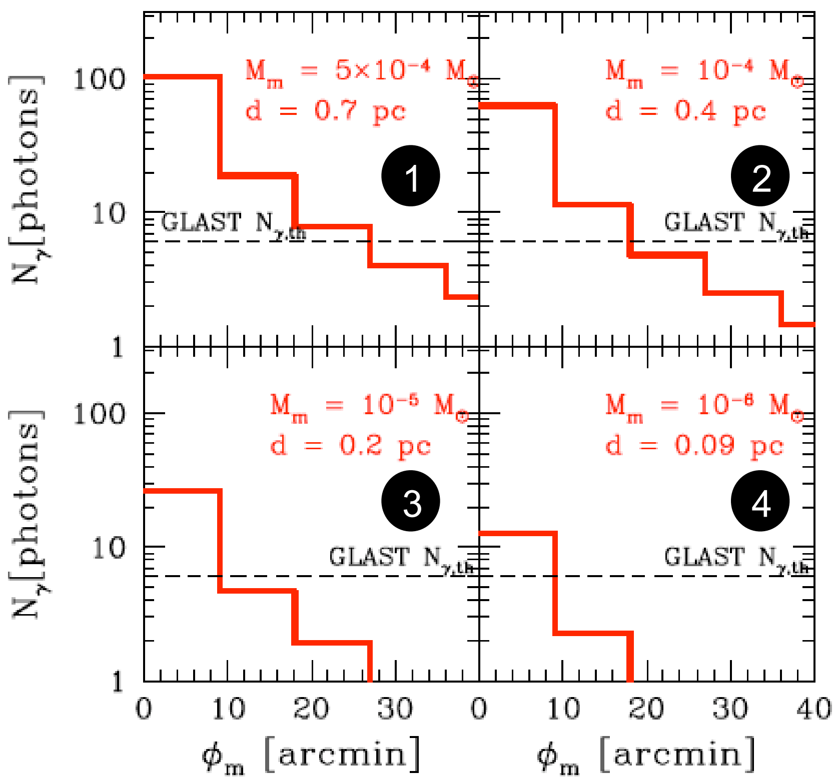
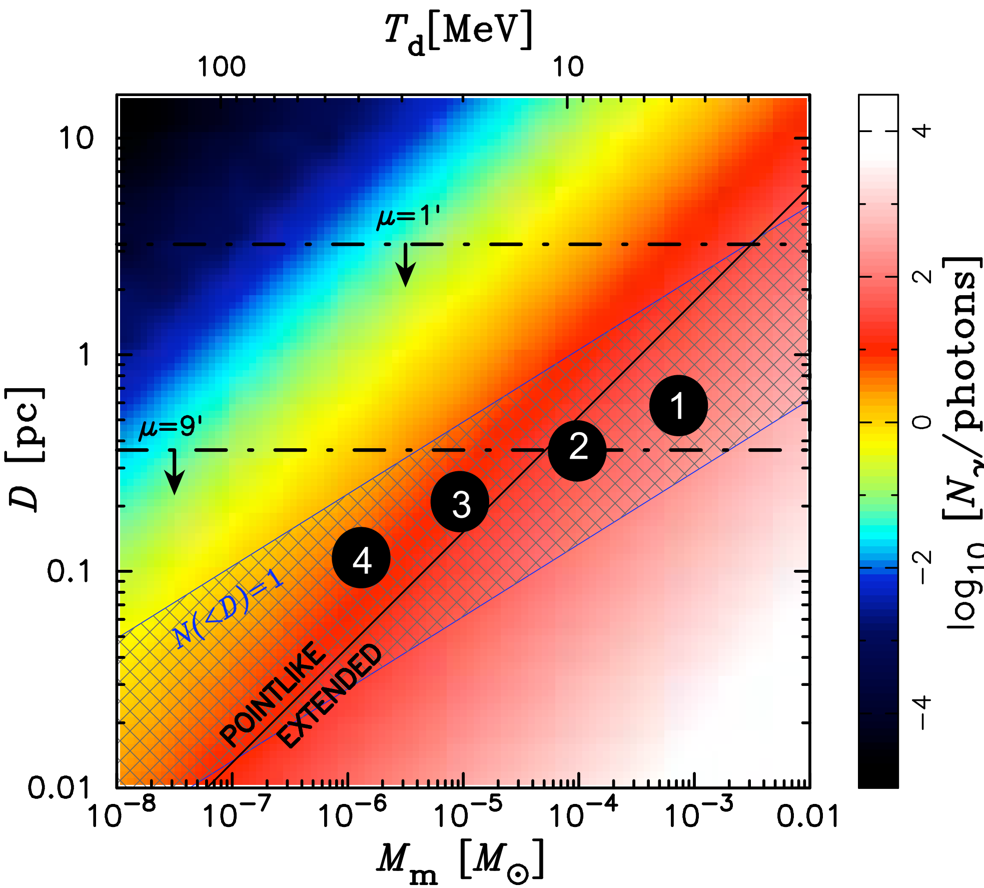
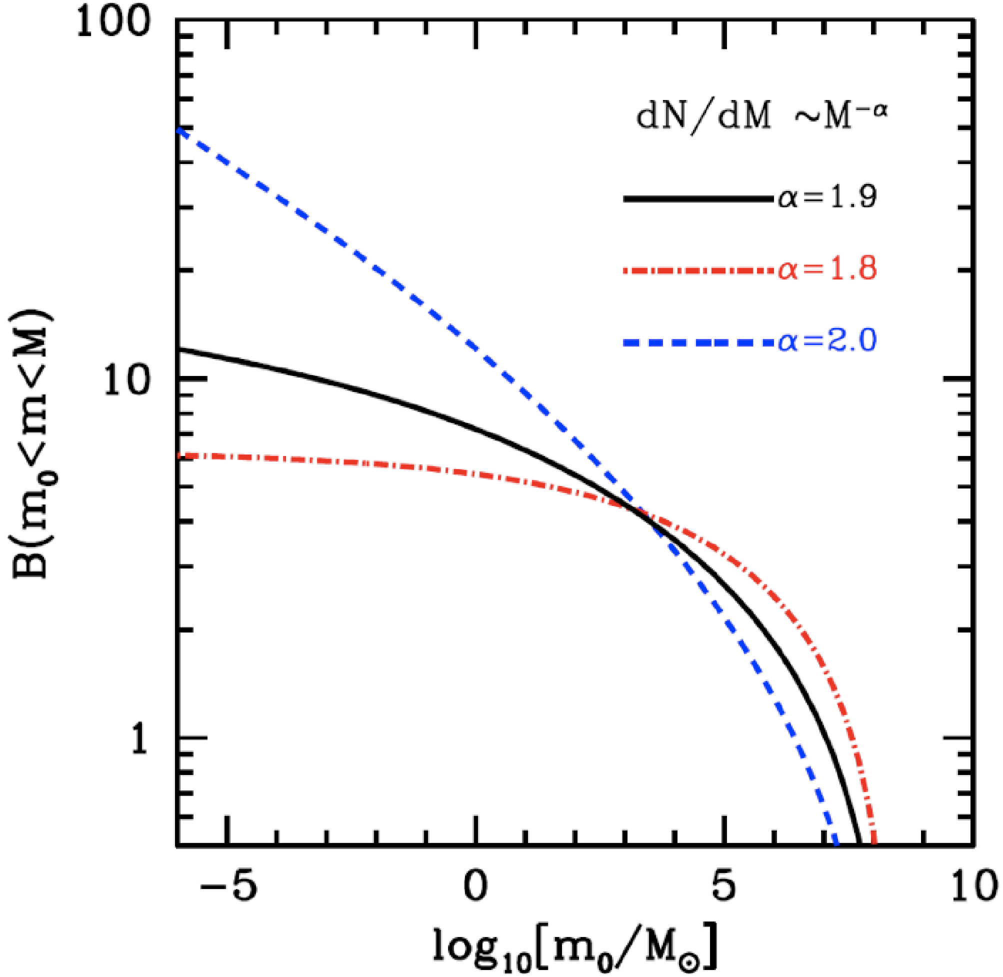
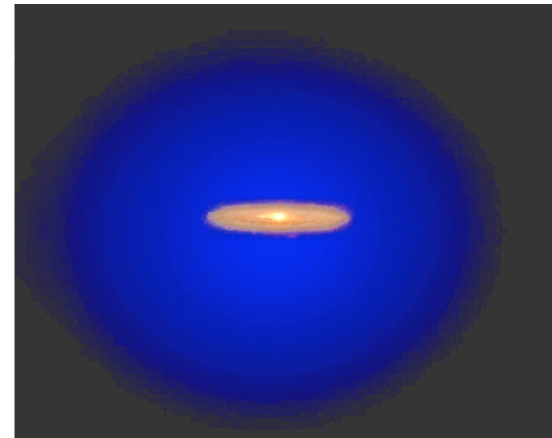




The “boost” factor

Substructure can enhance the prospects for detection by enhancing the annihilation rate





Strigari, Koushiappas, Bullock & Kaplinghat, Phys. Rev. D 75, 083506 (2007)

Strigari, Koushiappas, Kaplinghat, Bullock, Simon, Geha & Willman, arXiv:0709.1510 (2007)

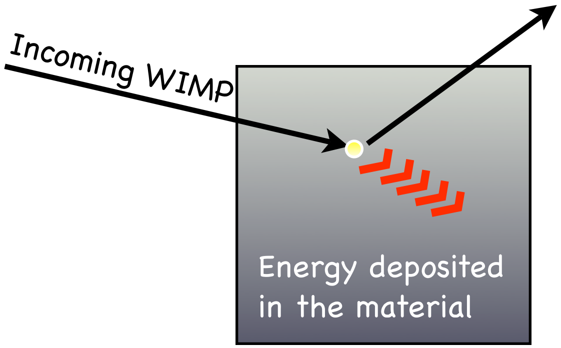
Direct detection

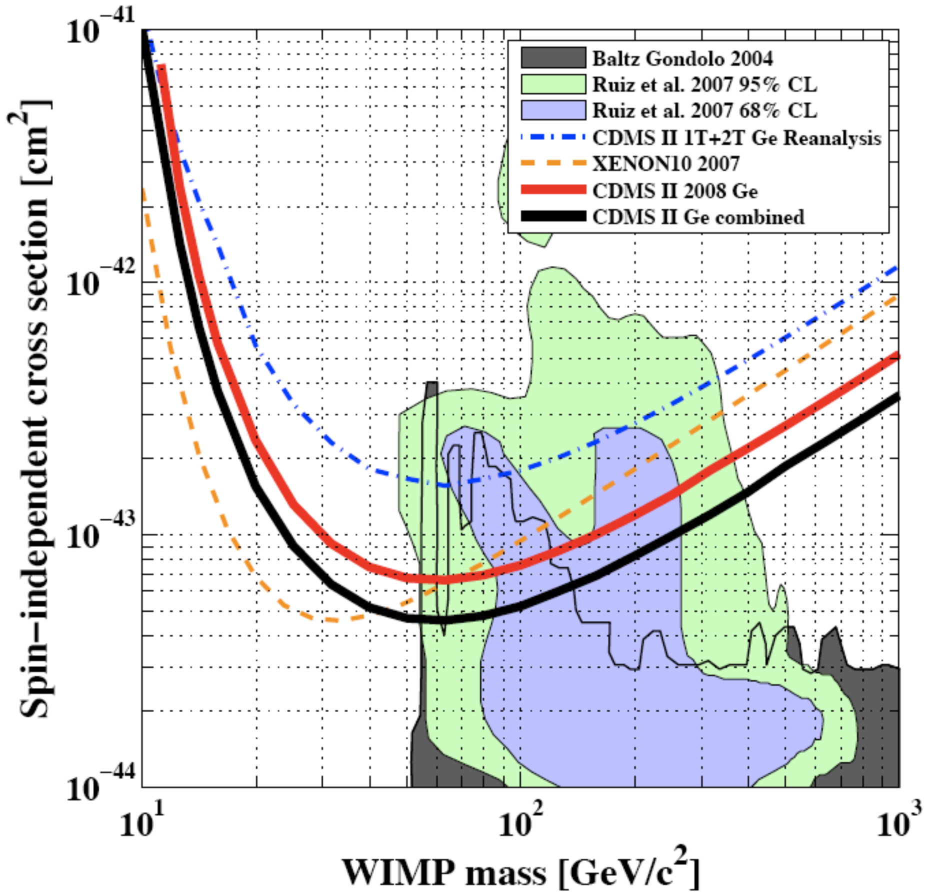
Scalar scattering of the dark matter particle off a nucleus

Observable: Energy deposited

$$\frac{d\Gamma}{dE} = \rho_\odot \frac{\sigma_0 F^2(E)}{2 m_\chi m_r^2} \int_{v_{\min}}^{\infty} \frac{f(v)}{v}\, dv$$

Depends on the local dark matter density





Ahmed et al. (CDMS collaboration) arXiv: 0802.3530

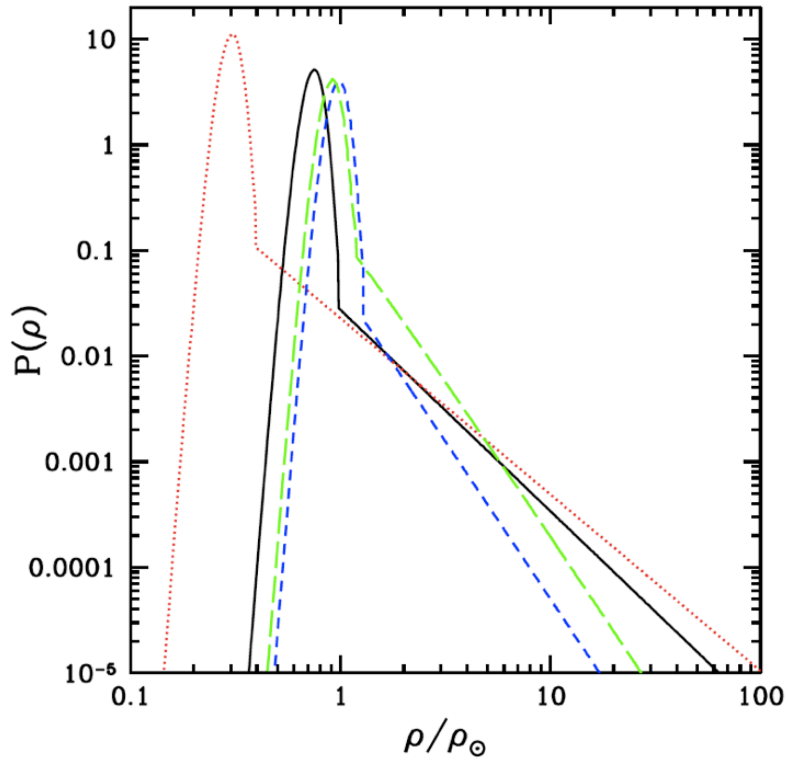
Direct Detection

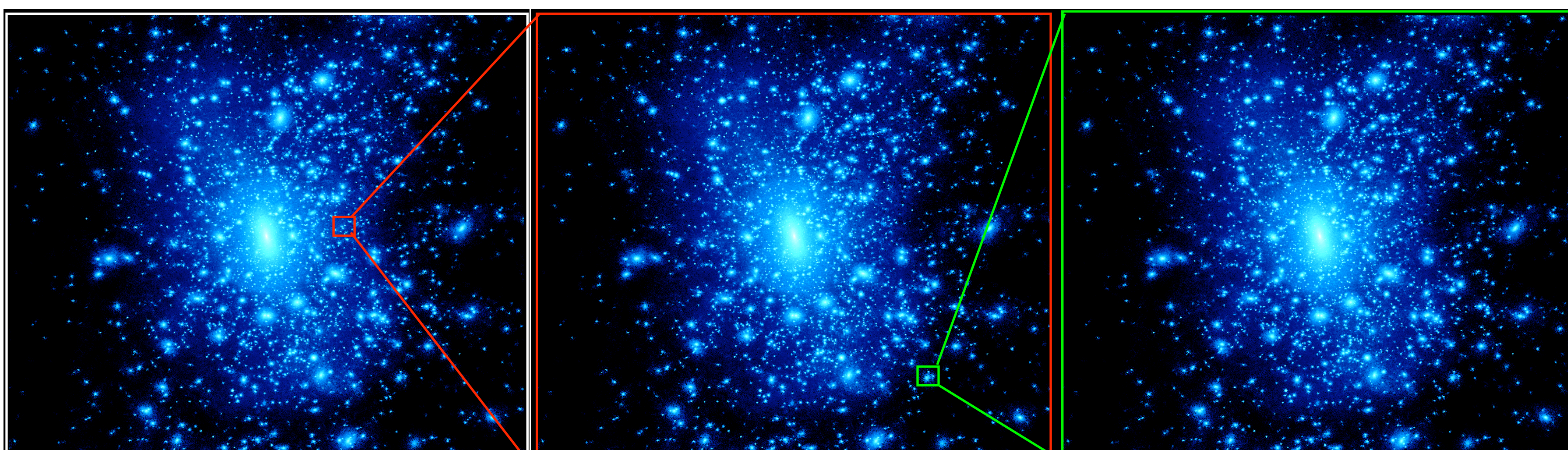
$$\frac{d\Gamma}{dE} = \rho_{\odot} \frac{\sigma_0 F^2(E)}{2 m_\chi m_r^2} \int_{v_{\min}}^{\infty} \frac{f(v)}{v}\, dv$$

$\rho_{\odot}$ → ≈ 0.4 GeV/cm^3

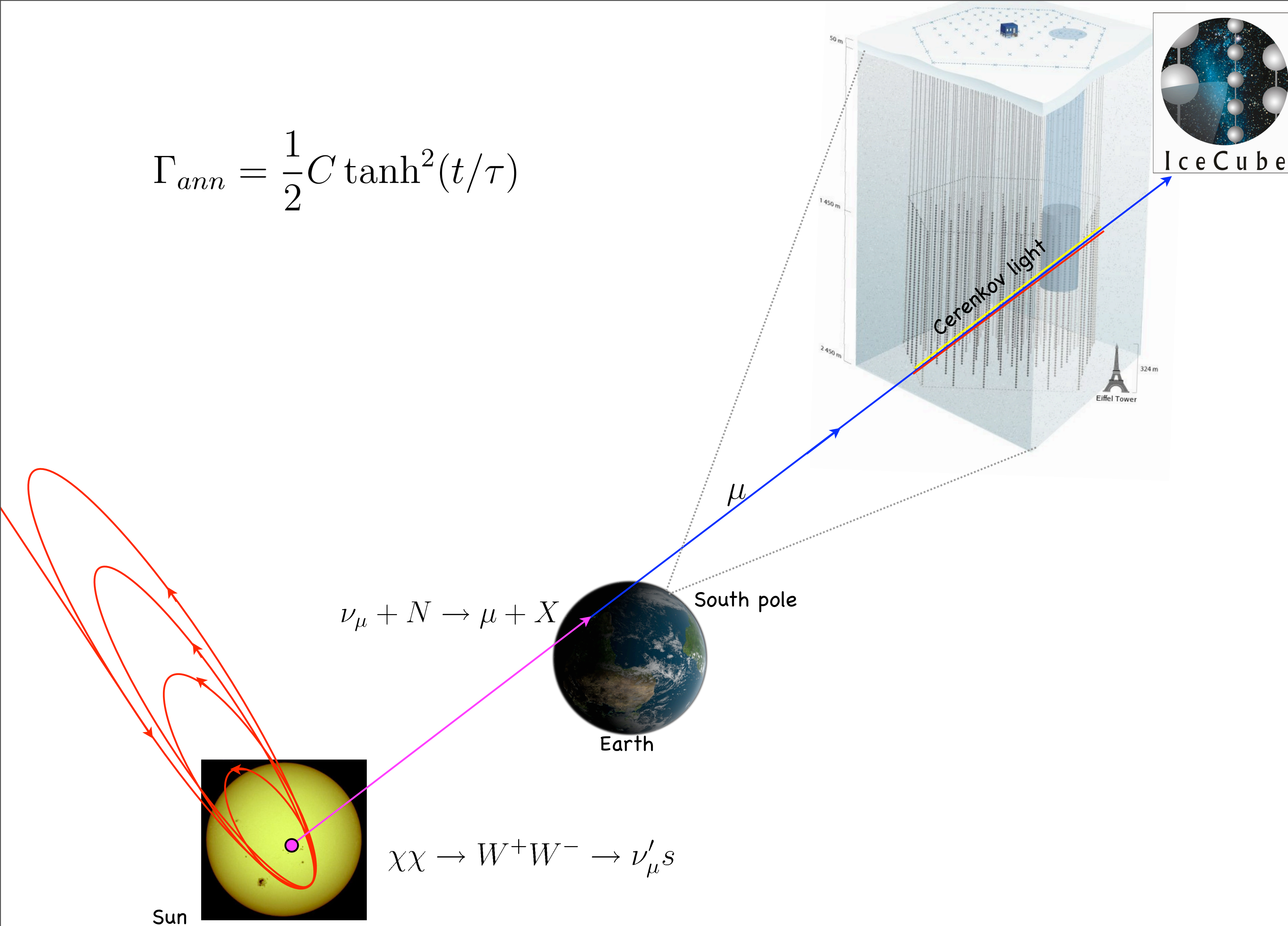
Local dark matter density can be as small as 1/10th the canonical value, though most likely no less than 0.1 GeV/cm^3

Kamionkowski & Koushiappas, Phys. Rev. D 77, 103509 (2008)



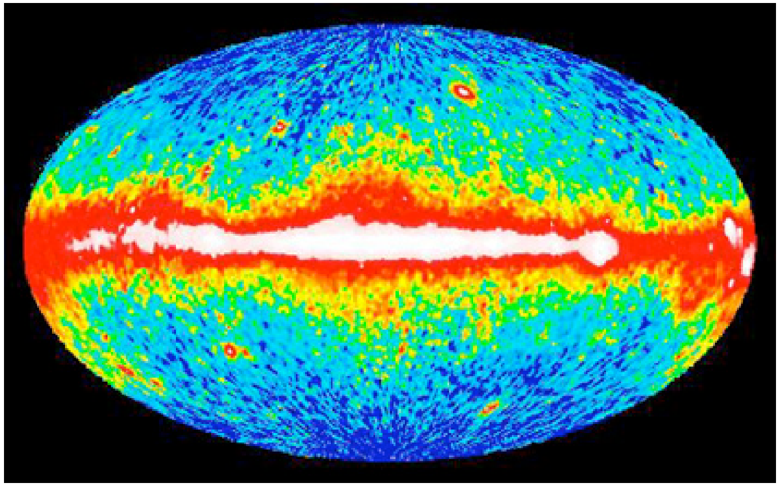


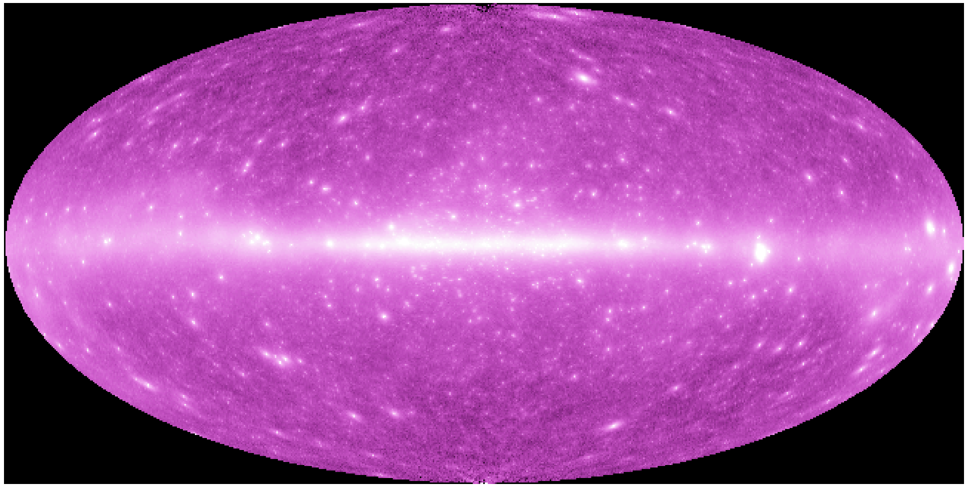
$$\Gamma_{ann} = \frac{1}{2} C \tanh^2(t/\tau)$$

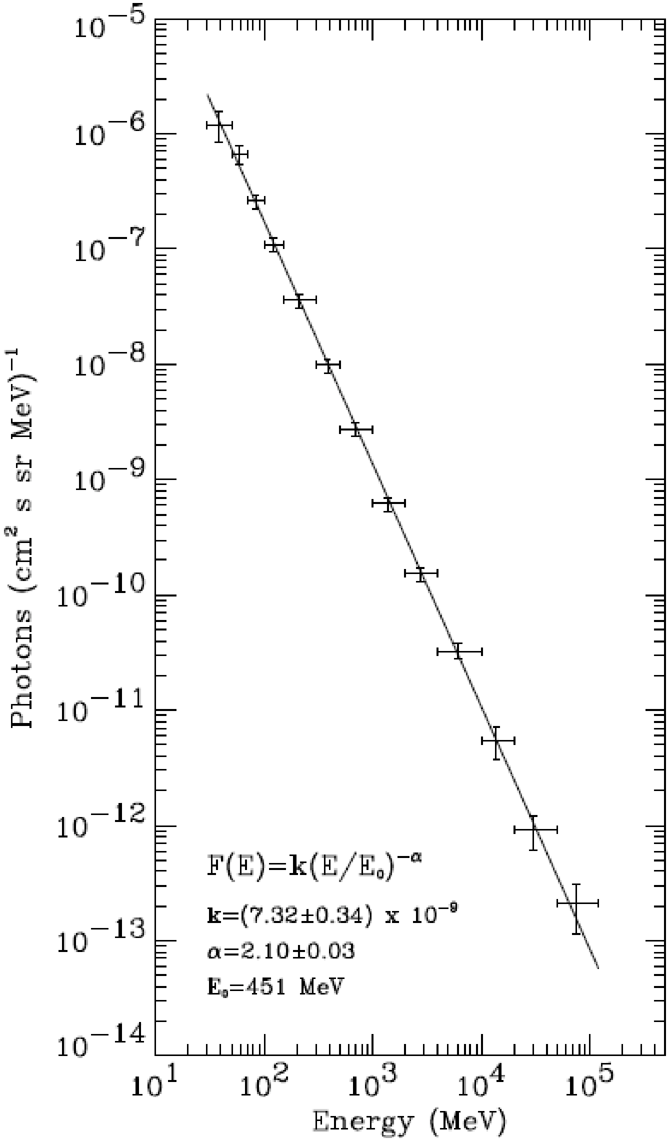


Koushiappas & Kamionkowski in preparation

Fluctuations in the gamma-ray background

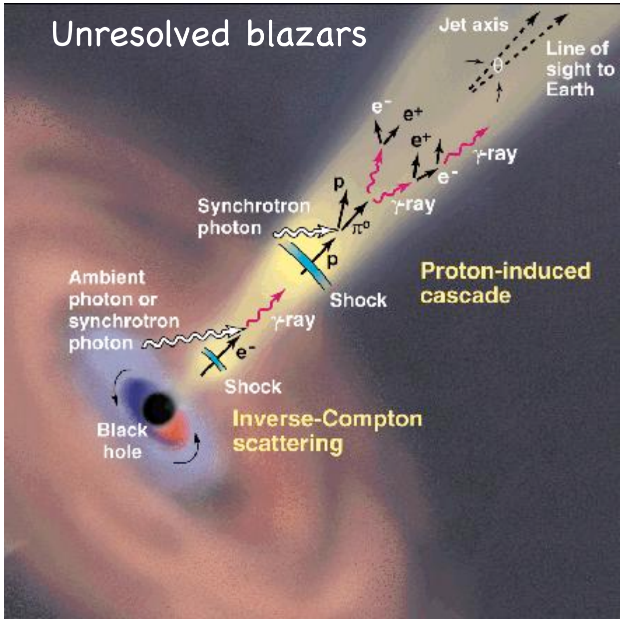


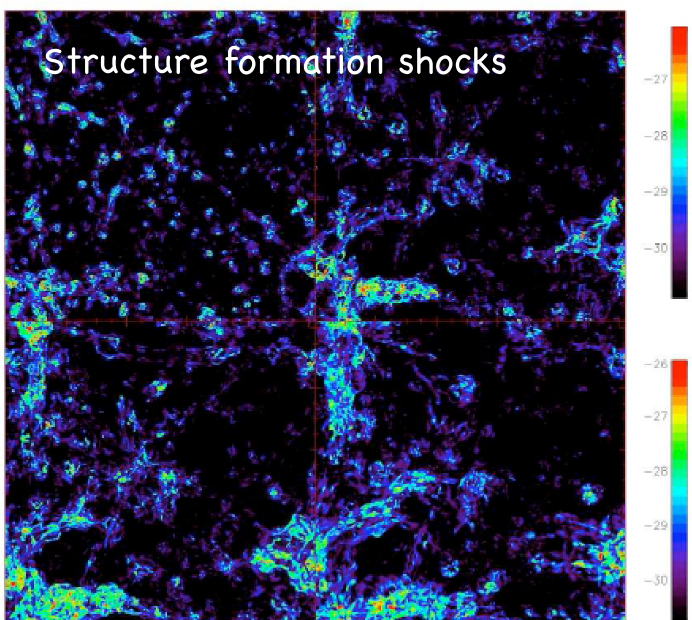


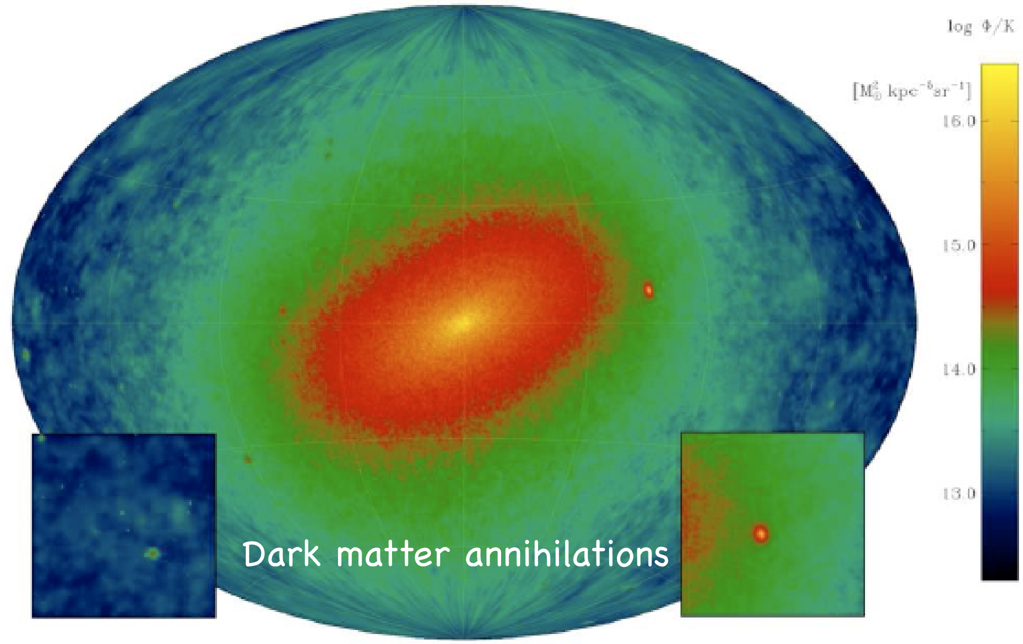


Sreekumar et al. (1998), but see also Strong & Moskalenko (2004)

Fluctuations in the gamma-ray background

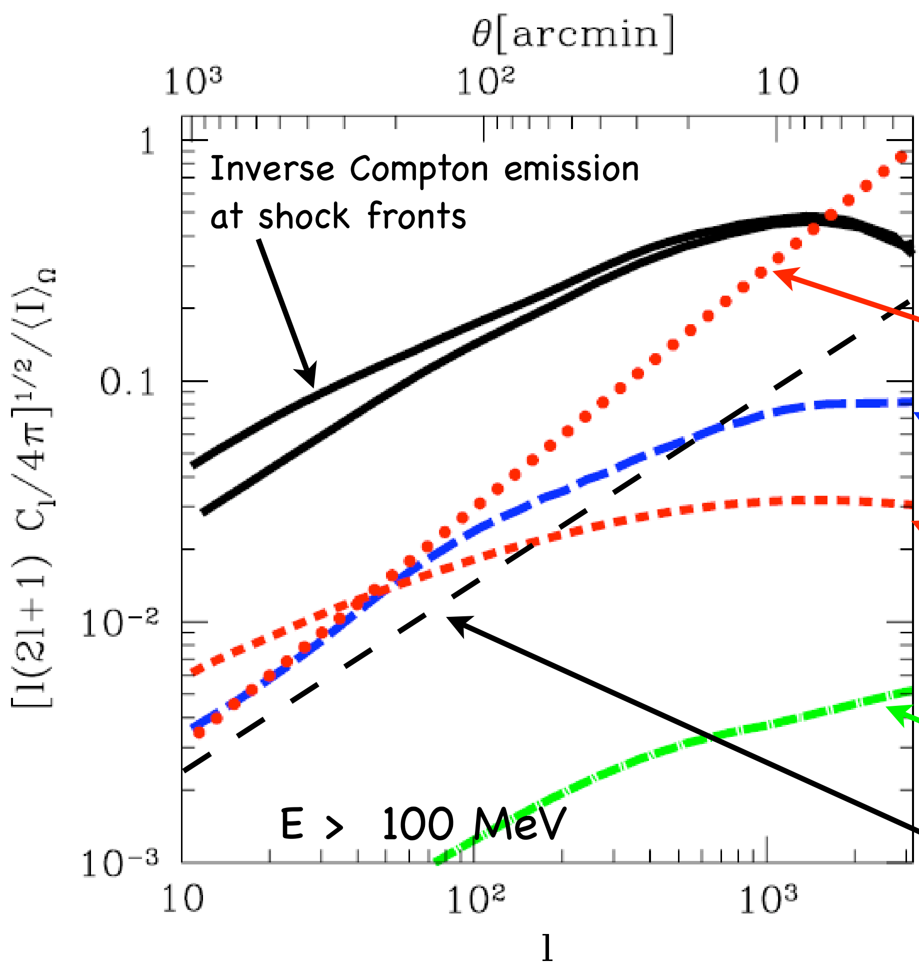






Fluctuations in the gamma-ray background

$$\delta I(\hat{v}) \equiv I(\hat{v}) - \langle I \rangle_\Omega \qquad C(\theta) = \langle \delta I(\hat{v}) \delta I(\hat{u}) \rangle$$



$$C_l^P = \frac{1}{(4\pi)^2} \int_0^{z_{\max}} dz \, \frac{dV/dz}{(4\pi d_L^2)^2} \int_0^{L_{\lim}(z)} dL_\gamma \, \mathcal{L}_\gamma L_{\rm ph}^2$$

Hadronic emission in the center of clusters

Blazar model 1

Blazar model 2

Dark matter annihilations

Miniati, Koushiappas & Di Mateo, ApJ 667, L1 (2006)

Conclusion

1. Cosmological parameters and physical processes in the early Universe affect the distribution of dark matter in dark matter halos.

2. Understanding the structure and rich substructure of dark matter halos is imperative in any future potential discovery of the dark matter particle in any direct or indirect detection experiment.