Keck INSTITUTE FOR SPACE STUDIES
CALIFORNIA INSTITUTE OF TECHNOLOGY
JET PROPULSION LABORATORY

Shedding Light on the Nature of Dark Matter
July 13 – 24 2009

Numerical Simulations – Now and in the future

Michael Kuhlen
Institute for Advanced Study
Princeton, NJ

Caltech, Jul. 14th 2009

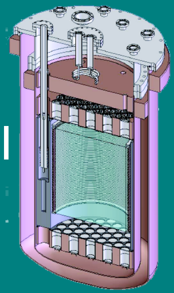
Now is the time ...

LHC

LHC might produce WIMPs!

Direct Detection

Solid Scintillation
DAMA/LIBRA, KIMS



Liquid/Gas Xenon
XENON-10, ZEPLIN-II
Tonne-scale experiments planned

Cryogenic Detectors
CDMS-II,
CRESST

Indirect Detection

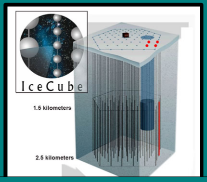
γ-rays
Fermi Space Telescope

A.C.T.'s (VERITAS, H.E.S.S., etc.)

anti-matter
PAMELA satellite

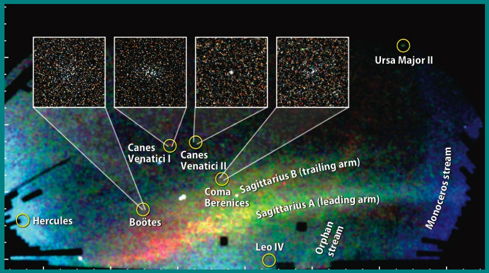
balloon-borne: ATIC, PPB-BETS

neutrinos
AMANDA, ANTARES, IceCube



Astronomical Surveys and Observations

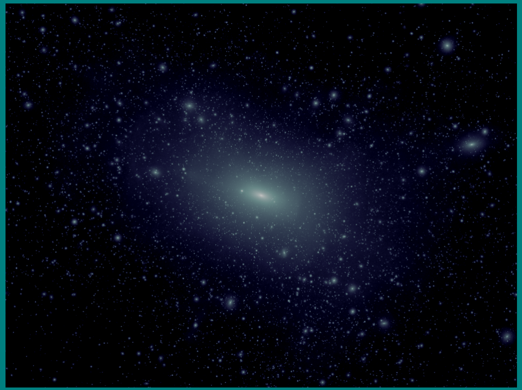
SDSS, LSST, Pan-STARRS, Keck, Gaia, SIM, TMT, etc.



Dark Matter Numerical Simulations

$O(>10^9)$ Particles

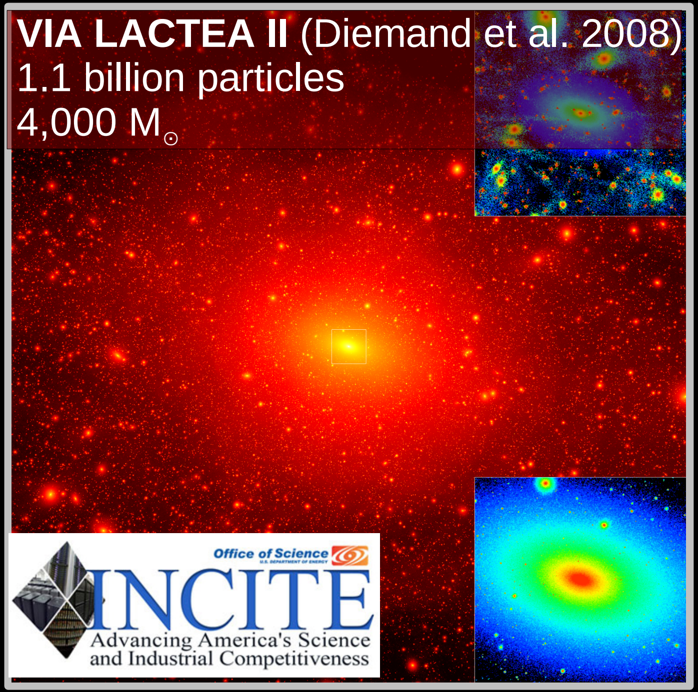
- *Via Lactea* Project
- Aquarius Project
- Millennium-II
- Bolshoi

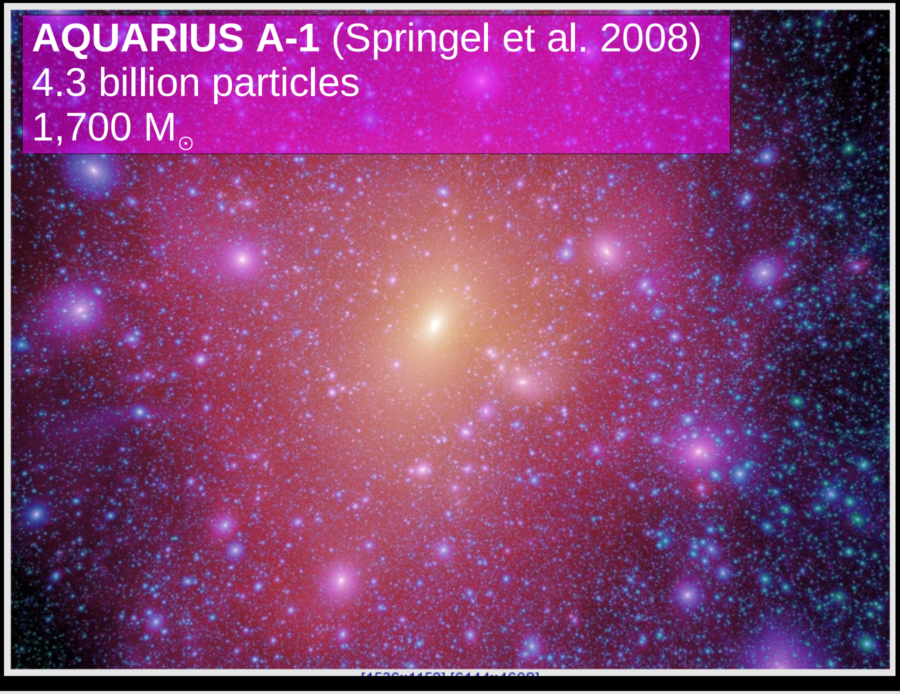


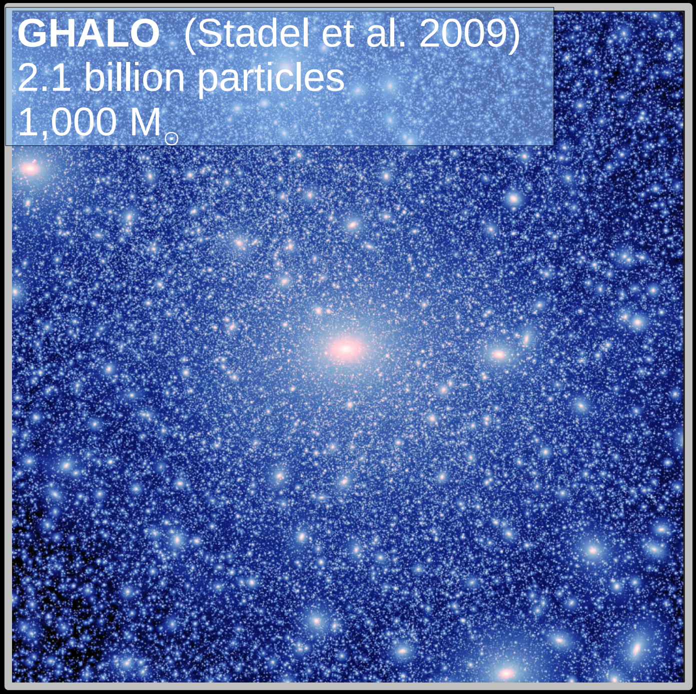
Outline of Talk

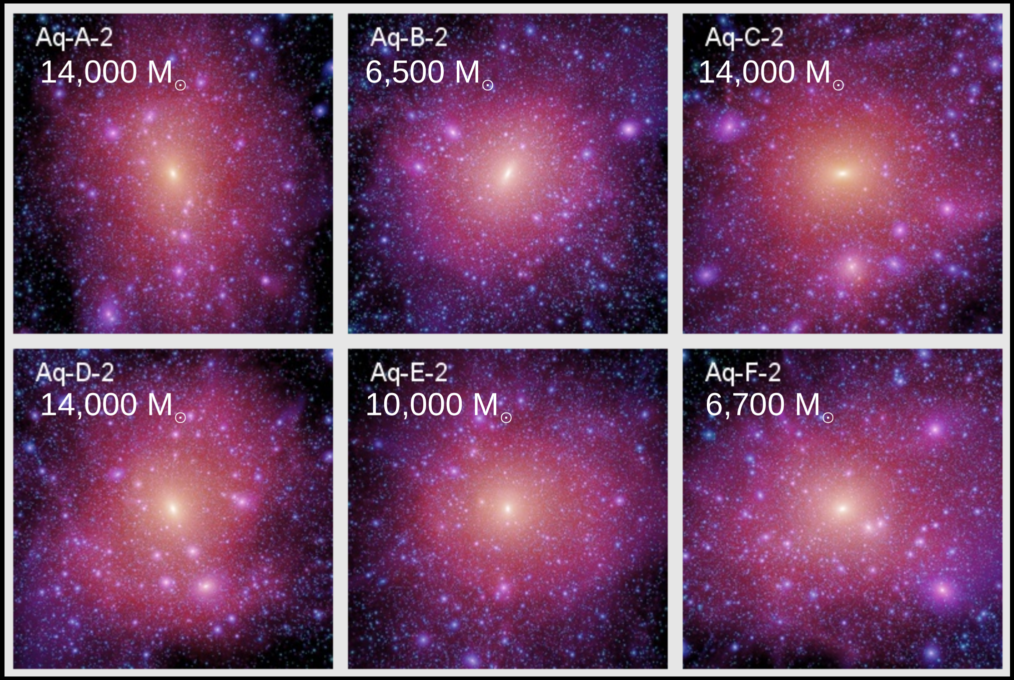
- Current state-of-the-art
  - ... of cosmological DM-only N-body simulations at the Galactic scale
- Examples of uses for DM question (past, present, and future)
  - Local Group dwarf galaxies (abundance, properties, formation history...)
  - Strong gravitational lensing effects
  - Direct detection experiments
  - Indirect detection efforts
  - Sommerfeld-enhanced subhalo annihilation signal
- Current limitations and future directions

The State-of-the-art in Cosmological DM-only N-Body Simulations

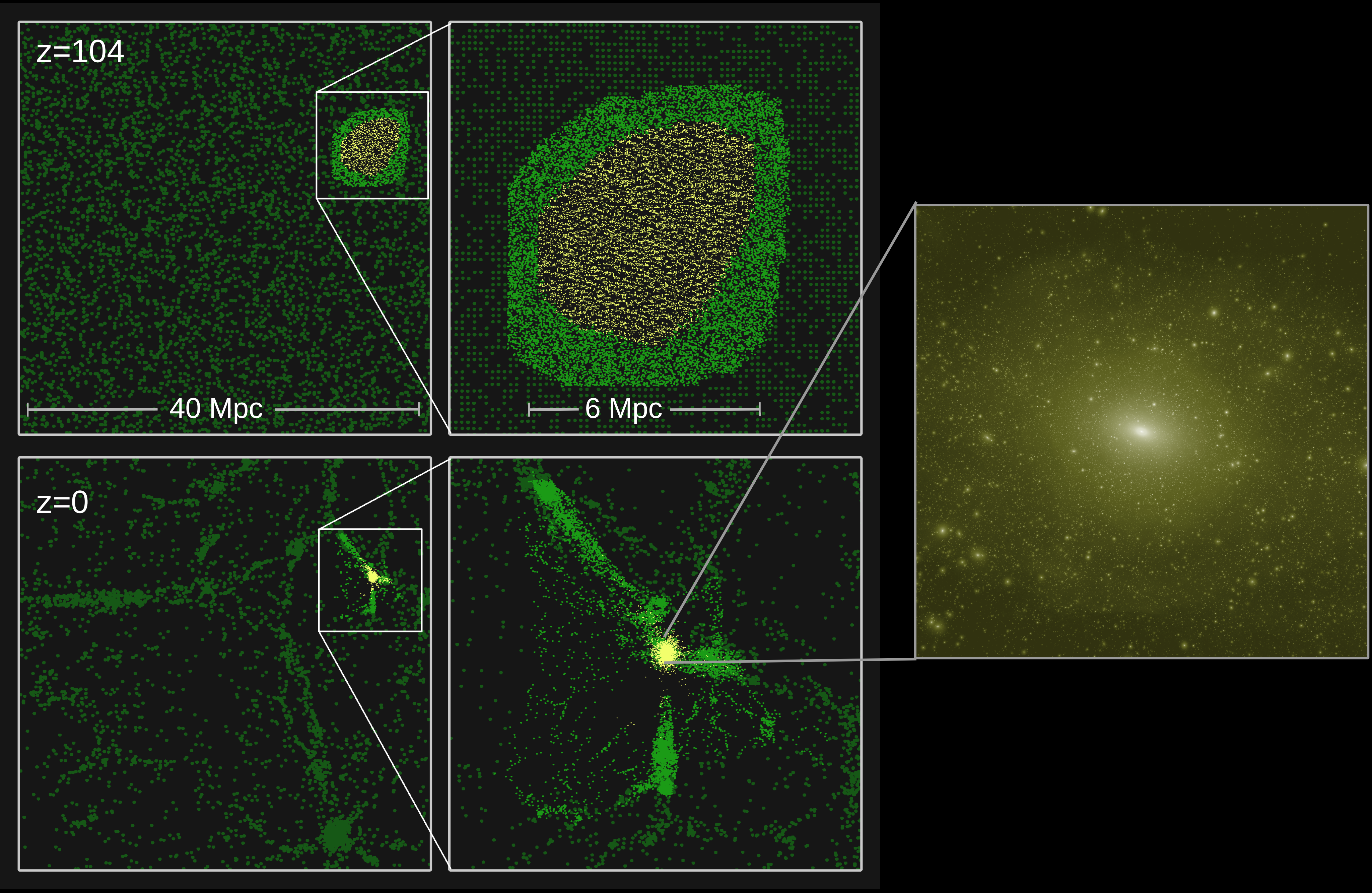






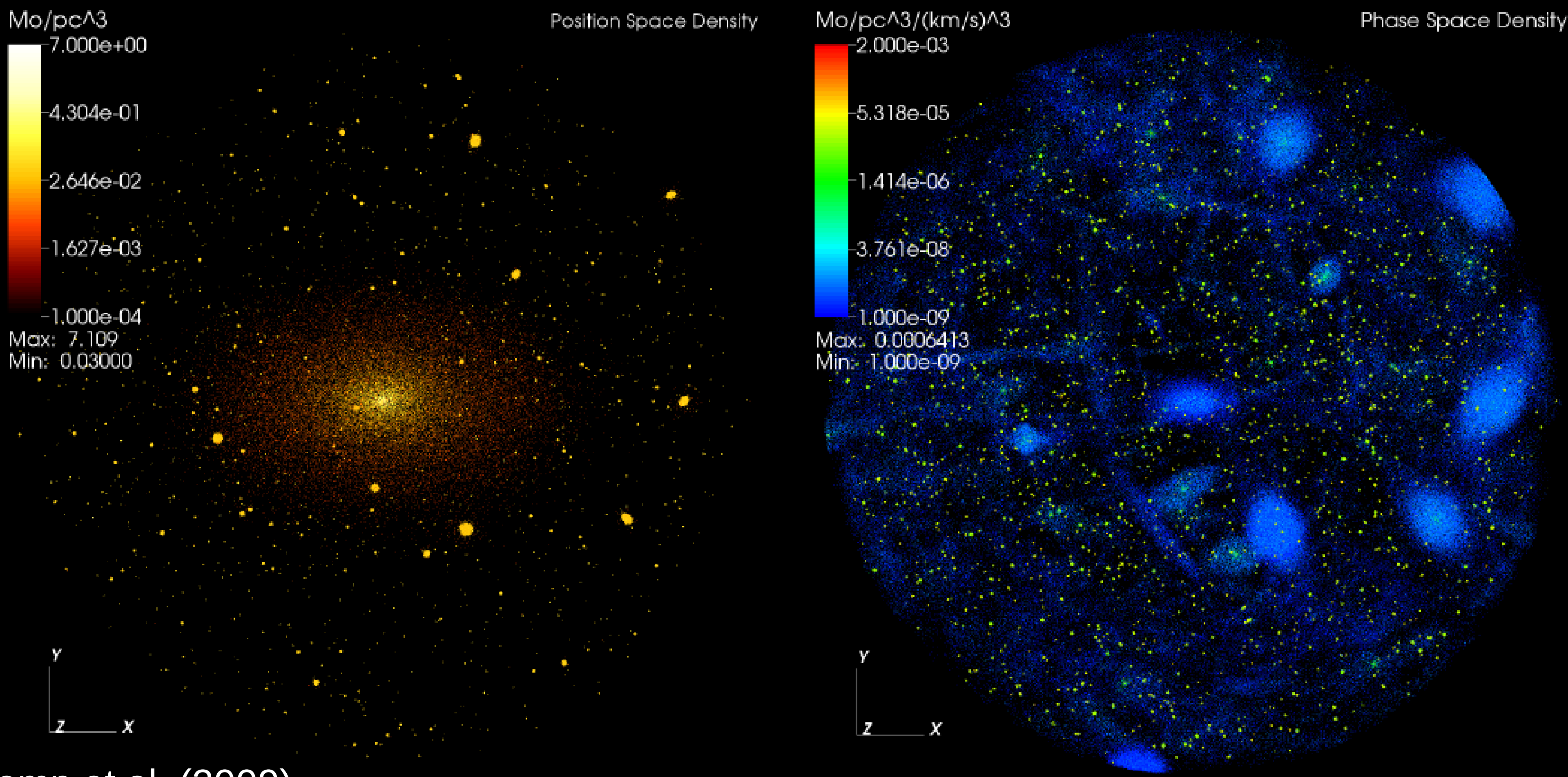


Multi-mass initial conditions



Via Lactea II – the inner 100 kpc

Whereas previous simulations were almost completely smooth in the central region, with VL-II we resolve lots of subhalos and tidal streams even down to 8 kpc.



Zemp et al. (2009)

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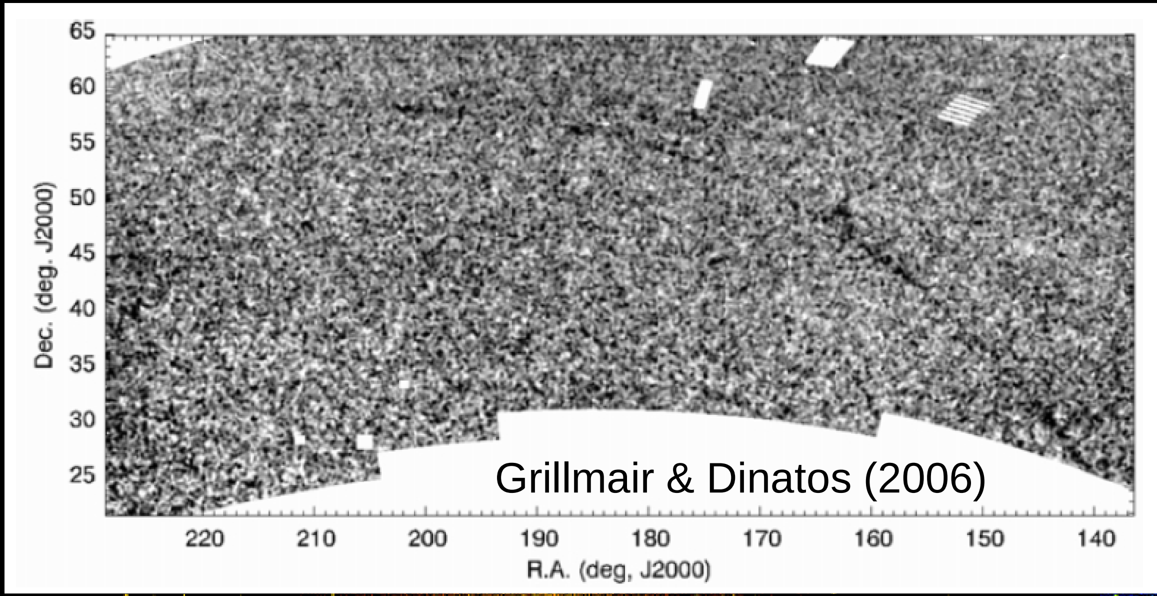

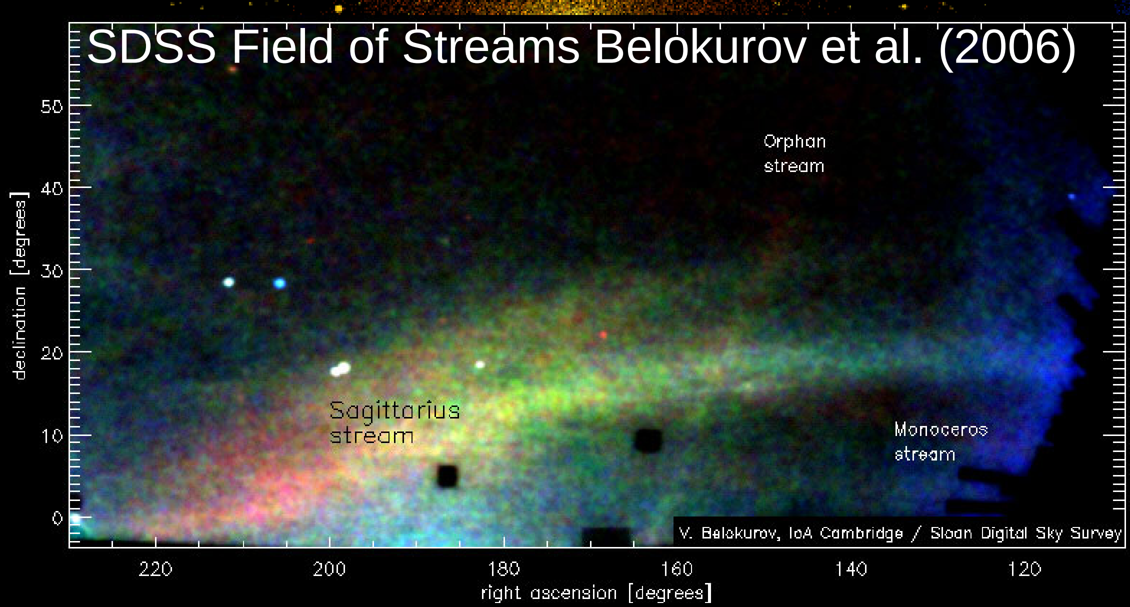

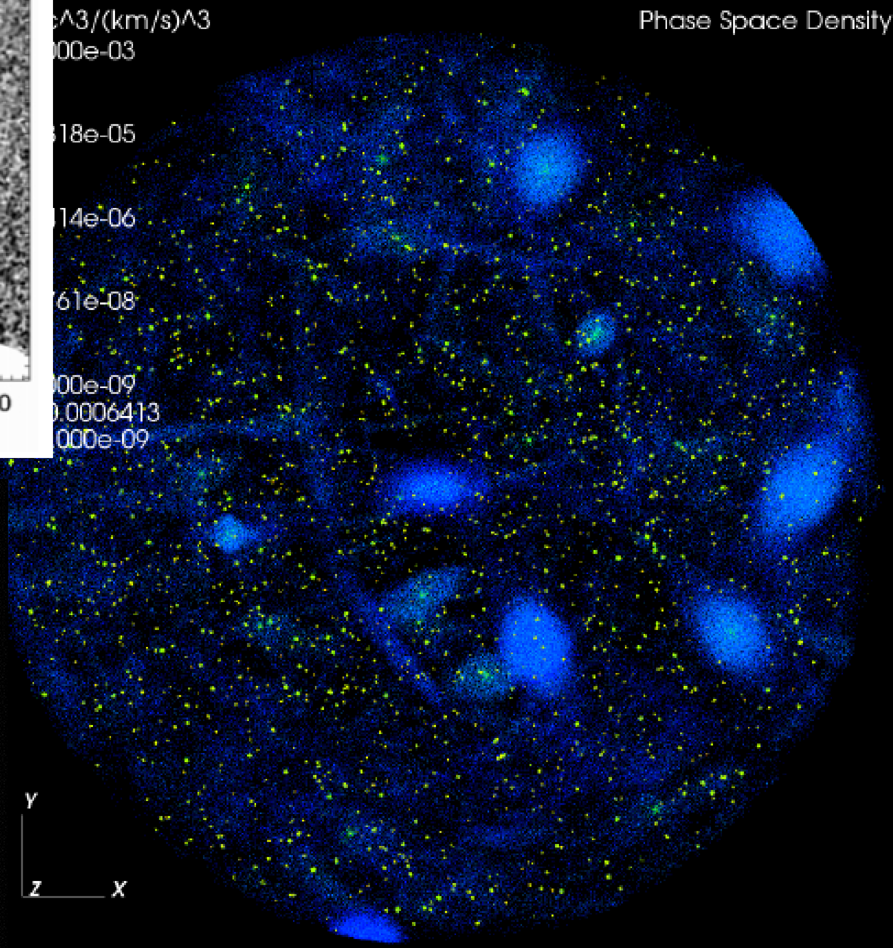

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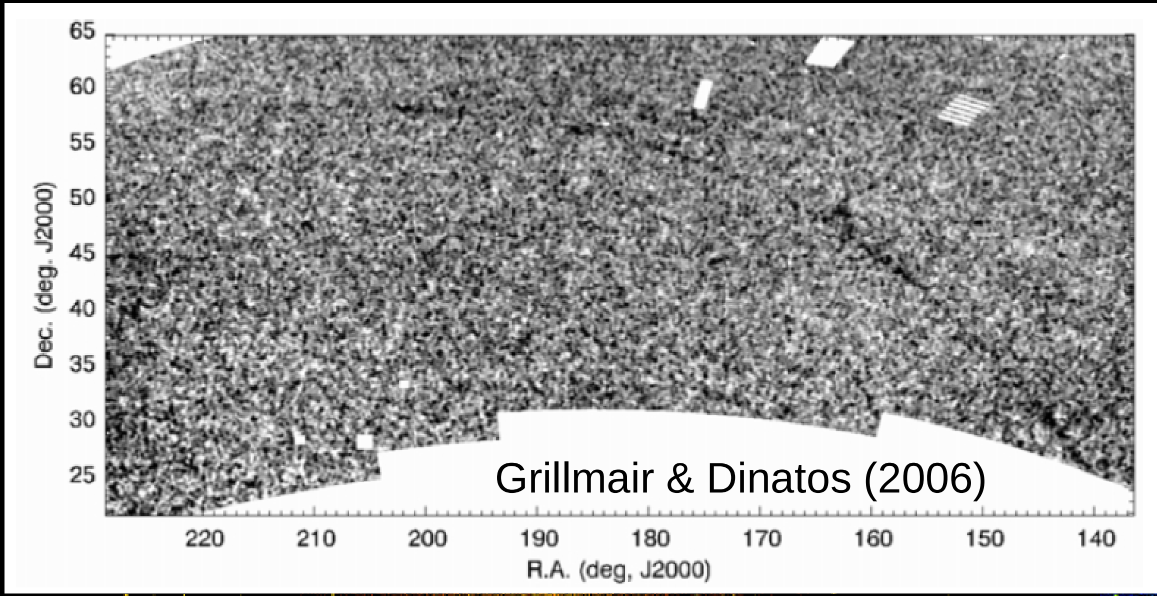
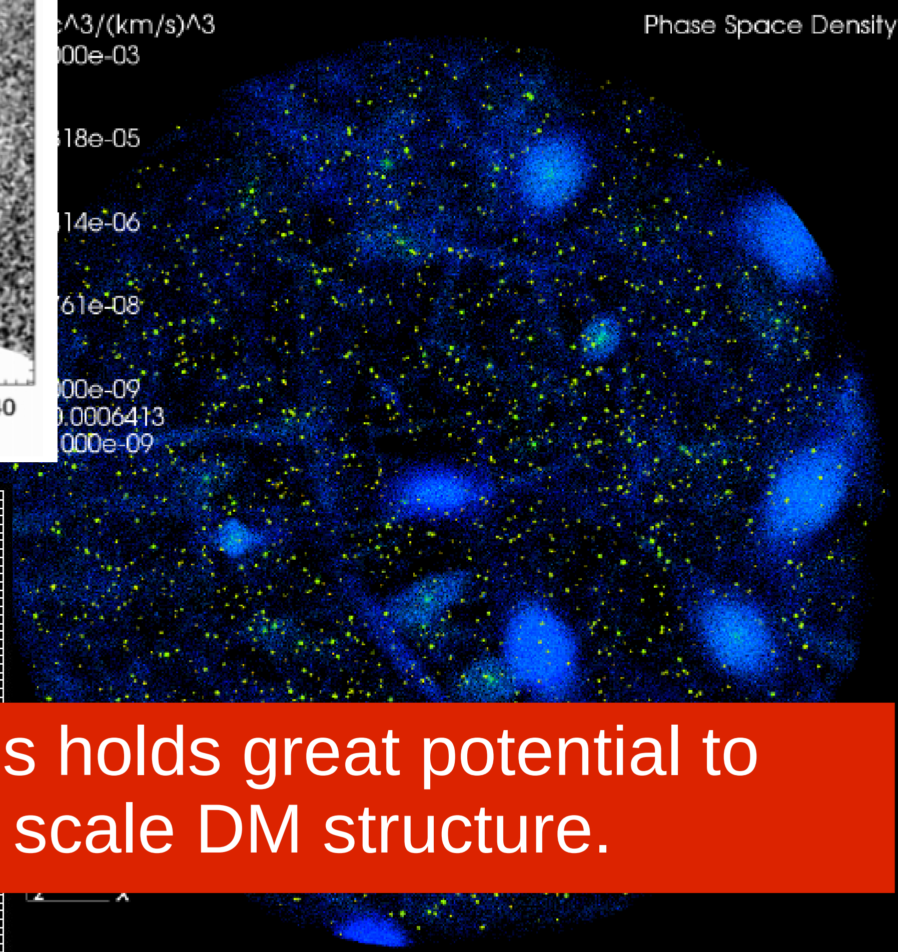
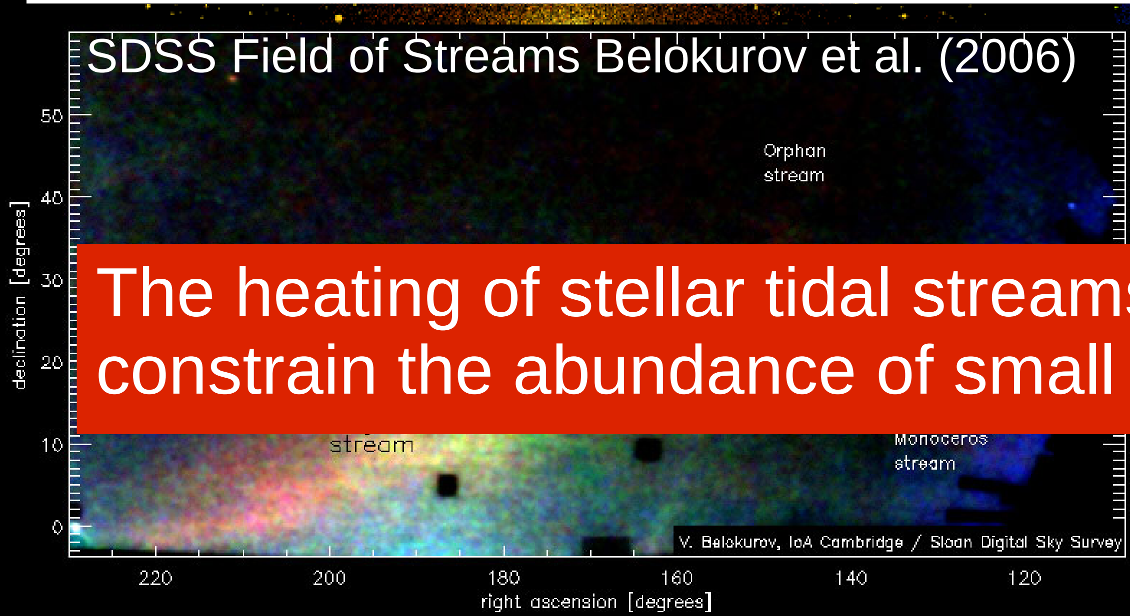
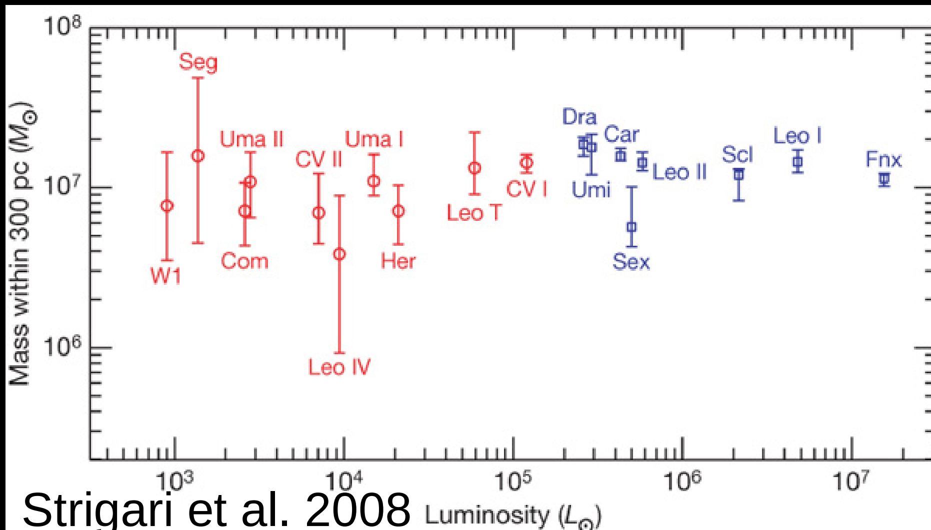






The heating of stellar tidal streams holds great potential to constrain the abundance of small scale DM structure.

Dwarf Spheroidal Satellite Galaxies



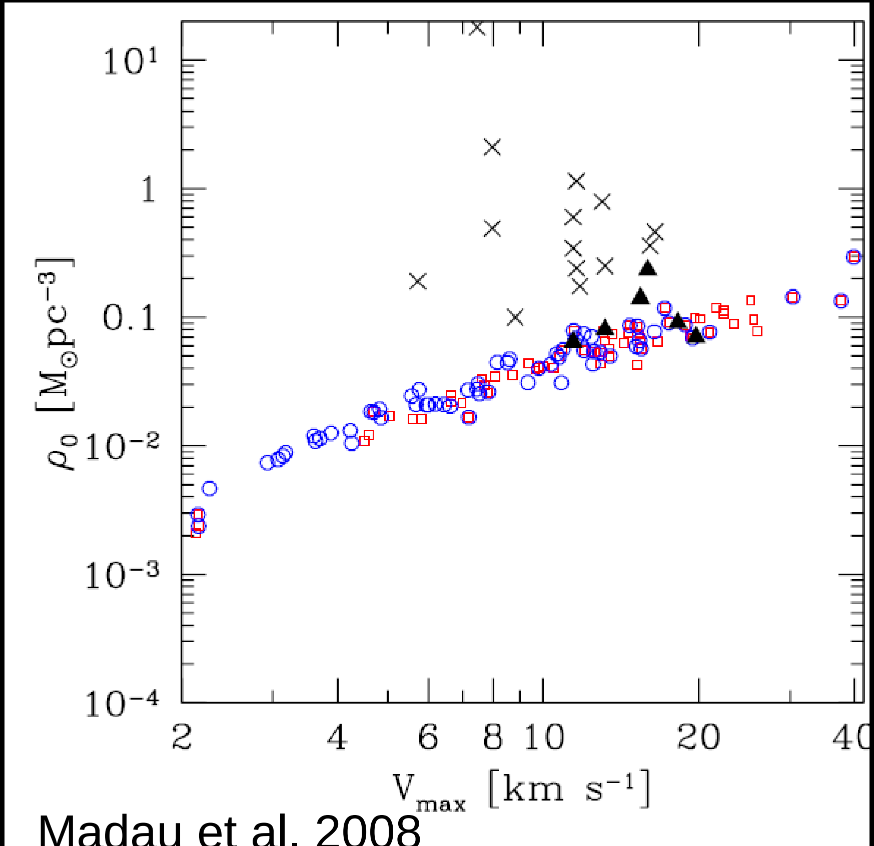
Strigari et al. 2008

Name	D [kpc]	$M_{0.3}$ [$10^7 M_\odot$]	V_{max} [km s^{-1}]	r_{Vmax} [kpc]	V_{peak} [km s^{-1}]	r_{Vpeak} [kpc]
Segue 1	23	$1.58^{+3.30}_{-1.11}$	$10\ \binom{17}{8.4}$	$0.43\ \binom{0.89}{0.29}$	$26\ \binom{55}{13}$	$2.4\ \binom{33}{1.4}$
Ursa Major II	32	$1.09^{+0.89}_{-0.44}$	$13\ \binom{17}{11}$	$0.59\ \binom{0.89}{0.31}$	$27\ \binom{33}{17}$	$3.3\ \binom{14}{2.4}$
Wilman 1	38	$0.77^{+0.89}_{-0.42}$	$8.3\ \binom{11}{7.5}$	$0.38\ \binom{0.62}{0.29}$	$15\ \binom{27}{10}$	$2.0\ \binom{3.9}{0.90}$
Coma Berenices	44	$0.72^{+0.36}_{-0.28}$	$9.1\ \binom{12}{8.2}$	$0.42\ \binom{0.62}{0.31}$	$15\ \binom{25}{11}$	$1.9\ \binom{3.4}{0.97}$
Ursa Minor	66	$1.79^{+0.37}_{-0.59}$	$18\ \binom{21}{15}$	$0.81\ \binom{1.8}{0.61}$	$30\ \binom{56}{21}$	$3.8\ \binom{9.7}{2.8}$
Draco	80	$1.87^{+0.20}_{-0.29}$	$19\ \binom{22}{17}$	$0.86\ \binom{2.4}{0.81}$	$28\ \binom{37}{26}$	$3.8\ \binom{32}{2.4}$
Sculptor	80	$1.20^{+0.11}_{-0.37}$	$13\ \binom{15}{12}$	$0.64\ \binom{1.0}{0.54}$	$20\ \binom{25}{16}$	$2.9\ \binom{5.6}{1.6}$
Sextans	86	$0.57^{+0.45}_{-0.14}$	$9.7\ \binom{12}{8.5}$	$0.52\ \binom{0.89}{0.37}$	$14\ \binom{19}{11}$	$1.6\ \binom{3.0}{0.97}$
Carina	101	$1.57^{+0.19}_{-0.10}$	$17\ \binom{22}{16}$	$1.00\ \binom{2.3}{0.69}$	$30\ \binom{42}{24}$	$3.8\ \binom{32}{3.3}$
Ursa Major I	106	$1.10^{+0.70}_{-0.29}$	$14\ \binom{17}{13}$	$0.84\ \binom{1.3}{0.61}$	$20\ \binom{30}{16}$	$3.2\ \binom{6.8}{1.6}$
Fornax	138	$1.14^{+0.09}_{-0.12}$	$15\ \binom{16}{14}$	$1.1\ \binom{1.3}{0.64}$	$20\ \binom{24}{18}$	$3.0\ \binom{6.1}{1.9}$
Hercules	138	$0.72^{+0.51}_{-0.21}$	$11\ \binom{14}{9.4}$	$0.69\ \binom{1.1}{0.45}$	$14\ \binom{20}{12}$	$1.9\ \binom{3.8}{1.2}$
Canes Venatici II	151	$0.70^{+0.53}_{-0.25}$	$11\ \binom{13}{8.9}$	$0.67\ \binom{1.1}{0.44}$	$14\ \binom{19}{11}$	$1.8\ \binom{3.7}{1.1}$
Leo IV	158	$0.39^{+0.50}_{-0.29}$	$5.0\ \binom{7.2}{4.2}$	$0.35\ \binom{0.57}{0.22}$	$6.7\ \binom{10}{5.0}$	$0.84\ \binom{1.7}{0.48}$
Leo II	205	$1.43^{+0.23}_{-0.15}$	$18\ \binom{21}{16}$	$1.5\ \binom{2.1}{0.93}$	$24\ \binom{28}{19}$	$4.1\ \binom{8.2}{2.4}$
Canes Venatici I	224	$1.40^{+0.18}_{-0.19}$	$18\ \binom{20}{16}$	$1.5\ \binom{2.1}{1.0}$	$22\ \binom{29}{18}$	$2.9\ \binom{6.1}{2.1}$
Leo I	250	$1.45^{+0.27}_{-0.20}$	$19\ \binom{21}{17}$	$1.7\ \binom{3.1}{1.1}$	$25\ \binom{27}{19}$	$2.9\ \binom{6.3}{2.1}$
Leo T	417	$1.30^{+0.88}_{-0.42}$	$16\ \binom{21}{13}$	$1.2\ \binom{2.4}{0.85}$	$19\ \binom{26}{17}$	$2.4\ \binom{6.1}{1.6}$

Kuhlen 2009

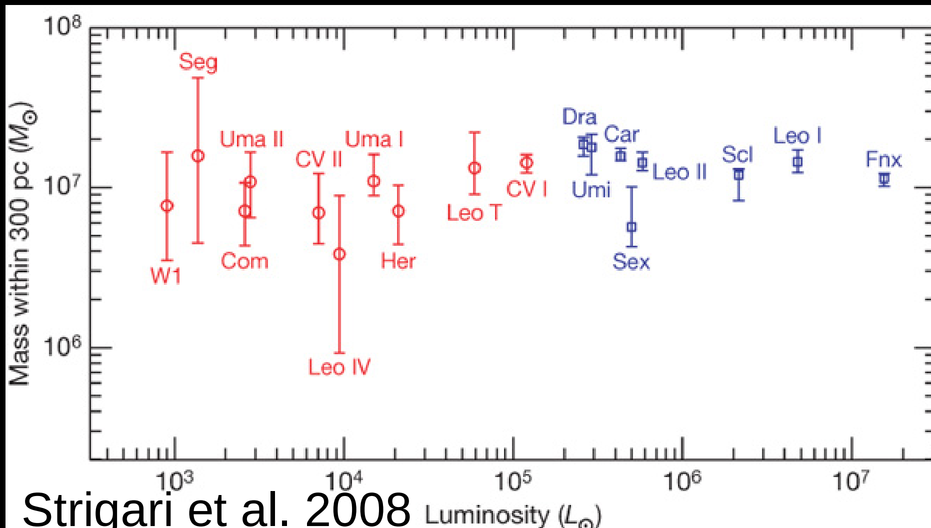
Central masses and densities within ~300 pc are well constrained observationally and in the numerical simulations.

This will allow **direct tests of CDM** theory!



Madau et al. 2008

Dwarf Spheroidal Satellite Galaxies



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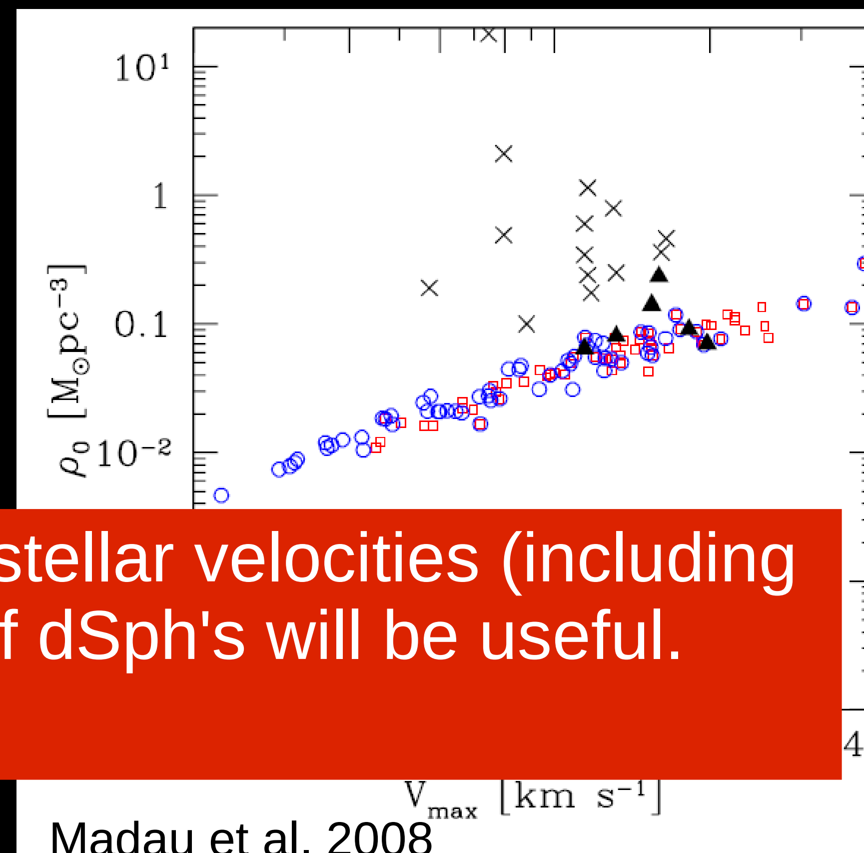
Kuhlen 2009

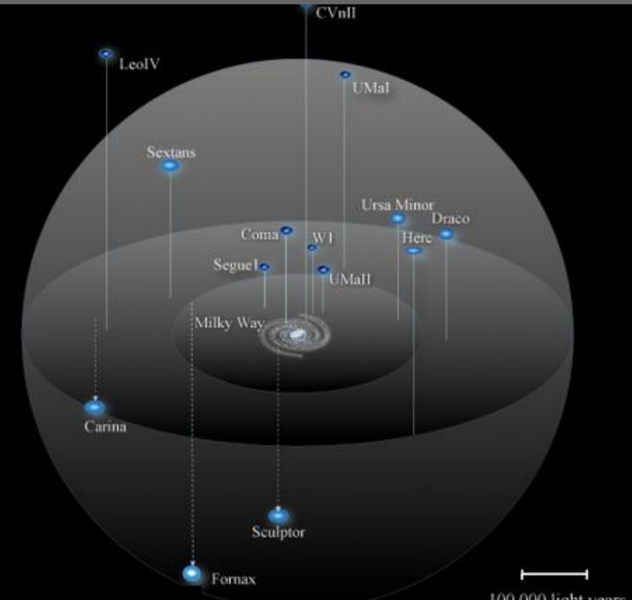


Madau et al. 2008

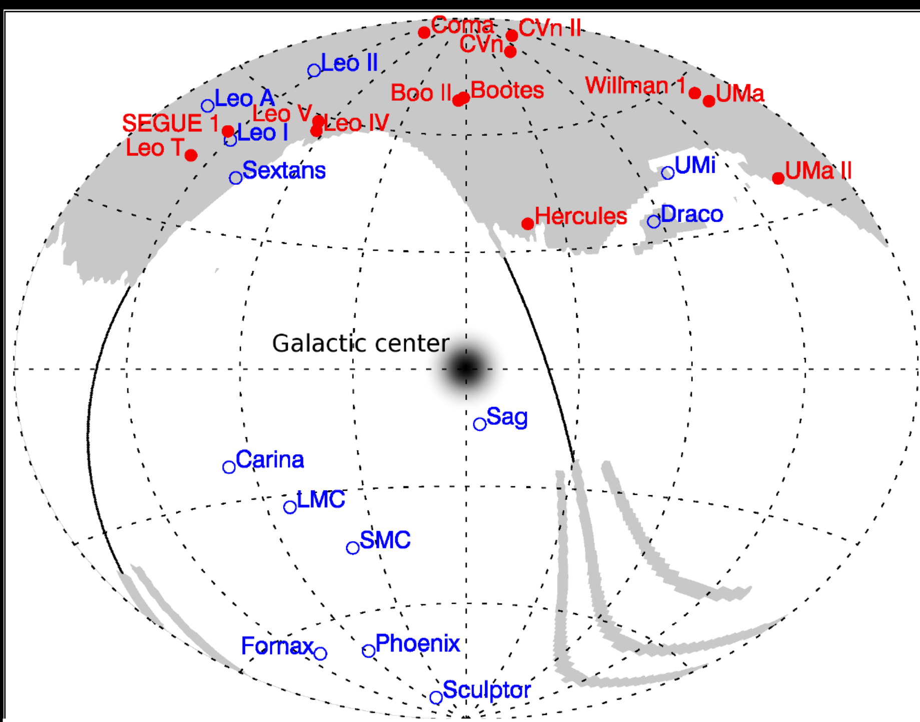
More and better measurements of stellar velocities (including proper motions?!?) in the centers of dSph's will be useful.

Higher resolution simulations, too.

The *Missing Satellites “Problem”*...



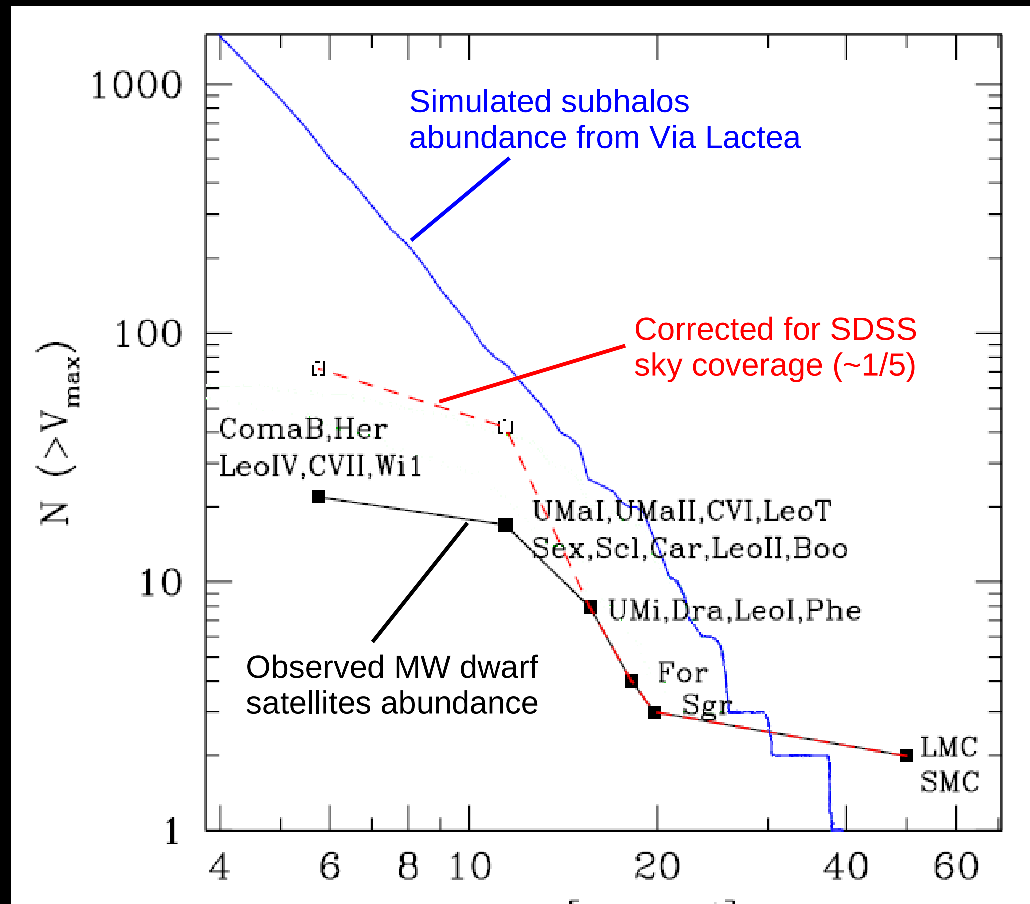
Bullock, Geha, & Powell



Walsh, Wilman, & Jerjen (2008)

There appears to be a discrepancy between the number of luminous satellites and the number of dark matter halos predicted from simulation.

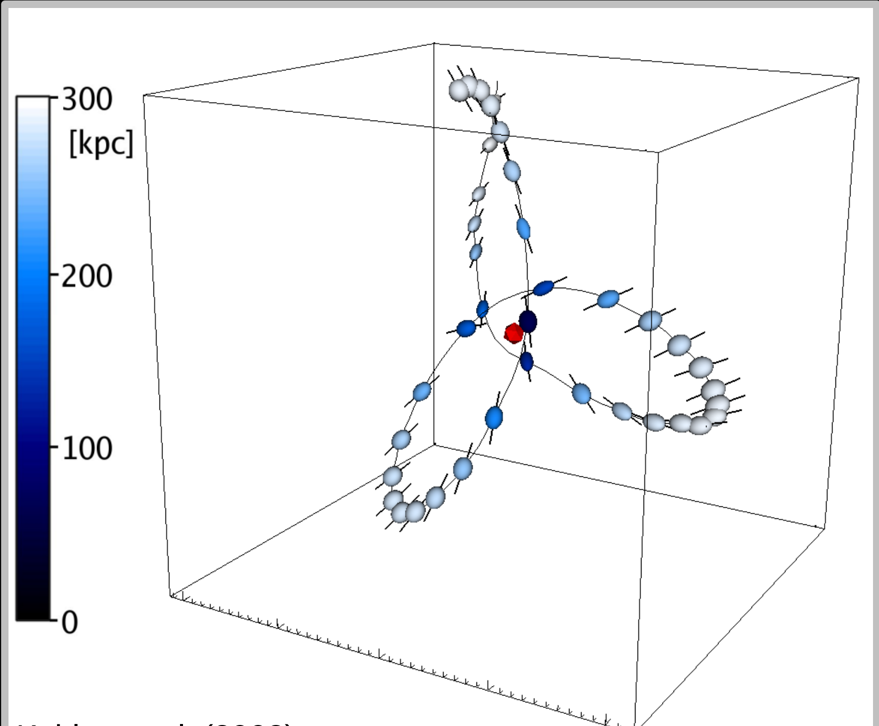
Solutions: Observational Completeness? Astrophysics? Particle physics?



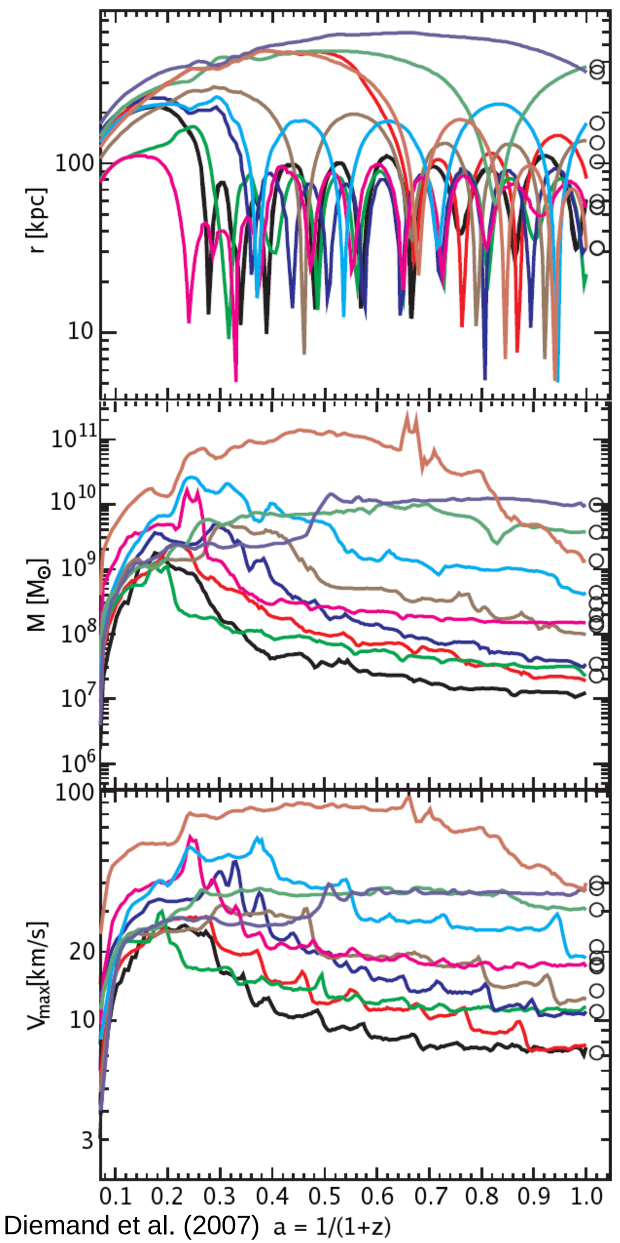
Madau et al. (2008)

The Subhalo Population – Tidal Mass Loss

- Subhalos orbit through host halo and are subject to tidal interactions.
- Strongest during peri-center passage.
- Tidal mass loss from outside in.
- Diverse amount of tidal mass loss.
- Reduces M_t, V_{max}, R_{Vmax}.



Kuhlen et al. (2008)



Diemand et al. (2007)

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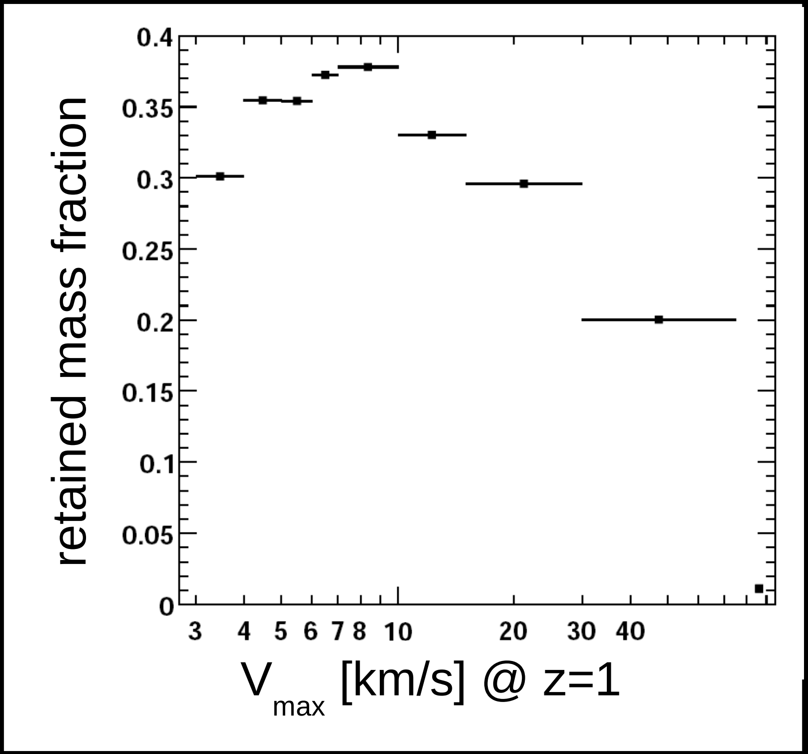
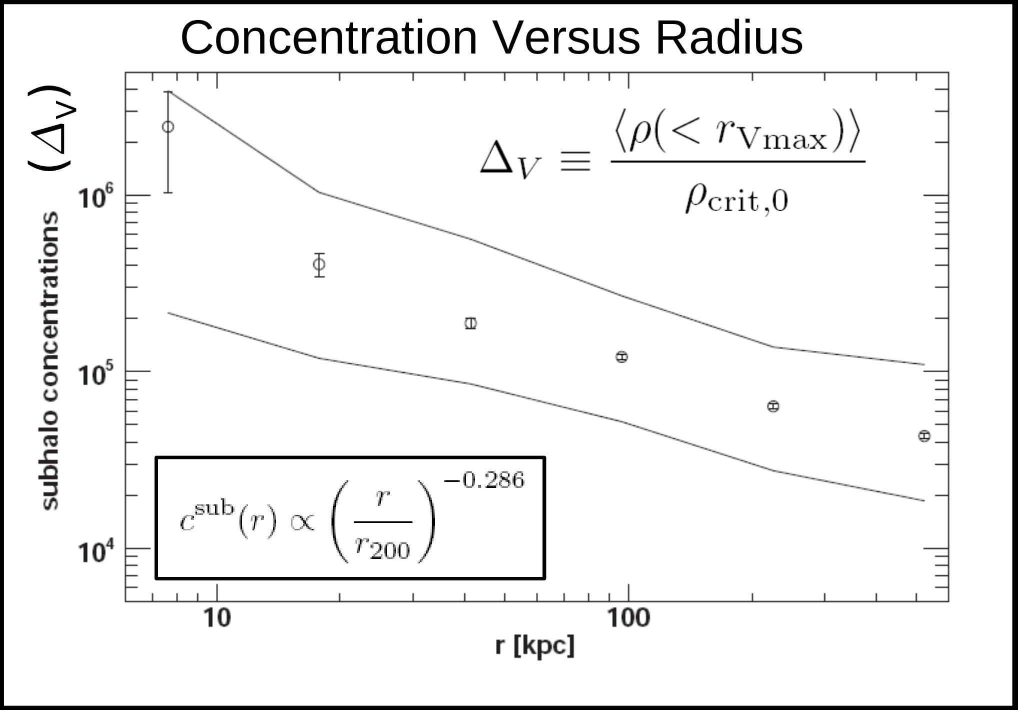
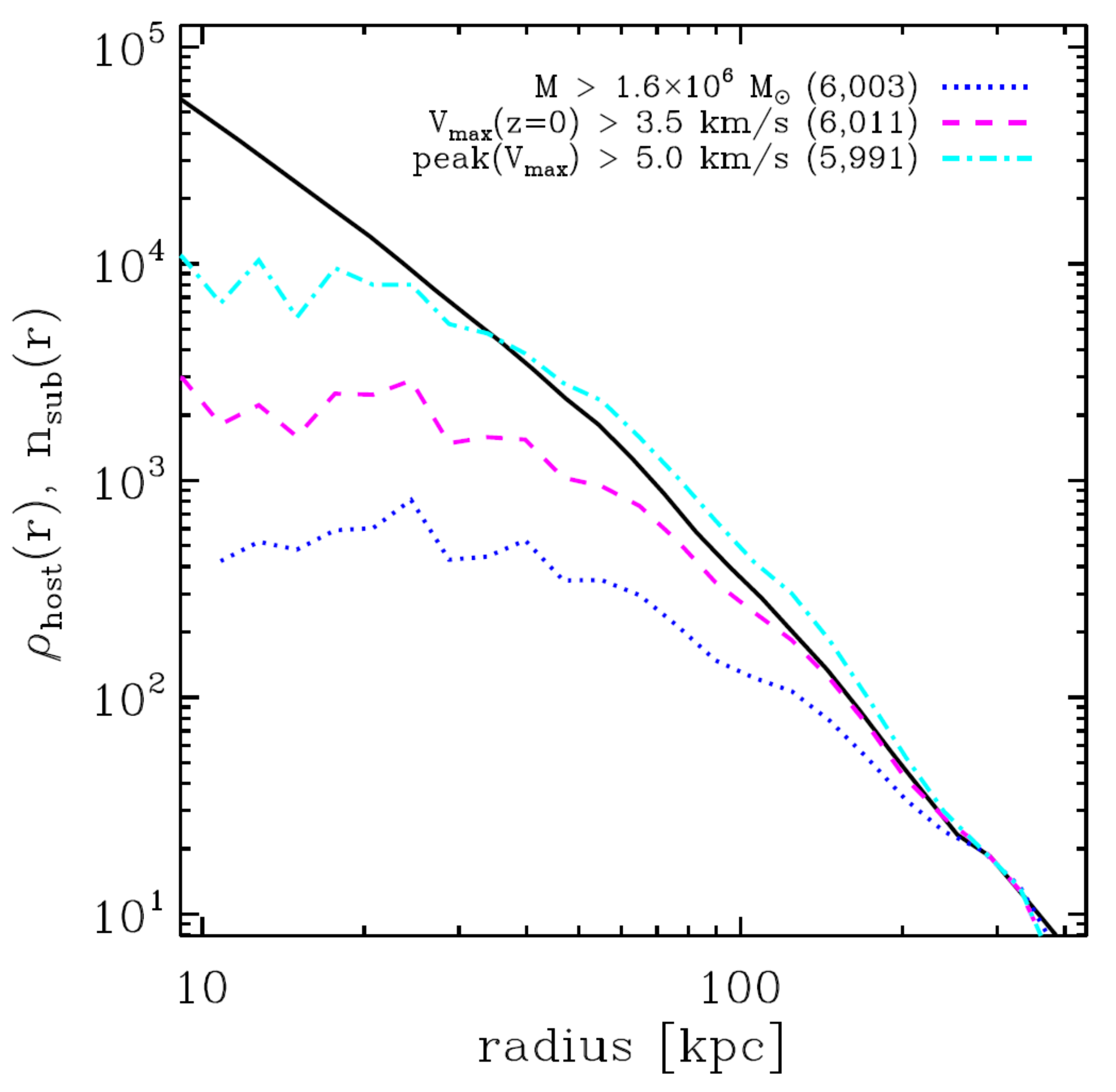




- Tidal mass loss is stronger for more massive halos (higher V_{max} @ z=1).
- Halos with V_{max}=10 km/s retain about 40% of their mass from z=1 to today.
- 97% of all z=1 subhalos still have an identifiable remnant at z=0.

- Subhalos are more concentrated in the inner regions.
- This due to both tidal stripping and an earlier formation time.
- c(r=8kpc) $\approx$ 3 $\times$ c(field)

The Subhalo Population – Spatial Distribution



The subhalo radial distribution is **anti-biased** with respect to the DM density: fewer subhalos in the center.

(cf. Ghigna et al. 2000; de Lucia et al. 2004)

Depends on selection:

- strongest for M(z=0)-selected,
- weaker for Vmax(z=0)-selected,
- disappears down to ~30 kpc for peak(Vmax)-selected.

(cf. Nagai & Kravtsov 2005; Faltenbacher & Diemand 2006)

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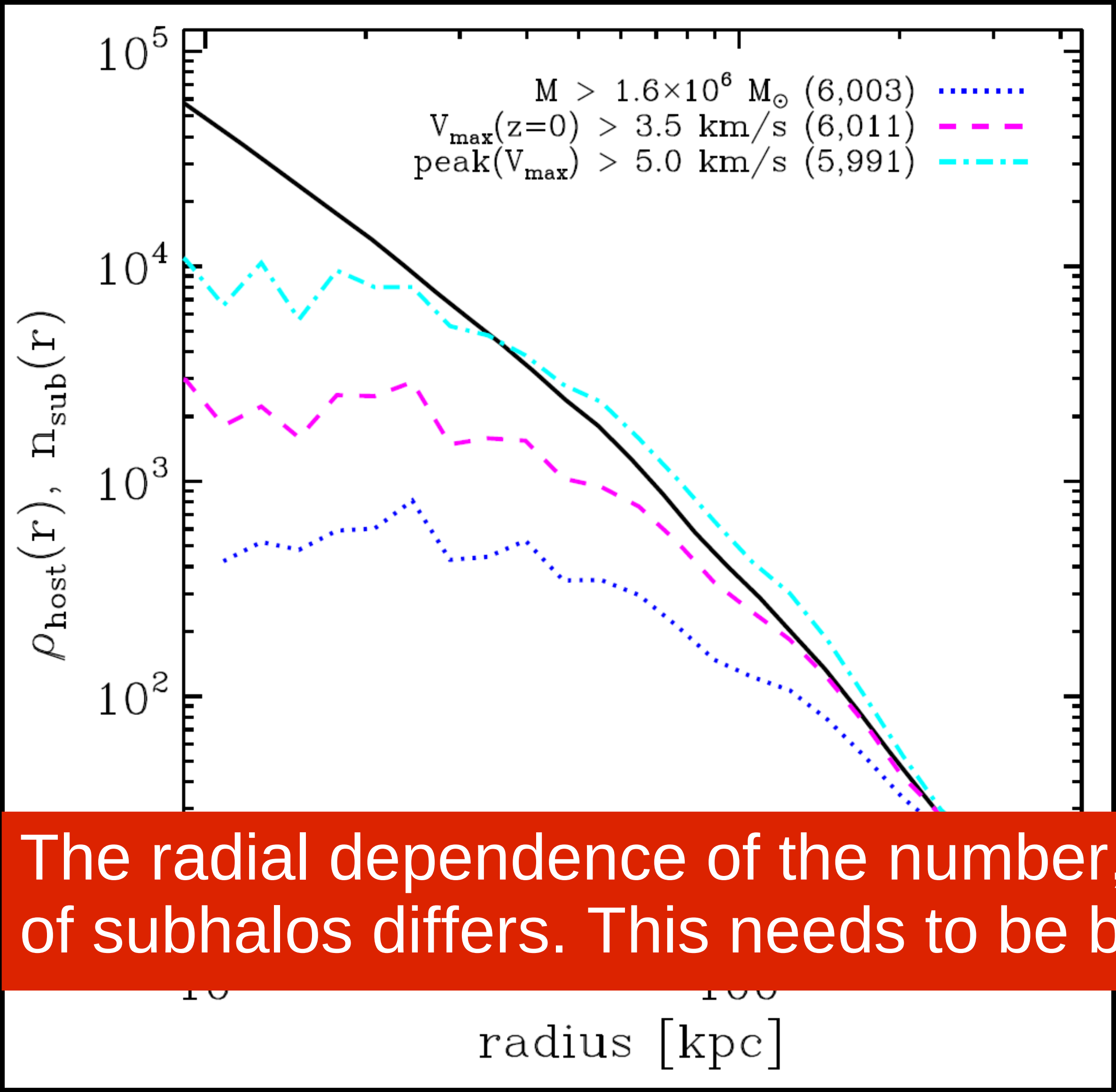

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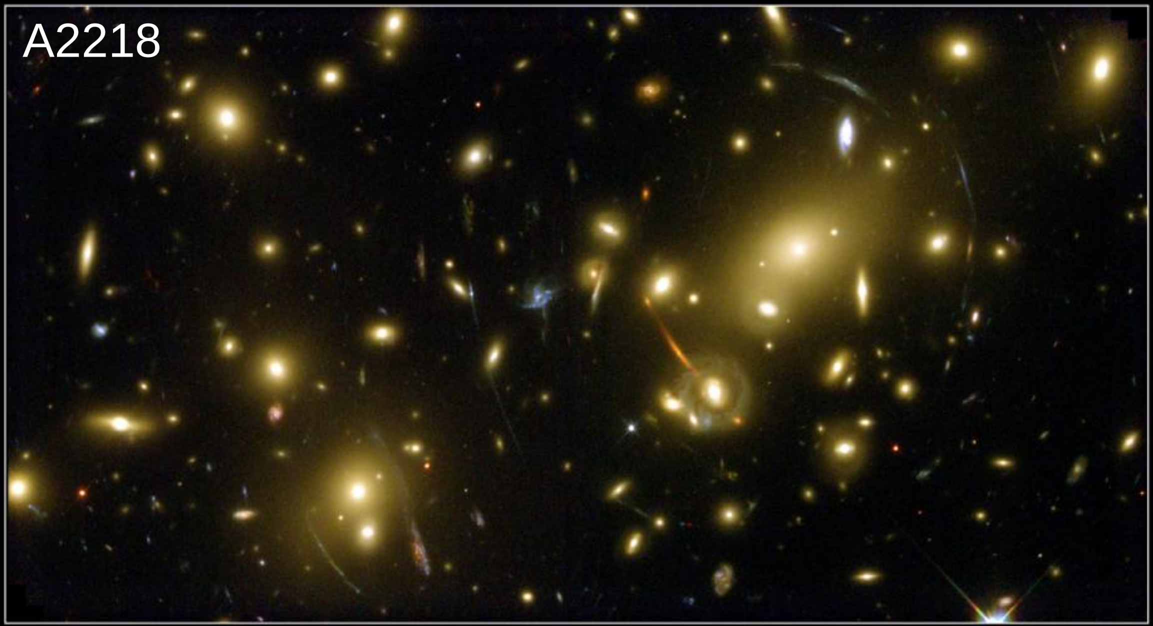
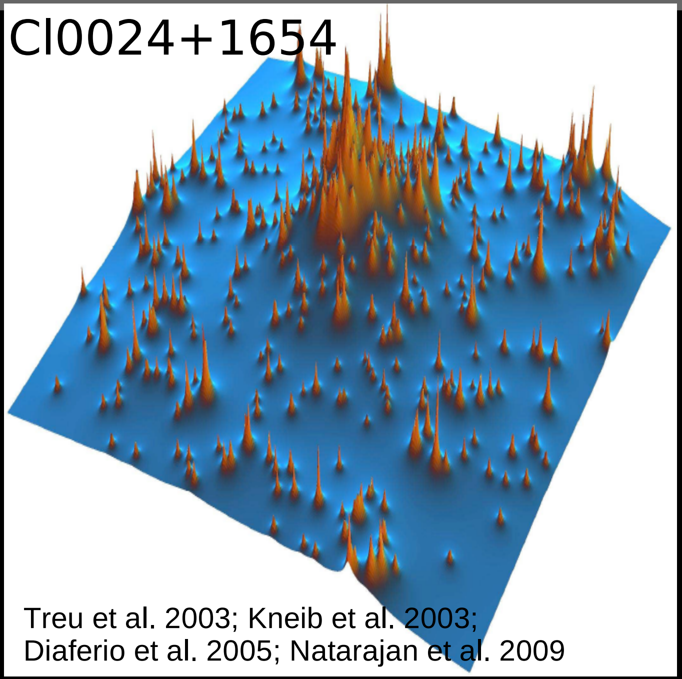
&

The radial dependence of the number, mass, and luminosity of subhalos differs. This needs to be better understood.

Strong Gravitational Lensing Effects



Cl0024+1654



Treu et al. 2003; Kneib et al. 2003;
Diaferio et al. 2005; Natarajan et al. 2009

Flux ratio anomalies

(Metcalf & Madau 2001, Dalal & Kochanek 2002, etc.)

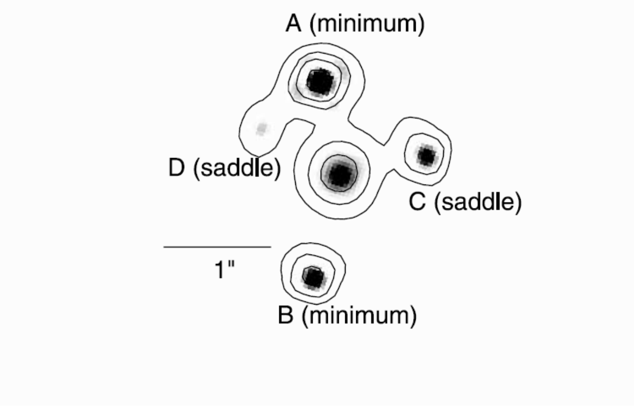
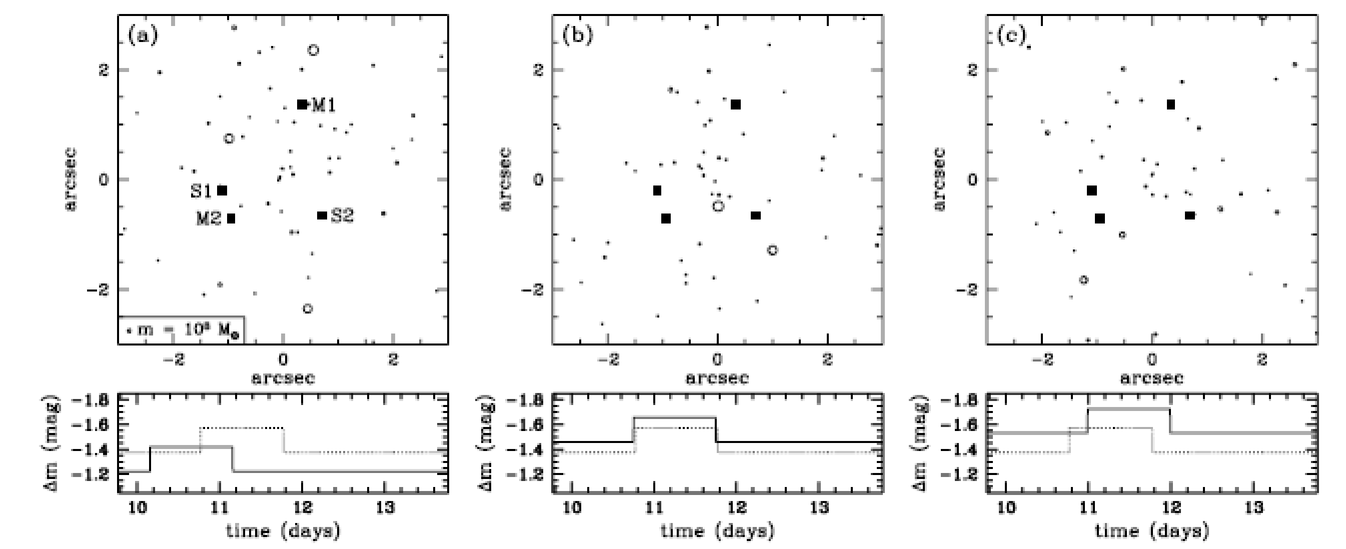
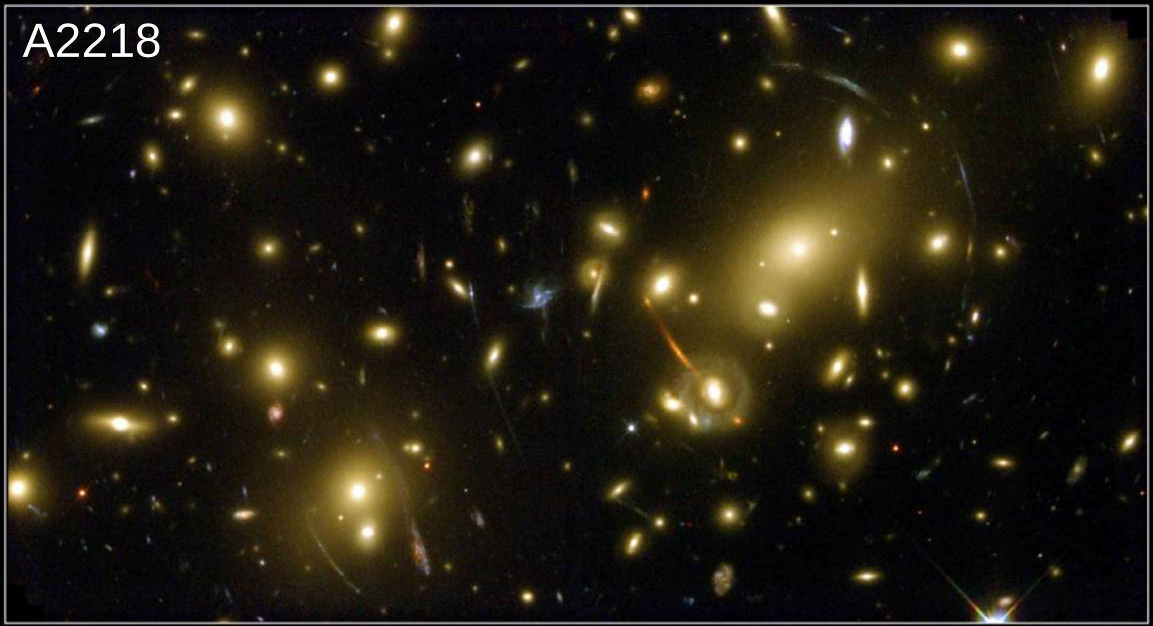


FIG. 2.—The most spectacular example of a suppressed saddle point, SDSS J0924+0219 (Inada et al. 2003). The D image should be comparable in brightness to the A image, but is actually an order of magnitude dimmer. The A and B images are minima, while C and D are saddle points. The contours are spaced by factors of 2 from the peak of the A image. The lens galaxy is seen at the center. In this infrared image, the suppression of the saddle point could be due to either microlensing or substructure.

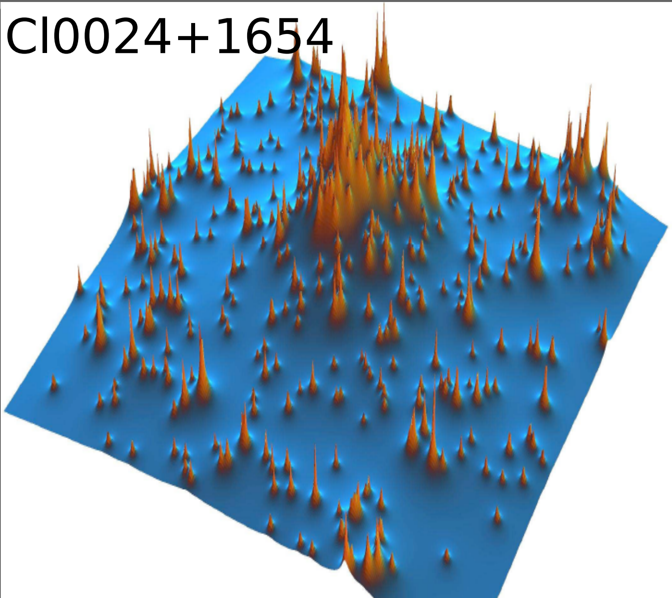
Time delay perturbations



Strong Gravitational Lensing Effects



Cl0024+1654



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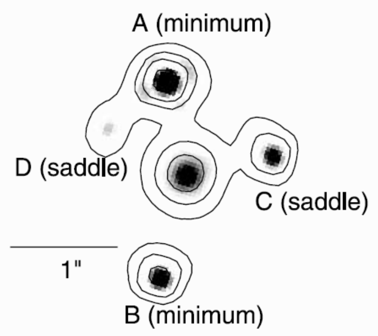

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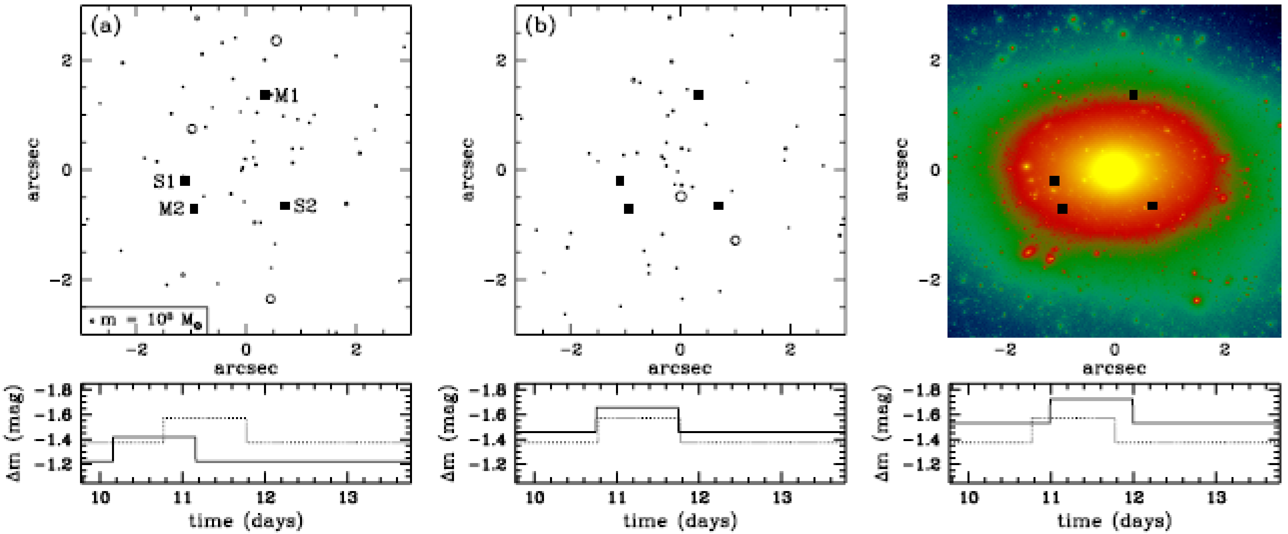
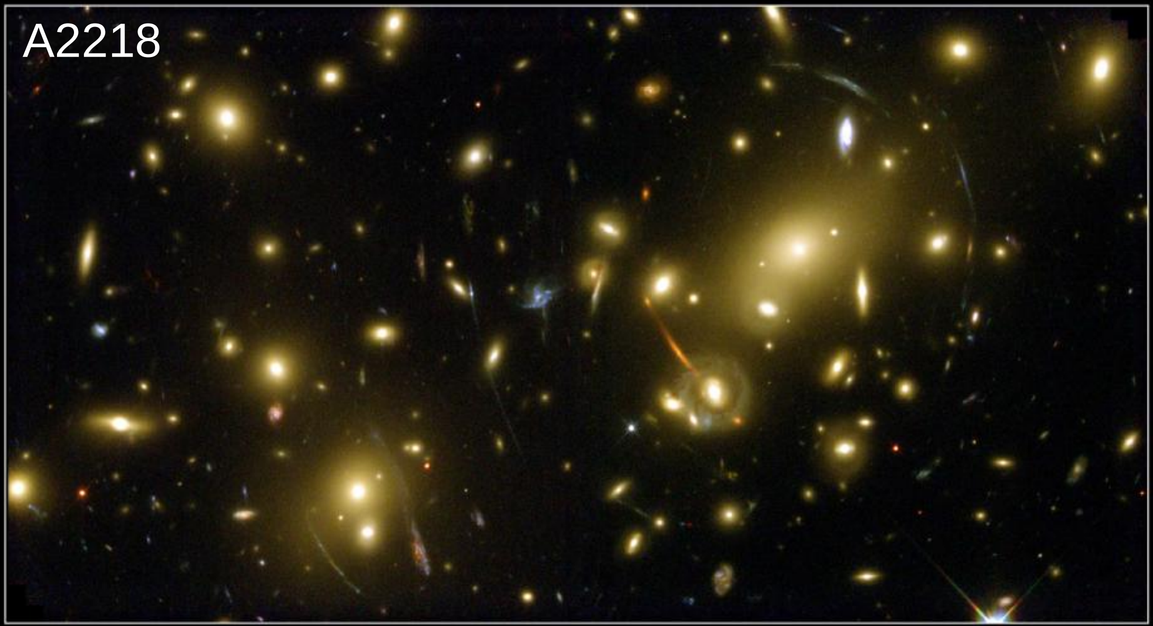
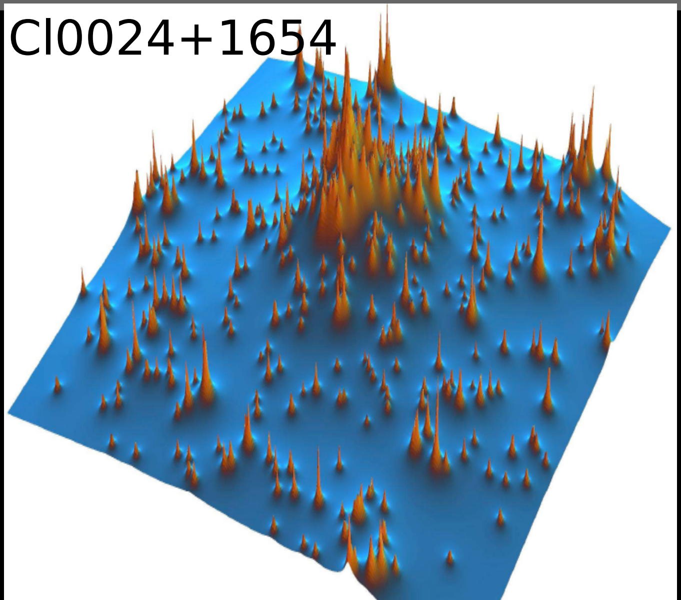
Time delay perturbations

KEETON & MOUSTAKAS



Strong Gravitational Lensing Effects





Treu et al. 2003; Kneib et al. 2003;
Diaferio et al. 2005; Natarajan et al. 2009

Flux ratio anomalies

(Metcalf & Madau 2001, Dalal & Kochanek 2002, etc.)

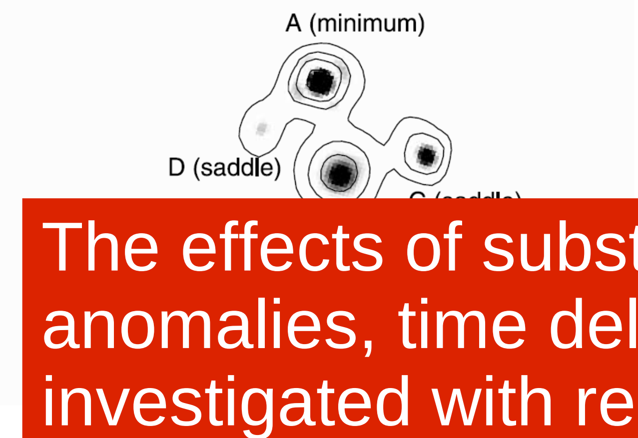
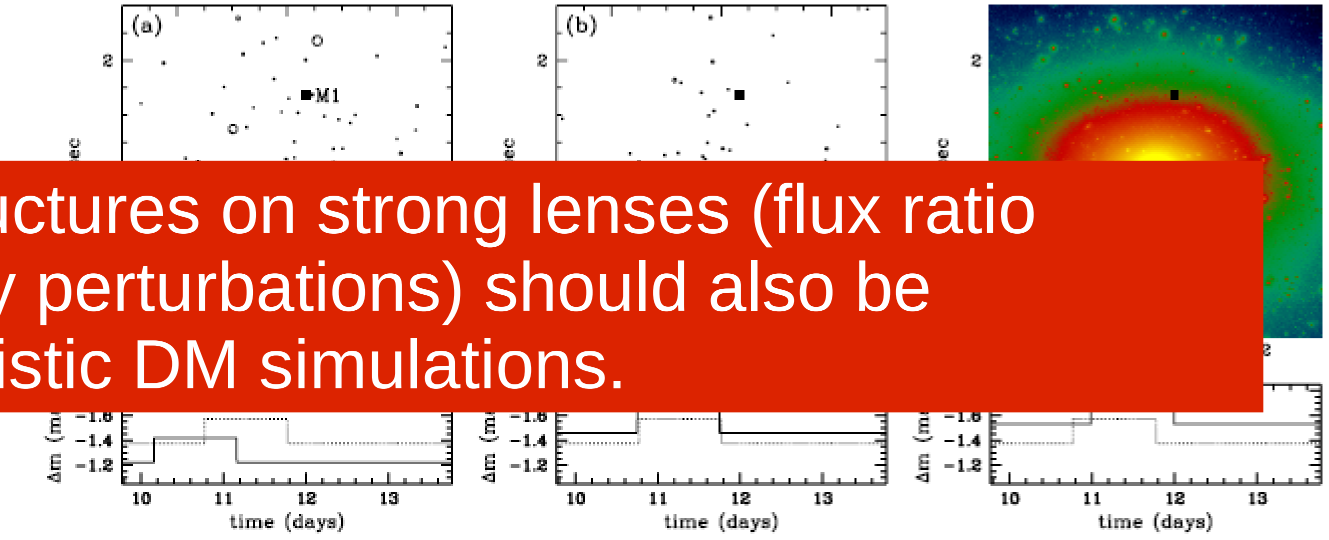


FIG. 2.— The most spectacular example of a suppressed saddle point, SDSS J0924+0219 (Inada et al. 2003). The D image should be comparable in brightness to the A image, but is actually an order of magnitude dimmer. The A and B images are minima, while C and D are saddle points. The contours are spaced by factors of 2 from the peak of the A image. The lens galaxy is seen at the center. In this infrared image, the suppression of the saddle point could be due to either microlensing or substructure.

Time delay perturbations

KEETON & MOUSTAKAS



The effects of substructures on strong lenses (flux ratio anomalies, time delay perturbations) should also be investigated with realistic DM simulations.

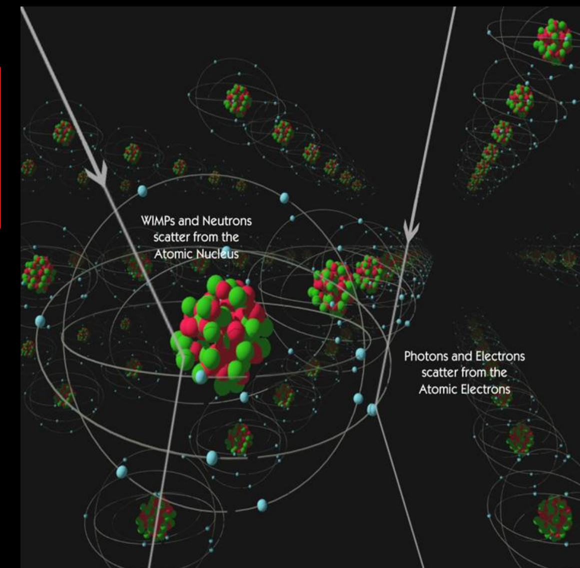
Direct Detection

The scattering event rate (events/recoil energy) is given by:

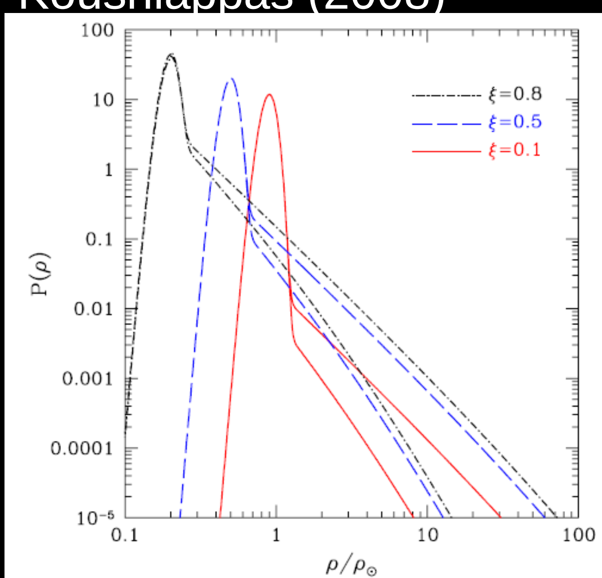
$$\frac{dR}{dE_R} = N_T M_N \frac{\boxed{\rho_\chi}\,\sigma_n}{2 m_\chi \mu_{ne}^2} \frac{(f_p Z + f_n(A-Z))^2}{f_n^2} F^2[E_R] \boxed{\int_{\beta_{min}}^{\infty} \frac{f(v)}{v} dv}$$

This depends on the local DM density ρ_χ and the velocity distribution function f(v).

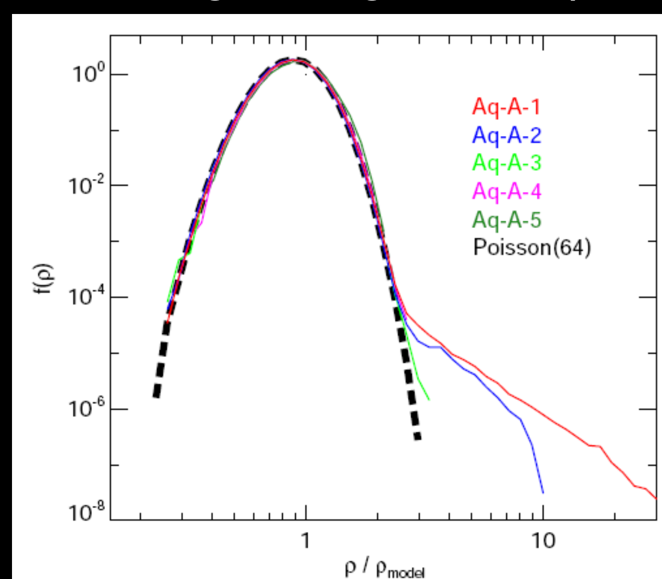
A typical assumption is ρ_χ=0.3 GeV/cm^3 and f(v) a Maxwellian with σ = 220 km/s truncated at an escape speed of 500-600 km/s.



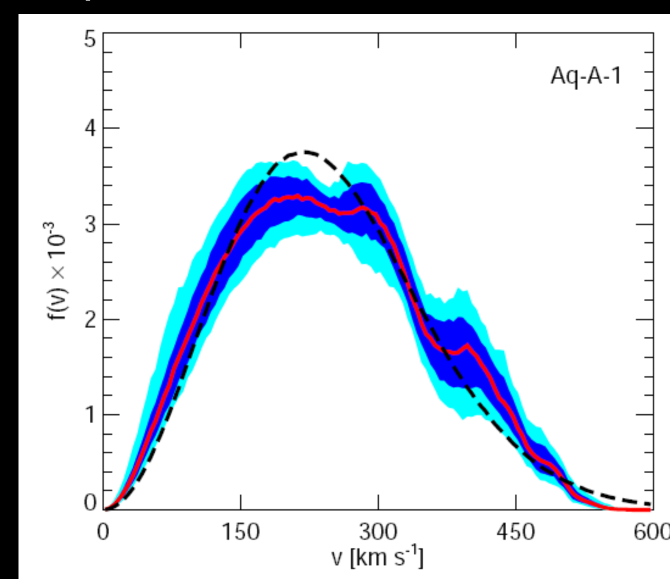
Kamionkowski & Koushiappas (2008)



Vogelsberger et al. (2009)

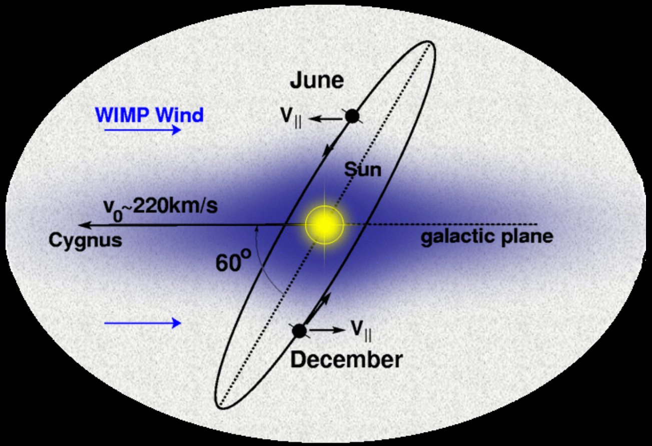


Aquarius Simulations

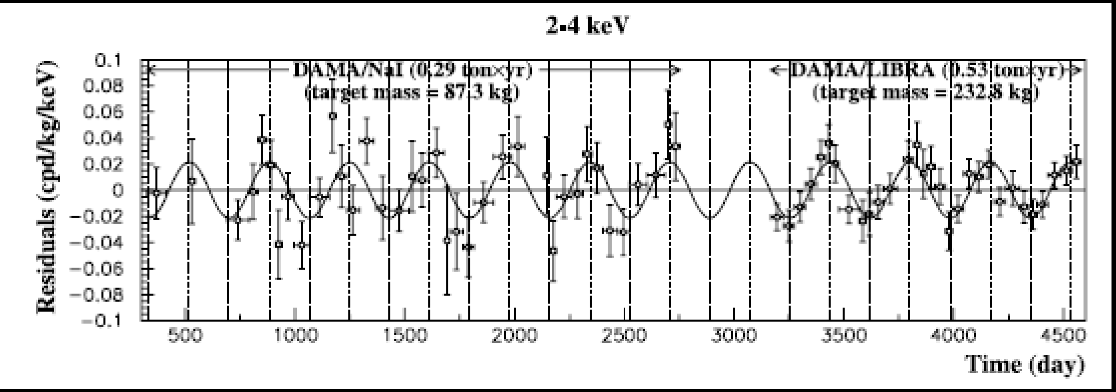


The DAMA controversy

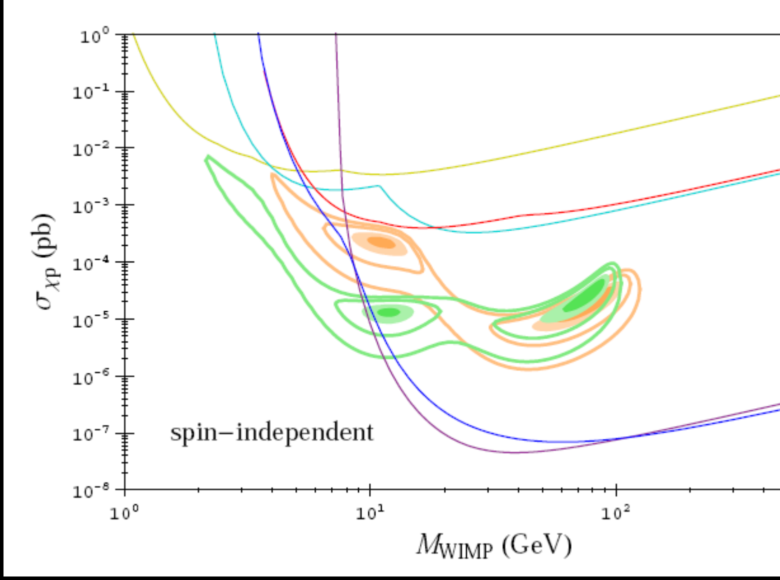
An **annual modulation** of the scattering rate is expected, owing to the motion of the Earth around the Sun, which itself is moving through a Galactic DM “wind”.



The DAMA collaboration has a reported an **8-σ detection** of this modulation and interpreted it as WIMP scattering.

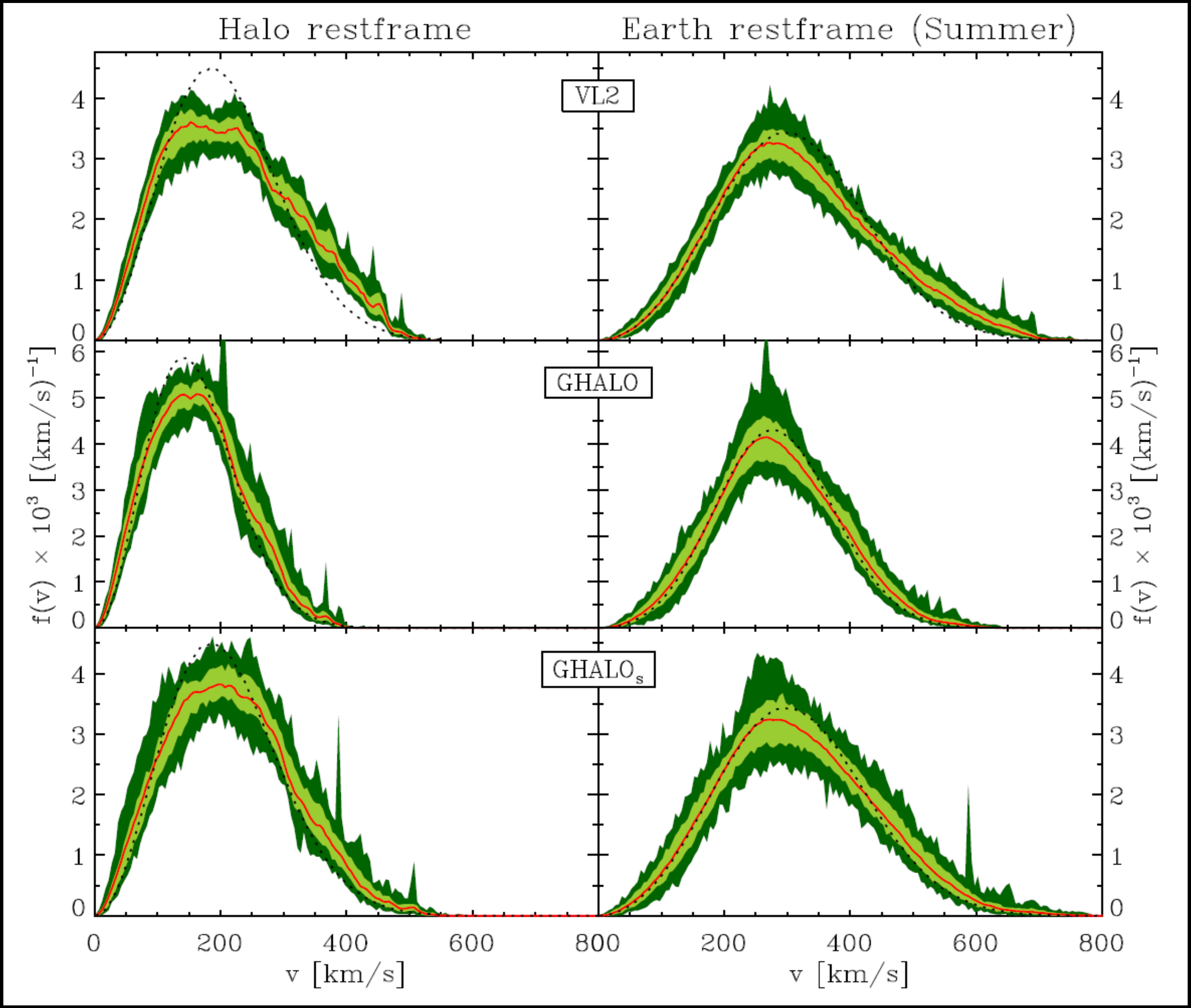


Conventional DM models that fit the DAMA result appear to excluded by other experiments!



Savage et al. (2008)

Velocity Distribution in Via Lactea/GHALO



Inelastic Dark Matter

Inelastic Dark Matter (Tucker-Smith & Weiner 2001) provides one way to **reconcile DAMA with other experiments**.

iDM is a simple extension of standard WIMP DM, with 2 new properties:

1) the DM particle χ **has an excited state χ*** with $m_{\chi^*}-m_\chi = \delta$ ~100 keV
2) **only inelastic scattering** is permitted: $\chi\,N \rightarrow \chi^*\,N$

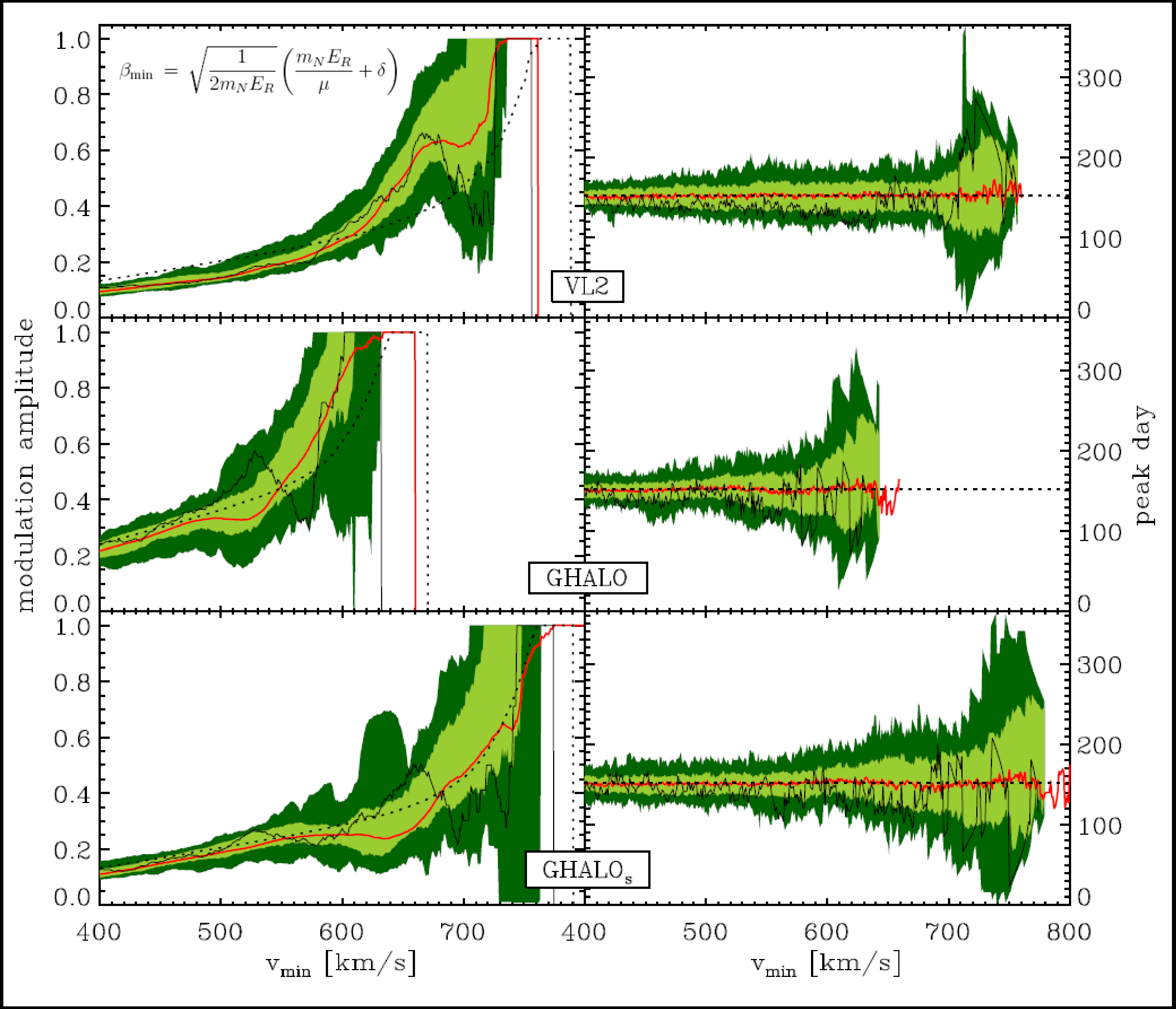
Only encounters with enough kinetic energy to excite the DM particle will lead to scattering:

$$\boxed{\beta_{\min} = \sqrt{\frac{1}{2m_N E_R}}\left(\frac{m_N E_R}{\mu} + \delta\right)}$$

Consequences:

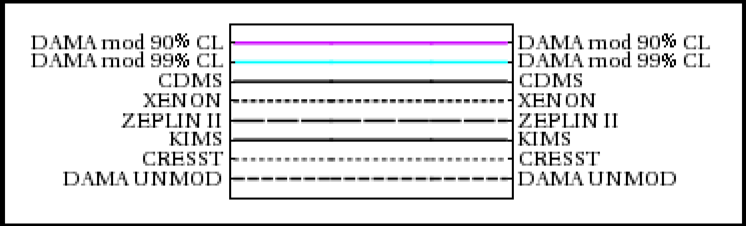
- **Easier to scatter off heavier targets**: favors DAMA (I, A=127) over CDMS (Ge, A=73).
- Must sample the high-v tail of f(v), **increases annual modulation**: favors DAMA.
- The recoil spectrum is altered, with **fewer (or no) low energy events**: favors DAMA over XENON

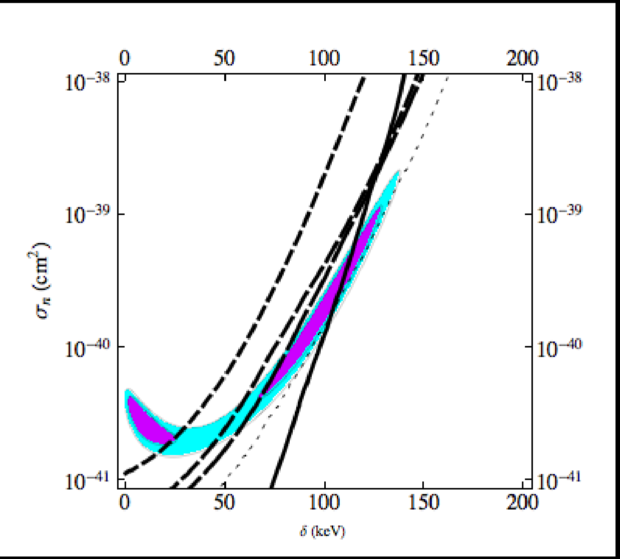
Annual Modulation and Peak Day



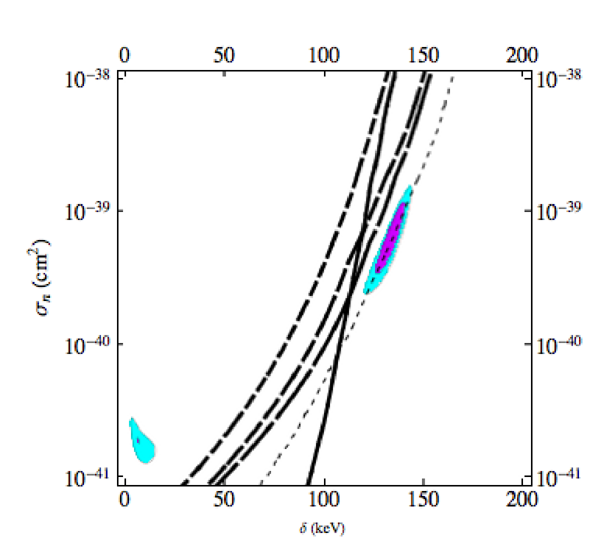
Inelastic DM and Via Lactea

An example: M_χ=150 GeV, exclusion plots in (δ,σ_N) space.

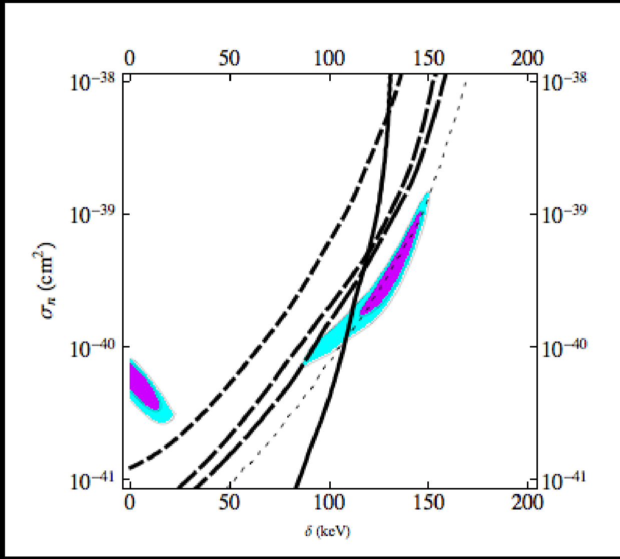




VL-II best-fit Maxwellian



All VL-II particles with 8kpc < D < 9kpc



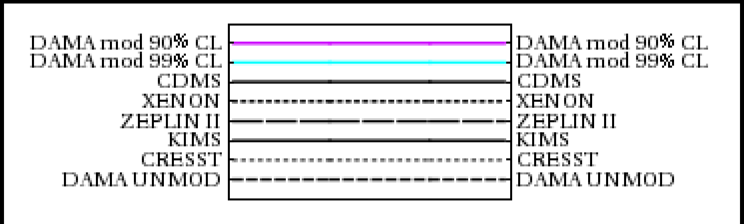
Favorable sample sphere (r=2kpc)

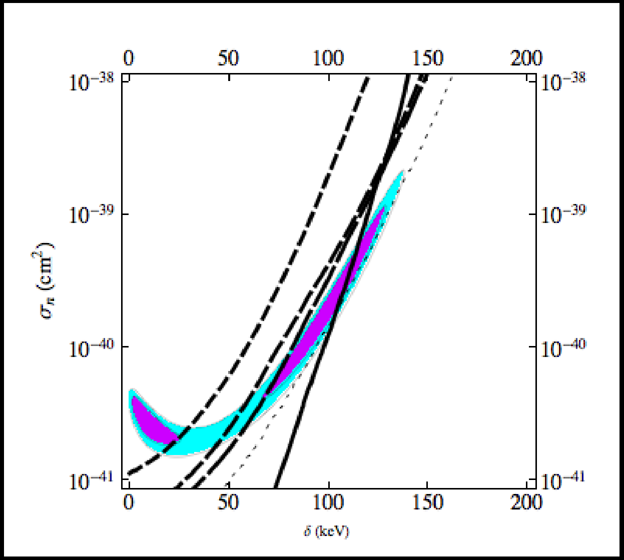
The shape, location, and extent of the iDM parameter space preferred by the DAMA measurement depends quite sensitively on f(v).

Global epartures from M-B and local variations can make the DAMA measurement **compatible with all current experimental limits**.

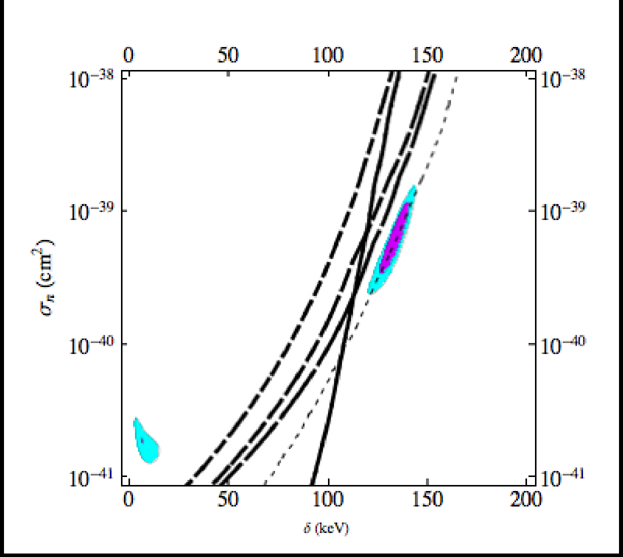
Inelastic DM and Via Lactea

An example: M_χ=150 GeV, exclusion plots in (δ,σ_N) space.

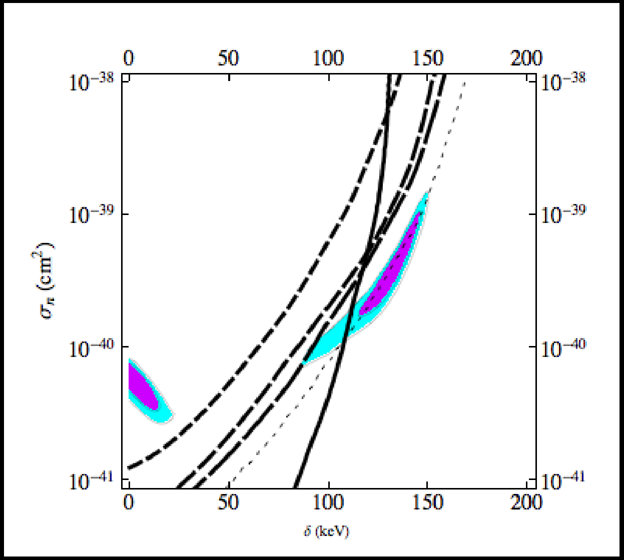




VL-II best-fit Maxwellian



All VL-II particles with 8kpc < D < 9kpc



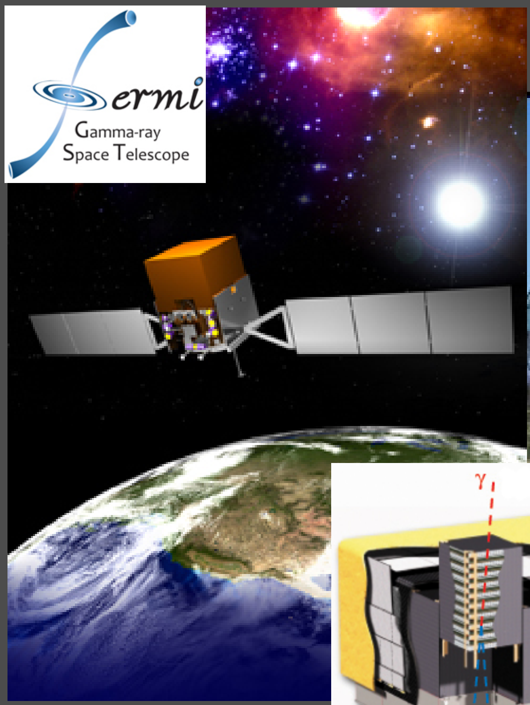
Favorable sample sphere (r=2kpc)

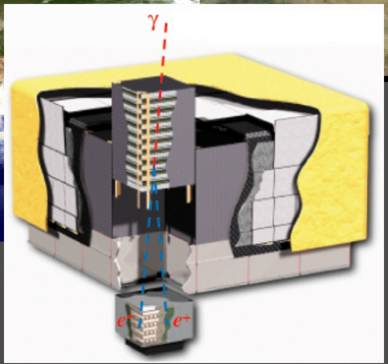
Direct detection event rates can depend significantly on the local phase-space distribution of DM, especially for inelastic DM. Directionally sensitive experiments are being designed...

compatible with all current experimental limits.

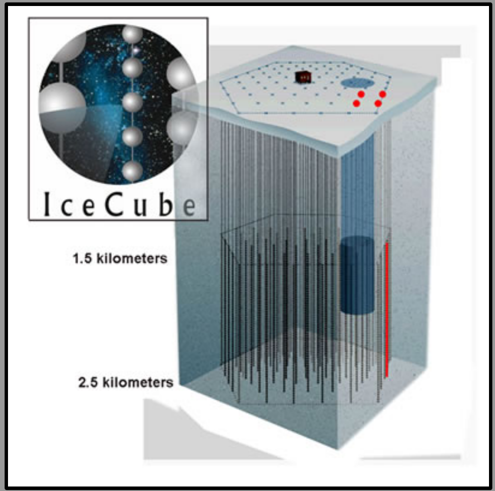
Indirect Detection

Gamma Rays



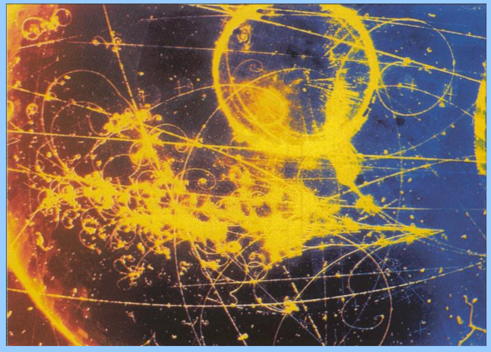


Neutrinos

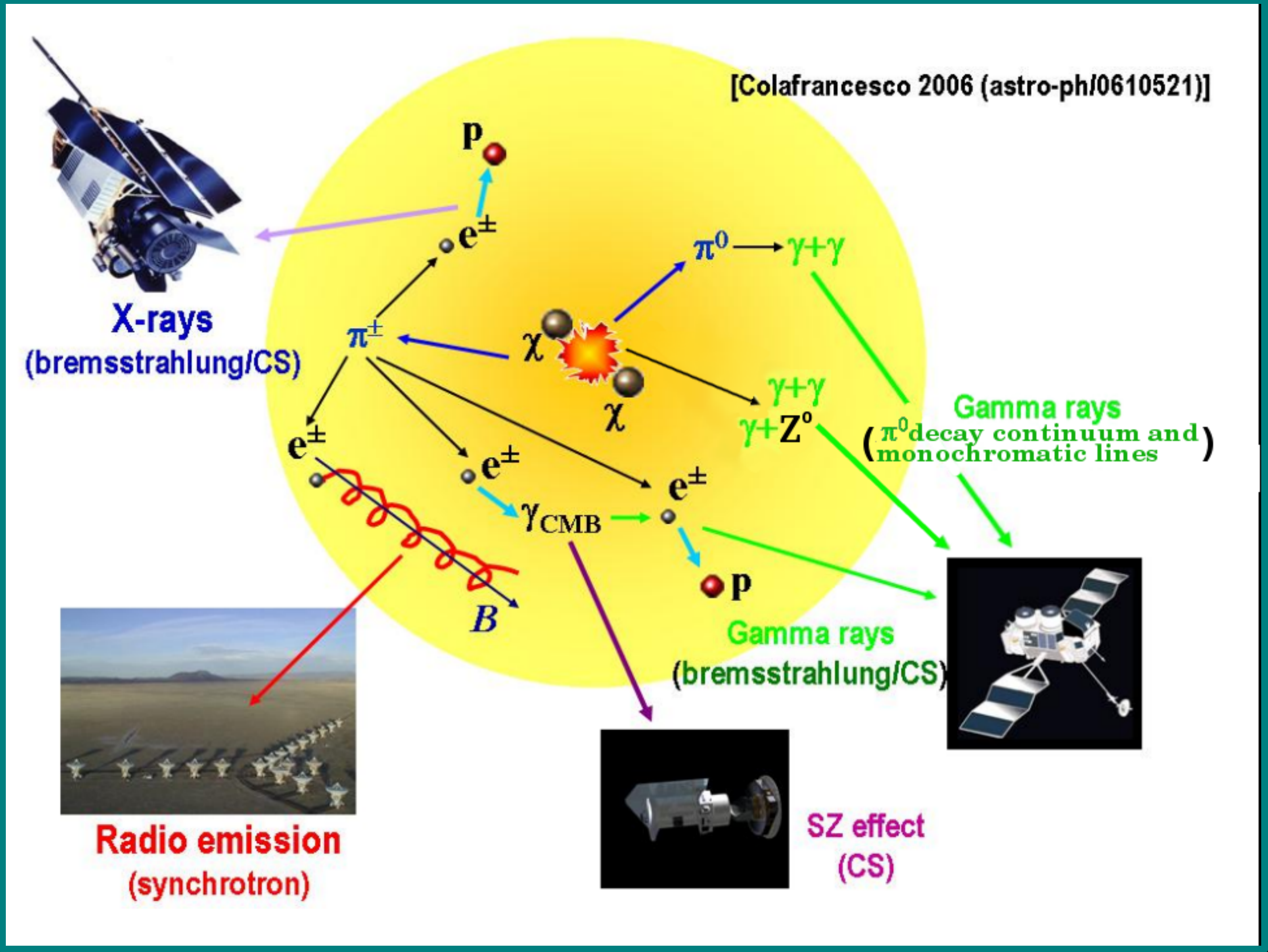


Positrons

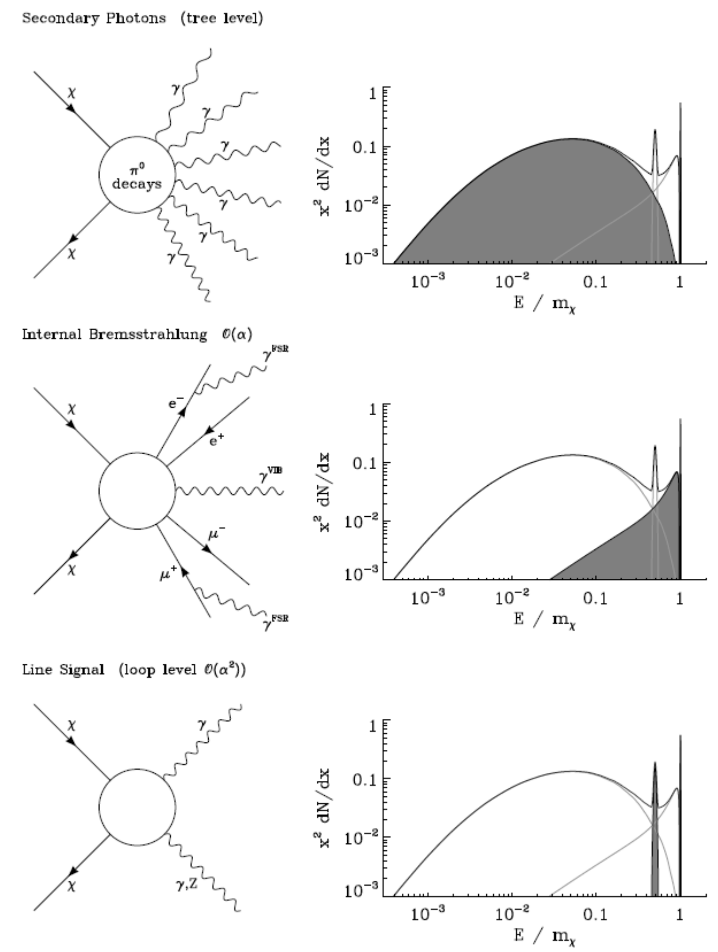
Indirect Detection



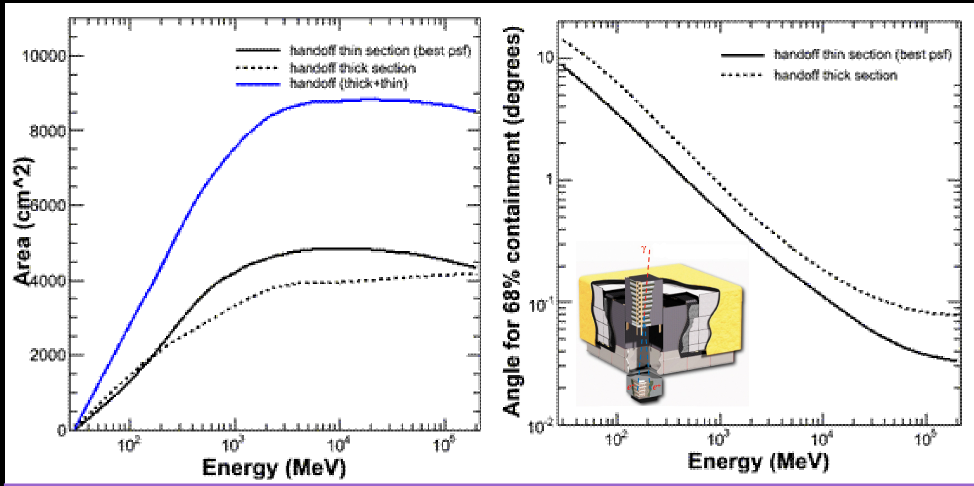
DM (WIMP) annihilation signal



3 ways to get gamma-rays:



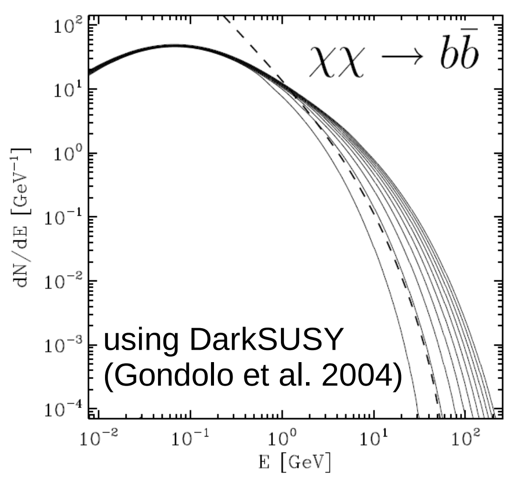
Astro physics



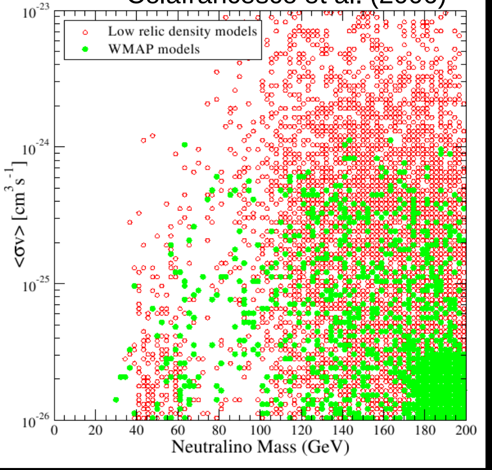
Detector properties

$$N_\gamma = \left[\int_{\text{line of sight}} \rho_{\mathrm{DM}}^2 \, dl(\psi)\right] \frac{\langle\sigma v\rangle}{2 M_\chi^2} \left[\int_{E_{th}}^{M_\chi} \left(\frac{dN_\gamma}{dE}\right)_{\mathrm{SUSY}} A_{\mathrm{eff}}(E)dE\right] \frac{\Delta\Omega}{4\pi} \tau_{\mathrm{exp}}$$

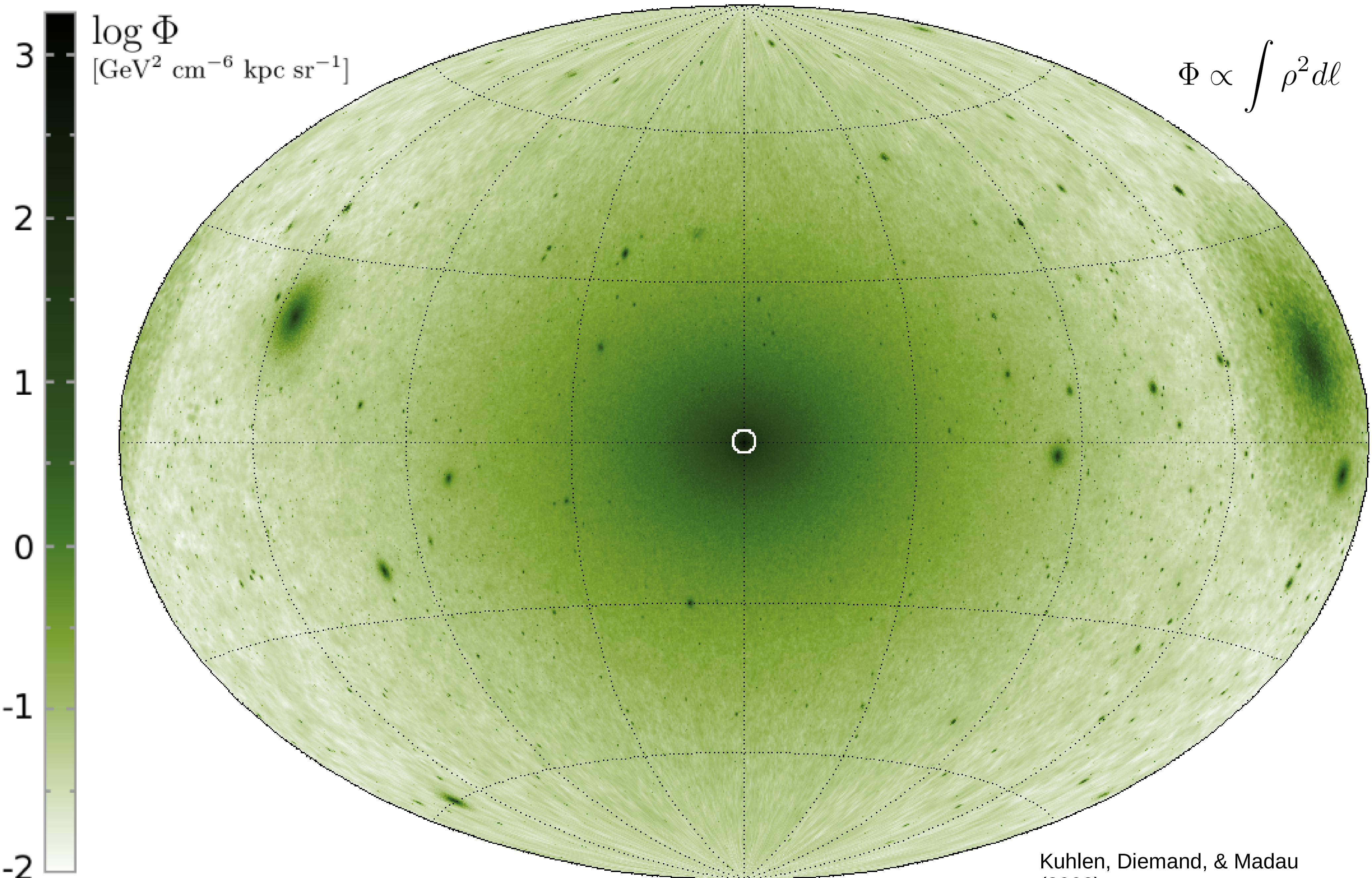
Particle physics



Colafrancesco et al. (2006)

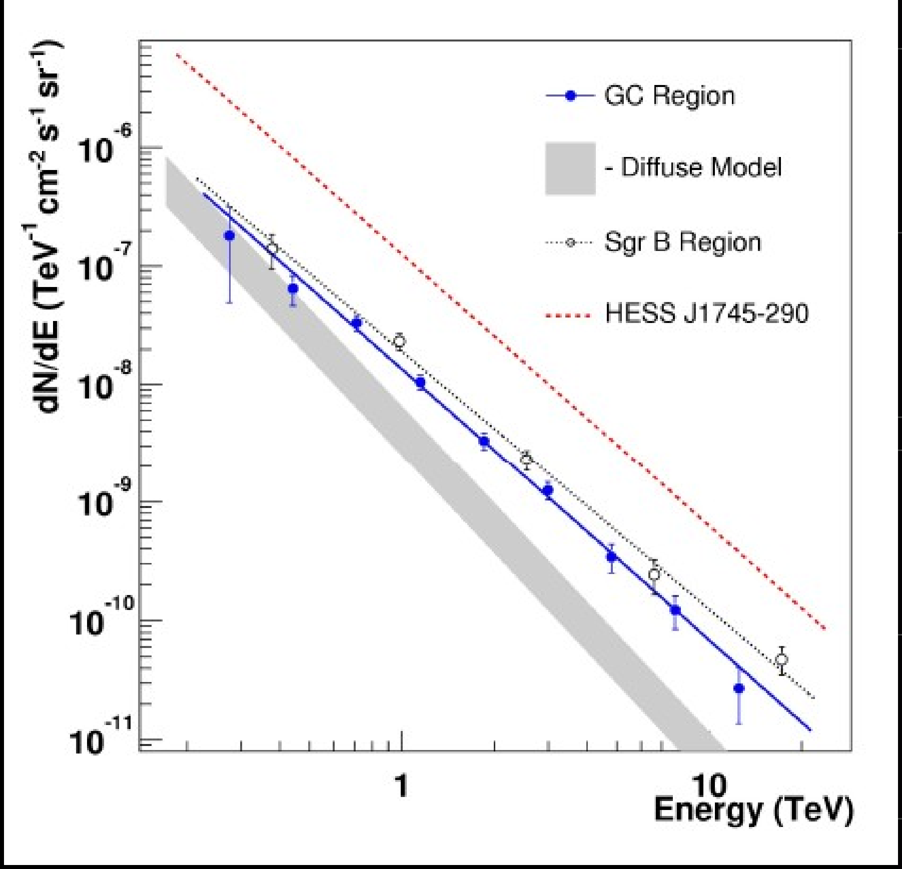


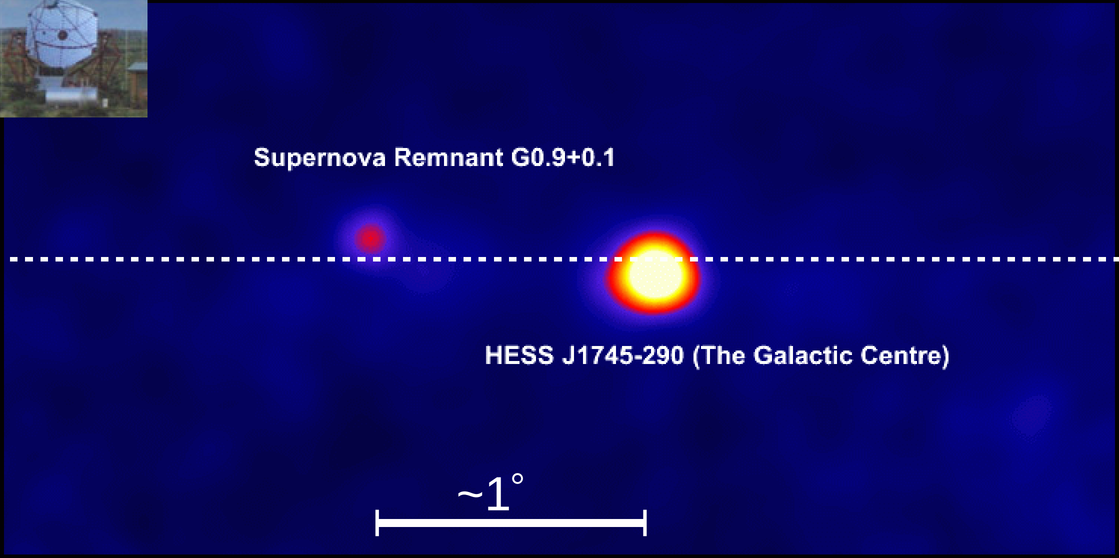
Simulated Dark Matter Annihilation Map

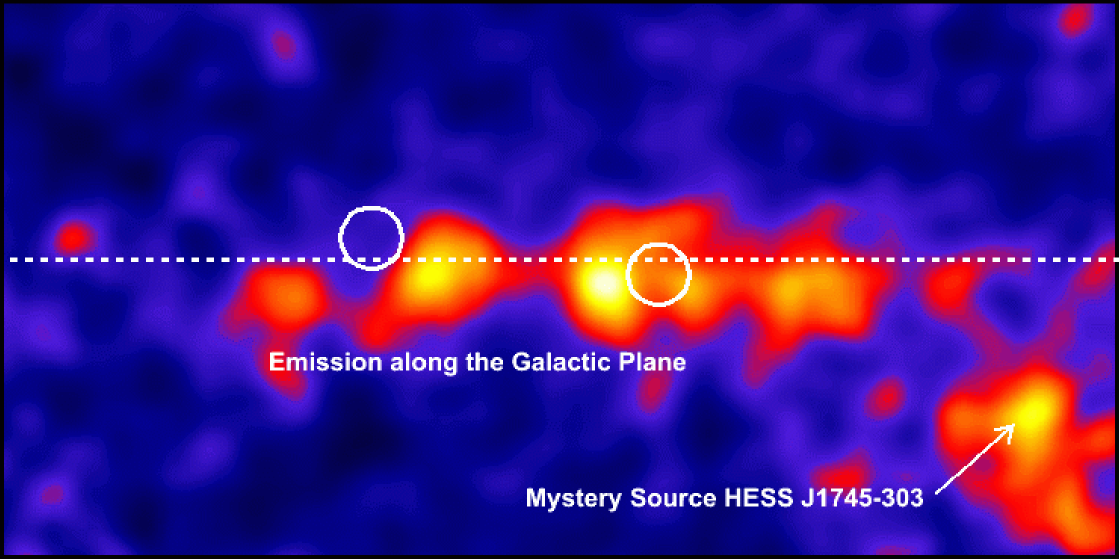


Kuhlen, Diemand, & Madau (2008)

Galactic Center: GR Point Sources

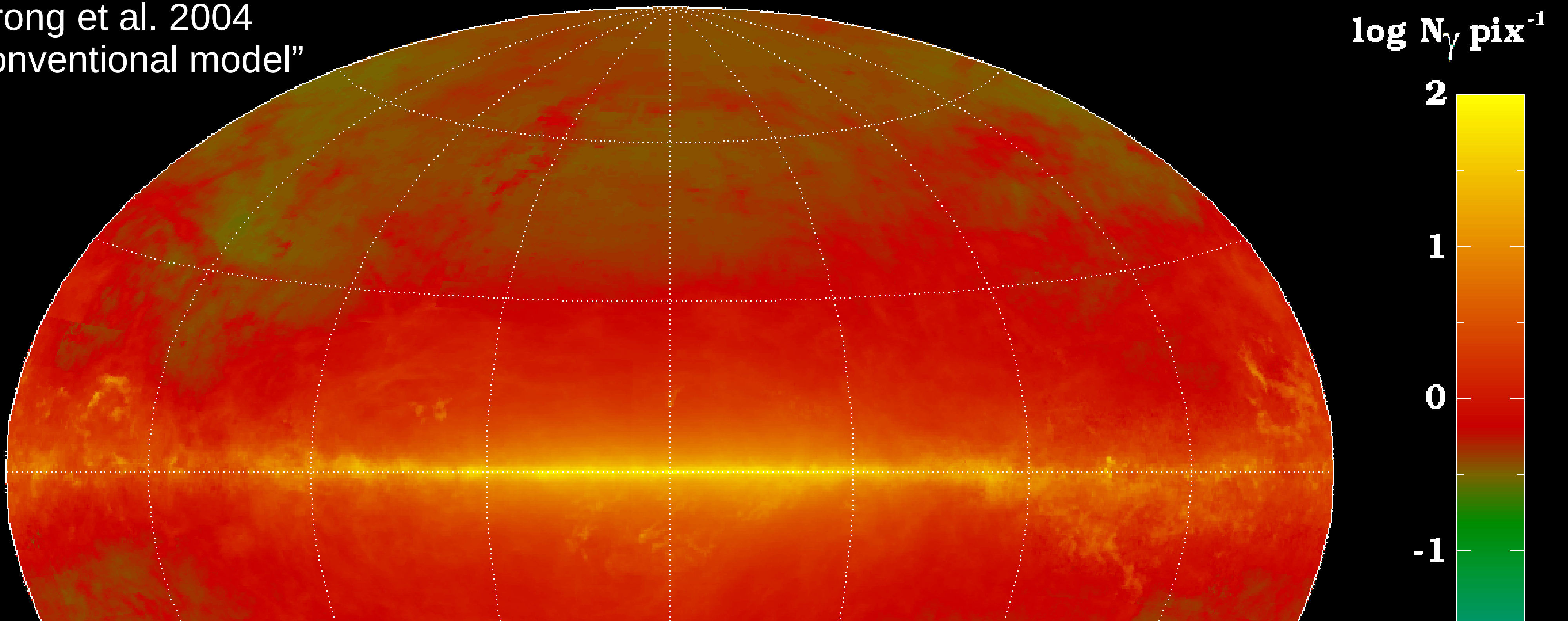




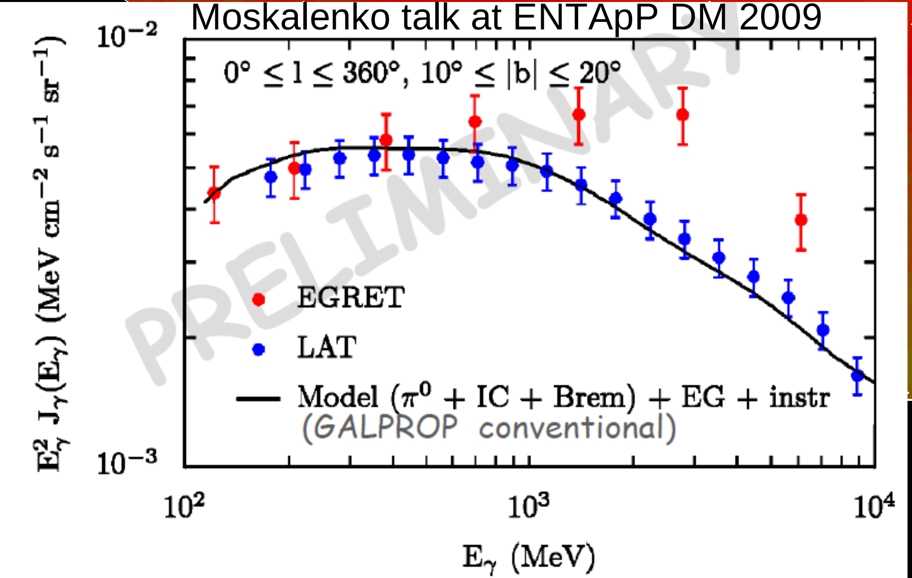


Backgrounds: Galactic GR Background

Strong et al. 2004
“conventional model”

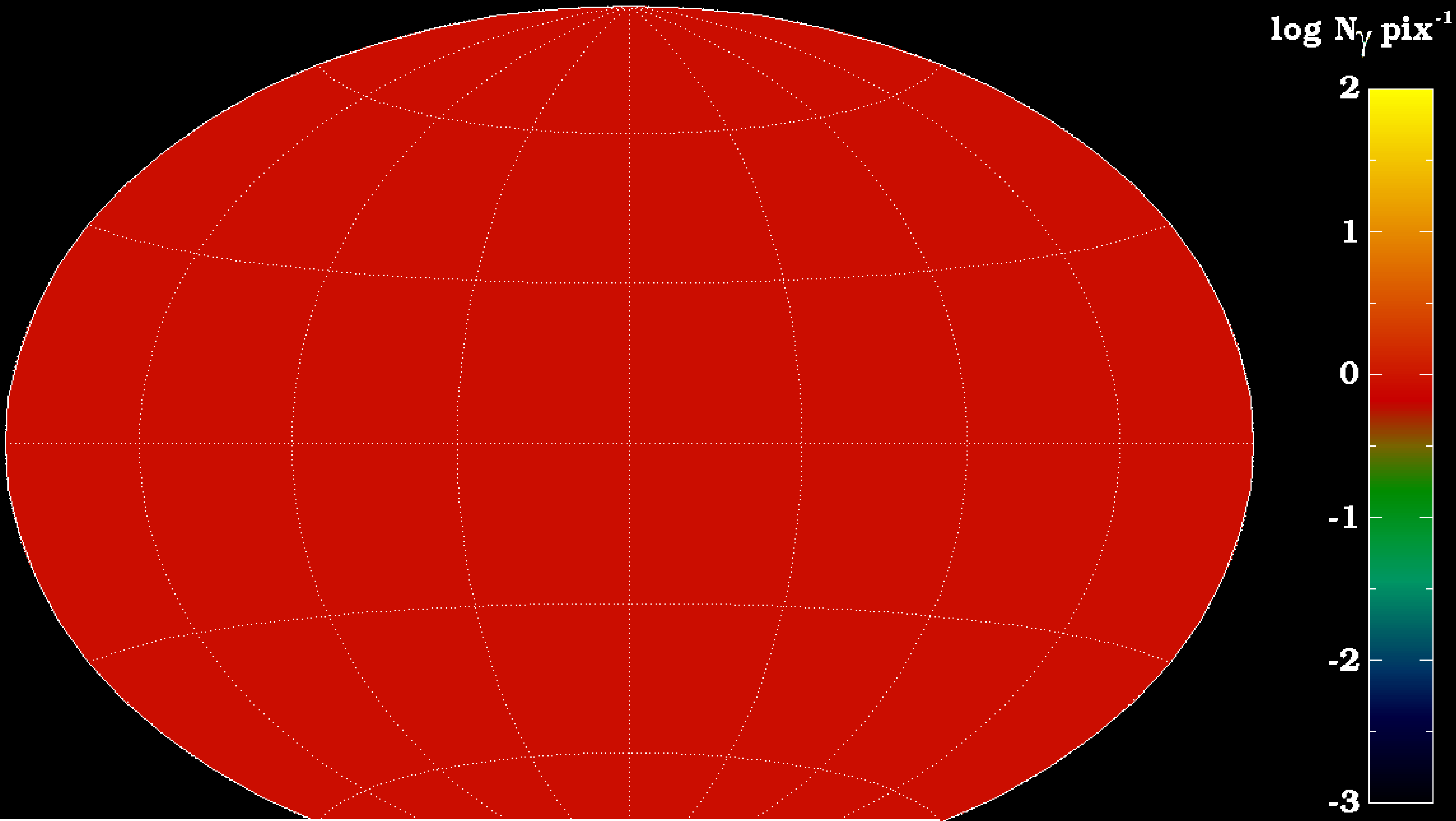


Moskalenko talk at ENTApP DM 2009



GALPROP: Moskalenko & Strong

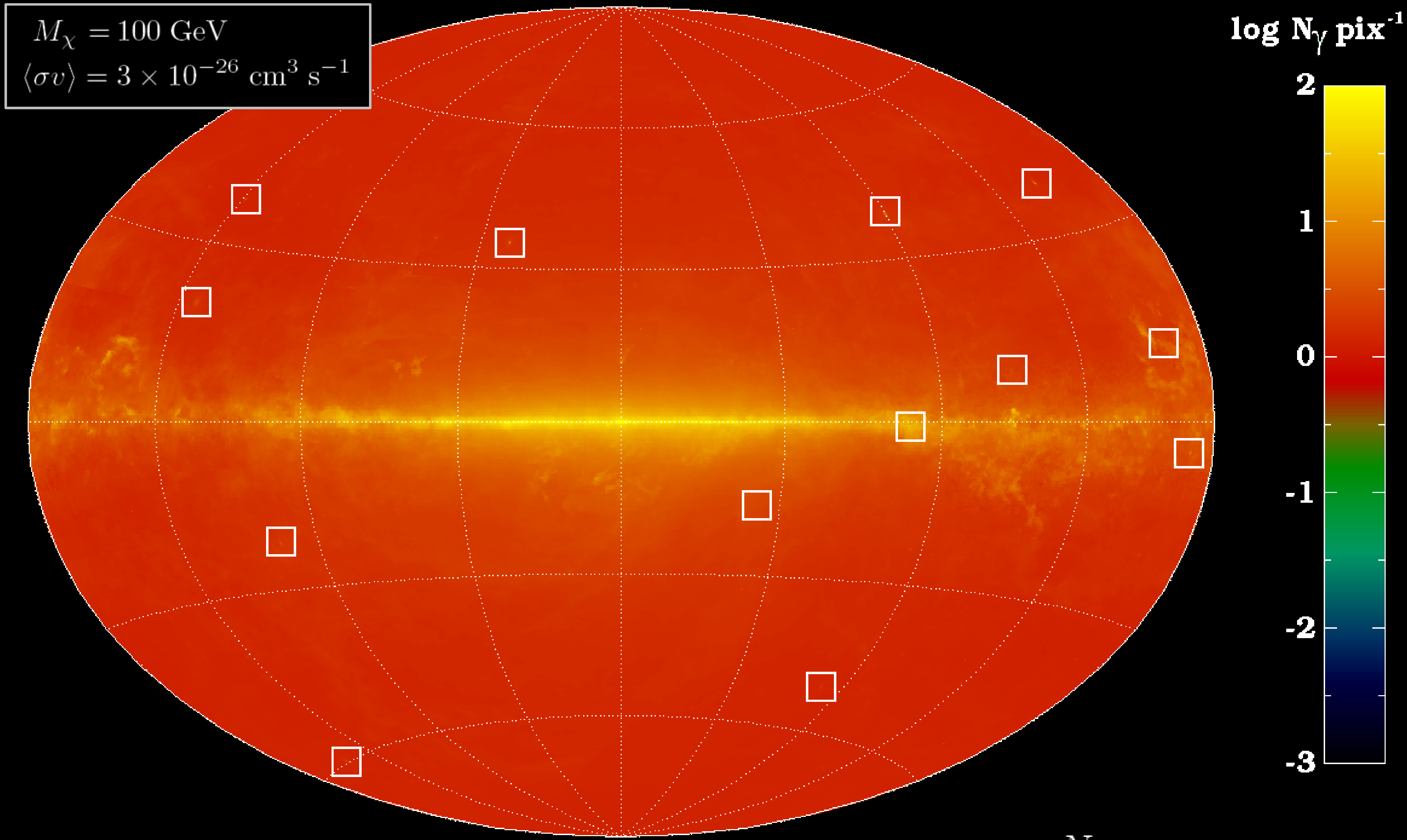
Backgrounds: Extragalactic GR Background



$$\frac{\mathrm{dN}}{\mathrm{dE\ dA\ dt\ d\Omega}} = 1.32 \times 10^{-6} \left(\frac{E}{1\mathrm{GeV}}\right)^{-2.1} \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

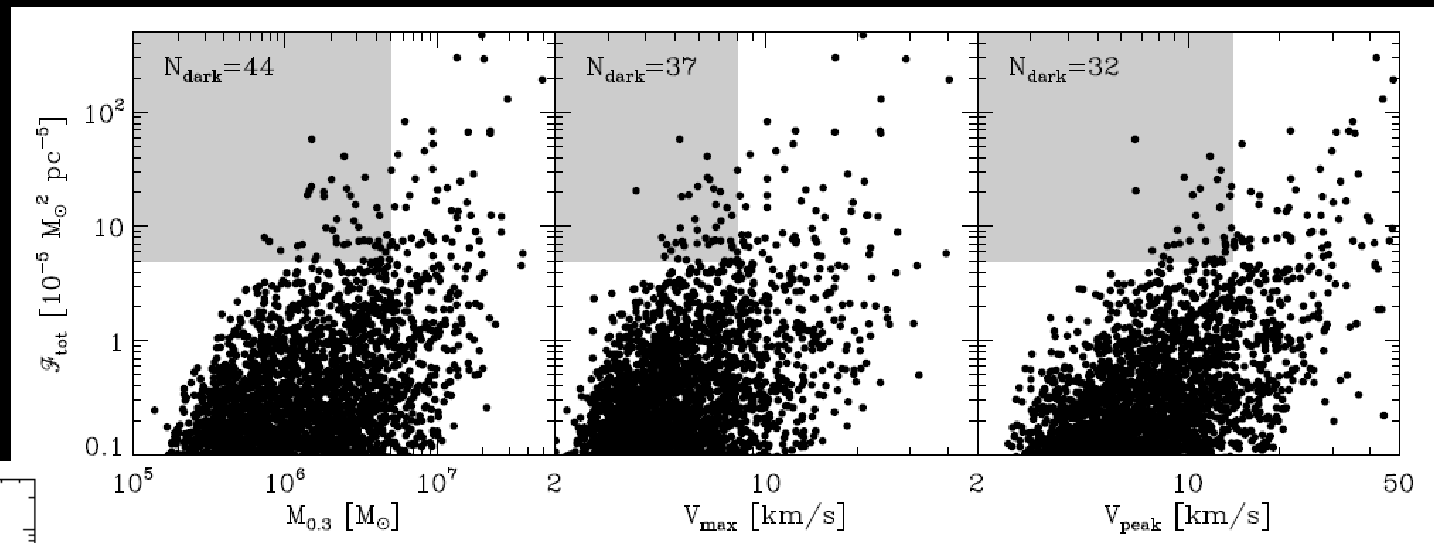
From EGRET: Sreekumar et al. 1998 and Baltz et al. 1999

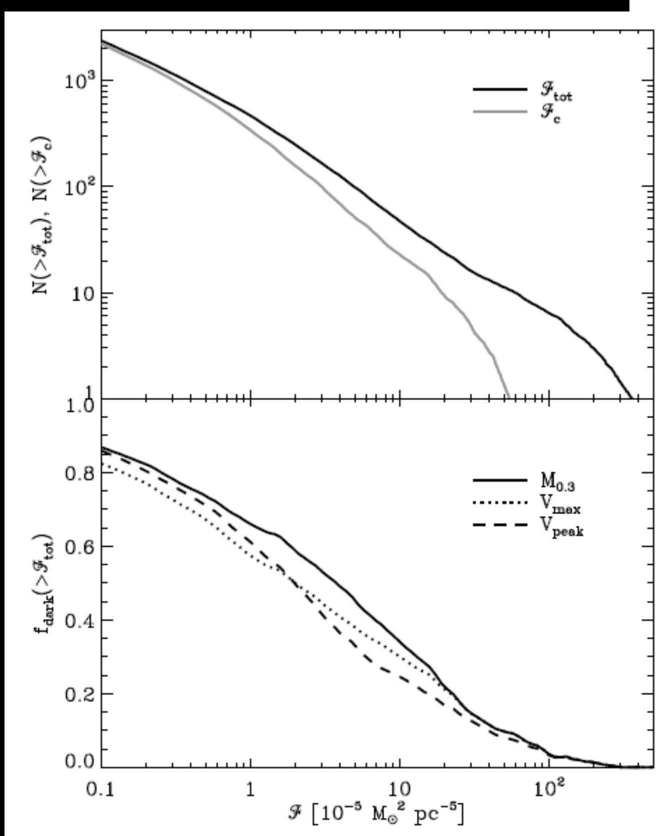
The Total Signal



We calculate a signal-to-noise ratio for every subhalo: $S/N = \dfrac{N_s}{\sqrt{N_s + N_b}}$

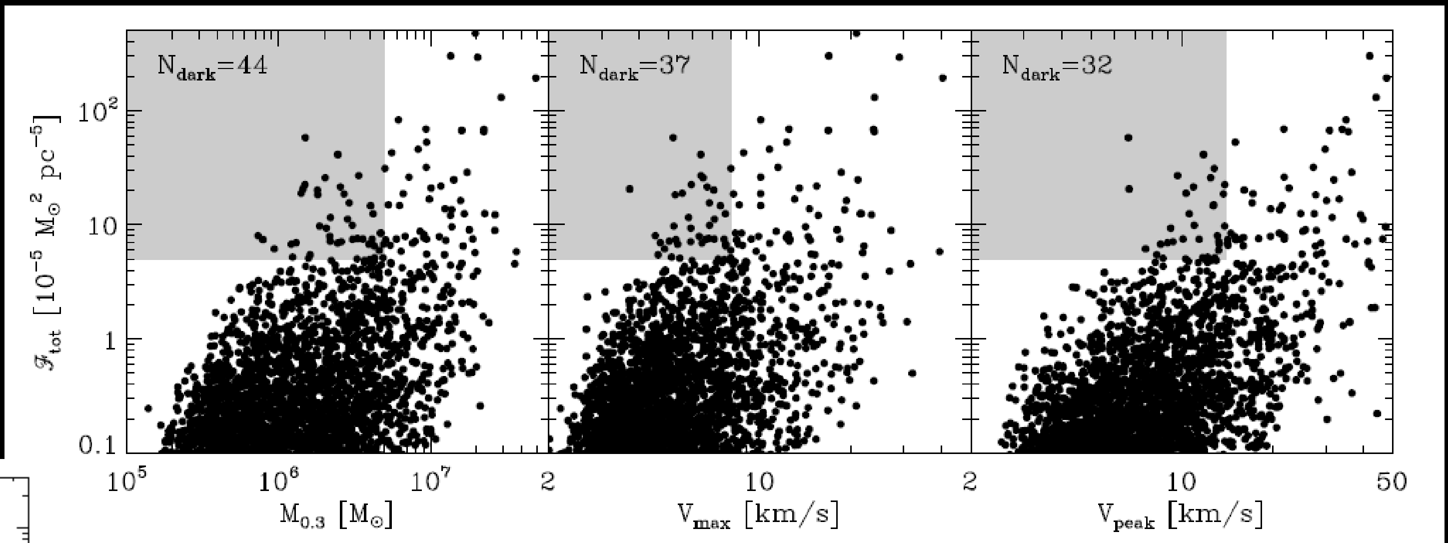
Known MW dSph Satellites as Annihilation Sources

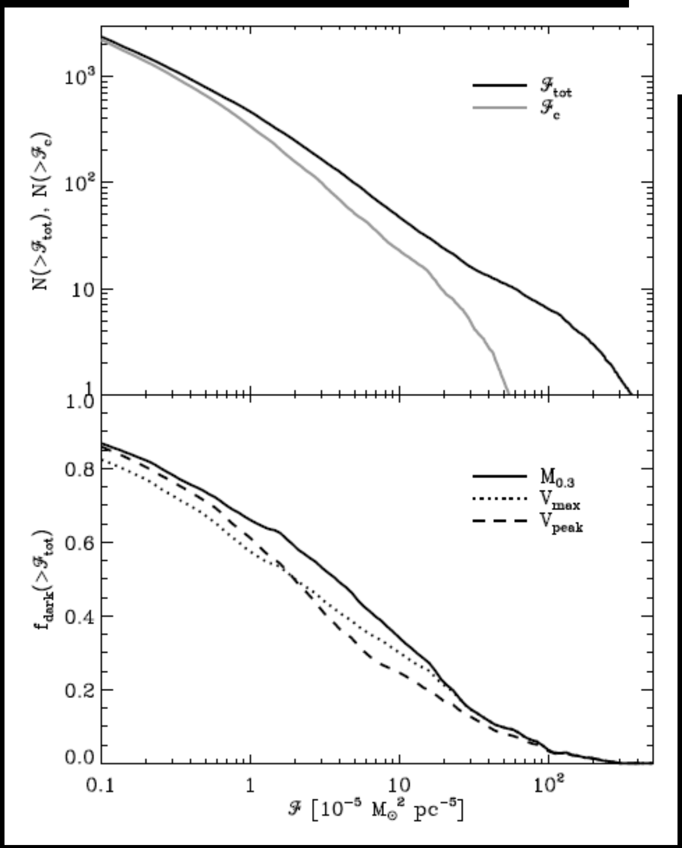




Name	D [kpc]	$\mathcal{L}_{tot}$ [$10^6 M_\odot^2$ pc^{-3}]	$\mathcal{L}_{0.3}$ [$10^6 M_\odot^2$ pc^{-3}]	$\mathcal{F}_{tot}$ [$10^{-5} M_\odot^2$ pc^{-5}]	$\mathcal{F}_c$ [$10^{-5} M_\odot^2$ pc^{-5}]
Segue 1	23	$2.8\ (^{7.2}_{0.93})$	$2.5\ (^{6.1}_{0.89})$	$41\ (^{110}_{14})$	$12\ (^{34}_{5.6})$
Ursa Major II	32	$3.5\ (^{7.2}_{2.8})$	$3.1\ (^{6.1}_{2.5})$	$28\ (^{56}_{21})$	$9.5\ (^{18}_{7.7})$
Ursa Minor	66	$6.2\ (^{9.4}_{5.1})$	$4.7\ (^{7.3}_{3.1})$	$11\ (^{17}_{9.3})$	$5.2\ (^{8.4}_{2.5})$
Draco	80	$7.0\ (^{9.9}_{6.0})$	$5.6\ (^{8.2}_{3.1})$	$8.8\ (^{12}_{7.4})$	$4.3\ (^{6.4}_{1.7})$
Carina	101	$7.0\ (^{9.4}_{4.8})$	$5.6\ (^{7.3}_{3.5})$	$5.5\ (^{7.3}_{3.7})$	$3.1\ (^{3.8}_{1.6})$
Wilman 1	38	$0.88\ (^{2.9}_{0.55})$	$0.85\ (^{2.7}_{0.53})$	$4.9\ (^{16}_{3.0})$	$2.6\ (^{6.4}_{1.5})$
Coma Berenices	44	$1.2\ (^{2.8}_{0.78})$	$1.1\ (^{2.5}_{0.70})$	$4.8\ (^{11}_{3.2})$	$2.5\ (^{5.1}_{1.6})$
Sculptor	80	$2.9\ (^{3.7}_{2.3})$	$2.5\ (^{3.3}_{2.0})$	$3.7\ (^{4.6}_{2.8})$	$2.0\ (^{2.8}_{1.6})$
Ursa Major I	106	$3.3\ (^{5.4}_{2.3})$	$2.5\ (^{4.5}_{1.9})$	$2.3\ (^{3.8}_{1.6})$	$1.3\ (^{2.4}_{0.91})$
Fornax	138	$3.5\ (^{4.4}_{3.0})$	$2.9\ (^{3.3}_{2.3})$	$1.4\ (^{1.8}_{1.3})$	$1.00\ (^{1.2}_{0.74})$
Sextans	86	$1.2\ (^{2.0}_{0.77})$	$1.1\ (^{1.8}_{0.69})$	$1.3\ (^{2.1}_{0.83})$	$0.86\ (^{1.4}_{0.55})$
Leo II	205	$4.6\ (^{6.5}_{3.8})$	$3.1\ (^{4.7}_{2.1})$	$0.88\ (^{1.2}_{0.73})$	$0.55\ (^{0.85}_{0.37})$
Canes Venatici I	224	$4.6\ (^{7.9}_{3.8})$	$3.1\ (^{5.0}_{2.3})$	$0.73\ (^{1.3}_{0.60})$	$0.48\ (^{0.79}_{0.35})$
Leo I	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Known MW dSph Satellites as Annihilation Sources





Name	D [kpc]	$\mathcal{L}_{tot}$ $[10^6 M_\odot^2\ pc^{-3}]$	$\mathcal{L}_{0.3}$ $[10^6 M_\odot^2\ pc^{-3}]$	$\mathcal{F}_{tot}$ $[10^{-5} M_\odot^2\ pc^{-5}]$	$\mathcal{F}_c$ $[10^{-5} M_\odot^2\ pc^{-5}]$
Segue 1	23	2.8 $\binom{7.2}{0.93}$	2.5 $\binom{6.1}{0.89}$	41 $\binom{110}{14}$	12 $\binom{34}{5.6}$
Ursa Major II	32	3.5 $\binom{7.2}{2.8}$	3.1 $\binom{6.1}{2.5}$	28 $\binom{56}{21}$	9.5 $\binom{18}{7.7}$
Ursa Minor	66	6.2 $\binom{9.4}{5.1}$	4.7 $\binom{7.3}{3.1}$	11 $\binom{17}{9.3}$	5.2 $\binom{8.4}{2.5}$
Draco	80	7.0 $\binom{9.9}{6.0}$	5.6 $\binom{8.2}{3.1}$	8.8 $\binom{12}{7.4}$	4.3 $\binom{6.4}{1.7}$
Carina	101	7.0 $\binom{9.4}{4.8}$	5.6 $\binom{7.3}{3.5}$	5.5 $\binom{7.3}{3.7}$	3.1 $\binom{3.8}{1.6}$
Wilman 1	38	0.88 $\binom{2.9}{0.55}$	0.85 $\binom{2.7}{0.53}$	4.9 $\binom{16}{3.0}$	2.6 $\binom{6.4}{1.5}$
Coma Berenices	44	1.2 $\binom{2.8}{0.78}$	1.1 $\binom{2.5}{0.70}$	4.8 $\binom{11}{3.2}$	2.5 $\binom{5.1}{1.6}$
Sculptor	80	2.9 $\binom{3.7}{2.3}$	2.5 $\binom{3.3}{2.0}$	3.7 $\binom{4.6}{2.8}$	2.0 $\binom{2.8}{1.6}$
Ursa Major I	106	3.3 $\binom{5.4}{2.3}$	2.5 $\binom{4.5}{1.9}$	2.3 $\binom{3.8}{1.6}$	1.3 $\binom{2.4}{0.91}$
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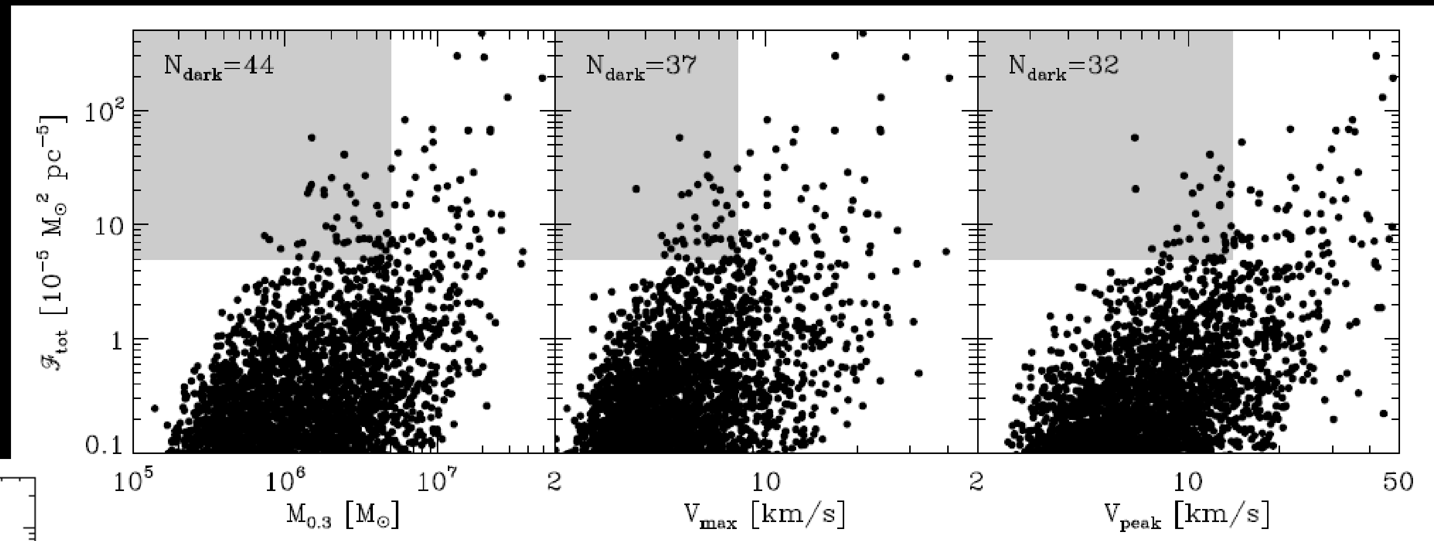
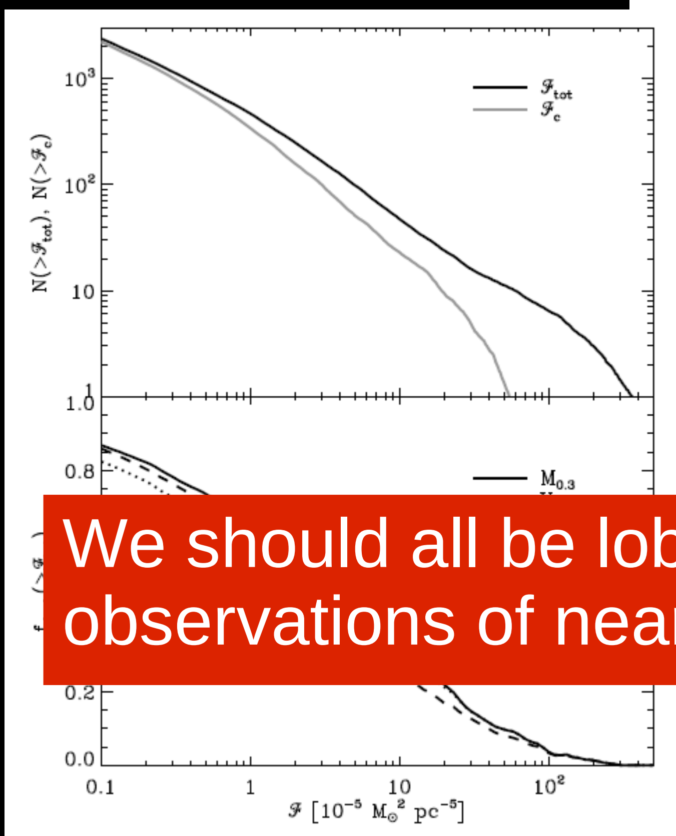
Sextans	86	1.2 $\binom{2.0}{0.77}$	1.1 $\binom{1.8}{0.69}$	1.3 $\binom{2.1}{0.83}$	0.86 $\binom{1.4}{0.55}$
Leo II	205	4.6 $\binom{6.5}{3.8}$	3.1 $\binom{4.7}{2.1}$	0.88 $\binom{1.2}{0.73}$	0.55 $\binom{0.85}{0.37}$
Canes Venatici I	224	4.6 $\binom{7.9}{3.8}$	3.1 $\binom{5.0}{2.3}$	0.73 $\binom{1.3}{0.60}$	0.48 $\binom{0.79}{0.35}$

Known MW dSph Satellites as Annihilation Sources





Name	D [kpc]	$\mathcal{L}_{tot}$ [$10^6 M_\odot^2$ pc^{-3}]	$\mathcal{L}_{0.3}$ [$10^6 M_\odot^2$ pc^{-3}]	$\mathcal{F}_{tot}$ [$10^{-5} M_\odot^2$ pc^{-5}]	$\mathcal{F}_c$ [$10^{-5} M_\odot^2$ pc^{-5}]
Segue 1	23	$2.8\ (^{7.2}_{0.93})$	$2.5\ (^{6.1}_{0.89})$	$41\ (^{110}_{14})$	$12\ (^{34}_{5.6})$
Ursa Major II	32	$3.5\ (^{7.2}_{2.8})$	$3.1\ (^{6.1}_{2.5})$	$28\ (^{56}_{21})$	$9.5\ (^{18}_{7.7})$
Ursa Minor	66	$6.2\ (^{9.4}_{5.1})$	$4.7\ (^{7.3}_{3.1})$	$11\ (^{17}_{9.3})$	$5.2\ (^{8.4}_{2.5})$
Draco	80	$7.0\ (^{9.9}_{6.0})$	$5.6\ (^{8.2}_{3.1})$	$8.8\ (^{12}_{7.4})$	$4.3\ (^{6.4}_{1.7})$
Carina	101	$7.0\ (^{9.4}_{4.8})$	$5.6\ (^{7.3}_{3.5})$	$5.5\ (^{7.3}_{3.7})$	$3.1\ (^{3.8}_{1.6})$
Fornax	138	$3.5\ (^{4.4}_{3.0})$	$2.9\ (^{3.3}_{2.3})$	$1.4\ (^{1.8}_{1.3})$	$1.00\ (^{1.2}_{0.74})$
Sextans	86	$1.2\ (^{2.0}_{0.77})$	$1.1\ (^{1.8}_{0.69})$	$1.3\ (^{2.1}_{0.83})$	$0.86\ (^{1.4}_{0.55})$
Leo II	205	$4.6\ (^{6.5}_{3.8})$	$3.1\ (^{4.7}_{2.1})$	$0.88\ (^{1.2}_{0.73})$	$0.55\ (^{0.85}_{0.37})$
Canes Venatici I	224	$4.6\ (^{7.9}_{3.8})$	$3.1\ (^{5.0}_{2.3})$	$0.73\ (^{1.3}_{0.60})$	$0.48\ (^{0.79}_{0.35})$

We should all be lobbying ACT "TAC"'s to give more time to observations of nearby Milky Way dwarf satellite galaxies!

Indirect Detection: the **leptonic** signal

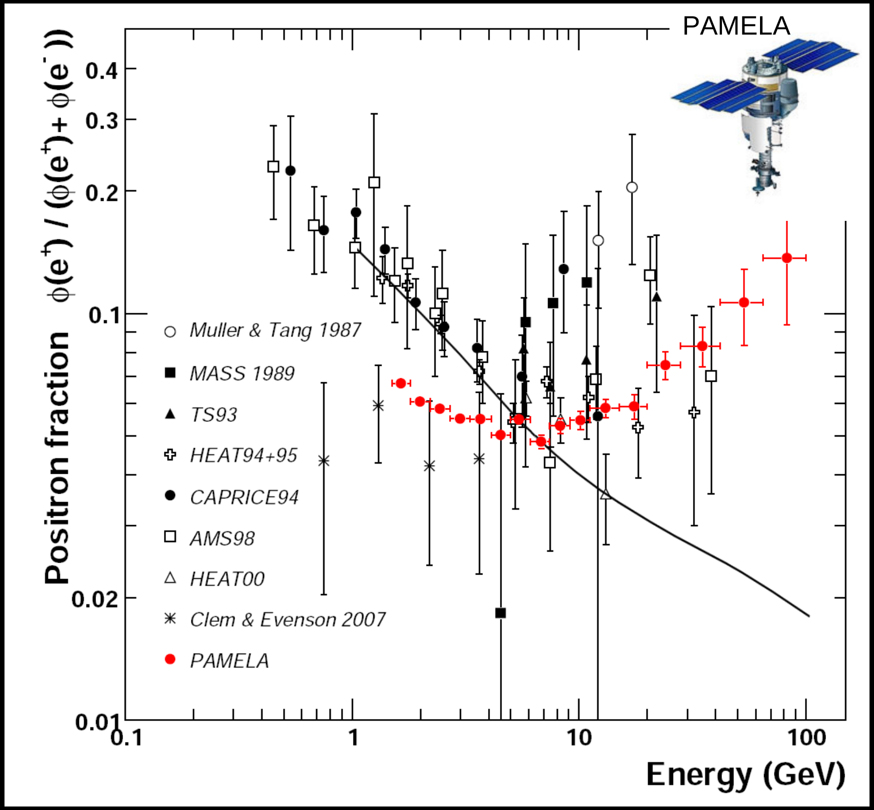
There are currently at least four unexplained observations of energetic electrons and positrons in the Milky Way halo.

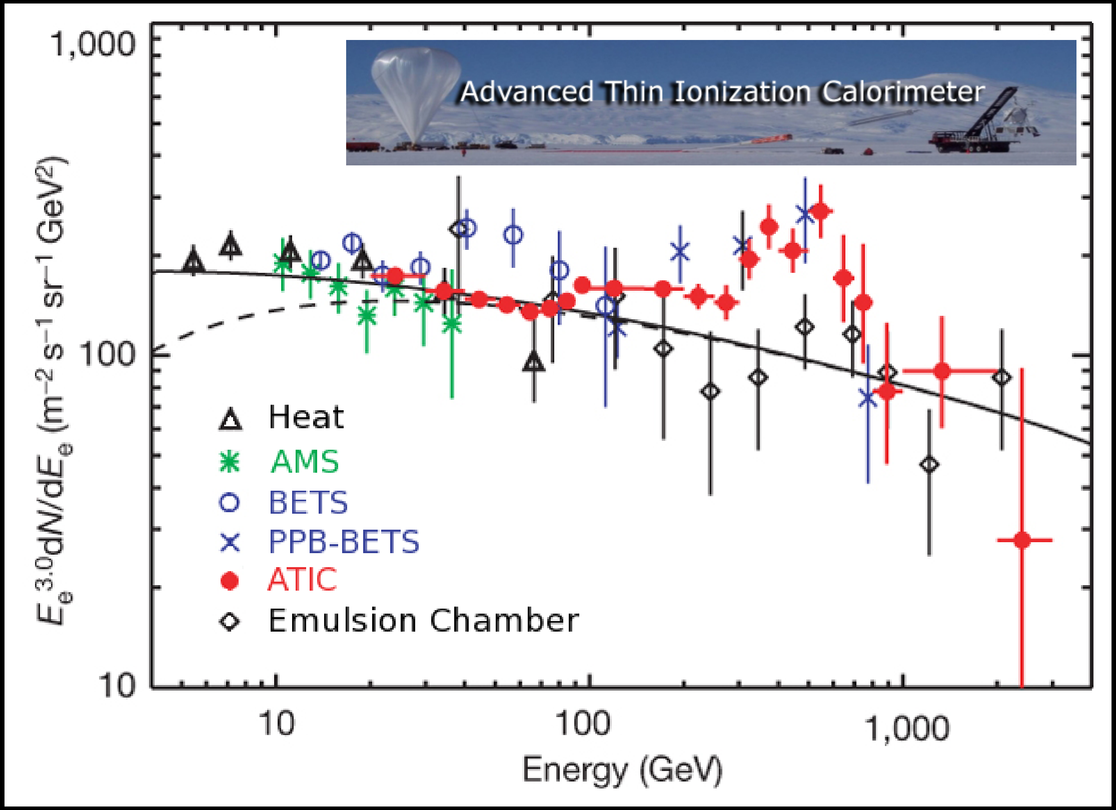
1) The WMAP "haze"

2) The INTEGRAL/SPI 511 keV Galactic Center signal

3) The PAMELA measurement of a positron excess at E > 10 GeV.

4) The ATIC and PPB-BETS measurements of an (e^++e^-) bump at E ~ 500 – 800 GeV.





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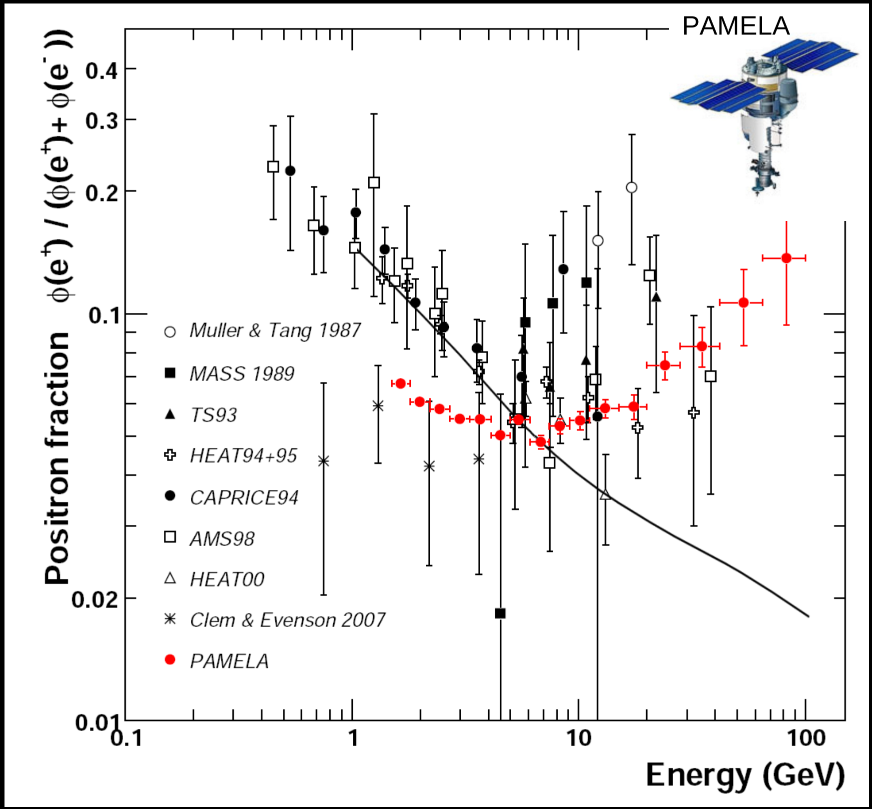
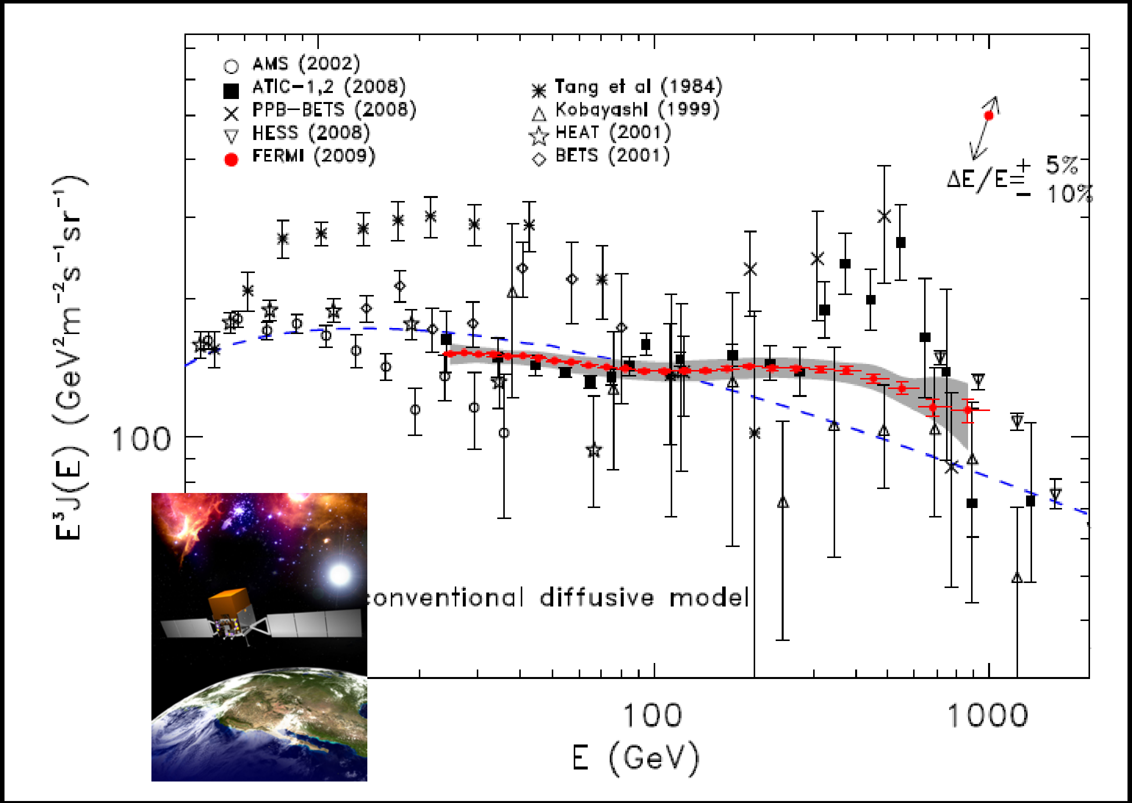
4) Fermi does not see the ATIC/PPB-BETS bump. Lack of feature implies M_χ > ~1 TeV.

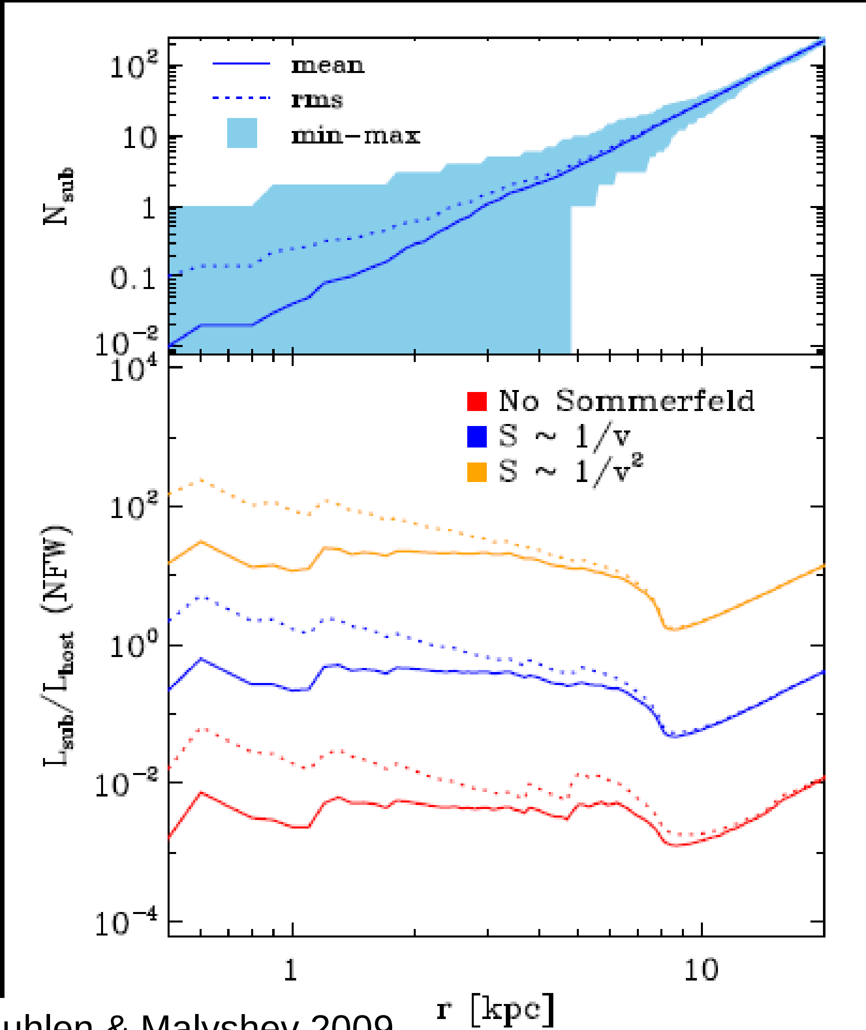




Could this be DM annihilation?

A typical M_χ~1 TeV WIMP DM particle would need to have a **cross section ~1000 larger** than the thermal relic value to explain the PAMELA and ATIC/PPB_BETS/Fermi results.

The local DM distribution is **not clumpy enough** to give such a large boost factor.



Kuhlen & Malyshev 2009

Extrapolating the VL-II subhalo abundance in mass, taking into account radial anti-bias, gives a local boost factor of B = 1.4 .

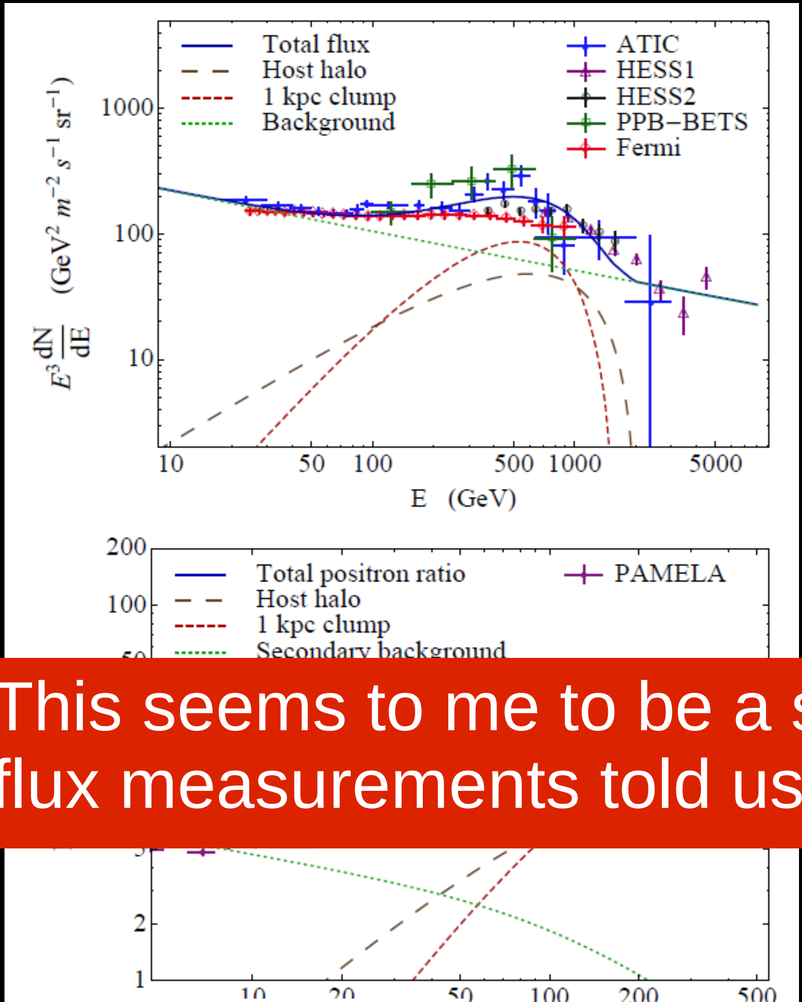
In VL-II about 1% of locations at 8kpc happen to be close enough to a subhalo to give B~10.

Need some other mechanism to increase the cross section
→ Sommerfeld enhancement?

Could this be DM annihilation?

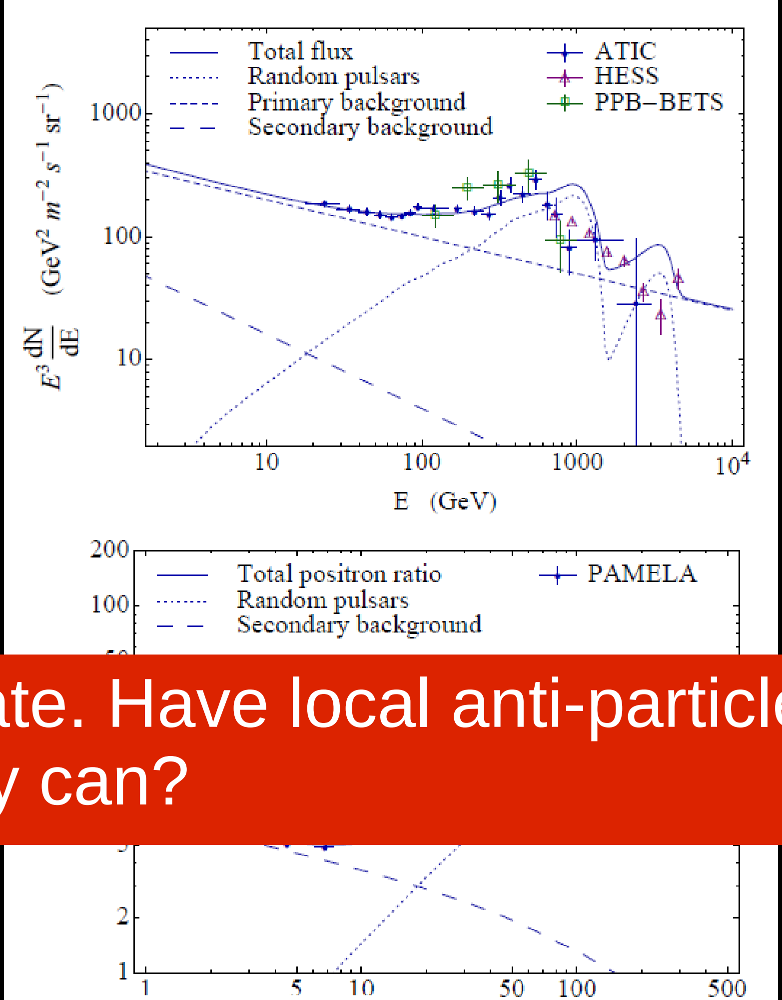
A typical M_χ~1 TeV WIMP DM particle would need to have a huge cross section to explain the PAMELA and ATIC/PPB_BETS/Fermi results.

With Sommerfeld enhancement and a ~TeV particle, the data can be nicely fit:



Kuhlen & Malyshev 2009

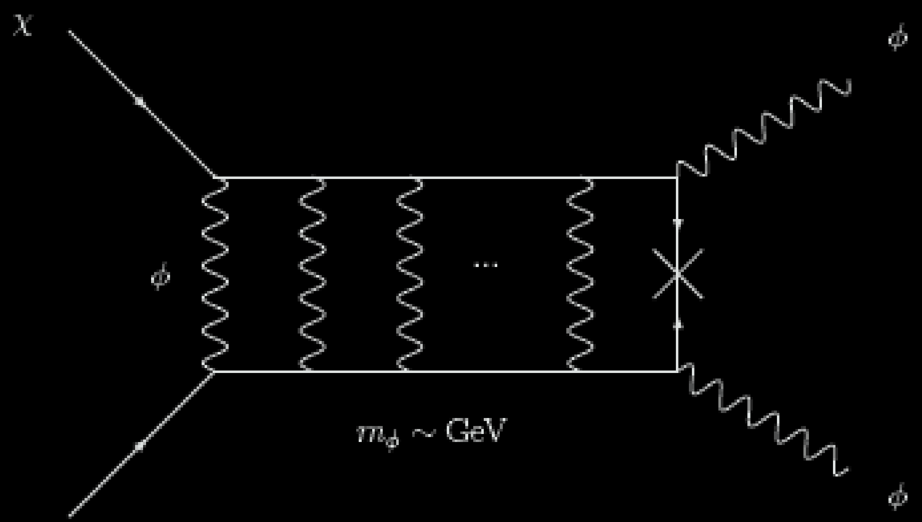
But so can, for example, pulsars...



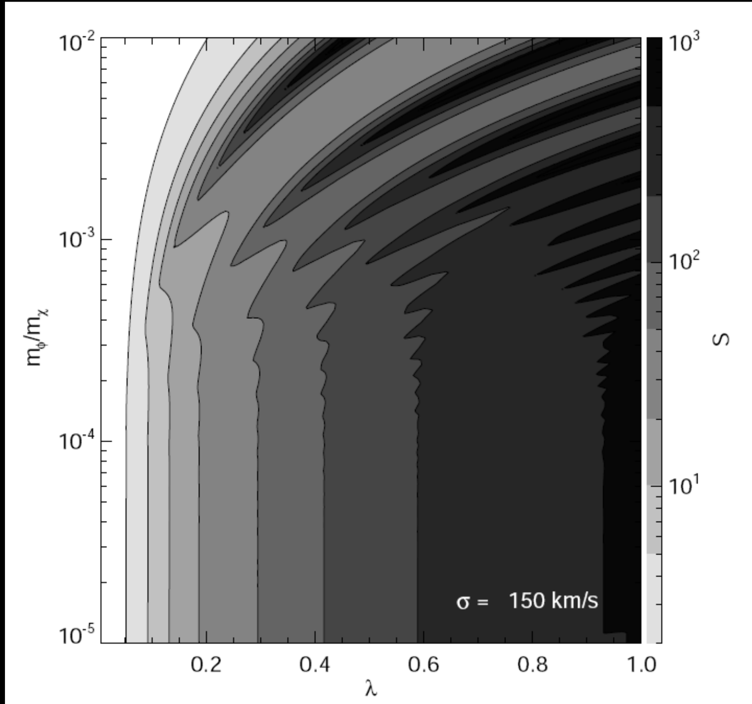
Malyshev et al. 2009

This seems to me to be a stalemate. Have local anti-particle flux measurements told us all they can?

Example: Sommerfeld-enhanced subhalo annihilation signal



$$\alpha = \lambda^2/4\pi, \ \epsilon_v = \frac{v}{\alpha}, \ \epsilon_\phi = \frac{m_\phi}{\alpha m_\chi}$$



Arkani-Hamed et al. (2008)

Three regimes: (cf. Lattanzi & Silk 2008)

I. Large velocities (ϵ_v>1): no enhancement

II. Intermediate velocities (ϵ_ϕ<ϵ_v<1): $S \sim \pi \frac{\alpha}{v}$

III. Low velocities (ϵ_v<ϵ_ϕ), depends on m_χ:

either saturation: $S = 1/\epsilon_\phi$

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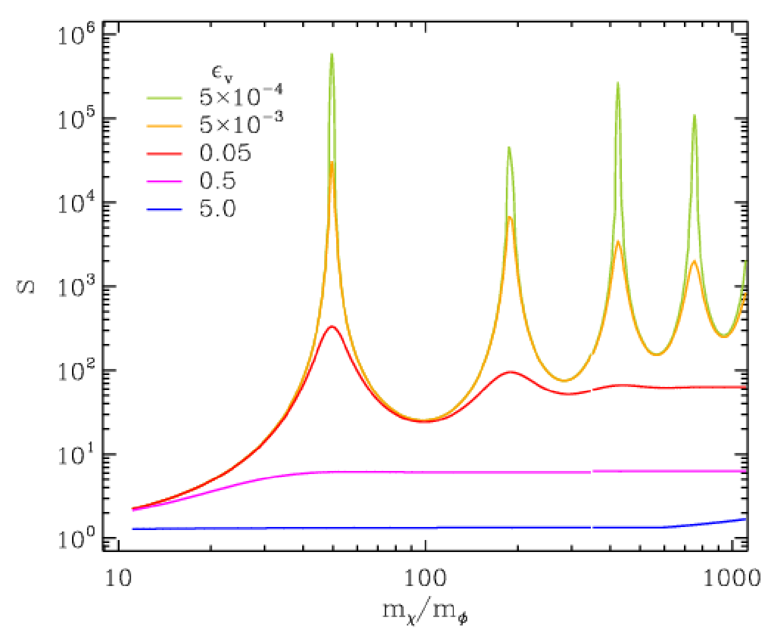
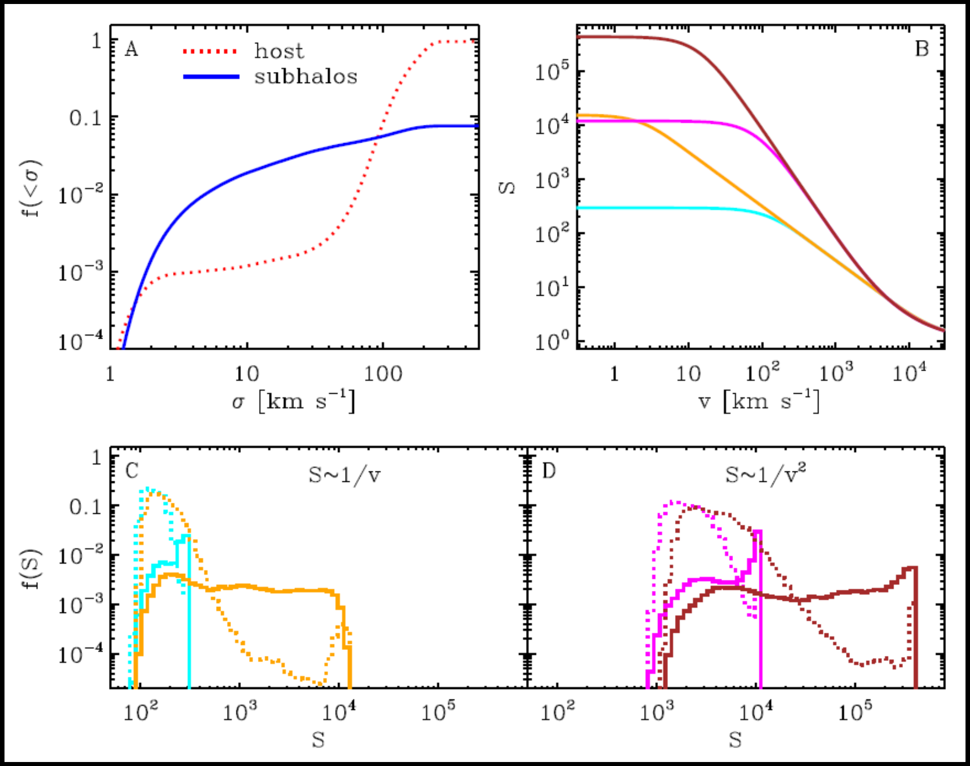
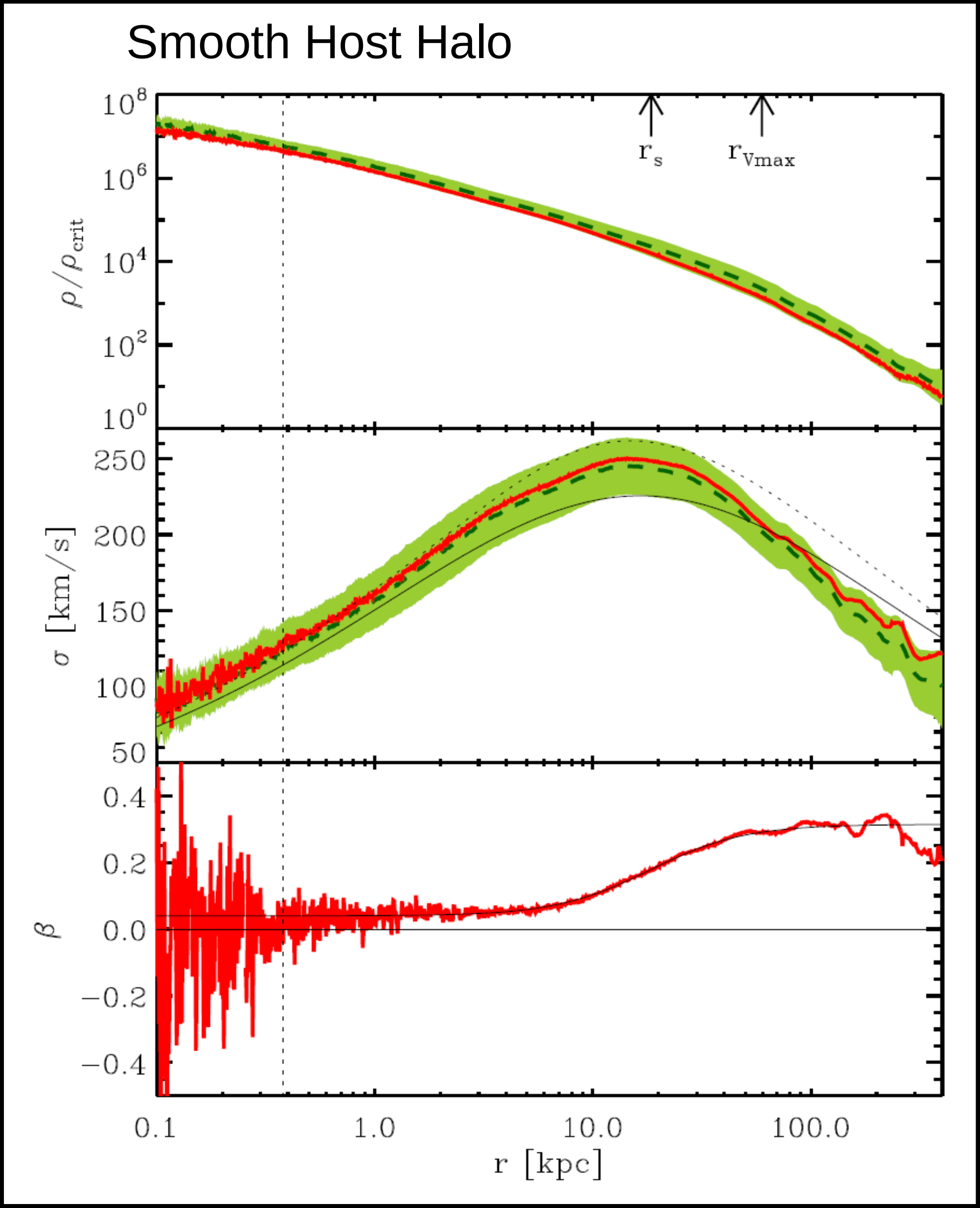


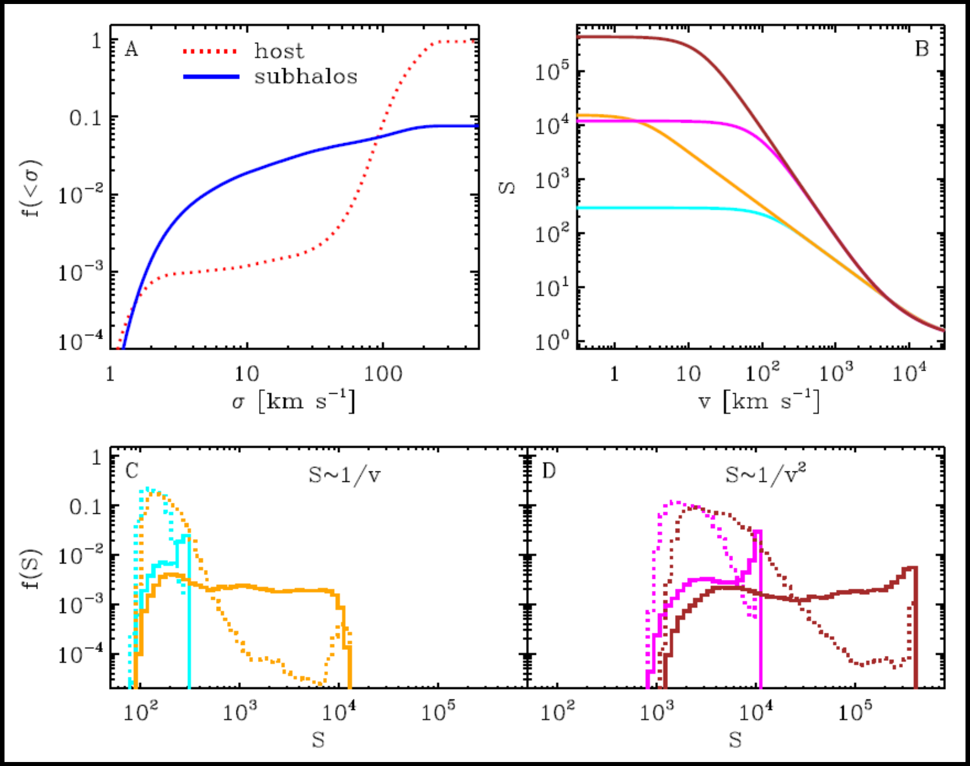
Velocities in Via Lactea II





Velocity distribution in host and subhalos and resulting Sommerfeld enhancement factors

Velocities in Via Lactea II



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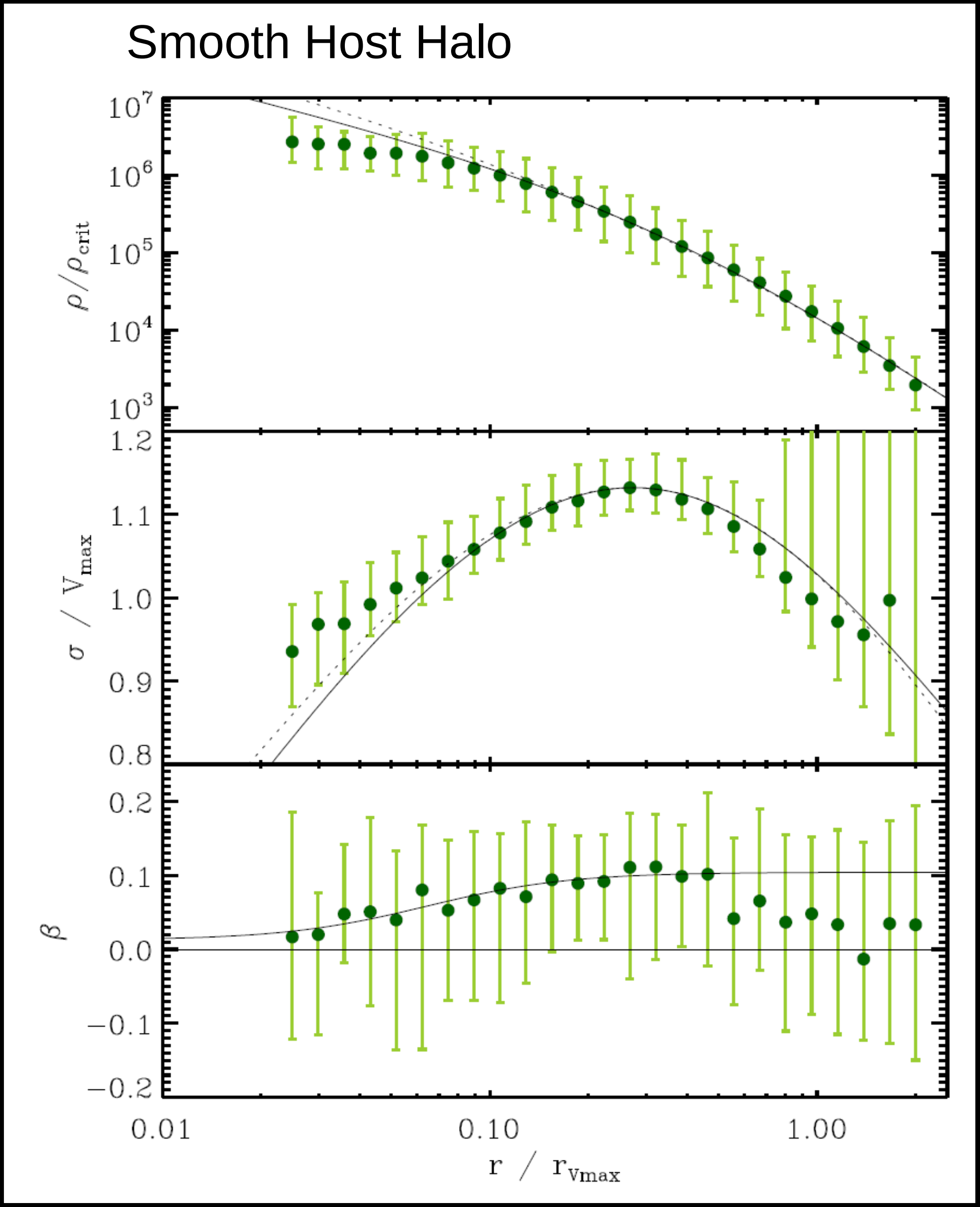
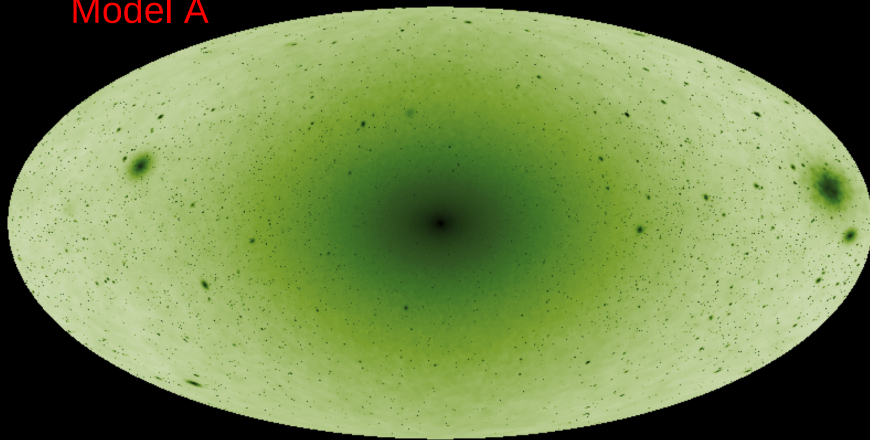


With Sommerfeld Enhancement

Model A



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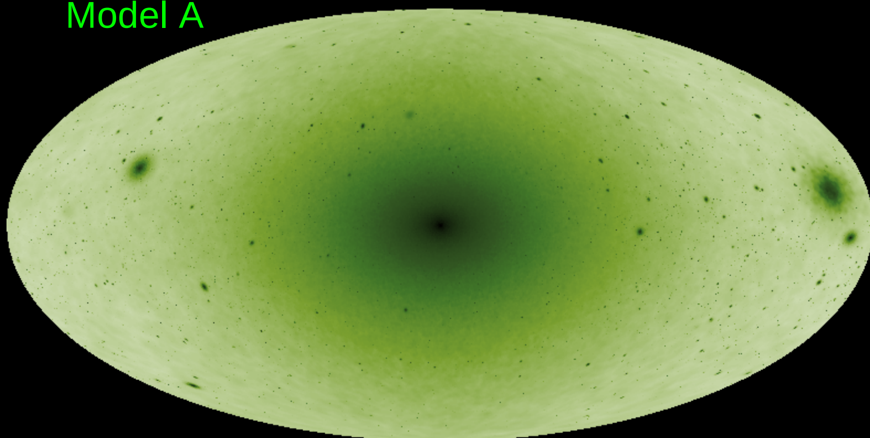
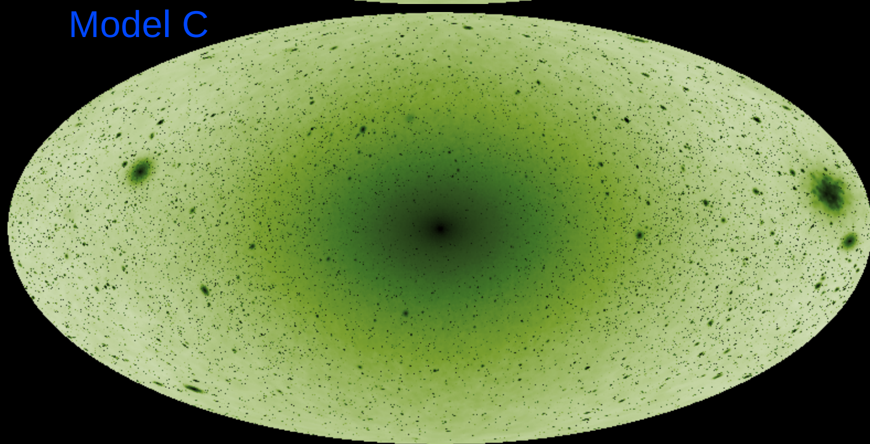


Model C



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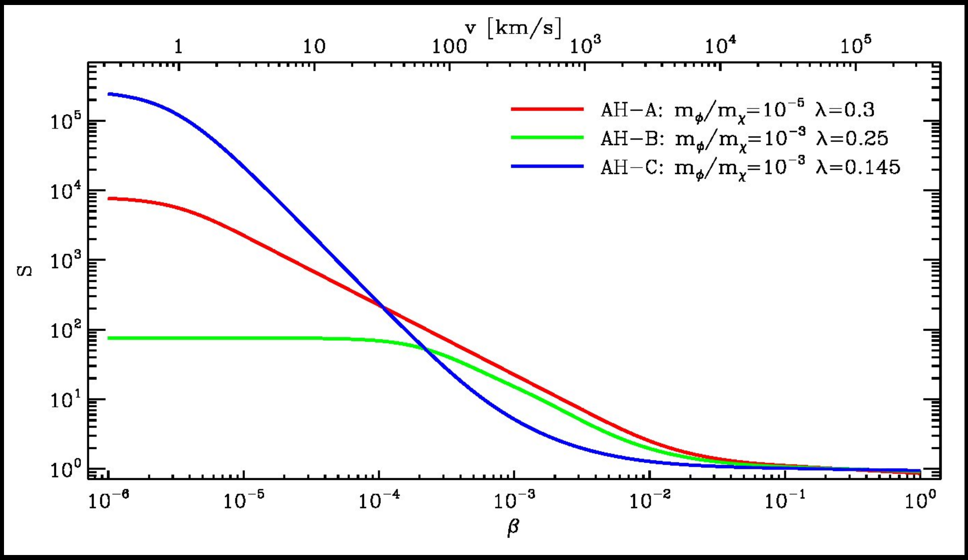
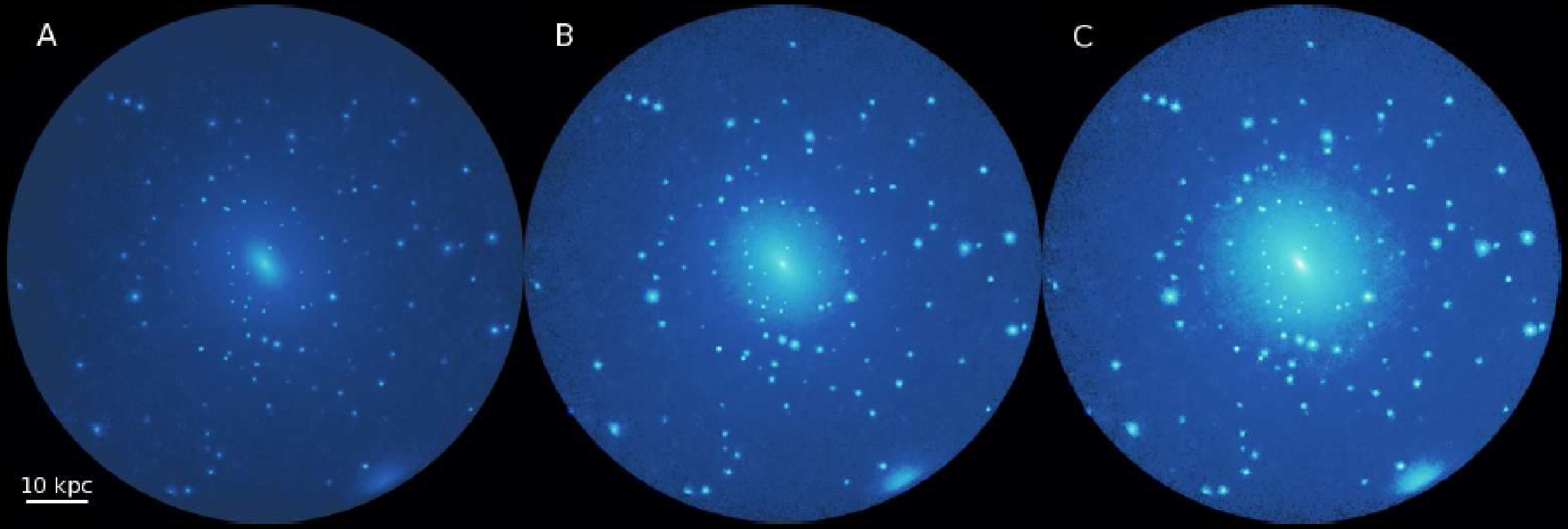


With Sommerfeld Enhancement

The Sommerfeld enhancement also brightens the central regions of subhalos!



Many of these Sommerfeld models will be strongly constrained by Fermi data.

Model	m_χ (TeV)	m_ϕ (GeV)	$\alpha \times 100$	$S_{\rm max}$	$v_{\rm sat}$ (km s^{-1})
LS-1	4.30	90	3.307	1,500	80
LS-2	4.45	90	3.297	12,000	28
LS-3	4.50	90	3.288	70,000	12
LS-4	4.55	90	3.281	430,000	4.7
MPV-1a	1.0	0.2	4.000	3,000	7.4
MPV-1b	1.0	0.2	3.739	16,000	2.4
MPV-2a	0.25	0.2	4.000	480	40
MPV-2b	0.25	0.2	4.500	40,000	3.3

Table 2: Detectable Subhalos. The number of subhalos that would be detected with $> 5\sigma$ significance by *Fermi* after 1, 2, 5, and 10 years in orbit, for different Sommerfeld-enhanced dark matter particle models. In the two right-most columns we give the median distance and mass of the detectable clumps after 5 years in orbit.

Model	1 yr	2 yr	5 yr	10 yr	$\tilde{D}$ (kpc)	$\tilde{M}_{\rm sub}$ ($M_\odot$)
LS-1	12	19	29	38	24	1.4×10^7
LS-2	72	99	167	244	42	9.5×10^6
LS-3	225	311	457	583	56	6.2×10^6
LS-4	410	528	730	919	66	4.9×10^6
MPV-1a	5	7	12	15	16	9.8×10^7
MPV-1b	9	14	25	36	25	4.4×10^6
MPV-2a	12	18	29	38	24	1.4×10^7
MPV-2b	187	254	397	518	55	4.5×10^6

Current Limitations and Future Directions

For DM-only simulations like the ones I discussed:

1) We're only beginning to **resolve the ~100 parsec scale** in subhalos

- Better match between observationally constrained properties and simulated subhalos: $M_{0.3}$, central (phase-space) densities.

2) Local phase-space structure at ~8kpc has not yet converged

- Implications for direct detection (especially for inelastic DM), and local DM annihilation (positron fraction, e^+e^- flux, neutrinos, ...).
- Relevance for stellar tidal streams?

3) Cosmic variance?

- How representative is any one high resolution numerical simulation?

4) More analysis of the existing simulations is needed

- time evolution, subhalo merger trees, tidal streams, etc.

Current Limitations and Future Directions

Absence of Baryonic Physics!!!

Current Limitations and Future Directions

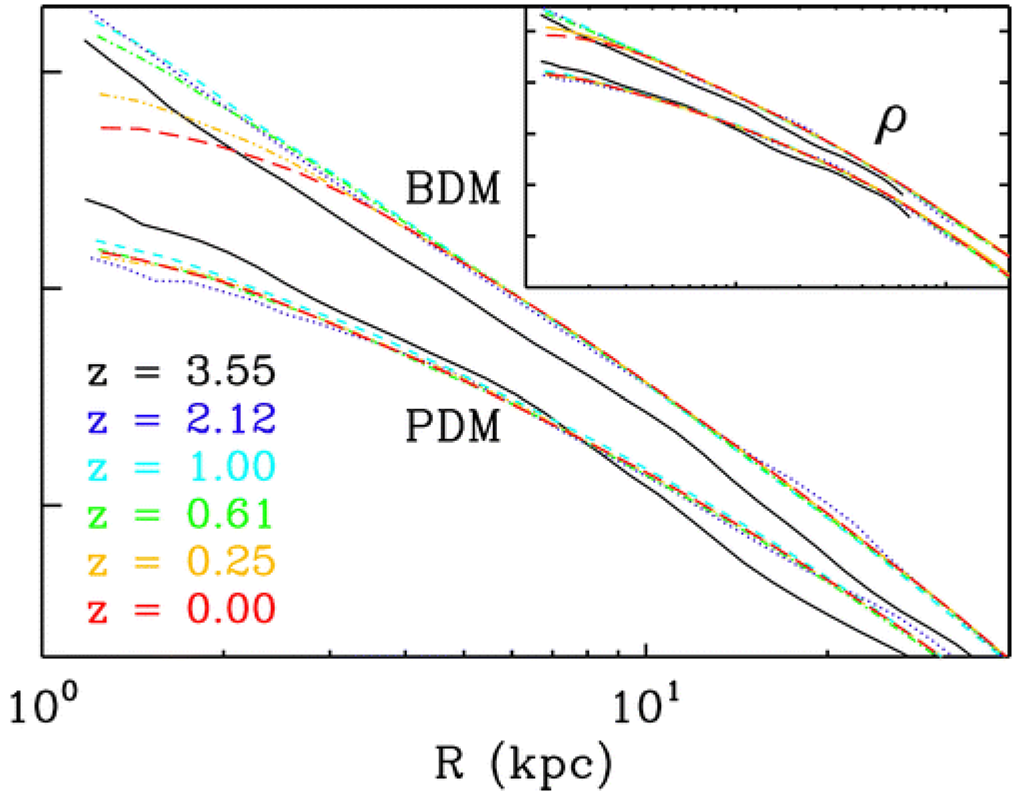
Absence of Baryonic Physics!!!

Where is it most critical and likely to change things?

1) For the Galactic Center and the smooth host halo profile

- Gas cooling and settling drags DM to center: adiabatic contraction
- Dynamical friction of infalling satellites with dense baryonic condensations can remove DM from center
- So can stellar bars and a binary SMBH...

Romano-Diaz et al. 2008



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3) Increase disk heating? (e.g. Kazantzidis et al. 2009)

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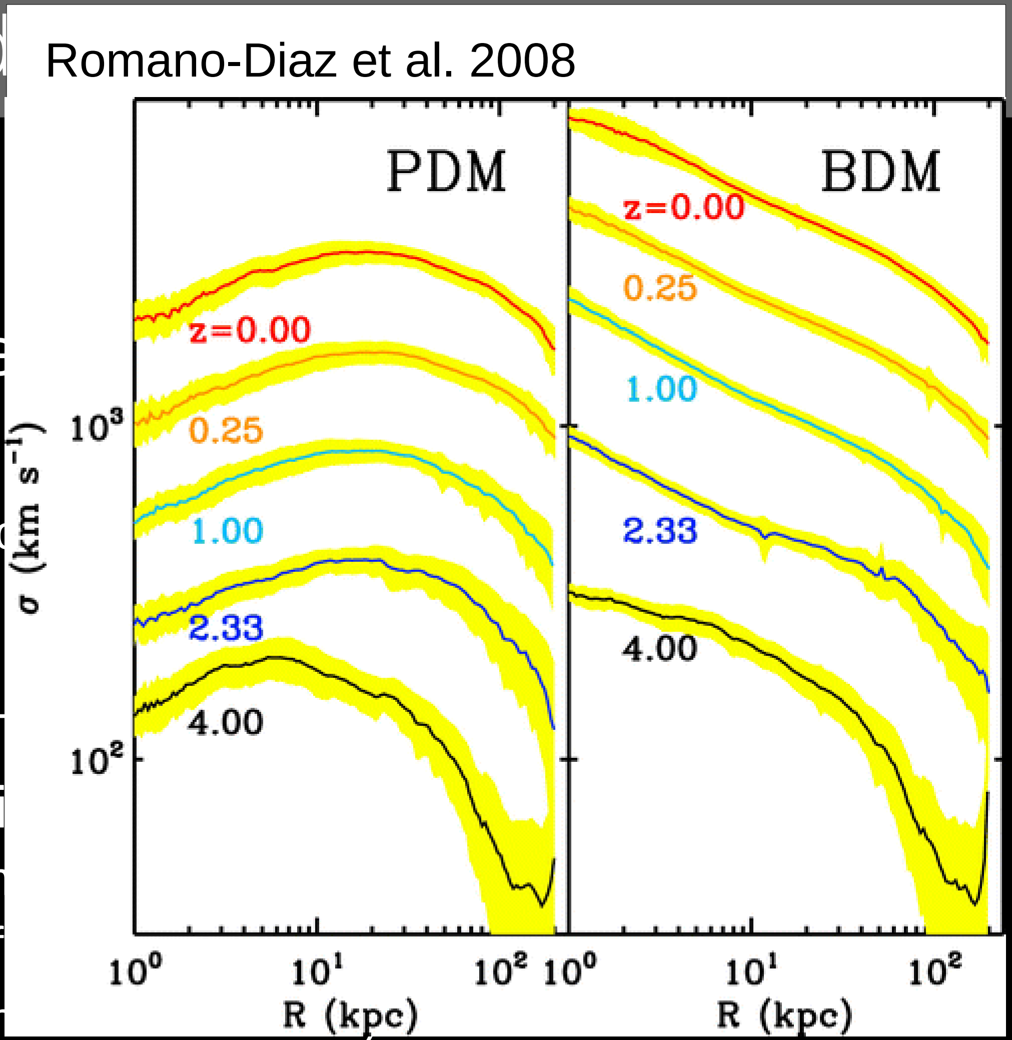

4) Modify DM velocity dispersions in the host halo, in subhalos?

- Implications for Sommerfeld-enhanced models

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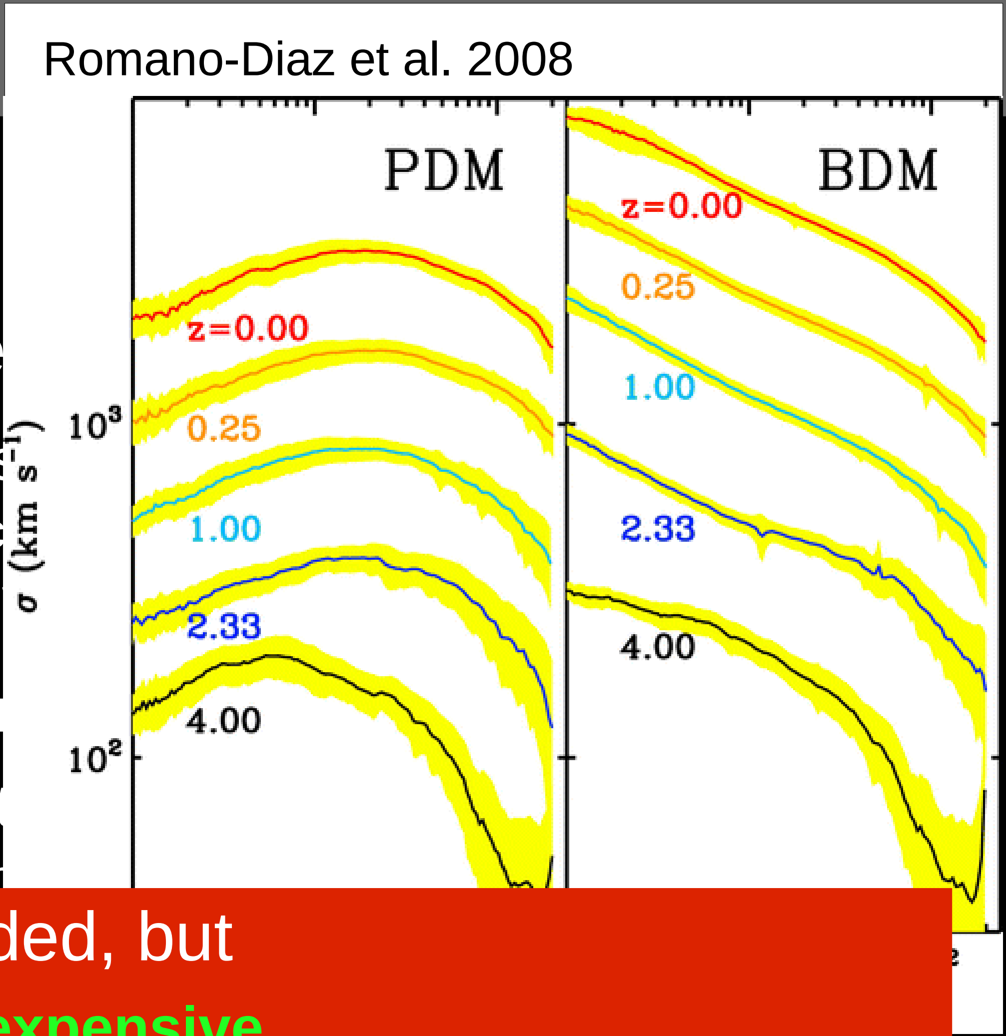

Baryonic physics must be included, but

- It's computationally much **more expensive**
- It makes the results **dependent on subgrid physics**, ad-hoc assumptions about gas cooling, star formation, feedback, etc.