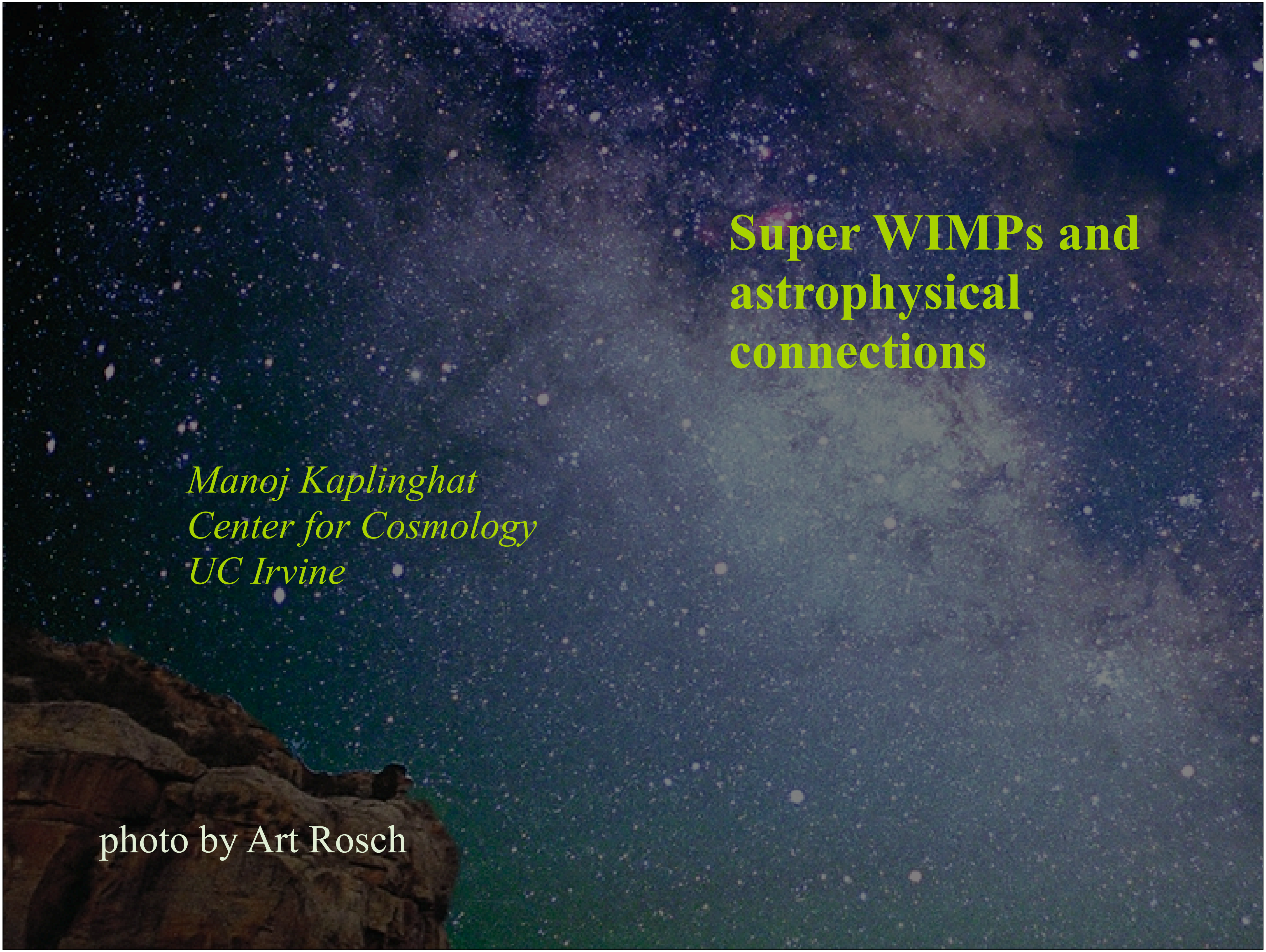


Super WIMPs and astrophysical connections

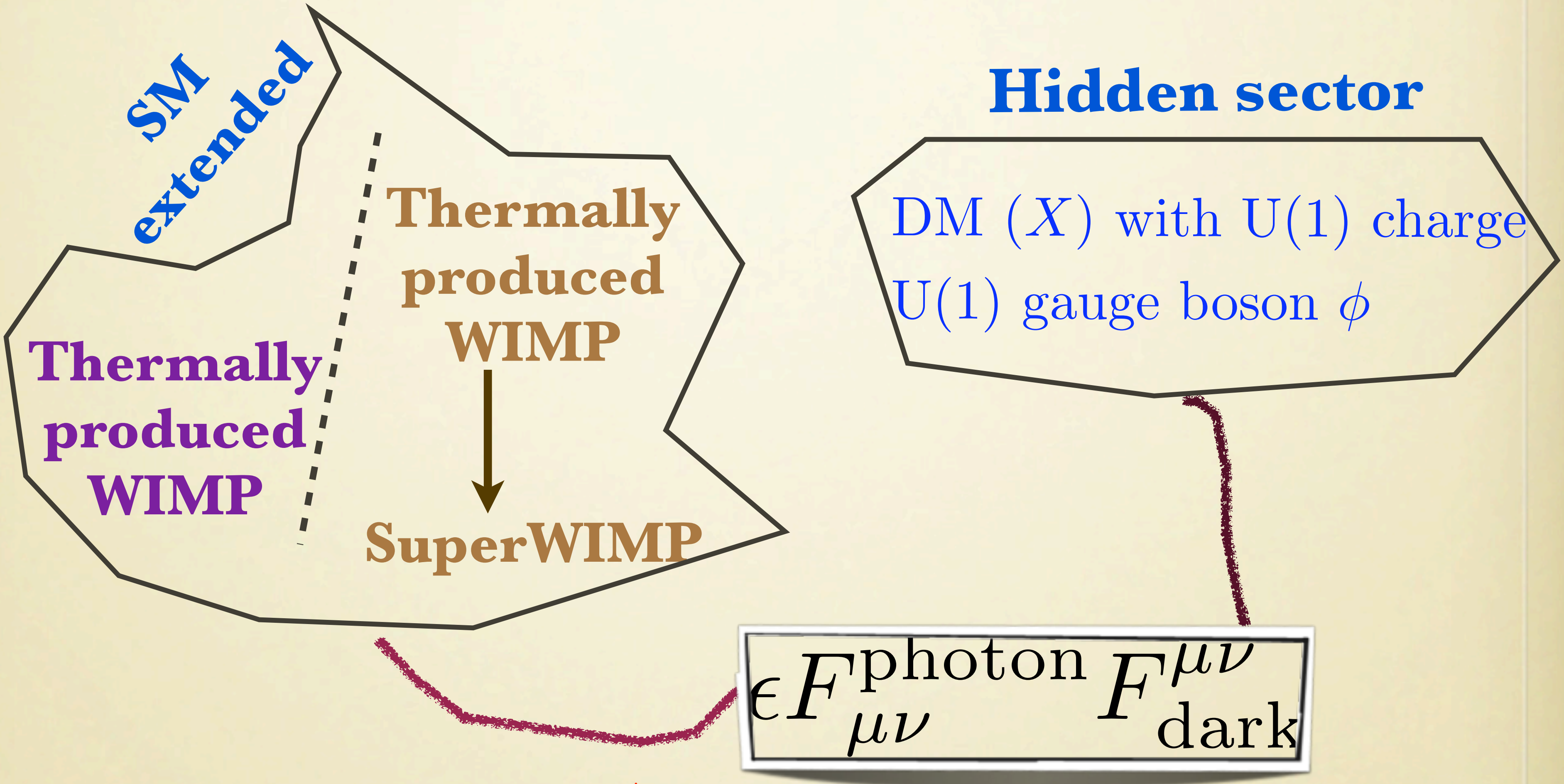
Manoj Kaplinghat
Center for Cosmology
UC Irvine

photo by Art Rosch

Dark Matter Particles

- What we know
  - Non-relativistic (at present)
  - Gravitational interactions same as normal matter
  - Cannot be "too warm"
- What is commonly assumed
  - Effectively collision-less *except in the* ***very early universe*** *and or in the* ***innermost regions*** *of dark matter halos*. This is true for typical SUSY models
- In general, collisional cross section could be much larger or non-existant than typical weak scale cross sections. *Example: Sommerfeld models and GeV force searches*

Weak scale hidden sectors (minimal scenarios)



$$\phi \to e^+e^-$$

$$XX \to \phi\phi \to 2e^+2e^-$$

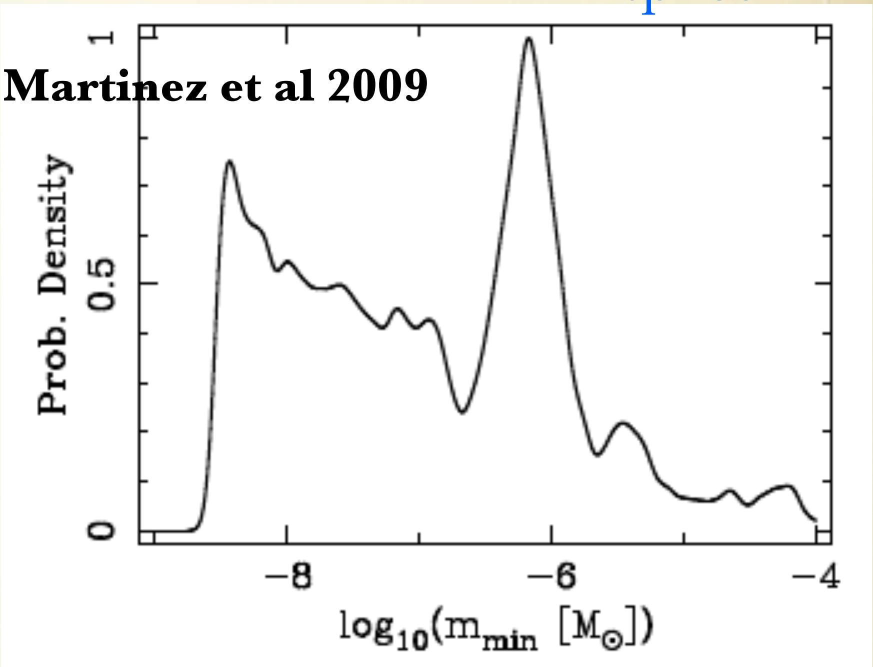
No hidden sector : Cold Dark Matter

- Example: Neutralino LSP
  - Weak scale sets the relic abundance
  - Kinetic decoupling 10-100 MeV
    - Cold Dark Matter with large primordial phase space density (Mass per unit volume in 6D phase space)

$$Q_{\mathrm{CDM}} = 10^{14}\frac{\mathrm{M}_\odot}{\mathrm{pc}^3}\left(\frac{\mathrm{km}}{\mathrm{s}}\right)^{-3}\left(\frac{\mathrm{M}}{100\mathrm{GeV}}\right)^{3/2}$$

  - Minimum halo mass ~ earth mass (with big spread)
    - related to coldness of the particle at kinetic decoupling : colder particle = smaller the minimum halo mass

Minimum halo mass in CMSSM space



Hofmann, Schwarz and Stoecker 2001
Green, Hofmann and Schwarz 2004
Loeb and Zaldarriaga 2005
Bertschinger 2006
Profumo, Sigurdson, Kamionkowski 2006

No hidden sector : Cold to Warm Dark Matter

- Example: NLSP stau decays to LSP gravitino with lifetime ~ $1/(8\pi G M_{weak}^3)$ ~ days.
  [Feng, Rajaraman and Takayama, 2003]

- Example: axino LSP
  [Covi, Kim and Roszkowski 1999]

- Example: Charged WIMP
  [Sigurdson and Kamionkowski 2003]

- **These particles could be warm (sliding scale) or a mix of warm and cold**
  [Kaplinghat 2005, Cembranos et al 2005, Jedamzik, Lemoine, Moultaka 2005, Pradler, Steffen 2007]

- Minimum halos mass could be large enough to be ruled out by current observations. Many models have minimum mass around dwarf galaxy scale.

- Small phase space density, Q ~ 1 (with huge spread) in the same units as last slide

- **Gravitino LSP** : Weak scale **sets** the relic abundance if mass of Gravitino ~ mass of other superpartners (as in SUGRA).
  [Feng, Rajaraman and Takayama, 2003]

Distinguishing DM from decays and CDM

- Accelerator searches
    - Look for signatures of long-lived charged particles at LHC [Hamaguchi et al 2004, Feng and Smith 2004]
- Early Universe
    - **stau (charged particle) decaying to Gravitino will change Big Bang Nucleosynthesis**
    - Also change black body spectrum of CMB [Feng, Rajaraman and Takayama, 2003]
- Late Universe : small scale structure formation
    - **Minimum mass halo**
    - **Density profile of dark**

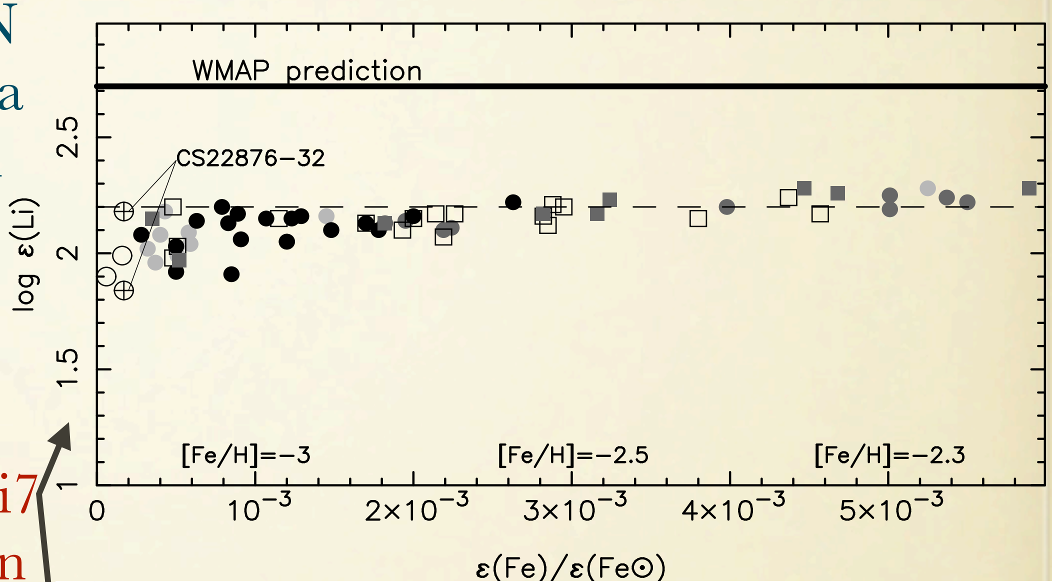
Charged particle BBN

- Long history [Dimopoulos, Esmailzadeh, Hall, Starkman 89; Khlopov, Levitan, Sedelnikov, Sobol 94; Kawasaki, Moroi 95; ...]
- Bound states of charged particles and nuclei not considered until recently [Cahn, Glashow 91; Pospelov 07; Kohri, Takayama 07; Kaplinghat, Rajaraman 07]
- "Atoms" of negatively charged heavy (mass >> GeV) particles (X) and Helium-4 (to be concrete)

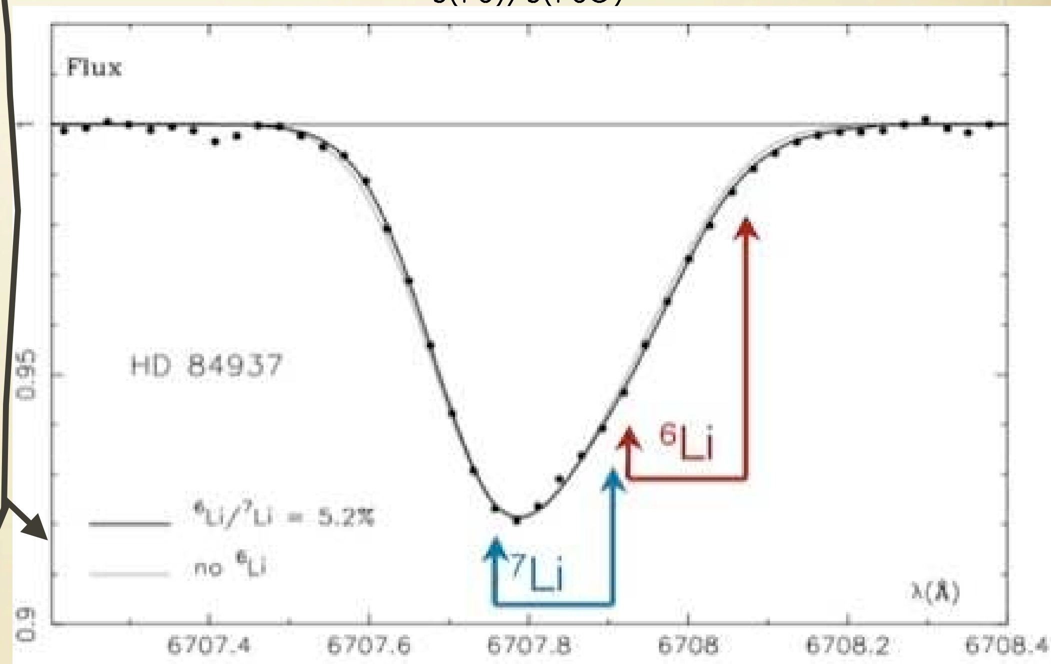
- He4 is the "electron"
- Binding energy ~ 0.3 MeV
- "Bohr radius" ~ 3.6 fm
- Expect (He4X) bound states to form in earnest around 10 keV
- **Many different effects**: biggest one is the enhanced cross section for **Lithium 6** formation via (He4X) + D to Li6 + X [Pospelov 07]

Lithium abundances

- Lithium-7 problem: Standard BBN prediction of Li^7/H ($3\text{-}5 \times 10^{-10}$) is a factor of 3-5 larger than measured "primordial" abundance ($1\text{-}1.5 \times 10^{-10}$) [Asplund et al 06]



- Lithium-6 problem: Some measurements indicative of Li6/Li7 of few % : O(100) times larger than typical BBN prediction [Asplund et al 06, 08; but see Cayrel et al 07, Garcia Perez et al.09]



- Solve both these problems in the context of decaying particles with lifetime ~ 1000 s? [Jedamzik 07]

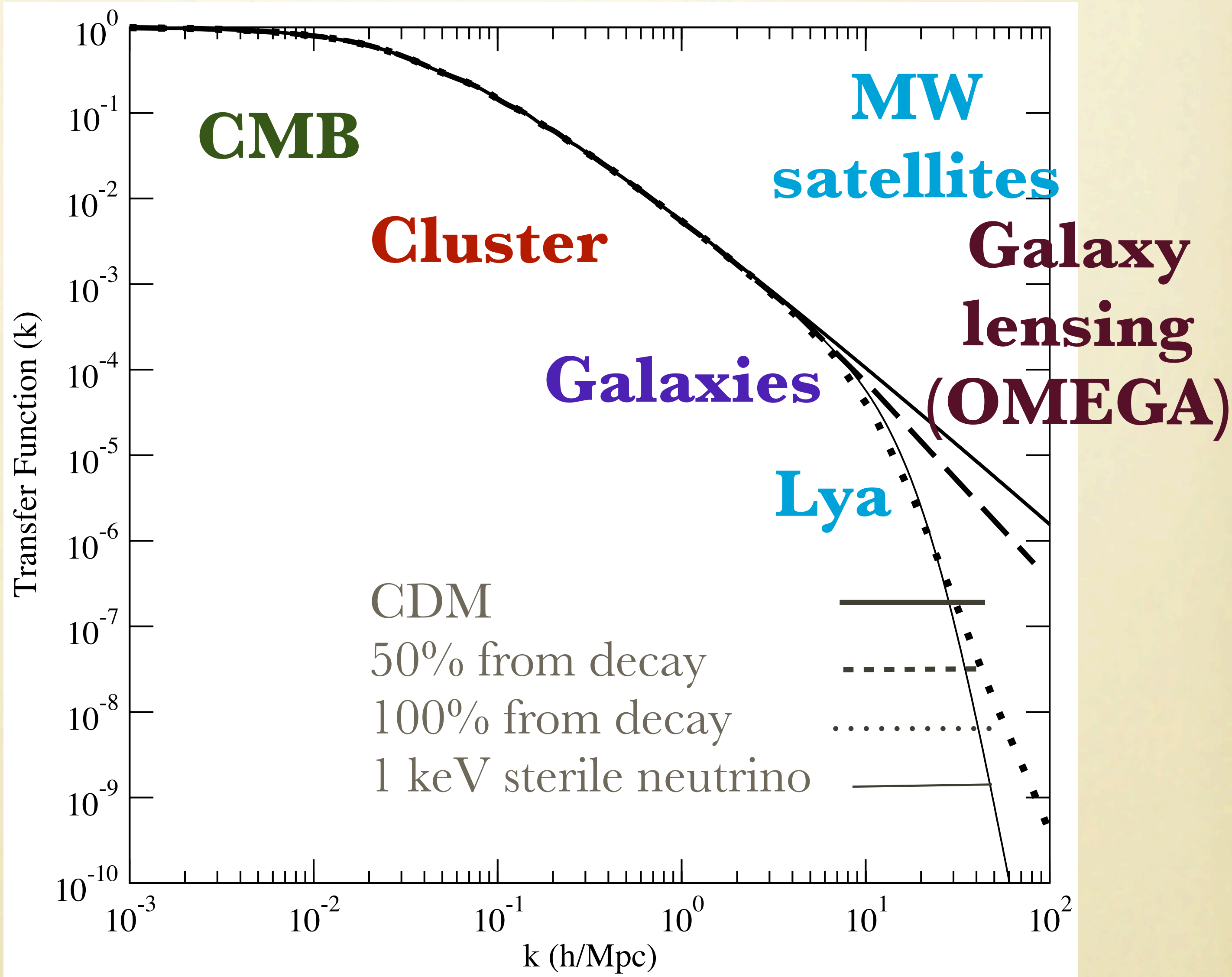
Plots from recent review paper by Spite and Spite

Distinguishing DM from decays and CDM

- Accelerator searches
  - Look for signatures of long-lived charged particles at LHC [Hamaguchi et al 2004, Feng and Smith 2004]
- Early Universe
  - **Big Bang Nucleosynthesis**
  - CMB black body
- Late Universe
  - Small scale structure formation
    - **Minimum mass halo**
    - **Density profile of dark matter halos**

Power spectrum of linear fluctuations : sets the minimum halo mass

Perturbations are erased below the free-streaming length/damping length



No Deviations from CDM predictions seen

Distinguishing DM from decays and CDM

- Accelerator searches
  - Look for signatures of long-lived charged particles at LHC [Hamaguchi et al 2004, Feng and Smith 2004]
- Early Universe
  - **Big Bang Nucleosynthesis**
  - CMB black body
- Late Universe
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    - **Minimum mass halo**
    - **Density profile of dark matter halos**

Density profile of dark matter halos

Deviations from the collision less Cold Dark Matter paradigm (think susy neutralino) ?

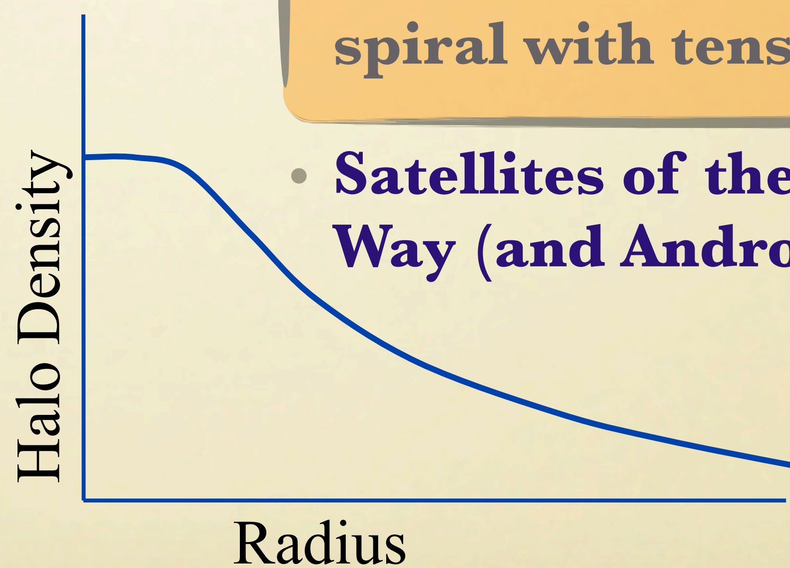
- Core or cusp?
  - **Does the inner density vs radius relation in galaxies flatten?**
  - **CDM *predicts(?)* that density increases with decreasing radius on observable scales.**
  - **Warm dark matter (e.g., sterile neutrino, super WIMP) predicts cores on observable scales**

Core or cusp?

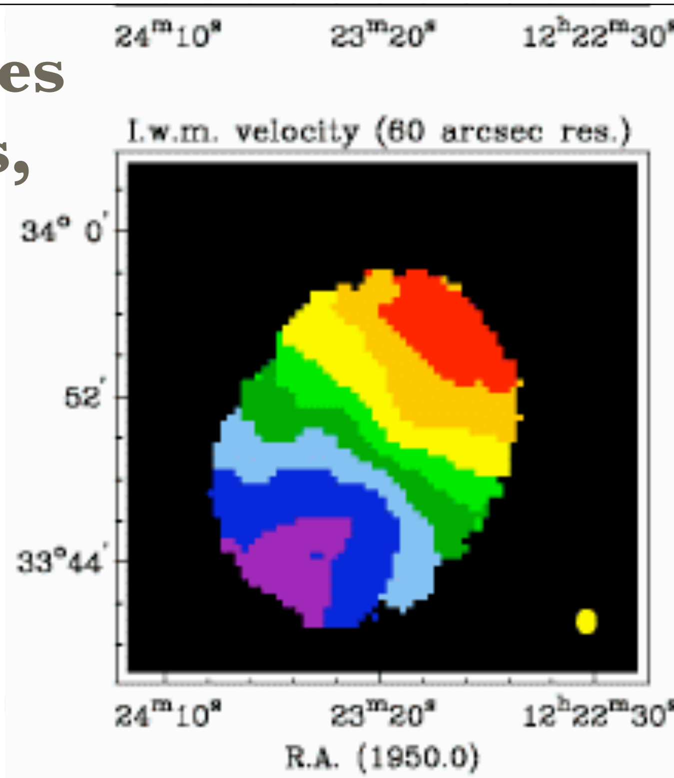
- *Most CDM simulations (except for some recent work including baryons) show that density of dark matter in a galactic halo increases with decreasing radius on observable scales.* Is this the case observationally?

- ***Self-interactions***, ***self-annihilations*** *and* ***finite primordial phase space density*** *will all stop this increasing density trend.* But at what radius?

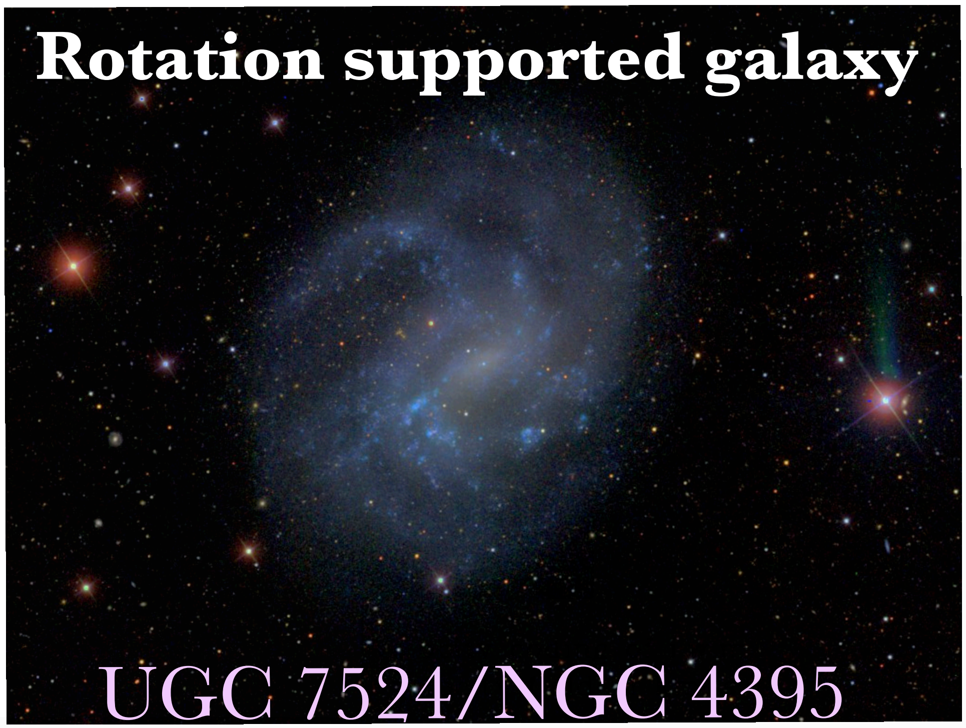
- **Which galaxies should we look at?**
  - **Close-by and dark matter dominated**
  - **Low surface brightness spiral with tens of Mpc**
  - **Satellites of the Milky Way (and Andromeda)**



What about cores in spiral galaxies with very low surface brightness, only tens of Mpc away?

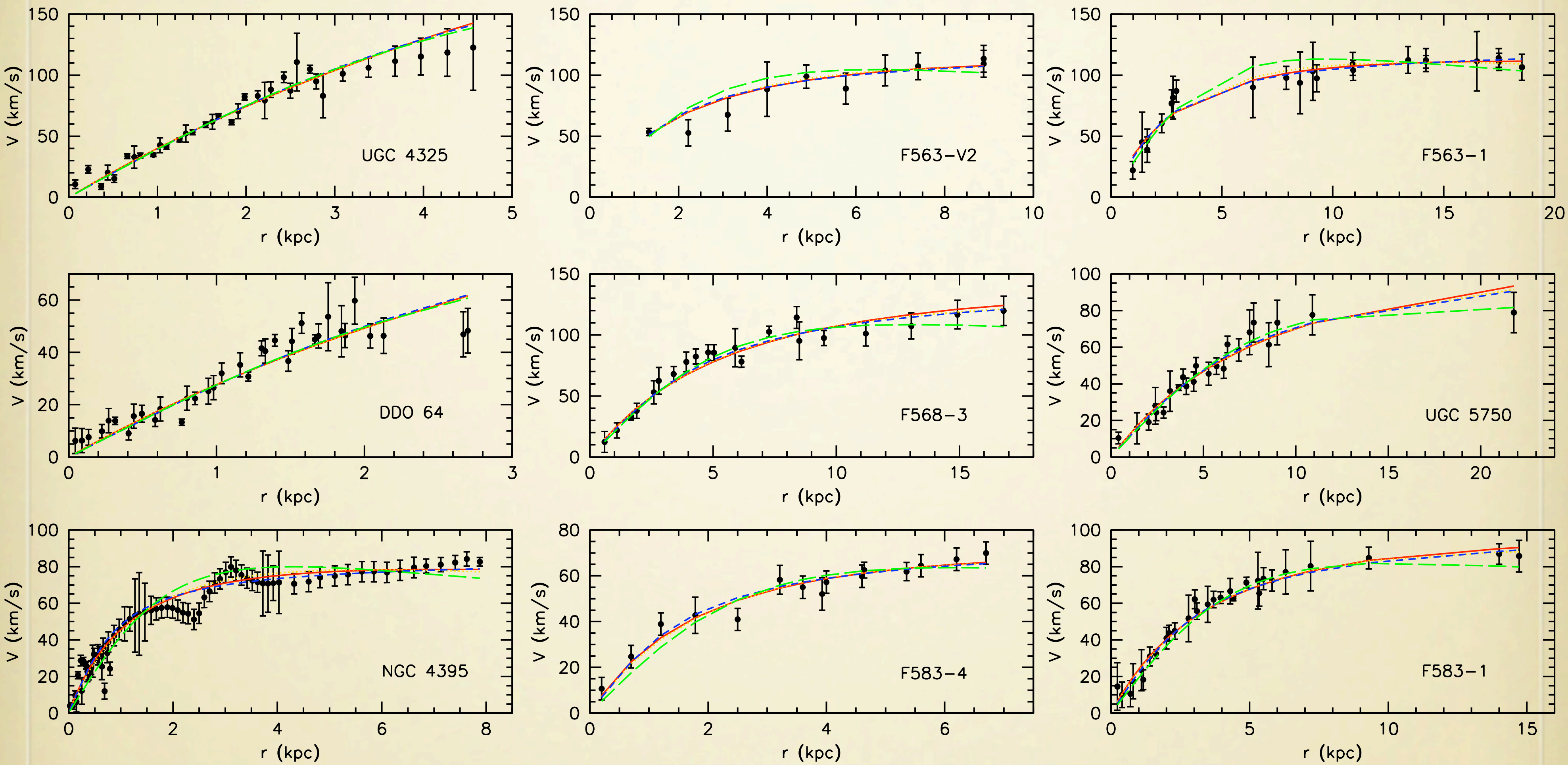


For many of these galaxies, dark matter dominates the total mass budget all the way to the center



Galaxy:	UGC 7524
Distance:	4.3 Mpc
Type:	.SAS9*.
B^0_T:	10.55
Inclination:	34°
Optical size:	13.'2 x 10.'8
Total HI mass:	$14.4 \times 10^8\ M_\odot$

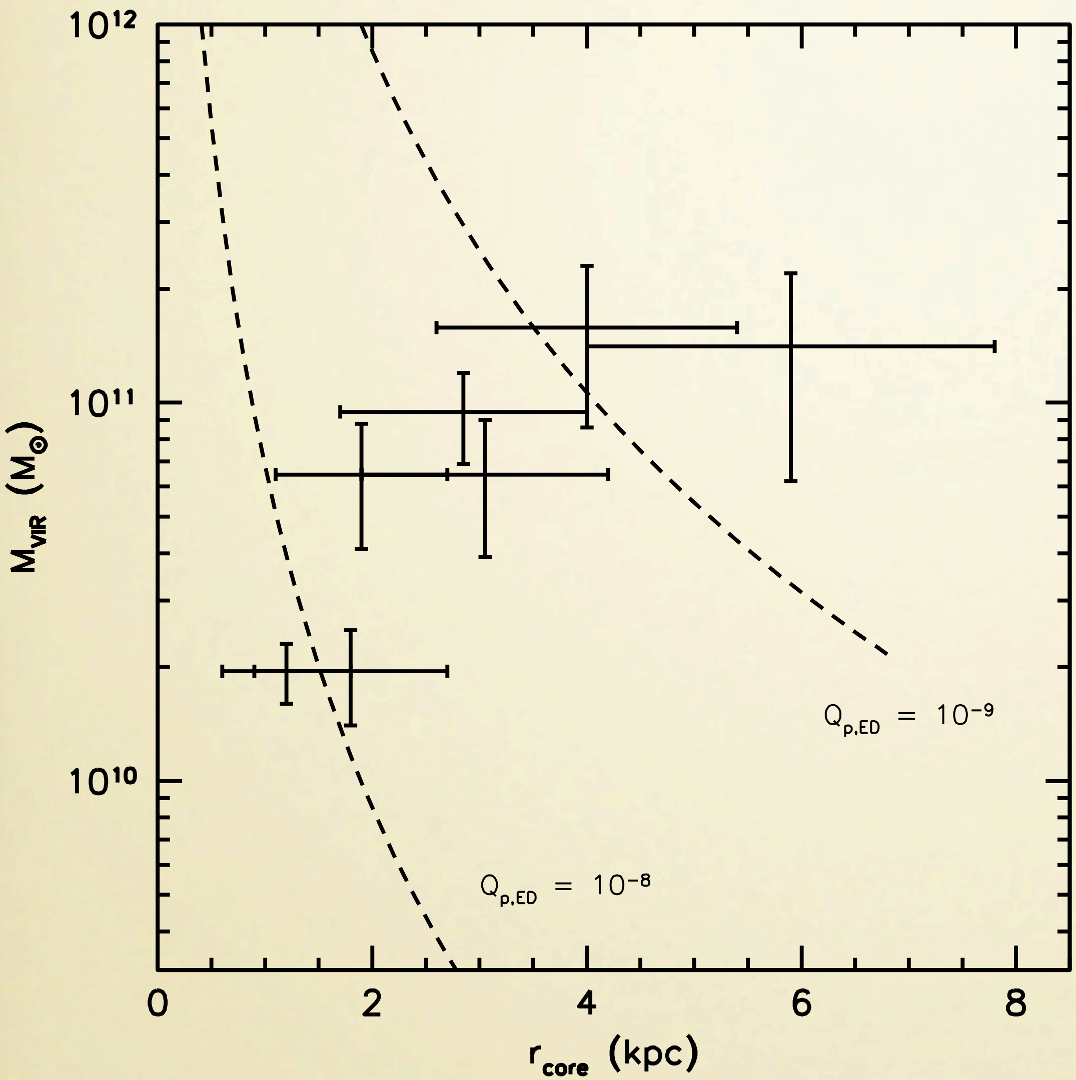
Nearby Low Surface Brightness spirals



Kuzio de Naray, Martinez, Bullock, Kaplinghat, ApJL 2010

Note the linear rise in rotation velocity at small radii for all galaxies => constant density cores

One primordial phase space density?

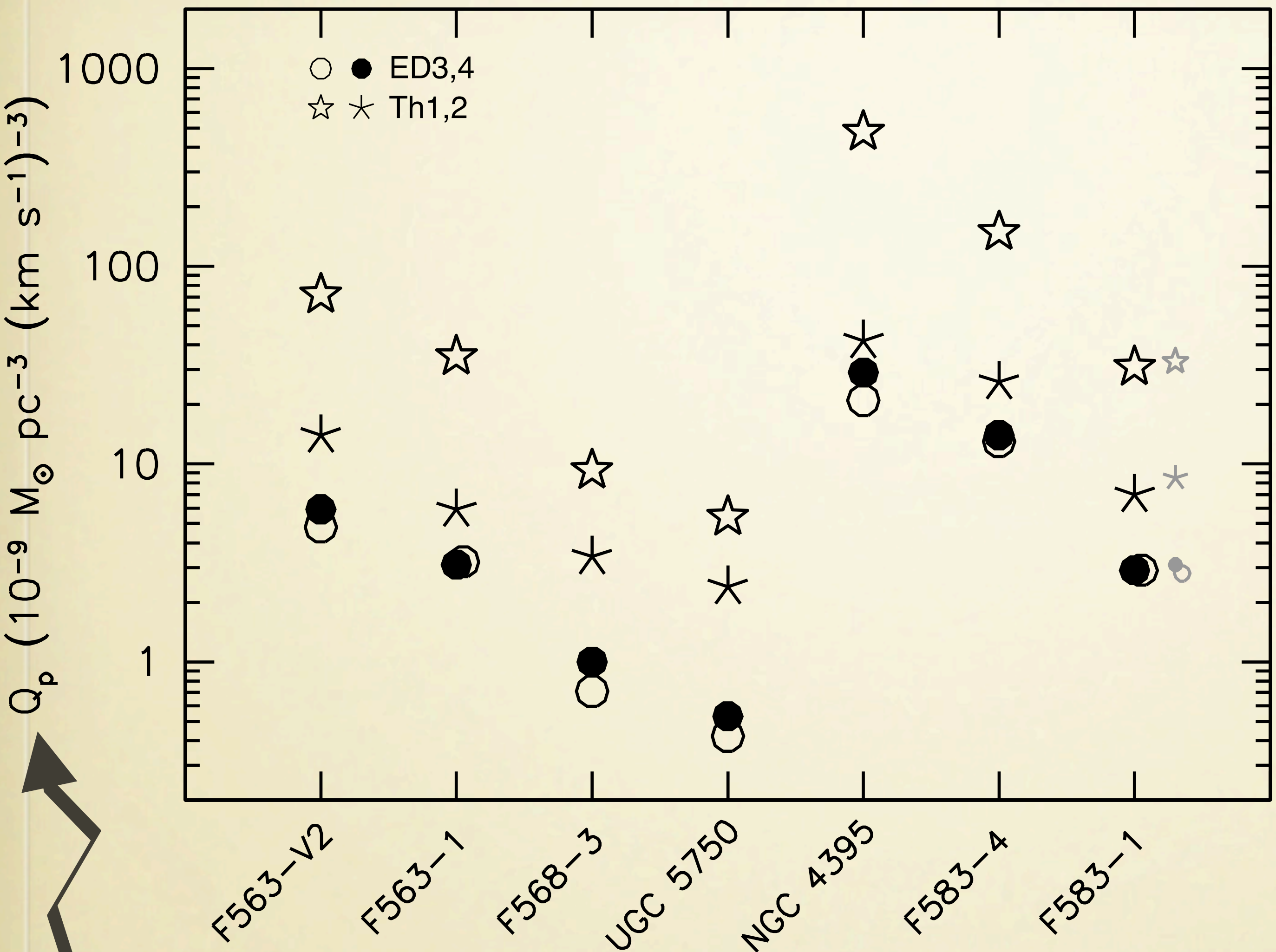


A basic prediction of phase space limited cores is that smaller mass halos should have larger cores. This is not borne out by the data.

Kuzio de Naray, Martinez, Bullock, Kaplinghat, ApJL 2010

The values of Q (primordial) are 5-6 orders of magnitude larger than the constraints from Lyman-alpha forest PS measurements

One primordial phase space density?



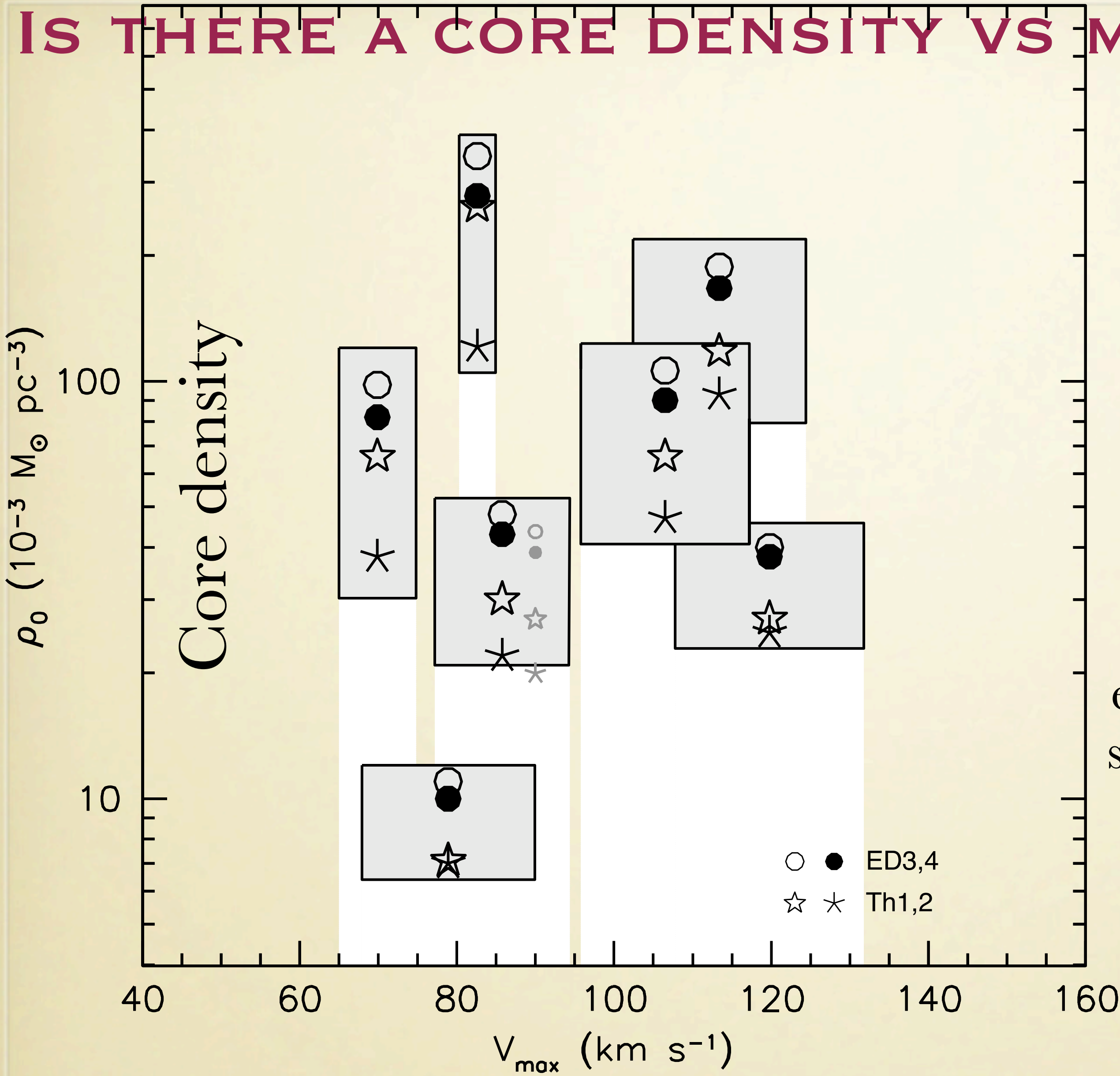
[Warm dark matter does not naturally explain the spread in the values of Q]

Note that we are not excluding the possibility that dark matter particle is warm with Q_p larger than those measured in these LSBs

Kuzio de Naray, Martinez, Bullock, Kaplinghat, ApJL 2010

Q_p = phase space density defined as density divided by RMS velocity cube

Is there a core density vs mass relation?



No.

This scatter is not explained by self-interactions, however this deserves further work

Note that we are not excluding the possibility of self interactions that would give rise to cores smaller than those here.

Kuzio de Naray, Martinez, Bullock, Kaplinghat, ApJL 2010

Core or cusp?

- *Most CDM simulations (except for some recent work including baryons) show that density of dark matter in a galactic halo increases with decreasing radius on observable scales.* **Is this the case observationally?**
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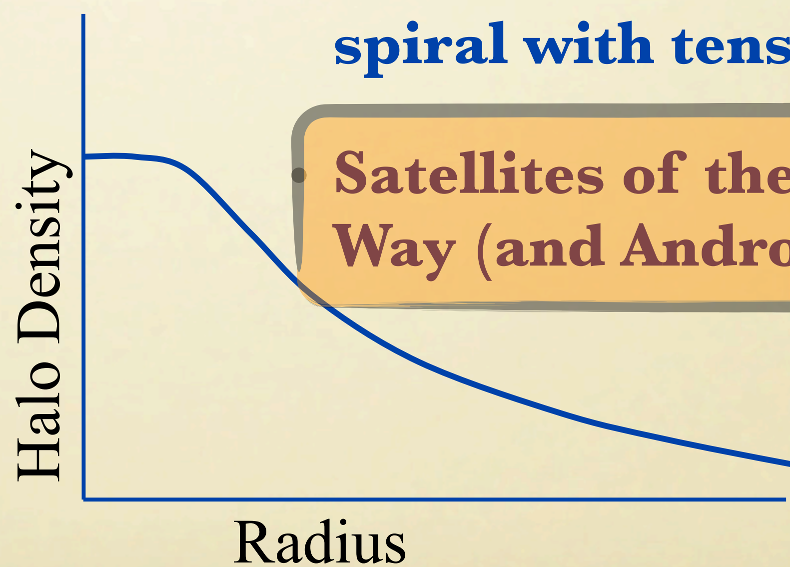
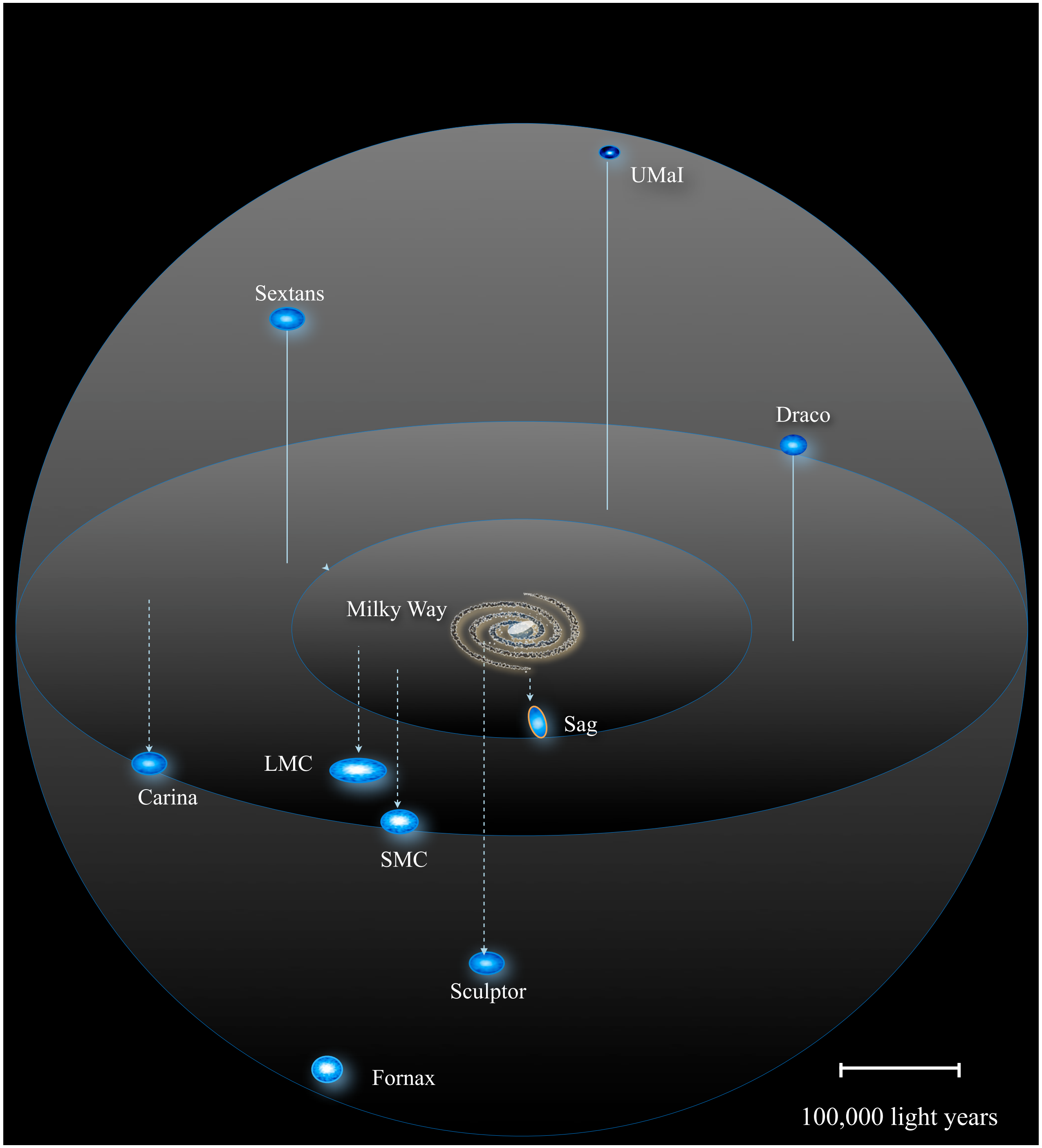


Milky Way circa 2004

~11 Dwarf Satellites

Name	Year Discovered
LMC	1519
SMC	1519
Sculptor	1937
Fornax	1938
Leo II	1950
Leo I	1950
Ursa Minor	1954
Draco	1954
Carina	1977
Sextans	1990
Sagittarius	1994

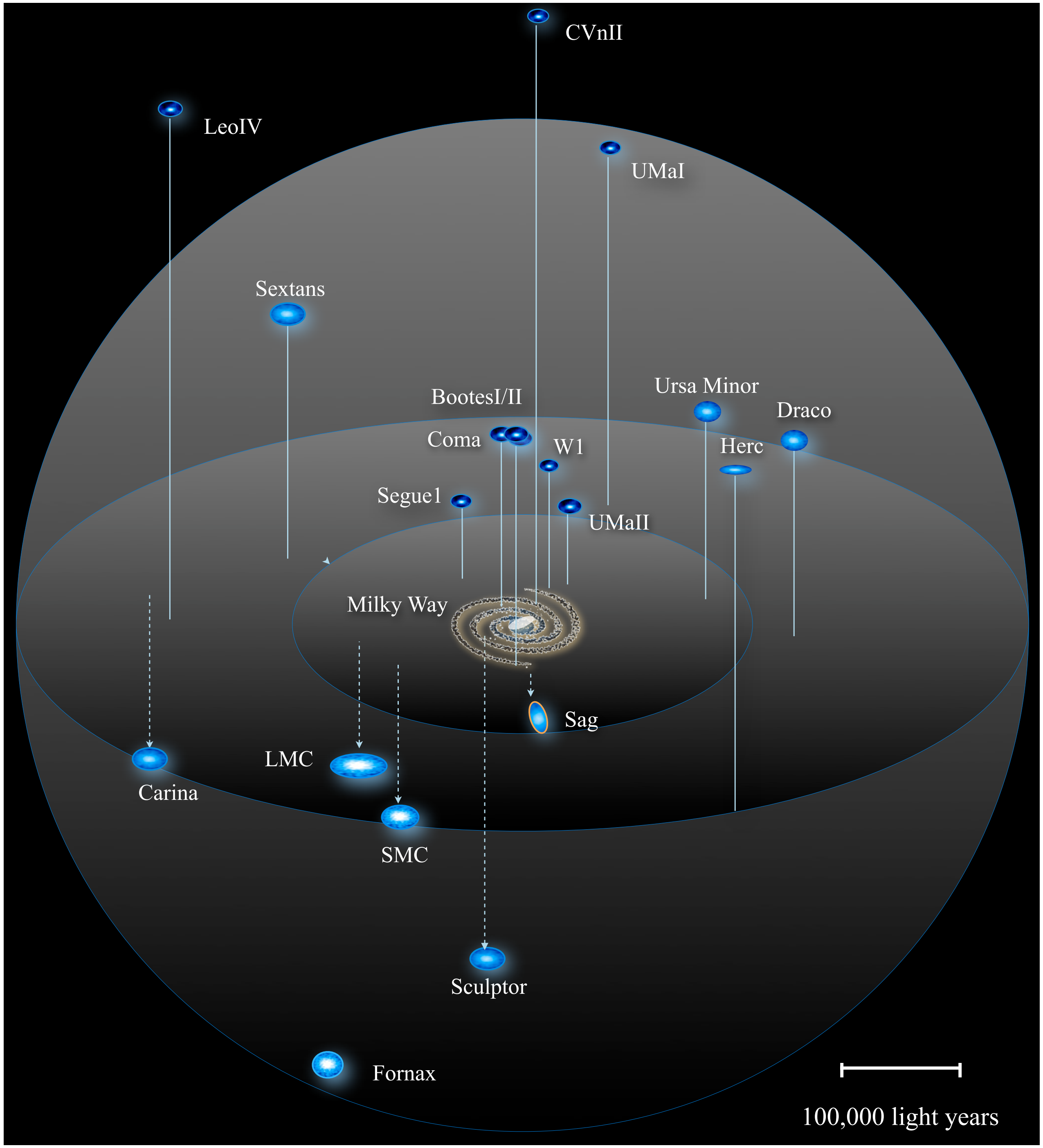


J Bullock, M Geha and L Strigari

Milky Way circa 2008

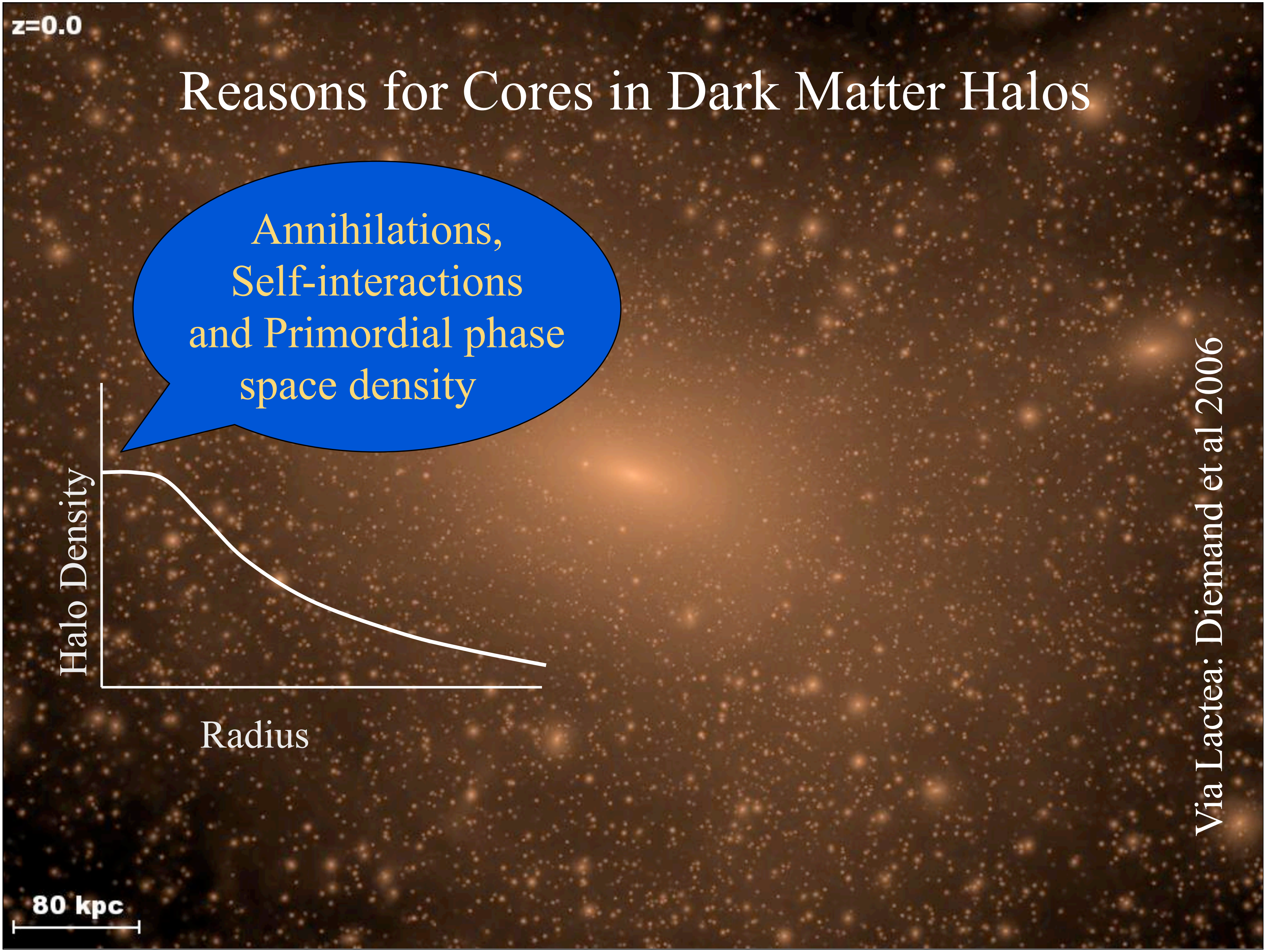
Name	Year Discovered
LMC	1519
SMC	1519
Sculptor	1937
Fornax	1938
Leo II	1950
Leo I	1950
Ursa Minor	1954
Draco	1954
Carina	1977
Sextans	1990
Sagittarius	1994
Ursa Major I	**2005**
Willman I	**2005**
Ursa Major II	**2006**
Bootes	**2006**
Canes Venatici I	**2006**
Canes Venatici II	**2006**
Coma	**2006**
Segue I	**2006**
Leo IV	**2006**
Hercules	**2006**
Leo T	**2007**
Bootes II	**2007**
LeoIV	**2008**

CAN WE EXPECT TO SEE DEVIATIONS FROM CDM?



J Bullock, M Geha and L Strigari

Reasons for Cores in Dark Matter Halos



We can't (yet) measure the slope of the density profile in the satellites

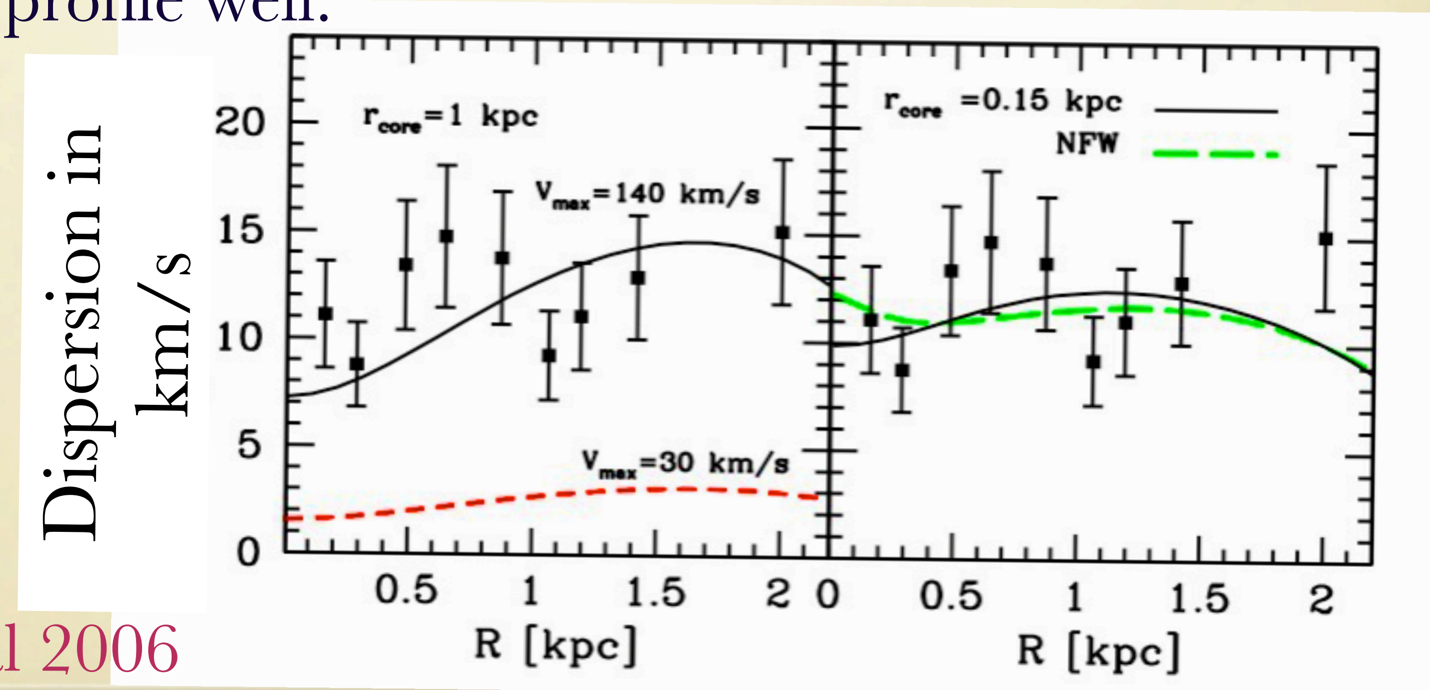
Observation: Line of sight velocity of individual stars

Infer: Intrinsic dispersion

Estimate: Gravitational potential well that results in this dispersion assuming equilibrium -- mass of dark matter halo

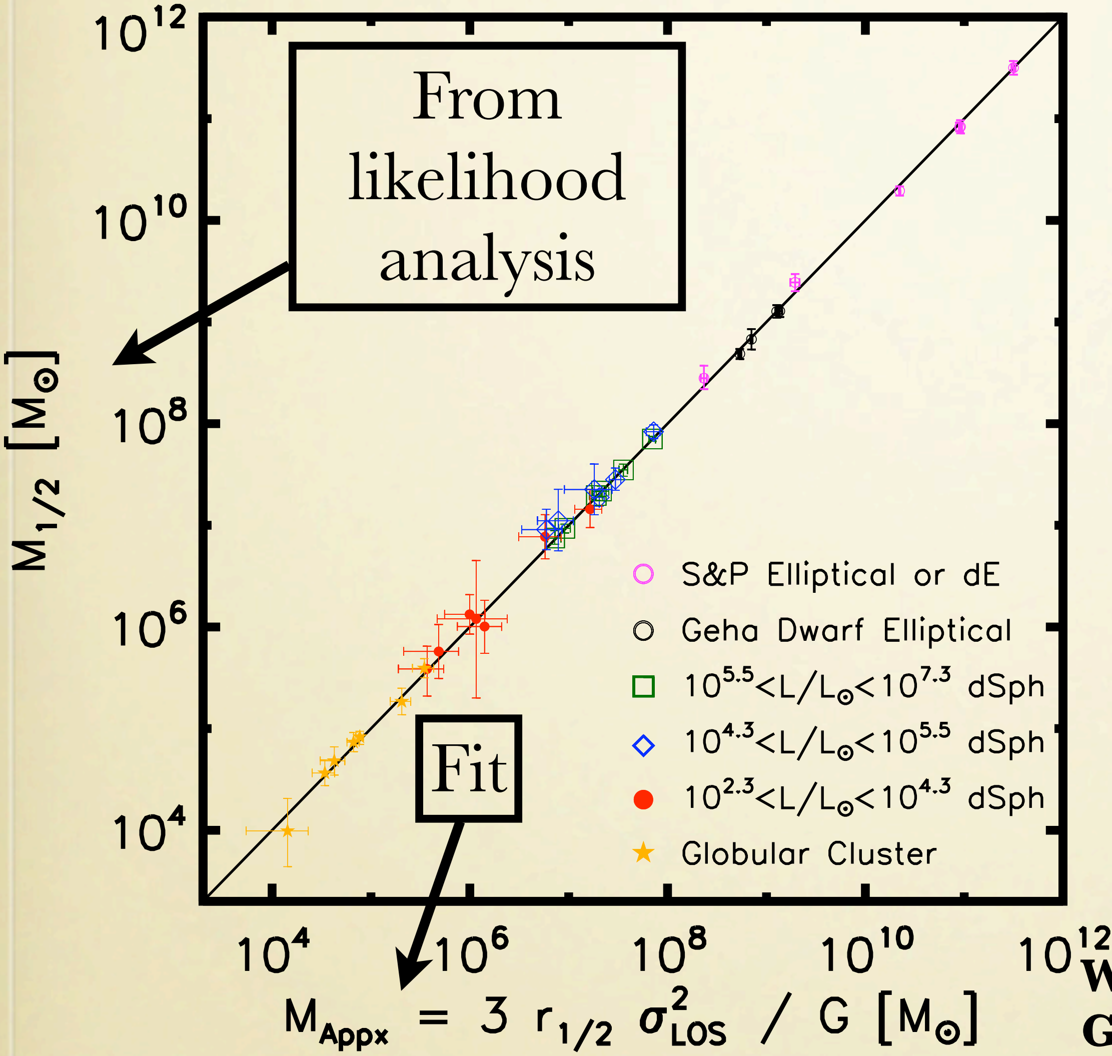
There is a fundamental degeneracy with the velocity dispersion anisotropy of stars that prevents one from measuring the profile well.

Black lines are for cored density profile



Strigari et al 2006

What can we measure in the satellites?



Answer: Mass within the half-light radius of stars. An excellent fit is given by

$$M_{1/2} = \frac{3r_{1/2}\langle\sigma^2_{\rm LOS}\rangle}{G}$$

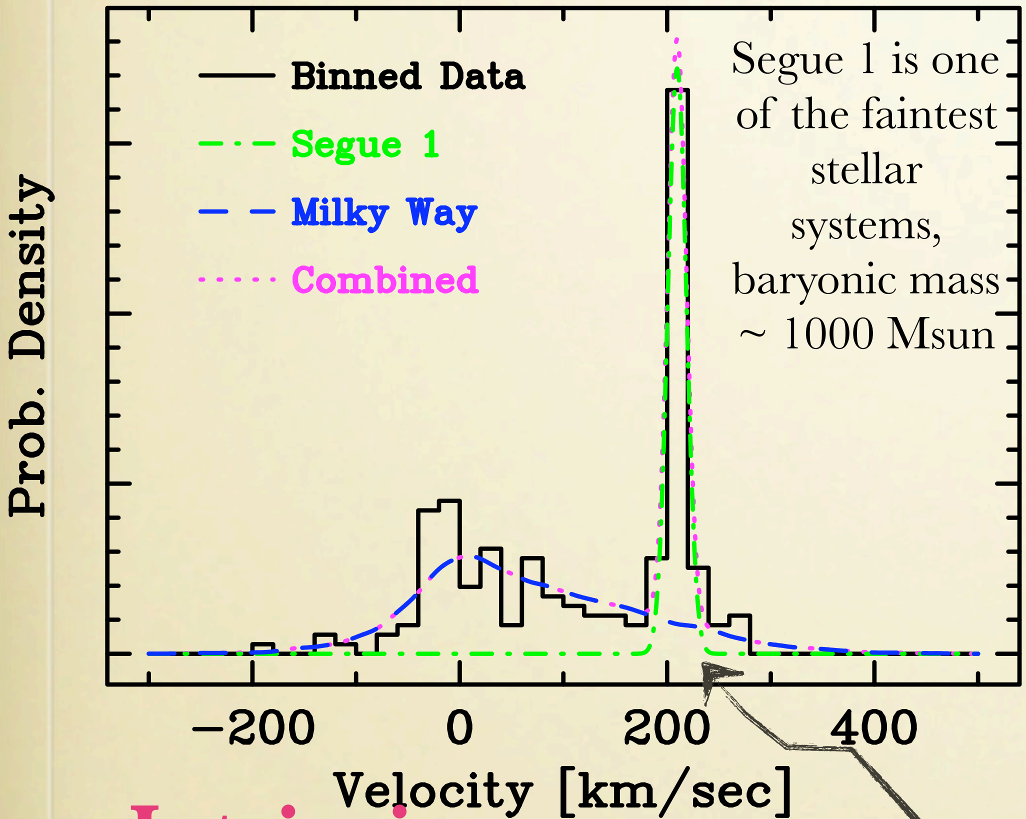
$r_{1/2}$: 3D half-light radius

$M_{1/2}$: total mass (almost all dark matter) within half-light radius

Wolf, Martinez, Bullock, Kaplinghat, Geha, Munoz, Simon, Avedo MNRAS 2010

Similar results from Walker, Mateo, Olszewski, Penarrubia, Evans, Gilmore ApJ 2009

Measuring dark matter mass in an SDSS ultra-faint dwarf: Segue 1 (about 23 kpc from sun)



Intrinsic dispersion ~3.7 km/s

$$M(r < r_{1/2}) = \frac{3 r_{1/2} \langle \sigma^2_{\rm LOS} \rangle}{G}$$

$$= \frac{3 \times 38\mathrm{pc} \times (3.8\mathrm{km/s})^2}{0.0043\,\mathrm{pc}\,\mathrm{M}_\odot^{-1} (\mathrm{km/s})^2}$$

$$= 3.8 \times 10^5\,\mathrm{M}_\odot$$

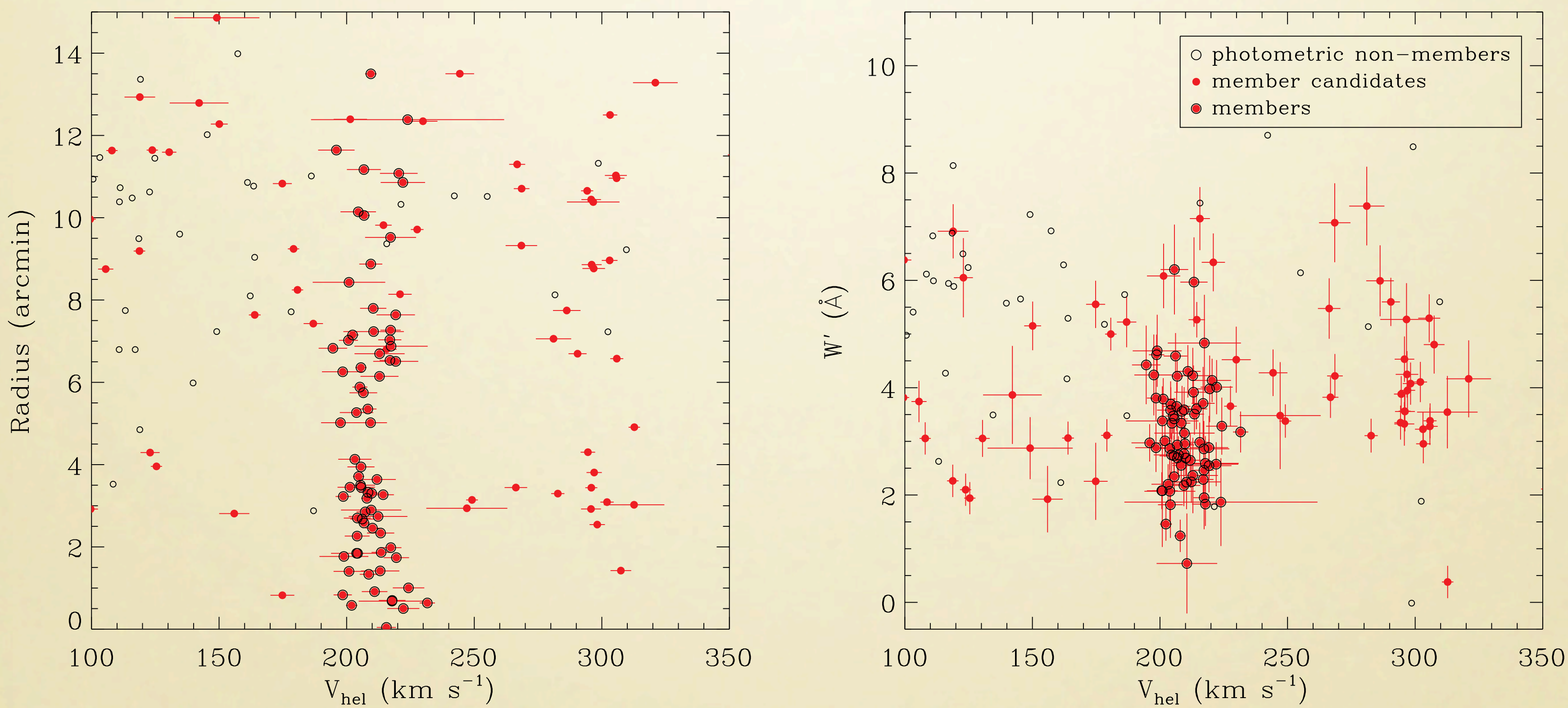
$$\rho(r < r_{1/2}) = 1.7\,\frac{\mathrm{M}_\odot}{\mathrm{pc}^3}$$

Simon, Geha et al, arxiv: 1007.4198
Martinez, Minor et al, in prep

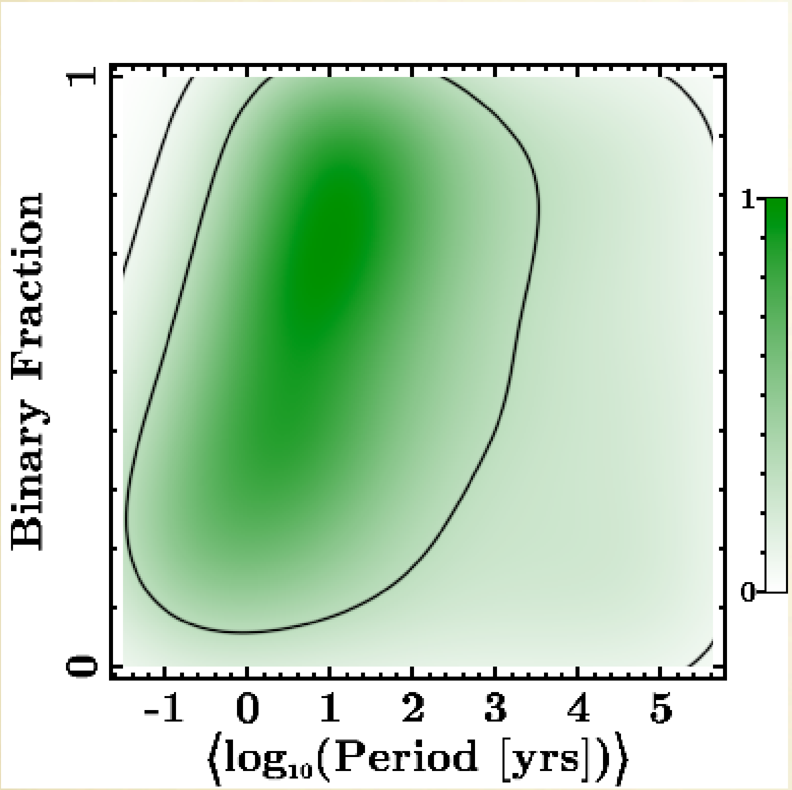
WHY SEGUE 1 IS NOT A GLOBULAR CLUSTER

Tidal radius without dark matter about the same as the radius that contains half the light : *this should have been ripped apart*

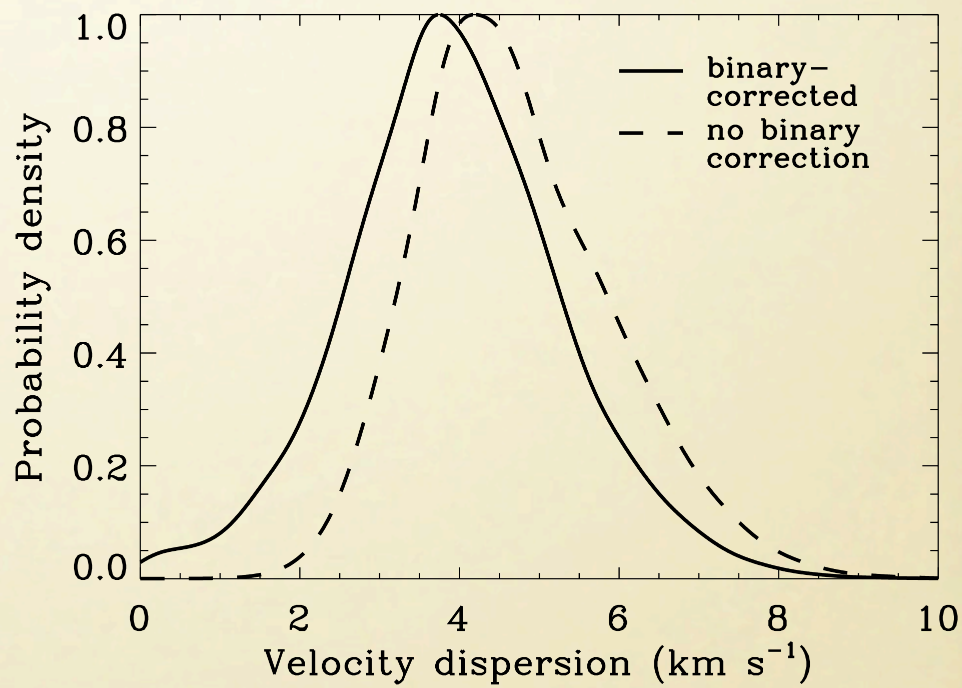
Existence of extremely metal poor stars : *not found in star clusters or streams*



Measuring dark matter mass in Segue 1: effect of binary stars



Some part of the measured velocity of a star is due to orbital motion



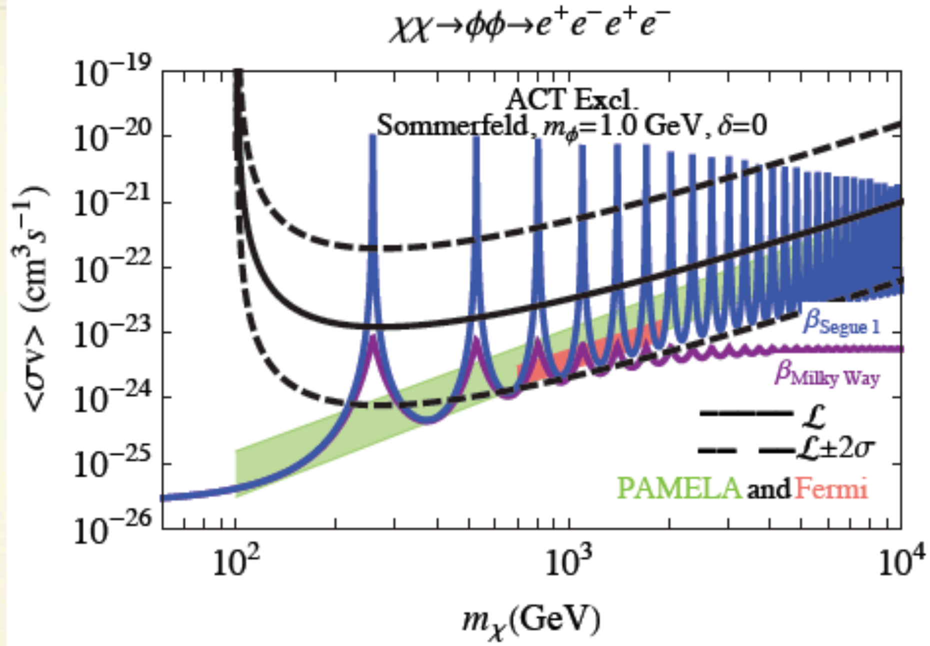
Repeat measurements at about 1 year interval for many stars needed to constrain binary properties and estimate dark matter mass

Simon, Geha et al, arXiv: 1007.4198
Martinez, Minor et al, in prep

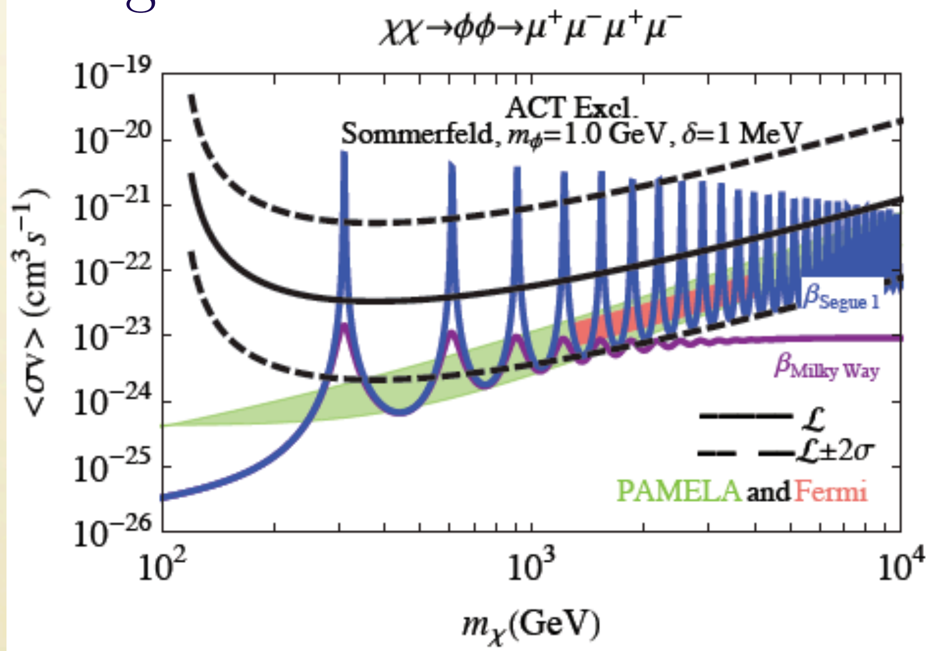
Segue 1 constraints on Sommerfeld enhanced explanations of PAMELA and Fermi

Fermi analysis with about 20 months of data and a new analysis of stellar data in about 2 months

I am estimating a factor of 2 better constraints

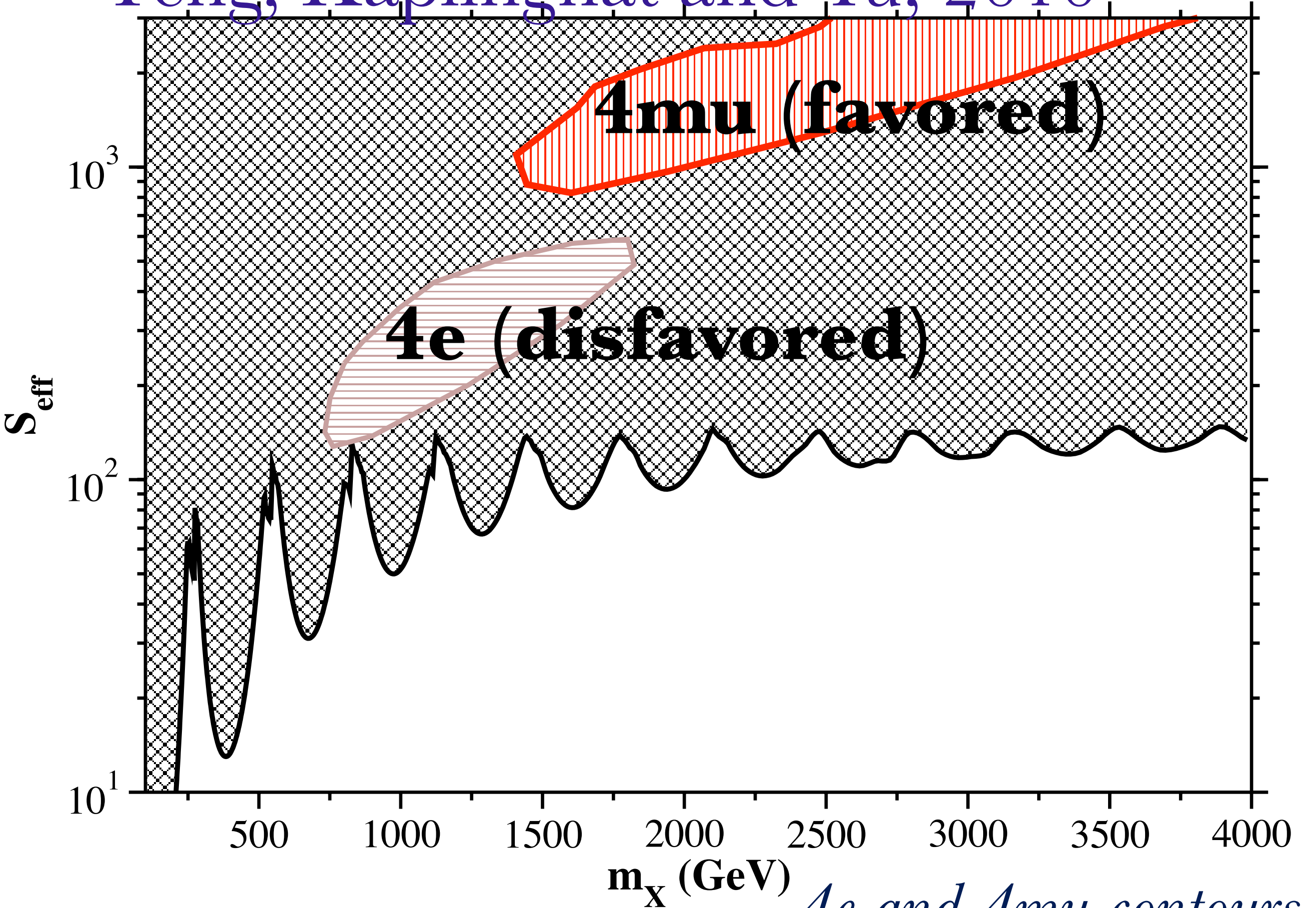


Essig et al arxiv:1007.4199



Importance of getting the relic density right

Feng, Kaplinghat and Yu, 2010



Demand the right relic density

CMB constraints (from Slatyer, Padmanabhan & Finkbeiner 2009) included here

4e and 4mu contours from Meade et al 2009

Bound states only important for large dark matter masses (not a significant factor here) and when they are important, they tend violate the CMB bound

Conclusions

- **Viable dark matter parameter space is large : even within the context of SUSY models, there are both warm and cold dark matter models**
- **Sommerfeld enhanced explanations of PAMELA and Fermi electron and positron anomalies have not been shown to self-consistently explain the observed relic density**
- **Segue 1 is a dark matter dominated galaxy : current analysis shows this is among the most promising candidates for indirect detection experiments**
- **Nearby low surface brightness galaxies <u>do show</u> evidence for large cores : not likely a result of dark matter properties**
- **No conclusive evidence for cores or cusps in MW satellites**