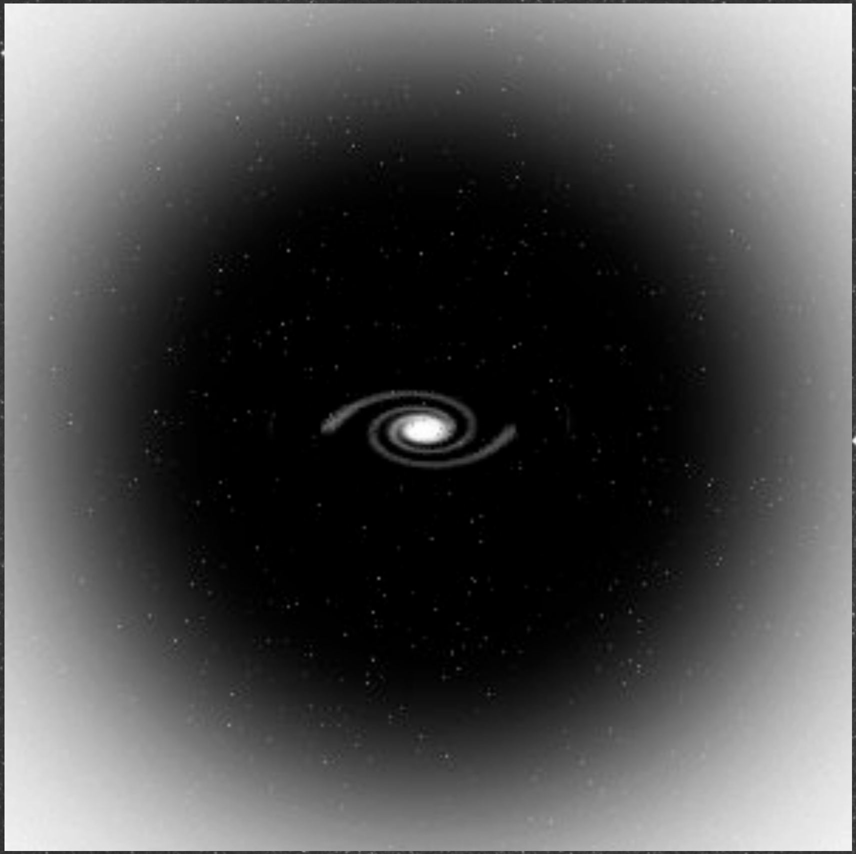
Galactic Dynamics and the Nature of Dark Matter



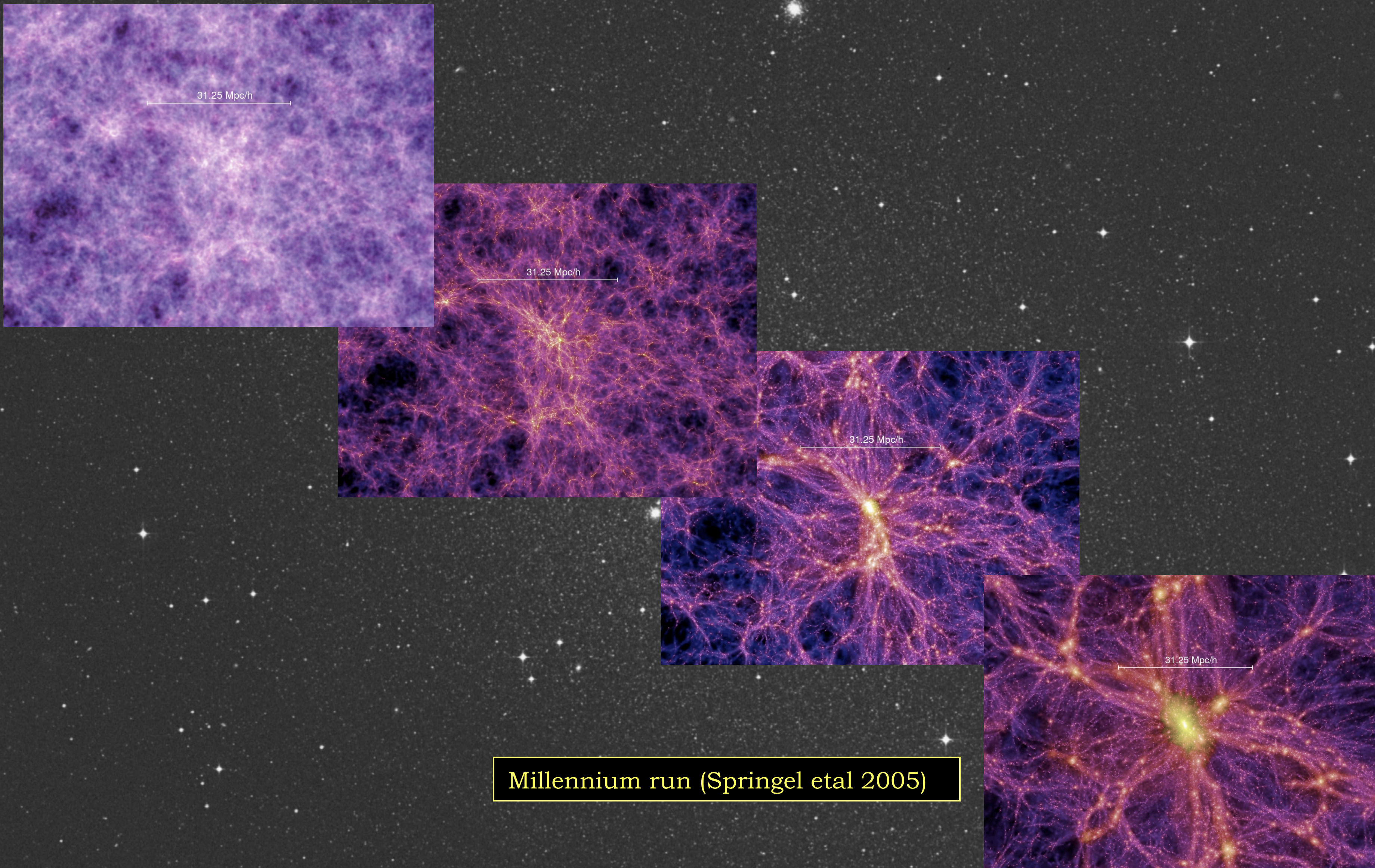
Matthew Walker – Harvard/CfA

Ecole Internationale Daniel Chalonge

17th Paris Cosmology Colloquium

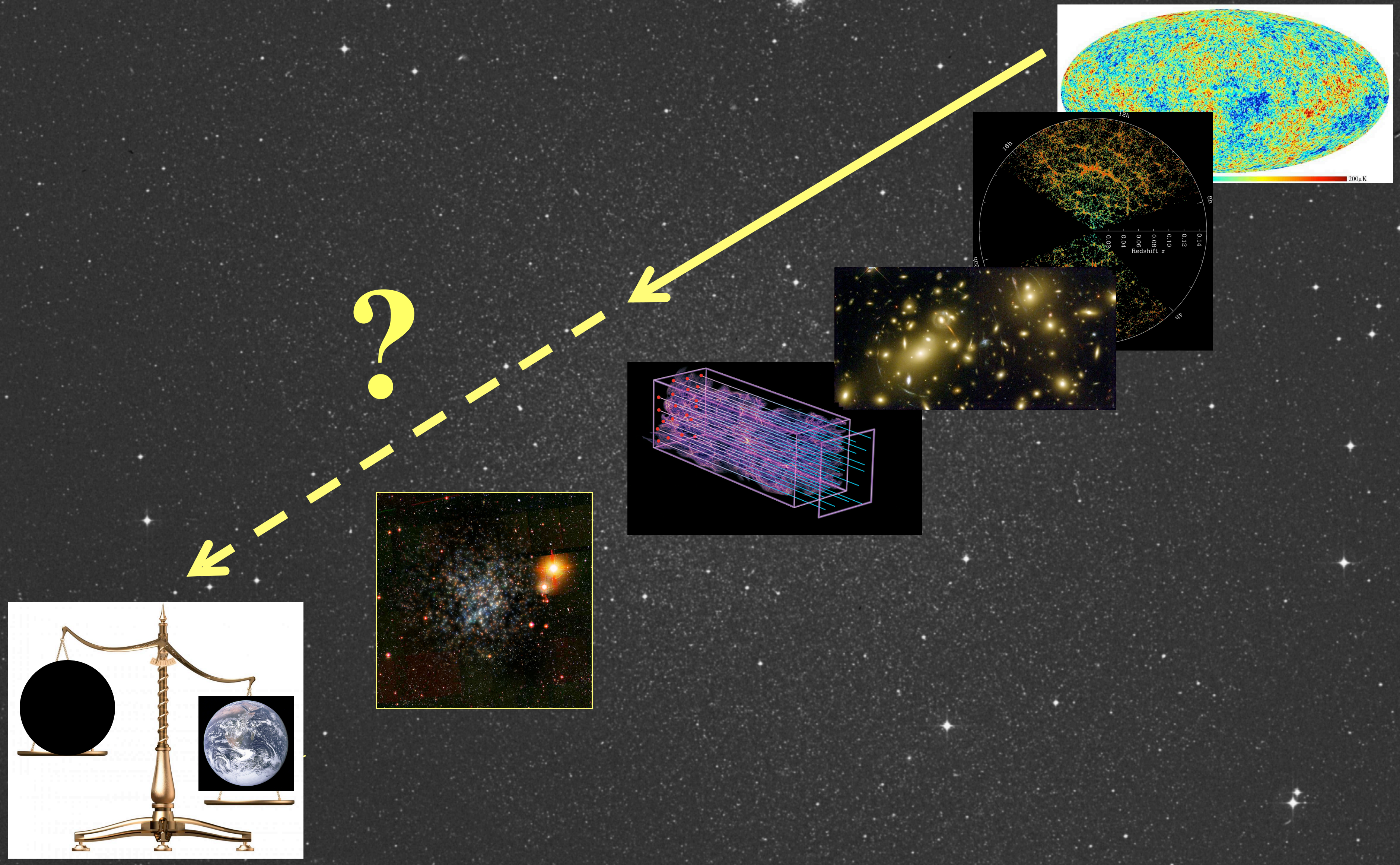
25 July 2013

Hypothesis: Collisionless, Cold Dark Matter

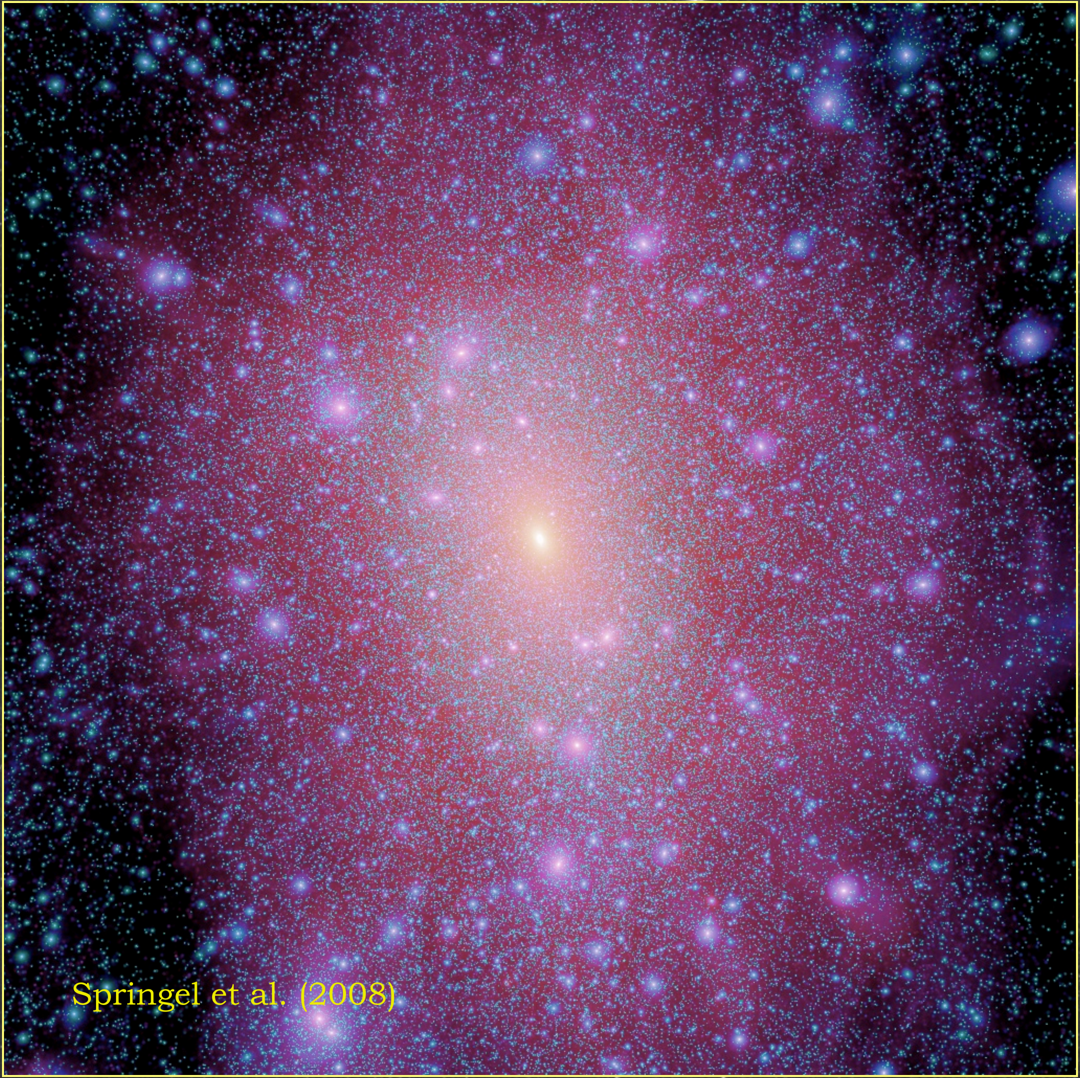


Millennium run (Springel etal 2005)

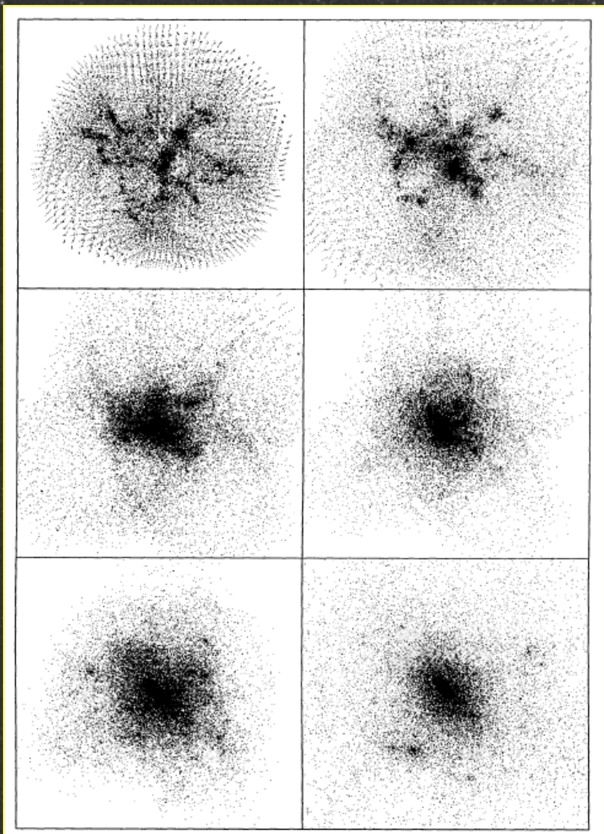
Hypothesis: Collisionless, Cold Dark Matter



Halo Mass Function (dN/dM)



Internal Halo Structure



THE STRUCTURE OF COLD DARK MATTER HALOS

JOHN DUBINSKI AND R. G. CARLBERG
Department of Astronomy, University of Toronto, Toronto, Ontario, Canada M5S 1A1
Received 1990 December 26; accepted 1991 March 22

ABSTRACT

The density profiles and shapes of dark halos are studied using the results of N-body simulations of the gravitational collapse of density peaks. The simulations use from 3×10^4 to 3×10^5 particles, which allow density profiles and shapes to be well resolved. The core radius of a typical dark halo is found to be no greater than the softening radius, $\epsilon = 1.4$ kpc. The density profiles can be fitted with an analytical model with an effective power law which varies between -1 in the center to -4 at large radii. The dark halos have circular velocity curves which behave like the circular velocity contribution of the dark component of spiral galaxies inferred from rotation curve decompositions. The halos are strongly triaxial and very flat, with $\langle c/a \rangle = 0.50$ and $\langle b/a \rangle = 0.71$. There are roughly equal numbers of dark halos with oblate and prolate forms. The distribution of ellipticities in projection for dark halos reaches a maximum at $\epsilon = 0.5$, in contrast to the ellipticity distribution of elliptical galaxies, which peaks at $\epsilon = 0.2$.

Subject headings: dark matter — galaxies: structure — numerical methods

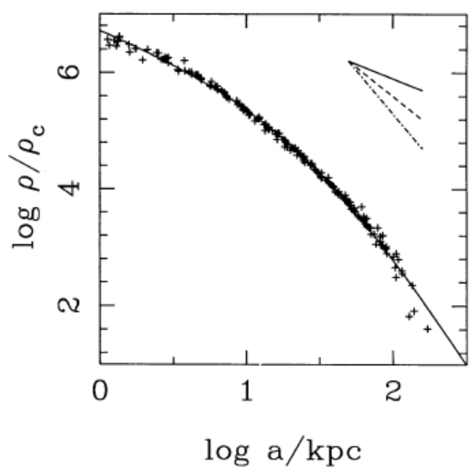
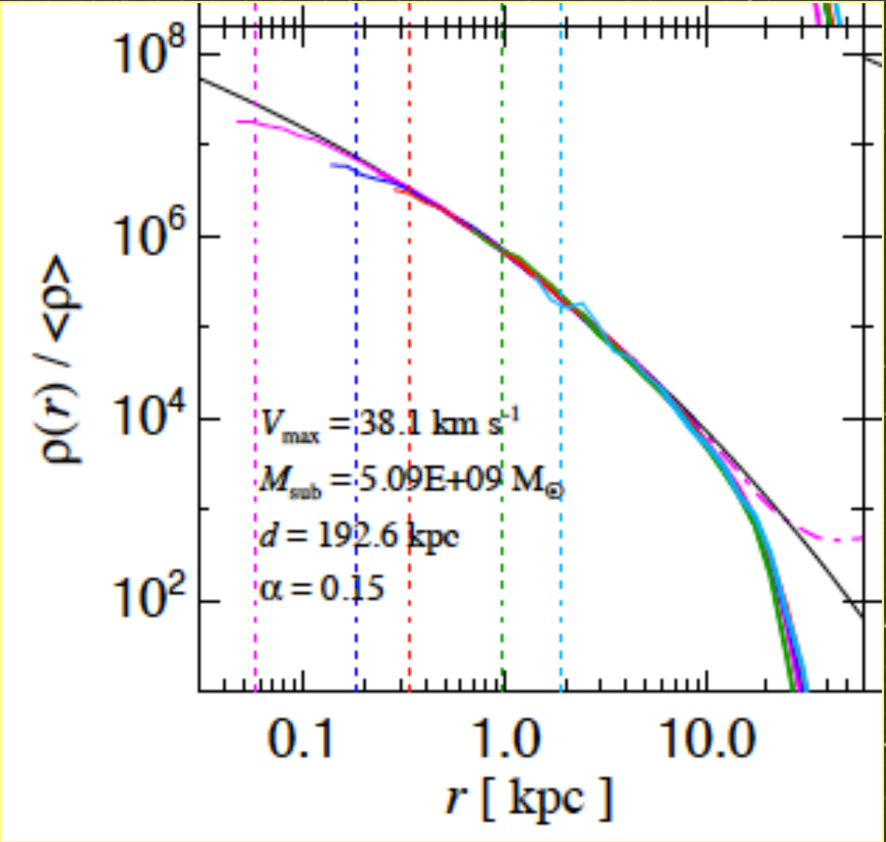


FIG. 2.—Density profiles of dark halos. Density is in units of the critical density ρ_c, and the elliptical radius a is in kpc. Thirteen points were used for the two-parameter fit of Hernquist's profile for each of the 14 halos. Each set of points has been renormalized to the fiducial Hernquist profile, with $r_s = 28$ kpc and $M_s = 2.1 \times 10^{12}\ M_\odot$ represented by the solid line. The lines in the upper right-hand corner present power-law slopes of -1, -2, and -3, respectively.

Internal Halo Structure

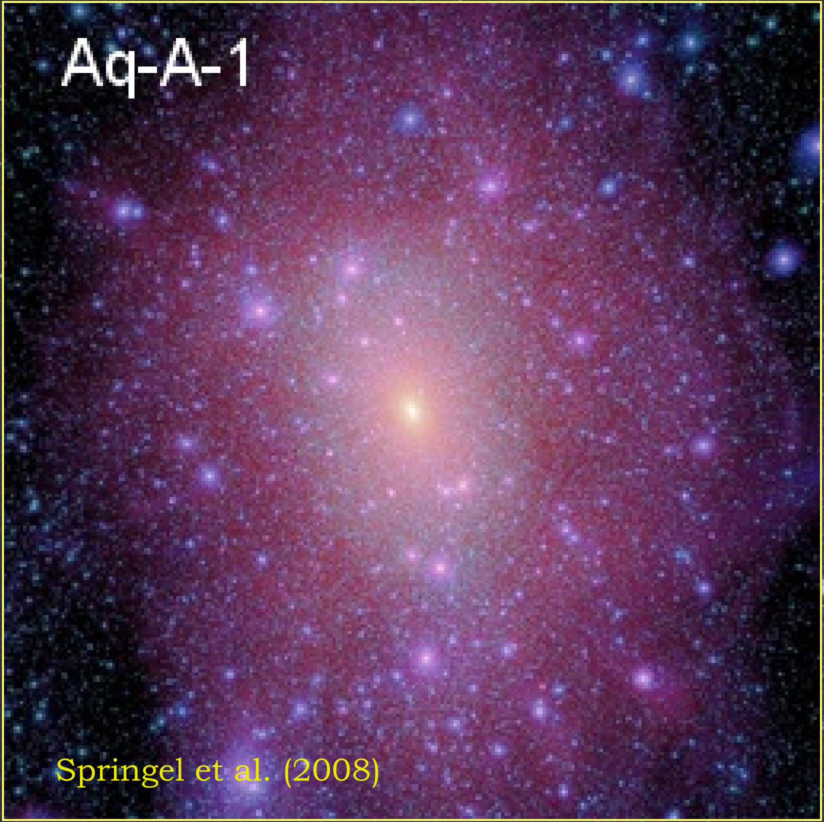


Springel etal. 2008, also Diemand et al. 2007, etc.

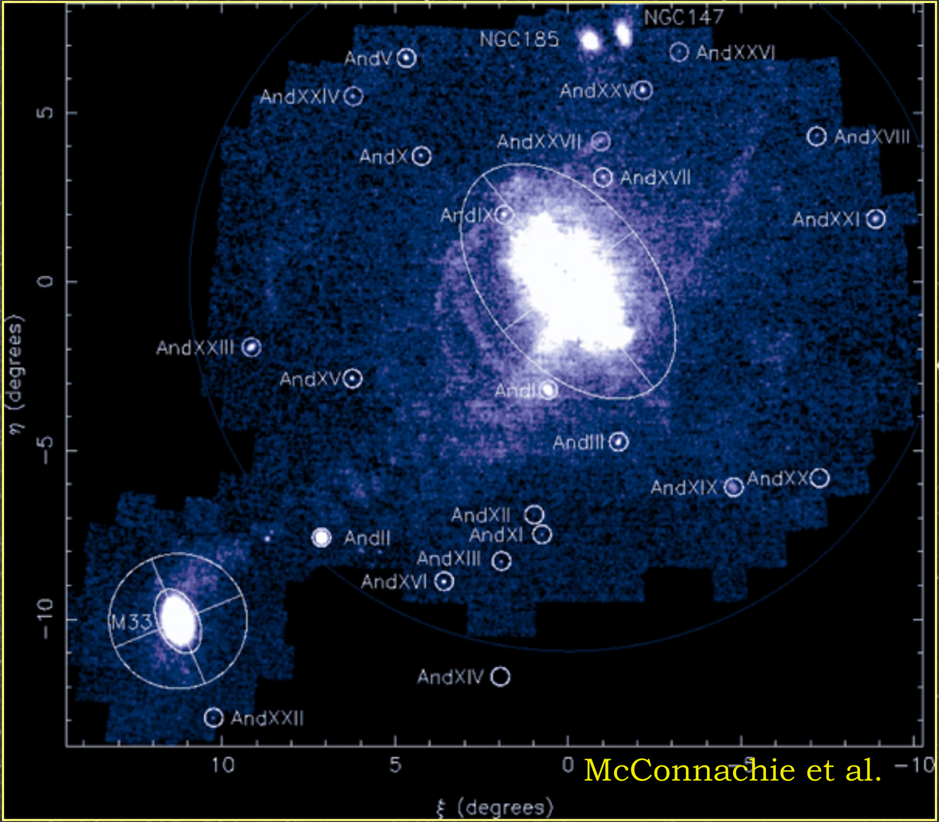
$$\frac{\rho(r)}{\rho_{\rm crit}} = \frac{\delta_c}{(r/r_s)(1 + r/r_s)^2}$$

NFW(1997)

'Missing Satellites' Problem



Springel et al. (2008)



McConnachie et al.

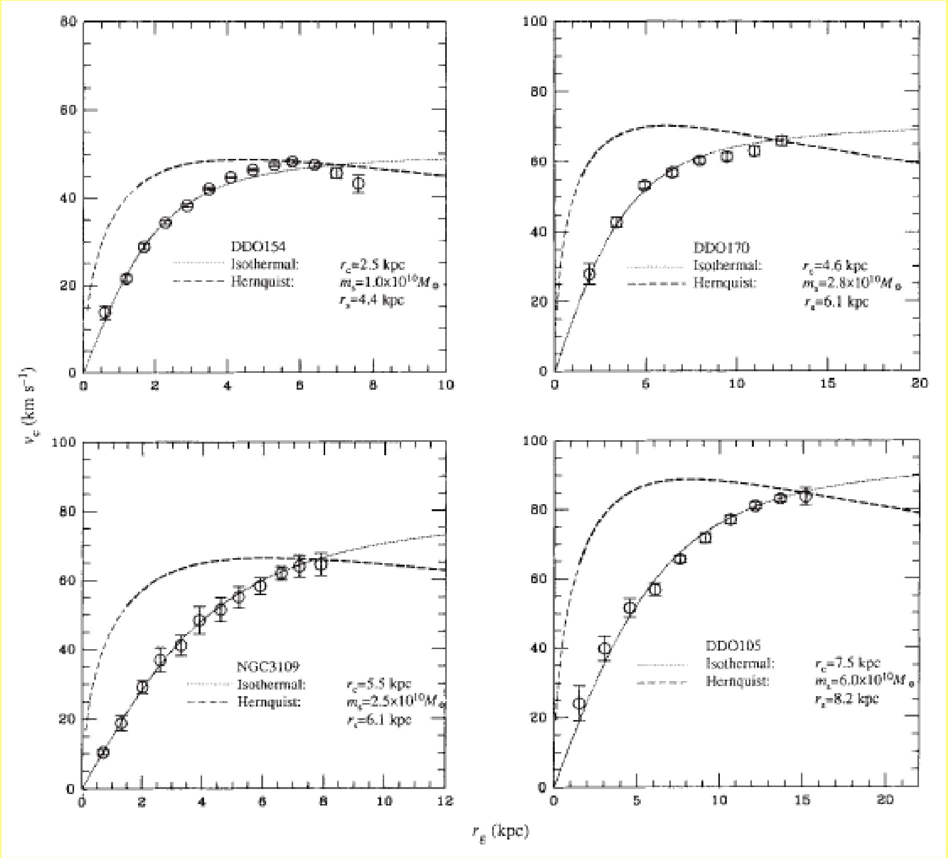
core/cusp problem

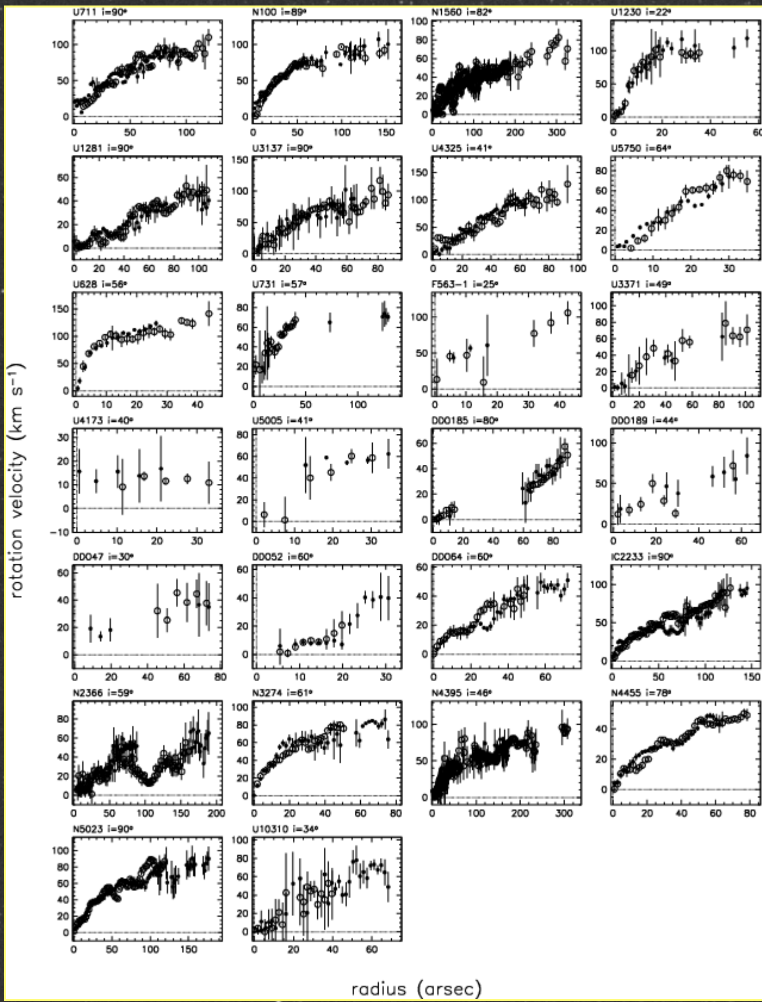
letters to nature

Nature **370**, 629 - 631 (25 August 1994); doi:10.1038/370629a0

Evidence against dissipation-less dark matter from observations of galaxy haloes

BEN MOORE*





High-resolution rotation curves of low surface brightness galaxies*

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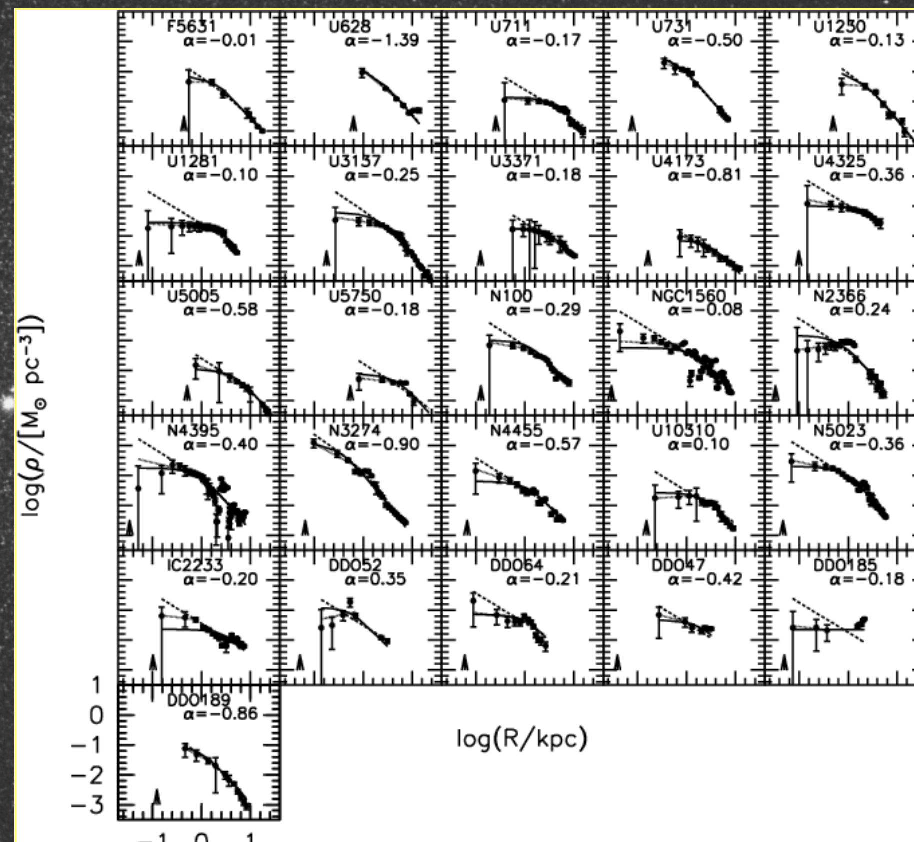
[1] ATNF, CSIRO, PO Box 76, Epping NSW 1710, Australia
[2] Observatoire de Marseille, 2 place Le Verrier, 13248 Marseille Cedex 4, France

Received 18 July 2001 / Accepted 15 January 2002

Abstract. We present high-resolution rotation curves of a sample of 26 low surface brightness galaxies. From these curves we derive mass distributions using a variety of assumptions for the stellar mass-to-light ratio. We show that the predictions of current Cold Dark Matter models for the density profiles of dark matter halos are inconsistent with the observed curves. The latter indicate a core-dominated structure, rather than the theoretically preferred cuspy structure.



MASS MODELS FOR LOW SURFACE BRIGHTNESS GALAXIES WITH HIGH RESOLUTION OPTICAL VELOCITY FIELDS

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Center for Cosmology, Department of Physics and Astronomy, University of California, Irvine, CA 92697-4575

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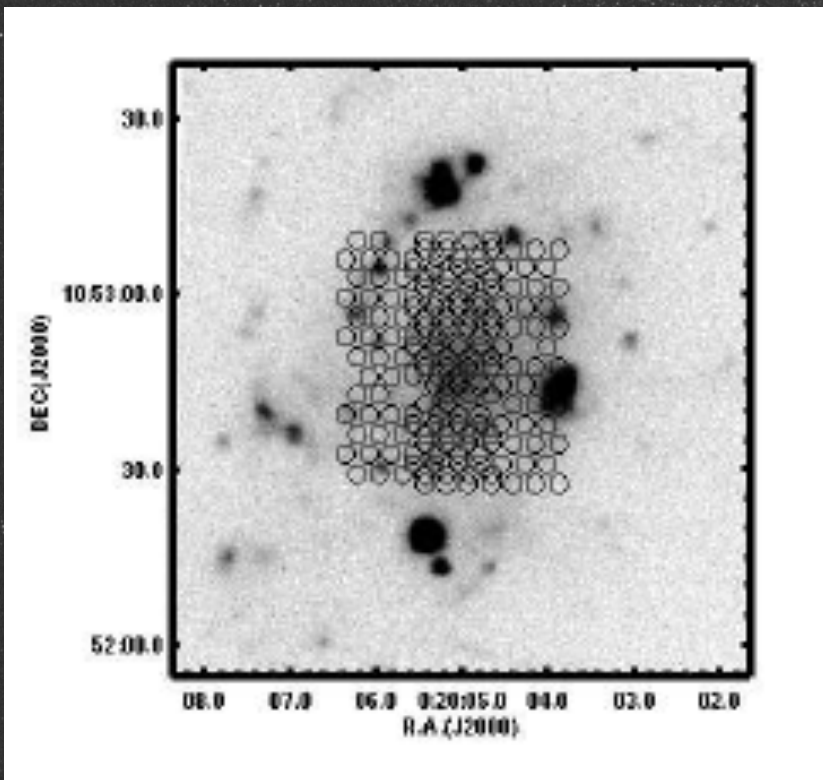
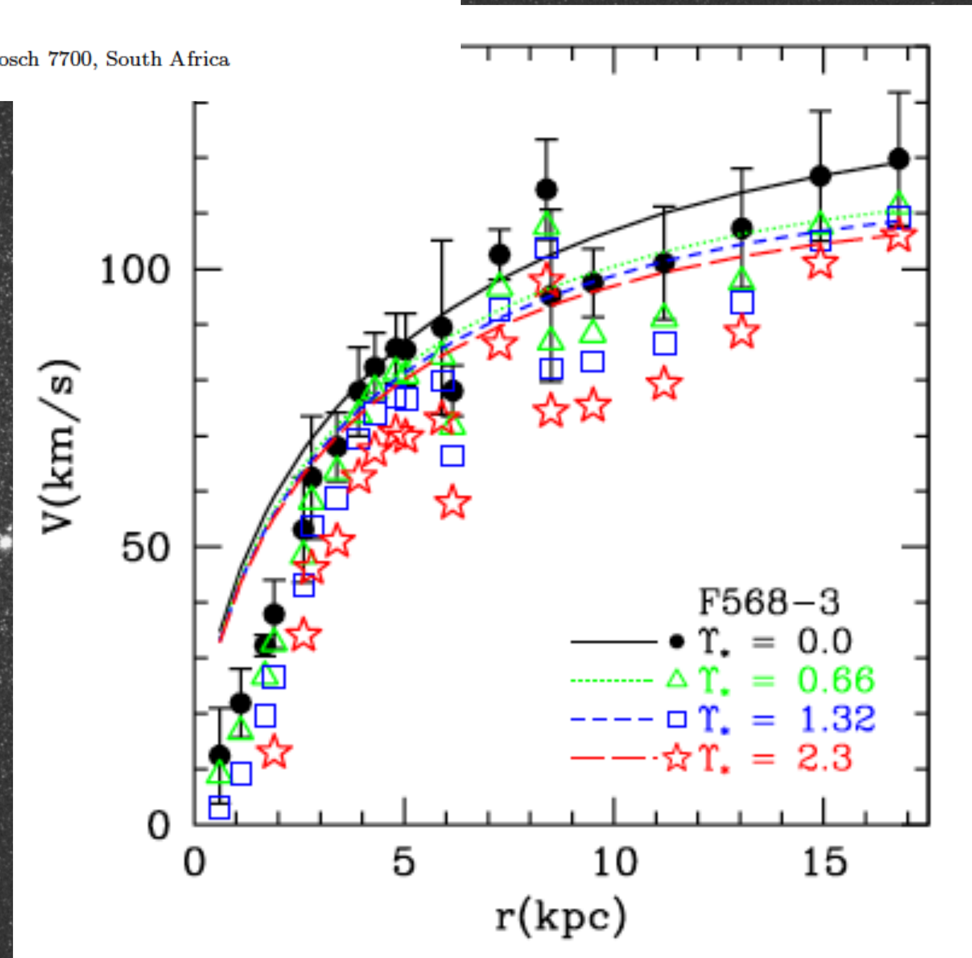
Accepted to ApJ

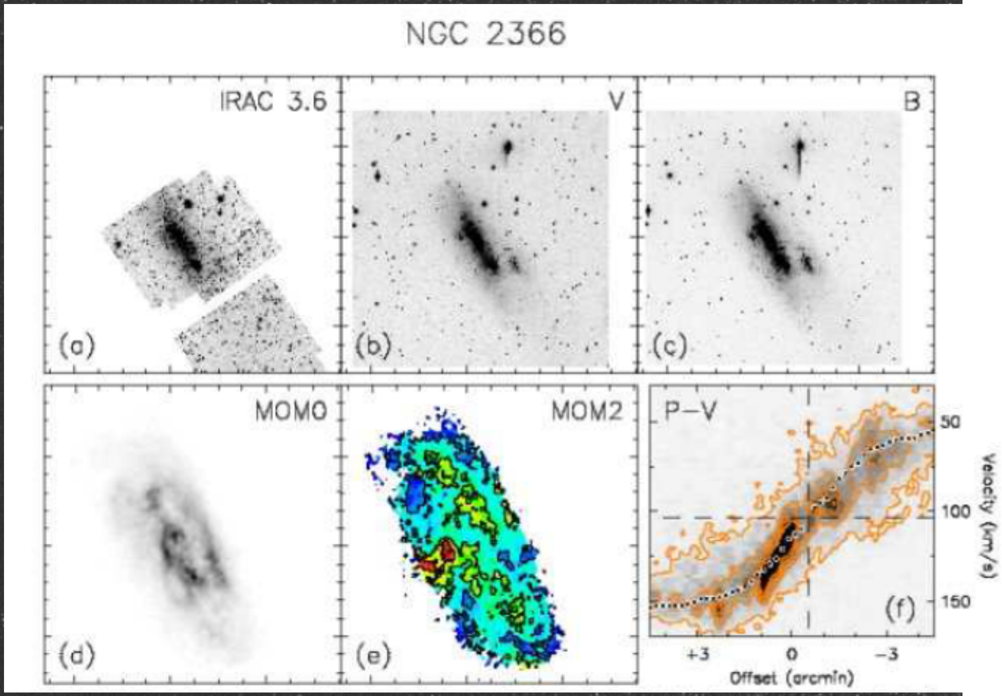


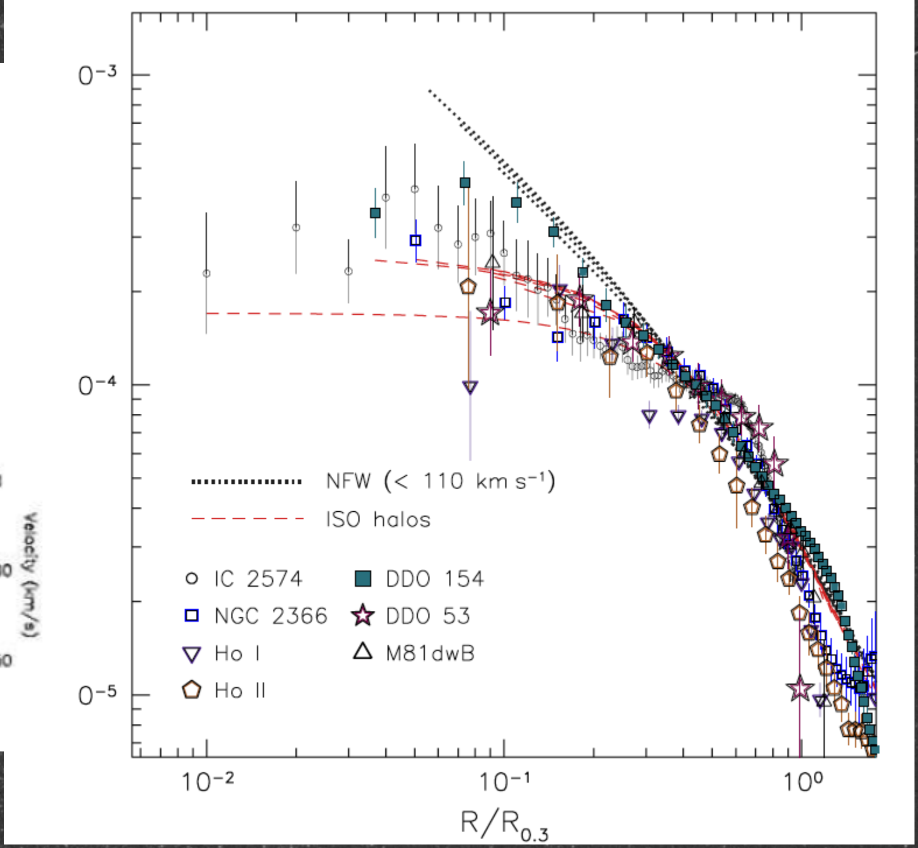


DARK AND LUMINOUS MATTER IN THINGS DWARF GALAXIES

SE-HEON OH[1,5], W. J. G. DE BLOK[1], ELIAS BRINKS[2], FABIAN WALTER[3] AND ROBERT C. KENNICUTT, JR.[4]

Draft version April 18, 2011





How supernova feedback turns dark matter cusps into cores

Andrew Pontzen[1,2,3]*, Fabio Governato[4]
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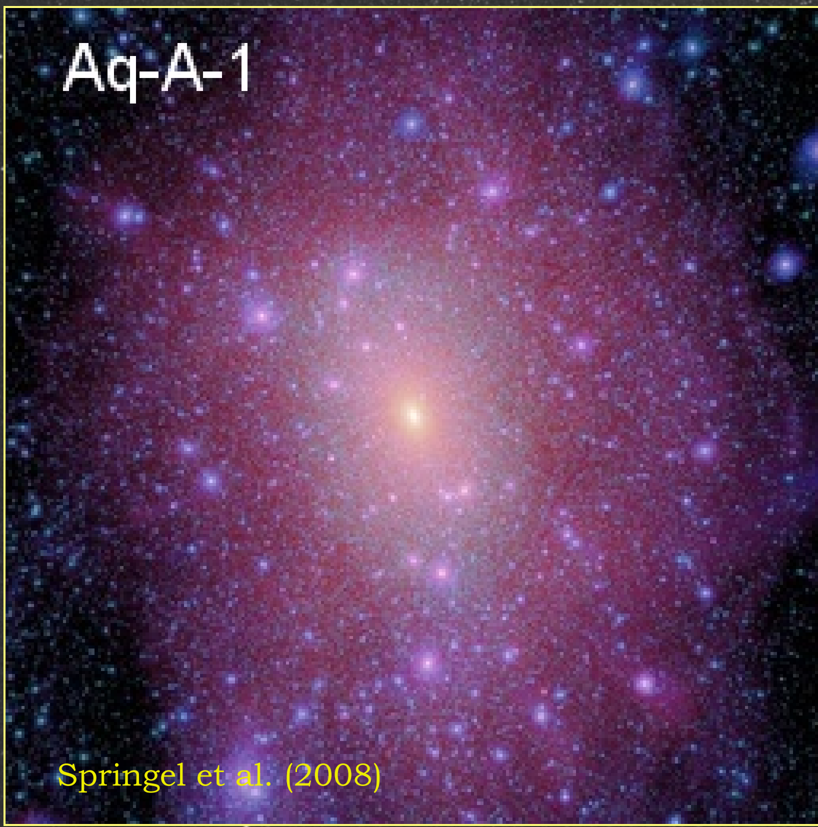
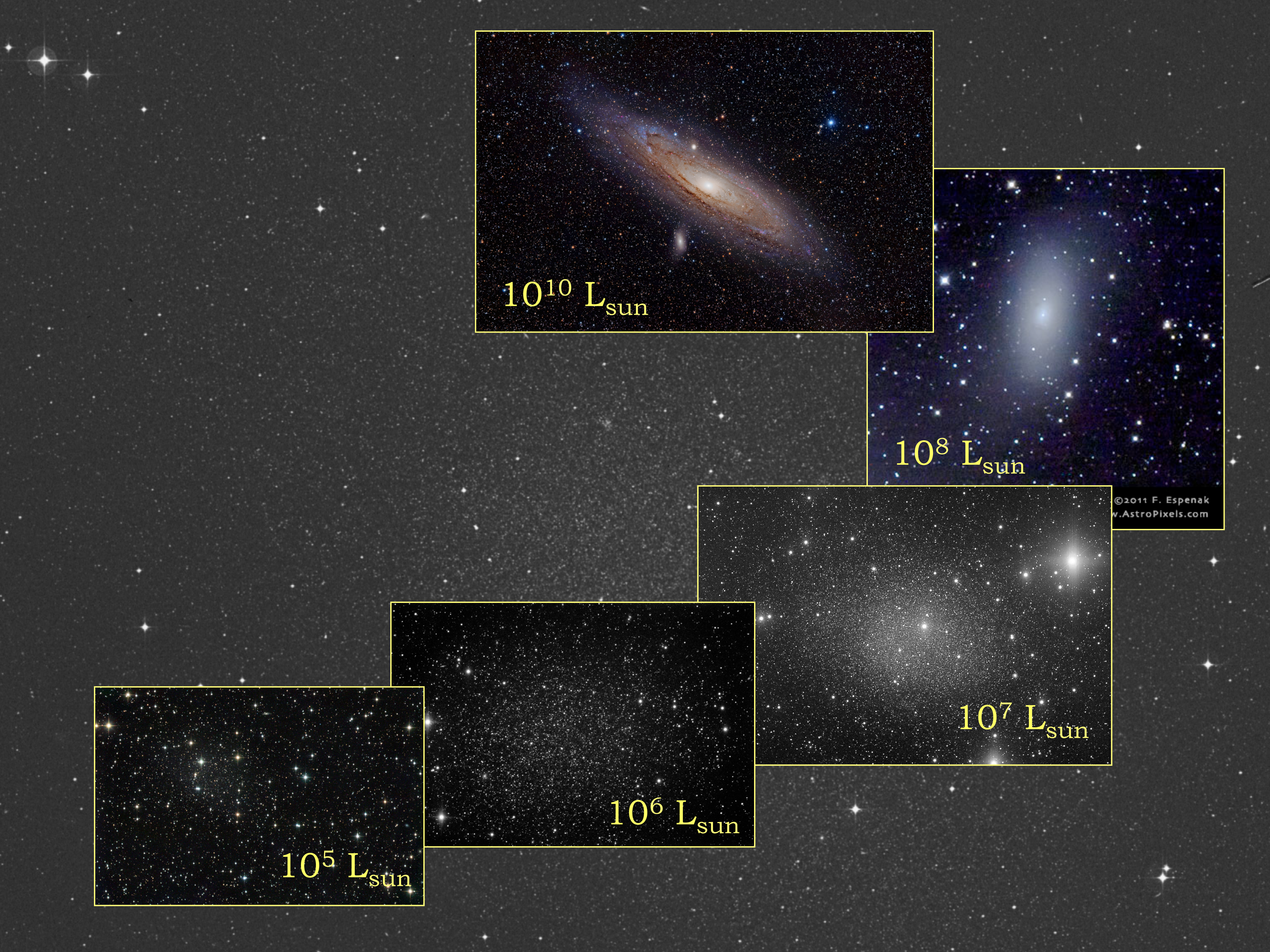
[2] Emmanuel College, St Andrew's Street, Cambridge, CB2 3AP UK
[3] Oxford Astrophysics, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK
[4] Astronomy Department, University of Washington, Seattle, WA 98195, USA



Also: Navarro etal (1996), Read & Gilmore (2005), Mashchenko etal. (2006), ...


$10^{10}\ L_{sun}$
$10^{8}\ L_{sun}$
©2011 F. Espenak
w.AstroPixels.com
$10^{7}\ L_{sun}$
$10^{6}\ L_{sun}$
$10^{5}\ L_{sun}$

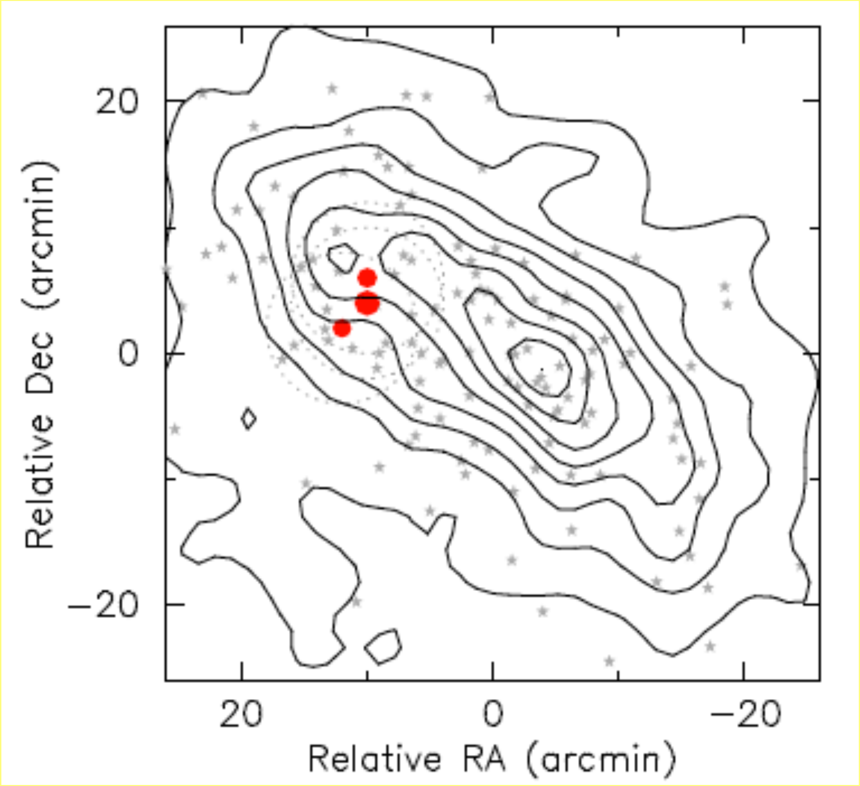
(Indirect) Evidence for Cores in Galactic dSphs

Fornax globular clusters → core

Goerdt et al. (2006)

Cole et al (2011)

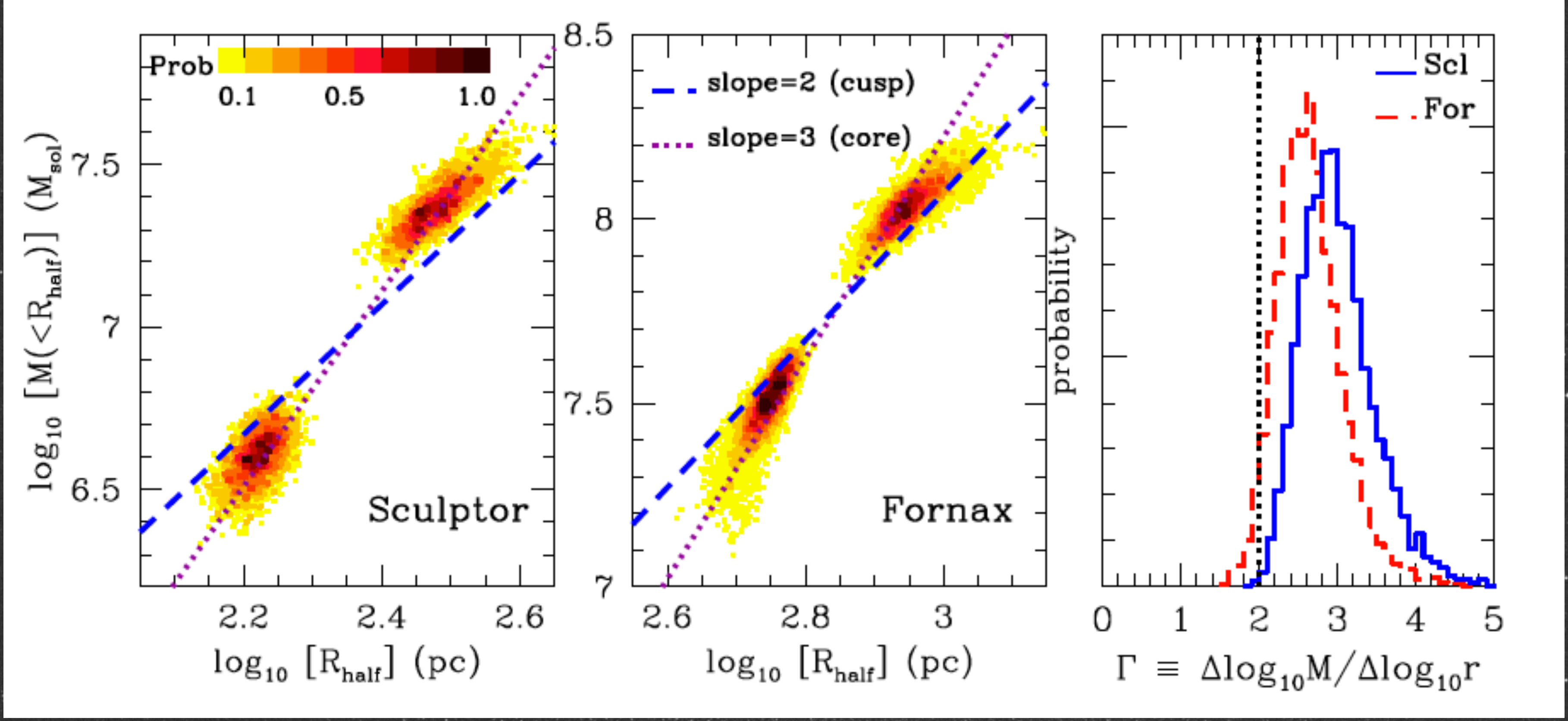
Ursa Minor substructure → core



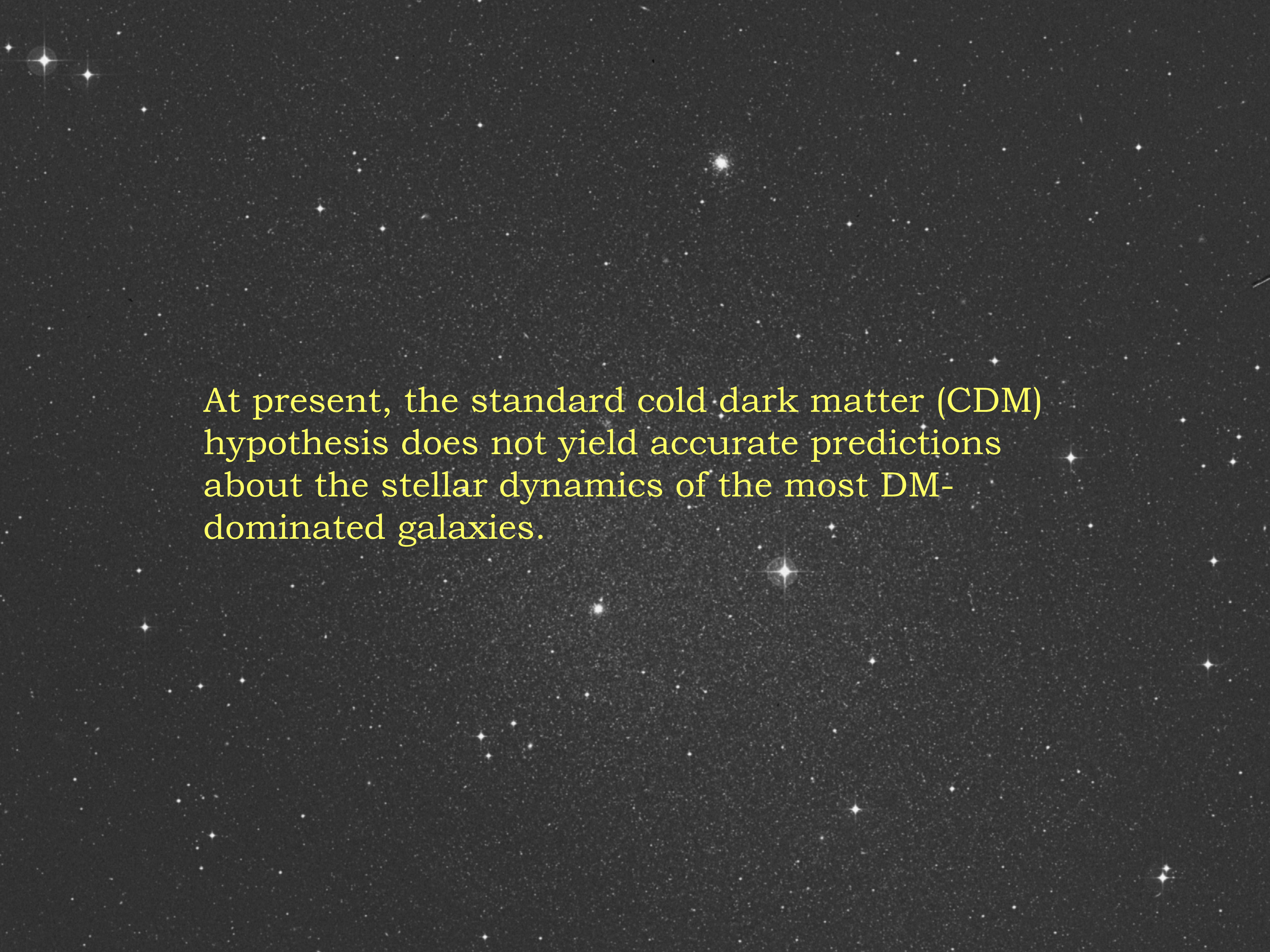
Kleyna et al. (2003)

A METHOD FOR MEASURING (SLOPES OF) THE MASS PROFILES OF DWARF SPHEROIDAL GALAXIES

MATTHEW G. WALKER[1,2,3] & JORGE PEÑARRUBIA[2]



see also: Amorisco & Evans (2012), Agnello & Evans (2012), Battaglia et al (2008)



At present, the standard cold dark matter (CDM) hypothesis does not yield accurate predictions about the stellar dynamics of the most DM-dominated galaxies.

~~Collisionless~~ Cold Dark Matter

Observational evidence for self-interacting cold dark matter

David N. Spergel and Paul J. Steinhardt
Princeton University, Princeton NJ 08544 USA

Cores in Dwarf Galaxies from Dark Matter with a Yukawa Potential

Abraham Loeb[1] and Neal Weiner[2,3]

Subhaloes in Self-Interacting Galactic Dark Matter Haloes

Mark Vogelsberger[1*], Jesus Zavala[2,3]†, Abraham Loeb[1]

Constraining Self-Interacting Dark Matter with the Milky Way's dwarf spheroidals

Jesús Zavala[1,2*], Mark Vogelsberger[3]† and Matthew G. Walker[3]‡,

Cosmological Simulations with Self-Interacting Dark Matter I: Constant Density Cores and Substructure

Miguel Rocha[1*], Annika H. G. Peter[1], James S. Bullock[1], Manoj Kaplinghat[1],
Shea Garrison-Kimmel[1], Jose Oñorbe[1], and Leonidas A. Moustakas[2]

Collisionless ~~Cold~~ Dark Matter

HALO FORMATION IN WARM DARK MATTER MODELS

PAUL BODE AND JEREMIAH P. OSTRIKER
Princeton University Observatory, Princeton, NJ 08544-1001
AND
NEIL TUROK

The haloes of bright satellite galaxies in a warm dark matter universe

Mark R. Lovell[1*], Vincent Eke[1], Carlos S. Frenk[1], Liang Gao[2,1], Adrian Jenkins[1], Tom Theuns[1,3], Jie Wang[1], Simon D. M. White[4], Alexey Boyarsky[5,6],

Dark Matter Halo Merger Histories Beyond Cold Dark Matter: I - Methods and Application to Warm Dark Matter

Andrew J. Benson[1*], Arya Farahi[2], Shaun Cole[3], Leonidas A. Moustakas[4], Adrian Jenkins[3], Mark Lovell[3], Rachel Kennedy[3], John Helly[3] & Carlos Frenk[3]

Warm dark matter at small scales: peculiar velocities and phase space density.

Daniel Boyanovsky[1,*]

Fermionic warm dark matter produces galaxy cores in the observed scales because of quantum mechanics

C. Destri[a], H. J. de Vega[b,c,1], N. G. Sanchez[c]

The Galactic Halo in Mixed Dark Matter Cosmologies

D. Anderhalden[a] J. Diemand[a] G. Bertone[b]
A. V. Macciò[c] A. Schneider[a]

Collisionless Cold Dark Matter (+ baryons?)

How supernova feedback turns dark matter cusps into cores

Andrew Pontzen[1,2,3*], Fabio Governato[4]

WHY BARYONS MATTER: THE KINEMATICS OF DWARF SPHEROIDAL SATELLITES

ALYSON M. BROOKS[1], ADI ZOLOTOV[2]

Mass loss from dwarf spheroidal galaxies: the origins of shallow dark matter cores and exponential surface brightness profiles

J. I. Read and G. Gilmore
Institute of Astronomy, Cambridge University, Madingley Road, Cambridge, CB3 0HA

Cosmological puzzle resolved by stellar feedback in high redshift galaxies

Sergey Mashchenko[1], H. M. P. Couchman[1] & James Wadsley[1]

Cusp-core transformations in dwarf galaxies: observational predictions

Romain Teyssier[1,4*], Andrew Pontzen[2], Yohan Dubois[3] and Justin I. Read[5,6]

Cuspy No More: How Outflows Affect the Central Dark Matter and Baryon Distribution in ΛCDM Galaxies.

F.Governato[1*] A.Zolotov[2], A.Pontzen[3], C.Christensen[4], S.H.Oh[5,6], A. M.Brooks[7], T.Quinn[1], S.Shen[8], J.Wadsley[9]

Cuspy No More: How Outflows Affect the Central Dark Matter and Baryon Distribution in ΛCDM Galaxies.

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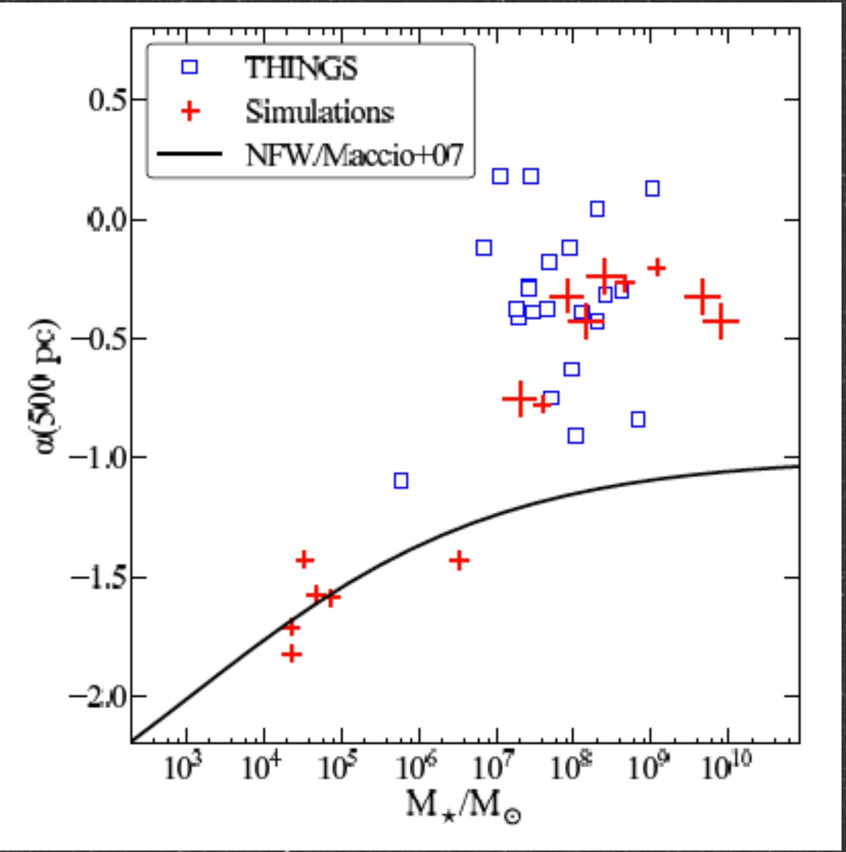
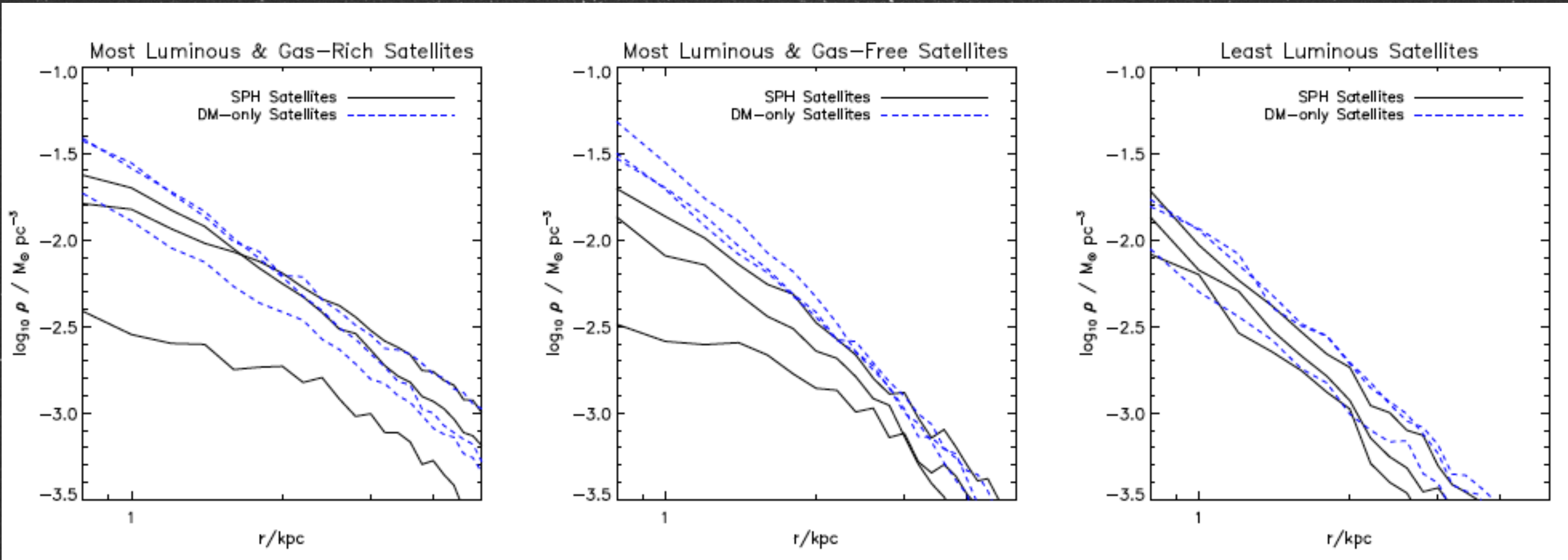


BARYONS MATTER: WHY LUMINOUS SATELLITE GALAXIES HAVE REDUCED CENTRAL MASSES

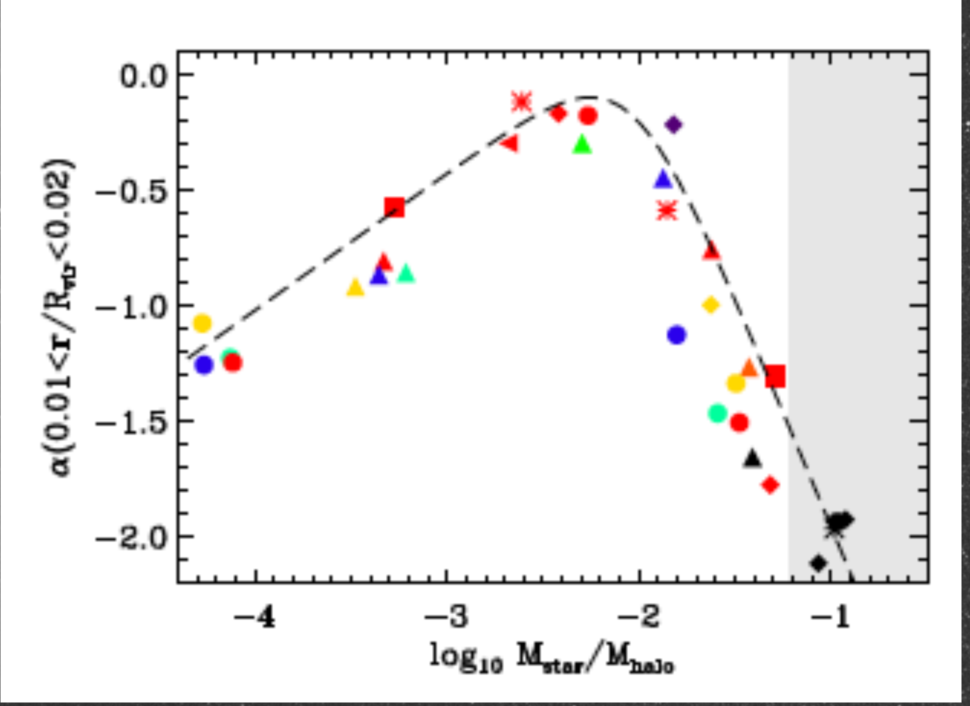
Adi Zolotov[1], Alyson M. Brooks[2], Beth Willman[3], Fabio Governato[4], Andrew Pontzen[5], Charlotte Christensen[6], Avishai Dekel[1], Tom Quinn[4], Sijing Shen[7], James Wadsley[8]

(Dated: December 5, 2012)
Accepted for publication in ApJ



The dependence of dark matter profiles on the stellar to halo mass ratio: a prediction for cusps vs cores

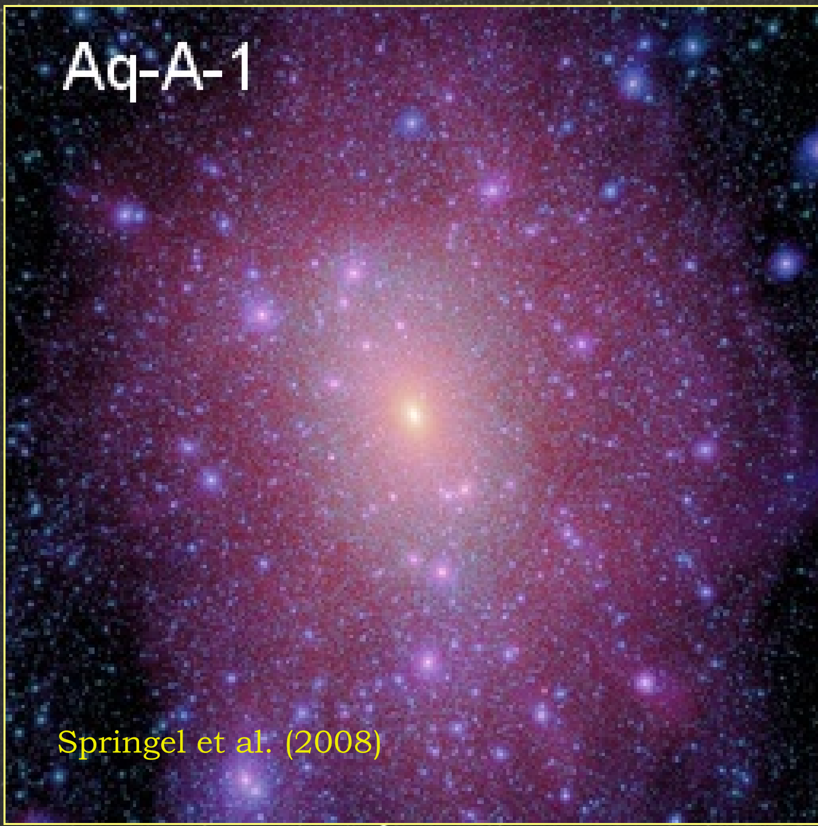
Arianna Di Cintio[1,2★], Chris B. Brook[1], Andrea V. Macciò[3], Greg S. Stinson[3], Alexander Knebe[1], Aaron A. Dutton[3], James Wadsley[4]
[1]*Departamento de Física Teórica, Módulo C-15, Facultad de Ciencias, Universidad Autónoma de Madrid, 28049 Cantoblanco, Madrid, Spain*
[2]*Physics Department G. Marconi, Università di Roma Sapienza, Ple Aldo Moro 2, 00185 Rome, Italy*
[3]*Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany*
[4]*McMaster University, Hamilton, Ontario, L8S 4M1, Canada*

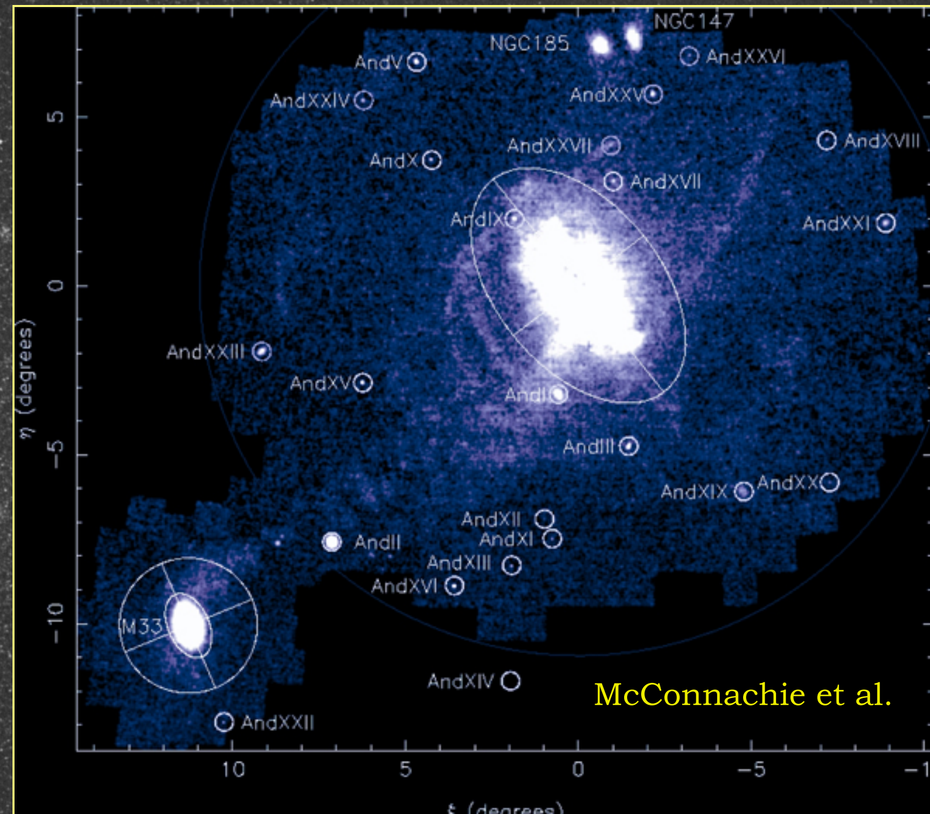


THE COUPLING BETWEEN THE CORE/CUSP AND MISSING SATELLITE PROBLEMS

JORGE PEÑARRUBIA[1,2], ANDREW PONTZEN[3], MATTHEW G. WALKER[4] & SERGEY E. KOPOSOV[2,5]

Draft version July 13, 2012





THE COUPLING BETWEEN THE CORE/CUSP AND MISSING SATELLITE PROBLEMS

Jorge Peñarrubia[1,2], Andrew Pontzen[3], Matthew G. Walker[4] & Sergey E. Koposov[2,5]

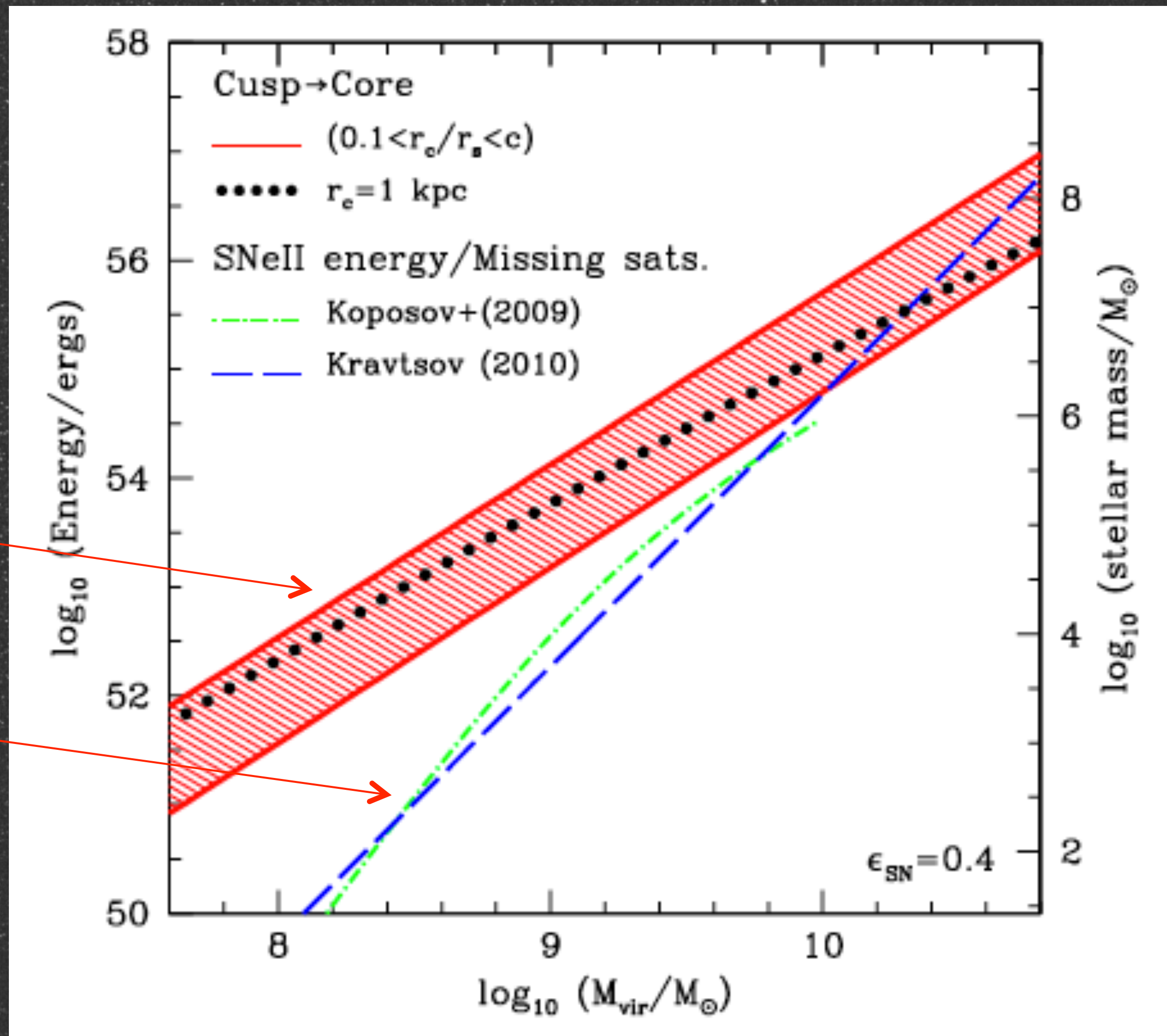
Draft version July 13, 2012

$$\rho(r) = \frac{\rho_0 r_s^3}{(r_c + r)(r_s + r)^2}$$

Energetics

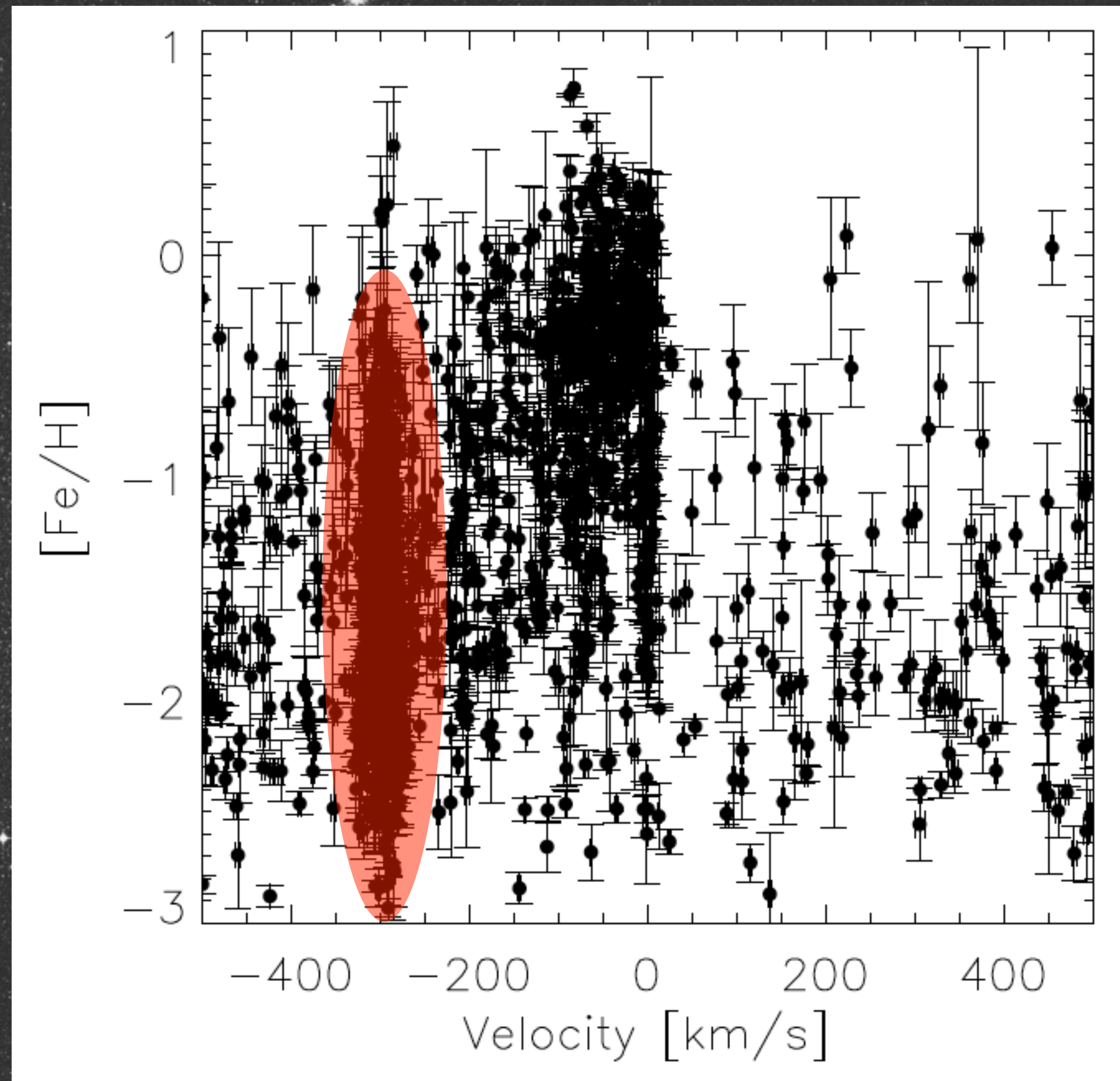
required

available

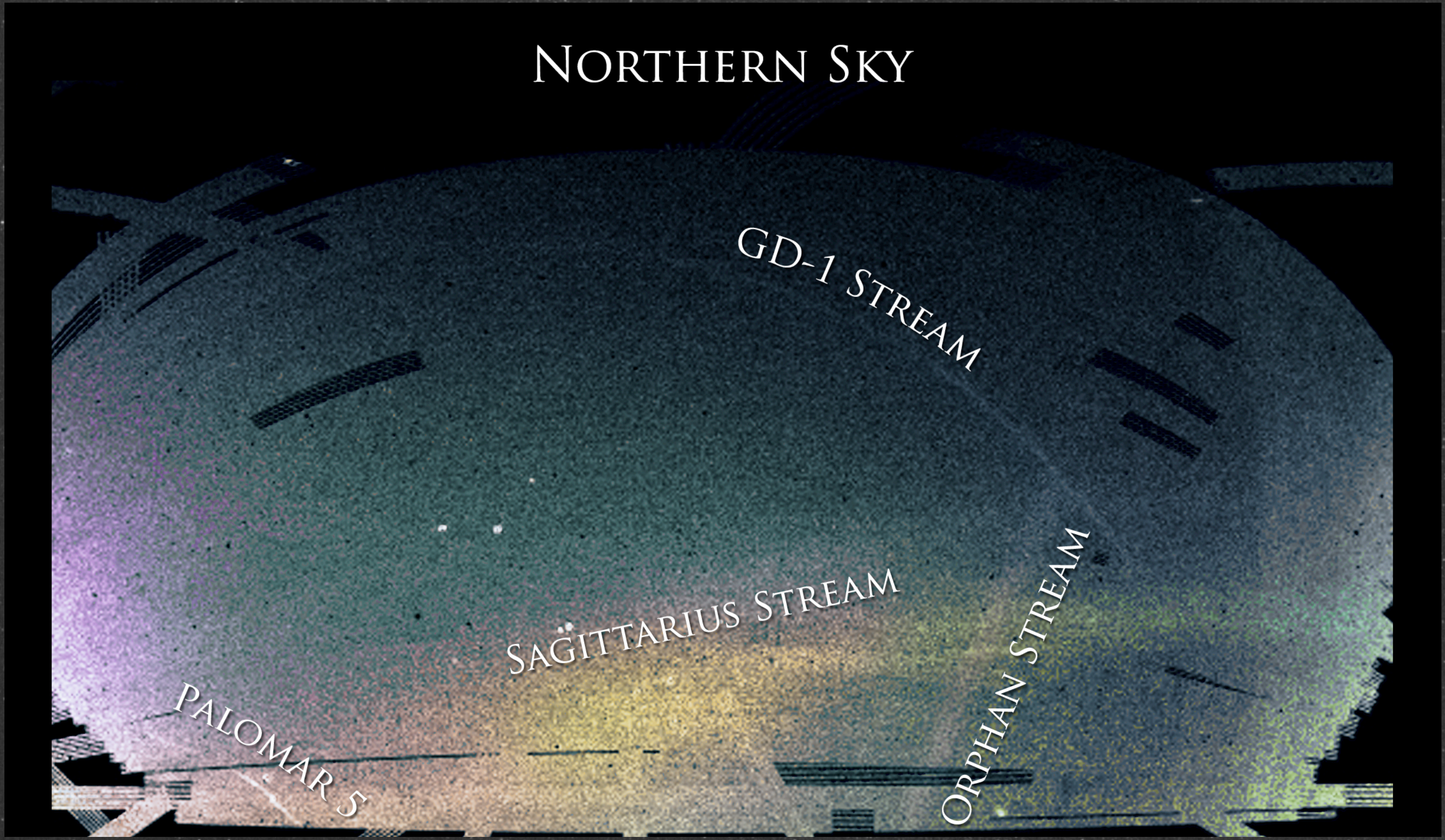


MMT/Hectochelle Spectroscopic Survey of Northern Satellites

PRELIMINARY



Streams in the Galactic halo:
→ The *Primordial* Luminosity Function



Streams in the Galactic halo:
→ The *Primordial* Luminosity Function

Gaia

-launch: 2013

-catalog: 10^9 stars to V~20

-parallax: 4 μas at V~10, 160 μas at V~20

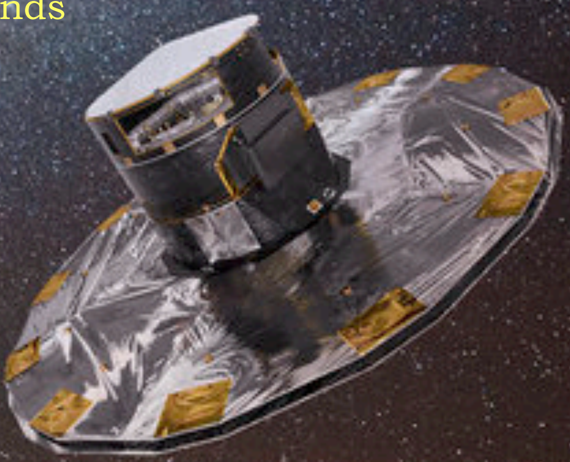
-distance: 1% for 10^6 stars, 10% for 10^8 stars

-proper motions: 0.5 km/s for 10^7 stars

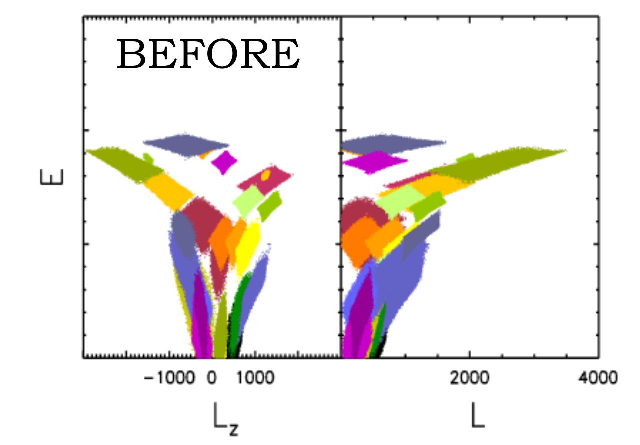
-radial velocities: 1-10 km/s for V~16-17

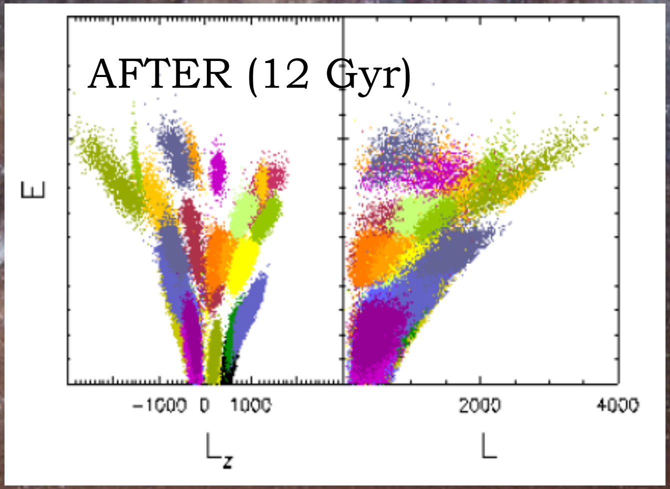
-photometry: V~20 in 4 broad bands, 11 medium bands

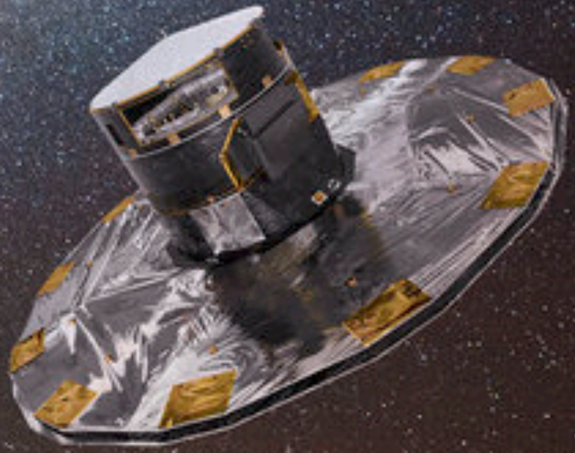
-~300,000 asteroids, many(?) near-earth objects



Streams in the Galactic halo:
→ The *Primordial* Luminosity Function

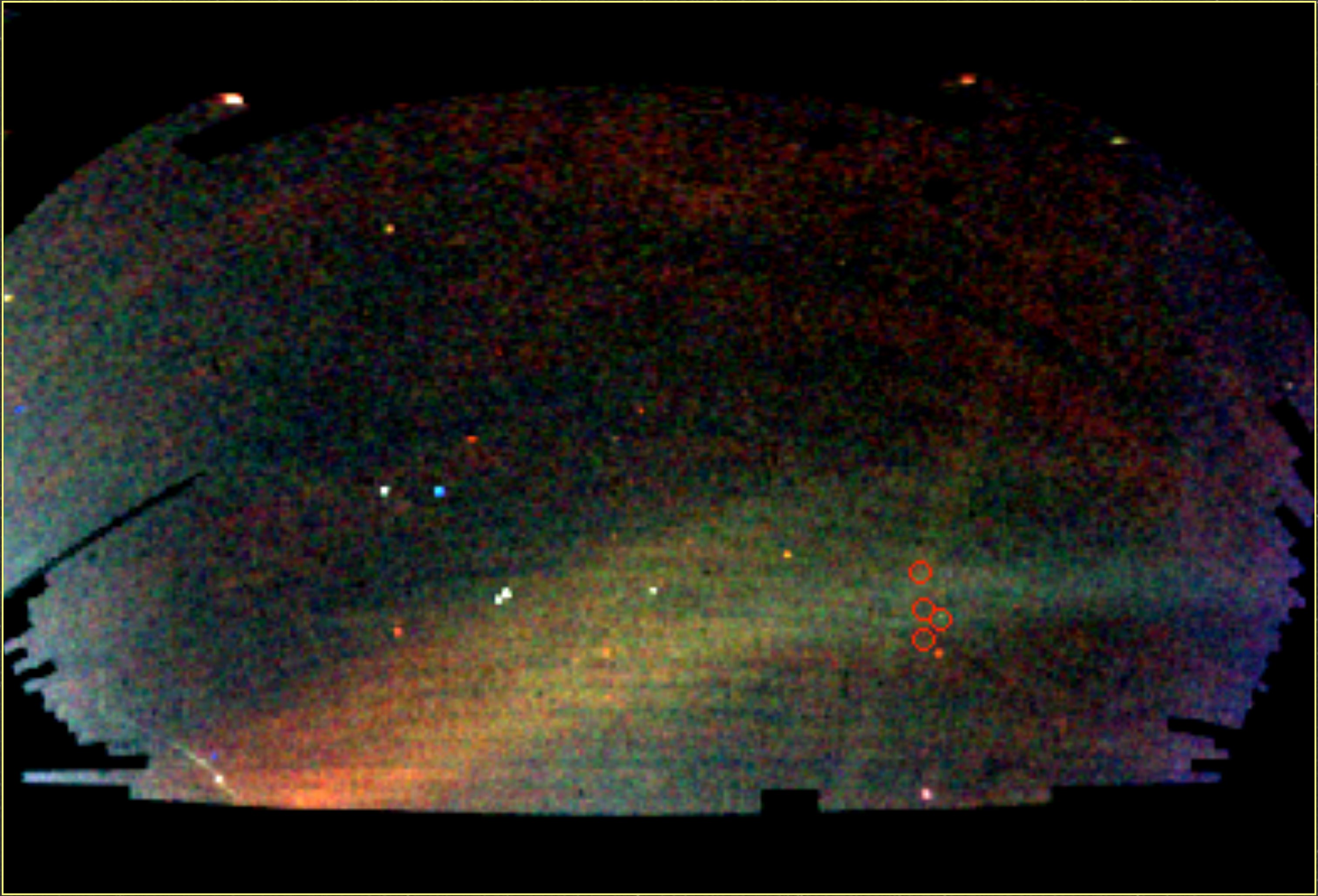






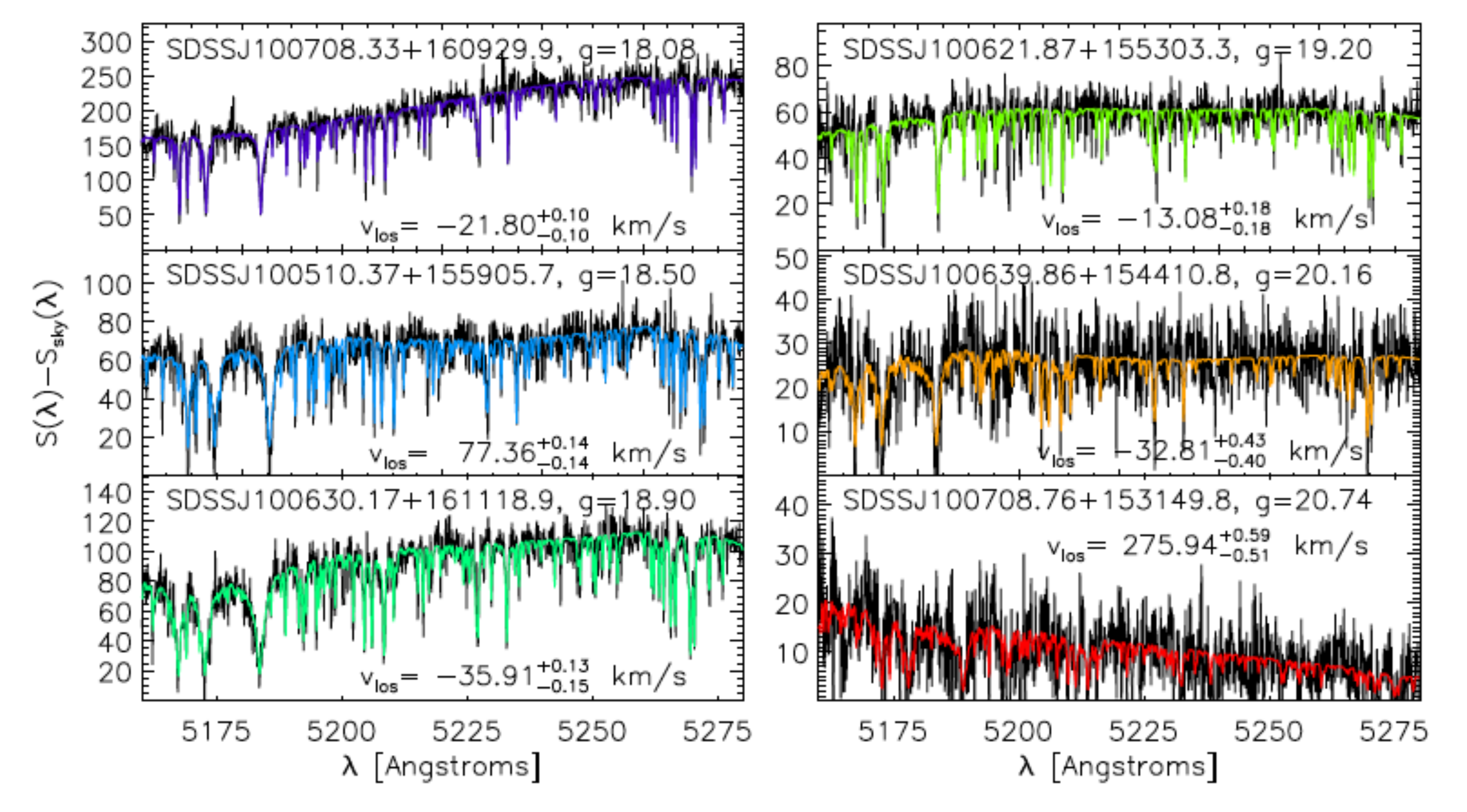
Helmi & de Zeeuw (2000)

Streams in the Galactic halo: MMT/Hectochelle Spectroscopic Survey



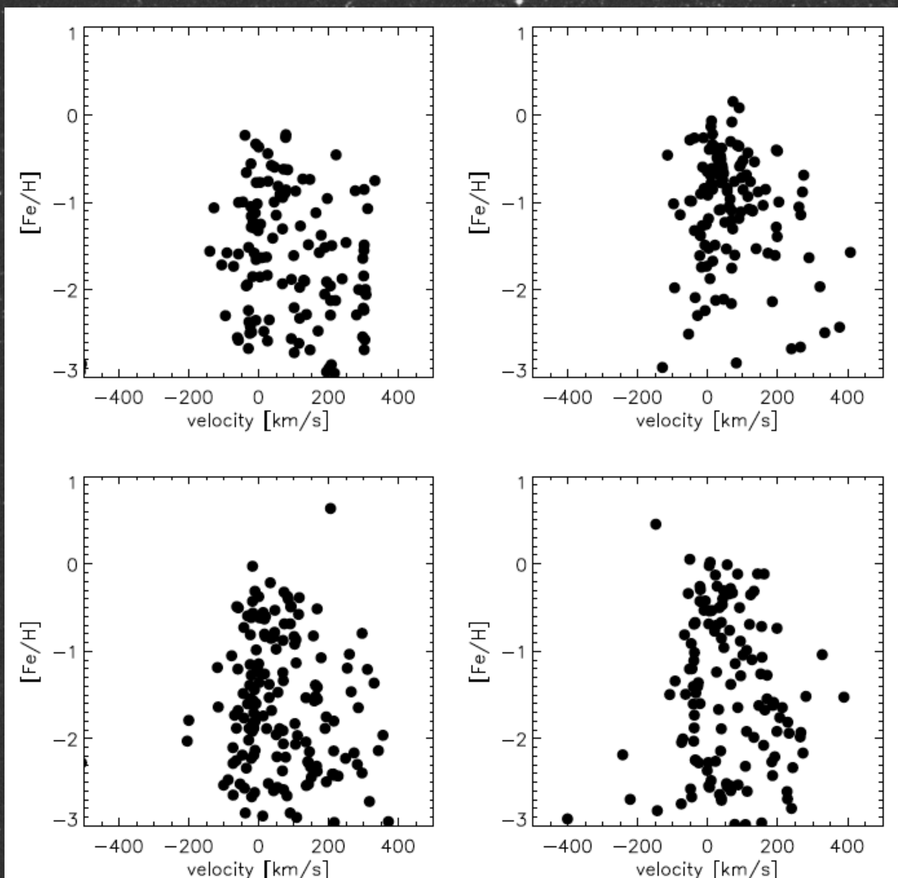
Belokurov etal (2006); Belokurov, Koposov, Walker et al (in preparation)

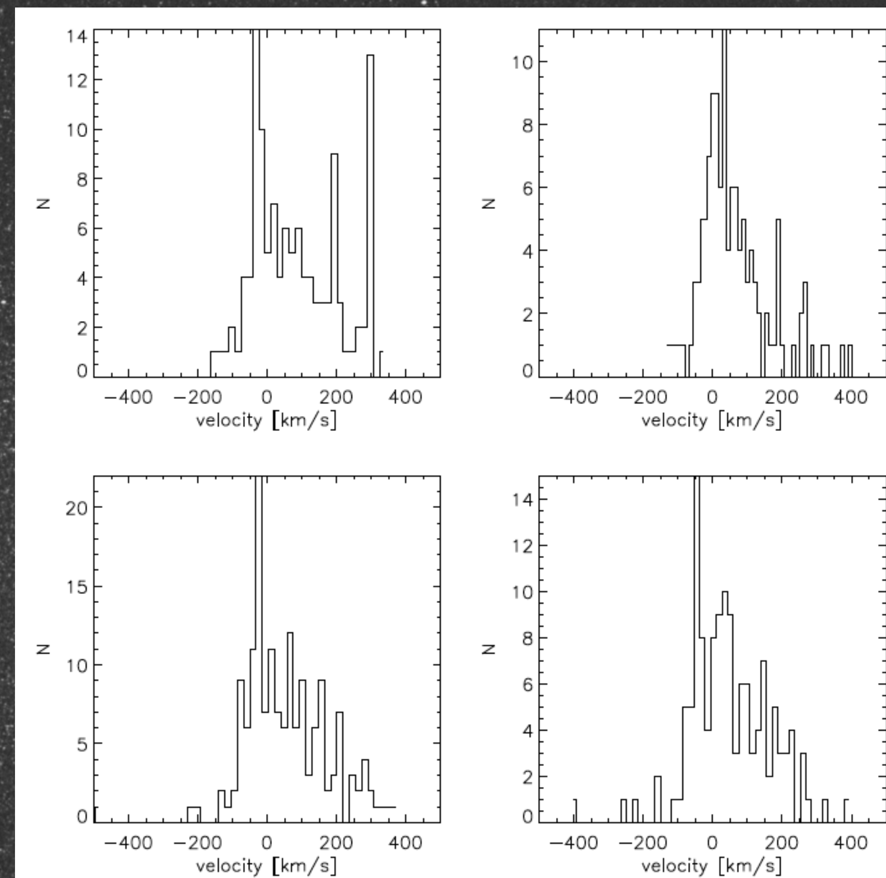
Streams in the Galactic halo: MMT/Hectochelle Spectroscopic Survey



Walker et al. (in preparation)

(near) FUTURE WORK: Streams in the Galactic halo:





Walker et al. (in preparation)

Conclusions

- Galactic dynamics has implications for particle physics.
- CDM model needs rescuing by baryon physics. But there is tension among solutions to `missing satellite' and `core/cusp' problems.
  - inefficient star formation to suppress low-mass galaxies
  - efficient star formation to alter halo structure
- If CDM escapes this tension, evidence will be observable in the Galactic halo.
- Otherwise, dark matter model will require more complexity.

Non-gravitational detections of dark matter?

$$\frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}E_\gamma}(E_\gamma, \Delta\Omega) = \Phi^{\mathrm{PP}}(E_\gamma) \times J(\Delta\Omega)$$

$$= 0.$$

$$\Phi^{\mathrm{PP}}(E_\gamma) \equiv \frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}E_\gamma} = \frac{1}{4\pi}\frac{\langle\sigma_{\mathrm{ann}} v\rangle}{2m_\chi^2} \times \frac{dN_\gamma}{dE_\gamma}$$

$$J = \int_{\Delta\Omega}\int \rho_{\mathrm{DM}}^2(l,\Omega)\, dl d\Omega.$$

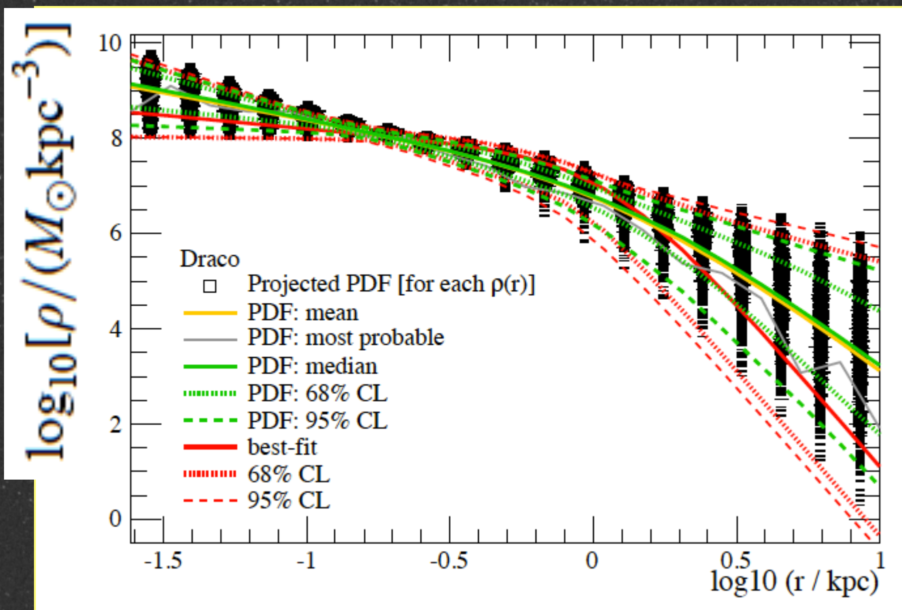
27 October, 2011

ITC Luncheon

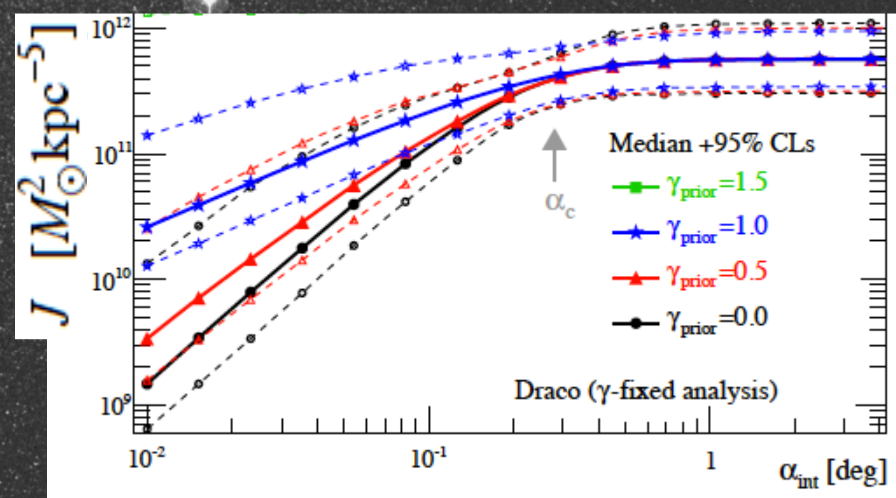
J from stellar kinematics

$$J = \int_{\Delta\Omega} \int \rho_{\rm DM}^2(l, \Omega)\, dl d\Omega.$$

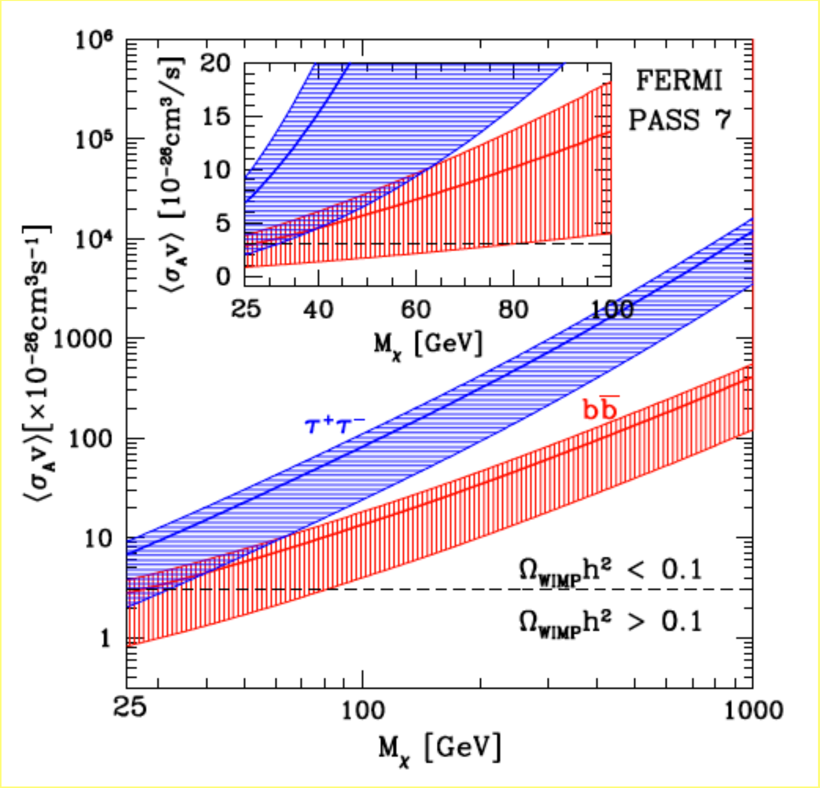
$$\rho(r) = \rho_0 \left(\frac{r}{r_0}\right)^{-\gamma} \left[1 + \left(\frac{r}{r_0}\right)^{\alpha}\right]^{\frac{\gamma-\eta}{\alpha}}$$



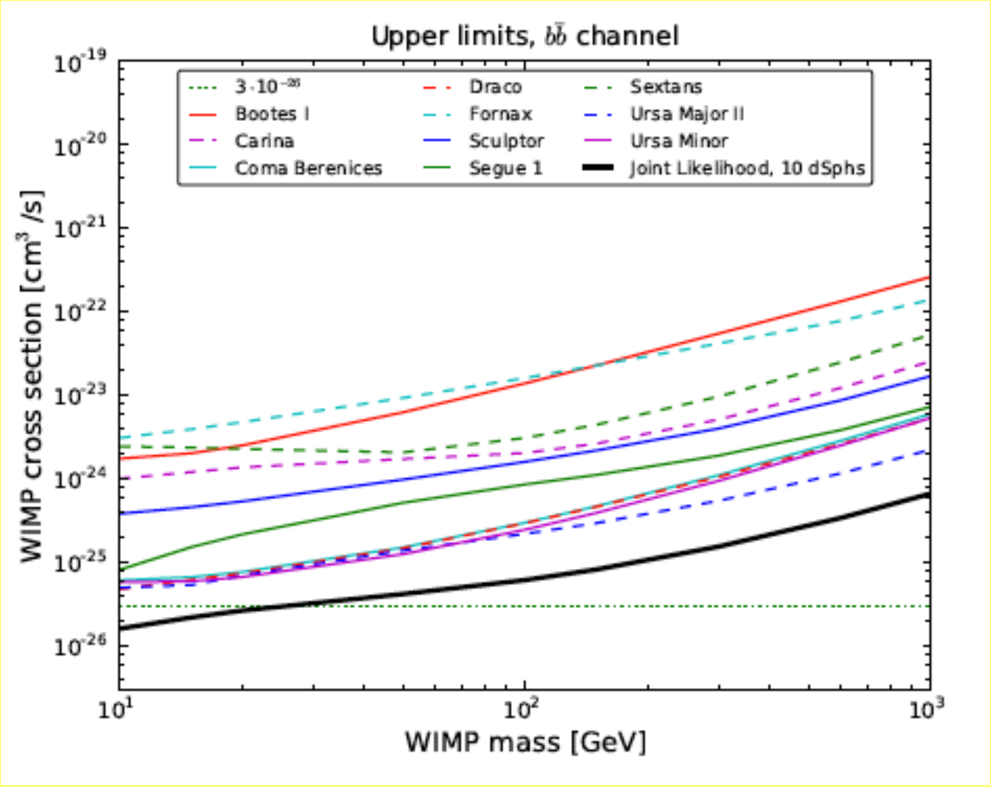
Charbonnier et al. (arXiv:1104.0412)



published constraints from Fermi non-detections



Geringer-Sameth & Koushiappas (arXiv:1108.2914)



Fermi Collaboration (arXiv:1108.3546)

How to improve particle physics limits?

- Find more satellites, especially in the southern hemisphere
- Modelling uncertainties:
  - Centers of satellites
  - Non-spherical shapes of satellites
  - Contamination from foreground
  - Binary stars

A QUANTITATIVE EXPLANATION OF THE OBSERVED POPULATION OF MILKY WAY SATELLITE GALAXIES

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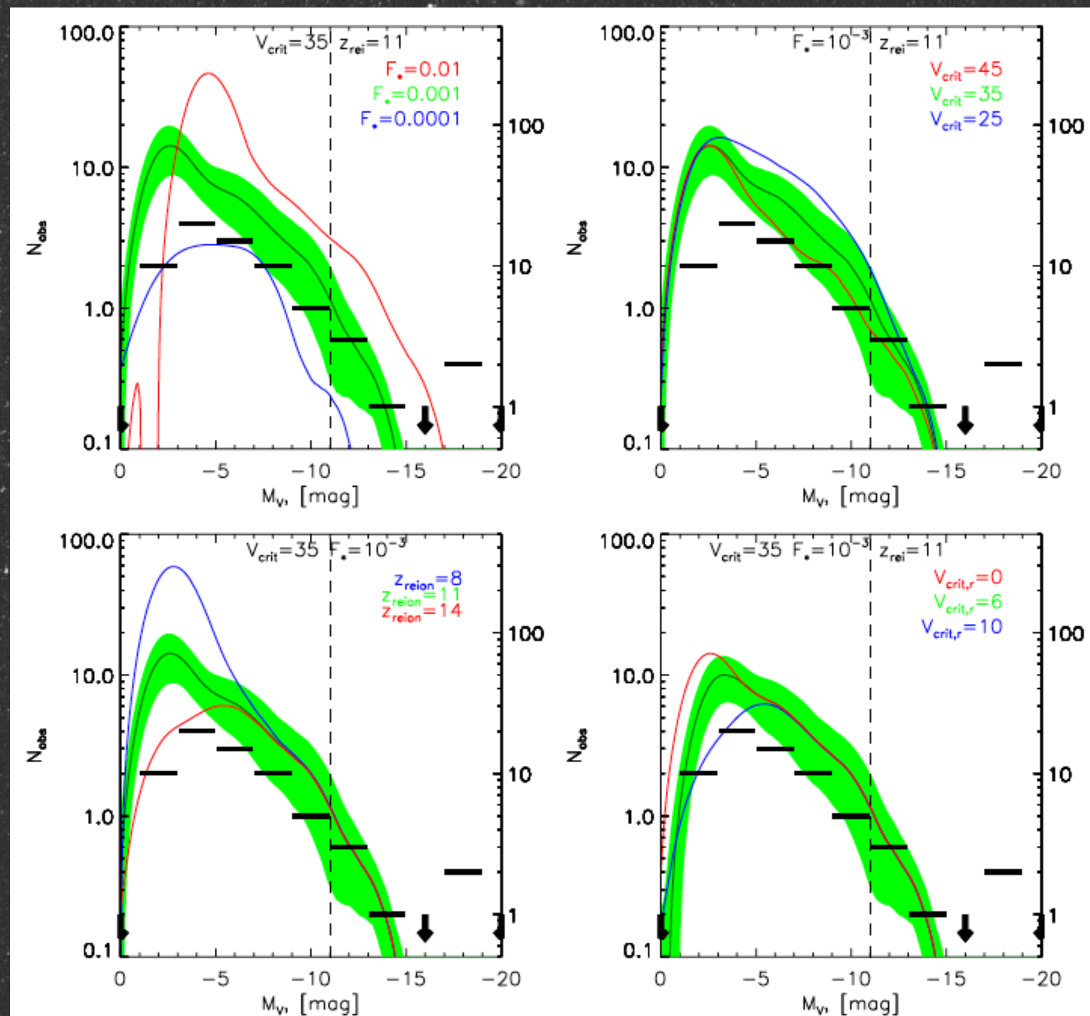
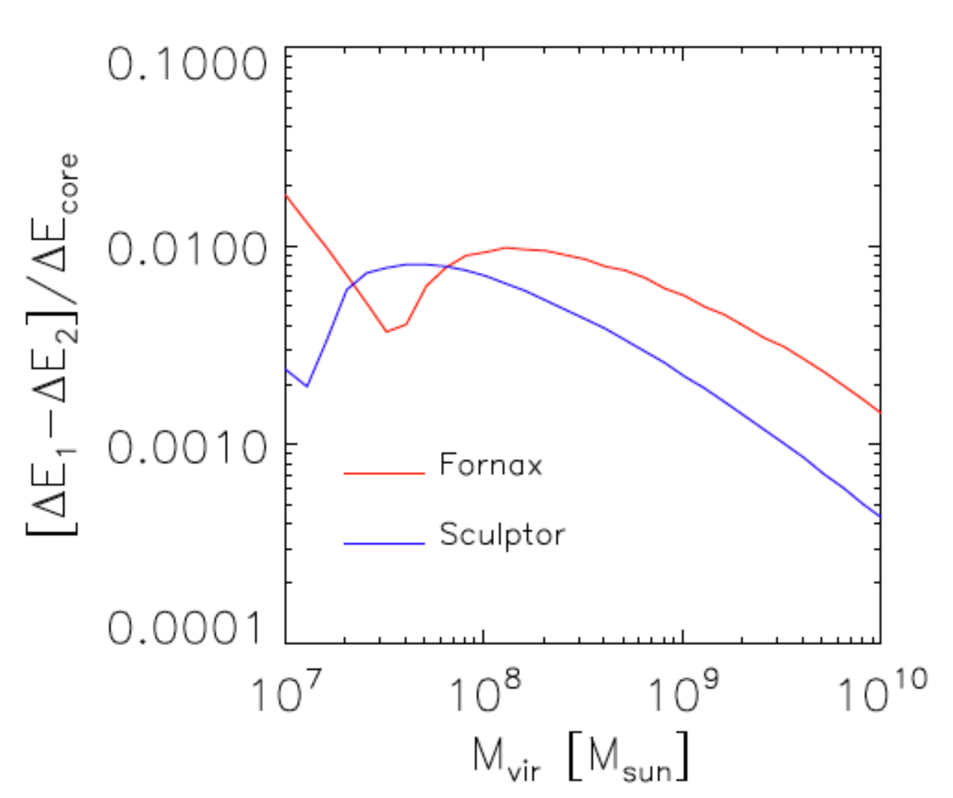
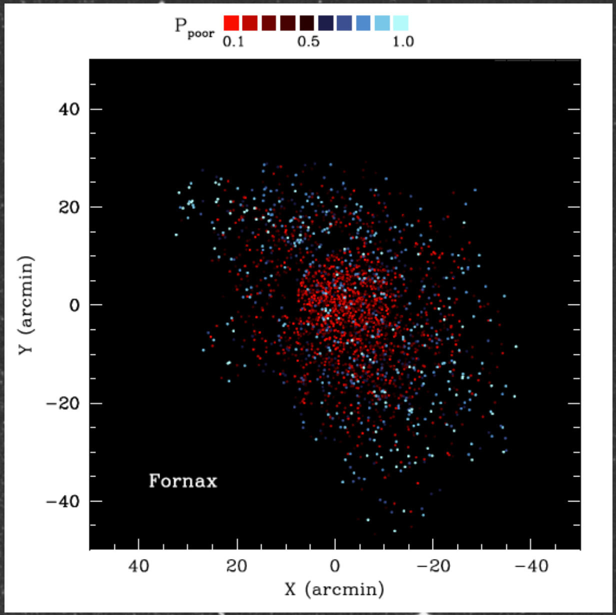
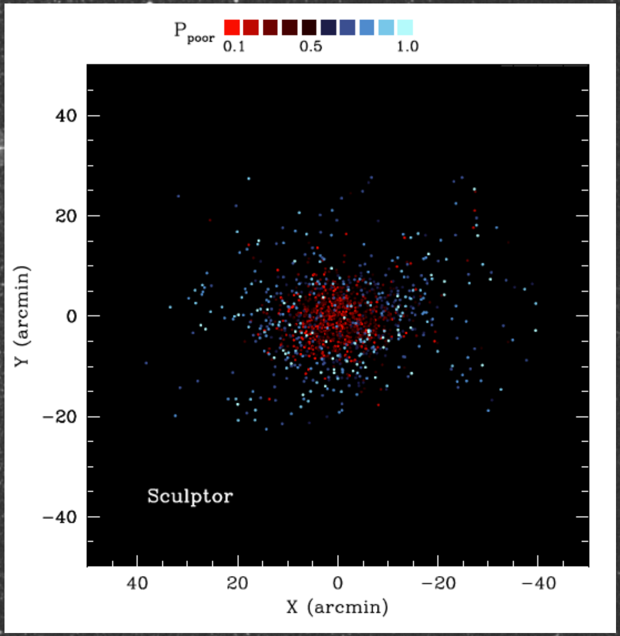



0.1000
0.0100
0.0010
0.0001
$[\Delta E_1 - \Delta E_2]/\Delta E_{core}$
Fornax
Sculptor
10^7
10^8
10^9
10^{10}
M_{vir} [M_{sun}]

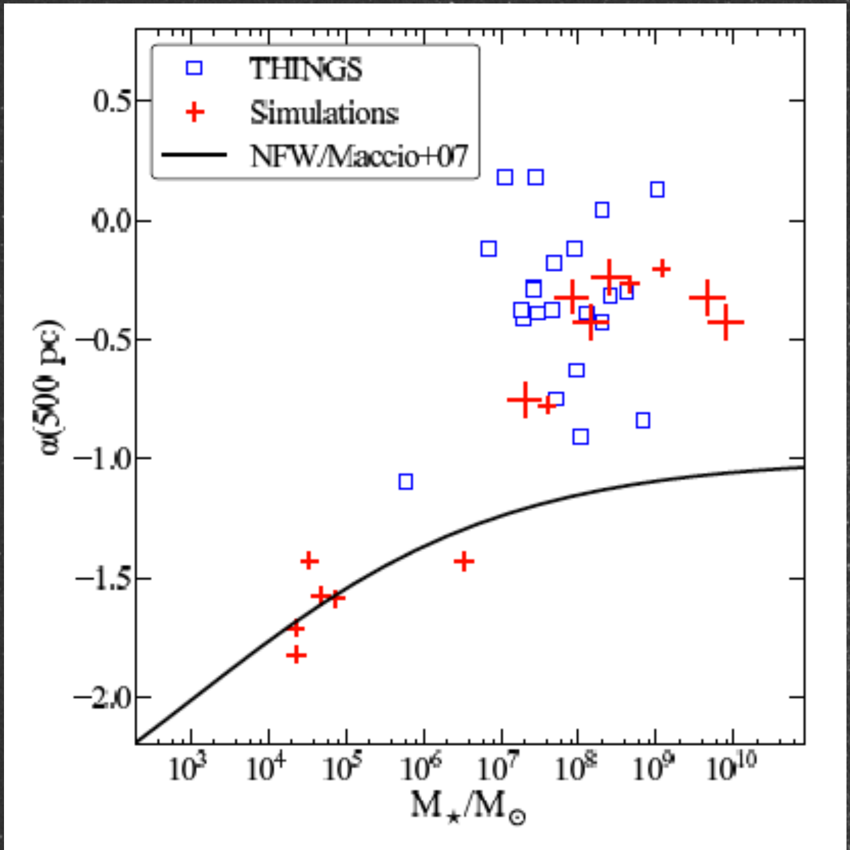

P_{poor}
0.1
0.5
1.0
Fornax
Y (arcmin)
X (arcmin)

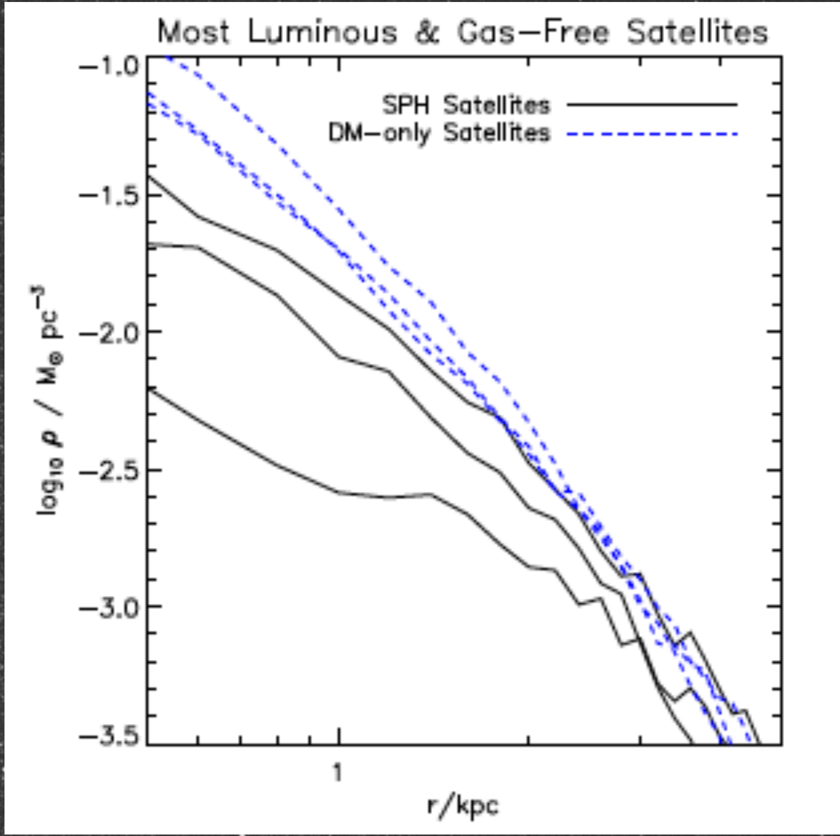

P_{poor}
0.1
0.5
1.0
Sculptor
Y (arcmin)
X (arcmin)

BARYONS MATTER: WHY LUMINOUS SATELLITE GALAXIES HAVE REDUCED CENTRAL MASSES

ADI ZOLOTOV[1], ALYSON M. BROOKS[2], BETH WILLMAN[3], FABIO GOVERNATO[4], ANDREW PONTZEN[5], CHARLOTTE CHRISTENSEN[6], AVISHAI DEKEL[1], TOM QUINN[4], SIJING SHEN[7], JAMES WADSLEY[8]

(Dated: July 12, 2012)
Submitted for publication in ApJ





Cuspy No More: How Outflows Affect the Central Dark Matter and Baryon Distribution in ΛCDM Galaxies.

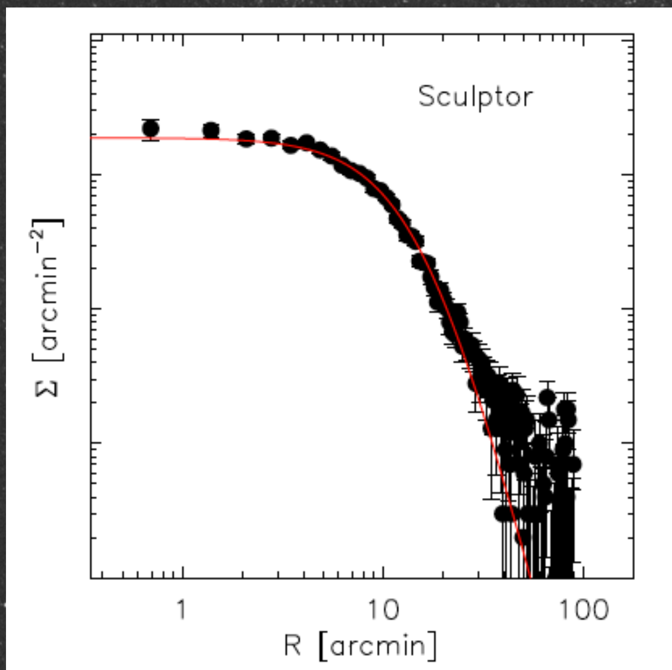
F.Governato[1*] A.Zolotov[2], A.Pontzen[3], C.Christensen[4], S.H.Oh[5,6], A. M.Brooks[7], T.Quinn[1], S.Shen[8], J.Wadsley[9]

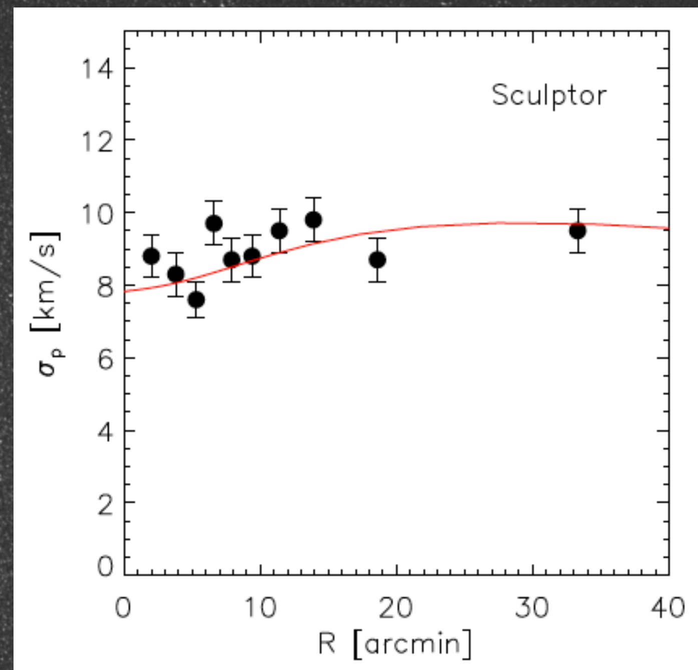
J from stellar kinematics

$$J = \int_{\Delta\Omega} \int \rho_{\mathrm{DM}}^2(l, \Omega)\, dl d\Omega.$$

$$\sigma_p^2(R)\Sigma(R) = 2\int_R^{\infty}\left(1-\beta\frac{R^2}{r^2}\right)\frac{\nu(r)v_r^2 r}{\sqrt{r^2-R^2}}dr$$

$$\rho(r) = \rho_0\left(\frac{r}{r_0}\right)^{-\gamma}\left[1+\left(\frac{r}{r_0}\right)^{\alpha}\right]^{\frac{\gamma-\eta}{\alpha}}$$

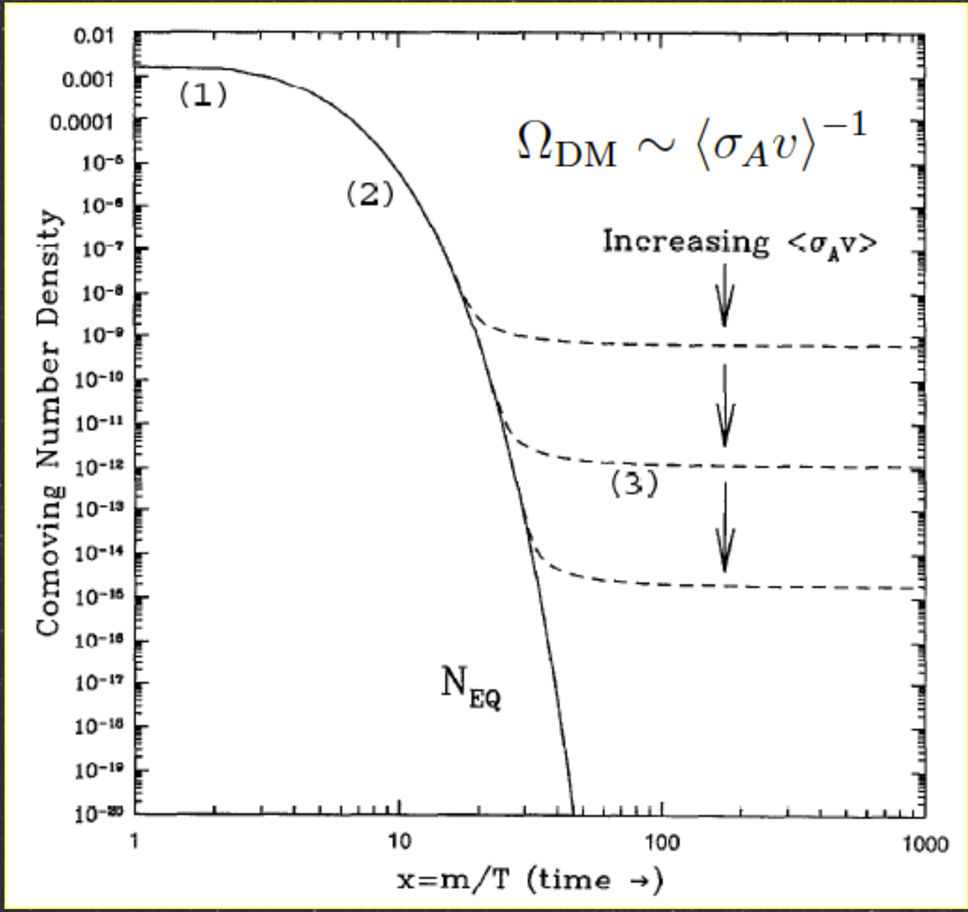




Assumptions:

- -spherical symmetry
- -dynamical equilibrium
- -negligible binary motions
- -parametric density profile

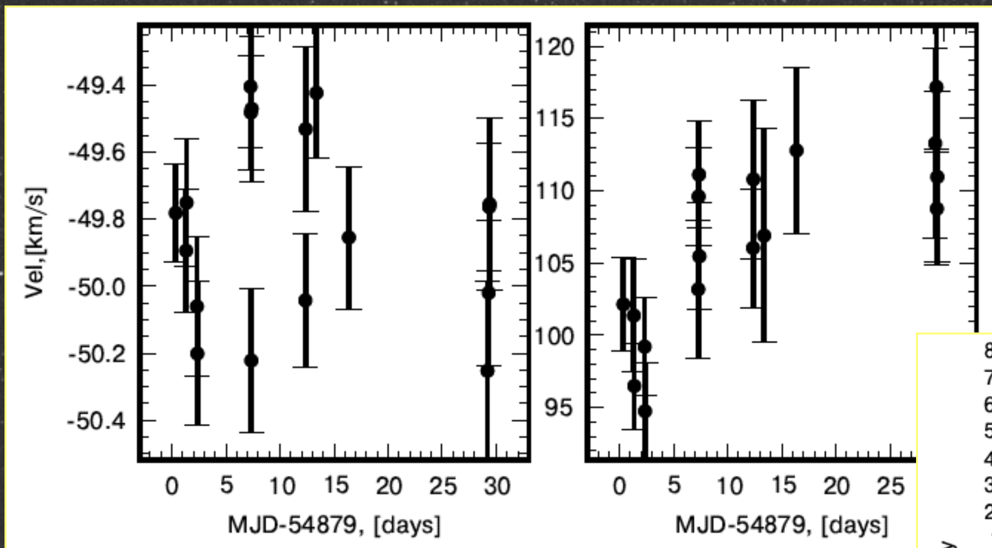
WIMPs

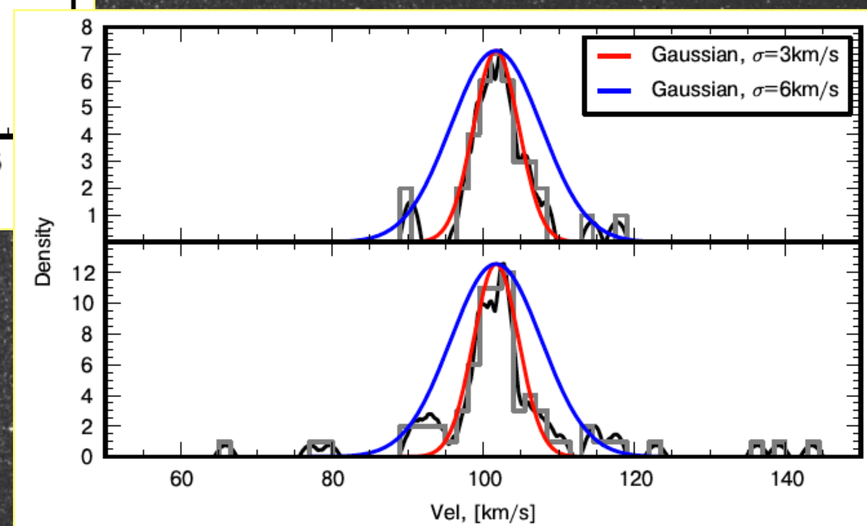


$$\sigma_A v = k \frac{4\pi\alpha_1^2}{m_\chi^2}$$

Jungman, Kamionkowski & Griest (1996)

BooI w/ VLT





Koposov et al. (2011)

Assumptions of Jeans Modeling:

- -spherical symmetry
- -dynamical equilibrium
- -negligible binary motions
- -parametric density profile

THE DIFFERENCE BETWEEN COLD DARK MATTER'S CORE/CUSP AND TOO-BIG-TO-FAIL PROBLEMS

MATTHEW G. WALKER[1,2] & JORGE PEÑARRUBIA[3]