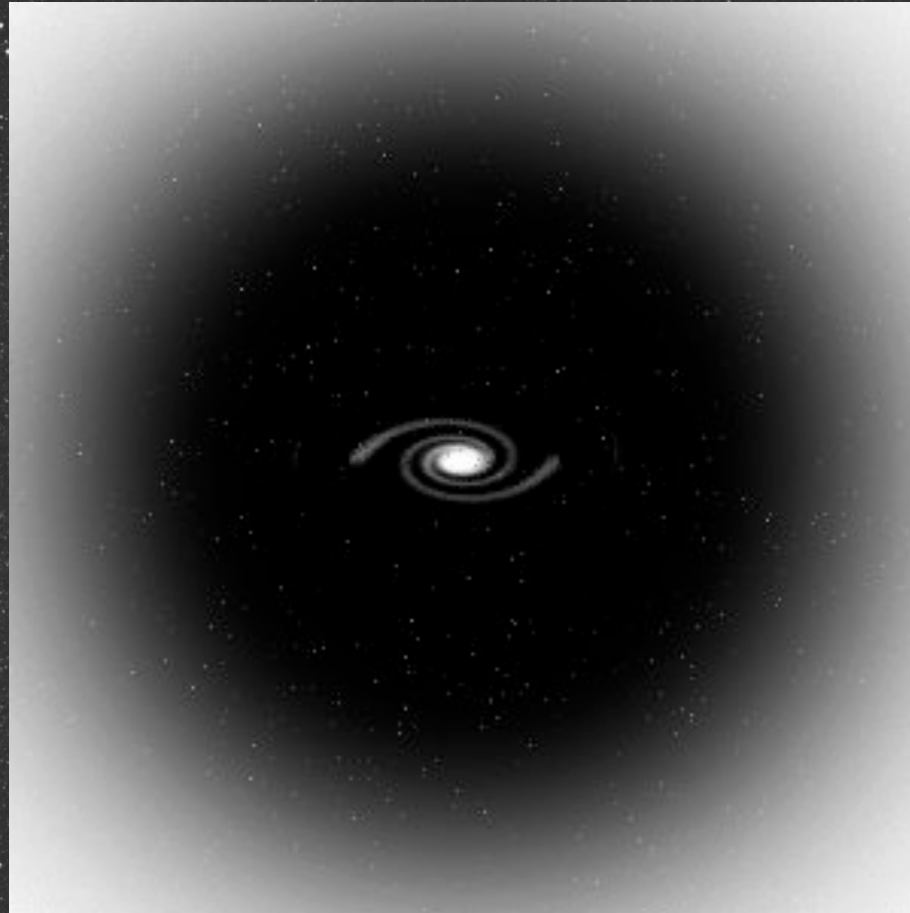
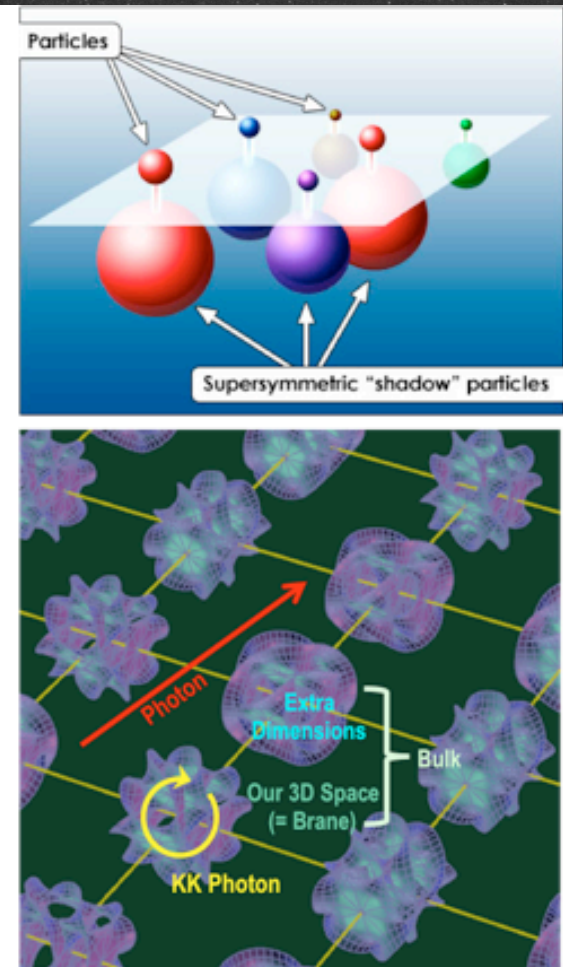
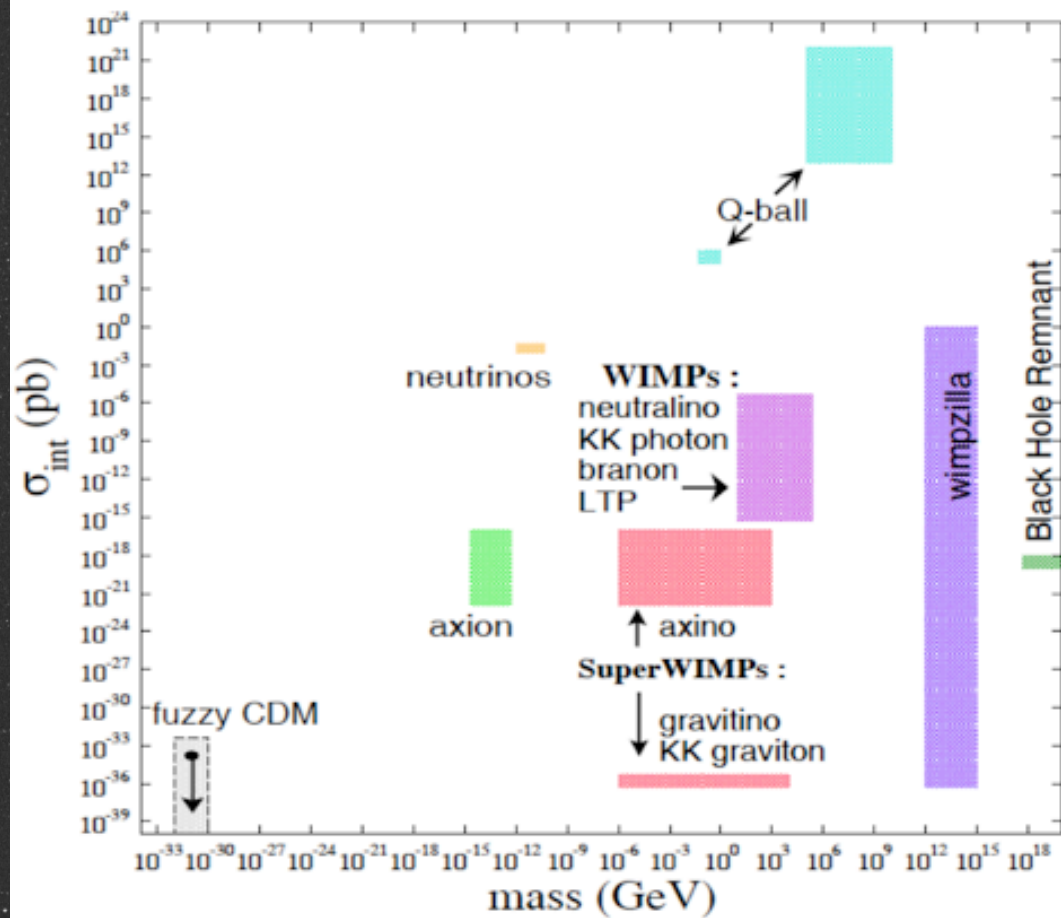


# Galactic Dynamics and the Nature of Dark Matter



Matthew Walker – Harvard/CfA

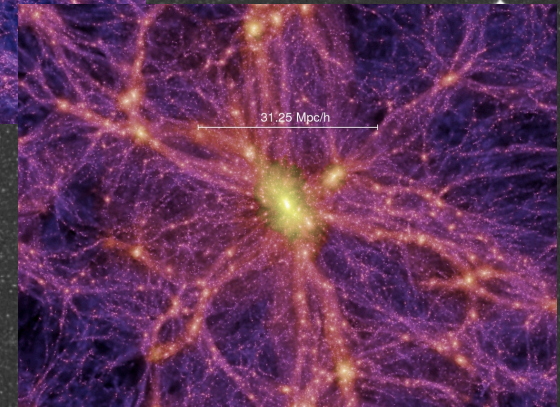
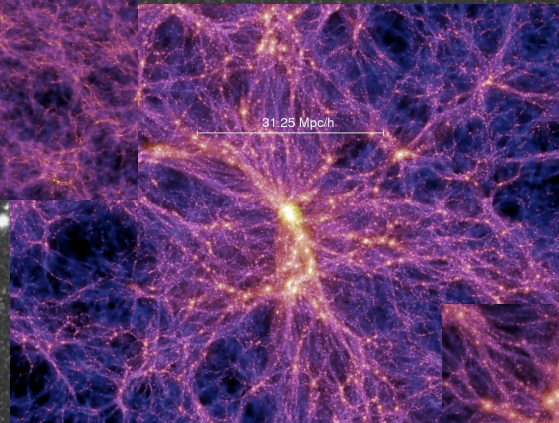
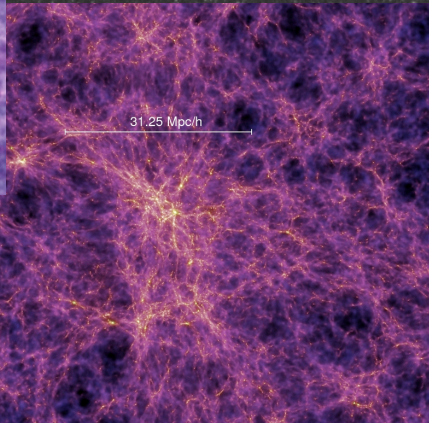
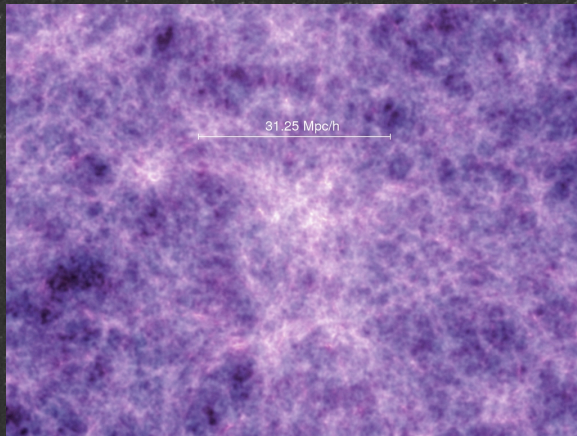
Grenoble, 11 July 2013



Sobel et al. (2007; Dark Matter Scientific Assessment Group)



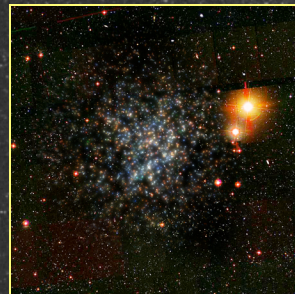
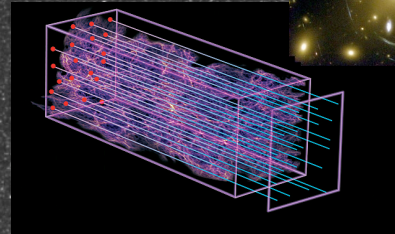
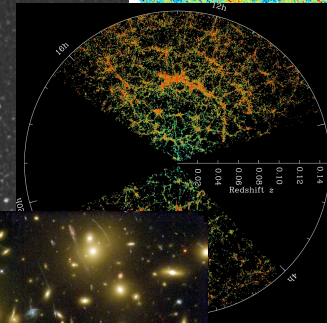
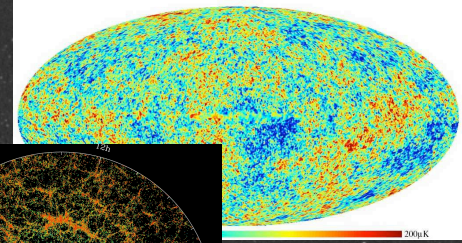
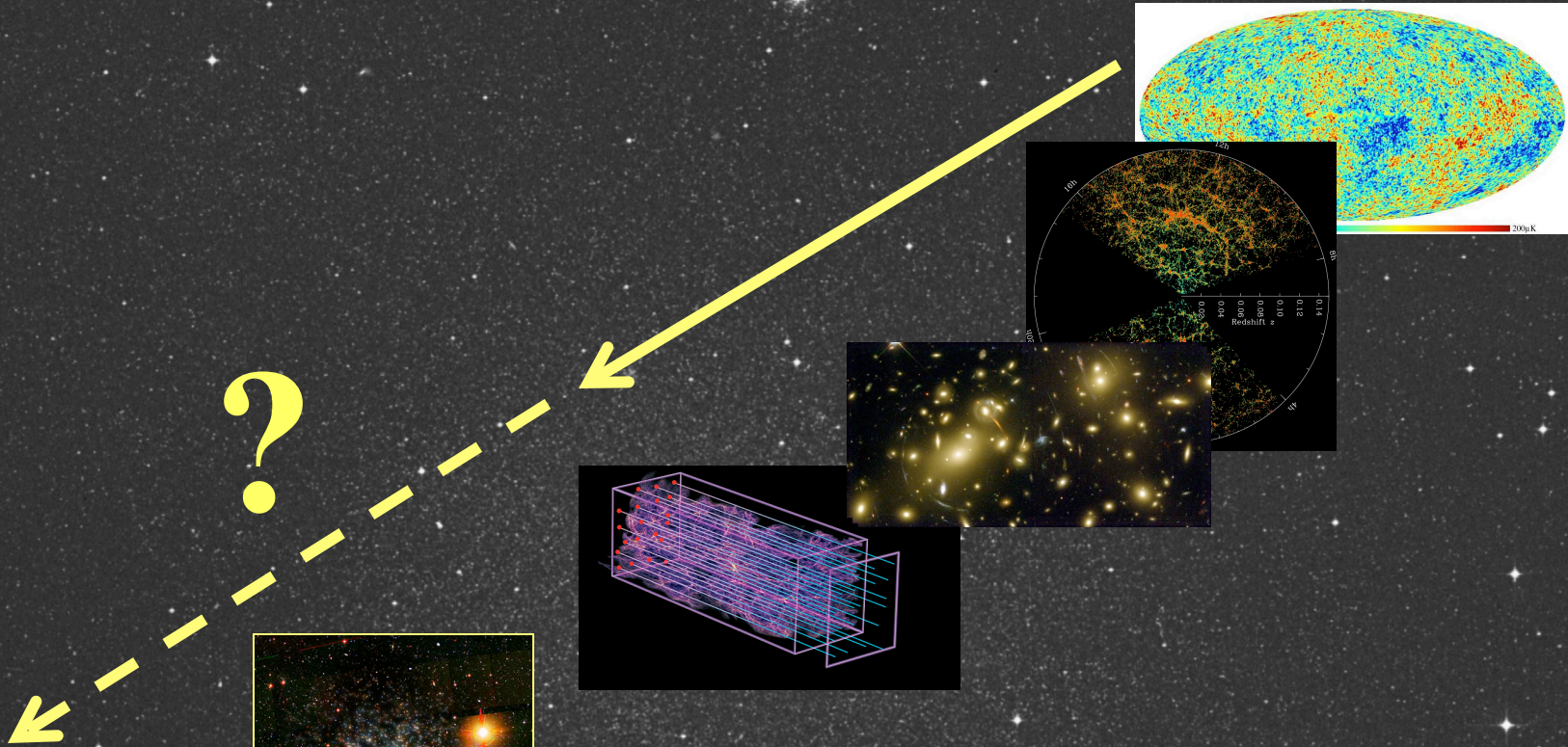
# Hypothesis: Collisionless, Cold Dark Matter



Millennium run (Springel et al 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  $3 \times 10^4$  to  $3 \times 10^5$  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

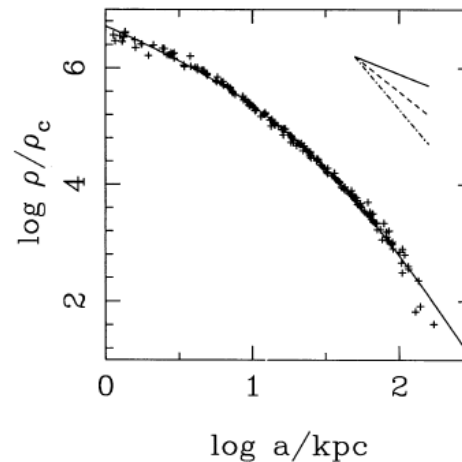
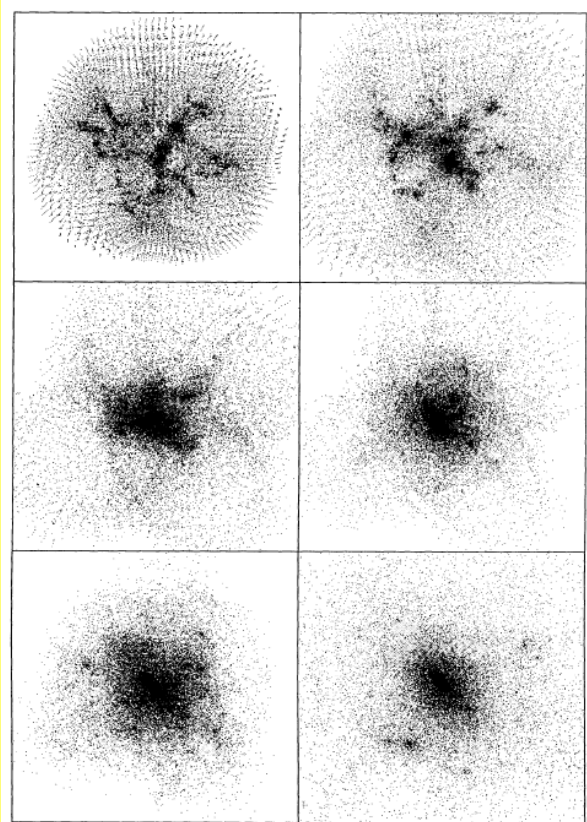
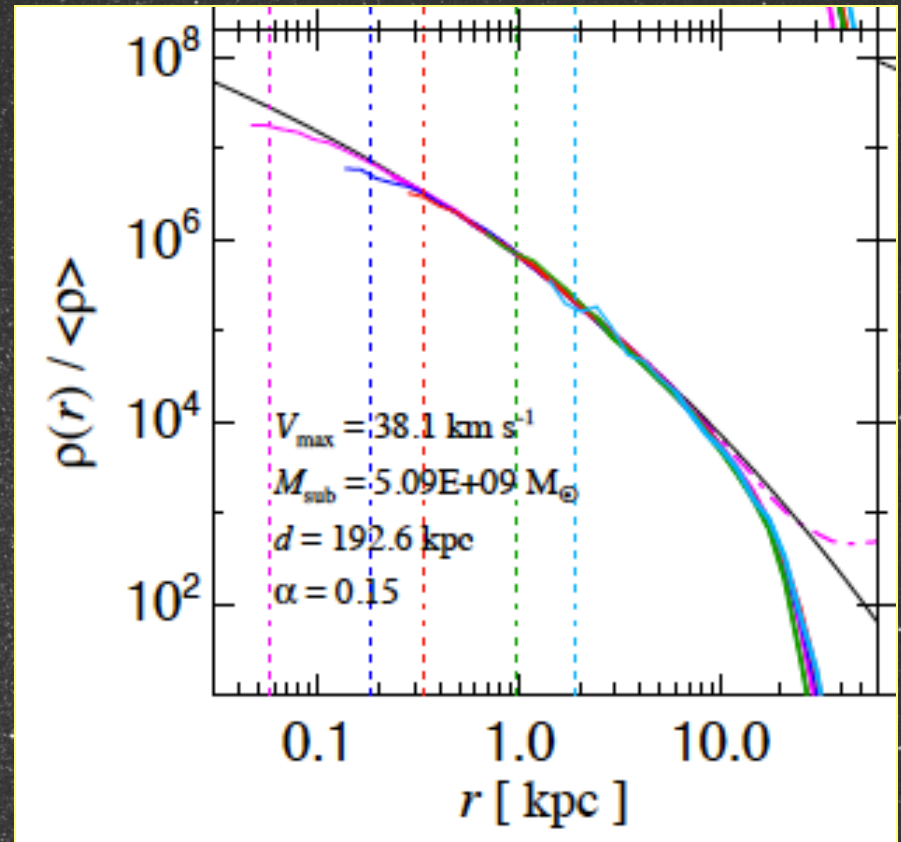


FIG. 2.—Density profiles of dark halos. Density is in units of the critical density  $\rho_c$ , and the elliptical radius  $a$  is in kpc. Thirteen points were used for the two-parameter fit of Hernquist's profile for each of the 14 halos. Each set of points has been renormalized to the fiducial Hernquist 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



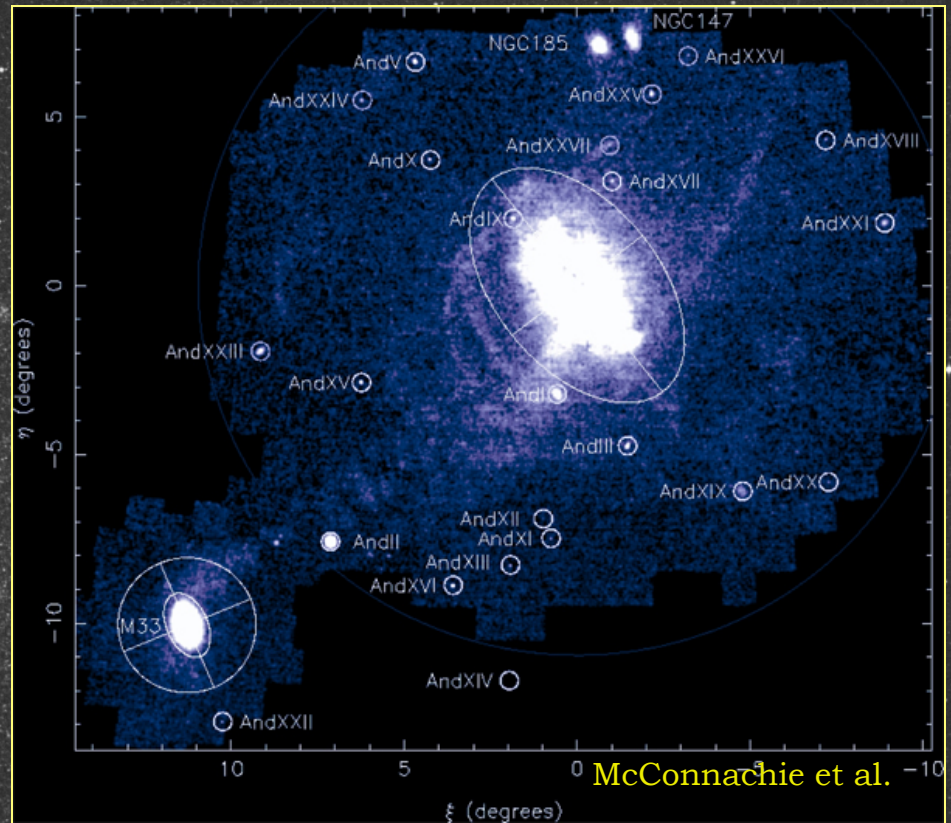
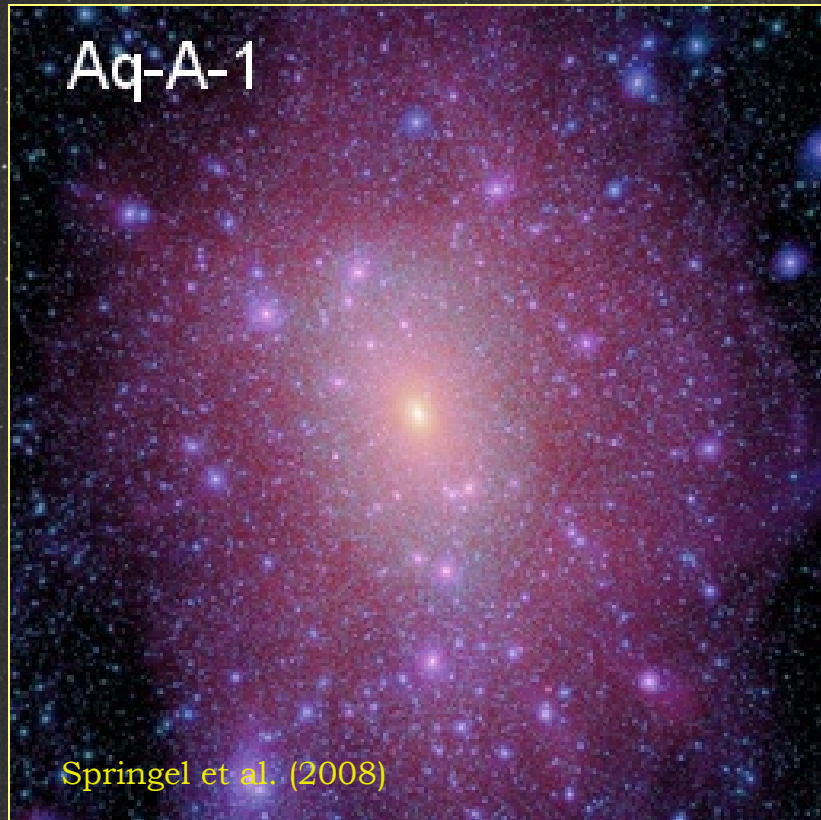
Springel et al. 2008, also Diemand et al. 2007, etc.

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

NFW(1997)

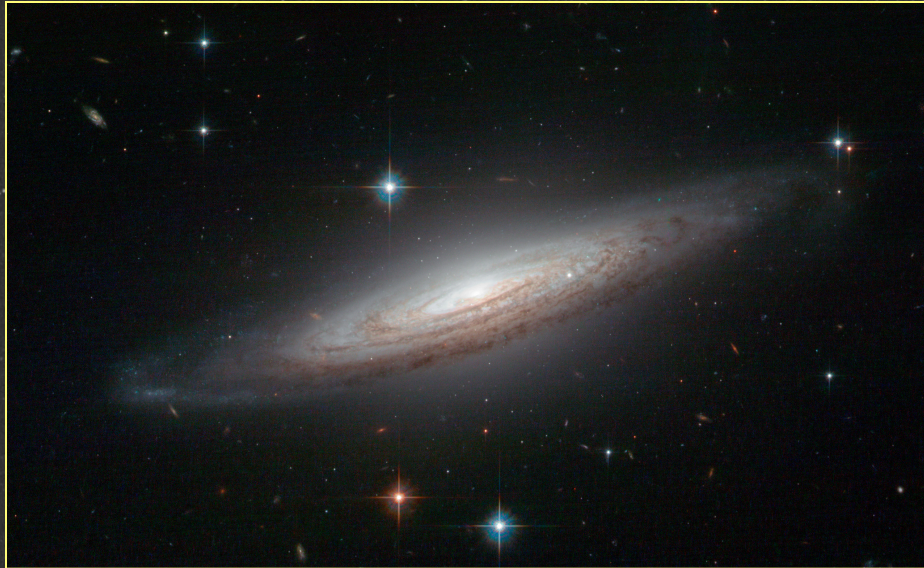


# 'Missing Satellites' Problem

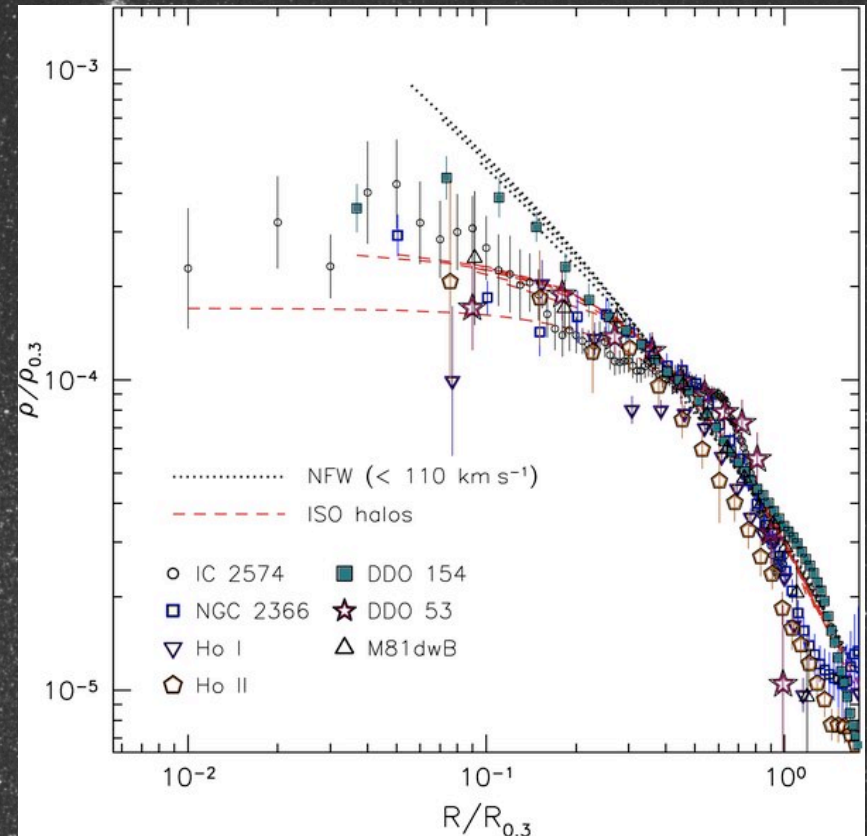




# core/cusp problem



$$v_{\text{circ}}^2 = \frac{GM(r)}{r}$$



Oh et al (2011; also Moore 1994, Flores & Primack 1994, de Blok & Bosma 2002, Kuzio de Naray 2008, de Blok 2010 & references therein)



# How supernova feedback turns dark matter cusps into cores

Andrew Pontzen<sup>1,2,3\*</sup>, Fabio Governato<sup>4</sup>

<sup>1</sup>*Kavli Institute for Cosmology and Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK*

<sup>2</sup>*Emmanuel College, St Andrew's Street, Cambridge, CB2 3AP UK*

<sup>3</sup>*Oxford Astrophysics, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK*

<sup>4</sup>*Astronomy Department, University of Washington, Seattle, WA 98195, USA*

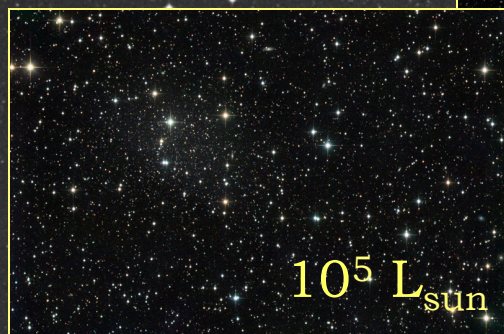
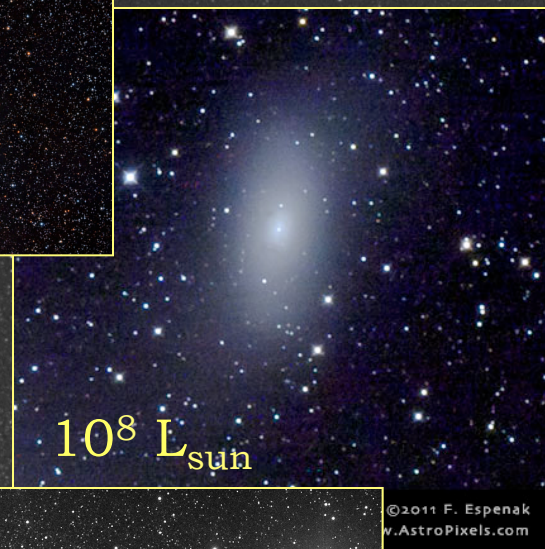
Aq-A-1

Springel et al. (2008)



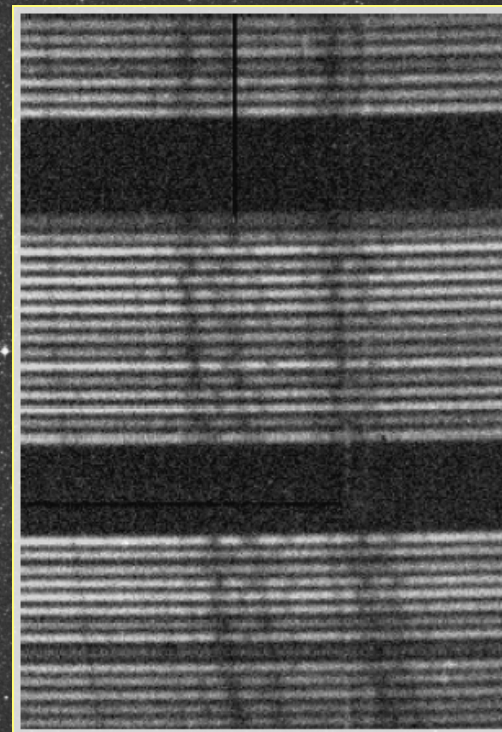
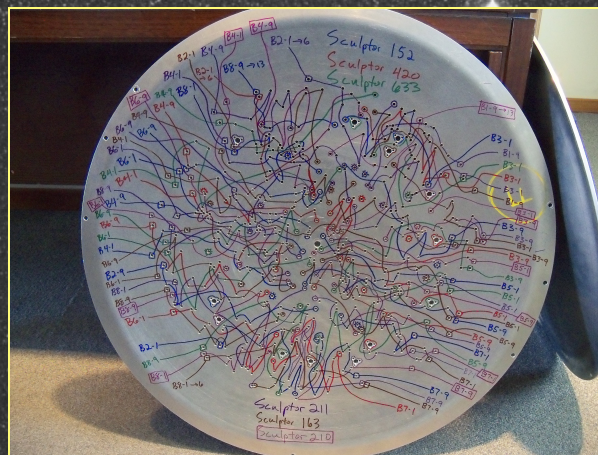
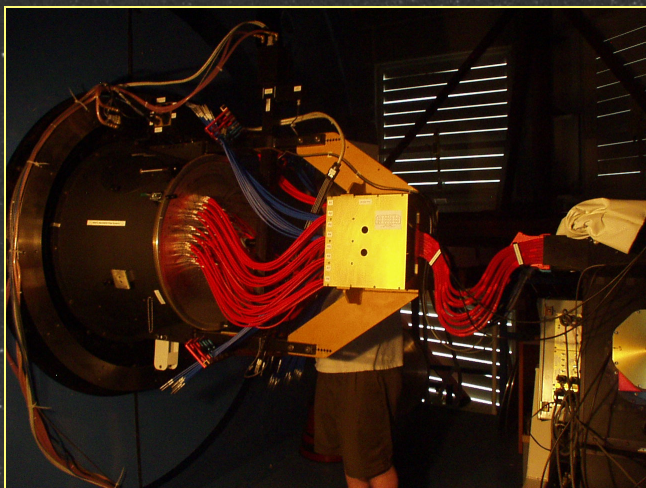
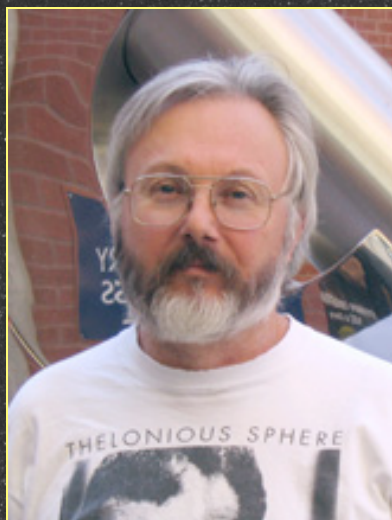
[www.creationofuniverse.com](http://www.creationofuniverse.com)



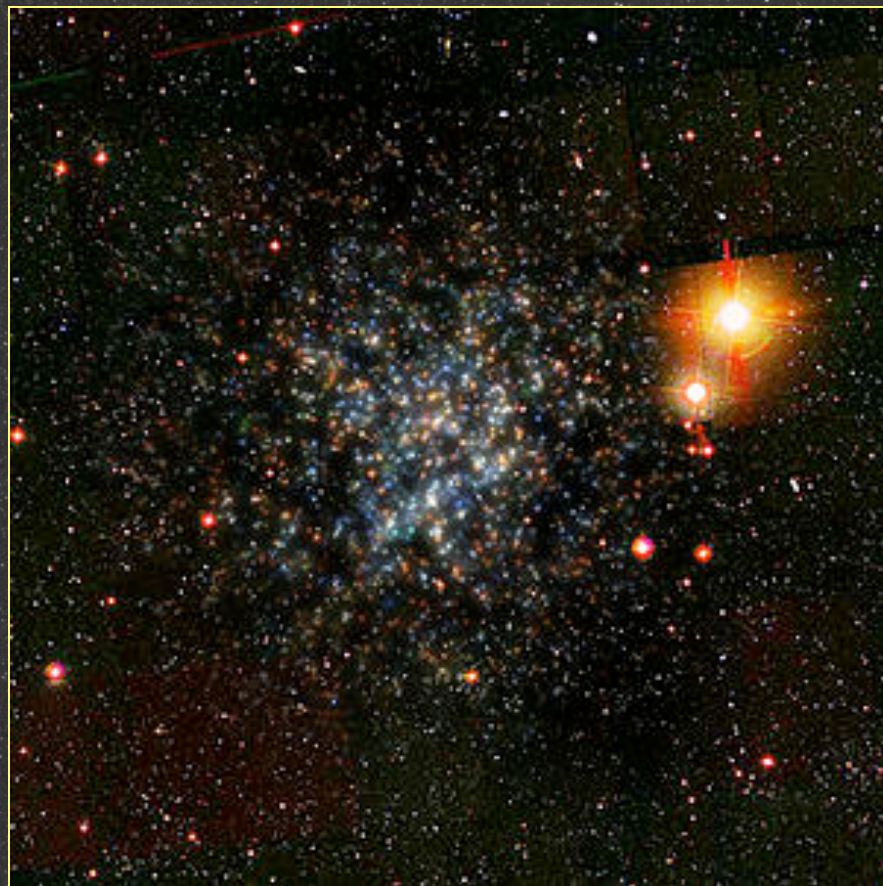




# Magellan Spectroscopy w/ Mario Mateo & Ed Olszewski



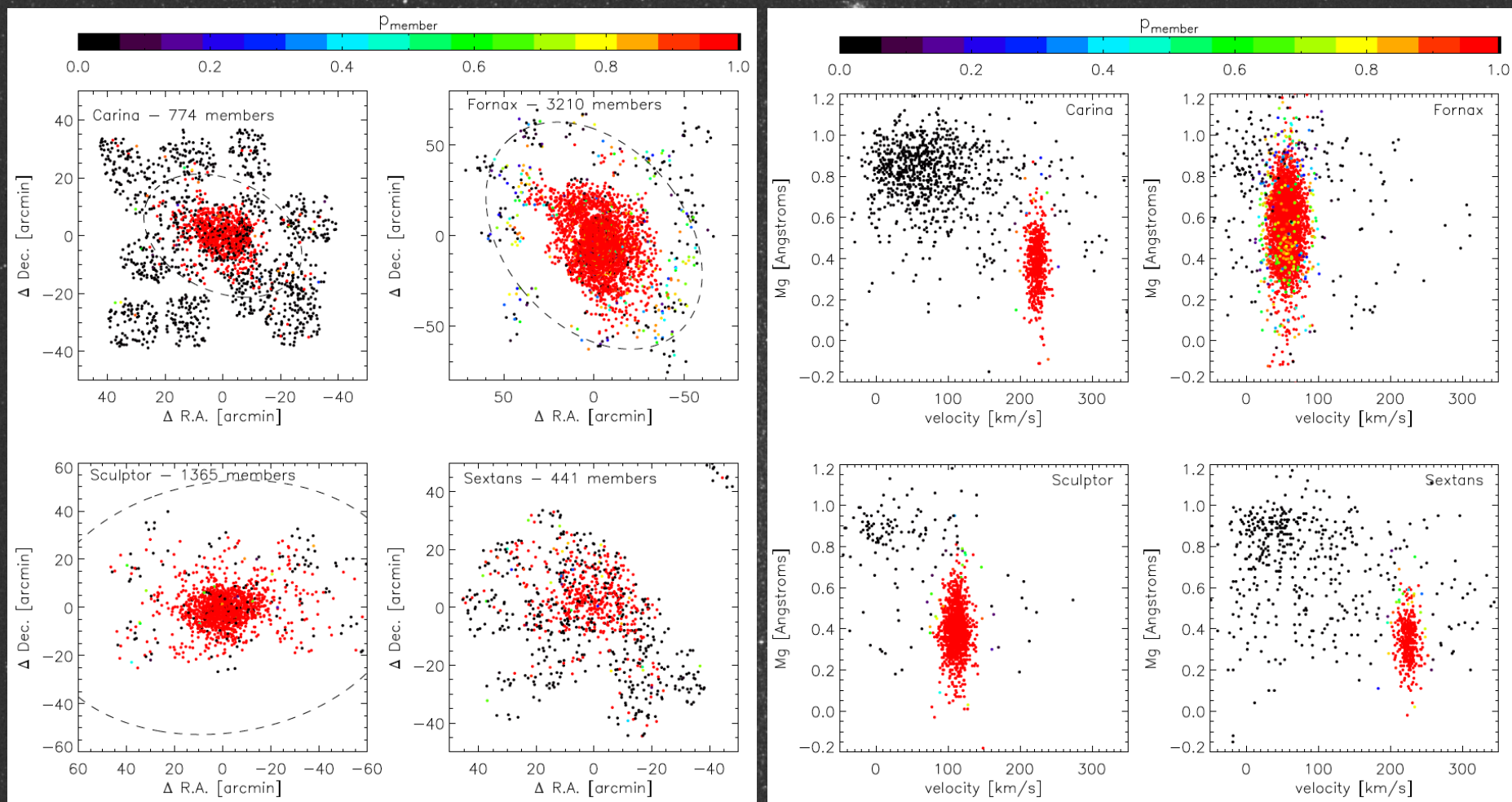




X, Y,  $V_z$ , Mg



# Data: Magellan Samples



Walker, Mateo & Olszewski (2009)



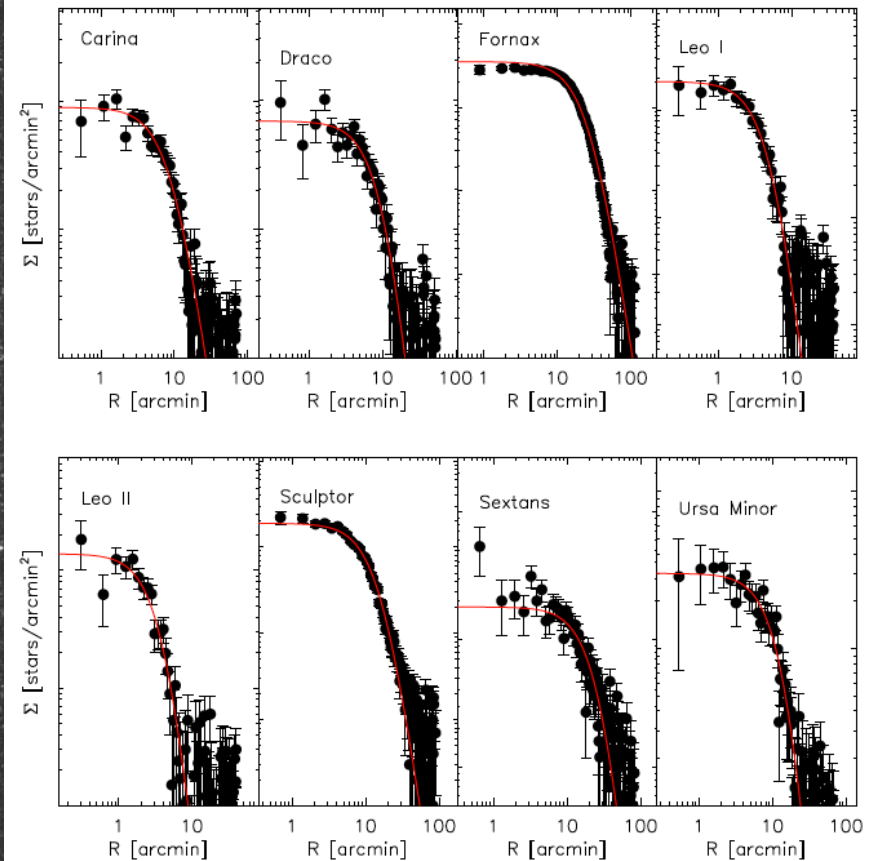
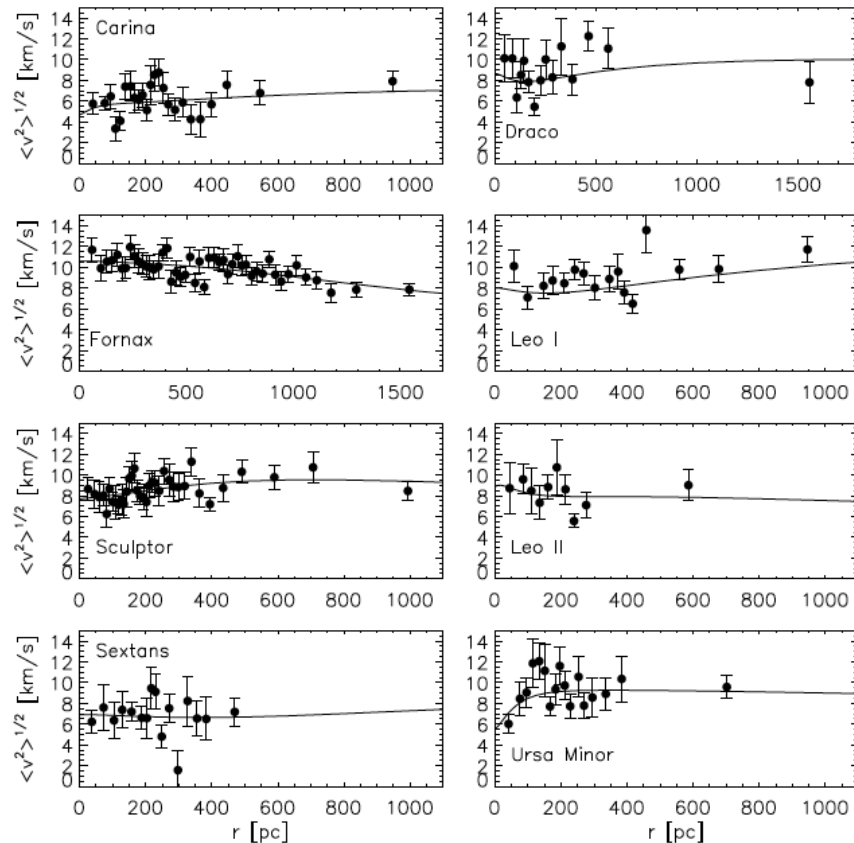
# Kinematics with the Jeans Equation

$$\sigma_p^2(R) = \frac{2}{I(R)} \int_R^\infty \left( 1 - \beta \frac{R^2}{r^2} \right) \frac{\nu(r) \bar{v}_r^2 r}{\sqrt{r^2 - R^2}} dr$$



Observed

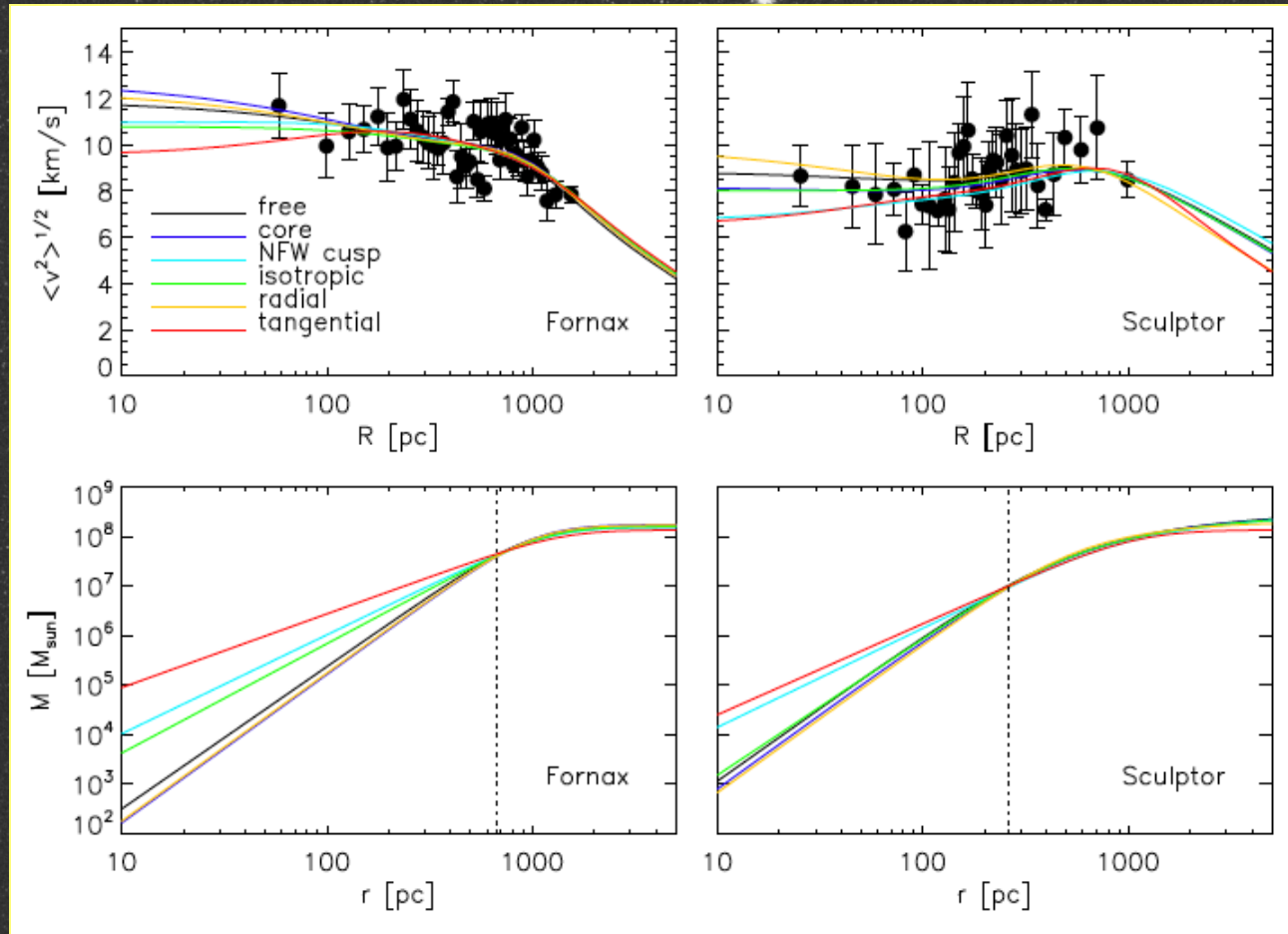
Not Observed



Walker, Mateo & Olszewski (2009)



# Kinematics with the Jeans Equation



$$M(R_{\text{half}}) \sim 5\sigma_V^2 \frac{R_{\text{half}}}{2G}$$

Walker & Peñarrubia 2011



$$M(r_h) \approx \frac{5r_h\sigma_V^2}{2G}$$

v:astro-ph/0411029v1 1 Nov 2004

## Two distinct ancient components in the Sculptor Dwarf Spheroidal Galaxy: First Results from DART<sup>1</sup>

Eline Tolstoy<sup>2</sup>, M.J. Irwin<sup>3</sup>, A. Helmi<sup>2</sup>, G. Battaglia<sup>2</sup>, P. Jablonka<sup>4</sup>, V. Hill<sup>4</sup>, K.A. Venn<sup>5</sup>,  
M.D. Shetrone<sup>6</sup>, B. Letarte<sup>2</sup>, A.A. Cole<sup>2</sup>, F. Primas<sup>7</sup>, P. Francois<sup>4</sup>, N. Arimoto<sup>8</sup>, K.  
Sadakane<sup>8</sup>, A. Kaufer<sup>9</sup>, T. Szeifert<sup>9</sup>, T. Abel<sup>10</sup>,

### ABSTRACT

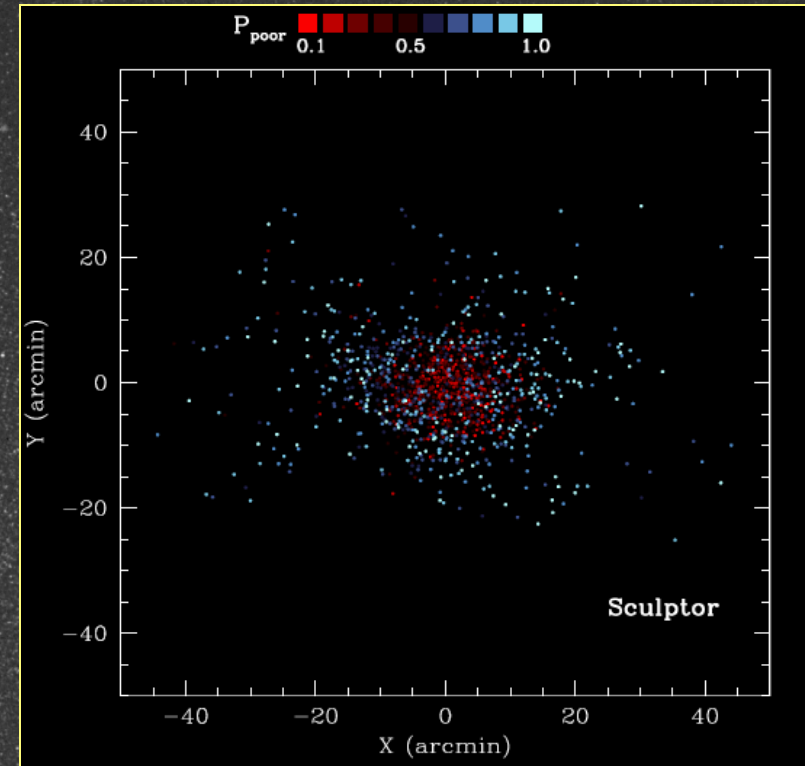
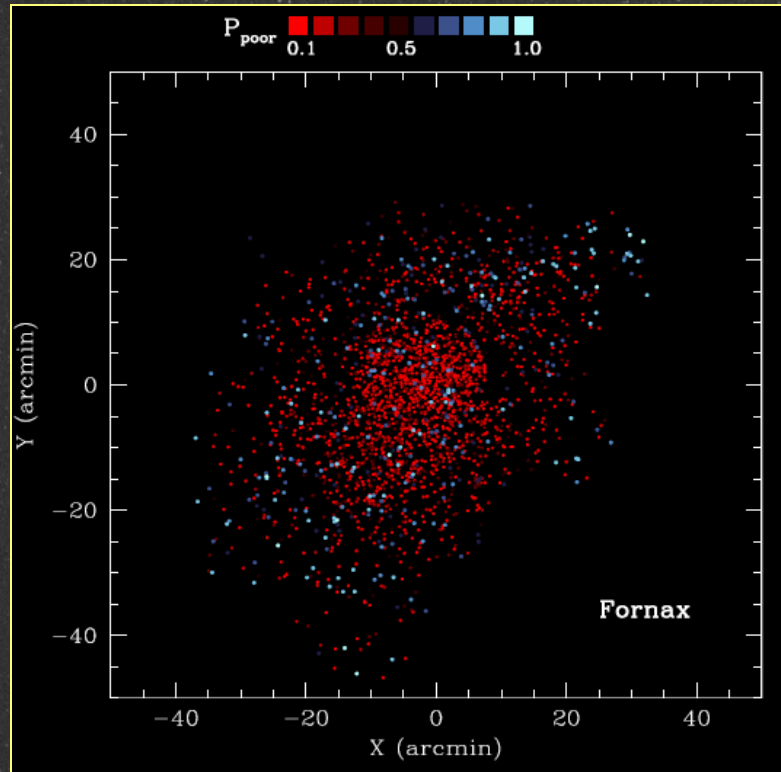
We have found evidence for the presence of two distinct ancient stellar components (both  $\geq 10$  Gyr old) in the Sculptor dwarf spheroidal galaxy. We used the ESO Wide Field Imager (WFI) in conjunction with the VLT/FLAMES spectrograph to study the properties of the resolved stellar population of Sculptor out to and beyond the tidal radius. We find that two components are discernible in the spatial distribution of Horizontal Branch stars in our imaging, and in the [Fe/H] and  $v_{hel}$  distributions for our large sample of spectroscopic measurements. They can be generally described as a “metal-poor” component ([Fe/H]  $< -1.7$ ) and a “metal-rich” component ([Fe/H]  $> -1.7$ ). The metal-poor stars are more spatially extended than the metal-rich stars, and they also appear to be kinematically distinct. These results provide an important insight into the formation processes of small systems in the early universe and the conditions found there. Even this simplest of galaxies appears to have had a surprisingly complex early evolution.

Also:  
Fornax (Battaglia et al. 2006)  
Sextans: (Battaglia et al. 2010)



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

MATTHEW G. WALKER<sup>1,2,3</sup> & JORGE PEÑARRUBIA<sup>2</sup>

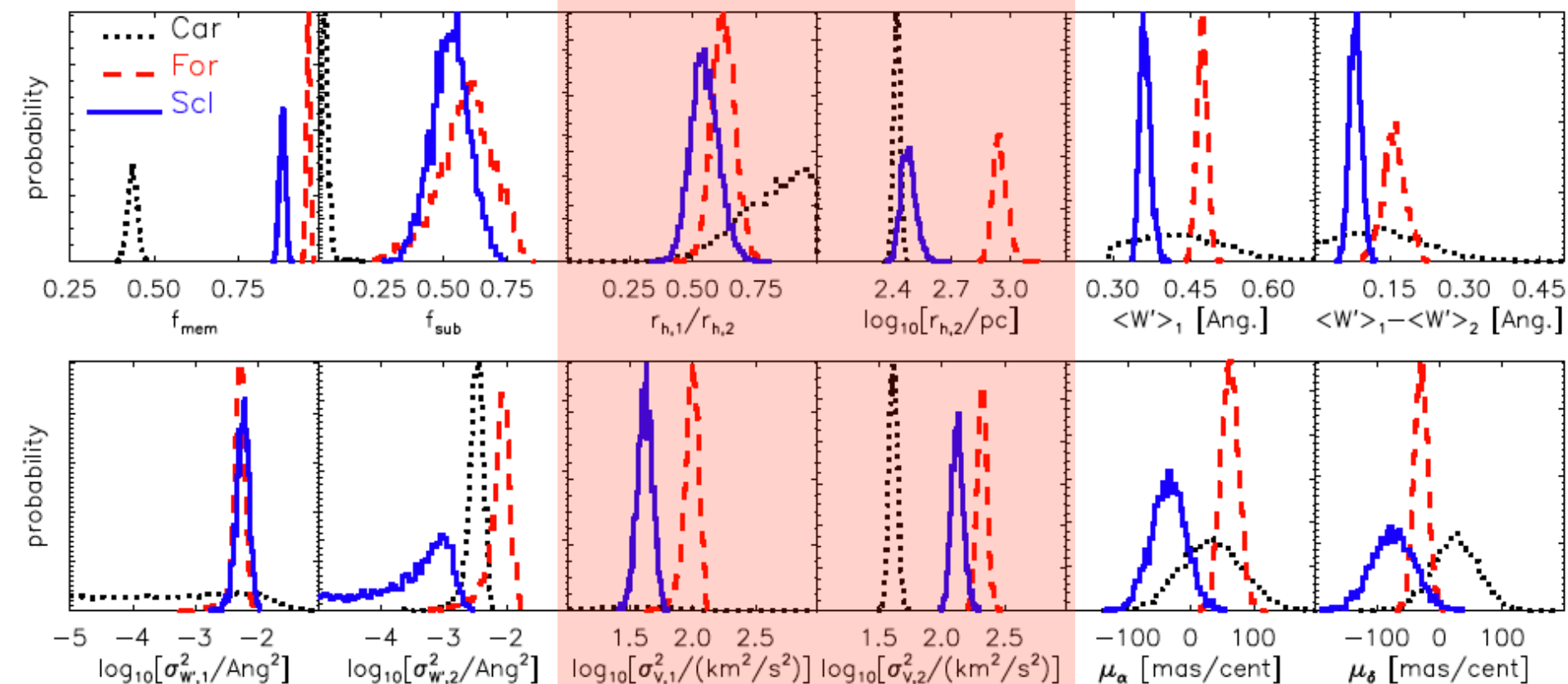


$$L(\{R_i, V_i, W'_i\}_{i=1}^{N_{\text{sample}}} | \vec{S}) = \prod_{i=1}^{N_{\text{sample}}} \left[ f_1 \frac{w(R_i) p_1(R_i, V_i, W'_i)}{\int \int \int w(R) p_1(R, V, W') dR dV dW'} + f_2 \frac{w(R_i) p_2(R_i, V_i, W'_i)}{\int \int \int w(R) p_2(R, V, W') dR dV dW'} \right. \\ \left. + (1 - f_1 - f_2) \frac{w(R_i) p_{\text{MW}}(R_i, V_i, W'_i)}{\int \int \int w(R) p_{\text{MW}}(R, V, W') dR dV dW'} \right]$$



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

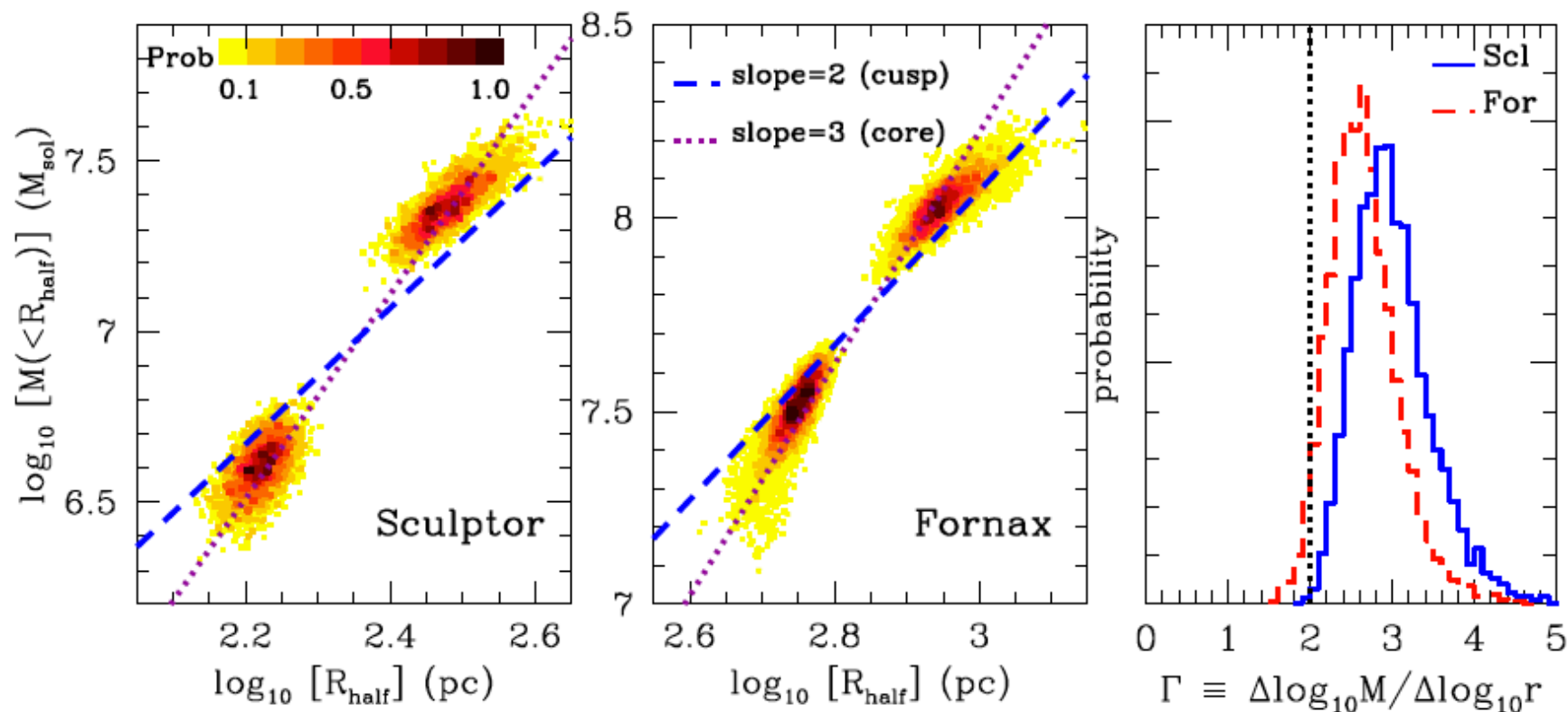
MATTHEW G. WALKER<sup>1,2,3</sup> & JORGE PEÑARRUBIA<sup>2</sup>





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

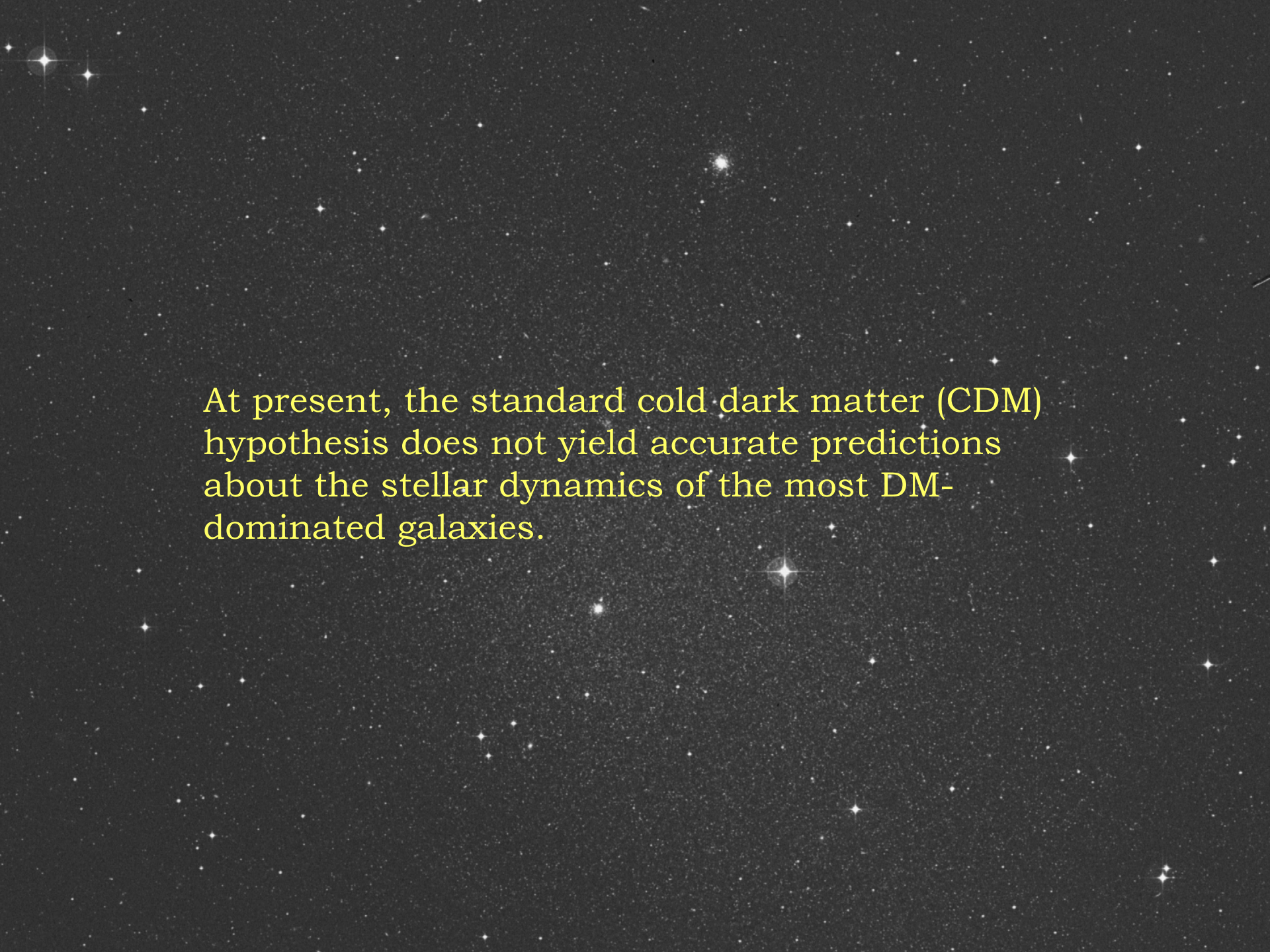
MATTHEW G. WALKER<sup>1,2,3</sup> & JORGE PEÑARRUBIA<sup>2</sup>



Walker & Peñarrubia 2011

$$\Gamma \equiv \frac{\Delta \log M}{\Delta \log r} = \frac{\log[M_2/M_1]}{\log[r_2/r_1]} = 1 + \frac{\log[v_2^2/v_1^2]}{\log[r_2/r_1]}$$





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<sup>1</sup> and Neal Weiner<sup>2,3</sup>

## Subhaloes in Self-Interacting Galactic Dark Matter Haloes

Mark Vogelsberger<sup>1\*</sup>, Jesus Zavala<sup>2,3†</sup>, Abraham Loeb<sup>1</sup>

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

Jesús Zavala<sup>1,2\*</sup>, Mark Vogelsberger<sup>3†</sup> and Matthew G. Walker<sup>3‡</sup>,

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

Miguel Rocha<sup>1\*</sup>, Annika H. G. Peter<sup>1</sup>, James S. Bullock<sup>1</sup>, Manoj Kaplinghat<sup>1</sup>,  
Shea Garrison-Kimmel<sup>1</sup>, Jose Oñorbe<sup>1</sup>, and Leonidas A. Moustakas<sup>2</sup>



# Collisionless ~~Cold~~ Dark Matter

## HALO FORMATION IN WARM DARK MATTER MODELS

PAUL BODE AND JEREMIAH P. OSTRICKER  
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<sup>1\*</sup>, Vincent Eke<sup>1</sup>, Carlos S. Frenk<sup>1</sup>, Liang Gao<sup>2,1</sup>, Adrian Jenkins<sup>1</sup>, Tom Theuns<sup>1,3</sup>, Jie Wang<sup>1</sup>, Simon D. M. White<sup>4</sup>, Alexey Boyarsky<sup>5,6</sup>,

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

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

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

Daniel Boyanovsky<sup>1,\*</sup>

## Cores in warm dark matter haloes: a *Catch 22* problem

Andrea V. Macciò<sup>1\*</sup>, Sinziana Paduroiu<sup>2</sup>, Donnino Anderhalden<sup>3</sup>  
Aurel Schneider<sup>3</sup>, Ben Moore<sup>3</sup>

## The Galactic Halo in Mixed Dark Matter Cosmologies

D. Anderhalden<sup>a</sup> J. Diemand<sup>a</sup> G. Bertone<sup>b</sup>  
A. V. Macciò<sup>c</sup> A. Schneider<sup>a</sup>



# Collisionless Cold Dark Matter (+ baryons?)

## How supernova feedback turns dark matter cusps into cores

Andrew Pontzen<sup>1,2,3\*</sup>, Fabio Governato<sup>4</sup>

## WHY BARYONS MATTER: THE KINEMATICS OF DWARF SPHEROIDAL SATELLITES

ALYSON M. BROOKS<sup>1</sup>, ADI ZOLOTOV<sup>2</sup>

## 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<sup>1</sup>, H. M. P. Couchman<sup>1</sup> & James Wadsley<sup>1</sup>

## Cusp-core transformations in dwarf galaxies: observational predictions

Romain Teyssier<sup>1,4\*</sup>, Andrew Pontzen<sup>2</sup>, Yohan Dubois<sup>3</sup> and Justin I. Read<sup>5,6</sup>

## Cuspy No More: How Outflows Affect the Central Dark Matter and Baryon Distribution in $\Lambda$ CDM Galaxies.

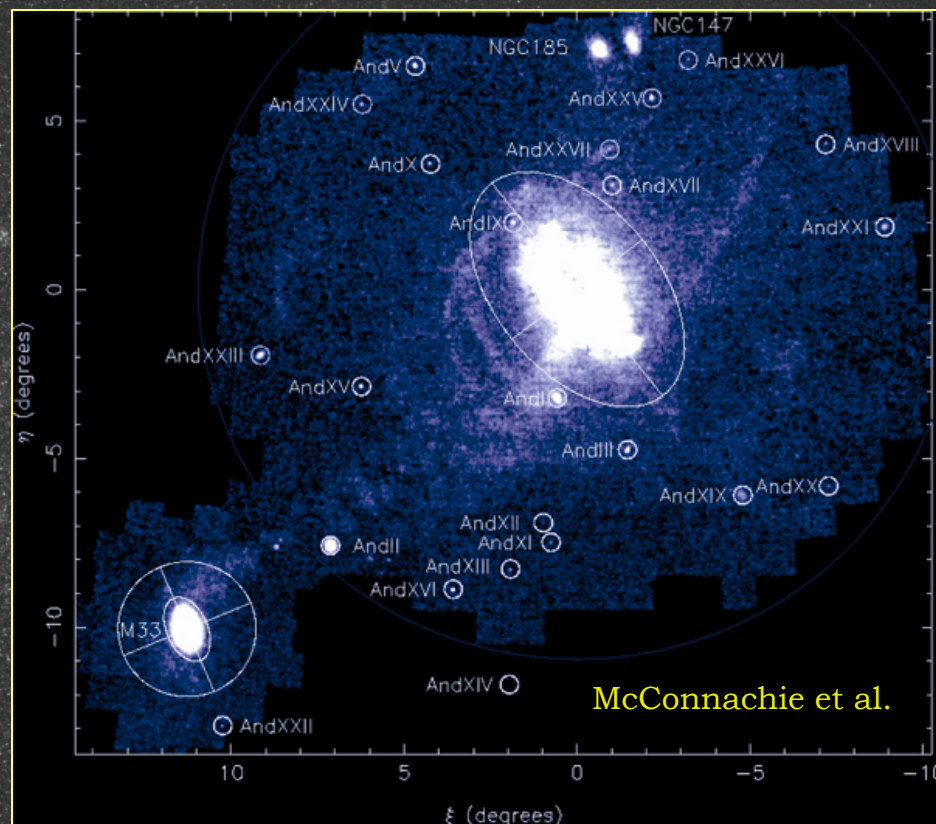
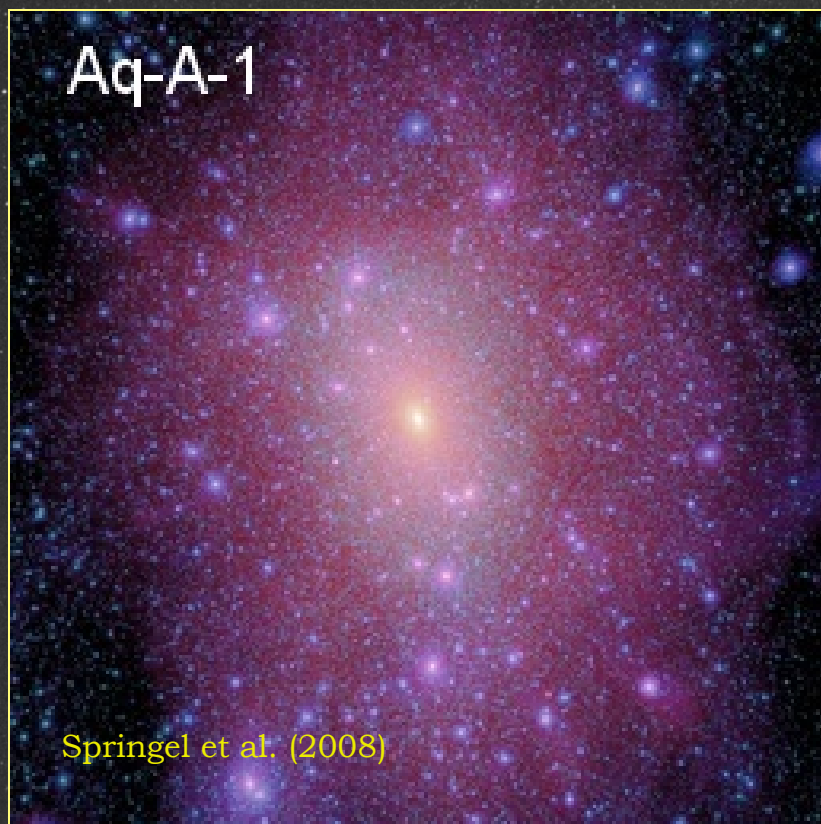
F.Governato<sup>1\*</sup>, A.Zolotov<sup>2</sup>, A.Pontzen<sup>3</sup>, C.Christensen<sup>4</sup>, S.H.Oh<sup>5,6</sup>, A.M.Brooks<sup>7</sup>, T.Quinn<sup>1</sup>, S.Shen<sup>8</sup>, J.Wadsley<sup>9</sup>



# THE COUPLING BETWEEN THE CORE/CUSP AND MISSING SATELLITE PROBLEMS

JORGE PEÑARRUBIA<sup>1,2</sup>, ANDREW PONTZEN<sup>3</sup>, MATTHEW G. WALKER<sup>4</sup> & SERGEY E. KOPOSOV<sup>2,5</sup>

*Draft version July 13, 2012*





# THE COUPLING BETWEEN THE CORE/CUSP AND MISSING SATELLITE PROBLEMS

JORGE PEÑARRUBIA<sup>1,2</sup>, ANDREW PONTZEN<sup>3</sup>, MATTHEW G. WALKER<sup>4</sup> & SERGEY E. KOPOSOV<sup>2,5</sup>

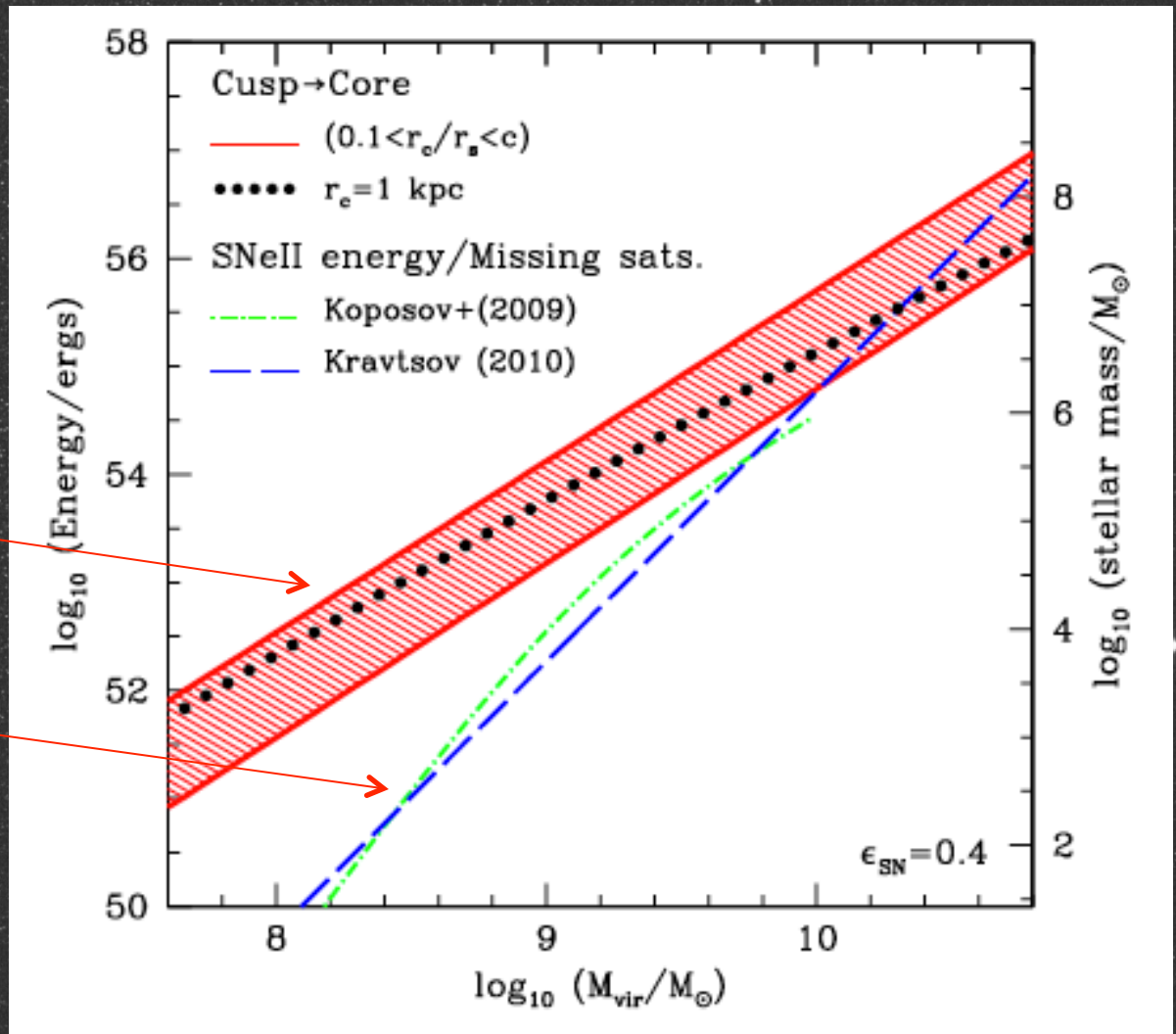
*Draft version July 13, 2012*

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

Energetics

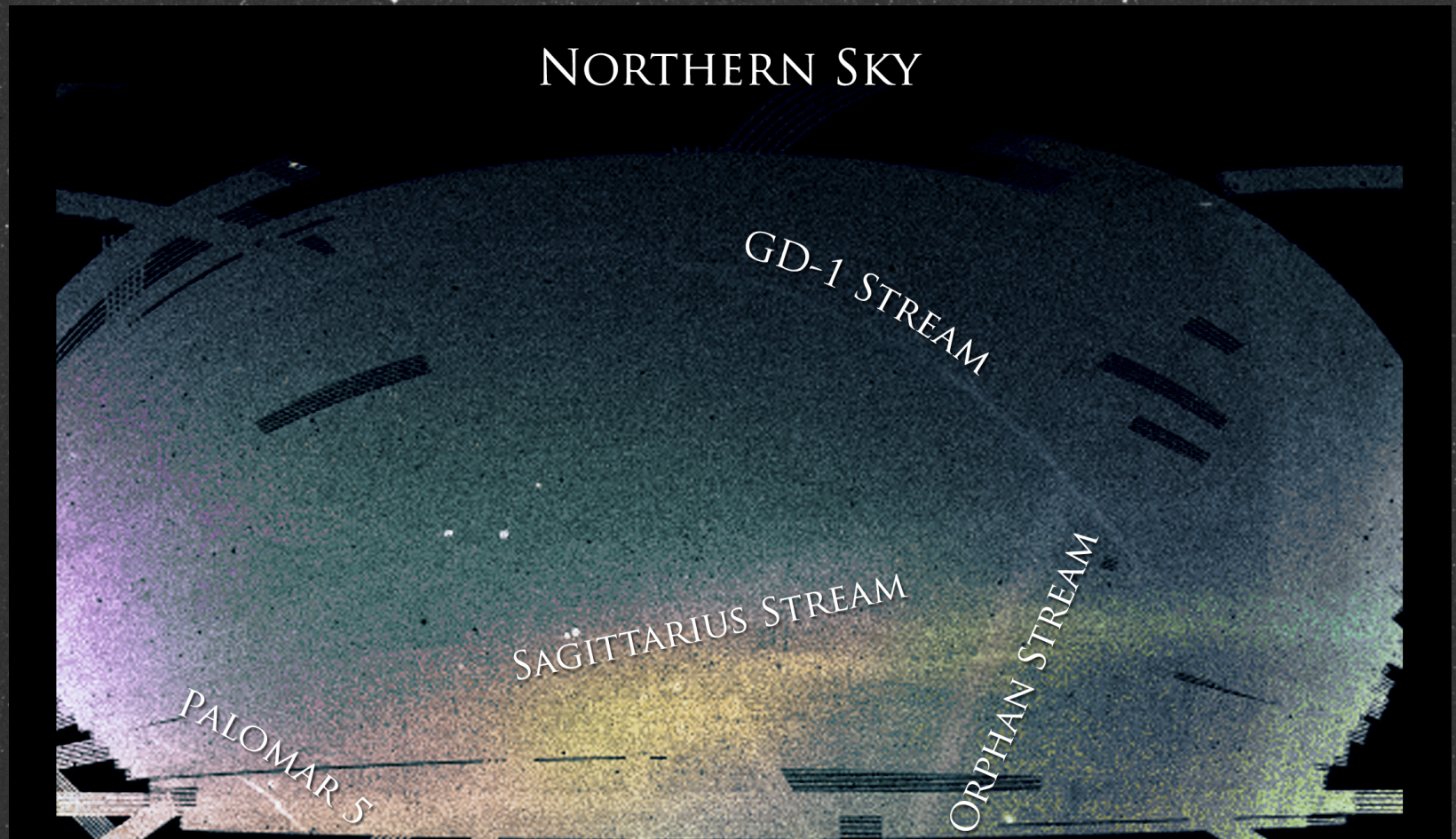
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FUTURE WORK - Streams in the Galactic halo:  
→ The *Primordial* Luminosity Function

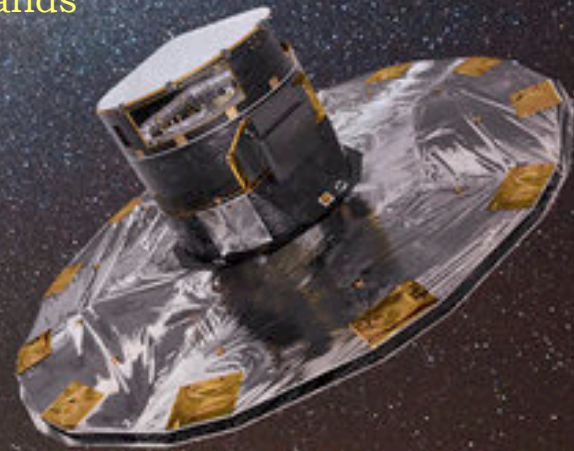




# FUTURE WORK - Streams in the Galactic halo: → The *Primordial* Luminosity Function

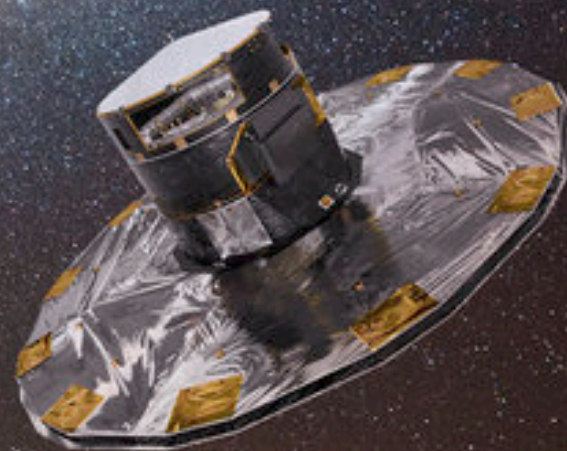
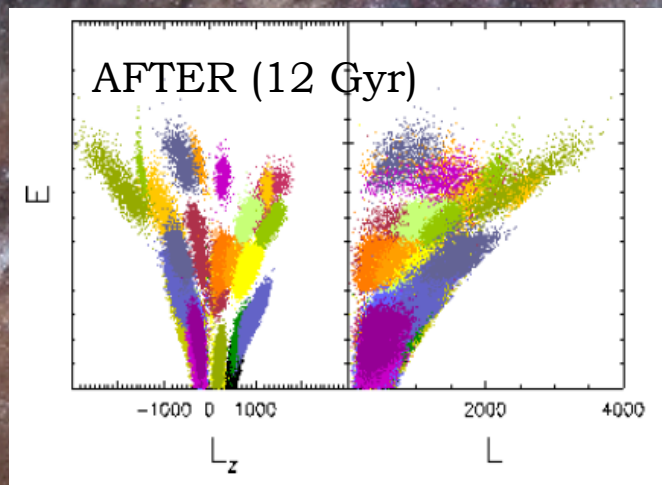
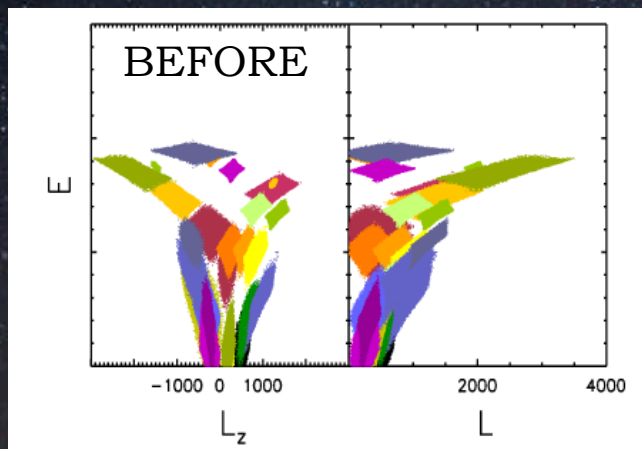
## Gaia

- launch: Aug 2013
- catalog:  $10^9$  stars to  $V \sim 20$
- parallax:  $4 \mu\text{as}$  at  $V \sim 10$ ,  $160 \mu\text{as}$  at  $V \sim 20$
- distance: 1% for  $10^6$  stars, 10% for  $10^8$  stars
- proper motions:  $0.5 \text{ km/s}$  for  $10^7$  stars
- radial velocities:  $1\text{-}10 \text{ km/s}$  for  $V \sim 16\text{-}17$
- photometry:  $V \sim 20$  in 4 broad bands, 11 medium bands
- ~300,000 asteroids, many(?) near-earth objects





# FUTURE WORK - Streams in the Galactic halo: → The *Primordial* Luminosity Function



Helmi & de Zeeuw (2000)



# Conclusions

- Galactic dynamics has implications for particle physics.
- CDM model needs rescuing by baryon physics.
  - efficient star formation to alter halo structure
  - inefficient star formation to suppress low-mass galaxies
- 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?



$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \Delta\Omega) = \Phi^{\text{pp}}(E_\gamma) \times J(\Delta\Omega) = 0.$$

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

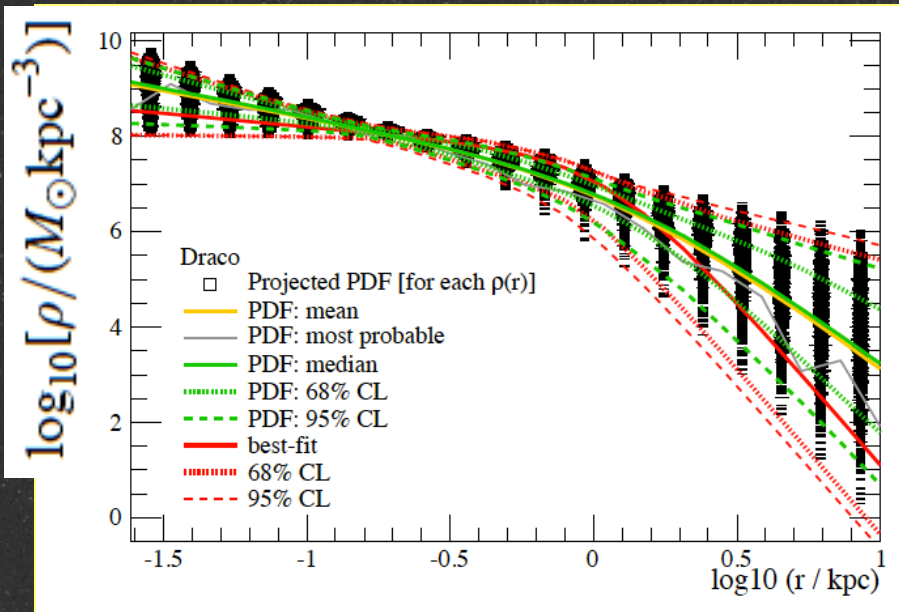
$$J = \int_{\Delta\Omega} \int \rho_{\text{DM}}^2(l, \Omega) dl d\Omega.$$



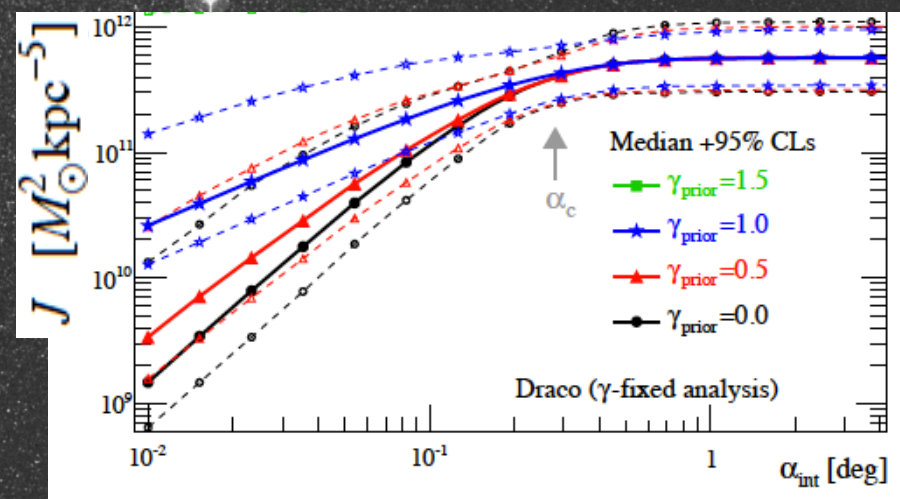
# J from stellar kinematics

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

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

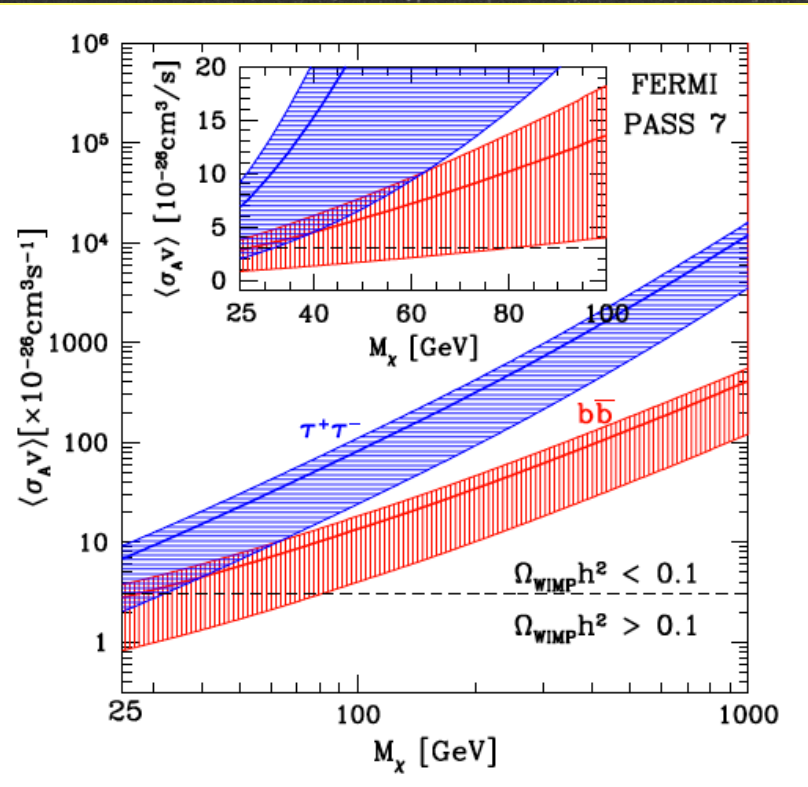


Charbonnier et al. (arXiv:1104.0412)

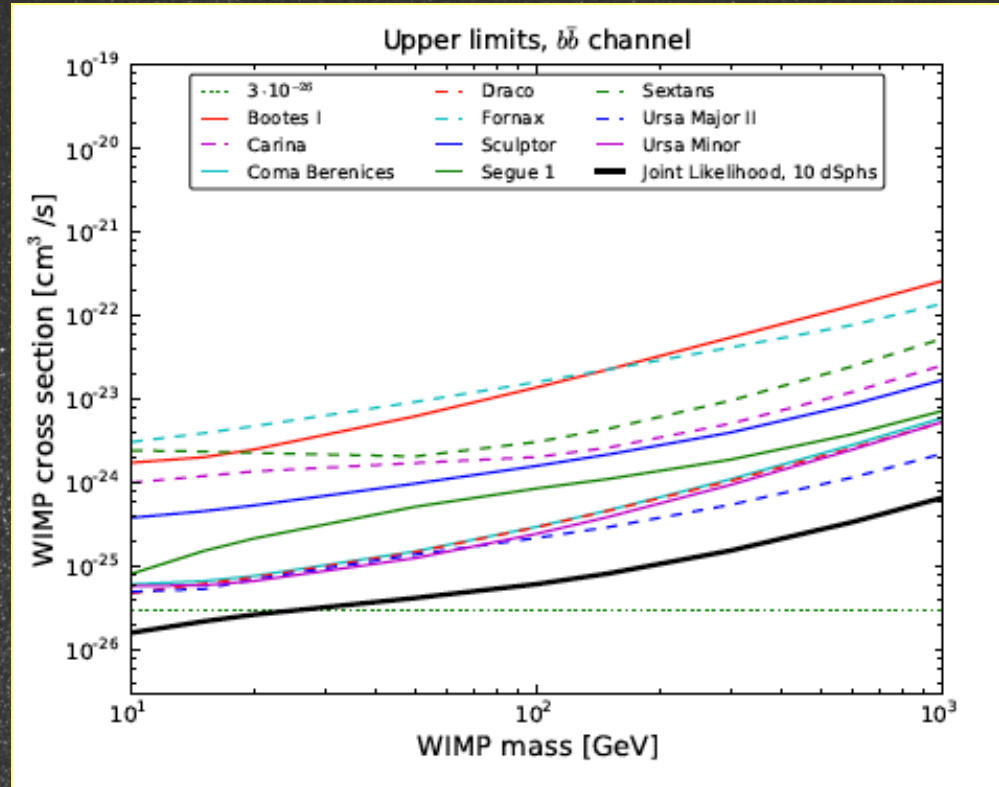




# published constraints from Fermi non-detections



Geringer-Sameth & Koushiappas (arXiv:1108.2914)



Fermi Collaboration (arXiv:1108.3546)



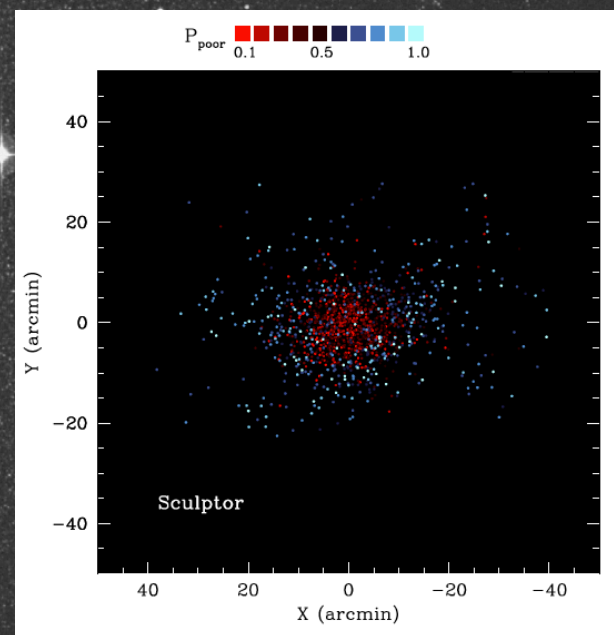
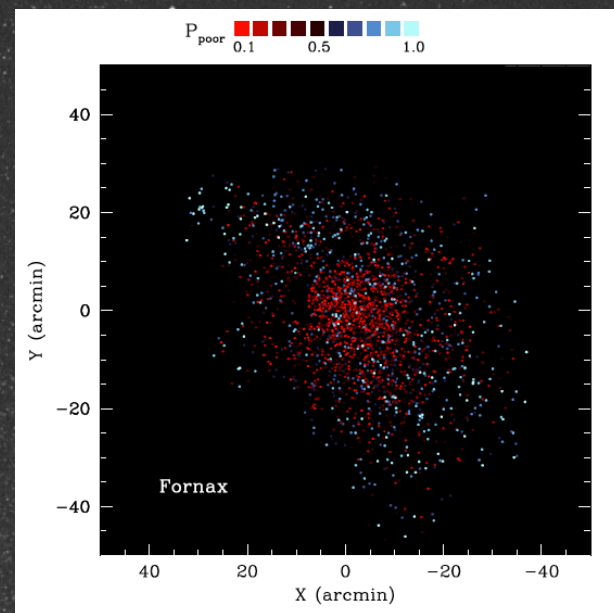
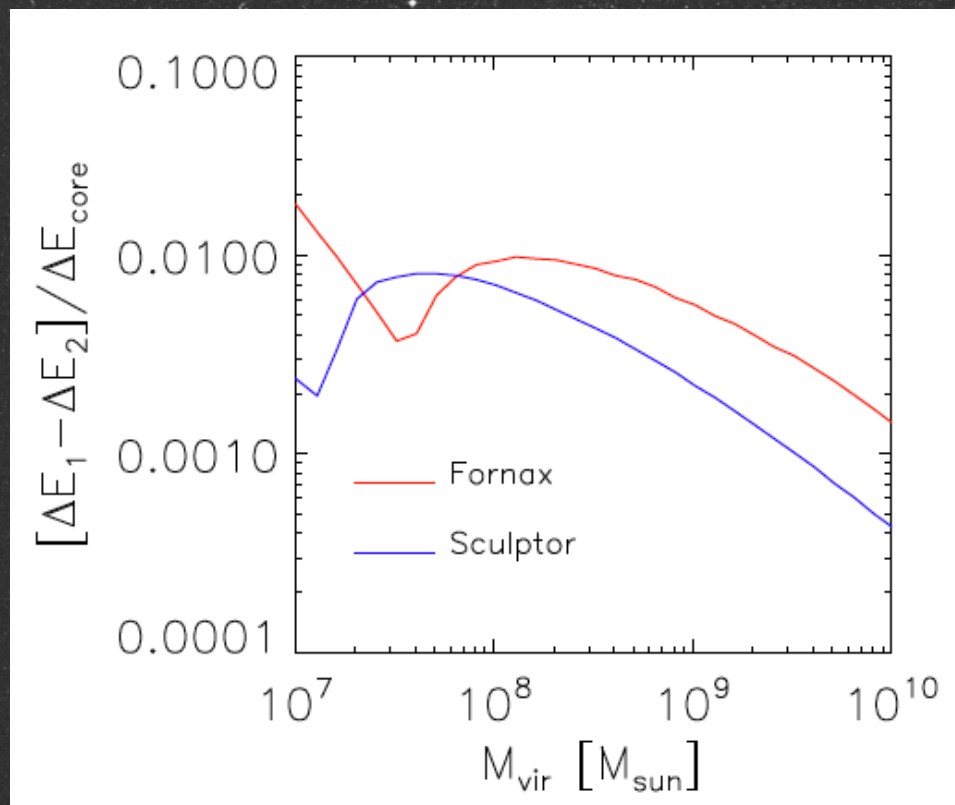
# How to improve particle physics limits?

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







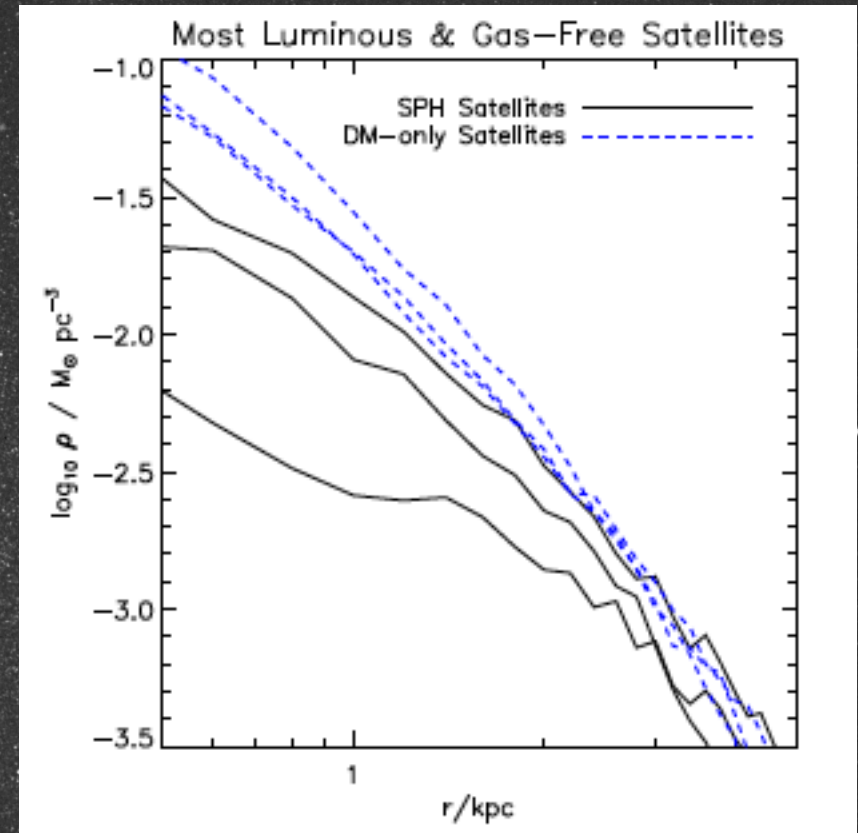
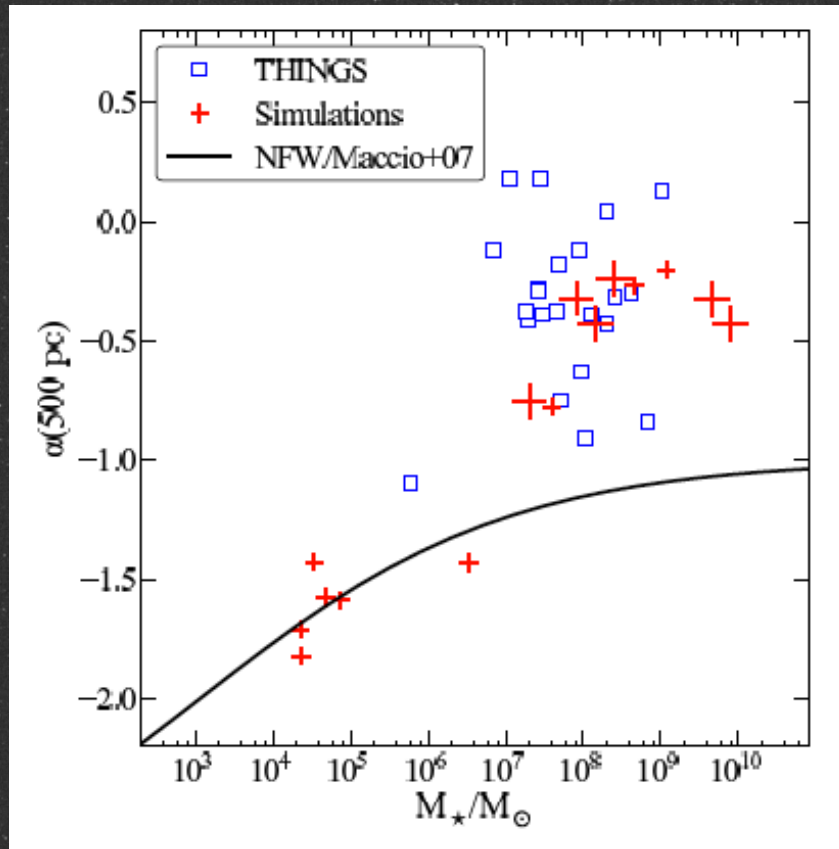




# BARYONS MATTER: WHY LUMINOUS SATELLITE GALAXIES HAVE REDUCED CENTRAL MASSES

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

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



## Cuspy No More: How Outflows Affect the Central Dark Matter and Baryon Distribution in $\Lambda$ CDM Galaxies.

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

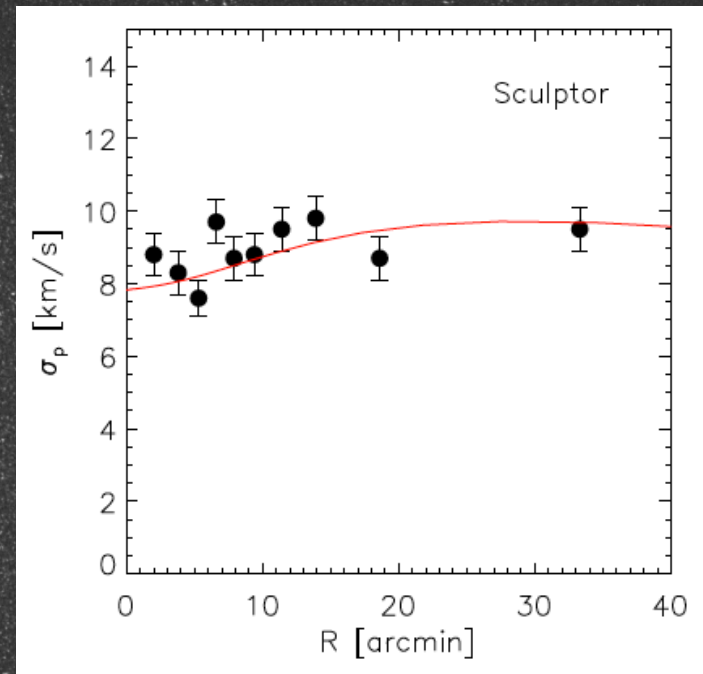
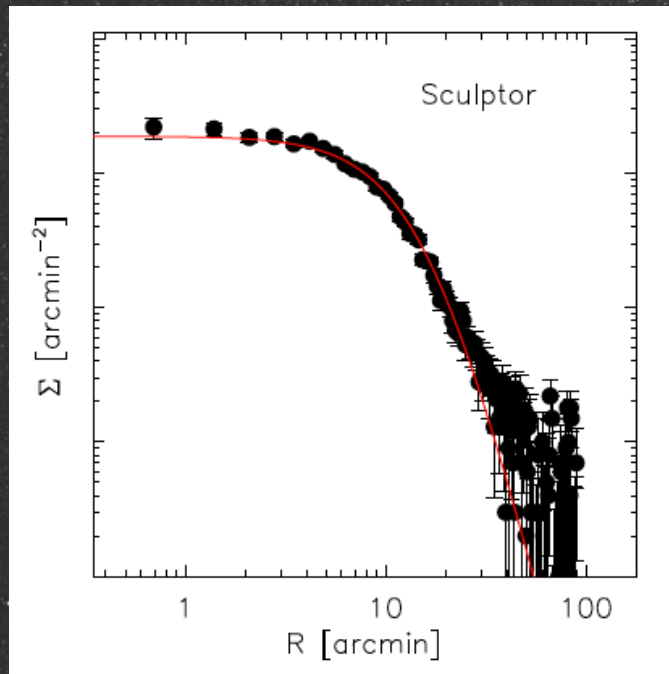


# J from stellar kinematics

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

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

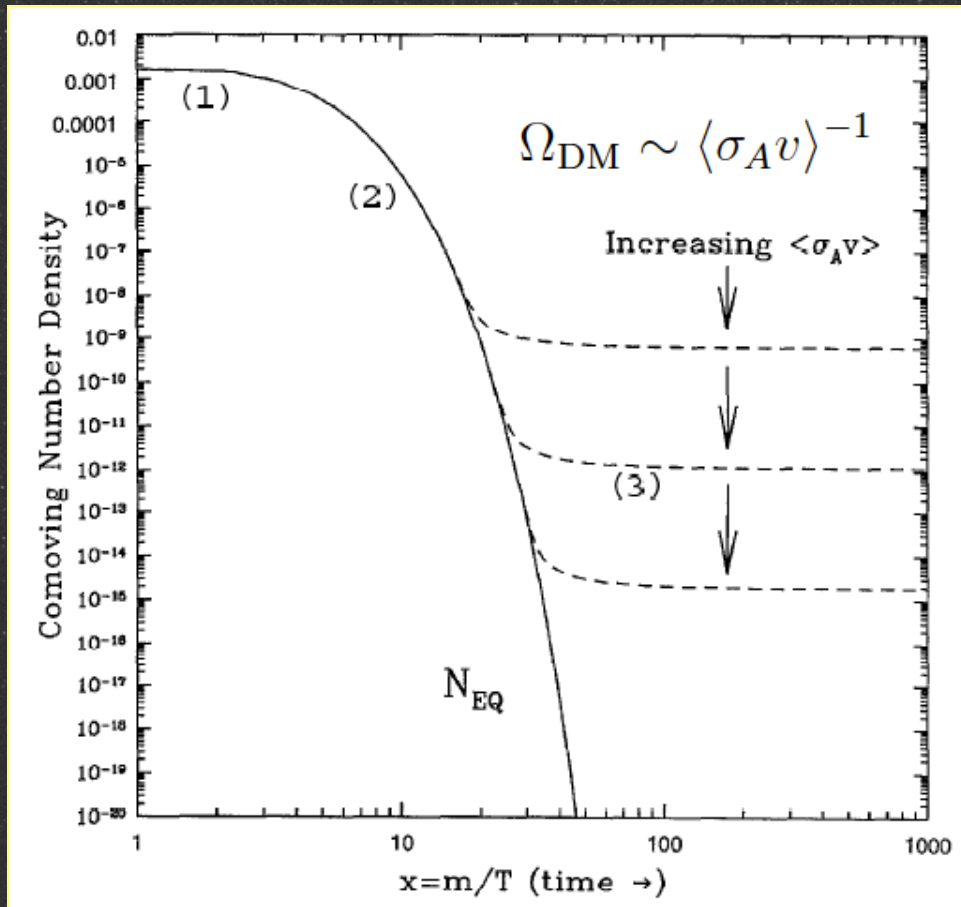
$$\rho(r) = \rho_0 \left(\frac{r}{r_0}\right)^{-\gamma} \left[1 + \left(\frac{r}{r_0}\right)^\alpha\right]^{\frac{\gamma-\eta}{\alpha}}$$



## Assumptions:

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

# WIMPs

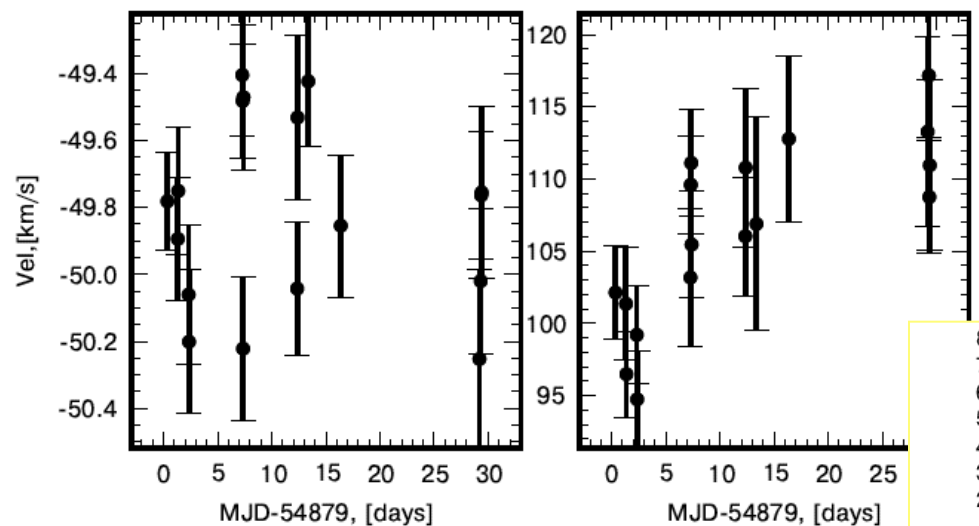


$$\sigma_A v = k \frac{4\pi\alpha_1^2}{m_\chi^2}$$

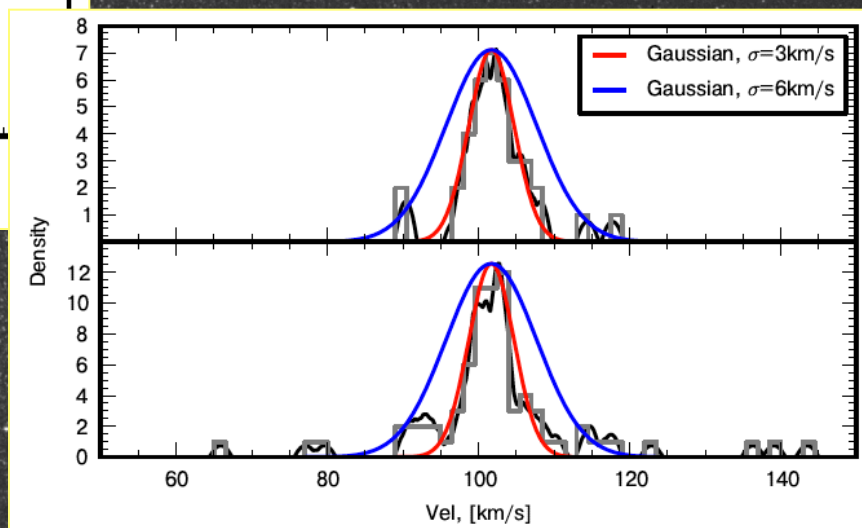
Jungman, Kamionkowski & Griest (1996)



# 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<sup>1,2</sup> & JORGE PEÑARRUBIA<sup>3</sup>

