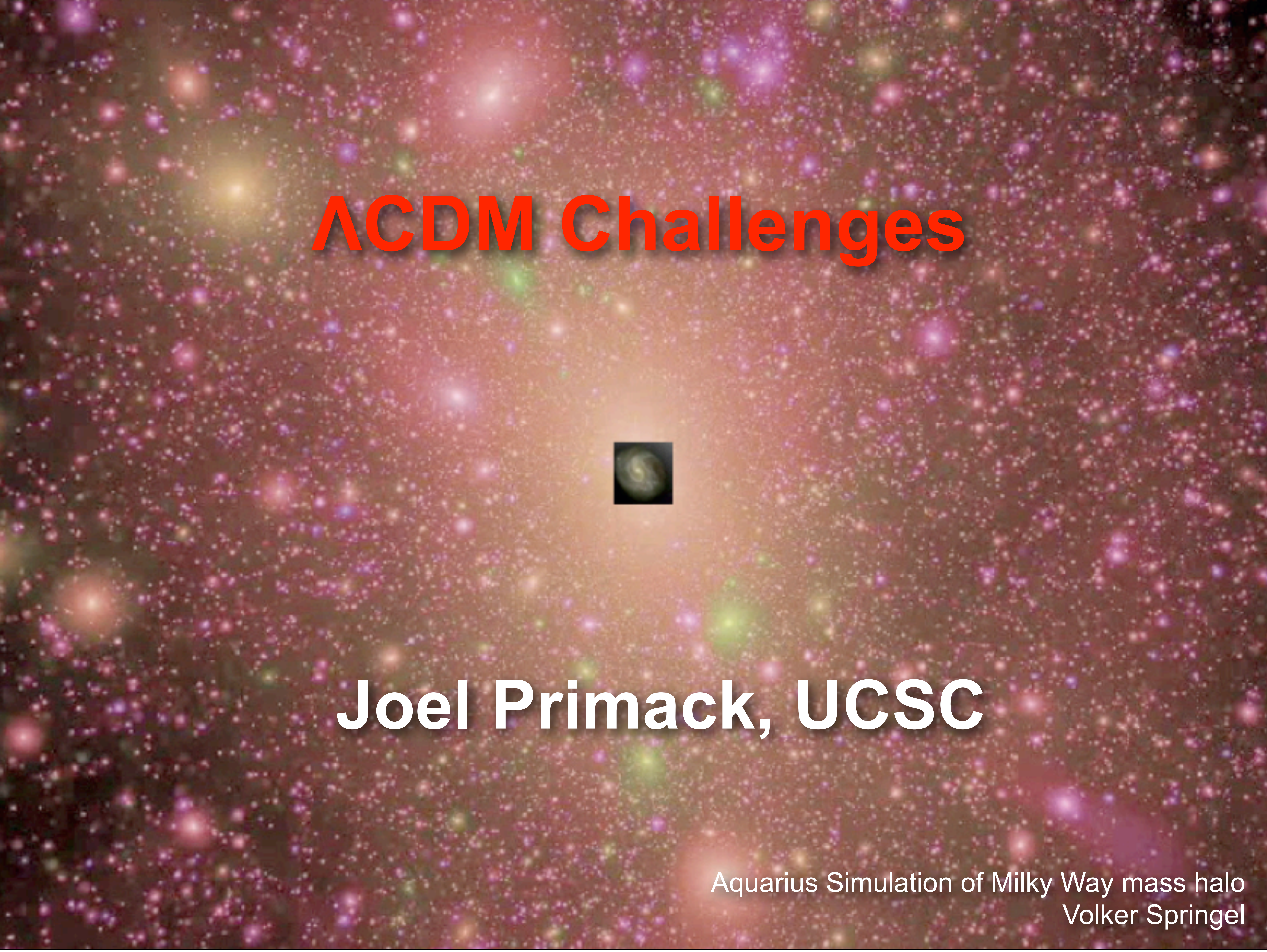
ΛCDM Challenges

Joel Primack, UCSC



Aquarius Simulation of Milky Way mass halo
Volker Springel

Ann. Phys. (Berlin) 524, No. 9–10, 535–544 (2012) / DOI 10.1002/andp.201200077

Special Issue
on Dark Matter

annalen der physik

Review Article

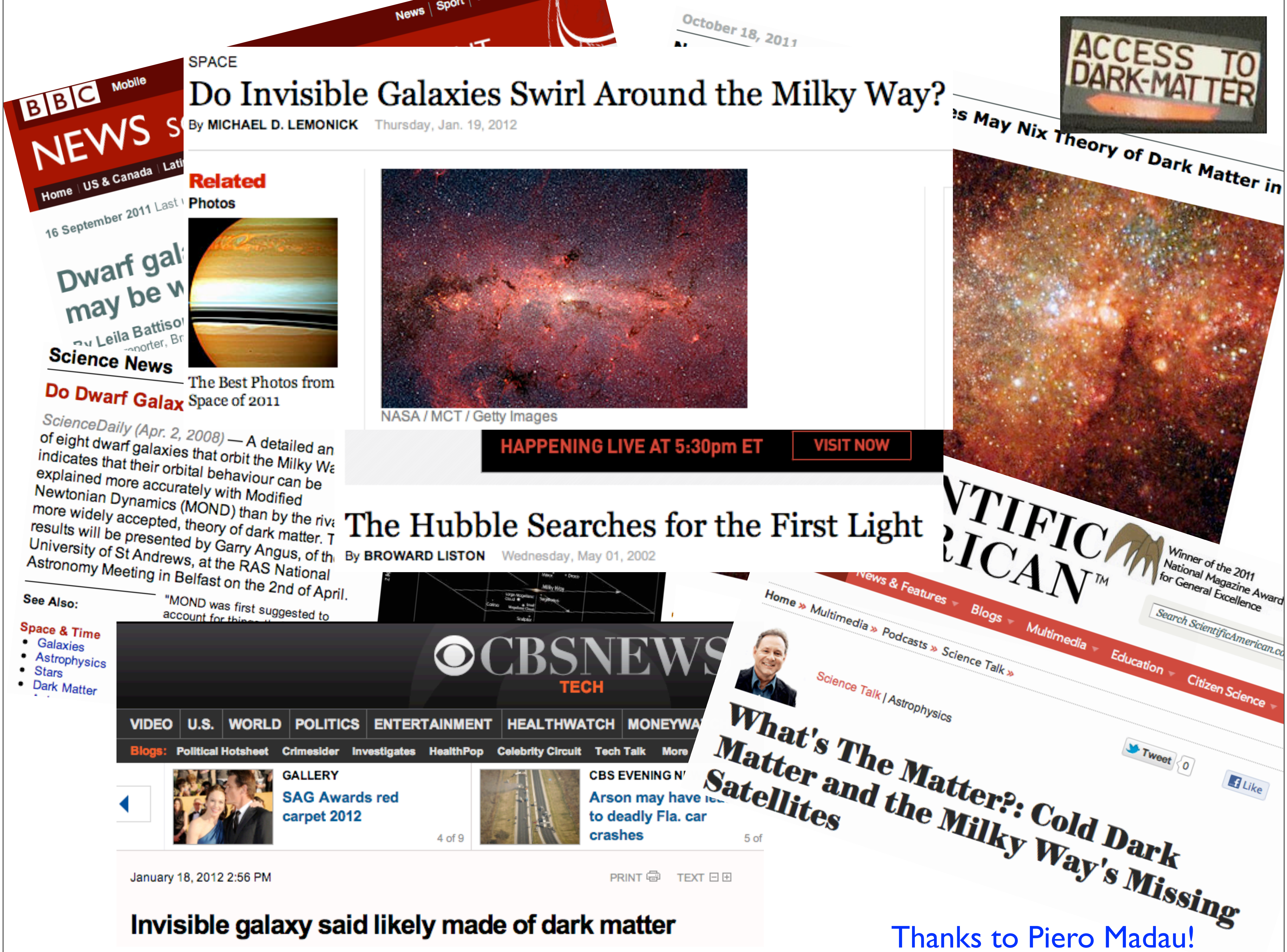
Triumphs and tribulations of ΛCDM, the double dark theory

Joel R. Primack *

goo.gl/TFDYf

Received 1 April 2012, revised 8 May 2012, accepted 23 May 2012
Published online 5 July 2012

ΛCDM has become the standard cosmological model because its predictions agree so well with observations of the cosmic microwave background and the large-scale structure of the universe. However ΛCDM has faced challenges on smaller scales. Some of these challenges, including the "angular momentum catastrophe" and the absence of density cusps in the centers of small galaxies, may be overcome with improvements in simulation resolution and feedback. Recent simulations appear to form realistic galaxies in agreement with observed scaling relations. Although dark matter halos start small and grow by accretion, the existence of a star-forming band of halo masses naturally explains why the most massive galaxies have the oldest stars, a phenomenon known as known as galactic "downsizing." The discovery of many faint galaxies in the Local Group is consistent with ΛCDM predictions, as is the increasing evidence for substructure in galaxy dark matter halos from gravitational lensing flux anomalies and gaps in cold stellar streams. However, the "too big to fail" (TBTF) problem challenges ΛCDM. It arose from analysis of the Acquarius and Via Lactea very high-resolution ΛCDM simulations of dark matter halos like that of the Milky Way. Each simulated halo has ~ 10 subhalos that were so massive and dense that they would appear to be too big to fail to form lots of stars. The TBTF problem is that none of the observed satellite galaxies of the Milky Way or Andromeda have stars moving as fast as would be expected in these densest subhalos. This may indicate the need for a more complex theory of dark matter – or perhaps just better understanding of dark matter simulations and/or baryonic physics.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Dwarf gal
may be w
By Leila Battiso
reporter, Br
Science News
Do Dwarf Galax
ScienceDaily (Apr. 2, 2008) — A detailed an of eight dwarf galaxies that orbit the Milky Wa indicates that their orbital behaviour can be explained more accurately with Modified Newtonian Dynamics (MOND) than by the riva more widely accepted, theory of dark matter. T results will be presented by Garry Angus, of th University of St Andrews, at the RAS National Astronomy Meeting in Belfast on the 2nd of April.
See Also:
"MOND was first suggested to account for thin
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Thanks to Piero Madau!

small scale issues

Angular momentum

The Eris simulation shows that ΛCDM simulations are increasingly able to form realistic spiral galaxies, as resolution improves and feedback becomes more realistic.

Cusps

WDM doesn't resolve cusp issues. New observations and simulations suggest that velocity structure of LSB, dSp, and dSph galaxies may be consistent with cuspy ΛCDM halos.

Satellites and Subhalos

The discovery of many faint Local Group dwarf galaxies is consistent with ΛCDM predictions. Lensing flux anomalies gaps in stellar streams require the substructure predicted by CDM. But the "too big to fail" problem needs solution.

Can ΛCDM Simulations Form Realistic Galaxies?

The Angular Momentum Catastrophe

Cooling was too effective particularly in low-mass halos at early times.

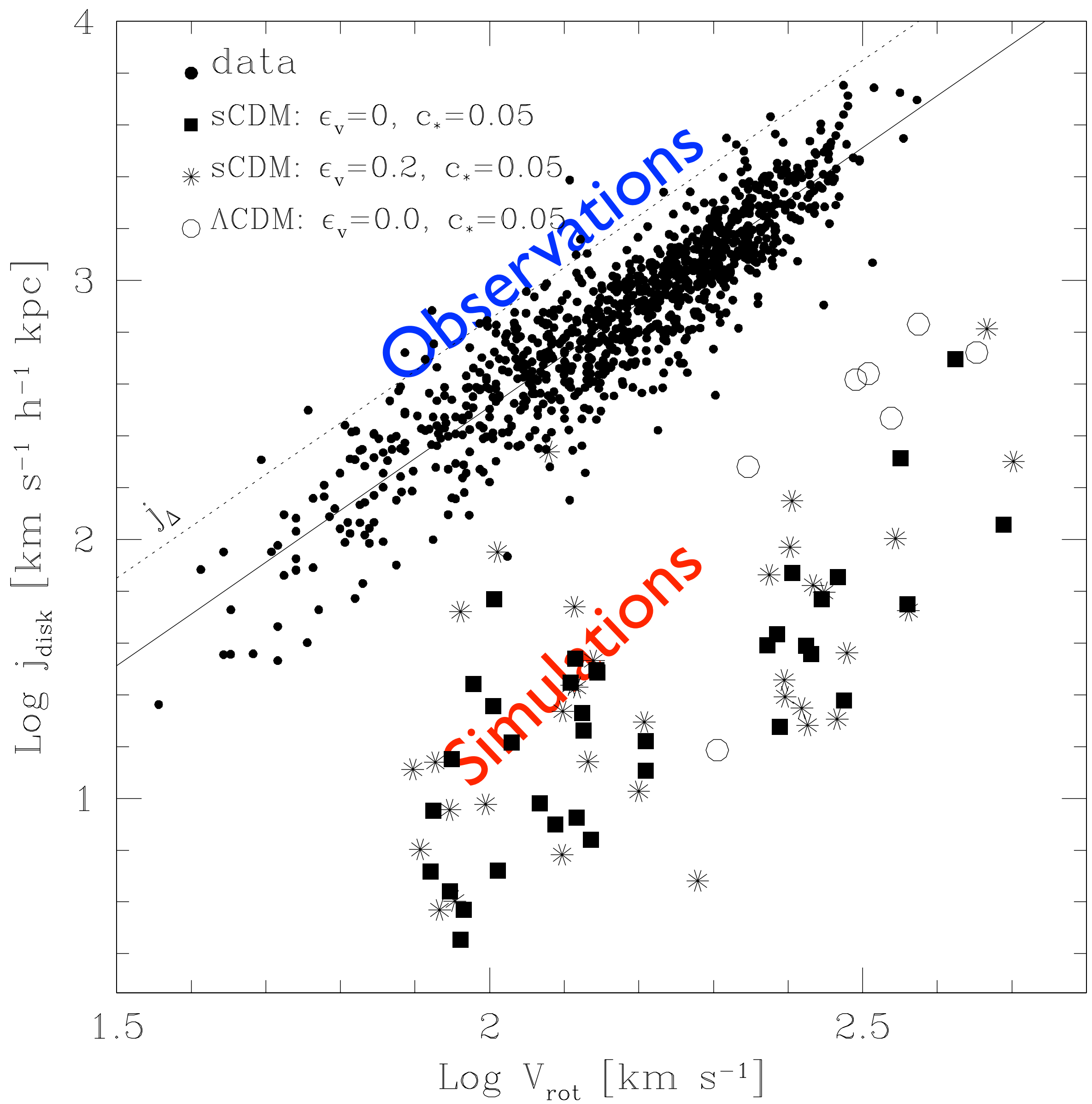


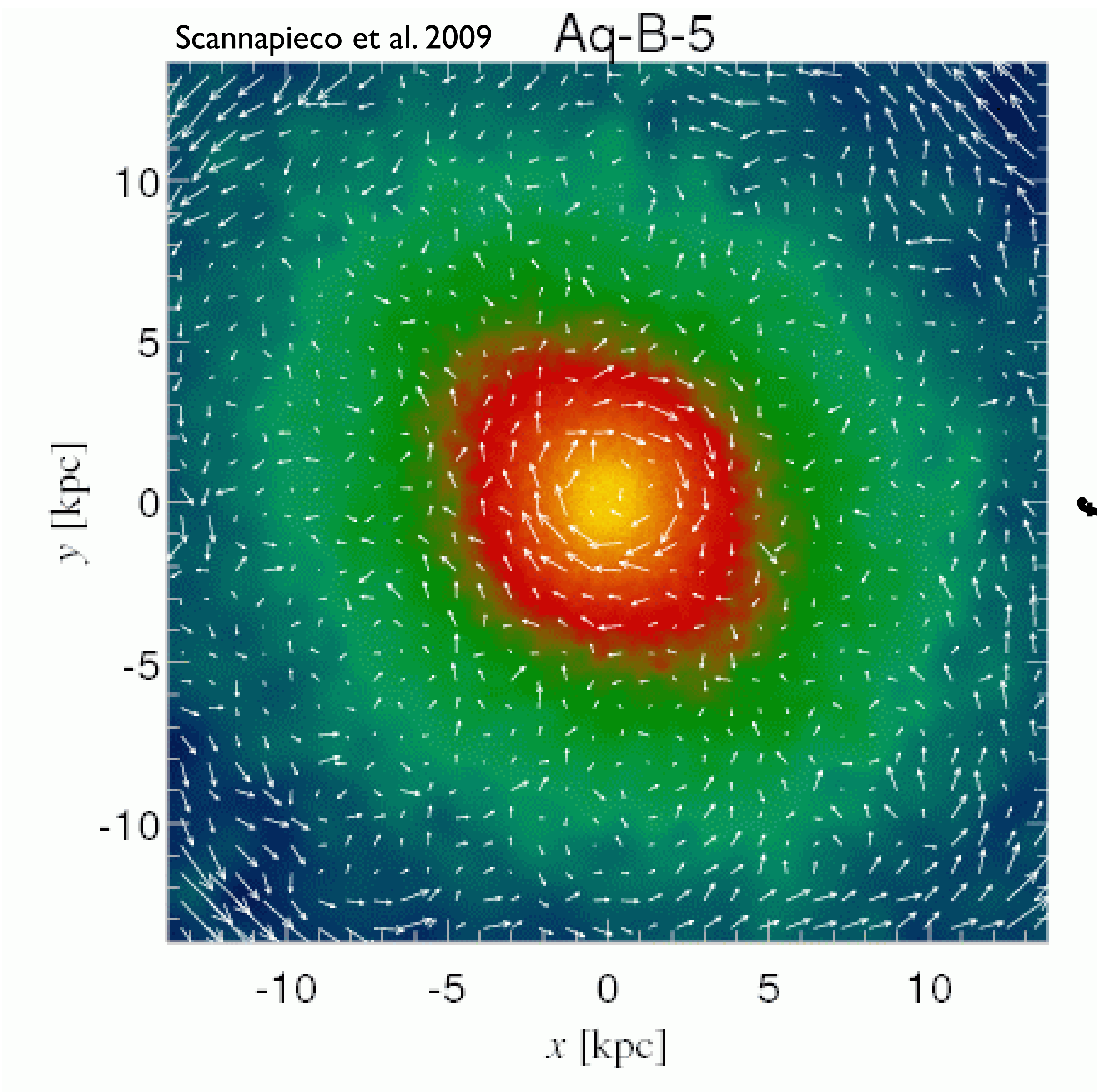
FIG. 3.—Specific angular momentum vs. circular velocity of model galaxies compared with observational data. Data correspond to the samples of Courteau (1997), Mathewson et al. (1992), and the compilation of Navarro (2000). Specific angular momenta are computed from disk scale lengths and rotation speeds, assuming an exponential disk model with a flat rotation curve.

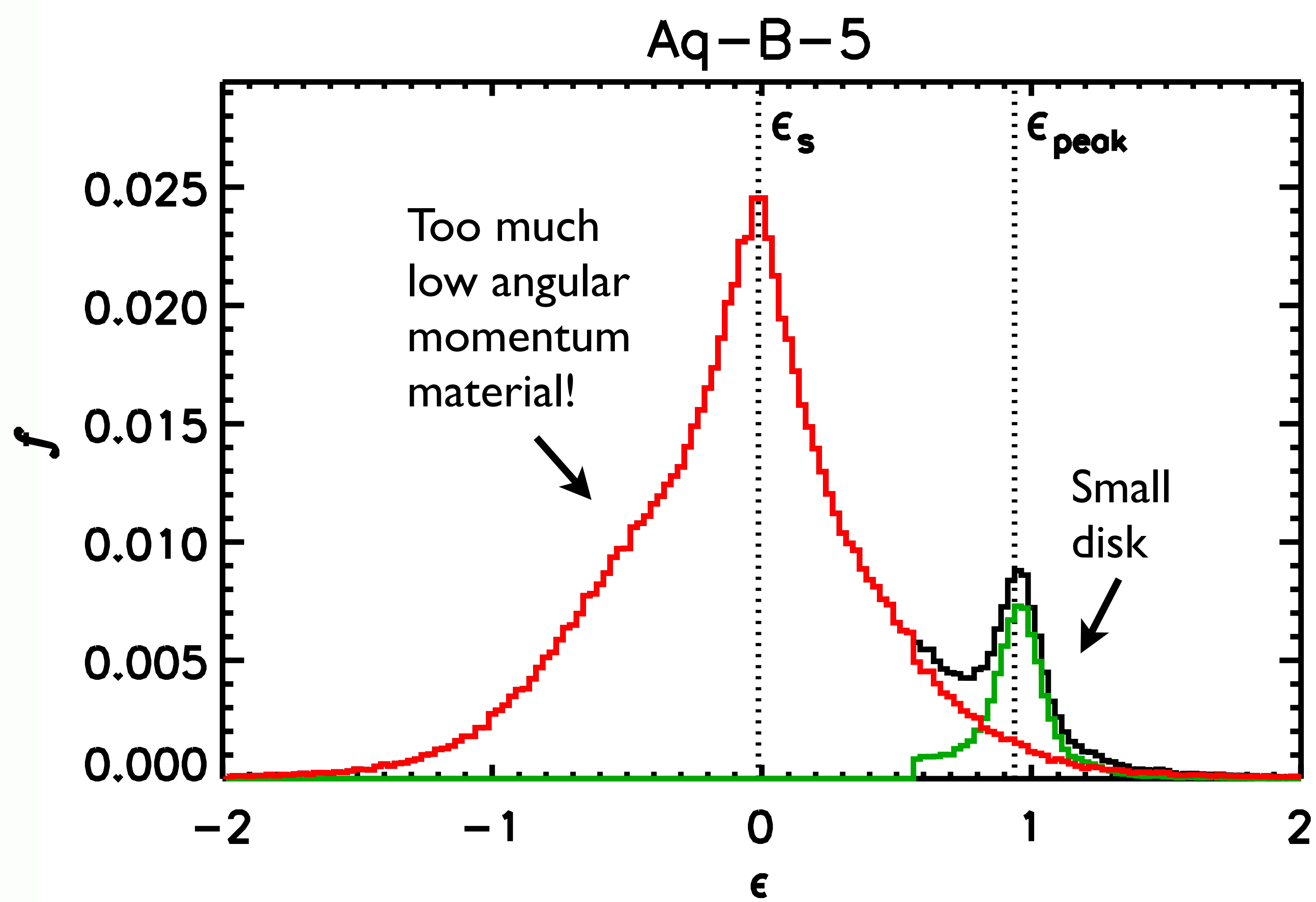
"Agreement between model and observations appears to demand substantial <u>revision to the CDM scenario or to the manner in which baryons are thought to assemble</u> and evolve into galaxies in hierarchical universes."

Navarro & Steinmetz 2000 ApJ

The Angular Momentum Catastrophe

In practice it is not trivial to form galaxies with massive, extended disks and small spheroids.
The angular momentum content of the disk determined its final structure.





Javiera Guedes

The Angular Momentum Catastrophe

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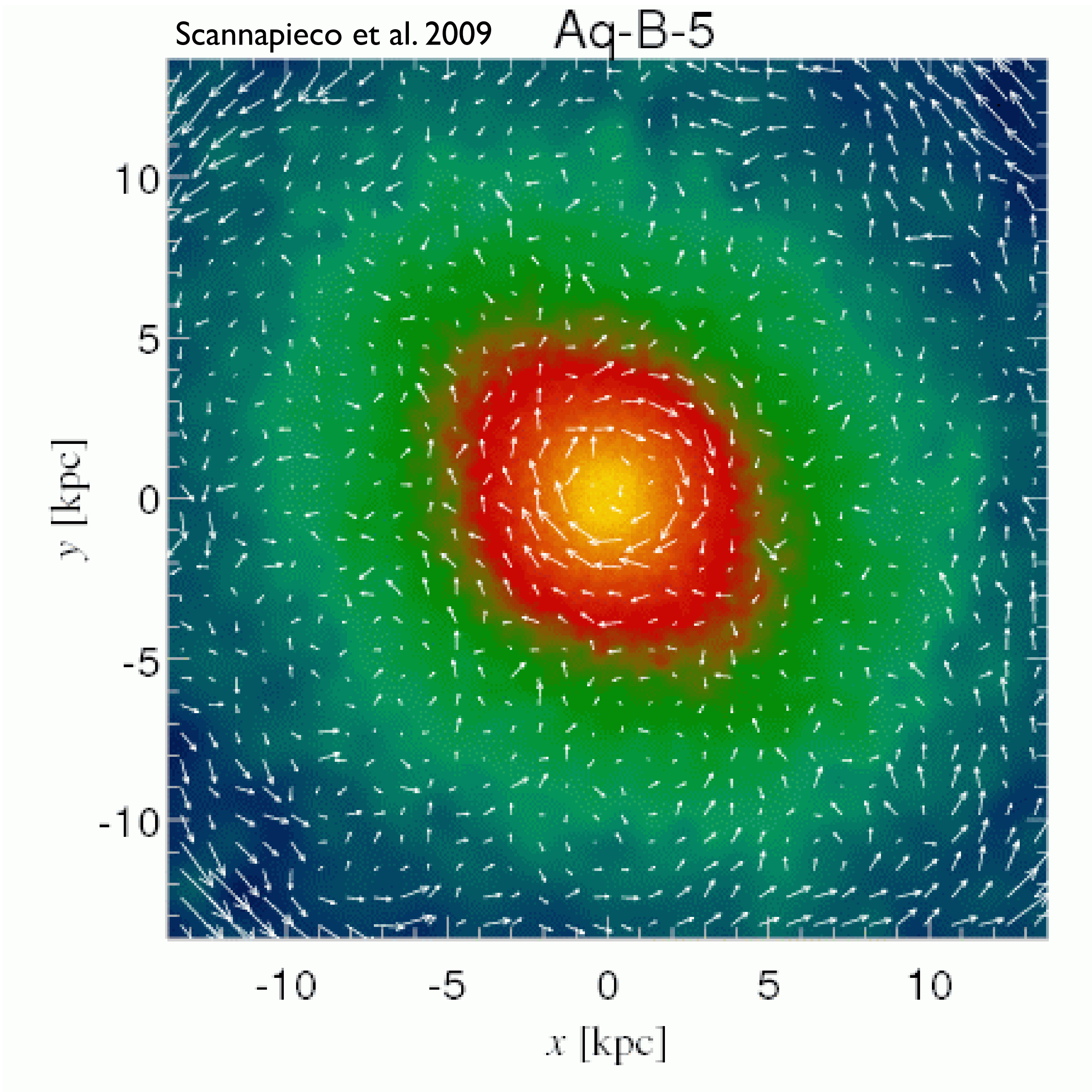

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Solution: Stop cooling via SN feedback, AGN, preheating, etc.

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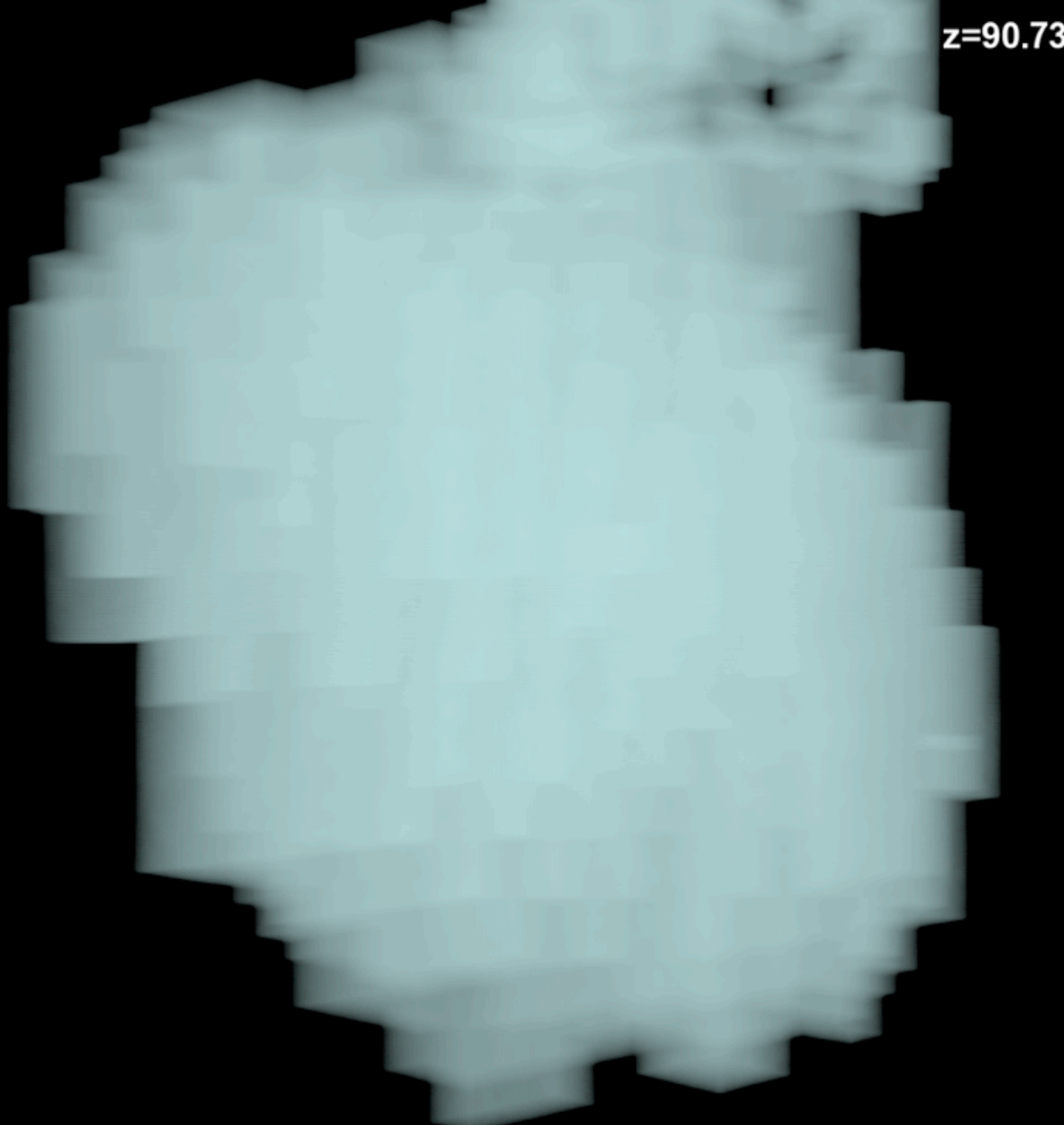
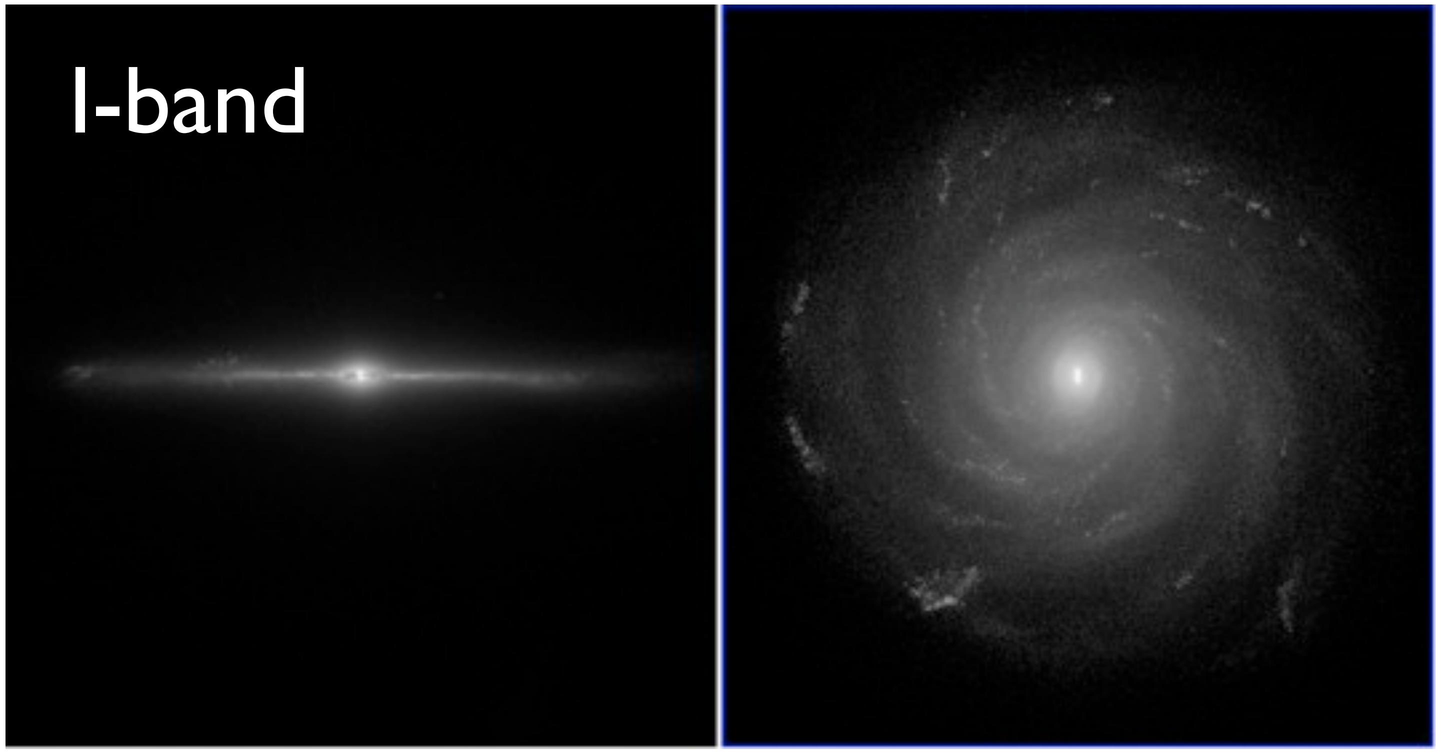
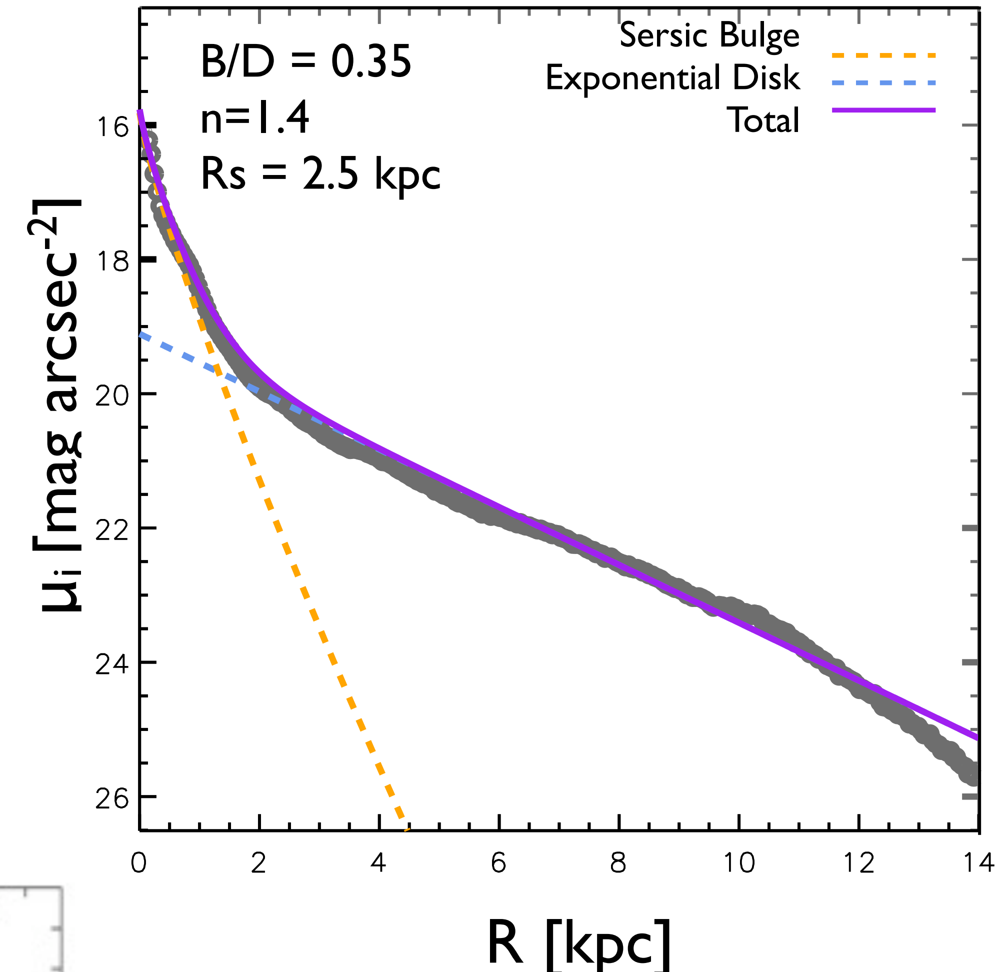


Eris

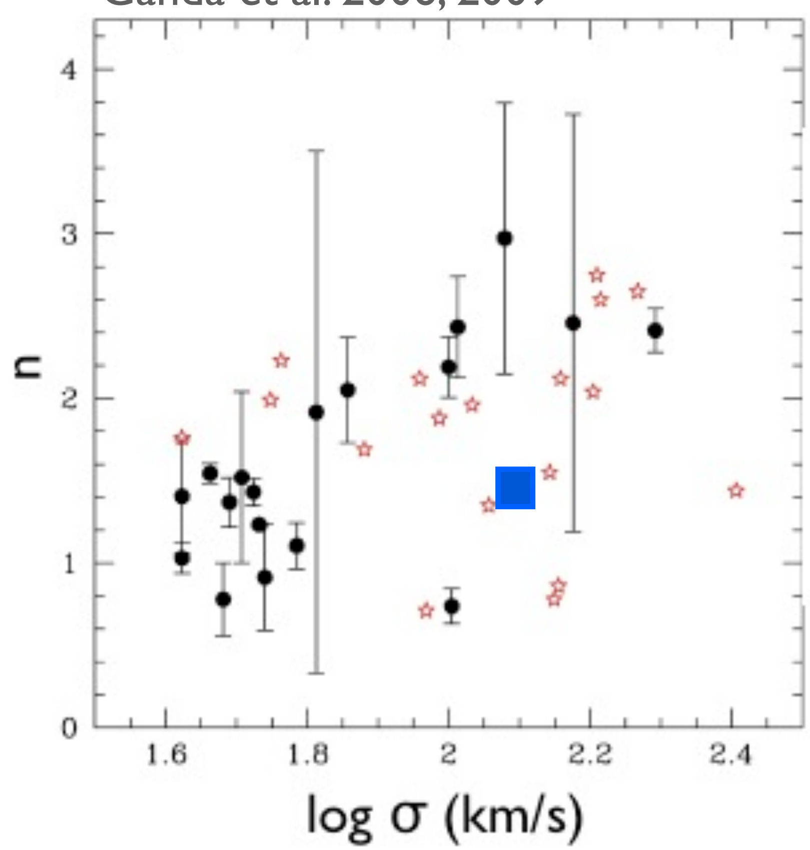
Simulation
Guedes et al.

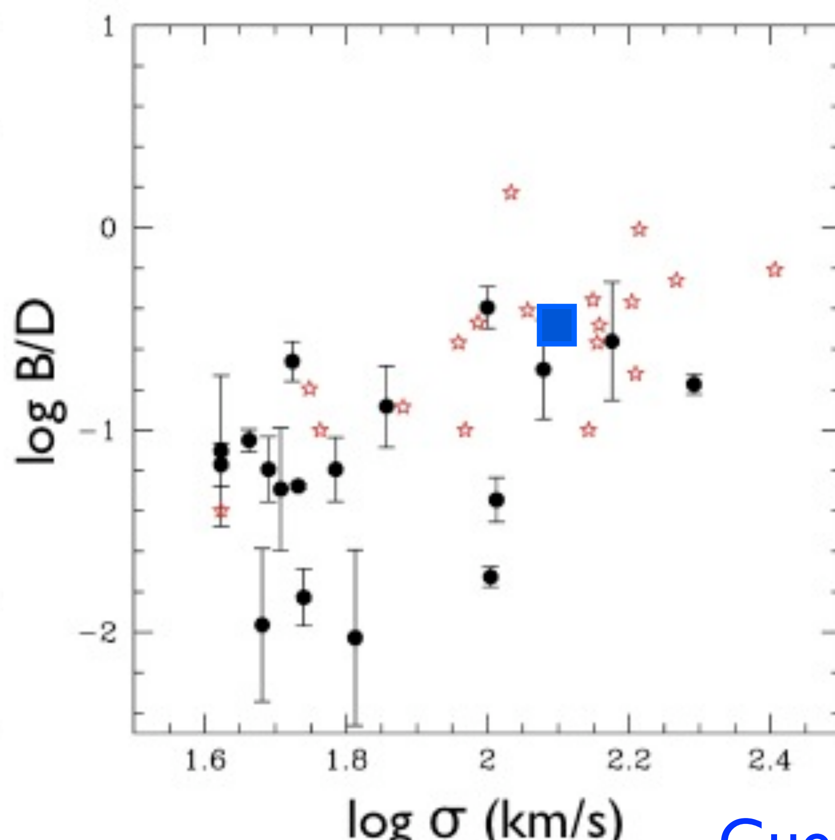
Structural Properties: Eris Bulge-to-Disk Ratio





Ganda et al. 2006, 2009





Photometric decomposition in i-band using Galfit (Peng et al. 2002)

- ● Late-type spirals
- ☆ Early-type spirals
- ■ Eris

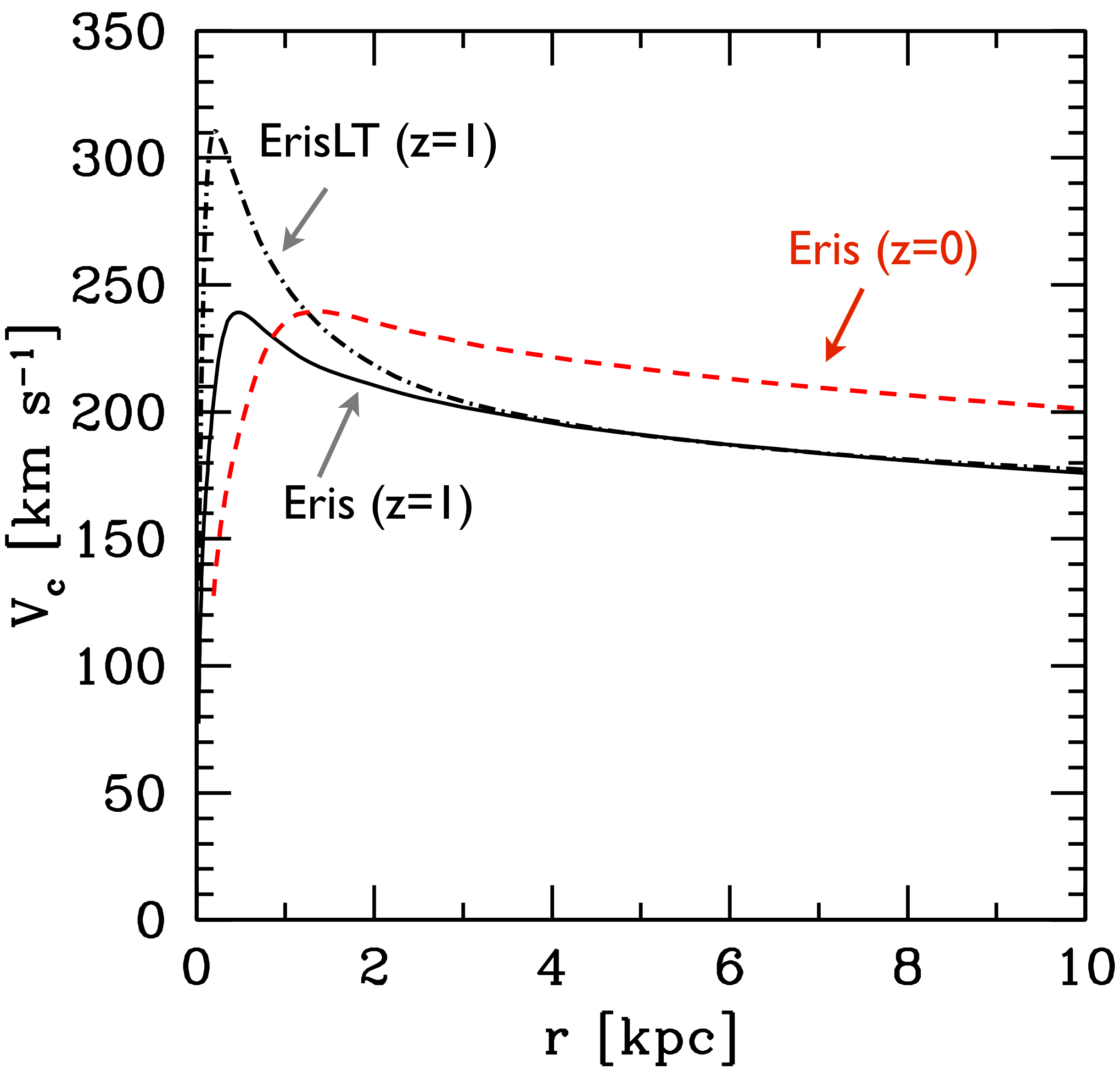
Guedes, Callegari, Madau, Mayer 2011 ApJ

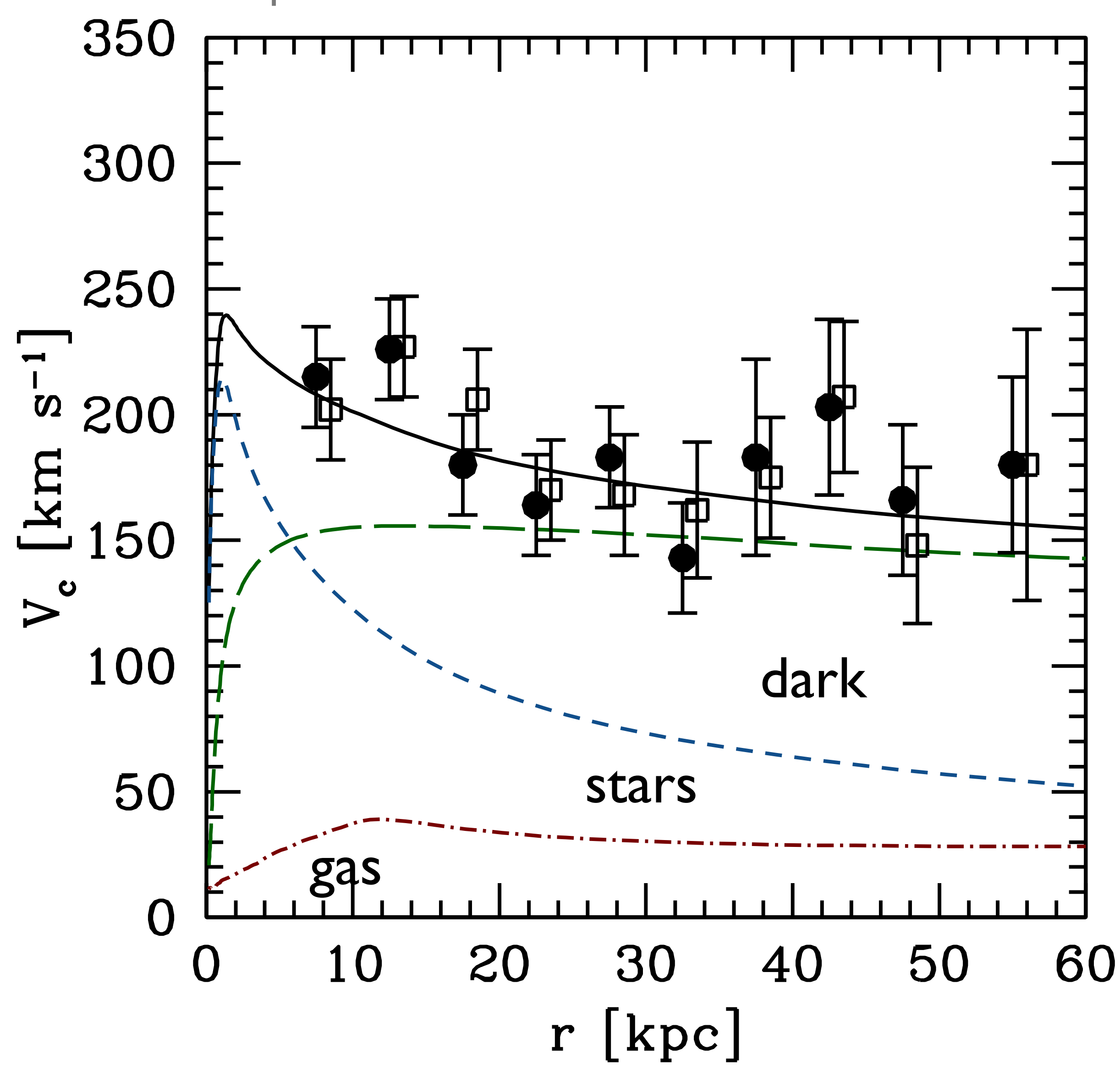
Eris Rotation Curve

Javiera Guedes, et al. 2011 ApJ

The z=0 is not highly peaked at the center, and falls slowly at large radii, in agreement with observations.

data points from SDSS blue HB stars Sofue et al. '09





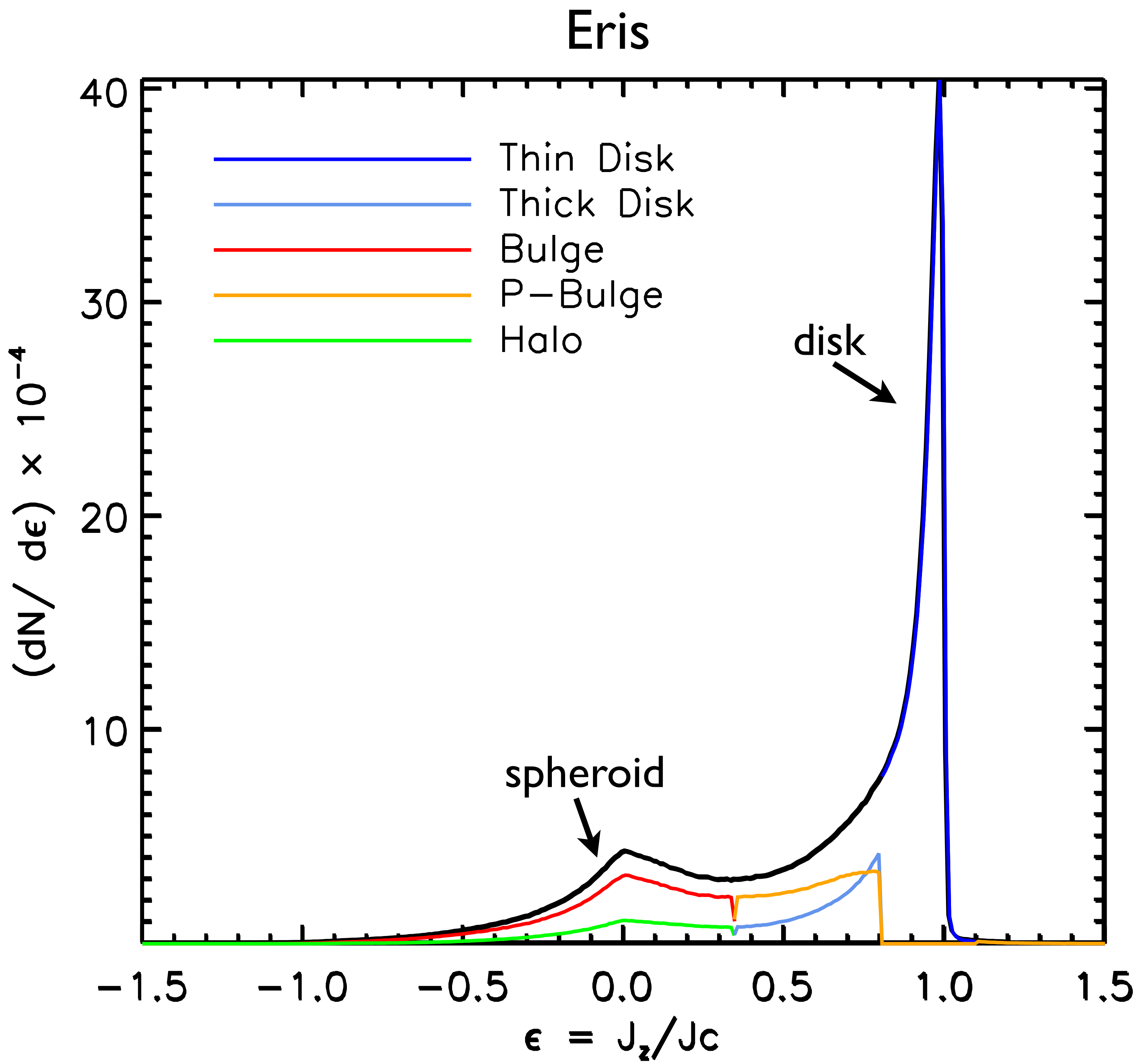
Solution:

* Mimic star formation as occurs in real galaxies, i.e. localized, on high-density peaks only.

* Feedback from SN becomes more efficient in removing gas from high-density regions. Outflows remove low angular momentum material, suppressing the formation of large bulges.

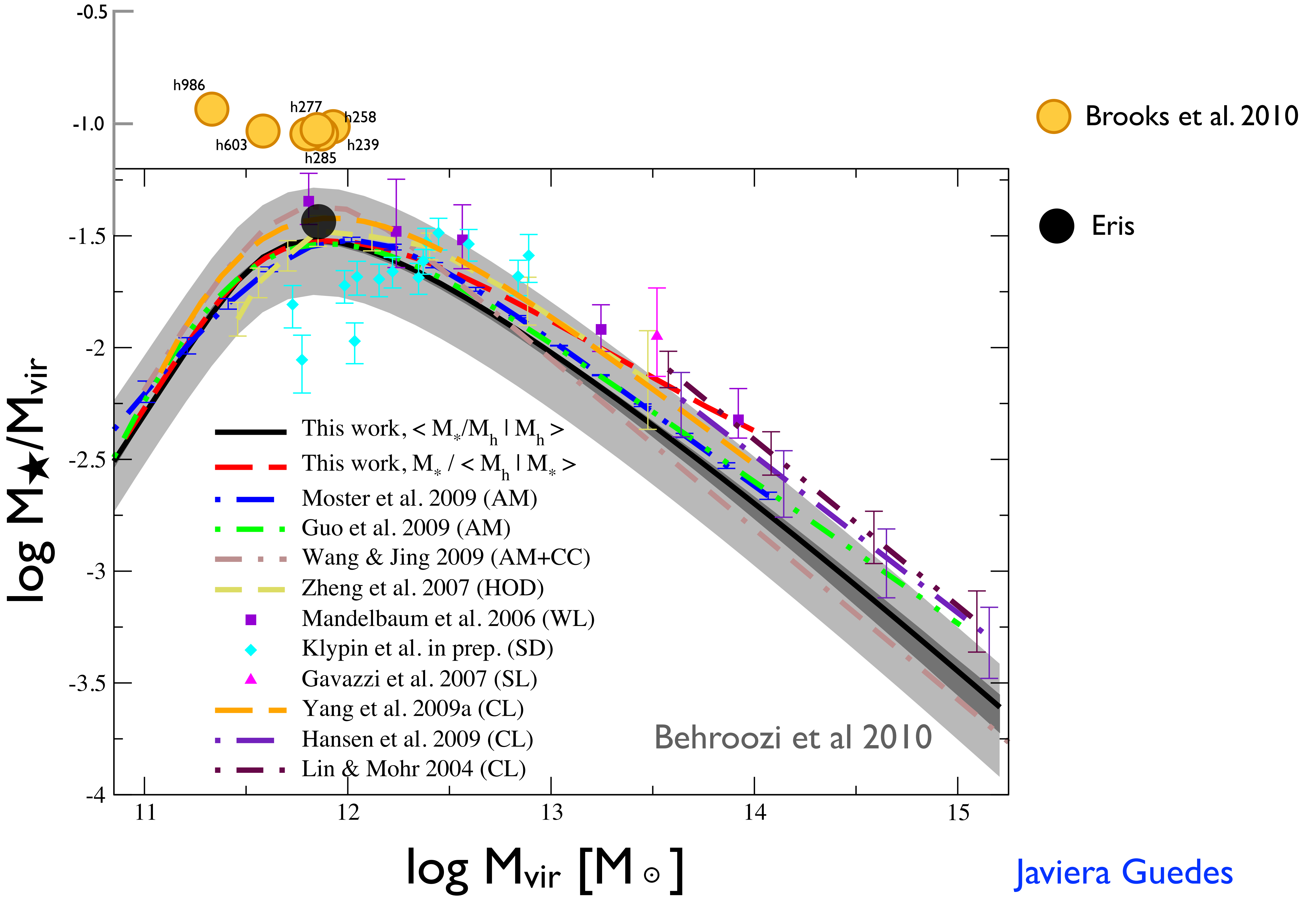
Structural Properties: Kinematic Decomposition

A kinematic decomposition can help identify the disk, bulge, stellar halo, pseudo-bulge, thick disk, and satellites.



Javiera Guedes

The M_{star}-M_{halo} Relation



Javiera Guedes

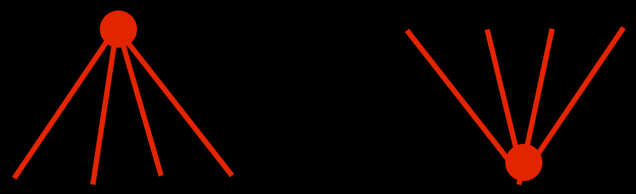
Cusps

CDM predicts cuspy halos $\rho_{DM} \sim r^{-1}$. WDM doesn't resolve cusp issues. New observations and simulations suggest that observed velocity structure of LSB and dSpiral galaxies may be consistent with cuspy ΛCDM halos.

New Developments

- New observations call into question some previous evidence for dark matter cores in dwarf galaxies
- The properties of density cores of dwarf spiral galaxies are inconsistent with expectations from WDM
- New simulations show that gas blowout during evolution of dwarf spiral galaxies can remove cusps

Legal Logic vs. Scientific Logic



New observations call into question some previous evidence for dark matter cores in dwarf galaxies

Beware of darkness: A cuspy dark matter halo from stellar kinematics where gas shows a core

NGC 2976 presented in ApJ, Vol. 745, 92, 2012; 10 more galaxies coming in future papers

Joshua J. Adams[1], Joshua D. Simon[1], Karl Gebhardt[2], Guillermo A. Blanc[1], Maximilian H. Fabricius[3], Gary J. Hill[4], Jeremy D. Murphy[2], Remco C.E. van den Bosch[5], Glenn van de Ven[5]

We here present measurements and anisotropic Jeans models for late-type dwarfs obtained from stellar kinematics. Until recently, DM mass profiles in such systems have been obtained exclusively from atomic or ionized gas. The nearby member of the M81 group, NGC 2976 (SAc), has been measured in ionized gas to have a DM core with a strong constraint on the DM power law index of $0.01<\alpha<0.17$ (Simon et al. 2003), where $\alpha=1$ corresponds to the center of an NFW profile. **In our first work on NGC 2976, we confirm that the simplest models from gas kinematics reveal a cored DM halo but find that the stellar kinematics are most consistent with an NFW profile. We advocate the stellar kinematics as more robust due to the tracer's collisionless nature while the gas is subject to more uncertainties from radial motion, warped disks, and pressure support.** We are making an ongoing study by which the type, strength, and conditions of feedback can be constrained from new measurements and comparison to simulations.

Joshua Adams poster at KITP Conference "First Light and Faintest Dwarfs" February 2012

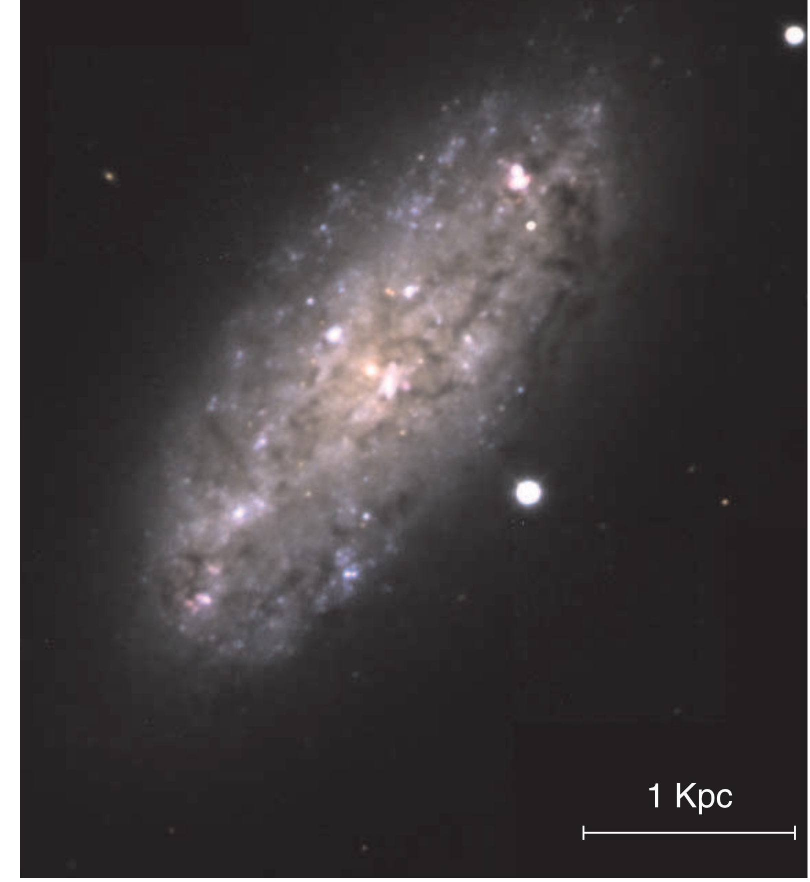
NGC 2976 was least cuspy galaxy in Simon+05

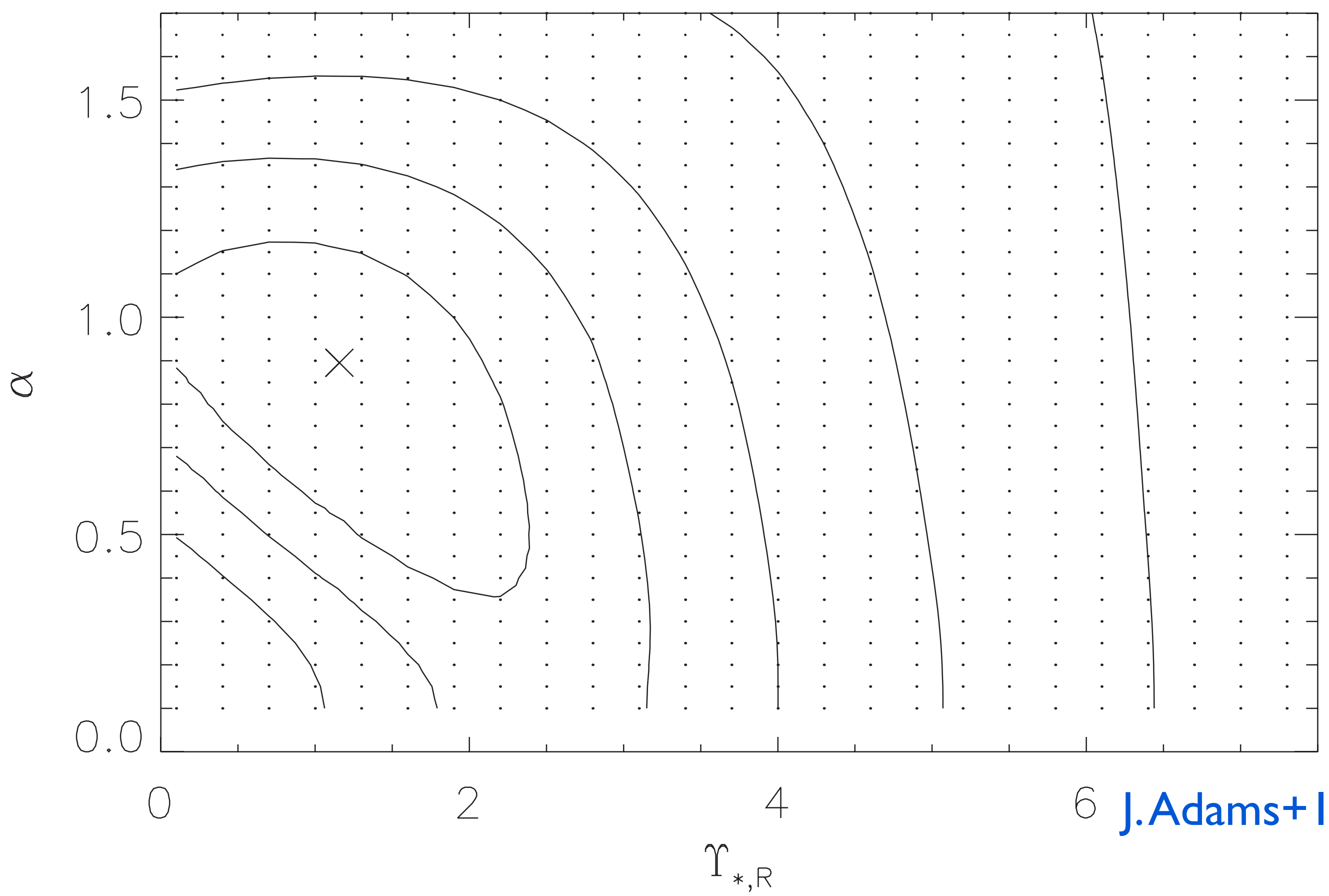
TABLE 3
Limits on Dark Matter Density Profile Slopes

Galaxy	Maximum Disk α_{DM}	Minimum Disk α_{DM}
NGC 2976...........	0.01 ± 0.13	0.27 ± 0.09
NGC 4605...........	0.71 ± 0.06	0.90 ± 0.02
NGC 5949...........	0.79 ± 0.17	0.93 ± 0.04
NGC 5963...........	0.75 ± 0.10	1.41 ± 0.03
NGC 6689...........	0.43 ± 0.18	1.07 ± 0.06

J. Simon+05

$\rho_{DM} \sim r^{-\alpha_{DM}}$





J. Adams+12

NGC 2976 has α≈1 cusp using stellar as well as gas kinematics, and Stellar Pop Synthesis modeling to determine ϒ=M/L

Joshua Adams presented additional preliminary results consistent with $\alpha_{DM} \approx 1$ for several other similar galaxies including UGC 2002 and UGC 4325 at the Ringberg conference April 2012

http://mpia.de/~dynamics/ringberg/files/adams.pdf

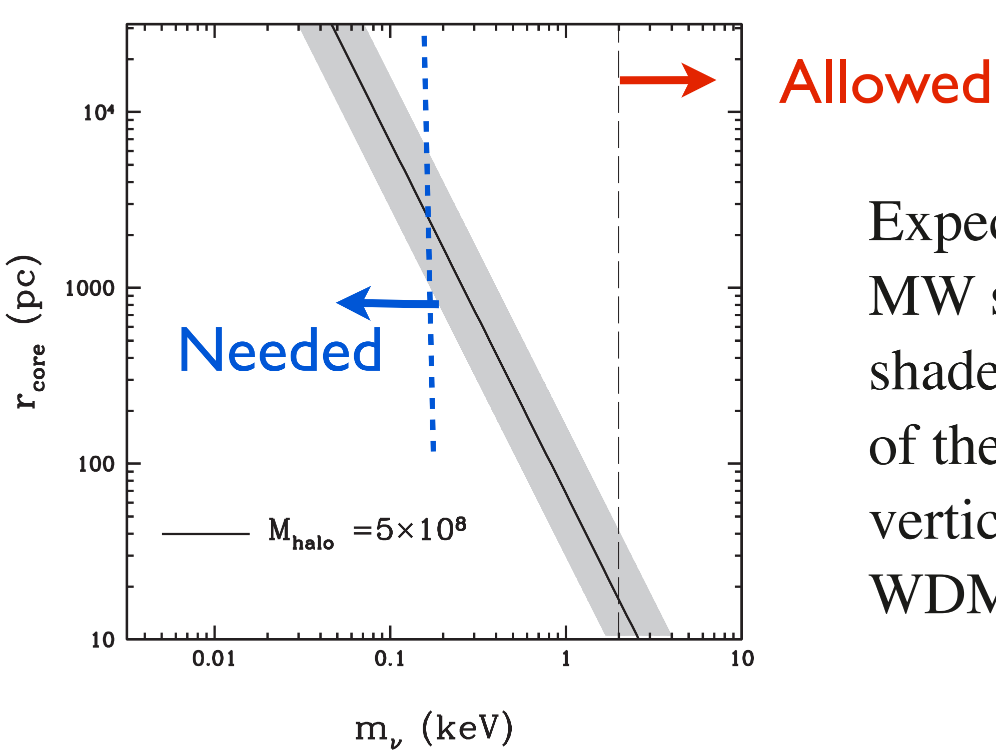
Mon. Not. R. Astron. Soc. **424,** 1105–1112 (2012)

Cores in warm dark matter haloes: a Catch 22 problem

Andrea V. Maccio, Sinziana Paduroiu, Donnino Anderhalden, Aurel Schneider and Ben Moore

ABSTRACT

The free streaming of warm dark matter particles dampens the fluctuation spectrum, flattens the mass function of haloes and sets a fine-grained phase density limit for dark matter structures. The phase-space density limit is expected to imprint a constant-density core at the halo centre in contrast to what happens for cold dark matter. We explore these effects using high-resolution simulations of structure formation in different warm dark matter scenarios. We find that the size of the core we obtain in simulated haloes is in good agreement with theoretical expectations based on Liouville's theorem. However, our simulations show that in order to create a significant core ($r_c \sim 1$ kpc) in a dwarf galaxy ($M \sim 10^{10}\, M_\odot$), a thermal candidate with mass as low as 0.1 keV is required. This would fully prevent the formation of the dwarf galaxy in the first place. For candidates satisfying large-scale structure constraints (m_ν larger than ≈1–2 keV), the expected size of the core is of the order of 10 (20) pc for a dark matter halo with a mass of 10^{10} (10^8) $M_\odot$. We conclude that 'standard' warm dark matter is not a viable solution for explaining the presence of cored density profiles in low-mass galaxies.



WDM doesn't resolve cusp issues

Expected core size for the typical dark matter mass of MW satellites as a function of the WDM mass m_ν. The shaded area takes into account possible different values of the local density parameter $0.15 < \Omega_m < 0.6$. The vertical dashed line shows the current limits on the WDM mass from large-scale structure observations

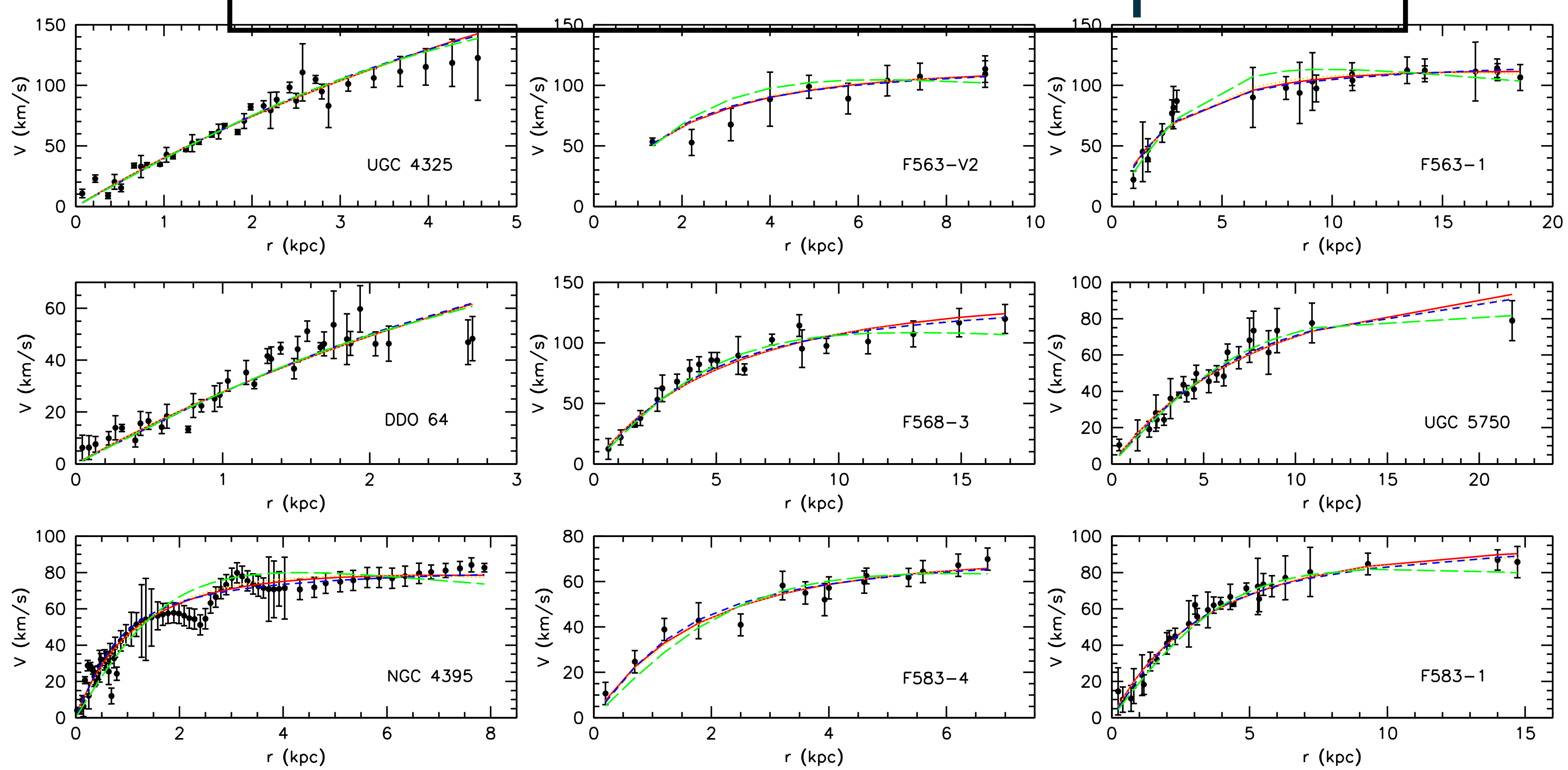
The Case Against Warm or Self-Interacting Dark Matter as Explanations for Cores in Low Surface Brightness Galaxies

Rachel Kuzio de Naray, Gregory D. Martinez, James S. Bullock, Manoj Kaplinghat **2010, ApJ, 710L, 161**

Warm dark matter (WDM) and self-interacting dark matter (SIDM) are often motivated by the inferred cores in the dark matter halos of low surface brightness (LSB) galaxies. We test thermal WDM, non-thermal WDM, and SIDM using high-resolution rotation curves of nine LSB galaxies. If the core size is set by WDM particle properties, then **even the smallest cores we infer would require primordial phase space density values that are orders of magnitude smaller than lower limits obtained from the Lyman alpha forest power spectra.** We also find that the dark matter halo core densities vary by a factor of about 30 while showing no systematic trend with the maximum rotation velocity of the galaxy. This strongly argues against the core size being directly set by large self-interactions (scattering or annihilation) of dark matter. **We therefore conclude that the inferred cores do not provide motivation to prefer WDM or SIDM over other dark matter models.**

WDM doesn't resolve cusp issues

We fit these dark matter models to the data and determine the halo core radii and central densities. While the minimum core size in WDM models is predicted to **decrease** with halo mass, we find that the inferred core radii **increase** with halo mass and also cannot be explained with a single value of the primordial phase space density.



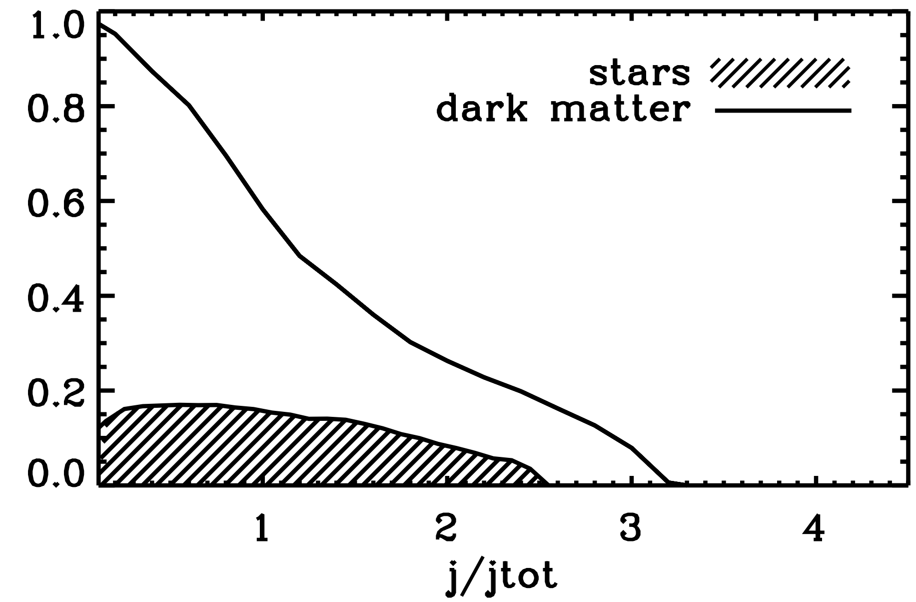
The Dwarf Galaxy Cuspy Dark Matter Profile Problem

Governato et al. 2010

Bullock et al. 2001b showed that much of the dark matter in CDM halos has low angular momentum.

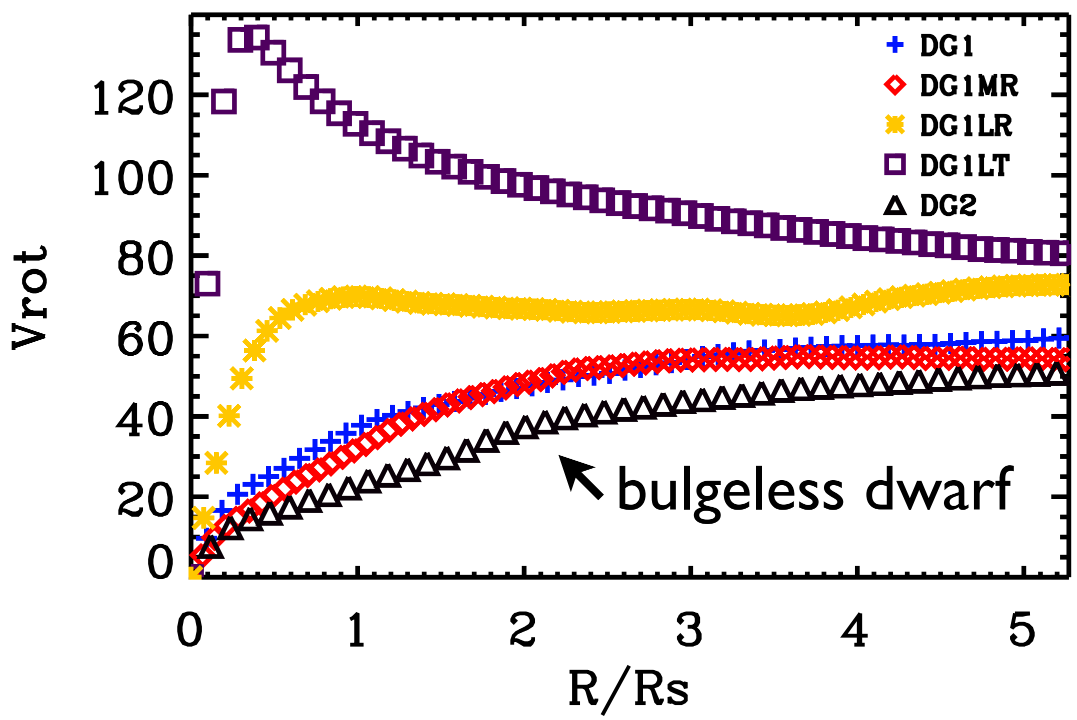
The assumption that stars have the same angular momentum distribution as the dark matter yield centrally concentrated galaxies and cuspy dark matter profiles.

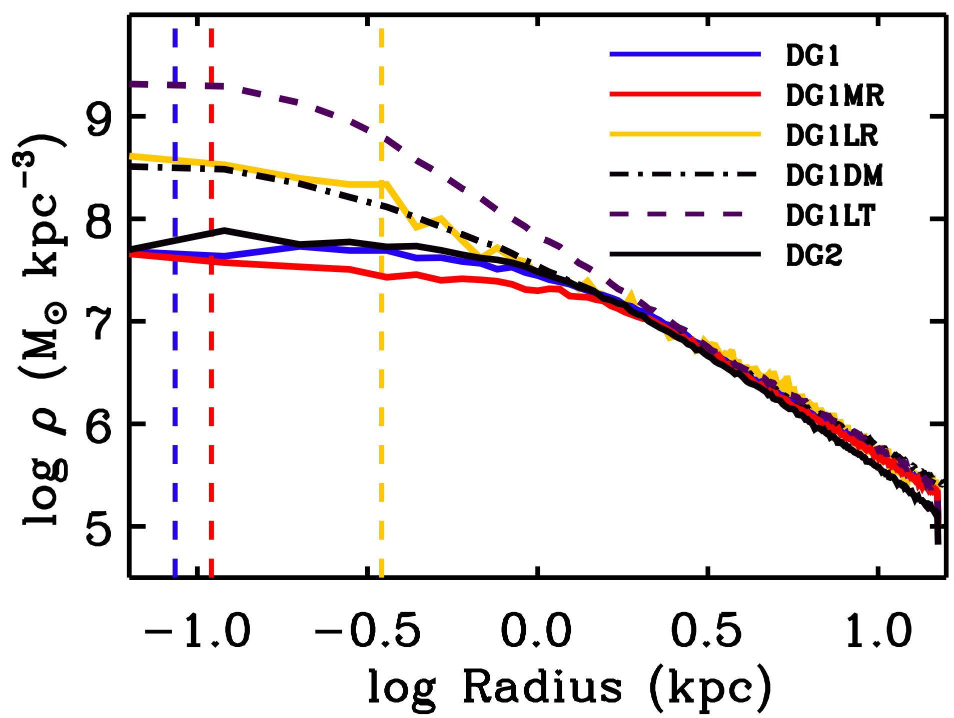
But dwarf galaxies are observed to be bulgeless.



High resolution simulations with a high threshold for star formation can *erode* the dark matter distribution.

Governato et al. 2010



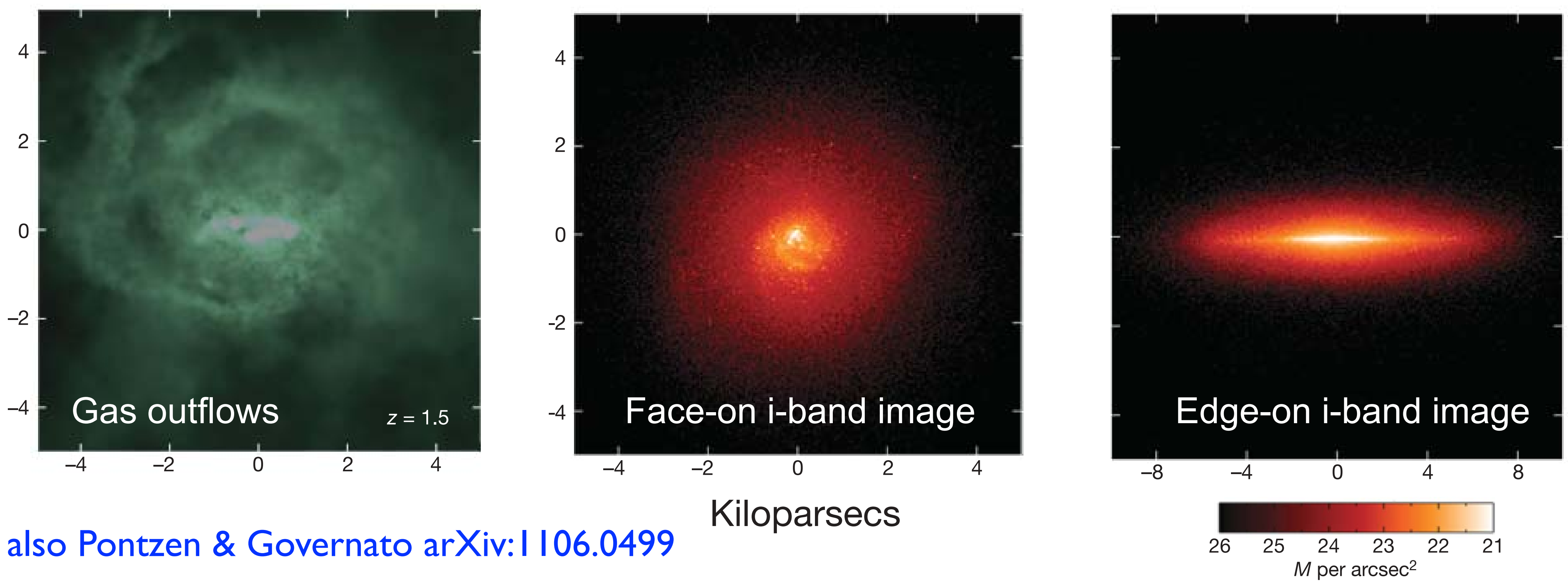


New simulations show that several episodes of gas blowout during evolution of dwarf spiral galaxies can remove cusps

Bulgeless dwarf galaxies and dark matter cores from supernova-driven outflows

F. Governato, C. Brook, L. Mayer, A. Brooks, G. Rhee, J. Wadsley, P. Jonsson, B. Willman, G. Stinson, T. Quinn & P. Madau **Nature** 463, 203 (Jan 2010)

Most observed dwarf galaxies consist of a rotating stellar disk embedded in a massive dark-matter halo with a near-constant-density core. Models based on CDM, however, invariably form galaxies with dense spheroidal stellar bulges and steep central dark-matter profiles, because low-angular-momentum baryons and dark matter sink to the centers of galaxies through accretion and repeated mergers. Here we report hydrodynamical simulations in which the inhomogeneous interstellar medium is resolved. **Strong outflows from supernovae remove low-angular-momentum gas, which inhibits the formation of bulges and decreases the dark-matter density to less than half of what it would otherwise be within the central kiloparsec. The analogues of dwarf galaxies—bulgeless and with shallow central dark-matter profiles—arise naturally in these simulations.** Simulations using the same implementation of star formation and feedback reproduce some global scaling properties of observed galaxies across a range of masses and redshifts.



See also Pontzen & Governato arXiv:1106.0499

FLATTENING DARK MATTER CUSPS

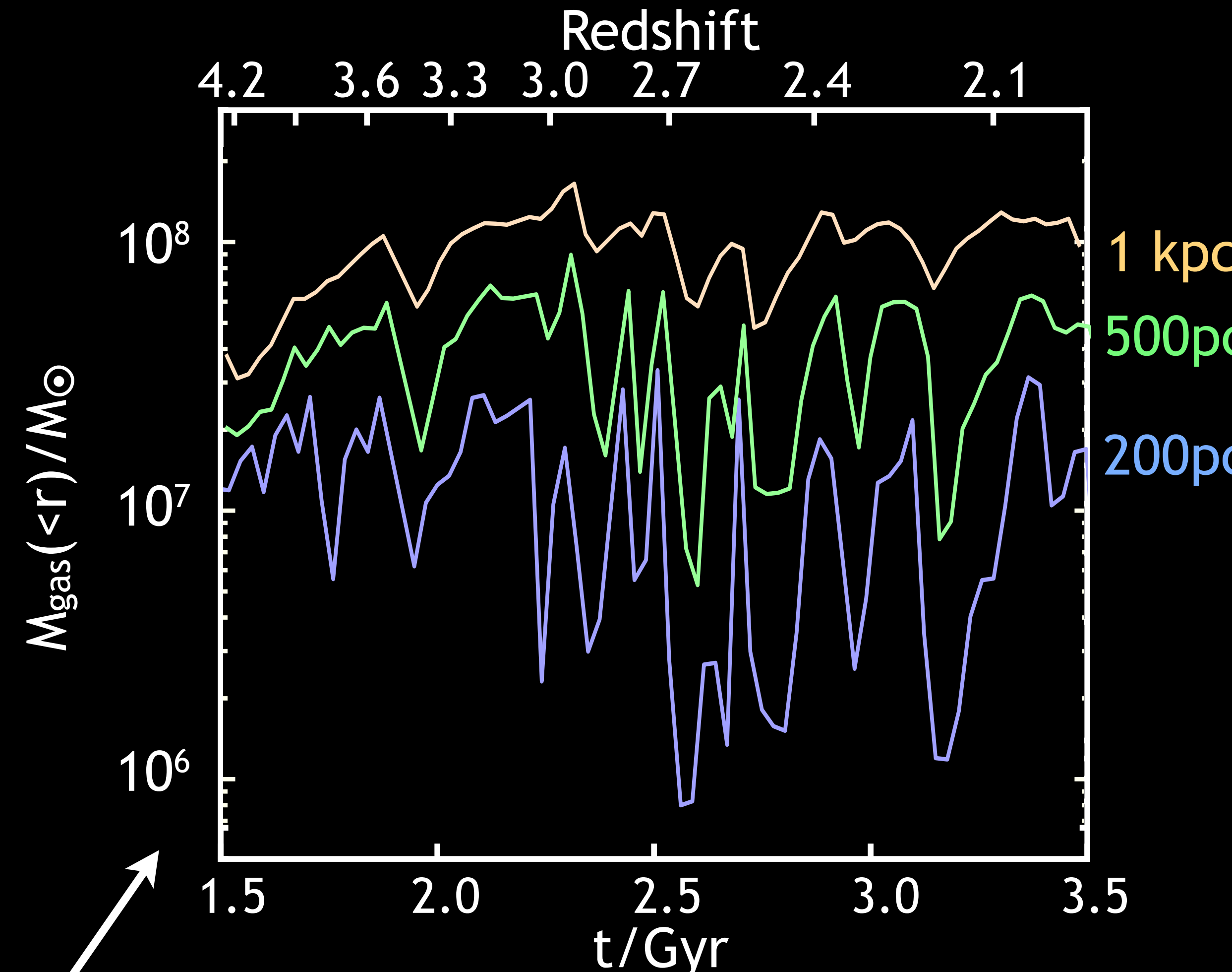
WITH

Super Nova® FEEDBACK

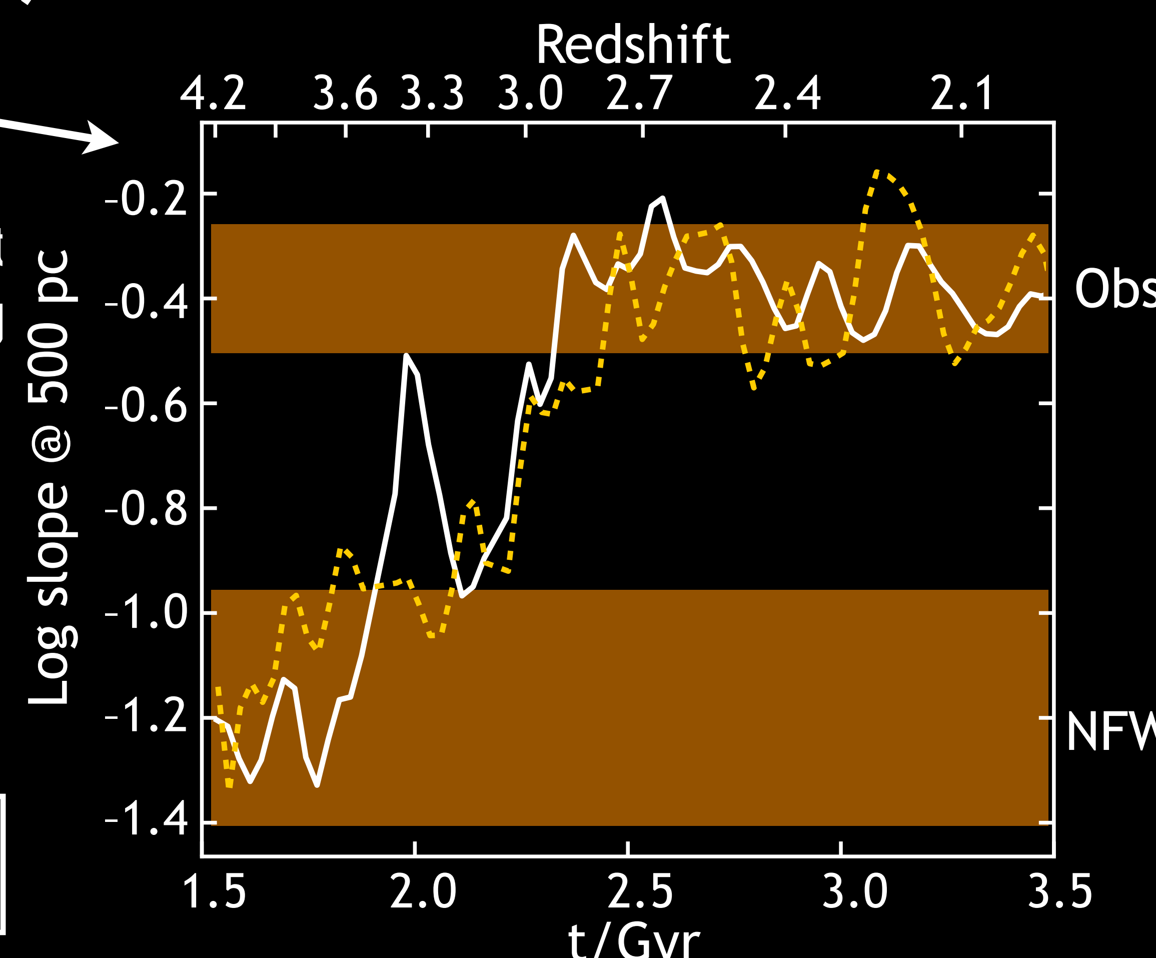
arXiv:1106.0499

Andrew Pontzen
IoA, Cambridge

Fabio Governato, UW, Seattle



Rapidly changing mass interior to a given radius causes expansion of the dark matter profile.



NB similarity with Maschenko/Wadsley work, but the new picture has no small lumps – everything coherent on kiloparsec scales – and no special resonant frequency. Also Read/Gilmore suggested the possibility of multiple epochs of outflows/condensation, an effect we are now confirming and quantifying through better simulations and new mathematical modelling.

Andrew Pontzen @ Durham Conf

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]

MNRAS 2012

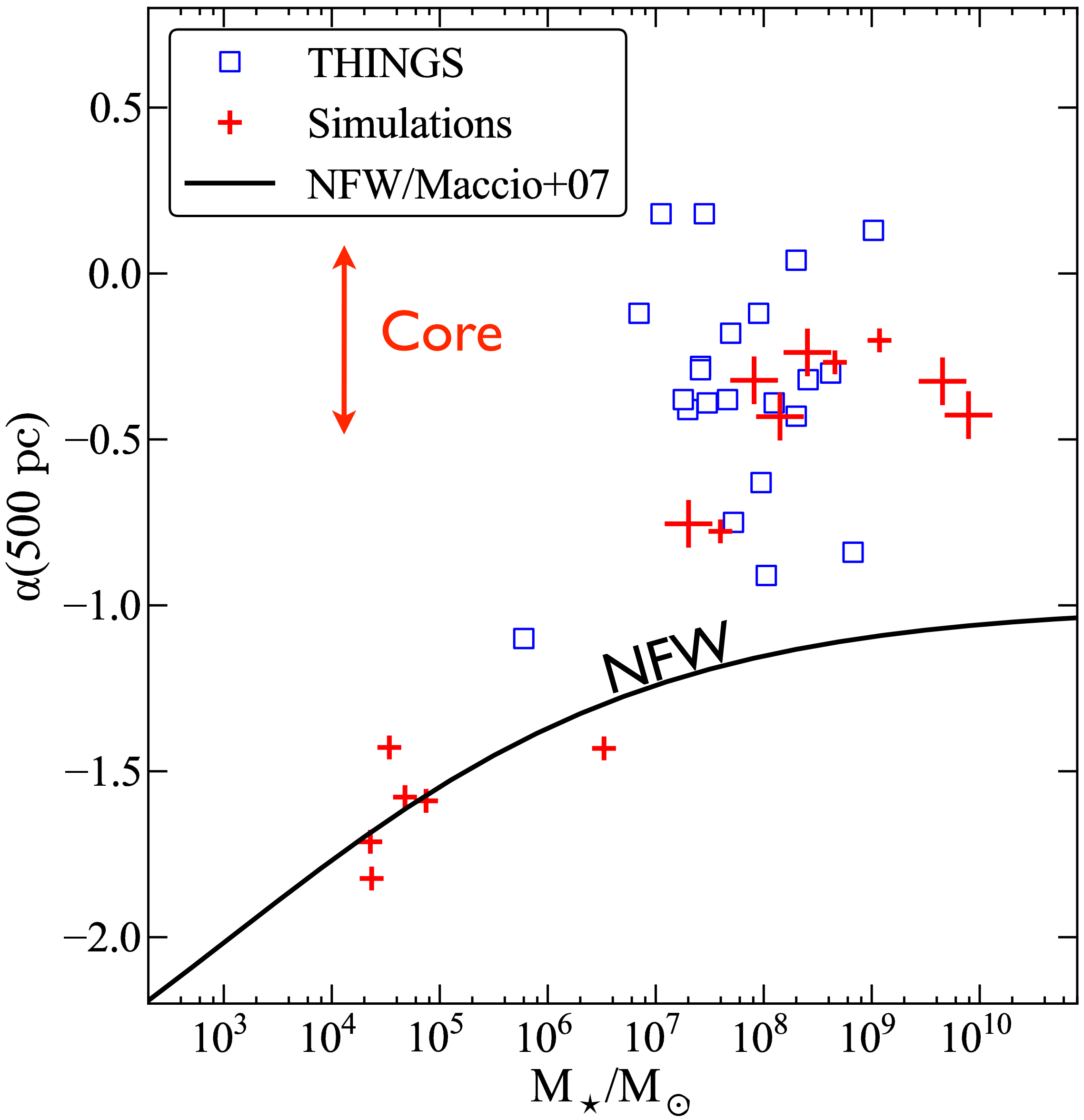


Figure 1. *The slope of the dark matter density profile α vs stellar mass measured at 500 pc and z=0 for all the resolved halos in our sample.* The Solid 'DM-only' line is the slope predicted for the same CDM cosmological model assuming i) the NFW concentration parameter trend given by Macció et al (2007) and ii) the same stellar mass vs halo mass relation as measured in our simulations to convert from halo masses. Large Crosses: haloes resolved with more than 0.5×10^6DM particles within R_{vir}. Small crosses: more than 5×10^4 DM particles. The small squares represent 22 observational data points measured from galaxies from the THINGS and LITTLE THINGS surveys.

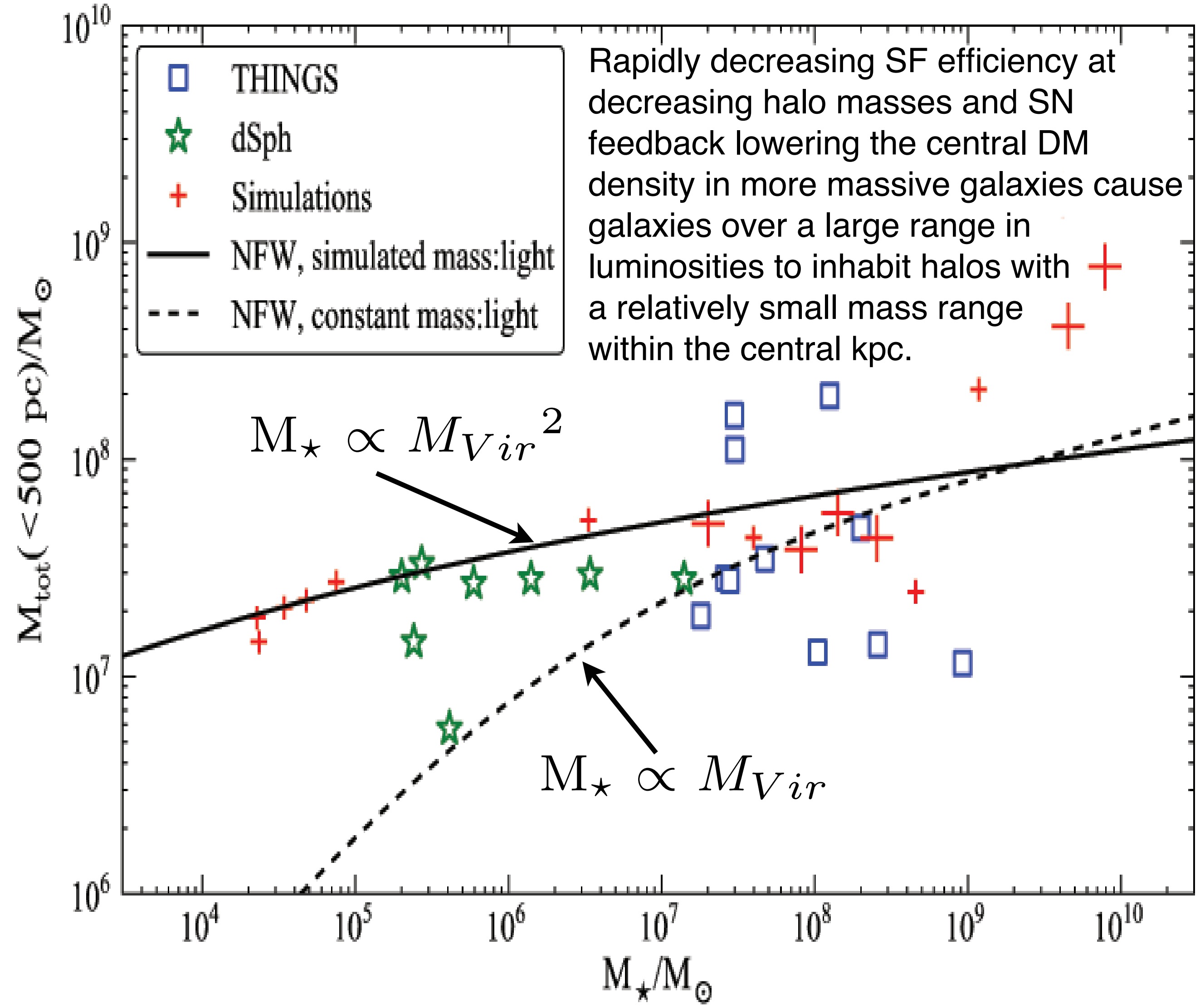


Figure 4. The total mass (baryons and DM) within the central 500 pc as a function of stellar mass: Large and small crosses: simulations. Open squares: galaxies from THINGS (Oh et al. in prep). Stars: dSph from Walker (priv. comm.). Theoretical predictions reproduce the observed flat trend from 10^5 to 10^9 M⊙. This is largely due to the large drop in SF efficiency at small halo masses, that stretches the range of galaxy luminosities over a relatively smaller halo mass range. The solid and dashed lines assume different stellar mass - total halo mass relations. A close fit to the simulations as $M^* \sim M_{Vir}{}^2$ (solid) and one showing $M^* \sim M_{Vir}$ (dashed). Only when the star formation efficiency is a steep function of halo mass it is possible to reproduce the observed trend, as discussed in §4. More massive galaxies above the solid line have a small bulge component.

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

MATTHEW G. WALKER[1,2,3] & JORGE PEÑARRUBIA[2] 2011 ApJ

Using separately higher metal stars at lower radiu plus lower metal stars farther out gives dm radial slope inconsistent with NFW at high confidence for Sculptor and Fornax dwarf spheroidal MWy satellites.

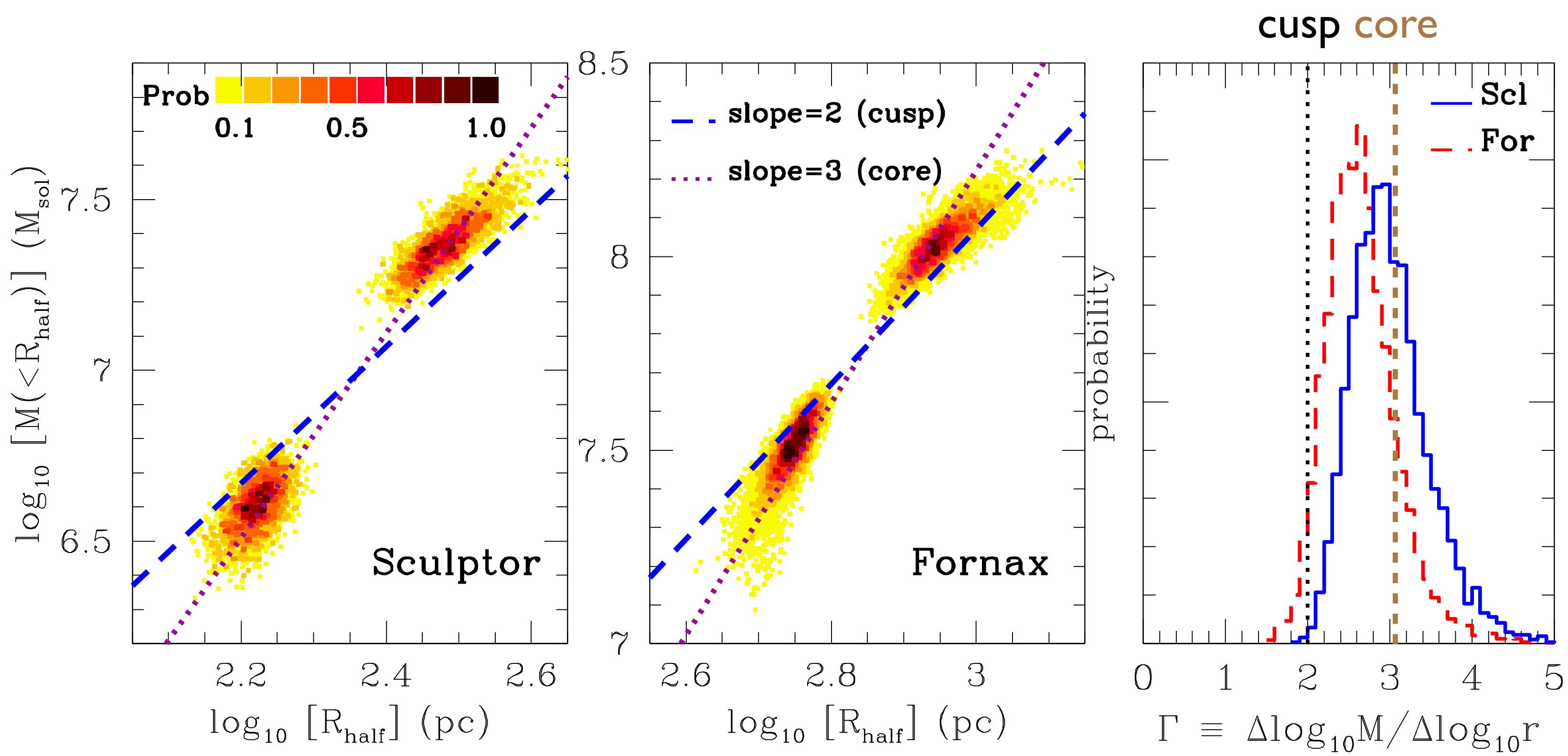


FIG. 10.— *Left, center:* Constraints on halflight radii and masses enclosed therein, for two independent stellar subcomponents in the Fornax and Sculptor dSphs. Plotted points come directly from our final MCMC chains, and color indicates relative likelihood (normalized by the maximum-likelihood value). Overplotted are straight lines indicating the central (and therefore maximum) slopes of cored ($\lim r \to 0\ d \log M/d \log r] = 3$) and cusped ($\lim r \to 0\ d \log M/d \log r] = 2$) dark matter halos. *Right:* Posterior PDFs for the slope Γ obtained for Fornax and Sculptor. The vertical dotted line marks the maximum (i.e., central) value of an NFW profile (i.e., cusp with $\gamma_{DM} = 1$, $\lim r \to 0\ [d \log M/d \log r] = 2$). These measurements rule out NFW and/or steeper cusps ($\gamma DM \geq 1$) with significance $s \geq 96\%$ (Fornax) and $s \geq 99\%$ (Sculptor).

Similar results for Sculptor in Amorisco & Evans 2012 MNRAS. Jardel & Gebhardt present a Schwarzschild model fit to the Fornax dwarf, again favoring core rather than cusp. But this isn't a problem for CDM if cusps are removed in galaxies of this mass by episodes of slow infall and rapid expulsion of gas in the centers of these halos.

Satellites and Subhalos

The discovery of many faint Local Group dwarf galaxies is consistent with ΛCDM predictions. Satellites, reionization, lensing flux anomalies, stellar streams, and Lyα forest data imply that WDM must be Tepid or Cooler.

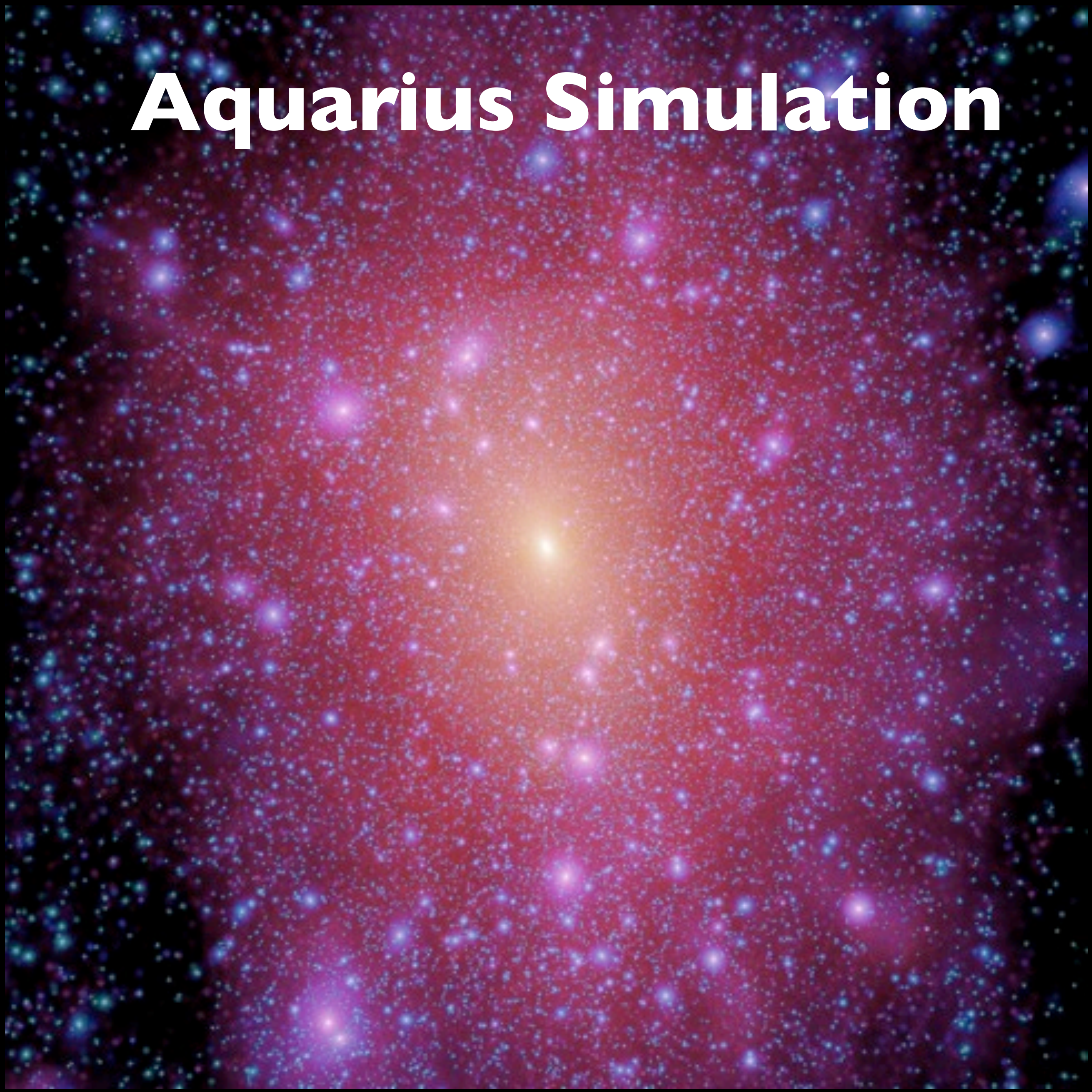
New Developments

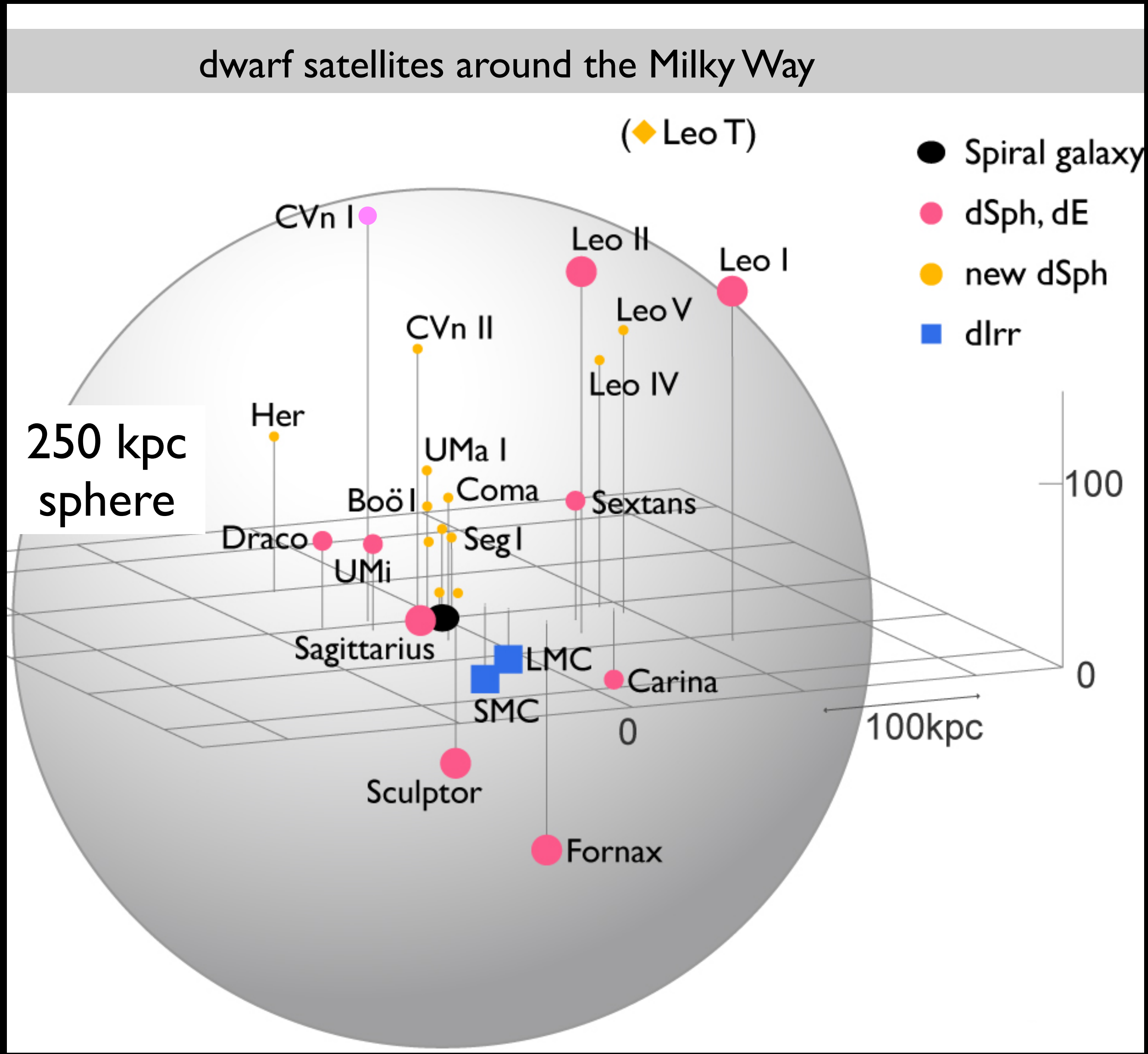
- The "too big to fail" problem appears to be the most serious current challenge for ΛCDM, and may indicate the need for a more complex theory of dark matter.
- High resolution ΛCDM simulation substructure is consistent with quad-lens radio quasar flux and galaxy-galaxy lensing anomalies and indications of substructure by stellar stream gaps.
- ΛCDM predicts that there is a population of low-luminosity stealth galaxies around the Milky Way. Will new surveys with bigger telescopes find them?

The "too big to fail" problem

ΛCDM subhalos vs. Milky Way satellites

"Missing satellites": Klypin et al. 1999, Moore et al. 1999





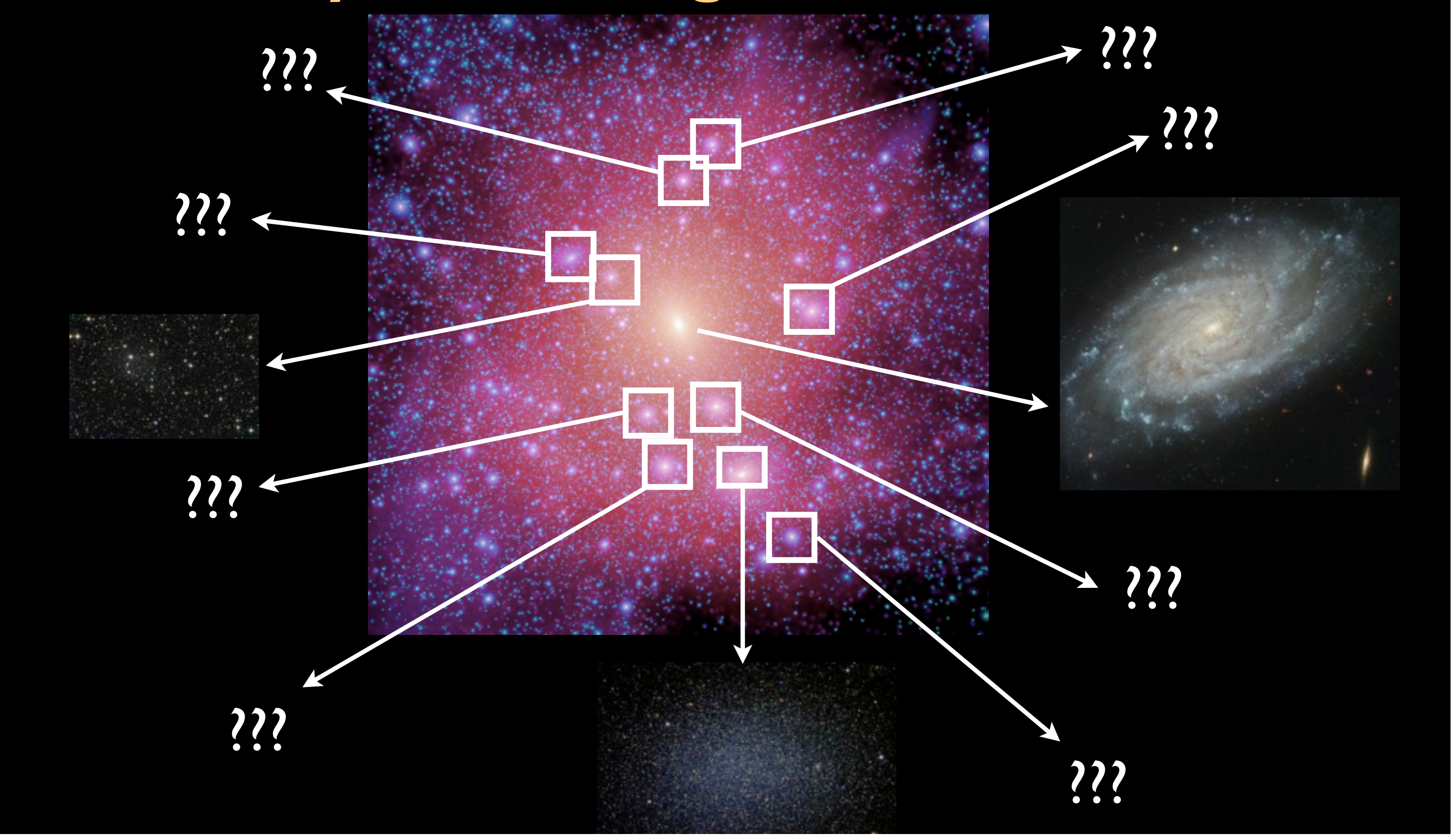
$>10^5$ identified subhalos

12 bright satellites $(L_V > 10^5 L_\odot)$

V. Springel / Virgo Consortium

S. Okamoto

Of the ~10 biggest subhalos, ~8 cannot host *any* known bright MW satellite

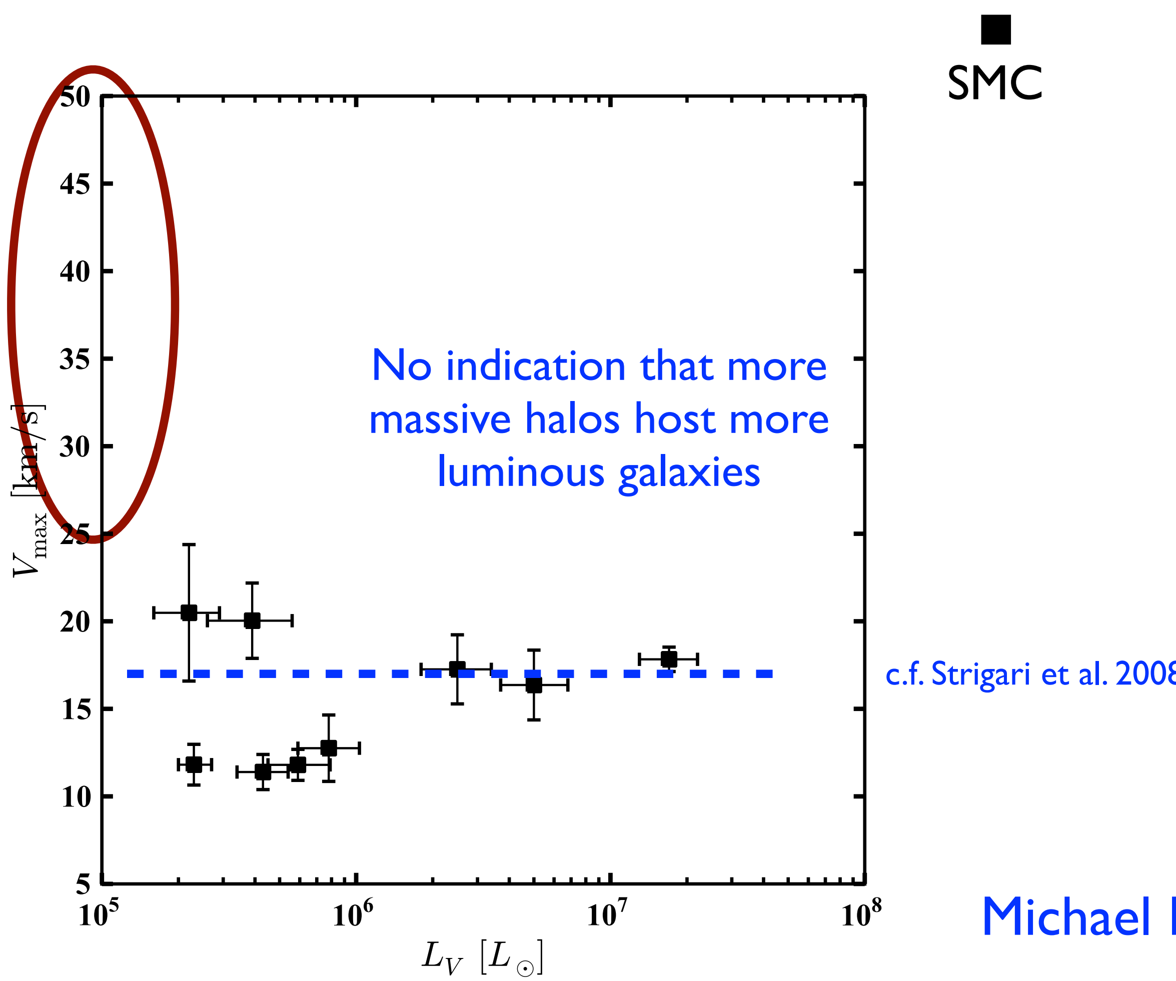


Observed Milky Way Satellites

"massive failures": highest resolution LCDM simulations predict ~10 subhalos in this range in the MW, but we don't see ***any*** such galaxies [except Sagittarius (?)]

All of the bright MW dSphs are consistent with $V_{\rm max} \lesssim 25\,{\rm km/s}$

(see also Strigari, Frenk, & White 2010)



LMC

Possible Solutions to "too big to fail"

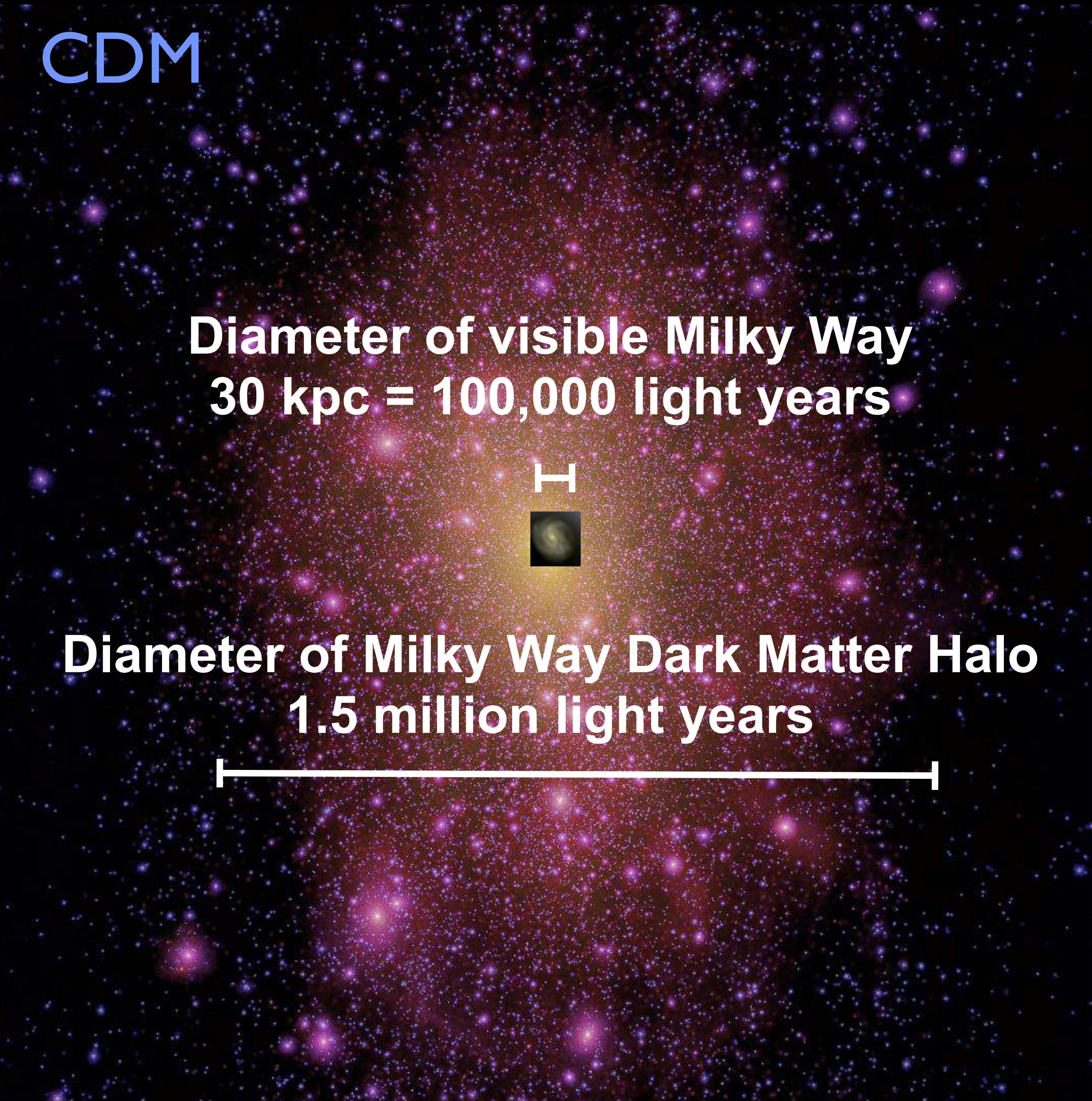
The Milky Way is anomalous?

The Milky Way has a low mass dark matter halo?

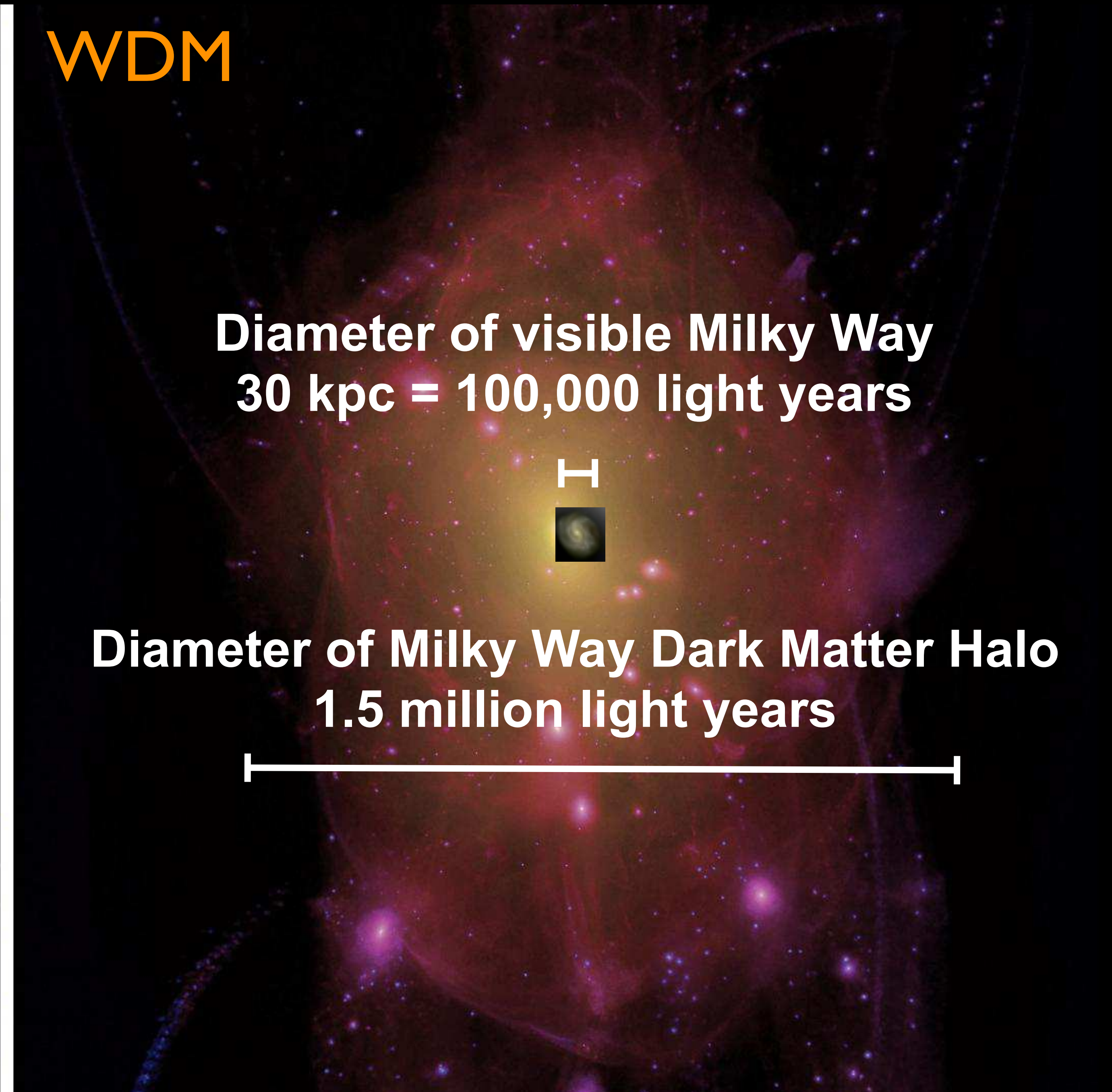
Galaxy formation is stochastic at low masses?

Dark matter is not just CDM -- maybe WDM or even self-interacting?

Michael Boylan-Kolchin, Bullock, Kaplinghat 2011, 2012



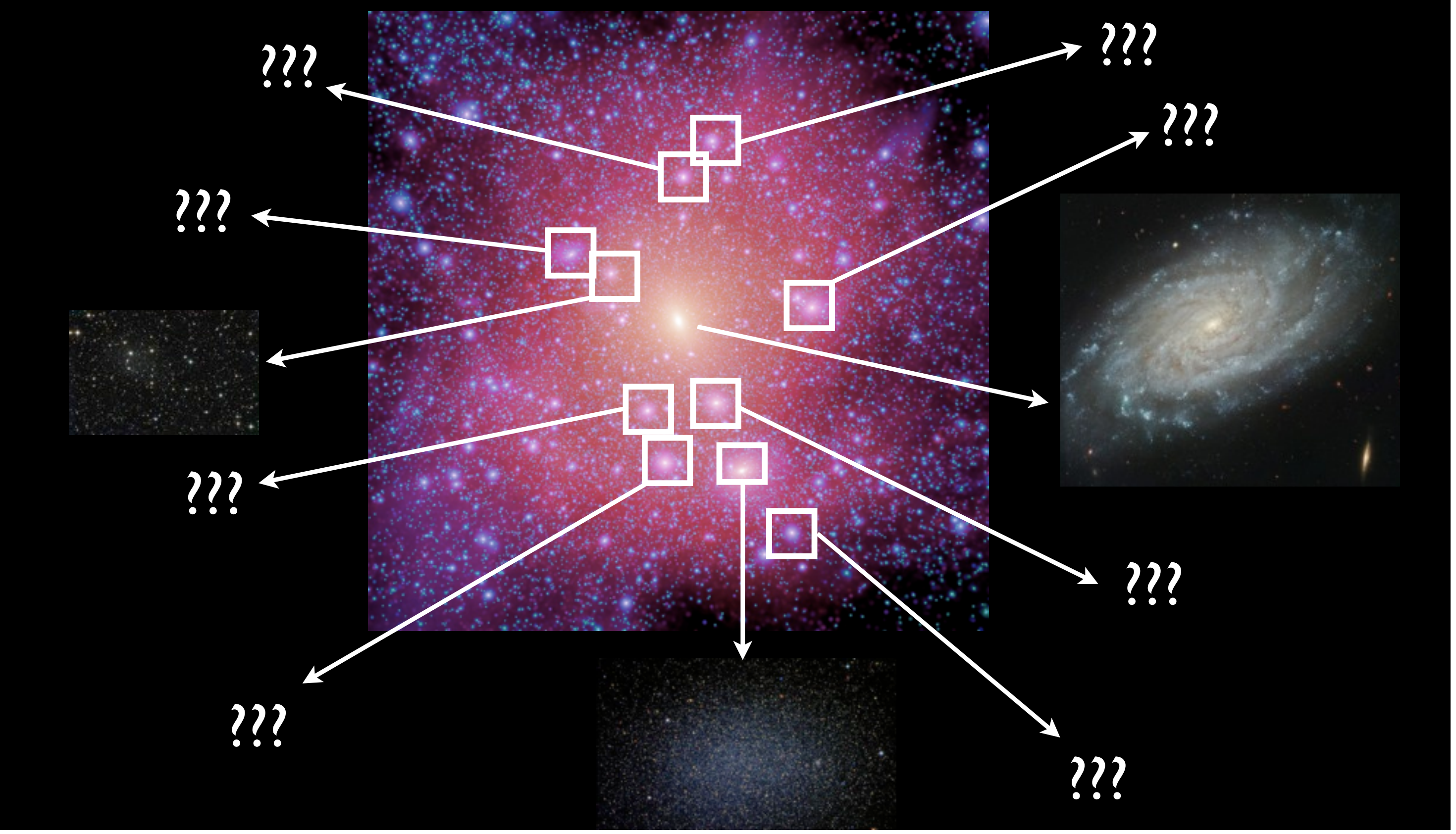
Aquarius simulation. Springel et al. 2008



Lovell, Eke, Frenk, et al. 2011

WDM simulation at right has no "too big to fail" subhalos, but it doesn't lead to the right systematics to fit dwarf galaxy properties as Kuzio de Naray et al. showed. It also won't have the subhalos needed to explain radio flux anomalies and gaps in stellar streams.

Of the ~10 biggest subhalos, ~8 cannot host *any* known bright MW satellite



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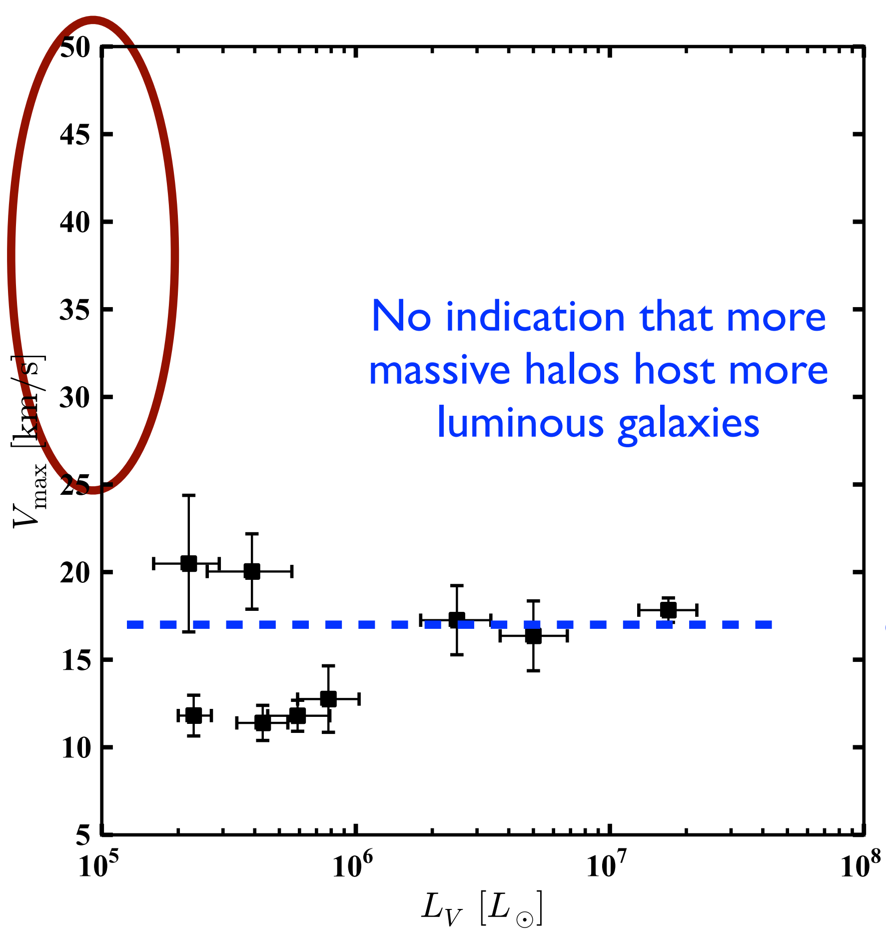

c.f. Strigari et al. 2008

All of the bright MW dSphs are consistent with $V_{max} \lesssim 25\,\mathrm{km/s}$

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Possible Solutions to “too big to fail”

The Milky Way is anomalous?

The Milky Way has a low mass dark matter halo?

Galaxy formation is stochastic at low masses?

Dark matter is not just CDM -- maybe WDM or even self-interacting?

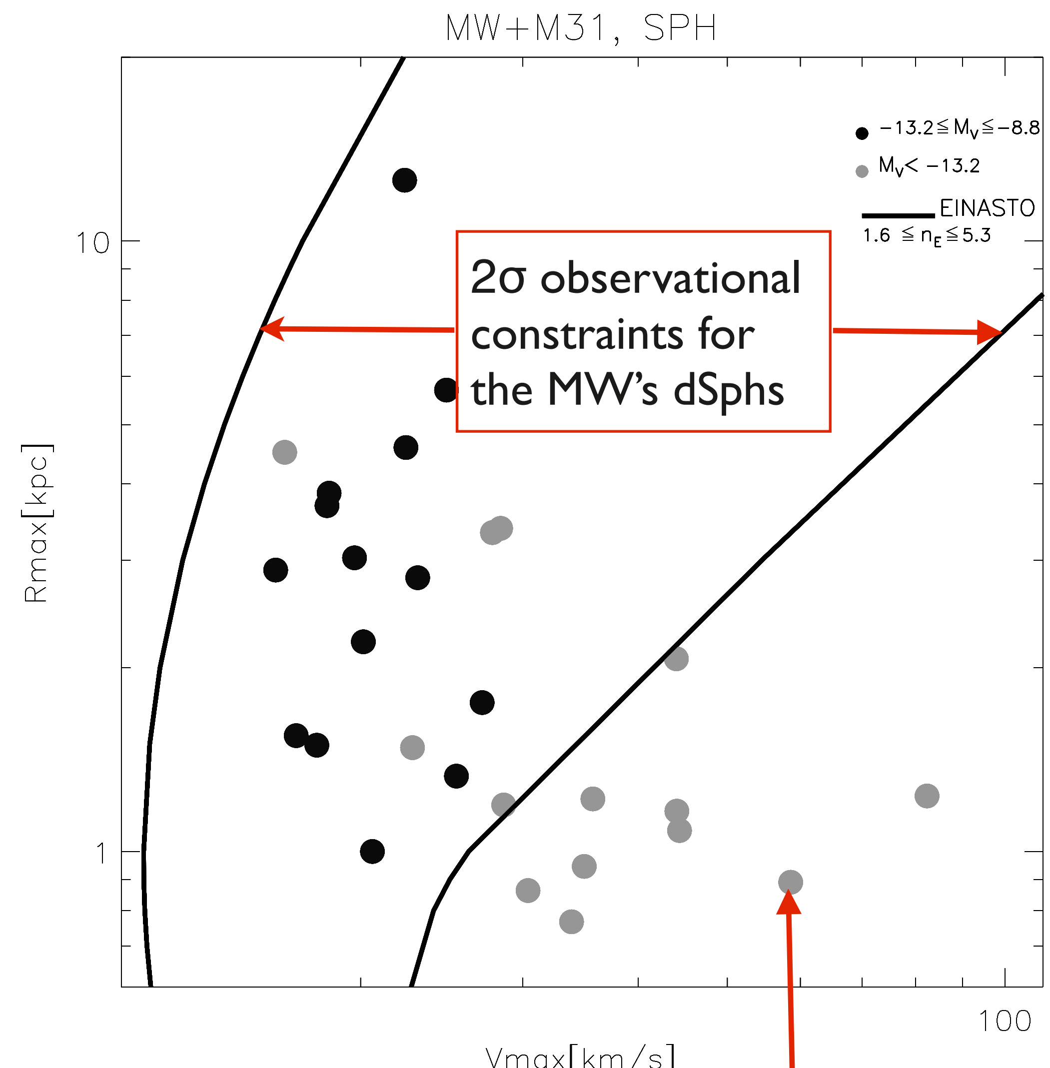
Or maybe high-resolution CDM simulations are being misinterpreted? Maybe baryons strongly modify the structure of subhalos?

Michael Boylan-Kolchin, Bullock, Kaplinghat 2011, 2012

Size matters: the non-universal density profile of subhaloes in SPH simulations and implications for the Milky Way's dSphs

Arianna Di Cintio, Alexander Knebe, Noam I. Libeskind, Chris Brook, Gustavo Yepes, Stefan Gottlober, Yehuda Hoffman (Arianna's poster and arXiv:1204.0515)

ABSTRACT We use dark matter only and full hydrodynamical Constrained Local UniversE Simulations (CLUES) of the formation of the Local Group to study the density profile of subhaloes of the simulated Milky Way and Andromeda galaxies. We show that **the Einasto model provides the best description of the subhaloes' density profile**, as opposed to the more commonly used NFW profile or any generalisation of it. We further find that **the Einasto shape parameter n_E is strongly correlated with the total subhalo mass**, pointing towards the notion of a non-universality of the subhaloes' density profile. Assuming now that the dSphs of our Galaxy thus follow the Einasto profile and using the maximum and minimum values of n_E from our SPH simulations as a gauge, we can improve the observational constraints on the R_{max}-V_{max} pairs obtained for the brightest satellite galaxies of the Milky Way. When considering only the subhaloes with $-13.2 < M_V < -8.8$, i.e. the range of luminosity of the classical dwarfs, **we find that all our simulated objects are consistent with the observed dSphs if their haloes follow the Einasto model with $1.6 < nE < 5.3$**. The numerically motivated Einasto profile for the observed dSphs as well as the observationally motivated magnitude cut for the simulated subhaloes will **eliminate the "massive failures" problem** and results in a perfect agreement with observations.

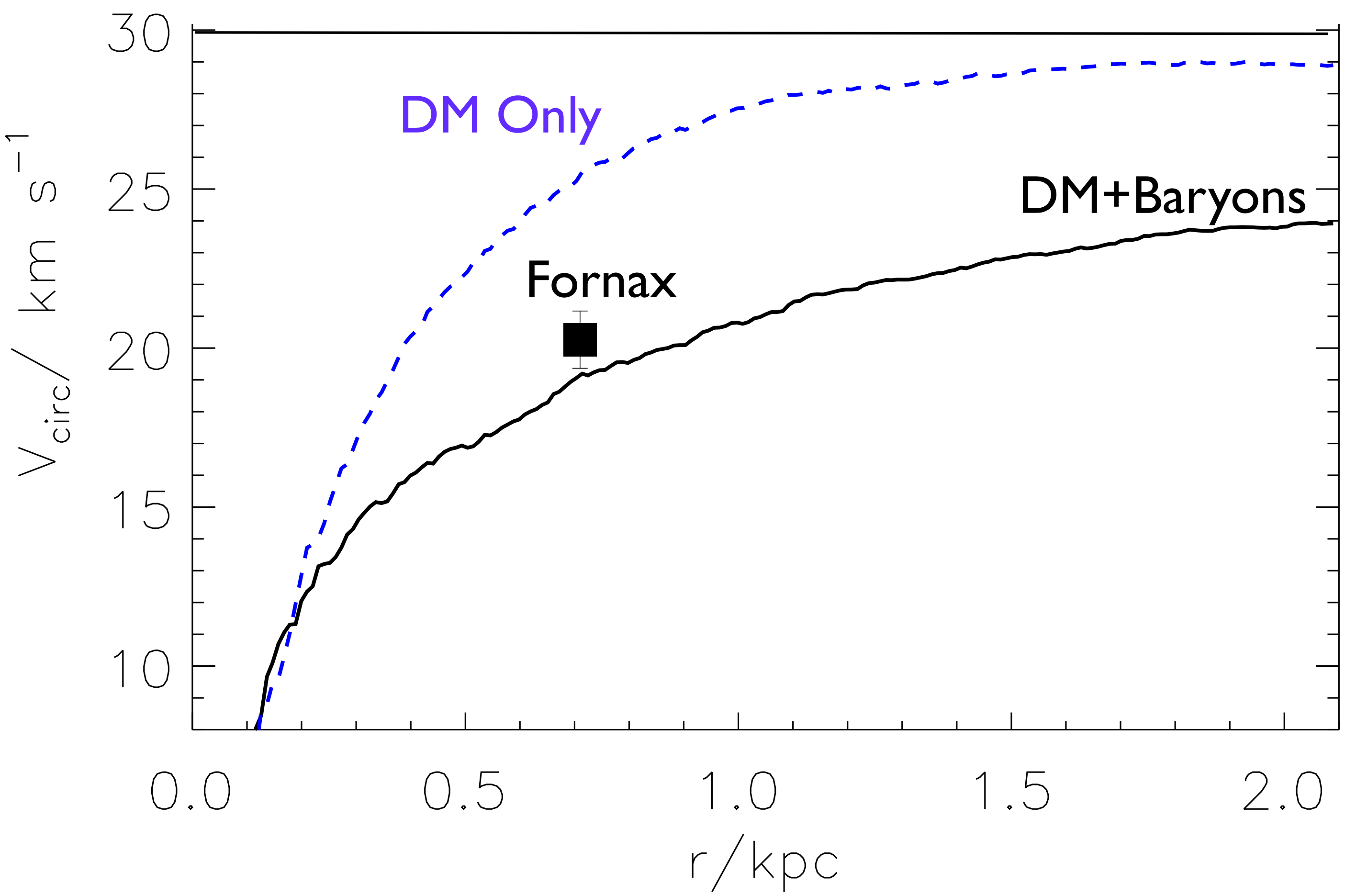


Where are those massive luminous subhaloes seen in the simulation hiding in the real Local Group?

WHY BARYONS MATTER: THE KINEMATICS OF DWARF SPHEROIDAL SATELLITES

Alyson M. Brooks & Adi Zolotov - Submitted to ApJ Letters

We use some of the highest resolution cosmological simulations ever produced of Milky Way-mass galaxies that include both baryons and dark matter to show that baryonic physics (energetic feedback from supernovae and subsequent tidal stripping) significantly reduces the dark matter mass in the central regions of luminous satellite galaxies. The reduced central masses of the simulated satellites reproduce the observed internal dynamics of Milky Way and M31 satellites as a function of luminosity. Including baryonic physics in Cold Dark Matter models naturally explains the observed low dark matter densities in the Milky Way's dwarf spheroidal population. Our simulations therefore resolve the tension between kinematics predicted in Cold Dark Mater theory and observations of satellites, without invoking alternative forms of dark matter.



The z = 0 rotation curves of a simulated satellite and its DM-only counterpart. The Vcirc for Fornax is over-plotted, based on the data in Walker et al. (2009). The combination of SN feedback (before infall) and tidal stripping (after infall) substantially lower the vc of the SPH satellite by z = 0, and is in good agreement with the observed vc of Fornax.

For almost all of our satellites, the DM-only runs produce satellites with 2-4 times more mass in the central 1 kpc than their SPH counterparts.

If a satellite fainter than $M_V \sim -12$ underwent substantial stripping (~90% of its total mass, Peñarrubia et al. 2008), it could have started off as a more luminous dSph with a DM core.

The presence of cored density profiles at radii under ~ 500 pc in satellites fainter than MV ~ –12 is not ruled out by our simulations, as we do not resolve this region.

Regardless of the density profile, the tidal effects of the disk can dramatically lower the central DM mass of any satellite, depending on infall time and orbital eccentricity.

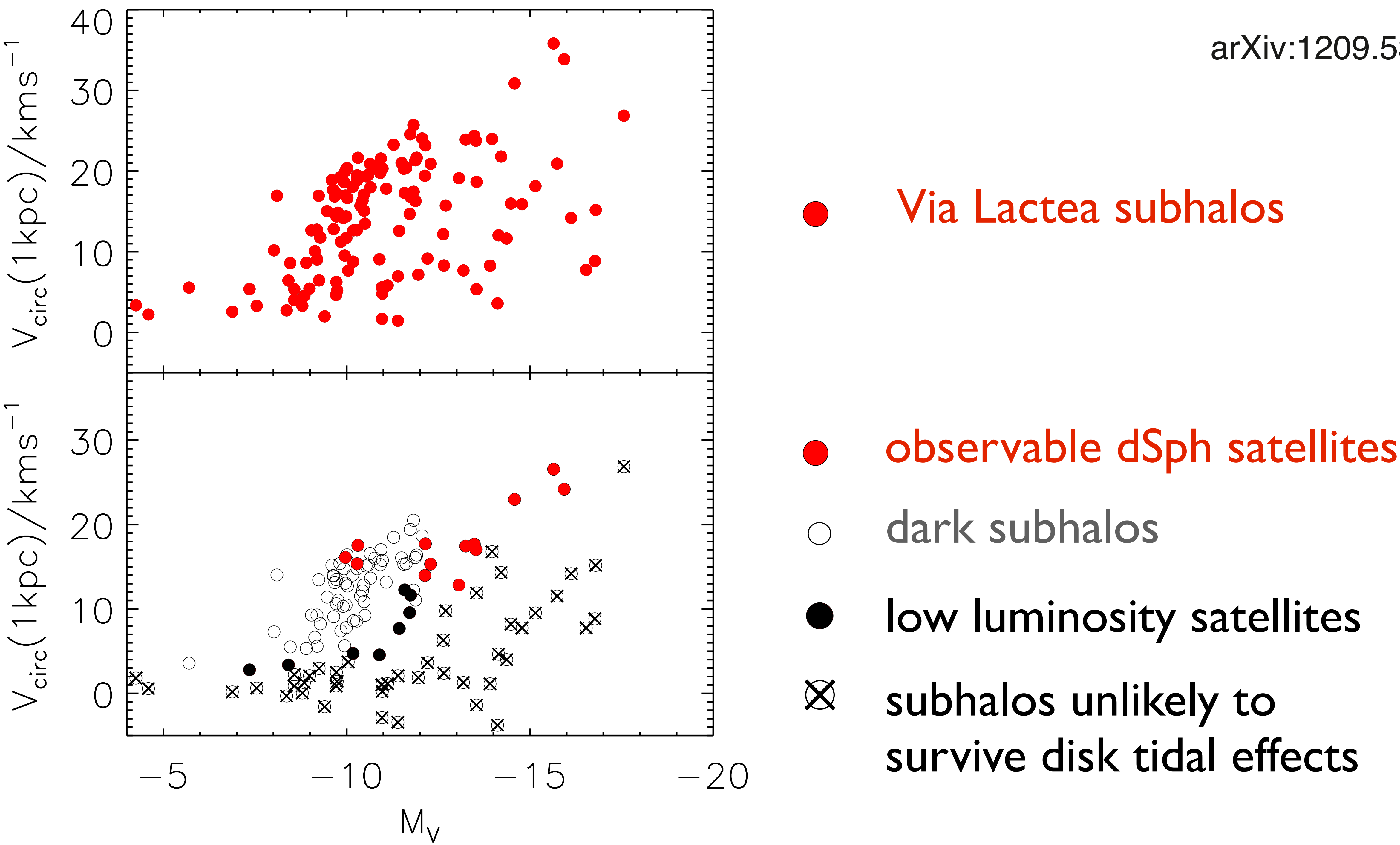
Based on simulations in Zolotov+2012 with force softening 174 pc, $M_{DM} = 1.3\times10^5\ M_\odot$, and $M_{baryon} = 2.7\times10^4\ M_\odot$. This is at best barely adequate resolution.

A BARYONIC SOLUTION TO THE MISSING SATELLITES PROBLEM

Alyson M. Brooks, Michael Kuhlen, Adi Zolotov, Dan Hooper

Zolotov et al. (2012) have suggested a correction to be applied to the central masses of dark matter-only satellites in order to mimic the effect of the flattening of the dark matter cusp due to supernova feedback in luminous satellites, and enhanced tidal stripping due to the presence of a baryonic disk. In this paper, we apply this correction to the z=0 subhalo masses from the high resolution, dark matter-only Via Lactea II simulation, and find that the number of massive subhalos is dramatically reduced. We conclude that baryonic processes have the potential to solve the missing satellites problem.

arXiv:1209.5394



Effects of baryons on the circular velocities of dwarf satellites

Kenza Arraki, Anatoly Klypin, Shurud More, Sebastian Trujillo-Gomez (arXiv:1212.6651)

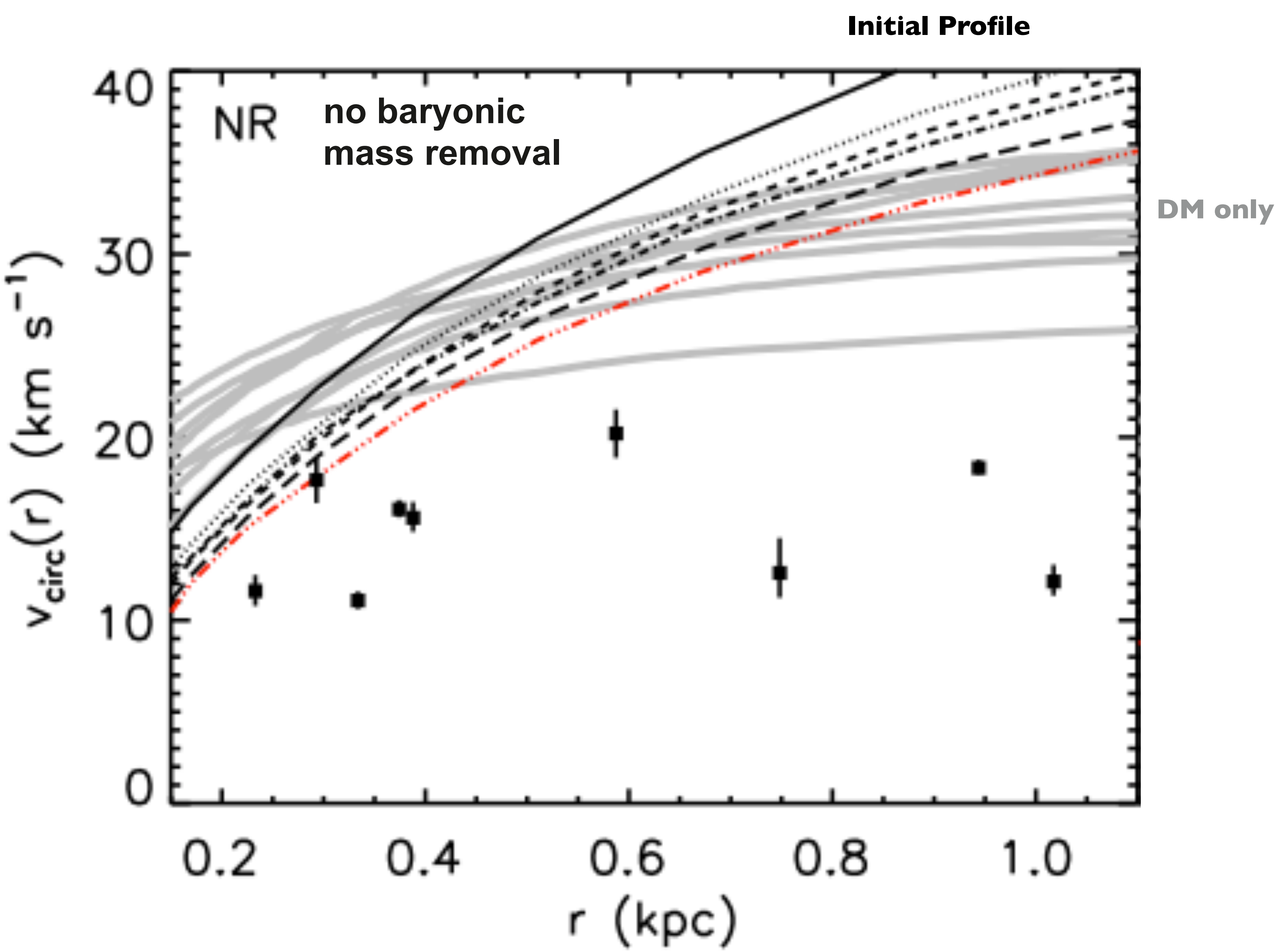
(and Kenza's poster)

High resolution N-body simulations: 20 pc, $m_1 = 10^3$ Msun

Satellites: r_s=4 kpc v_{max}=63 km/s m_0=3.20x10^{10}

MW halo: r_s=25 kpc v_{max}=180 km/s m_0=1.4x10^{12}

MW disk: r_0=3.0 kpc m_0=6x10^{10}



- Effects of baryons on dSph is unexpectedly strong, ~ $(1 - f_b)^4 \approx 50\%$
- Fast or slow removal of a large fraction of baryons from the central region results in adiabatic expansion of the dwarf
- Interaction with central disk on close orbits further reduces satellite central density and V_{circ}
- Annihilation signal may be overestimated with a large boost factor from substructure.

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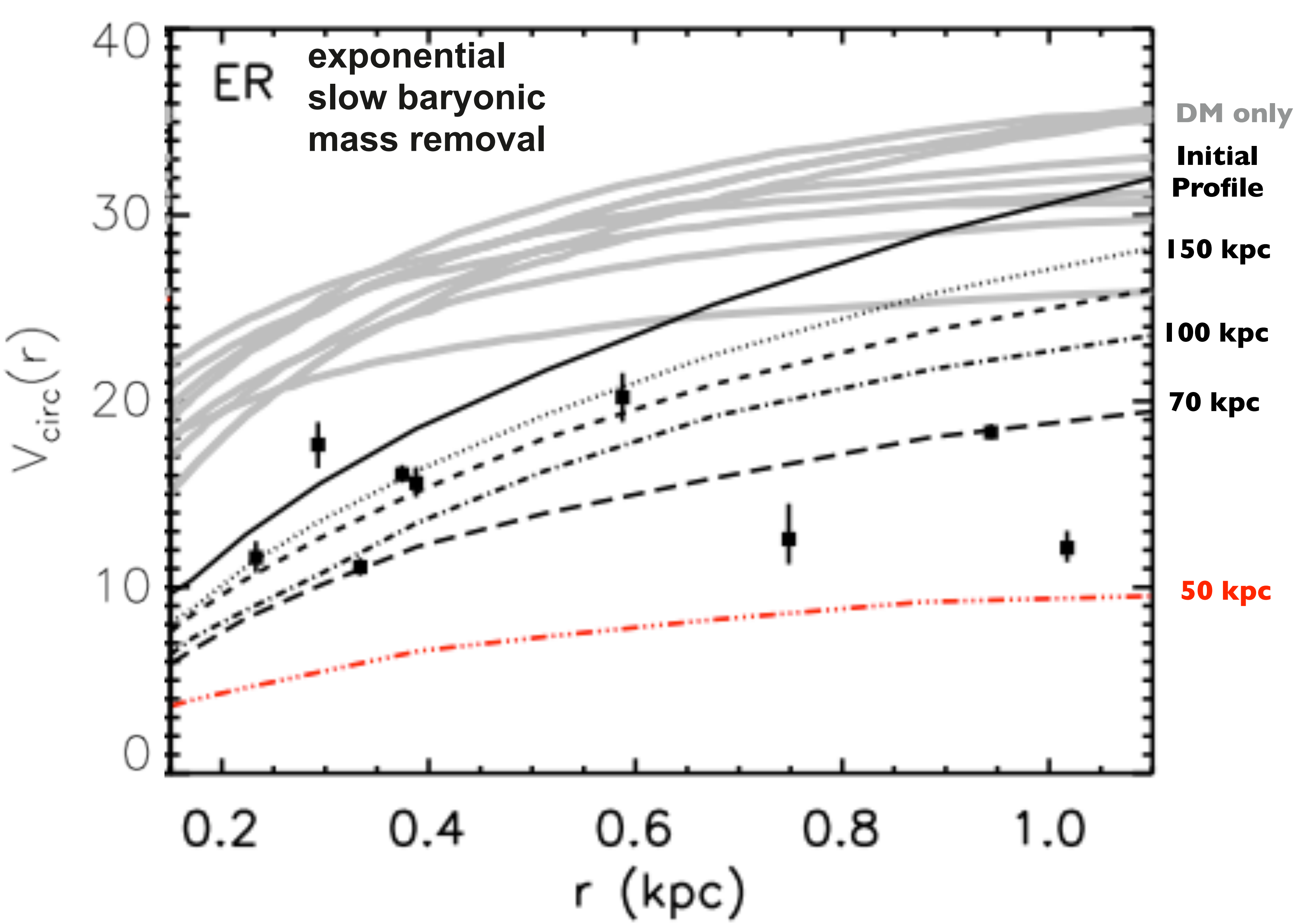

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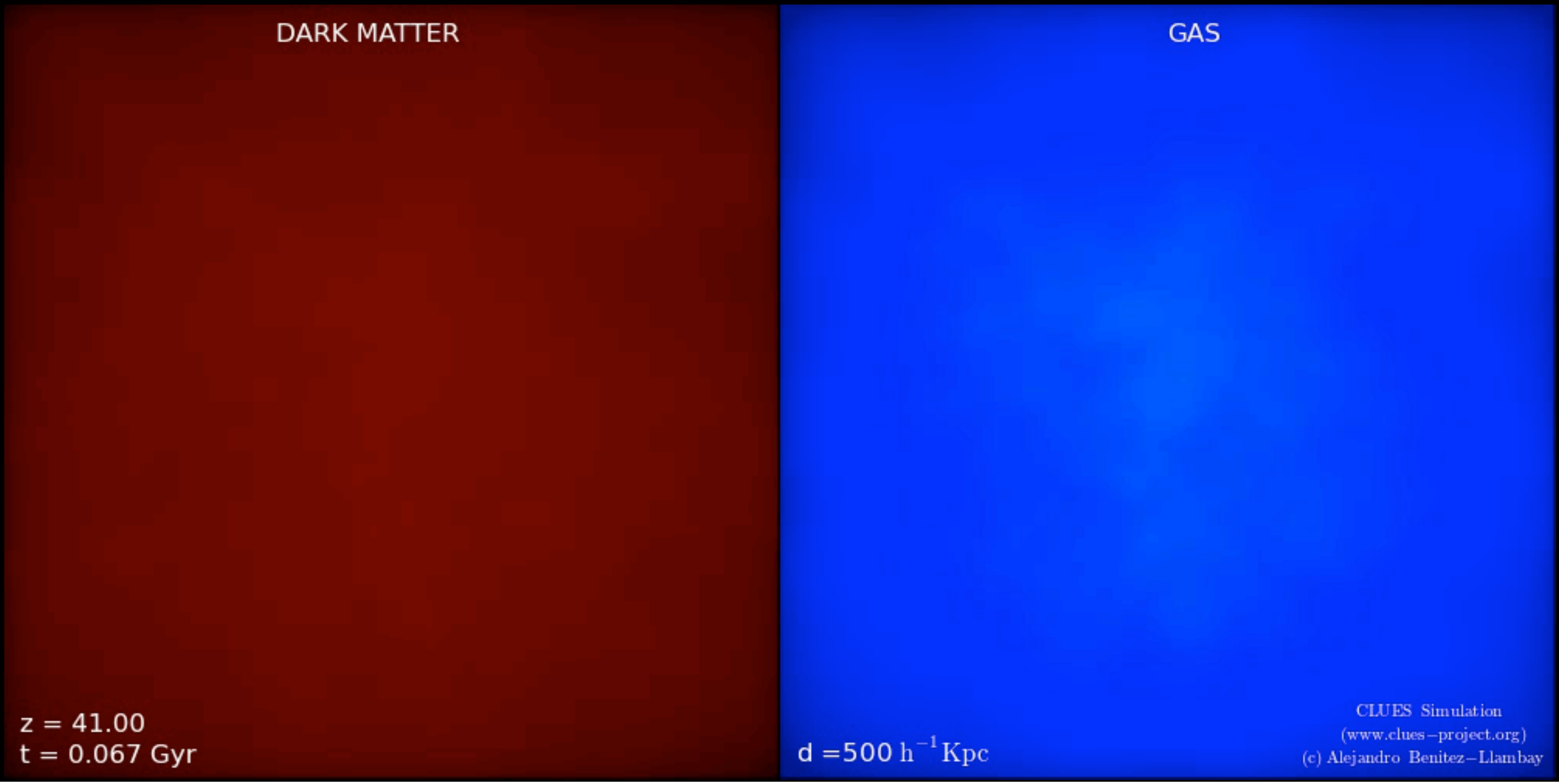
DWARF GALAXIES AND THE COSMIC WEB

arXiv:1211.0536

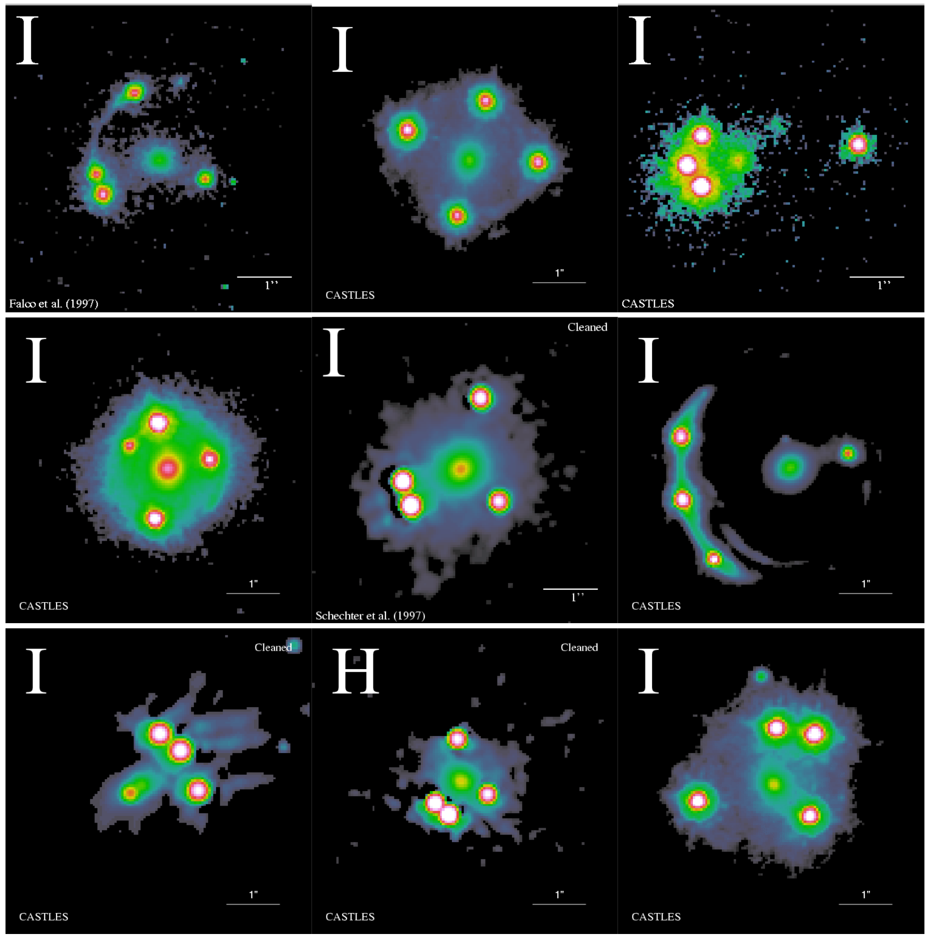
Alejandro Beń ıtez-Llambay, Julio F. Navarro, Mario G. Abadi, Stefan Gottlöber, Gustavo Yepes, Yehuda Hoffman, Matthias Steinmetz

We use a cosmological simulation of the formation of the Local Group of Galaxies to identify a mechanism that enables the removal of baryons from low-mass halos without appealing to feedback or reionization. As the Local Group forms, matter bound to it develops a network of filaments and pancakes. This moving web of gas and dark matter sweeps a large volume, overtaking many halos. Their gas can be efficiently removed by ram-pressure. This "cosmic web stripping" may help to explain the scarcity of dwarf galaxies compared with the numerous low-mass halos expected in ΛCDM.



Radio flux-ratio anomalies

Quasar lenses



(CASTLES project, http://www.cfa.harvard.edu/castles)

Radio flux-ratio anomalies ⇒

Strong evidence for dark matter clumps with M ~ 10^6 - 10^8 Msun as expected in ΛCDM

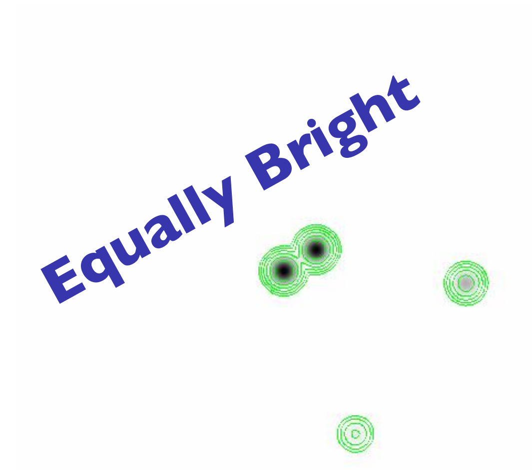
Flux ratio anomalies are generic

"Easy" to explain image positions (even to ∼0.1% precision)

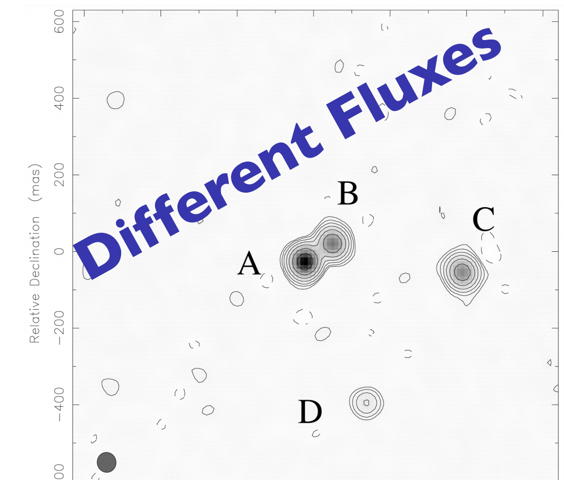
- ellipsoidal galaxy
- tidal forces from environment

But hard to explain flux ratios!

expected



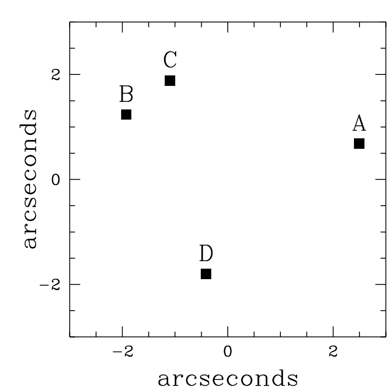
observed *(Marlow et al. 1999)*

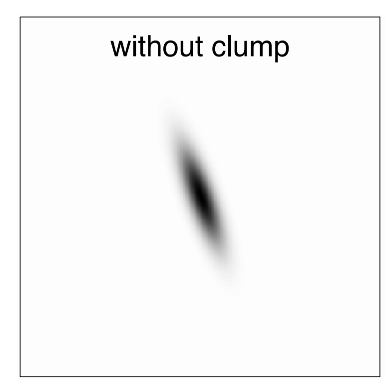


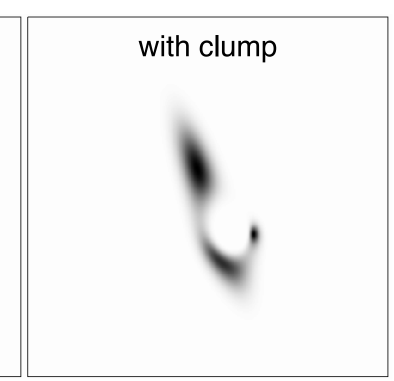
Substructure and lensing

Q) What happens if lens galaxies contain mass clumps?

A) The clumps distort the images on small scales.







(cf. Mao & Schneider 1998; Metcalf & Madau 2001; Chiba 2002)

Chuck Keeton

The Aquarius simulations have not quite enough substructure to explain quad-lens radio quasar flux anomalies -- but perhaps including baryons in simulations will help.

Effects of dark matter substructures on gravitational lensing: results from the Aquarius simulations

D. D. Xu, Shude Mao, Jie Wang, V. Springel, Liang Gao, S. D. M. White, Carlos S. Frenk, Adrian Jenkins, Guoliang Li and Julio F. Navarro

MNRAS **398,** 1235–1253 (2009)

We conclude that line-of-sight structures can be as important as intrinsic substructures in causing flux-ratio anomalies. ... This alleviates the discrepancy between models and current data, but a larger observational sample is required for a stronger test of the theory.

Effects of Line-of-Sight Structures on Lensing Flux-ratio Anomalies in a ΛCDM Universe

D. D. Xu, Shude Mao, Andrew Cooper, Liang Gao, Carlos S. Frenk, Raul Angulo, John Helly

MNRAS (2012)

We investigate the statistics of flux anomalies in gravitationally lensed QSOs as a function of dark matter halo properties such as substructure content and halo ellipticity. ... The constraints that we are able to measure here with current data are roughly consistent with ΛCDM N-body simulations.

Constraints on Small-Scale Structures of Dark Matter from Flux Anomalies in Quasar Gravitational Lenses

R. Benton Metcalf, Adam Amara

MNRAS 419, 3414 (2012)

Substructure in lens galaxies: first constraints on the mass function

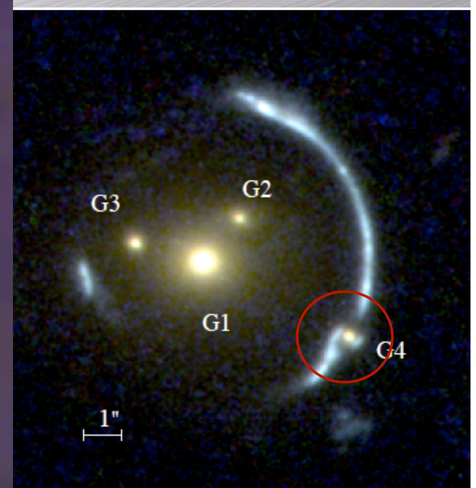
Simona Vegetti (MIT)

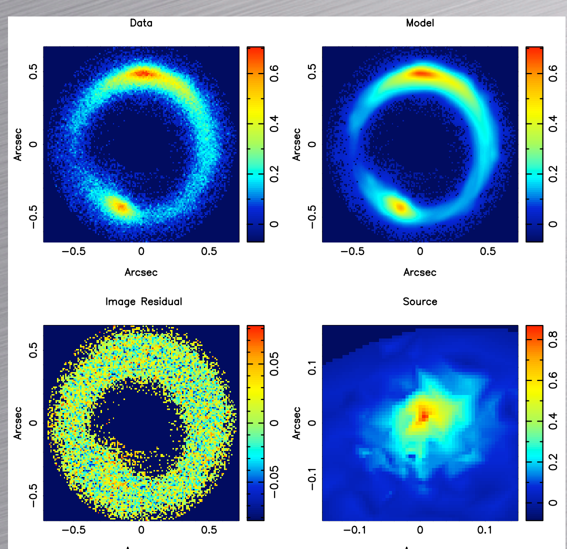
Gravitational detection of a low-mass dark satellite galaxy at cosmological distance, 2012 Nature

Talk at KITP conference "First Light and Faintest Dwarfs"

How do we recognise the effect of substructure?

Extended galaxy





Substructure as a truncated pseudo Jaffe

$$M_{sub} = (1.9 \pm 0.1) \times 10^8 M_\odot$$

$$M(<0.6) = (1.15 \pm 0.06) \times 10^8 M_\odot$$

$$M(<0.3) = (7.24 \pm 0.6) \times 10^7 M_\odot$$

Substructure as SIS

$$M(<0.3) = 3.4 \times 10^7 M_\odot$$

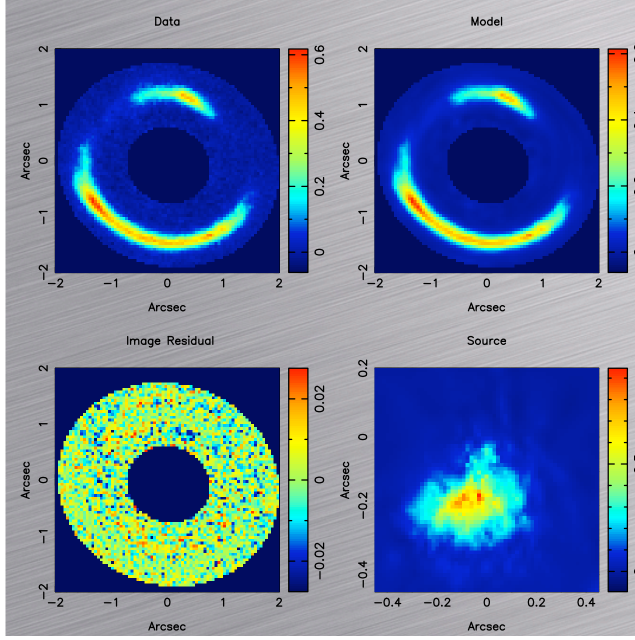
$$\sigma_v \approx 16 \ km \ s^{-1}$$

$$V_{max} \approx 27 \ km \ s^{-1}$$

$\Delta \log E = 65.0$ $\quad 12 \ \sigma \ detection$

J0946+1066 - Double ring

Power-Law smooth model + Power-Law substructure



$$M_{\rm sub} = (3.51 \pm 0.15) \times 10^9 M_\odot$$

$$r_t = 1.1 \ kpc$$

$$\Delta \log \mathcal{E} = -128.0$$

equivalent to a ~16σ detection

$$M_{\rm 3D}(<0.3) = 5.83 \times 10^8 M_\odot$$

"Our results are consistent with the predictions from cold dark matter simulations at the 95 per cent confidence level, and therefore agree with the view that galaxies formed hierarchically in a Universe composed of cold dark matter." Vegetti et al. 2012 Nature 481, 341.

Conclusions

- Surface brightness anomalies can be used to find low mass galaxies at high z
- Simulations show that with HST quality data, 10 systems are sufficient to constrain the mass function
- Using high resolution adaptive optics data and the gravitational imaging technique we discovered an analogue of the Fornax satellite at redshift about 1
- The first constraints on the mass function are consistent with prediction from CDM (large errors ....)

Dark Matter Substructure Detection Using Spatially Resolved Spectroscopy of Lensed Dusty Galaxies Yashar Hezaveh, Neal Dalal, Gilbert Holder, Michael Kuhlen, Daniel Marrone, Norman Murray, Joaquin Vieira arXiv:1210.4562

We find that in typical dusty star forming galaxy (DSFG) lenses, there is a ~ 55% probability of detecting a substructure with $M > 10^8 M_\odot$ with more than 5σ detection significance in ***each*** lens with spatially resolved spectroscopy, if the abundance of substructure is consistent with previous lensing results. The full ALMA array, with its significantly enhanced sensitivity and resolution, should improve these estimates considerably. Given the sample of ~ 100 lenses provided by surveys like the South Pole Telescope, our understanding of dark matter substructure in typical galaxy halos is poised to improve dramatically over the next few years.

Constraining the substructure of dark matter haloes with galaxy-galaxy lensing Ran Li, Houjun Mo, Zuhui Fan, Xiaohu Yang, Frank C. van den Bosch arXiv:1210.6358

Our results show that for SDSS-like surveys, we can only set a loose constraint on the mean mass of subhaloes. With LSST-like surveys, however, both the mean mass and the density profile of subhaloes can be well constrained.

Detection of Substructure in the Gravitationally Lensed Quasar MG0414+0534 using Mid-Infrared and Radio VLBI Observations

Chelsea L. MacLeod, Ramsey Jones, Eric Agol, and Christopher S. Kochanek arXiv:1212.2166

While the observations used here were technically difficult, surveys of flux anomalies in gravitational lenses with the James Webb Space Telescope will be simple, fast, and should well constrain the abundance of substructure in dark matter haloes.

CLUMPY STREAMS FROM CLUMPY HALOS: DETECTING MISSING SATELLITES WITH COLD STELLAR STRUCTURES

Joo Heon Yoon[1*], Kathryn V. Johnston[1], and David W. Hogg[2]

2011 ApJ 731, 58

ABSTRACT

Dynamically cold stellar streams are ideal probes of the gravitational field of the Milky Way. This paper re-examines the question of how such streams might be used to test for the presence of "missing satellites" — the many thousands of dark-matter subhalos with masses $10^5 - 10^7 M_\odot$ which are seen to orbit within Galactic-scale dark-matter halos in simulations of structure formation in ΛCDM cosmologies. Analytical estimates of the frequency and energy scales of stream encounters indicate that these missing satellites should have a negligible effect on hot debris structures, such as the tails from the Sagittarius dwarf galaxy. However, long cold streams, such as the structure known as GD-1 or those from the globular cluster Palomar 5 (Pal 5) are expected to suffer many tens of direct impacts from missing satellites during their lifetimes. Numerical experiments confirm that these impacts create gaps in the debris' orbital energy distribution, which will evolve into degree- and sub-degree-scale fluctuations in surface density over the age of the debris. Maps of Pal 5's own stream contain surface density fluctuations on these scales. The presence and frequency of these inhomogeneities suggests the existence of a population of missing satellites in numbers predicted in the standard ΛCDM cosmologies.

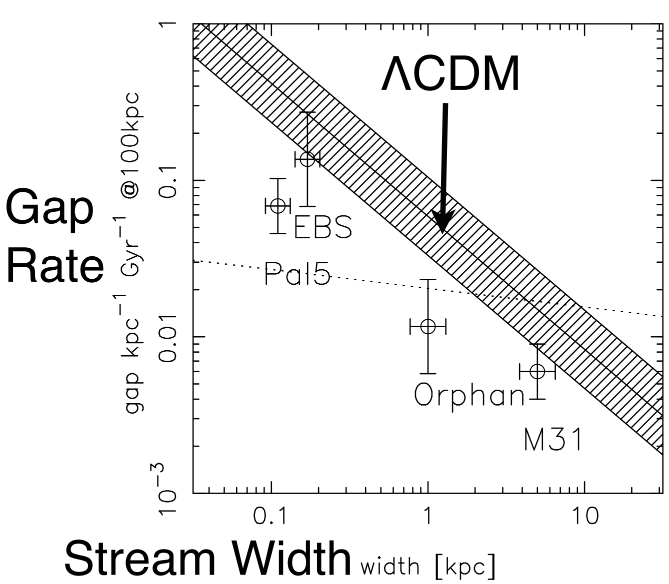


Fig. 11.— The estimated gap rate vs stream width relation for M31 NW, Pal 5, the EBS and the CDM halo prediction. All data have been normalized to 100 kpc. The width of the theoretical relation is evaluated from the dispersion in the length-height relation of Fig. 8. Predictions for an arbitrary alternative mass functions, $N(M) \propto M^{-1.6}$ normalized to have 33 halos above $10^9\,M_\odot$ is shown with a dotted line.

DARK MATTER SUB-HALO COUNTS VIA STAR STREAM CROSSINGS

R. G. Carlberg[1] 2012 ApJ 748, 20

Comparison of the CDM based prediction of the gap rate-width relation with published data for four streams shows generally good agreement within the fairly large measurement errors. **The result is a statistical argument that the vast predicted population of sub-halos is indeed present in the halos of galaxies like M31 and the Milky Way.** The data do tend to be somewhat below the prediction at most points. This could be the result of many factors, such as the total population of sub-halos is expected to vary significantly from galaxy to galaxy, allowing for the stream age would lower the predicted number of gaps for the Orphan stream and possibly others as well, and most importantly these are idealized stream models.

THE PAL 5 STAR STREAM GAPS

R. G. Carlberg[1], C. J. Grillmair[2], and Nathan Hetherington[1]

2012 ApJ 760, 75

ABSTRACT

Pal 5 is a low-mass, low-velocity-dispersion, globular cluster with spectacular tidal tails. We use the Sloan Digital Sky Survey Data Release 8 data to extend the density measurements of the trailing star stream to 23 deg distance from the cluster, at which point the stream runs off the edge of the available sky coverage. The size and the number of gaps in the stream are measured using a filter which approximates the structure of the gaps found in stream simulations. We find 5 gaps that are at least 99% confidence detections with about a dozen gaps at 90% confidence. The statistical significance of a gap is estimated using bootstrap resampling of the control regions on either side of the stream. The density minimum closest to the cluster is likely the result of the epicyclic orbits of the tidal outflow and has been discounted. To create the number of 99% confidence gaps per unit length at the mean age of the stream requires a halo population of nearly a thousand dark matter sub-halos with peak circular velocities above 1 km s^{-1} within 30 kpc of the galactic center. These numbers are a factor of about three below cold stream simulation at this sub-halo mass or velocity but, given the uncertainties in both measurement and more realistic warm stream modeling, are in substantial agreement with the LCDM prediction.

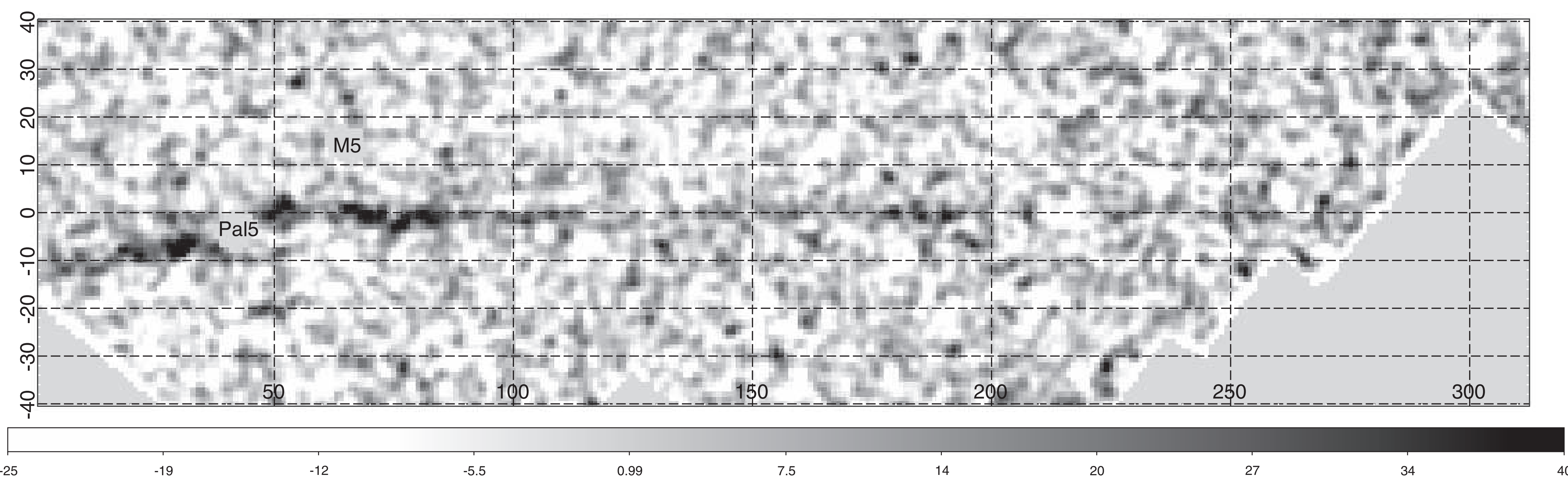


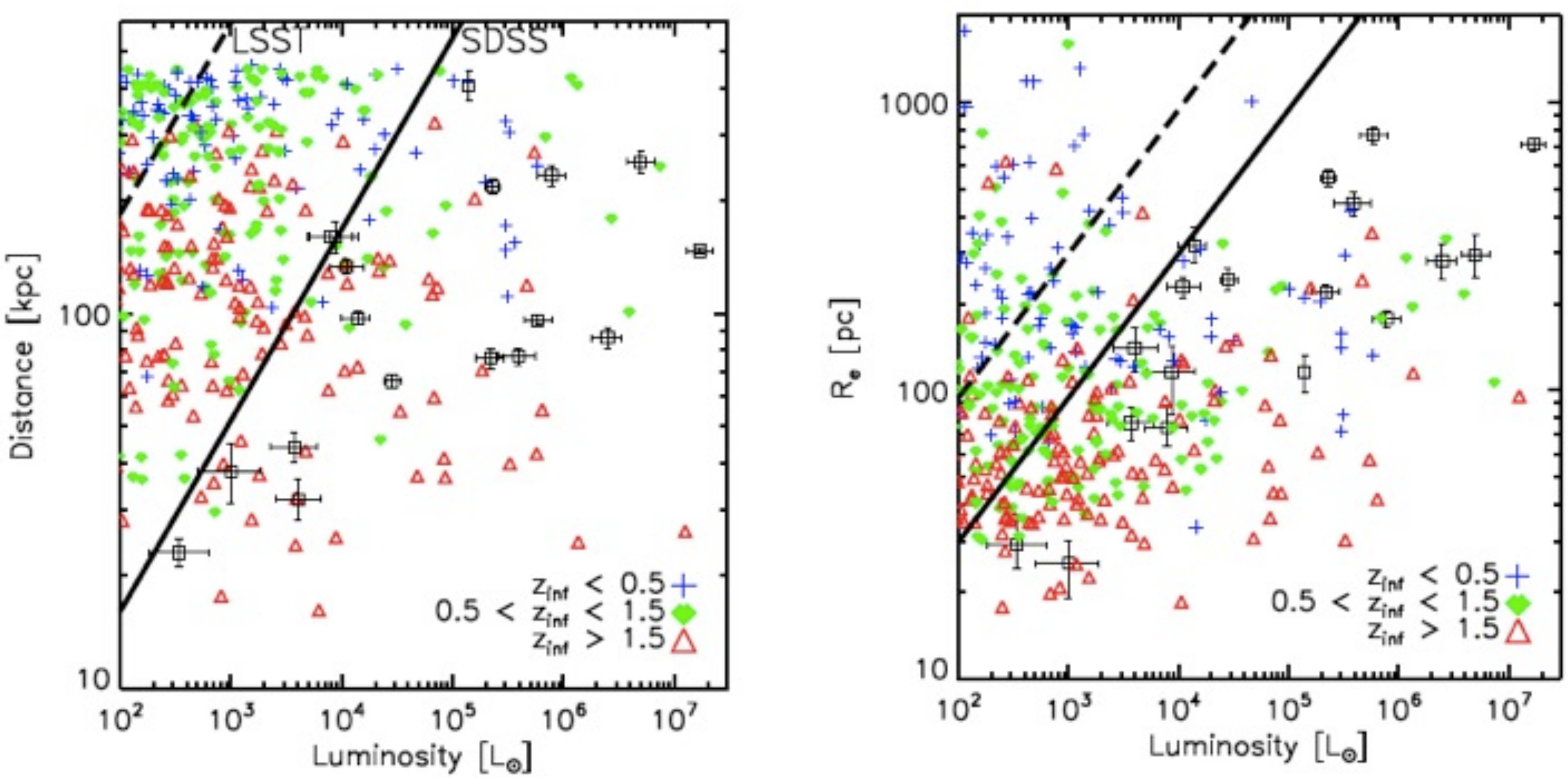
Figure 2. Matched filtered star map of the Pal 5 field, with Pal 5 and the foreground M5 cluster masked out. To remove the varying background, the masked image ha[s] been smoothed over 4° subtracted from the original image, and then smoothed with a 2 pixel, or, 0°.2 Gaussian. The analysis is conducted on the original uncorrelate[d] pixels. We have made no attempt to straighten the southern part of the stream, left of the cluster in this image.

ΛCDM predicts that there is a population of low-luminosity stealth galaxies around the Milky Way. 2010 ApJ

STEALTH GALAXIES IN THE HALO OF THE MILKY WAY

James S. Bullock, Kyle R. Stewart, Manoj Kaplinghat, and Erik J. Tollerud

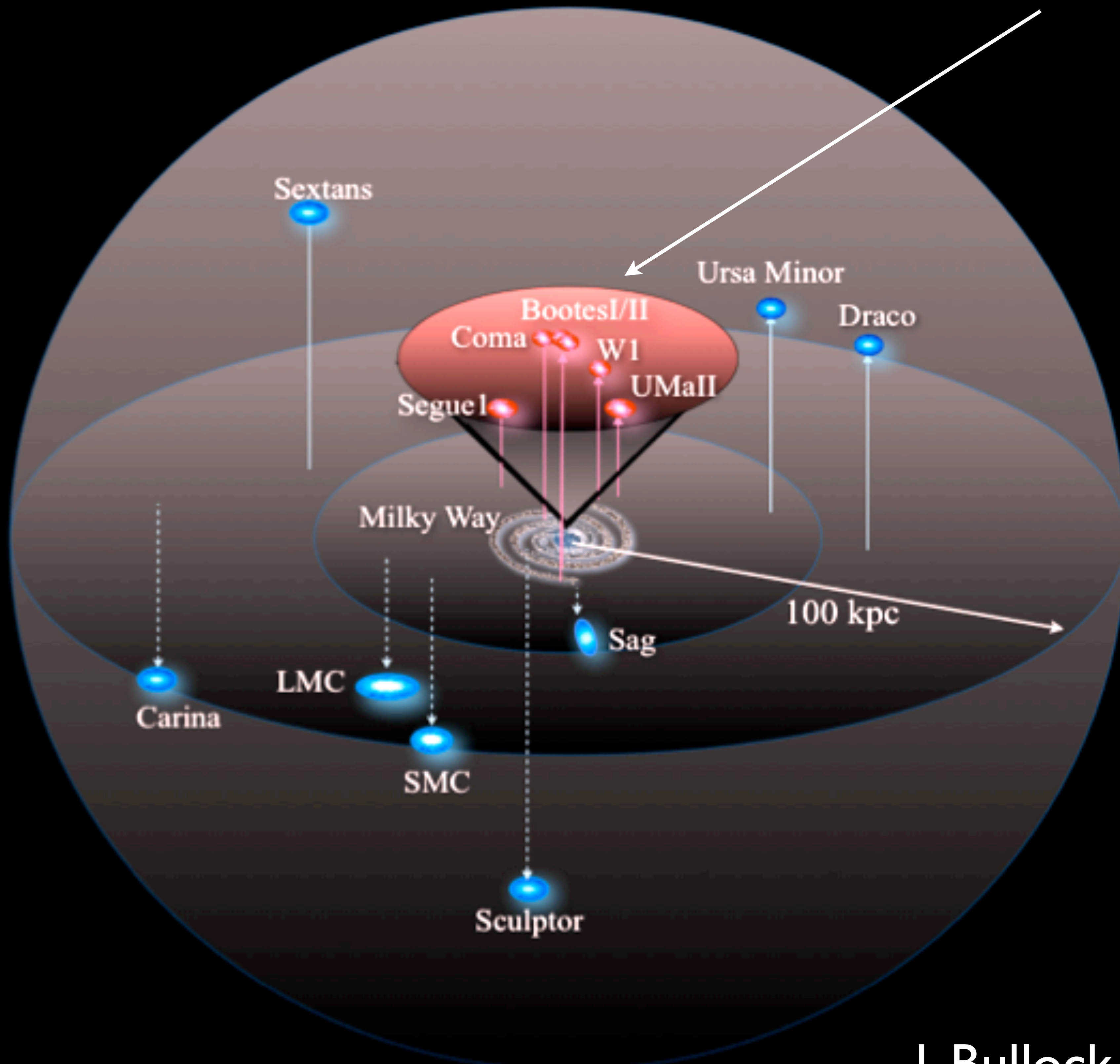
We predict that there is a population of low-luminosity dwarf galaxies with luminosities and stellar velocity dispersions that are similar to those of known ultrafaint dwarf galaxies but they have more extended stellar distributions (half light radii greater than about 100 pc) because they inhabit dark subhalos that are slightly less massive than their higher surface brightness counterparts. One implication is that **the inferred common mass scale for Milky Way dwarfs may be an artifact of selection bias.** A complete census of these objects will require deeper sky surveys, 30m-class follow-up telescopes, and more refined methods to identify extended, self-bound groupings of stars in the halo.



Satellite Infall redshift

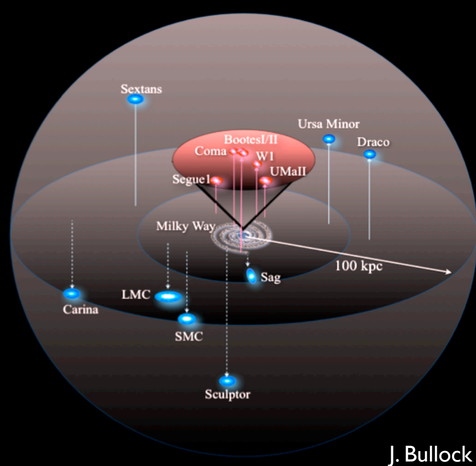
$z_{inf} < 0.5$
$0.5 < z_{inf} < 1.5$
$z_{inf} > 1.5$

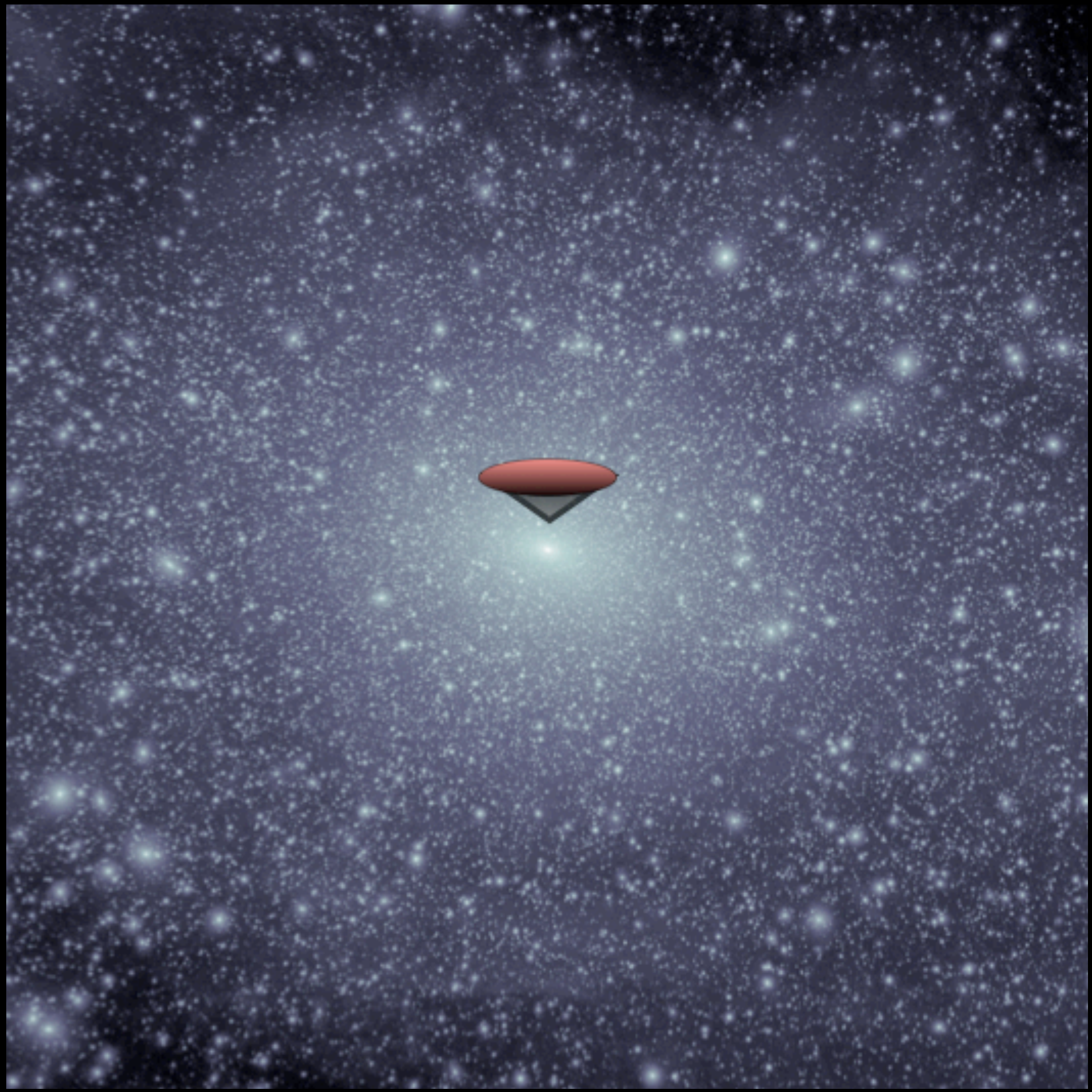
SDSS satellite search



J. Bullock

The search for faint Milky Way satellites has just begun





The Dark Energy Survey will cover a larger region of the Southern Sky, and LSST will go much deeper yet

Conclusions

- CMB and large-scale structure predictions of ΛCDM with WMAP5/7/9 cosmological parameters are in agreement with observations. There are no known discrepancies.
- On galaxy and smaller scales, many of the supposed former challenges to ΛCDM are now at least partially resolved. The "angular momentum catastrophe" in galaxy formation appears to be resolved with better resolution and more realistic feedback. Cusps can be removed by starbursts blowing out central gas.
- Lensing flux anomalies and gaps in cold stellar streams appear to require the sort of substructure seen in ΛCDM simulations. However, the biggest subhalos in ΛCDM MWy-type dark matter halos do not host observed satellites. This "too big to fail" problem may indicate the need for a more complex theory of dark matter -- but it now seems increasingly likely to just require better understanding of the effects of baryonic physics.