Globular Clusters: Chemodynamical Tracers of Galaxy Assembly

Study
Astrophysics of
Globular
clusters in
Extragalactc
Systems

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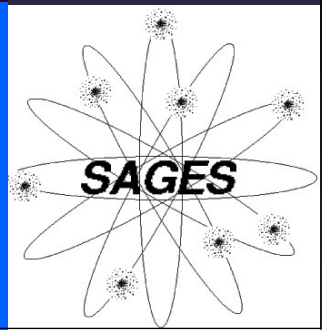
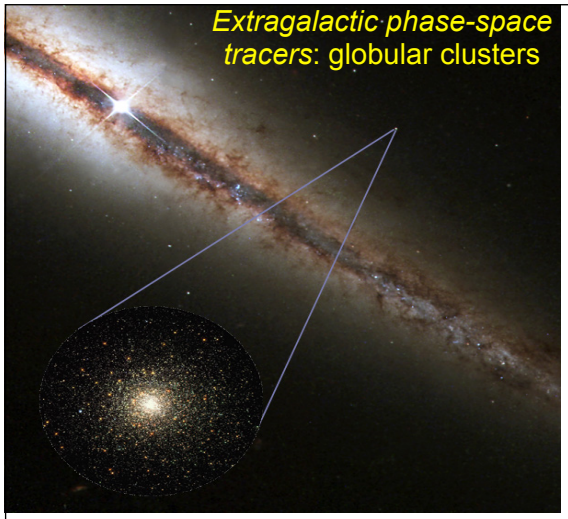
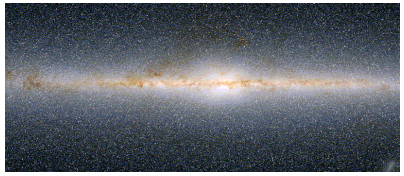
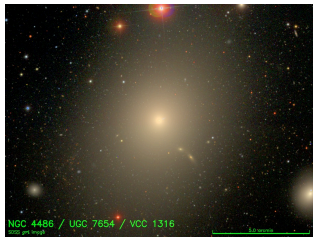




- Almost all galaxies >10^9 $M_\odot$ host GC systems
- GC formation accompanies all major star formation
- Bright (10^5-10^6 $M_\odot$) fossils
- Spectroscopy feasible to ~ 50 Mpc
  - estimate abundance of elements (Fe...)
  - key extension of phase-space
- Used to establish accretion (2-phase) origin of Milky Way halo
  (Searle & Zinn 1978)





Dwarfs: 0 to 10s

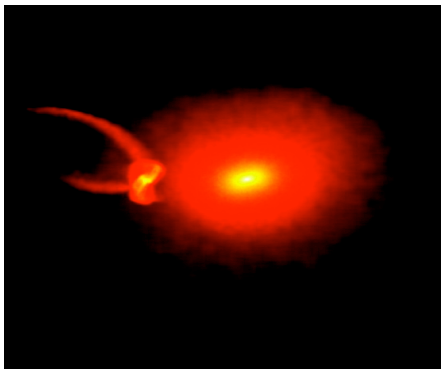
Disks: 10s to 100s

Es: 100s to > 10^4

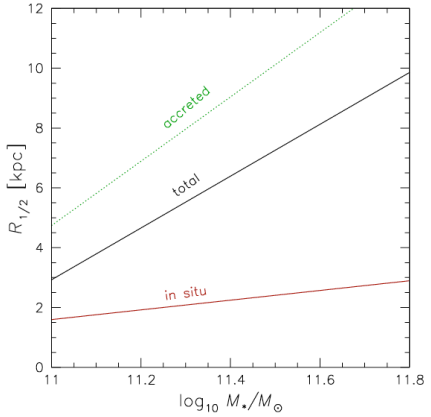
Two-phase galaxy formation

- Motivated by observations of strong size-redshift evolution + theoretical support

Feldmann+2008; Naab+2009; Hopkins+2009; Bezanson+2009; van der Wel+2009; van Dokkum & Brammer 2010; Oser+2010, 2011; Dominguez-Tenreiro+2011



Half-light radius (z=0) versus mass
(after Oser+2010)

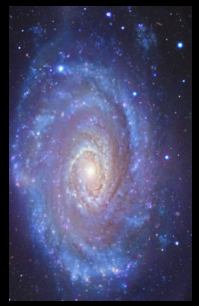


e.g., Khochfar & Silk 2006; Feldmann+2008; Naab+2009; Hopkins+2009; Bezanson+2009; van der Wel+2009; van Dokkum & Brammer 2010; Oser+2010; Dominguez-Tenreiro +2011)

Galaxy assembly: from UCDs to cDs…


UCD


Im


Sc


E/S0

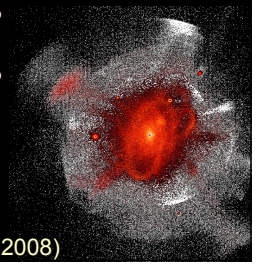

cD

→ *which galaxy types are now assembling most actively?*

→ *(how) can we study ongoing accretion events?*

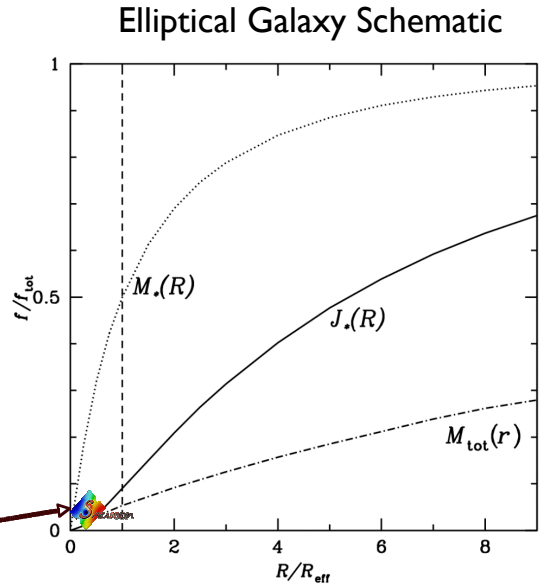
→ *(how) can we constrain past accretion events?*

→ *do the accretion histories agree with ΛCDM?*


(Font+2008)

GCs and stars - unveiling surprises at large radii

>90% of total mass and angular momentum outside 1R_{eff}



Limit of traditional integrated stellar spectroscopy

idealized deVaucouleurs law with dark halo and constant rotation profile

The SLUGGS Survey

http://sluggs.ucolick.org/

SAGES Legacy Unifying Globulars and Galaxies Survey

Chemodynamics for

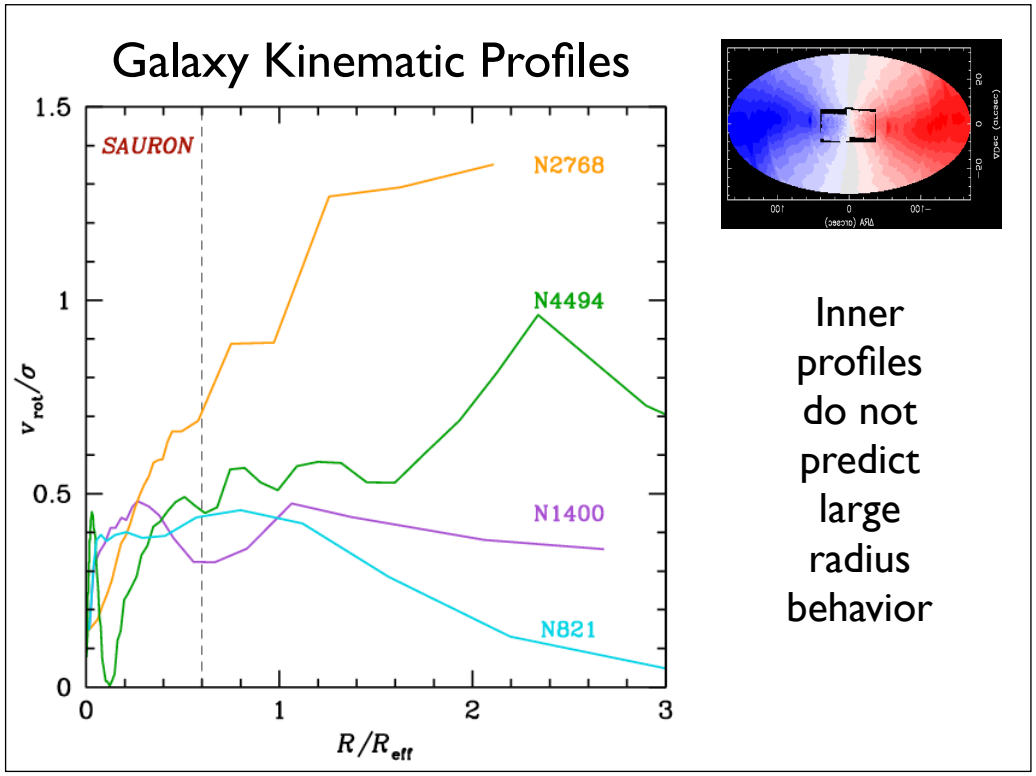
26 nearby early-type galaxies; range of properties (M, env, σ, v/σ.....)

Photometry (Subaru) and spectroscopy (Keck)

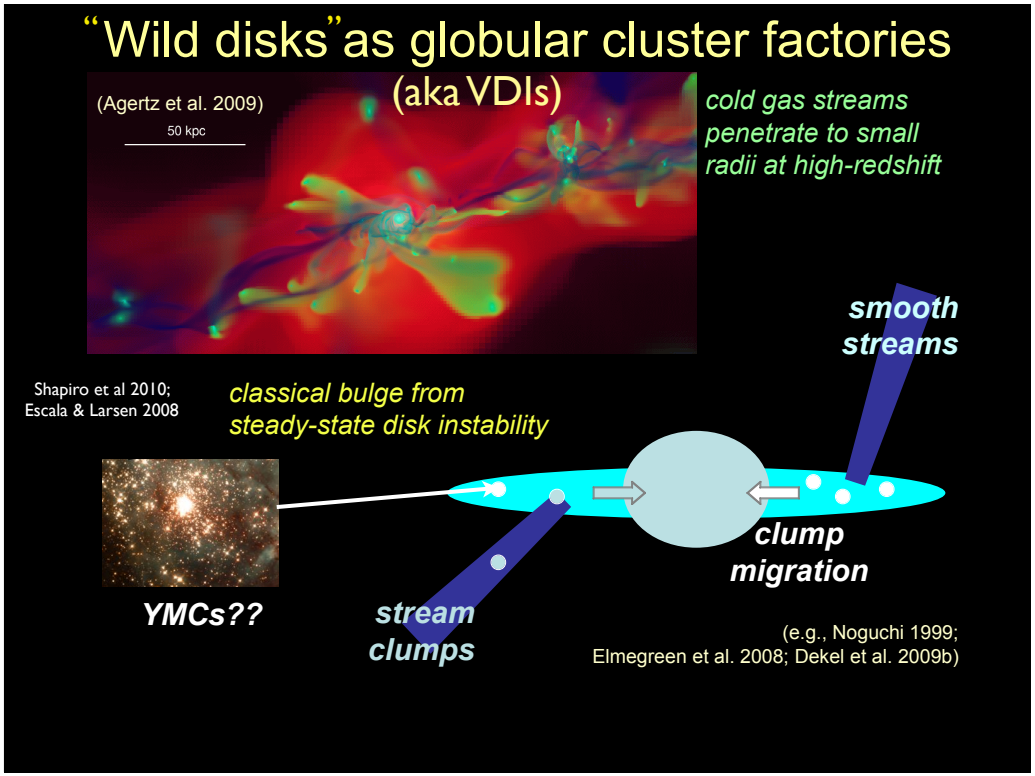
Globular clusters to ~10 r_{eff}

Field stars to ~ 3 r_{eff}

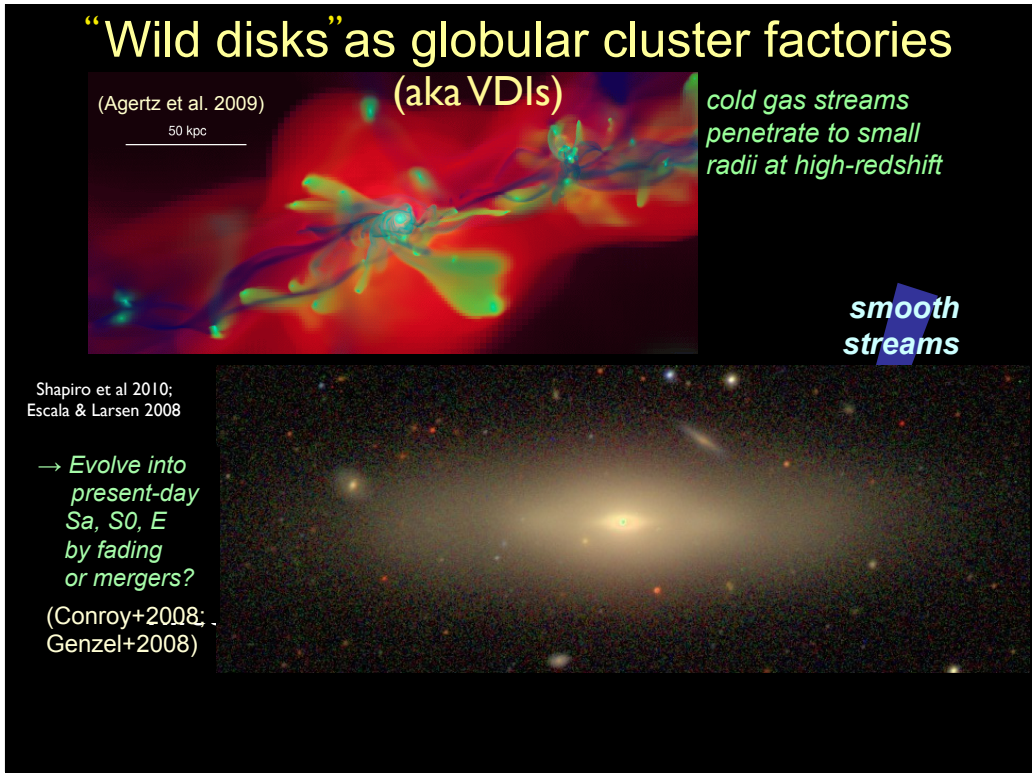
Spectroscopic Mapping of Early-type Galaxies to their Outer Limits



Shows how in the SAURON region, things may look roughly the same (for the fast rotators) but then diverge at large radii
N4494 has a decoupled nuclear disk
Rm = circular-equivalent radius



classical means r^1/4 bulge



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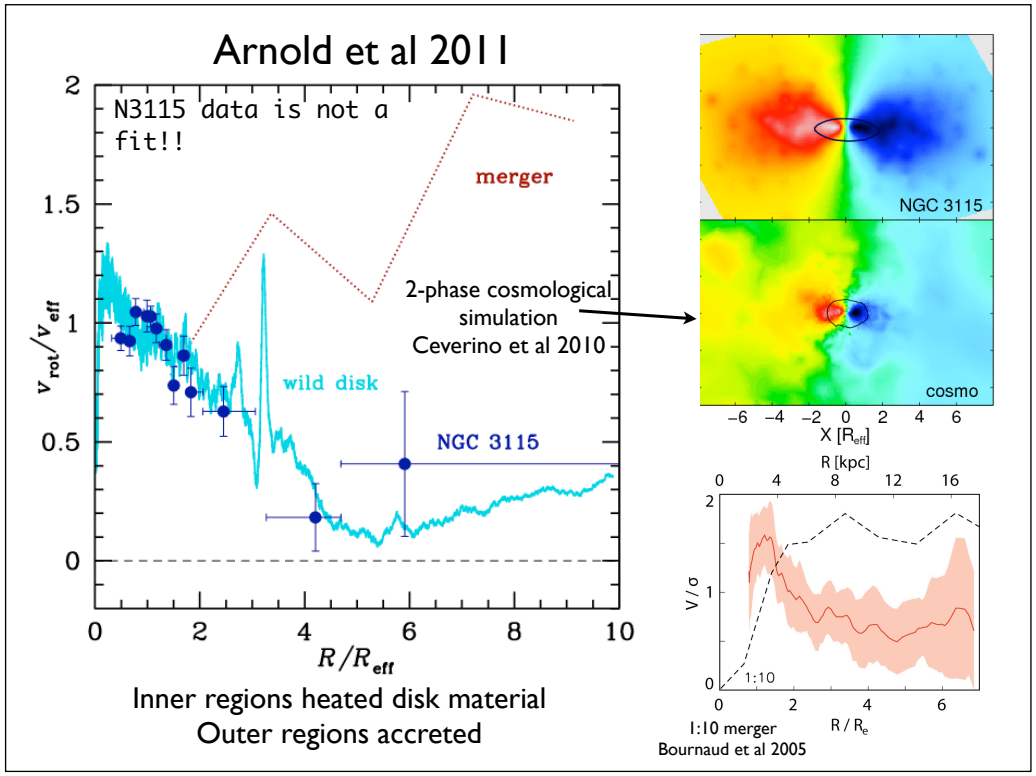
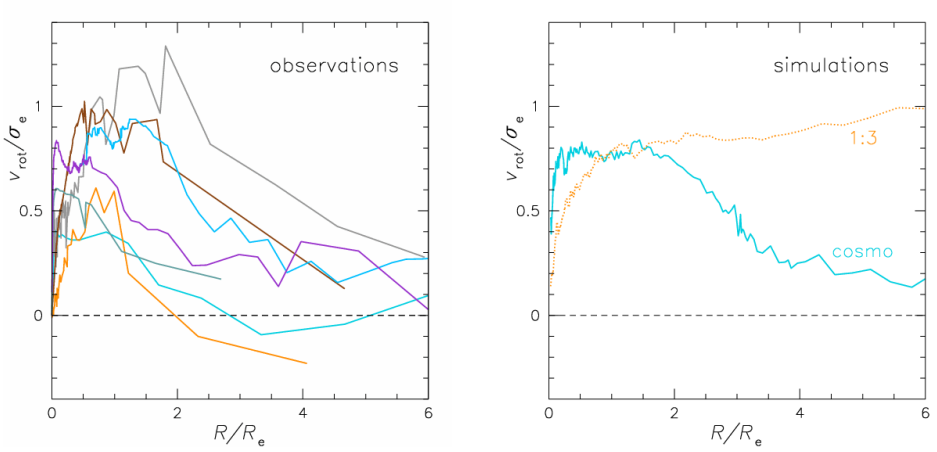


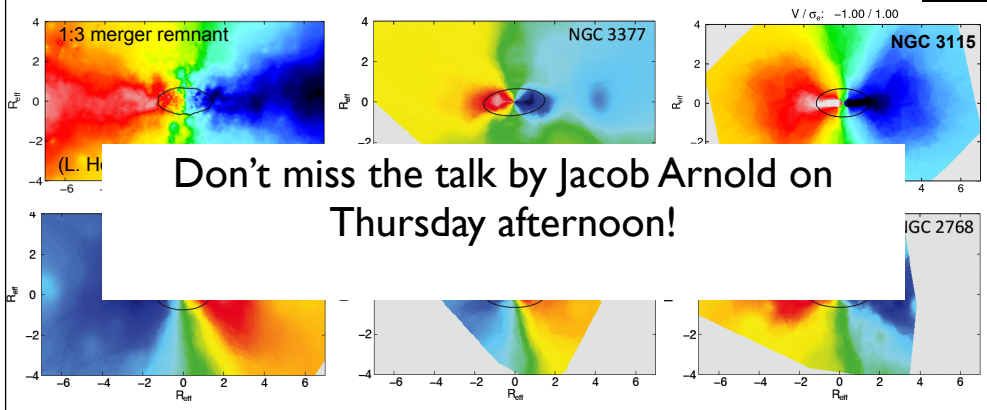
Rotation summary plot. The N3115 data are shown, along with sample predictions. MRGCs and stars (both data and simulations). The GCs/ stars are from a wild disk simulation (Ceverino et al. 2010), and the galaxy merger simulation is Bekki & Peng (2006).
The science point to make here is that N3115 seems to be a two-component system, with a rotating inner component (not just the disk but also the bulge) and a slowly rotating outer component. The wild disk simulations seem to reproduce this, probably by forming the inner regions from heated disk material, and the outer regions from accreted material. You can see that the "GCs" in the simulations go out only so far: these are the ones formed in the disk clumps, and it seems the large-radius material must have come from somewhere else.

Rotation profiles: observations vs simulations



- Outer, slow-rotating envelopes in cosmo sims built up by accretion
- Minor mergers predicted to dilute rotation

(Vitvitska+2002; Abadi+2006; Bournaud+2007)

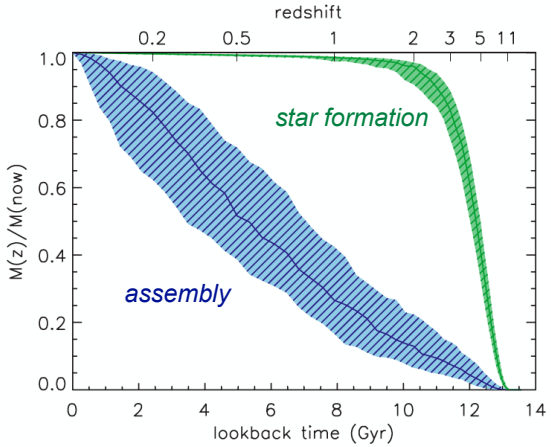


Don't miss the talk by Jacob Arnold on Thursday afternoon!

→ Observed rotation declines outside ~2 R_e *(missed by SAURON)*

→ Predicted major-merger spin-up not found

Brightest cluster galaxies: extreme late assemblers?



(De Lucia & Blaizot 2007)

M87

ΛCDM BCG semi-analytic models:
half the stars **formed** by $z \sim 5$
but not **assembled** until $z \sim 0.5$

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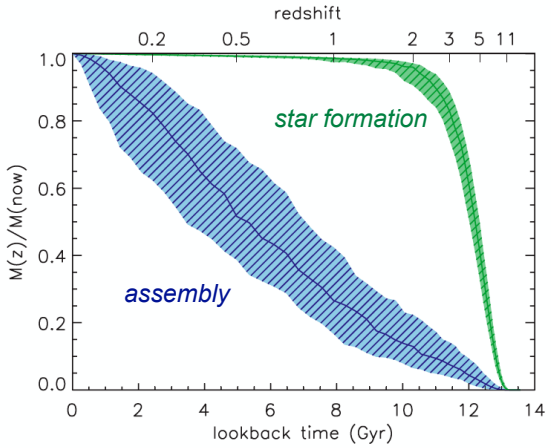

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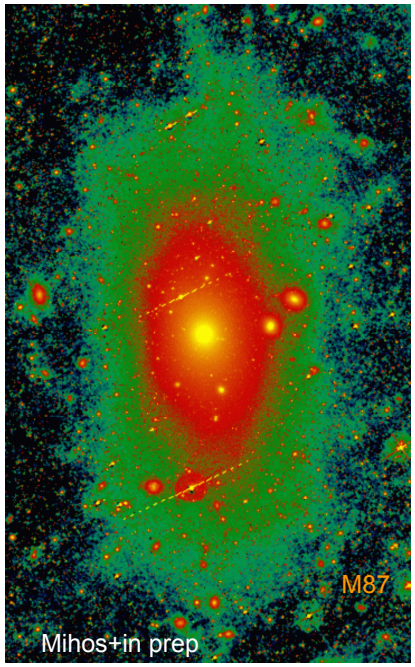
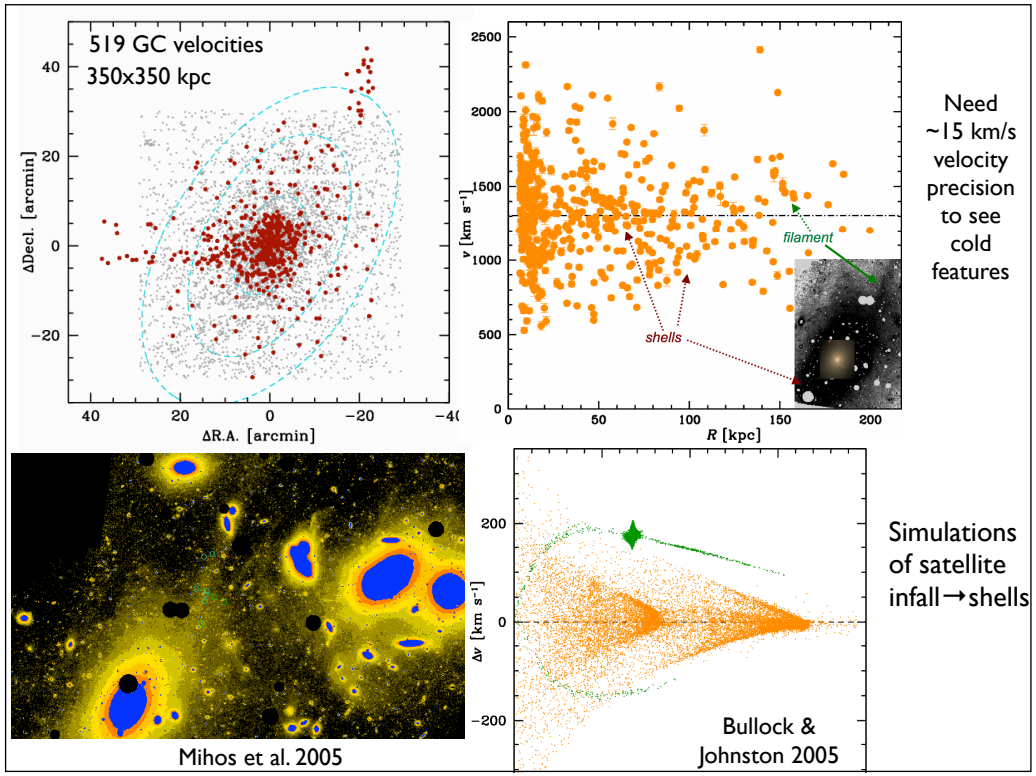
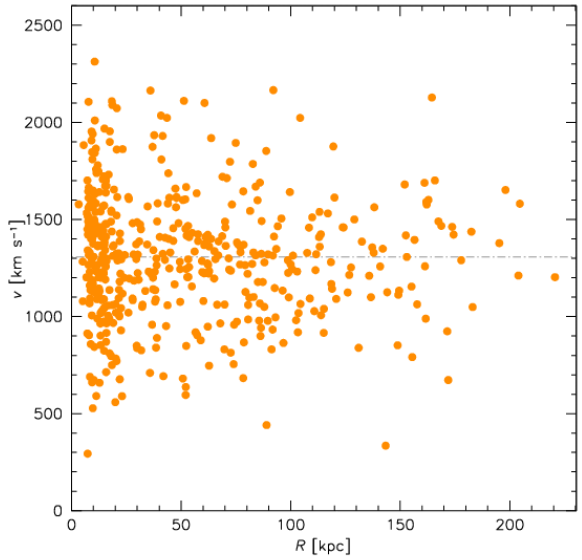




The first shows the 2D distribution of new velocities from the literature, DEIMOS, and MMT/Hectospec: 519 in all! The region shown here is 350x350 kpc. The red dots are the GCs with RVs, the grey dots are the photometrically selected GCs from CFHT/Megacam.
The next plot shows the RVs vs radius. You can see the two V-shaped features which are probably signatures of "shells" of material on near-radial orbits (deposited there by a merger). The point here is that one needs the ~10 km/s velocity precision provided by DEIMOS and Hectospec to see cold features like this.
next is a plot showing the V-features in simulations. The idea is that one can use them to get a nice independent measure of the gravitational potential without using the Jeans equations.
W is line-of-sight velocity, and x is position, defined as some axis along the direction of the collision (of the satellite) - basically a radial distance.

M87: phase-space substructure



Romanowsky+ 2012

High velocity precision reveals cold kinematic structure in halo

Chevron morphology is classic signature of accretion shell

Inferred N_{GC} + coldness of shell →
~ 1/2 L^* galaxy bringing in a few hundred GCs in past ~ 1 Gyr

Supports ΛCDM prediction of recent assembly of BCGs
(e.g., De Lucia & Blaizot 2007)

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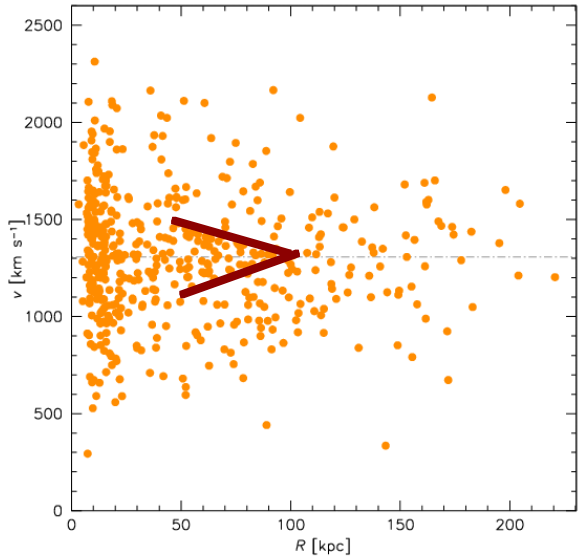

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theoretically BCGs should be very actively accreting c.f. e.g. MW where things are dribbling in
but couldn't really look for it until now (using GCs)

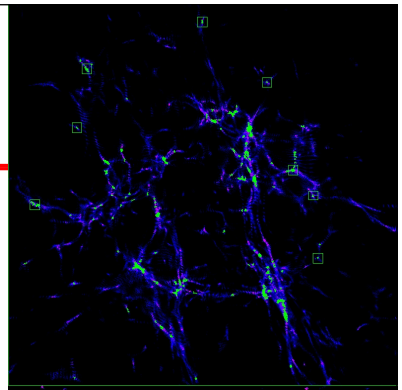
SAGES

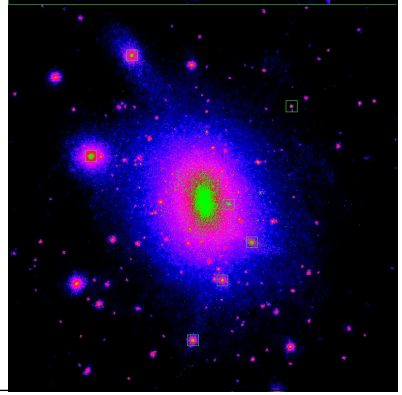
Cosmic Reionization and Metal Poor GCs

N-body simulations suggest that dark matter halos "sitting" on top of large overdensities collapse first (z>10)

MP GCs formed in early DM halos
Formation trucated by reionization?

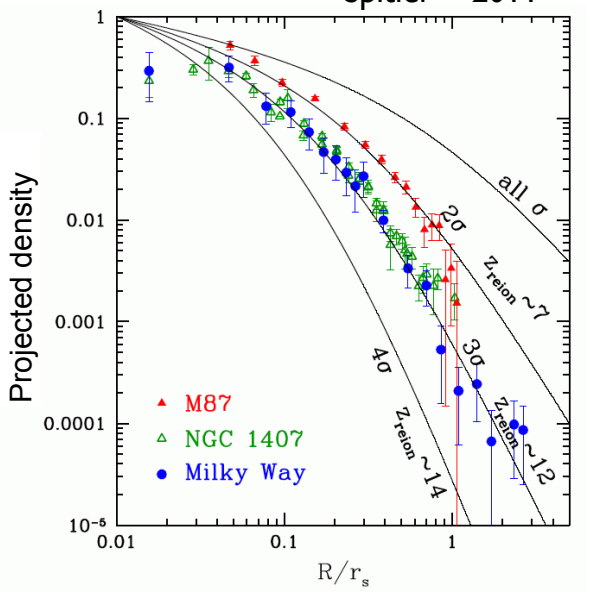
Courtesy
Juerg Diemand





Local constraints on reionization from GCs

Spitler + 2011



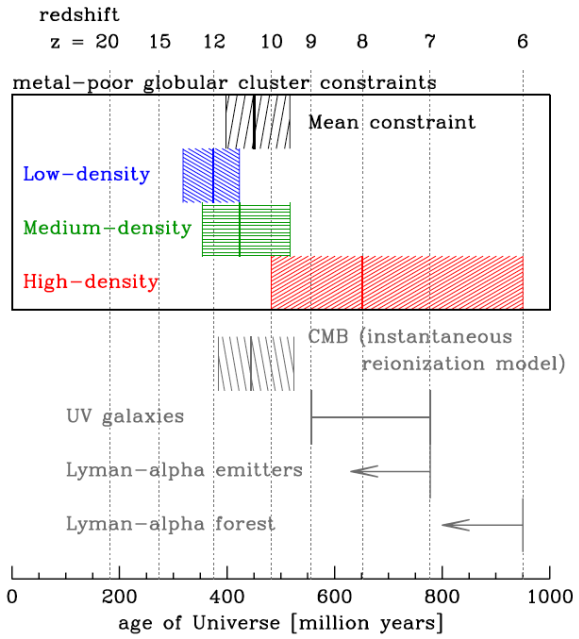
Early formation means more concentrated distribution

Earliest assembling DM subhalos (and associated stars/GCs) are biased toward center of host

Diemand+2005; Moore+2006)

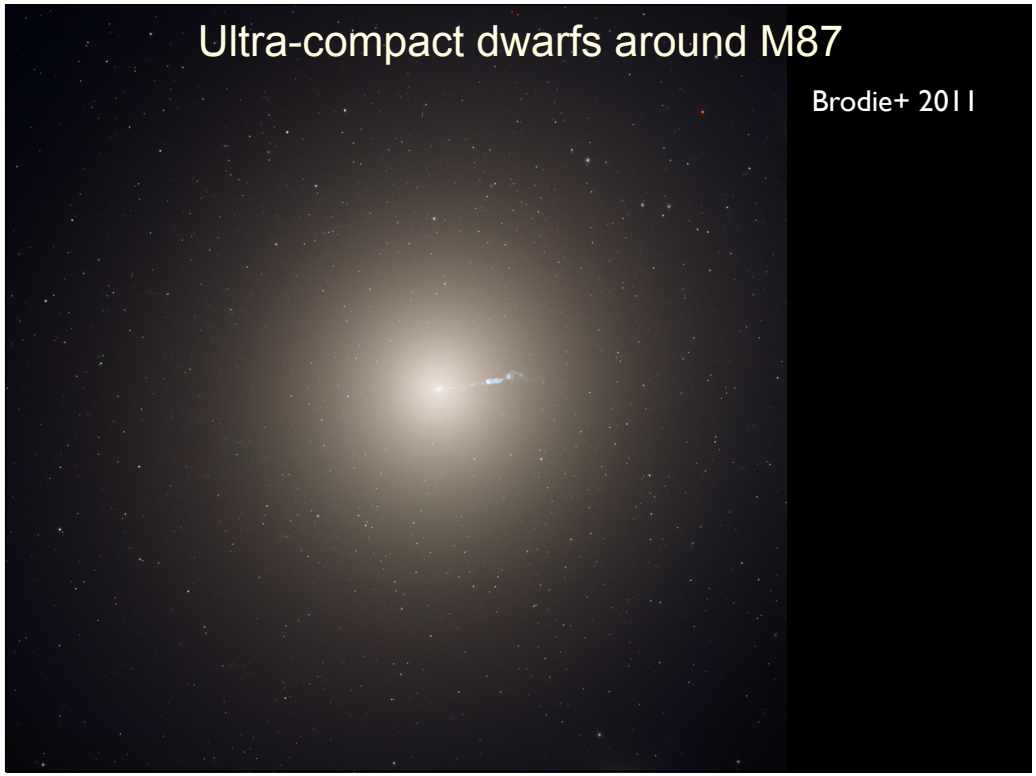
N1407 MP surface density profile,
fitted to a projected fitting function developed by Diemand et al. 2005 to constrain the nu-sigma peak of a given surface density profile. It is a modified NFW. 6.1 kpc/arcmin. HST and Subaru

Local constraints on reionization from GCs



Spitler + 2012

3 galaxies:
z_{reion} = 10.5 ± 1.0
+ environment anti correlation


Ultra-compact dwarfs around M87
Brodie+ 2011

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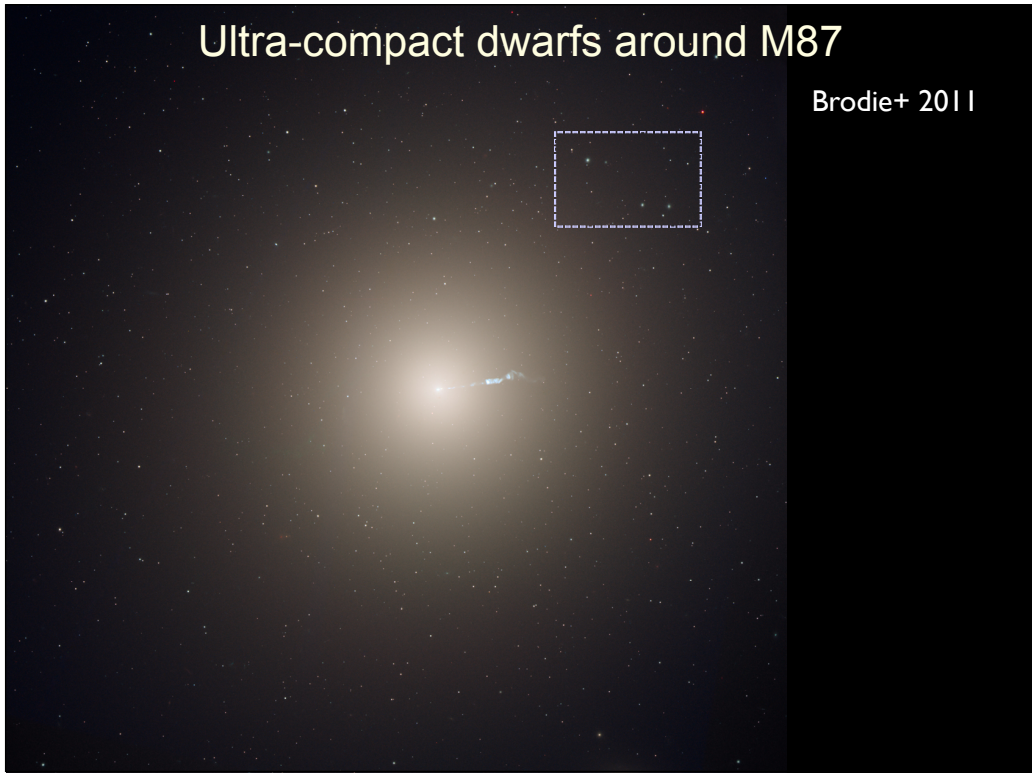
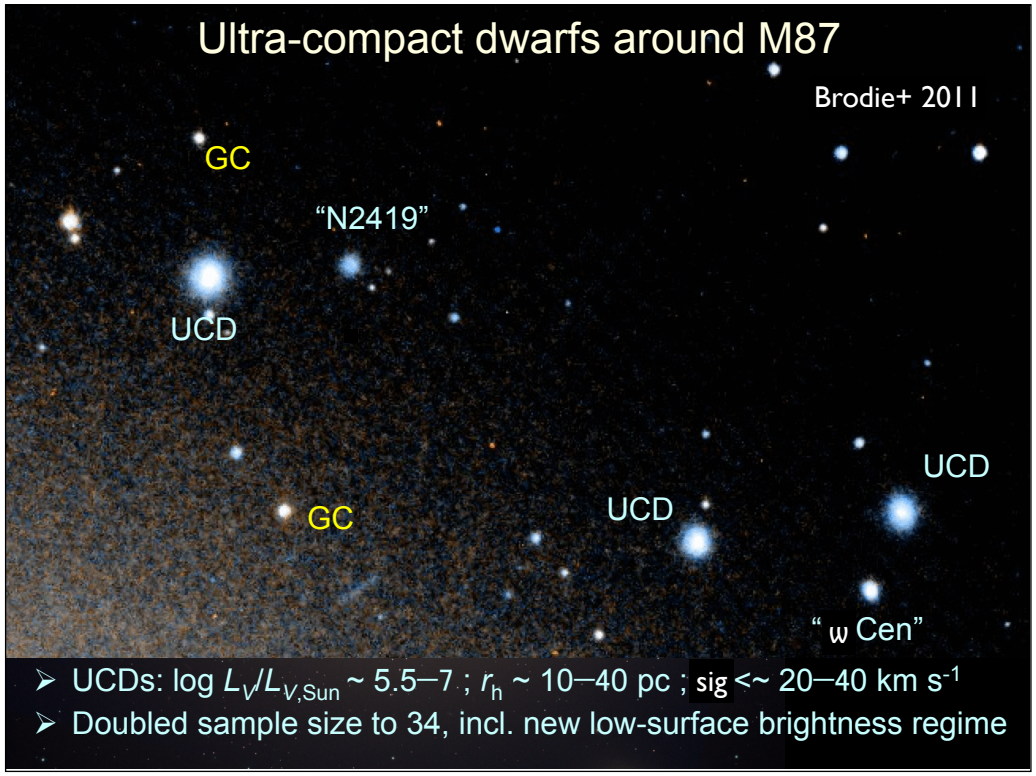
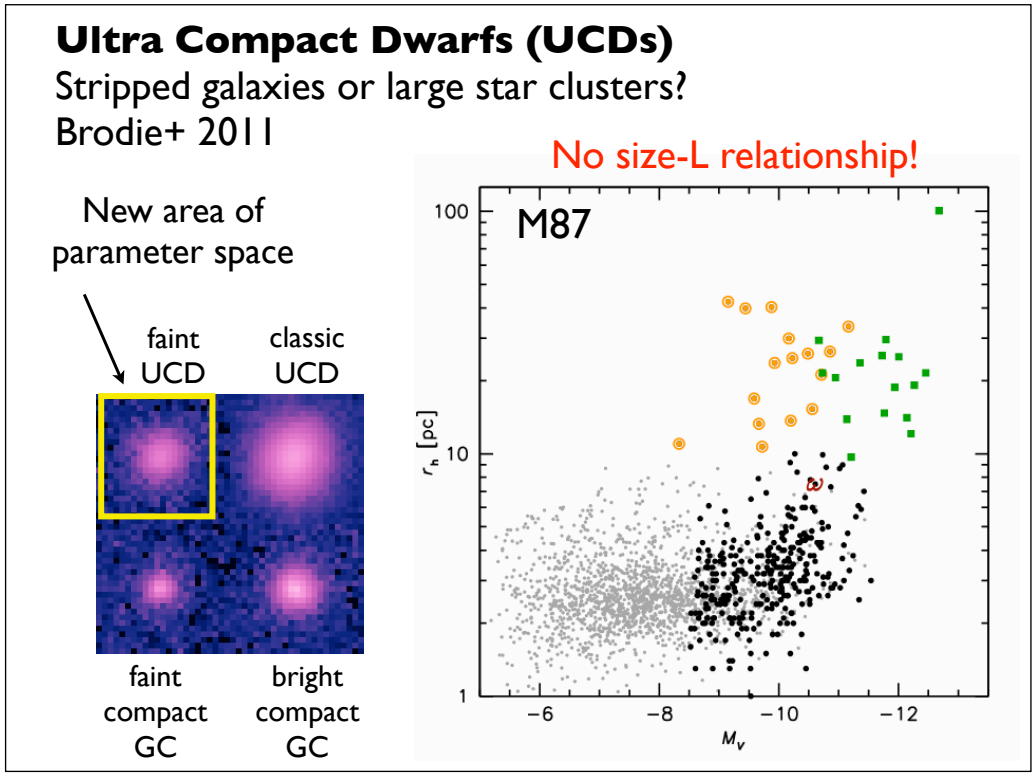



Ultra-compact dwarfs around M87
Brodie+ 2011
GC
"N2419"
UCD
UCD
GC
UCD
" ω Cen"
➢ UCDs: log $L_V/L_{V,Sun}$ ~ 5.5–7 ; r_h ~ 10–40 pc ; sig <~ 20–40 km s^{-1}
➢ Doubled sample size to 34, incl. new low-surface brightness regime

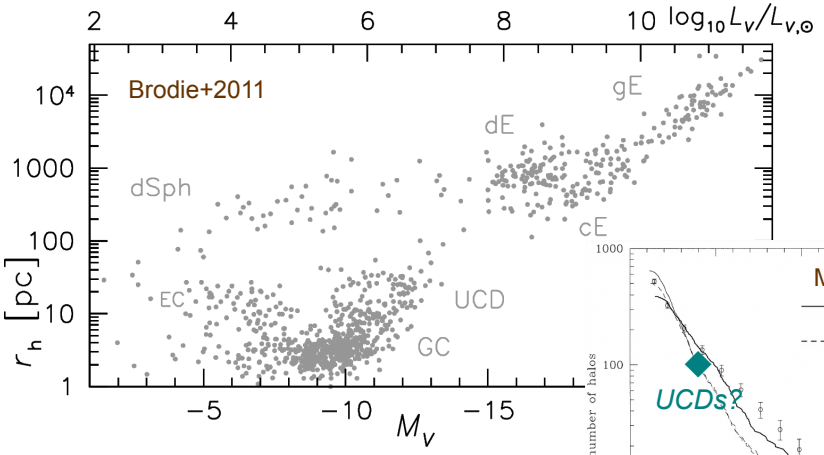


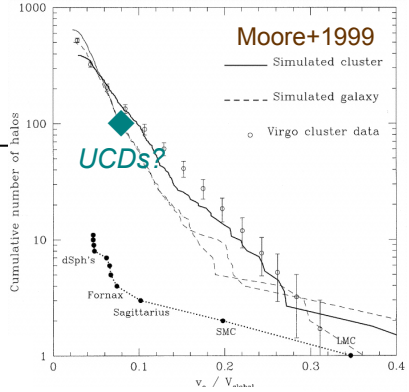
i=19.5, i=21

Clockwise from top-right: classic UCD (####: i=19.5, rh=34 pc), bright compact GC (####: i=19.5, r~3 pc), faint compact GC (####: i=21, r~3 pc), faint UCD (####: i=21, rh=24 pc).

Follows on from M87 sluggs survey

M87 UCDs: *accreted dwarf galaxies?*





~100 UCDs out to ~200 kpc:
significant addition
to subhalo counts

Do UCDs have DM now?
Unclear how to assign to DM halos
but may significantly affect cosmic accounting

SUMMARY

sluggs.ucolick.org

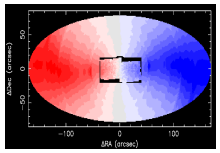
SLUGGS

SAGES Legacy Unifying Globulars and Galaxies Survey

Chemodynamics for 26 nearby ETGs, range of M, env, σ, v/σ.....

Globular clusters to ~10 r_{eff}

Starlight to ~3-4 r_{eff}



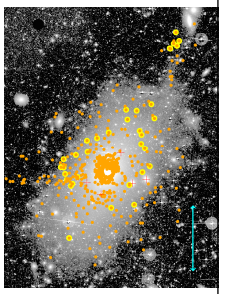
2-PHASE GALAXY ASSEMBLY

GC and stellar kinematics

Halo build up is dominated by minor mergers

Major mergers inconsistent with rapid inner + low outer rotation

Cosmological simulations of "wild disks" + accretion preferred



GC KINEMATICS IN M87

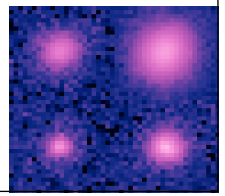
~ 500 wide-field, high-precision (**± 15 km/s**) velocities

→ Enormous shell in phase-space

Recent massive accretion event → M87 is in *active* formation

REIONIZATION

MPGC spatial profiles may trace epoch and inhomogeneity of reionization → z~10.5±1 and environmental dependence



UCDs

Faint UCDs discovered in M87 (spectra + HST)

New parameter space for UCDs + largest sample in any galaxy

Majority of UCDs: nuclei of threshed dwarf ellipticals

~100 in M87's inner halo → constraint on cosmological simulations