Connecting Stars and Globular Clusters

Study
Astrophysics of
Globular
clusters in
Extragalactc
Systems

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UC Observatories

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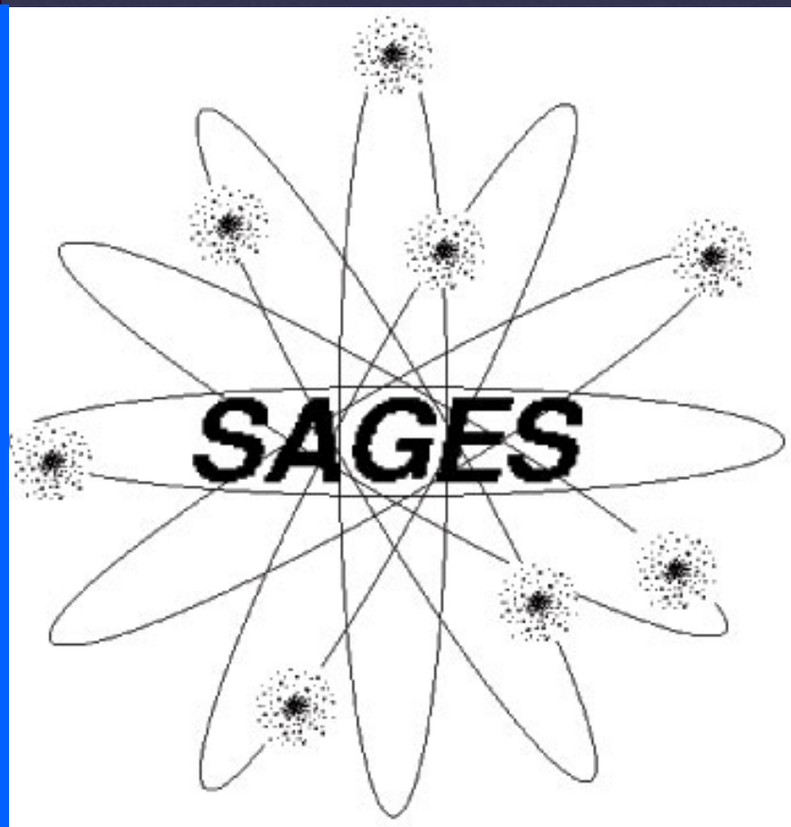
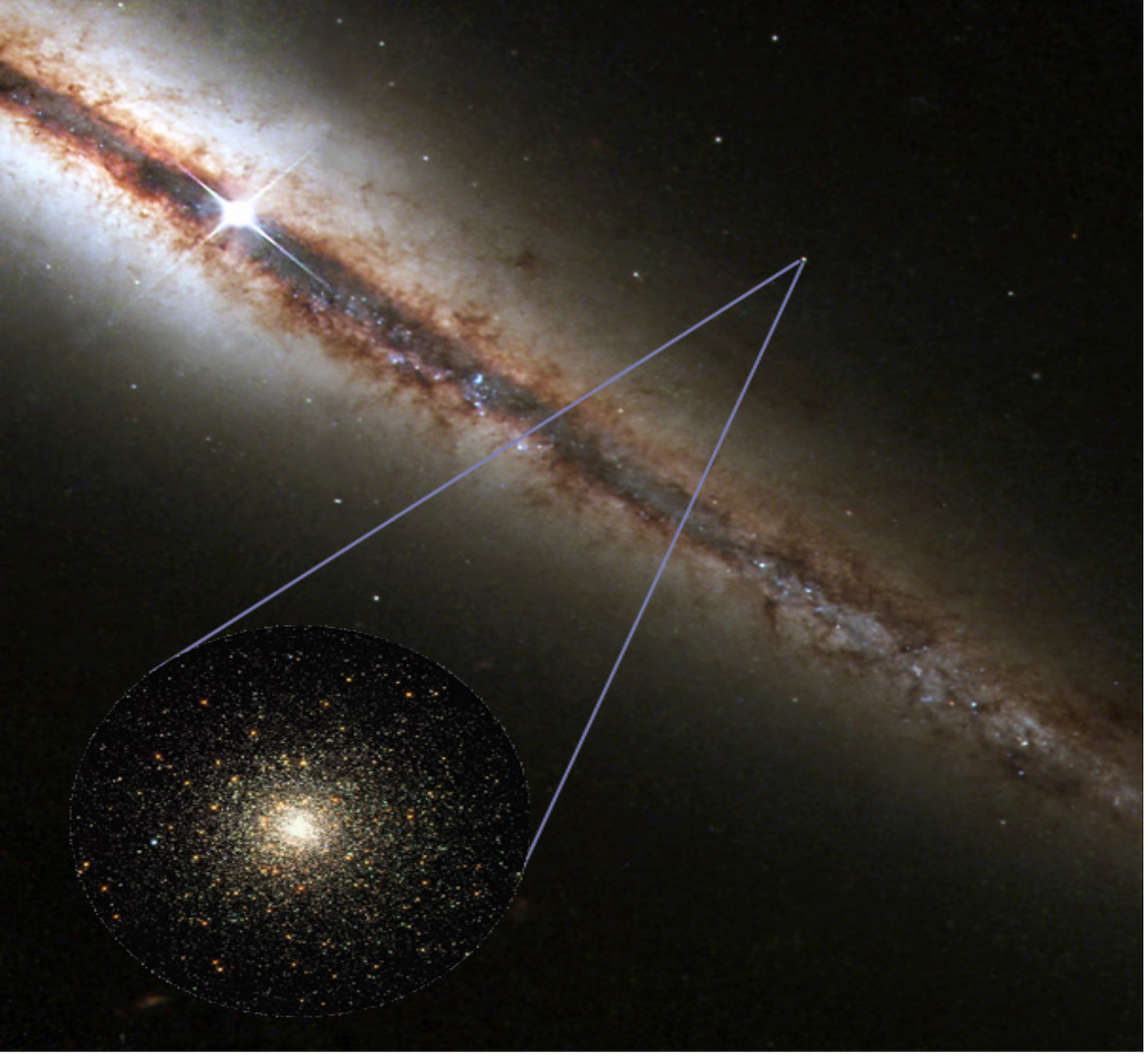
Nicola Pastorello
Mark Peacock
Vincenzo Pota
Aaron Romanowsky
Lee Spitler
Jay Strader
Chris Usher
Alexa Villaume





Almost all galaxies >10^9 $M_\odot$ host GC systems

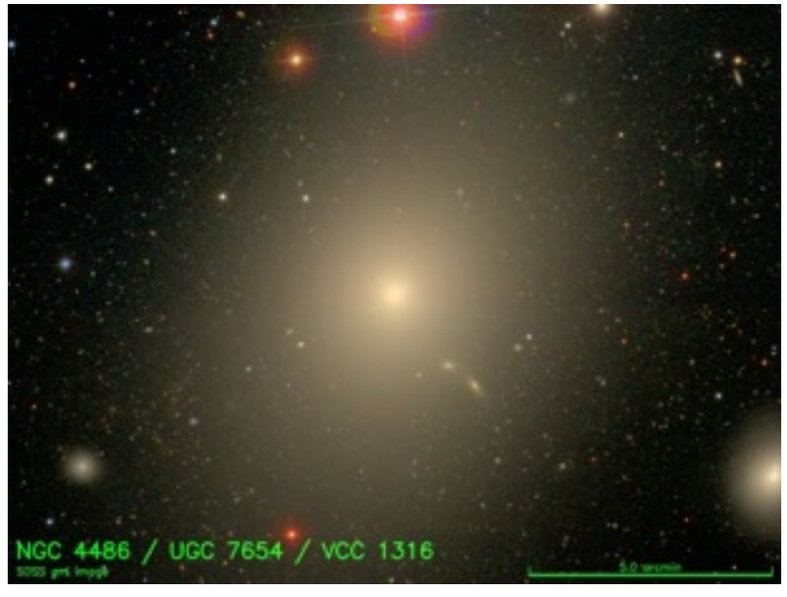
GC formation accompanies all major star formation

Bright (10^5–10^6 $M_\odot$) fossils

Spectroscopy feasible to ~ 50 Mpc

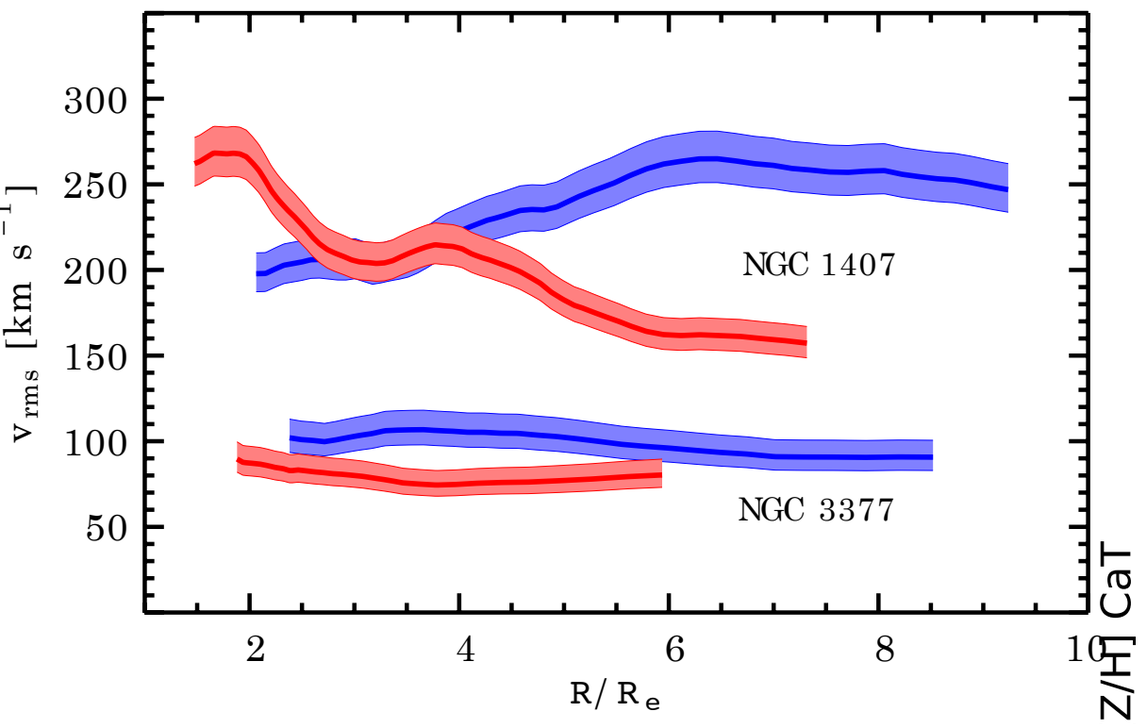
Dwarfs: 0 to 10s

Disks: 10s to 100s



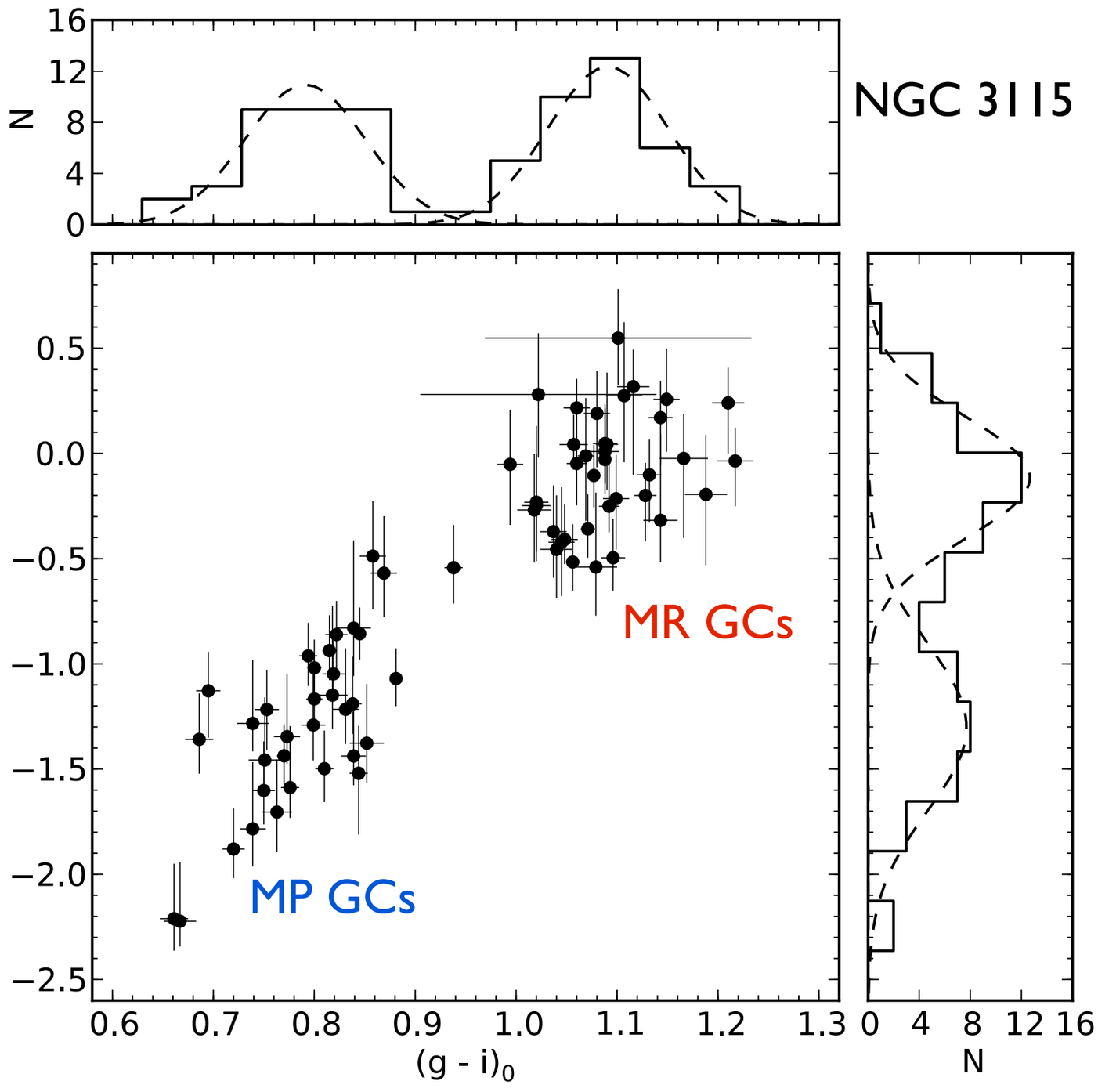
Es: 100s to > 10^4

GC Metallicity Bimodality

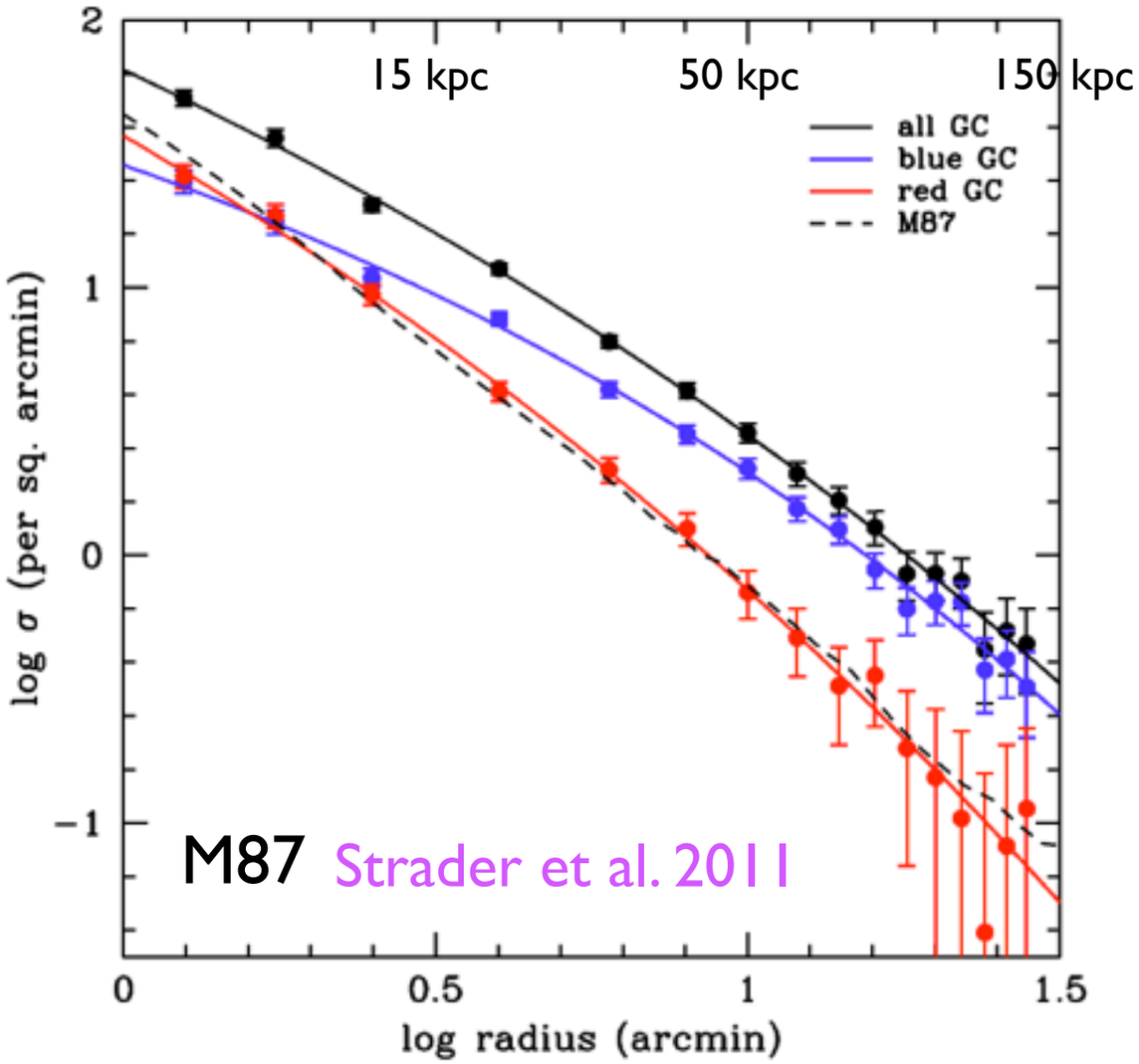


Subpopulations are kinematically distinct
Pota et al. 2013

Brodie et al 2012

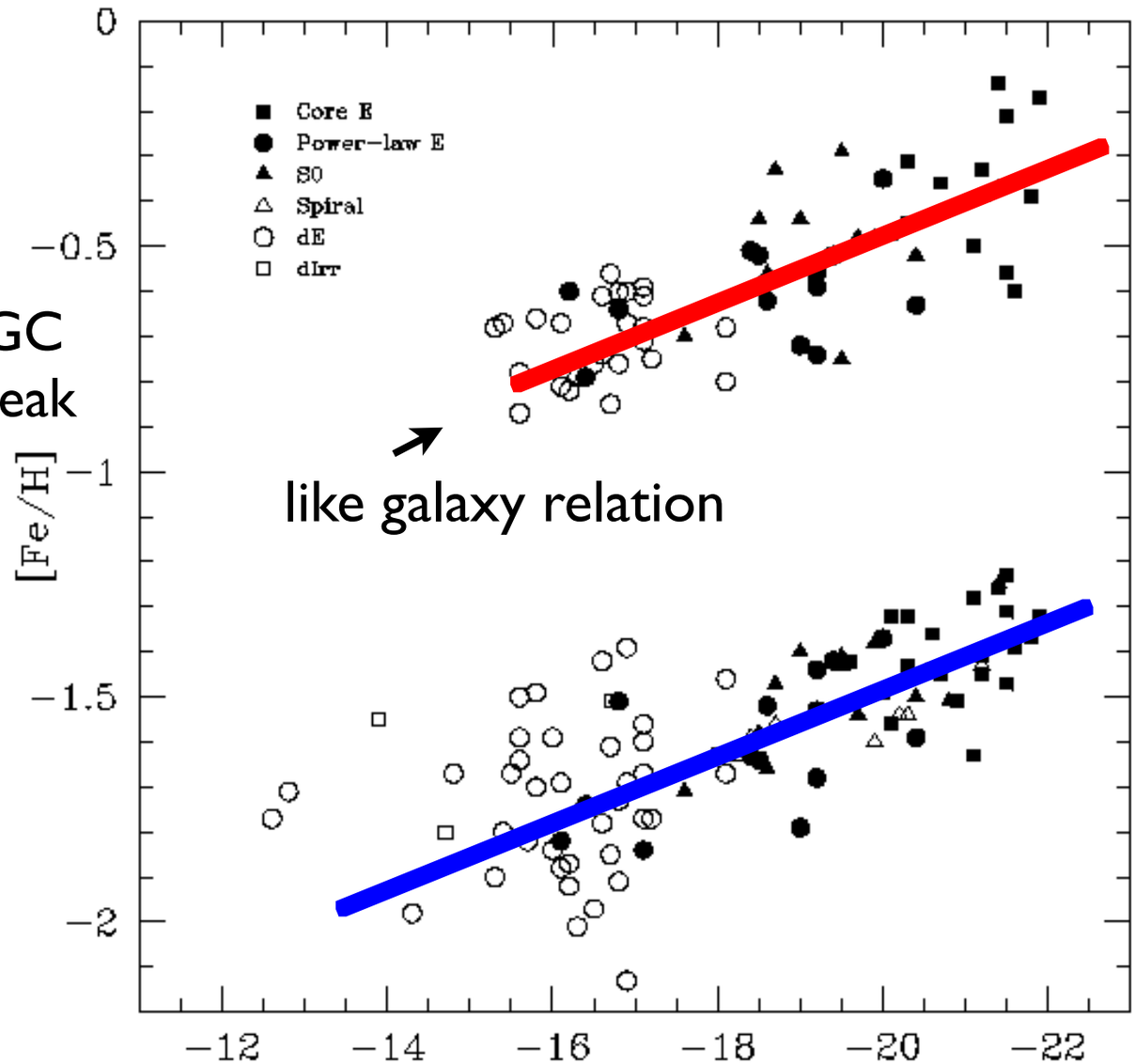


Blue GC trace halos, Red GCs trace bulges



Blue GCs more extended
Red GCs follow the bulge light

ONLY way to trace MP halos beyond LG



Brodie & Strader ARAA 2006

Peng et al 2006

How alike are the GC systems of the Milky Way and M31?

Milky Way	M31
~150 GCs	~400 GCs
$N_{MP} \approx 2 \times N_{MR}$	$N_{MP} \approx N_{MR}$

Number of MR GCs per unit bulge light is very similar

MR GCs trace build up of bulges

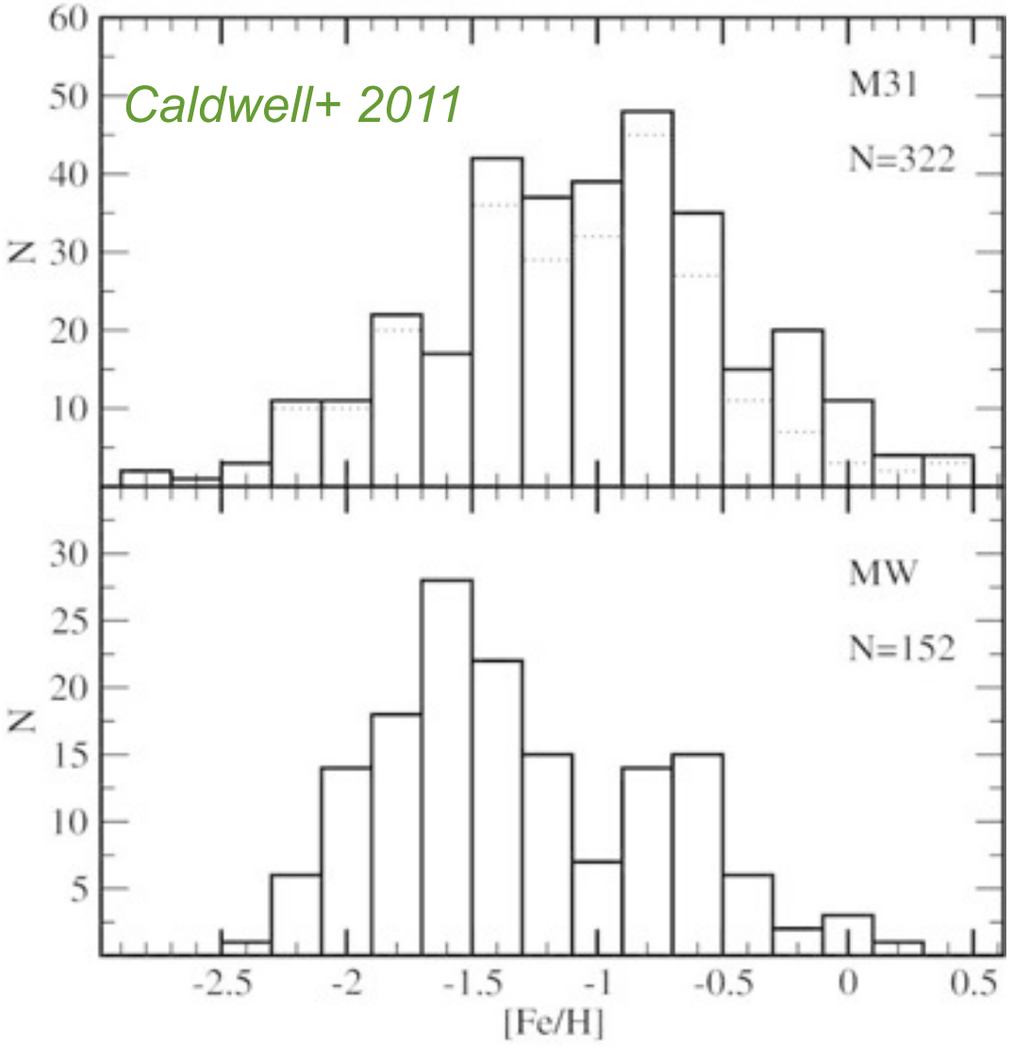
MR GCs form with similar efficiencies w.r.t. stars in M31 and MW bulges

Significant number of MP GCs revealed MP halo in M31 long before discovery in halo starlight

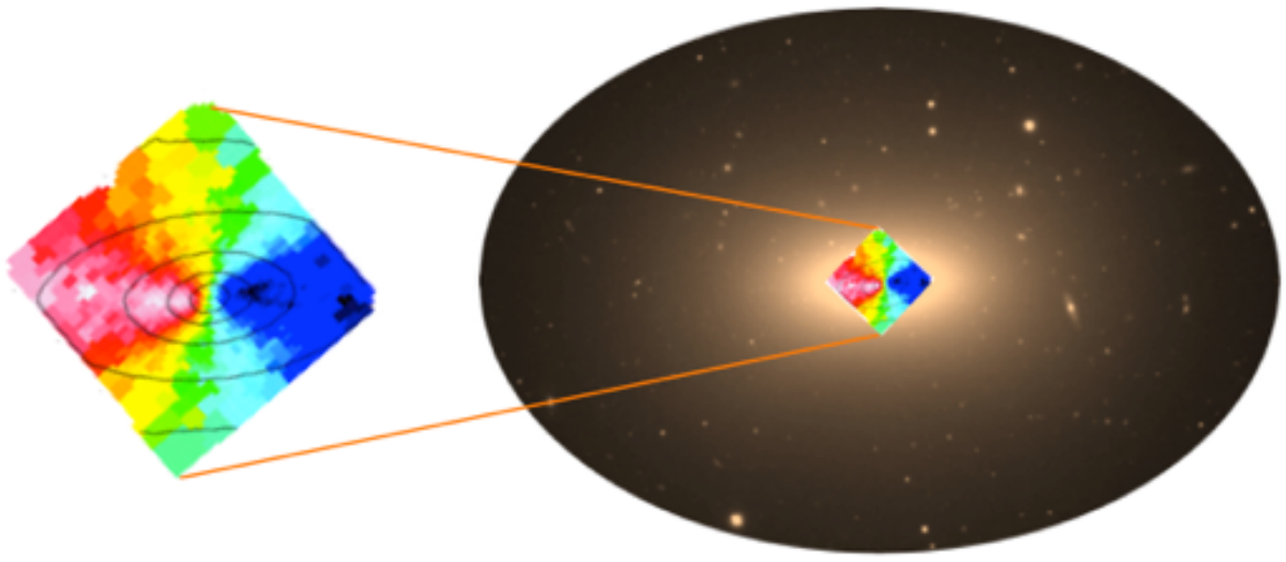
Lack of simple bimodality in M31

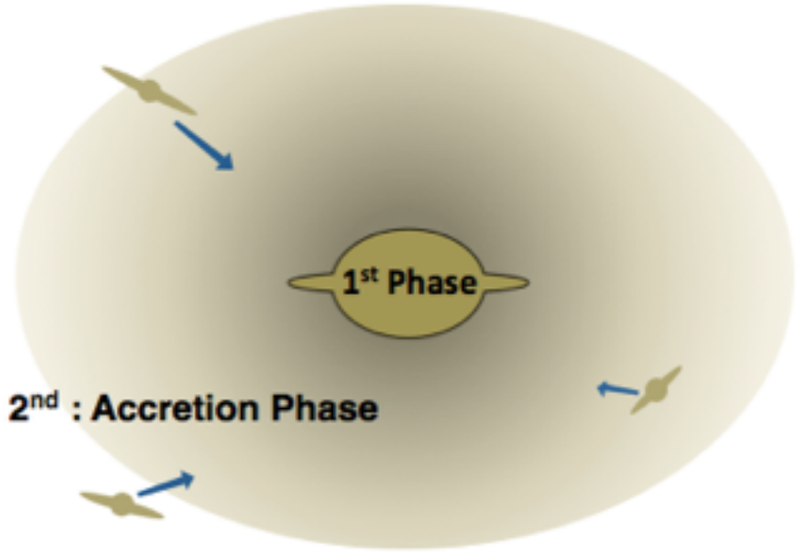
→ **more complex history**

of minor mergers and accretions compared to MW

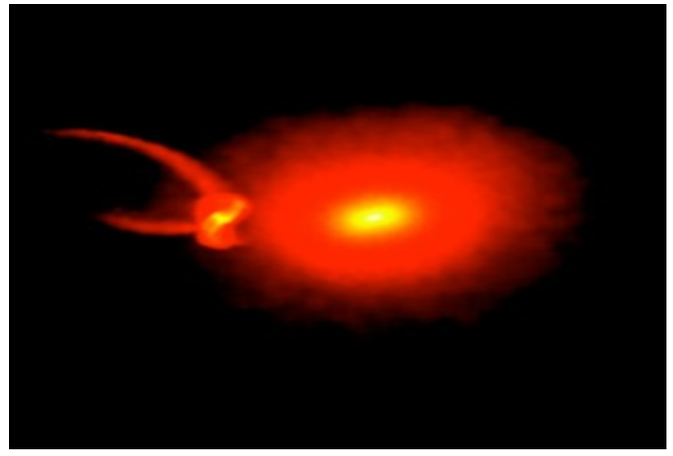


2-Phase Galaxy Formation





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



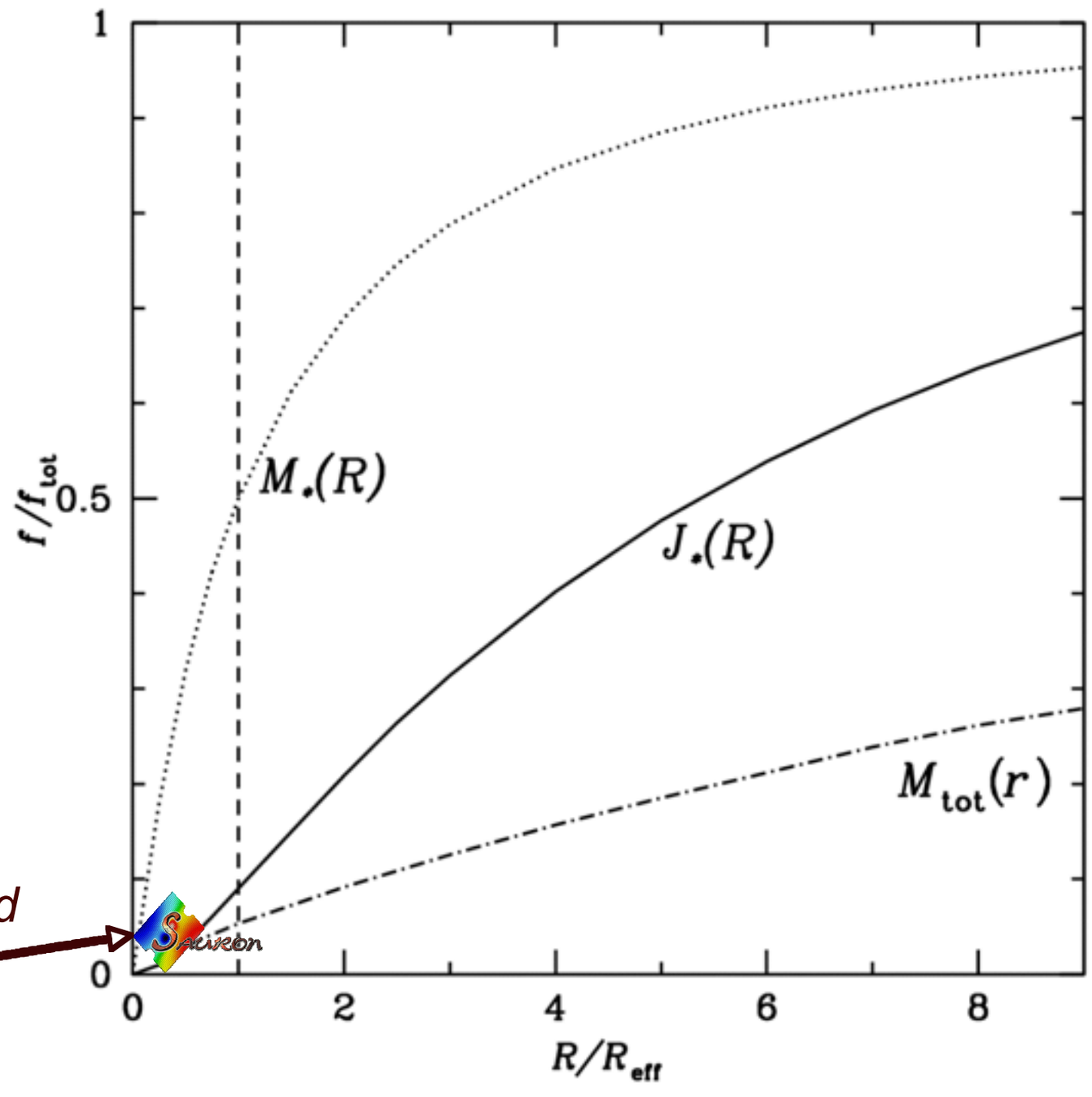
Feldmann+2008; Naab+2009; Hopkins+2009; Bezanson+2009; van der Wel+2009; van Dokkum & Brammer 2010; Oser+2010, 2012; Dominguez-Tenreiro+2011

GCs and stars - unveiling surprises at large radii

>90% of total mass and angular momentum outside 1Reff

Limit of traditional integrated stellar spectroscopy

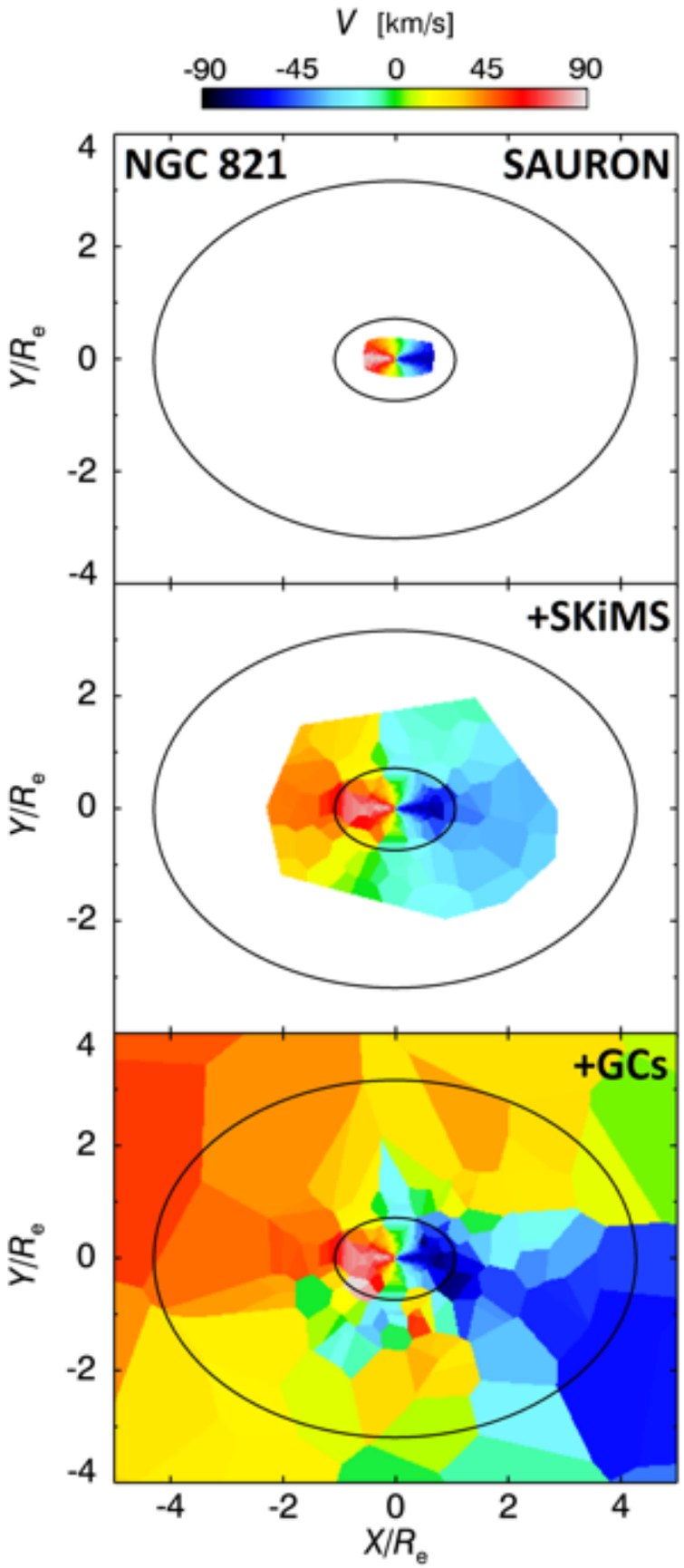
Elliptical Galaxy Schematic



The SLUGGS Survey

Brodie+ 2014

SAGES **L**egacy **U**nifying **G**lobulars and **G**alaxie**S**



Photometry (Subaru) and spectroscopy (Keck) DEIMOS

Chemodynamics for 25+ nearby early-type galaxies; range of properties (M, env, σ, v/σ.....)

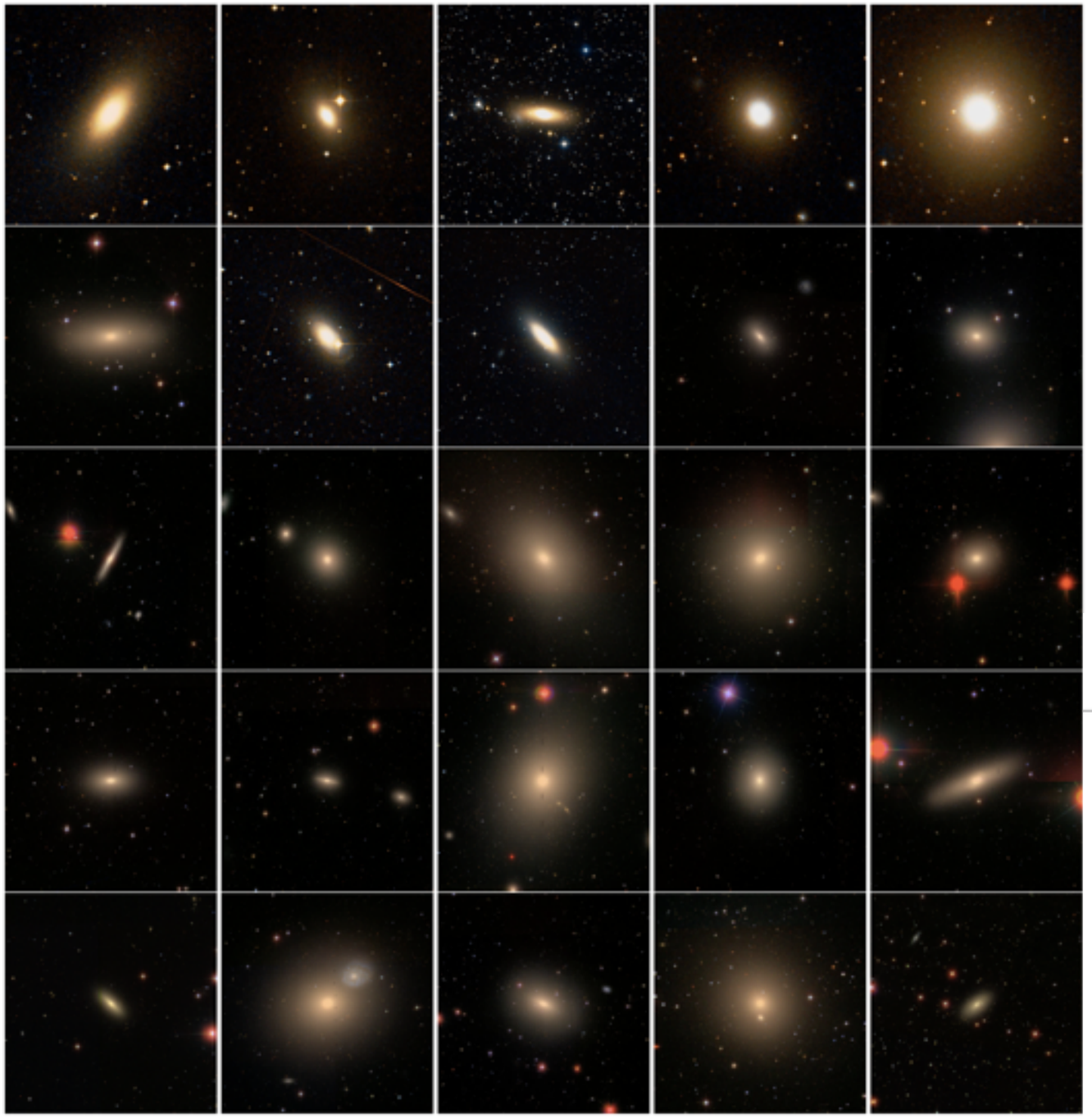
Field stars to ~ 3 r_{eff}

Globular clusters to ~10 r_{eff}

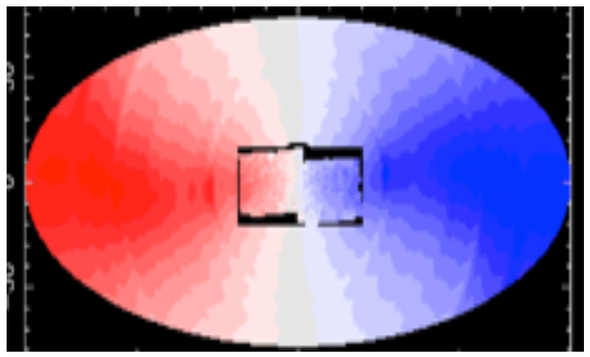
2-D kinematic and metallicity maps for GCs and galaxy stars

Observations nearing completion

~45 papers now published/ submitted (see sluggs.ucolick.org)



SLUGGS Brodie+ 2014



~12 km/s

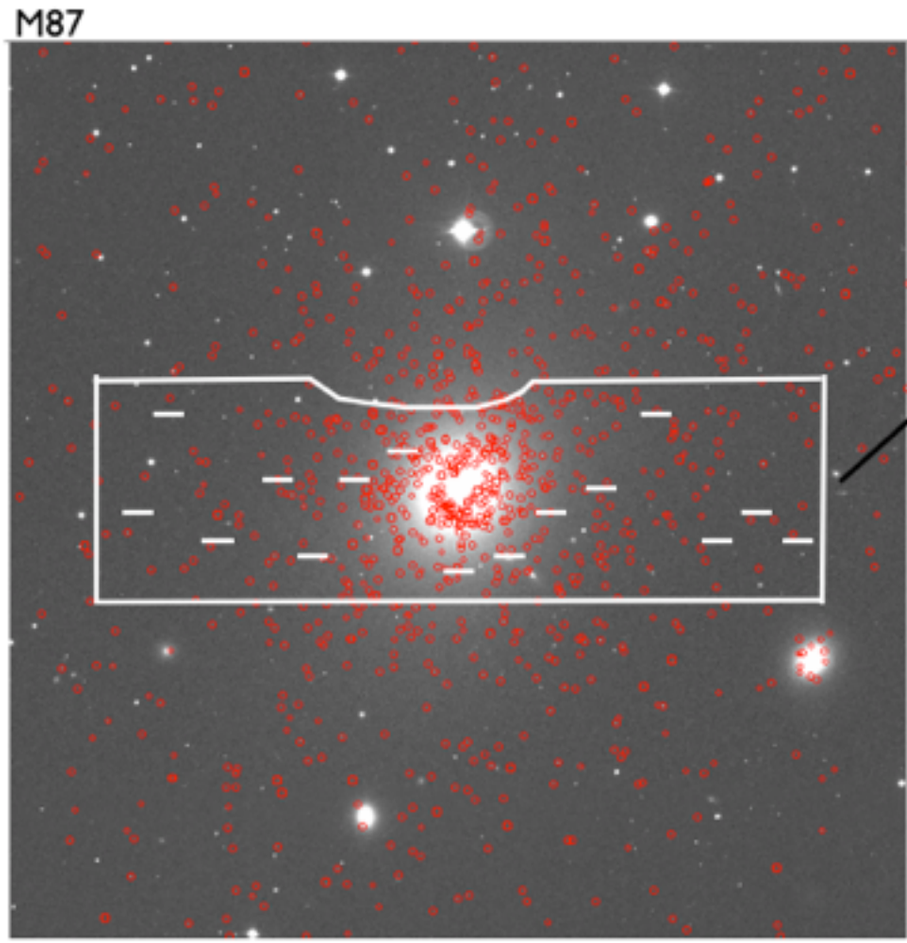
DEIMOS = Psuedo IFU

Early-type galaxies – old stellar populations, regular morphology (25 + 3 SLUGGSplus)
10 to 30 Mpc away
1.6×10^{10} to 2.0×10^{11} $M_\odot$ Stellar Mass
Brightest Group Galaxies to Isolated Lenticulars

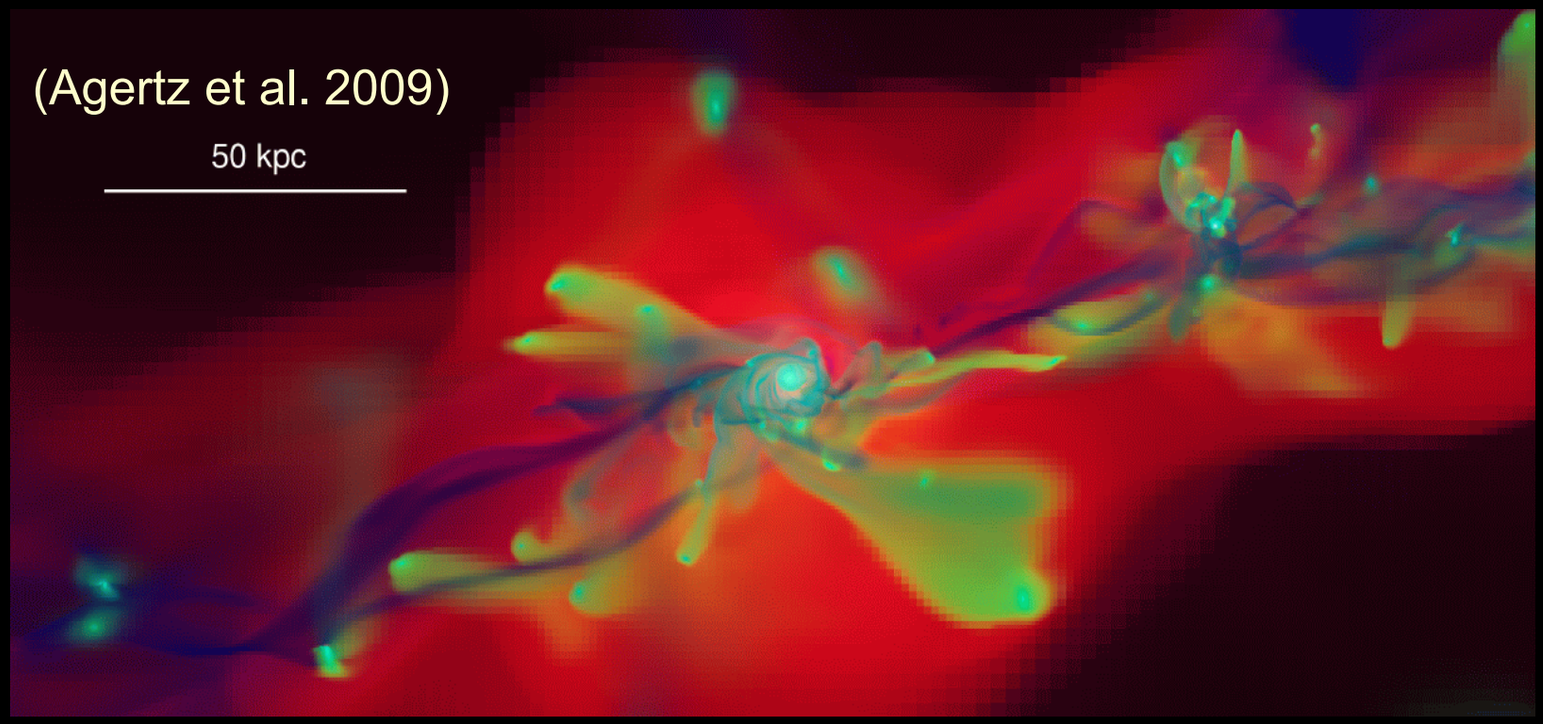
Schematic Spectroscopy

"SKiMS": Stellar Kinematics with Multiple Slits

20 arcmin



Wild disks as globular cluster factories



cold gas streams penetrate to small radii at high-redshift

smooth streams

Shapiro et al 2010

classical bulge from steady-state disk instability

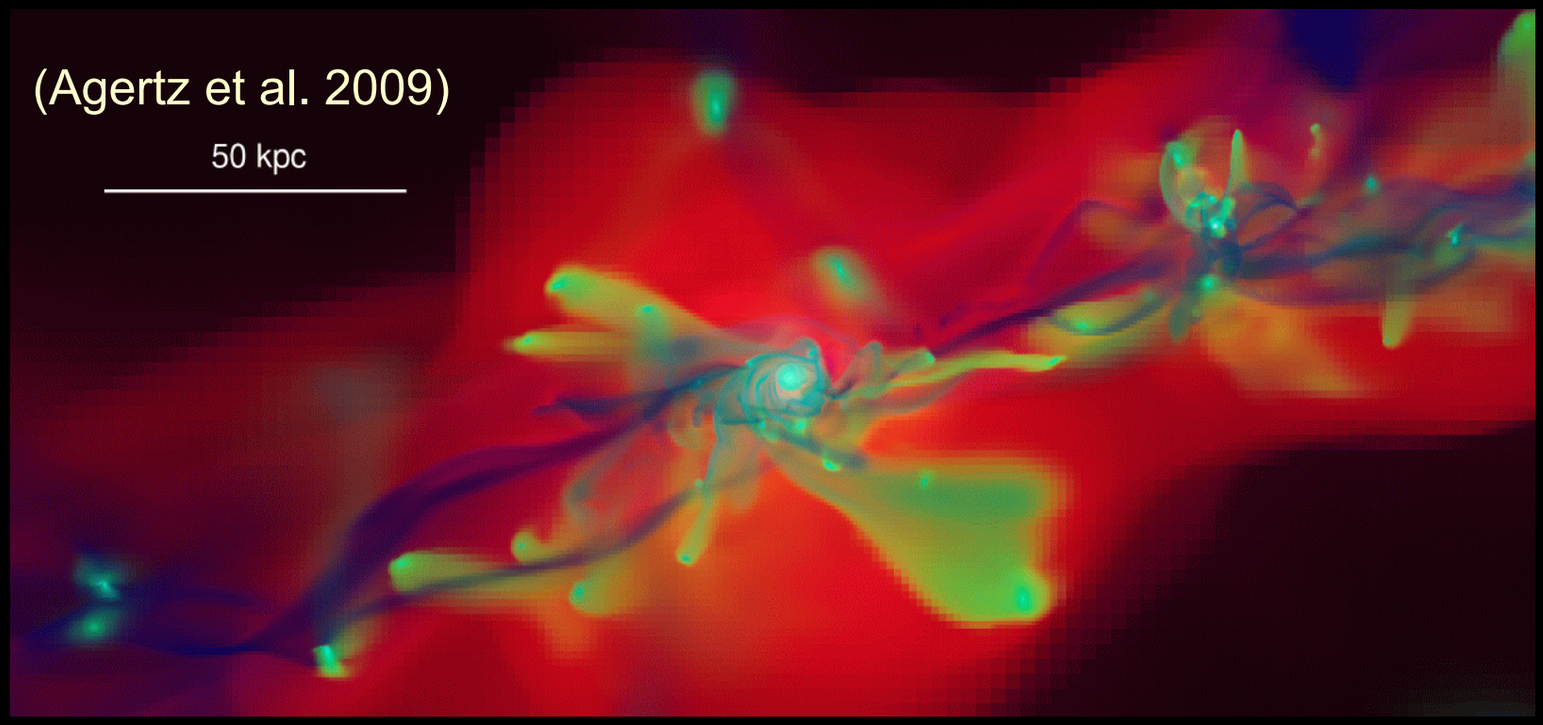
YMCs??

stream clumps

clump migration

(e.g., Noguchi 1999; Elmegreen et al. 2008; Dekel et al. 2009b)

Wild disks as globular cluster factories



cold gas streams penetrate to small radii at high-redshift

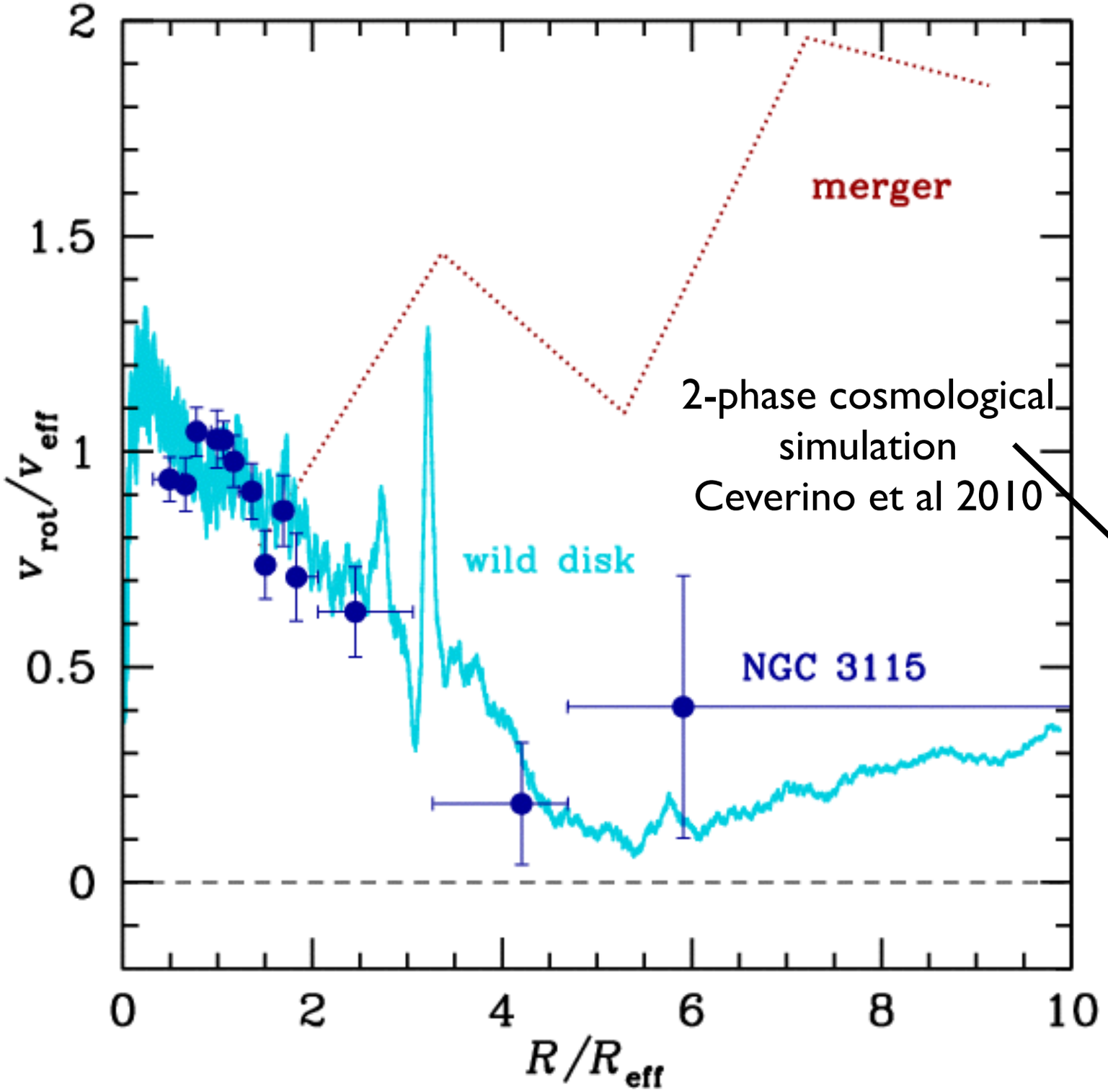
smooth streams

Shapiro et al 2010

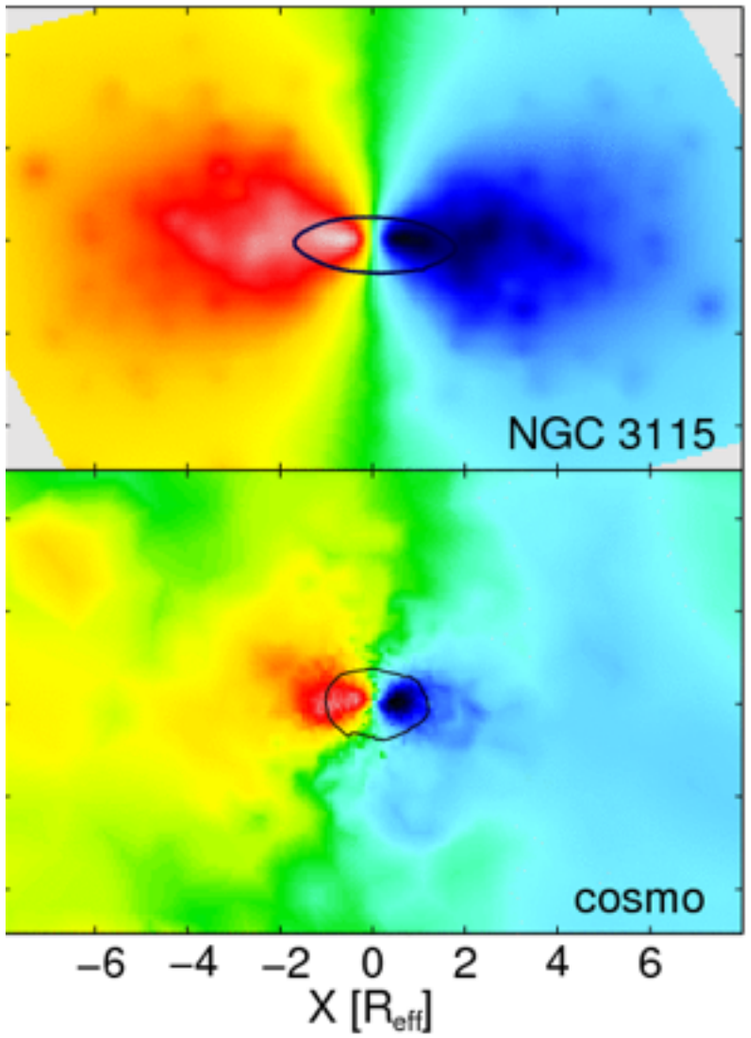
→ *Evolve into present-day Sa, S0, E by fading or mergers?*

(Conroy+2008; Genzel+2008)

Arnold+ 2011



2-phase cosmological simulation
Ceverino et al 2010

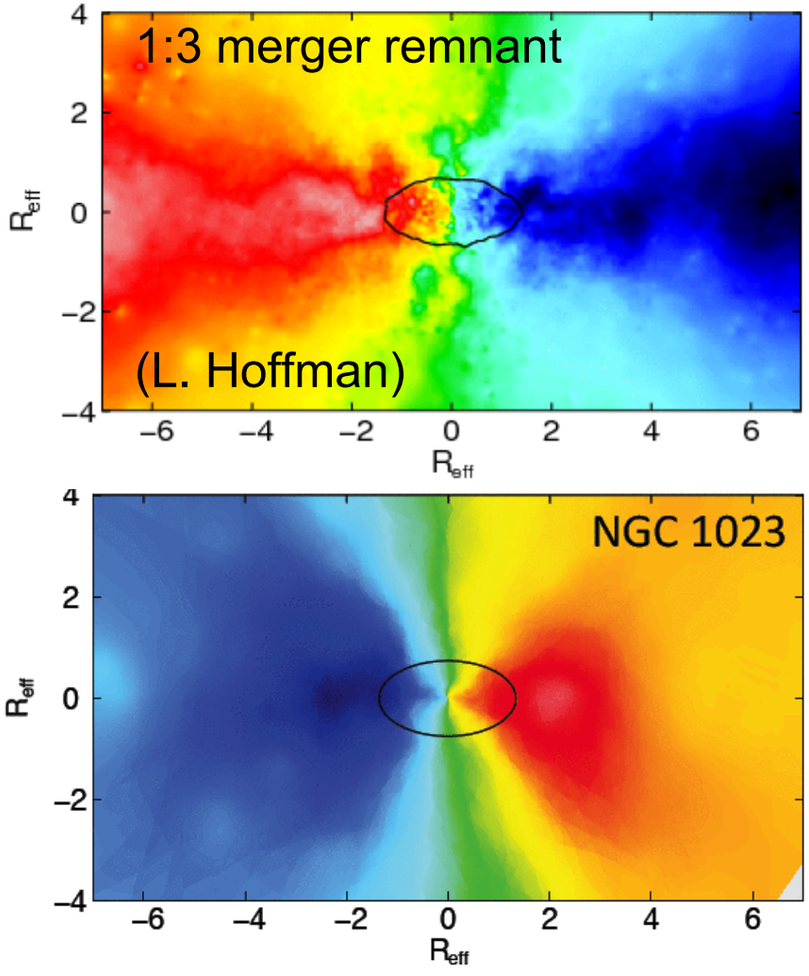


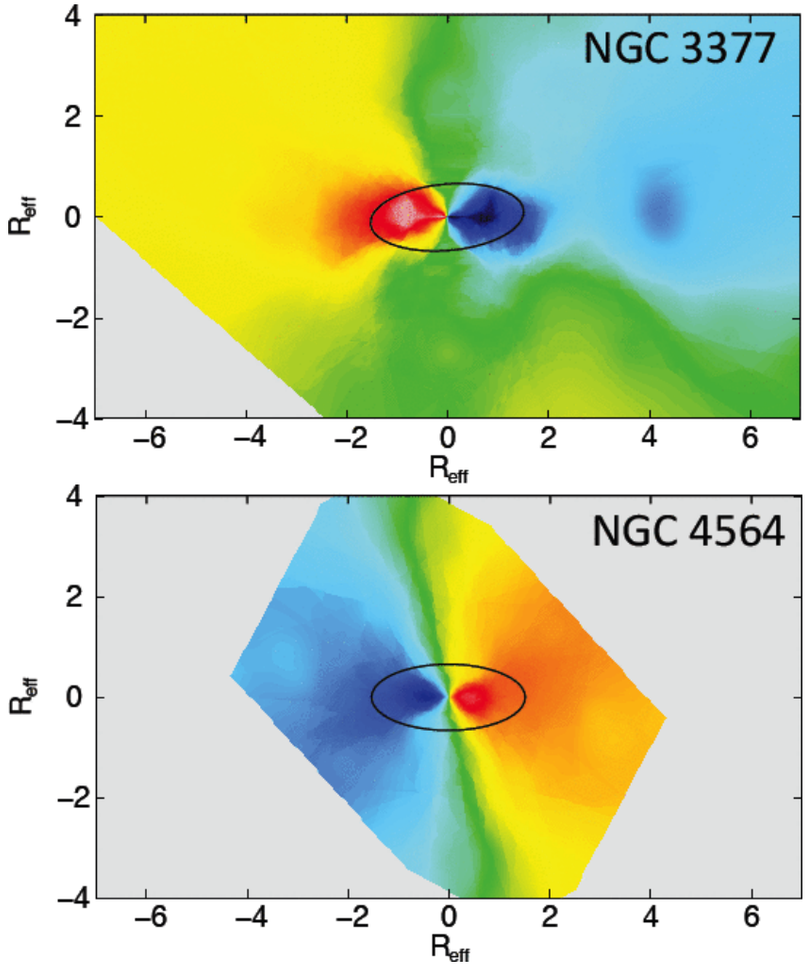
Inner regions heated disk material
Outer regions accreted

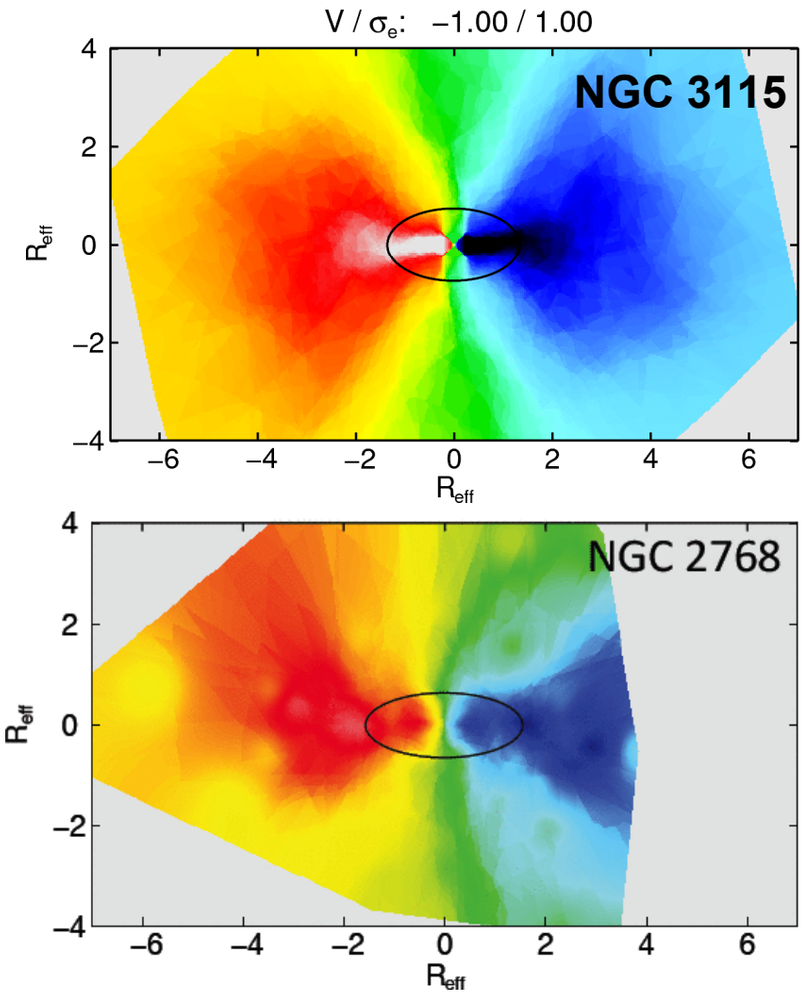
Rotation maps of early-type galaxies

Flattened (~edge-on) cases for minimal ambiguity

(Proctor+09; Coccato+09; Arnold+11; Pota+2012; Romanowsky+2012)



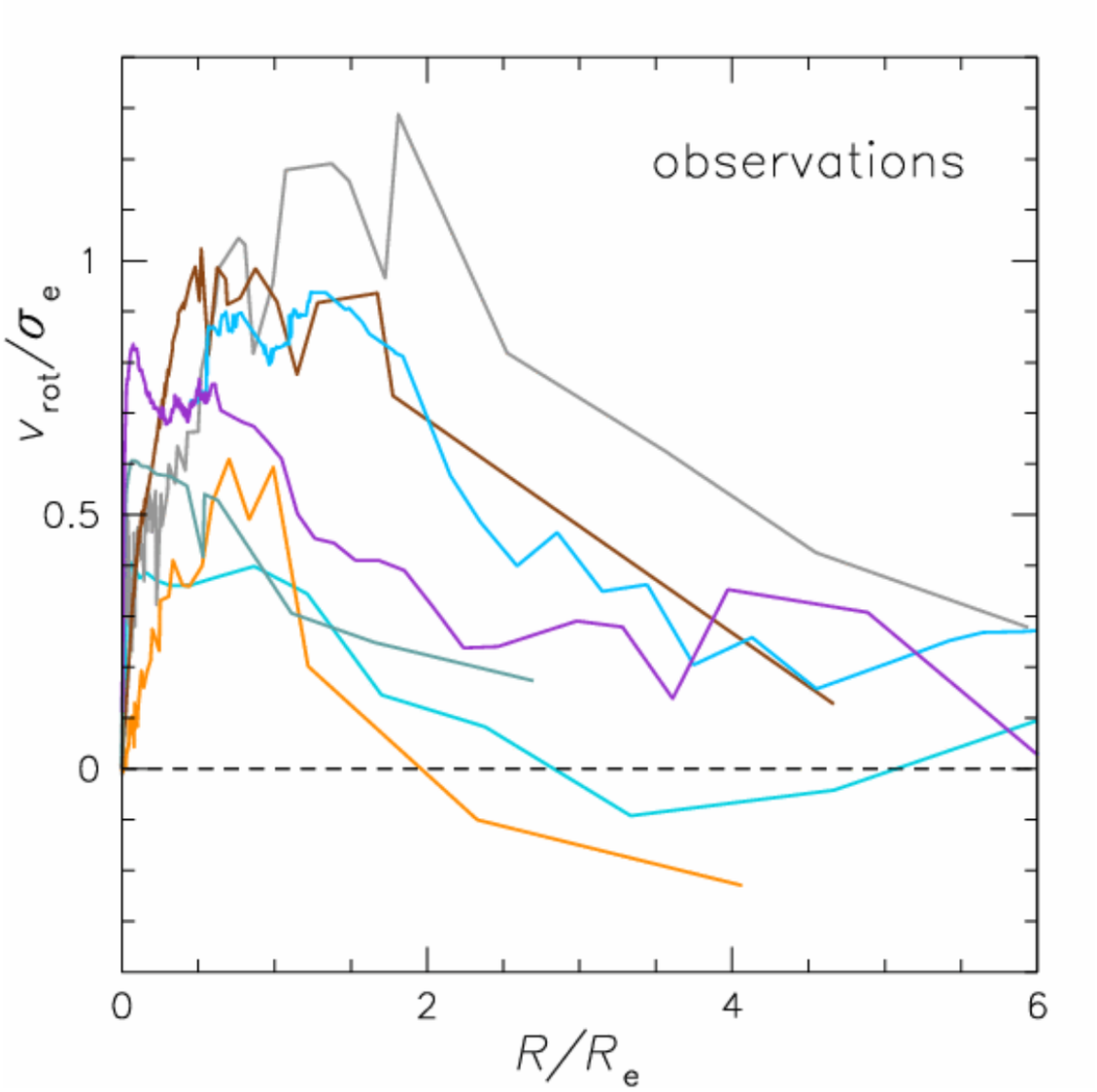


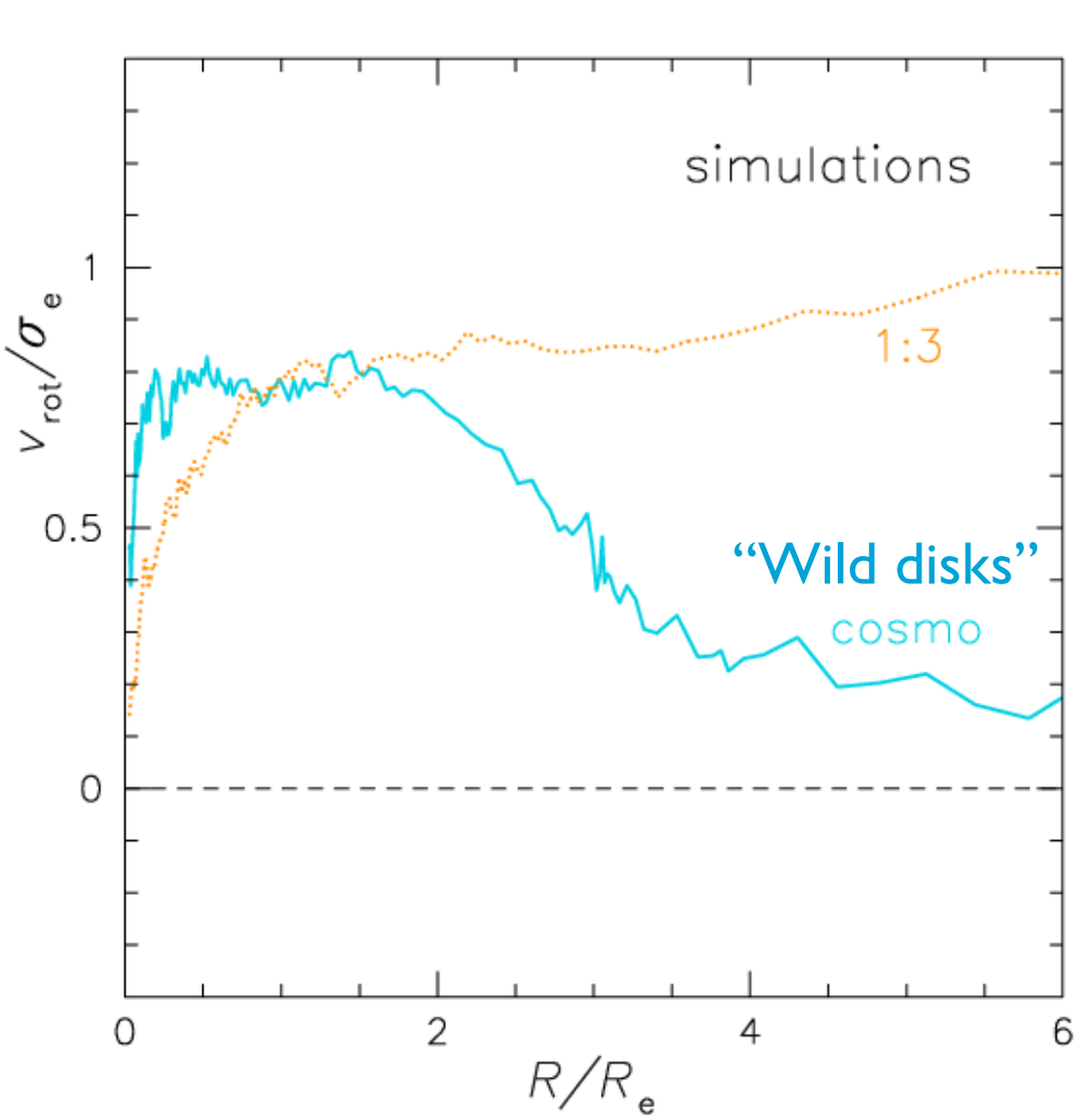


→ Observed rotation declines outside ~2 R_e *(missed by SAURON)*

→ Predicted major-merger spin-up not found

Rotation profiles: observations vs simulations



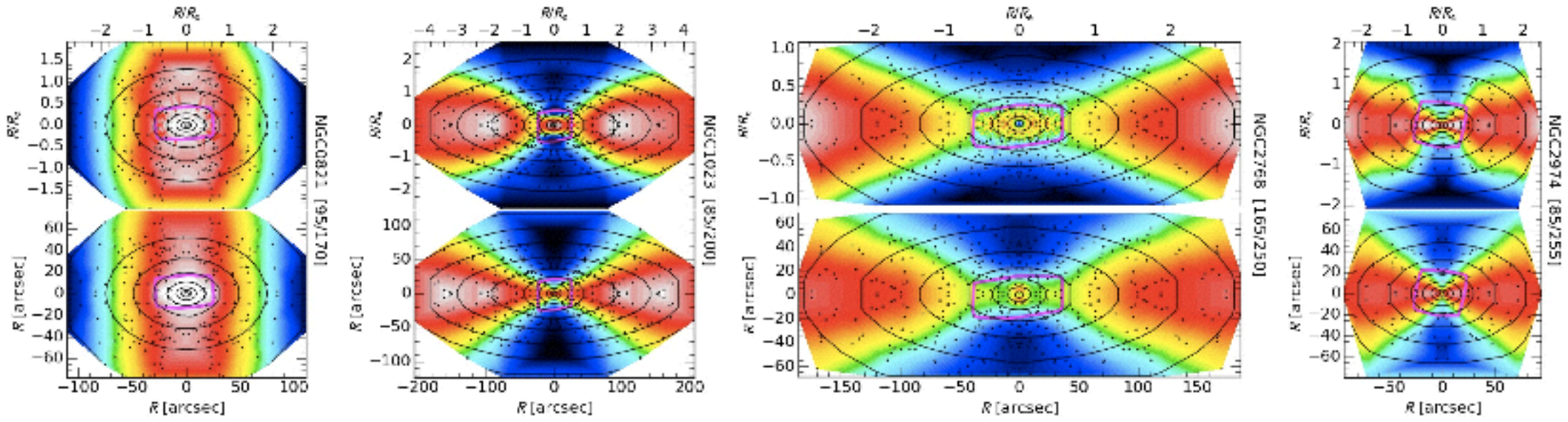


- Outer, slow-rotating envelopes in cosmo sims built up by accretion from mix of major and minor mergers
- Minor mergers predicted to dilute rotation

"Wild disks" Bulges built from merged clumps (sites of MR GC formation) in z~2 disks (result of disk instabilites - Elemegreen et al 2008; Dekel+2009)

SLUGGS + Atlas^{3D} for 14 fast rotators
→ starlight out to 4 Re

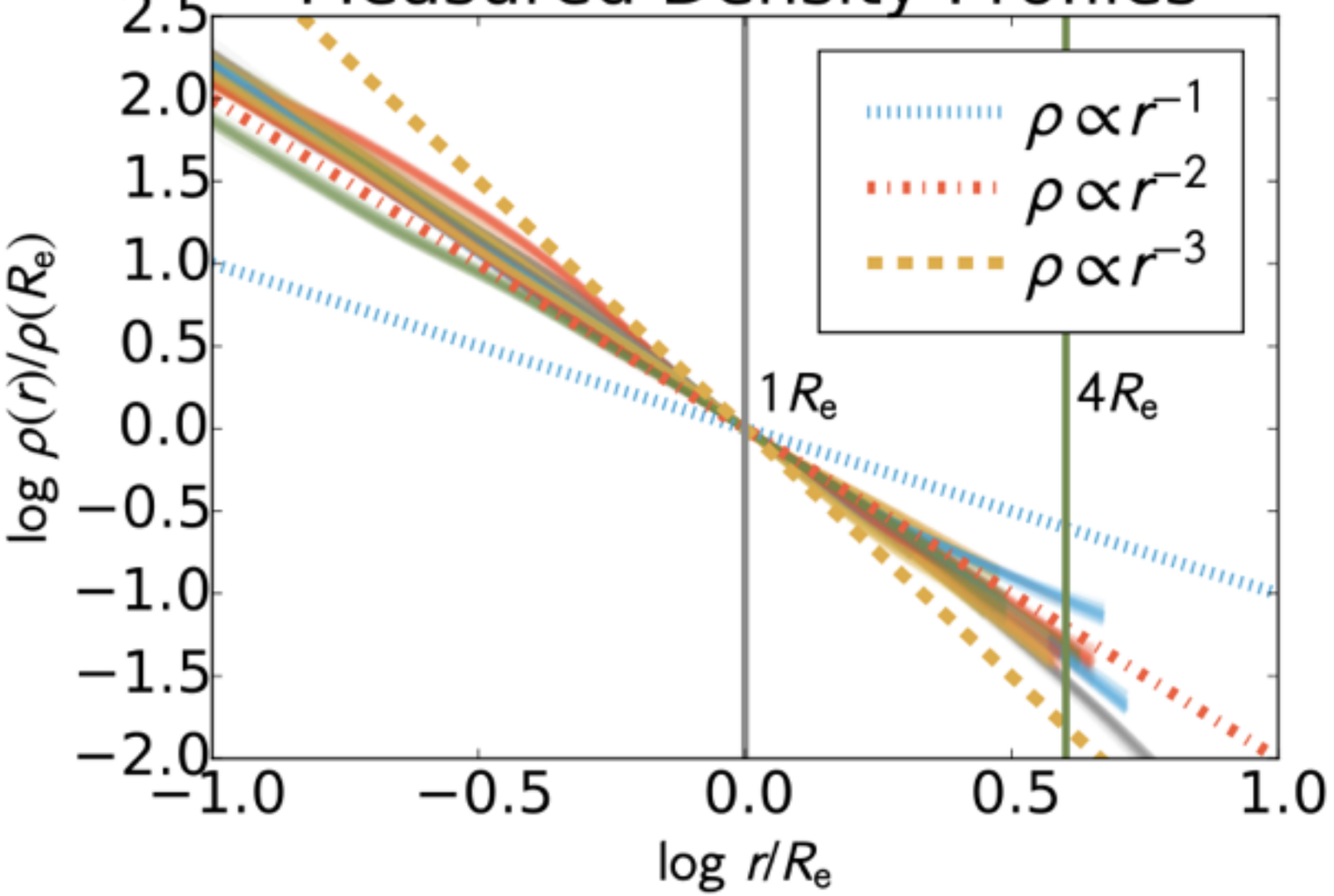
Cappellari+ 2015
Jeans Axisymmetric Models



V_{rms}
Observed

JAM

Measured Density Profiles



JAM models allow:

- Spatially varying anisotropy
- Quite general profiles for the dark halos - no restriction on slope

Simple axisymmetric model fits data remarkably well
Power law density profile for
0.1Re > r > 4Re
$r^{-\gamma}$ with $\gamma = 2.19 \pm 0.04$

Tight constraints on galaxy formation models

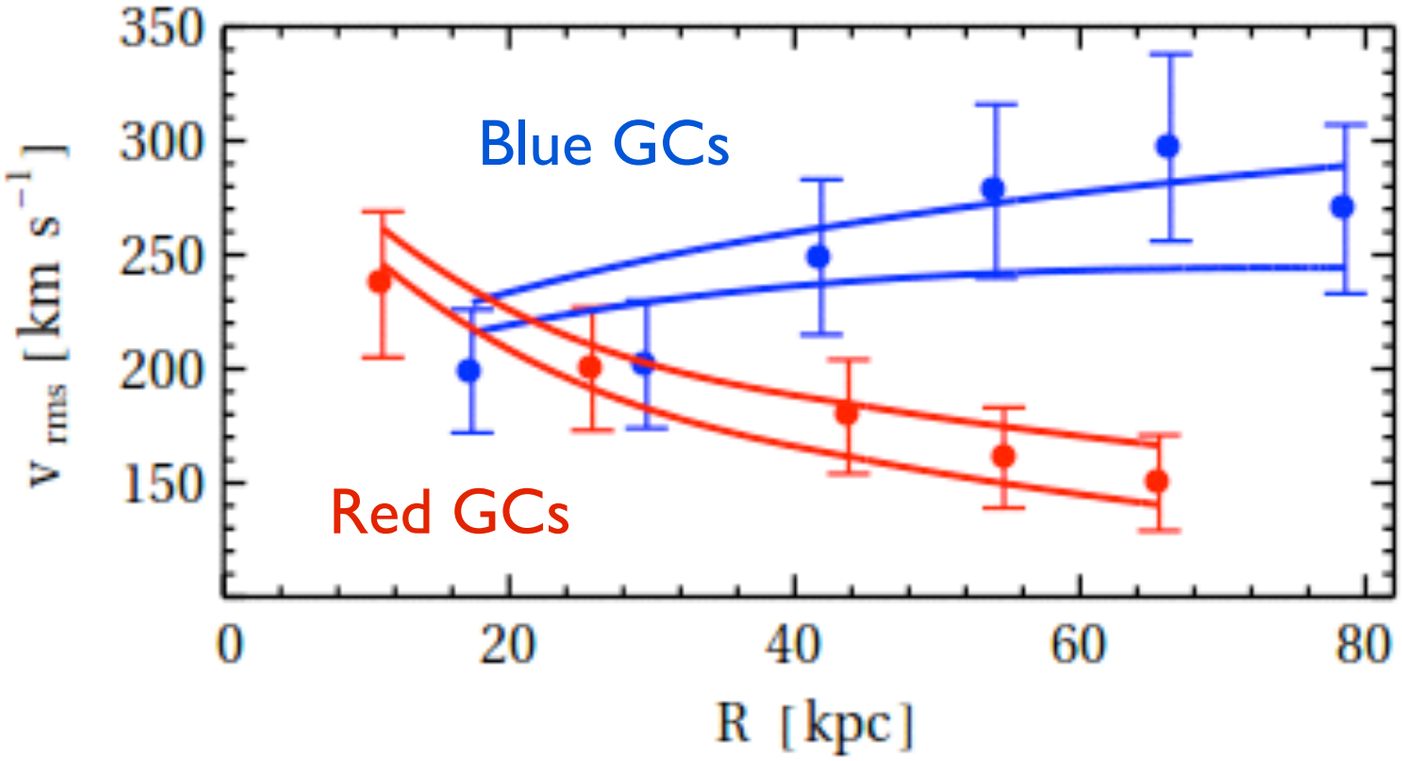
Mass and Dark Matter

Multi-population dynamical modeling (spherical Jeans)

NGC 1407

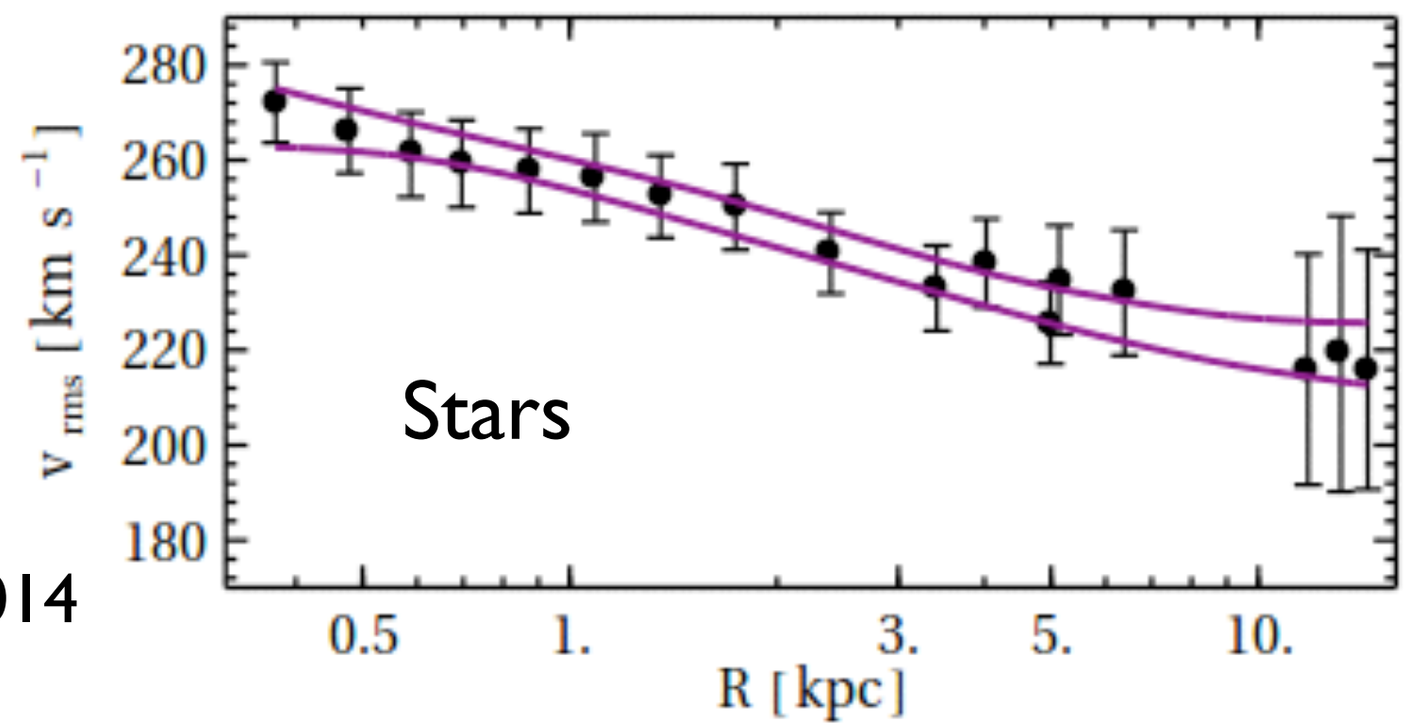
Pota+ 2015

Stars + GCs (MR & MP)
independent constraints on
DM distribution
Bayesian analysis with MCMC



Best fit to the
velocity dispersion
profiles - gNFW

Different anisotropies are needed to fit these profiles

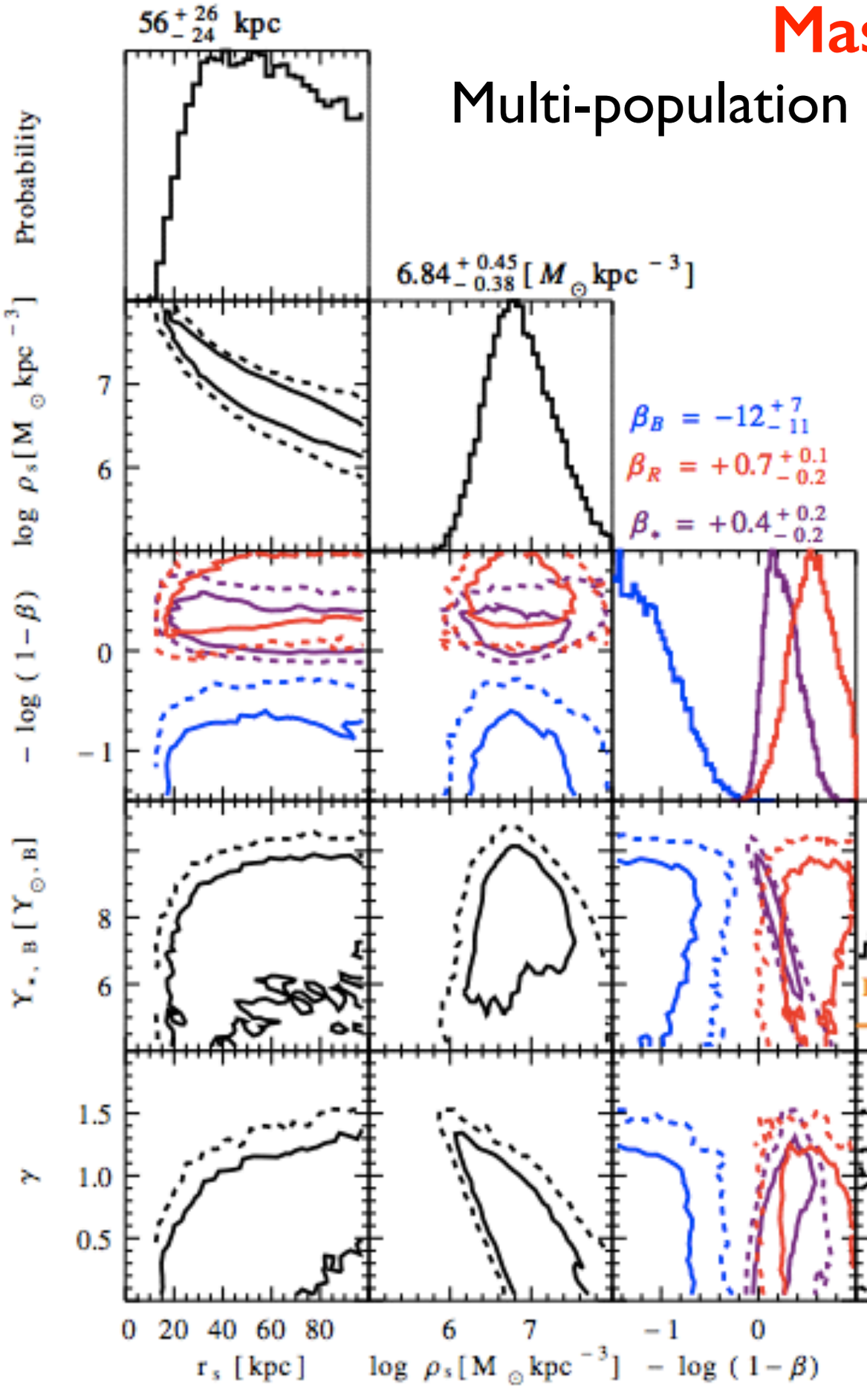


also Napolitano+ 2014, Agnello+ 2014
mutli-GC pop tracers

Mass and Dark Matter

Multi-population dynamical modeling (spherical Jeans)

NGC 1407 Pota+ 2015



MP GCs have unexplained tangential anisotropy!

<1 R_e

$M_{tot} = 4.2^{+0.1}/_{-0.2} \times 10^{11} M_\odot$

fDM =0.37±0.13

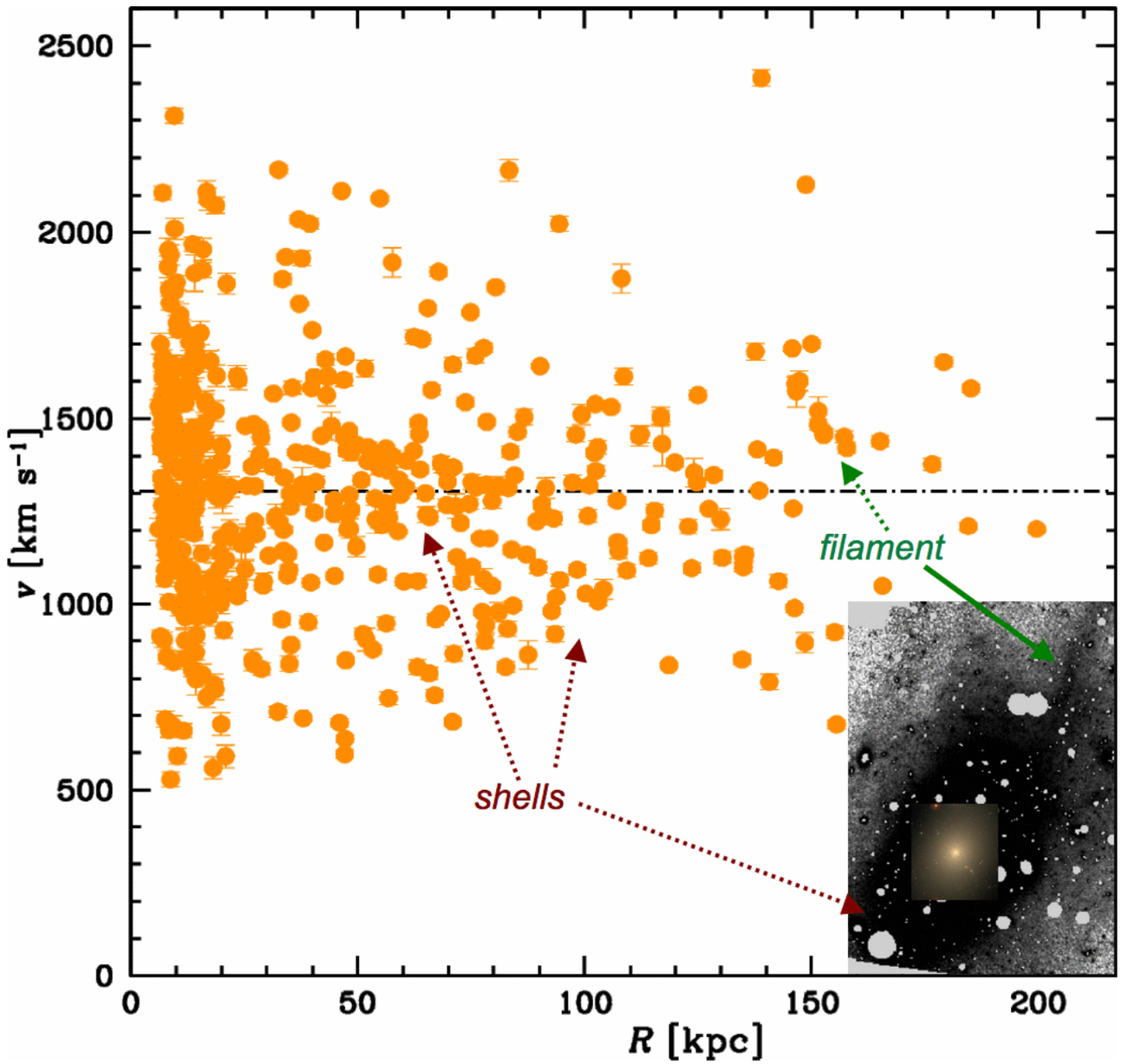
— stars

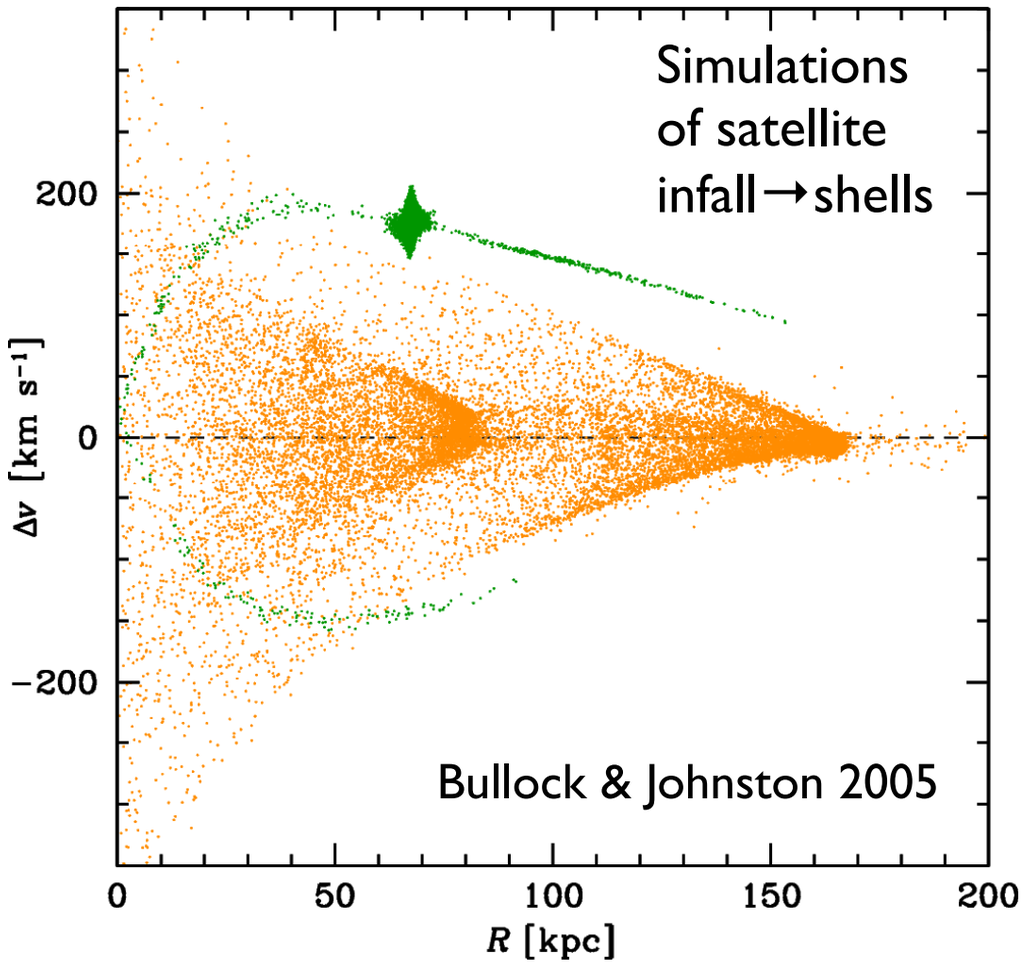
— red GCs

— blue GCs

Velocity-Position Phase Space: M87

GCs Romanowsky+ 2012



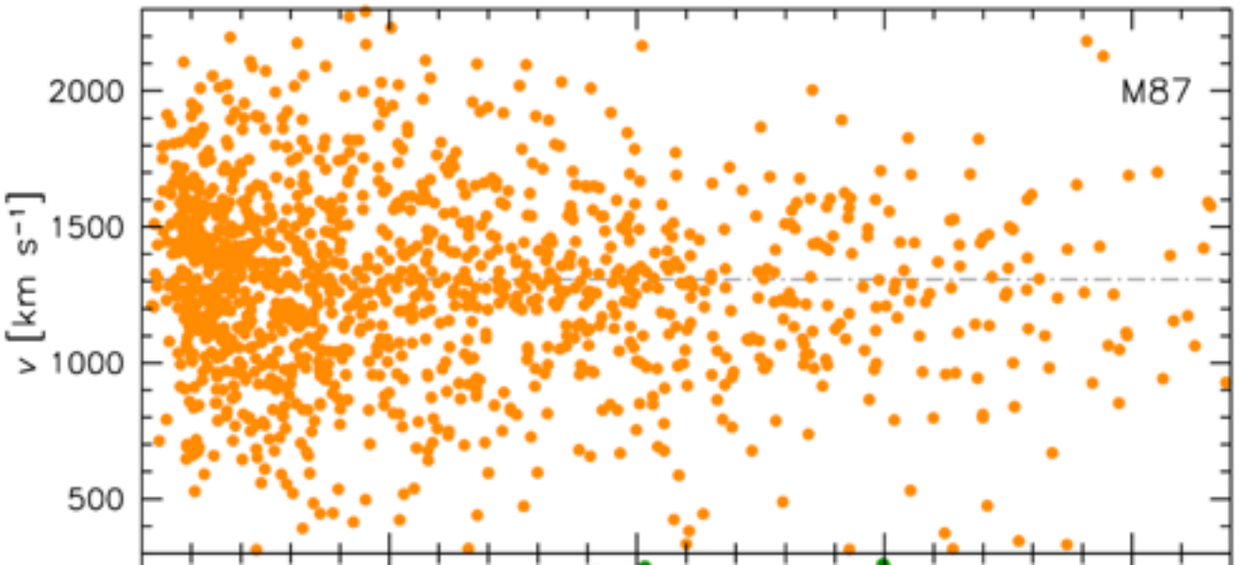


~L* galaxy bringing in
~1000 GCs in last ~1 Gyr

Now have ~1700 GC spectra →

Need ~15 km/s velocity precision
to see cold features

PNe Longobardi+ 2015



Ultra-compact dwarfs around M87

(Brodie+2011)

Ultra-compact dwarfs around M87

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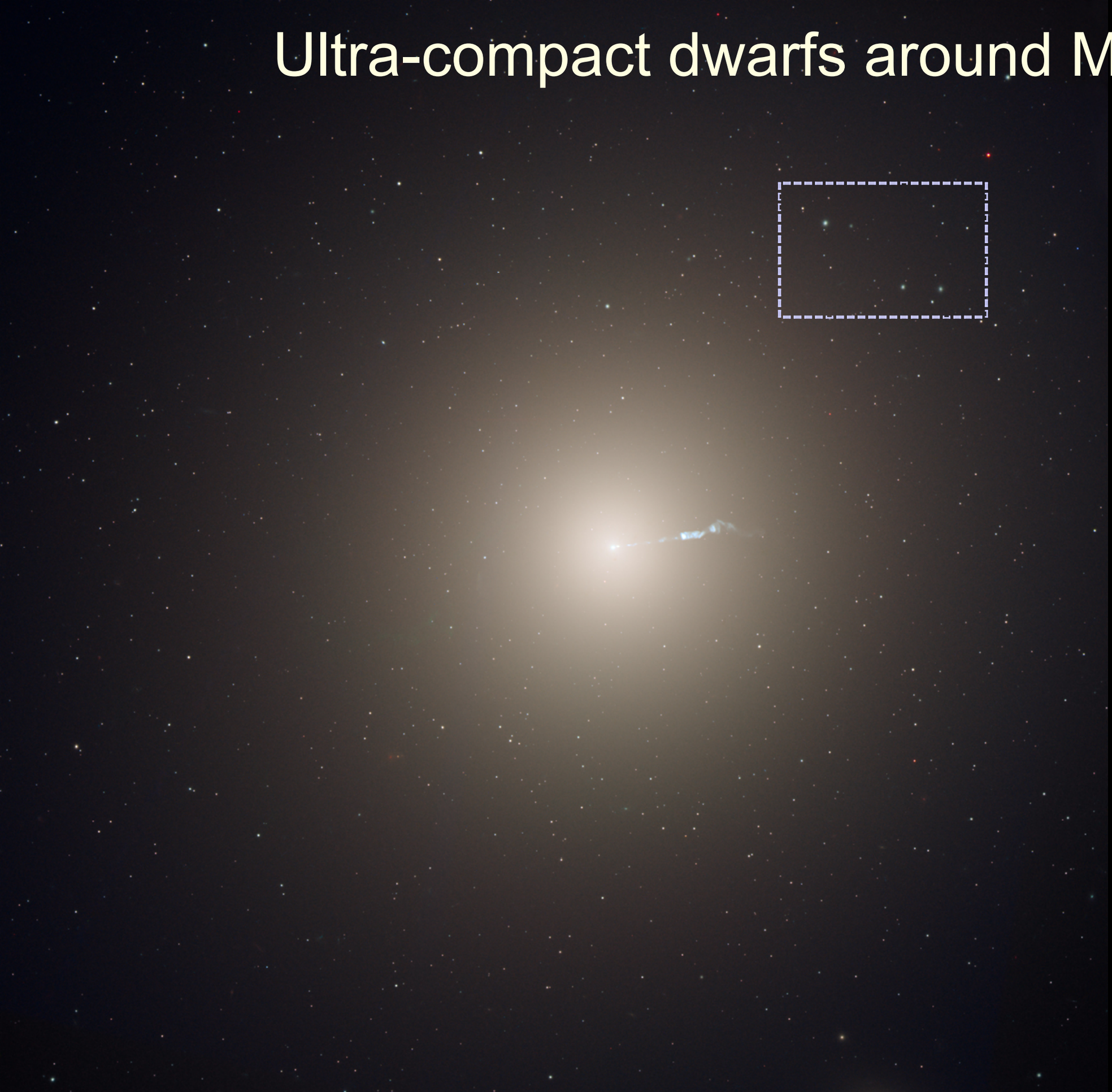


Ultra-compact dwarfs around M87

(Brodie+2011)

GC

“N2419”

UCD

GC

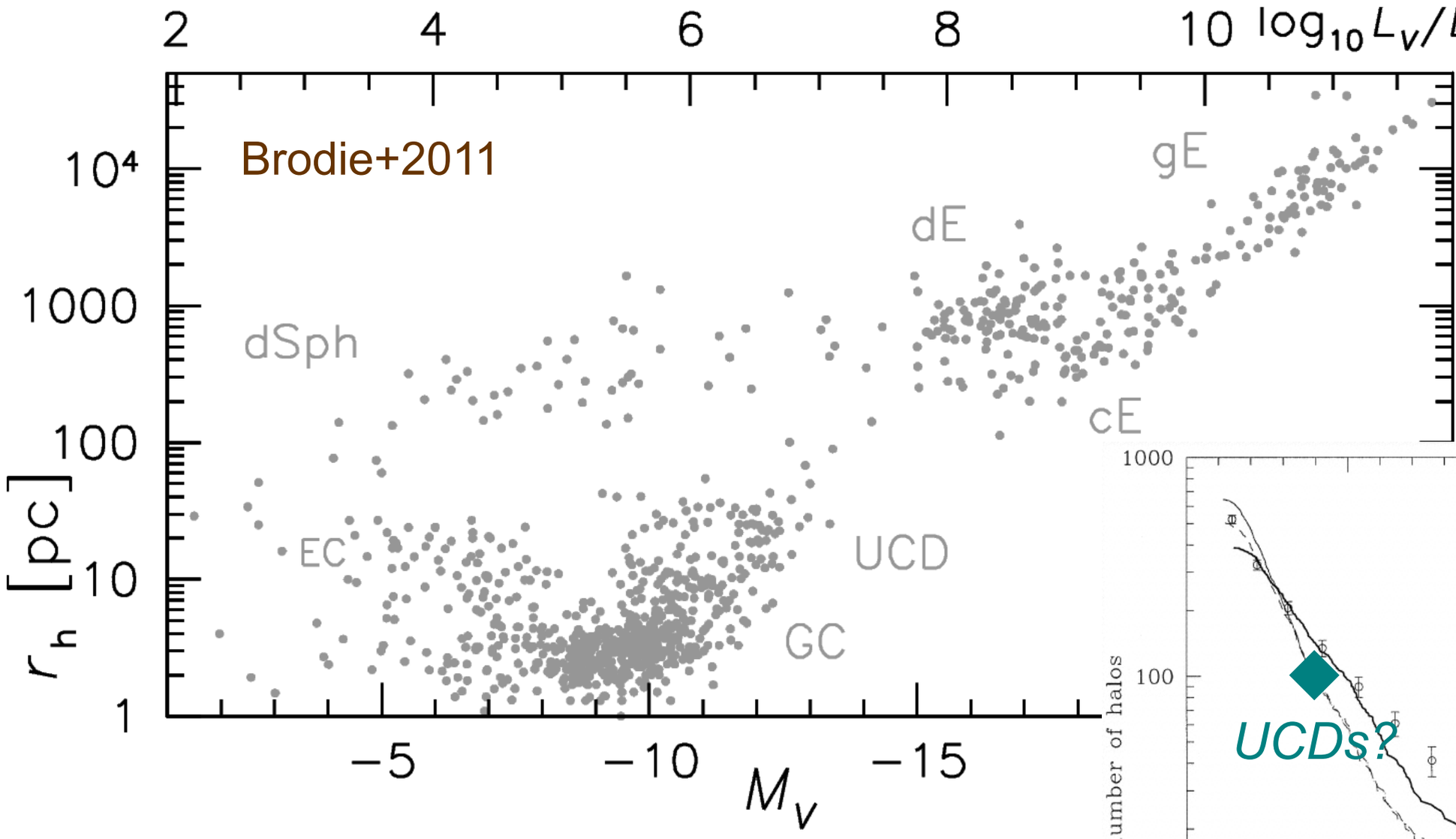
UCD

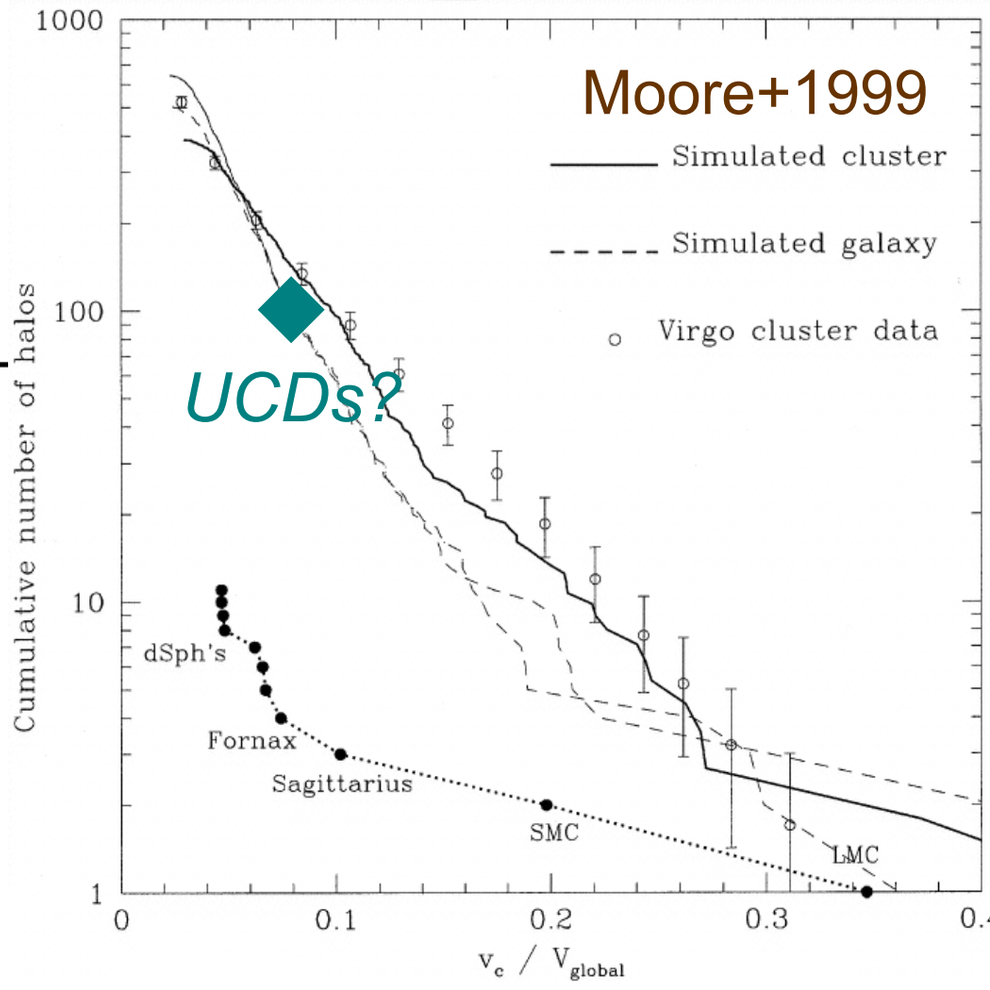
UCD

“ω Cen”

- UCDs: log $L_V/L_{V,\mathrm{Sun}}$ ~ 5.5–7 ; r_h ~ 10–40 pc sigma ~20–40 km s^{-1}
- Doubled sample size to 34, incl. new low-surface brightness regime

The Everything Plot





M87 ~100 UCDs out to ~200 kpc:
significant addition
to subhalo counts

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

The Densest Galaxy

M60-UCD1 Strader et al 2013

Most massive UCD known

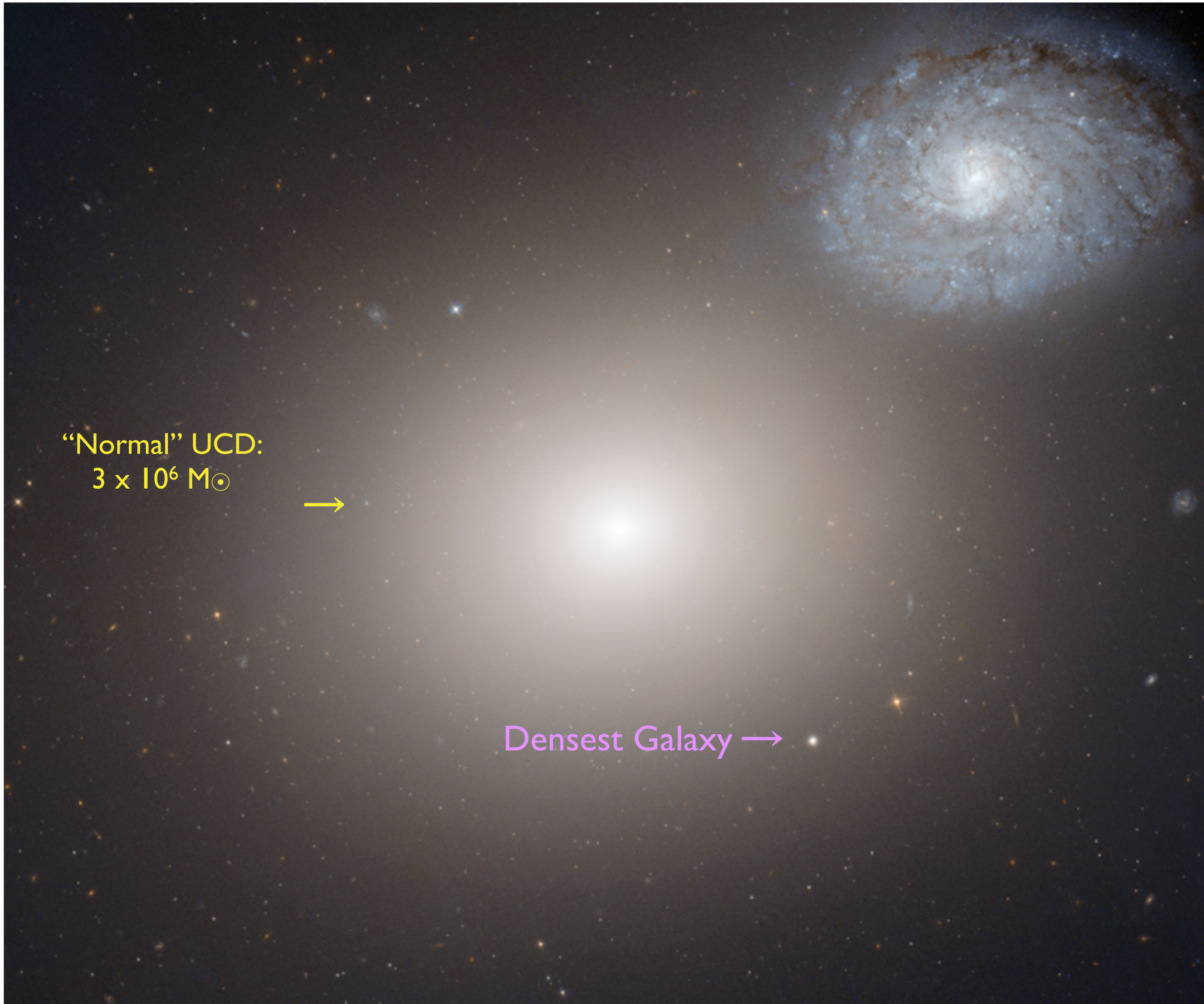
$2 \times 10^8 M_\odot$

$R_h \sim 24$ pc

$\sigma \sim 70$ km/s

2 structural components

Central X-ray source → black hole?

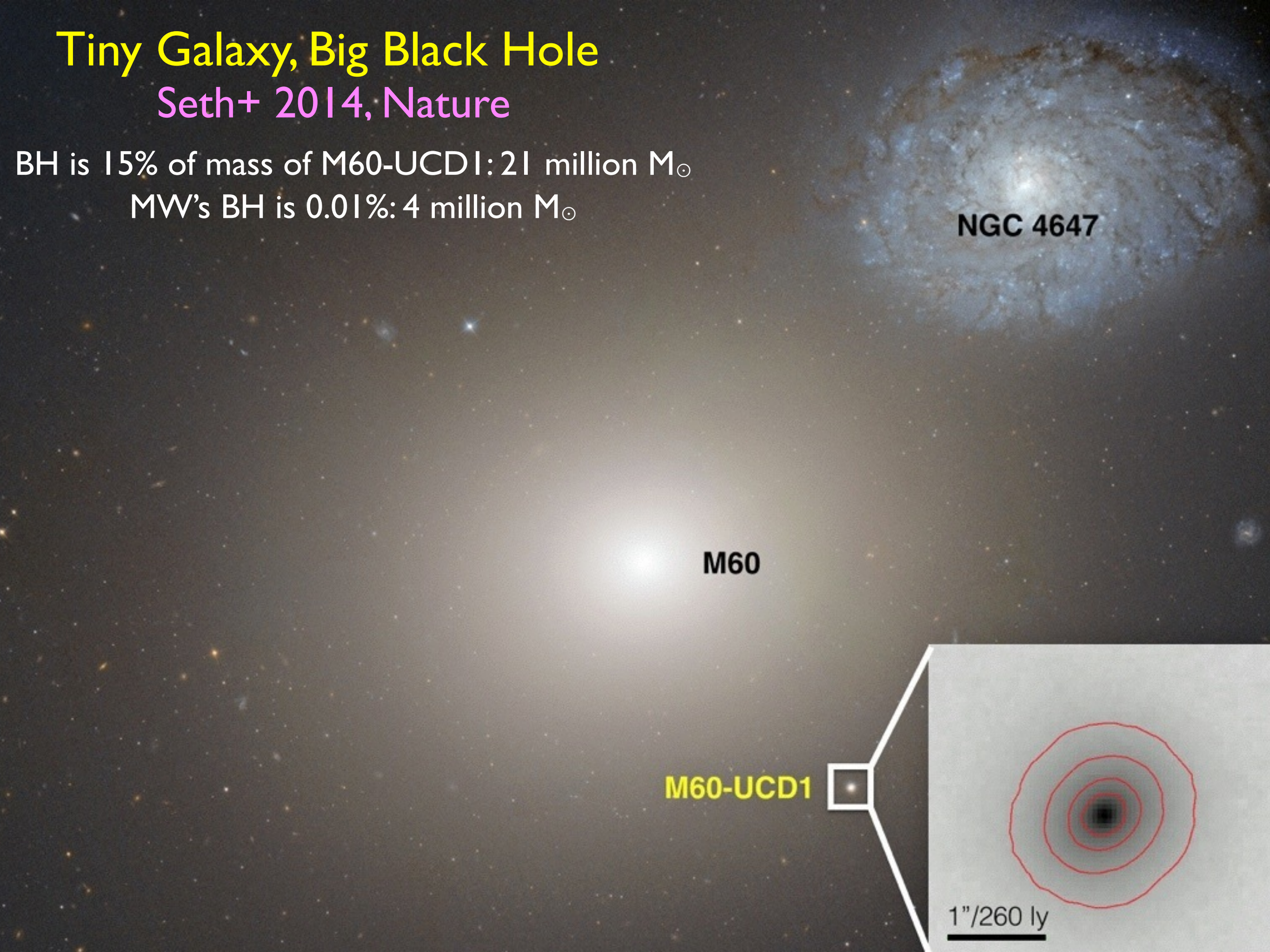


Tiny Galaxy, Big Black Hole

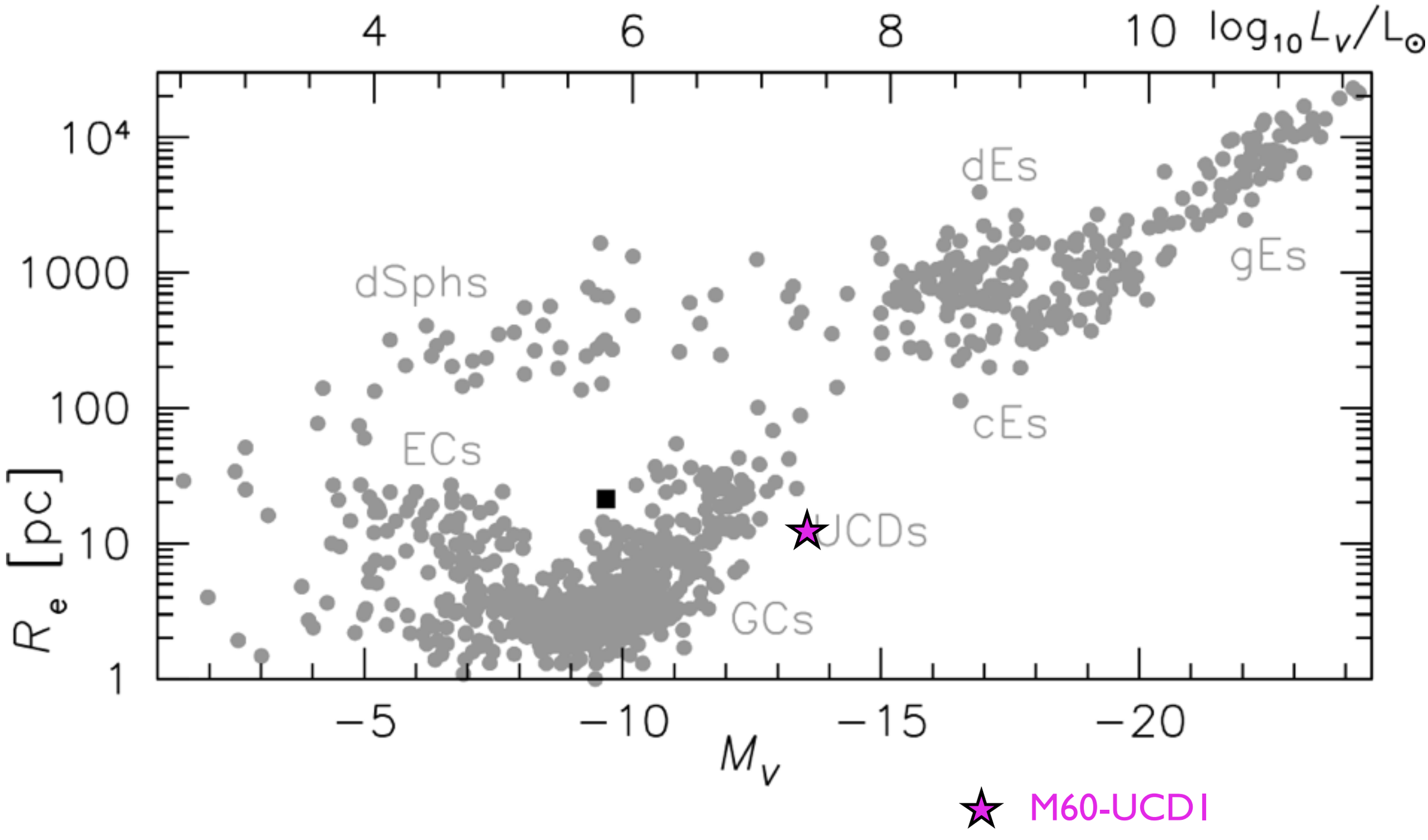
Seth+ 2014, Nature

BH is 15% of mass of M60-UCD1: 21 million $M_\odot$

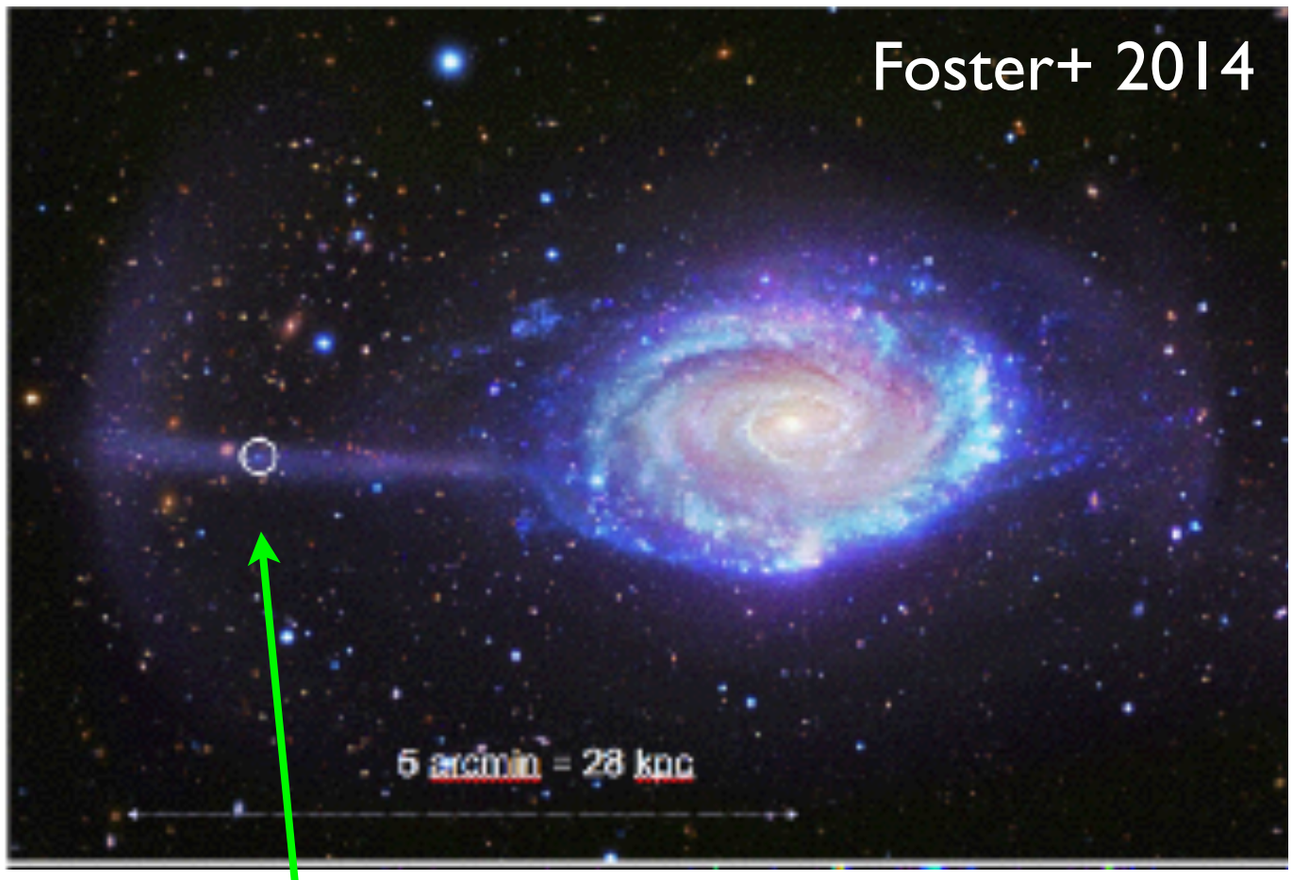
MW's BH is 0.01%: 4 million $M_\odot$



The Everything Plot circa 2011

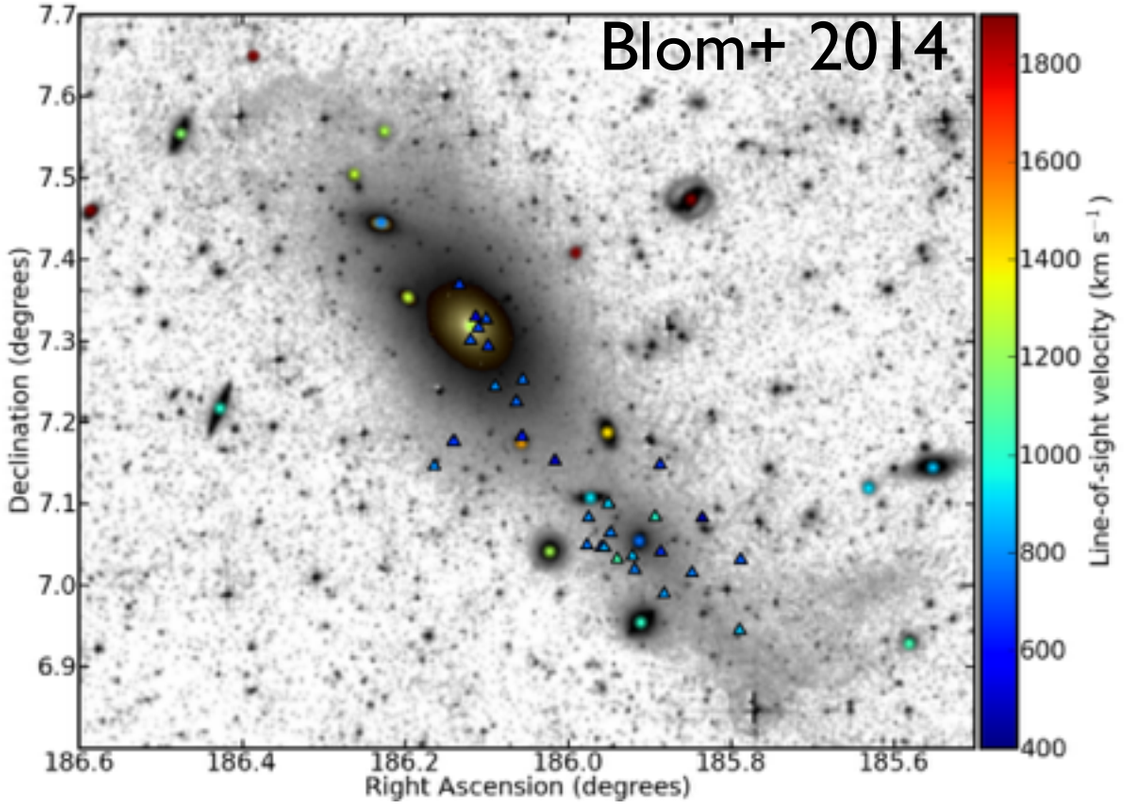


Novelties: Markers of tidal interactions/mergers



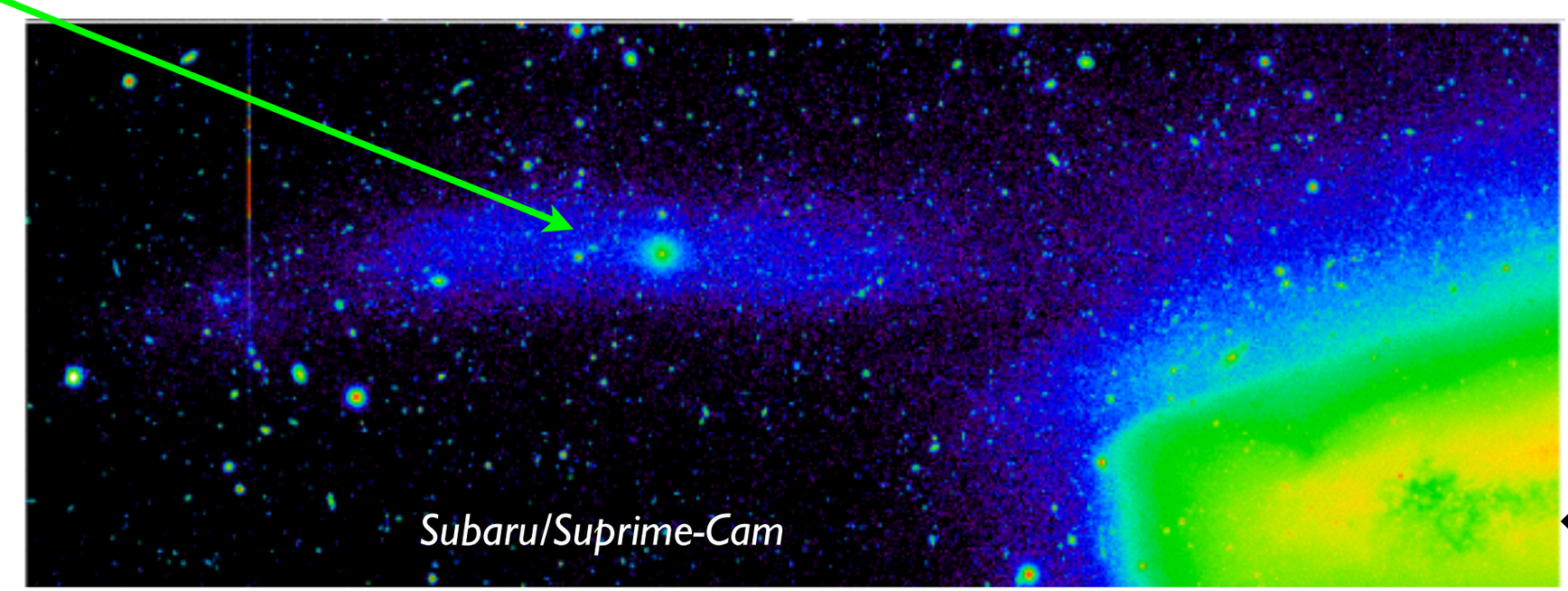
NGC 4651
GC embedded in Sgr stream analog

Omega Cen in formation!



Red nugget NGC 4342 is being stripped by NGC 4365
GCs and stream stars share velocity and stellar pop characteristics

NGC 3628-UCD1 embedded in tidal stream
$L_I \sim 1.4 \times 10^6\ L_\odot$
$R_h \sim 10$pc

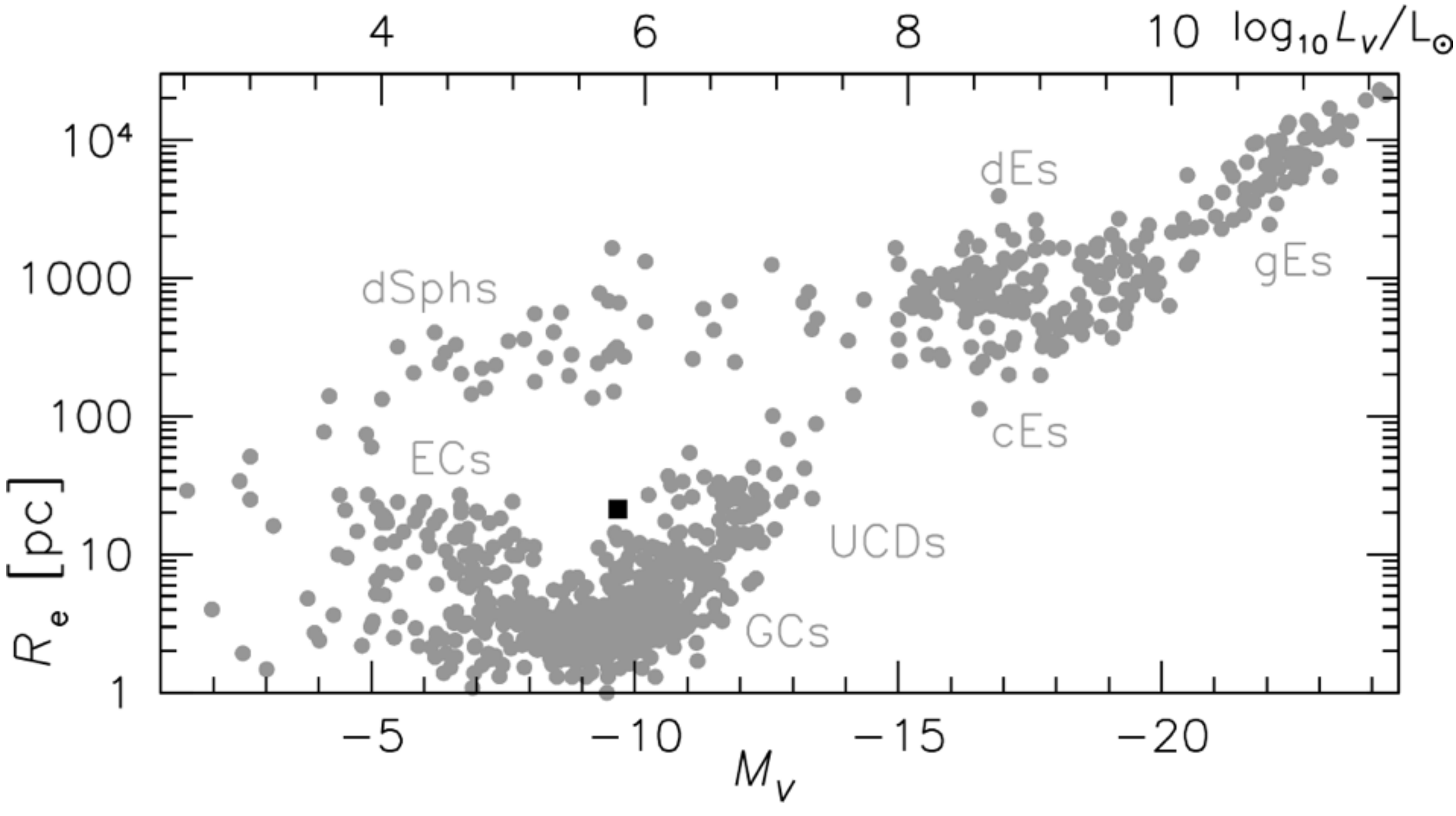


Jennings+ 2015

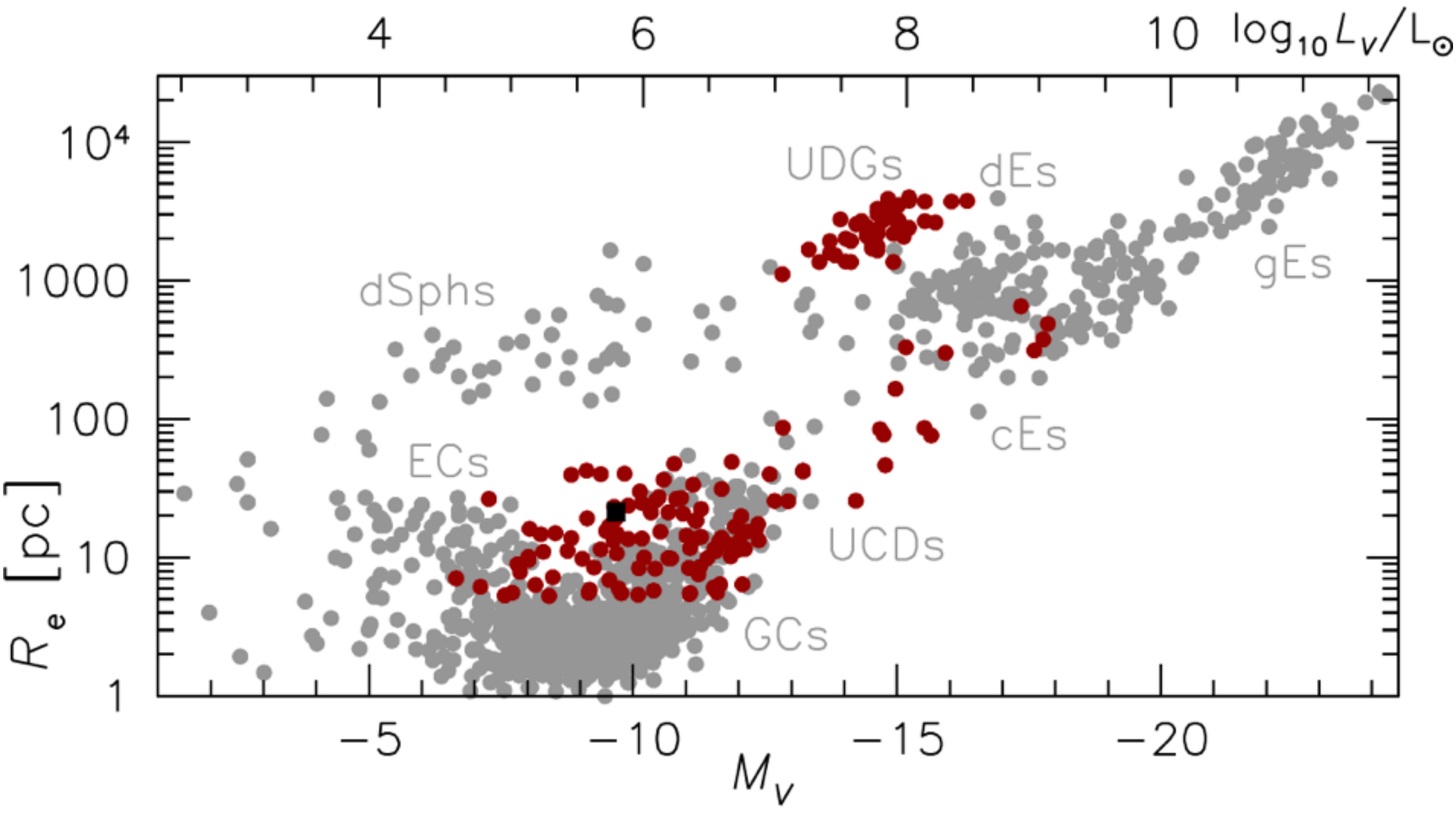
Progenitor
$L > 10^9\ L_\odot$

←disturbed spiral

The Everything Plot circa 2011



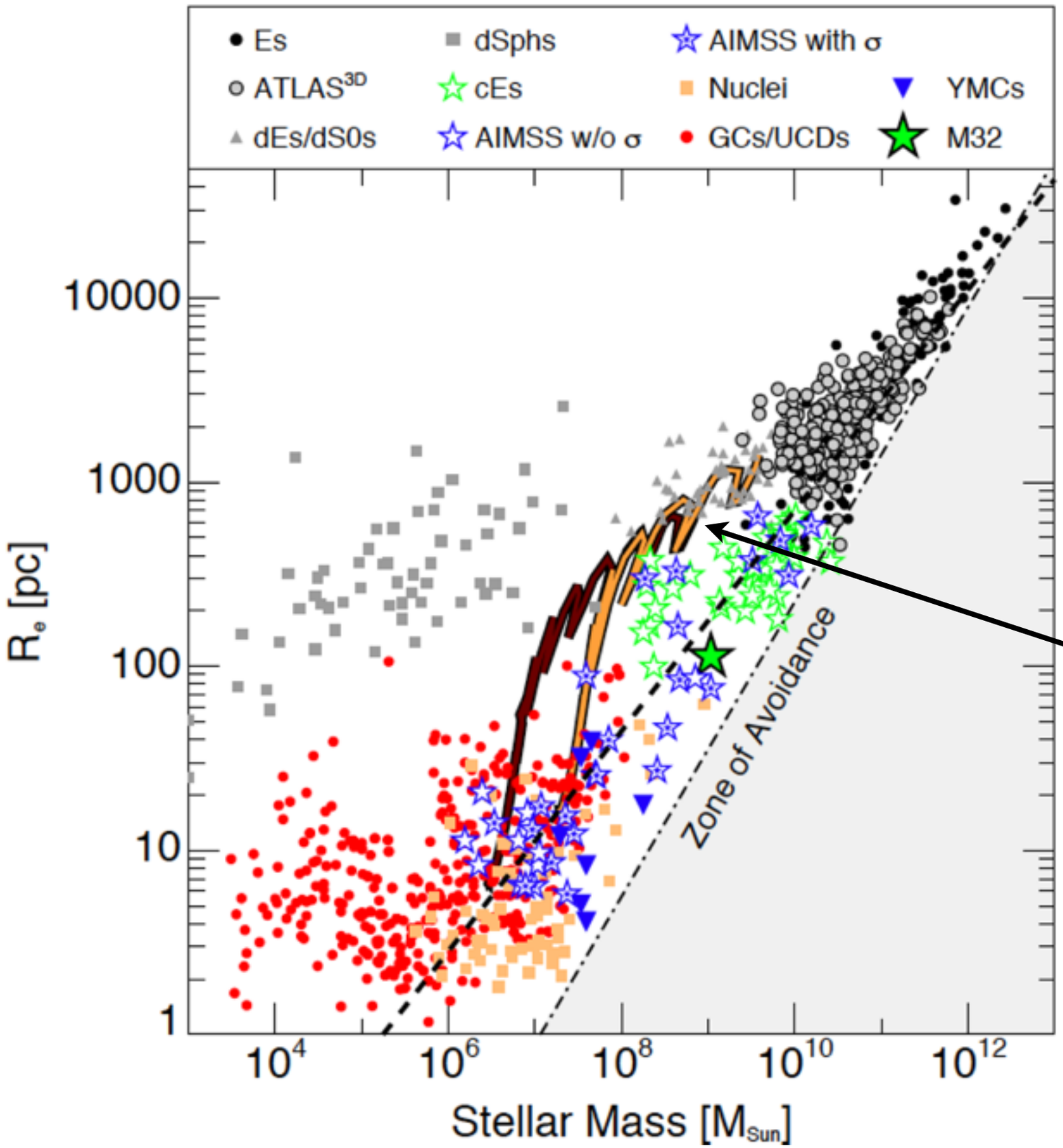
The Everything Plot circa 2015



AIMSS CSS Survey - HST archive + Keck, SOAR, SALT

Archive of Intermediate Mass Stellar Systems

Norris + 2014



Space between clusters and galaxies entirely filled with CSSs

Stripping trajectories for nucleated dwarfs
Pfeffer & Baumgardt 2013

Summary

SLUGGS Chemodynamical survey of 25 (+3) nearby ETGs
Range of M, env, σ, v/σ..... Globular clusters to ~10 $r_{eff,}$ Starlight to ~3 r_{eff}

http://sluggs.ucolick.org

GC metallicity bimodality - distinct kinematics

MR GCs trace build up of bulges
MP GCs trace build up of halos

M31 had more complex accretion vs MW

2-D wide-field data → disk instabilities "wild disks" + accretions, *not* major mergers

Multipopulation dynamical modeling (stars + GC subpops) → independent constraints on DM distribution → DM density, total enclosed mass, β, $\mathrm{M/L}$

JAM for stars from ATLAS^{3D} + SLUGGS → power law density profiles ($\gamma = 2.19 \pm 0.04$) for 14 fast rotators, out to 4Re

New classes of UCD/stripped galaxy remnants – easily observable tracers of minor mergers

Open questions:

What proportion of UCDs and local "red nuggets" are stripped galaxies? Affects cosmic accounting and inferences for halo build up.

Is there a genuine distinction between star clusters, UCDs and galaxies?

What is the DM content of UCDs and are there enough of them to solve the missing satellite problem?

Will JAM (Jeans Axisymmetric Model) simplicity hold for larger, more diverse samples of galaxies?

Why do blue GCs display tangential anisotropy?

What are the theoretical predictions for MP stellar halos?