Globular clusters and halo stars as tracers of galaxy assembly

Study
Astrophysics of
Globular
clusters in
Extragalactc
Systems

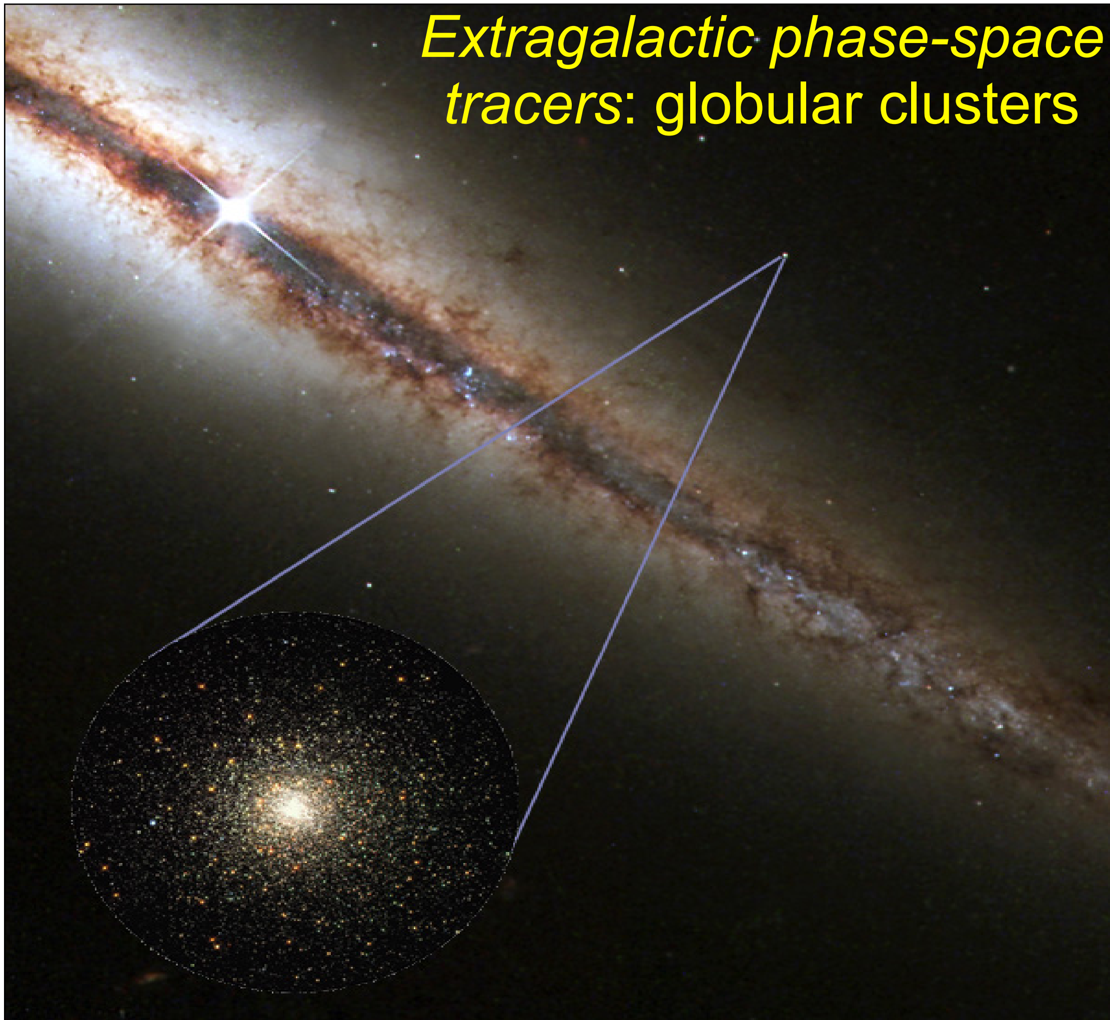
Jean Brodie
UC Observatories

COLLABORATORS

Jacob Arnold
Christina Blom
Ana Chies-Santos
Duncan Forbes
Caroline Foster
Zachary Jennings
Justin Kader
Sreeja Kartha
Soeren Larsen
Nicola Pastorello
Vincenzo Pota
Robert Proctor
Joel Roediger
Aaron Romanowsky
Navtej Singh
Lee Spitler
Jay Strader
Tomar Tal
Chiara Tonini
Chris Usher
Alexa Villaume
Kristin Woodley

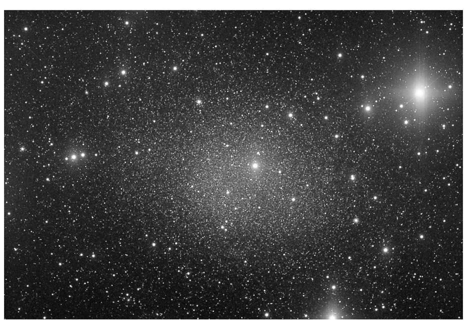
SAGES

Extragalactic phase-space tracers: globular clusters



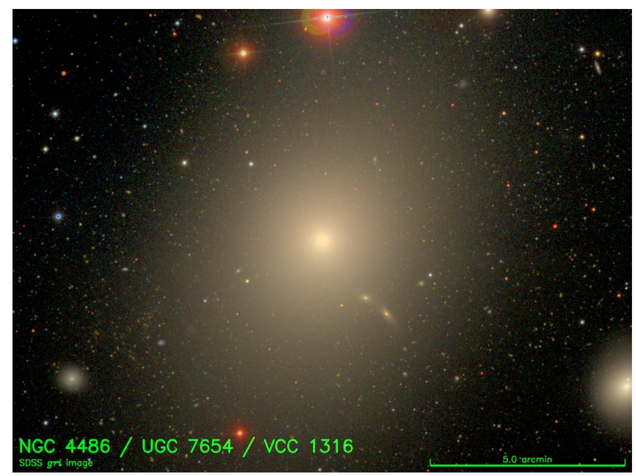
- Almost all galaxies >10^9 M$_\odot$ host GC systems
- GC formation accompanies all major star formation
- Bright (10^5-10^6 M$_\odot$) fossils
- Spectroscopy feasible to ~ 50 Mpc
  - estimate abundance of elements (Fe...)
  - key extension of phase-space
- Used to establish 2-phase formation of the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

  (Searle & Zinn 1978)



Dwarfs: 0 to 10s

Disks: 10s to 100s

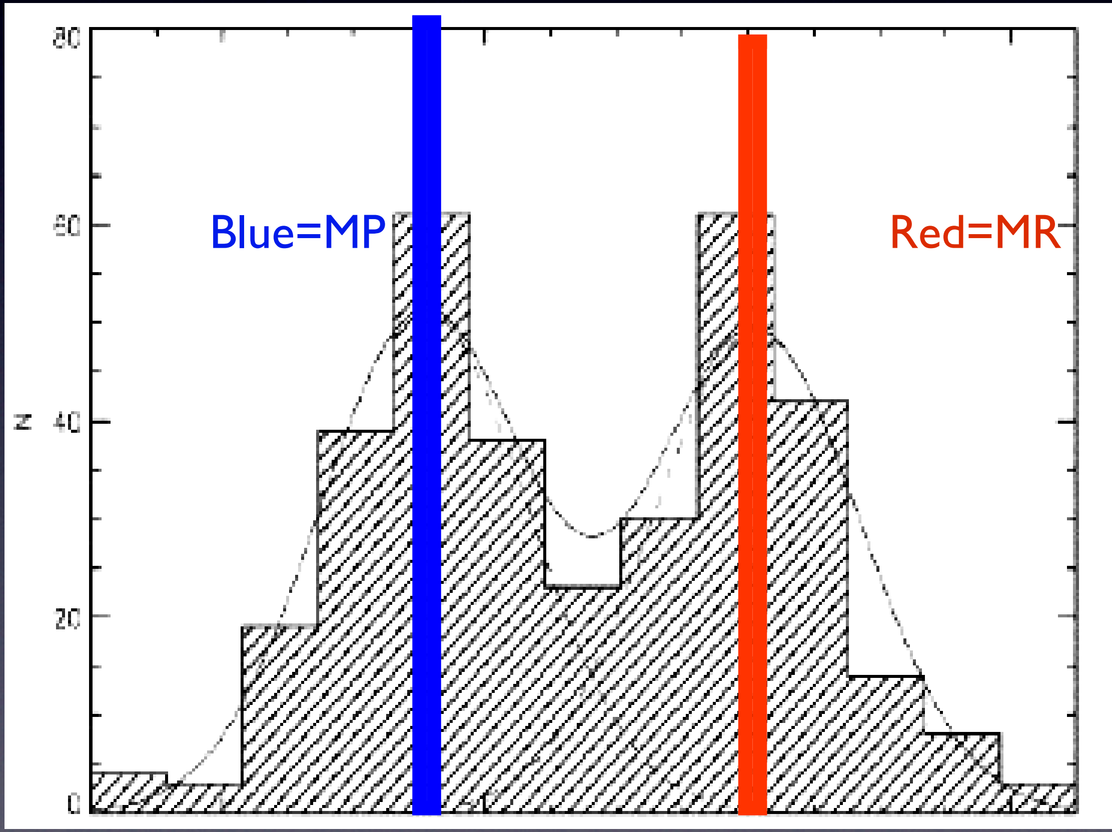


Es: 100s to > 10^4

BIMODALITY

Most (perhaps all) large galaxies possess two distinct sub-populations of globular clusters.

Both subpops are old >10Gyr
Blues likely older than reds
but ages only accurate to ± 1-2 Gyr
z_{form} 8→3 only 1Gyr!



truncation of GC formation at z≥~5?

[Fe/H] = -1.5 -0.5

V-I = 0.95 1.15

GC-galaxy properties

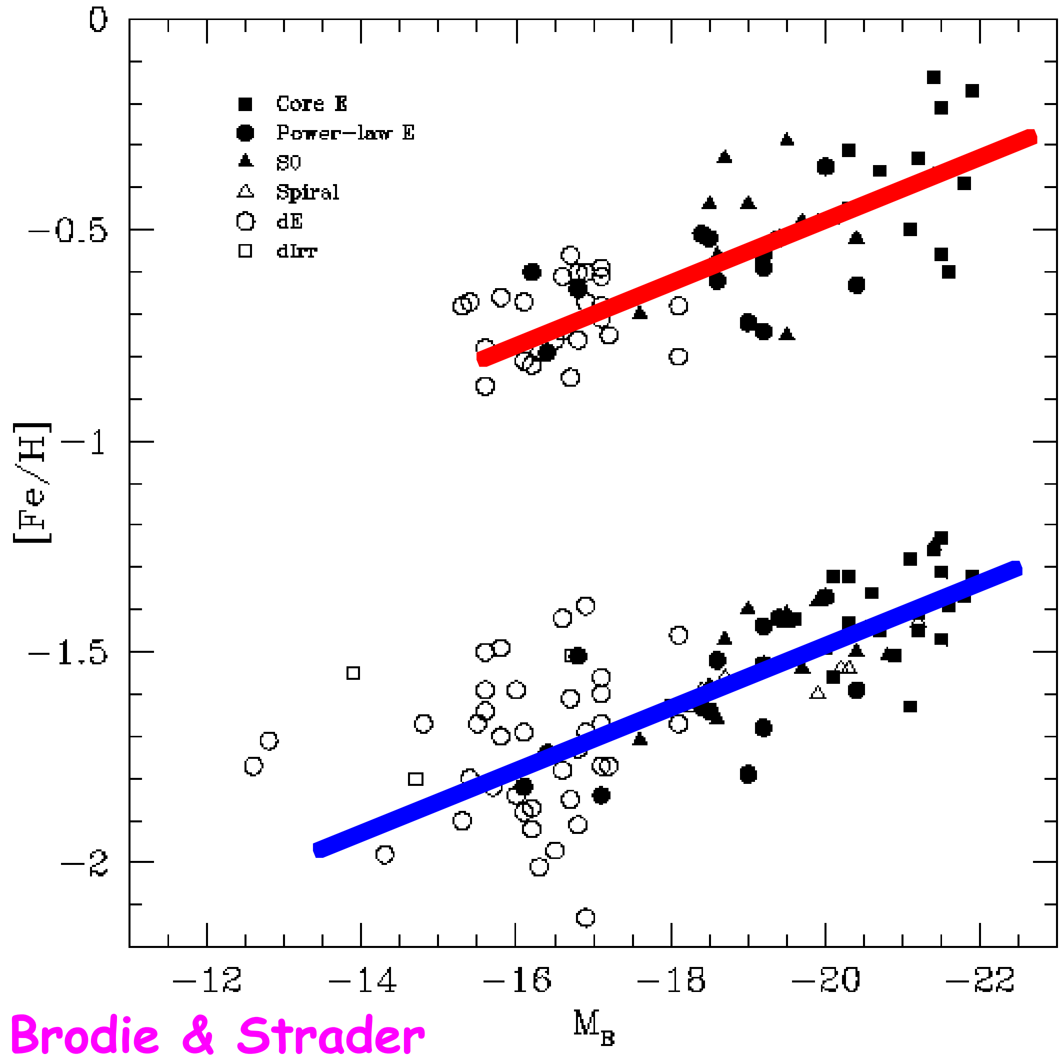
MR GCs
Similar slope to star-galaxy relation

MP GCs forming at very high z "knew" the galaxy to which they would ultimately belong

GC scaling relations constrain hierarchical growth

red GCs trace bulge formation?

blues GCs trace DM halos at earliest times?

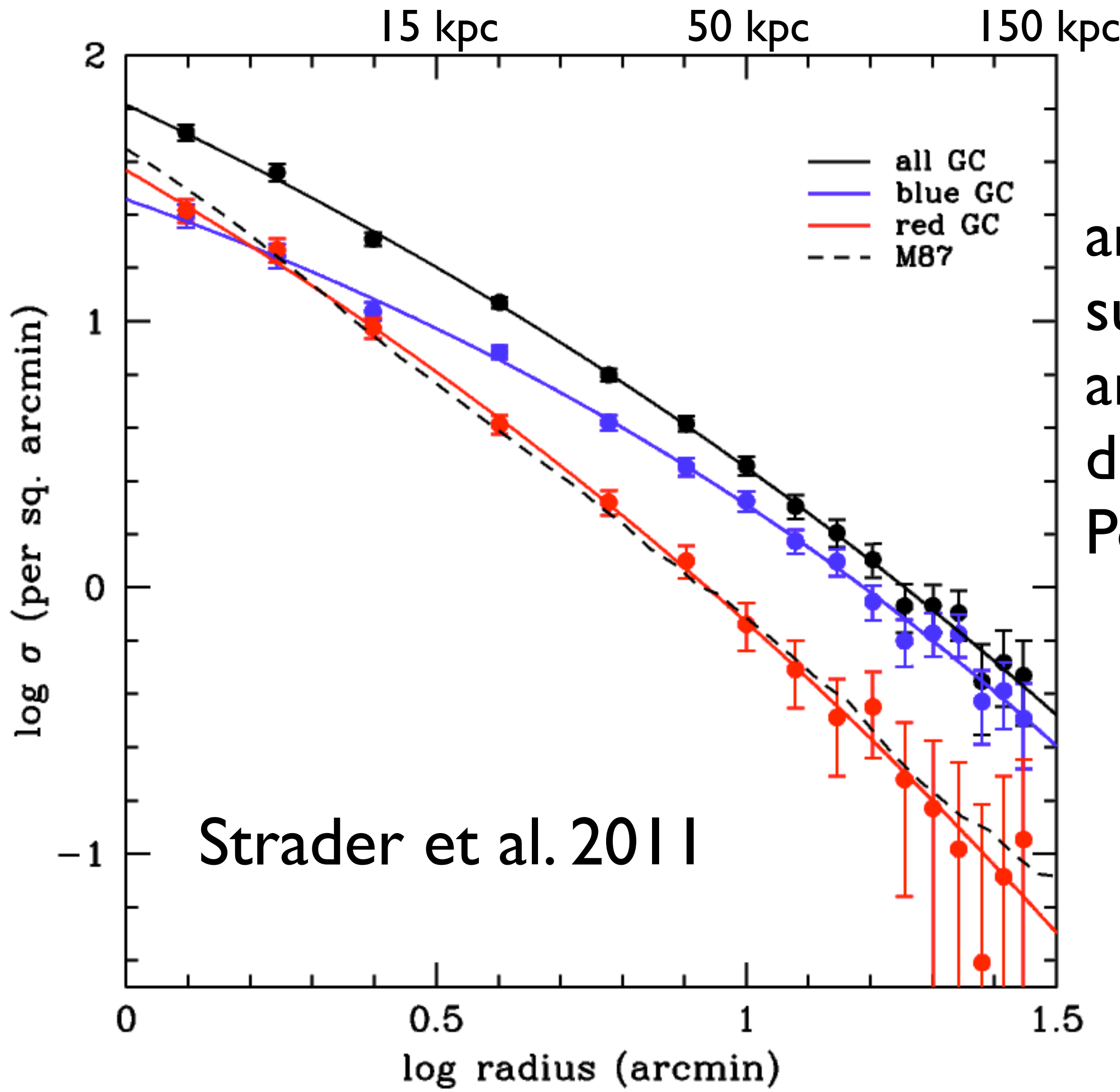


Brodie & Strader ARAA 2006

Peng et al 2006

M87: Spatial Distribution

Blue GCs more extended
Red GCs trace the bulge



and metallicity subpopulations are kinematically distinct
Pota+ (2012)

Metaillity bimodality results naturally from hierarchical galaxy assembly

Merger rates as a function of mass from dark matter simulations

Mass-metallicity relation → accreted galaxies (and their GCs) are lower mass and lower metallicity – dominate the blue peak

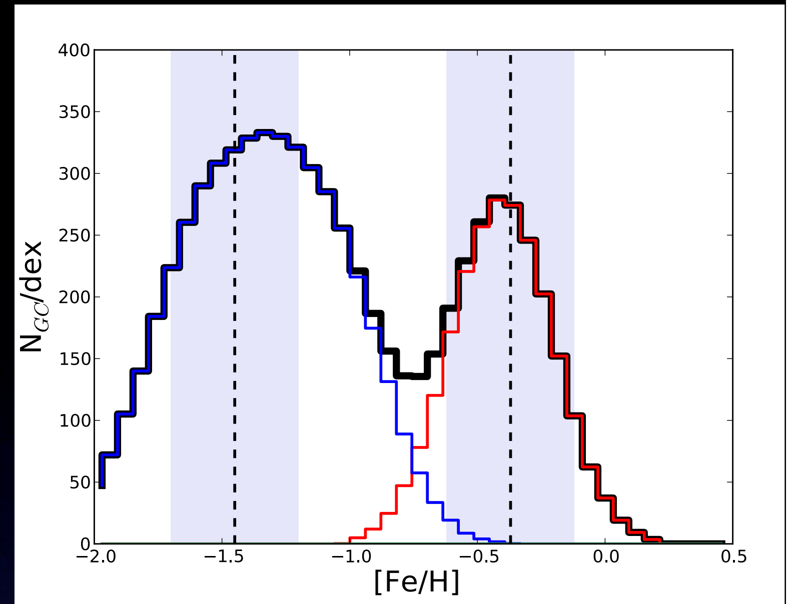
Assumes GCs share metallicity of their original parent galaxy at the time of formation

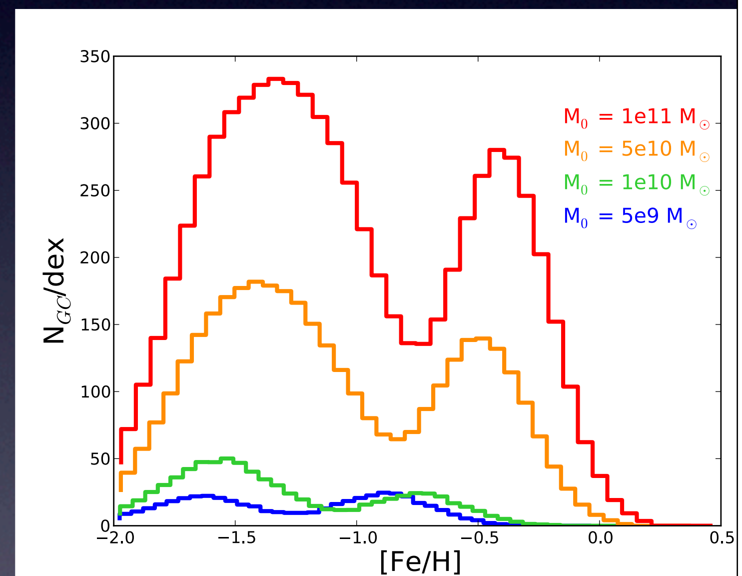
Red GCs form at z~2
Blue GCs form at z~3–4

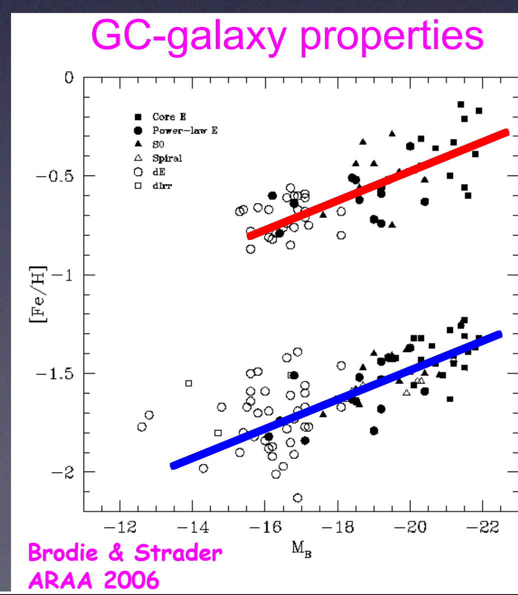
Model reproduces the observed relations

Tonini (2011)

$M_{gal} = 10^{11}\ M_\odot$ at $z = 0$

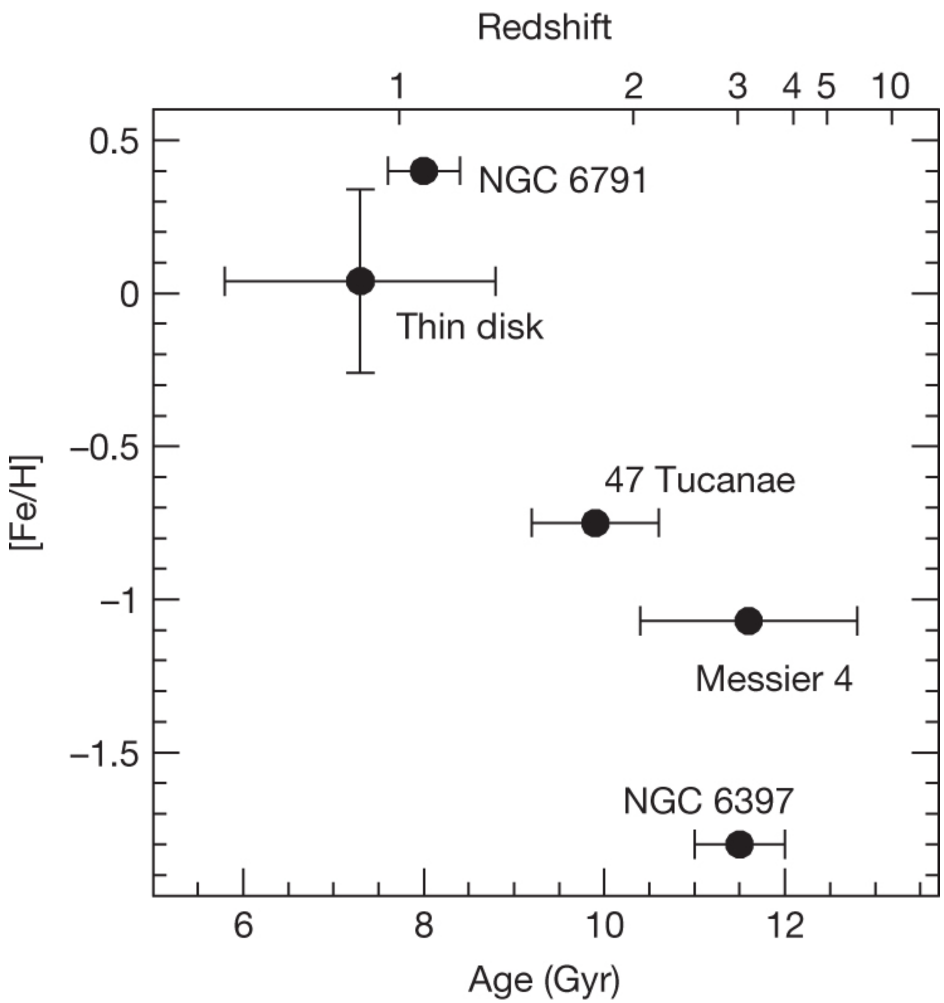






Important new result on GC ages

Age–metallicity relation based on white dwarfs.



BMS Hansen *et al.* *Nature* **500**, 51-53 (2013) doi:10.1038/nature12334

Red GCs are indeed ~1−2 Gyr younger than blue GCs

Red GCs formed at z~2

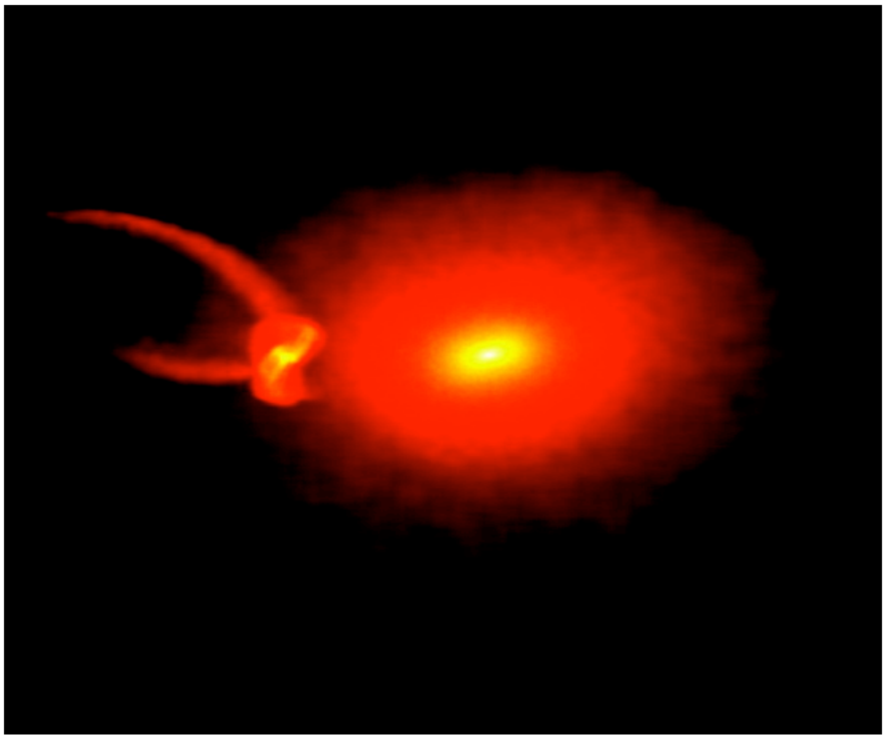
Errors on age now ~0.5 Gyr

nature

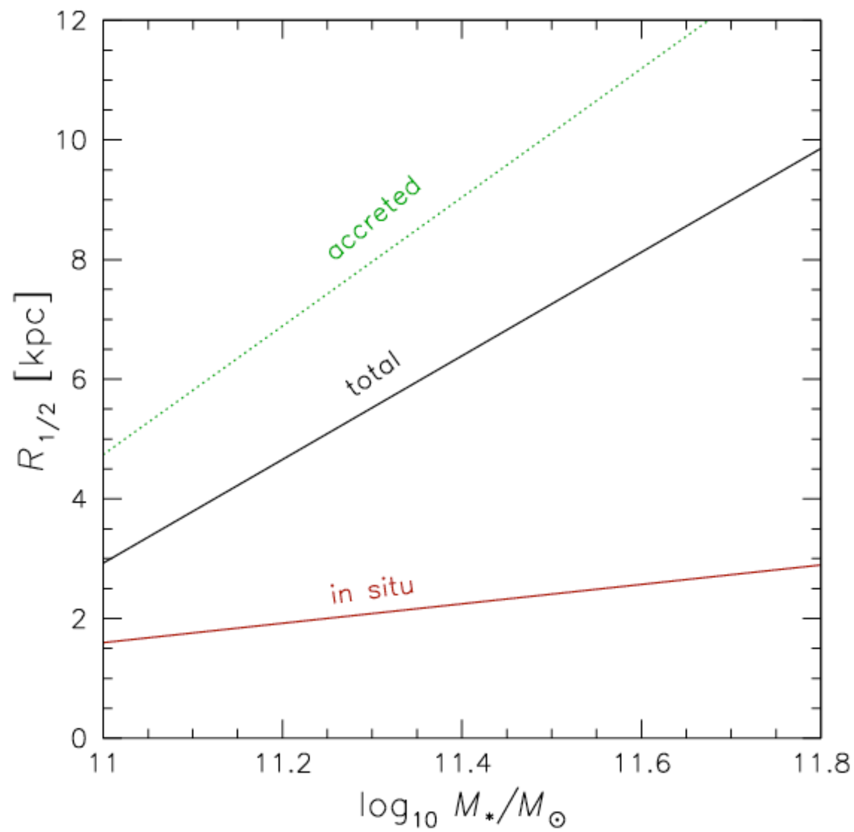
Two-phase galaxy formation

- 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)

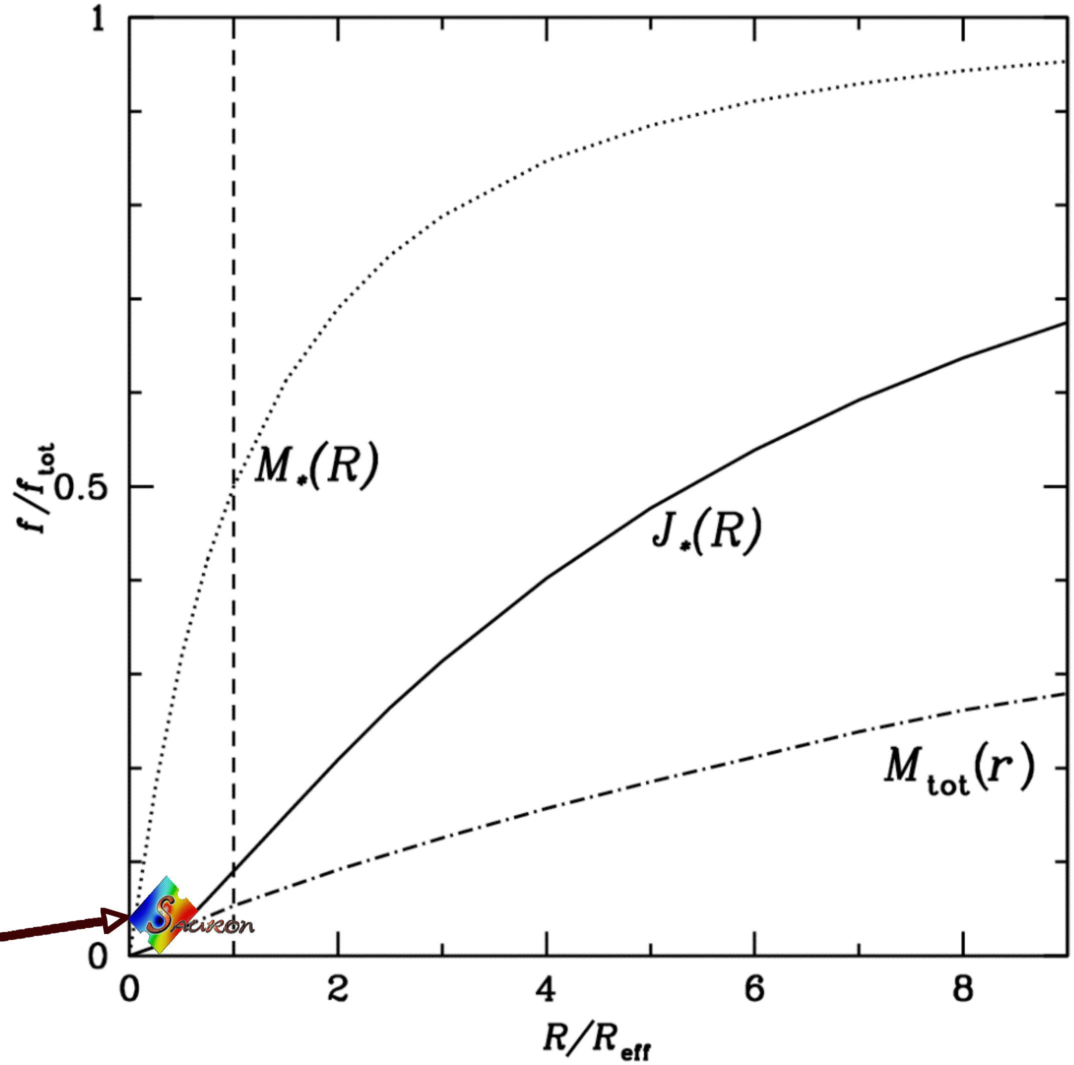


GCs and stars - unveiling surprises at large radii

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

Limit of traditional integrated stellar spectroscopy

Elliptical Galaxy Schematic



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)

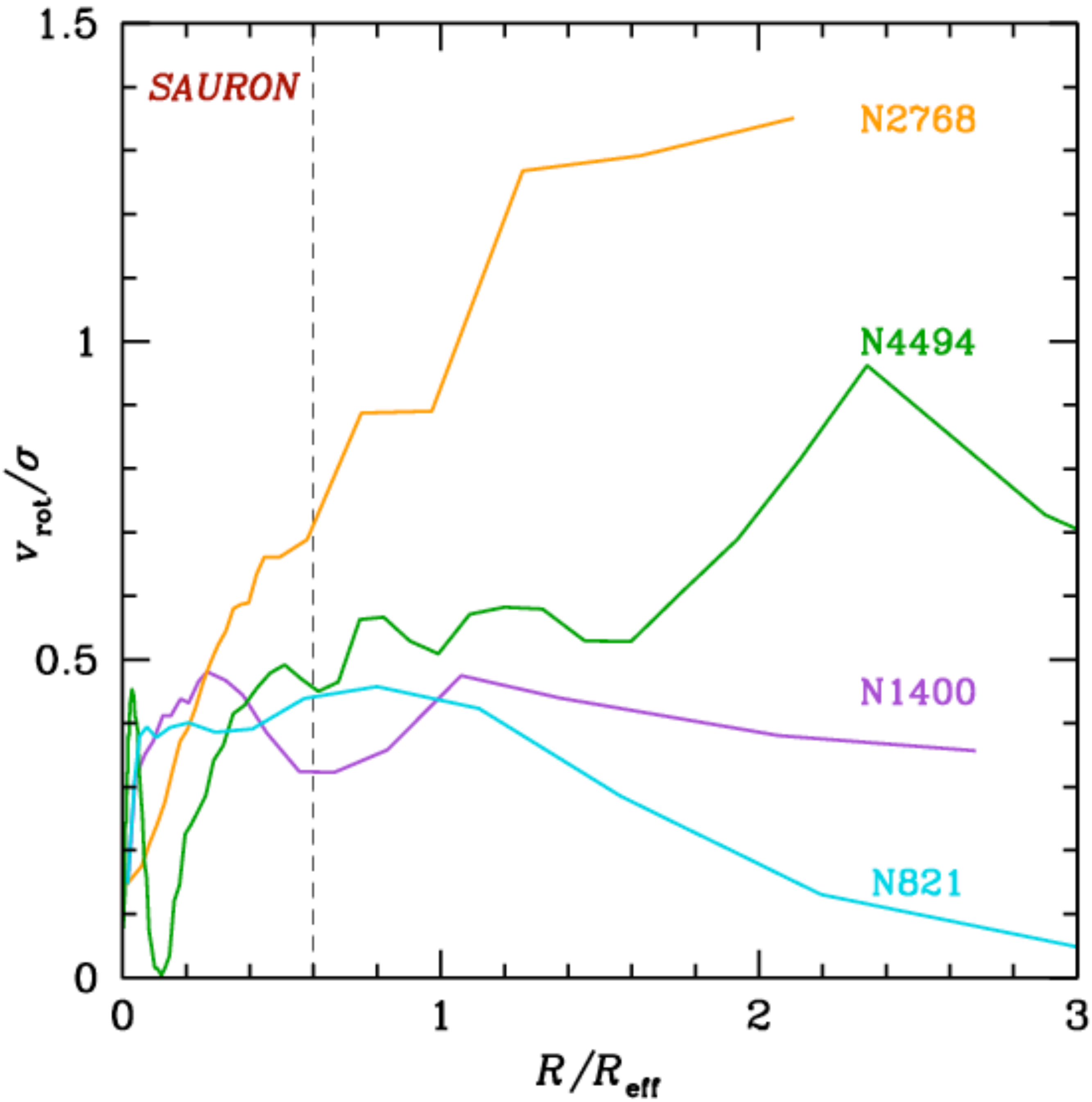
Globular clusters to ~10 r_{eff}

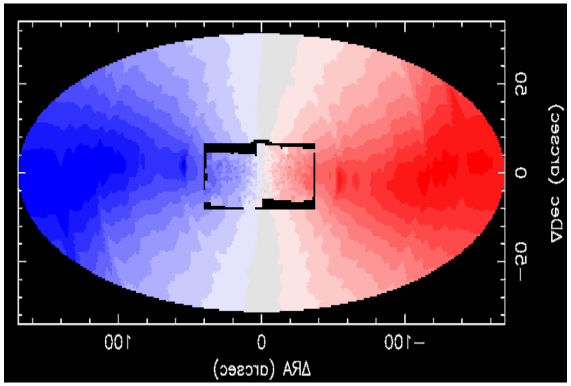
Field stars to ~ 3 r_{eff}

SMEAGOL

Spectroscopic Mapping of Early-type Galaxies to their Outer Limits

Galaxy Kinematic Profiles

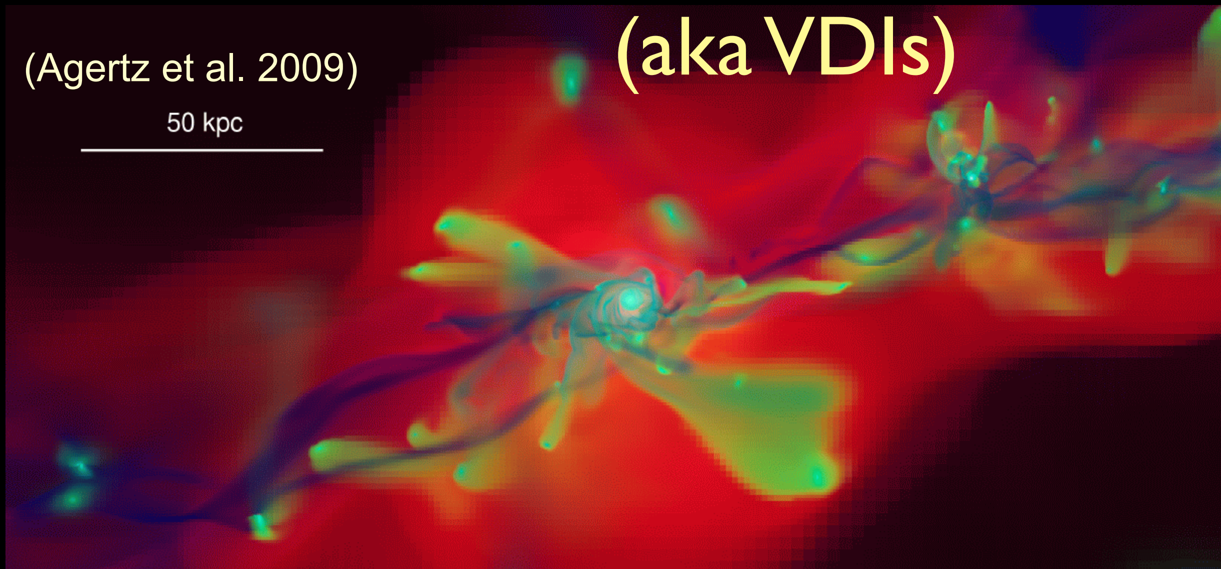




DEIMOS as a psuedo IFU

Inner profiles do not predict large radius behavior

"Wild disks" as globular cluster factories
(aka VDIs)

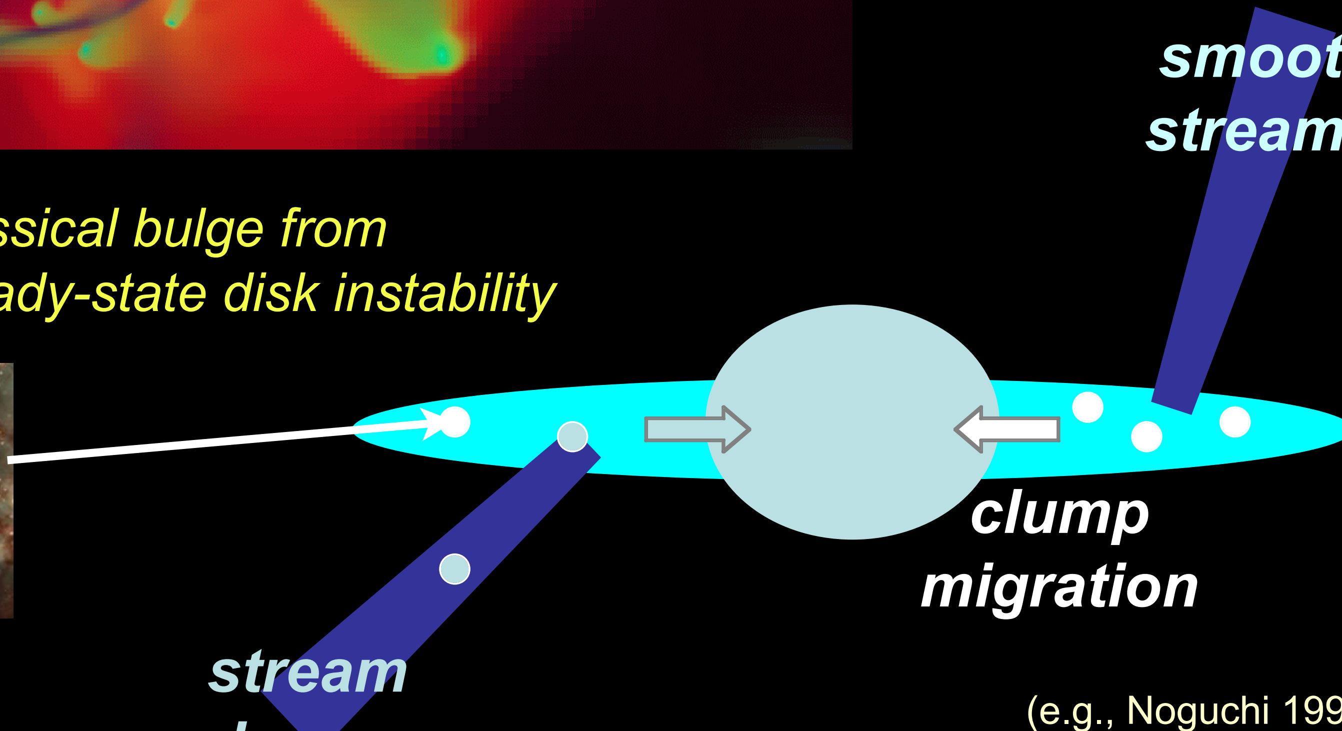


cold gas streams penetrate to small radii at high-redshift

Shapiro et al 2010;
Escala & Larsen 2008

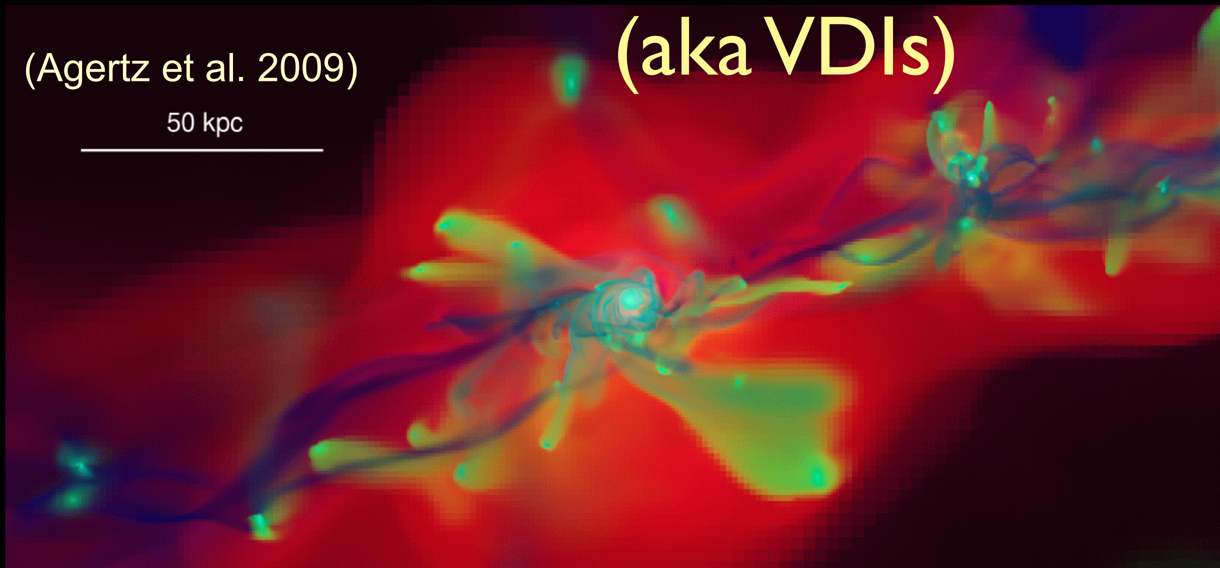
classical bulge from steady-state disk instability

YMCs??



(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;
Escala & Larsen 2008

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

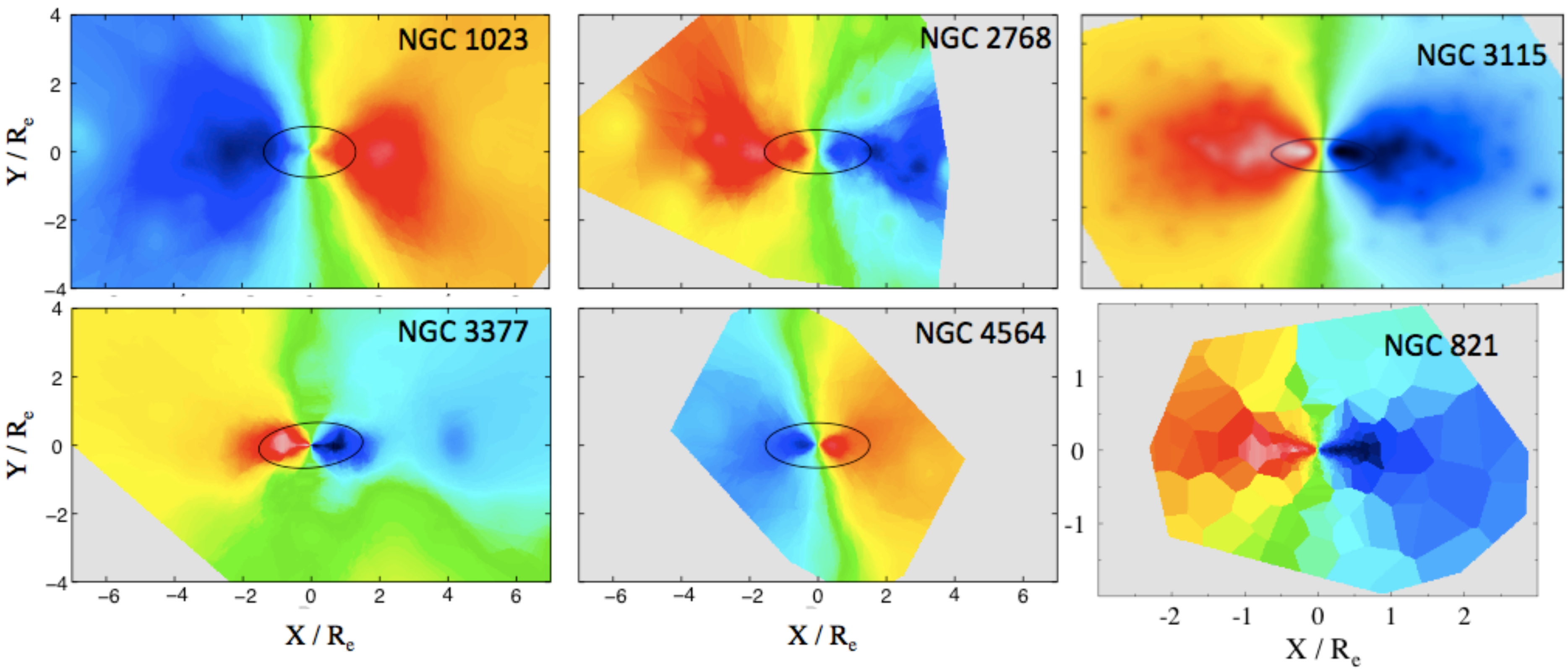
(Conroy+2008;
Genzel+2008)

Full velocity maps: stars+PNe+GCs

PN.S

(8) flattened (~edge-on) cases for minimal ambiguity

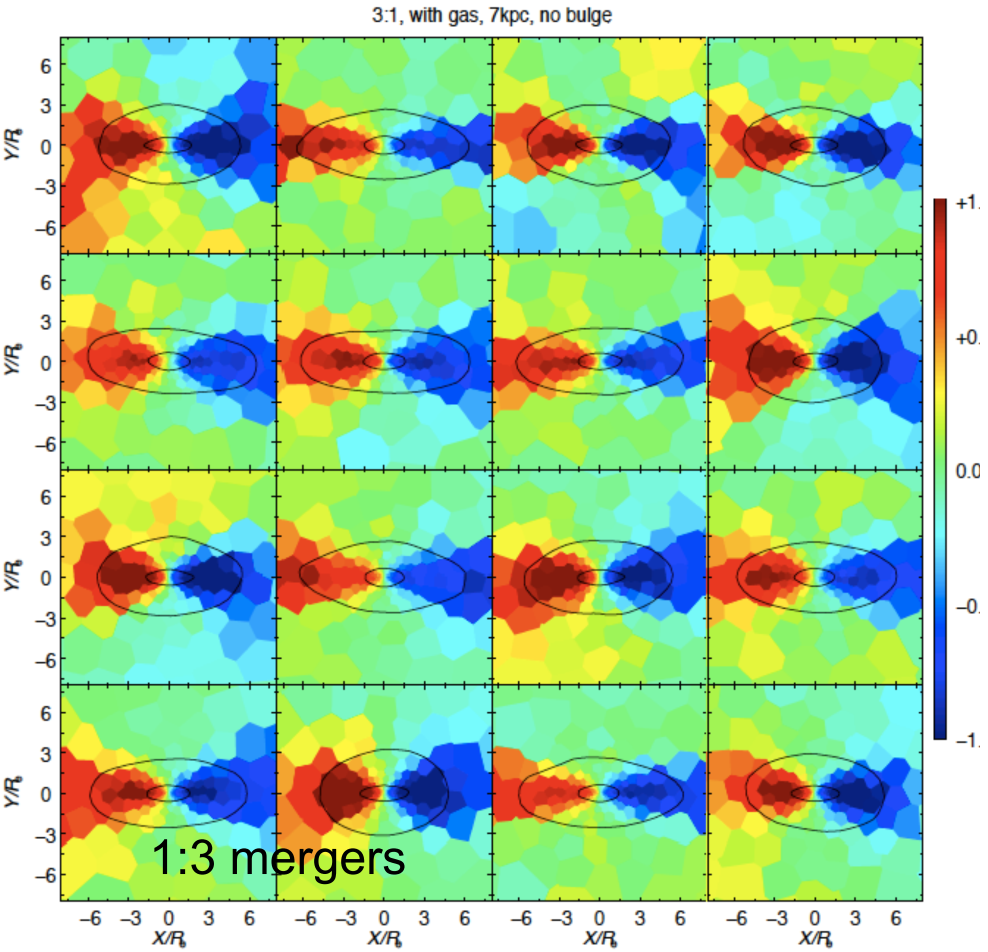
(Proctor+09; Coccato+09; Arnold+11; Pota+13; Romanowsky++ in prep)

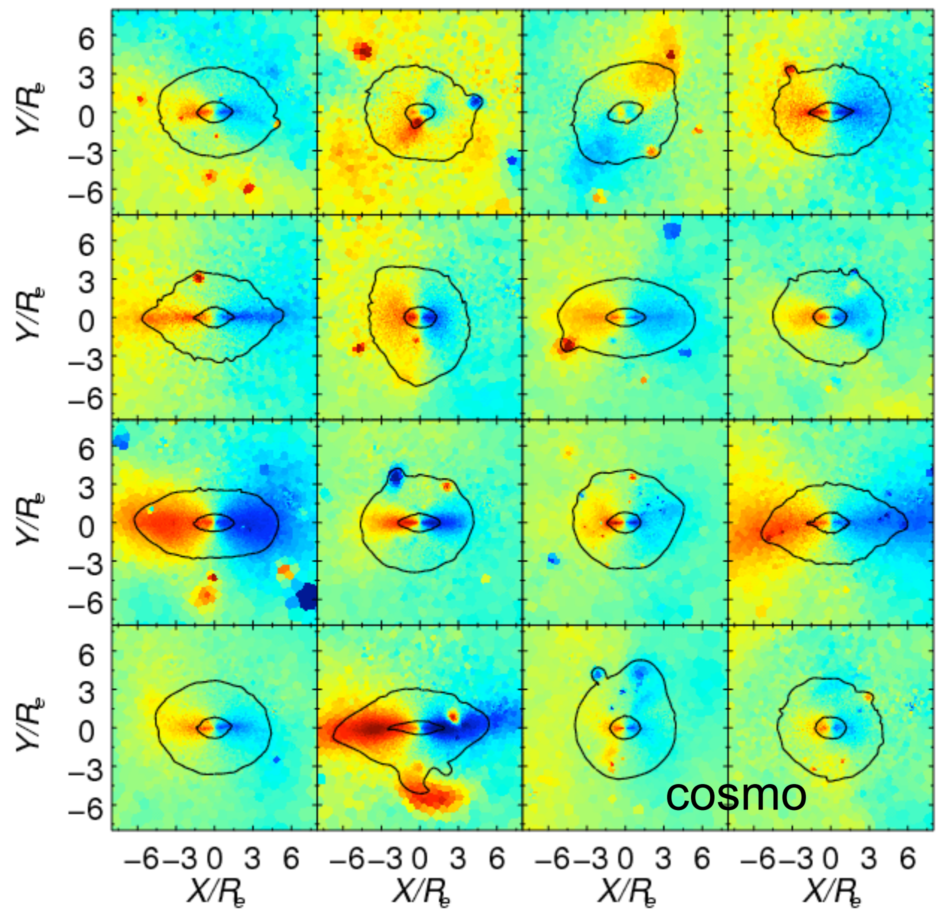


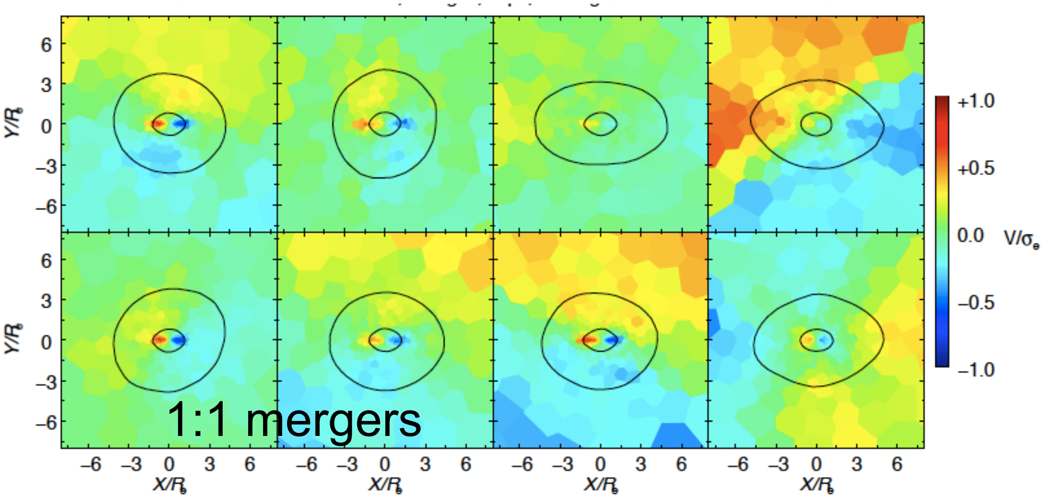
→ observed rotation declines outside ~2 R_e *(missed by SAURON)*

→ generally mild kinematic twists

Wide-field mean velocity maps of simulations





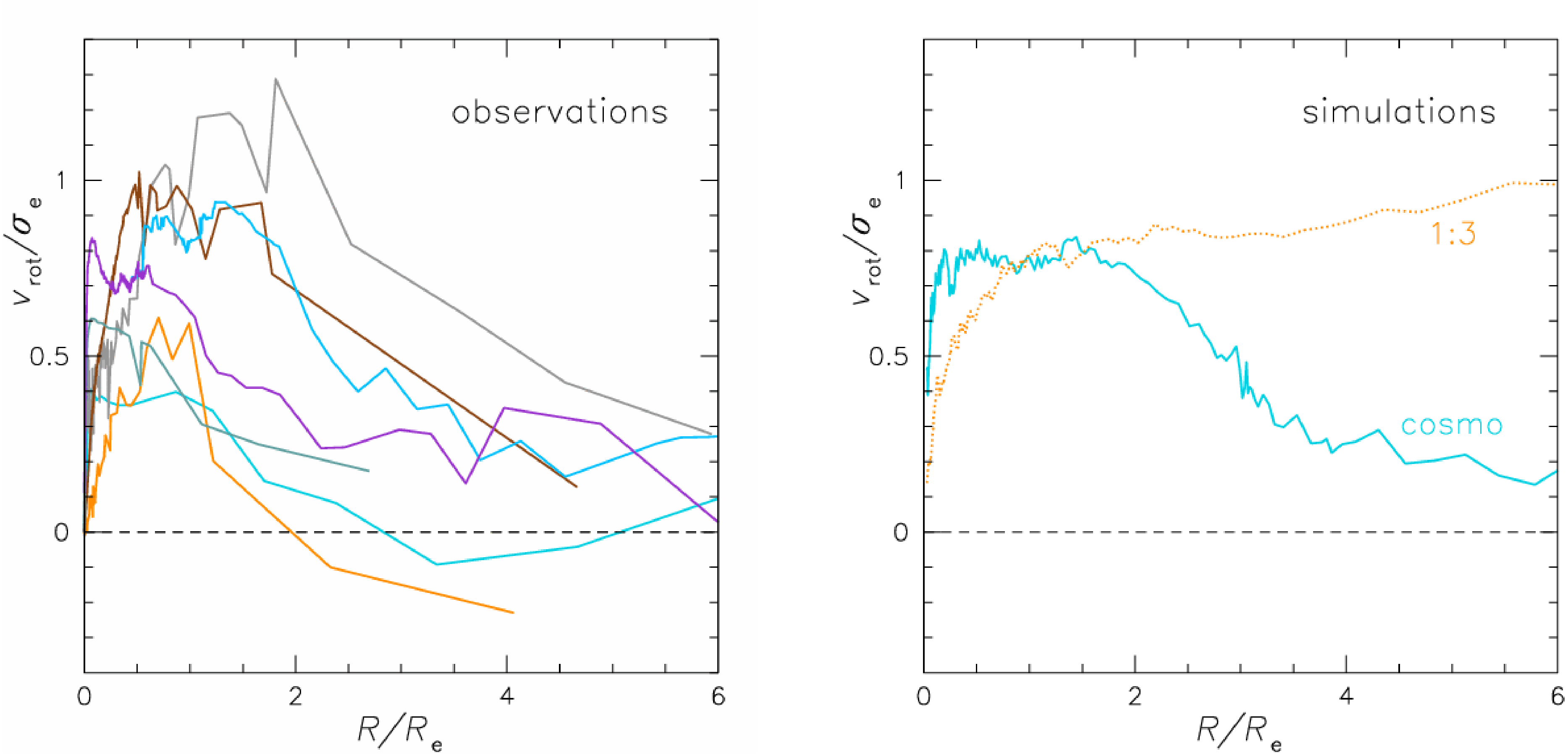


1:3 mergers: strong, aligned rotation to large radii

1:1 mergers: weak central disk, often strong kinematic twists

cosmo: (aligned) fast-slow transition

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)

Predicted major mergers spin up not found

SLUGGs UPDATE

Observations nearing completion

SAGES in Chile

Coming soon

30+ papers now published
from the SLUGGs survey
(see sluggs.ucolick.org)

Some recent highlights:

2500 GC velocities in 12 galaxies →
metallicity subpopulations are kinematically distinct (Strader + 2011; Pota + 2012; Blom + 2012)

968 GC spectroscopic metallicity measurements (Usher + 2012)
confirm generality of metallicity bimodality; color-metallicity transformation (broken) linear but depends on galaxy mass

2-D Stellar velocity maps for 23 galaxies, – galaxy classifications (Arnold+ 2013)

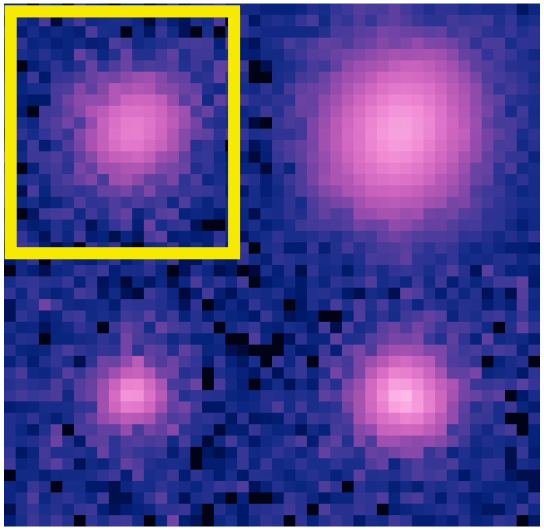
SLUGGs UPDATE

2-D Stellar, PNe, GC velocity maps – falling velocity profiles argue against major mergers (Romanowsky+ 2013)

2-D Stellar metallicity maps for ~10 galaxies, from CaT, comparisons with theoretical expectations (Pastorello+ 2013)

Radial color/metallicity gradients provide evidence of 2-phase galaxy assembly and constraints on progenitor mass ratios in accretion events (Forbes + 2011; Arnold + 2011)

Substructure revealed in velocity-position phase space allows mass estimates of accreted galaxies and event timing (Romanowsky + 2011; Strader +2011)



Serendipity

New class of UCD (Brodie+ 2012)

The densest galaxy (Strader+ 2013)

GC subpopulations trace bulge (red) and halo (blue) build up

Stars, GCs and PNe provide strong constraints on galaxy assembly

More SLUGGs work in talks by ROMANOWSKY Dynamics of accretion in halos and WOODLEY Mass modeling/DM distributions (today)
FORBES Metallicity maps (Thursday)

SUMMARY

sluggs.ucolick.org

RECENT RESULTS

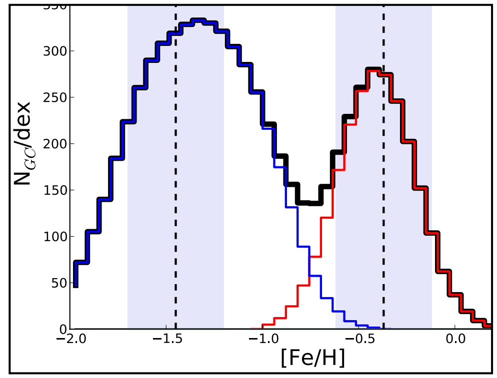
Metallicity bimodality real and ubiquitous

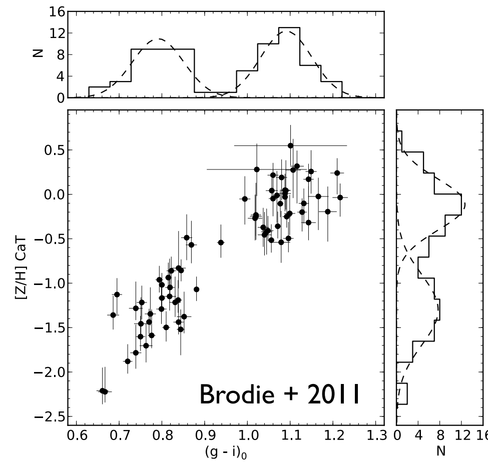
Brodie + (2011), Usher + (2012)

Occurs naturally in models of hierarchical galaxy assembly *Tonini (2011)*

WD cooling ages confirm MR (red) GCs ~ 2 Gyr younger than MP (blue) GCs

Hansen + (2013) Nature





IMPLICATIONS

GC scaling relations constrain hierarchical galaxy assembly

MR (red) GCs trace bulge formation

MP (blue) GCs trace build up of halos

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

+ LOTS MORE ! (see sluggs.ucolick.org)