Unveiling the kinematic complexity of globular clusters

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+ HSTPROMO Collaboration
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NOW

13 Gyr ago

?

Galactic globular clusters

Old and simple stellar systems

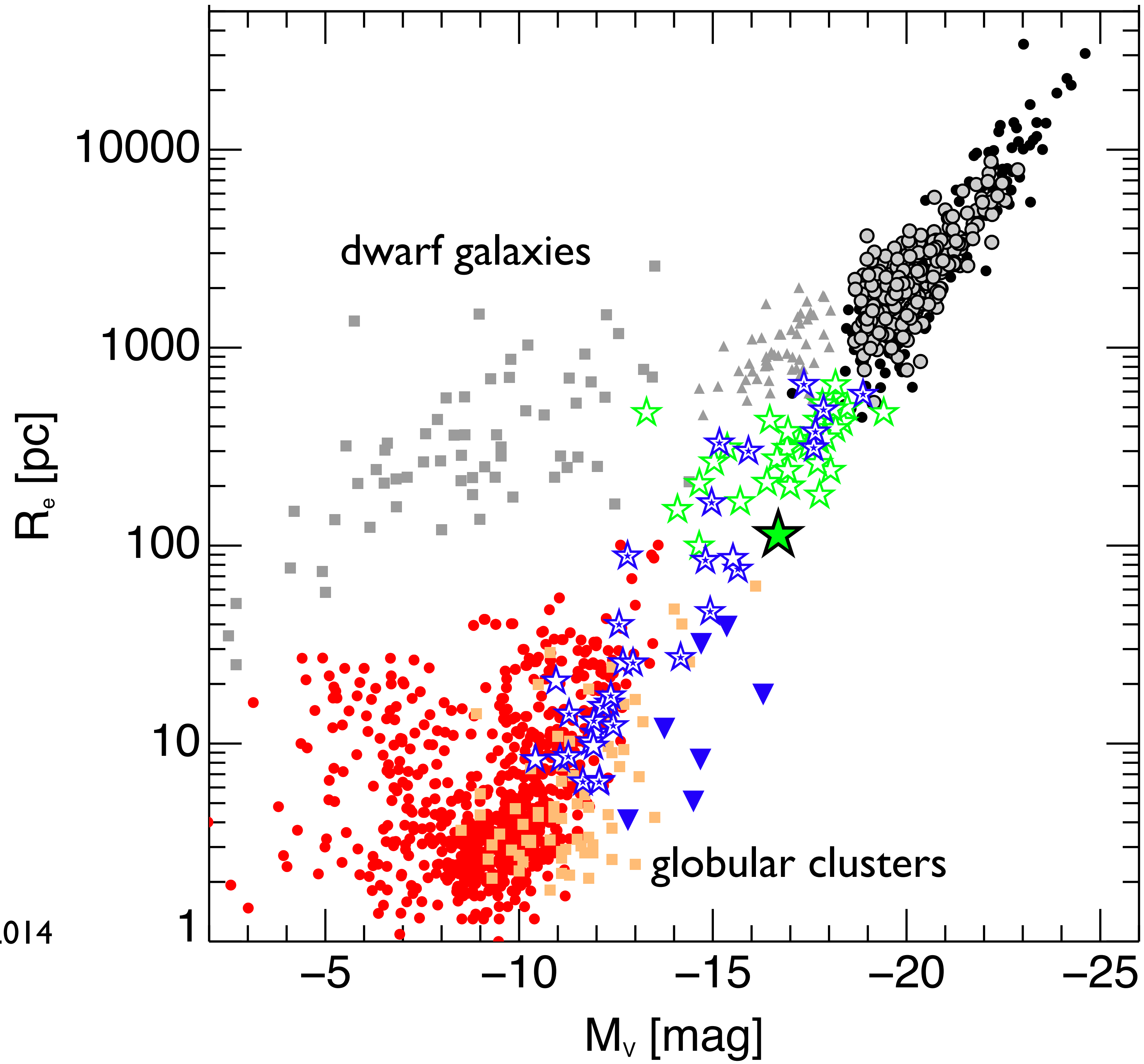
- homogenous chemical composition
- spherical
- non-rotating
- isotropic

This is not true!
+
formation* is unknown

Exploit GCs complexity to unveil their formation

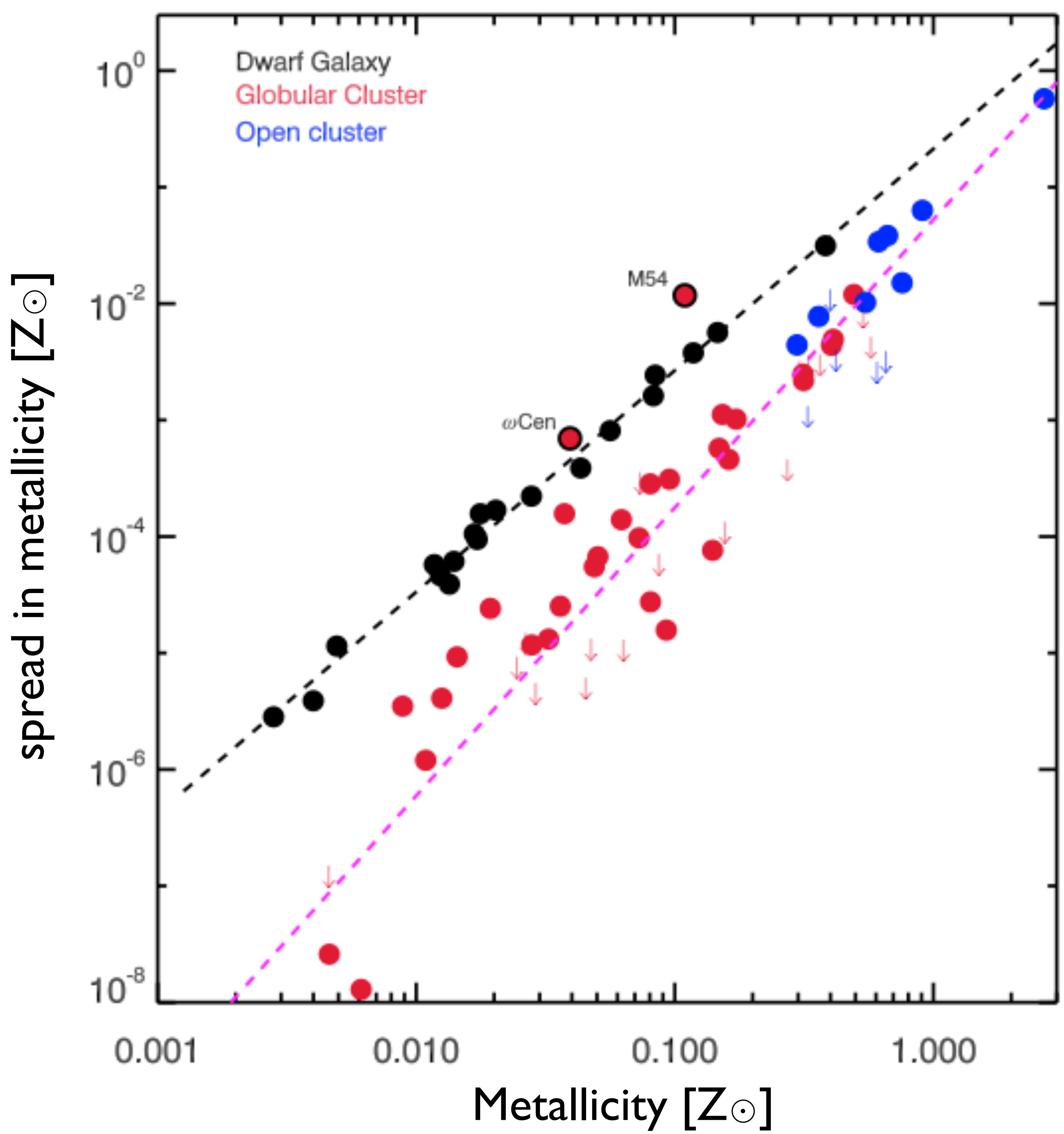
* I don't claim I have an answer to the formation problem

The "Zoo"



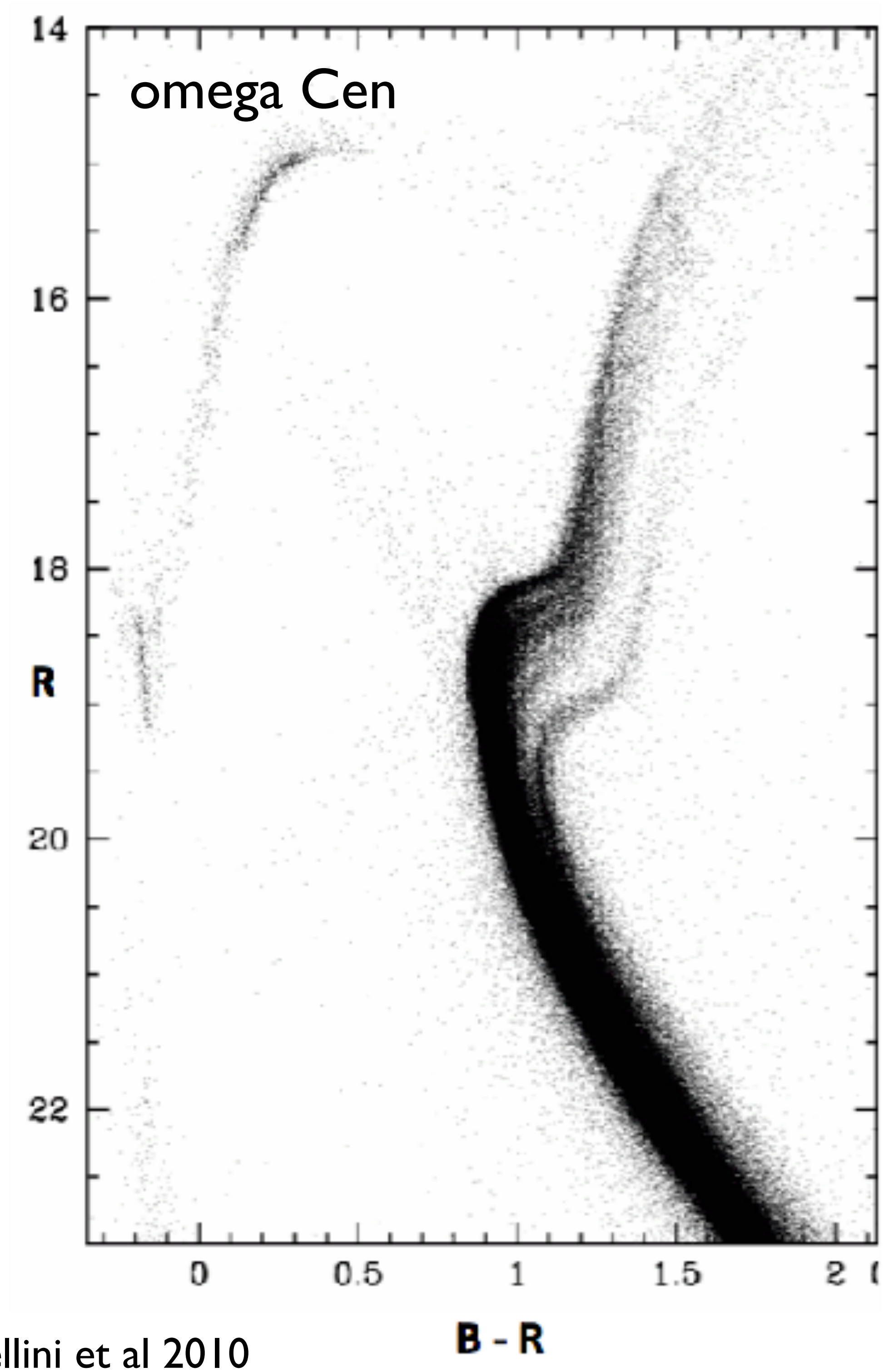
Norris et al. 2014

Dwarf galaxies vs. GCs



Leaman 2012

Dwarf galaxies vs. GCs

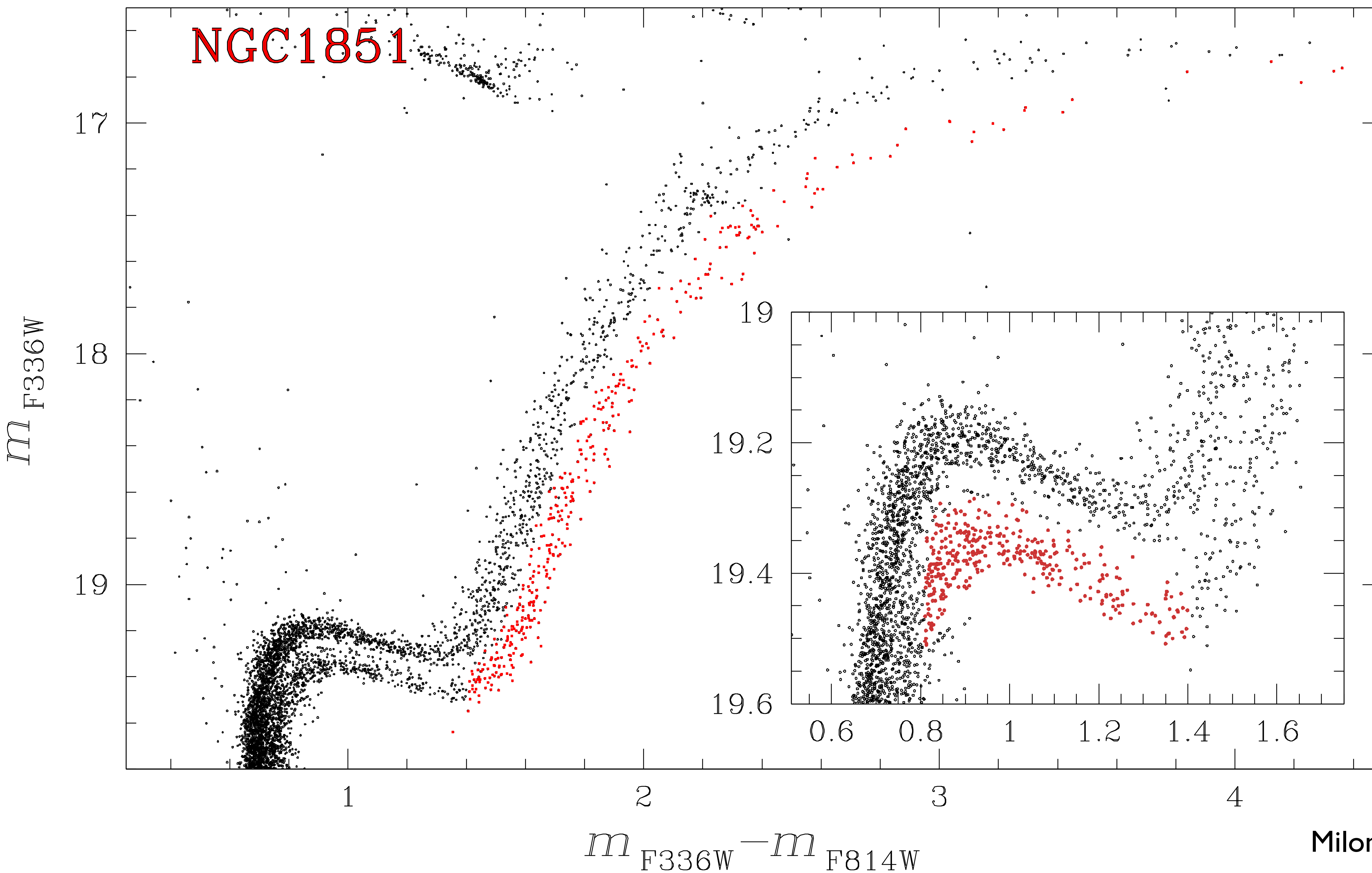


Bellini et al 2010

Omega Cen - a stripped dwarf?

- complex chemistry (iron spread)
  (Johnson & Pilachowski 2010)
- complex internal dynamics
  (van de Ven et al. 2006)
- central massive black hole?
  (Anderson & van der Marel 2010, Noyola et al. 2010, Zocchi et al. 2017)

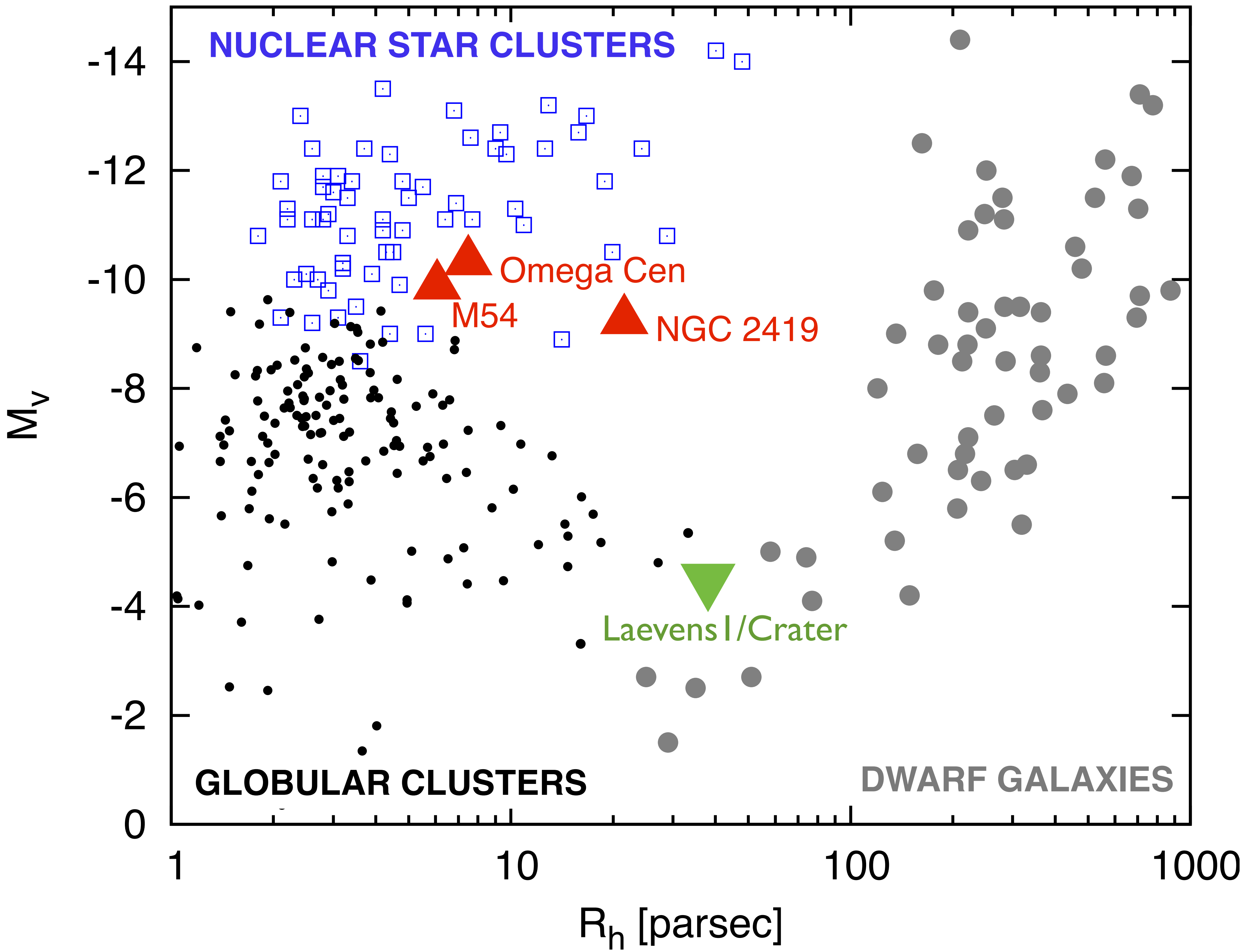
“Normal” GCs



Milone et al. (2016)

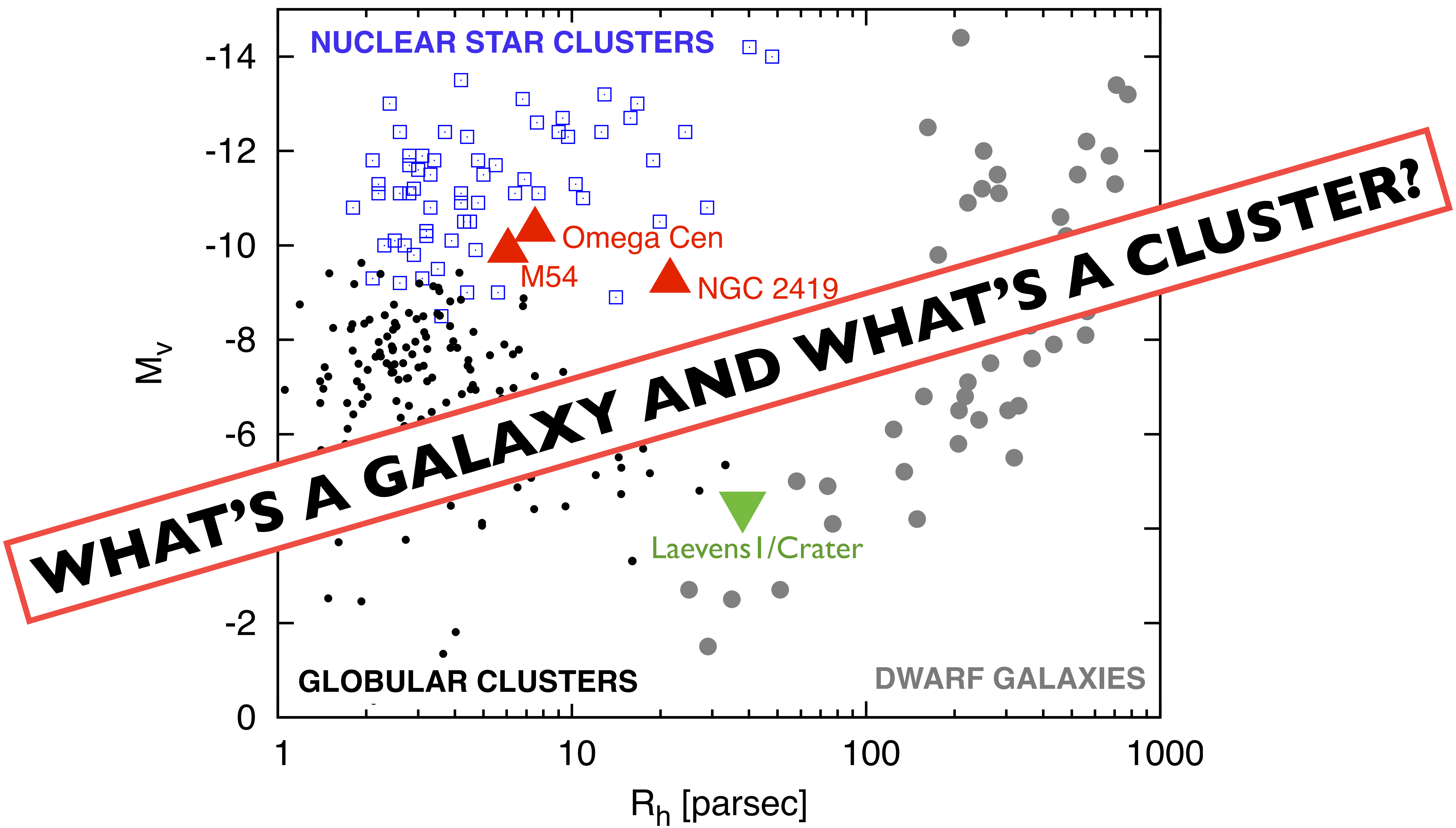
<u>Multiple stellar populations</u>: variations in the light elements abundances

The "Zoo"



NUCLEAR STAR CLUSTERS
Omega Cen
M54
NGC 2419
Laevens1/Crater
GLOBULAR CLUSTERS
DWARF GALAXIES
-14
-12
-10
-8
-6
-4
-2
0
M_V
1
10
100
1000
R_h [parsec]

The "Zoo"


NUCLEAR STAR CLUSTERS
Omega Cen
M54
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GLOBULAR CLUSTERS
DWARF GALAXIES
WHAT'S A GALAXY AND WHAT'S A CLUSTER?
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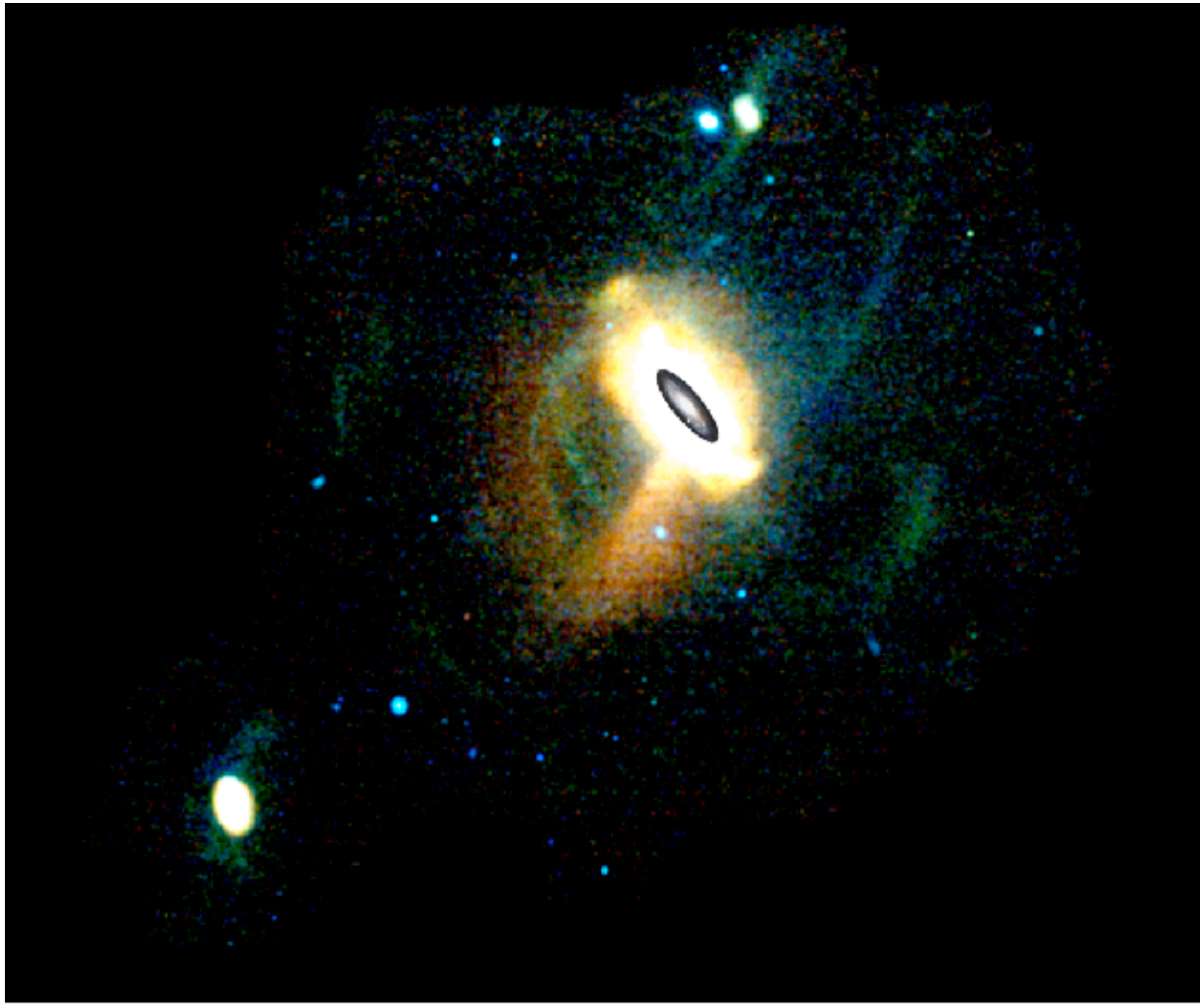
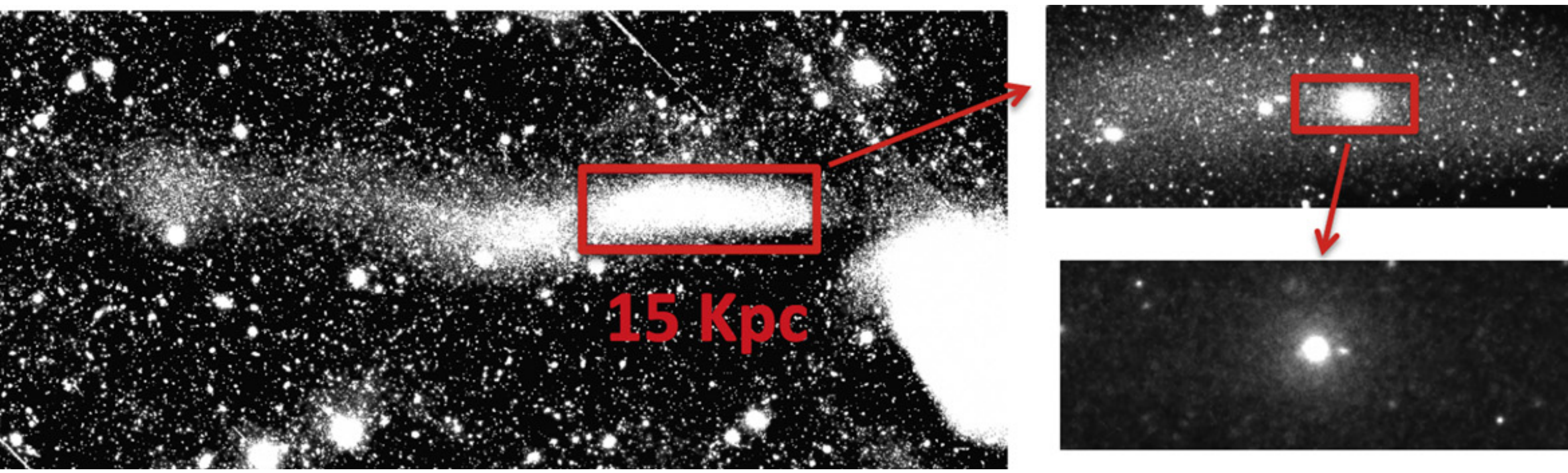
Accreted origin of GCs?



PAndAS Team (A. McConnachie, N. Martin, et al.)

Accreted origin of GCs?

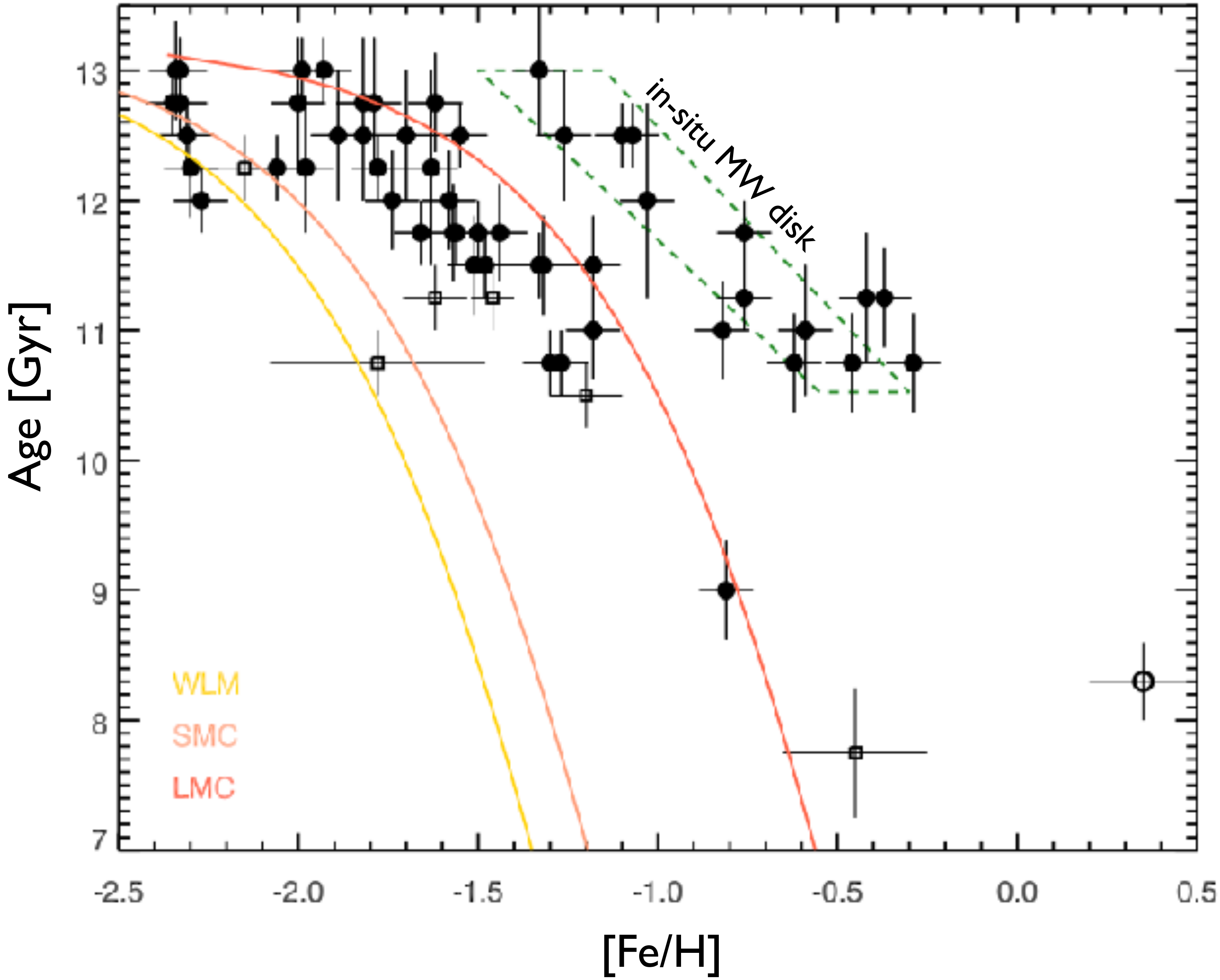
Omega Centauri-like object in stellar stream of NGC3628



Jennings et al. 2015

Accreted origin of GCs?

Leaman, VandenBerg & Mendel (2013)



In-situ GCs

- GCs in disk-like orbits, consistent with age-metallicity of MW disk

Accreted GCs

- 2/3 of GCs in halo-like orbits
- accreted as part of disrupted dwarf host galaxies

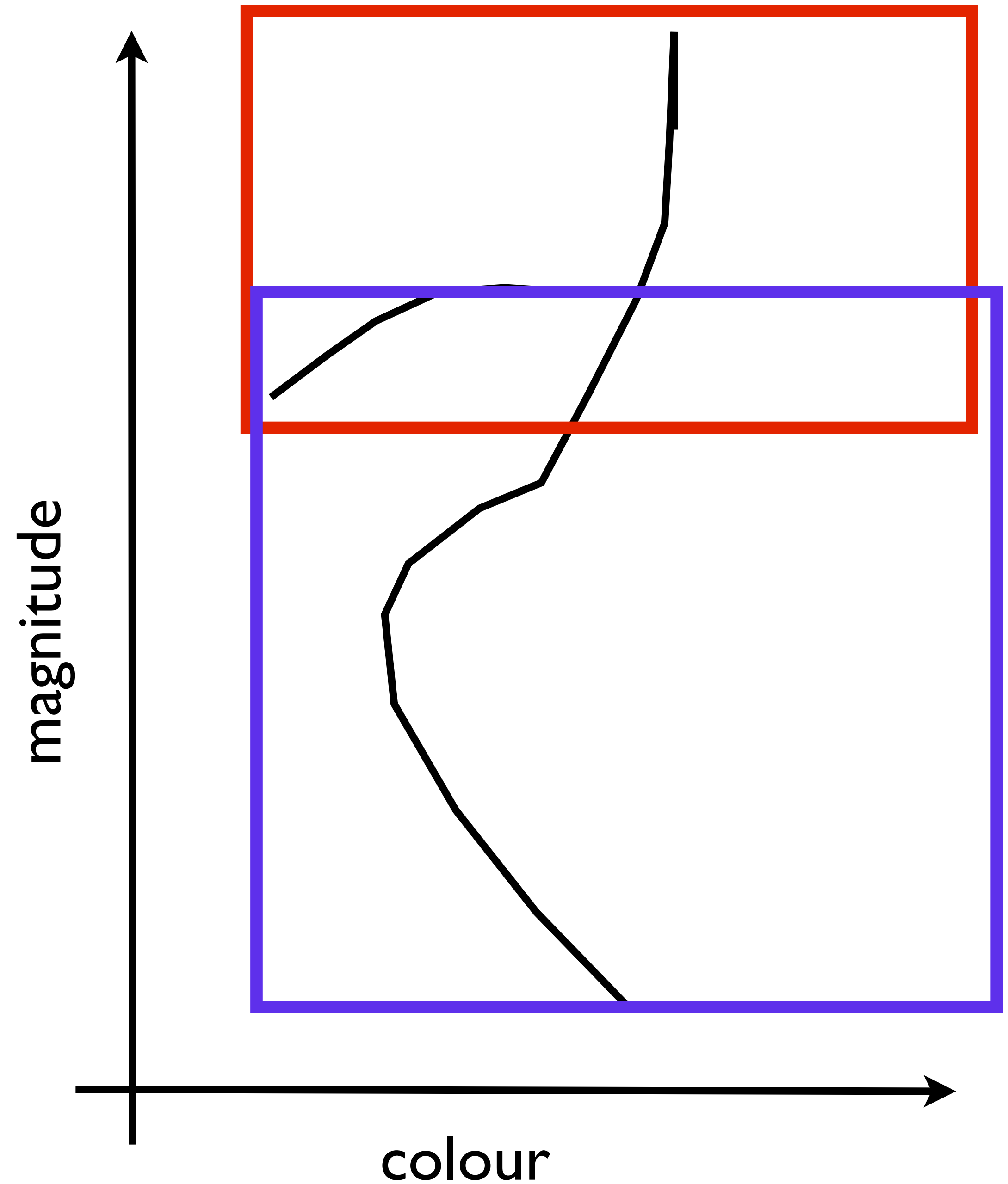
The problem of GC formation

GCs today are the result of 13 Gyr long evolution

stellar evolution
internal dynamical evolution
interaction with host galaxy's tidal filed

Strategy: internal kinematics

- kinematics provide a long lasting fossil record of formation
- revolutionary kinematic data are NOW available:



Traditional **line-of-sight velocities** from spectroscopy:

- bright (massive) stars only
- 100-1000 data per GCs

HST proper motions:

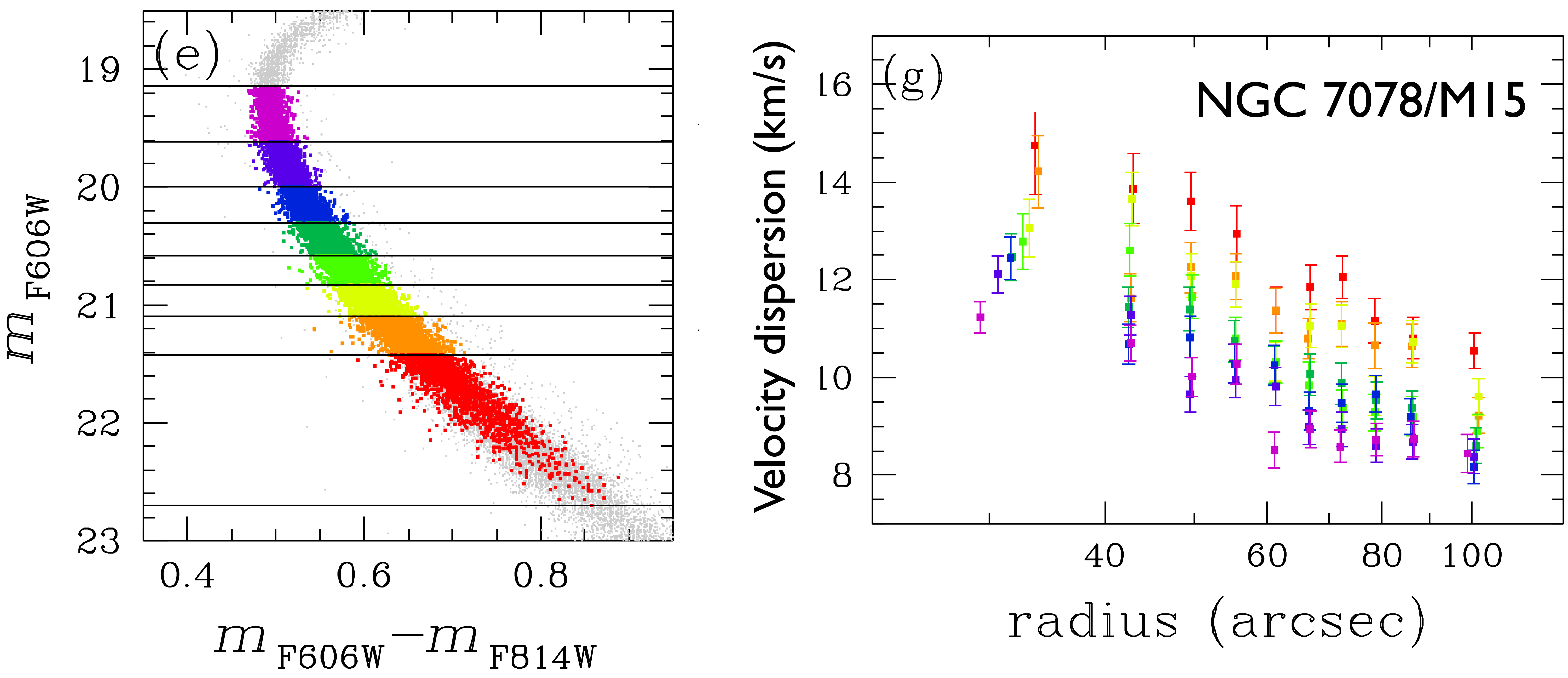
- both faint and bright stars
- 100,000 per GCs
- 2D-velocity information

HSTPROMO collaboration
(Bellini et al. 2014, Watkins+2015a,b)

+ **Gaia** proper motions and Line-of-sight for bright stars soon!

Kinematic observations

HST Proper Motions (HSTPROMO collaboration)



Bellini, Anderson, van der Marel, Watkins, King, **Bianchini** et al. 2014

Unveiling the complexity in the kinematics

1. Energy equipartition
2. Evolution of the mass-to-light ratio
3. Velocity anisotropy & tidal field

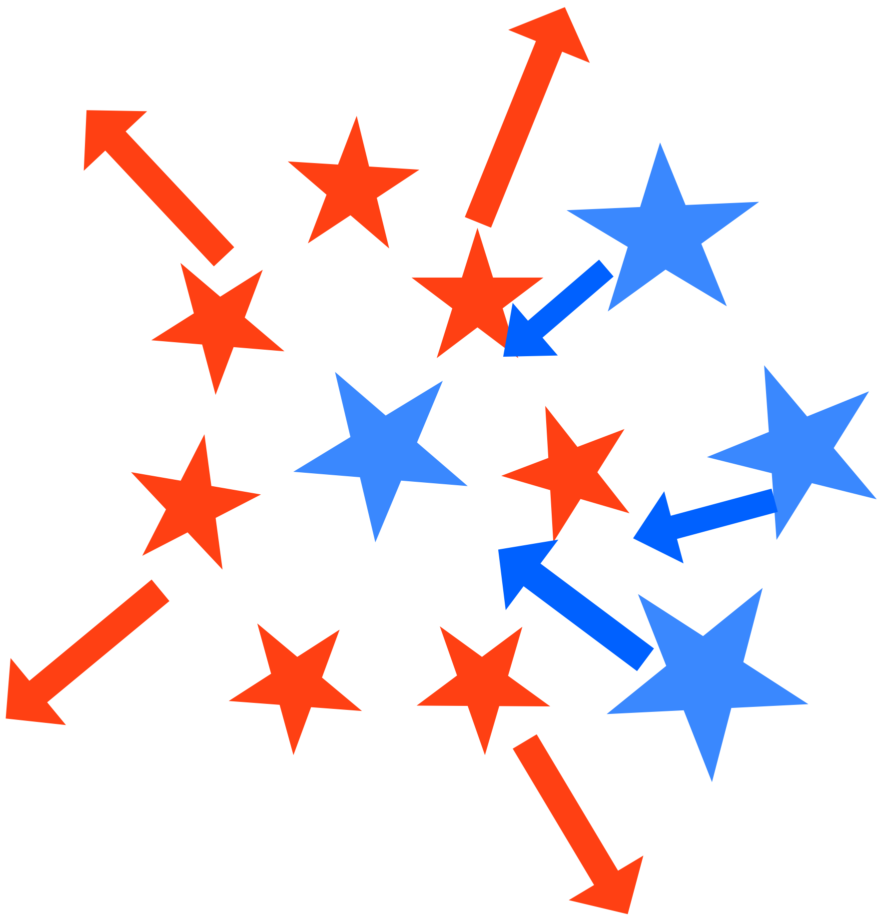
1. Energy equipartition

- GCs are OLD: >10 Gyr of dynamical evolution
- effect of 2-body interactions: energy exchange between stars

high-mass stars (up to ~0.9 $M_\odot$)

low-mass stars

1. Energy equipartition



- GCs are OLD: >10 Gyr of dynamical evolution
- effect of 2-body interactions: energy exchange between stars

$$m_i\sigma_i^2 = m_j\sigma_j^2$$
$$\sigma \propto m^{-0.5}$$

- partial energy equipartition

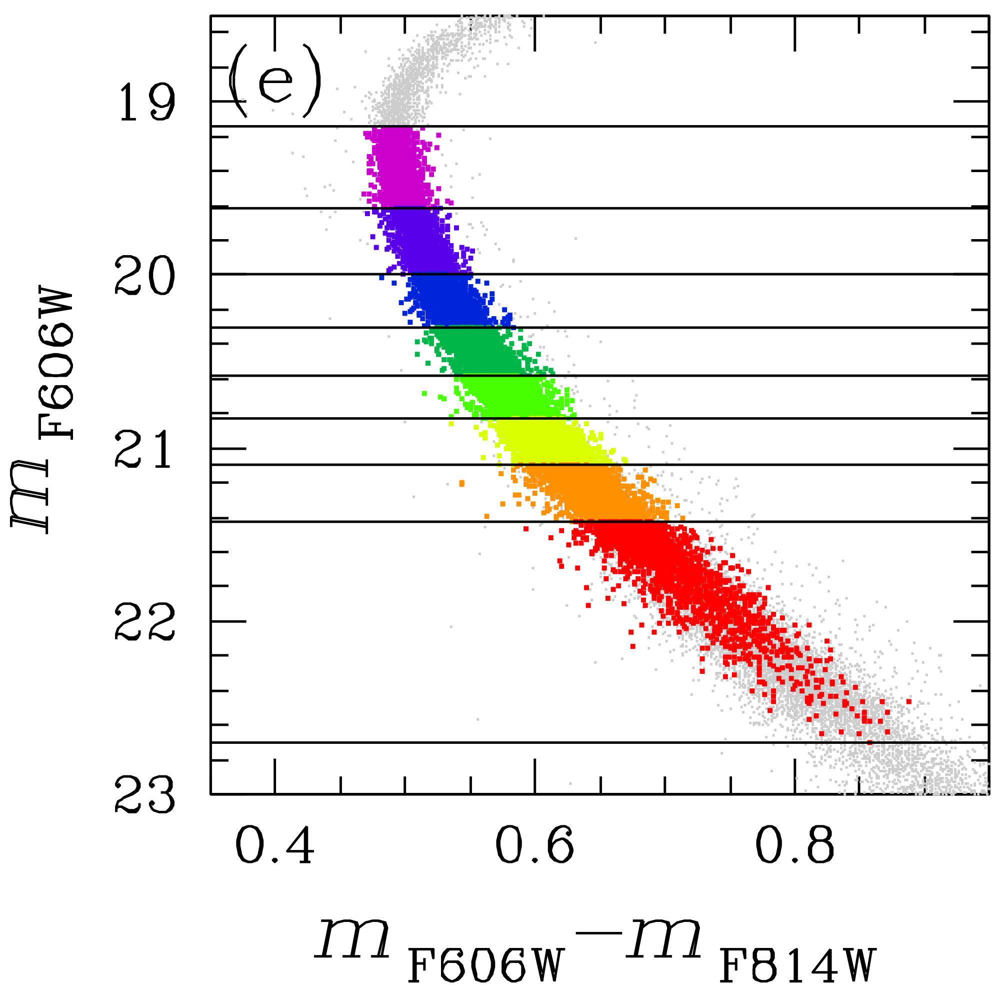
(e.g., Spitzer 1969, Vishniac 1978, … Trenti & van der Marel 2013)
see Spera et al. 2016 for open clusters

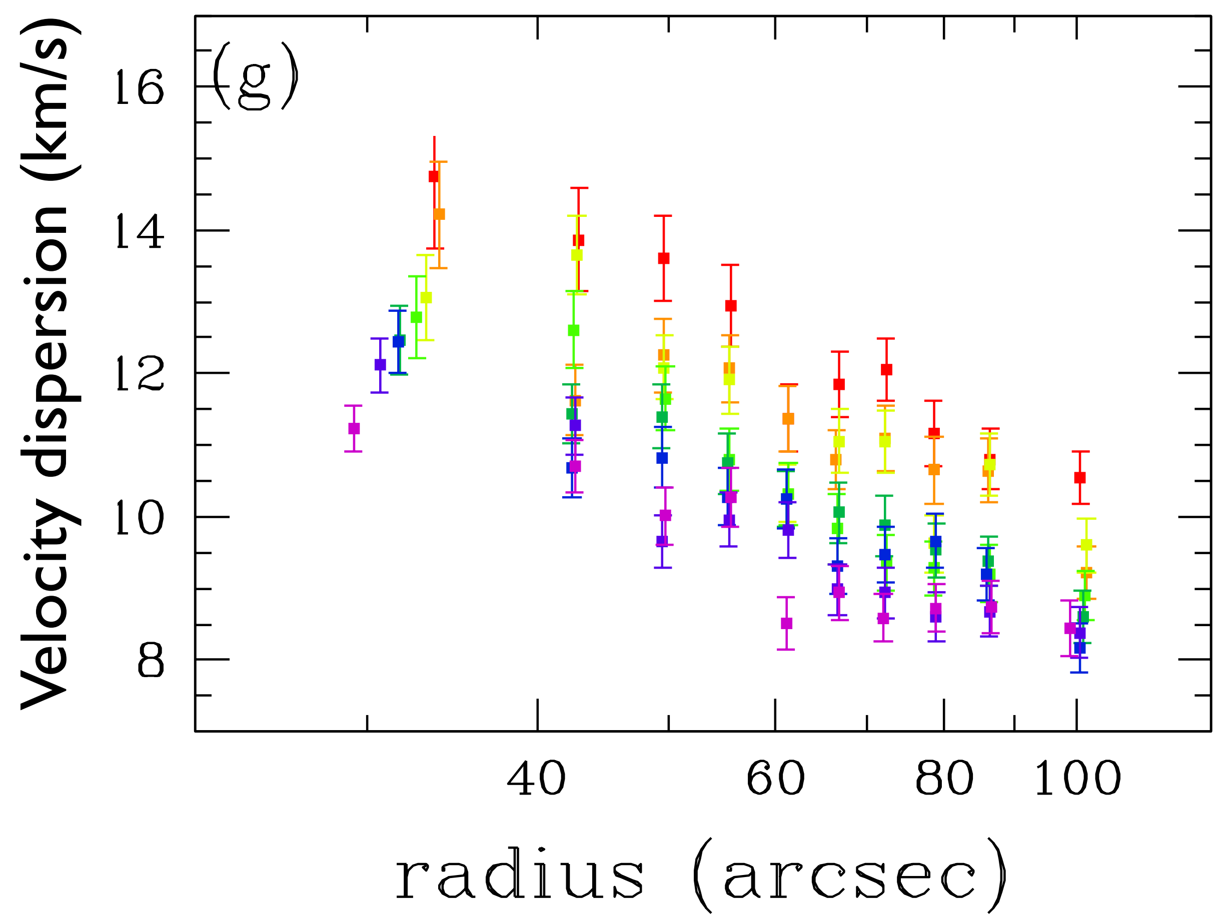
mass-dependent kinematics

(Effect mostly neglected!)
See however **recent modelling effort**:
Gieles & Zocchi 2015, de Vita et al. 2016, Peuten et al. 2017

Kinematic observations

HST Proper Motions (HSTPROMO collaboration)



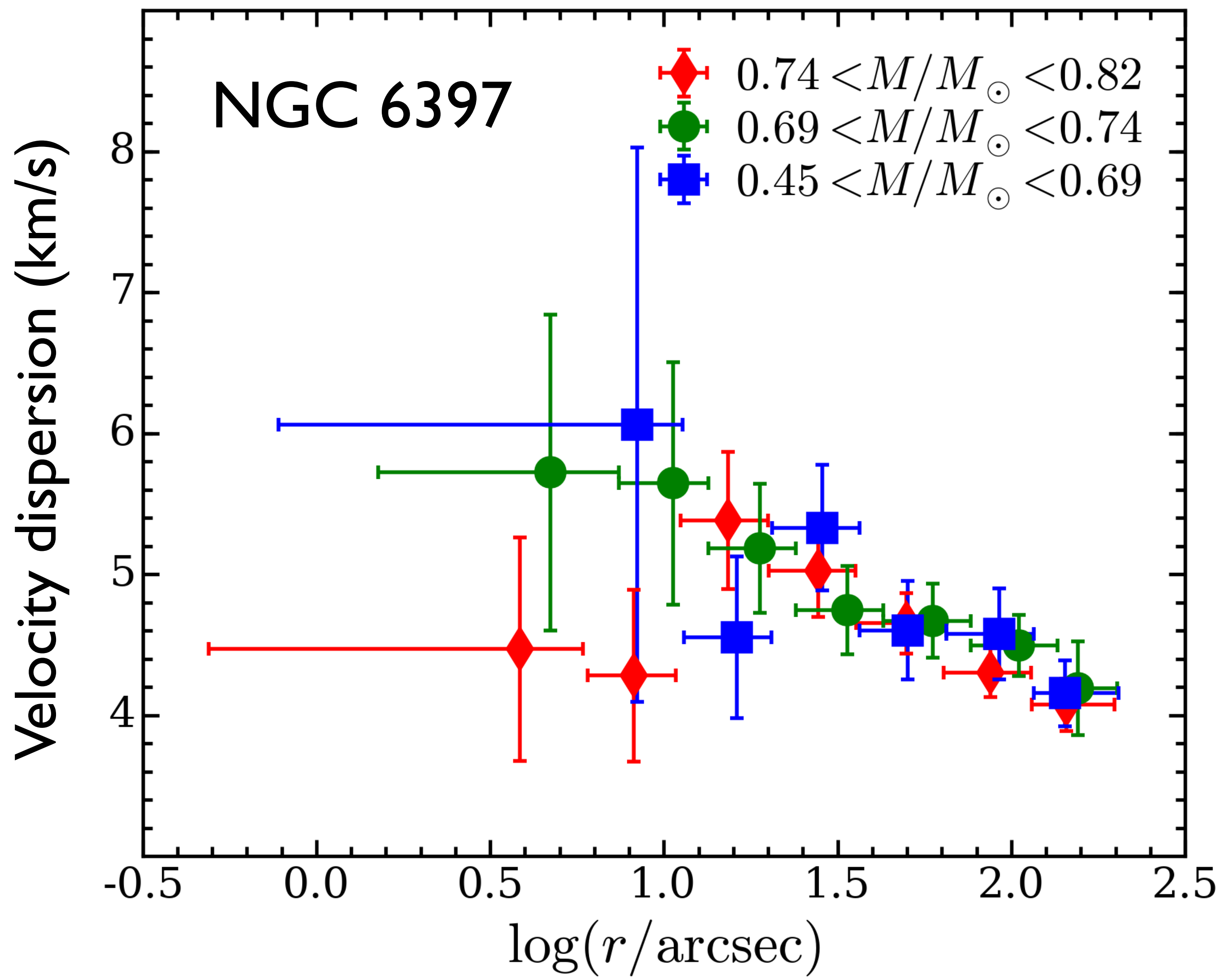


Bellini, Anderson, van der Marel, Watkins, King, **Bianchini** et al. 2014

Kinematic observations

- combination of line-of-sight velocities + proper motions

e.g. , VLT/MUSE data



Kamann et al. 2016

Goals

(1) - Describe the **mass-dependence of kinematics $\sigma(m)$**

- Applicability to both observations and simulations

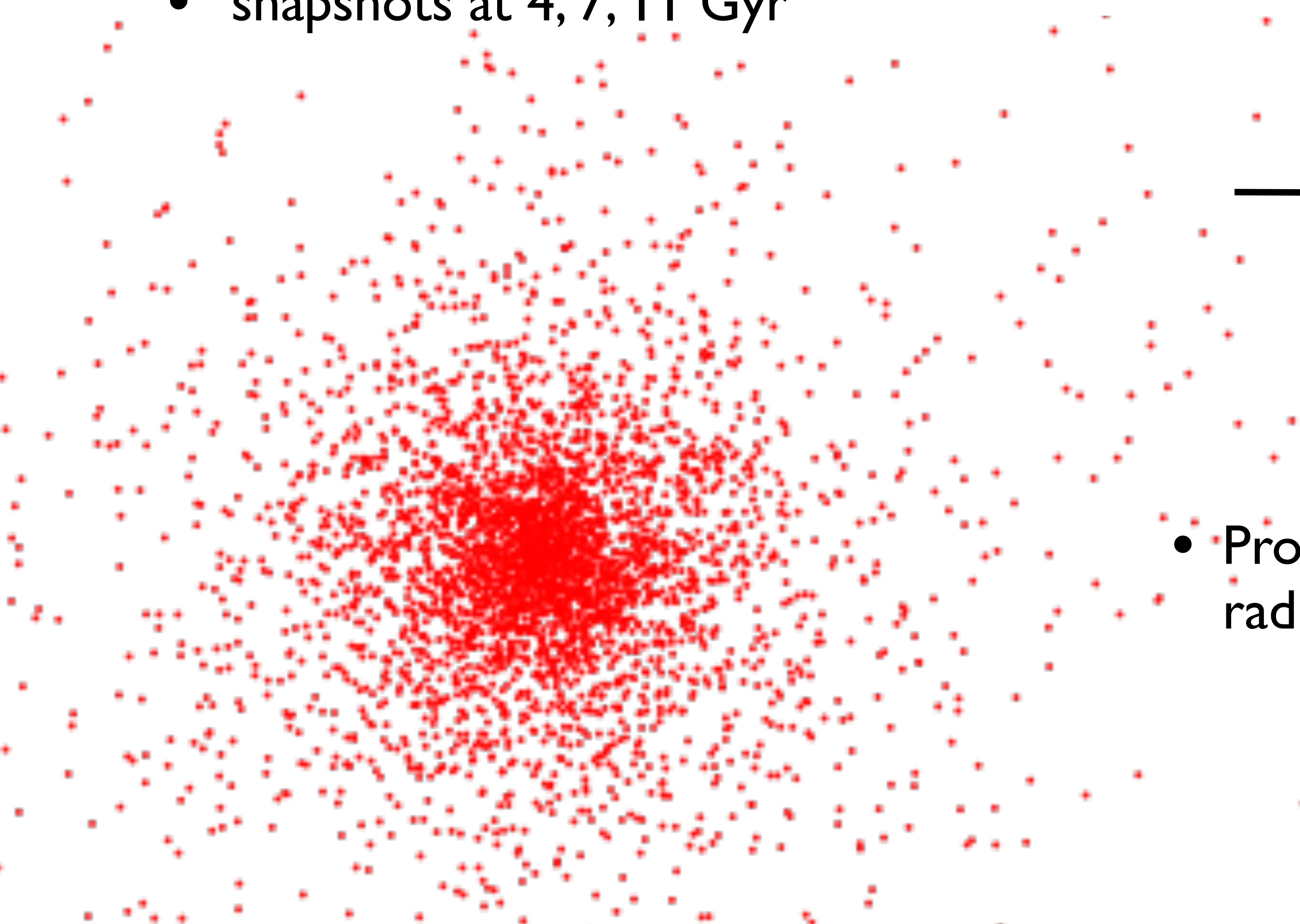
- Quantify the degree of partial energy equipartition

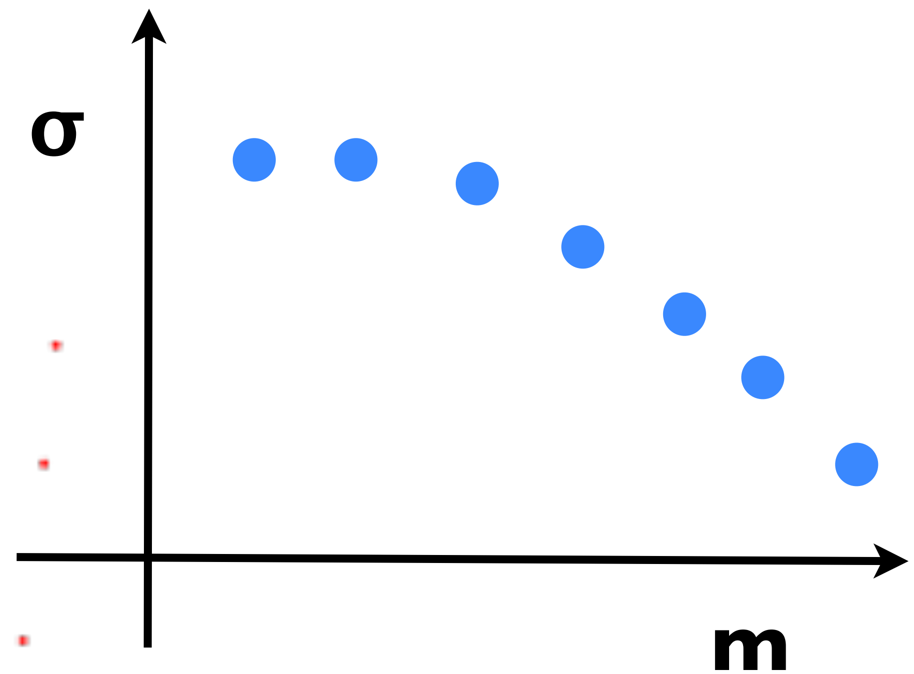
(2) How does equipartition relate to GCs properties?

Bianchini et al. 2016
Bianchini et al. 2017
(see also Webb & Vesperini 2017)

Simulations

- Monte Carlo cluster simulations (Downing et al. 2010) in isolation
- N=500,000 and 2,000,000 particles
- 10% and 50% initial binary fraction
- concentration C=1.00-2.00
- snapshots at 4, 7, 11 Gyr





σ(m) profiles:

- Projected profiles within the half-light radius

Fitting function

~~$\sigma \propto m^{-0.5}$~~

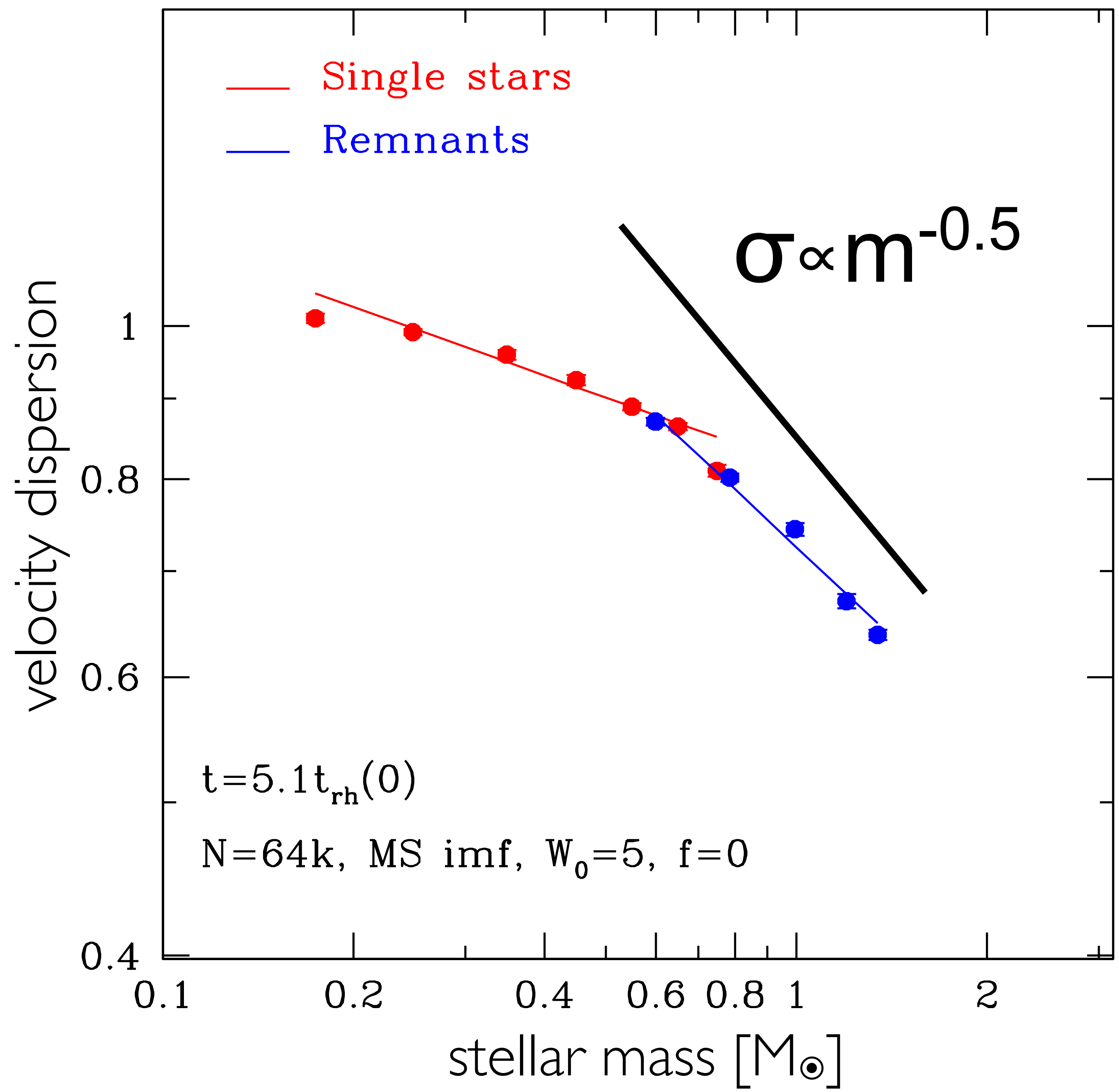
full
energy equipartition

partial energy equipartition

$\sigma \propto m^{-\eta}$

$\eta < 0.5$

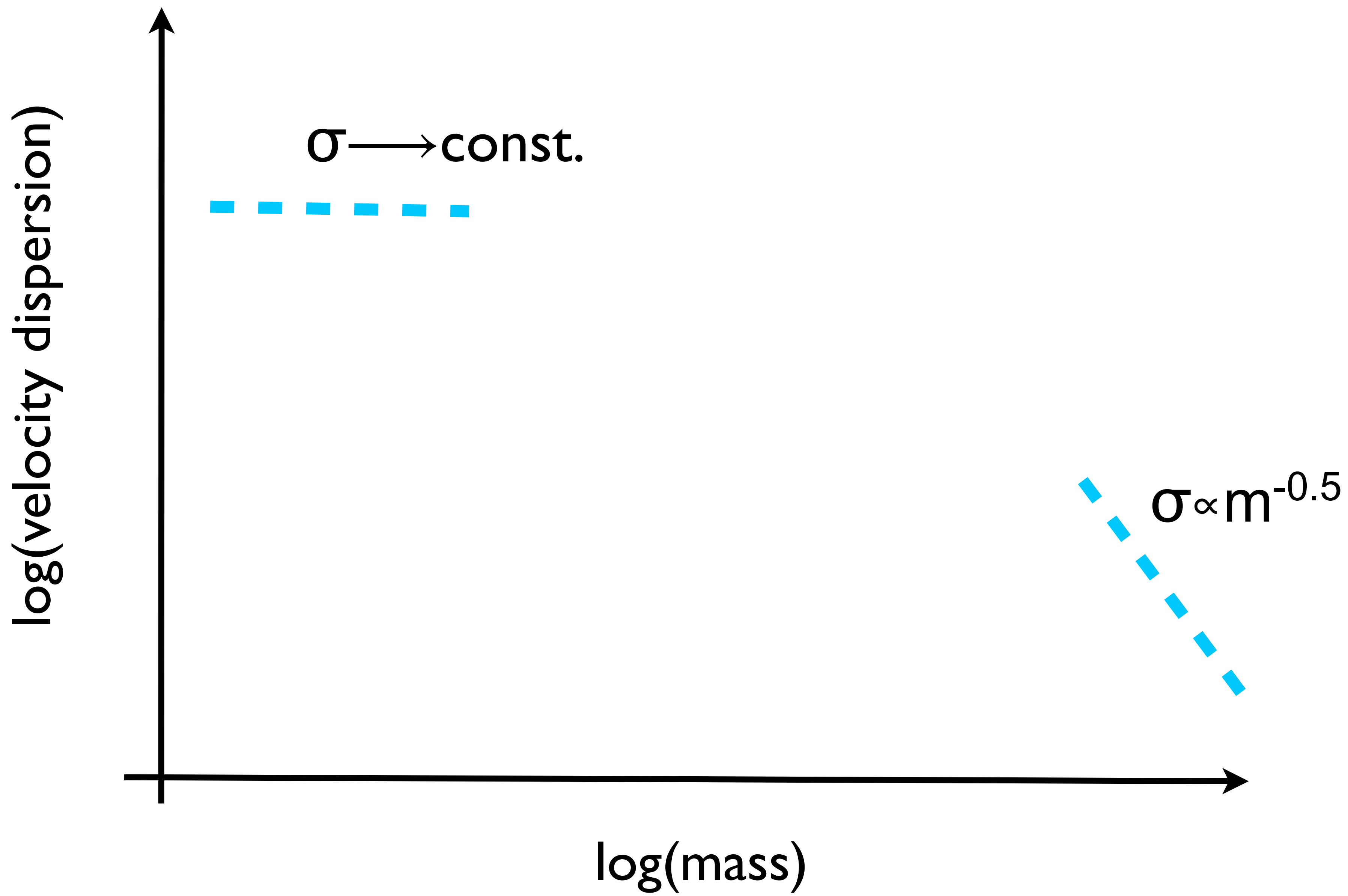
A single power-law does not satisfactory explain the σ(m)



Trenti & van der Marel 2013

Fitting function

~~$\sigma \propto m^{-0.5}$~~ → partial energy equipartition



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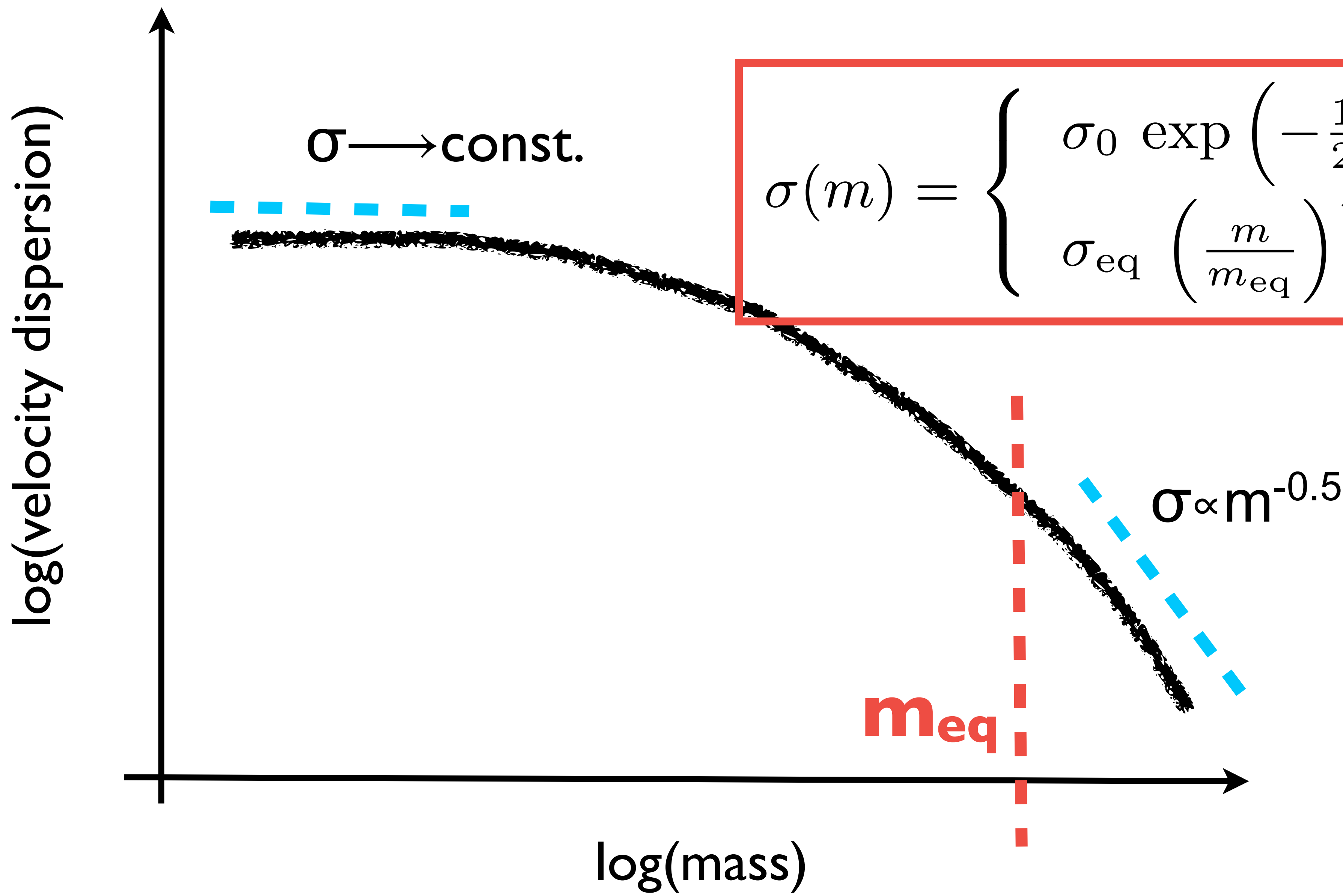

$$\sigma(m) = \begin{cases} \sigma_0 \, \exp\left(-\frac{1}{2}\frac{m}{m_{\rm eq}}\right) & \text{if } m \le m_{\rm eq} \\ \sigma_{\rm eq} \left(\frac{m}{m_{\rm eq}}\right)^{-1/2} & \text{if } m > m_{\rm eq} \end{cases}$$

Fitting function

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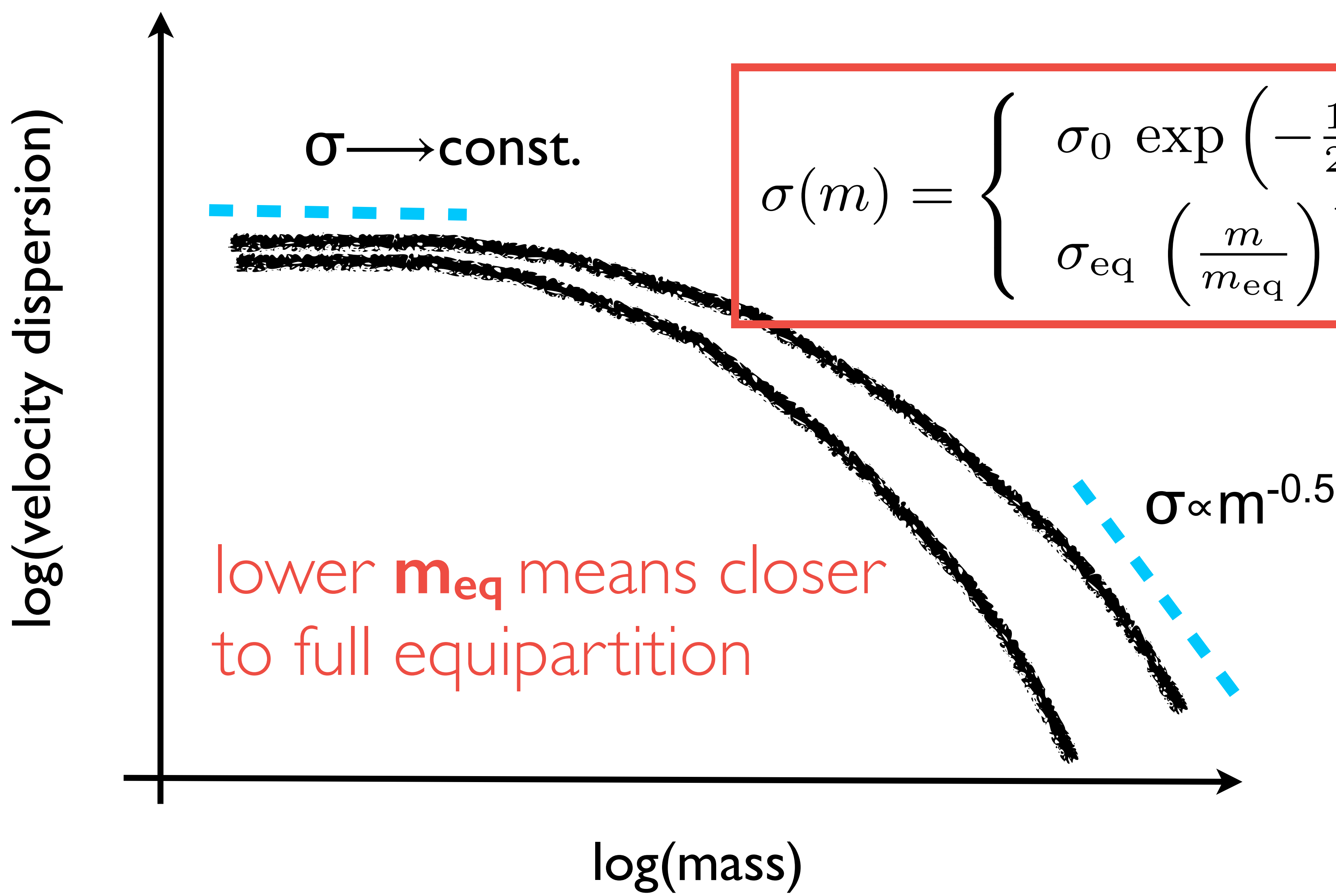
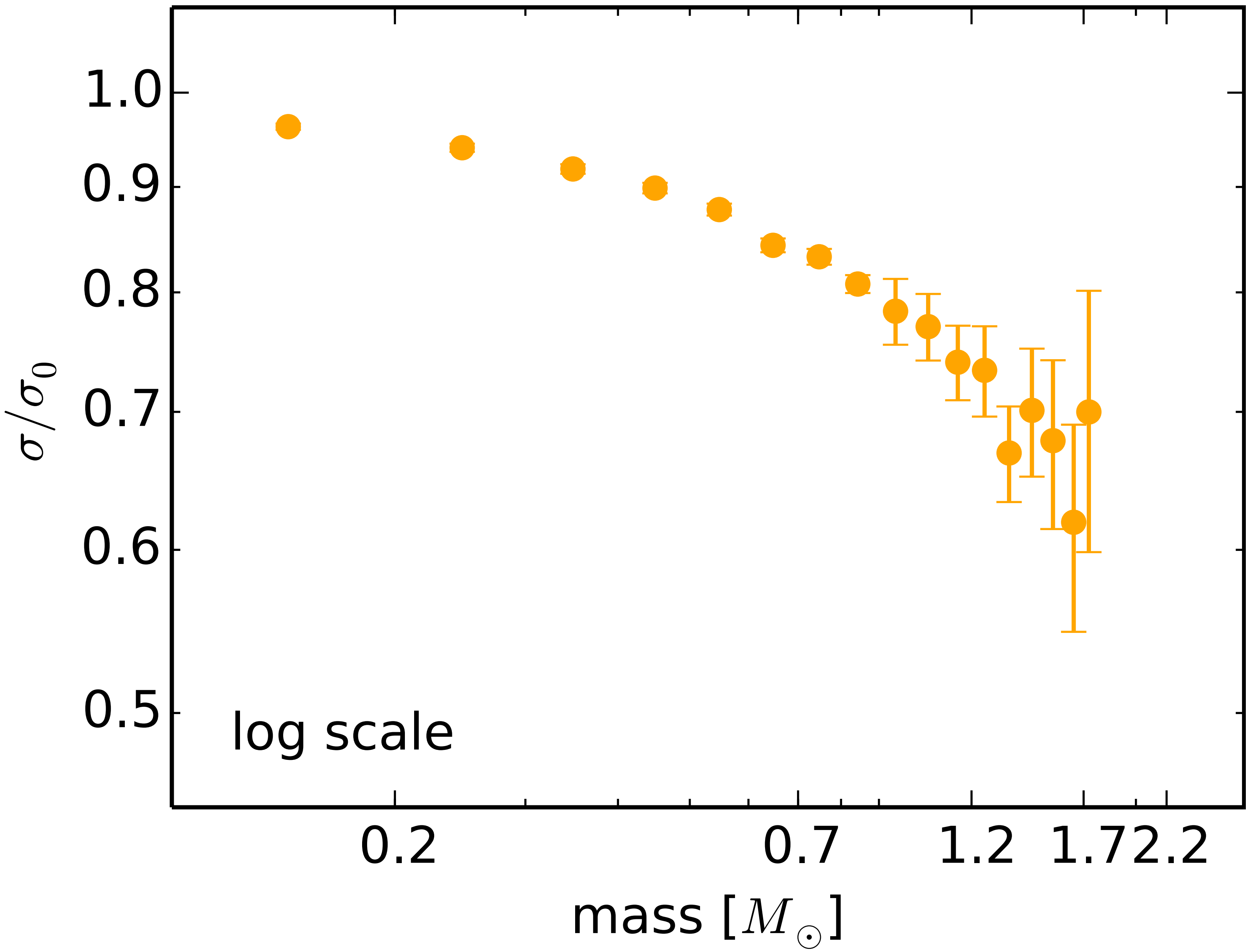


Application to simulations

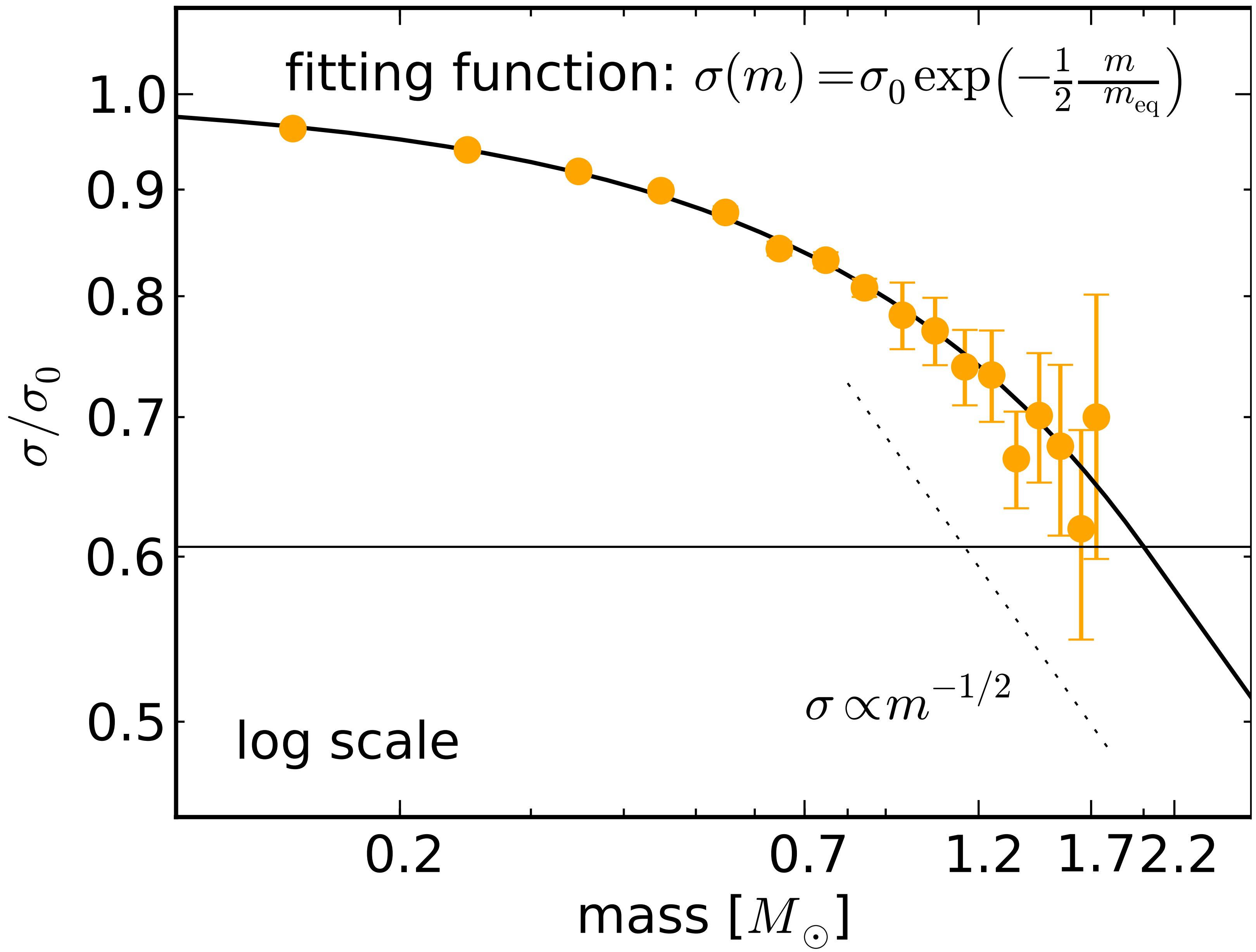
Fit to binned profiles for **all the data** in the simulations



- projected velocity dispersion
- within half-light radius

Application to simulations

Fit to binned profiles for **all the data** in the simulations

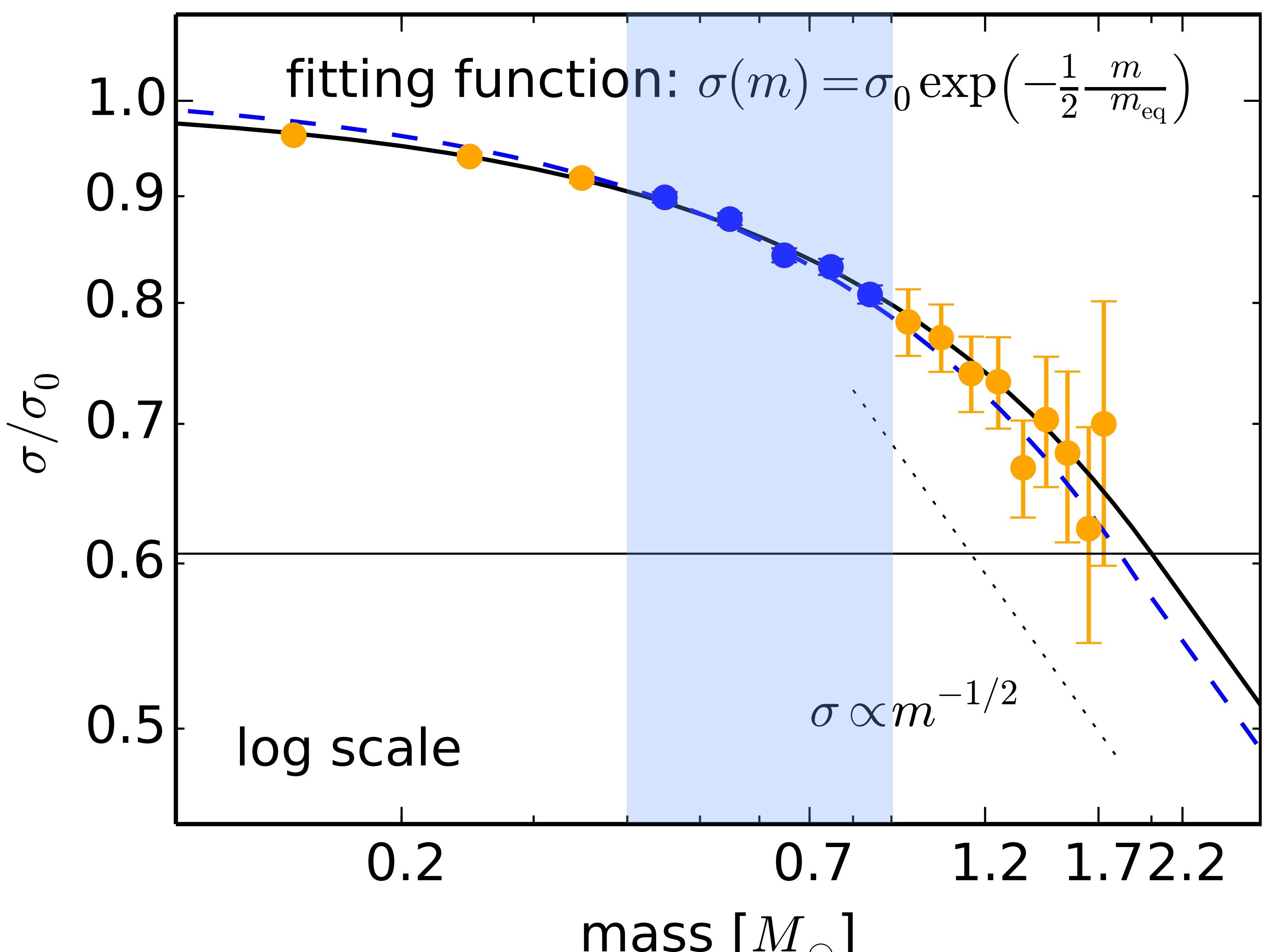


- projected velocity dispersion
- within half-light radius

m_{eq}=2.0±0.1 $M_\odot$

Application to simulations

Discrete fitting (no binning) to **observational-like** data



- only observable stars with 0.4<m<0.9 M⊙ (LOS + PMs)
- likelihood function
- errors or contamination sources can be easily taken into consideration
- excellent description for all simulations at very time snapshot

Goals

(1) - Describe the **mass-dependence of kinematics σ(m)**

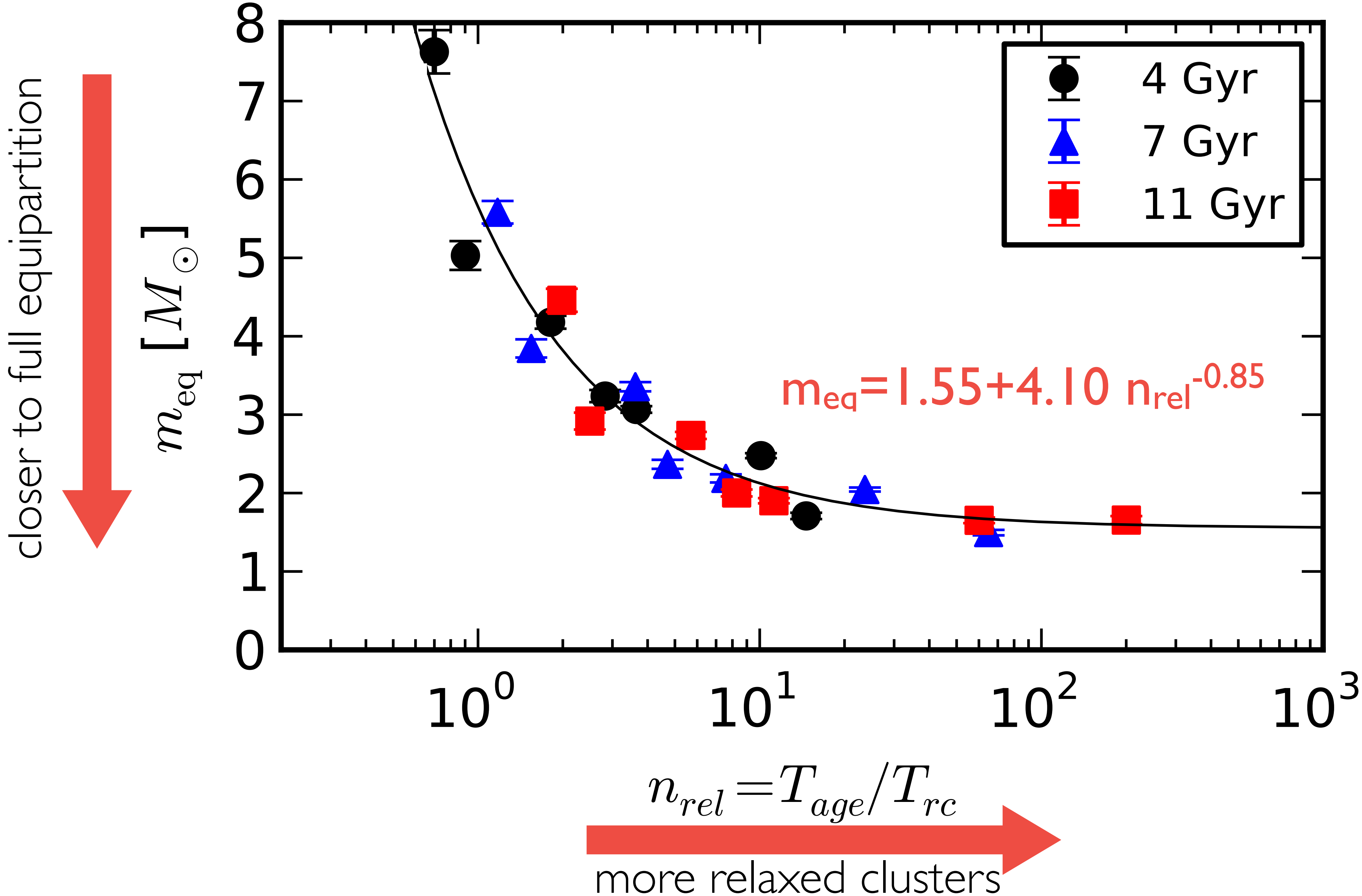
- Applicability to both observations and simulations

- Quantify the degree of partial energy equipartition

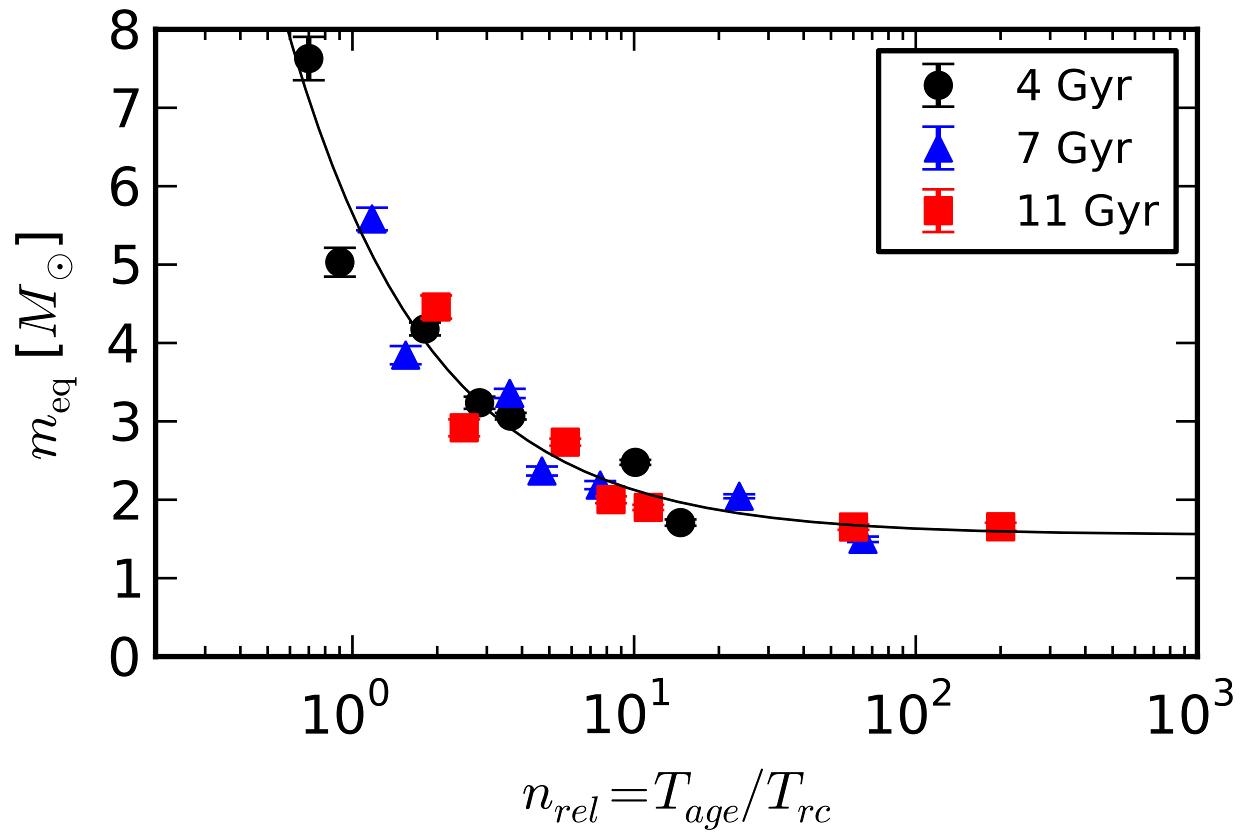
(2) How does equipartition relate to GCs properties?

Measuring the dynamical state

- tight relation between degree of equipartition and relaxation state of a cluster **(m_{eq}-n_{rel} relation)**



Measuring the dynamical state



m_{eq}-n_{rel} relation

(for isolated clusters)

1. $m_{eq} \longrightarrow n_{rel}$

measuring m_{eq}, we can **estimate the dynamical state of a cluster**

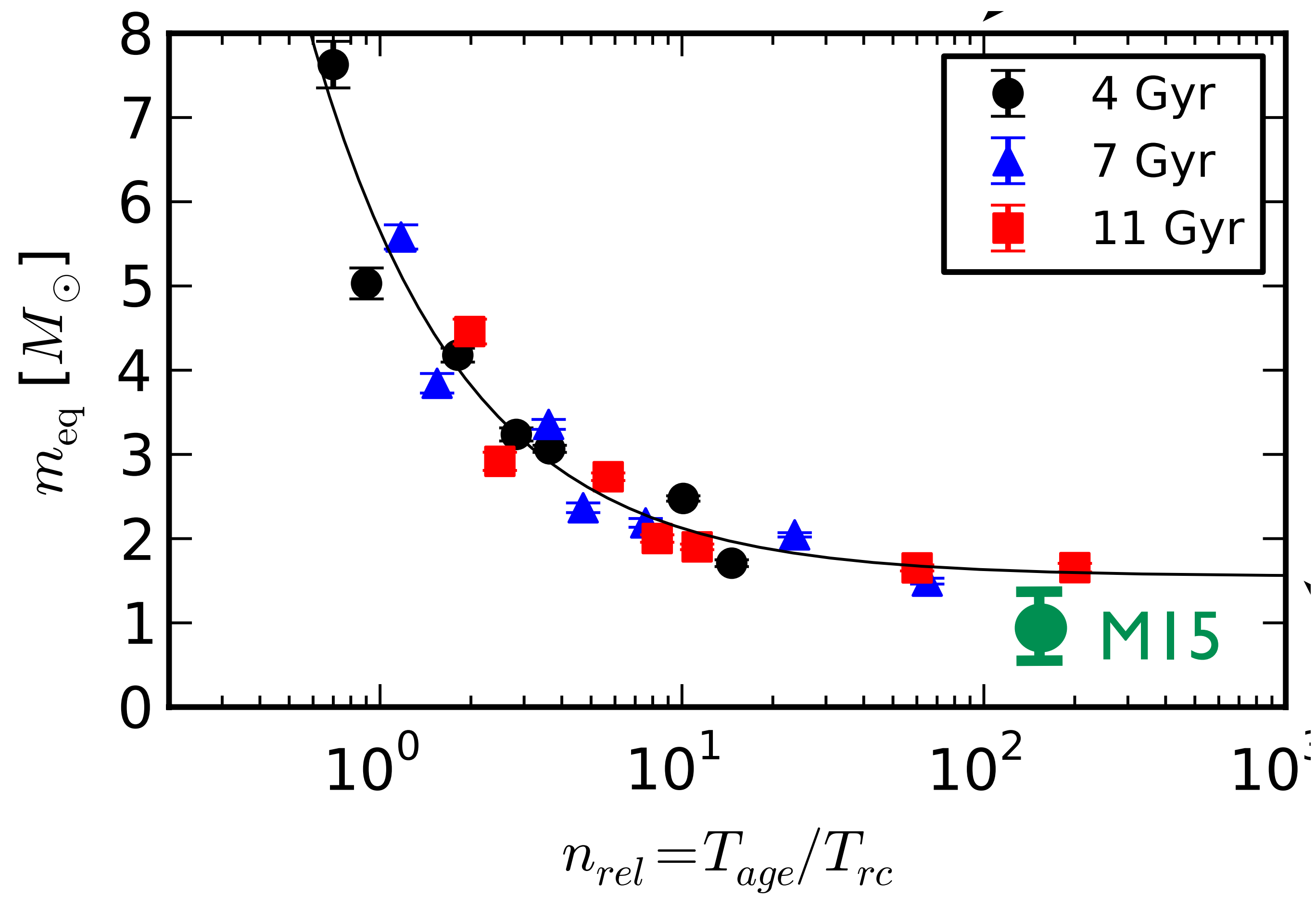
2. $n_{rel} \longrightarrow m_{eq}$

predict the mass-dependence of kinematics (m_{eq}): e.g., predict the kinematics for non-measurable low-mass stars, stellar remnants, binary stars (Bianchini et al. 2016), blue straggler stars (Baldwin et al. 2016)

Why is this exciting?

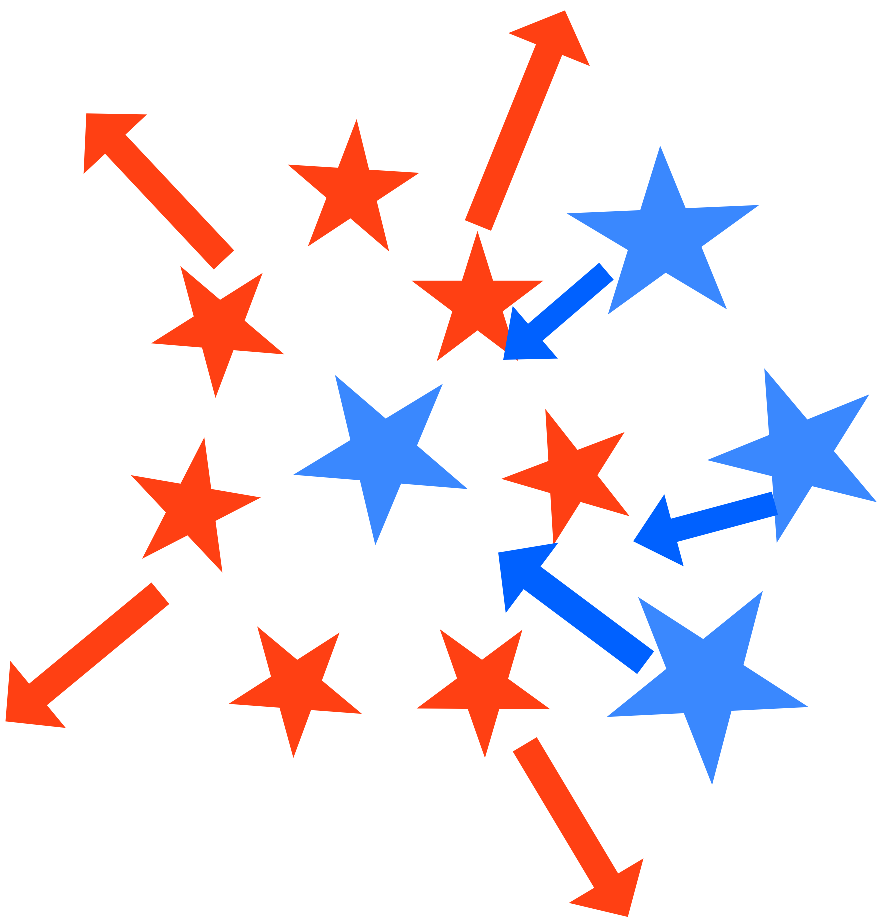
Applications of the "equipartition-relaxation" relation

- intermediate-mass black holes?
- nucleus of dwarf galaxies?
- in-situ vs. accreted clusters?
- complex dynamical history?



Bianchini et al. 2016

2. Mass-to-light ratio



GCs are mass segregated

Massive stars sink into the centre and less massive stars move toward the outskirts as a result of redistribution of energy.

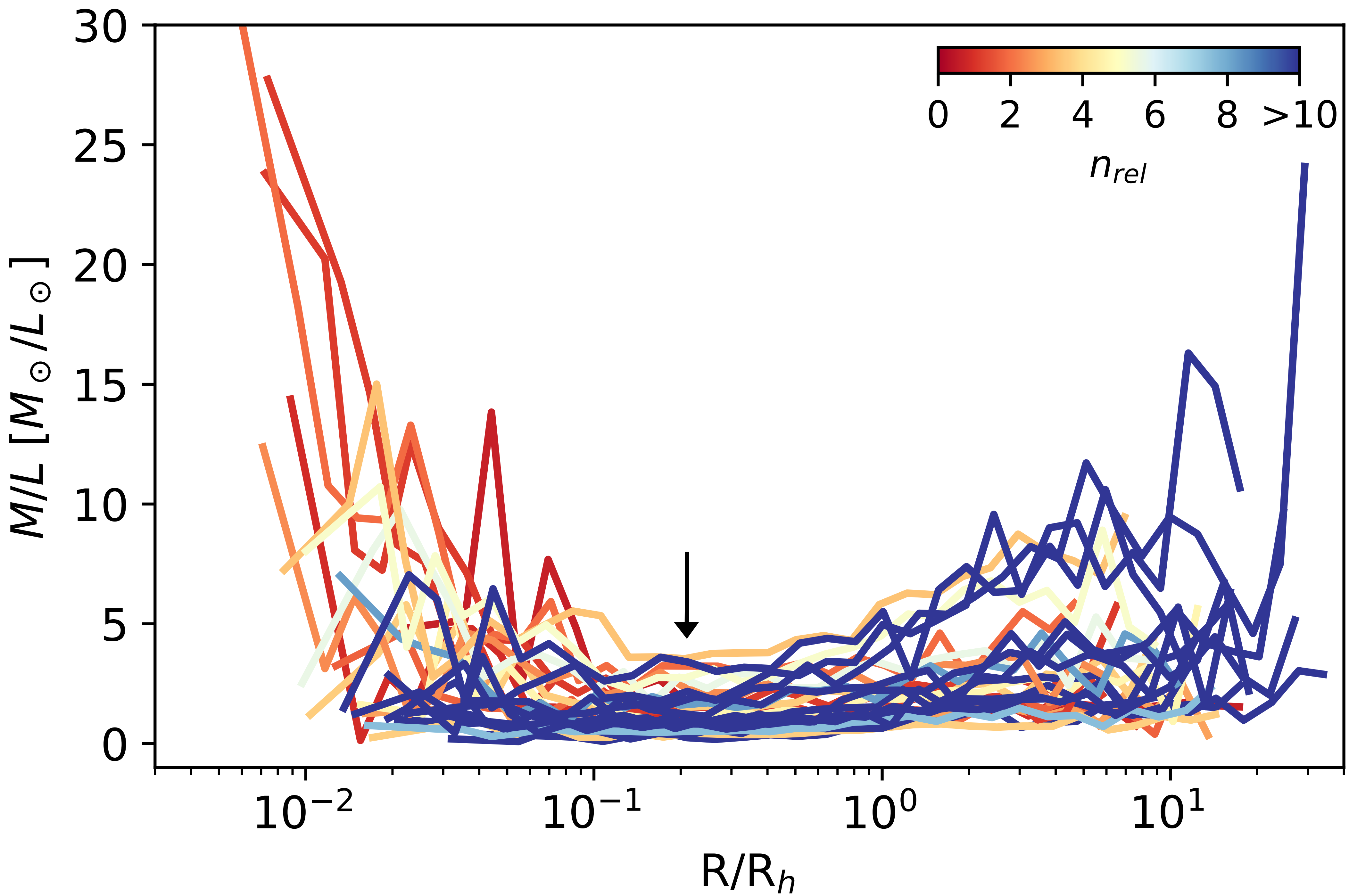
LOW M/L objects:
high-mass bright stars (giant stars, ~0.8 M_sun)

HIGH M/L objects
low-mass faint stars (main sequence stars)
dark remnants (black holes, neutron stars, ~a few M_sun)

non-trivial variations of the M/L are expected, however dynamical modelling usually assume constant M/L

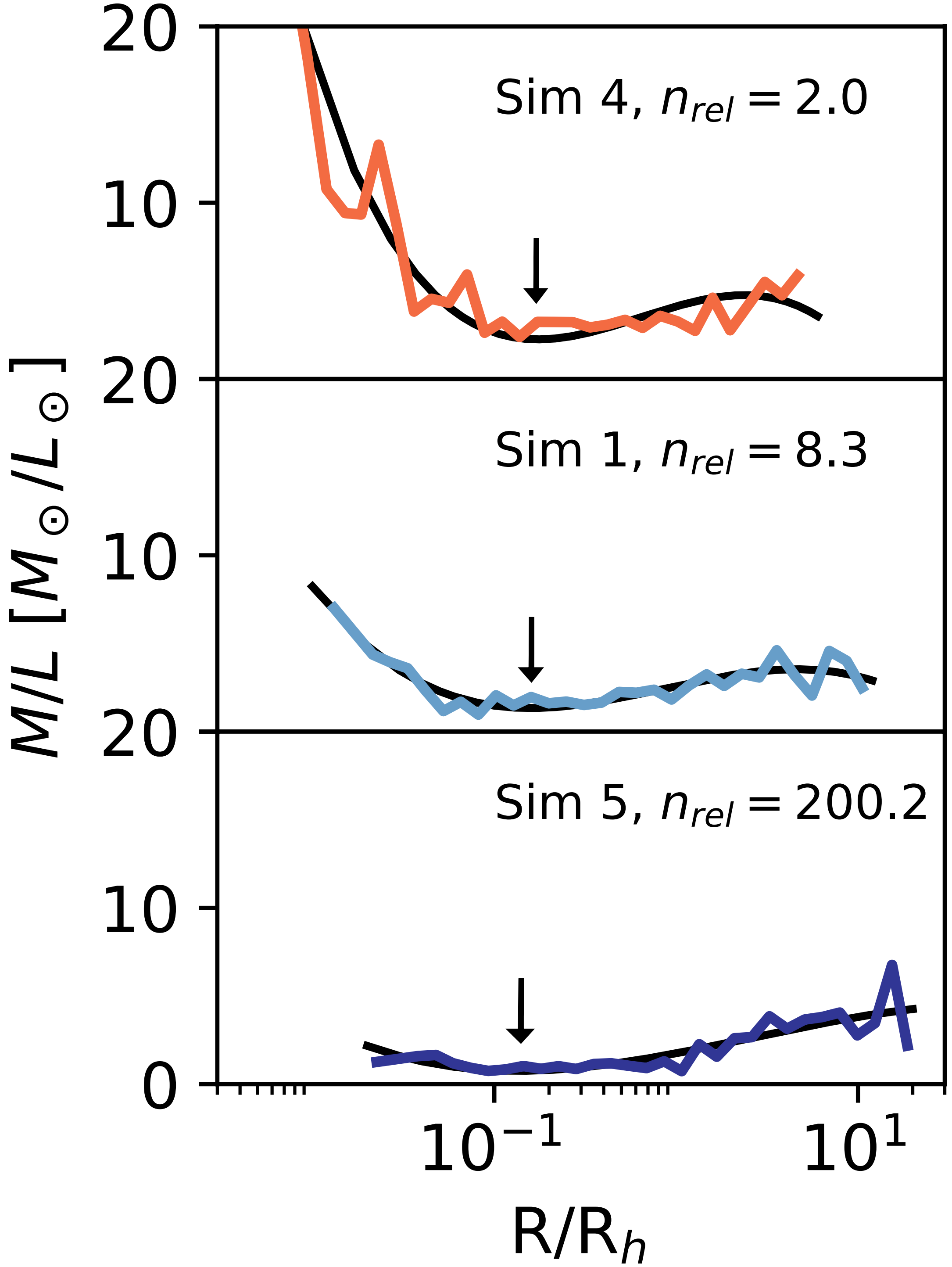
Multi-mass models: Da Costa & Freeman 1976; Gieles & Zocchi 2015; Zocchi et al. 2016; de Vita et al. 2016, Peuten et al. 2017

M/L and the dynamical state



Bianchini, Sills, van de Ven, Sippel 2017

M/L and the dynamical state



Variety of shapes of M/L profiles:

-central peak
-rise in the outer part
-common minimum

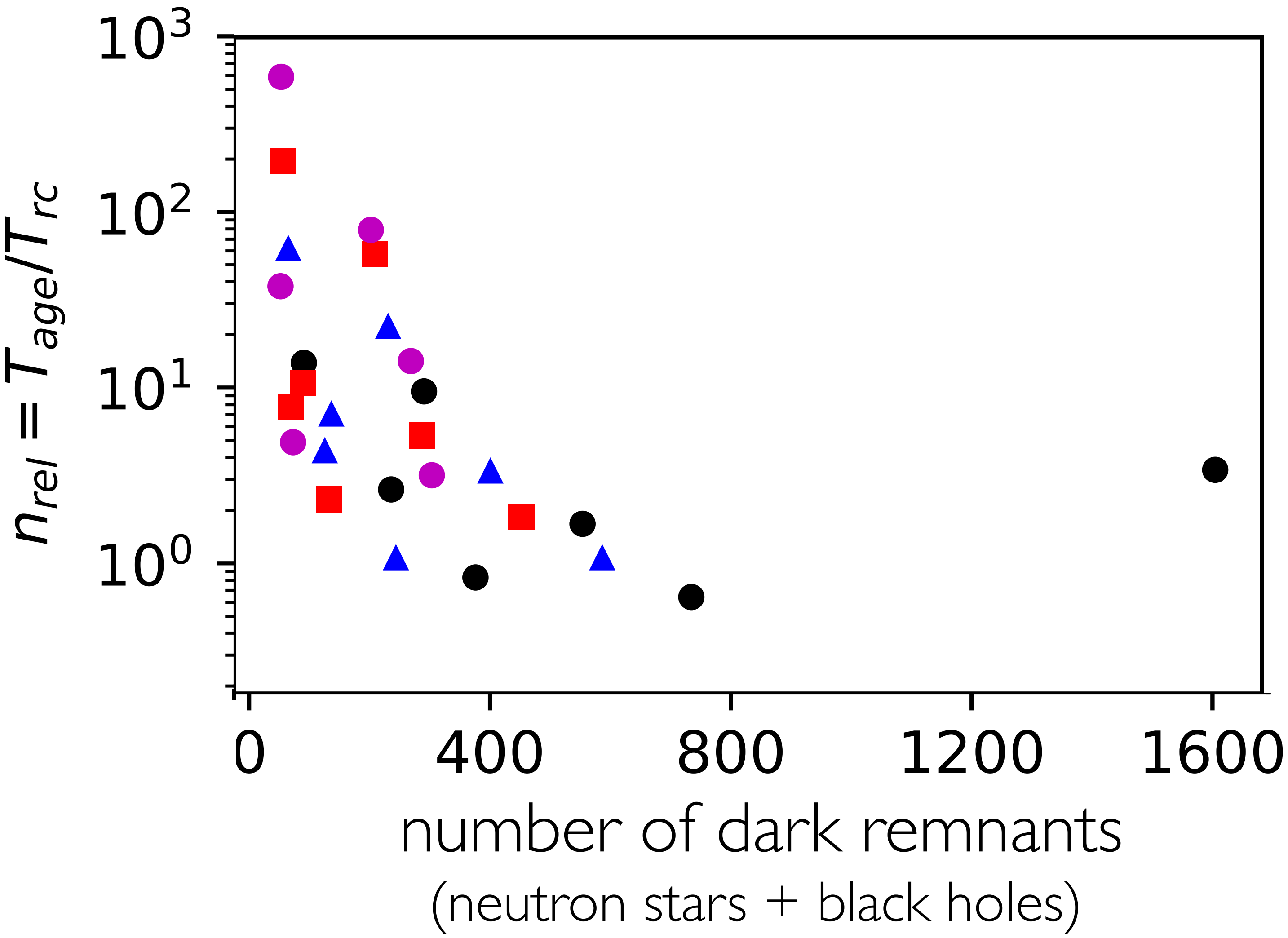
Correlation with relaxation state:

Dynamically young clusters display central peak that flattens out for dynamically older clusters.

Central peak is due to retention of dark remnants. Clusters with shorter relaxation times (dynamically old) have efficiently ejected remnants.

Bianchini, Sills, van de Ven, Sippel 2017

M/L and the dynamical state



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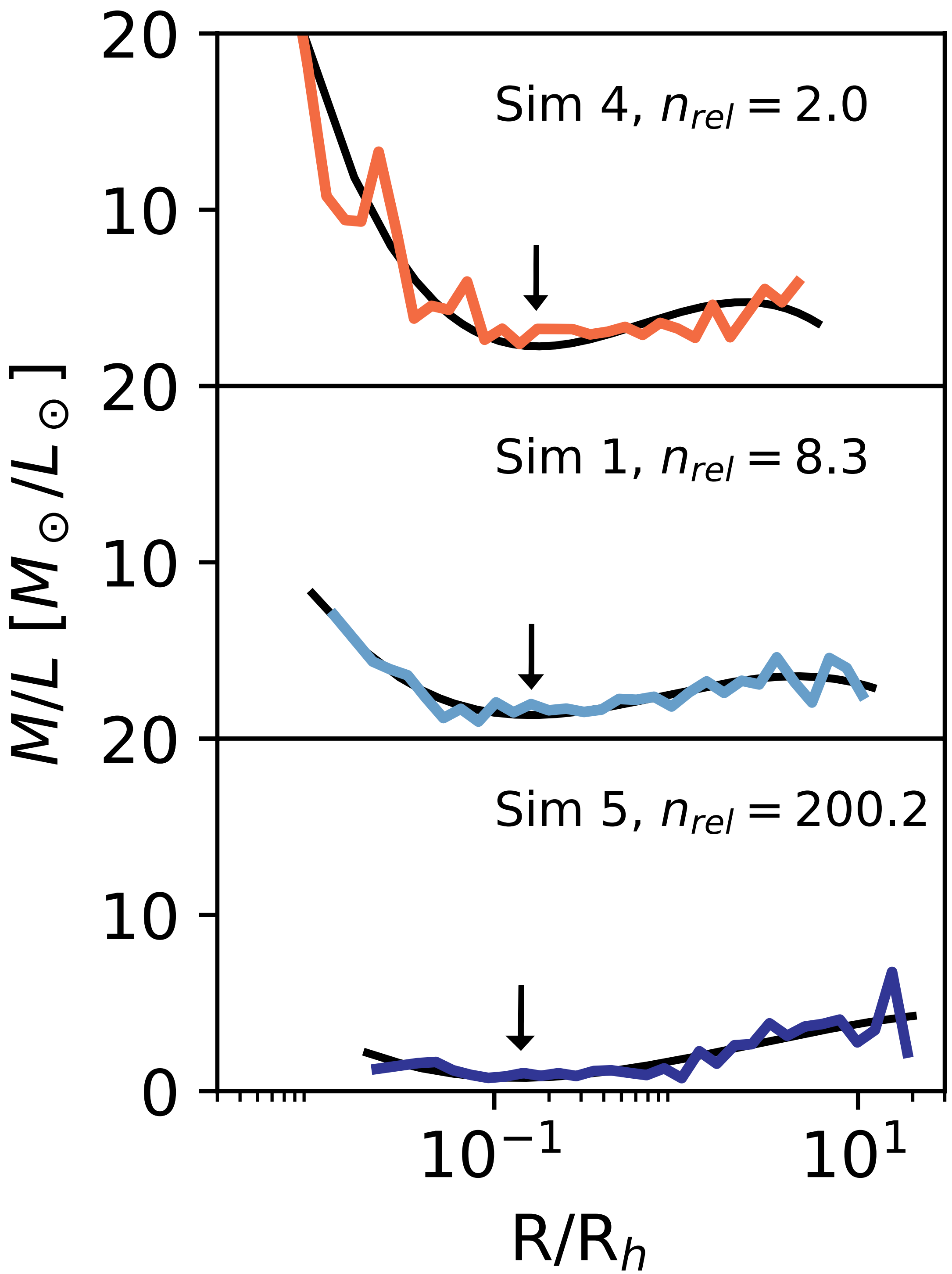
Bianchini, Sills, van de Ven, Sippel 2017

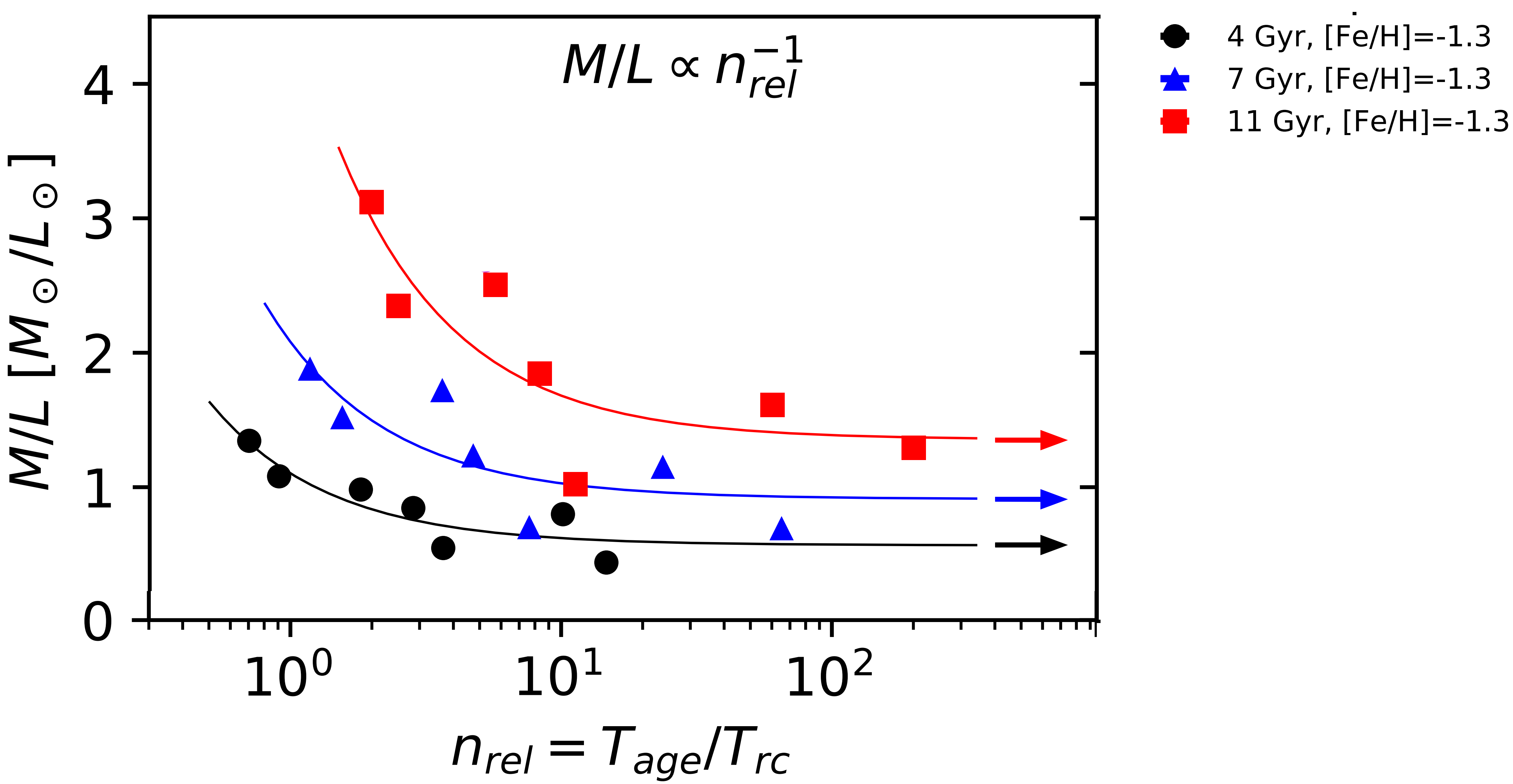
M/L and the dynamical state



Dynamically young clusters:
massive GCs or Ultra Compact Dwarfs

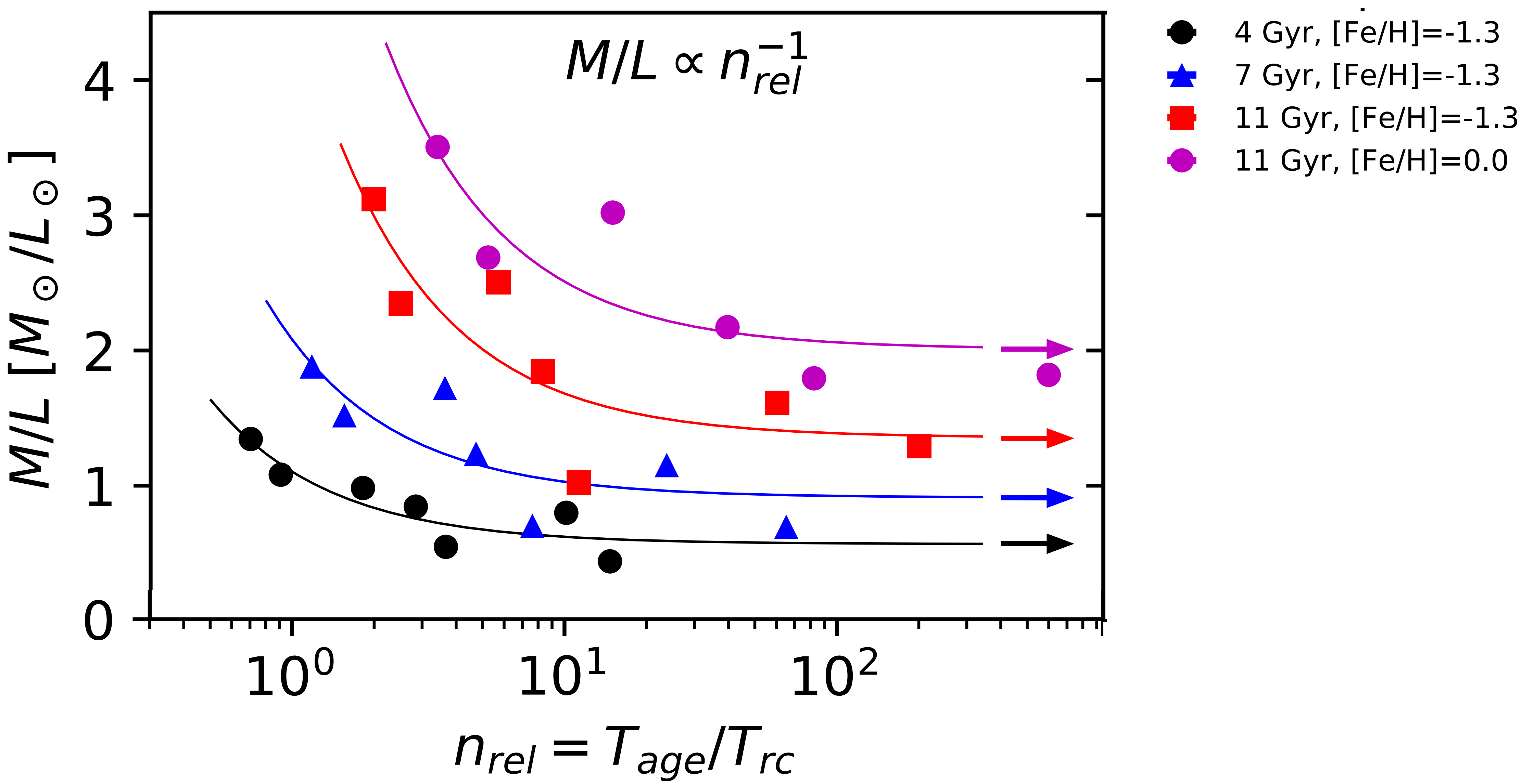
Possible degeneracy with IMBH signatures?

M/L and the dynamical state



Bianchini, Sills, van de Ven, Sippel 2017

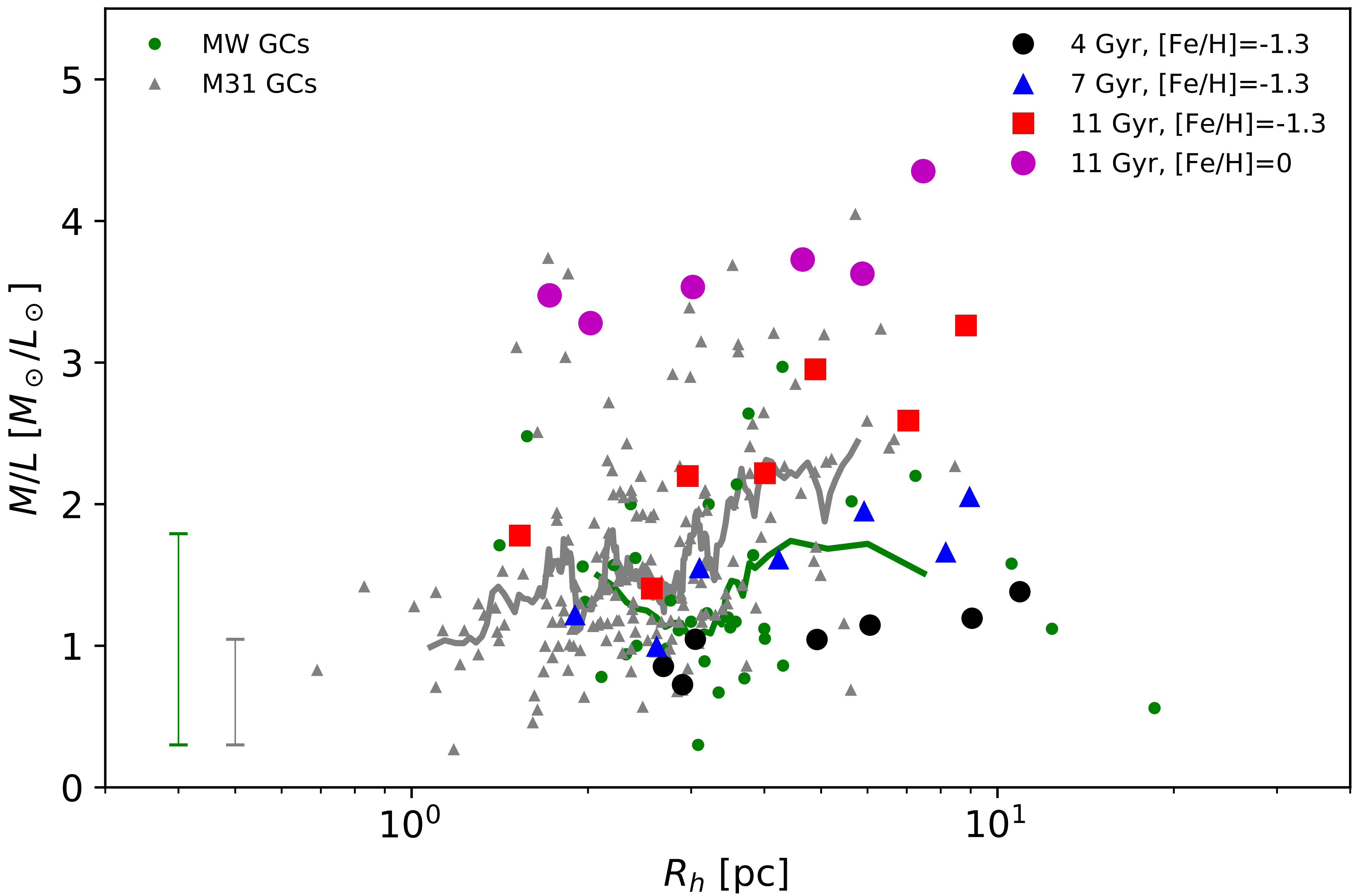
M/L and the dynamical state



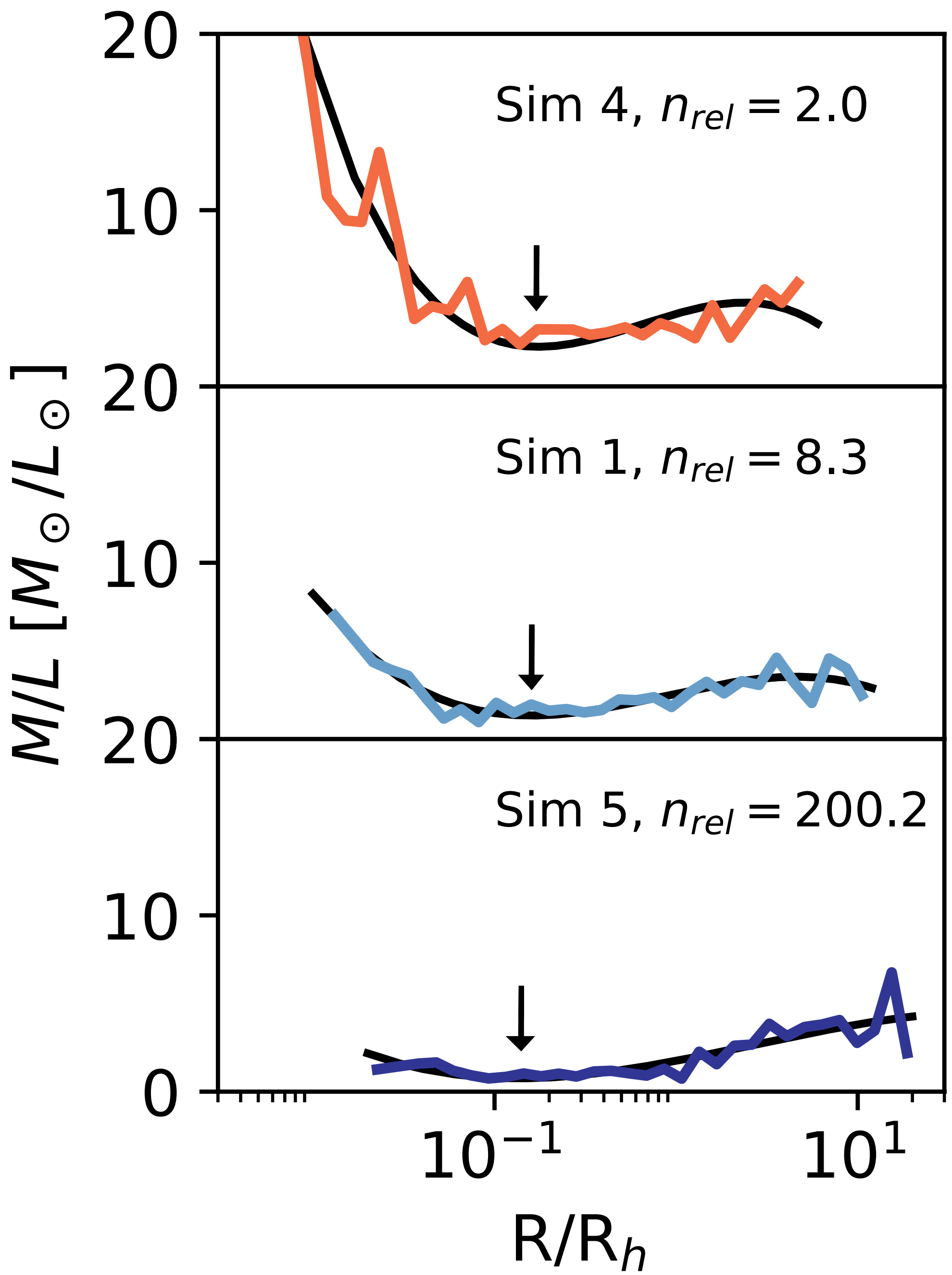
Given an age and metallicity **the relaxation state of a cluster determines its M/L**

Bianchini, Sills, van de Ven, Sippel 2017

M/L and the dynamical state



2. Mass-to-light ratio

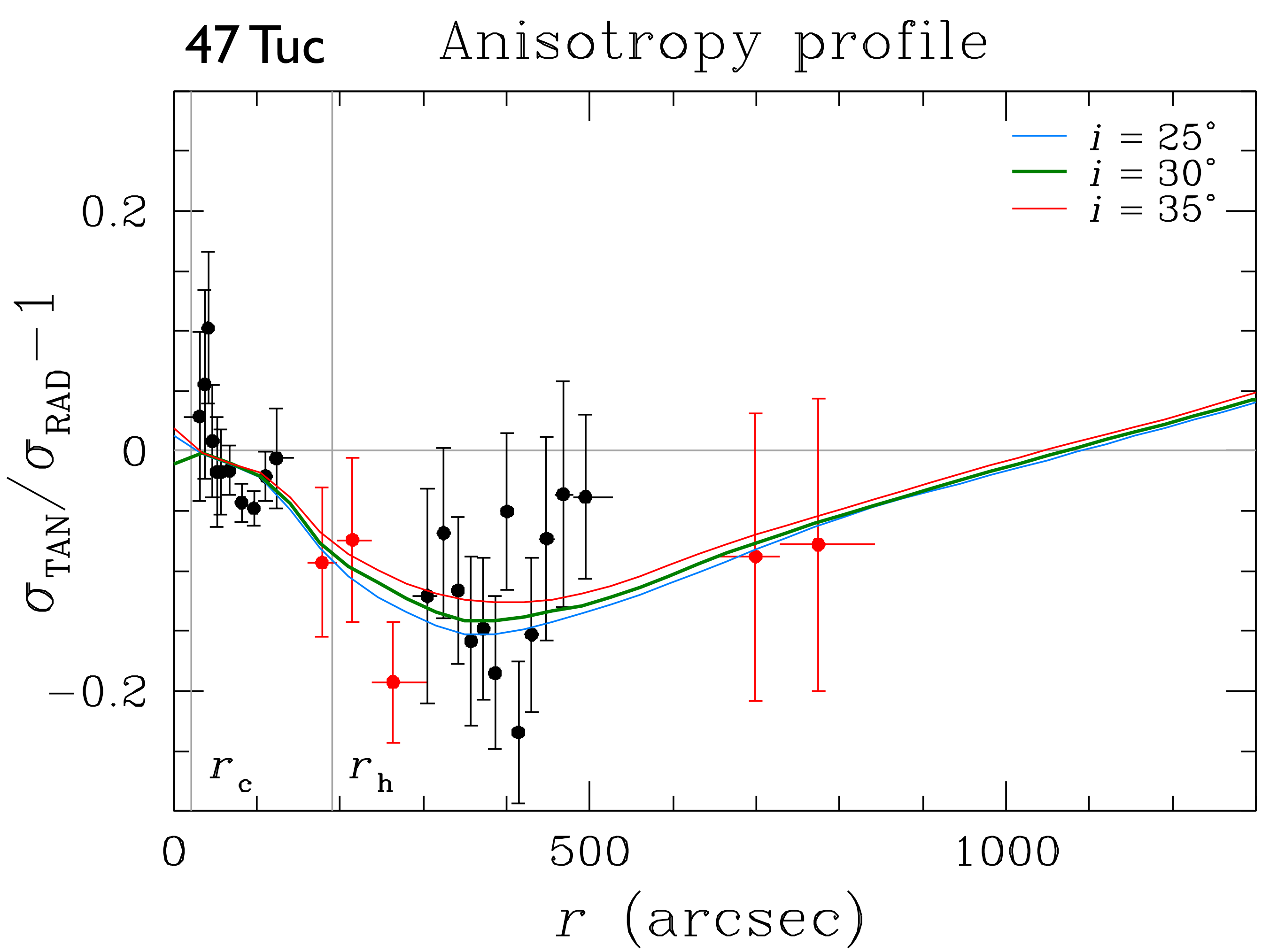


M/L & dynamical state

WHAT DID WE LEARN?

- **M/L profiles are not constant**: given the relaxation state of a cluster we can predict a physically motivated M/L profile
- break the degeneracy between dark remnants and **IMBHs**
- **Dark remnants** significantly shape the M/L: possibility of inferring the number of remnants from accurate measurements of M/L?

3. Velocity anisotropy



Bellini, **Bianchini** + HSTPROMO submitted

GCs are mildly anisotropic

Observations show:

- isotropy in the centre
- mild radial anisotropy in the intermediate regions
- tangential anisotropy / isotropy in the outer parts

e.g. HST proper motion observations: Watkins+2015, Bellini+2015 Richer+2014, vanLeeuwen+2000

3. Velocity anisotropy

GCs are mildly anisotropic

Simulations show:

Anisotropy is shaped by a combination of

1) primordial formation processes (Lynden-Bell 1967, Vesperini+2014)
2) internal relaxation processes (Spitzer1987, Giersz & Heggie 1996)
3) interaction with external tidal field (Giersz & Heggie 1997, Takahashi+1997)

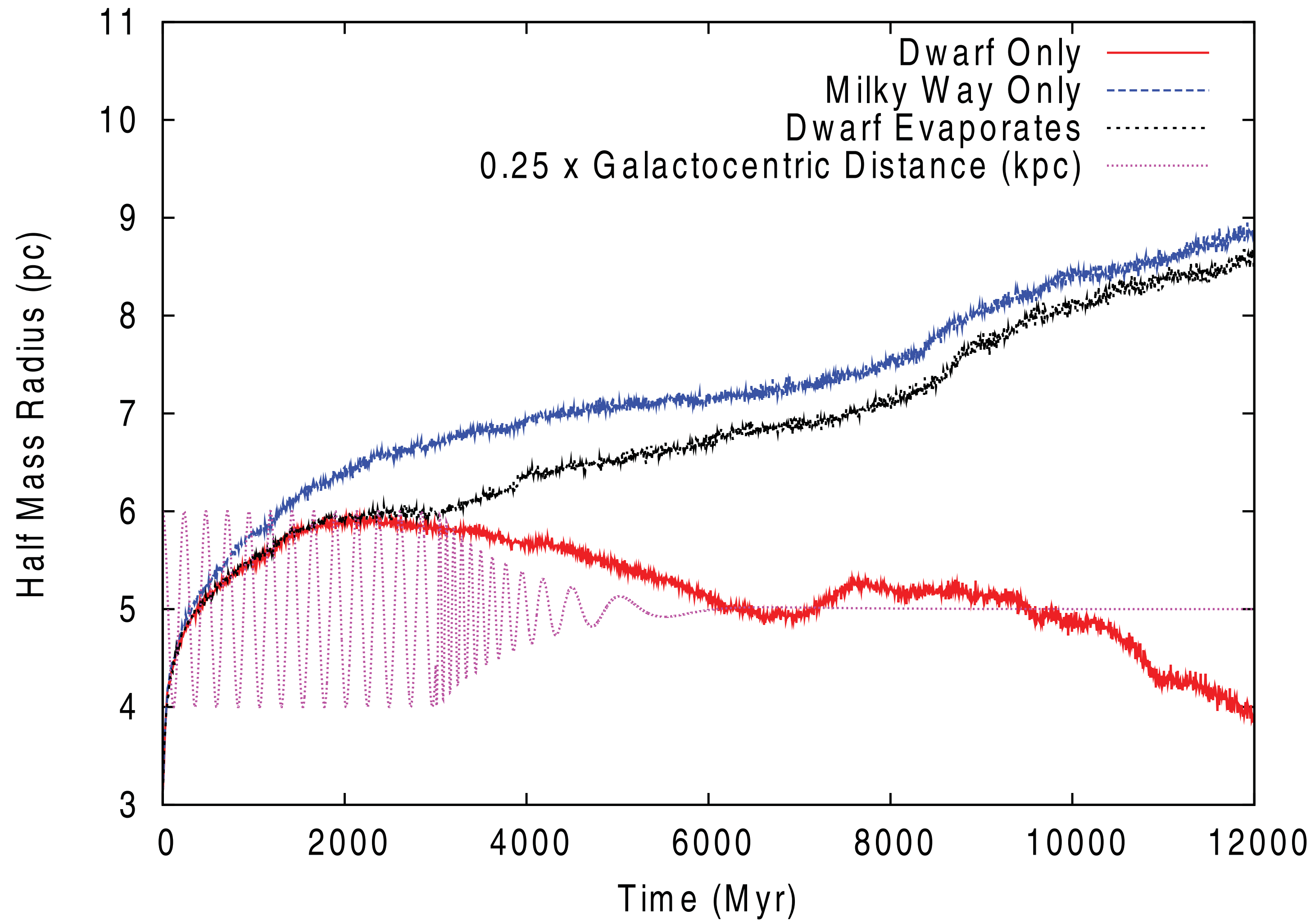
More recently: Tiongco+2016, Zocchi+2016, Sollima+2015

Is the anisotropy affected by the birth environment?

Accreted vs. in-situ GCs

Miholics, Webb & Sills 2016

- ~2/3 of MW GCs *suspected* to be accreted systems (age-metallicity relation)
- ωCen and M54 *suspected* to be nuclei of dwarf galaxies
- No signatures of accretion in the internal structure
  Miholics+2016, 2014; **Bianchini**+2015



Can we find a unique kinematic signature of an accretion process?

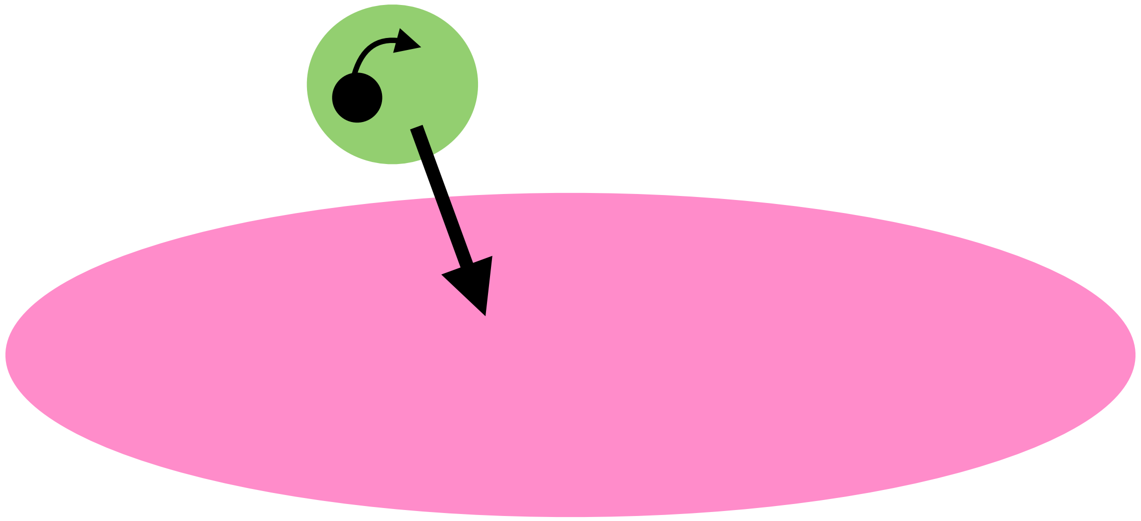
Simulating an accretion process

SIMULATIONS: time-dependent tidal field (Nbody6tt, Renaud+2015)
set of simulations from Miholics et al. 2016

GCs: 50,000 particles, Kroupa mass function, tidally under filling configurations

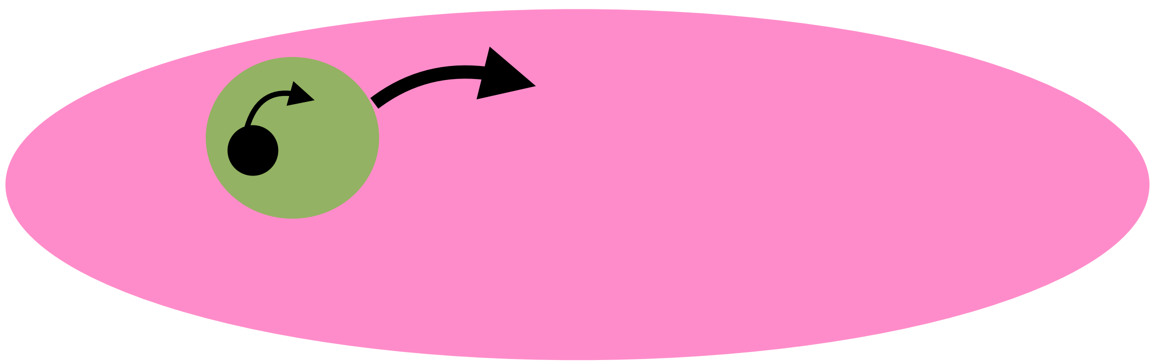
MW: bulge + disk + logarithmic halo

Dwarf: point mass (10^9-10^{10} $M_\odot$)



Scenario 1: Dwarf falls
the GC experiences an increasing tidal field
until it reaches the final position at ~6 Gyr

Scenario 2: Dwarf evaporates
the GC is released into the MW potential,
while the dwarf loses mass until 6 Gyr



Anisotropy as a fossil record

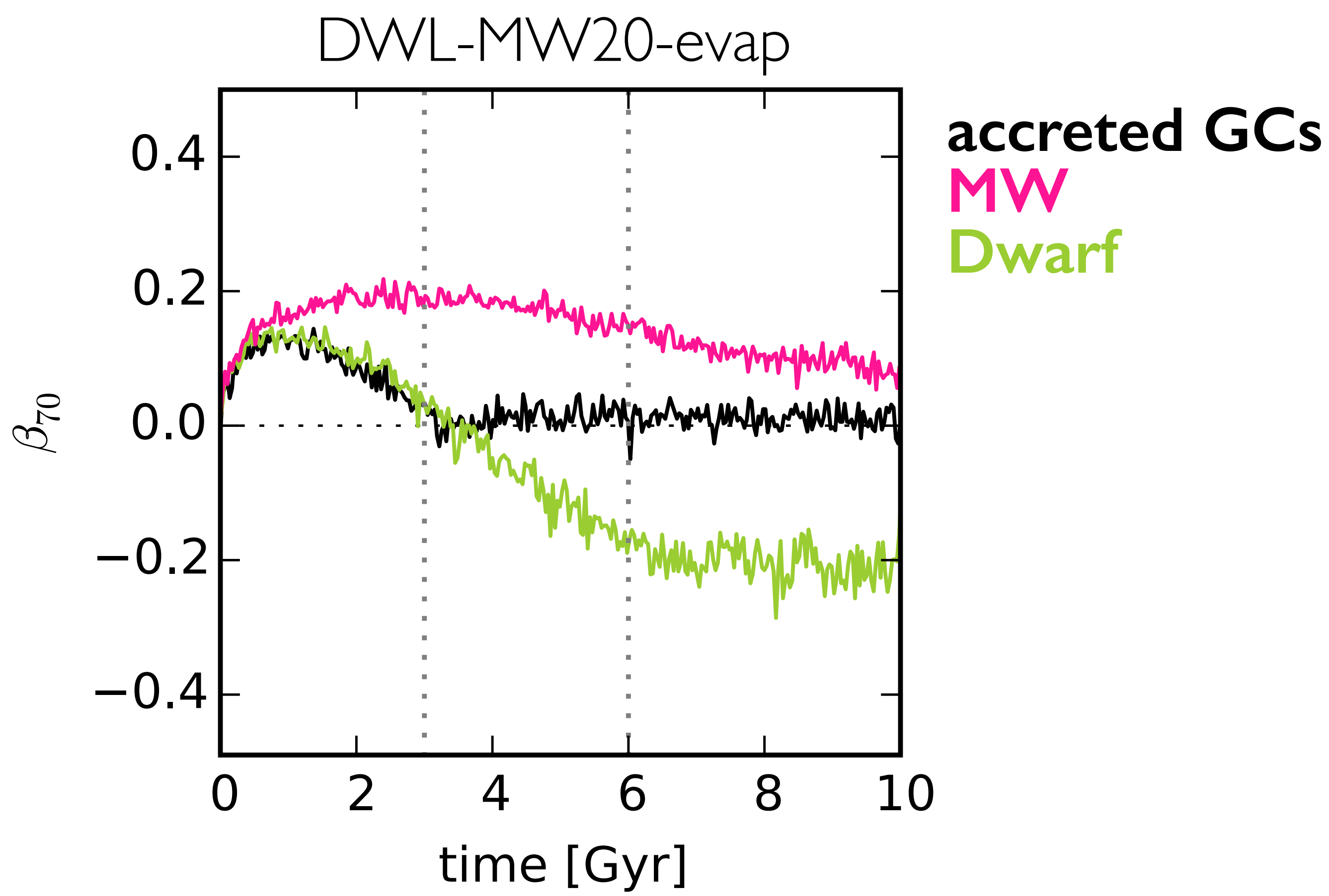
$$\beta = 1 - (\sigma^2_\varphi + \sigma^2_\theta)/2\sigma^2_r$$

$\beta > 0$ radial anisotropy

$\beta < 0$ tangential anisotropy

$\beta = 0$ isotropy

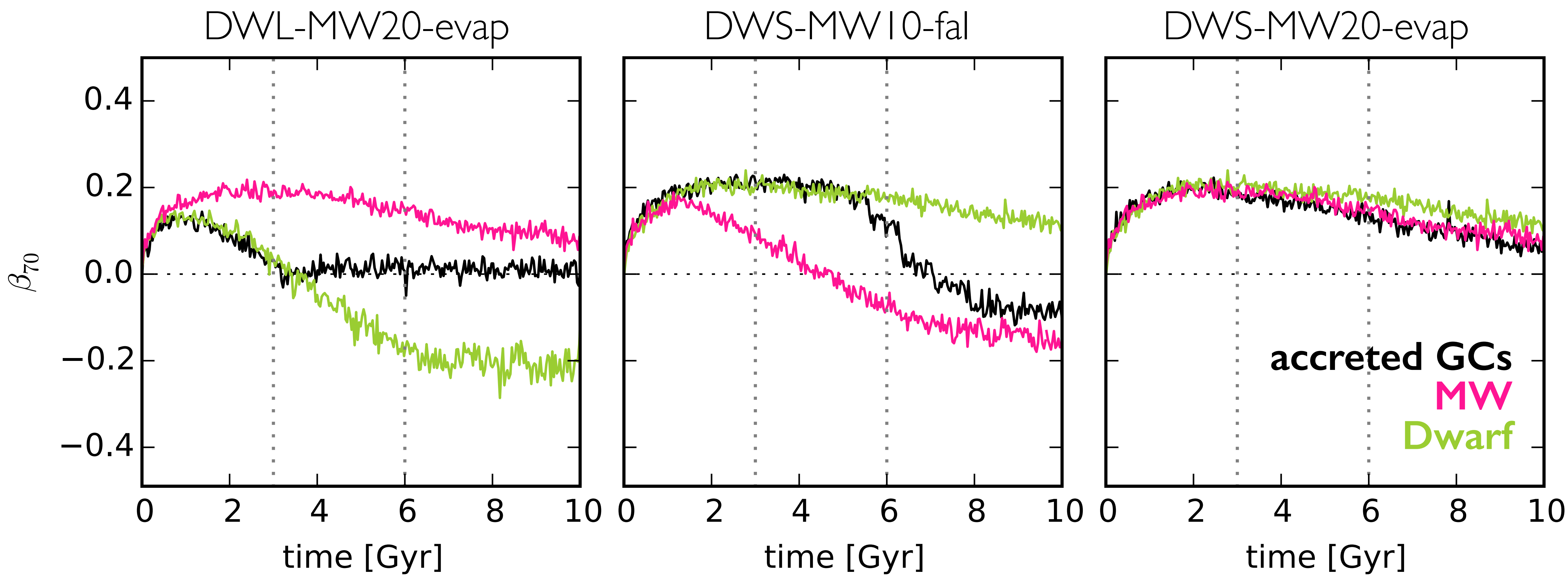
Anisotropy as a fossil record



- At early phases, the velocity anisotropy is determined by the tidal field of the dwarf
- The clusters will adapt to the new tidal environment in a few relaxation times

Bianchini, Sills & Miholics submitted

Anisotropy as a fossil record

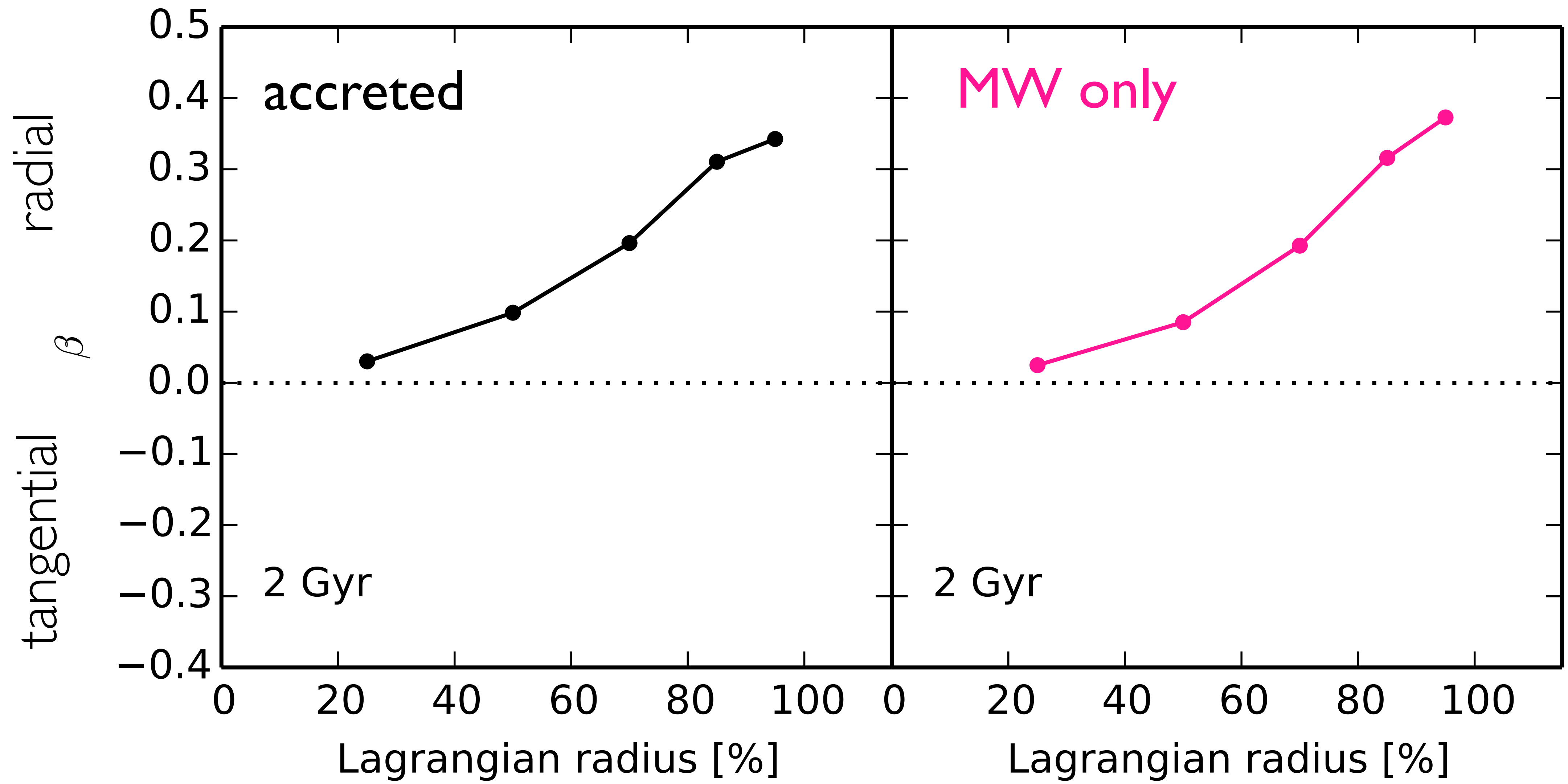


- At early phases, the velocity anisotropy is determined by the tidal field of the dwarf
- The clusters will adapt to the new tidal environment in a few relaxation times
- If any, the **signatures in anisotropy are not unique**

Bianchini, Sills & Miholics submitted

Anisotropy as a fossil record

right before the accretion starts



Dwarf evaporates

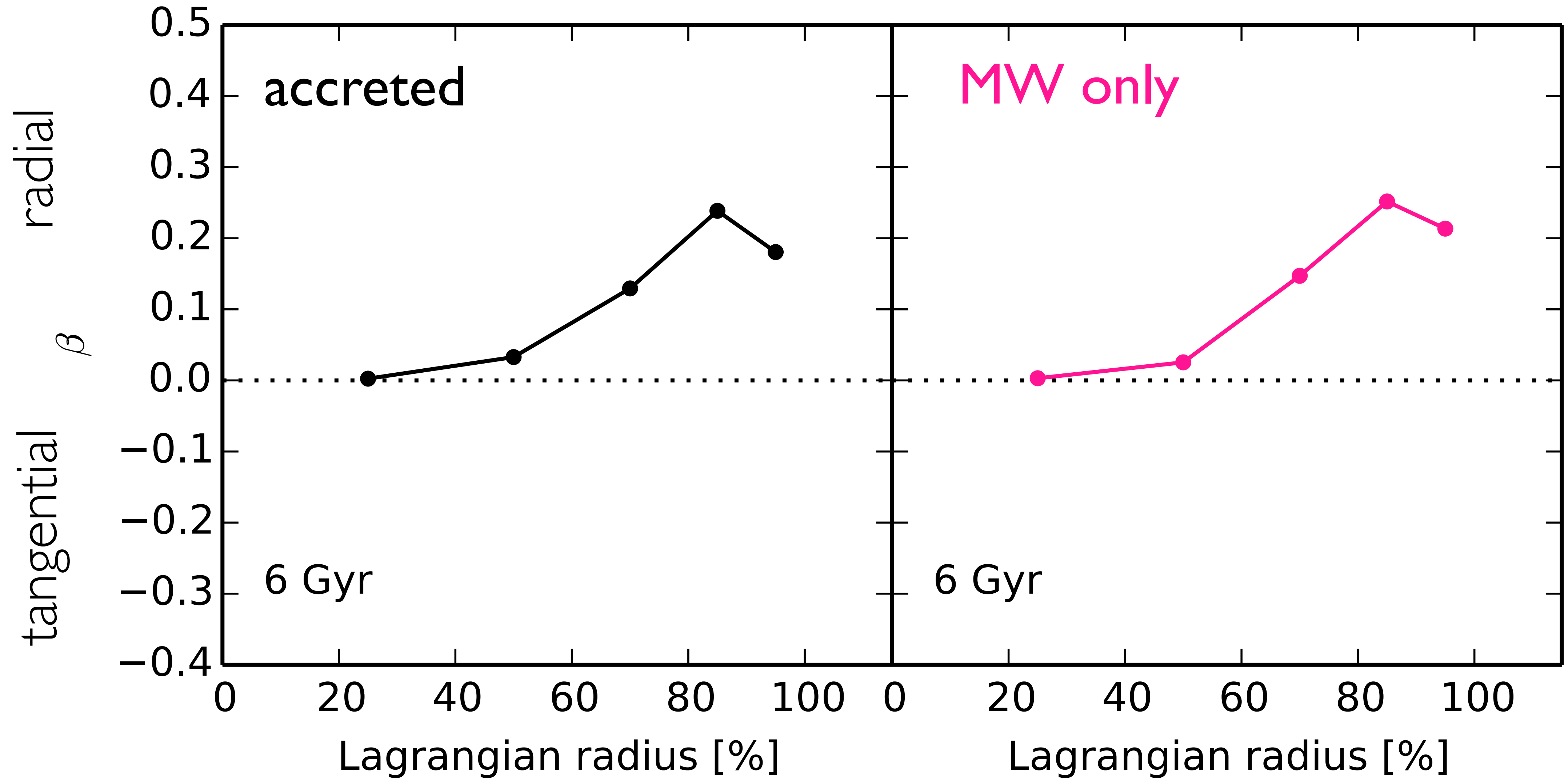
Dwarf initial mass $= 10^9\ M_\odot$

Distance from MW centre = 20 kpc

Bianchini, Sills & Miholics submitted

Anisotropy as a fossil record

right after accretion is over (dwarf mass = 0)



Dwarf evaporates

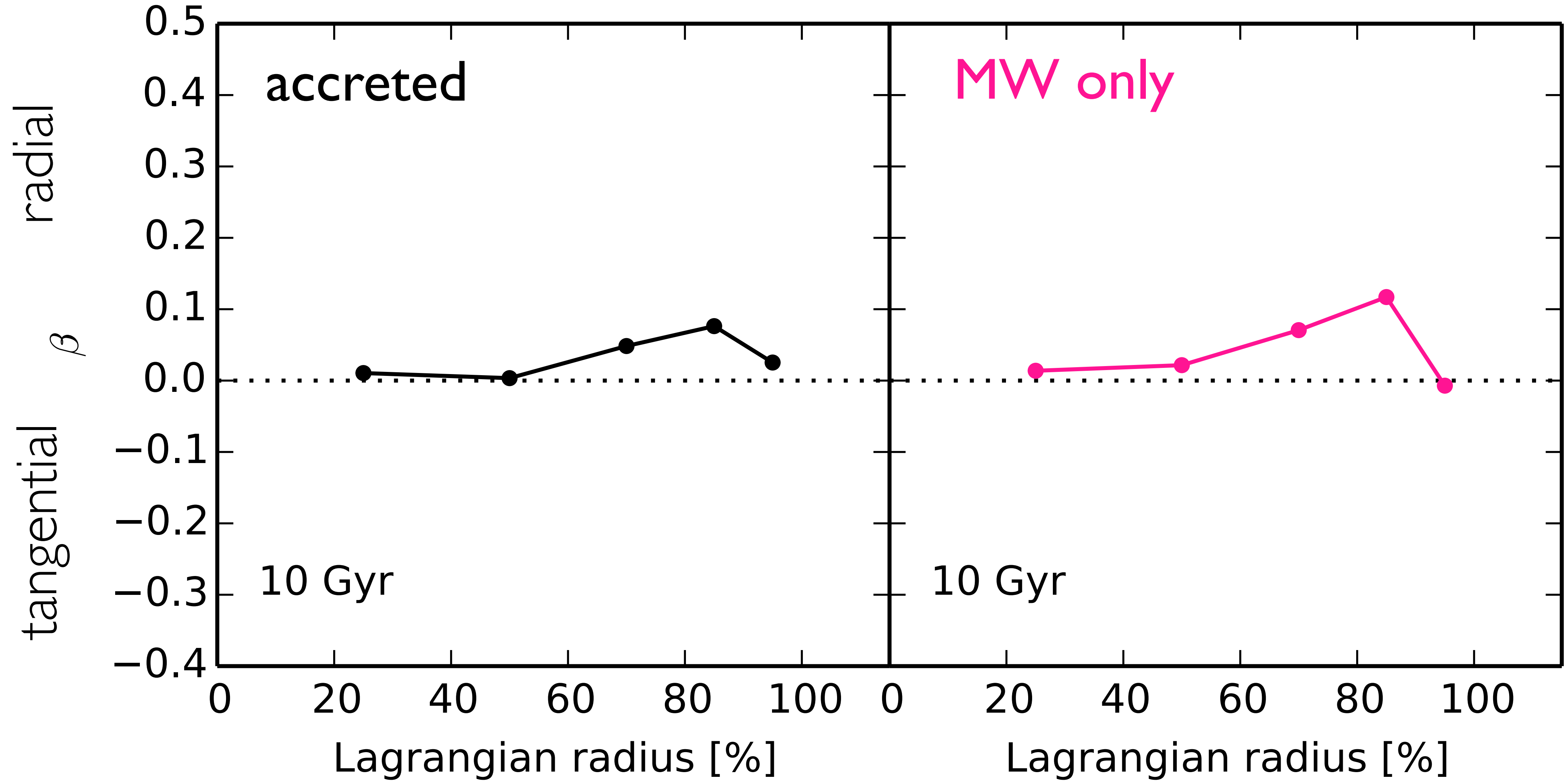
Dwarf initial mass = 10^9 $M_\odot$

Distance from MW centre = 20 kpc

Bianchini, Sills & Miholics submitted

Anisotropy as a fossil record

At 10 Gyr



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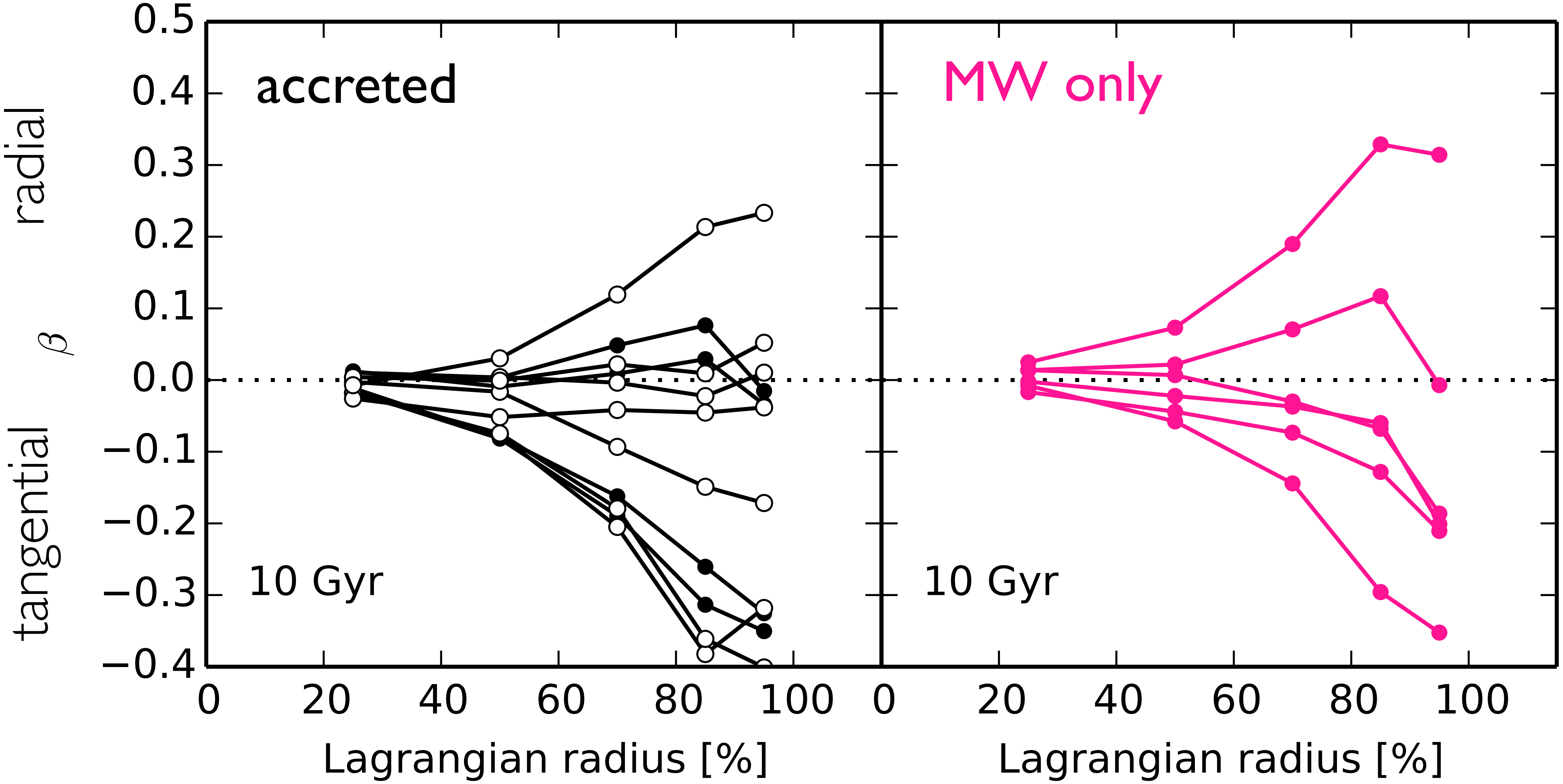
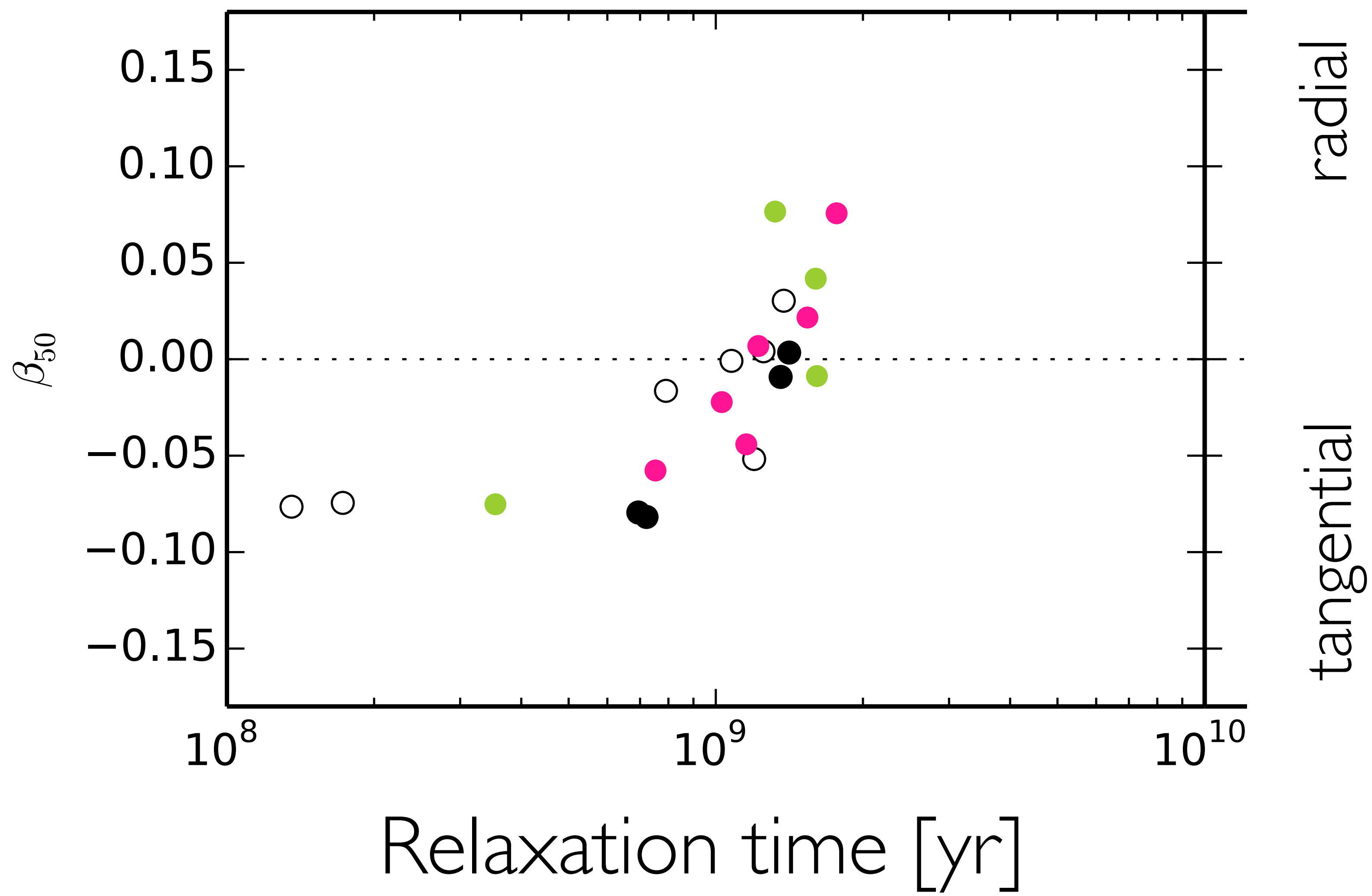


Consistent with Tiongco+2016 and Zocchi+2016
but larger varieties of profiles

Anisotropy as a fossil record

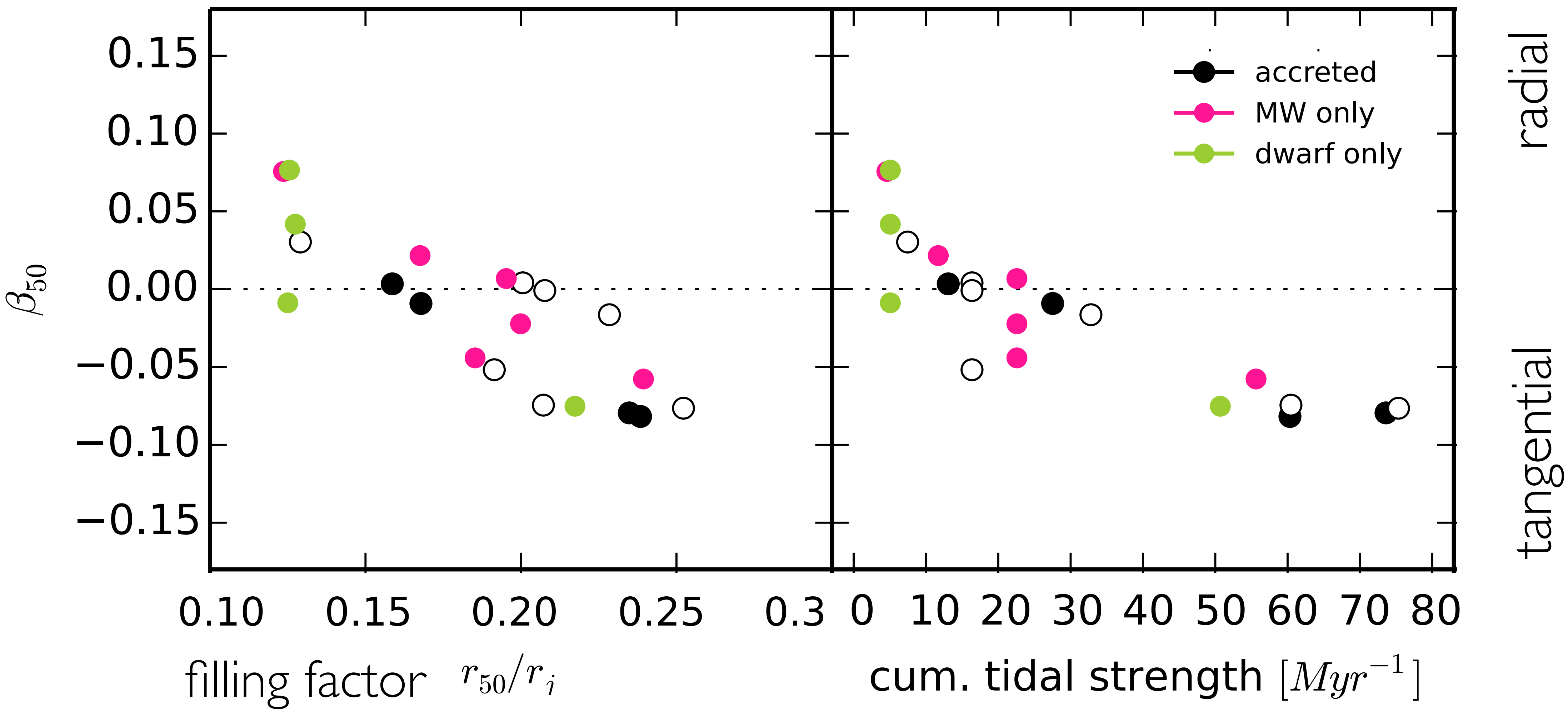


More relaxed clusters have isotropic/ tangential velocity distributions: consistent with HST observations (Watkins+2015)

Preferentially stripping of low-mass stars in radial orbits (e.g. Baumgardt & Makino 2003)

Bianchini, Sills & Miholics submitted

Anisotropy as a fossil record



The flavour of the velocity anisotropy depends o the strength of the tidal field and not on the accreted/in-situ origin

Bianchini, Sills & Miholics submitted

Anisotropy as a fossil record

Characterization of velocity anisotropy in a variety of different time-dependent tidal fields:

- **No unique and distinctive signatures** for accreted GCs

- at 10 Gyr a **variety of anisotropy profiles** are recovered: **isotropic, radial and tangential**

isotropy/tangentiality: $r_{50}/r_j > 0.17$

$t_{rel} < 10^9$ Gyr

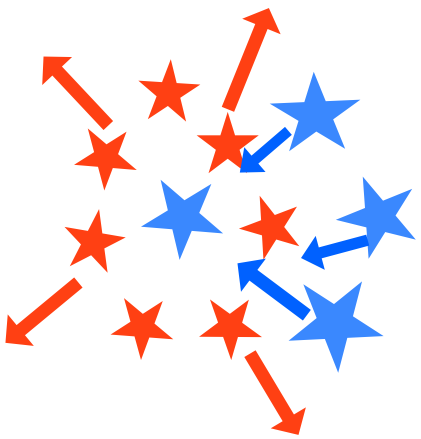
mass loss > 60%

Key for the interpretation of current and upcoming data
(HST proper motions within half-light radius and Gaia proper motions for the outer parts)

Conclusions

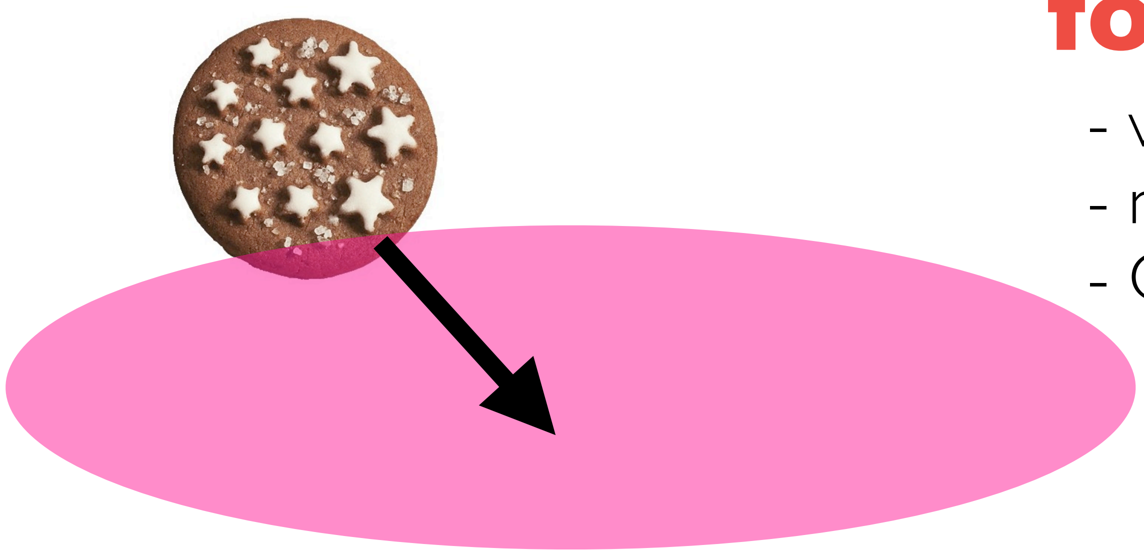
energy equipartition

- unveils the dynamical state of a cluster
- provides a tool to detect peculiar dynamical evolution (e.g. post-core collapse clusters)



mass-to-light ratio

- dynamical evolution & presence of remnants shape the M/L
- fundamental for dynamical modeling



fossil record of accretion

- velocity anisotropy traces formation and evolution
- no signatures of accretion in velocity anisotropy
- GCs as galactic nuclei?

Conclusions

- kinematics: powerful tool to unveil the richness of GCs
  PROPER MOTIONS provide a revolutionary tool
- synergy between modelling and observations
- think bigger:

  line-of-sight velocities + HST proper motions + Gaia