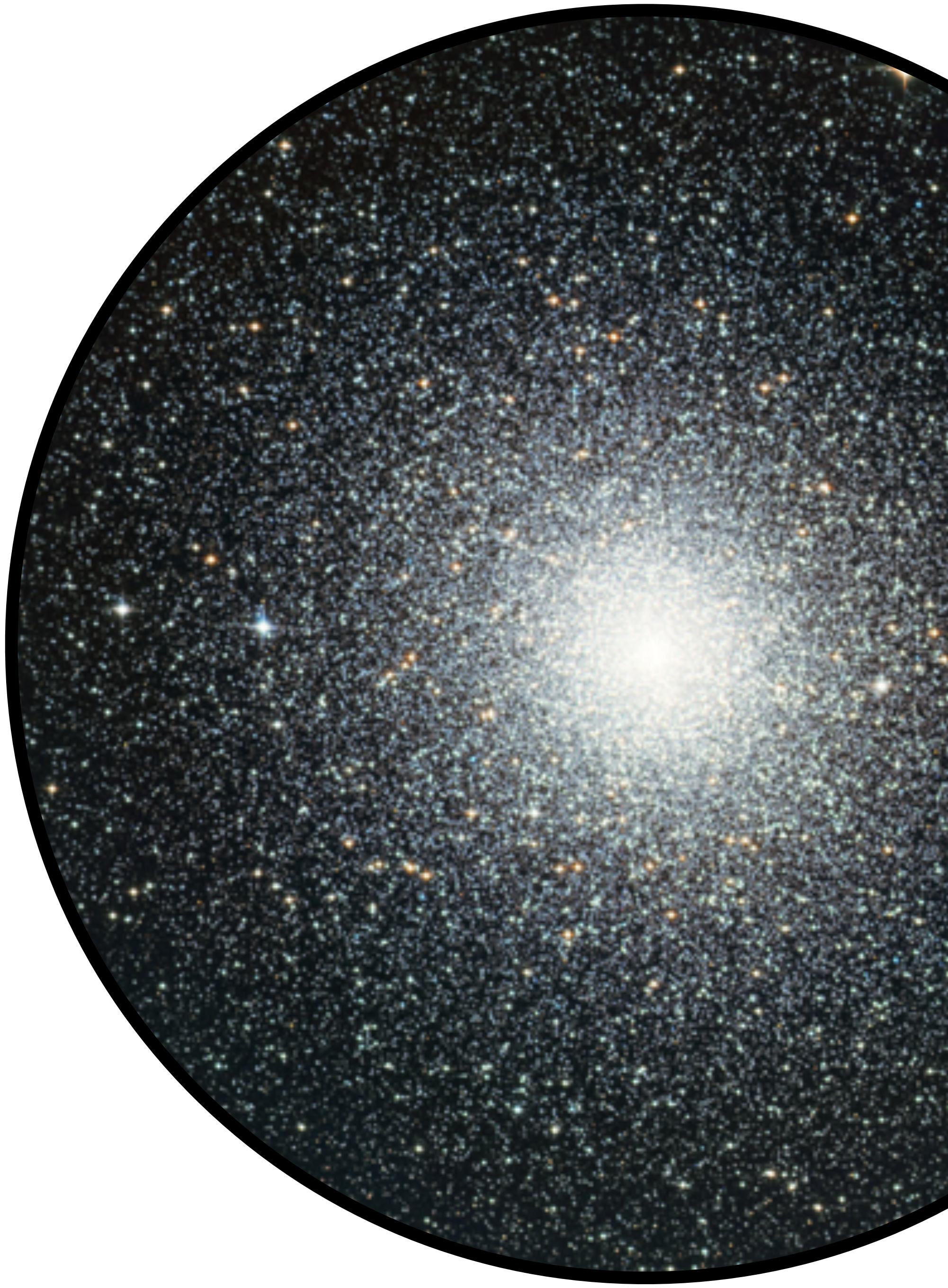
Probing the formation of globular clusters and their MPs with (chemo)dynamics



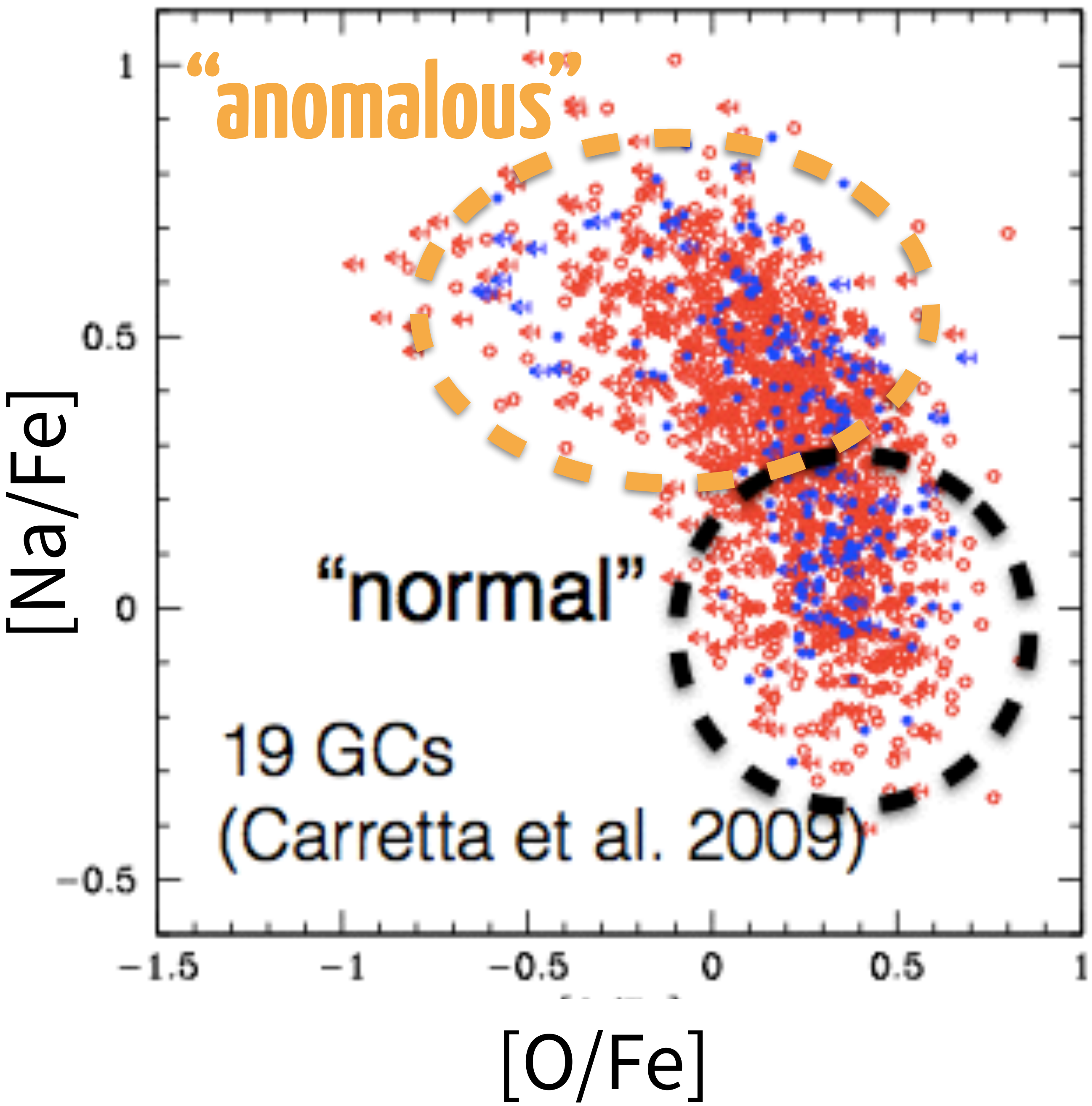
Vincent Hénault-Brunet

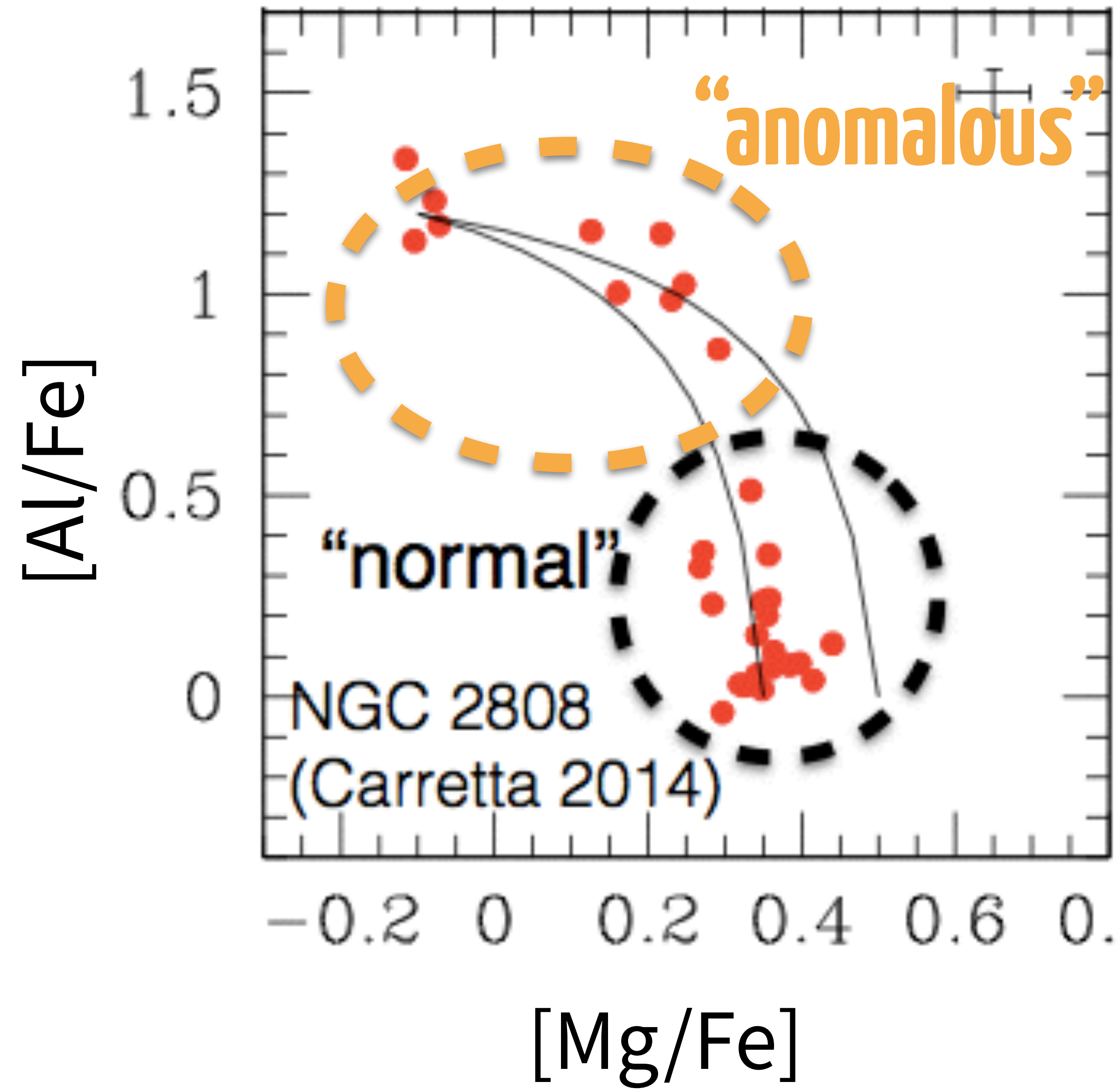
Excellence Initiative Fellow

Radboud University

For one of these Bologna specialties, the recipe is still a mystery…

Multiple populations in GCs: spectroscopic evidence

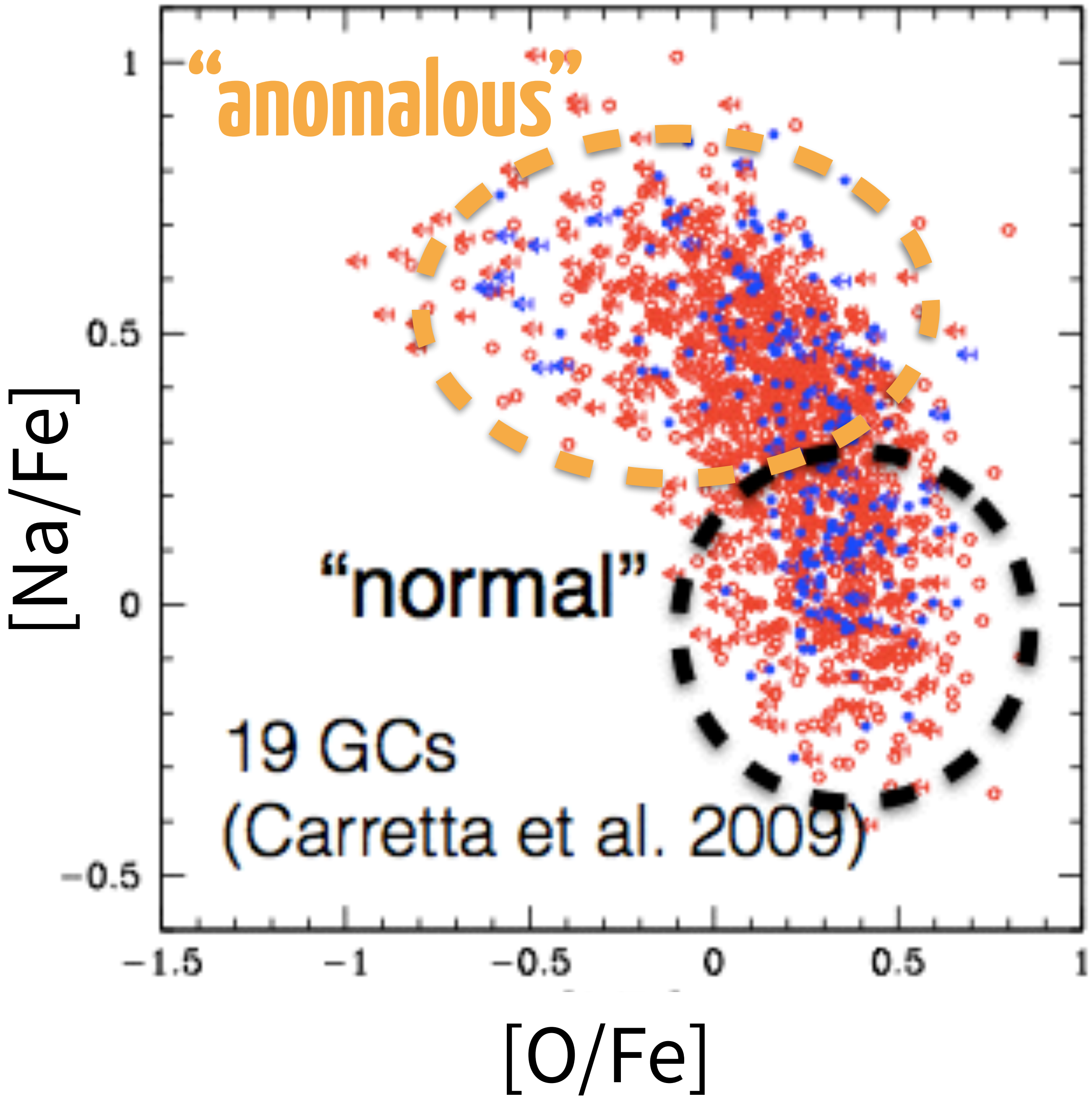




C↓	N↑	O↓	Na↑	Mg↓	Al↑	He↑	& no Fe variations*

* but a few exceptions

Multiple populations in GCs: spectroscopic evidence

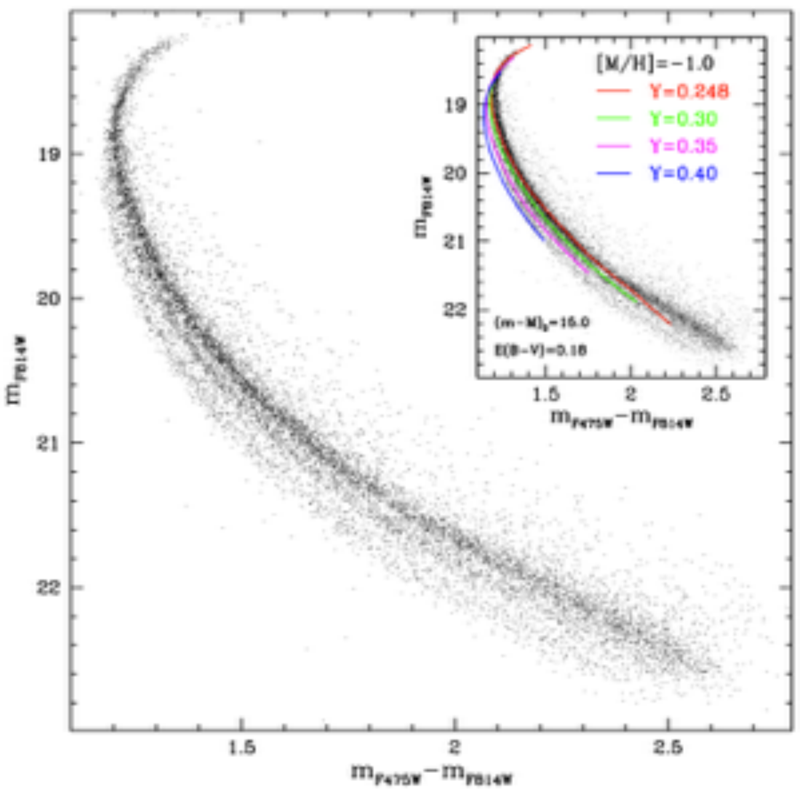


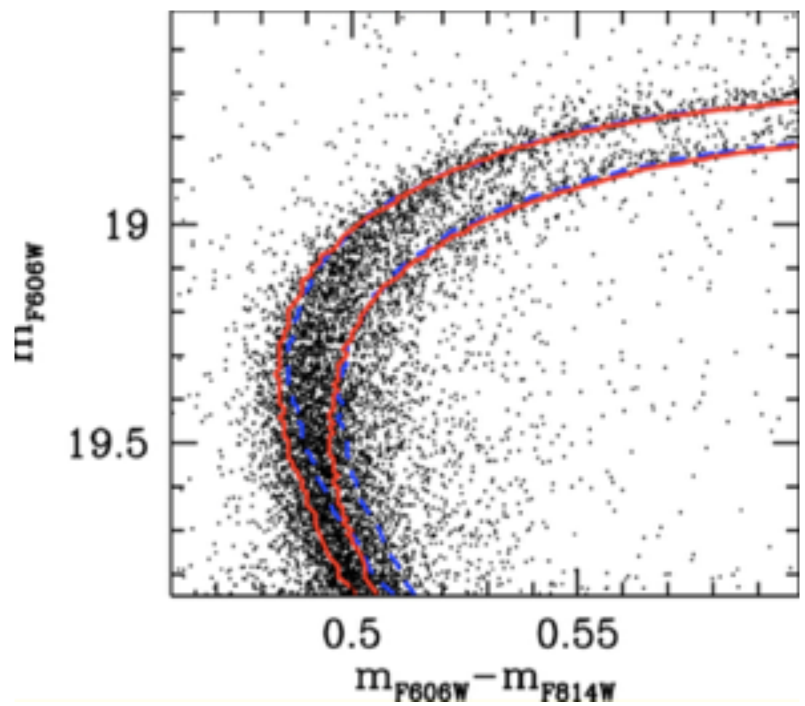
- Na-O anti-correlation present in (almost) all old GCs observed to date
- anomalous stars: typically >50 % of GC stars (only ~3% of field stars)
- seen in RGB stars, but also SGB and main sequence stars
- signature of matter processed in high-temperature stellar interiors

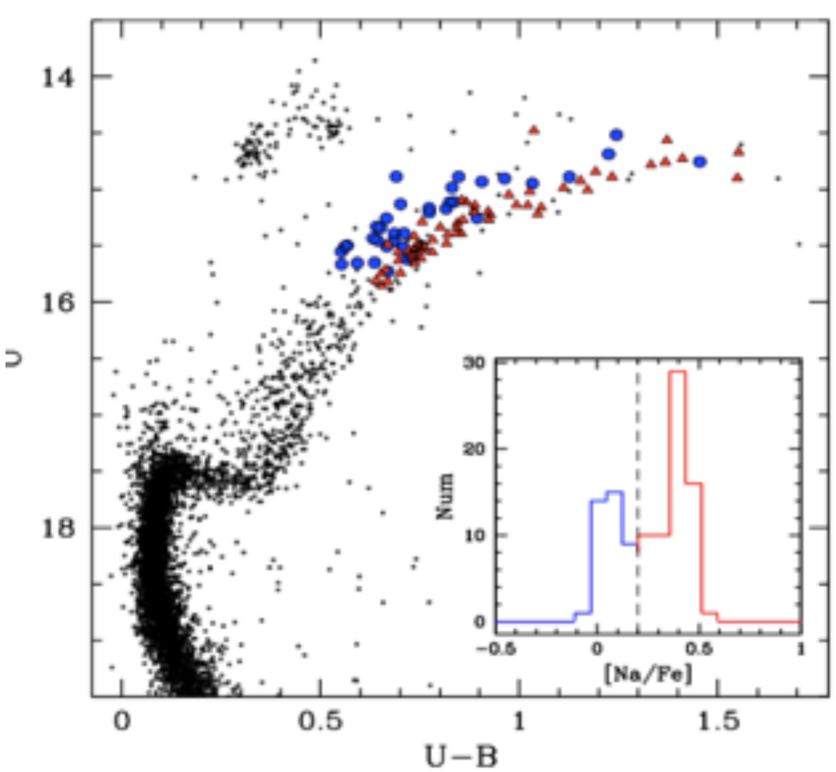
C↓	N↑	O↓	Na↑	Mg↓	Al↑	He↑ & no Fe variations*

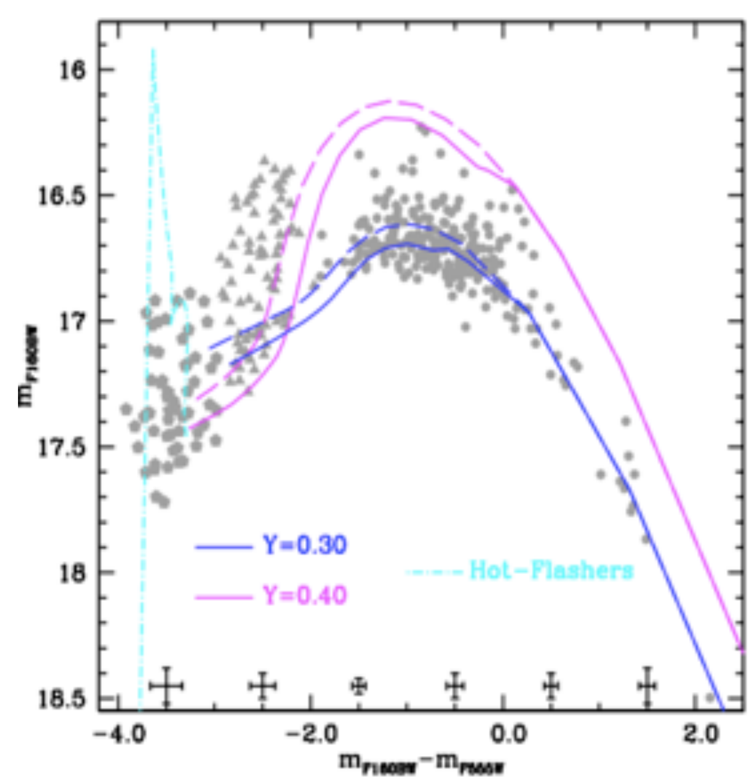
* but a few exceptions

Multiple populations in GCs: photometric evidence









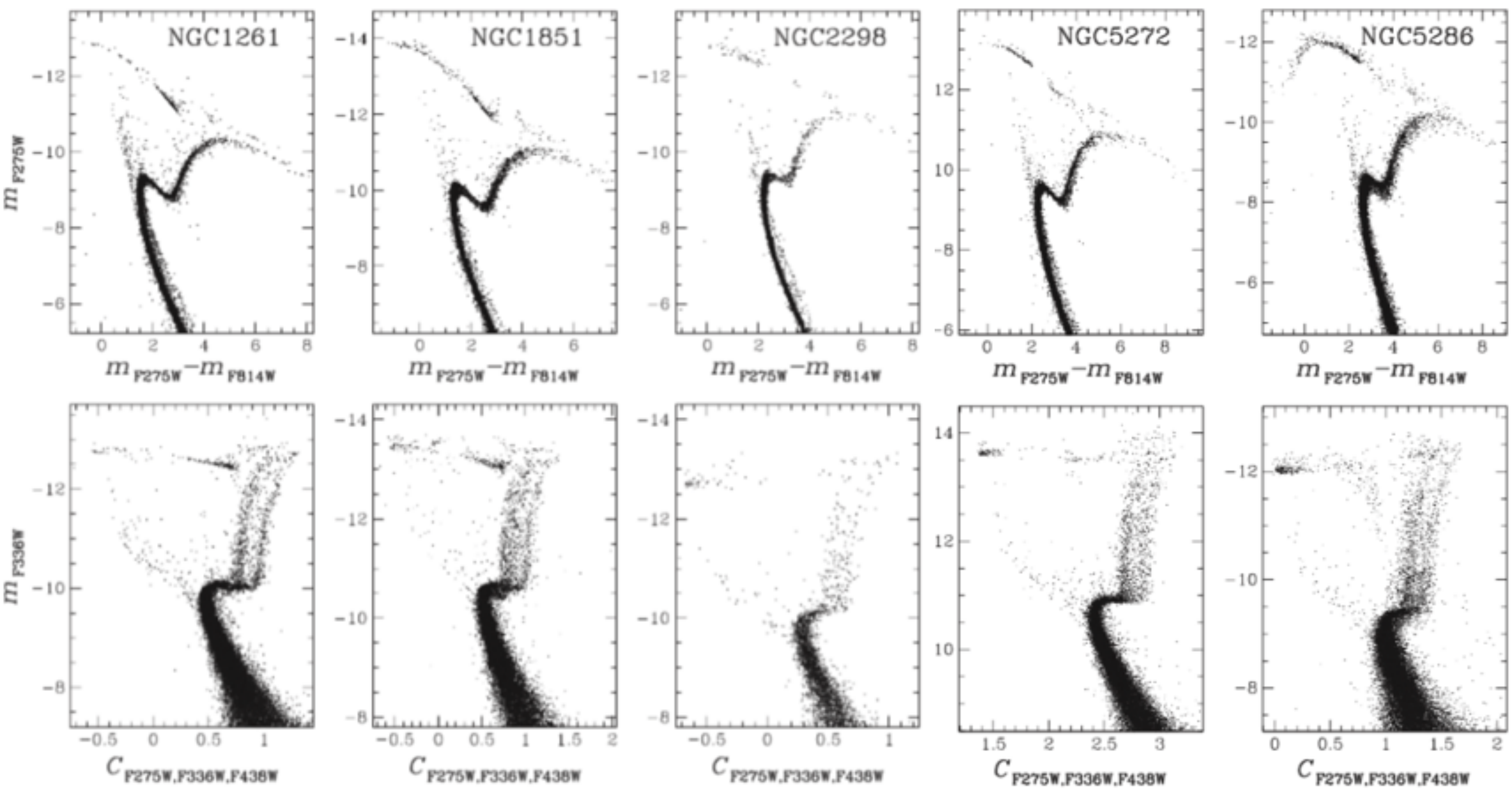
Complex CMDs: multiple main sequences, double SGB, multi-modal RGB, multi-modal HB…

Features can be explained by **He enrichment** or **light-element abundance spreads**

Multiple populations in GCs: photometric evidence

Large **variety** in the observed pattern of MPs from one GC to the other

\+ **discreteness** of subpopulations

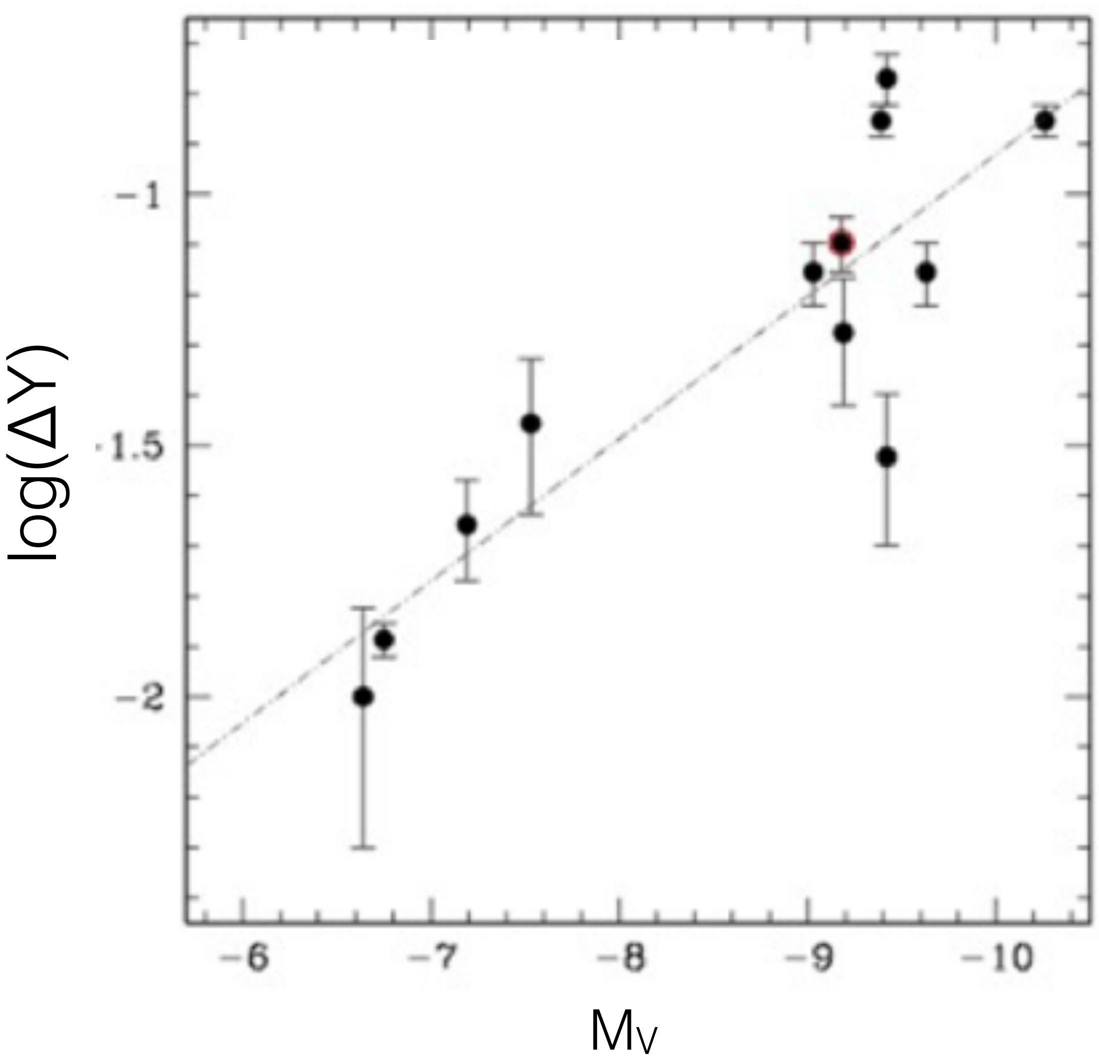


HST UV Legacy survey - Piotto et al. 2015

Multiple populations in GCs: additional facts

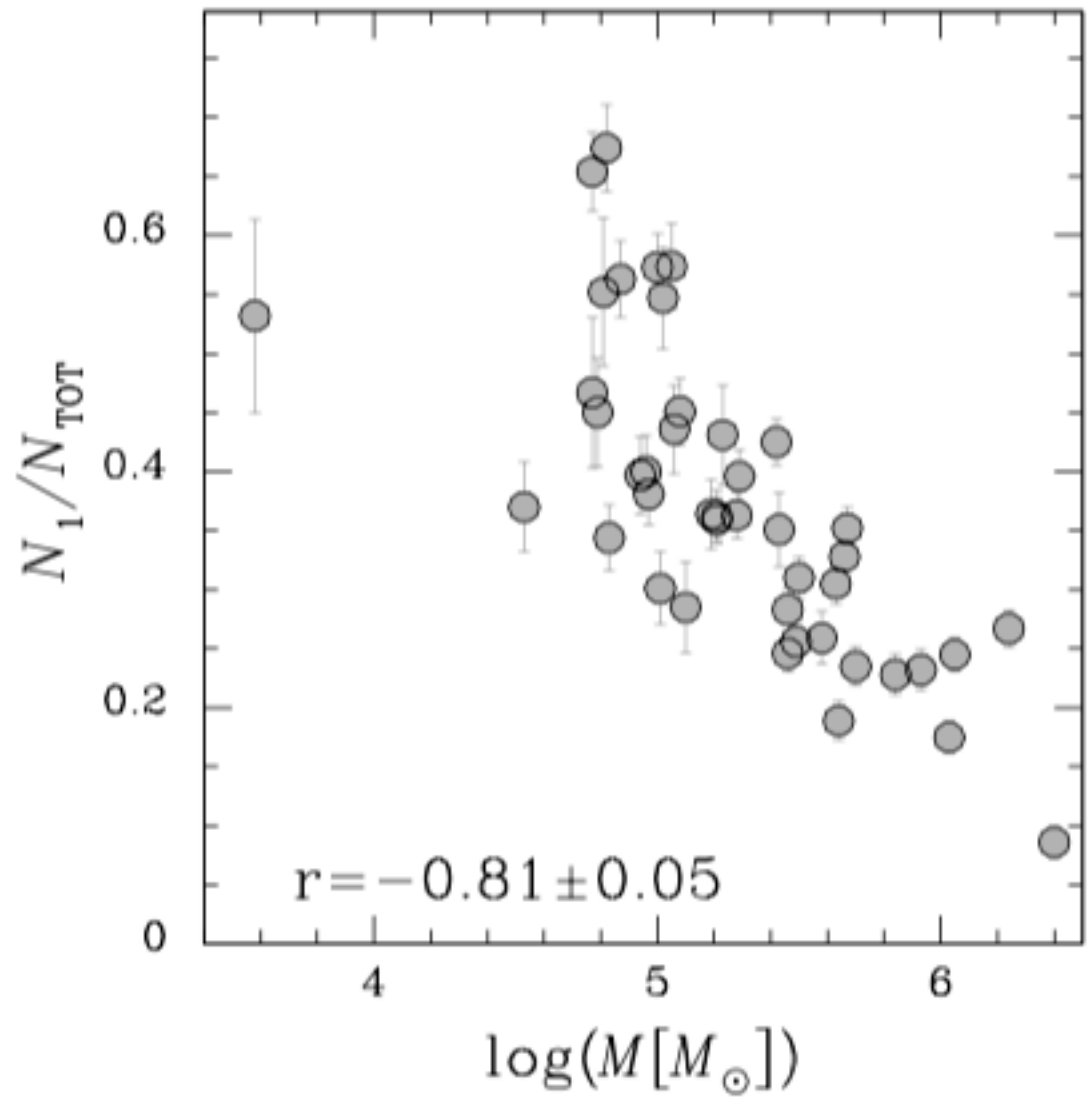
Anomalous (SG) stars typically outnumber “normal” (FG) stars

Light-element and He abundance spreads, and fraction of “anomalous” (“second generation” - SG) stars correlate with cluster mass



e.g. Milone 2014,

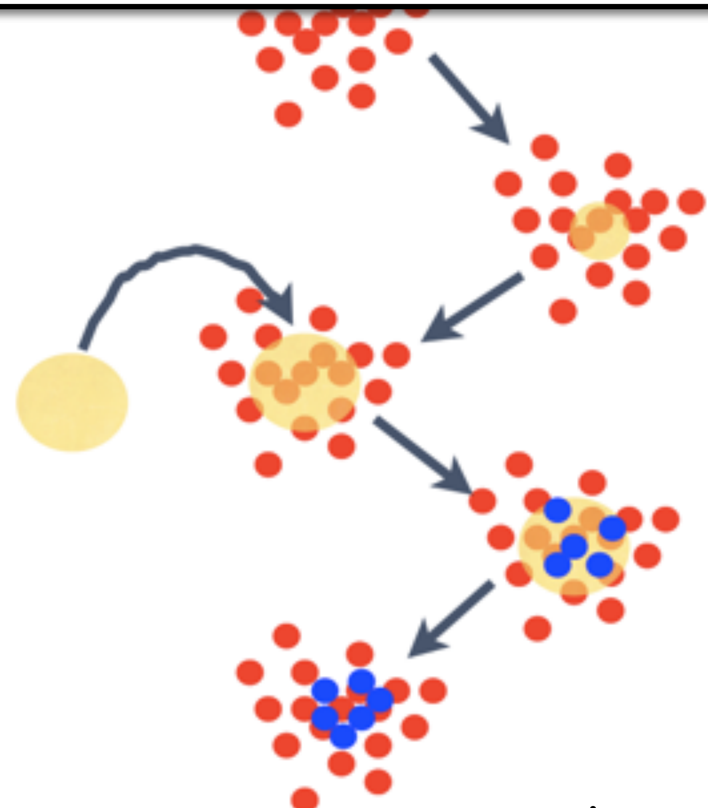
Schiavon et al. 2013



Milone et al. 2016

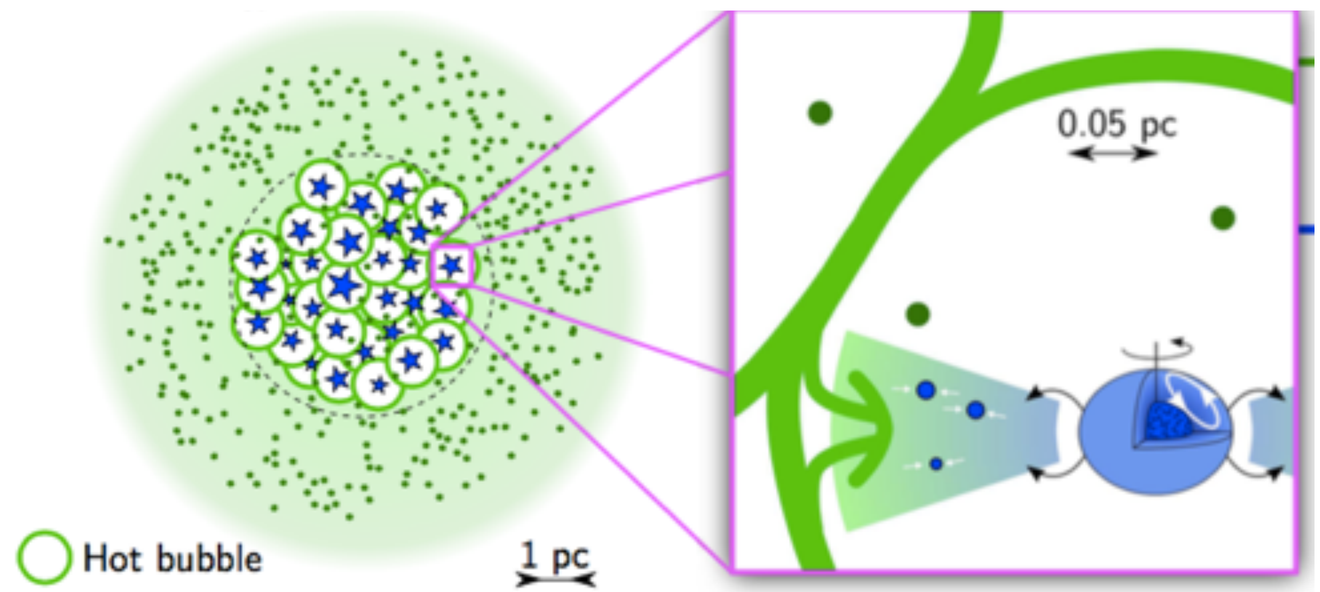
Formation scenarios for MPs

AGB polluters & multiple generations



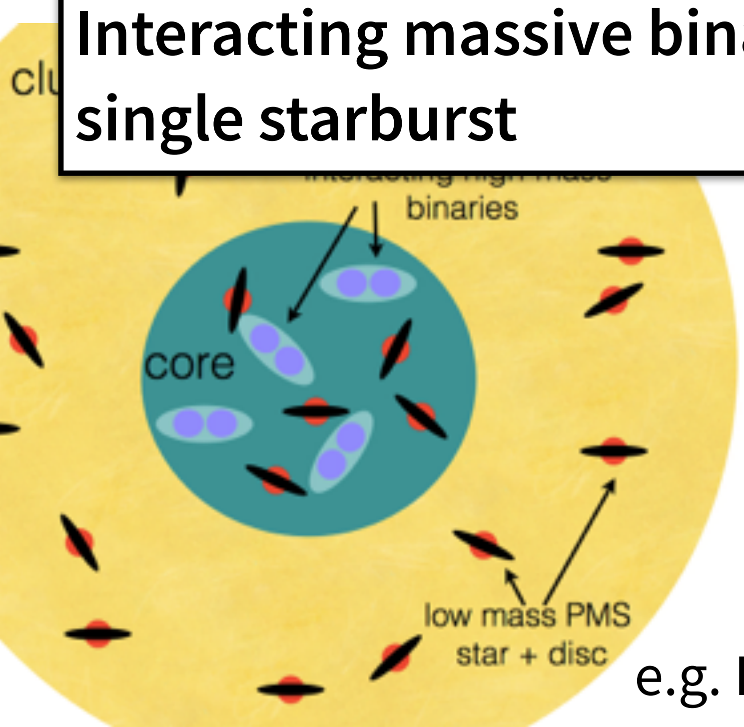
e.g. D'Ercole et al. 2008

Fast-rotating massive stars polluters & multiple generations



e.g. Decressin et al. 2008

Interacting massive binaries polluters single starburst



e.g. Bastian et al. 2013

Supermassive stars polluters

e.g. Denissenkov et al. 2015

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Modelling the long-term kinematic imprints of MPs

Hénault-Brunet et al. 2015

Searching for kinematic imprints: the case of M13

Cordero, Hénault-Brunet et al. 2016

Mass modelling GCs: weighing dark remnants

Hénault-Brunet, Gieles & Gaia Challenge collaboration, in prep.

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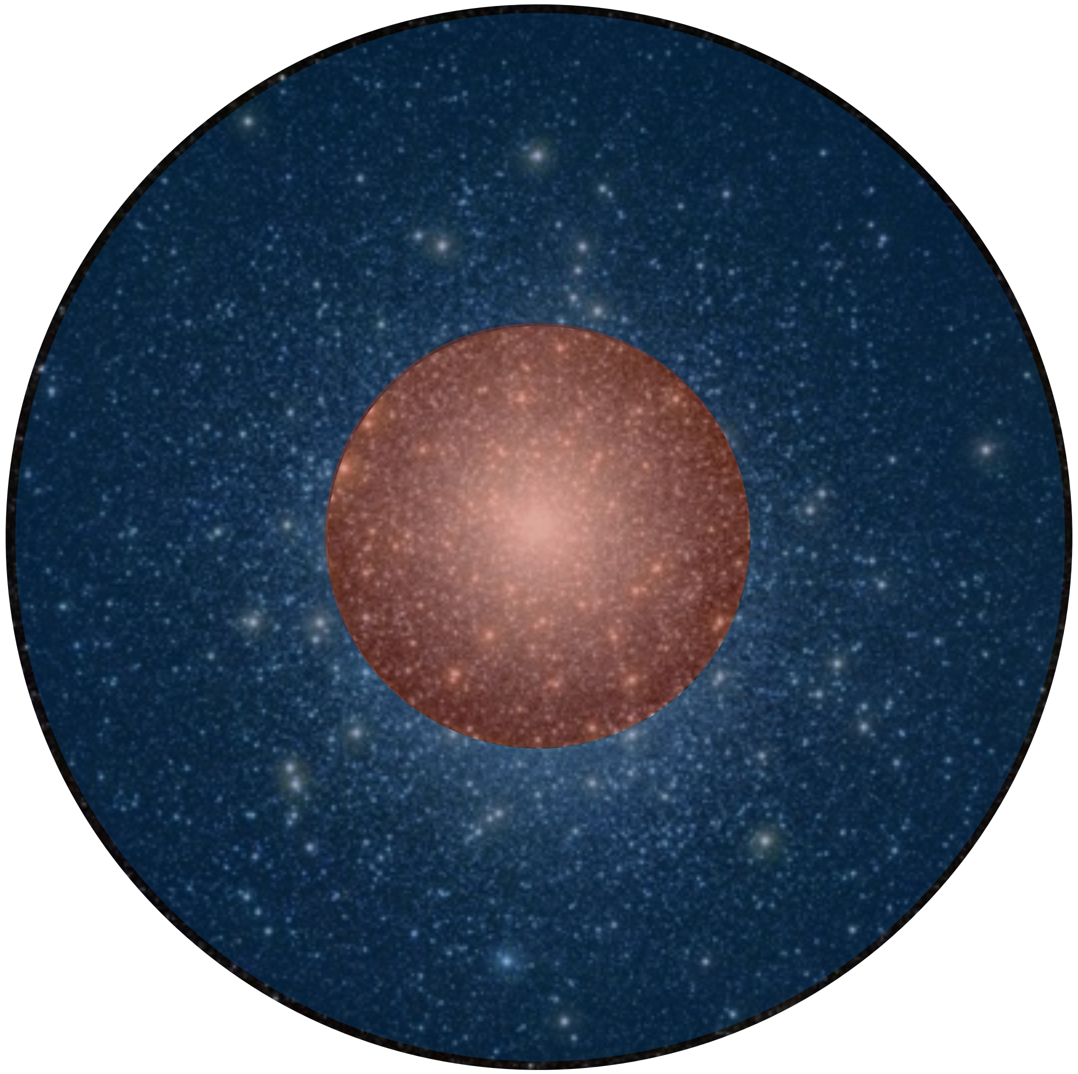
GCs are collisional systems

Two-body relaxation progressively erases memory of the initial conditions…

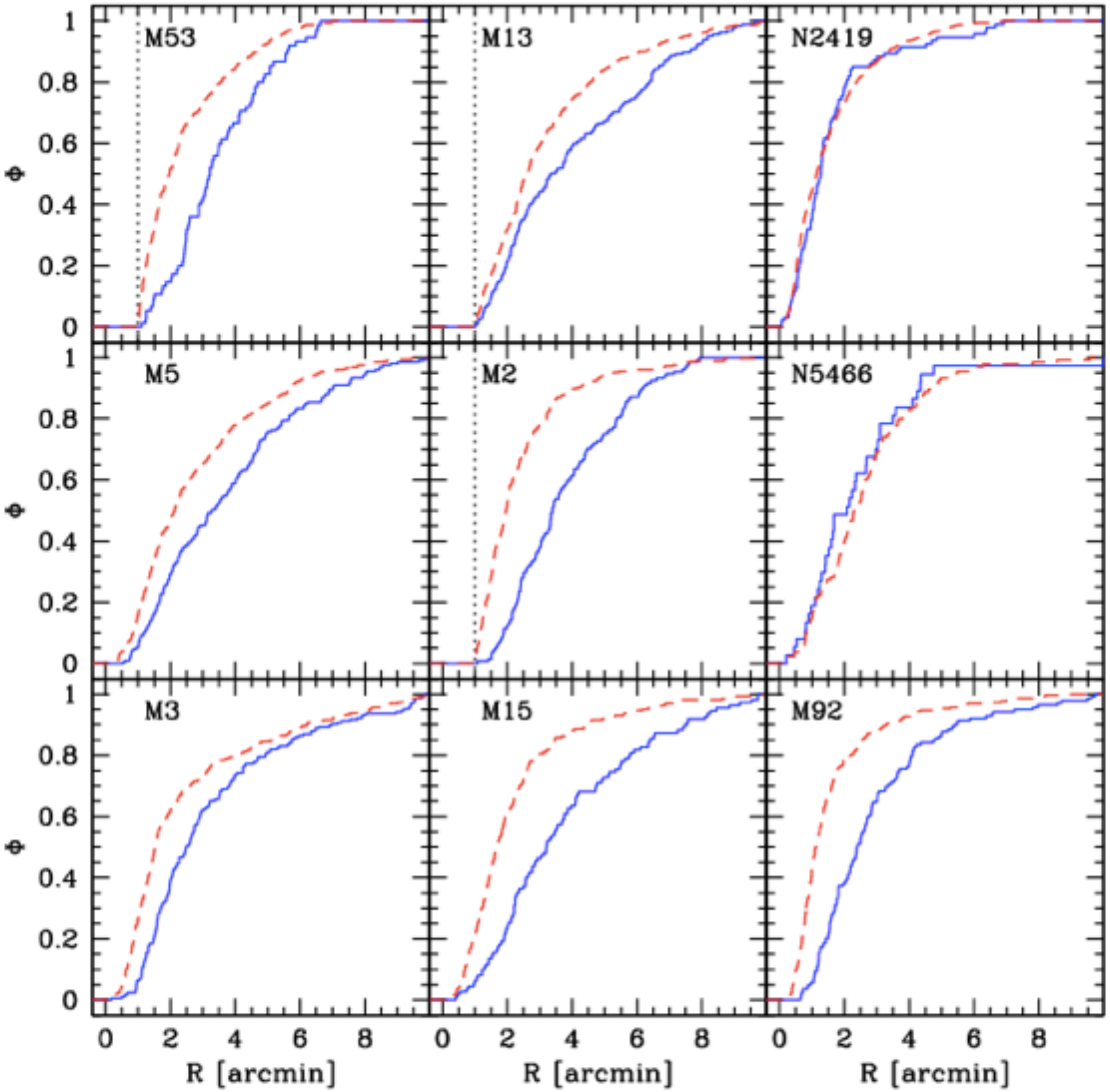
… but less so in the outer parts of clusters

$$t_{\rm rl} \propto \frac{\langle v^2 \rangle^{3/2}}{\langle m \rangle \ \rho}$$

$t_{\rm rl} > t_{\rm rl}$



Spatial distribution of MPs



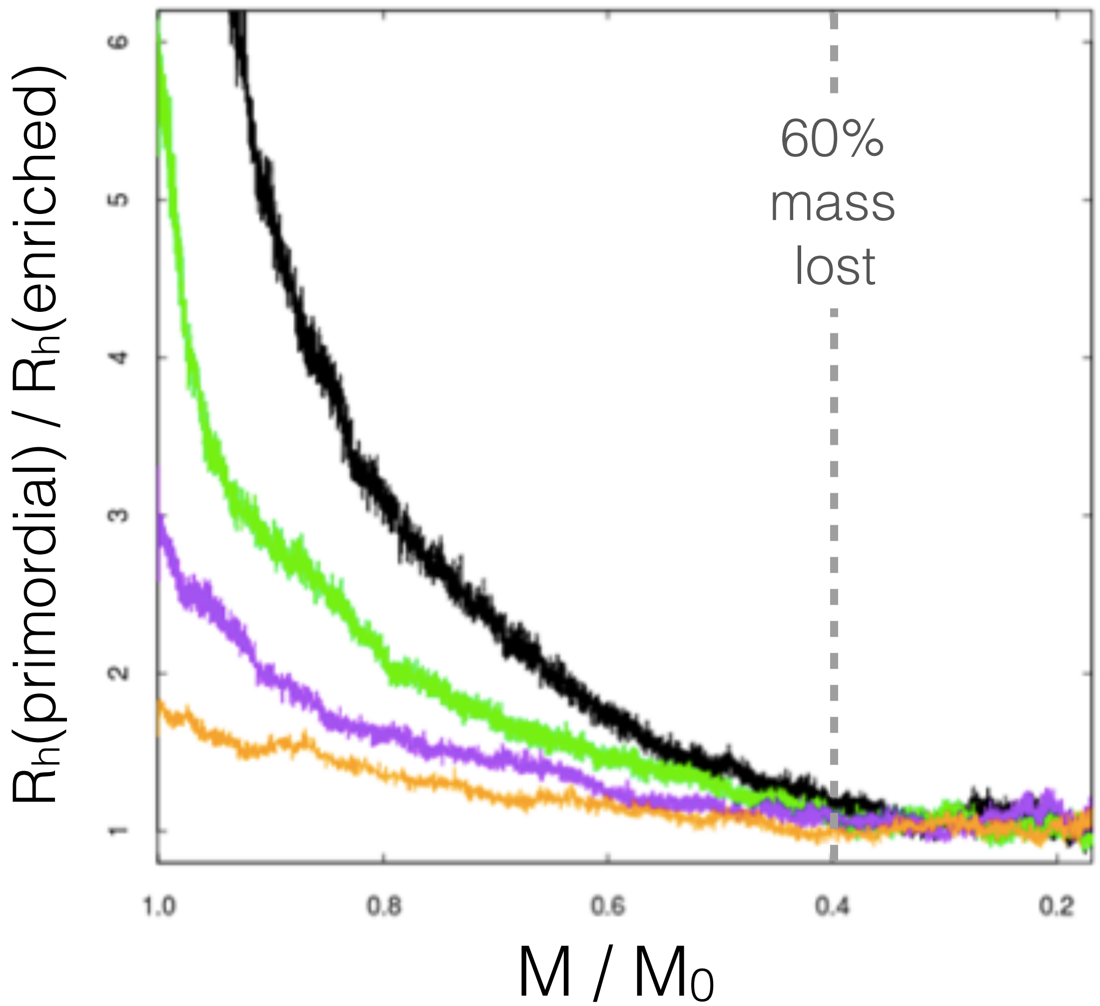
When differences are found, **SG stars are usually more centrally concentrated than FG stars**, as predicted or designed by the various formation scenarios proposed.

e.g. Lardo et al. 2011

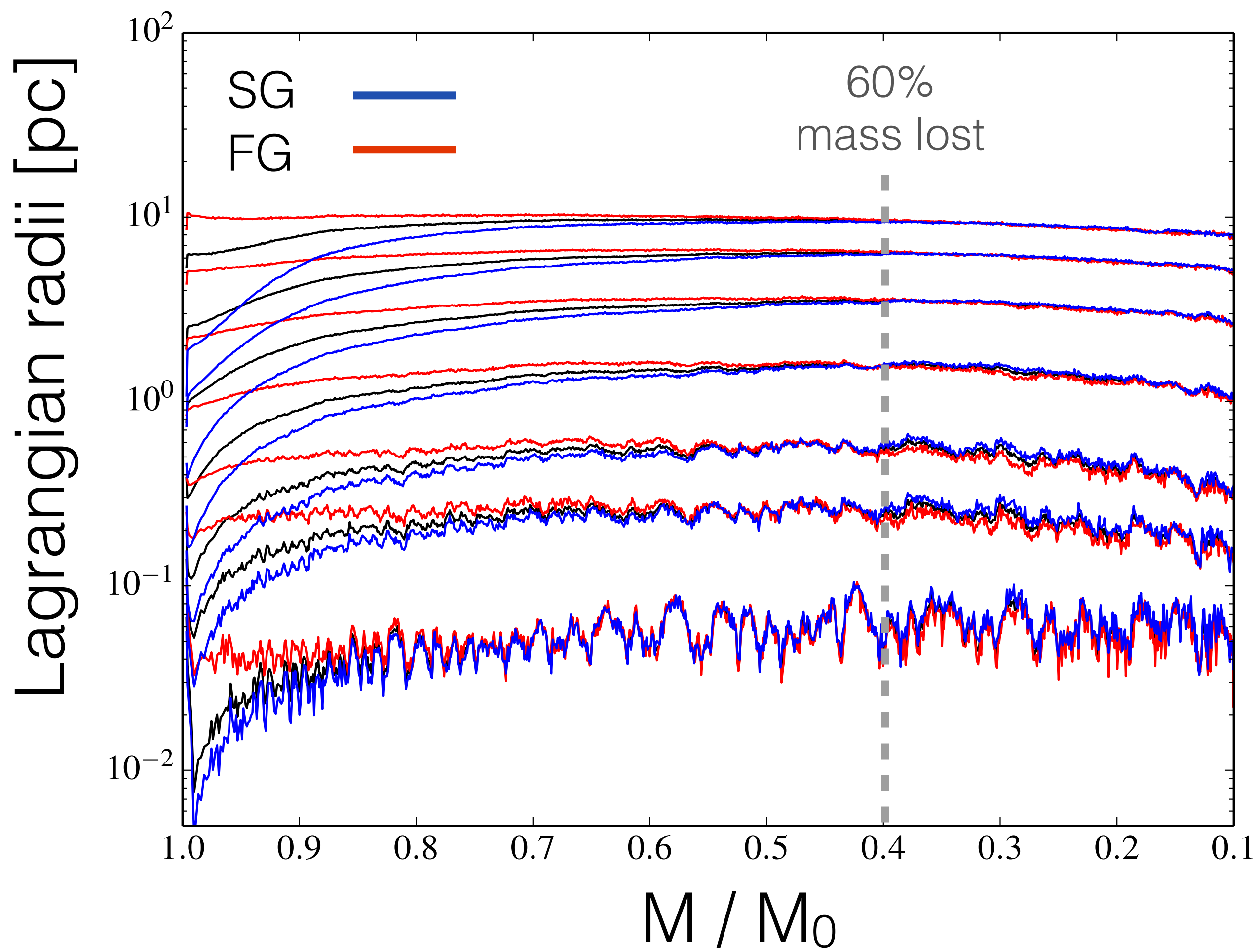
Spatial and kinematic mixing of MPs

ICs: spatially segregated populations, $N_{2G}/N_{1G} = 1$

Complete spatial and kinematic mixing when 60-70% of mass lost due to two-body relaxation (70-80% when including stellar evolution mass lost)



Vesperini et al. 2013



Hénault-Brunet et al. 2015

see also Miholics et al. 2015

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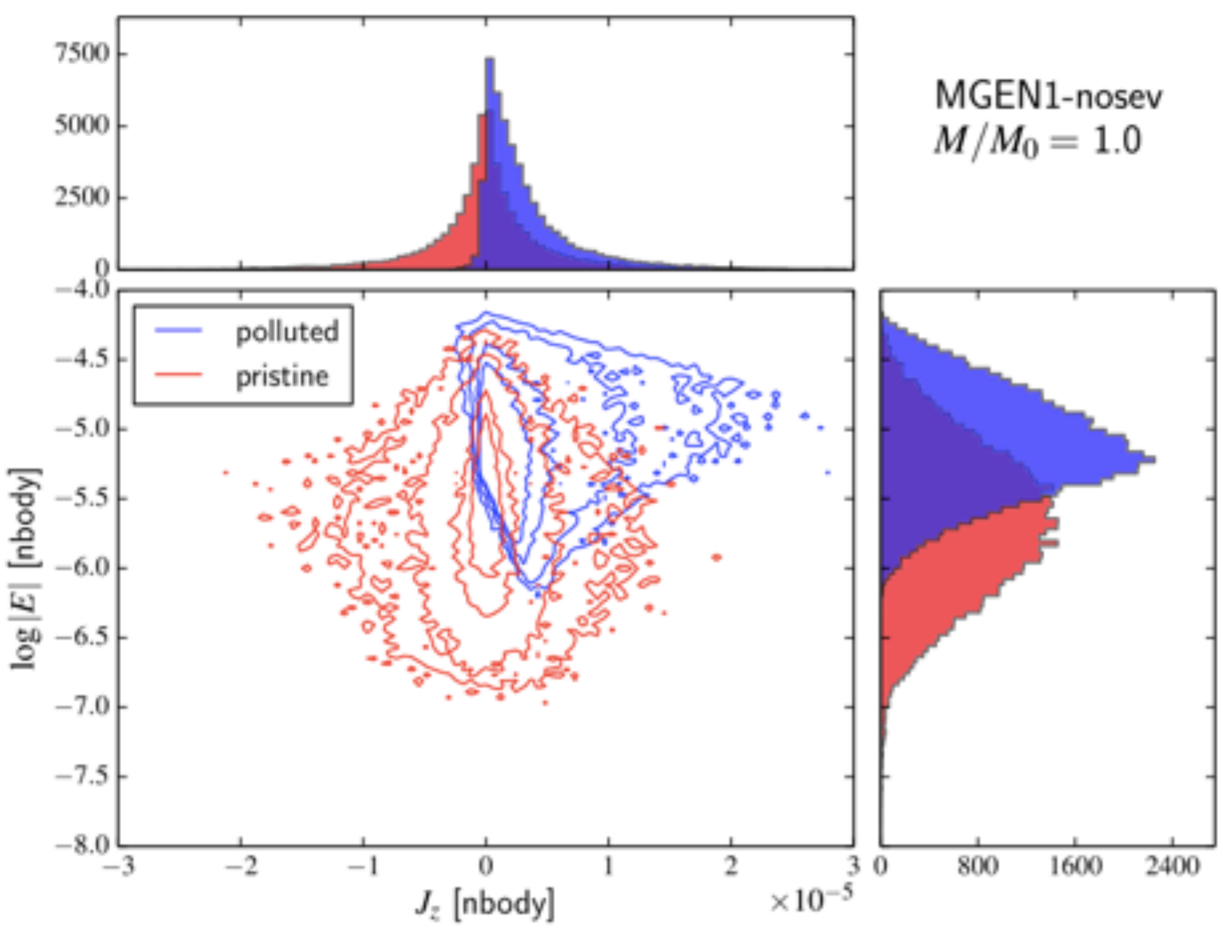
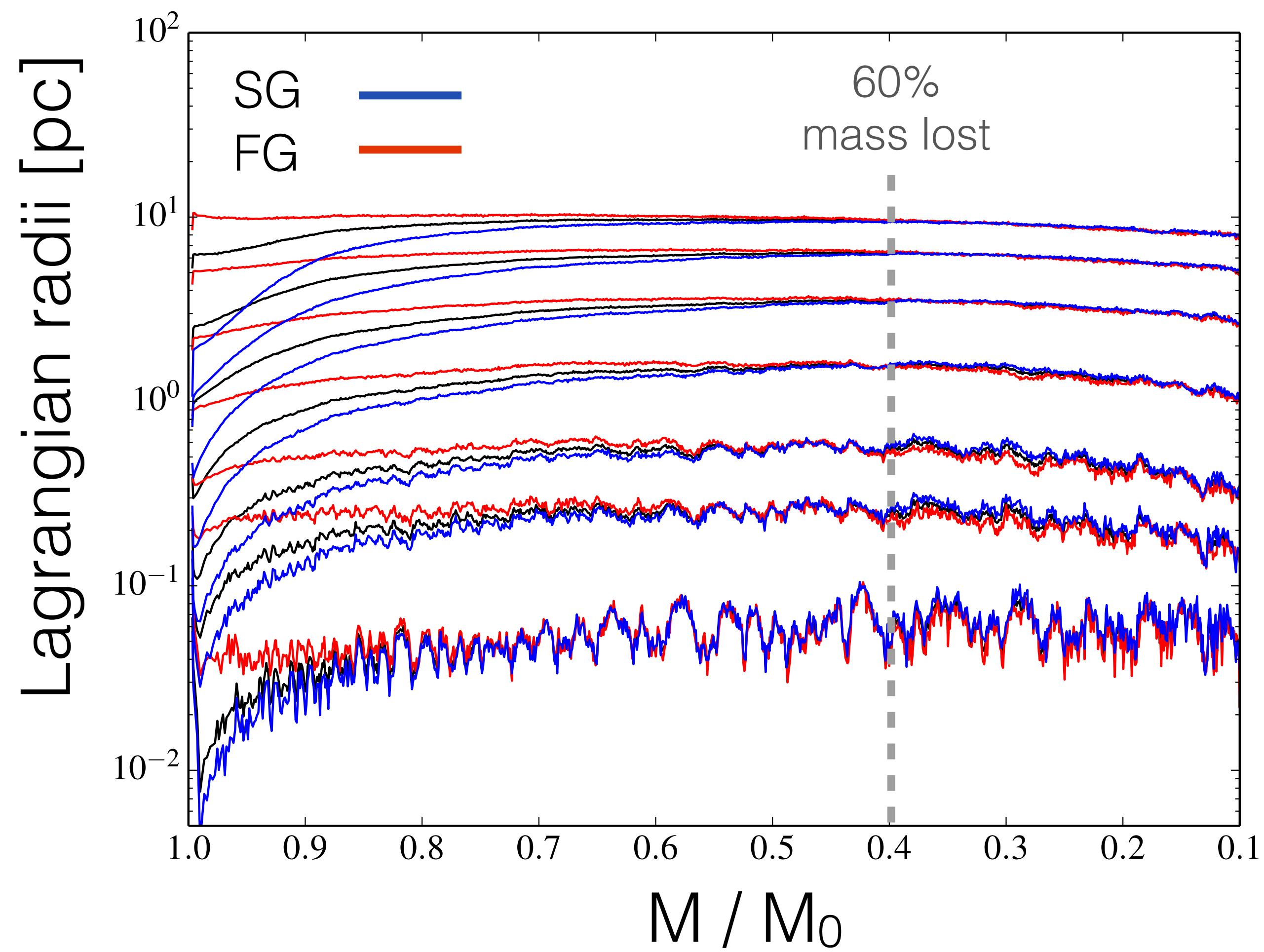


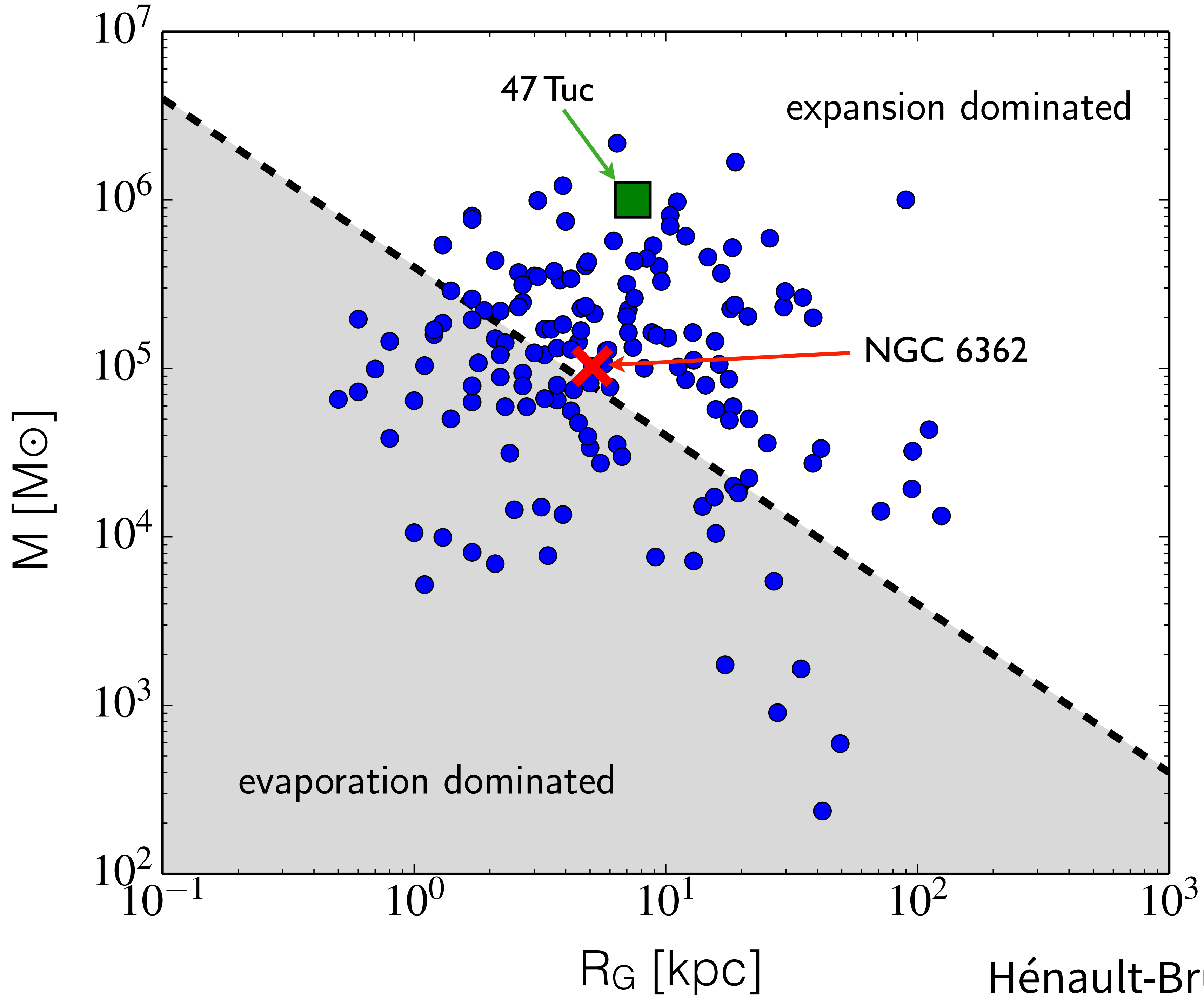


Hénault-Brunet et al. 2015

see also Miholics et al. 2015

Spatial and kinematic mixing of MPs

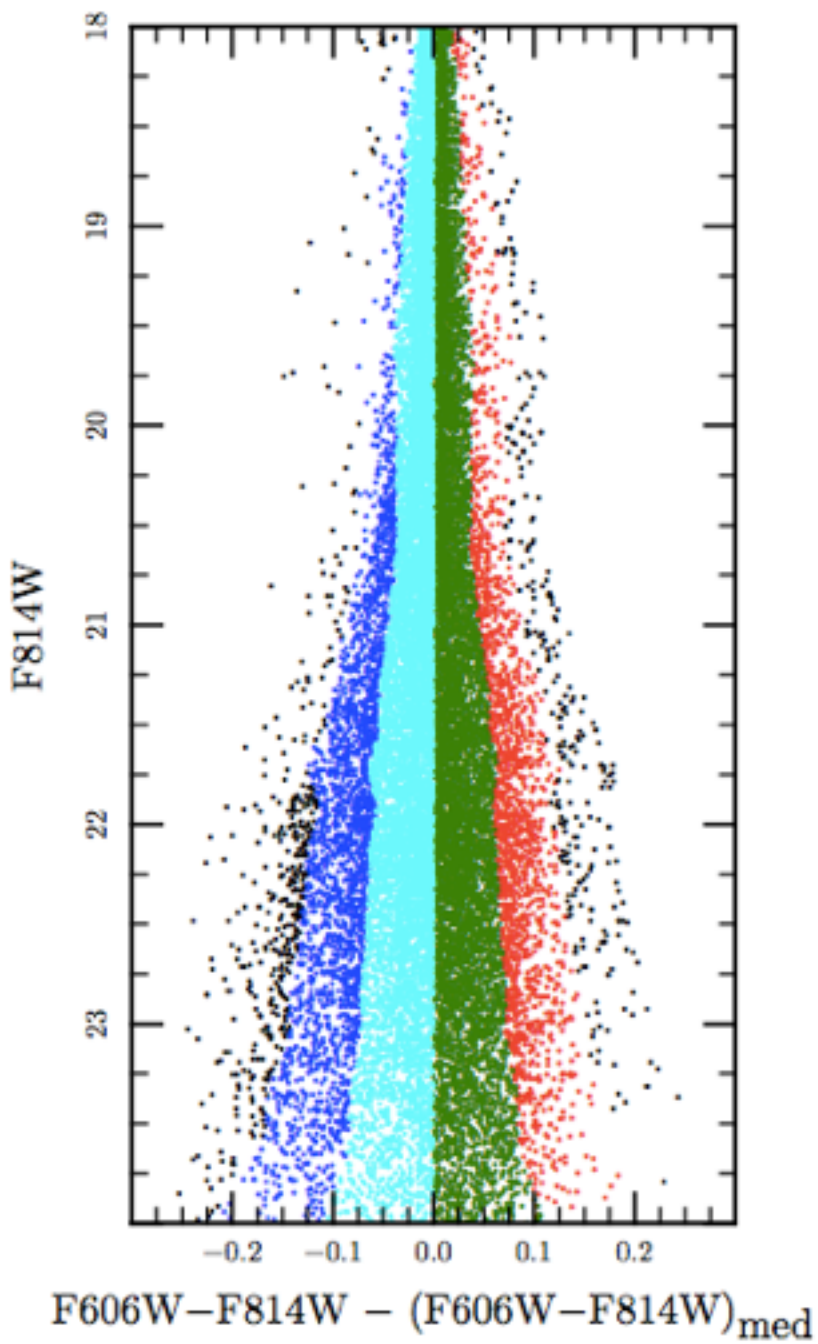
Some memory of ICs should be preserved in outer parts of many GCs



Hénault-Brunet et al. 2015

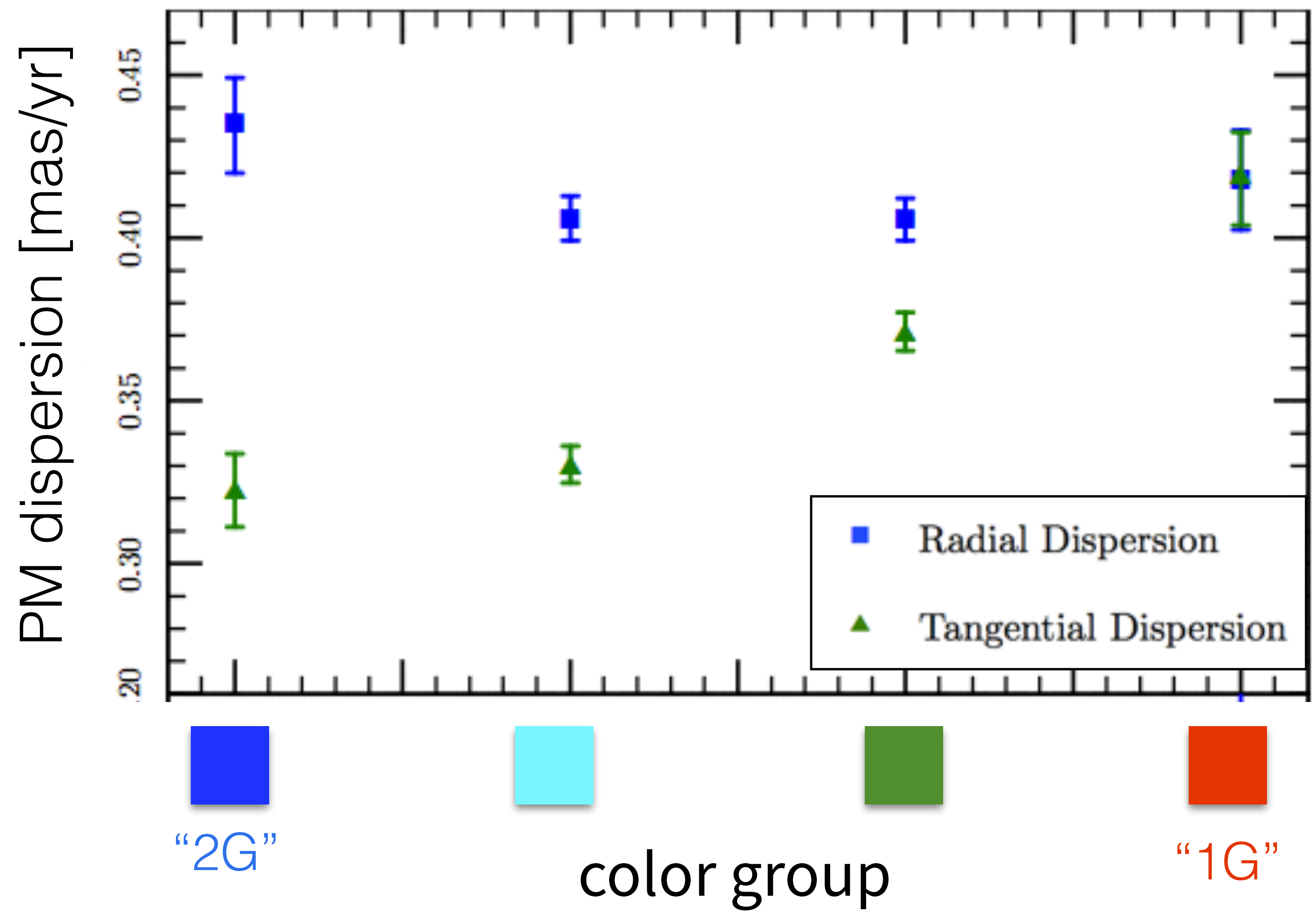
see also Gieles et al. 2011

Kinematic differences: anisotropy



47 Tuc - HST proper motions near R ~2 r_h

SG stars -> more radially anisotropic velocity distribution

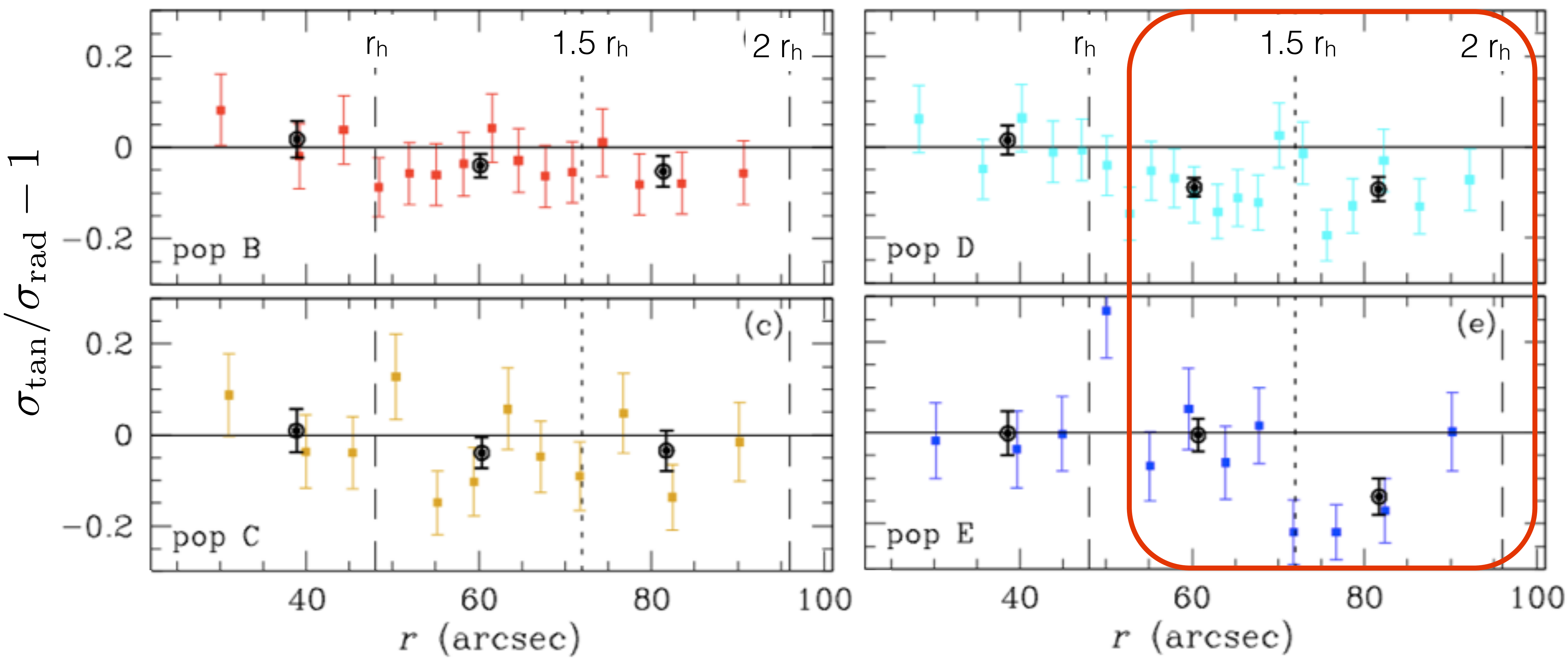


Richer et al. 2013

Kinematic differences: anisotropy

NGC 2808 - HST proper motions

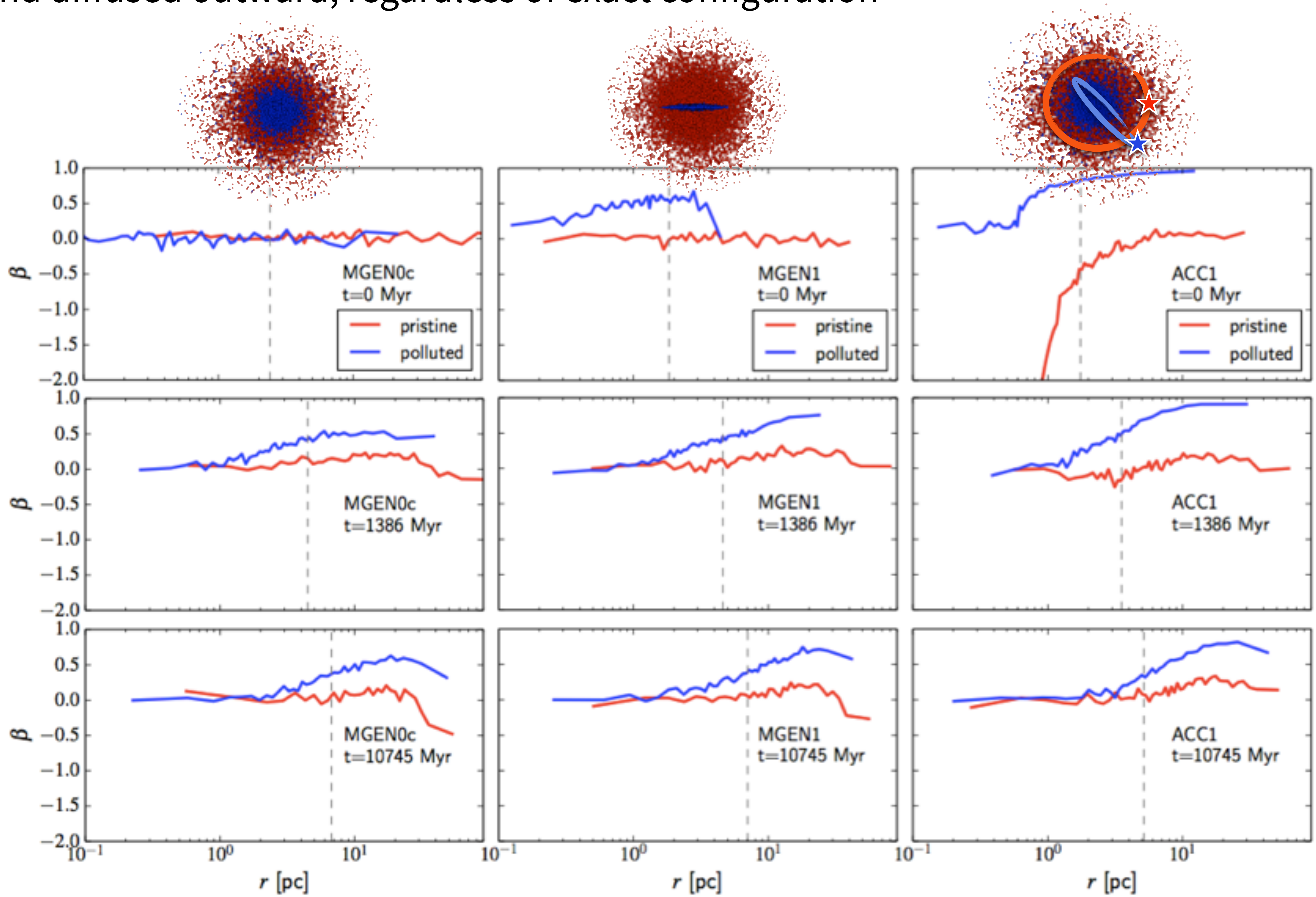
SG stars -> more radially anisotropic velocity distribution beyond R ~ r_h



Bellini et al. 2015

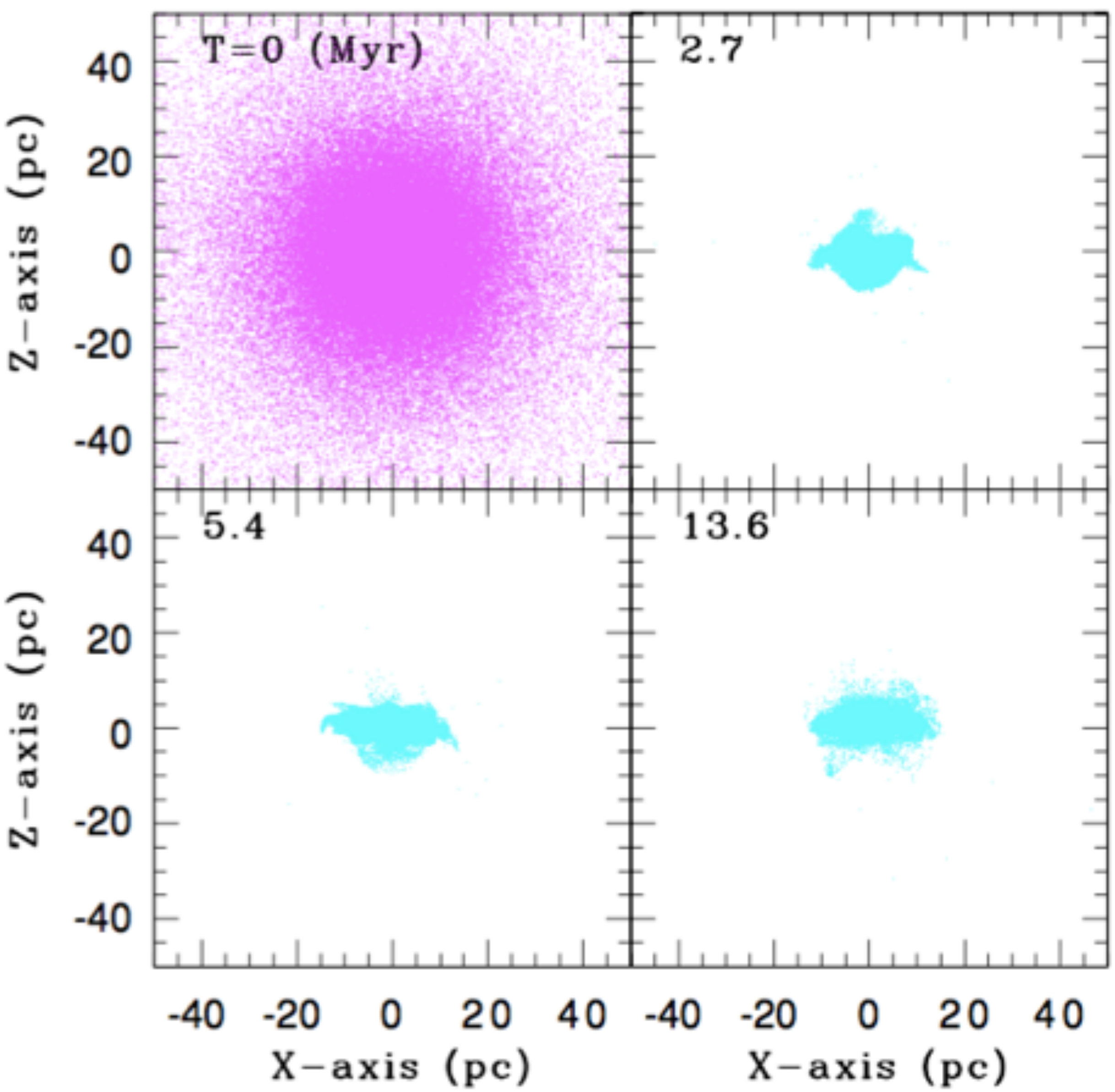
Kinematic differences: anisotropy

More radially biased velocity anisotropy expected if SG started more centrally concentrated and diffused outward, regardless of exact configuration

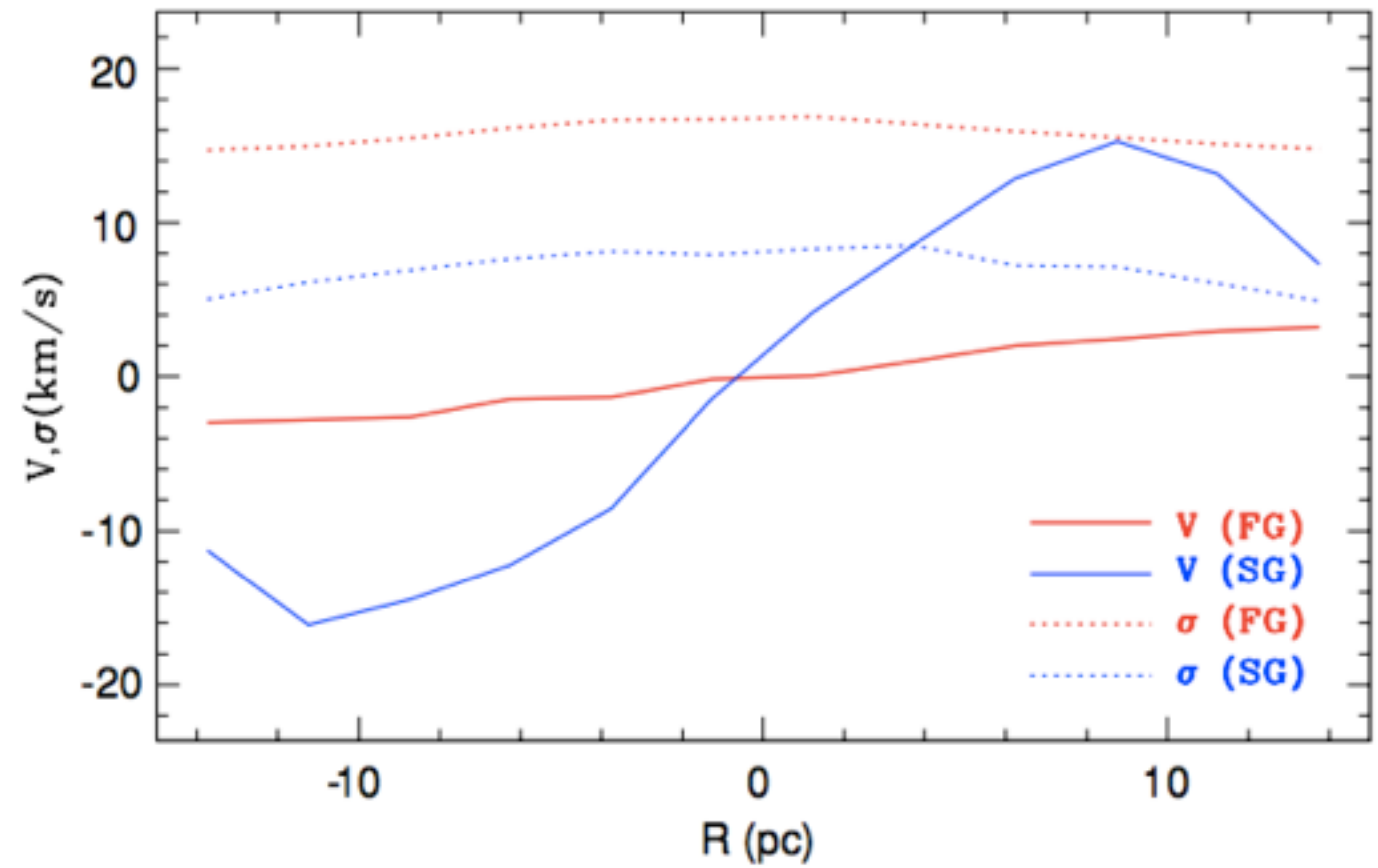


Hénault-Brunet et al. 2015

Kinematic differences: rotation



Dissipative accretion of AGB ejecta in cluster core could produce flattened and rotating SG

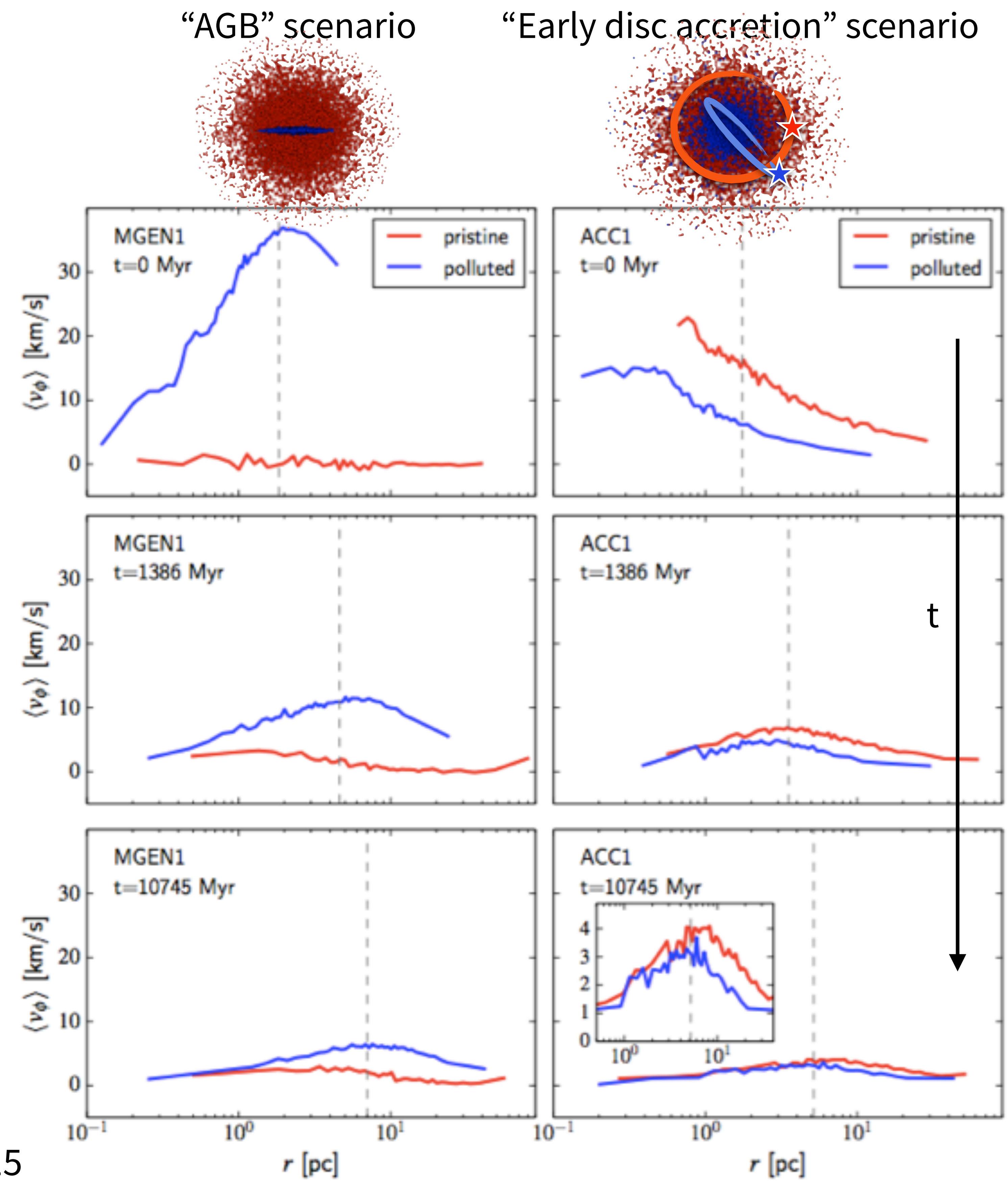


Bekki 2010, 2011

Kinematic differences: rotation

Differences in rotation amplitude a potential way to distinguish between scenarios and probe initial orbital configuration of subpopulations

Hints in some GCs studied by Bellazzini et al. (2012), but they could not reach definitive conclusions due to small sample sizes



Hénault-Brunet et al. 2015

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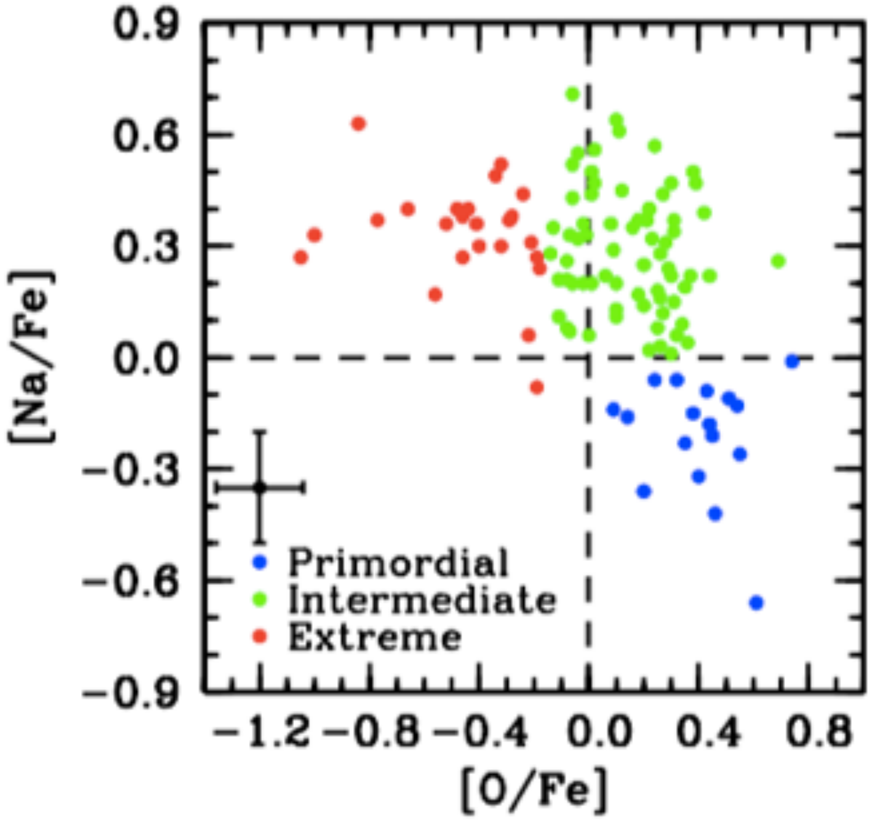
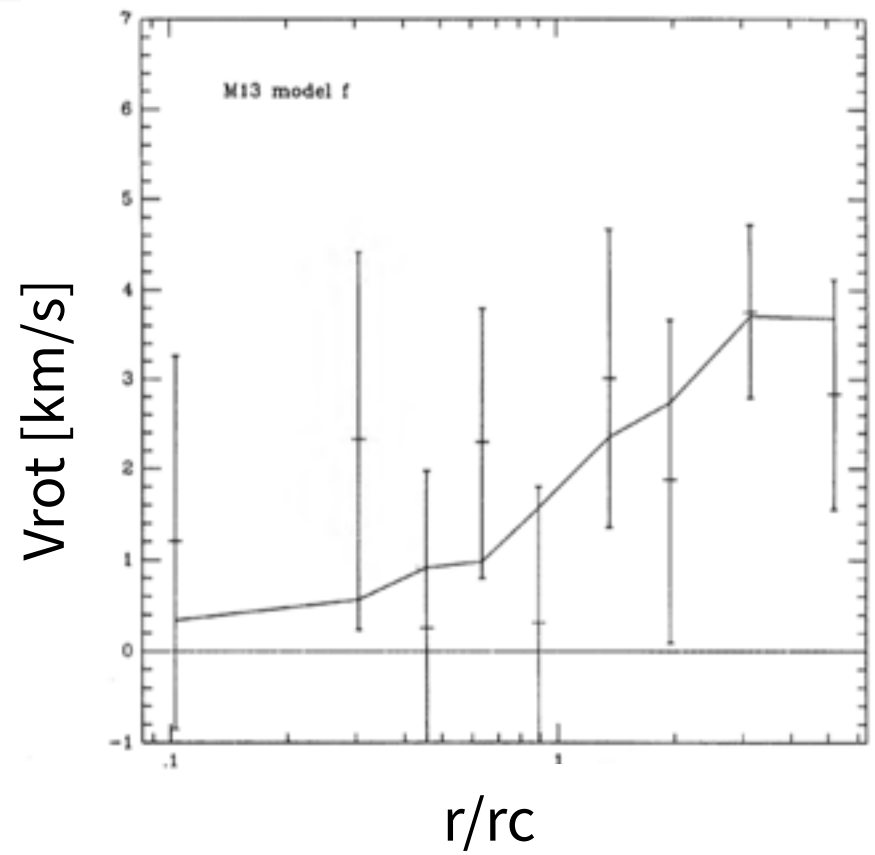
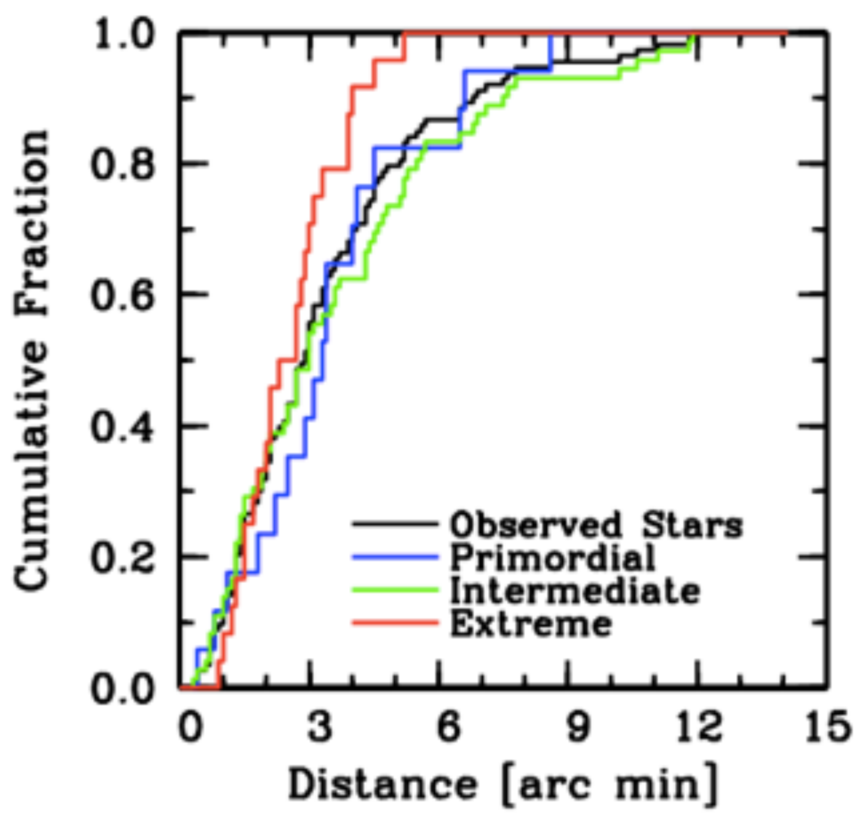
Hénault-Brunet, Gieles & Gaia Challenge collaboration, in prep.

Kinematics of MPs: M13 - an ideal candidate

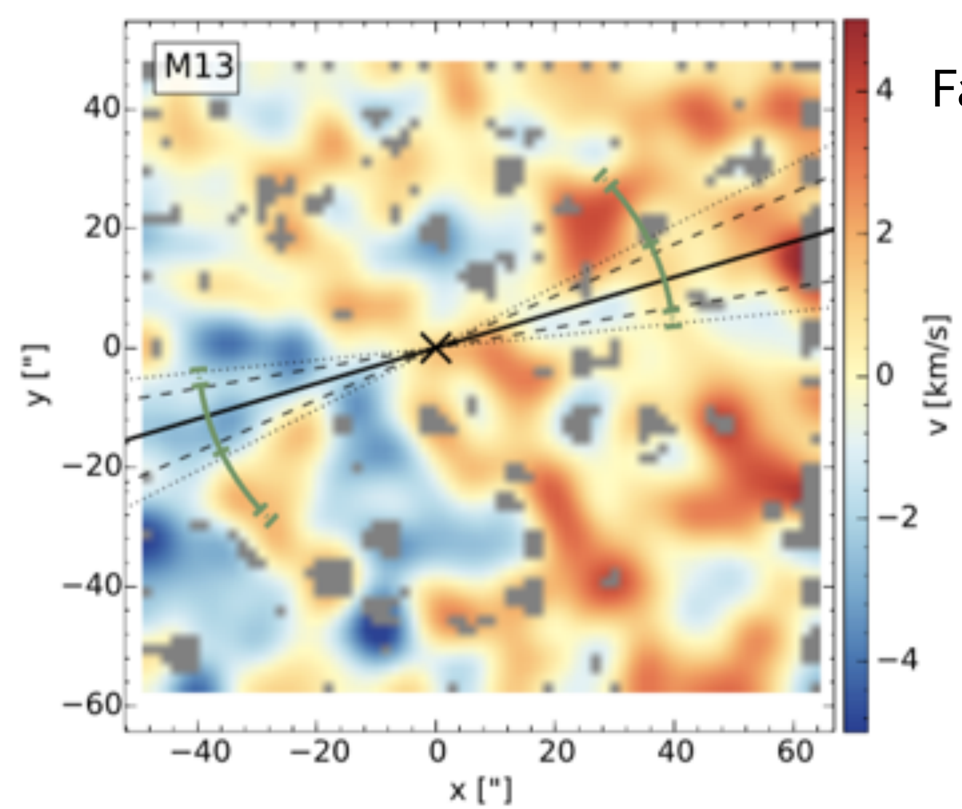




Lupton et al. 1987



Johnson & Pilachowski 2012



Fabricius et al. 2014

Kinematics of MPs: Bayesian analysis

l.o.s. dispersion profile: $$\sigma^2(R) = \frac{\sigma_0^2}{\sqrt{1 + R^2/a^2}}$$ Plummer (1911)

Rotation curve: $$V_{\rm rot} \sin i(X_{\rm PA_0}) = \frac{2\,A_{\rm rot}}{R_{\rm peak}} \frac{X_{\rm PA_0}}{1 + (X_{\rm PA_0}/R_{\rm peak})^2}$$

c.f. Lagoute & Longaretti (1996)
Varri & Bertin (2012)

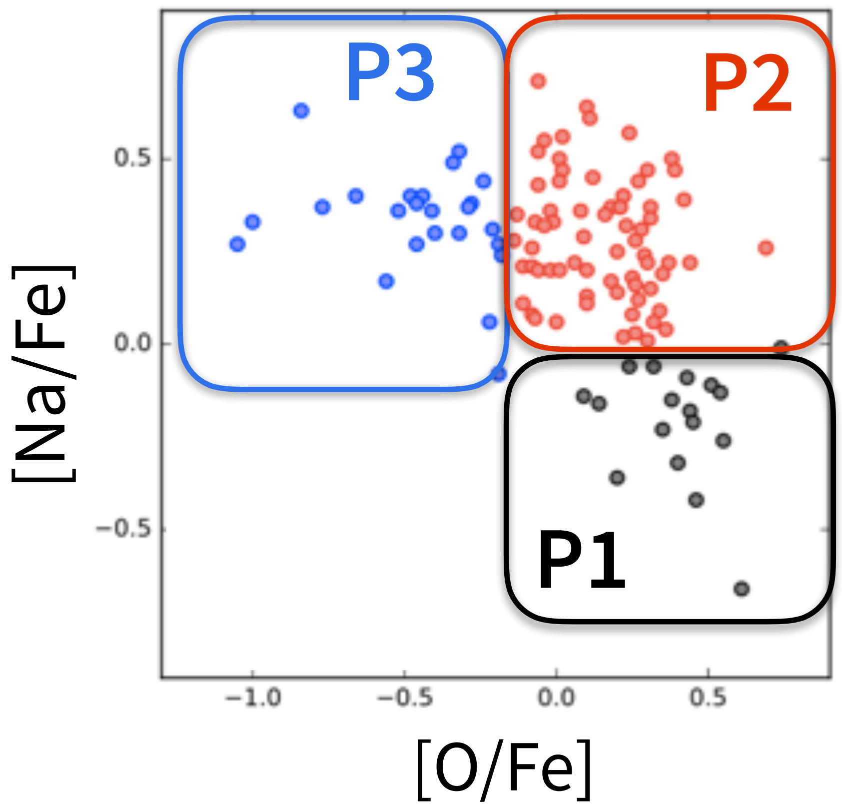
Likelihood function based on purely kinematic model with six free parameters (***v_0*, *$A_{\rm rot}$*, *$R_{\rm peak}$*, PA$_0$, σ$_0$, *a*):**

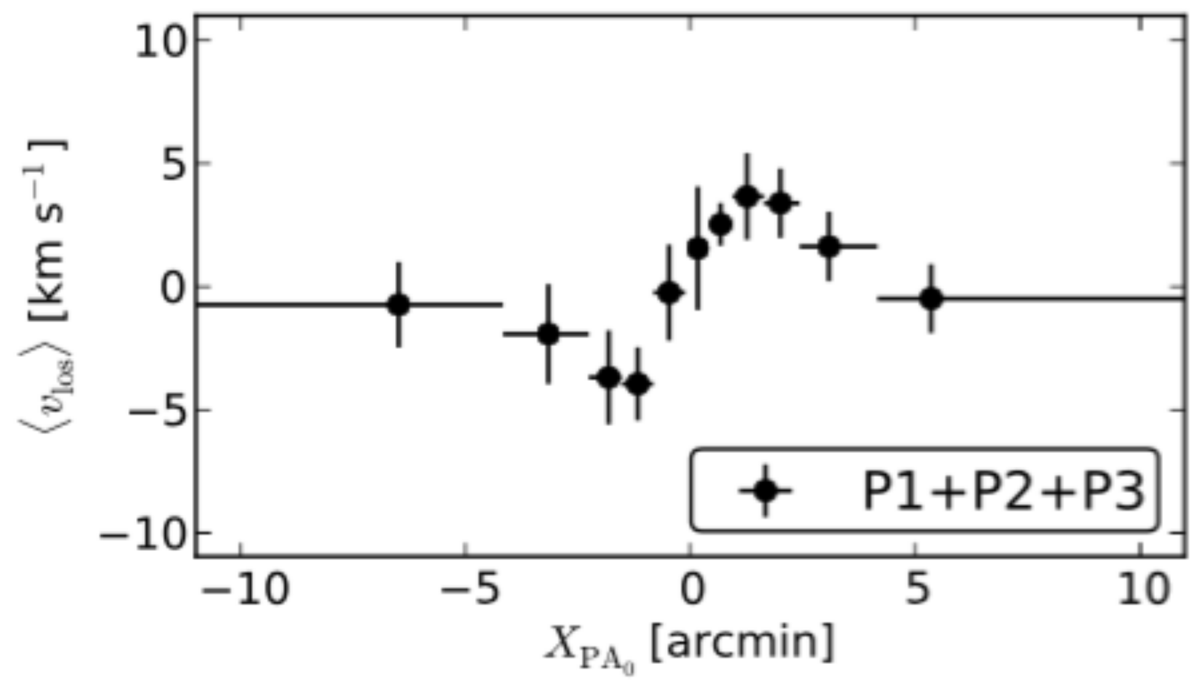
$$\Lambda_i(\boldsymbol{x}_i|\Theta) = \frac{1}{\sqrt{2\,\pi\,(\sigma_{v,i}^2 + \sigma^2)}} \exp\left[\frac{-(v_i - v_0 - V_{\rm rot}\sin i)^2}{2\,(\sigma_{v,i}^2 + \sigma^2)}\right]$$

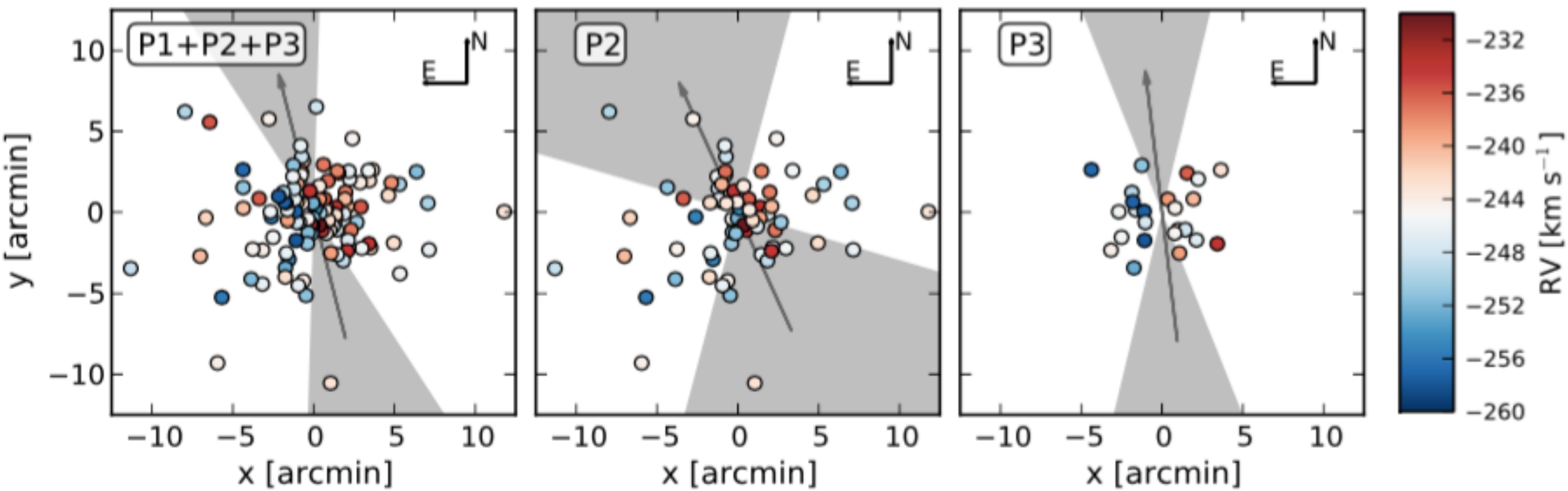
Cordero, Hénault-Brunet et al. 2016

Kinematics of MPs in M13: results

Cordero, Hénault-Brunet et al. 2016

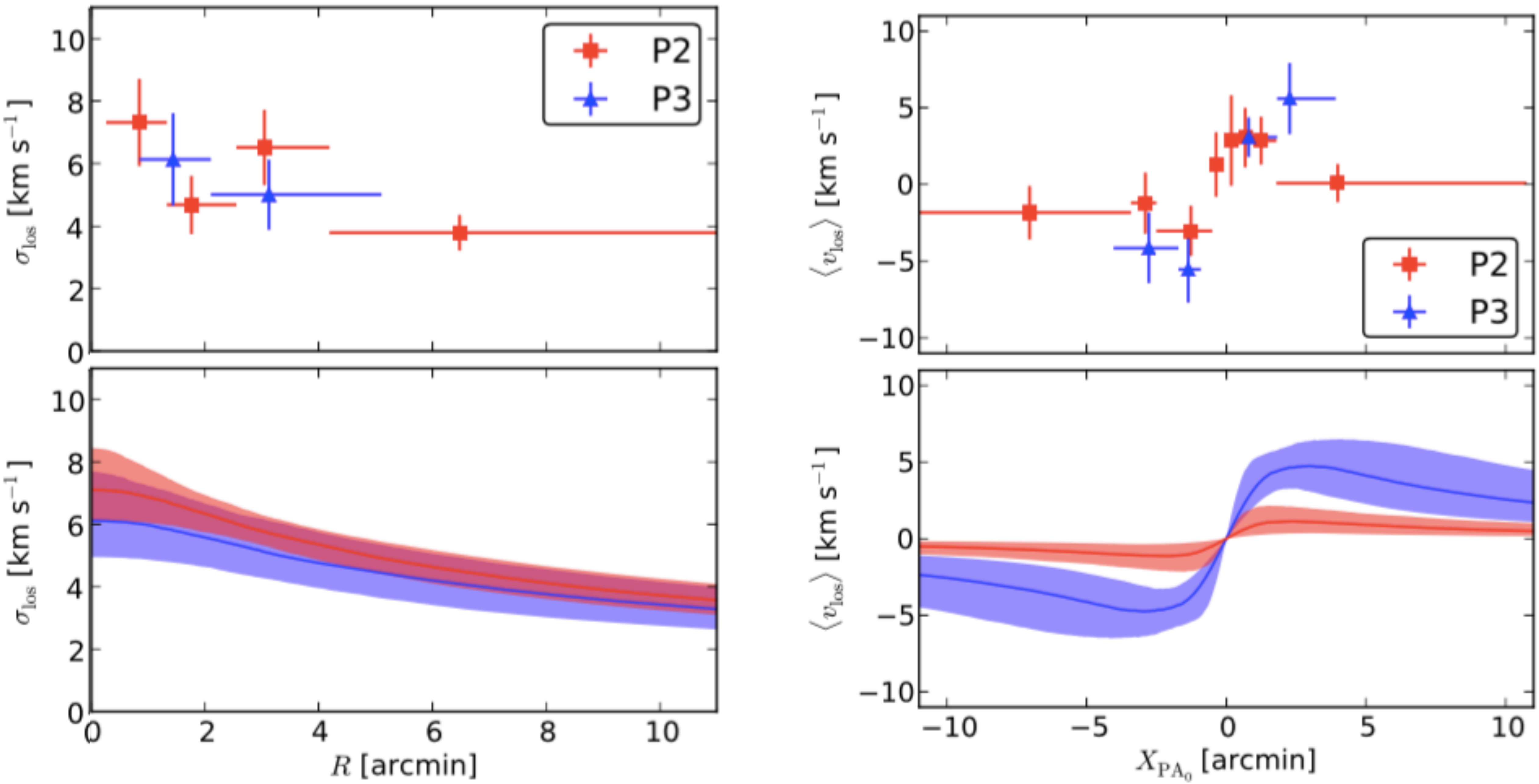






Kinematics of MPs in M13: results

Faster rotation for the "extreme" subpopulation



Cordero, Hénault-Brunet et al. 2016

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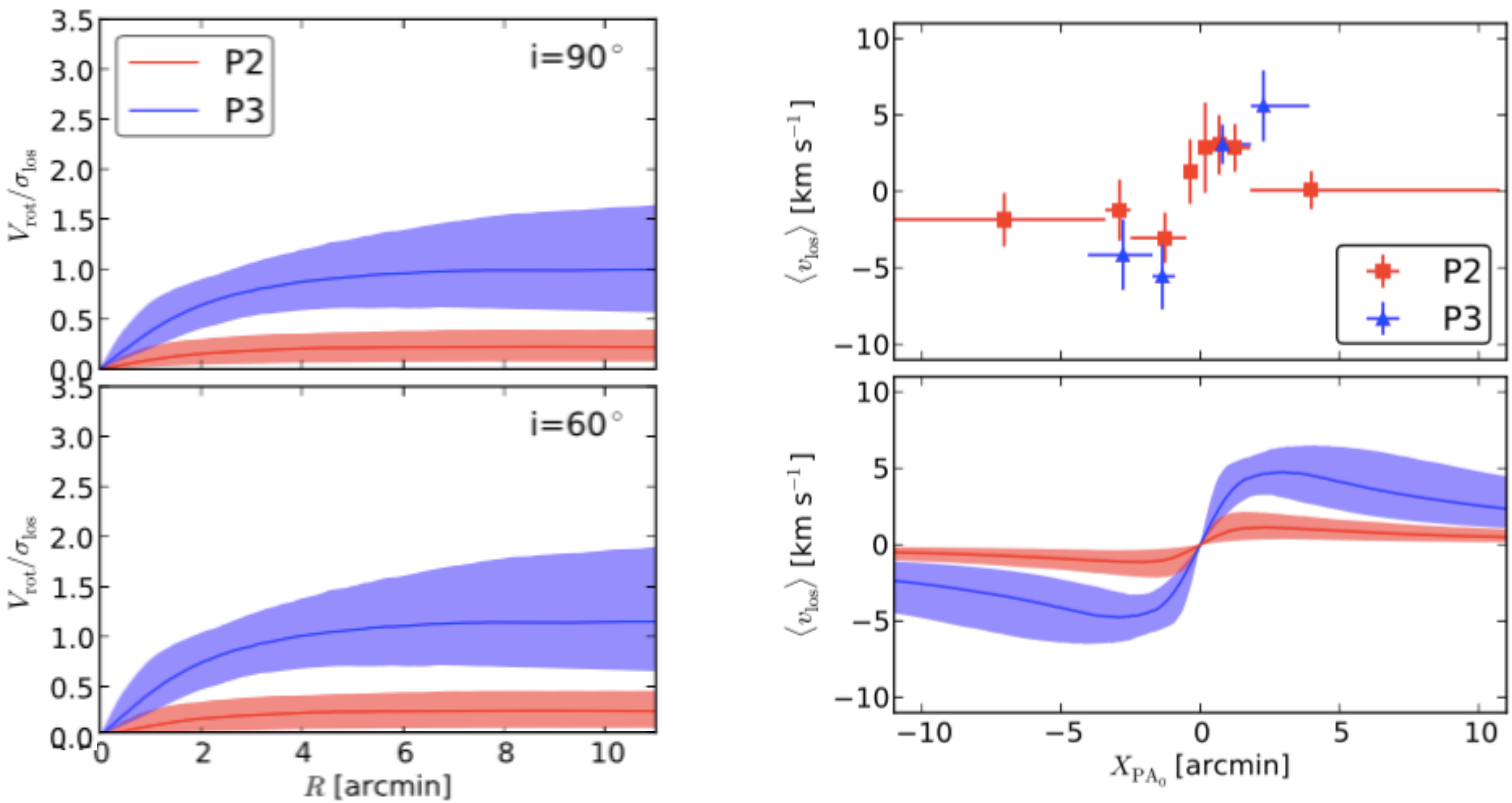
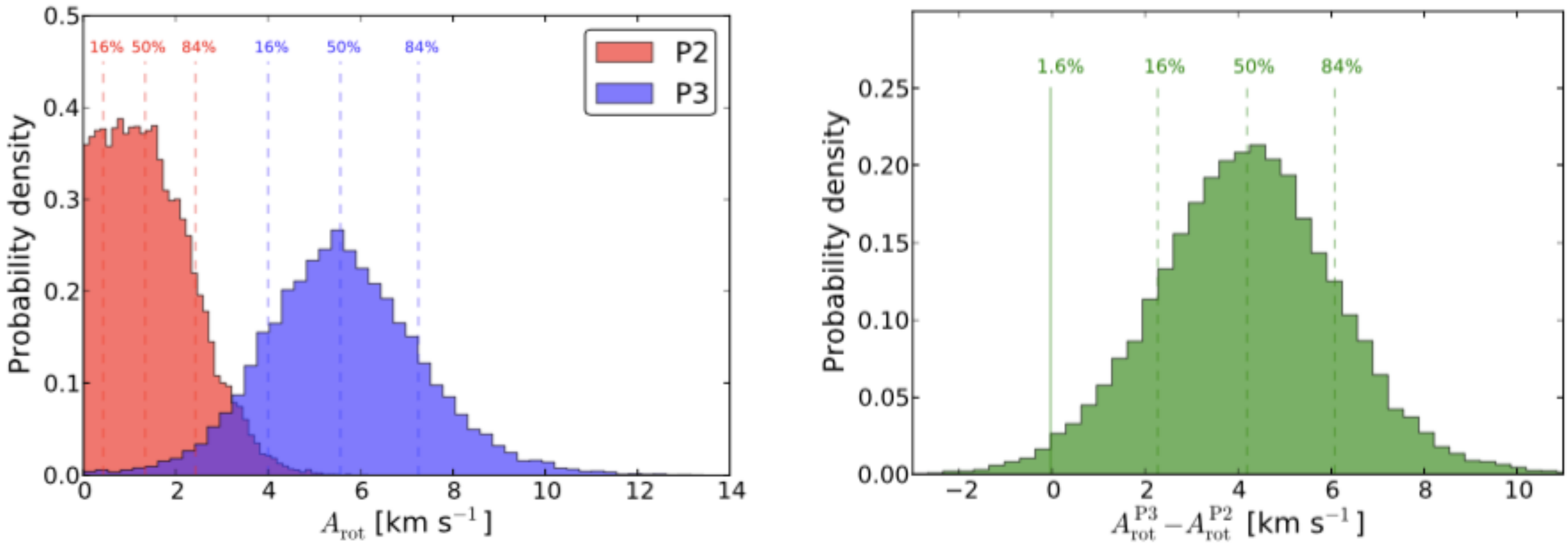


Cordero, Hénault-Brunet et al. 2016

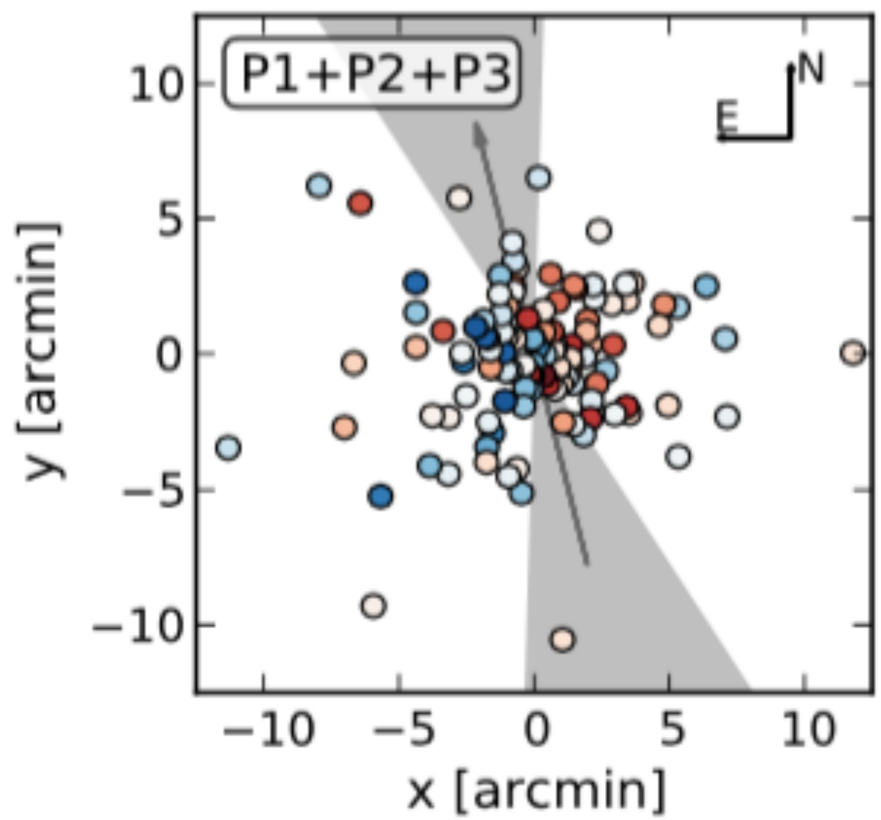
Kinematics of MPs in M13: results

Difference in rotational amplitude of ~4 km/s between
“extreme” and “intermediate” populations

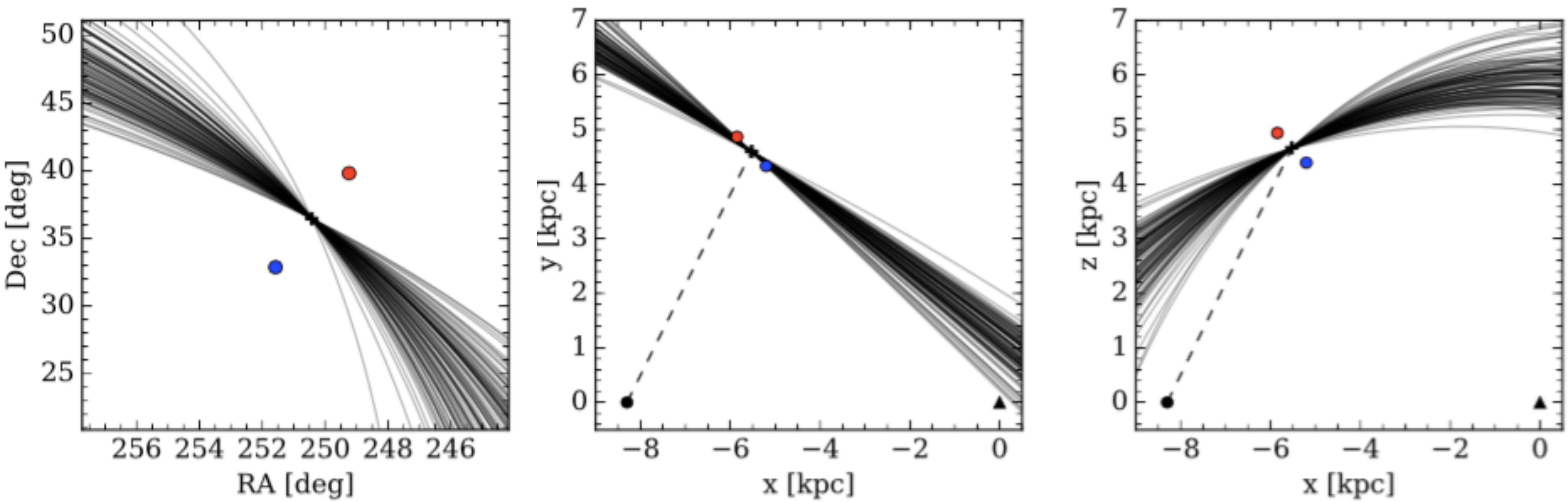


Cordero, Hénault-Brunet et al. 2016

Possible sources of contamination to rotation signal



Velocity gradient not from geometrical projection effect due to proper motion of the cluster, nor a spurious feature from alignment of tidal tails/Lagrange points with the line of sight.

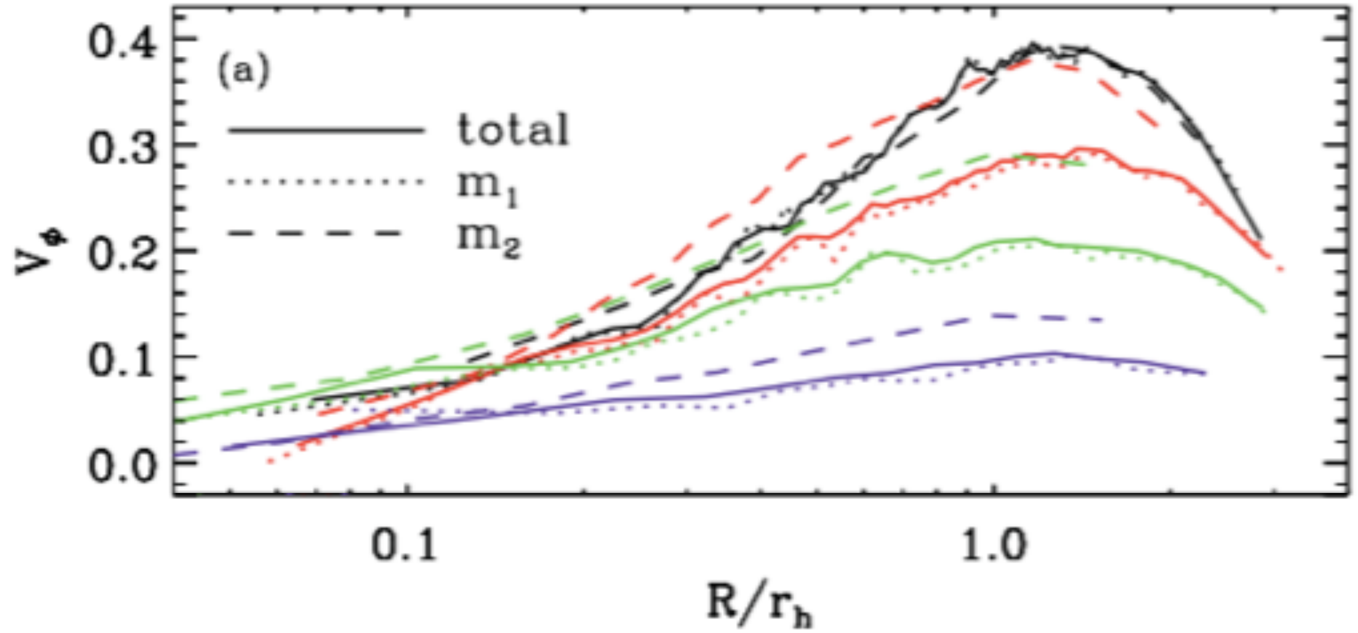


Cordero, Hénault-Brunet et al. 2016

Faster rotation of “extreme” pop.: interpretation?

Dynamical evolution effect?

Hong et al. 2013



Unlikely.

“extreme” population He-rich

↓

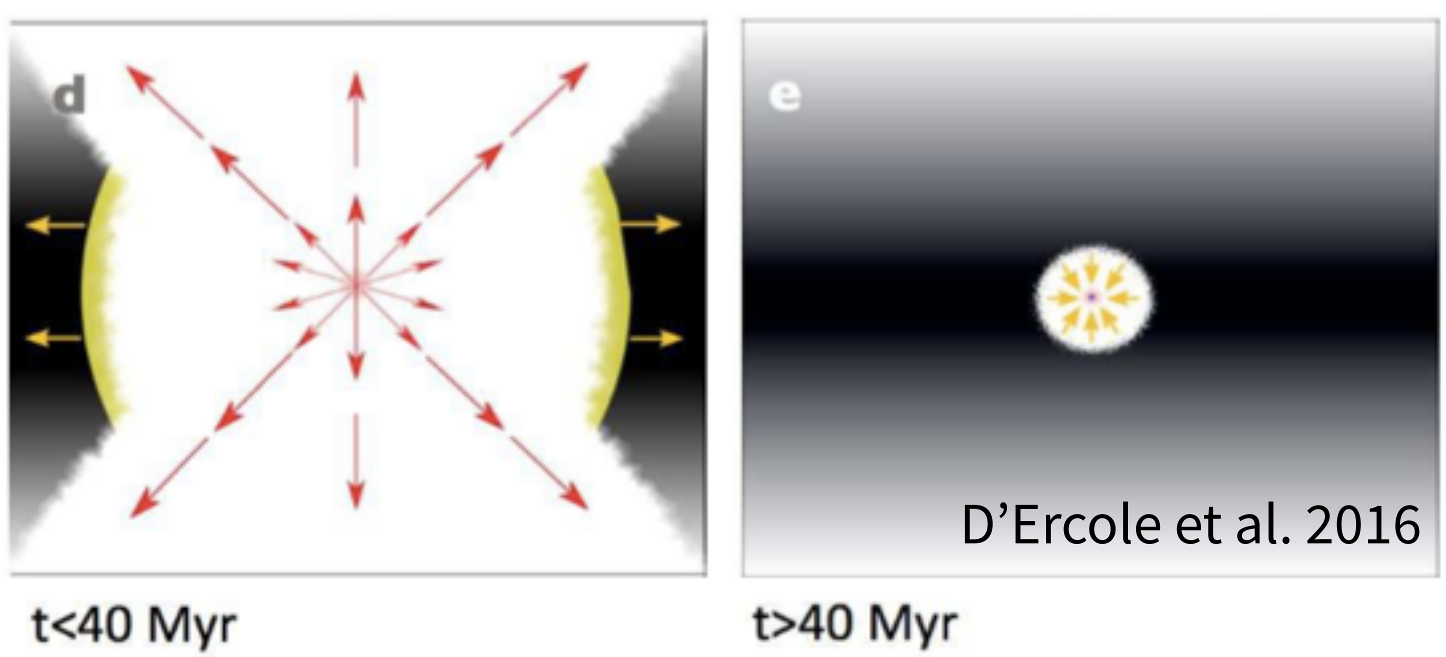
stars less massive at a given age

More likely originates from the formation of this subpopulation

Then it invalidates the “early disc accretion” scenario

Stellar collisions?

Dissipative collapse?



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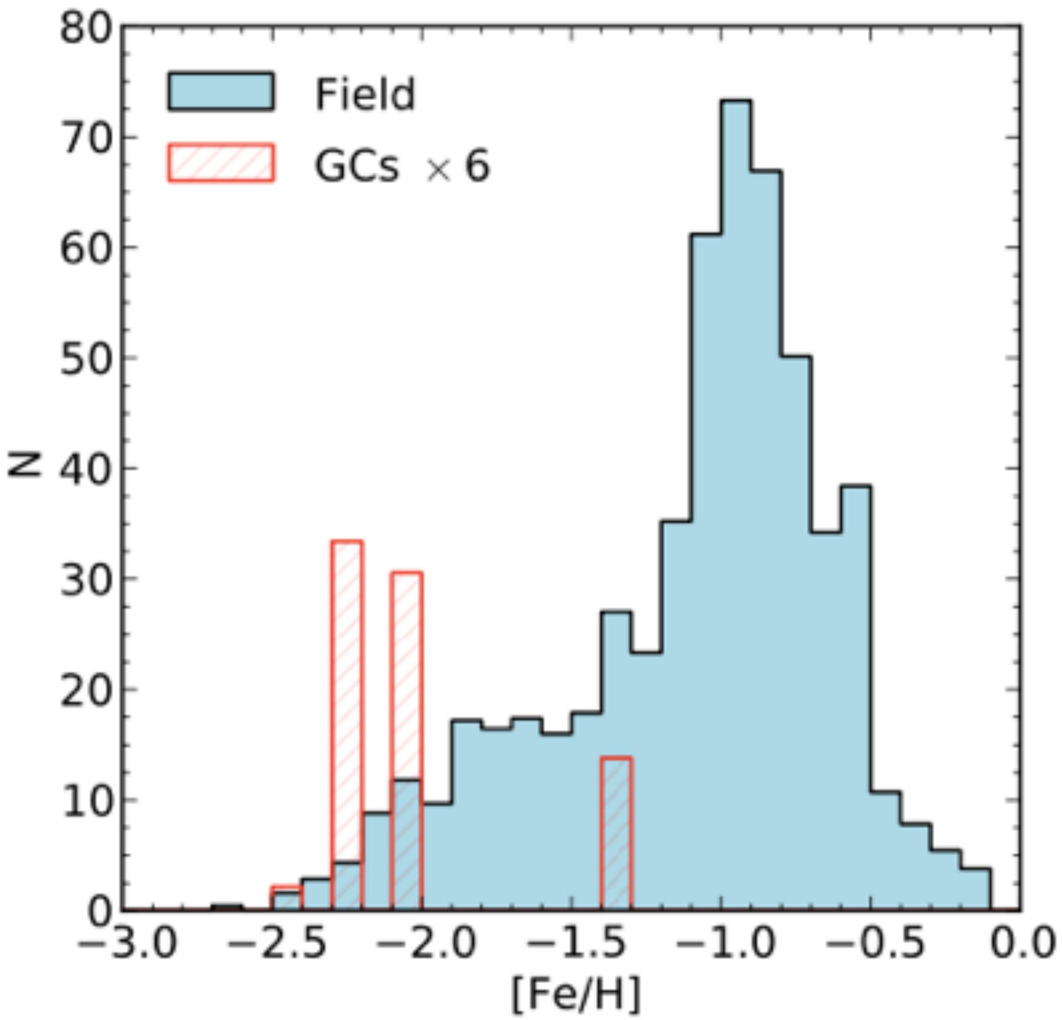
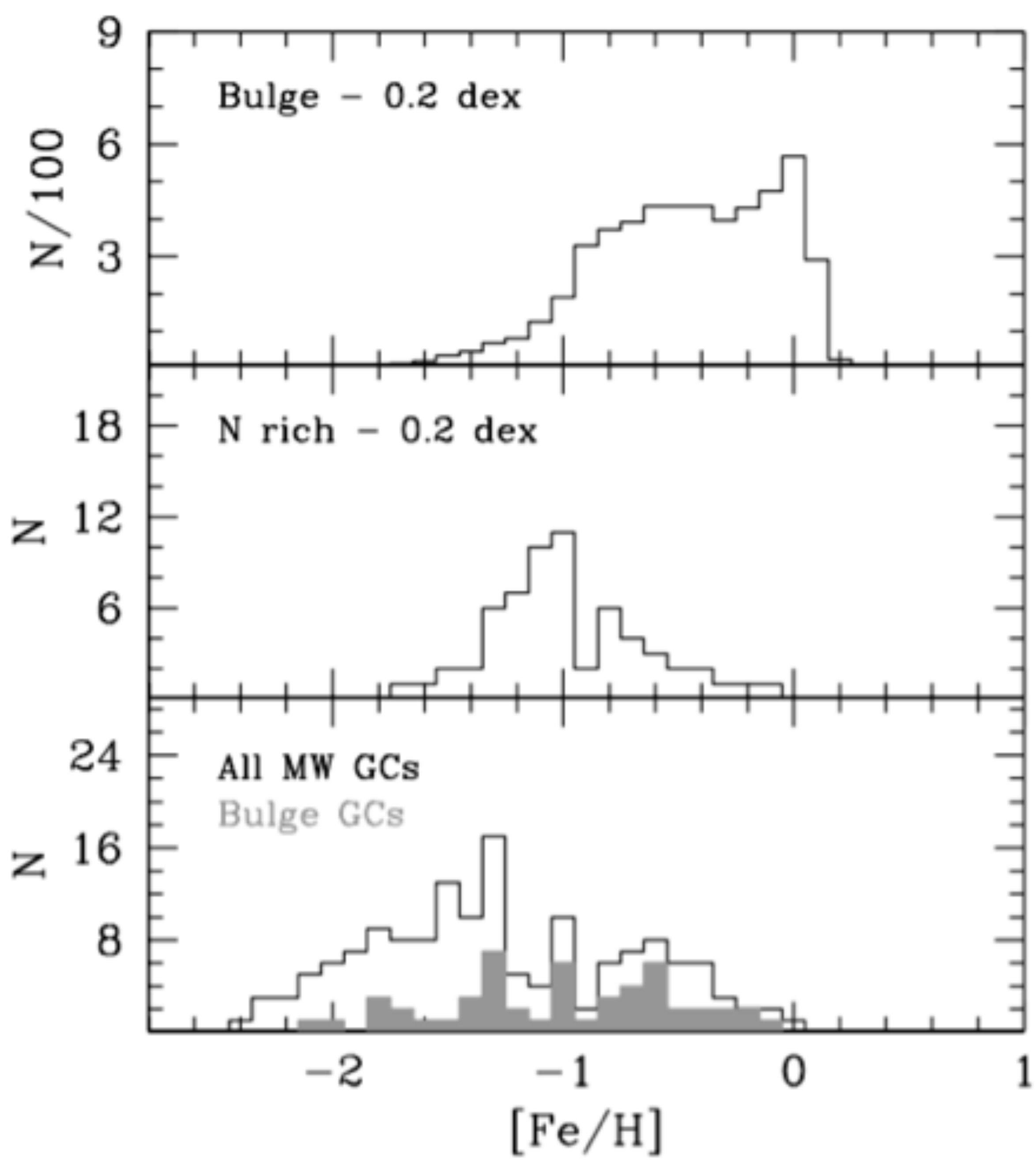
MPs and the mass-budget problem

Upper limit on mass lost from GCs and initial FG population, based ratio of field and GC stars in dwarf galaxies and in the inner regions of the MW.

Is tweaking the IMF of GCs a way to offset/mitigate the mass budget problem?

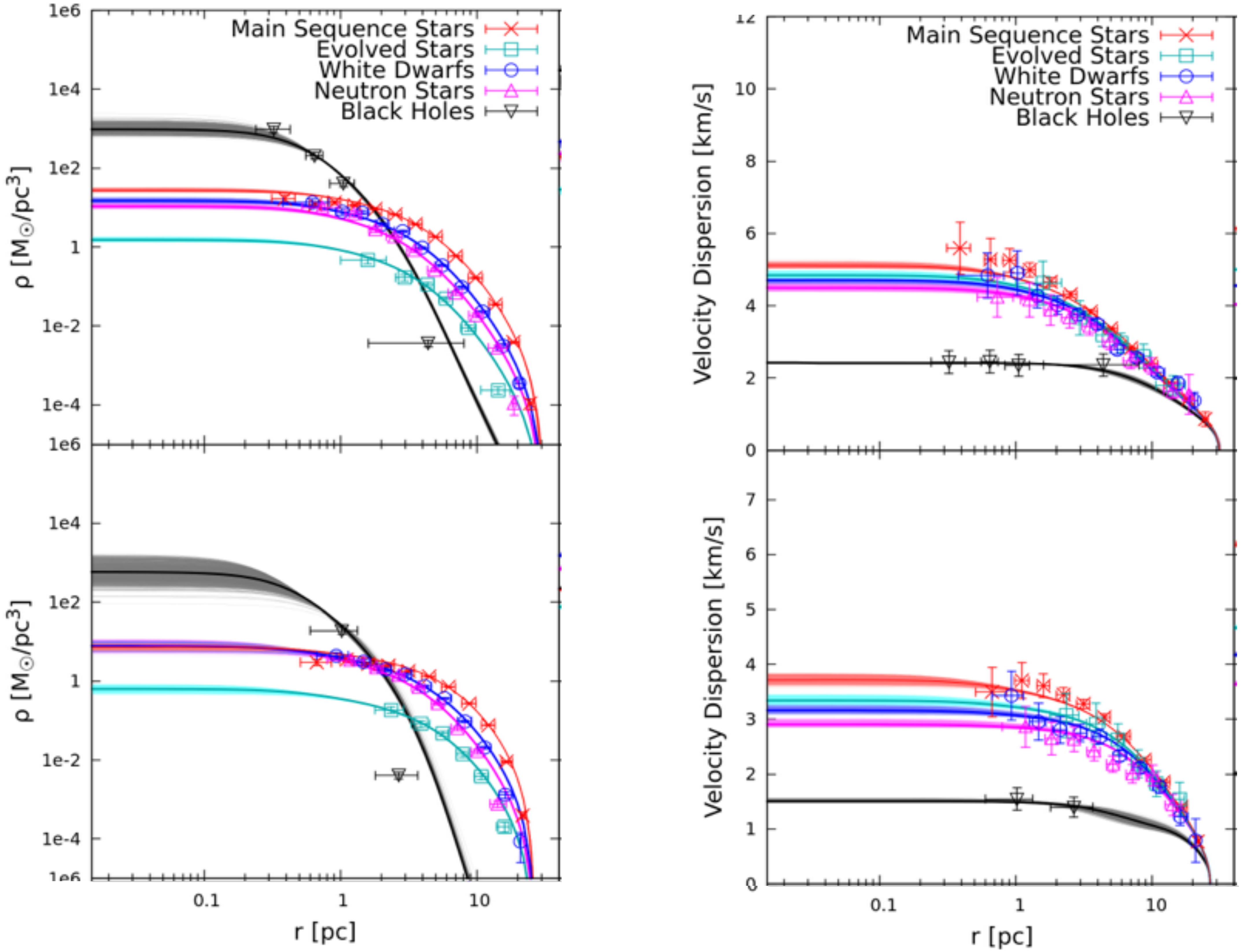


Larsen et al. 2012



Schiavon et al. 2016

Equilibrium multi-mass models of GCs vs. *N*-body



Zocchi et al. 2016; Peuten et al., in prep.; using LIMEPY models (Gieles & Zocchi 2015)

Fitting multi-mass models to data

Free parameters: ϕ_0, g, r_a, M, r_h α_1, α_2, α_{dark}, M_{dark}/M D

LIMEPY model parameters

distance

Present-day mass function

$$\frac{dN}{dm} \propto \begin{array}{ll} m^{-\alpha_1} & \text{for} \quad m < 0.5 M_\odot \\ m^{-\alpha_2} & \text{for} \quad m > 0.5 M_\odot \end{array}$$

$$\frac{dN}{dm} \propto m^{-\alpha_{\rm dark}}$$ for dark remnants (WDs, NS, BHs)

From models compute:
- **Surface brightness & number density profiles**
- **Velocity dispersion & anisotropy profiles**
- **Local stellar mass function**

✔ flexible (e.g. freedom about MF & remnants) ✔ physically motivated

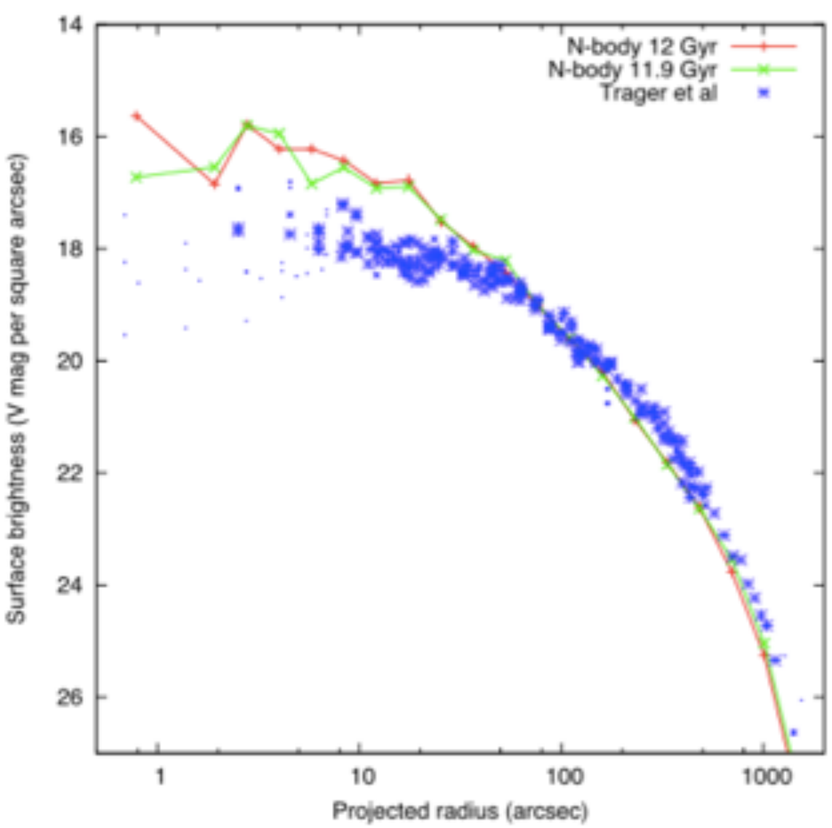
✔ fast to solve (-> MCMC)

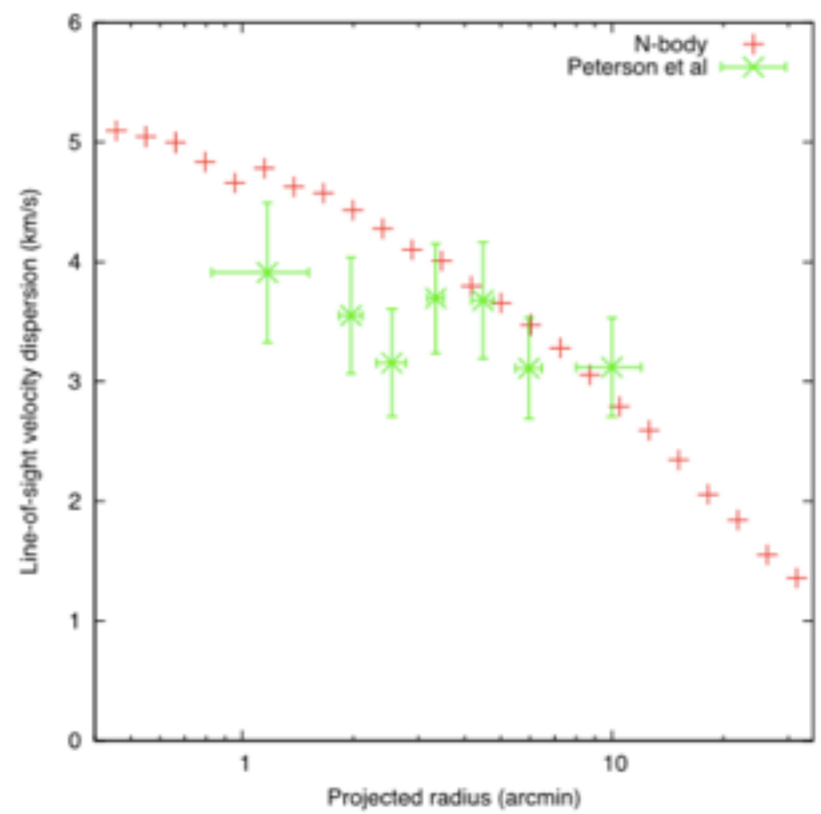
Mock data: *N*-body simulation of M4

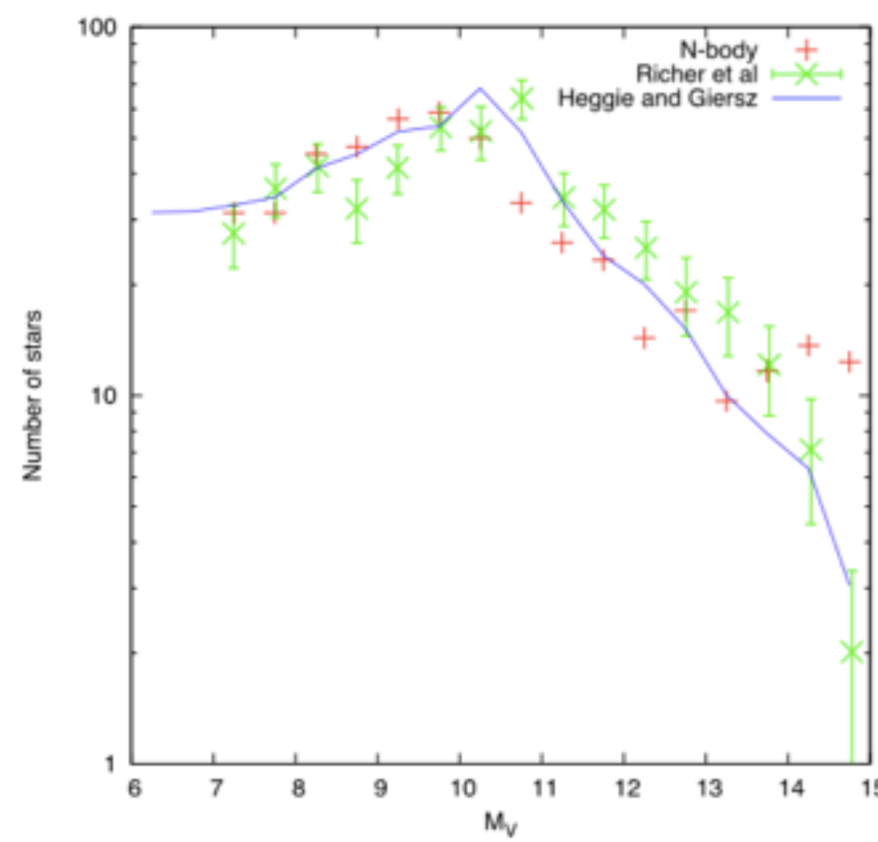
- Star by star *N*-body simulation of GC M4 (Heggie 2014)

- After 12 Gyr of dynamical and stellar evolution, matches M4 main observables (surface brigthness and velocity dispersion profiles, local luminosity function)

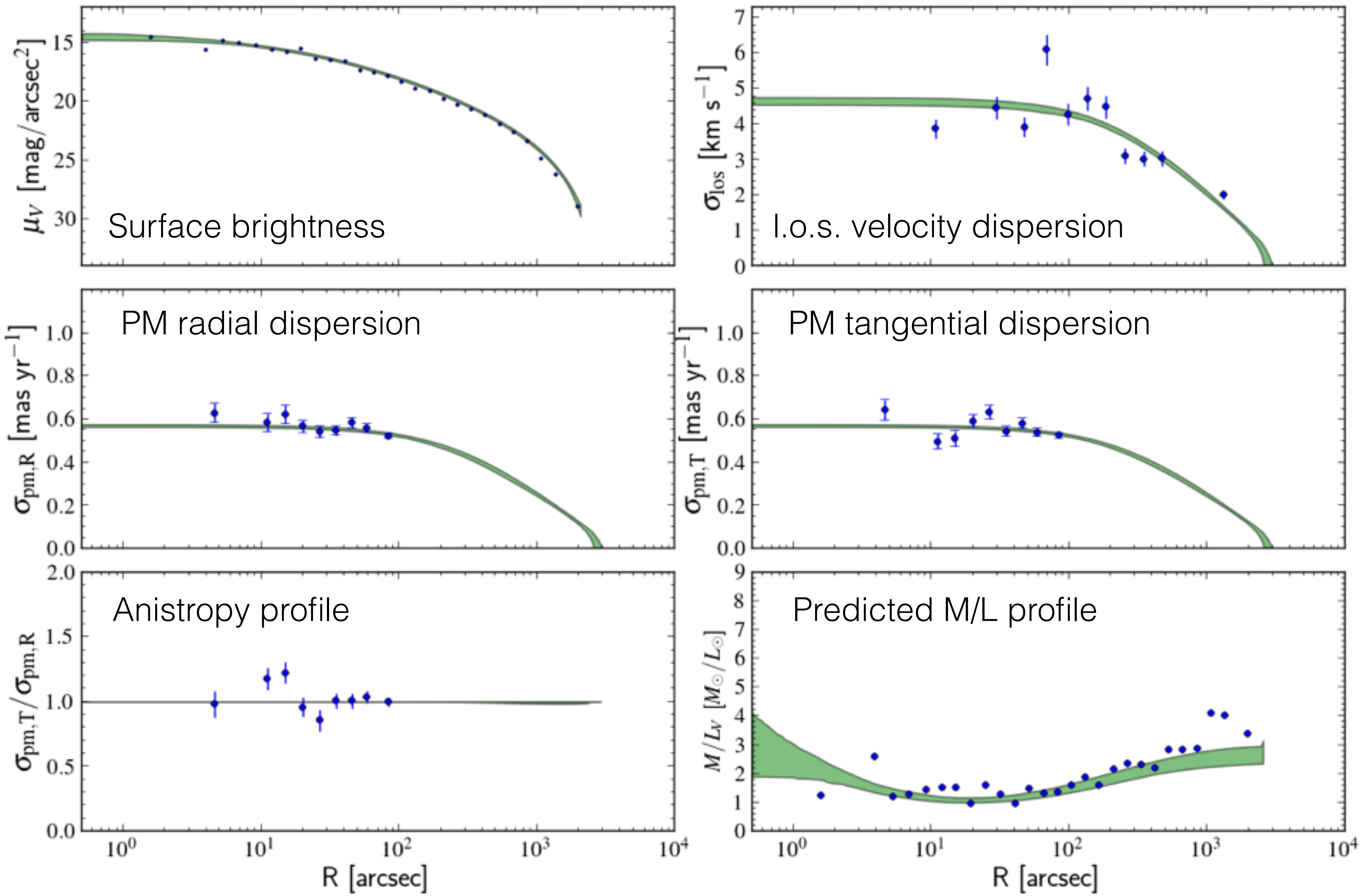
- Used to build mock observations to test mass modelling methods





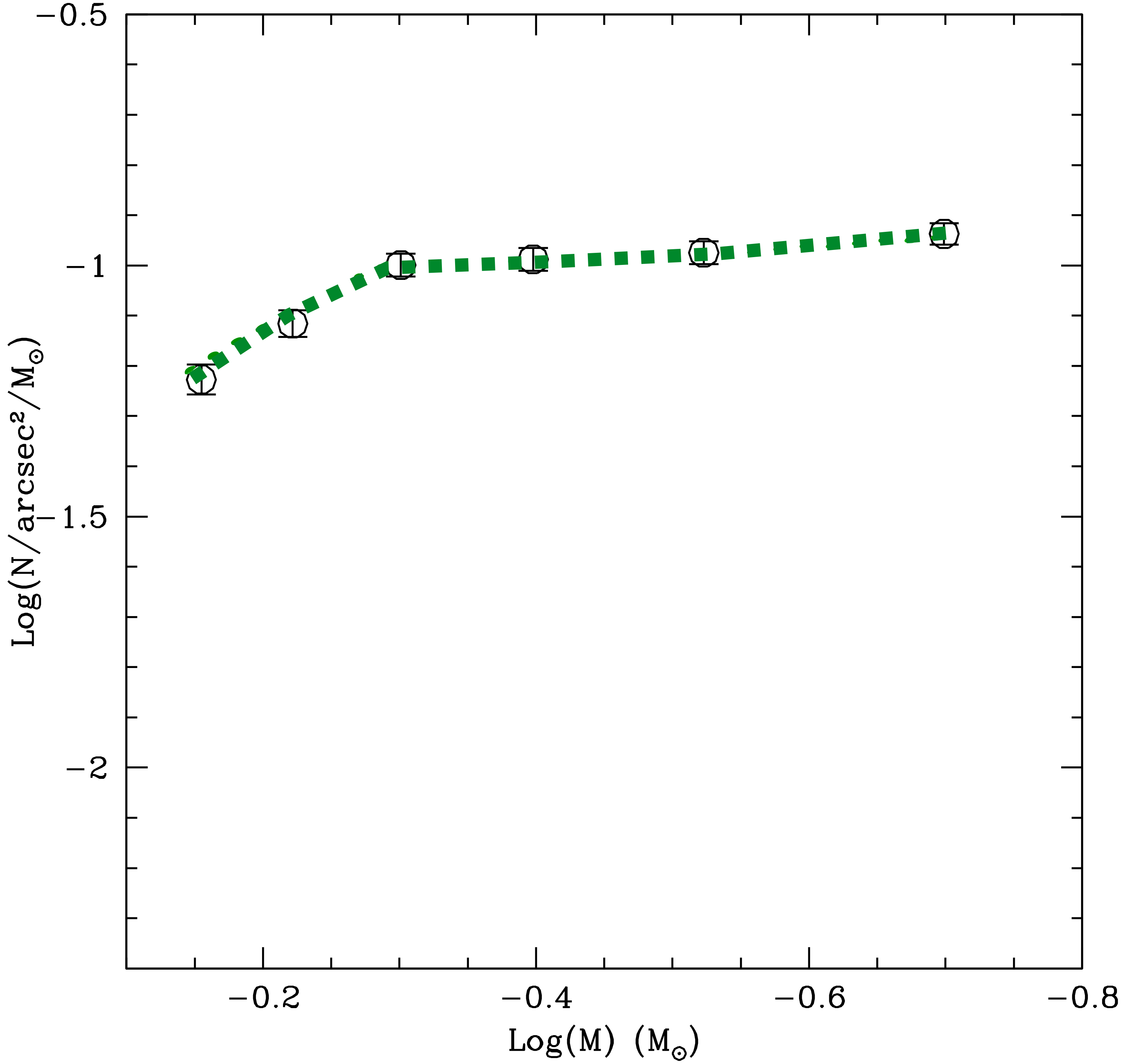


Fitting multi-mass models to M4 mock

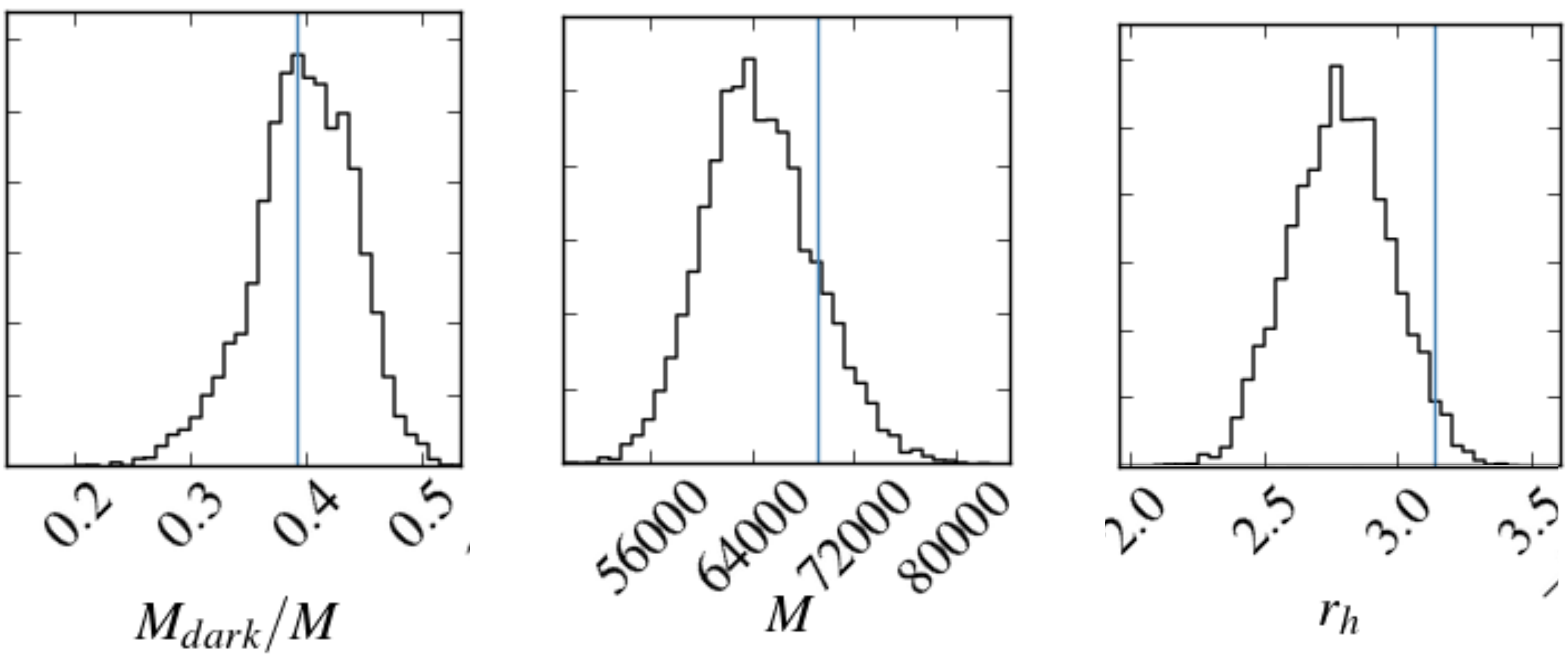


Fitting multi-mass models to M4 mock

Best-fit “observed” mass function near the half-mass radius



Weighing the dark remnants



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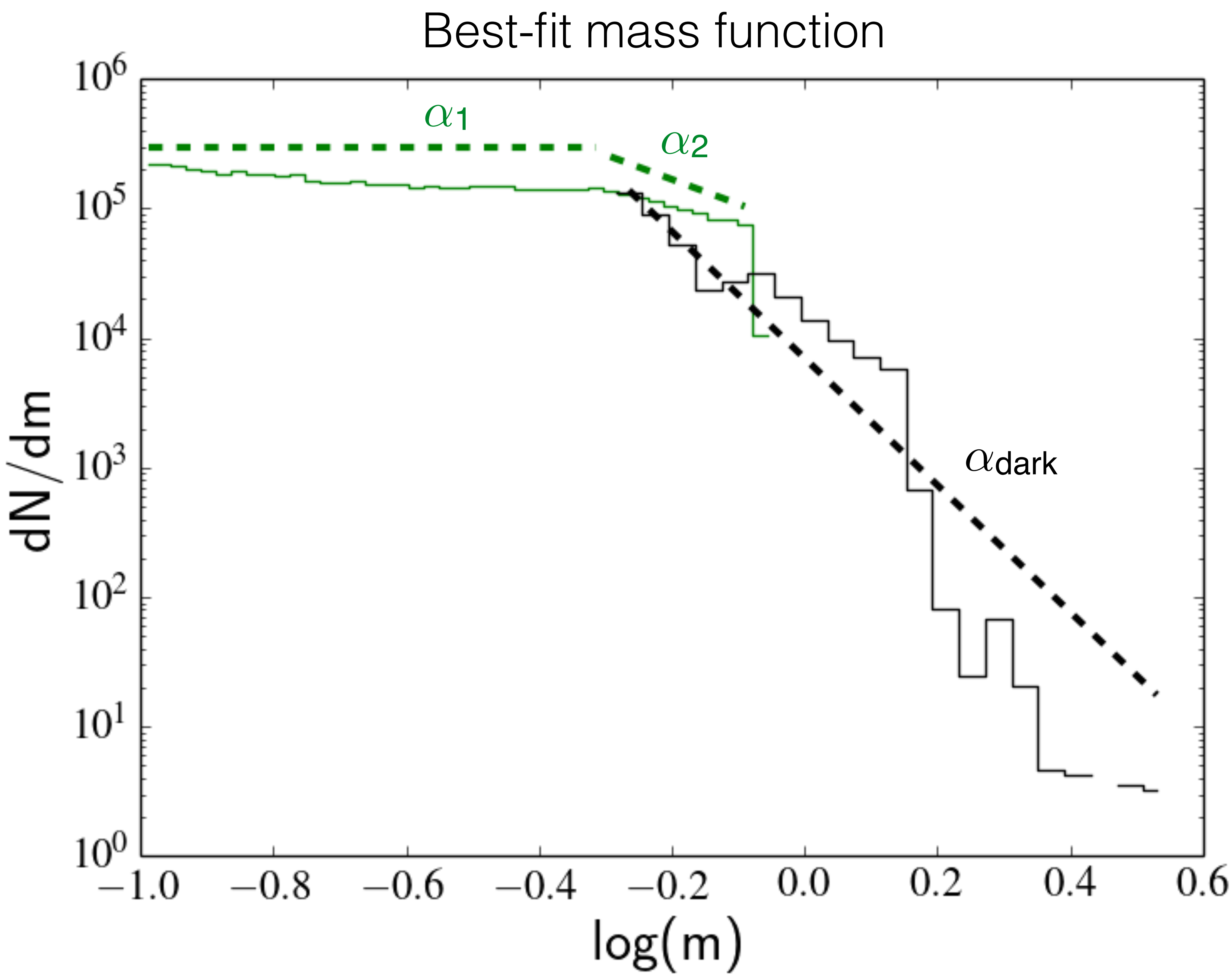

Summary

Long-term kinematic imprints of the formation of multiple populations can survive to the present day in the outer parts MW GCs.

Differences in the rotational amplitude of subpopulations provide new constraints on formation scenarios.

In M13, the “extreme” population appears to rotate faster than other subpopulations. This is most likely a remnant of its formation process rather than an effect of dynamical evolution.

Multi-mass models fitted to observational constraints (kinematics, structural data, main-sequence stellar mass function) can be used to “weigh” dark remnants in GCs.