MARIE CURIE ACTIONS

The Leverhulme Trust

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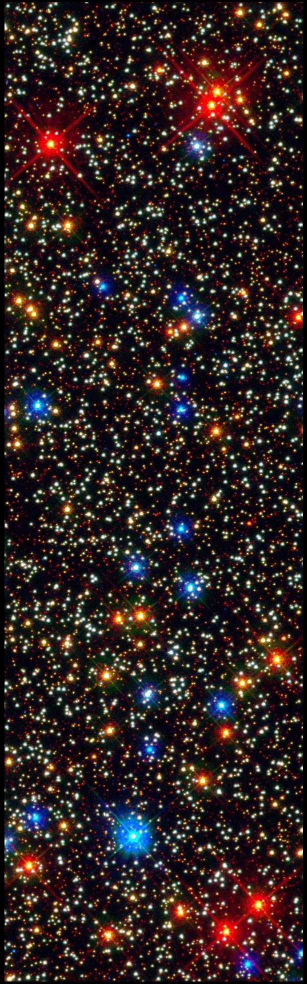
Kinematic evolution of star clusters



Globular clusters?

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spherical, non-rotating, isotropic, stellar systems with a single, coeval stellar population

$$f_K(E) = \begin{cases} A\left[\exp(-aE) - \exp(-aE_0)\right] & \text{if } E \leq E_0 \\ 0 & \text{if } E > E_0 \end{cases}$$

$$E = \frac{1}{2}(\dot{x}^2 + \dot{y}^2 + \dot{z}^2) + \Phi_c$$

King 1966 AJ

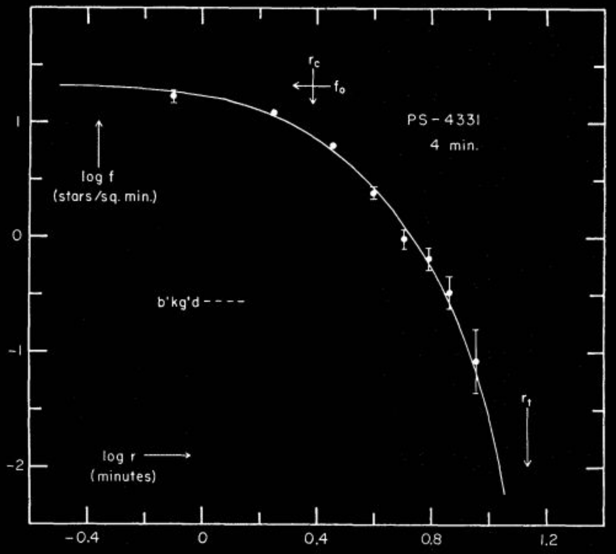

FIG. 3. Comparison of star counts in NGC 5053 with theoretical curve for $\log(r_t/r_c) = 0.75$. Medium-exposure 48-in. Schmidt plate.

Globular clusters? *not simply*
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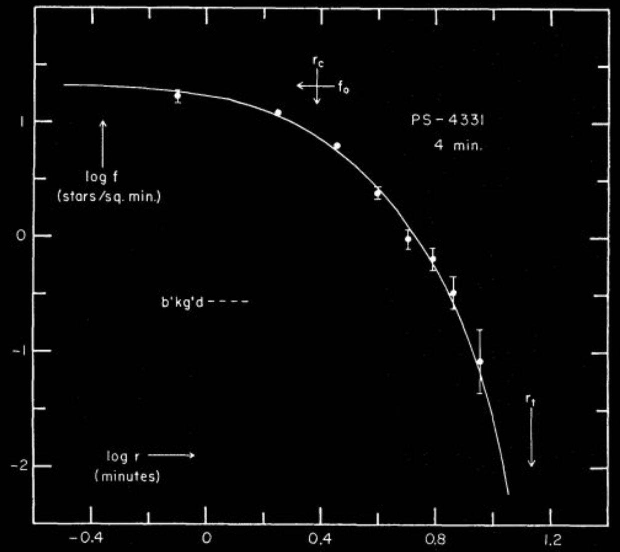

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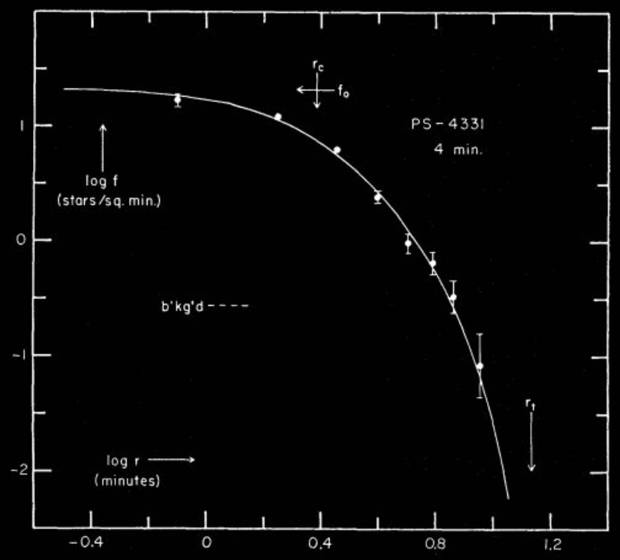
A paradigm shift is much needed, as we are about to enter a new *"golden age"* for star cluster dynamics, as determined by three revolutions.



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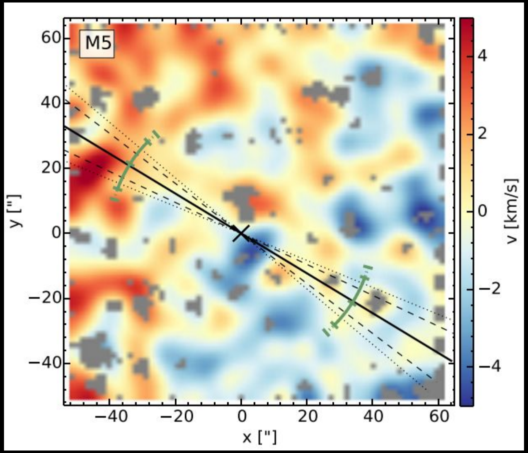
I. Conceptual revolution

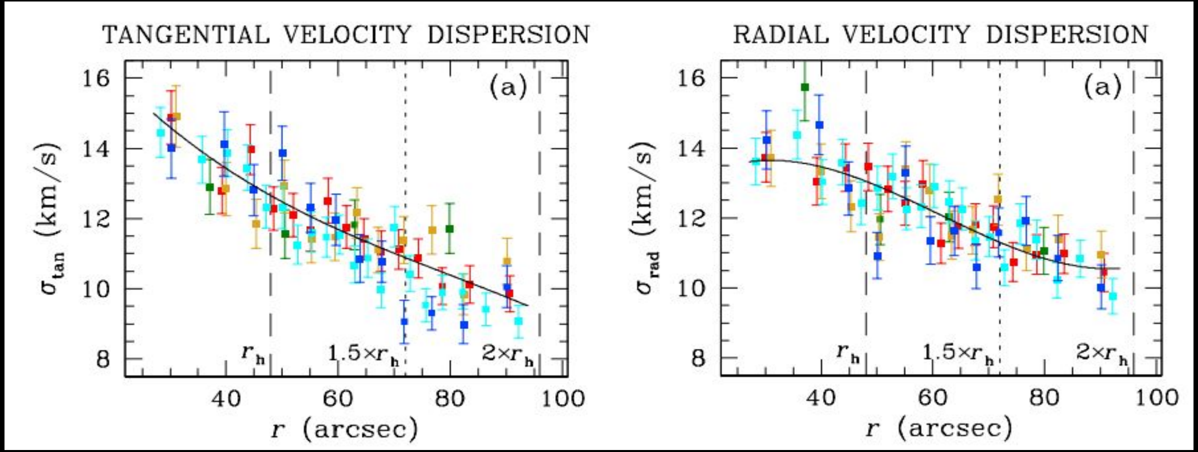
(a) New phase space laboratories: emerging kinematic complexity

Internal rotation



M5 | Fabricius et al. 2014 ApJL

Velocity anisotropy $\sigma_{ii} \neq \sigma_{jj} \quad i,j = 1,2,3$

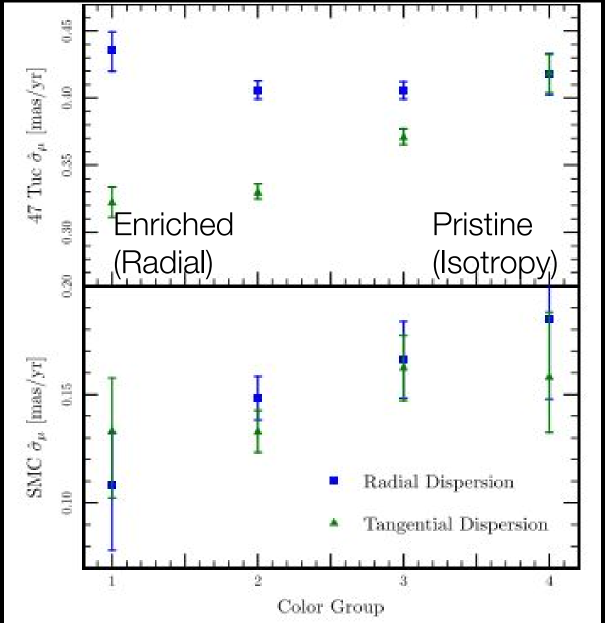


NGC 2808 | Bellini, Vesperini et al 2015, see also Watkins et al 2015a,b ApJ (HSTPROMO)

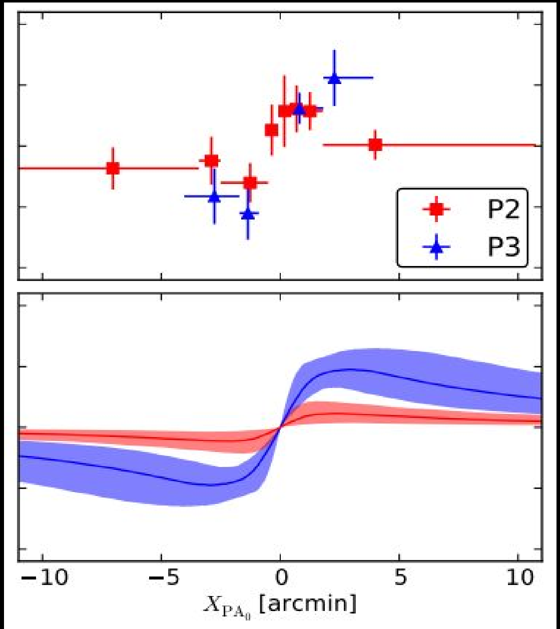
I. Conceptual revolution

(a) New phase space laboratories: emerging kinematic complexity

(b) Challenging chemodynamical puzzles: multiple stellar populations



47 Tuc | Richer et al. 2013 ApJL
NGC 2808 | Bellini et al. 2015 ApJL



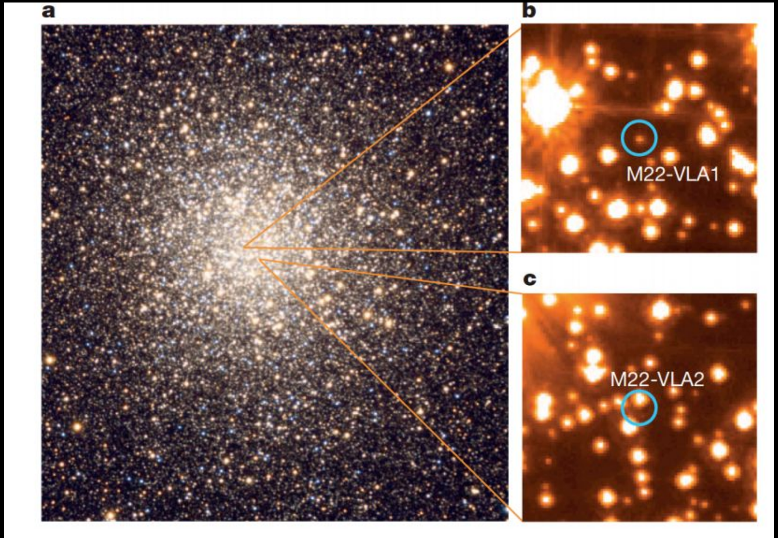
M13 | Cordero et al. 2017 MNRAS

P2 = Moderate enrichment (slower rotation)

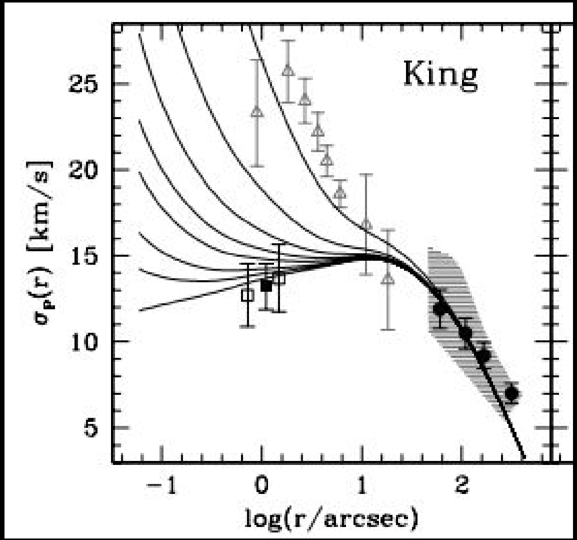
P3 = ‘Extreme’ enrichment (faster rotation)

I. Conceptual revolution

(a) New phase space laboratories: emerging kinematic complexity
(b) Challenging chemodynamical puzzles: multiple stellar populations
(c) Black holes cradles? Stellar-mass and (possibly) intermediate-mass scale



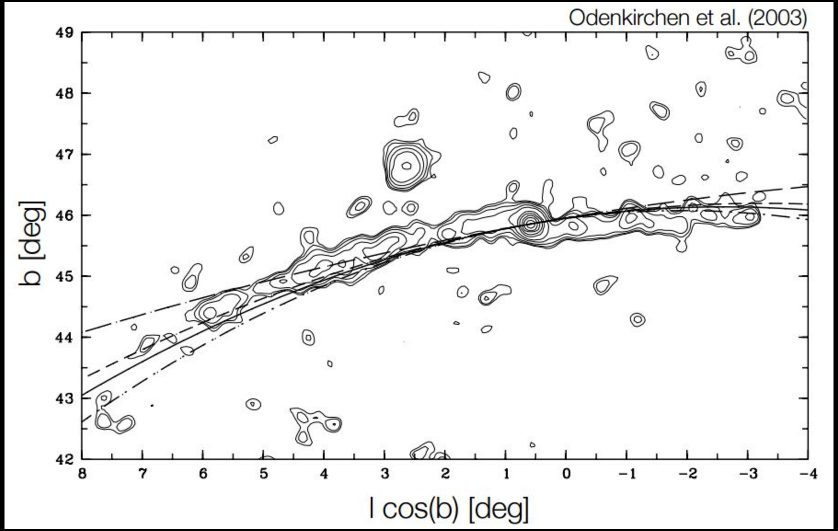
M22 | Strader et al. 2012 Nature



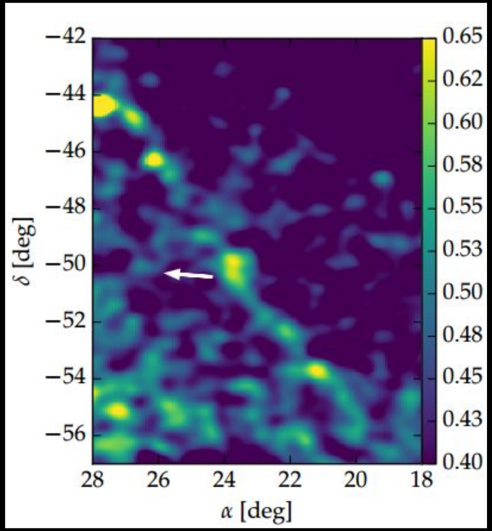
NGC 6388 | Lanzoni et al. 2013 ApJ;
Luetzgendorf et al 2011/13/15 A&A

I. Conceptual revolution

(a) New phase space laboratories: emerging kinematic complexity
(b) Challenging chemodynamical puzzles: multiple stellar populations
(c) Black holes cradles? Stellar-mass and (possibly) intermediate-mass scale
(d) Galactic beacons: progenitors of streams, contributors to Galactic halo assembly history



Palomar 5 | for modelling see Kuepper et al. 2015 MNRAS

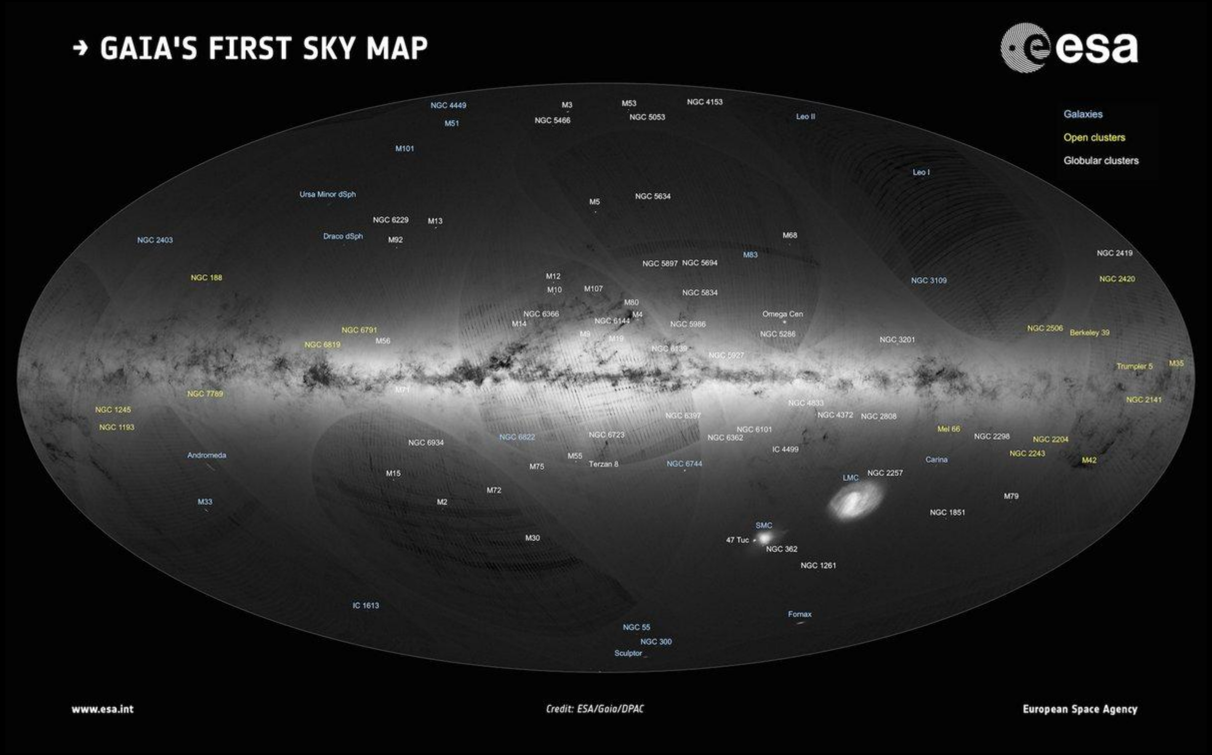


Phoenix stream | Balbinot et al 2016 ApJ (DES)

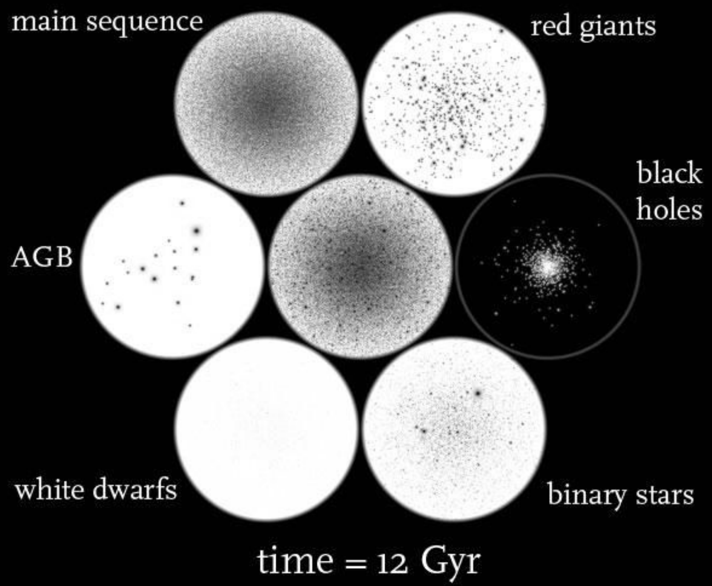
II. Observational revolution

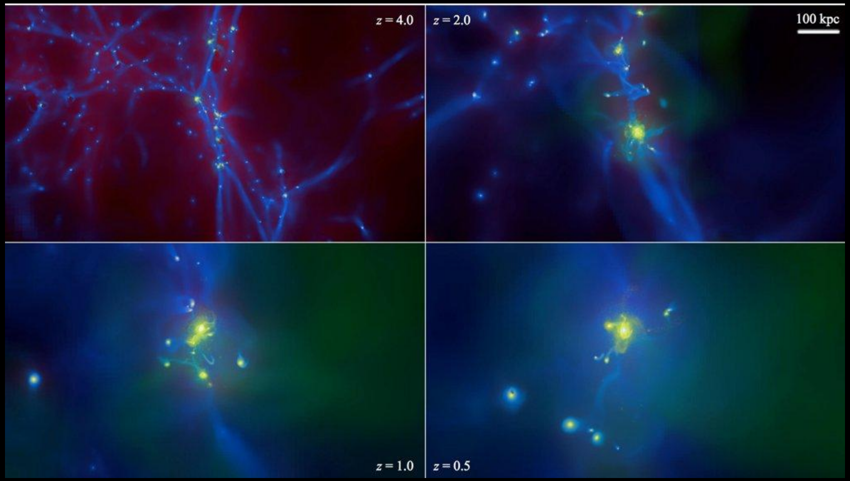
Synergy between Gaia and HST proper motions, plus high-quality spectroscopy (e.g., Gaia-ESO, WEAVE, 4MOST)

Phase-space properties of many Galactic globular clusters soon unlocked for the first time



III. Computational revolution





DRAGON series of N-body simulations | Wang et al. 2016 ApJ
N-body model of M4 (N=484710) | Heggie 2014 MNRAS

GC formation in cosmological simulations | Renaud et al. 2017
(see also Carlberg 2017, Li, Gnedin, Gnedin 2017...)

Renewed efforts in theoretical understanding are needed, towards a more realistic dynamical paradigm

A. Anisotropy in the velocity space
B. Angular momentum
C. External tidal field
D. Multiple stellar populations
E. Mass spectrum (and dark remnants)
F. Non-baryonic dark matter (!)
G. SMBHs /IMBHs (?)

Two statements

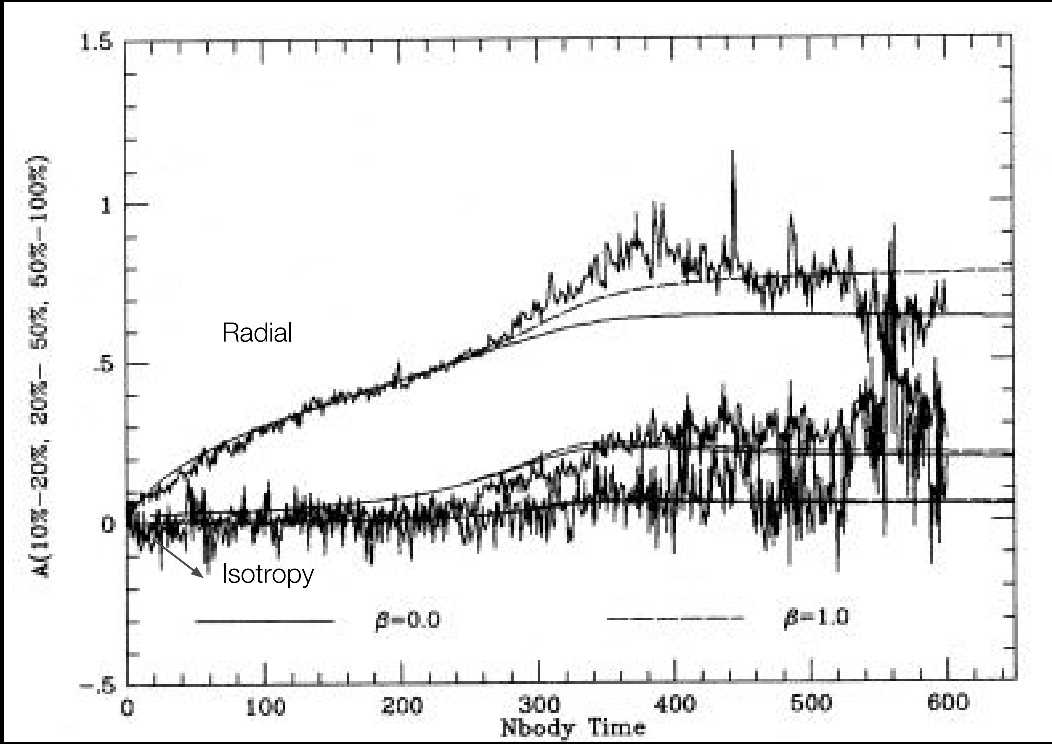
and one question

#1

Kinematic properties of collisional systems
are a natural outcome
of their long-term dynamical evolution

“Evolutionary” anisotropy
<u>in isolated clusters</u>

radial anisotropy
in the outer regions
(due to stars ejected
from the core to the halo
preferentially on radial orbits)

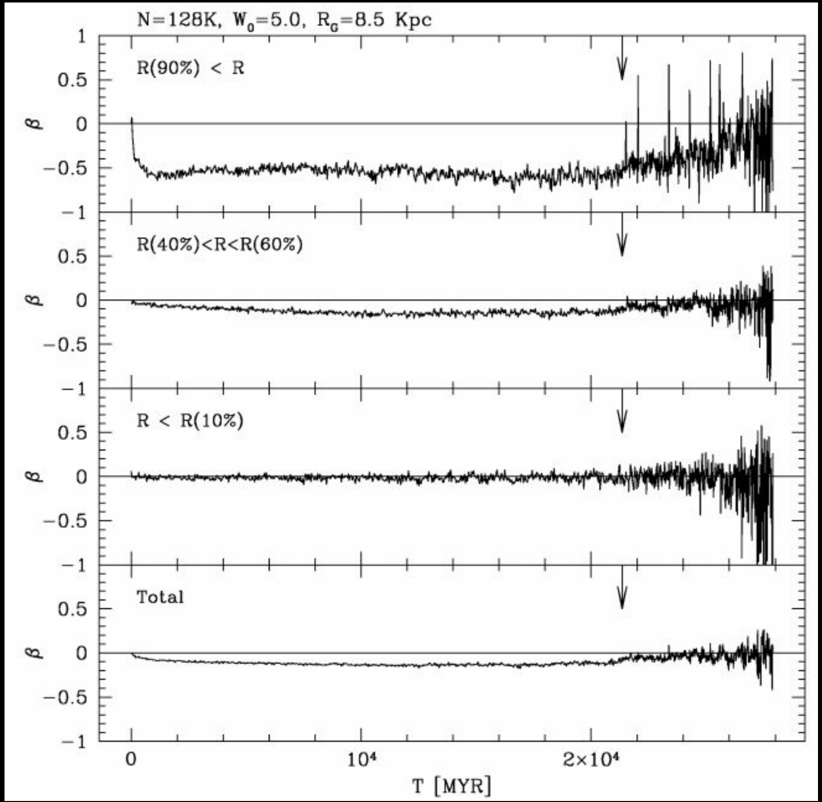


Statistics of N-body simulations I - Equal masses before core-collapse
Giersz & Heggie 1994, MNRAS, 268, 257

See also Henon 1971, Spitzer & Shapiro 1972, Bettwieser & Spurzem 1986, Takahashi 1995 ...

“Evolutionary” anisotropy
<u>in tidally perturbed clusters</u>

radial anisotropy
in the intermediate parts,
isotropy (even tangentiality)
in the outer regions
(due to preferential loss
of stars on radial orbits)



Dynamical evolution of star clusters in tidal fields
Baumgardt & Makino 2003, MNRAS, 340, 227

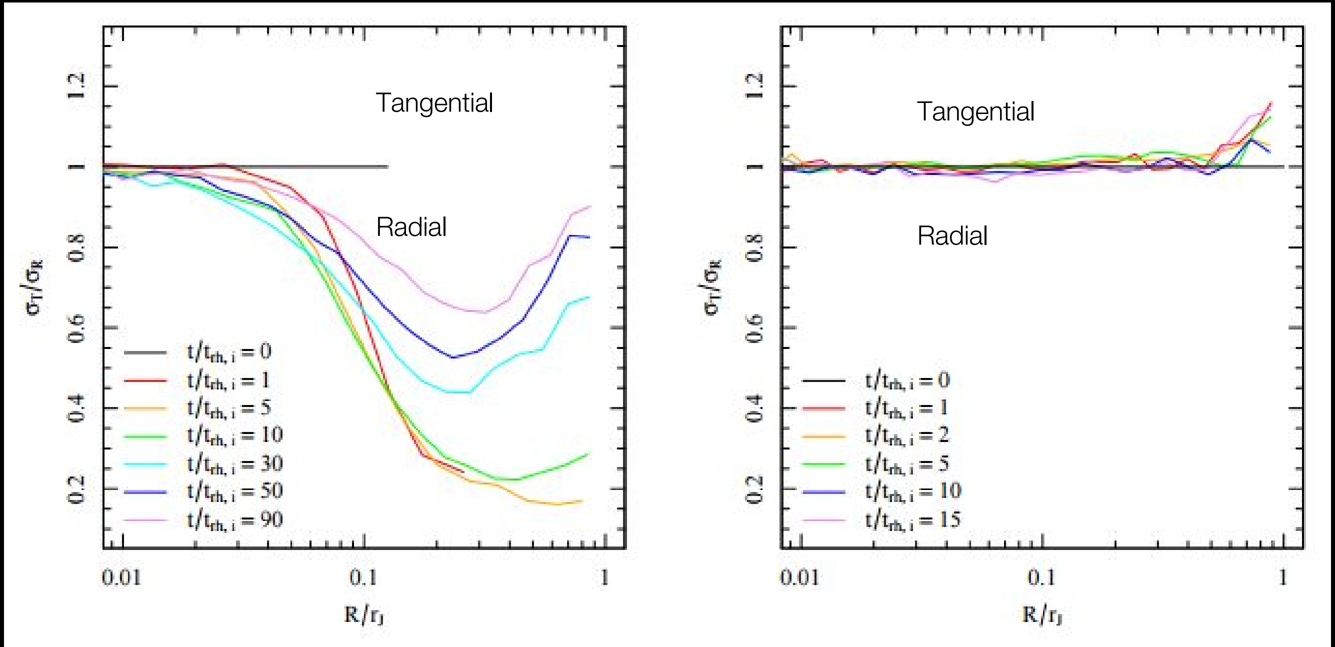
See also Takahashi et al. 1997, Giersz & Heggie 1997, Hurley 2012

“Evolutionary” anisotropy <u>in tidally perturbed clusters</u>

anisotropy
flavour and strength
linked to
the tidal regime

Roche underfilling: rh/rJ=0.015 (rt/rJ=0.125)

Critically filling: rh/rJ=0.116 (rt/rJ=1)





Velocity anisotropy in tidally limited star clusters
Tiongco, Vesperini, Varri 2016a, MNRAS, 455, 3693

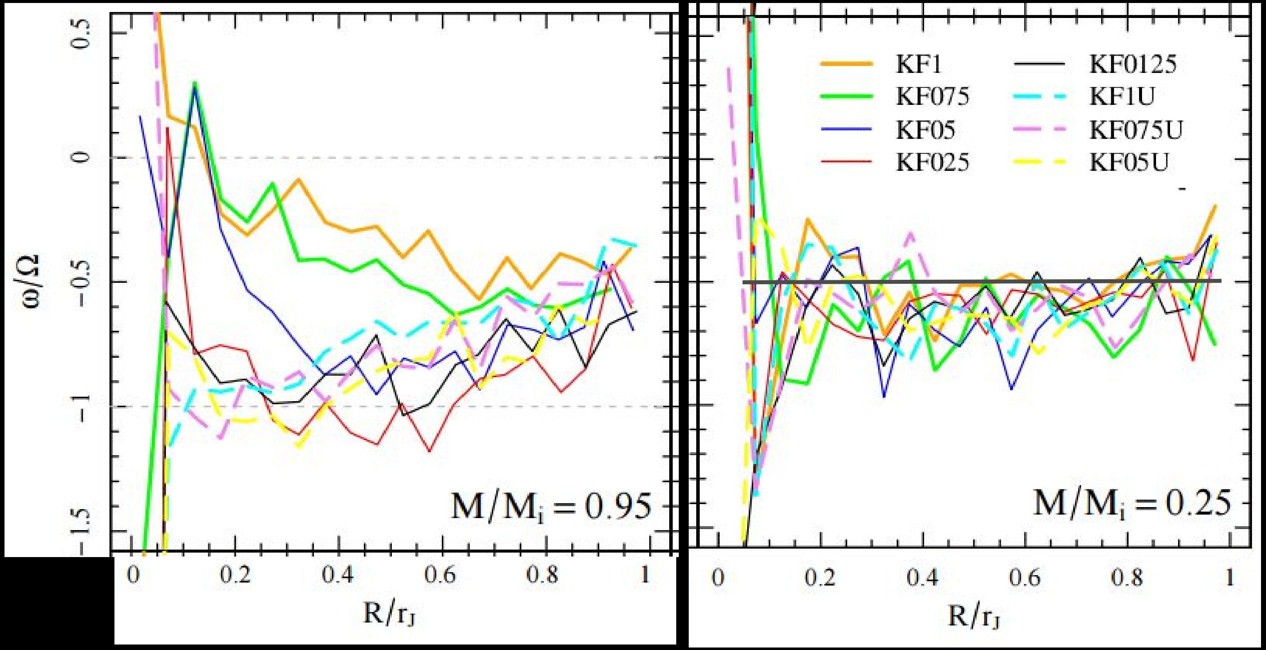
See also Sollima et al. 2015, Zocchi et al. 2016

Rotation as a natural outcome of long-term dynamical evolution

<u>Partial synchronization</u>

$\varpi \sim -0.5\ \Omega$

Internal angular velocity equal to about half of the angular velocity of the cluster orbital motion in the host galaxy



Kinematical evolution of tidally limited clusters: the role of retrograde stellar orbits

Tiongco, Vesperini, Varri 2016b, MNRAS, 461, 402

See also Claydon et al. 2017

#2

Kinematic properties of collisional systems
are possible* fingerprints of
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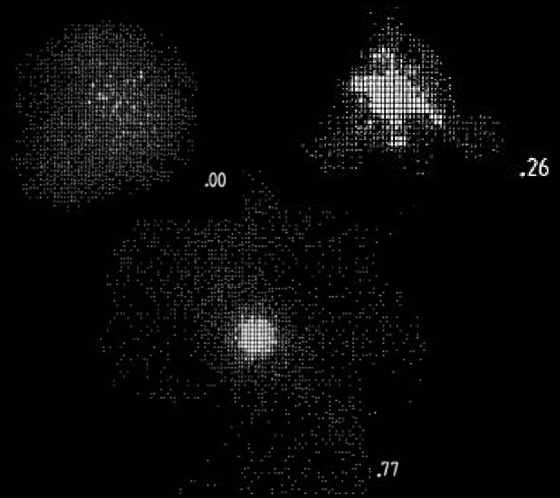
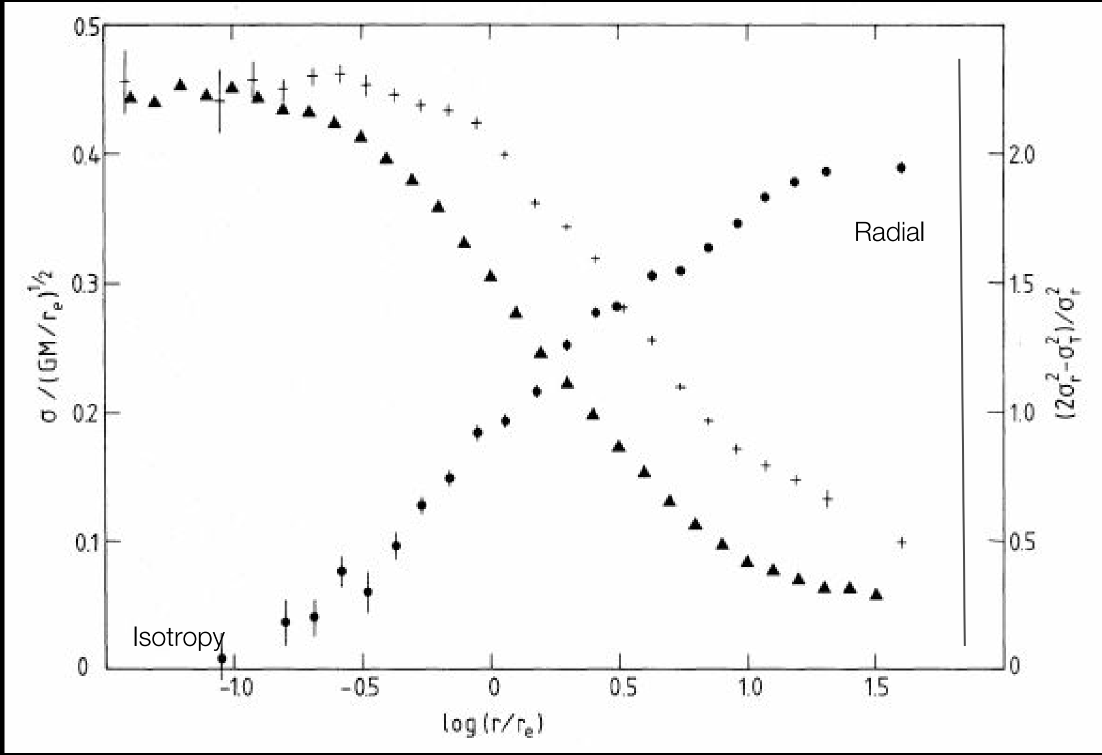
their formation process

* it much depends on their relaxation conditions, of course

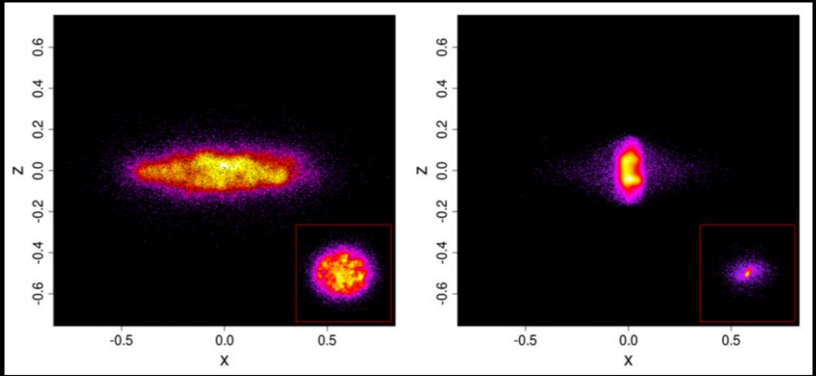
“Primordial” anisotropy
as a signature
of the formation process
<u>for isolated clusters</u>

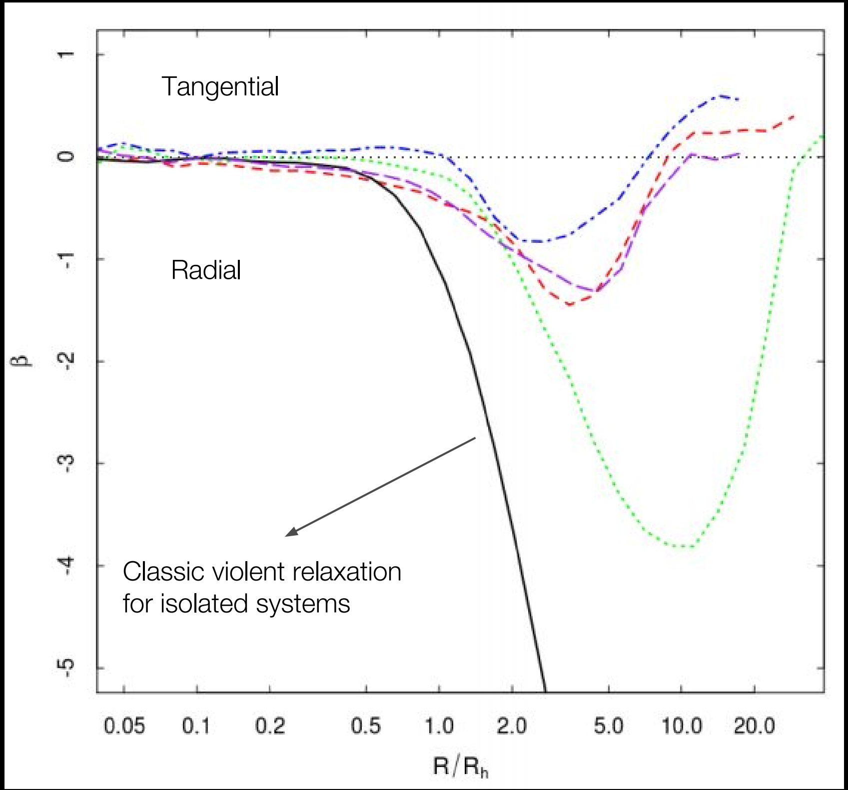




Dissipationless galaxy formation and R to the ¼ power law
van Albada 1982, MNRAS, 201, 939

“Primordial” anisotropy
as a signature of the
formation process
<u>for clusters in a tidal field</u>



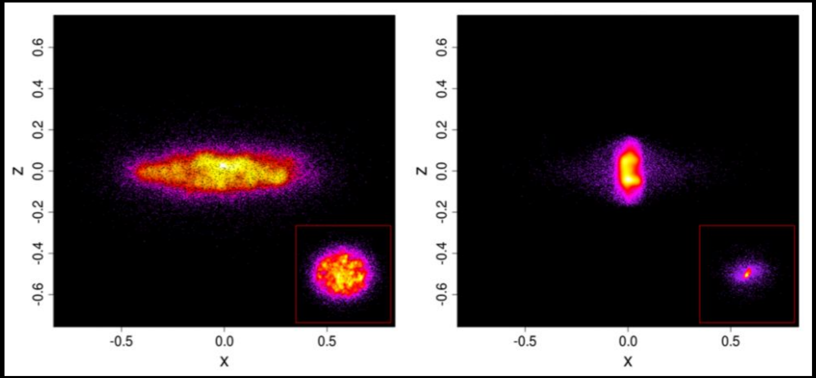


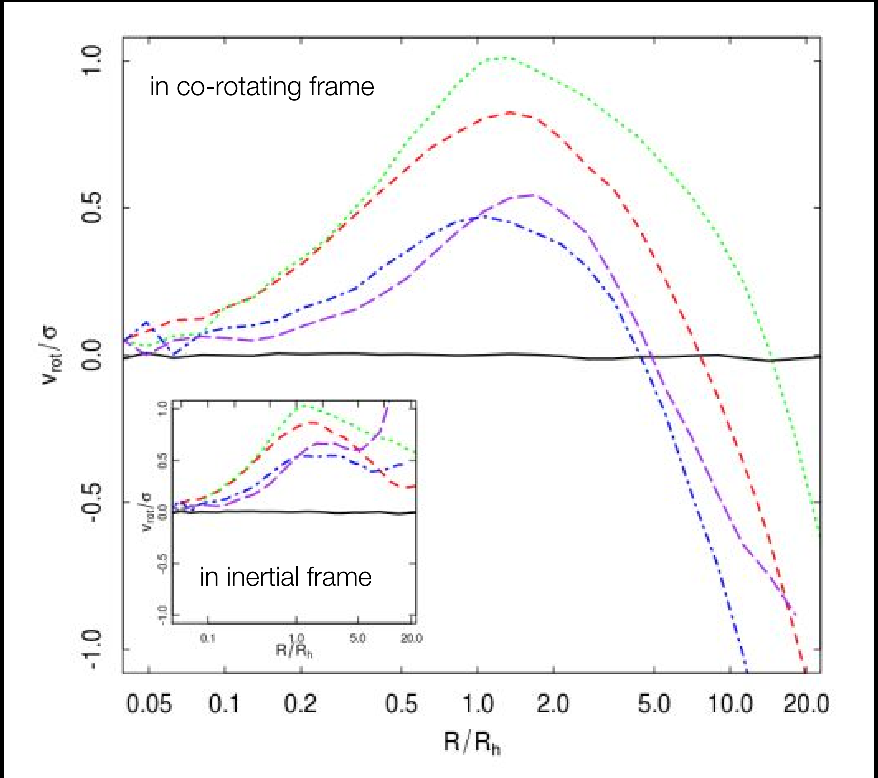
   

Kinematical fingerprints of star clusters early dynamical evolution
Vesperini, Varri, McMillan, Zepf 2014, MNRAS Letters, 449, L79

… and a rotation curve naturally appears!

no magic involved, just
conservation of angular momentum





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Differentially rotating models (= rotation + anisotropy)

$$f^d_{WT}(I) = A e^{-aE_0}\left[e^{-a(I-E_0)} - 1 + a(I - E_0)\right]$$

$$E < E_0$$

$$I(E, J_z) \equiv E - \frac{\omega J_z}{1 + bJ_z^{2c}}$$

$I \sim H = E - \omega J_z$ for low $|J_z|$

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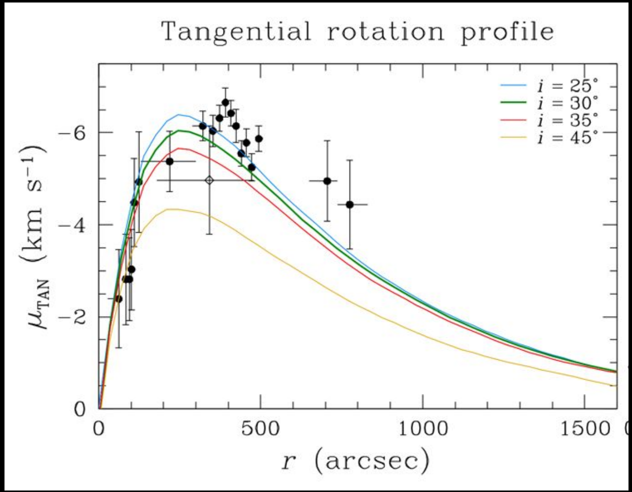

Bellini, Bianchini, Varri et al. 2017 ApJ
The rapid rotation of 47 Tuc, modelled in 3D

Self-consistent models of quasi-relaxed rotating stellar systems
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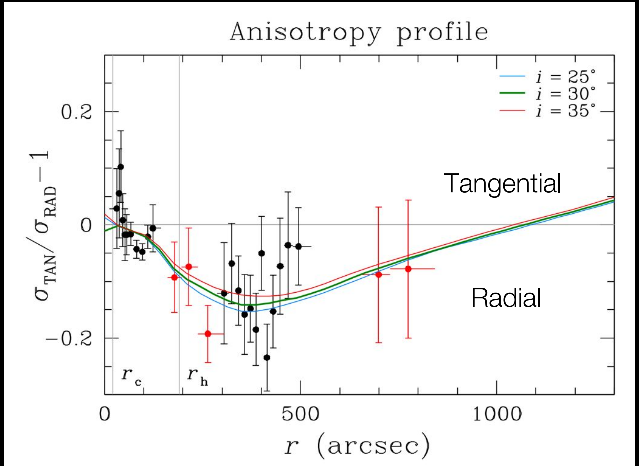

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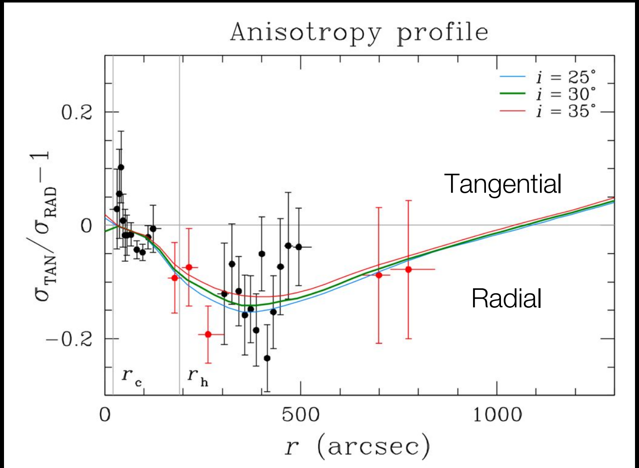
More in Andrea Bellini's talk



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#3

What does it happen when
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are evolved?

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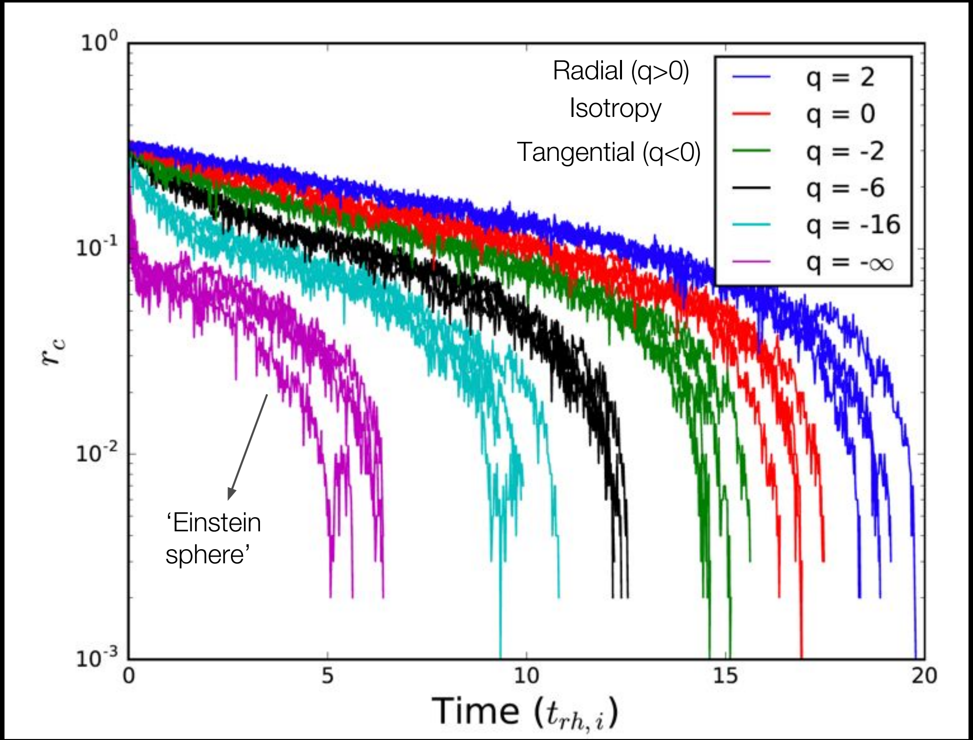
collisional systems
with non-trivial “primordial” kinematics
are evolved?

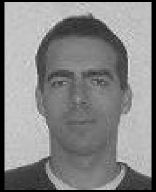
i.e., should N-body lovers worry at all about this stuff
when designing their initial conditions?

Tangentially (radially) anisotropic equilibria* reach core collapse earlier (later) than isotropic ones!

Catastrophic behaviour for highly tangential models

* with the same spatial properties and same initial half-mass relaxation time (Anisotropic Plummer, Dejonghe 1987)





The kinematic richness of star clusters I. spherical anisotropic models with primordial anisotropy
Breen, Varri, Heggie, MNRAS 2017, 471, 2778

What happens when the assumptions of synchronization and coplanarity are relaxed?

Precession of the main rotation axis, counter-rotating cores, isophote twisting and more …

Stay tuned!



The complex kinematics of rotating clusters in a tidal field
Tiongco, Vesperini, Varri - about to be submitted

Parting thoughts

#0 - A new golden age for the internal dynamics of globulars is about to start. Paradigm shift needed.

Synergy between ground-based spectroscopic surveys and HST + Gaia proper motions will be key. Access to phase space!

#1 - Kinematic properties of collisional systems are the outcome of their long-term evolution

Velocity anisotropy, but also rotation. Non-trivial Interplay between internal and orbital angular momentum.

#2 - Kinematic properties of collisional systems are possible fingerprints of their formation process

Violent relaxation in a tidal field leaves distinctive features in velocity space, consistent with properties of some present-day clusters.

#3 - What does it happen when collisional systems with non-trivial primordial kinematics are evolved?

Lots of wonderful things. Stay tuned.

Investigation of the role of “classical” physical ingredients is the essential foundation for understanding *any* dynamical signature of more complex phenomena (IMBHs, MSPs, DM).