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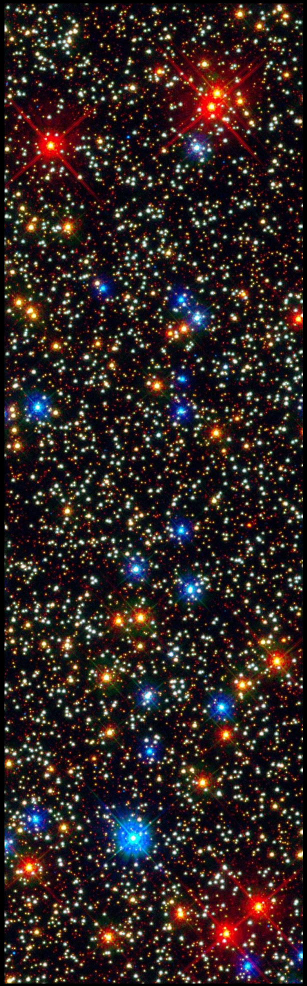
Maria Tiongco, Enrico Vesperini (Indiana)

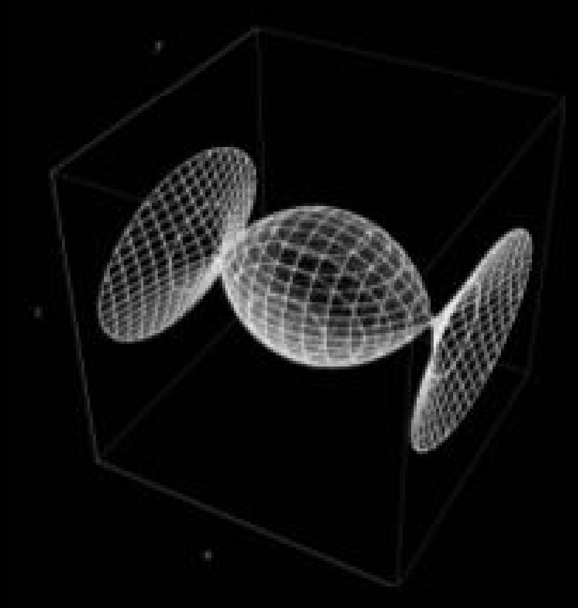
Gaia Challenge: Alice Zocchi (Bologna), Mark Gieles (Surrey),
Vincent Hénault-Brunet (Nijmegen), Antonio Sollima (Bologna), Elena Pancino (Arcetri)

Paolo Bianchini (McMaster), Giuseppe Bertin (Milano), Steve McMillan (Drexel)
Phil Breen, Douglas Heggie (Edinburgh)

Kinematic signatures of tidally perturbed star clusters



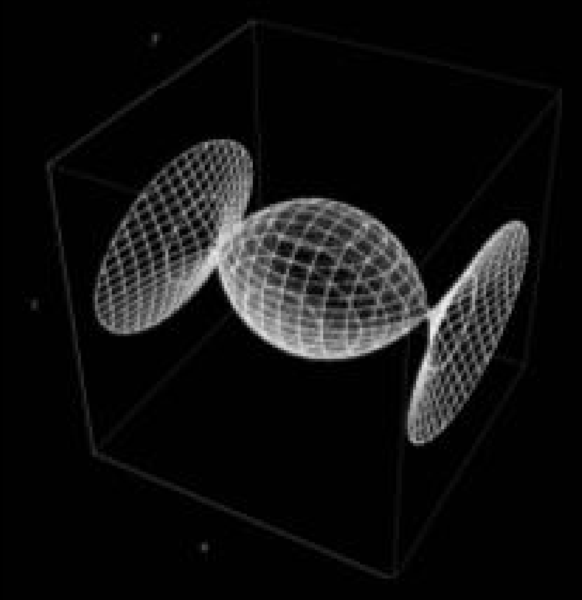
Tidal field shapes the structure and dynamics of a star cluster



$$f_K(H) = \begin{cases} A\left[\exp\left(-aH\right) - \exp\left(-aH_0\right)\right] & \text{if } H \leq H_0 \\ 0 & \text{if } H > H_0 \end{cases}$$

Heggie & Ramamani 1995, MNRAS, 272, 317
Bertin & Varri 2008, ApJ, 689, 1005

Tidal field shapes the structure and dynamics of a star cluster



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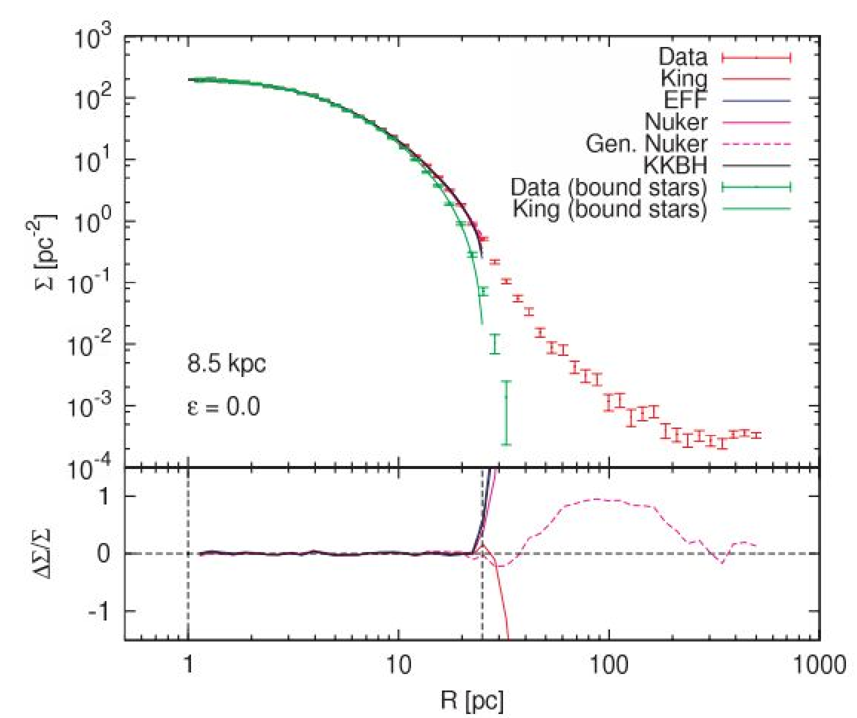
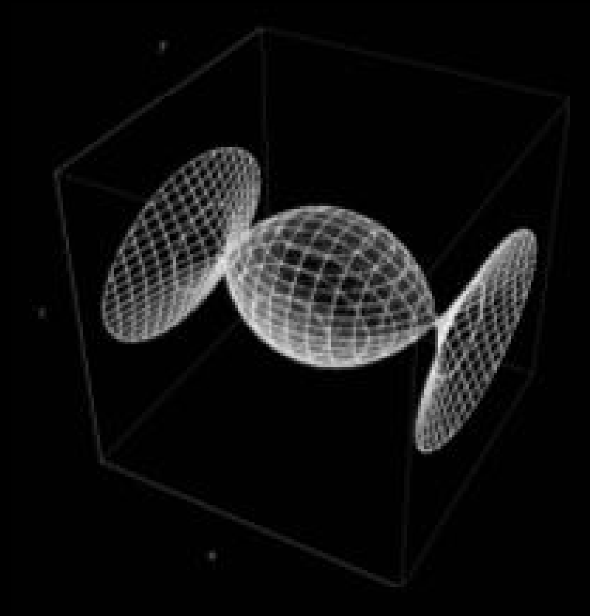


Peculiarities in velocity dispersion and surface density profiles of star clusters
Kuepper, Kroupa, Baumgardt, Heggie, 2010, MNRAS, 407, 2241

Tidal field shapes the structure and dynamics of a star cluster



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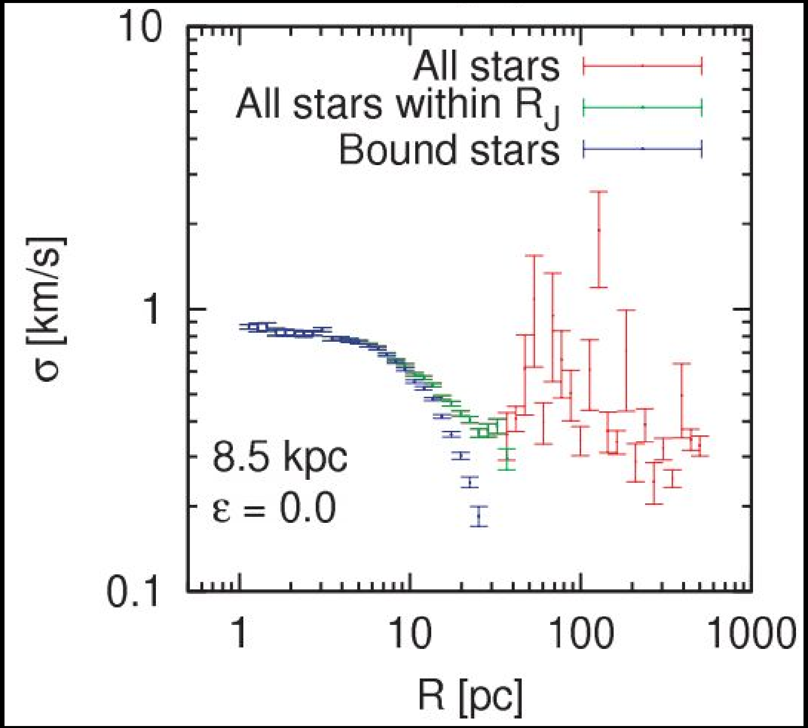
Bertin & Varri 2008, ApJ, 689, 1005



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Kuepper, Kroupa, Baumgardt, Heggie, 2010, MNRAS, 407, 2241

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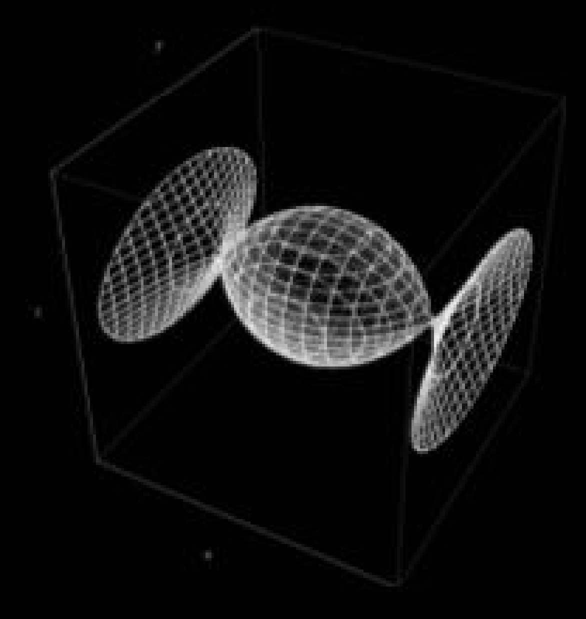

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Heggie & Ramamani 1995, MNRAS, 272, 317
Bertin & Varri 2008, ApJ, 689, 1005

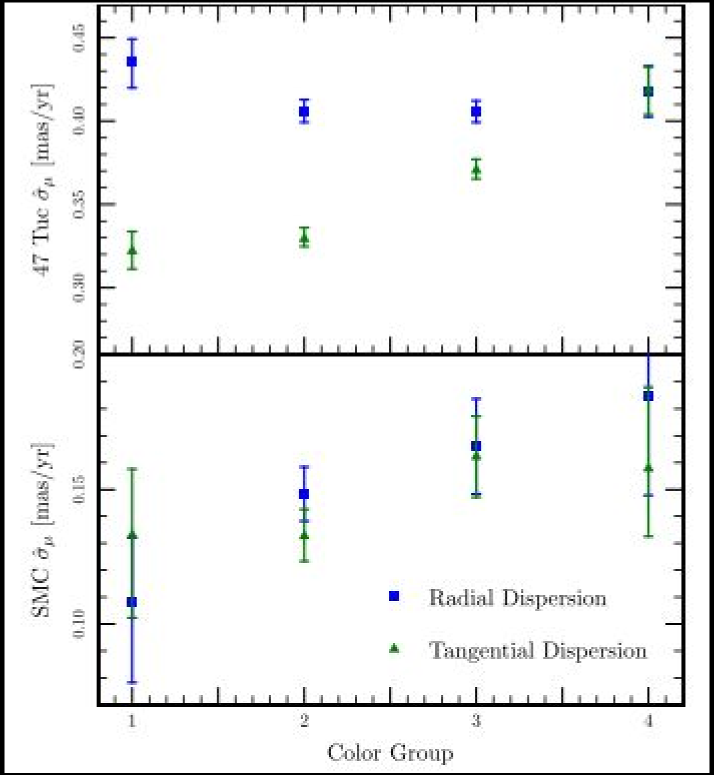
... and it leaves signatures in the three-dimensional velocity space:

Anisotropy

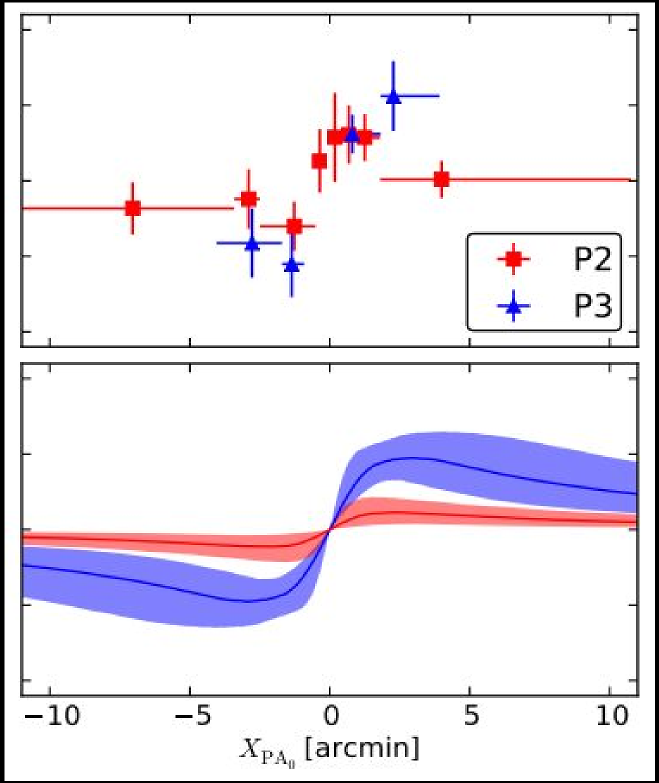
Rotation

Why should we care?

Because we still need to figure out the dynamics (and much more…) of multiple stellar populations



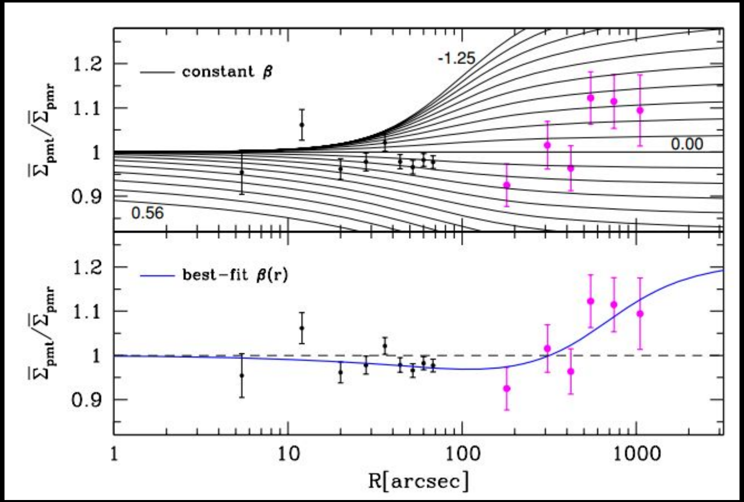
47 Tuc | Richer+ 2013
NGC2808 | Bellini, Vesperini+ 2015



M13 | Cordero+ 2017

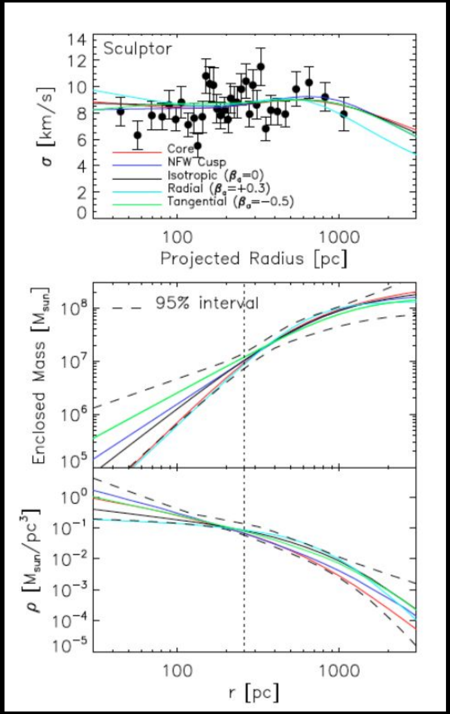
Why should we care?

New chapter of our fundamental understanding of stellar dynamics



ω Cen | van der Marel et al. 2010

Star Clusters: IMBH or Anisotropy?



Sculptor | Walker 2012

Dwarf galaxies: Core or Cusp?

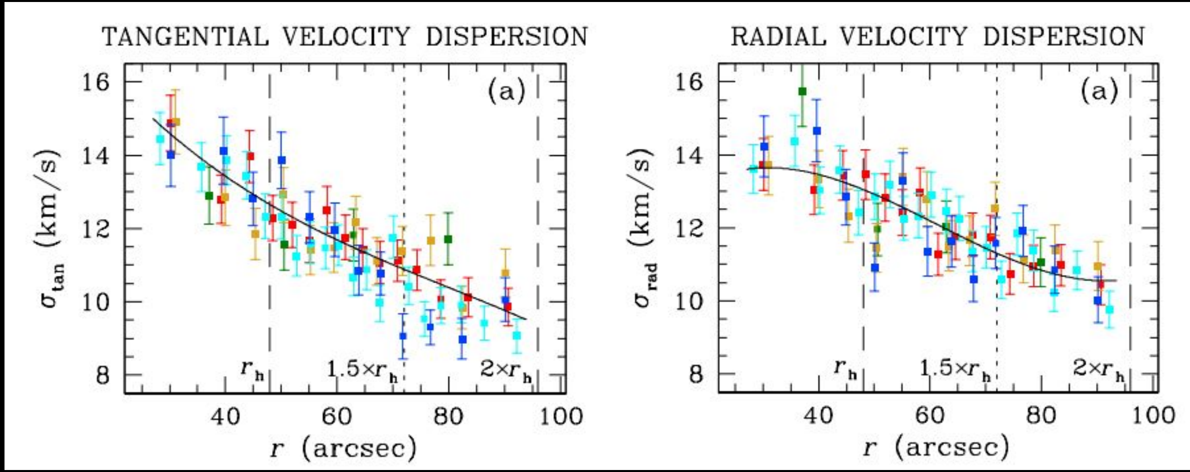
Because it would be *great* to have some physical insight on the degree of anisotropy (and rotation), whenever we make an inference based on density and/or kinematic slopes!

Why now?

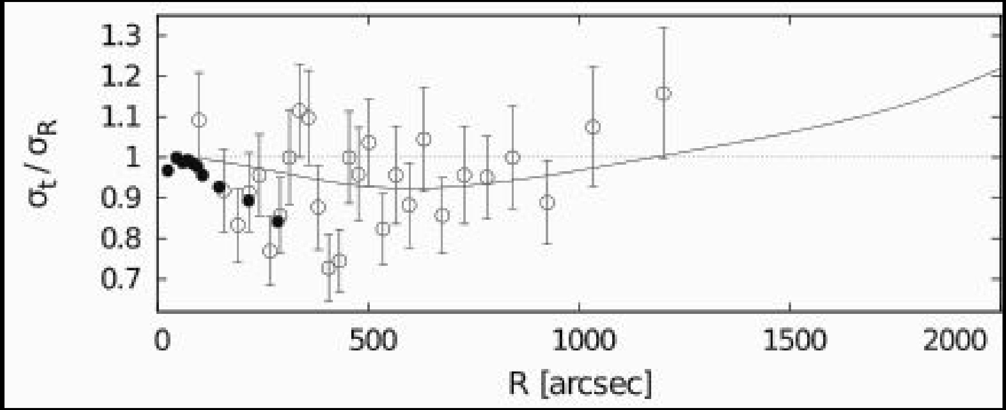
Synergy between Gaia and HST proper motion studies, supplemented by high-quality radial velocities (Gaia-ESO)

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

New "golden age" for star cluster dynamics is about to start!



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



ω Cen | Bianchini et al. 2013 [PM: van Leeuwen+ 2000 (HIPPARCOS), Anderson & van der Marel 2010 (HST)]

Two statements

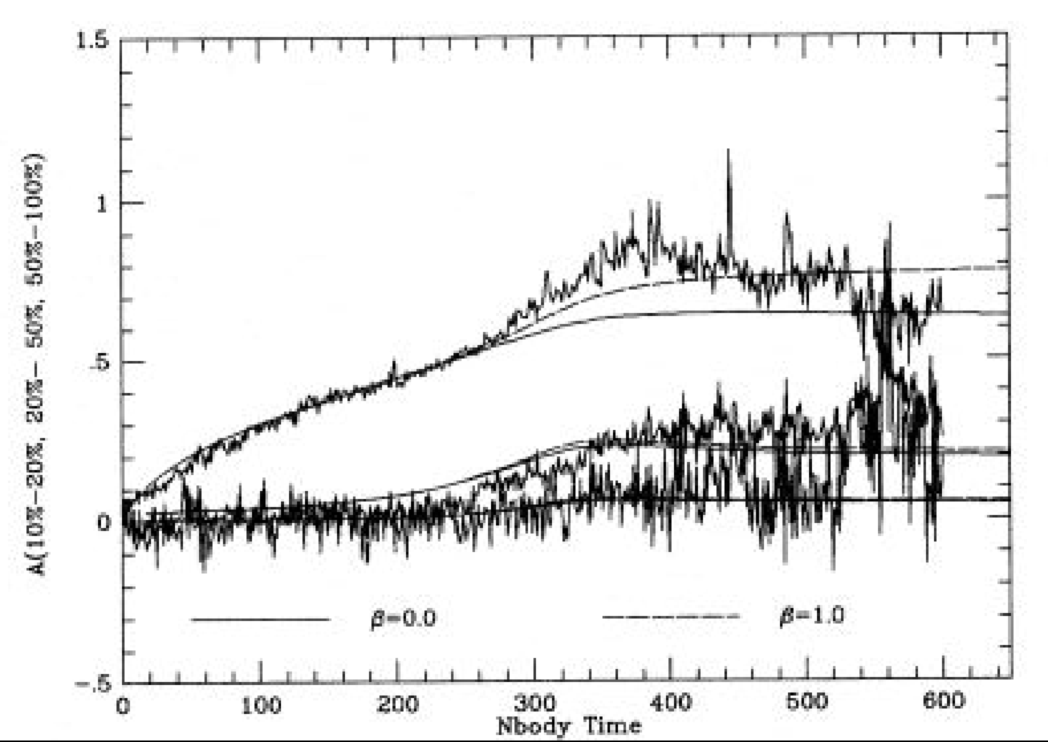
and one question

#1

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

Anisotropy as a natural outcome of long-term dynamical evolution for isolated systems:

radial anisotropy in the outer regions



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

Anisotropic models - I

$$f = Ae^{-aE_0}[e^{-a(E-E_0)} - 1]e^{-\beta J^2} \quad E < E_0$$

On the distribution of high energy stars in spherical stellar systems
1963, MNRAS, 125, 127

Anisotropic models - I

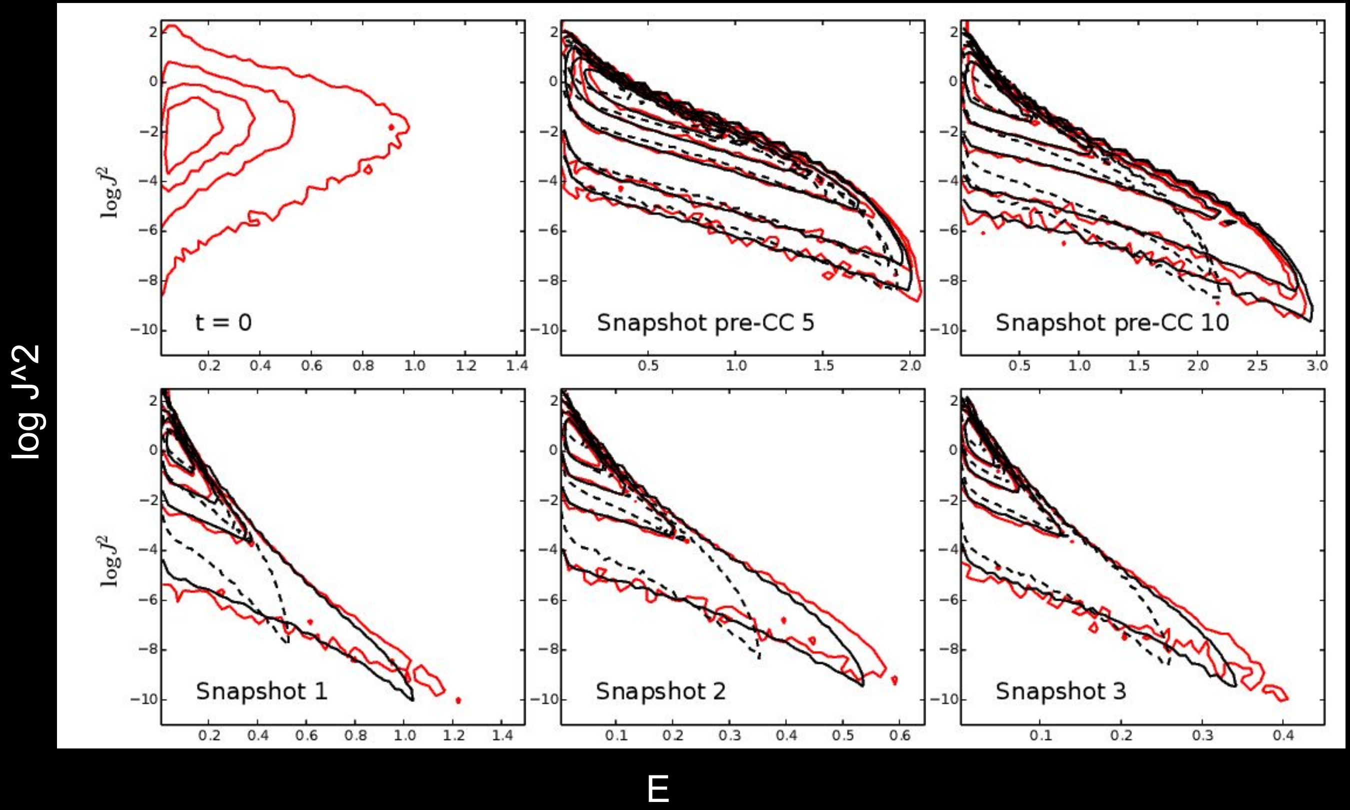
$$f = Ae^{-aE_0}[e^{-a(E-E_0)} - 1]e^{-\beta J^2} \quad E < E_0$$

$$f = A\exp\left(-\frac{J^2}{2r_{\rm a}^2 s^2}\right) E_\gamma\left(g, -\frac{E-\phi(r_{\rm t})}{s^2}\right) \qquad E \leqslant \phi(r_{\rm t}).$$

A family of lowered isothermal models
2015, MNRAS, 454, 576

Comparison between DF-based models and N-body simulation.

Growth of radial anisotropy and central concentration

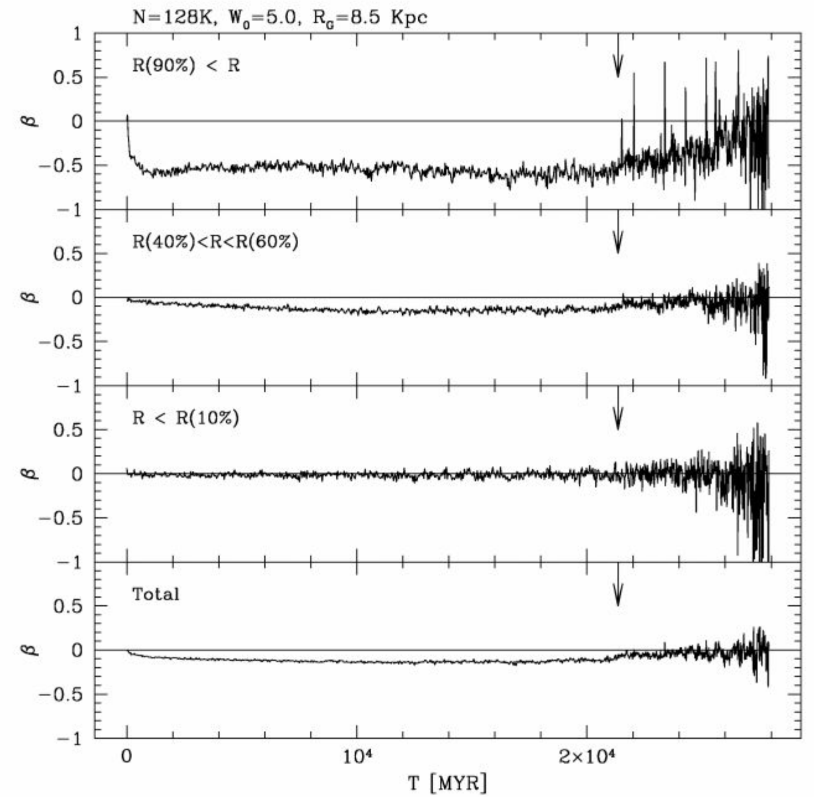





Testing lowered isothermal models with direct N-body simulations of globular clusters
2016, MNRAS, 462, 696

Anisotropy as a natural outcome of long-term dynamical evolution
for systems in a tidal field:

radial anisotropy in the intermediate part,
isotropy (tangentiality?)
in the outer regions



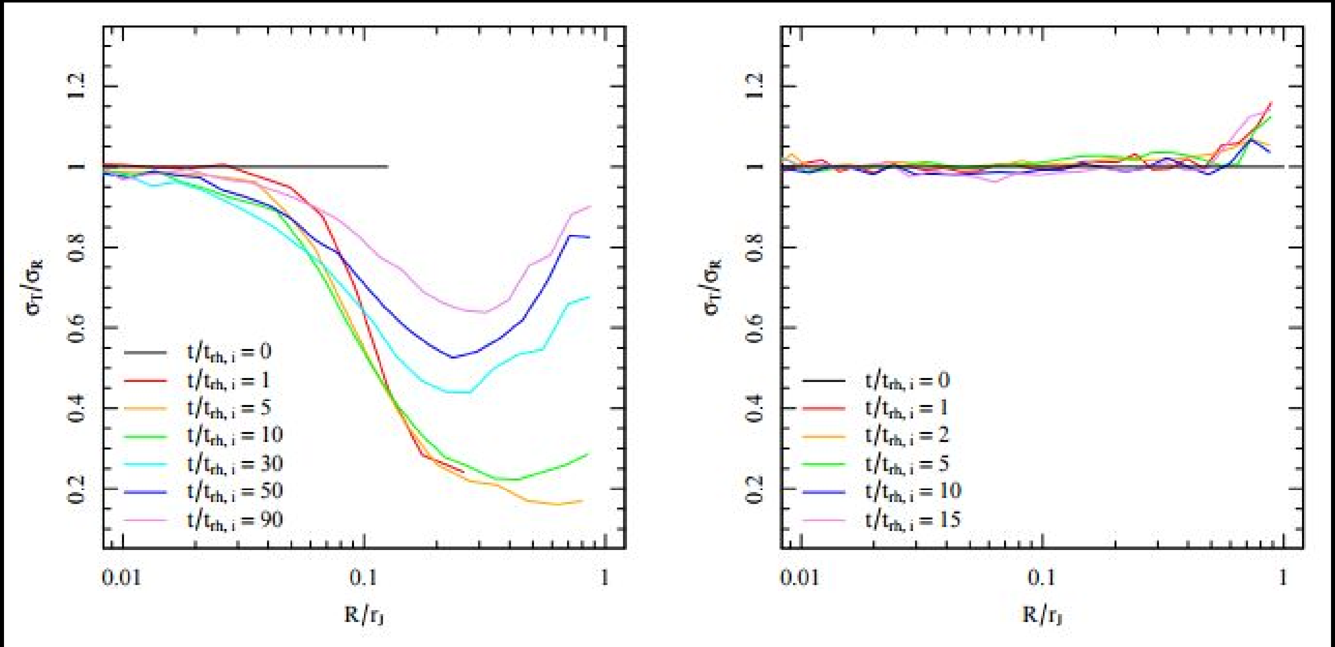
Dynamical evolution of star clusters in tidal fields
2003, MNRAS, 340, 227

Anisotropy as a natural outcome of long-term dynamical evolution:

anisotropy strength
linked to
the tidal regime

rh/rJ=0.015 (rt/rJ=0.125)

rh/rJ=0.116 (rt/rJ=1)

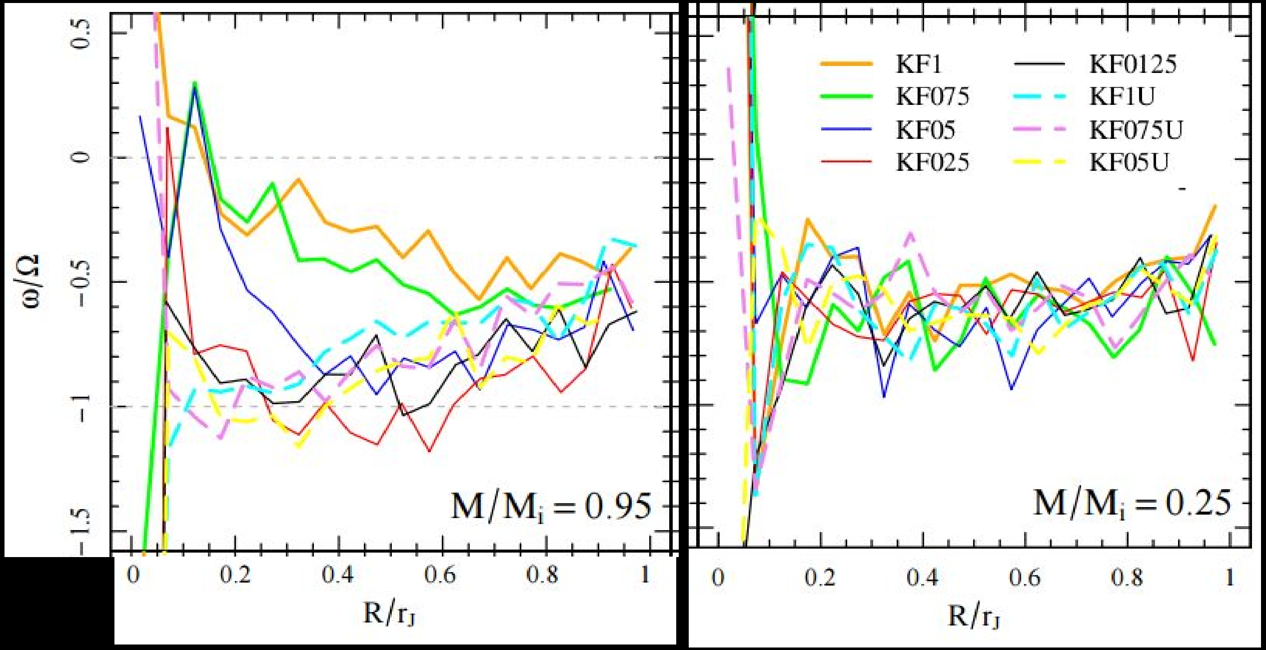




Velocity anisotropy in tidally limited star clusters
2016, MNRAS, 455, 3693

Rotation as a natural outcome of long-term dynamical evolution:

Angular velocity equal to about half of the angular velocity of the cluster orbital motion around the host galaxy



Kinematical evolution of tidally limited clusters: the role of retrograde stellar orbits
2016, MNRAS, 461, 402

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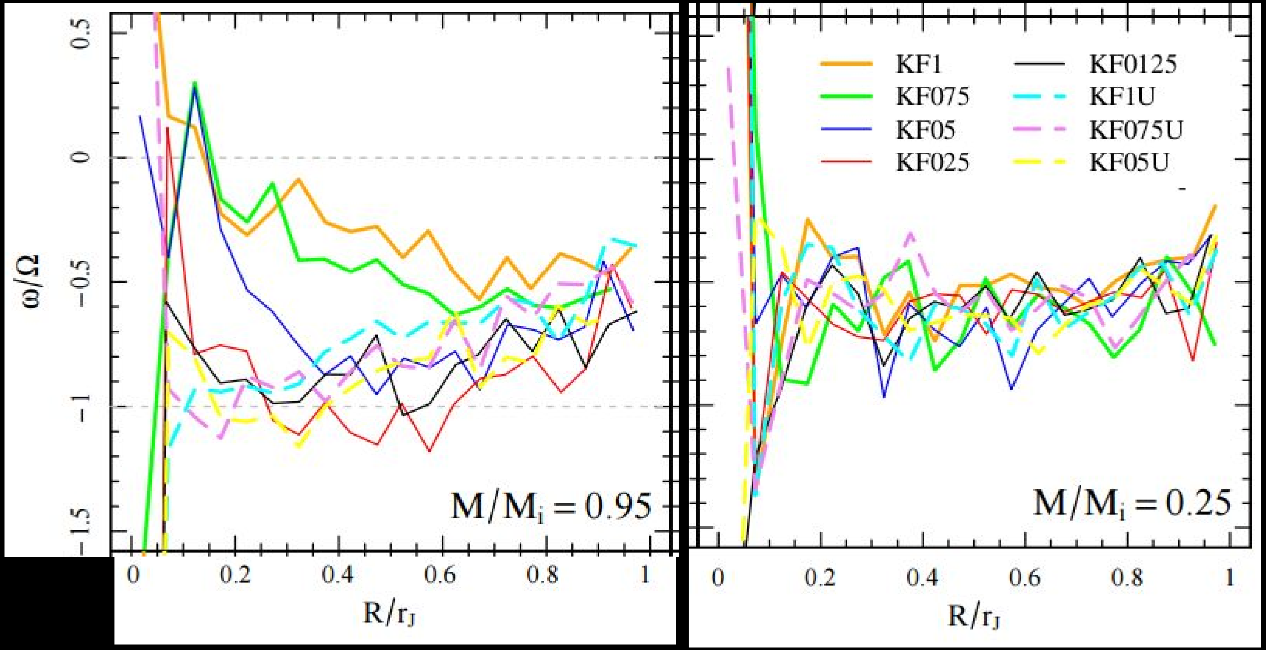
Angular velocity equal to about half of the angular velocity of the cluster orbital motion around the host galaxy



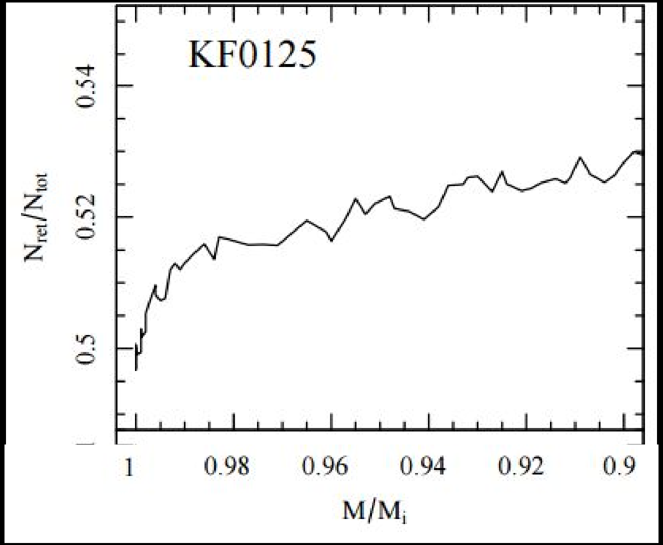


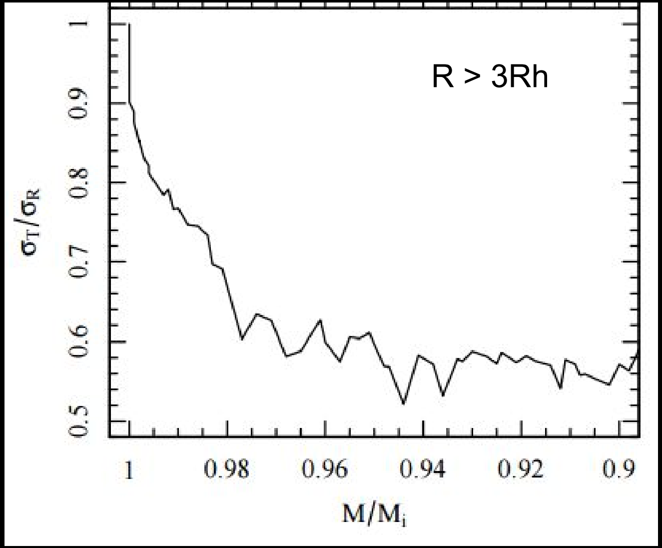
Kinematical evolution of tidally limited clusters: the role of retrograde stellar orbits
2016, MNRAS, 461, 402

See also Claydon, Gieles, Zocchi, MNRAS submitted (arXiv:1612.02253)

Prediction of Keenan & Innanen 1975 in action!
+
Increase of the fraction of retrograde orbits, without significant mass loss:

development of radial orbits, especially outer parts







Kinematical evolution of tidally limited clusters: the role of retrograde stellar orbits
2016, MNRAS, 461, 402

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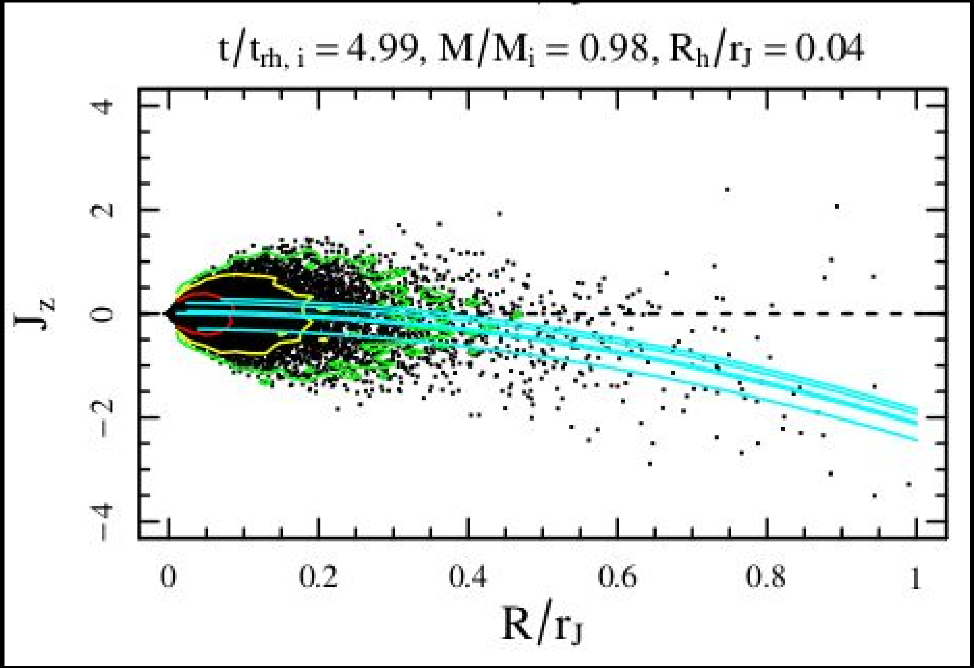
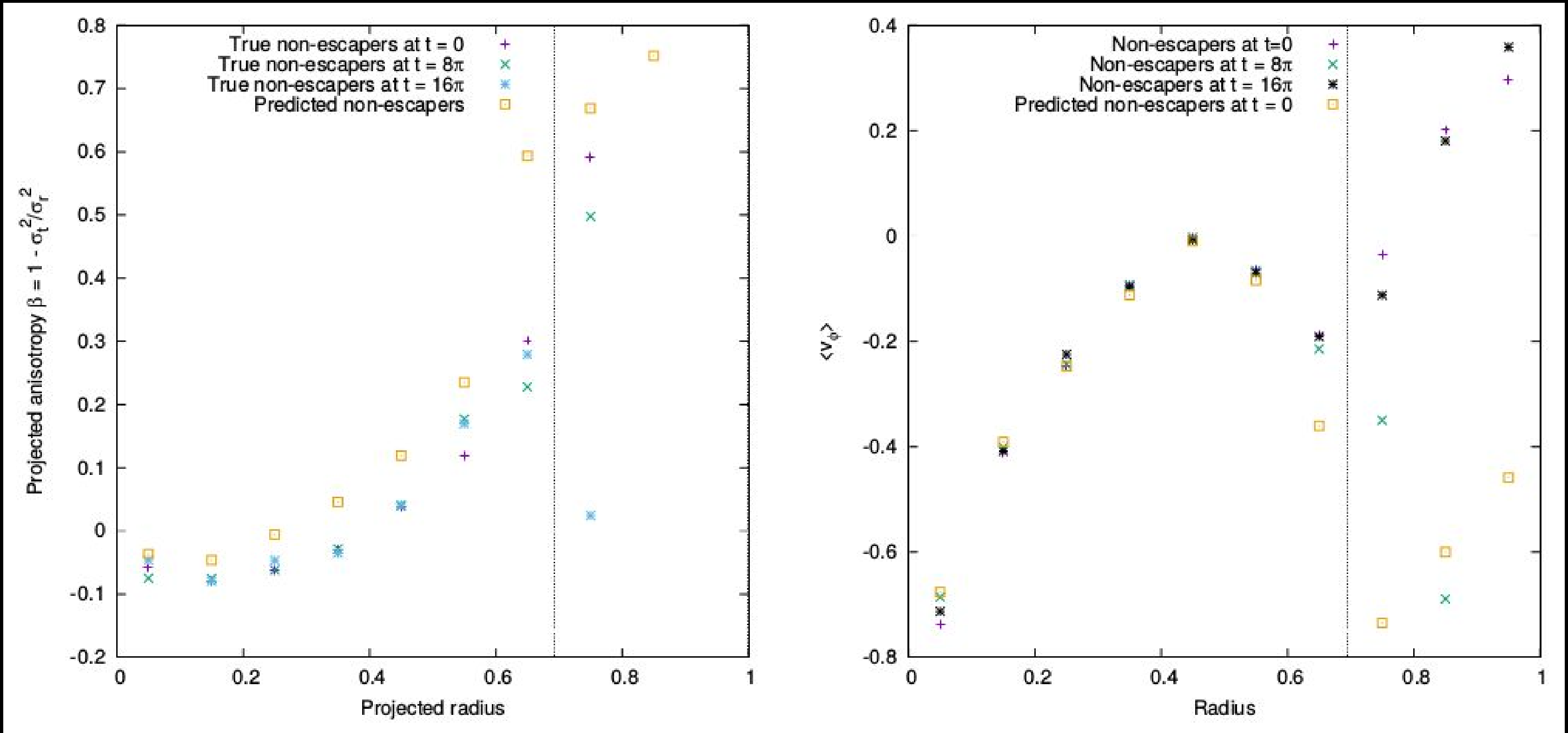


conservation of angular momentum ⟶ slowdown

Kinematical evolution of tidally limited clusters: the role of retrograde stellar orbits
2016, MNRAS, 461, 402



An approximate analytical model for a star cluster with potential escapers

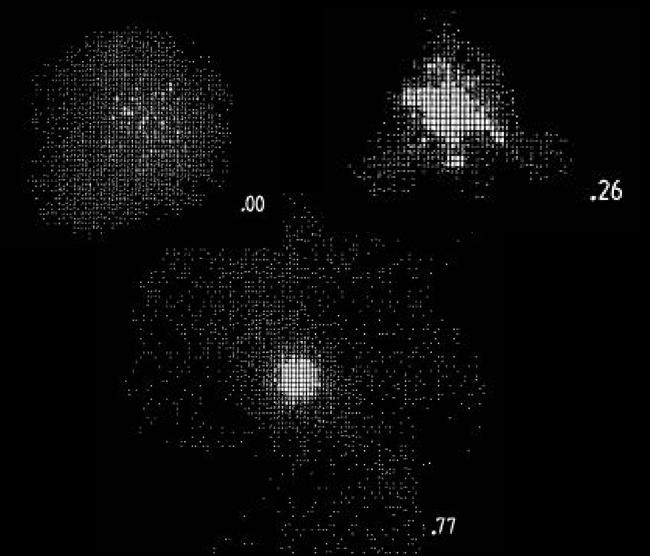
Under review

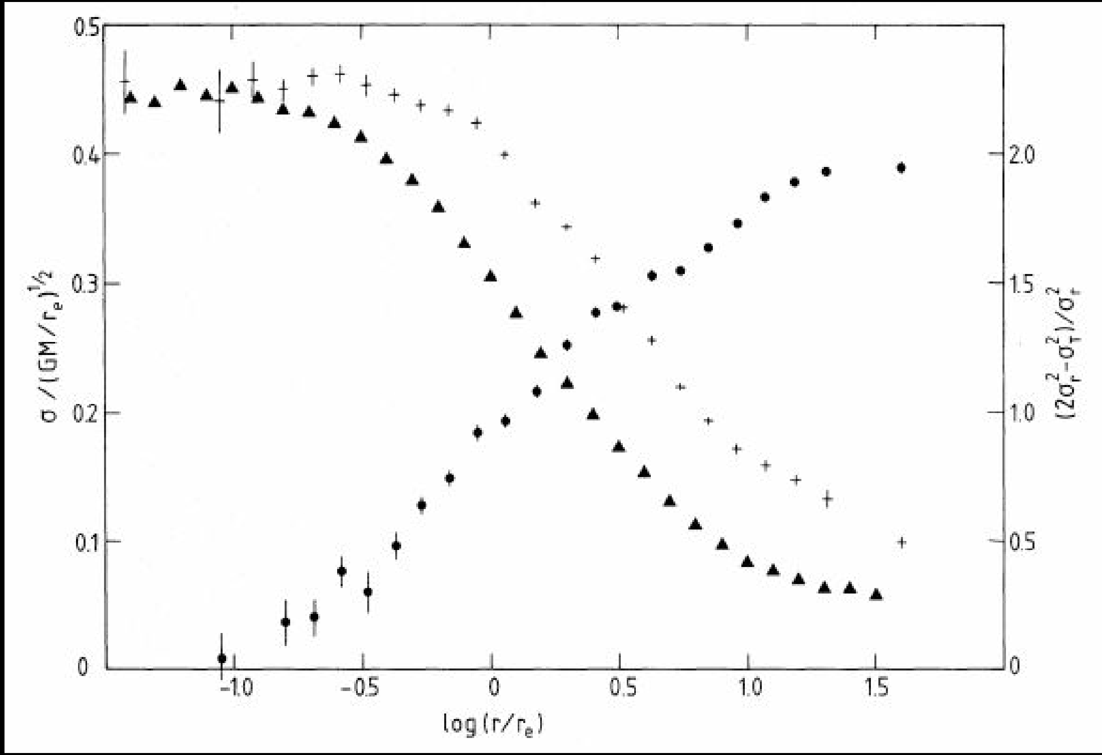
#2

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

* it much depends on their relaxation conditions, of course.

Anisotropy as a signature of the formation process for isolated systems



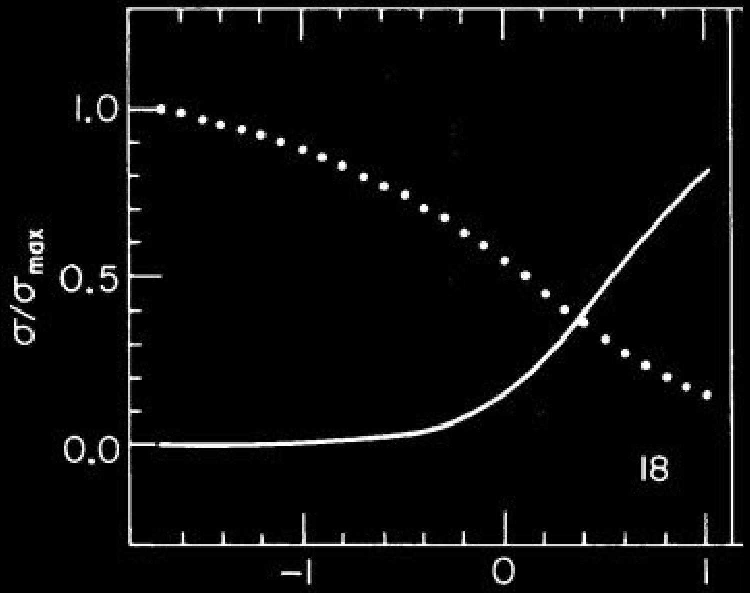


Dissipationless galaxy formation and R to the ¼ power law
1982, MNRAS, 201, 939

Anisotropic models - II

$$f_\infty = A(-E)^{3/2}\exp\left(-aE - b\frac{J_z^2}{2} - cI_3\right)$$

$$I_3 \sim \frac{(v_\theta^2 + v_\phi^2)\, r^2}{2} + \eta(\beta\cos\theta)$$

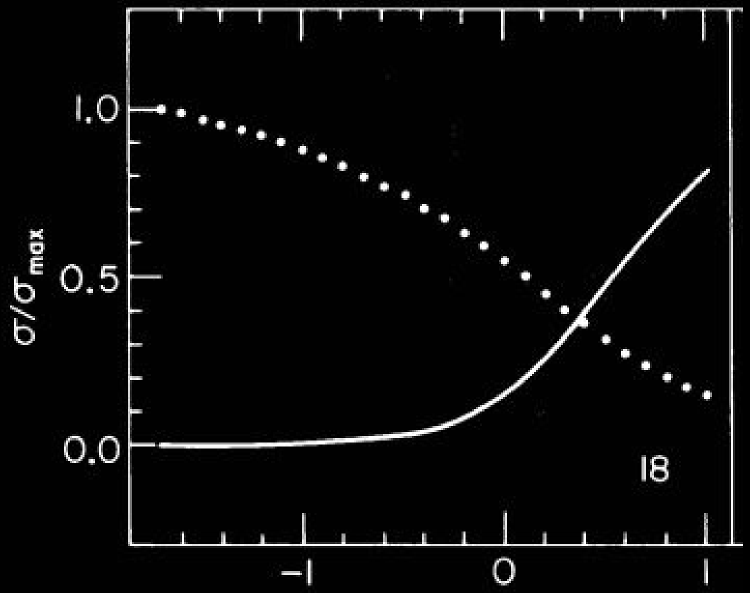


Statistical mechanics and equilibrium sequences of ellipticals
1985, MNRAS, 229, 61

Anisotropic models - II

$$f_\infty = A(-E)^{3/2}\exp\left(-aE - b\frac{J_z^2}{2} - cI_3\right)$$

$$f^{(\nu)} = A\exp\left[-aE - d\left(\frac{J^2}{|E|^{3/2}}\right)^{\nu/2}\right]$$



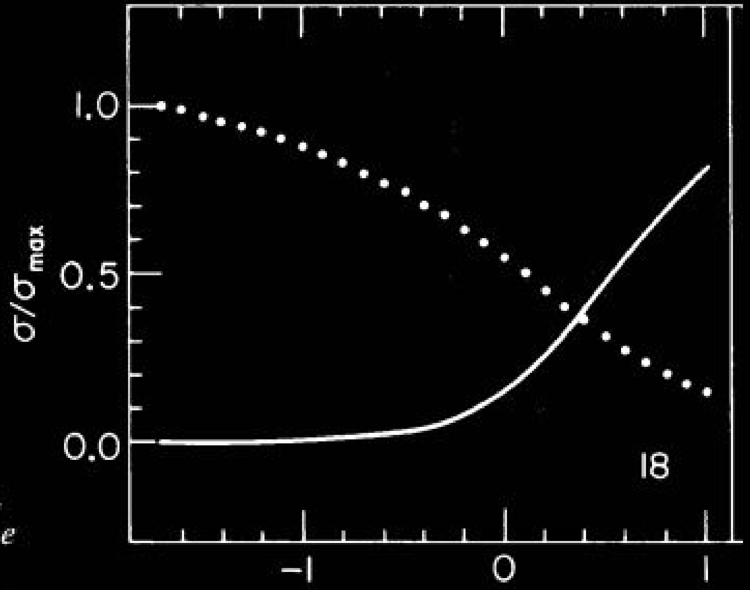
A family of models of partially relaxed stellar systems I - Dynamical properties
2005, A&A, 429, 161

Anisotropic models - II

$$f_{\infty} = A(-E)^{3/2}\exp\left(-aE - b\frac{J_z^2}{2} - cI_3\right)$$

$$f^{(\nu)} = A\exp\left[-aE - d\left(\frac{J^2}{|E|^{3/2}}\right)^{\nu/2}\right]$$

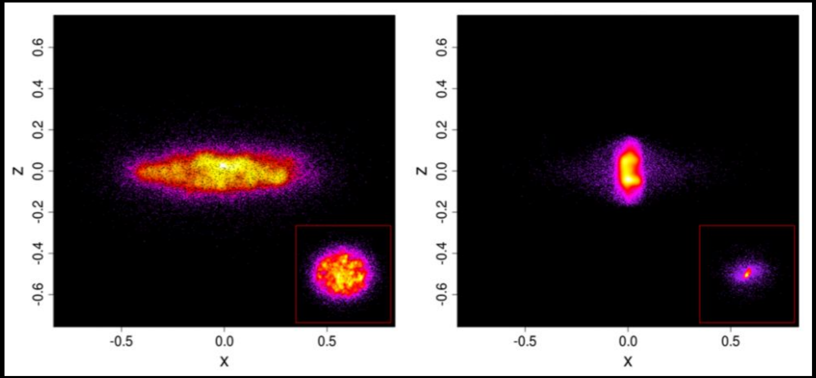
$$f_T^{(\nu)} = \begin{cases} A\exp\left[-a(E-E_e) - \frac{dJ}{|E-E_e|^{\frac{3}{4}}}\right] & \text{if } E < E_e \\ 0 & \text{if } E \geq E_e \end{cases}$$

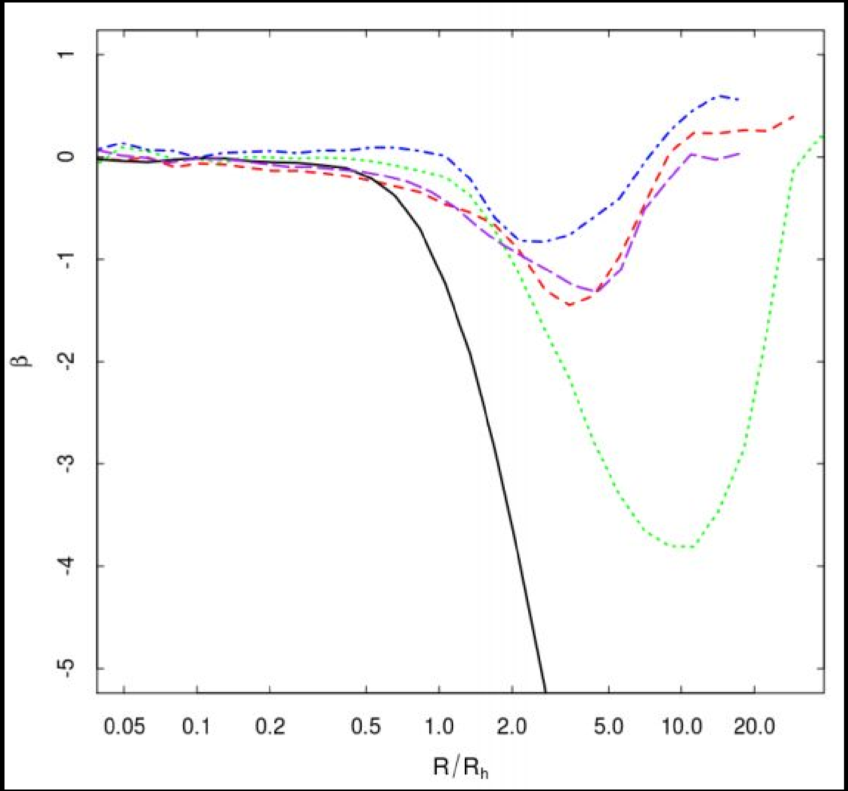




A class of spherical, truncated, anisotropic model for applications to GCs
2016, A&A, 590, 16

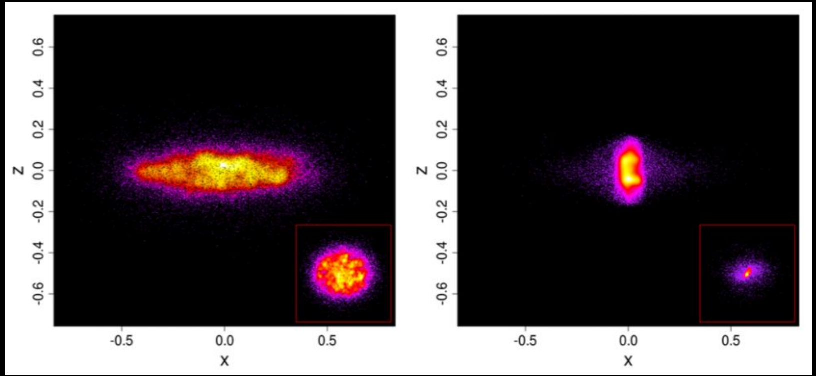
Anisotropy as a signature of the formation process for systems in a tidal field

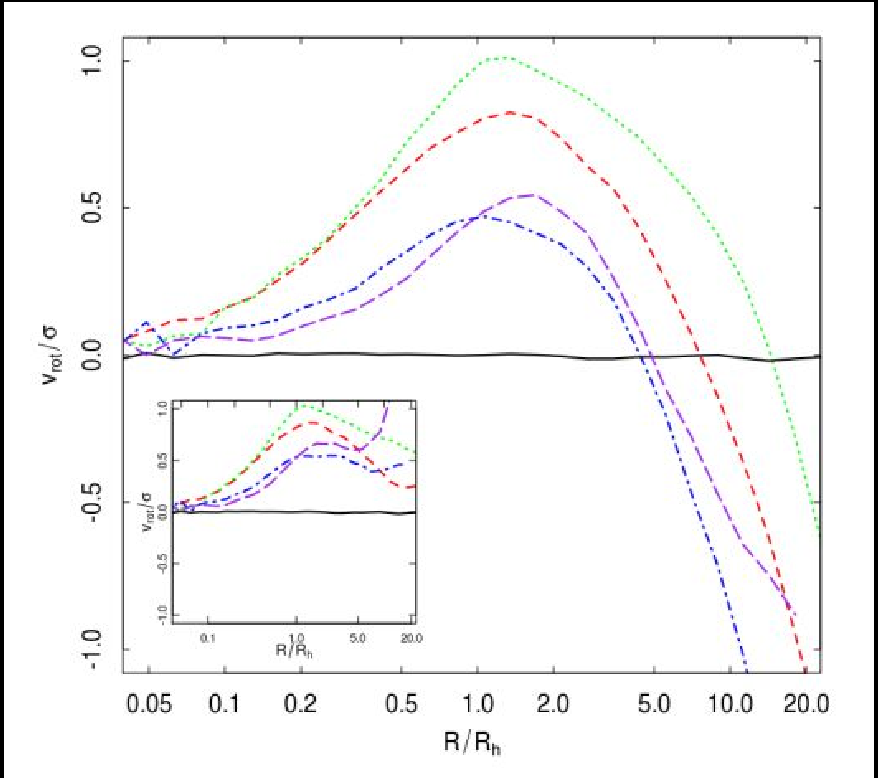




Kinematical fingerprints of star clusters early dynamical evolution
2014, MNRAS, 449, L79

… and a rotation curve naturally appears!








Kinematical fingerprints of star clusters early dynamical evolution
2014, MNRAS, 449, L79

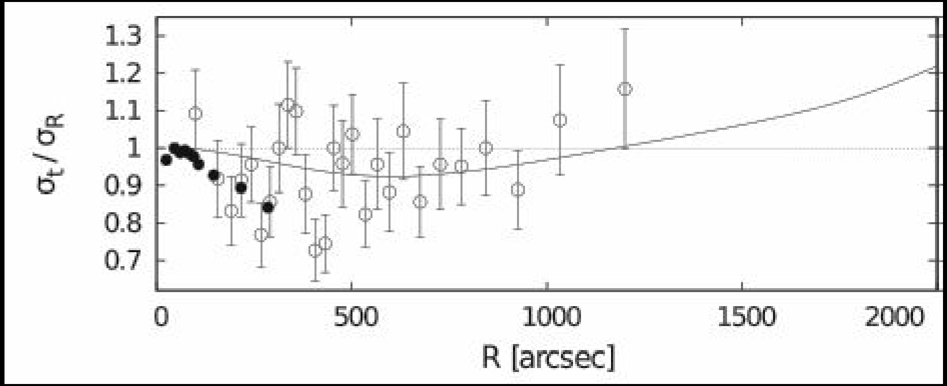
Differentially rotating models (= rotation + anisotropy)

$$f^{d}_{WT}(I) = A\mathrm{e}^{-aE_0}\left[\mathrm{e}^{-a(I-E_0)} - 1 + a(I - E_0)\right] \qquad E < E_0$$

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

$$I \sim H = E - \omega J_z \qquad \text{for low } |J_z|$$

$$I \sim E \qquad \text{for high } |J_z|$$



Bianchini, Varri, Bertin, Zocchi [Omega Centauri]
Rotating Globular Clusters, 2013, ApJ, 772, 67

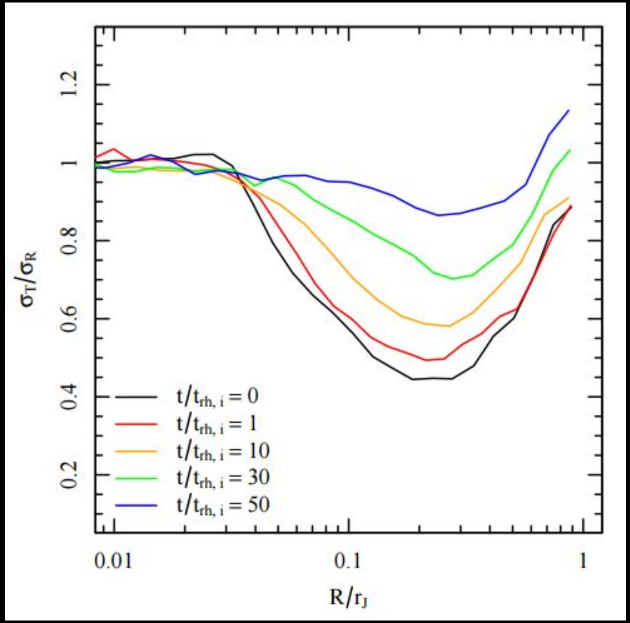
Self-consistent models of quasi-relaxed rotating stellar systems
2012, A&A, 540, 94

#3

What does it happen when collisional systems with non-trivial initial kinematics are evolved?

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

rL/rJ=0.2



If the initial anisotropy was induced by the tidal field, the evolution is almost self-similar!

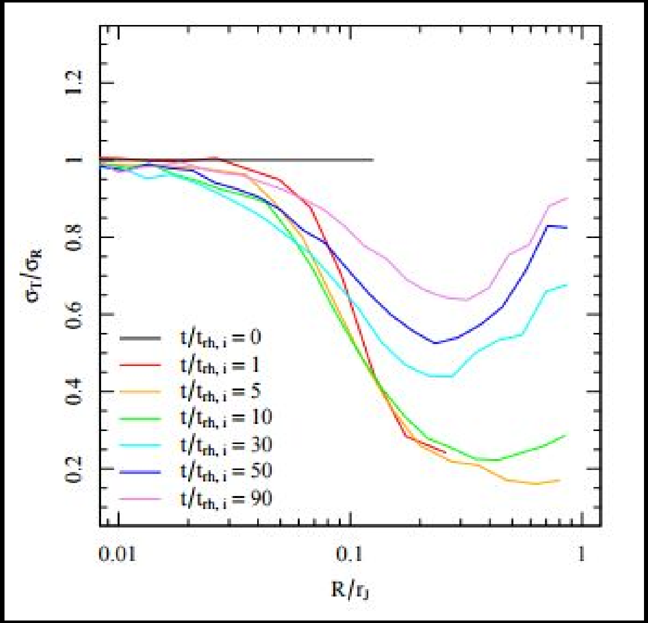
Initial conditions from violent relaxation in tidal field

Velocity anisotropy in tidally limited star clusters
2016, MNRAS, 455, 3693

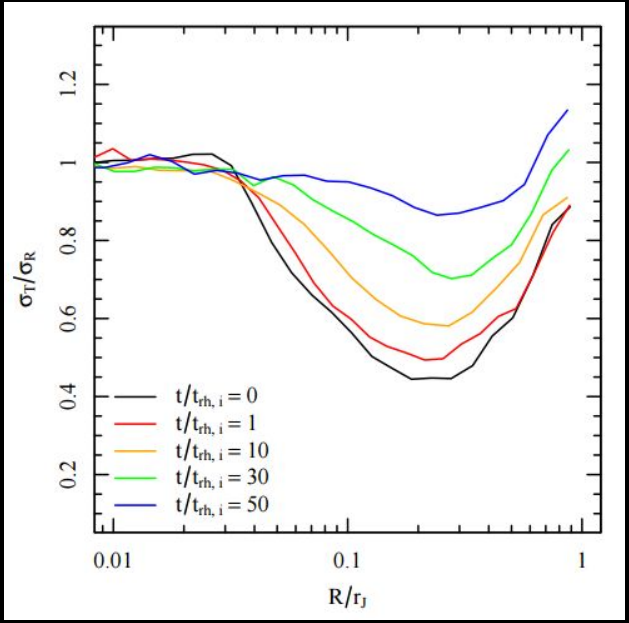
If the initial anisotropy was induced by the tidal field, the evolution is almost self-similar!

Initial conditions from violent relaxation in tidal field

rh/rJ=0.015 (rt/rJ=0.125)



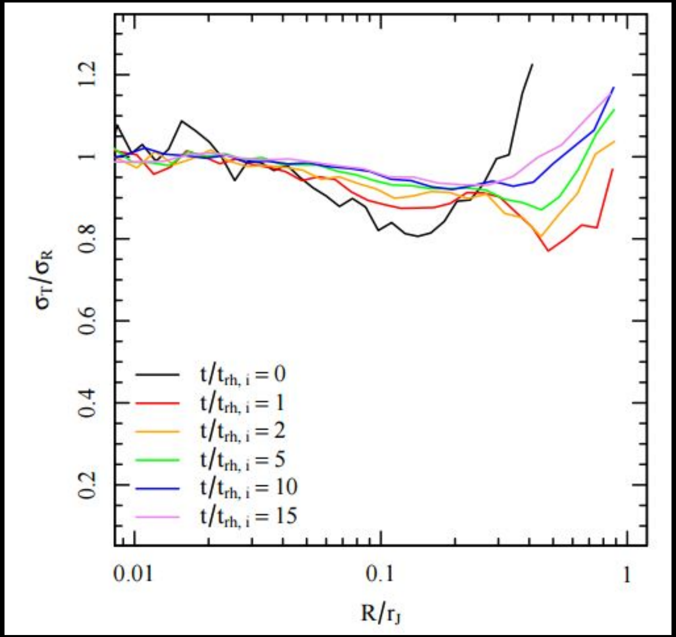
rL/rJ=0.2





Velocity anisotropy in tidally limited star clusters
2016, MNRAS, 455, 3693

rh/rJ=0.116 (rt/rJ=0.5)



… otherwise,
it leaves an imprint
for many
relaxation times

Initial conditions from
differentially rotating models



Velocity anisotropy in tidally limited star clusters
2016, MNRAS, 455, 3693

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… otherwise,
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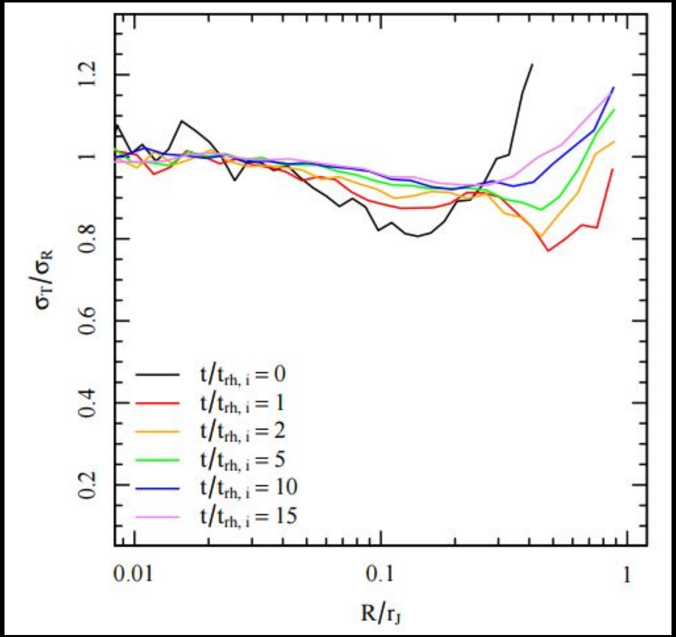

Initial conditions from
differentially rotating models

Several other effects
of angular momentum
on the formation
and dynamical evolution
of collisional systems.

If you wish to know more,
just ask!

But brace yourself for a long conversation
about violent relaxation,
gravogyro catastrophe
and much more.

Velocity anisotropy in tidally limited star clusters
2016, MNRAS, 455, 3693

… and if you think to know what happens
to initially anisotropic *isolated* systems,

well, think again!



Core collapse times in anisotropic Plummer models
Poster, to be written up soon …

Kinematic properties of star clusters are a non-trivial product of their formation *and* evolution

(especially when tidally perturbed)

Signatures of the tidal field in the 3D velocity space may be long-lived. Let's not waste them!

Soon available full phase space information *screams* for a proper treatment of physical ingredients traditionally considered as "second order complications". DF-based equilibria are a very natural tool.

Synergy between ground-based spectroscopic surveys and HST + Gaia PMs will be key. We are getting ready for it.

Interesting (new) science often lives at the intersections.

rotation $\cap$ anisotropy, anisotropy $\cap$ tides, rotation $\cap$ tides

Investigation of the role of "classical" physical ingredients is a key step to understand *any* dynamical signature of more complex phenomena in star clusters (e.g., IMBHs and MSPs)