The new phase space complexity of old globular clusters

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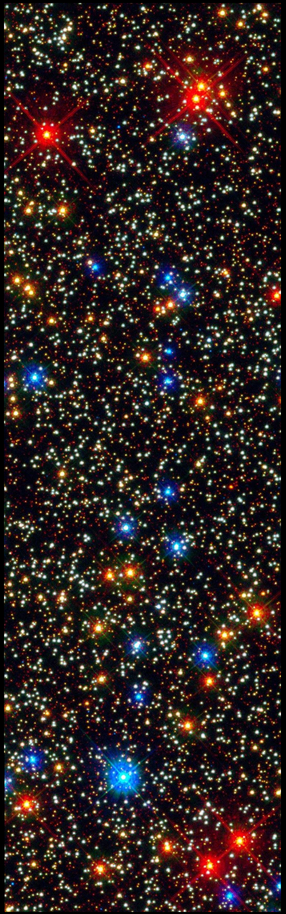
Michiko Fujii (Tokyo)

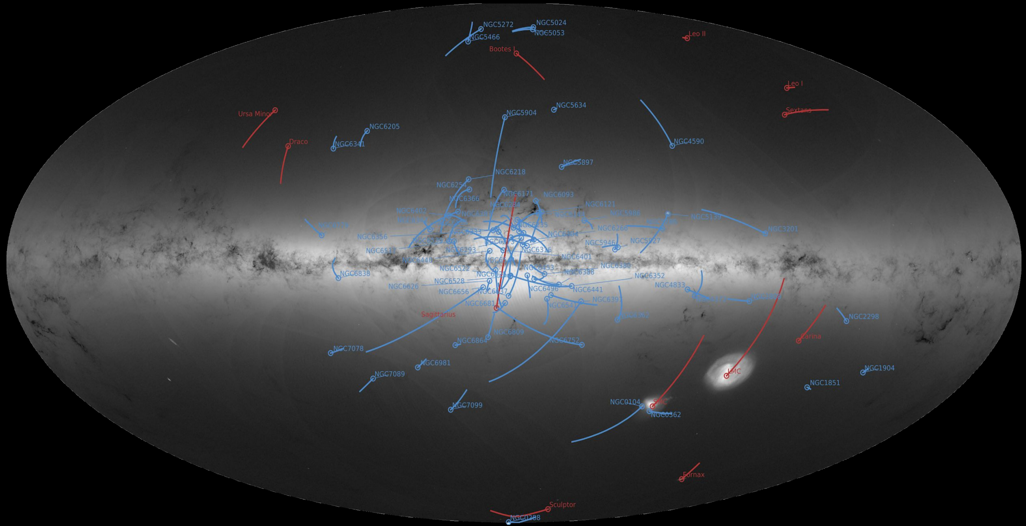


NASA, ESA, J. Anderson and R. van der Marel (STScI)

A new *‘golden age’*
for star cluster dynamics
has just started,
as determined by the alignment of
three transformative shifts
in Galactic studies

I. Observational revolution

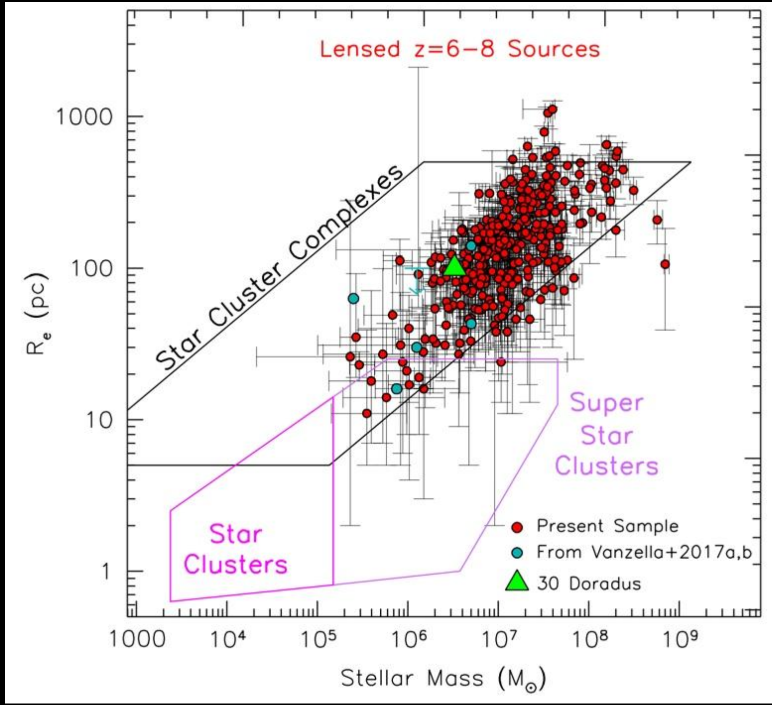
Local Universe (Gaia, HST)



Helmi et al. 2018 (Gaia DR2), plus many recent and upcoming studies

Synergy between Gaia and HST proper motions, plus high-quality spectroscopy (e.g., Gaia-ESO, WEAVE, MOONS, 4MOST ...) will **unlock for the first time the full phase space of several nearby GCs**

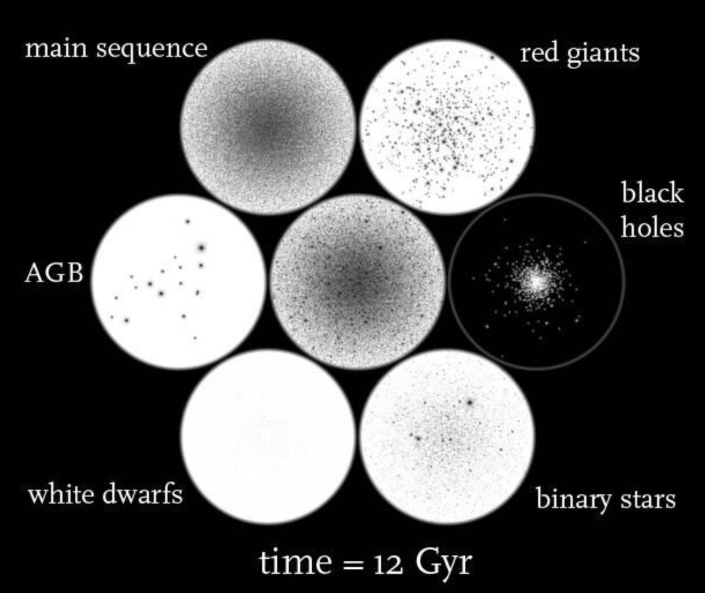
Early Universe (waiting for JWST, ELTs ...)



Star-forming sources in Hubble Frontier Field | Bouwens+ 2017a,b ApJ
see also Elmegreen^2 2017 ApJL, Vanzella+ 2017a,b ApJ ...

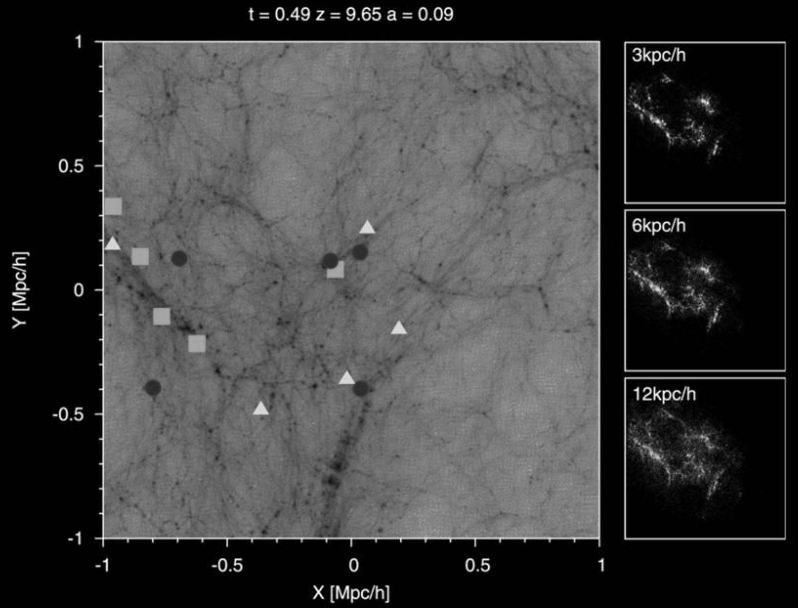
II. Computational revolution

Gravitational million-body problem 'solved'



DRAGON series of N-body simulations | Wang+ 2016 ApJ
N-body model of M4 (N=484710) | Heggie 2014 MNRAS
… thanks to NBODY6-GPU (Nitadori & Aarseth 2012) and 15+ years of GRAPE development!

Towards GC formation in a cosmological context



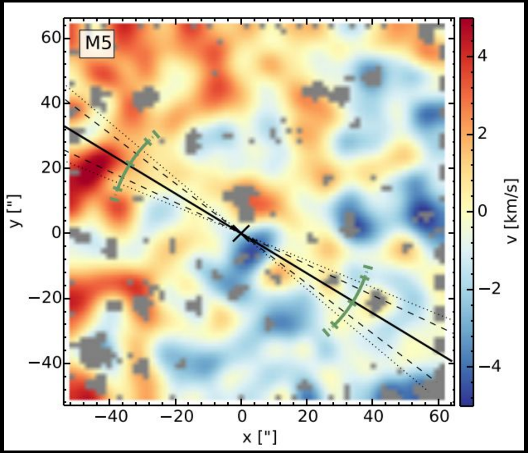
Evolution of GCs in CosmoGrid | Rieder+2013, Ishiyama+ 2013 MNRAS, Renaud+ 2017 MNRAS; Carlberg 2017 ApJ; Li, Gnedin^2 2017 ApJ

… also, role during reionization? Ricotti 2004, Boylan-Kolchin 2017a,b ...

III. Conceptual revolution

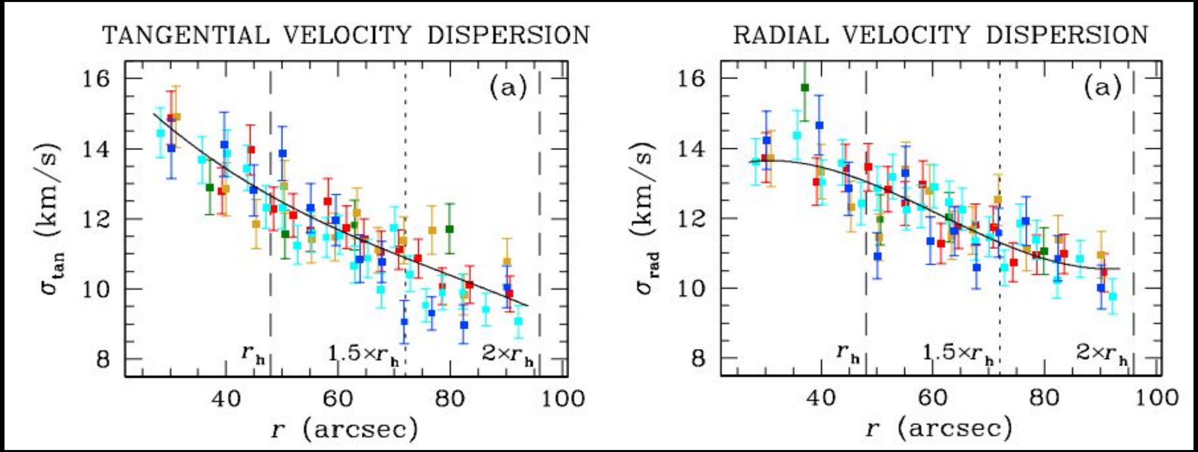
(a) New phase space laboratories: emerging kinematic complexity

Internal rotation



M5 | Fabricius+ 2014 ApJL,
Kamann+ 2018 MNRAS, Ferraro+2018 ApJ

Velocity anisotropy

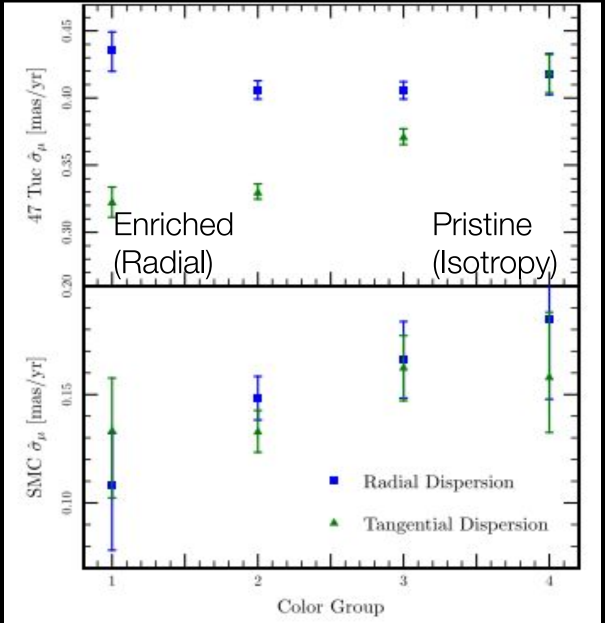


NGC 2808 | Bellini+ 2015 ApJL, see also Watkins+ 2015a,b ApJ and other HSTPROMO projects

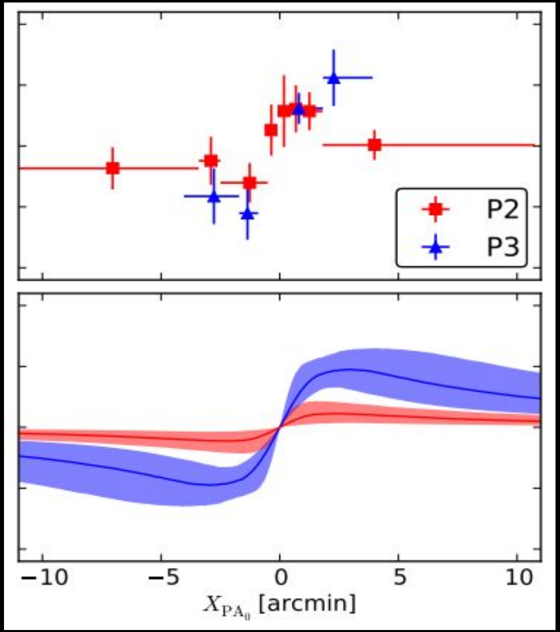
III. Conceptual revolution

(a) New phase space laboratories: emerging kinematic complexity

(b) Challenging chemodynamical puzzles: multiple stellar populations



47 Tuc | Richer+ 2013 ApJL
NGC 2808 | Bellini+ 2015 ApJL



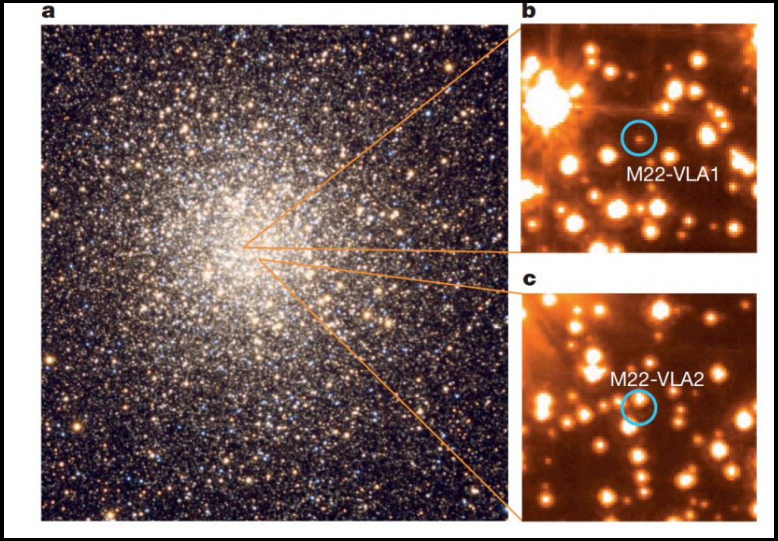
M13 | Cordero+ 2017 MNRAS

P2 = Moderate enrichment (slower rotation)

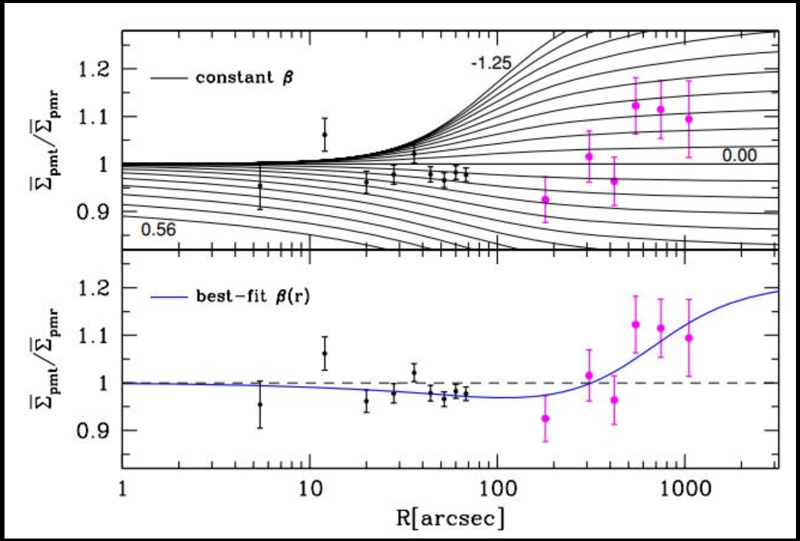
P3 = ‘Extreme’ enrichment (faster rotation)

III. 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



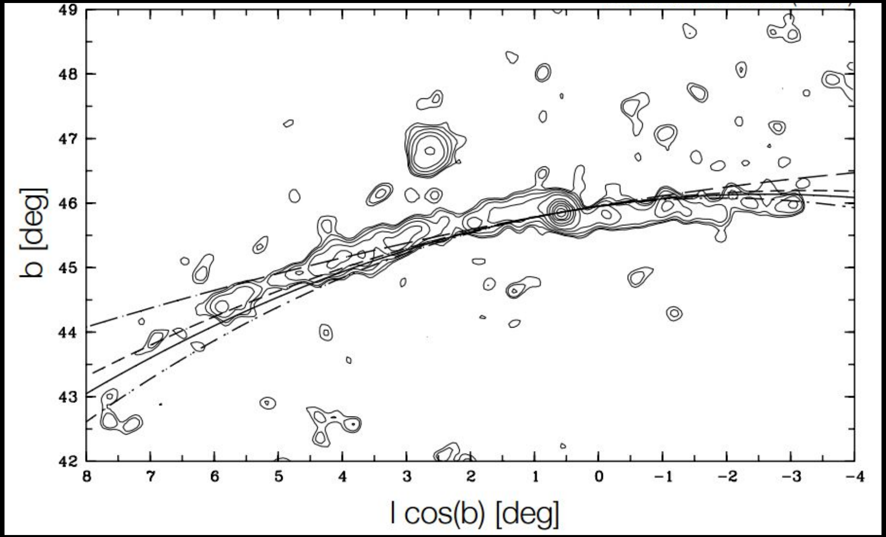
M22 | Strader+ 2012 Nature



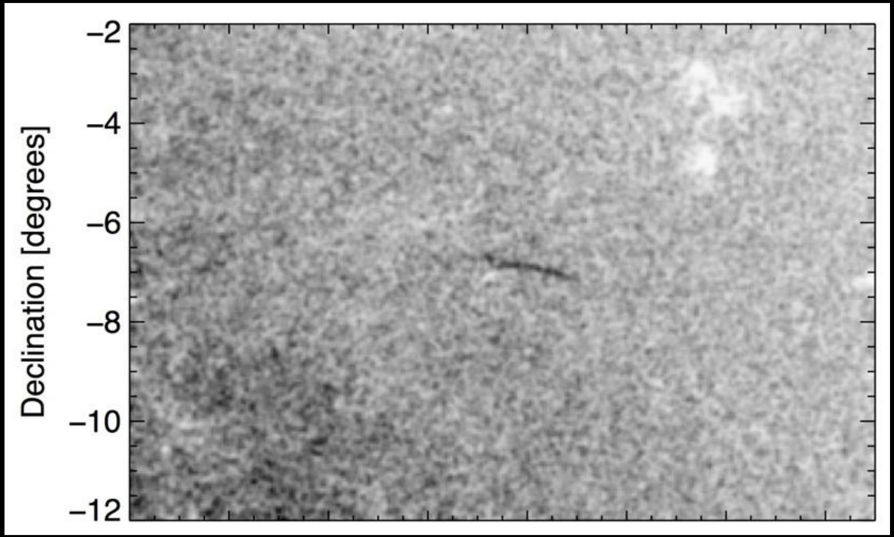
ω Cen | van der Marel & Anderson 2010 ApJ

III. Conceptual revolution

(a) New phase space laboratories: emerging kinematical 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 | Odenkirchen+ 2003, Kuepper+ 2015 MNRAS ...



New Ophiucus stream | Bernard, Ferguson+ 2014 (Pan-STARRS)

A programme to explore the fundamental implications of the new 'phase space richness' of (old) star clusters.

Goal 1: to understand and, ideally, discriminate between 'primordial' and 'evolutionary' features as determined by formation and evolution processes of collisional stellar systems, with focus on the effects of angular momentum, anisotropy, tides, and their interplay.

Goal 2: to fill the gap between the complex end state predicted by numerical simulations of star formation in a clustered environment and the extremely simplified initial conditions that are usually adopted to study the long-term evolution of star clusters.

Goal 3: to prepare the ground to *properly* understand the phase space signatures of more complex phenomena (MSPs, IMBHs?, DM?), in the era of Gaia + aLIGO + JWST.

Two *old* questions on the *new* “kinematic complexity”

angular momentum and pressure anisotropy

Old question #1

What are the stability properties of rotating, anisotropic spheroidal equilibria?

Old question #1

$$F_q(E,L) = \frac{3\Gamma(6-q)}{2(2\pi)^{\frac{5}{2}}\Gamma(q/2)} E^{\frac{7}{2}-q} H\left(0, \frac{1}{2}q, \frac{9}{2}-q, 1; \frac{L^2}{2E}\right)$$

Equilibria have the *same* (Plummer) structure,
and ‘controlled’ kinematics:

$$\sigma_r^2(r) = \frac{1}{6-q}\frac{1}{\sqrt{1+r^2}}$$

$$\beta = 1 - \frac{\sigma_\varphi^2}{\sigma_r^2} = 1 - \frac{\sigma_\theta^2}{\sigma_r^2} = \frac{q}{2}\frac{r^2}{1+r^2}$$

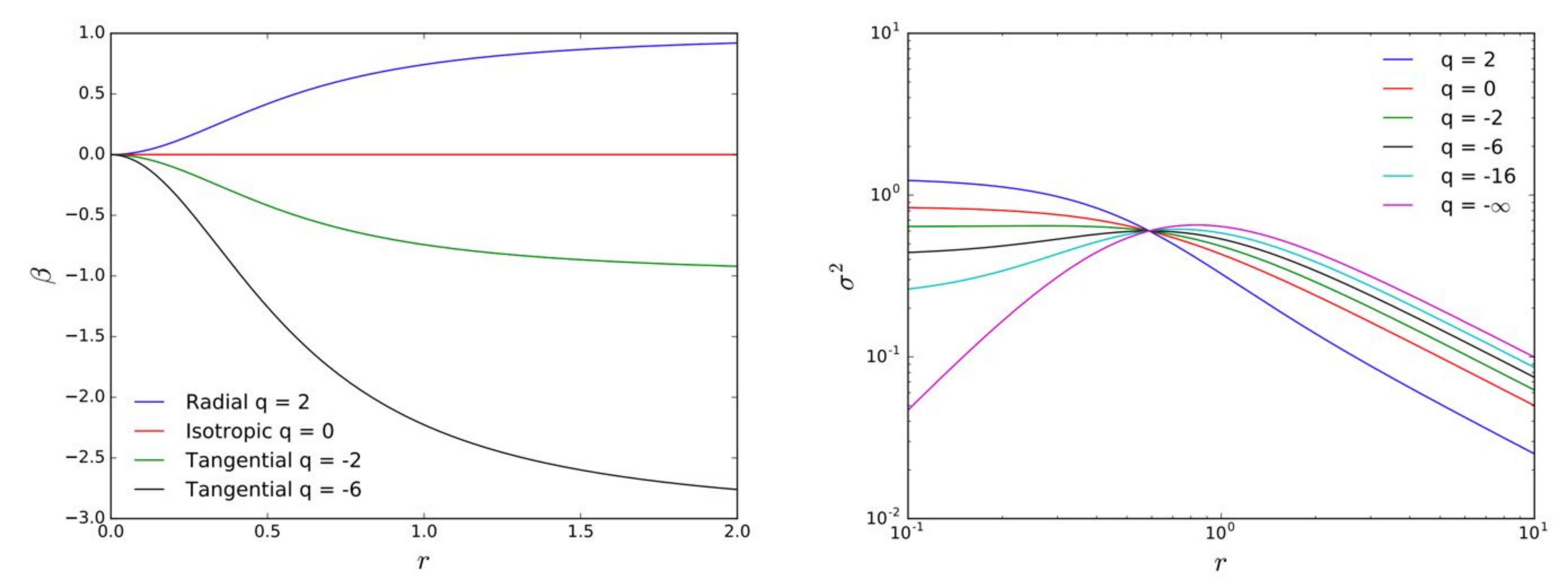
$$\sigma_\varphi^2(r) = \sigma_\theta^2(r) = \frac{1}{6-q}\frac{1}{\sqrt{1+r^2}}\left(1 - \frac{q}{2}\frac{r^2}{1+r^2}\right)$$

$q>0$ Radial
$q=0$ Isotropic
$q<0$ Tangential

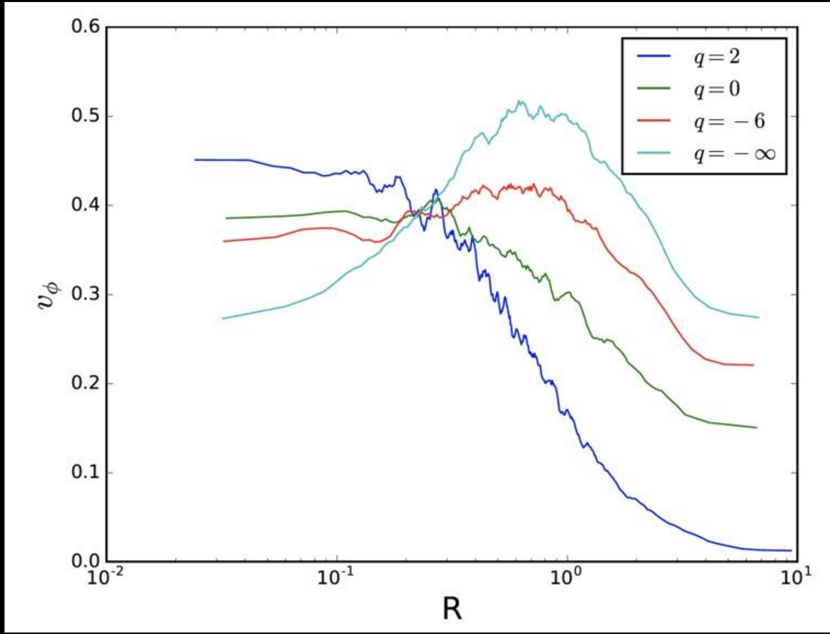
Limiting case (fully tangential): ‘Einstein sphere’
Radial regime may be extended ($q>2$) with Osipkov-Merritt’s Plummer spheres (but ROI unstable).

Old question #1

$$F_q(E,L) = \frac{3\Gamma(6-q)}{2(2\pi)^{\frac{5}{2}}\Gamma(q/2)} E^{\frac{7}{2}-q} H\left(0, \frac{1}{2}q, \frac{9}{2}-q, 1; \frac{L^2}{2E}\right)$$



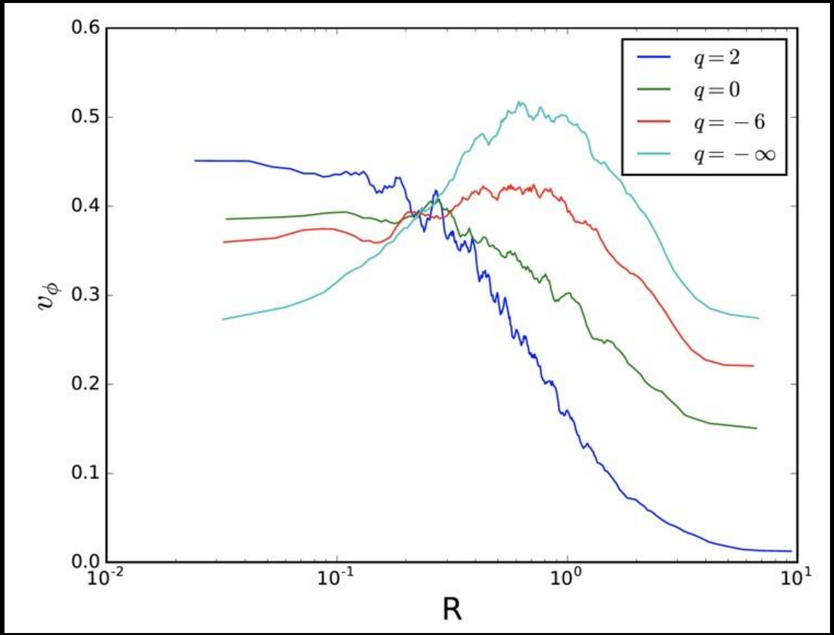
Old question #1



$$f(E, L_z) = \alpha(E, L)\mathcal{H}(L_z)f(E) - (1 - \alpha(E, L))\mathcal{H}(-L_z)f(E) \qquad |\alpha| \leqslant 1$$

https://github.com/pgbreen/PlummerPlus

Old question #1



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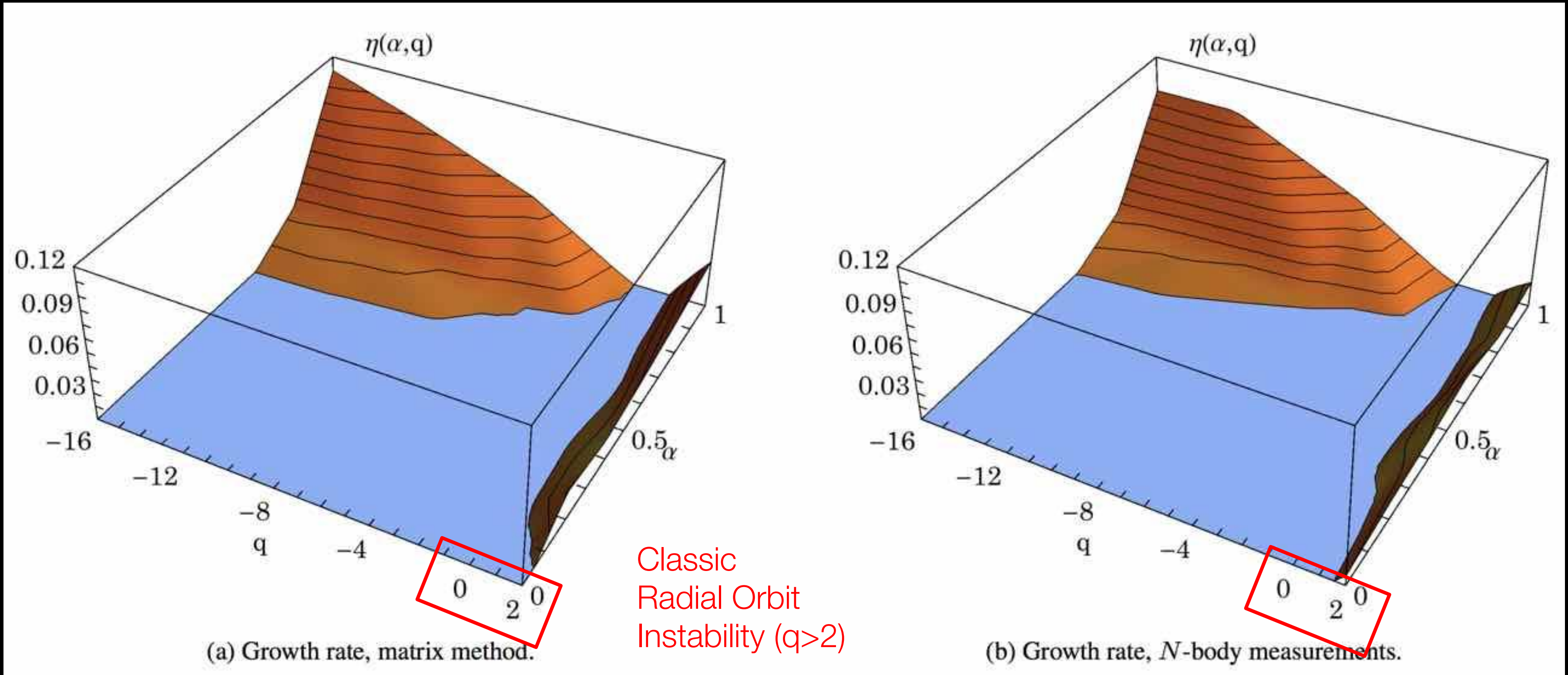
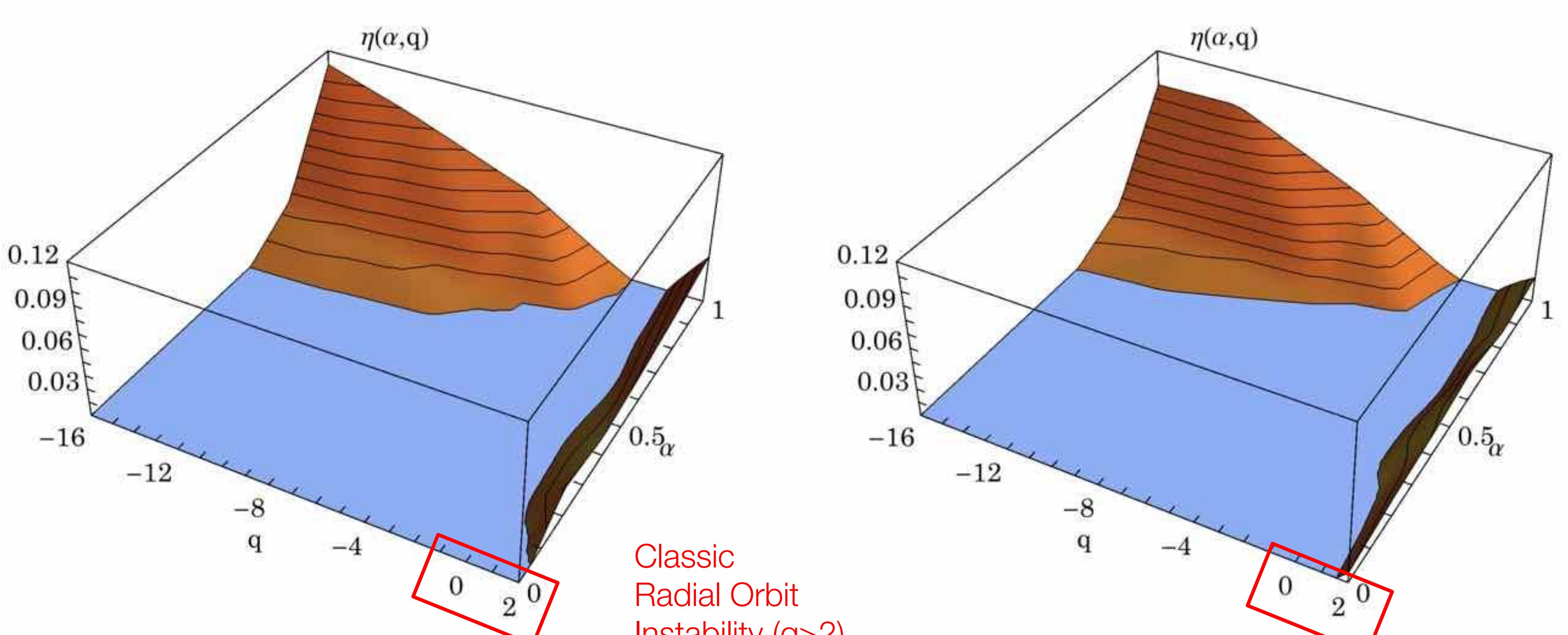


(a) Growth rate, matrix method.

(b) Growth rate, N-body measurements.

Rozier, Fouvry, Breen, Varri, Pichon, Heggie 2019 MNRAS

Old question #1



(a) Growth rate, matrix method.

(b) Growth rate, N-body measurements.

Rozier, Fouvry, Breen, Varri, Pichon, Heggie 2019 MNRAS

Old question #2

What are the implications of ‘kinematic complexity’ on the long-term evolution of collisional systems?

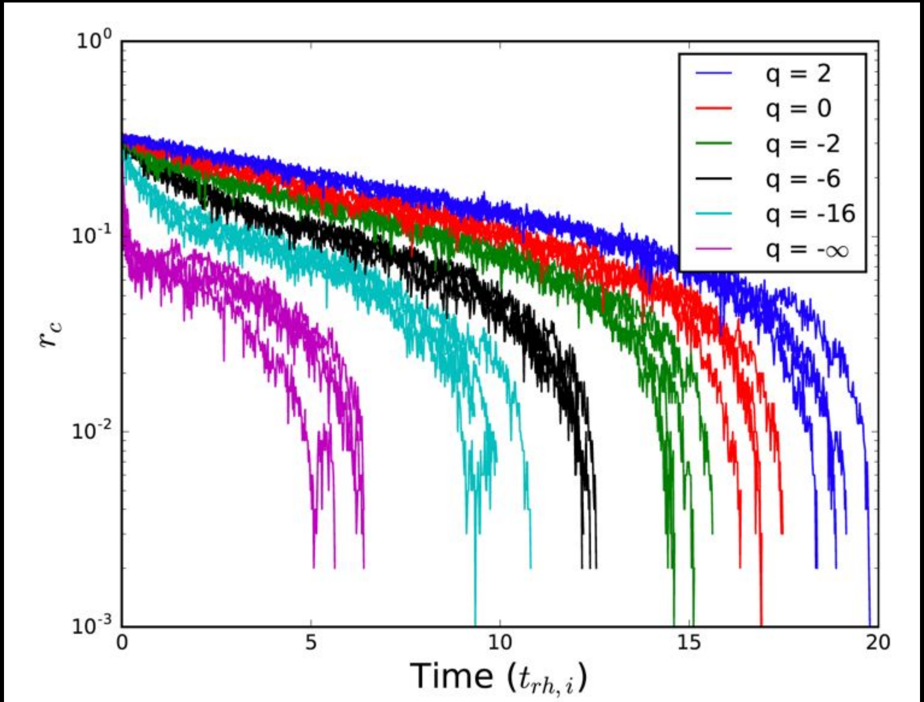
Old question #2

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)

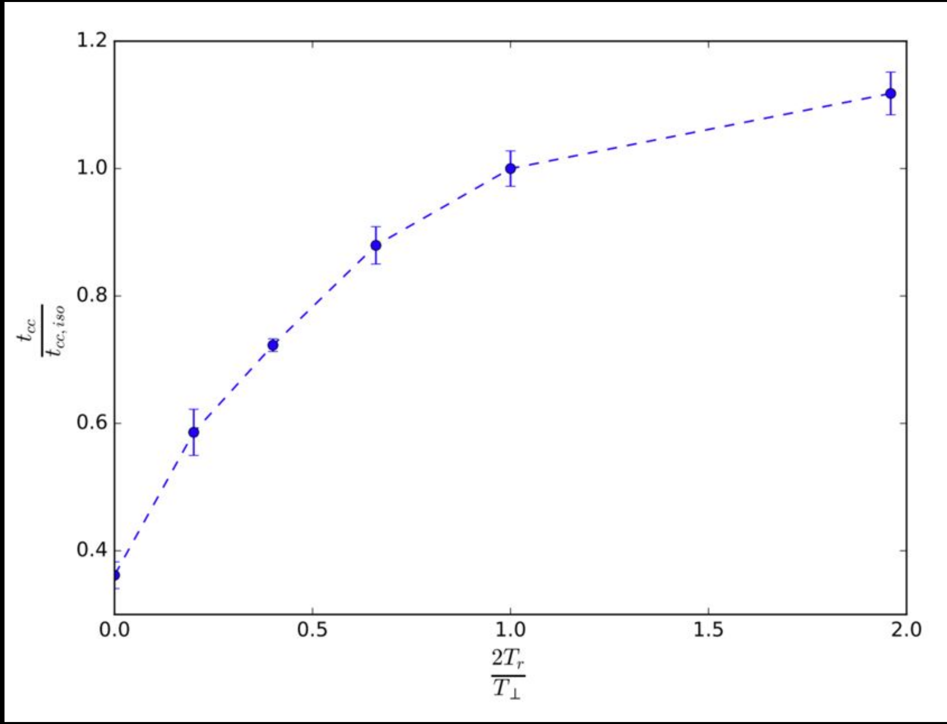
Non-rotating anisotropic spheres



Breen, Varri, Heggie 2017 MNRAS

Monotonic relation between core collapse time and flavour and strength of anisotropy

q	N	N_{rel}	t_{cc}	Δt_{cc}	$2T_r/T_\perp$
2	8192	4	19.05 ± 0.57	2.01	1.96
0	8192	4	17.04 ± 0.47	0.00	1.00
-2	8192	4	14.99 ± 0.50	-2.05	0.66
-6	8192	4	12.32 ± 0.17	-4.73	0.40
-16	8192	4	9.99 ± 0.62	-7.06	0.20
$-\infty$	8192	4	6.16 ± 0.36	-10.88	0.00



Formulation of a coherent theoretical picture, encompassing also the role of the angular momentum, currently in progress.

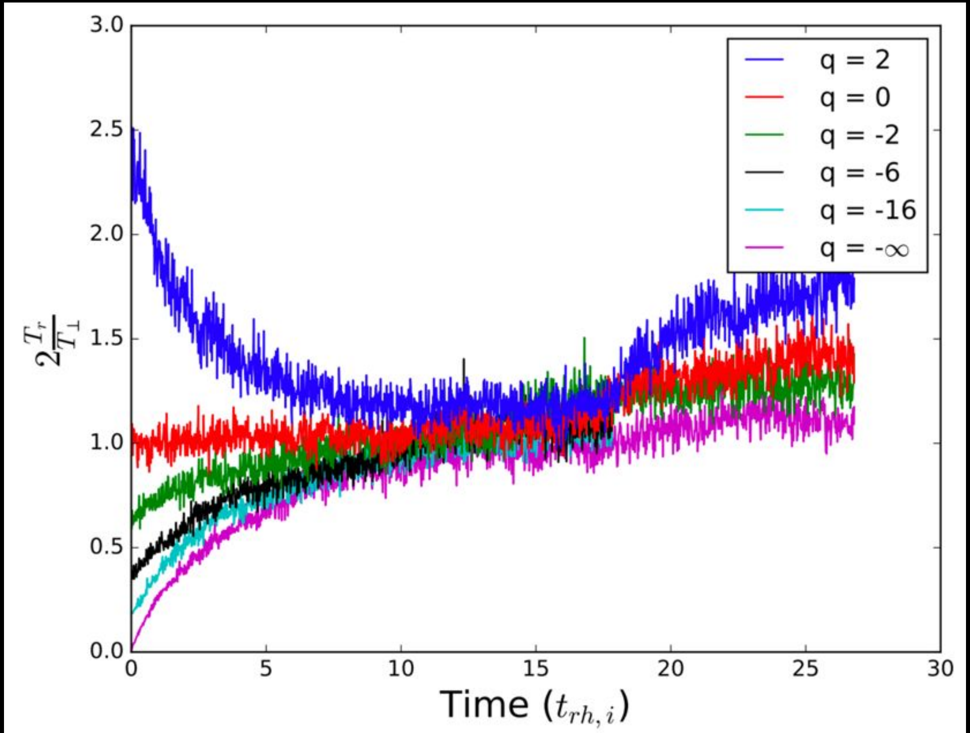
Breen, Varri, Heggie 2017 MNRAS (Part I)
Part II (spherical rotating anisotropic equilibria) in preparation

‘Primordial’ vs. ‘evolutionary’ anisotropy

(Possibly catastrophic) evolution towards isotropy, than subsequent generation of the usual ‘evolutionary’ radially-biased anisotropy, mainly in the outer region, in isolation.

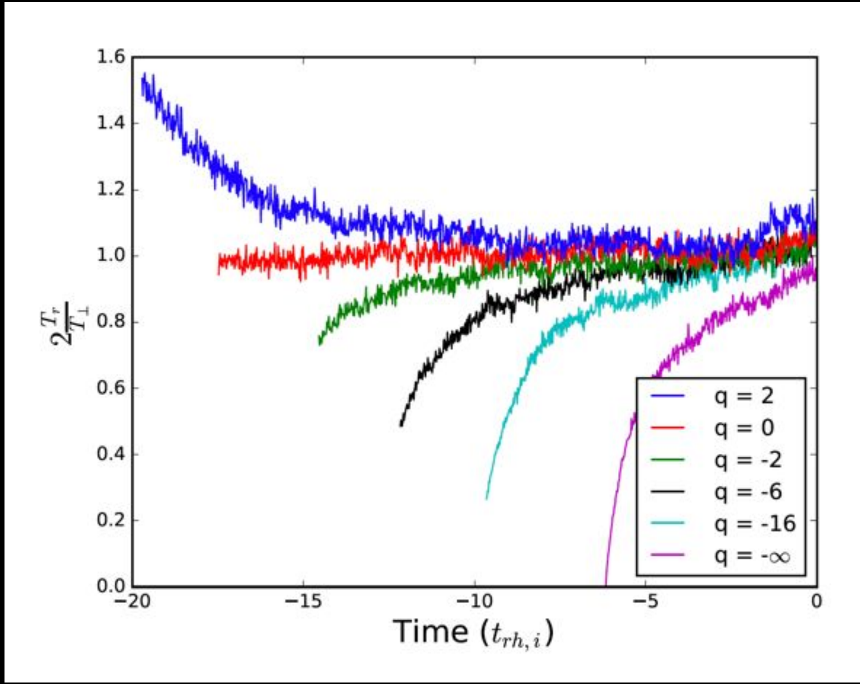
On ‘evolutionary’ anisotropy, as driven by two-body relaxation:
Henon 1971, Spitzer & Shapiro 1972, Bettwieser & Spurzem 1986, Spurzem 1991, Giersz & Heggie 1994, Takahashi 1995 ...
(in isolation);
Giersz & Heggie 1997, Takahashi et al. 1997, Baumgardt & Makino 2003, Tiongco et al. 2016, Zocchi et al. 2016 … (in a tidal field).

On ‘primordial’ anisotropy, as imprinted by various processes, e.g., ‘incomplete violent relaxation’:
van Albada 1982, Trenti, Bertin, van Albada 2005 ... (in isolation);
Vesperini, Varri, McMillan, Zepf 2014 (in a tidal field).

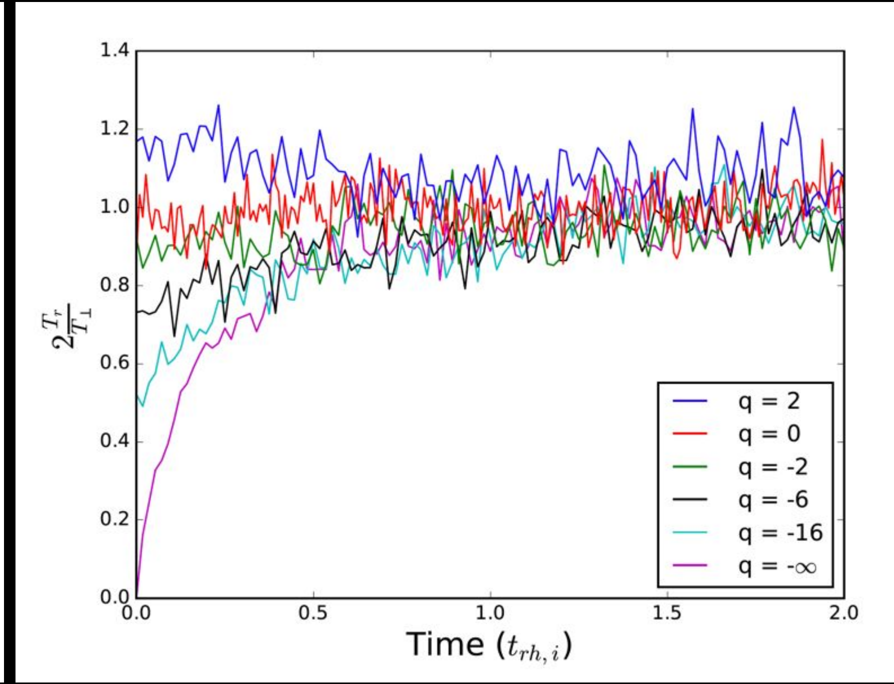


Breen, Varri, Heggie 2017 MNRAS

(Catastrophic) evolution towards isotropy

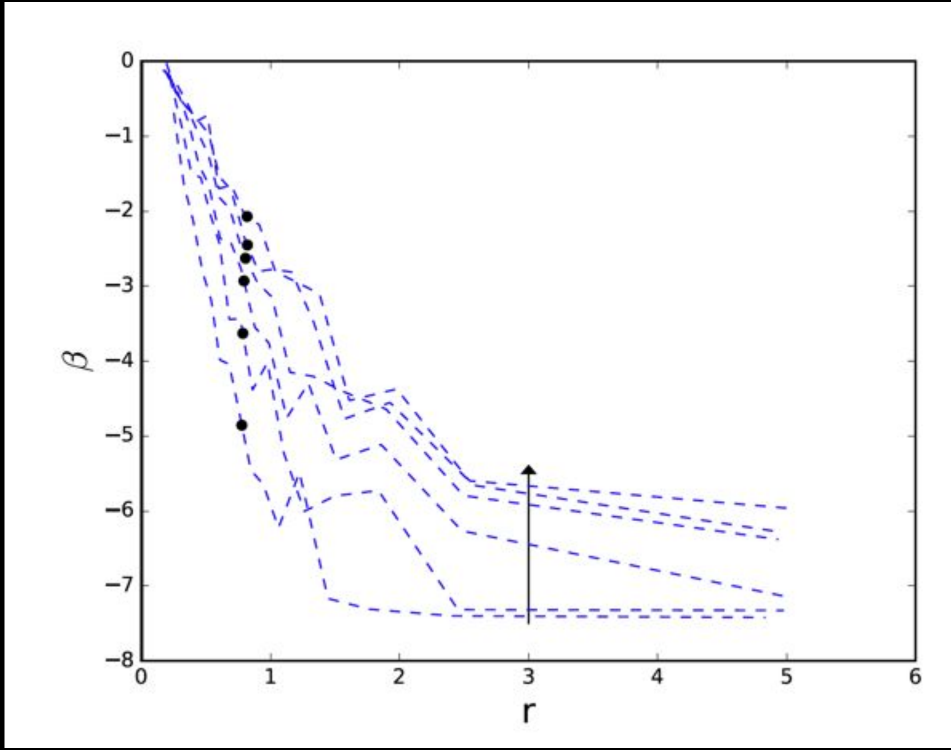


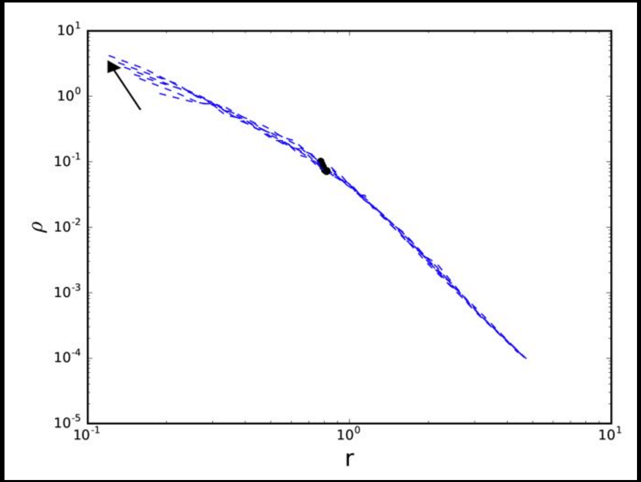
within half-mass radius

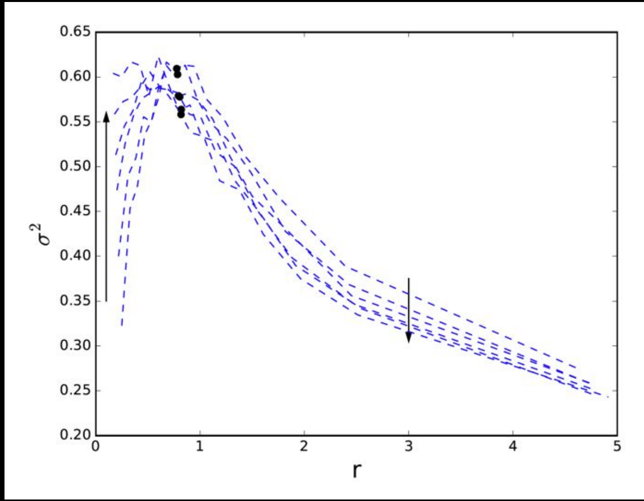


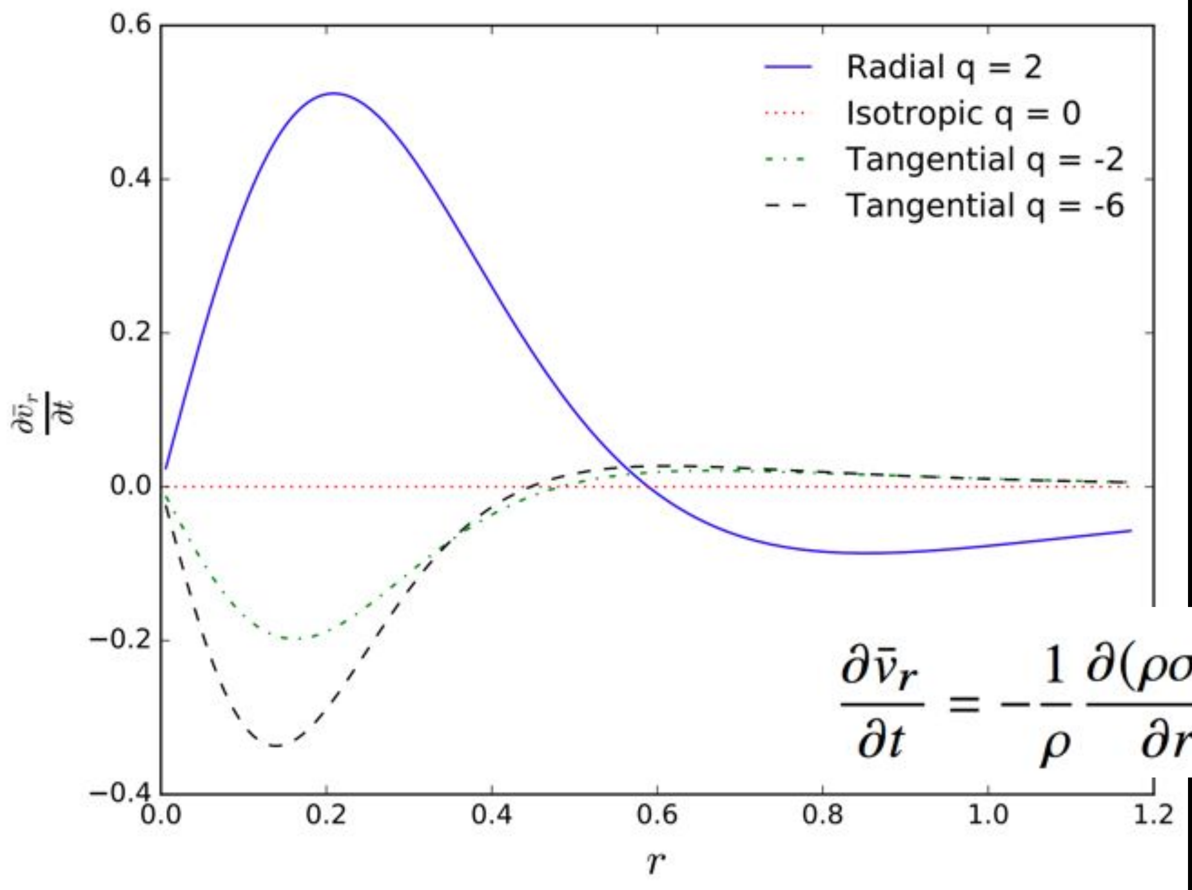
within 10% radius

Early evolution of intrinsic properties
(q = -16)



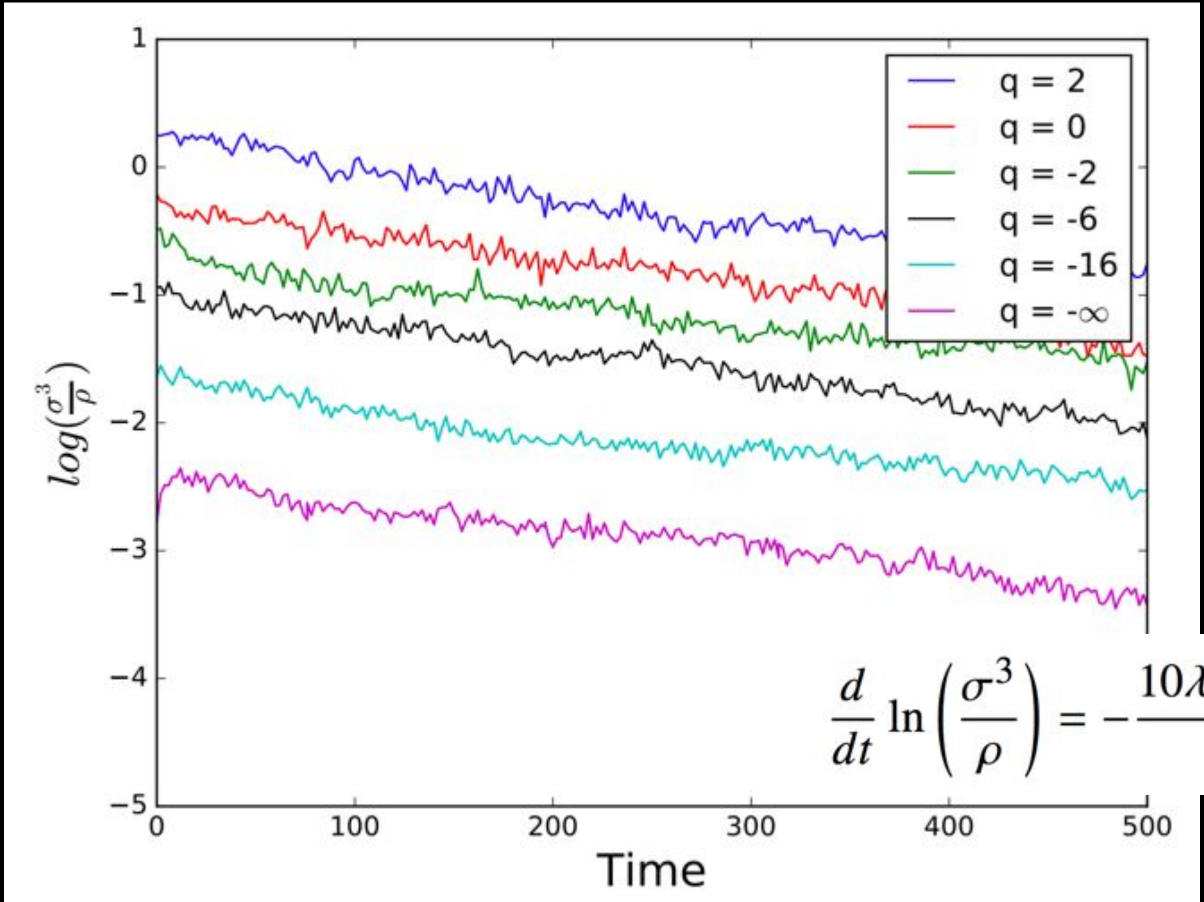






‘Anisotropic response’ (assuming hydrostatic equilibrium, and simple evolution)

$$\frac{\partial \bar{v}_r}{\partial t} = -\frac{1}{\rho}\frac{\partial(\rho\sigma_r^2)}{\partial r} - \frac{(2\sigma_r^2 - \sigma_t^2)}{r} - \frac{\partial \Phi}{\partial r}.$$



Early evolution of central specific entropy (interpretation based on anisotropic gaseous model, à la Louis & Spurzem 1991)

$$\frac{d}{dt}\ln\left(\frac{\sigma^3}{\rho}\right) = -\frac{10\lambda(3+2q)\sqrt{6-q}}{\sqrt{\pi}}\frac{\log N}{N}\left(\frac{GM}{a^3}\right)^{1/2}$$

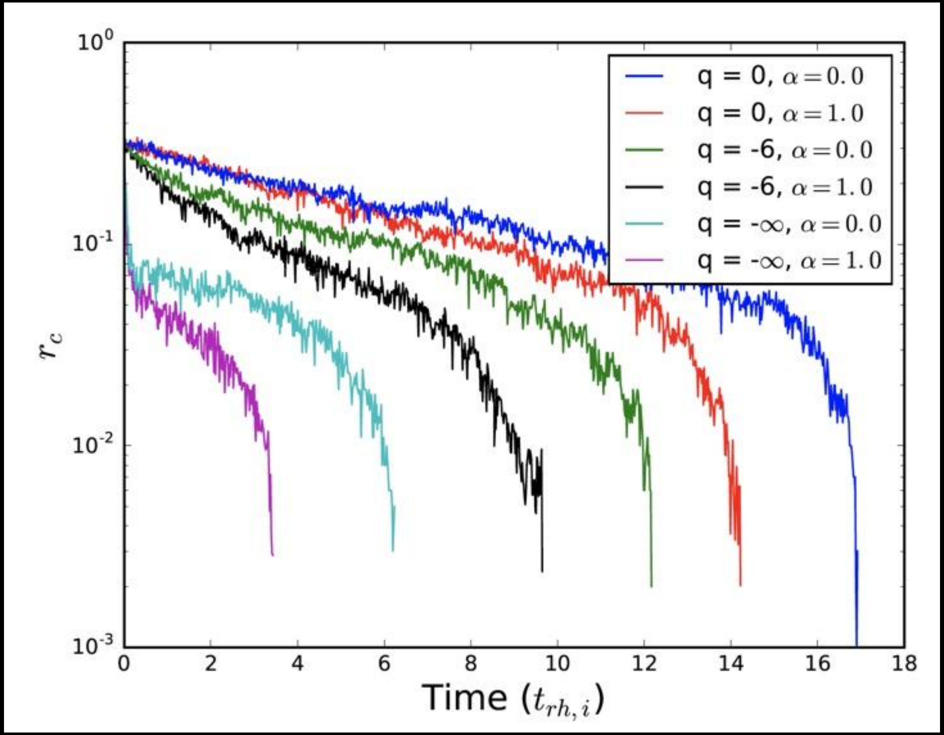
Old question #2

Rotating systems reach core collapse earlier than their non-rotating counterpart

Previous investigations by
Rainer Spurzem and Hyung Mok Lee,
with their collaborators
(Fokker-Planck and N-body approaches).

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

Rotating anisotropic spheres



Breen, Varri, Heggie, in preparation

Implications and questions

multiple stellar populations and black holes

The nexus between phase space complexity and multiple populations

Implications and questions

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Implications and questions

What is the phase space structure of multiple population clusters?

The nexus between phase space complexity and multiple populations

Implications and questions

What is the phase space structure of multiple population clusters?

Different degree of rotation for different pops: Cordero+ 2017 [M13]
Different degree of anisotropy for different pops: Richer+ 2013 [47 Tuc], Bellini+ 2015 [NGC 2808], Bellini+ 2018 [o Cen]

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Implications and questions

What is the phase space structure of multiple population clusters?

What is the long-term evolution of the kinematics of multiple populations?

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Implications and questions

What is the phase space structure of multiple population clusters?

What is the long-term evolution of the kinematics of multiple populations?

Many, purely dynamical, questions:

Transport of angular momentum? Phase space mixing?
Coupling of angular momentum vectors? Counterpart of two-stream instabilities?

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Can phase space properties unravel clues of their puzzling formation process?

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Can phase space properties unravel clues of their puzzling formation process?

Chemo-dynamical analysis (of Gaia + HST + spectroscopic data) essential to have a fresh look on the problem, currently stalled.
Key to formulate new constraints, more than distinguishing different scenarios.

Local (Galactic) hi-res investigations of present-day GCs are complementary to high-redshift low-res first studies of proto-GCs, in preparation for JWST and ELTs.

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Implications and questions

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Implications and questions

What is the phase-space structure of rotating, anisotropic equilibria with a BH?

The nexus between phase space complexity and black holes

What is the phase-space structure of rotating, anisotropic equilibria with a BH?

Key question for both globular (as possible IMBH hosts) and nuclear star clusters - very few studies.

NGC 1277: van den Bosch+ 2012, Yildirim+ 2015; NGC 4486B: Kormendy+ 1997
M32: van der Marel+ 1994, Qian, de Zeeuw+ 1995

The nexus between phase space complexity and black holes

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What is the phase-space structure of rotating, anisotropic equilibria with a BH?

Stability of such equilibria? Secular behaviour?

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Stability of such equilibria? Secular behaviour?

Missing chapter in fundamental stellar dynamics - very few studies.

Rotation: Kuijken & Dubinski 1994; van der Marel+ 1997
Anisotropy: Polyachenko & Shukhman 1984; Barnes, Hut, Goodman 1986; Dejonghe & Merritt 1988

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Equilibrium and stability of rotating fluid and stellar systems

A class of dynamical instabilities in differentially rotating stellar systems (Varri+, submitted),
with striking analogies with behaviour of rotating polytropes (“low T/W” instabilities, see Centrella+ 2001)

Much of the current understanding still relies on Eriguchi’s and Hachisu’s studies of rotating polytropic sequences!

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Ask me more!

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Stability of such equilibria? Secular behaviour?

Long-term collisional evolution? Mass segregation?

The nexus between phase space complexity and black holes

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Only a few people took it seriously: Rainer Spurzem, Hyung Mok Lee and their groups (Fokker-Planck and N-body approaches)

Even without IMBH - Existence of stellar dynamical counterpart of ‘gravo-gyro’ instability? (Inagaki & Hachisu 1978, Hachisu 1982 PASJ...)
Work in progress in Edinburgh, with Douglas Heggie and Phil Breen

The nexus between phase space complexity and black holes

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Effects on the ‘fast’ and ‘slow’ processes for IMBH formation scenarios?

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Effects on the ‘fast’ and ‘slow’ processes for IMBH formation scenarios?

Both Portegies Zwart+ 2004 (runaway collision scenario) and Giersz+ 2015 (slow growth scenario) consider only spherical, isotropic, non-rotating initial conditions.

Catastrophic behaviours (and efficient IMBH formation) may exist in regimes so far unexplored!

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Effects on the ‘fast’ and ‘slow’ processes for IMBH formation scenarios?

Effects on BH retention efficiency? BBH merger rates? TDE rates?

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Effects on the 'fast' and 'slow' processes for IMBH formation scenarios?

Effects on BH retention efficiency? BBH merger rates? TDE rates?

Breen & Heggie 2013 should be generalized. Amaro-Seoane+ 2010 [IMBH binary evol], Gualandris+ 2012 [spin flip], Petrovich & Antonini 2017 [non-sphericity & StMBH merger], Lezhnin & Vasiliev 2016 [non-sphericity & TDEs], Stone+ 2017 [aniso & TDEs]

Predictions for aLIGO and KAGRA?

Four parting thoughts

#1 - A new 'golden age' for the study of the internal dynamics of globular clusters has started.

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

#2 - Their emerging phase space complexity *screams* for a proper treatment of physical ingredients traditionally considered as '2nd-order complications'. Paradigm deserves to be enriched.

It's time to attack several aspects of collisional gravitational dynamics, some new and others long-forgotten.

#3 -Fingerprints of formation *and* signatures of evolution are hidden in kinematic properties.

Some degeneracies, but also some distinctive features.

#4 - Interesting (new) science often lives at unexplored intersections.

rotation ∩ tides, rotation ∩ anisotropy, anisotropy ∩ tides

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