Phase space complexity of star clusters: fresh observables for old and new questions

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in collaboration with many,
to be gratefully acknowledged along the way

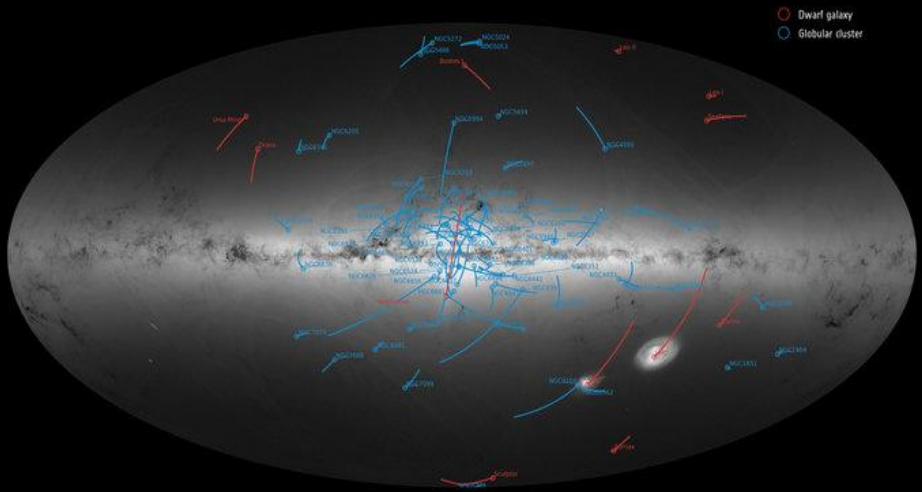
With thanks to the Bauhaus-Aspen connection!

Aspen Winter Conference 2022 | Illuminating Galaxy Formation
with Ancient GCs and their progenitors

A new *observational* landscape

A new *observational* landscape

Local Universe (Gaia, HST)



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**

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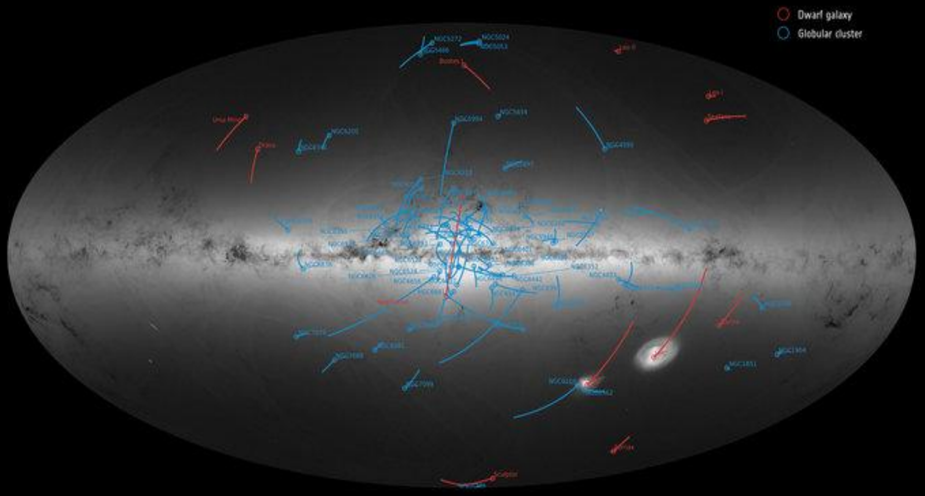

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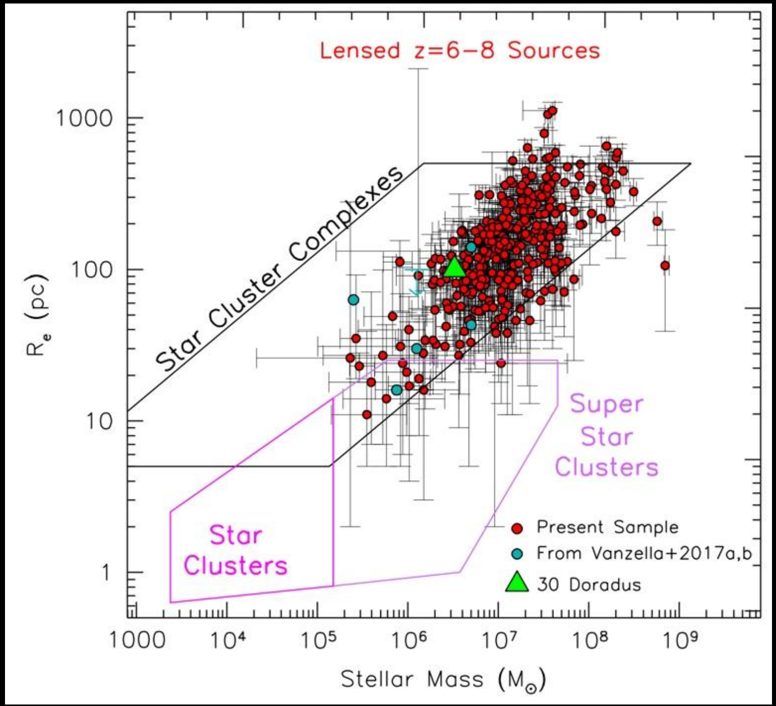
Early Universe (JWST, ELTs ...)



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

Fresh observables

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Internal rotation

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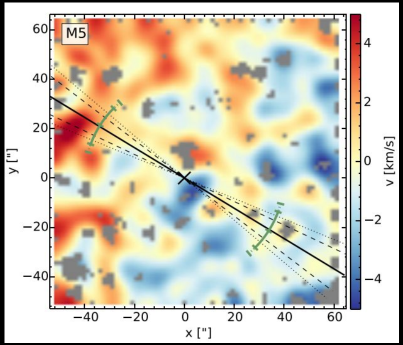
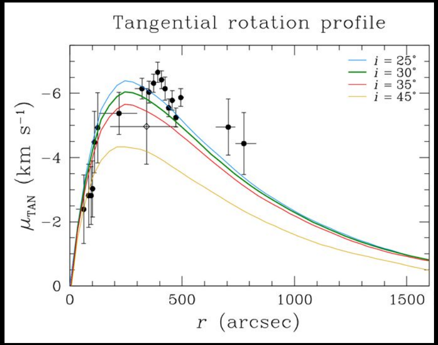


M5 | Fabricius et al. 2014 ApJL



47 Tuc | Bellini et al 2017 ApJ (HSTPROMO)

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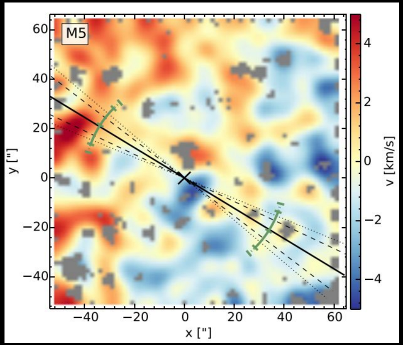

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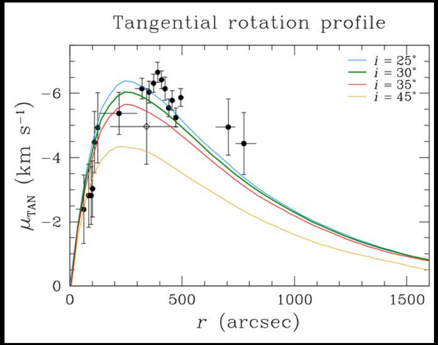

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Velocity anisotropy

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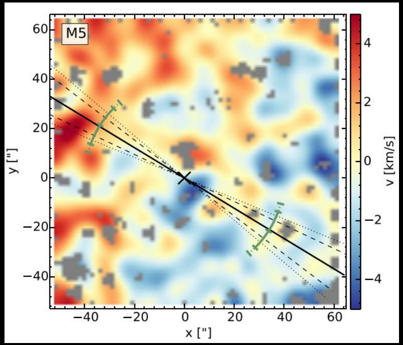

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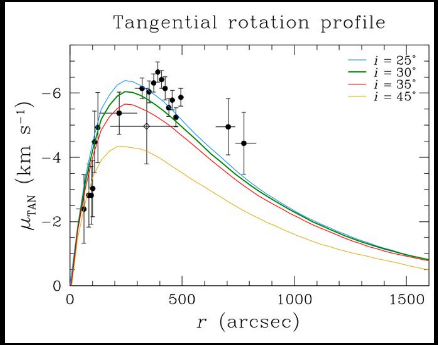

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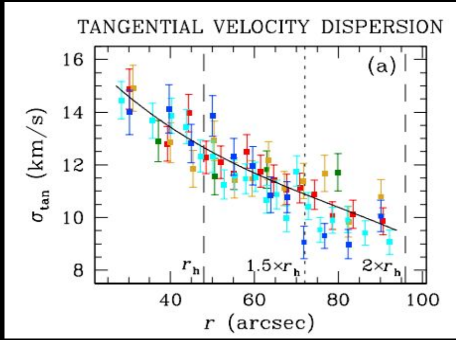

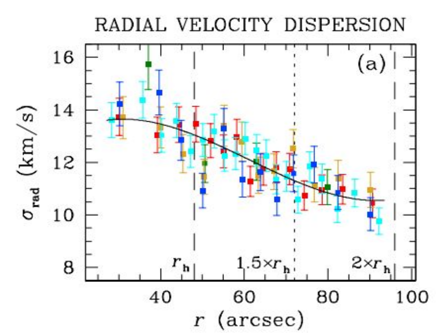

NGC 2808 | Bellini et al. 2015 ApJL, see also Watkins et al 2015a,b ApJ (HSTPROMO)

Fresh observables

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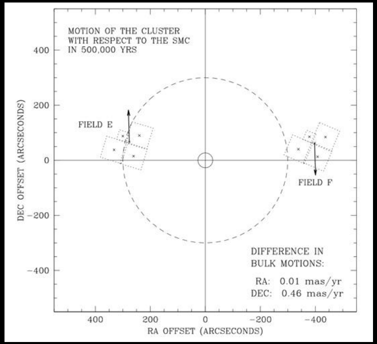
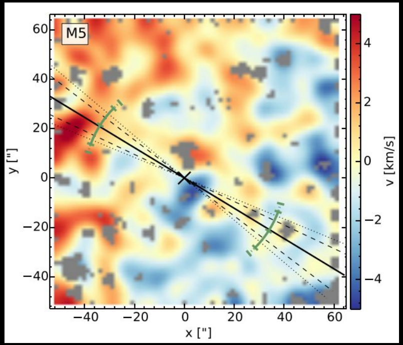


47 Tuc | Anderson & King 2003 AJ



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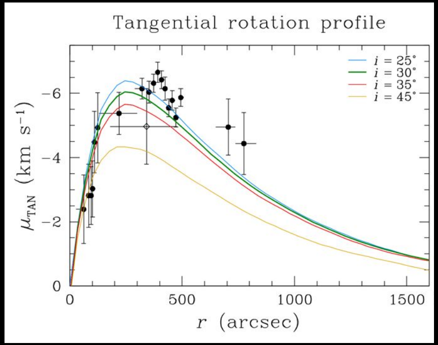

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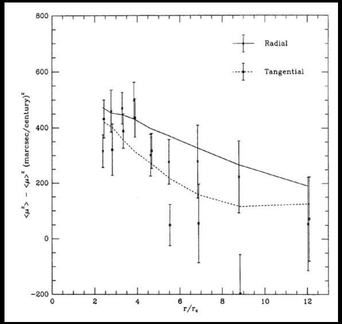
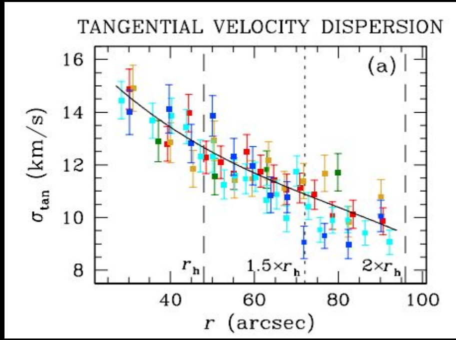
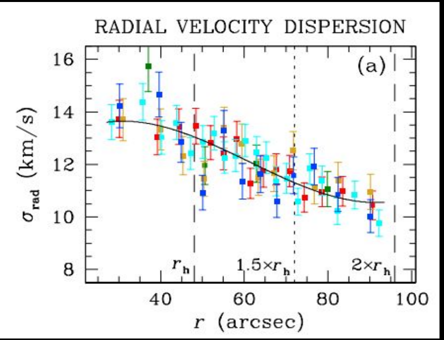


M13 | Lupton, Gunn, Griffin ApJ 1987





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A new *computational* landscape

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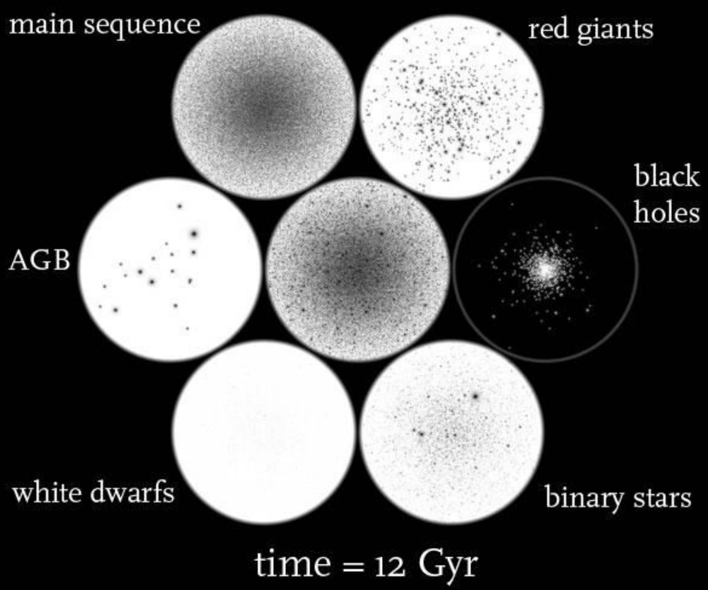
Gravitational million-body problem ‘solved’



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

A new *computational* landscape

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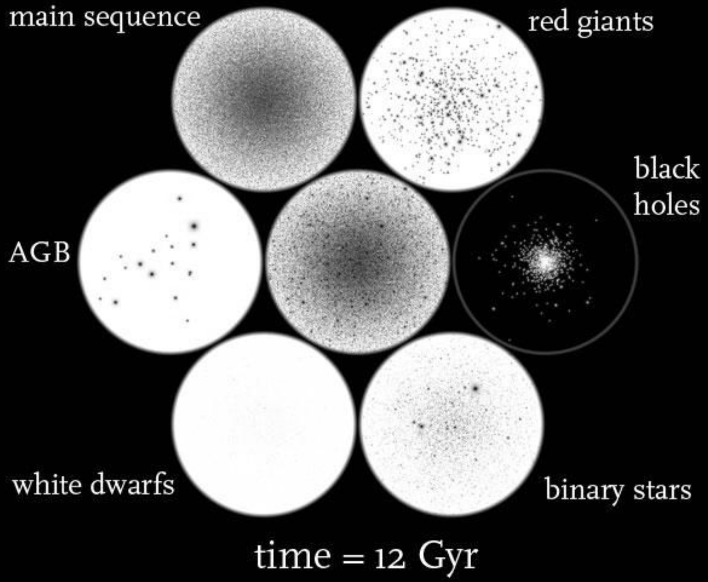

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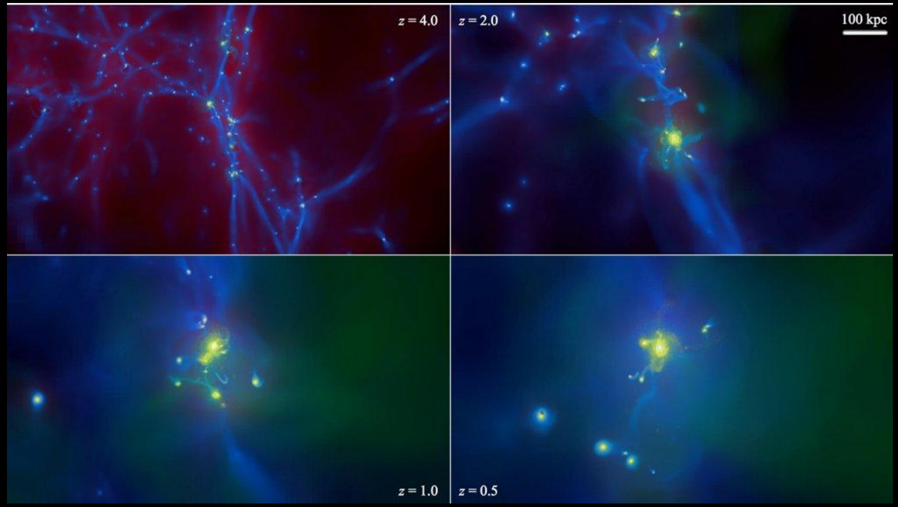
Towards GC formation in a cosmological context



Renaud+ 2017 MNRAS; Carlberg 2017 ApJ; Li, Gnedin^2 2017 ApJ ...
Also, role during reionization? Ricotti 2004, Boylan-Kolchin 2017a,b ...

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

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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 + JWST + LIGO.

Old question #1

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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

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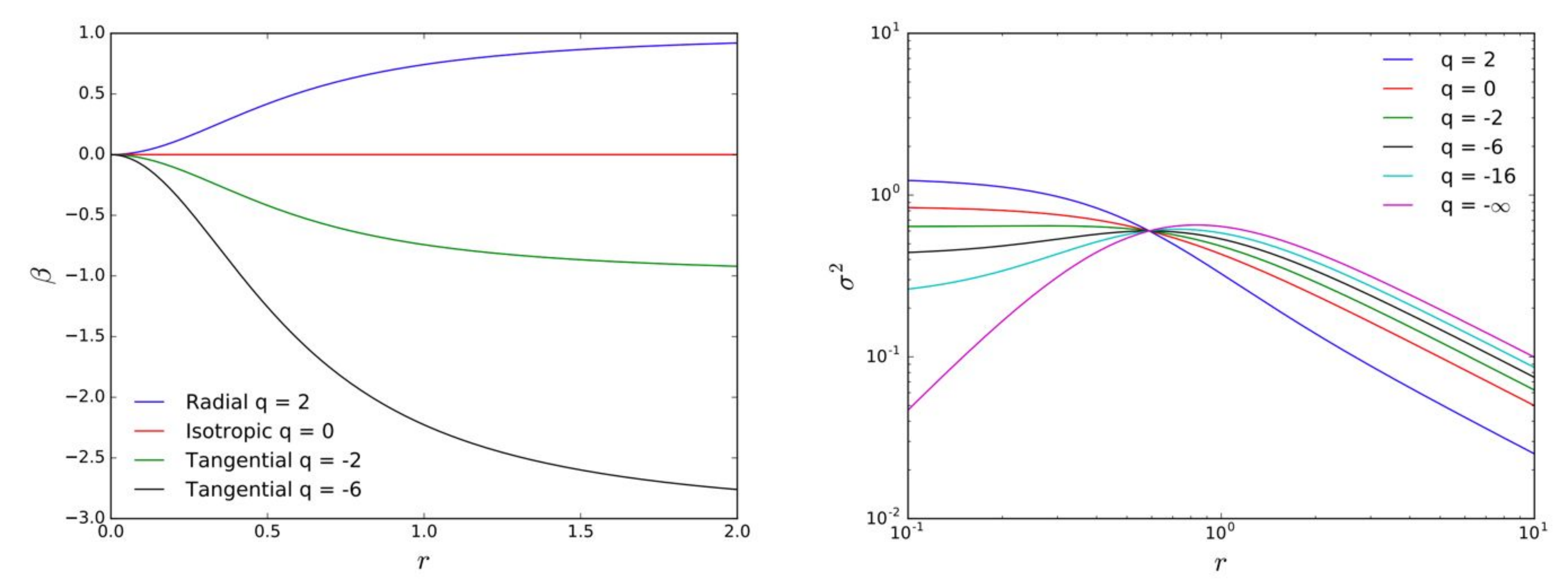

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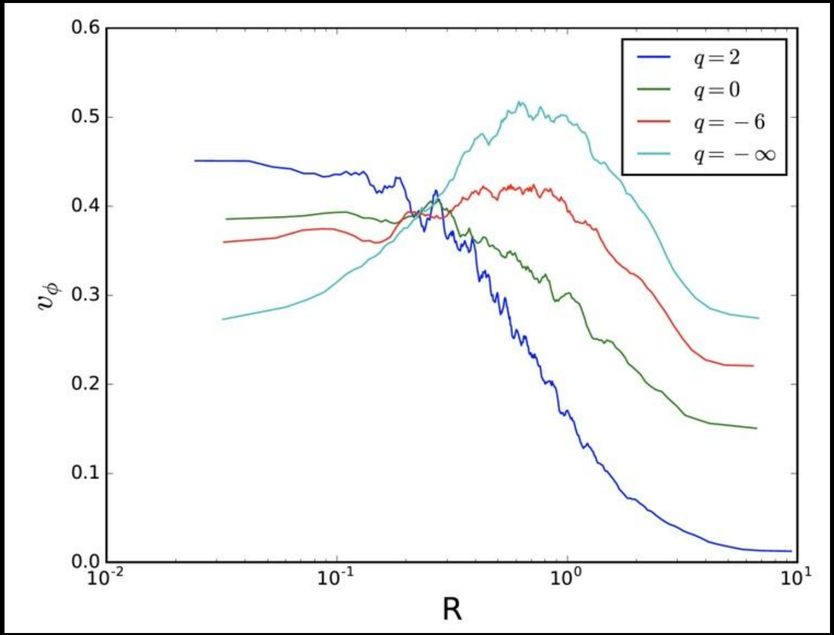


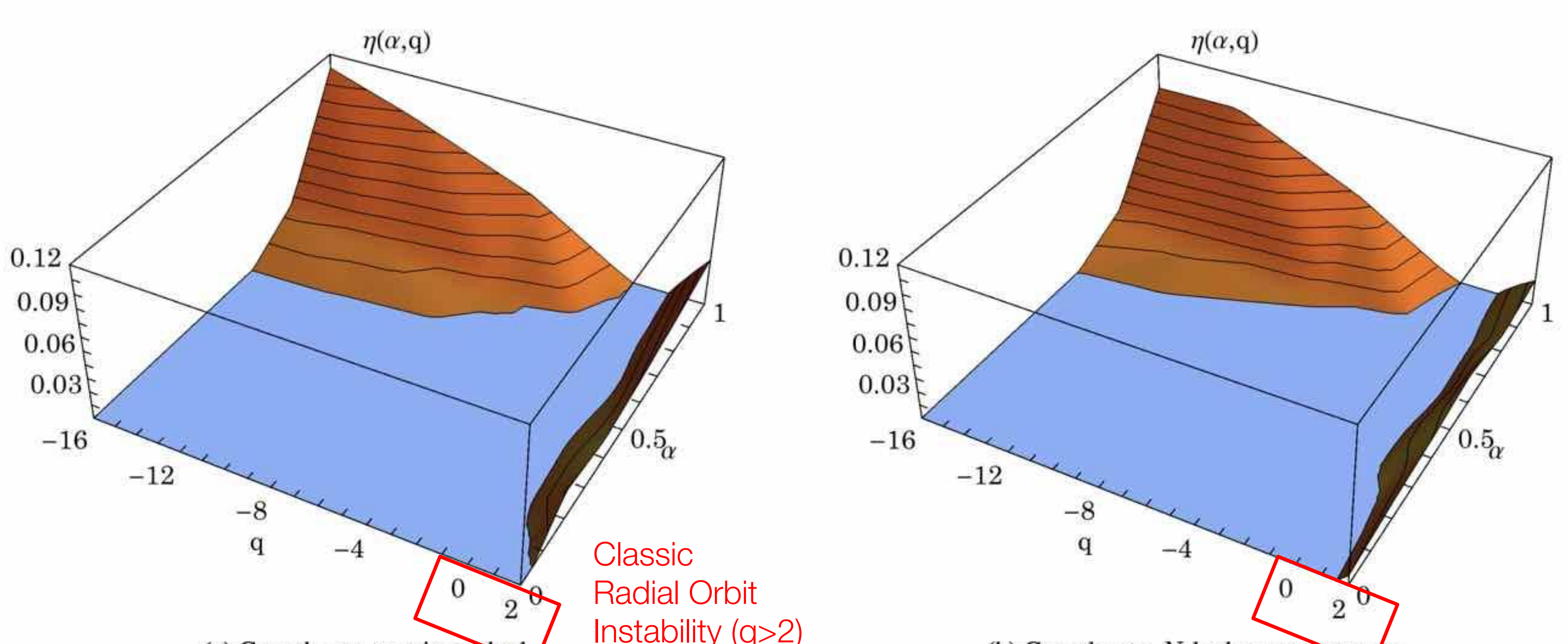
"Lynden-Bell's deamon"

flip the sign of azimuthal velocity component for a fraction (alpha) of stars

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

https://github.com/pgbreen/PlummerPlus

Old question #1



(a) Growth rate, matrix method. (b) Growth rate, N-body measurements.

Rozier, Fouvry, Breen, Varri, Pichon, Heggie 2019 MNRAS
Breen, Rozier, Heggie, Varri 2021 MNRAS

Old question #2

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

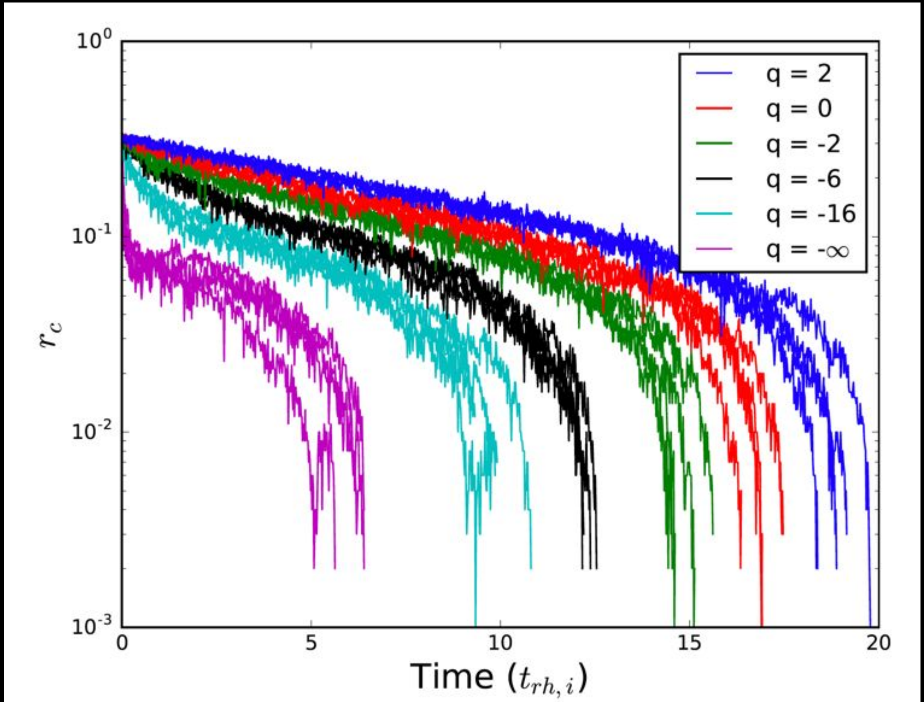
Old question #2

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

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).

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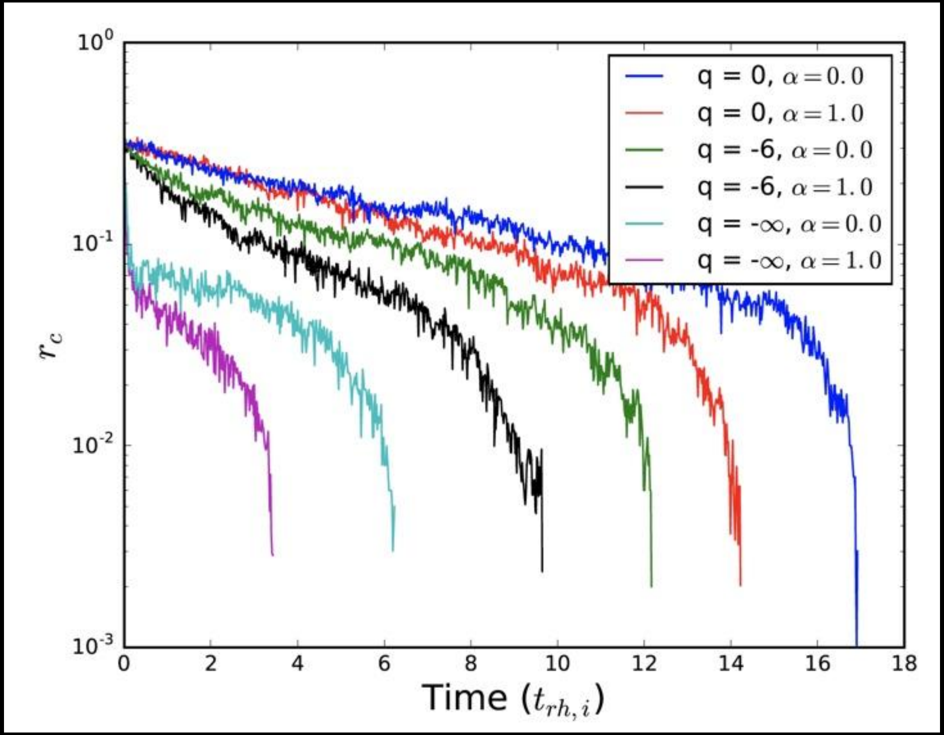
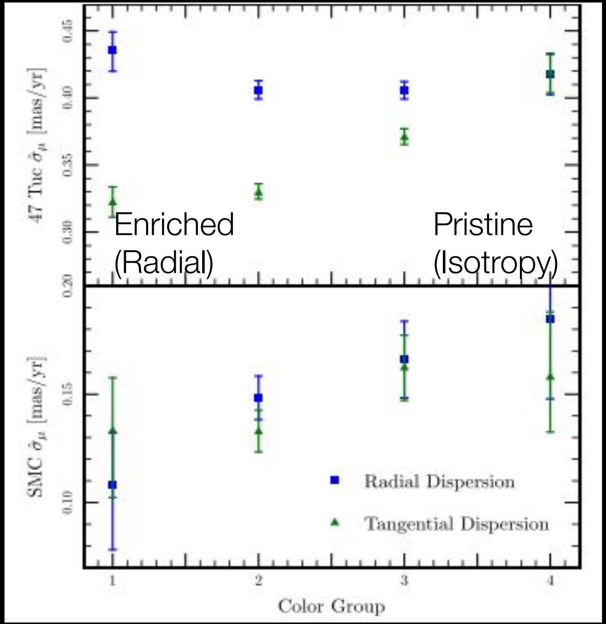
Rotating anisotropic spheres

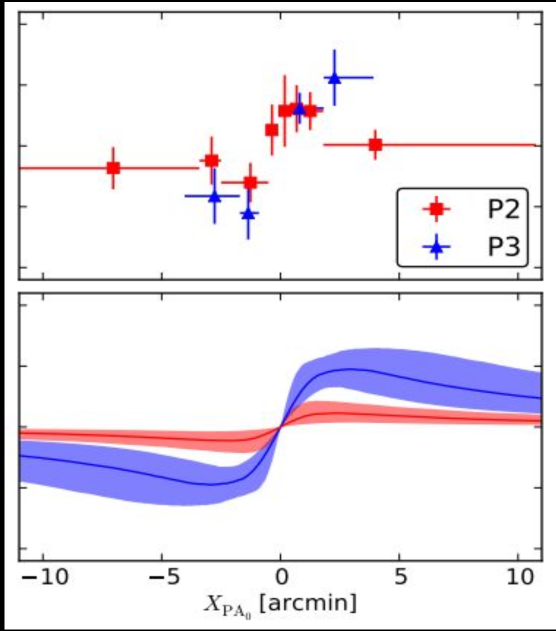


Breen, Varri, Heggie - in preparation

Fresh observables



47 Tuc | Richer+ 2013 ApJL
NGC 2808 | Bellini+ 2015 ApJL
NGC 5904 | Cordoni + 2020 ApJ



M13 | Cordero+ 2017, Milone+ 2018 MNRAS
M22 | Cordoni+ 2020 ApJ
M80 | Kamann+ 2020 MNRAS

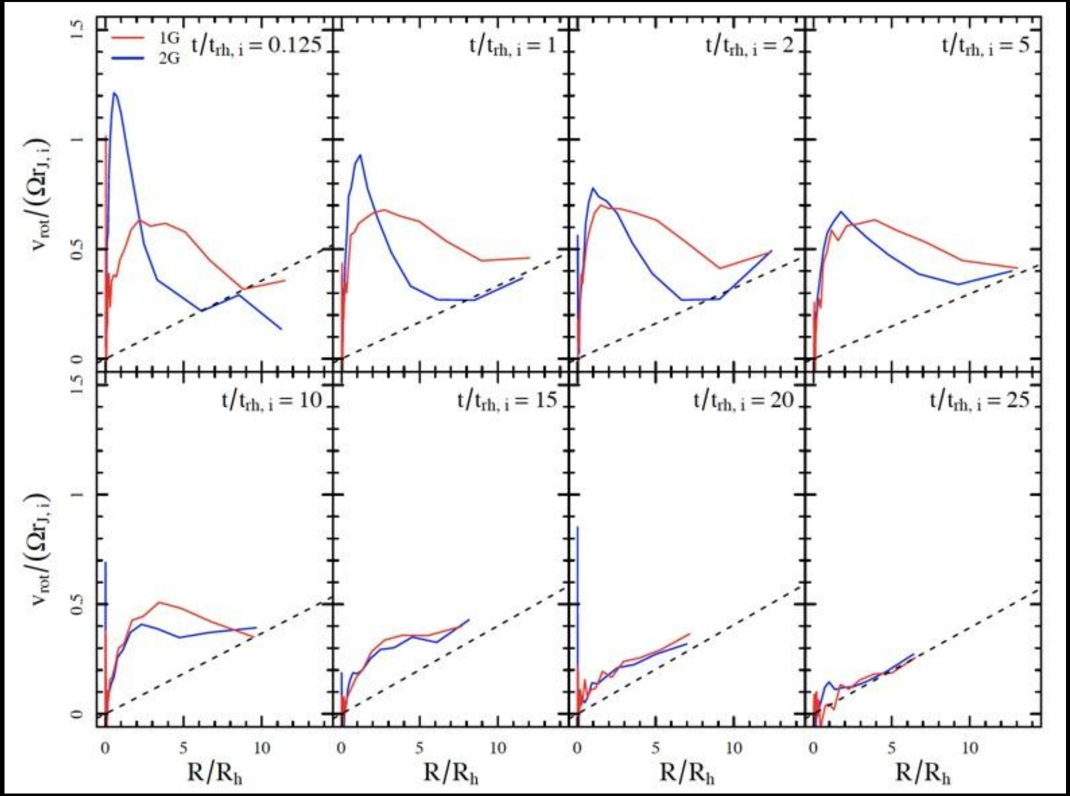
P2 = Moderate enrichment (slower rotation)

P3 = ‘Extreme’ enrichment (faster rotation)

New question #3

What is the degree of ‘phase space hysteresis’ of collisional systems?

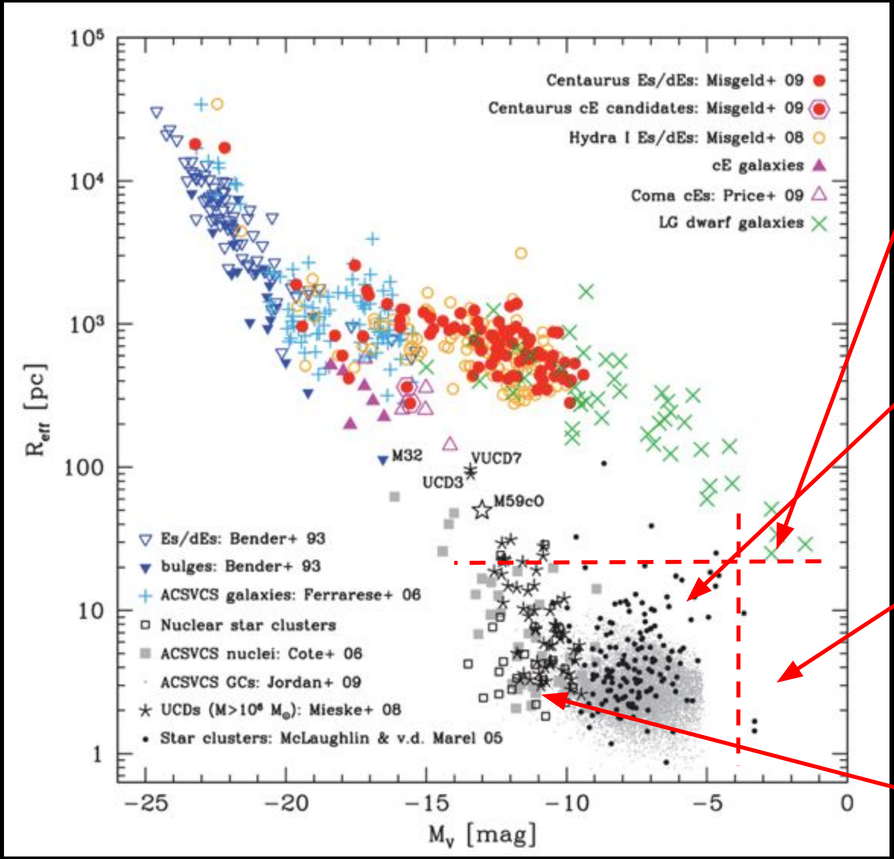
New question #3



Tiongco, Vesperini, Varri 2019 MNRAS

Fresh observables

Misgeld & Hilker 2011 MNRAS, Norris & AIMSS Coll. 2014 MNRAS



Ultra-faint 'satellites' *[lots of DM?]*
r_eff > 20pc; M < -3.5

Hydra II, Laevens 2, Pegasus III, Ret II, Eridanus II, Tucana II, Horologium I, Pictoris I, Phoenix II, Draco II, Sagittarius II, Horologium II, Grus II, Tucana III, Columba I, Tucana IV, Reticulum III, Tucana V, Crater 2, Acquarius 2, Pictoris II, Segue 1

Extended clusters and 'faint fuzzies' *[no DM?]*
10pc < r_eff < 20pc

Discovered in outskirts of MW, M31, M33, many Local dwarfs ...

Ultra-faint star clusters *[no DM?]*
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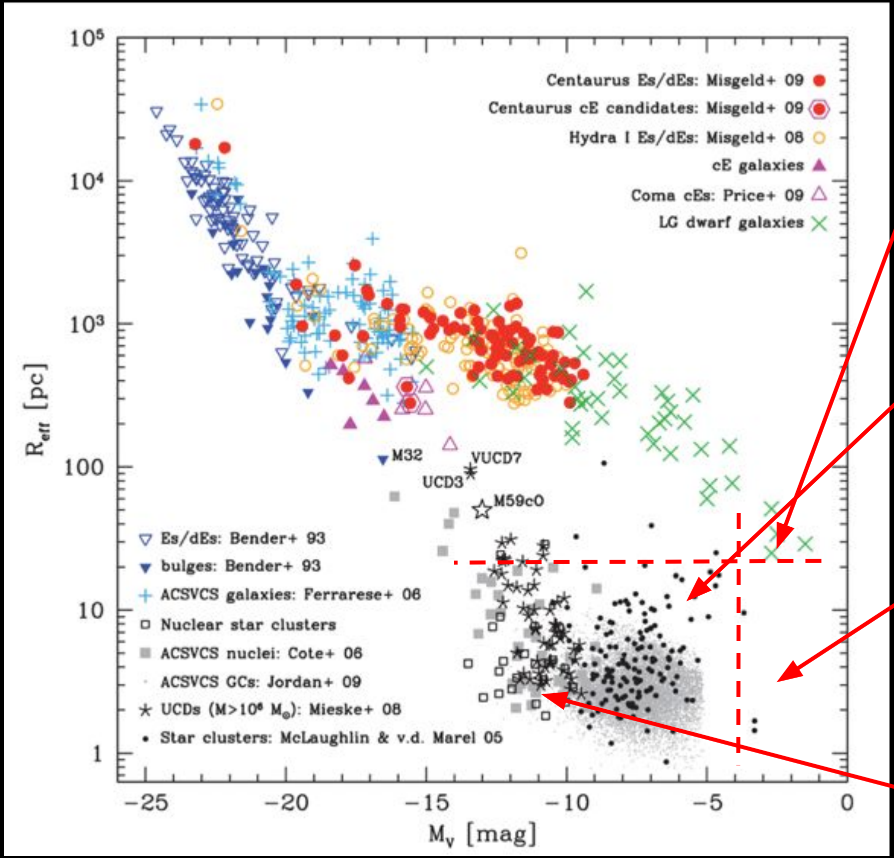
Segue 3, Munoz 1, Balbinot 1, Laevens 1/Crater, Laevens 3, Kim 1, Kim 2, Eridanus III, DES 1, Kim 3

Ultra-compact dwarfs *[DM? central BH?]*
massive globulars or stripped dwarfs?

Fresh observables

Frederika Phipps' talk



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New question #4

How should we approach the regime
'in between' collisional and collisionless dynamics?

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Collisional dynamics within a small dark matter halo

Dynamical evolution of low-mass stellar systems changes dramatically!
Profound implications on the ‘star cluster - galaxy divide’

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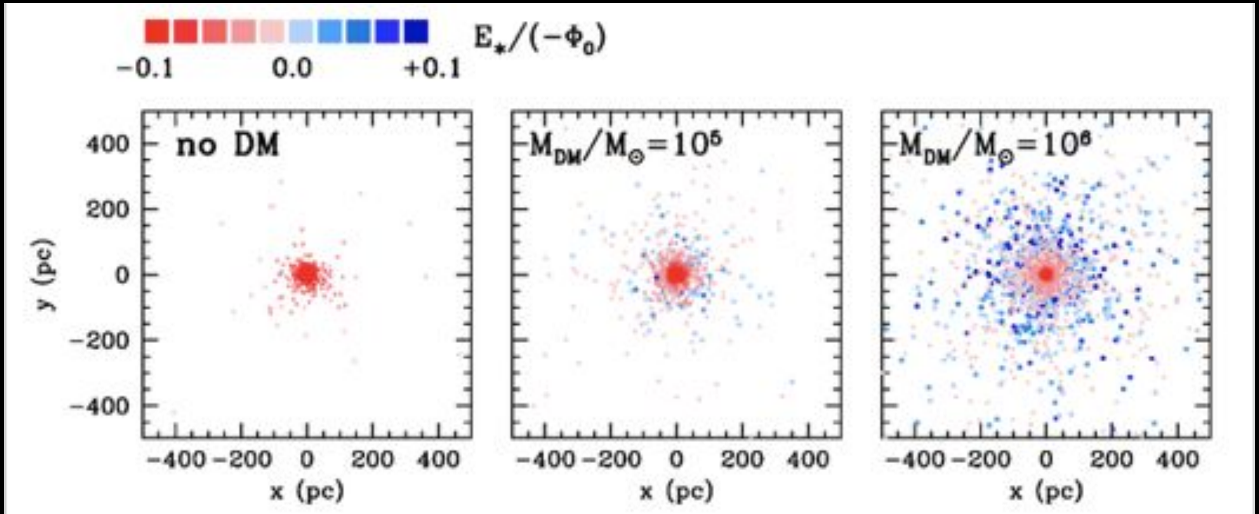

Penarrubia, Varri, Breen et al. 2017 MNRAS

Four questions, old and new. One parting thought.

#1 What are the stability properties of rotating anisotropic spheroidal equilibria?

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

#3 What is the degree of ‘phase space hysteresis’ of collisional systems?

#4 How should we approach the regime ‘in between’ collisional and collisionless dynamics?

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Even castles in the sky
can do with a fresh coat of paint

Haruki Murakami
国境の南、太陽の西(1992)