Blurring the star cluster - galaxy divide

Anna Lisa Varri

UKRI Future Leaders Fellow | Univ. of Edinburgh ⇄ Univ. of Tokyo

in collaboration with

Phil Breen, Jorge Peñarrubia (Edinburgh),
Douglas Heggie (Edinburgh), Kate Daniel (Bryn Mawr)

Annette Ferguson, Pete Kuzma, Ruben Sanchez-Janssen (Edinburgh)

Michiko Fujii, Naoki Yoshida (UTokyo),
Yuya Sakurai (Georgia Tech), Yutaka Hirai (RIKEN Kobe)

UK Research and Innovation

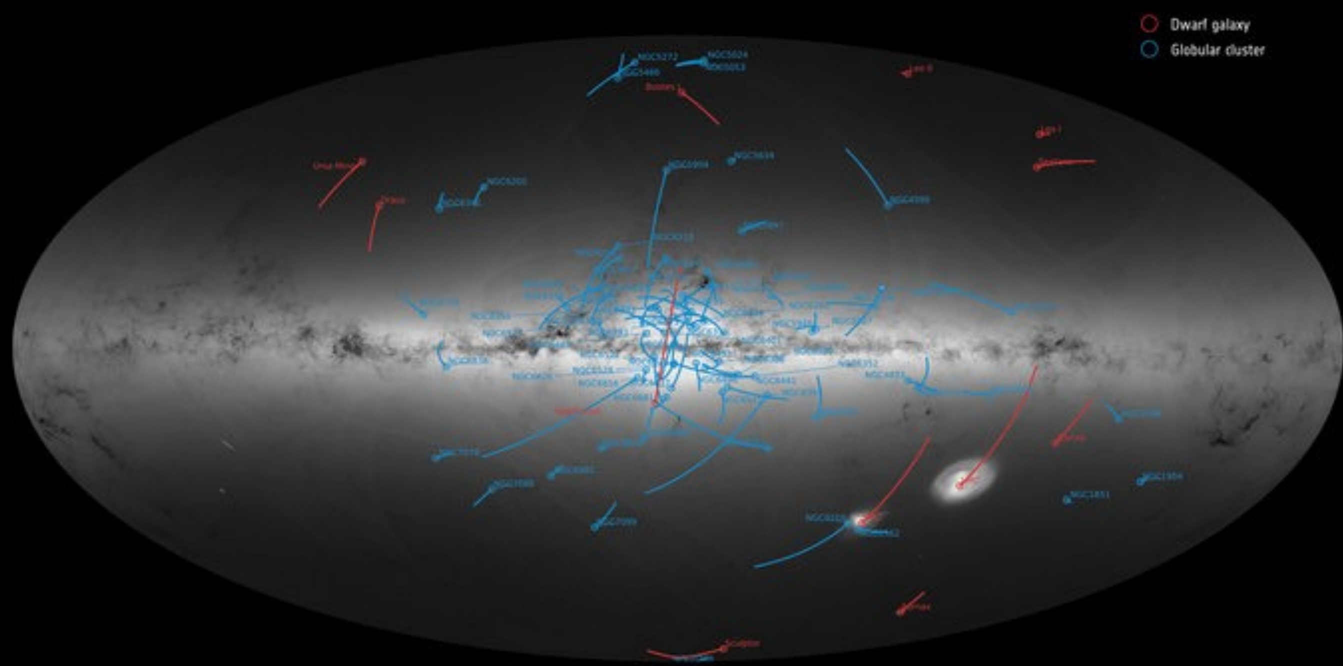
LEVERHULME TRUST

日本学術振興会 Japan Society for the Promotion of Science

THE ROYAL SOCIETY

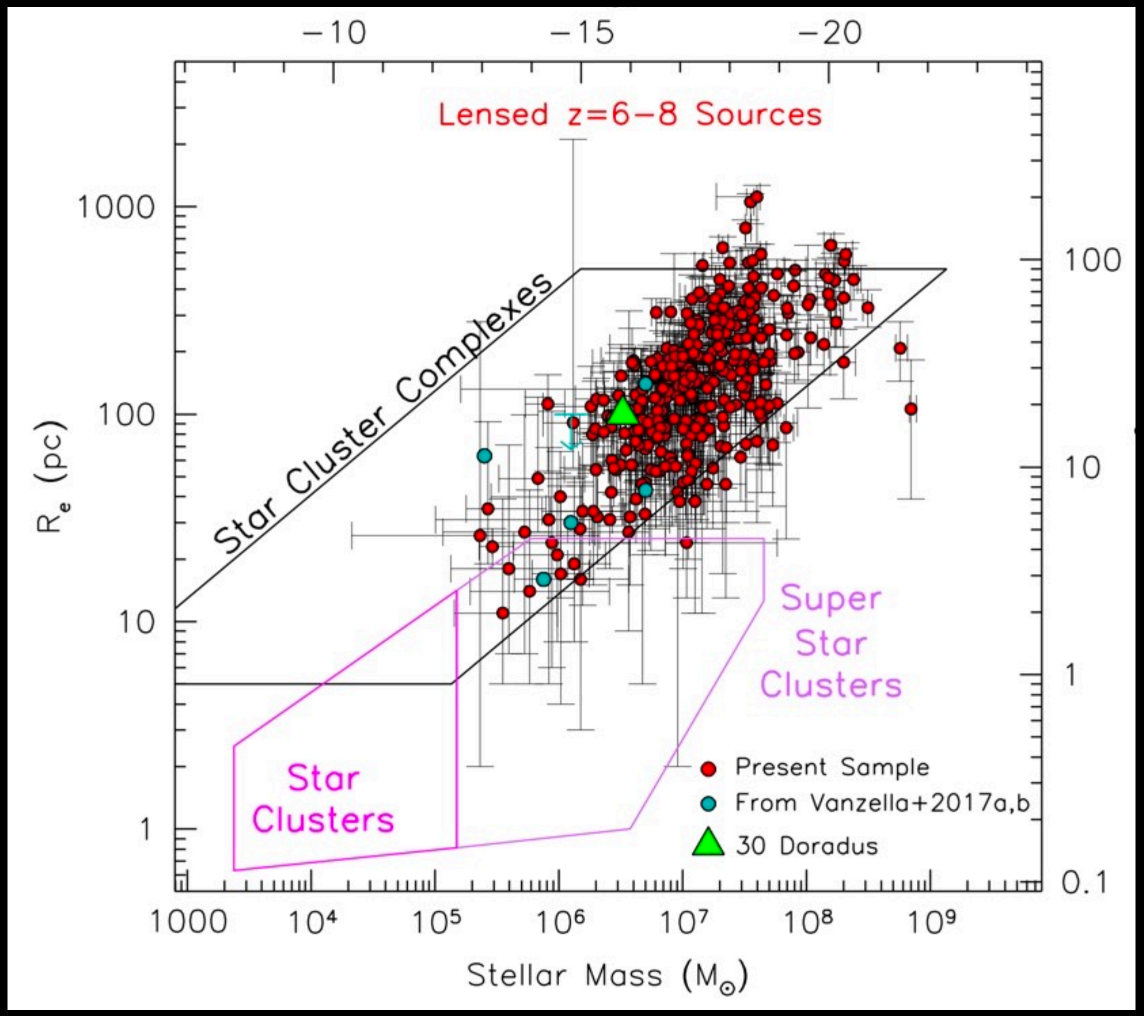
A new *observational* landscape

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 globular clusters.

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

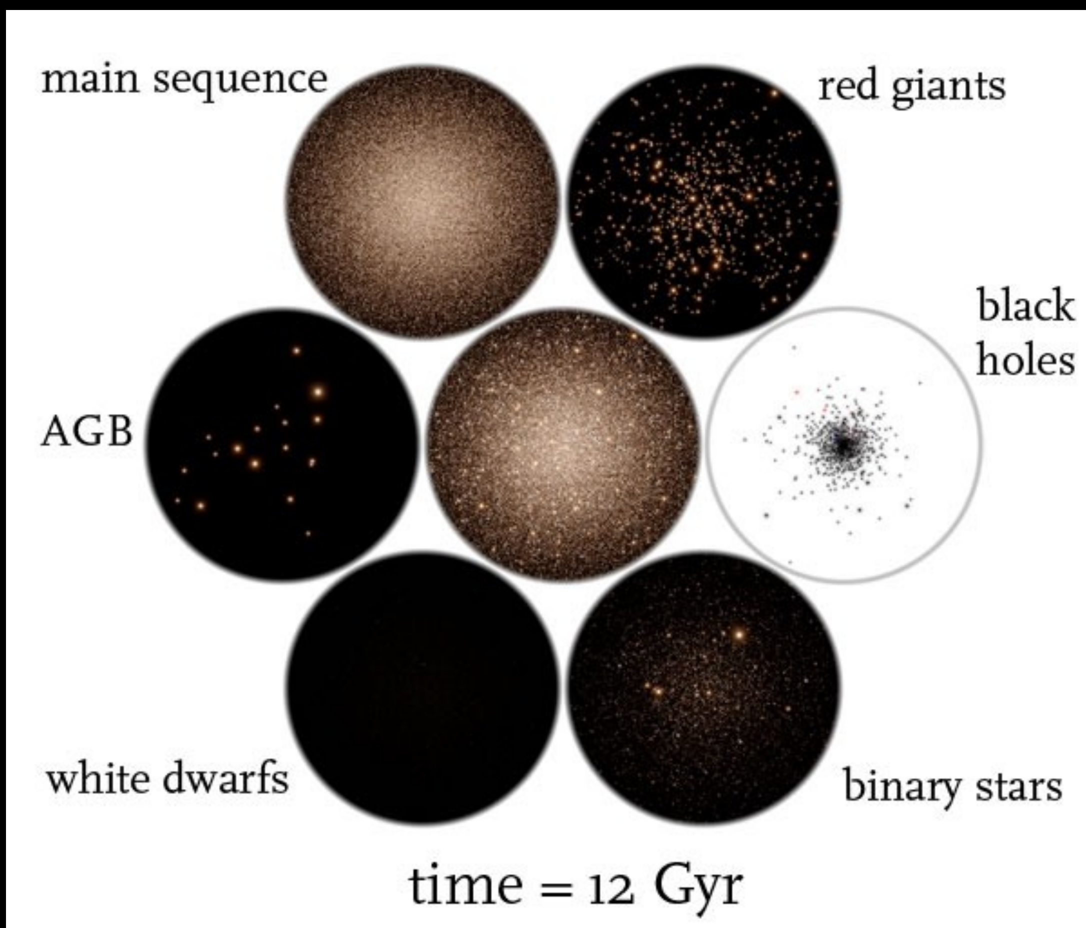


Star-forming sources in Hubble Frontier Field as precursor of globular clusters?
Bouwens+ 2017a,b ApJ, Elmegreen^2 2017 ApJL, Vanzella+ 2017a,b ApJ, 2019a,b MNRAS, Renzini+ 2017, Pozzetti+2019

See talks on Day 3

A new *computational* landscape

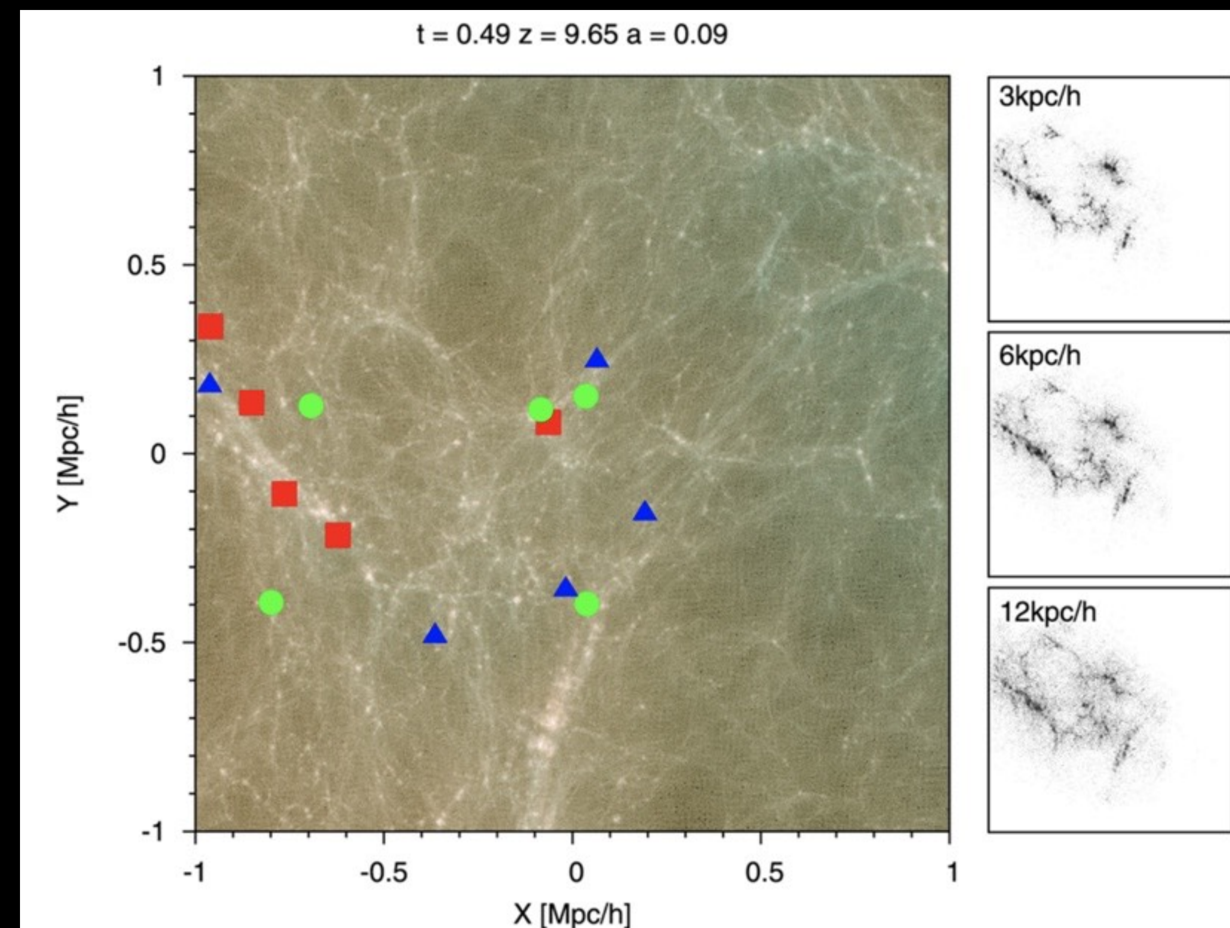
Gravitational million-body problem ‘solved’



DRAGON N-body simulations | Wang+ 2016 ApJ
N-body model of M4 | Heggie 2014 MNRAS

See Naoto Yoshinari’s talk

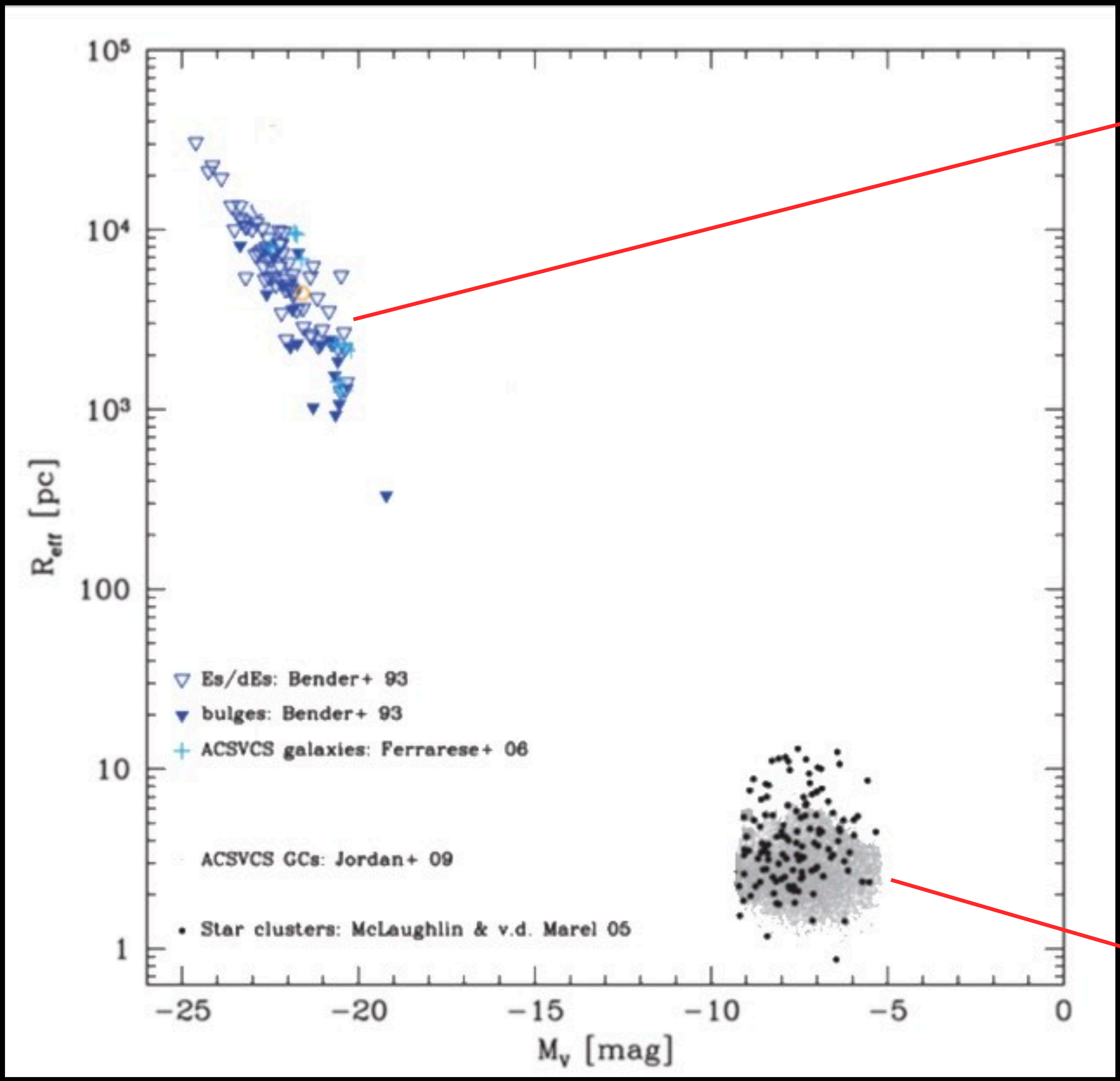
Towards GC formation in a cosmological context



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 ...

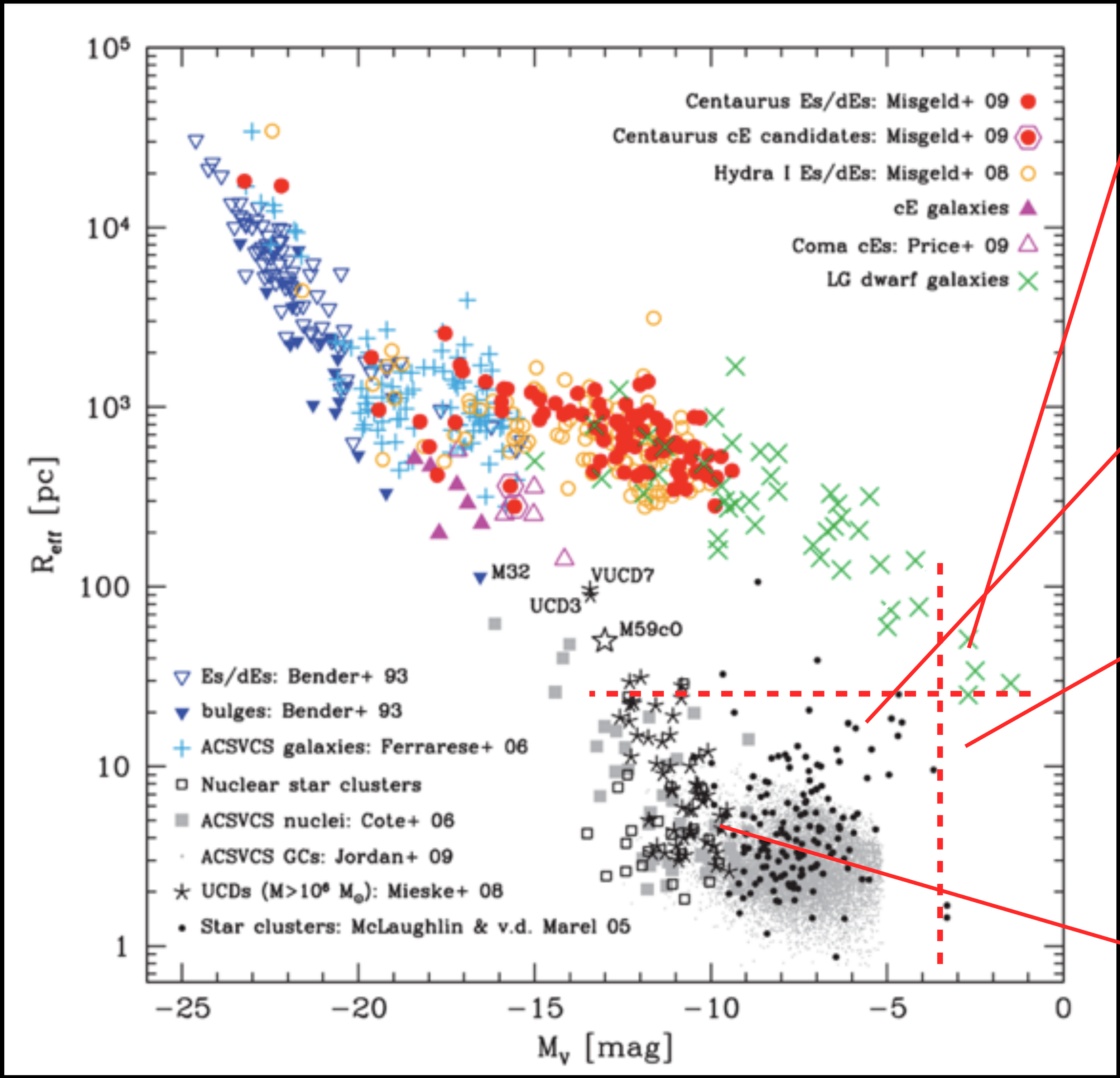
When (a dynamicist's) life was simple



Ellipticals and bulges
R_eff ~ 5 kpc; M ~ -22

Star clusters
(Galactic and extragalactic)
R_eff ~5 pc; M ~ -7

When (a dynamicist's) life is a nightmare



Ultra-faint 'satellites' *[lots of DM?]*
r_eff > 20 pc; 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, 'faint fuzzies' *[no DM?]*
10 pc < r_eff < 20 pc

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

Ultra-faint star clusters *[no DM?]*
r_eff < 20 pc; M < -3.5

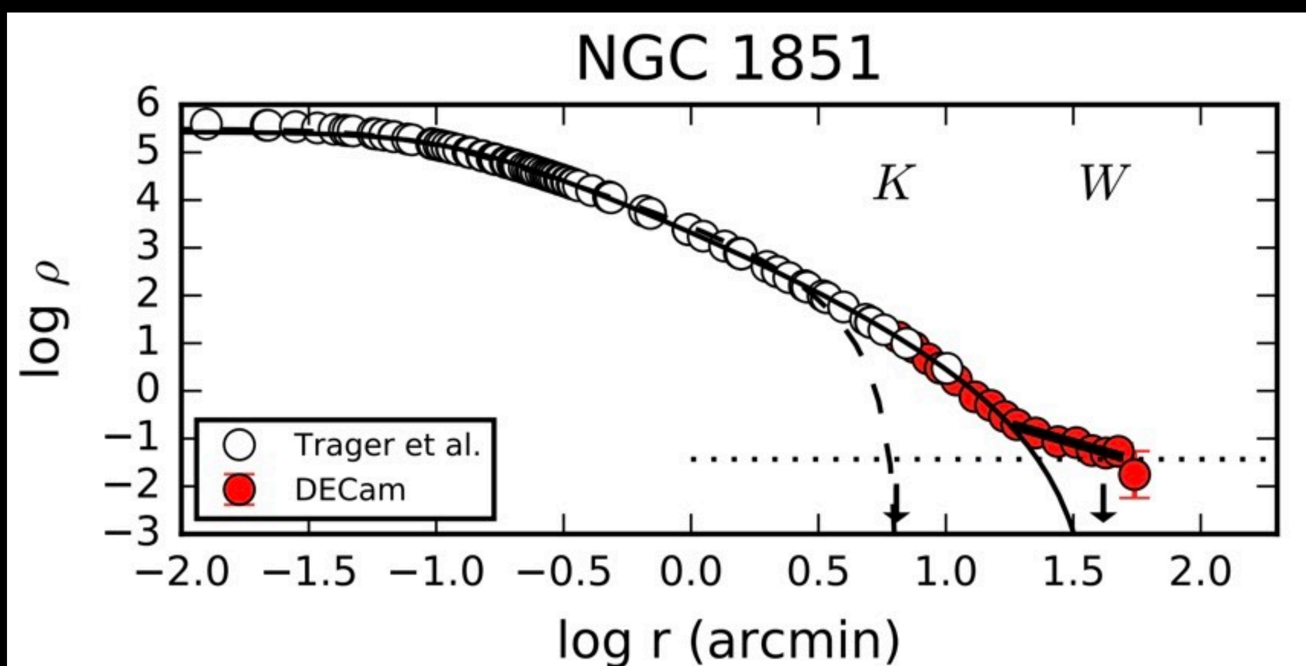
Segue 3, Munoz 1, Balbinot 1, Laevens 1/Crater, Laevens 3, Kim 1, Kim 2, Eridanus III, DES 1, Kim 3

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

Misgeld & Hilker 2011 MNRAS, see also AIMSS project (Norris et al. 2014)

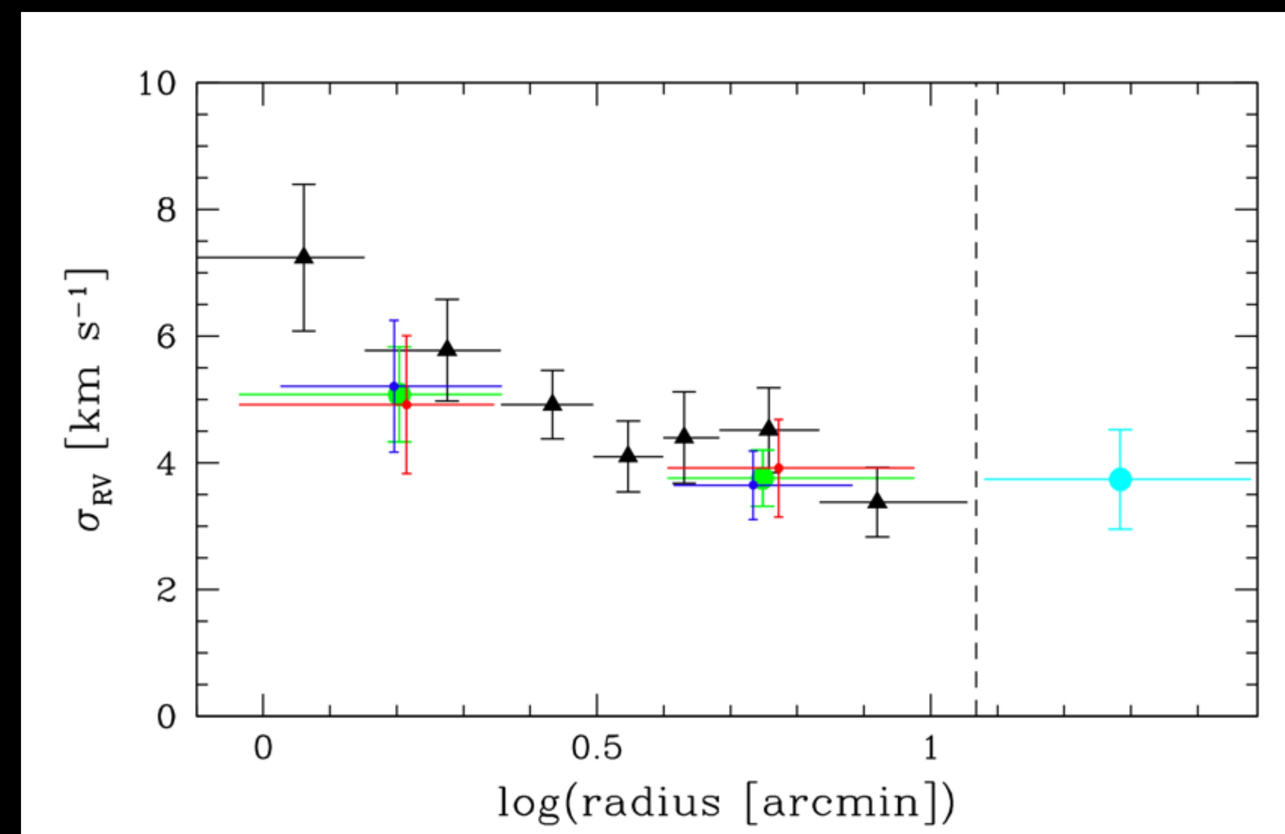
Some recent oddities in globulars

Growing number of (very) extended, spherical, tenuous halo of stars surrounding globulars



Kuzma et al. 2017,2018 MNRAS, first noted by Olszewski et al. 2009 (see also M2, NGC 5694, M92 … by Correnti et al. 2011, Piatti et al. 2017, 2018, Sollima et al. 2018). **More with Gaia!**

Growing number of clusters with untruncated, flattened velocity dispersion profiles

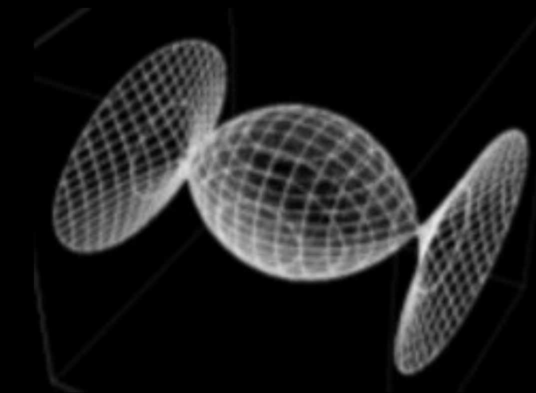


Marino et al. 2014 MNRAS (see also M15, ω Cen, M92, NGC 5694 … by Drukier et al. 1997,1998, Da Costa 2012, Bellazzini et al. 2015)

Existence of high velocity stars

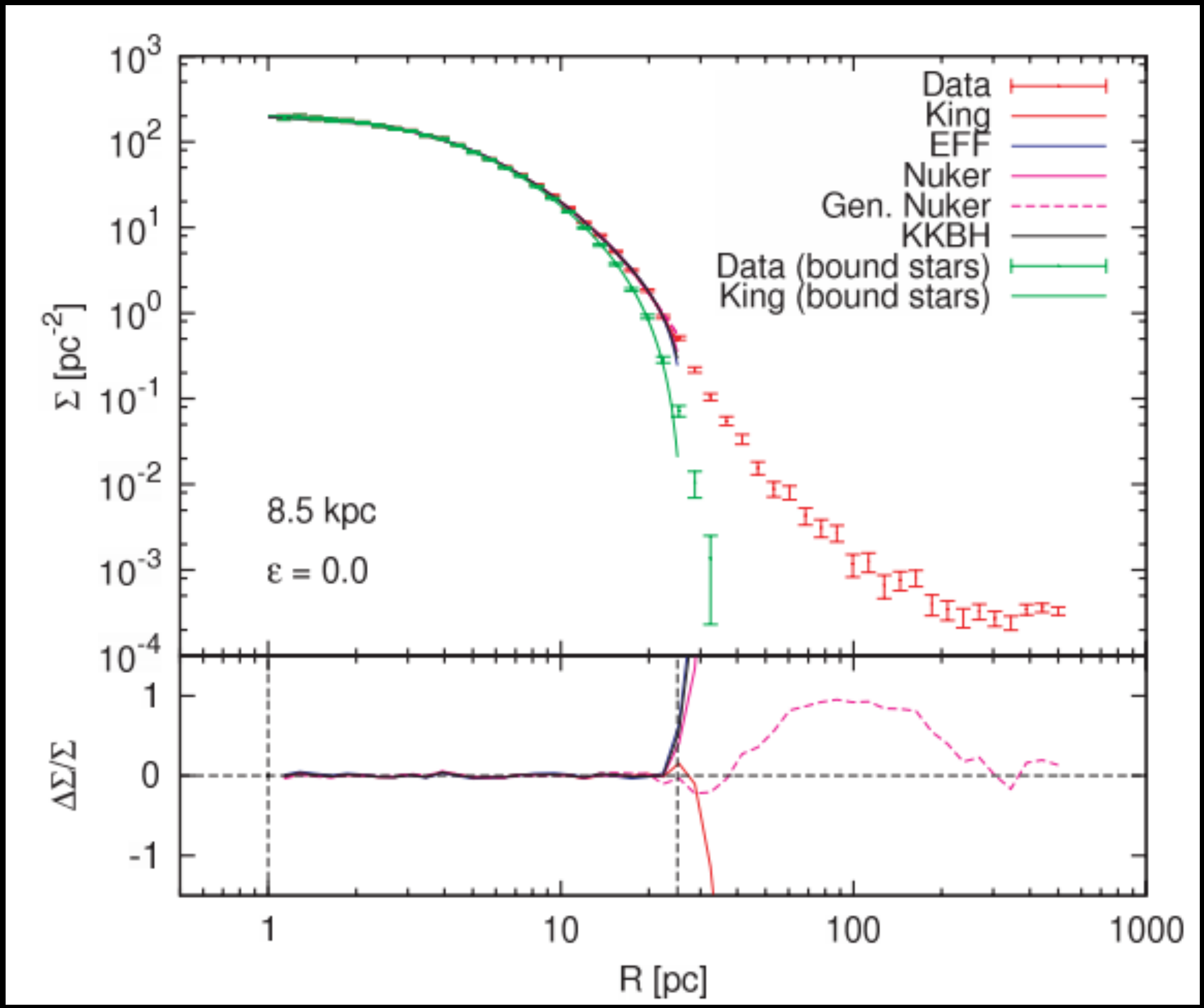
("Cannonballs" in 47 Tuc, Meylan et al. 1990 A&A)

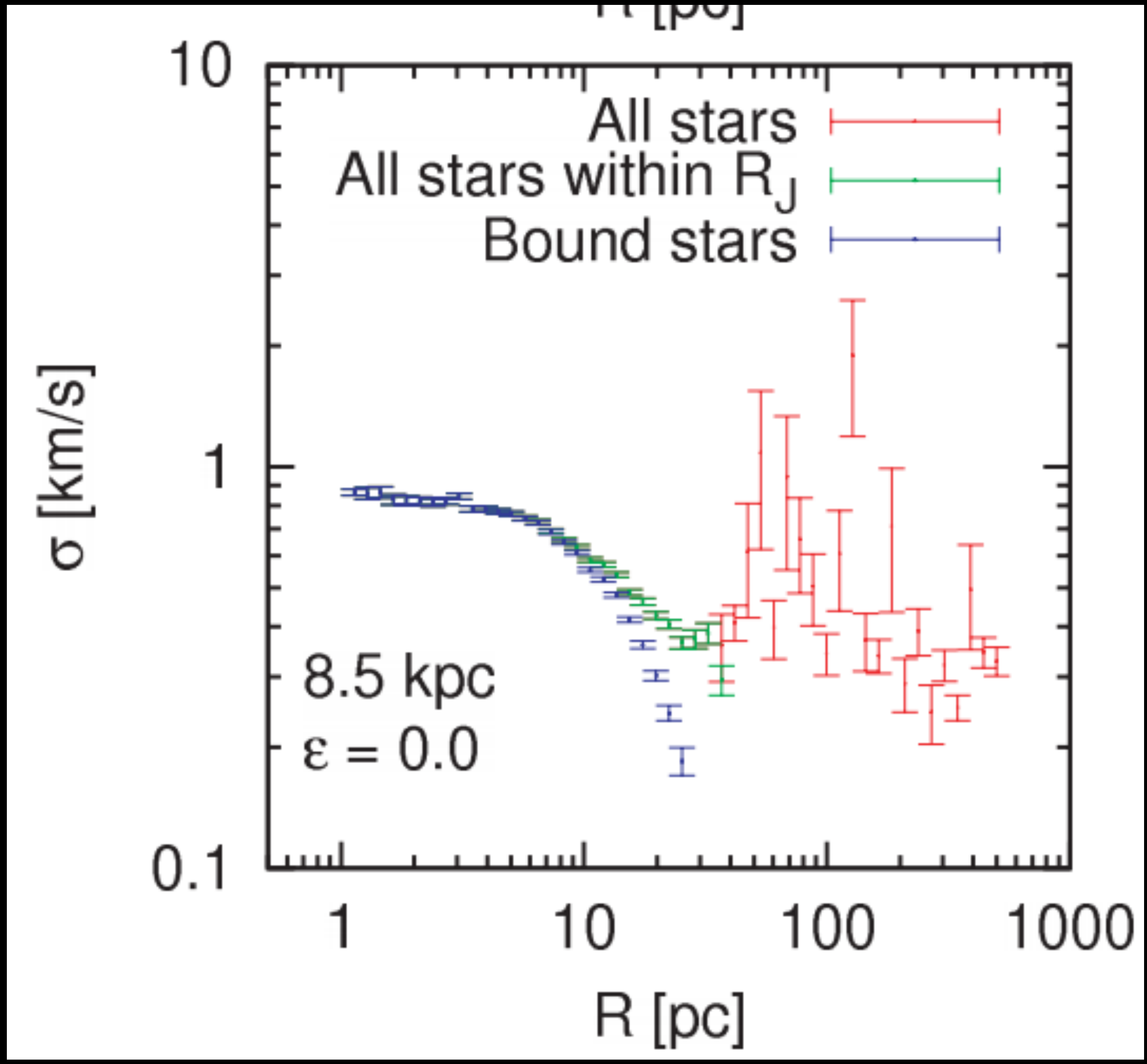
On the bright side



‘potential escapers’

energetically unbound stars which are confined within the critical Jacobi equipotential surface



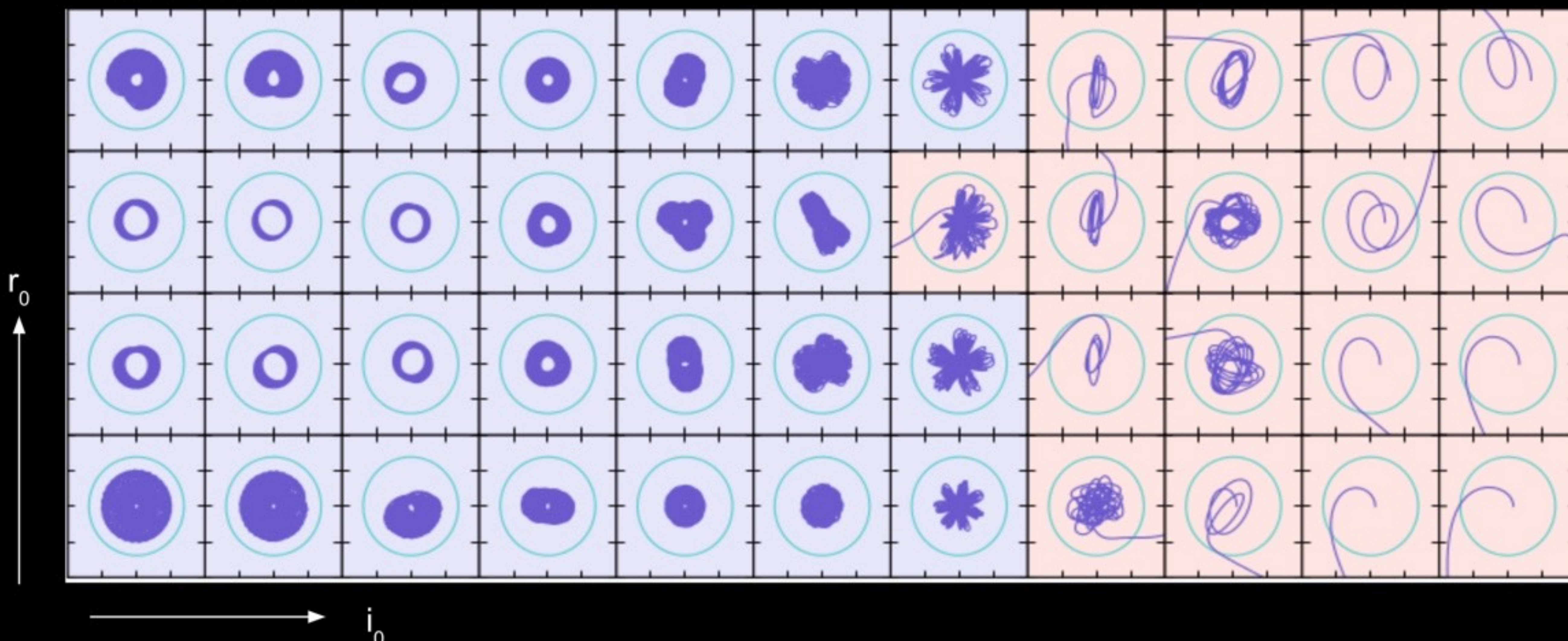


Kuepper, Kroupa, Baumgardt, Heggie 2010 MNRAS
see also Claydon, Gieles, Zocchi 2017 MNRAS

On the bright side

First (approximate) analytic model of a star cluster that includes potential escapers

Daniel, Heggie, Varri 2017 MNRAS



Inspired by Hénon's family " f " (periodic orbits, among solutions of the circular Hill's problem)
High-inclination orbits behave as Lidov-Kozai theory (in quadrupole approximation)

On the bright side

First (approximate) analytic model of a star cluster that includes potential escapers

Kepler energy, averaged over Kepler motions

$$\langle H_K \rangle = H_K(0) + \Phi_t(0) - \langle \Phi_t \rangle$$

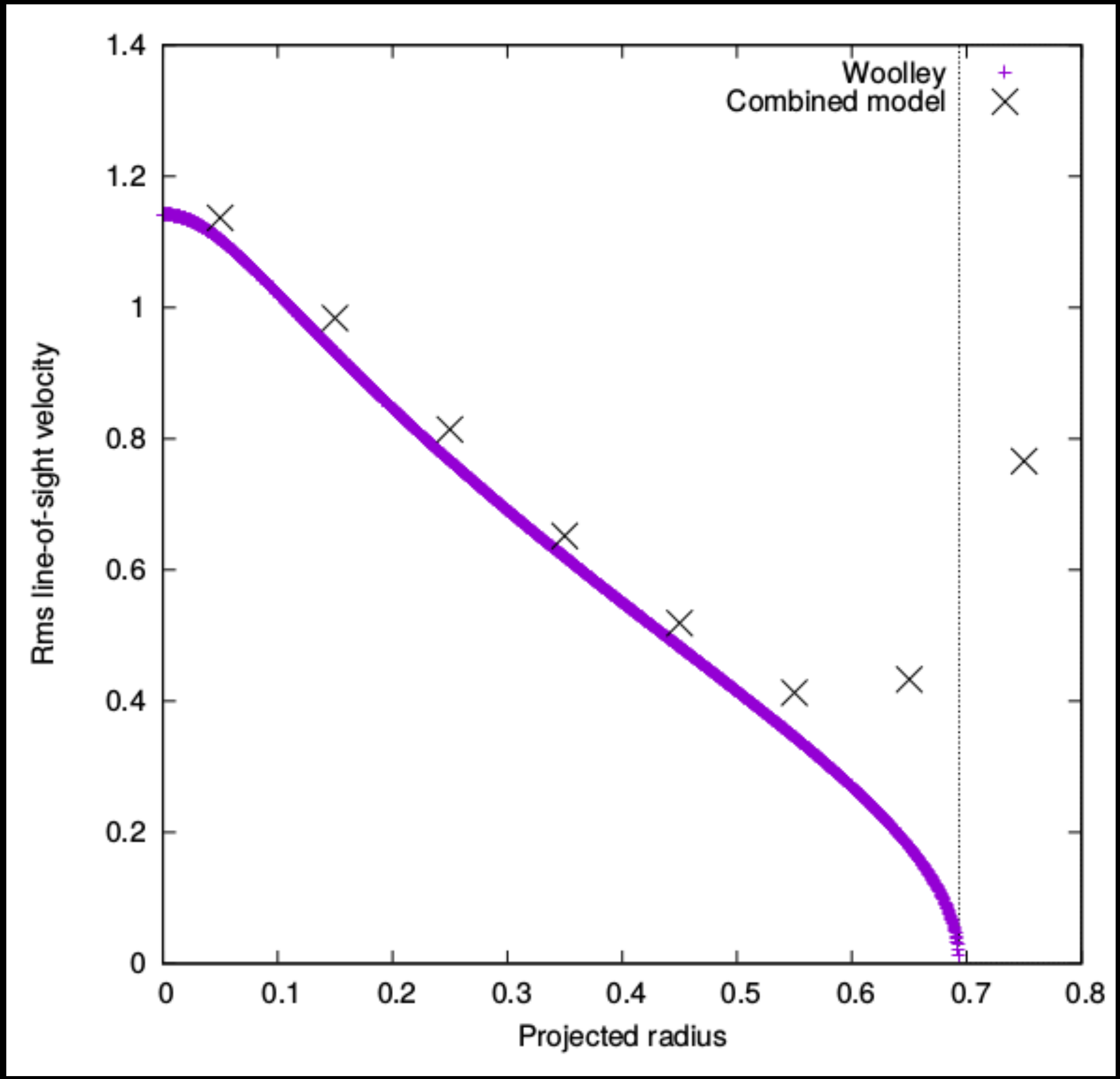
$$\Phi_t(x, y, z) = -\frac{3}{2}x^2 + \frac{1}{2}r^2,$$

z-component of angular momentum, averaged over Kepler and orbital motions

$$\langle J_{zN} \rangle \;=\; J_{zN0} + \frac{1}{2}(A \sin 2\Omega_0 - B \cos 2\Omega_0)$$

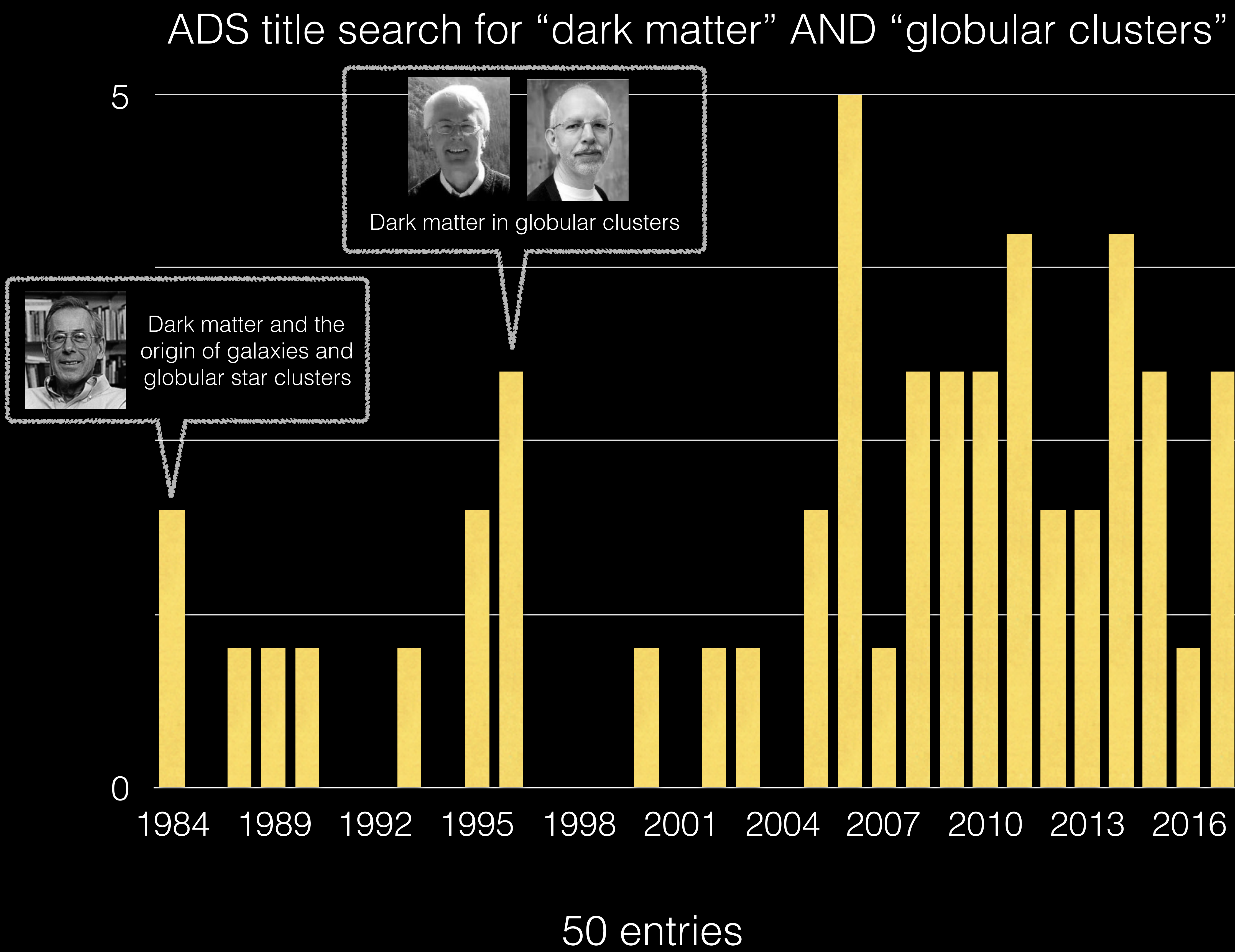
Three integral of motion used to identify ‘potential escapers’ in phase space (via discrimination criterion)

$$\{\Gamma, \langle H_K \rangle, \langle J_{zN} \rangle\}$$



Daniel, Heggie, Varri 2017 MNRAS

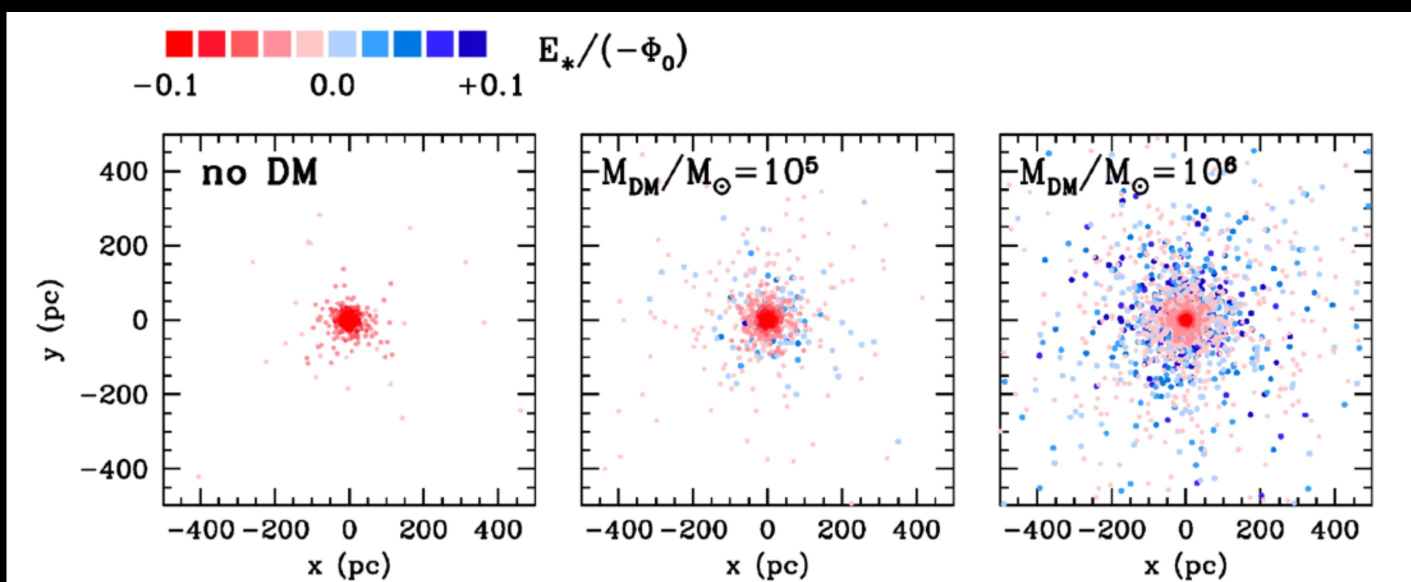
see also Claydon, Gieles, Varri et al. 2019 MNRAS

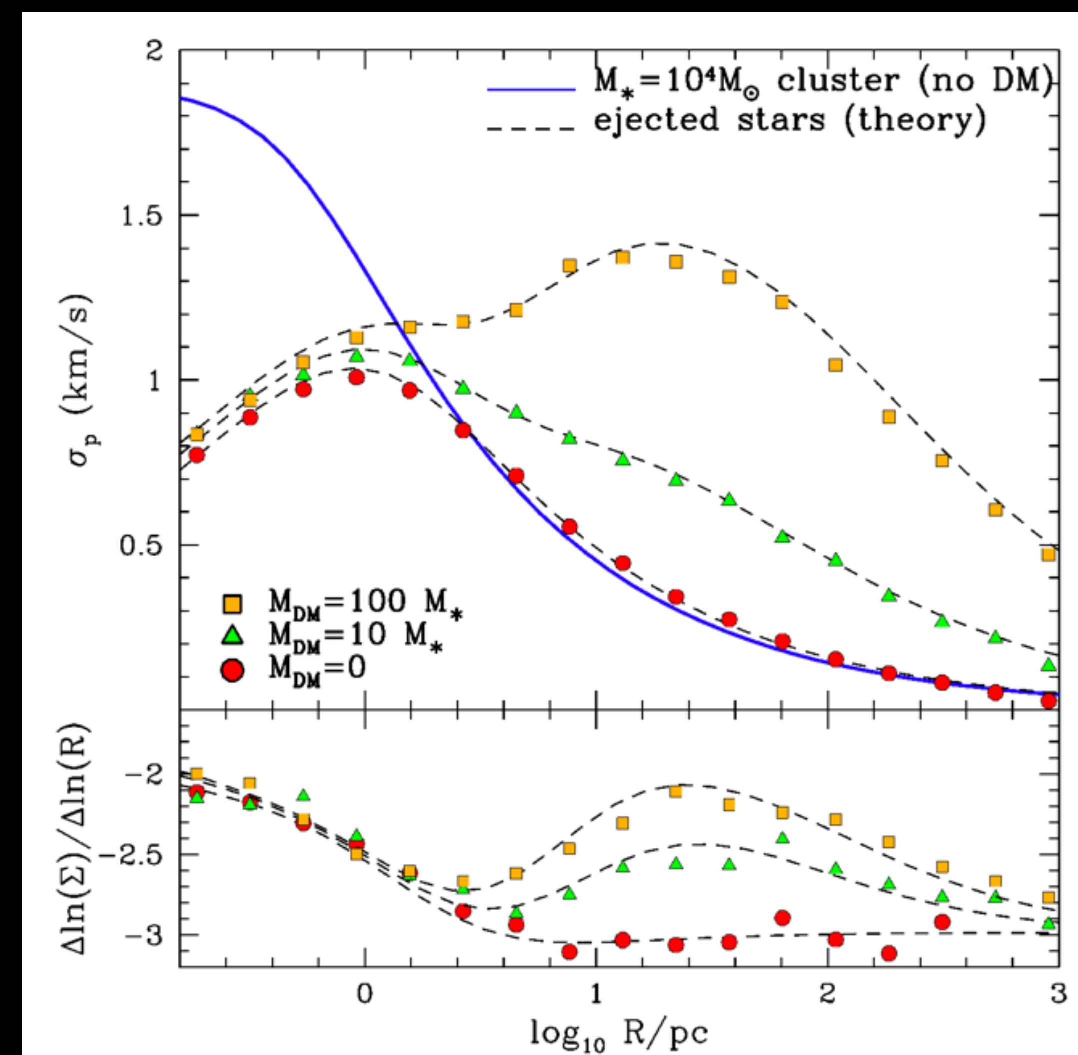


ADS title search for “dark matter” AND “globular clusters”
5
0
1984
1989
1992
1995
1998
2001
2004
2007
2010
2013
2016
Dark matter and the origin of galaxies and globular star clusters
Dark matter in globular clusters
50 entries

On the dark side

Stellar envelopes of globular clusters embedded in dark matter mini-halos





$$\Phi = \Phi_\star + \Phi_{\rm DM}$$

$$M_\star = 10^4 M_\odot$$

$$r_{\rm DM}/a \sim 25\text{–}65$$

$$M_{\rm DM}/M_\odot = 10^5 \text{ and } 10^6$$

$$\Phi_\star(r) = -\frac{GM_\star}{\sqrt{r^2+a^2}}$$

$$\Phi_{\rm DM}(r) = -\frac{GM_{\rm DM}}{r+r_{\rm DM}}$$

Peñarrubia,Varri, Breen et al. 2017 MNRAS Lett

On the dark side

Stellar envelopes of globular clusters embedded in dark matter mini-halos

Peñarrubia,Varri, Breen et al. 2017 MNRAS Lett.

$$N(E,L) = \frac{p[v_r(E)]}{[2(E-\Phi_0)]^{1/2}}\delta(L)$$

$$\omega(E,L) = 8\pi^2 LP(E,L)$$

$\longrightarrow$

$$f_{\rm eq}(E,L) = f_0 \frac{p[v_r(E)]}{[2(E-\Phi_0)]^{1/2}} \frac{\delta(L)}{8\pi^2 LP(E,L)}$$

$$\rho(r) \equiv \int d^3v f_{\rm eq} = \frac{f_0}{4\pi r^2}\int_{\Phi(r)}^{0} {\rm d}E \frac{p[v_r(E)]}{[2(E-\Phi_0)]^{1/2}} \frac{1}{[2(E-\Phi)]^{1/2}P(E,0)}$$

$$\sigma_r^2(r) \equiv \frac{\int d^3v v_r^2 f_{\rm eq}}{\int d^3v f_{\rm eq}} = \frac{f_0}{4\pi r^2\rho(r)}\int_{\Phi(r)}^{0} {\rm d}E \frac{p[v_r(E)]}{[2(E-\Phi_0)]^{1/2}} \frac{[2(E-\Phi)]^{1/2}}{P(E,0)}$$

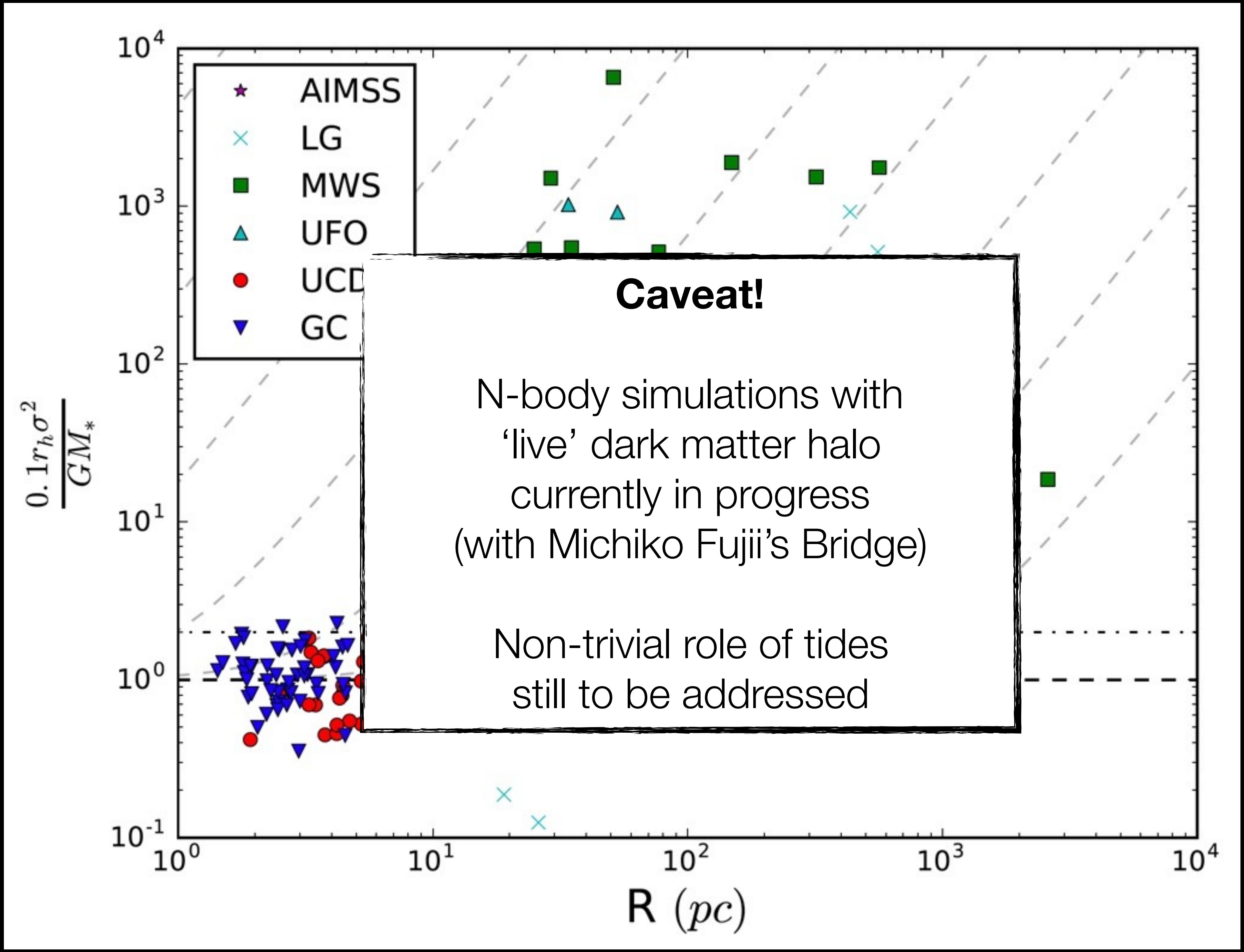
$r \ll r_c$ $\quad \rho(r) \sim r^{-2}$ $\quad \sigma_r \sim \text{const}$

$r \gg r_c$ $\quad \rho \sim r^{-4}$ $\quad \sigma_r \sim r^{-1/2}$

Ellipticals as end-products of violent relaxation, see also Bertin & Stiavelli 1984, Jaffe 1987, Makino 1990, Aguilar 2008

Collisional dynamics with dark matter

A possible dynamical framework to interpret the uncharted territory between 'star clusters' and 'galaxies'



Caveat!

N-body simulations with 'live' dark matter halo currently in progress (with Michiko Fujii's Bridge)

Non-trivial role of tides still to be addressed

Breen, Varri, Peñarrubia et al. to be submitted

Parting thoughts

The presence of a dark halo changes dramatically the dynamical evolution of collisional stellar systems. Refreshingly new take on the classical paradigm.

The moment of core collapse gets delayed, the size of the core changes, the core-halo gravothermodynamics is different … so much to explore!

We might gain a new framework to explore the uncharted territory between collisional and collisionless dynamical systems.

Some zoo-keeping at the low-end of the galaxy mass function is very much needed.

The star cluster - galaxy divide is the small-scale frontier of galaxy formation and a central challenge for 'near-field' cosmology in the era of Gaia, JWST, ELTs.

Deep implications for fundamental physics - dark matter clustering scale and beyond.

I am based at UTokyo (in Fujii's Group) until Nov. 2019 - let's talk about low-mass stellar systems!

Hongo, Science Bldg.1, 11F annalisa.varri@gmail.com @parallasseh