Star cluster dynamics – what we don't know

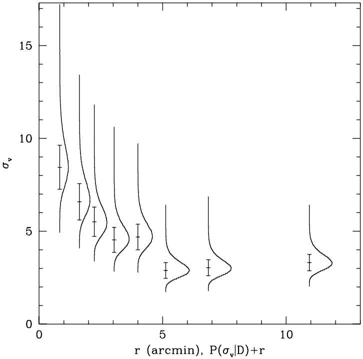
ISIMA projects proposed by Douglas Heggie and Anna Lisa Varri

University of Edinburgh, UK

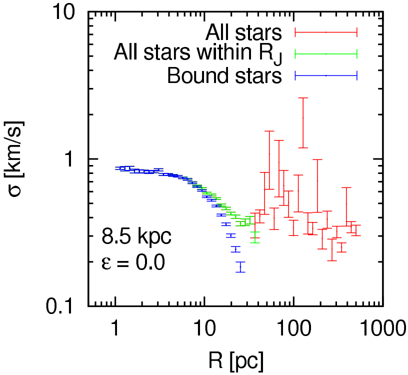
Theme 1: External tidal field

Theme 2: Internal rotation

(C) Kinematic signatures of the tidal field



- Velocity dispersion profile of M15
- Note rise (at least, no Keplerian fall) towards tidal radius at 24'
- Inconsistent with all models such as King
- Drukier+ 1998



- *N*-body simulation from Küpper+ 2010
- Velocity dispersion elevated by "unbound" stars within the tidal radius; called *potential escapers*

(C) Kinematic signatures of the tidal field

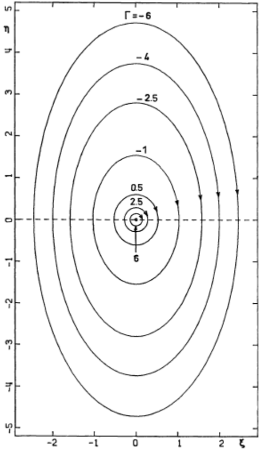


Fig. 3. Family *f* of periodic orbits. All orbits are stable

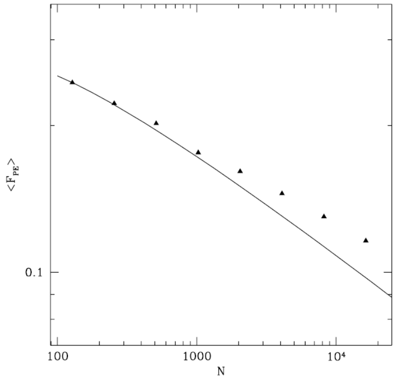
- Hénon 1969
- Lagrangian points $(\pm 0.69, 0)$, "energy" 4.3

- A section of this stable family of periodic orbits lies inside the tidal radius, and are unbound ($\Gamma < 4.3$)
- These orbits may give the cluster a definite rotation

The project

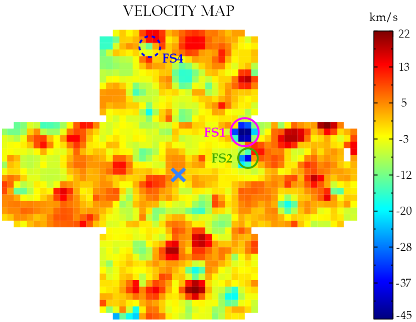
- Repeat simulations like those of Küpper+ 2010; circular Galactic orbit
- Analyse kinematics of stars inside the tidal radius, in terms of profile of radial and transverse velocity components (to measure anistropy), and to measure rotation.
- Understand the results in terms of orbit structure (e.g. Hénon's Family f)
- Extend to elliptic Galactic orbit

(B) Model of a star cluster with potential escapers



- Mean fraction of potential escapers as a function of N, from Baumgardt 2001 (MNRAS)
- Decreases more slowly than $N^{-1/4}$

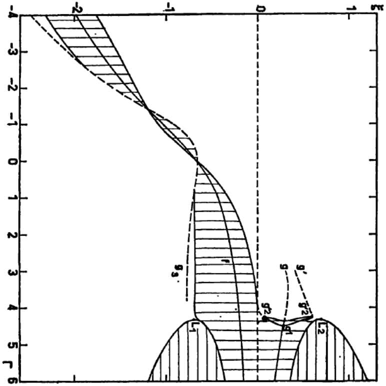
- Mean fraction several percent for $N = 10^6$
- No snapshot model (King etc) includes this population
- May explain stars with speeds above the escape speed (Gunn & Griffin 1979, Meylan+ 1991, Lützgendorf 2012)



(B) Model of a star cluster with potential escapers

Aim: to construct a model star cluster including potential escapers
Method:

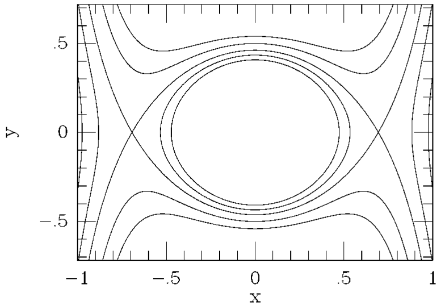
- Start with the potential $\phi(\mathbf{r})$ of some standard model (e.g. King)
- Locate Hénon's family f (numerically and/or by perturbation theory)
- Find the zone of stable quasiperiodic orbits around family f



Hénon 1970

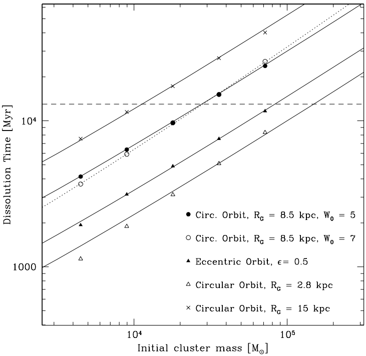
- Construct a second invariant J_2 (in addition to the Jacobi integral J_1) which delineates this region of phase space
- Invent suitable $f(J_1, J_2)$
- Compute density $\rho(\mathbf{r})$ and $\phi(\mathbf{r})$ using a Poisson solver
- Iterate

- For a cluster on a circular Galactic orbit, each star in a cluster moves on orbit with constant Jacobi integral $J_1 = \frac{1}{2}(\dot{x}^2 + \dot{y}^2 + \dot{z}^2) + \omega\omega' R x^2 + \frac{1}{2}\omega^2 z^2 + U$ where $\omega(R)$ is Galactic angular velocity at radius R, $U(x, y, z)$ is cluster potential at position (x, y, z) of star.
- Hence motion constrained by equipotentials:



- Note Lagrangian points L (critical points of the effective potential)
- Escape only possible if J_1 above $J_1(L)$
- Time scale for escape of stars of "energy" J_1 is proportional to $(GM)^{4/3}\omega^{4/3}(J_1 - J_1(L))^{-2}$ (Fukushige & H 2000), where M is cluster mass.

- Because escaping stars may take a long time to escape, the lifetime of a cluster changes from being proportional to t_r to being proportional to $t_r^{3/4} t_{cr}^{1/4}$, where t_r, t_{cr} are relaxation and crossing times (Baumgardt 2001)



- Note cluster on elliptic orbit (apo- and peri-Galactic distances 8.5, 2.8 pc) behaves like a cluster on a circular orbit (at an intermediate radius)
- For a cluster on an elliptic Galactic orbit
  - Equations of motion change
  - Even if the acceleration derivable from a potential, it is not a steady one
  - No conserved quantity analogous to J_1
  - No Lagrangian points (no equilibria of equations of motion)

Motivation of the project

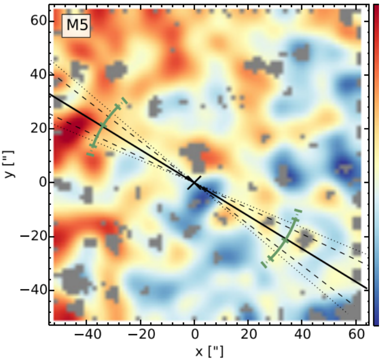
- Why is the scaling of lifetime with N the same as for circular orbits, when none of the basic arguments are applicable?
- Why is lifetime a linear function of e? (Mark Gieles)

Organisation of the project

- Find the equations of motion for a star in a cluster in an elliptic orbit
  - Analogy with circular case derived in lectures
- Find the generalisation of the Lagrangian points
  - If the Galaxy is represented as a point mass, could adopt results from the three-body problem
  - Generalisation may be a periodic orbit
- Generalise analysis of Fukushige & H 2000
  - Instead of computing flux of phase space, calculate the volume of phase space ejected in each Galactic orbit
  - Consider perturbation calculation (small eccentricity)
  - Alternative approach: adapt analysis of Murali & Weinberg 1997

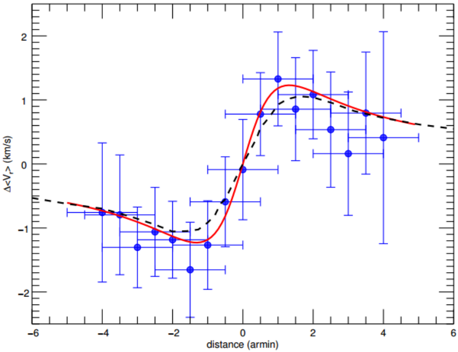
An increasing number of globular clusters are being observed to have significant evidence of internal rotation.

- *What is the role of angular momentum in their dynamical evolution?*
- *How does the presence of internal rotation affect mass segregation?*



Velocity field of the central regions of M5

Fabricius+ ApJL 2014



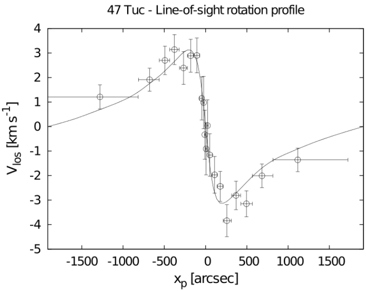
Rotation curve of NGC 4372 (red line: Mackey+ 13 rotation profile, black dashed line: VB12 model). Kacharov+ A&A 2014

1. Survey of N-body simulations starting from initial configurations with moderate differential rotation and a mass spectrum.

(see Varri & Bertin A&A 2012, Bianchini+ ApJ 2013, Kacharov+ A&A 2014)

- Characterize main observables
- Study transport of angular momentum
- Effects on "gravogyro" instability?

  (see Einsel & Spurzem MNRAS 1999, Ernst+ MNRAS 2007)



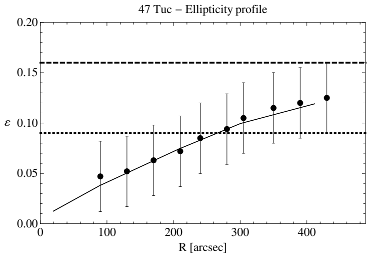
2. Family of differentially rotating models with multiple self-consistent components, to interpret the end products of the simulations (and fit observational data).

- Which prescription should be used?

  (see Gunn & Griffin AJ 1979, Miocchi MNRAS 2006)

- Energy equipartition?

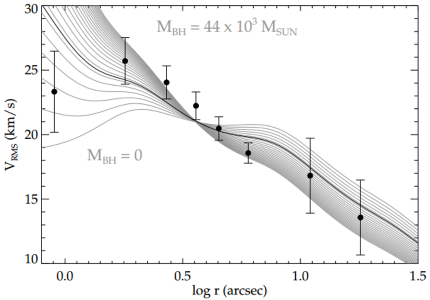
  (see Trenti & Van der Marel MNRAS 2013)



47 Tucanae - Best fit VB12 model. Bianchini+ ApJ 2013

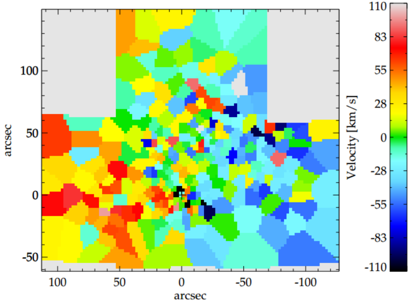
- *Globular star clusters:* dynamical studies investigating the possible presence of central IMBHs in GCs often *assume* the absence of internal rotation. (e.g., see Lützgendorf+ A&A 2011, Lanzoni+ ApJ 2013)
- *Nuclear star clusters:* Realistic dynamical models with internal rotation and deviations from spherical symmetry may offer useful clues to the formation scenario of this class of stellar systems.

(see Hartmann+ MNRAS 2011, De Lorenzi+ MNRAS 2013, Schödel+ A&A 2014, Chatzopoulos+ under review)



Velocity dispersion of NGC 6388 and isotropic Jeans models

with different M_{BH}. Lützgendorf+ A&A 2011



Velocity map of the MWNSC (from CO lines)

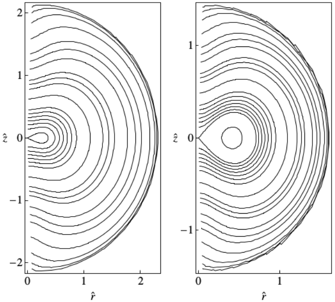
Feldmeier+ A&A 2014

(E) Differentially rotating models with a central massive black hole

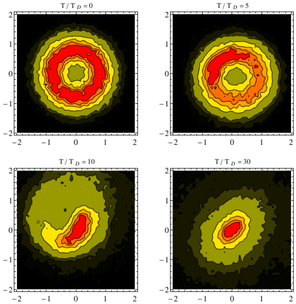
- Stellar systems characterized by a high degree of differential rotation can show a central toroidal structure, resulting from the interplay between self-gravity and centrifugal effects.

  (see Lynden-Bell MNRAS 1962, Prendergast & Tomer AJ 1970, Kuijken & Dubinski MNRAS 1994, Varri & Bertin A&A 2012).

- Equilibria with low values of $K_{rot}/|W|$ and high degree of differential rotation can be dynamically unstable with respect to $m = 1, 2$ modes. Striking similarities with dynamical instabilities in differentially rotating fluid polytropes. (see Centrella+ ApJL 2001, Varri+ under review)



Meridional section of isodensity contours of models with intermediate (left) and strong (right) differential rotation. Varri & Bertin 2012



Evolution of an unstable model with $K_{rot}/|W| = 0.16$

Varri+, under review

(E) Differentially rotating models with a central massive black hole

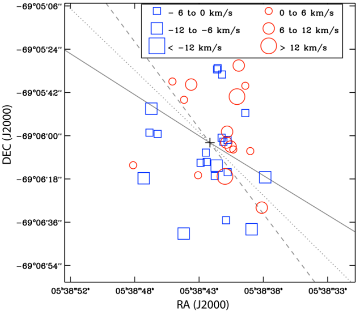
Starting from an existing family of self-consistent axisymmetric models with differential rotation (configurations are obtained by solving the Poisson equation via a spectral iteration method):

1. Generalization to include the presence of a central BH:
   - Appropriate new term(s) in DF
   - Well-posed initial conditions in the definition of Cauchy problems for the radial coefficients of the spectral expansion of the density and potential
   - Asymptotic analysis at small radii to characterize the solution (and the main observables) in the central regions
2. Exploration of the effects of the BH in different rotation regimes:
   - *Resulting morphologies?*
   - *Global/local kinematical signatures?*
3. Analysis (via N-body simulations) of the stability properties of the resulting configurations:
   - *How does the presence of a central BH affect the conditions for the emergence of rotational (dynamical) instabilities?*
   - Any analogies with fluid dynamical models?

- So far, the collisional evolution of rotating stellar systems has been explored exclusively in the regime of moderate rotation.

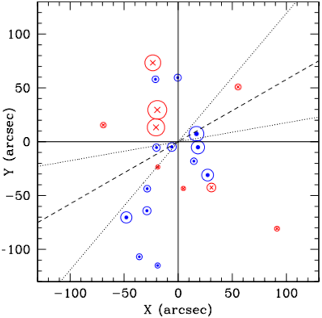
  (e.g., see Einsel & Spurzem MNRAS 1999, Ernst+ MNRAS 2007)

- Yet, recent observational studies have shown that young and intermediate-age star clusters can have high values of V_{rot}/σ.



Schematic view of the velocity field of R136

($V/\sigma \approx 0.6$). Vincent Hénault-Brunet+ A&A 2012a,b



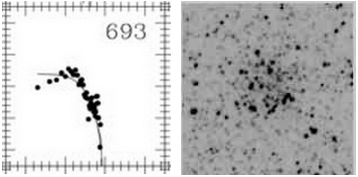
Schematic view of the velocity field of NGC 1846

($V/\sigma \approx 0.8 - 1.0$). Mackey+ ApJ 2013

- In addition, a sizable fraction of star clusters in SMC, LMC, M33, M31 have peculiar morphologies ("ring clusters") that may suggest the presence of a significant degree of differential rotation.

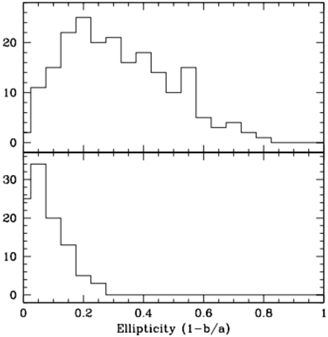
  (see Hill & Zaritsky AJ 2006, Werchan & Zaritsky AJ 2011, San Roman+ MNRAS 2012, Weng & Ma AJ 2013)

- Furthermore, star clusters in the LMC, SMC are known to be significantly flattened and more extended than GGCs, but the physical origin of such structural properties is still poorly understood. (see Frenk & Fall MNRAS 1982, Han & Ryden ApJ 1994, van den Bergh AJ 2008)



Surface brightness profile and V-band image f LMC 693

Werchan & Zaritszky AJ 2011



Distribution of ellipticites of star clusters in the SMC (top) and MW (bottom). Hill & Zaritszky AJ 2006

Survey of N-body simulations to explore the long-term evolution of stellar systems in the regime of strong differential rotation, currently unexplored. The first phase of investigation should focus on isolated, one-component models:

- *Dynamically stable equilibria: morphological and kinematical evolution of the central toroidal structure?*
- *Dynamically unstable equilibria: any special signature in phase space?*

In both cases:

- Characterize the main observables (surface brightness, velocity dispersion, mean velocity profiles)
- Special attention to the structural evolution (isodensity maps, ellipticity profiles) ...
- ... as potentially linked to the dynamical evolution induced by the transport of angular momentum

Any new insight about the morphological and dynamical evolution of star clusters in the Magellanic Clouds?