Tracing dark remnant populations in GCs with multimass models
(and implications for IMBH detections)

NGC 6624
HST

47 Tuc
ESO/VISTA

ω Cen
ESO/WFI

Vincent Hénault-Brunet
Plaskett Fellow
NRC Herzberg

M. Gieles, M. Peuten, E. Balbinot
(Surrey)

A. Zocchi (ESA/ESTEC)
To address present-day dynamical properties (e.g. What is the global mass function, remnant content? Is there an IMBH?) equilibrium models can be sufficient.

DF-based models are **fast** to compute, **flexible**, but still **physically motivated**.
Multimass LIMEPY* DF models

\[ f(E, J^2) = A \exp \left( -\frac{J^2}{2r_a^2 s^2} \right) \exp \left( \frac{\phi_t - E}{s^2} \right) \frac{\gamma \left( g, \frac{\phi_t - E}{s^2} \right)}{\Gamma(g)} \]

radial anisotropy in outer parts

isothermal core

polytropic envelope

\[
\text{Multiple mass components:}
\]

\[ f = \sum_j f_j \]

\text{Mass segregation} from imposed mass-dependence of velocity scale:

\[ s_j \propto s \, m_j^{-\delta} \]

\[ \delta = 0.5 \]

Gieles & Zocchi 2015
see also Gomez-Leyton & Velazquez 2014

https://github.com/mgieles/limepy
Validating multimass LIMEPY: comparison to NBODY6 models

Density and velocity dispersion profiles of the different mass components well reproduced in all evolutionary phases and for different contents of neutron stars and BHs.

- **no BHs**
  - Density and velocity dispersion profiles show different behaviors for WDs, MS stars, and NS.

- **100% initial BH retention**
  - Density and velocity dispersion profiles now include BHs along with WDs, MS stars, and NS.

Peuten+ 2017
\[ \sigma_{1d,0} \propto m^{-1/2} \] ("full equipartition")

100% initial BH retention  
30% BH retention  
0% BH retention
Fitting multimass models to mock observations

N-body model of M4 (Heggie 2014) snapshot at ~12 Gyr ➔ mock observations

Hénault-Brunet+ 2018, to be submitted
Fitting multimass models to mock observations

\[ \text{Inferred properties (not directly fitted!)} \]

\[ \text{Remnants} \]

\[ \text{Multimass LIMEPY} \]

\[ \text{Multimass GG79} \]

\[ \text{Stars} \]

\[ \text{Global mass function} \]

\[ \text{Global mass function} \]

\[ \text{N-body model of M4 (Heggie 2014) snapshot at \( \sim 12 \) Gyr} \]

\[ \text{mock observations} \]

\[ \text{Hénault-Brunet+ 2018, to be submitted} \]
Pulsar timing as a probe of the gravitational potential

\[ a_{GC} = \frac{c}{P} \left( \dot{P}_m - \dot{P}_i \right) \]

measured

intrinsic

Phinney 1993; Prager+ 2016
NGC 6624: IMBH evidence from pulsar timing?

PSR A <0.5” from cluster centre

Spin period derivatives from ~25 years of timing

Large acceleration used by Perera et al. (2017) to argue for a central IMBH of several ~10³-10⁴ M☉

Conclusions also based on higher order spin derivatives to constrain Keplerian orbit and IMBH mass, but in dense cluster environment these should be dominated by neighbouring stars (Phinney 1993)...
Multimass model of NGC 6624 (without IMBH)

- Core-collapsed (expect large core radius with an IMBH) e.g. Heggie+ 2007
- Mass segregated (expect IMBH to quench mass segregation) e.g. Gill+2008

**Surface brightness**

- $\mu_v$ [mag/arcsec$^2$]
- $\log R [\text{arcsec}]$
- Trager+ 1995

**PM velocity dispersion**

- $\sigma_{\text{pm}}$ [mas/yr]
- $\log R [\text{arcsec}]$
- Watkins+ 2015

**Mass function**

- $\log dN/dm [M_\odot] + \text{constant}$
- $\log m [M_\odot]$
- Gieles+ 2017

Saracino+ 2016

Trager+ 1995

Watkins+ 2015

Saracino+ 2016

Gieles+ 2017
PSR A acceleration: no need for an IMBH

Increase in central M/L dominated by white dwarfs (~60% of cluster mass)

Acceleration of PSR A consistent with multimass model

Gieles+ 2017
Central IMBH of \( \sim 2200 \, M_\odot \) reported by Kiziltan et al. (2017)

comparison of pulsar accelerations with \( N \)-body models with and w/o IMBH

Assumptions: Isolated models (but 47 Tuc has depleted low-mass mass function)

e.g. Giersz & Heggie 2011

\( D=4 \) kpc (but CMD-based and recent kinematic distances \( \sim 4.5-4.7 \) kpc...)

Kiziltan+ 2017

Freire+ 2017
47 Tuc: pulsar accelerations as evidence for an IMBH?

Underestimating the distance would lead to underestimating the maximum line-of-sight acceleration…

Freire+ 2017
**Multimass model of 47 Tuc without an IMBH**

- **Surface brightness**
  - Trager+ 1995

- **I.o.s. dispersion**
  - Baumgardt 2017

- **Radial dispersion**
  - Watkins+2015 (upper MS & giants)
  - Heyl+2017 (MS)

- **Tangential dispersion**
  - Watkins+2015 (upper MS & giants)
  - Heyl+2017 (MS)

- **Anisotropy**
  - Watkins+2015 (upper MS & giants)
  - Heyl+2017 (MS)

- **HST local mass functions**
  - $0'<R<0.4'$
  - $0.4'<R<0.8'$
  - $0.8'<R<1.2'$
  - $1.2'<R<1.6'$
Multimass model of 47 Tuc without an IMBH

“Predictions” (not fitted)

Radial distribution of MSPs

Core radius vs. mass

pulsar data from Freire+ 2017

data from Goldsbury+ 2013

Hénault-Brunet+ 2018, in prep.
Evidence for an IMBH in $\omega$ Cen?

Elevated velocity dispersion within $\sim 0.1 \, r_h$

![Graph showing velocity dispersion vs. radius with two curves: one for no IMBH and one for $M_{IMBH} = 4.0 \times 10^4 \, M_\odot$.](image)

Baumgardt 2017
A two-component model of $\omega$ Cen with stellar-mass BHs

A population of stellar-mass BHs could produce an increase in the central velocity dispersion.

$\omega$ Cen is a good candidate to have retained a significant population of stellar-mass BHs.

Massive, large escape velocity at time of BH formation (especially if a remnant of a disrupted dwarf galaxy).

Age $\sim$ relaxation time.

Equipartition timescale of two-component system:

$$\tau_{eq} \simeq \left( \frac{m_1}{m_2} \right) \tau_{rh}$$

Stellar-mass BHs are an order of magnitude more massive than the stars -> enough time to segregate.

Little mass segregation between visible stars, so two-component model justified.
A two-component model of $\omega$ Cen with stellar-mass BHs

Central kinematics from HST proper motions well matched by models with 4-5% of total mass in stellar-mass BHs with a mean mass of 6-7 $M_\odot$
**Summary**

**Multimass models:**
- useful and reliable way to trace the mass distribution in mass segregated clusters, accounting for the effect of stellar remnants
- can be used to weigh populations of remnants

**NGC 6624 & 47 Tuc:**
no need for an IMBH to explain the pulsar accelerations

**ω Cen:**
the effect of stellar-mass BHs needs to be considered before inferring the presence/mass of an IMBH