IMBH Fingerprints in Globular Clusters
(from stellar dynamics)

Michele Trenti
University of Colorado at Boulder
Intermediate Mass Black Holes

Black holes of $10^2$-10$^5$ Msun, missing link between stellar and supermassive BHs

Have been predicted in different astrophysical scenarios:

- Remnants of Population III stars (Heger et al. 2003)
- Runaway collapse in young star clusters (Portegies-Zwart et al. 2004)

Globular clusters may be the best place to look for them

But unambiguous detection is hard to achieve
Searching for IMBHs in GCs

Globular clusters have very little gas: x-ray/radio emission is faint

Sphere of influence of the BH is small (a few arcsecs): Limited direct BH Influence

~40000 Msun IMBH claimed in Omega Cen from Gemini IFU data + HST-WFPC2 imaging (Noyola et al. 2008)
The case of Omega Cen

But the claim disappears at higher resolution

Kinematic measured from HST proper motions of individual stars

New data set upper limit at 10000 Msun
(van der Marel & Anderson 2010)
Proper motion studies can provide the best evidence for IMBH based on dynamics but these are expensive.

Multiyear HST observations needed for GCs.

Are we focusing on the right GCs candidates?

Can we identify fingerprints for the IMBH presence?
Efficient IMBH heating leads to Universal large $r_c/r_h$ after a few relaxation times But... there are other (equally) efficient heating sources Stellar evolution (Hurley 07), WD kicks (Fregeau et al. 09), Stellar collisions (Chatterjee et al. 09), Stellar BHs (Mackey et al. 08)
Shallow cusps in surface brightness profile proposed as IMBH fingerprint: \[ \mu \sim R^{-0.2} \] (Baumgardt et al. 2004, Trenti et al. 2007, Miocchi 2007, Umbreit et al. 2010)

Shallow cusps are observed from HST data (Noyola & Gebhardt 2006)

Is this a unique sign associated to an IMBH?
IMBH fingerprint: shallow cusps

But shallow cusps do not necessarily imply an IMBH:

always present during and after core collapse (Trenti et al. 2010, Vesperini & Trenti 2010)

NGC5694 likely undergoing core collapse: $\alpha \sim -0.2$ naturally expected

(large) observational errors and intrinsic scatter present

Direct N-body run, N=64k, no IMBH from Trenti et al. (2010)
IMBH fingerprint: shallow cusps II

In addition:

Shallow cusps always present if a few percent binaries are present (Vesperini & Trenti 2010)

Shallow cusps are NOT reliable tracers of IMBH presence

See poster by Cseh for IMBH limits in NGC 6388

Direct N-body run, N=32k, no IMBH, 5% binaries

"IMBH region" in past studies
our NO IMBH runs

Vesperini & Trenti, submitted
In a GC the most massive stars segregate toward the center of the system (energy equipartition).

Simulations with an IMBH have less mass segregation (Baumgardt et al. 2004, Trenti et al. 2007).

Effect well beyond the BH sphere of influence!
Quenching of mass segregation

IMBH quickly gains at least one tightly bound massive star:

A super-scatter machine is born!

Three body encounters with the BH scatter out incoming stars independently of their mass

No strong dependence on BH mass expected or seen in simulations when $m_{BH} \gg m_{\text{star}}$

Random walk of the IMBH within the core: loss cone is constantly replenished, high rate of interactions over time
Our Modeling

- Direct N-body simulations with Aarseth’s NBODY6:
  - NO softening
  - Exact treatment of all strong interactions including those with the BH
  - Up to N=65536 (Trenti et al. 2010)

- Grid of initial conditions

- “Late Time” Mass function, Primordial Binary Fraction, Tidal Field, Concentration

- IMBH mass about 1% of total mass of the system

- Runs carried out until tidal dissolution (about 15 \( t_{\text{rh}} \))
Measuring Mass Segregation

Mass segregation $\Delta <m>$ is measured as the difference in average main sequence mass between the center and the half mass radius.

Differential measure:

Erases dependence on the IMF

Based on star counts:

Less sensitive to fluctuations in light profile due to giant stars

$\Delta <m> = <m(r = 0)> - <m(r = rh)>$
Mass Segregation Results: Simulations

- Simulations start with no mass segregation
- After about 5 relaxation times equilibrium value of mass segregation is reached
- Good separation of runs with and without an IMBH

Gill, Trenti et al. (2008)
Search for IMBH fingerprint can be applied to well relaxed clusters ($t_{\text{rh}} < 1 \text{Gyr}$)

Detailed Star Counts are needed, with coverage to at least half-mass radius

Data and Simulations need to be treated self-consistently

e.g. completeness, FOV, measure of structural parameters
NGC2298 dataset

Cluster properties

\[ t_{rh} = 10^{8.41} \text{ yr} \]

\[ rh = 49'' \]

\[ M_{\text{tot}} = 3 \times 10^4 \text{ Msun} \]

Data Reduction: DeMarchi & Pulone (2007)

HST-ACS WFC F606W & F814W

\[ 10\sigma \text{ limit } @ m_{606} = 26.5, m_{814} = 25.0 \]

>50% completeness @ 0.2 Msun
NGC2298: predictions from simulations

Simulations analyzed between 7 and 9 $t_{\text{rh}}$

Full radial mass segregation profile has been obtained

Plot shows 1 and 2$\sigma$ scatter of the simulated clusters

Sample of runs (270 snapshots), sample of random projections

Good separation IMBH vs NO BH in the center
NGC2298: comparison with simulations

Observed mass segregation profile is matched very well by simulations.

Cluster is too segregated to be likely to host an IMBH.

Formal limit from the inner two points: >300M sun BH excluded at 3σ CL.
NGC2298: comparison with simulations

NGC2298 has a peculiar mass function (very deficient in low mass stars)

General analysis includes an ensemble of IMFs

Restricting to a MF representative of 2298 yields more stringent prediction for $\Delta m(r)$

Stronger IMBH rejection

Excellent data-model match!

Pasquato, Trenti et al. (2009)
Mass segregation: M10

Similar analysis also carried out for M10

IMBH excluded at $\sim 1.5\sigma$ confidence level

Most likely explanation of measured level of mass segregation is $\sim 5\%$ primordial binaries

Beccari et al. (2010)
Mass segregation analysis for Omega Cen

IMBH in Omega Cen debated in the community

Spatial mass segregation analysis cannot be applied because relaxation time too long

But... mass-dependent kinematic at the center is available from proper motions

Velocity dispersion versus star mass shows system not in equipartition

Central velocity dispersion vs. star mass

Trenti & van der Marel, in preparation
Mass segregation analysis for Omega Cen

Omega Cen is closer to energy equipartition than expectations from N-body simulations with a central IMBH.

Simulations without IMBH provide better match.

But... there is a caveat to be explored: effects of primordial mass segregation.

Time evolution for $\sigma \sim m^k$

$k = -0.5$ (Equipartition)

Trenti & van der Marel, in preparation
Proper motions: best available (but expensive in telescope time)

Large rc/rh: necessary, not unique

Shallow surface brightness cusps: not unique

Mass segregation: good for relaxed (small) globular clusters (+ exciting prospects if 2D kinematics is available)