Searching in the dark: the dark mass content of globular clusters

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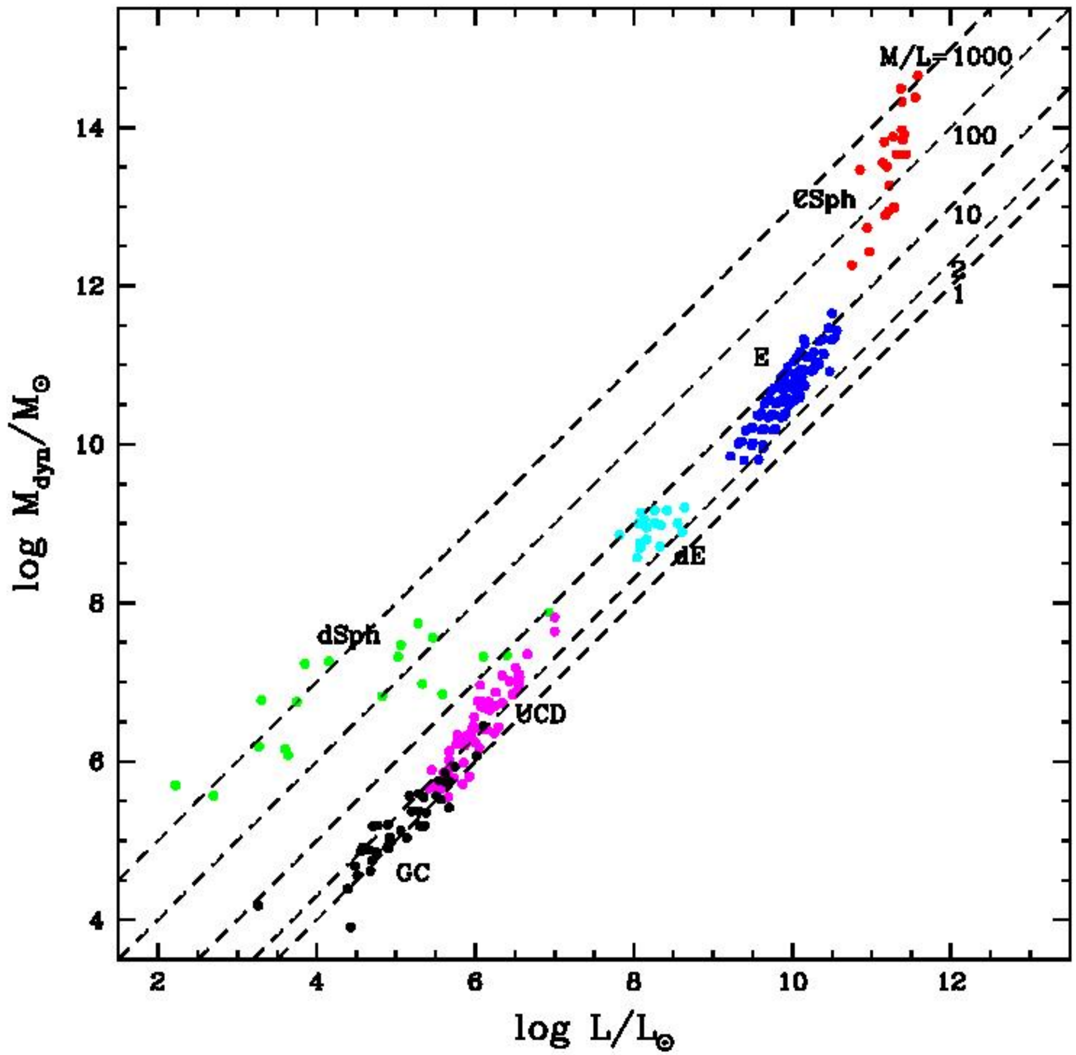
M-L relation for pressure-supported stellar systems

Pressure-supported stellar systems lie on a well-defined M-L relation

GCs seem to be deprived of DM

Tollerud et al. (2011)

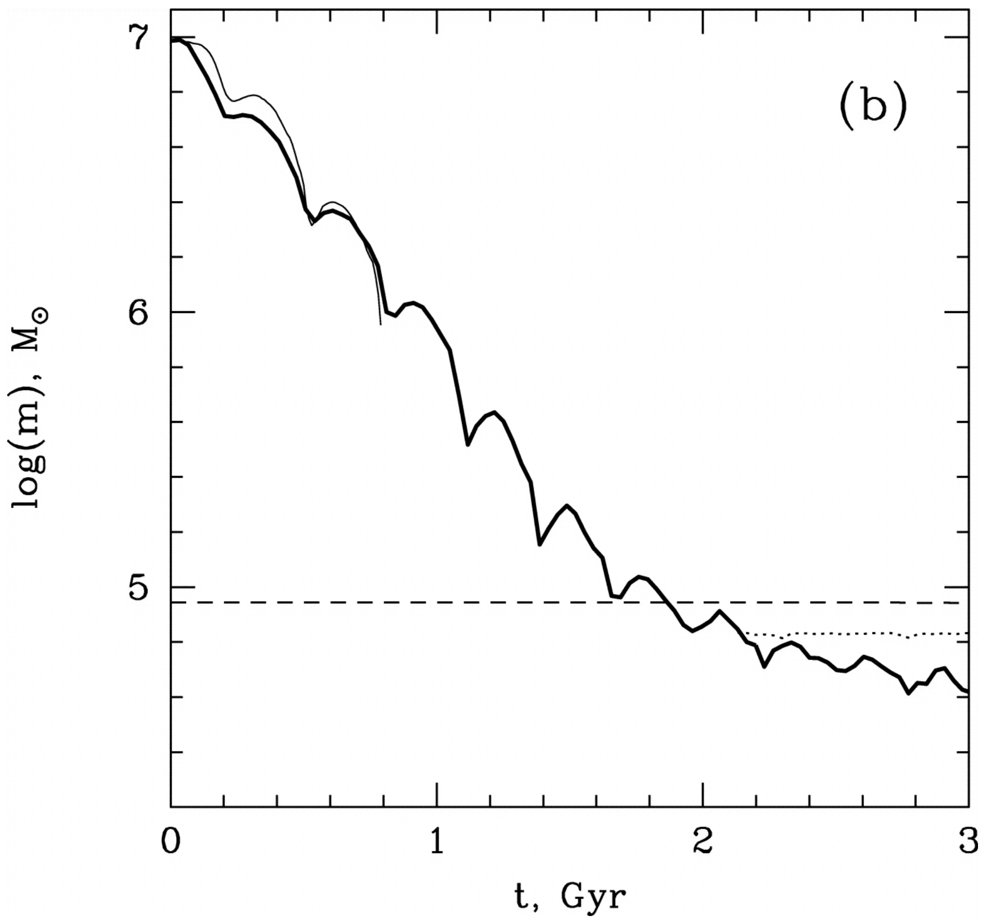


Models of GC formations

- GCs may form in collapsing DM-free clouds (Peebles & Dicke 1968)
- …or from gas cooling within a relatively small DM halo (Peebles (1984)

Most of the DM is expected to be stripped by the tidal interaction with the Milky Way

Mashchenko & Sills (2005)



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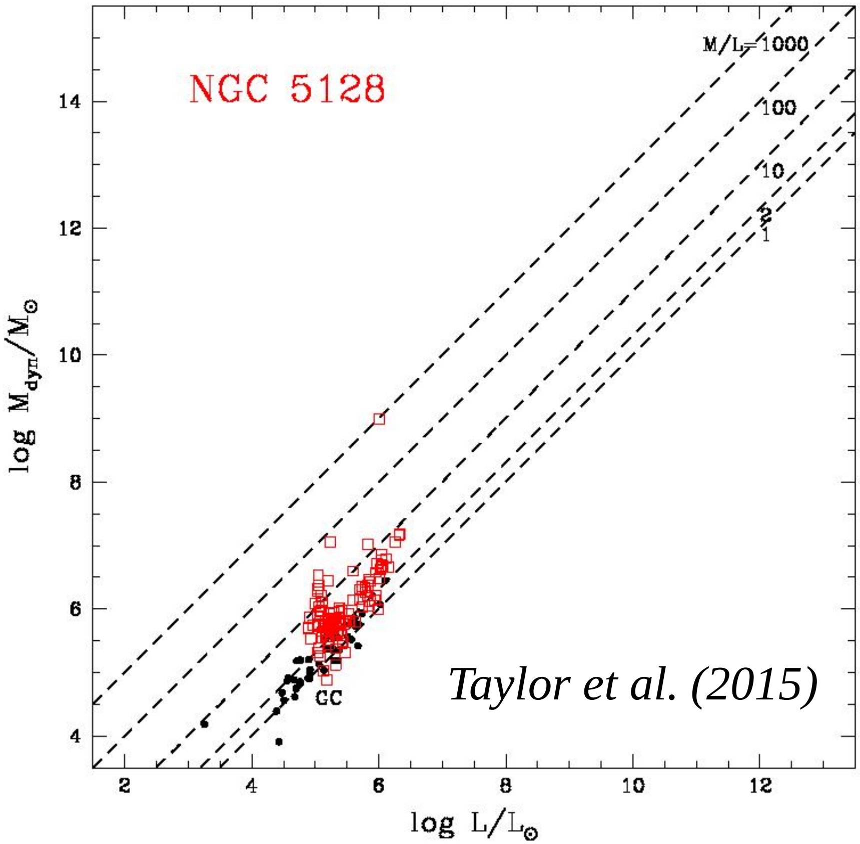
Temptative evidence of DM in GCs has been claimed in NGC 5128

But M/L depend on many parameters (MF, remnant fraction, age, [Fe/H], tides, binaries, etc.) which cannot be deduced from integrated light



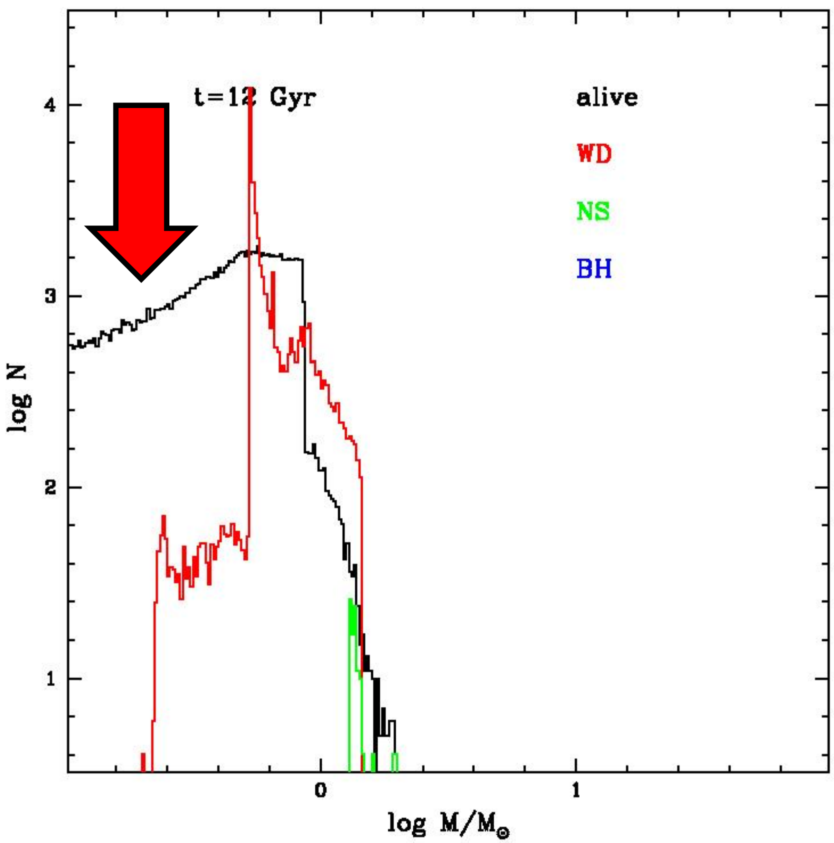
Dark remnants

During cluster evolution massive stars leave a dark remnant (WD, NS, BH)

NS are promptly ejected after formation by natal kicks

BH are quickly removed by "Spitzer instability"

Low-mass MS stars progressively evaporate because of tidal interaction with the host galaxy



Heggie (2014)

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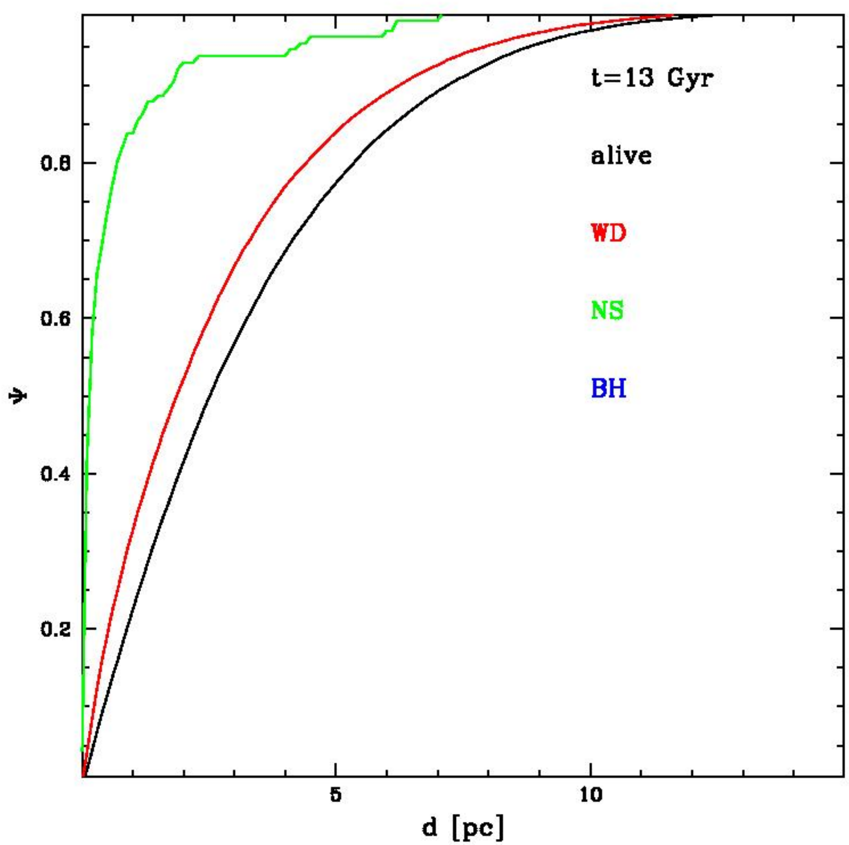
Remnants are generally more concentrated than other stars



Heggie (2014)

Previous works

After a boost of interest in the '90…

cluster	reference	f_{dark}
NGC6397	*Meylan & Mayor (1991)* *Heggie & Hut (1996)*	22-30% 53%
M13	*Leonard et al. (1992)*	46%
M107	*Piatek et al. (1994)*	61-80%
47Tuc	*Meylan (1989)* *Heggie & Hut (1996)*	16-23% <70%

INCOMPLETE!!

Large uncertainties because of the lack of information on the low-mass end of the MF and small RV dataset

…the attention recently moved to IMBHs

Noyola et al. (2010), Anderson & van der Marel (2010), Lützgendorf et al. (2013), Lanzoni et al. (2013), Kamann et al. (2014)… But their masses depend on the amount and distribution of remnants

Estimate of the dark mass fraction

Simultaneous fit of LF and σ_{LOS} profile with multimass King-Michie models

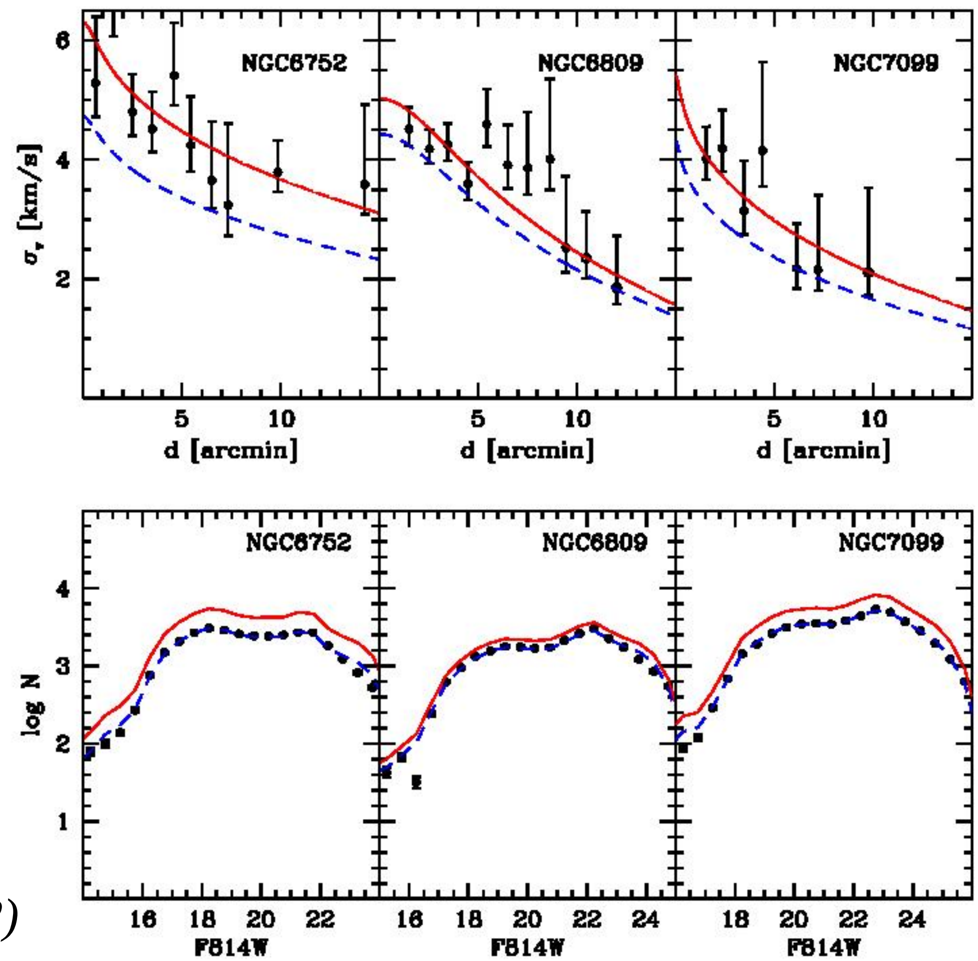
No agreement assuming
$25\% < f_{remn} < 40\%$

Dynamical masses are ≈40% larger than luminous ones

BUT

Results depend on the reliability of the adopted model

No information about the distribution of dark mass



Sollima et al. (2012)

Non-parametric estimate of the luminous mass

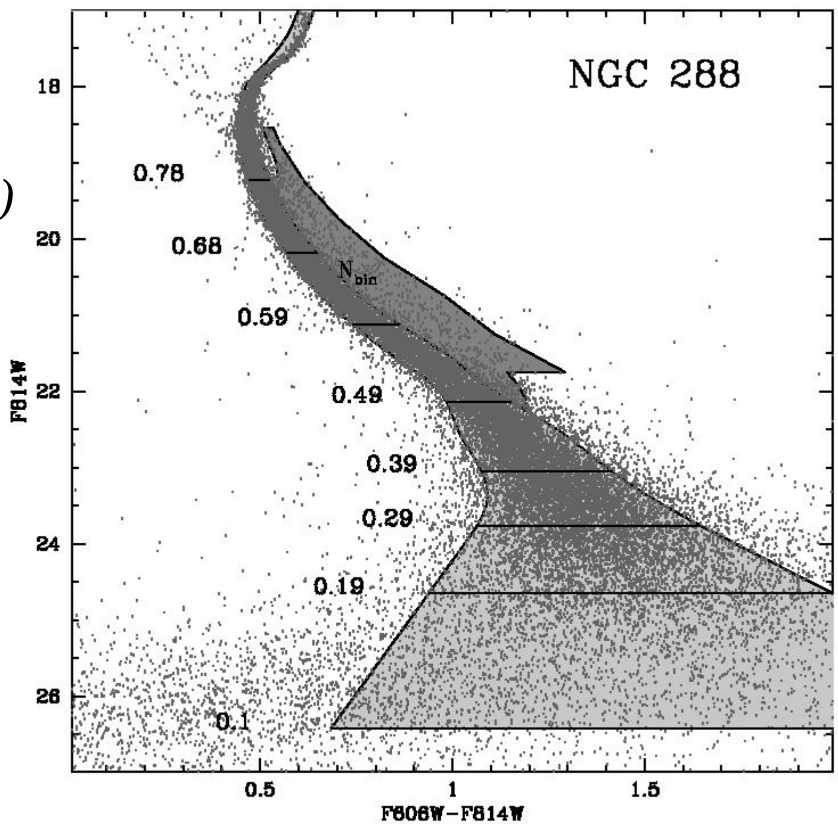
Luminous mass can be estimated in a straightforward way by using deep high-resolution photometry

to each star a mass, a completness factor and a binary probability is associated

$$M_*(r) = \sum_{d_i<r} \frac{m_i}{c_i}$$

ACS@HST
''GC treasury project''

Sarajedini et al. (2007)

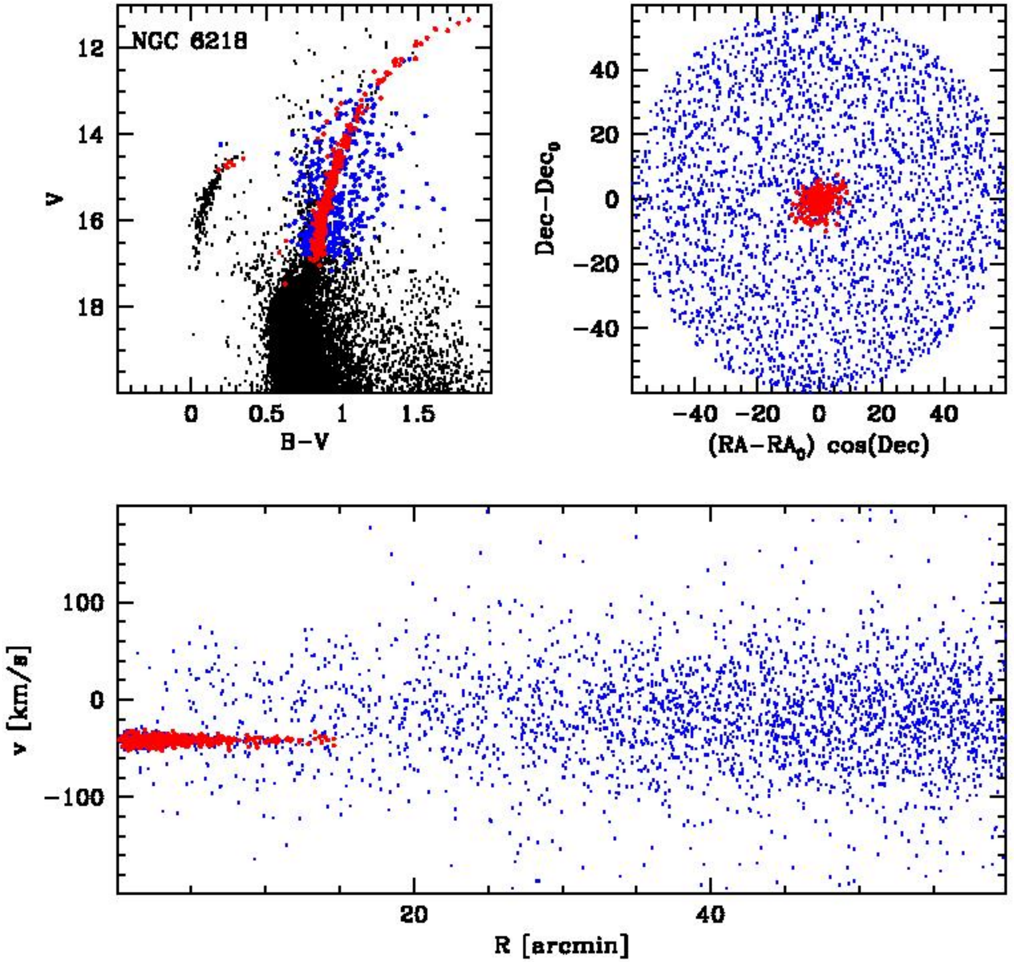


Non-parametric estimate of the total mass

Dynamical mass can be estimated using kinematics as tracers

FLAMES@VLT
''GC Large program''

Ferraro et al. (2014)



>2000 radial velocities (≈500 members) out to 1 deg from the cluster center with δv <1 km/s

Estimate of the dark mass fraction

Dynamical mass can be estimated using by solving the Jeans equation

$$M(r) = \frac{r^2}{G}\left(\frac{\sigma^2}{\rho}\frac{d\rho}{dr} + \frac{d\sigma^2}{dr} + 2\beta\frac{\sigma^2}{r}\right)$$

WARNING!

Noise enhanced in derivatives

ρ and σ² profiles are interpolated with a multi-gaussian expansion using a controlled MCMC scheme

$$\rho = \sum_{i=1}^{M} \mu_i e^{-\frac{r^2}{2{s_i}^2}}$$

$$\sigma^2 = \sum_{i=1}^{M} \xi_i e^{-\frac{r^2}{2{s_i}^2}}$$

Sollima et al. (in prep.)

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WARNING!

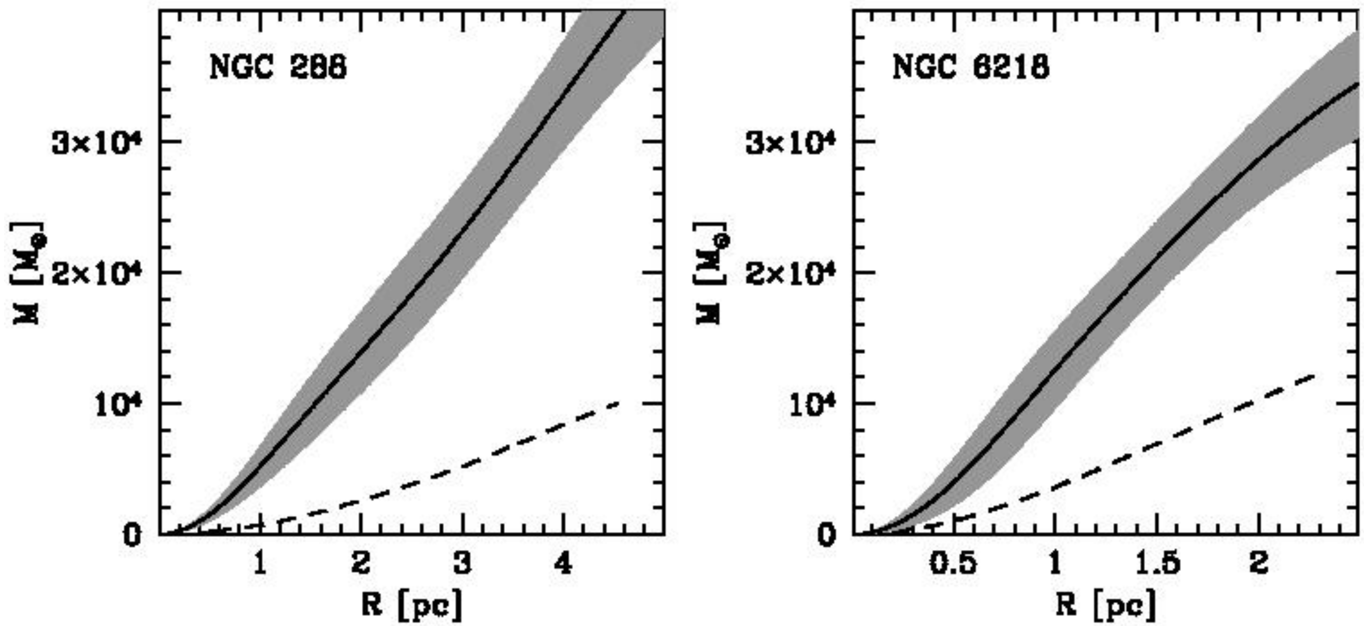
Could lead to unphysical solutions

At each step the DF is calculated using the Eddington formula

$$f(E) = \frac{1}{2\sqrt{2}\pi^2}\left[\int_0^E \frac{d^2\rho}{d\psi^2}\frac{d\psi}{\sqrt{E-\psi}} + \frac{1}{\sqrt{E}}\left(\frac{d\varrho}{d\psi}\right)_0\right]$$

Only the domain of physically meaningful solutions (f(E)>0) is surveyed

Results



Sollima et al. (in prep.)

More than 60% of the mass in both clusters is dark

Dark mass is more concentrated than any other group of stars

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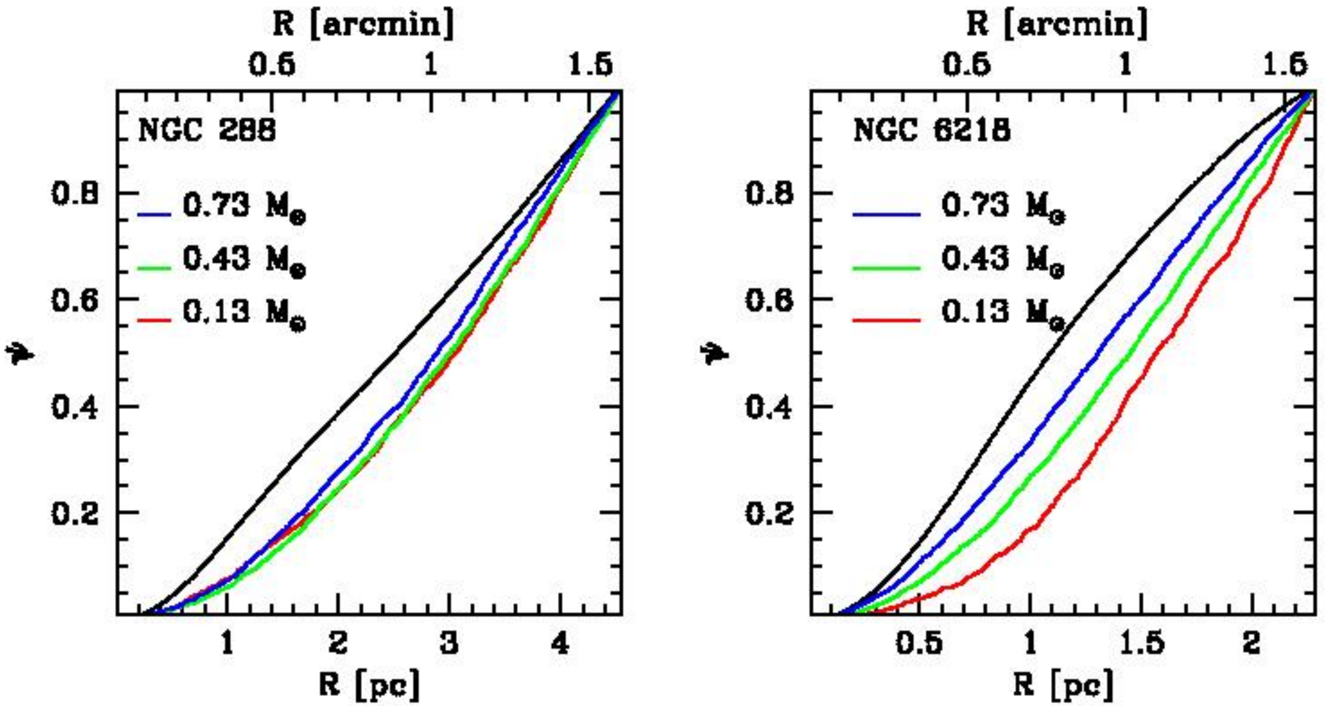

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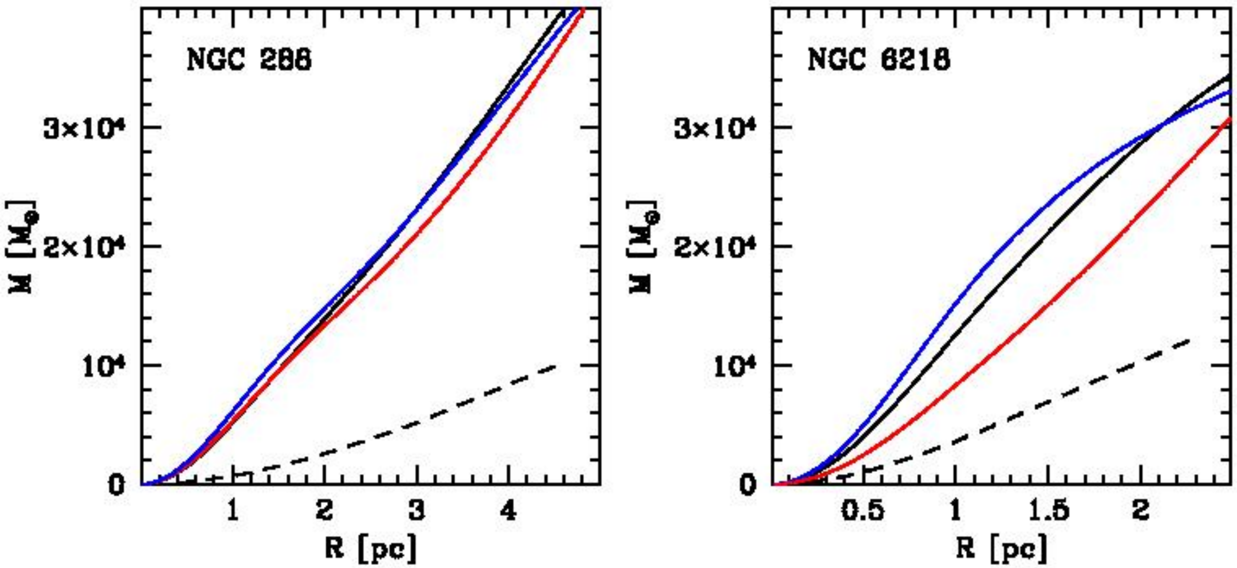
Spurious effects: anisotropy

Some degree of anisotropy affect the mass estimate

$$M(r) = \frac{r^2}{G}\left(\frac{\sigma^2}{\rho}\frac{d\rho}{dr} + \frac{d\sigma^2}{dr} + 2\beta\frac{\sigma^2}{r}\right)$$

$$\beta(r) = \pm\frac{r^2}{r^2 + {r_a}^2}$$



No significant effect across the analysed FoV

Sollima et al. (in prep.)

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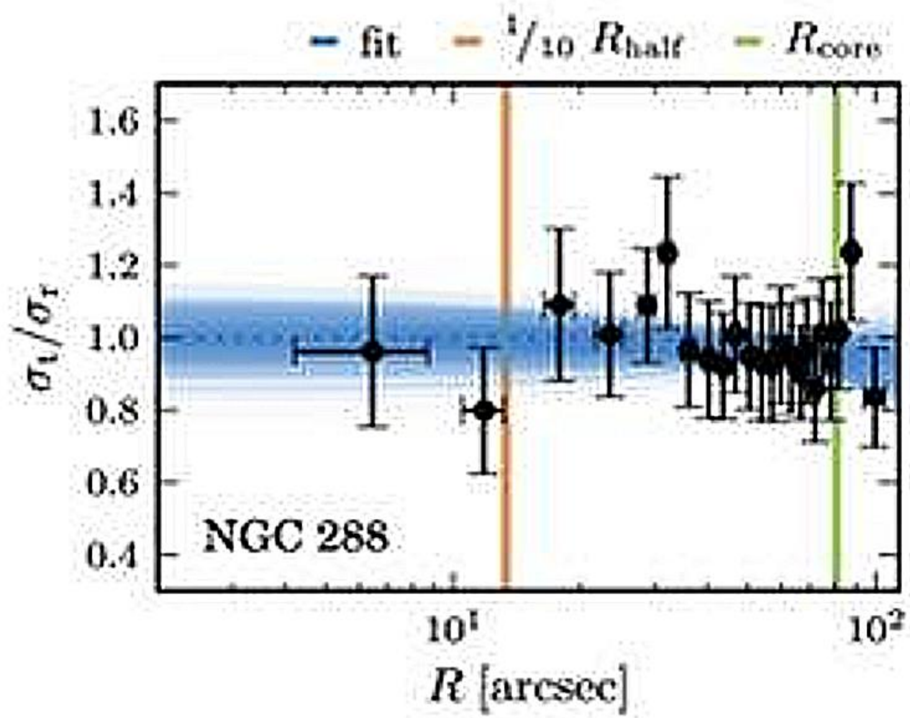
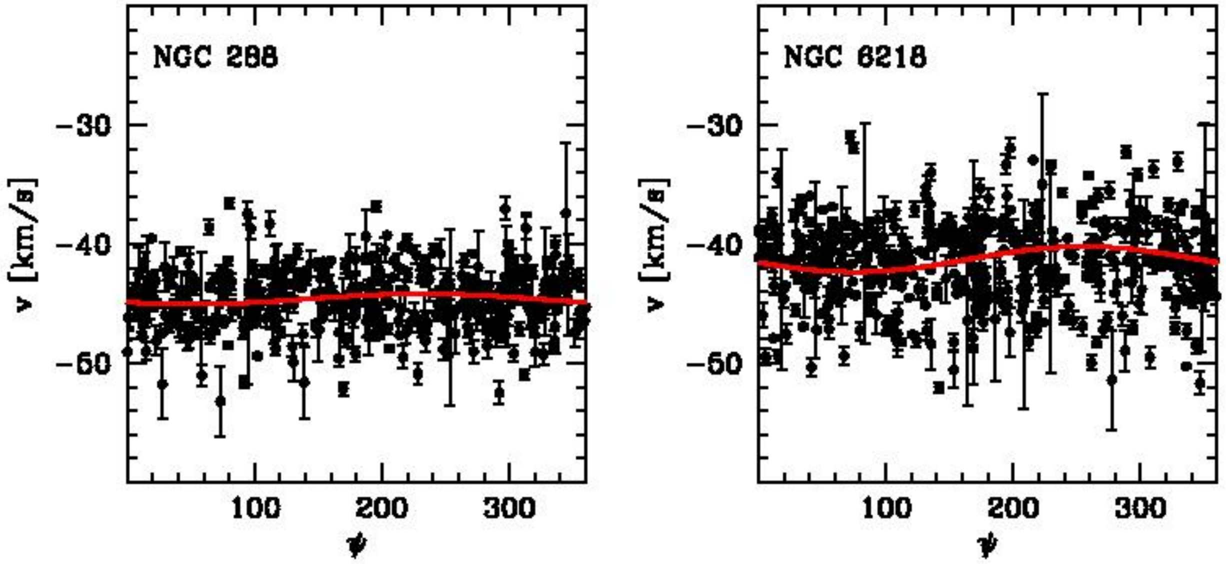


GCs appear to be isotropic in their centers

Watkins et al. (2015)

Spurious effects: rotation

The adopted formulation of the Jeans equation is valid only for spherical non-rotating systems



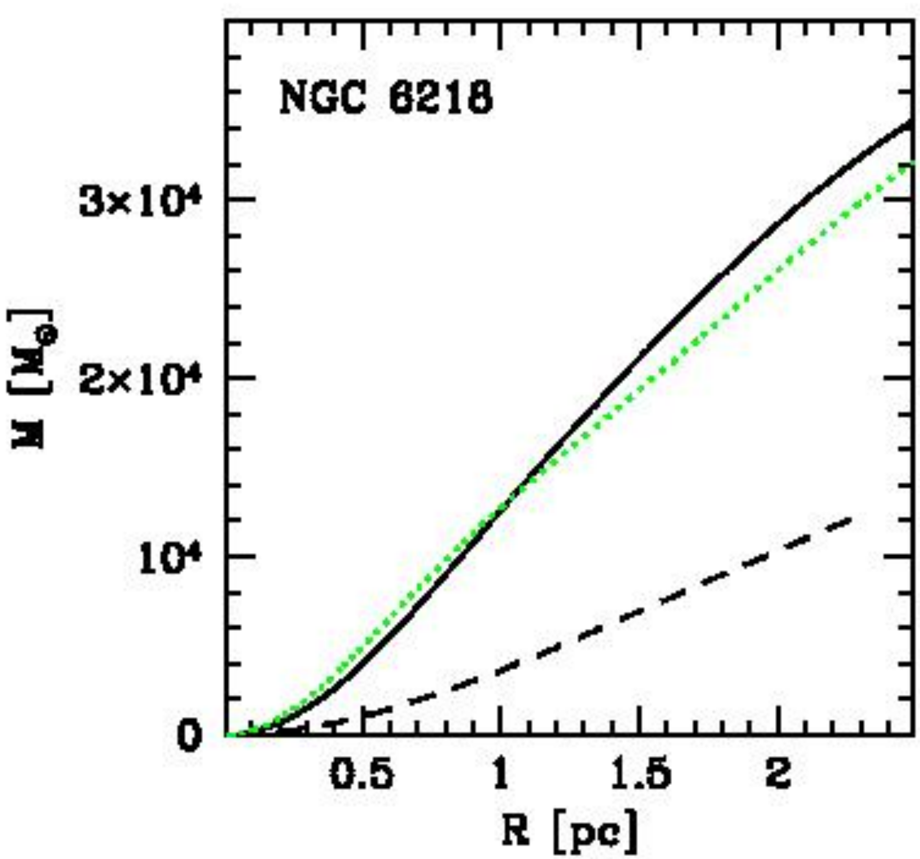
A_{rot}<0.4 km/s

No significant rotation in both clusters

Sollima et al. (in prep.)

Spurious effects: binaries

A significant binary fraction can spuriously inflate the velocity dispersion



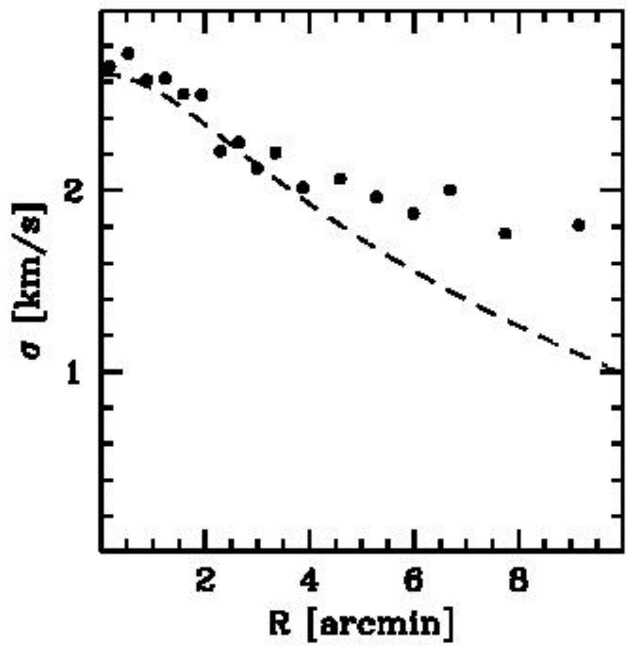
Only stars with multiple RV measurements and P_{bin}<1%

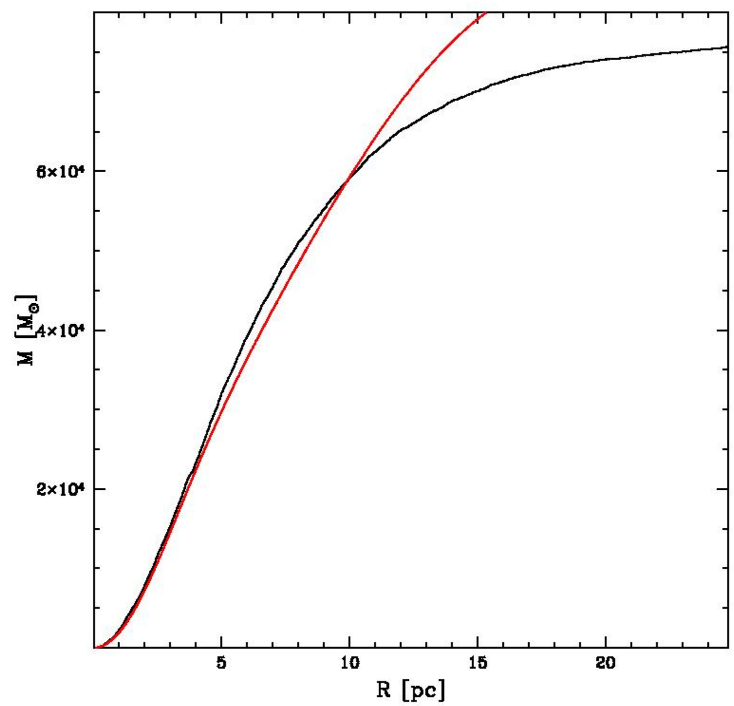
No appreciable variation in binary-free sample

Sollima et al. (in prep.)

Spurious effects: tidal heating

Interaction with the Milky Way tidal field can spuriously inflate the velocity dispersion





Collisionless N-body simulation with the orbit of NGC288

Tidal heating effective only at R>10 pc

Sollima et al. (in prep.)

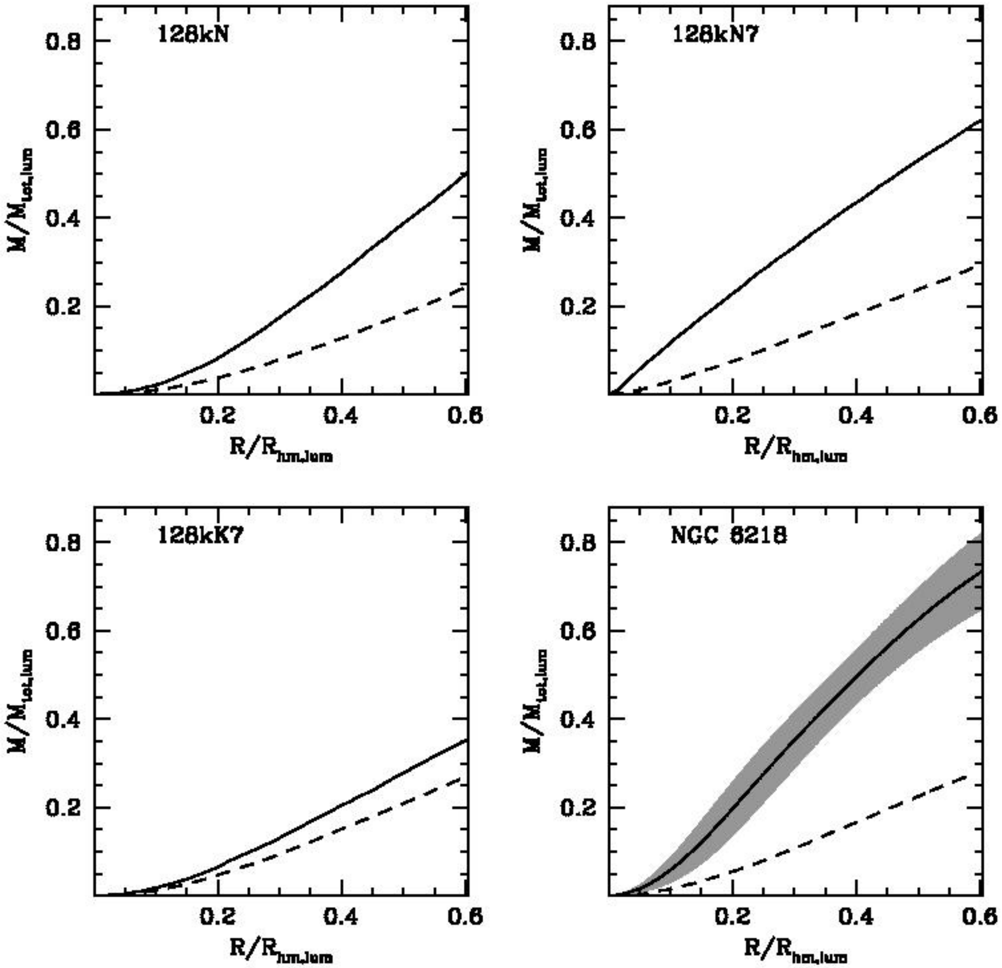
Comparison with N-body simulations

The remnant fraction and distribution is reproduced by some N-body simulations

BUT

Simulations are not tailored on

real GCs



Contenta et al. (2015)
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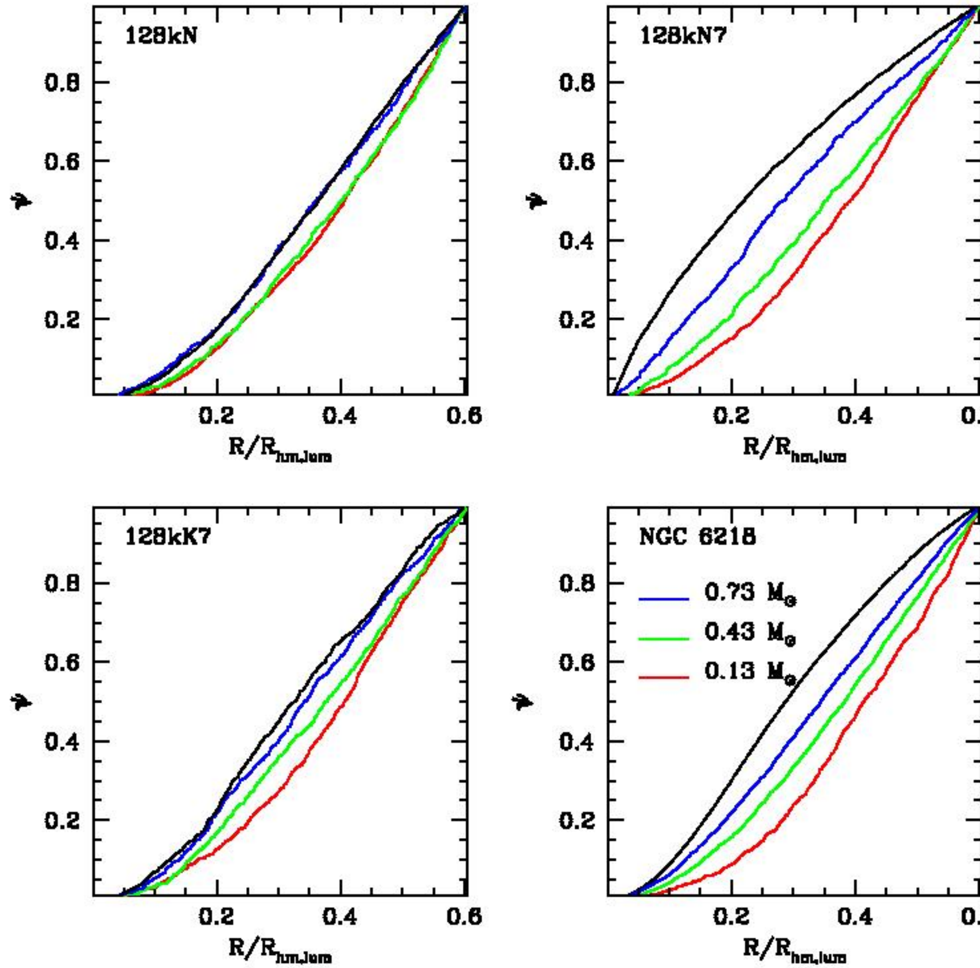

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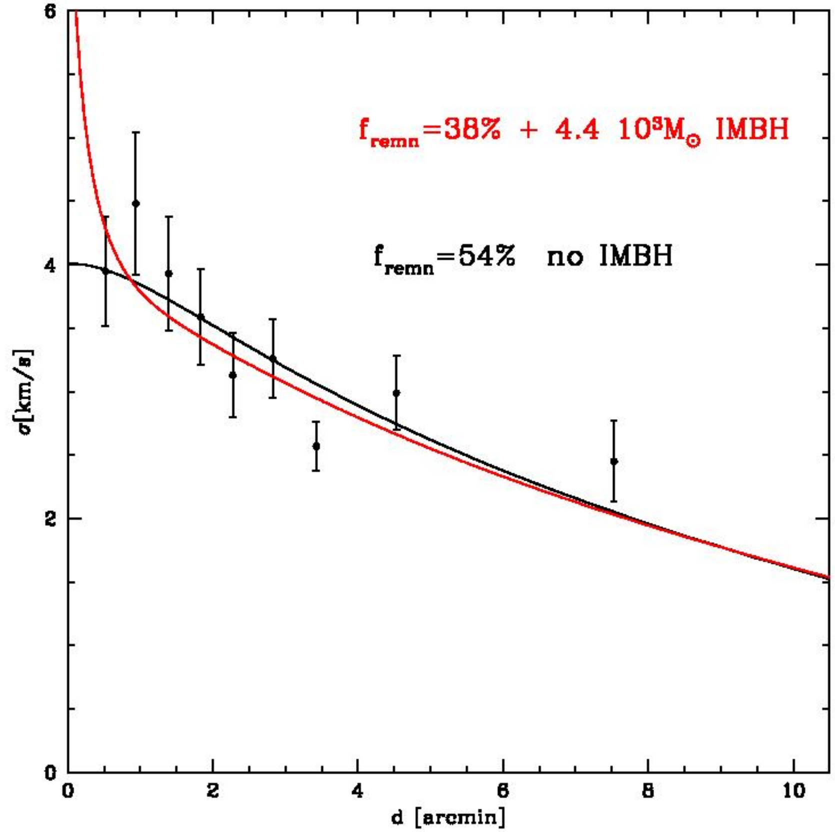
IMBH?

The same result can be obtained assuming a single IMBH in the cluster center

$\chi^2_{IMBH} \approx \chi^2_{remn}$

The mass of the hypothetical IMBH depends on the fraction of dark remnants



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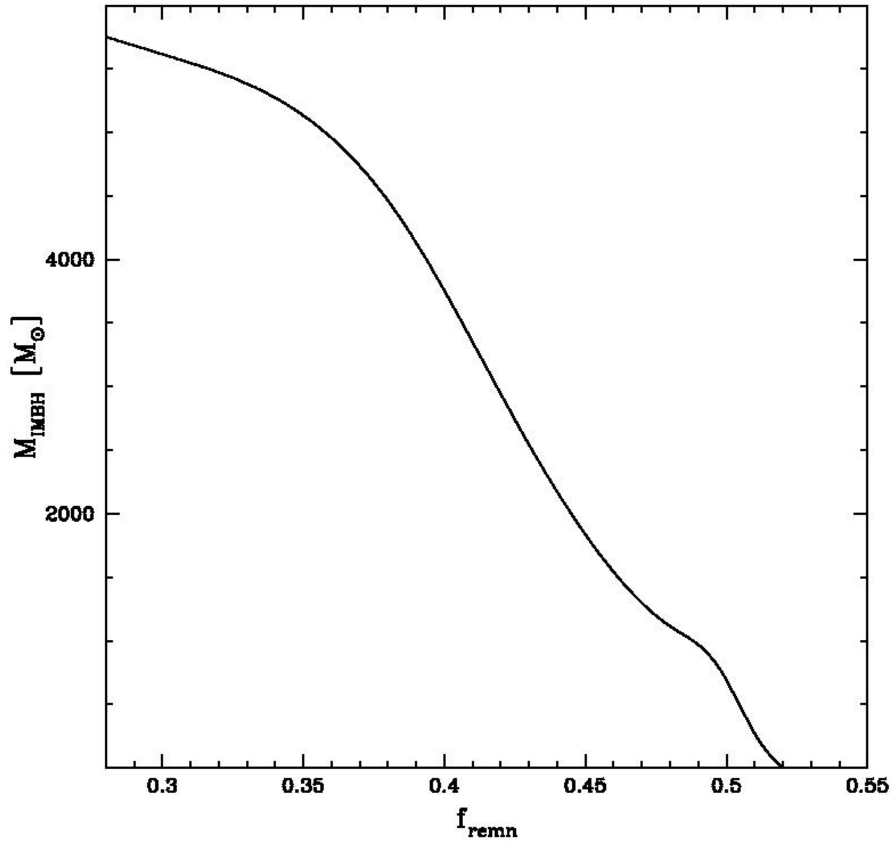

Sollima et al. (in prep.)

Summary

- More than 60% of the mass within the innermost region of NGC288 and NGC6218 is dark
- The dark mass is more concentrated than any other group of stars suggesting to be constituted by dark remnants
- A large fraction of dark remnants is expected in those clusters subject to strong mass-loss (strong tides, efficient two-body relaxation)
- The detection of IMBH signature is hampered by the uncertainties on the fraction and distribution of dark remnants

Next steps:

- Extend the survey to GCs with different orbits and t_{rh}
- Run N-body simulations calibrated on the observed GCs