GCs: a little of dynamics and King models

Two-body relaxation time

Because $F_{grav} \sim 1/\mathrm{r}^2$, even distant gravitational encounters do matter in any gravitational system. The cumulative effect of mutual gravitational interactions among stars significantly modify their initial orbits. Accordingly, the structure of the system becomes less and less dependent on initial conditions, until it completely lose memory of them.

This process occurs in a time-scale which is called “**2-body relaxation time**” and can be roughly estimated as:

$$t_{2b} \sim \frac{0.1\,\mathrm{N}}{\ln \mathrm{N}} \times t_{cross}$$

where N=number of stars in the system

$t_{cross} = R/v$ = **crossing time**

$\left(\begin{array}{l} \text{characteristic time-scale needed to a star with typical velocity } v \\ \text{to cross the entire system of radius } R \end{array} \right)$

- if $t_{2b} >> t_{age}$ => **collisionless** system

stars move under the influence of the ***mean*** potential generated by all the other stars - *smooth distribution*

- if $t_{2b} << t_{age}$ => **collisional** system

individual stellar encounters play a significant role and gradually perturb stars from the trajectories they would have taken if the distribution of matter was perfectly smooth

Galaxies:

$$\left.\begin{array}{l} \mathrm{N} \approx 10^{11} \\ t_{cross} \approx 10^{8}\ \mathrm{yr} \end{array}\right\} \quad t_{2b} \sim \frac{0.1\,\mathrm{N}}{\ln \mathrm{N}} \times t_{cross} \sim 10^{16}\,\mathrm{yr} \;=\; 10^{7}\ \mathrm{Gyr} \;>>\; t_{age}$$

=> **collisionless** systems

Globular clusters:

$$\left.\begin{array}{l} \mathrm{N} \approx 10^{5} \\ t_{cross} \approx 10^{5}\ \mathrm{yr} \end{array}\right\} \quad t_{2b} \sim \frac{0.1\,\mathrm{N}}{\ln \mathrm{N}} \times t_{cross} \sim 9 \times 10^{7}\,\mathrm{yr} \;\sim\; 0.1\ \mathrm{Gyr} << t_{age}$$

=> **collisional** systems

NB1: strictly speaking, thinks are more complicated and relaxation depends on the local density: $t_{2b} \propto 1/\rho$

NB2: any stellar system can be approximated as collisionless on sufficiently short time-scales; viceversa, any system is collisional on a sufficiently long times

GCs are collisional systems, where relaxation is driven by stellar encounters.

The exchanges in kinetic energies among the stars are <u>random</u> in nature and therefore lead to the phenomenon called “relaxation of the velocity distribution”: the system tend to acquire a **Maxwellian velocity distribution.**

The stellar-dynamical model where the velocity distribution is Maxwellian at each point is called “**isothermal sphere**”. Its total mass is, however, *infinite*.

In fact, the Maxwellian distribution allows a fraction of stars to have $v \rightarrow \infty$
However, the escape velocity of real systems has a *finite* value.
Hence real clusters cannot maintain a Maxwellian velocity distribution.

Thus a realistic model of GC must have a distribution function **close to isothermal in the inner regions** and **going to zero for v close to the system escape velocity**. Moreover it reasonably should have a ***finite* limiting radius** (because of the Galactic field effect).

This is the basic idea behind the so-called **King models** (King 1966), where the distribution function (for spherical & isotropic systems) is expressed as:

$$f(E) = \begin{cases} C\,(e^{-E/\sigma^2} - 1) & \text{if } E < 0 \\ 0 & \text{if } E \geq 0 \end{cases}$$

where

- E is the energy per unit mass: $E = v^2/2 + \Psi(r)$
- $\Psi(r)$ is the mean potential defined so as to have: $\Psi(r_t) = 0$
- r_t is the truncation radius (stars at $r > r_t$ are not included since they have $E > 0$, i.e., velocities > escape velocity)
- C is a constant related to the density (and hence to the mass)
- σ is a parameter connect to the velocity dispersion

King models

Prof. Ivan King
PhD in Harvard in 1952

King models

Widely used to model GCs

- because, by construction, they describe stellar systems that reached a state of equilibrium with a Maxwellian velocity distribution
- because they do well reproduce the observed density (or surface brightness) profiles

King density profiles

→ flat core and decreasing behaviour outwards

→ *one*-parameter family:

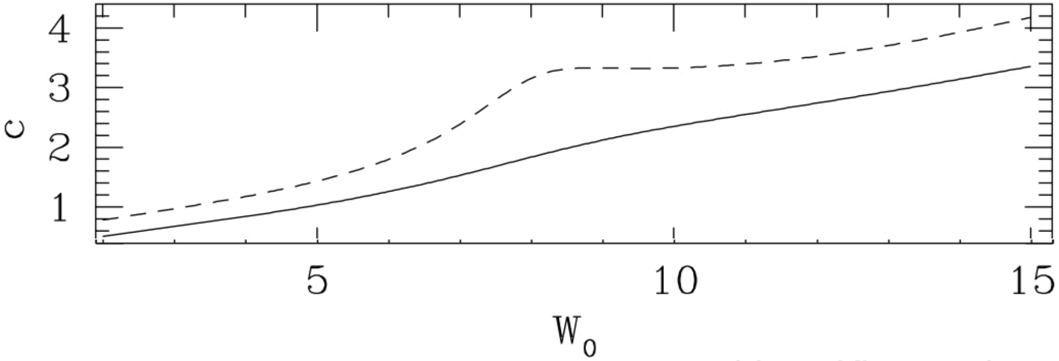
the *shape* of the density profile is uniquely determined by a *single* parameter.

This is either:

W_0 = dimensionless parameter proportional to the central potential

or

c = concentration parameter



solid: King model
dashed: Wilson model

Concentration parameter: $c = \log\left(\frac{r_t}{r_0}\right)$

where:

r_t is the **truncation radius**

r_0 is the **King radius** (characteristic scale length of the model)

The **King radius** is close (but not equal) to the **core radius (r_c)** which is an observational quantity:

r_c is defined as the radius at which the projected density (or SB) becomes equal to half its central values: $\Sigma_*(r_c) = 1/2\ \Sigma_*(0)$.

For highly-concentrated models ($W_0 \rightarrow \infty$), $r_c \rightarrow r_0$

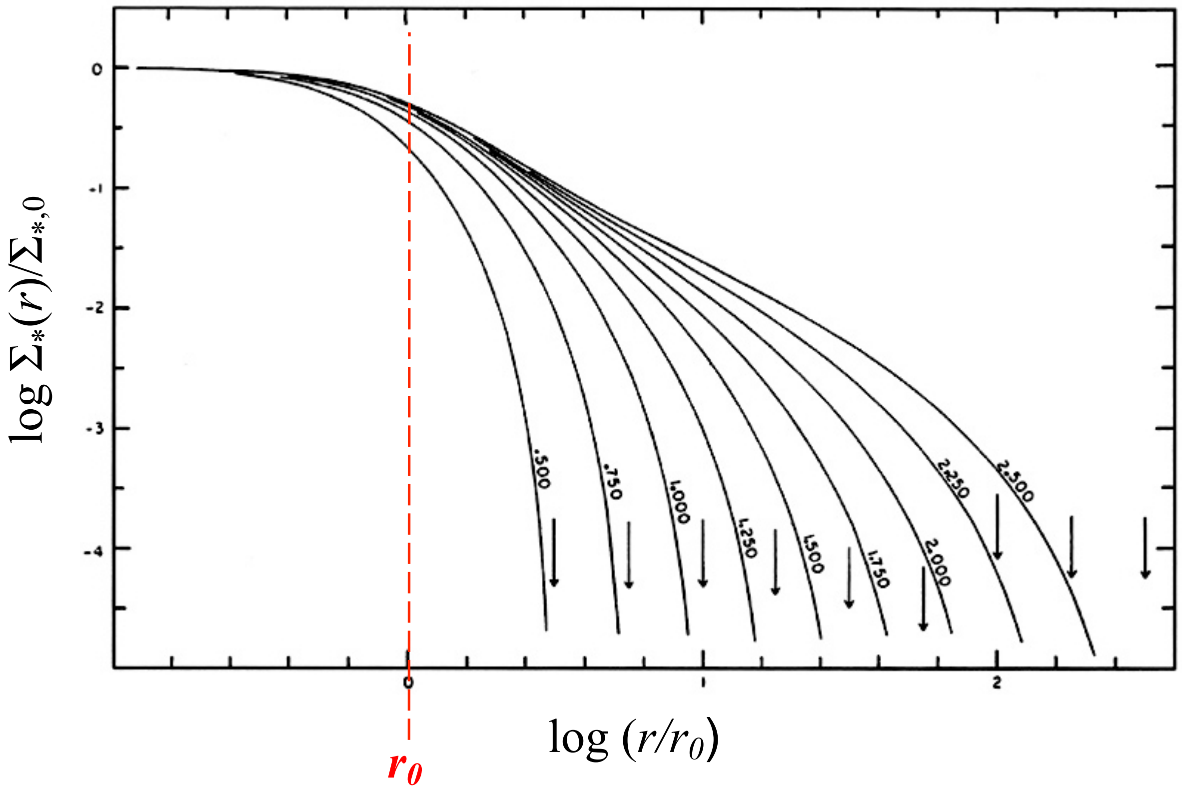
Quite often r_c and r_0 are confused...

NB: always pay attention to the parameter definition when comparing models to observations!

Many theoretical quantities cannot be observed.

Many observational quantities suffer from some degree of arbitrariness.

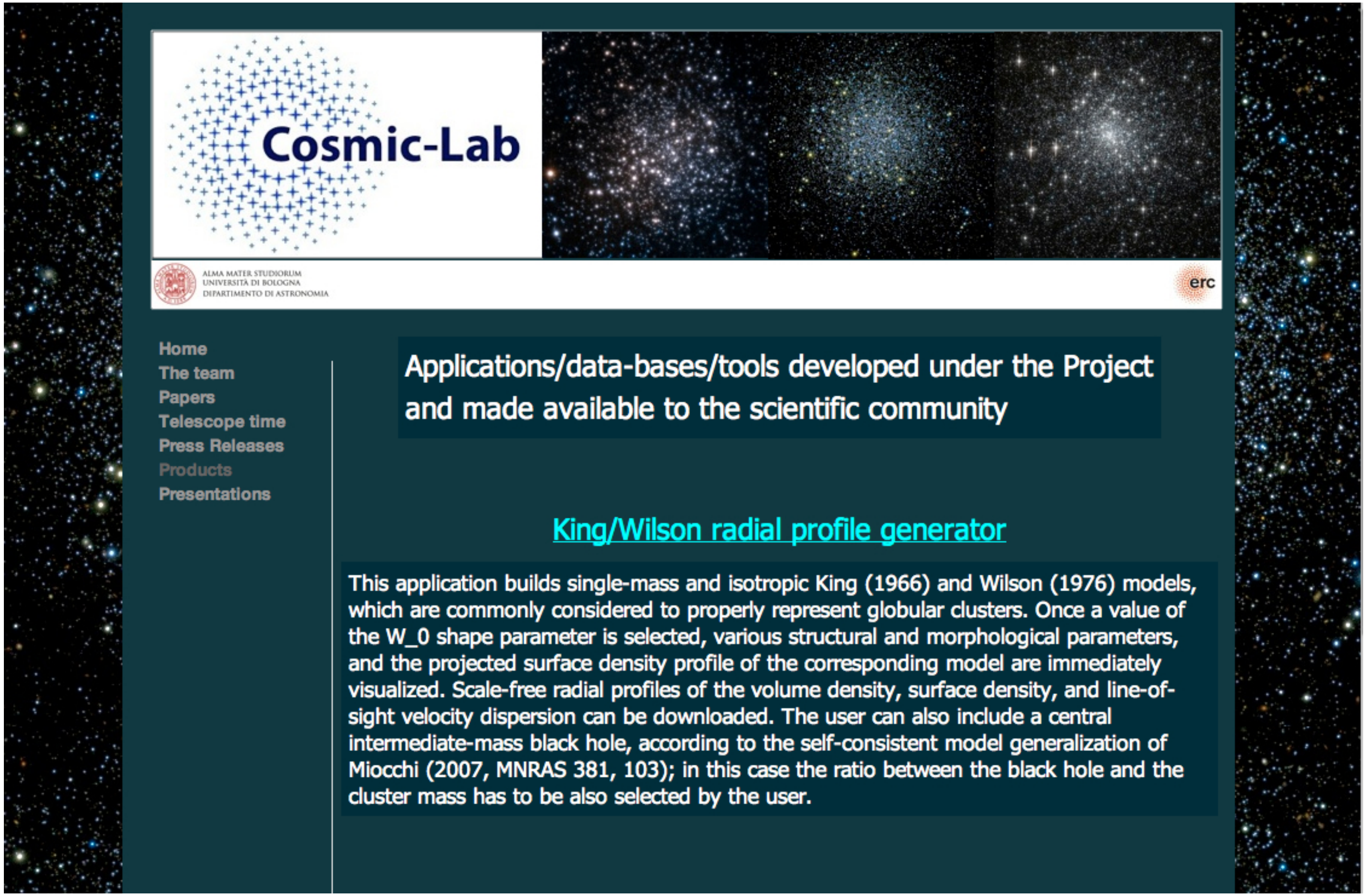
King density profiles



c = [0.5,2.5]

arrows: location of r_t

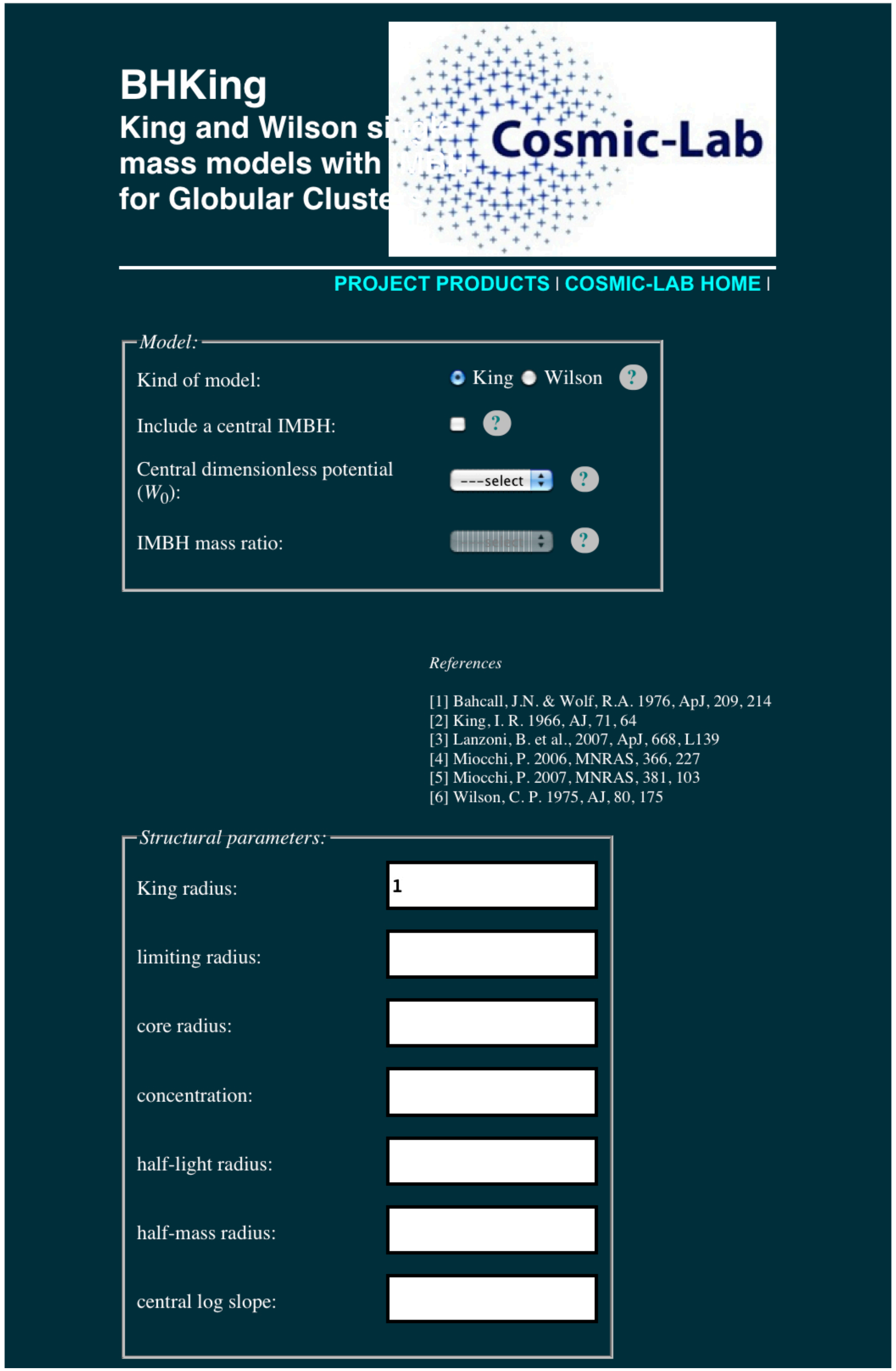
King/Wilson (+IMBH) density & velocity dispersion profiles generator freely available at: www.cosmic-lab.eu/Cosmic-Lab/Products.html



Applications/data-bases/tools developed under the Project and made available to the scientific community

King/Wilson radial profile generator

This application builds single-mass and isotropic King (1966) and Wilson (1976) models, which are commonly considered to properly represent globular clusters. Once a value of the W_0 shape parameter is selected, various structural and morphological parameters, and the projected surface density profile of the corresponding model are immediately visualized. Scale-free radial profiles of the volume density, surface density, and line-of-sight velocity dispersion can be downloaded. The user can also include a central intermediate-mass black hole, according to the self-consistent model generalization of Miocchi (2007, MNRAS 381, 103); in this case the ratio between the black hole and the cluster mass has to be also selected by the user.



BHKing

King and Wilson si
mass models with
for Globular Cluste

Cosmic-Lab

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Model:

Kind of model: ● King ○ Wilson ?

Include a central IMBH: ☐ ?

Central dimensionless potential (W_0): ---select ?

IMBH mass ratio: ?

References

[1] Bahcall, J.N. & Wolf, R.A. 1976, ApJ, 209, 214
[2] King, I. R. 1966, AJ, 71, 64
[3] Lanzoni, B. et al., 2007, ApJ, 668, L139
[4] Miocchi, P. 2006, MNRAS, 366, 227
[5] Miocchi, P. 2007, MNRAS, 381, 103
[6] Wilson, C. P. 1975, AJ, 80, 175

Structural parameters:

King radius: 1

limiting radius:

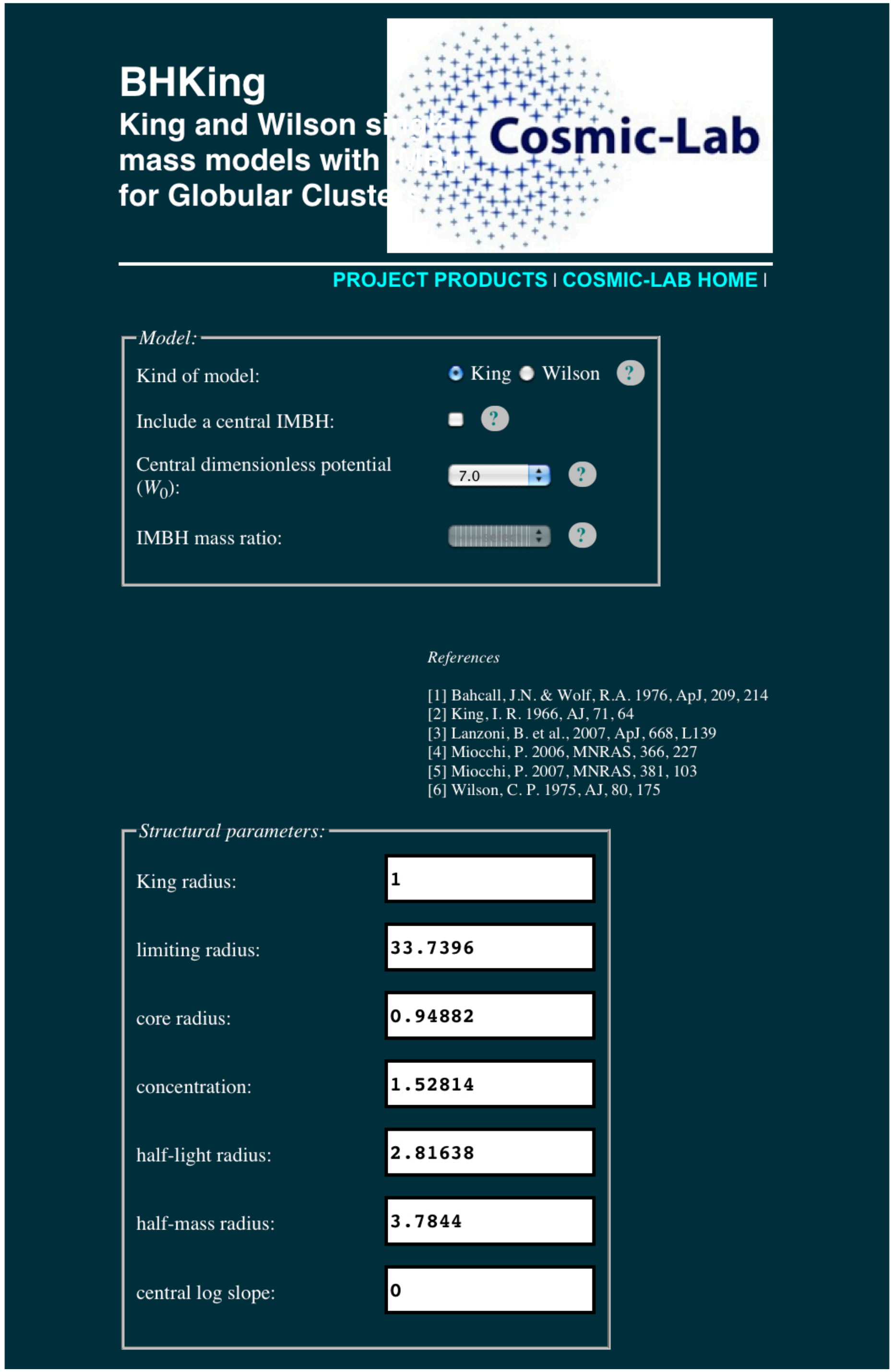
core radius:

concentration:

half-light radius:

half-mass radius:

central log slope:



BHKing

King and Wilson si
mass models with
for Globular Cluste

Model:

Kind of model: ● King ○ Wilson

Include a central IMBH: ☐

Central dimensionless potential (W_0): 7.0

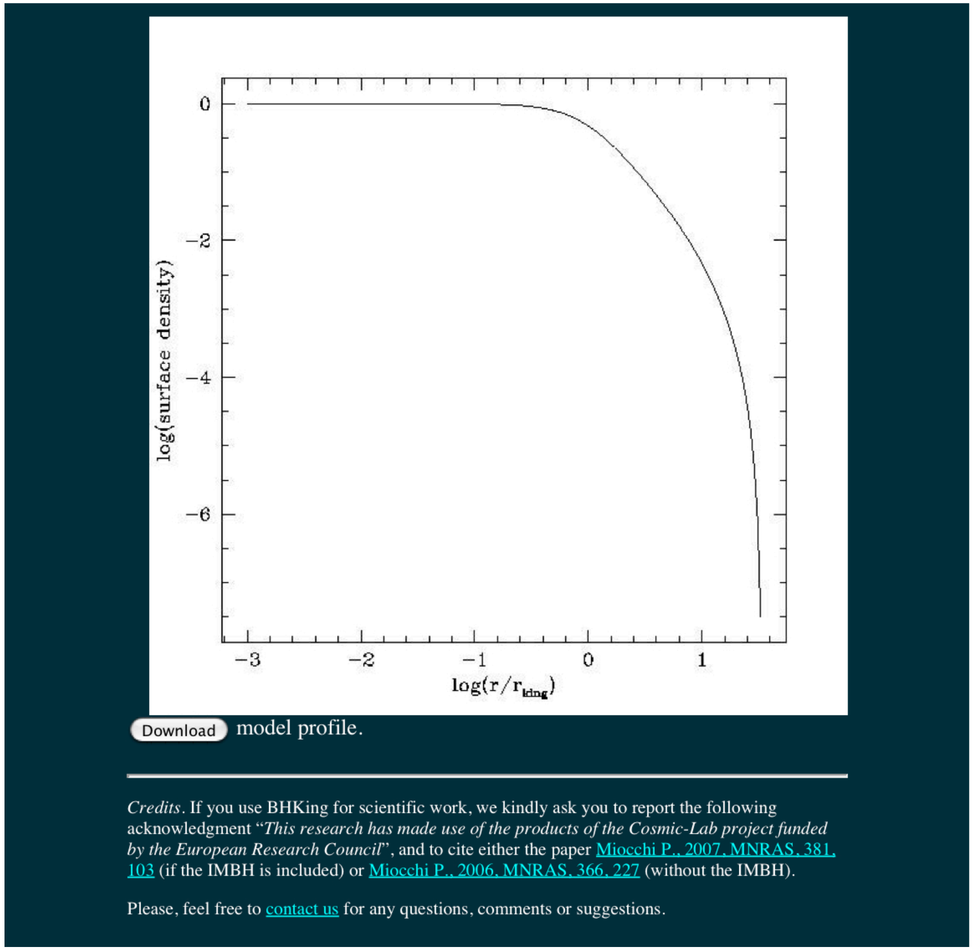
IMBH mass ratio:

References

[1] Bahcall, J.N. & Wolf, R.A. 1976, ApJ, 209, 214
[2] King, I. R. 1966, AJ, 71, 64
[3] Lanzoni, B. et al., 2007, ApJ, 668, L139
[4] Miocchi, P. 2006, MNRAS, 366, 227
[5] Miocchi, P. 2007, MNRAS, 381, 103
[6] Wilson, C. P. 1975, AJ, 80, 175

Structural parameters:

King radius:	1
limiting radius:	33.7396
core radius:	0.94882
concentration:	1.52814
half-light radius:	2.81638
half-mass radius:	3.7844
central log slope:	0



model profile.

Credits. If you use BHKing for scientific work, we kindly ask you to report the following acknowledgment “*This research has made use of the products of the Cosmic-Lab project funded by the European Research Council*”, and to cite either the paper Miocchi P., 2007, MNRAS, 381, 103 (if the IMBH is included) or Miocchi P., 2006, MNRAS, 366, 227 (without the IMBH).

Please, feel free to contact us for any questions, comments or suggestions.

King model fit to observed density profiles

Three parameters have to be adjusted in order to fit observations with King models:

- **the shape of the profile →** c (or W_0)
- **the scale radius →** r_0
- **the normalization**

Observed density profile:

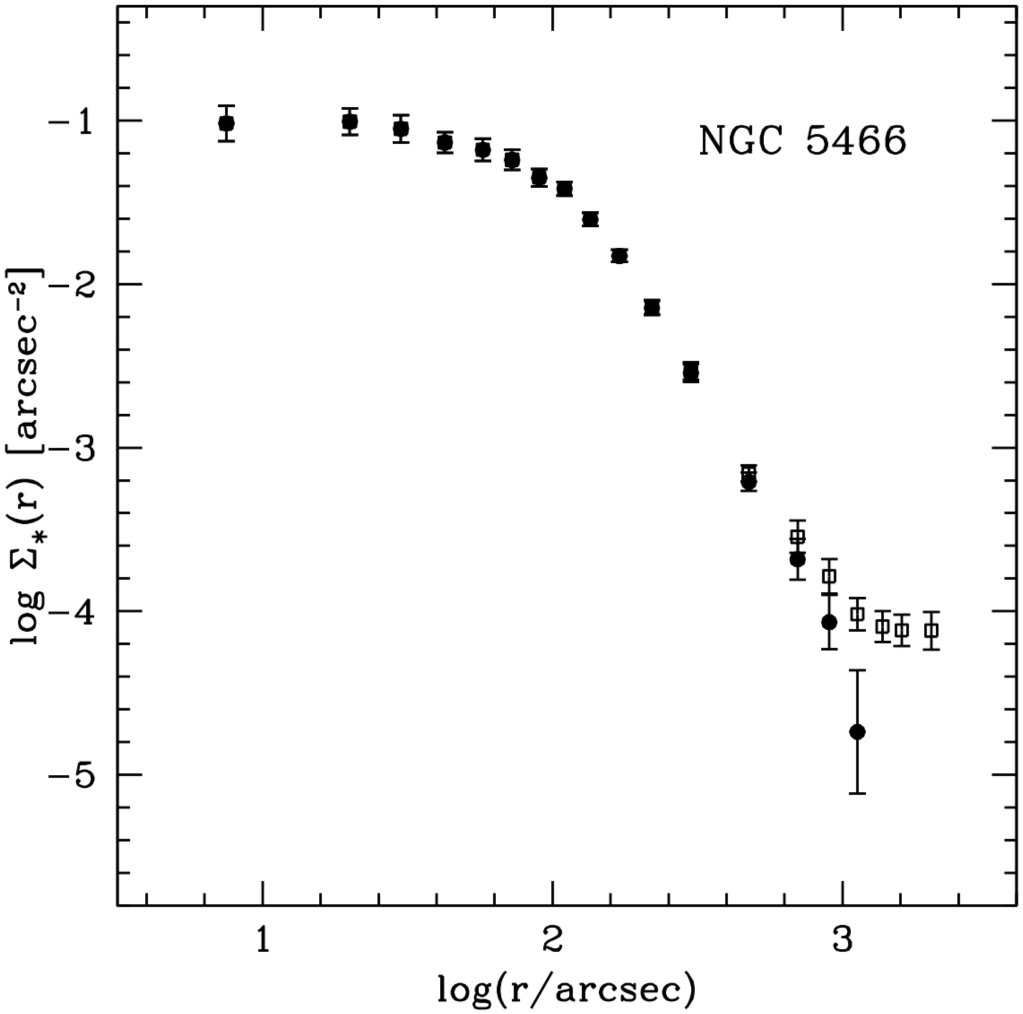
star counts in concentric annuli

(surface brightness can be biased by a few bright stars)

○ observed

● Galactic background subtracted

— best-fit King model



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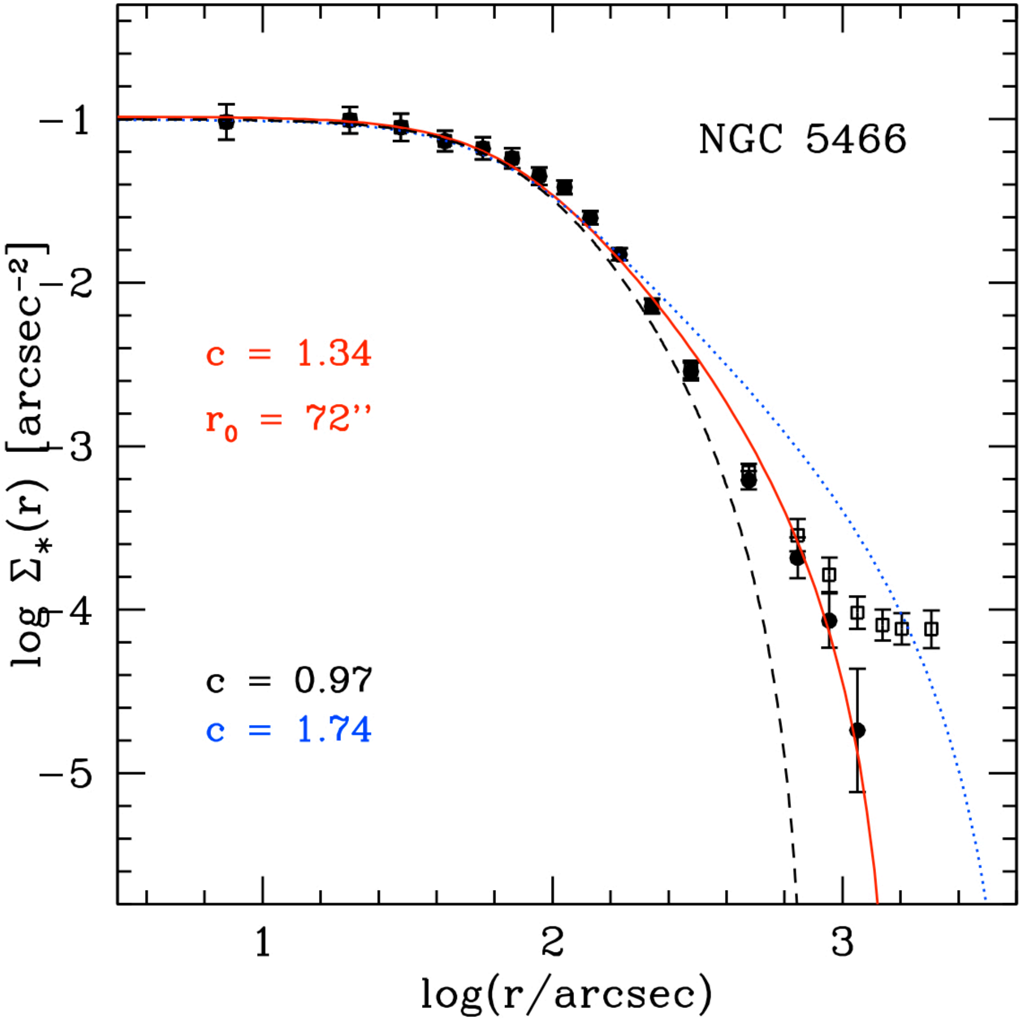


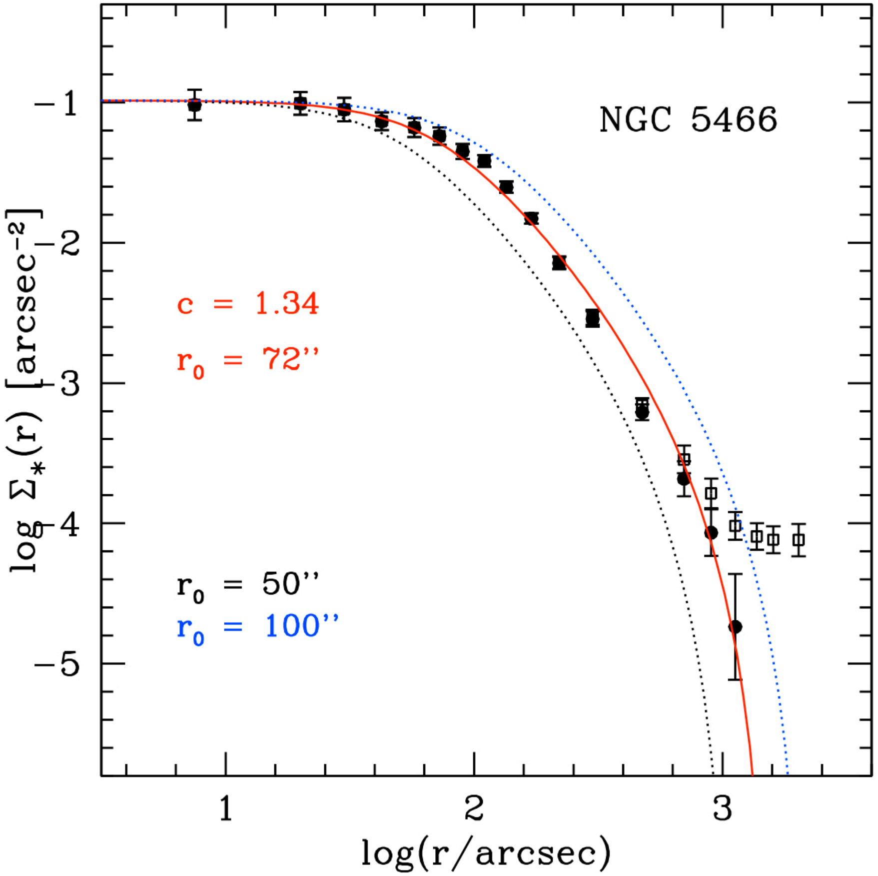
○ observed

● Galactic background subtracted

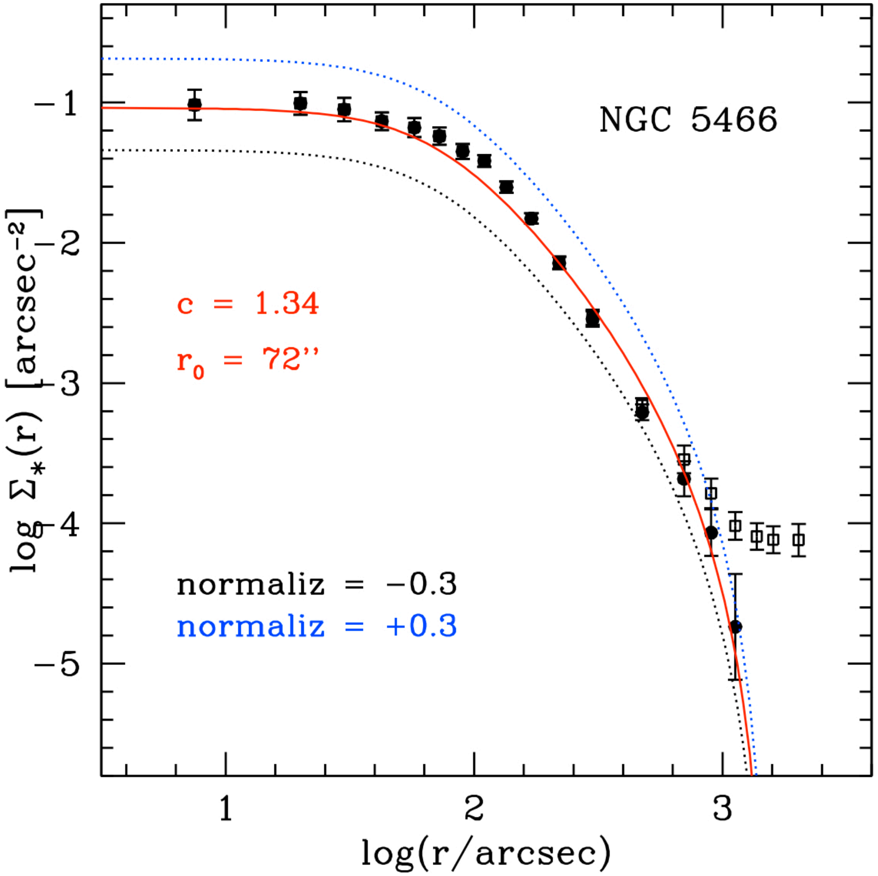
— best-ft King model

King model fit to observed density profiles

varying r_o

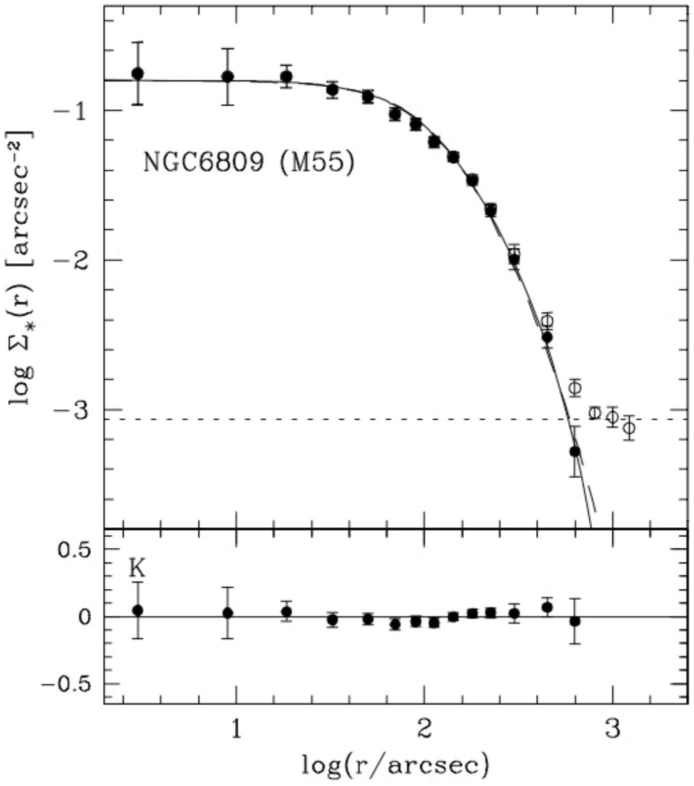


varying the normalization

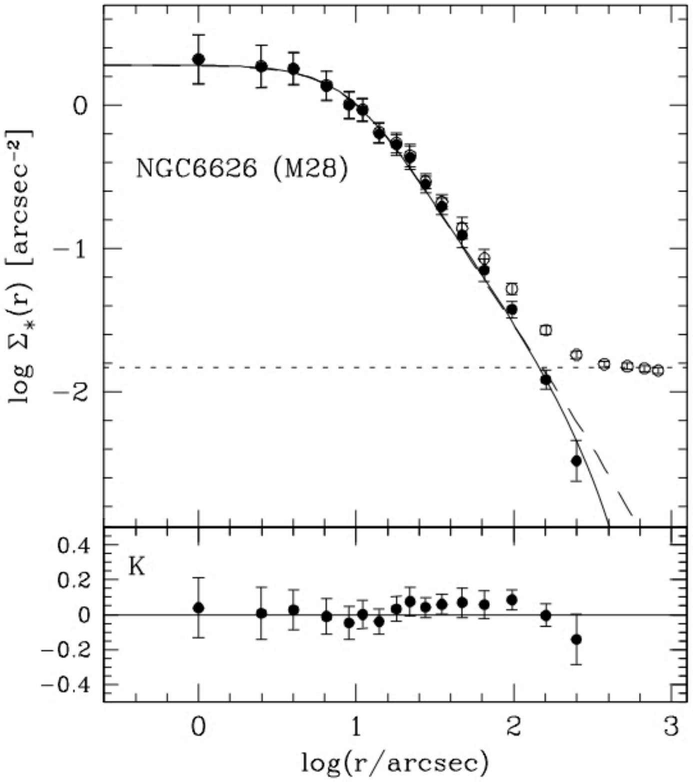


Observed density profiles & best-fit King models

different c, similar r_t



W_0= 5.0
c = 1.02
r_0 = 113”
r_t = 20’
r_c = 99”



W_0= 8.6
c = 2.01
r_0 = 10.8”
r_t = 19’
r_c = 10.5”

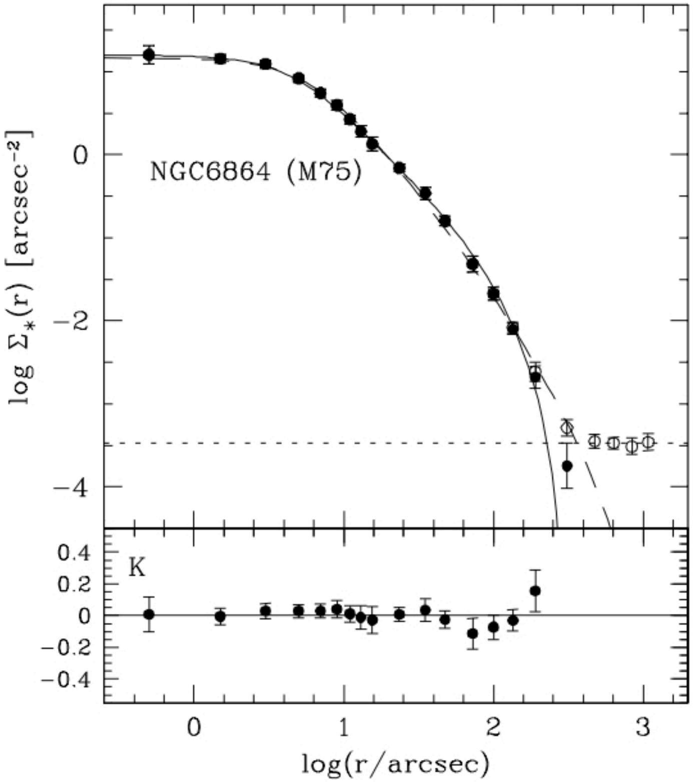
○ observed

● Galactic background subtracted

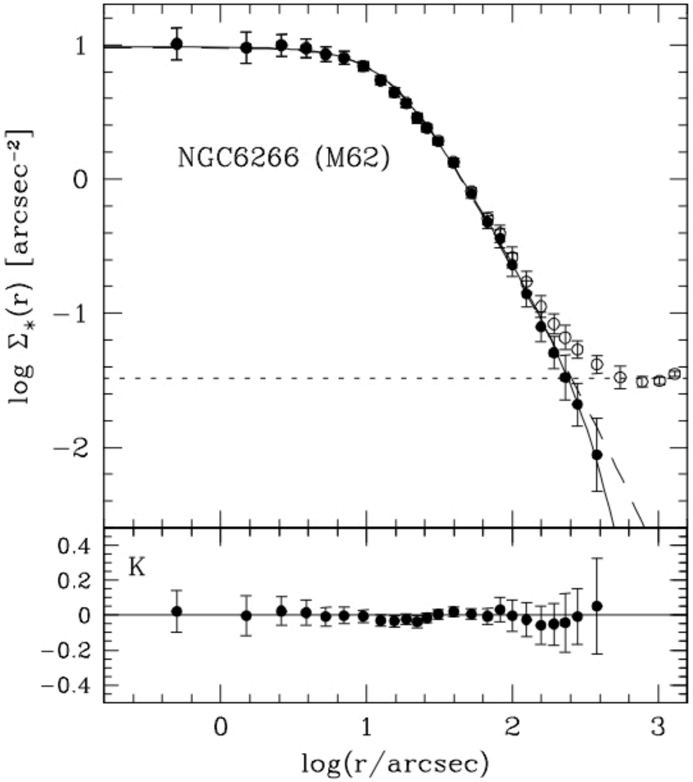
— best-ft King model

Observed density profiles & best-fit King models

similar c, different r_t



W_0= 7.85
c = 1.79
r_0 = 5.1”
r_t = 5’
r_c = 4.9”



W_0= 7.85
c = 1.79
r_0 = 15.9”
r_t = 16’
r_c = 15.4”

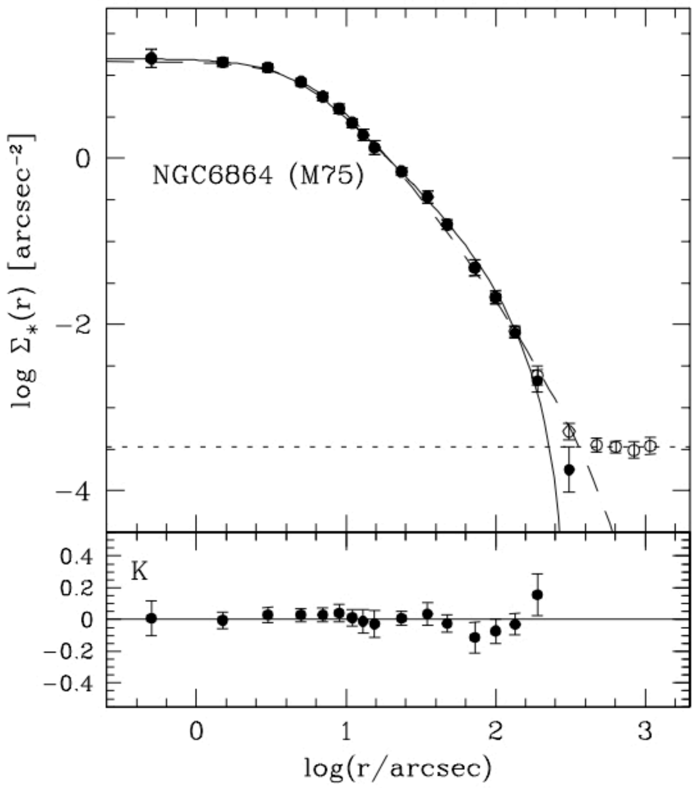
○ observed

● Galactic background subtracted

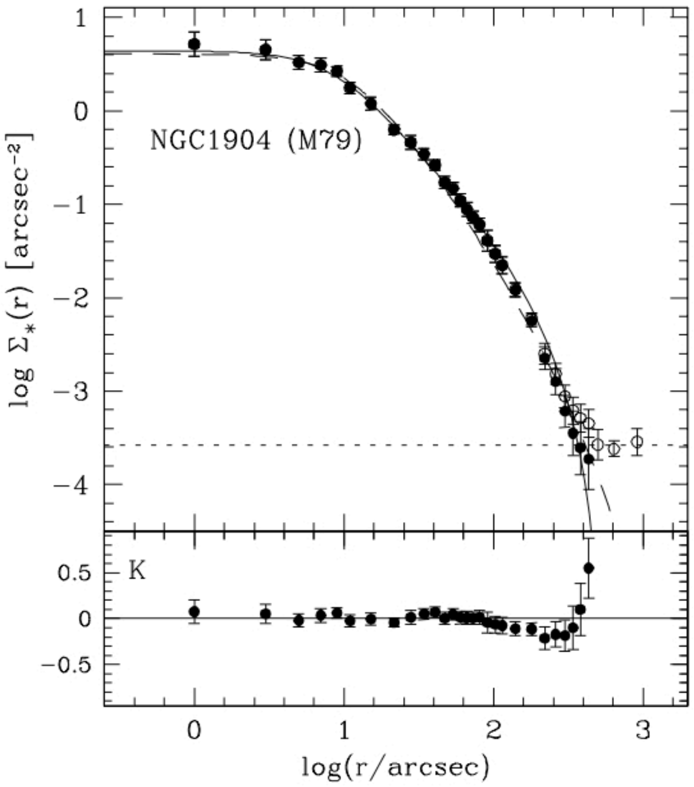
— best-ft King model

Observed density profiles & best-fit King models

overall similar



W_0= 7.85
c = 1.79
r_0 = 5.1”
r_t = 5’
r_c = 4.9”



W_0= 7.75
c = 1.76
r_0 = 9.8”
r_t = 9.3’
r_c = 9.4”

- ○ observed
- ● Galactic background subtracted
- — best-ft King model

Energy equipartition .... core collapse

Stars in GSs have **different masses**

Stellar encounters tend to produce **equipartition of kinetic *energy*** ($K=1/2\ m\ v^2$)

=>

=>

massive stars tend to **lose** kinetic energy
ant thus **sink** towards the centre
→ **mass segregation**

low-mass stars tend to **gain** kinetic energy
and thus move **outwards**
→ **evaporation of the lightest stars**

Evaporation of the lightest stars => the system loses kinetic energy

Hence (for the Virial Theorem) the **system contracts** =>

=> higher density => stellar interactions (energy exchanges from the centre to the outskirts) become more and more efficient

=> core contracts in a sort of runaway process: **core collapse!**

Core collapse is thought to be halted by hard binaries:

hard binary + single star => binary shrinks & star gains energy

=> hard binaries act as an energy source that can halt the core collapse

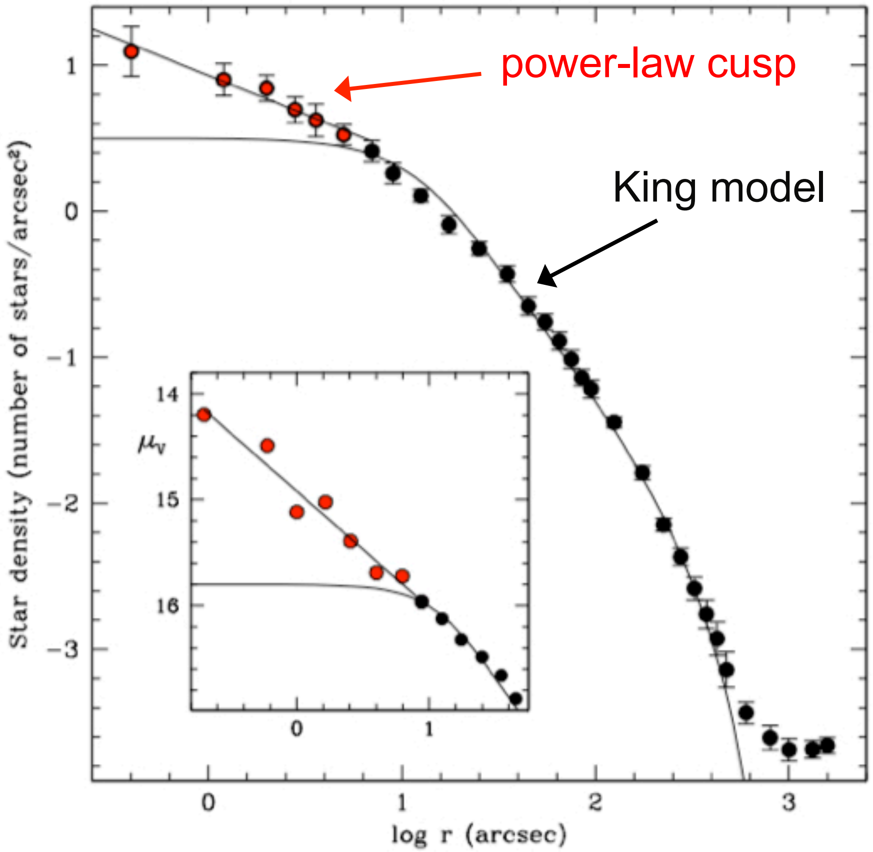
During core collapse the central density highly increases

=> King models (flat core) unable to reproduce the density profiles of post-core collapse GCs, which exhibit a **central a power-law cusp**:

$$\Sigma_*(r) \propto r^{\alpha} \text{ with slope } \alpha \sim -0.7, -1$$

Indeed, ~15%-20% of the observed Galactic GCs show such a kind of profile.

M30


power-law cusp

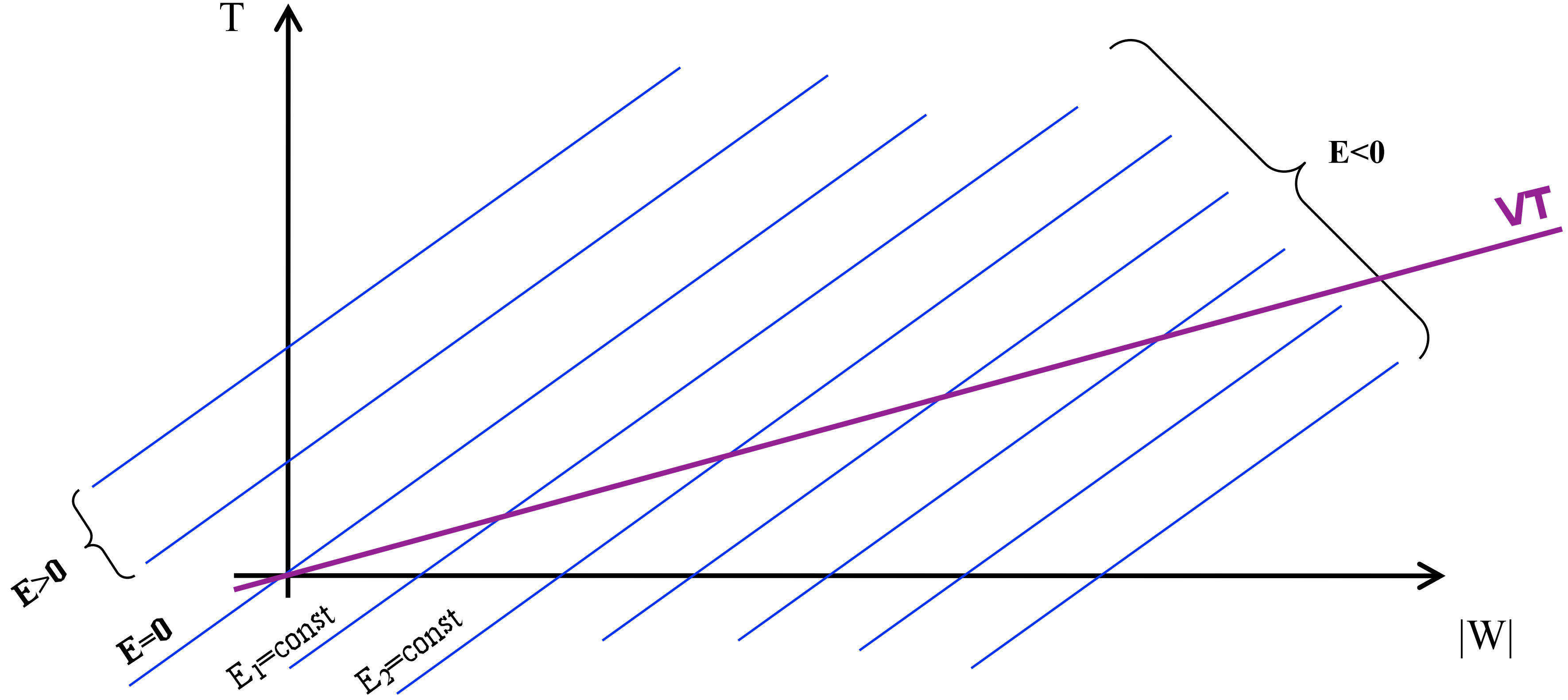
King model

Gravothermal catastrophe

Virial Theorem: $T = \frac{|W|}{2}$ → in a plane (|W|,T) this is a line with slope =1/2 and intercept=0

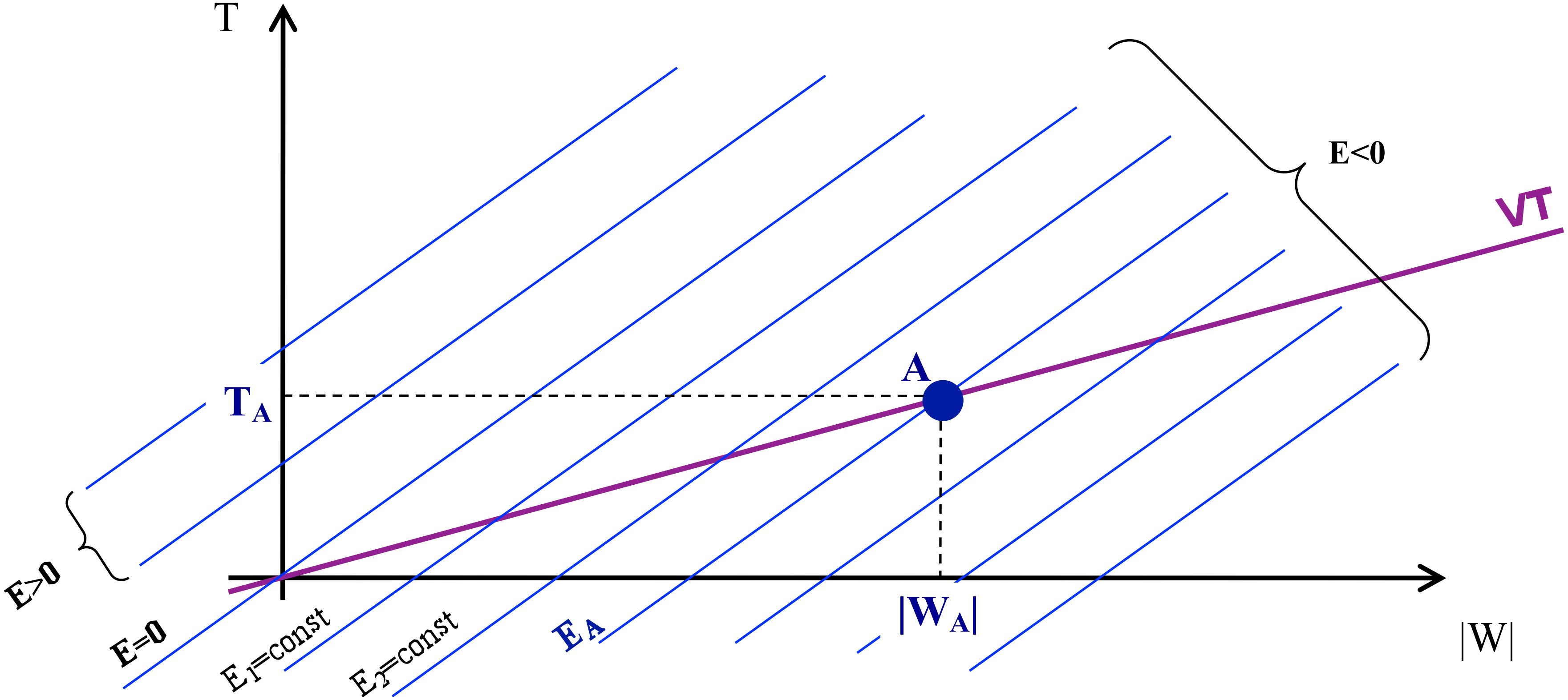
Total Energy: $E = T + W = T - |W| \Rightarrow T = |W| + E$

→ in a plane (|W|,T) the curves at E=const are line with slope =1 and intercept=E



Gravothermal catastrophe

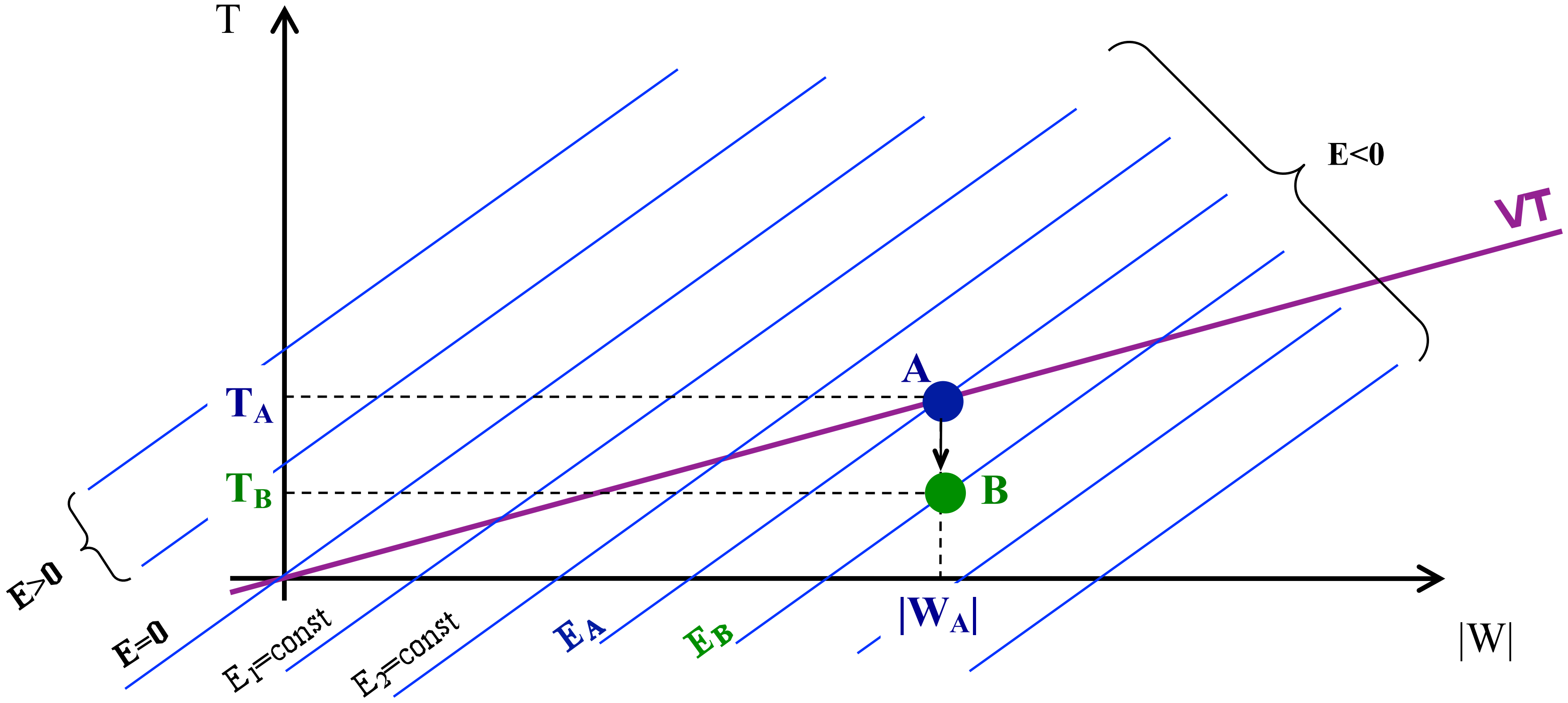
Let's assume that the core of a GC in in Virial equilibrium with $T_A = |W_A| + E_A$



Gravothermal catastrophe

Let’s assume that the core of a GC in in Virial equilibrium with $T_A = |W_A| + E_A$

Because of energy equipartition, the kinetic energy of the core decreases (T_B)
=> the total energy of the core decreases (E_B)



Gravothermal catastrophe

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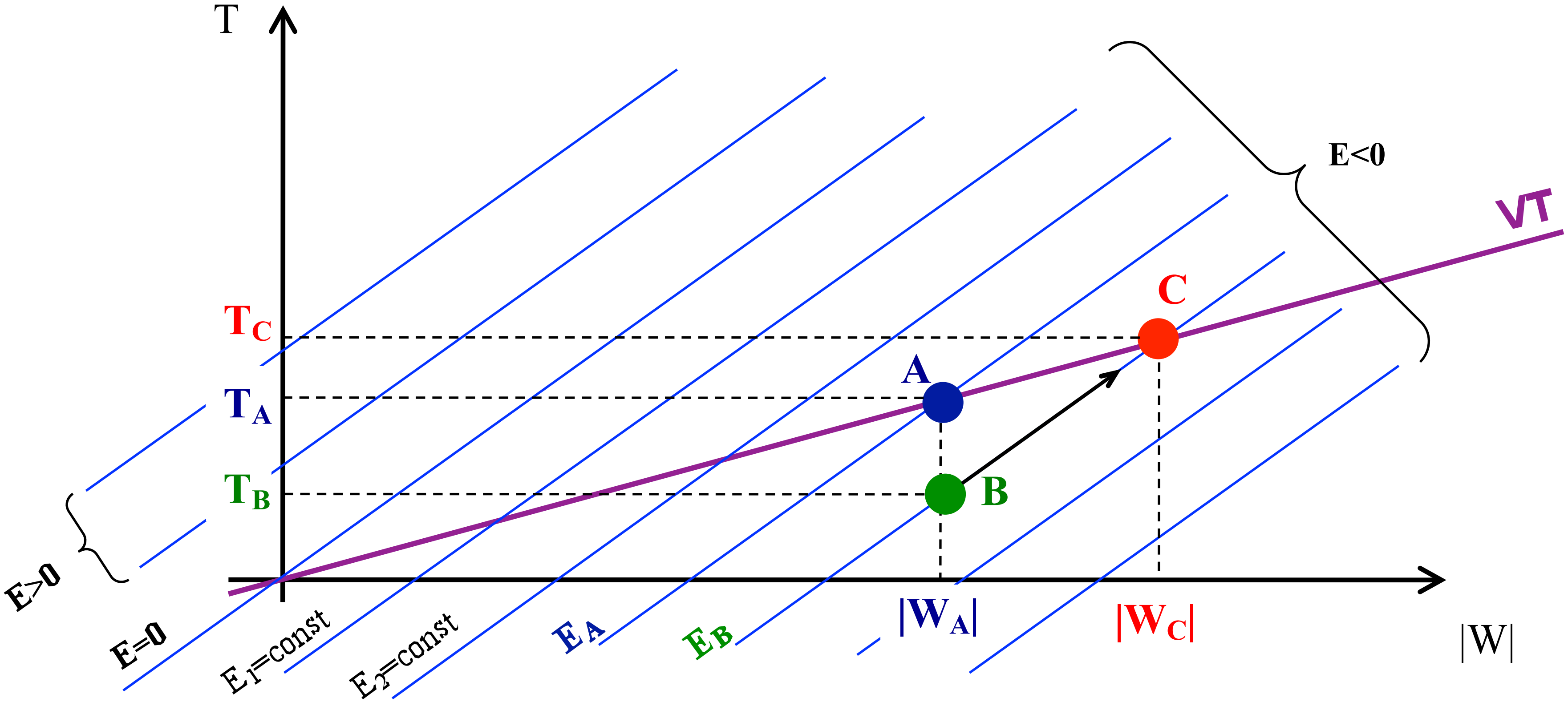
Because of energy equipartition, the kinetic energy of the core decreases (T_B)
=> the total energy of the core decreases (E_B)

To establish Virial equilibrium, the point moves along the constant-energy line, up to the VT line => point C, with $T_C = |W_C| + E_B$.   (Note that $T_C > T_A$)



Gravothermal catastrophe

Let’s assume that the core of a GC in in Virial equilibrium with $T_A = |W_A| + E_A$

Because of energy equipartition, the kinetic energy of the core decreases (T_B)
=> the total energy of the core decreases (E_B)

To establish Virial equilibrium, the point moves along the constant-energy line, up to the VT line => point C, with $T_C = |W_C| + E_B$. (Note that $T_C > T_A$)

in gravitational systems, subtracting energy means ...heating!
(this is a <u>crucial</u> difference with respect to gaseous systems)

This is a runaway process:
the heater is the core, the more kinetic energy is subtracted,
=> heating increases ... core collapses!

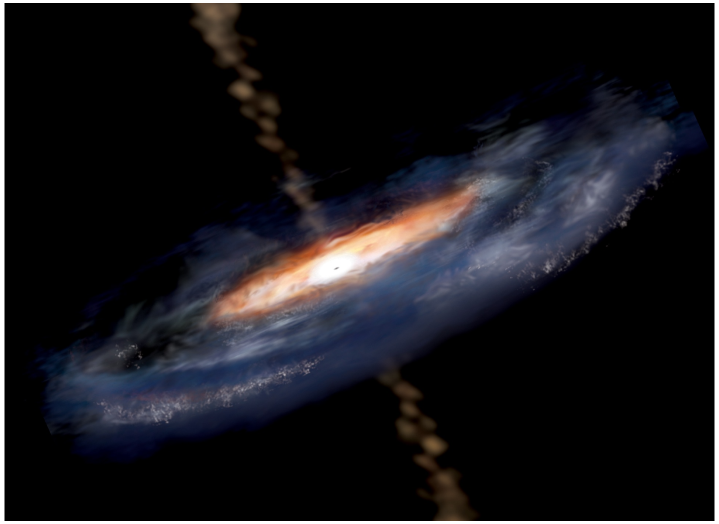
INTERMEDIATE-MASS BLACK HOLES IN GCs

stellar-mass BHs

($M_{BH} \leq$ 20 $M_{\odot}$)

super-massive BHs

(SMBHs: $10^6 < M_{BH}/M_{\odot} < 10^9$)



?

IMBHs

$M_{BH} \sim 10^2$-10^5 $M_{\odot}$

IMBHs: why interesting?

1. can probe a new BH mass range, between stellar BHs and SMBHs

2. could be the seeds SMBHs

QSO observed up to z>6 (Fan et al. 2001)

At z=6, $t_H \sim 1$ Gyr

=> not enough time to merge > 10^5 stellar mass BHs!

How did SMBHs form??!

IMBHs could be the answer!

IMBHs are crucial for our understanding of:

- galaxy formation
- AGN formation
- co-evolution of galaxies & AGNs

IMBHs: why interesting?

1. can probe a new BH mass range, between stellar BHs and SMBHs

2. could be the seeds SMBHs

3. could explain the origin of ultraluminous X-ray sources (ULX: $L_X > 10^{40}$ erg/s) detected in nearby galaxies

$$\left.\begin{array}{l}\text{ULX: } L_X \approx 10^{40}\text{ erg/s} \\ \text{Eddington Luminosity: } L_{Edd} \approx 10^{38}\, M_{BH}/M_\odot\end{array}\right\} \Rightarrow M_{BH} \geq 10^2\, M_\odot$$

(IMBHs)

IMBHs: why interesting?

1. can probe a new BH mass range, between stellar BHs and SMBHs

2. could be the seeds SMBHs

3. could explain the origin of ultraluminous X-ray sources (ULX: $L_X > 10^{40}$ erg/s) detected in nearby galaxies

4. could allow to finally detect gravitational waves

IMBHs expected to be strong gravitational wave emitters
if found in Galactic GCs (relatively close to Earth) $\Bigg\}$ =>

=> the probability of detection is significantly enhanced !!

IMBHs: why interesting?

1. **can probe a new BH mass range, between stellar BHs and SMBHs**

2. **could be the seeds SMBHs**

3. **could explain the origin of ultraluminous X-ray sources (ULX: $L_X > 10^{40}$ erg/s) detected in nearby galaxies**

4. **could allow to finally detect gravitational waves**

5. **may have a role in the dynamical evolution & stability of GCs**

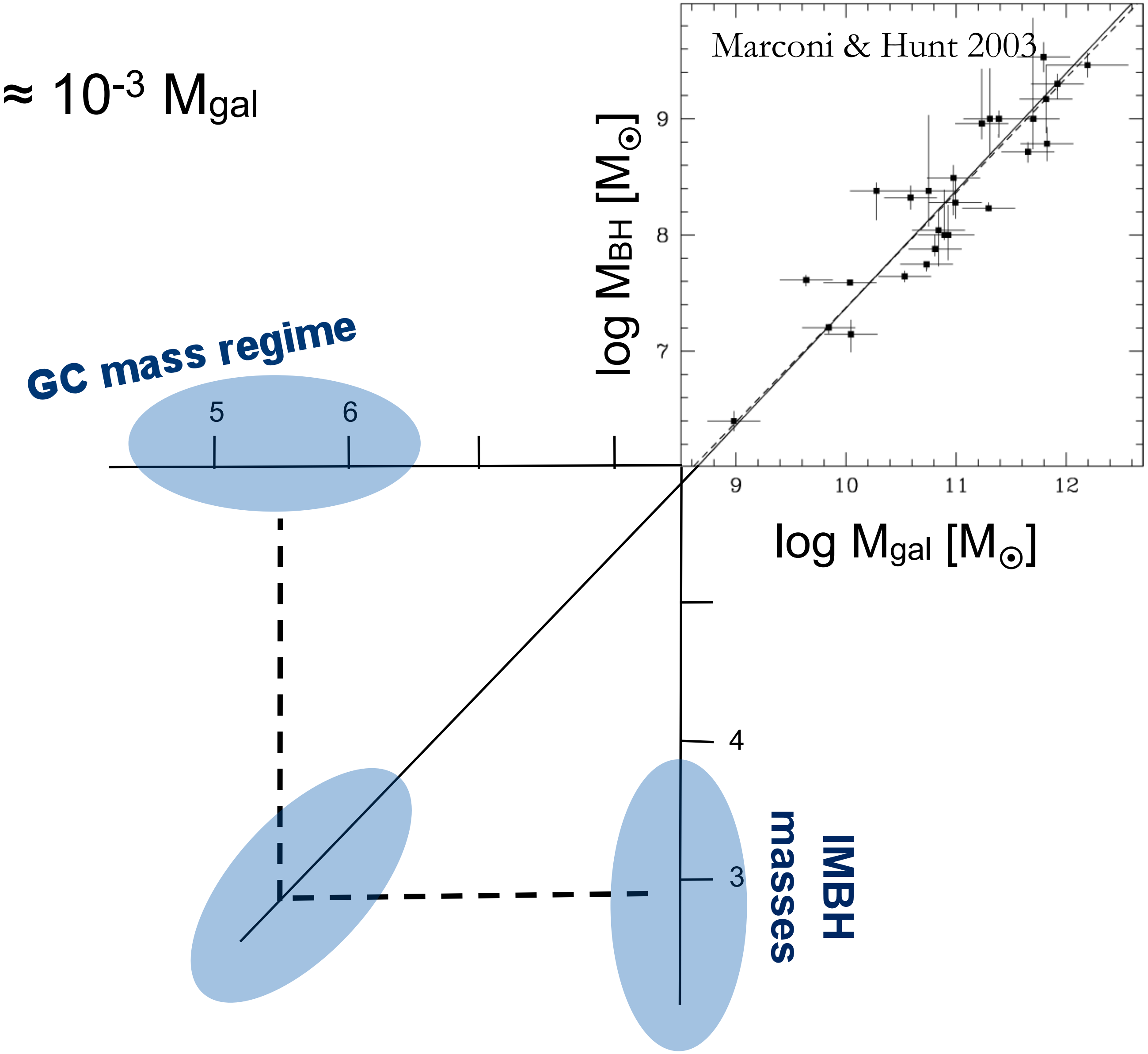
   (IMBHs in GCs can affect density profile, mass segregation, UV-bright pop, position of MSPs)

... but do they exist ??

IMBHs: they are expected (especially in GCs)

1. Extrapolation of the "Magorrian relation" to GC scales

$M_{BH} \approx 10^{-3}\, M_{gal}$



IMBHs: they are expected (especially in GCs)

1. Extrapolation of the "Magorrian relation" to GC scales

2. Several plausible formation scenarios:

- evolution of first stars **(Pop III)** with masses > 250 $M_\odot$
  (e.g., Madau & Rees 2001)
- repeated **merging of stellar-mass BHs**
  (Miller & Hamilton 2002)
- accretion of interstellar **gas onto stellar-mass BHs**
  (Kawakatu & Umemura 2005)
- (some) GCs may be remnant **nuclei of disrupted dwarfs** with possible IMBHs (e.g., Freeman 1993; Greene & Ho 2004)
- **runaway collisions** of massive (50-120 $M_\odot$) MS stars in the core of high-density clusters in their early stages of evolution
  (e.g. Portegies Zwart +04; Freitag +07)

runaway collisions of massive (50-120 $M_\odot$) MS stars in the core of high-density clusters in their early stages of evolution (e.g. Portegies Zwart +04; Freitag +07)

high-density GC => $t_{MASS\ SEGR} < t_{MS}$ (~ 3-4 Myr)

=> strong segregation of massive MS stars

=> collisions & merging

=> cross section increases

=> further collisions & merging….

Magorrian relation!

=> a star with $M \sim 10^{-3}\ M_{cl}$ forms and it collapses into an IMBH !

GCs → ideal habitat for IMBH formation

IMBH fingerprints

(Baumgardt et al. 2005; Miocchi 2007; Heggie et al. 2007; Trenti et al. 2007, 2010; Dukier & Bailyn 2003; Maccarone 2004, 2007; Gill et al. 2008;....)

An IMBH is expected to:

1) increase the density of stars in its vicinity

→ **shallow density cusp at the very centre**

- "standard" GCs: King model (flat core) with concentration c ≈ 0.5÷2
- post-core collapse GCs: central power-law deviation $\Sigma(r) \sim r^{\nu}$ with $\nu \sim -0.8$

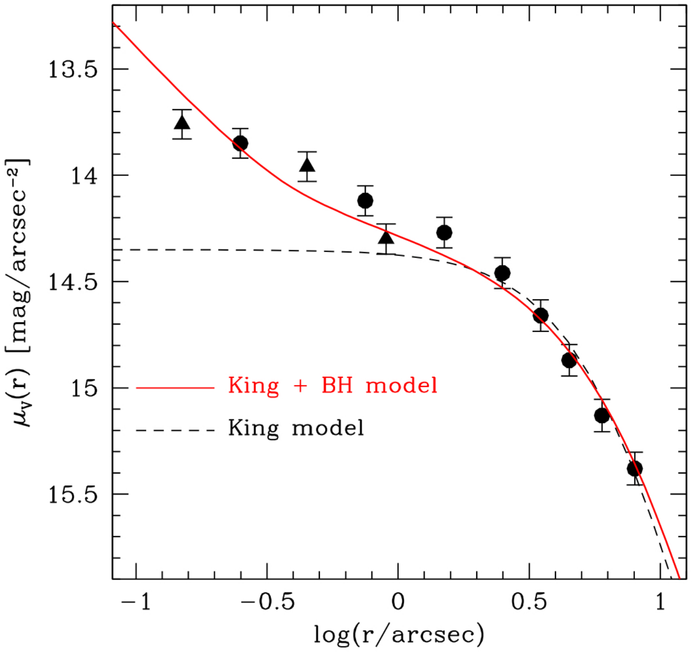
  high-concentration (c>2) & virtually zero r_c
- GCs with central IMBH:

  high stellar density in the IMBH vicinity

  => enhanced rate of close encounters

  => energy generation

  => expansion of the core



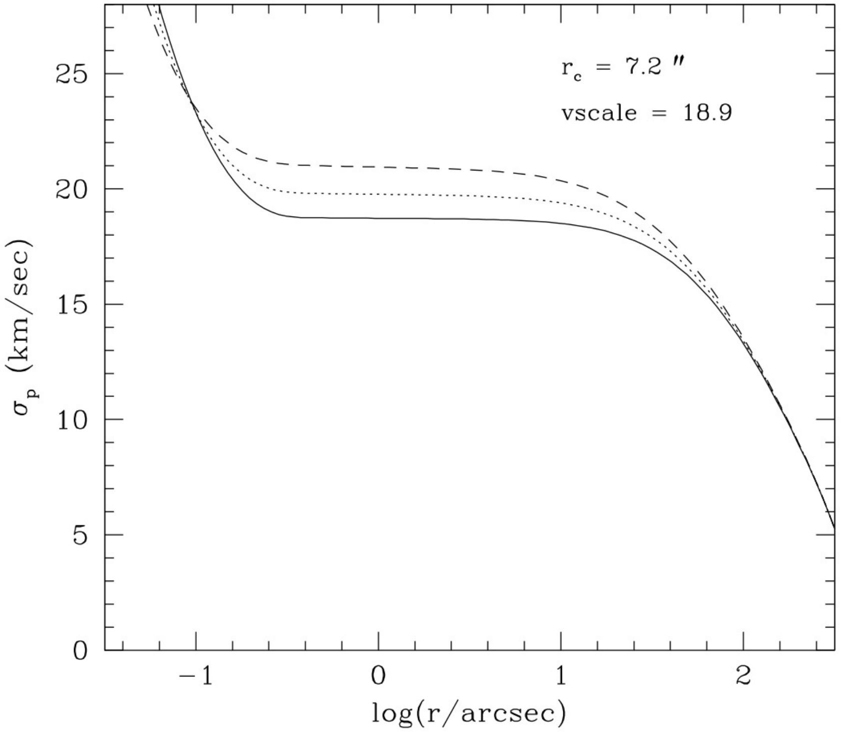
- intermediate concentration (c ≈ 1.5) King profile
- sizeable r_c ($r_c/r_h > 0.1$)
- shallow power-law cusp at the very centre:

  $\Sigma(r) \sim r^{\nu}$ with $\nu > -0.3$ at $r < 0.1\ r_c$ ($r \approx 0.1$ pc)

2) induce Keplerian behaviour ($v \sim r^{-1/2}$) to stellar velocities at the very centre

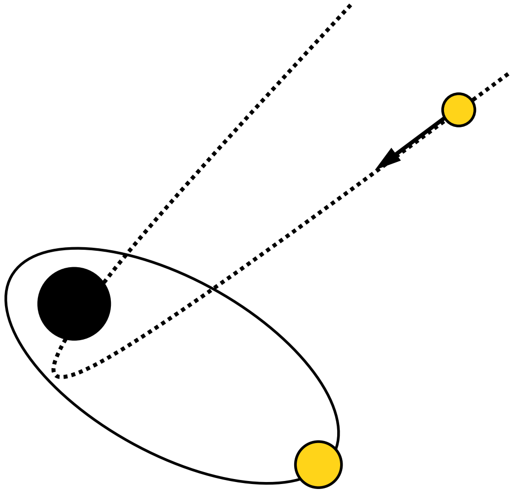
→ steep cusp in the velocity dispersion profile within the BH sphere of influence

$$\boxed{r_{BH} = G\,\frac{M_{BH}}{\sigma^2}}$$



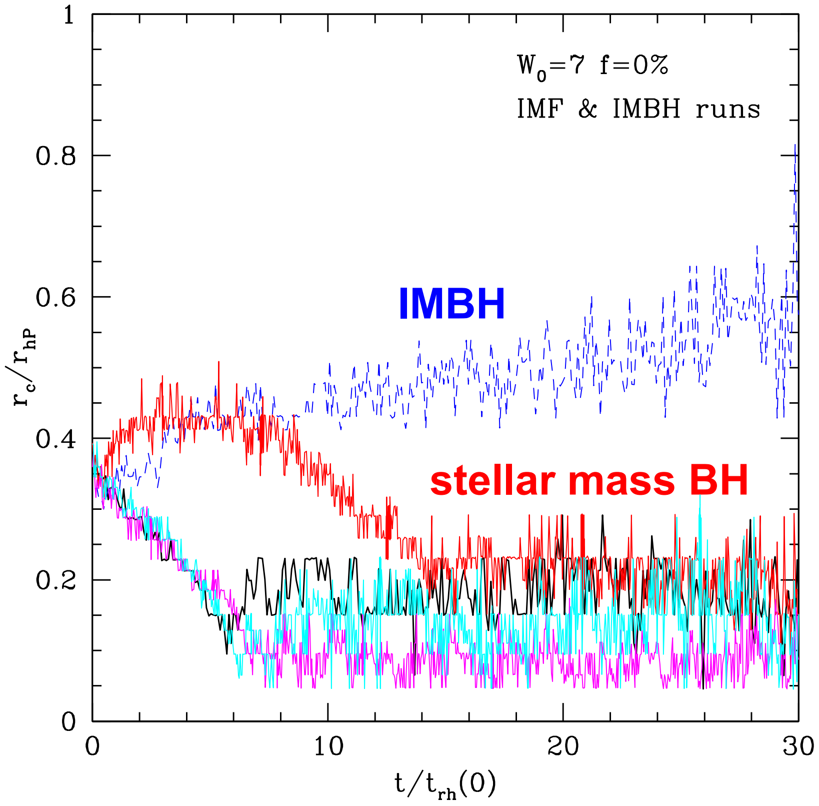
3) accelerate a **few stars to very high-velocities** (even v ~ 100 km/s) and lead to **“anomalous” positions/acceleration of some MSPs**

An IMBH quickly gains at least one tightly bound massive star:
a super-scatter machine is born!



4) lead to universal **large core to half-mass radii ratios (r_c/r_h)**

(because the “super-scatter machine” acts as a central energy source)

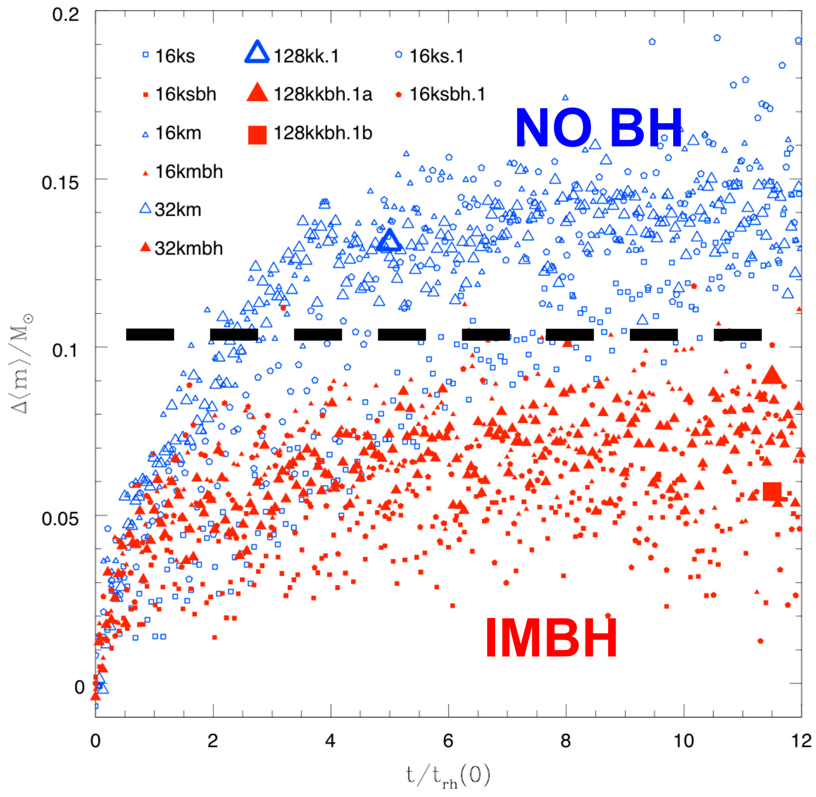


5) induce a **quenching of mass segregation**

Dynamical interactions between IMBH & cluster stars:

- “massive” MS stars sinking to the core (after energy exchanges with other stars) are “heated up” and scattered away

quenching of mass segregation with respect to GCs with no IMBH



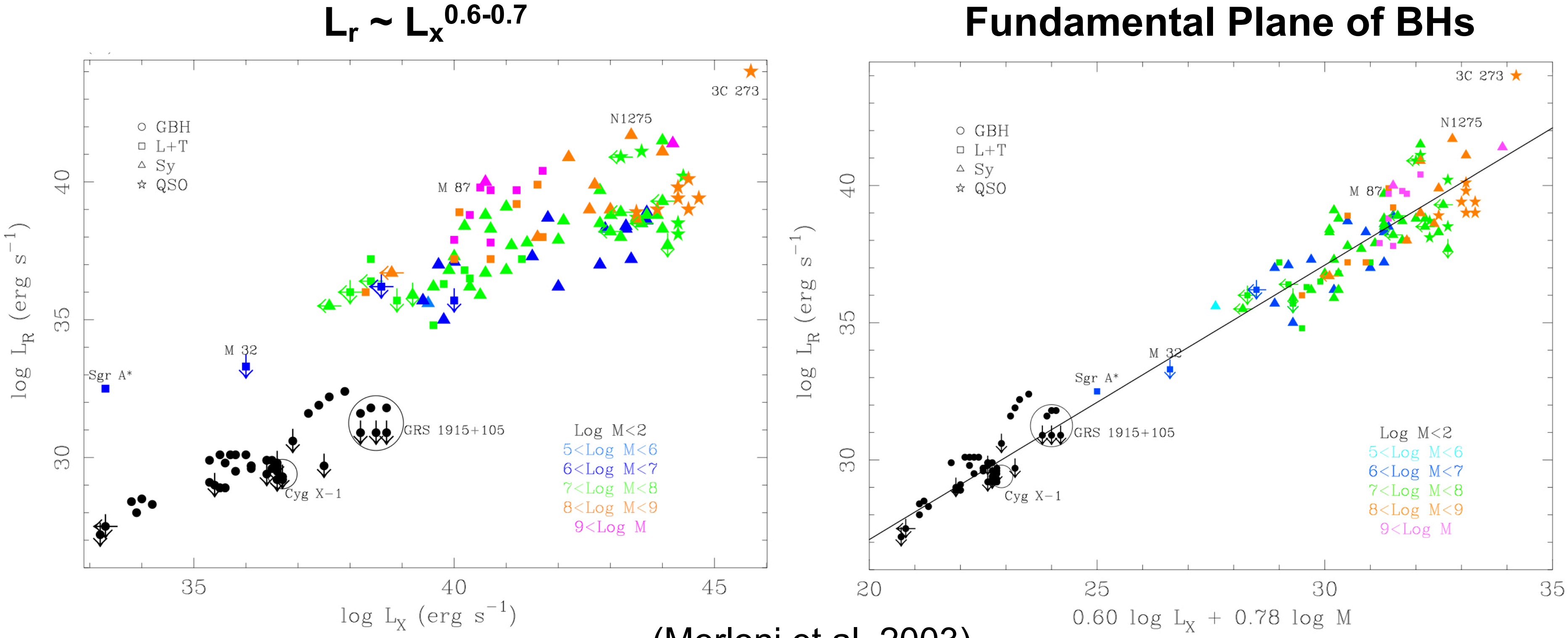
$$\Delta\langle m\rangle = \langle m\rangle_{r=0} - \langle m\rangle_{r=rh}$$

6) produce **X-ray and radio emission** from accreting material

→ **X-ray:** strong, compact, power-law X-ray emission commonly associated to the inner part of an accretion flow

→ **radio:** relativistic jets emitting synchrotron radiation

related to each other



$L_r \sim L_x^{0.6-0.7}$

Fundamental Plane of BHs

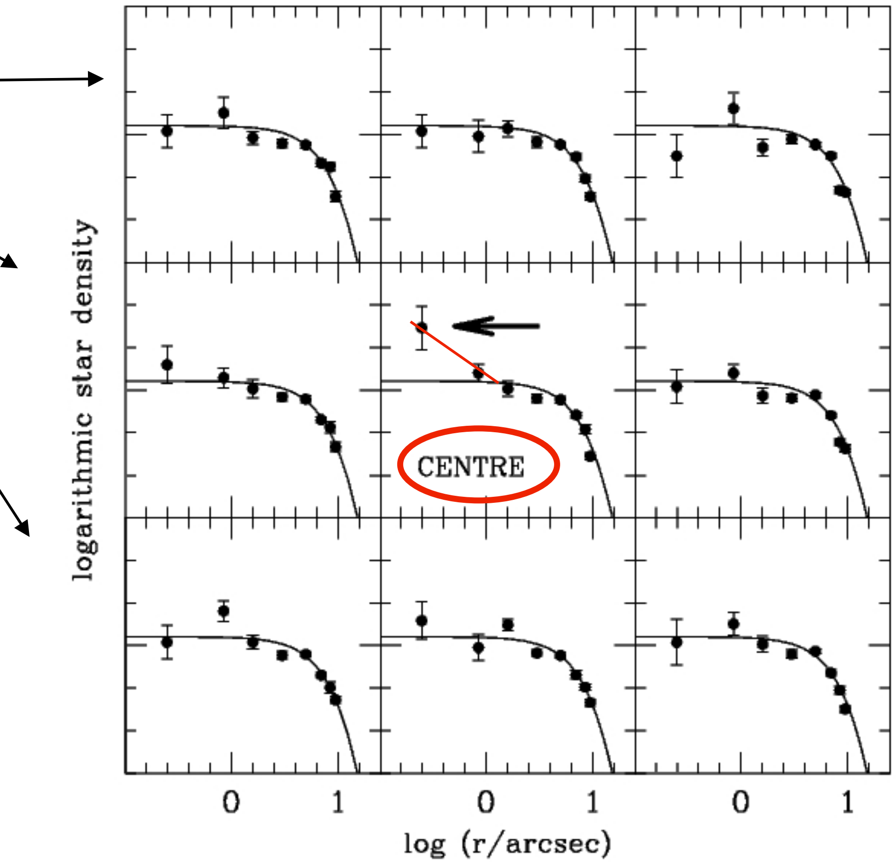
(Merloni et al. 2003)

IMBH fingerprints: difficulties

1) shallow density cusp at the very centre

- need of **high-resolution & high-precision photometry**
- crucial step: determination of the cluster **centre**

shifts of ± 0.5” only with respect to the right centre !



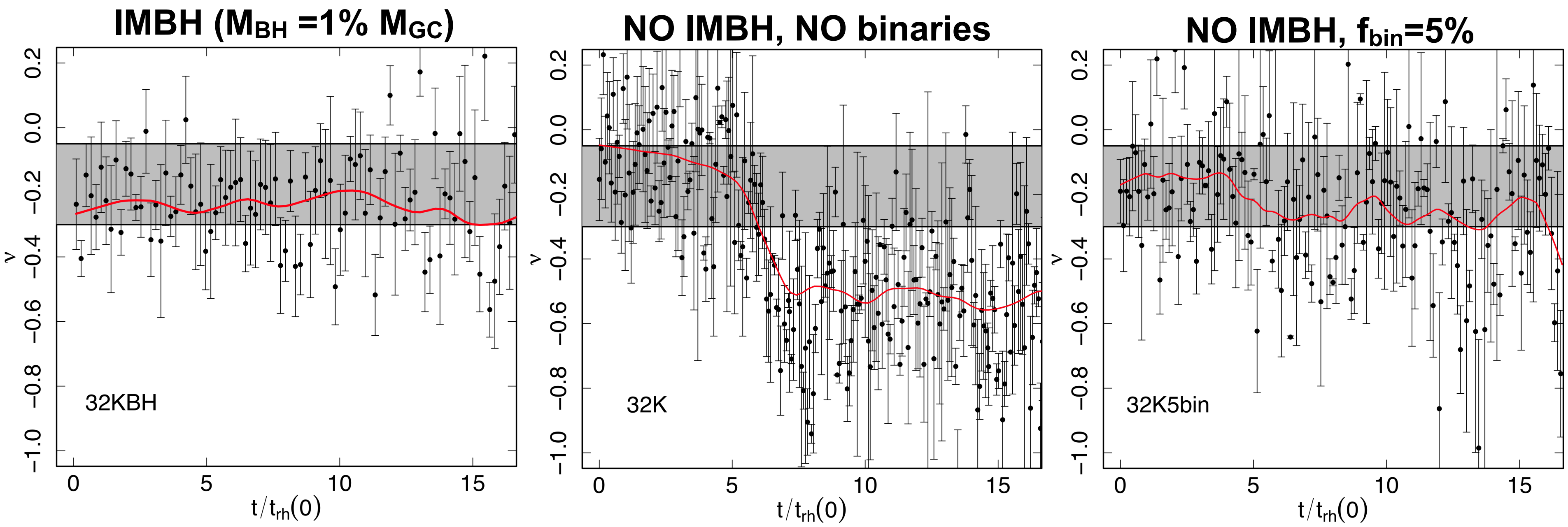
even an error of a few 0.1" is sufficient to artificially flatten the derived profile and hide the central cusp!

IMBH fingerprints: difficulties

1) shallow density cusp at the very centre

- need of **high-resolution & high-precision photometry**
- crucial step: determination of the cluster **centre**
- shallow central does **NOT necessarily** imply the presence of an IMBH

simulations with NO IMBH show $\nu > -0.3$ during:
- pre-core collapse phase
- core collapse phase
- post-core collapse phase if $f_{bin}>3\%$



2) steep velocity dispersion cusp within r_{BH}

$$\boxed{r_{BH} = G\,\frac{M_{BH}}{\sigma^2}}$$

$G = 4.32\ 10^{-3}\ \mathrm{M}_{\odot}^{-1}\ (\mathrm{km/s})^2\ \mathrm{pc}$ => $$\boxed{r_{BH} = 4.32 \times 10^{-3}\ \frac{M_{BH}}{\mathrm{M}_{\oplus}} \left(\frac{\sigma}{\mathrm{km/s}}\right)^{-2}\ \mathrm{pc}}$$

$r_{\mathrm{pc}} = r''\ \dfrac{\pi}{180 \times 3600}\ \mathrm{d}_{\mathrm{pc}} = r''\ \dfrac{\pi \times 10^3}{180 \times 3600}\ \mathrm{d}_{\mathrm{kpc}}$ => $$\boxed{r''_{BH} = 0.89\ \frac{M_{BH}}{\mathrm{M}_{\oplus}} \left(\frac{\sigma}{\mathrm{km/s}}\right)^{-2}\ \frac{1}{\mathrm{d}_{\mathrm{kpc}}}}$$

$$\left.\begin{array}{l} M_{BH} = 10^3\ \mathrm{M}_{\odot} \\ \sigma = 10\ \mathrm{km/s} \end{array}\right\} \Rightarrow \quad r_{BH} = 4.32 \times 10^{-3}\ 10^3/10^2\ \ \mathrm{pc}\ = \ 0.04\ \mathrm{pc}$$

$\mathrm{d} = 10\ \mathrm{kpc}$ => $$r_{BH} = 0.89\ 10^3/(10^2 \times 10)\ \ \mathrm{pc}\ = \ 0.89''$$

(HST/ACS-WFC –photometry– spatial resolution = 0.25”)

2) steep cusp in velocity dispersion within r_{BH}

- need to measure velocity dispersion within the central 1”-2” or even less!

This is **extremely** difficult!

Methods to measure velocity dispersion:

- **line broadening in integrated-light spectra**
- **dispersion of radial velocities of individual stars**

Line broadening in integrated-light spectra:

✓ relatively easy to perform

✗ high risk to be biased by the light of a few giants

if 2-3 bright stars dominate the sampled light,
the spectrum does not sample the underlying stellar distribution,
but the radial velocities of those 2-3 giants

=> this is NOT a measure of the stellar velocity dispersion

... a drawback of resolving stellar populations!

Dispersion of radial velocities of individual stars:

✓ direct, straightforward, not affected by similar bias

✗ extremely difficult to perform, especially in dense environments

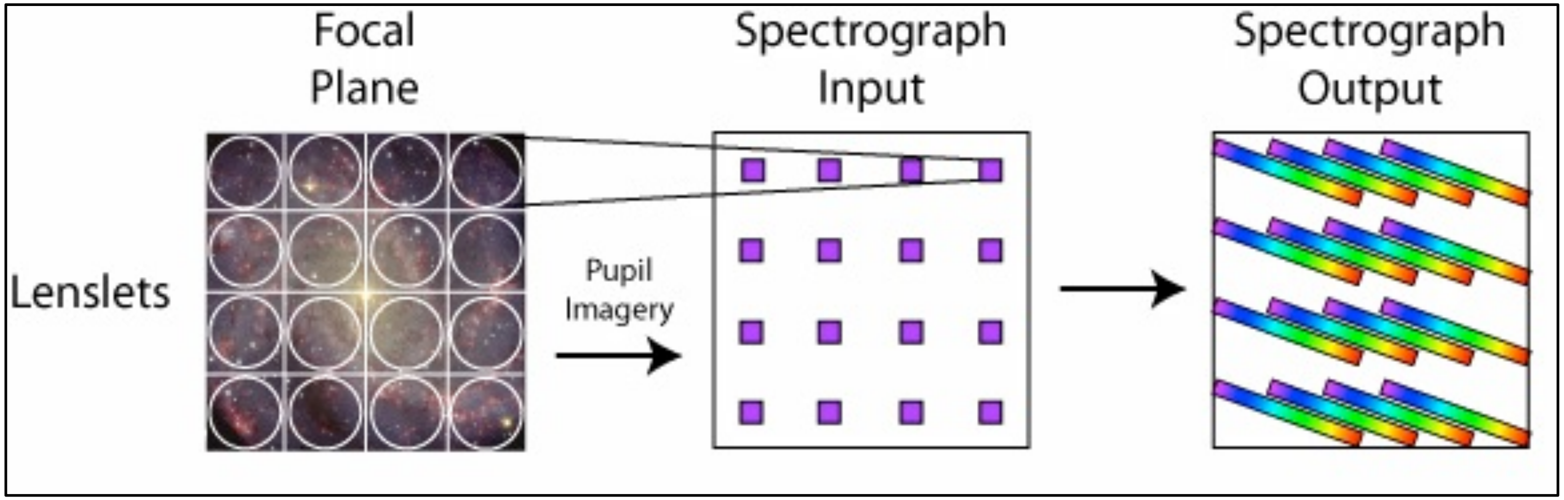
high number statistics required => multi-object spectrographs

high spatial resolution => ~~space~~ or AO

NO multi-object spectrographs exist on board the HST

AO-assisted IFU spectrographs at VLT or GEMINI

IFU= Integral Field Units



2) steep cusp in velocity dispersion within r_{BH}

- **hard to measure**
- **uncertainties in the modelling**

  (isotropic/anisotropic velocity dispersion, spherical/non-spherical symmetry, rotation, contribution of dark remnants to central M/L, ...)

Very promising alternative: proper motions

x require high-resolution & deep imaging (for crowded regions & high nb. statistics)

x require multi-epoch imaging separated by long baselines

x very accurate photometric & astrometric analysis

(1 km/s at 5 kpc => 0.004 ACS/WFC pixels every 5 years!)

✓ much easier than spectroscopy

✓ individual radial velocities also for faint stars (=> high nb. statistics)

✓ full 2D coverage

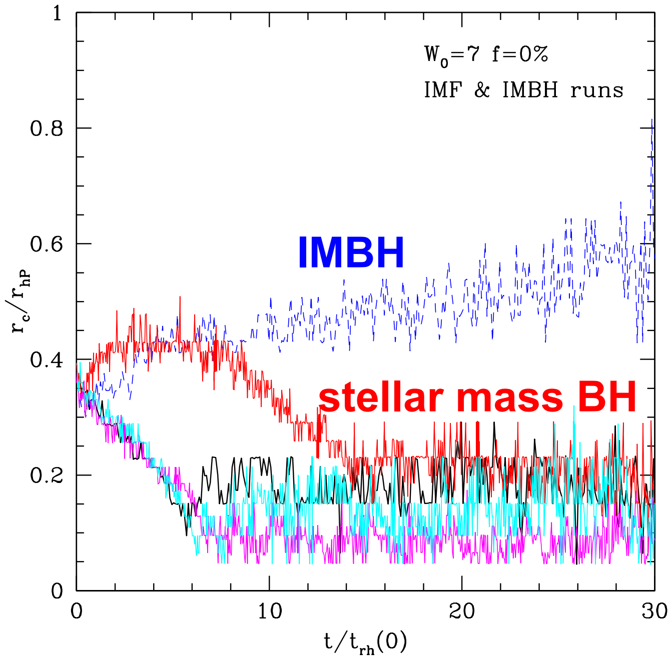
✓ two components of motion: anisotropy measured

3) high-velocity stars and/or "anomalous" positions/acceleration of some MSPs

- quite **rare** events
- **if velocity non aligned** along line of sight => lower (even normal) values of v
- **non-univocal** interpretation
  (for instance: high-velocity star of star not belonging to the cluster?
  effect of a binary NS?)

4) large core to half-mass radii ratios (r_c/r_h)

- IMBH **non-univocal** heating source
  (other possibilities: WD kicks, stellar collisions)
- **stellar BHs** can mimic the signal for several relaxation times



5) quenching of mass segregation

- **hard to measure**

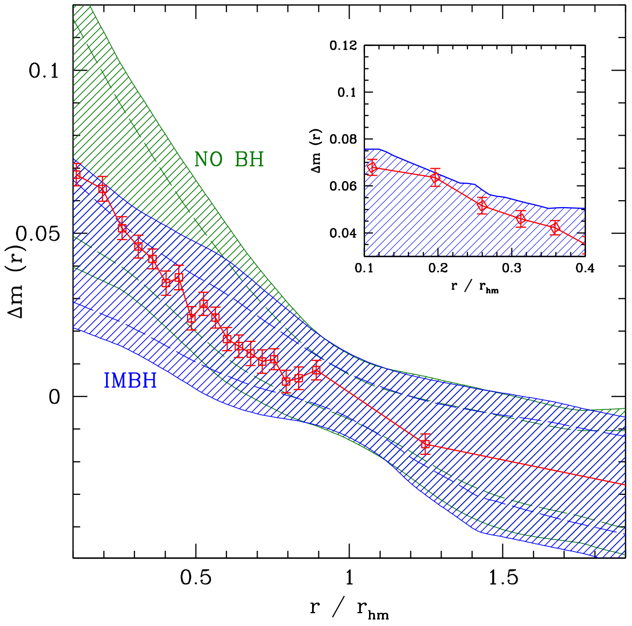
need to resolve MS stars down to faint magnitudes and measure <*m*>
both in the centre and at r_h => high-res, wide-field, deep, high-precision photometry

- **hard to interpret**

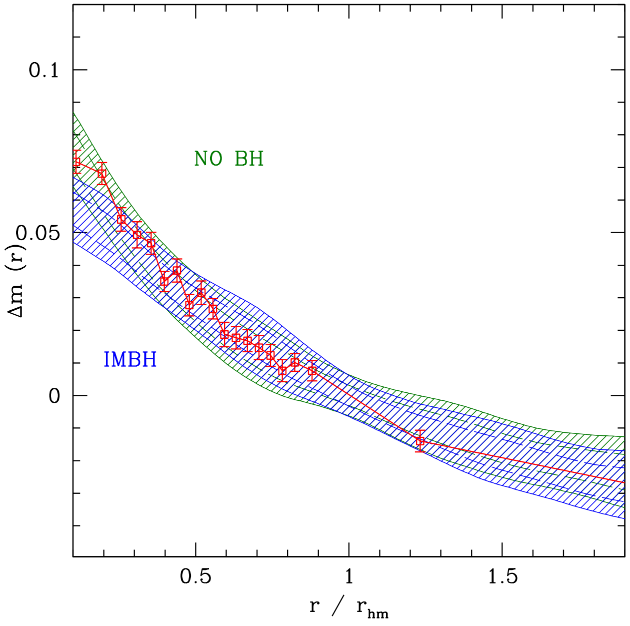
need to run specific N-body simulations for any given GC
with/without IMBH & binaries

- **possible degeneracy with binary population**

no binaries



5% binaries



5) quenching of mass segregation

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- **hard to interpret**

need to run specific N-body simulations for any given GC
with/without IMBH & binaries

- **possible degeneracy with binary population**

- **limited range of applicability**

applicable only to well relaxed GCs, where mass segregation attained equilibrium:
→ GCs with half-light relaxation time < 1 Gyr
→ GCs not too influenced by the Galactic tidal field
(hence: ~30 Galactic GCs, over a total of ~150)

6) X-ray & radio emission

- **many uncertainties**
  - interstellar gas density?
    (generally unconstrained and low: n_e ~ 0.2 atoms/cm^3 in 47Tuc)
  - accretion rate (Bondi or a fraction of Bondi)?
  - conversion efficiency from accreted mass to radiated energy (L_{bol})?
  - bolometric correction (from observed L_X to predicted L_{bol}) ?
  - accretion symmetry?
  - variability?
  - other X-ray and radio sources in GCs (e.g., NSs)
  - scaling relations valid for SMBHs & stellar-mass BHs not necessarily hold also for IMBHs

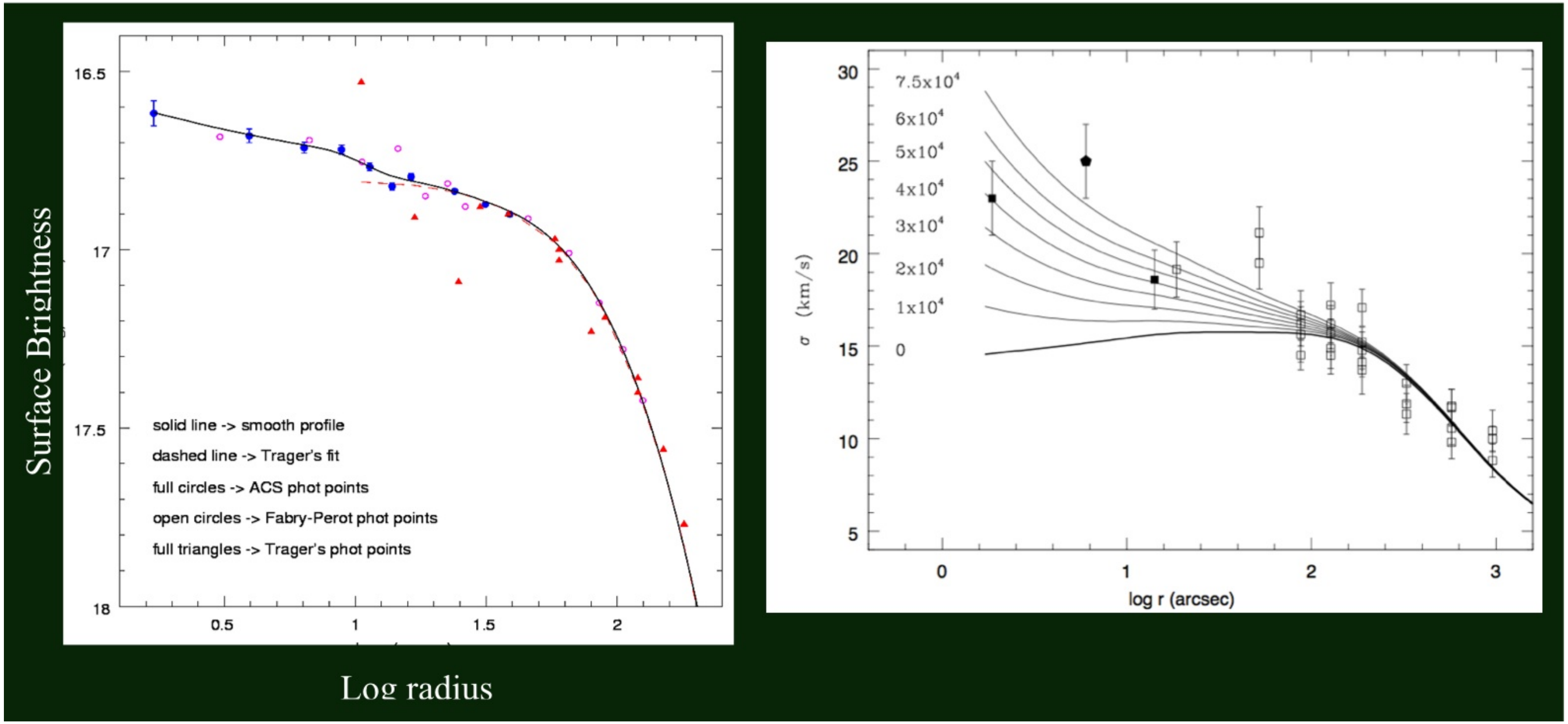
(some) results

ωCentauri

Noyola et al. (2008, 2010), from:

- density profile *(Fingerprint 1)*
- velocity dispersion profile *(Fingerprint 2)*
- specific dynamical models

$M_{BH} \sim 4\text{x}10^4\ M_\odot$



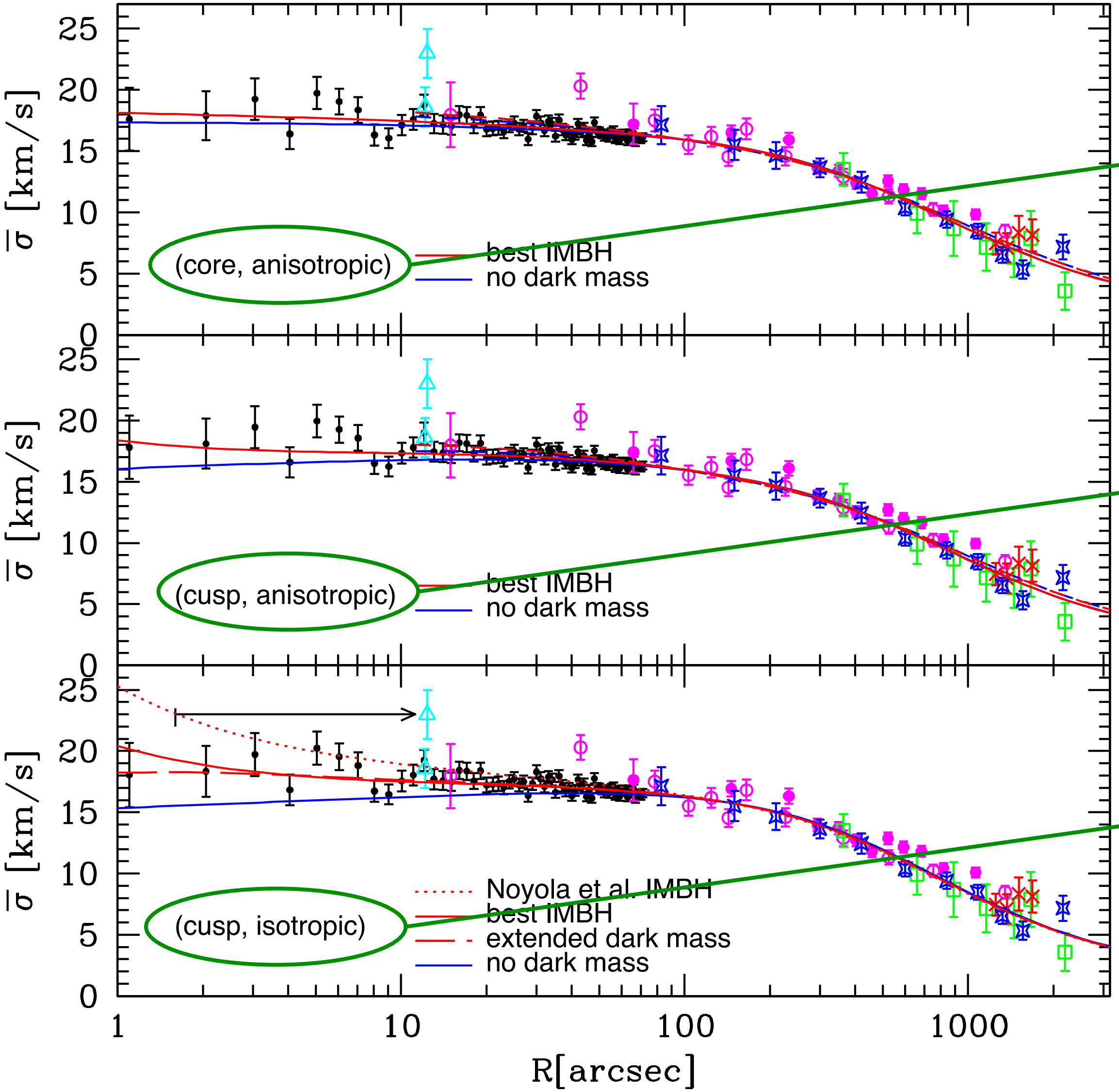
ωCentauri

However, van der Marel & Anderson (2010):

- a different centre
- flat “density” profile (despite the same ACS data set)
- flat velocity dispersion profile from proper motions
- several dynamical models

ωCentauri

van der Marel & Anderson 2010:



- **best-fit: NO IMBH**
- otherwise:
  $M_{BH} \approx 4 \times 10^3 M_\odot$

- $M_{BH} \approx 9 \times 10^3 M_\odot$

- $M_{BH} \approx 2 \times 10^4 M_\odot$

ωCentauri

- radio + X-ray observations (Lu &Kong 2011): $M_{BH} \lesssim 1000\text{-}5000\ M_{\odot}$

- no X-ray emission from the core of the cluster (Haggard+13)
  (despite the deepest X-ray search for IMBH in GCs: 291 ks)

Tentative suggestions (of IMBH/dark mass) for:

M15: $(3.9 \pm 2.2) \times 10^3\ M_\odot$ (van der Marel et al. 2002; Gerssen et al. 2002)

G1: $(1.8 \pm 0.5)\ 10^4\ M_\odot$ (Gebhardt et al. 2002, 2004)

47 Tuc: $(900 \pm 900)\ M_\odot$ (van der Marel et al. 2006)

M54: $\leq 9.4 \times 10^3\ M_\odot$ (Ibata et al. 2009)

NGC6388: $(1.7 \pm 0.9) \times 10^4\ M_\odot$ (Lutzgendorf et al. 2011)

NGC1904: $(3 \pm 1) \times 10^3\ M_\odot$ (Lutzgendorf et al. 2012)

NGC6266: $(2 \pm 1) \times 10^3\ M_\odot$ (Lutzgendorf et al. 2012)

However:

→ in all cases, the different fingerprints brought to the **different results**

→ in all cases, just a **few-sigma significance**

(note that 1-2 sigma detections happen by chance 1/3 of the time....)

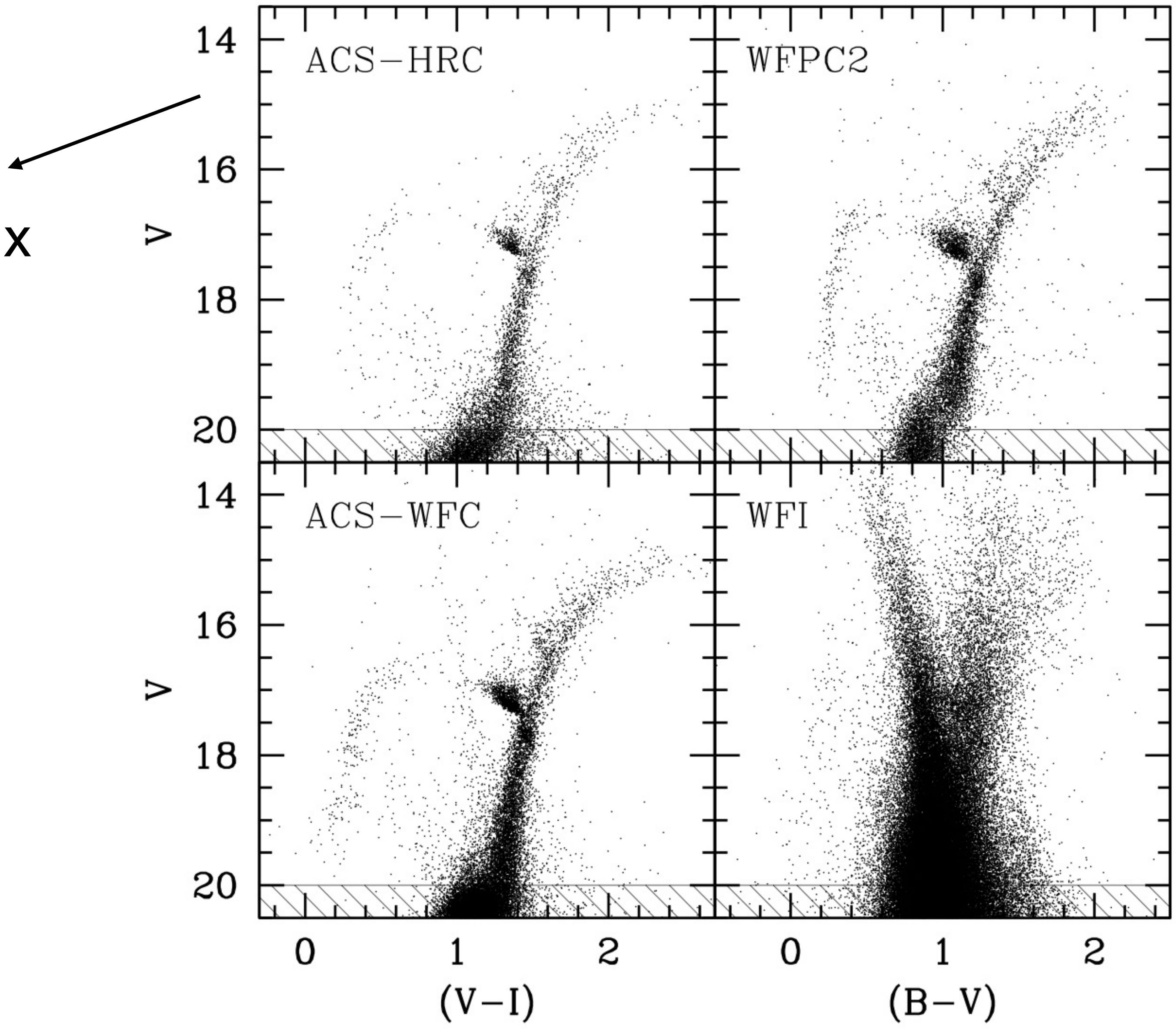
→ any systematic error **biases M_{BH} upward**

NGC 6388

26" x 29" FoV

0.027 arcsec/pix

Photometric data set



NGC 6388

Determination of the centre

$V < 20$ (~ 4000 stars)

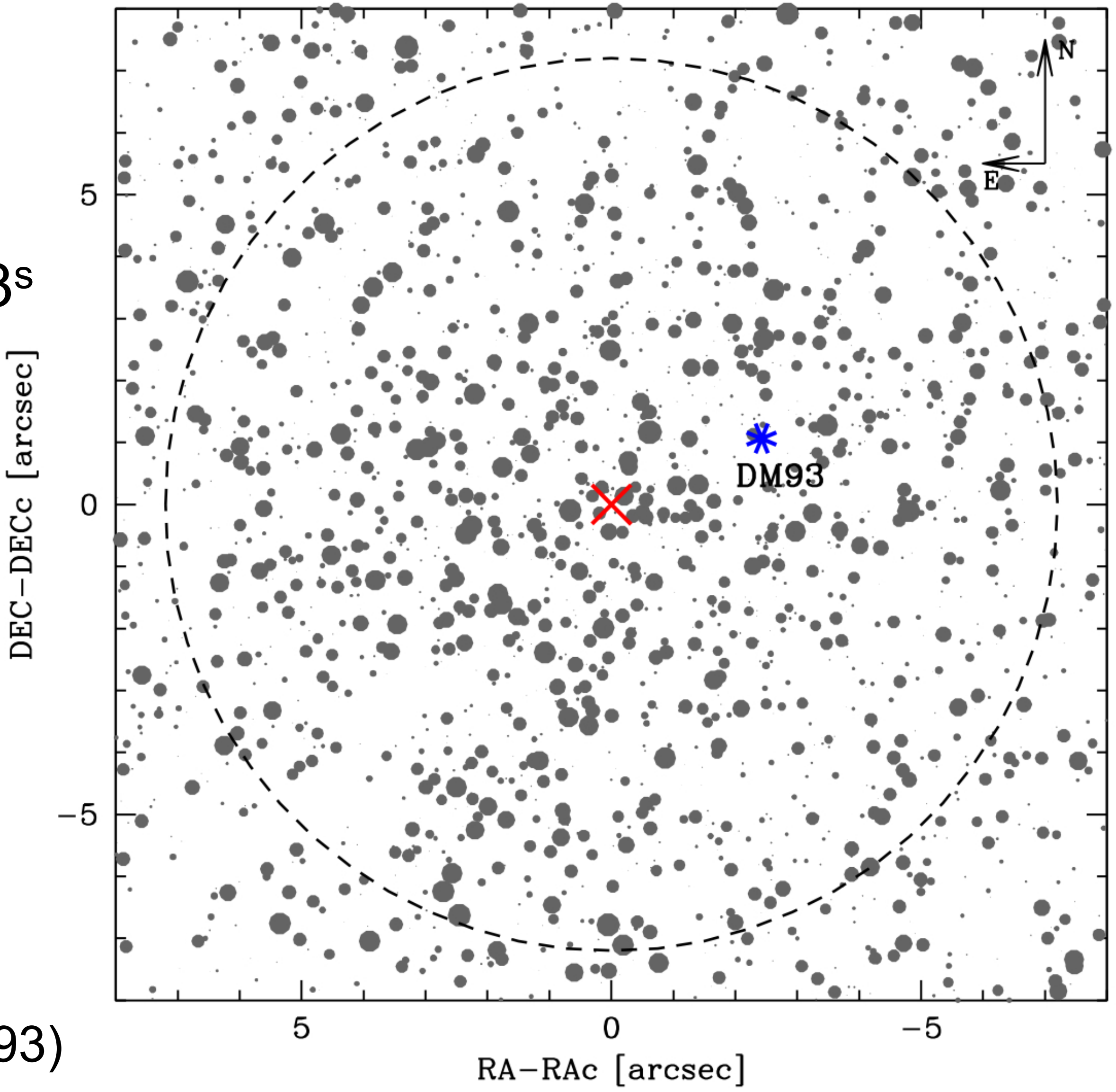
$\alpha_{J2000} = 17^h\ 36^m\ 17.23^s$

$\delta_{J2000} = -44^o\ 44'\ 7.1''$

$\boxed{\Delta\alpha,\ \Delta\delta \sim 0.2''\text{-}0.3''}$

~2.6” south-east from the “literature” centre

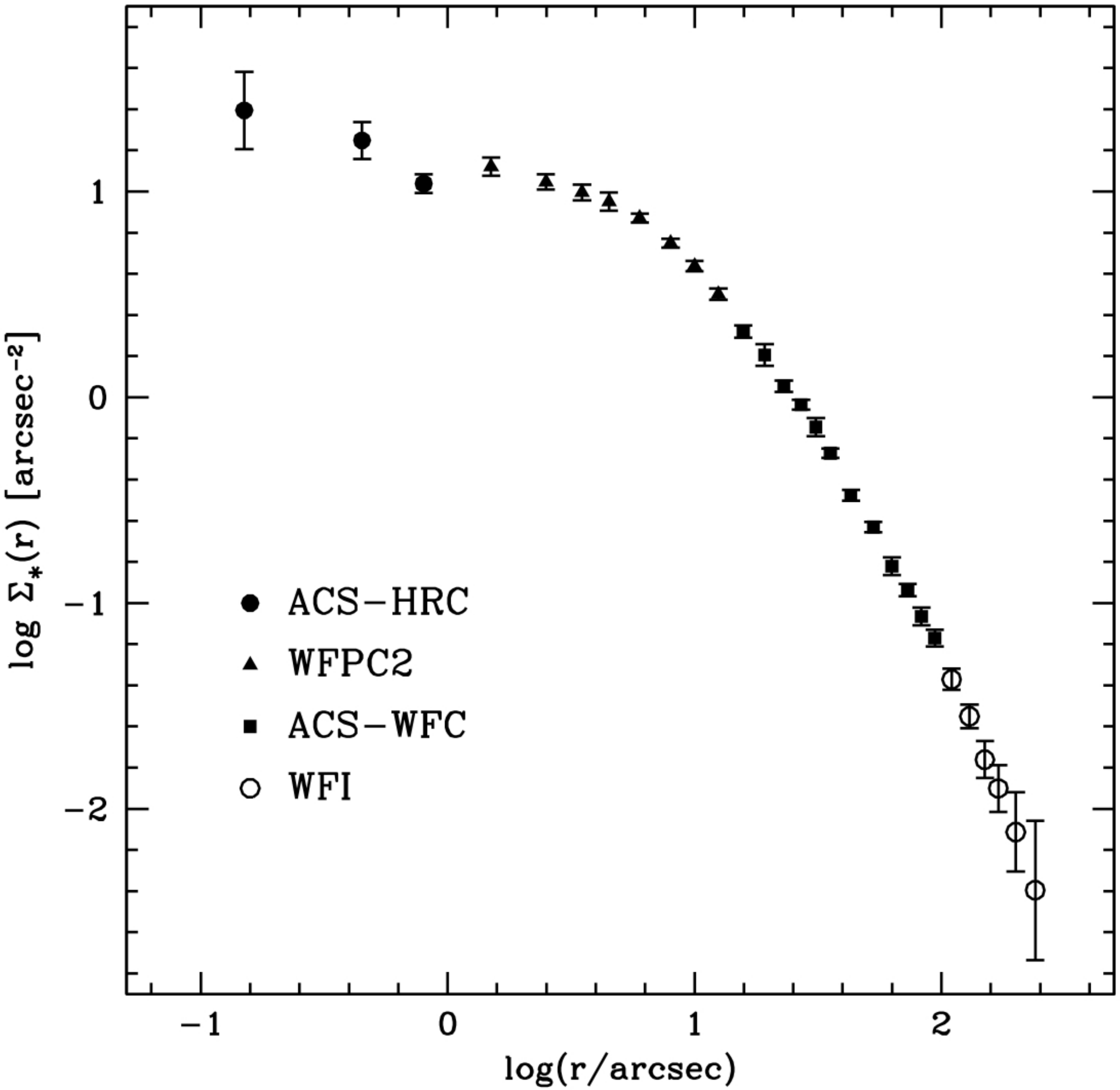
(Djorgovski & Meylan 1993)



NGC 6388

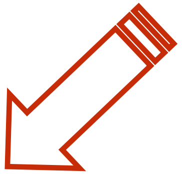
Projected density profile

(star counts in annuli)



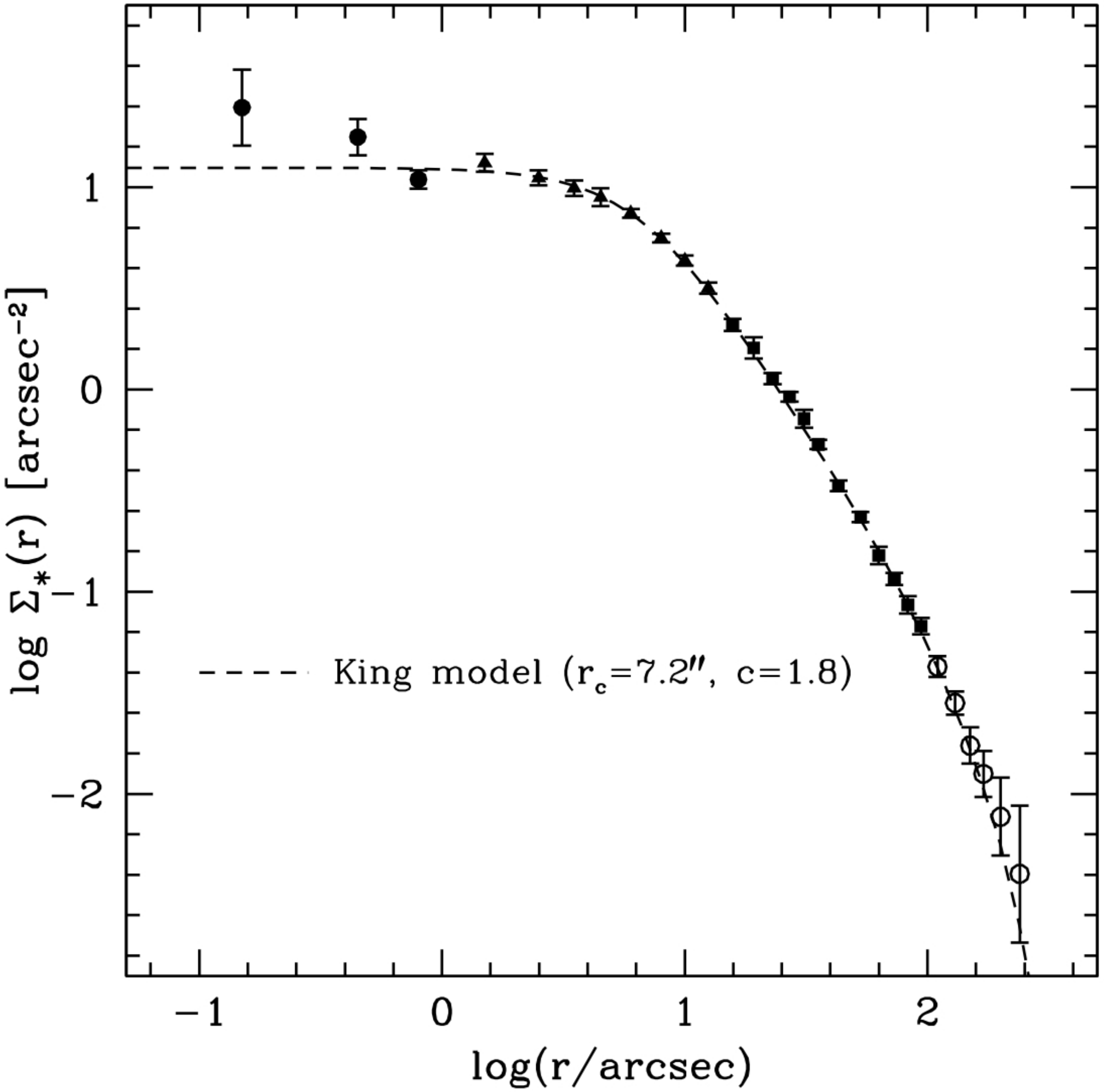
NGC 6388

Projected density profile

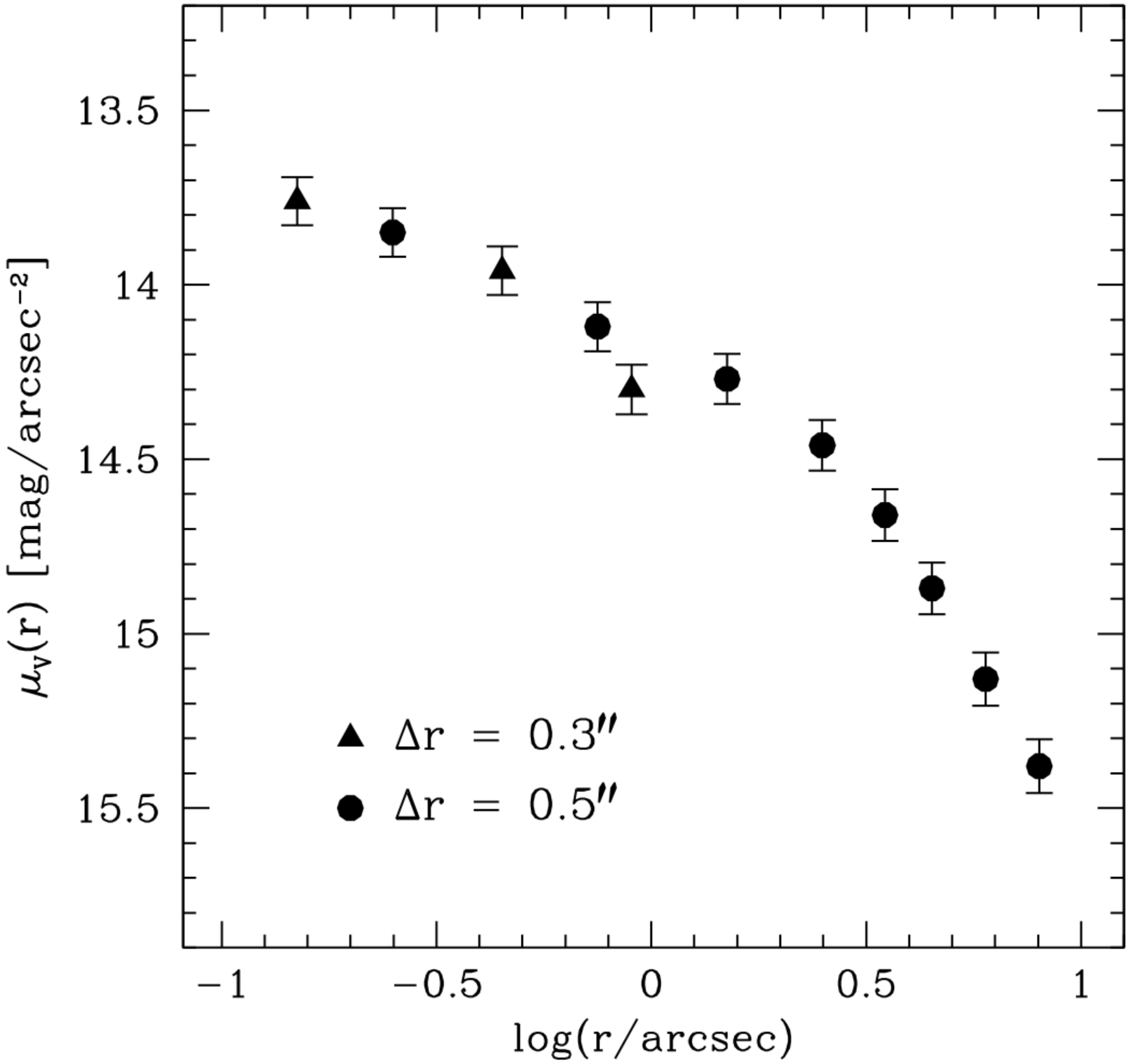


deviation from
a King profile
at r < 1”

… but only 7 stars
at r < 0.3”….

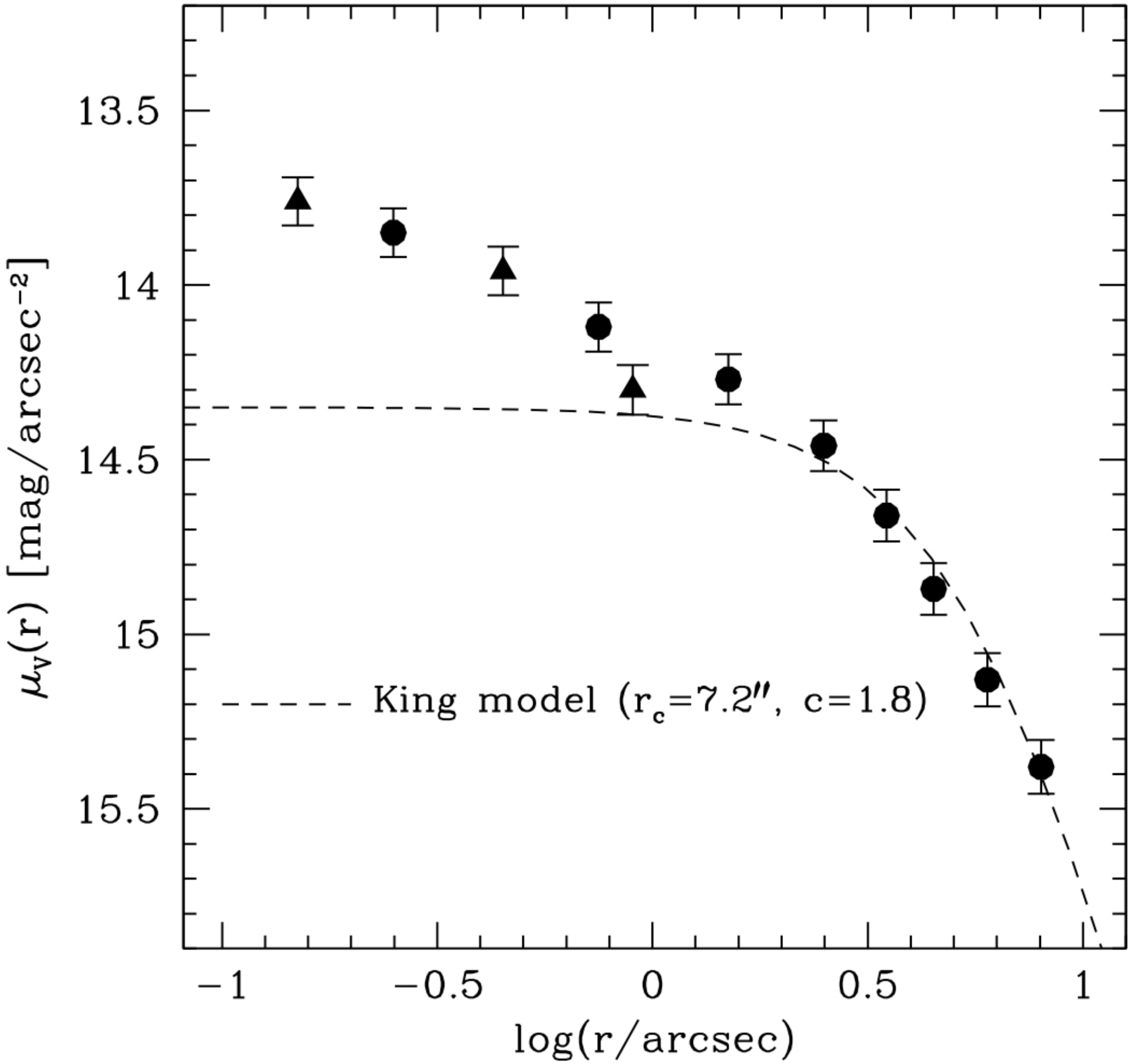


Surface brightness profile



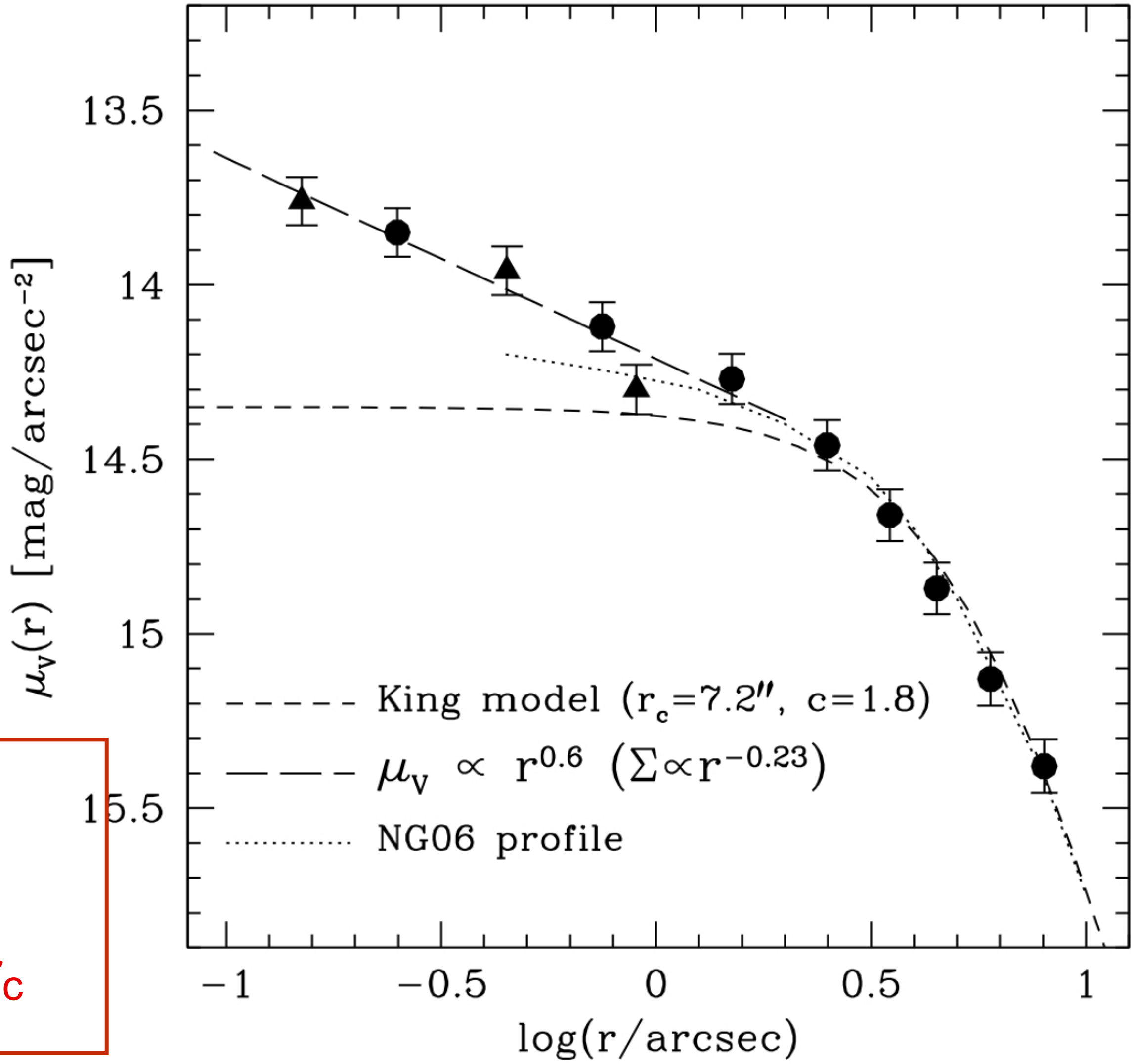
NGC 6388

Surface brightness profile



NGC 6388

Surface brightness profile



Fingerprint 1:

c ~ 1.8

$\Sigma(r) \sim r^{-0.2}$ at $r < 0.1\, r_c$

NGC 6388

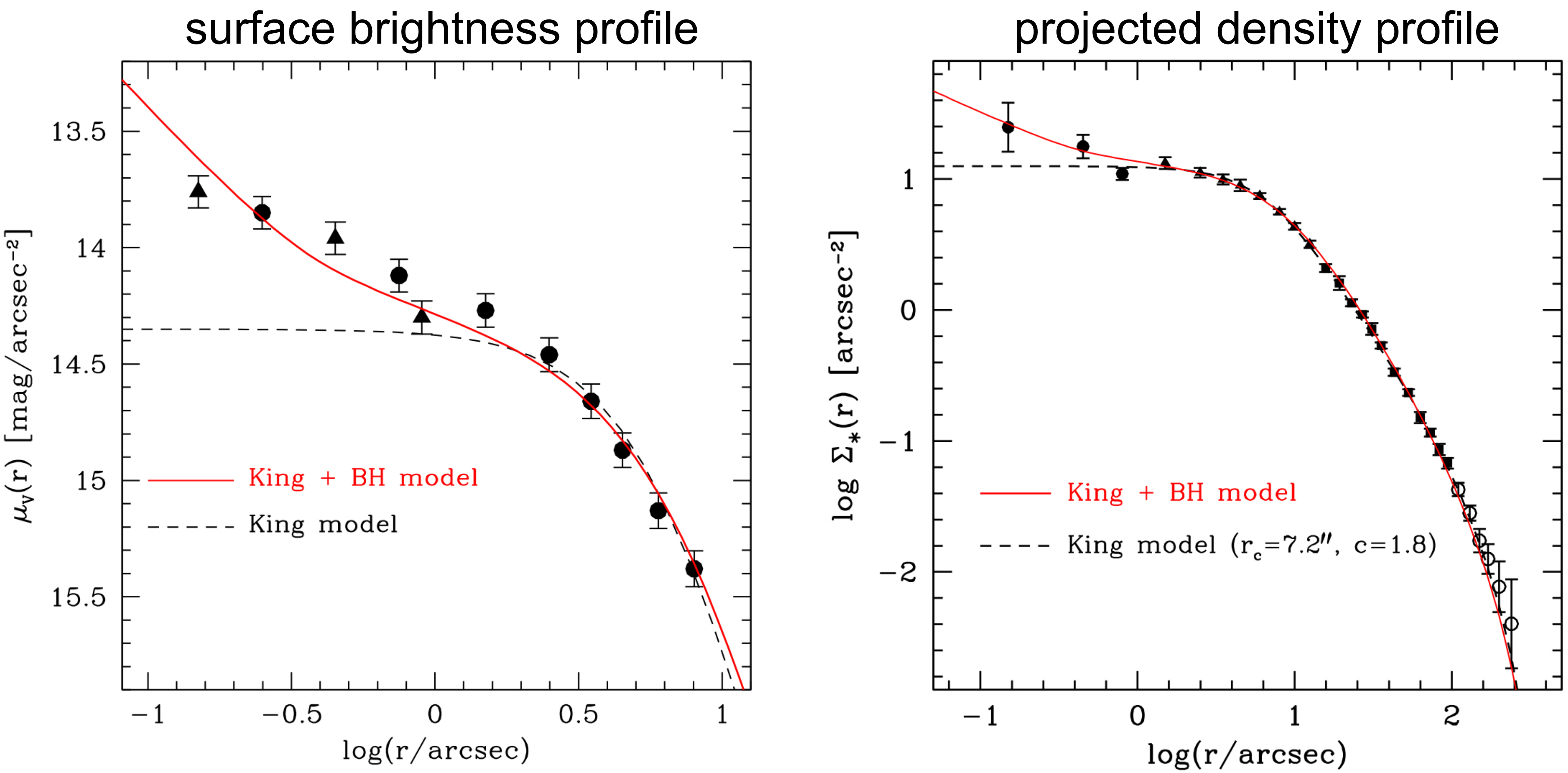
Dynamical modelling (Miocchi 2007)

Multi-mass, isotropic, spherical King model with central BH
(included via the phase-space distribution function of Bahcall & Wolf 1976):

$$f(E) = \begin{cases} c\,(-E)^{1/4} & \text{if } E < -W_{BH} \\ (2\pi)^{-3/2}\,(e^{-E} - 1) & \text{if } -W_{BH} \le E < 0 \\ 0 & \text{if } E \ge 0 \end{cases}$$

where W_{BH} is the potential on the surface of the BHIS

NGC 6388



$c = 1.8$

$r_C = 7.2''$

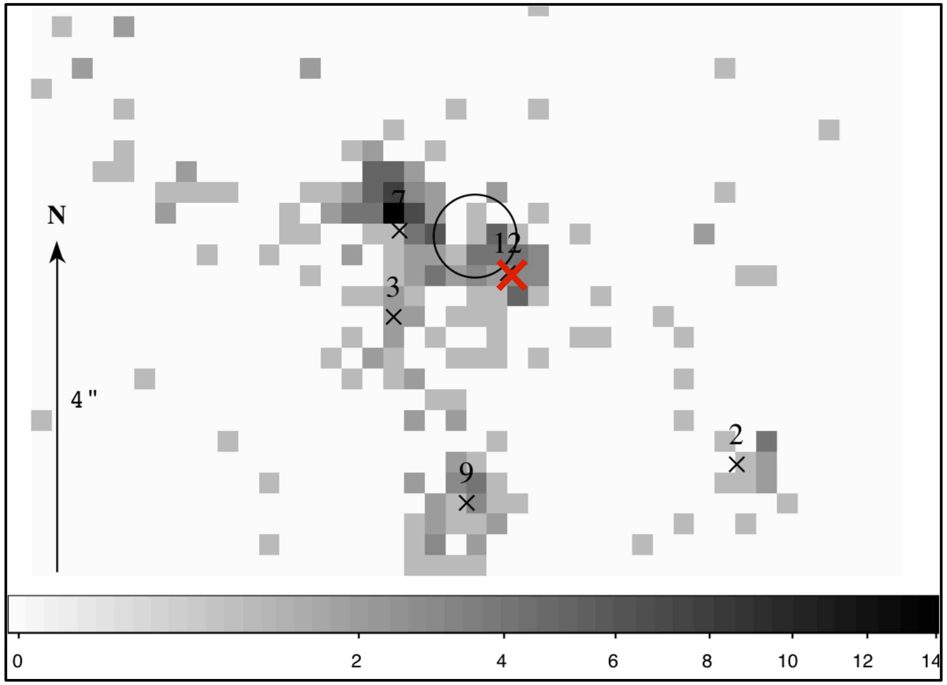
$M_{BH} \sim 2\ 10^{-3}\ M_{GC} \sim 6\ 10^{3}\ M_{\odot}$

(Lanzoni et al. 2007)

• X-ray and radio observations: $M_{BH} < 600\ M_\odot$

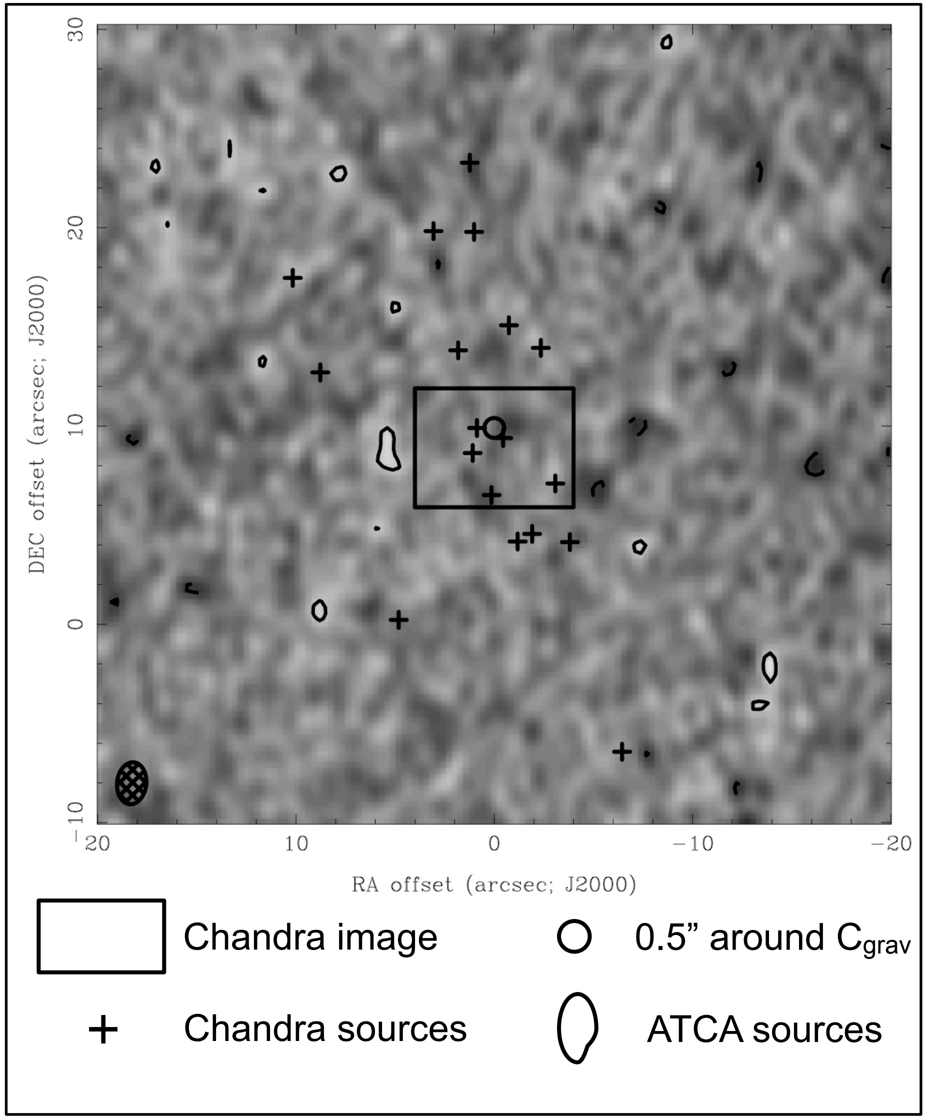
NGC 6388

Chandra



source 12: $L_X \simeq 8.3 \times 10^{32}$ erg/s

ATCA

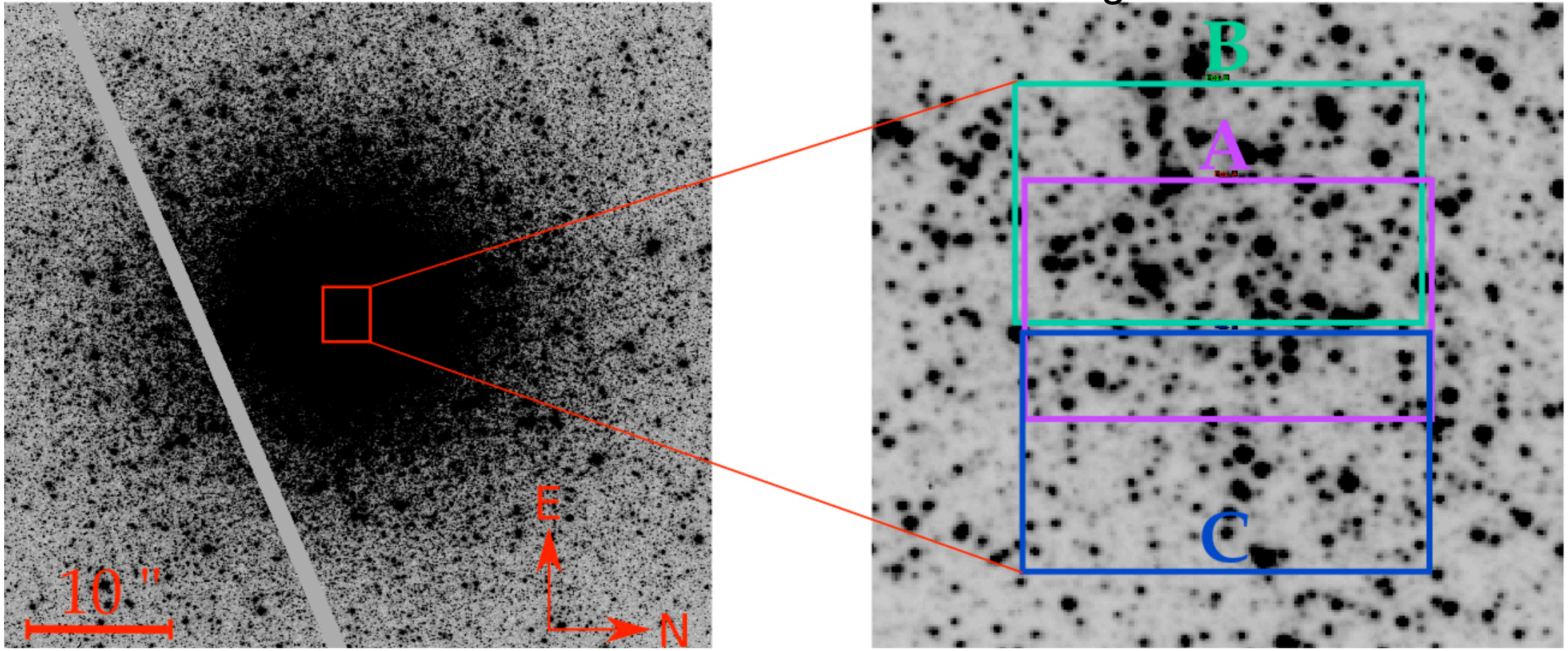


NO radio sources correspond to C_{grav} or X-ray sources

(Nucita et al. 2008; Cseh et al. 2010; Bozzo et al. 2011)

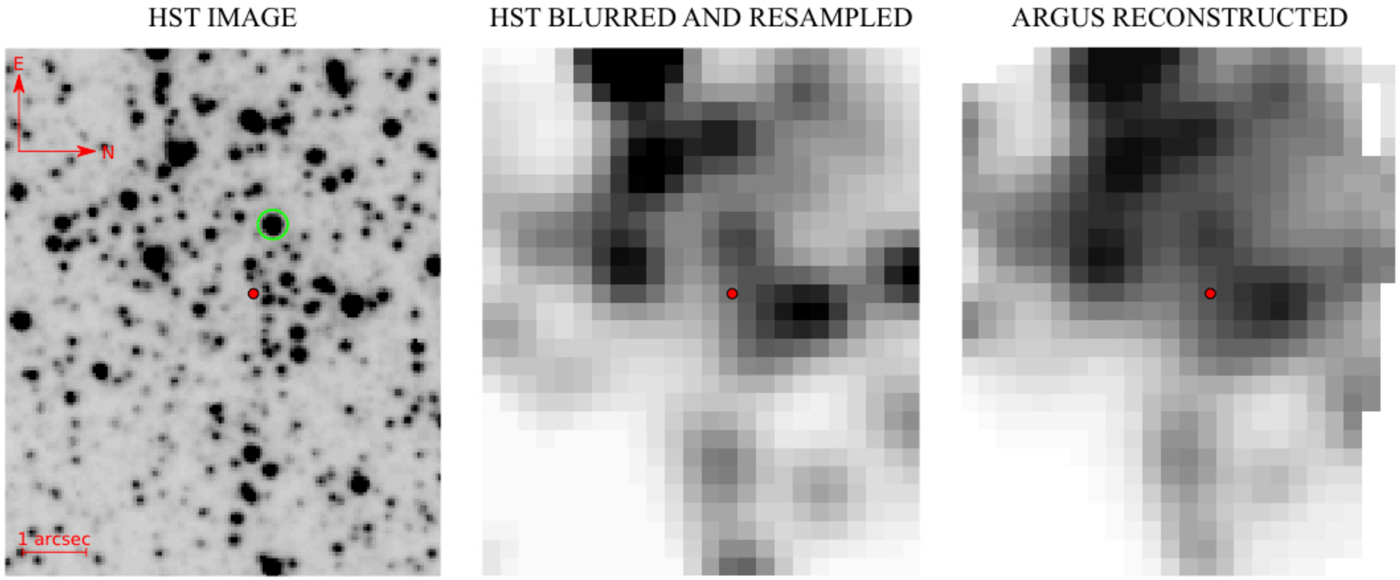
• Integrated light spectroscopy (Lützgendorf et al. 2011 – L11)

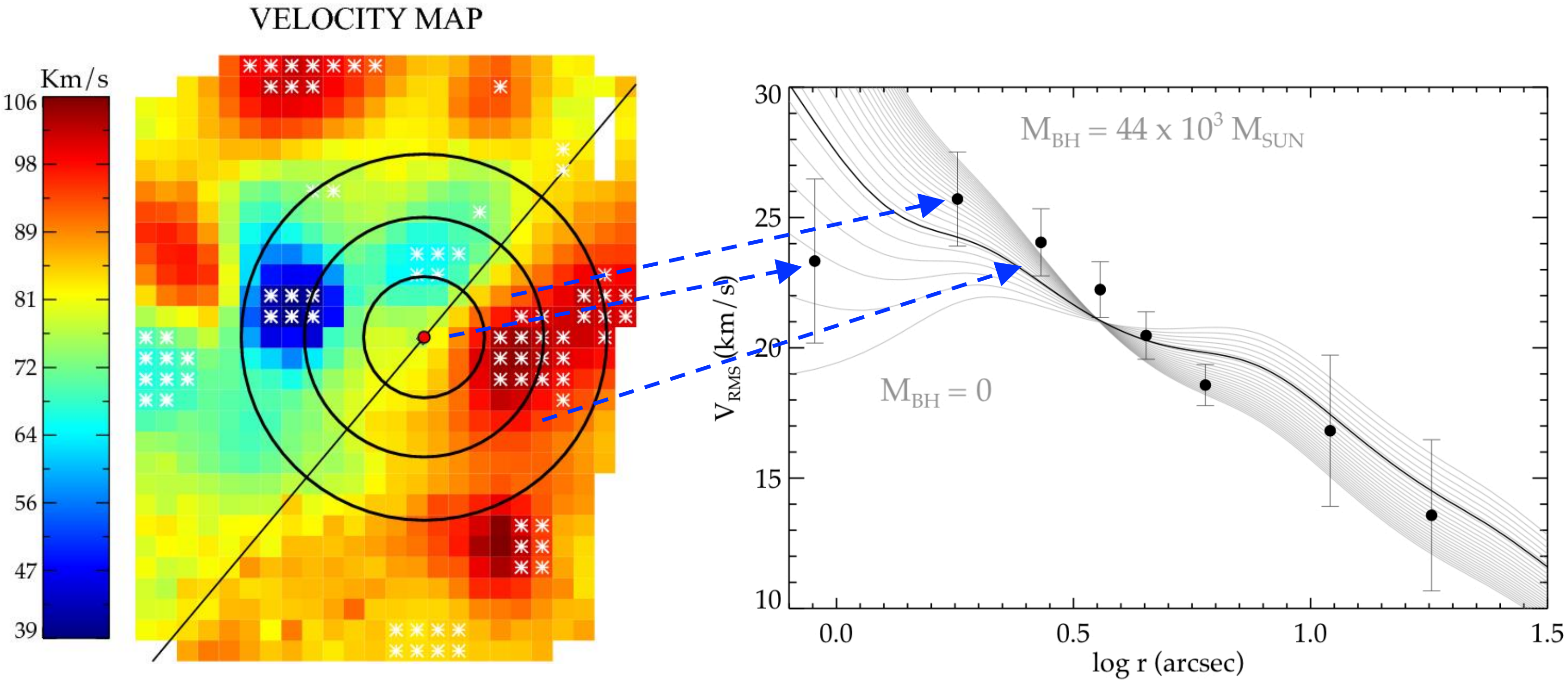
VLT/ARGUS: NON-AO assisted IFU → pixel size: 0.3″ (but seeing limited)



HST image + 3 ARGUS fields

- **Integrated light spectroscopy** (Lützgendorf et al. 2011 – L11)

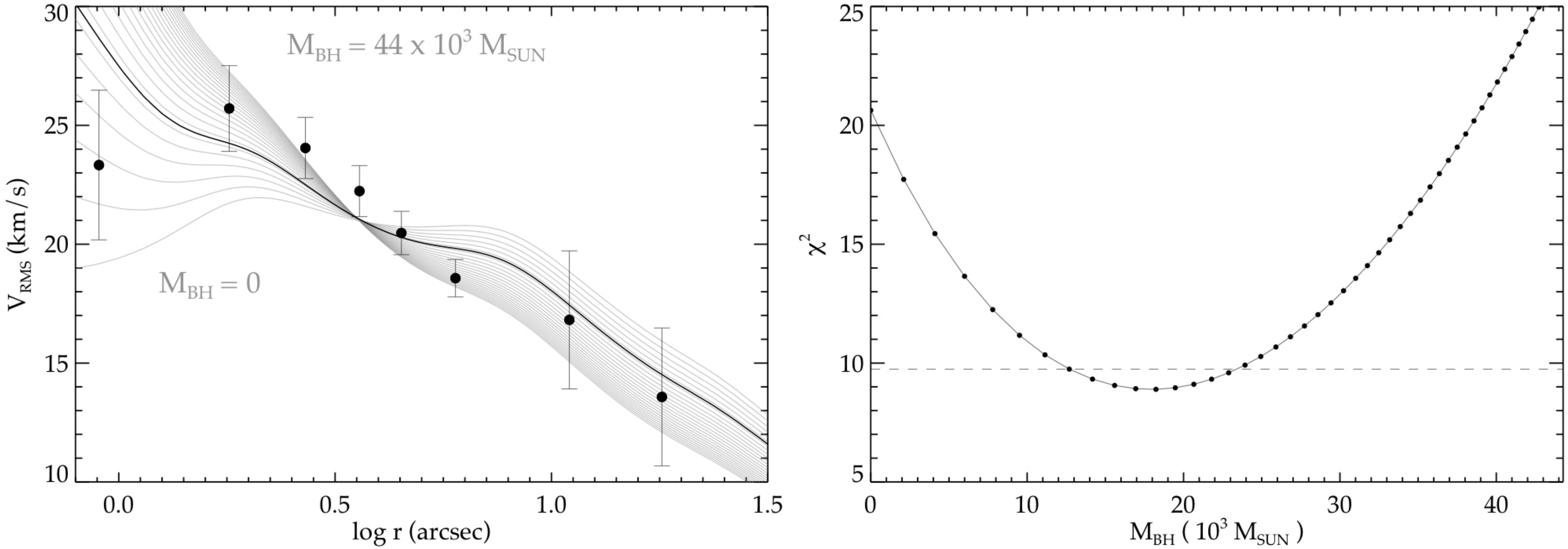




Lützgendorf et al. 2011 (L11):

- **cuspy velocity dispersion profile, σ_0~23-25 km/s**
  (from the line broadening of integrated-light spectra)

- **IMBH of ~1.7 10^4 $M_\odot$**
  (from spherical Jeans models with constant M/L)



- **Individual star spectroscopy** (Lanzoni et al. 2013)

- **ESO-VLT/SINFONI:** AO-assisted IFU spectrograph, R=4000, K-band grating (1.95-2.45 μm), spatial resolution=0.1”, FoV=3.2”x3.2”

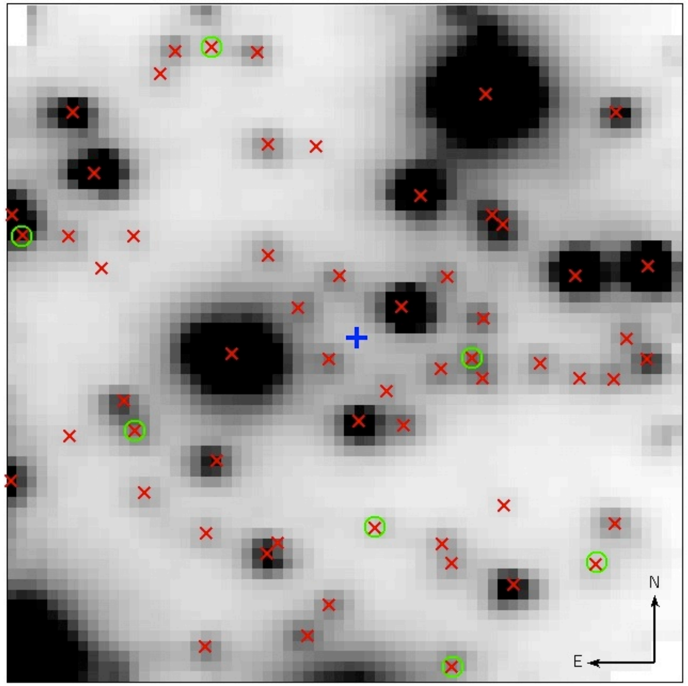
  → **central σ(r)**

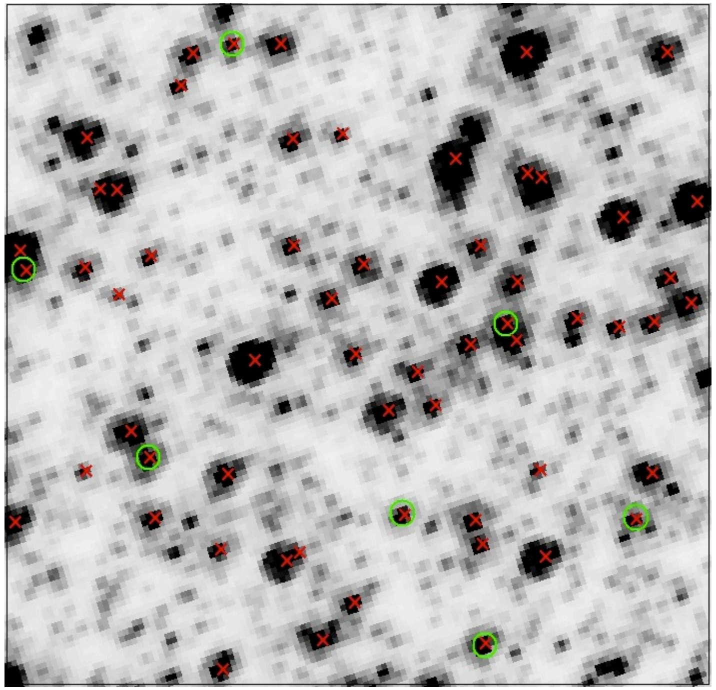
- **ESO-VLT/FLAMES-GIRAFFE in MEDUSA mode:** multi-object spectrograph (132 fibres), high spectral resolution (R>10,000), optical (Ca triplet, Fe, ..), FoV of 25’ in diameter

  → **external σ(r)**

SINFONI (central) sample

- cross-correlation between SINFONI and HST/HRC
- spectrum extracted from central spaxel only
- excluded low-quality spectra & blended sources


SINFONI

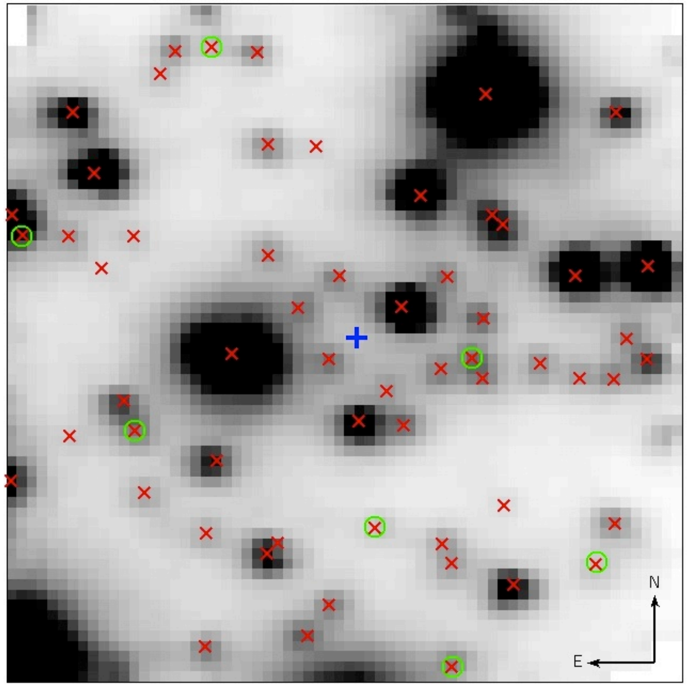

HST/ACS-HRC

SINFONI (central) sample

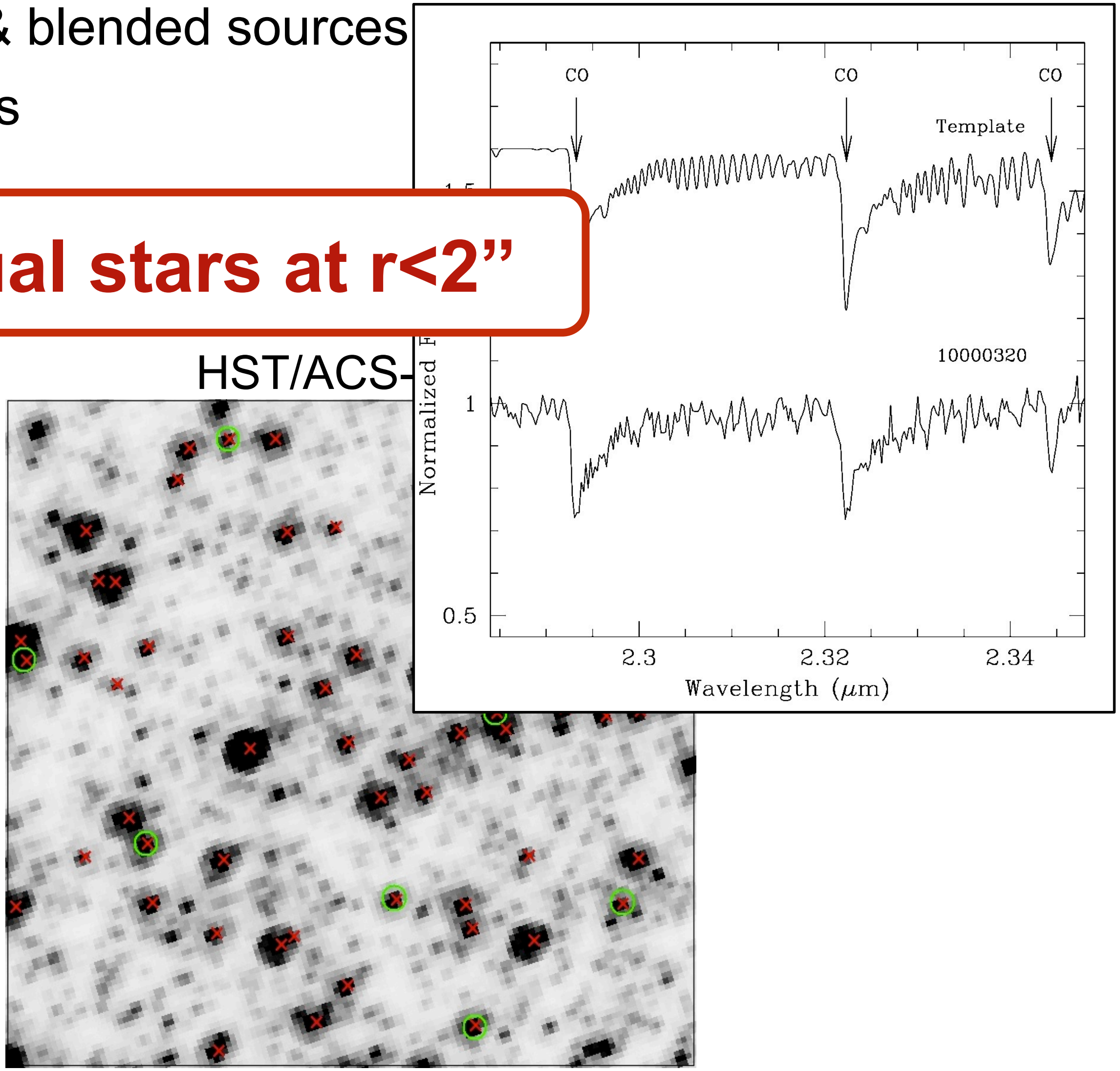
- cross-correlation between SINFONI and HST/HRC
- spectrum extracted from central spaxel only
- excluded low-quality spectra & blended sources
- V_r mainly from CO band-heads

→ V_r for 52 individual stars at r<2”

SINFONI



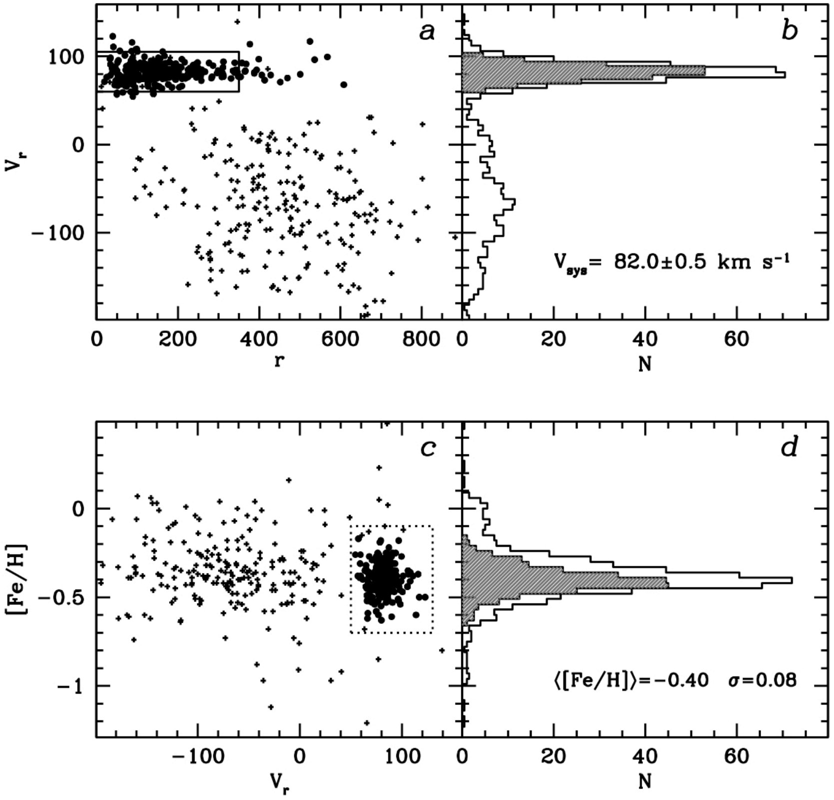
HST/ACS-



FLAMES (external) sample

Programs: 381.D-0329(B), PI: Lanzoni
073.D-0211; PI: Carretta
073.D-0760; PI: Catelan

V_r & [Fe/H] for 508 stars



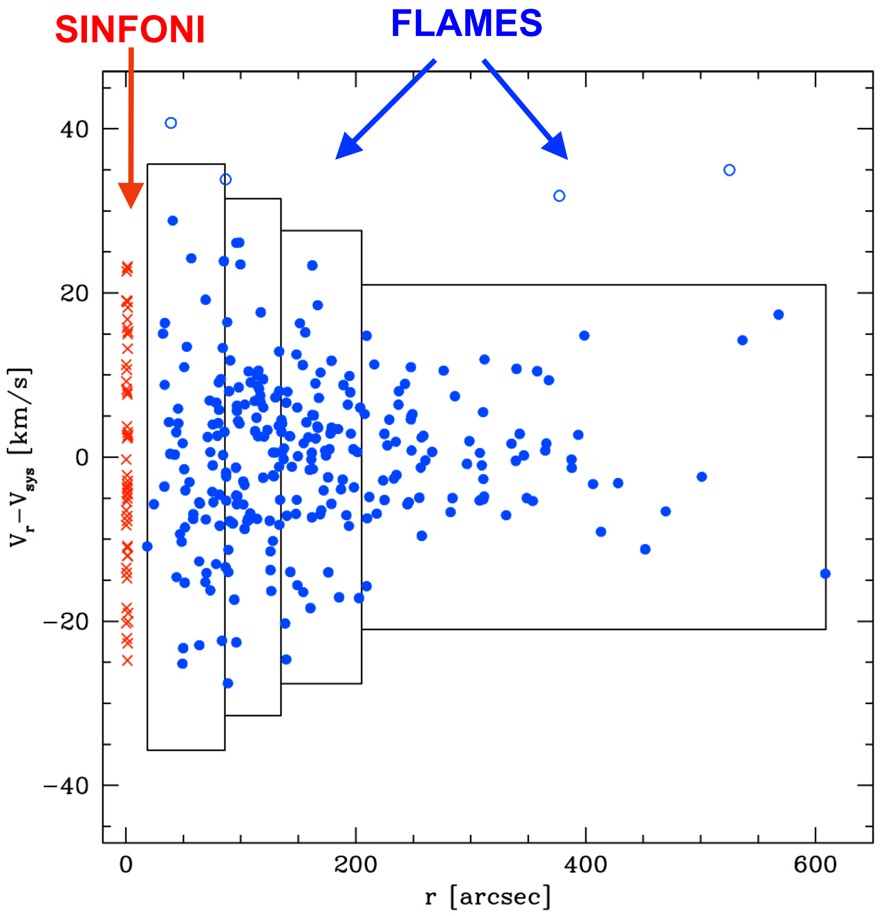
276 cluster members

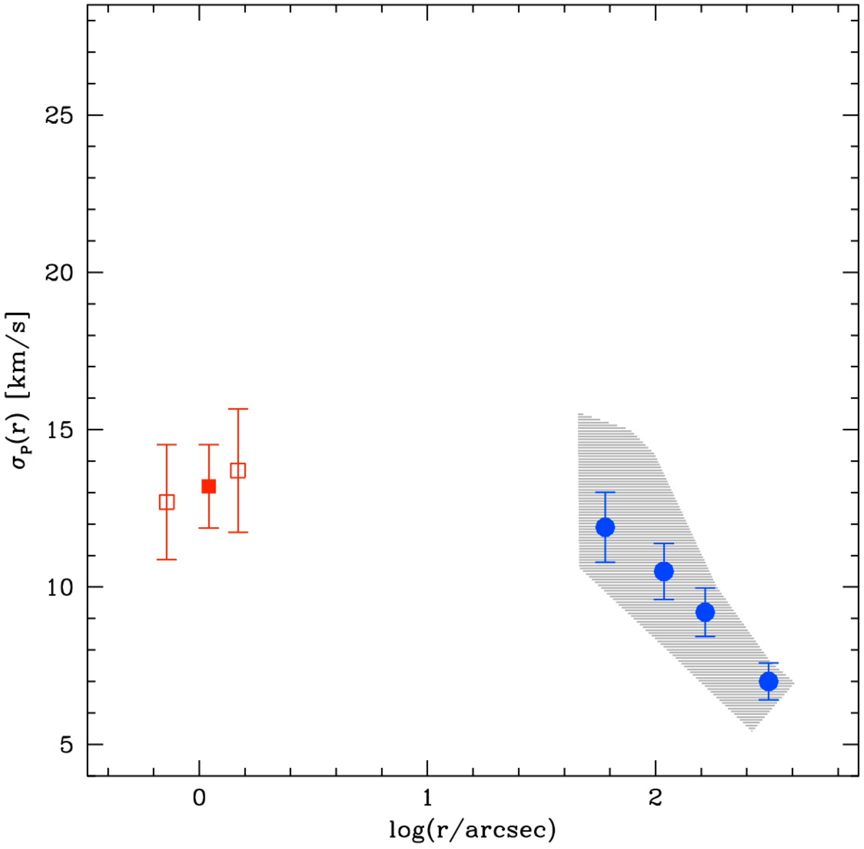
V_r for 276 individual stars at 18”<r<600”

Velocity dispersion profile

$\sigma(r)$ from the dispersion of V_r in radial bins of ≥ 50 stars

(following the Maximum Likelihood method of Walker et al. 2006)





Velocity dispersion profile

$\sigma(r)$ from individual V_r

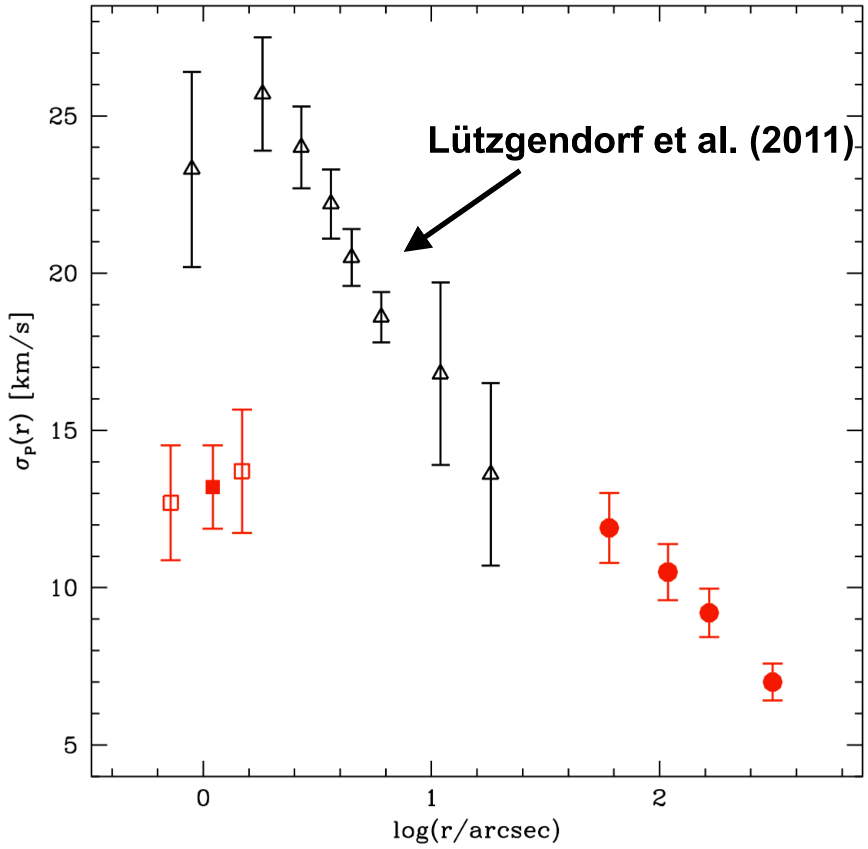
($\sigma_0 \sim$ 13-14 km/s)

incompatible with

$\sigma(r)$ from the line broadening of integrated-light spectra

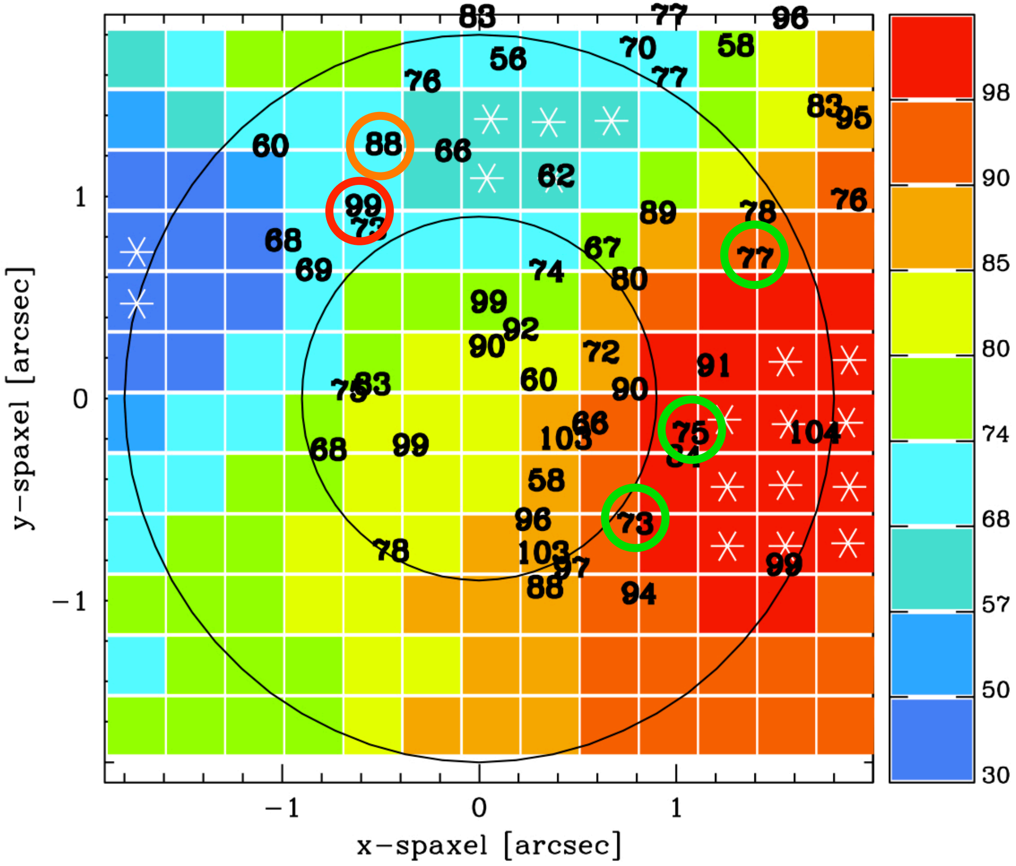
($\sigma_0 \sim$ 23-25 km/s)

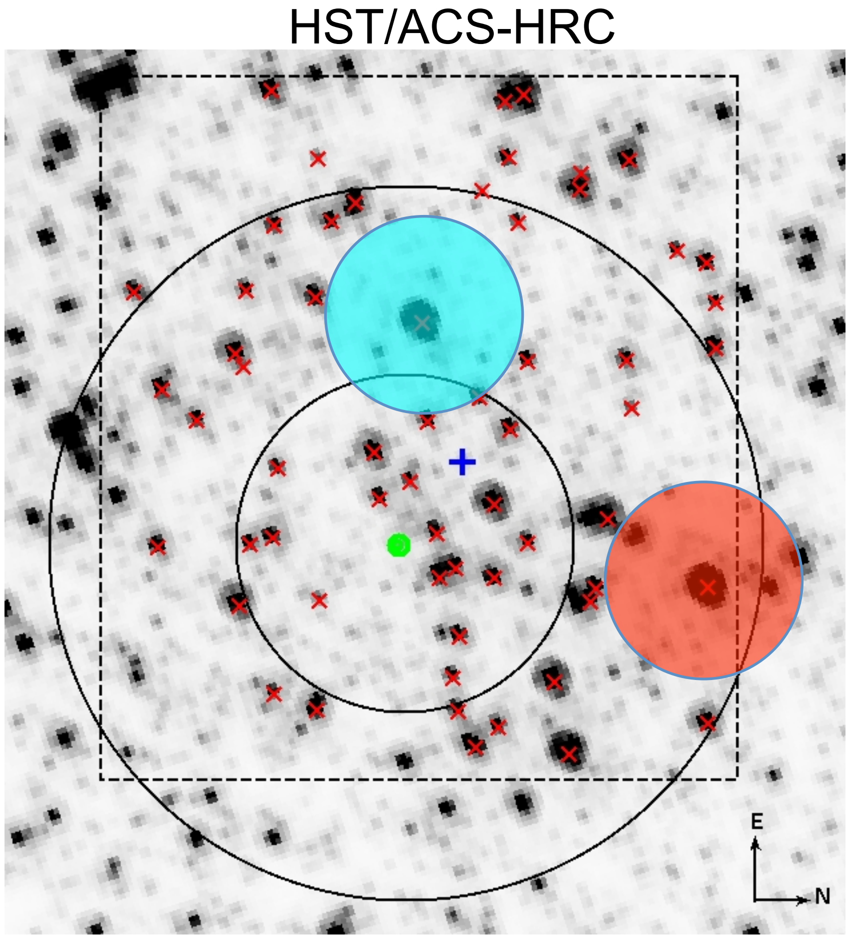
WHY ?



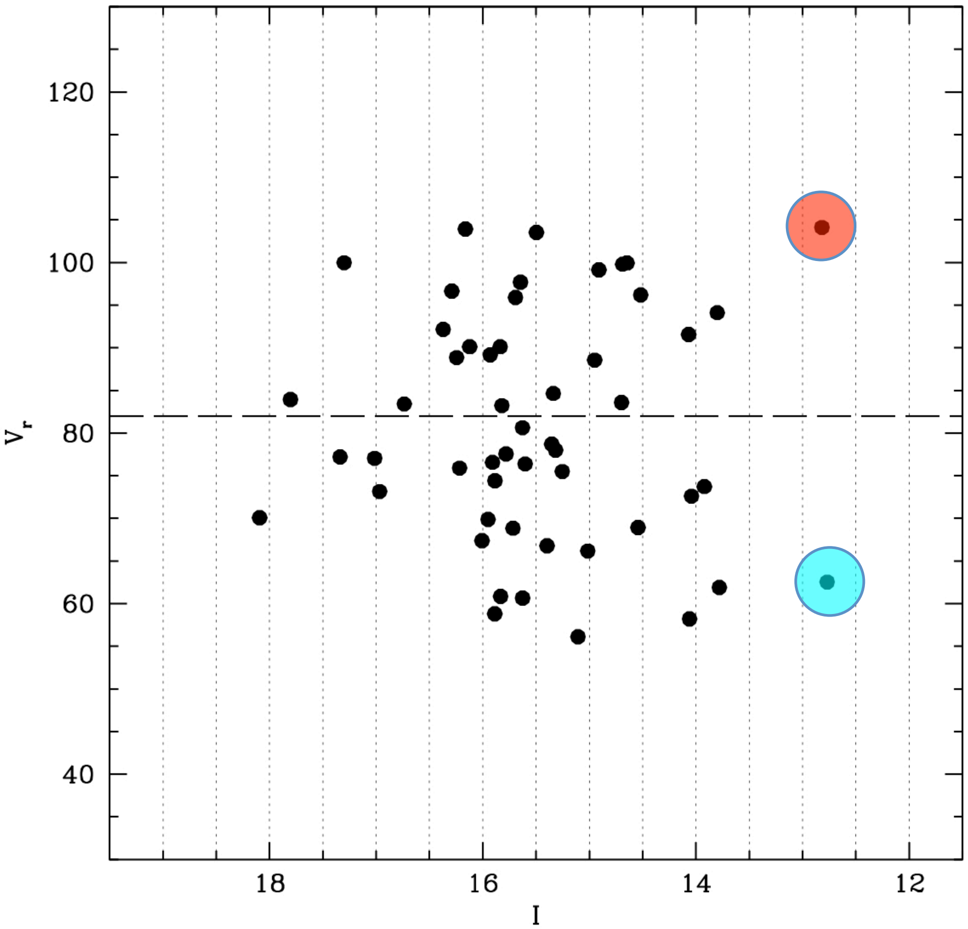
Insufficient shot-noise correction?

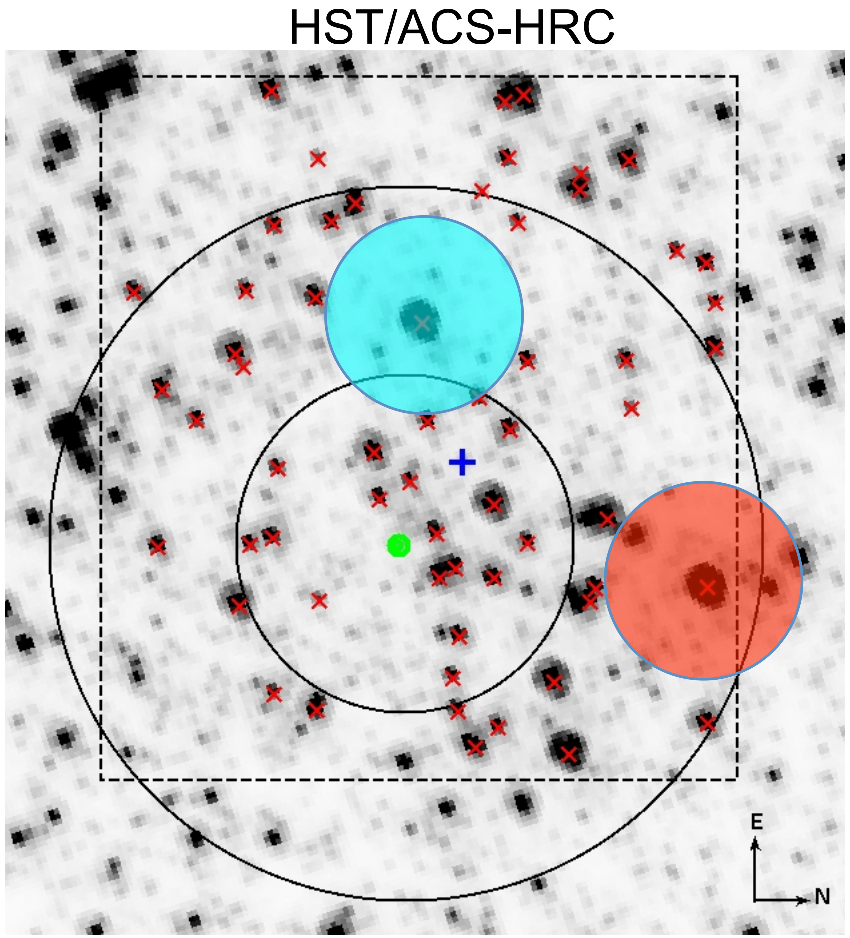
→ **colours**: radial velocity map of L11
→ **white asterisks:** spaxels excluded by L11
for shot noise correction
→ **black values:** our V_r measurements





Insufficient shot-noise correction?

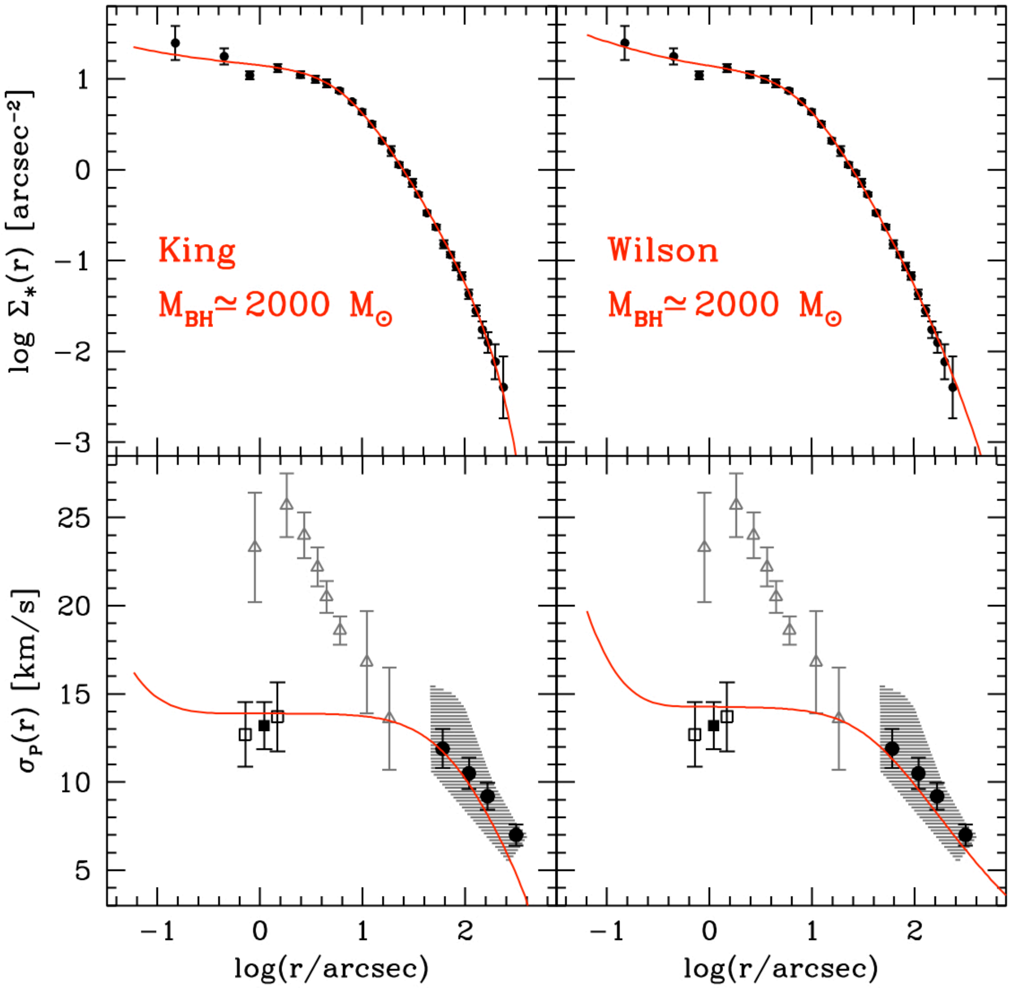




Comparison with models: IMBH mass

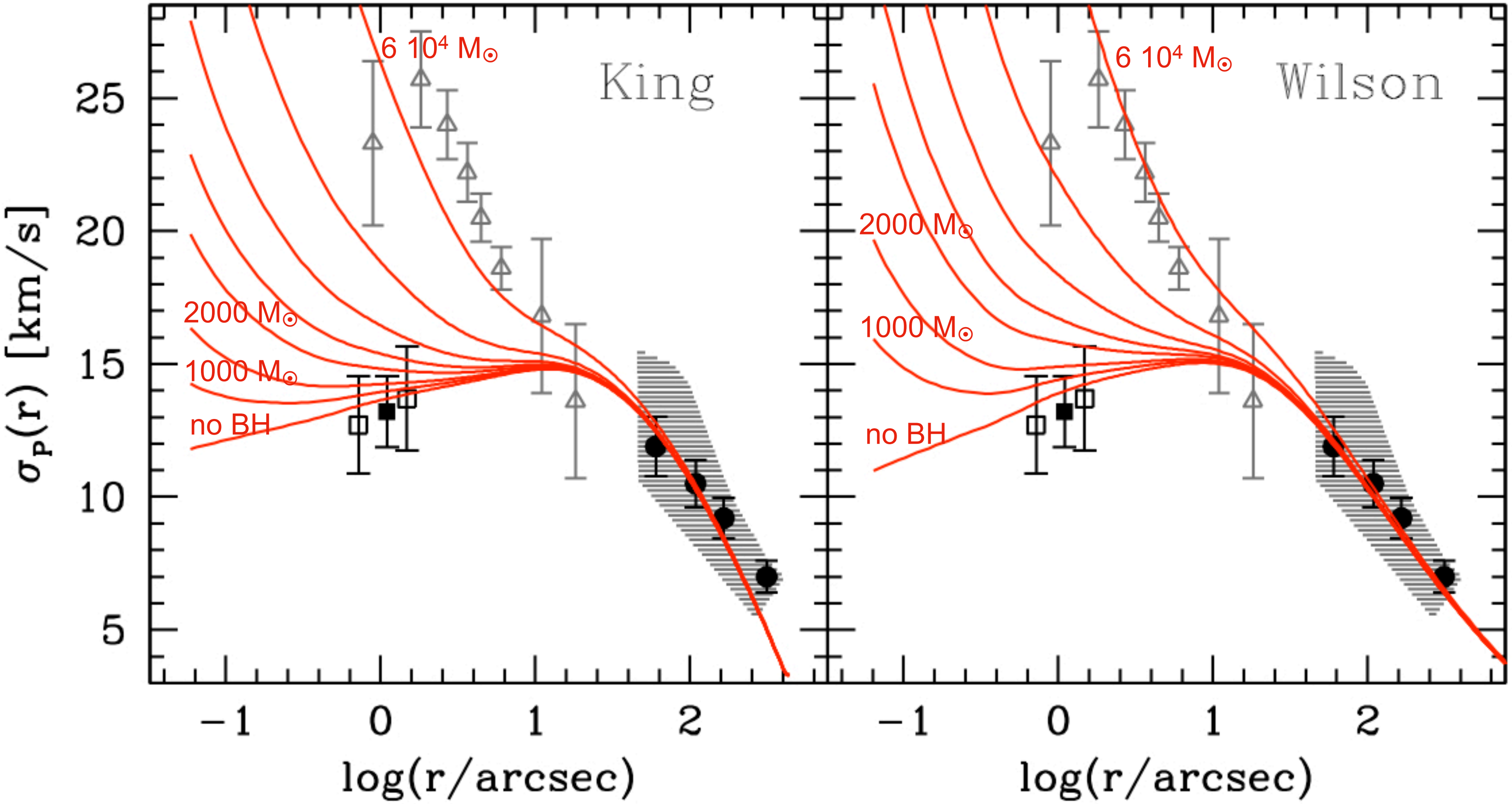
(1) self-consistent, isotropic, spherical **King & Wilson models** with **central BH**
(included via the phase-space distribution function of Bahcall & Wolf 1976; Miocchi 07)

M_{BH} ~ 2000 $M_\odot$



Comparison with models: IMBH mass

(2) solution of the spherical **Jeans equation** with density given by the observed one plus a variable central point mass (as in L11)



$M_{BH} \leq 2000\ M_\odot$

General conclusion

$\sigma(r)$ from individual V_r is incompatible with

$\sigma(r)$ from the line broadening of integrated-light spectra

which is the correct way to measure $\sigma(r)$ in Galactic GCs?

needed (& urged!) a detailed comparison between $\sigma(r)$ derived from

- individual V_r measurements
- integrated-light spectroscopy
- proper motions

Conclusion about IMBHs

no solid & convincing detection yet

... let’s keep searching!

(both with observationally & theoretically)