Searching for intermediate-mass black holes in Galactic globular clusters

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✦ 5-year project

✦ *Advanced Research Grant* funded by the European Research Council (ERC)

✦ PI: Francesco R. Ferraro (Dip. of Physics & Astronomy – Bologna University)

✦ AIM: **to understand the complex interplay between dynamics & stellar evolution**

✦ HOW: using **globular clusters** as cosmic laboratories and

Blue Straggler Stars
Millisecond Pulsars
Intermediate-mass Black Holes

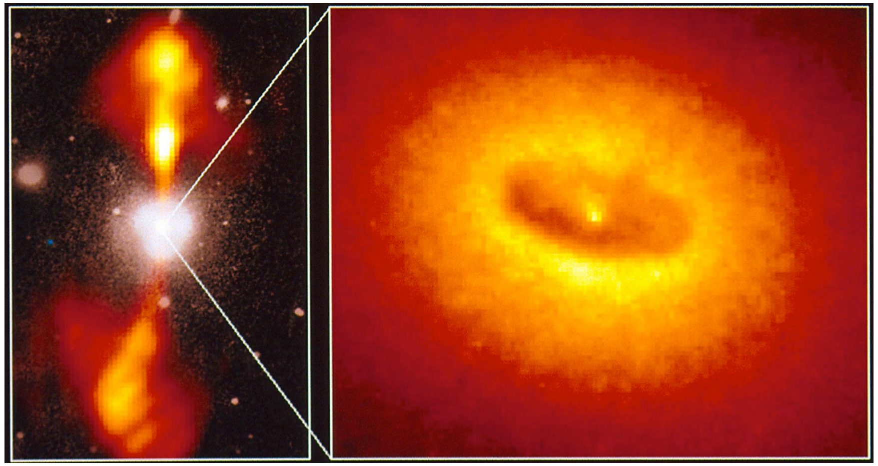
} as probe-particles

You can download this presentation at:
http://www.cosmic-lab.eu/Cosmic-Lab/Presentations.html

Intermediate-mass Black Holes (IMBHs)

stellar-mass ($\leq$ 20 $M_{\odot}$)

super-massive (10^6 – 10^9 $M_{\odot}$)



IMBHs

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

IMBHs: why interesting?

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

2. **could be the seeds SMBHs**

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 crucial role in the dynamical evolution & stability of GCs**
   (affecting the density and velocity dispersion profiles, the degree of 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" (M_{BH} – M_{gal}) to GC scales

2. Several plausible formation scenarios (Giersz's talk):

- evolution of first stars **(Pop III)** with masses > 250 $M_\odot$
  (e.g., Fryer et al. 2001; Madau & Rees 2001)
- repeated **merging of stellar-mass BHs**
  (Miller & Hamilton 2002)
- accretion of interstellar **gas onto stellar-mass BHs**
  (Kawakatu & Umemura 2005": Leigh et a. 2013)
- (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; Gurkan et al. 2004; Freitag +07)
- new MOCCA scenario

IMBHs: several fingerprints in GCs predicted

(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; Vesperini & Trenti 2010; Noyola & Baumgardt 2011; Umbreit & Rasio 2013; ...)

1) shallow density cusp at the very centre

2) steep inner cusp in the velocity dispersion profile

4) a few stars accelerated to very high-velocities (even v ~ 100 km/s)

3) universal, large core to half-mass radii ratios (r_c/r_h >0.1)

5) quenching of mass segregation

6) X-ray and radio emission

IMBHs:

- ✦ have deep implications in many fields of the Astrophysics and Physics research
- ✦ are expected to exist (especially in GCs)
- ✦ several predicted fingerprints

... however NO solid detection yet!

Why?

- challenging observations (sub-arcsec BH sphere of influence)
- uncertainties on expected X-ray and radio emission
- controversial theoretical predictions (e.g., density cusp → Vesperini & Trenti 2010)
- controversial observational results...

Many suggestions of IMBHs (... or central mass concentration) in GCs:

(Gebhardt+2005; Miller-Jones+2012; Gebhardt+1997; van der Marel+2002, 2010; Gerssen +2002;den Brok+14; Miller-Jones+2012; , Kirsten+2012, 2014; Ibata+2009; Wrobel+2011; Noyola +2008, 2010; Jalali+2011; Lutzgendorf+2011, 2012; Feldmeier+2013; Maccarone+2008; Bash +2008; Strader+2012, Miller Jones+2013; ....)

G1 in M31

M15

47 Tuc

ω Cen

M54

NGC1904

NGC 6266

NGC 1851

NGC 2808

NGC6388

NGC 5286

NGC 5694

NGC 5824

M 80

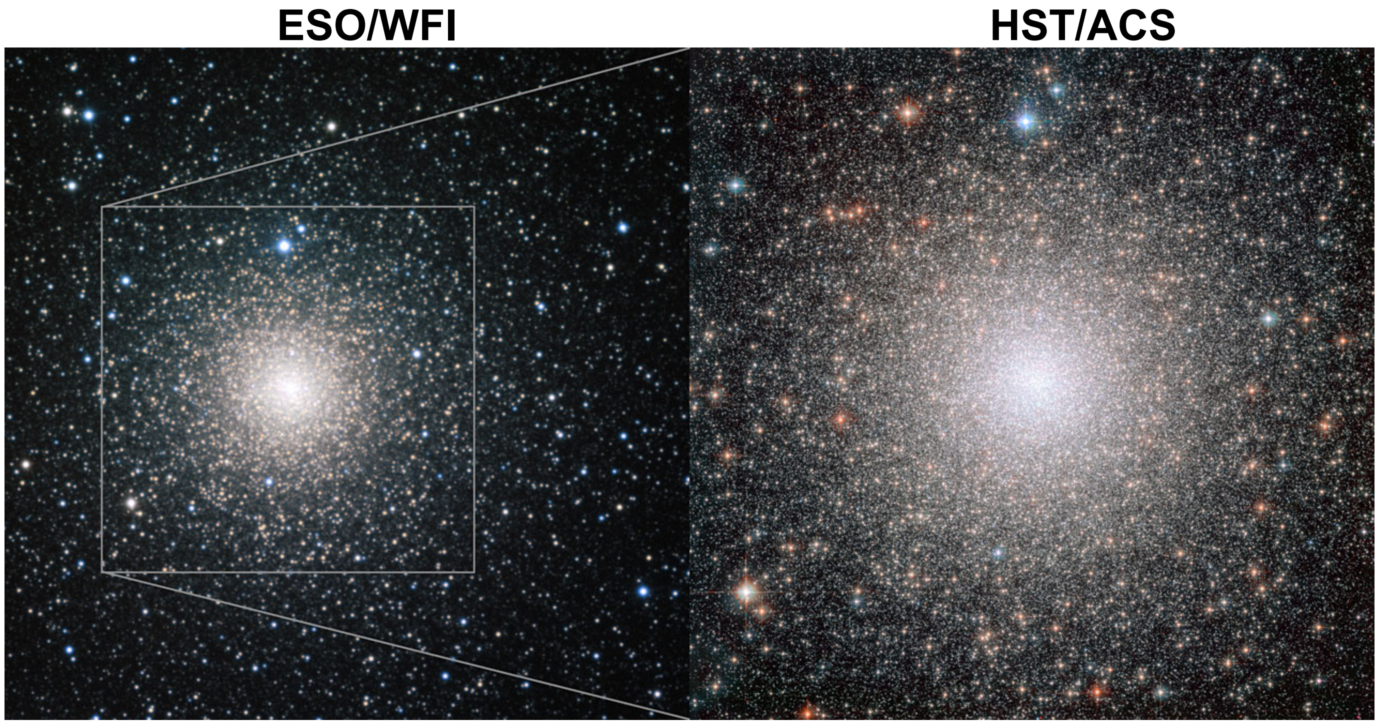
However:

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

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

→ in at least one case,
the **same** fingerprint brought to **different results**

NGC 6388

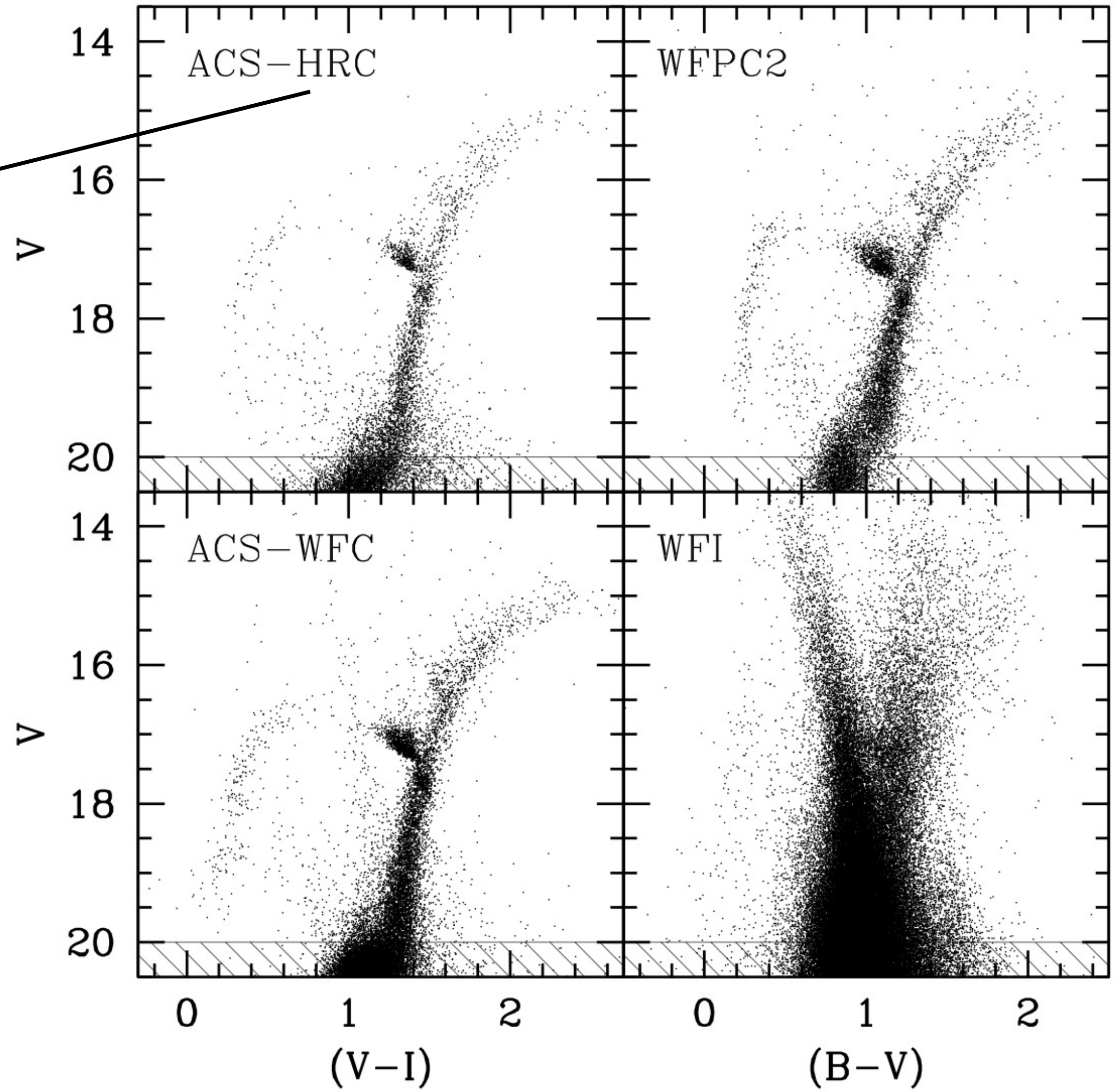


- one of the most massive Galactic GCs: $M \sim 2.6\ 10^6\ M_\odot$
- metal-rich: [Fe/H]=-0.44 (Carretta et al. 2007)
- HB with extended blue tail (Rich et al. 1997)
- multiple populations (Bellini et al. 2013)

Photometric data set

26” x 29” FoV

0.027 arcsec/pix

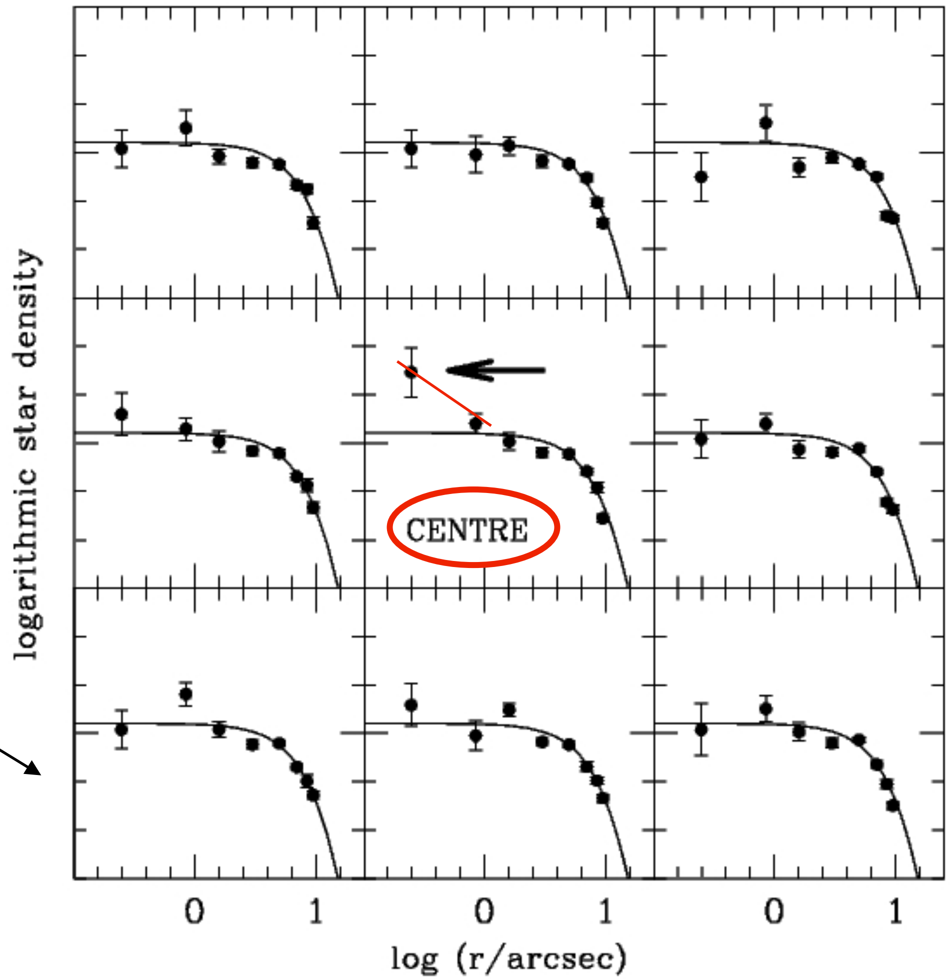


(Lanzoni et al. 2007)

Determination of the centre

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

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



Determination of the centre

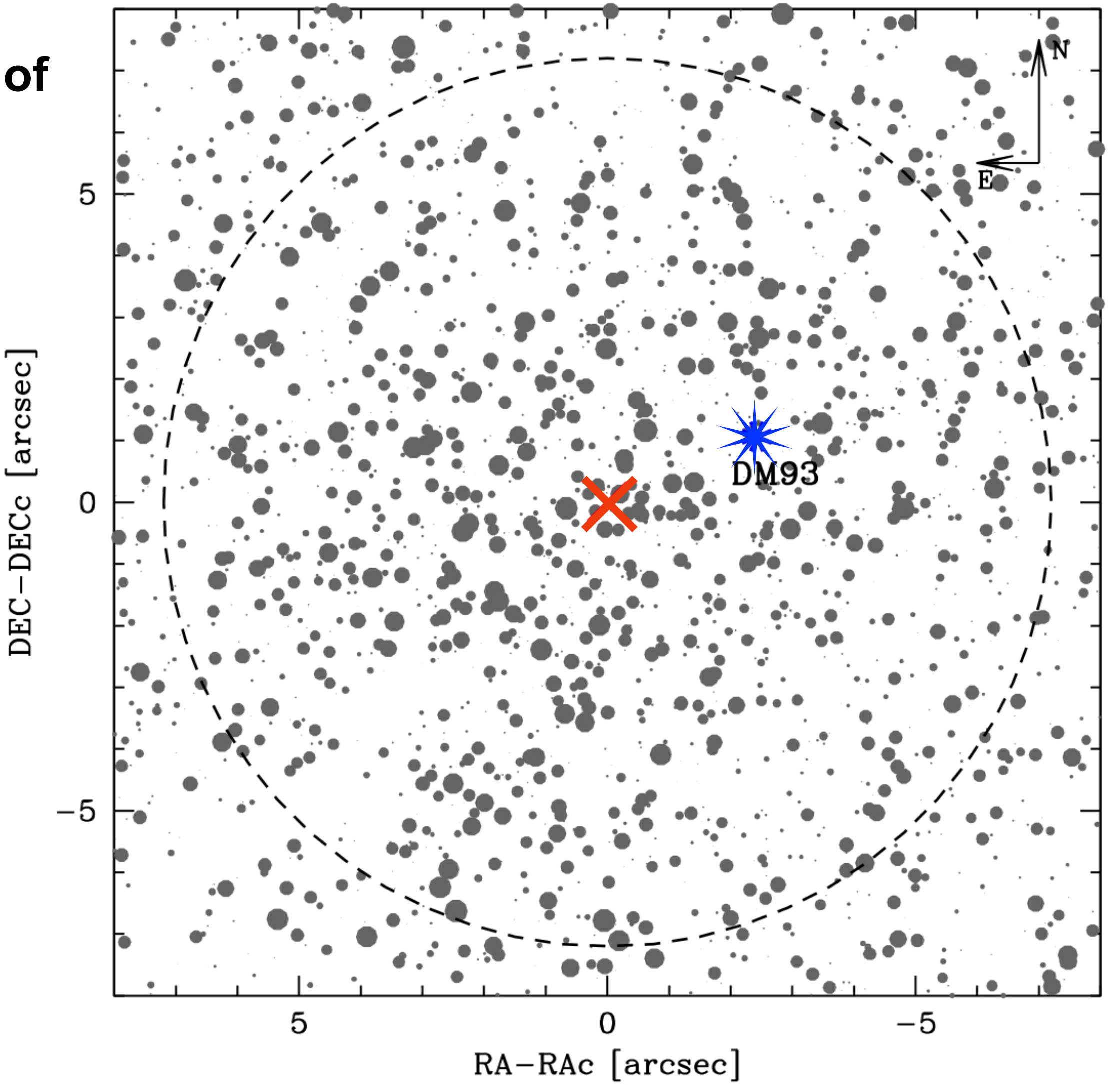
by averaging the positions of ~ 4000 stars at V<20:

α_{J2000}= 17^h 36^m 17.23^s

δ_{J2000}= -44^o 44' 7.1''

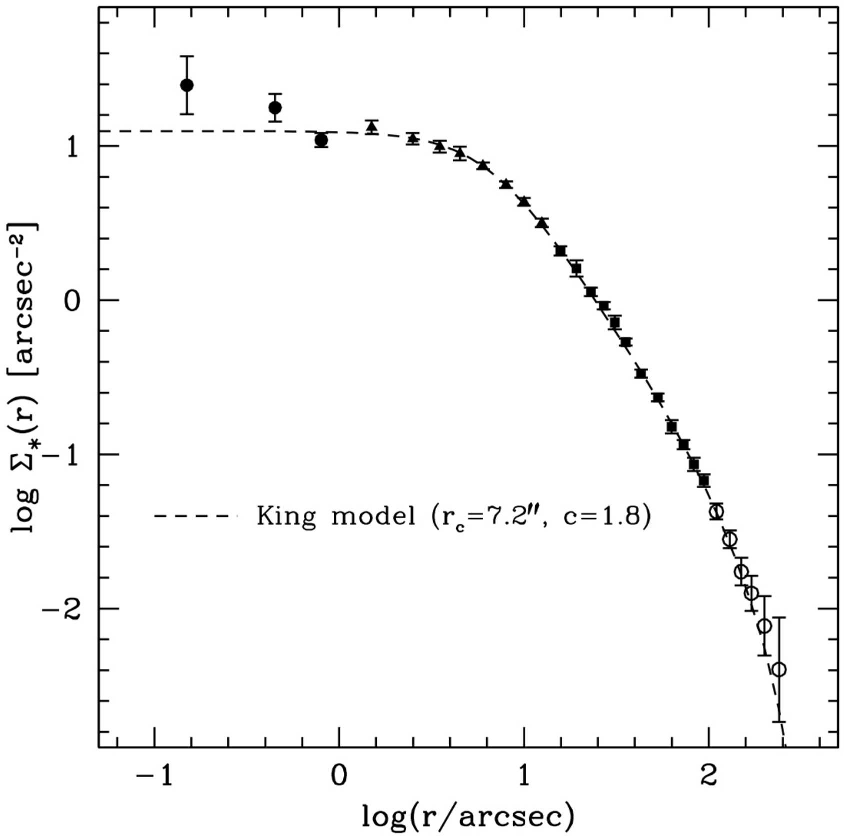
~2.6'' south-east of Djorgovski & Meylan 1993

perfect agreement with Goldsbury et al. (2010)

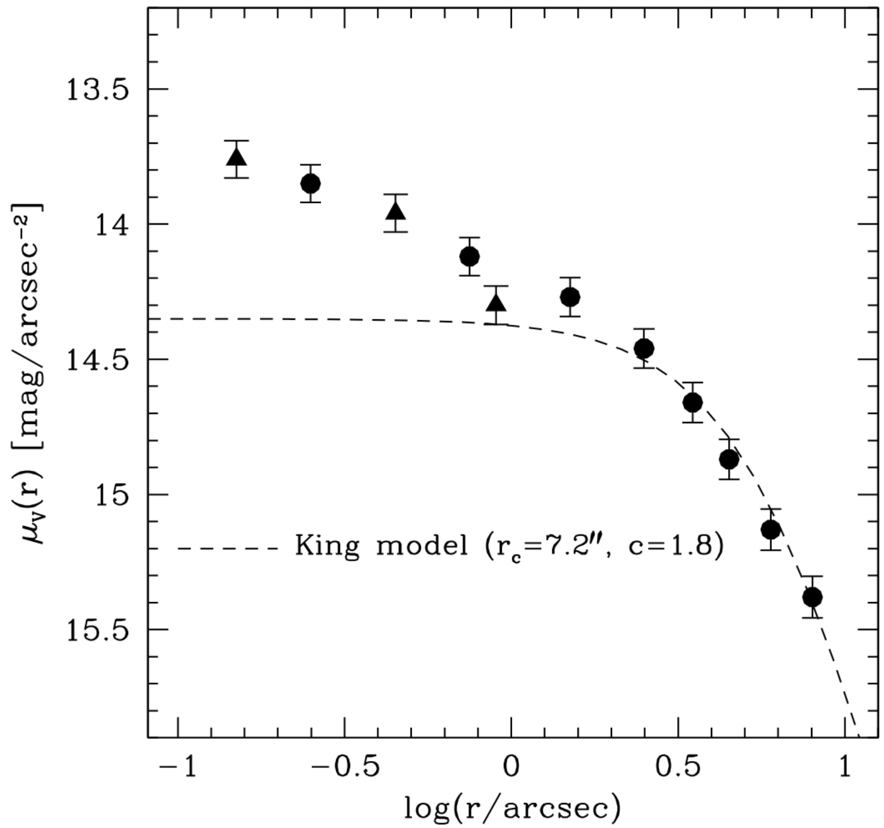


Projected density profile

(star counts in annuli)

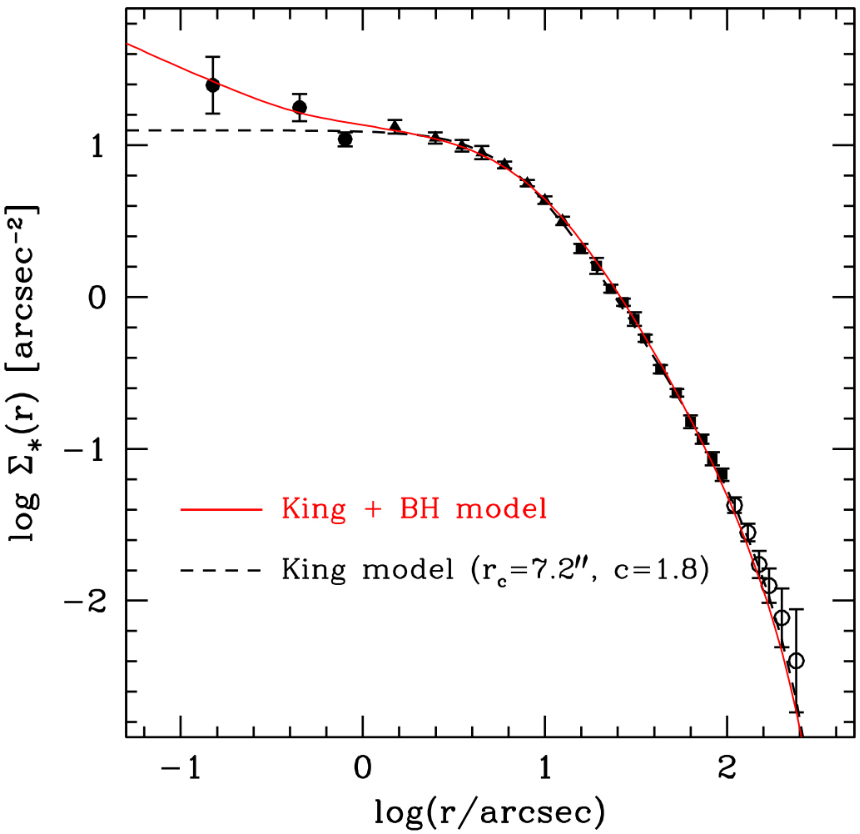


Surface brightness profile

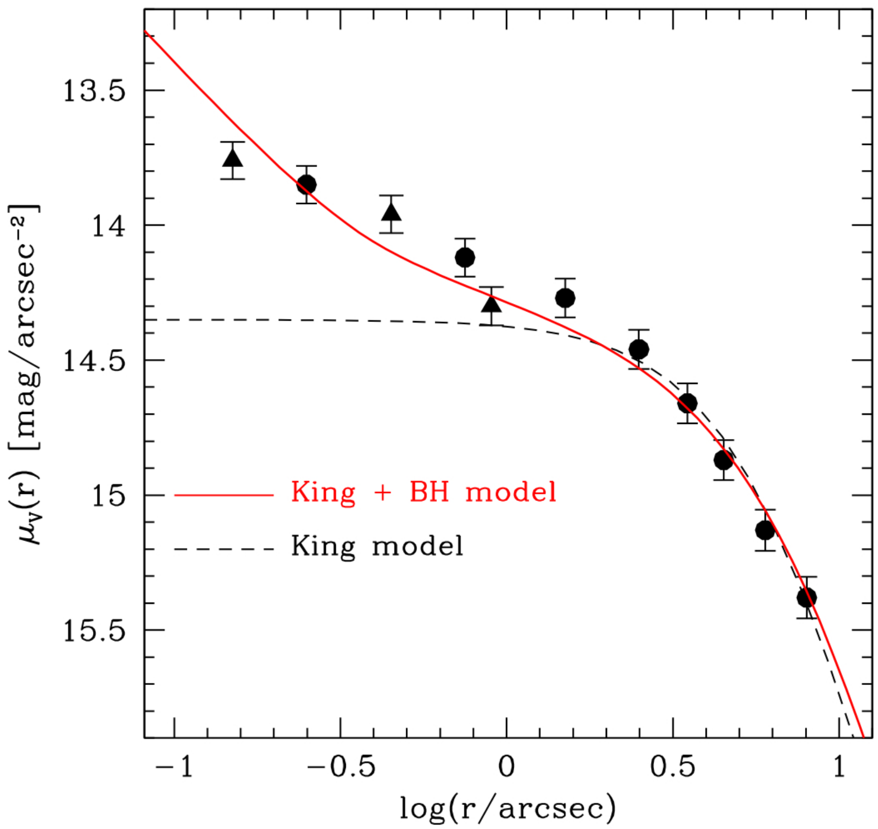


deviation from a King profile at r < 1”

projected density profile



surface brightness profile

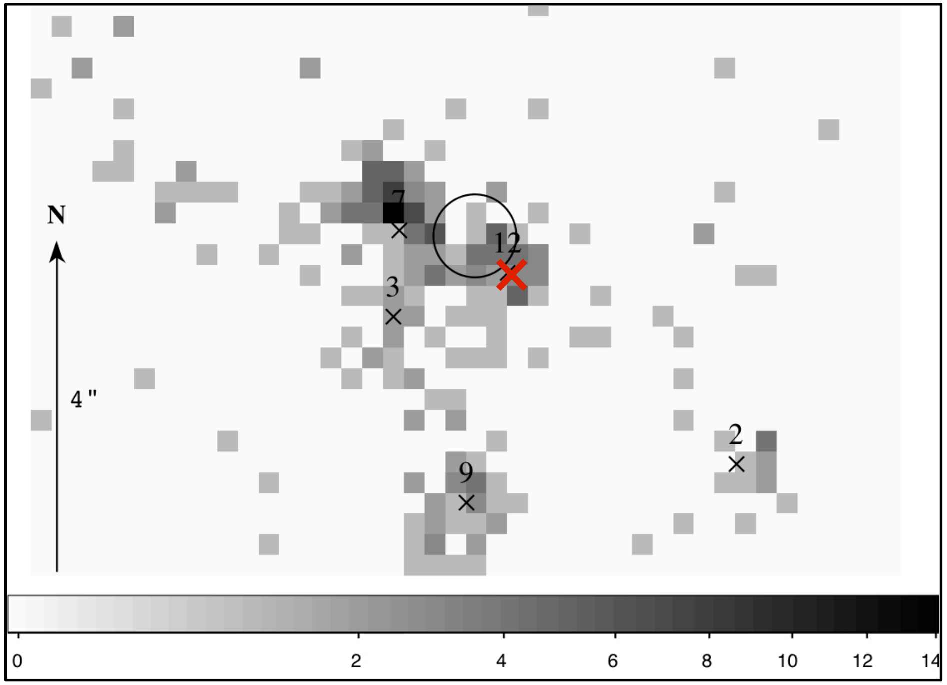


self-consistent, multi-mass, spherical, isotropic, King models with central BH (from Miocchi 2007) ➔ **$M_{BH} \sim 6\ 10^3\ M_\odot$**

(Lanzoni et al. 2007)

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

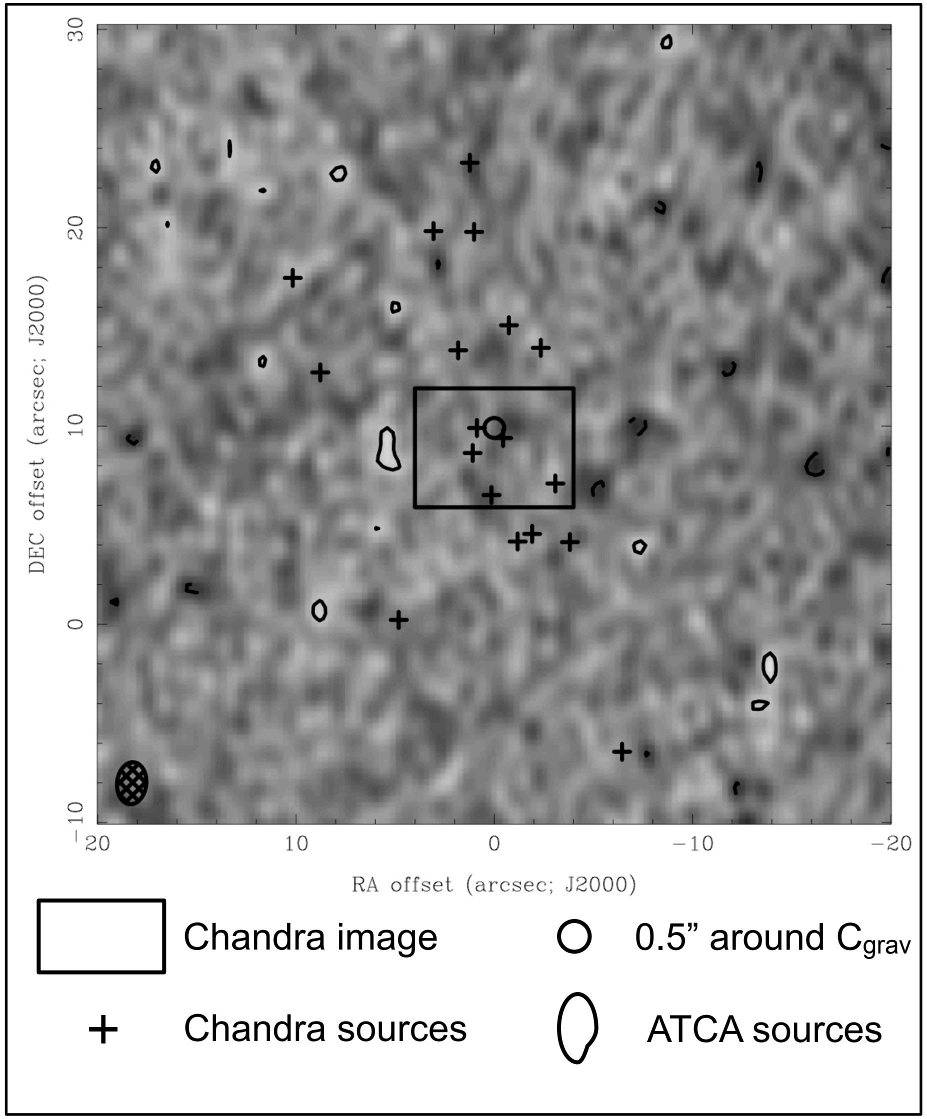
Chandra



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

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

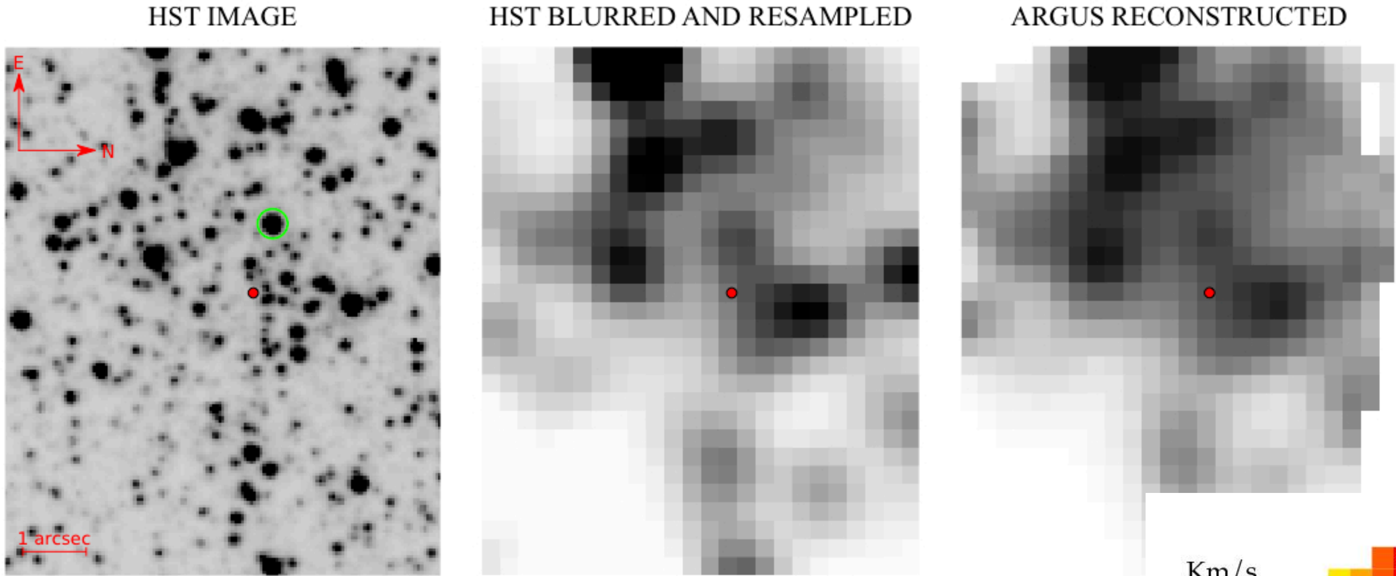
ATCA

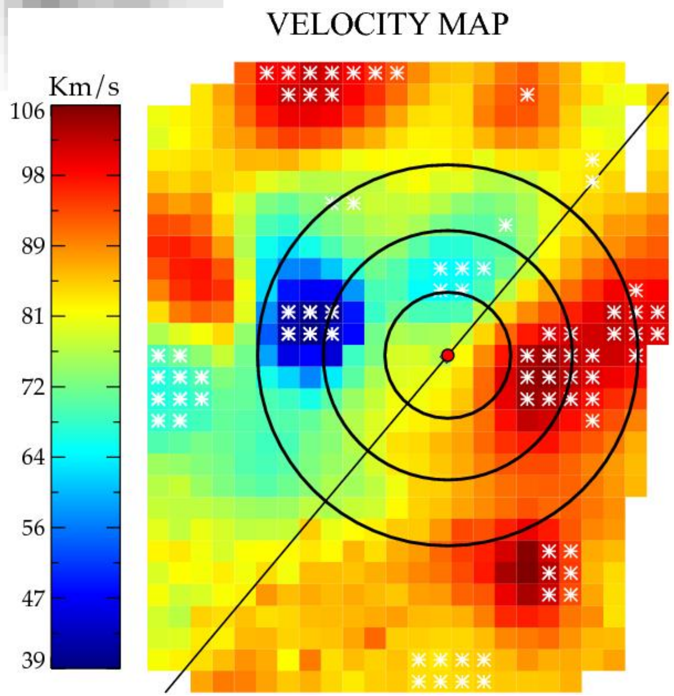


(Nucita et al. 2008, 2013; Cseh et al. 2010; Bozzo et al. 2011)

• Velocity dispersion from integrated light spectroscopy

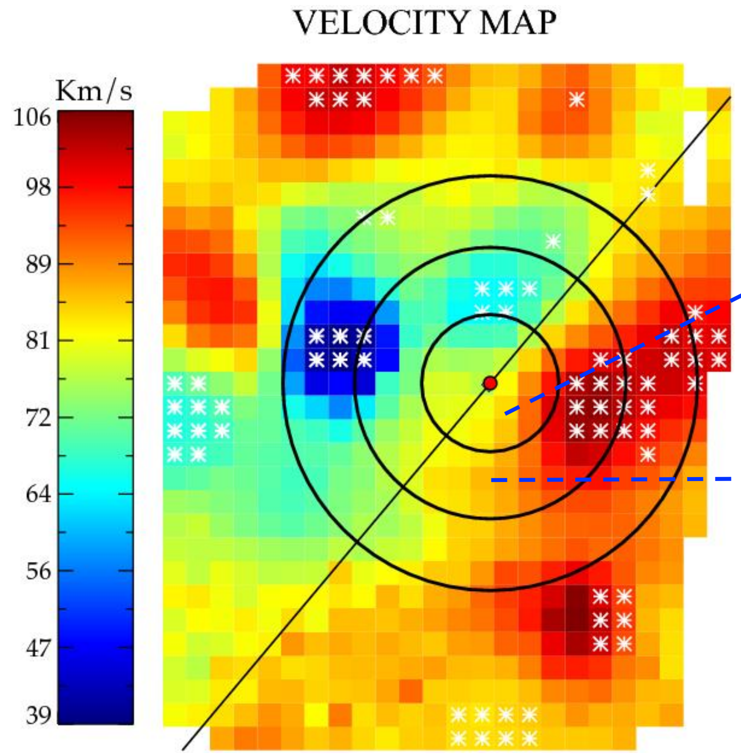
ARGUS (non-AO assisted IFU@VLT)

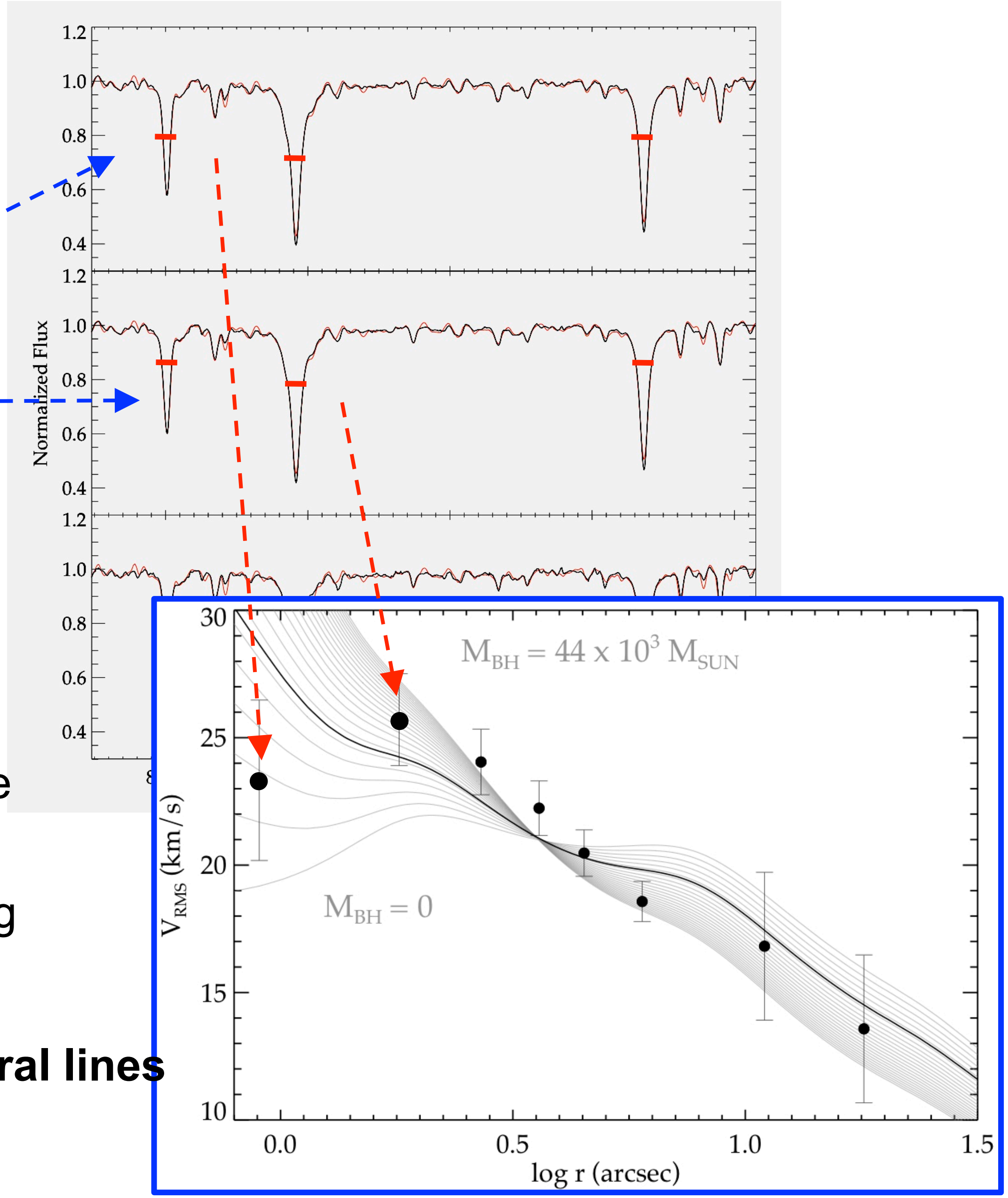




(Lützgendorf et al. 2011 – L11)

• Velocity dispersion from integrated light spectroscopy





- exclude spaxels dominated by the light of individual bright stars (white asterisks: shot noise correction)
- combine spectra from all remaining spaxels in each radial bin
- measure the **broadening of spectral lines**

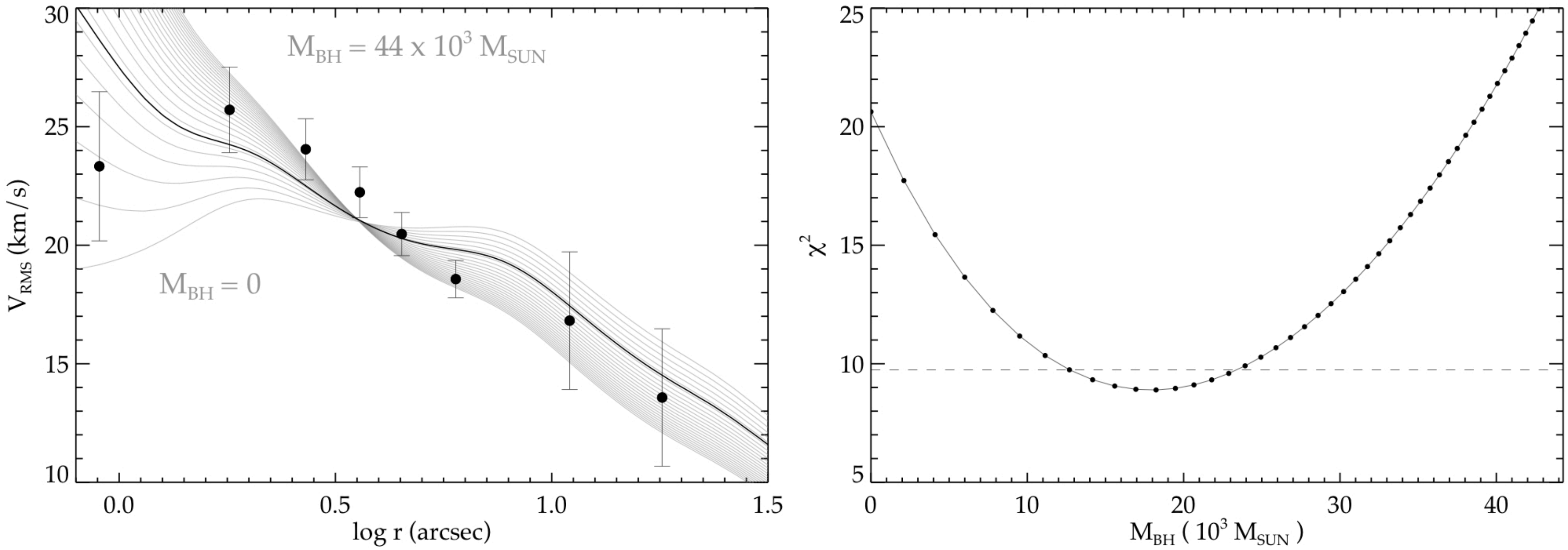
• **Velocity dispersion from integrated light spectroscopy**

• **cuspy velocity dispersion profile, σ_0~23-25 km/s**

(from the line broadening of integrated-light spectra)

• **IMBH of ~1.7 10^4 $M_\odot$**

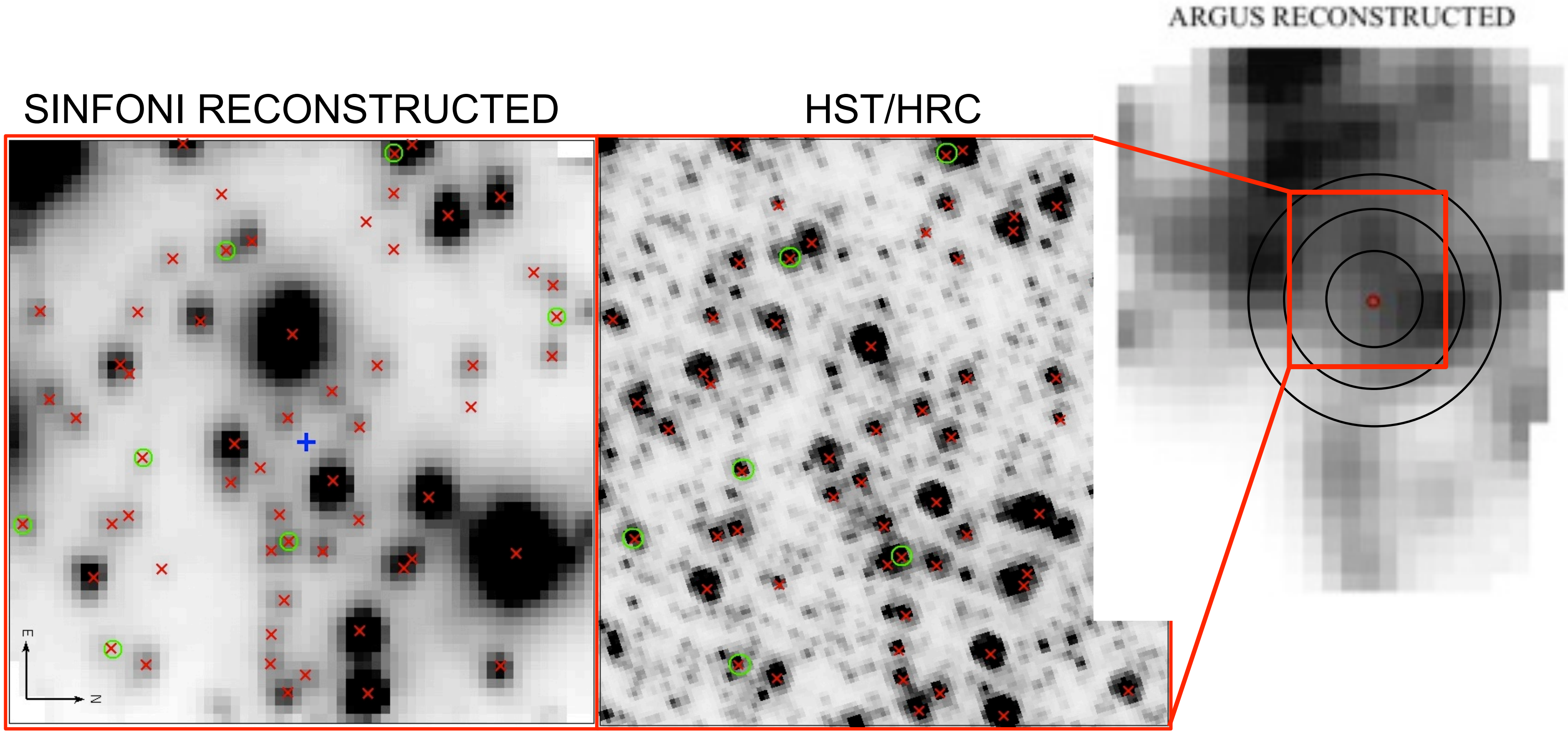
(from spherical Jeans models with constant M/L)



• Velocity dispersion from radial velocity of individual stars

SINFONI (AO assisted IFU@VLT)

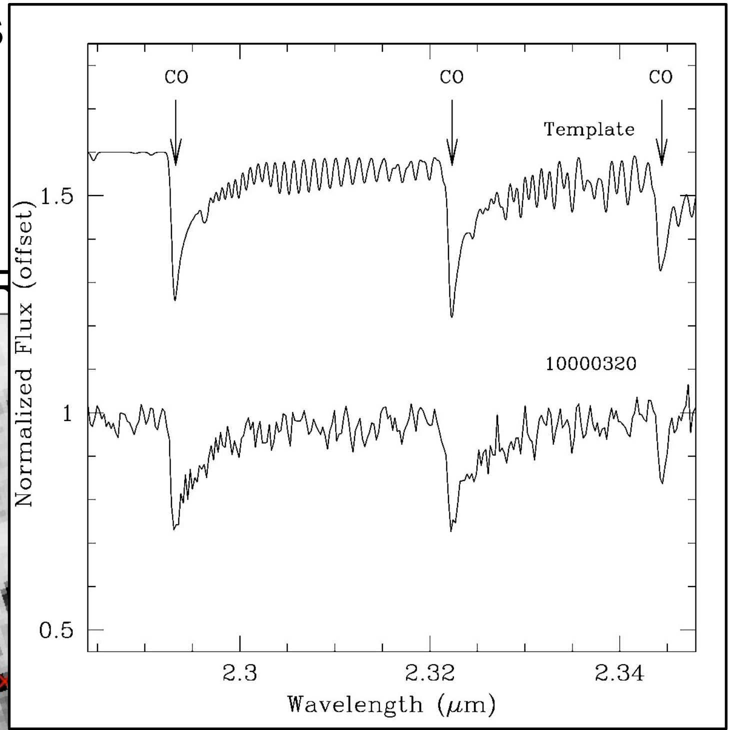
R=4000, K-band grating (1.95-2.45 μm), spatial resolution=0.1", FoV=3.2"x3.2"



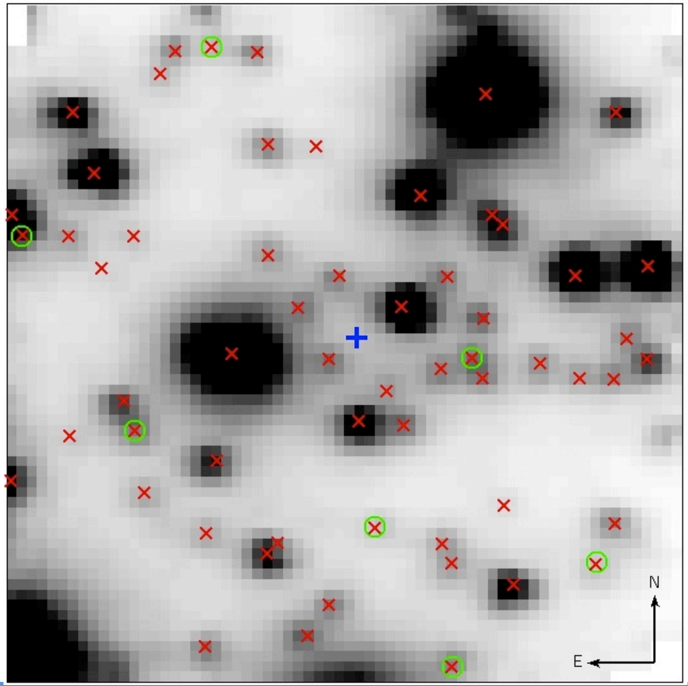
(Lanzoni et al. 2013)

SINFONI (central) sample

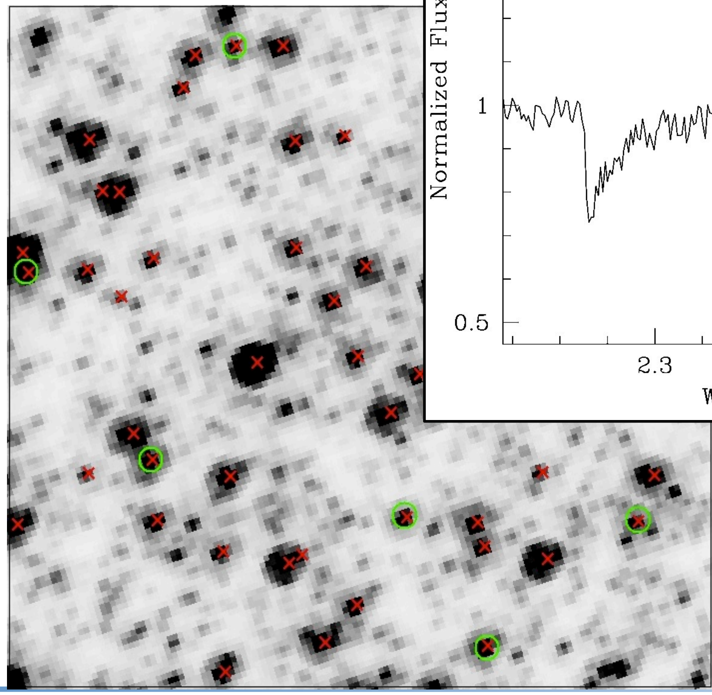
- cross-correlation between SINFONI and HST/HRC
- spectrum extracted from central spaxel only
- excluded low-quality spectra & blended sources
- V_r mainly from CO band-heads



SINFONI



HST/HR



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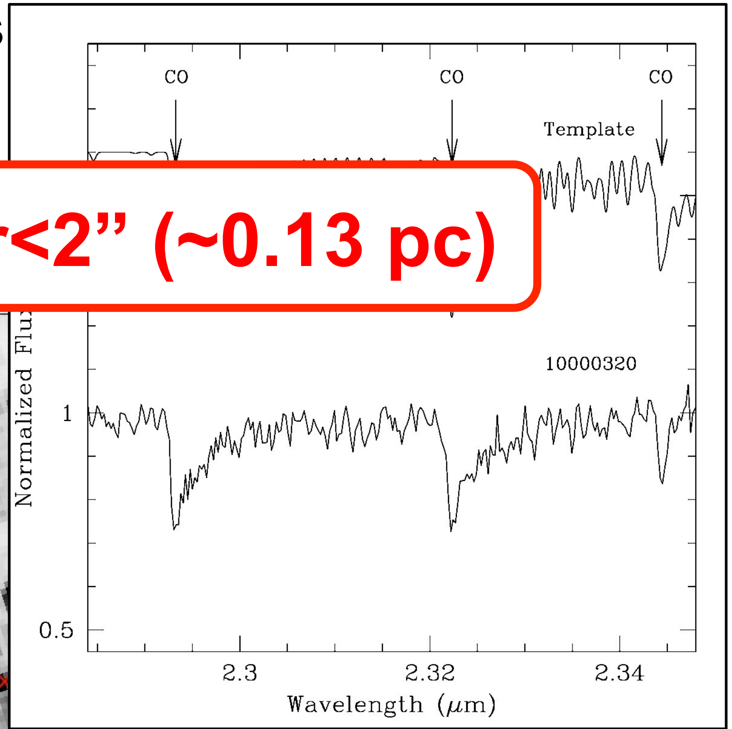
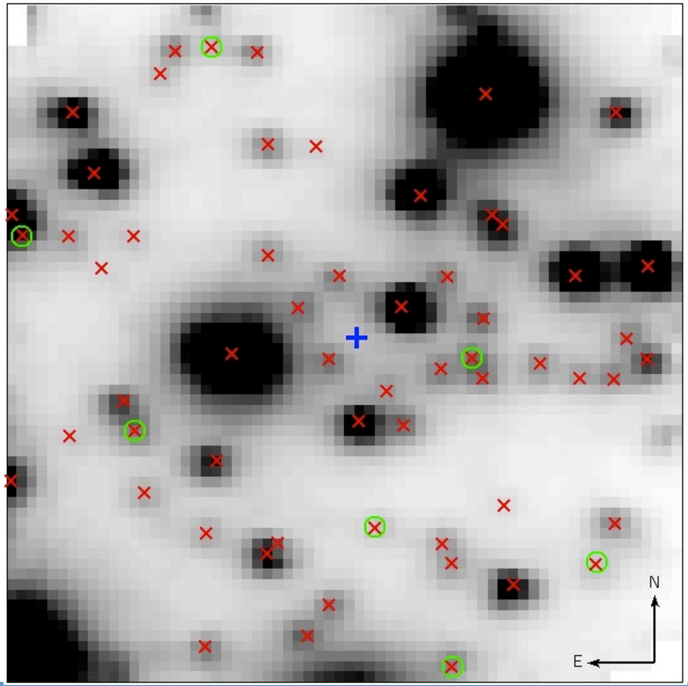
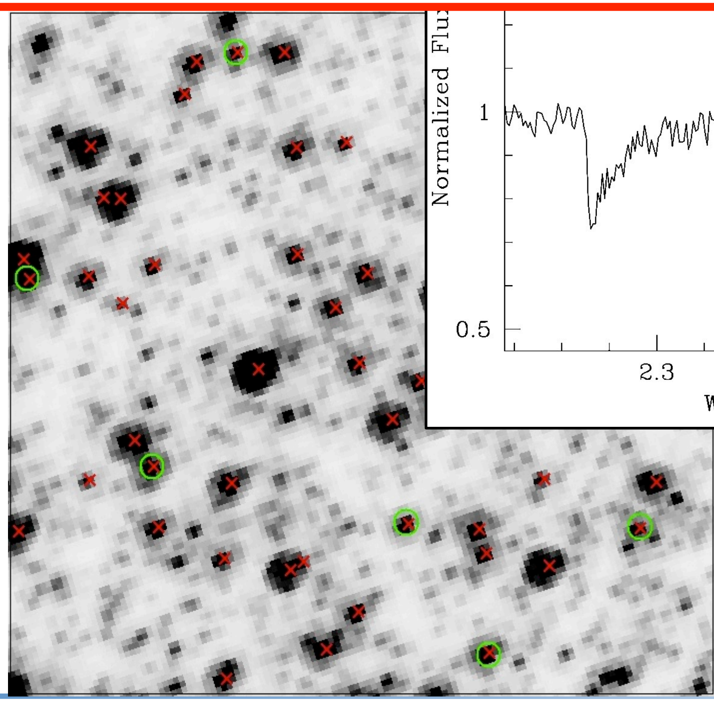


→ V_r for 52 individual stars at r<2" (~0.13 pc)





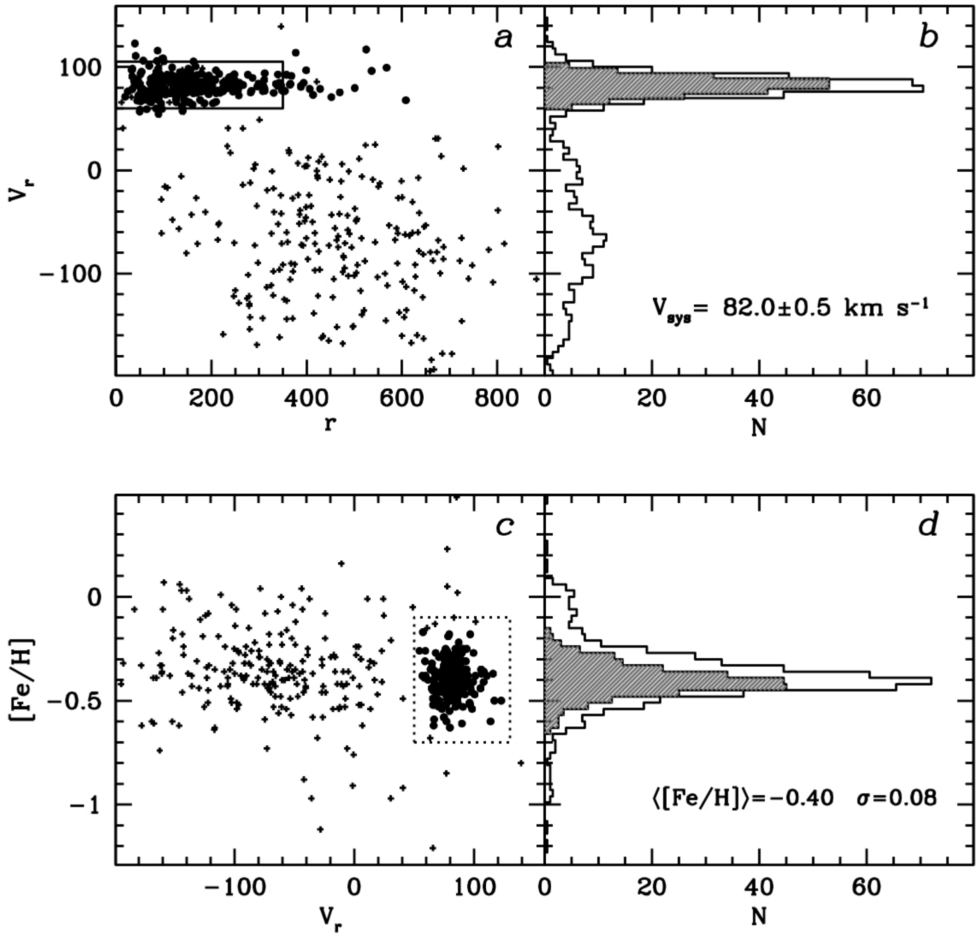
FLAMES (external) sample

- **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

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

} **V_r & [Fe/H] for 508 stars**

FLAMES (external) sample



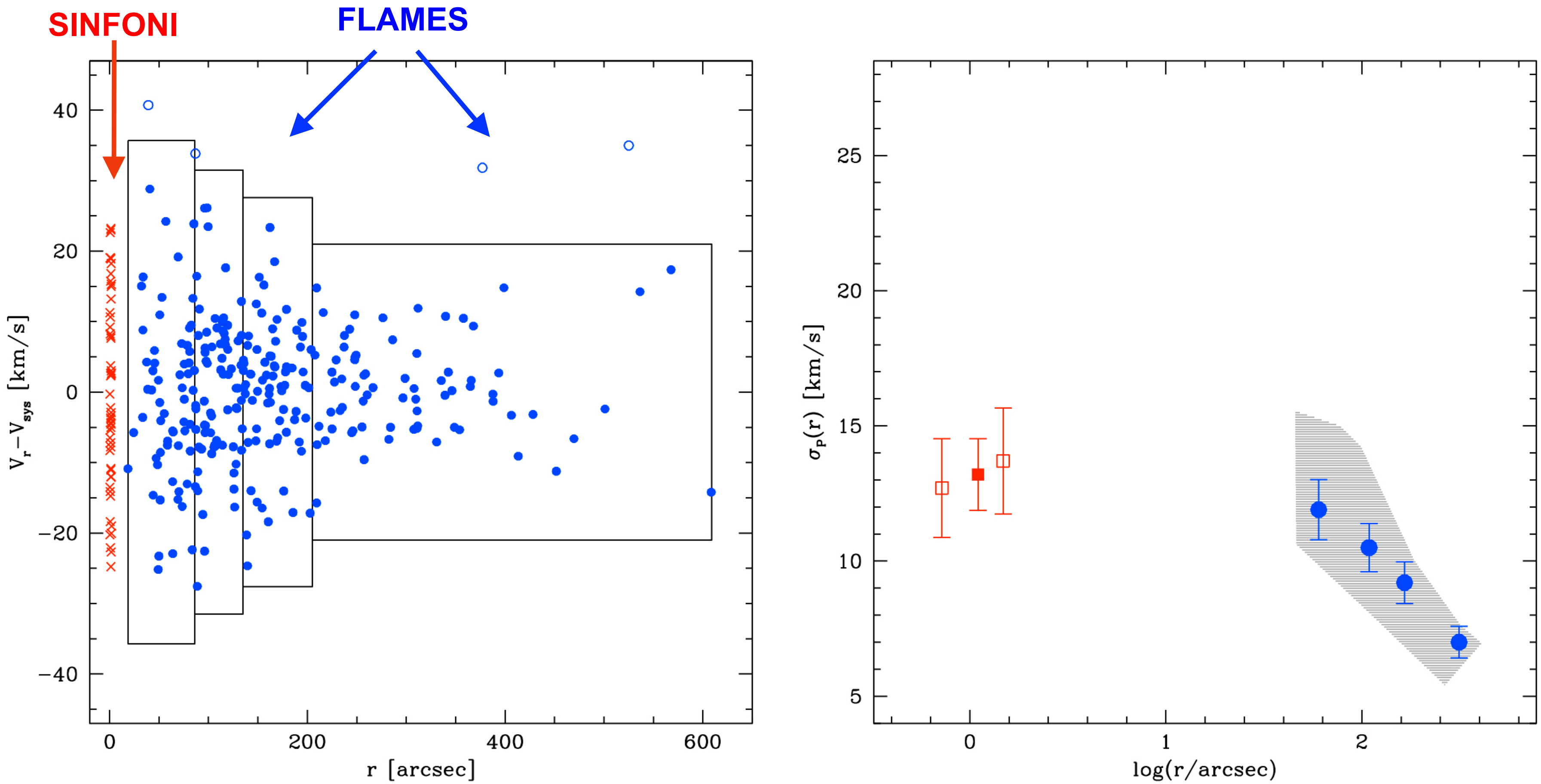
276 cluster members

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

Velocity dispersion profile

σ(r) from the dispersion of V_r in radial bins of ≥ 50 stars

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



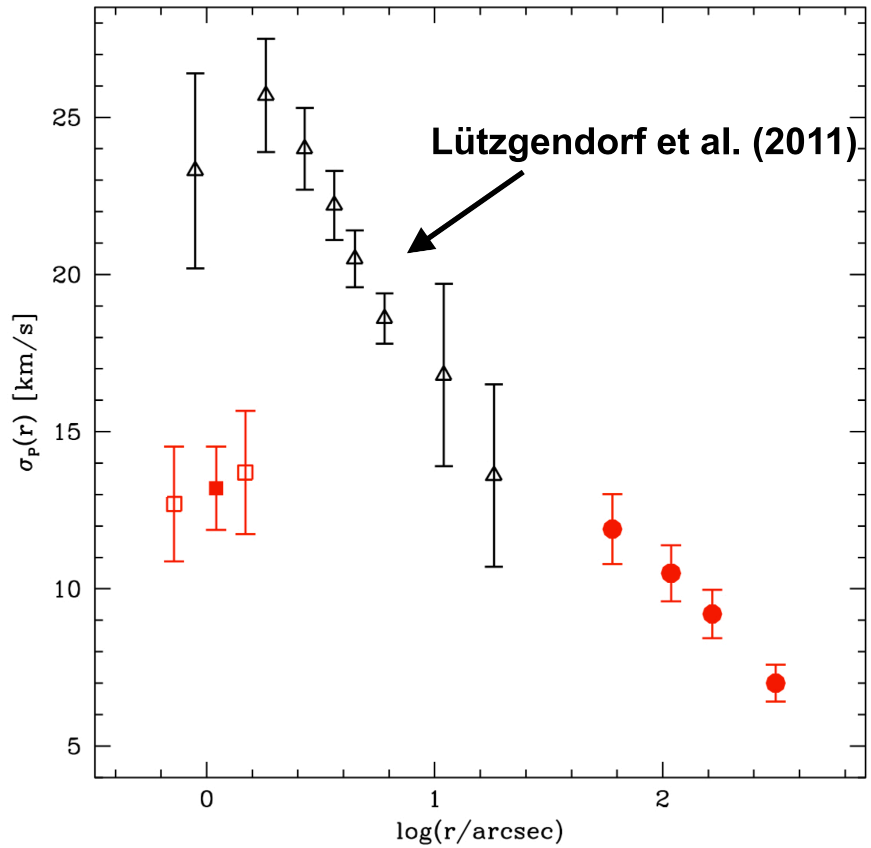
Velocity dispersion profile

$\sigma(r)$ from individual V_r
($\sigma_0 \sim$ 13-14 km/s)

incompatible with

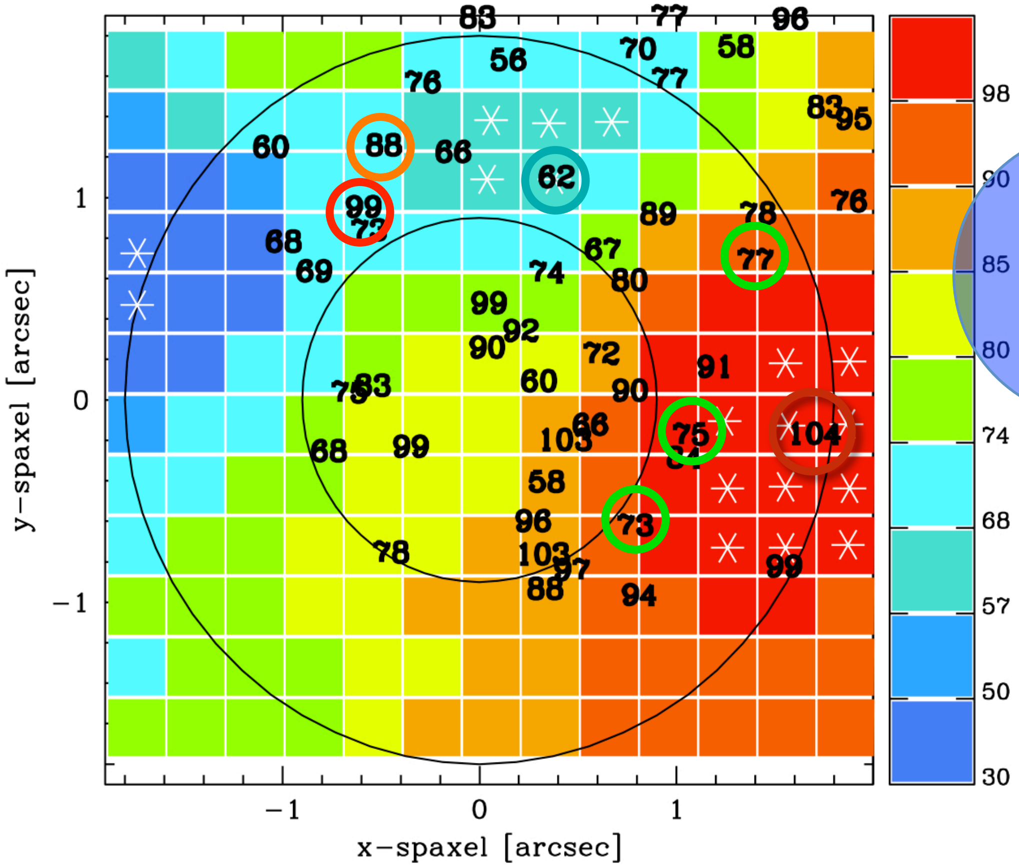
$\sigma(r)$ from the line broadening of integrated-light spectra
($\sigma_0 \sim$ 23-25 km/s)

WHY ?

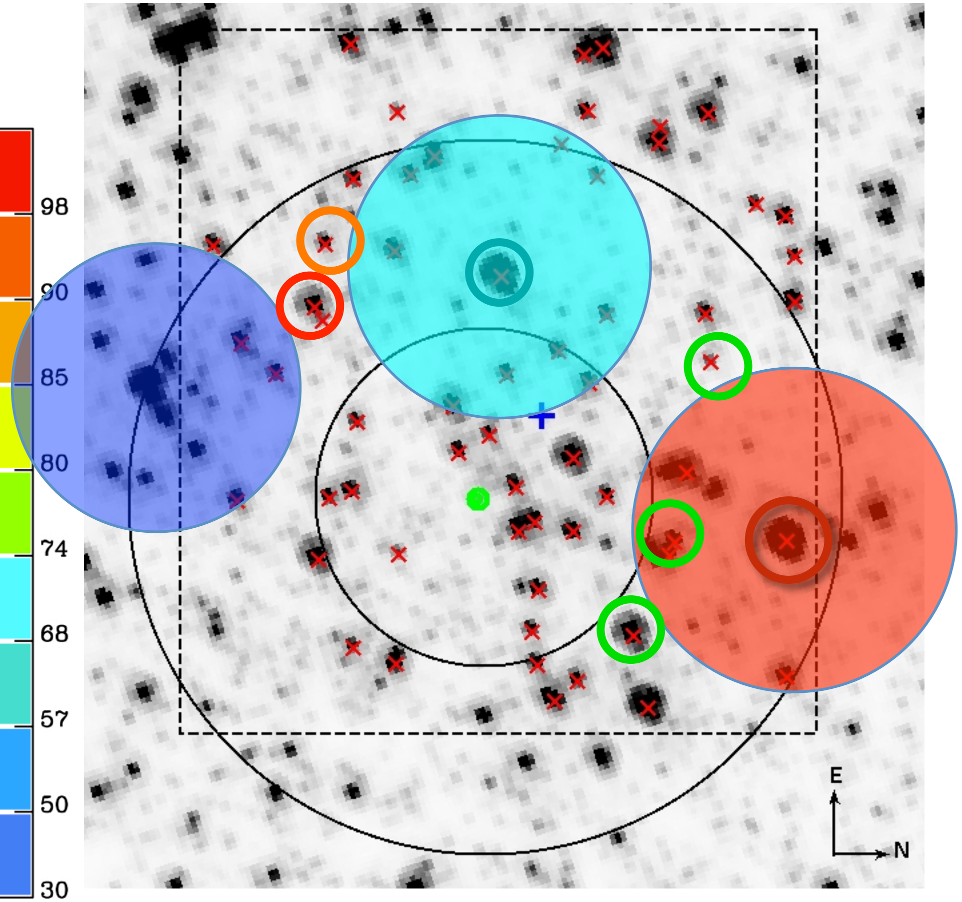


Insufficient shot-noise correction

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



HST/ACS-HRC

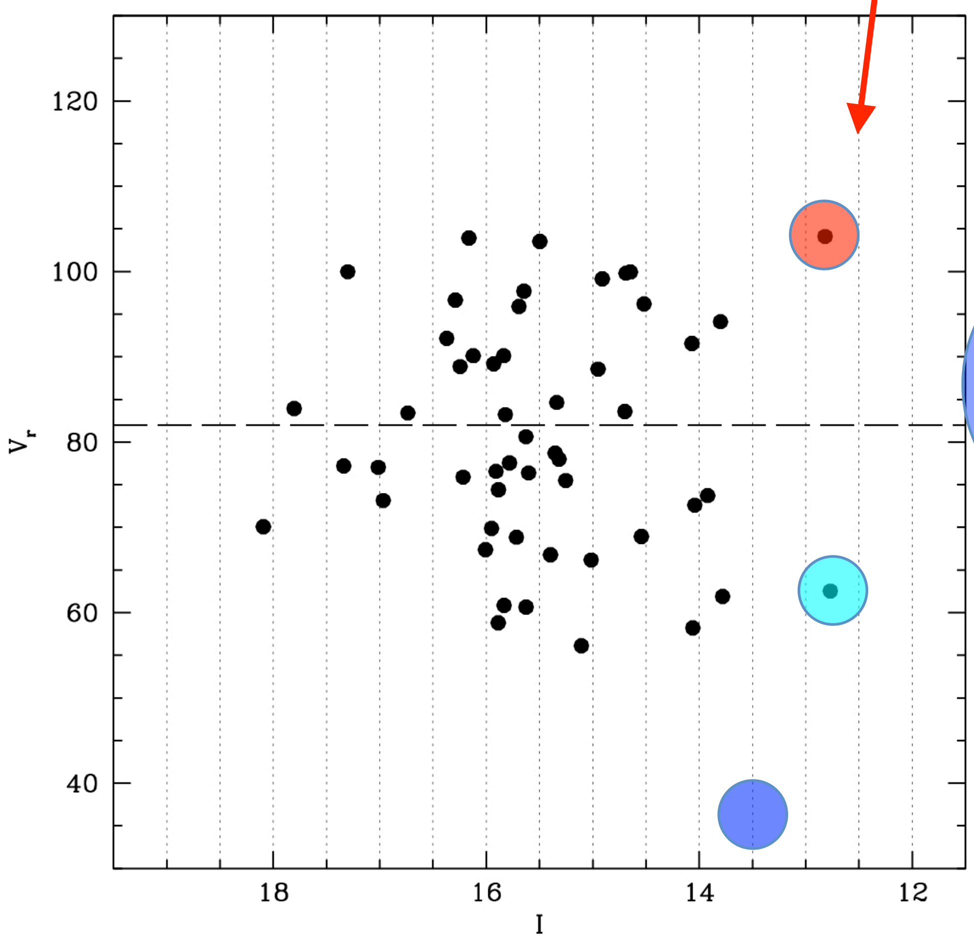


Spectra dominated by the light of a few bright stars with quite different V_r

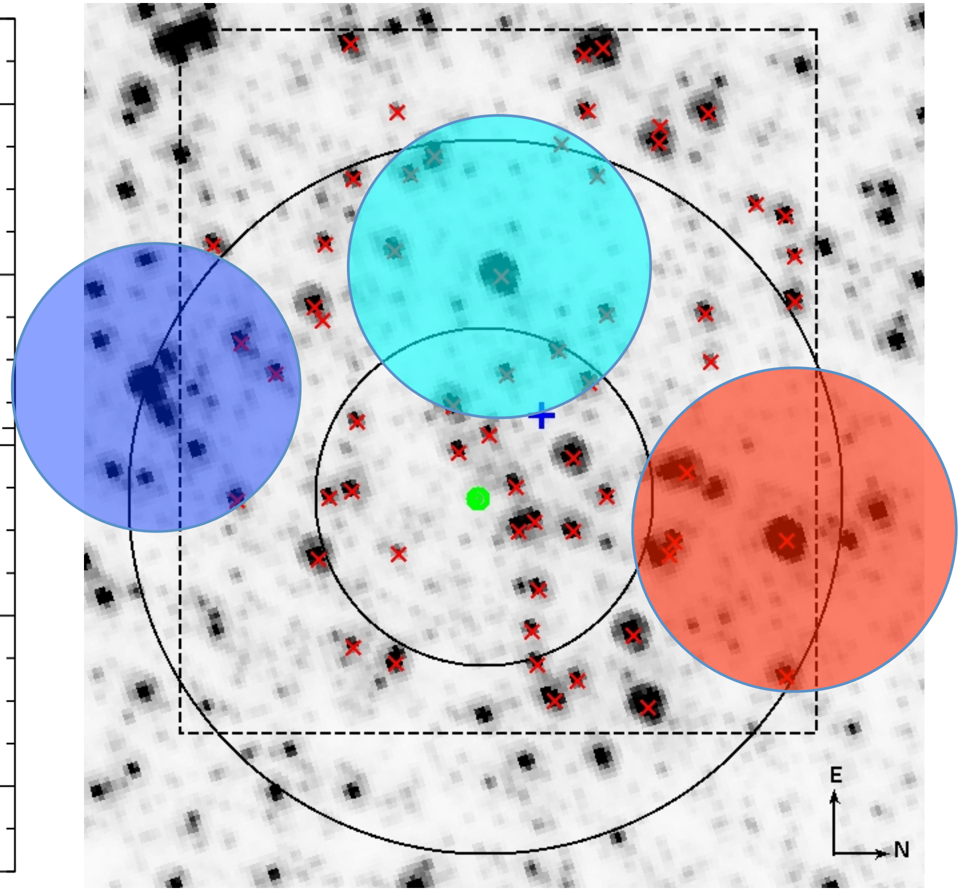
=> artificial line broadening

=> overestimate of σ(r)

=> overestimate of IMBH mass



HST/ACS-HRC



Many suggestions of IMBHs (... or central mass concentration) in GCs:

(Gebhardt+2005; Miller-Jones+2012; Gebhardt+1997; van der Marel+2002, 2010; Gerssen +2002;den Brok+14; Miller-Jones+2012; , Kirsten+2012, 2014; Ibata+2009; Wrobel+2011; Noyola +2008, 2010; Jalali+2011; Lutzgendorf+2011, 2012; Feldmeier+2013; Maccarone+2008; Bash +2008; Strader+2012, Miller Jones+2013; ....)

G1 in M31

M15

47 Tuc

ω Cen

M54

NGC1904

NGC 6266

NGC 1851

NGC 2808

NGC6388

NGC 5286

NGC 5694

NGC 5824

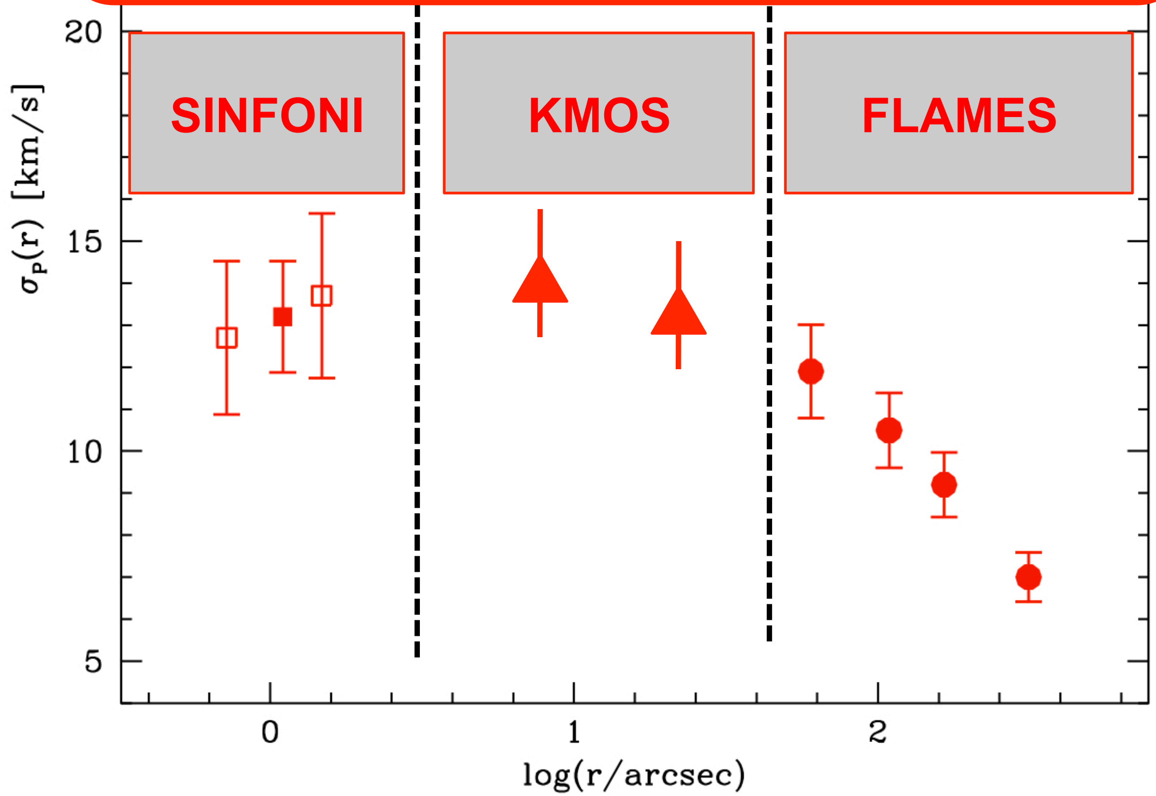
M 80

integrated-light spectra

A NEW GENERATION OF GC VELOCITY DISPERSION PROFILES FROM THE RADIAL VELOCITY OF INDIVIDUAL STARS, WITH THE ESO-VLT

ESO-VLT LARGE PROGRAMME (P93+94+95)

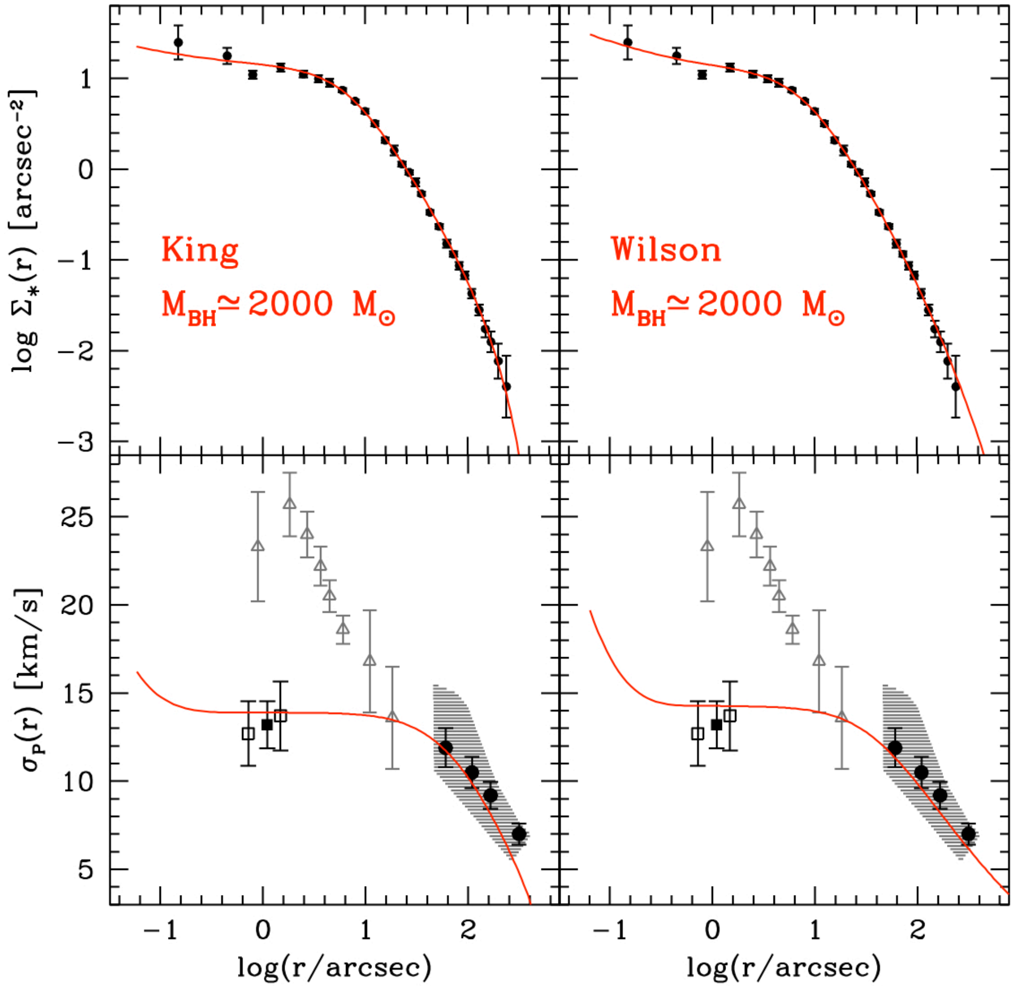
KMOS + FLAMES	PI: Ferraro	194 hours
SINFONI	PI: Lanzoni	31 hours
Grand total	30 GGCs	225 hours



(see the poster)

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)

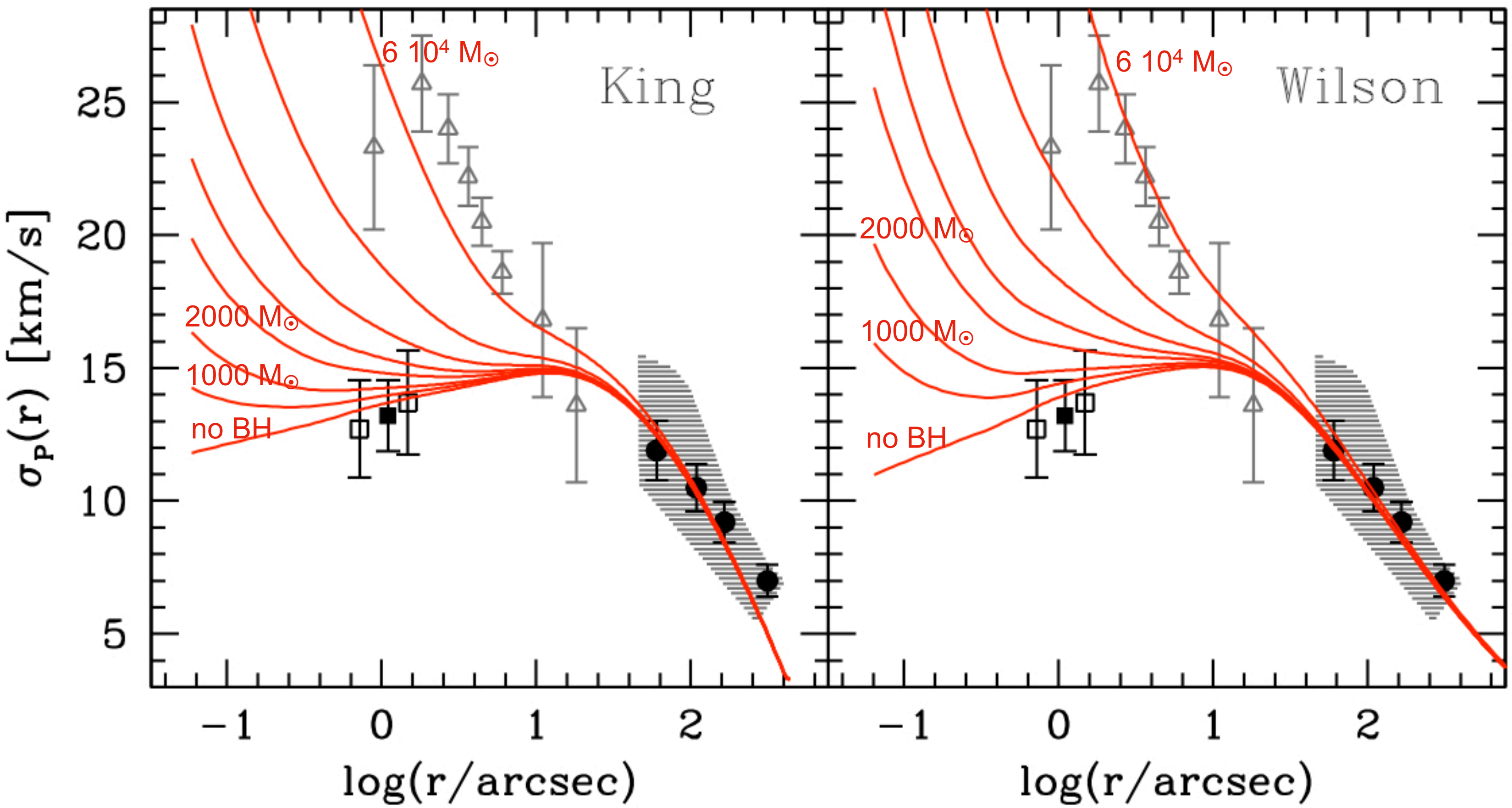


M_{BH} of ~ 2 10^3 $M_\odot$

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)

NO BH (or M_{BH} of ~ 2 10^3 $M_\odot$ at most)



Conclusions

- searching for **IMBHs in GCs** important and intriguing
- **many uncertainties (both theoretical and observational)**
- **quite challenging from the observational point of view**
- **many claims could be premature**
- **finding several fingerprints in the same cluster could be the only way?**
- **details of modelling do matter**

... let's keep on searching....

Thank you
for your attention

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You can download this presentation at:
http://www.cosmic-lab.eu/Cosmic-Lab/Presentations.html