Searching for IMBHs in globular clusters through the radial velocity of individual stars

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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

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

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

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!

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✦ are expected to exist (especially in GCs)

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... however NO solid detection yet!

Why?

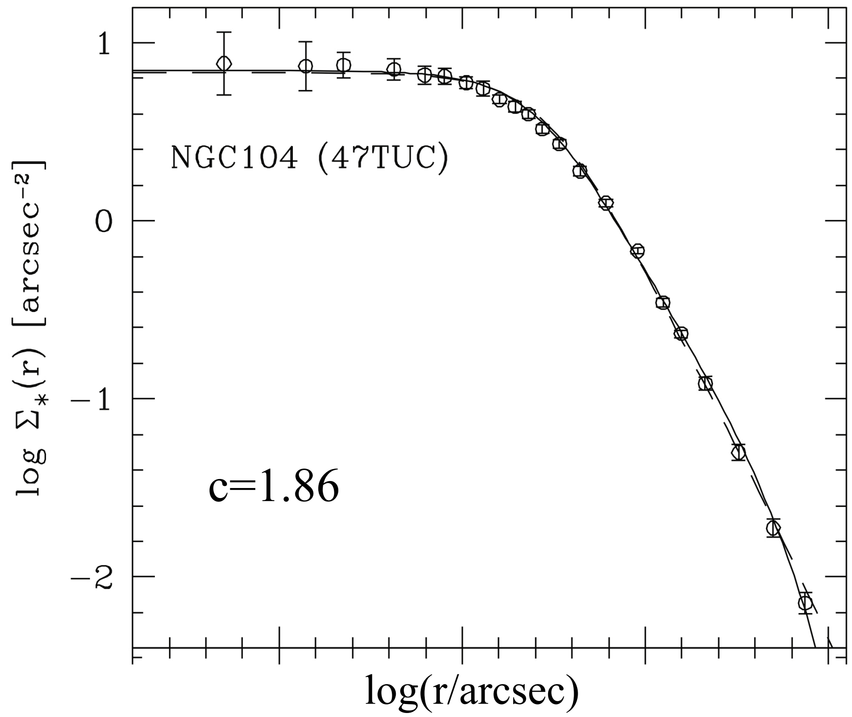
Either because they do not exist....

or because of:

- uncertainties on expected X-ray and radio emission
- controversial theoretical predictions (e.g., density cusp → Vesperini & Trenti 2010)
- challenging observations

1) shallow density cusp at the very centre

- **"standard" GCs:** King model (flat core) with concentration c ≈ 0.5÷2

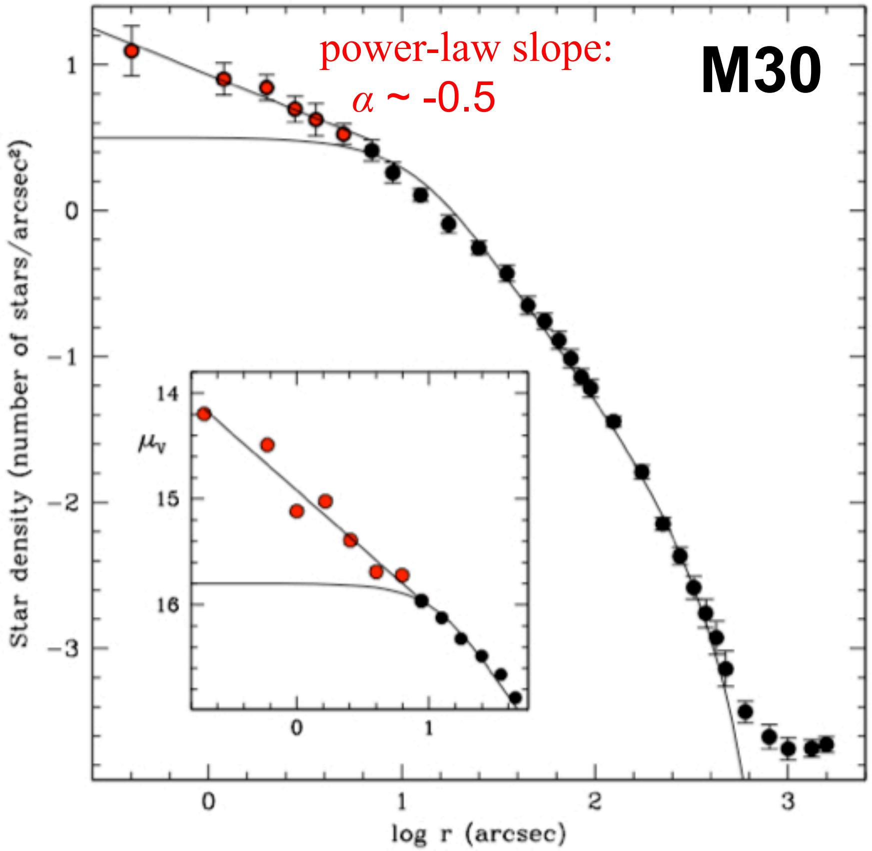


Miocchi et al. 2013

1) shallow density cusp at the very centre

- **<u>"standard" GCs</u>:** King model (flat core) with concentration c ≈ 0.5÷2

- **<u>post-core collapse GCs</u>:** central power-law deviation $\Sigma(r) \sim r^{\alpha}$ with $\alpha \sim -0.7$
  high-concentration (c>2) & virtually zero r_c



Ferraro et al. 2009

1) shallow density cusp at the very centre

- **<u>"standard" GCs</u>:** King model (flat core) with concentration c ≈ 0.5÷2

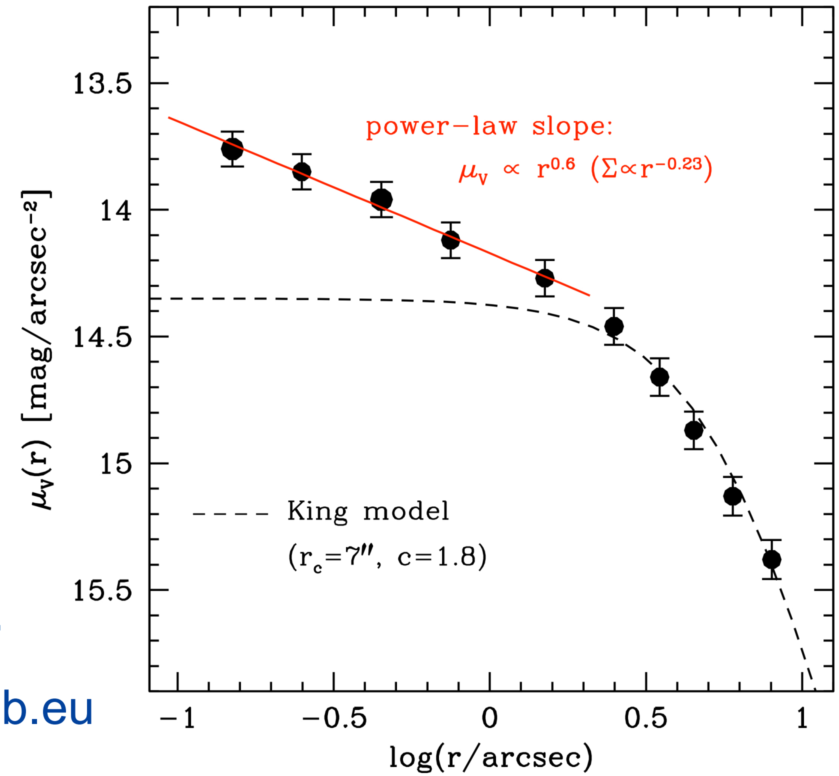
- **<u>post-core collapse GCs</u>:** central power-law deviation $\Sigma(r) \sim r^{\alpha}$ with $\alpha \sim -0.8$

  high-concentration (c>2) & virtually zero r_c

- **<u>GCs with central IMBH</u>:**

  - King profile with intermediate concentration (c ≈ 1.5)
  - sizeable r_c
  - shallow power-law cusp at the very centre:

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



Need of

high resolution + wide field, high precision photometry

to

• build the entire **density** profile (from **resolved star** number counts)

surface brightness profile can be biased
by the presence of a few bright stars

Need of

high resolution + wide field, high precision photometry

to

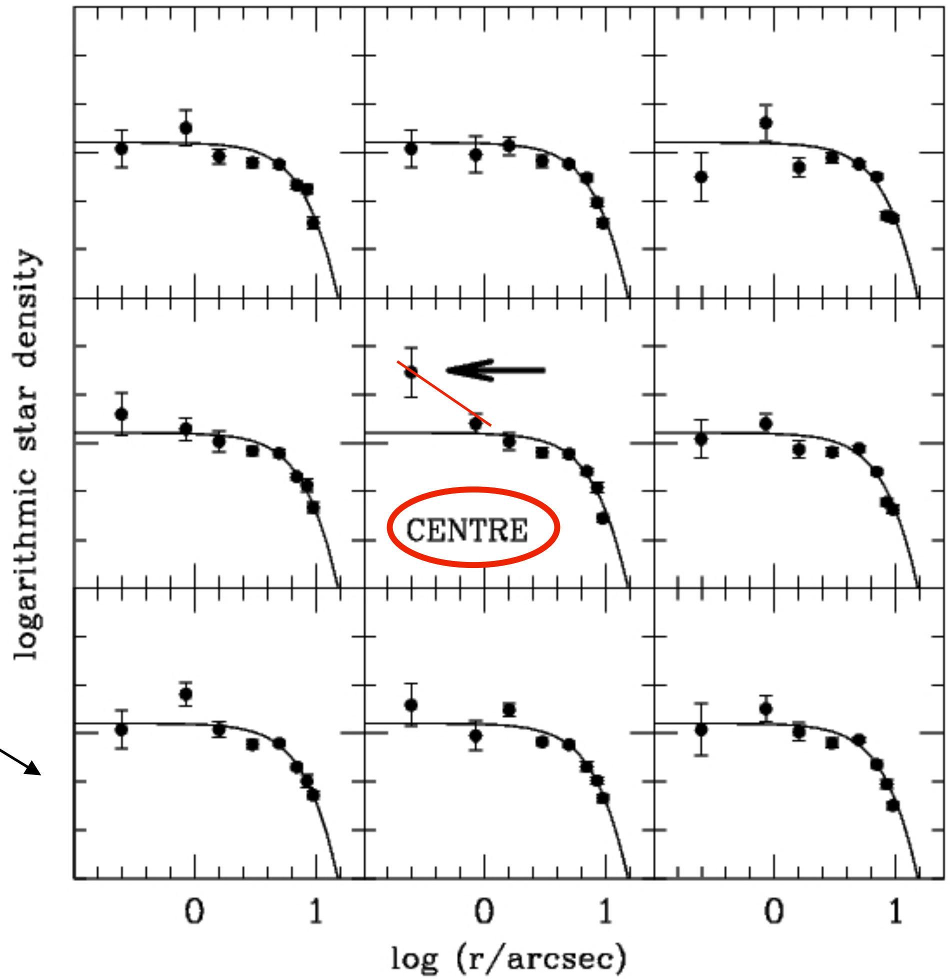
- build the entire density profile (from star number counts)
- precisely determine the **cluster centre** (from the position of **resolved stars**)

luminosity centre can be biased
by the presence of a few bright stars

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!

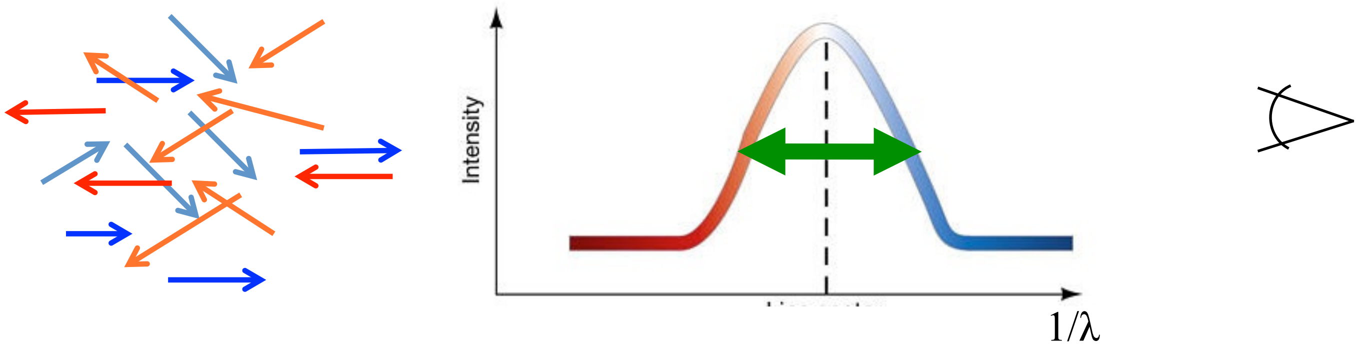
shifts of ± 0.5” only with respect to the right centre !



2) steep inner cusp in the velocity dispersion profile

Need to measure velocity dispersion within the central 1”-2”: is extremely difficult!

line broadening in integrated-light spectra



✓ relatively easy to measure

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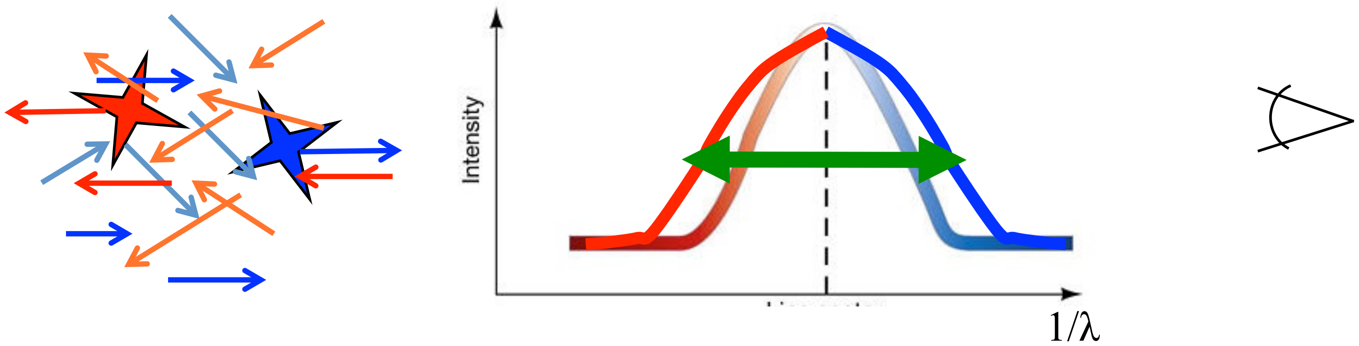

✓ relatively easy to measure

✕ high risk to be biased by the light of a few giants (**shot noise bias**)

if 2-3 bright stars dominate the sampled light,
the spectrum does not sample the underlying stellar distribution,
but just the radial velocities of those 2-3 giants
=> this is NOT a measure of the stellar velocity dispersion

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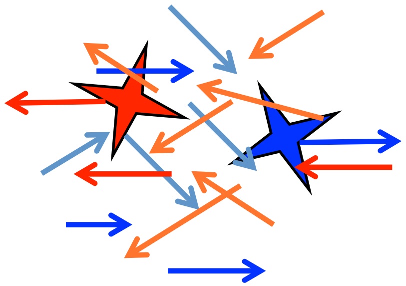
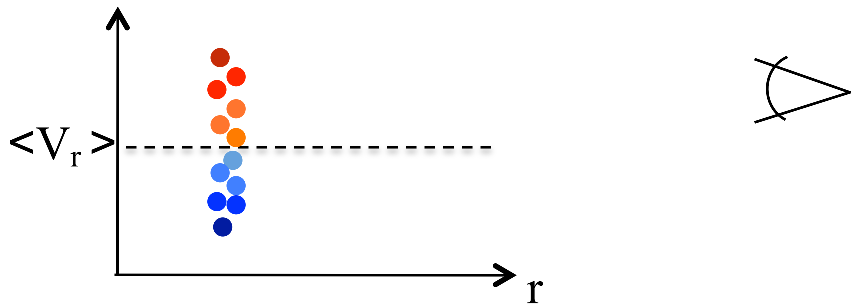


dispersion about the mean of the radial velocities of individual stars



✓ not affected by obvious biases

✗ extremely difficult to perform, especially in dense environments

high number statistics + high spatial resolution
=> multi-object + adaptive optics spectroscopy on 10m-class telescopes

2) steep inner cusp in the velocity dispersion profile

proper motions

- ✓ much easier than spectroscopy
- ✓ individual velocities also for faint stars (=> high number statistics)
- ✓ full 2D spatial coverage
- ✓ two components of motion => estimate of anisotropy

- 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)
- x very challenging analysis procedures (including correction of systematic errors)
- x still very dependent on photometric precision

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; Lützgendorf+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 bring to **different results**

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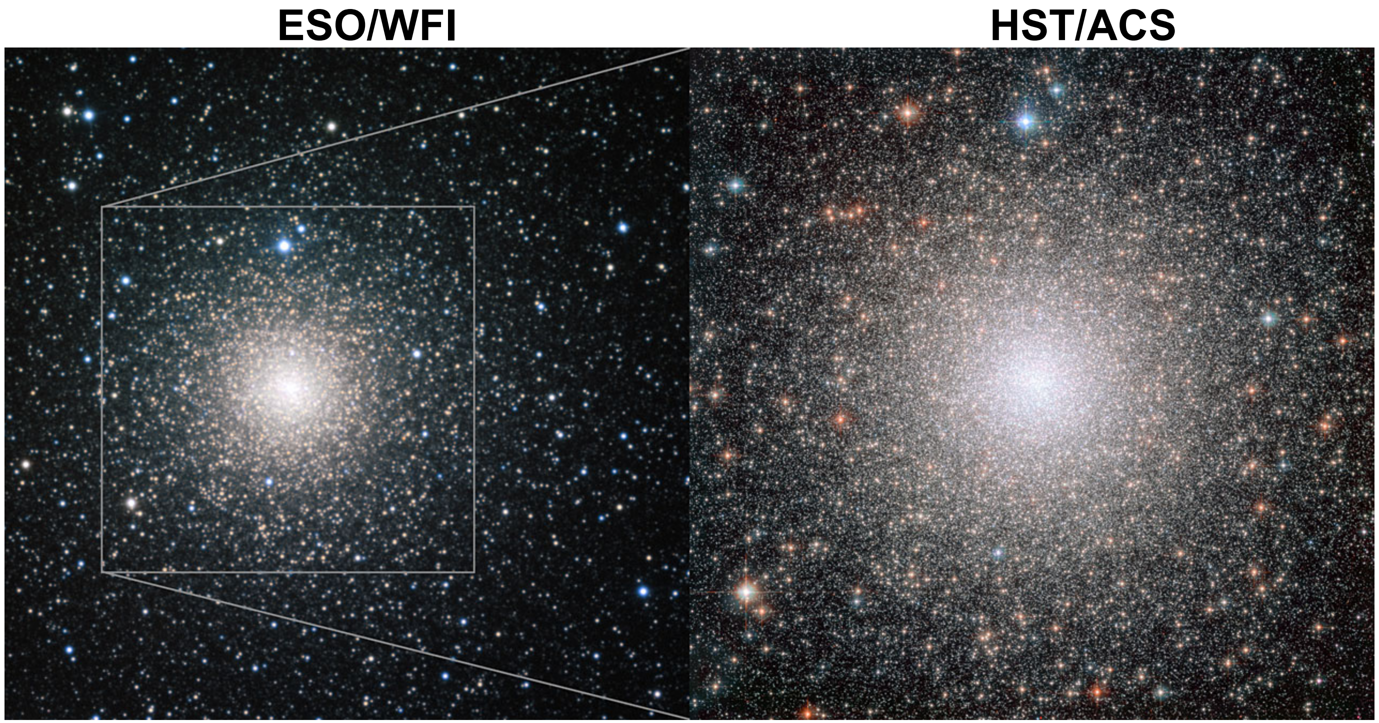
However:

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

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

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

NGC 6388

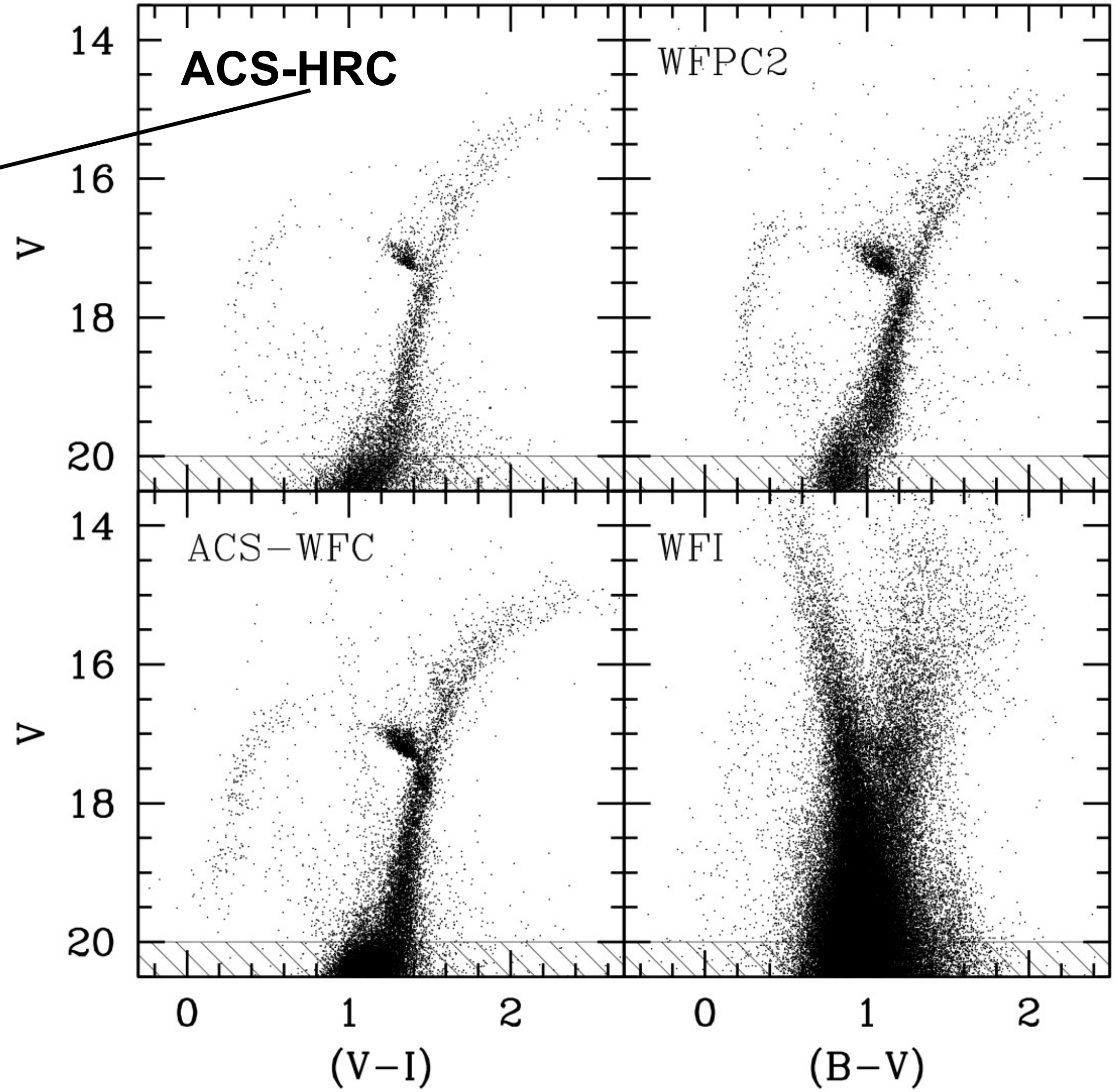


- one of the most massive Galactic GCs: M ~ 2.6 10^6 $M_\odot$
- metal-rich: [Fe/H]=-0.44 (Carretta et al. 2007)
- HB with extended blue tail (Rich et al. 1997)
- multiple populations (Bellini et al. 2013)

Photometric data set

26” x 29” FoV

0.027 arcsec/pix



(Lanzoni et al. 2007)

Determination of the centre

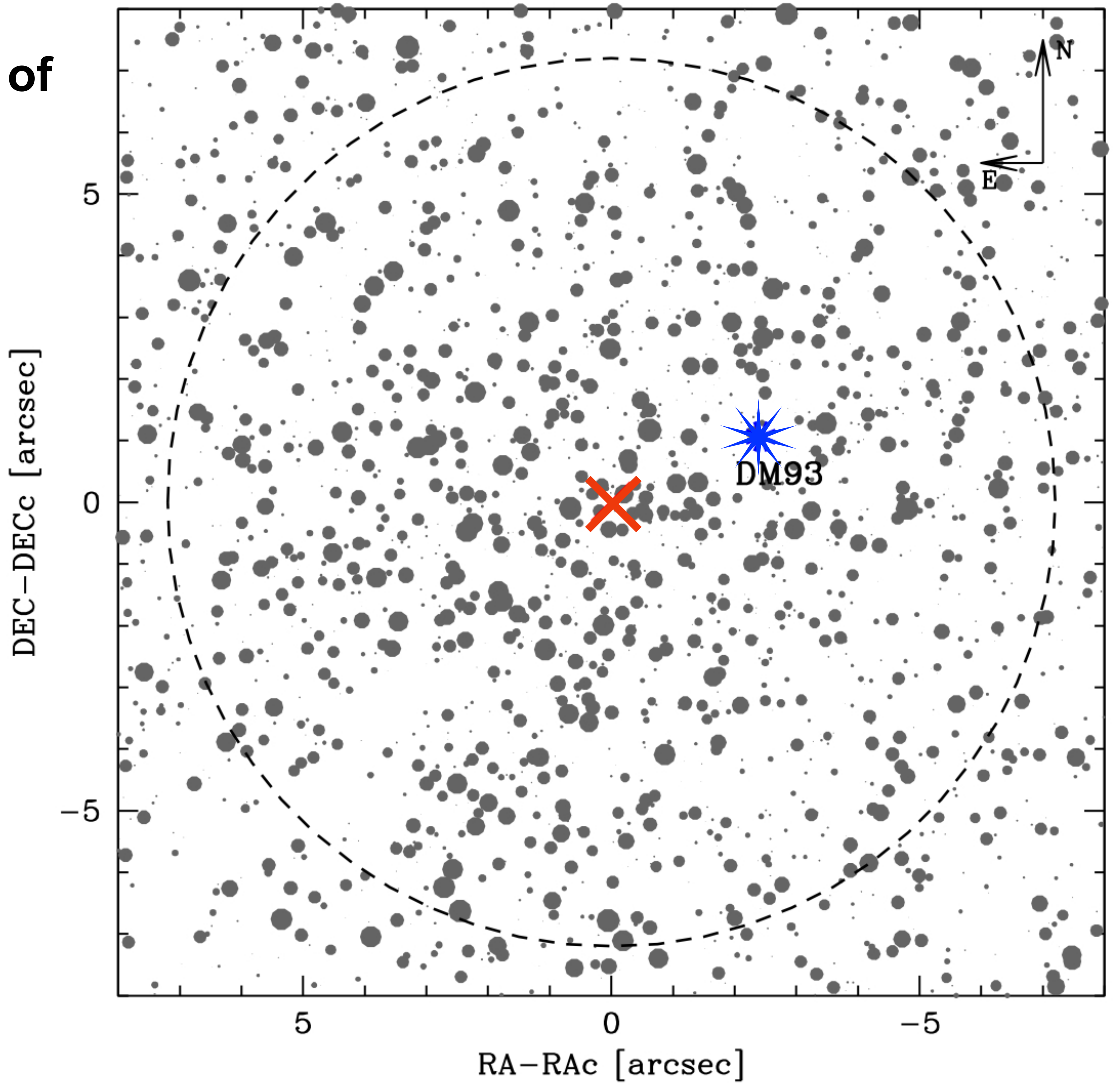
by averaging the positions of ~ 4000 stars at V<20:

α_{J2000}= 17^h 36^m 17.23^s

δ_{J2000}= -44^o 44' 7.1"

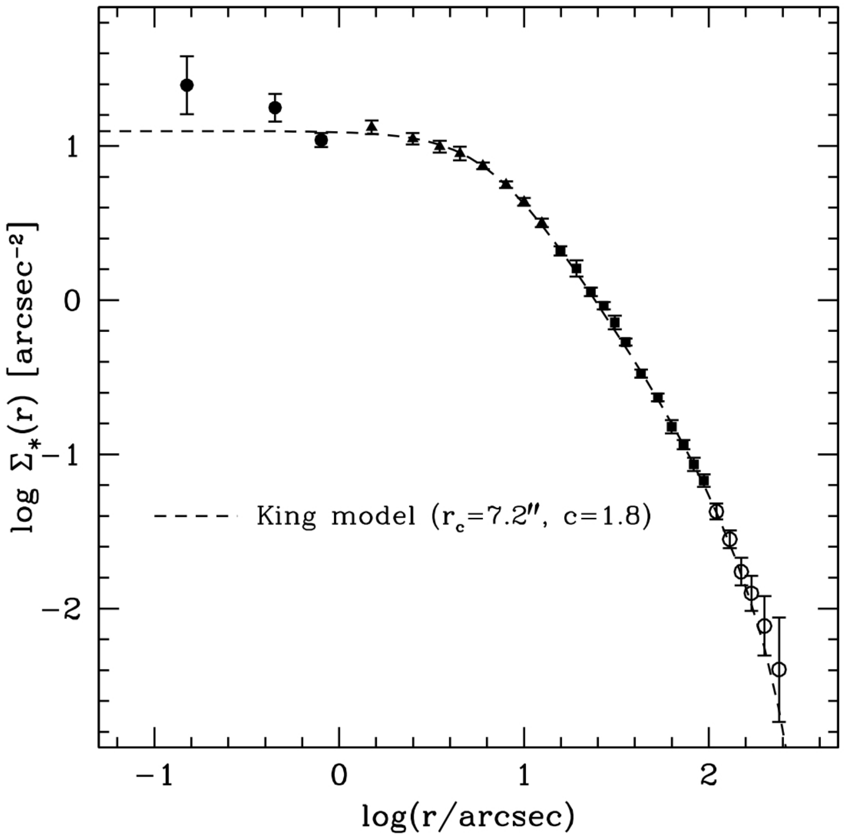
~2.6" south-east of Djorgovski & Meylan 1993

later confirmed by Goldsbury et al. (2010)

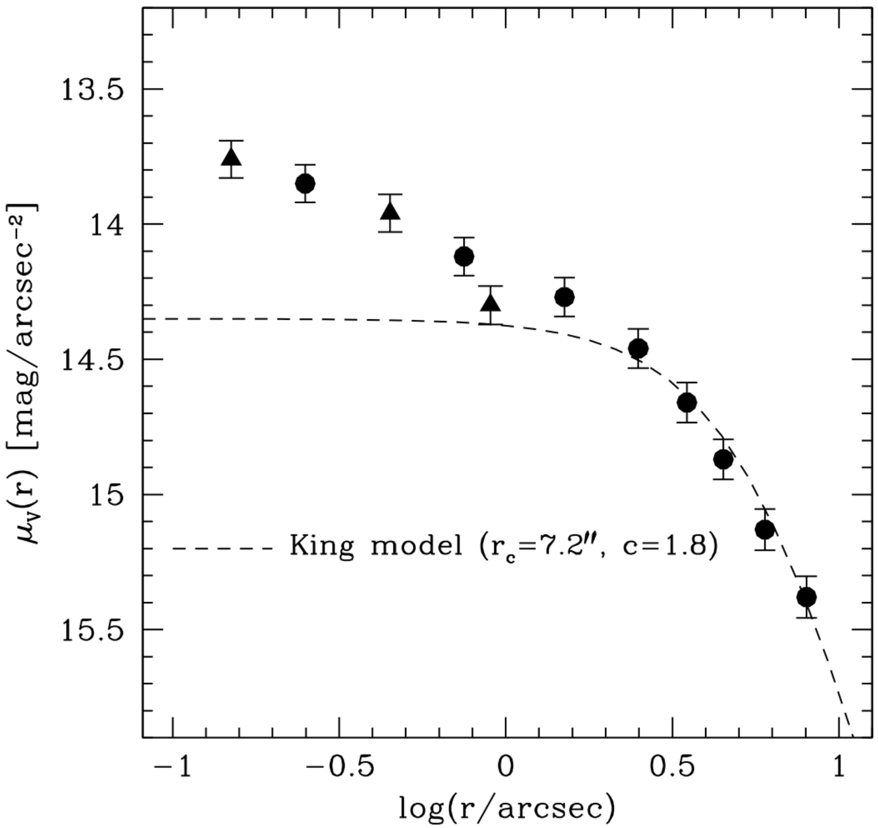


Projected density profile

(star counts in annuli)



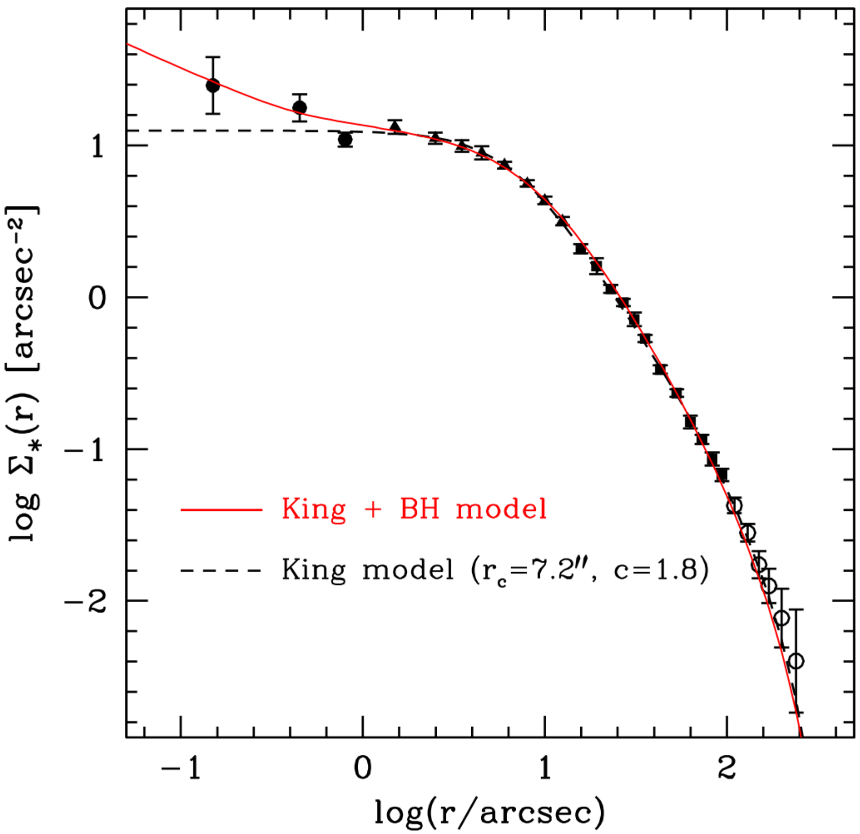
Surface brightness profile



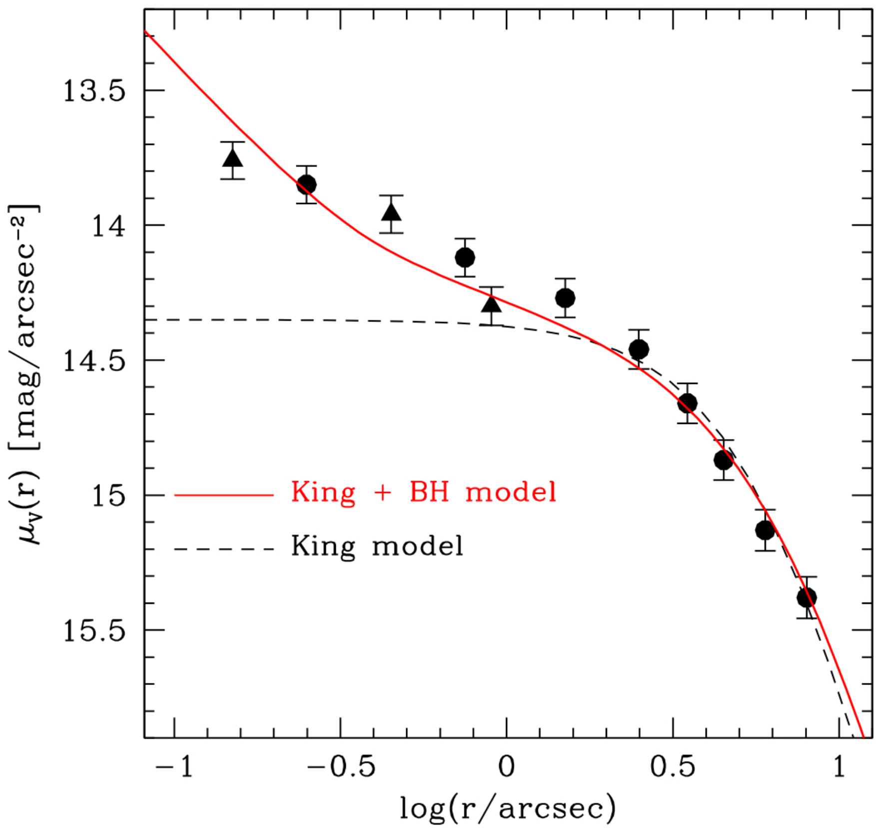
deviation from a King profile at r < 1”

slope: α ~ -0.2

projected density profile



surface brightness profile

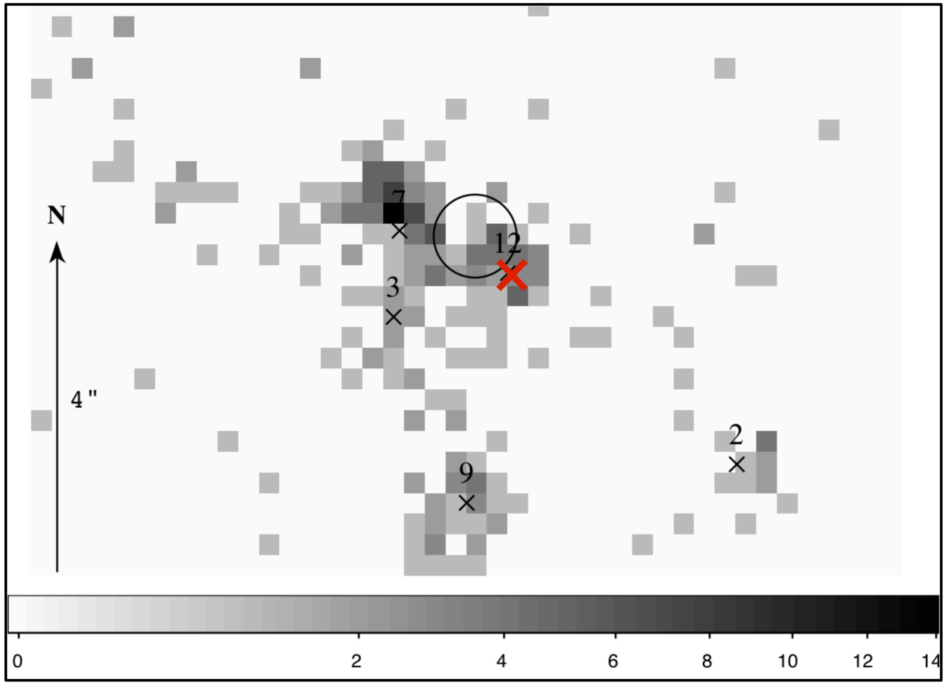


self-consistent, multi-mass, spherical, isotropic, King models with central BH (from Miocchi 2007) ➔ $M_{BH} \sim 6\ 10^3\ M_{\odot}$

(Lanzoni et al. 2007)

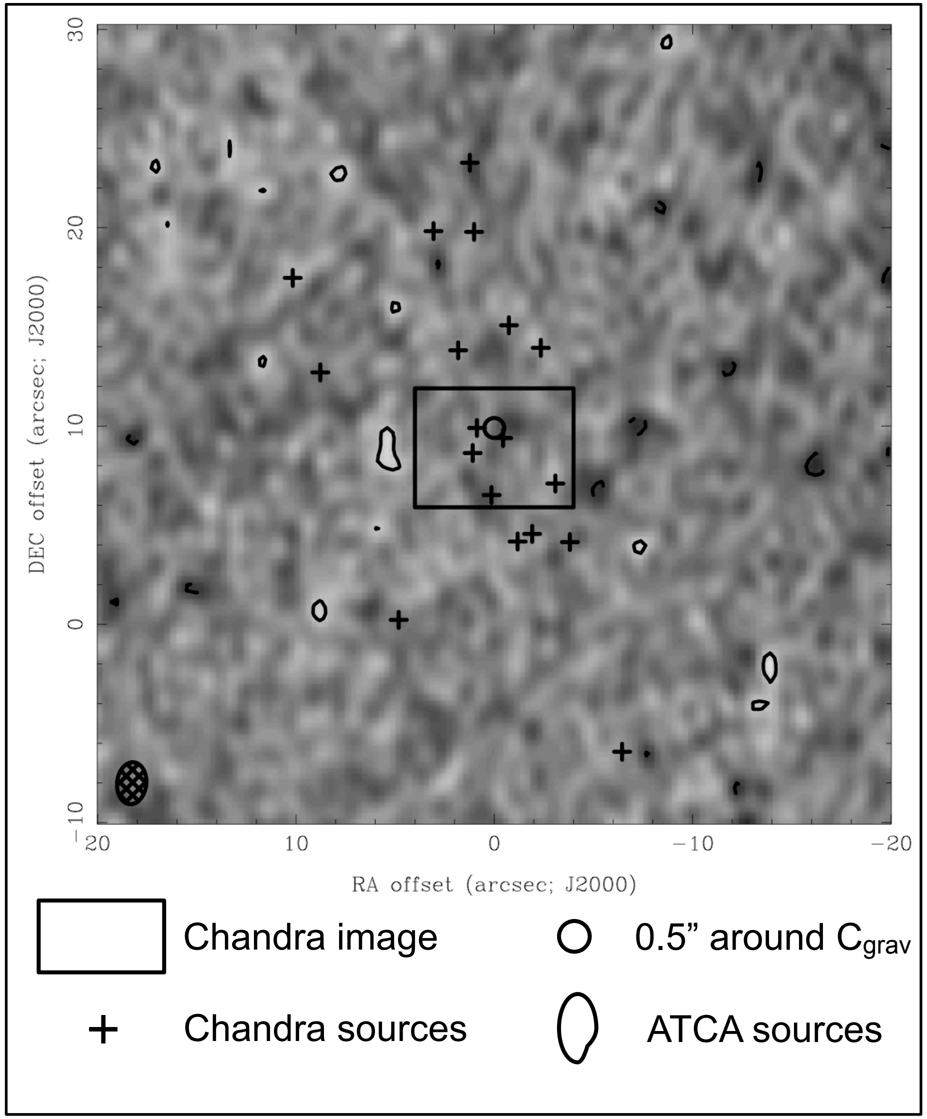
• X-ray and radio observations: $M_{BH} < 600\ M_{\odot}$

Chandra



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

ATCA

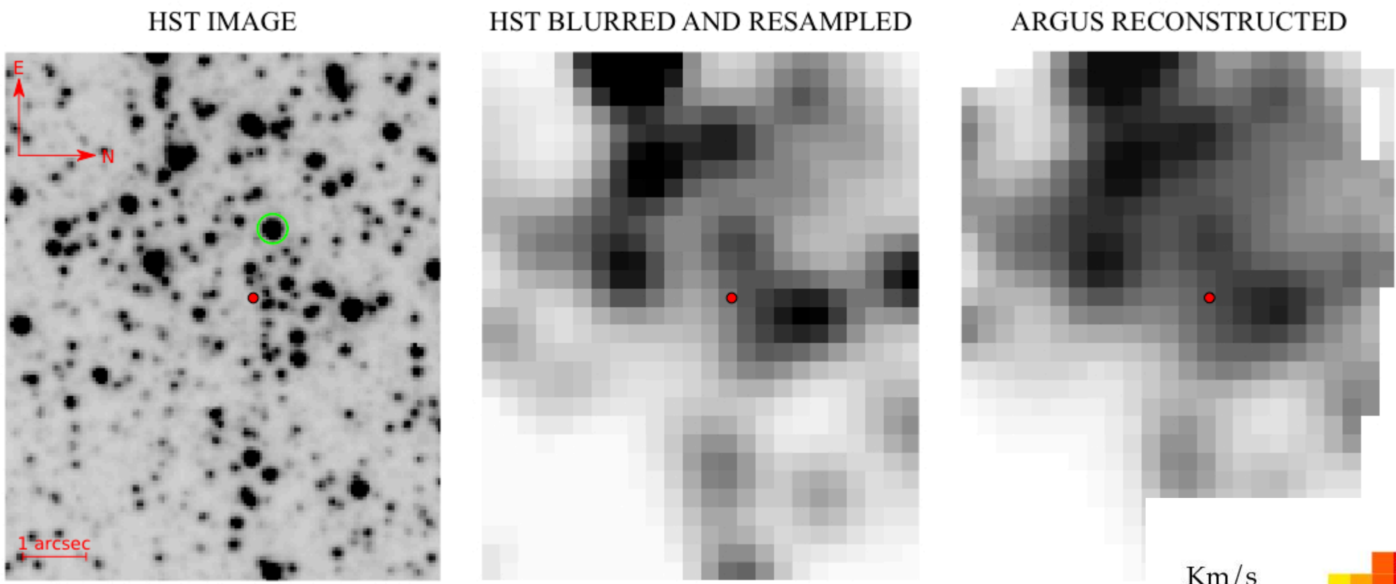


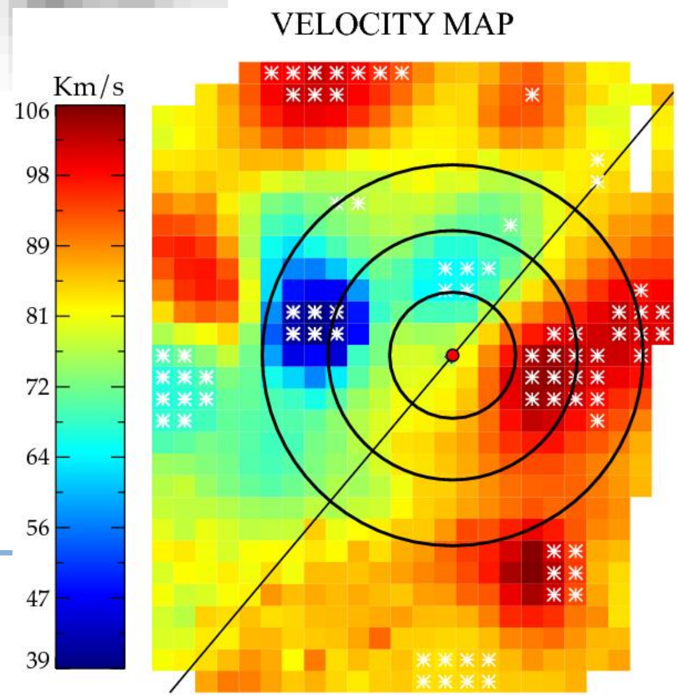
NO radio sources correspond to C_{grav} or X-ray sources

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

• Velocity dispersion from integrated light spectroscopy

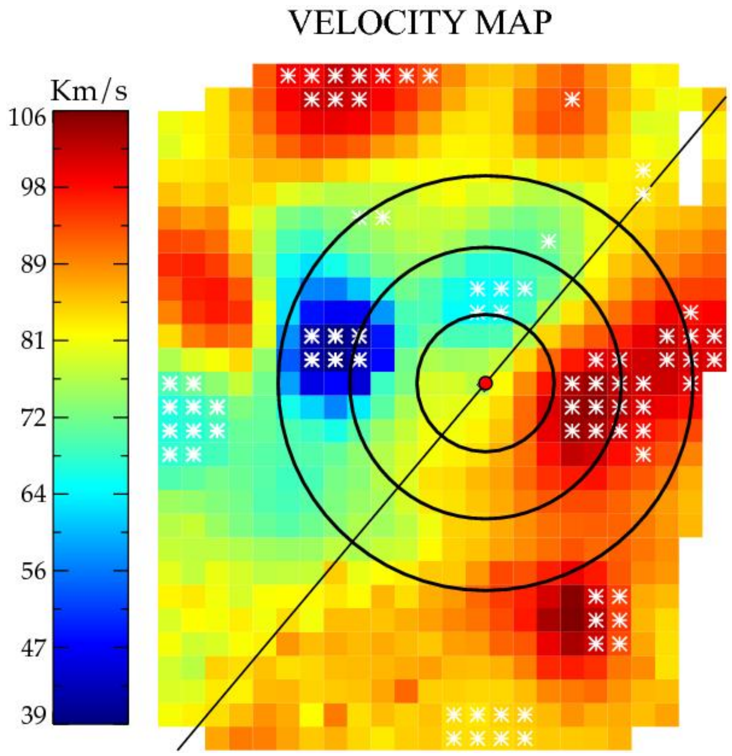
ARGUS (non-AO assisted IFU@VLT)





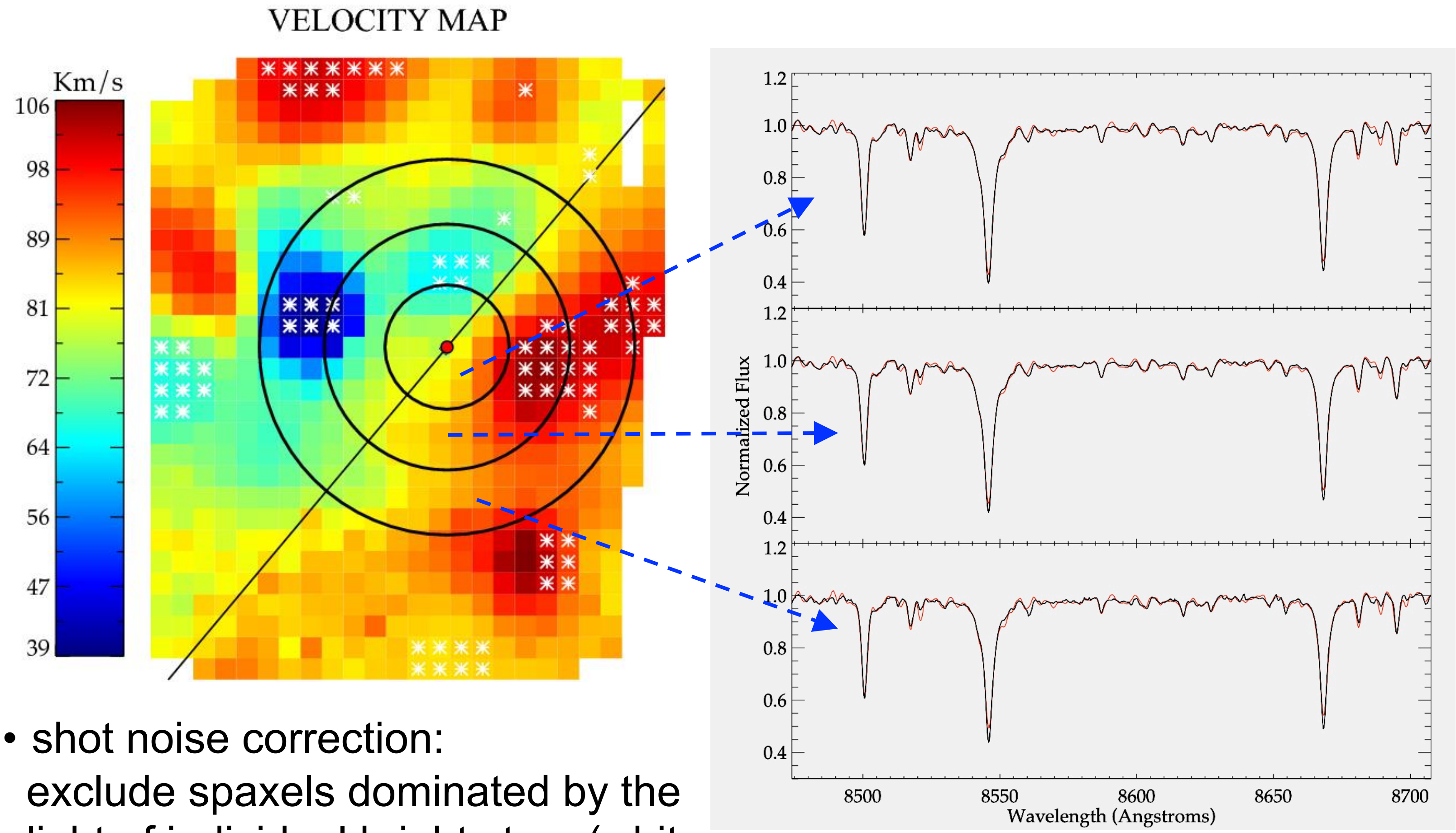
(Lützgendorf et al. 2011 – L11)

• Velocity dispersion from integrated light spectroscopy



• shot noise correction:
exclude spaxels dominated by the light of individual bright stars (white asterisks)

• Velocity dispersion from integrated light spectroscopy



- shot noise correction:
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- combine spectra from all remaining spaxels in each radial bin

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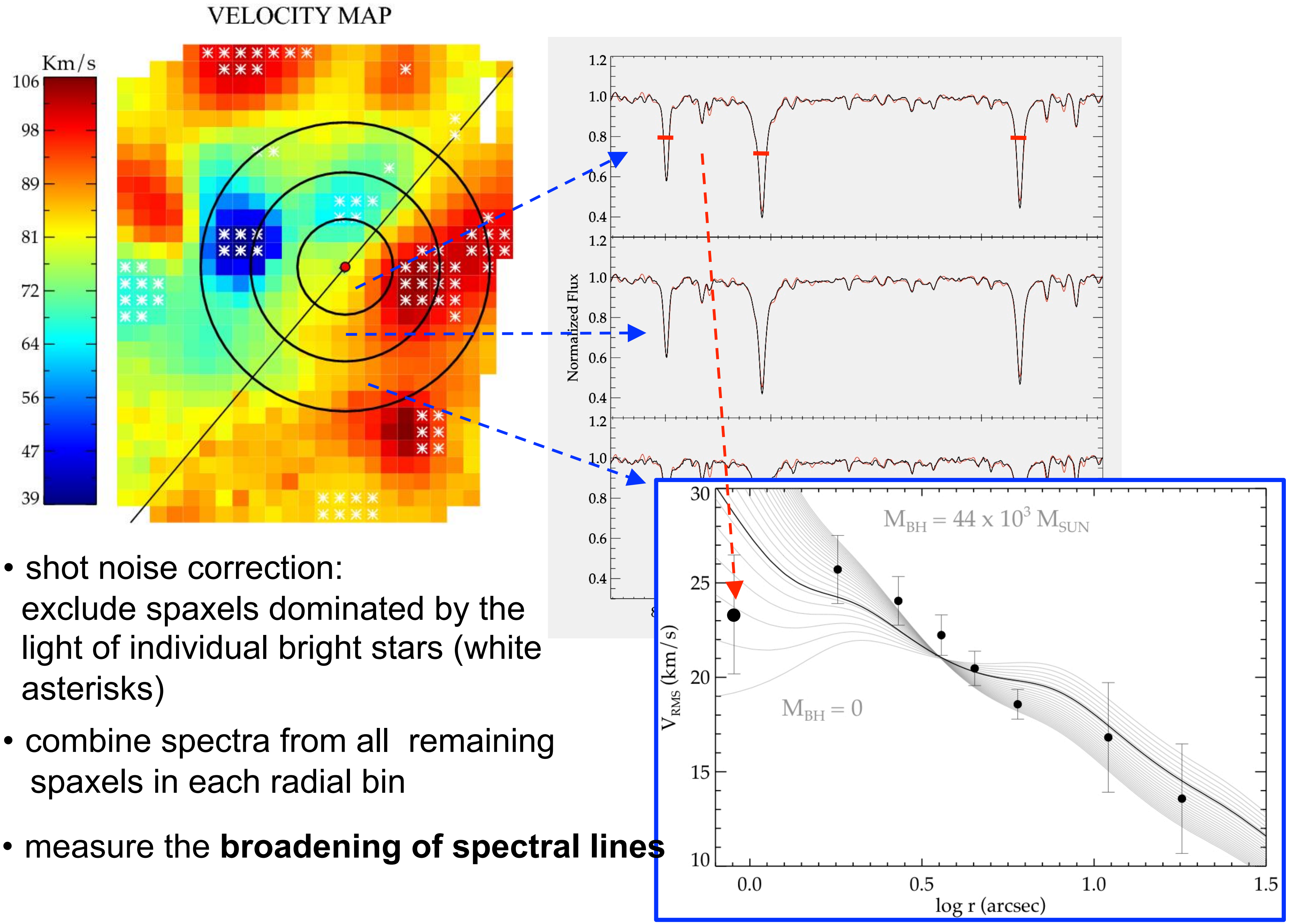

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- measure the **broadening of spectral lines**

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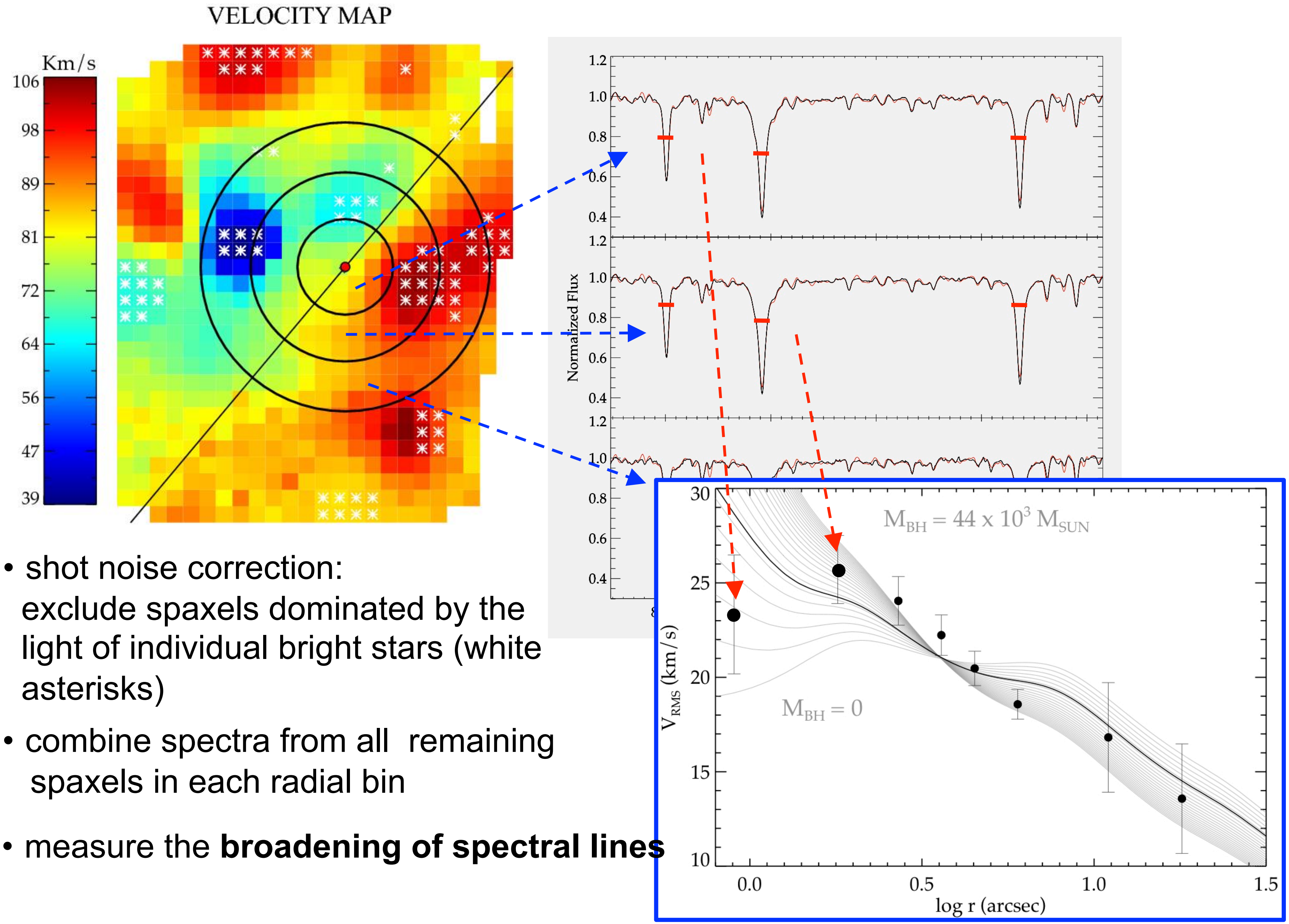

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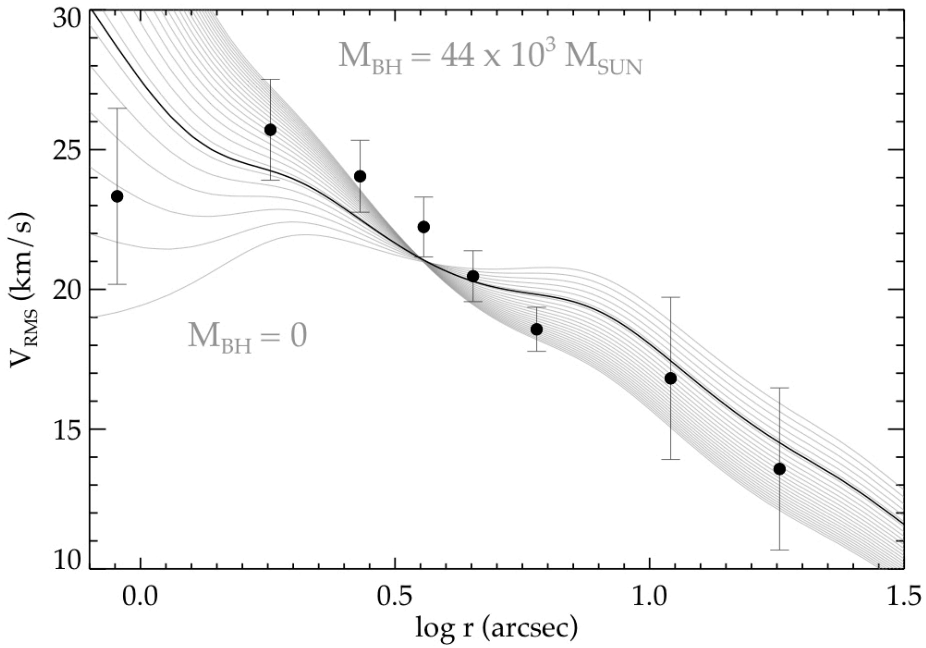
• **Velocity dispersion from integrated light spectroscopy**

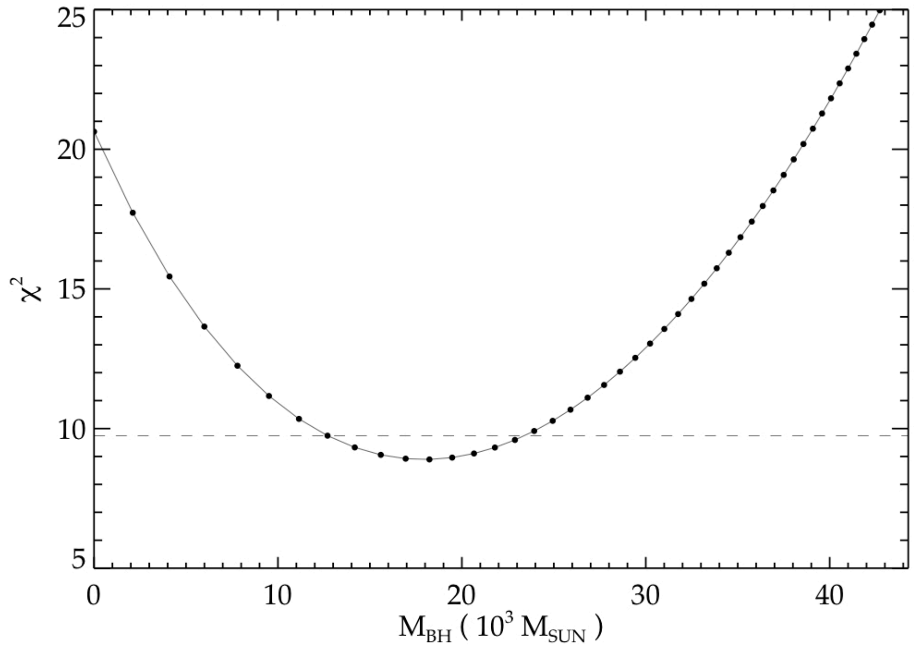
• **cuspy velocity dispersion profile, σ_0~23-25 km/s**

(from the <u>line broadening of integrated-light spectra</u>)

• **IMBH of ~1.7 10^4 $M_\odot$**

(from spherical Jeans models with constant M/L)

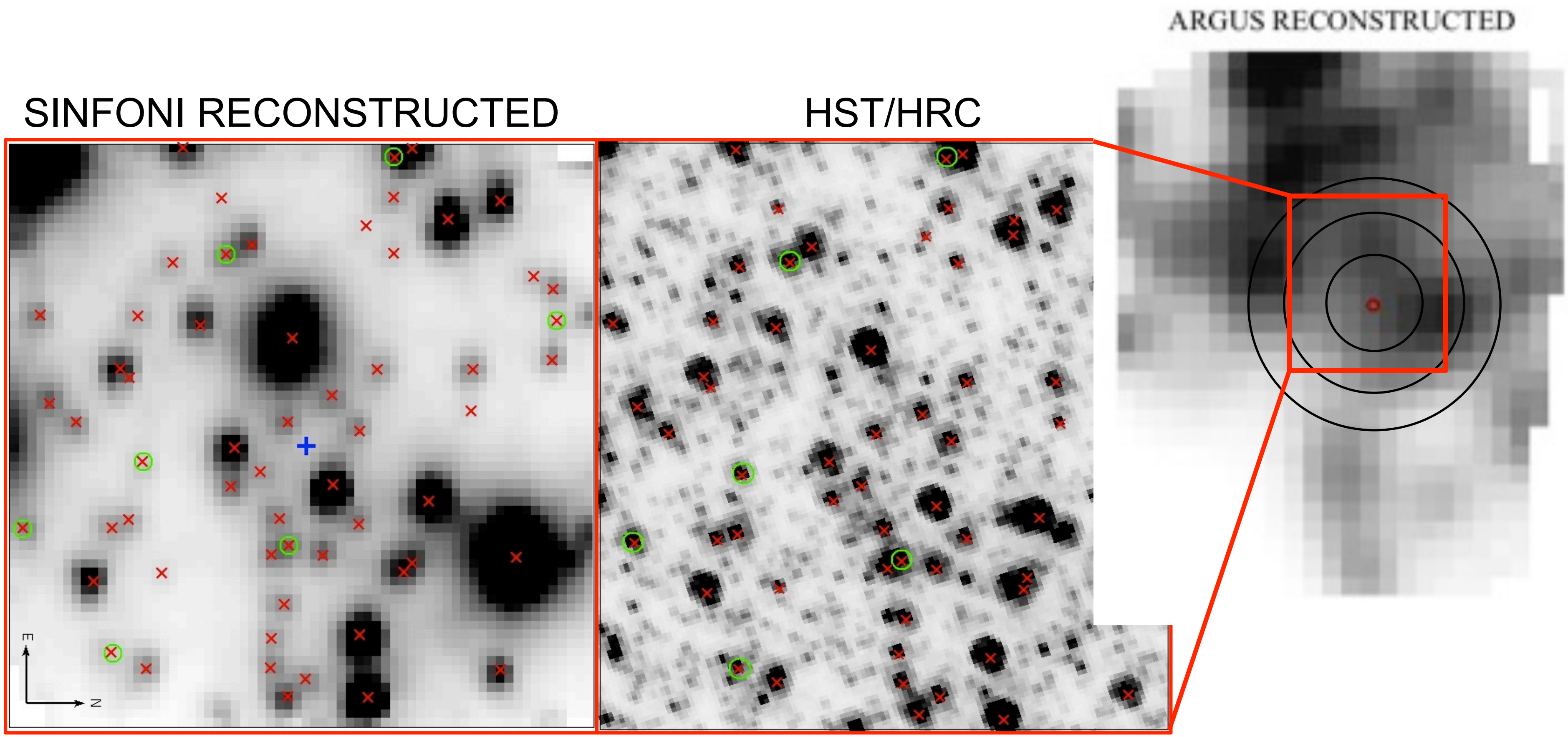




• **Velocity dispersion from radial velocity of individual stars**

SINFONI (AO assisted IFU@VLT)

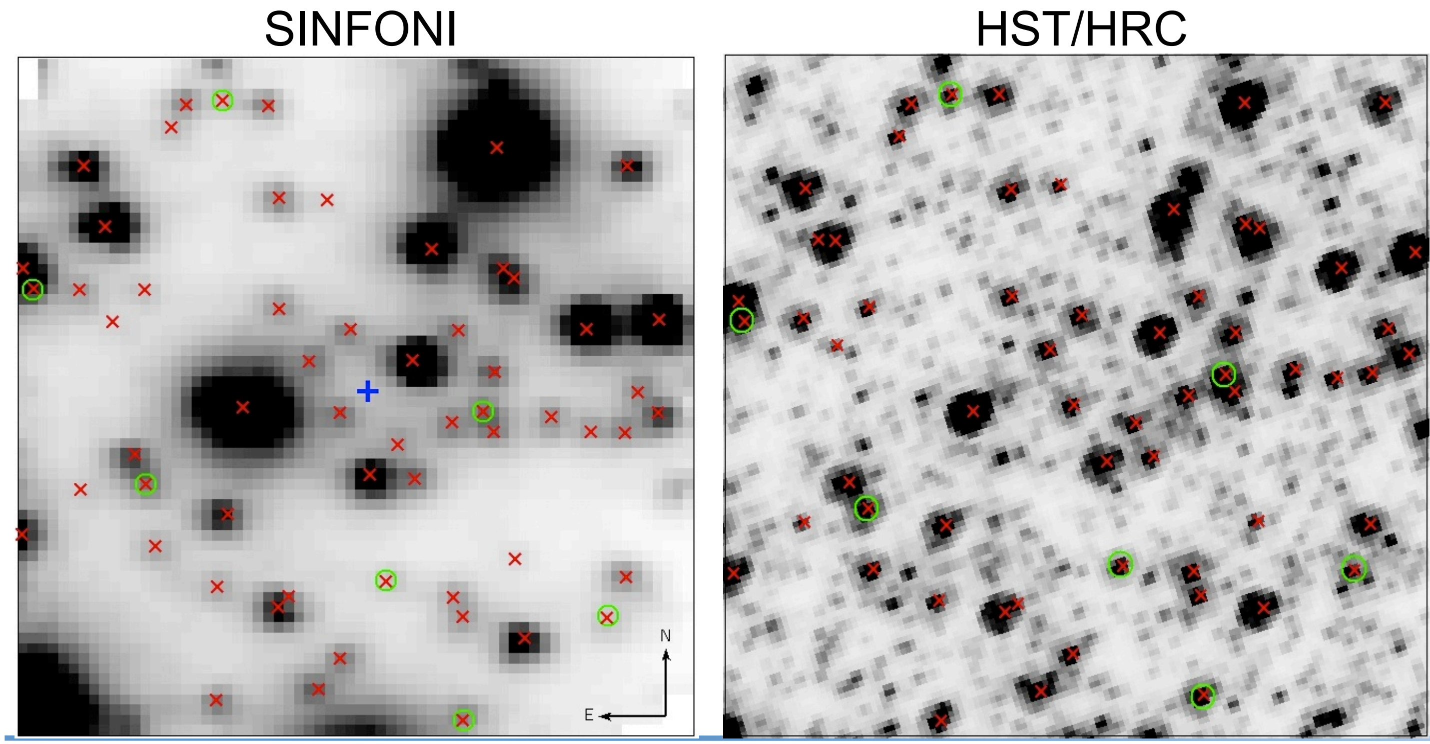
R=4000, K-band grating (1.95-2.45 μm), spatial resolution=0.1”, FoV=3.2”x3.2”



(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



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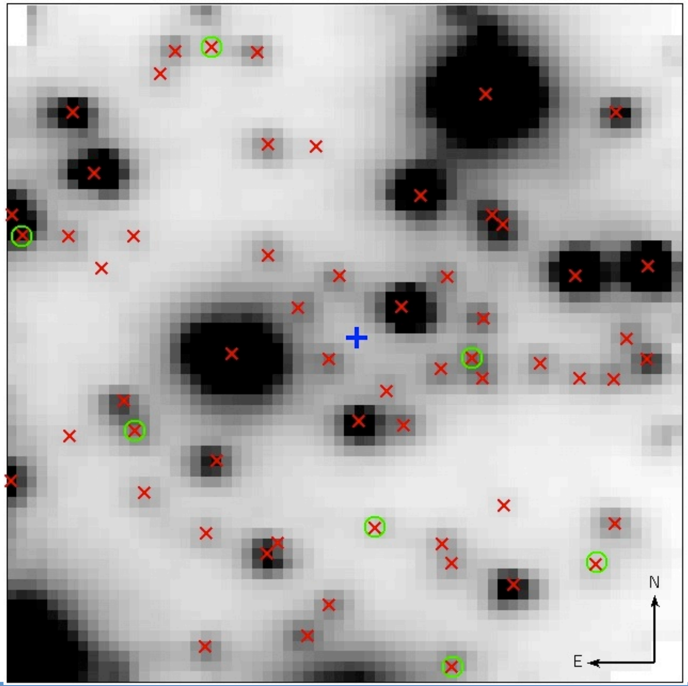
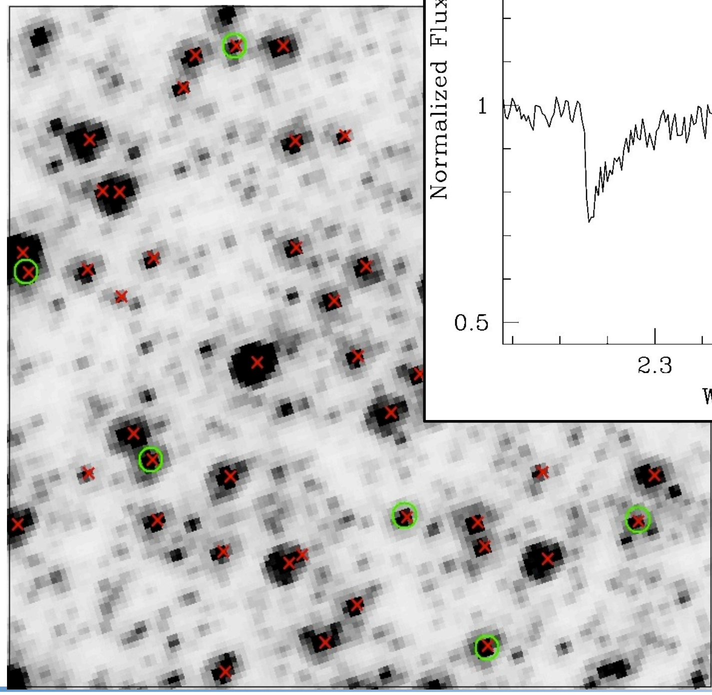
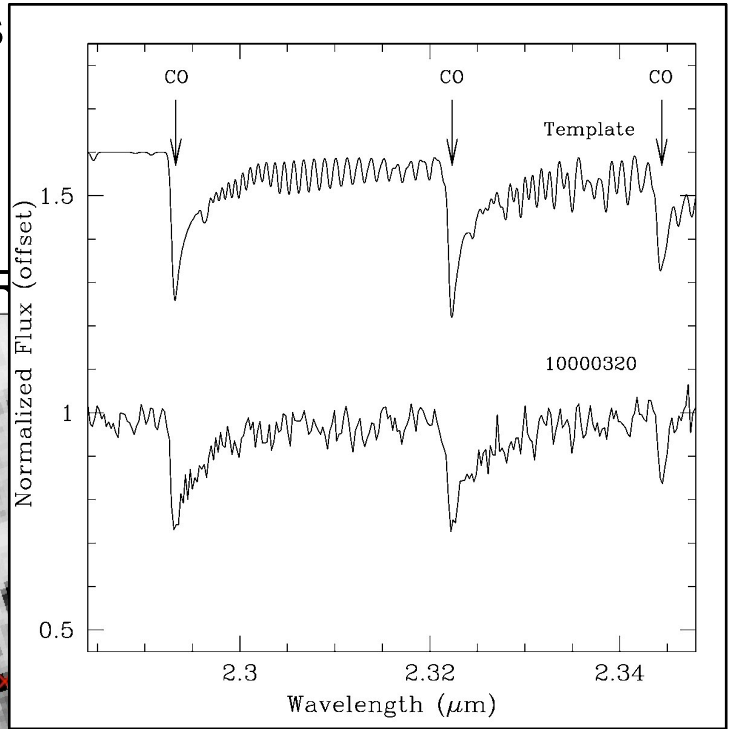
SINFONI







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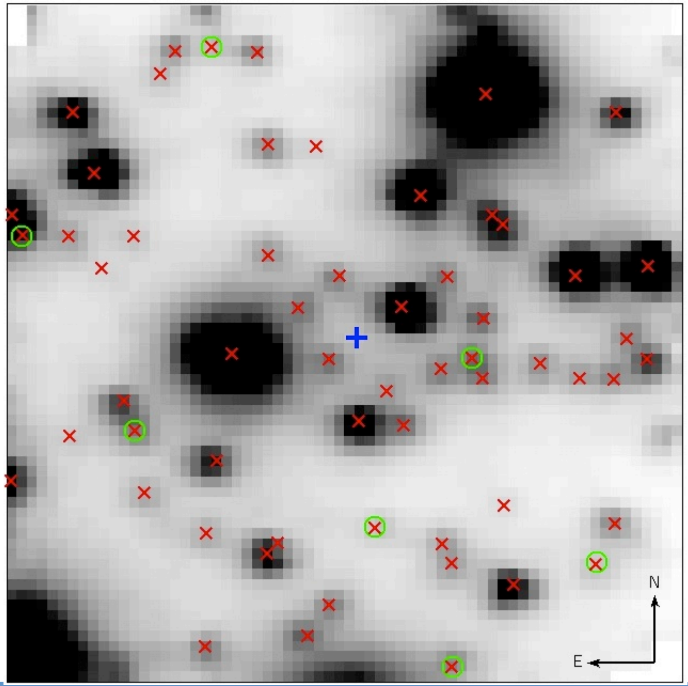
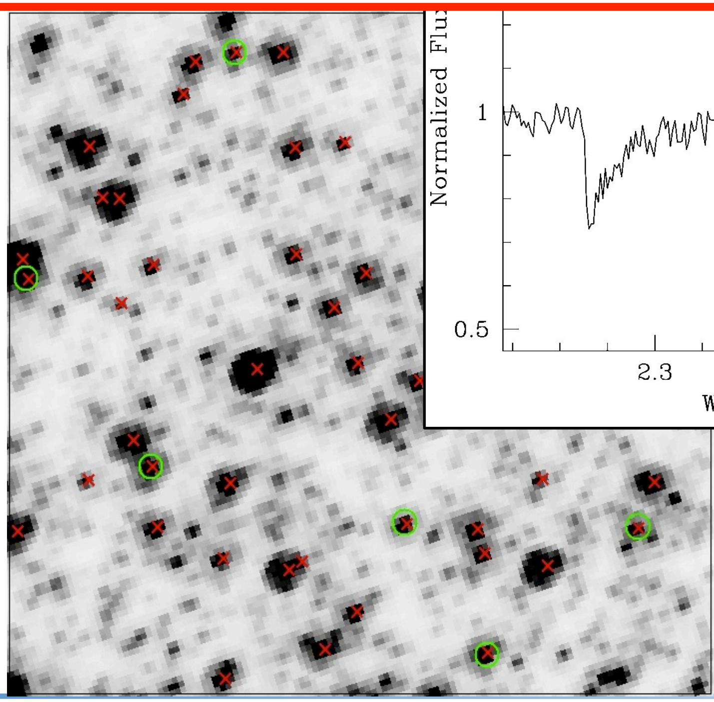
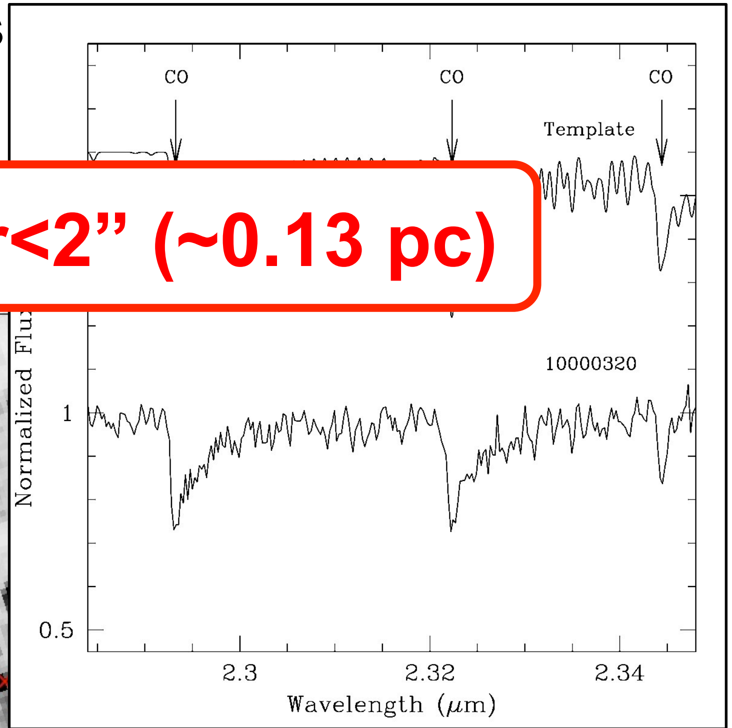
- V_r mainly from CO band-heads

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







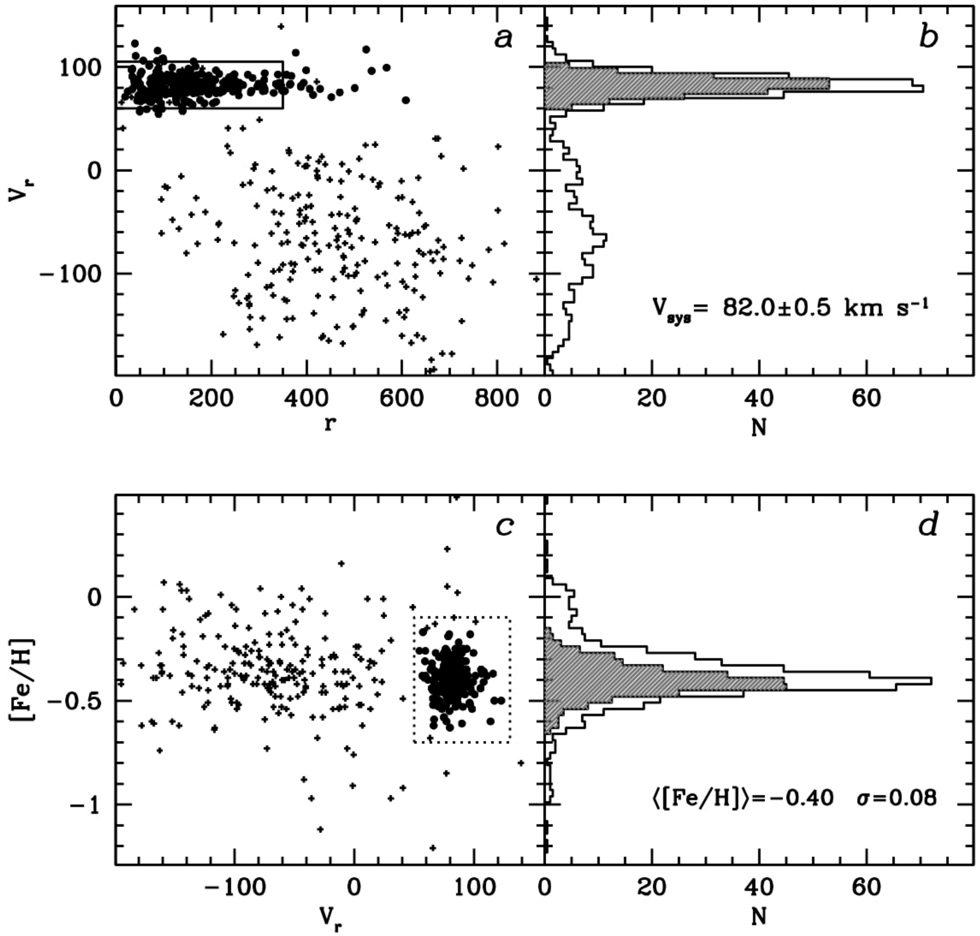
FLAMES (external) sample

- **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

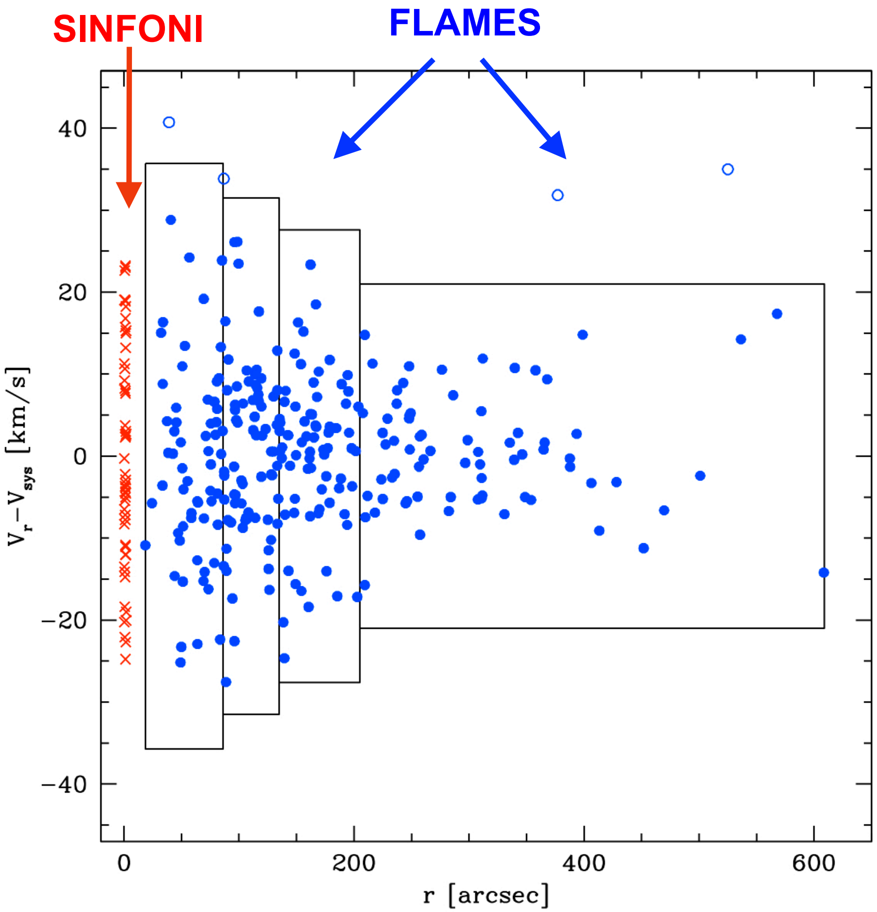
V_r & [Fe/H] for 508 stars

FLAMES (external) sample



276 cluster members

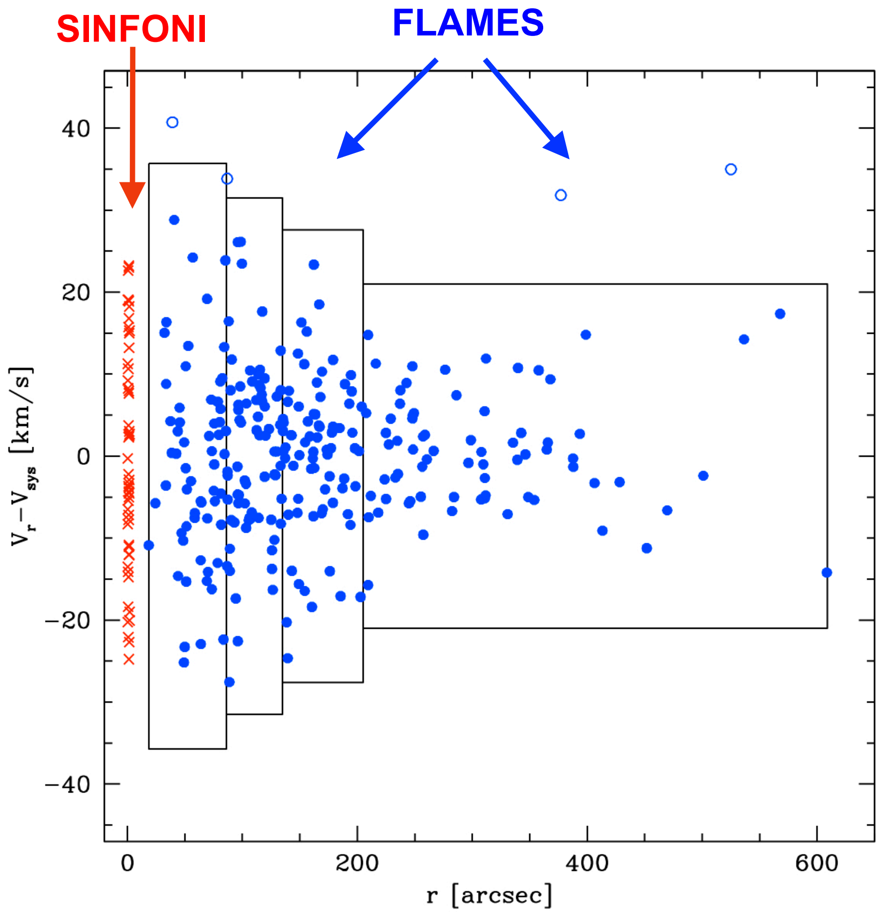
V_r for 276 individual stars at 18”<r<600”


SINFONI
FLAMES
$V_r - V_{sys}$ [km/s]
r [arcsec]
40
20
0
−20
−40
0
200
400
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)



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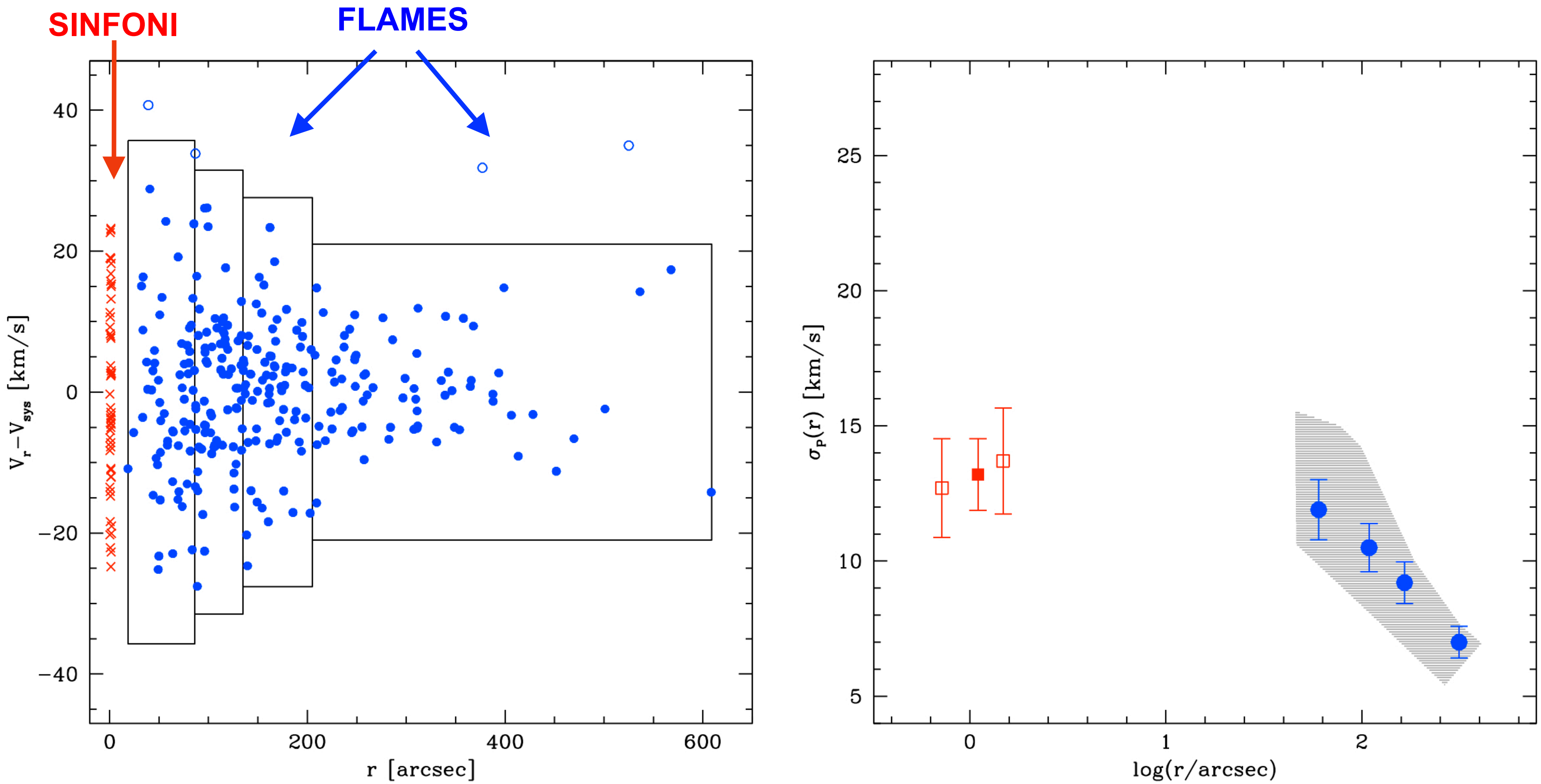
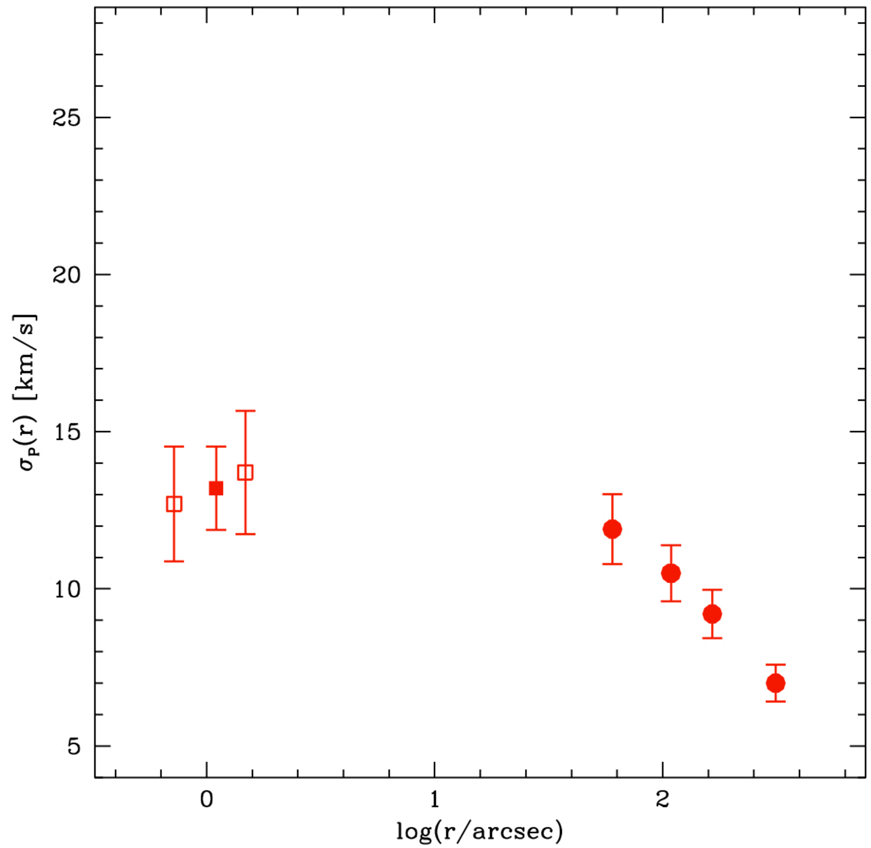


Velocity dispersion profile

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



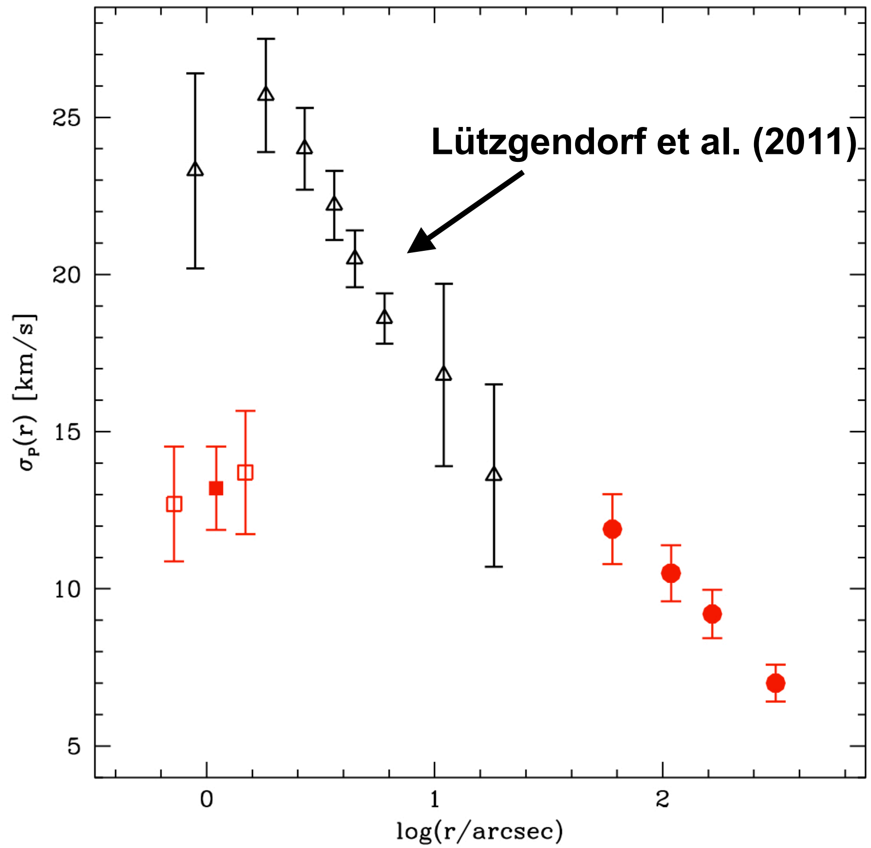
Velocity dispersion profile

σ(r) from individual V_r
(σ_0 ~ 13-14 km/s)

incompatible with

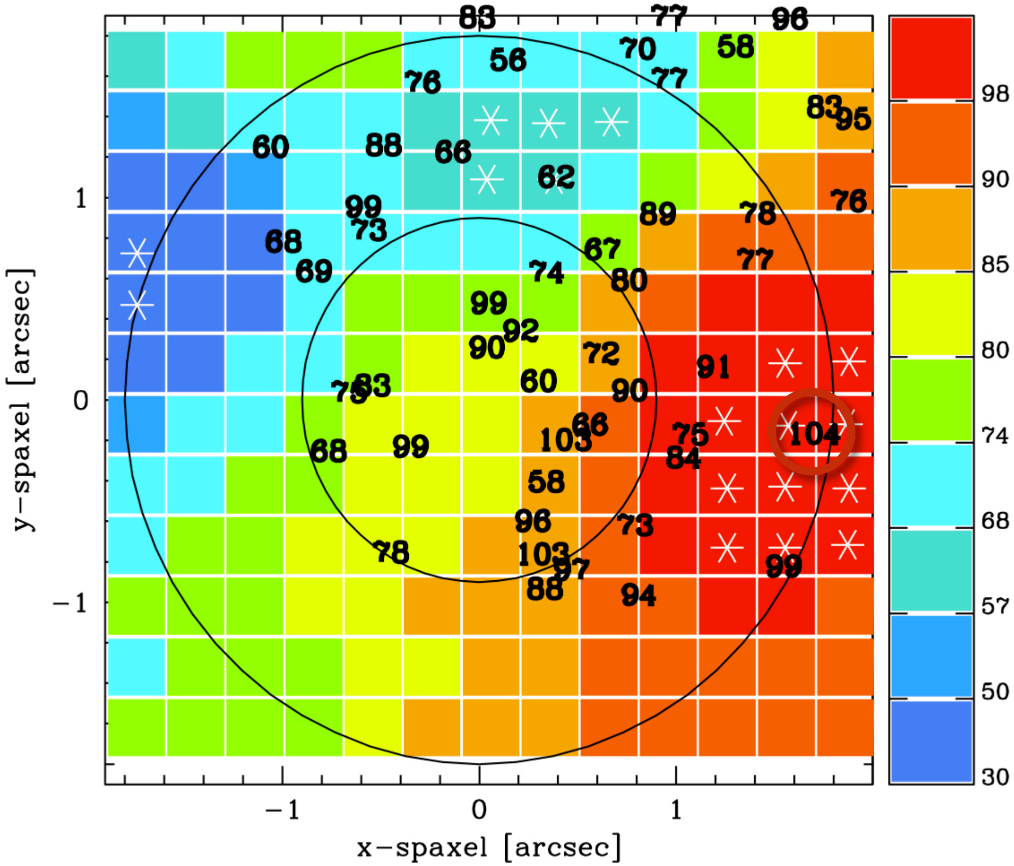
σ(r) from the line broadening of integrated-light spectra
(σ_0 ~ 23-25 km/s)

WHY ?

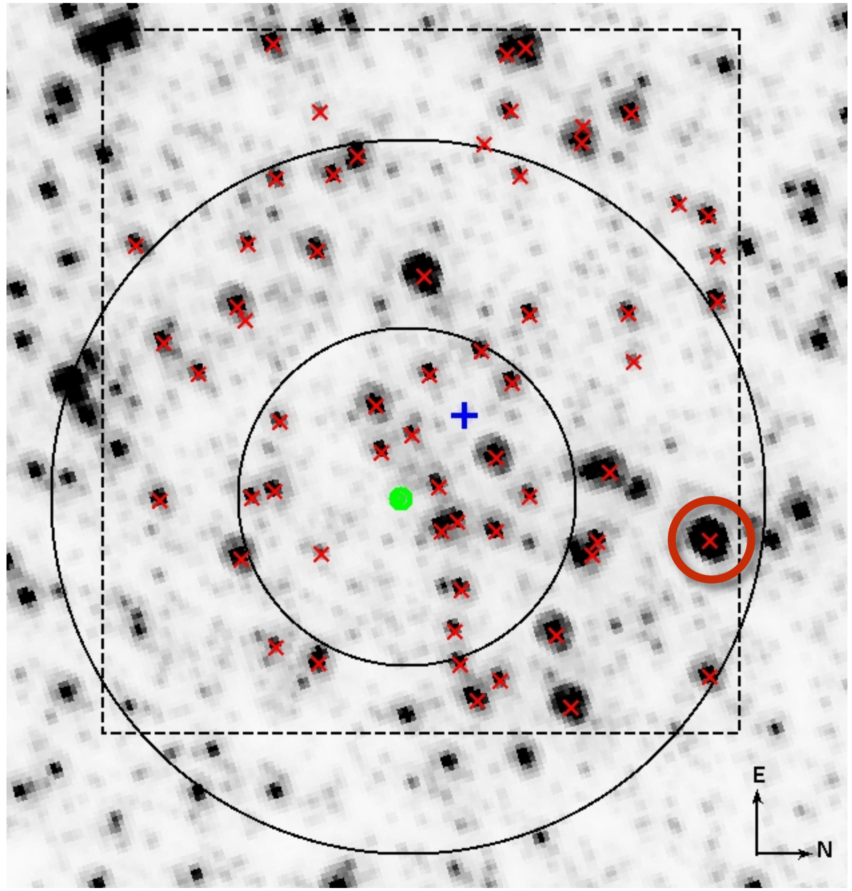


Insufficient shot-noise correction

→ **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



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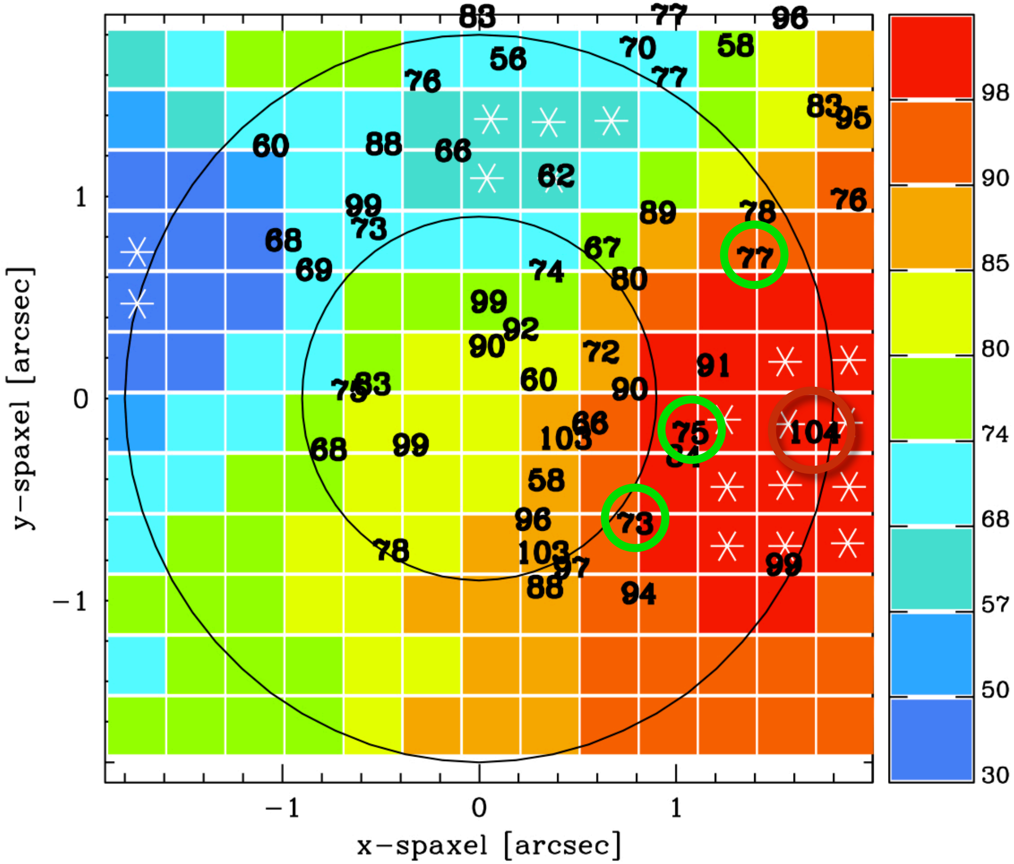

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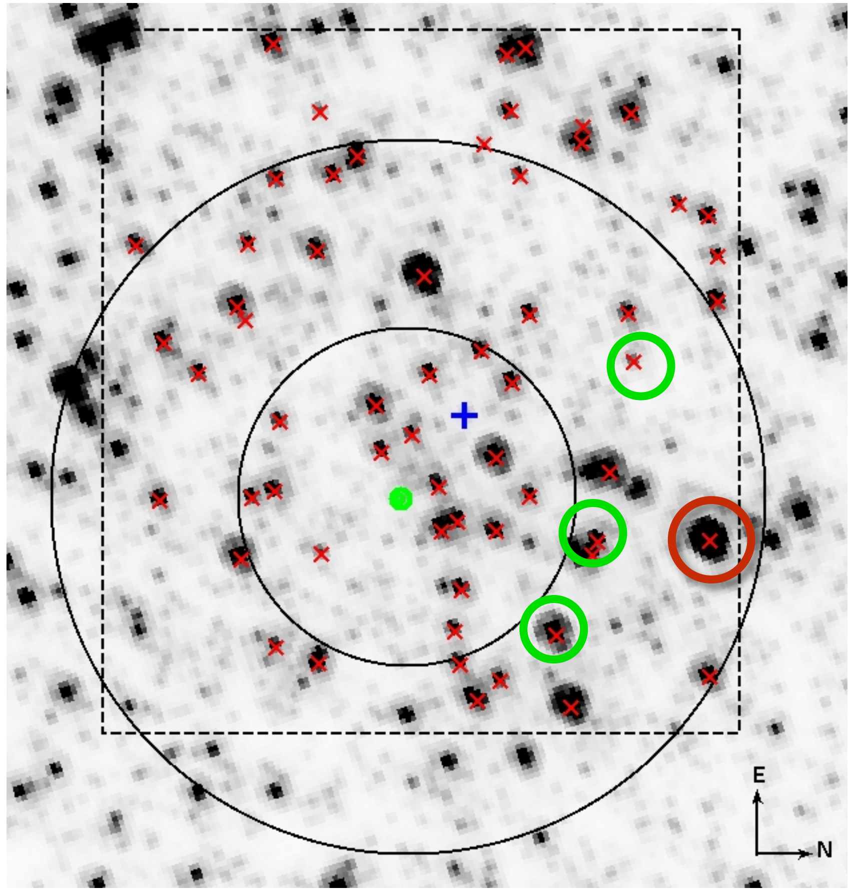

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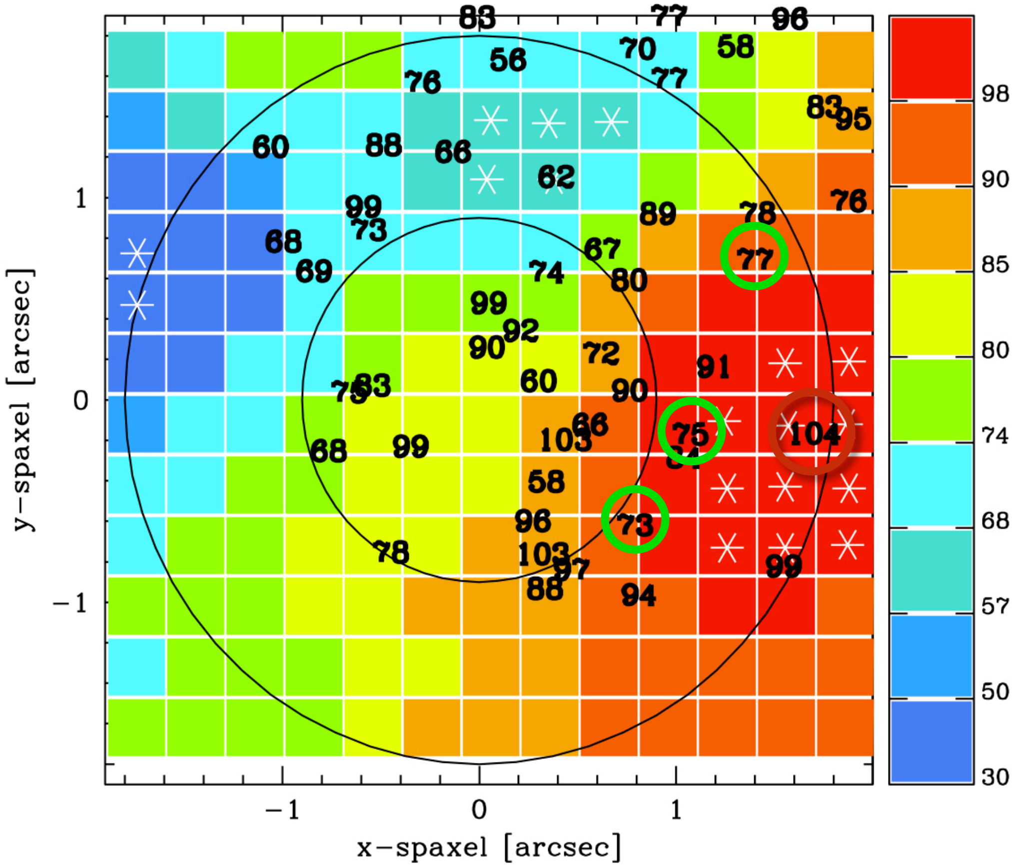
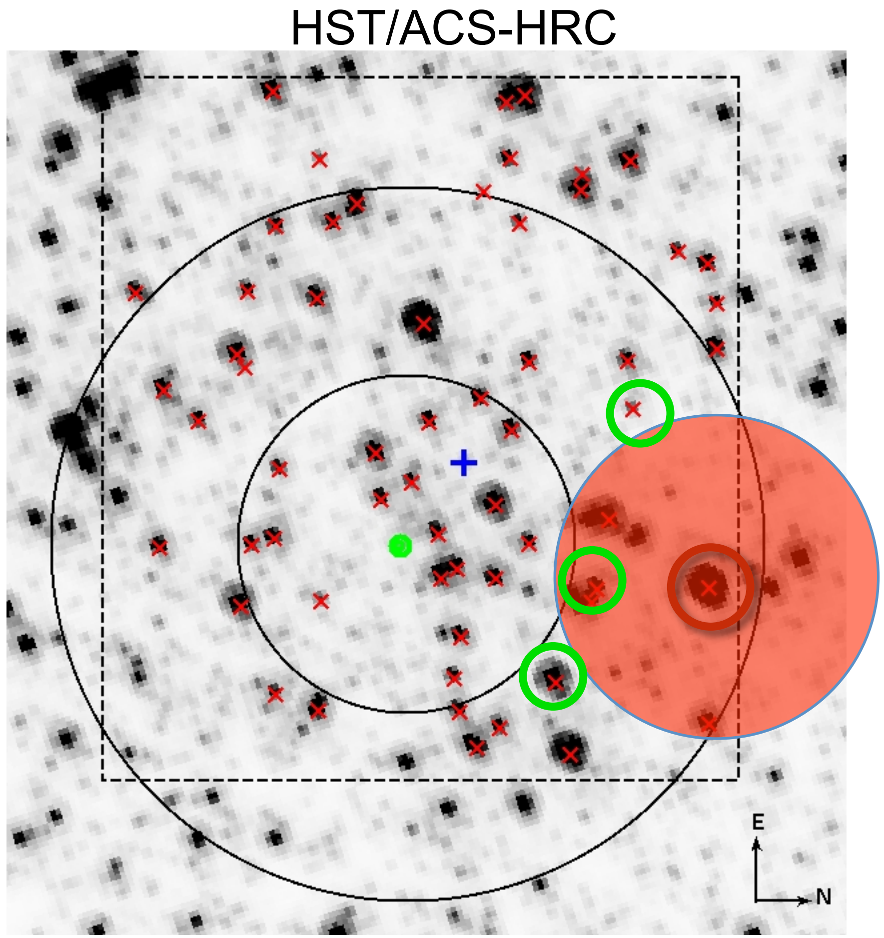
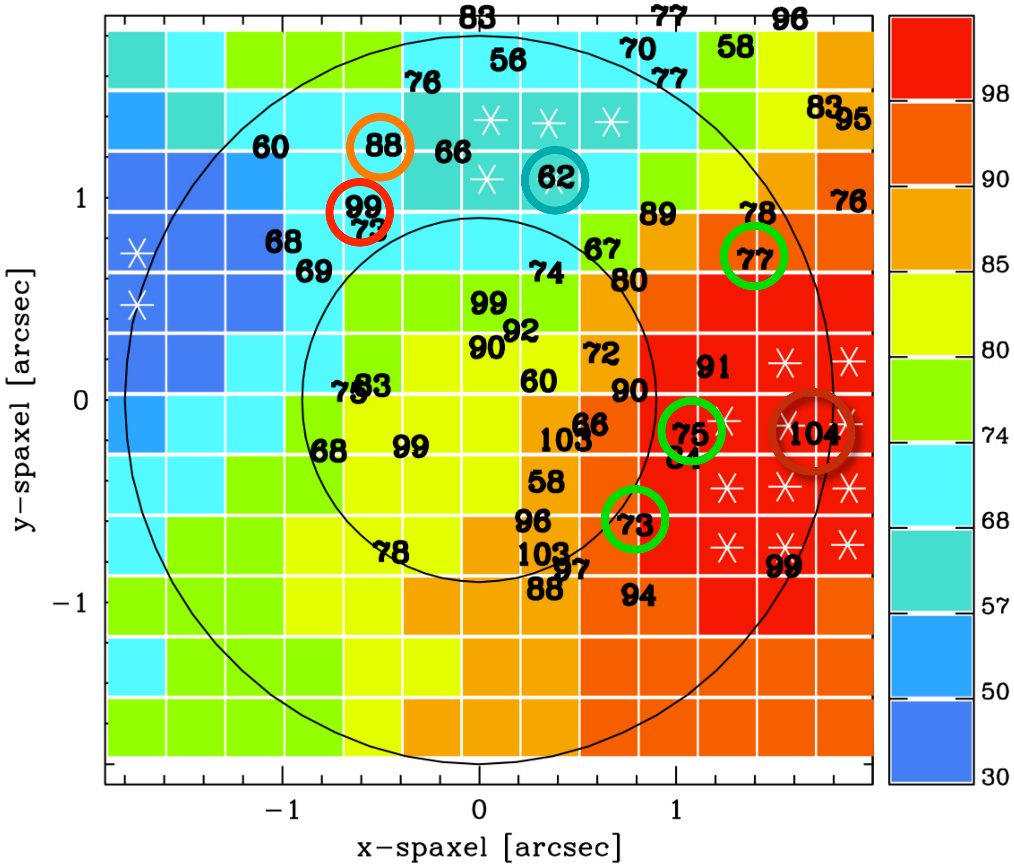


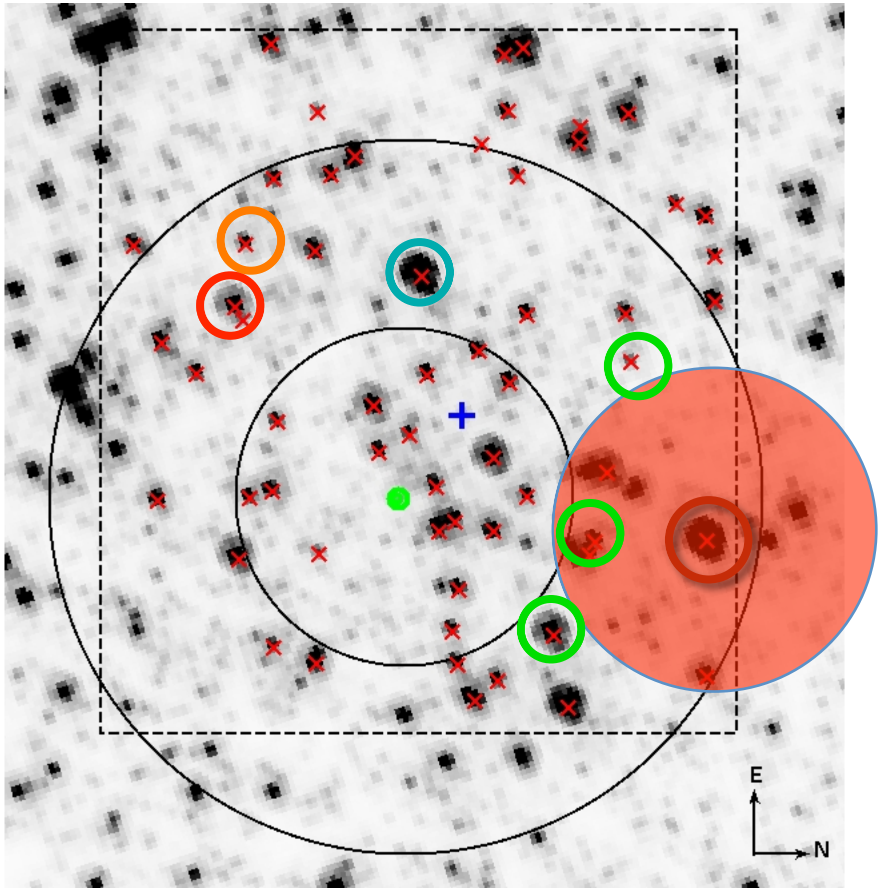


Insufficient shot-noise correction

→ **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



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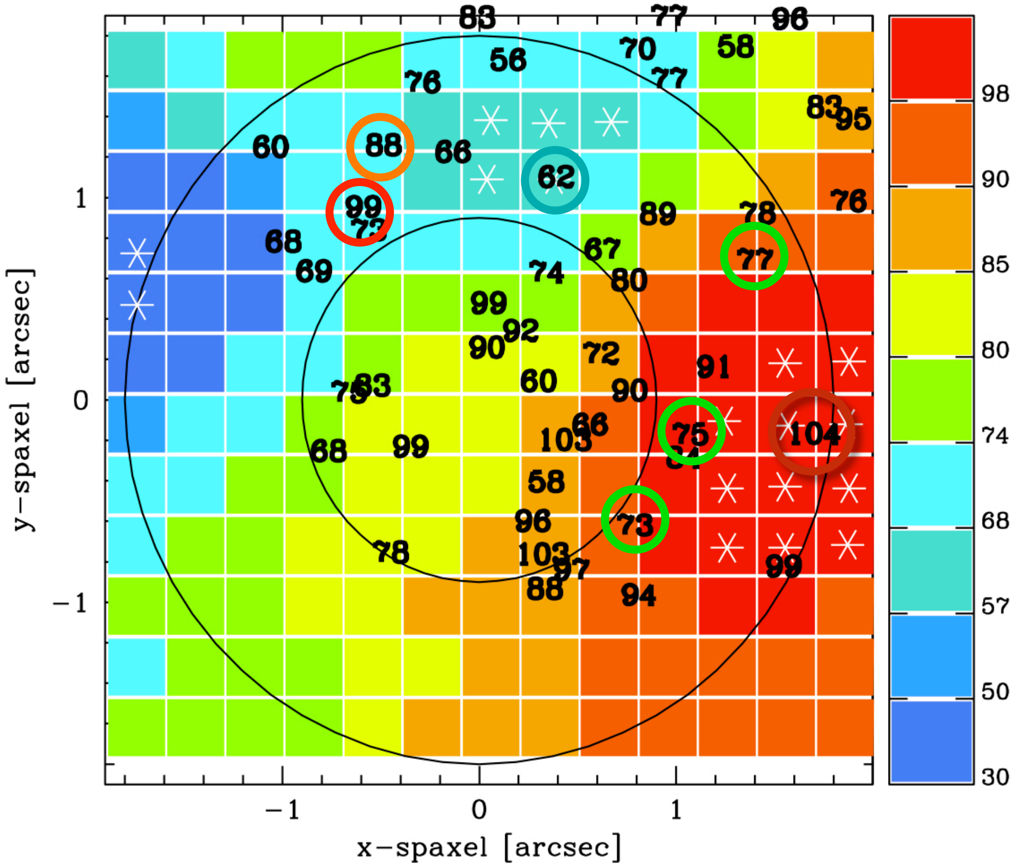

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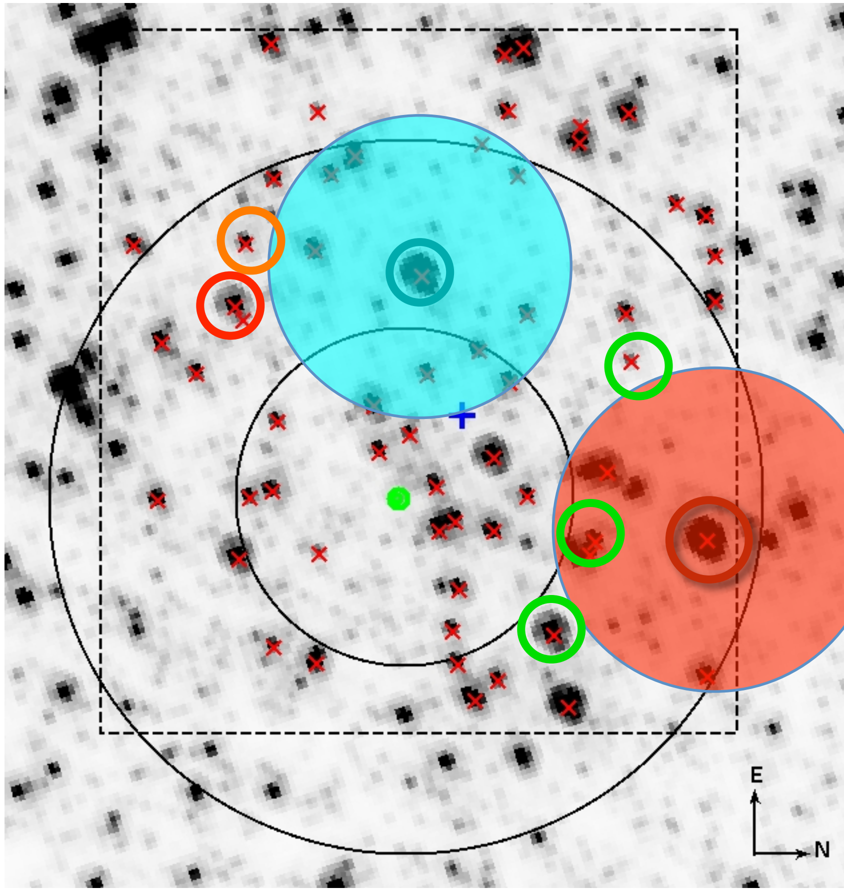

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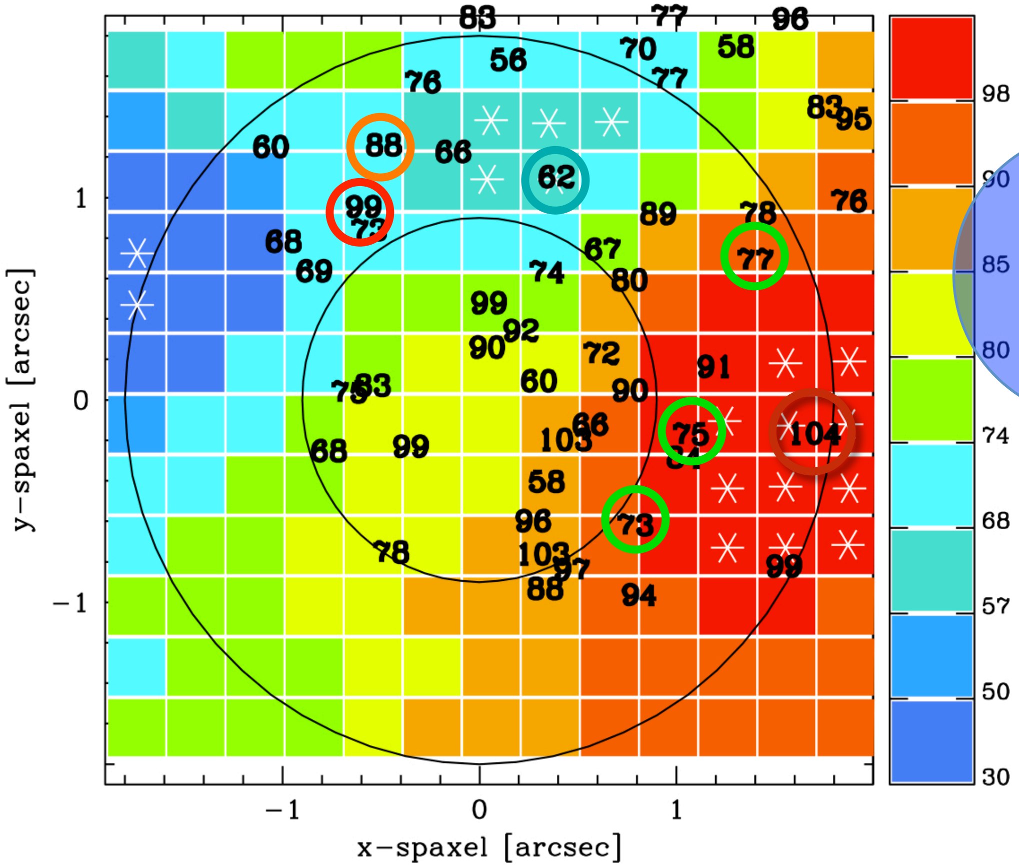

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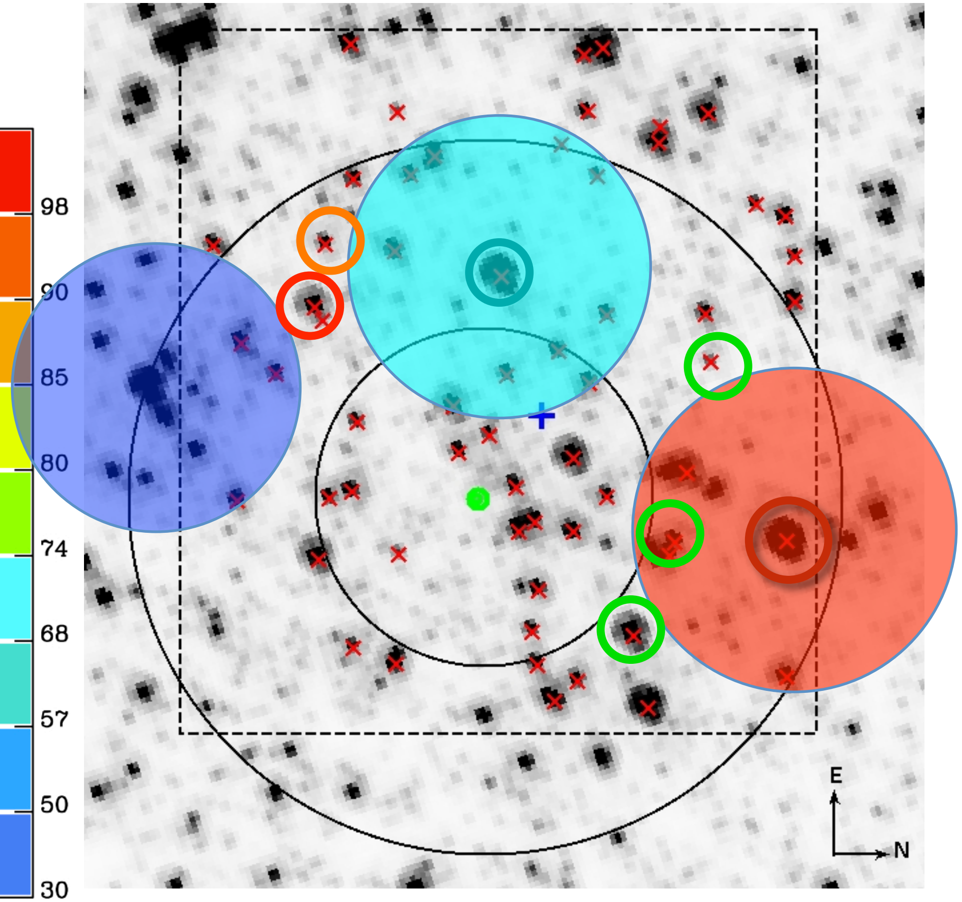
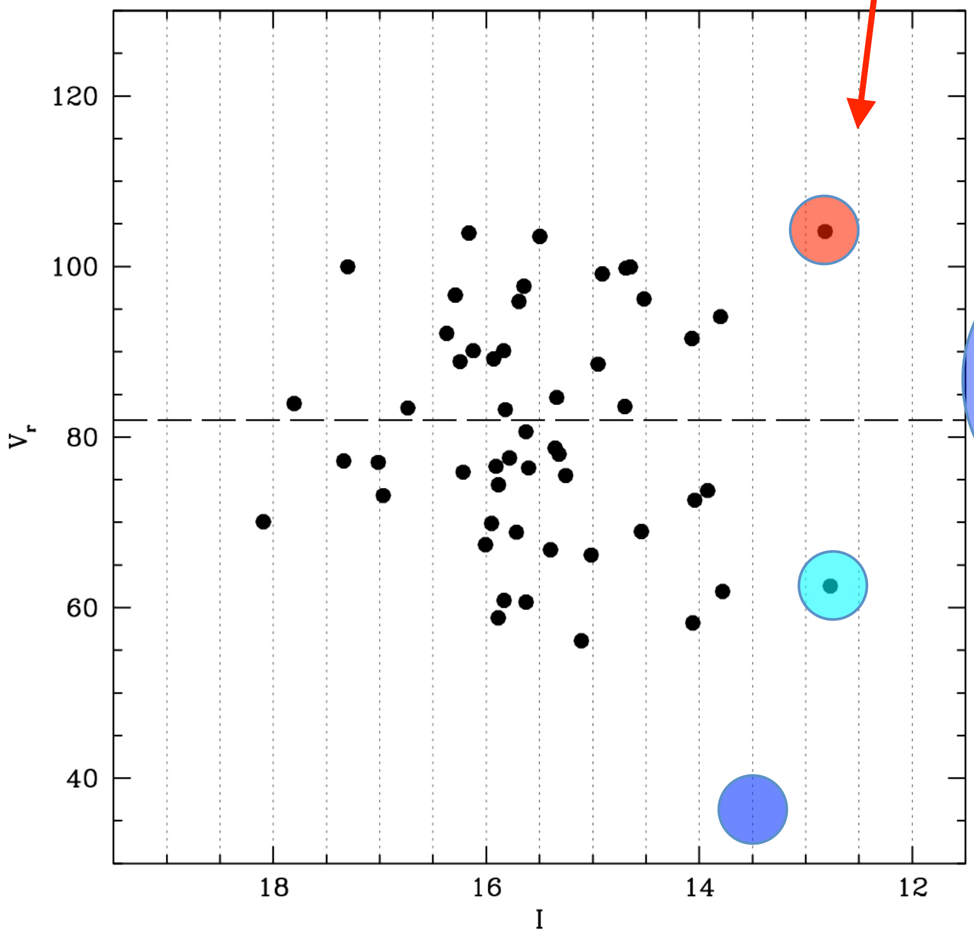


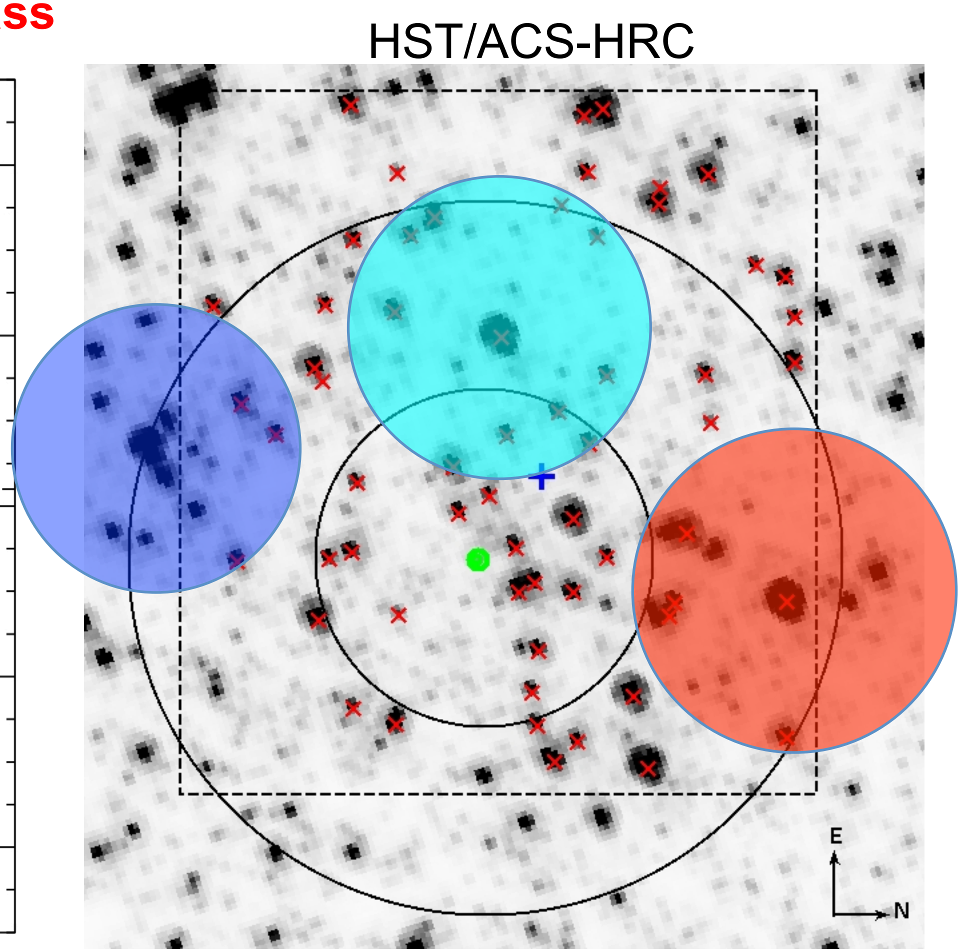
Spectra dominated by the light of a few bright stars with quite different V_r

=> artificial line broadening

=> overestimate of σ(r)

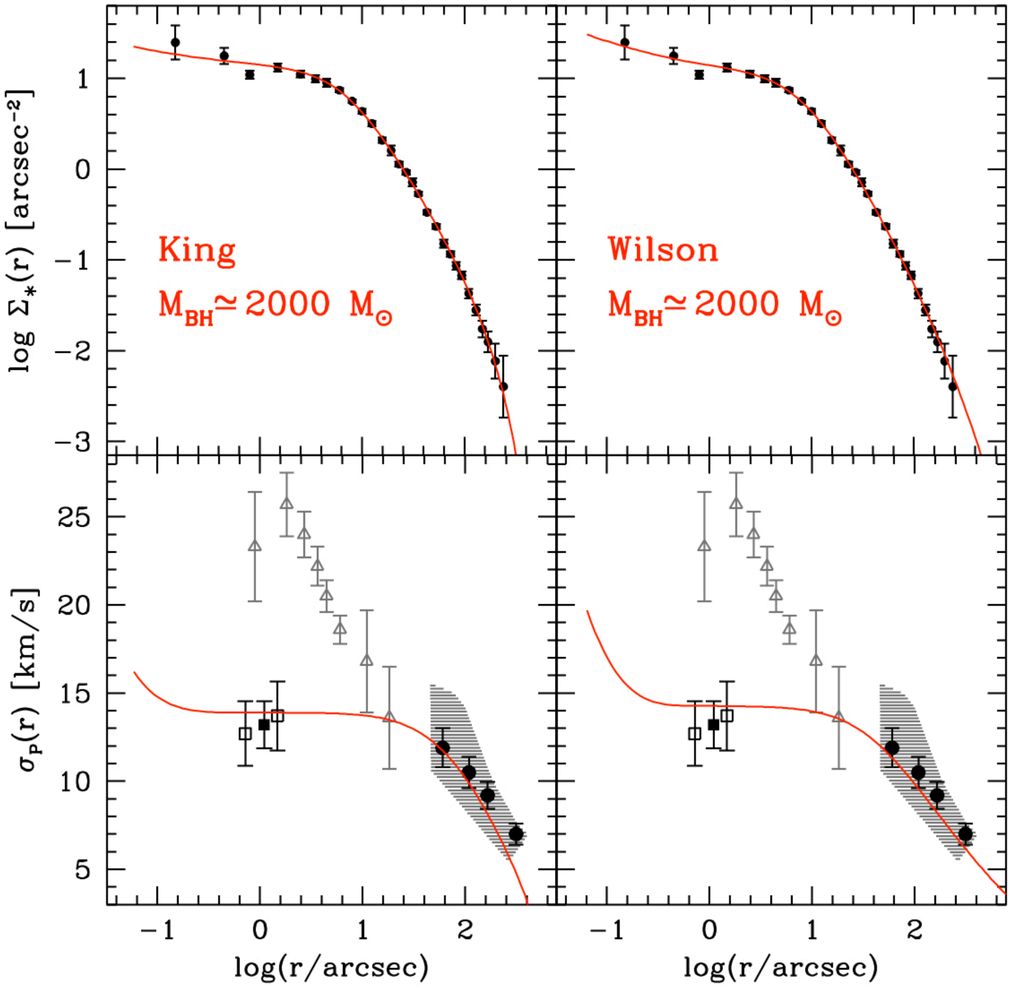
=> overestimate of IMBH mass





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)

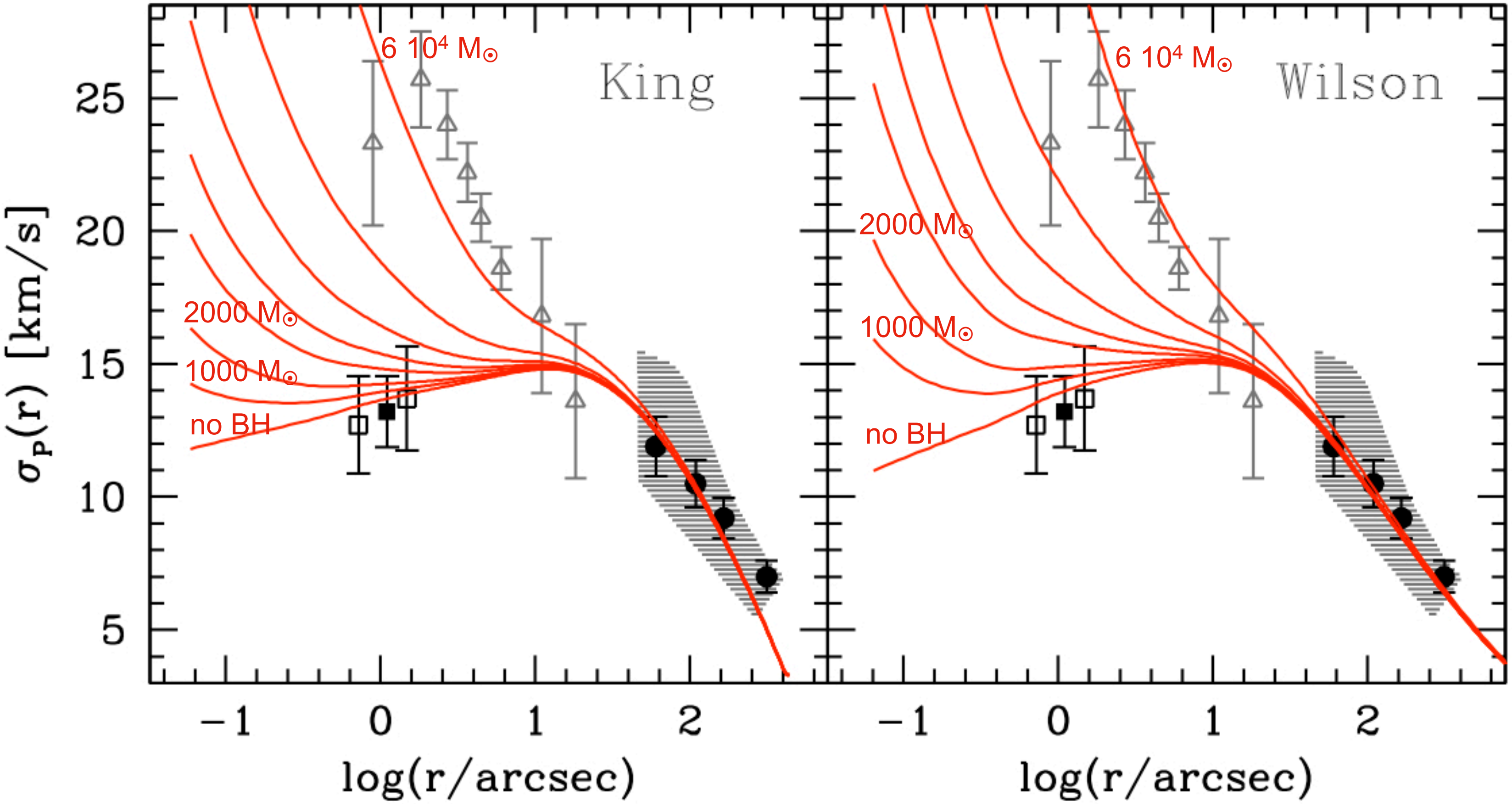


M_{BH} of ~ 2 10^3 $M_\odot$

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)



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; Lützgendorf+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**

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M15

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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; PI: Ferraro; 194 hours)

→ **FLAMES** for the **external** regions
(130 fibers in 25' diameter FOV)

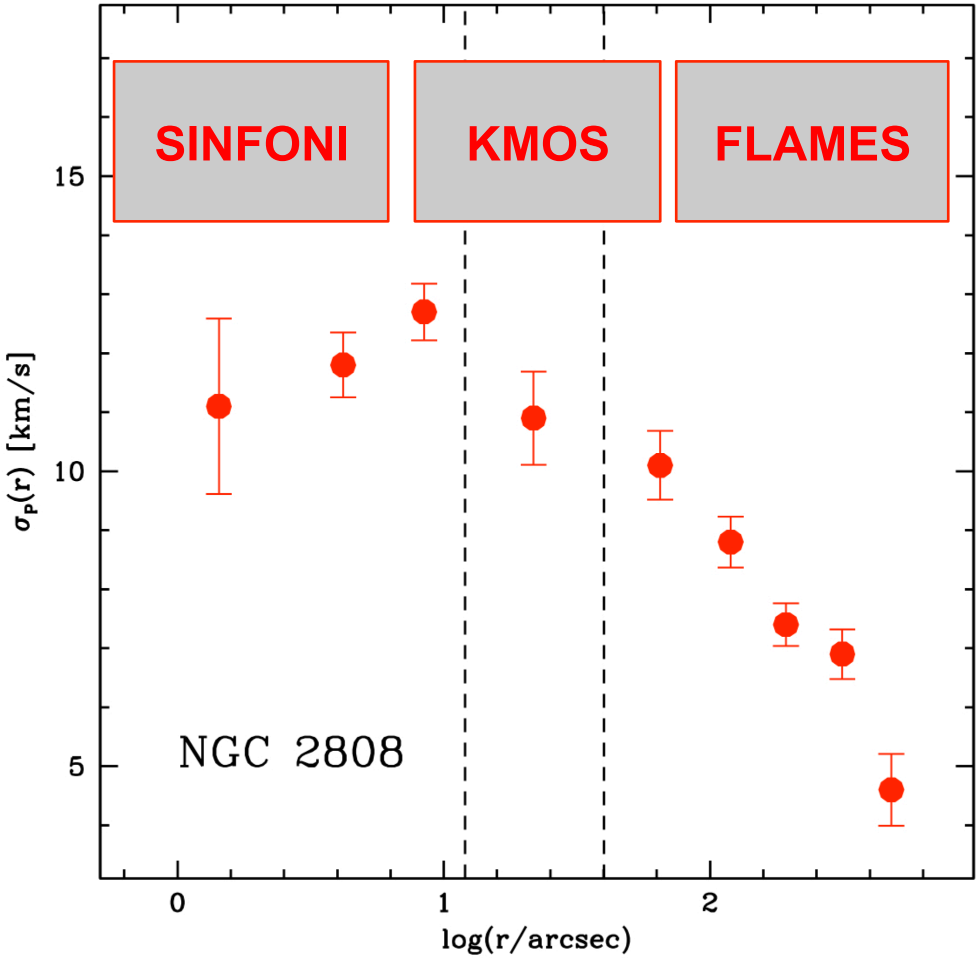
→ **KMOS** for the **internal/intermediate** regions
(24 deployable IFUs in 7.2' diameter FOV)

COMPANION PROGRAMMES
(P92+93; PI: Lanzoni; 48 hours)

→ **SINFONI** for the **innermost regions** of the **densest clusters**
(AO-assisted IFU)

Very preliminary results for NGC 2808

- **FLAMES** (external regions): ~ 790 stars, mainly at 40”<r<700”
- **KMOS** (intermediate region): ~ 96 stars, mainly at 12”<r<40”
- **SINFONI** (innermost region): ~ 700 stars, at 0.5”<r<12” (7 fields of 8”x8” each)



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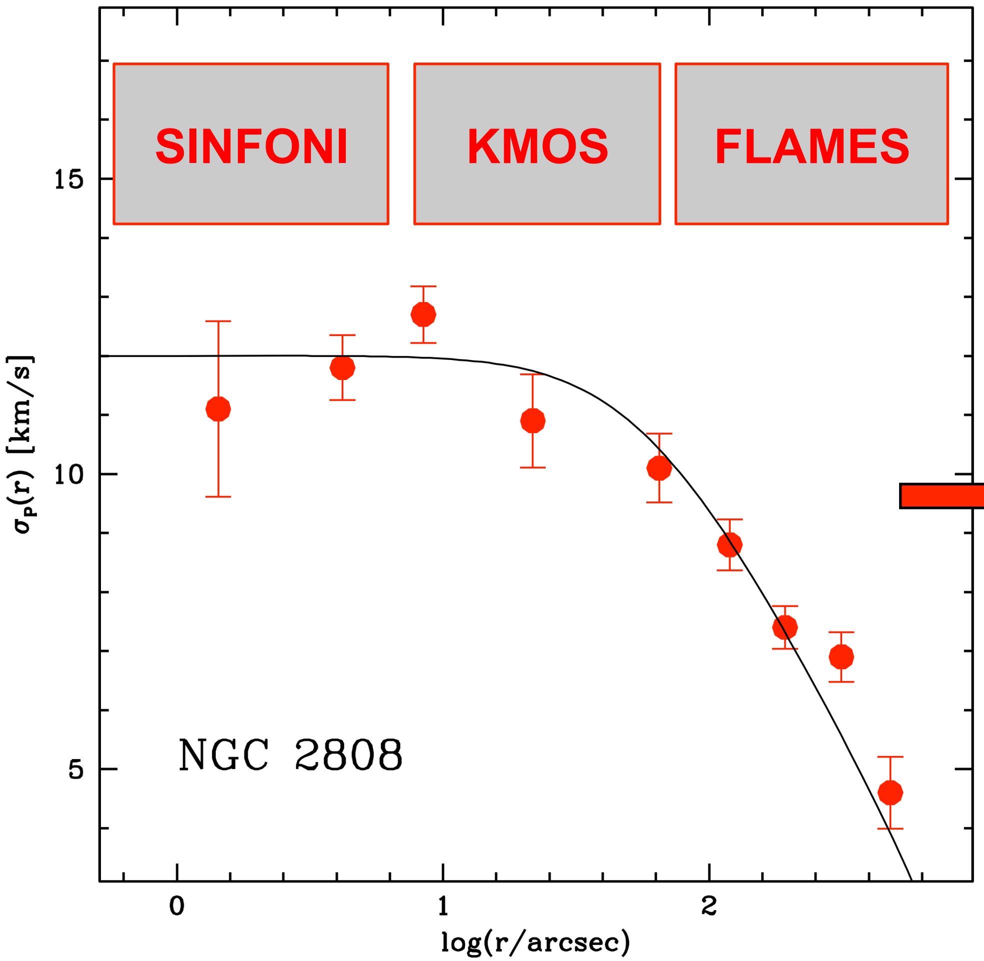
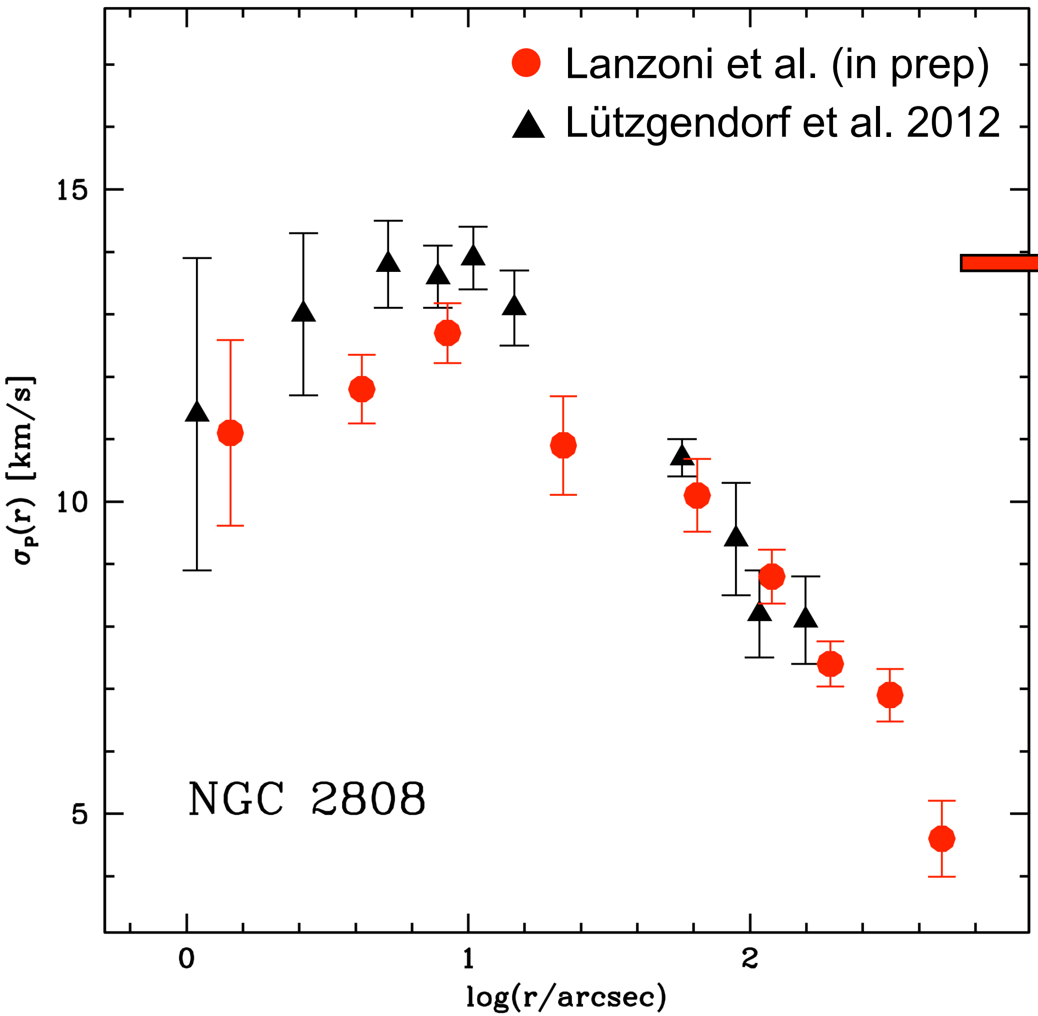


NO IMBH

Cosmic-Lab

erc

Very preliminary results for NGC 2808



Good agreement
with integrated-light results
(Lützgendorf et al. 2012)

Conclusions

- radial velocities of individual stars are crucial to properly study the l.o.s. velocity dispersion
- proper motions will hopefully have an important role as well
- still many uncertainties (both theoretical and observational)
- details of modelling do matter (isotropy, spherical symmetry, M/L,...)
- detecting several fingerprints in the same cluster is the only way?

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

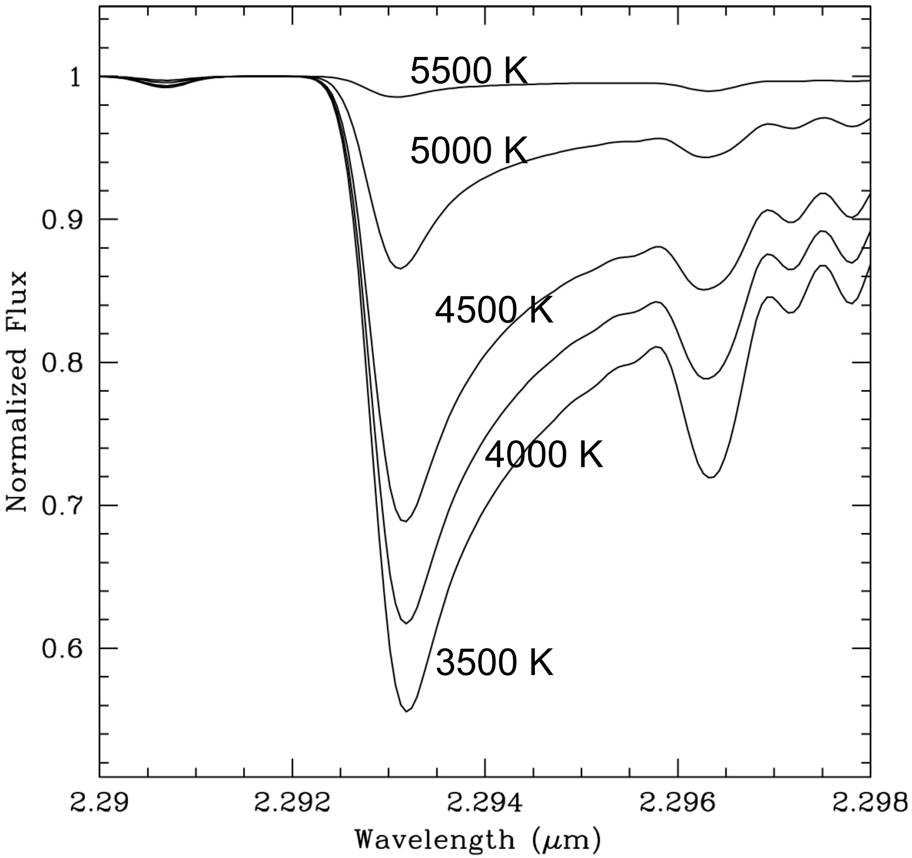
Thank you for your attention

BARBARA LANZONI

Physics & Astronomy Department – University of Bologna (Italy)

Contamination from unresolved background

CO band-head at varying Teff



SINFONI CMD