

# SNOWPAC 2013

March 17-23, 2013

Snowbird, Utah

**BLACK HOLE FINGERPRINTS**  
Dynamics, Disruptions & Demographics

## **Kinematics of NGC 6388 from the radial velocity of individual stars**

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(Italy)



- ✦ 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**

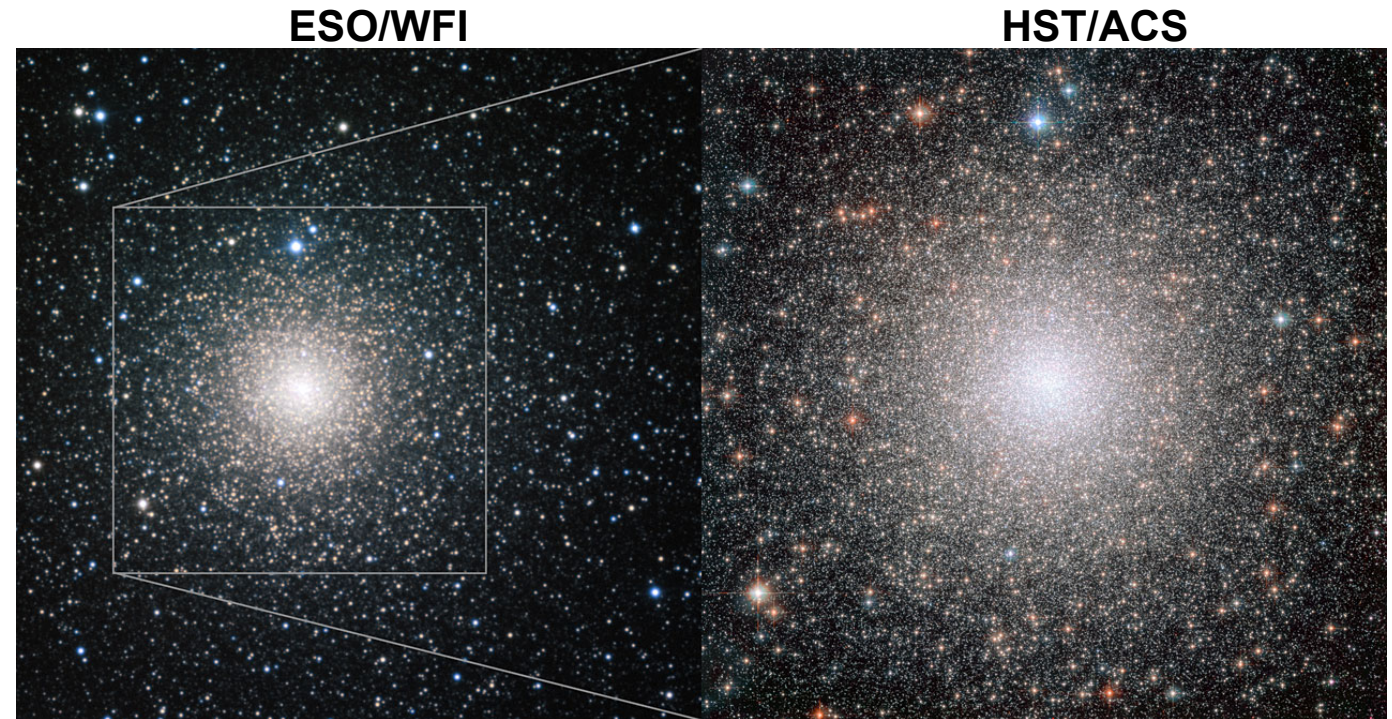
**Millisecond Pulsars**

**Intermediate-mass Black Holes**

} as probe-particles



# NGC 6388



- one of the most massive Galactic GCs:  $M \sim 2.6 \cdot 10^6 M_{\odot}$
- 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)

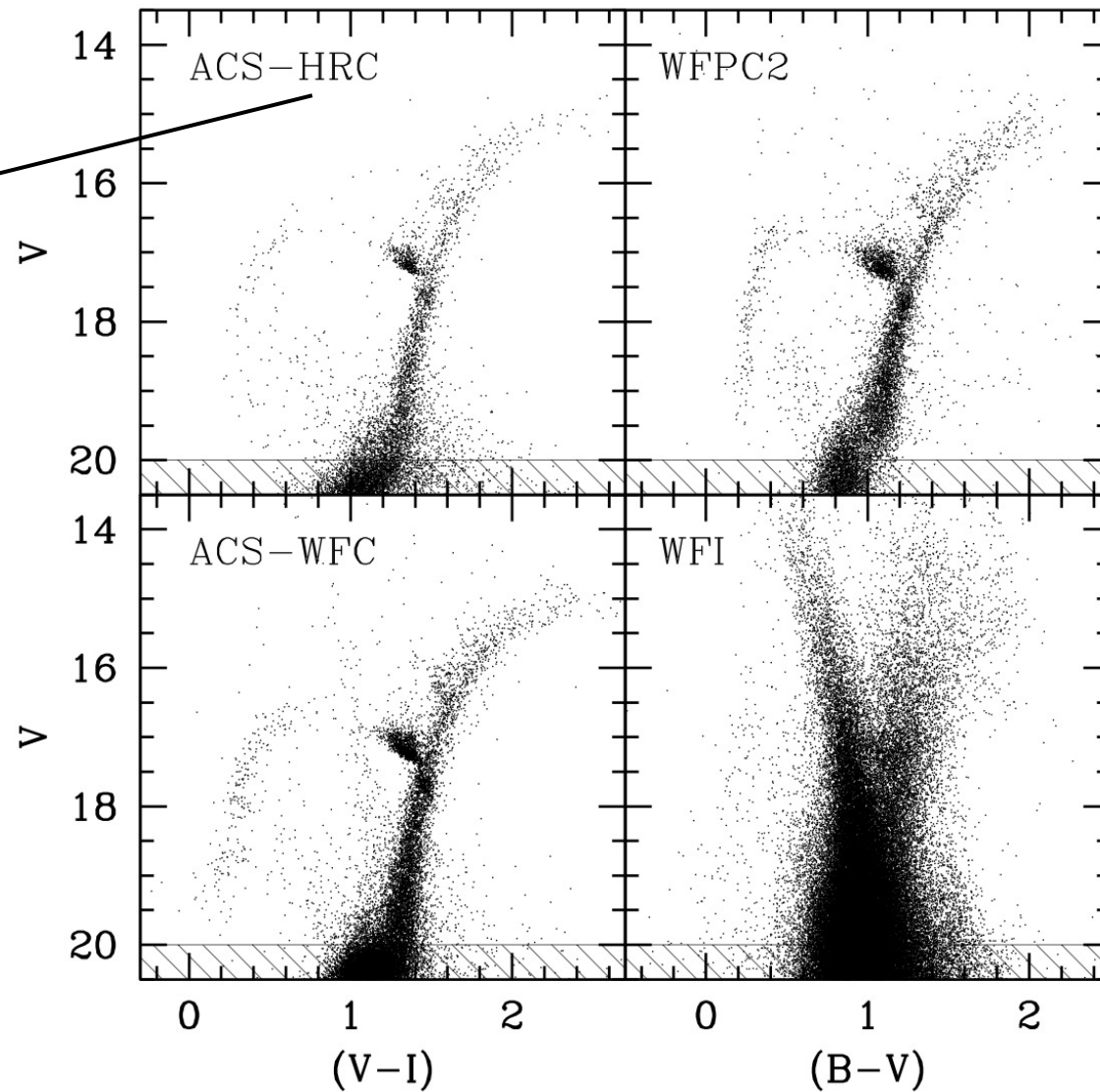
- shallow cusp in SB:  $I \sim r^\alpha$ ,  $\alpha = -0.13$  (Noyola & Gebhardt 2006)
- IMBH in the centre? (Baumgardt et al. 2005; Miocchi 2007;  
....but see Vesperini & Trenti 2010)

# Photometric data set

(Lanzoni et al. 2007, ApJ 668, L139)

26" x 29" FoV

0.027 arcsec/pix

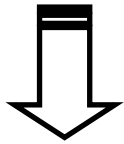


# Determination of the centre

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

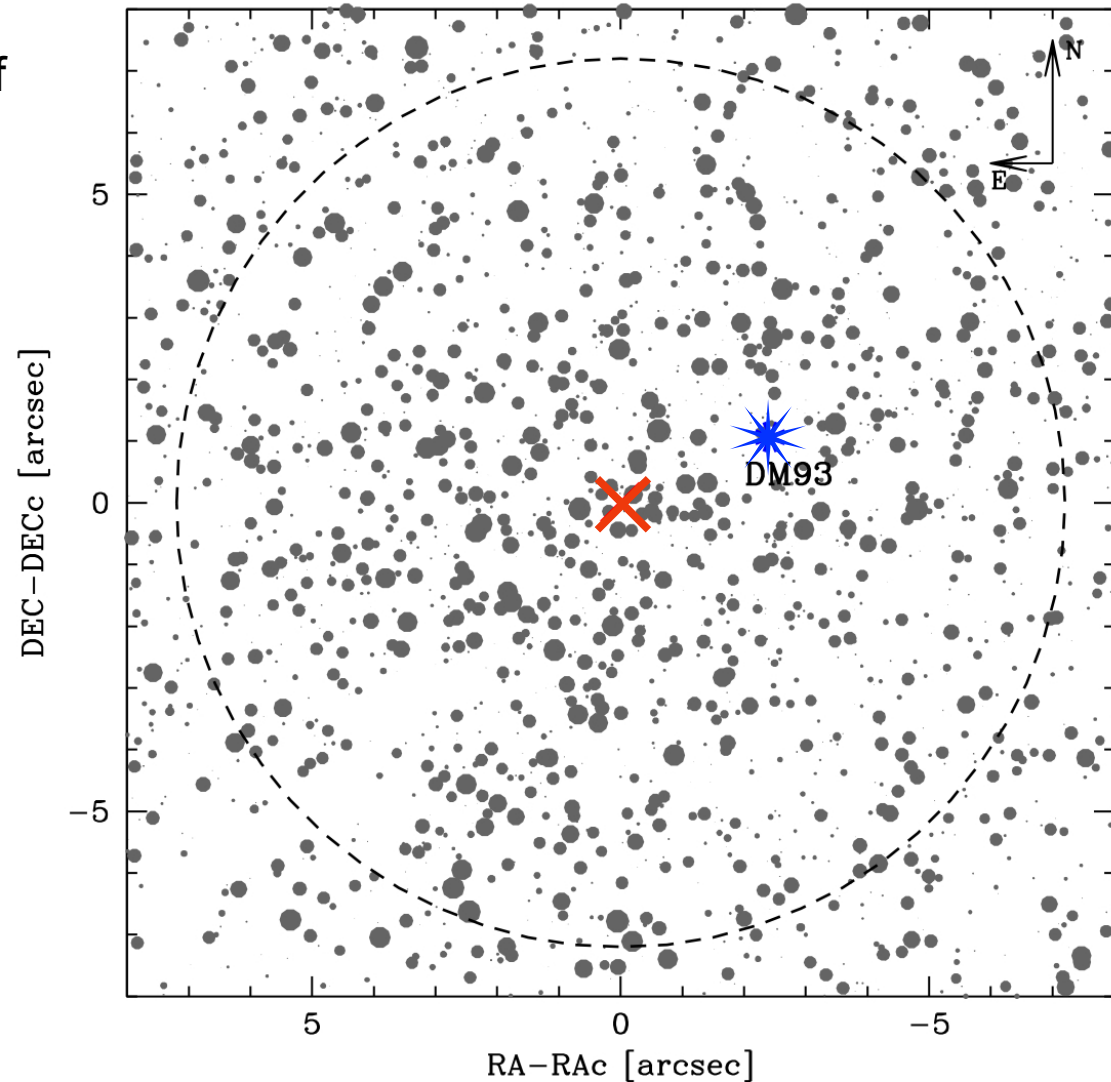
$$\alpha_{J2000} = 17^{\text{h}} 36^{\text{m}} 17.23^{\text{s}}$$

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



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

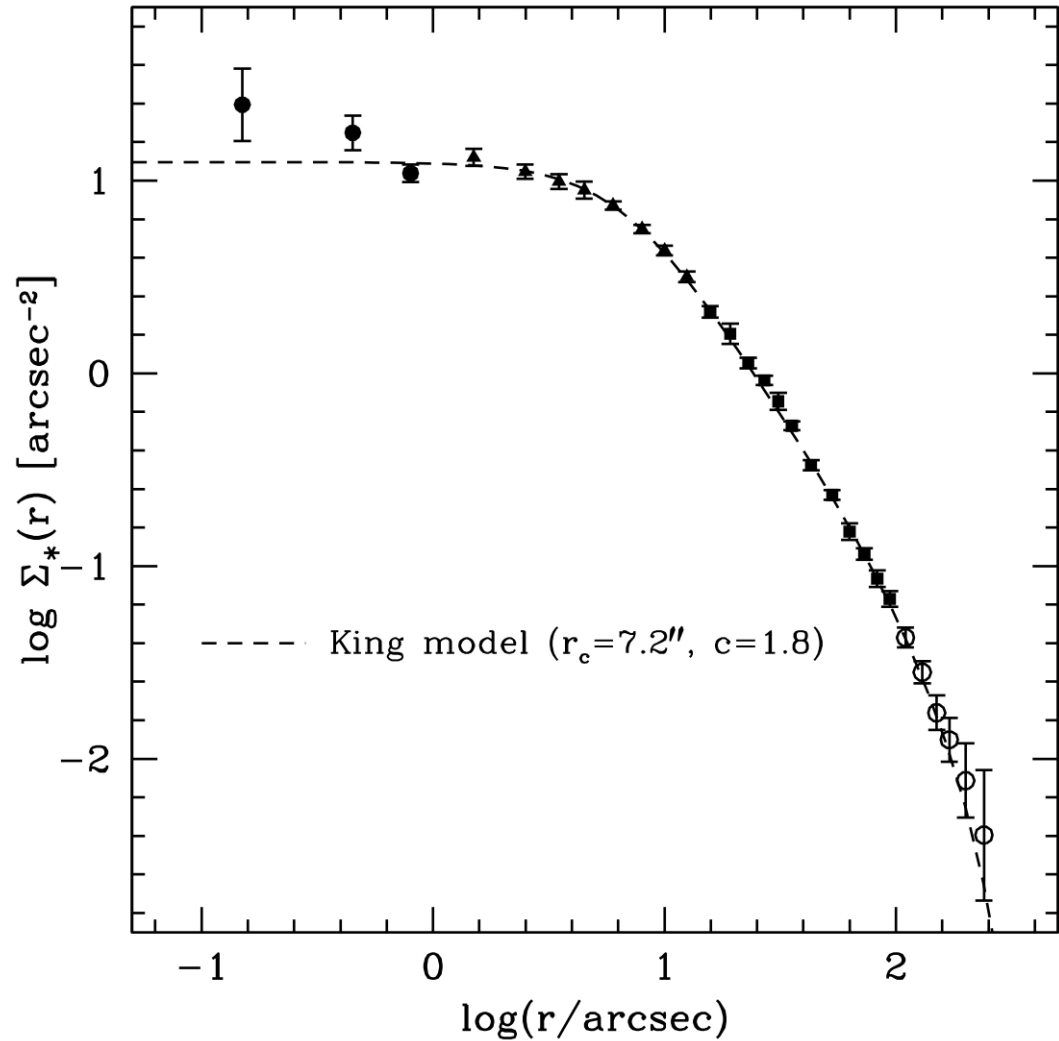
perfect agreement with  
Goldsbury et al. (2010)



# Projected density profile

(star counts in radial annuli)

deviation from  
a King profile  
at  $r < 1''$





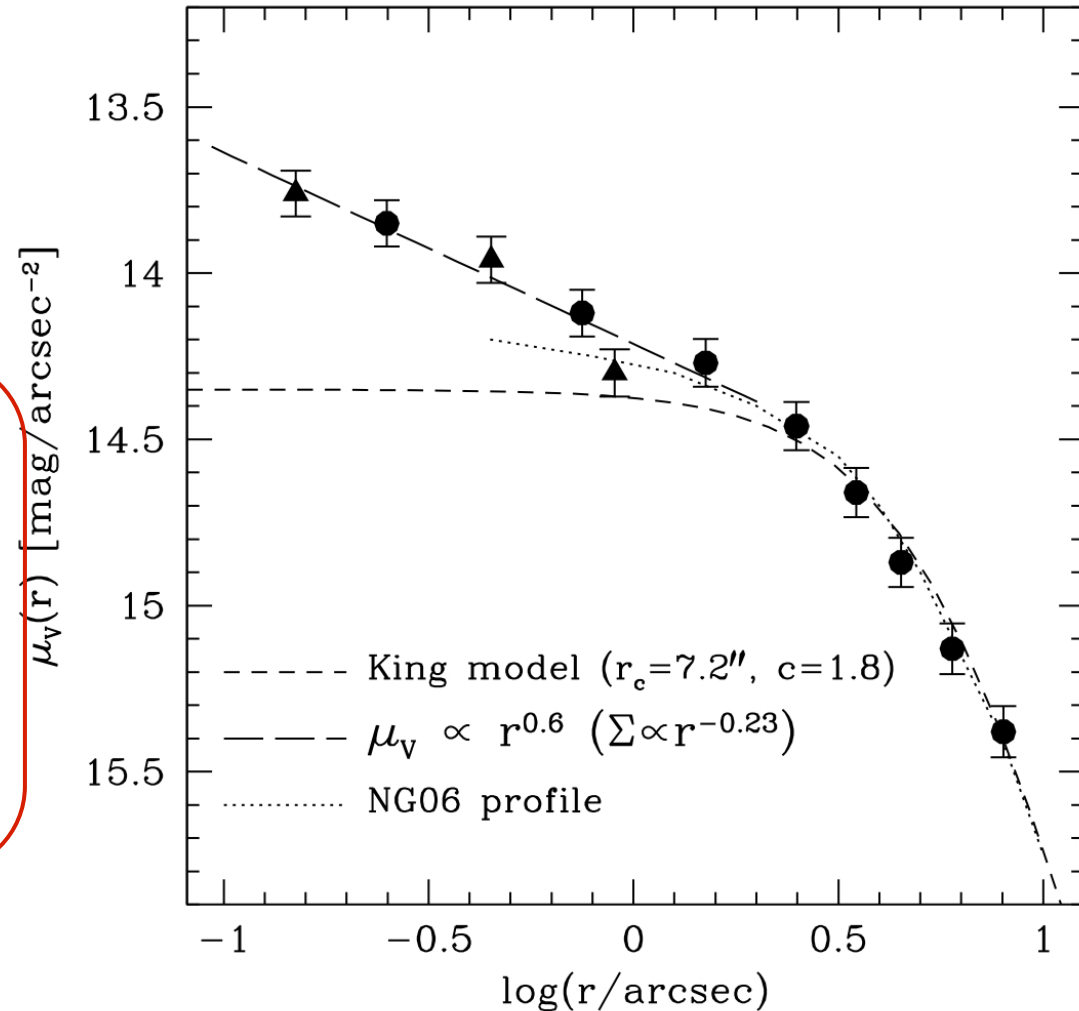
# Surface brightness profile

## Signatures of IMBH

(Baumgardt et al. 2005;  
Miocchi 2007):

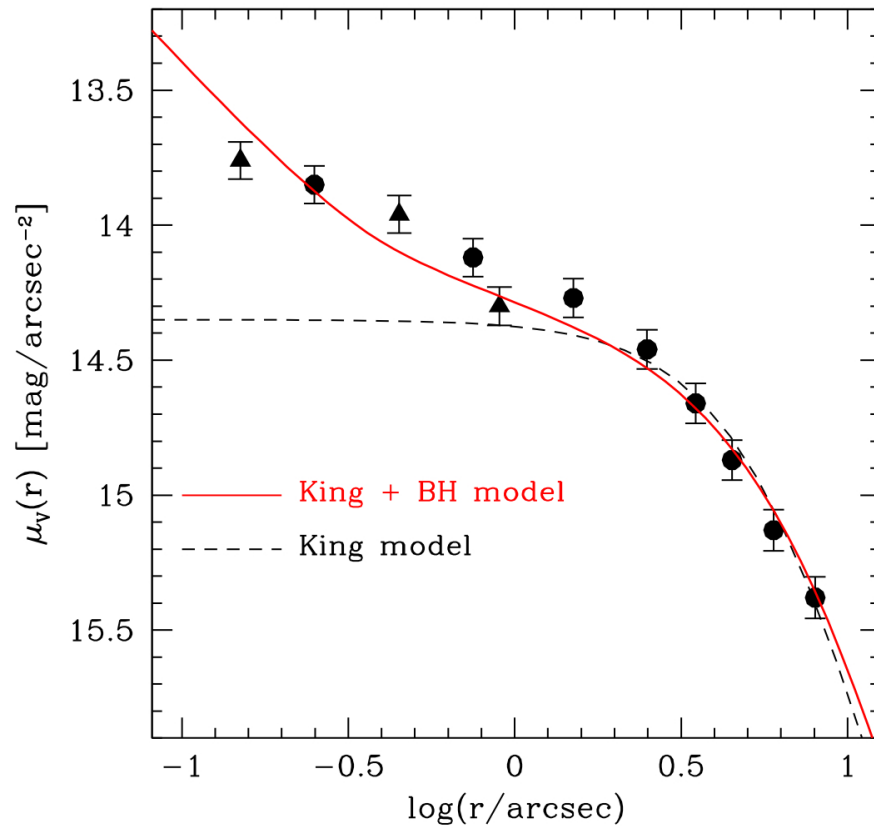
$$c \sim 1.8$$

$$I(r) \sim r^{-0.23} \text{ at } r < 0.1 r_c$$

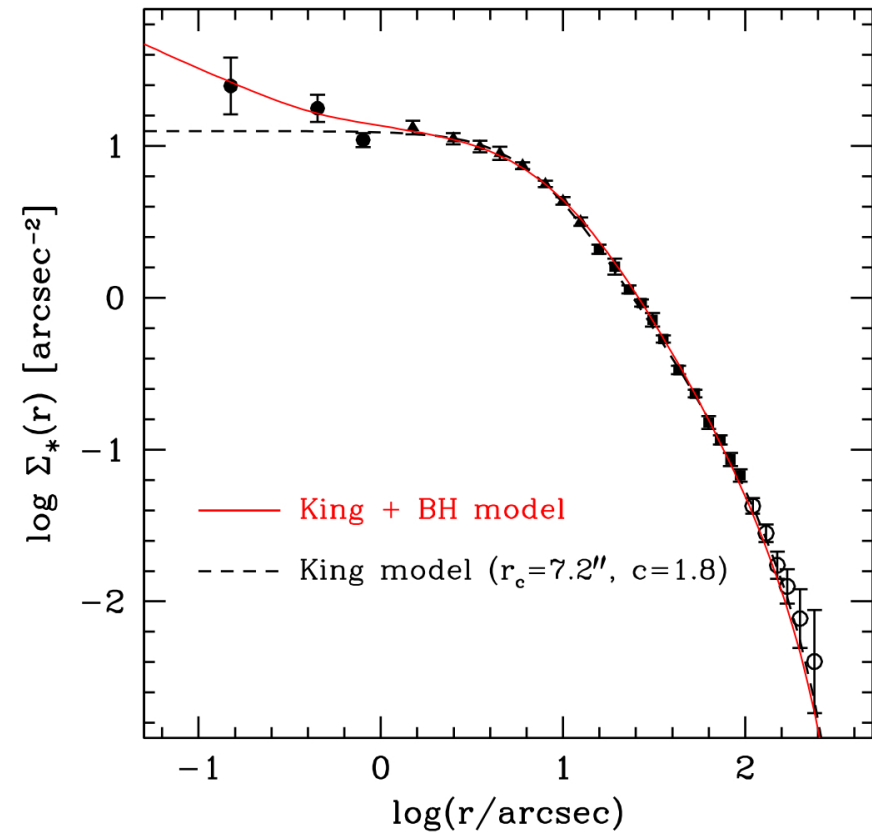




surface brightness profile



projected density profile



self-consistent, multi-mass, spherical, isotropic, King models with central BH

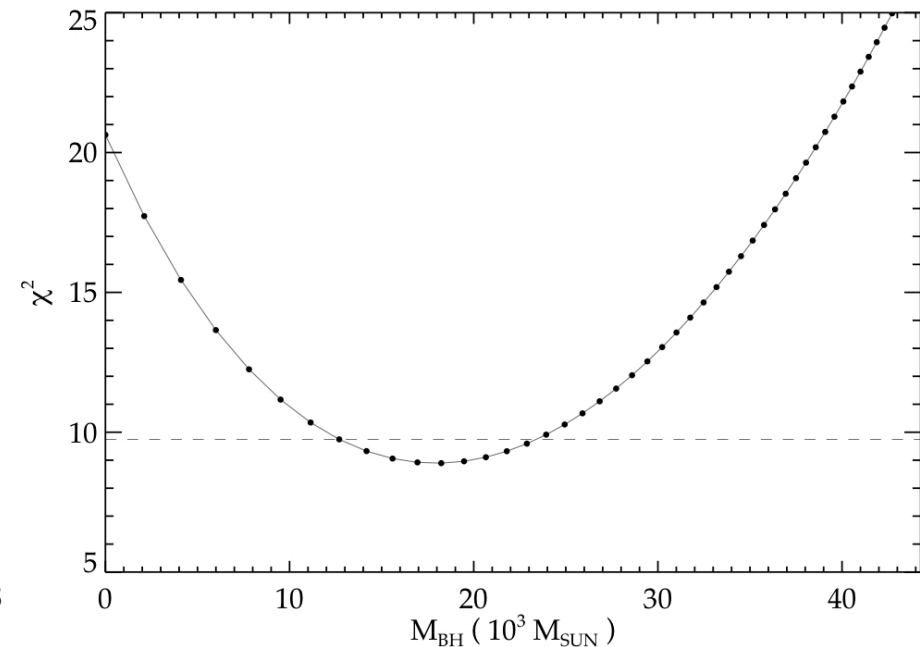
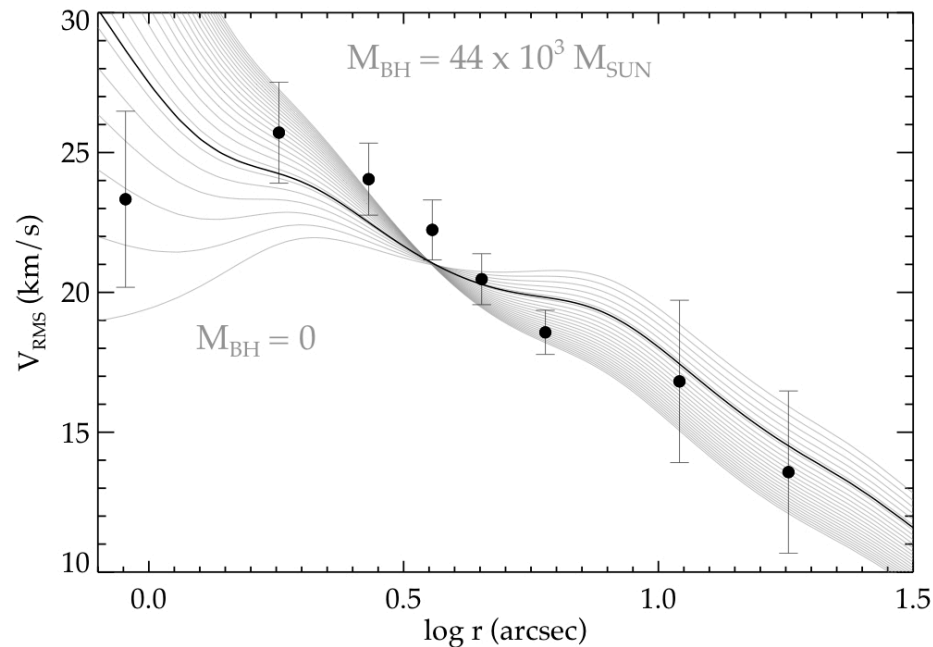
$$\rightarrow M_{\text{BH}} \sim 2 \cdot 10^{-3} M_{\text{clust}} \sim 6 \cdot 10^3 M_{\odot}$$

(Lanzoni et al. 2007, ApJ 668, L139)

- shallow cusp in SB:  $I \sim r^\alpha$ ,  $\alpha = -0.13$  (Noyola & Gebhardt 2006)
- IMBH in the centre? (Miocchi 2007)
- **$a \sim 6 \cdot 10^3 M_\odot$  IMBH in the centre** (Lanzoni et al. 2007)
- X-ray and radio observations:  $M_{\text{BH}} < 600 M_\odot$   
(Nucita et al. 2008; Cseh et al. 2010; Bozzo et al. 2011)

## Lützgendorf et al. 2011 (L11):

- **cuspy velocity dispersion profile,  $\sigma_0 \sim 23\text{-}25 \text{ km/s}$**   
(from the line broadening of integrated-light spectra)
- **IMBH of  $\sim 1.7 \cdot 10^4 M_\odot$**   
(from spherical Jeans models with constant M/L)



# Velocity dispersion from the radial velocities of individual stars

(Lanzoni et al. 2013, ApJ submitted)

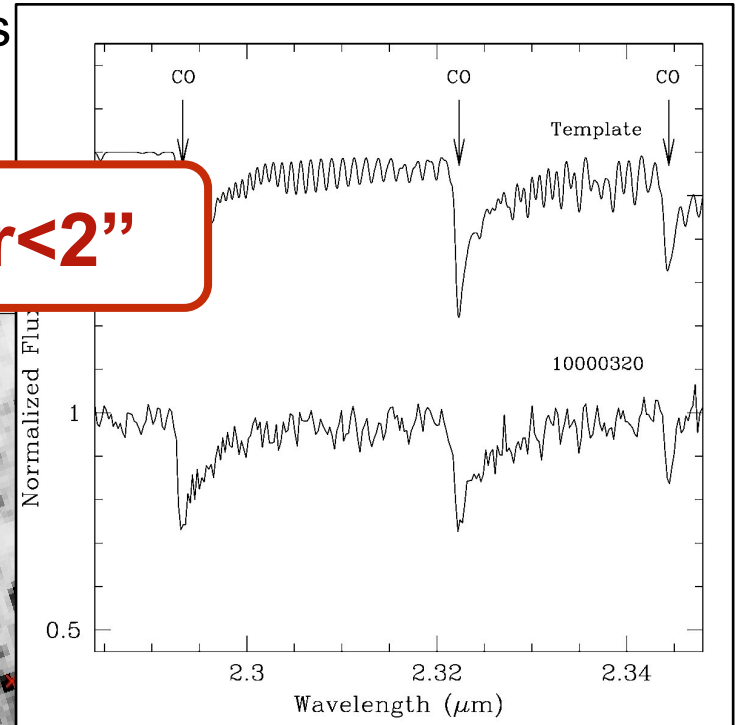
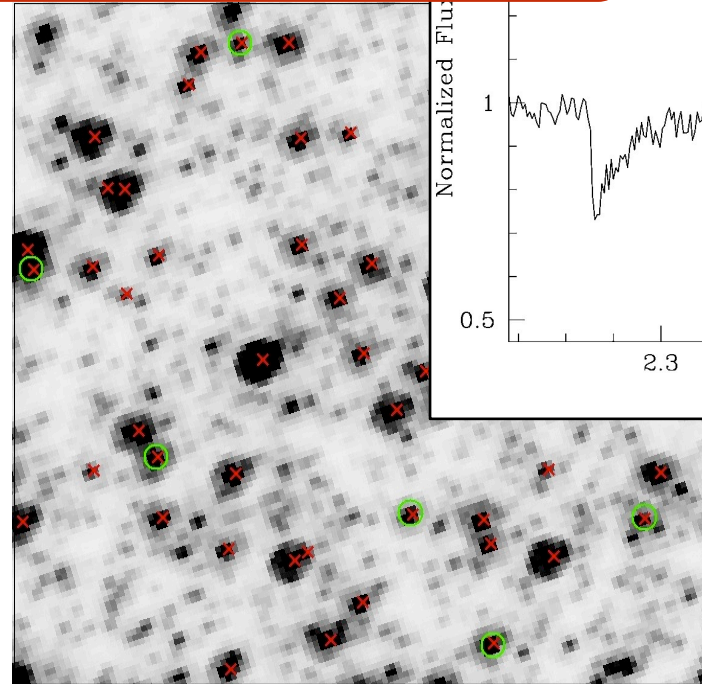
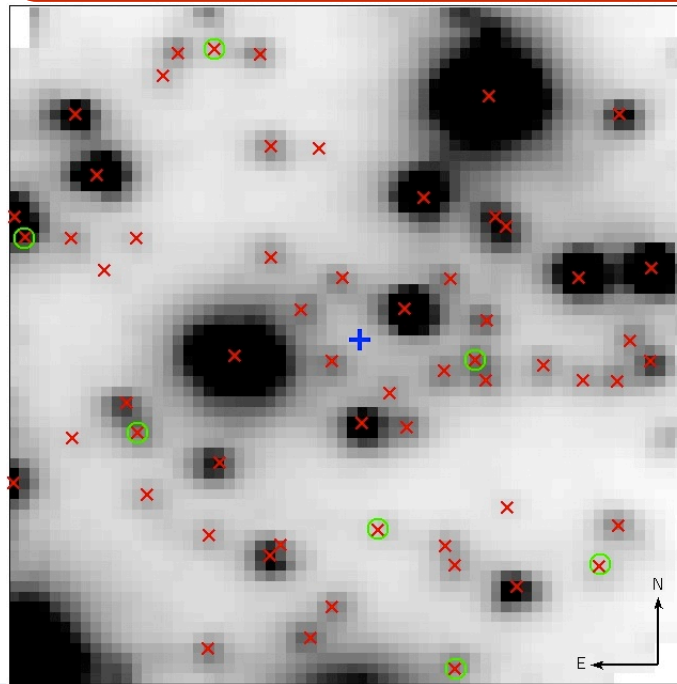
- **ESO-VLT/SINFONI:** AO-assisted IFU spectrograph,  $R=4000$ , K-band grating (1.95-2.45  $\mu\text{m}$ ), spatial resolution=0.1", FoV=3.2"x3.2"  
→ **central  $\sigma(r)$**
- **ESO-VLT/FLAMES-GIRAFFE in MEDUSA mode:** multi-object spectrograph (132 fibres), high spectral resolution ( $R>10,000$ ), optical (Ca triplet, Fe, ..), FoV of 25' in diameter  
→ **external  $\sigma(r)$**



# 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  $r < 2''$



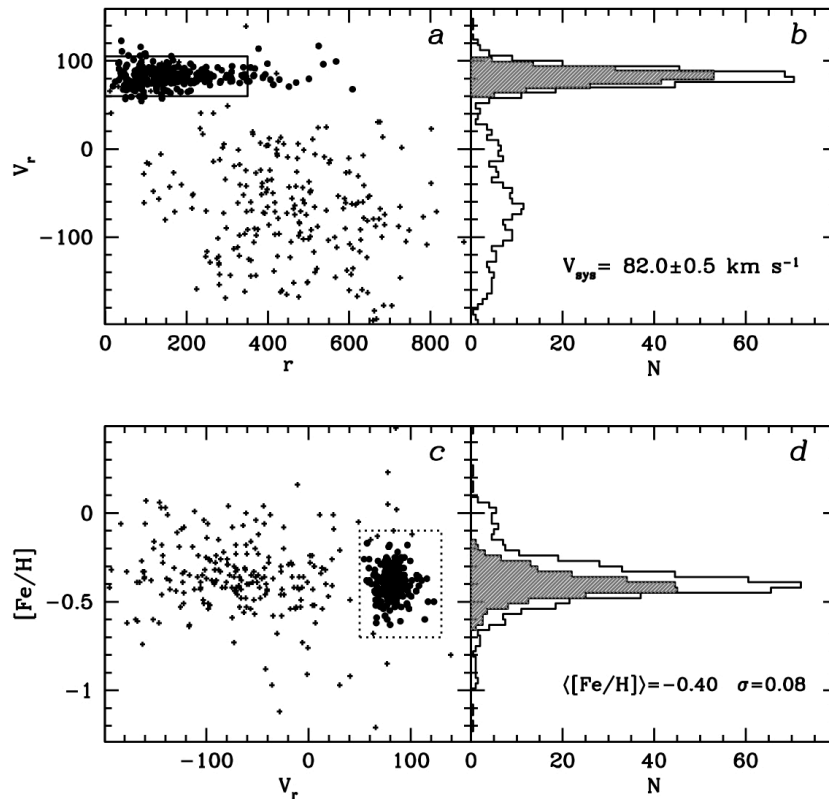
# FLAMES (external) sample

Programs: 381.D-0329(B), PI: Lanzoni

073.D-0211; PI: Carretta

073.D-0760; PI: Catelan

$V_r$  &  $[\text{Fe}/\text{H}]$  for 508 stars



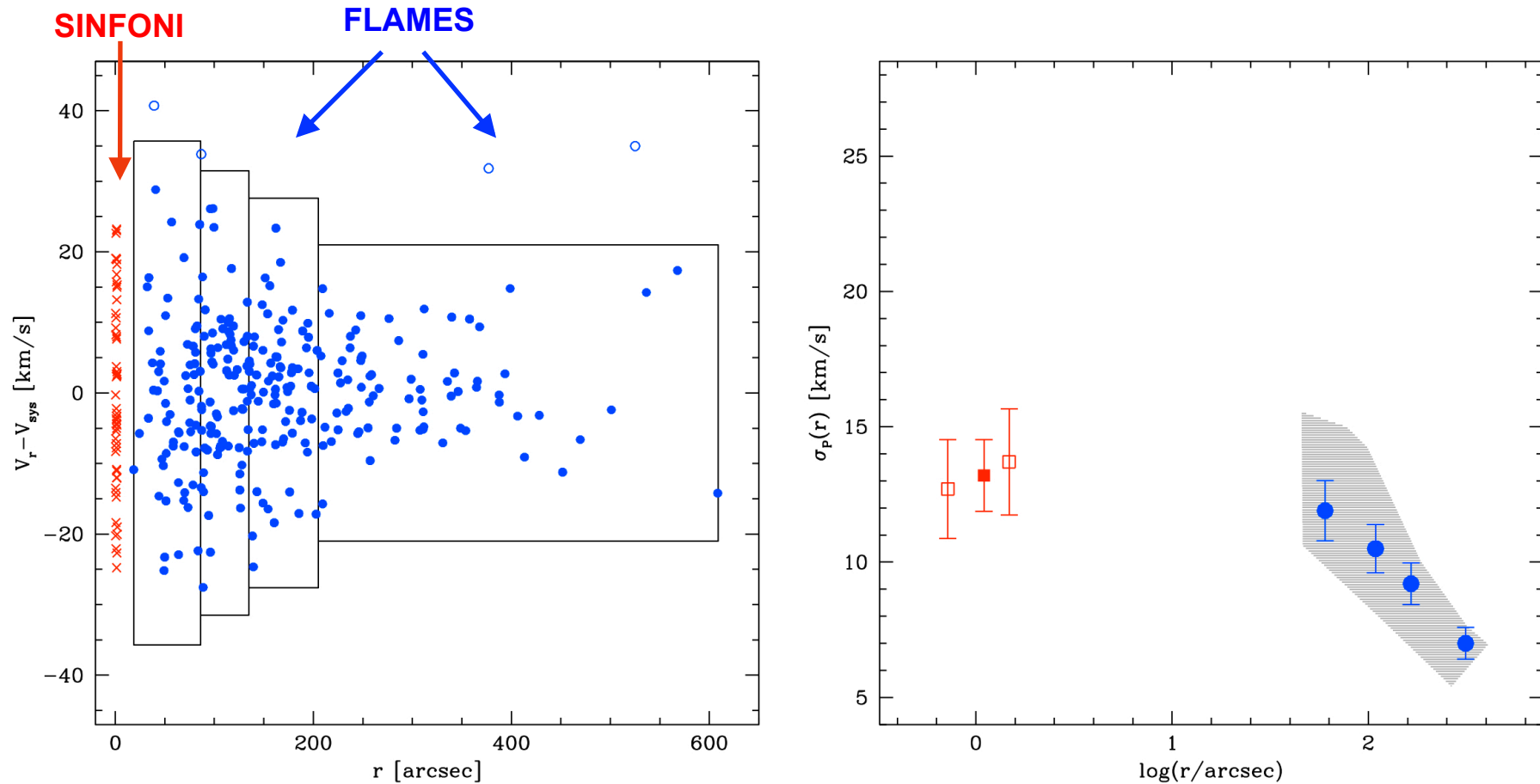
276 cluster members

$V_r$  for 276 individual stars  
at  $18'' < r < 600''$

# Velocity dispersion profile

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

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



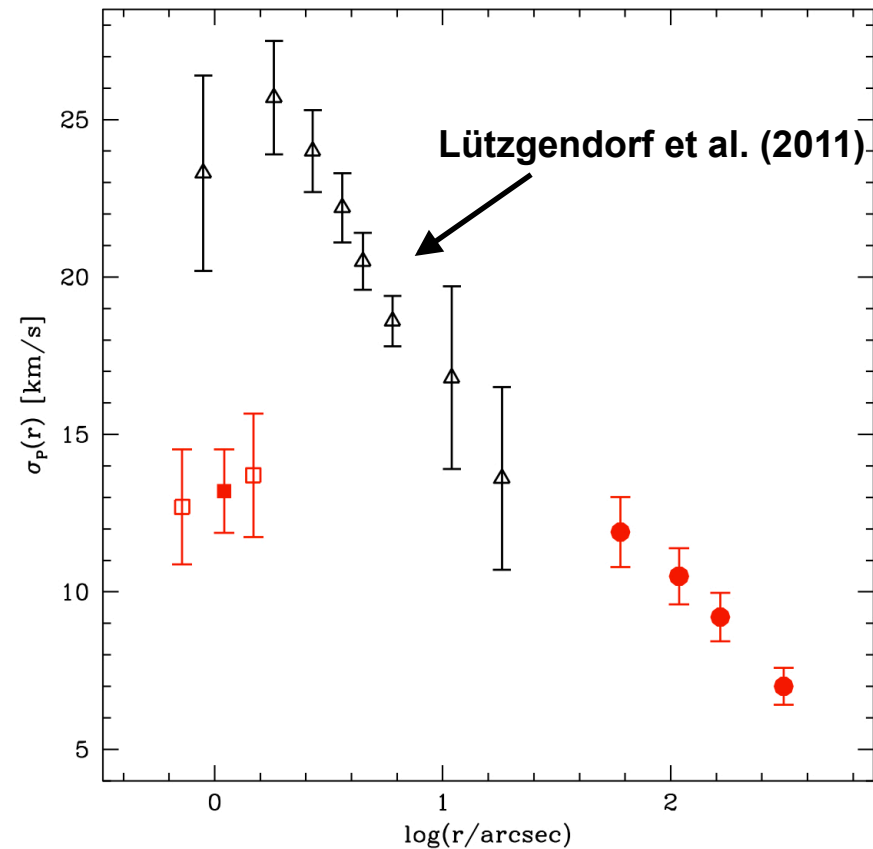
# Velocity dispersion profile

$\sigma(r)$  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 ?





- **different cluster centre?**

**NO:**

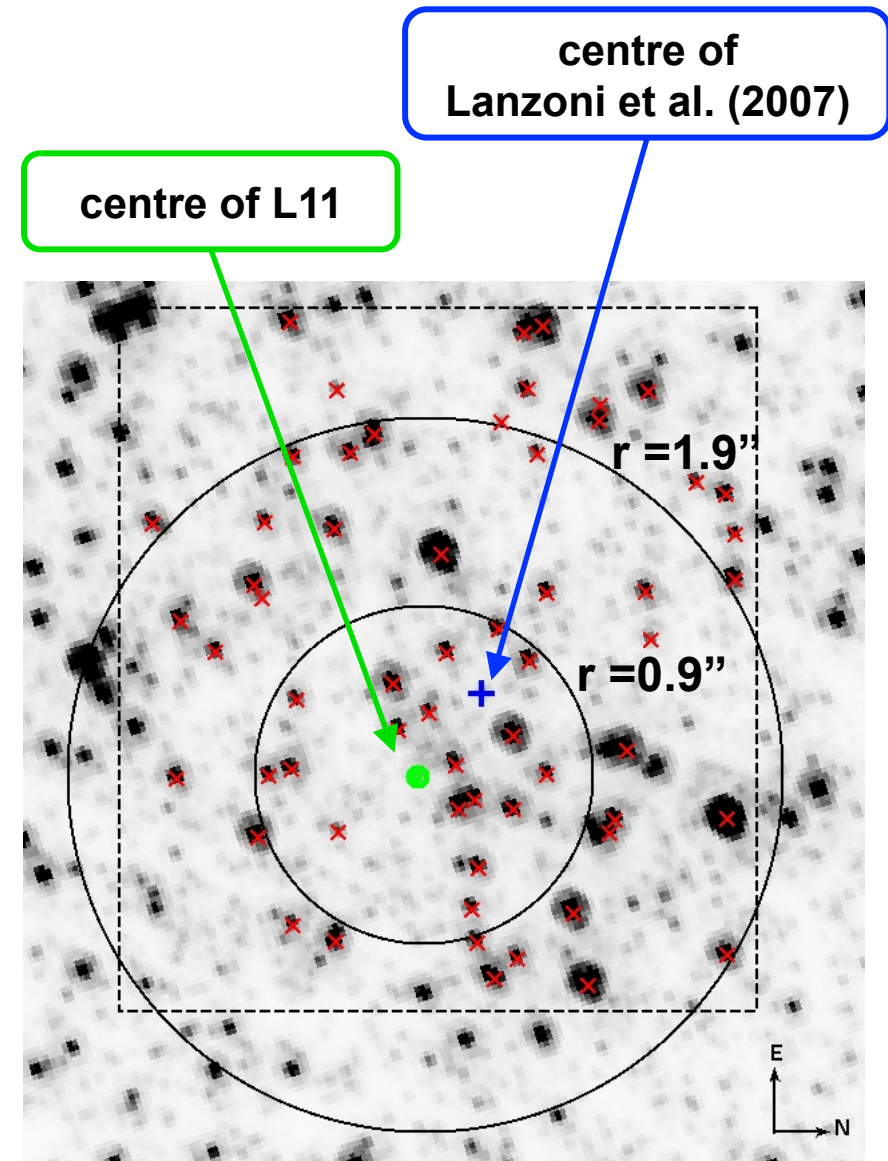
adopting centre & radial bins of L11  
from individual  $V_r$  we obtain:

→  $\sigma(<0.9'') = 14.5 \text{ km/s}$  (17 stars)

→  $\sigma(0.9'' < r < 1.9'') = 12.4 \text{ km/s}$  (27 stars)

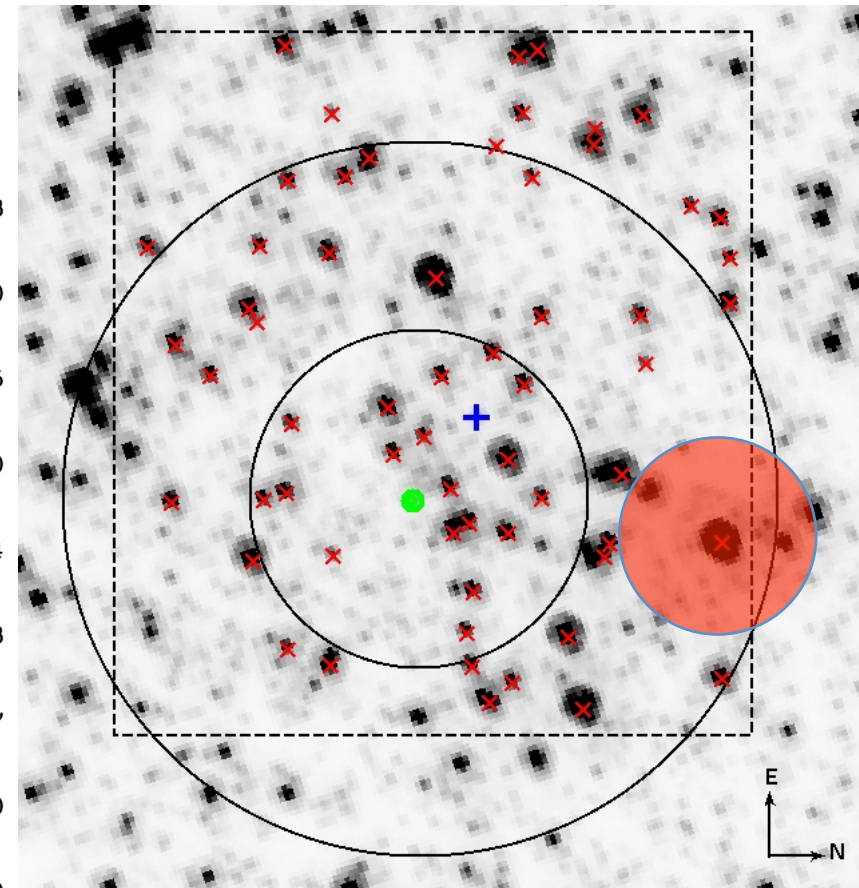
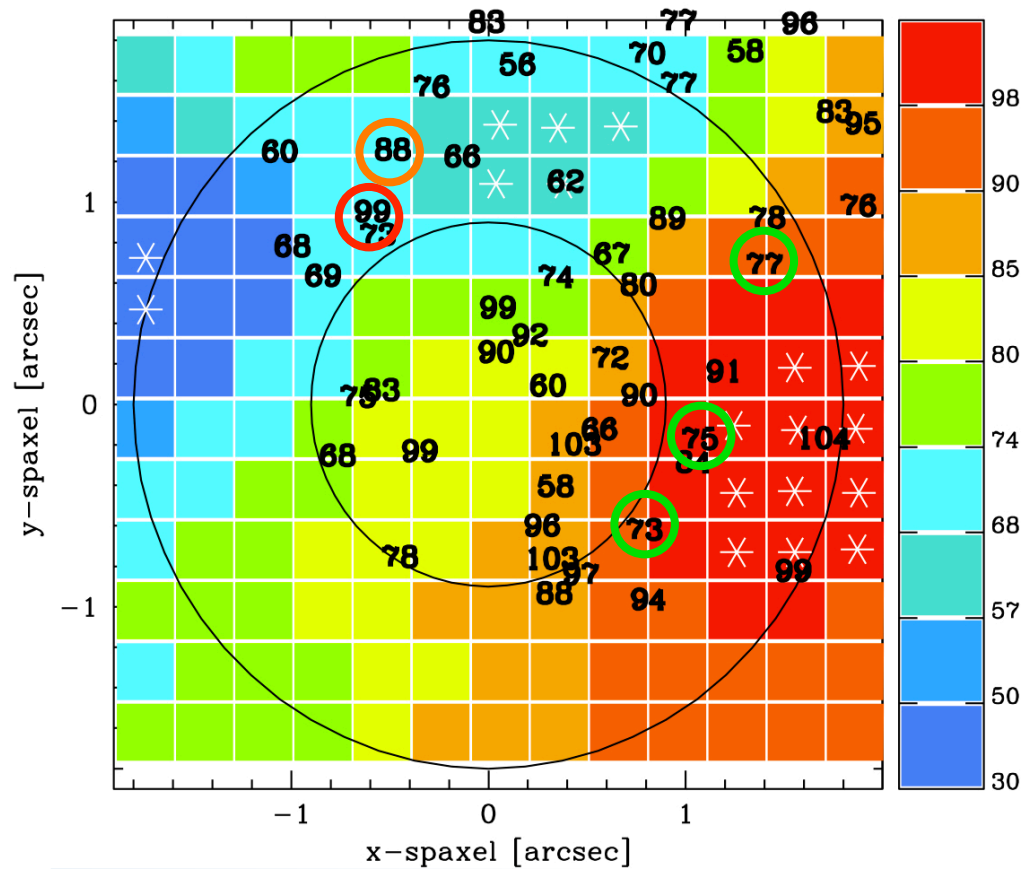
→  $\sigma(r < 1.9'') = 13.1 \text{ km/s}$  (44 stars)

(instead of 23-25 km/s)



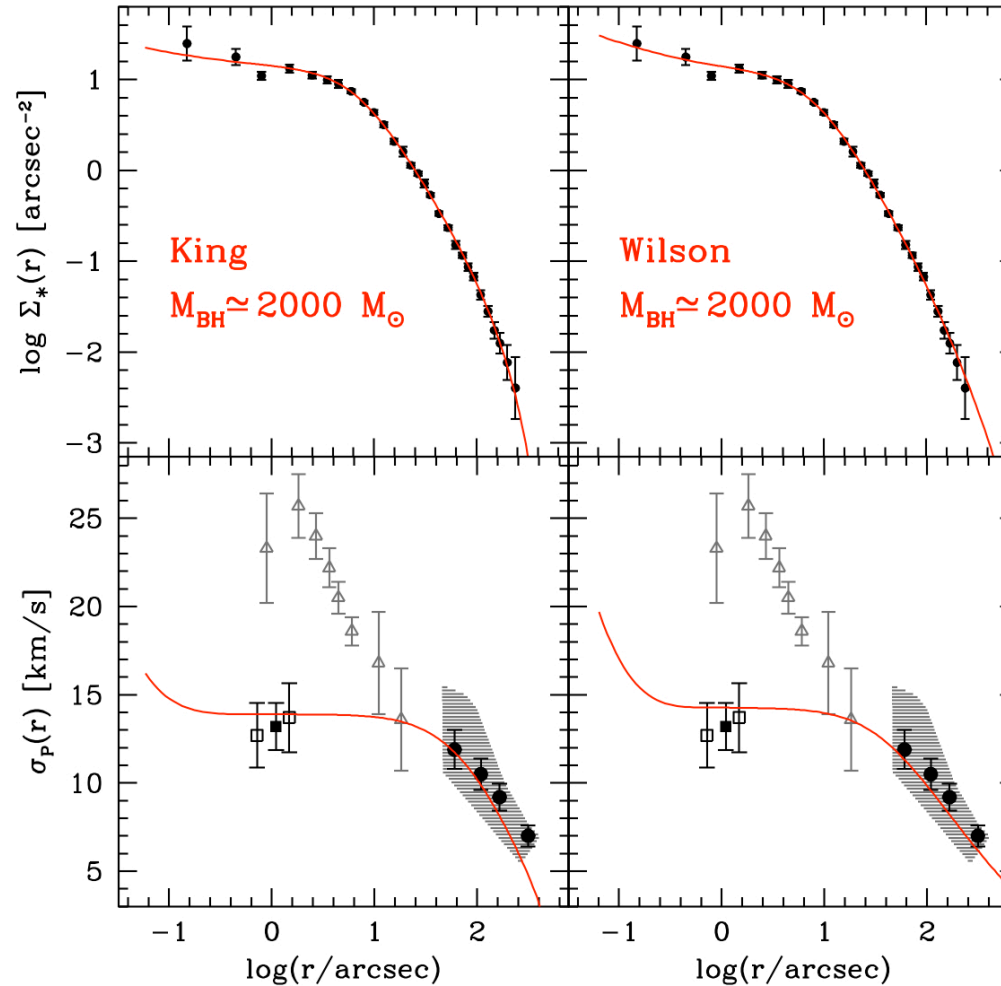
# • insufficient shot-noise correction? MAY BE...

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



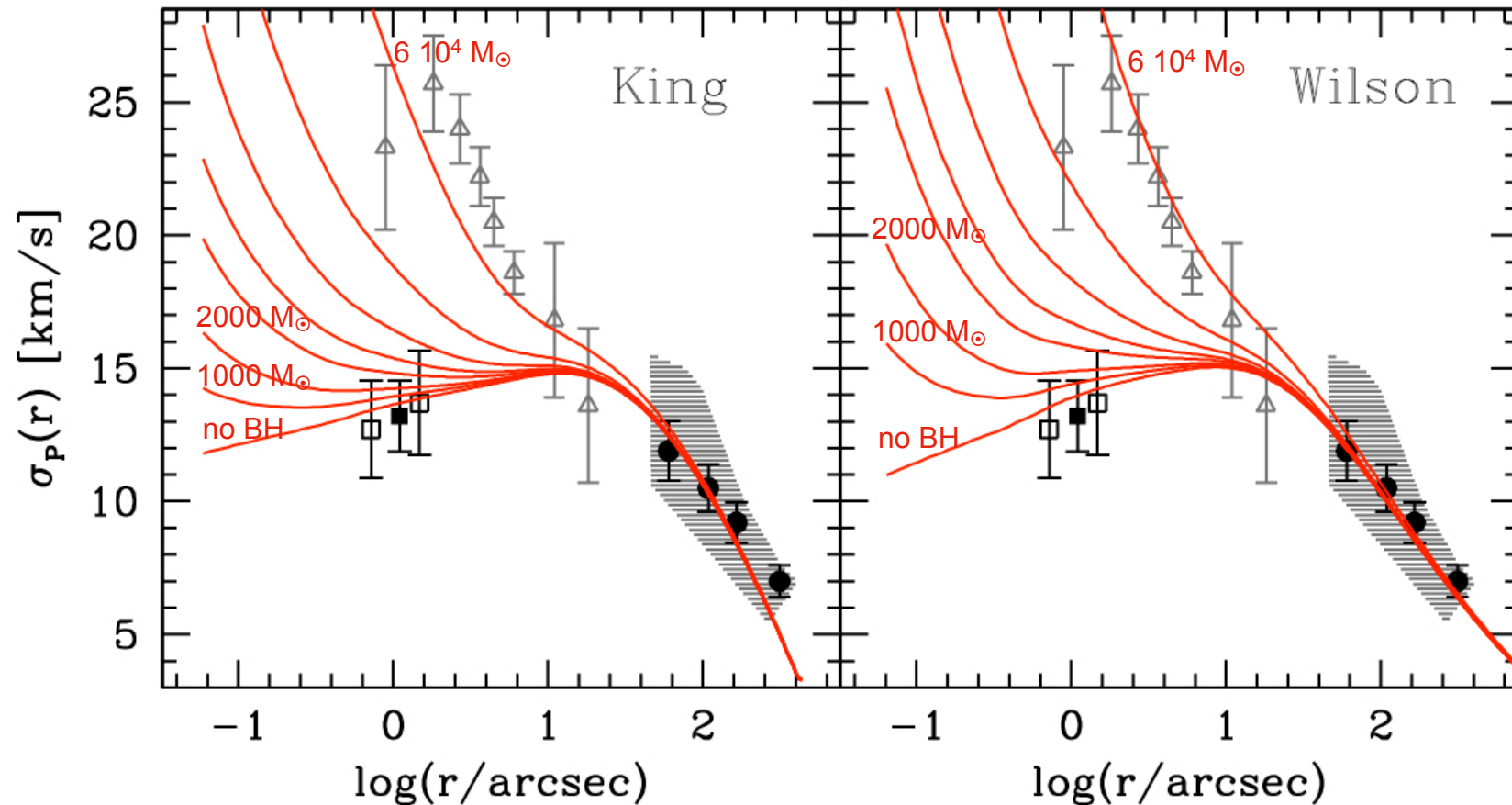
# Comparison with models: IMBH mass

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



## 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)



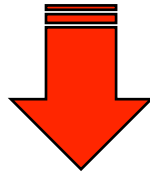


# Conclusions

- **velocity dispersion profile of NGC 6388 from  $V_r$  of individual stars:**  
52 stars at  $r < 2''$  (ESO-VLT/SINFONI)  
276 stars at  $18'' < r < 600''$  (ESO-VLT/FLAMES)
- **central velocity dispersion:  $\sigma_0 = 13\text{-}14$  km/s**
- **$M_{\text{BH}} \leq 2000 M_{\odot}$**  (from self-consistent and Jeans modelling)
- **hints of systemic rotation**  
with amplitude  $\sim 8$  km/s at  $r < 2''$   
and  $\sim 3$  km/s at  $18'' < r < 160''$

# Conclusions

$\sigma(r)$  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?**

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**Thank you  
for your attention!**

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