Searching for intermediate-mass black holes in (Galactic) globular clusters

BARBARA LANZONI

Physics & Astronomy Department – University of Bologna (Italy)

Cefalu`, September 8, 2017

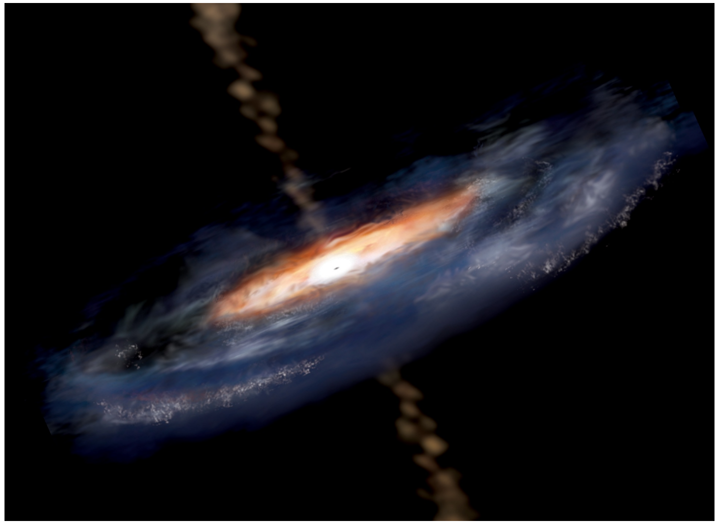
Intermediate-mass black holes (IMBHs)

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 $M_{\odot}$

Why interesting?

- would **fill the** (unnatural?) **gap** between stellar-mass and super-massive BHs

- could be the **seeds of SMBHs**
  (→ **galaxy formation & co-evolution with AGN)**

- could be at the origin **of ultra-luminous X-ray sources (ULX)**

- **expected in dense stellar systems**, affecting their **dynamical evolution**

- IMBHs in <u>Galactic GCs</u> would be **prime targets for gravitational wave** searches (close to the Earth & high probability of interactions with other compact objects: stellar-mass BHs, neutron stars)

Expected to exist (especially **in GCs**)

1. **Extrapolation of the "Magorrian relation" to GC scales**
   ($M_{IMBH} \sim 10^{-3} M_{GC}$)

2. Several plausible formation scenarios:

- **dynamical interactions** of hard binaries with BH
  (Giersz et al. 2015)
- **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+04; Freitag +07; Mapelli+16)
- (some) GCs may be remnant **nuclei of disrupted dwarfs** with possible IMBHs (e.g., Freeman 1993; Greene & Ho 2004)
- **gas accretion** of onto stellar-mass BHs
  (Kawakatu & Umemura 2005; Leigh et a. 2013)
- evolution of first stars **(Pop III)** with masses > 250 $M_\odot$
  (e.g., Fryer et al. 2001; Madau & Rees 2001)
- repeated **mergers of stellar-mass BHs**
  (Miller & Hamilton 2002)

✦ IMBHs in GCs: several fingerprints 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 cusp in velocity dispersion (VD) at r<1"-2" from the centre

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

3) universal & large ratio of core to half-mass radii (r_c/r_h >0.1)

5) quenching of mass segregation

6) X-ray and radio emission

✦ IMBHs in Galactic GCs: not confirmed yet

Claims:

Table 1. IMBH candidates in globular clusters

Name		M_{BH} $[M_\odot]$	References
47 Tuc		$2.2^{+1.5}_{-0.8} \times 10^3$	Kızıltan et al. (2017)
G1†		$(1.8 \pm 0.5) \times 10^4$	Gebhardt et al. (2005)
NGC 1851		$< 2 \times 10^3$	Lützgendorf et al. (2013)
NGC 1904	M79	$(3 \pm 1) \times 10^3$	Lützgendorf et al. (2013)
NGC 2808		1×10^4	Lützgendorf et al. (2012)
NGC 5139	ωCen	$(4.7 \pm 1.0) \times 10^4$	Noyola et al. (2010)
NGC 5286		$(1.5 \pm 1.0) \times 10^3$	Feldmeier et al. (2013)
NGC 5694		$< 8 \times 10^3$	Lützgendorf et al. (2013)
NGC 5824		$< 6 \times 10^3$	Lützgendorf et al. (2013)
NGC 6093	M80	$< 8 \times 10^2$	Lützgendorf et al. (2013)
NGC 6266	M62	$(2 \pm 1) \times 10^3$	Lützgendorf et al. (2013)
NGC 6388		$(2.8 \pm 0.4) \times 10^4$	Lützgendorf et al. (2015)
NGC 6715	M54	9.4×10^3	Ibata et al. (2009)
NGC 7078	M15	$(3.9 \pm 2.2) \times 10^3$	Gerssen et al. (2002)

(Mezcua 2017, arXiv1705.09667)

However:

→ disproved by a more complete analysis of pulsar timing (Freire+2017) [47 Tuc]

Integrated-light spectroscopy → shot-noise bias (e.g., Dubath+97, Lanzoni+13, Bianchini+15, de Vita+16) [NGC 1851 – NGC 6388]

→ compact remnants instead of an IMBH (Baumgardt et al. 2003; van den Bosch et al. 2006) [NGC 7078]

✦ IMBHs in GCs: not confirmed yet

- **non univocal fingerprints:**
  - density cusp during evolution also in GCs with no IMBH (Vesperini & Trenti 2010)
  - VD cusp due to pressure anisotropy (Zocchi et al. 2016, 2017)
  - quenching of mass segregation: degeneracy with binaries (Gill et al. 2008)
  - high-velocity stars or non-cluster members?
  - **uncertainties on expected X-ray and radio emission** (gas density? accretion efficiency?)

- **challenging observations:** sub-arcsecond BH sphere of influence

  → especially for the detection of a **central VD cusp**...

How to measure velocity dispersion (VD) in Galactic GCs?

Two main differences *wrt* distant (unresolved) galaxies/stellar systems

1) no gas => only **stellar** velocity dispersion

2) close to Earth => stars are **resolved**

In principle, VD can be measured from

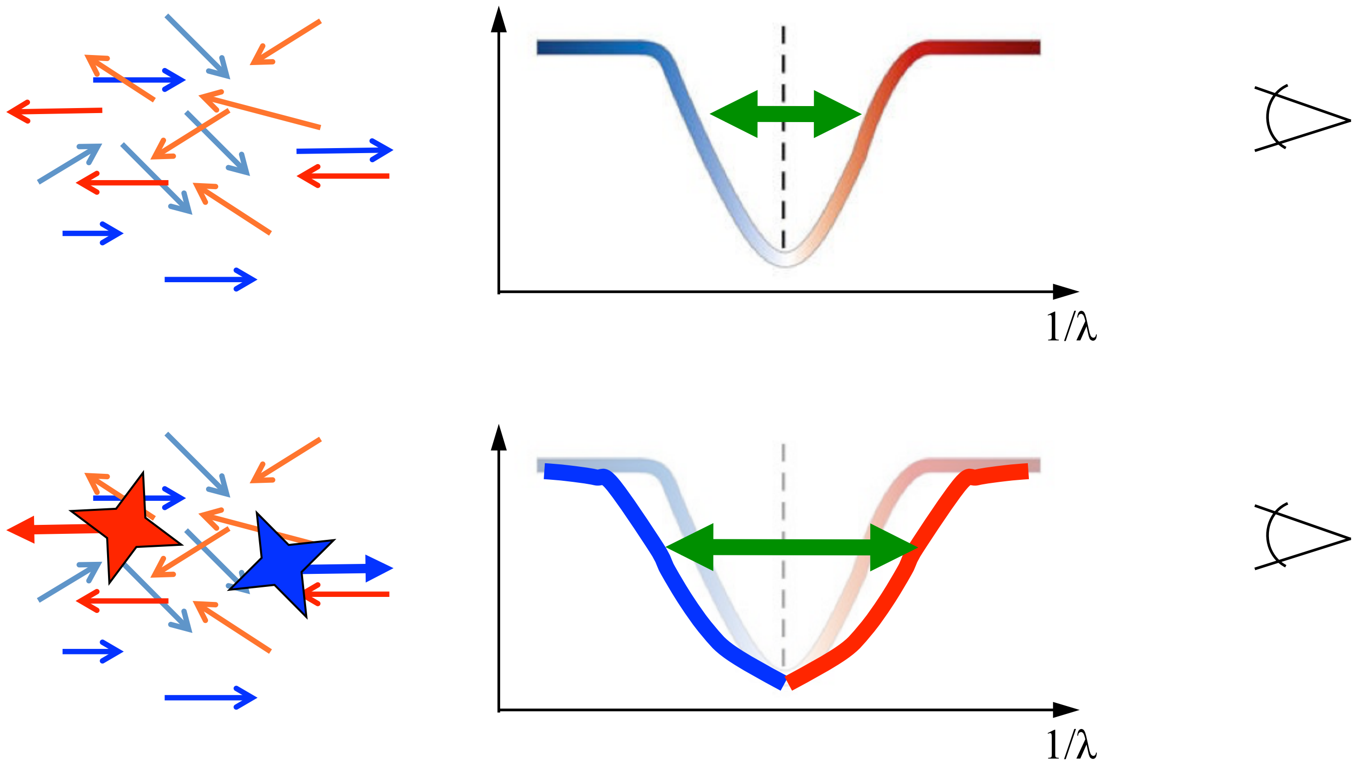
~~line broadening of **integrated-light** spectra (VD along the line of sight)~~

shot-noise bias

radial velocities of **individual** stars (VD along the line of sight)

proper motions of **individual** stars (VD on the plane of the sky)

line broadening in integrated-light spectra



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 few giants

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

How to measure velocity dispersion (VD) in Galactic GCs?

Two main differences *wrt* distant (unresolved) galaxies/stellar systems

1) no gas => only **stellar** velocity dispersion

2) close to Earth => stars are **resolved**

In principle, VD can be measured from

~~line broadening of **integrated-light** spectra (VD along the line of sight)~~

shot-noise bias

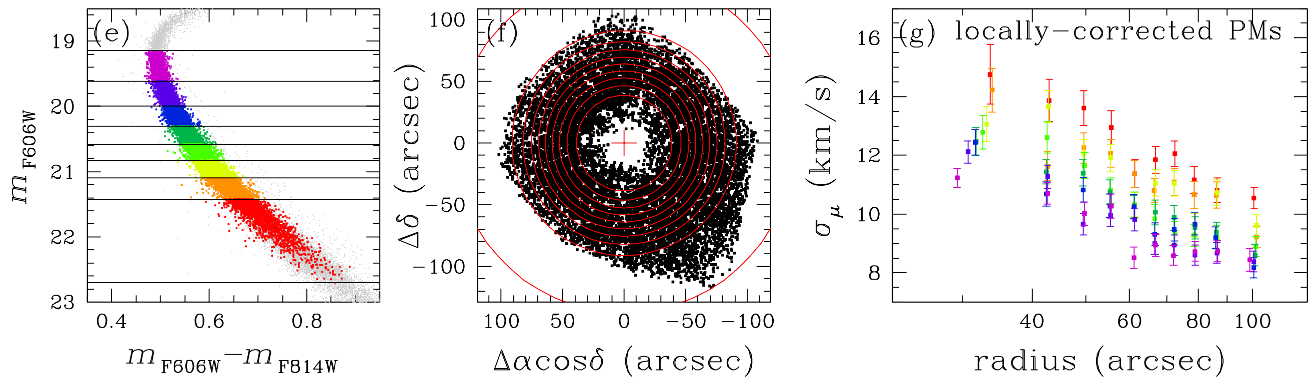
radial velocities of **individual** stars
(VD along the line of sight)

proper motions of **individual** stars
(VD on the plane of the sky)

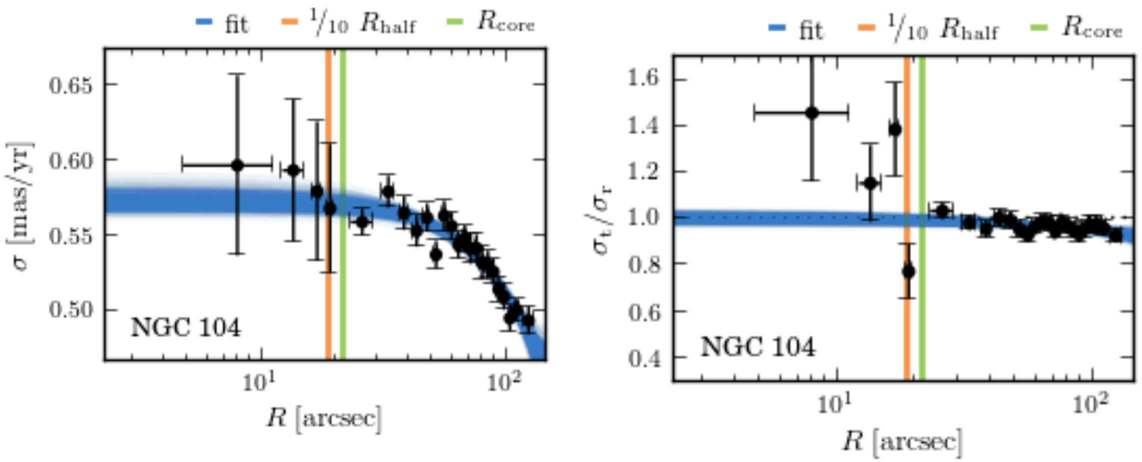
large samples of stars at r<1”-2”

Proper motions

- ✓ 2 VD components => also orbital anisotropy information
- ✓ VD for different stellar mass
- x still miss the very central regions (stellar crowding)



Bellini et al. 2014
(M15)



Watkins et al. 2015
(22 GGCs)

Radial velocities (RVs) of **individual** stars at **all** distances

MULTI-INSTRUMENT approach

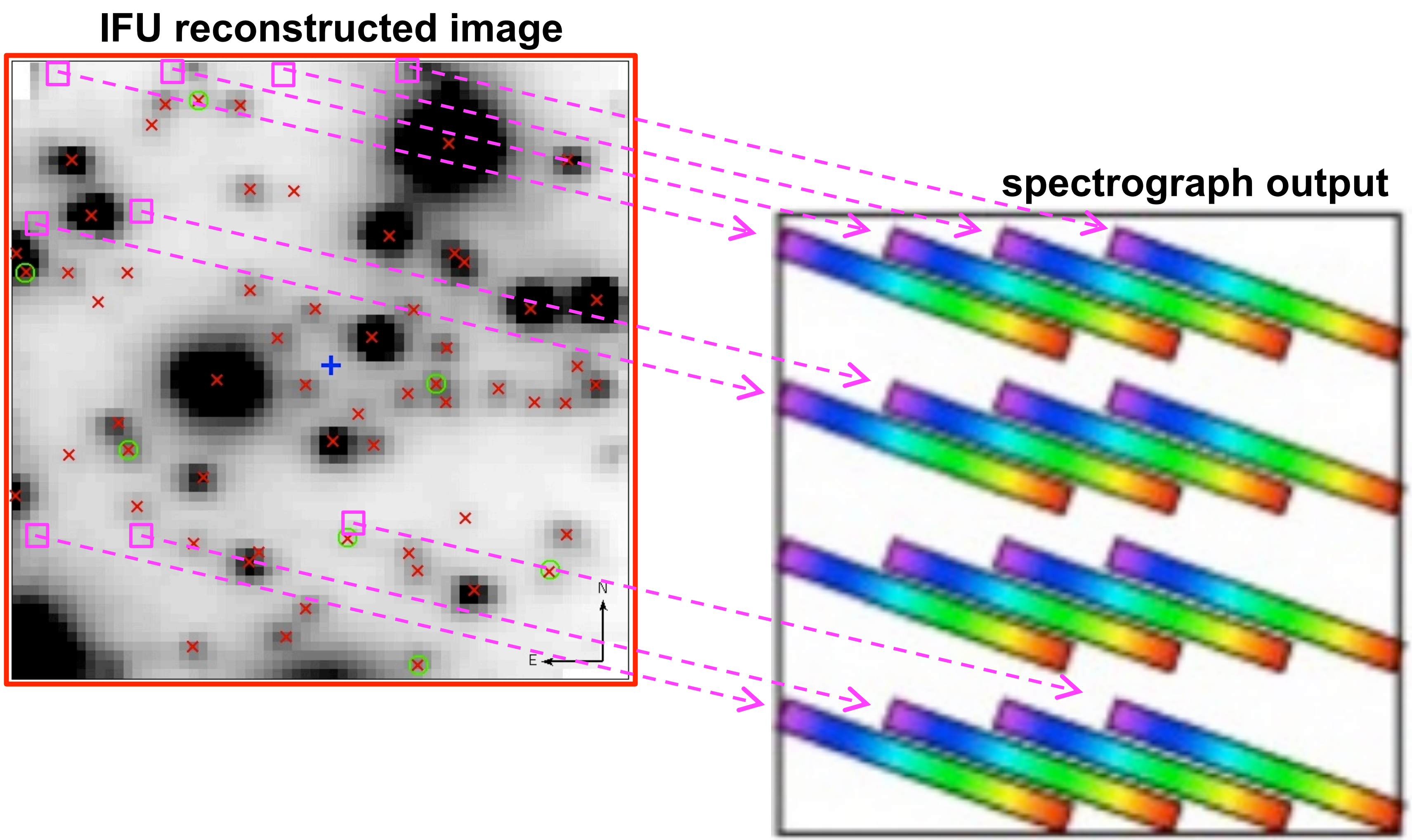
+

UNCONVENTIONAL use of last-generation spectrographs

Central VD (from individual RVs)

Integral Field Unit (IFU) spectroscopy

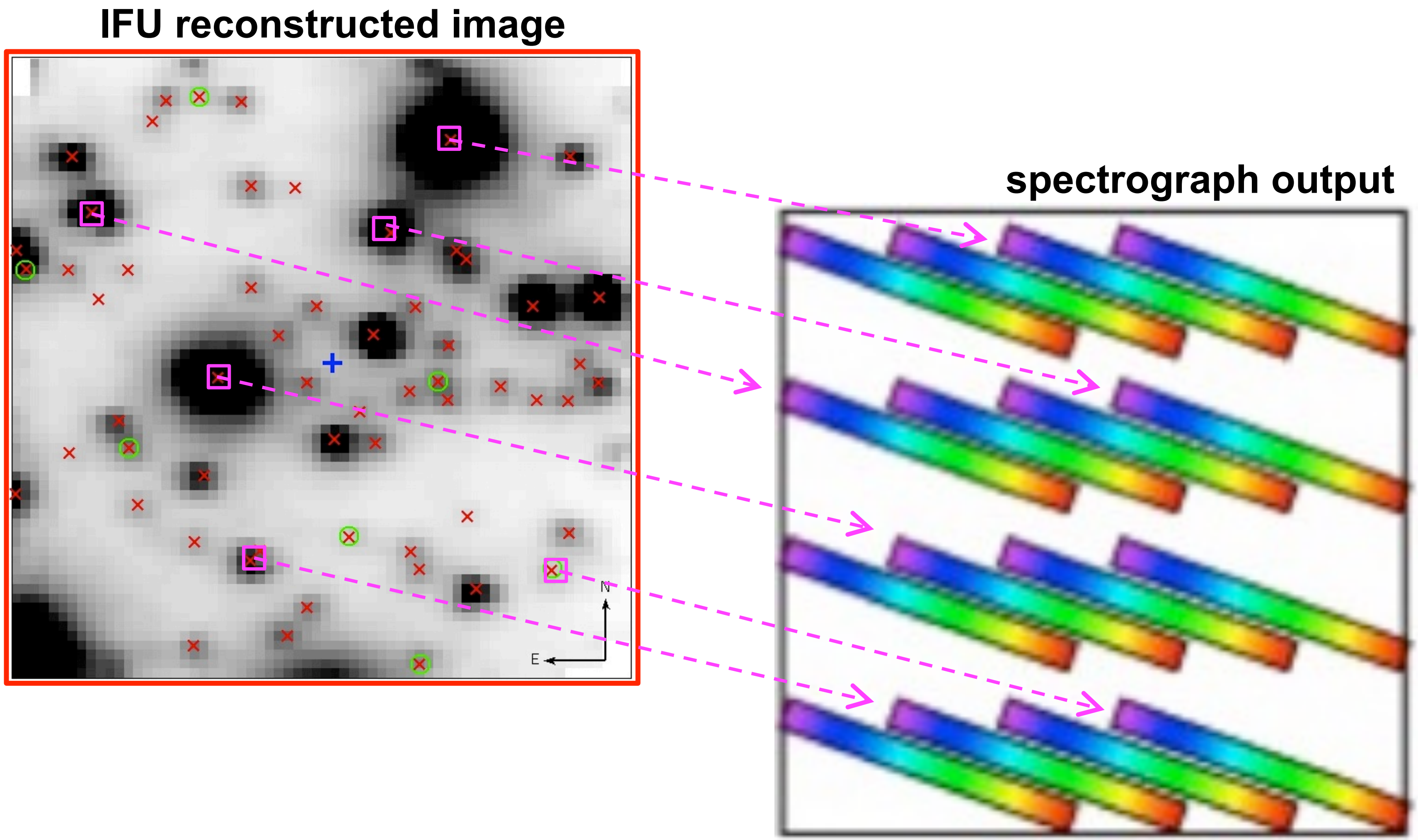
(a spectrum for every spaxel)



Central VD (from individual RVs)

Integral Field Unit (IFU) spectroscopy

Unconventional use → **spectra only from the spaxels corresponding to the stellar centroids**



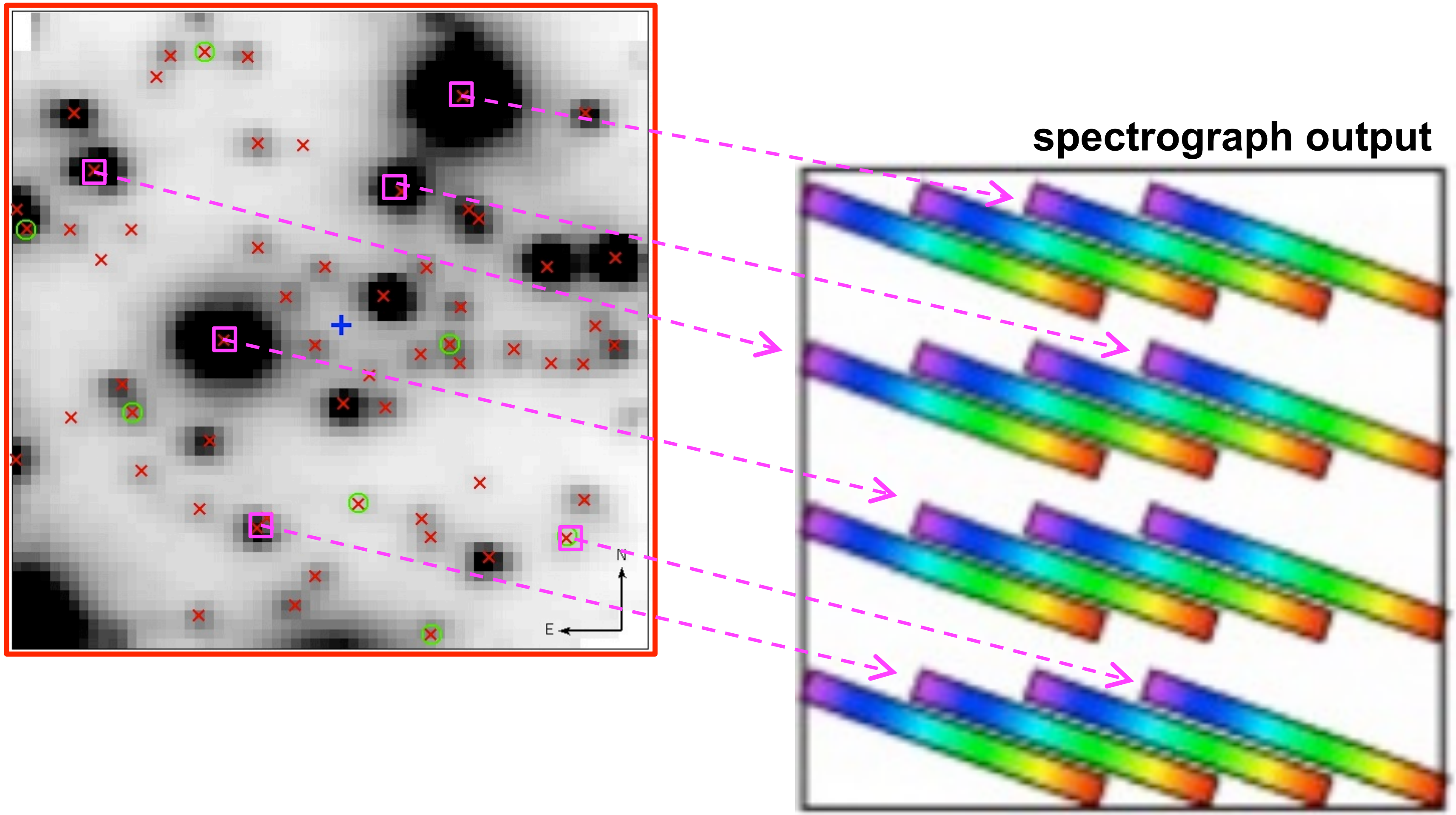
Central VD (from individual RVs)

AO-assisted Integral Field Unit (IFU) spectroscopy

Unconventional use → spectra only from the spaxels corresponding to the stellar centroids

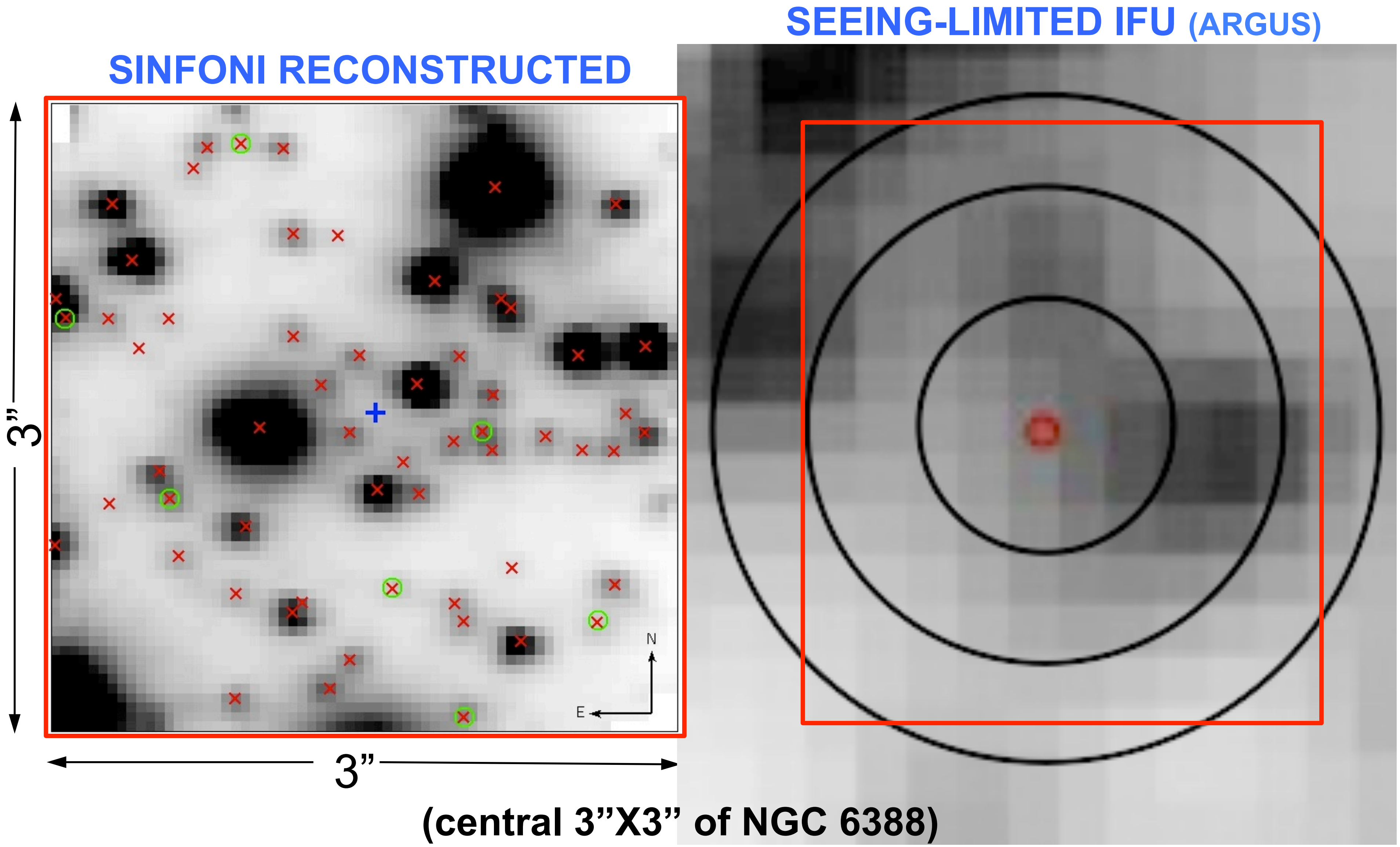
IFU reconstructed image

spectrograph output



SINFONI

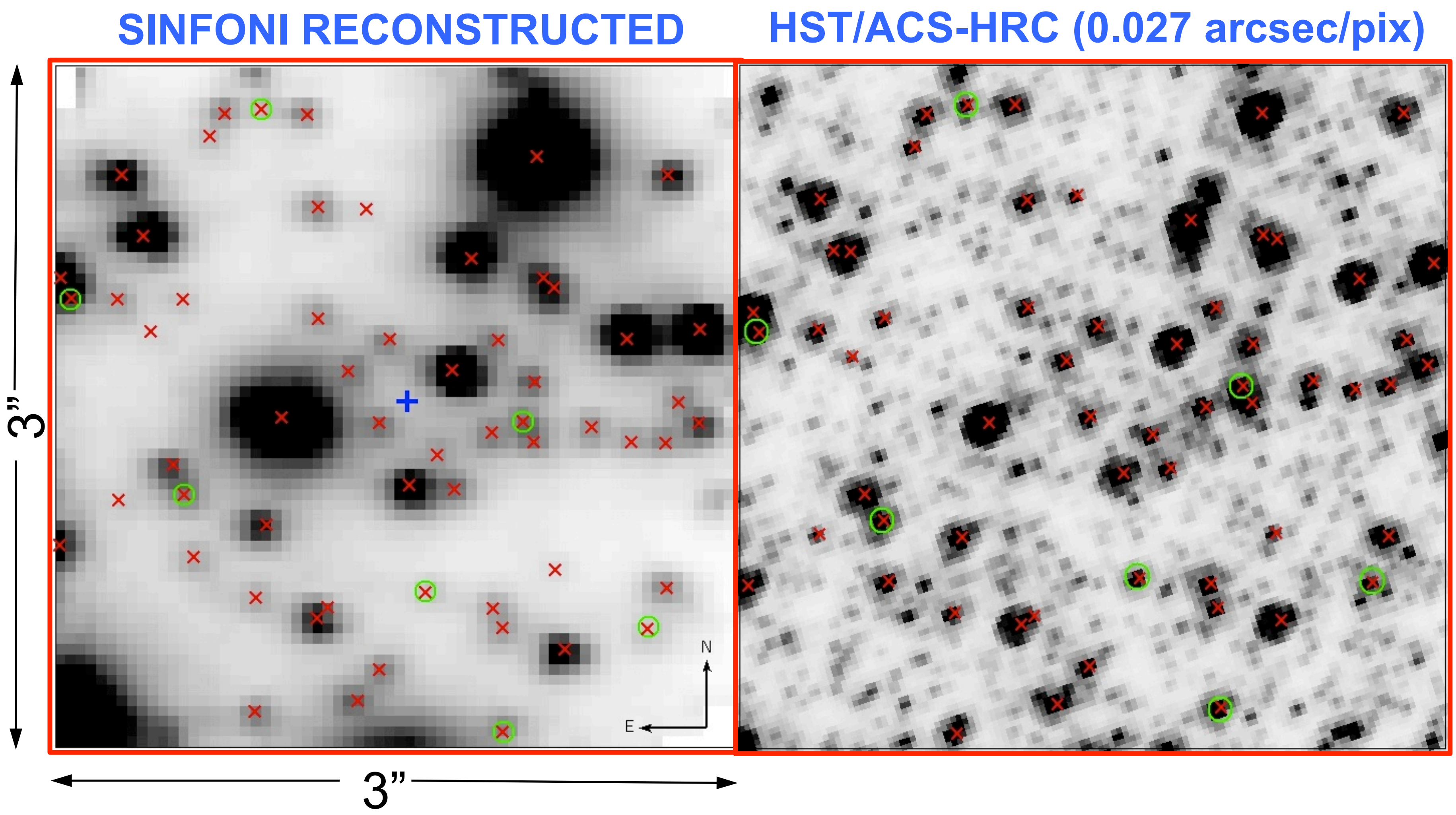
AO-assisted IFU, 0.1” spatial resolution, FoV=3.2”x3.2”



(central 3”X3” of NGC 6388)

SINFONI

AO-assisted IFU, 0.1” spatial resolution, FoV=3.2”x3.2”

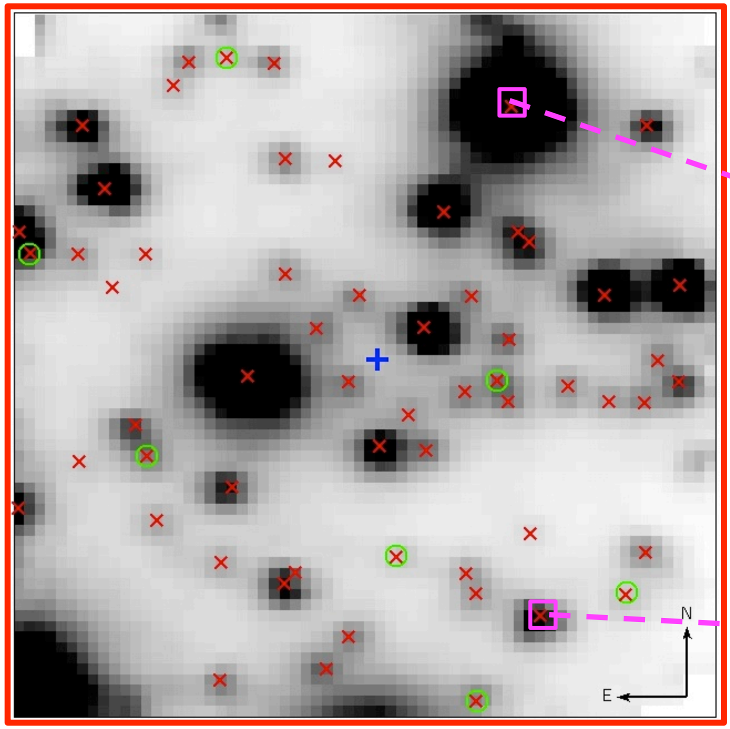


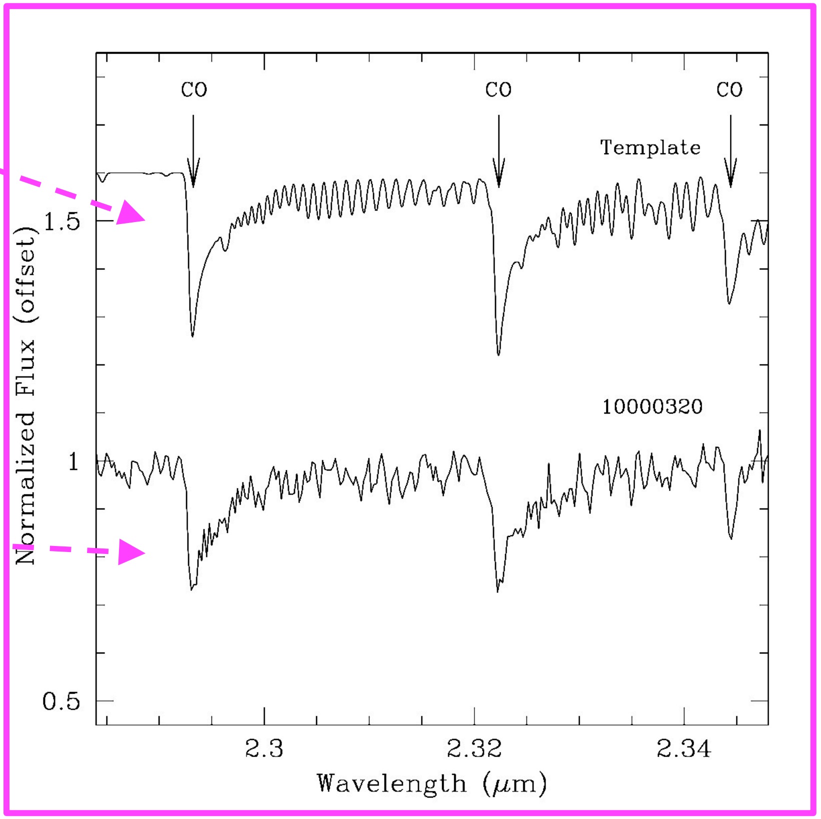
(central 3”X3” of NGC 6388)

SINFONI

AO-assisted IFU, 0.1” spatial resolution, FoV=3.2”x3.2”
K-band grating (1.95-2.45 μm) → **CO band-heads**

SINFONI RECONSTRUCTED IMAGE

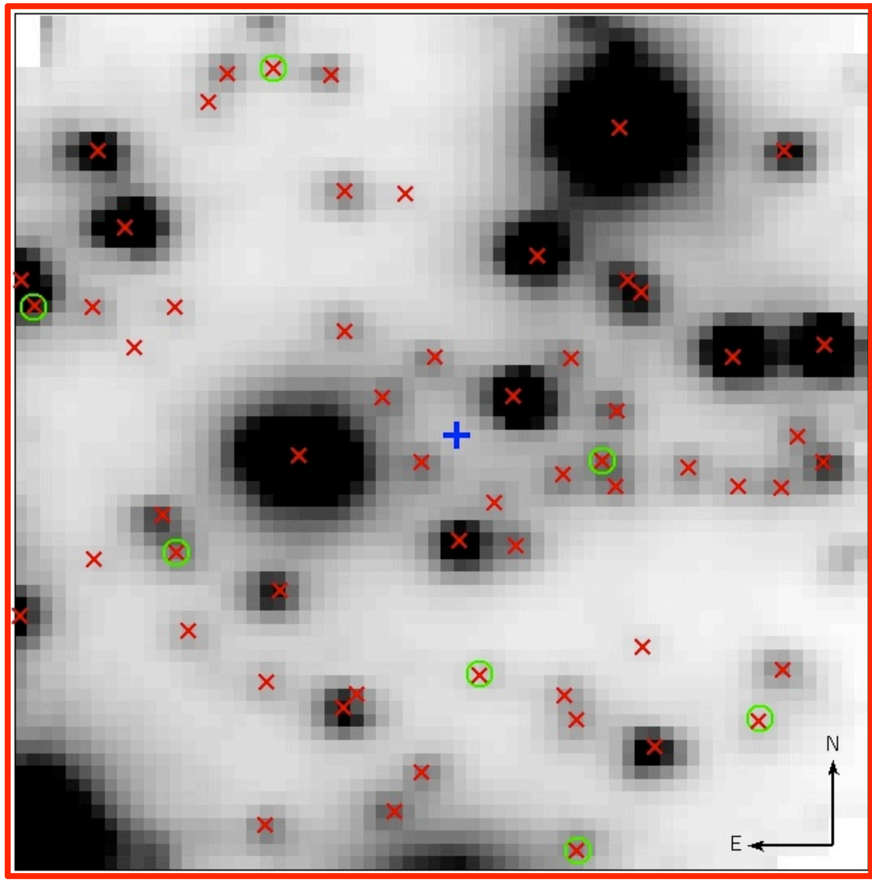


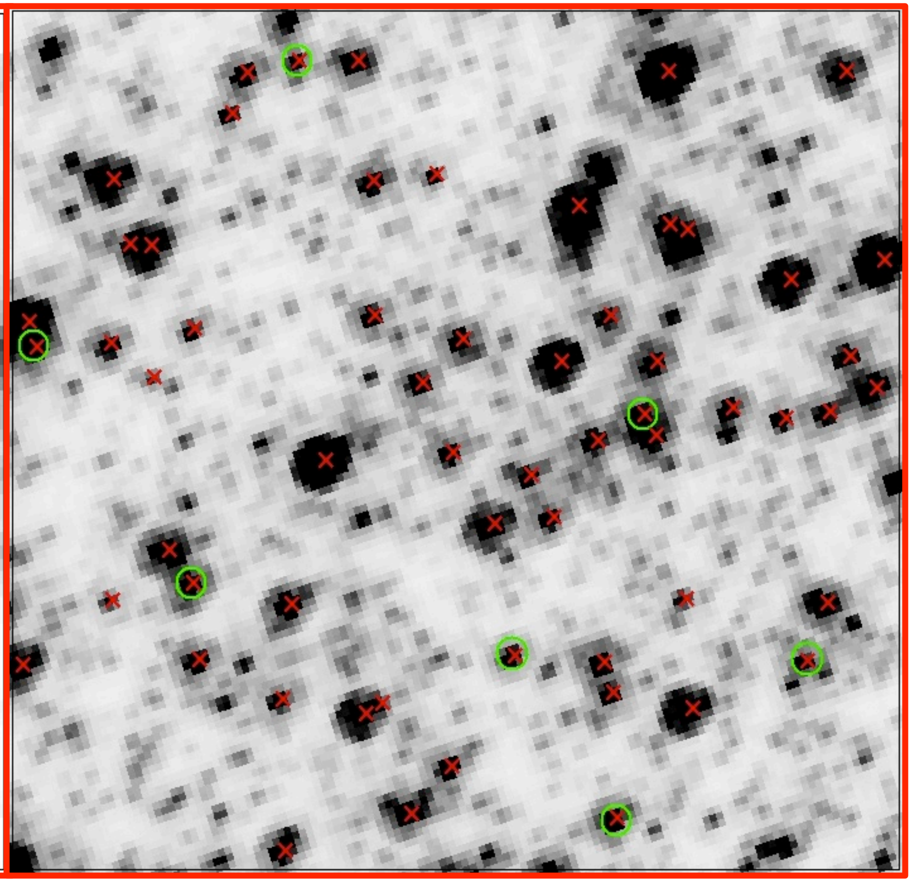


NGC 6388 (r_c=7", ρ_0= 2.3 10^5 $L_{\odot}/pc^3$)

→ **RVs of 52 individual stars at r<2" (~0.13 pc) !!!**

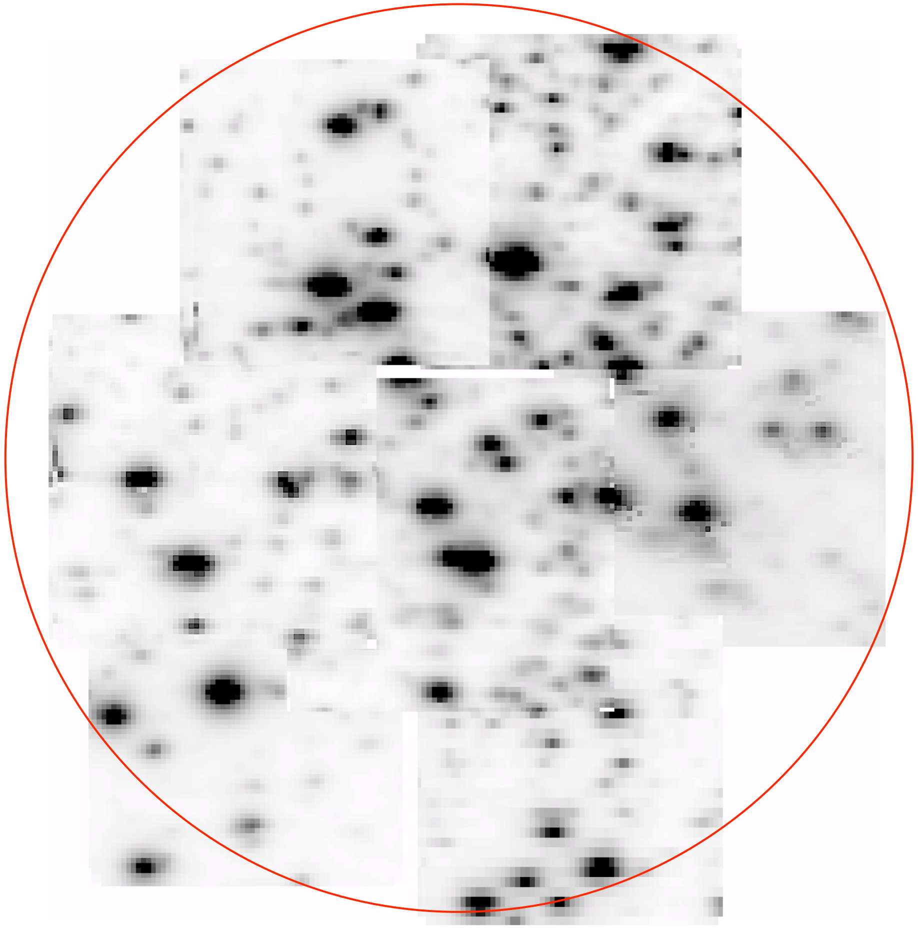
SINFONI RECONSTRUCTED **HST/ACS-HRC (0.027 arcsec/pix)**





NGC 2808 (r_c=15", ρ_0= 0.5 10^5 $L_\odot/pc^3$)

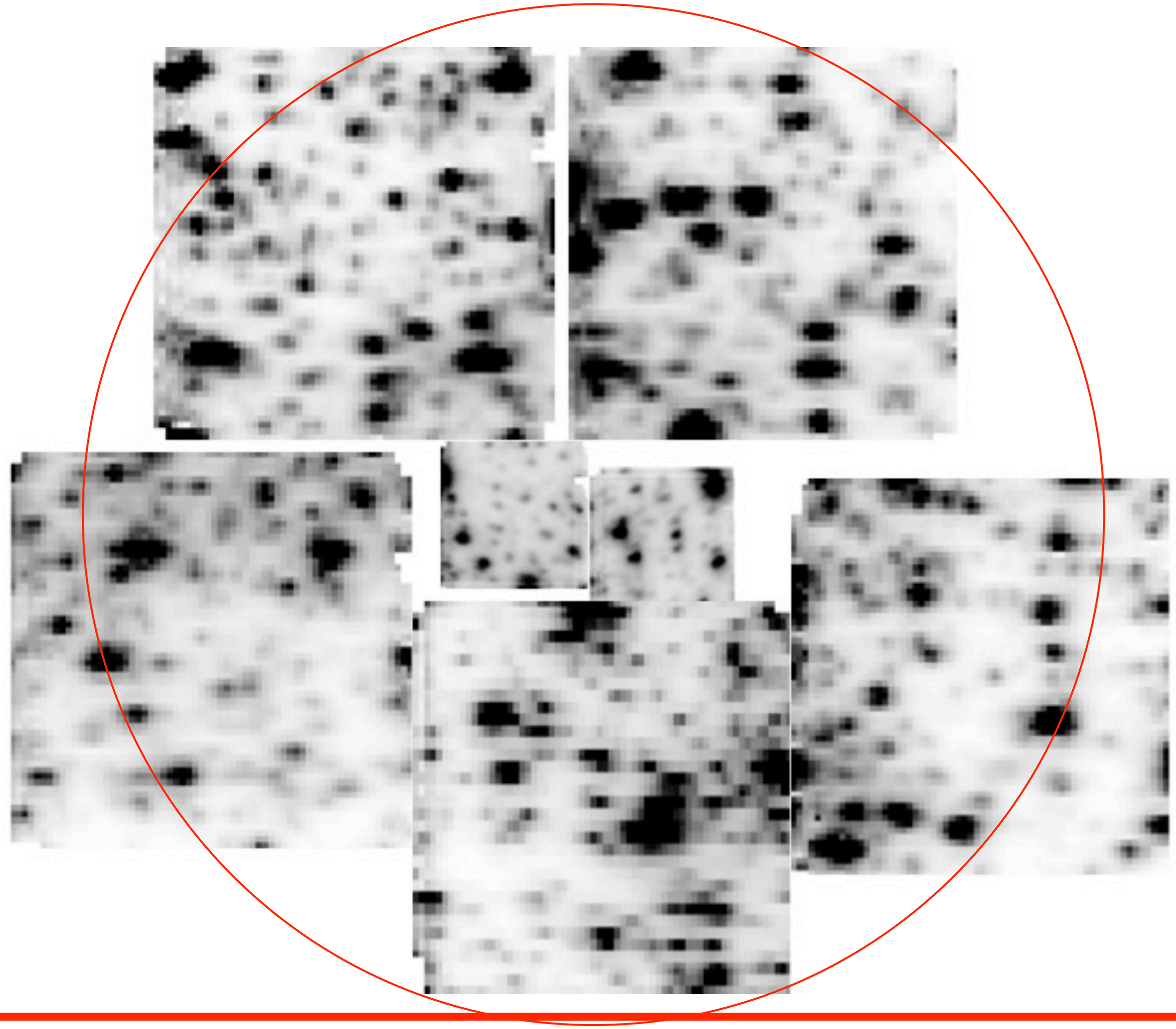
mosaic of 7 SINFONI fields



→ **RVs of 800 individual stars at r<12" (~0.6 pc) !!!**

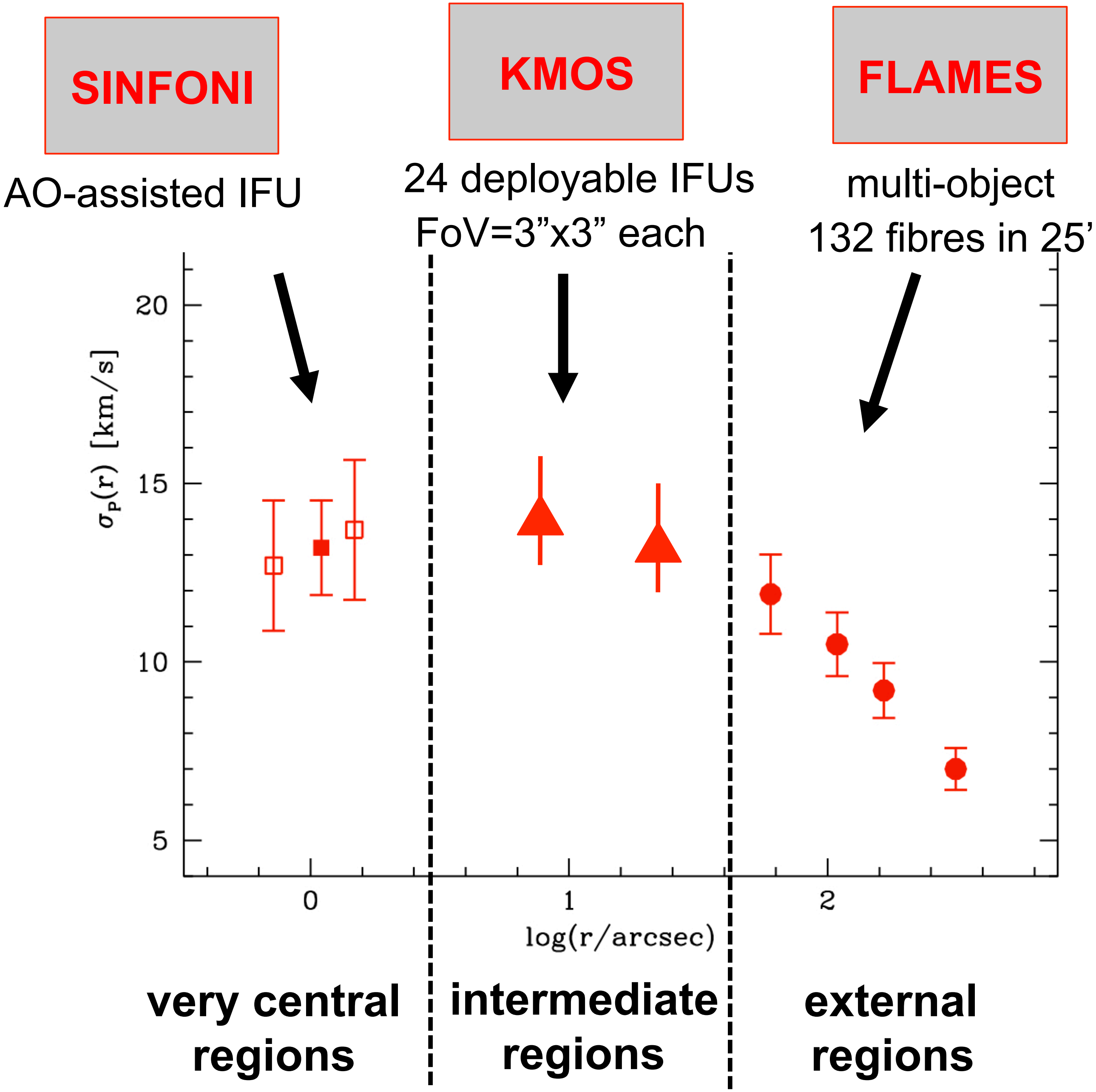
NGC 6441 (r_c=8", ρ_0= 1.8 10^5 $L_\odot/pc^3$)

mosaic of 2 HR + 5 LR SINFONI fields



→ **RVs of 700 individual stars at r<17" (~ 1pc) !!!**

ENTIRE radial profile: a MULTI-INSTRUMENT approach



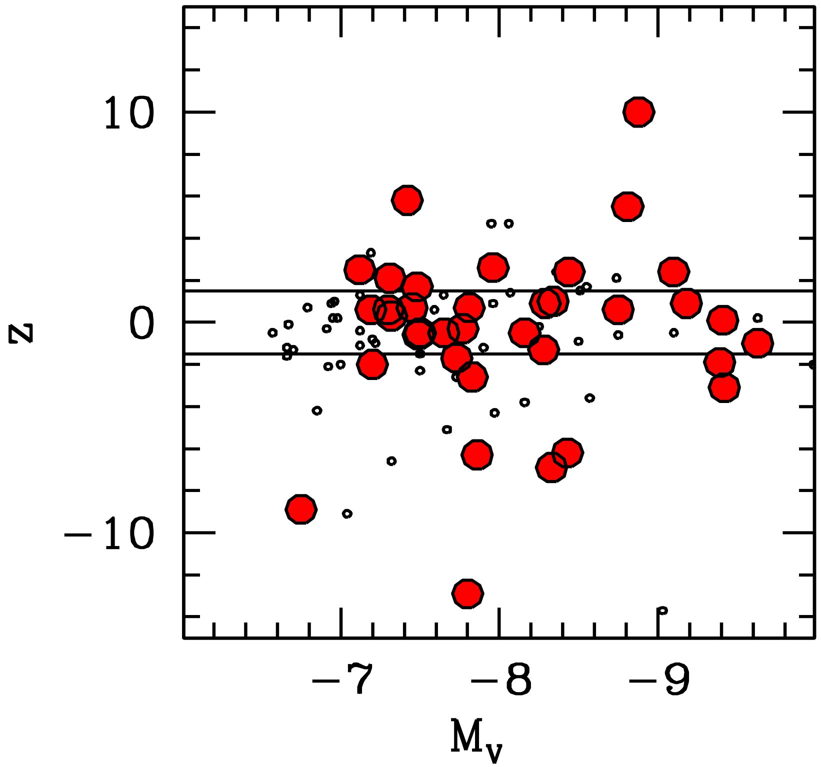
THE DATA-SET

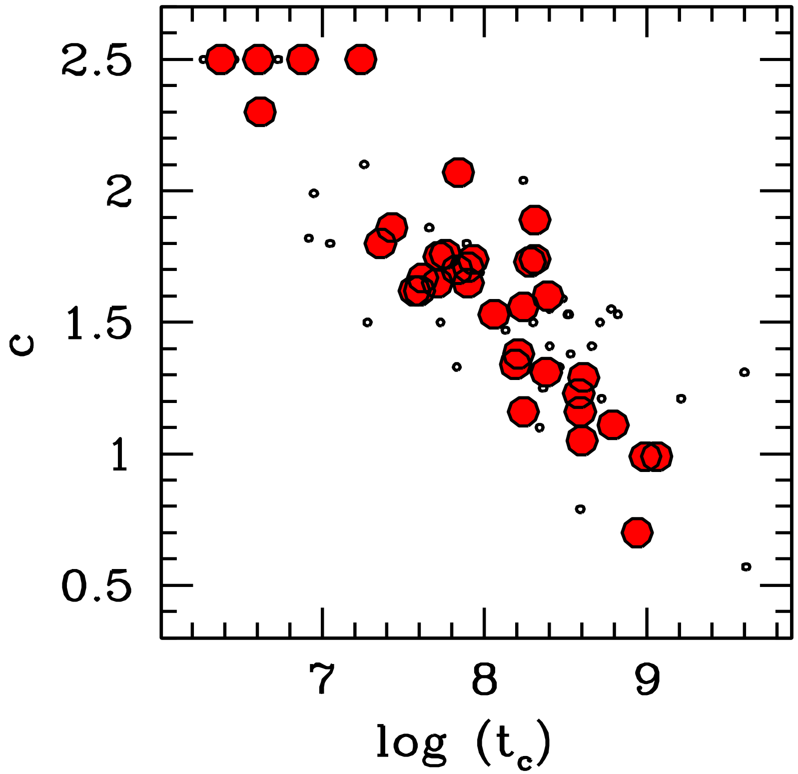
- **ESO Large Programme 193.D-0232 (PI: Ferraro):**
  194 hours
  KMOS + FLAMES
  30 Milky Way GCs
  2/3 acquired and 1/3 partially analyzed

- **ESO Large Programme 195.D-0750 (PI: Ferraro):**
  101 hours
  SINFONI
  15 high-density Milky Way GCs
  ½ acquired

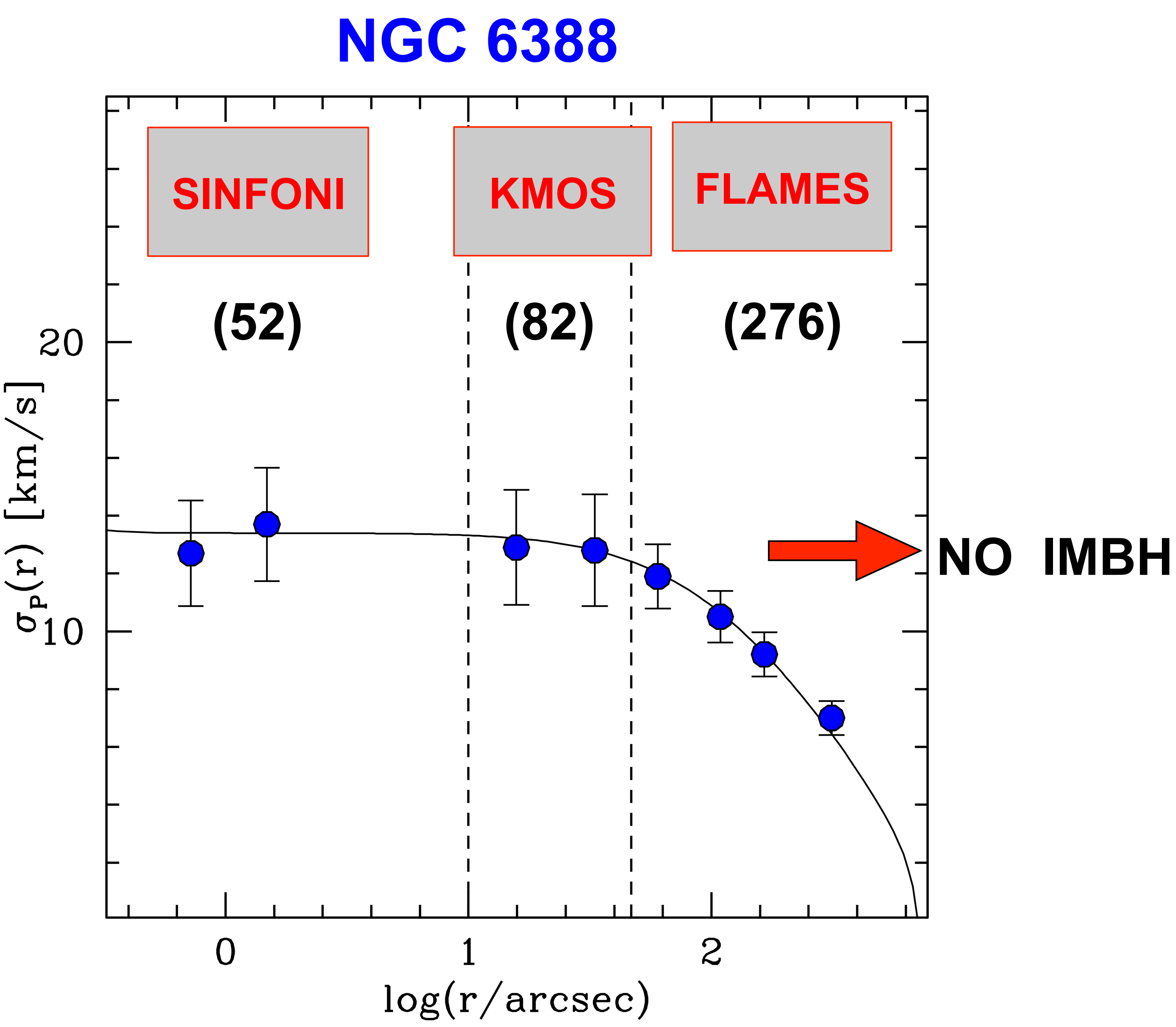
- **a few additional programmes @Keck:**
  OSIRIS + MOS-FIRE + DEIMOS

THE TARGETS (~30)



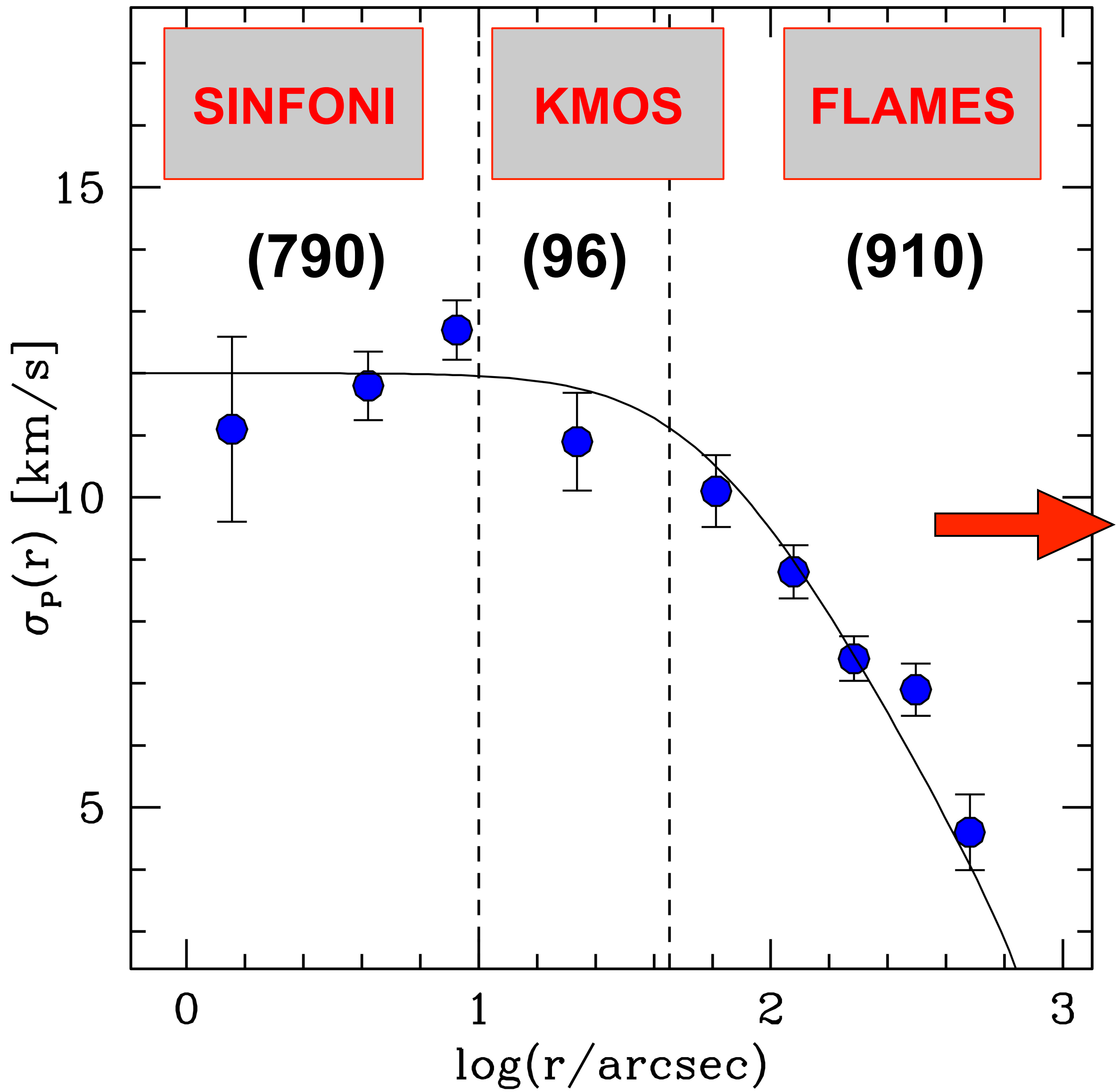


- massive (M > 5x10^5 M$_\odot$)
- spanning large ranges of log **ρ**, c and relaxation times
- covering different stages of dynamical evolution, including PCC
- spanning different environmental conditions (bulge/disk & halo populations)



NGC 6388
SINFONI
KMOS
FLAMES
(52)
(82)
(276)
NO IMBH
σP(r) [km/s]
20
10
0
1
2
log(r/arcsec)

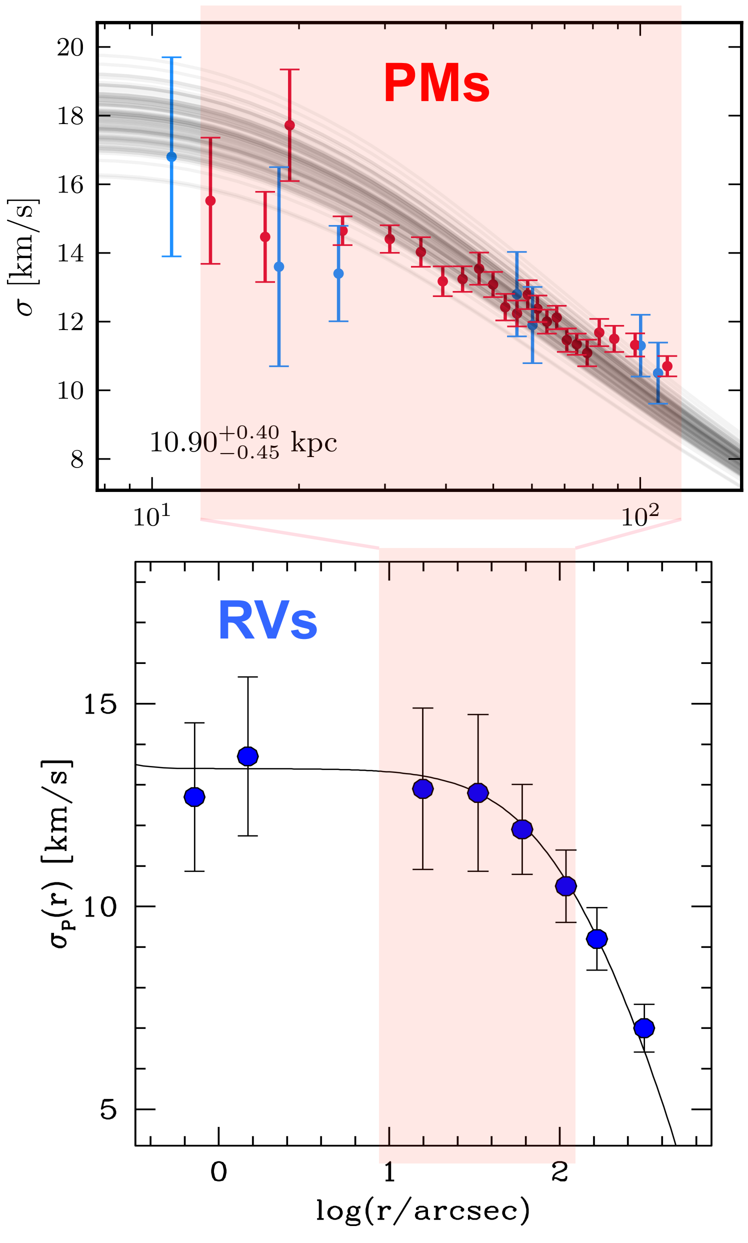
NGC 2808 (preliminary)



NO IMBH

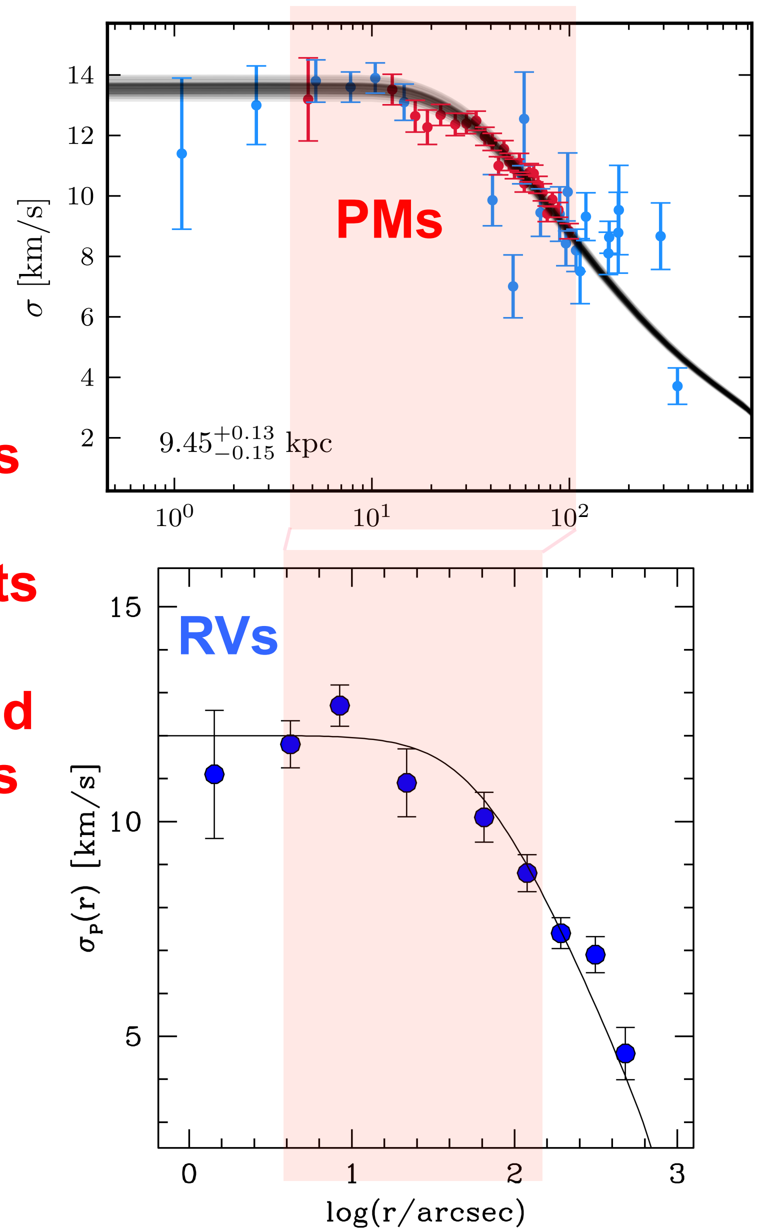
HSTPROMO PMs (Watkins et al. 2015)

NGC 6388

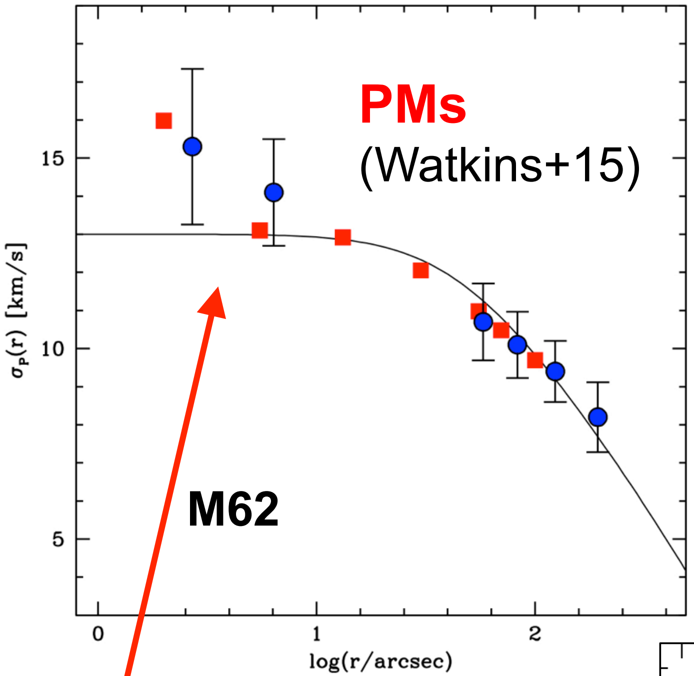


centres & outskirts non sampled by PMs

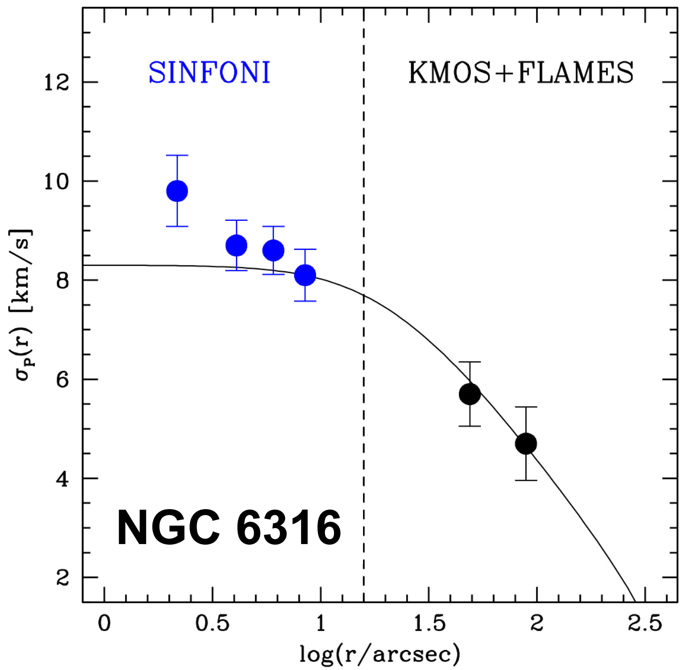
NGC 2808

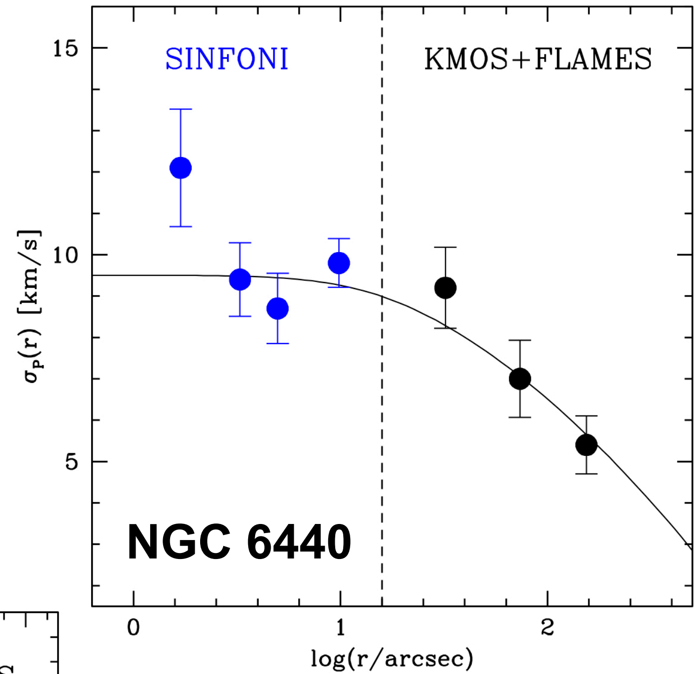


Hint of central cusp (preliminary): IMBHs??

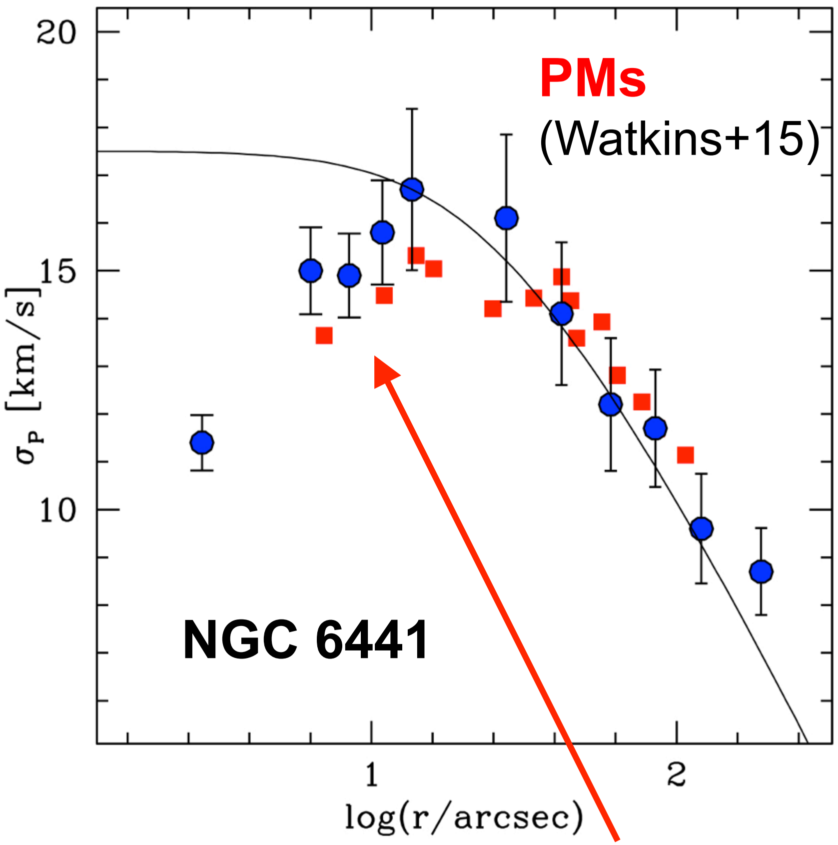


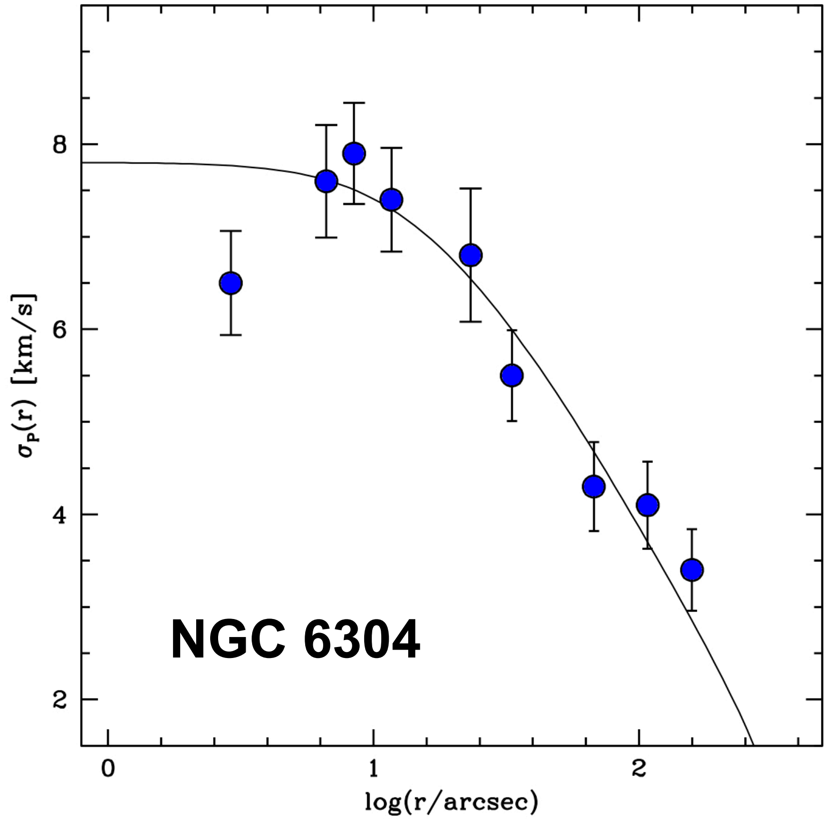
central cusp confirmed by PMs





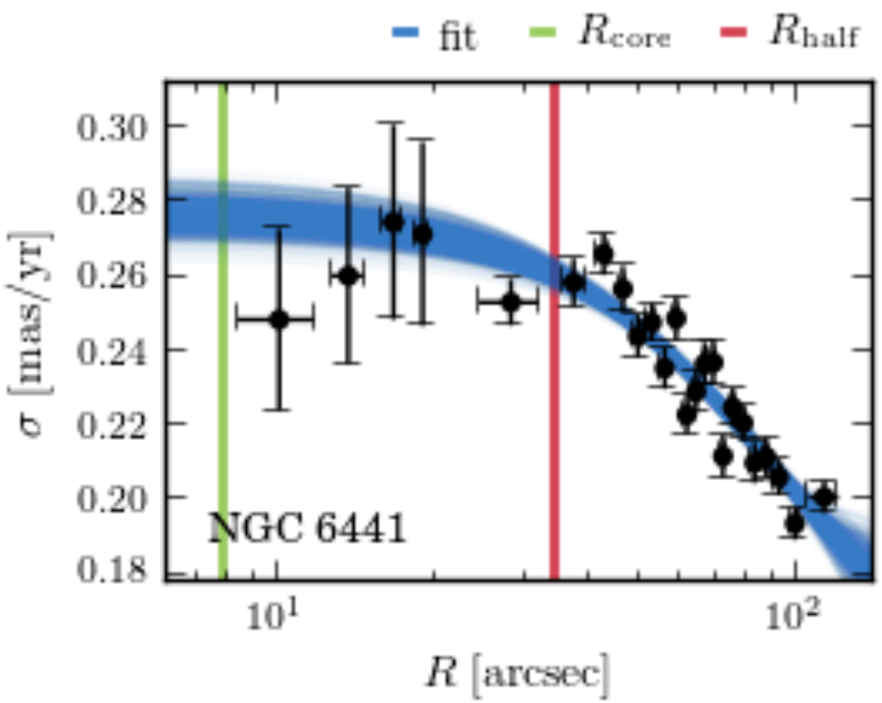
Unexpected behaviours: central drop

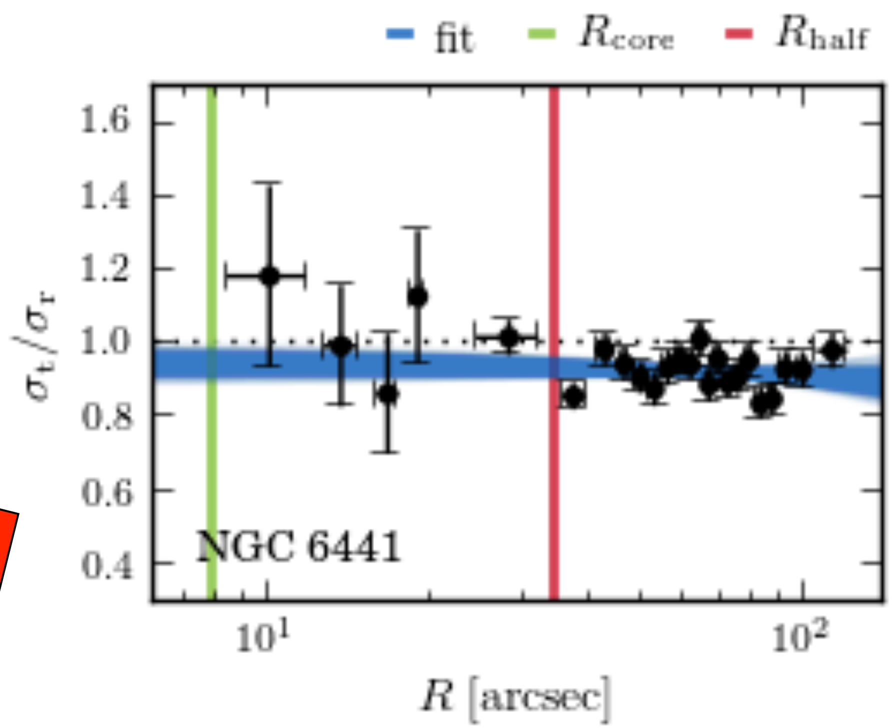




central drop
confirmed
by PMs

NGC 6441: PMs (Watkins et al. 2015)





tangential anisotropy effect?

CONCLUSIONS

- IMBHs in Galactic GCs: worth to be searched for

- No conclusive evidence yet (observational difficulties, contradictory observational results, uncertain fingerprints, partial/limited modelling)

- RVs of *individual* stars with AO-assisted IFU spectroscopy: very effective to determine central (few arcsec) VD

- No evidence of central VD cusp in NGC6388, NGC2808

- Possible central VD cusp in M62 (confirmed by PMs), NGC6440, NGC6316

- Interesting features emerging: central VD drop in NGC6441, NGC6304

- Synergy with PM measurements is crucial → 3D kinematics!

- Appropriate modelling (pressure anisotropy, dark remnants,..) is mandatory!

Thank you