Dynamical black-hole masses from SINFONI observations

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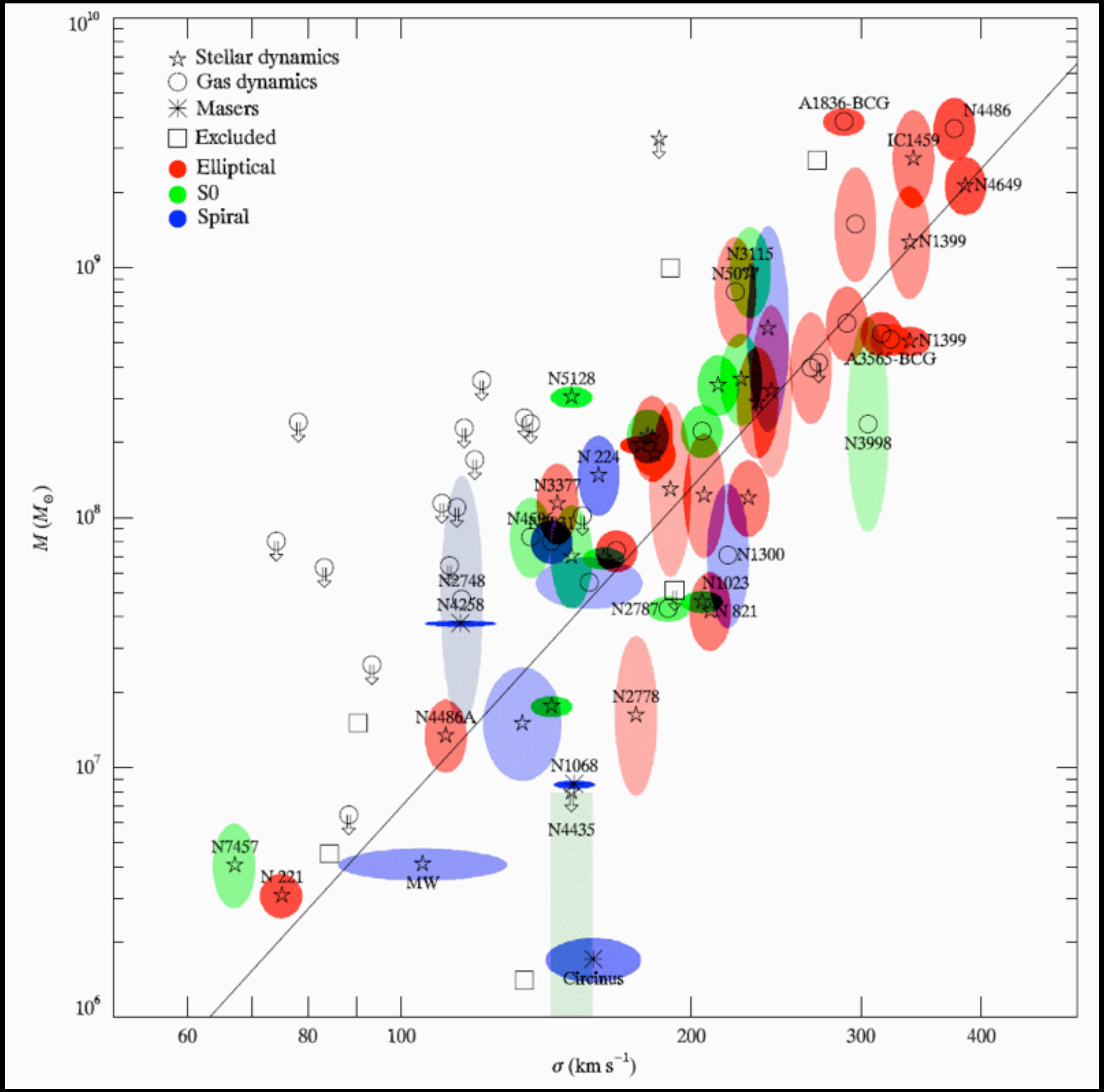
- introduction
- SINFONI program to measure BH masses in local galaxies from stellar kinematics
- dynamical models of low-mass galaxies
  NGC 3368, NGC 3489 (multi-component bulges)
  NGC 5102 (sigma ~ 66 km/s)
- summary

BH scaling relations

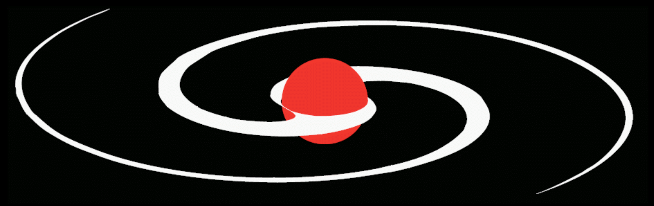
- direct, dynamical BH mass determinations for ~50 galaxies
- BH masses scale with
  - bulge velocity dispersion
  - bulge luminosity
  - bulge stellar mass
  - (e.g. Marconi & Hunt 2003, Haering & Rix 2004, Ferrarese & Merritt 2000, Gebhardt+ 2000 ...)
- evolution of BHs and hosts:
  - slope, scatter,
  - fundamental relation?
- lack of measurements at
  - high masses σ > 300 km/s
  - low masses σ < 120 km/s



(from Gueltekin et al. 2009)

different bulge types

- bulges come in two flavours (e.g. Kormendy & Kennicutt 2004)
- *classical bulges*:
  "mini-ellipticals"
  relatively round
  dispersion dominated kinematics
  steep surface-brightness profiles



- *pseudo-bulges*:
  flattened & oriented more like disks
  rotation-dominated kinematics
  substructure (spiral arms, dust, ...)

- probably different formation mechanisms
  (merging vs. secular evolution)
- differences in BH growth & BH scaling relations?
  (e.g. Kormendy 2001, Hu 2008, Greene+ 2008, Gadotti & Kauffmann 2009)

SINFONI program

- a sample of 33 galaxies observed with SINFONI at the VLT
  in particular at the high & low mass end
  almost doubles existing dyn. BH masses
- advantages of SINFONI
  AO resolution ~ 0.15”
  integral-field kinematics (IFU)
  -> better data-coverage increases
  reliability of dynamical models
  infrared kinematics important for low-mass galaxies (dust)
  large collective power (core ellipticals)

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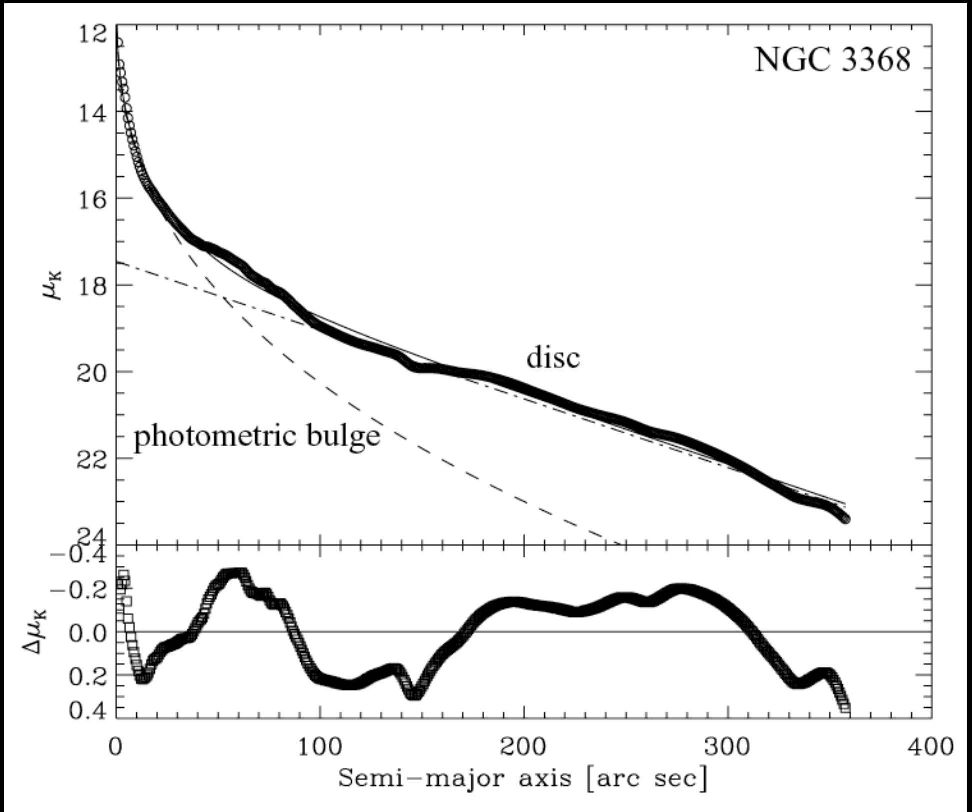
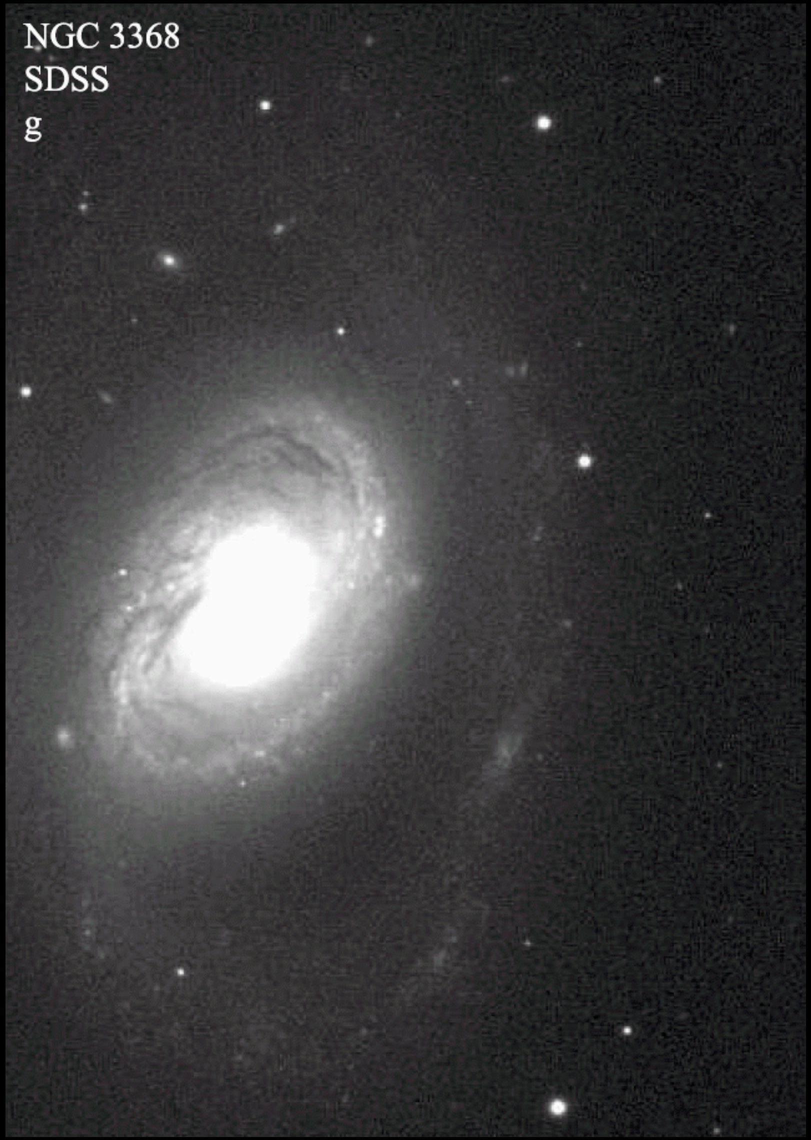
- eight galaxies with σ <120 km/s
  NGC3368, NGC3489, NGC5102
  NGC3412, NGC3627, NGC4371, NGC4486a, NGC4569

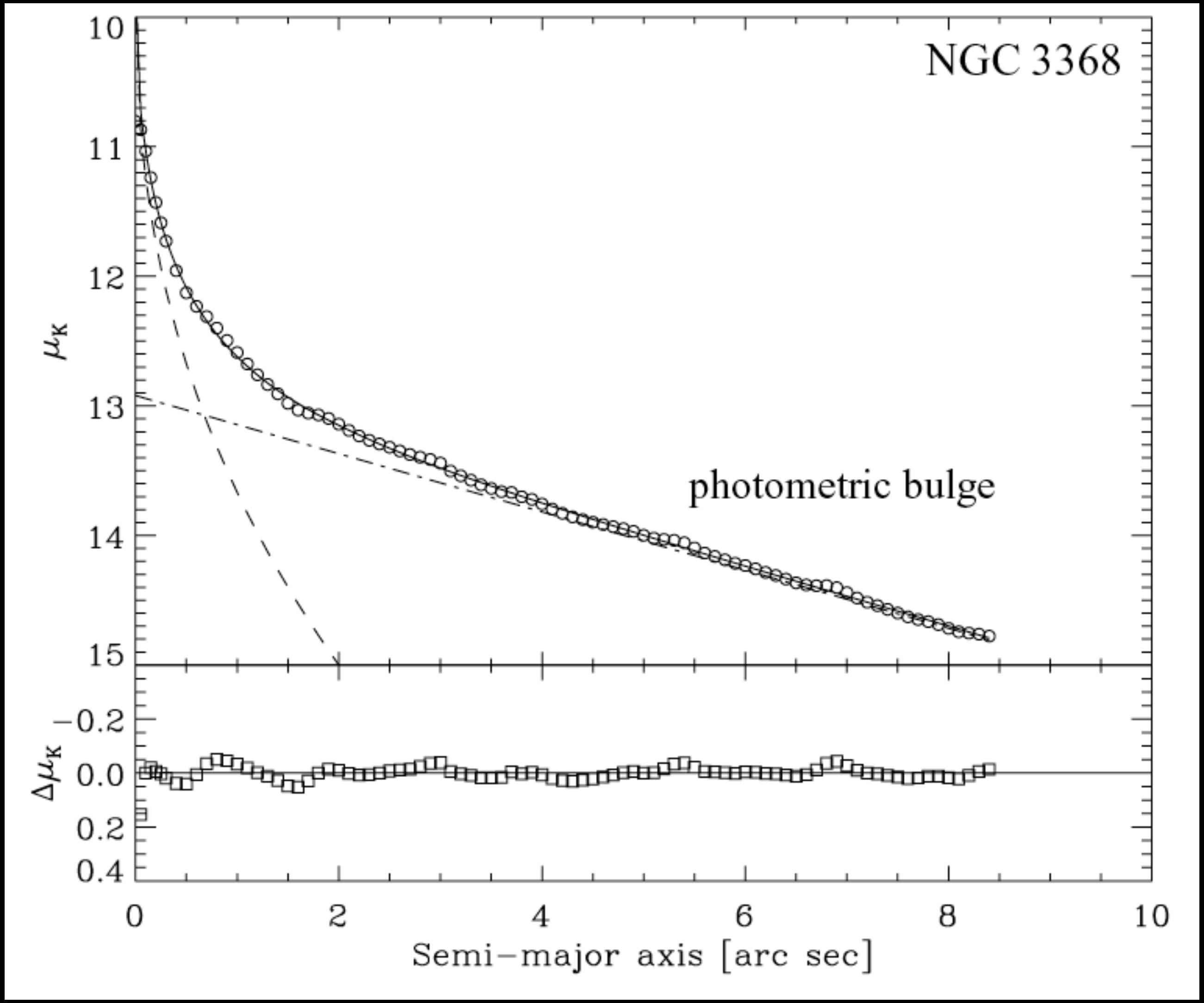
NGC 3368: photometry





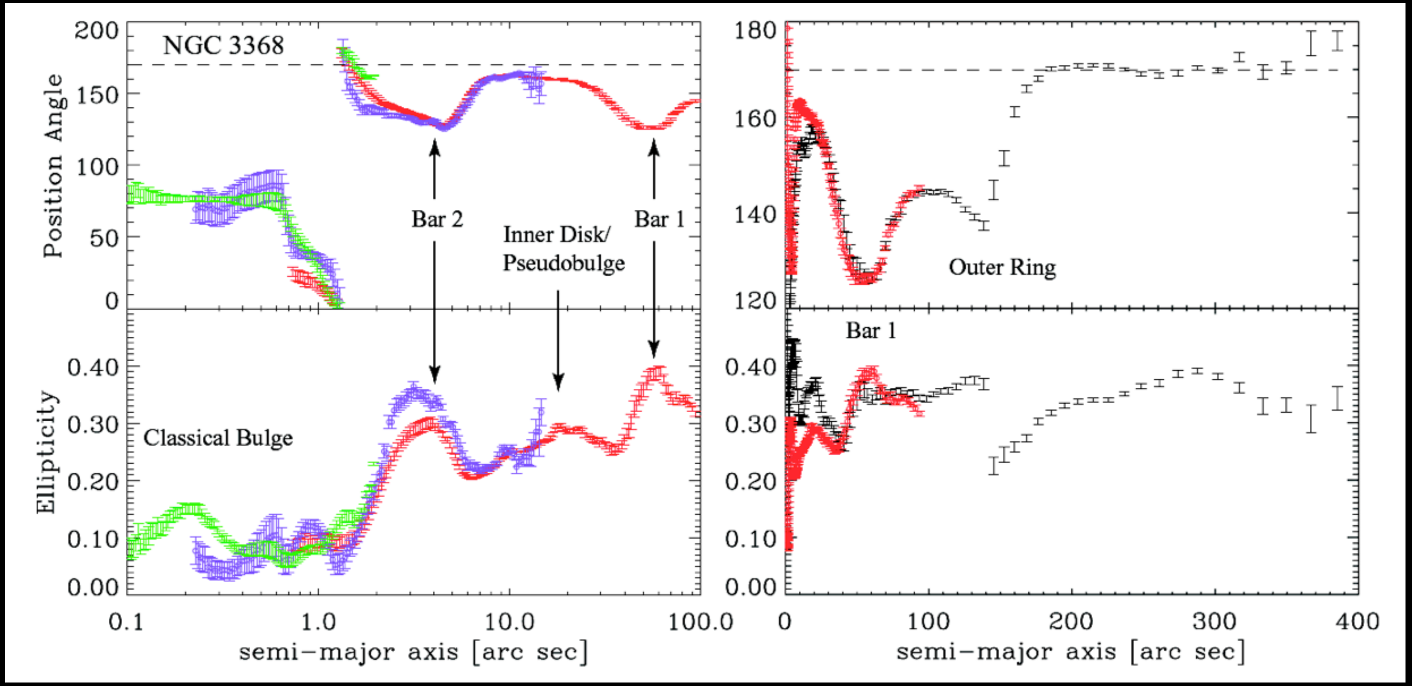
- double-barred spiral galaxy
- r<50”:
  excess-light with respect to inward extrapolation of outer exponential disk SB-profile
  -> photometric bulge

NGC 3368: bulge light profile



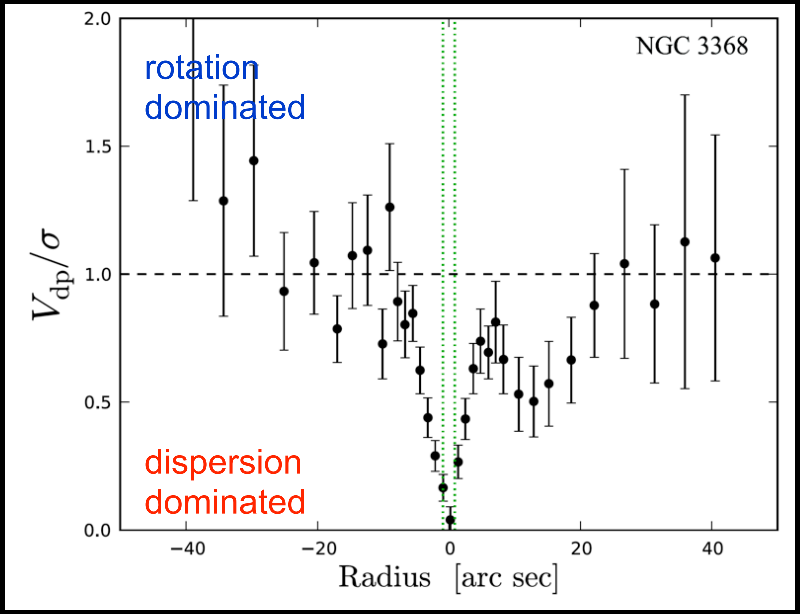
- 1" < r < 50": bulge can be well described by an exponential SB
- r < 1": excess light with respect to exponential SB

NGC 3368: a composite bulge



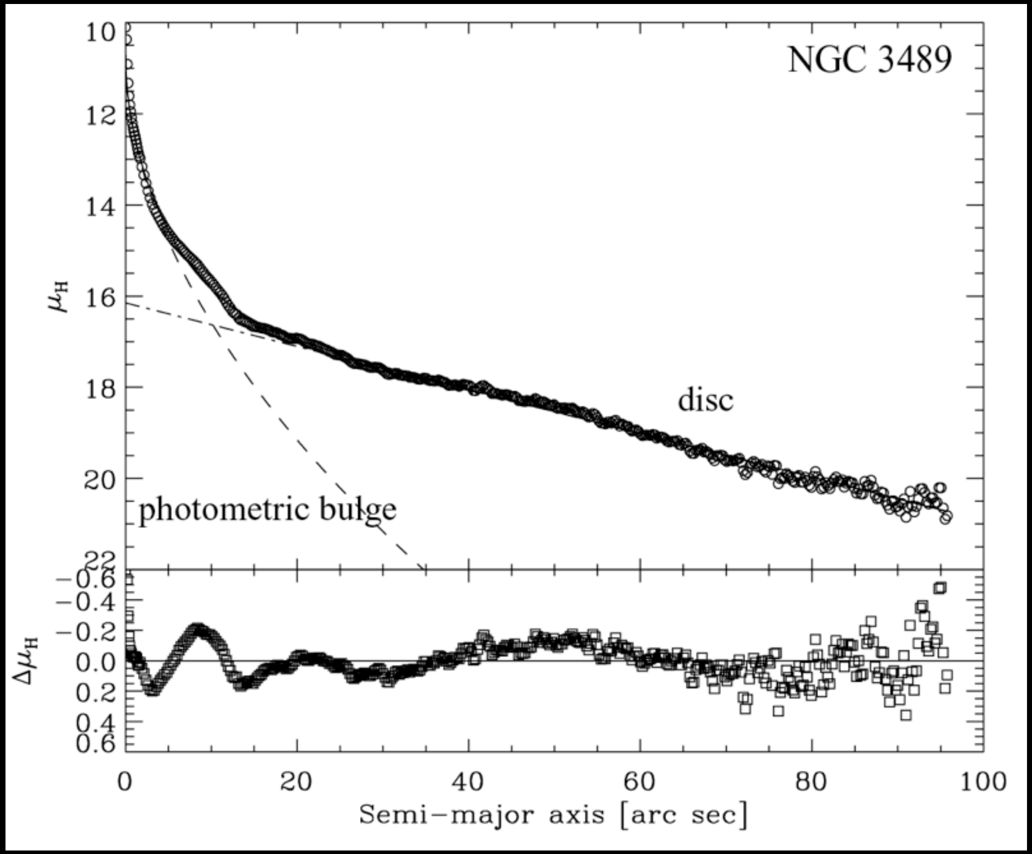
photometric data:
K-band (Knapen et al. 2003)
NICMOS2 F160W
SINFONI image
SDSS r-band

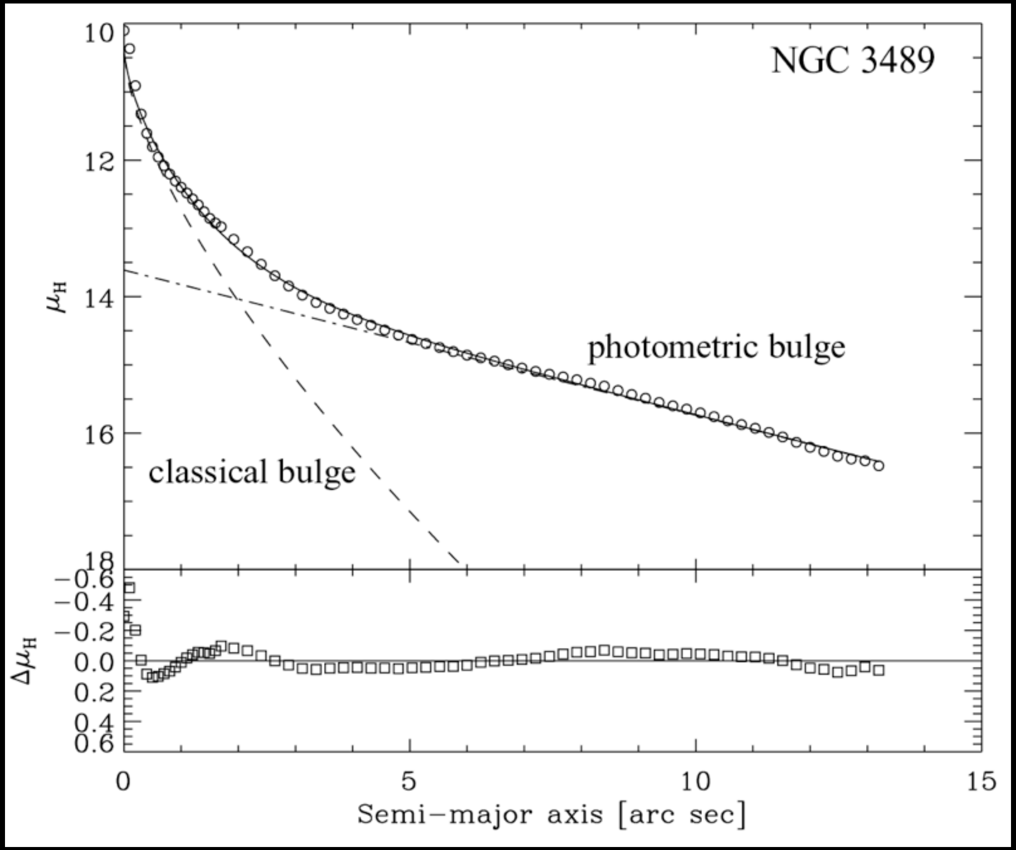
- **1” < r < 50”:**
  bulge flattened & oriented like disk, rotation dominated
- **r < 1”:**
  round & dispersion dominated
- **composite bulge**
  ***classical bulge* r<1”**
  ***pseudo-bulge* 1” < r < 50”**



(kin. from Heraudeau+ 99)

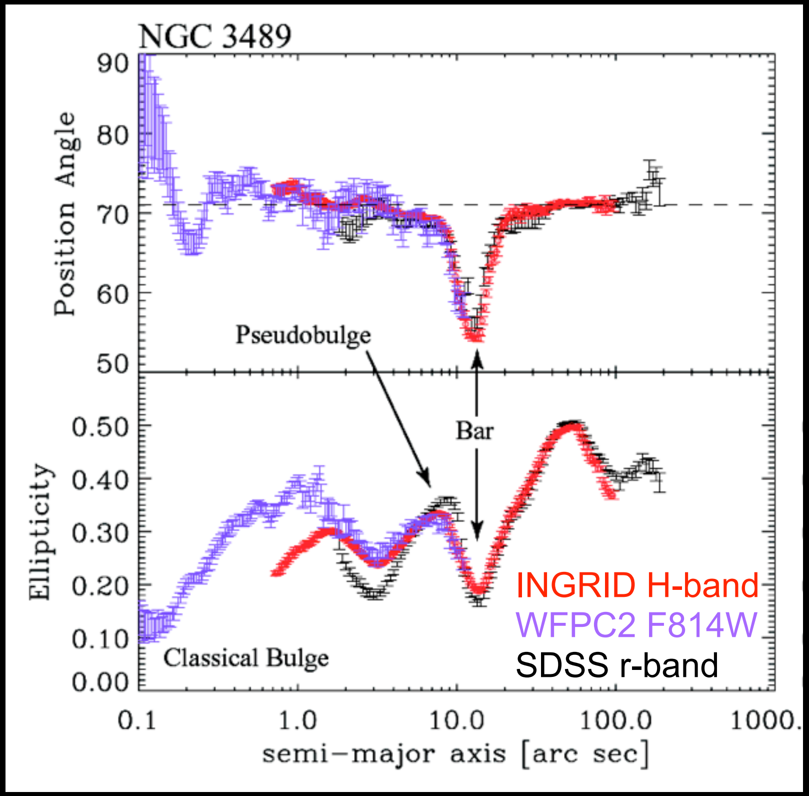
NGC 3489: bulge light profile

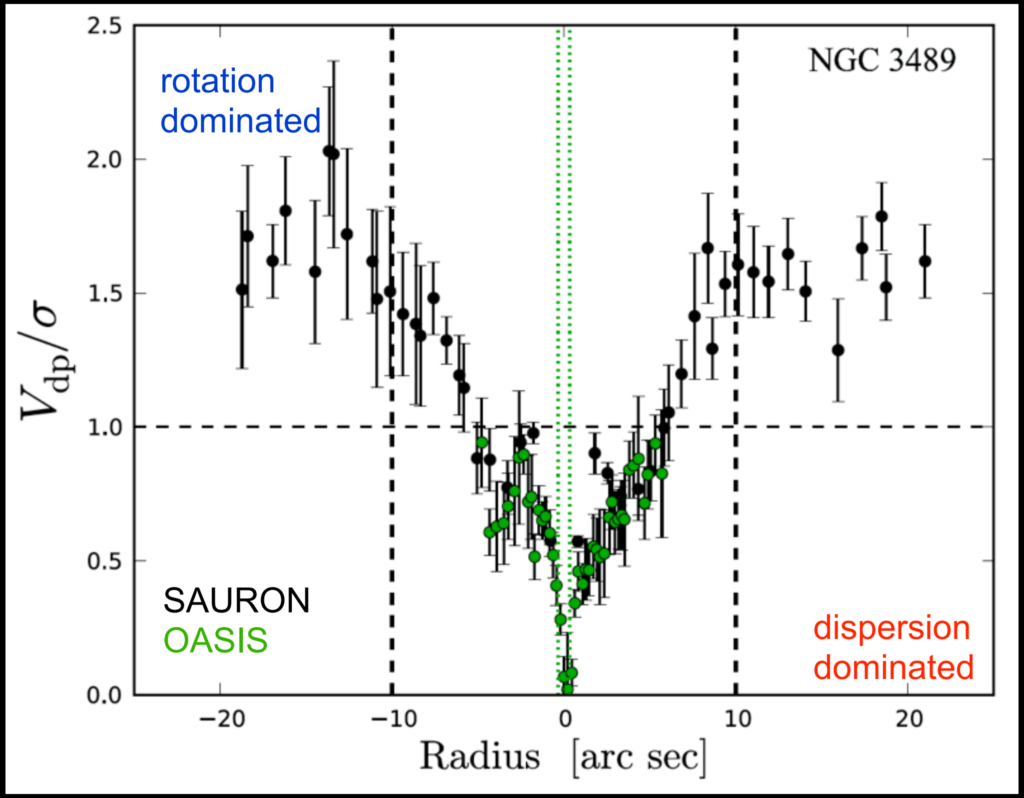




- **similar structure as NGC 3368 (but single-barred)**
  outer photometric bulge (r>2”): exponential surface-brightness
  inner photometric bulge (r<2”): light excess

NGC 3489: a composite bulge

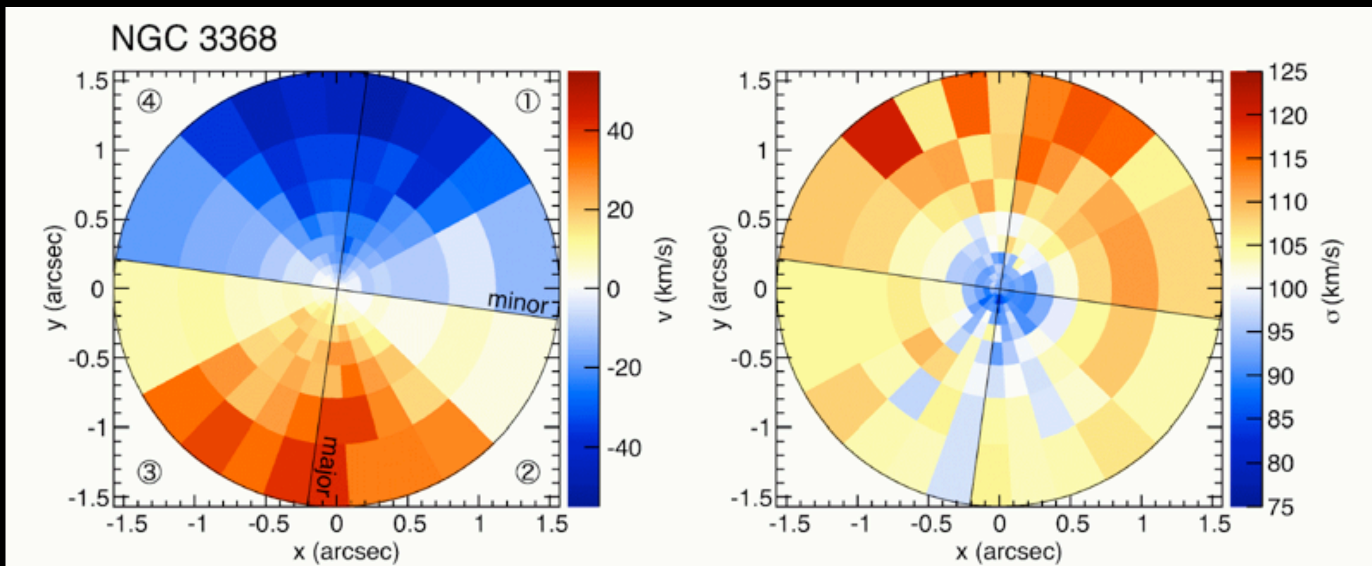




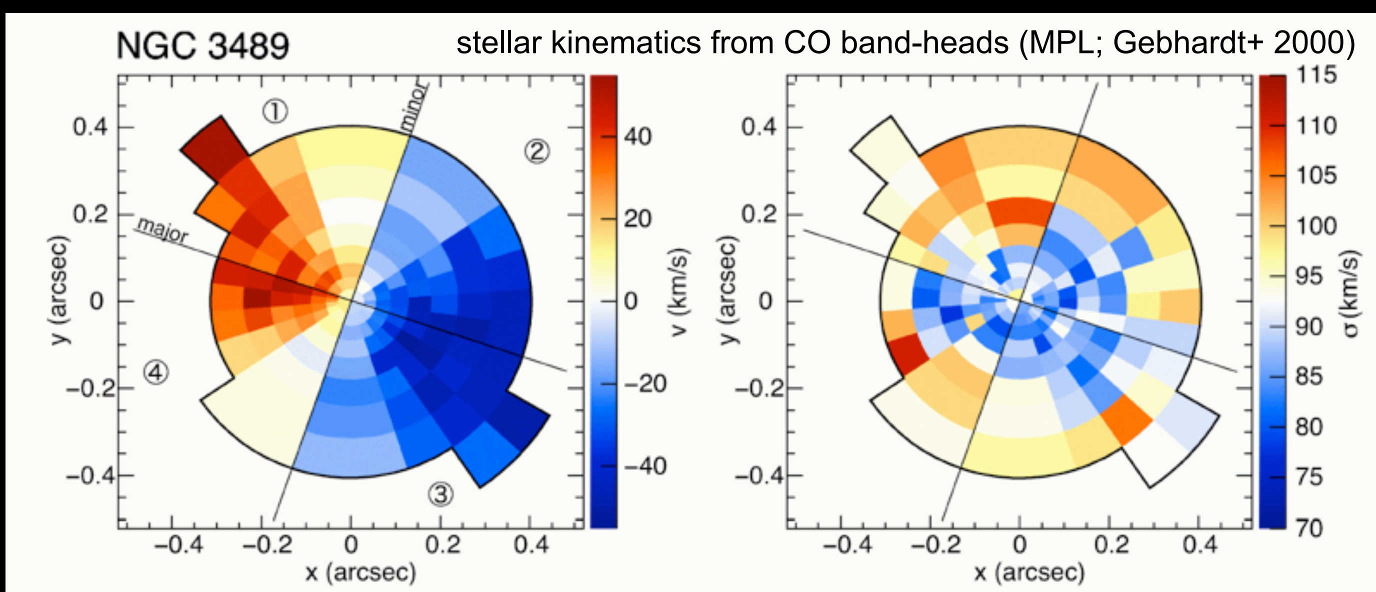
- similar composite bulge structure as in NGC 3368
  - *classical bulge* r < 2"
    - round & dispersion dominated
  - *pseudo-bulge* 2" < r < 10"
    - flattened & oriented like outer disk, rotation dominated

SINFONI kinematics

do the BH masses scale with classical or total bulge luminosity?



SINFONI
100mas resolution
FWHM = 0.165”
Strehl = 14%
sigma = 98.5 km/s



SINFONI
25 mas resolution
FWHM ~ 0.08”
Strehl = 43%
sigma = 91 km/s

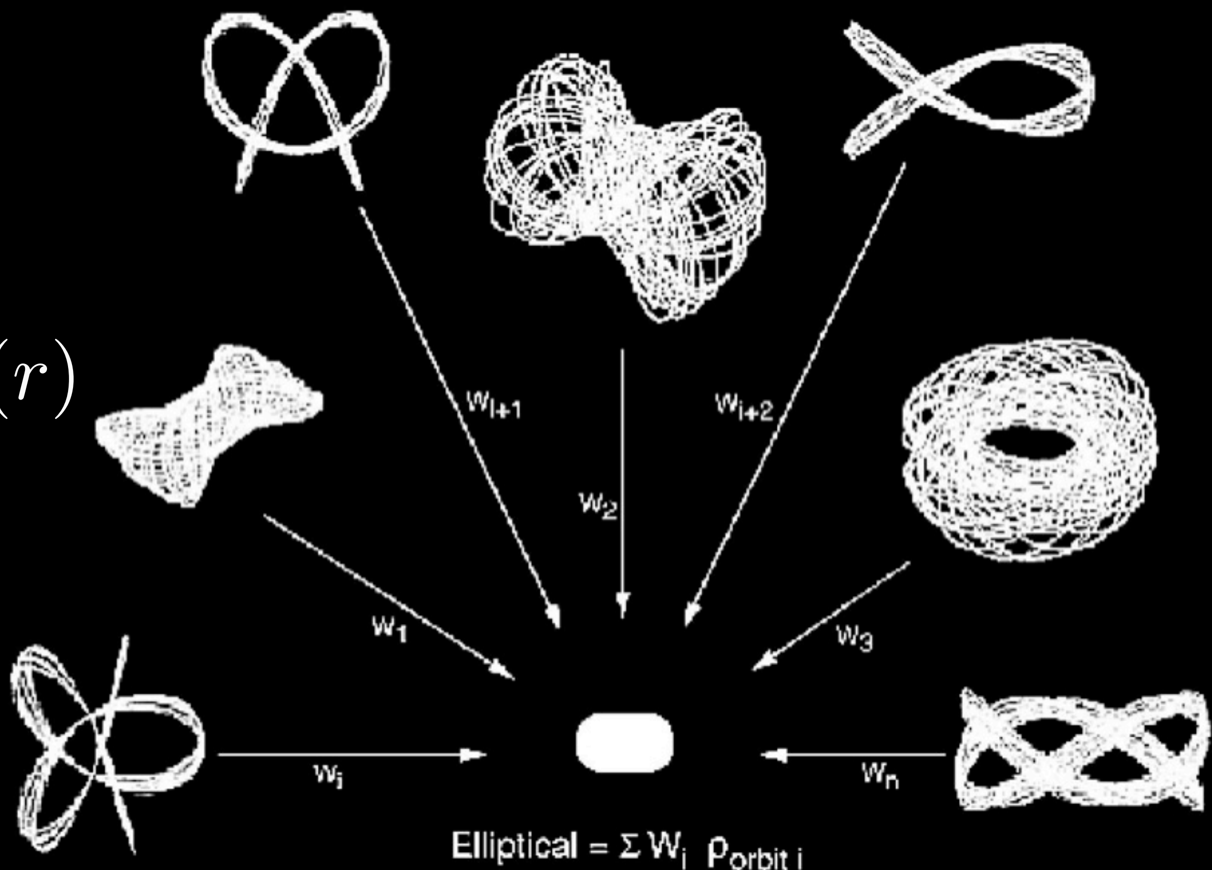
Schwarzschild modelling

- ***deprojection***
  3d light distribution

- ***trial mass model***
  $$\rho = \Upsilon_* \nu_* + M_{\rm BH}\,\delta(r)$$

- ***orbit library***

- ***orbit superposition***
  determine light w_i
  on each orbit from light distribution and kinematics



- ***best-fit mass parameters*** from chisquare analysis

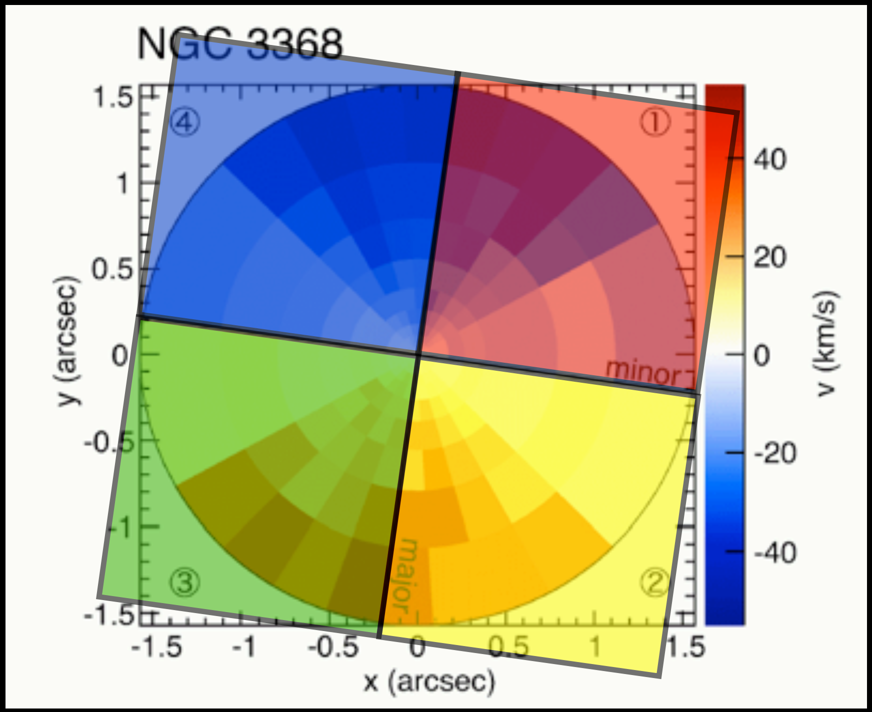
- ***axisymmetric models***

Gebhardt, Richstone & Tremaine
(Thomas et al. 2004,2005,2007)

dynamical models

- Schwarzschild models can account for any orbital structure in a given symmetry
- codes have been tested against analytic models (Siopis et al. 2009)
- symmetry: axisymmetric, triaxial? (van den Bosch & de Zeeuw 2010)

advantage of IFU data



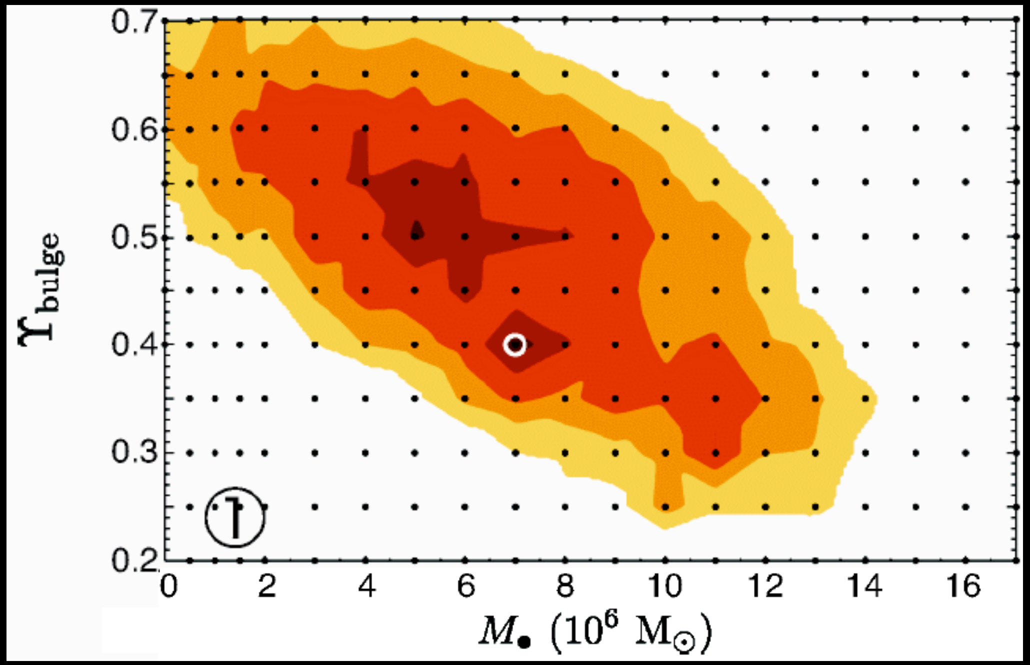
modelling individual quadrants separately:

model 1 -> $M_{BH,1}$
model 2 -> $M_{BH,2}$
model 3 -> $M_{BH,3}$
model 4 -> $M_{BH,4}$

- if galaxy is axisymmetric: models of individual quadrants should be consistent within the errors
- if models are different: estimate on systematic errors from model to model variation
- even without systematic variations triaxiality remains possible

dynamical models

- Schwarzschild models can account for any orbital structure in a given symmetry
- models have been tested against analytic models (Siopis et al. 2009)
- symmetry: axisymmetric, triaxial? (van den Bosch & de Zeeuw 2009)
- sphere of influence not well resolved: degeneracy between BH and stellar mass-to-light
- stellar mass-to-light ratio needs to be well constrained
- stellar M/L can be biased too high e.g. by DM (Gebhardt & Thomas 2010) or too low (if stellar M/L changes with r)



degeneracy between M_{BH} and Υ_{bulge} in NGC3368

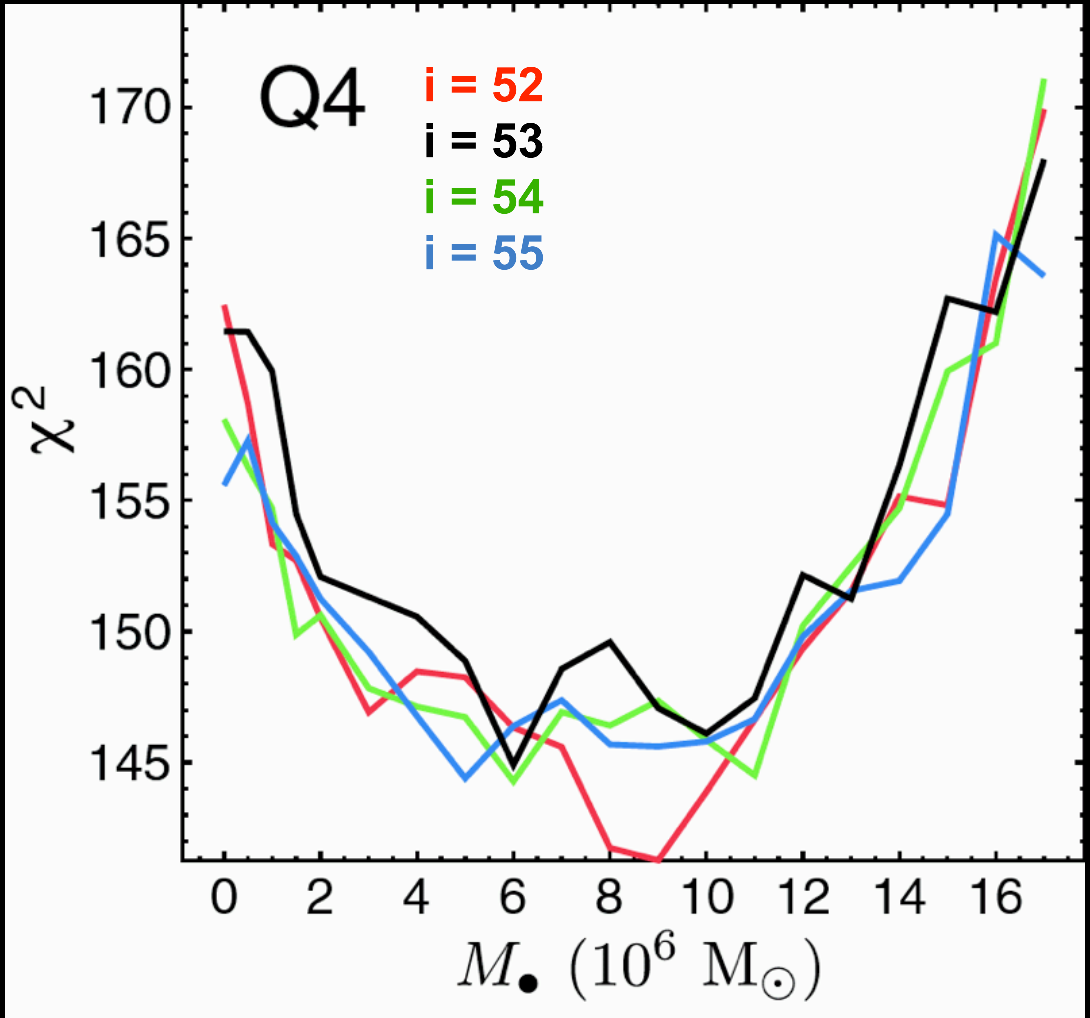
dynamical modelling

to get unbiased stellar M/L and BH masses:

classical bulge region & rest of galaxy
are treated as separate components in dynamical models

fit for Υ_{class}, Υ_{rest}, M_{BH}

NGC 3368: BH fits



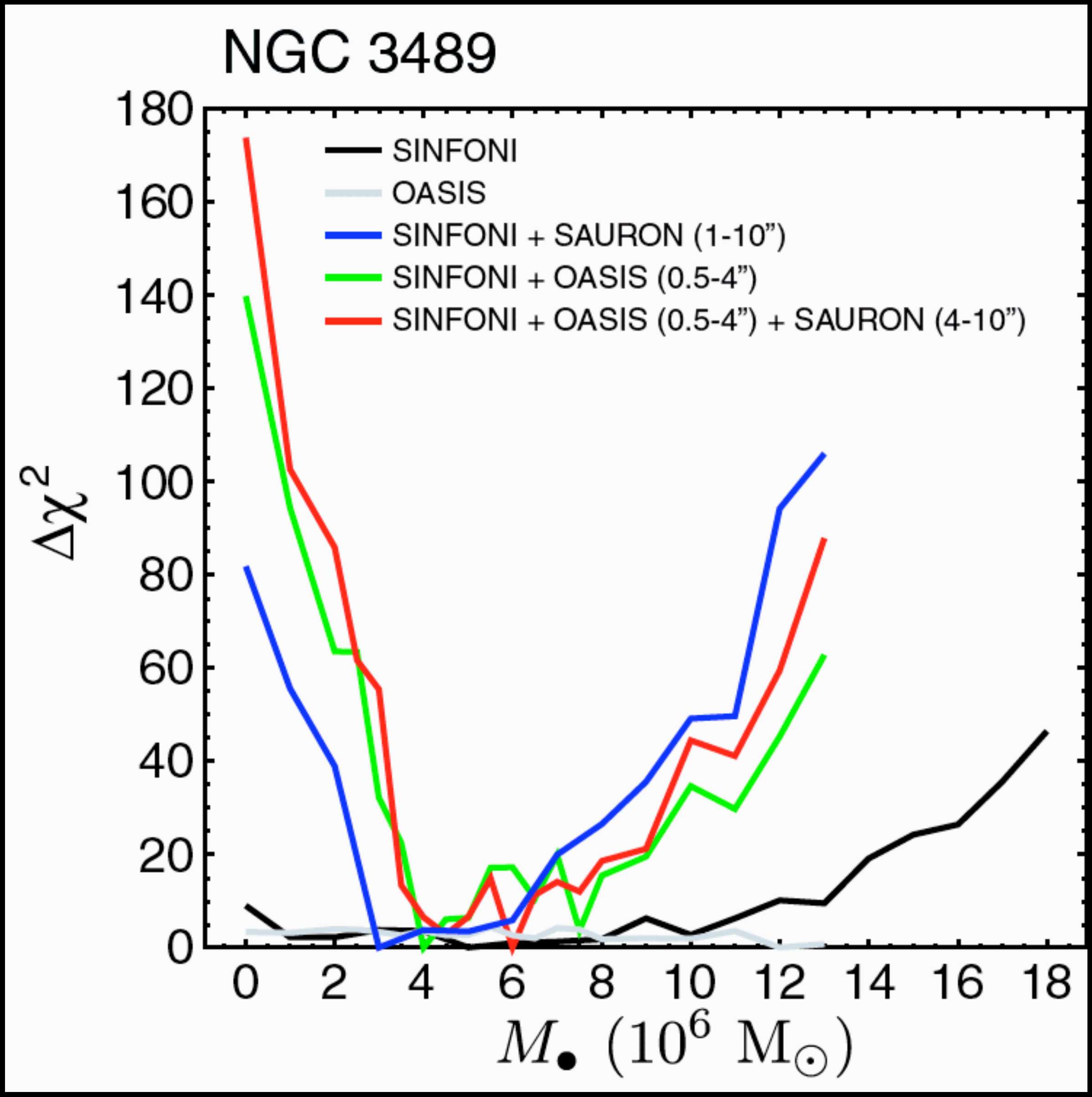
example of model results for one quadrant

$$\chi^2 = \sum \left(\frac{\mathrm{LOSVD_{mod}} - \mathrm{LOSVD_{dat}}}{\Delta \mathrm{LOSVD_{dat}}} \right)^2$$

(N_{data} = 900)

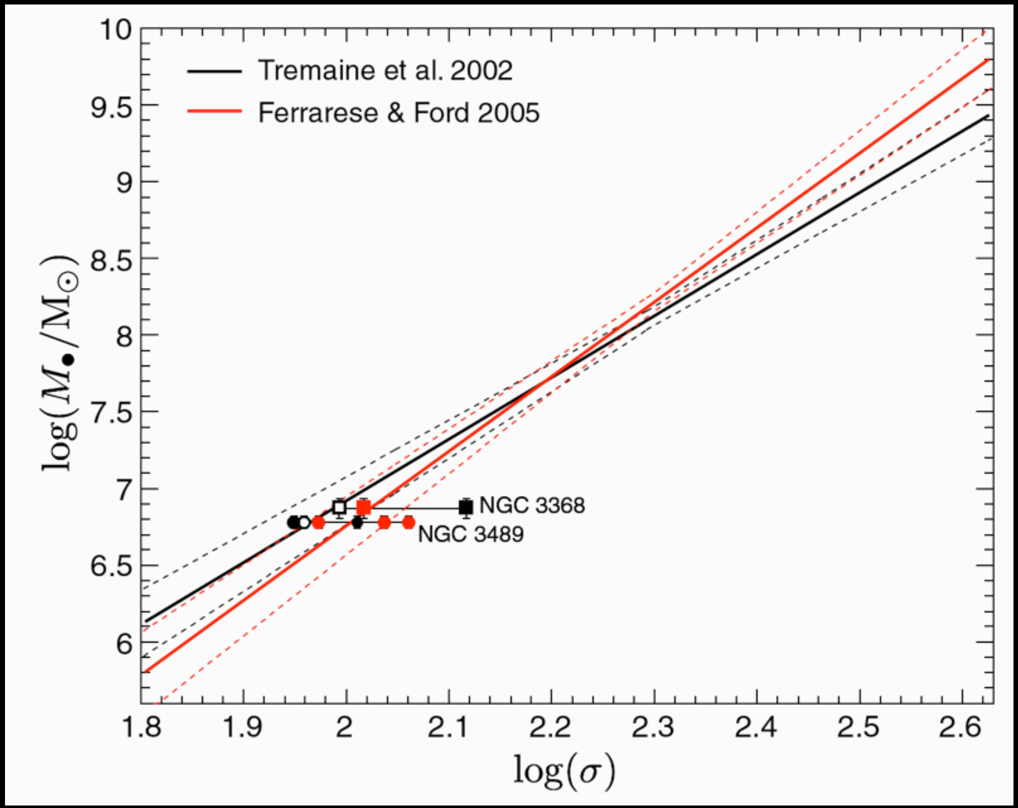
- inclination not further constrained by dynamical models, but does not influence results
- four quadrants:
  $M_{BH,1} = 7 \times 10^6\ M_{sun}$
  $M_{BH,2} = 8 \times 10^6\ M_{sun}$
  $M_{BH,3} = 9 \times 10^6\ M_{sun}$
  $M_{BH,4} = 6 \times 10^6\ M_{sun}$
  $\langle M_{BH} \rangle = (7.5 \pm 1.5) \times 10^6\ M_{sun}$
- rms-scatter consistent with M_{BH} errors in individual quadrants ($1.6 \times 10^6\ M_{sun}$)
- no evidence for systematic differences between quadrants
- (details in Nowak et al. 2010)

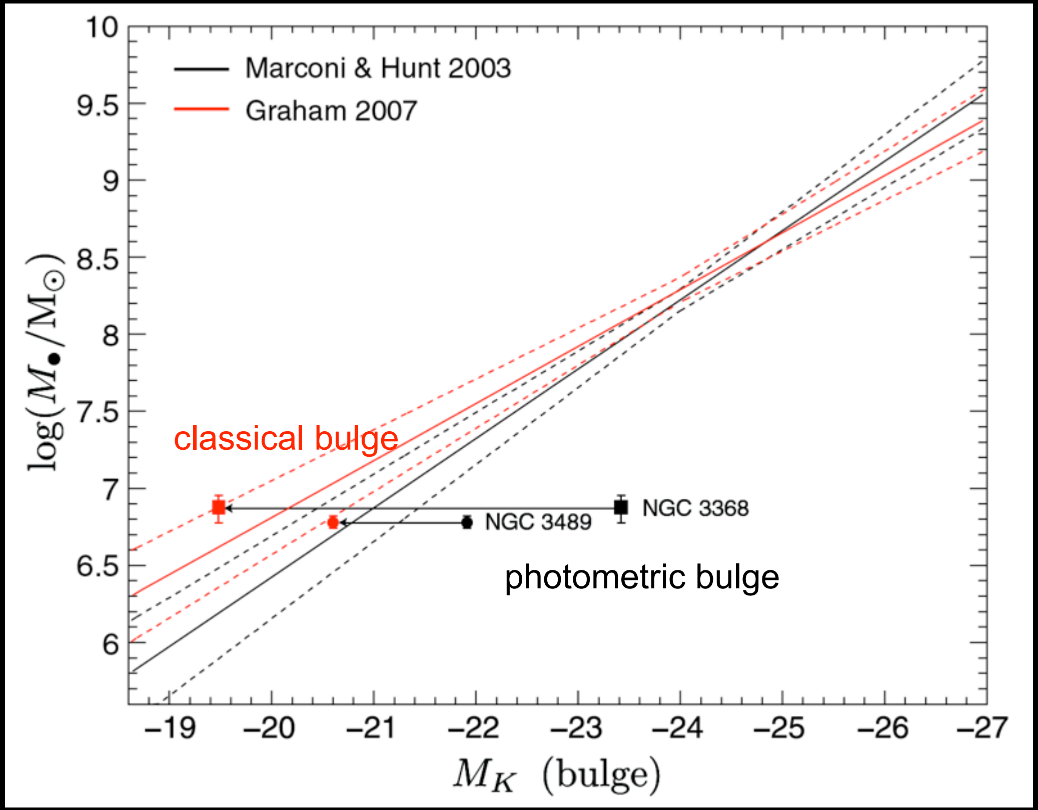
NGC 3489: BH fits



- no difference between ind. quadrants when using SINFONI data alone
- BH not constrained with SINFONI alone
- other kinematics for the outer parts:
  SAURON (r<10"; res. 1.1")
  OASIS (r<4"; res. 0.7")
- outer kinematics constrain the bulge M/L and, thus, the BH mass
  $M_{BH} = (6+/-0.5)x10^6 M_{sun}$
  sys. error = $0.64x10^6 M_{sun}$

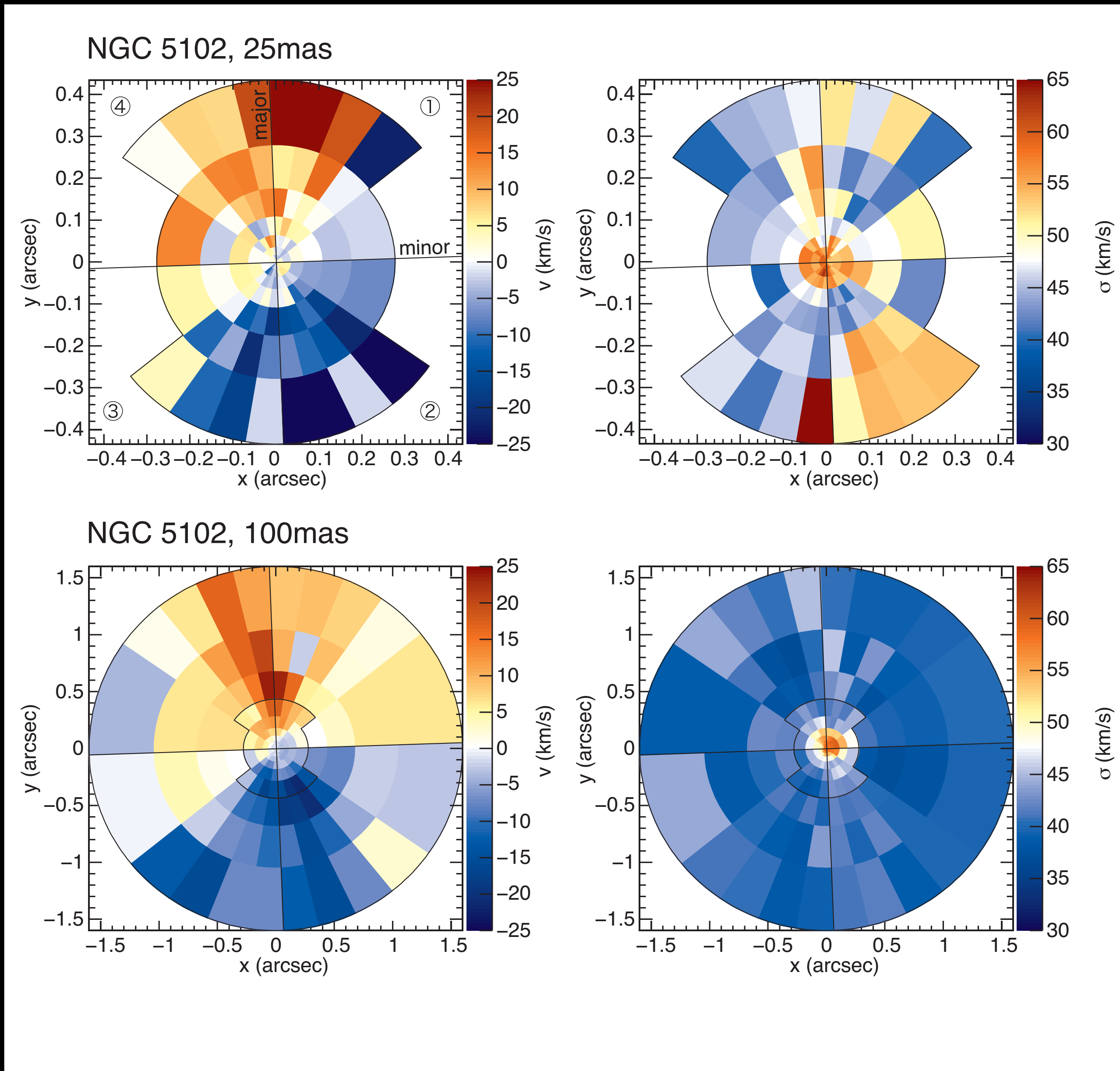
NGC 3368 & NGC 3489: BH scalings





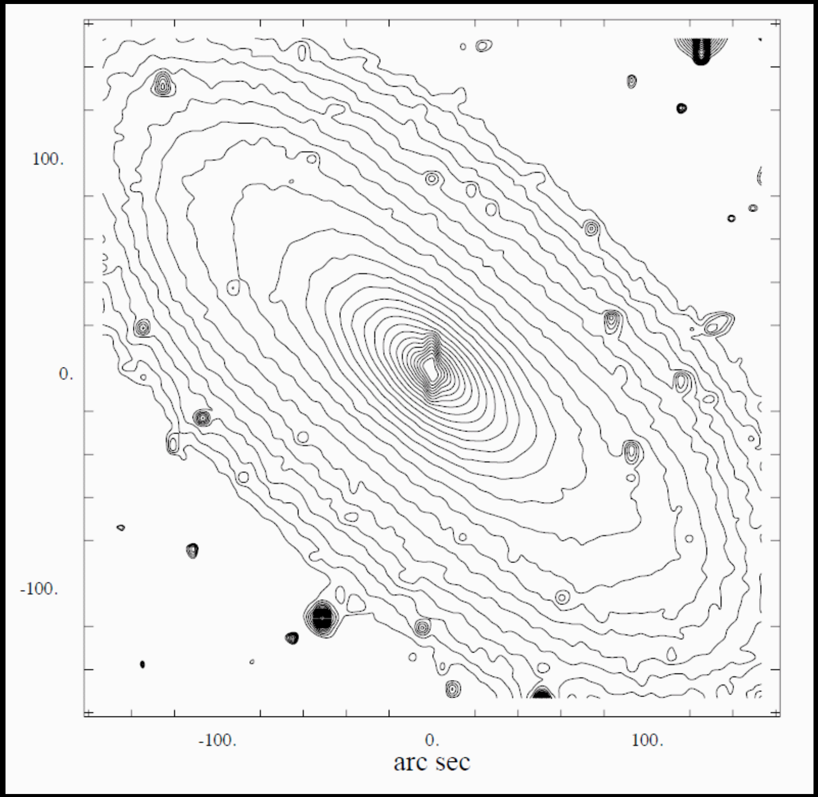
- NGC 3368 & NGC 3489 consistent with M_{BH} - sigma relation
- NGC 3368 & NGC 3489 fall below the M_{BH} - M_K relation when using the total (photometric) bulge, but not when only the inner (classical) bulge regions are considered

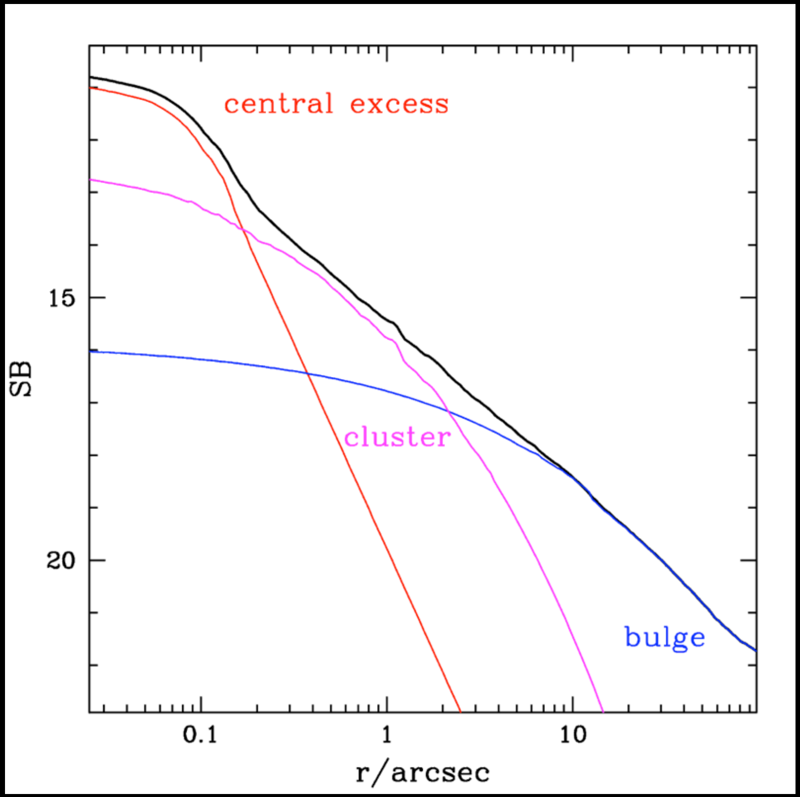
NGC 5102



- low-luminosity S0 with a large (classical) bulge
- velocity dispersion ~ 66 km/s (smallest in our sample)
- observed in two resolutions FWHM ~ 0.08”

NGC 5102





- three-component structure: bulge & central cluster & light excess in the very centre
- preliminary upper limit $M_{BH} < 4 \times 10^5\ M_{sun}$
  small BH mass with respect to both σ and L_{bulge}
- $M_{cen} = 2.2 \times 10^6\ M_{sun}$ $M_{cl} + M_{cen} = 1.1 \times 10^7\ M_{sun}$

summary & outlook

- SINFONI BH mass measurements will almost double the number of existing direct dynamical BH detections

- galaxy sampling at low-mass and high-mass end improves measurements of
  - the slope in scaling relations
  - the scatter at the low-mass and high-mass end

- NGC 3368 & NGC 3489: composite (pseudo + classical) bulges:
  - BH masses consistent with velocity dispersion
  - BH masses low with respect to the whole photometric bulge, but not, if only the classical bulge region is considered

- NGC 5102: lowest velocity dispersion galaxy (66 km/s)
  - upper limit of BH mass $< 4 \times 10^5\ M_{sun}$
  - low compared to dispersion & bulge luminosity