# How stellar population gradients shape dynamical SMBH masses in massive ETGs

by
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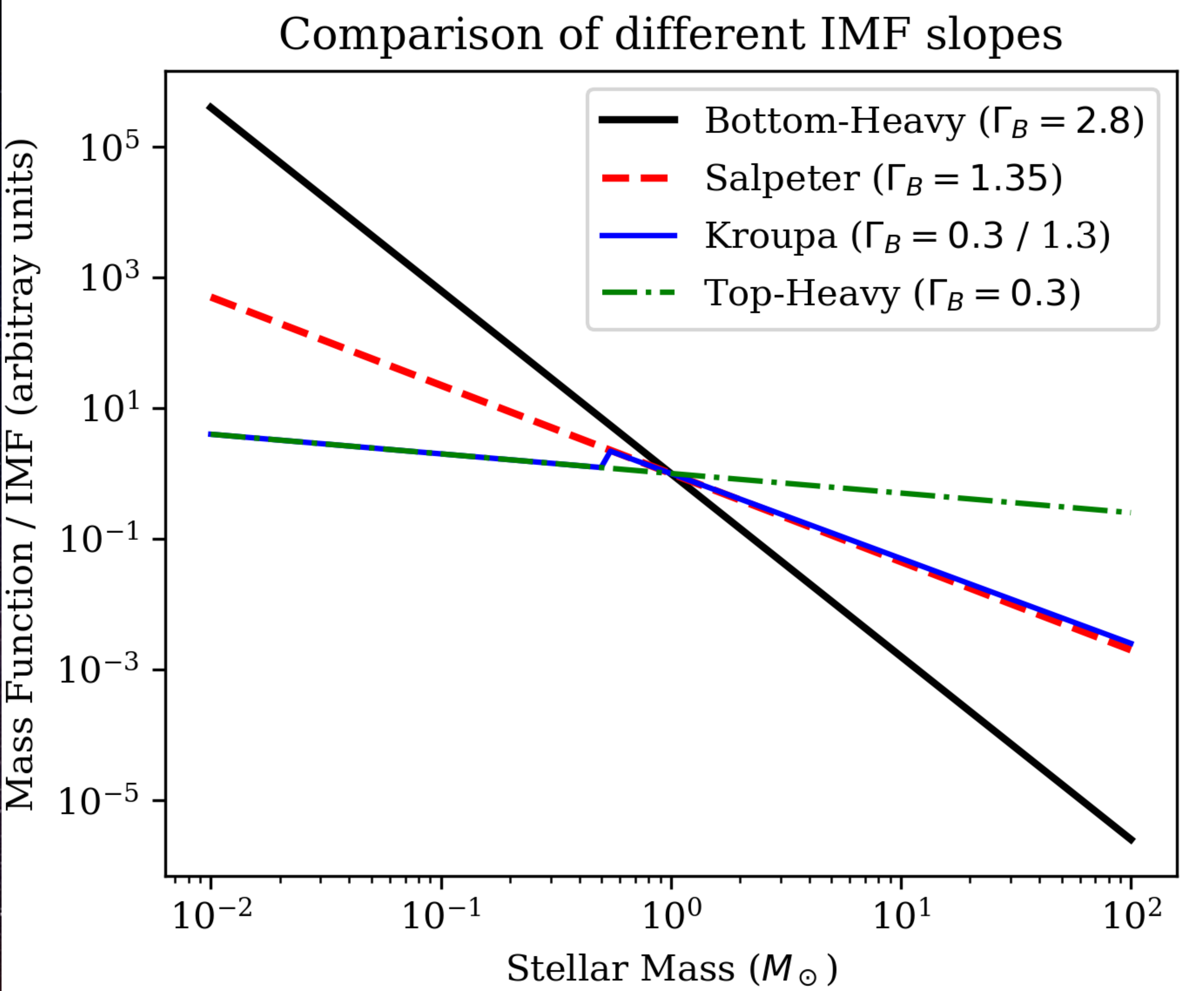
# Background

## Initial mass function

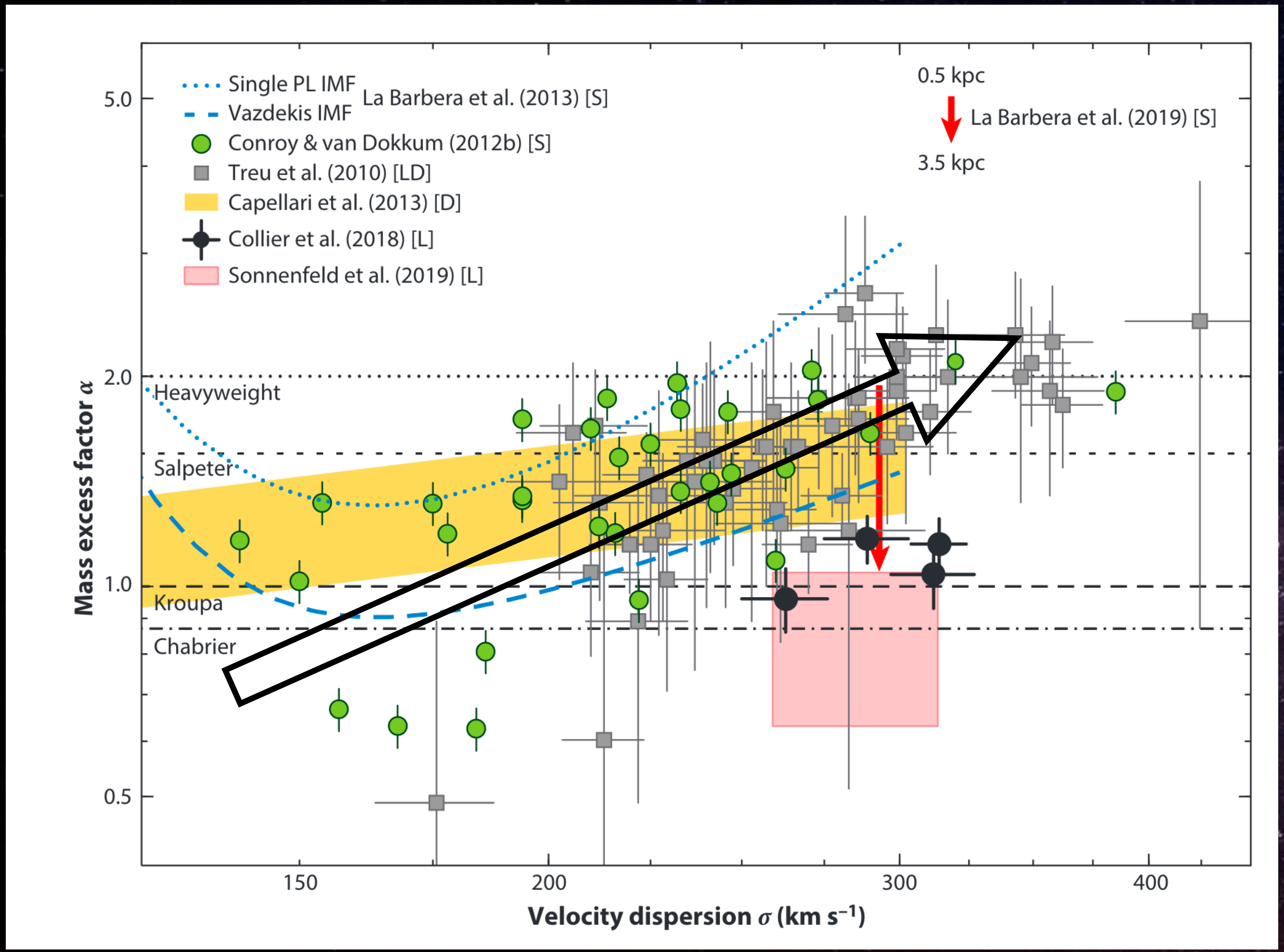
IMF : Mass distribution function of stars during the star formation events

- Process of star formation through the molecular clouds
- Feedback and chemical enrichment & Galaxy evolution
- Fundamental in converting observable to modelled quantities



## Initial mass function

### Constant or Variable ?




IMF mass-normalisation vs velocity dispersion

Credit :Smith+ 2020

## Initial mass function

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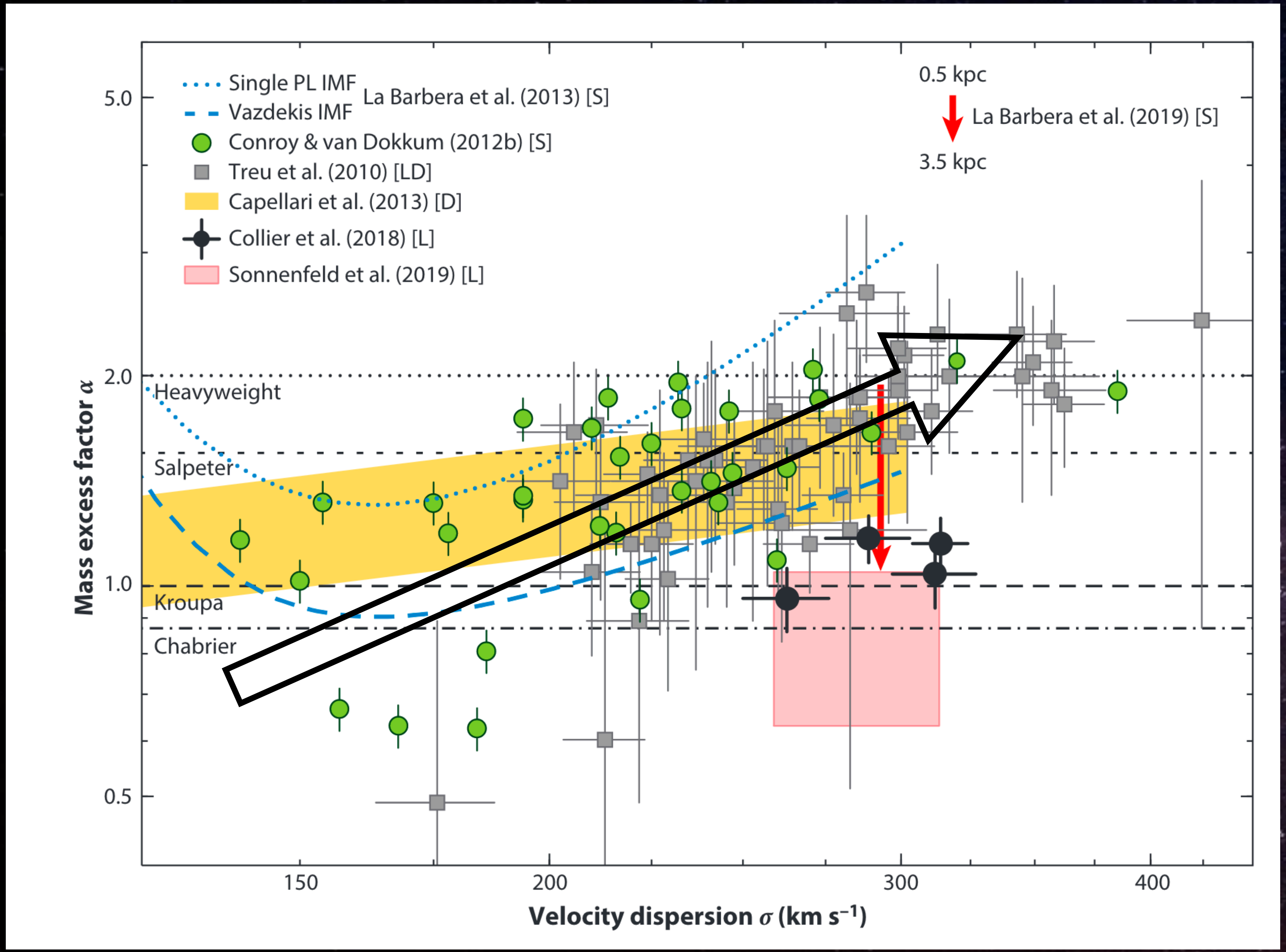


IMF mass-normalisation vs velocity dispersion

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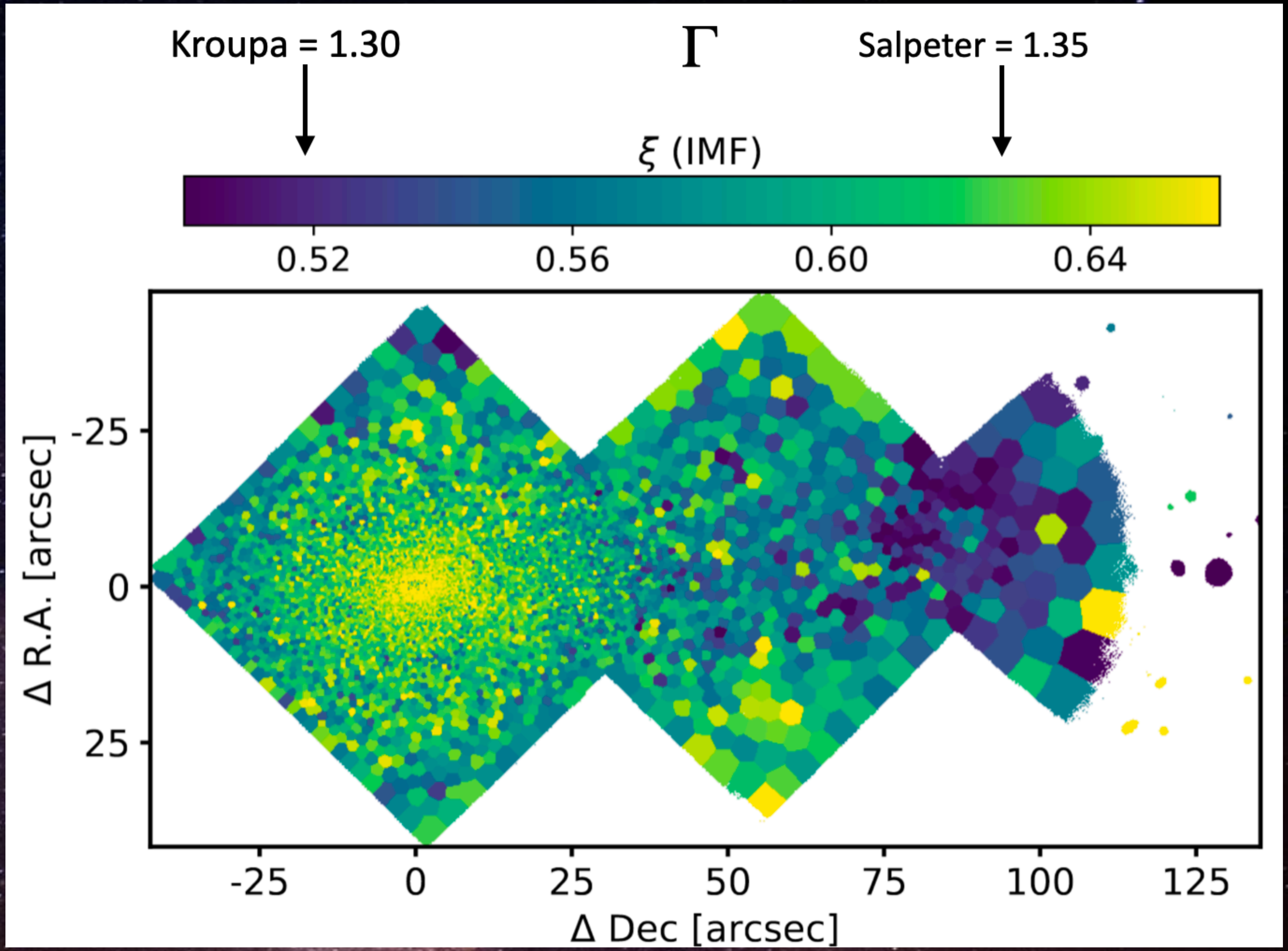



Example of IMF map of NGC1380 galaxy

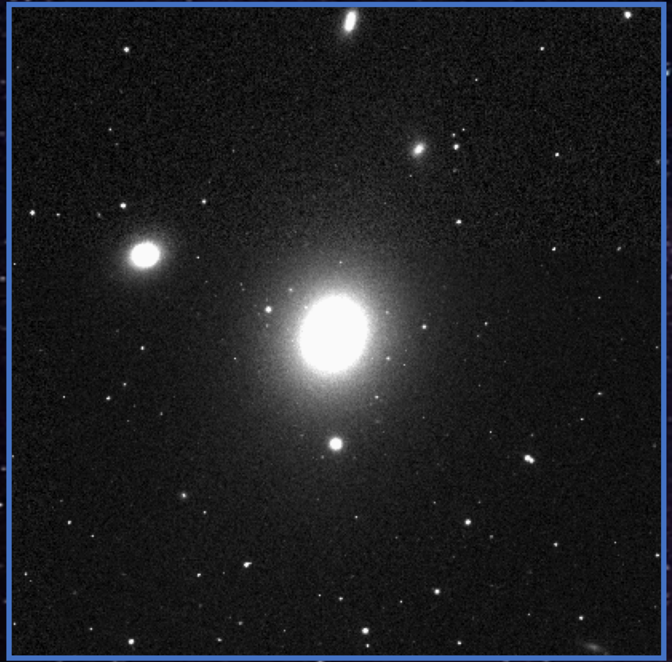
Credit :Navarro+ 2020

# Impact of IMF on BH estimates

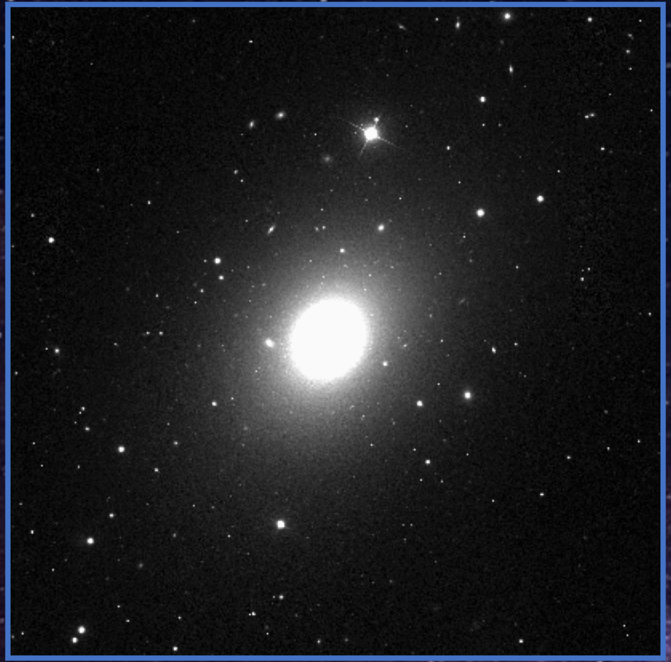
Investigating the impact of variable IMF (M/L) on the BH mass measurement of massive galaxies with Triaxial Schwarzschild orbit based modelling.

NGC 3923

NGC 4261

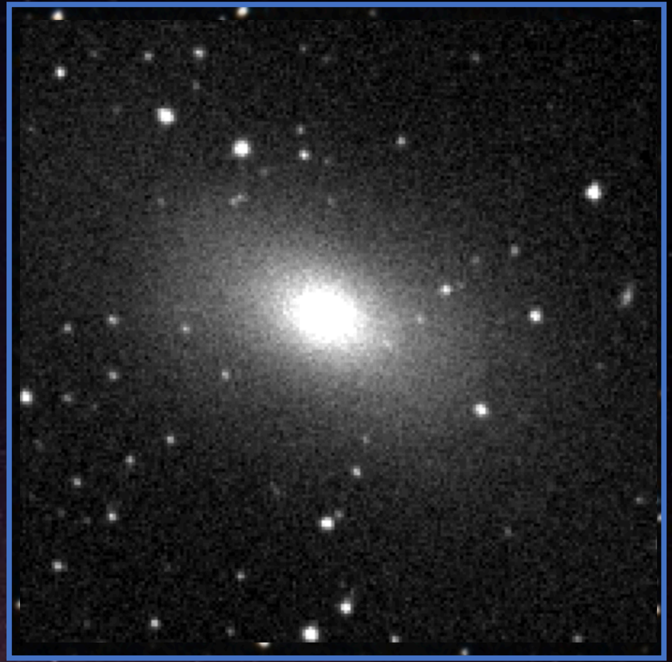


NGC 4636



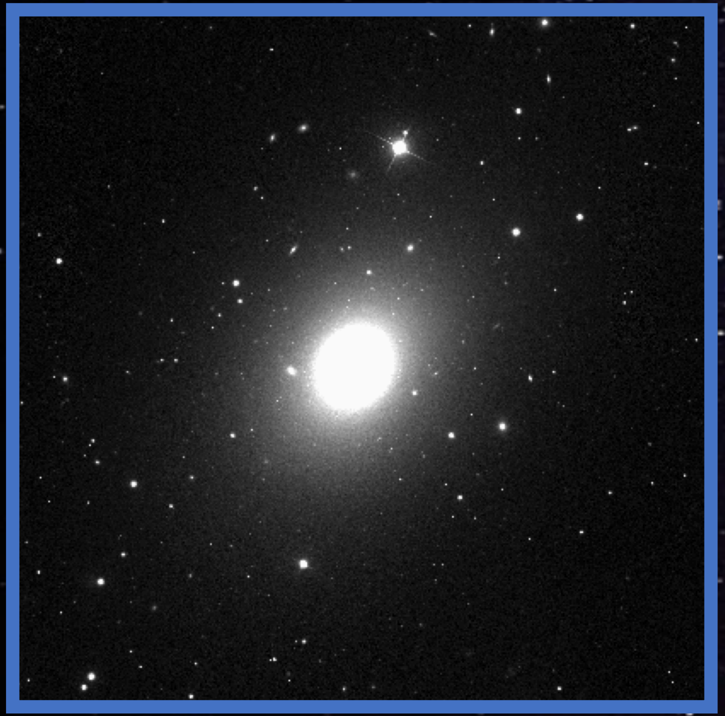
IC 4296

IC 4329

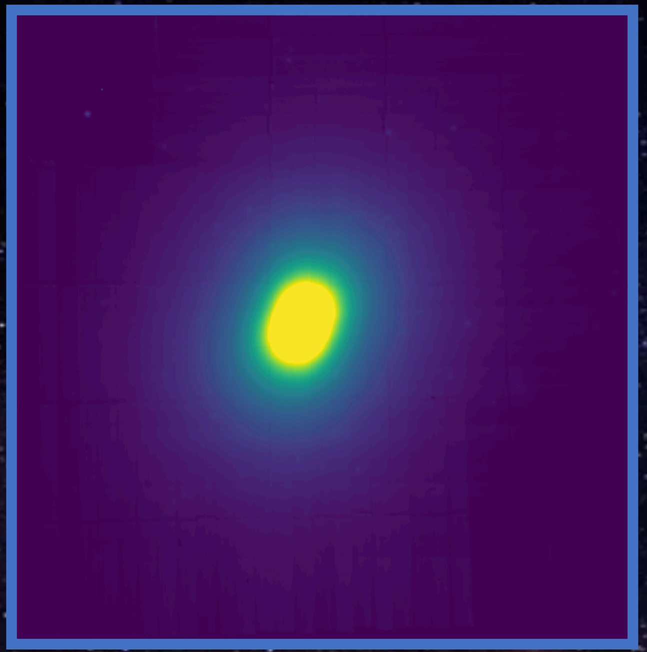


# Observations

NGC 4636

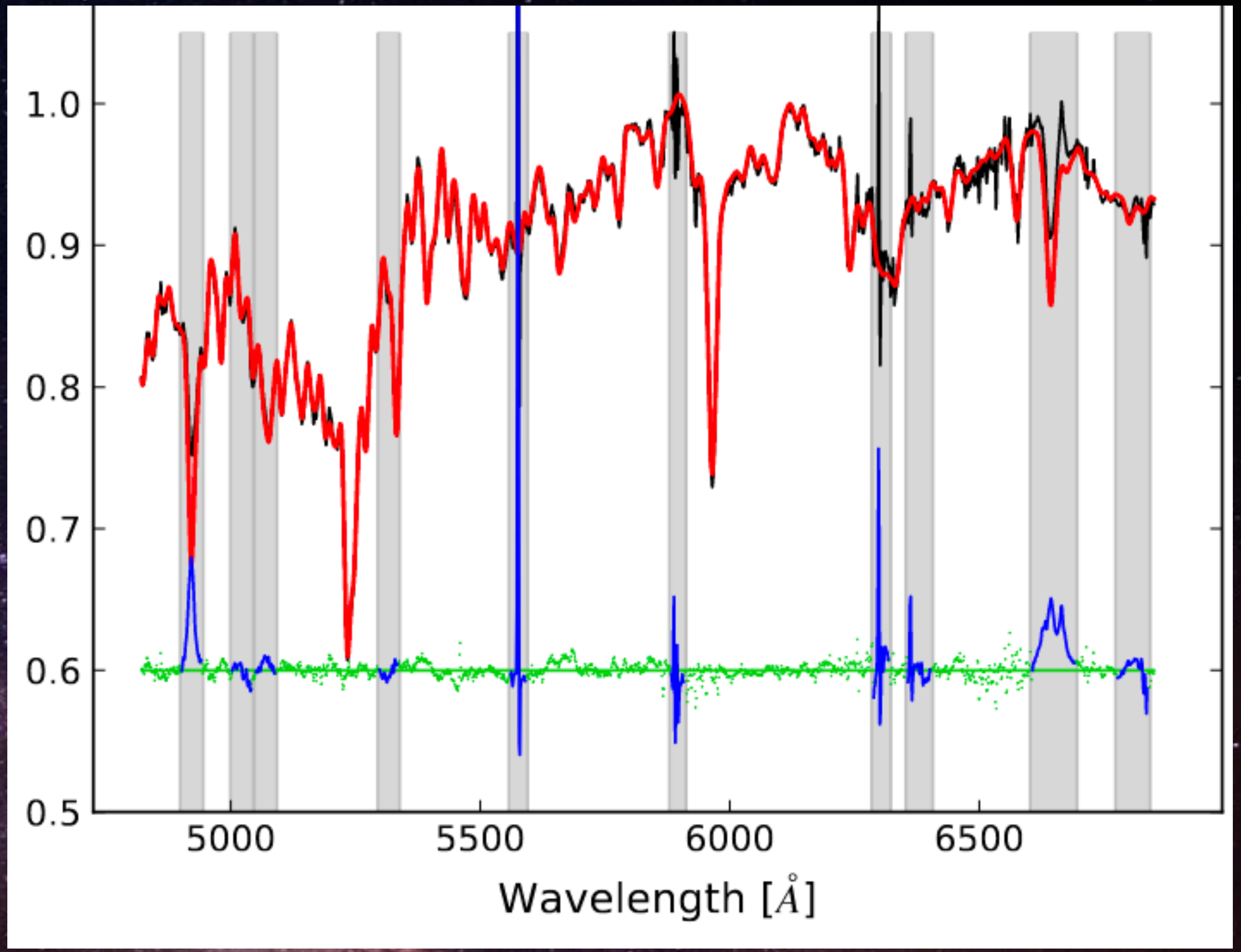


MUSE



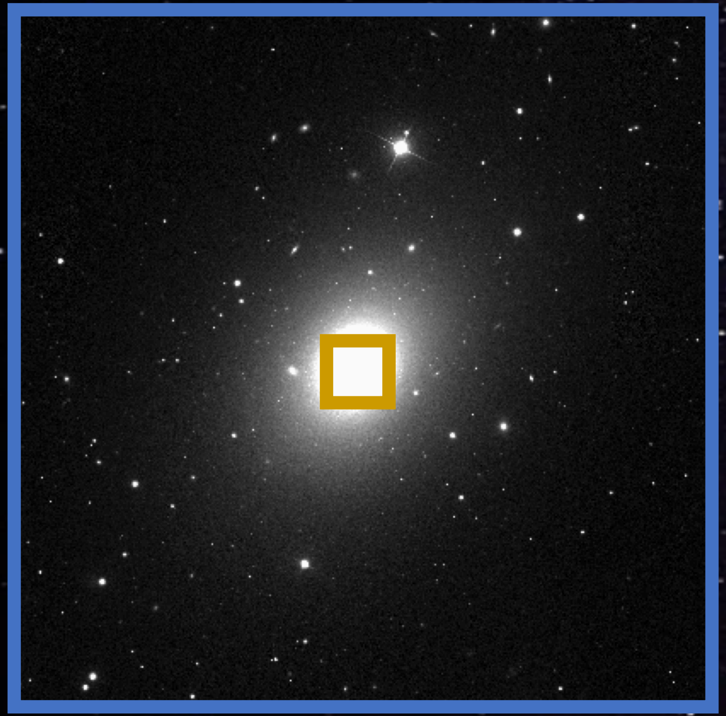
MUSE

- Optical observation
- Constraining intrinsic shape and DM halo

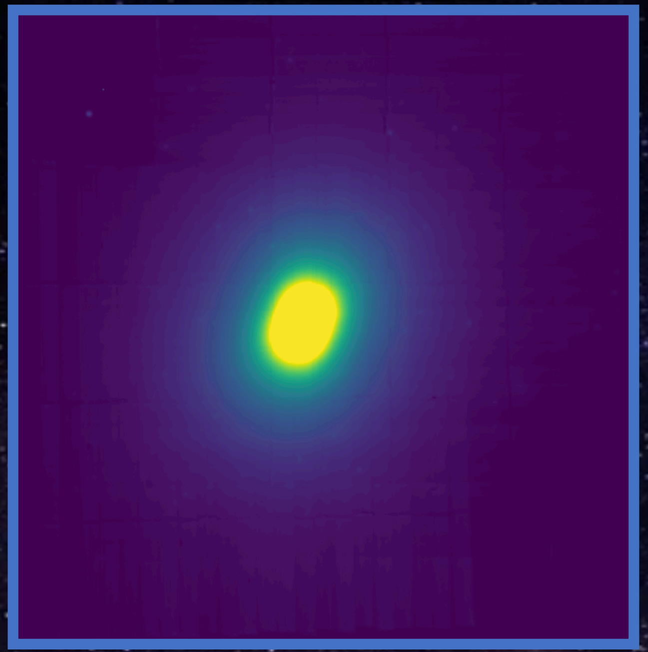


# Observations

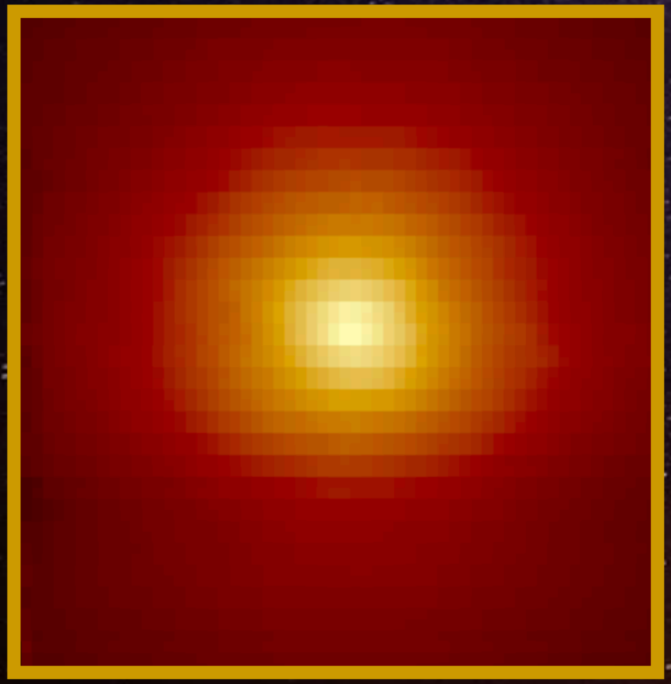
NGC 4636



MUSE

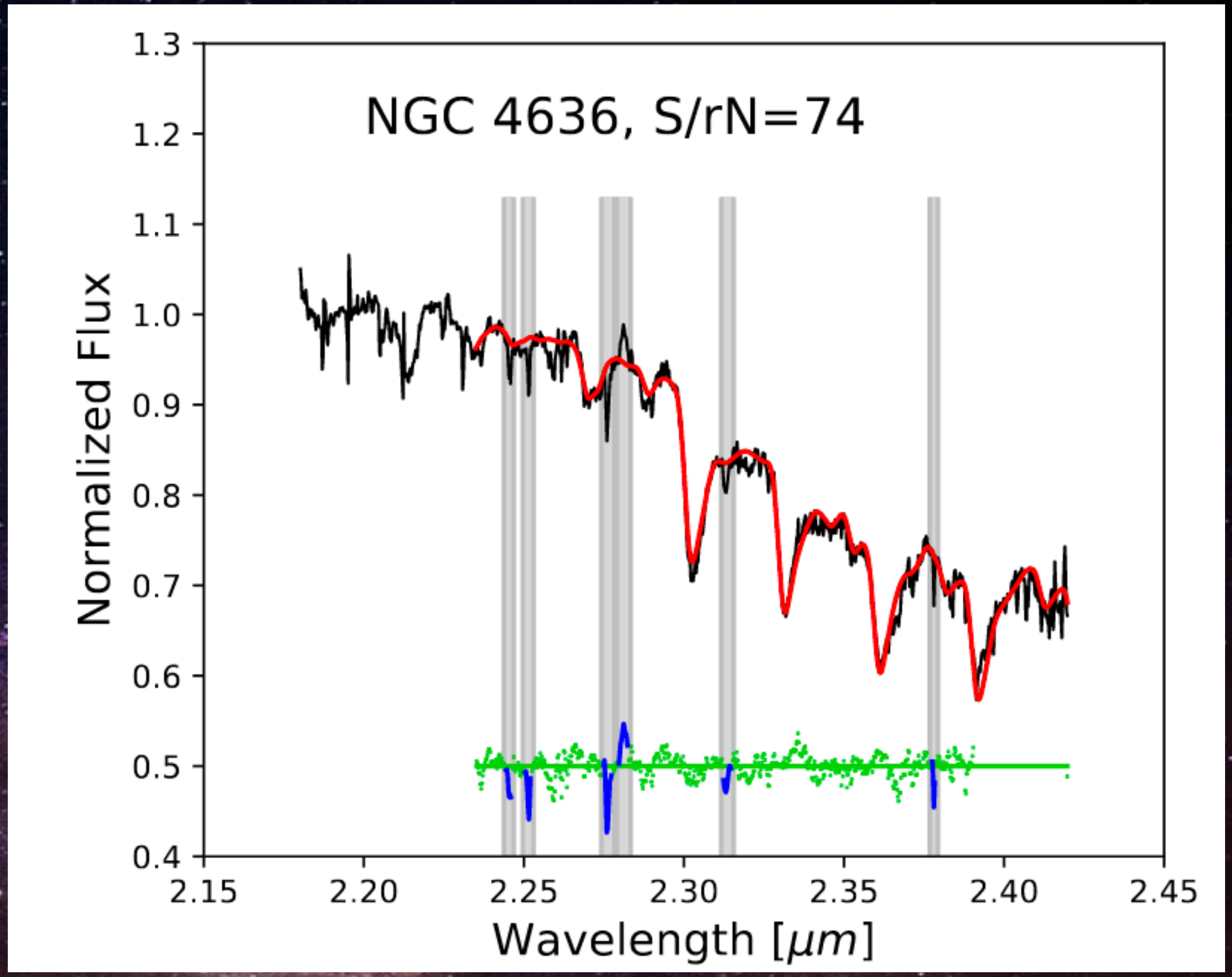


SINFONI

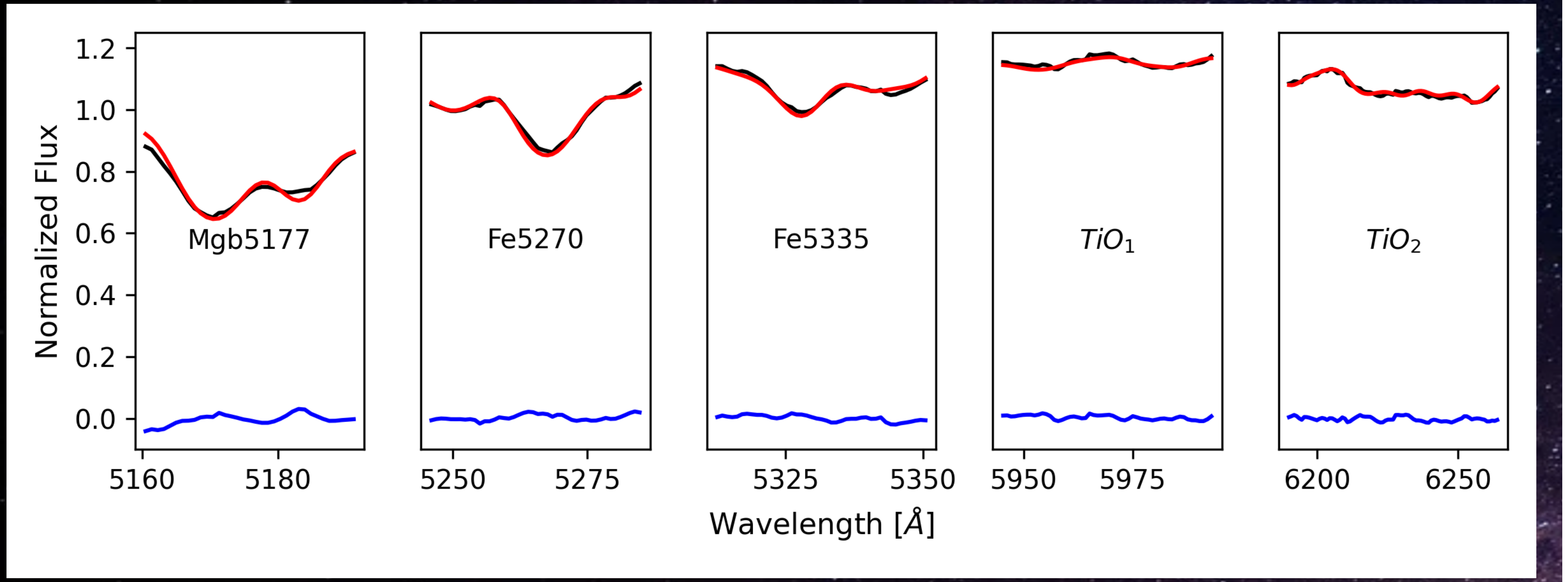


SINFONI

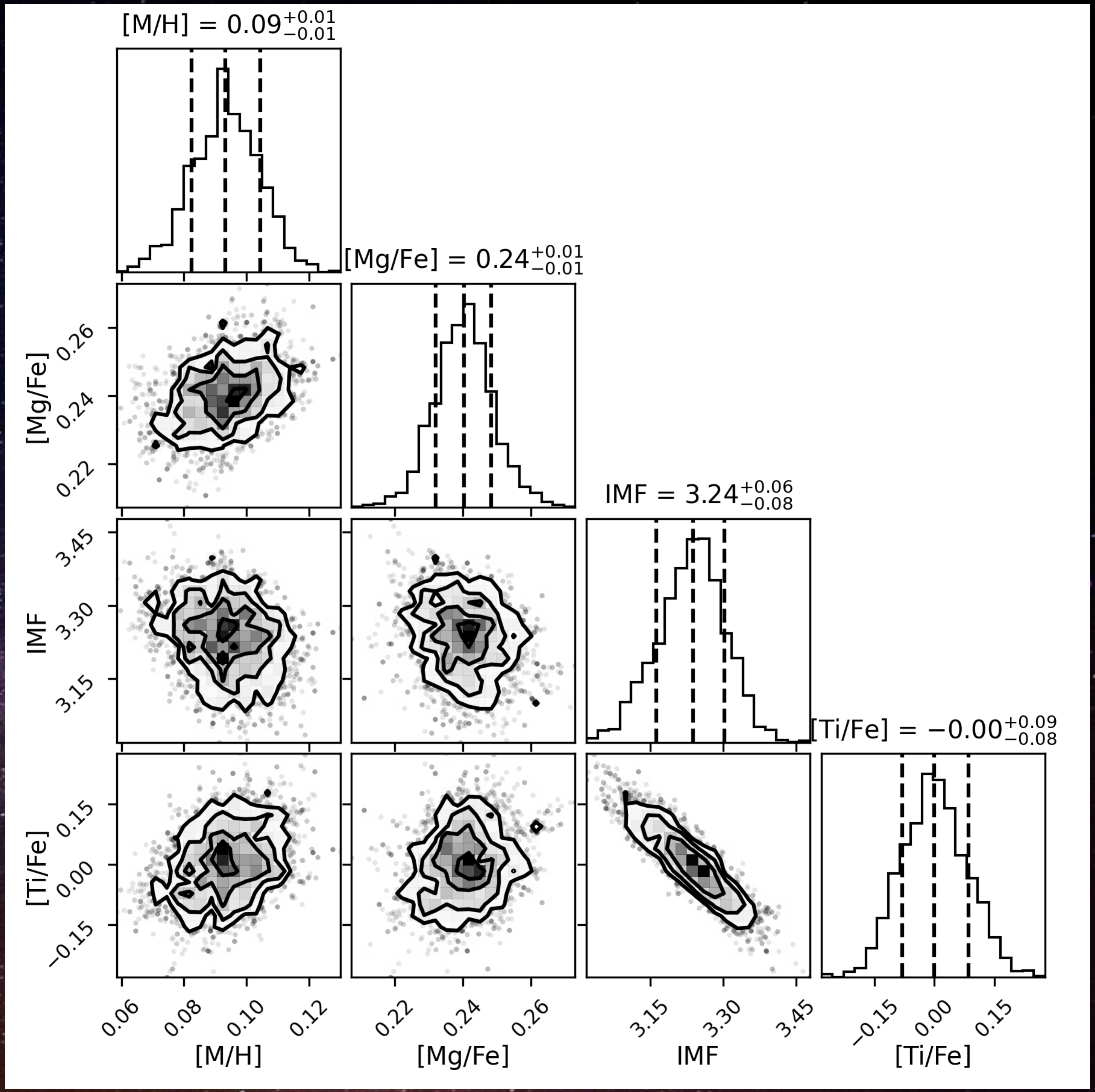
- Near infrared observation
- Resolving black hole sphere of influence



Full Index Fitting (FIF) method (Navarro+ 2019, 2021, 2023)




Example of full index fitting method




Posterior distribution of FIF parameters

# Dynamical modelling

Schwarzschild orbit based modelling (Schwarzschild+ 1979)

1) Model gravitational potential

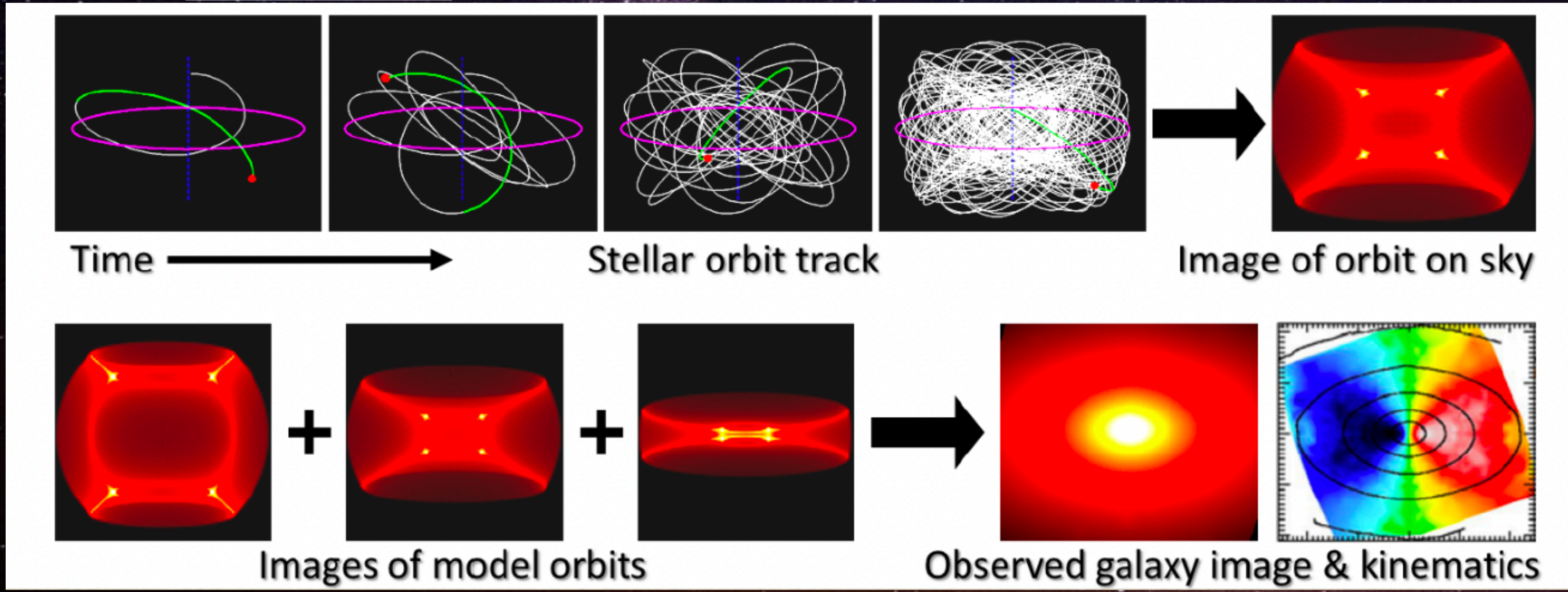
$$\Phi_{\rm grav} = \underbrace{\Phi_{\rm stellar}}_{L_{\rm stellar} \times M/L} + \Phi_{\rm BH} + \Phi_{\rm DM}$$

2) Orbit based libraries are generated

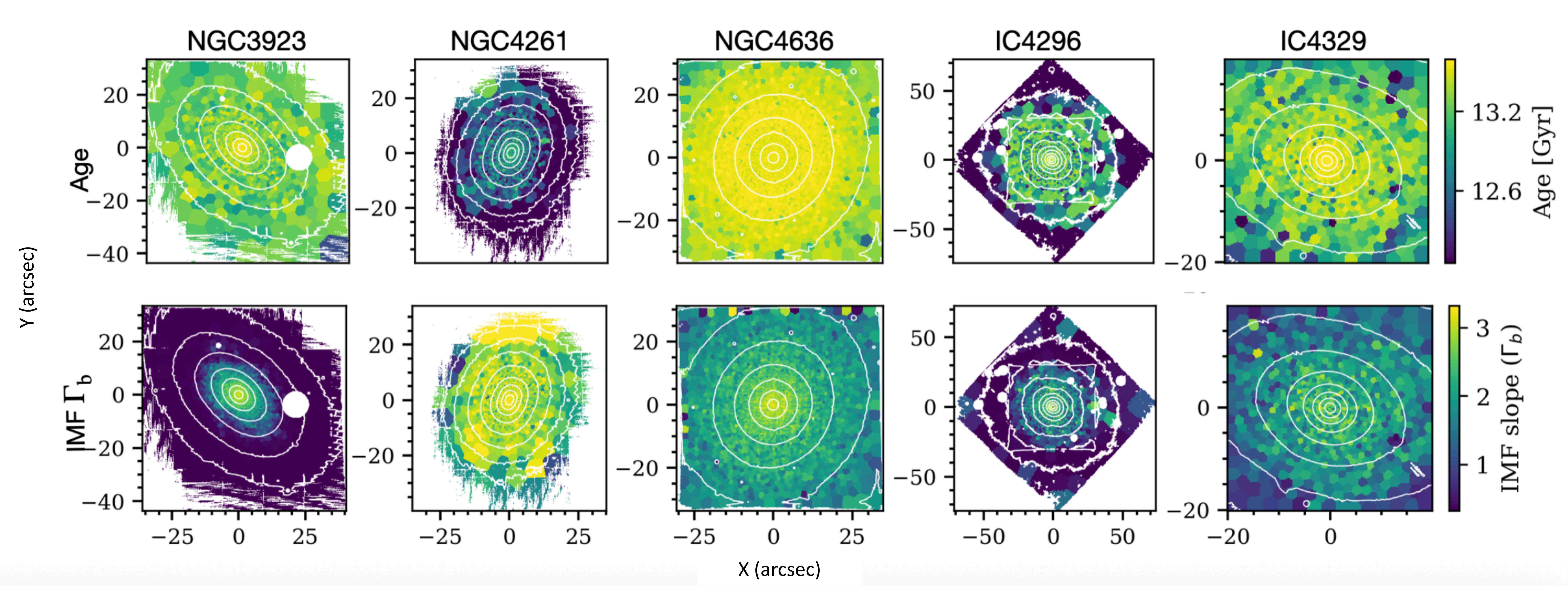
3) Finding combinations of orbits producing the observed kinematics and luminosity

$$\underbrace{\Phi_{\rm stellar}}_{L_{\rm stellar} \times M/L}$$

Variable M/L from SPS modelling



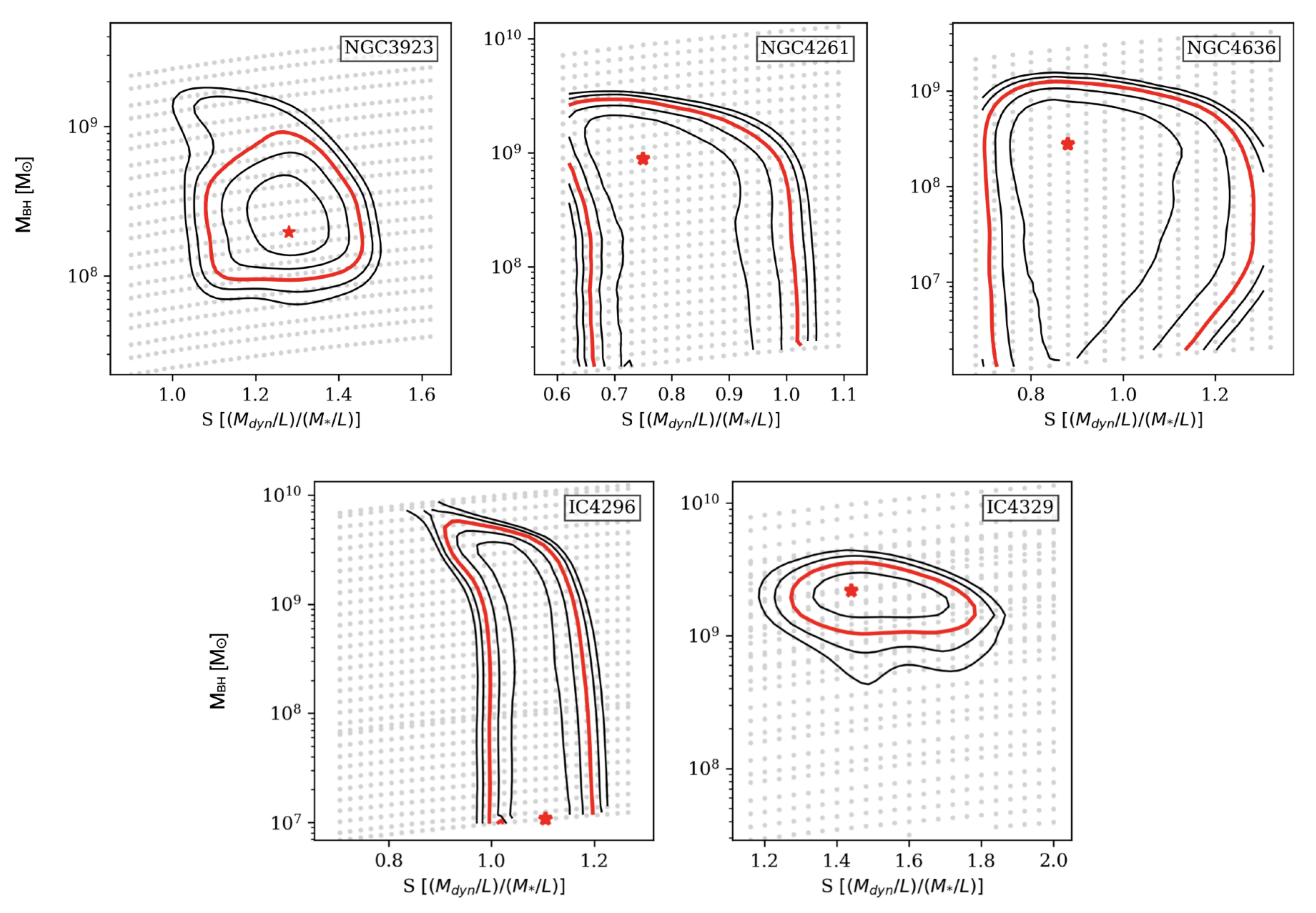
# Stellar Population



# Dynamical modelling and BH mass

$\chi^2$ distribution of modelled MUSE and SINFONI kinematics

| Galaxy | $M_{BH}$ | S |
|---|---|---|
| | ($10^8$ $M_\odot$) | $(M_{dyn}/L)/(M_*/L)$ |
| (1) | (2) | (3) |
| **NGC3923** | $1.94^{+8.51}_{-0.93}$ | $1.30^{+1.45}_{-1.14}$ |
| **NGC4261** | $< 8.91$ | $0.74^{+0.97}_{-0.51}$ |
| **NGC4636** | $< 2.75$ | $0.87^{+1.23}_{-0.51}$ |
| **IC4296** | $< 33.88$ | $1.11^{+1.19}_{-0.99}$ |
| **IC4329** | $18.19^{+31.91}_{-9.37}$ | $1.48^{+1.70}_{-1.20}$ |




10-30 (50) % change in BH mass due to varying IMF

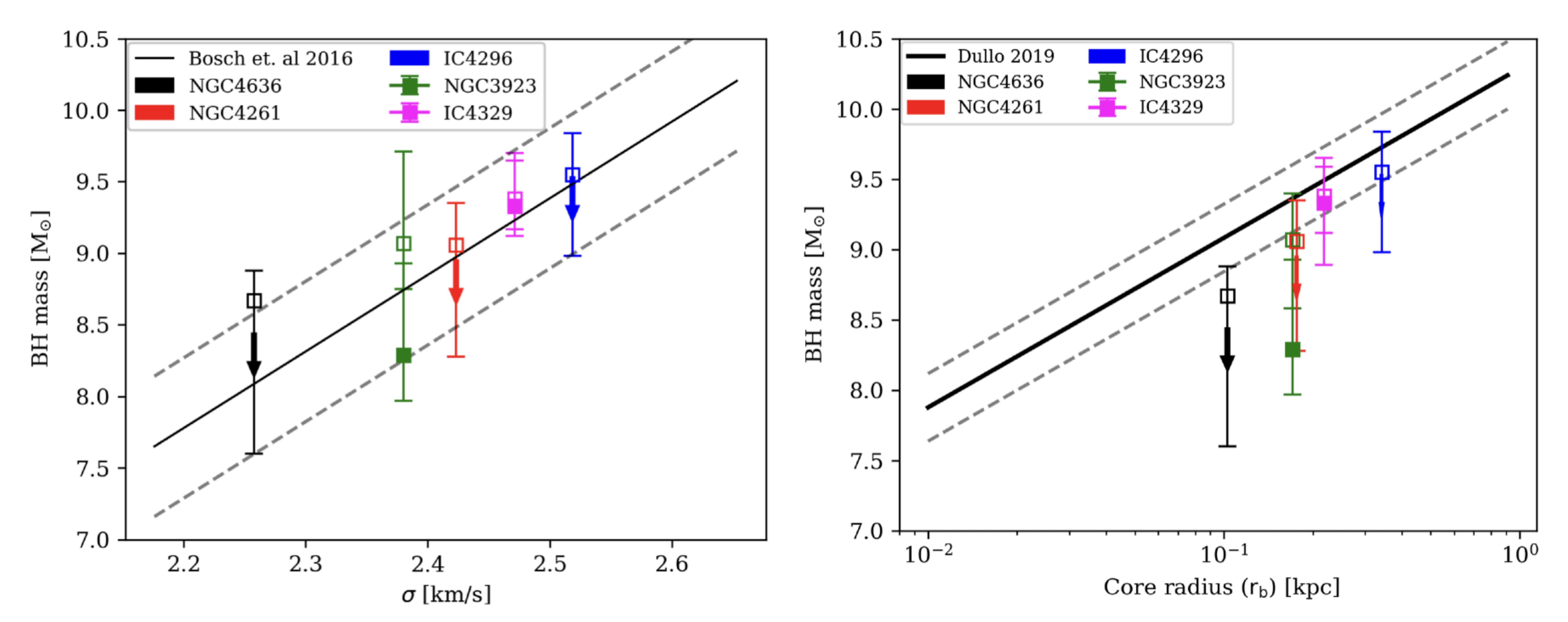
Chaturvedi+ 2025b, in review A&A
Thater+2025, accepted A&A

# Dynamical modelling and BH mass

## Scaling relation between BH mass and known galaxy properties

$M_{BH}$ versus velocity dispersion

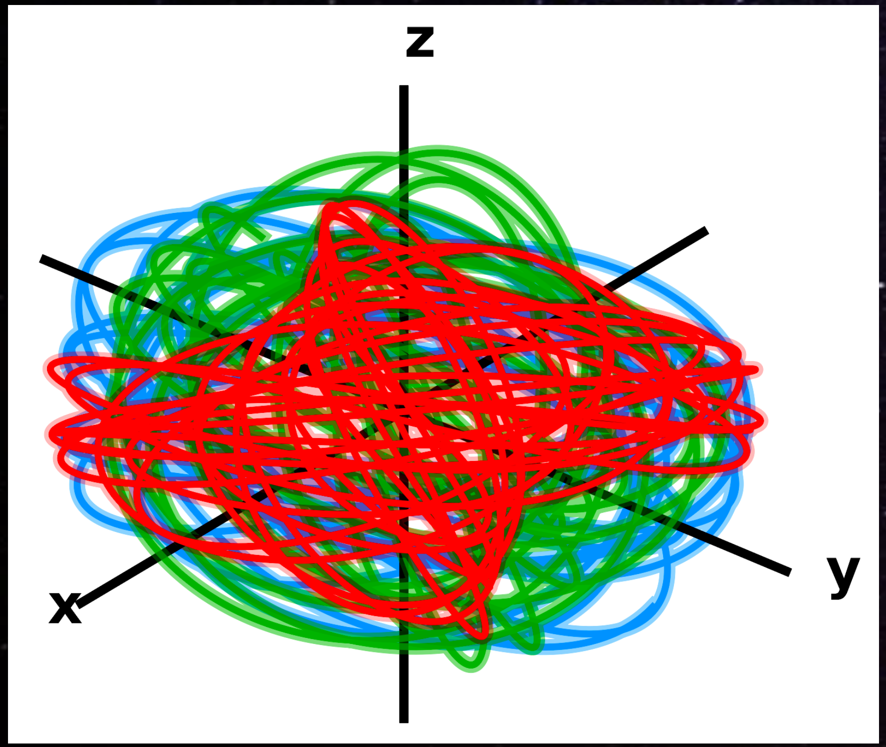
$M_{BH}$ versus core-radius



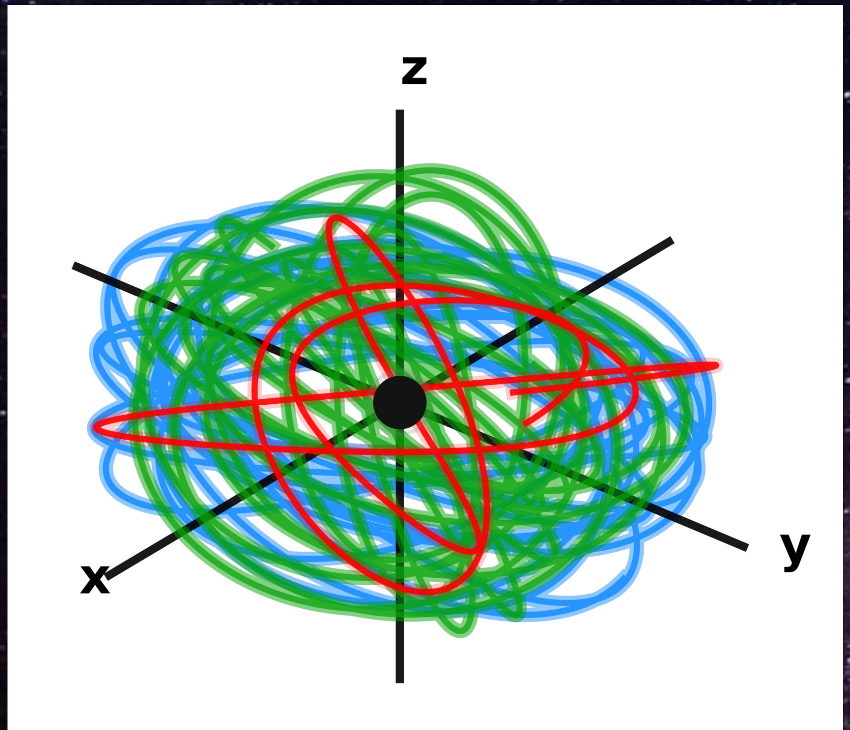

Chaturvedi+ 2025b, in review A&A, Thater+2025 in review

# Impact of SMBHs on stellar orbits

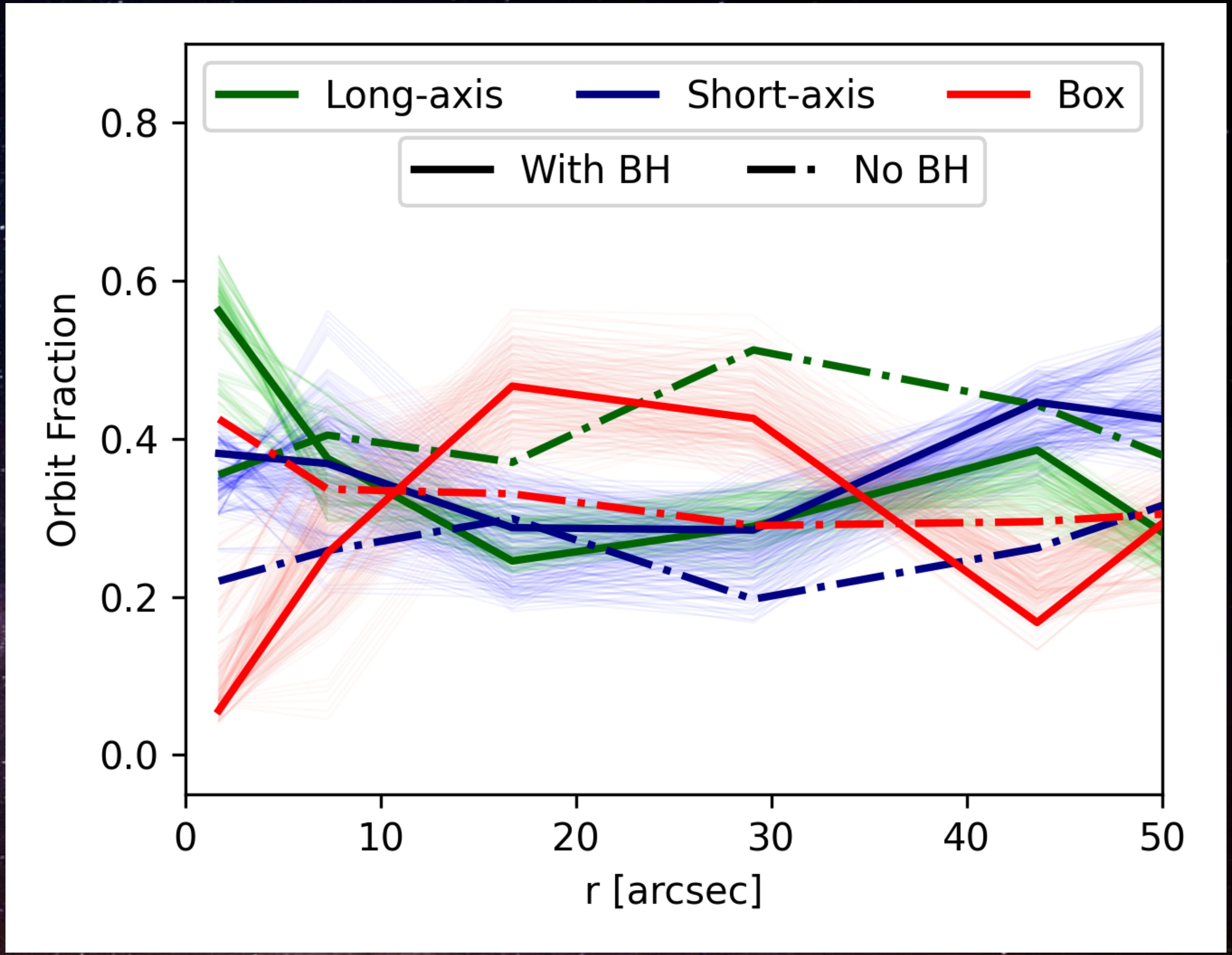
Impact of SMBHs on the stellar orbital distribution ?




Stellar orbits with no BH




Stellar orbits with BH



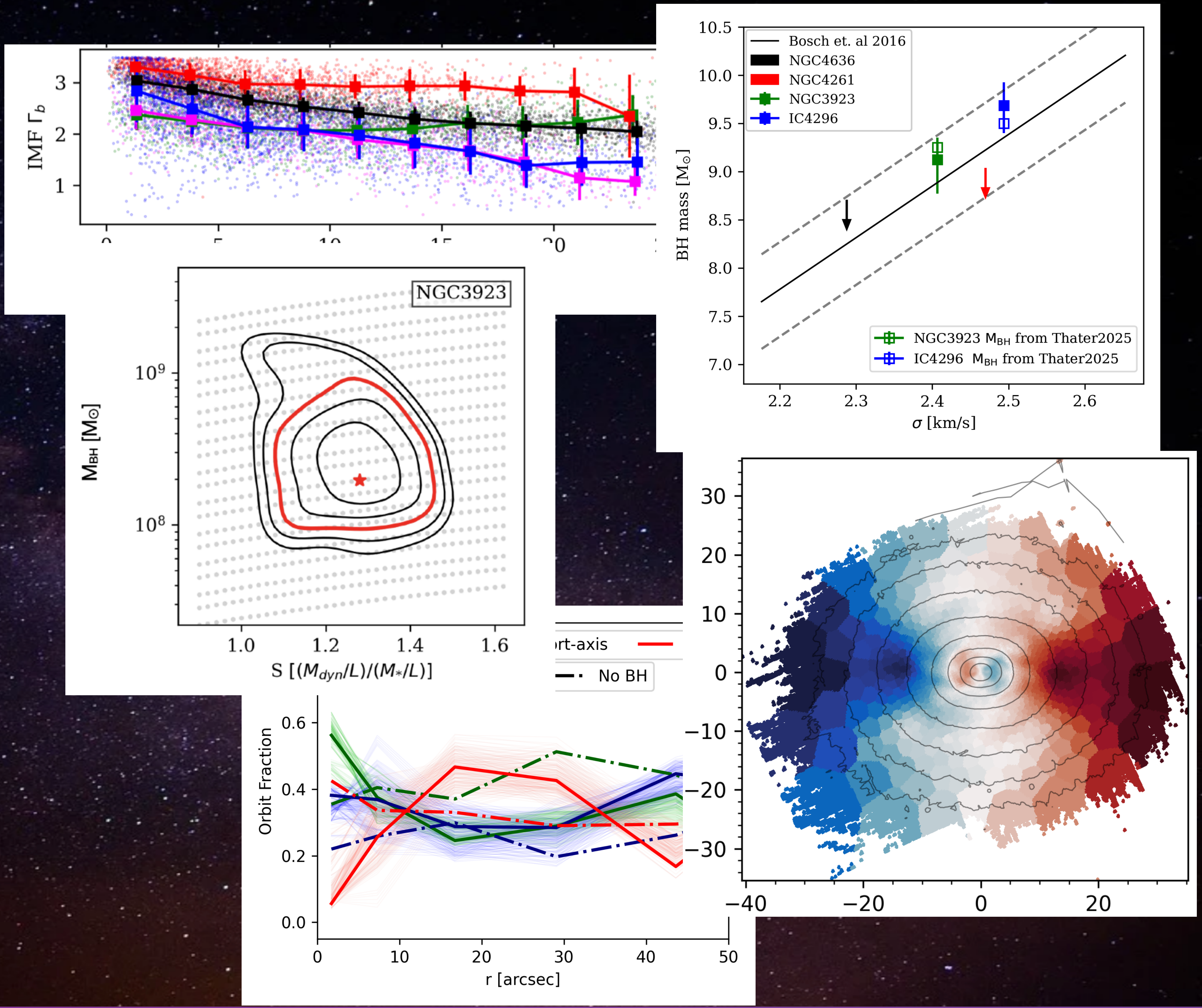

Chaturvedi+ 2026, in prep.

# Summary and Conclusions: IMF, SMBHs and Stellar orbits

- Linked stellar population with the dynamical BH mass measurement.
- Detected super-Salpeter IMF: Excess of low mass stars.

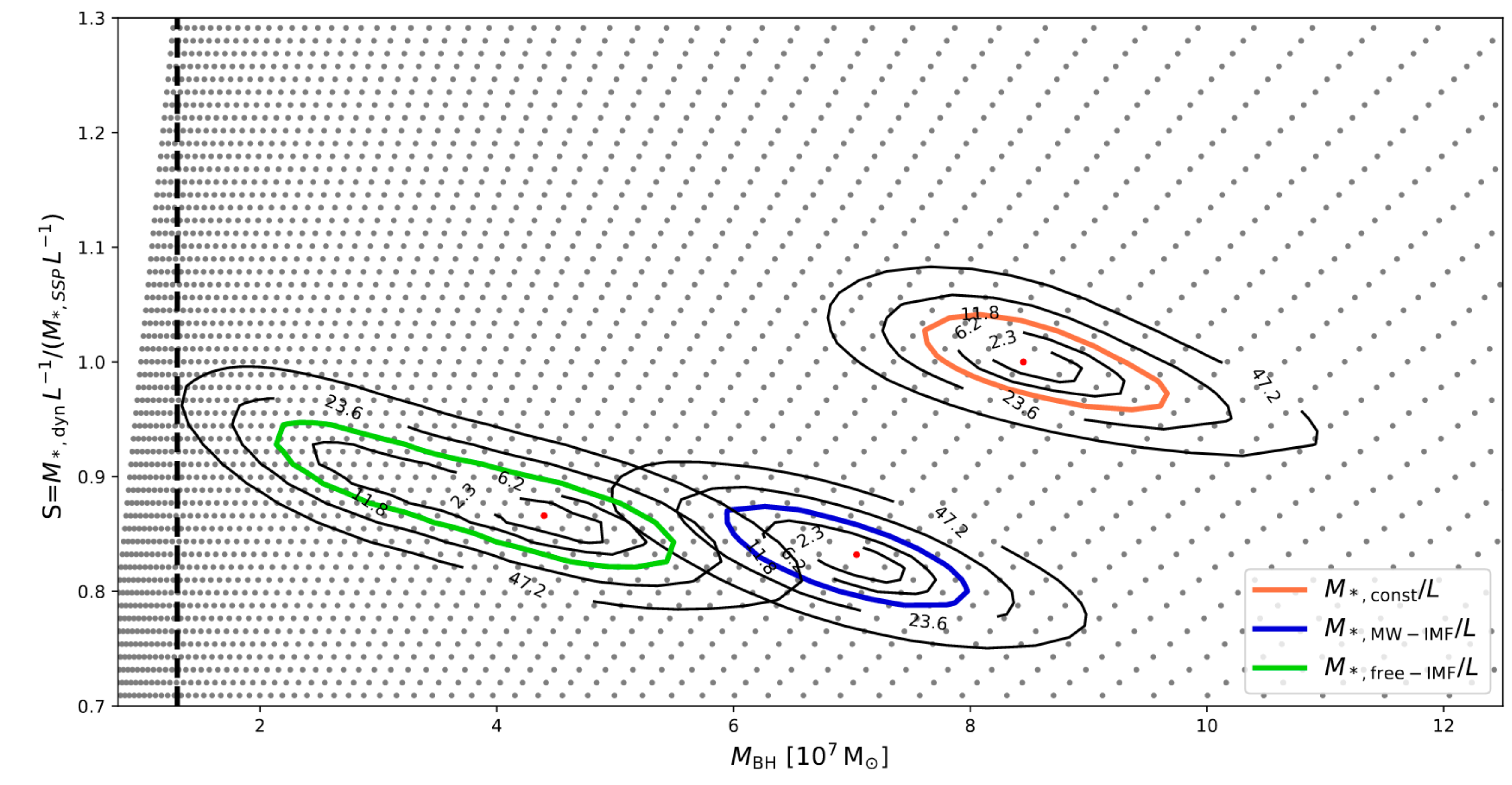
- Detection of BH of mass of for NGC 3923: $1.94^{+8.51}_{-0.93} \times 10^{8}$ M$_{\odot}$
  IC4296 : $18.19^{+31.91}_{-9.37} \times 10^{8}$ M$_{\odot}$.
- Variable IMF produces a change unit 10-50 %.
- Future: Quantify the impact of IMF on SMBHs

- ETGs shows large radial orbital distribution.
- Kinematic substructures are observable and detectable in decomposed maps.
- Presence of SMBHs can influence the stellar orbits.



Impact on BH mass estimate

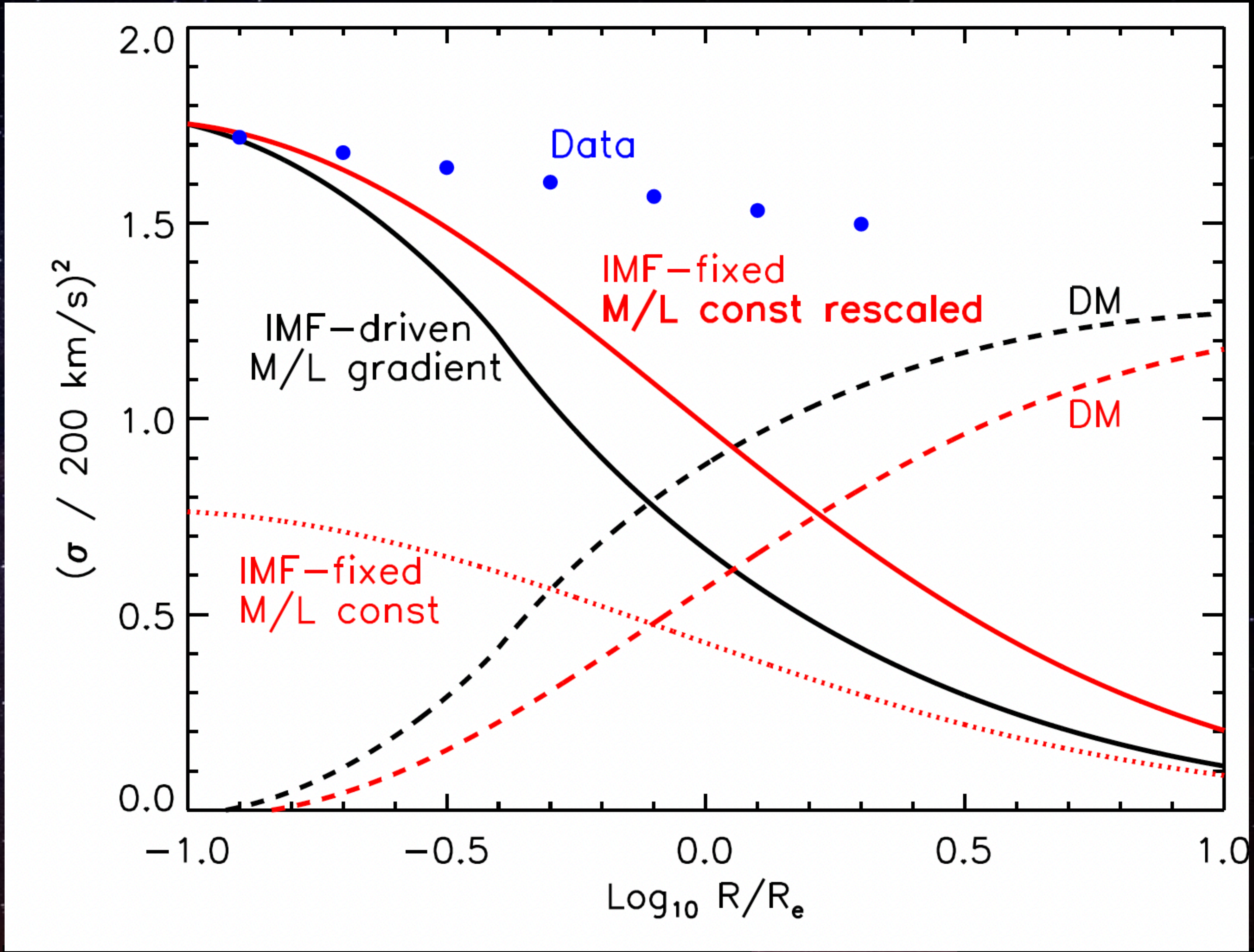
Variation in BH mass upto 15 to 50 % change.




Credit : Thater+ 2023

## Impact of varying IMF

- A variable IMF will introduce a varying stellar $M_*/L$ ratio
- Implication on dynamical mass estimates of BH and DM mass.

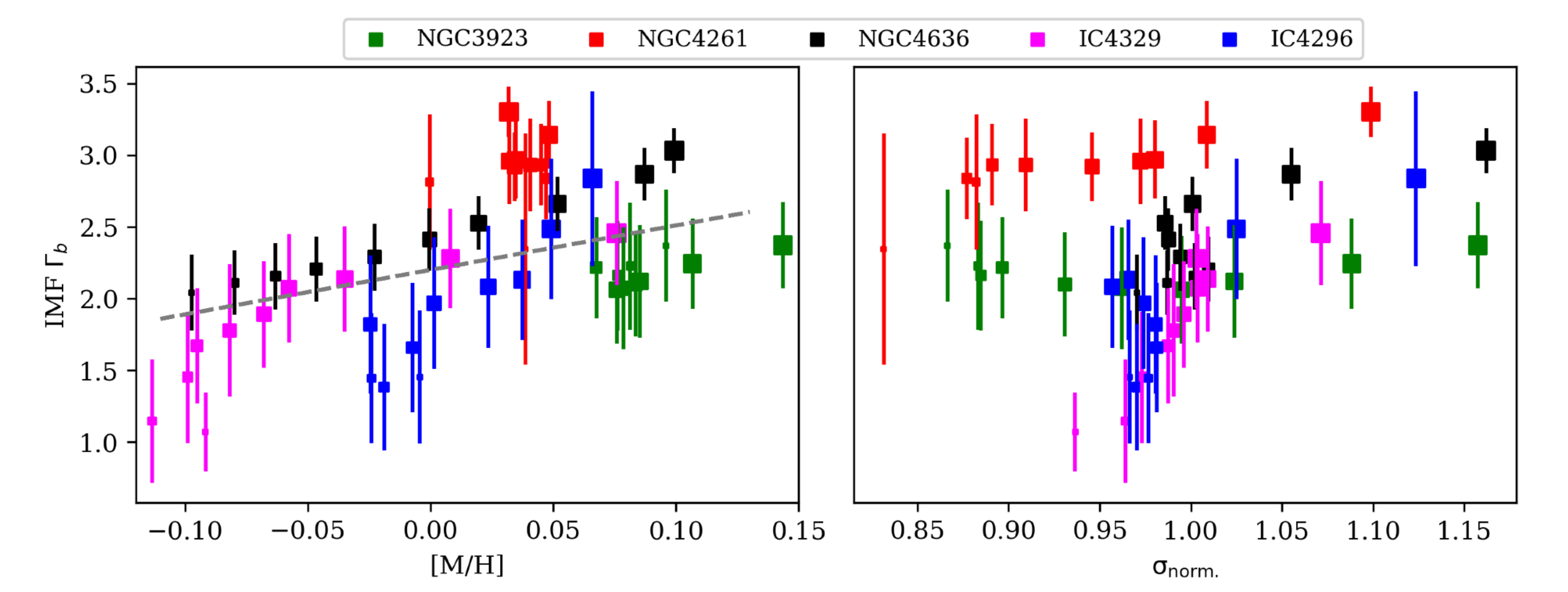



Impact of M/L gradient driven due to IMF variation

Credit :Bernardi+ 2018

Physical driver behind IMF variation :

1) Metallicity [M/H] 2) Velocity dispersion




Dashed line IMF-metallicity relation of Navarro+2015

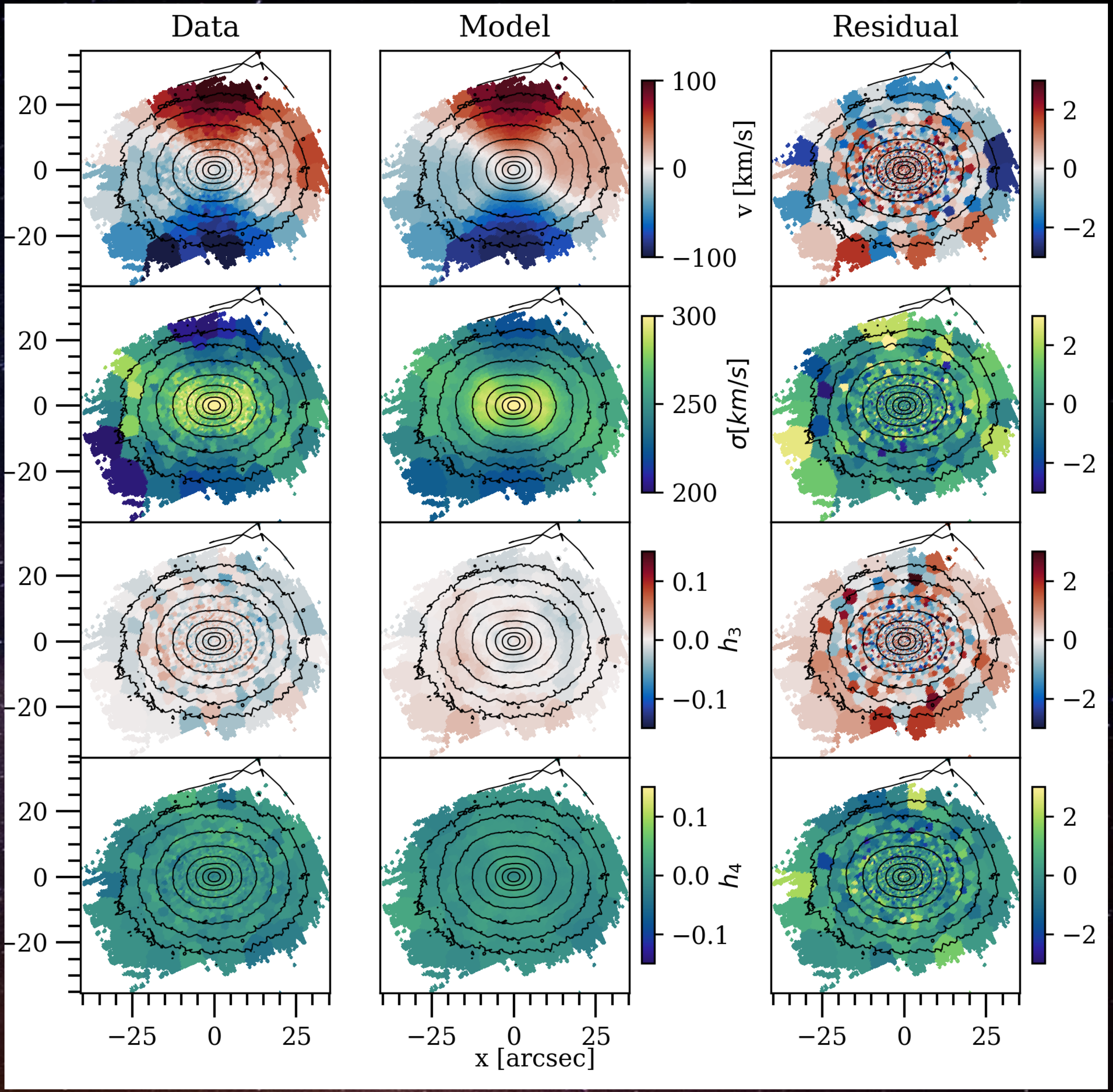
# Dynamical modelling and BH mass

- DYNAMITE Code (Bosch+2008, Thater+2022)
- In total we have six parameters : $M_{BH}$, S, p, q and u, and $M_{200}$

Two main steps

First:

- Model MUSE data and constrain the inner shape and DM halo parameters.




Modelled MUSE kinematics of galaxy NGC4261

# Dynamical modelling and BH mass

- DYNAMITE Code (Bosch+2008, Thater+2022)
- In total we have six parameters : $M_{BH}$, S, p, q and u, and $M_{200}$

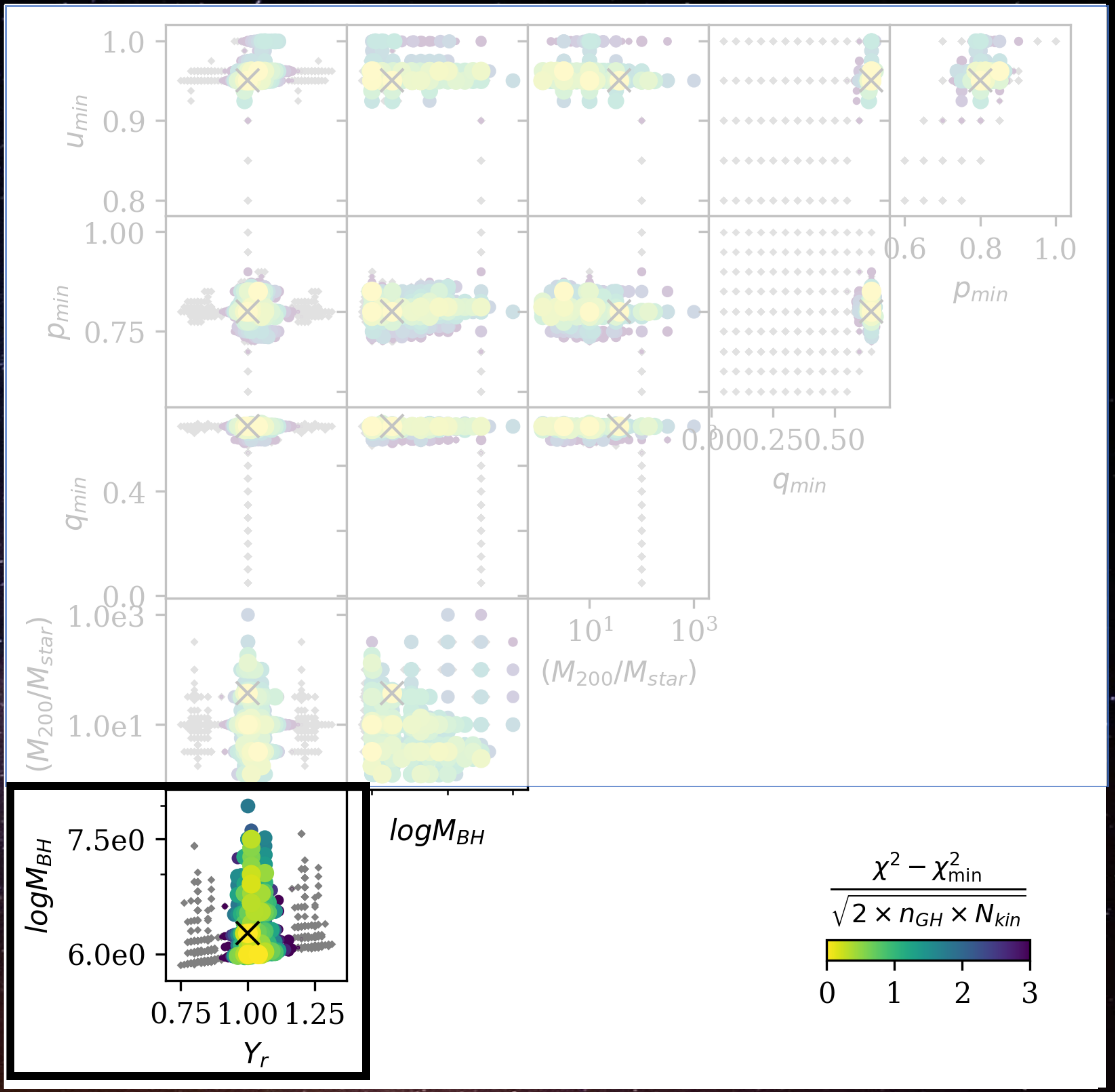
Two main steps

First:

- Model MUSE data and constrain the inner shape and DM halo parameters.

Second:

- Fit SINFONI + MUSE data : BH estimate

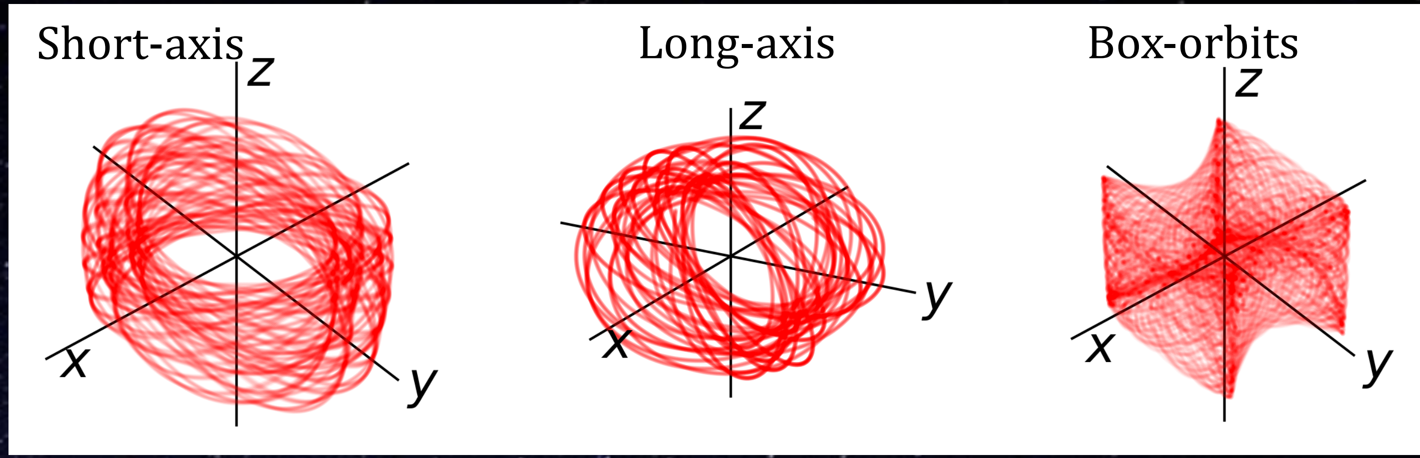


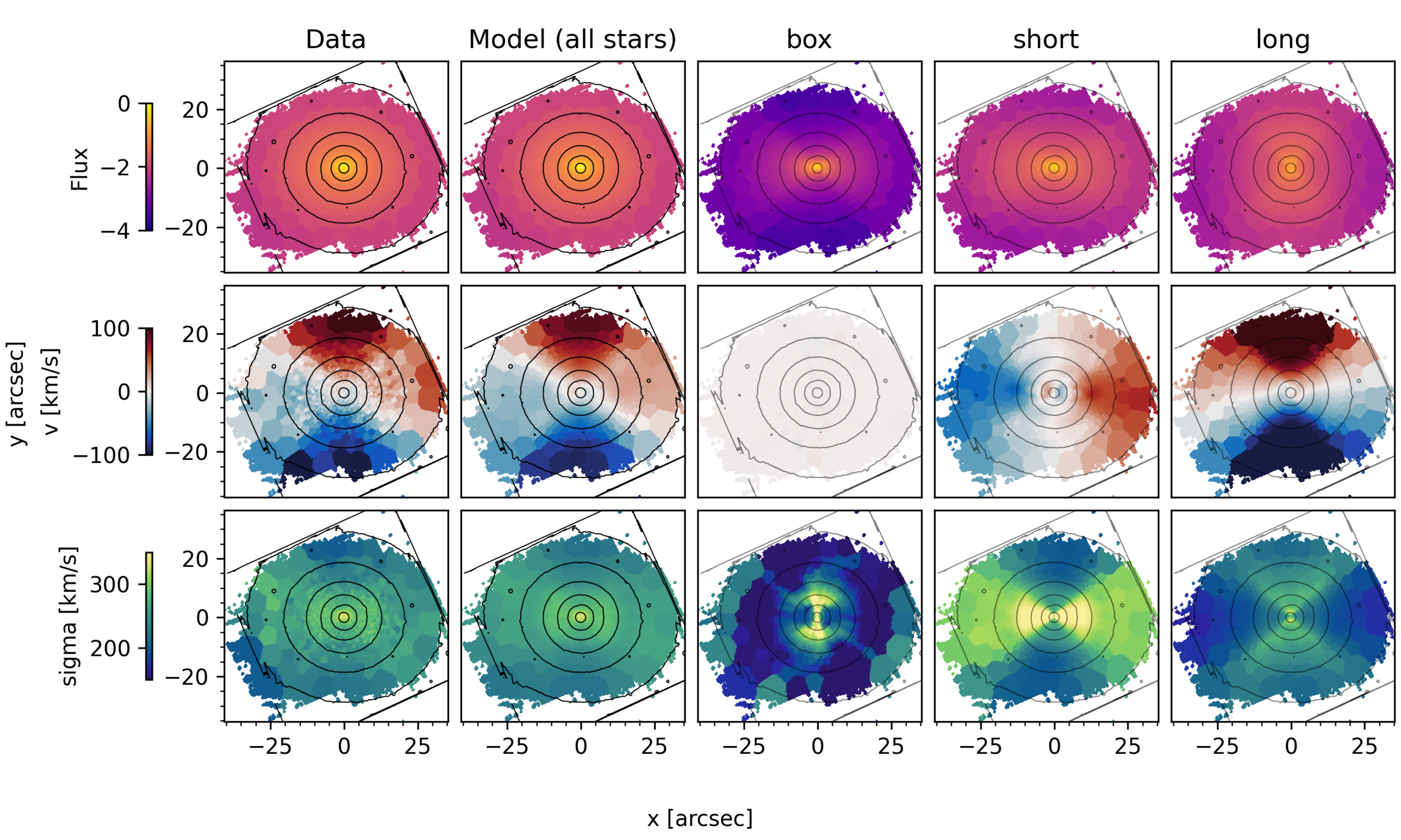

Full grid of $\chi^2$ distribution of galaxy NGC4261

# Results

## Observed velocity fields

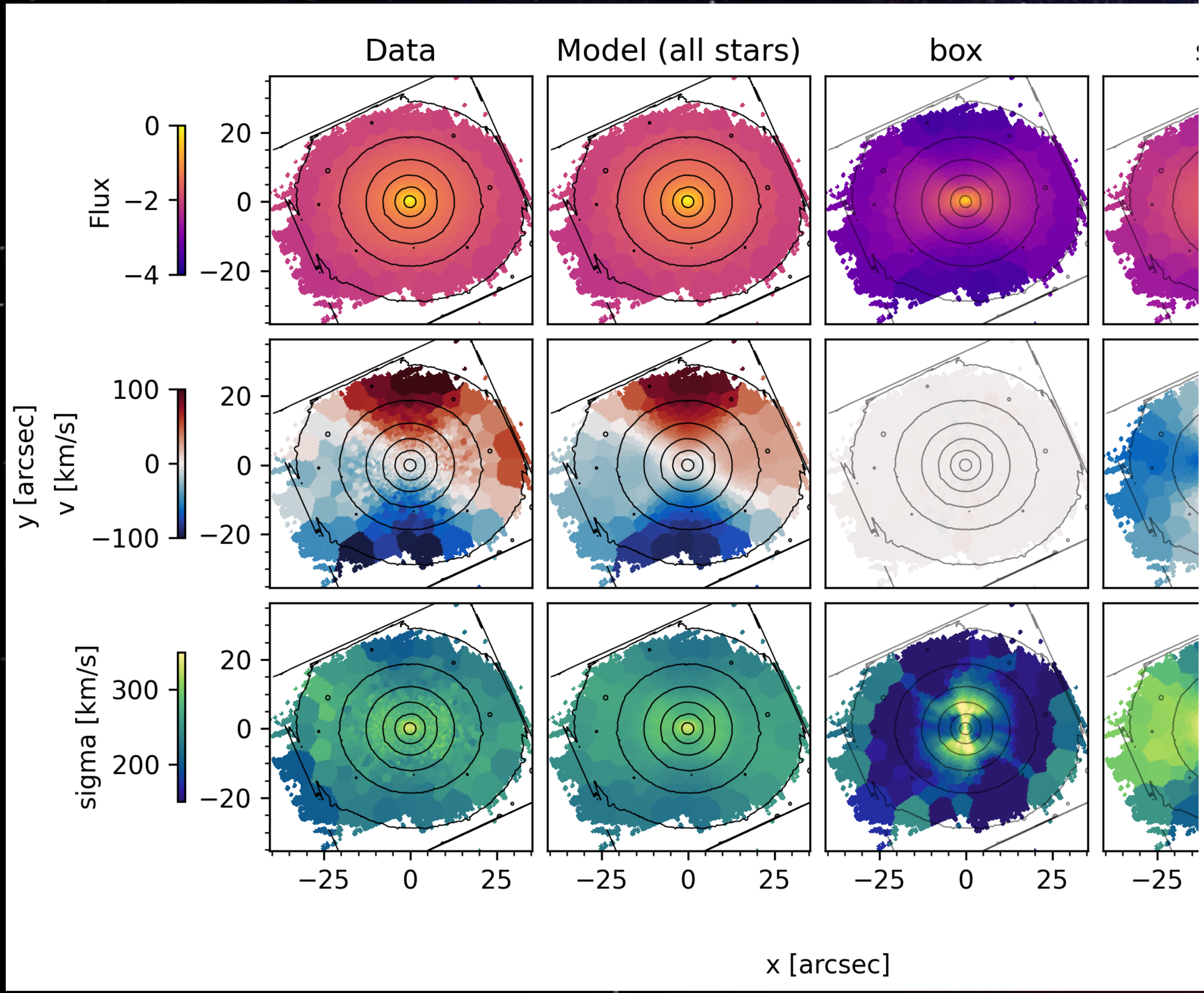
Decomposed kinematics maps by different orbital types

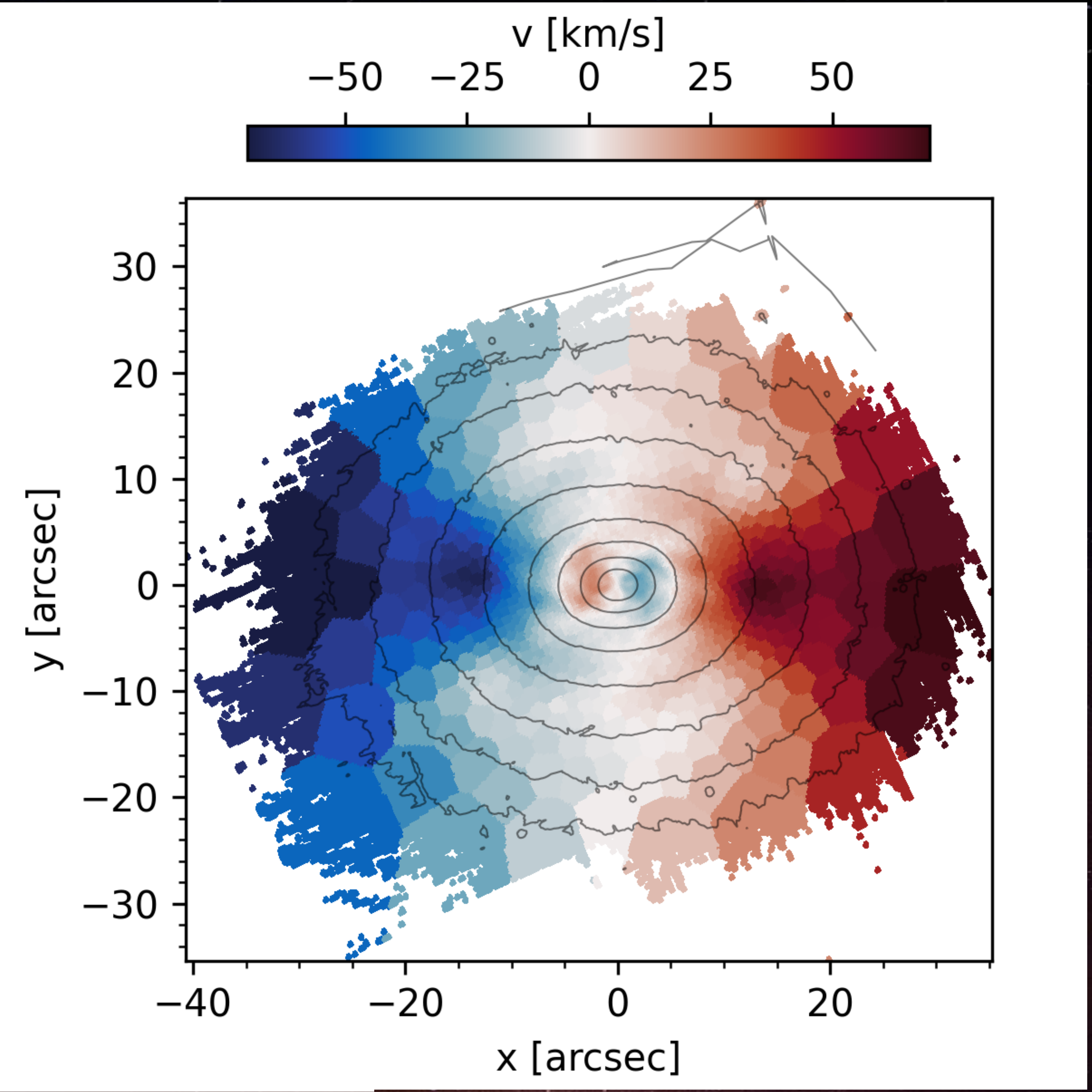


# Observed velocity fields

Decomposed kinematics maps by different orbital types

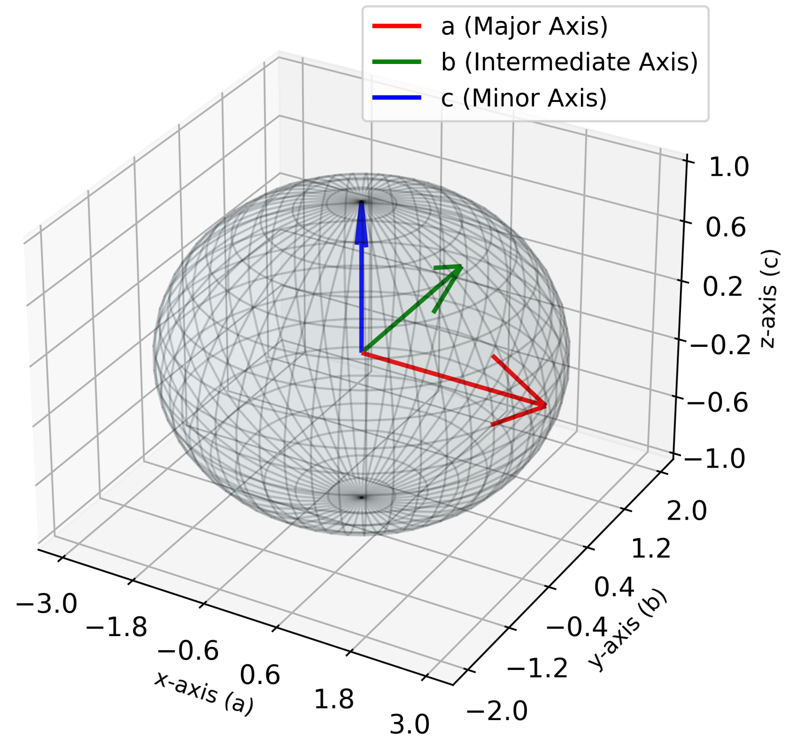


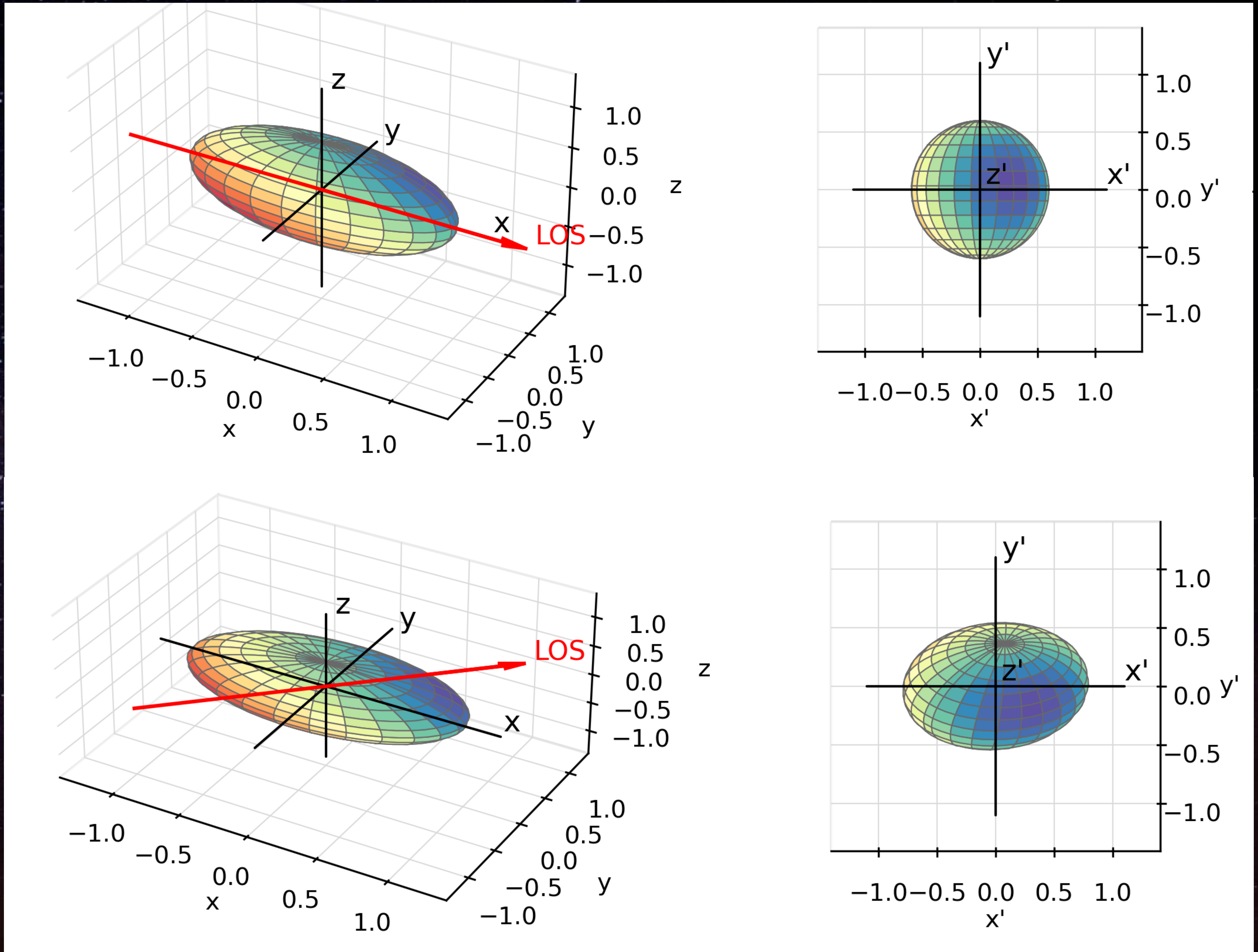
# Results

## Intrinsic shape of ETGs

All galaxies shows triaxial nature




- NGC4636 and NGC4261 showing prolate behaviour and then strong triaxial.
- IC4296 and NGC3923 maintains strong triaxiality.



# Dynamical modelling and BH mass

**Table 1.** The galaxy sample

| Galaxy (1) | Type (2) | Distance (Mpc) (3) | Scale (pc arcsec$^{-1}$) (4) | $M_K$ (mag) (5) | $R_b$ (arcsec) (6) | $R_e$ (arcsec) (7) | $\sigma_e$ (km s$^{-1}$) (8) | $i$ (°) (9) | SB profile (10) | Large Scale (11) |
|---|---|---|---|---|---|---|---|---|---|---|
| NGC 3706 | E | 36.0 | 175 | -25.10 | 0.11 | 30.6 | 270 | 79 | core | SINFONI |
| NGC 3923 | E4-5 | 21.0 | 102 | -25.09 | – | 86.4 | 240 | 48 | power-law | MUSE |
| NGC 4261 | E2-3 | 30.8 | 149 | -25.18 | 1.18 | 38.0 | 265 | 89 | core | MUSE |
| NGC 4636 | E0-1 | 14.3 | 69 | -24.36 | 2.30 | 89.1 | 181 | 89 | core | MUSE |
| IC 4296 | E | 49.8 | 241 | -25.99 | 1.44 | 68.4 | 330 | 57 | core | MUSE |
| IC 4329 | S0 | 56.9 | 276 | -25.74 | 0.79 | 120.0 | 296 | 67 | core | MUSE |