The interplay between massive black holes and their host galaxies

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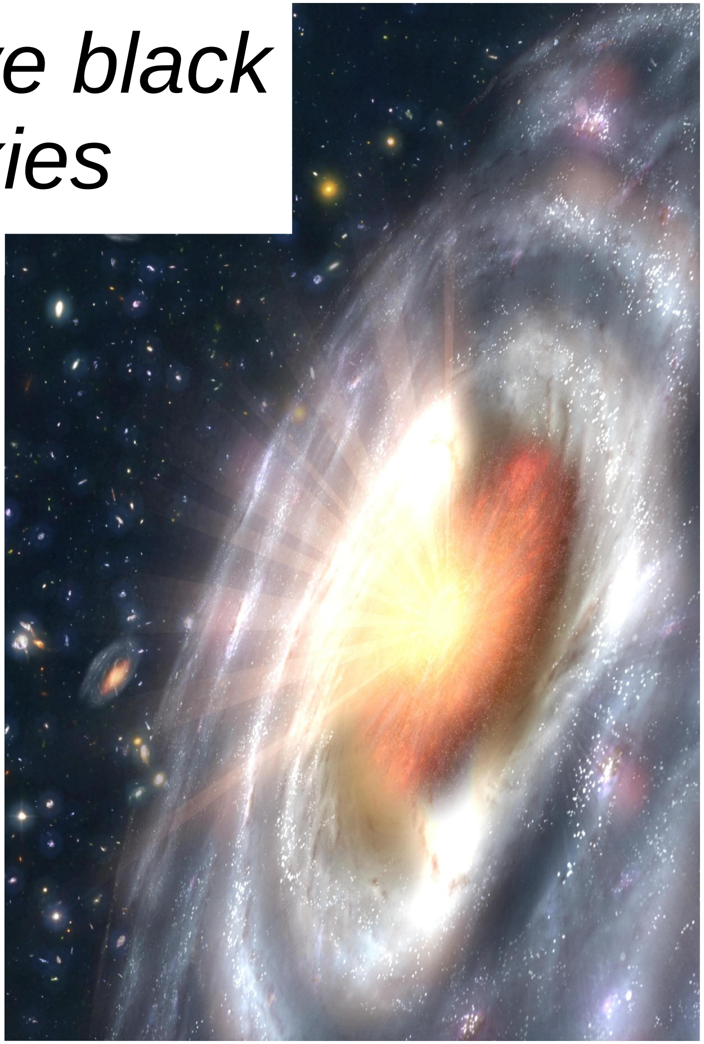
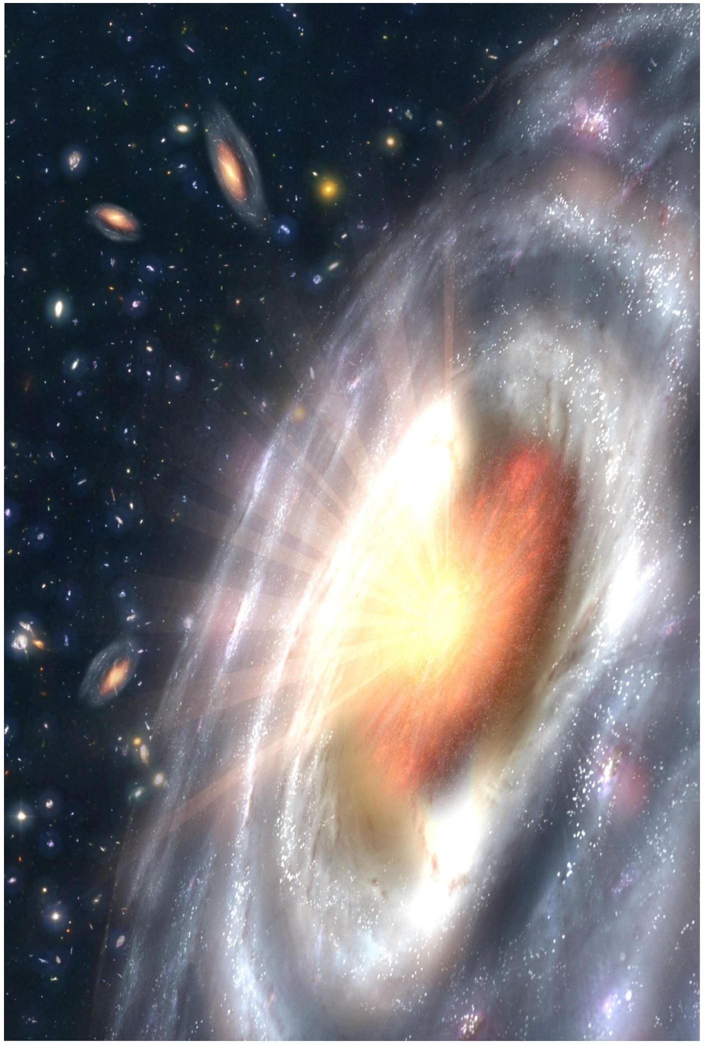


- A short history …
- BH demographics and correlations
- How to measure central black holes?
- A case study: NGC 4414
- Future outlook


NASA/JPL-Caltech

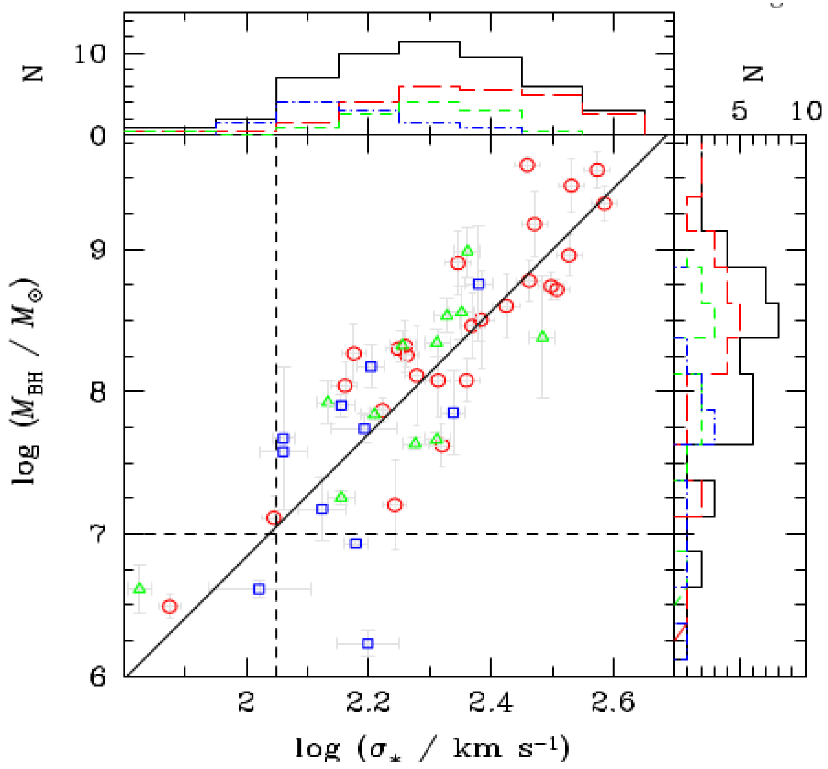
A short history ...

- 1783/1796: John Mitchell and Laplace first speculate of objects with such huge gravitation, that even light cannot escape
- 1954: AGN as very energetic phenomena, i.e. 3C 273
- 1969/1971: Lynden-Bell & Rees **suggest** that many galaxy might harbour a massive black hole in their center
- 1969/1972: Prediction of SMBH in the MW of about 30 × 10^6 $M_\odot$ (Lynden-Bell) or 0.6 × 10^6 $M_\odot$ (Sanders & Lowinger)
- 1978: Central black hole in M87
- 1993: Black hole mass might scale with different host galaxy properties
- 1998: Magorrian: “**Most** galaxies harbour a SMBH”
- 2004: 38 ; 2013: 89; 2016: 109 SMBH dynamical mass measurements

BH demographics

- More than 100 SMBH dynamical measurements for nearby galaxies
- Most mass measurements for elliptical galaxies
- Small number of galaxies measured below σ_* =100 km/s
- Dynamical measurements only for the nearby universe
- Compared to the number of AGNs, we expect a large fraction of massive black holes in quiescent galaxies

Greene+10



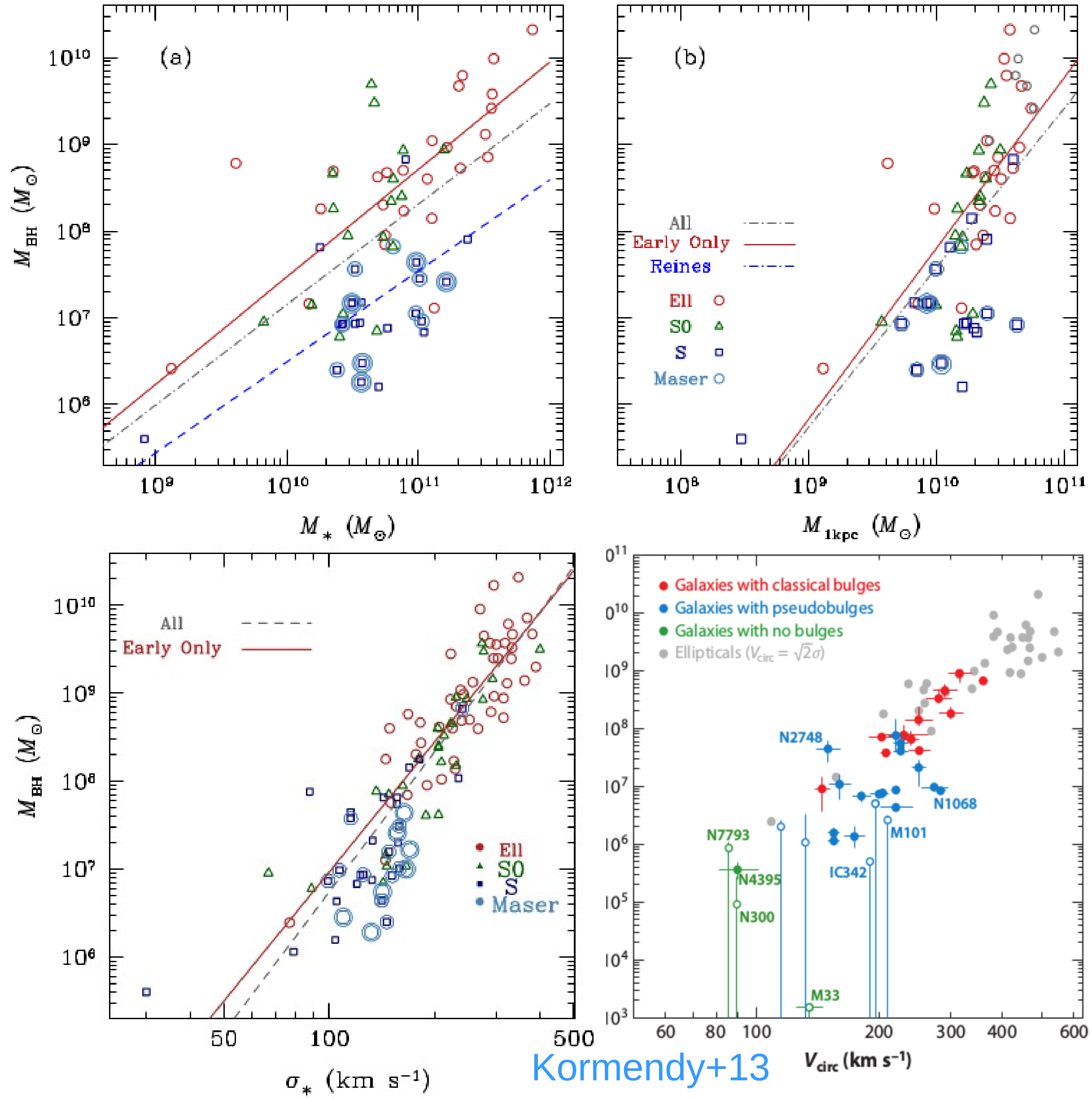
BH correlations

- Strong correlations between BH mass and different host galaxy bulge properties bridging vastly different spatial scales
- No correlation with dark matter halo or total galaxy mass
- Different correlations for different galaxy types
- Conclusion: BH-galaxy coevolution:

  - AGN feedback/ Mergers
- Outliers:

  - secular evolution/ bars

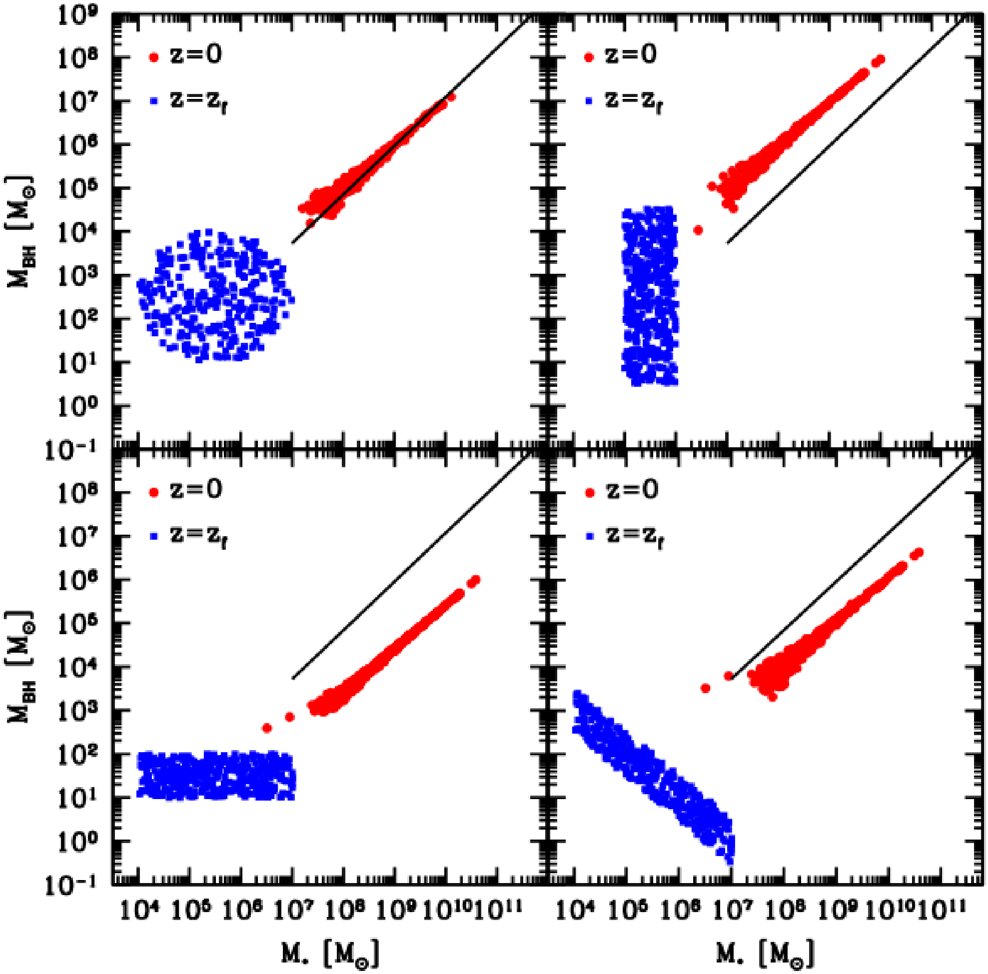
Greene+16



Kormendy+13

BH correlations – Convergence concept

- Result of a statistical convergence process (Peng 2007)
- Hierarchical assembly of black hole and stellar mass through galaxy merging of initially uncorrelated distributions
- Extreme M_{BH}/M_{bulge} ratios would be sorted out by the large number of mergers and the ensemble average
- Test: construct dark matter halo merger trees in a feedback and coupling-free environment
- Problem: Not enough major mergers in the past (Anglés-Alcázar et al. 2013)



Jahnke&Maccio2011

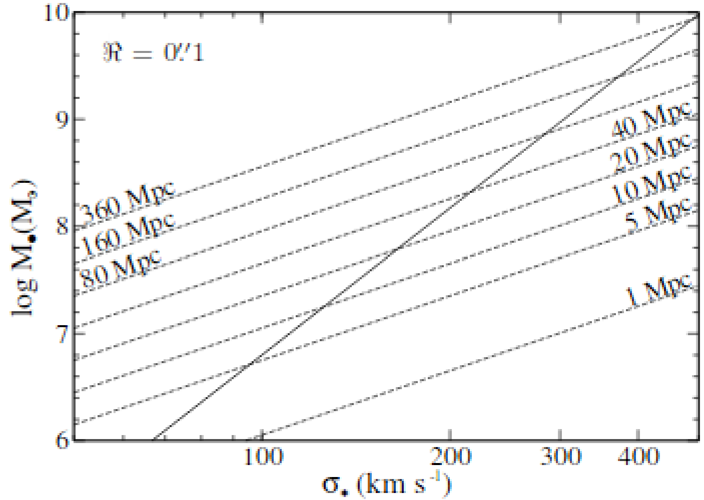
Resolving the sphere of influence

- Sphere of influence

$$r_{\rm BH} \simeq \frac{GM_{\rm BH}}{\sigma^2} = 11\ \text{pc}\left(\frac{M_{\rm BH}}{10^8\ M_\odot}\right)\left(\frac{\sigma}{200\ \text{km s}^{-1}}\right)^{-2}$$

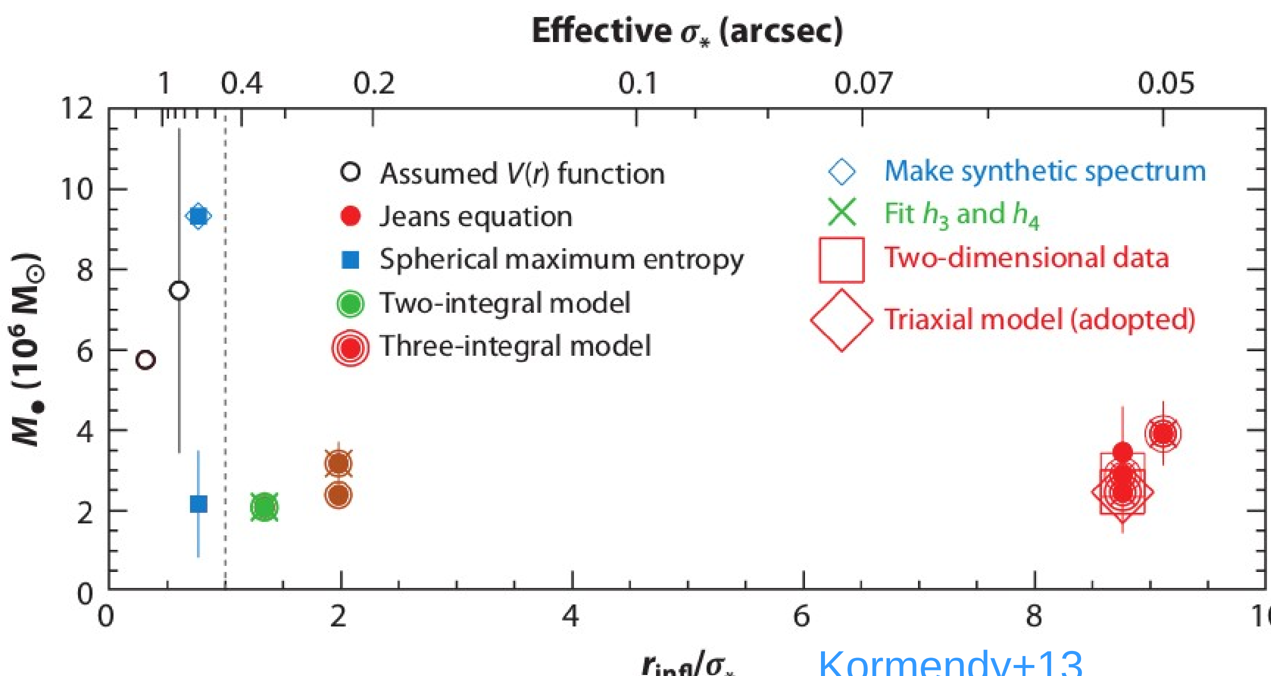
(isothermal sphere)

- With dynamical mass measurements we mainly probe distance scales up to 50-60 Mpc



Batcheldor2010

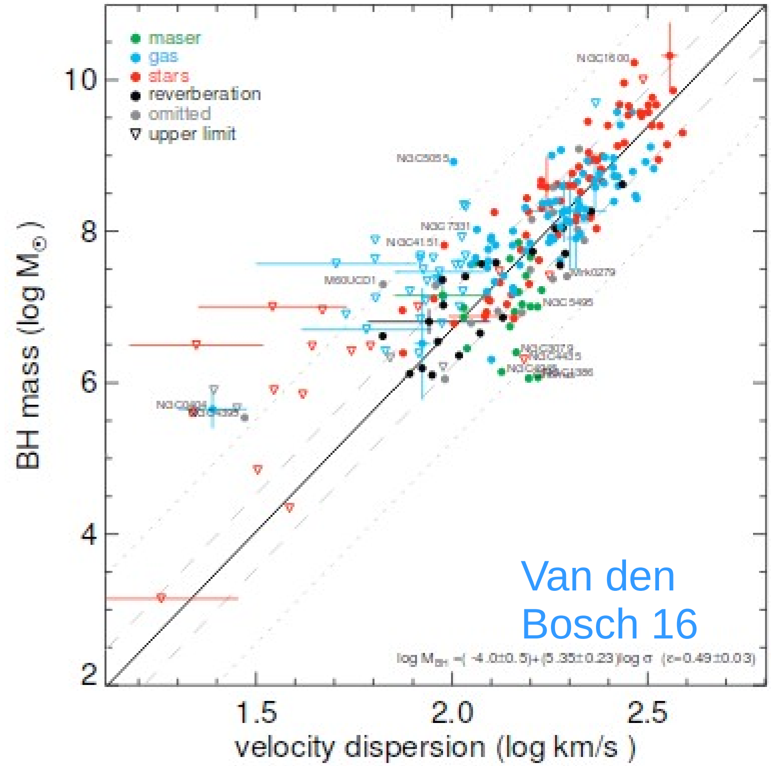
- Case of M32
- Resolving the sphere of influence could change th mass measurement by a factor of ~5



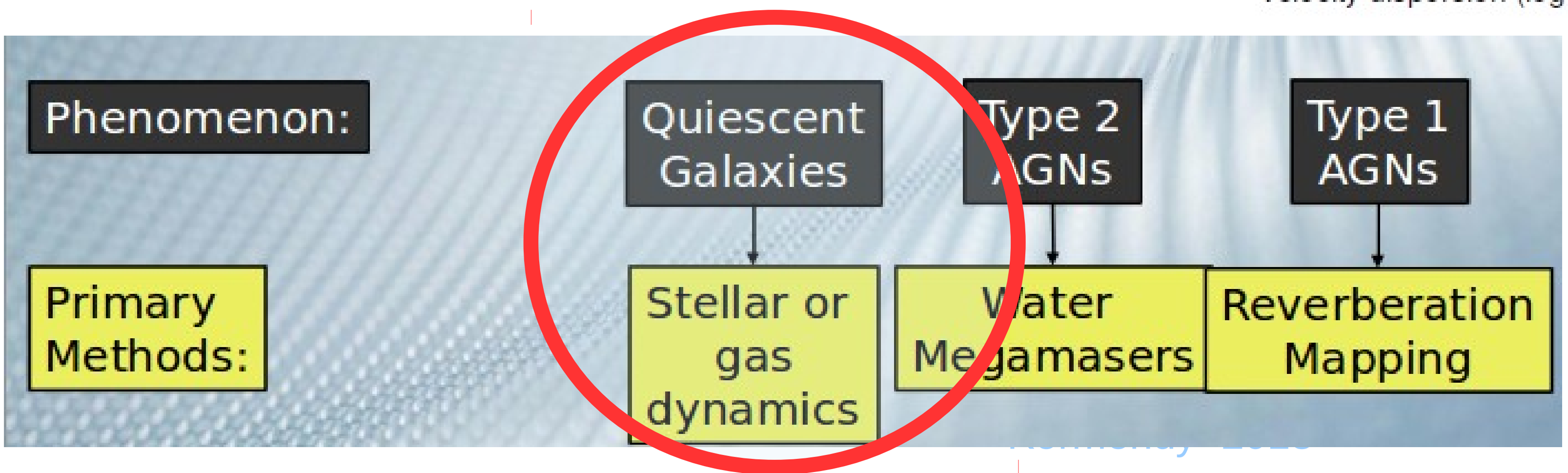
Kormendy+13

How to measure central black holes dyamically?

- Direct measurement: Use a dynamical tracer (gas/stars) which is accelerated by the black hole (→ Kinematics)
- The collective potential of stars or gas on scales of the black hole sphere of influence is modeled, with the central mass as a free parameter



$$\varphi_{all} = \varphi(M_{BH}) + \varphi(MGE \cdot M/L)$$



A case study: NGC 4414

- Coma Berenices

  (12h26m27.1s +31d13m25s)
- Isolated
- Distance Scale

  ≈ 18.0 ± 3.0 Mpc (z=0.002388)
- σ_e~110 km/s

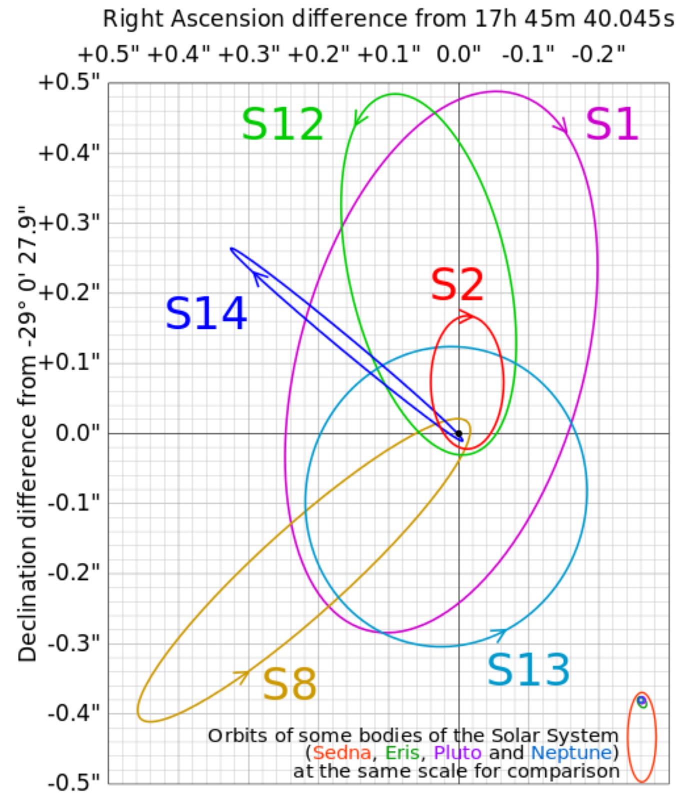
Kinematics: LOSVD

- Key ingredient to measure the mass of the SMBH with dynamic methods
- Milky Way:

  * 3d spatial coords (ang. Pos, parallaxes)

  * 3d velocities (proper motions, Doppler)

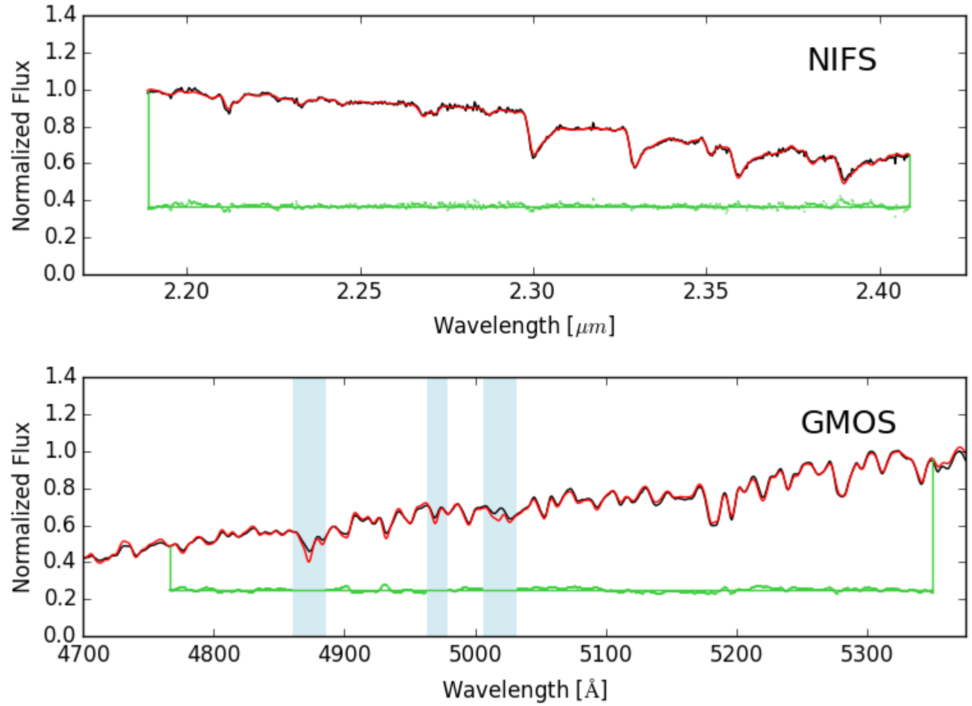
  → 6d phase space coordinates
- f(**r**,**v**,t) specifies how stars are distributed throughout the system and with which velocities
- → contributes to the shape of absorption/ emission lines
- For farther galaxies than Milky Way, we can only measure the collective motion of stars along the line of sight (LOSVD)

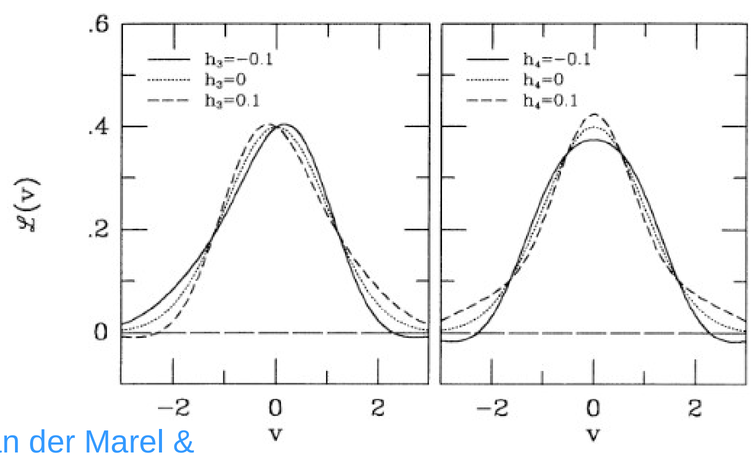


Eisenhauer+05

Extraction of Stellar Kinematics

- Kinematics extracted from 3-d NIFS/GMOS datacube by using pPXF (Cappellari & Emsellem 2004)
- Assumptions:
- $S(x) = T(x) \otimes B(x)$
- LOSVD Gaussian shaped (V, σ)
- Deviations from Gaussian given by Gauss-Hermite h3 (assymmetric), h4 (symmetric)

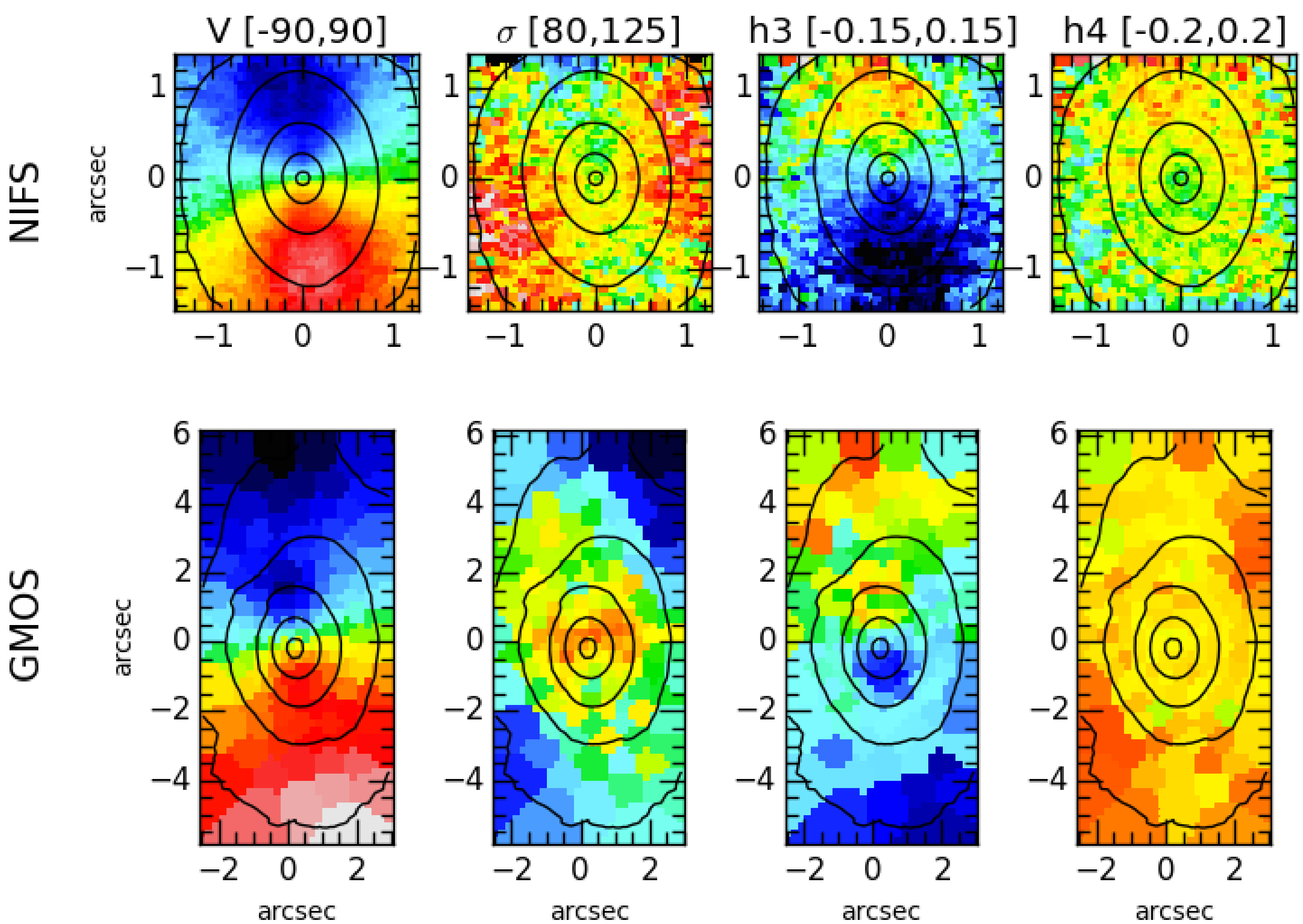


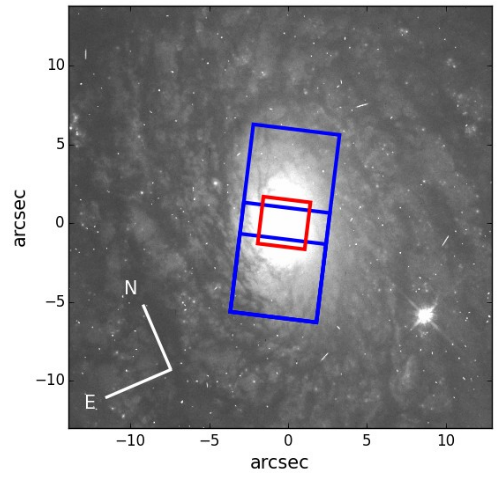


Van der Marel & Franx 1993

Stellar Kinematics

- Voronoi binning applied to ensure sufficient S/N
- Obtain V, sigma, h3 and h4 for each bin





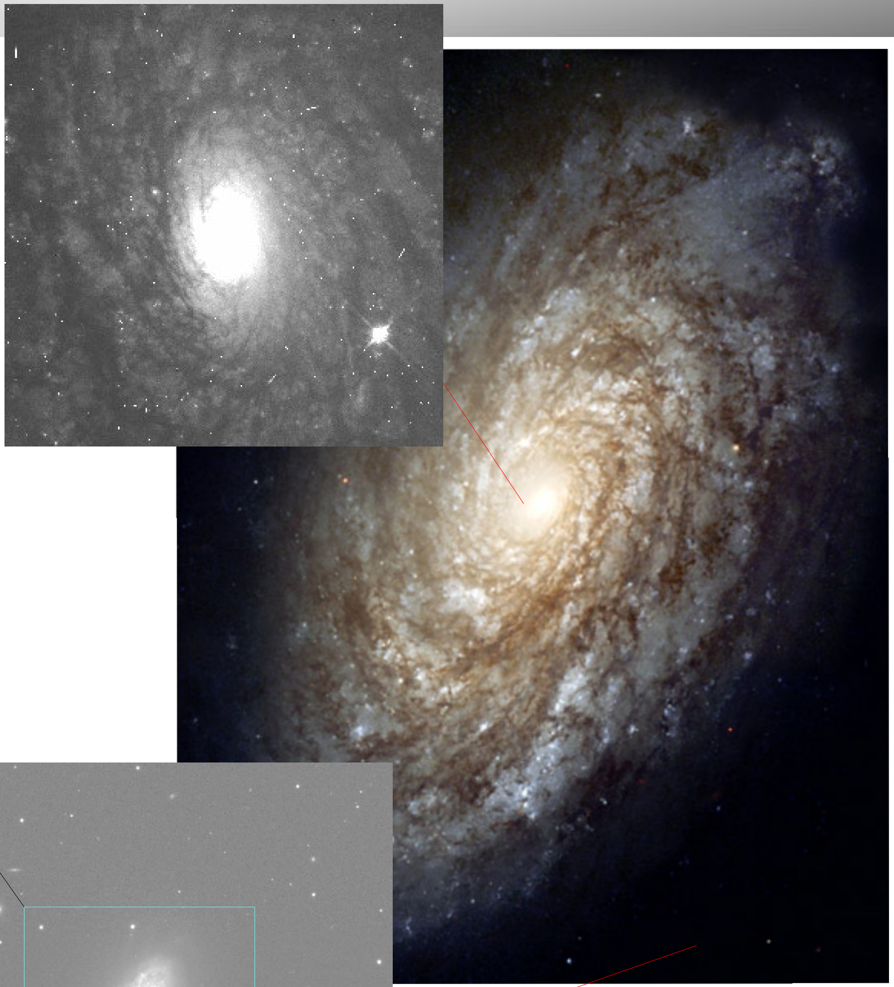
Stellar Mass Model

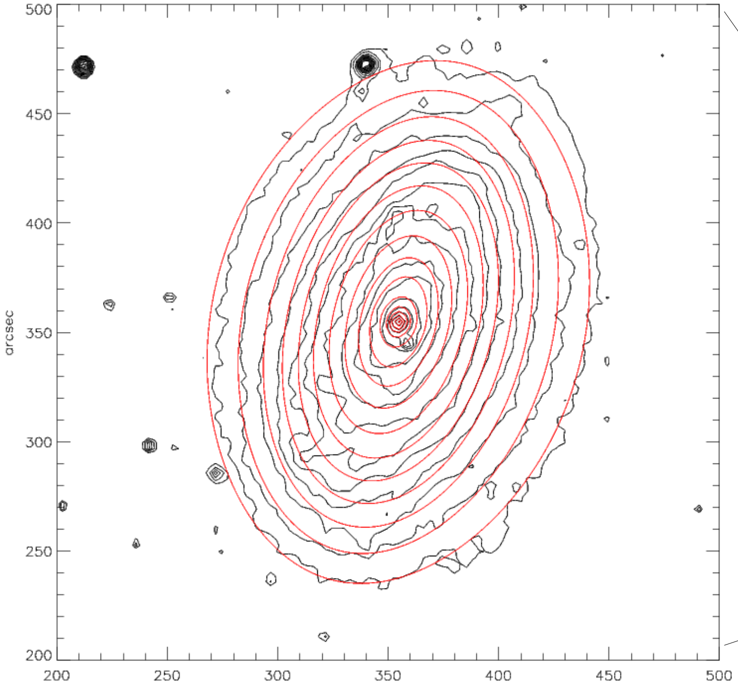
Parametrization of stellar surface brightness

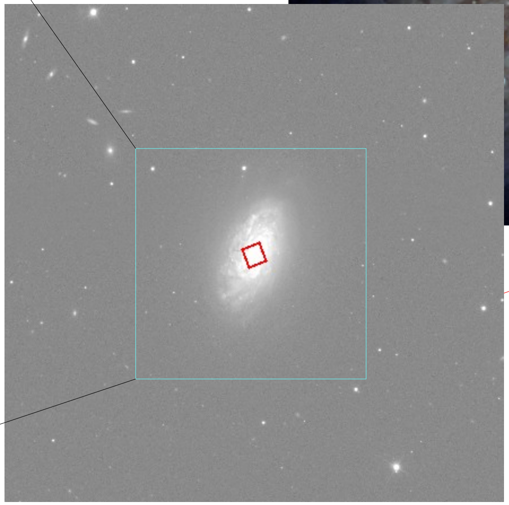
- from high-resolution HST/WFPC2/F606 data &

- large scale SDSS/r image data

(both dust-corrected)

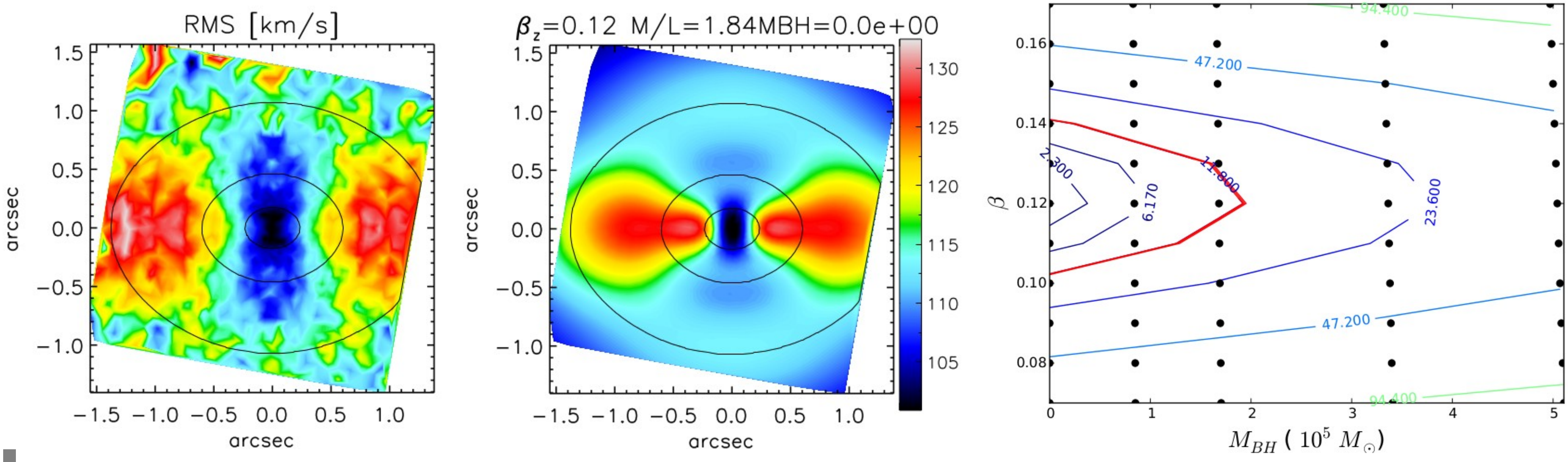




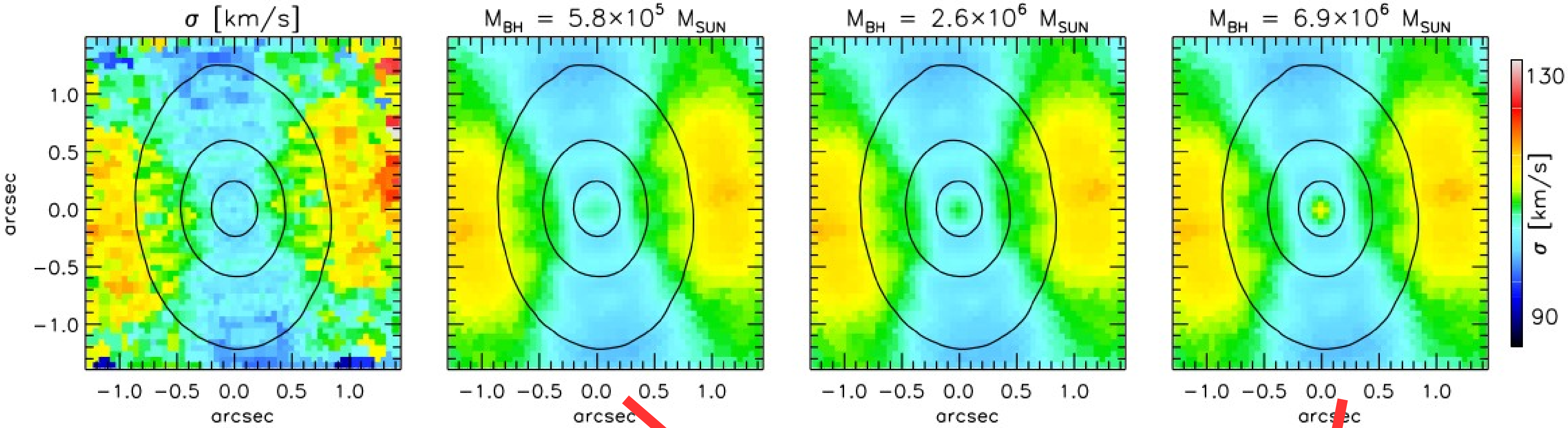


JAM models

- Give a solution of the Jeans Equations to model stellar kinematics
- Jeans equations relate the galactic gravitational potential to the second moments v_{los}^2, which are a good approximation for observed quantity (Cappellari 2008) $V_{rms} = \sqrt{V^2 + \sigma^2}$
- Anisotropy parameter describes the orbit configuration



Schwarzschild orbit based models



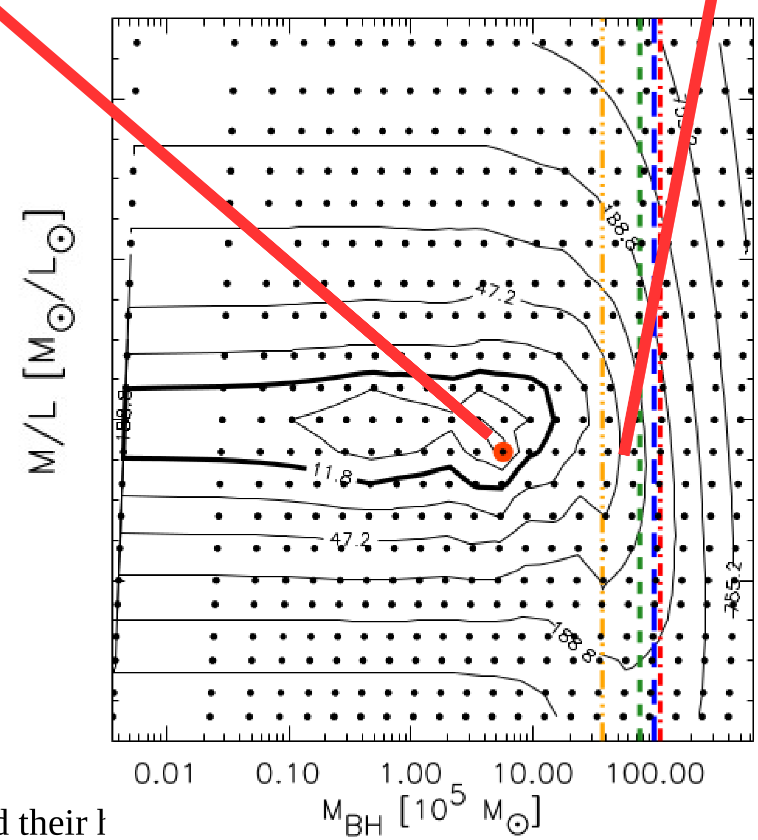
- Orbit superposition method (Schwarzschild 1979)
- Best model

  $M_{BH} < 1.6 \times 10^6 \, M_\odot$

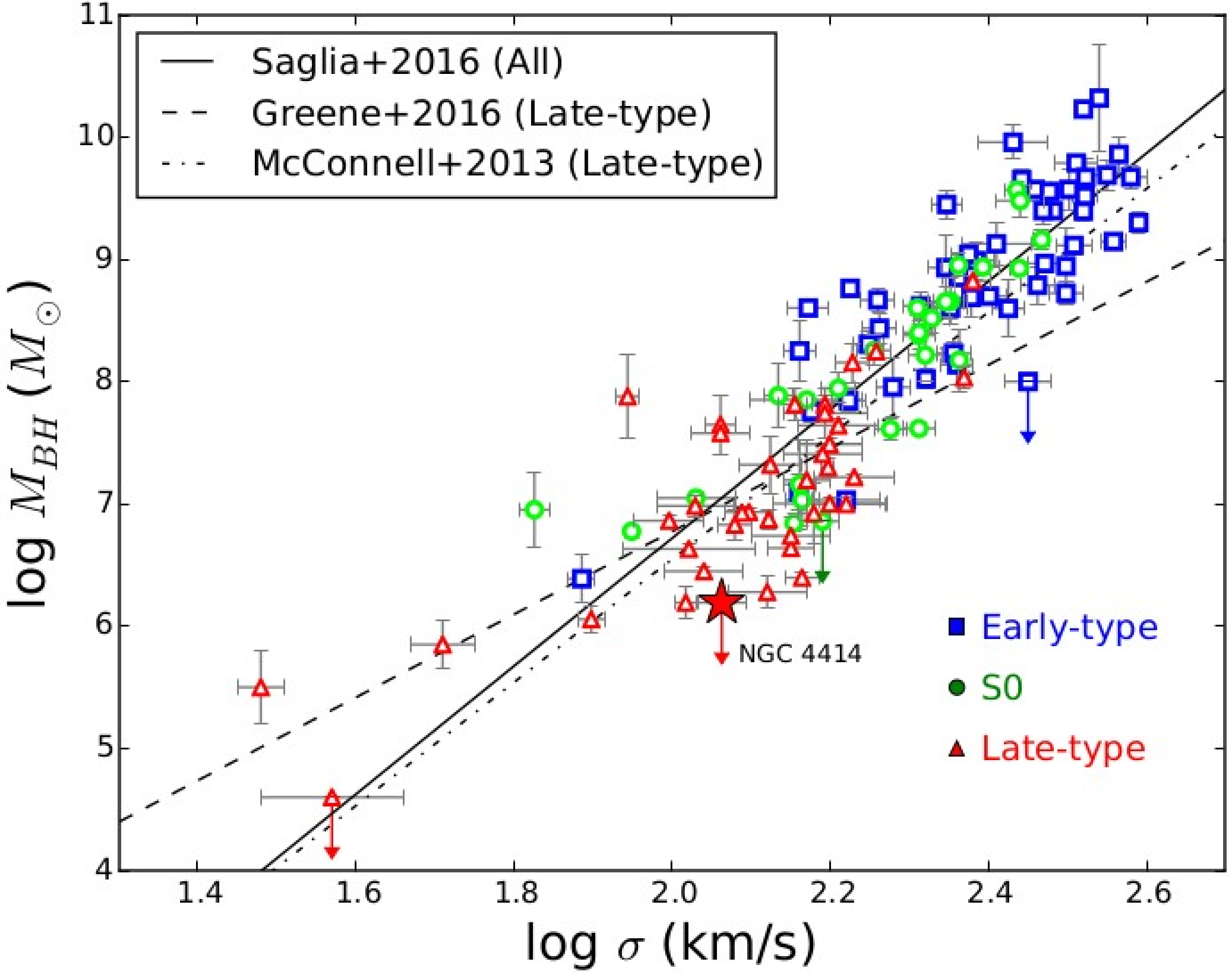
  $M/L = 1.76$

  $M_{BH,infl} < 7.5 \times 10^6 \, M_\odot$

- Via high quality IFU data, we can probe a measurement 5 times below resolution limit



BH compendium + NGC 4414



Error budget

- **Distance** : NED [5 – 25 Mpc](Tully-Fisher/Cepheids)

  → Distance ~ M_{BH}
- **Dust**: Underestimation of stellar light → very significant
- Variation in **stellar M/L** ~ M_{BH}
- **Inclination** of the galaxy
- **Dark matter** → Omission returns higher M/L → Under-assumption by up to 30% (Rusli 2013)

Outlook to the field

- Dynamic measurements

  * Fundamental plane of SMBH masses

  * Lower and upper mass SMBH region

  * Unification of the different methods

  * Redshift evolution of the scaling relations

- Black Holes

  * Learning about the evolution of black holes

  * Fundamental physical connection between black hole and bulge growth

  * How do over- and undermassive black holes w.r.t. to correlations form?

  * IMBH to fill the gap between stellar BHs and SMBHs

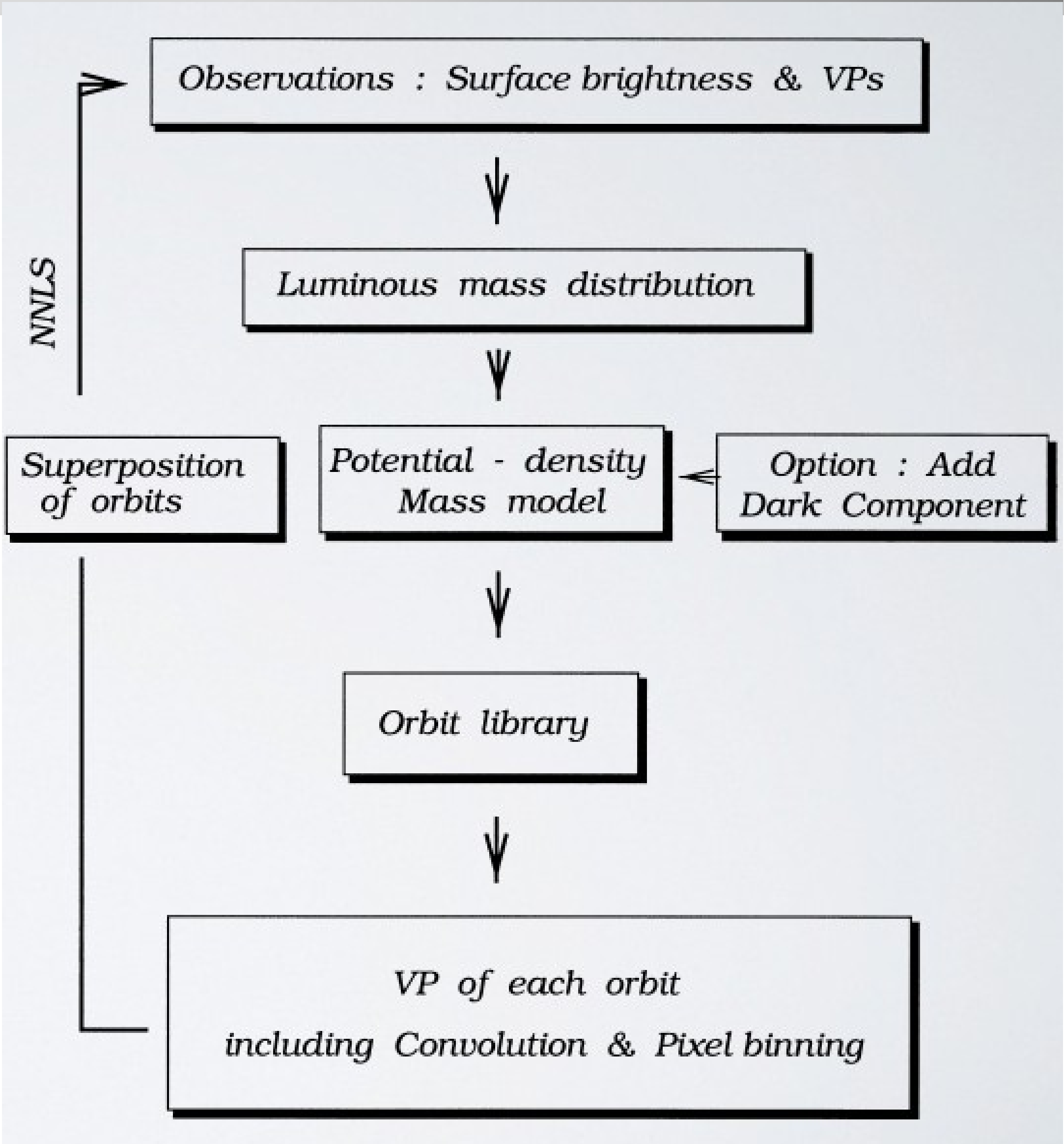
  * More component systems (–> LIGO) and BH merging

Summary

- A field of research that grows at a tearing pace
- SMBHs are thought to coevolve with their host galaxy bulge due to different correlations by AGN feedback and merging
- Details are still under debate!
- The data resolution is a limiting factor for the measurements
- Problems in adjusting different measurement methods

Schwarzschild method

- Orbit superposition dynamical models (Schwarzschild 1979)
- Assumption: geometry, dynamical equilibrium
- Integrate orbits from potential and store observables
- Generate orbit library
- Construct a superposition of orbits
- Simultanelously reproduces the total mass distribution and observed stellar kinematics
- Re-iterative process



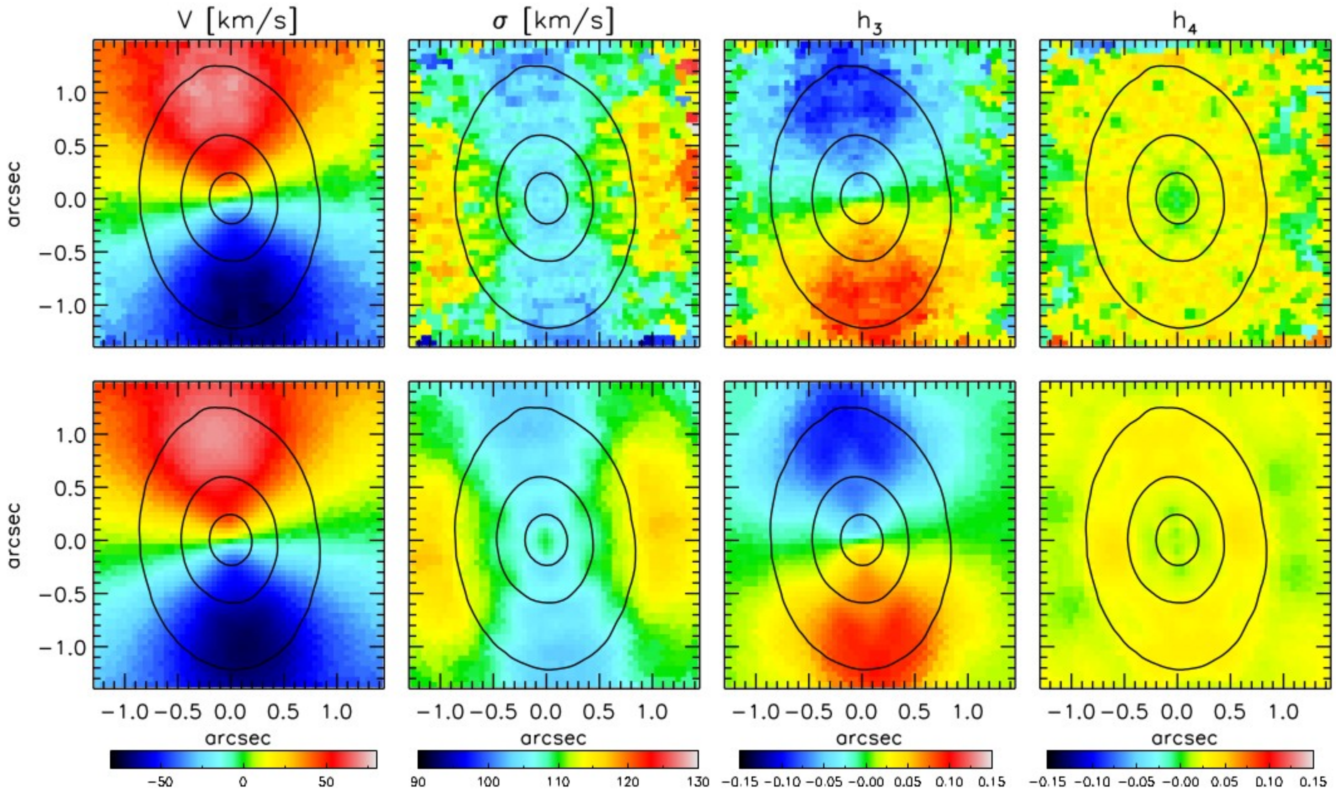
Cretton et al. 1998

Schwarzschild orbit based models

- Orbit superposition dynamical models (Schwarzschild 1979)
- Method: - Integrate orbits from potential and store observables
  - Generate orbit library and construct a superposition of orbits
- General method, but numerically expensive

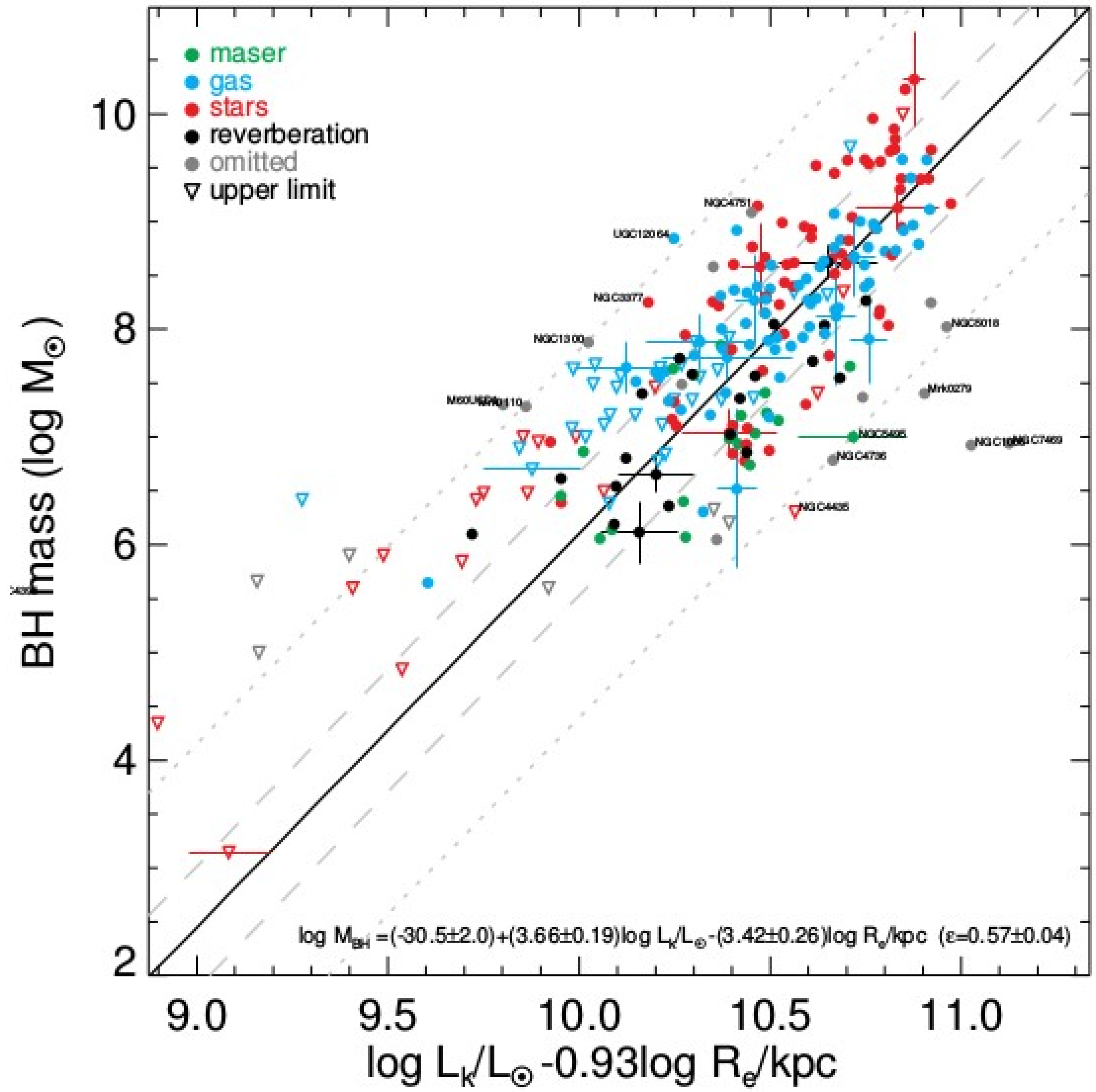
Observation

Model



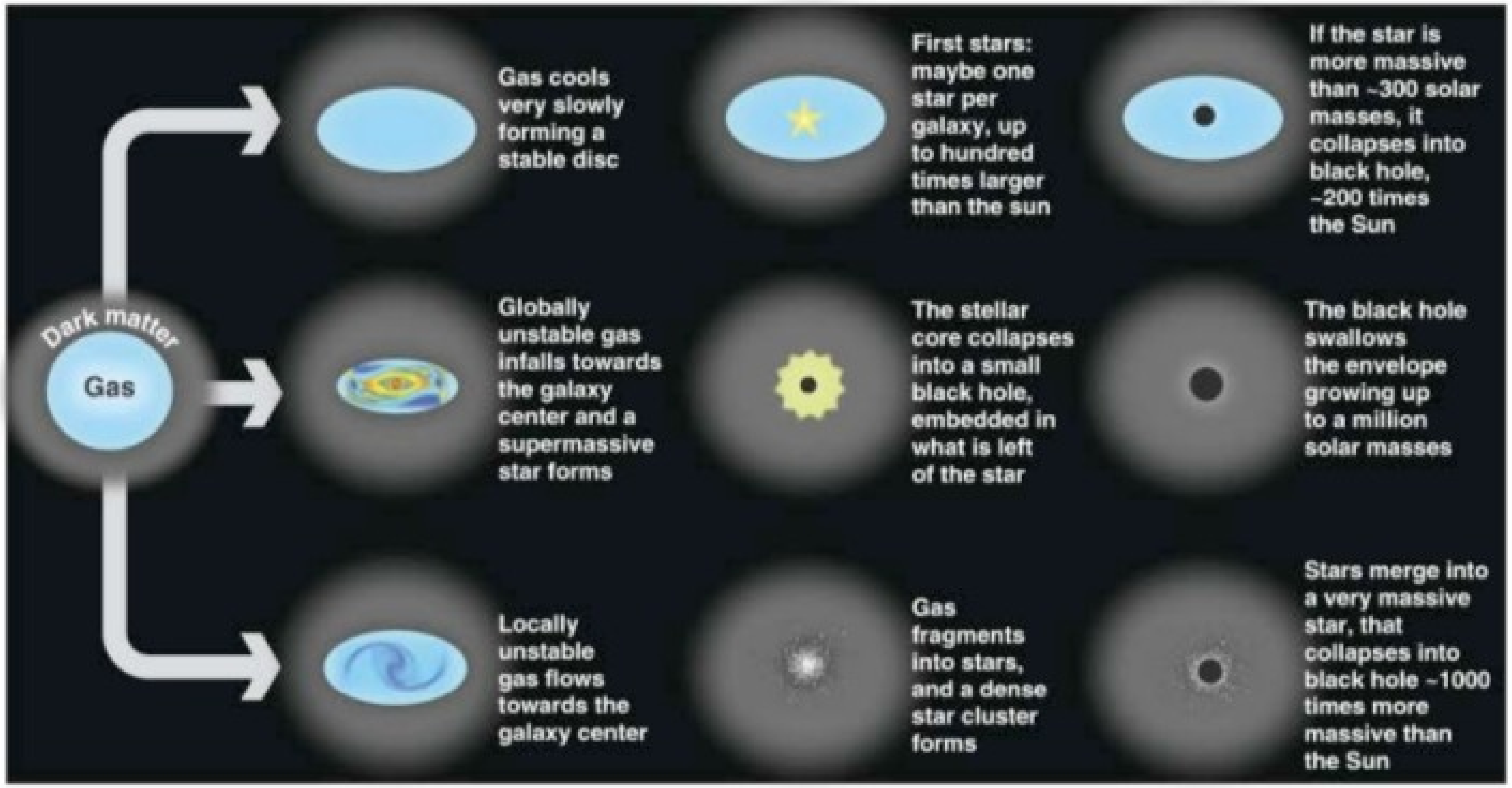
BH-size-luminosity relation

- Fundamental plane for black holes
- All gravitational systems sit on plane $GM_{1/2}=R_{1/2}\sigma_{1/2}^{2}$ (Virial Theorem)
- Here: Proxies



VandenBosch 2016

Implication on SMBH formation and evolution



Volonteri 1 x 33 picas

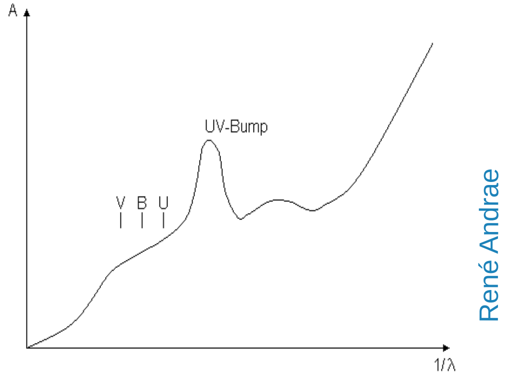
Dust correction – Method (Cappellari et al. 2002, Scott et al. 2012)

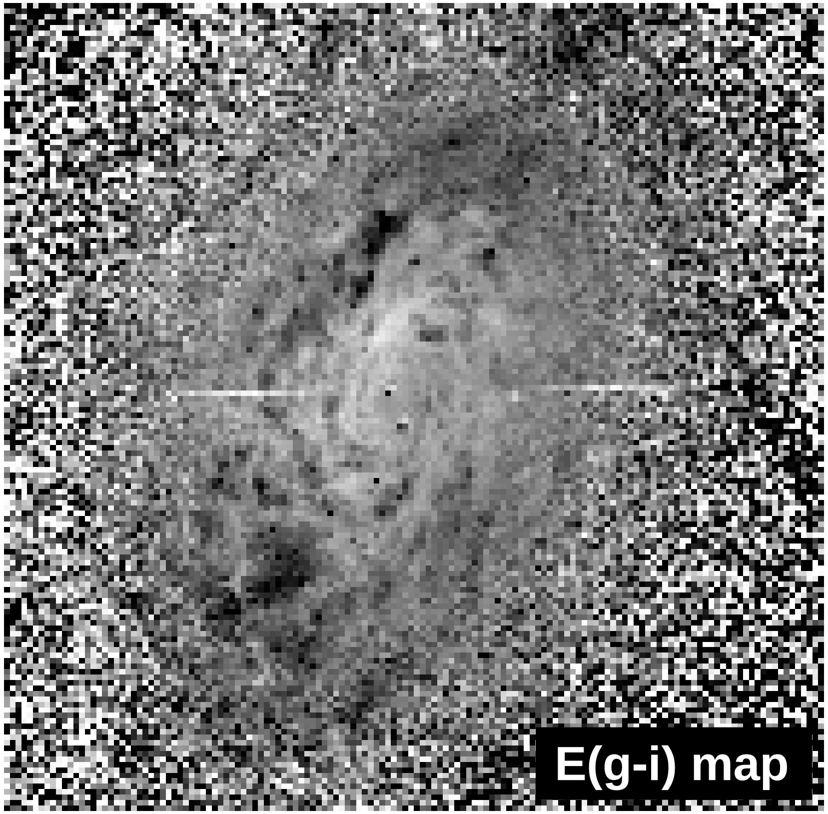
- Dust effects accuracy of MGE model
- Assumption: Dust as screen in front of stellar emission
- Interstellar Reddening

  $E(g\text{-}i) = (g\text{-}i)_{observed} - (g\text{-}i)_{intrinsic}$

- Extinction correction of dust with standard galactic extinction law (Schlegel 1998)

  $A_r = 1.15\ E(g\text{-}i)$





Dust Correction

- Perform straight line fit to pixel colors to determine underlying colour gradient of galaxy