Kinematic Scaling Relations: Decomposing Stellar and Gas Kinematics with 3D Spectroscopy

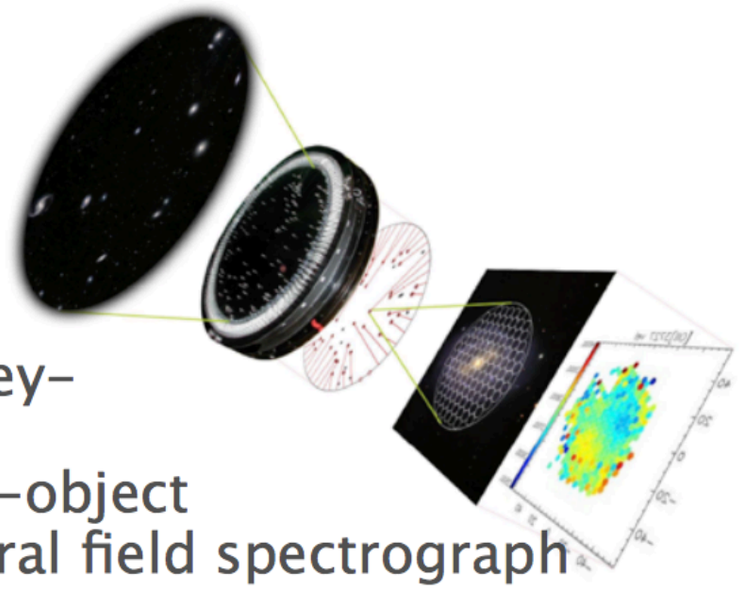


Image credit: ChatGPT
The conceptual artwork illustrating the impact of star formation and AGN feedback on the ionized gas kinematics

Sree Oh (Yonsei)
Matthew Colless (ANU)
and the SAMI team

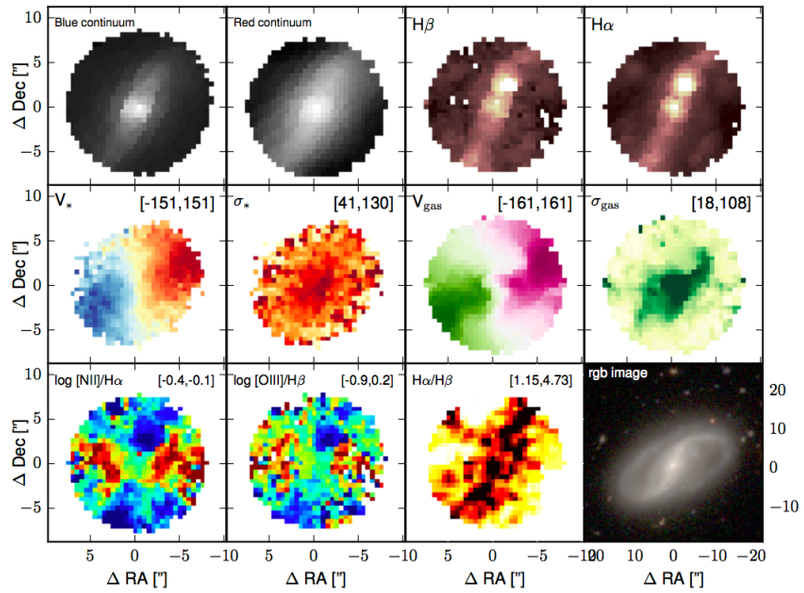
UNLOCKING THE UNIVERSE,
INSPIRING THE FUTURE

SAMI 3D spectroscopy survey



Sydney–
AAO
Multi-object
Integral field spectrograph

SAMI DR2 (Scott et al. 2018)



Optical integral field spectrograph (IFS) covering 3700-7500 Å

200 nights of 4 m AAT awarded from 2013 for 6 years

Survey completed ~ 3000 galaxies

Mass and volume limited selection ($z < 0.1$, $M_* > 10^8$)

A wide range in environments (fields to clusters)

Full range in morphology (spirals to ellipticals)

https://sami-survey.org

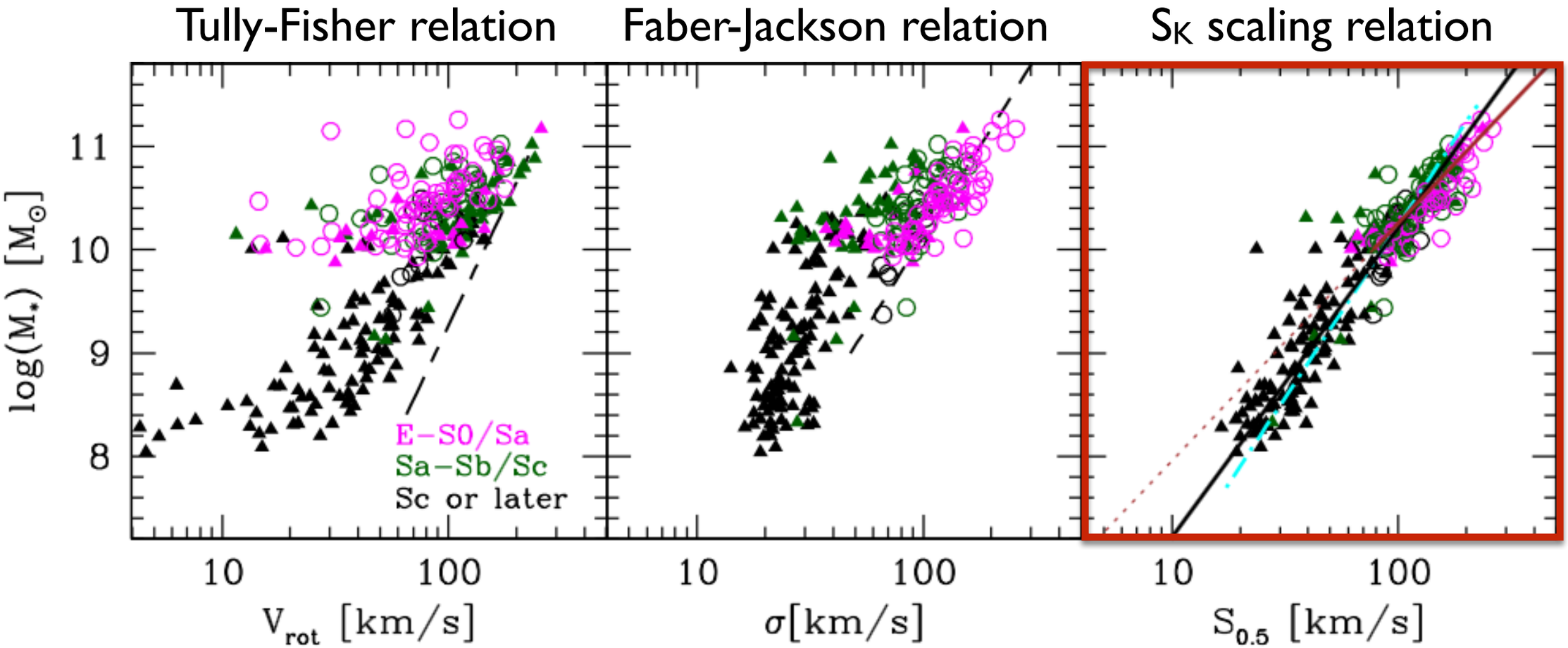
sami galaxy survey

A unified scaling relation for all galaxy types

One approach: combining rotation and dispersion

$$S_K = (KV_{rot}^2 + \sigma^2)^{1/2}$$

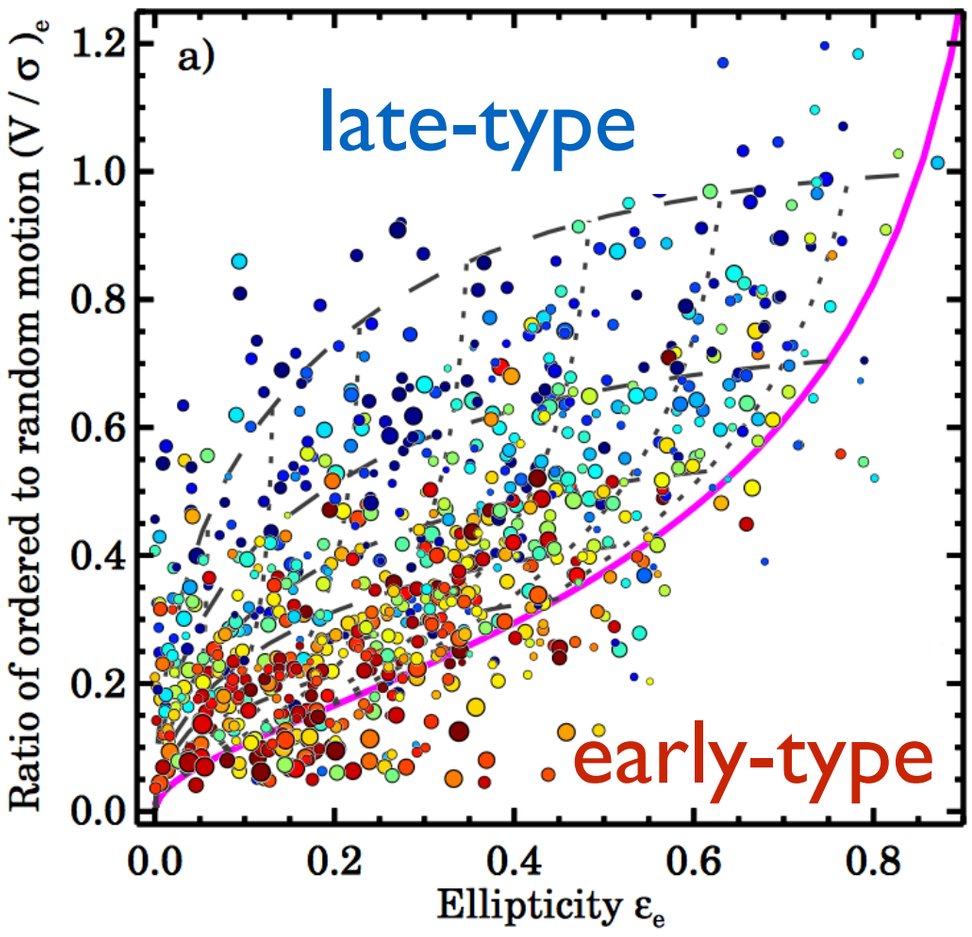
Cortese et al. (2014), Barat et al. (2020)



Succeed in putting all types of galaxies in one relation!

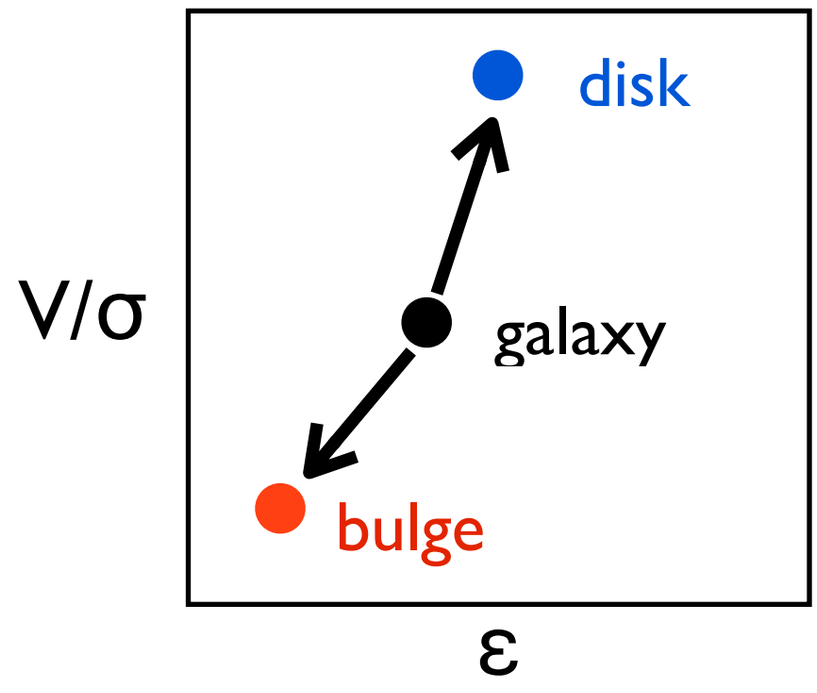
My approach: decomposing rotation and dispersion components

What determines stellar kinematics of galaxies?



van de Sande et al. (2018)

Galaxies show a wide range of kinematic properties that are known to be related to other observable quantities such as mass, morphology, population, and environment



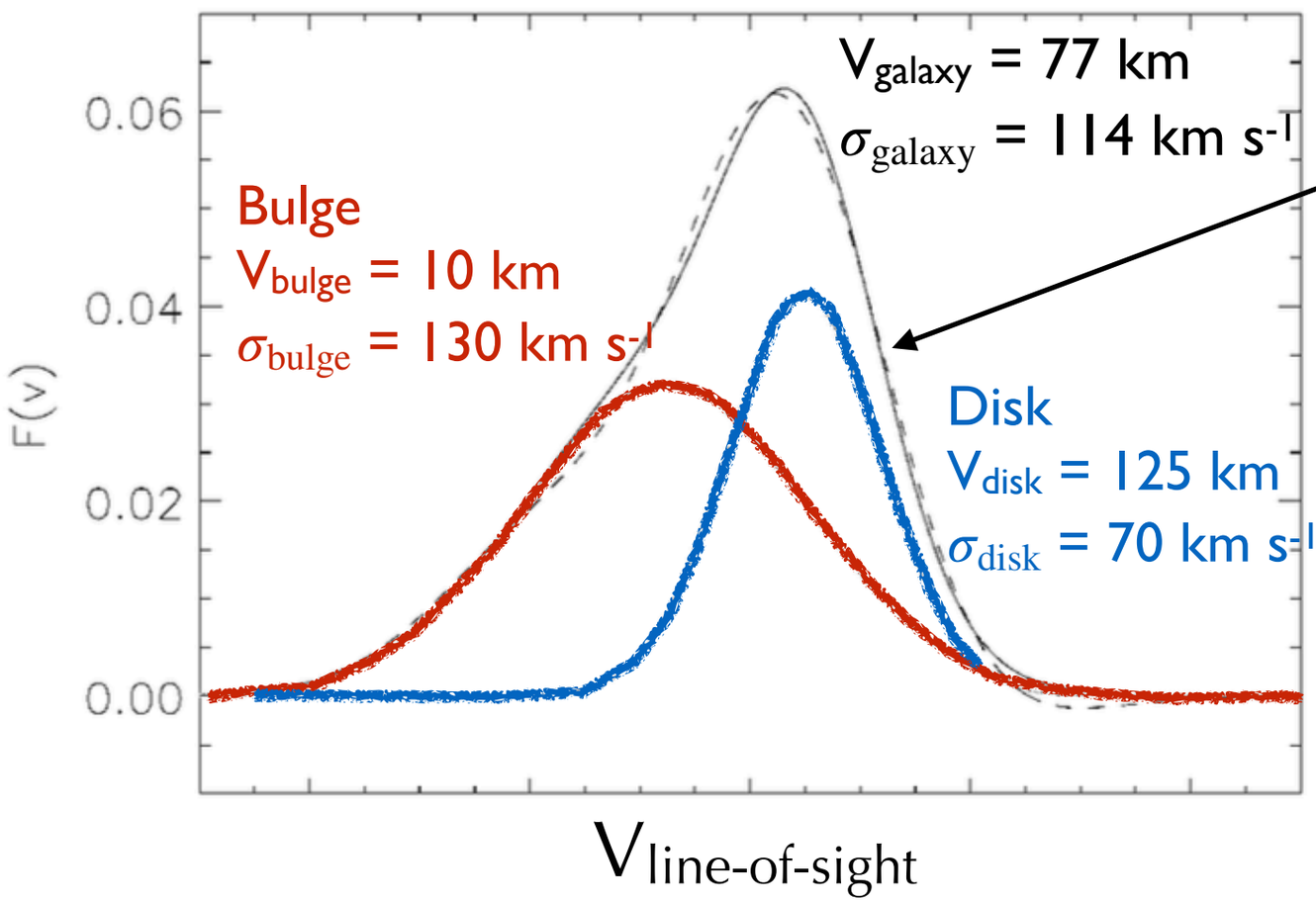
Goals for spectroscopic bulge-disk decomposition:

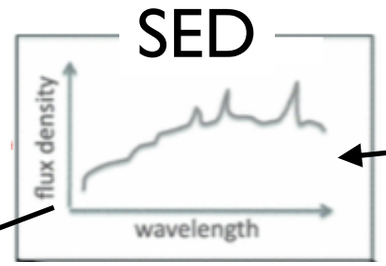
- to study the intrinsic kinematics of the galactic bulge and disk
- to encompass all galaxy types within unified scaling relations

Spectroscopic B/D decomposition using full spectral fitting, pPXF

Penalized Pixel-Fitting method (pPXF; Cappellari 2017)

Extract the kinematics and stellar population from galaxy spectra
via full spectrum fitting with a two-component kinematic model







$$F_{galaxy} = w_B F_B + w_D F_D$$

w_B ~ Bulge/Total, w_D ~ Disk/Total

$$F_b(v_{los}) = \frac{1}{\sqrt{2\pi}\,\sigma_b} \exp\left[\frac{-(v_{los} - V_b)^2}{2\sigma_b^2}\right]$$

$$F_d(v_{los}) = \frac{1}{\sqrt{2\pi}\,\sigma_d} \exp\left[\frac{-(v_{los} - V_d)^2}{2\sigma_d^2}\right]$$

> simultaneously estimate Vb, σb, Vd, σd

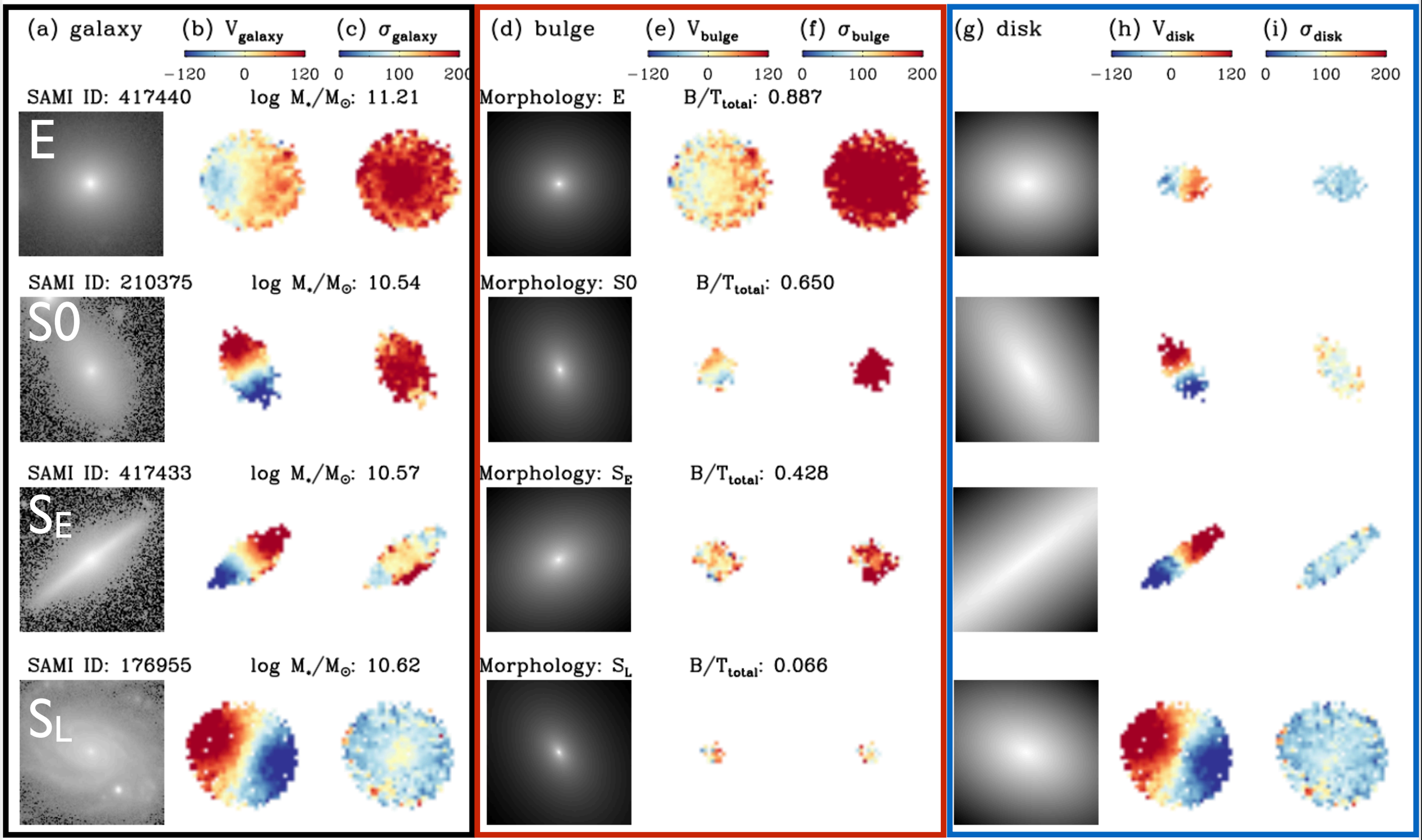
see also Tabor et al. (2017), Coccato et al. (2018)

Kinematic maps for 826 SAMI galaxies

Galaxy

Bulge

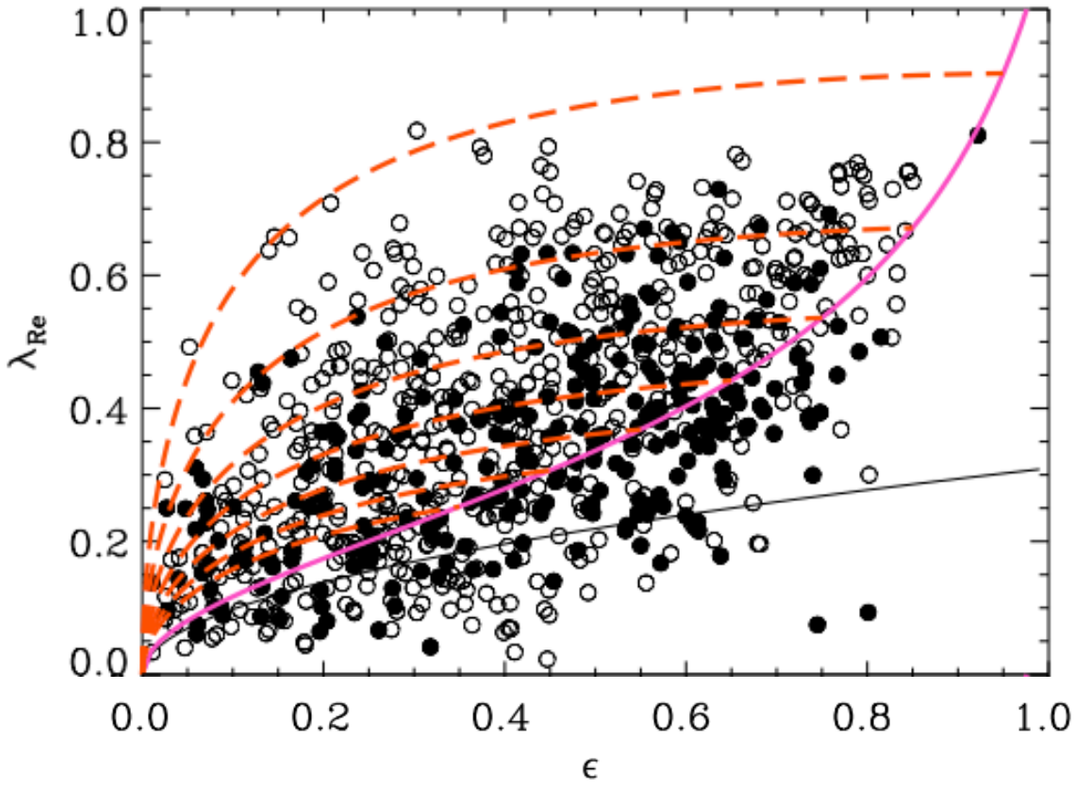
Disk



Oh et al. 2020 MNRAS 495 4638

λ_{Re} (spin parameter) - ellipticity plane

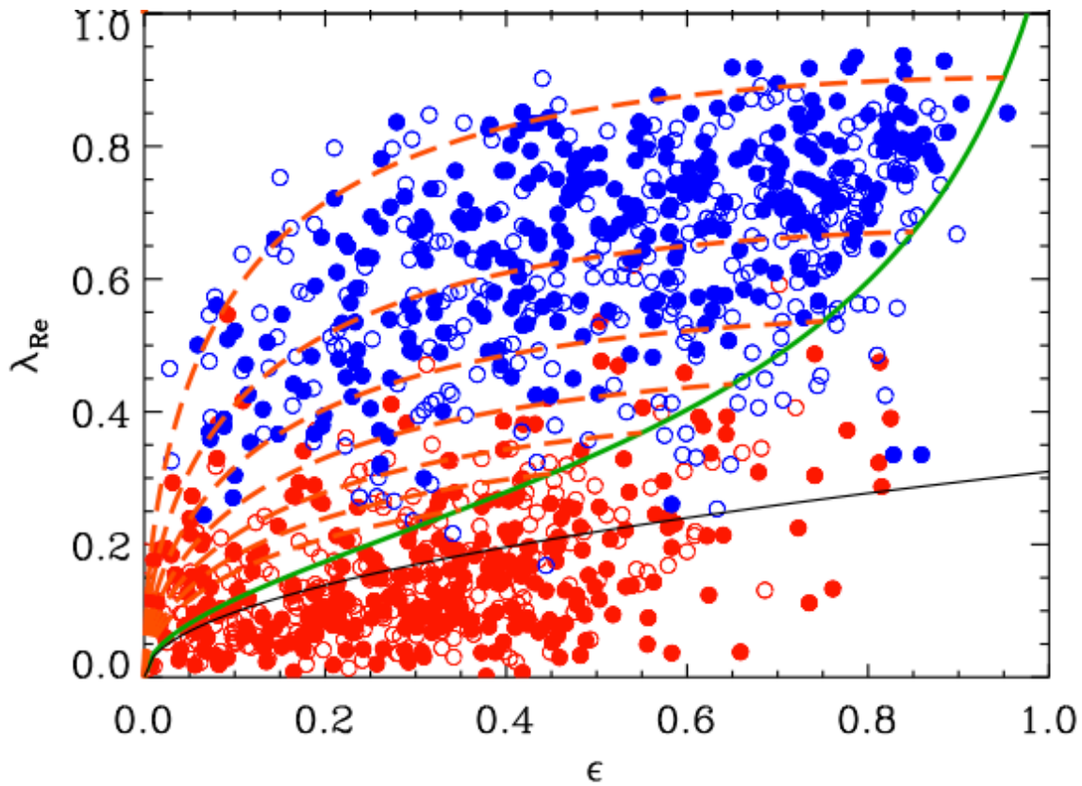
SAMI galaxy



fast rotator

slow rotator

bulge & disk



Bulges and disks are kinematically distinct

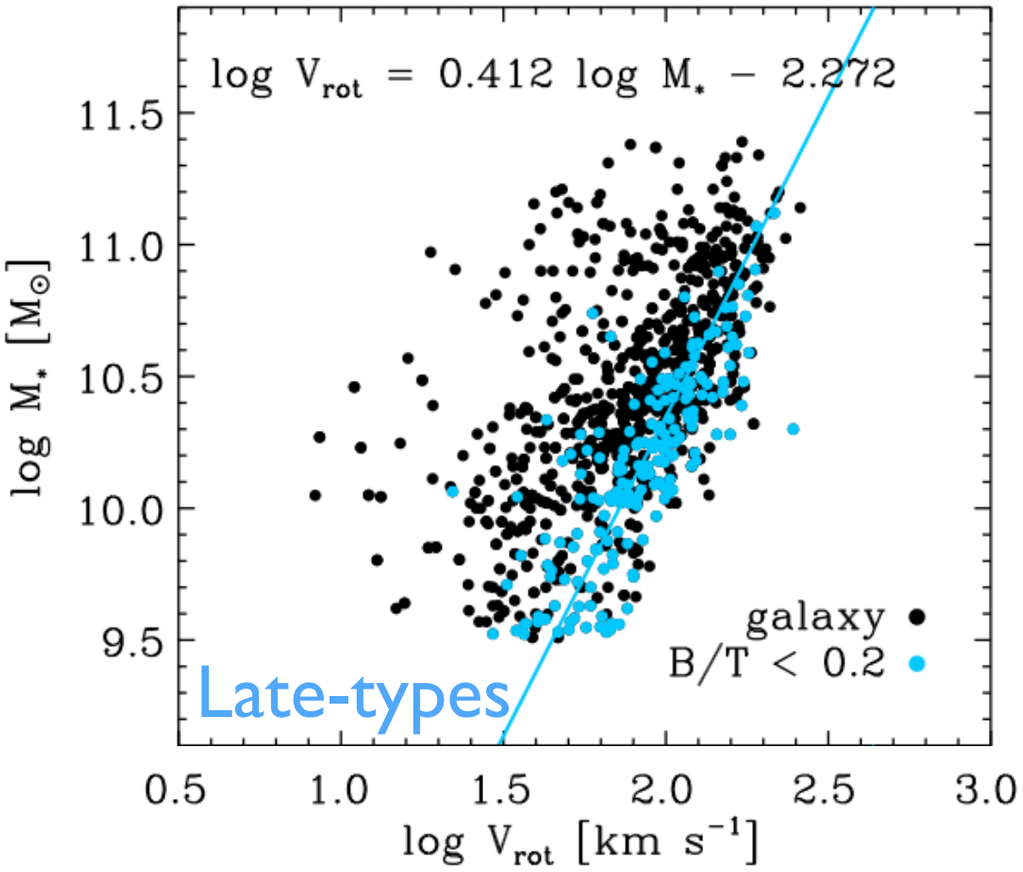
$$\lambda_R = \frac{\langle R|V|\rangle}{\langle R\sqrt{V^2+\sigma^2}\rangle} = \frac{\sum_{i=0}^{N_{spx}} F_i R_i |V_i|}{\sum_{i=0}^{N_{spx}} F_i R_i \sqrt{V_i^2+\sigma_i^2}} \sim V/\sigma$$

Emsellem et al. (2007)

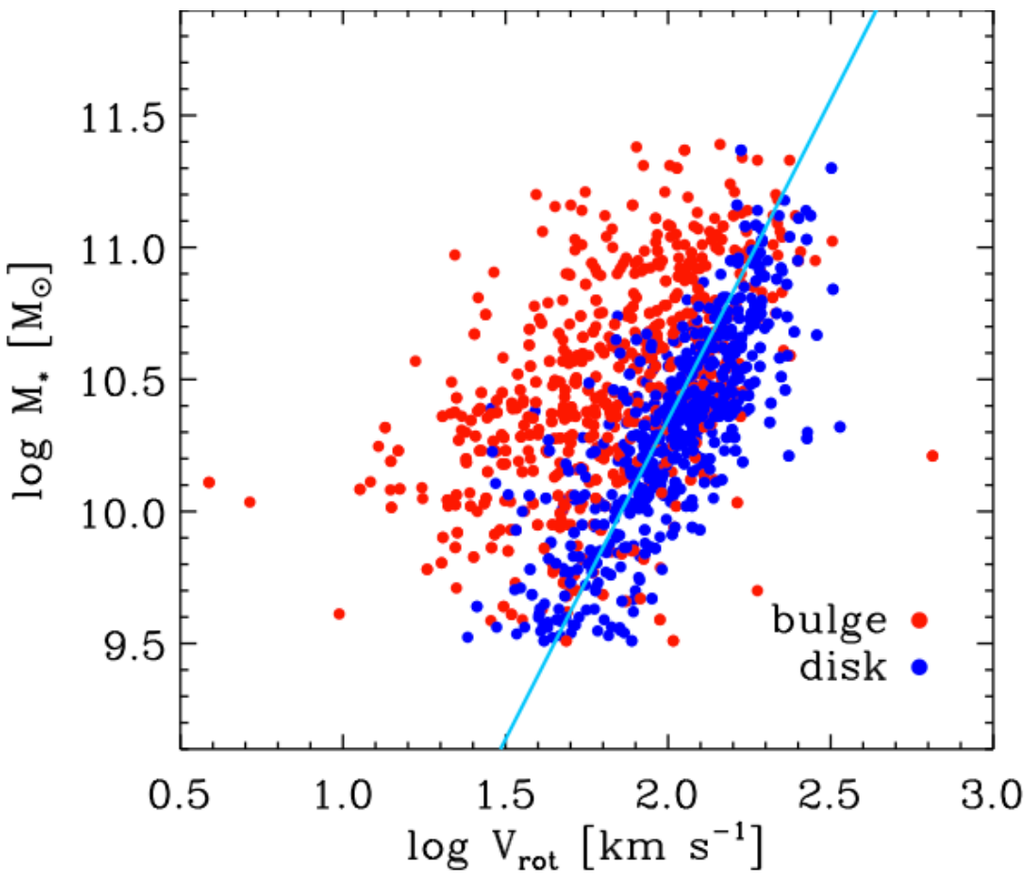
Oh et al. 2020 MNRAS 495 4638

$M_* - V_{rot}$ (Tully-Fisher) Relation

Galaxy



Bulge and Disk

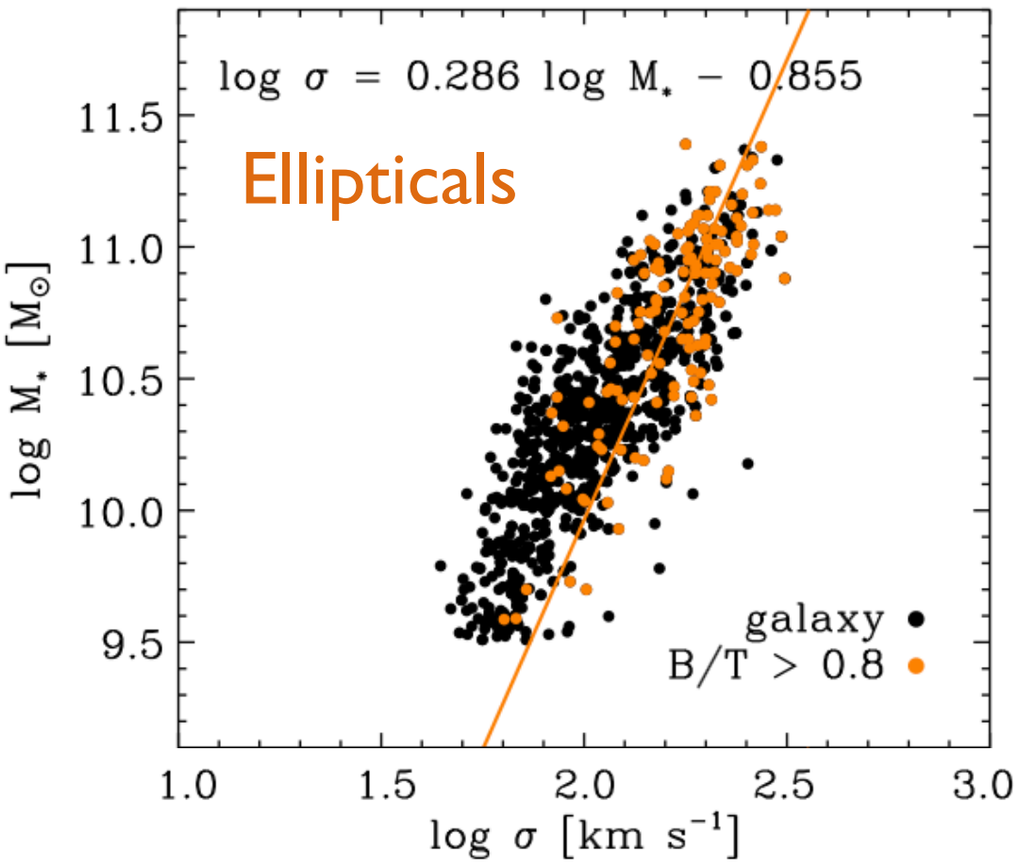


Tully-Fisher relation is not an exclusive relation for late-type galaxies but general mass scaling for rotating components (i.e. disks) of all galaxy types

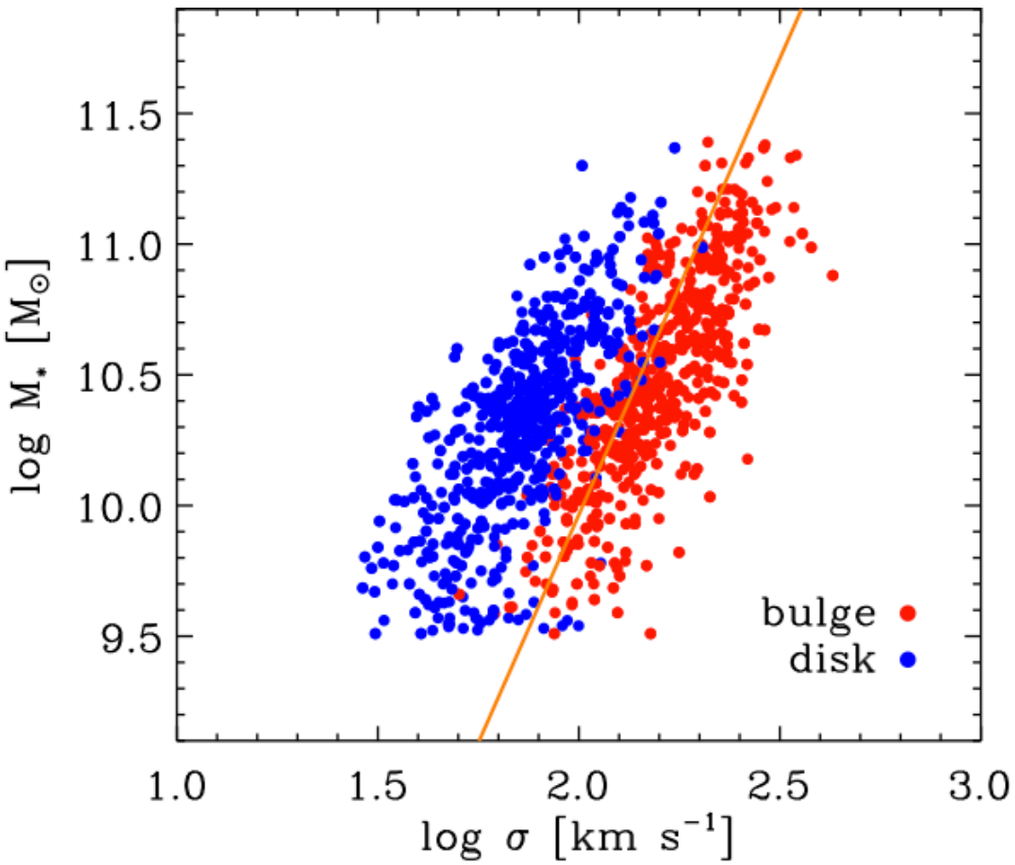
Oh et al. 2020 MNRAS 495 4638

$M_* - \sigma$ (Faber-Jackson) relation

Galaxy



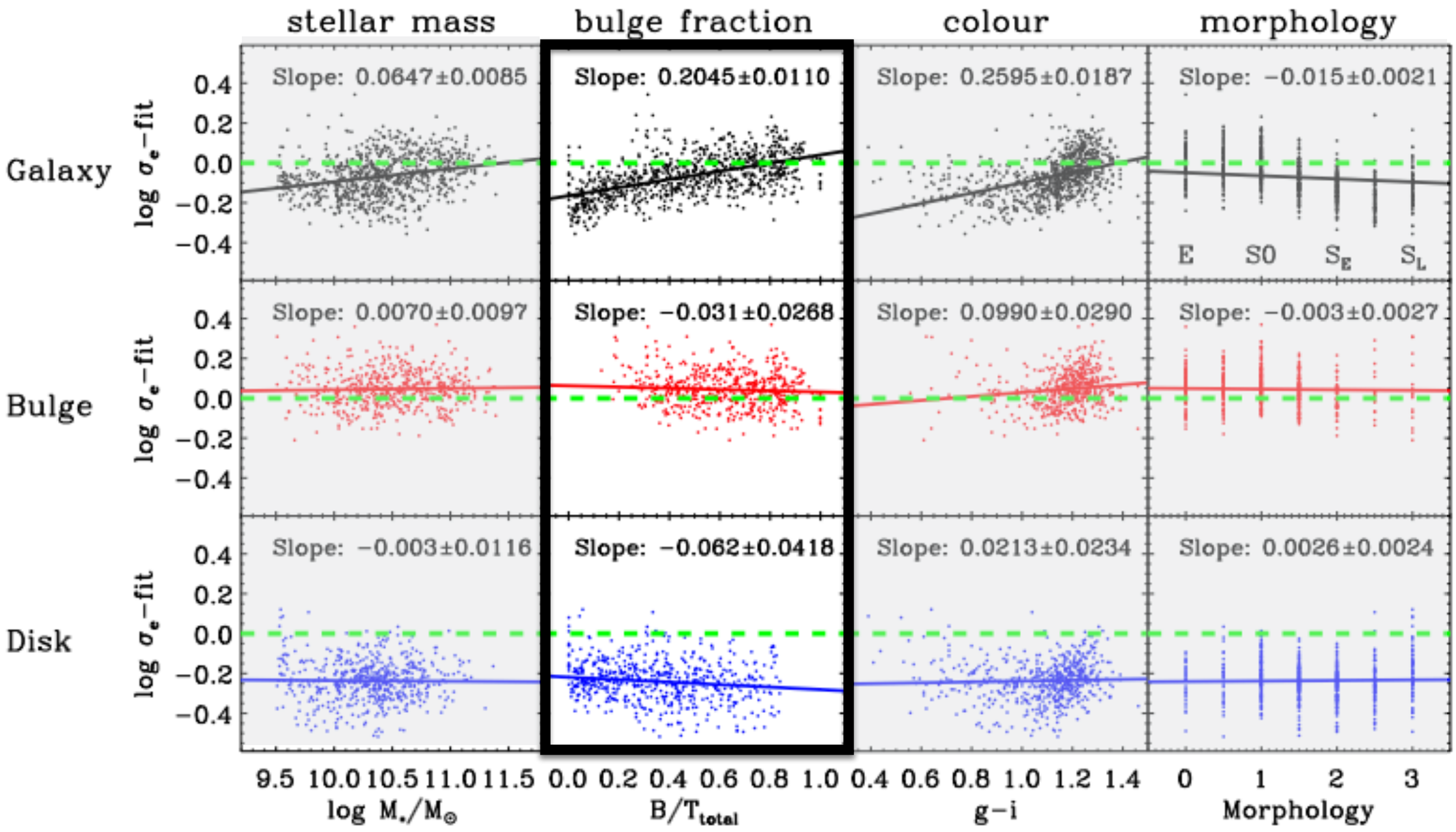
Disk and Bulge



Faber-Jackson relation applies to both bulge and disk component dispersions, with the same slope but with different zeropoints

Oh et al. 2020 MNRAS 495 4638

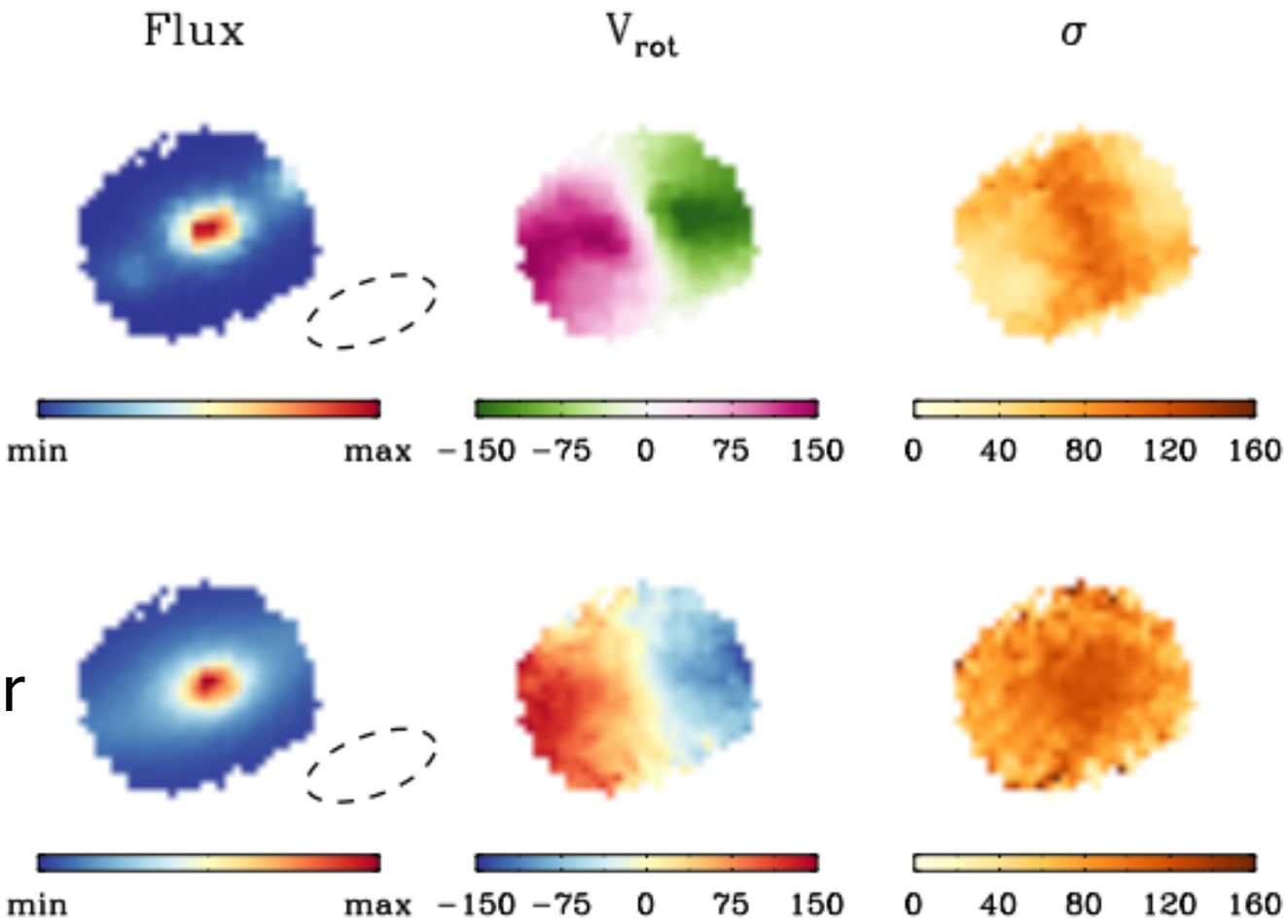
Residual trends in Faber-Jackson relation



- Bulge and disk components are kinematically distinct
- Bulge and disk kinematics do not vary with galaxy type
- The combination of two components creates the kinematic trends with galaxy types

Oh et al. 2020 MNRAS 495 4638

Ionised gas and stellar velocity dispersions



$$\sigma^2_{\rm gas} \equiv \frac{\sum_i^N \sigma^2_{gas,i}}{N}$$

$$\sigma^2_{*} \equiv \frac{\sum_i^N \sigma^2_{*,i}}{N}$$

$$\Delta\sigma \equiv \log\sigma_{\rm gas} - \log\sigma_{*}$$

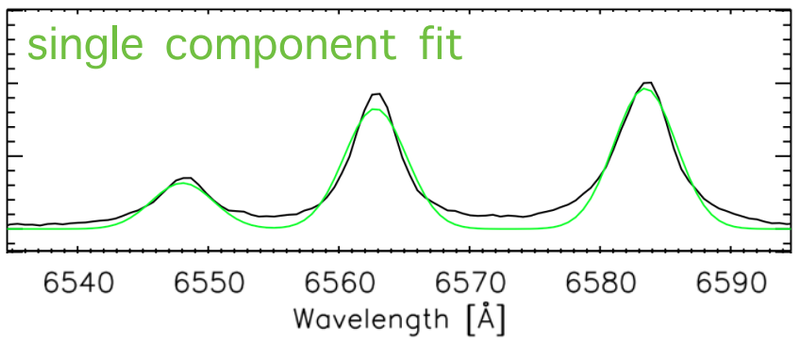
- Ionised gas and stars have different responses to non-gravitational feedback processes
- Stellar kinematics is less sensitive to non-gravitational processes and therefore served as a reference point

One-slide summary of Oh et al. 2022MNRAS.512.1765

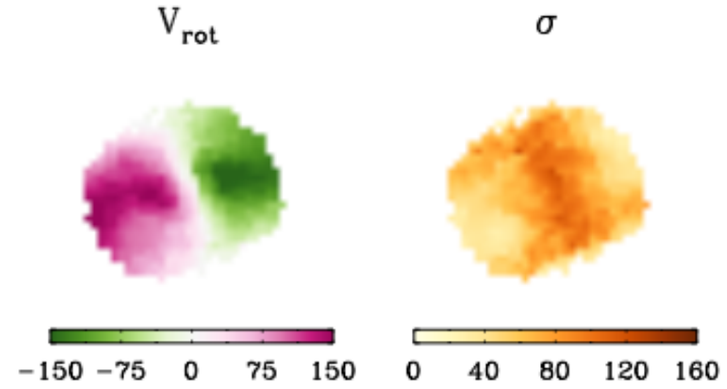
The difference between ionised gas and stellar velocity dispersions

SAMI data



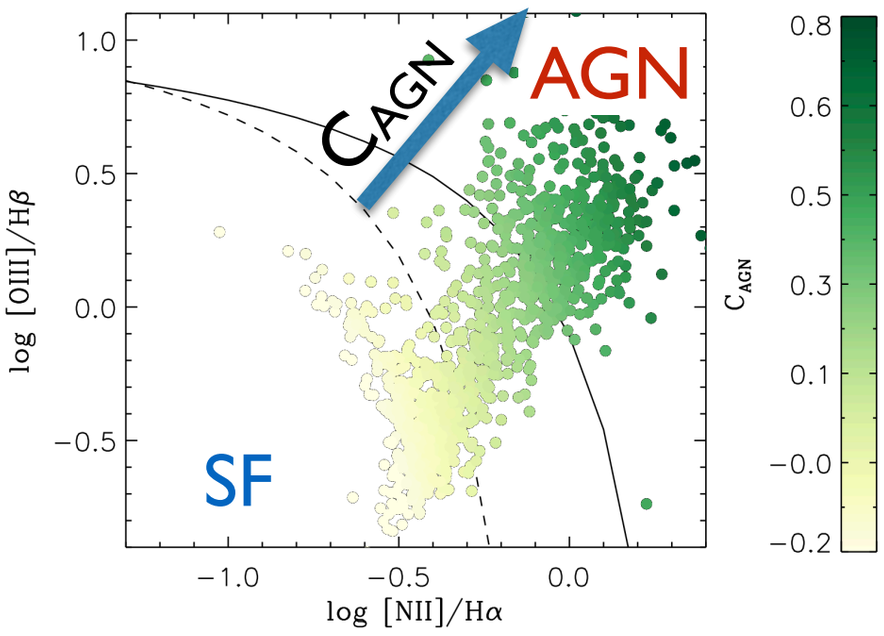


ionised gas kinematics

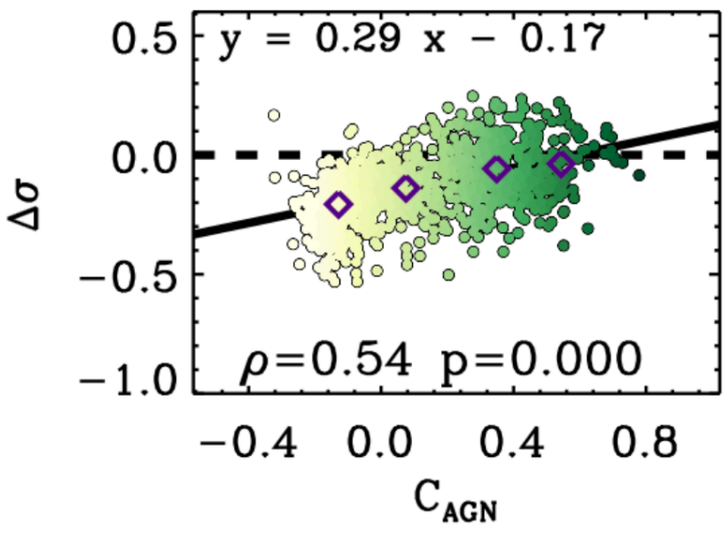


$$\Delta\sigma \equiv \log \sigma_{\rm gas} - \log \sigma_{*}$$

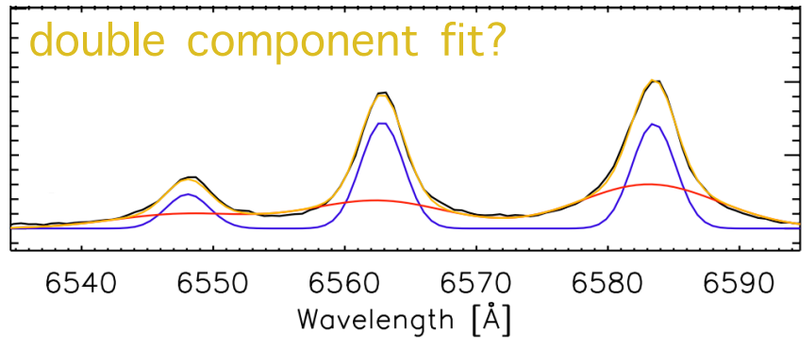
BPT emission line diagnostics



AGN feedback?



Oh et al. 2024MNRAS.531.4017



Oh et al. 2024MNRAS.531.4017

- Galactic outflows are powerful gas streams expelled by the momentum produced in various feedback processes, including starbursts and AGN

- We aim to investigate the influence of star formation and AGN driven outflows on the ionized gas kinematics in various types of galaxies

- Broad emission line components frequently serve as indicators of galactic outflows, providing evidence of feedback processes

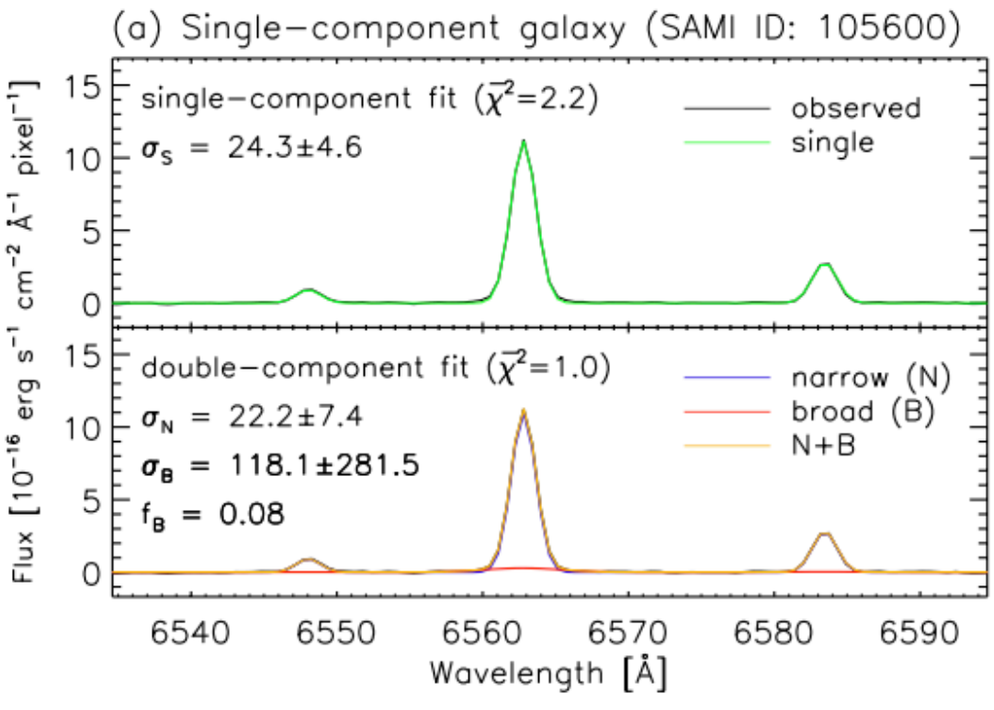
- We investigate the following aspects:
  - What types of galaxies exhibit broad emission line components
  - The kinematics of narrow and broad emission line components
  - Differences in the impact of star formation and AGN-driven outflows

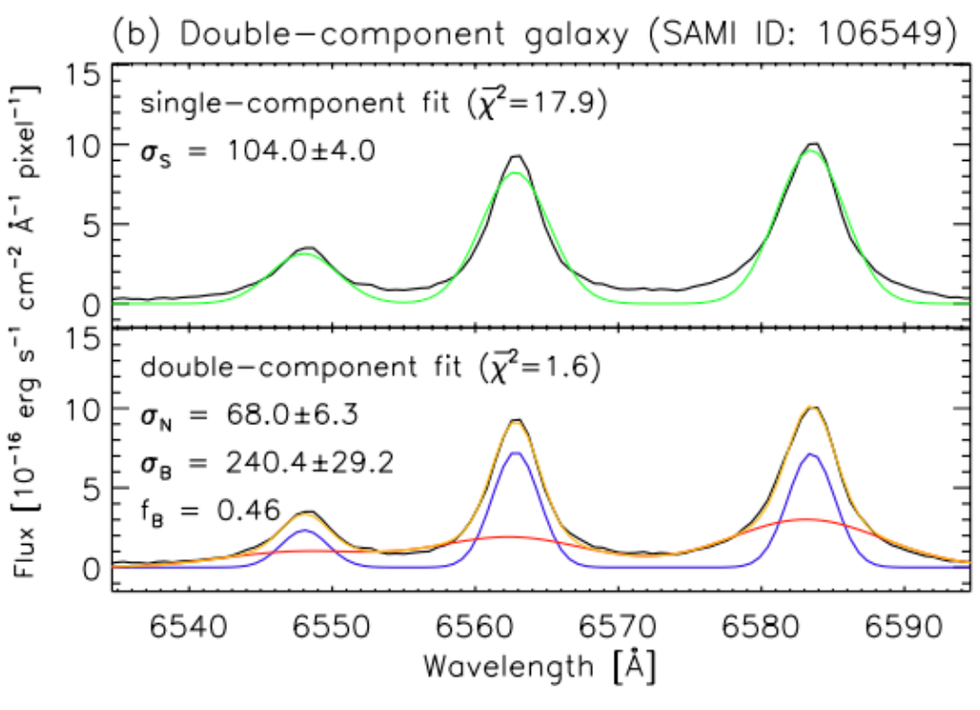
Identifying double-component galaxies

Emission-line galaxy from SAMI: 1258

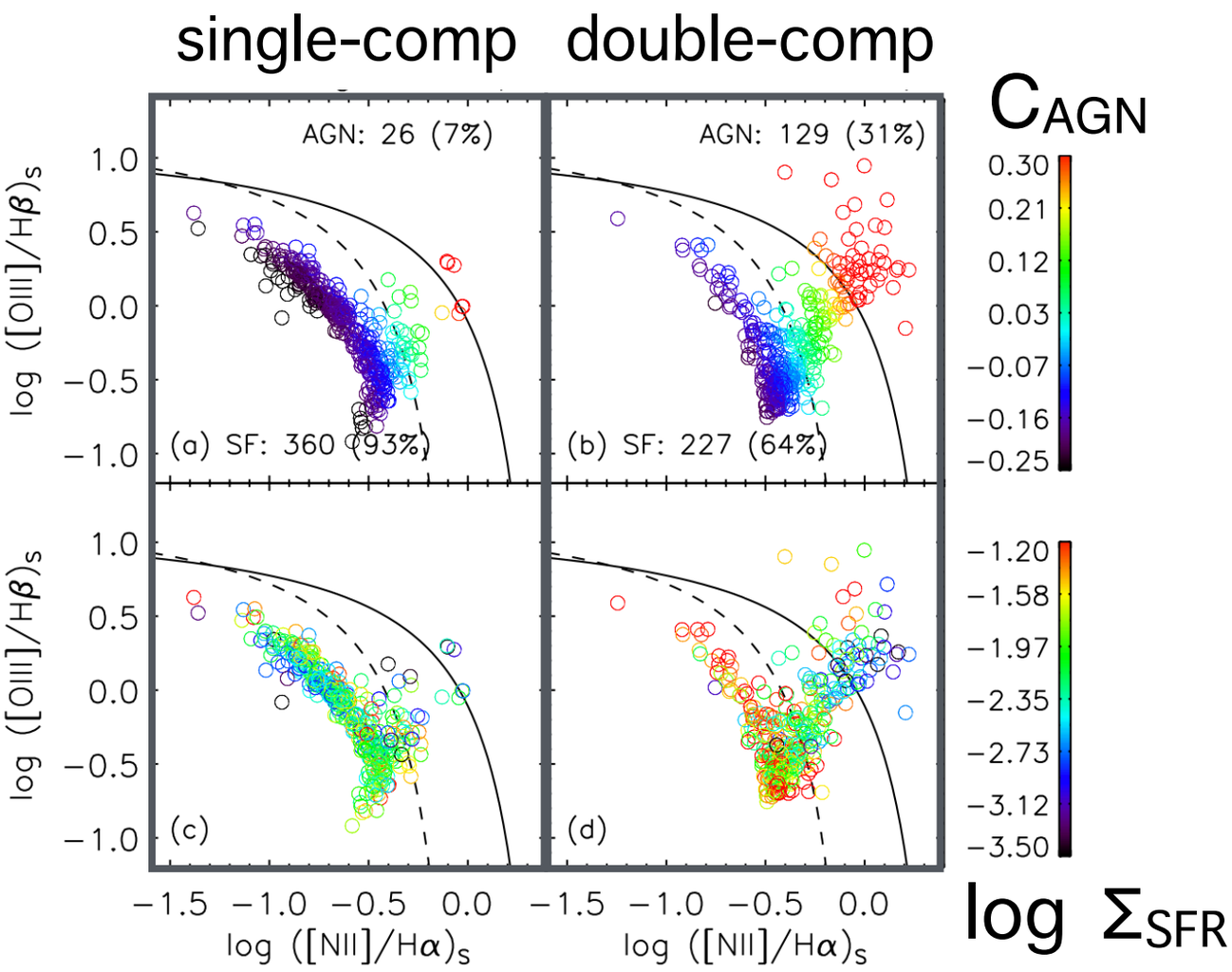
$A/N_{H\alpha,\ H\beta,\ [OIII],\ [NII]} > 5$ and $\log (M_*/M_\odot) > 9$

Single (narrow) component galaxies: 386	Double (narrow+broad) component galaxies: 356
$\chi_{single}^2 < \chi_{double}^2$ Broad component fraction < 0.1	$\chi_{single}^2 > \chi_{double}^2$ Broad component fraction > 0.1 $A/N_{H\alpha,\ H\beta,\ [OIII],\ [NII]} > 3$ for both components $\sigma_{broad} - \sigma_{broad,error} > \sigma_{narrow}$





Emission line (BPT) diagnostics



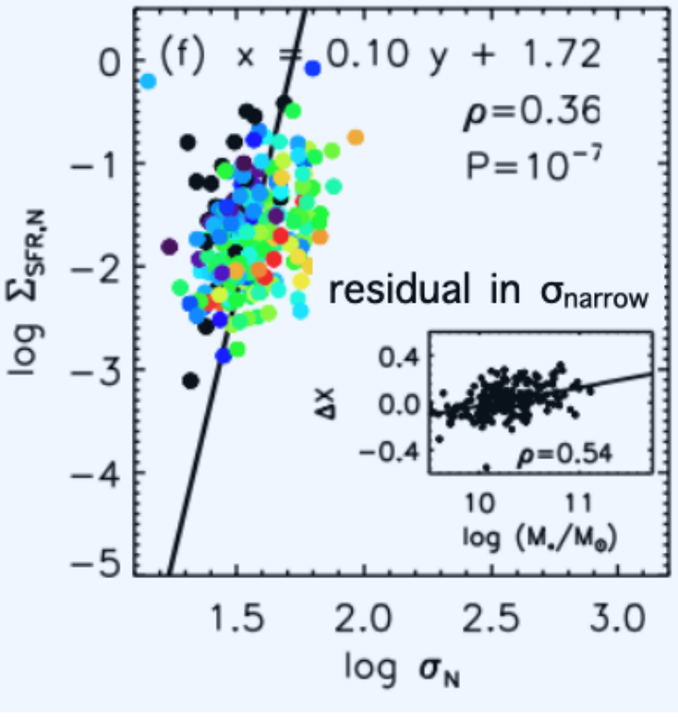
- The vast majority (93%) of single-component galaxies are found among star-forming galaxies (C_{AGN}<0; below the dashed line)

- Double-component galaxies that have an additional broad emission line component are typically either AGN (C_{AGN}>0) or star-forming galaxies with a high Σ_{SFR}

- Both active star formation and AGN presence contribute to the development of broad emission line components

Narrow component kinematics

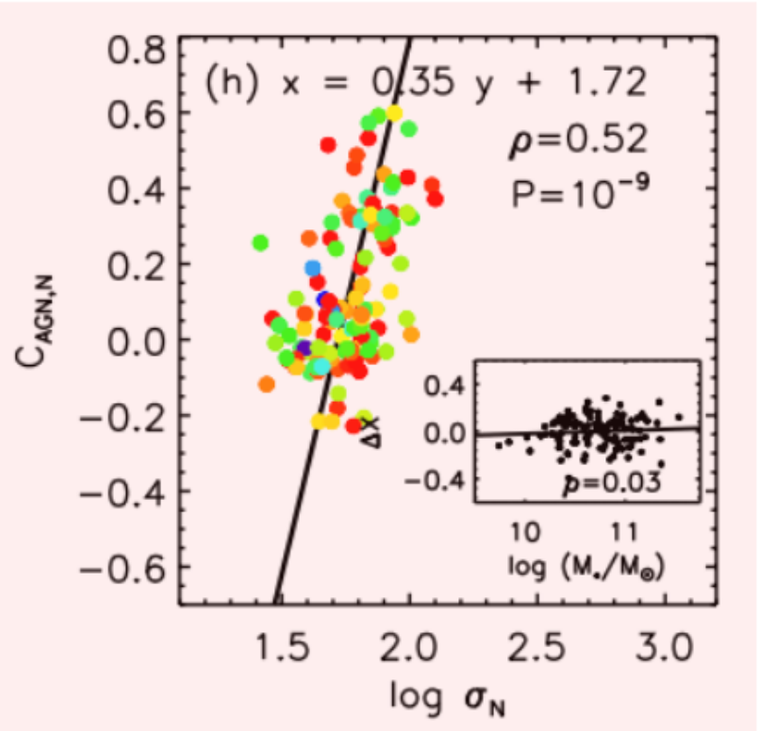
star-forming



- Both stellar mass and Σ_{SFR} independently contribute to the narrow-component kinematics of star-forming galaxies

gravitational potential + SF feedback

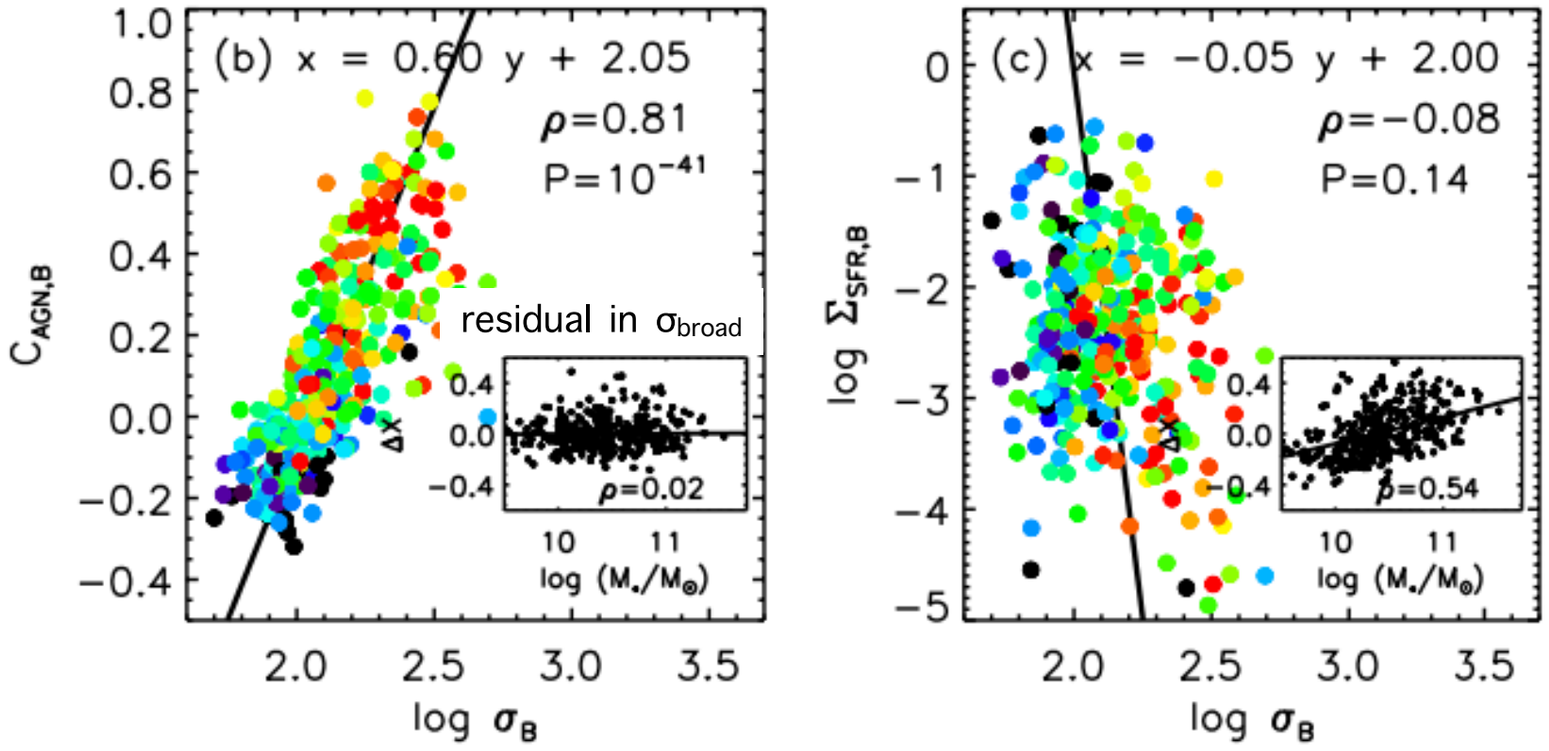
AGN



- AGN exhibit a strong correlation between C_{AGN} and σ_{Narrow}, but do not show any dependency of σ_{Narrow} on Σ_{SFR} or stellar mass

AGN feedback

Broad component kinematics



- σ_{Broad} is primarily determined by C_{AGN} and shows no residual correlations with Σ_{SFR} or stellar mass

- AGN feedback efficiently inflates gas velocity dispersions, whereas the influence of star-forming activities is considerably less effective

Conclusion

- The broad emission-line component inflates gas σ beyond what can be predicted by stellar mass alone
- Both strong star-forming and AGN activities drive galaxy outflows, as evidenced by these broad emission line components
- Star formation feedback increases σ_{Narrow} and contributes to the formation of broad components
- AGN feedback also contributes to the formation of broad components and amplifies both σ_{Narrow} and σ_{Broad}
- The influence of AGN on the kinematics of ionized gas is considerably more pronounced than that of star-forming activity