Understanding circumnuclear environments in closest galaxies with spatially resolved observations

-- Ionization mechanism in M31 and M81

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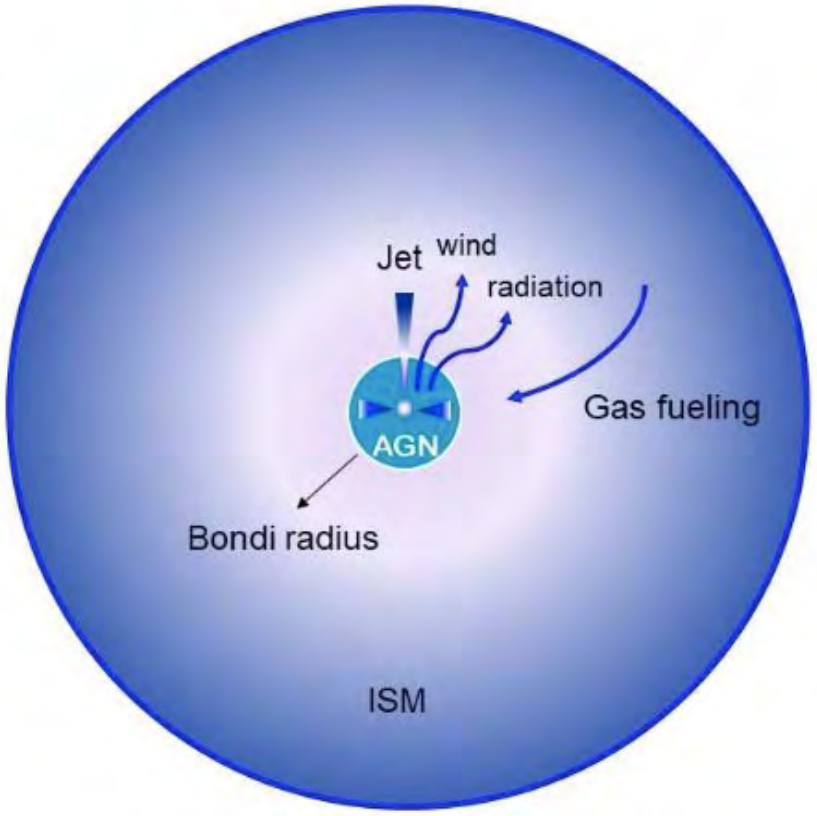
Galactic circumnuclear regions

- Circumnuclear region: central several hundred pc.
- Ingredients: SMBH, interstellar medium (ISM), stellar population, etc.

- Evidence of AGN feeding and feedback:

  Physical properties of Multi-phase ISM: radiation, inflow/outflow, etc. is key.

➢ Nearest galaxies have the most detailed view!



Yuan et al. 2018

Unique laboratories

❑ Sgr A*: heavily obscured ✗



❑ **M31*: Closest transparent nucleus** ✓

A quiescent nucleus

(dominant phase due to short AGN duty cycle)

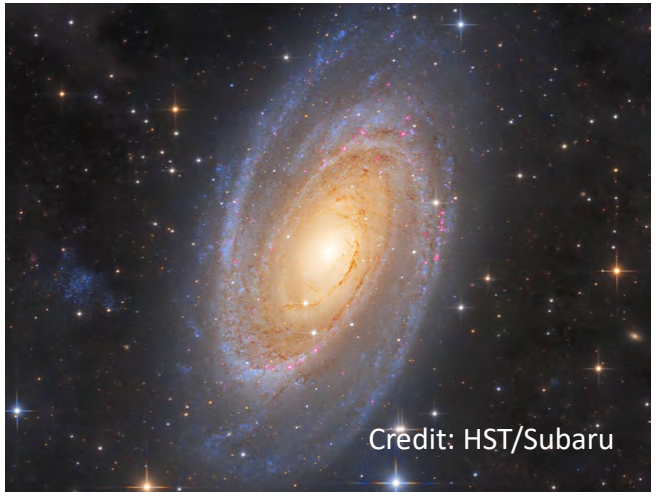
- A benchmark to the MW and normal quiescent galaxies.



❑ **M81*: Closest low luminosity AGN** ✓

A prototypical AGN

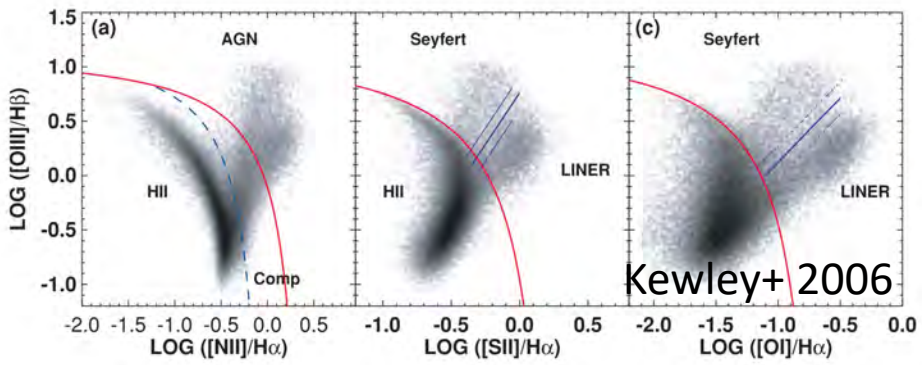
- Signatures of nuclear inflow/outflow
- The second closest massive spiral, good comparison to M31 and MW.



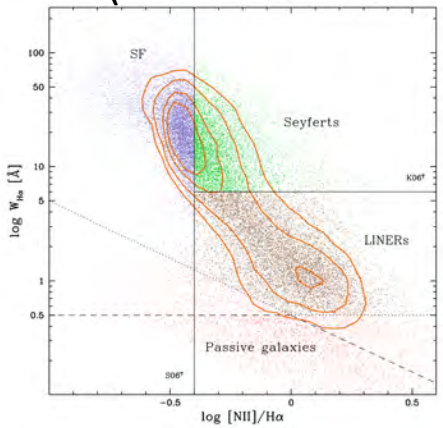
Ubiquitous and mysterious LINERs

❖ Low-ionization nuclear emission-line regions (LINERs; Heckman 1980): Strong low ionization N, O, S emission lines in central kpc. **Both M31 and M81 are LINERs.**

- Diagnostic diagram: BPT (Baldwin+ 1981)



WHAN (Cid Fernandes+ 2011)



❖ Possible ionization mechanisms:

- AGN: low luminosity AGN (LLAGN), past AGN activities. **Low-end of AGN?**
- Non-AGN: shocks, Wolf-Rayet stars, hot low mass evolved star (HOLMES), X-ray binaries, cosmic ray, etc.

Spatially-resolved observation
+ model is key!

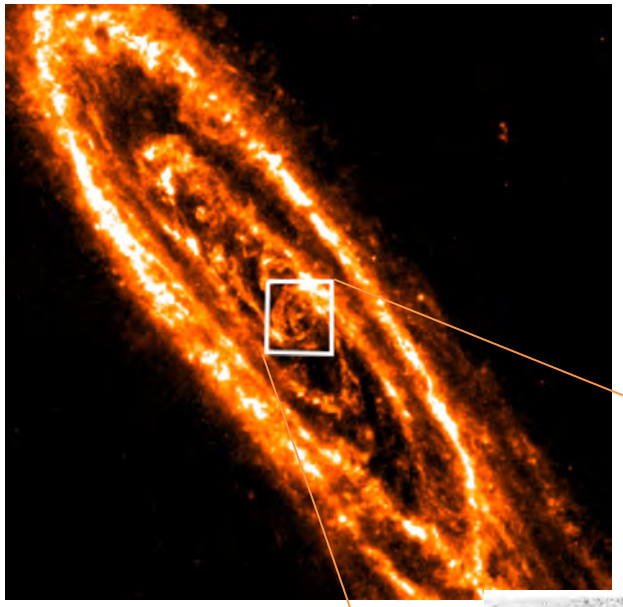
Circumnuclear environment in M31

- M31: D ~ 780 kpc, 1” ~ 4 pc, i=77°, $A_V \lesssim 1$ (Dong+ 2016).
- -> highest resolution

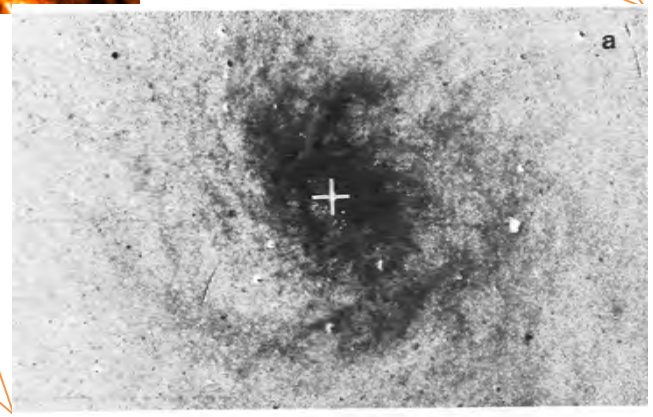
- SMBH mass: ~ 10^8 $M_\odot$; luminosity: 10^{37} erg/s, ~10^{-9} $L_{\rm Edd}$: little AGN activity

- Lack of recent SF and massive stars (Li+ 2009, Dong+ 2015), Well-constrained old stellar population (SP) properties.

- Closest LINER



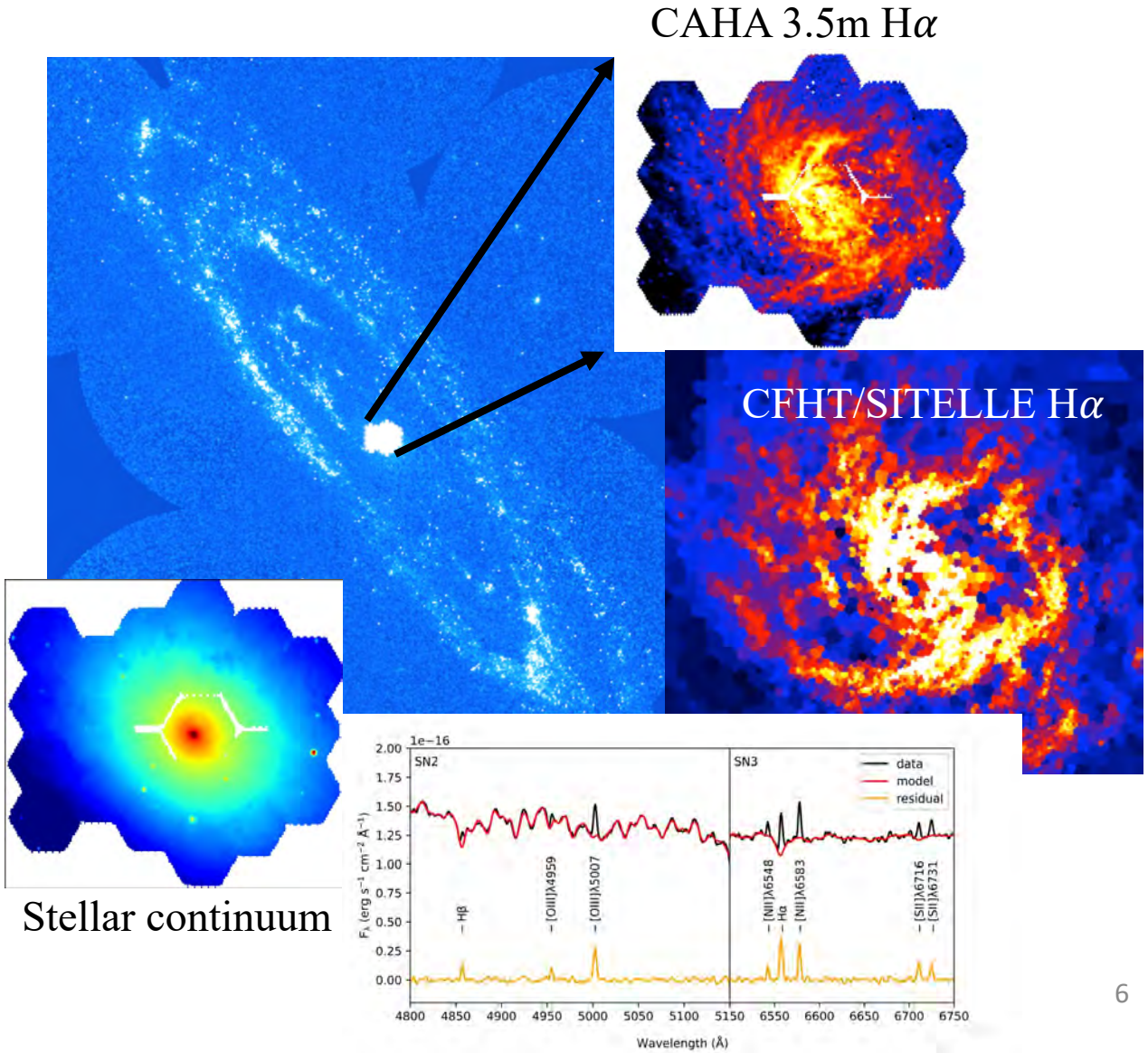
Hα nuclear spiral, LINER emission (Jacoby 1985, Ciardullo et al. 1988)



Ionized gas in the central 1 kpc

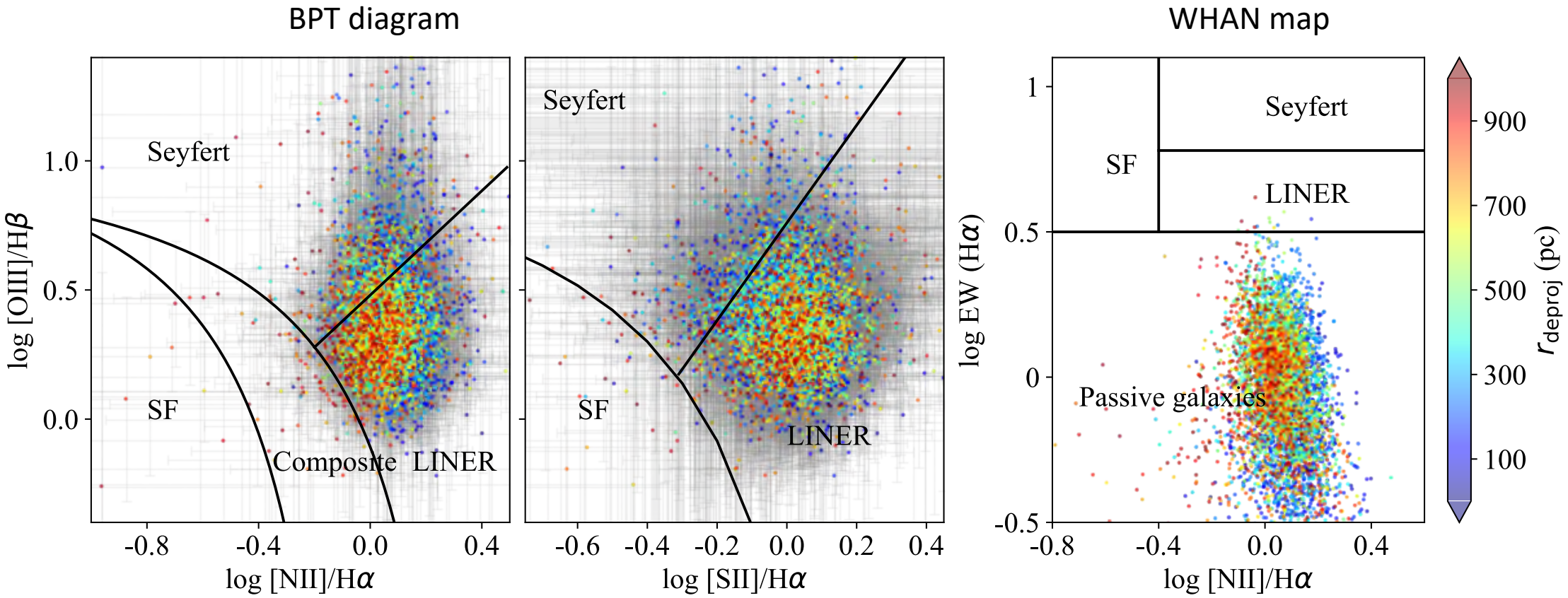
- Calar Alto Observatory (CAHA) 3.5 m IFU observations of 23 fields covering the central 1 kpc of M31.
- CFHT/SITELLE IFU of slightly larger FoV (Martin et al. 2018).
- Ionized gas emission + stellar population (SP, age, mass, metallicity)
- Ionized gas + SP + multiwavelength data + model: best constraints on ionization mechanisms

(Li et al. in prep)



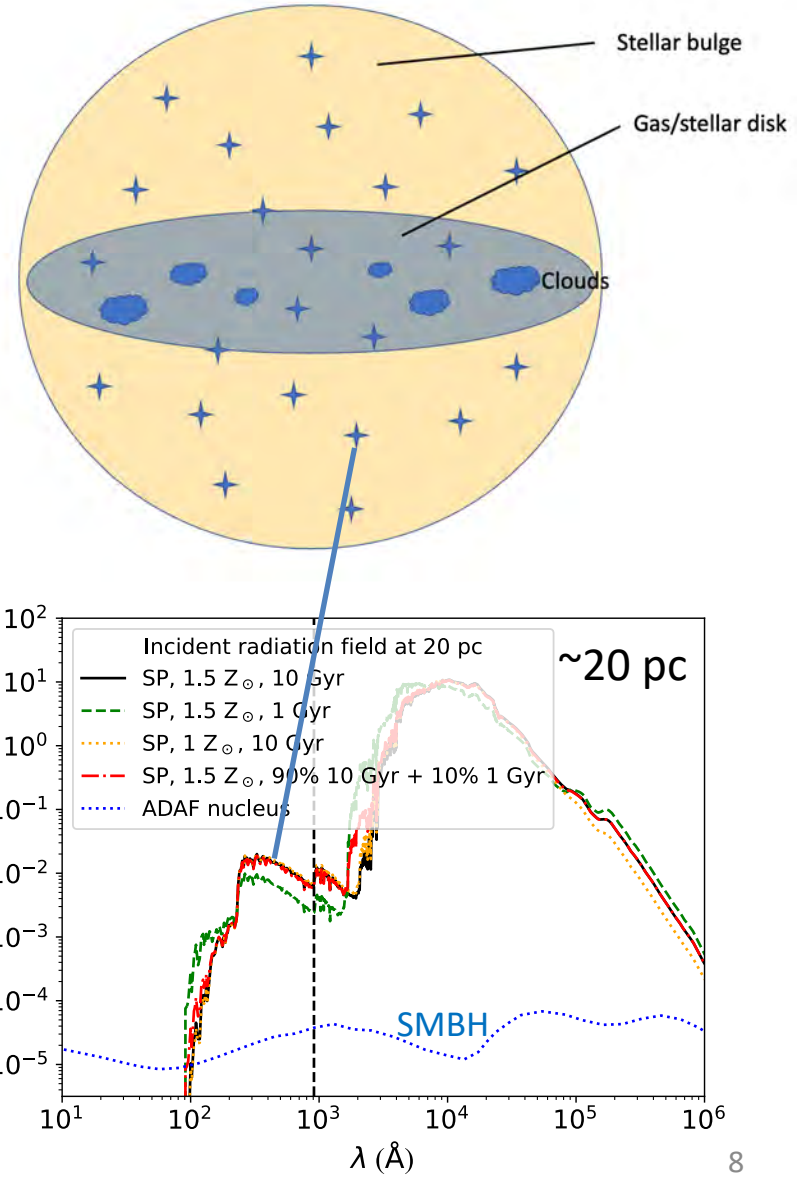
Line diagnostics

- BPT diagram: LINER + Seyfert, WAHN: LINER + passive
  -> HOLMES can explain the emission?

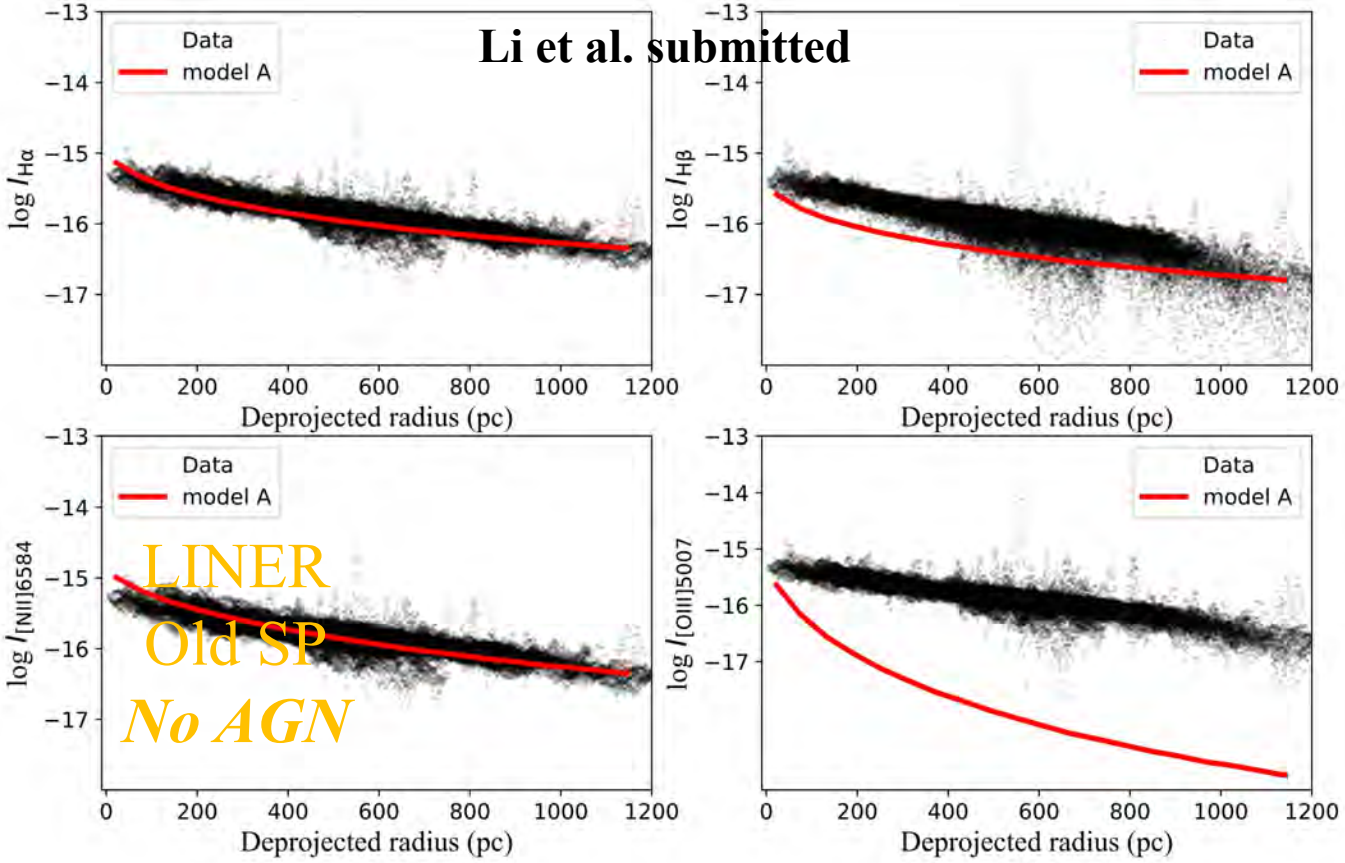


Photoionization model

- CLOUDY (Ferland 2017): 1-D radiative transfer code.
- A series of equally-spaced clouds in the disk with plane-parallel geometry.
- Well-constrained radiation field:
  - SP: bulge + disk star: deprojected 3D distribution.
    - SED: FSPS SSP model of metal-rich ($> Z_{\odot}$) and old (10 Gyr) stellar population (e.g. Saglia et al. 2010, this work).
  - No current AGN activity (Li et al. 2009).
- Electron density: [SII] doublet: ~ 100 cm^{-2}.



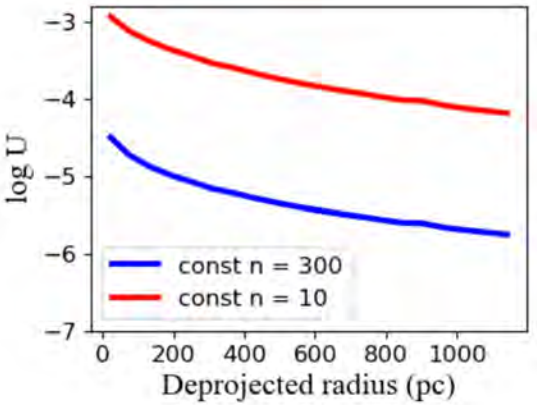
Model vs. observation

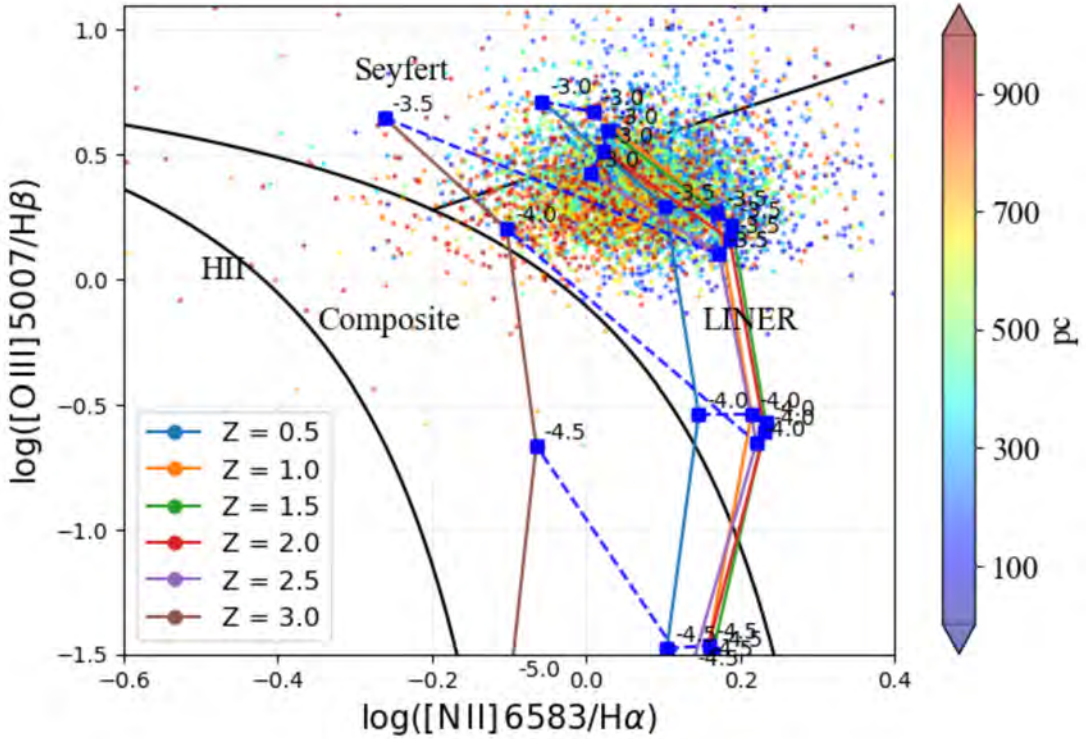


Models fall short of [OIII] by two orders of magnitude

Low ionization parameter!

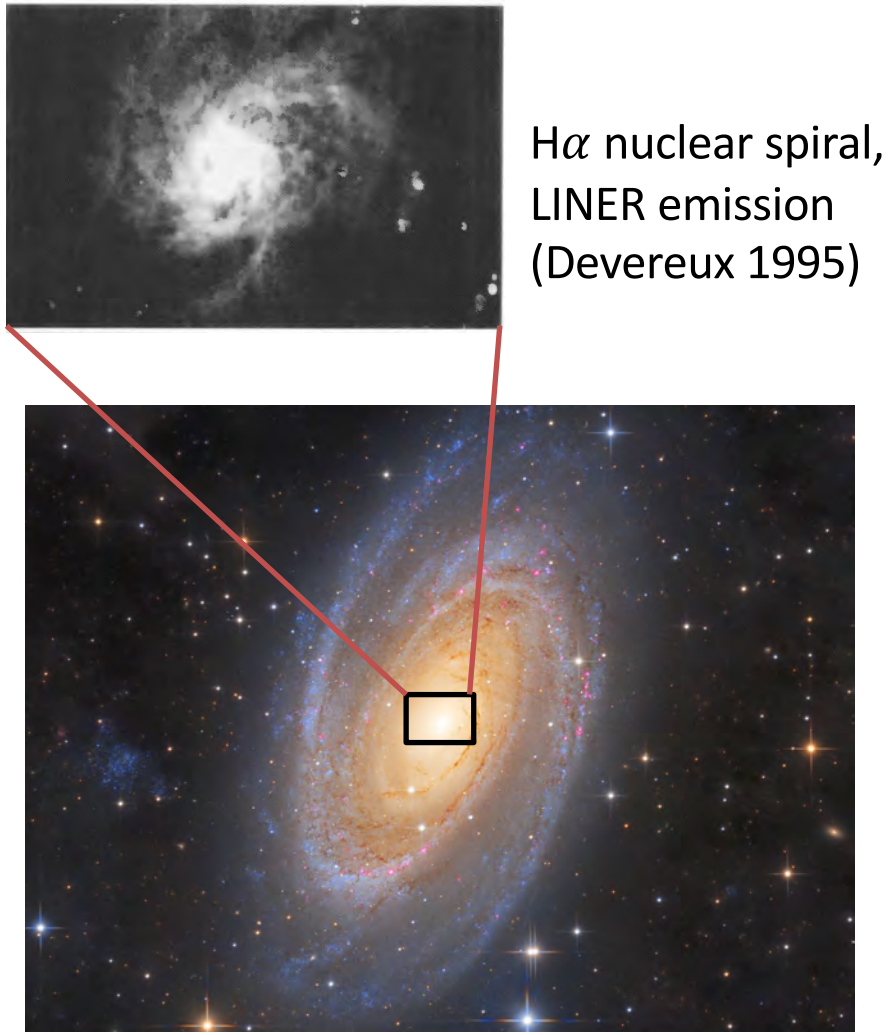
$$U = \frac{\Phi(\mathrm{H})}{n(\mathrm{H})c}$$





Circumnuclear environment in M81

- M81: D ~ 3.6 Mpc, 1” = 17.8 pc. Early-type spiral.
- The closest LLAGN: identified as both a Seyfert 1 and a LINER (Ho et al. 1996). SMBH mass: ~ 10^8 $M_\odot$; luminosity: 2 x10^{41} erg/s, ~10^{-5} $L_{\rm Edd}$
- Well-constrained LLAGN and stellar population (SP) properties.
- One of the best laboratories to test photoionization models in a spatially resolved way.

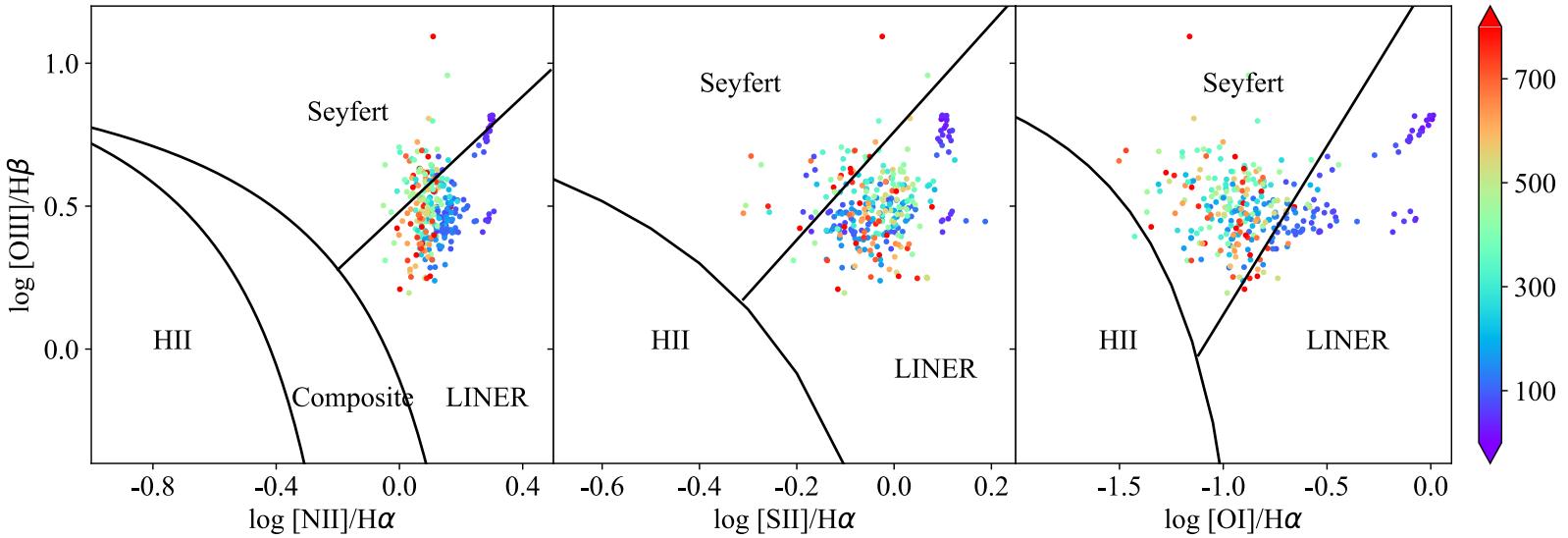


Hα nuclear spiral, LINER emission (Devereux 1995)

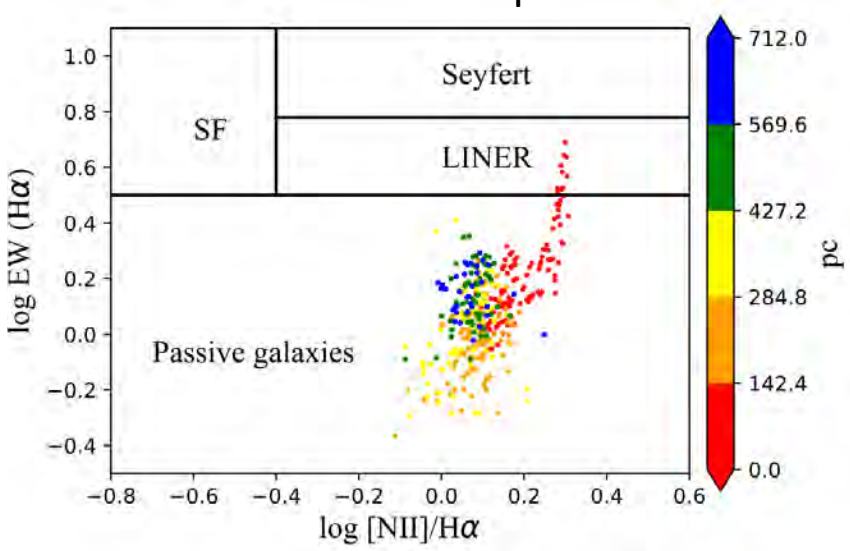
Line diagnostic diagrams

- CAHA IFU covering central kpc: ionized gas +SP properties
- BPT diagram: LINER + Seyfert
- WAHN: LINER + passive (> 100 pc)
- LLAGN+HOLMES may successfully explain the emission of M81 bulge?

BPT diagram

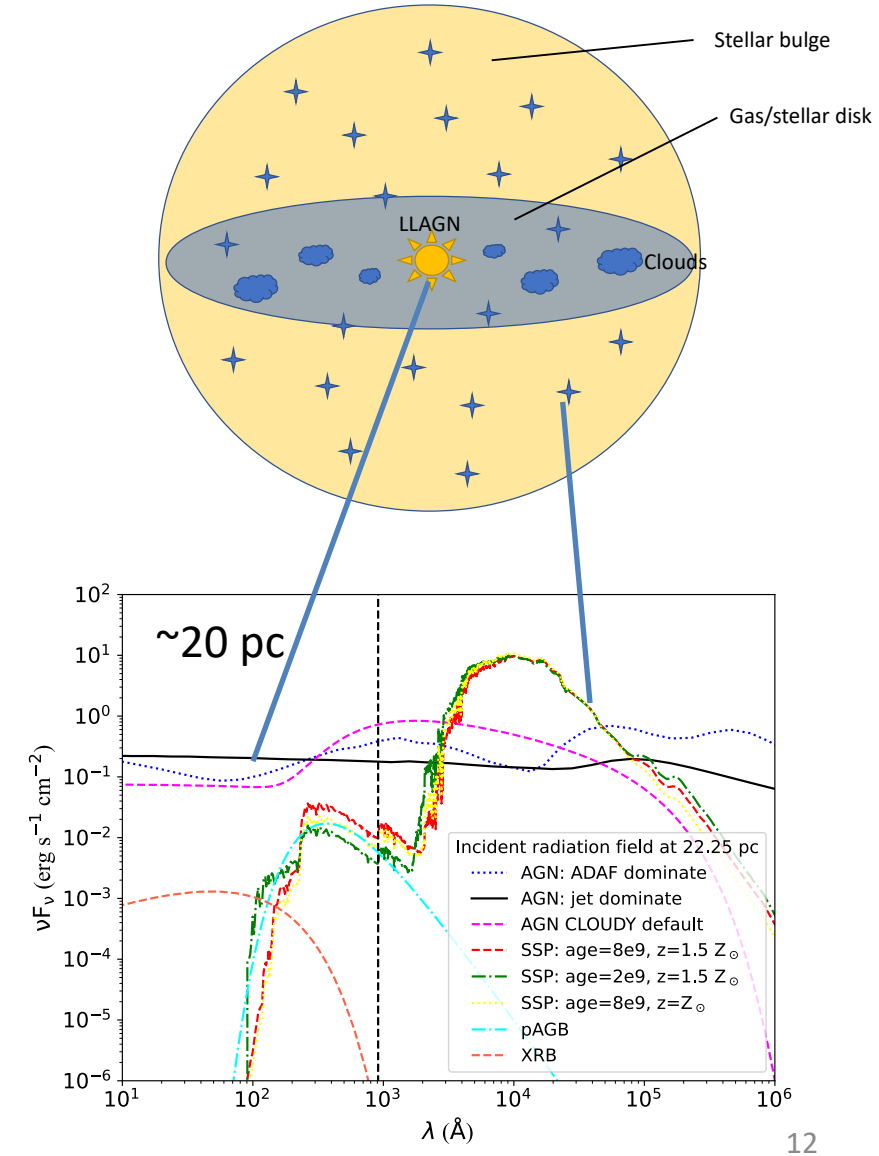


WHAN map



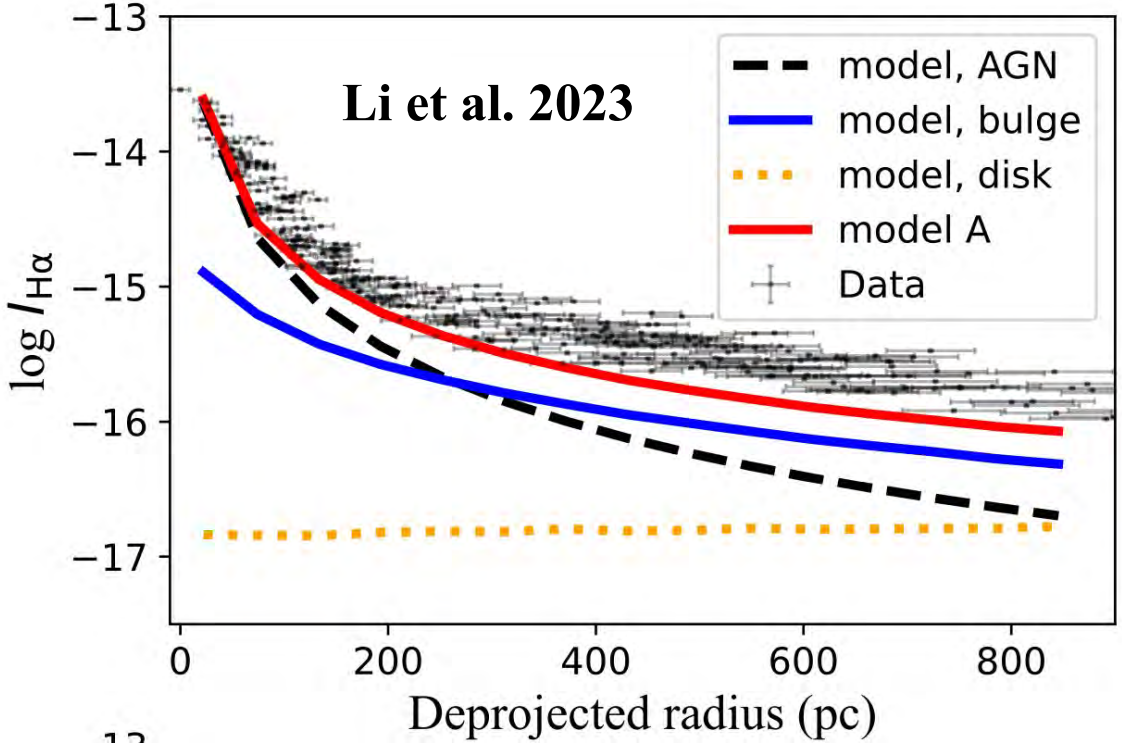
Photoionization model

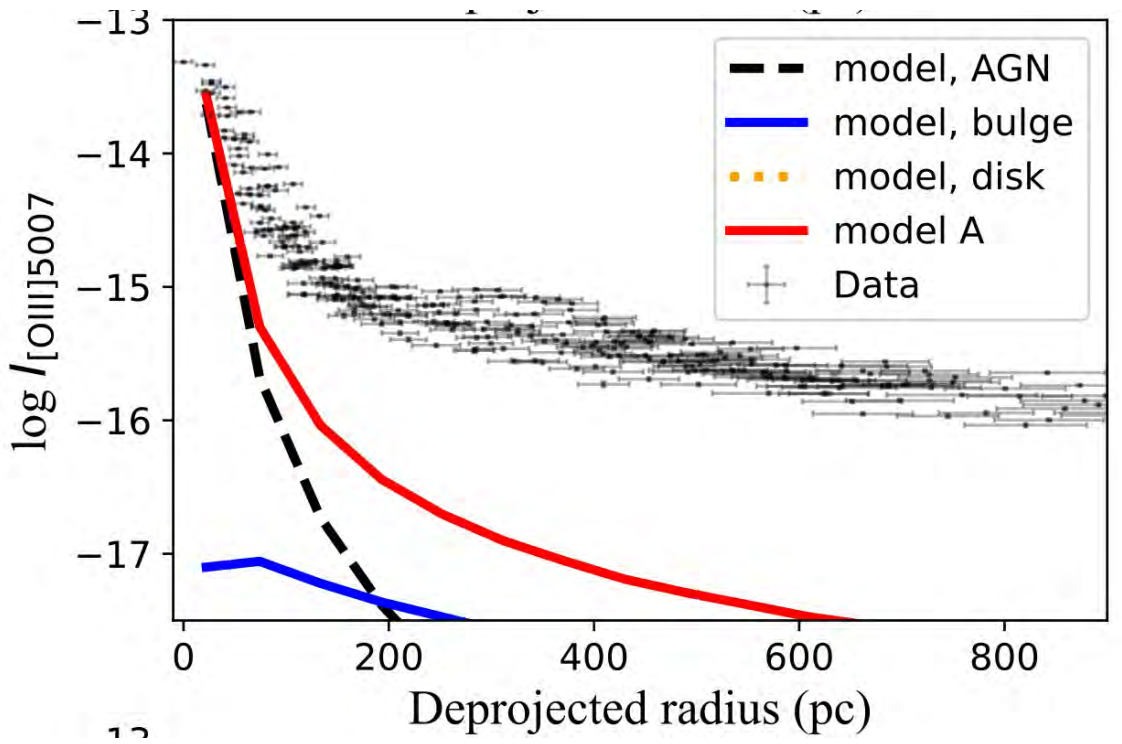
- CLOUDY (Ferland 2017): 1-D radiative transfer code.
- A series of equally-spaced clouds in the disk with plane-parallel geometry.
- Well-constrained radiation field:
  - LLAGN:
    - ADAF + jet + truncated disk model that best-fit the observed multiwavelength data (Nemmen et al. 2014)
  - SP: bulge + disk star: deprojected 3D distribution.
    - SED: FSPS SSP model of metal-rich and old stellar population (Kong 2000, Li et al. 2022).



Model results: line intensities

- All line intensity radial profile declines as $\sim r^{-1.5}$
- AGN **dominates in central 100 pc** and can explain the emission.
- LLAGN+SP can reproduce Ha, but not [OIII]. Two orders of magnitude lower at outer radius!

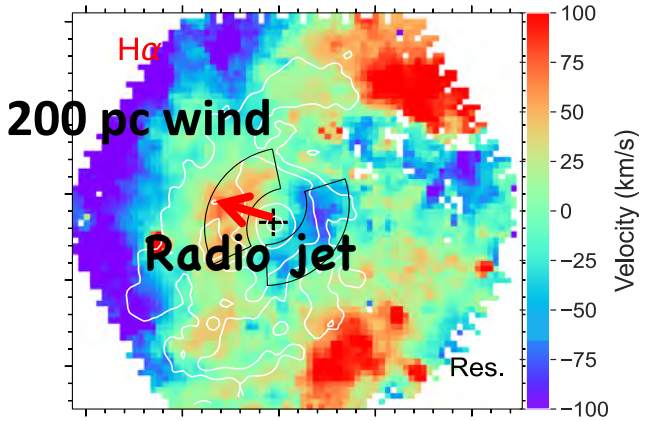


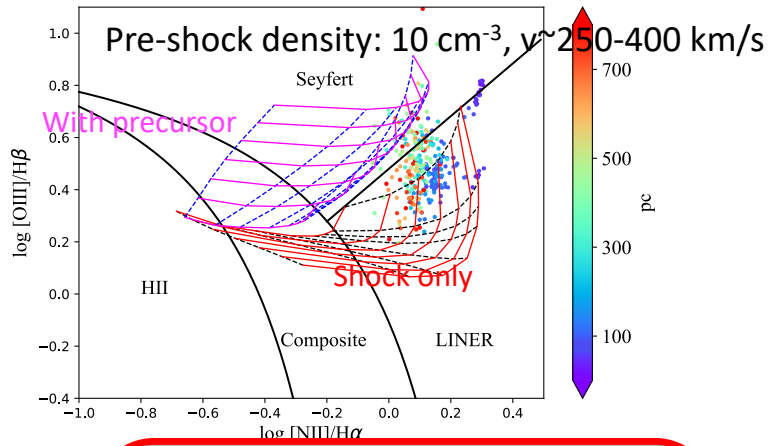


Possible solutions

$$U = \frac{\Phi(\mathrm{H})}{n(\mathrm{H})c}$$

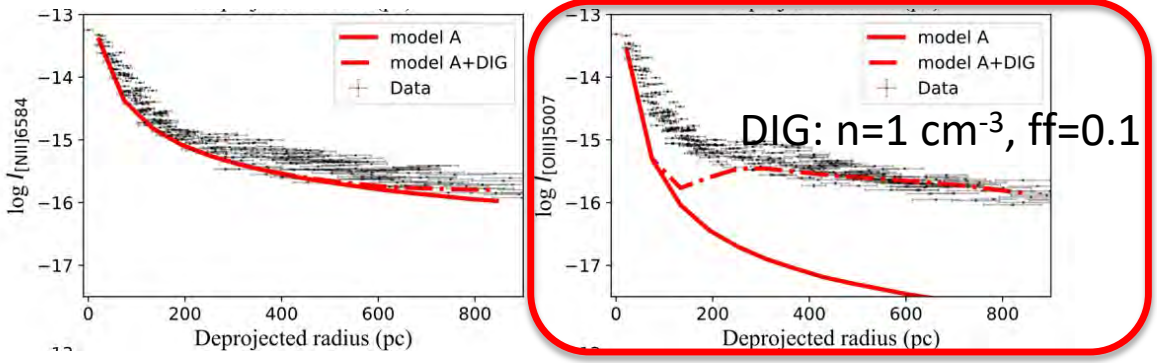
1. **Additional ionization source**
2. **Different density profile**





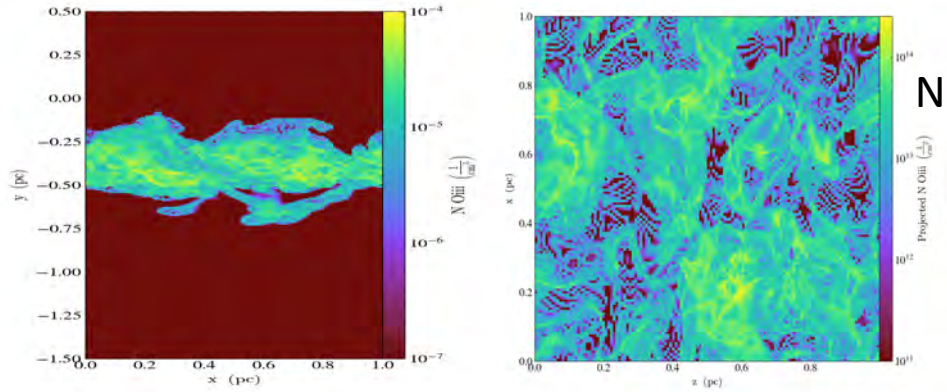
- Shocks?

- Additional diffuse component (DIG)?



❑ Other possibilities:

- Recurrent AGN flares/TDEs? ✗
- CR from type Ia supernovae? ✗
- Turbulent mixing layer (TML)?



$N_{[OIII]} \sim 10^{14\text{-}15}$ cm^{-2}

Summary

- The closest LINERs (M31 and M81) exhibits a **characteristic flat profile** in the main emission lines out to a deprojected radius of r ~ 1 kpc.

- LLAGN **dominates in central 100 pc** and can explain the emission.

- Pure photoionization models considering both AGN and old SP fail to explain [OIII] line profile: a **deficiency of high-energy ionizing photons**.

- Other mechanisms are required**: previous AGN activity (?), shocks, DIG (?), TML**, etc.

Thank you!