A Molecular Ring Hidden in the Sombrero

Sutter & Fadda, 2022b, arxiv: 2210.13527

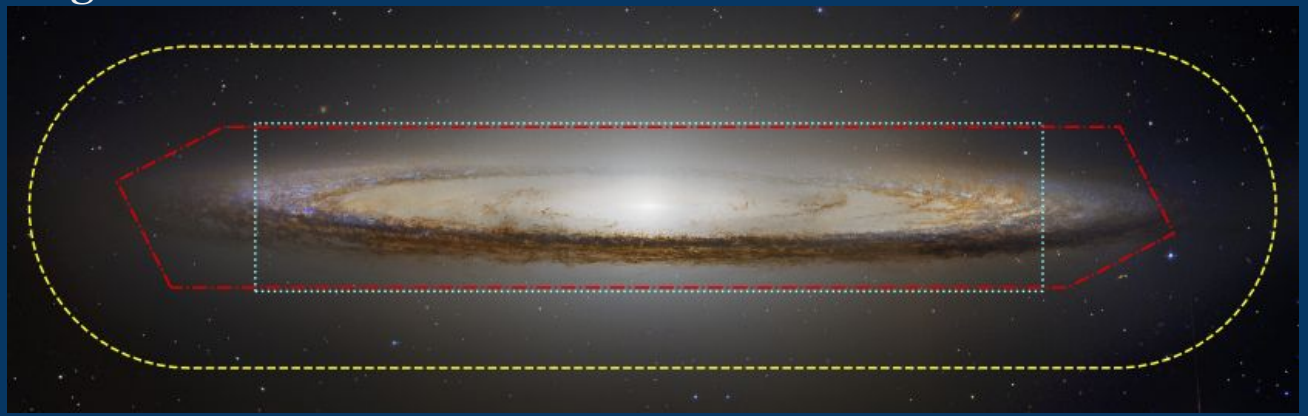
Outline

- Introduction
  - The interesting case of the Sombrero
- Datasets
  - PACS [CII]
  - MUSE Optical IFU
  - ALMA CO
- Analysis: a surprising lack of [CII]
- Conclusions

Image Credit: X-ray: NASA/UMass/Q.D.Wang et al.; Optical: NASA/STScI/AURA/Hubble Heritage; Infrared: NASA/JPL-Caltech/Univ. AZ/R.Kennicutt/SINGS Team

The Sombrero Galaxy (M104, NGC4594)

- Well-studied, Sa galaxy
- D = 9.2 Mpc, inclination = 84°
  - Close by, nearly edge on
- Hosts an AGN
- Dusty ring visible in the IR



Spiral or Elliptical?

- Some have questioned if the Sombrero is a spiral or elliptical galaxy
- Evidence for Elliptical:
  - Massive, low star formation rate
  - 1,900 globular clusters
- Evidence for spiral
  - Clear disk structure
- Maybe merger between the two?

Examining the Evidence: Archival data

- The Sombrero Galaxy has a wealth of available archival datasets
- Herschel PACS [CII]
  - Measure of the cooling in PDRs, often used as a star-formation rate indicator
- ALMA CO
  - Measure of the molecular gas
- MUSE IFU
  - Contains tracers of star-formation, information on source of ionizing radiation
- Multi-wavelength photometry
  - From FUV to FIR

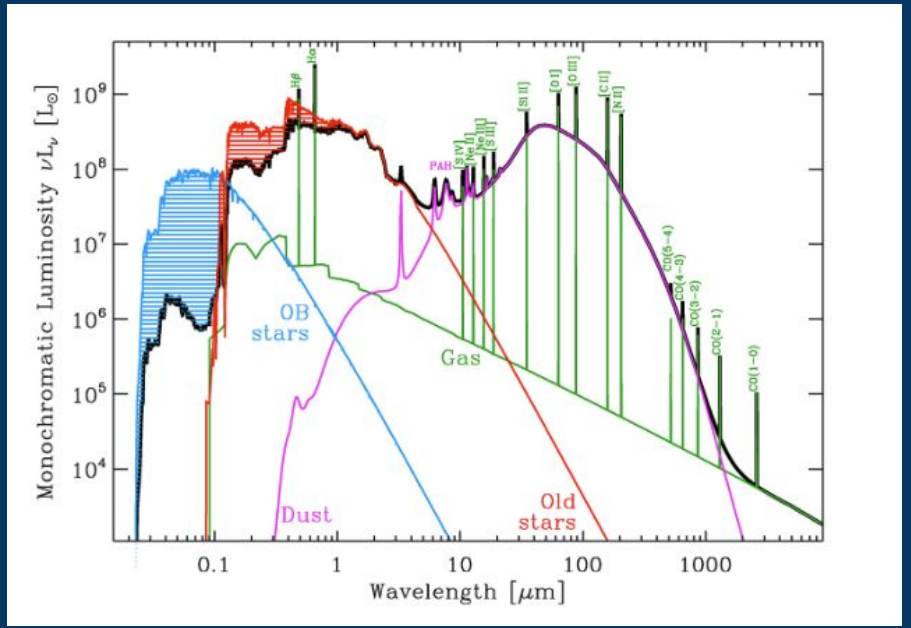
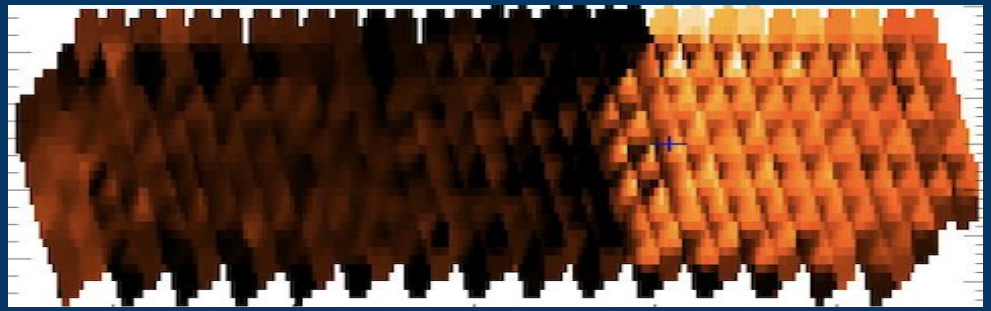


Image Credit: Galliano, 2017

PACS Reduction

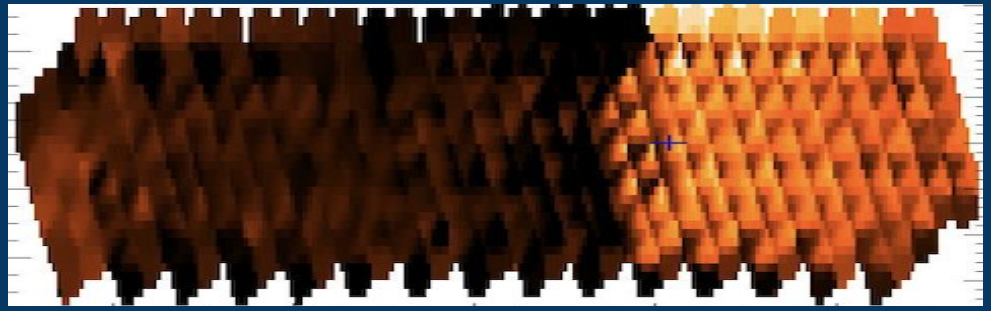
PACS data had not been published due to large transient effect in the PACS data



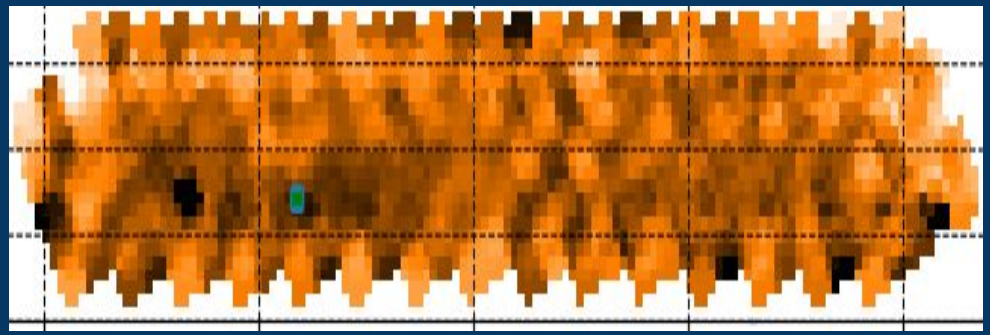
Before

PACS Reduction

PACS data had not been published due to large transient effect in the PACS data



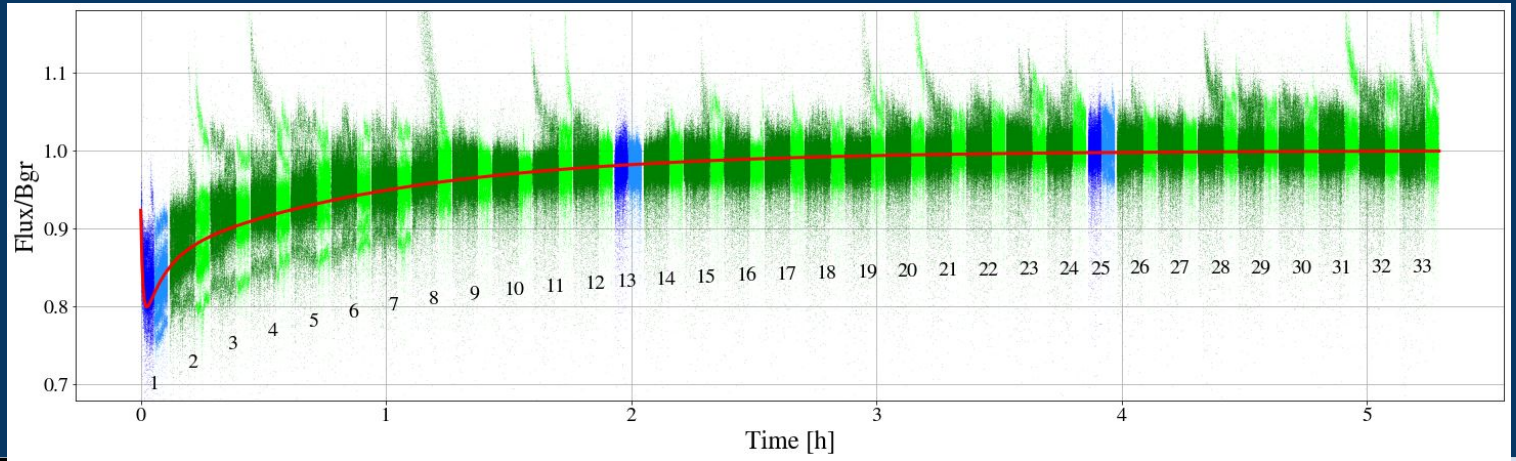
Before



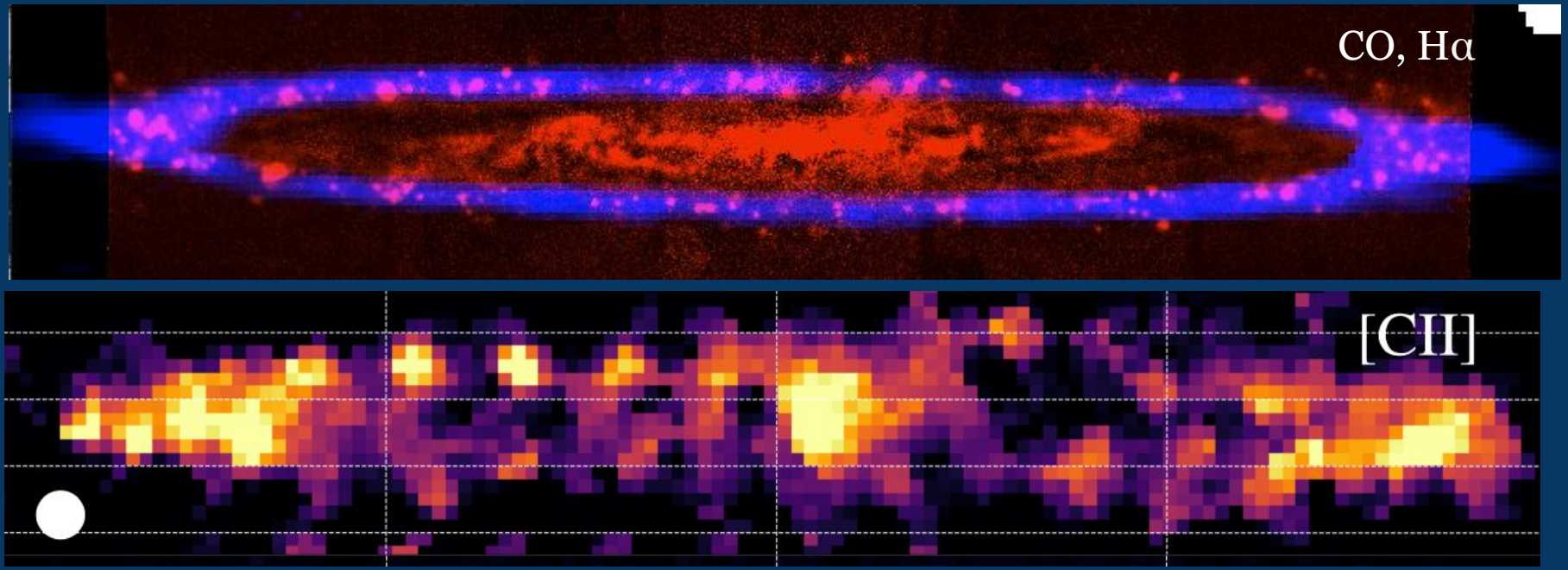
After

Long Term Transient

- Re-reduction of PACS data takes into account effects of the long term transient
- Observations made in unchopped mode
- Transient from observing calibration before source, correct by fitting a function and re-normalizing

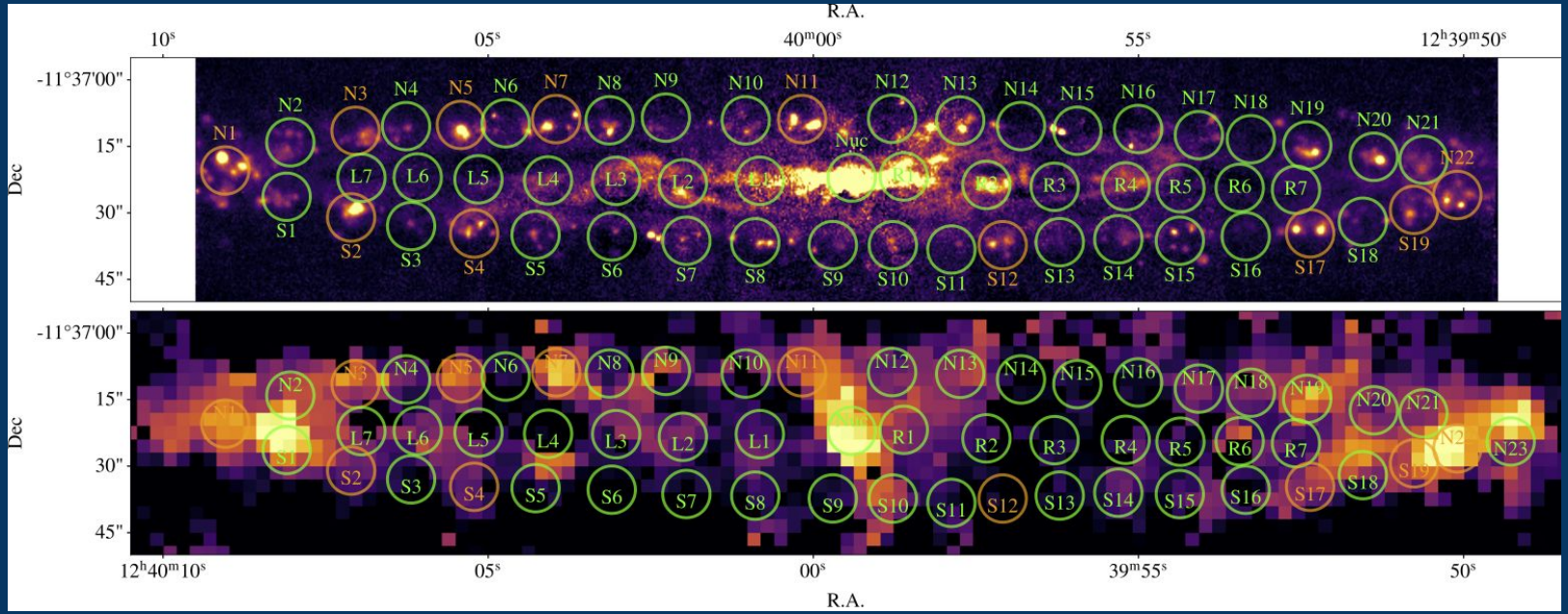


Archival Datasets

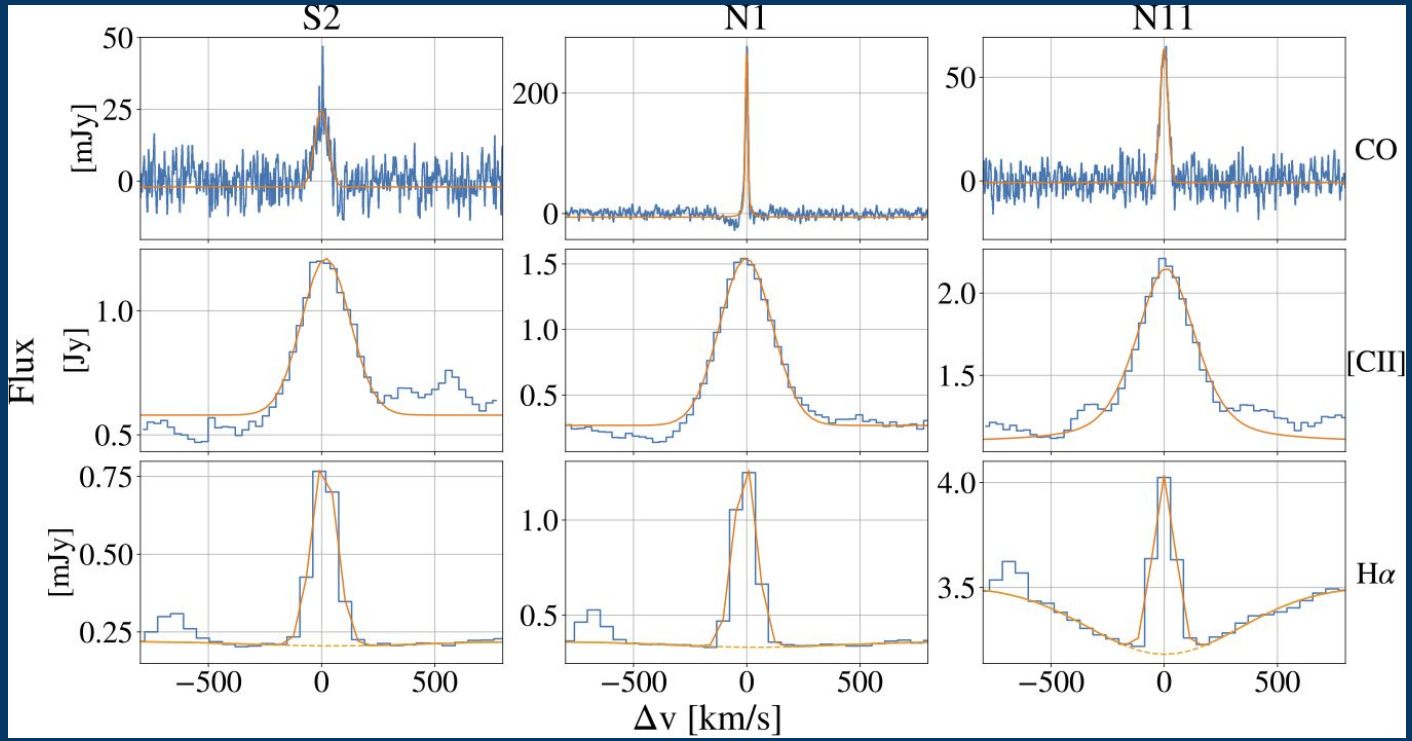


Defining Regions

- Region placement based on location of Hα emission

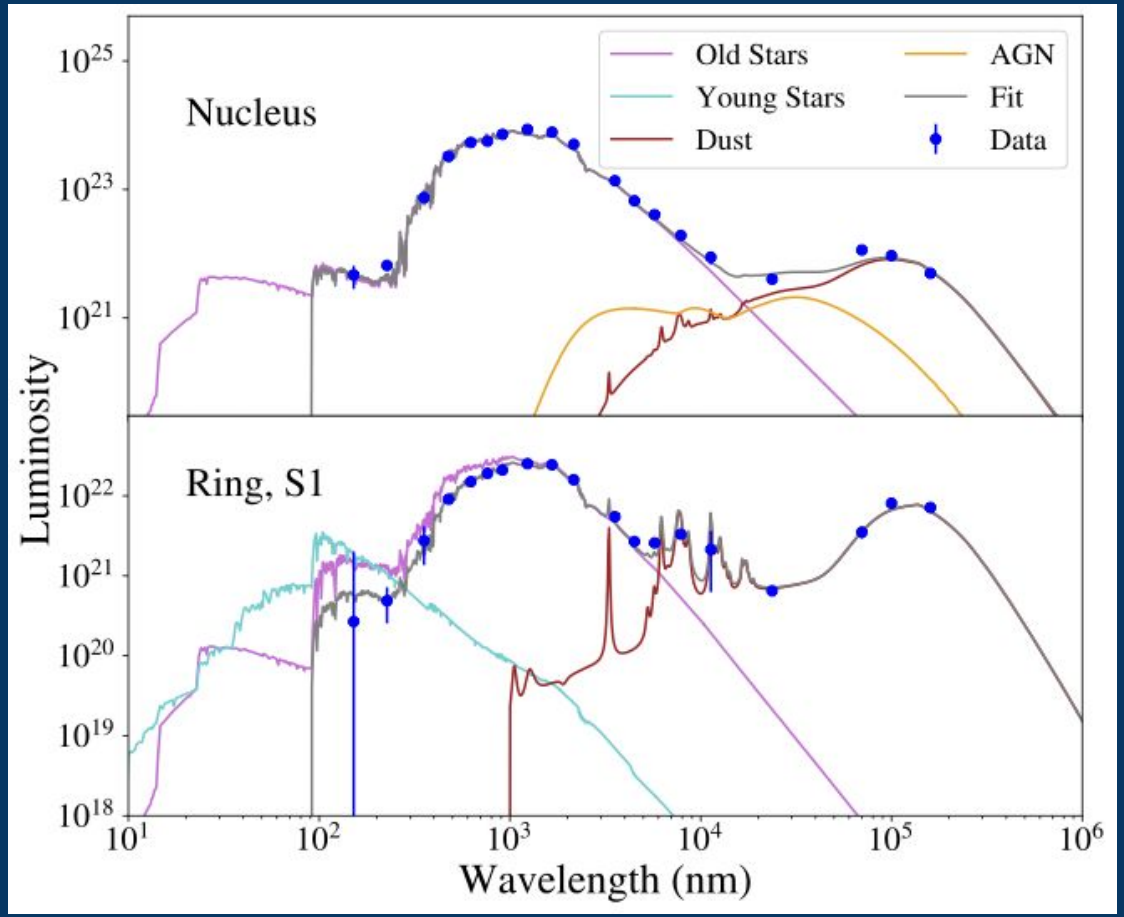


CO, [CII], and Hα Measurements



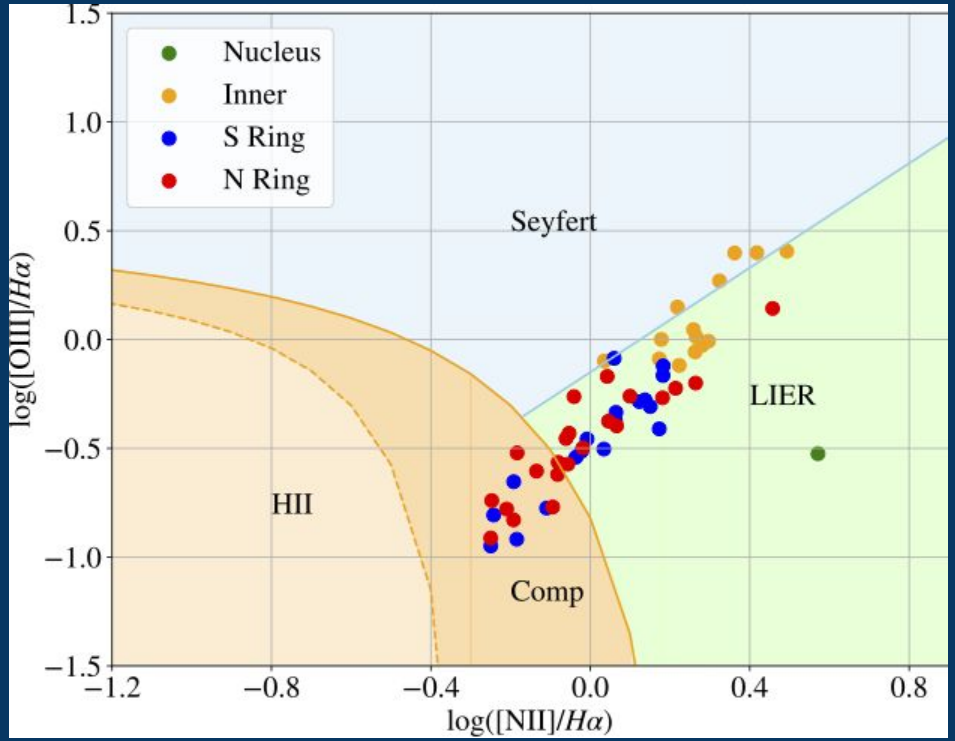
SED Modeling

- SED fits created using CIGALE
- Inner regions fit with an AGN, ring regions fit without AGN
- Photometry from Galex, SDSS, 2MASS, IRAC, WISE, MIPS, and PACS



Ionizing Radiation Source

- BPT diagram based on MUSE spectra
- Use to estimate what the ionizing source of radiation is in Sombrero
- Sombrero classified as a Weak Emission Line (WEL) galaxy
- Most regions fall in the Low-Ionization Emission line Regions (LIER) category



Heating and Cooling

- Young O and B stars heat the ISM through emission of UV photons
- PDRs surrounding sites of active star formation re-process this light
  - Dust absorbs UV light, emits in the IR
  - FIR cooling lines ([CII], [OI], and others) provide channel for energy to escape

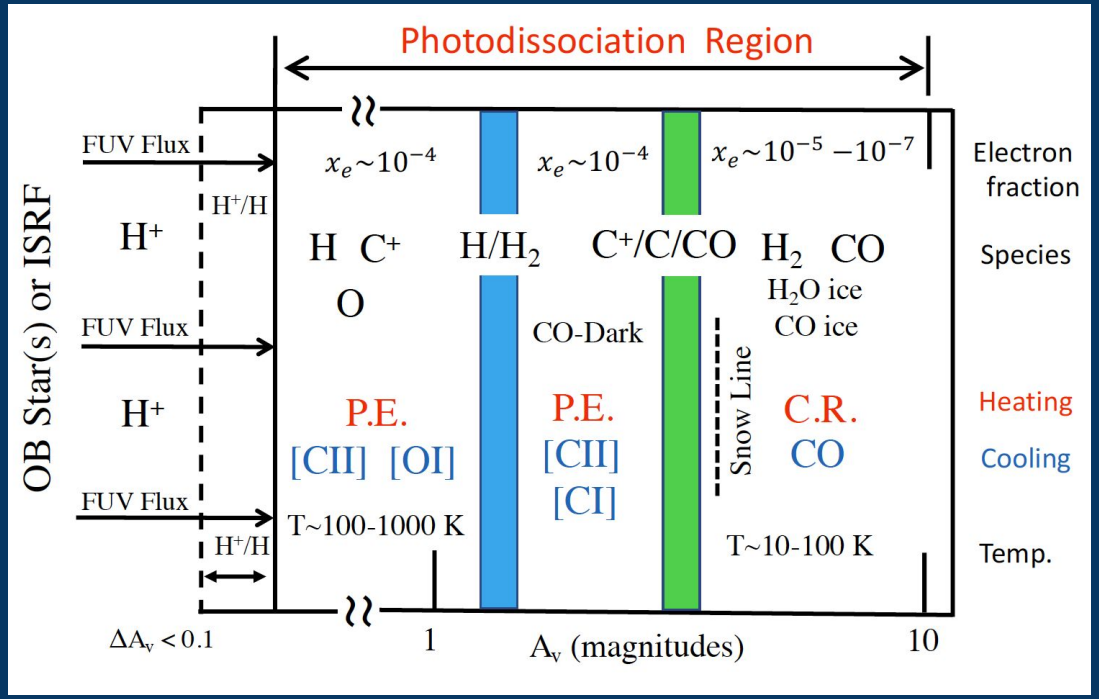
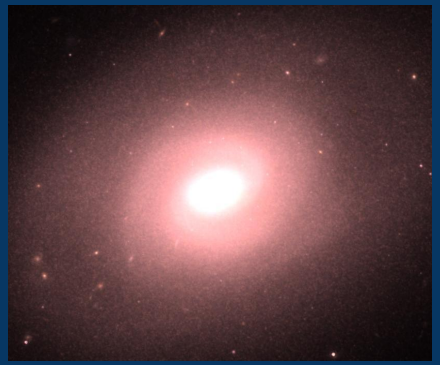
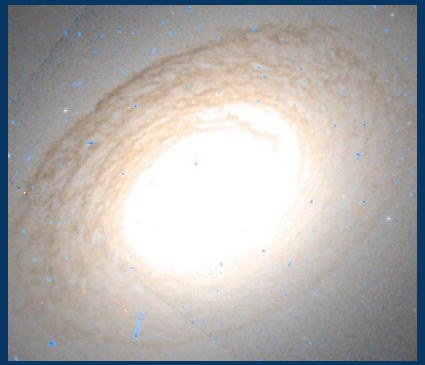


Image Credit: Wolfire, Vallini, & Chevance 2022

Comparison Sample: Early Type Galaxies (ETGs)



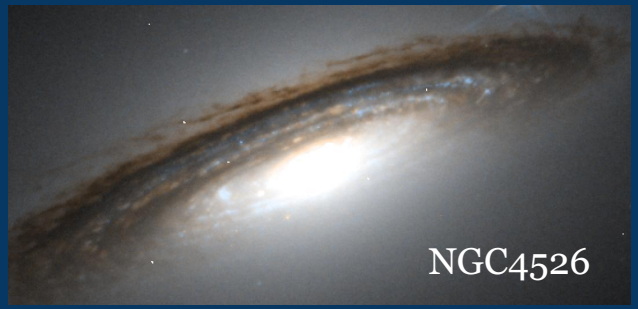
NGC1266



NGC3607

NGC5576, FIFI-LS

NGC5322, FIFI-LS



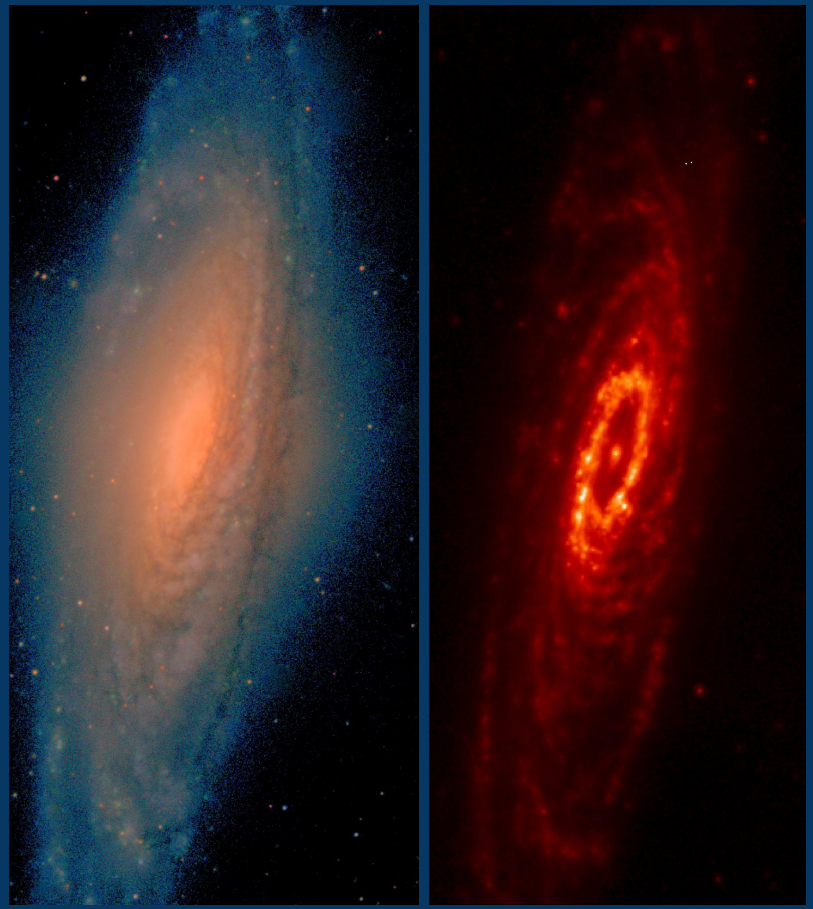
NGC4526

NGC4710

NGC5866

Comparison Sample: NGC 7331

- Nearby, edge-on spiral galaxy
- Milky Way analog
- See Sutter & Fadda, 2022a



Comparison Sample: KINGFISH

- Nearby (D < 30 Mpc) galaxies
- Sub-sample have [CII] measurements from PACS
  - Primarily star-forming galaxies
- See Kennicutt et al 2013, Sutter et al 2019

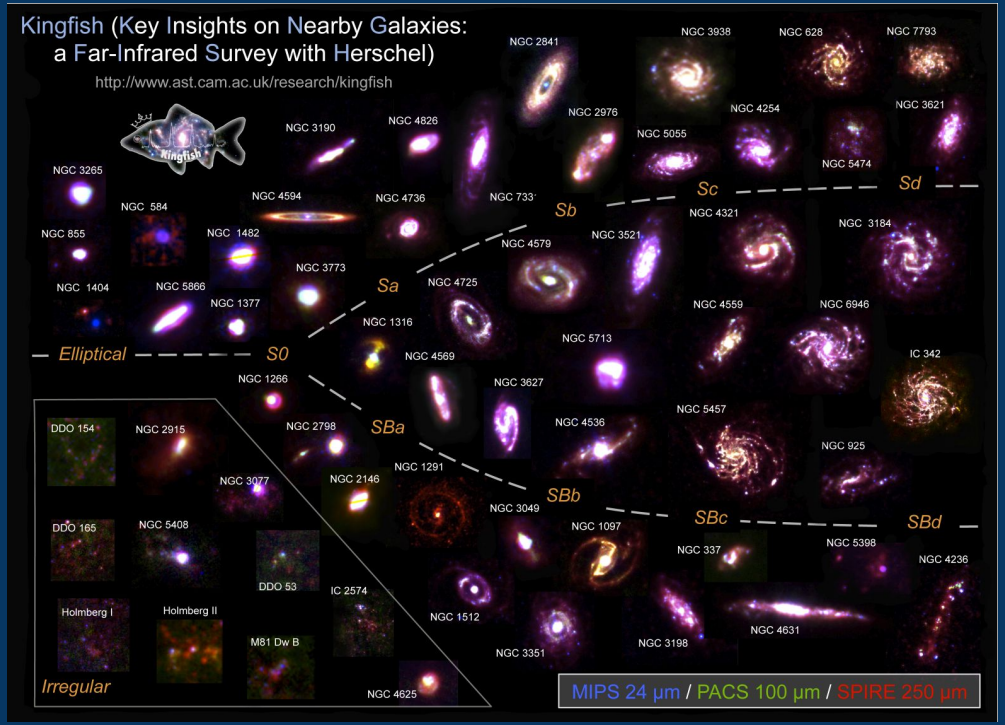


Image Credit: KINGFISH Collaboration

Comparison Sample: GOALS

- Great Observatories All-sky LIRG Survey
- (Ultra)/Luminous Infrared Galaxies
- See Diaz-Santos et al, 2017

NGC 3256, Image Credit: ESA/Hubble, NASA

Comparison Sample: Ibar+2015

- Galaxies from the H-Atlas sample
- Slightly higher redshift ($0.02<z<0.2$)
  - [CII] still observable by PACS

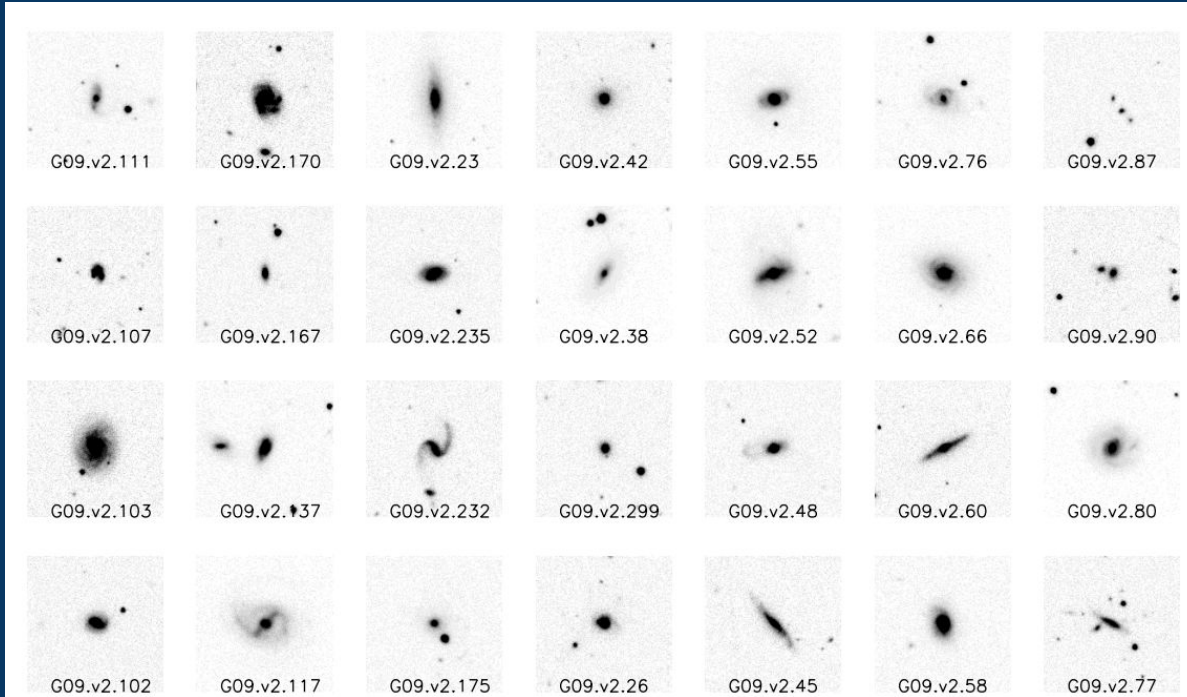


Image Credit: Ibar+2015

[CII]/FIR: The [CII] Deficit

- Decreasing trend in [CII]/FIR in galaxies/regions with increased SFR, IR radiation, hotter dust, etc.
- Implications for using [CII] as a star-formation rate indicator
- Suggests changes in the balance of heating and cooling in more active galaxies

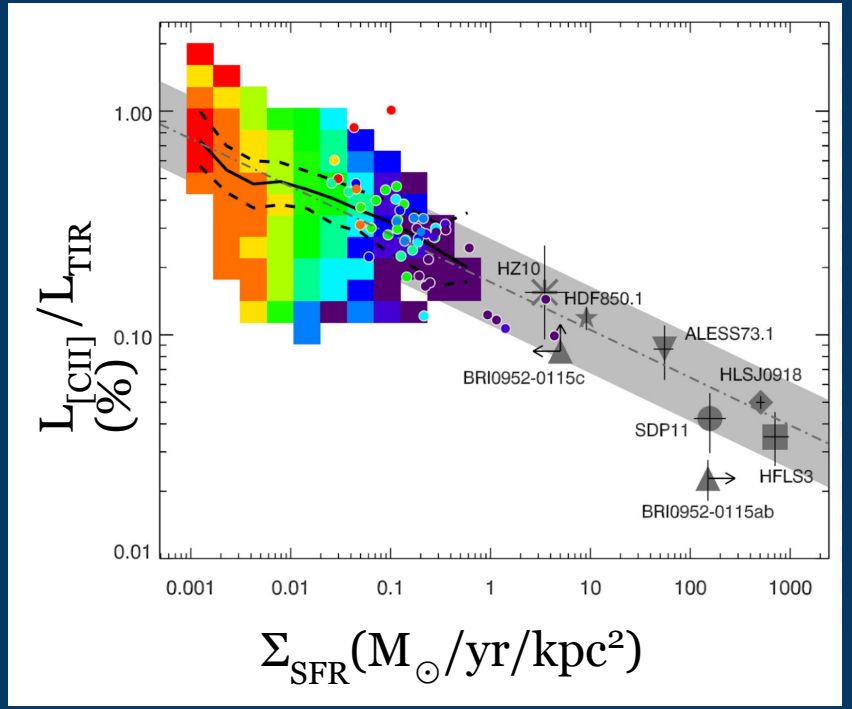
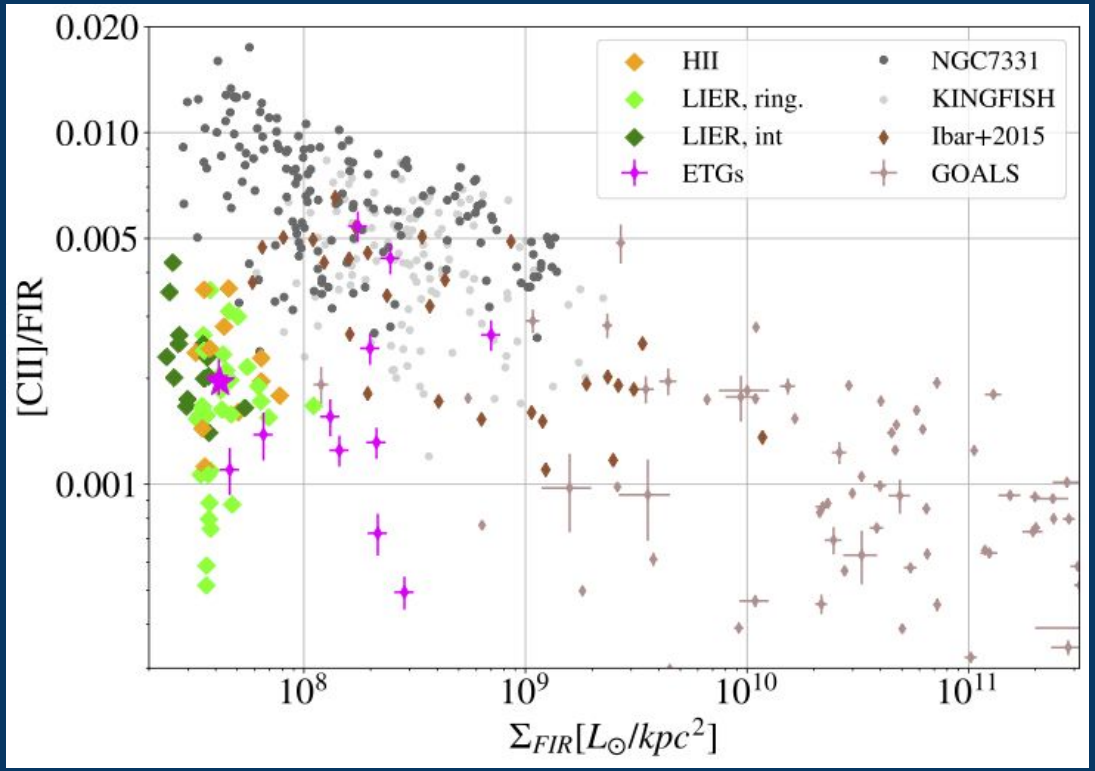


Image Credit: Smith et al, 2017

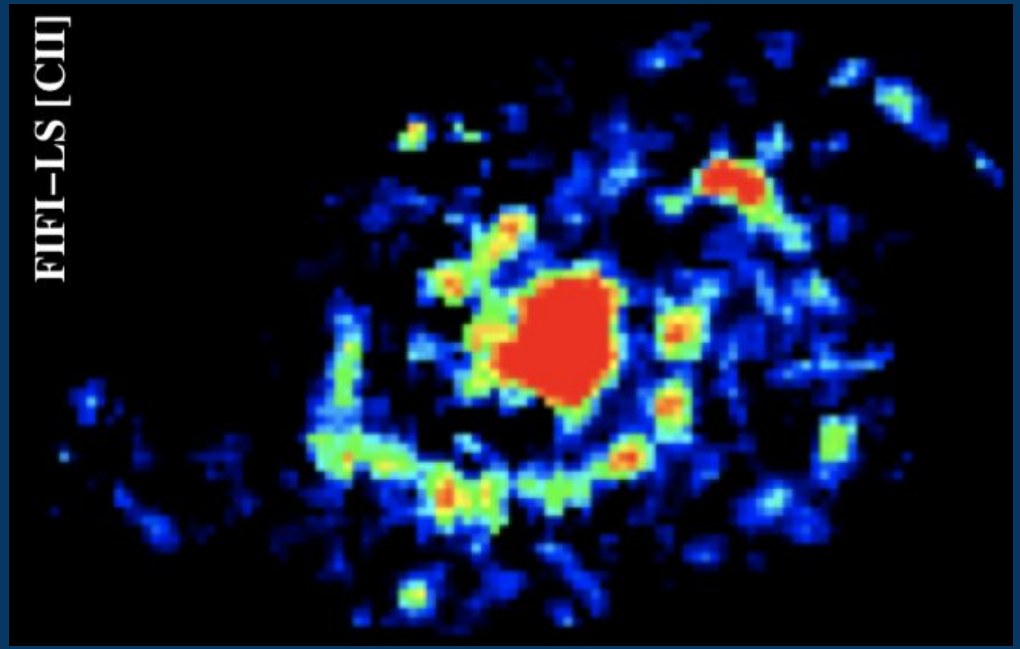
[CII]/FIR: The [CII] Deficit

- Regions from the Sombrero fall in a unique parameter space
- Subset of the ETGs fall in a similar space to the regions from the Sombrero
- Slight difference between regions classified as LIER and regions classified as HII



Why? Investigating the cause of the [CII] Deficit

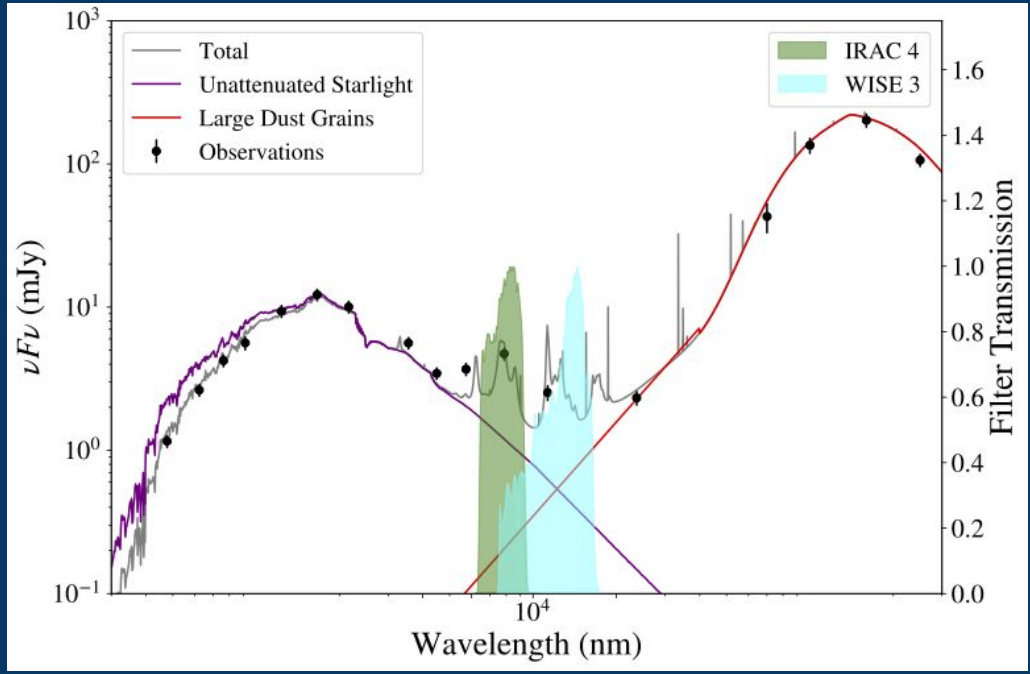
- Changes to PAH properties effects heating?
- Changes in source of ionizing radiation limits [CII]?
- AGN increases or decreases [CII] emission?
- [CII] self absorption?



M51, Image Credit: Pineda+2018

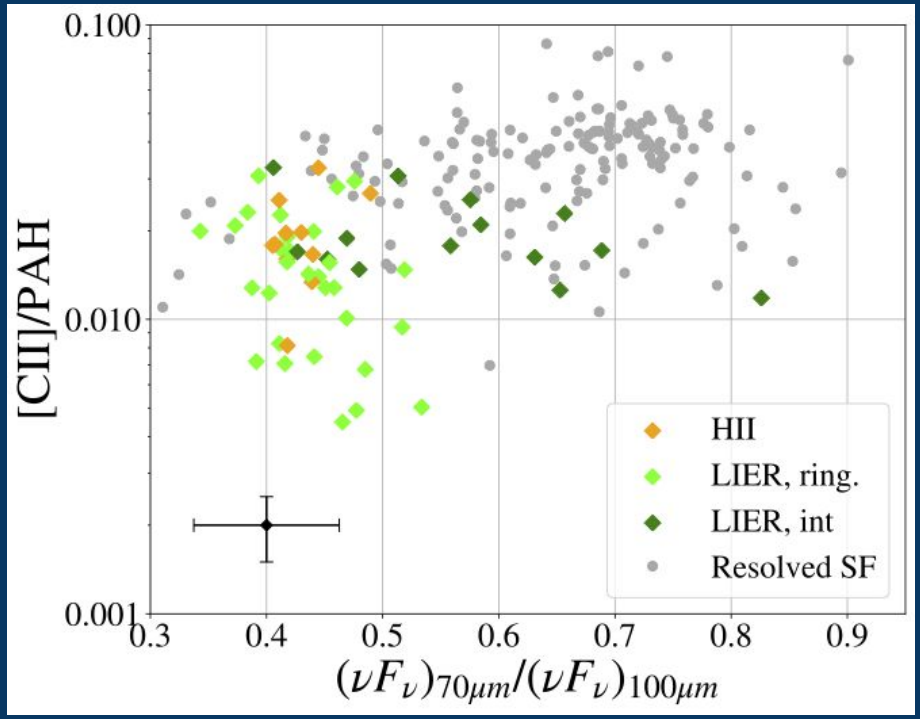
PAH Population Changes?

- Polycyclic Aromatic Hydrocarbons (PAHs) are a primary source of free electrons in PDRs
- Measure using IRAC4 and WISE3 photometry along with results of SED models
  - IRAC4 is centered at 8.0 microns, and includes the 7.7 micron PAH feature
  - WISE3 is centered at 11.2 microns, and includes the 11.3 micron PAH feature



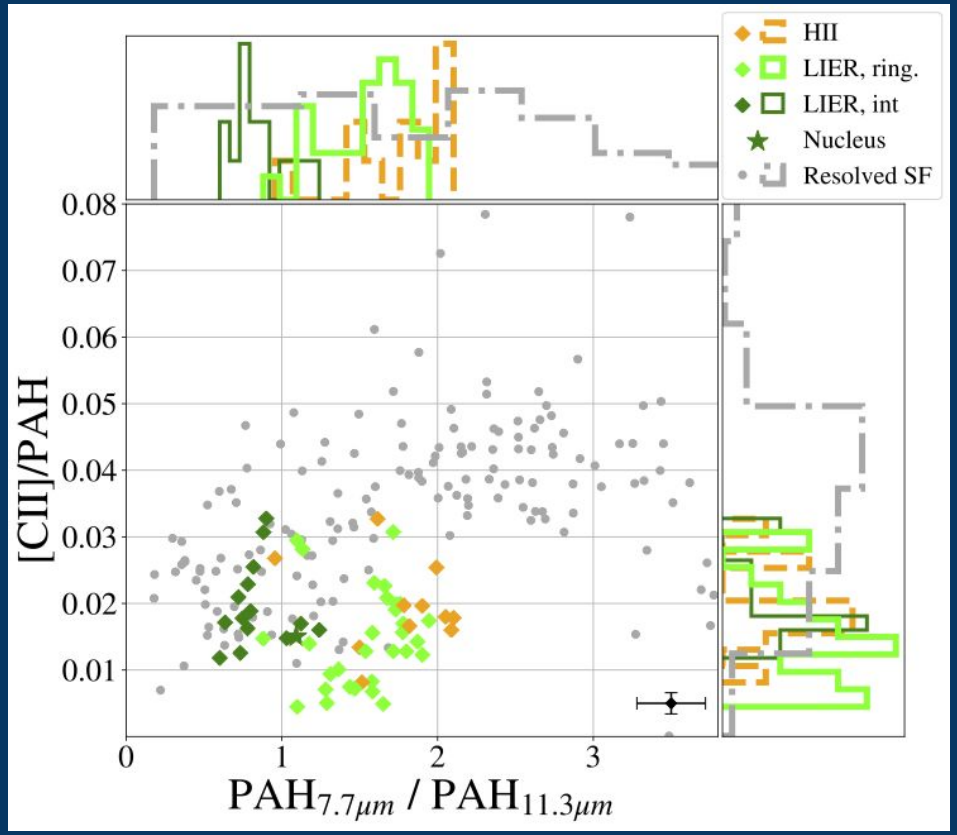
PAH population changes?

- [CII]/PAH has been suggested as an improved measurement of ϵ_{PH}
- See similar behavior between star forming galaxies and the Sombrero
- Differences in [CII]/PAH and [CII]/FIR



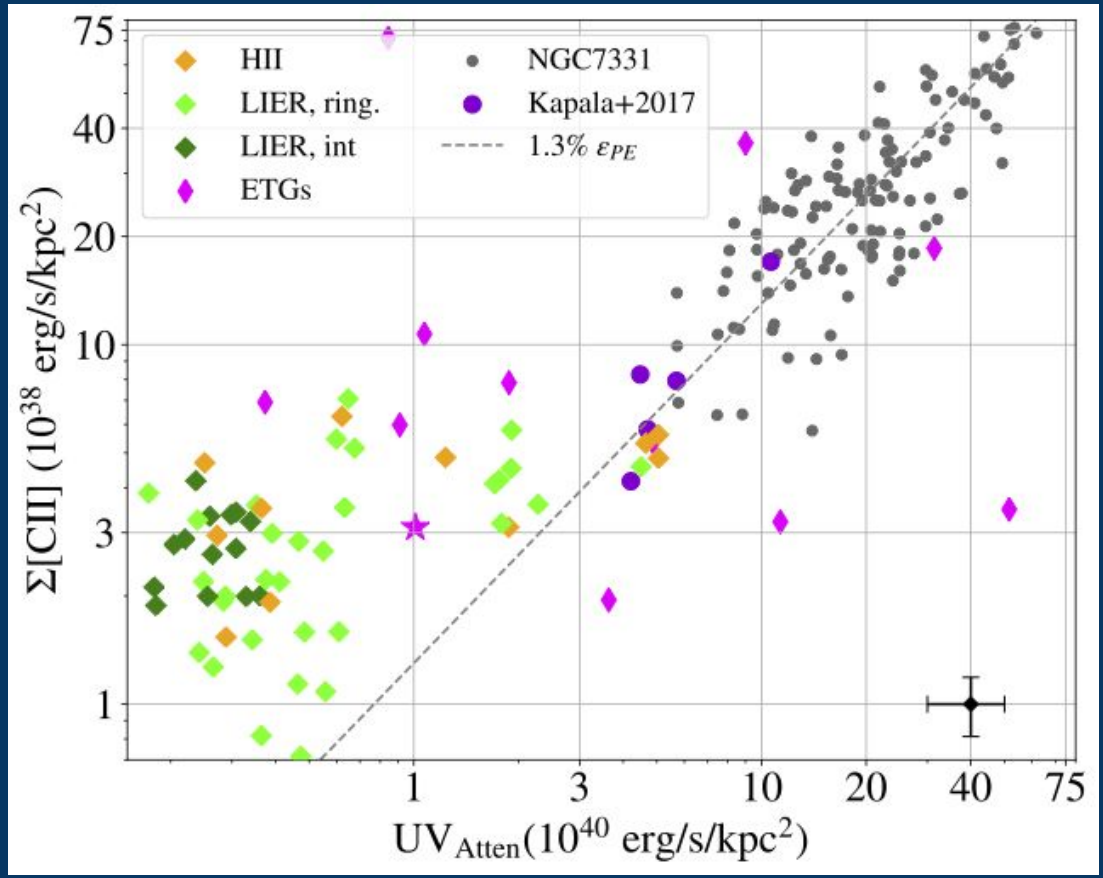
PAH population changes?

- PAH Charge measured by ratio of 7.7/11.3 micron PAH features
- Sombrero PAH charges overlap with NGC7331
  - ➢ Cover smaller parameter space
- Could effect cooling, but as there is still an offset does not explain difference between Sombrero and star-forming galaxies



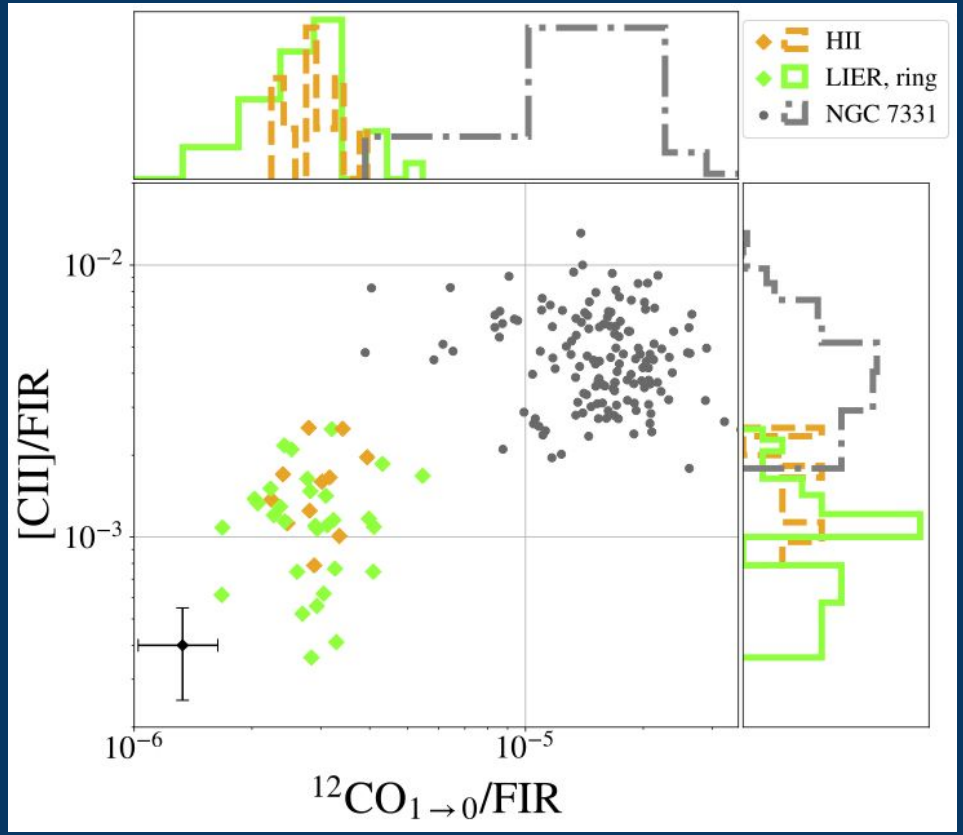
Changes in heating?

- Measure amount of attenuated UV light using results of SED modelling
- Sombrero and ETGs show low amounts of attenuated UV light
  - ➢ Few young stars



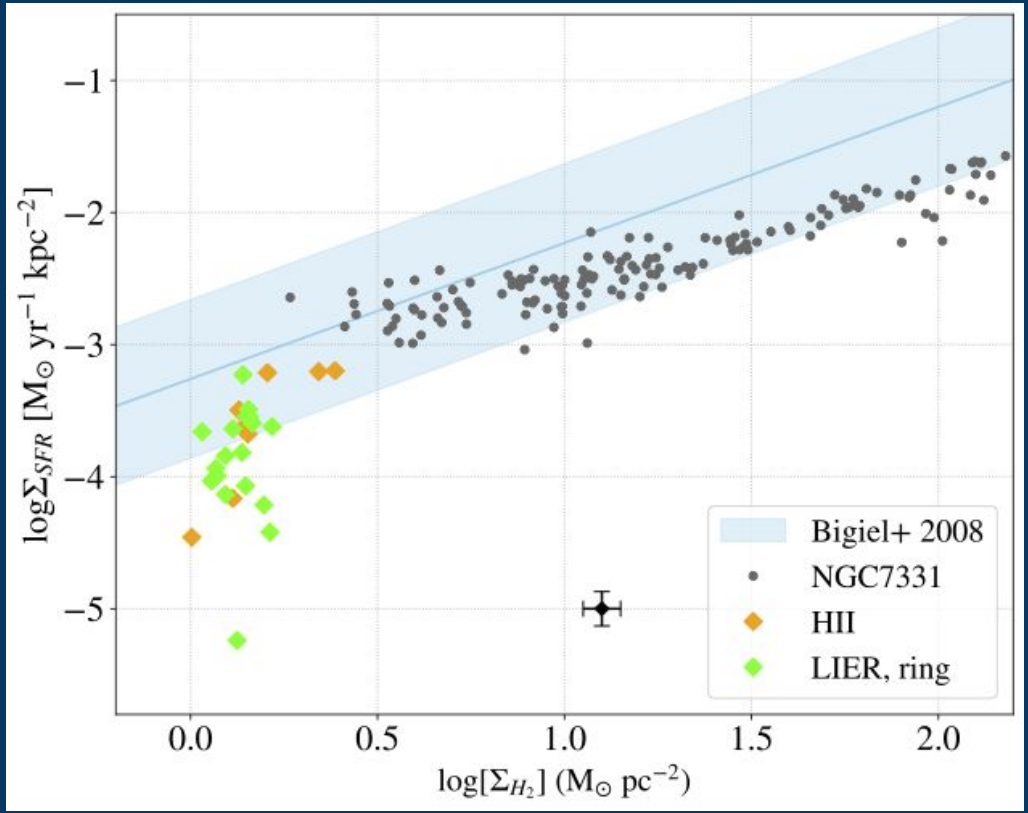
PDR properties?

- No measurements of CO from interior of the Sombrero
  - ➢ Why?
- Low values of CO across ring
- Lack of molecular gas?



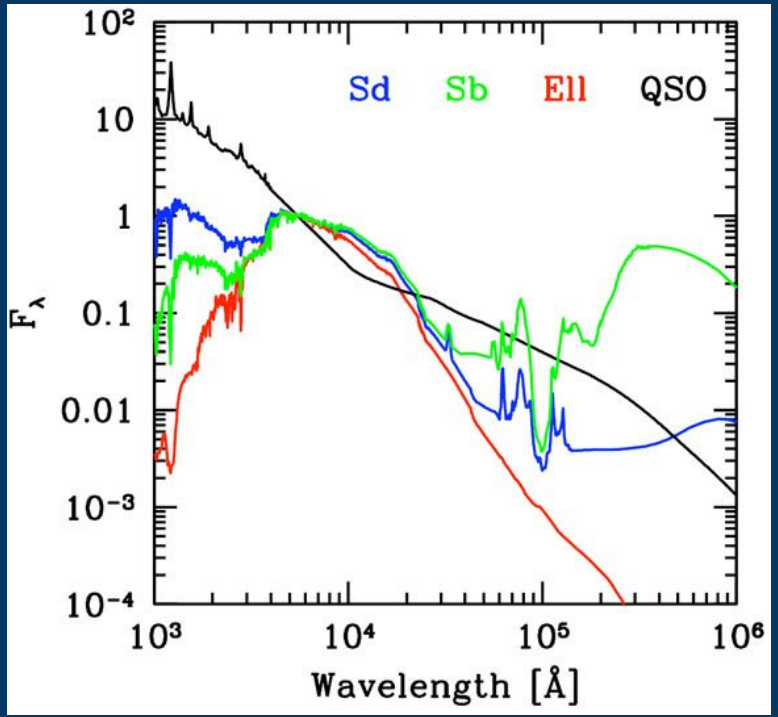
Lack of Molecular Gas

- Sombrero regions fall below Kennicutt Schmidt relationship
  - SFR measured using SED models
  - H_2 measured using CO
- See no linear trend
- Implying disconnect between molecular gas and star formation in the Sombrero



Conclusion: Changing radiation source alters [CII]/FIR

- The low [CII]/FIR measurements across the Sombrero seem to be tied to changes in the source of ionizing radiation
  - More old star heating
  - AGN/LIER emission as the ionizing radiation source
- The properties of the Sombrero are similar to early type galaxies



Further Questions

- Still many unanswered questions:
  - Why is there [CII] in the center, but no CO?
  - Why do the PAHs have such a limited range in charge?
  - What does this imply for high-z studies of [CII]?