Modeling Ionized Gas at Low Metallicities: The Wolf-Rayet Emission Nebula N76

Our Galactic Ecosystem: Opportunities and Diagnostics in the Infrared and Beyond

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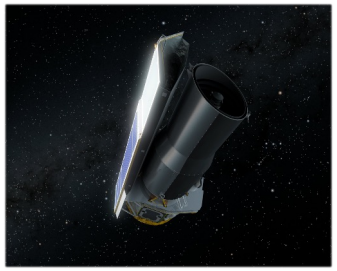
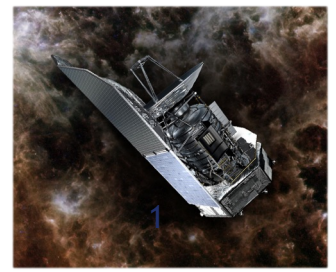
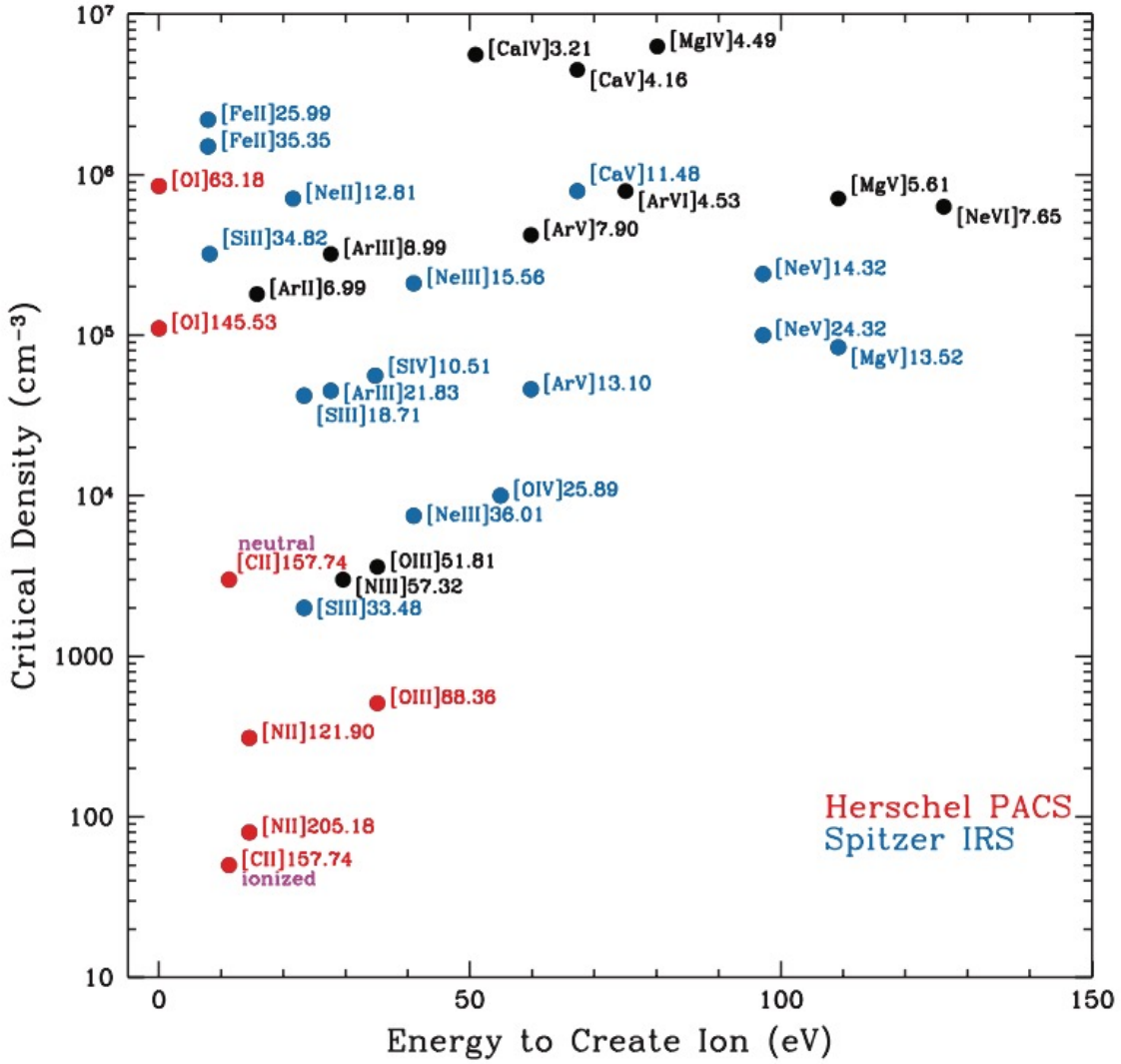




Infrared Emission Line Diagnostics

- Variety of lines, sensitive to physical conditions in the ISM
  - Extinction-free
  - Probe HII regions, photodissociation regions (PDRs), and the diffuse ionized gas
- Combining observations from a variety of IR observatories is a powerful tool
  - Synergies between *Spitzer, Herschel* SOFIA, and JWST

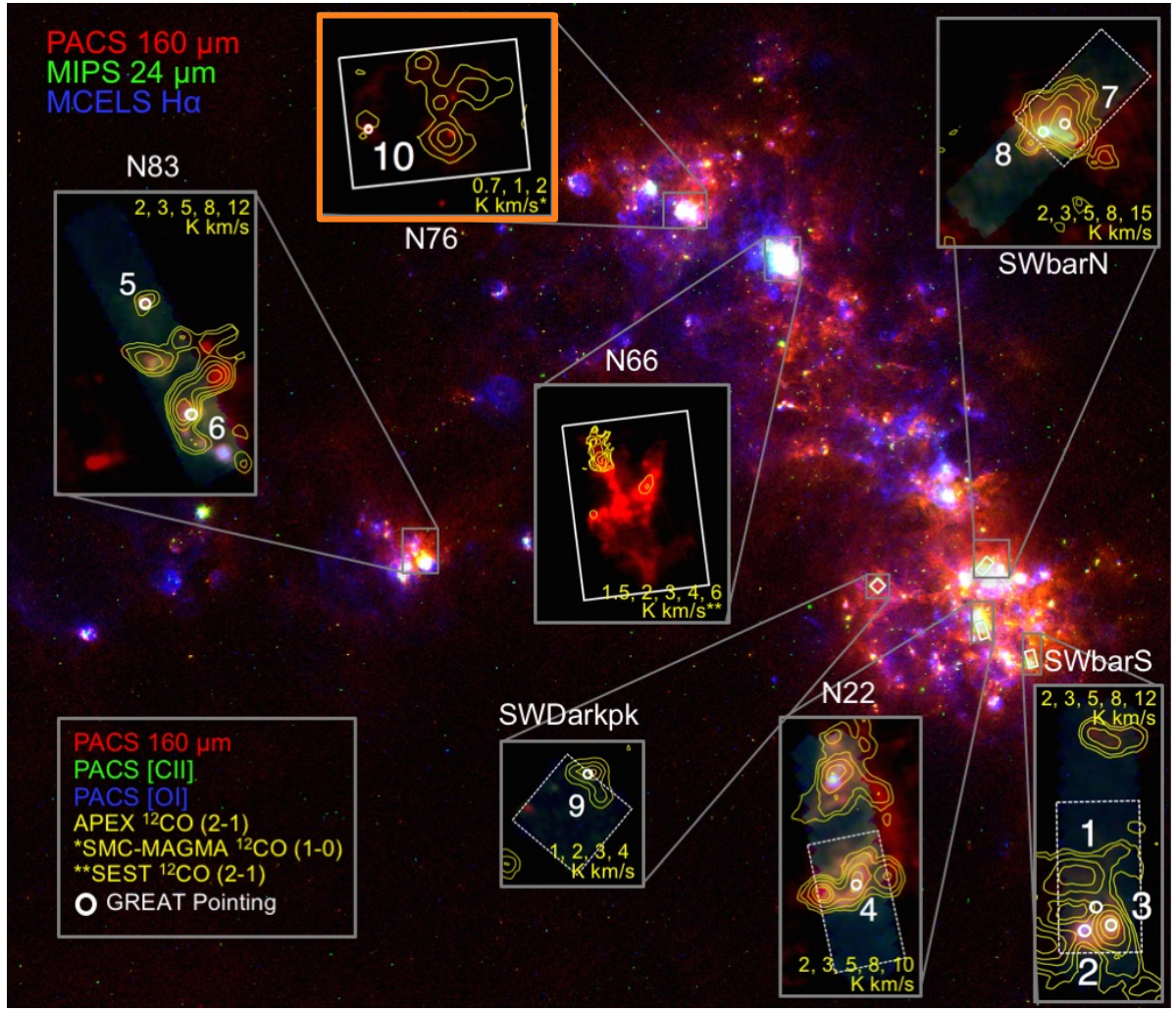


Kennicutt+ 2011

Ionized Gas Properties at Low Metallicities

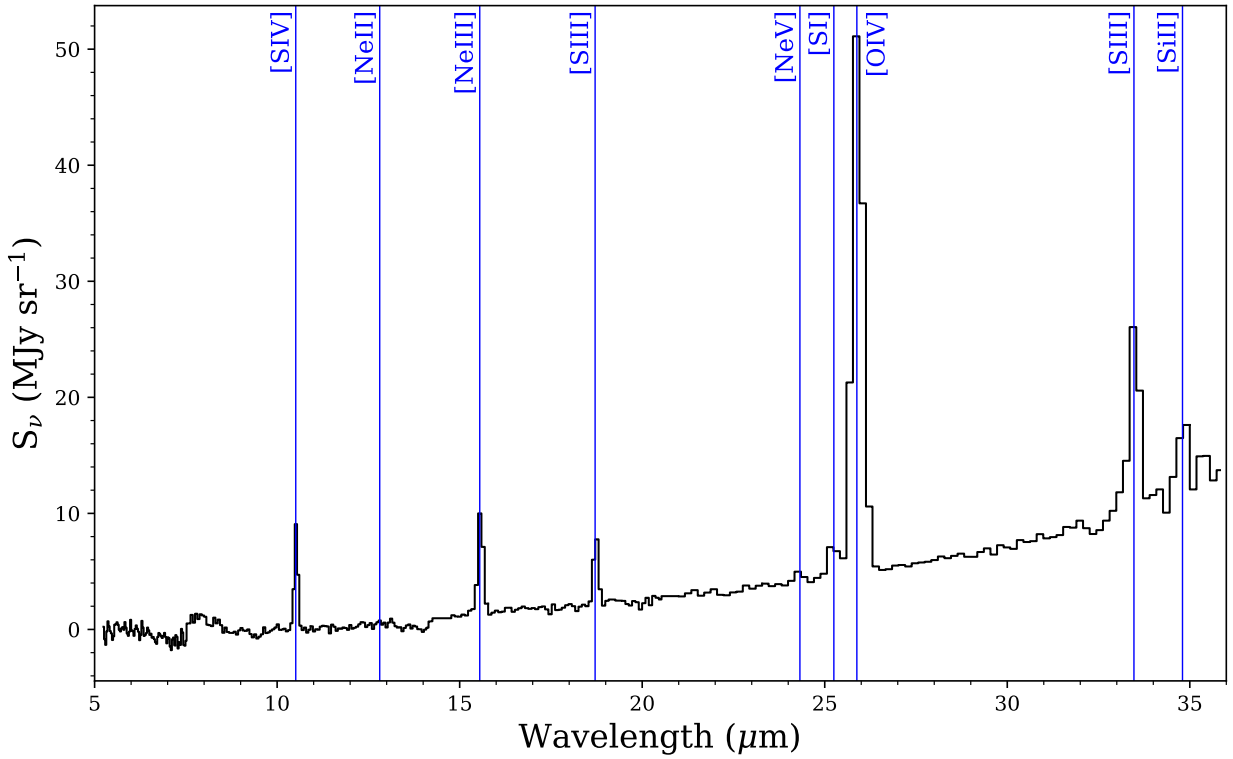
- Understanding effect of metallicity is **crucial**
- Observations of mostly unresolved low metallicity dwarf galaxies show: (Hunt+ 2010; Cormier+ 2015, 2019; Polles+ 2019)
  - Harder radiation fields
  - Bright, extended [OIII] emission
  - Porous structure

Our approach: use the Small Magellanic Cloud (1/5 $Z_{\odot}$) to determine the **resolved** properties of the ionized gas

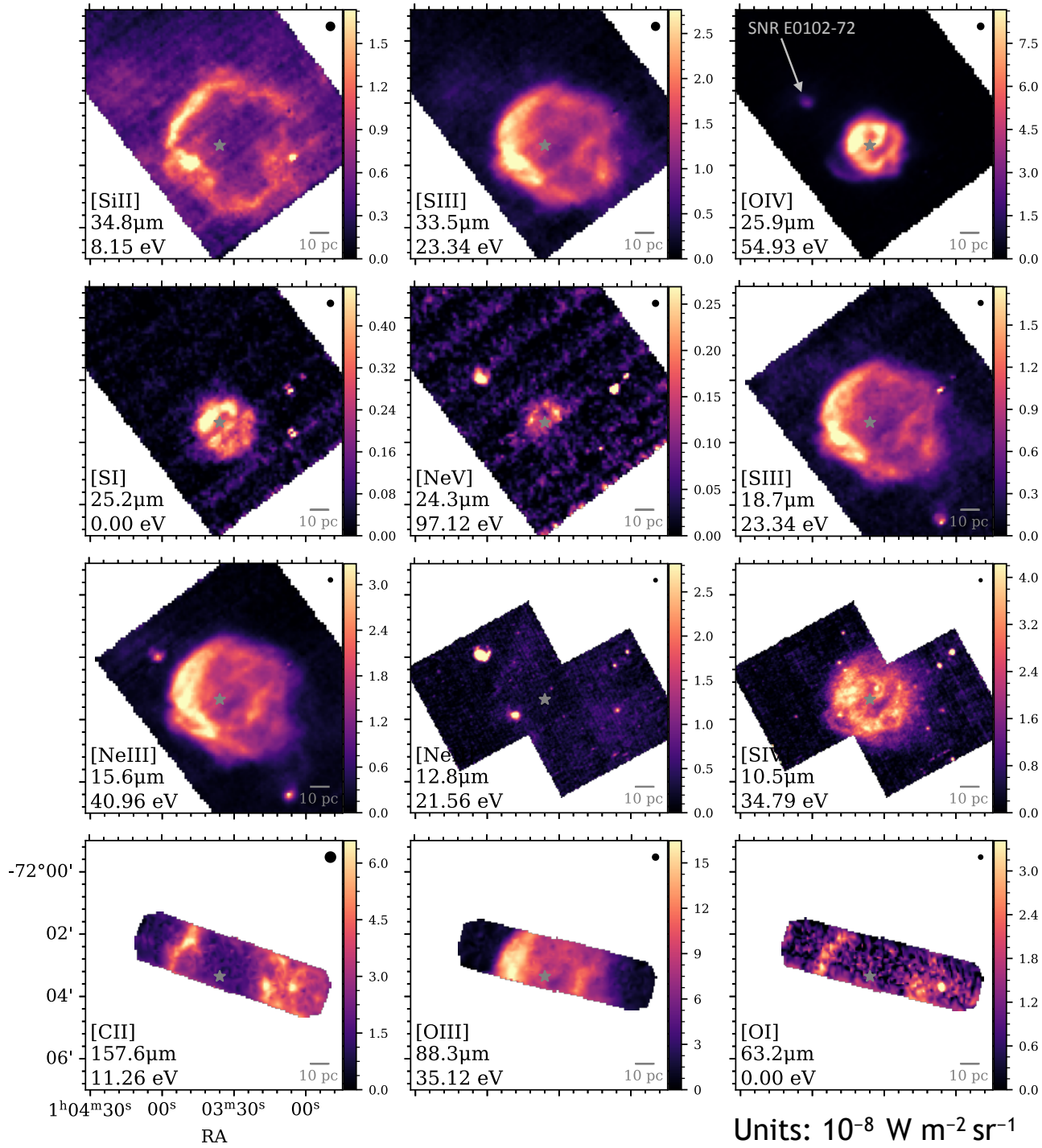


The N76 Wolf-Rayet Emission Nebula

- Simplest region in sample: roughly spherically symmetric with a single ionization source
- AB7: a WN4 + O6 binary (Shenar+ 2016)
  - $T_* = 105{,}000$ K
  - $L = 10^{6.1}\ L_\odot$
- *Spitzer*/IRS and *Herschel*/*PACS* spectroscopy



Spitzer/IRS spectrum



Emission Line Images

- Construct images through CUBISM (Smith+ 2007a) and PAHFIT (Smith+ 2007b)
  - ≈2-3 pc resolution

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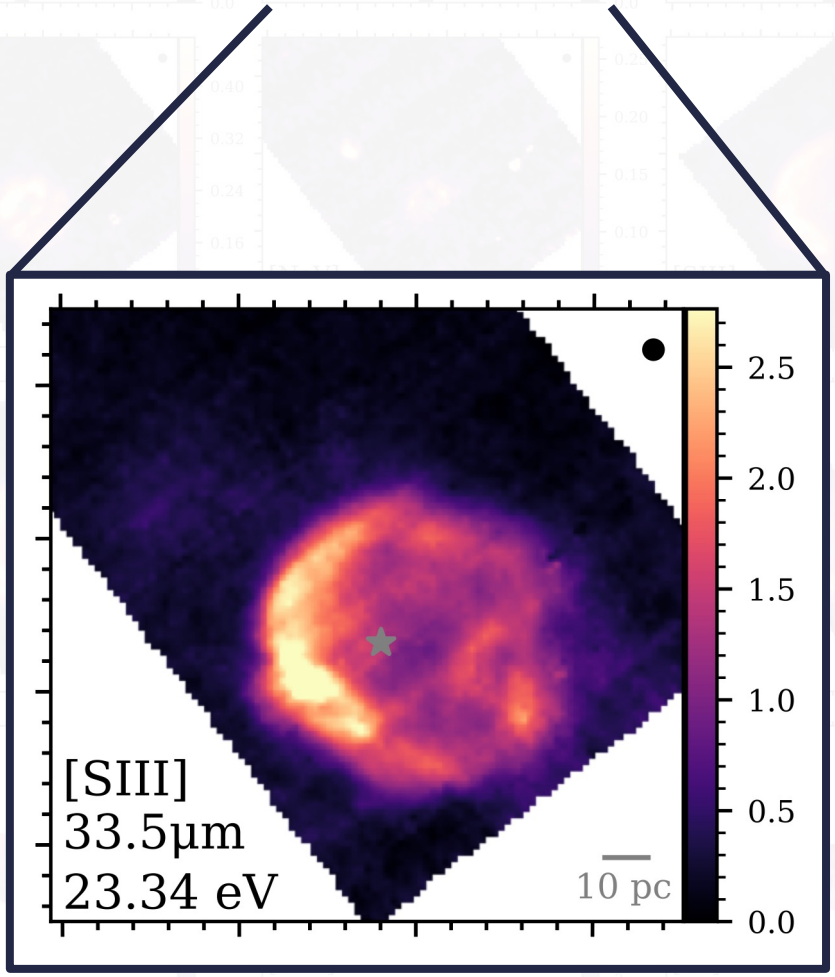
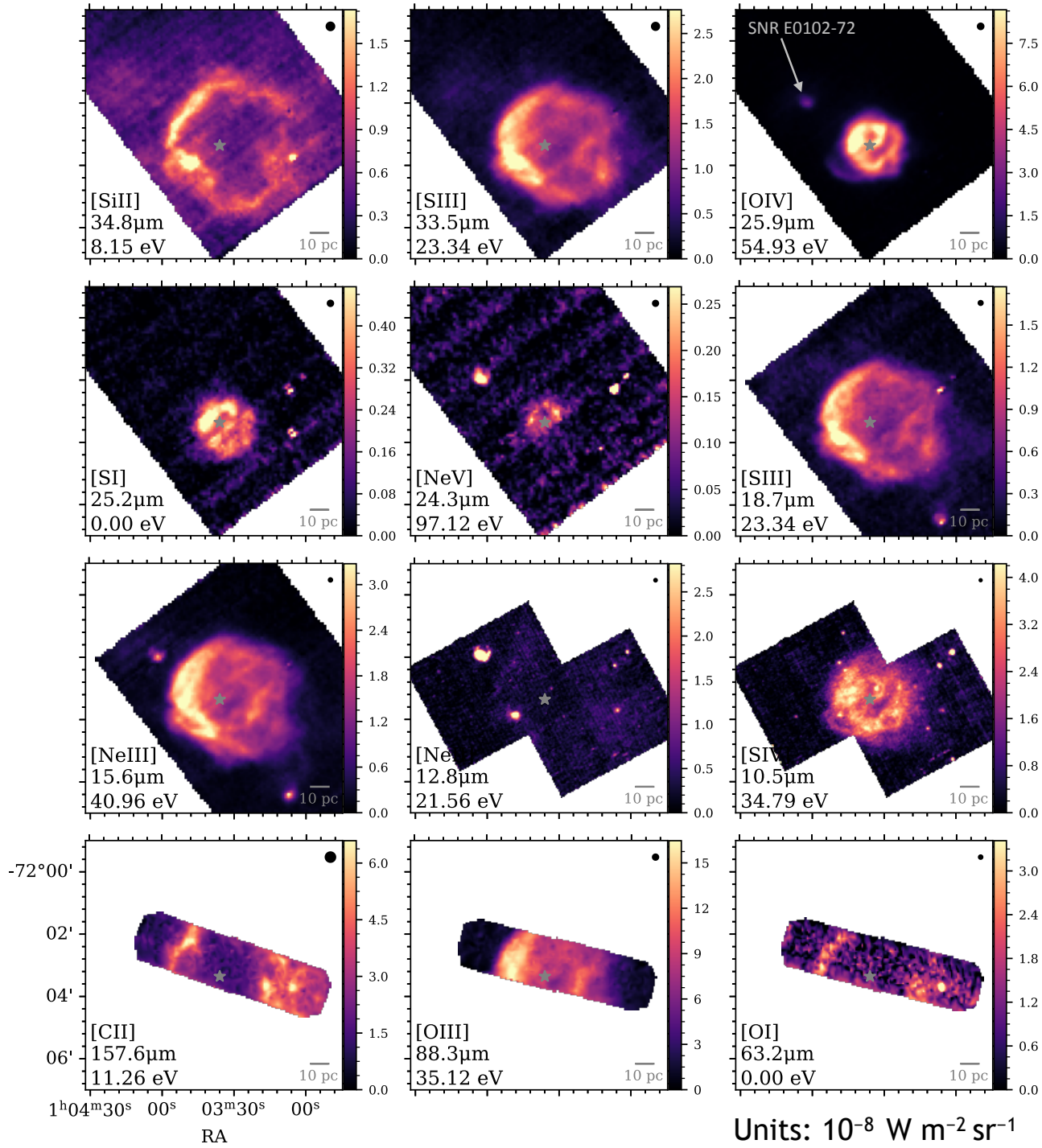


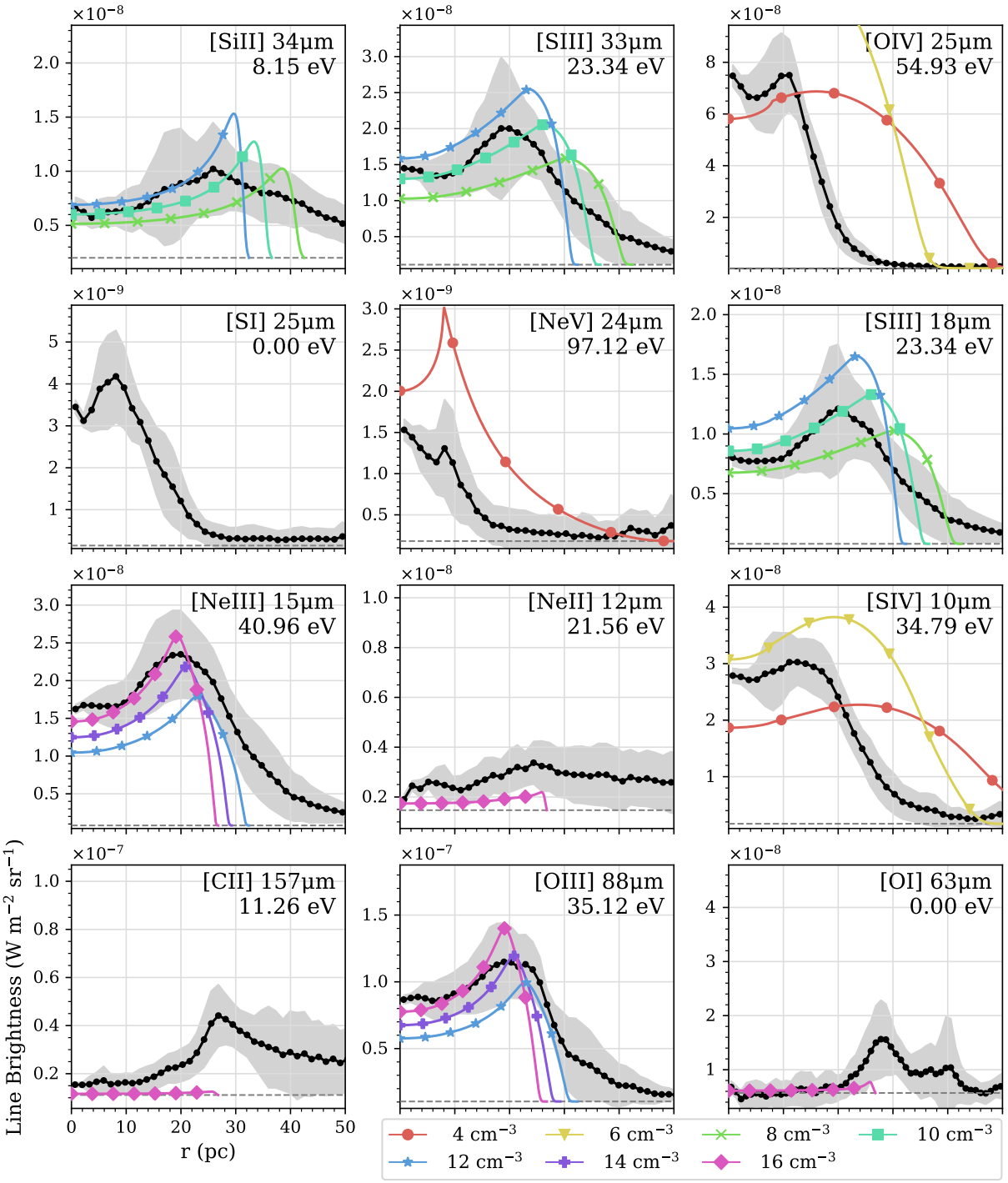
Units: 10^{-8} W m^{-2} sr^{-1}



Emission Line Images

- Construct images through CUBISM (Smith+ 2007a) and PAHFIT (Smith+ 2007b)
  - ≈2-3 pc resolution
- Cloudy photoionization modeling (Ferland+ 2017) conditions:
  - PoWR stellar atmosphere models for AB7's SED (Todt+ 2015)
  - 8 pc wind-blown cavity required by data
  - SMC abundances
  - Constant density
  - Only modeling HII region (not PDR)

Method: match radial brightness of the spatially resolved emission lines to projected values from Cloudy

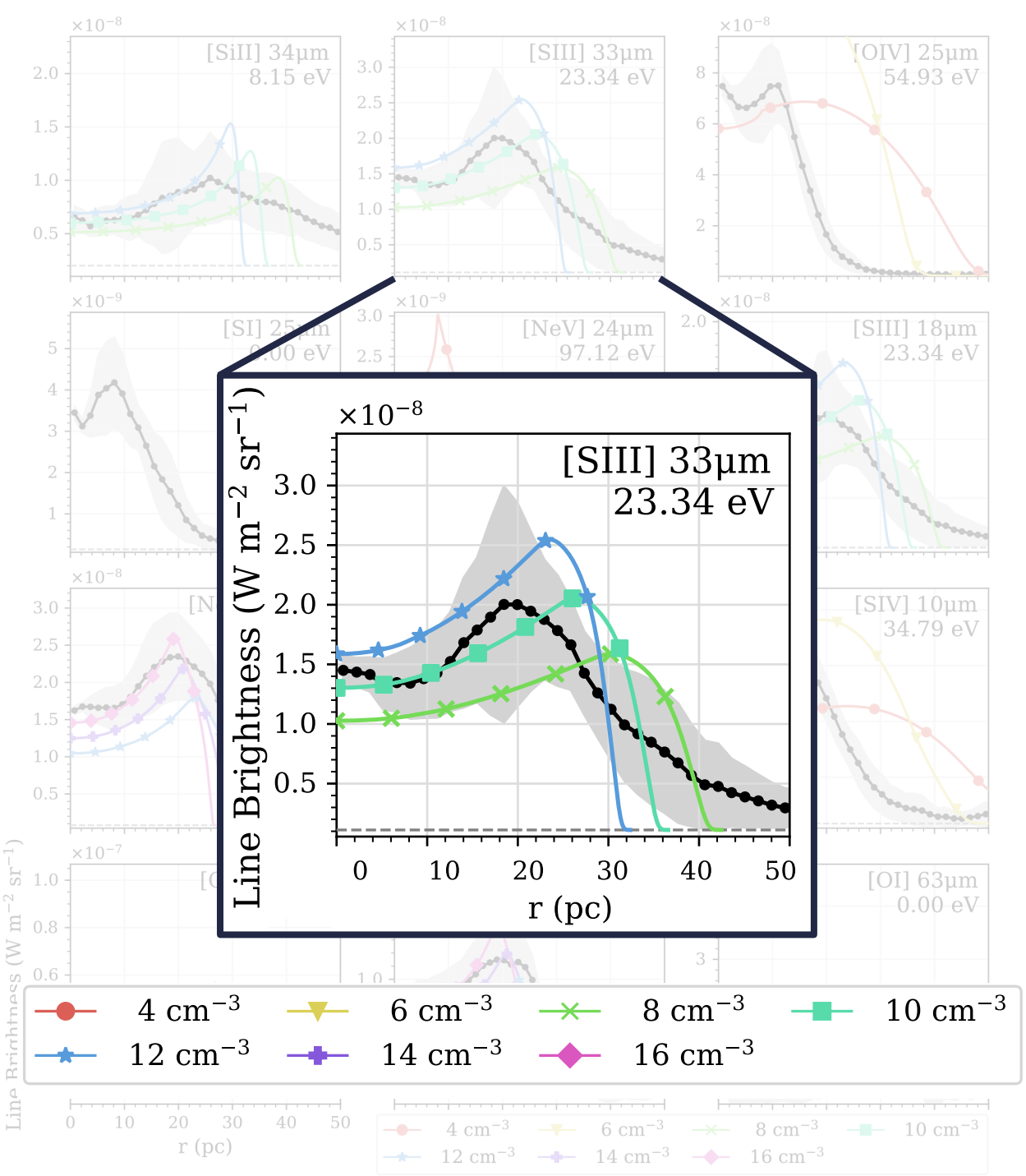


Results of Photoionization Models

- Constant density Cloudy models of $n_H \approx 4 - 16$ cm^{-3} reproduce the ionized gas ($E_{ion} > 13.6$ eV) emission lines well
  - Density (n_H) is very well constrained compared to integrated intensity measurements

Modeling the **spatially** resolved emission yields much more information than **unresolved** modeling

- [OIII] is the brightest line, similar to other work (e.g., Cormier+ 2015, 2019)
- Diffuse emission from [SIII], [NeII], and [NeIII] 100 pc away from AB7 may indicate photon leakage from N76



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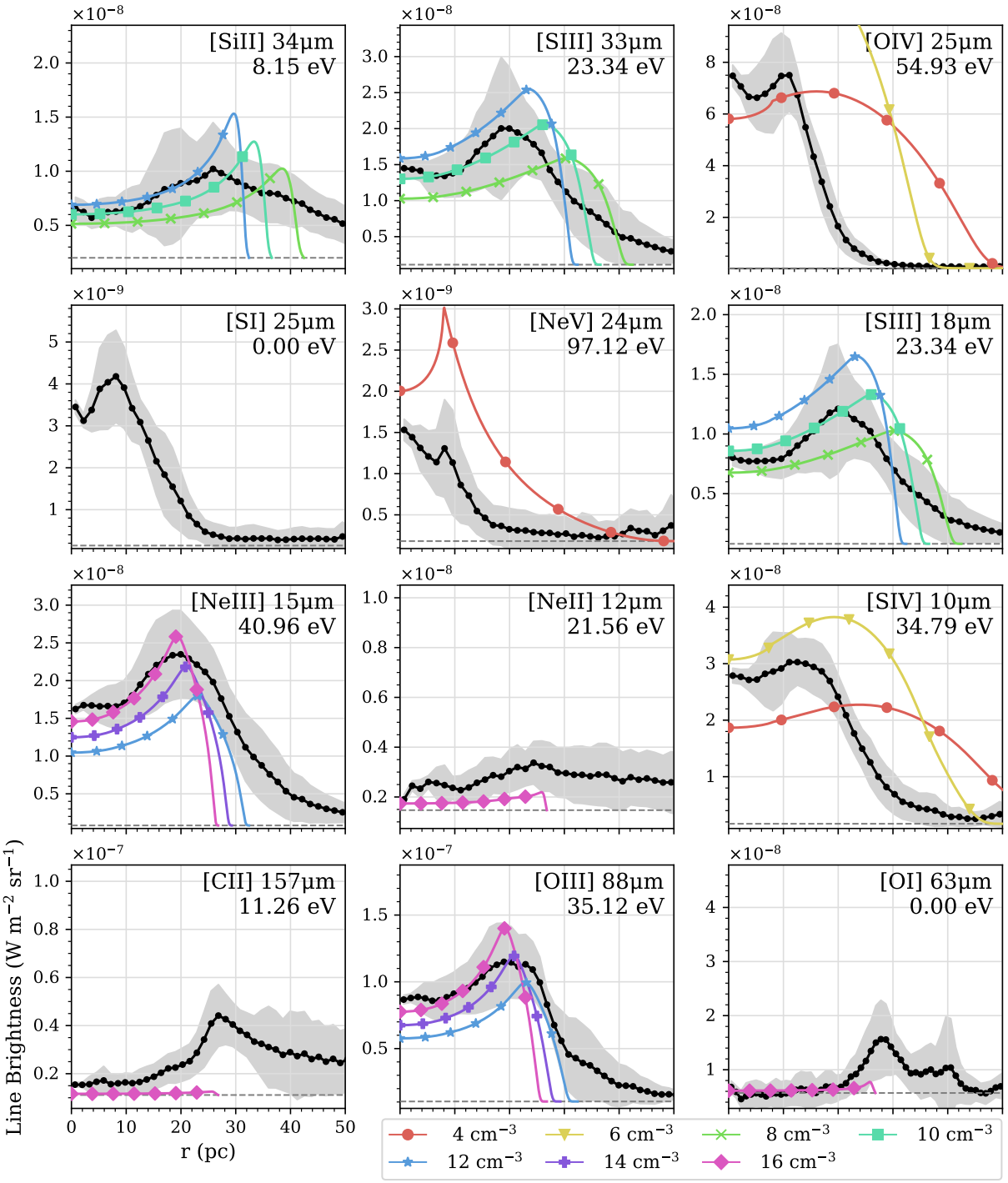

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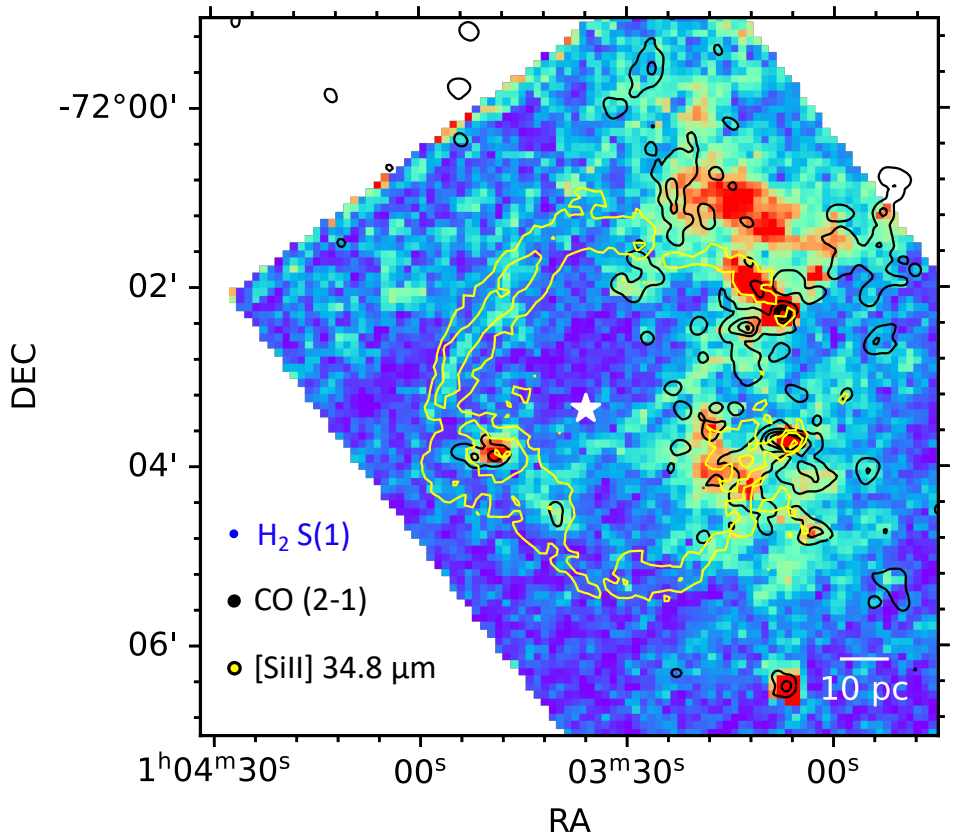
Neutral gas in N76

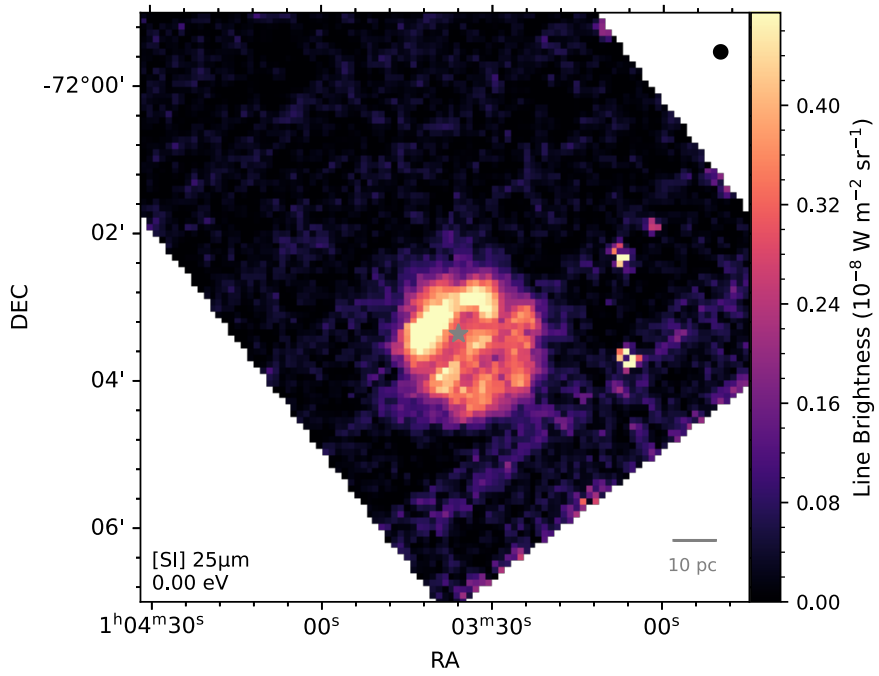


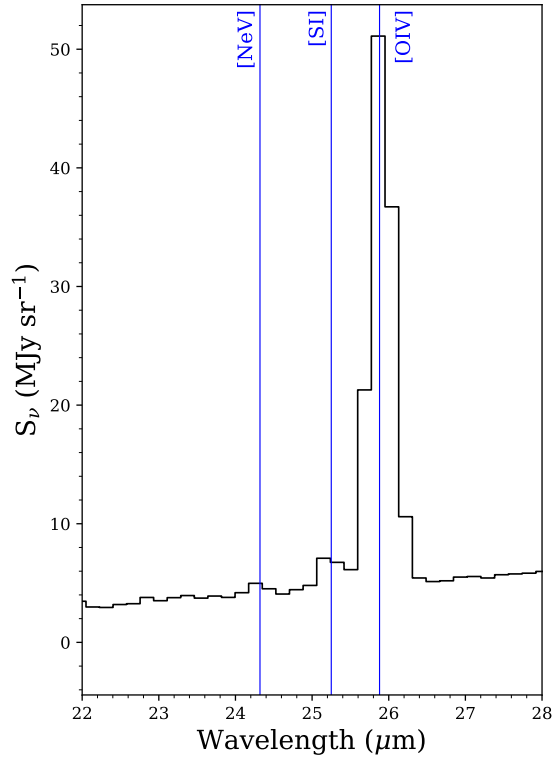
- Ionized gas contribution to neutral lines (E_{ion} < 13.6 eV)
  - **[SiII]: 90%,** assuming **δ**≈-0.5 (Tchernyshyov+ 2015, Jenkins+ 2019)
  - **[CII]: 3%**
  - **[OI]: 14%**

  } C and O are in other phases
- H_2 S(1) traces warm gas (E/k ~ 1000 K)
  - CO (2-1) from ALMA/ACA (Tokuda+ 2021) traces colder gas
- Powerful winds and strong photoionization: N76 feedback

The Mystery of [SI]

There is an emission line corresponding to [SI] 25.25 μm
What is its **origin**?



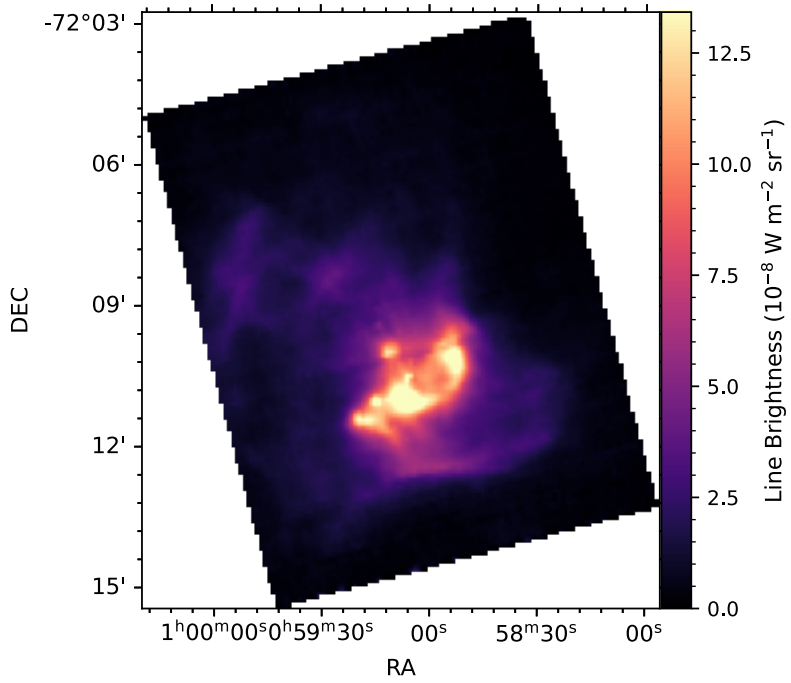


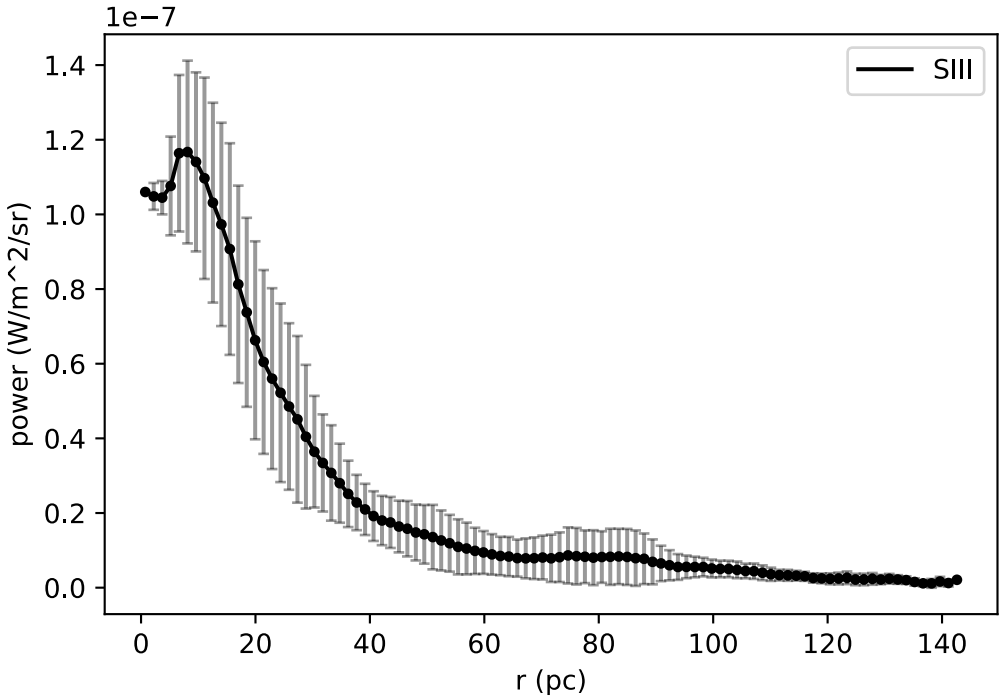
1. Contribution from other lines at a nearby wavelength?
   - ➢ Nearest line with a reasonable energy is [OIV] at 25.91 μm
2. Velocity shifted [OIV] emission?
   - ➢ Requires v≈7600 km/s, stellar winds are v≈2000 km/s (Shenar+ 2016)
3. Dust destruction from WR/O stellar winds?
   - ➢ Requires replenishing ≈1.5 × 10^{-3} $M_{\odot}$ of S^0 every 1.2 years

The N66/NGC 346 Region

[SIII] 33 μm

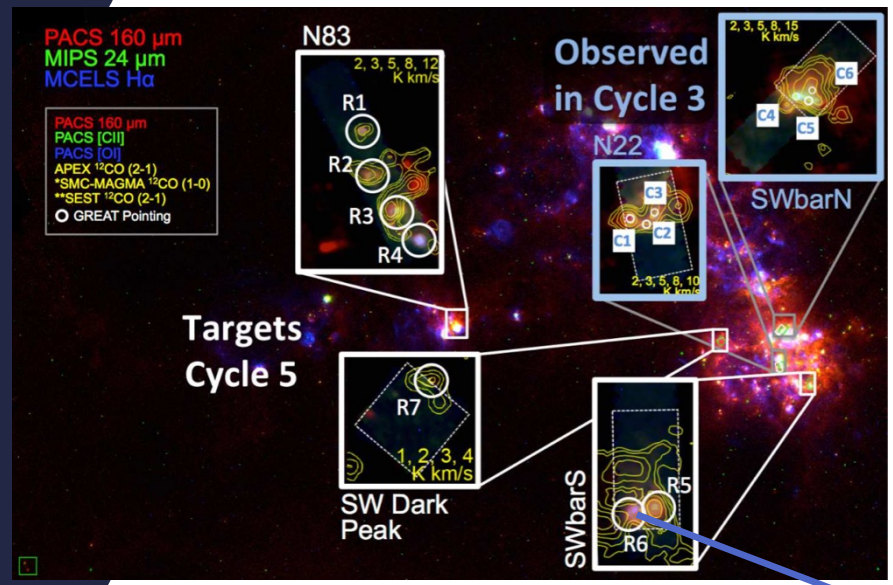
Work done by undergraduate at UMD: **Daniel Stapleton**



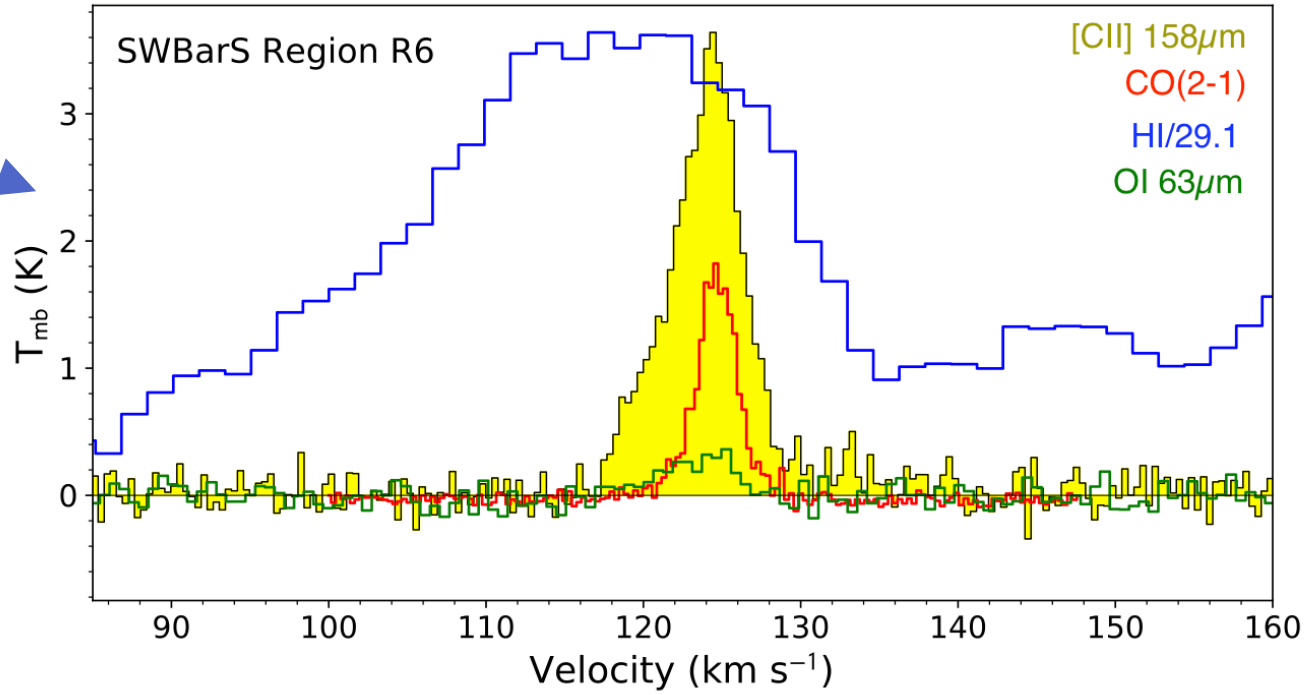


Complements JWST program: **GTO 1227** - NGC 346: Star Formation at Low Metallicity in the Small Magellanic Cloud (PI: M. Meixner, 29 hours)

SOFIA: Velocity resolved [CII] in the SMC



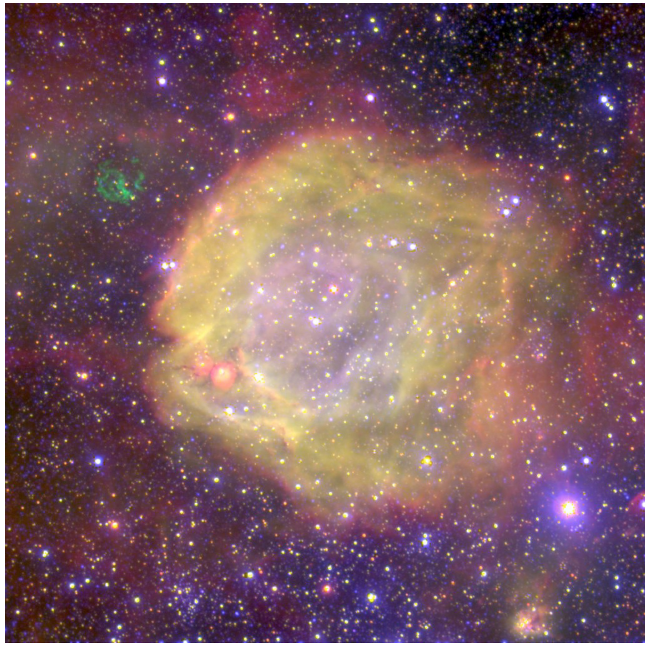
- Velocity resolved data can determine the origin of [CII] emission (e.g., Tarantino+ 2021)
- [CII] profile closer to CO than HI
  - Large component of CO-dark molecular gas likely (e.g., Lebouteiller+ 2019)



Summary and Conclusions

- Spatially resolved emission lines yield much more information than integrated quantities
- Photoionization models predict the intensity and distribution of most ionized gas emission lines in N76
  - Production of [SI] remains a mystery
- Continuing to model the SMC will reveal how HII region properties change across a galaxy
- JWST will be able to observe many of the emission lines in this work, up to 28.5 μm

Many synergies in the infrared with **JWST** and **SOFIA** together!



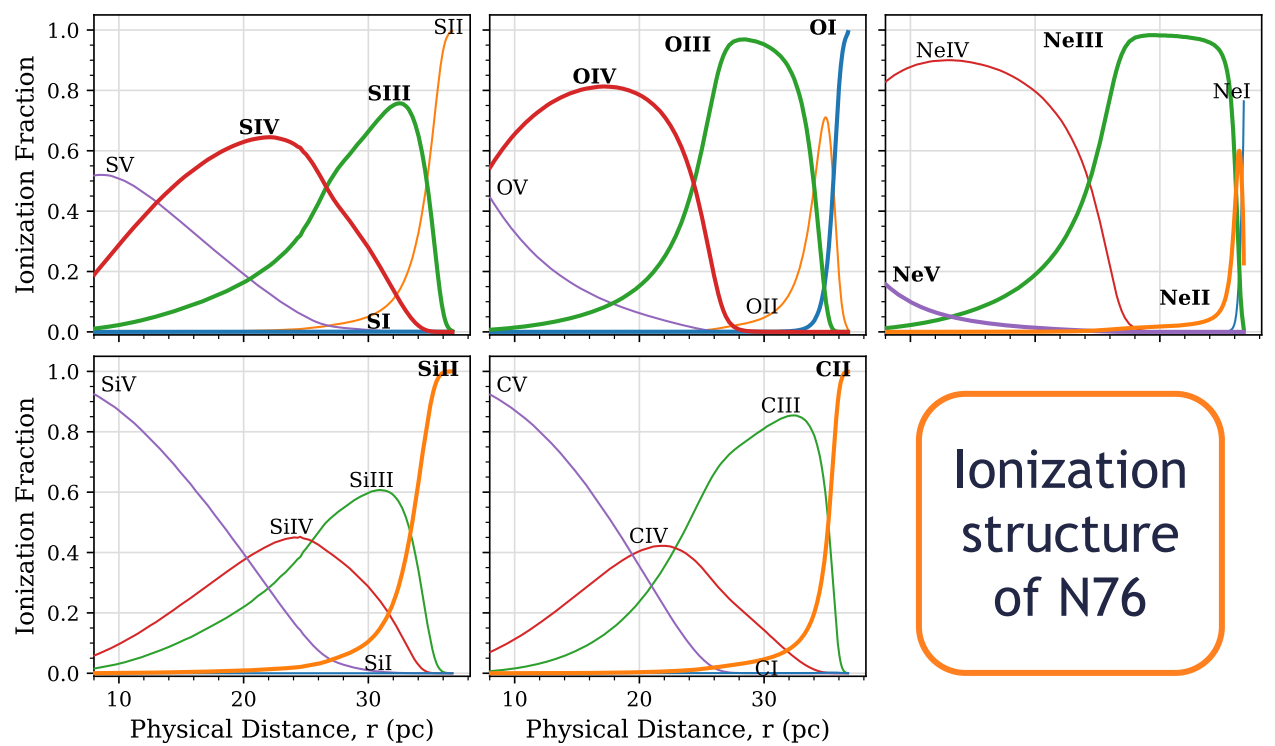
Thank you!!

Any questions?

Feel free to contact me at:
ejtino@astro.umd.edu

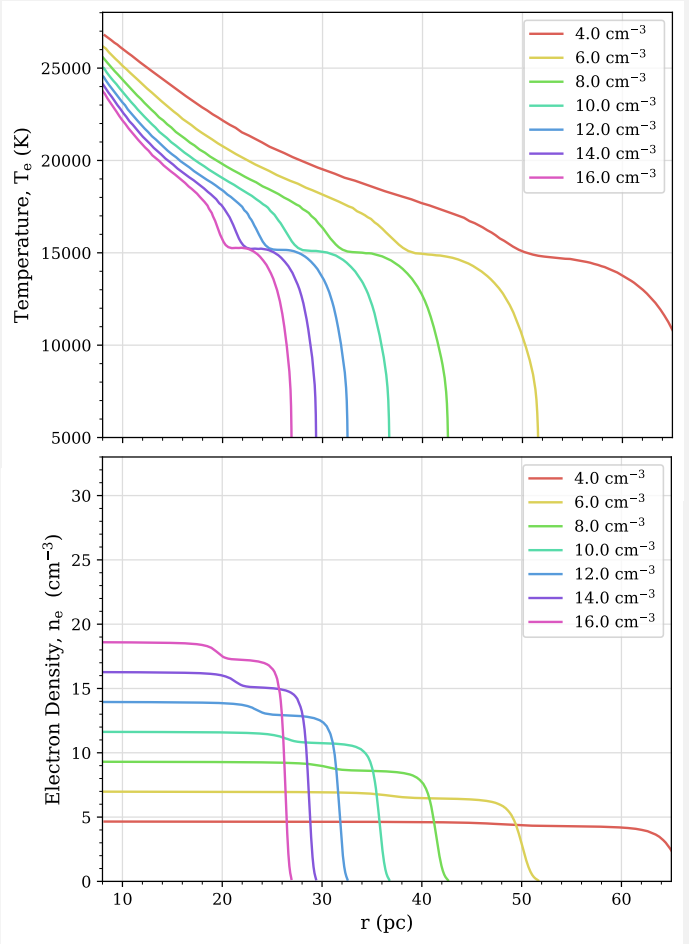
BACKUP SLIDES

Conditions in N76

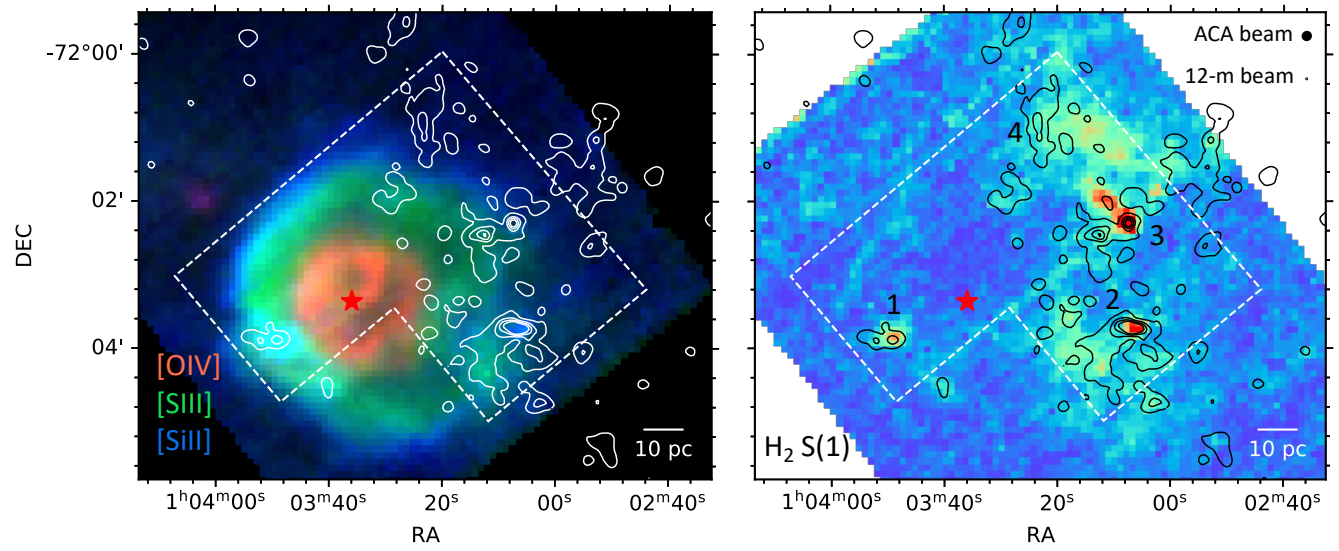


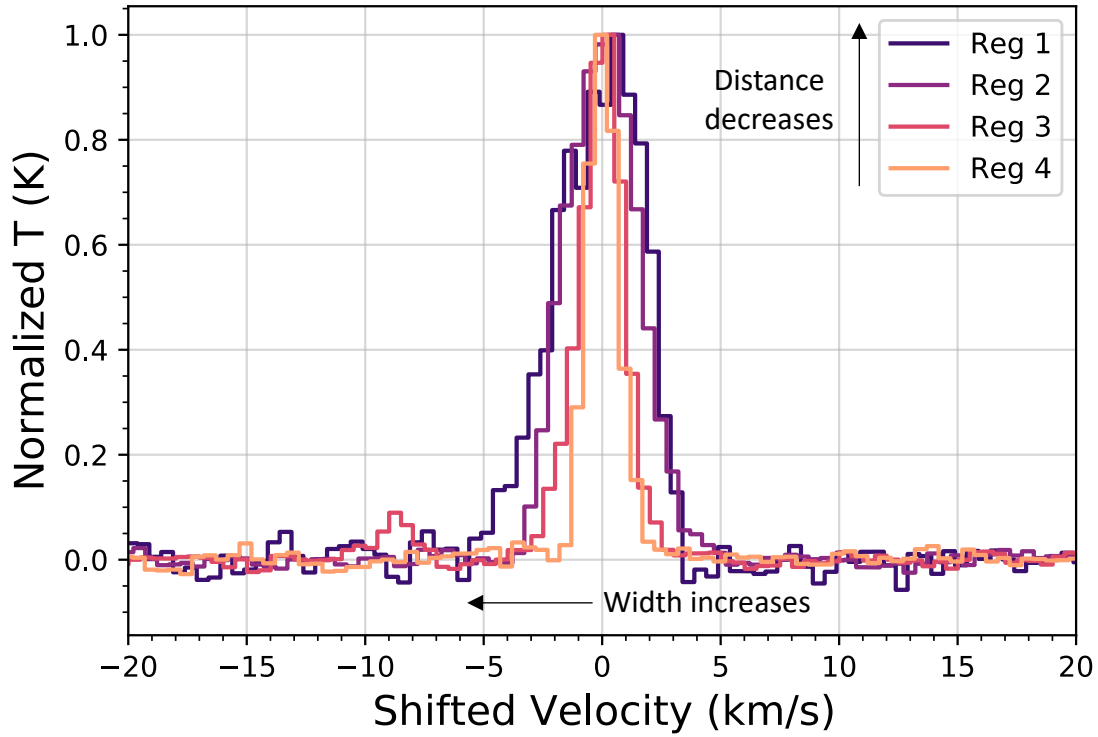
Ionization structure of N76

T_e and n_e



Velocity distribution of CO clumps





“Strip” profiles – non spherical symmetry