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# Infrared view of the multiphase ISM in the nucleus of NGC 253

On behalf of my collaborators:

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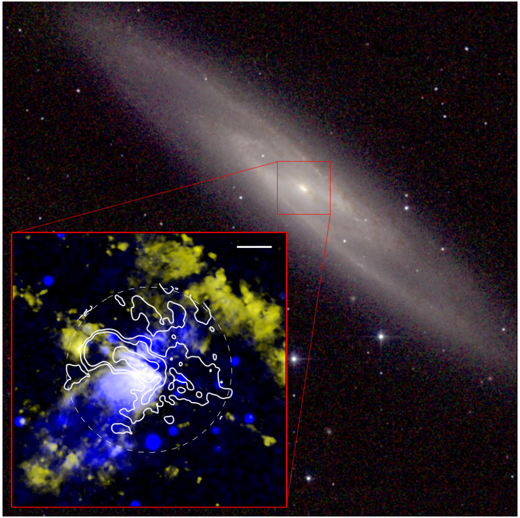
- Hans Zinnecker (Universidad Autonoma Santiago)

For details check: Beck et al. 2022, A&A, 665, A85 and Beck et al. (in prep.)

# NGC 253 (1)

- Nearby prototypical starburst galaxy
- $D = 3.5\,\mathrm{Mpc}$ Rekola+ 2005
- Edge-on $(i = 78^\circ)$ Pence 1981
- $\mathrm{SFR} = 3\,M_\odot\,\mathrm{yr}^{-1}$ Radovich+ 2001; $\sim 0.1\,M_\odot\,\mathrm{yr}^{-1}$ in the Galactic Centre
- Nuclear outflows $(3 - 9\,M_\odot\,\mathrm{yr}^{-1})$ in CO (contours), H$\alpha$ (yellow), X-ray (blue) Bolatto+ 2013, Leroy+ 2015, Walter+ 2017
- Near-infrared bar Iodice+ 2014
- $L_{\mathrm{stars}} \approx 5 \times 10^9\,L_\odot$ Beck+ 1984 ; $L_{\mathrm{TIR}} \approx 1 \times 10^{10}\,L_\odot$ Engelbracht+ 1998



Background: 2MASS J, H, K composite

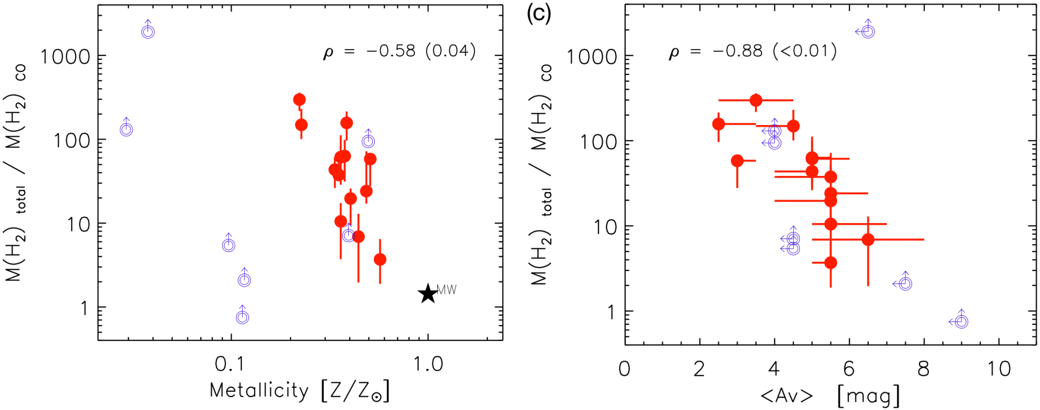
# NGC 253 (2)

- Ideal source to study
  - effects of a starburst and (hypothetical) AGN on surrounding ISM
  - origins and effects of nuclear outflows
  - contributions to star-formation of gas-flows along the bar
  - star-formation history from chemical composition

Questions and parameters tackled:

- Metallicity $Z = 0.3 - 1.5\,Z_\odot$ (Ptak+ 1997; Webster & Smith 1983)
- Extinction $A_V = 4.0 - 19\,\mathrm{mag}$ (Pérez-Beaupuits+ 2018; Engelbracht+ 1998)
- Presence of an AGN? Fernández-Ontiveros+ 2009
- Origin of [C II] $158\,\mu\mathrm{m}$ emission?

# Motivation (1)




Fraction of CO-dark gas in the Dwarf Galaxy Survey vs. $Z$ and $A_V$ (Madden+ 2020)

# Motivation (2)

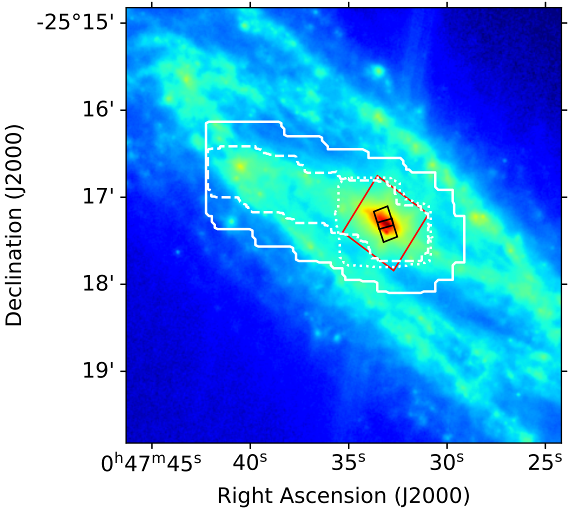
What excites [C II] $158\,\mu\mathrm{m}$ emission and where does it come from?

- Star-formation (e.g. Stacey+ 1991, Bigiel+ 2020)
- Diffuse ISM (+ star-formation, e.g. Kapala+ 2015, Sutter+ 2019)
- Jets (e.g. Appleton+ 2018)
- Active galactic nuclei (AGN, e.g. Herrara-Camus+ 2018)
- Origin of [C II] deficit? (e.g. Croxall+ 2012)

# Part I
# Observations

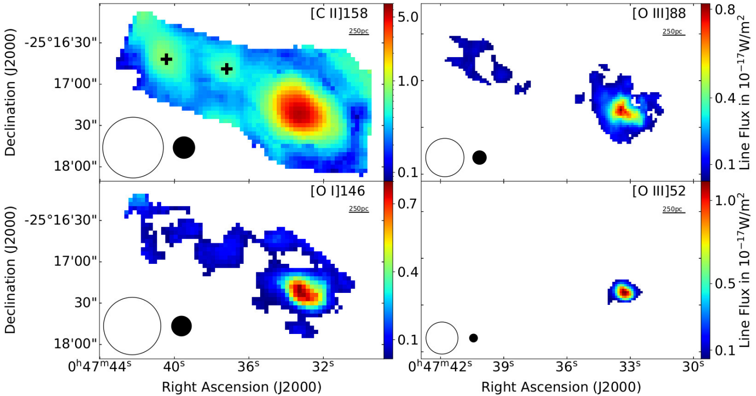
1

# Outline



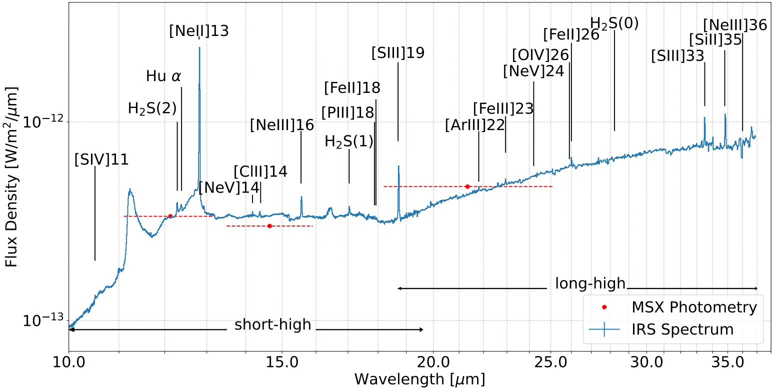

- Background: *Spitzer*/IRAC $8\,\mu m$ in logscale
- White: SOFIA/FIFI-LS
  - Solid: [O I] $146\,\mu m$ and [C II] $158\,\mu m$
  - Dashed: [O III] $88\,\mu m$
  - Dotted :[O III] $52\,\mu m$ (and [O I] $63\,\mu m$)
- Red: *Herschel*/PACS
- Black: *Spitzer*/IRS short-high and long-high

# SOFIA/FIFI-LS observations



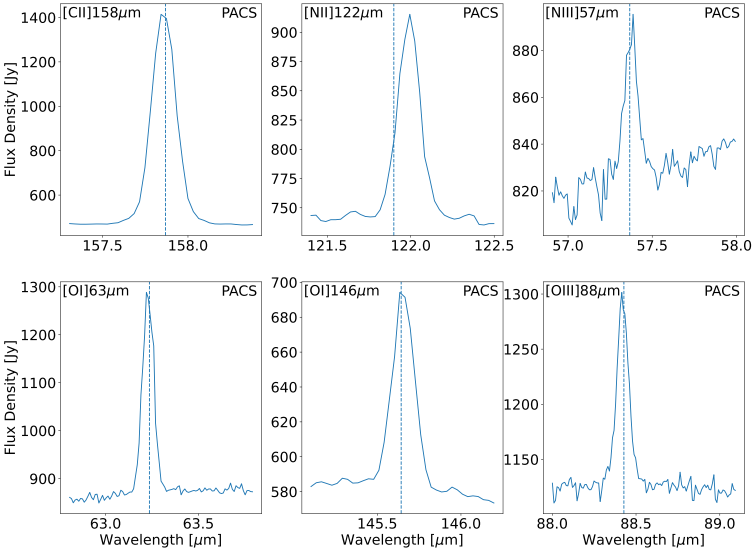

- Gaussian + linear continuum fit to spectrum in each pixel
- $\mathrm{SNR} \geqslant 3$
- Nucleus is semi-extended ($\sim 7''$)
- Empty circle: extraction aperture
- Filled circle: PSF size
- $[\text{C II}]\ 158\,\mu\mathrm{m}$ (in log) shows large emission along bar and bar-spiral (black cross)

# Additional data - *Spitzer*/IRS




- Spectrum from CASSIS database Lebouteiller+ 2015
- Short-high ($\sim$ $5'' \times 11''$) lacks of flux from nuclear region
- Scaling short-high to match long-high
- MSX photometry (red) to prove that no wavelength dependent scaling is needed

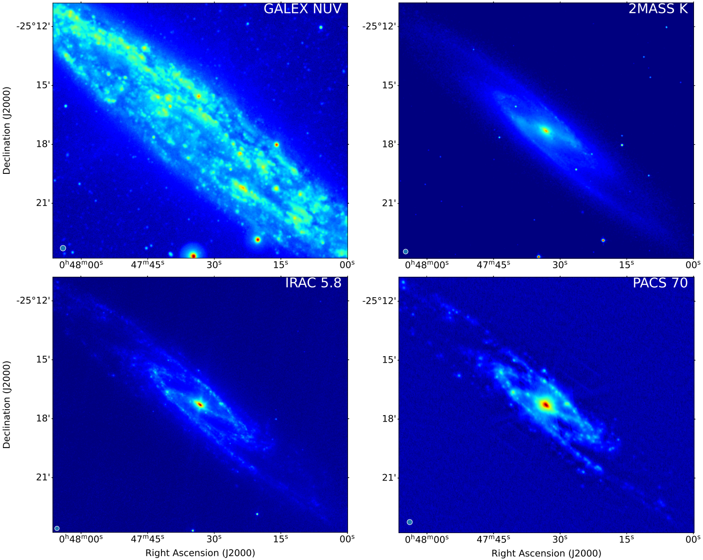
# Additional data - *Herschel*/**PACS**




- PACSman Lebouteiller+ 2012 to fit second order continuum + Gaussian in each spatial pixel
- Line flux from central $3\times3$ spaxel
- [O III] $88\,\mu$m, [O I] $146\,\mu$m, and [C II] $158\,\mu$m in good agreement with FIFI-LS

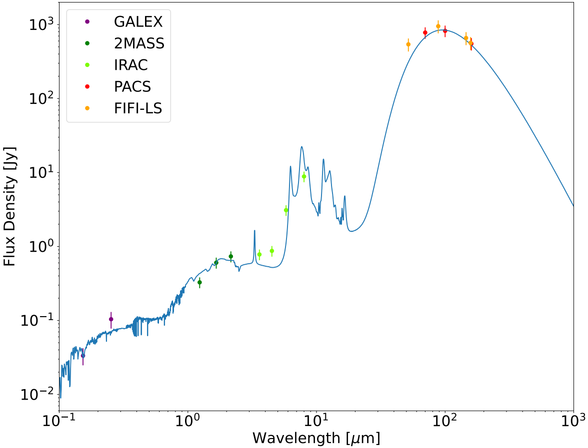
# Additional data - Photometry

- GALEX (FUV, NUV)
- 2MASS (J, H, K)
- *Spitzer*/IRAC ($3.6, 4.5, 5.8, 8.0\ \mu\mathrm{m}$)
- *Herschel*/PACS ($70, 100, 160$)



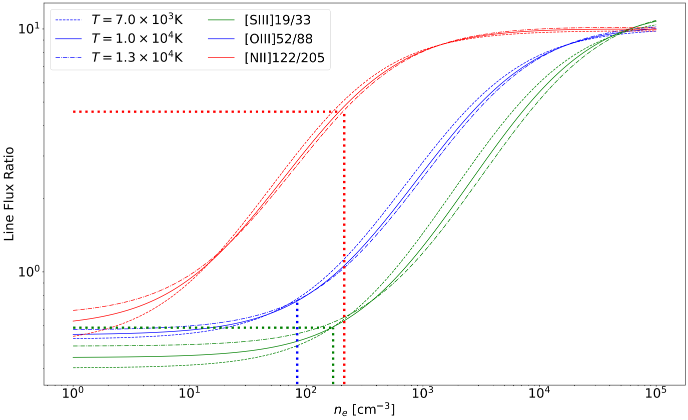
# SED modeling

- Convolution of respective beam-size with source-size
- SED fit with MagPhys (blue) (Multi-wavelength analysis of Galaxy physical properties, da Cunha+ 2008)
- FIFI-LS in good agreement
- $A_V = 4.35\,\mathrm{mag}$ and $L_{\mathrm{TIR}} = 9.2 \times 10^9\,L_\odot$
- Determined optical depth at MIR wavelengths (Weingartner & Draine 2001)
- Extinction correction negligible

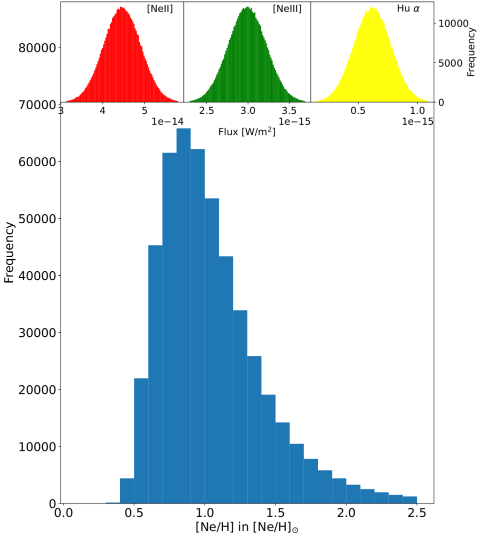


# Line ratios as probes of ISM conditions - Electron density

- [S III] $19/33\,\mu\mathrm{m}$, [O III] $52/88\,\mu\mathrm{m}$, and [N II] $122/205\,\mu\mathrm{m}$ ideal tracers of the density
- PyNeb Luridiana+ 2013 to calculate electron density
- Obtained electron density agrees between all line ratios despite different ionisation potentials and critical densities!
- [O III] $52/88\,\mu\mathrm{m}$ yields only an upper limit for $n_e$



# Line ratios as probes of ISM conditions - Metallicity




- $n_e$ from previous step
- Monte-Carlo method to determine Ne/H from ([Ne II] $13\,\mu\mathrm{m}$ + [Ne III] $16\,\mu\mathrm{m}$) / $\mathrm{Hu}\,\alpha$ line flux ratio
- $Z = 1.0 \pm 0.2\,Z_\odot$

# Part II

# Bayesian Modelling

2

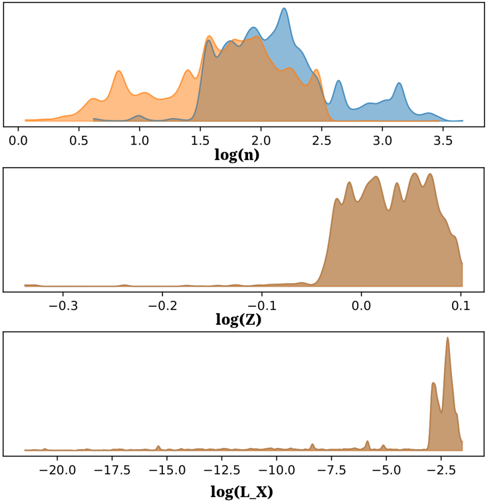
# *MULTIGRIS* - multi-dimensional grid search

- Details see Lebouteiller & Ramambason 2022
- Line fluxes and uncertainties (or upper/lower limits) as inputs/constraints
- Probabilistic approach to estimate PDFs of parameters in a grid of models (e.g. Cloudy)
- Allows prediction of other emission lines (e.g. CO) and secondary parameters ([C II] from the ionised, neutral atomic, molecular gas)
- Cloudy grid *star-forming galaxy with an X-ray source* (SFGX, Ramambason+ 2022)
  Parameters: $t$, $L$, $L_X$, $T_X$; $U$, $n$, $Z$, Depth

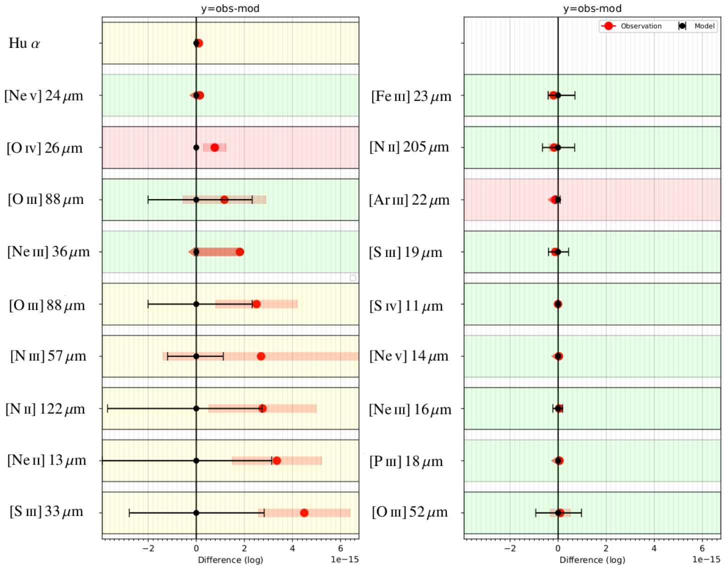
Goals:

- Determine metallicity and density from a larger set of emission lines
- Characterise X-ray source (AGN?)
- Determine [C II] from the different phases

# Results for the ionised gas (1)



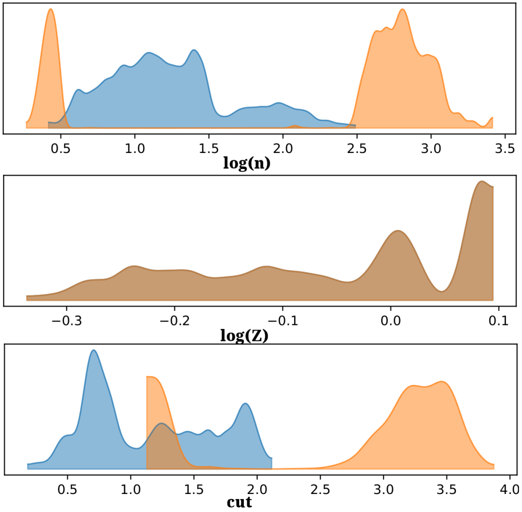

- PDFs for a 2 component model (blue and orange)
- Density and metallicity in good agreement with analytic results
- Low-luminosity AGN with $7.5 \times 10^5\ L_\odot$ ($1.2 \times 10^6$ Lopez+ 2022), comparable to Sgr A$^*$
- Run without X-ray source shows poorer agreement with observations




- Black: Predicted line flux and uncertainties
- Red: Observed line flux and uncertainties

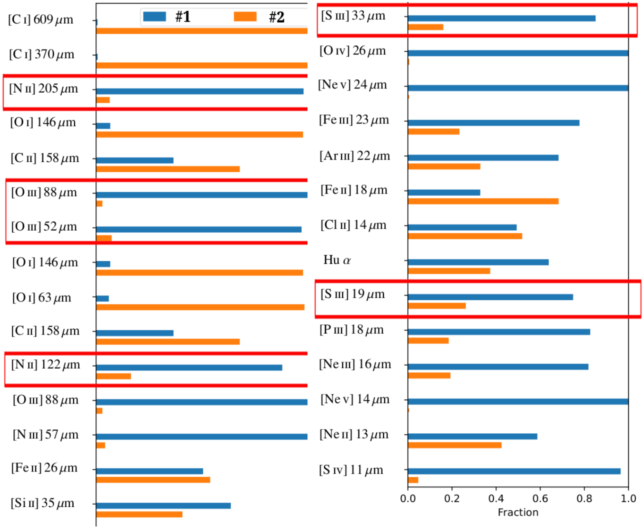
- Green background: observation lies within uncertainties of model
- Yellow background: uncertainties of model and observation overlap
- Red background: No agreement between model and observation

# Including lines from neutral atomic gas (1)



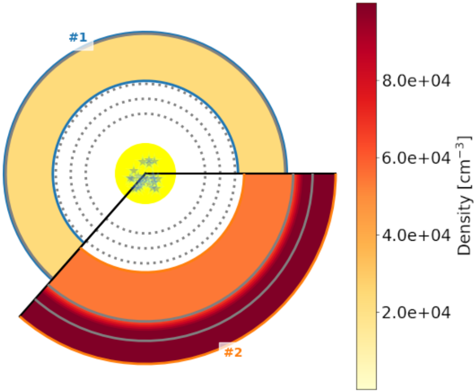

- Overall broader PDFs
- $\langle Z \rangle = 0.8\,Z_\odot$ still in good agreement
- Parameters of X-ray source do not change
- Cloud depth beyond the CO photo-dissociation front
  - $\mathrm{cut} = 1$: ionisation front
  - $\mathrm{cut} = 2$: $H_2$ photodissociation front
  - $\mathrm{cut} = 3$: CO photodissociation front
  - $\mathrm{cut} = 4$: $A_V = 10\,\mathrm{mag}$
- $\langle n_1 \rangle \sim 10\,\mathrm{cm}^{-3}$, $\langle n_2 \rangle \sim 350\,\mathrm{cm}^{-3}$

# Including lines from neutral atomic gas (2)



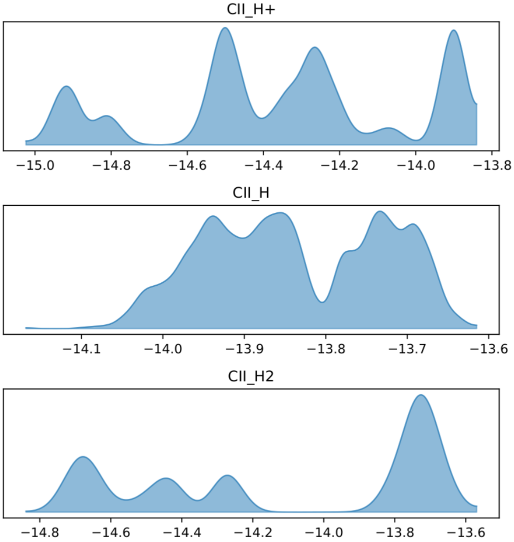

- [O III] and [N II] mostly coming from a diffuse component
- [S III] coming from both, diffuse and more dense component
- Analytic results are an average of two components

# Including lines from neutral atomic gas (3)




- Schematic view of ISM
- Nuclear star cluster (blue and bright yellow)
- Diffuse component (ochre) stopping at the ionisation front ($65\%$)
- Denser component going deep into the PDR ($35\%$)

# Predictions




- Multi-peaked PDFs
- $\log F([\text{C II}]) = -13.42\,\mathrm{W\,m^{-2}}$
- $\sim 12\%$ of [C II] from H II regions
- $\sim 37\%$ of [C II] from PDRs
- $\sim 40\%$ of [C II] from molecular gas
- Predictions for CO underestimated, $H_2$ overestimated
- Use CO and $H_2$ to better constrain the molecular gas

# Caveats and outlook

- Results so far have to be taken with care: $8$ of $33$ emission lines are not recreated
- Cosmic ray ionisation rate up to $3000\times$ larger Behrens+ 2022 (ALCHEMI)
- Use a continuous power-law for parameters instead of a discrete number of components (simulate several hundreds of components with linked parameters) Richardson+ 2016
- Include molecular lines (CO, $H_2$)

# Summary

- Created homogeneous dataset of $33$ emission lines and $12$ photometric bands from UV to submm range
- Obtained $L_{\mathrm{TIR}} = 9.2 \times 10^9\,L_\odot$ and $A_V = 4.35\,\mathrm{mag}$ from SED modeling
- Calculated $n \approx 10^2\,\mathrm{cm}^{-3}$ and $Z = 1.0\,Z_\odot$ analytically
  $\rightarrow \alpha_{\mathrm{CO}} = 3.8^{+5.8}_{-2.0}\,M_\odot \mathrm{pc}^{-2} \left(\mathrm{K\,km\,s^{-1}}\right)^{-1}$ (before $\sim 1$ up to $\sim 40$)
- Nuclear region contains a low-luminosity AGN
- Probabilistic approach confirms metallicity
- Mixing of a low-density (diffuse?) and higher density component
- Majority of [C II] coming from molecular gas