Radiative transfer in the interstellar medium

Aurore Bacmann
Institut de Planétologie et d'Astrophysique de Grenoble

Scientific goals

ISM
Gas tracers (molecules, ions) → spectra
Dust → continuum

1. Determine masses

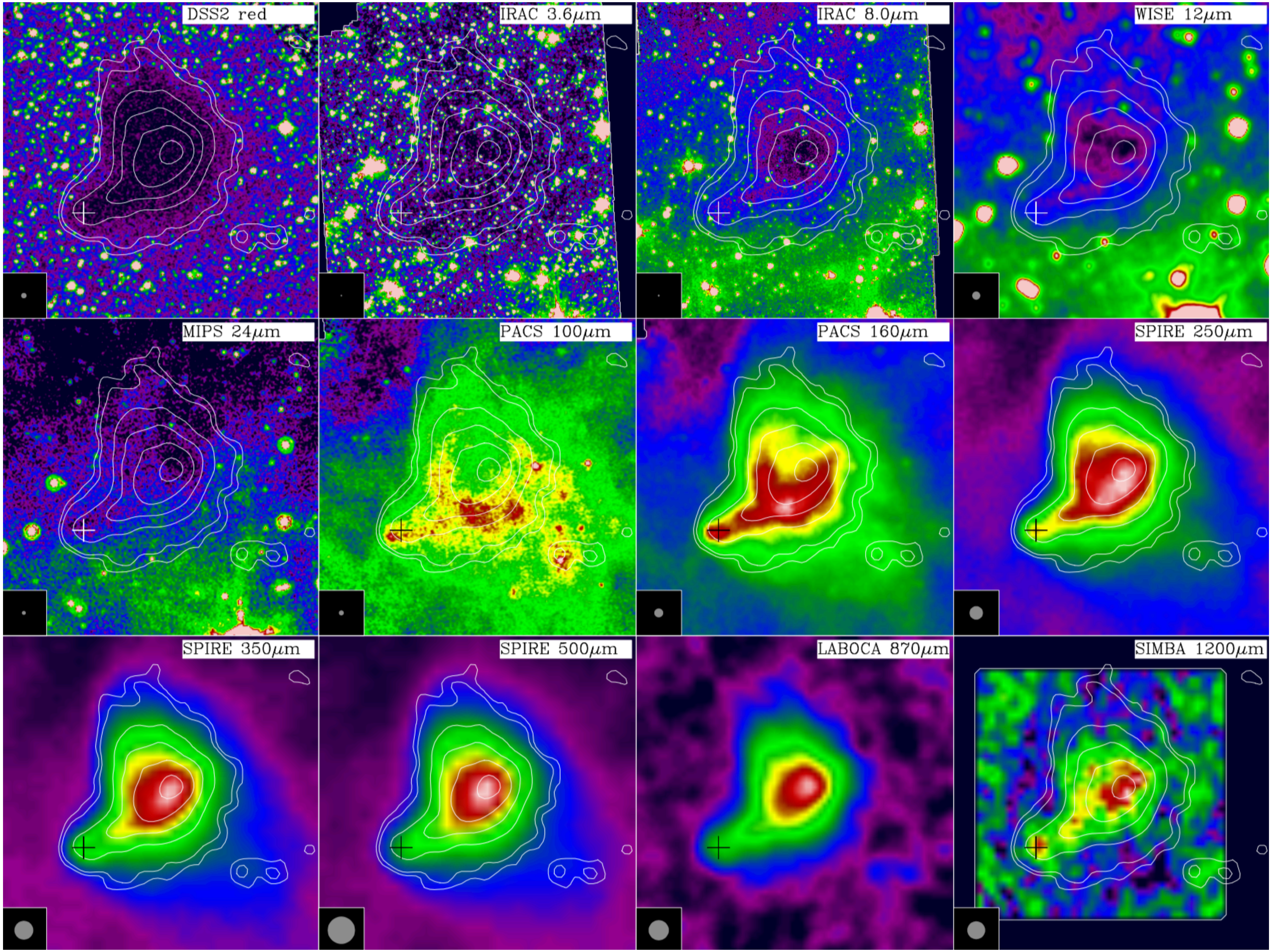
e.g. H_2 mass / column density (from dust continuum), molecular abundance

2. Model (multi-λ) image(s) or (multi-transition) spectral map(s)

- Derive physical properties: temperature or density profile
- Derive molecular abundance profile
- Derive velocity profile

3. Energy transport in (M)HD modelling

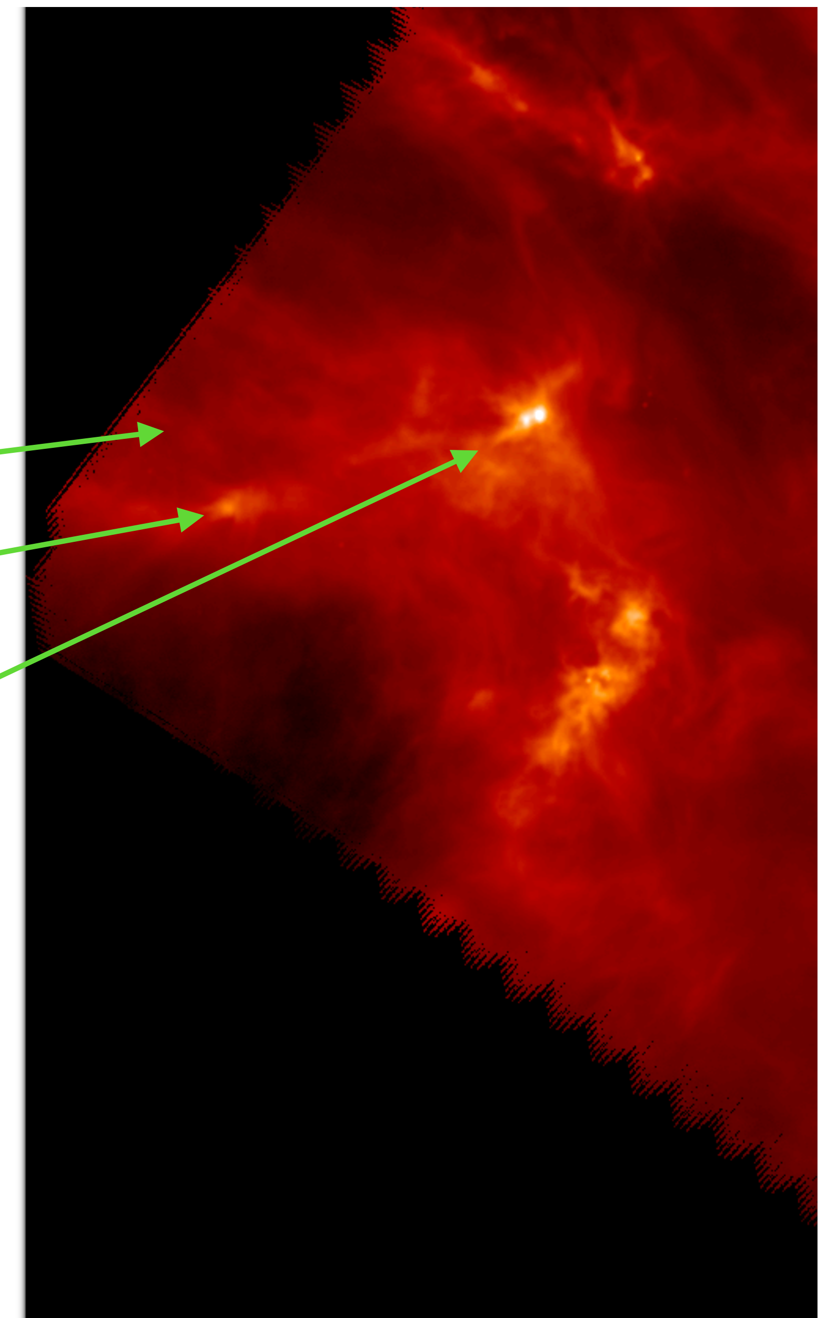
- Not stand-alone, simplifying assumptions



Nielbock et al. (2012)

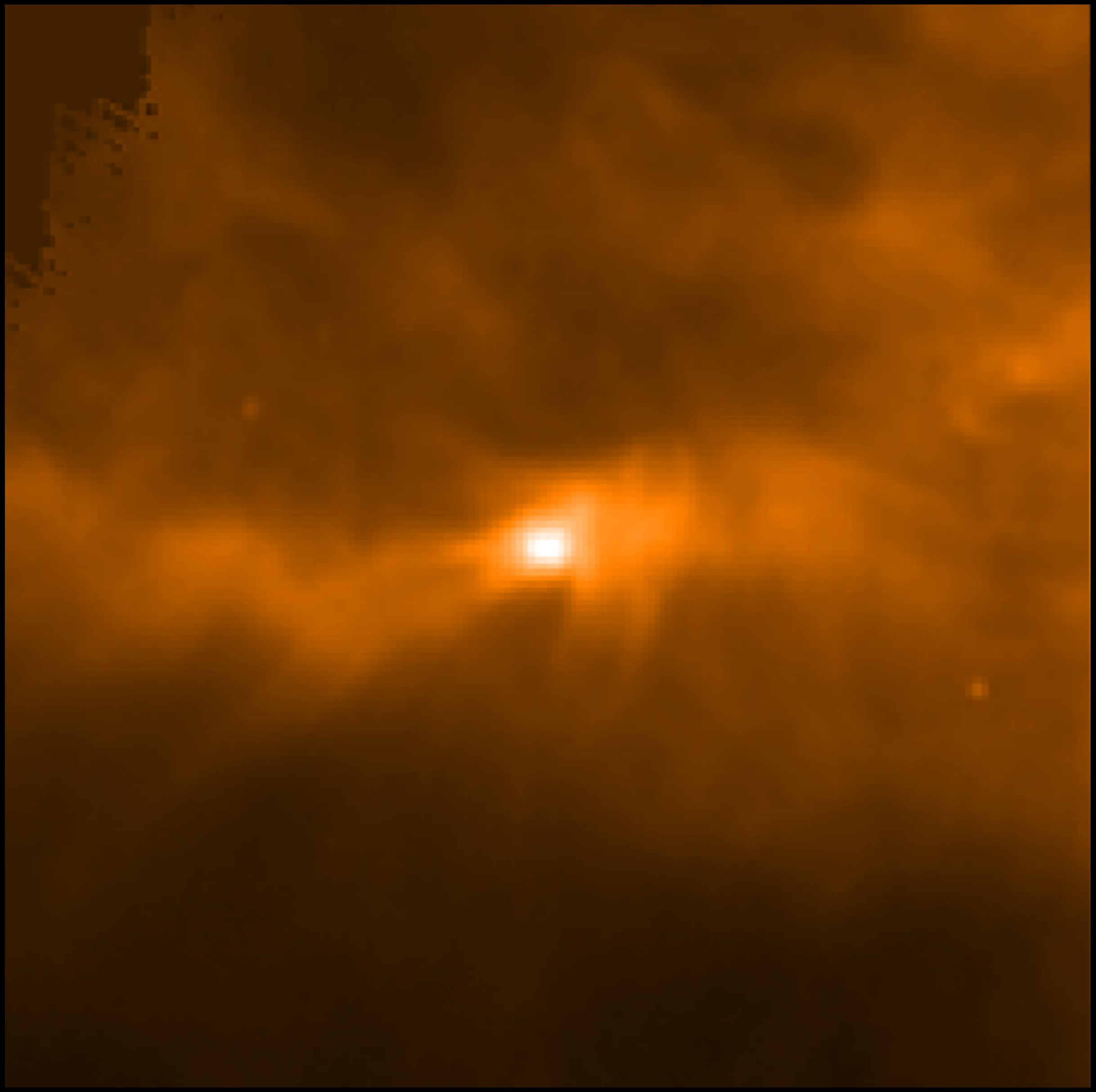
Specificities in the ISM

- Resolved sources
- Densities are very low
  → non-LTE treatment required
  - Molecular cloud: 10^2 - 10^3 cm^{-3}
  - Prestellar core: 10^5 - 10^6 cm^{-3}
  - Protostellar envelope: 10^5 - 10^8 cm^{-3}
- Geometry: extremely complex
  - 3D codes exist but difficult and slow
  - 1D (or 0D) approximations used



Herschel/SPIRE 350 μm Gould Belt Survey, André et al. (2010)

Example of real-world geometry



Opacities

❖ Lines

- Einstein coefficients experimentally determined: *many molecules are missing!*
- Collisional excitation: collisional coefficients need to be calculated with H_2, H, e^-, very difficult for large molecules, *many more molecules are missing*
- Databases for molecular Einstein coefficients (CDMS) and collisional rates (Basecol, Lamda)

❖ Continuum

- Large uncertainties on dust opacities: property change with temperature?

Others

Not taken into account:

- Magnetic fields: negligible effect (~μG)

- Self-consistent heating

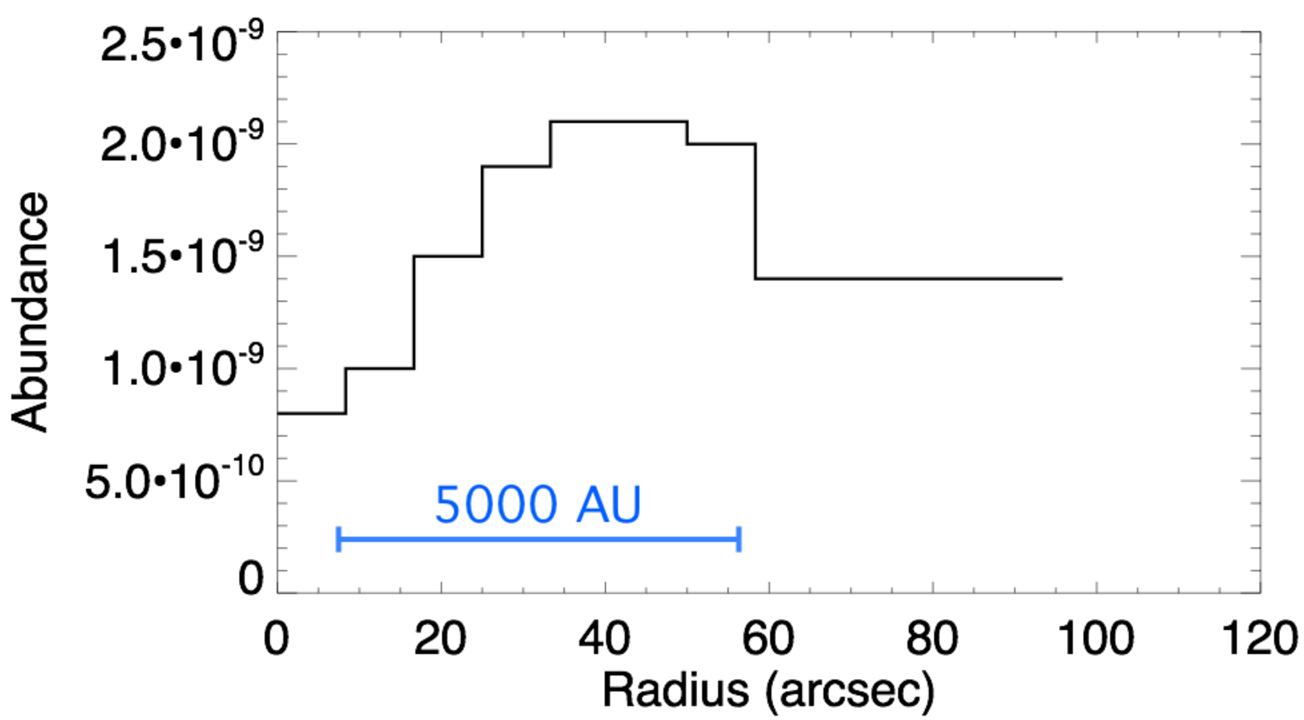
  Gas temperature depends on diverse and hard-to-model effects:
  - photoelectric effect
  - Coupling of gas with the dust at high densities (depends on ISRF)
  - Cosmic-ray heating
  - Molecular hydrogen formation
  - Gravitational contraction, ion-neutral slip
  - Radiative cooling

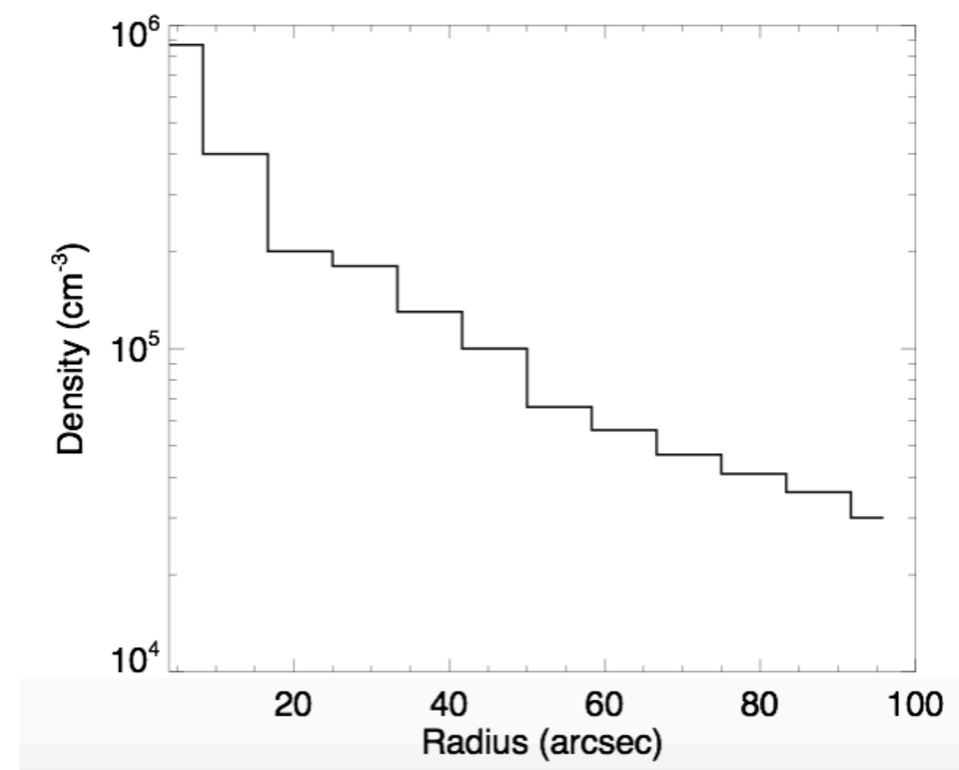
→ gas temperature is assumed

Input/output line transfer codes

❖ **Input**

- H_2 Density profile
- Kinetic temperature profile
- Molecular abundance spectrum
- Velocity profile (radial, rotation)

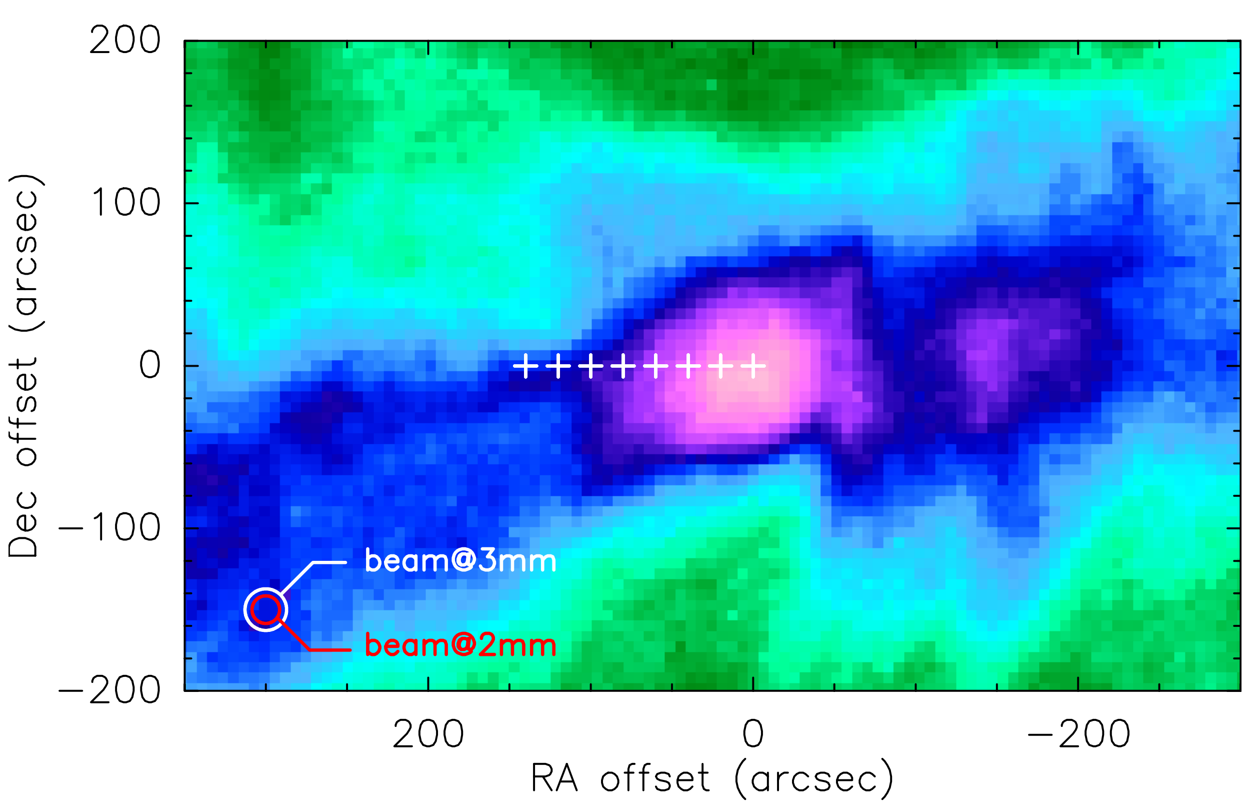


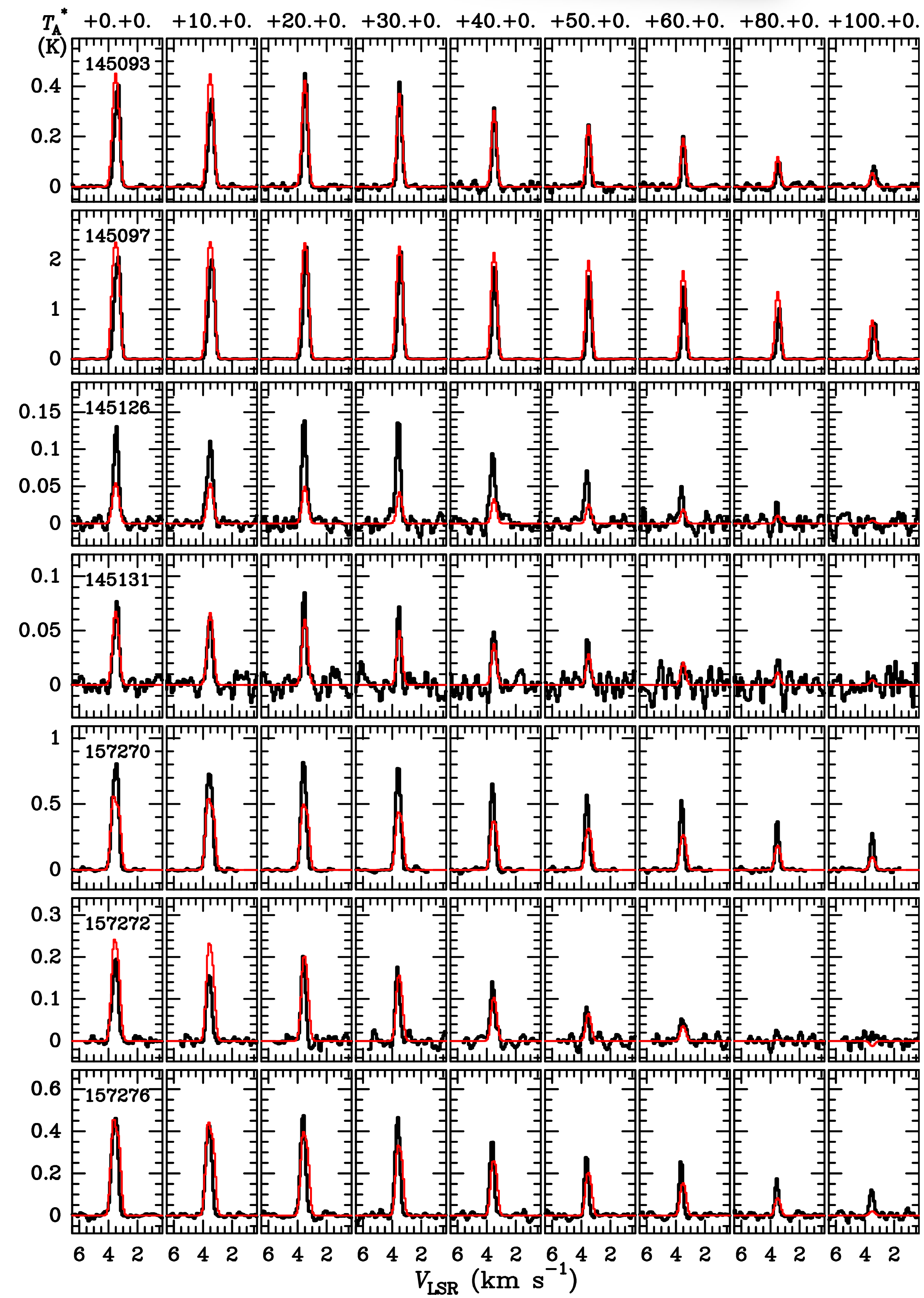


Input/output line transfer codes

❖ **Output**

- Maps of spectra
- No automatic optimization



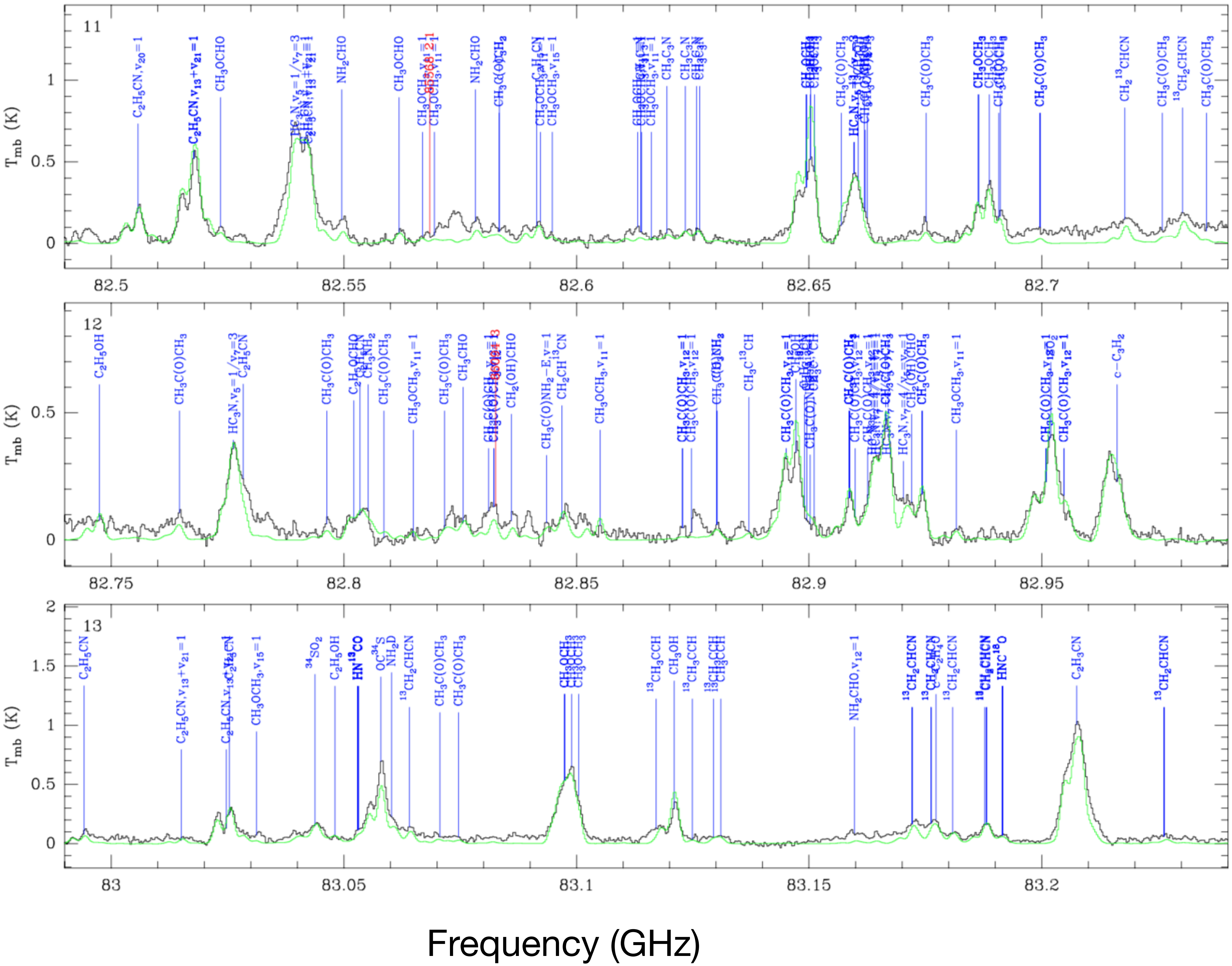


Codes

- **RATRAN** (Hogerheijde & van der Tak 2000)
  - “accelerated” Monte Carlo
  - Coupling with dust
  - 1D version open source, 2D version with collaboration

- **ALICO** (Daniel & Cernicharo 2008)
  - 1D, short characteristics method, line overlap included
  - Coupling with dust
  - Use on collaboration basis

- **MC Bernes** (Bernes 1979, Pagani et al. 2007)
  - 1+1D, Monte Carlo, line overlap included
  - No coupling with dust
  - Open source



Belloche et al. (2013)