Molecular Lines in Star Formation Regions – the ALMA Challenge

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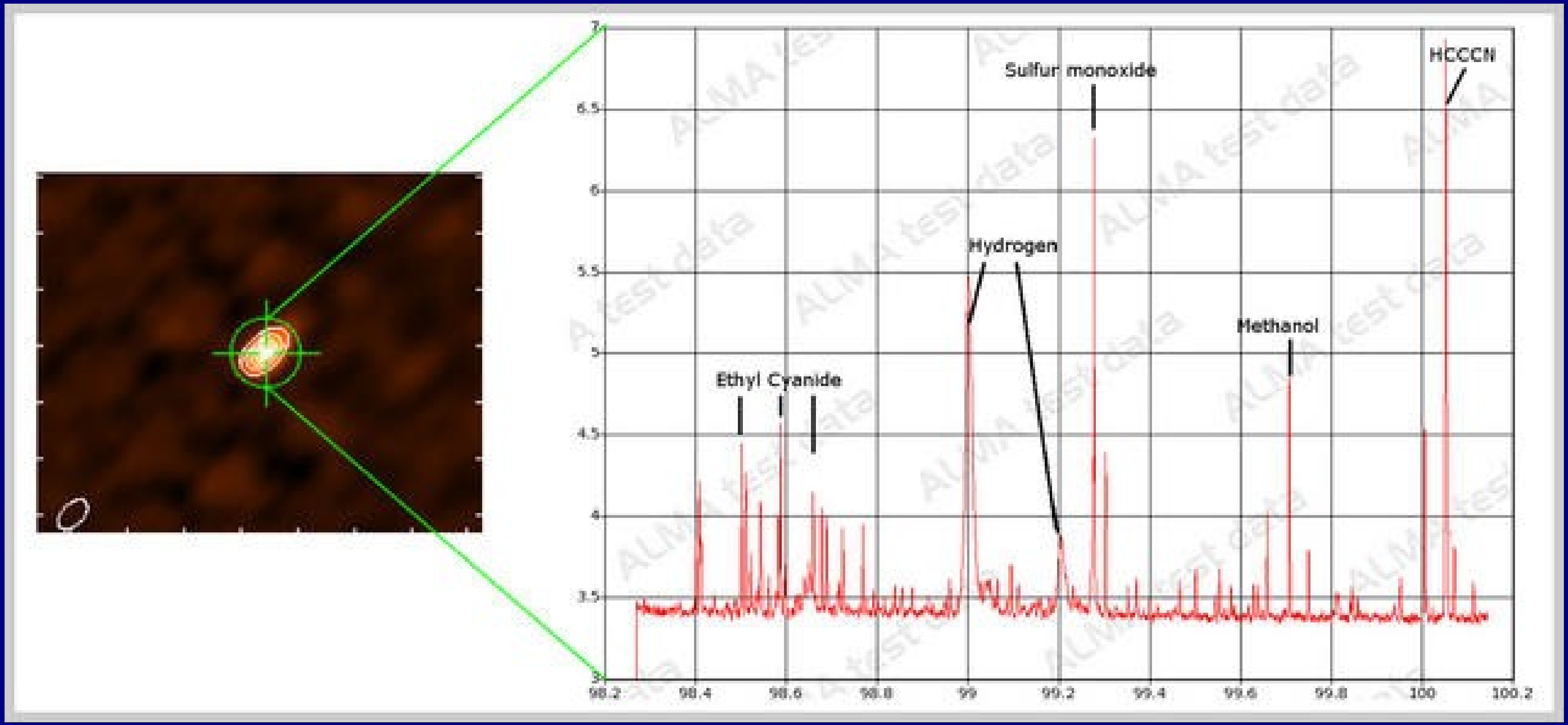
Molecular Lines in Star Formation Regions

- Molecular lines trace the **kinematics** and **chemistry** (composition) of molecular clouds.
- This is of particular interest in regions of star formation, where the densest regions are obscured by dust in optical and near-IR.
- The lines also trace physical conditions such as temperature and density, **complementary** to mm/sub-mm **dust continuum** data e.g. ATLASGAL and ALMA continuum.
- The **chemistry** can be used as a 'clock' of the star-formation process (in principle, that is subject to model limitations), as the chemical composition evolves in time and space with the protostar collapse compression, heating etc.

- ALMA will do multi-line imaging routinely, so get ready for a revolution BUT there are challenges in turning the flood of data into understanding.

Example ALMA data



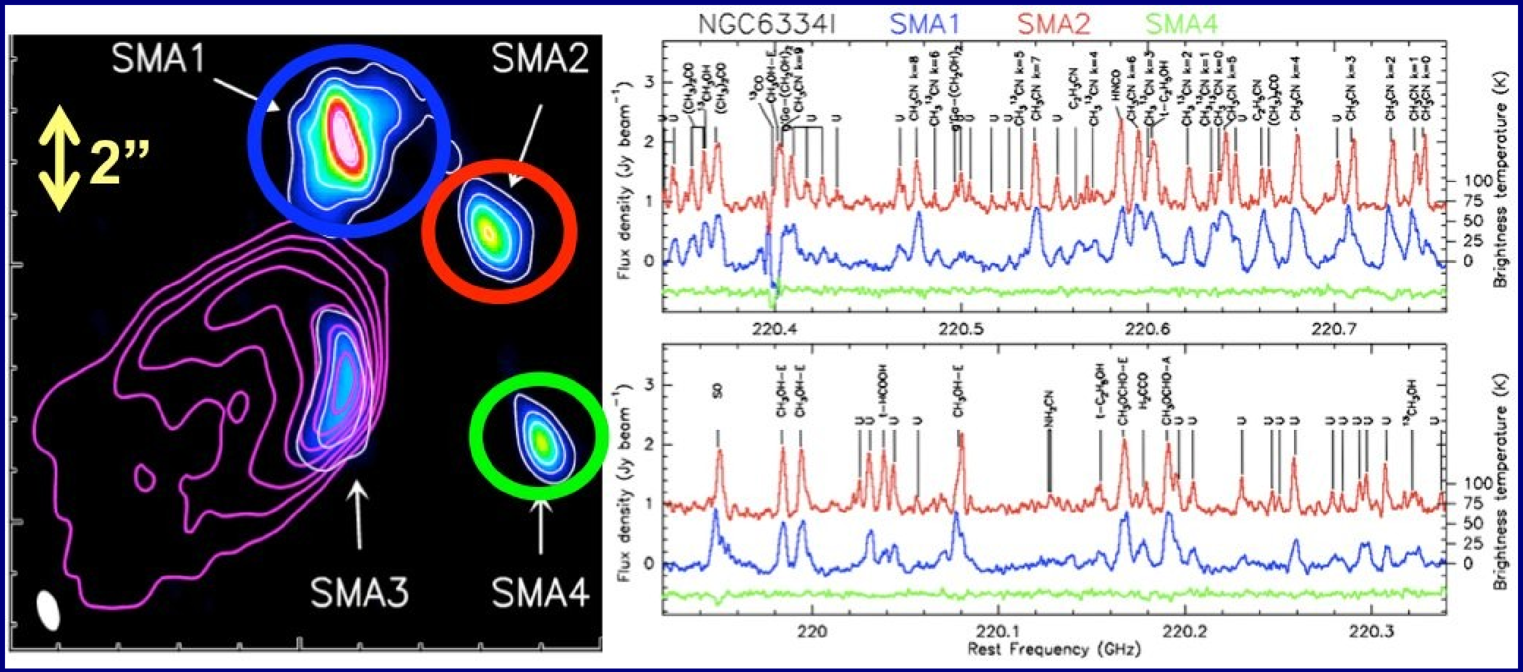
ALMA Test Image - November 2010

An example of ALMA’s potential as a spectroscopic instrument: on the left is the map of the molecular “hot core” G34.26+0.15, … a section of the spectrum near 100 GHz shows a “forest” of molecular lines. A few of the chemical species that are responsible for the emission lines are identified on the plot.

ALMA as a spectral line instrument

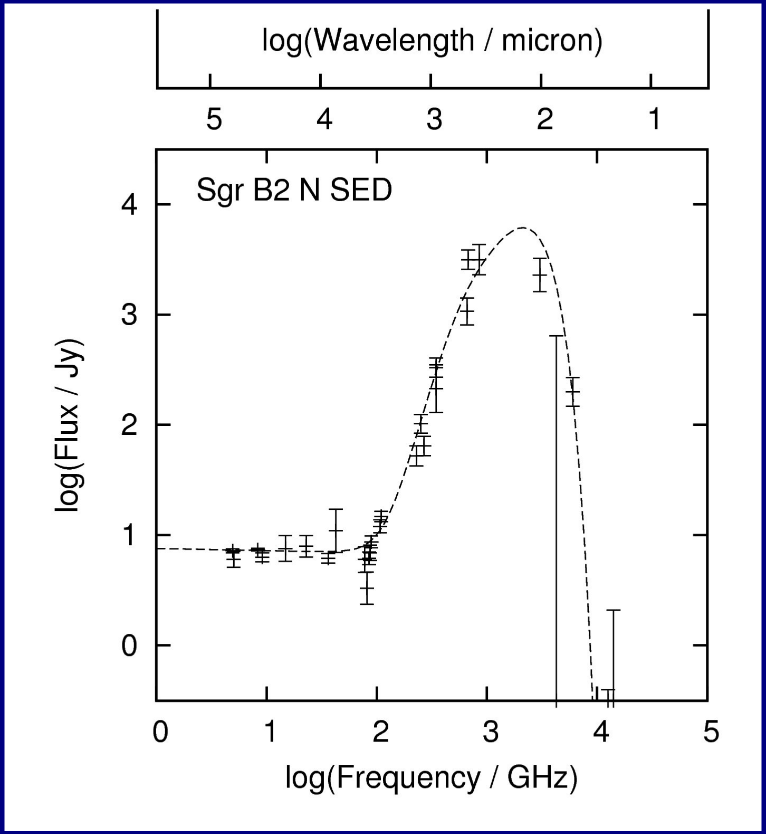
The combination of high sensitivity, powerful correlator modes (ie combination of large bandwidth, up to 4 x 2 GHz, and large number of channels) and mm/sub-mm bands, means that observations of star formation regions will be **filled** with molecular lines.

(From Brogan et al. 2011, in prep., and ALMA Early Science Primer)



Line contamination

Even if the primary goal is measuring the continuum for SEDs (spectral energy distributions) of cores, the lines can contribute of order 10 % of the flux, so for accurate SEDs it is probably necessary to do line observations to measure the continuum between the lines.



Aside - “Green Fuzzies” or “Extended Green Objects” (EGOs) were found in Spitzer GLIMPSE from anomalous extra emission at 4.5 μm, compared to 3.6 and 8.0 μm bands. This is due to emission lines, now followed up, BUT the phenomenon would have been clearer in spectral imaging observations.

Chemical complexity

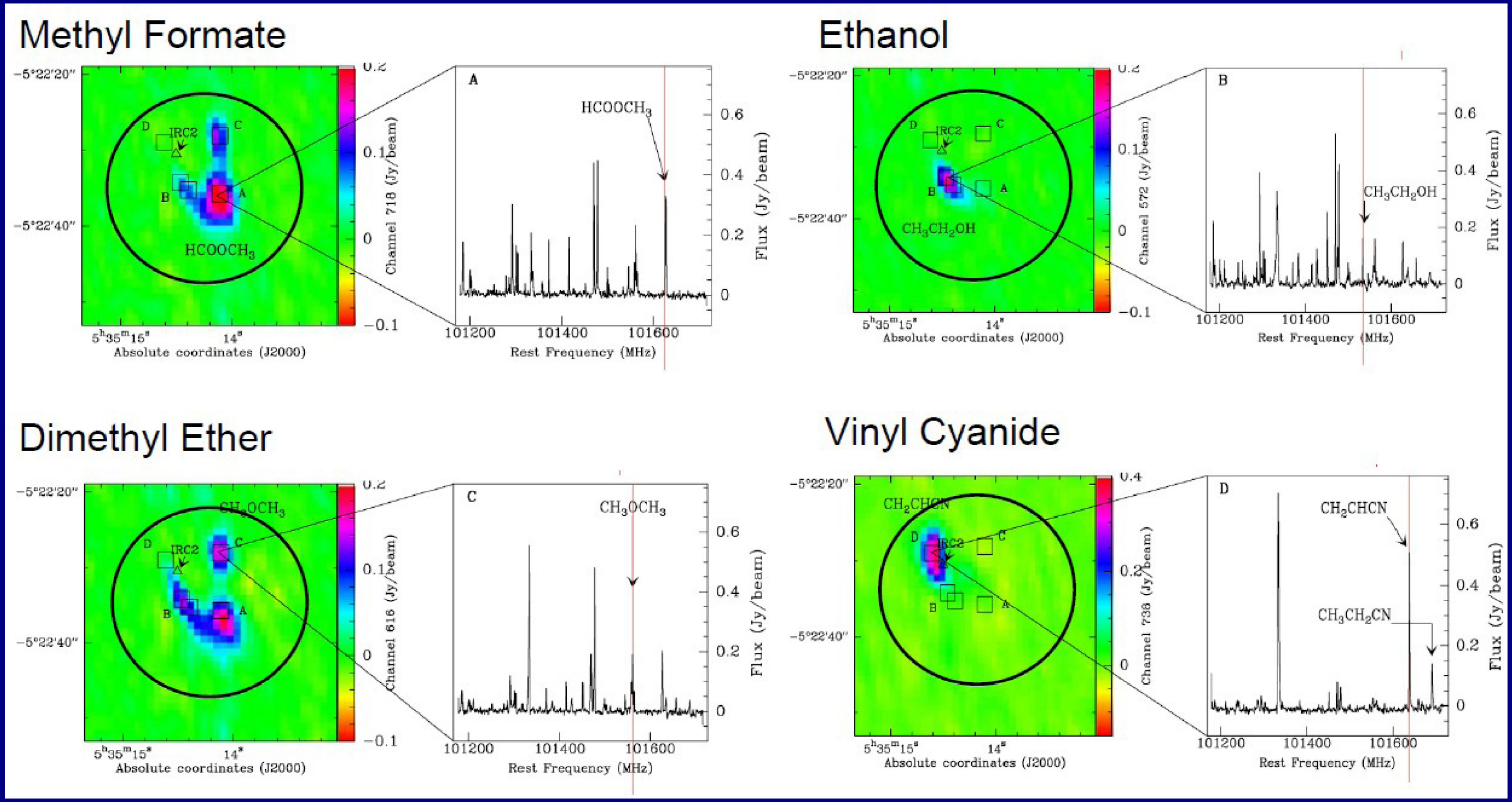
The “forest” of lines is due to more complex organics molecules, with many lines, as yet, unidentified (U).

Simple molecules (eg. SO) have fewer transitions, but strong (as spectral line flux distributed over fewer lines).
More complex molecules (eg. CH_3CN, CH_3OH) have more rotational, vibrational states, so many more transitions, so the lines are weaker (line flux distributed over many lines). They are also less abundant, **but** there are more possible molecules.

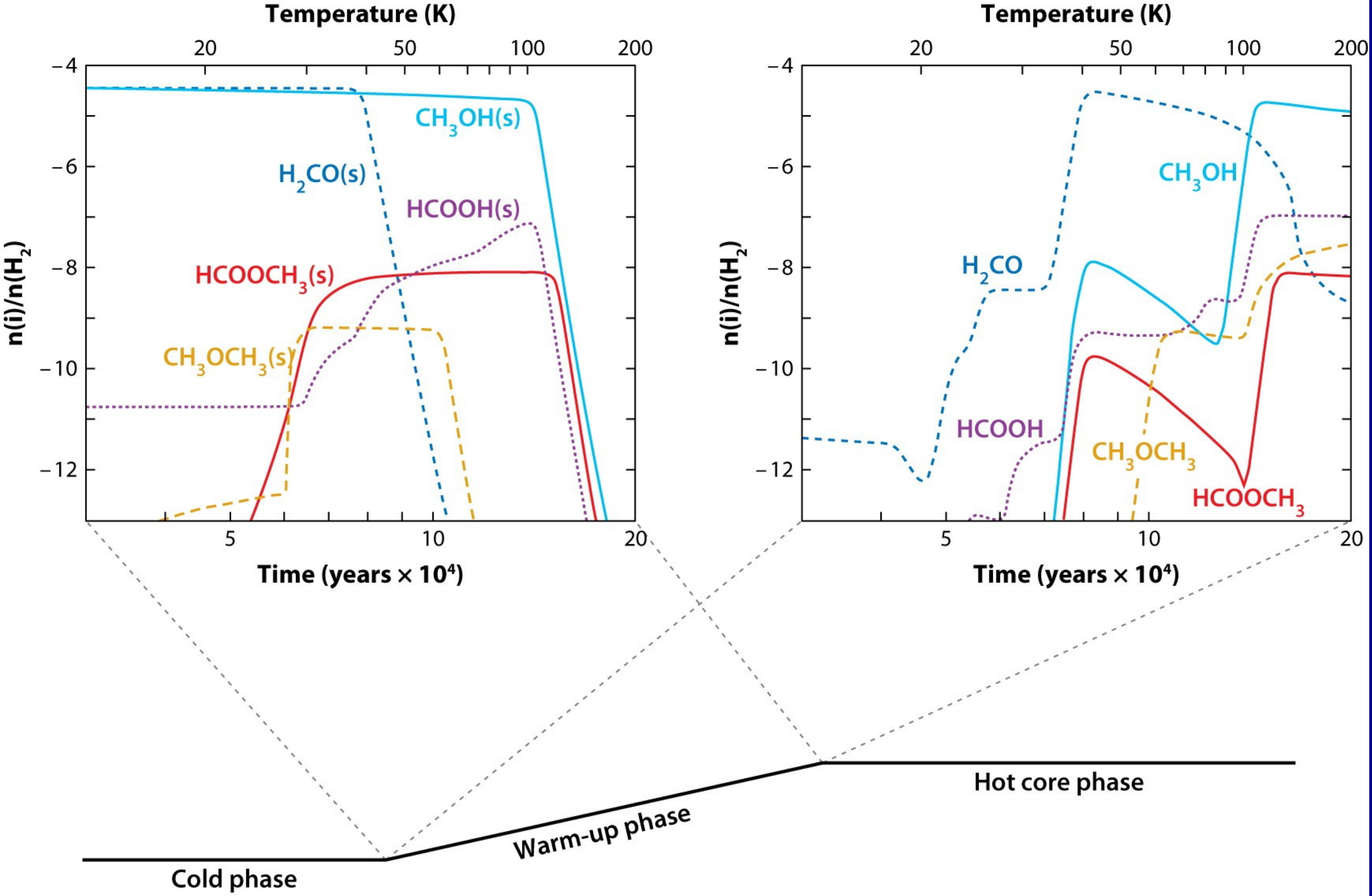
Tools for identification and spectroscopic parameters see http://www.splatalogue.net/

Spatial differentiation

Different lines and molecules highlight different
- physical conditions of temperature and density
- chemistry, which is predicted (models) to vary with the history:
  Cold - gas phase and grain surface
  Warm up – heating and grain-mantle sublimation
  Hot core – further gas phase and grain surface (while grains last)



Example of time-dependent modelling



Herbst E, van Dishoeck EF. 2009.
Annu. Rev. Astron. Astrophys. 47:427–80

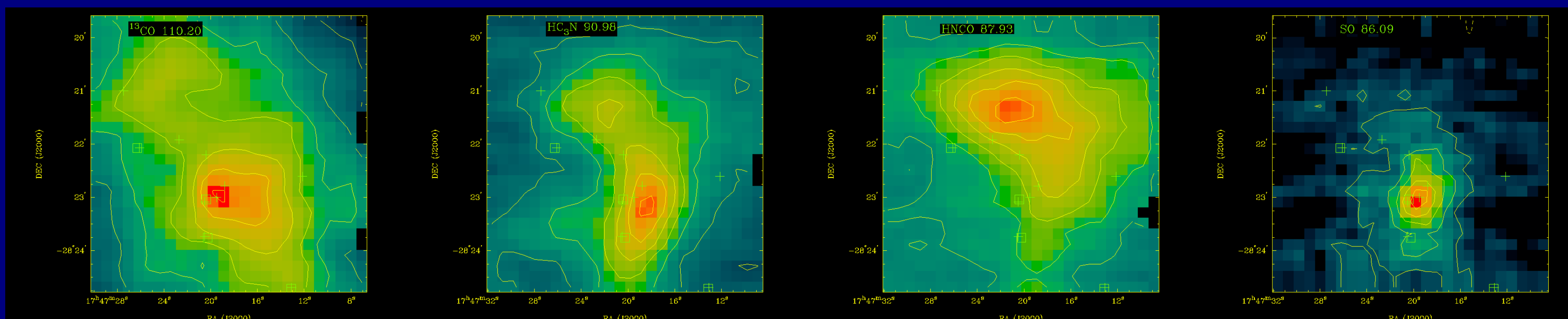
Present example from ATCA

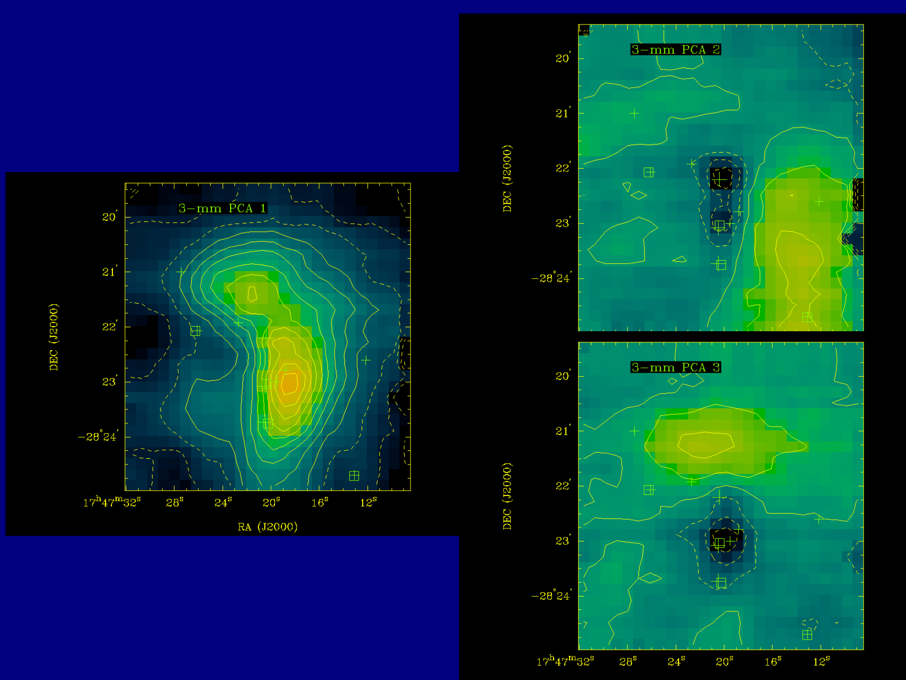
Work of UNSW (M.Phil.) student Egon Balnozan,
using data from project C2102, PI Tracey Hill
= 3-mm and 7-mm observations of “millimetre-only” cores,
presumed to be early stage, with CABB.

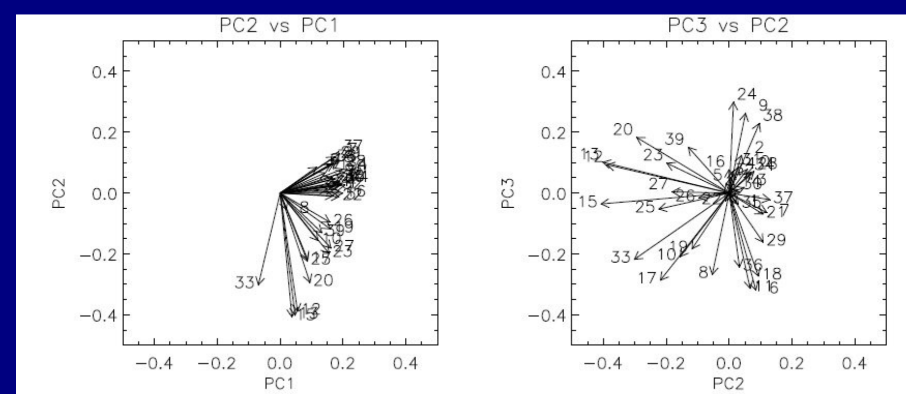
Even though the project was designed for continuum observations for SEDs, the 1 MHz channel data (3 and 7 km/s pixels) showed several **thousand** significant (> 5 σ) lines over the sample of sources. Most of these are unknown lines.
Several **hundred** lines are detected in more than one source, and can be identified with transitions already known in the ISM (NIST Lovas) or other transitions of molecules known in the ISM (JPL, CDMS etc) using splatalogue.
As this is ATCA imaging data (H75 and H214), we have images of the lines (ie cubes of data, but undersampled in velocity).

Analysis – example from Mopra

Multi-line imaging of Sgr B2 with Mopra in 3-mm and 7-mm bands (Jones et al. 2008, 2011) – dozens of lines - describe similarities and differences with Principal Component Analysis (PCA).



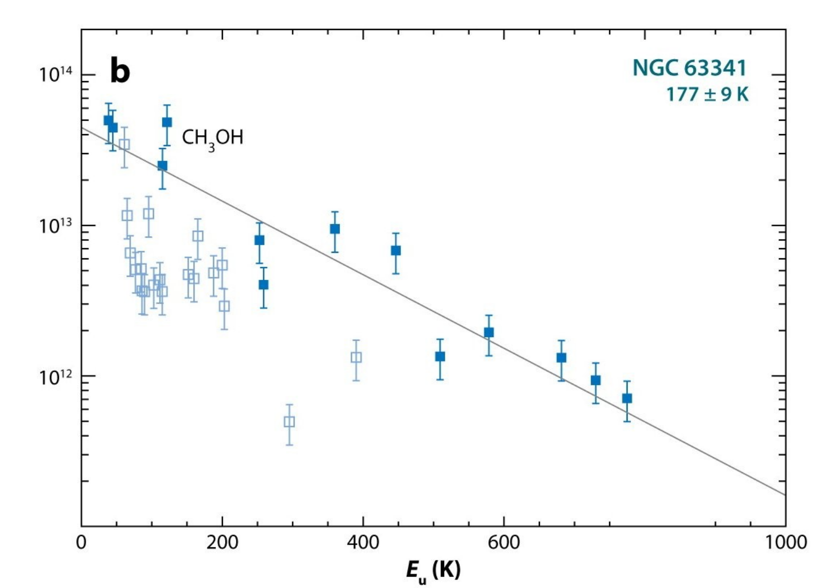




Analysis – excitation diagrams

$N_u/g_u = (N_{tot} /Q(T_{rot}))\ \exp(-E_u/T_{rot})$
$= 3k \int T_{MB}dV \,/\, 8\pi^3\nu\mu^2S$
for optically thin, local thermodynamic equilibruim (LTE), so $\int T_{MB}dV$ = brightness temperature, integrated over velocity is proportional to N_u = column density in upper level.

Plot N_u/g_u on log scale with
E_u = energy of upper level
to get intercept giving
N_{tot} = total column density
and
T_{rot} = rotational excitation temperature



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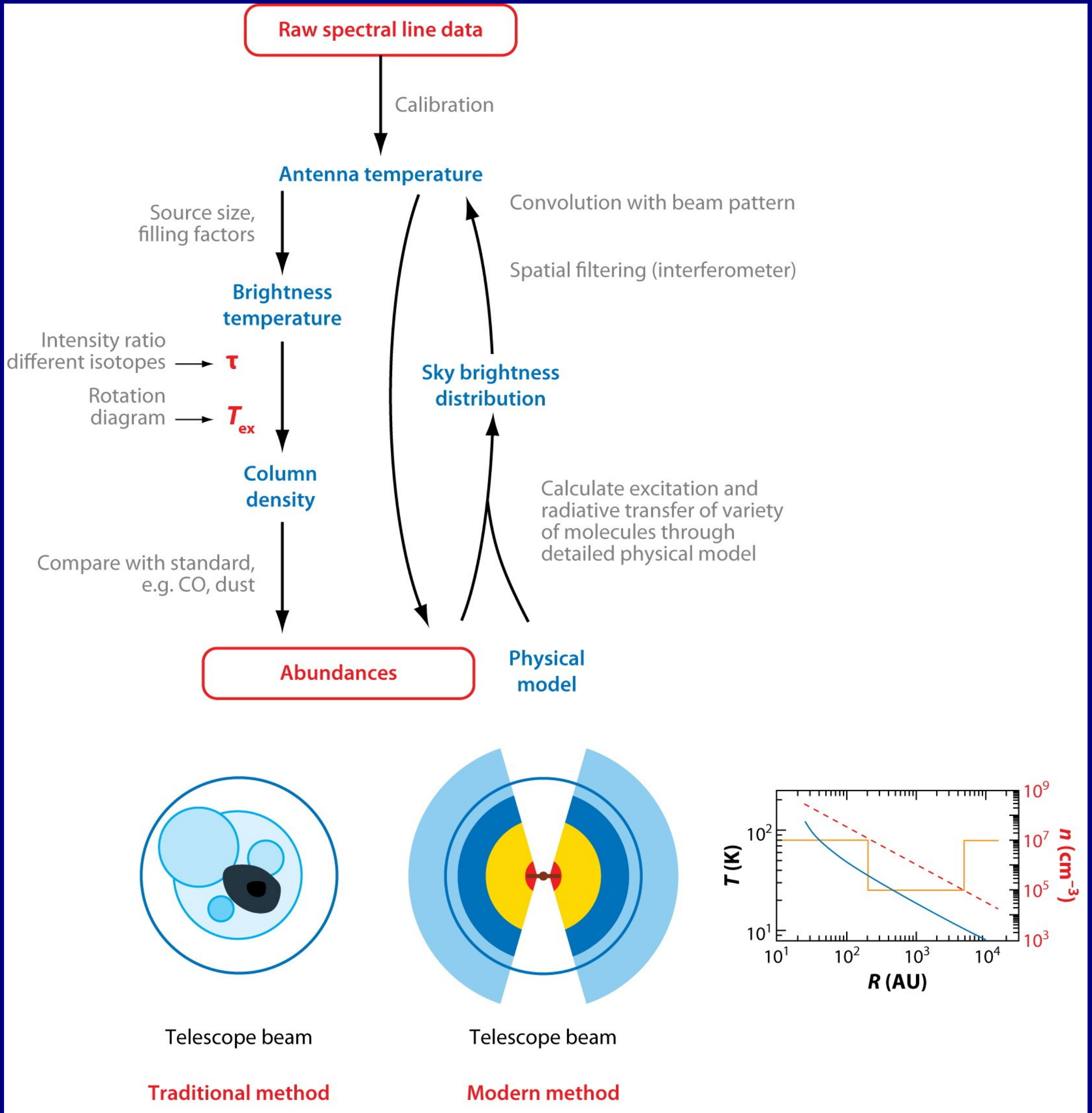
Analysis - really need ?

Often not LTE, or not optically thin, with 3D geometry etc, so better with physical modelling. Also
- constraints from multiple lines
- resolved sources



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Conclusions

Multi-line mm/sub-mm imaging of molecular lines is a powerful tool for studying star formation regions.

Such observations will be relatively easy with ALMA
BUT there are challenges

- many lines are accessible, but not all identified (unknown not very useful !)
- probably only some lines will be really useful for diagnostics, but it Is not obvious which ones
- excitation (temperature in LTE, non-LTE i.e. masers) and radiative transfer (optical depth, absorption) are important, so need for interpretation / modelling
- chemical composition, could in principle be used as a probe of the history (chemical “clock”), but it is not obvious that the models are good enough yet