Complex Molecules in Space – Present status and prospects with ALMA

(Some of) *The Big Themes*

Low-mass star formation: Shifting interests

→ Planetary system formation

- composition of gas and solids in different stages of star and planet formation
- What fraction of parental cloud goes into new solar systems
- Use molecules and dust to constrain physical conditions (T, n, v structure)
- Chemical diagnositics of different stages and components (outflow, infall,,disk)

Observations:

Outflows from very low luminosity objects ($L < 0.1\ L_{sun}$)

Formation of complex molecules

First generation (CH_3OH, H_2CO) forms on grain surfaces $\rightarrow$ evaporation $\rightarrow$ more complex species form in gas phase

Problem: Necessary reactions don't occur!

Heavy radicals react on grains and form more complex molecules, which are then evaporated

Complex questions:

Where do the widespread complex molecules in the galactic center come from?

Why is it interesting to detect ever more complex molecules?

Line surveys

Eminently useful tools to get

- chemical fingerprint of a region
- determine T, X_n, …
- identify new species

LTE assumption sufficient in many interesting cases (very line-rich dense hot cores)

THE **definitive spectral line database is urgently needed!**

Concerted effort by all involved parties needed to get (at least) a smart search engine that delivers usable information

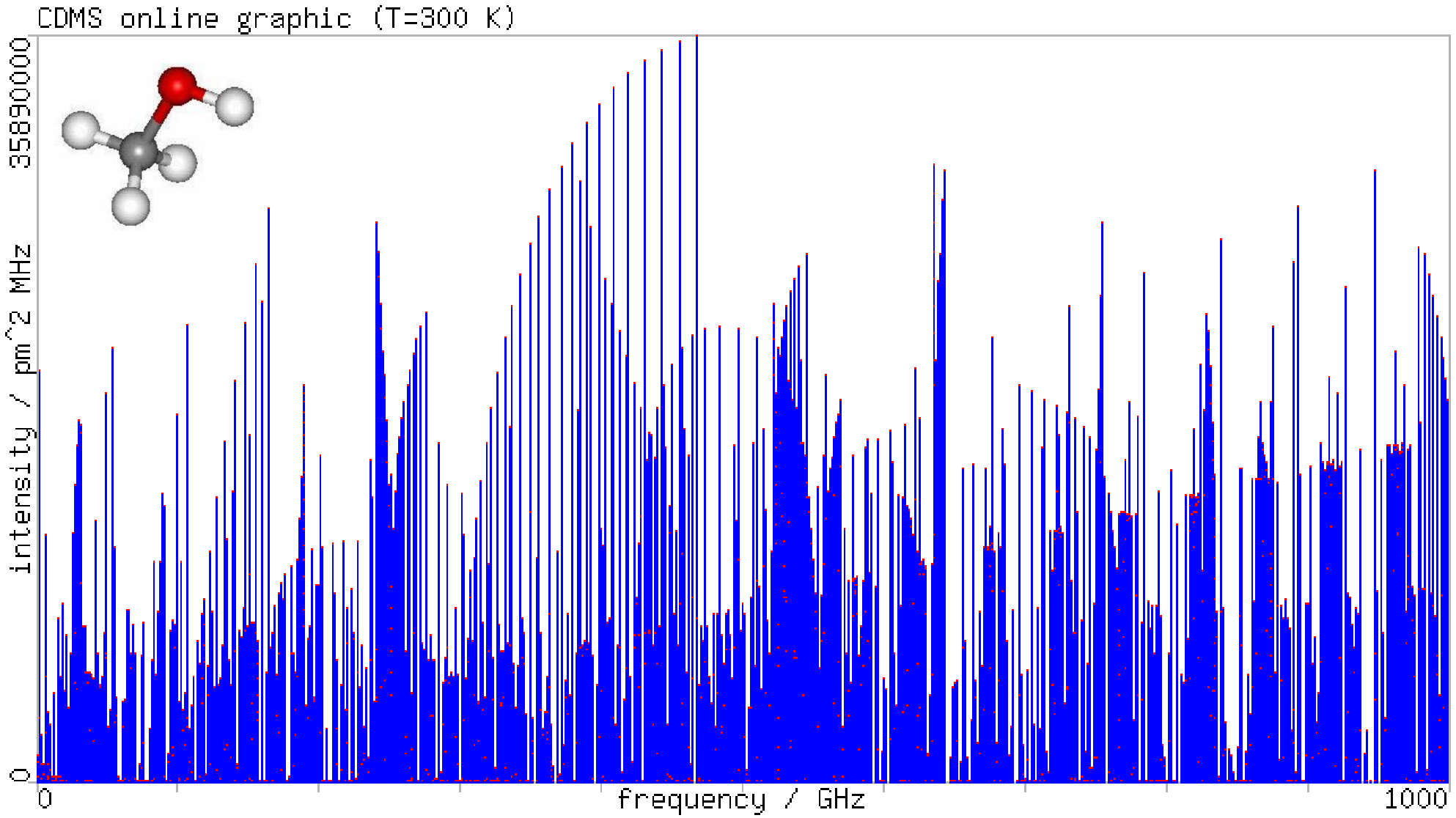
Do we need special databases for individual sources?

Problematic

Rather provide source type matrices?

(which CDMS has in rudimentary form)

Weed control



http://www.ph1.uni-koeln.de/cgi-bin/cdmsinfo?file=e032504.cat

Exterminating weeds:

Calculate whole spectra of all species

- what species?
- measurements at only two temperatures needed to predict spectrum at any temperature
- will enable optimum search strategy to find individually hidden, but collectively observable flowers

Questions: How well can whole spectrum be restored? How reliable are intensities?

Practical issues:

- How to make data available?

  Lists of lines – automatic extraction mechanism

Radiative transfer seems to be under control:

- Benchmarks ✓

But, do benchmarks also for other scenarios/geometries

- disks
- circumstellar envelopes

Promise and DANGER:

Going on autopilot, without really understanding what you are doing

(also true for ALMA calibration and imaging software)

So you've found lots of disks and hot cores – what do you do now?

Of course: Follow up with ALMA, which can address:

- **Efficient high resolution imaging for "plausibility" tests of new species IDs**
- **Energetics – relation to exciting source**

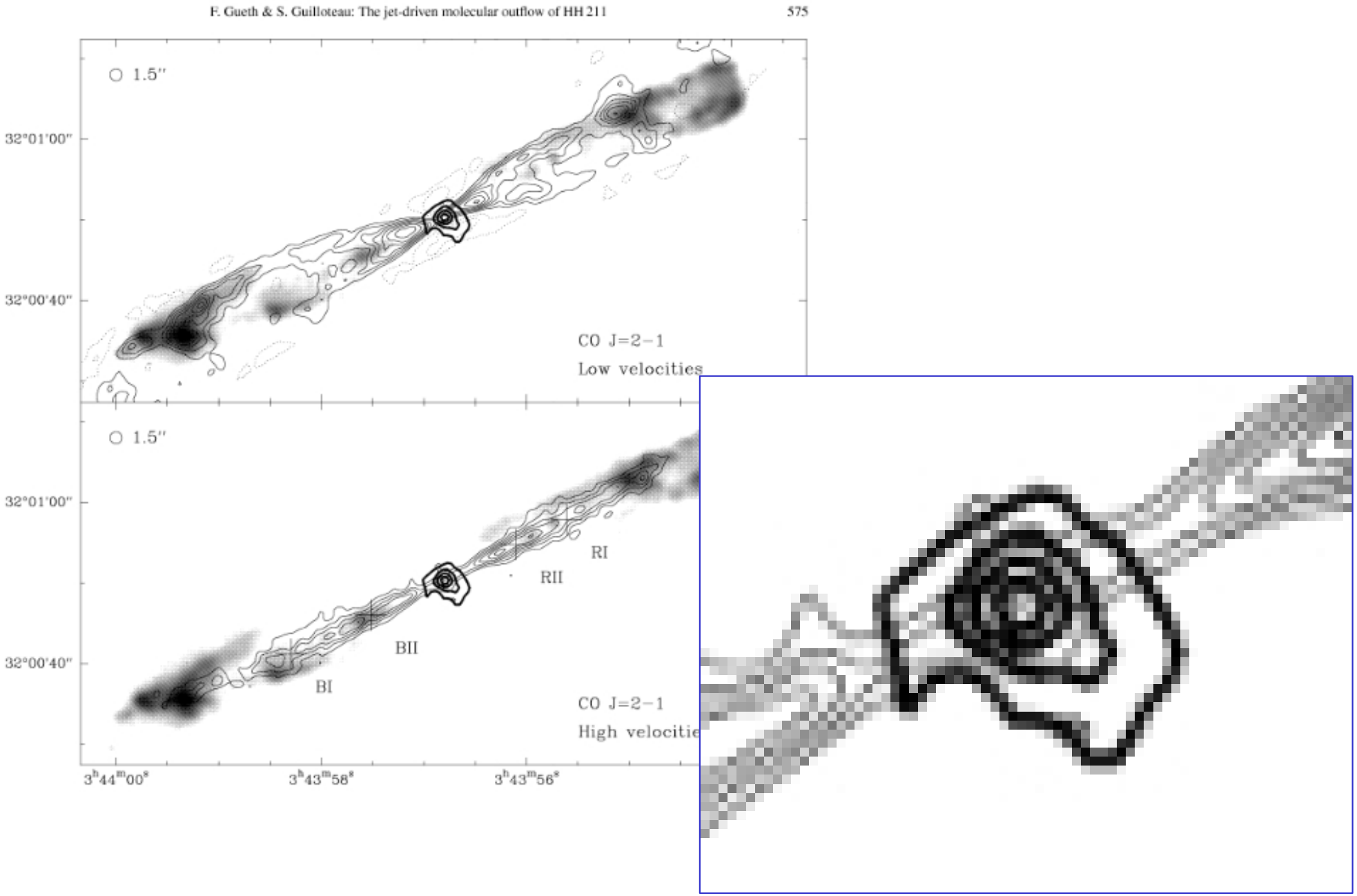
Example G29.96: hot molecules not associated with any continuum source

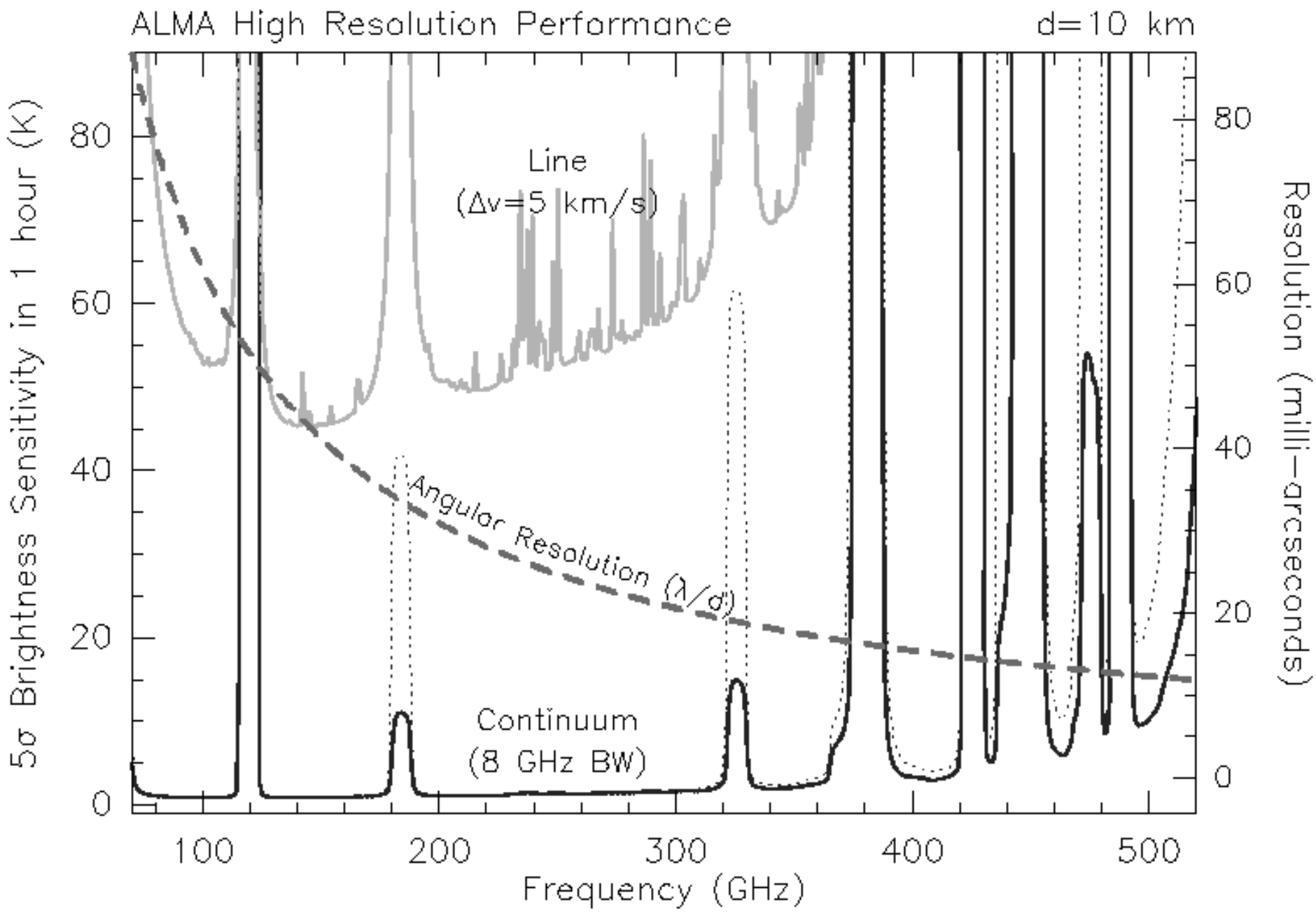
Significant offsets of ca. 0.3" (= 1500 AU)
r(100 K) for L =9 10^4 Lsun = 4600 AU

The problem is not so much how one produces the high molecular abundances where one observes them as *why* one produces them *there*

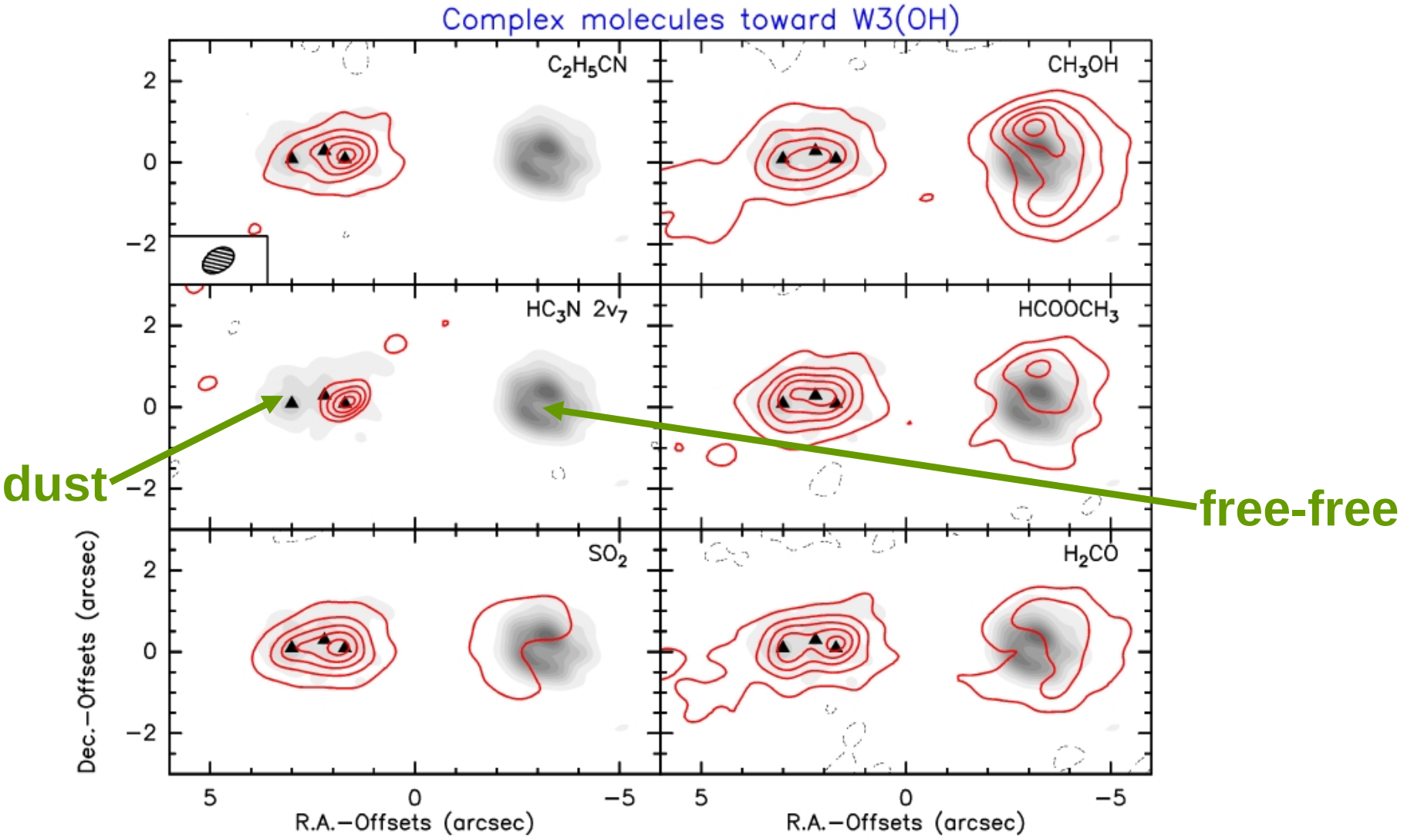
- **base of outflows**

How are bipolar outflows launched?



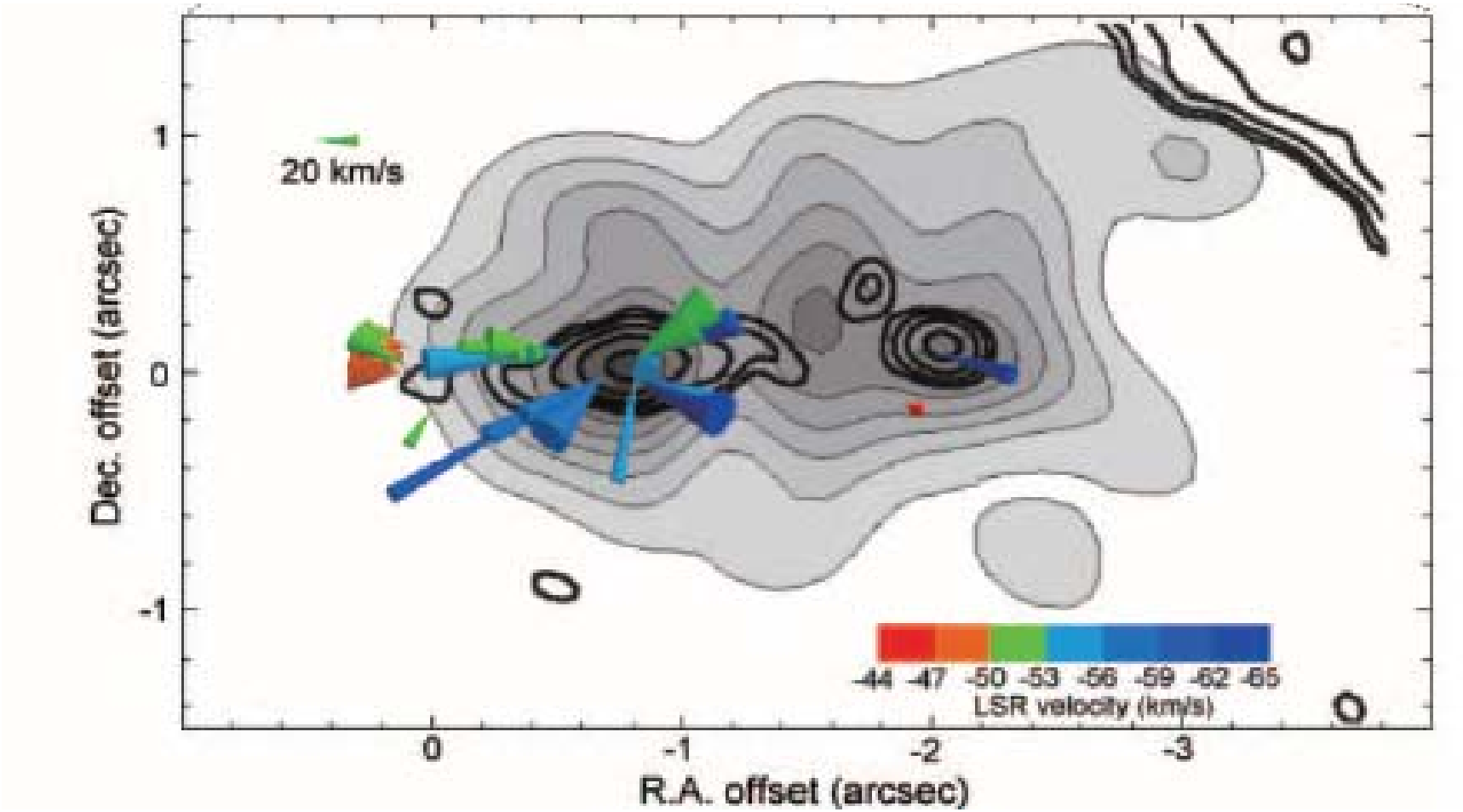

ALMA High Resolution Performance
d=10 km
5σ Brightness Sensitivity in 1 hour (K)
Resolution (milli-arcseconds)
Line
(Δv=5 km/s)
Angular Resolution (λ/d)
Continuum
(8 GHz BW)
Frequency (GHz)
0
20
40
60
80
100
200
300
400
500

Chemical Diversity: The W3(OH) Region



(Wyrowski et al. 1999)

W3(OH)-H_2O



Hachisuka et al. (2006)

$\Rightarrow$ D = 2.04 +/- 0.07 kpc

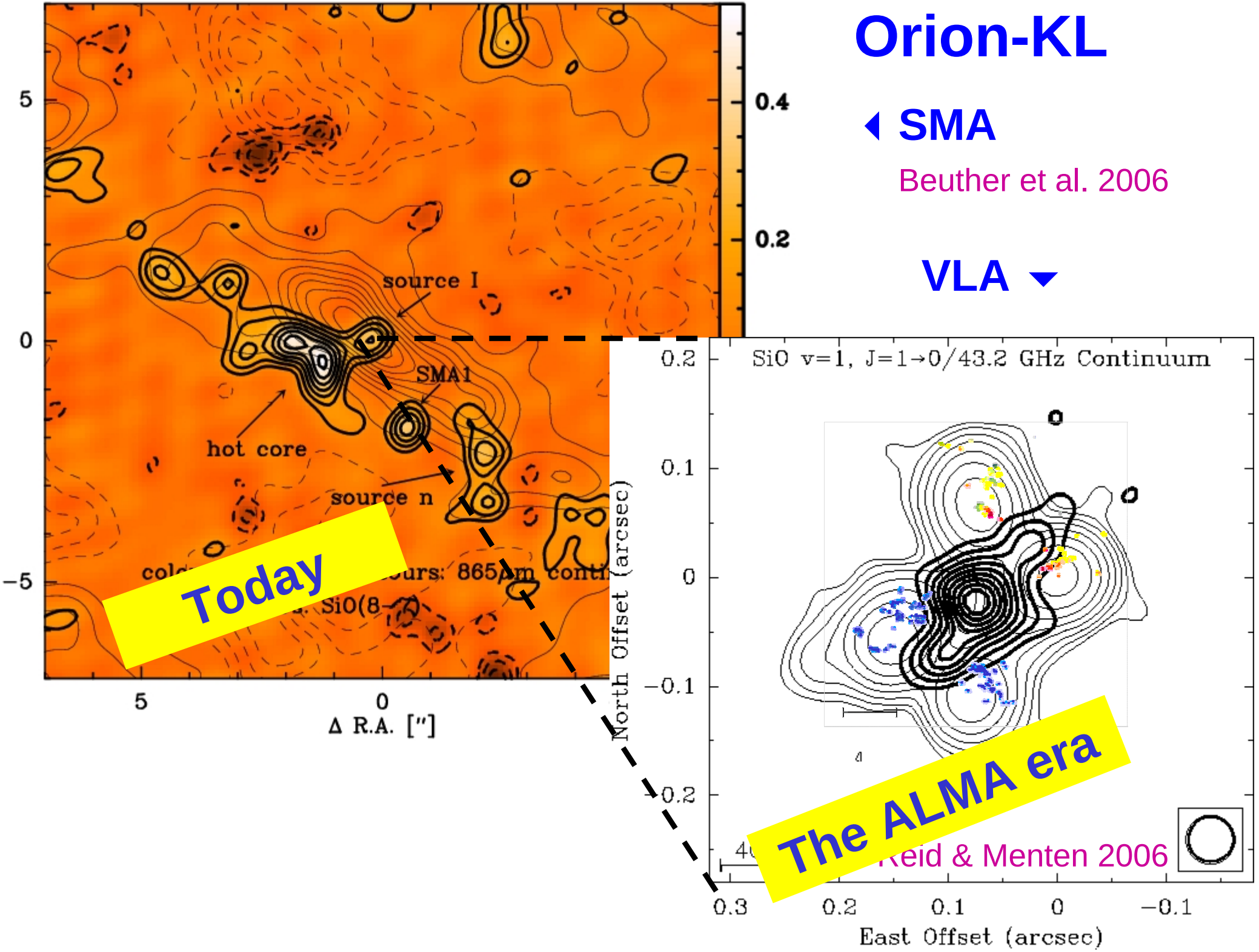
Orion-KL

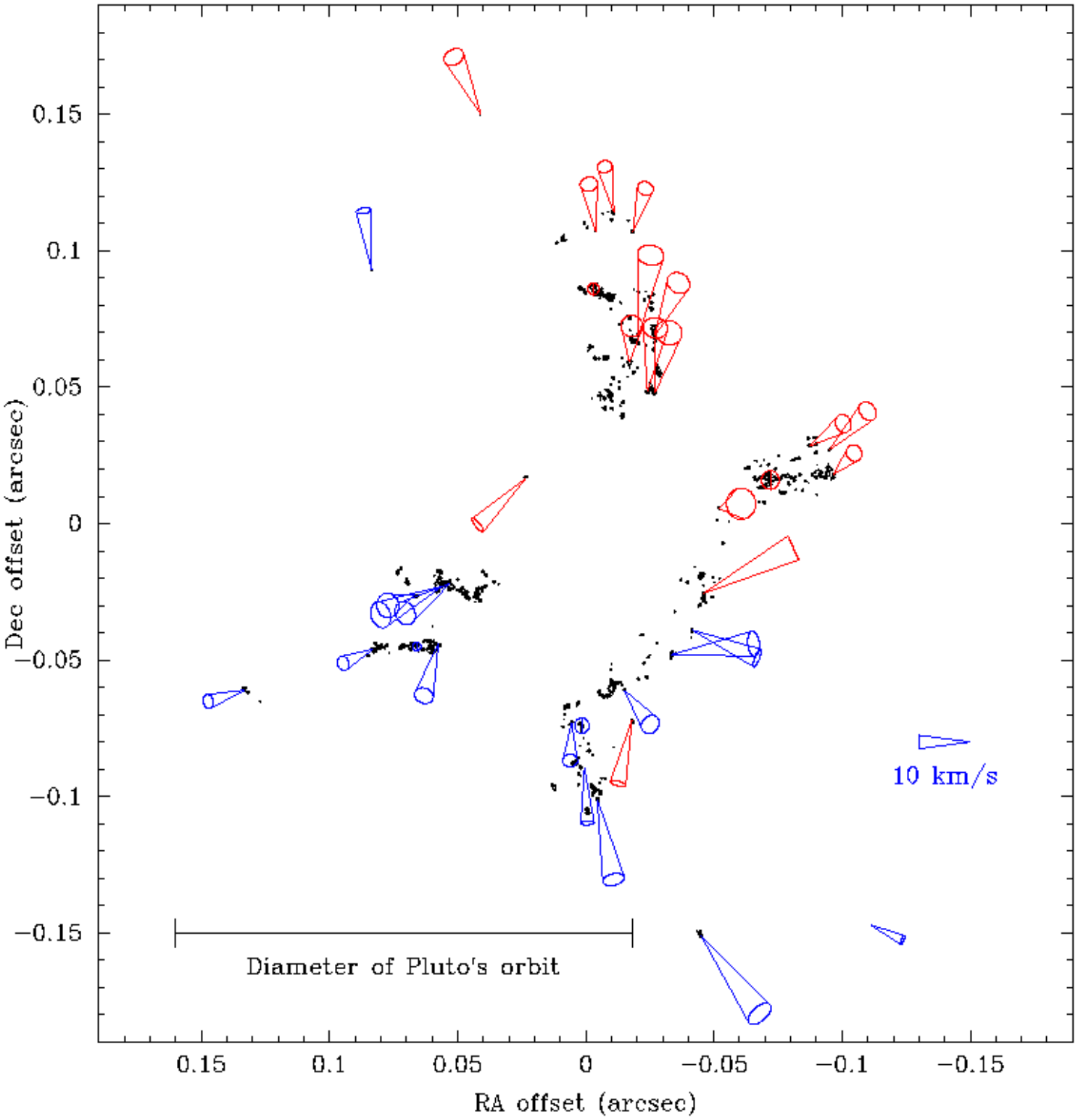
SMA

Beuther et al. 2006

VLA

Reid & Menten 2006

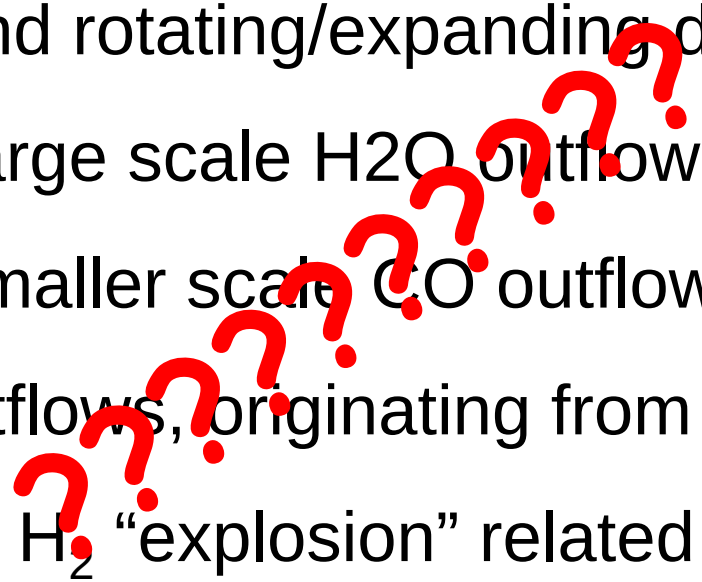




Chandler, Greenhill, et al.

Even a region as thorougly studied as Orion-KL has many mysteries left!

- SiO outflow and rotating/expanding disk
- (Unrelated) Large scale H2O outflow
- (Unrelated) Smaller scale CO outflow
- How many outflows, originating from where?
- Shock-excited H_2 “explosion” related to multiple merger event?
- Any evidence for H_2 explosion in (sub)mm emission?
- HH-objects



Promises and Challenges of ALMA observations:

- **structure on many scales from <0.01”**
  - **to tens of arc seconds (continuum) or**
  - **to arcseconds (hot lines)**

⇒ multi-configuration imaging

EVEN THEN:

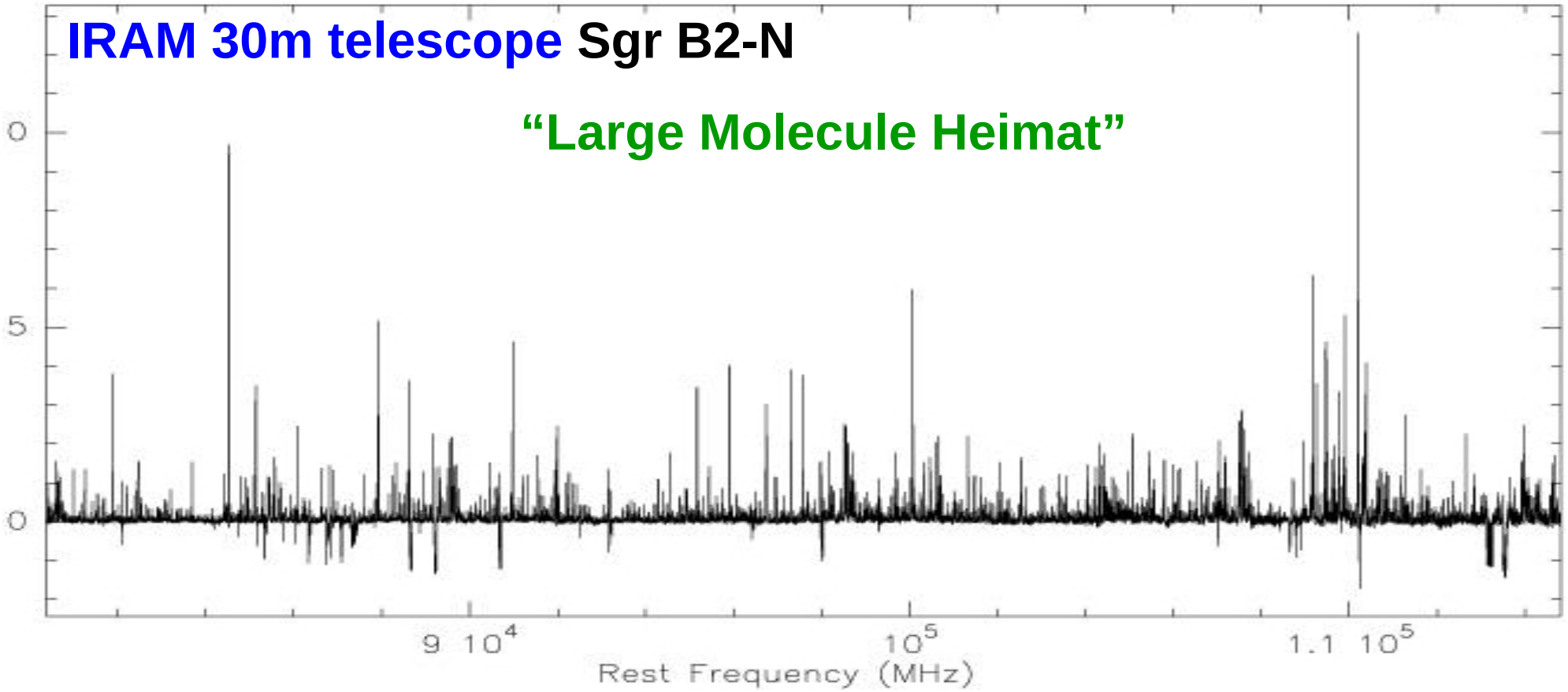
Severe 0-spacing problems:

Current interferometers often only see 10 – 20% of total flux

Very many lines from many molecules:
- **One *doesn’t* want maps of *S* (or T_B)**

but

- **maps of T_{kin}, *n*, X and fit dynamical models**



3 mm region (70 – 116 GHz) in 500 MHz chunks

3000 – 4000 lines!!!!

~10 minutes per spectrum → confusion limit

(Belloche, Comito, Hieret, Leurini, Menten, Schilke)

With ALMA it will be possible to observe that whole spectral range within *10 minutes* to confusion limit

To do science **with (3D) line surveys one needs very advanced data analysis tools:**

- **Automatic line identification and information extraction (fluxes, velocities)**
  - **requires up-tp-date "living" molecular spectroscopy database**
- **LTE analysis**

  $\rightarrow$ ***maps*** **of** N**(X),** $T_{\rm rot}$
- **non-LTE analysis (LVG/Monte Carlo least sqares method; see Leurini et al. 2004 for** CH_3OH**)**

  $\rightarrow$ ***maps*** **of** n**,** $T_{\rm kin}$**,** $[X/H_2]$
- **Fit dynamical models**

Astronomical Data Analysis Software and Systems XV
ASP Conference Series, Vol. XXX, 2005
C. Gabriel, C. Arviset, D. Ponz and E. Solano, eds.

Advanced Science Analysis Package and the prototype DALIA = Direct Approach to LIne Analysis

Frédéric Boone[1], Dirk Muders, Peter Schilke, Claudia Comito, Silvia Leurini, Bérengère Parise, Floris van der Tak and Karl Menten

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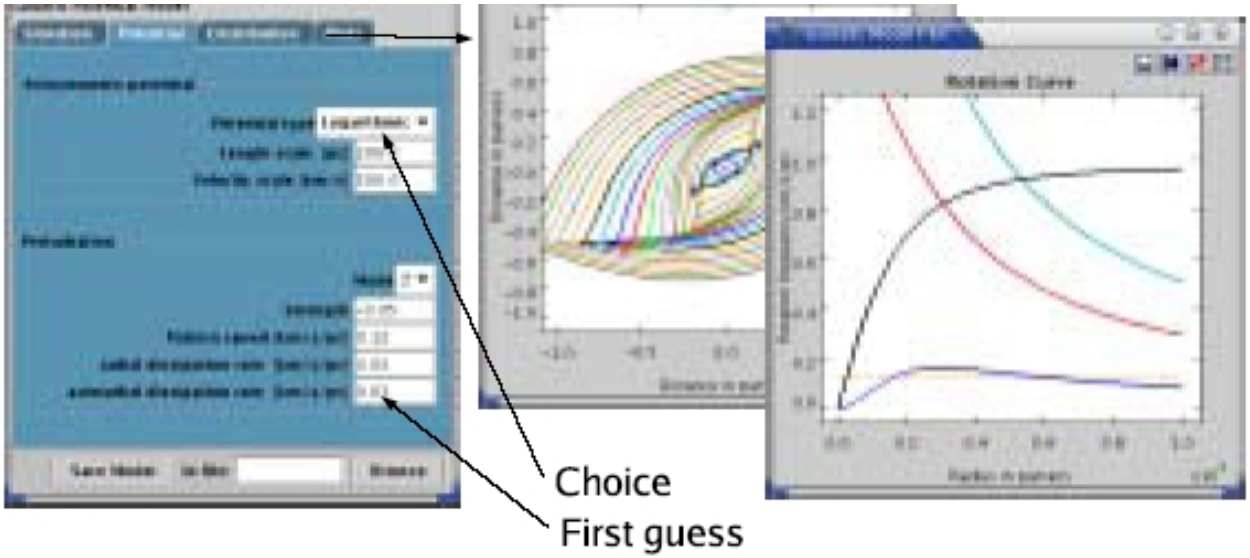


Figure 1. "Model Editor" window generated from the XML description of the model, in this case a galactic disk kinematic model. To create a model instance make the choices allowed for the model and edit the parameters to give a first guess.

What do we have *now*?

- **Not even a software package that provides basic imaging capability!**
- **Dispersed (and very low manpower level) efforts to develop data modeling and smart analysis tools**
- **Not yet the optimal solution for spectroscopy databases**

Even more basic…

Apart from smart data analysis tools, we need:

For observing, calibration, & imaging:

- **computer-aided observation preparation**
  *** (semi)automatic setup tools for frequency selection, mosaicing, …**
- **(largely) automatic**
  *** calibration**
  *** imaging + selfcalibration,**
  *** mosaicing, multi-configuration combination, 0-spacing addition**

… and we don't even have *aips*++ working!

On a more *positive* note…

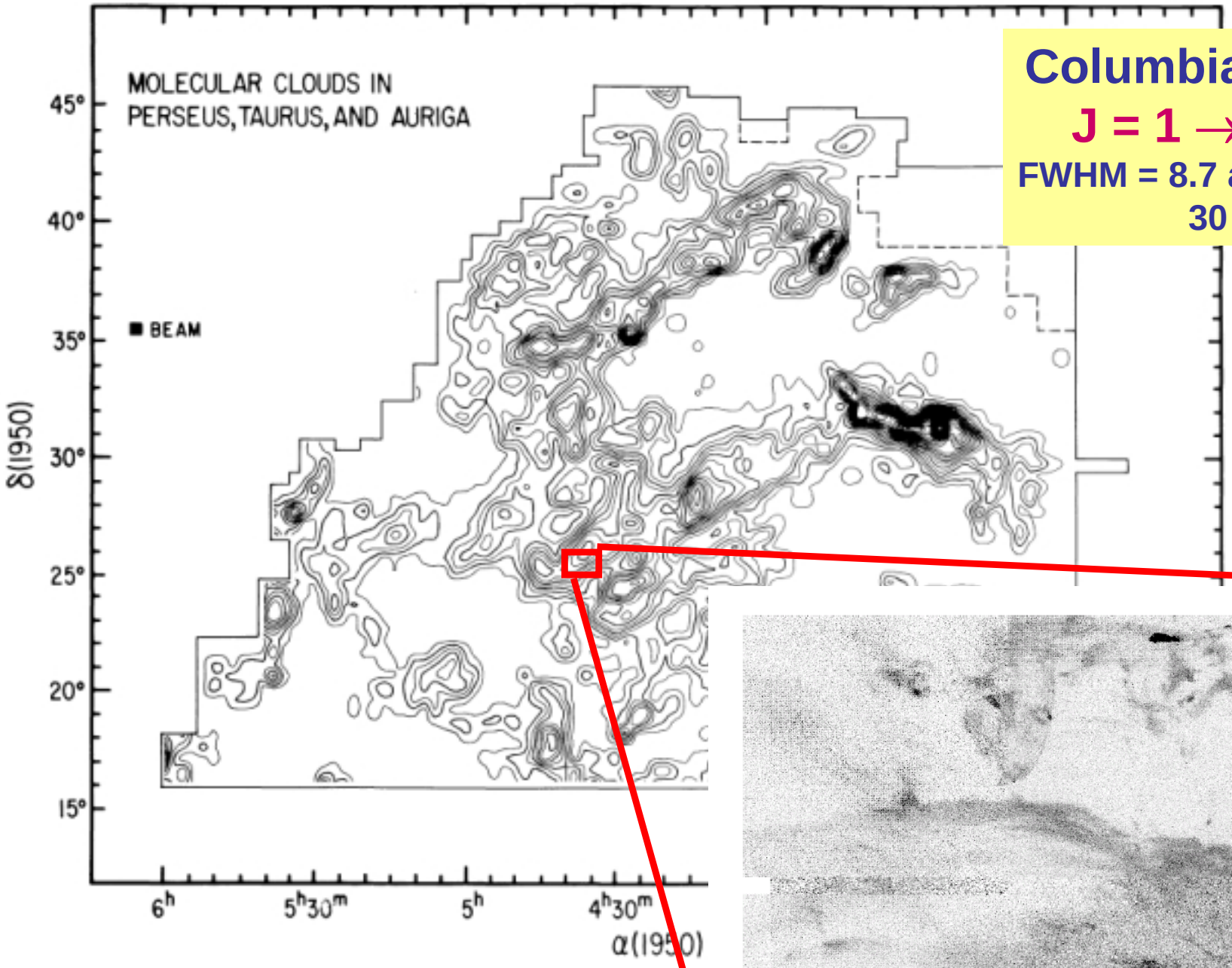
Considerable effort is put into Herschel/HIFI observing and data analysis software

Even ALMA will not be able to do everything!

JCMT Heterodyne Array Receiver Programme

- 16 elements
- 325 – 375 GHz
- 14" FWHM

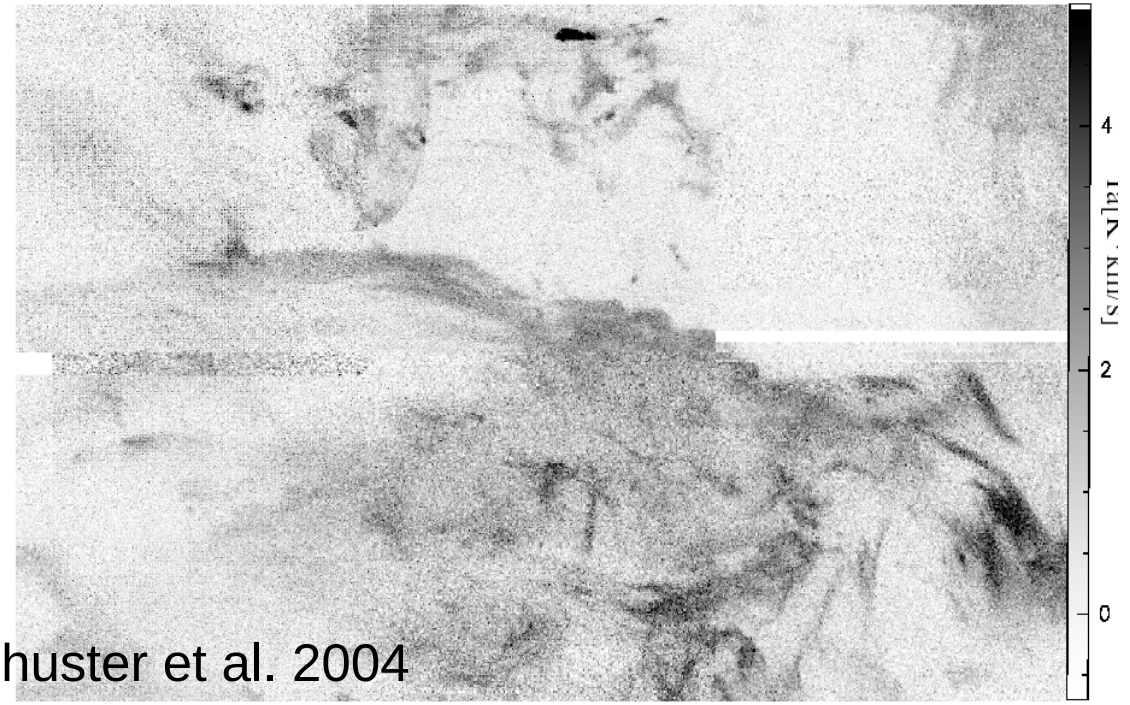
Will not only map very large areas in CO, but could also be used for finding interesting new hot cores



Columbia/CfA 1m CO

J = 1 → 0 (115 GHz)

FWHM = 8.7 arcmin FWHM$_{eff}$= 30 arcmin



Schuster et al. 2004

IRAM 30m

CO J = 2 → 1 (231 GHz)

HERA 9 x 11”

Even ALMA can't do everything!

H_2O!

Politics:

Do we really need multiple European ARC nodes?

If we think so, who will coordinate further-going software developments?

8:00

- within Europe
- in Coordination with N.A. and Japan

Thank you