Molecular richness around protostars

The ALMA/NOEMA revolution

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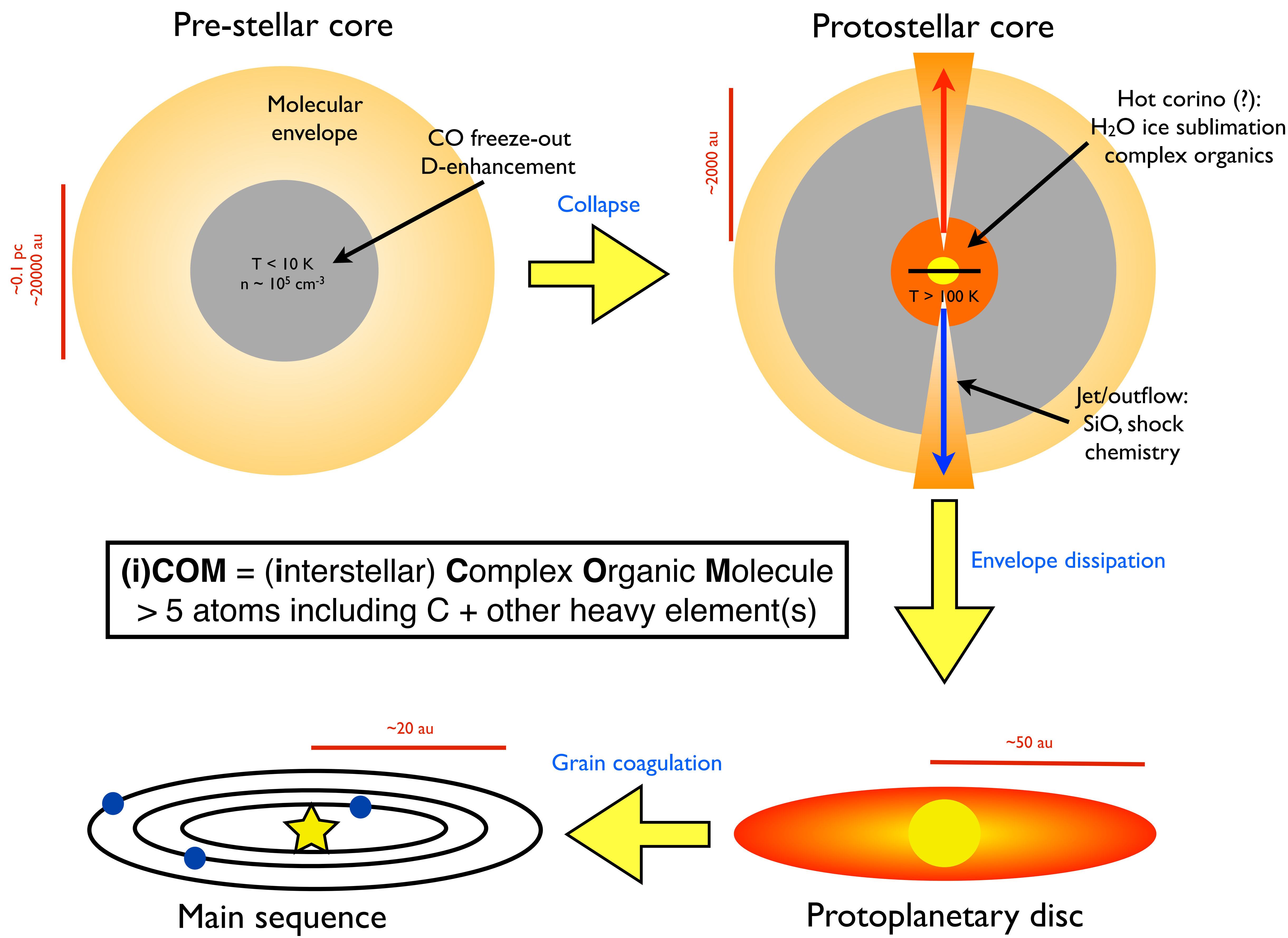
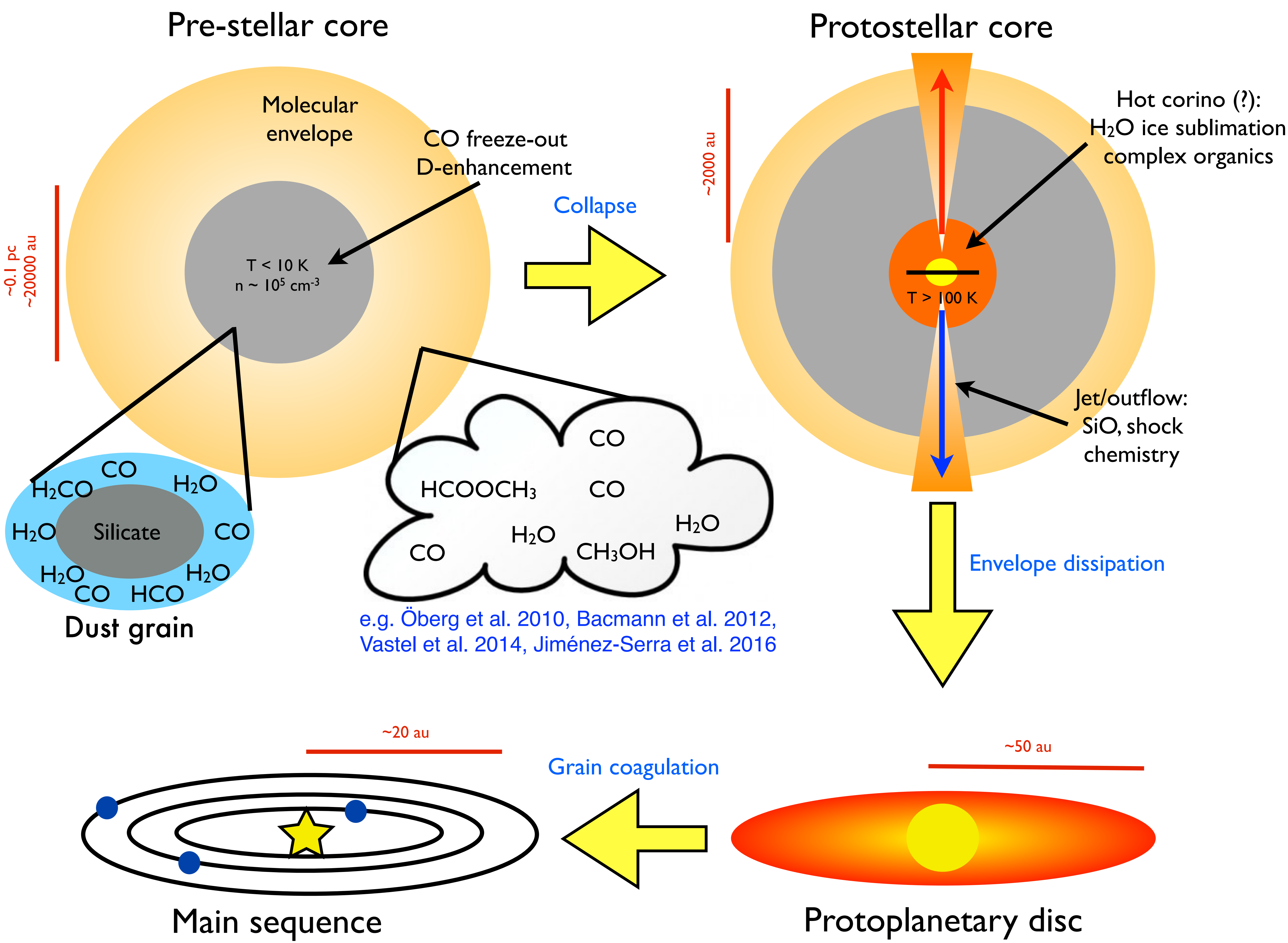
Institut de Radio Astronomie Millimétrique (FR)

S. Bottinelli (FR), P. Caselli (DE), C. Ceccarelli (FR), C. Favre (IT), F. Fontani (IT), R. Neri (FR), N. Sakai (JP), Y. Watanabe (JP), S. Yamamoto (JP) & many more!

KIDA2017, 27 Sep 2017, Bordeaux



Pre-stellar core
Molecular envelope
CO freeze-out
D-enhancement
T < 10 K
n ~ 10^5 cm^{-3}
~0.1 pc
~20000 au
Collapse
Protostellar core
~2000 au
Hot corino (?):
H_2O ice sublimation
complex organics
T > 100 K
Jet/outflow:
SiO, shock
chemistry
Envelope dissipation
(i)COM = (interstellar) Complex Organic Molecule
> 5 atoms including C + other heavy element(s)
~20 au
Grain coagulation
~50 au
Main sequence
Protoplanetary disc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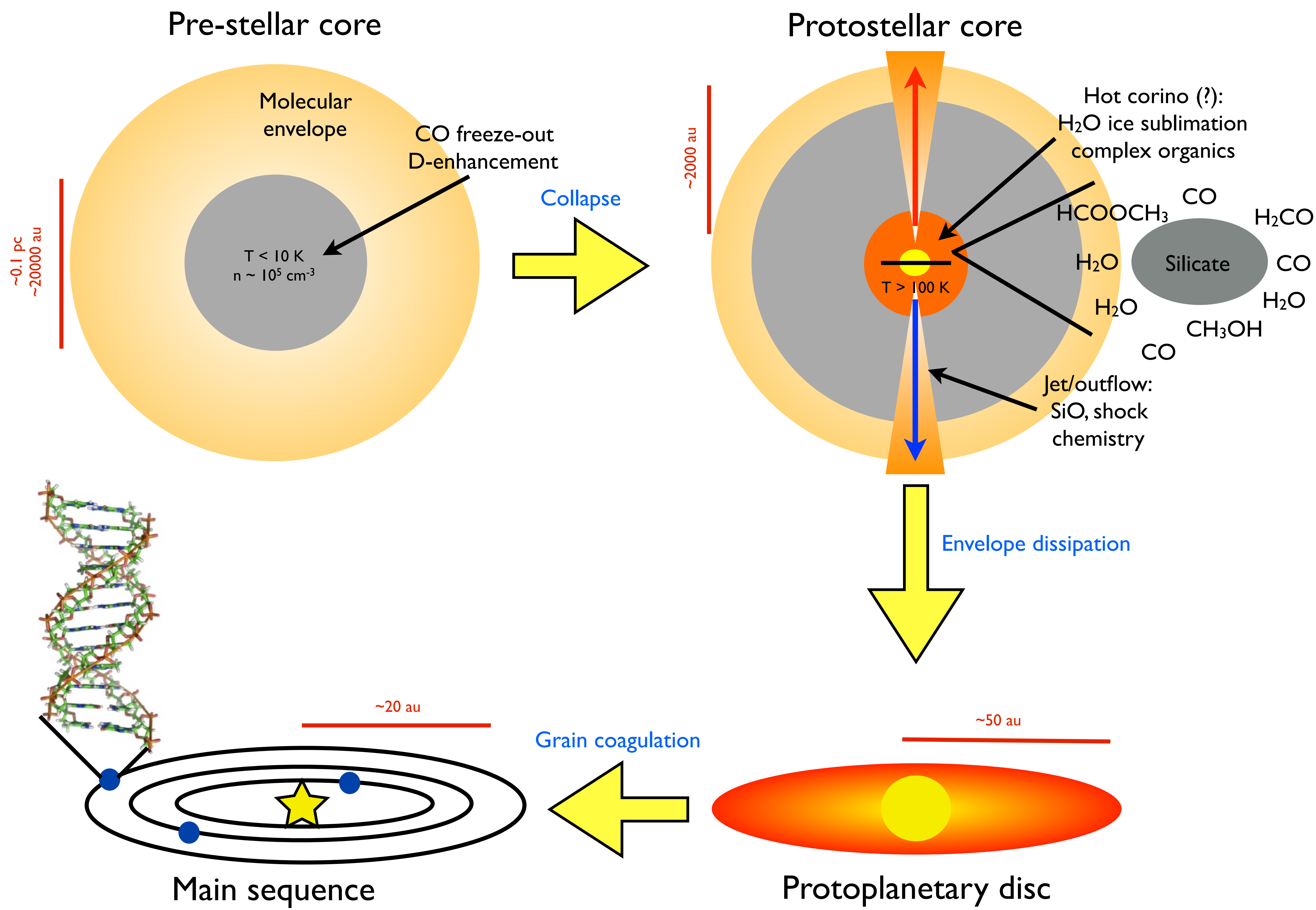
chemistry
CO
H_2CO
H_2O
Silicate
HCO
Dust grain
$HCOOCH_3$
CH_3OH
e.g. Öberg et al. 2010, Bacmann et al. 2012,
Vastel et al. 2014, Jiménez-Serra et al. 2016
Envelope dissipation
~20 au
Grain coagulation
~50 au
Main sequence
Protoplanetary disc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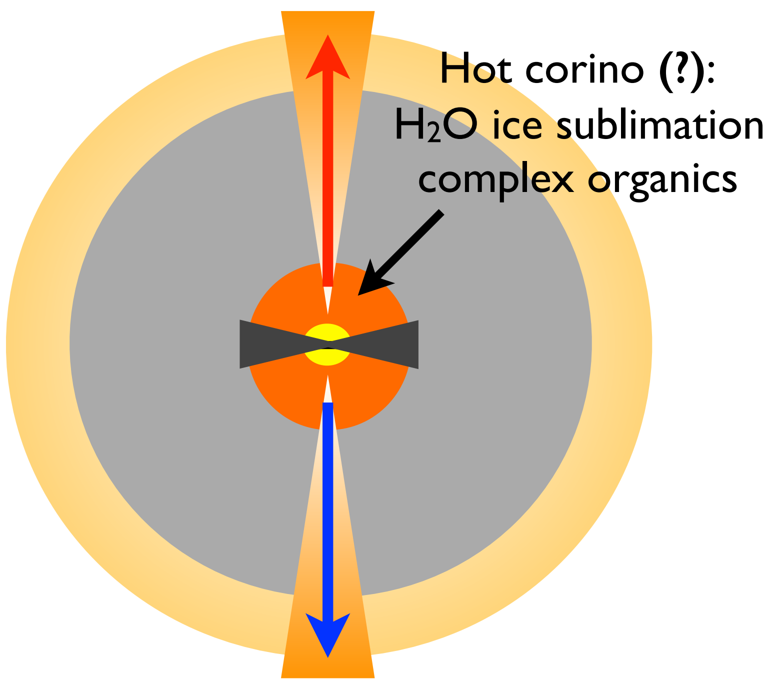
CO
T > 100 K
Jet/outflow:
SiO, shock
chemistry
Envelope dissipation
~50 au
Protoplanetary disc
Grain coagulation
~20 au
Main sequence

Outline

Protostellar core:
Onset of star formation



1. What is the typical molecular composition in protostellar objects?

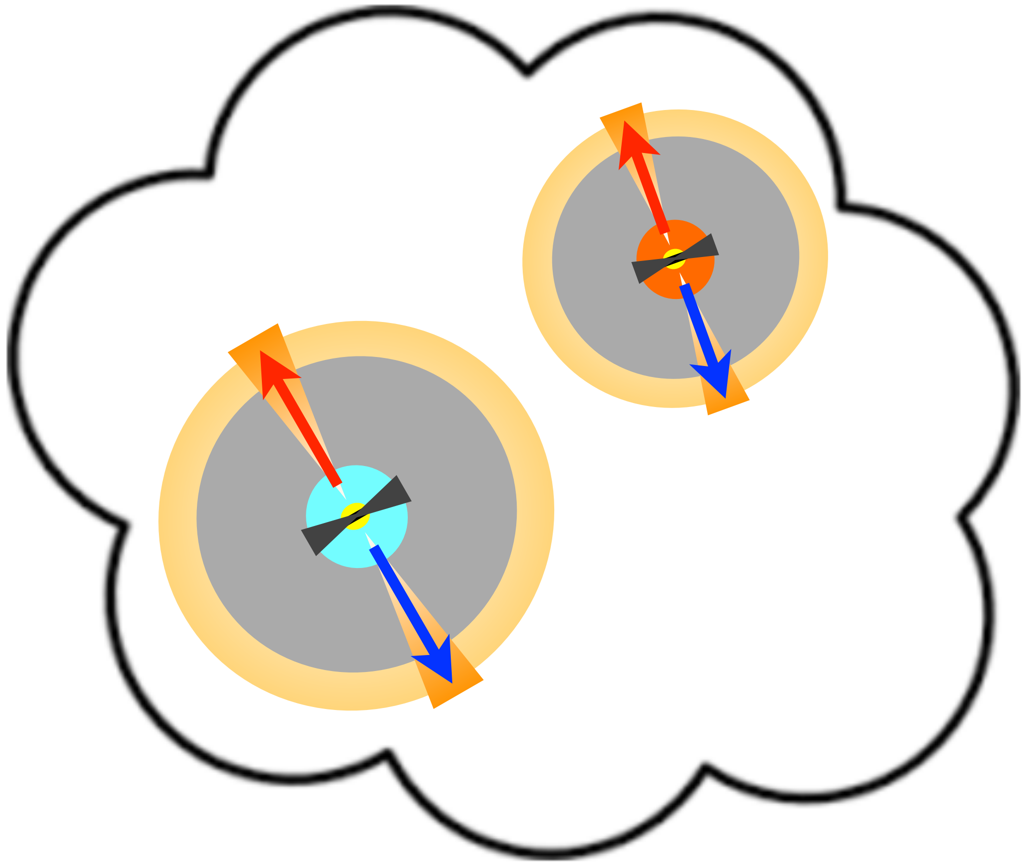
2. What molecular chemistry is present in a protosolar-like environment?

3. Summary & how to go forward

ALMA

NOEMA

Outline



1. What is the typical molecular composition in protostellar objects?

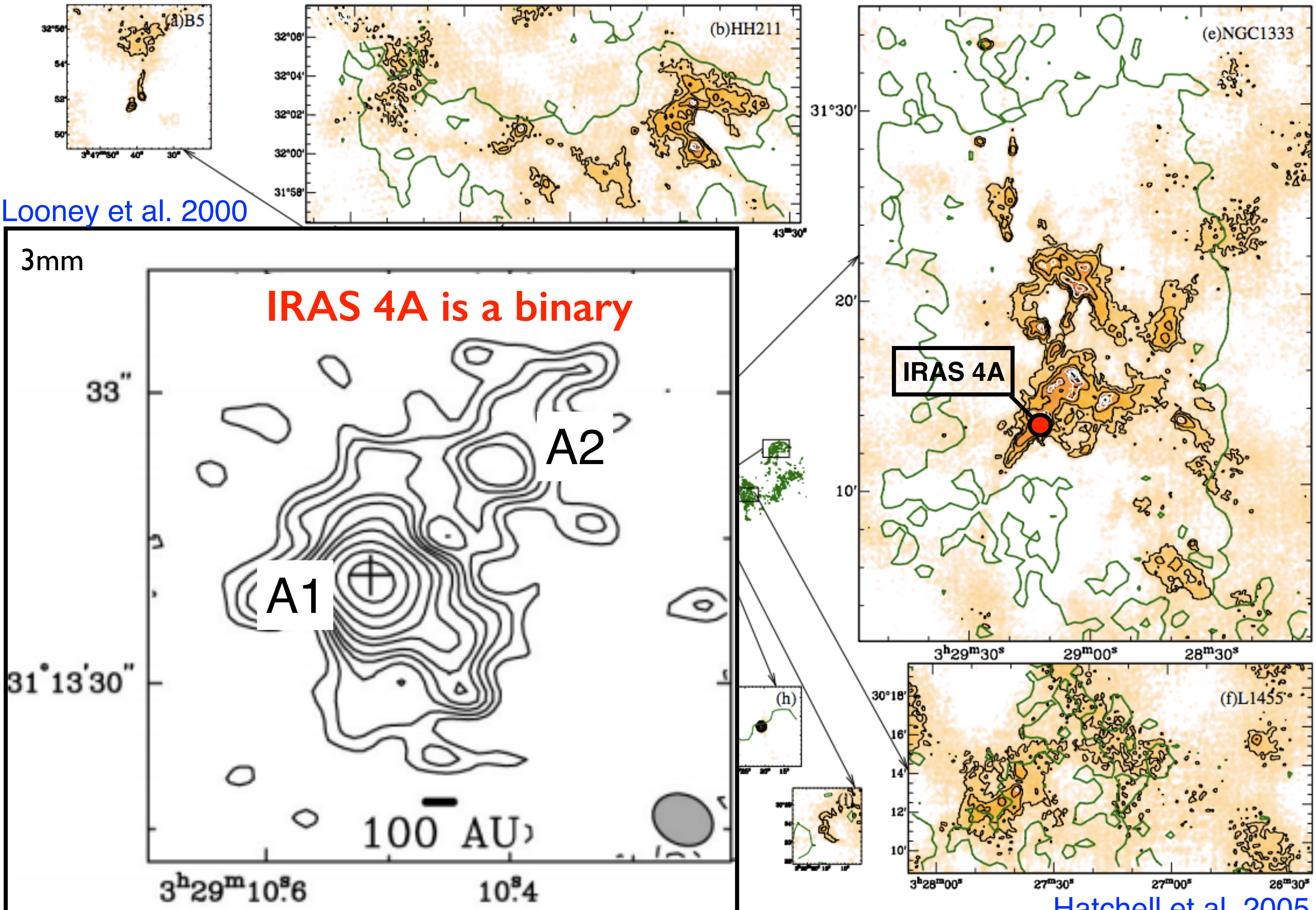
    IRAS 4A, protostellar binary

    Two chemically different neighbours

2. What molecular chemistry is present in a protosolar-like environment?

3. Summary & how to go forward

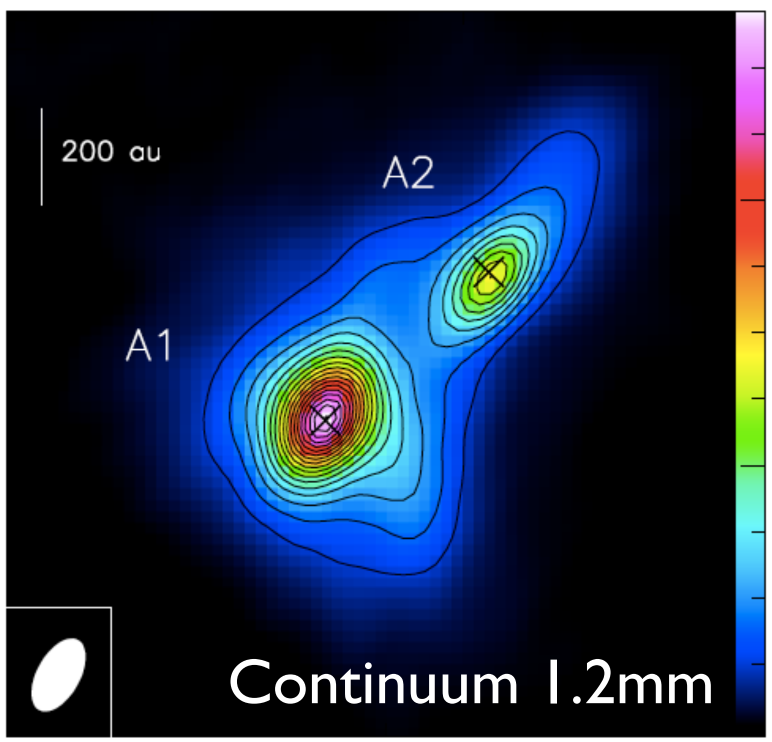
NGC 1333 IRAS 4A



IRAS 4A with ALMA and PdBI

2014, cycle 2 (P.I. N. Sakai)
Band 6: 1.2 mm
Beam size ~ 0.5”

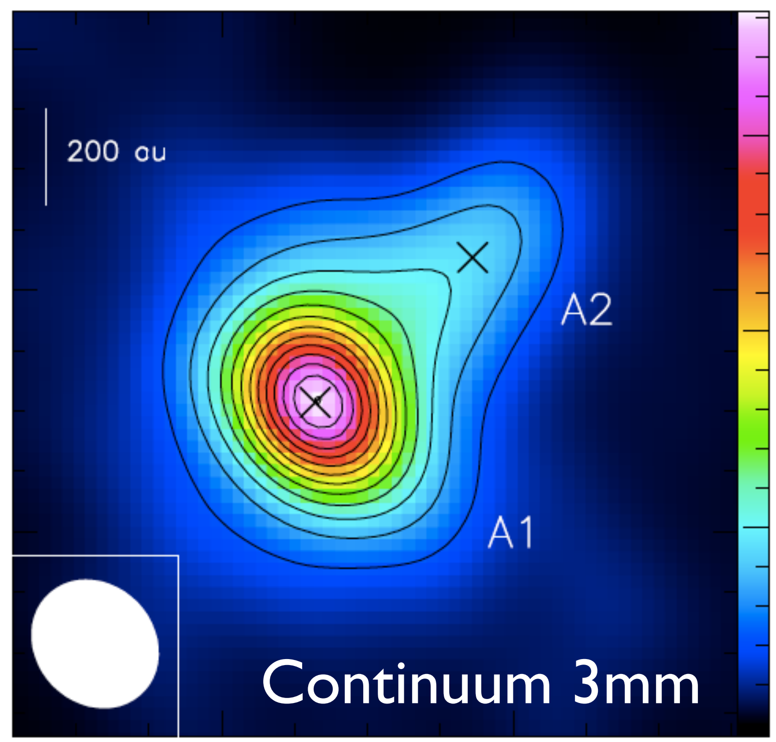
ALMA



López-Sepulcre et al. 2017

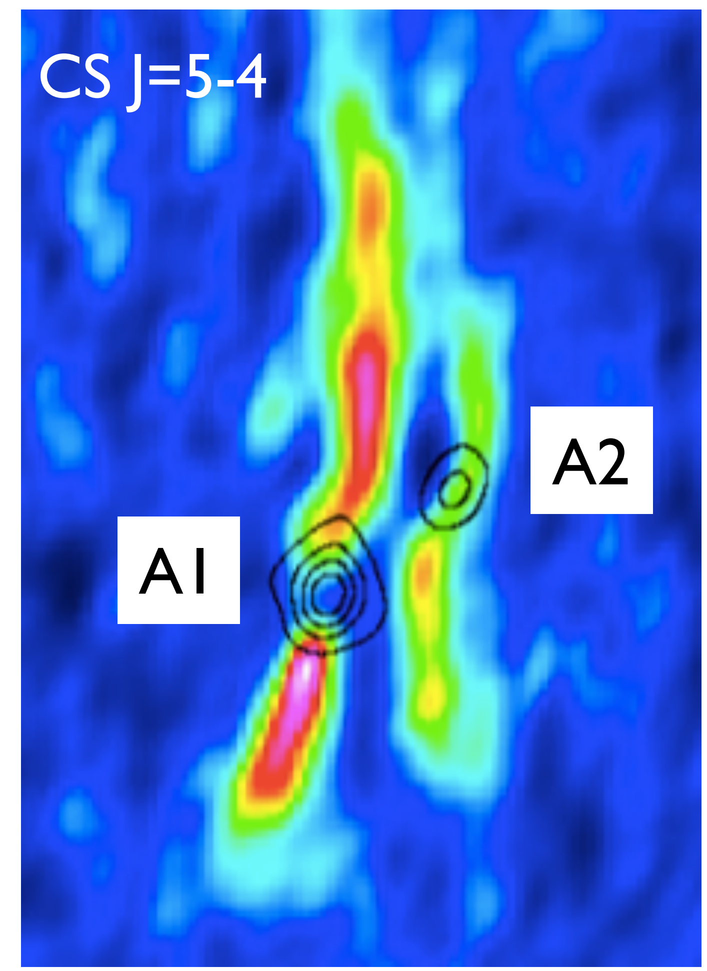
2005 (P.I. S. Bottinelli)
Band 1: 3 mm
Beam size ~ 1”

PdBI



López-Sepulcre et al. 2017

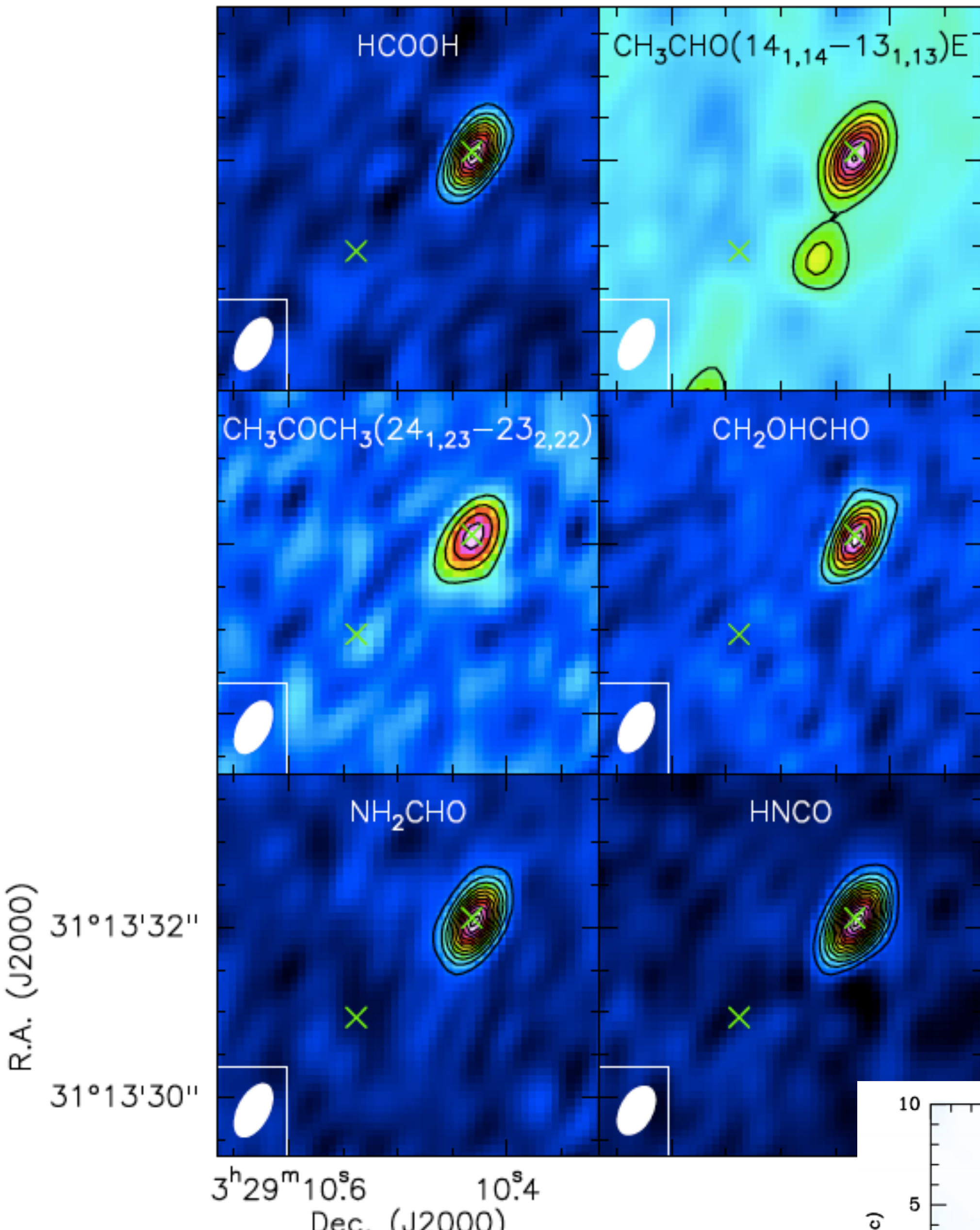
ALMA

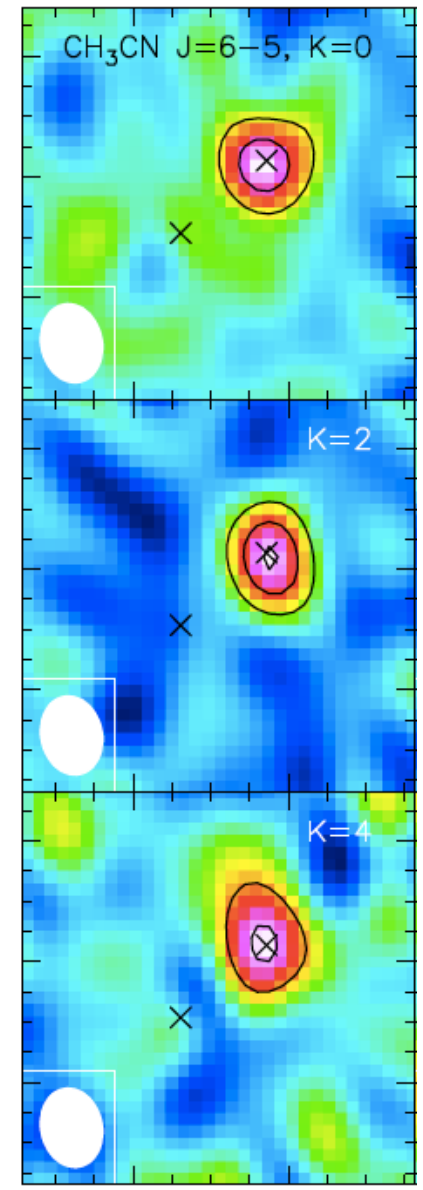


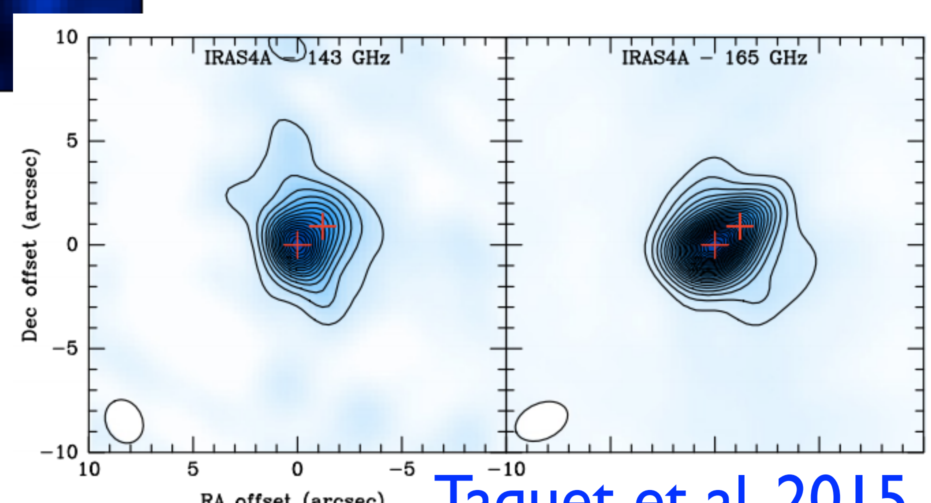
(see also Santangelo et al. 2015)

A protobinary with only one hot corino

López-Sepulcre et al. 2017

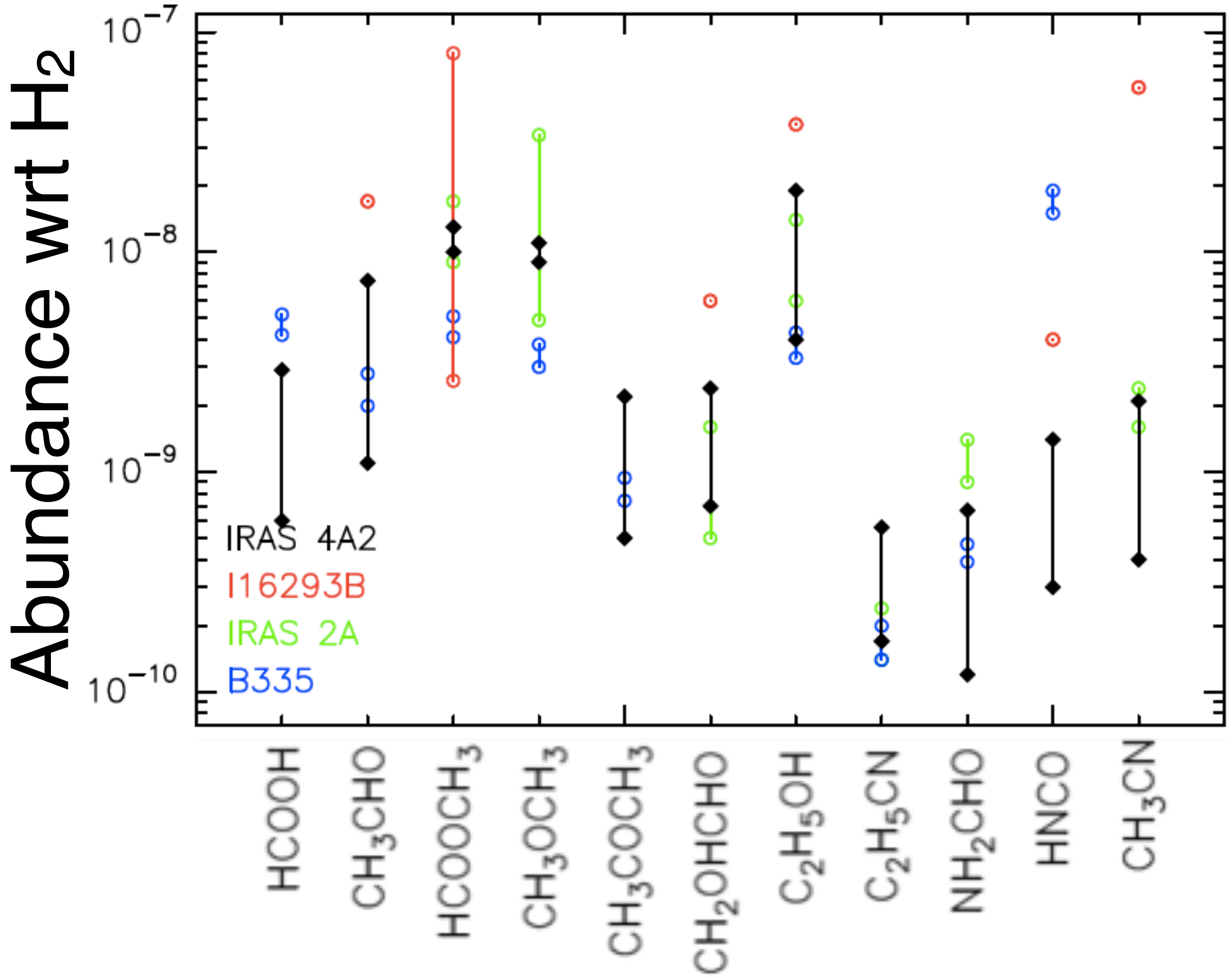






Taquet et al. 2015

Two very different protostellar cores



Bisschop et al. 2008
Jørgensen et al. 2012
Persson et al. 2012
Taquet et al. 2015
Imai et al. 2016

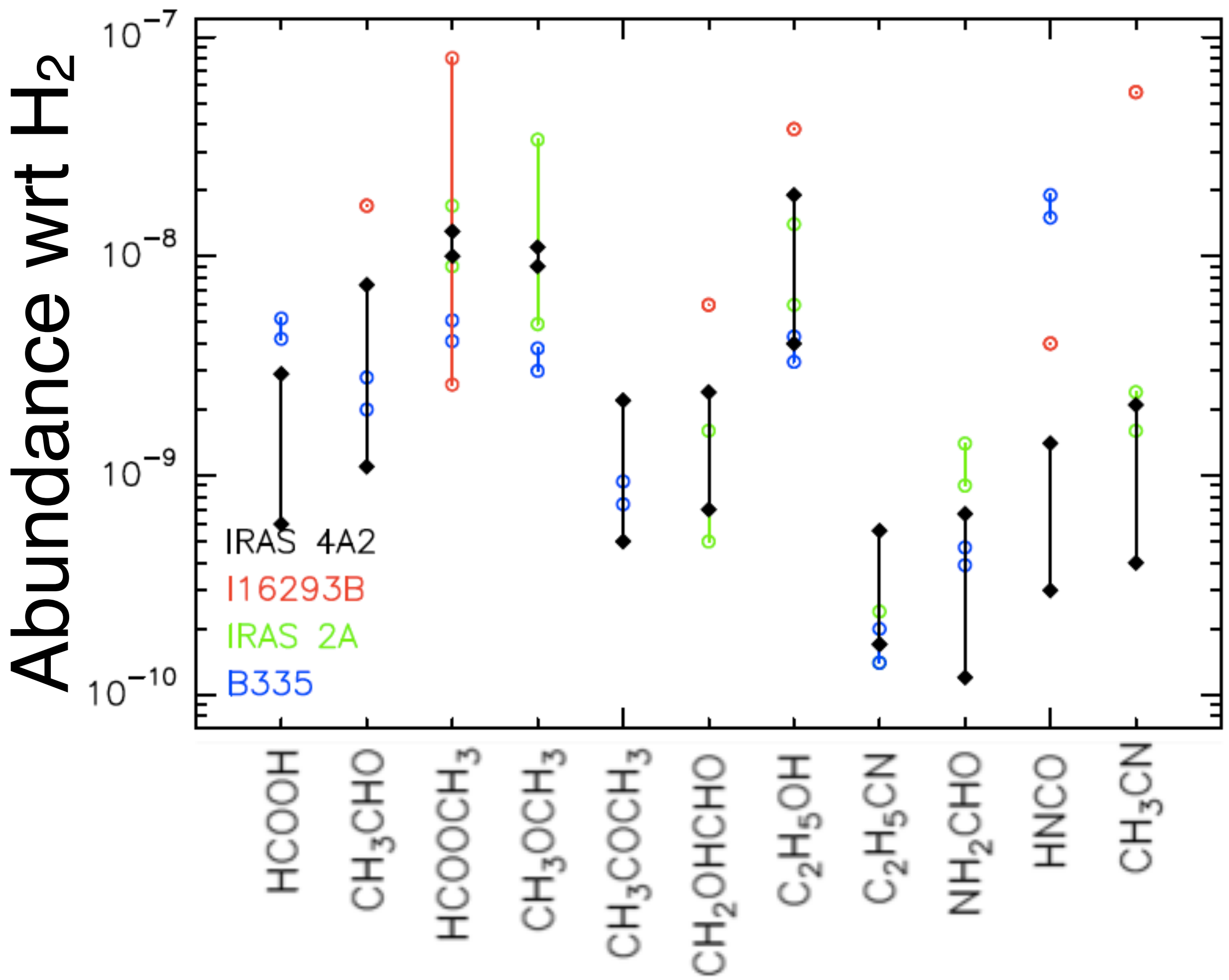
A2: abundances typical of hot corinos
Hot corino size ~70 au

A1: where is the hot corino??

1. ~~Dust is optically thick~~
2. Compact hot corino
3. No hot corino

López-Sepulcre et al. 2017

Two very different protostellar cores



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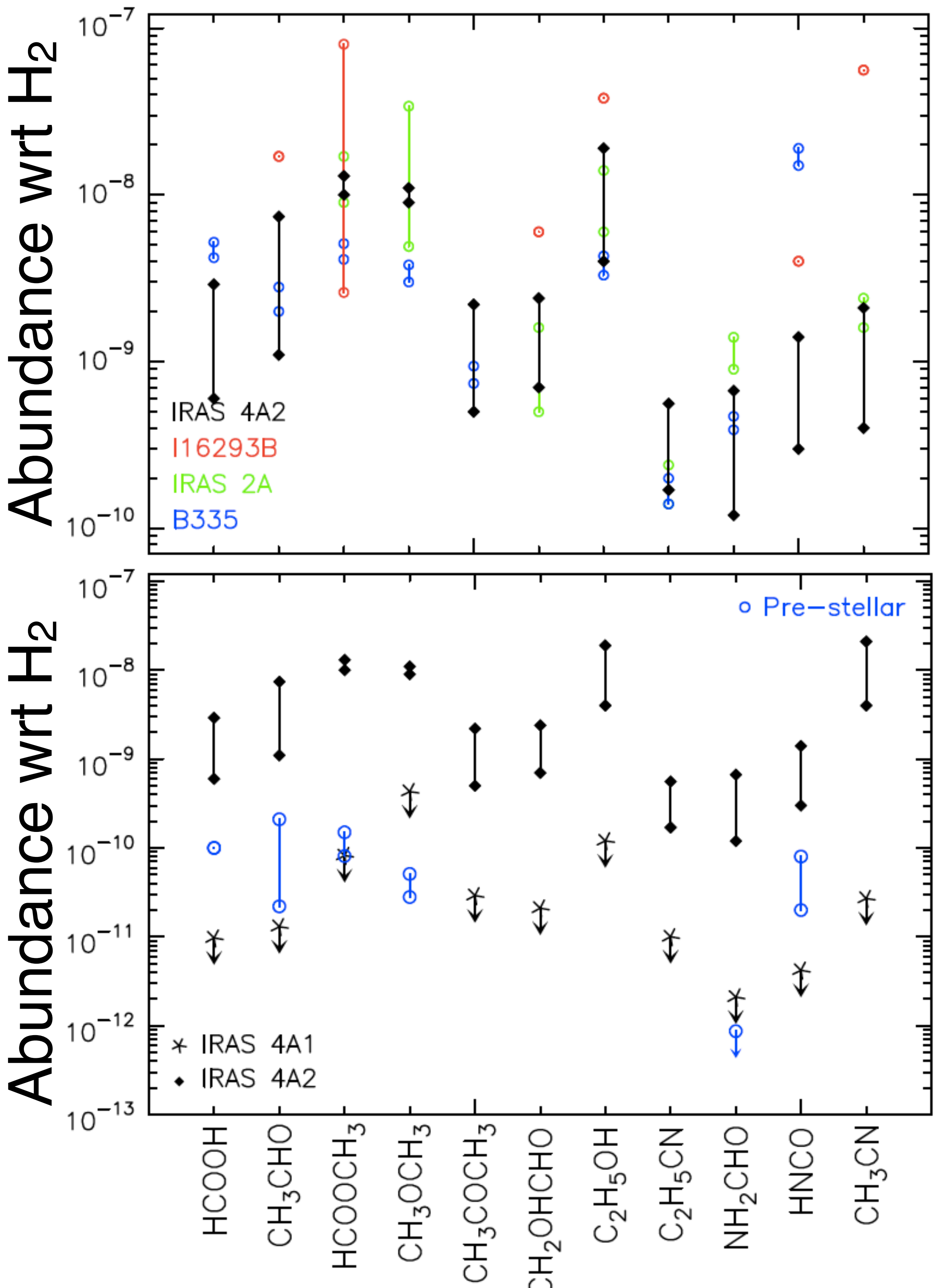
A2: abundances typical of hot corinos
Hot corino size ~70 au

A1: where is the hot corino??

1. ~~Dust is optically thick~~
2. Compact hot corino → **< 12 au**
3. No hot corino

López-Sepulcre et al. 2017

Two very different protostellar cores



López-Sepulcre et al. 2017

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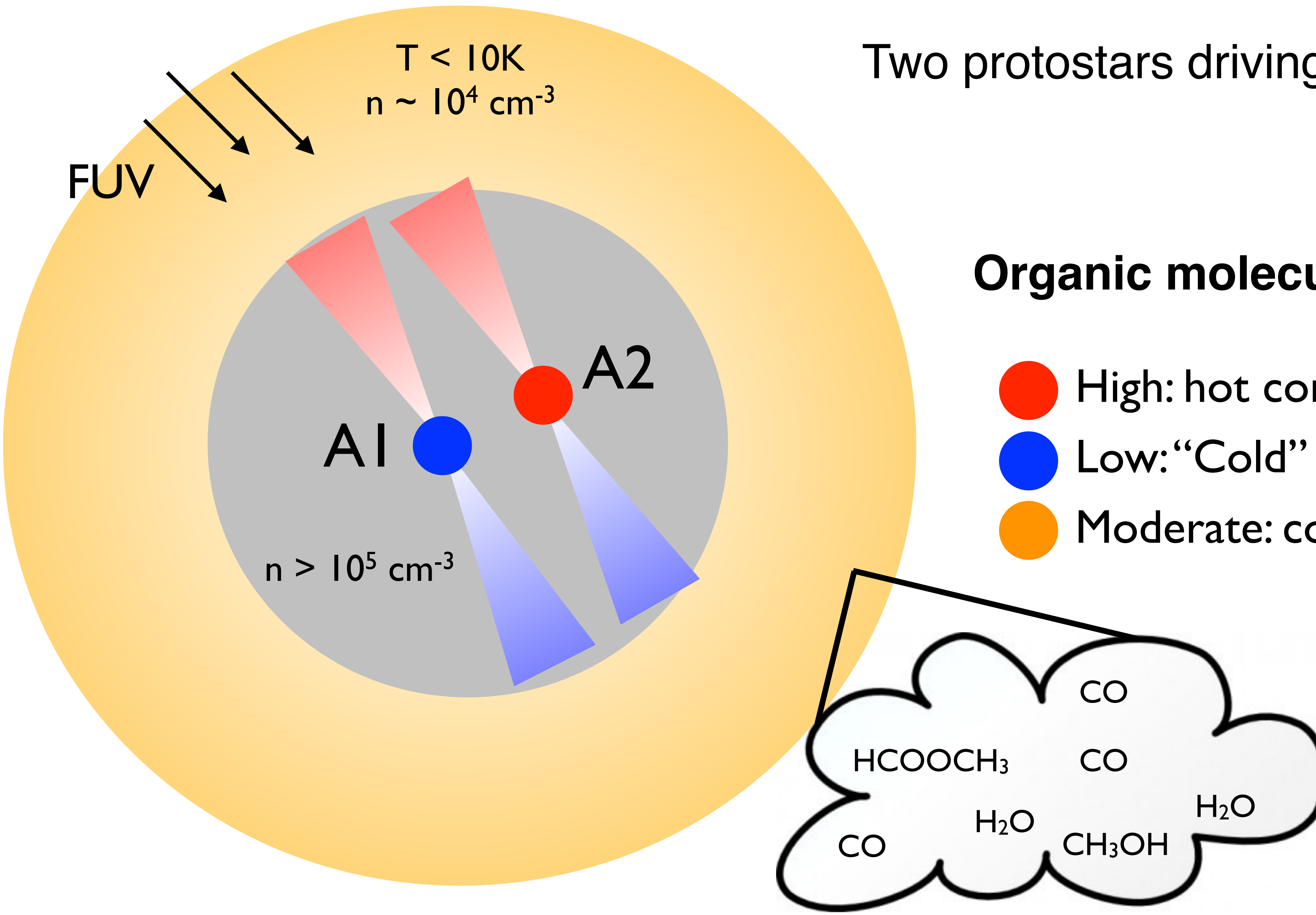
Abundances ~100 times larger in A2
A1: abundances below pre-stellar values

Vastel et al. 2014
Jiménez-Serra et al. 2016

A cartoon of IRAS 4A



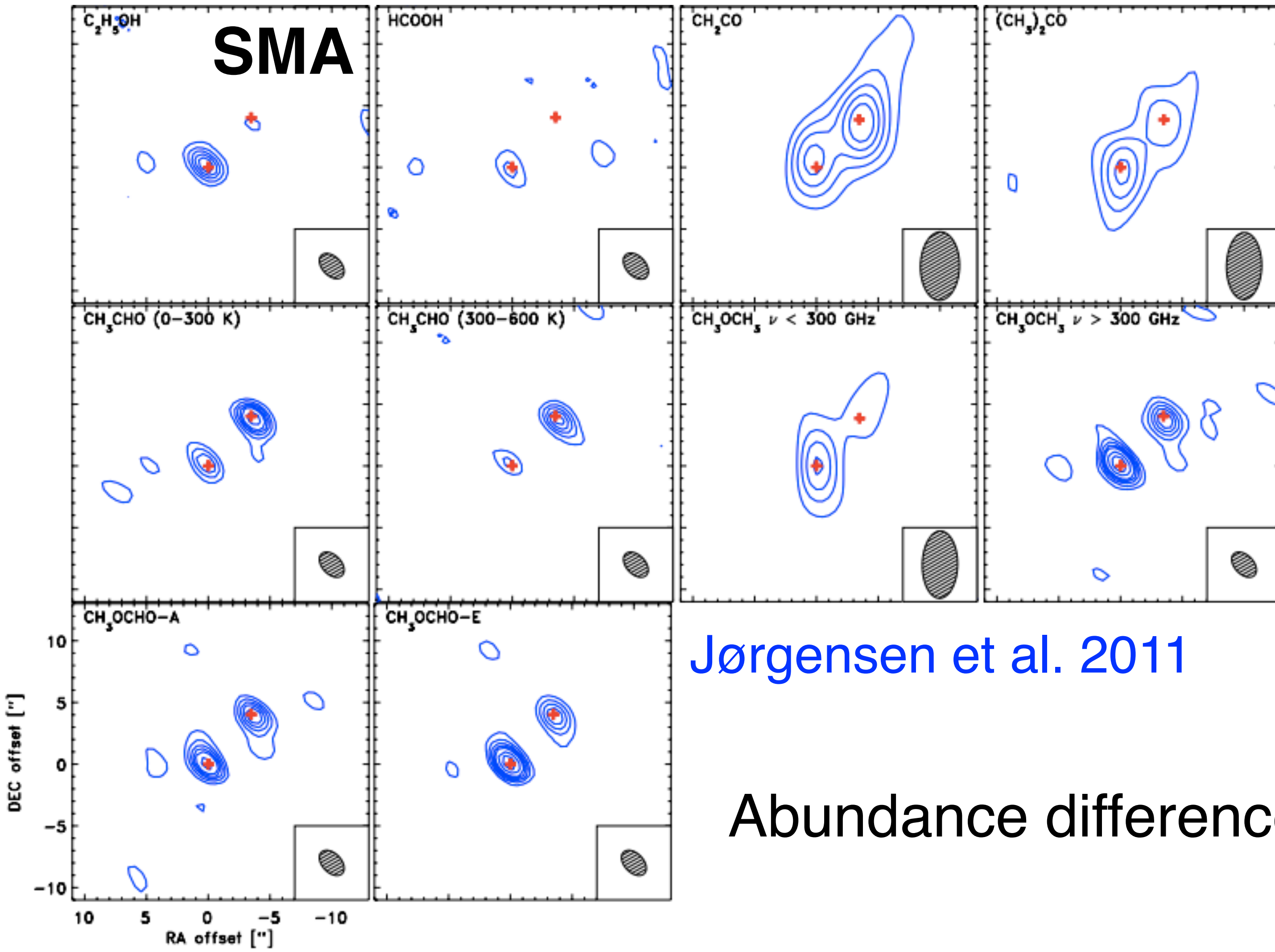
Two protostars driving molecular outflows

Organic molecule abundances:

- High: hot corino
- Low: "Cold" protostellar core
- Moderate: cold outer layer

A1: larger mass envelope, smaller fraction of envelope mass accreted
A2: higher protostellar mass, larger fraction of envelope mass accreted
(temporary event of heavier accretion (see e.g. Taquet et al. 2016)?)

Comparison with IRAS 16293-2422



Jørgensen et al. 2011

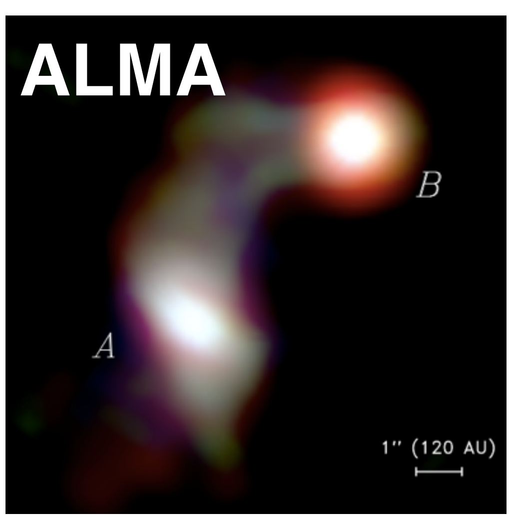
Source A contains a larger variety of COMs

Still, source B competes with A in some O-bearing COMs

see poster #5
S. Manigand

Abundance differences not larger than a factor ~10

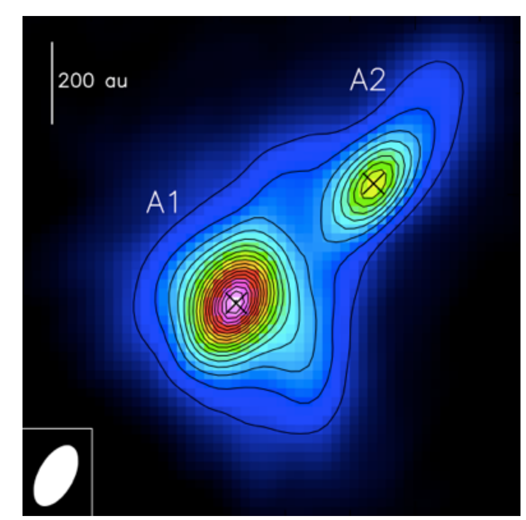
IRAS 16293-2422



Jørgensen et al. 2016

MORE EVOLVED THAN

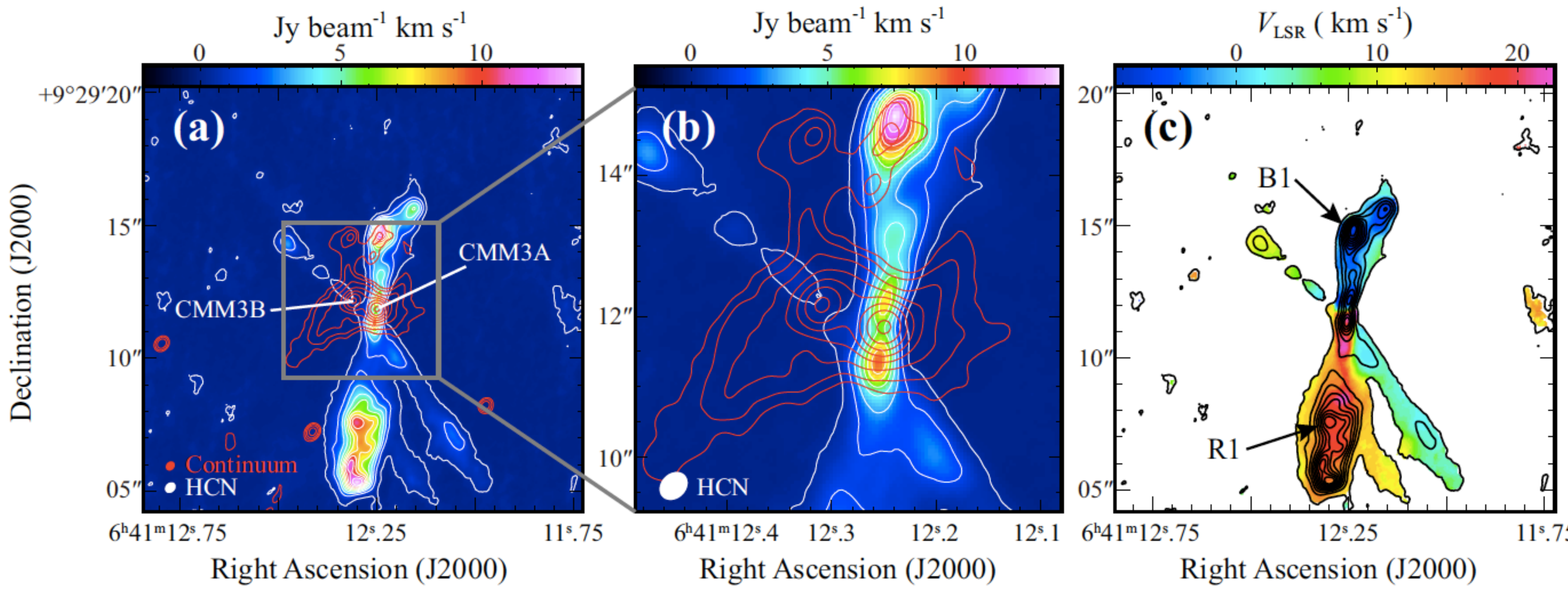
IRAS 4A



?

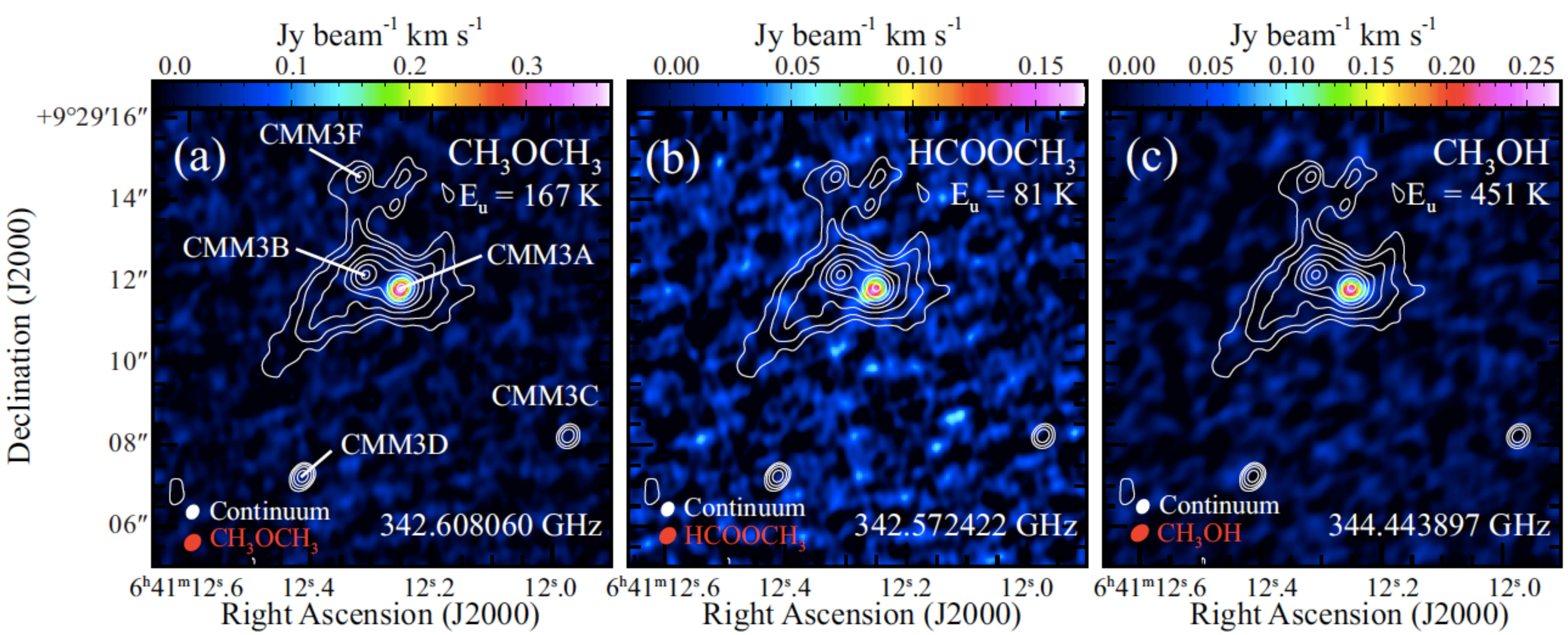
López-Sepulcre et al. 2017

Also at higher masses: NGC 2264-CMM3



Cycle 3 (P.I. Y. Watanabe)
Band 7: 0.8 mm
Beam size ~ 0.35” (270 au)

Two ~10 M_{sun} cores
Only A contains COMs



B younger?
A protostar more massive?
Dust optically thick in B?

Watanabe et al. 2017

Can we assume that all protostellar objects eventually develop a hot corino?

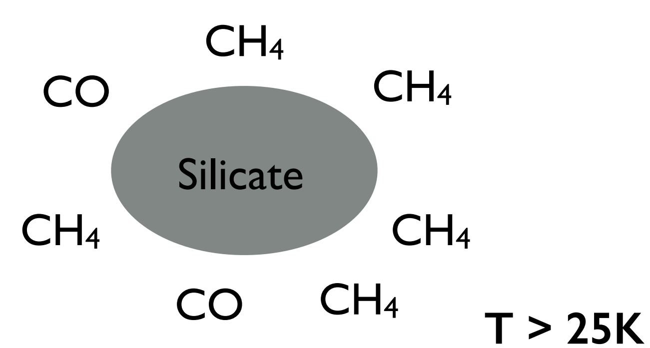
NO

Existence of a chemically different type of protostellar object, the **W**arm **C**arbon **C**hain **C**hemistry (WCCC) object

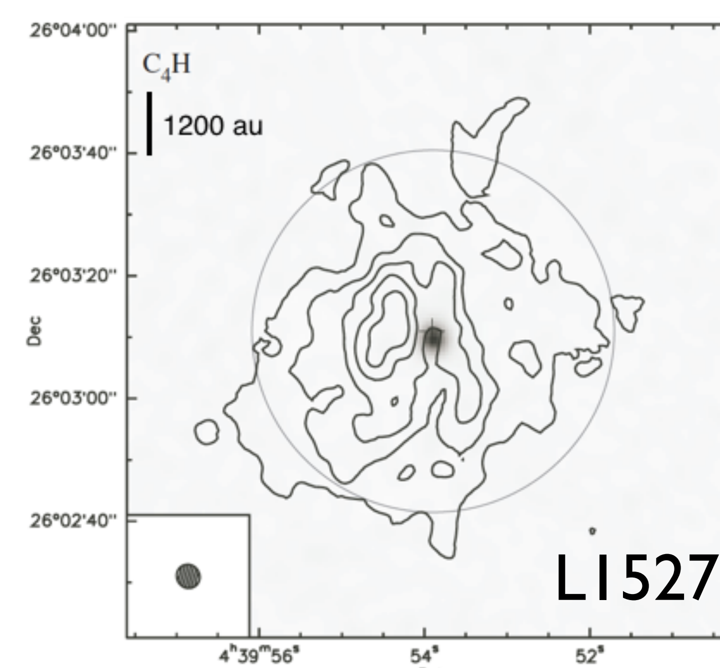
Warm protostellar envelope rich in carbon chains ~10 times more abundant than in hot corinos

No evidence of saturated COMs

Icy mantles contain large amounts of CH_4



Sakai et al. 2010

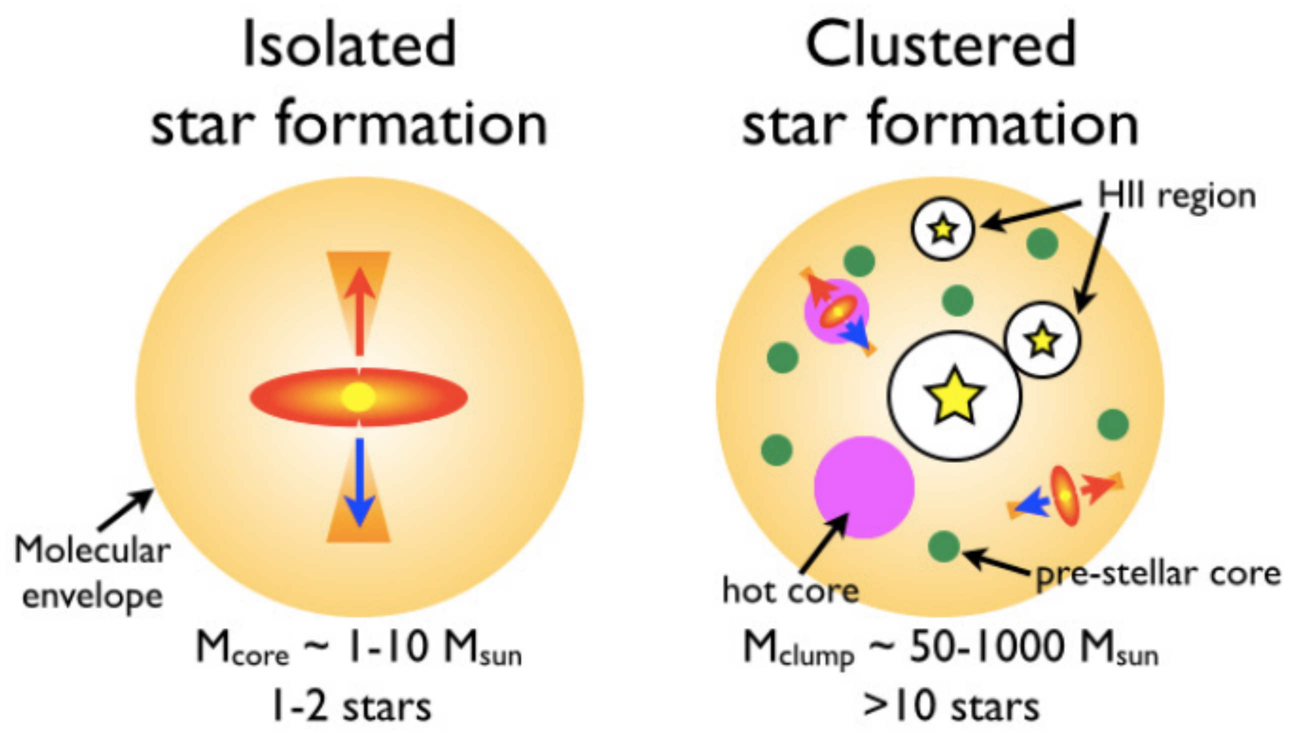


Did the Solar System go through a hot corino phase during its formation?

?

Search for proto-solar analogues

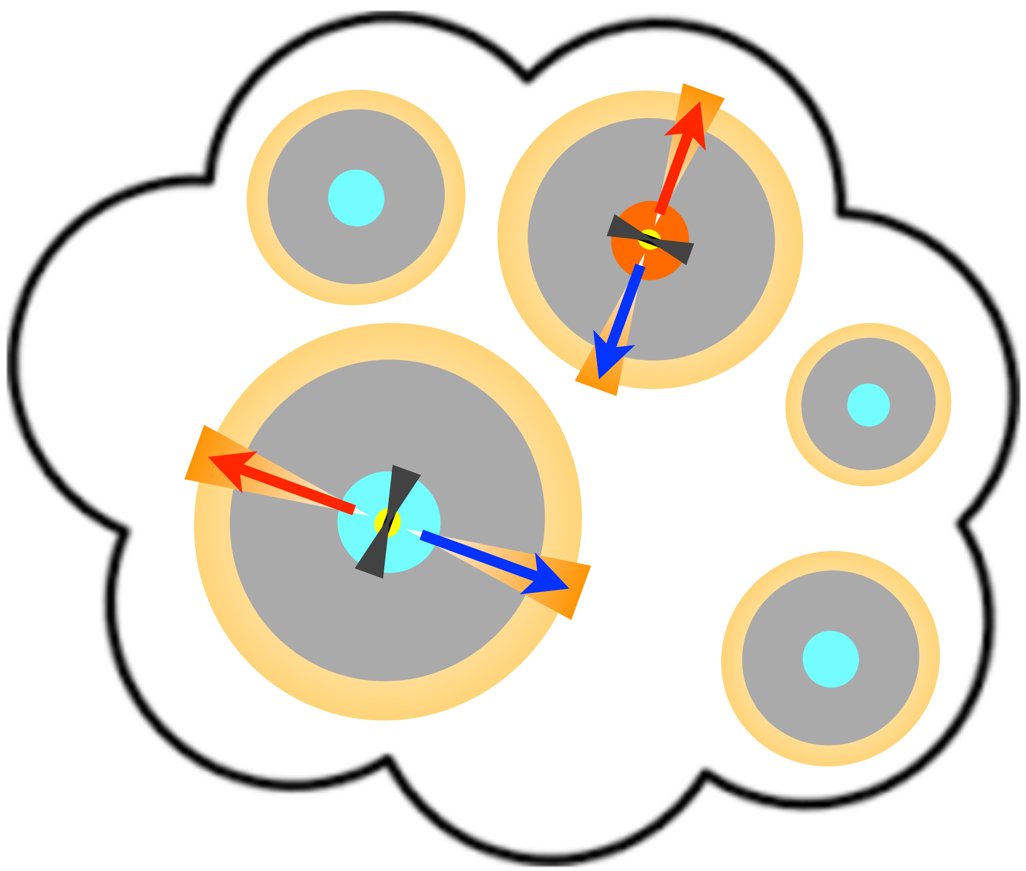
The formation of the Solar System



The Solar System very likely formed in a large stellar cluster, with high-mass stars in its vicinity (Adams et al. 2010, Pfalzner et al. 2015)

The formation of low-mass stars in massive star protoclusters should be investigated to better understand the birth of the Solar System

Outline



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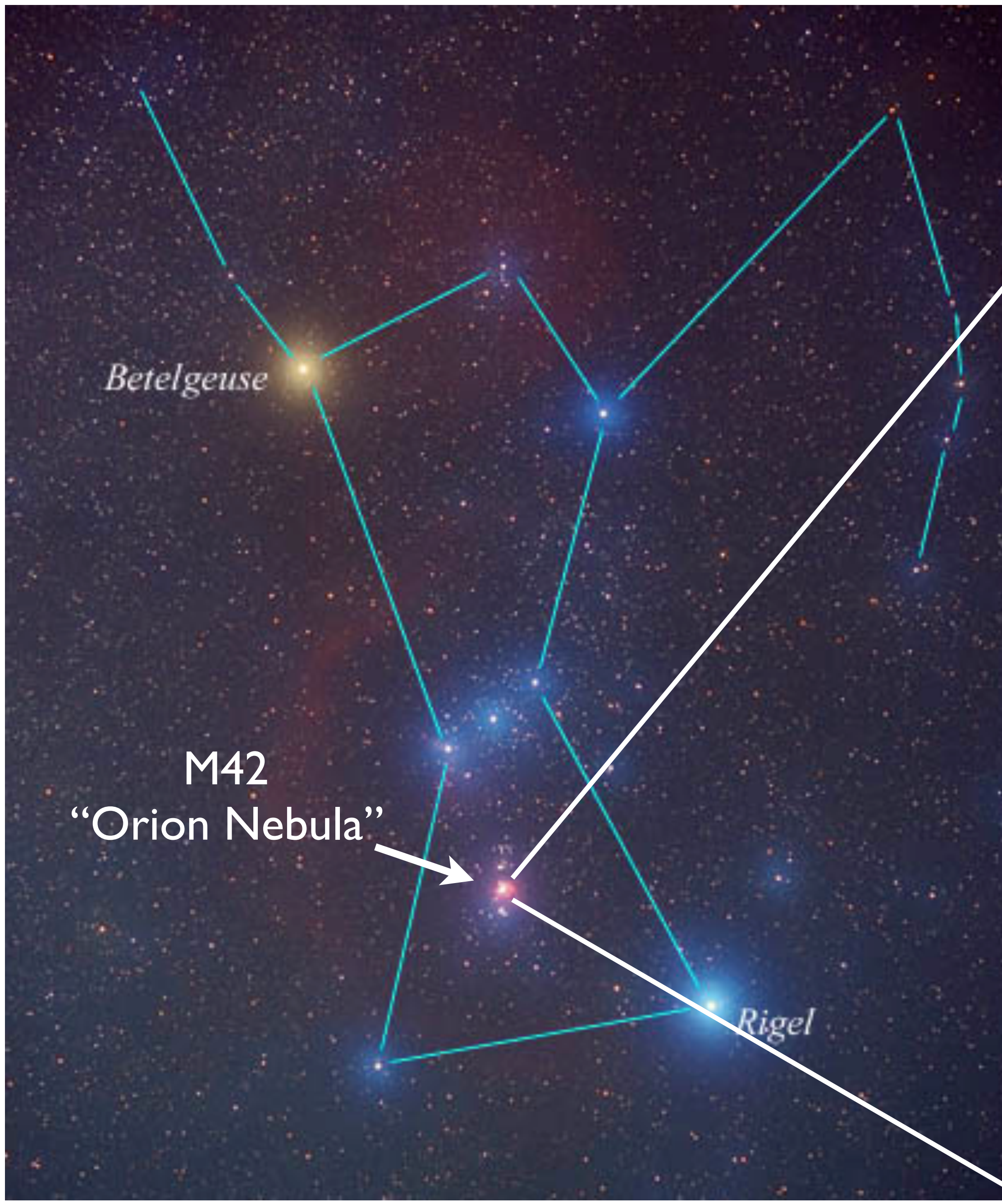
2. What molecular chemistry is present in a protosolar-like environment?

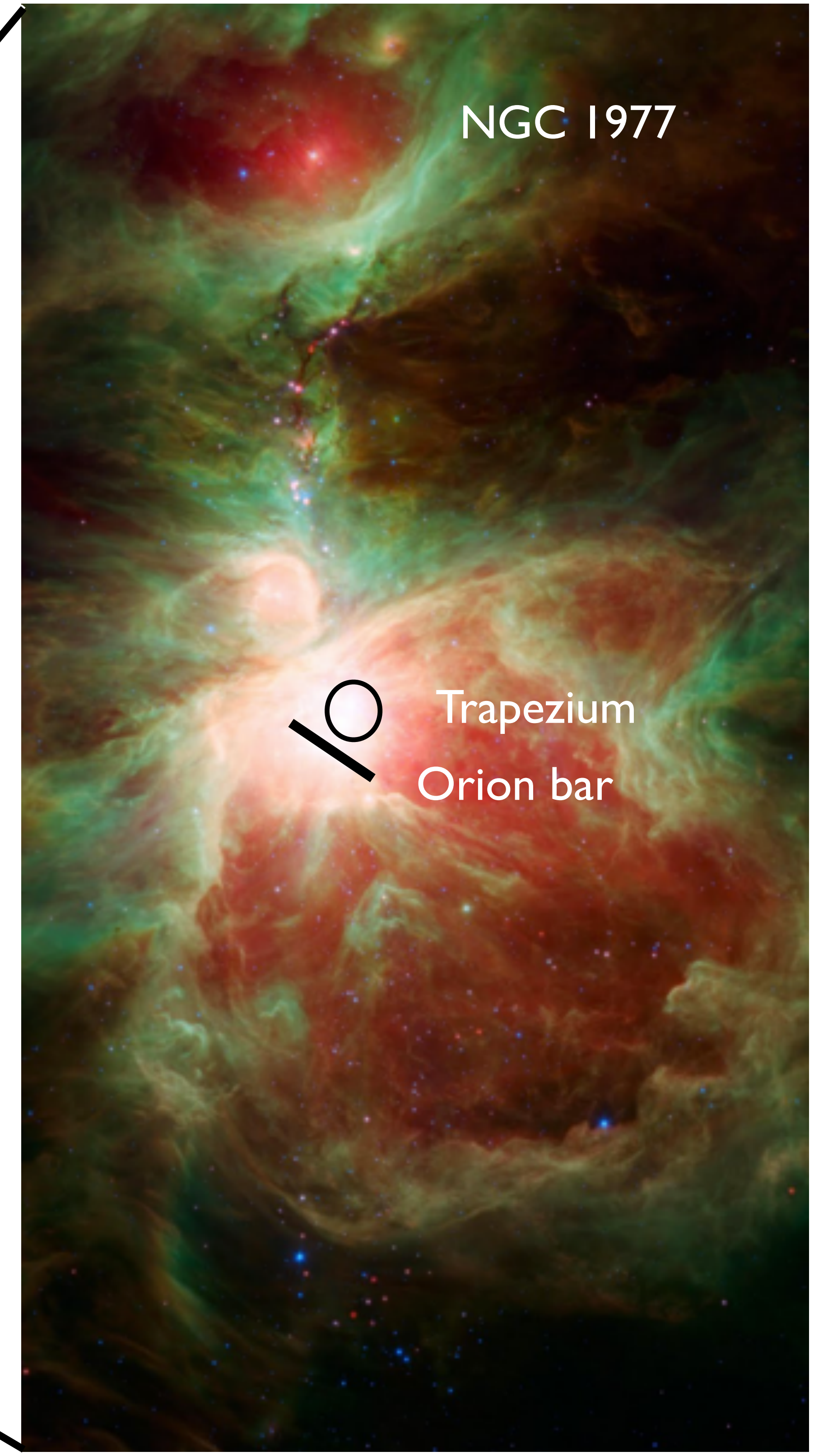
  OMC-2 FIR 4, protocluster

  Complex, "energetic", carbon-chain rich

3. Summary & how to go forward

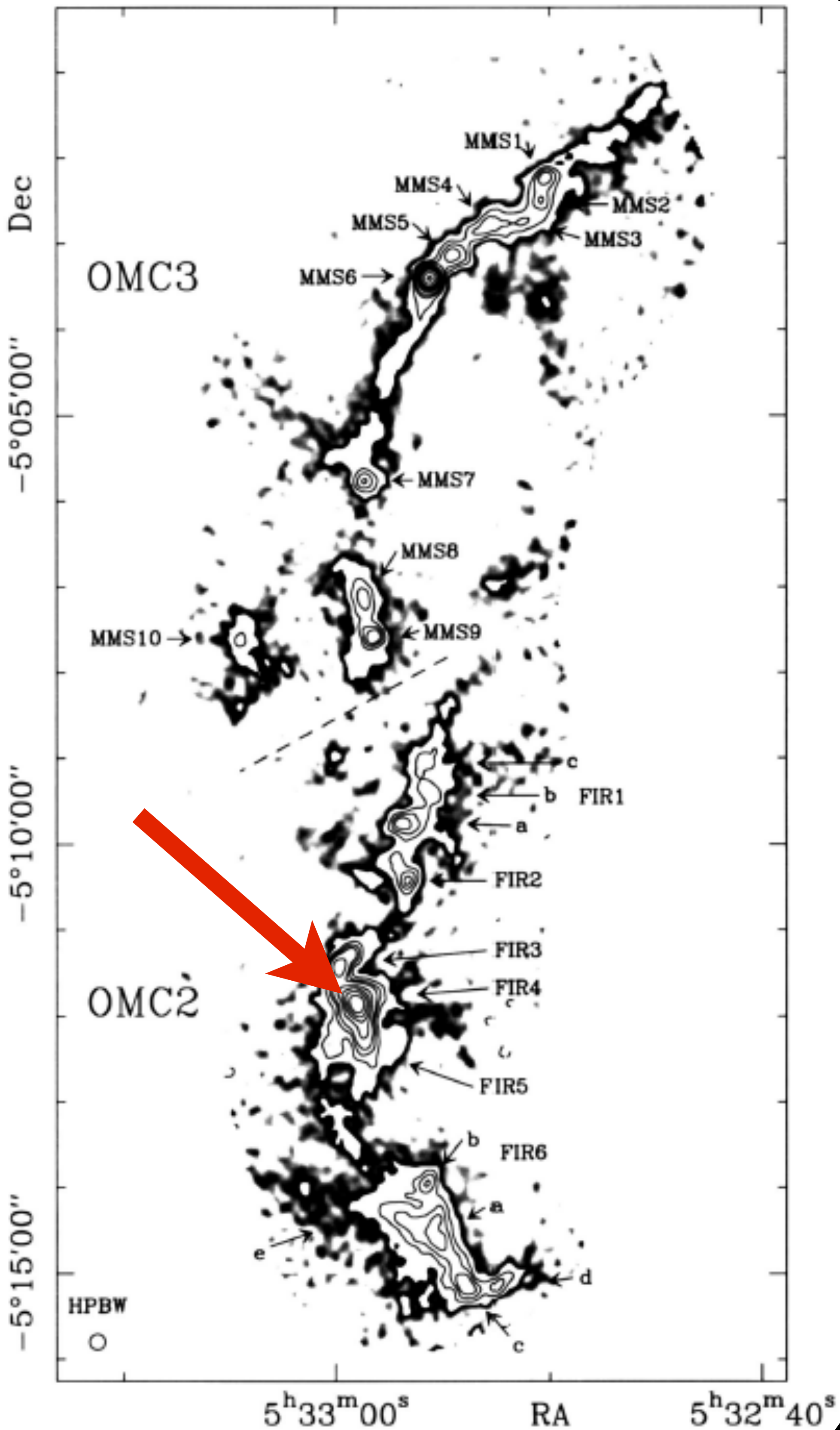
The Orion A complex



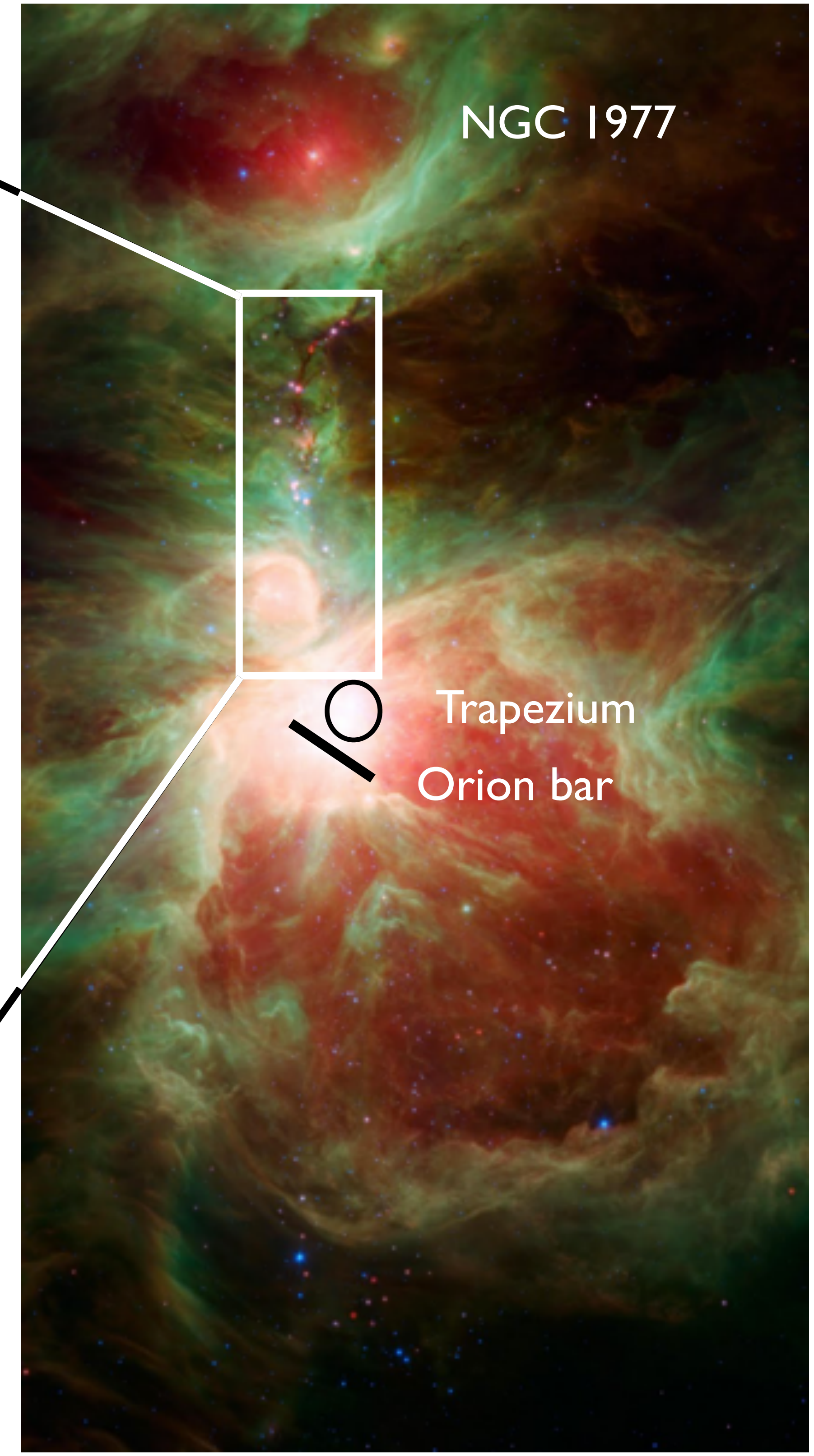


ORION A: 2.2mic 3.6mic 4.5mic
http://www.spitzer.caltech.edu

The Orion A complex



1mm; Chini et al. 1997

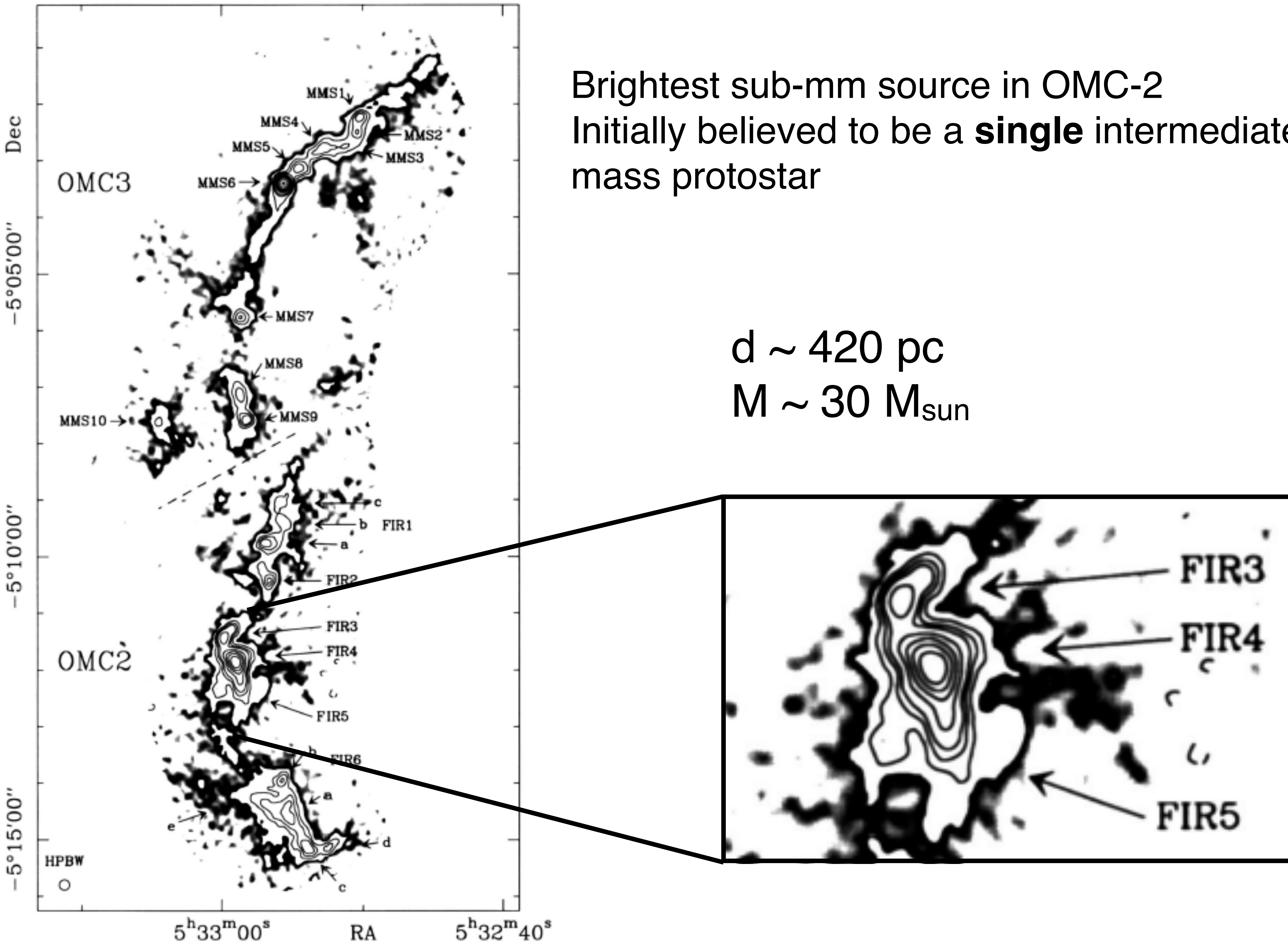


ORION A: 2.2mic 3.6mic 4.5mic
http://www.spitzer.caltech.edu

OMC-2 FIR 4

Brightest sub-mm source in OMC-2
Initially believed to be a **single** intermediate-mass protostar

d ~ 420 pc
M ~ 30 M_{sun}



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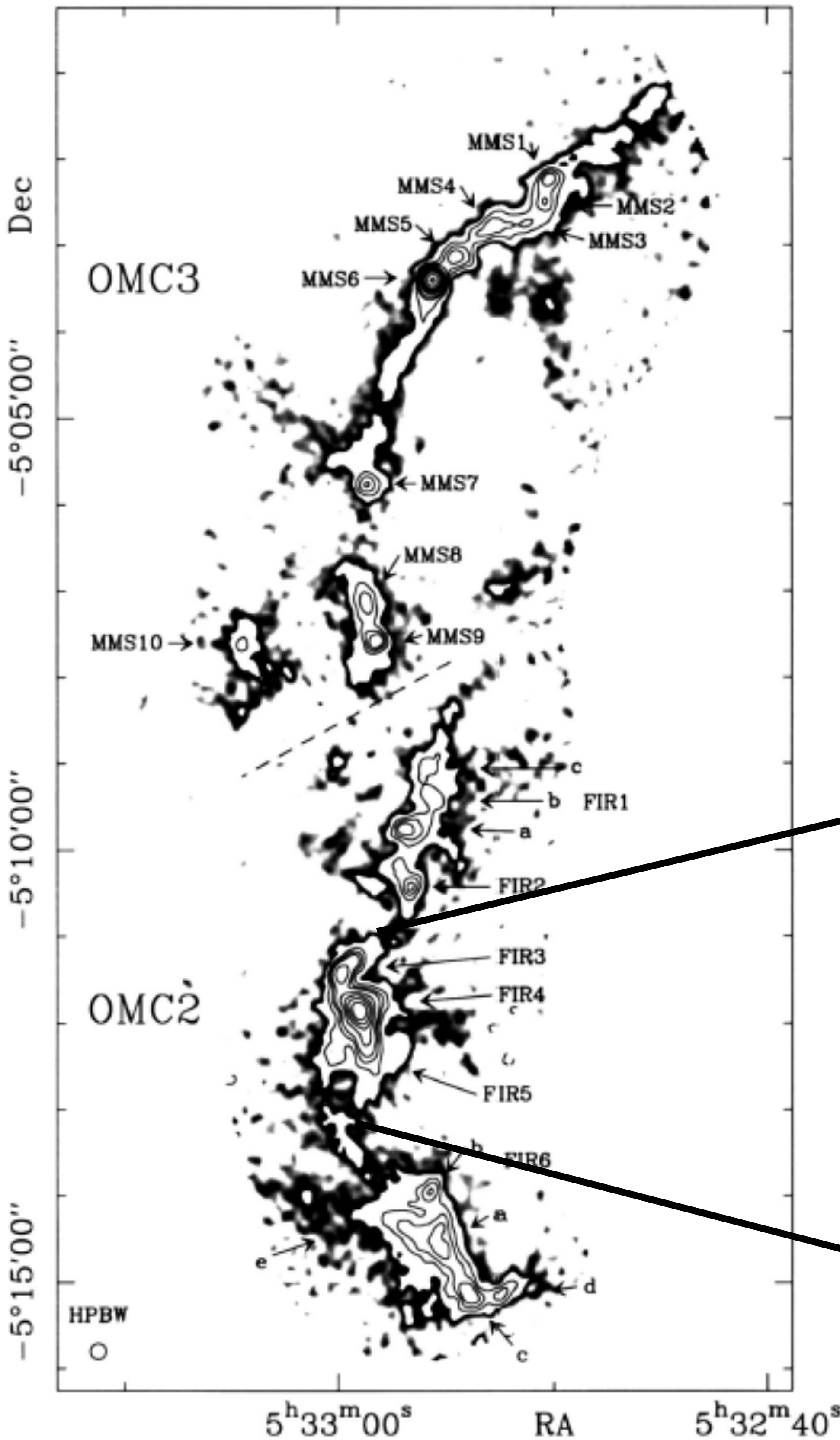
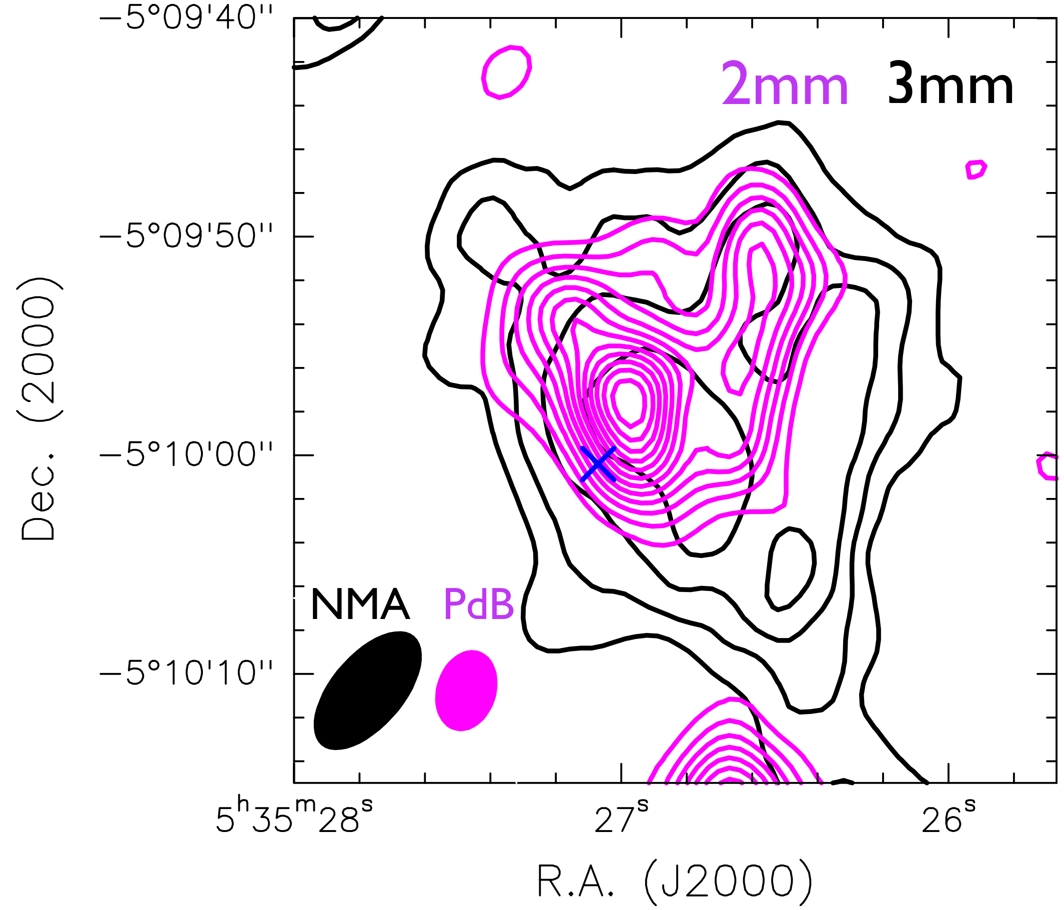
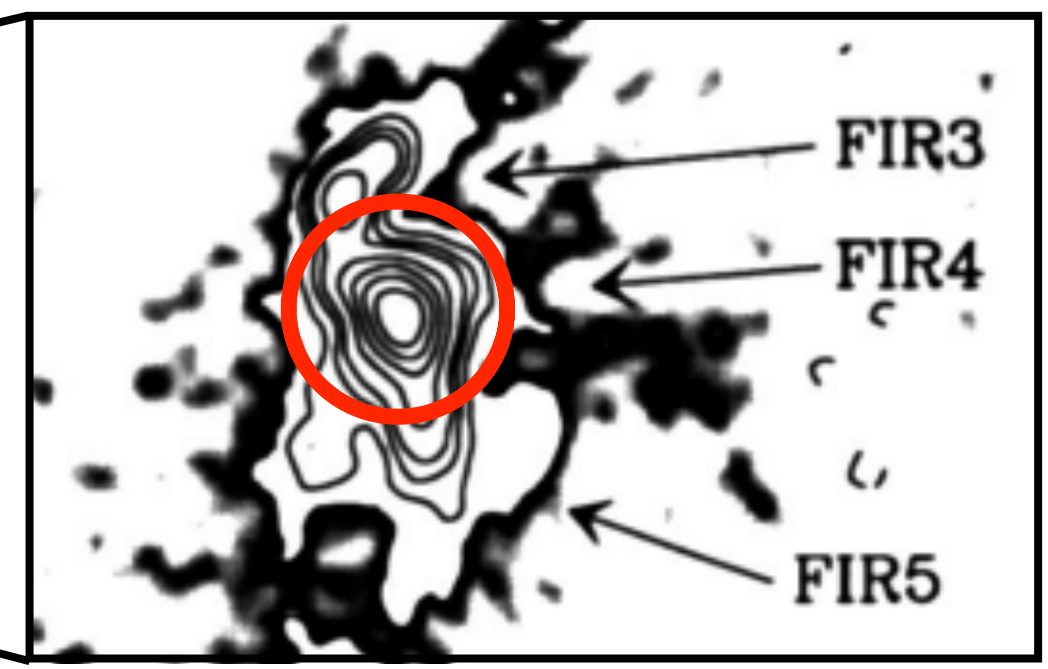


1mm; Chini et al. 1997

Shimajiri et al. 2008
López-Sepulcre et al. 2013

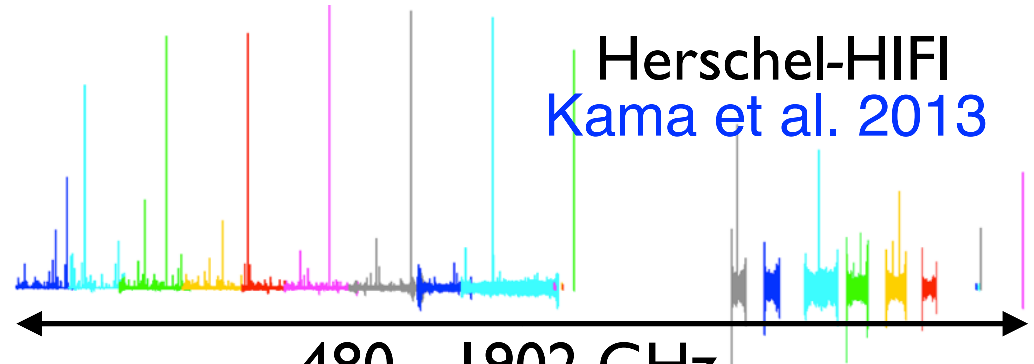


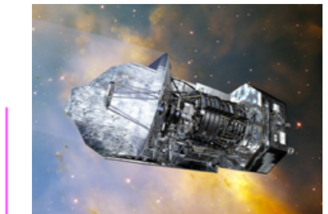


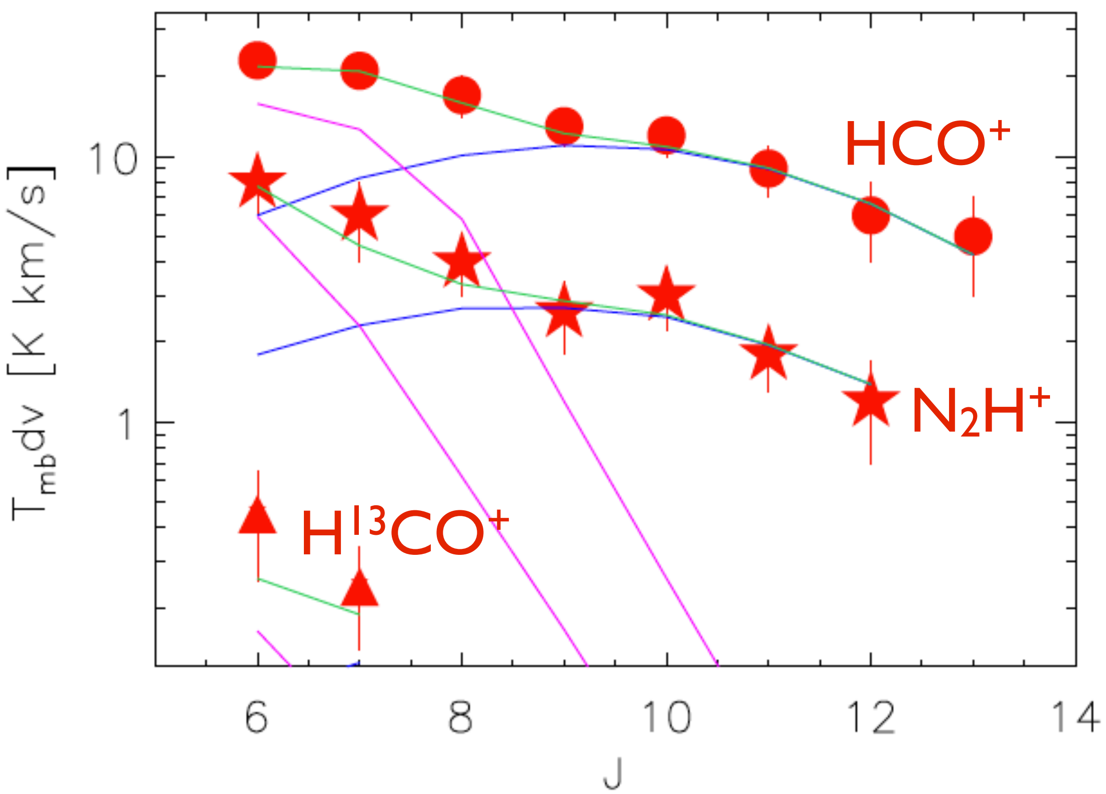
Internal source of high-E particles

Abundance ratio
HCO^+/N_2H^+ = 3-4

Large electron abundance







Ceccarelli et al. 2014

- High cosmic-ray ionisation rate (~10^{-14} s^{-1}) from an **internal source**
- Comparable to the dose recorded from ^{10}Be in meteoritic material, associated with early solar flaring events
- Not clearly observed in other protostellar objects (see Favre et al. 2017)

How is the chemistry of other molecules affected?

The IRAM large programme SOLIS

Seeds Of Life In Space

http://solis.osug.fr

P.I.s: C. Ceccarelli (IPAG, France)
P. Caselli (MPIA, Germany)

NOEMA array

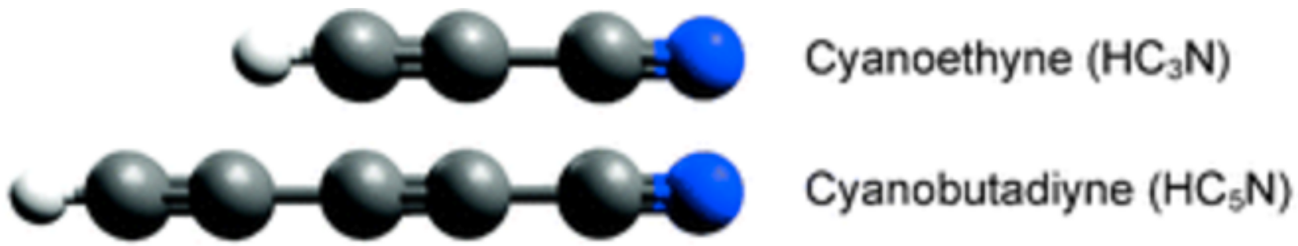
346 hours (almost done)

Systematic survey of a number of COMs (and many other molecules) toward a sample of low- and intermediate mass objects

- L1544
- L1521F
- IRAS 4A
- Cep E
- SVS 13A
- **OMC-2 FIR 4**
- L1157 B1

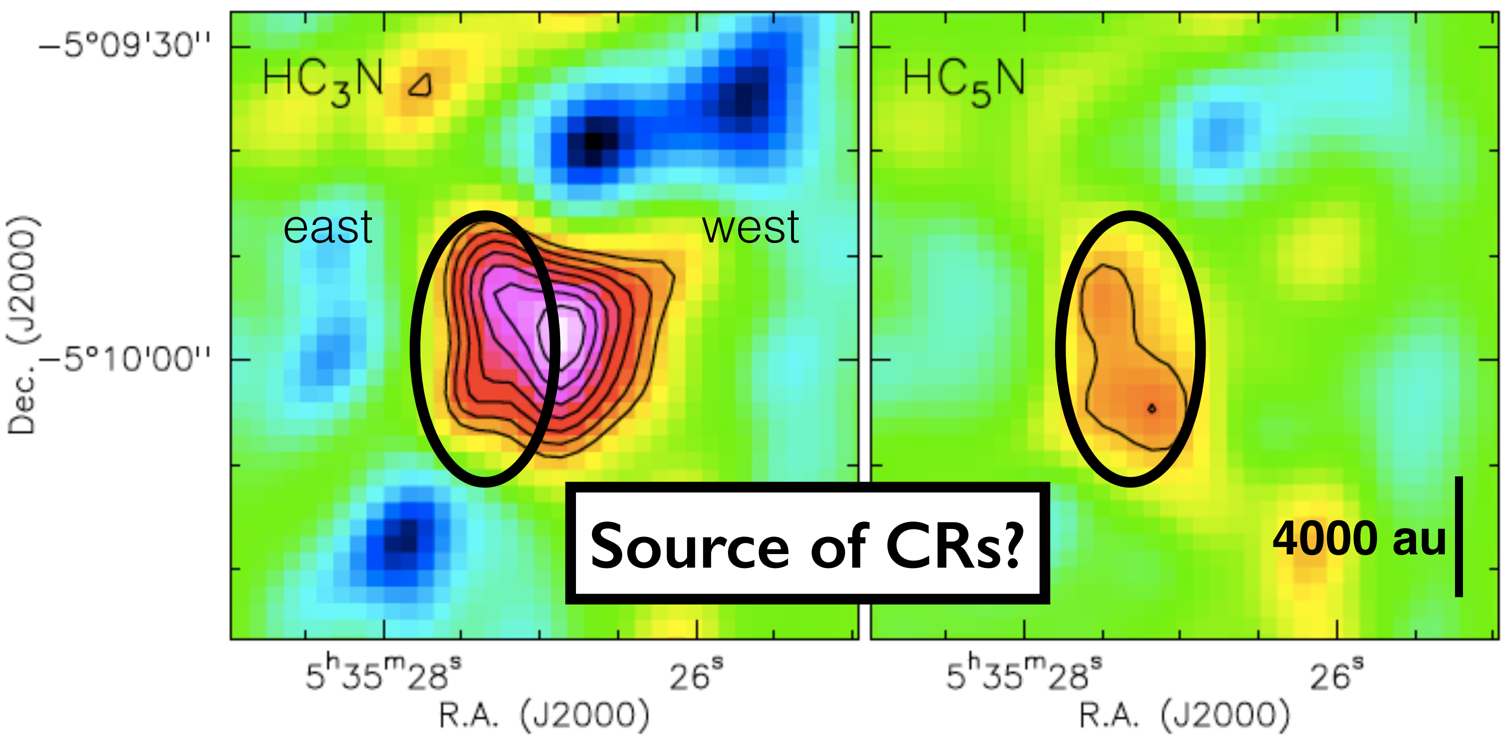
Ceccarelli et al. 2017

Carbon chain growth in OMC-2 FIR 4



Carbon chains such as cyanopolyynes can be important reservoirs of carbon

Fontani et al. 2017



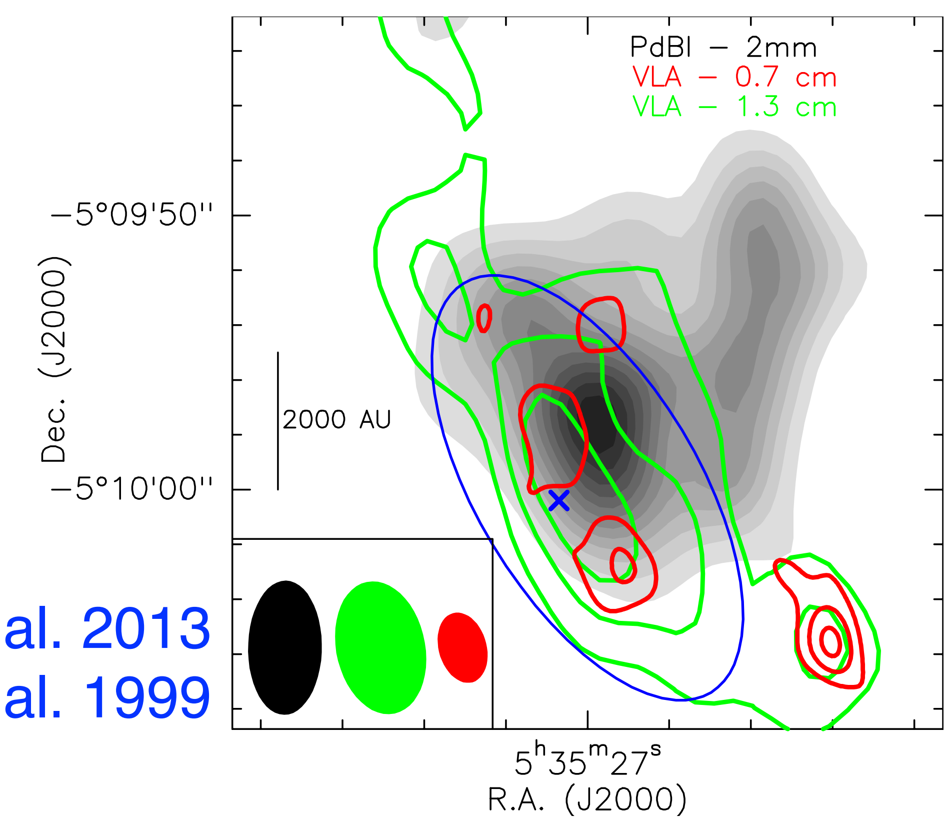
East: $[HC_3N]/[HC_5N]$ = 4 - 12
West: $[HC_3N]/[HC_5N]$ = 10 - 30

$[HC_3N]/[HC_5N] < 10$ only reproduced if the cosmic-ray ionisation rate is high ($\sim 10^{-14}$ s^{-1})

Energetic particles promote carbon chain growth

This might have contributed to produce important carbon reservoirs during Solar System formation

López-Sepulcre et al. 2013
Reipurth et al. 1999



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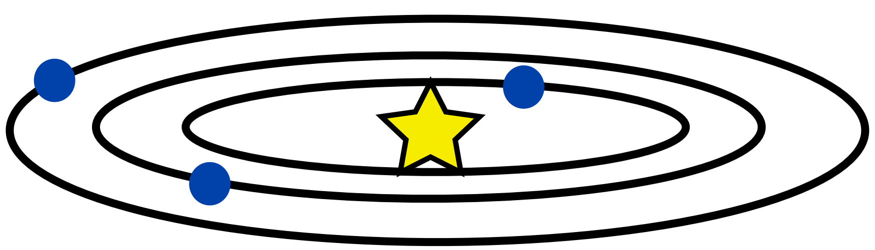
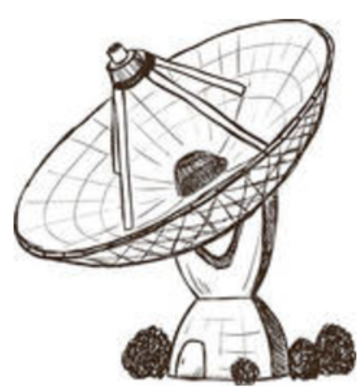
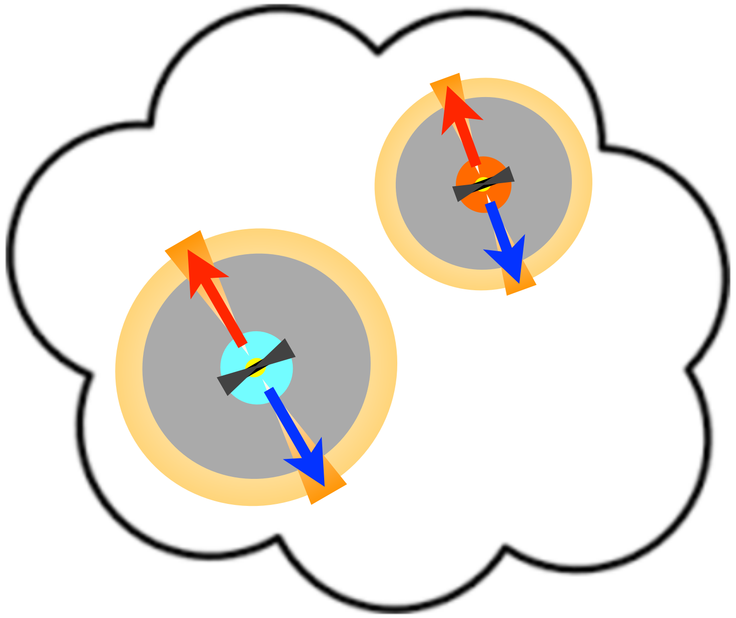


3. Summary & how to go forward



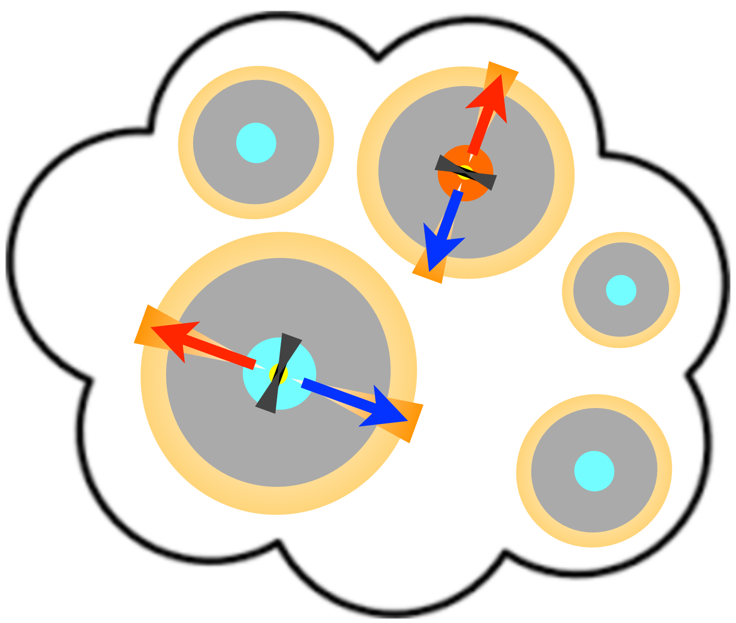
Summary



IRAS 4A, protobinary

Striking difference in chemical richness around two neighbouring protostars; similar cases in other binaries
—> Hot corinos may be transient and/or typically smaller

HOT CORINOS ARE NOT THE RULE!



OMC-2 FIR 4, protocluster

Closest known analogue of the formation environment of the Solar System
Carbon chain growth is enhanced by the presence of an internal source of energetic particles

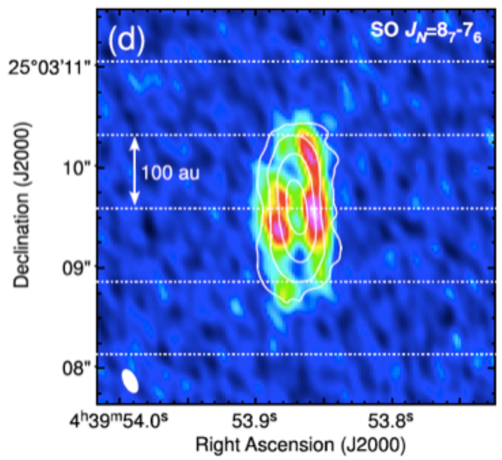
Number and nature of cores in OMC-2 FIR 4?
(Neri et al. *in prep.*)

Organic contents? Hot corino(s) present?
(Favre et al. *in prep.* and many more to come!)

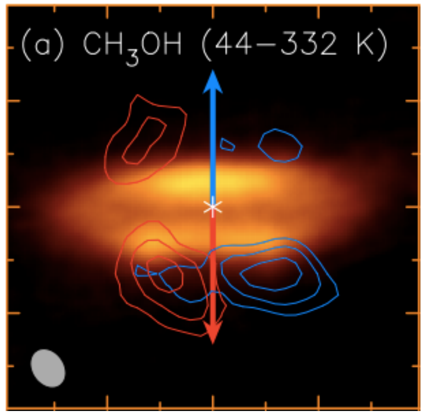
Three ways to go forward

1. HIGHER ANGULAR RESOLUTION

Hot corinos and protostellar disks have been barely resolved so far
First attempts with ALMA very promising (0.1" - 0.2" resolution)



L1527
Sakai et al. 2017



HH 212
Lee et al. 2017

2. BROADBAND SPECTRAL SURVEYS (INTERFEROMETERS)

More molecular lines observed simultaneously at high angular resolution
NOEMA (PolyFiX) moving in this direction; also ALMA in the future

3. IMPROVE STATISTICS!

The number of hot corinos clearly identified is VERY limited (<10): is there a "typical" or "dominant" molecular composition among protostellar objects?
(Higuchi et al. *in prep.*; Graninger et al. 2016, Lindberg et al. 2016)