OUR ASTROCHEMICAL HERITAGE

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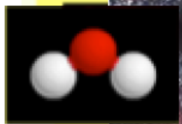
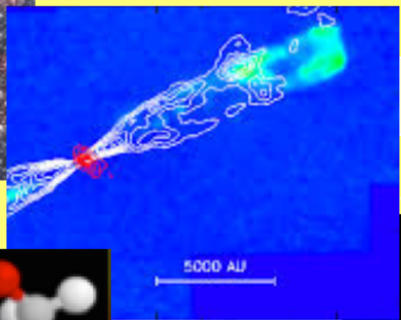
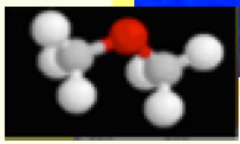


1- PRE-STELLAR PHASE: cold and dense gas

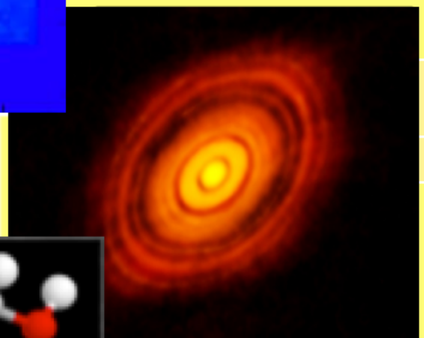
FORMATION OF SIMPLE AND COMPLEX MOLECULES. THICK ICY MANTLES.

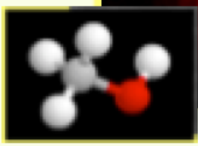




2- PROTOSTELLAR PHASE: collapsing, warm dense gas

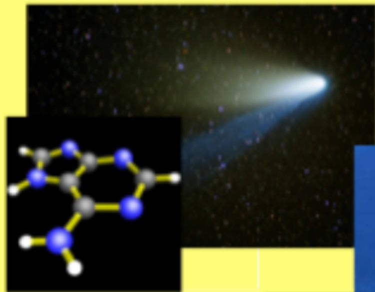
PARTIAL ICE SUBLIMATION. HOT/SHOCK CHEMISTRY.

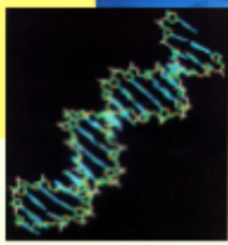




3- PROTOPLANETARY DISK PHASE:

DUST COAGULATION. GAS/ICE PROCESSING.



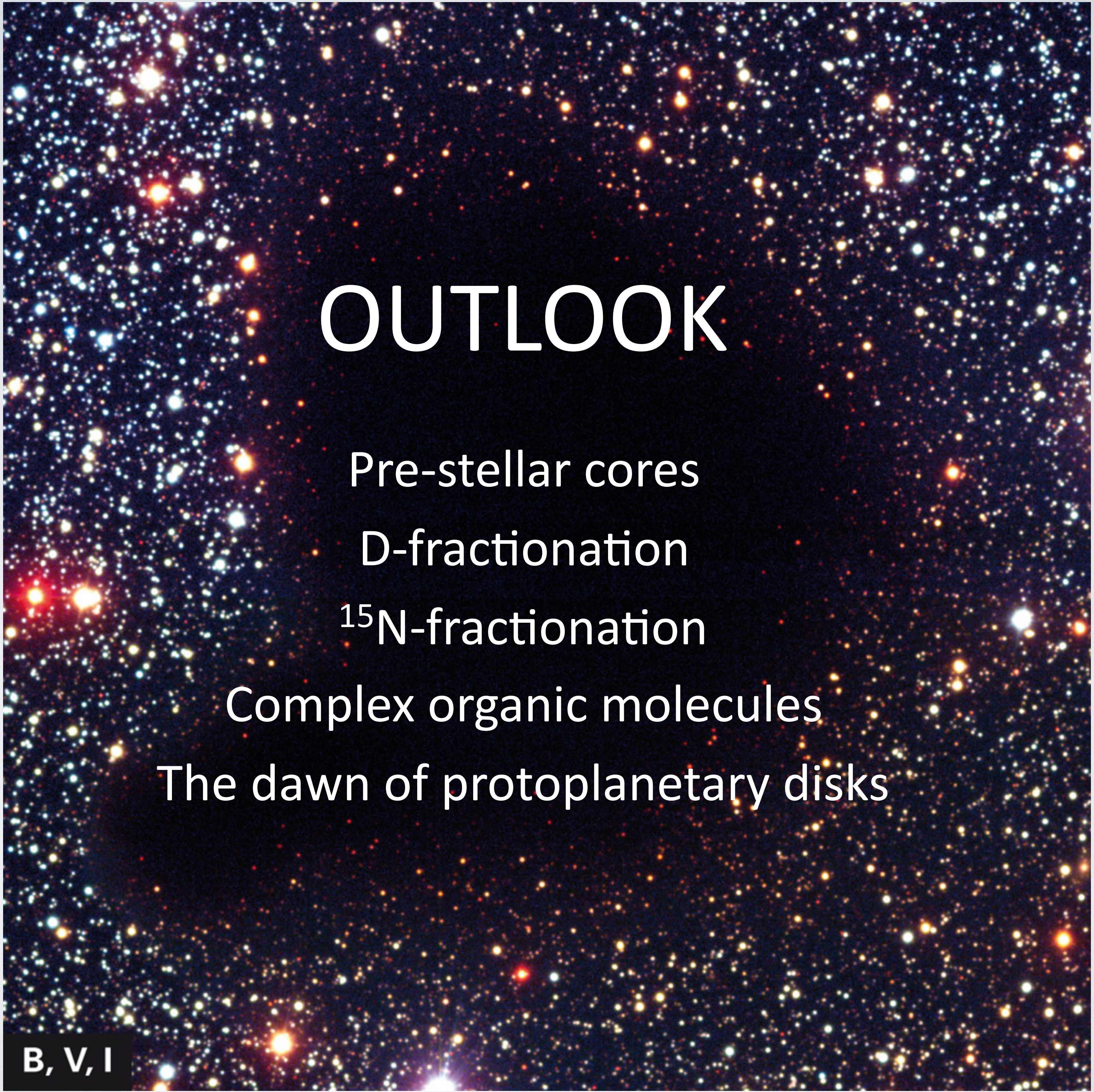


4- PLANETESIMAL FORMATION : grains agglomeration

5- PLANET FORMATION AND THE “COMET/ASTEROID RAIN”

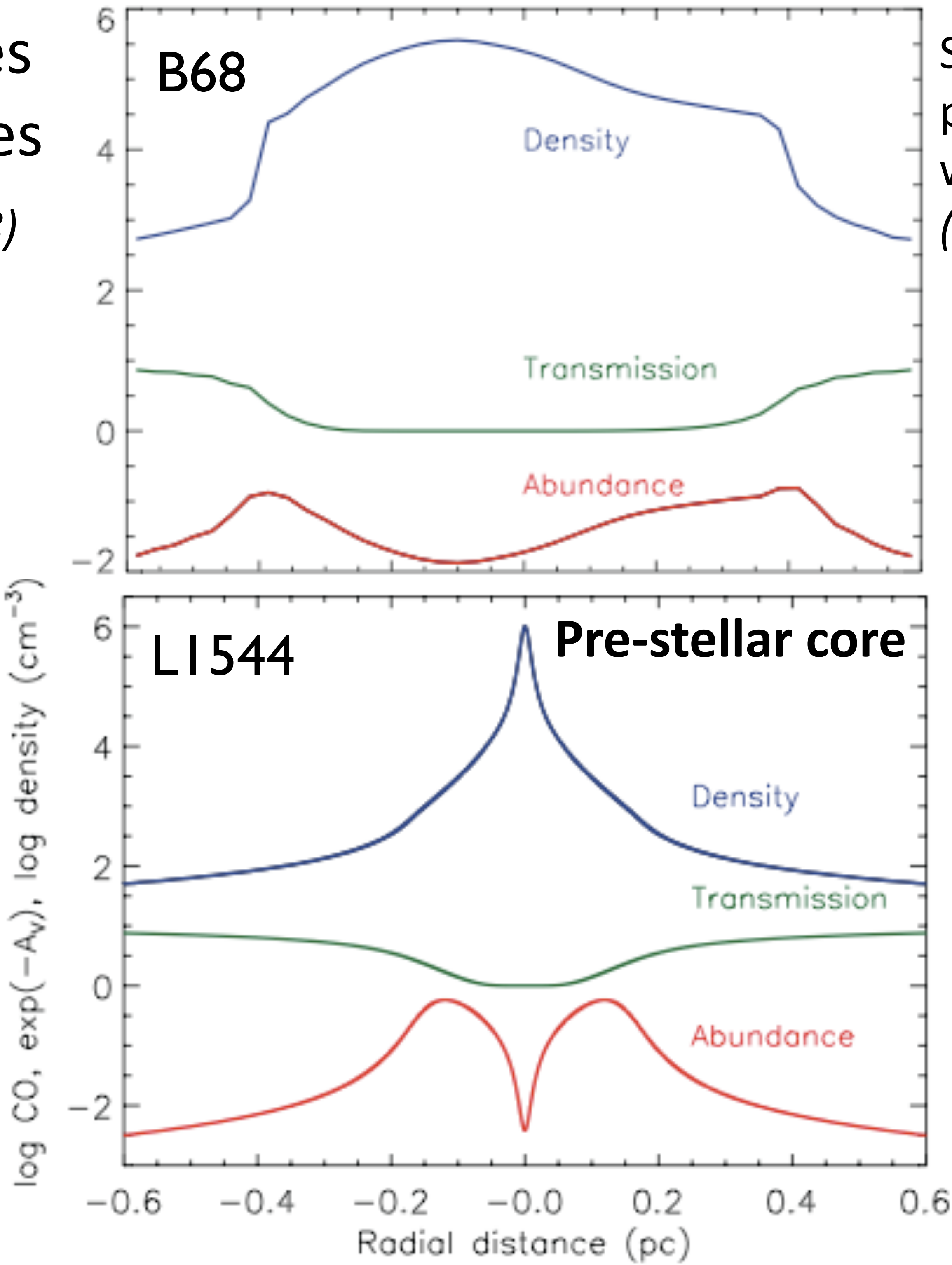
DELIVERY OF PROCESSED AND PRISTINE MATERIAL (?) + LIFE

Adapted from: Caselli & Ceccarelli 2012


OUTLOOK
Pre-stellar cores
D-fractionation
^{15}N-fractionation
Complex organic molecules
The dawn of protoplanetary disks
B, V, I

The two classes of starless cores

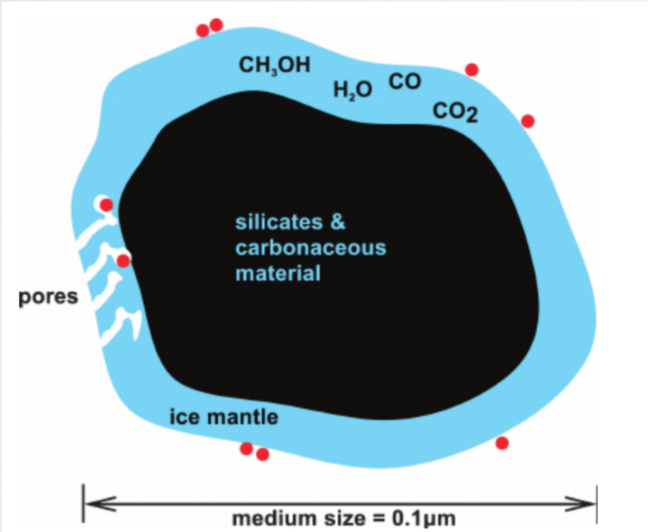
(Keto & Caselli 2008)



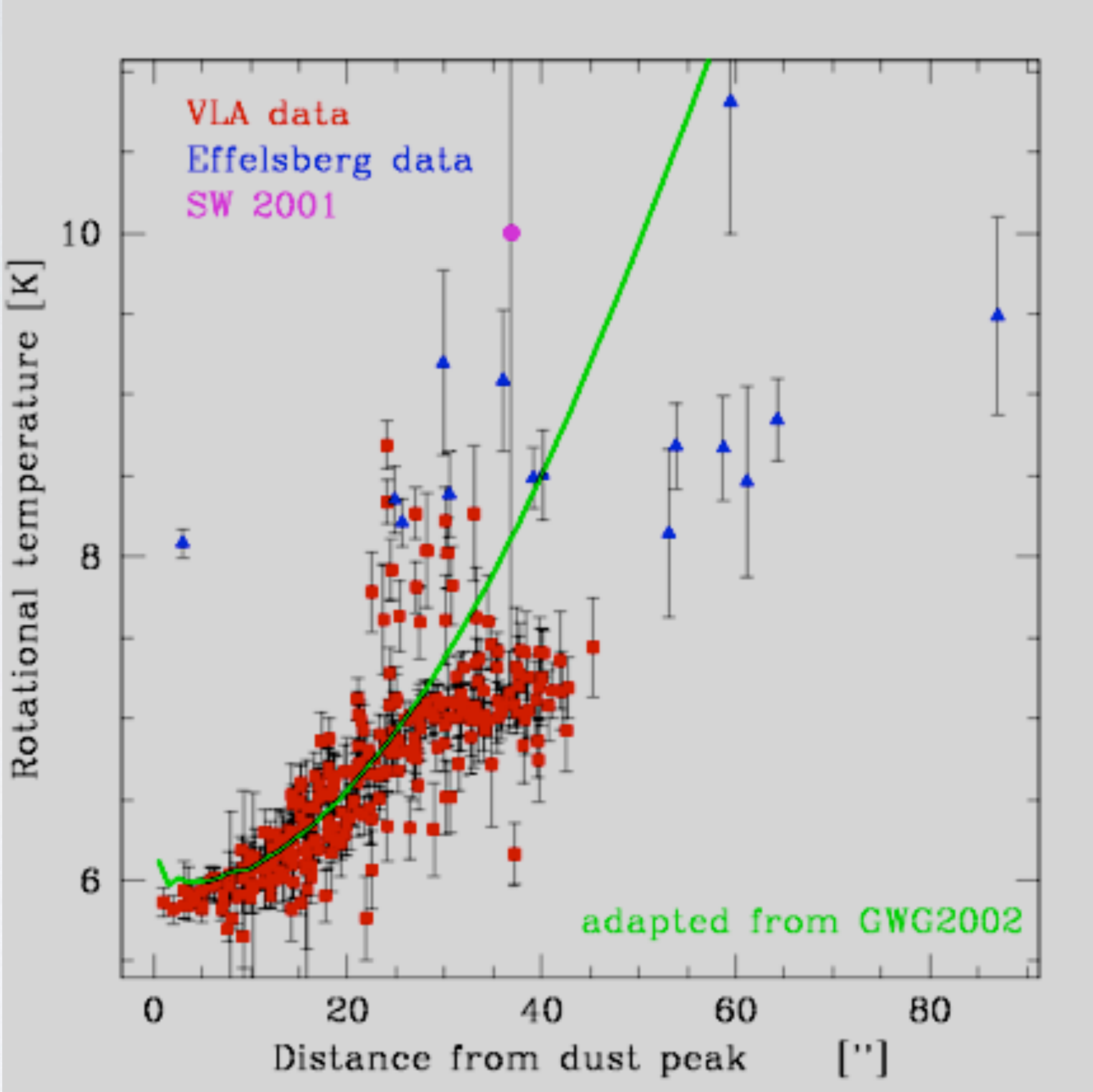
Spectral line profiles consistent with oscillations *(Lada et al. 2003)*

Spectral line profiles consistent with (subsonic) contraction motions *(Tafalla et al. 1998; Caselli et al. 2002)*

The gas temperature drops to ~6 K in the central few thousand AU of a pre-stellar core

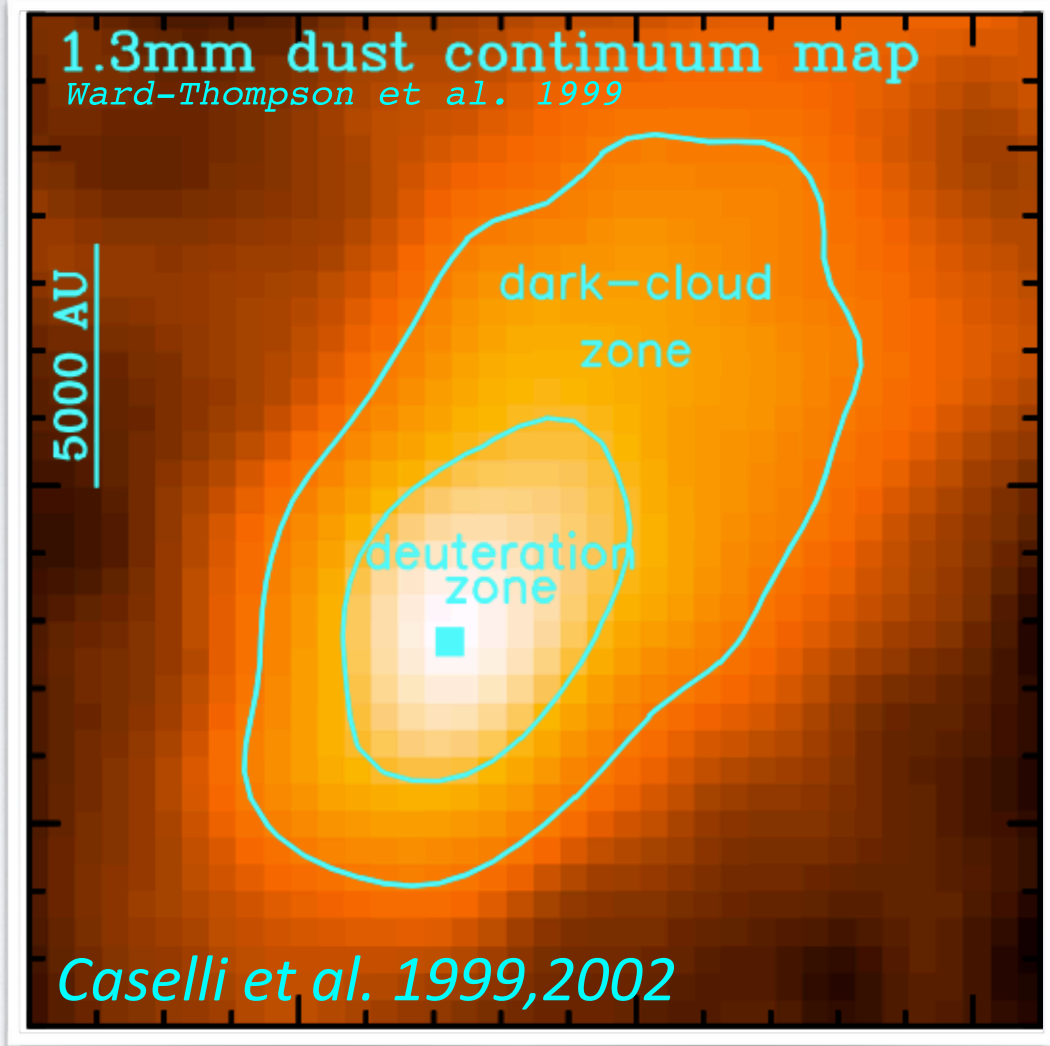


Karssemejer et al. 2012, PCCP



Crapsi, Caselli, Walmsley, Tafalla 2007

CO freeze out and the deuteration zone



$H_3^+ + HD \rightarrow H_2D^+ + H_2 + 230$ K *(Watson 1974)*

Neutral (O, CO) depletion *(Dalgarno & Lepp 1984)*

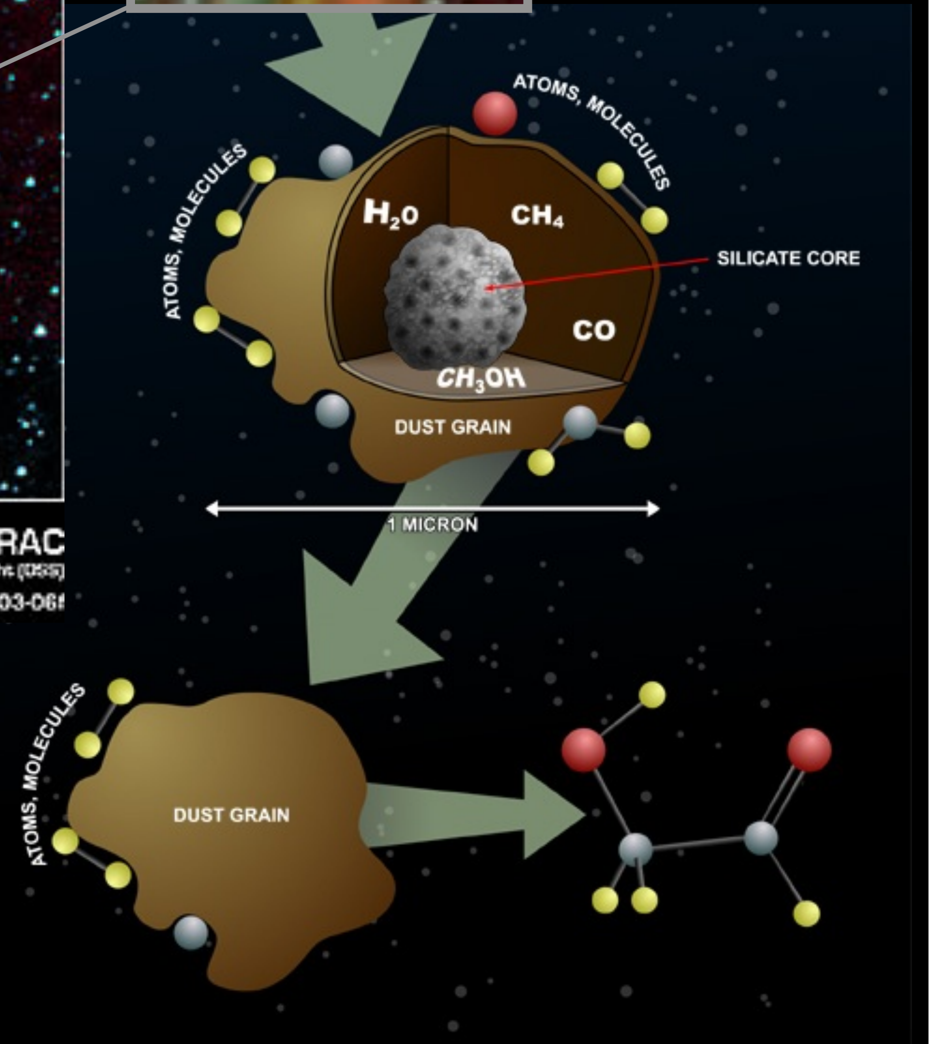
(see also Bacmann et al. 2002, 2003; Hirota et al. 2003; Pagani et al. 2007; Spezzano et al. 2016)

Deuteration in protostellar objects

Embedded Outflow in HH 46/47 Spitzer Space Telescope • IRAC

Inset: visible light (DSS)

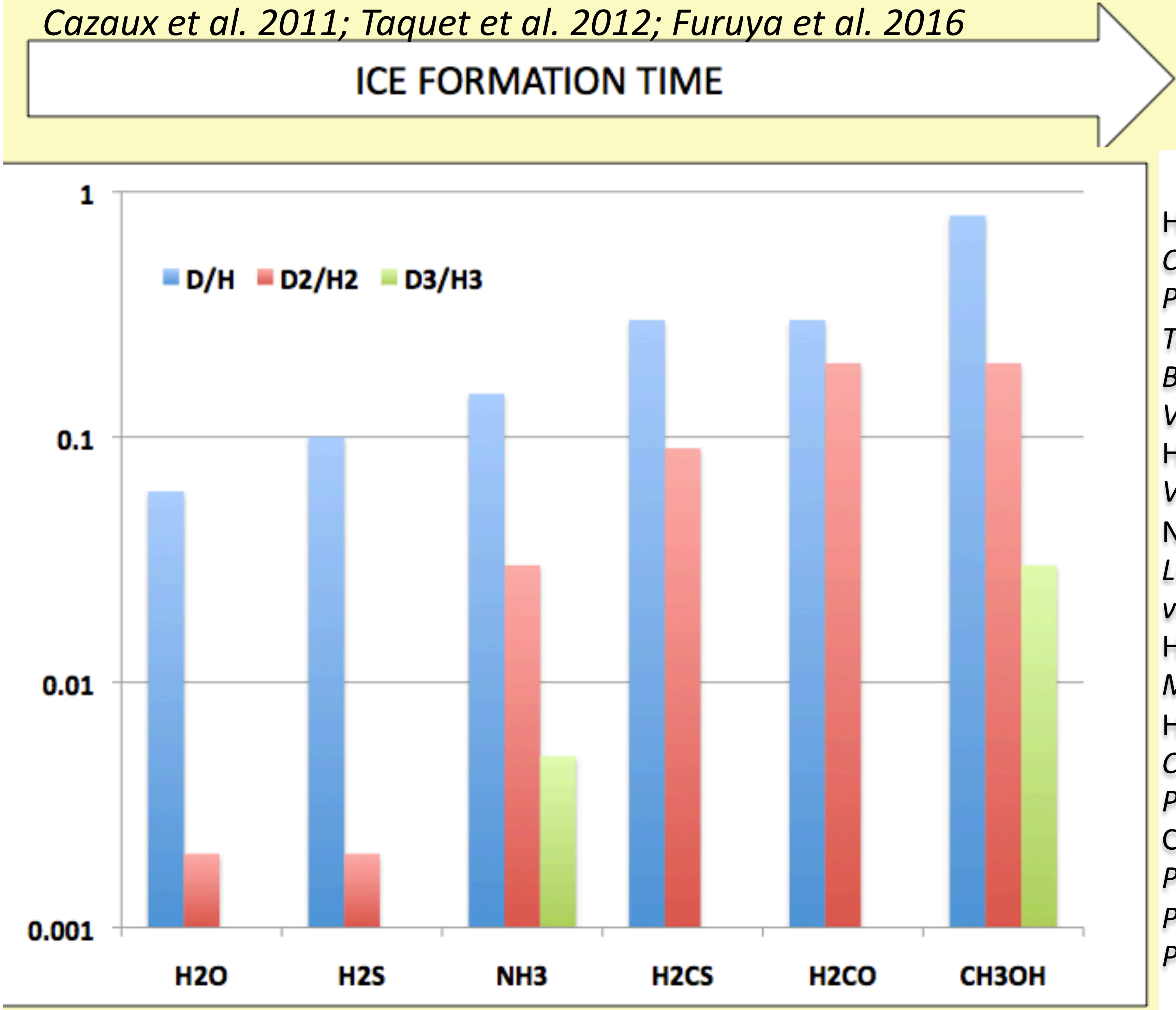
NASA / JPL-Caltech / A. Noriega-Crespo (SSC/Caltech) ssc2003-06f



• dust heating, X-rays nearby protostars (mantle processing and evaporation)

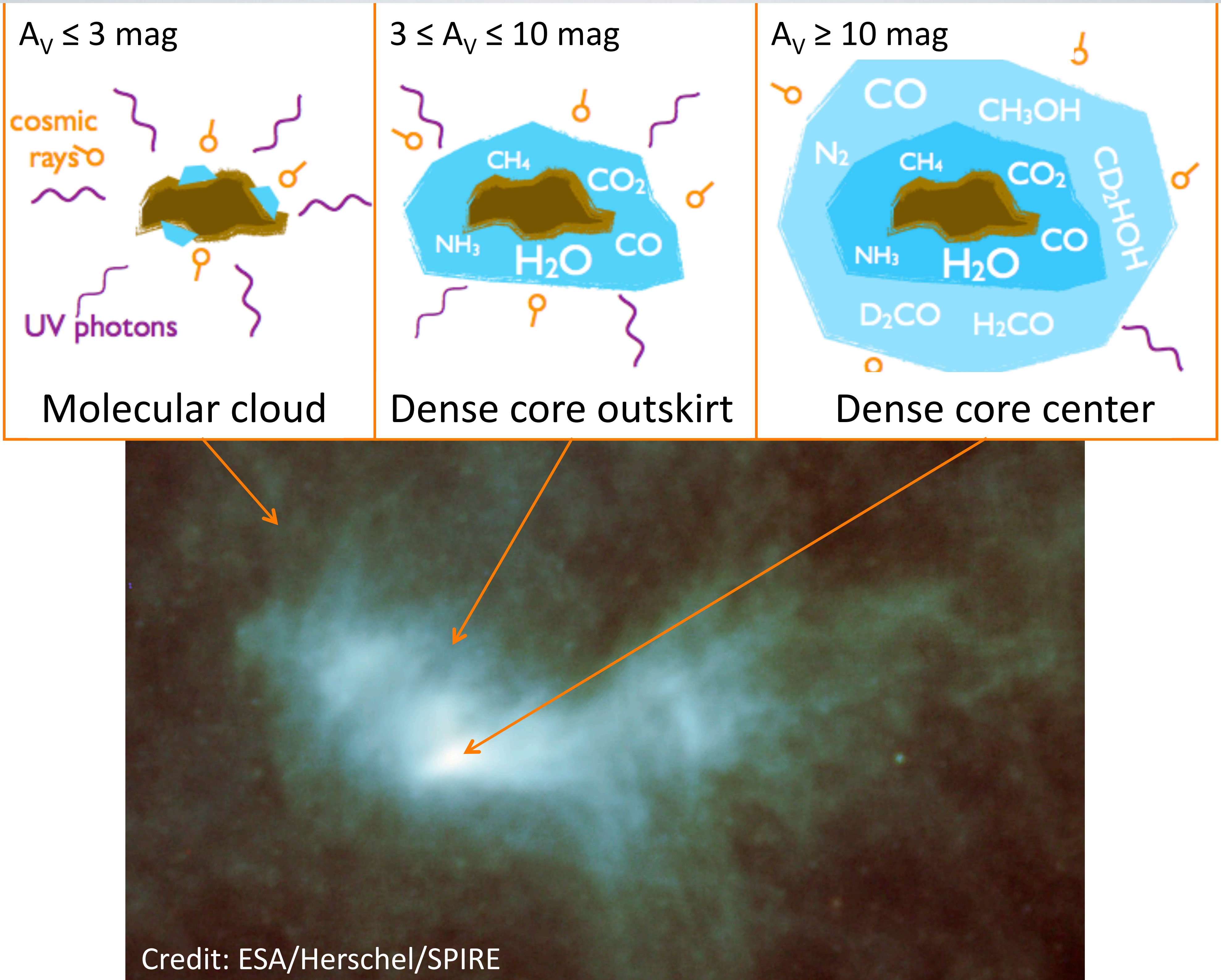
• dust (mantles and cores) sputtering + vaporization along protostellar outflows

Cazaux et al. 2011; Taquet et al. 2012; Furuya et al. 2016



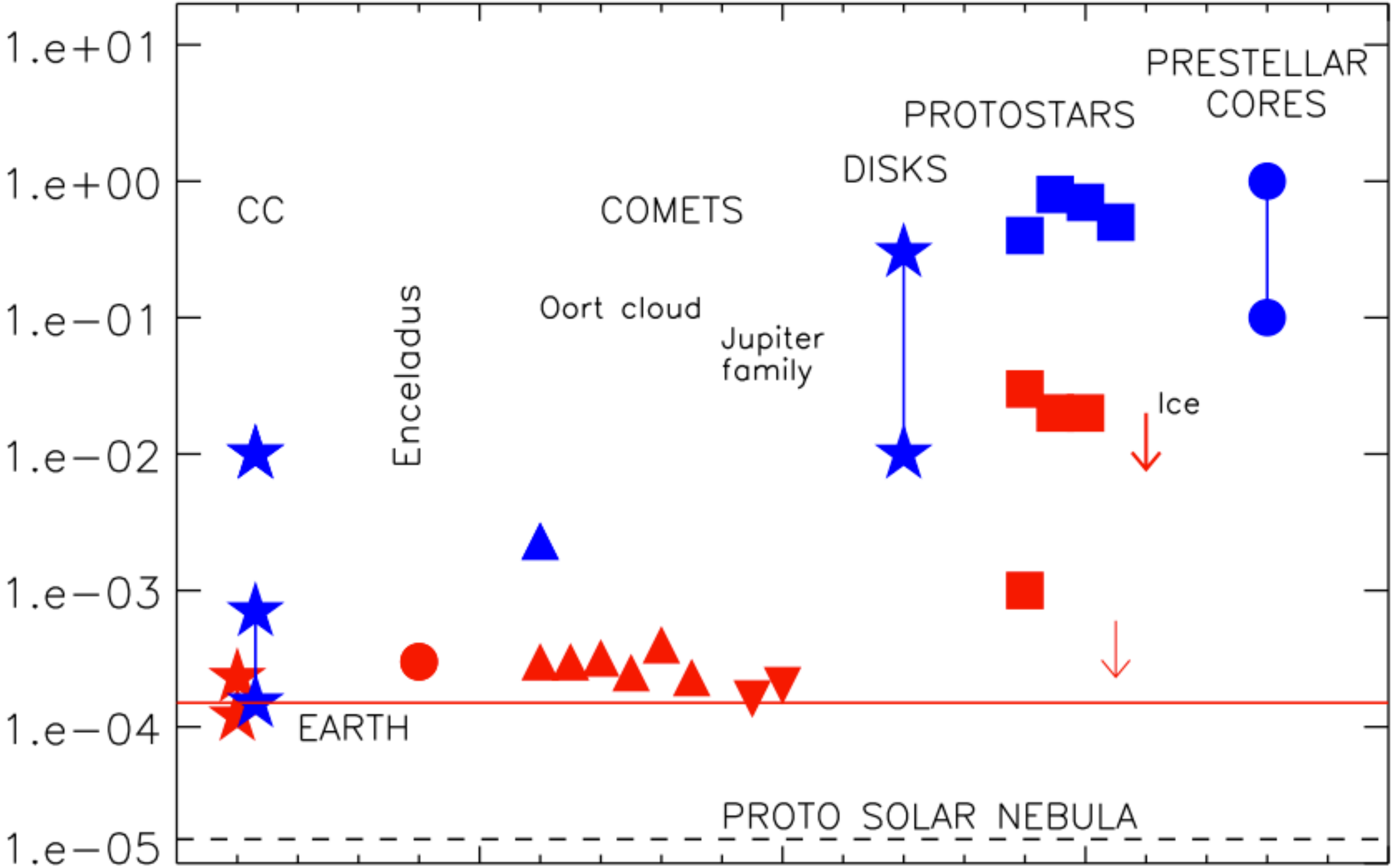
H_2O:
Coutens+ 2012,2013
Persson+ 2012
Taquet+ 2012,2013
Butner+ 2007
Vastel+ 2010
H_2S:
Vastel+ 2003
NH_3:
Loinard+ 2001
van der Tak+ 2002
H_2CS:
Marcelino+ 2005
H_2CO:
Ceccarelli+ 1998
Parise+ 2006
CH_3OH:
Parise+ 2002
Parise+ 2004
Parise+ 2006

From: Caselli & Ceccarelli 2012 *(see also Coutens et al. 2016, for D-frac of NH_2CHO and HNCO)*



A_V ≤ 3 mag
cosmic rays
UV photons
Molecular cloud
3 ≤ A_V ≤ 10 mag
CH4
CO2
NH3
H2O
CO
Dense core outskirt
A_V ≥ 10 mag
CO
CH3OH
N2
CH4
CO2
CD2HOH
NH3
H2O
CO
D2CO
H2CO
Dense core center
Credit: ESA/Herschel/SPIRE

D/H in water **D/H in organics**

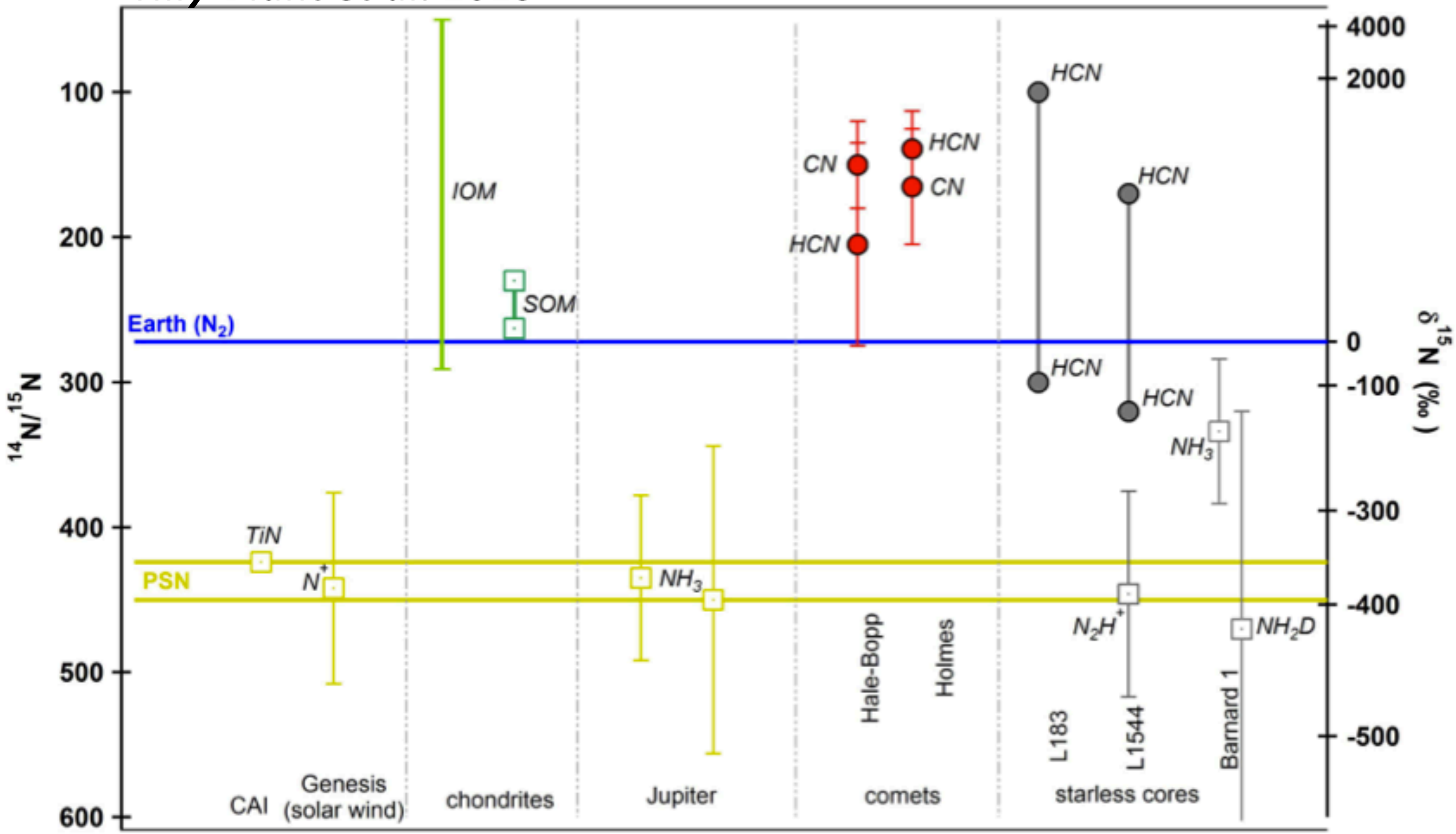


Ceccarelli, Caselli, Bocklelèe-Morvan, Mousis, Pizzarello, Robert, Semenov 2014, PPVI
(see also ***Bianchi et al. 2017, Poster #34; Chacon-Tanarro, Poster #4****)*

HDO/H_2O in our Solar System requires ice production during the cold phase (Cleeves et al. 2014) ➔ pre-stellar cores are important !

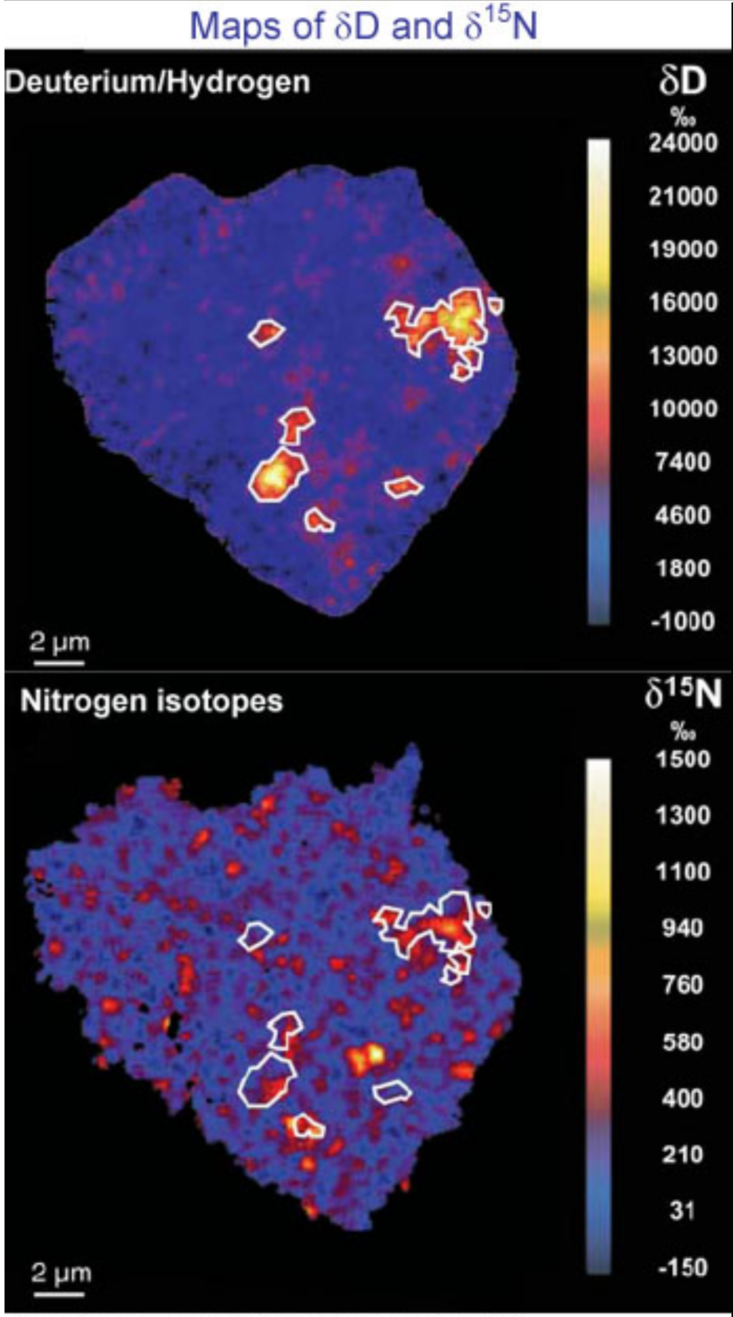
Differential ^{15}N enhancement between nitrile- and amine-bearing interstellar molecules. No correlation with D-frac.

Hily-Blant et al. 2013



*see also: Wampfler+2014 for **protostars** ($HCN/HC^{15}N$~150-400) and Guzmán+2017 for **protoplanetary disks** ($HCN/HC^{15}N$ ~80-160)*

The $^{14}N/^{15}N$ ratio



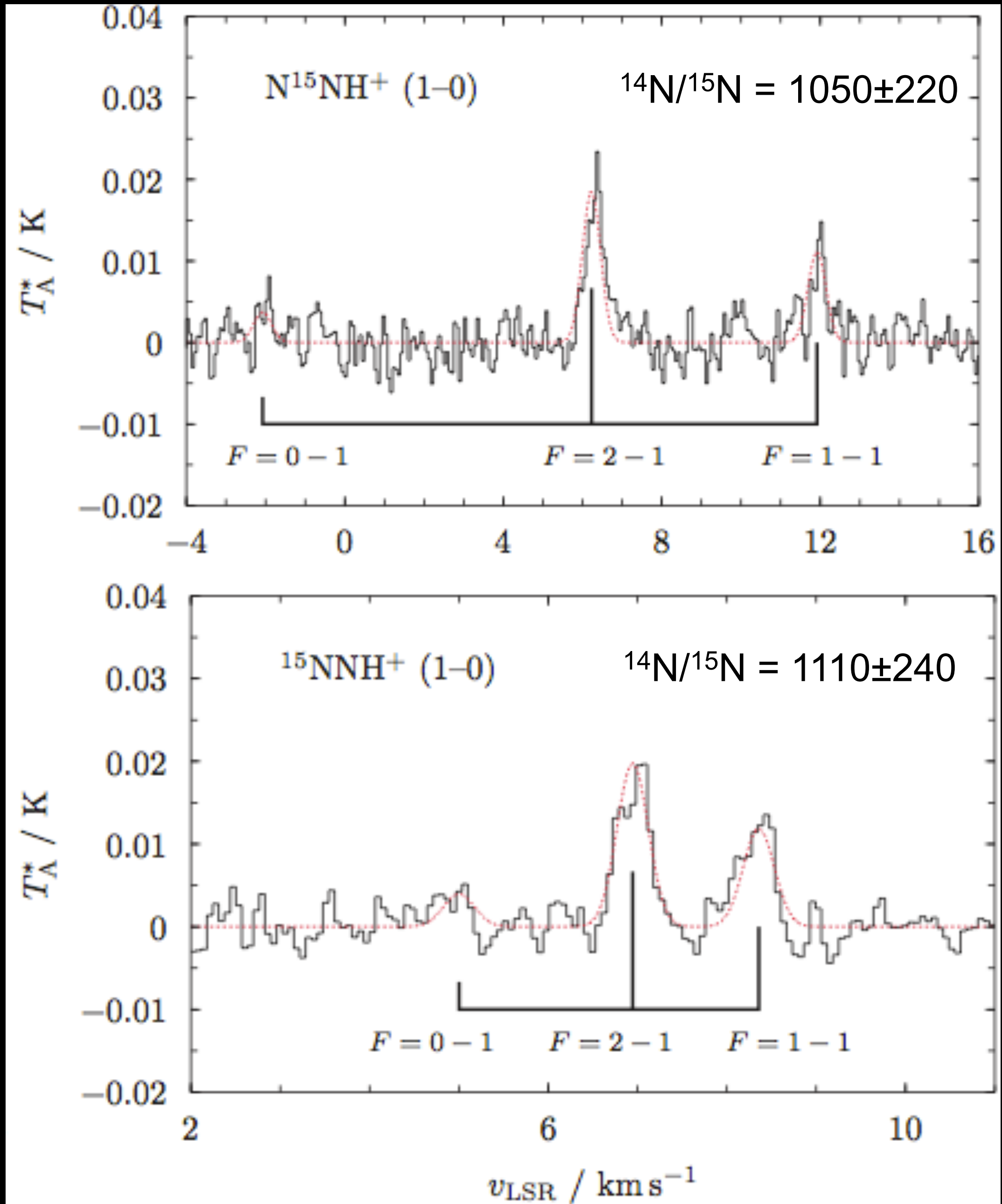
(From Busemann *et al.*, 2006, *Science*, v. 312, p. 728.)

Large ^{15}N excess is found in primitive material (meteorites, IDPs, cometary dust particles returned by *Stardust*): e.g. $^{14}N/^{15}N$ ~ 65 found in the "hot spots" of the meteorite Bells (*Buseman et al. 2006*).

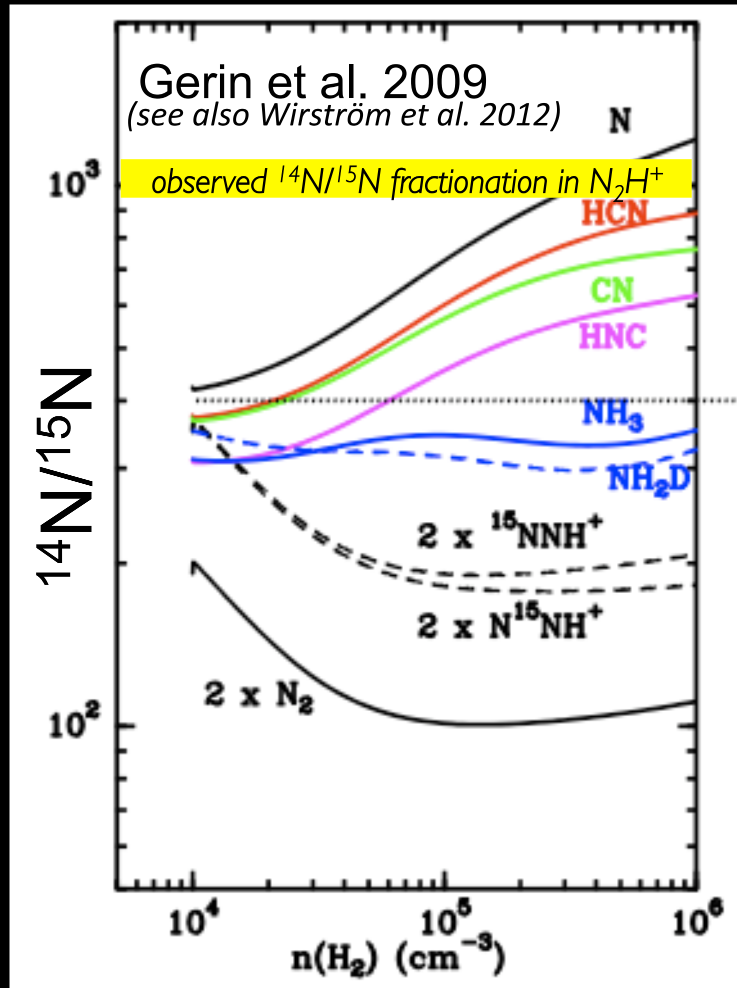
D-enriched spots do not always coincide with ^{15}N-enriched ones *(e.g. Buseman et al. 2010; Robert et al. 2006)*.

Differences are found between functional groups in "hot spots": ^{15}N fractionation larger in –CN than in $–NH_2$ and –NH functional groups *(van Kooten et al. 2017).*

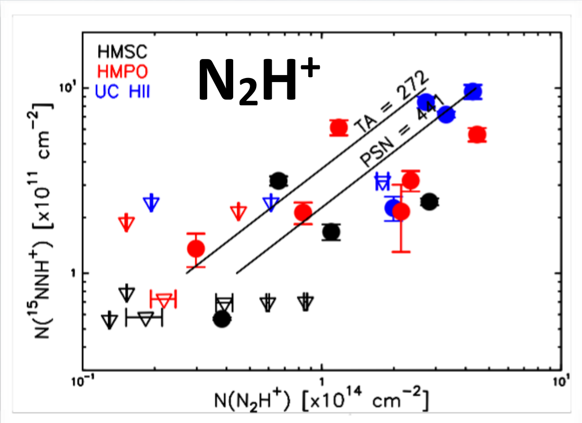
^{15}N-fractionation in N_2H^+ *(Bizzocchi et al. 2010, 2013)*

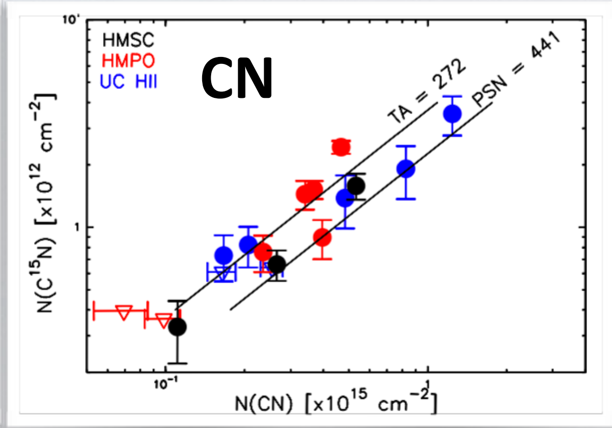


^{14}N/^{15}N in pre-stellar core higher than protosolar value! – disagreement with chemical models.



$^{14}N/^{15}N$ in high-mass star-forming regions

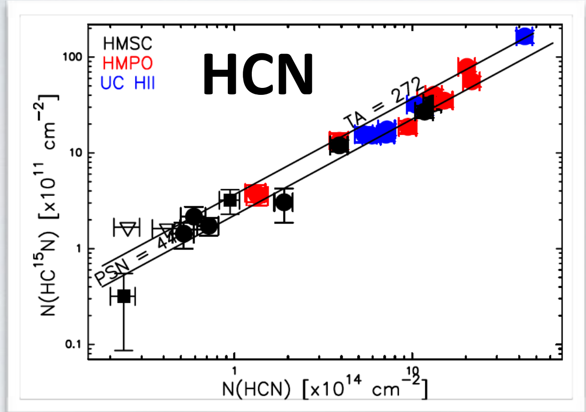


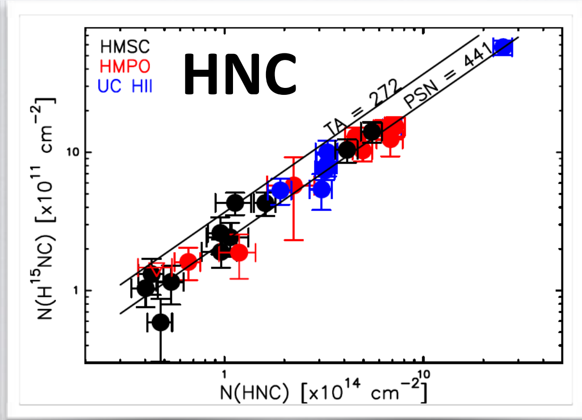


in N_2H^+ : ~180-1300

in CN : ~270-440

Fontani et al. 2015



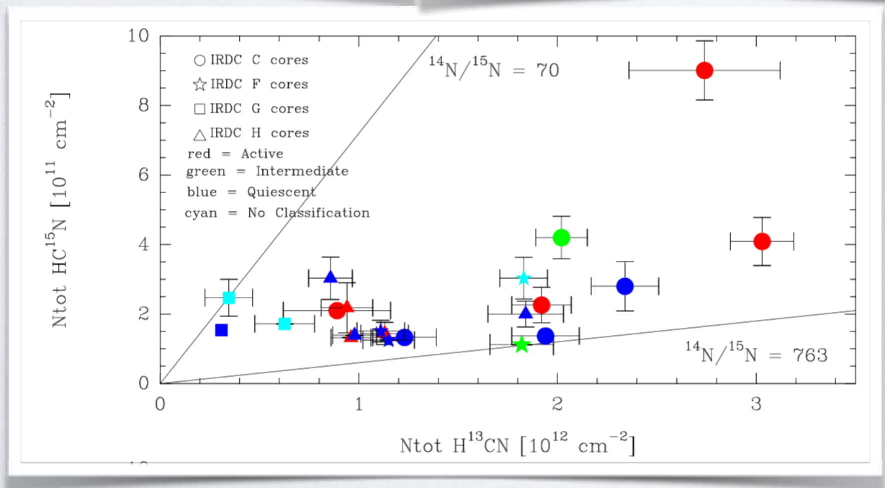


in HCN : 390±24

in HNC : 440±22

(no correlation between ^{15}N and D fractionation)

Colzi et al. 2017 (+ Poster #6!)

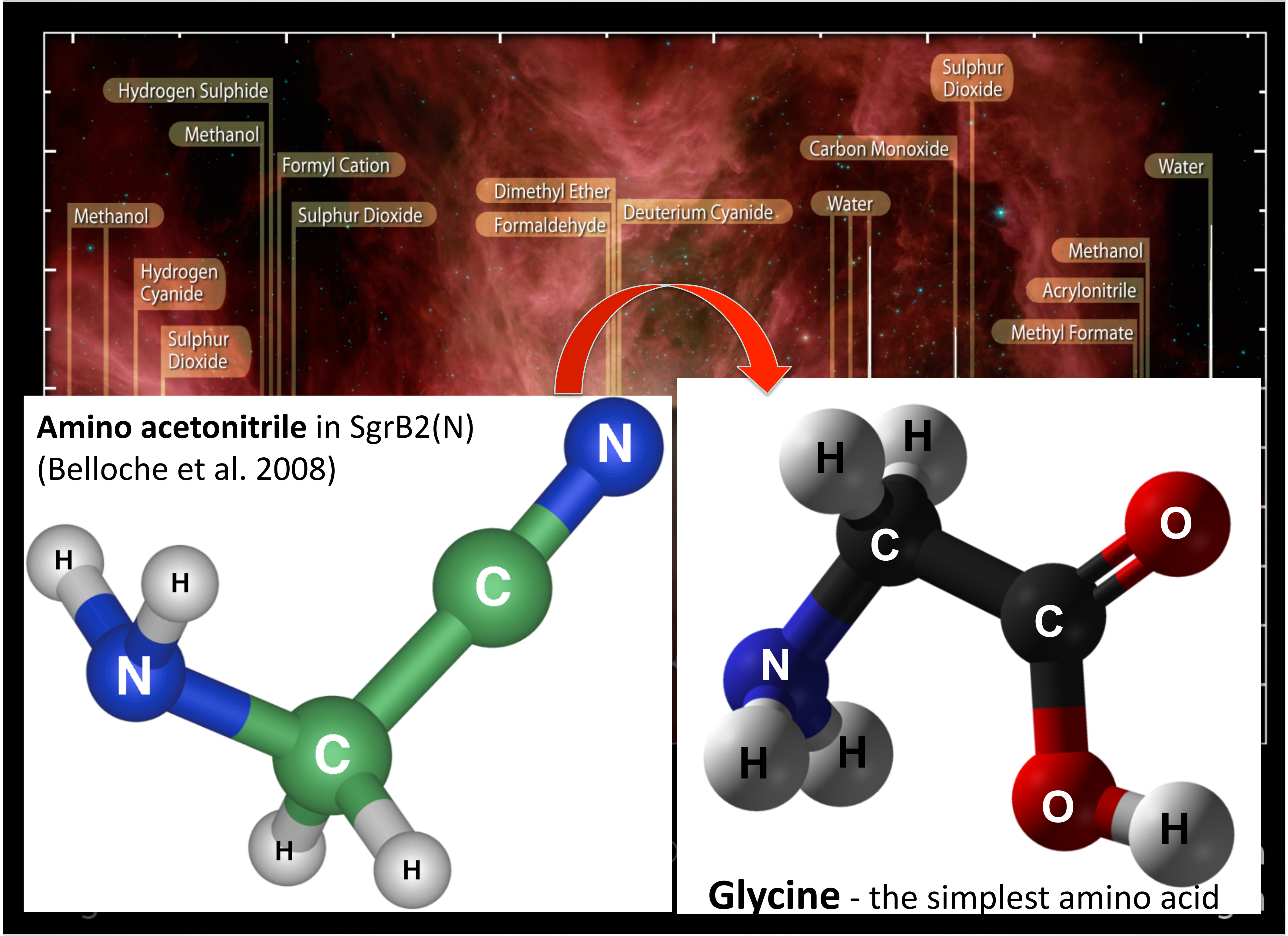


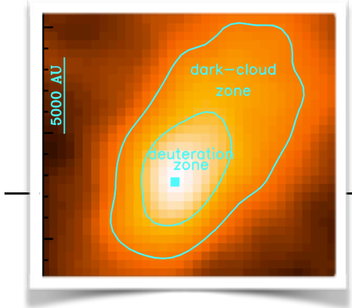
in HCN : ~70-760

in HNC : ~161-541

(lowest values toward least dense region)

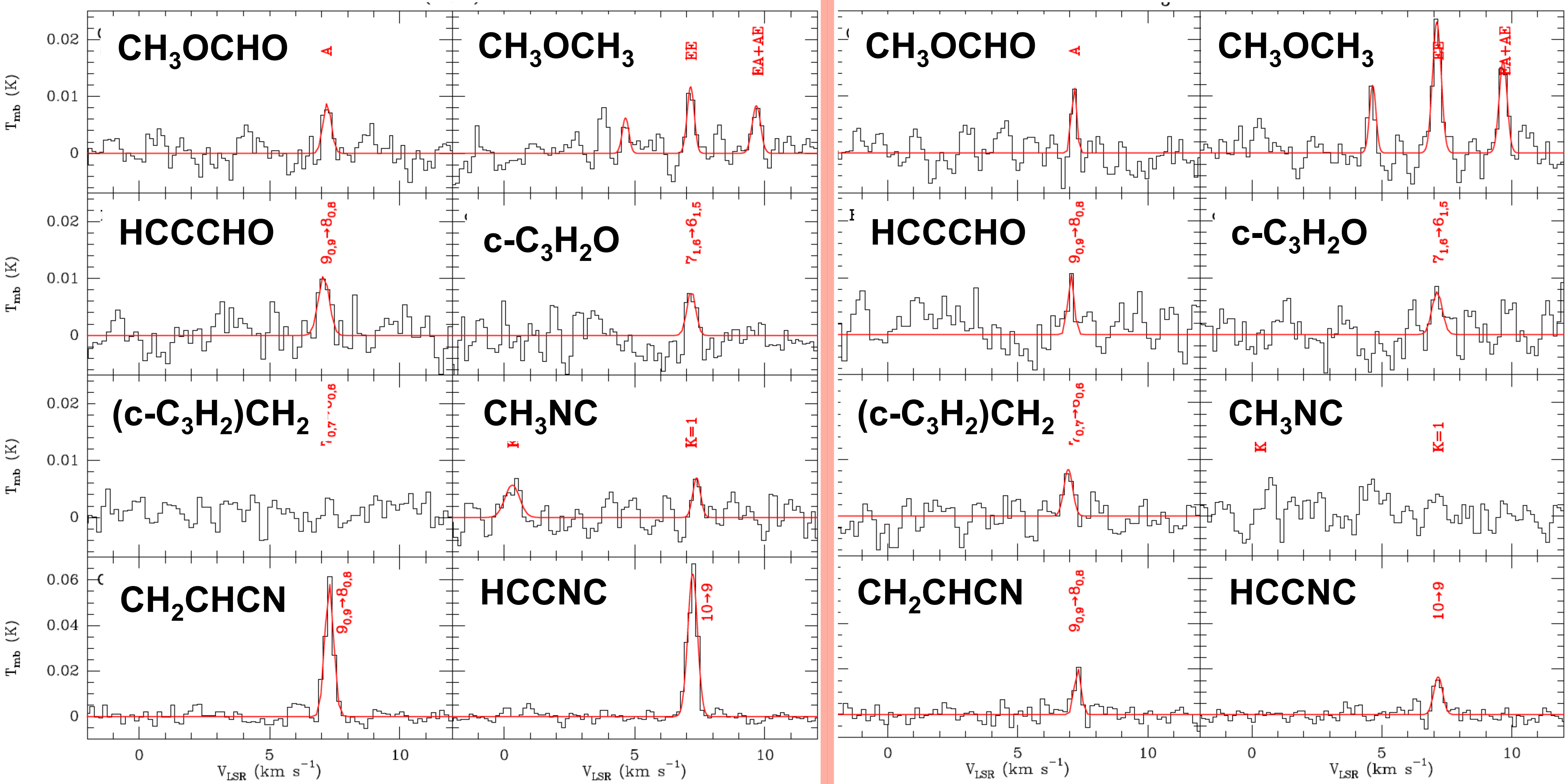
Zeng et al. 2017


Hydrogen Sulphide
Methanol
Formyl Cation
Methanol
Sulphur Dioxide
Hydrogen Cyanide
Sulphur Dioxide
Dimethyl Ether
Formaldehyde
Deuterium Cyanide
Water
Carbon Monoxide
Sulphur Dioxide
Water
Methanol
Acrylonitrile
Methyl Formate
Amino acetonitrile in SgrB2(N)
(Belloche et al. 2008)
H
H
N
C
N
C
H
H
H
H
C
O
C
N
H
H
O
H
Glycine - the simplest amino acid



COMs in pre-stellar cores

Cloud center | 4000 AU away from center



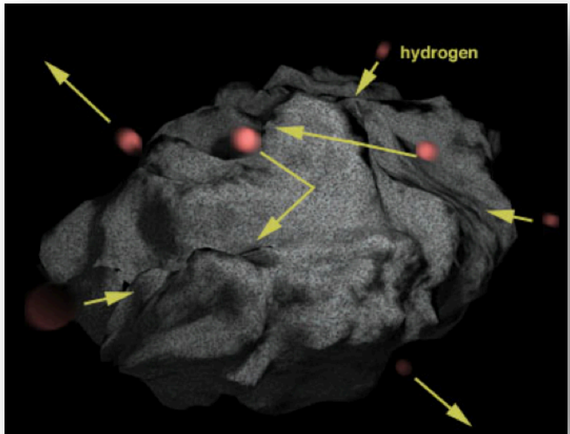
Jiménez-Serra et al. 2016

see also Öberg+2010; Bacmann+2013; Bizzocchi+2014; Vastel+2014; Bacmann & Faure 2016

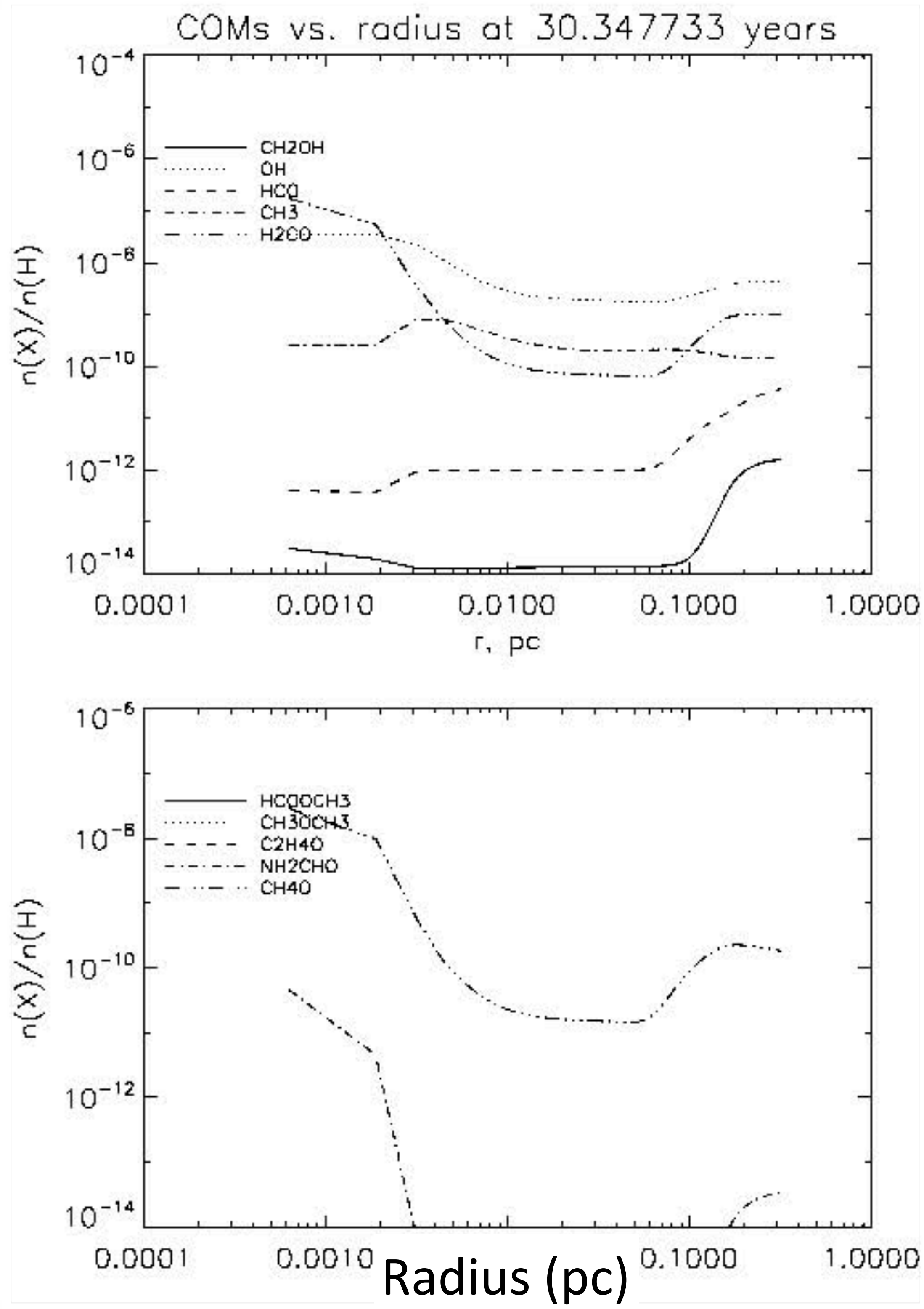
Gas + grain chemistry in L1544

- physical structure
- gas-grain chemistry
- reactive desorption
- photodesorption
- neutral-neutral reactions

(Shannon+2008; Balucani+2015; Barone+2015; Skouteris+2017)

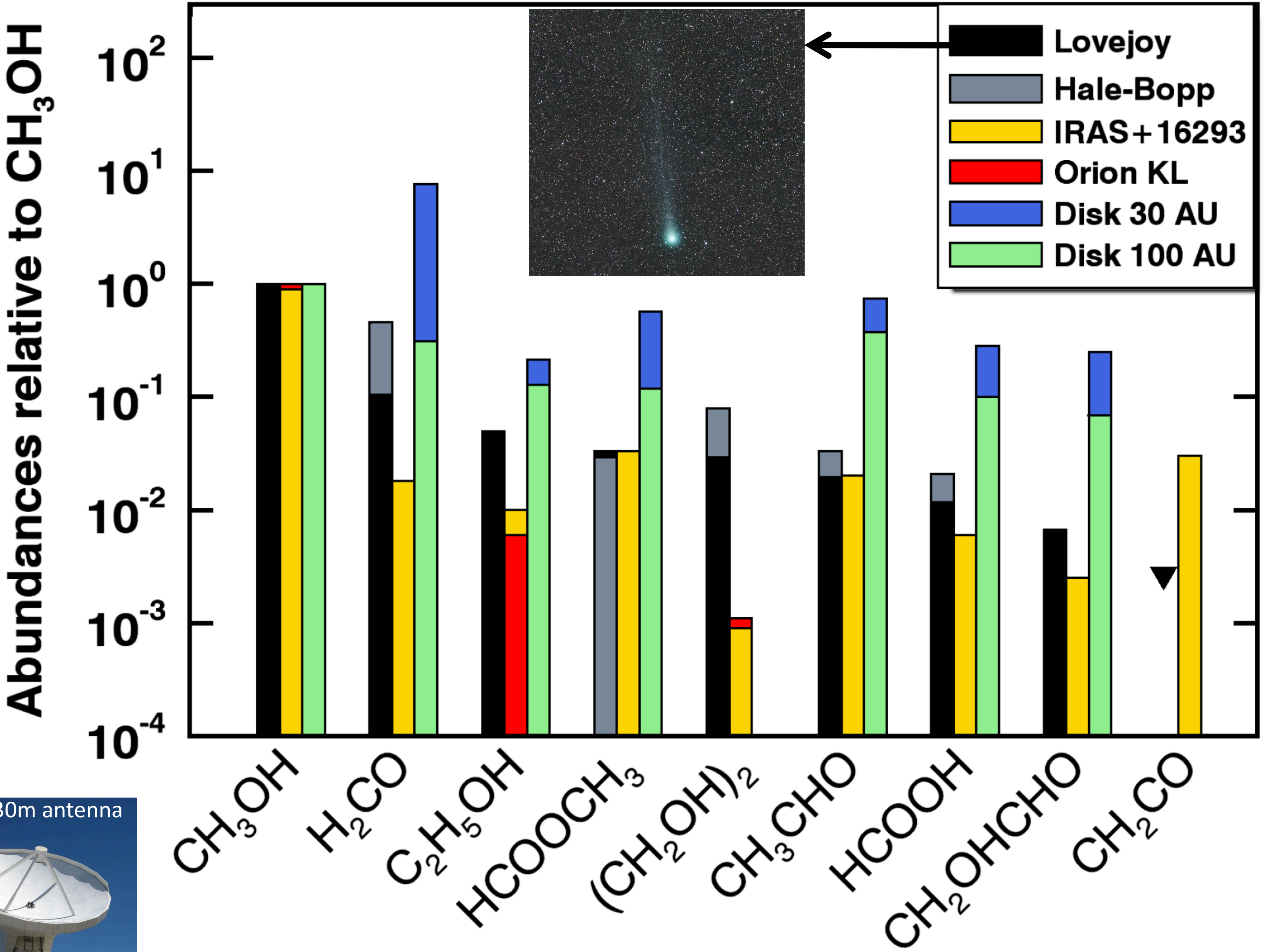


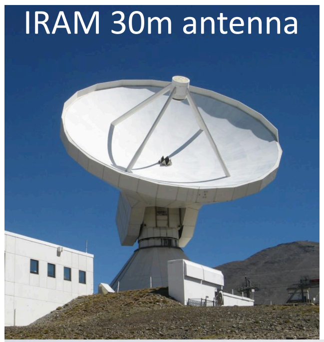
Abundance w.r.t. total H



Radius (pc)

Vasyunin et al. 2017





Biver et al. 2015 (see also Altwegg et al. 2016)

NOEMA Large Project: Ceccarelli & Caselli PIs

(see Poster #13 by López-Sepulcre)

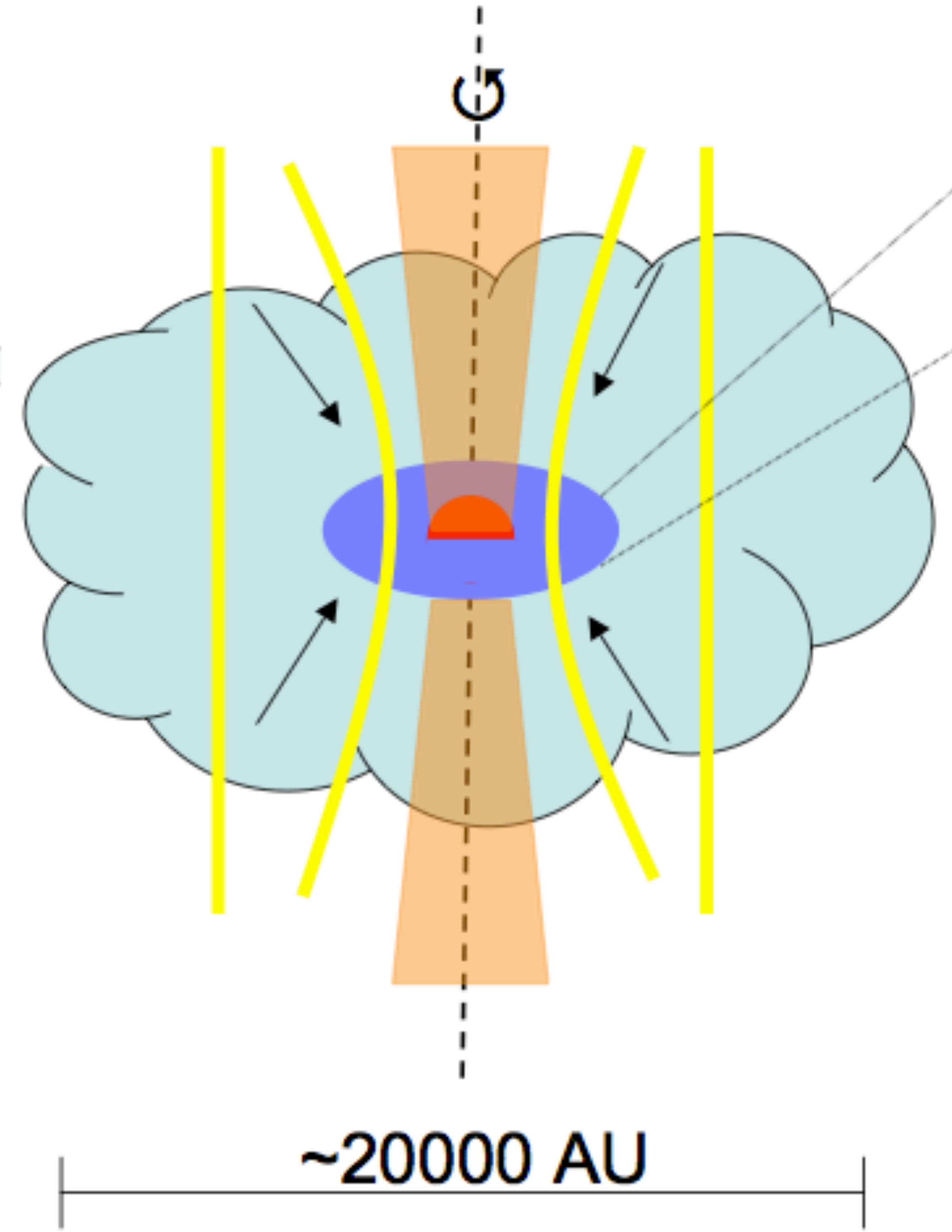
Codella+, sub.
Fontani+, sub.
Ceccarelli+, in prep.
Punanova+, in prep.
Neri+, in prep.
Feng+, in prep.

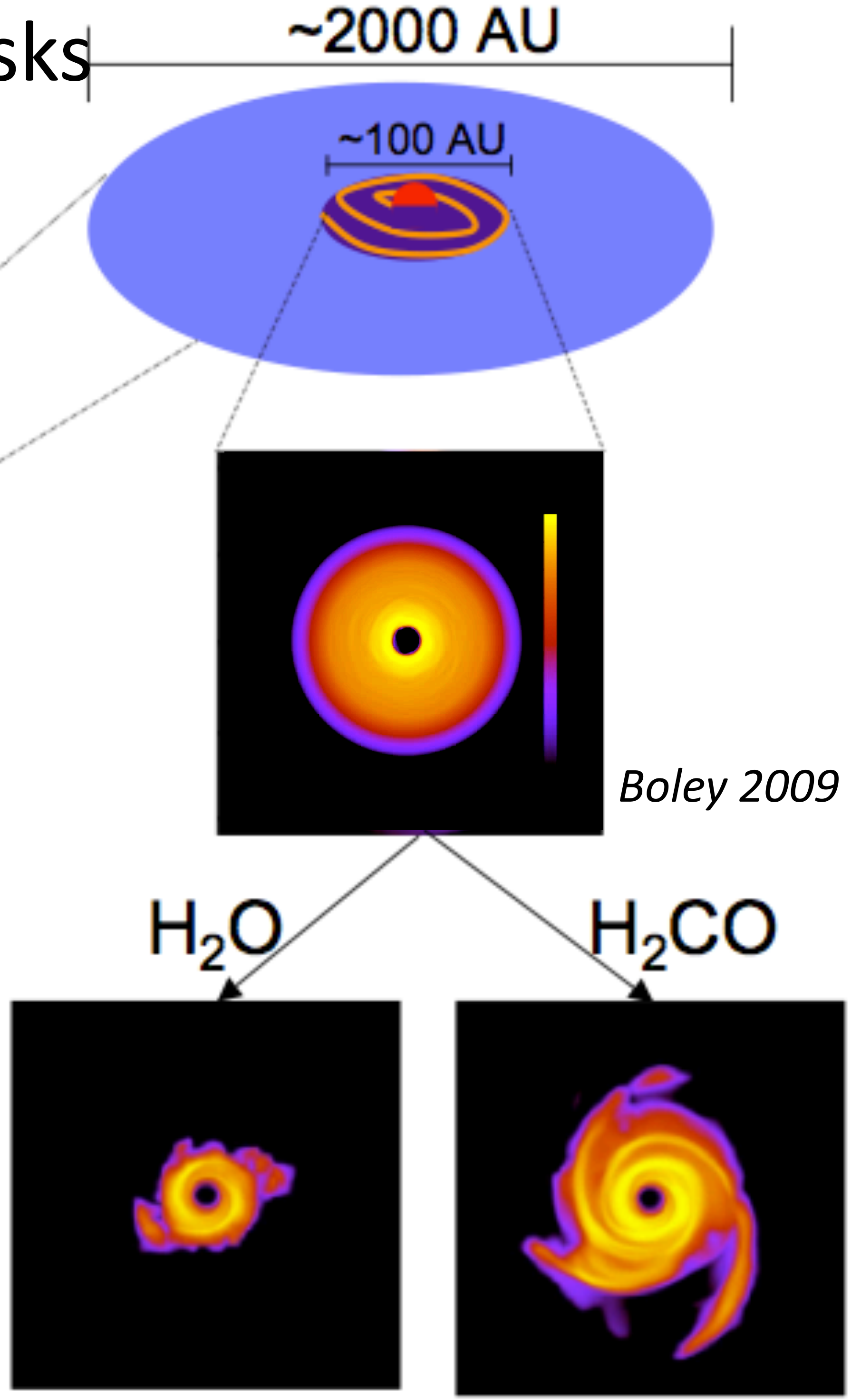
Seeds Of Life In Space

Origin and evolution of complex organic molecules in the early stages of formation of Solar-type systems

The dawn of protoplanetary disks

Caselli & Ceccarelli 2012

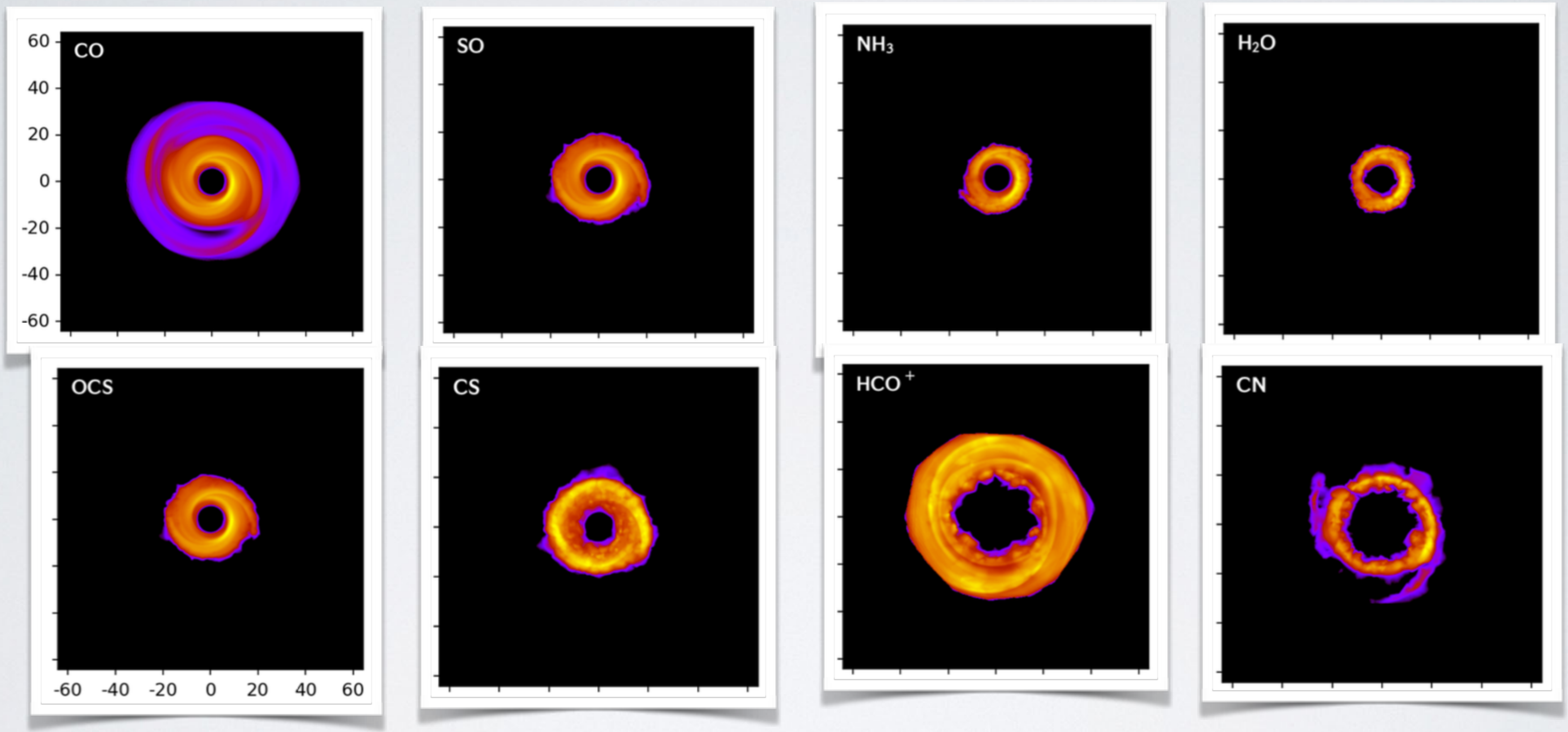




Boley 2009

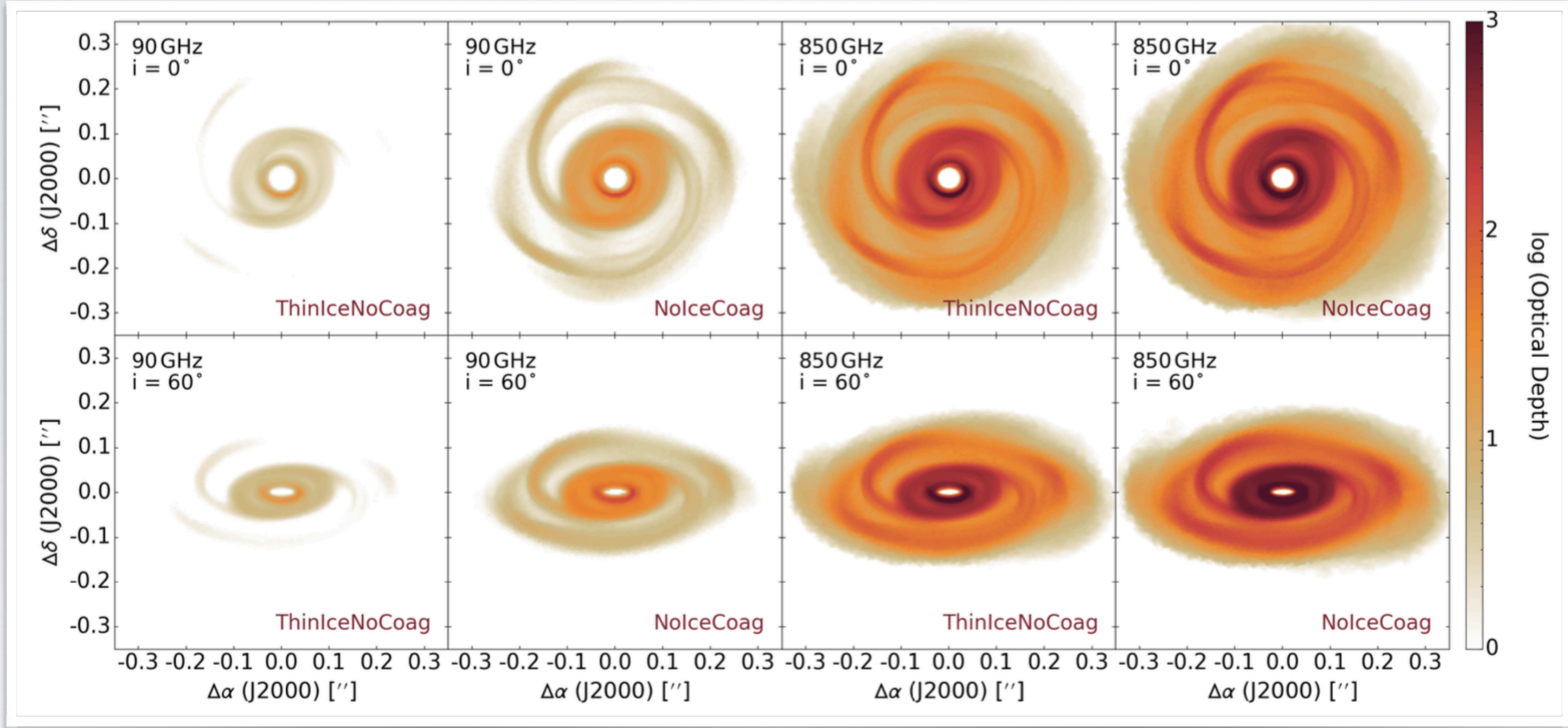
Ilee et al. 2011, Evans et al. 2015

Chemical inventory in a gravitationally unstable (proto-Solar) young disk



Evans et al. 2015

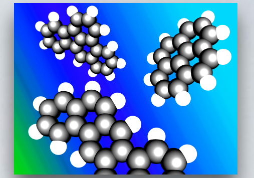
Optically thick dust continuum emission in a gravitationally unstable (proto-Solar) young disk



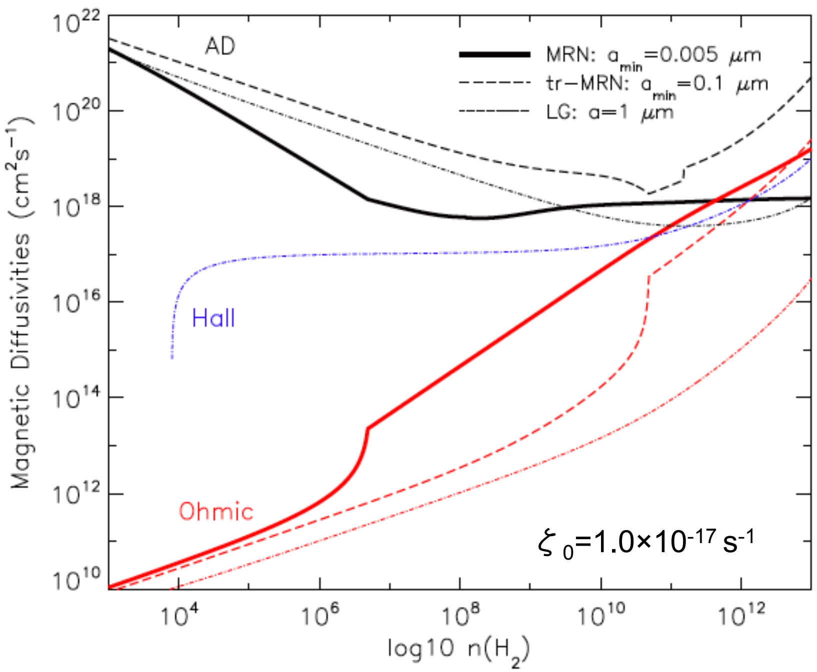
<u>ALMA observation simulations</u>: disk masses can be underestimated by at least a factor of 30 at 850 GHz and 2.5 at 90 GHz.

Evans et al. 2017

Protostellar disk formation enabled by removal of small dust grains

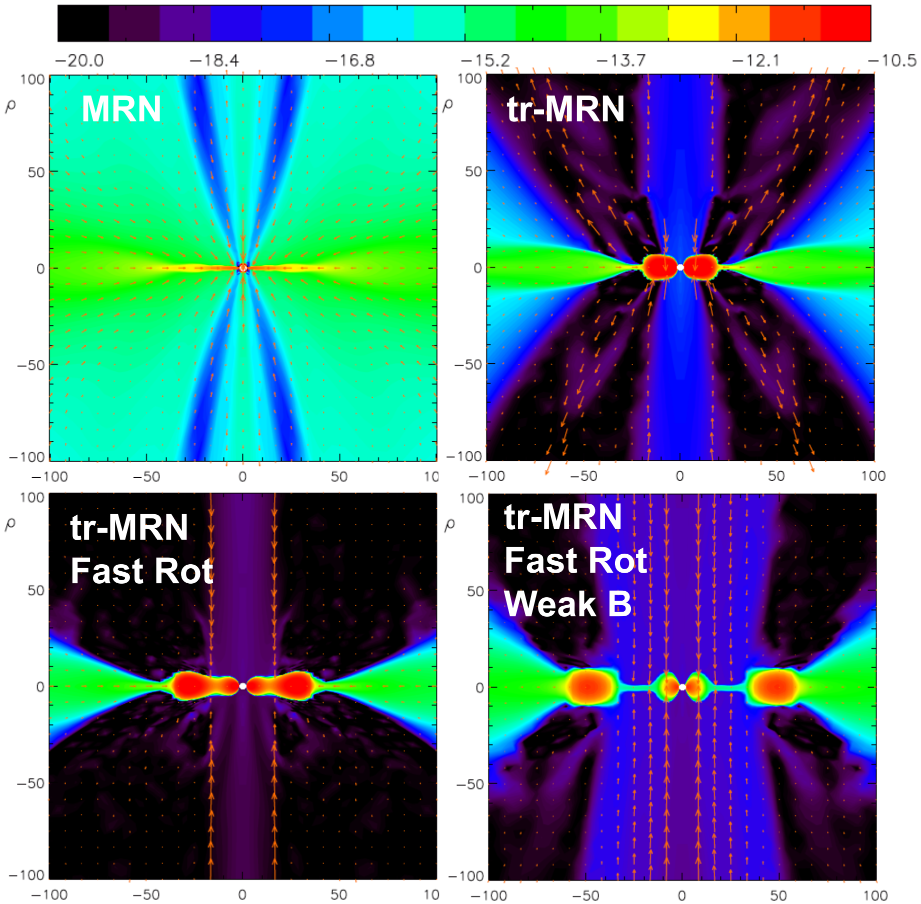


- Removing very small grains (VSGs: 10Å - few 100Å) enhances ambipolar diffusion (AD) by 1-2 orders of magnitude .
- VSGs are highly conductive:
  - well-coupled to magnetic field
  - "drag" neutral molecules more efficiently than ions.



- Efficient AD reduces magnetic flux and weakens magnetic braking:

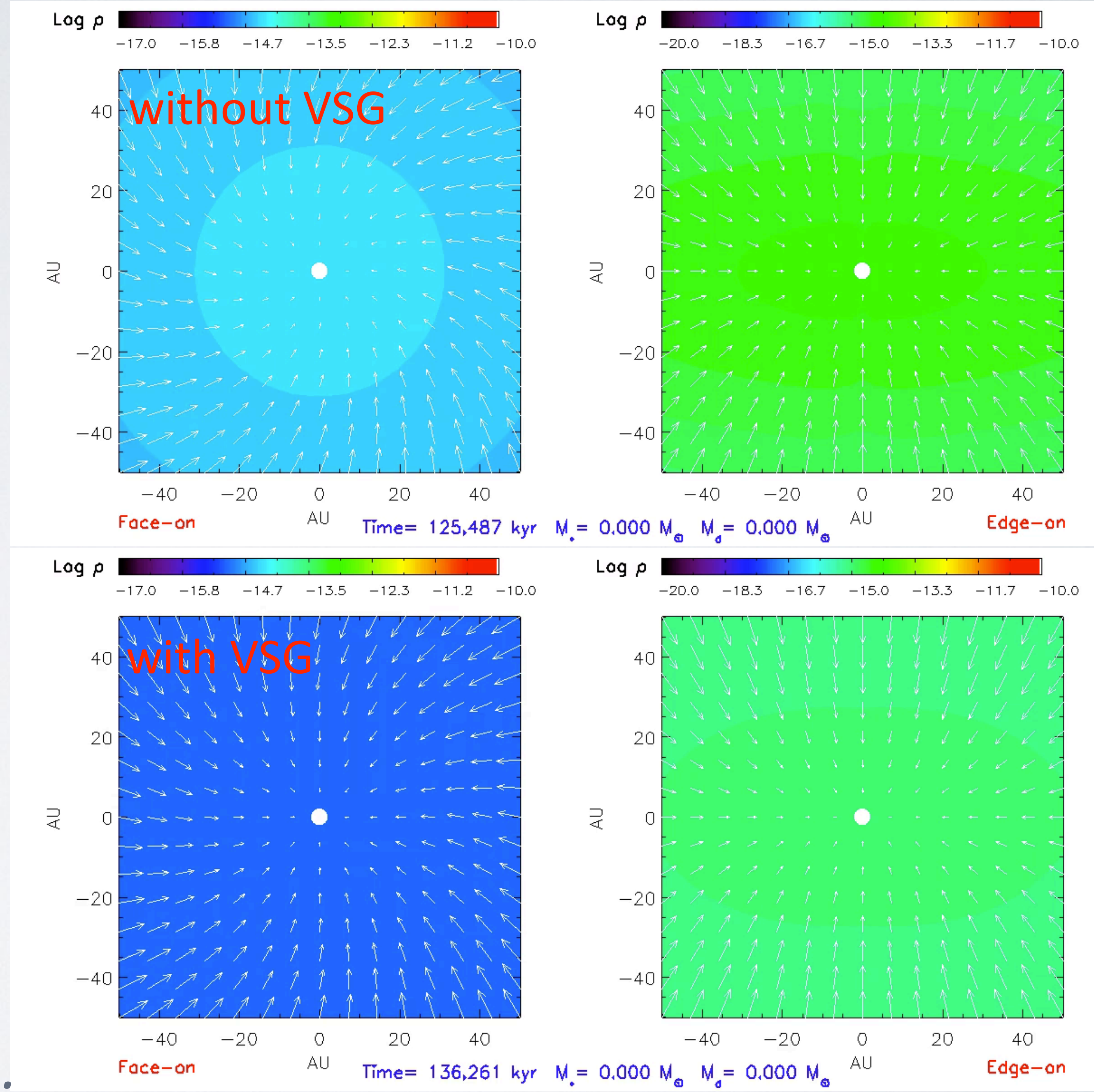
  → Enable the formation of rotationally supported disks of tens of AU in radius



Zhao et al. 2016

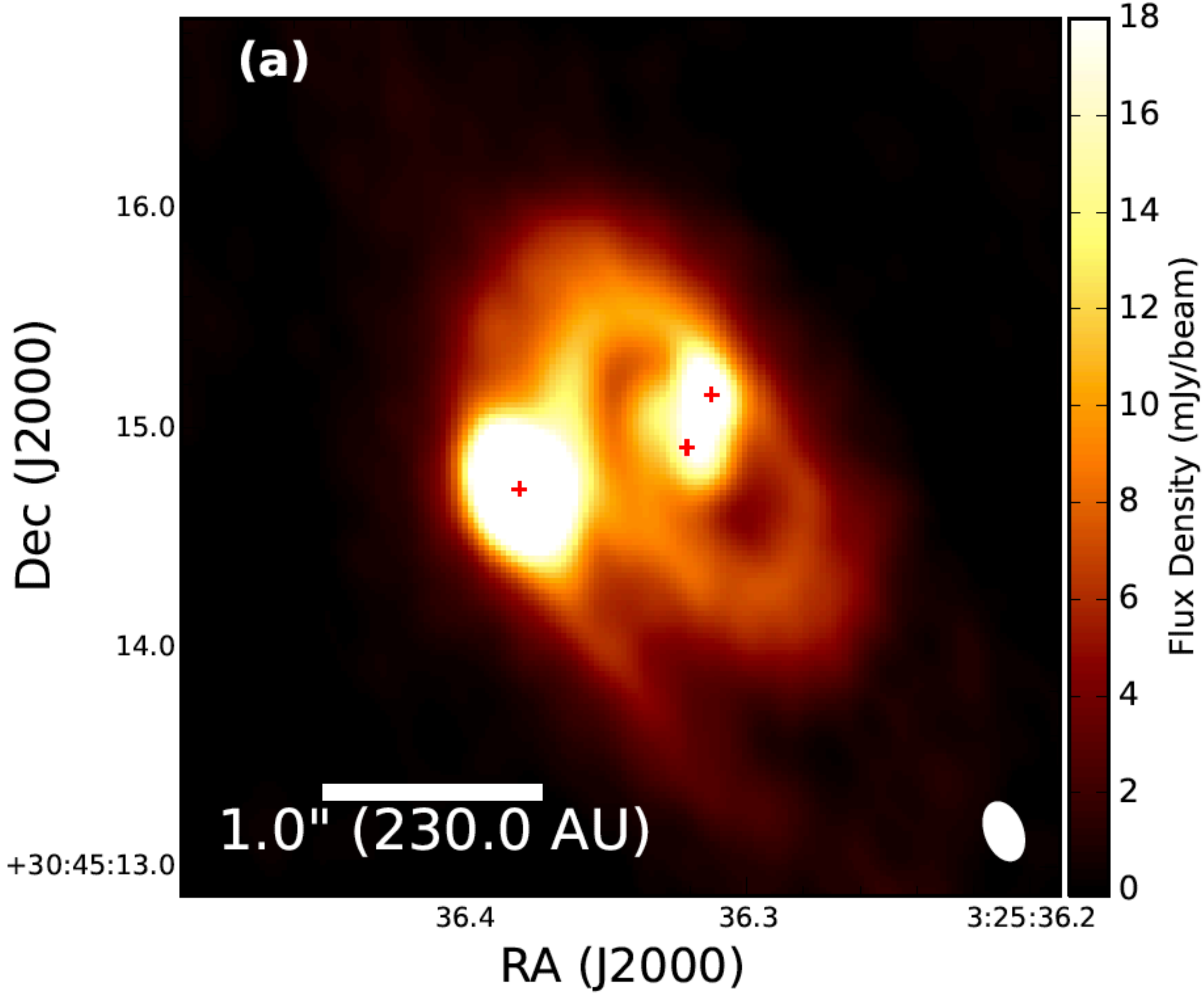
Disk formation and fragmentation in 3D

VSG removal allows formation of gravitationally unstable disks. Formation of Jupiter-mass fragments, a fraction of which accrete onto the protostar producing bursts.

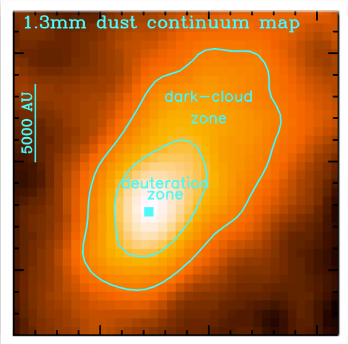


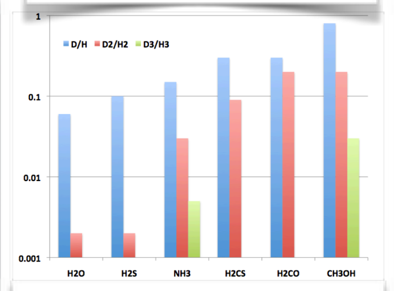
Zhao et al., subm.

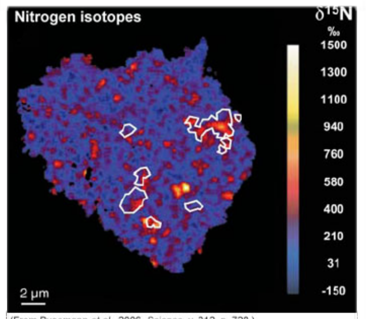
A TRIPLE PROTOSTAR SYSTEM FORMED VIA FRAGMENTATION OF A GRAVITATIONALLY UNSTABLE DISK



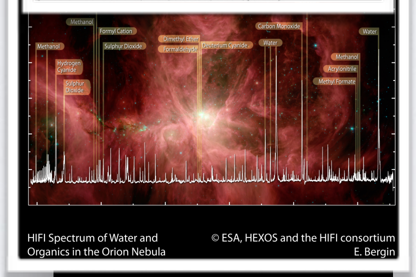
Tobin et al. 2016, Nature (see also Pérez et al. 2016, Science)

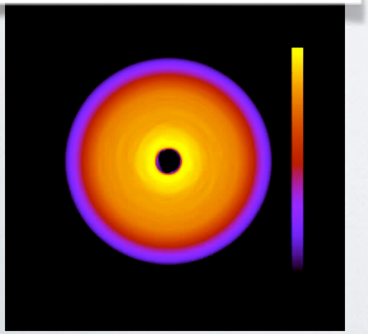






(From Busemann et al., 2006, Science, v. 312, p. 728.)





- Pre-stellar cores: $n_c > 10^5$ cm^{-3}, T_c = 6-7 K, quasi-static contraction, large CO freeze-out (>90%) & D-fraction (>10%) –*first steps toward pre-biotic chemistry.*

- Large D-fraction at all phases of star and planet formation (including Solar System), with D/H in organics > D/H in water —*storage of pre-stellar ice?*

- Different ^{15}N enhancement in CN- and NH-bearing ISM molecules and meteorites. ^{15}N and D fractionation not correlated. N_2H^+ fractionation not understood.

- COMs abundances in comets similar to those in star & planet forming regions —*Solar System chemistry not unique.*

- Depletion of very small grains enables disk formation. Shocks and fragmentation in early disks —*importance of microphysics + rich chemistry.*