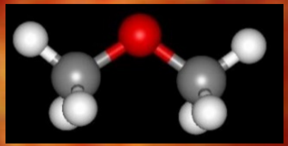
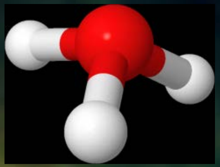
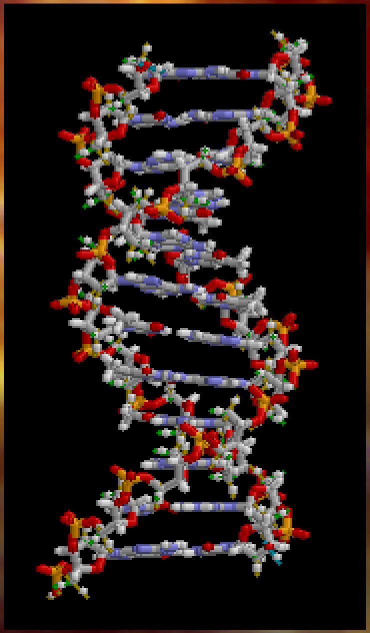
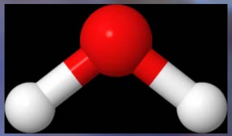
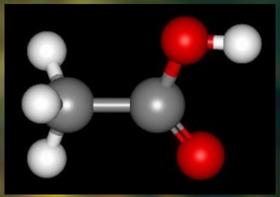
Astrochemistry:
the past and next 10 years

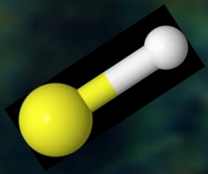


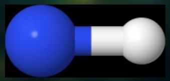












RCW120
Herschel
A. Zavagno

Ewine F. van Dishoeck
Leiden Observatory/MPE

Thanks to many colleagues for input and discussions

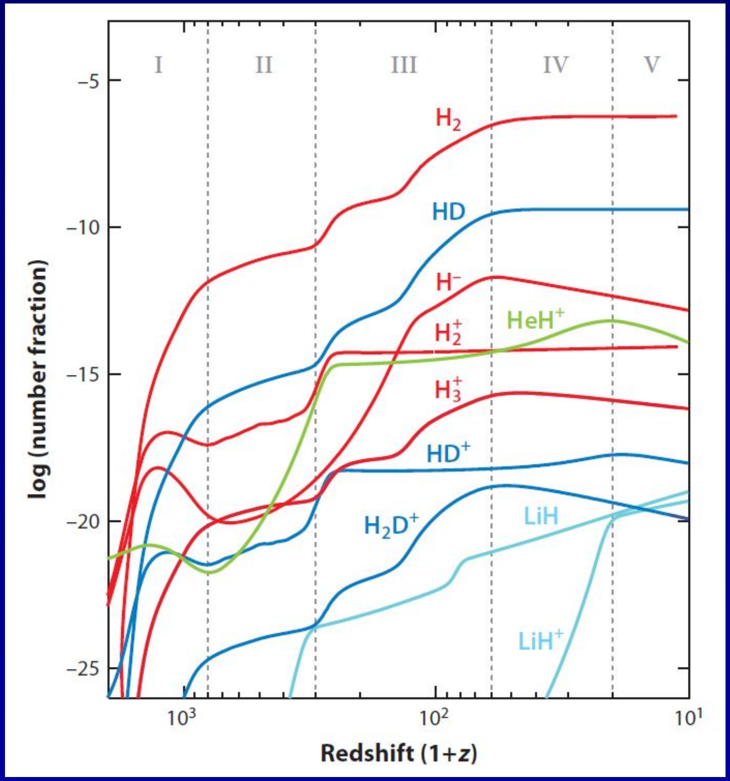
Apologies for not being able to cover all exciting results

A tribute to Francesco Palla

The Dawn of Chemistry

Daniele Galli, Francesco Palla
INAF-Osservatorio Astrofisico di Arcetri
Largo E. Fermi 5, 50125 Firenze, Italy

ARAA 2013



My first time at Ringberg

The dawn of EPOS

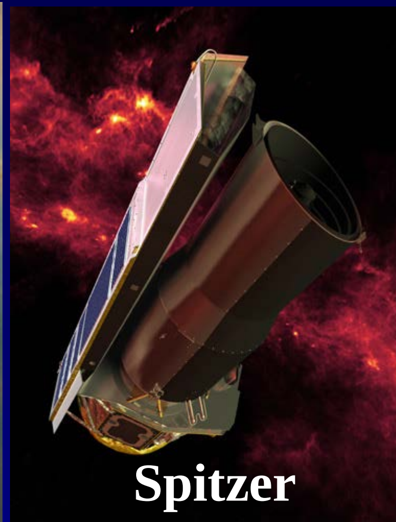
Jahresbericht 1995 Mitteilungen der ASTRONOMISCHEN GESELLSCHAFT **79** (1996), 443–468

6 Tagungen, Projekte am Institut und Beobachtungszeiten **JENA**

6.1 Tagungen und Veranstaltungen

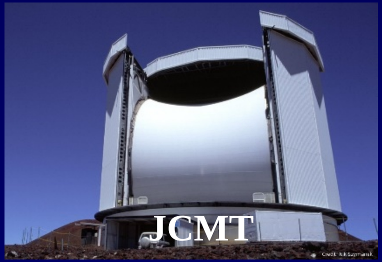
Die Arbeitsgruppe richtete eine internationale Tagung unter dem Titel „Galactic Star Formation and Early Stellar Evolution“ aus, die vom 29. Mai bis 2. Juni 1995 auf Schloß Ringberg/Bayern abgehalten wurde.

Fantastic facilities for astrochemistry



ALMA: *the* astrochemistry machine

NOEMA, SMA

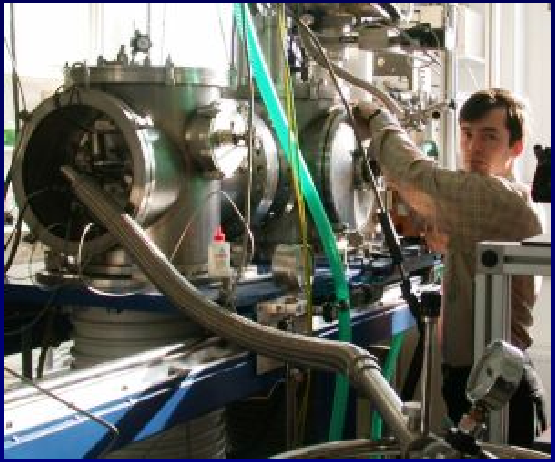


Lots of astrochemistry still based on single-dish data

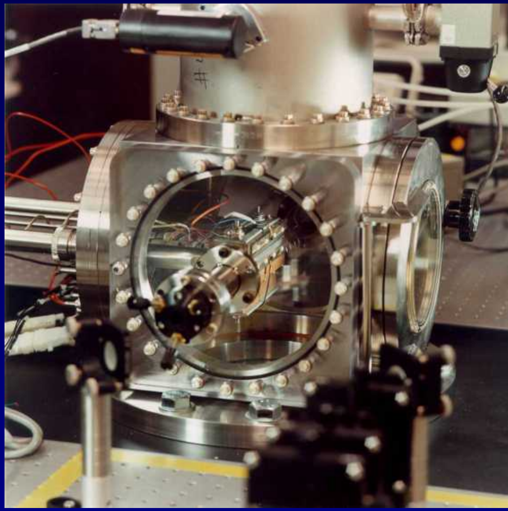
Fantastic new experiments and new groups!

Spectroscopy

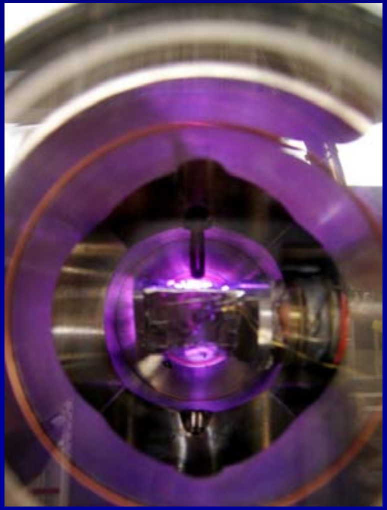
He droplets



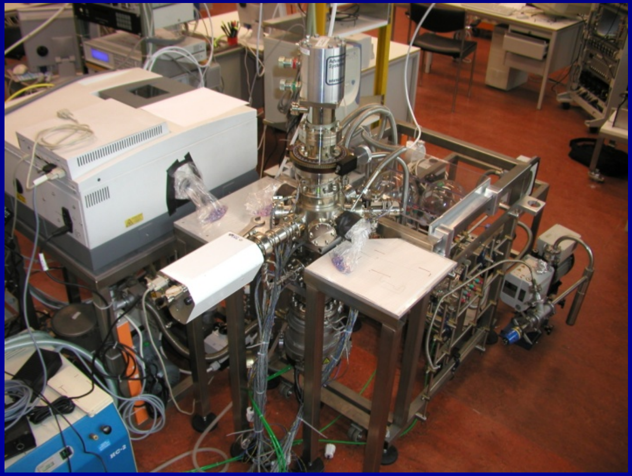
Cavity Ringdown Spectroscopy



UV plasma



UHV surface science



Crossed beam experiments

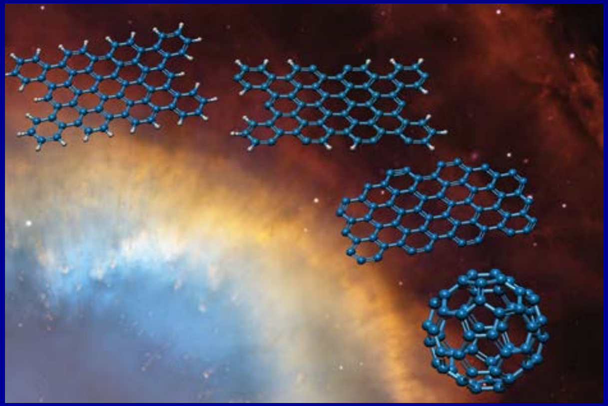
Outline

- Introduction
- *Herschel* legacy
  - Hydrides
  - Water
- ALMA
  - Spatially resolved chemistry
- Rosetta: link with solar system
- Some thoughts about future

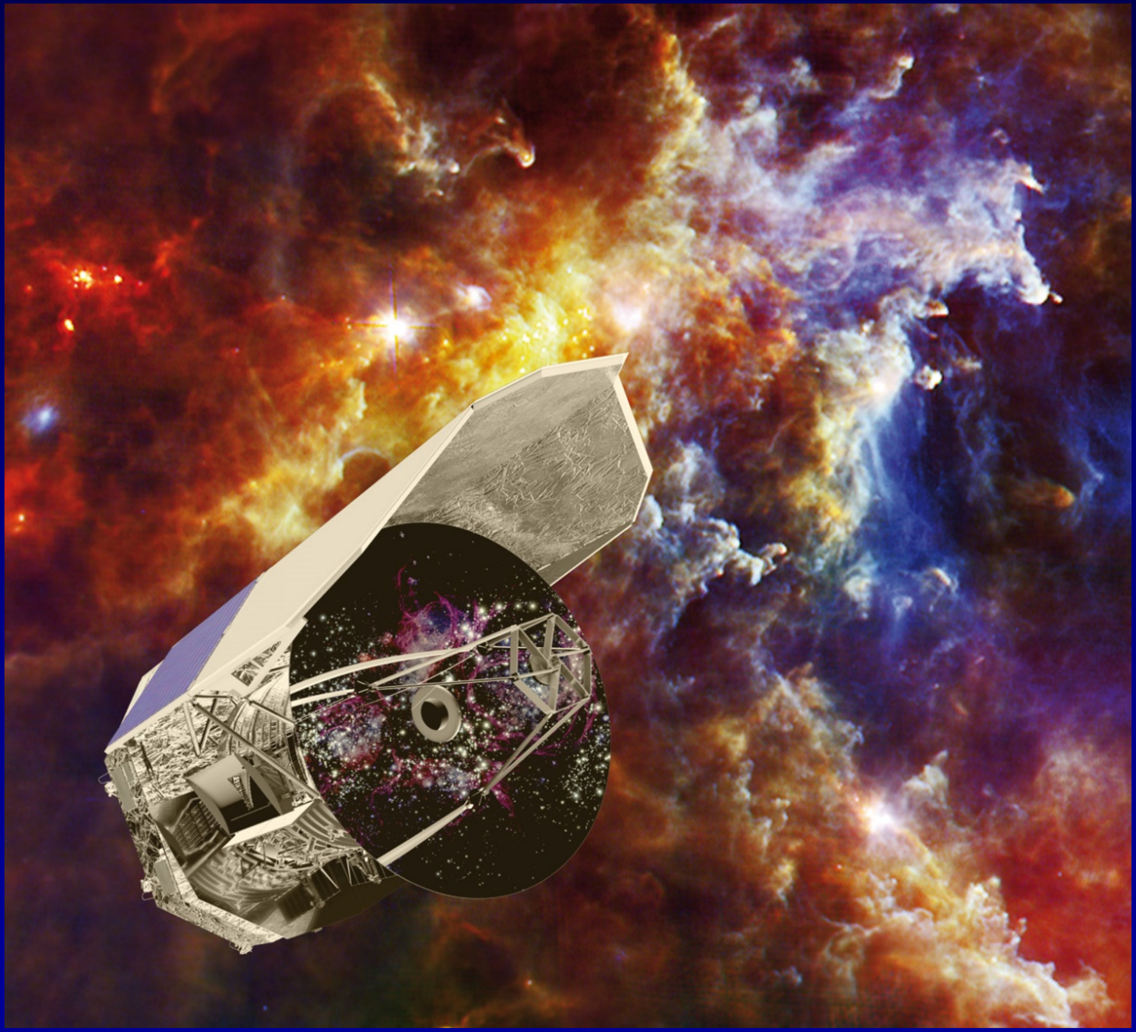
See reviews by Herbst & vD 2009, Caselli & Ceccarelli 2012, Tielens 2013, vD et al. 2014
special issue of Chemical Reviews 2013

Not covered here

- Starless cores
  - See talks Rachel Friesen, Aurore Bacmann
  - Recent work: effects of H_2 o/p, spin statistics, nitrogen isotopes, ...
- Episodic accretion effects
  - See talk Sybille Anderl
- Deuteration
- PAHs, fullerenes
- .....



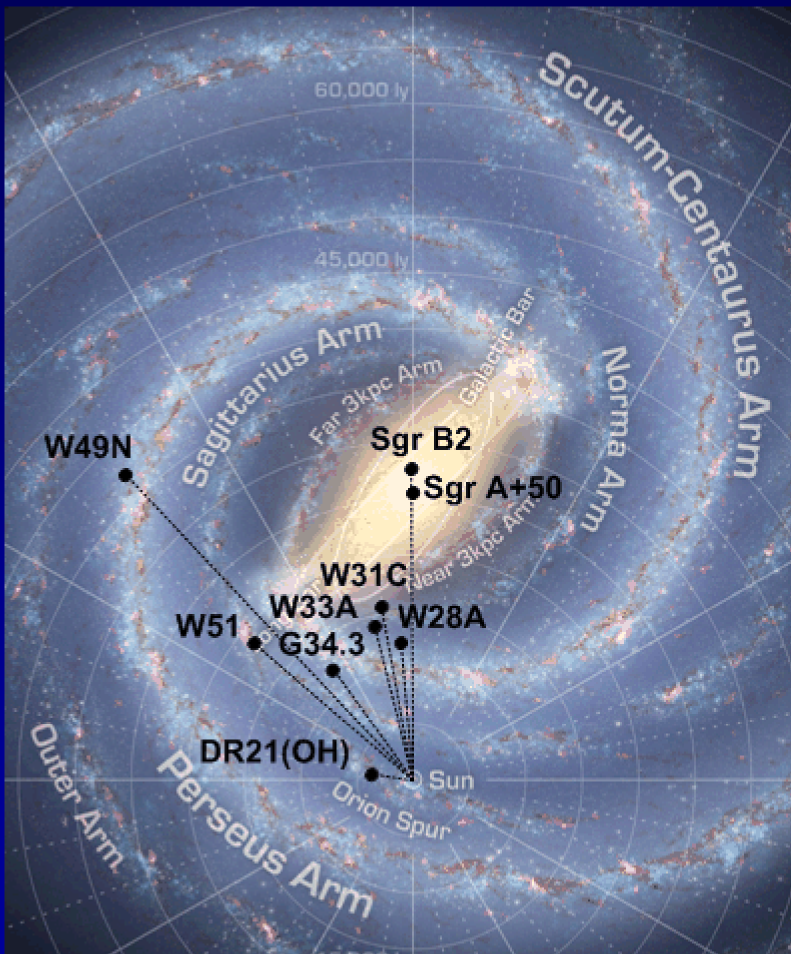
Herschel legacy



HIFI, PACS, SPIRE: 55-600 μm spectroscopy, $R=10^3$-10^7
Beam 20-47''

Diffuse and translucent clouds

Testing ion-molecule chemistry

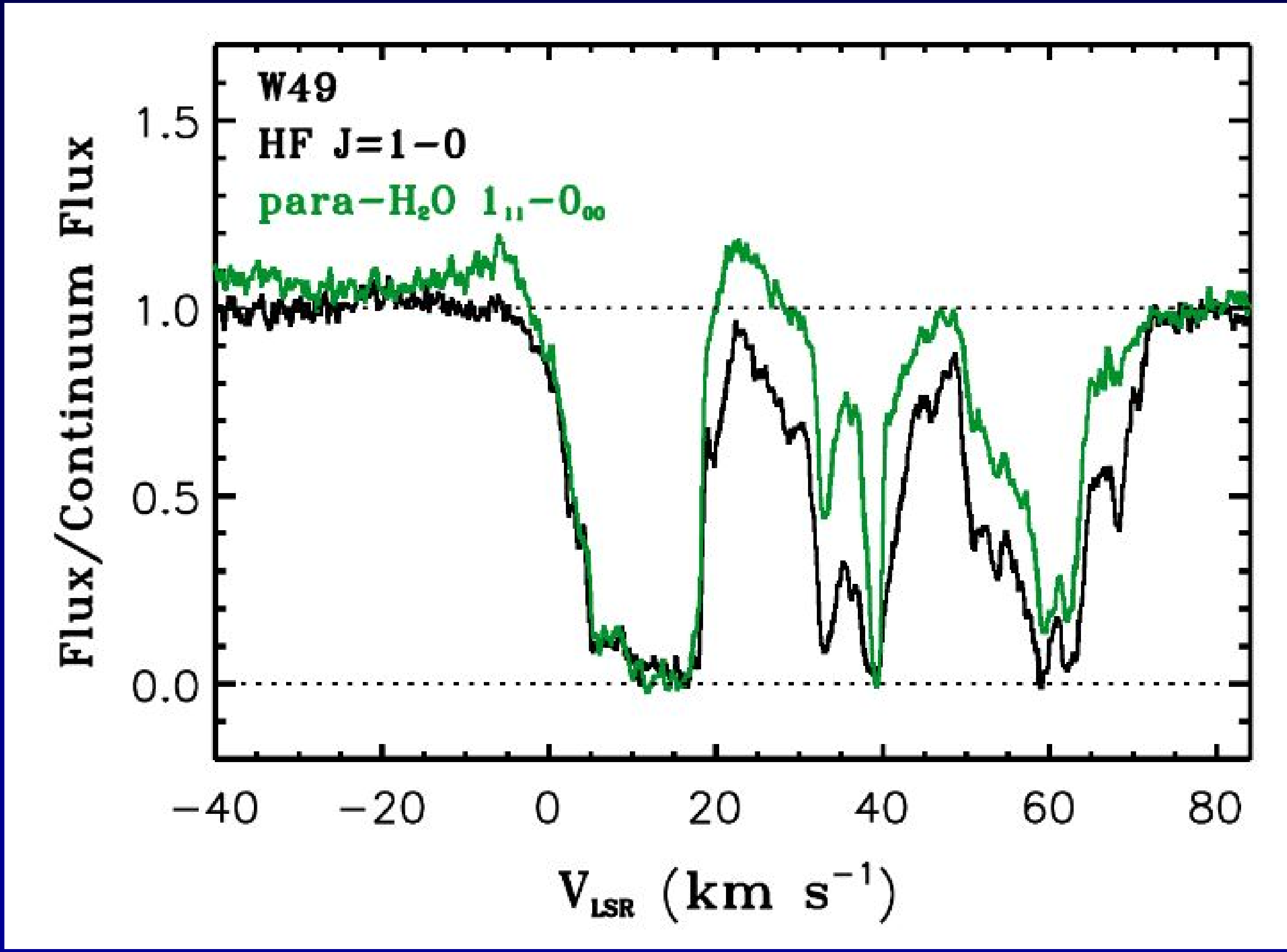


Gerin et al. 2016, ARA&A

- **Absorption against bright far-IR continuum**
- **Clouds A_V ~few mag**
- **All molecules in ground level→simple analysis**
- ***Precision astrochemistry* (factor of ~2)**

Gerin et al. 2010

Absorption lines

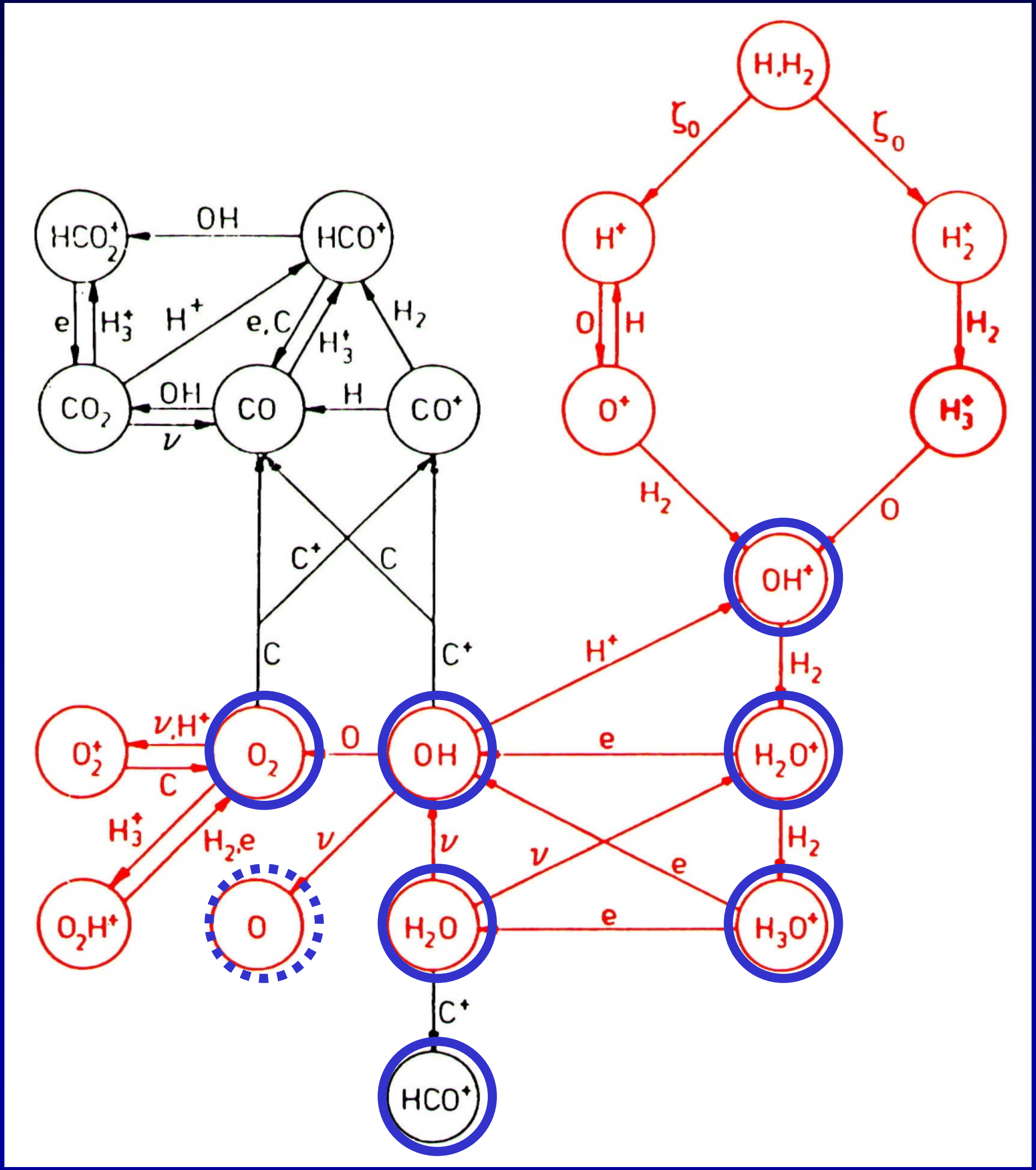


Water
o/p=3

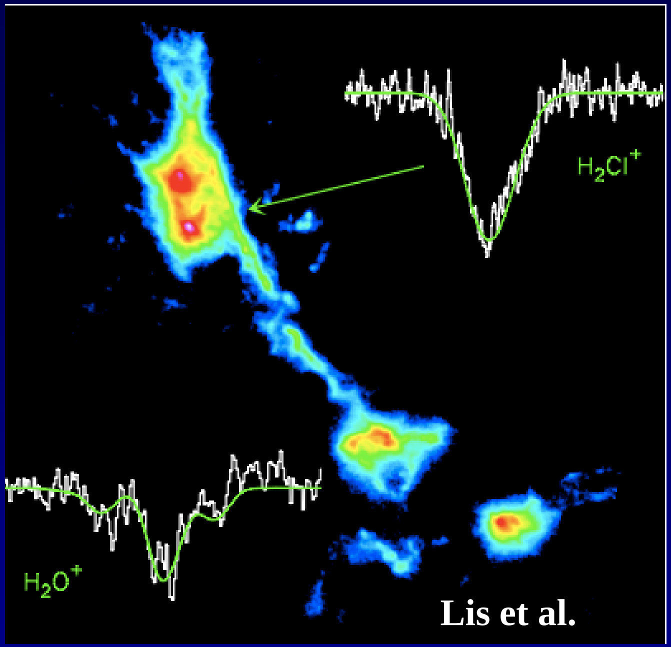
Neufeld et al. 2010,
Sonnetrucker et al. 2010
Godard et al. 2012
Emprechtinger et al. 2012
Flagey et al. 2013

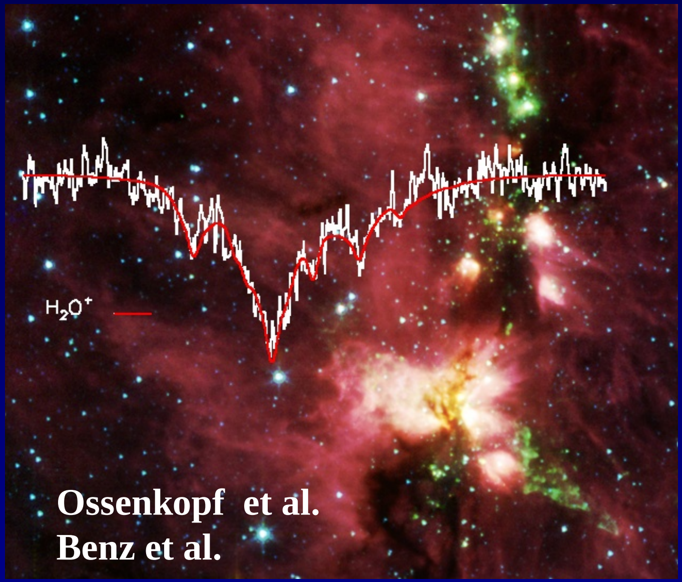
- **HF as tracer of H_2 column density because of simple chemistry**
- **Constant H_2O/H_2 abundance of $5x10^{-8}$, consistent with simple models**

All key species in oxygen chemistry detected!



Surprise: strong OH^+, H_2O^+

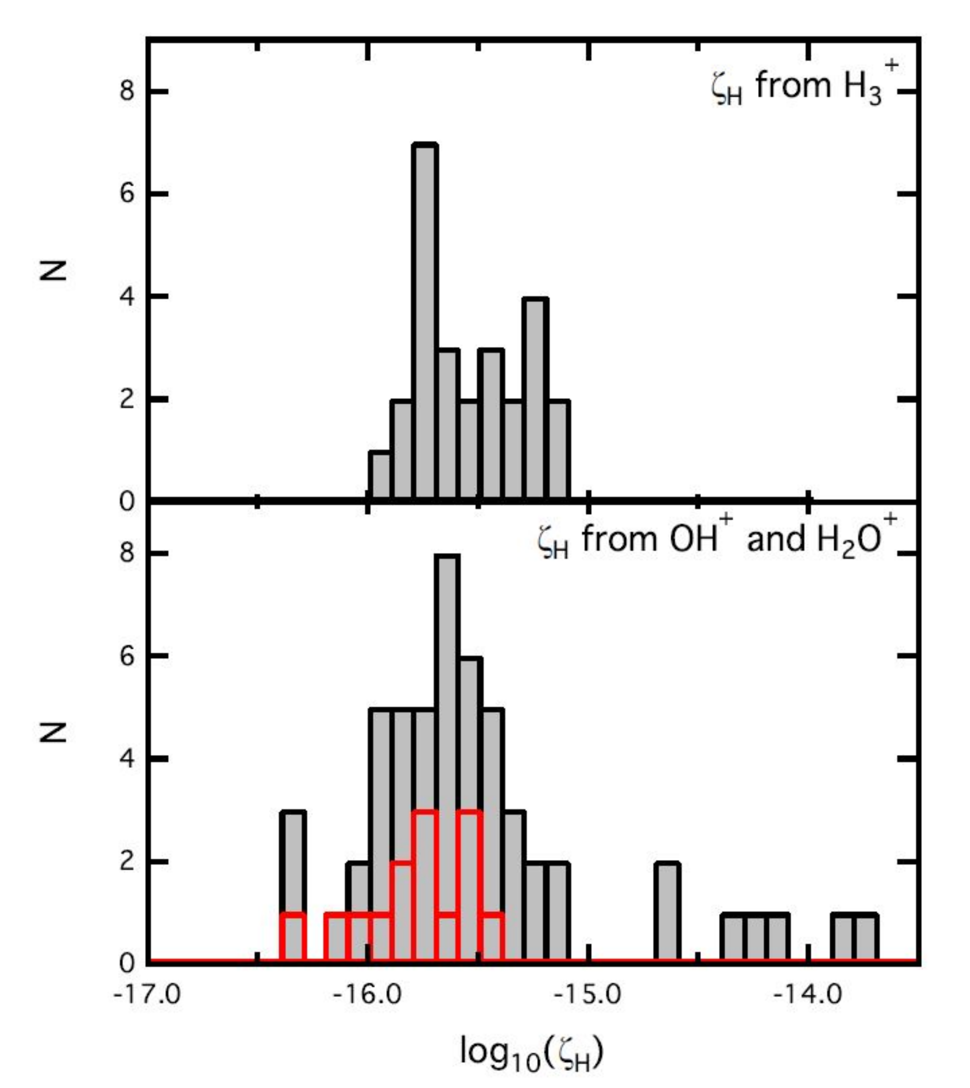




- **OH^+, H_2O^+ must arise in H_2 poor phase (H/H_2~10)**
- **OH^+, H_2O^+ constrain ζ**

Ossenkopf et al., Benz et al., Bruderer et al., Gerin et al., Wyrowski et al., Gupta et al., Schilke et al., Lis et al. 2010; Neufeld et al. 2012, de Luca et al. 2012, Indriolo et al. 2013, Monje et al. 2013....
OH^+ detection with APEX Menten et al. 2011

Cosmic ray ionization rates



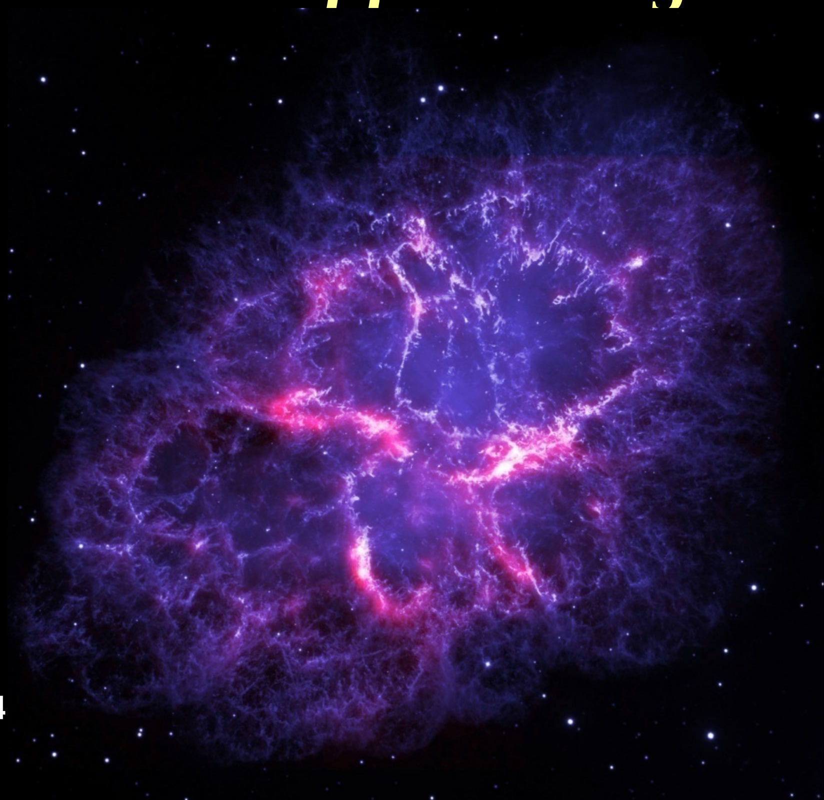
Red: denser material associated with continuum source

Indriolo et al. 2015

First interstellar noble gas molecule!

Probe of pure H I gas

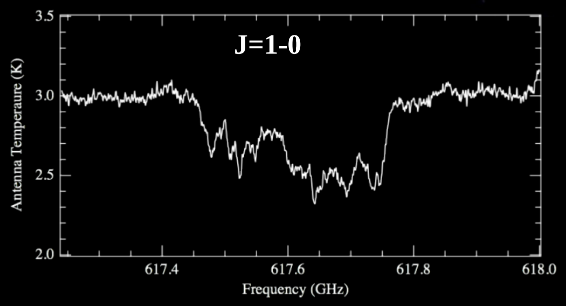
$^{36}ArH^{+}$

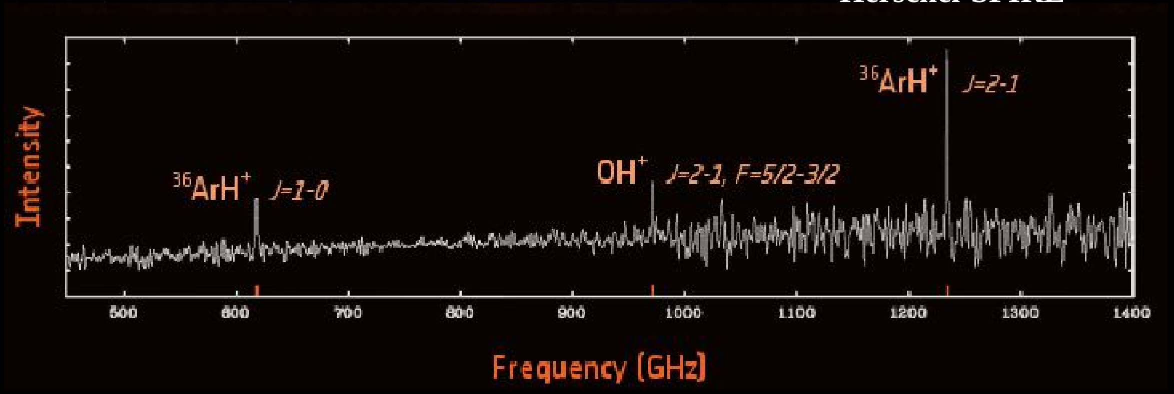


Crab nebula
Hubble+ Herschel

Implies $H/H_2 \sim 10^4$

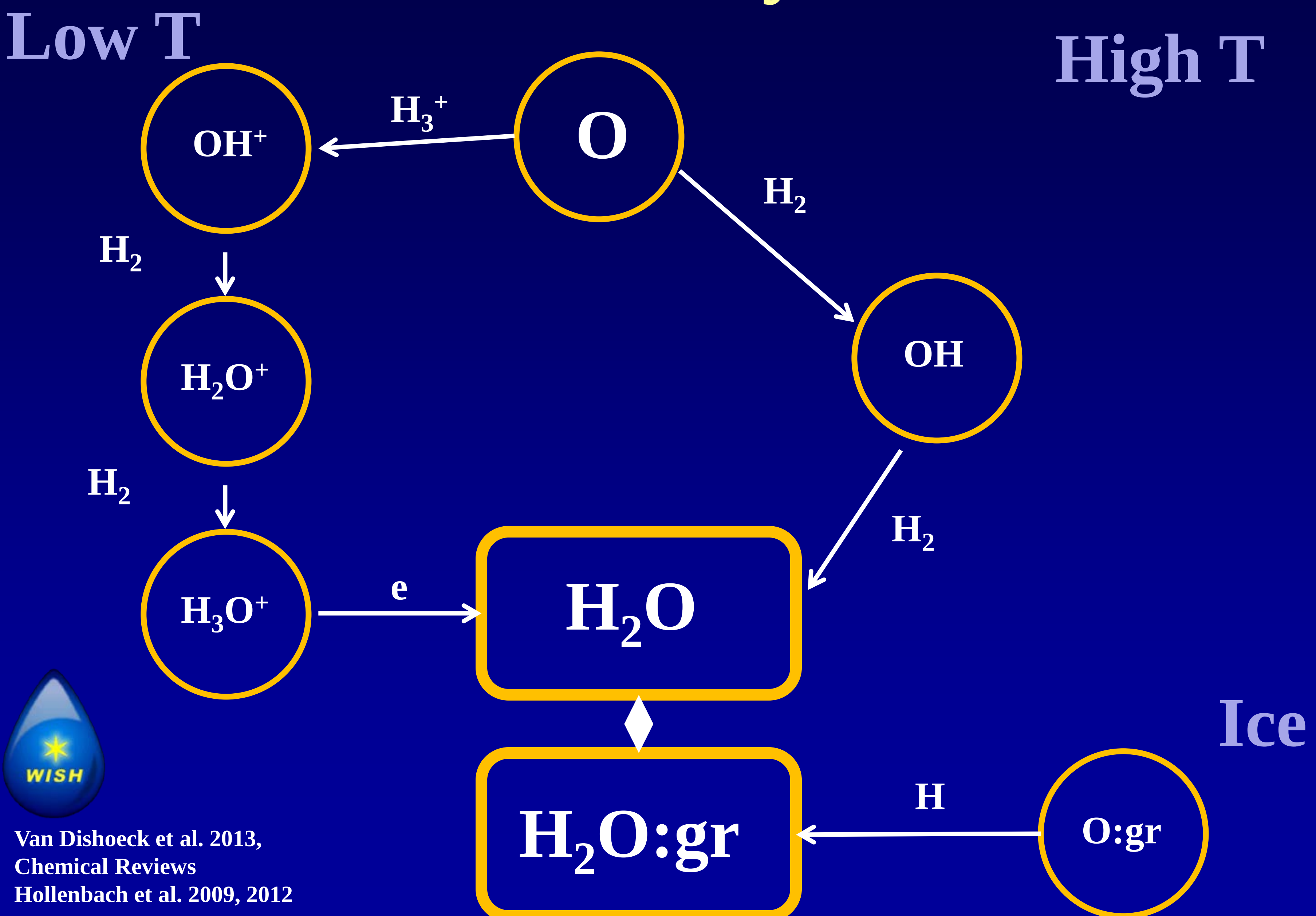
Barlow et al. 2013
Herschel-SPIRE





Schilke et al. 2014
Herschel-HIFI Sgr B2

Water chemistry: 3 routes



Van Dishoeck et al. 2013, Chemical Reviews
Hollenbach et al. 2009, 2012

Water In Star-forming regions with Herschel
The WISH team

Ringberg, January 2013

~80 sources
Low to high mass

Doubled with OT

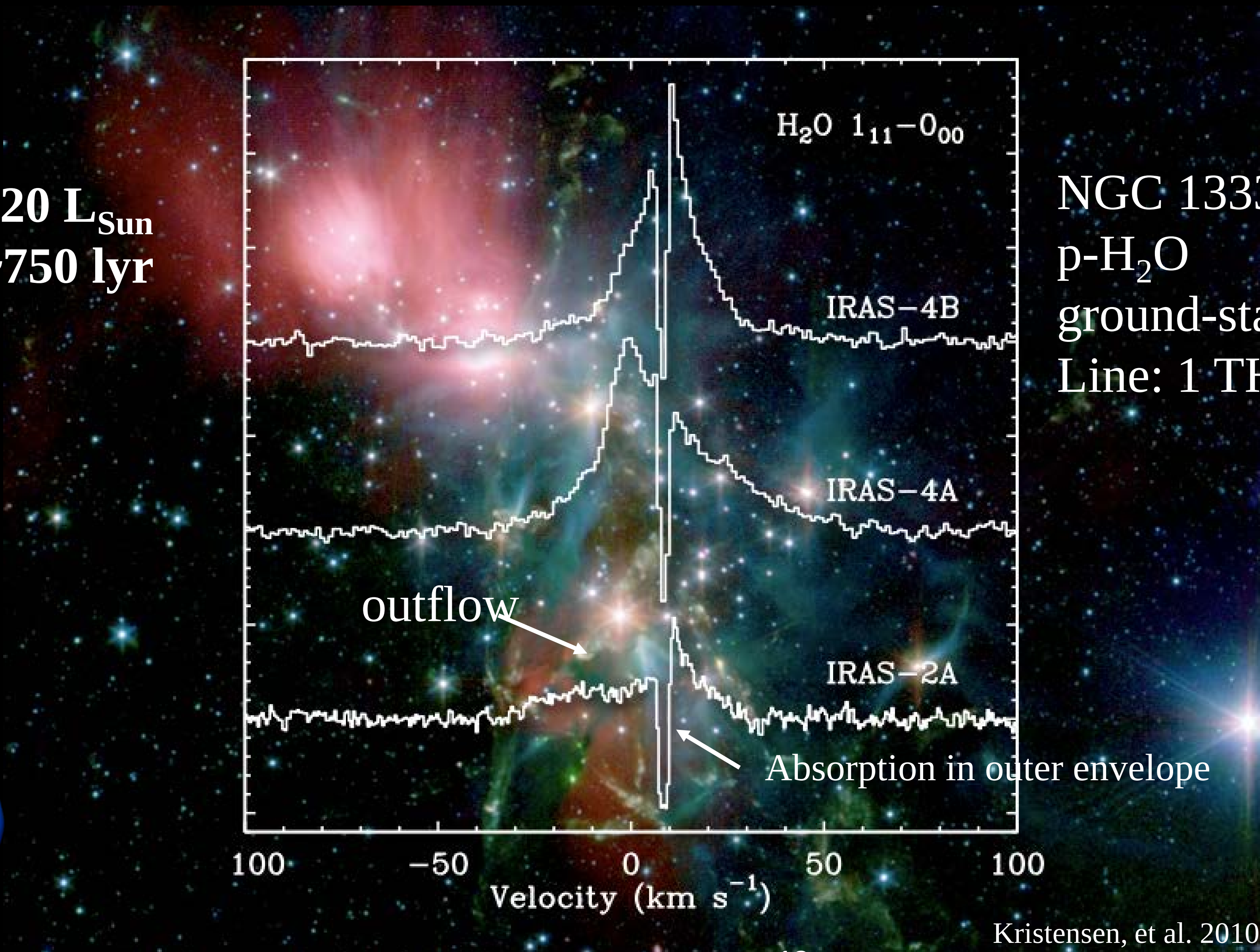
www.strw.leidenuniv.nl/WISH

~70 papers, initial summary in van Dishoeck et al. 2011, PASP
Bergin & van Dishoeck 2012, van Dishoeck et al. 2013, Chem. Rev. , 2014, PPVI

WISH

Water in low-mass protostars

L~20 L_{Sun}
D~750 lyr

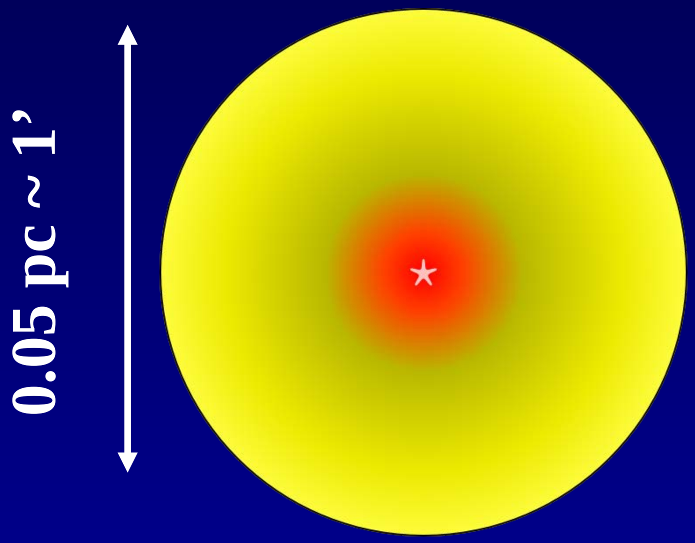


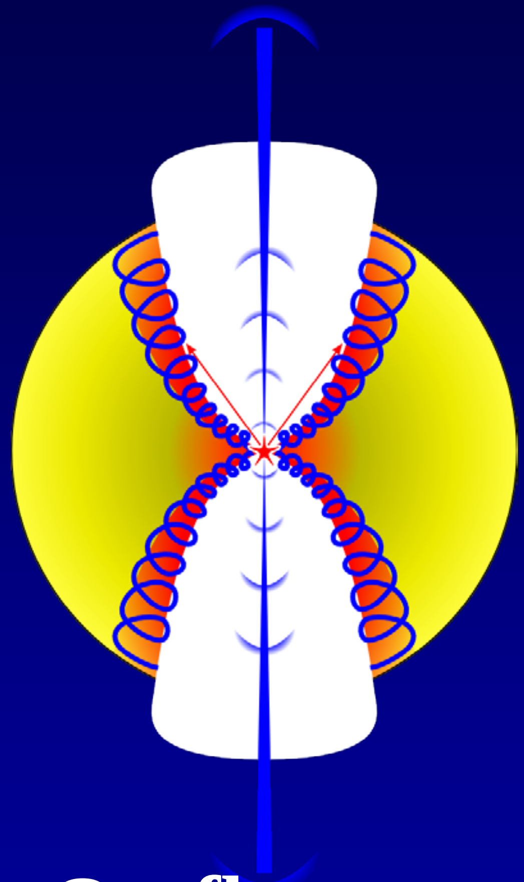
NGC 1333
p-H_2O
ground-state
Line: 1 THz

Broad: outflow dominates, even for $H_2{}^{18}O$

Kristensen, et al. 2010, 2012
Mottram et al. 2014

Importance of outflow cavity





Hot core

Compact (~200 AU) region where H_2O ice evaporates

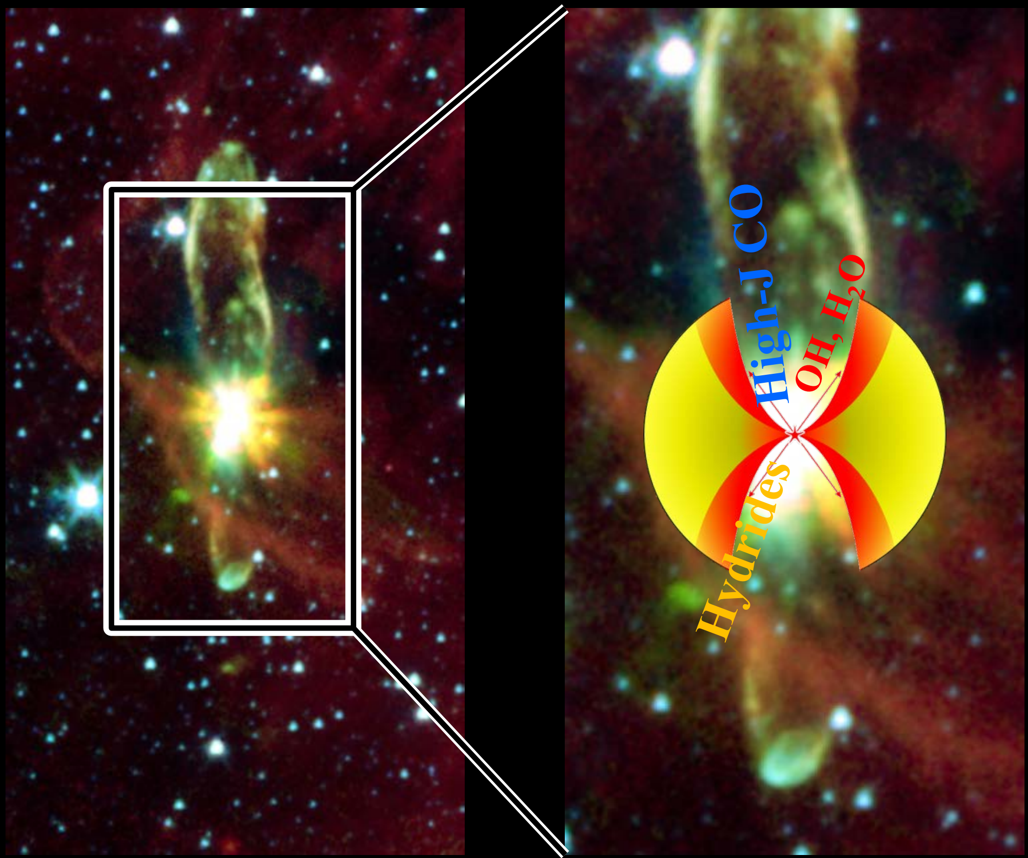
Dominates ALMA $H_2^{18}O$ emission

Outflows

Extended emission along outflow; H_2O enhanced in shock

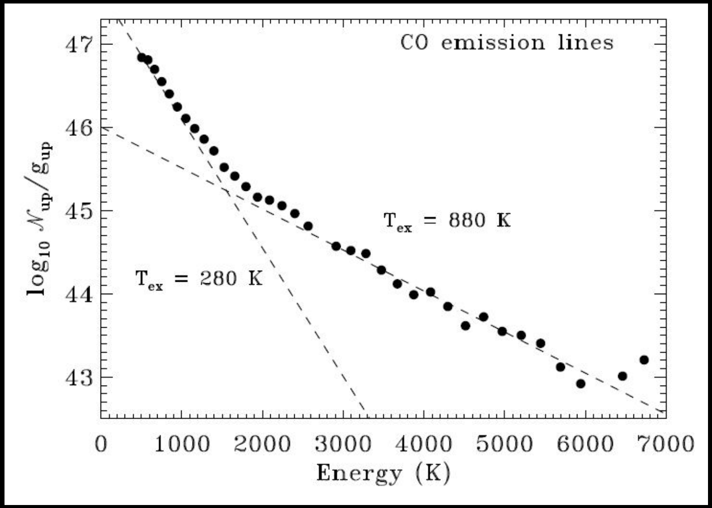
Dominates Herschel emission

UV-irradiated outflow cavity walls: ‘feedback’



Visser et al. 2012, Karska et al. 2013, 2015
Kaufman et al. 2016

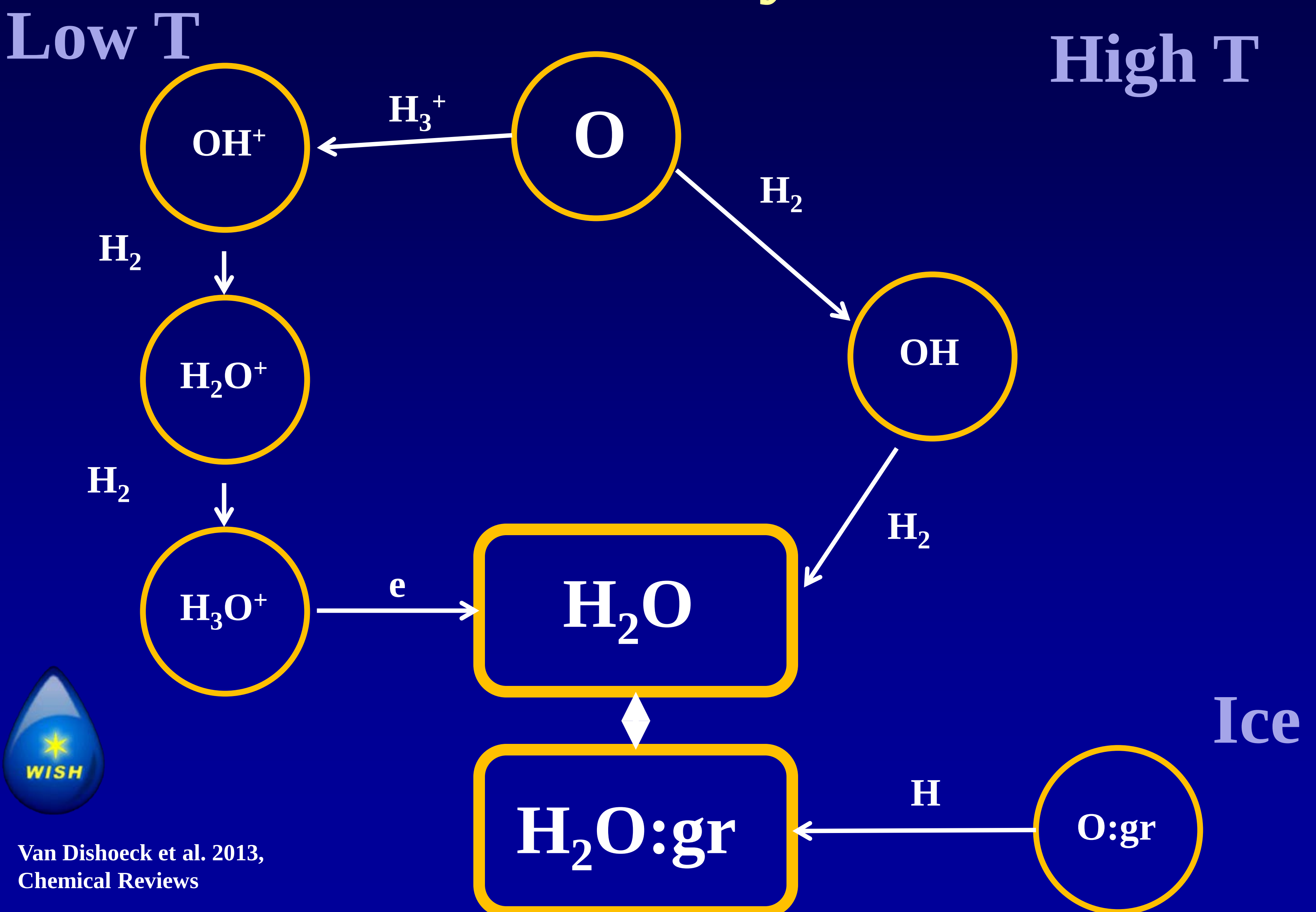
Universal CO ladders



Herczeg et al. 2012
Goicoechea et al. 2012
Manoj et al. 2013: HOPS
Green et al. 2013: DIGIT

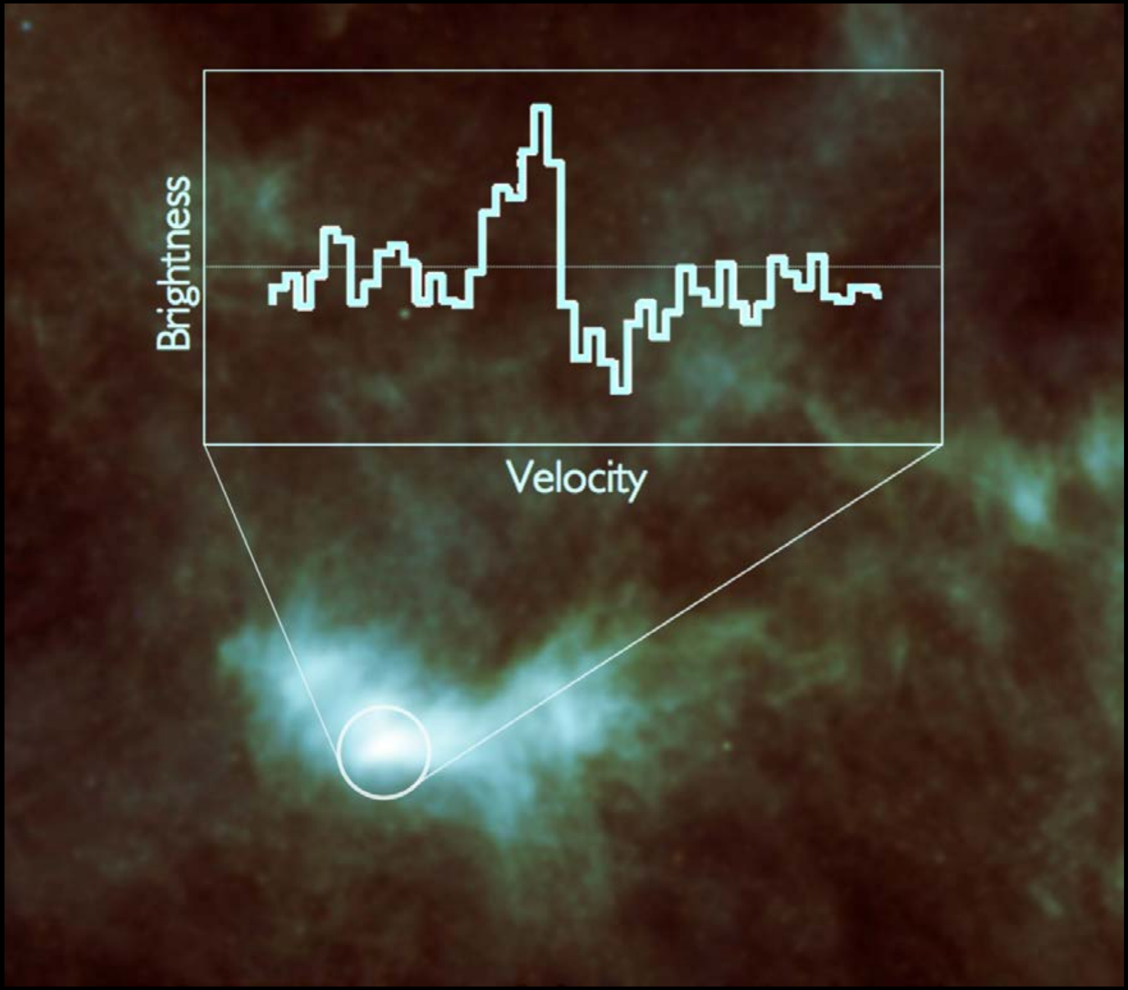
OH/H_2O higher than expected from shock models → *UV irradiated shocks*

Water chemistry: 3 routes



Van Dishoeck et al. 2013,
Chemical Reviews

Water formation: gaseous water reservoir with *Herschel*

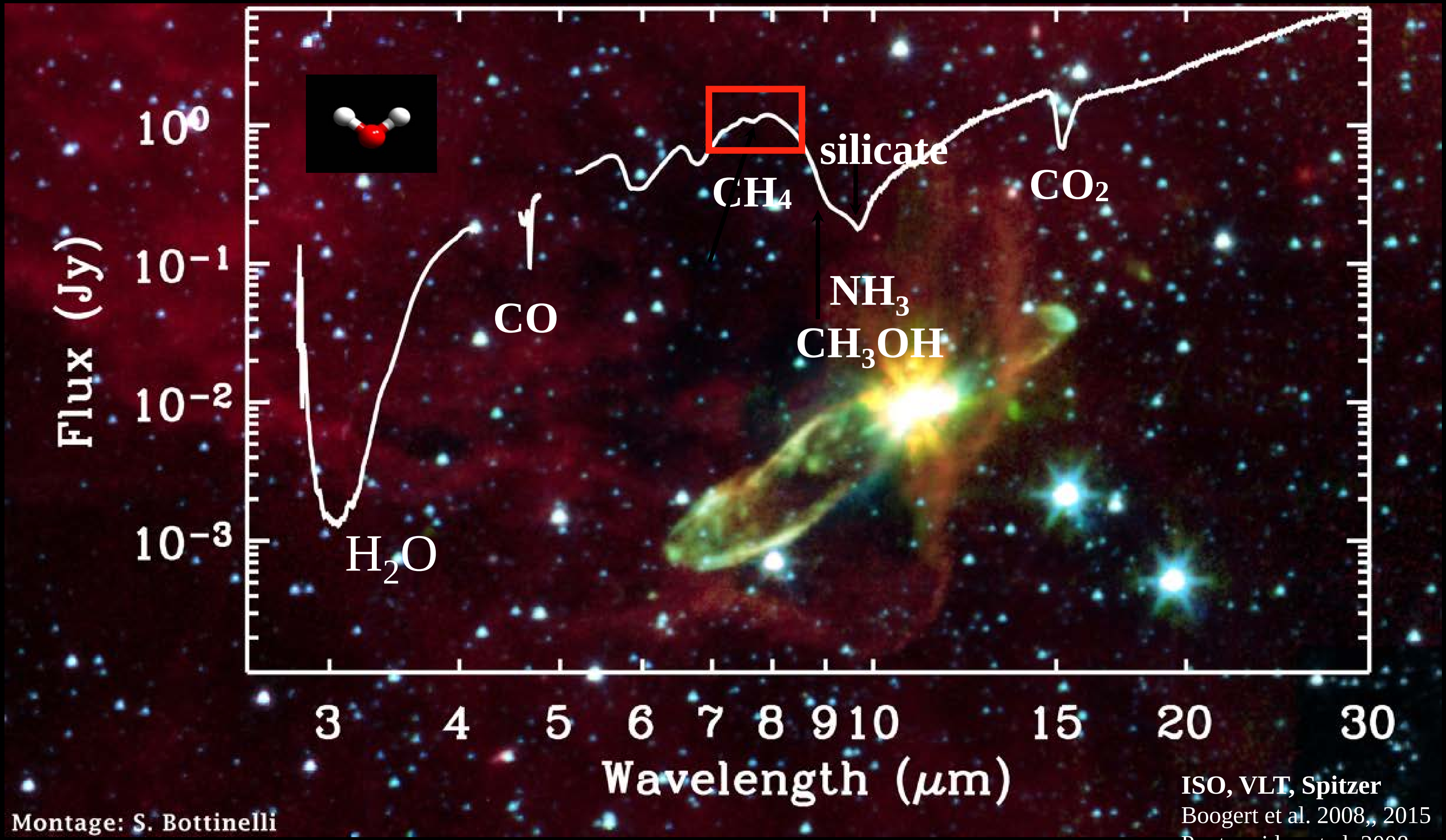


L1544
Pre-stellar core

Caselli et al. 2012
Mottram et al. 2013
Schmalzl et al. 2014

Most water molecules made on grains *before* cloud collapse
Simple chemistry reproduces abundance structure well

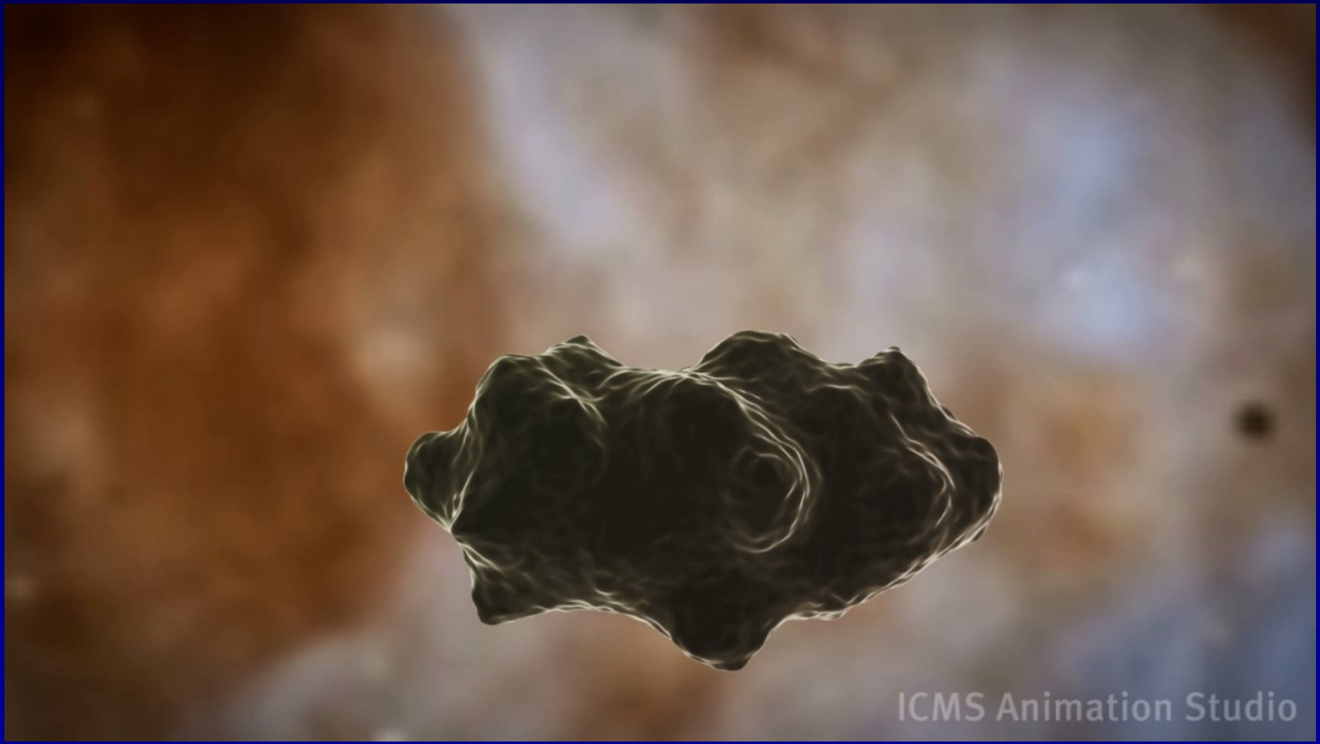
Water formation: interstellar ices



ISO, VLT, Spitzer
Boogert et al. 2008,, 2015
Pontoppidan et al. 2008,
Öberg et al. 2008, 2011
Gibb et al. 2004

- Ices can contain significant fraction (>50%) of heavy element abundances

Bulk of water is formed on grains



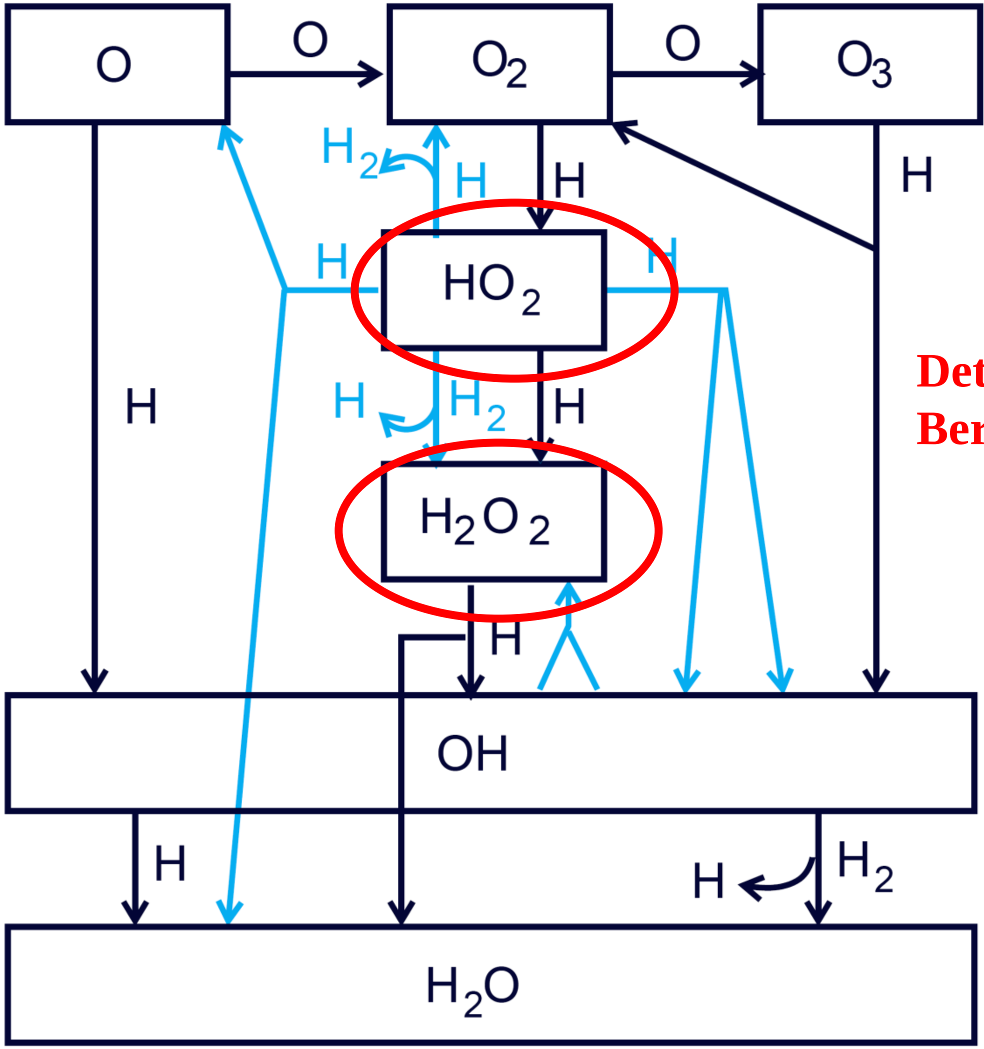
Ice formation starts in clouds with $A_V > 1$ mag

Based on laboratory data
Cuppen et al. 2010

Movie posted at www.strw.leidenuniv.nl/WISH

How to make water ice

A success story lab-observations

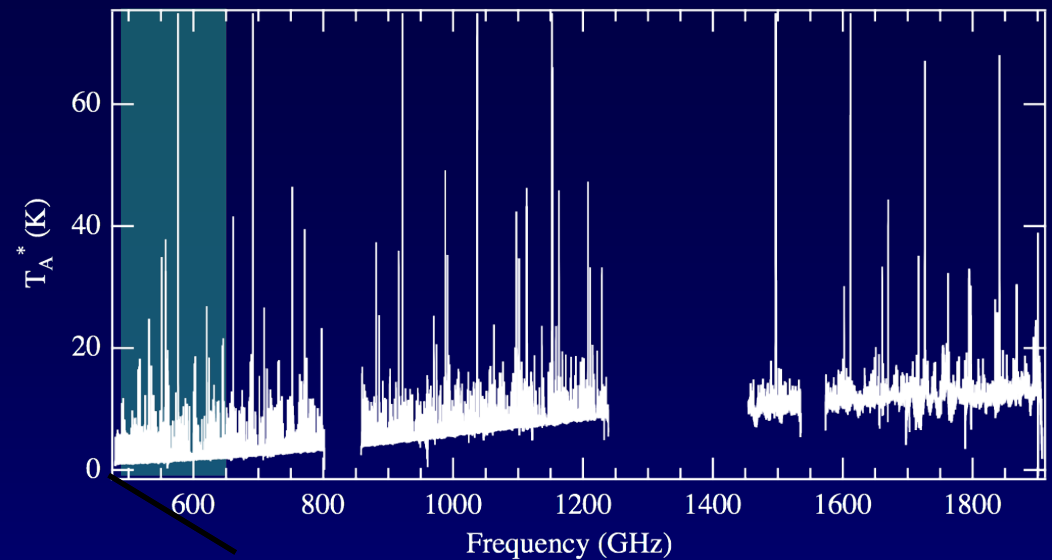


Detected in 2011 and 2012
Bergman, Parise et al.

Tielens & Hagen 82

Ioppolo et al. 08,10
Cuppen et al. 10
Watanabe+
Dulieu+

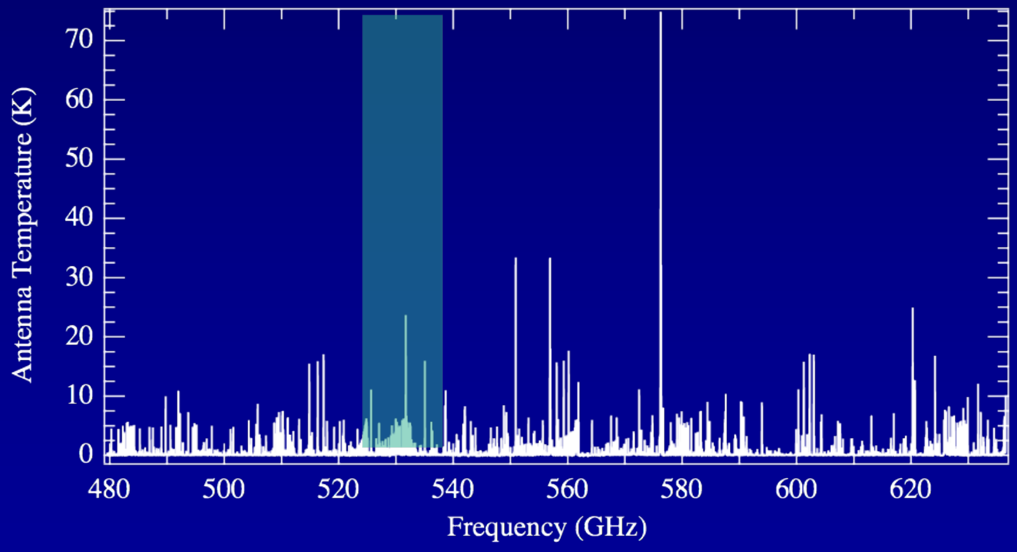
Detailed laboratory experiments reveal multiple routes at 10 K

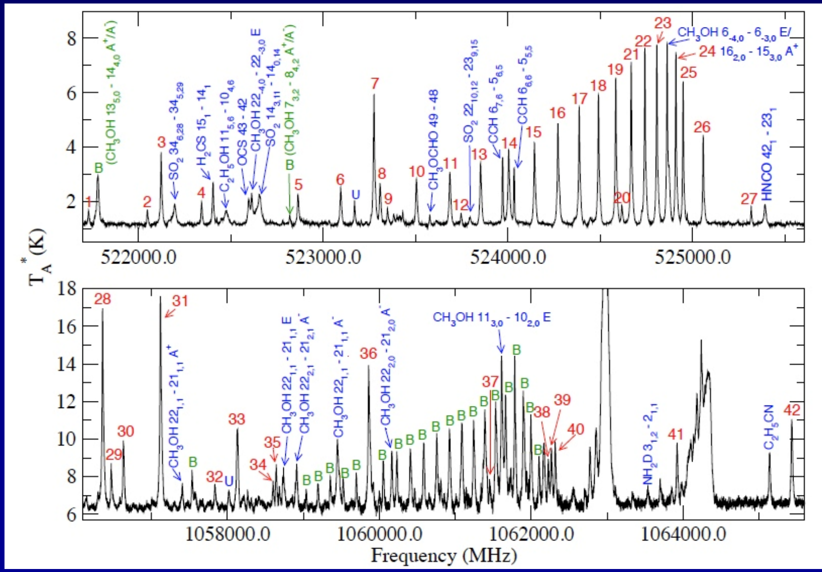


Line surveys

Orion-KL

Herschel-HIFI

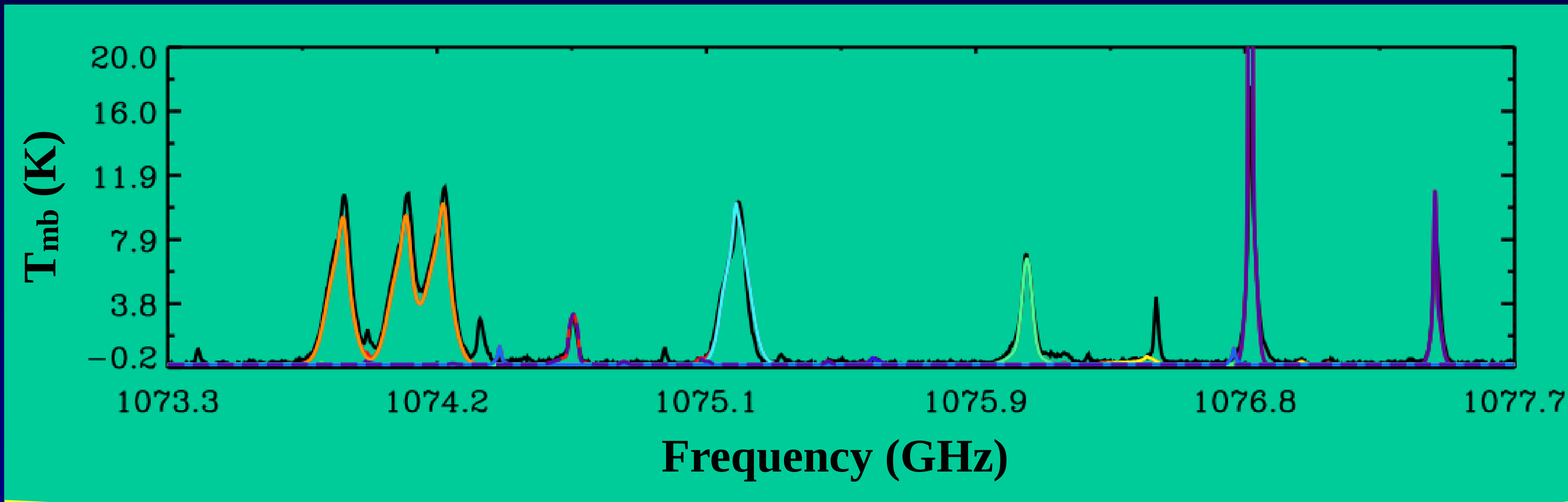


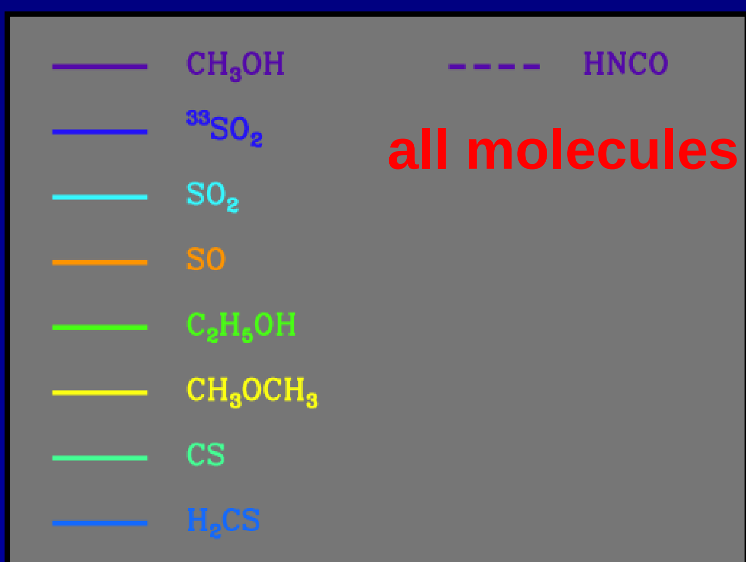


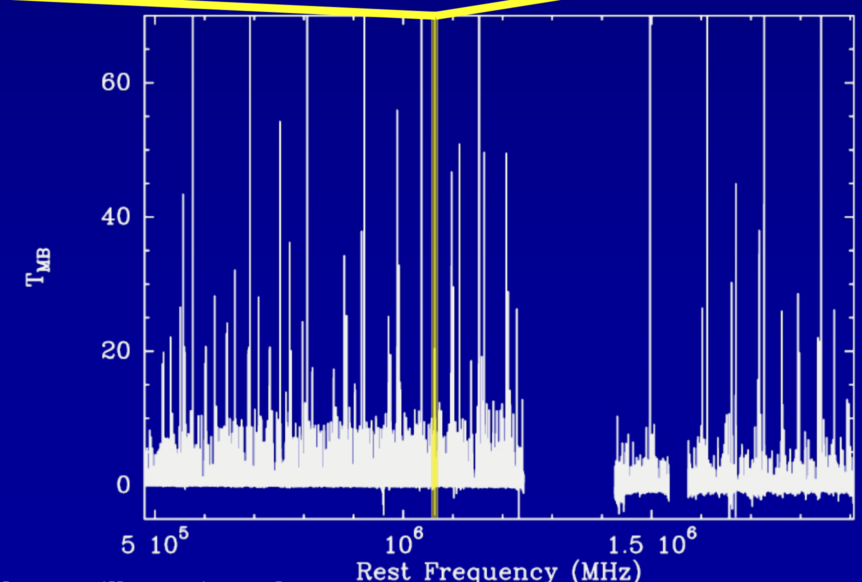
Bergin et al. 2010, Crockett et al. 2014

- Wide frequency range → E_u up to 3000 K
- 6-12% of channels unidentified

Identifying and modeling emission



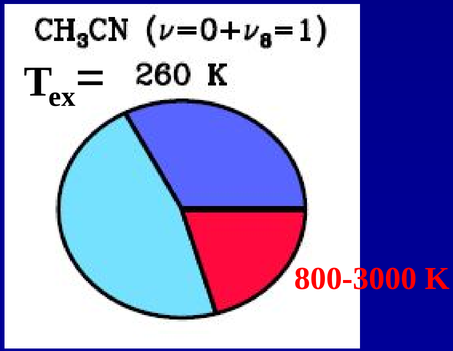


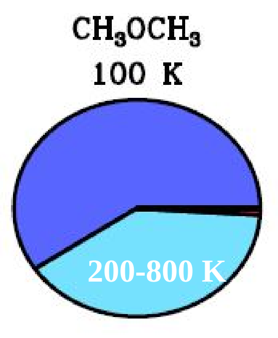


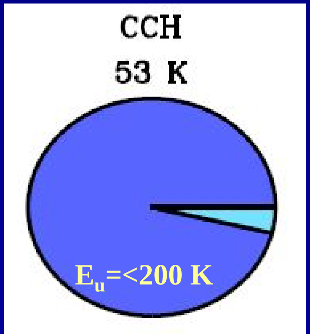
Crockett, Neill, Bergin et al. 2014, 2015

Line surveys results

- No new complex molecules (as expected)
- Identify complex molecules emitting in the hottest gas
  - N-species hotter than O-species



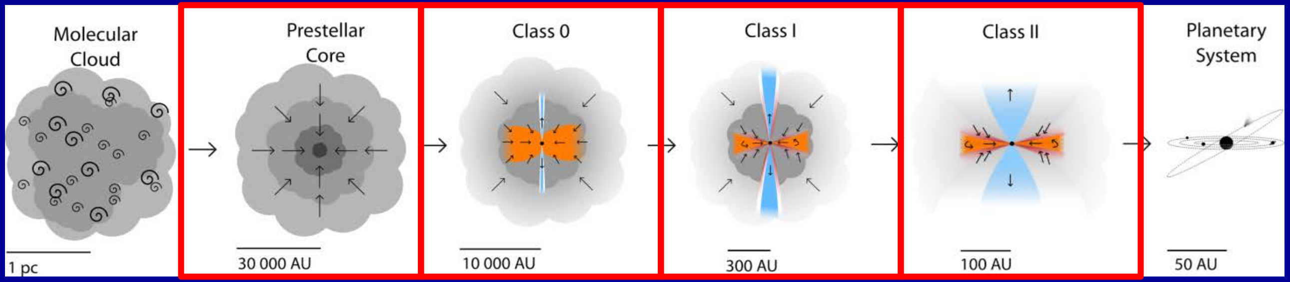




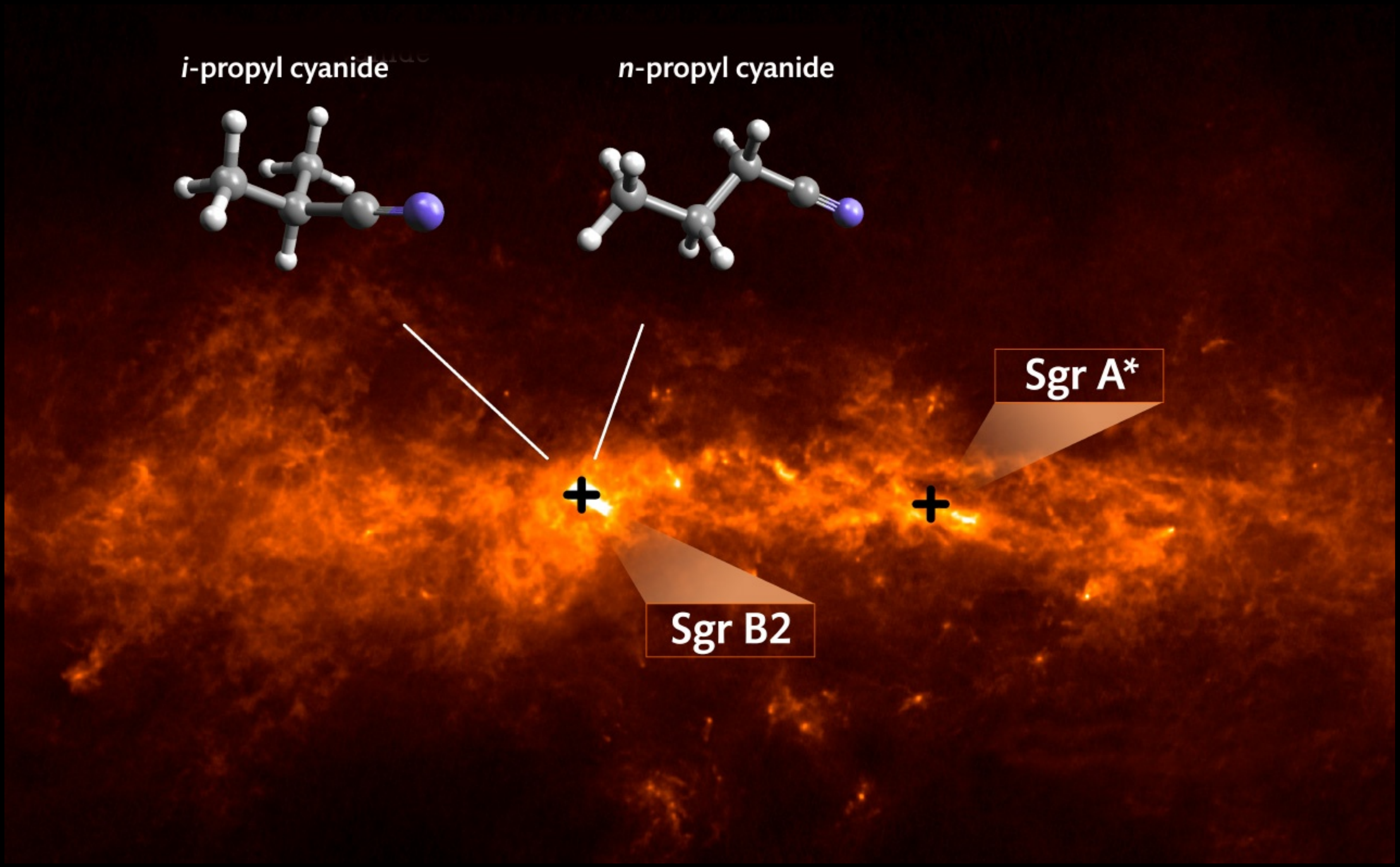
Crockett et al. 2015

Complex organic molecules

- **Full inventory with *Herschel*, IRAM, ...**
  - **Complex molecules found at *all* stages: in pre-stellar cores, protostars, shocks, disks**
    - **Pre-stellar cores: Bacmann et al. 2012, Vastel et al. 2014**
    - **Shocks: Arce et al. 2008, Codella et al.**
    - **Disks: CH_3CN Öberg et al. 2015; CH_3OH Walsh et al. 2016 ALMA**
- **New era with ALMA**
  - **ALMA can *image* each line**
  - **Sensitivity to more complex species**
  - **Sensitivity to solar-mass protostars, not just Orion-like**



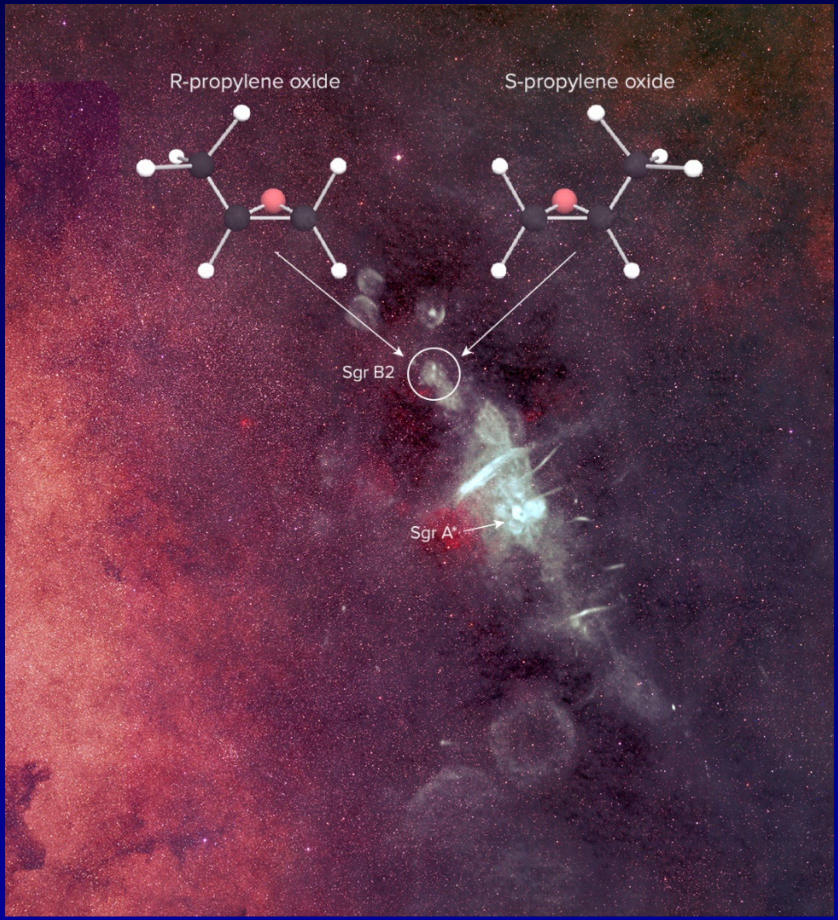
Detection of branched molecules 'branching out'

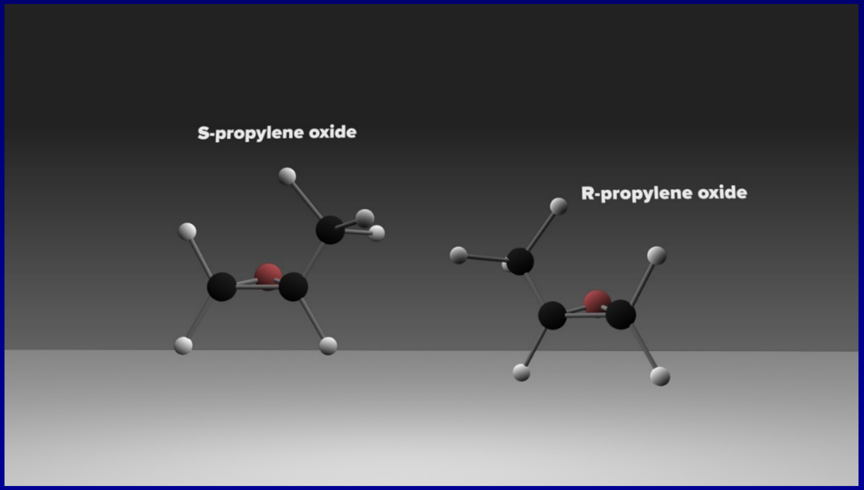


Belloche et al. 2014

Such side chains are characteristics of amino acids

First chiral molecule!

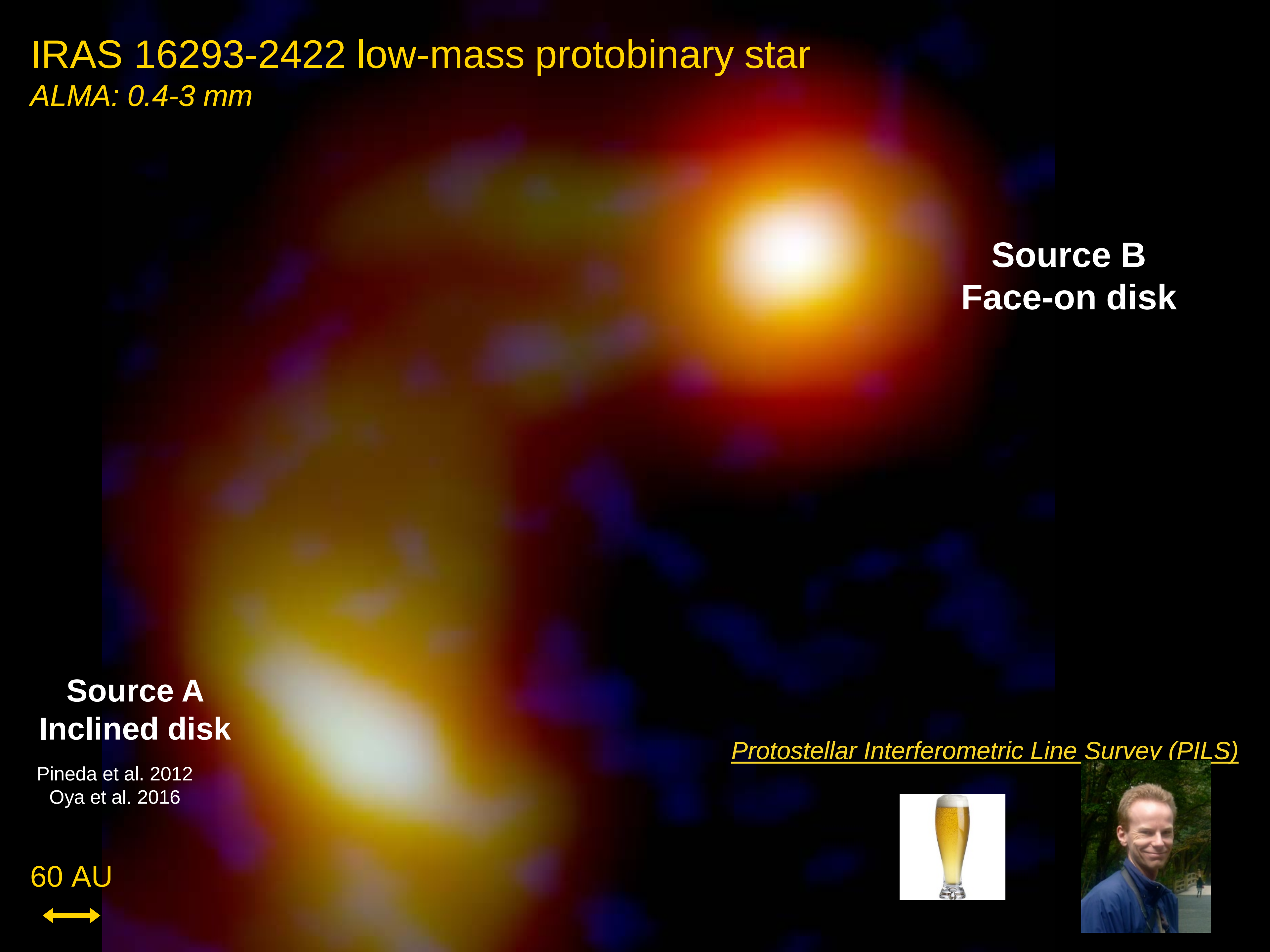




McGuire, Carroll, Blake et al. 2016
Science June 14

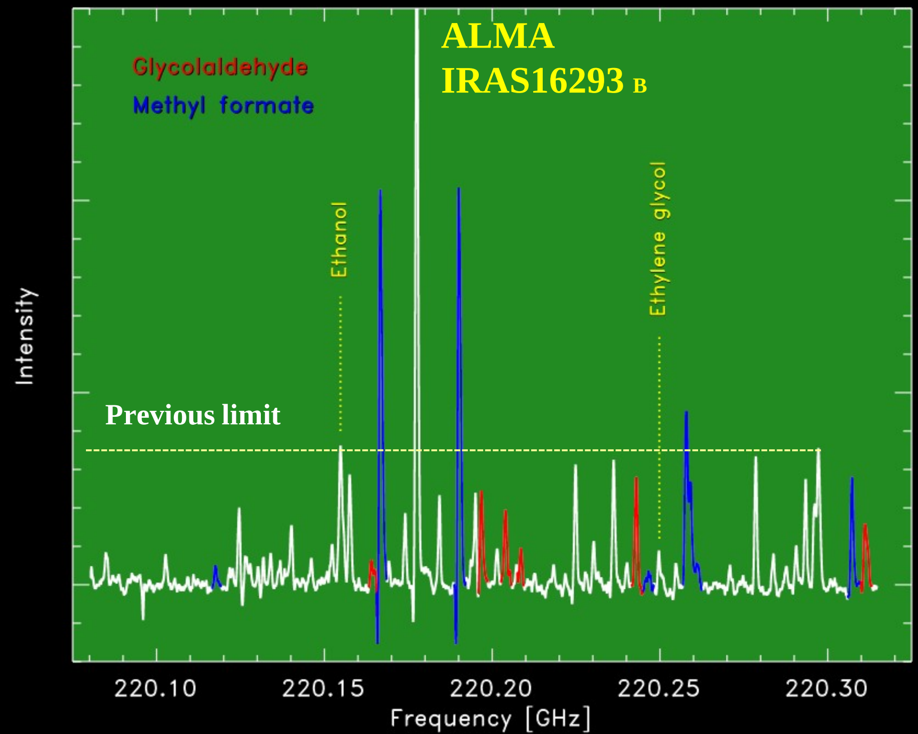
GBT, ATCA

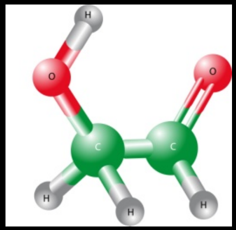
Note: not yet possible to measure left/right ratio, need polarized light


IRAS 16293-2422 low-mass protobinary star
ALMA: 0.4-3 mm
Source B
Face-on disk
Source A
Inclined disk
Pineda et al. 2012
Oya et al. 2016
60 AU
Protostellar Interferometric Line Survey (PILS)

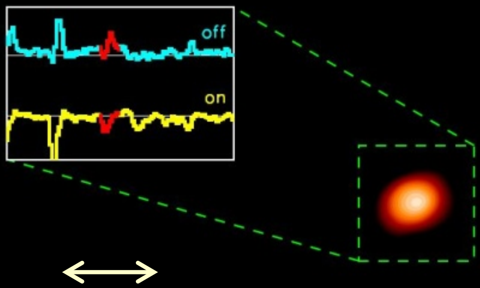
Detection of sugar near solar-mass protostar

Sweet result from ALMA





IRAS16293
d=125 pc



150AU

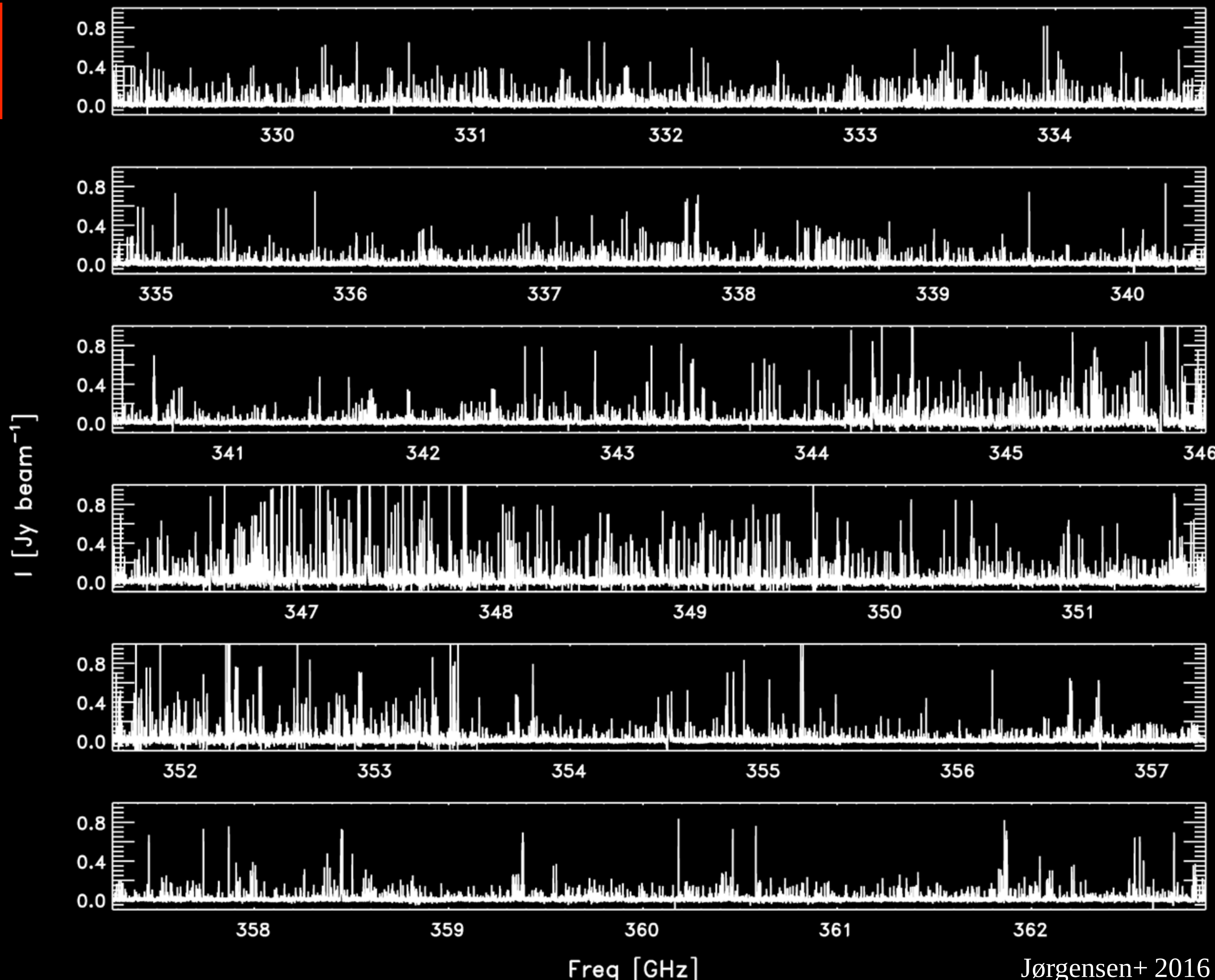
Band 9, 0.2”

6 glycolaldehyde lines in Band 6 and
7 lines in Band 9 identified; T_{ex}=300 K

Complex molecules found on solar system scales!
(orbit of Uranus, 25 AU)

Jørgensen et al. 12

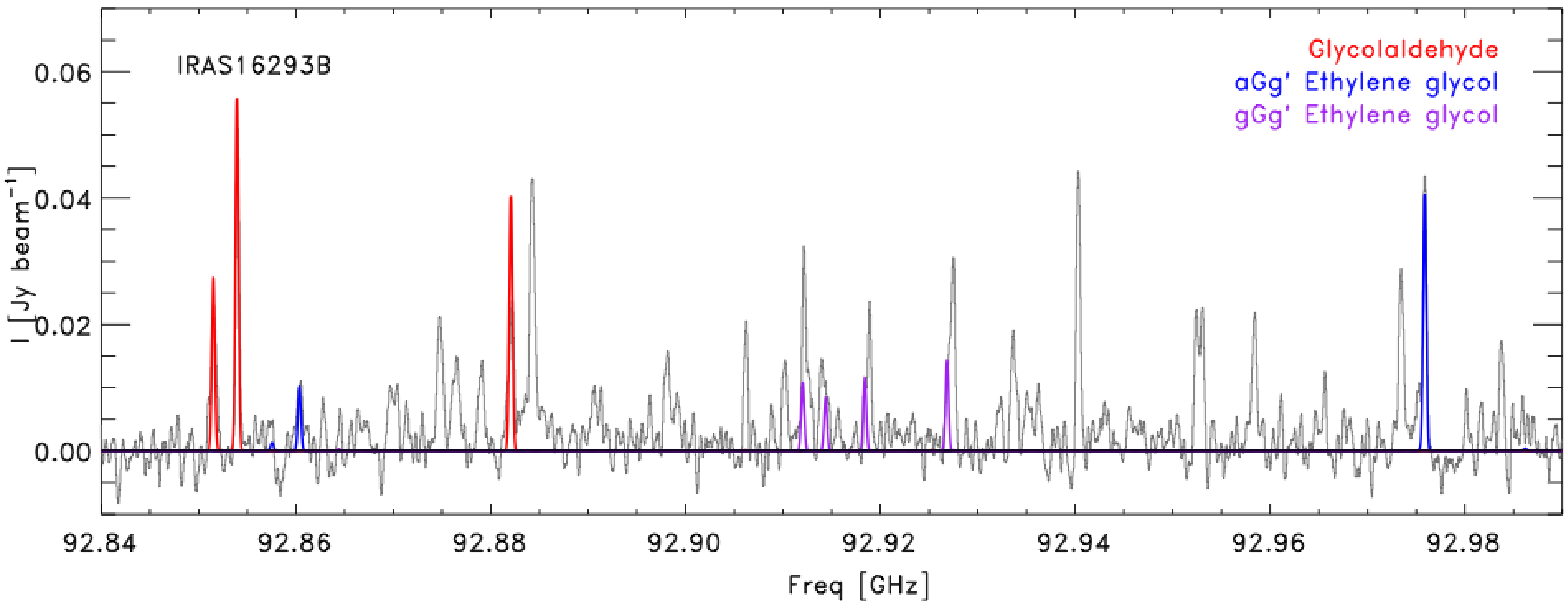
Full spectral survey of IRAS 16293–2422B



Jørgensen+ 2016

IRAS 16293-2422

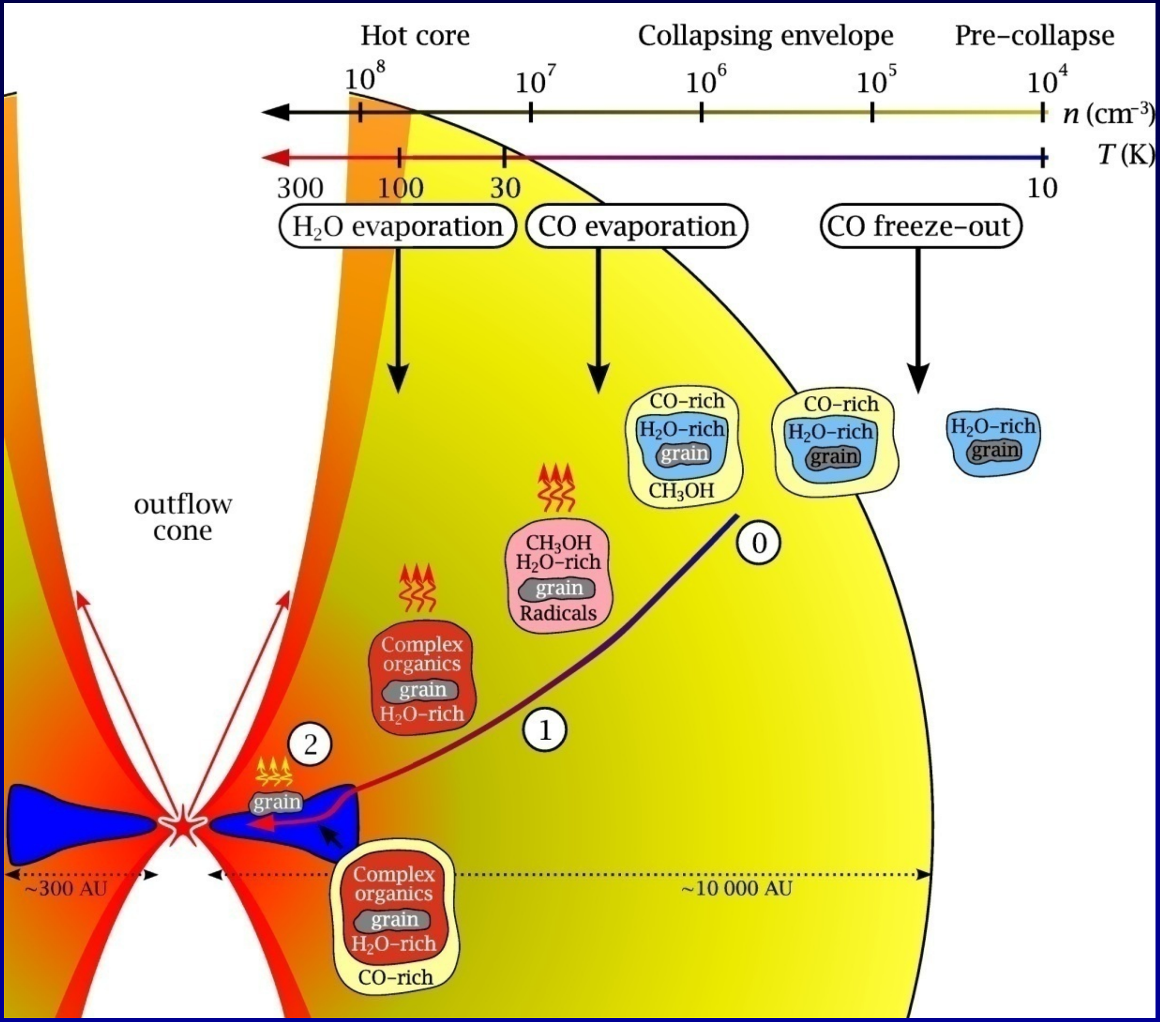
Glycolaldehyde and ethylene glycol confirmed



Jørgensen, Lykke et al. 2016

- **Propanal detected – 3-carbon atom molecule**
- **HNCO, NH_2CHO high deuteration:** Coutens et al. 2016

Scenario complex molecules formation



Herbst & vD
ARA&A 2009

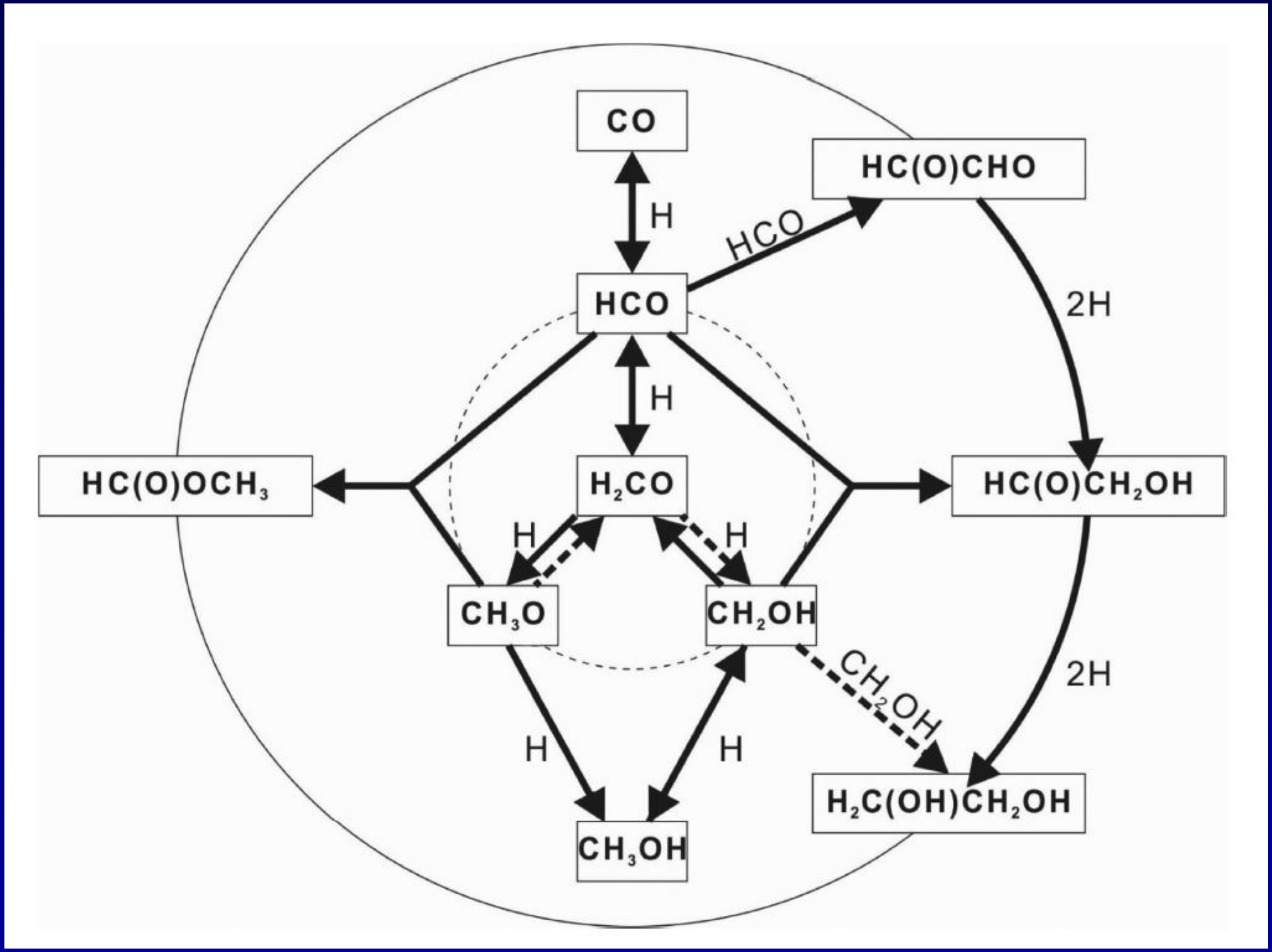
Visser et al. 2009

0th generation: cold ices: CO → CH_3OH + ?

1st generation: warm ices, radicals mobile: more complex organics

2nd generation: high-T gas-phase chemistry

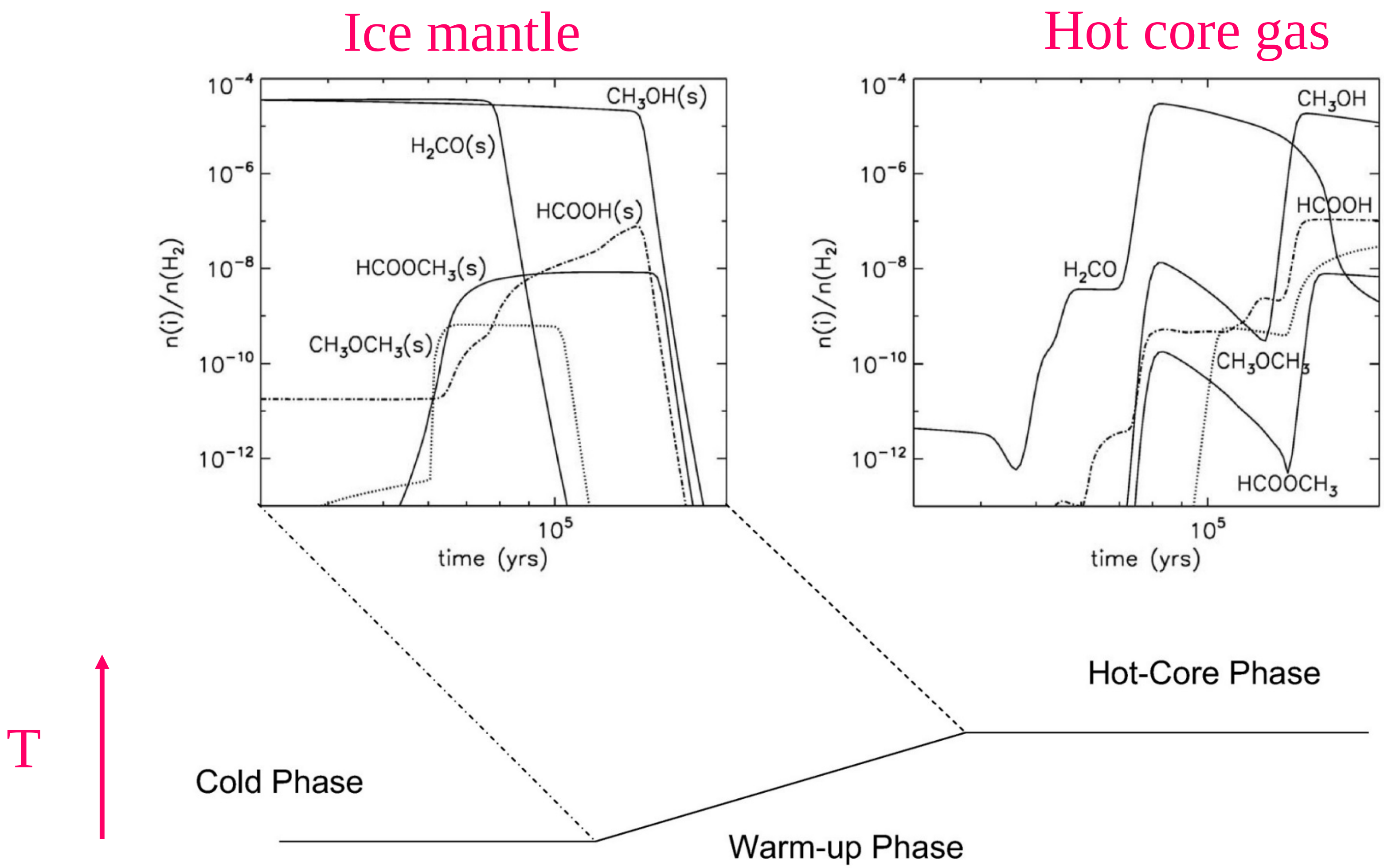
Making complex molecules at low *T*



Fedoseev et al. 2015
Chuang et al. 2016

Reactions proceed already at 15 K, without need for heating or UV!

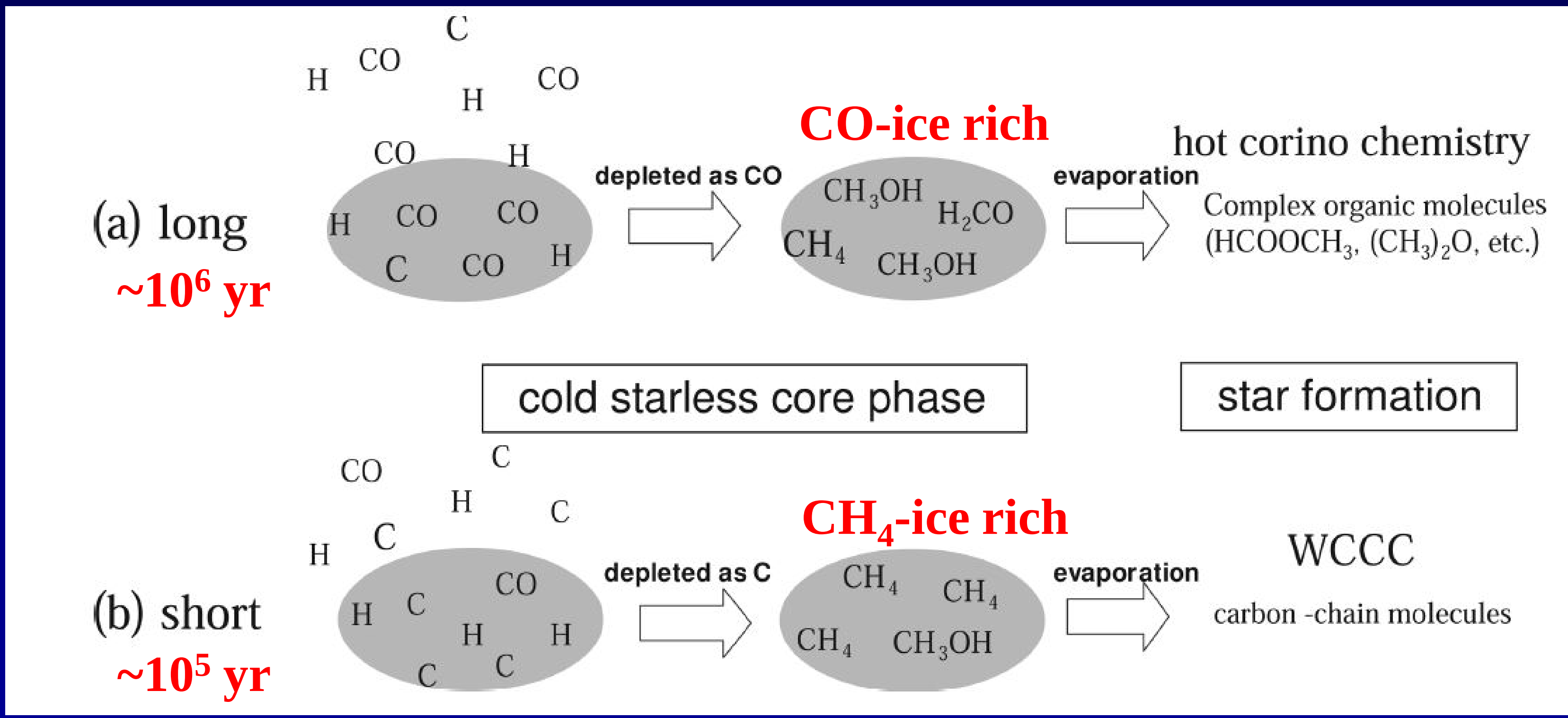
Models: producing complex organics on grains



- **Is warm-up or UV neeeded?**
- **Surface chemistry vs bulk ice**
- **Which species are produced in gas?**
- **Where do warm carbon chains fit in? (Poster Nami Sakai)**

Garrod & Herbst 2006
Garrod et al. 2008
Garrod 2013
Choudhury et al. 2015
+ many others

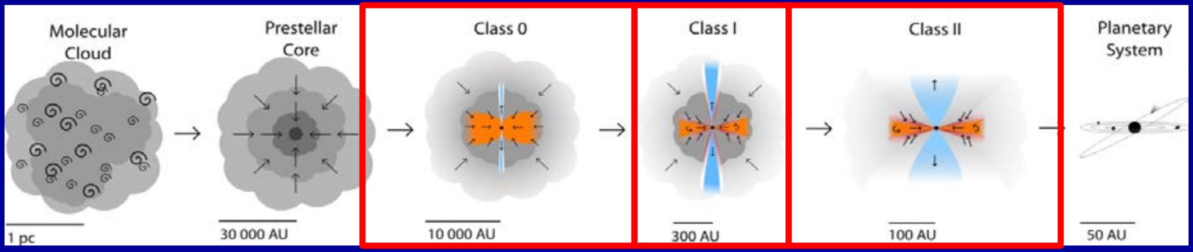
Warm carbon chains vs saturated COMs



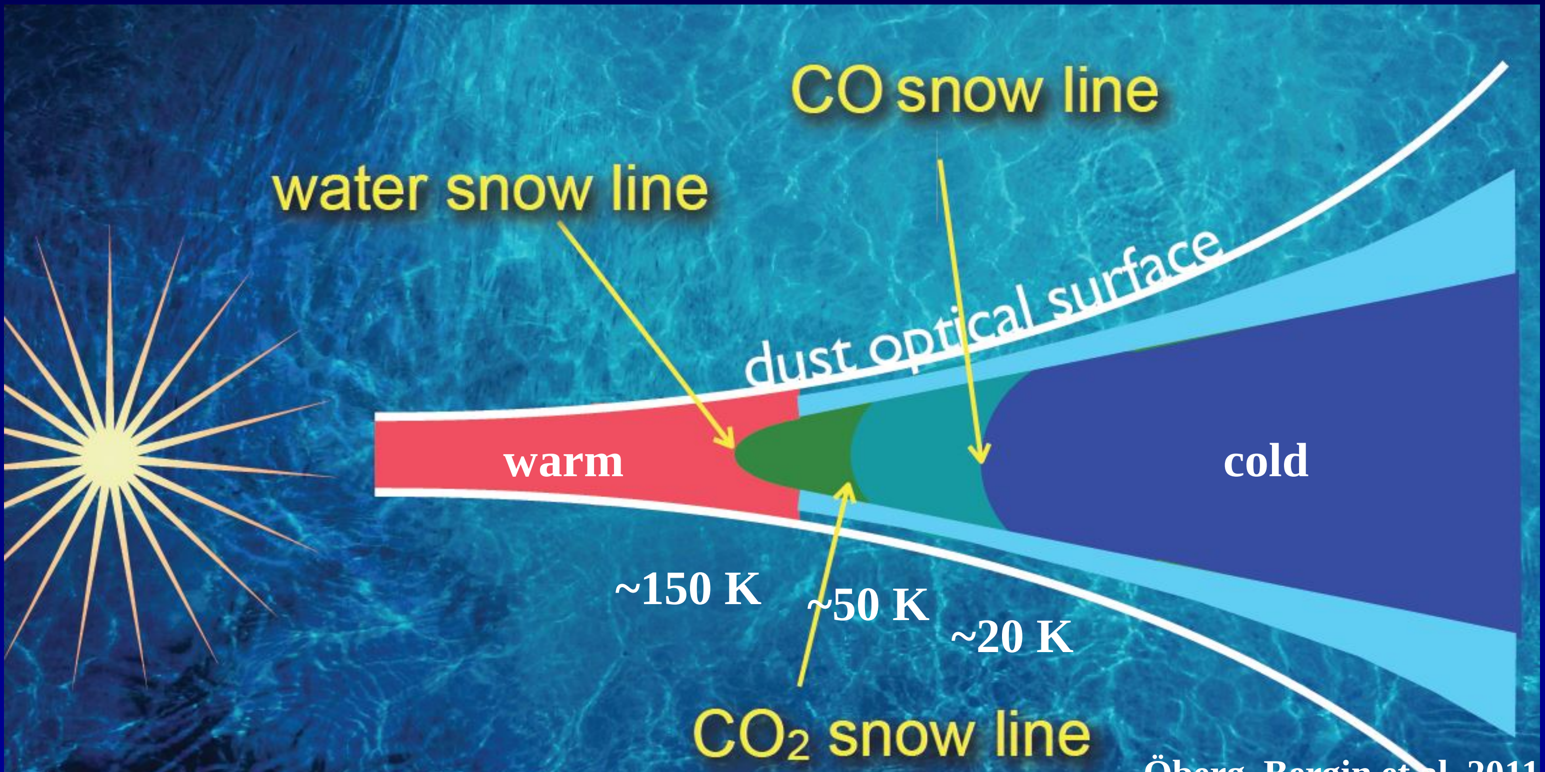
Sakai & Yamamoto 2013
Poster Nami Sakai

- **Most sources are in between extremes IRAS 16293 and L1527**
- **Beam-filling factor may also play a role**

Next 10 years:
Disks, snowlines



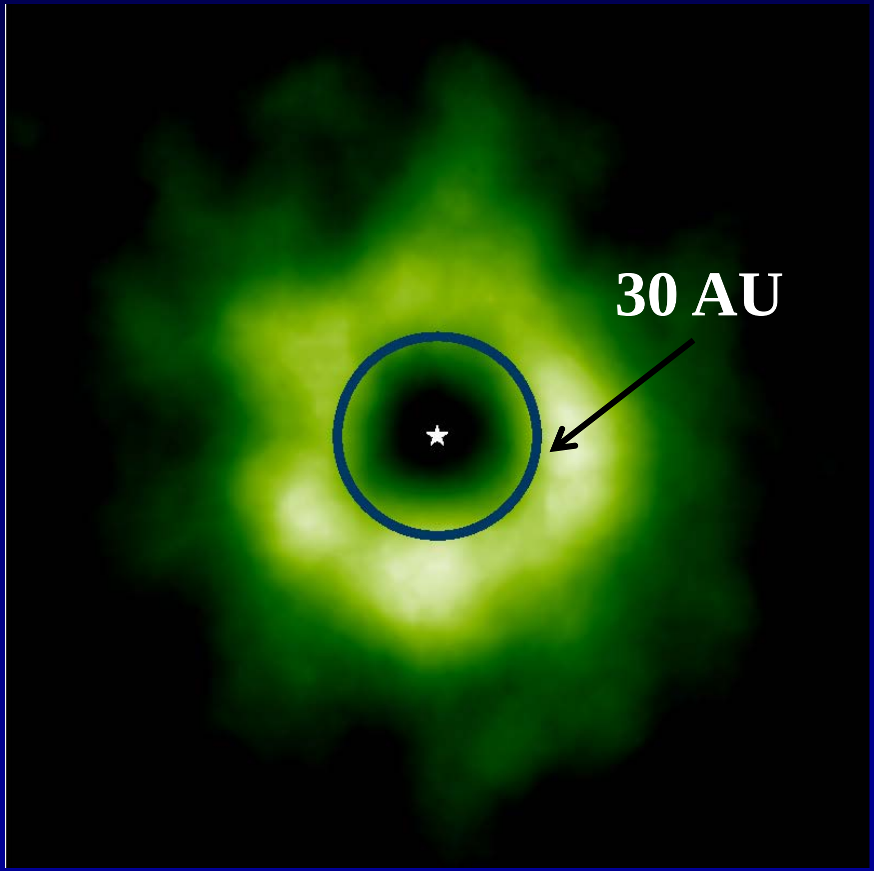
Importance of snowlines in disks



Öberg, Bergin et al. 2011

Snowline enhances mass of solids → planet formation
Differential freeze-out changes C/O ratio

Imaging the CO snowline with ALMA



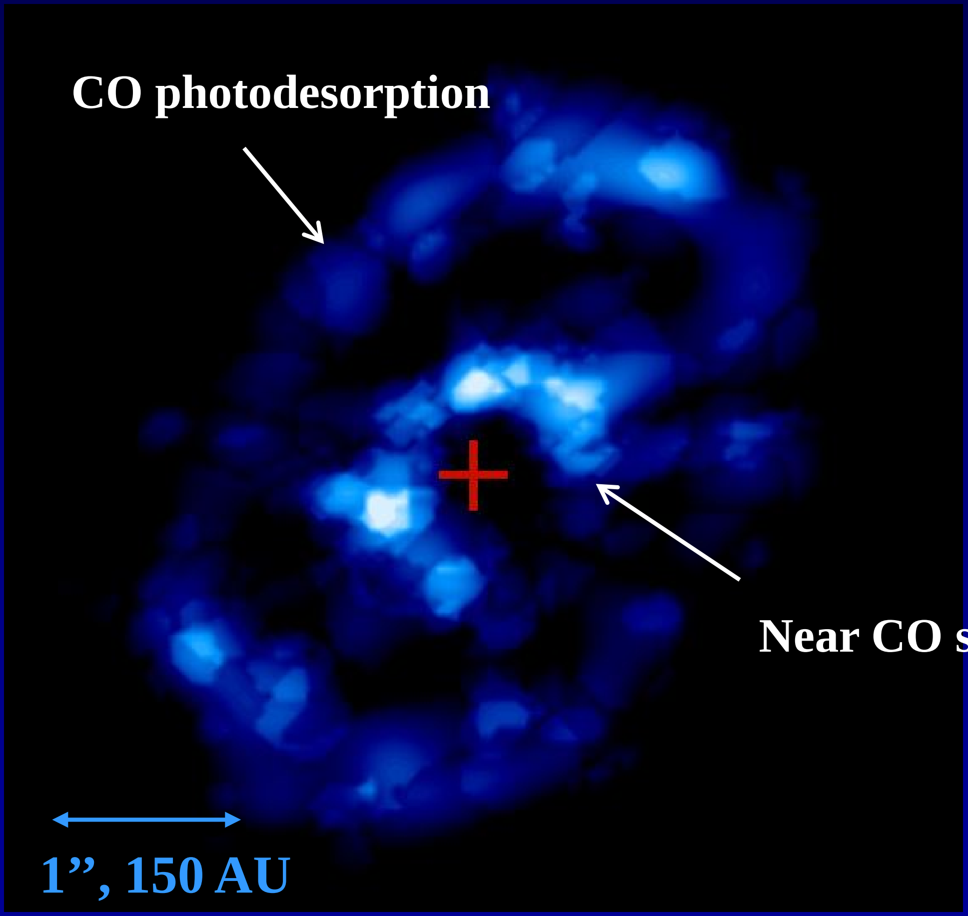
TW Hya
Face-on disk
d=68 pc

N_2H^+ 4-3

Qi, Öberg et al. 2013

N_2H^+ appears when CO freezes out
→ Tracer of snowline

Tracing the CO snowline



IM Lup
ALMA

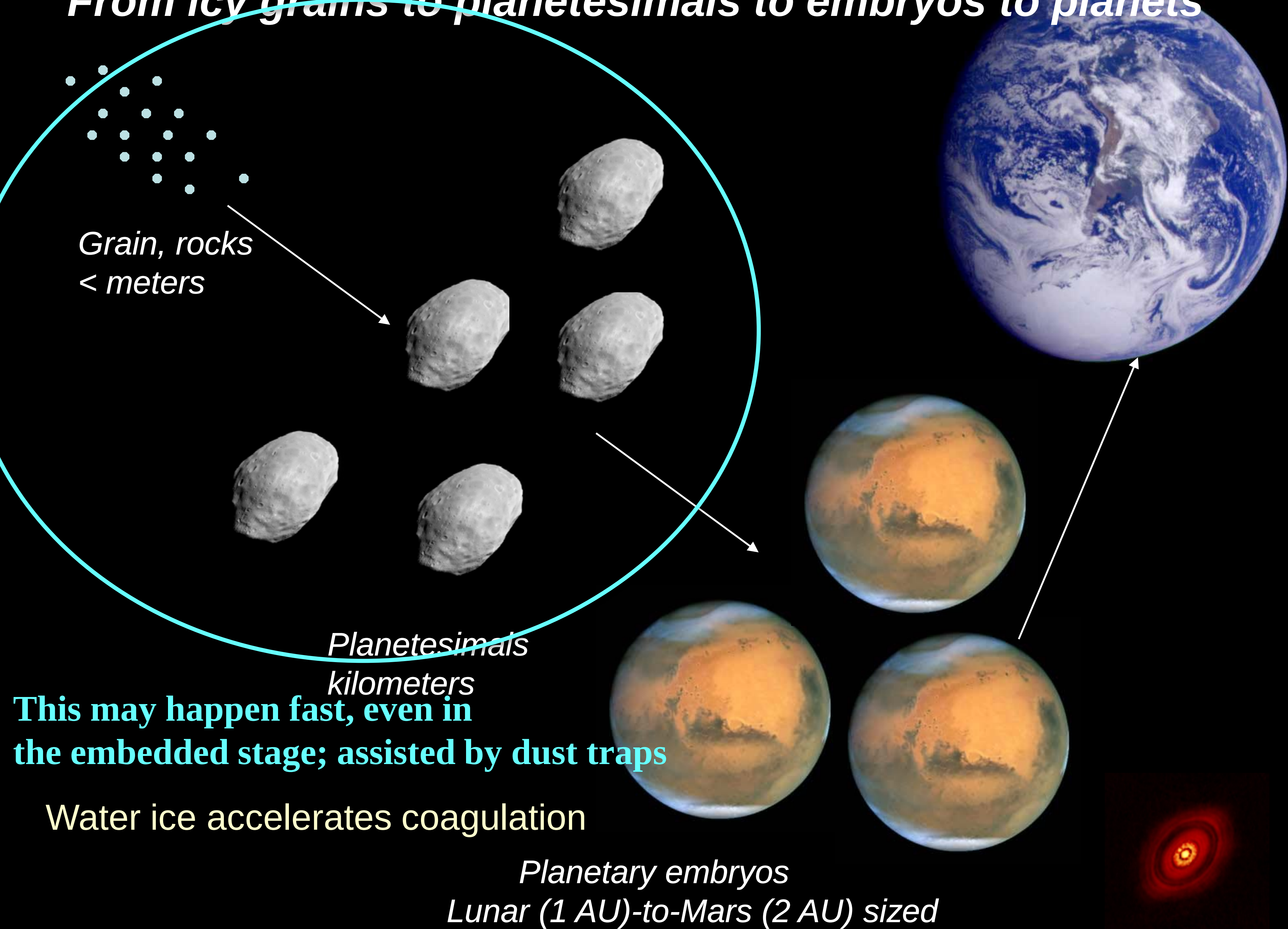
Double rings!

DCO^+ 3-2

Öberg et al. 2015

Can we image snowlines in - embedded disks?
- hot cores? (talks Anderl, Ginsburg)

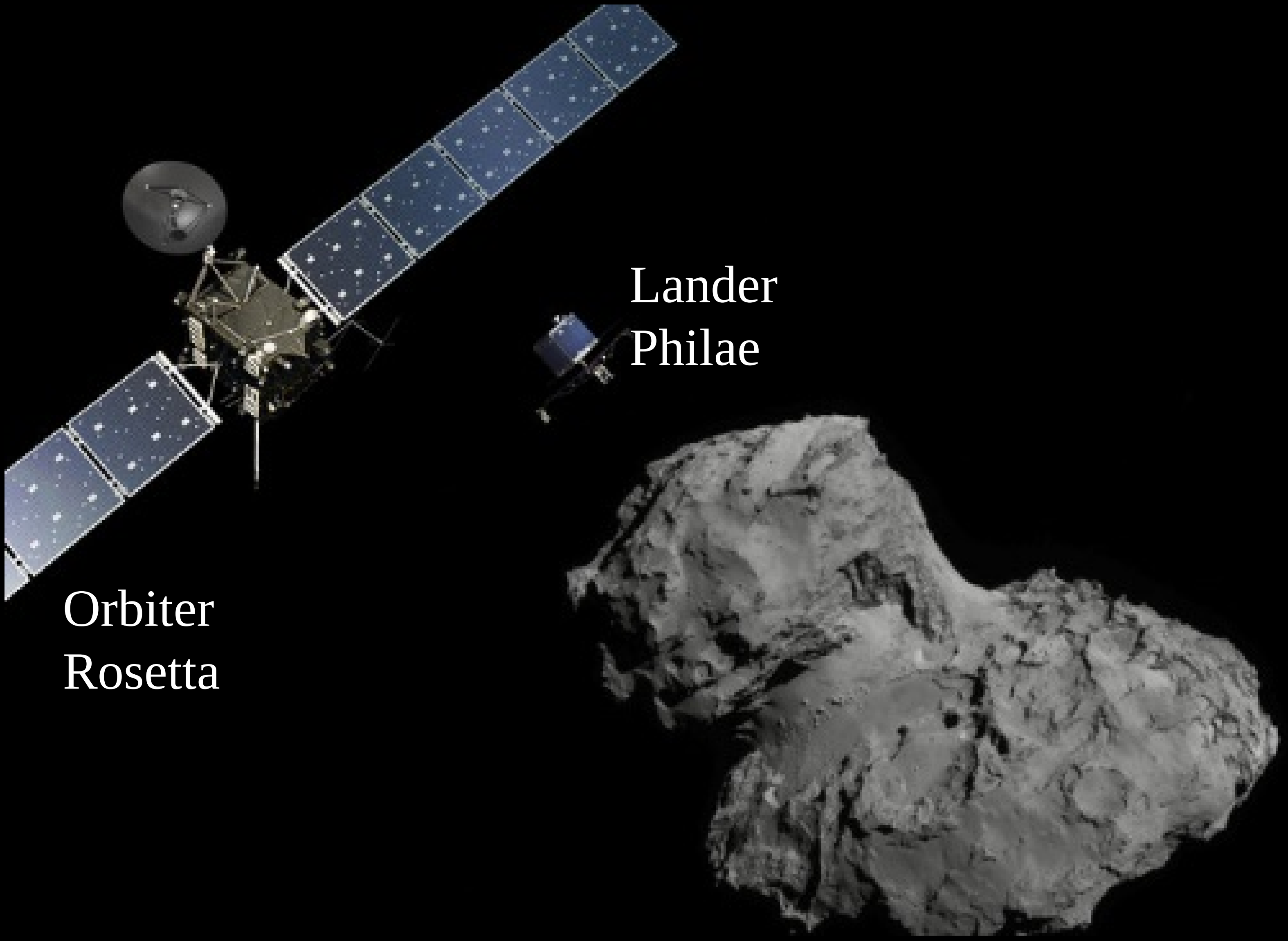
From icy grains to planetesimals to embryos to planets



This may happen fast, even in the embedded stage; assisted by dust traps

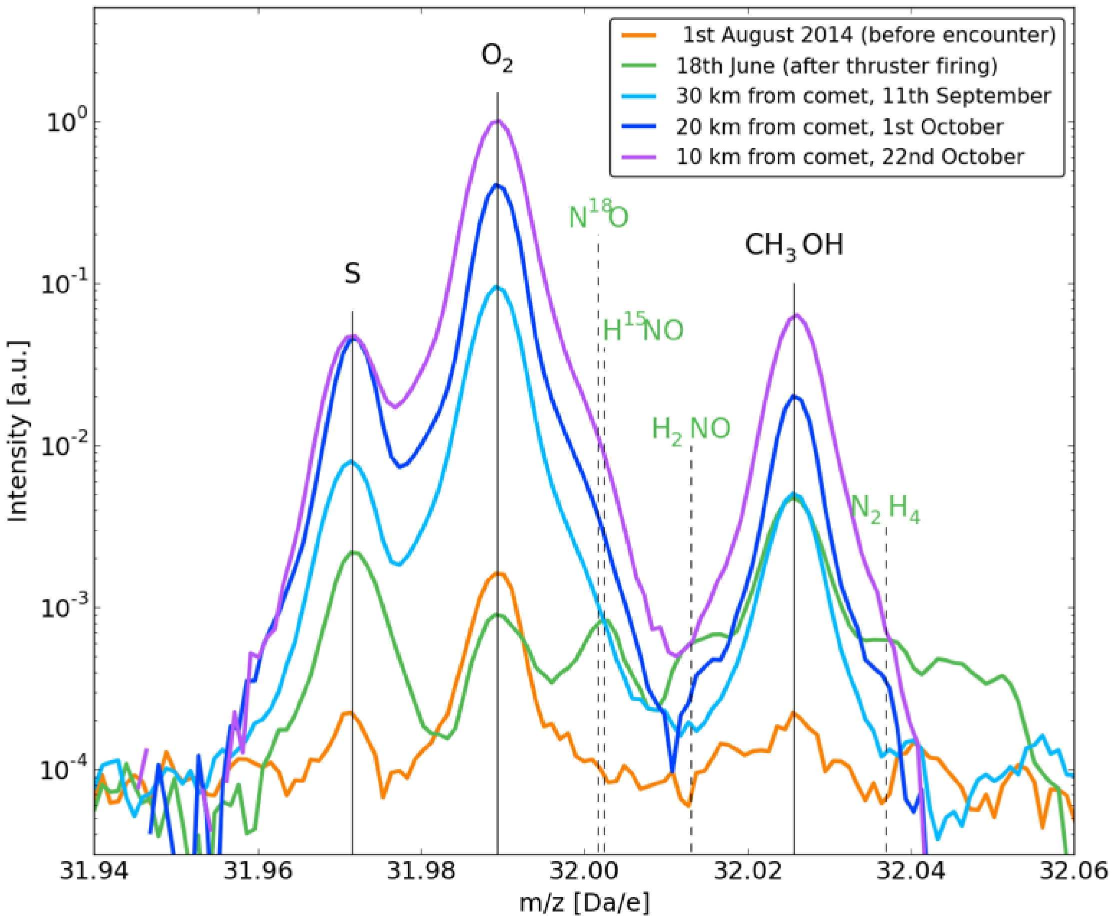
Water ice accelerates coagulation

The O_2 mystery



Abundant O_2

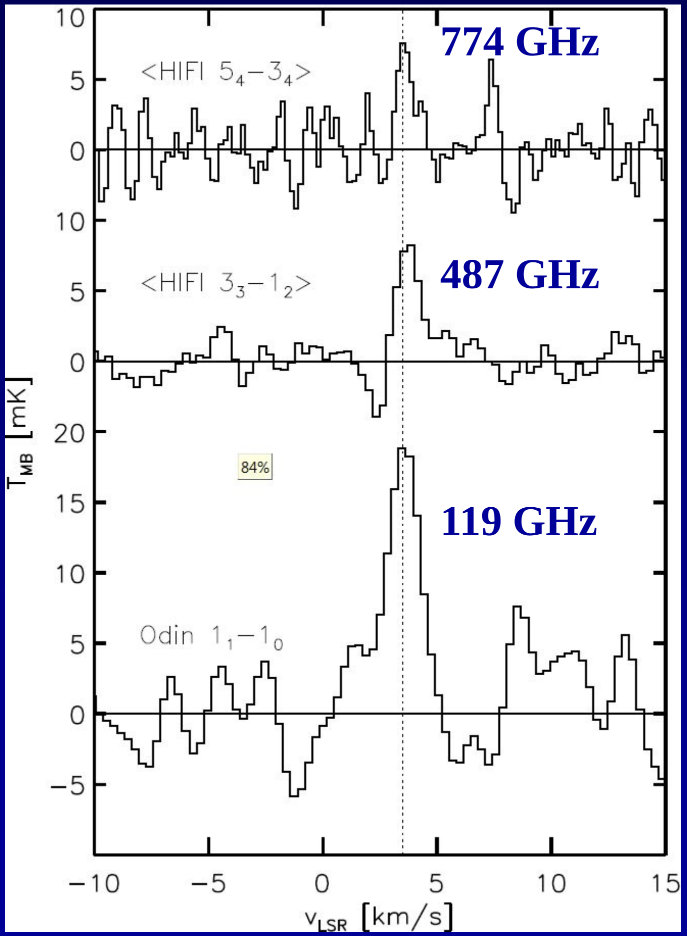
m/Δm>1000



Bieler et al. 2015

O_2/H_2O=3.7±1.5%

Interstellar O_2 is absent

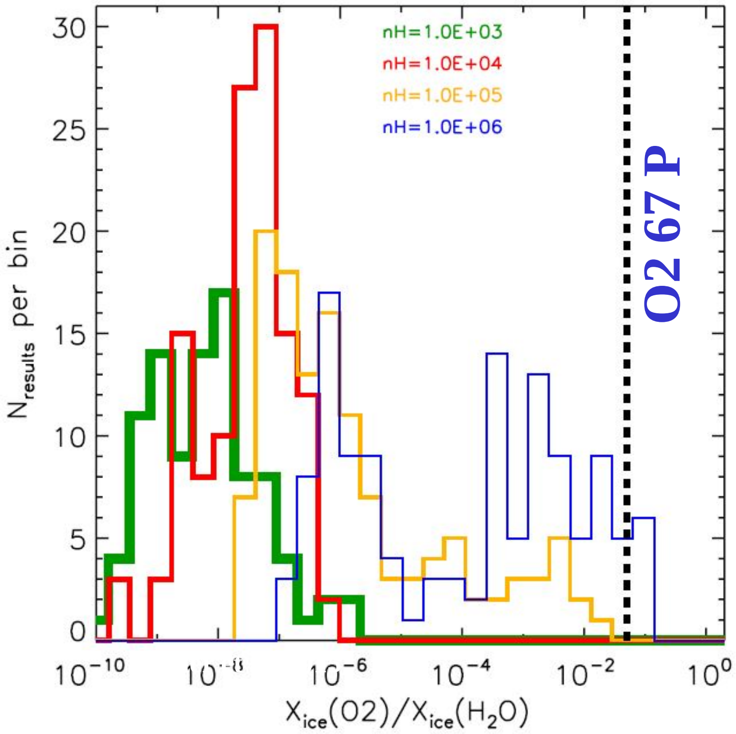


$O_2/H_2 = 5x10^{-8}$

- Deep searches O_2: only Orion, Oph A
- Most O and O_2 converted to H_2O
- O_2 only detected when grains warm enough to prevent O freeze-out

Liseau et al. 2012 Oph; Larsson et al. 2007
Goldsmith et al. 2011 Orion
Yildiz et al. 2013 NGC 1333 I4A

Abundant O_2 mystery



Parameter study

Taquet et al. 2016
Walsh et al. 2015

- Problem: O_2 readily transformed to H_2O in ice (as shown in lab exp)

- Only models with low H/O ratio (high density) and relatively warm conditions (*T*~20-30 K) can reproduce high observed O_2/H_2O ice ratio

Summary

- New insight into H/H_2 transition from hydrides
- Water chemistry: 3 routes
  - Importance of UV irradiated shocks and cavities
- Complex organic molecules formed at all stages
  - Importance of ice chemistry
    - No need for heat or UV to make them

Future: the ALMA (r)evolution

- New molecules
  - More complex (prebiotic) species
  - Follow trail to comets
- Spatial distribution
  - Resolve relevant physical-chemical scales
- New processes and excitation
  - Probe hotter gas
- Extragalactic chemistry
  - High-z galaxies like Orion 30yr ago

Let ALMA data speak for themselves!

Herbst 2008