The Chemistry and Physics of the Interstellar Medium

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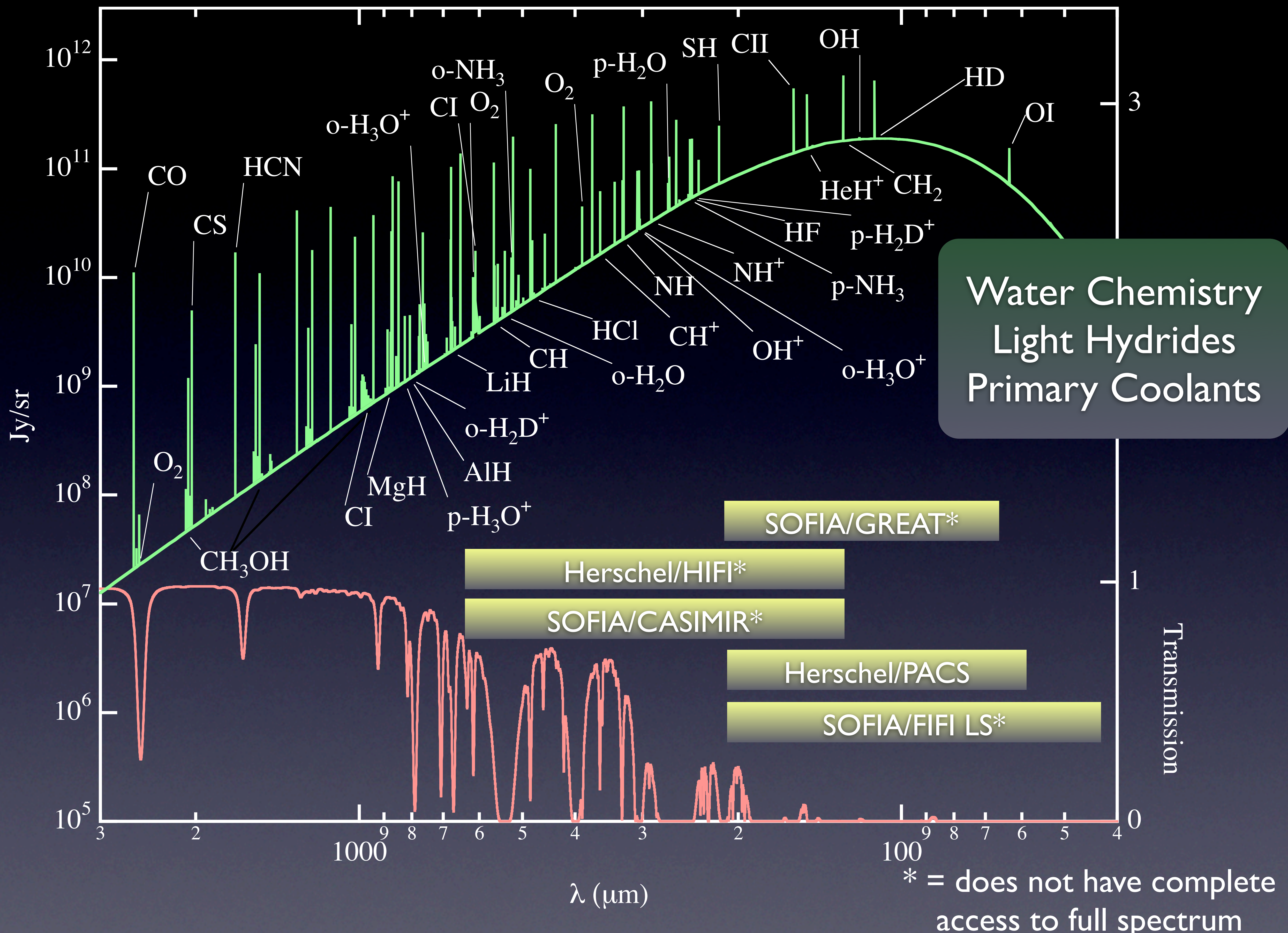
Big Picture

- Spectrum of Far-IR emission - we don't know what it looks like at high spectral resolution (an enabling goal)
- How do molecular clouds and stars form?
  - ➡ evolution of the cold neutral medium
- How do planets get water? - track water throughout each phase
- What is the full extent of interstellar chemistry?
- Deuterium in the Galaxy (Universe)

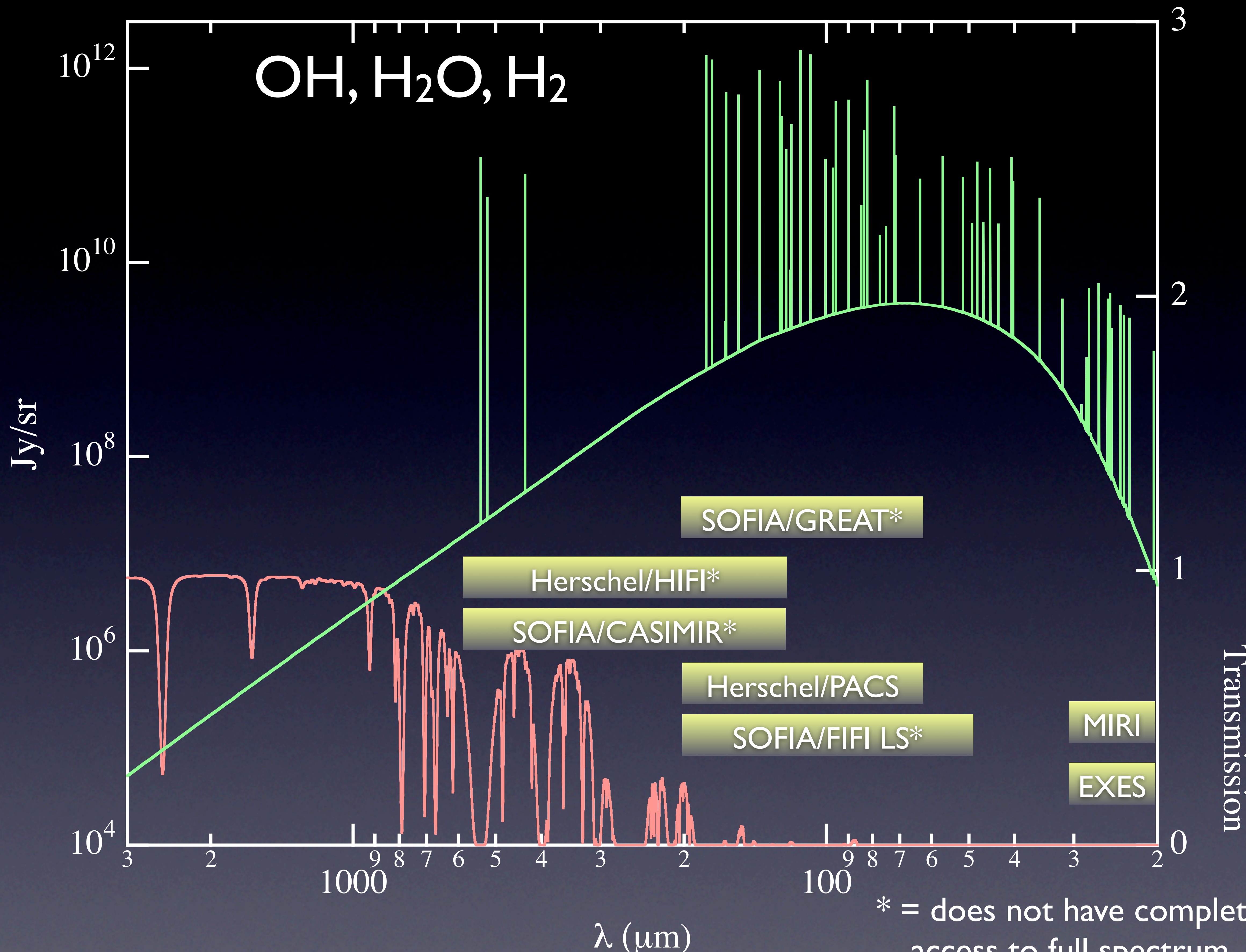
★ Herschel and SOFIA are happening (pathfinders)

★ Need to pay attention to ALMA's capabilities

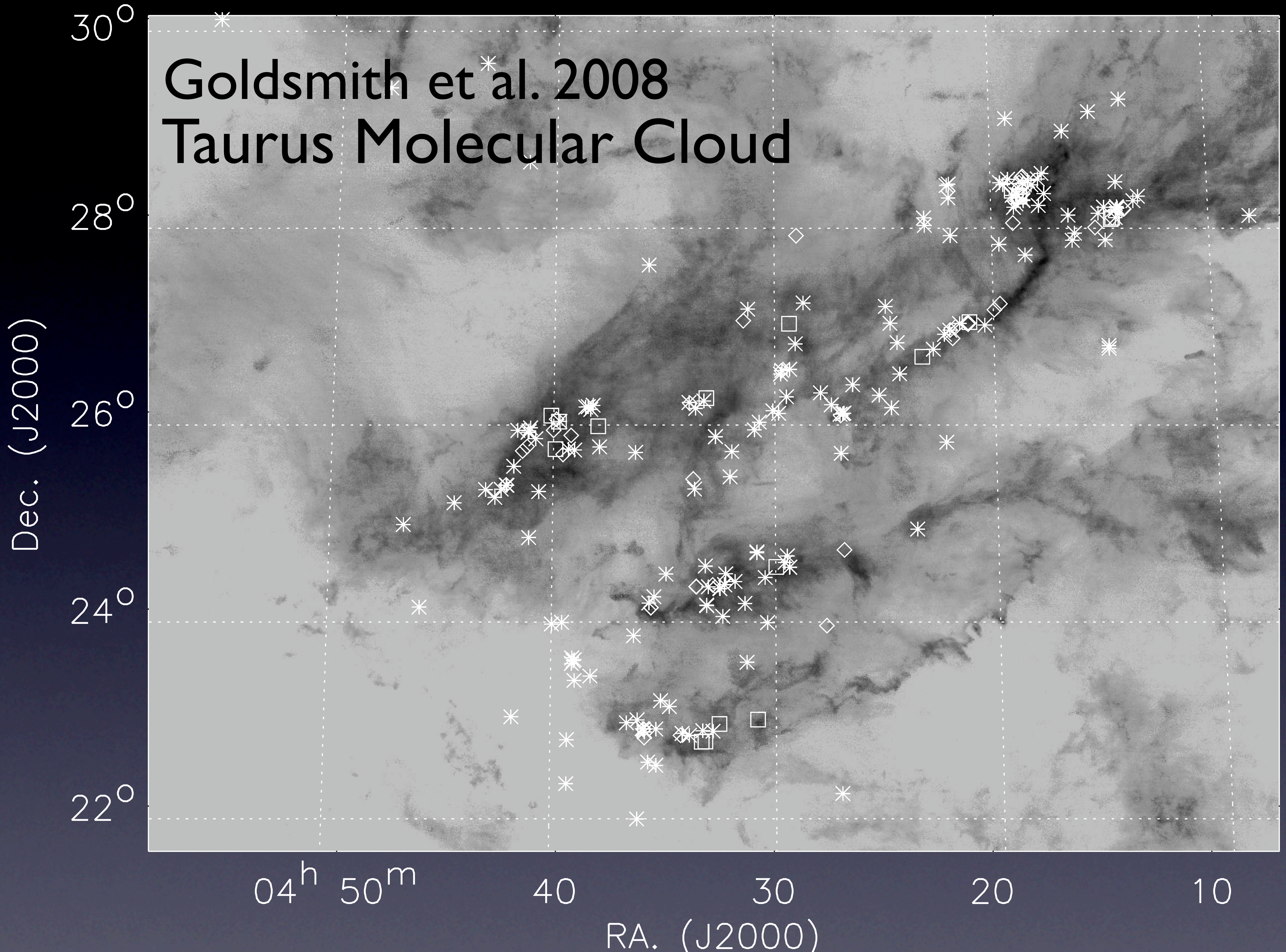


Finder Chart for the Future....

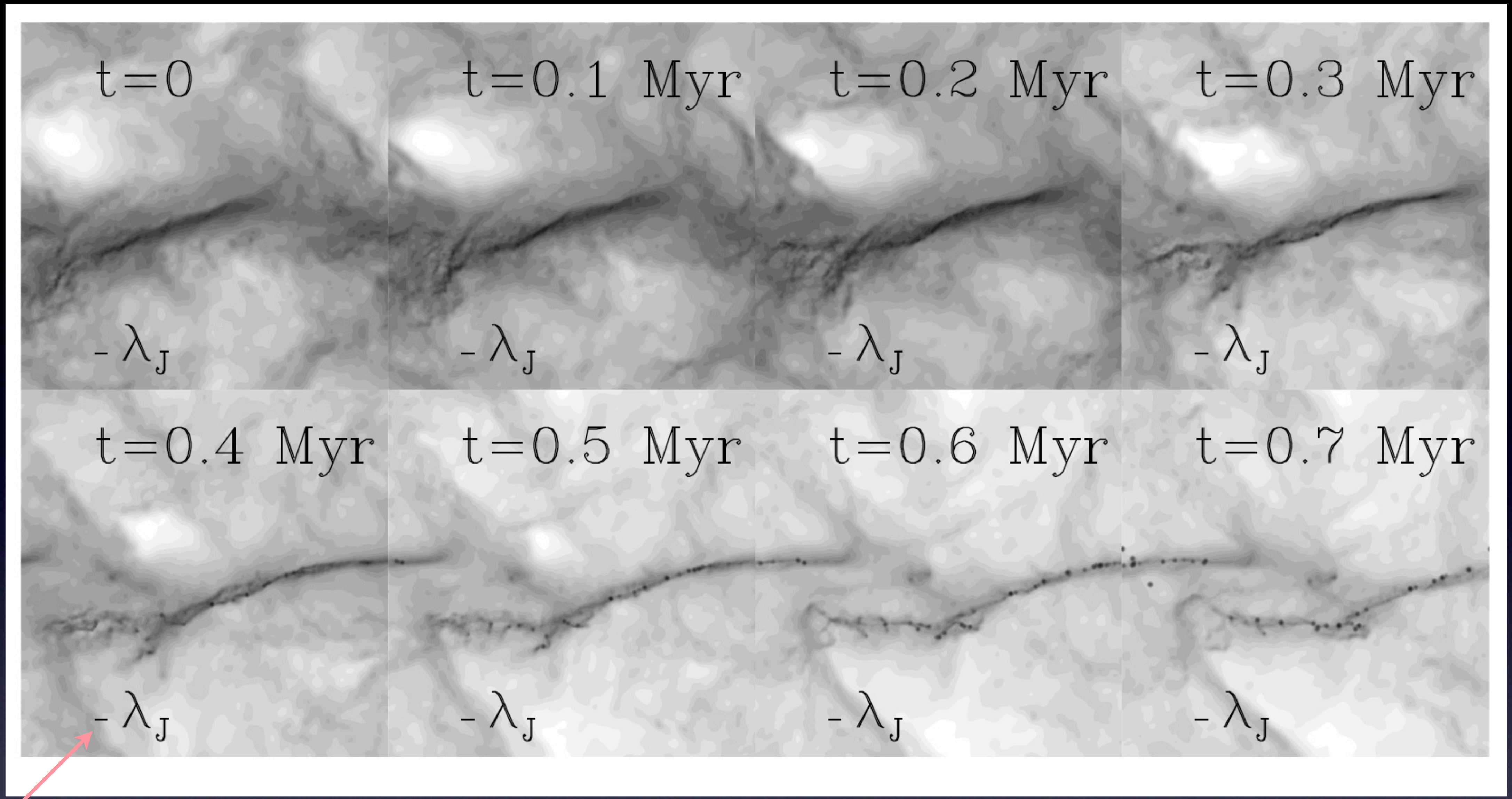
Shock Emission



* = does not have complete access to full spectrum



Stars are born in molecular clouds and follow distribution of molecular gas

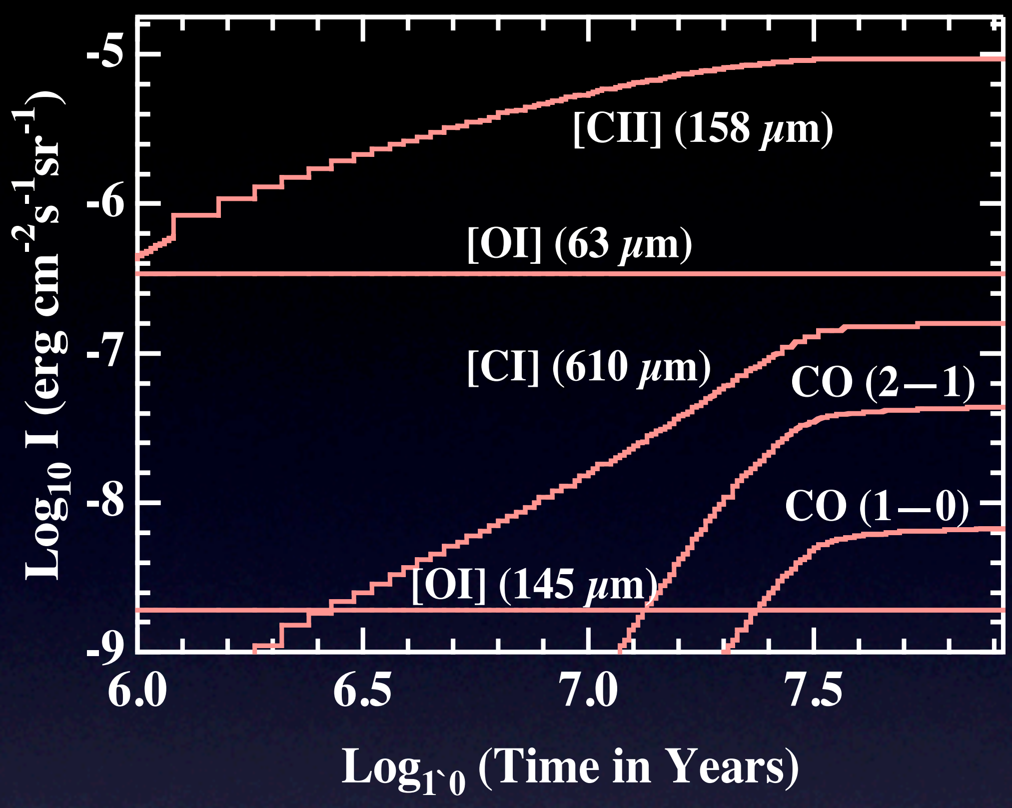


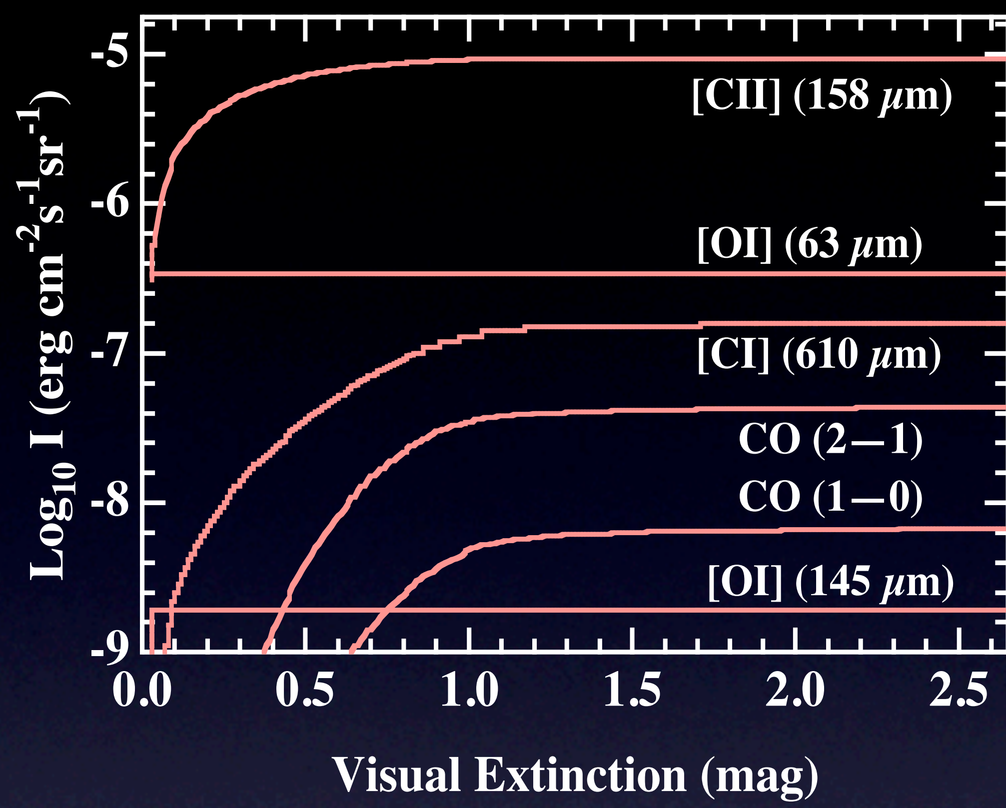
Klessen et al. 2004

1 Jeans length

Where did the cloud come from?

The Birth of Molecular Clouds





Bergin et al. 2003

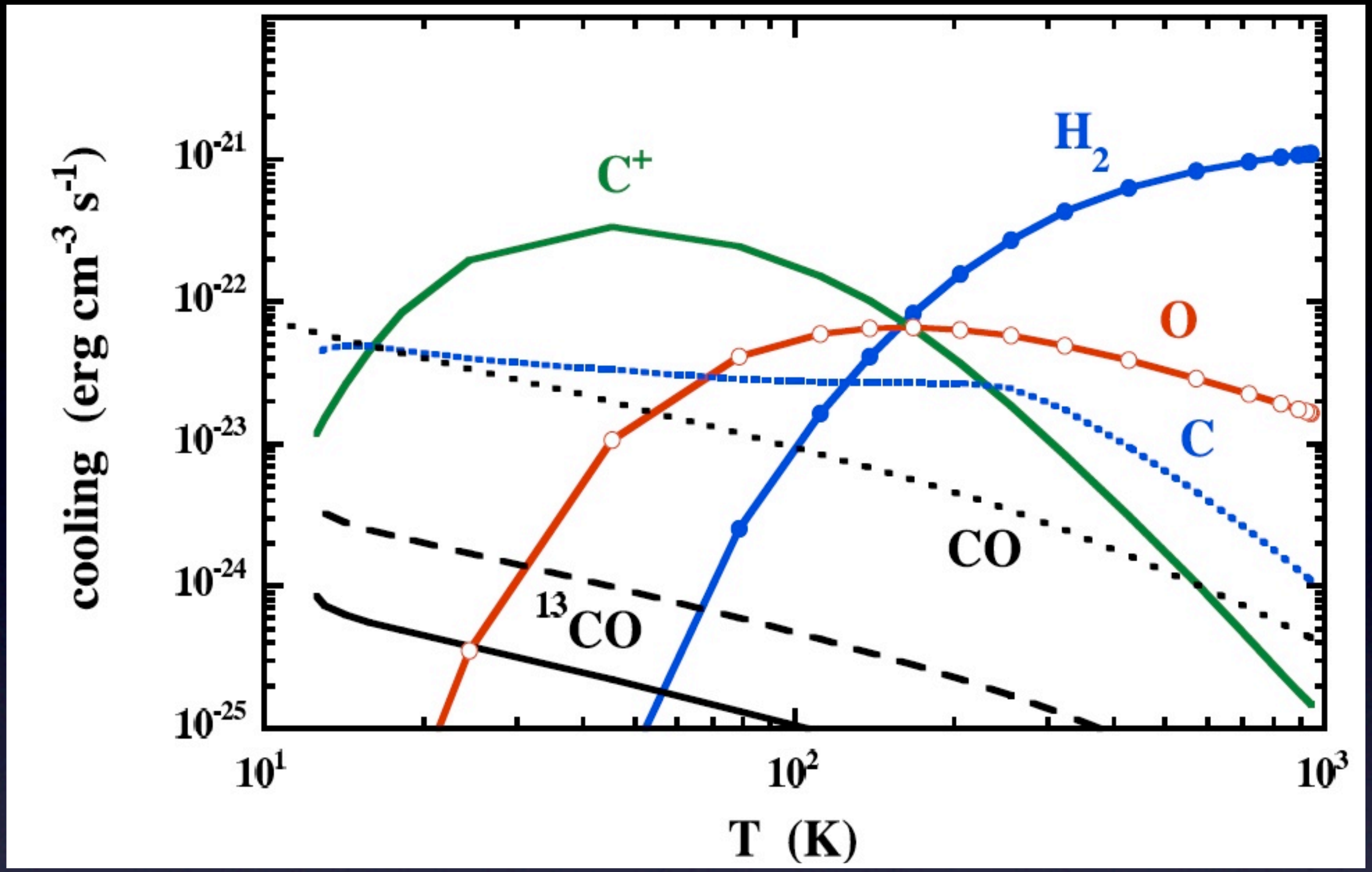
- Molecular clouds are formed from the atomic medium
- [C II] 158 μm is dominant coolant of CNM
- Primary coolants of cloud formation are found in the Far-IR
- Spectrally resolved observations can study the gas kinematics (Herschel/SOFIA)

Future

- Detect emission from H_2 formation? I(28 μm) ~ 10^{-8} ergs/s/cm^2/sr (Takahashi et al. 2001)
- Far-IR peak of dust spectral energy distribution - can study polarization
  - ➡ explore changes in magnetic field from the cloud to the filaments to inside cores
  - ➡ resolve the B-field in disks -- get at the mechanism of angular momentum transport

Turbulence

- Consensus emerging that turbulence and its decay are key to the formation of molecular clouds (McKee & Ostriker 2007; MacLow & Klessan 2004)

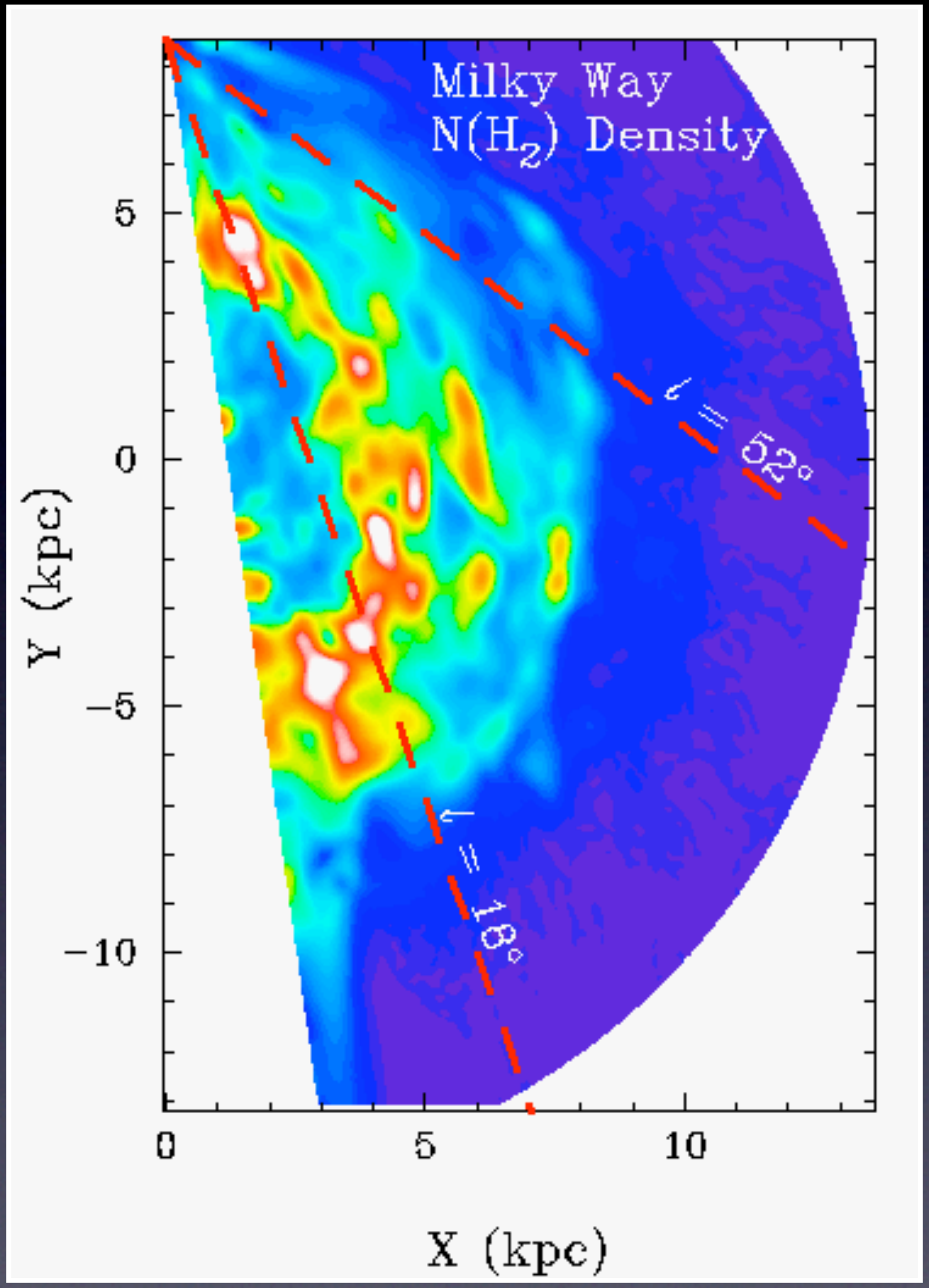


Falgarone

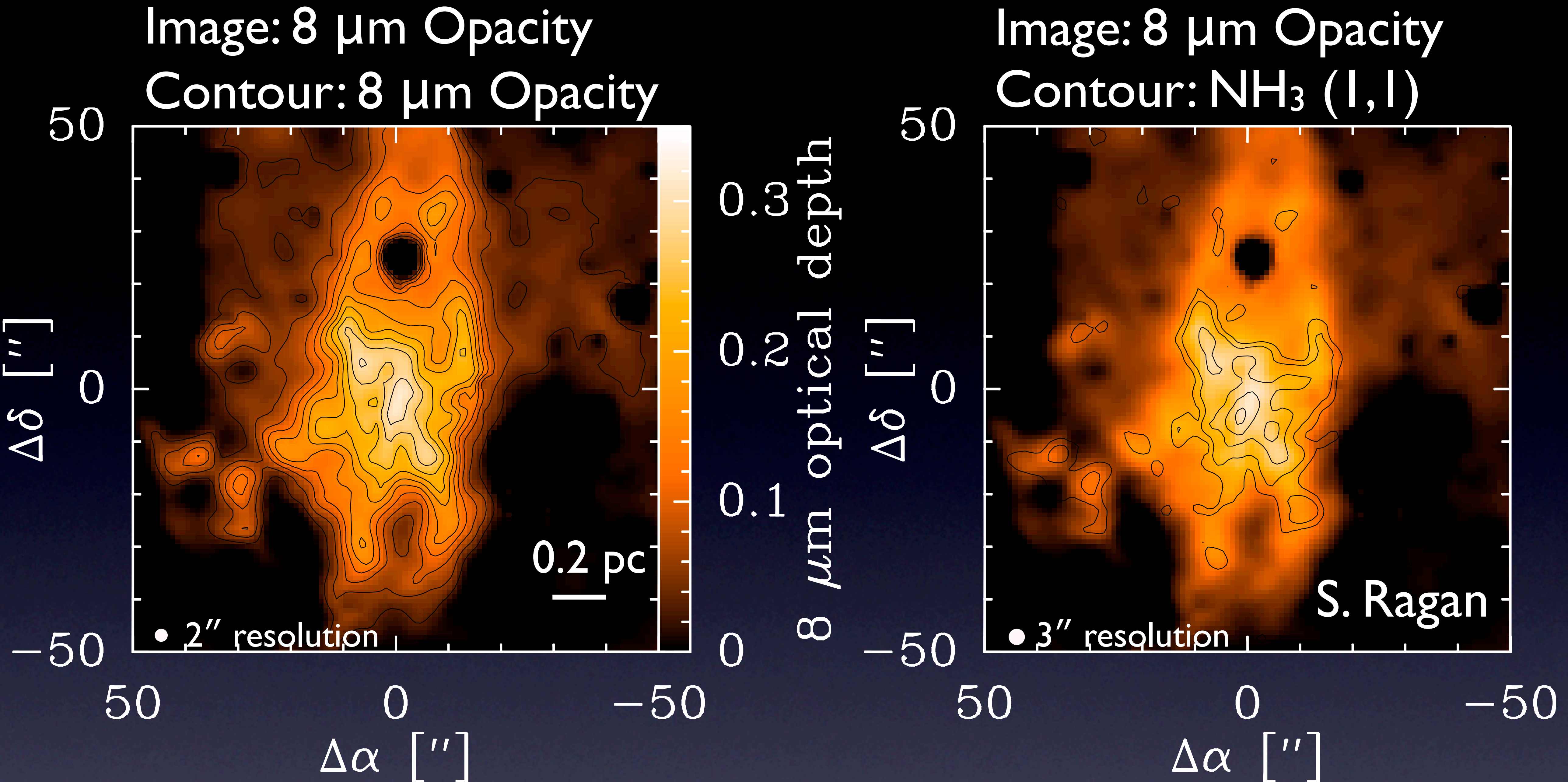
- Where does this energy go? Can we detect it?
  - ➡ [C II] comparison of line profile between core and envelope (Hershel/SOFIA)
  - ➡ Non-equilibrium chemistry (CH^{+} is one potential example)
  - ➡ Can we resolve close to dissipation scale??? (will likely need FIR tracers, greater angular resolution, and high spectral resolution)

The ISM and Massive Star Formation

- Where is star formation in the Milky Way?
- Distribution of molecular gas in the Milky Way peaks at 5 kpc from G.C.
- Contains ~ 2 x 10^9 $M_\odot$
- Is the heart of star formation in the Galaxy
- also the location of infrared dark clouds (Simon et al. 2006).
- identified as the birth sites of stellar clusters (Rathborne, Pillai, Ragan)



Galactic Ring Survey: Jackson et al. 2006

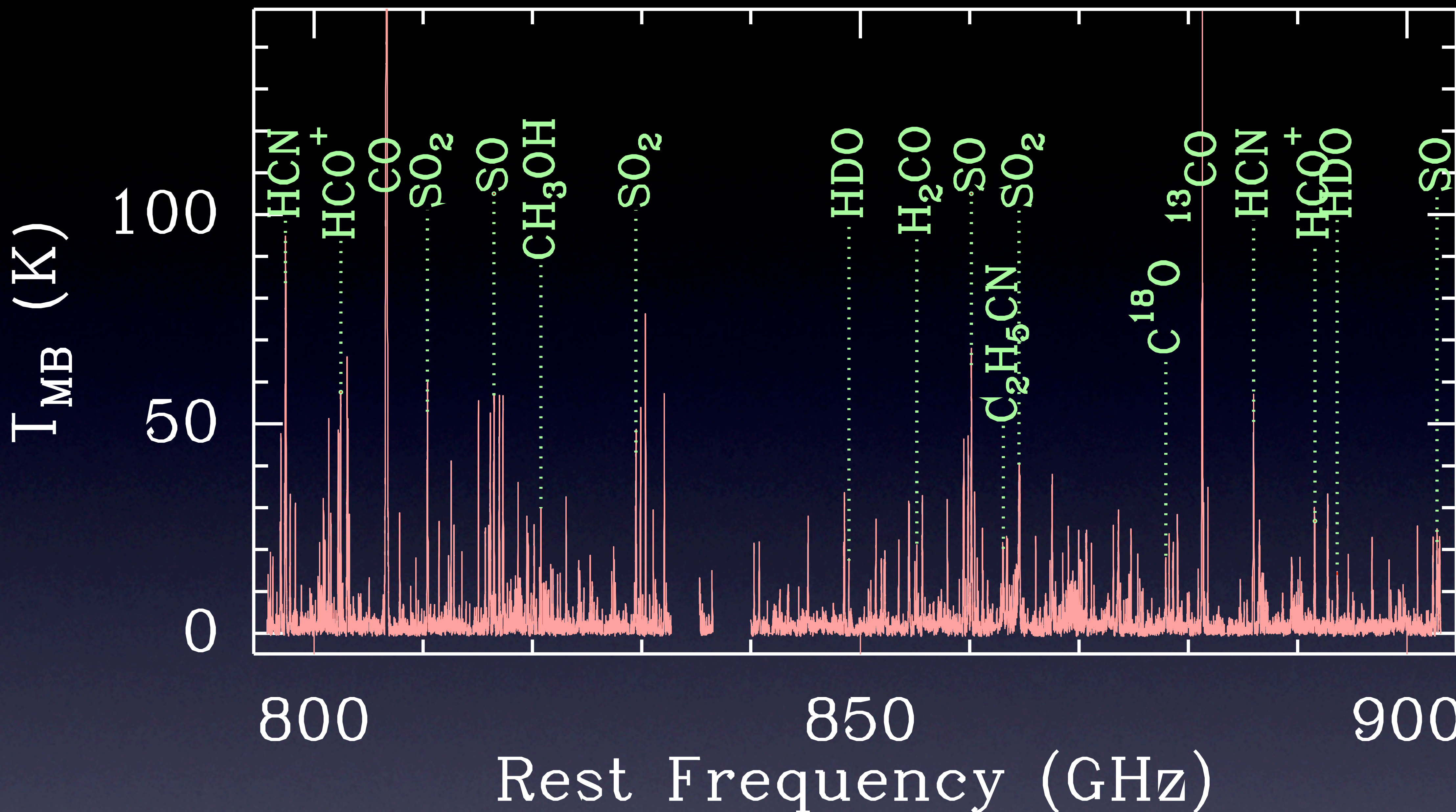


- ALMA -- resolution comparable to current for local clouds
- JWST can study absorption at higher resolution
- BUT will not get all primary gas coolants (beyond CO)
  - ➡ Hershel and SOFIA can characterize these areas but not at the scale of clumping (below 3″)
  - ➡ Fertile ground for future observatories (SAFIR/SPIRIT)

Massive Stars and the ISM

- Massive stars have a profound effect on the the surrounding gas.
  - ➡ Power photo-dissociation region -- main lines emit in far-IR (C II, O I, C I, high-J CO) - domain of Herschel/SOFIA/ SPICA
  - ➡ *PDR's are THE testbeds of the chemistry that ALMA will observe in protoplanetary disks -- what are basic rates of heating? cooling? freeze-out? need to test in ISM and extend to disks - we need Far-IR observatories to understand the birth of planets!*

Comito et al. 2005: Orion Hot Core



Massive Stars: Hot Cores

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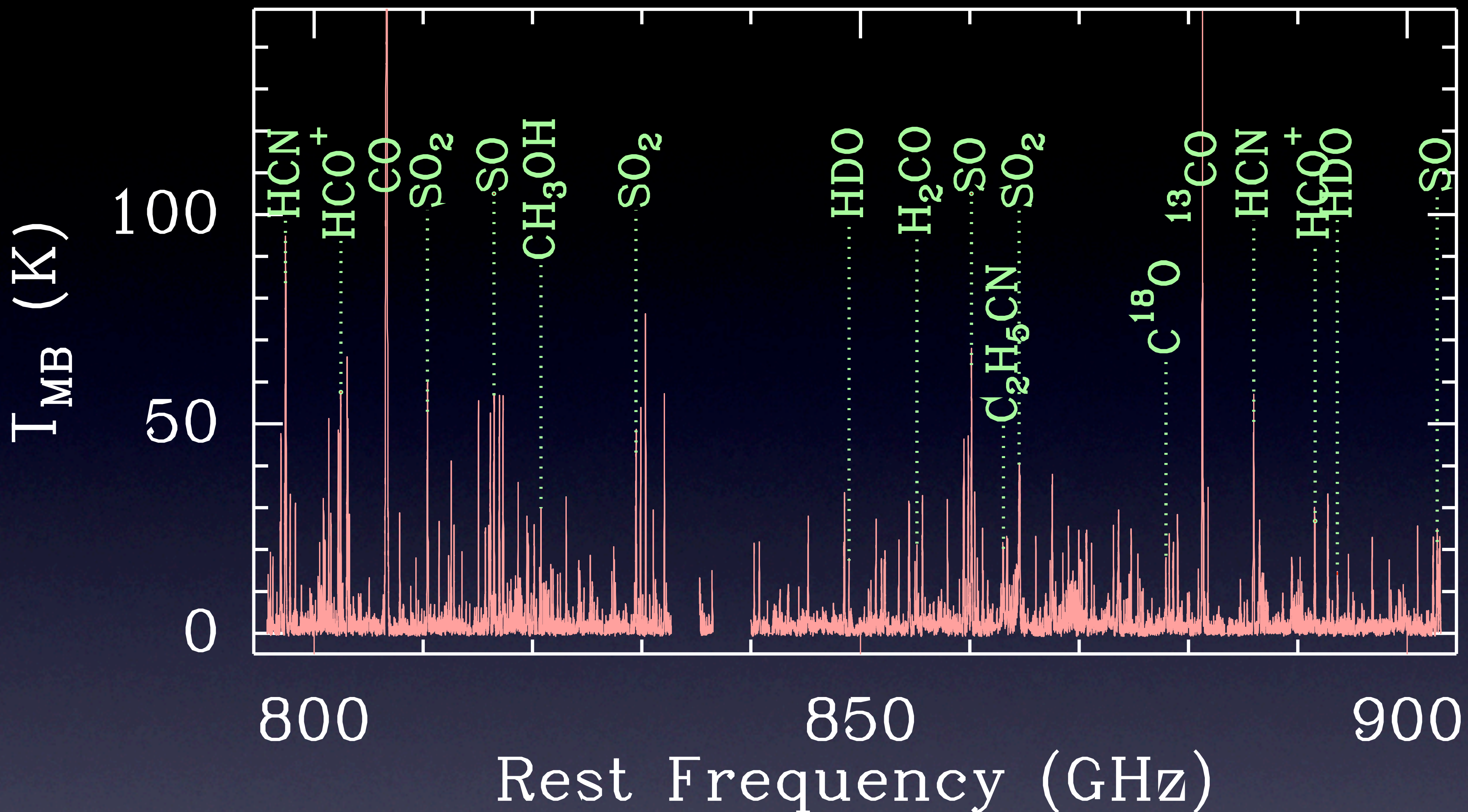
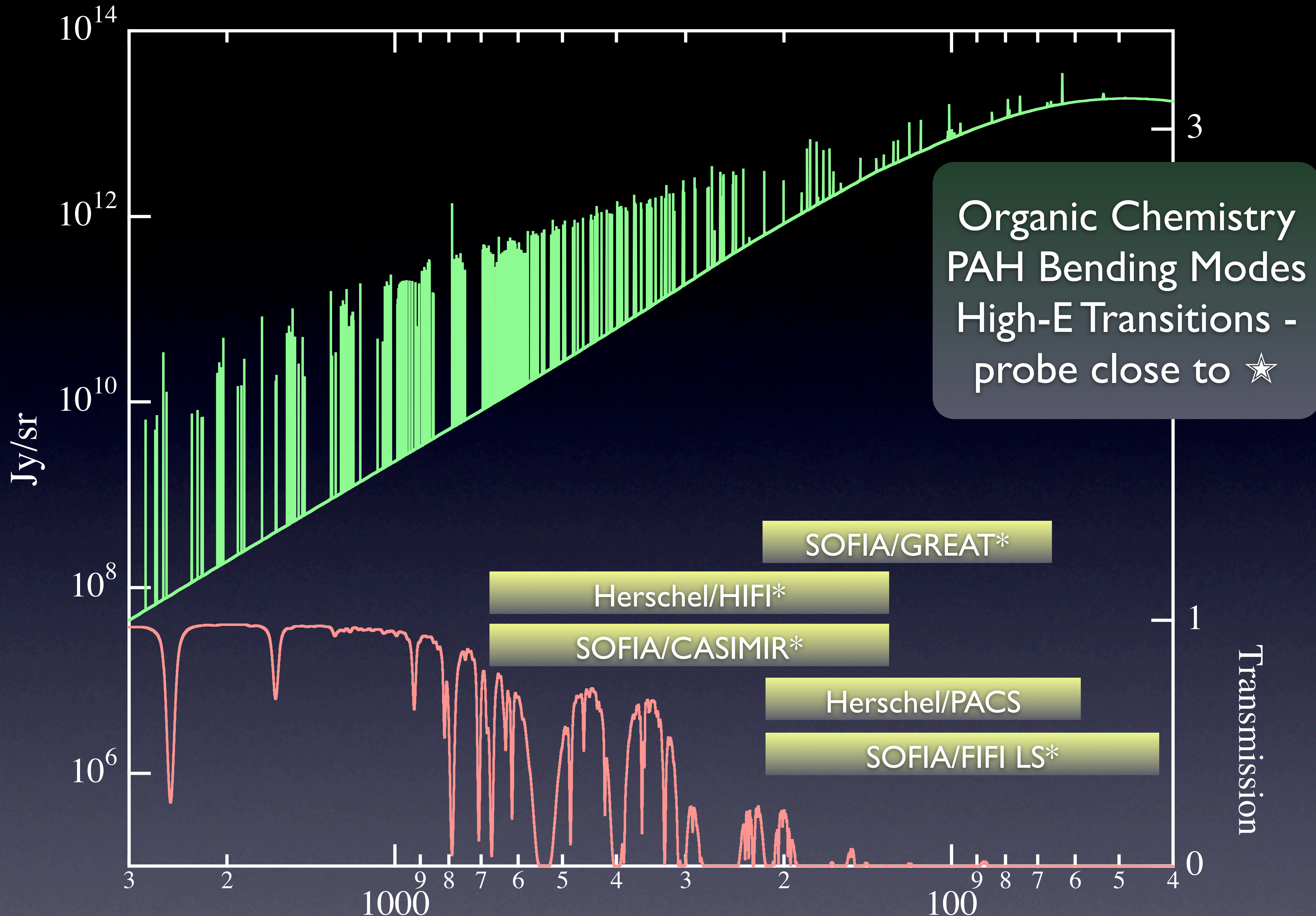


Herschel/SOFIA will provide complete chemical assays and constrain gas cooling in quiescent gas, shocks, pdrs....

Massive Stars: Hot Cores



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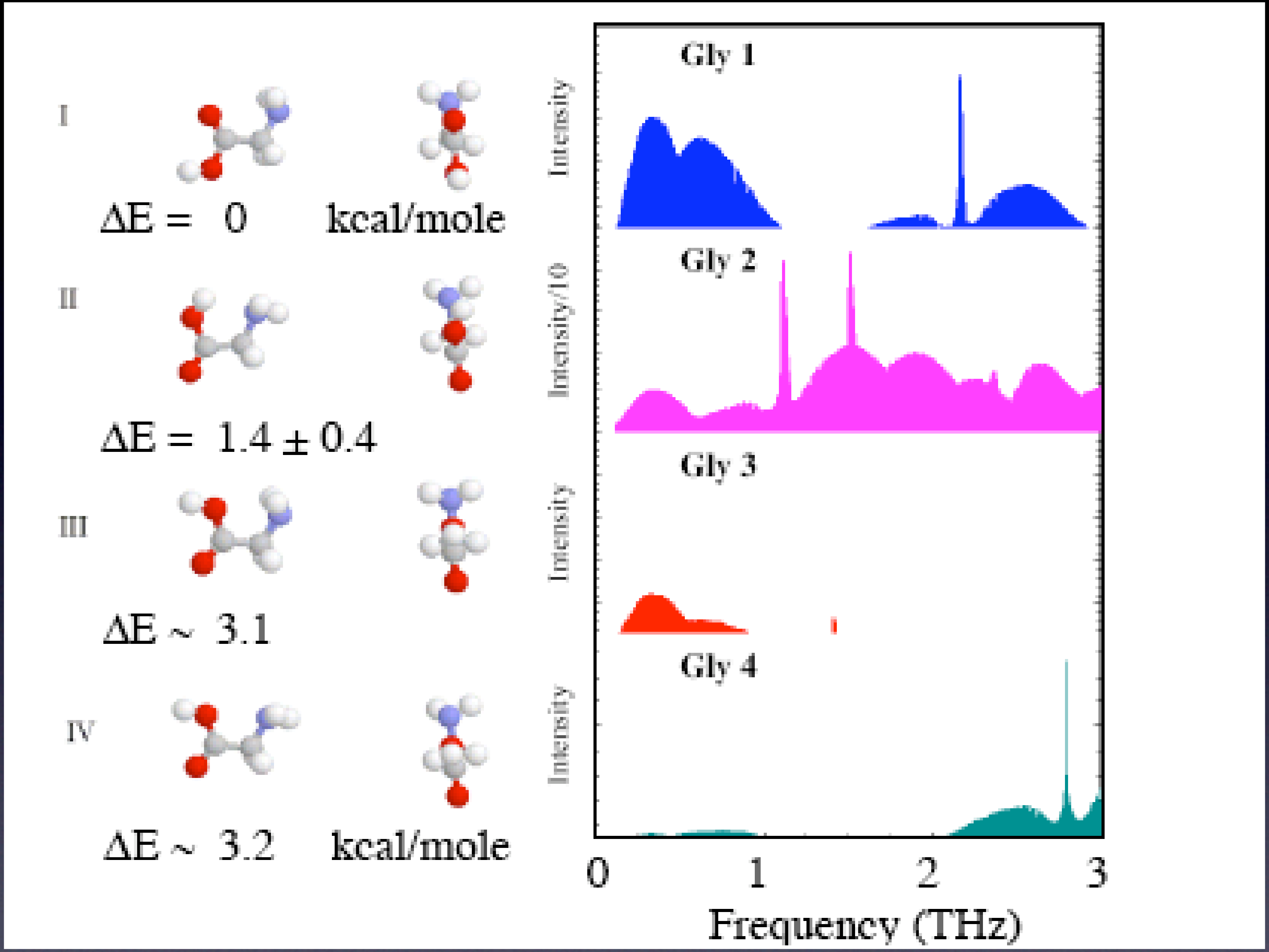
FIR Spectrum of Hot Core

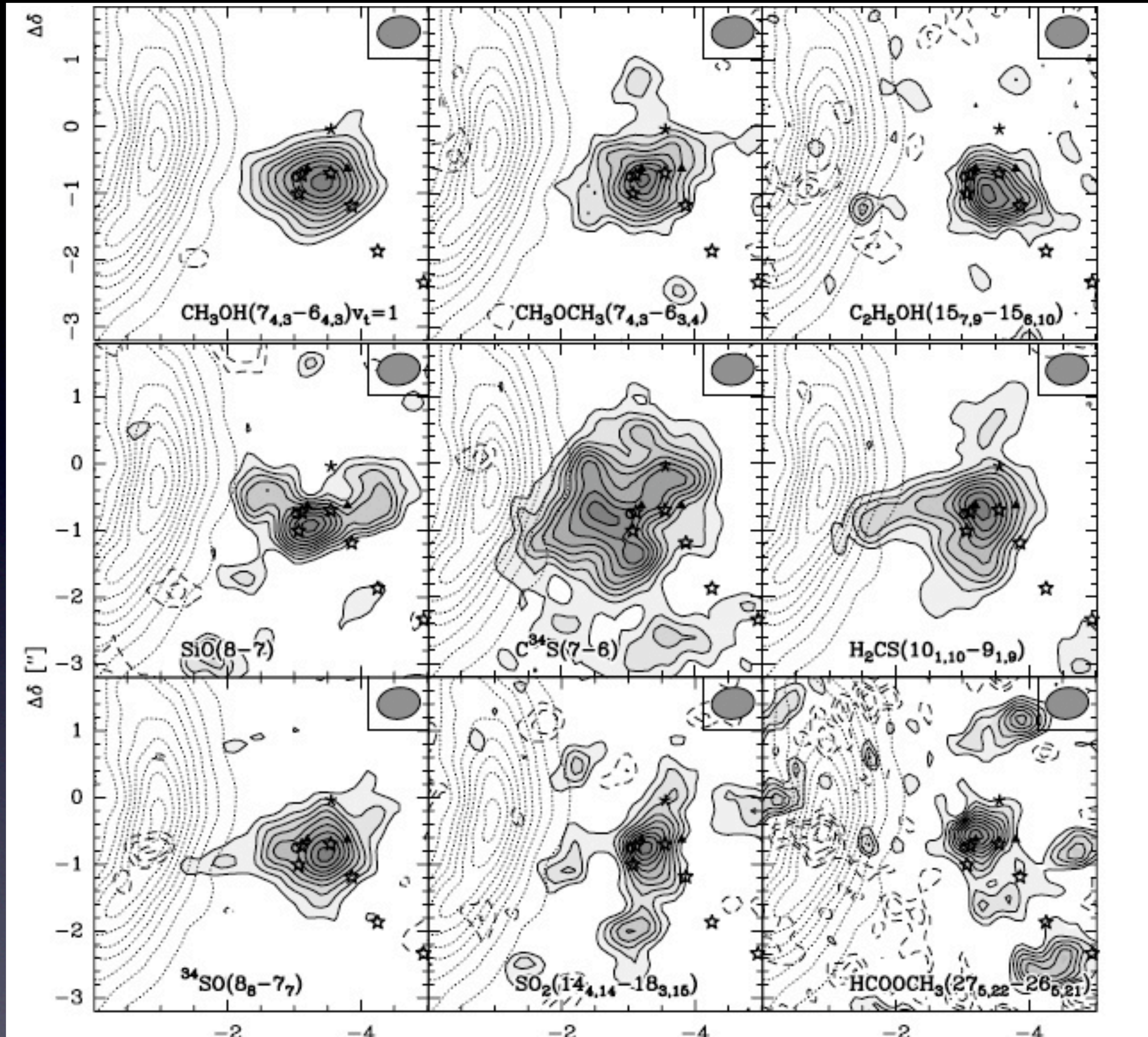
Glycine

Widicus-Weaver, Blake



Pre-biotic Organics

Beuther et al. 2007



High Spatial Resolution is the Future - but ALMA

The Water Cycle

- the water cycle:
  - ➡ O I in the cold neutral medium
  - ➡ makes water on grains during cloud/core formation -- at T ~ 10 - 20 K
  - ➡ provide to disk as ice during collapse
  - ➡ water ice incorporated into planetesimals
  - ➡ some returned to space eventually as O

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phase, o/p and D/H ratio

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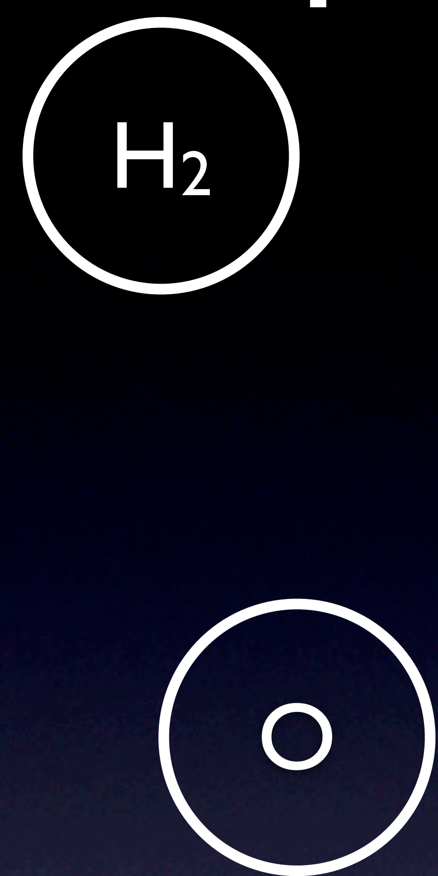
phase, o/p and D/H ratio

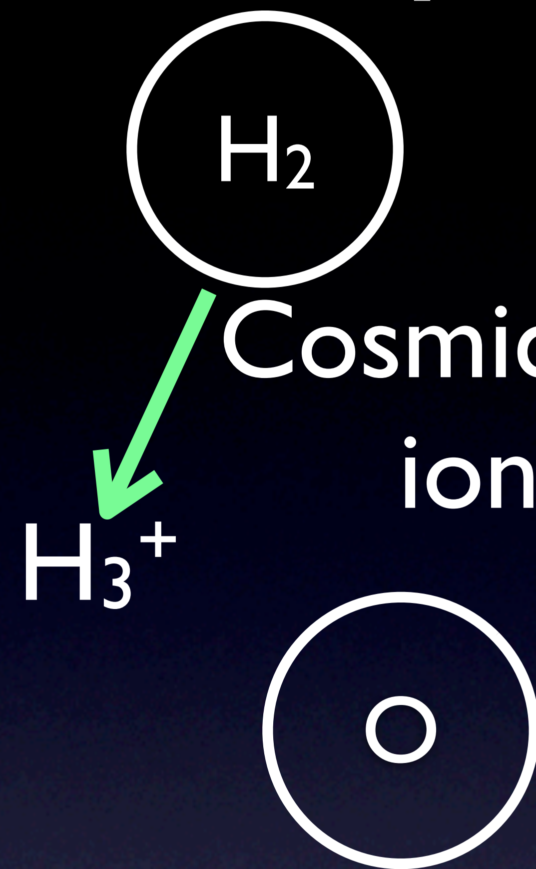
- Both ground- and space-based instruments are needed to understand where water is throughout star formation -- *AND how it gets into planets*

Initial Steps of Water Cycle



Gas-Phase Chemistry at
T < 100 K

Initial Steps of Water Cycle



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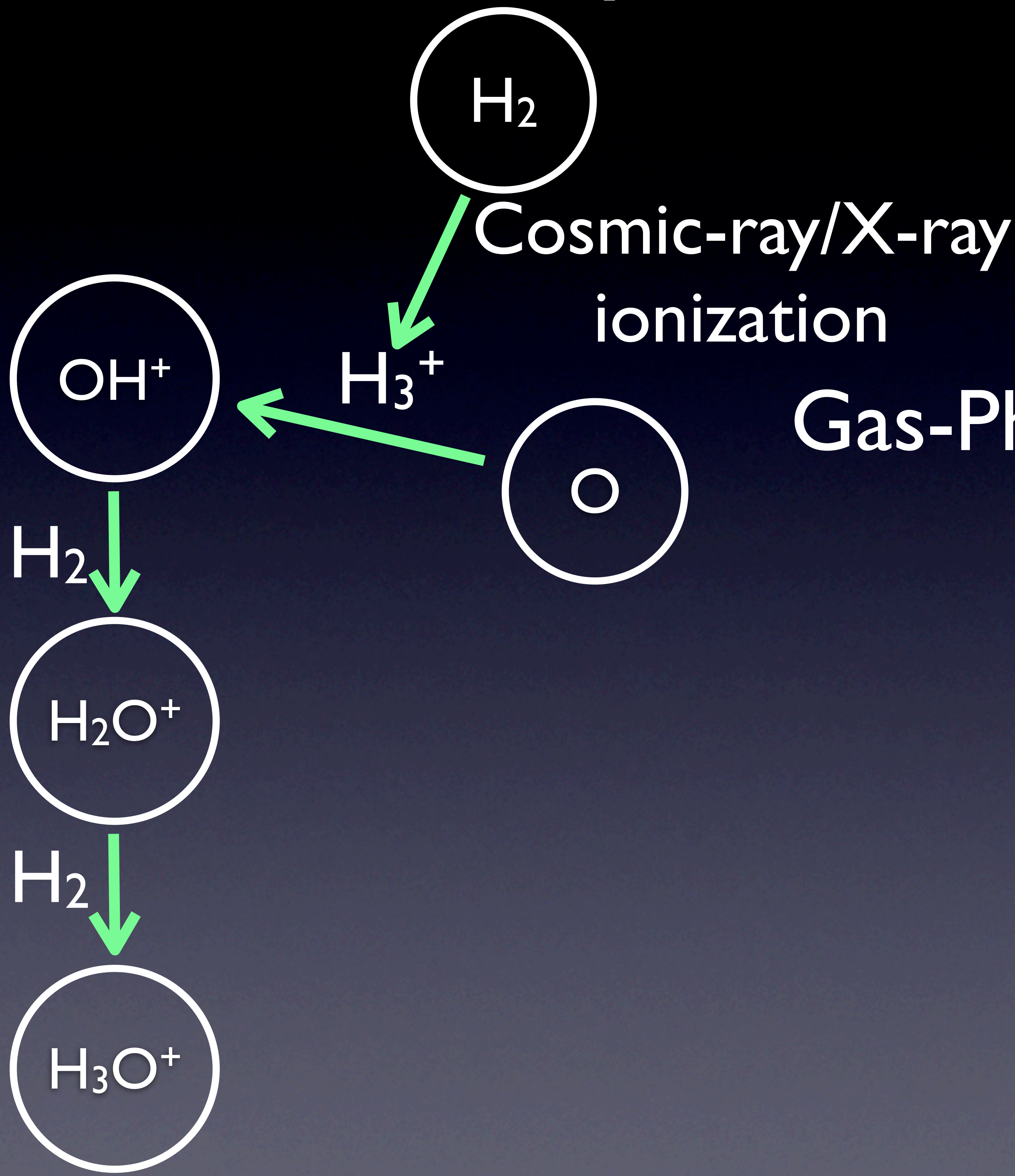

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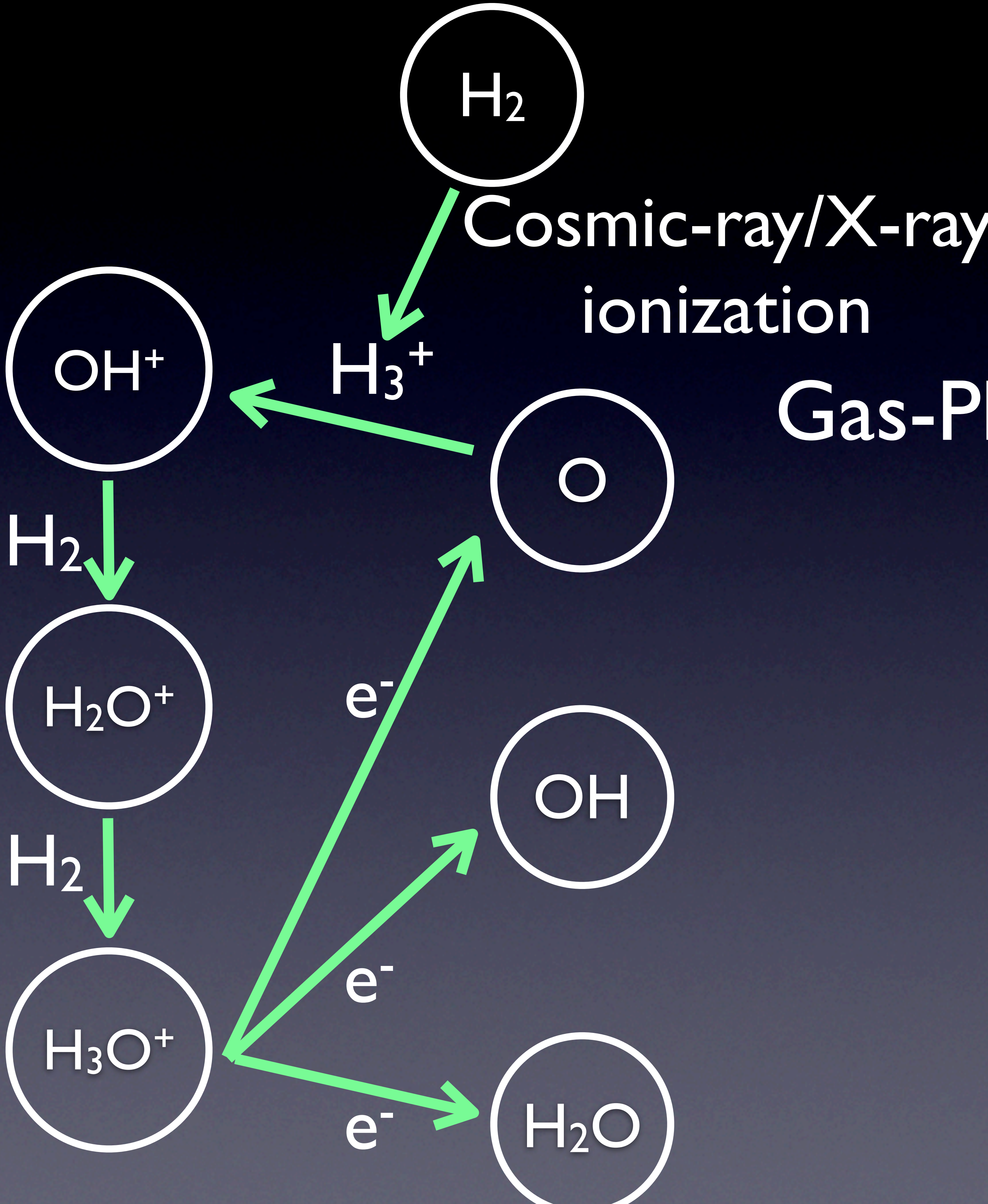

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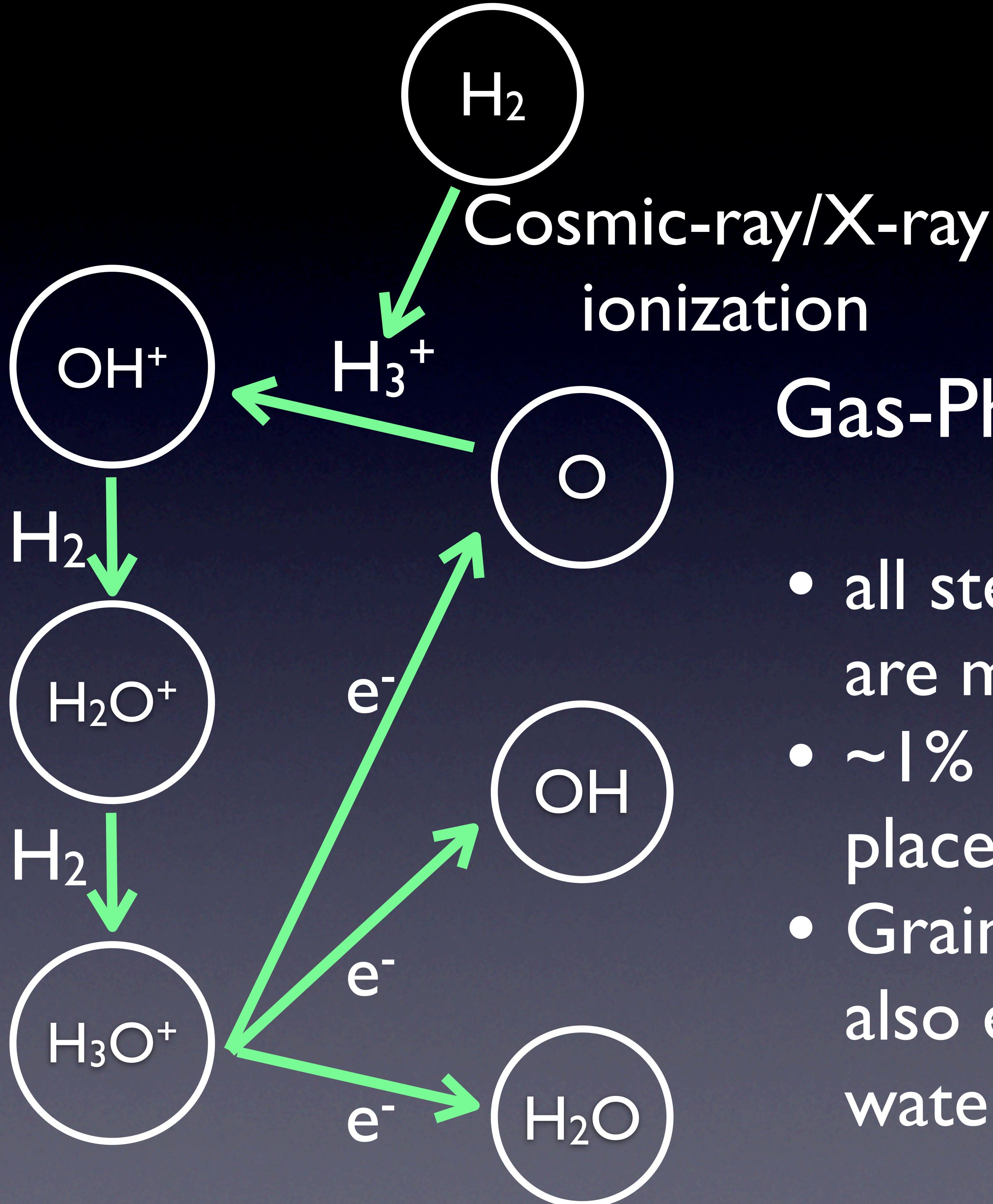
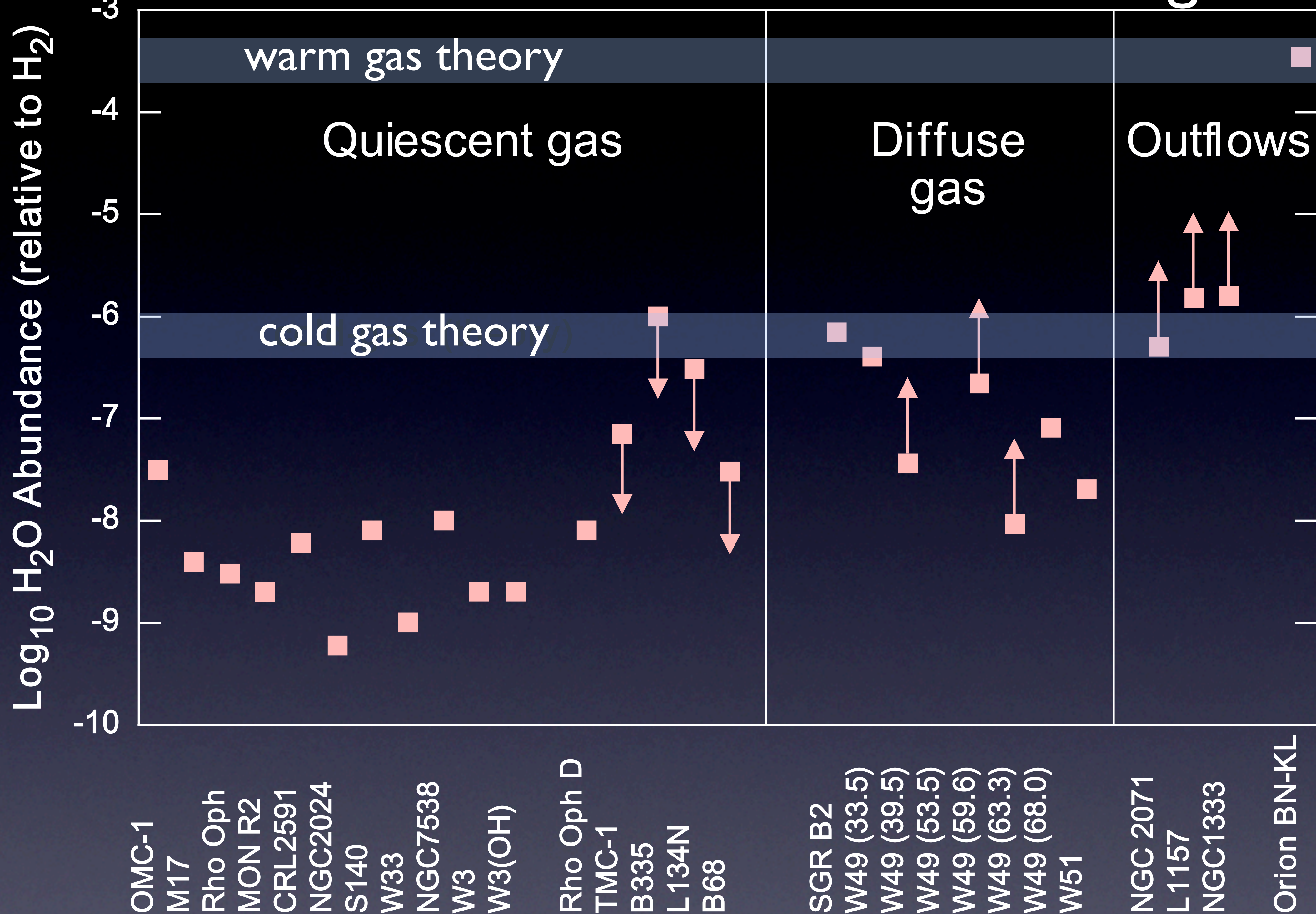


Gas-Phase Chemistry at T < 100 K

- all steps in this sequence are measured in the lab!
- ~1% of cosmic oxygen placed in H_2O
- Grain surface chemistry is also efficient in forming water ice

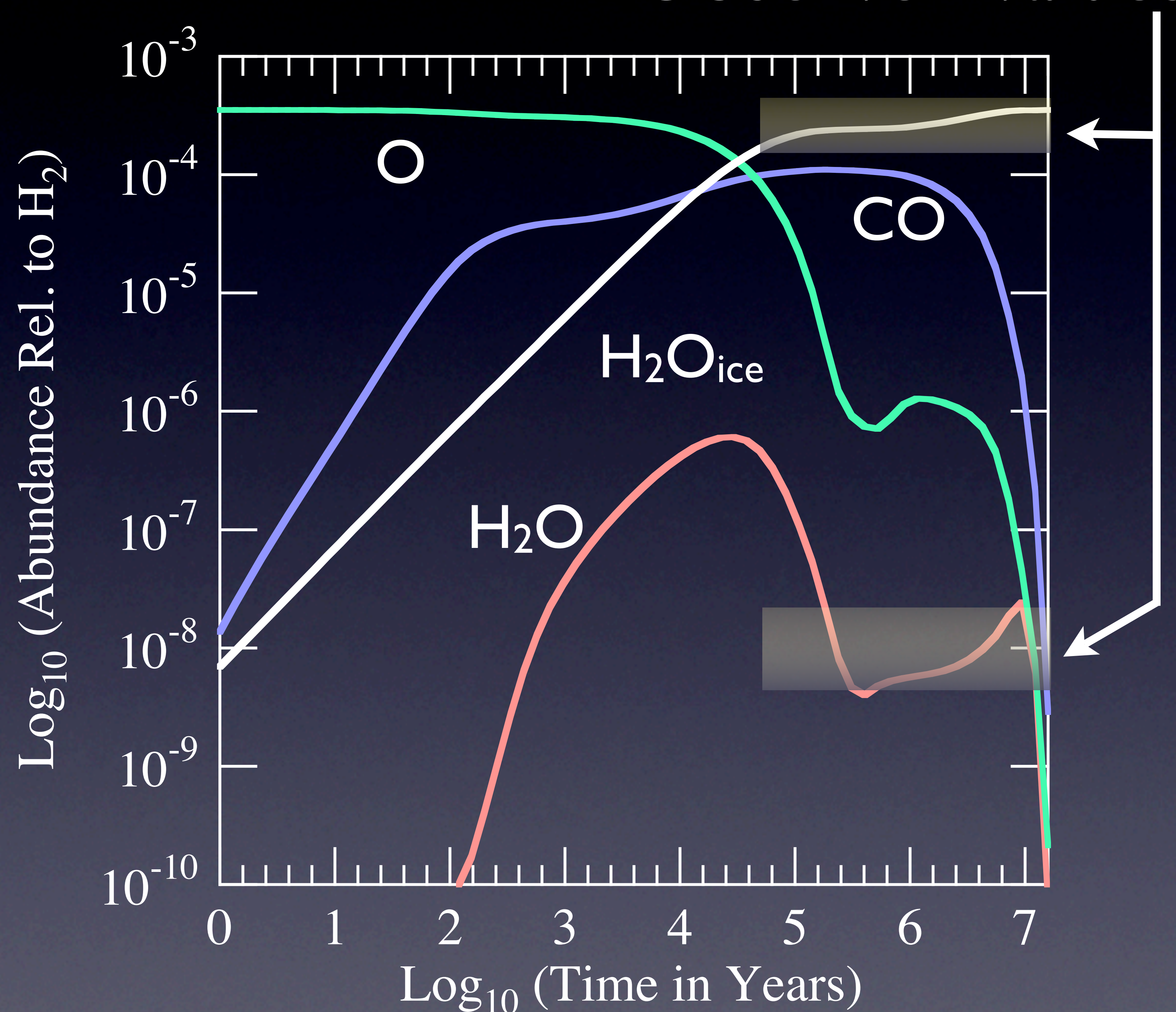
Melnick and Bergin 2005



Water Vapor in Space

Water in Space

- In dense ($n > 10^5$ cm^{-3}) cores of molecular clouds
  - ➡ surface chemistry creates water ice
- $H_2O_{ice}/H_2O_{gas} \sim 10^4$
- More recent models suggest water vapor emits from UV exposed surface
- Herschel! -- observe numerous transitions of ortho and para water

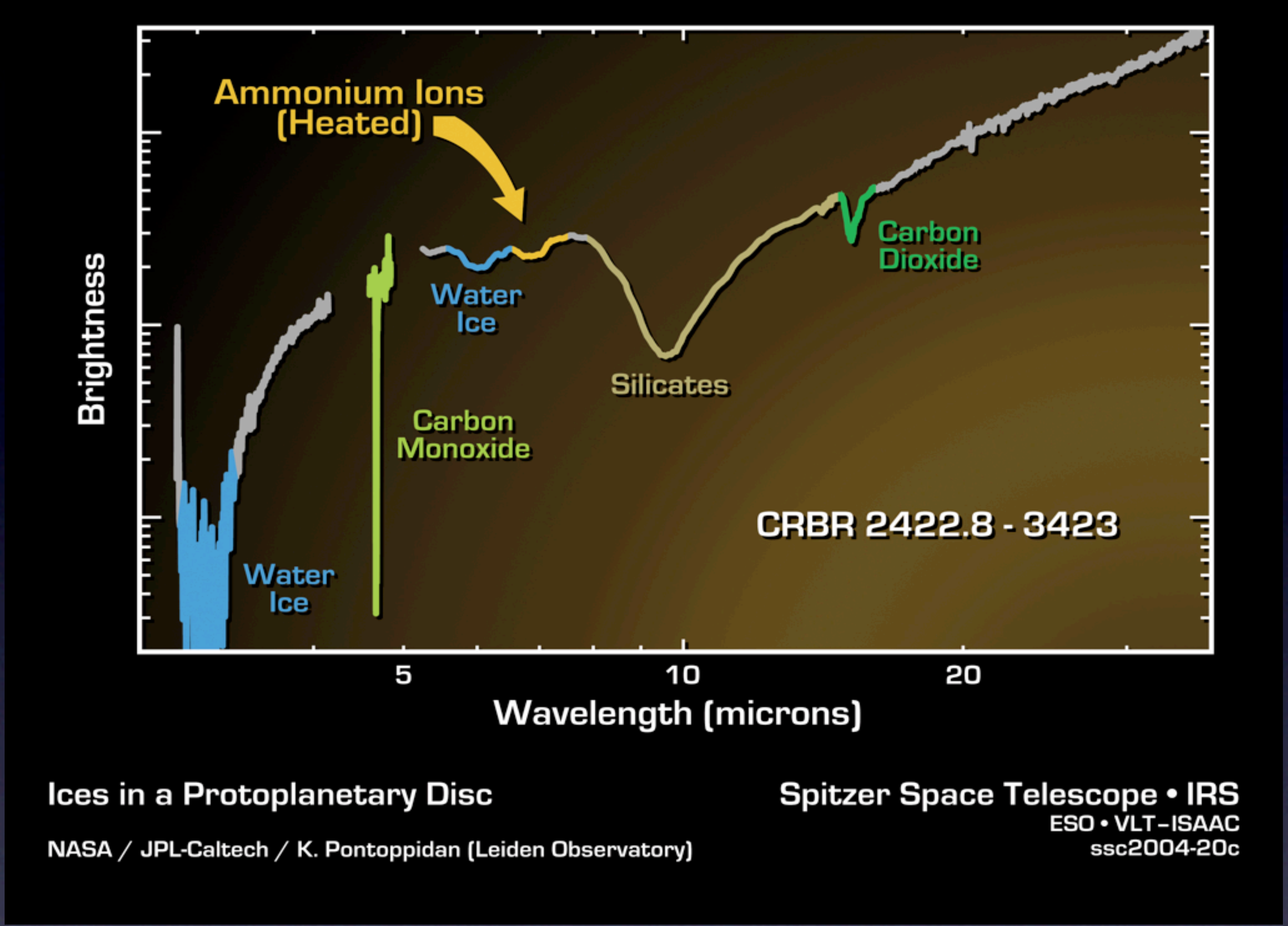


Bergin et al. 2000

Initial Steps of Water Cycle

- ISO observations of atomic oxygen in emission and absorption infer large O I/CO ratios (Lis et al., Vastel et al., Caux et al., see also Poglitsch et al.)
- implies most oxygen in atomic form in dense regions in direct conflict with interpretation of water observations.
- SOFIA/GREAT can spectrally resolve atomic oxygen lines to use line profile to aid in determining emission-absorption origin

Water in Disks

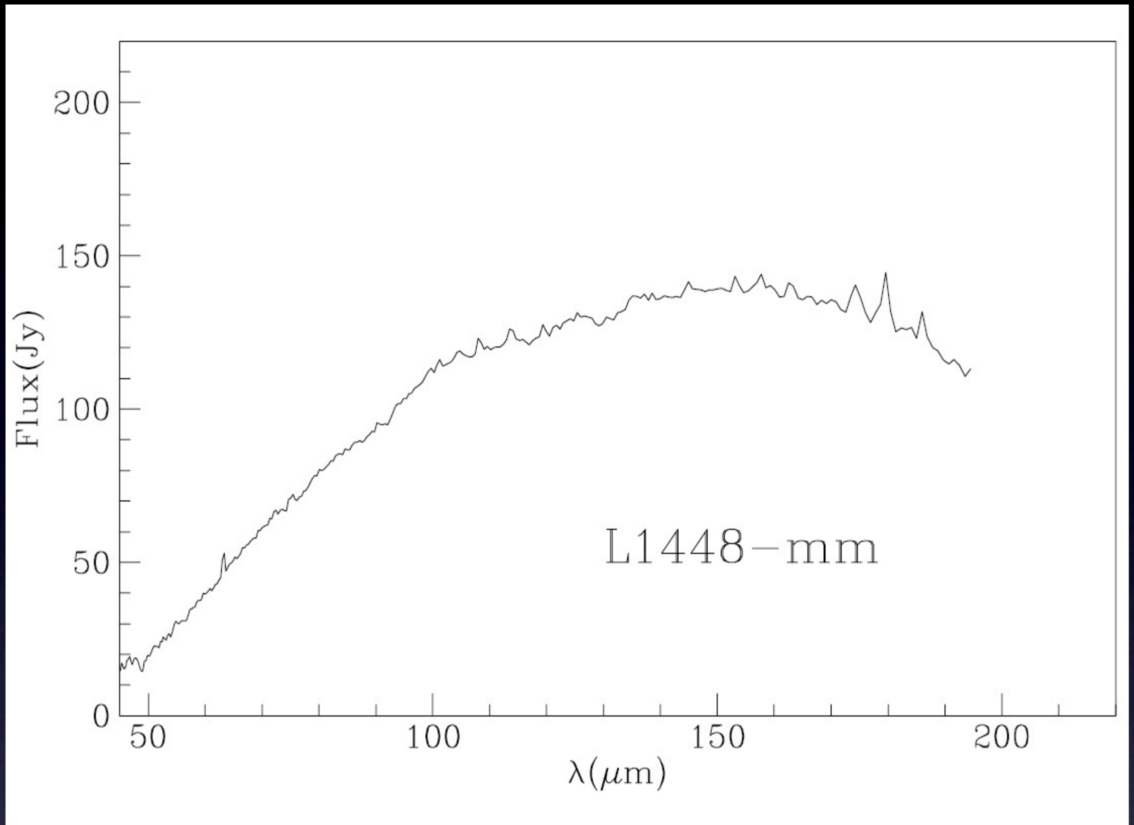


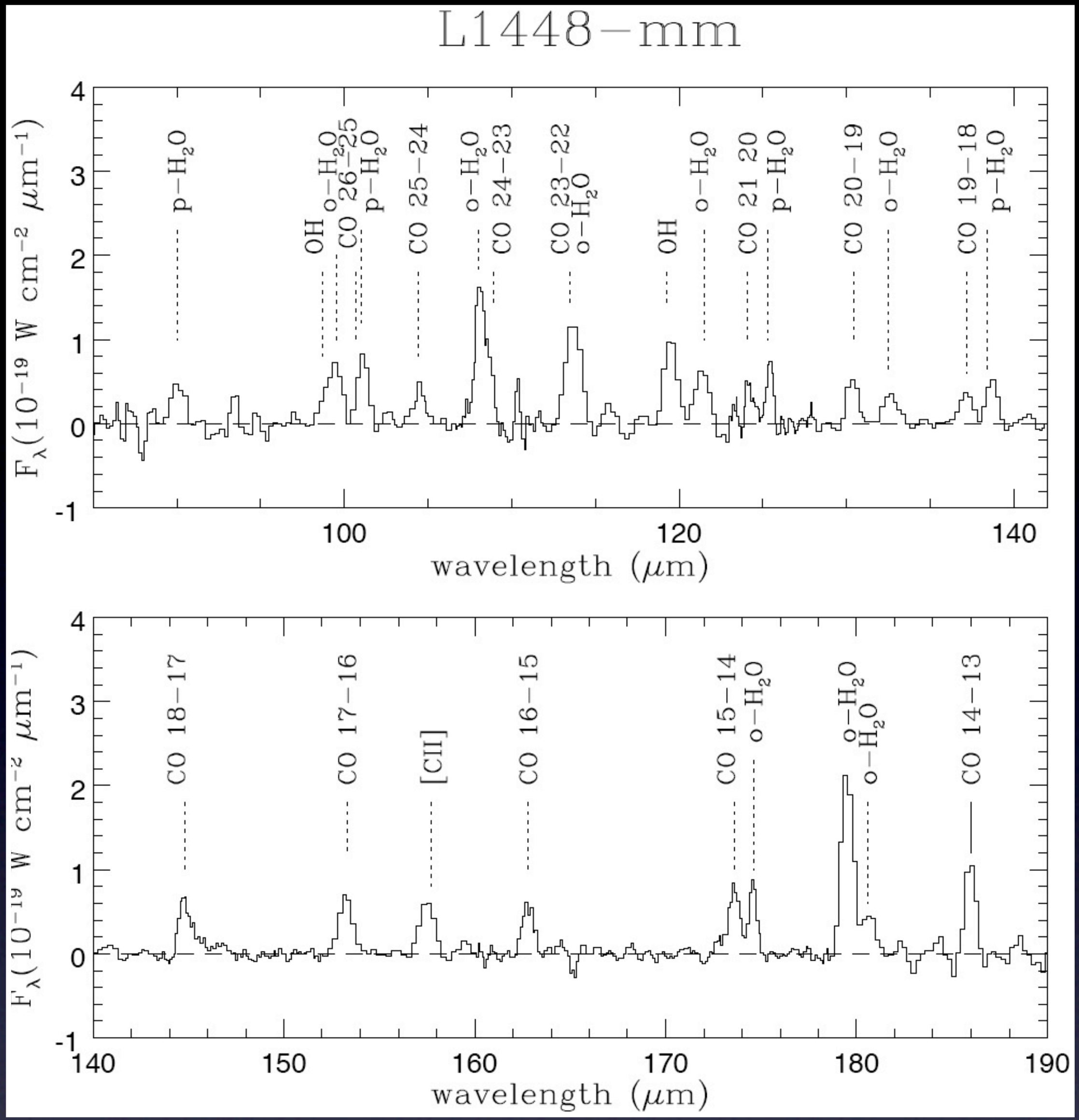
- ➡ Most of the water is frozen in planet forming disk
- ➡ ALMA - can do HDO and $H_2{}^{18}O$ - compare to comets and Earth water
- ➡ ALMA cannot observe $H_2{}^{16}O$ - $^{16}O/^{18}O$ may vary in the disk - link to planets and meteorites (Herschel/SPICA)
- ➡ need to resolve inside the "snow-line" (JWST 6µm in transition systems), but need sub-arcsec resolution to resolve thermal emission, sensitivity for isotopic species

Planet Formation

- how do planets get water?
  - ➡ simulations ("Nice" model) suggest that comets may not play a major role
  - ➡ icy planetesimals from outer asteroid belt or from hydrous minerals
  - ➡ far-IR has bands of hydrated silicates -- high angular resolution can resolve where they form in the disk
- how do gas disks dissipate?
  - ➡ spectrally and spatially resolved [C II] and [O I] may be the best tracers of disk dissipation flows!

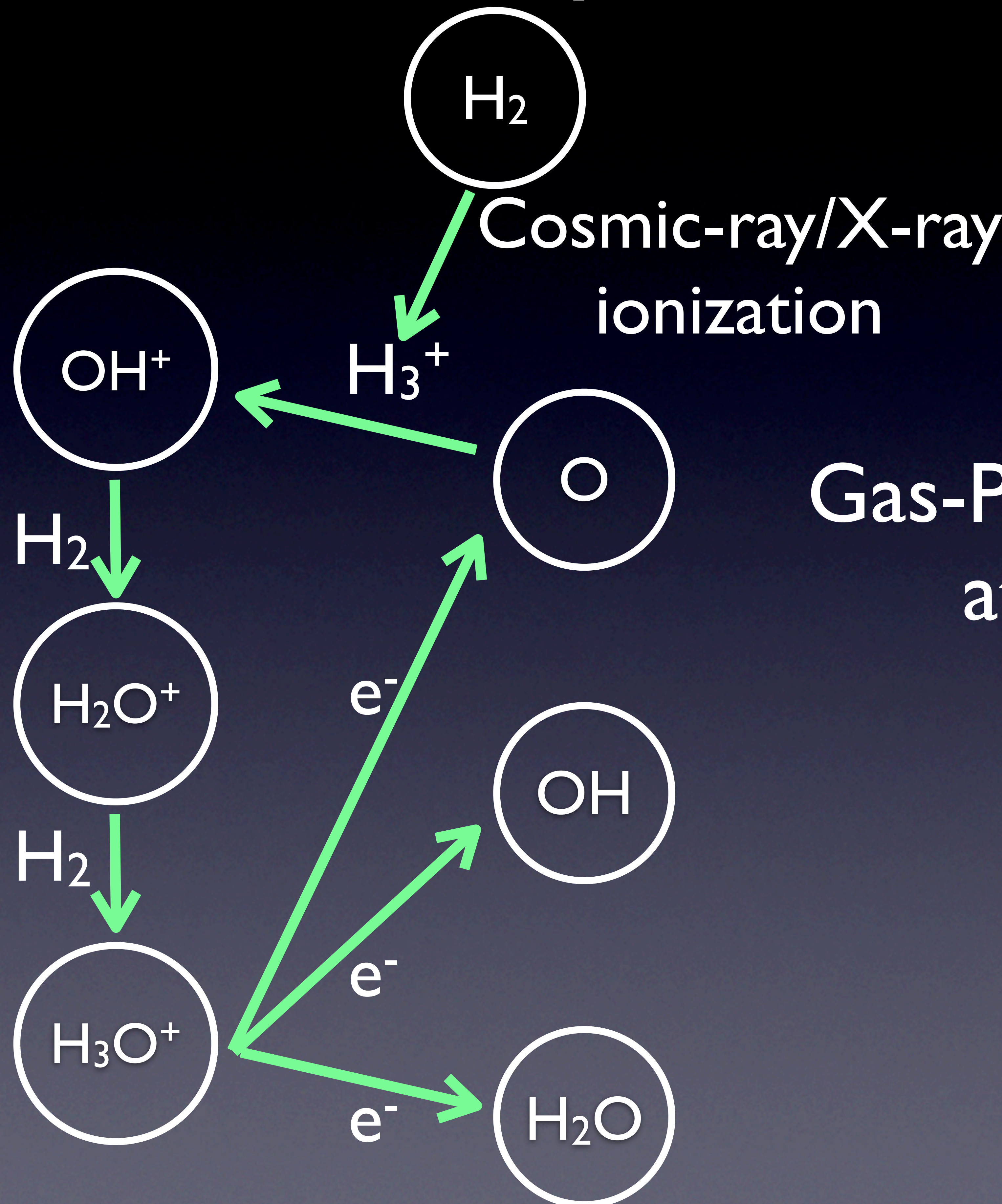
Stellar Birth





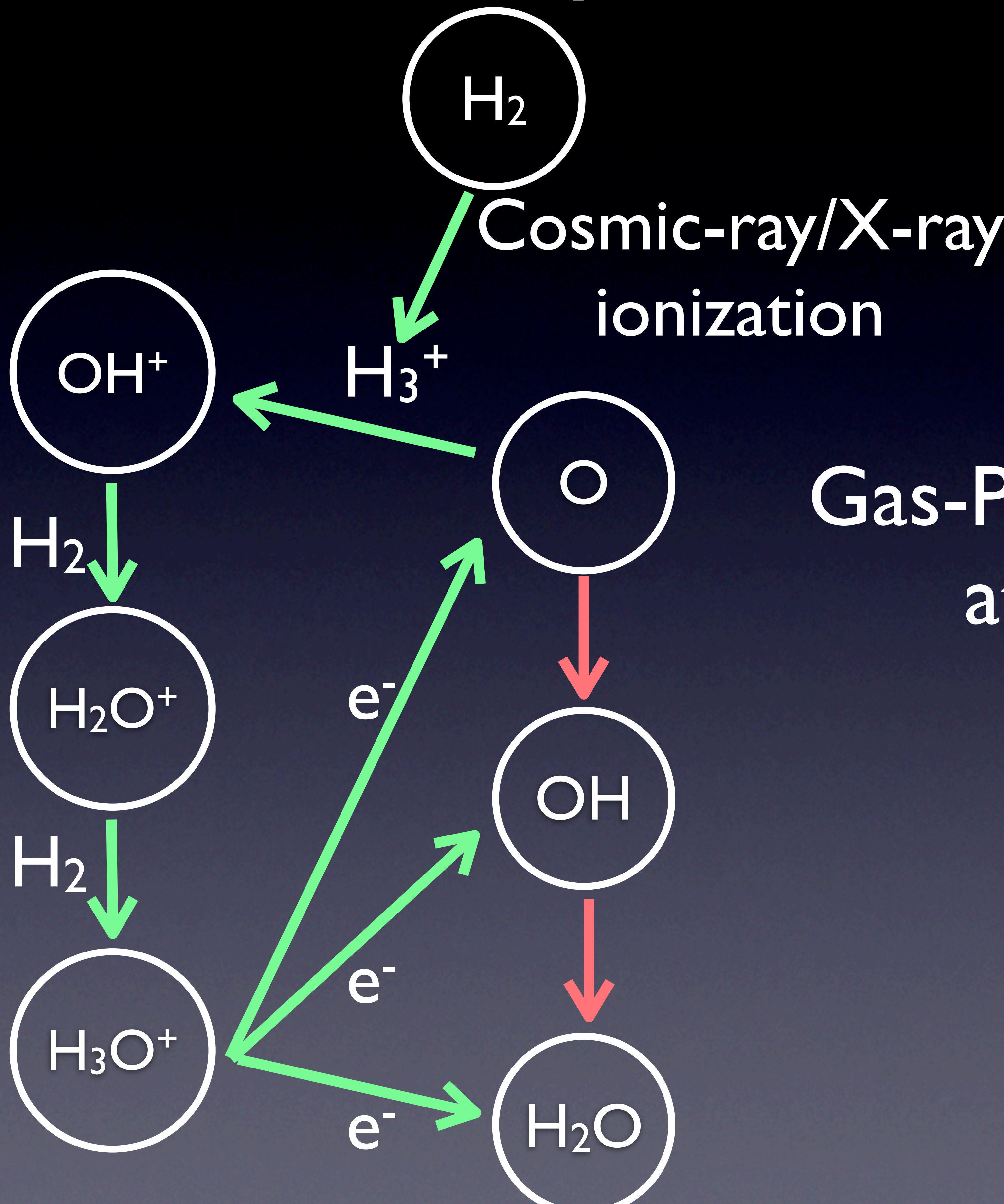
- can trace evaporated water ice - determine o/p and D/H ratio
- get cooling and chemistry of star formation
- Herschel initial surveys - both heterodyne and direct detection - SPICA more sensitivity - lower mass sources?
- SAFIR/SPIRIT: better resolution -- closer in to the star (better tests of physics) and more distant stellar clusters

Final Steps of Water Cycle



Gas-Phase Chemistry
at T > 400 K

Final Steps of Water Cycle



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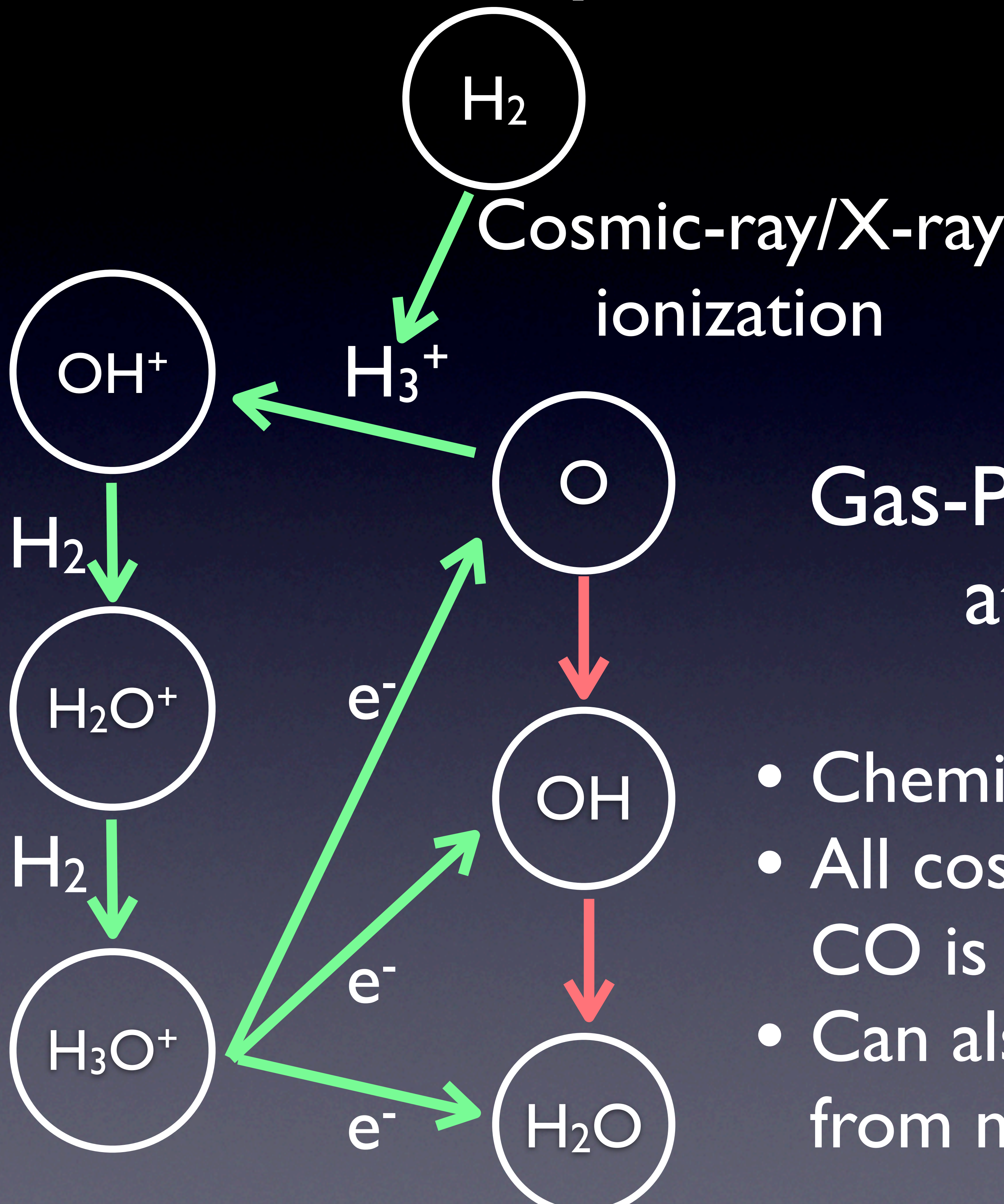
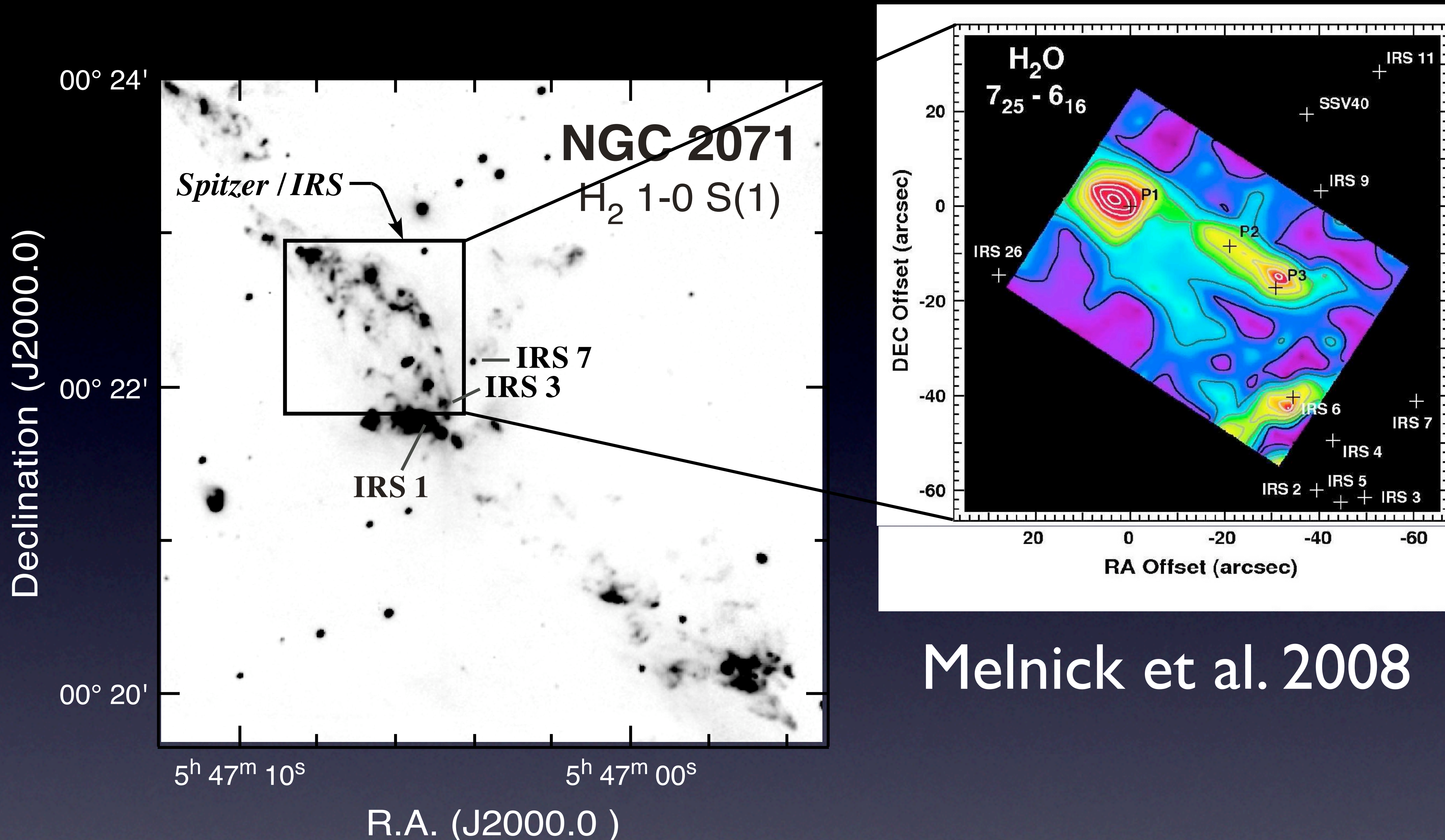


Gas-Phase Chemistry at T > 400 K

- Chemistry very efficient
- All cosmic oxygen not in CO is transferred into H_2O
- Can also sputter water ice from mantles in shock



Melnick et al. 2008

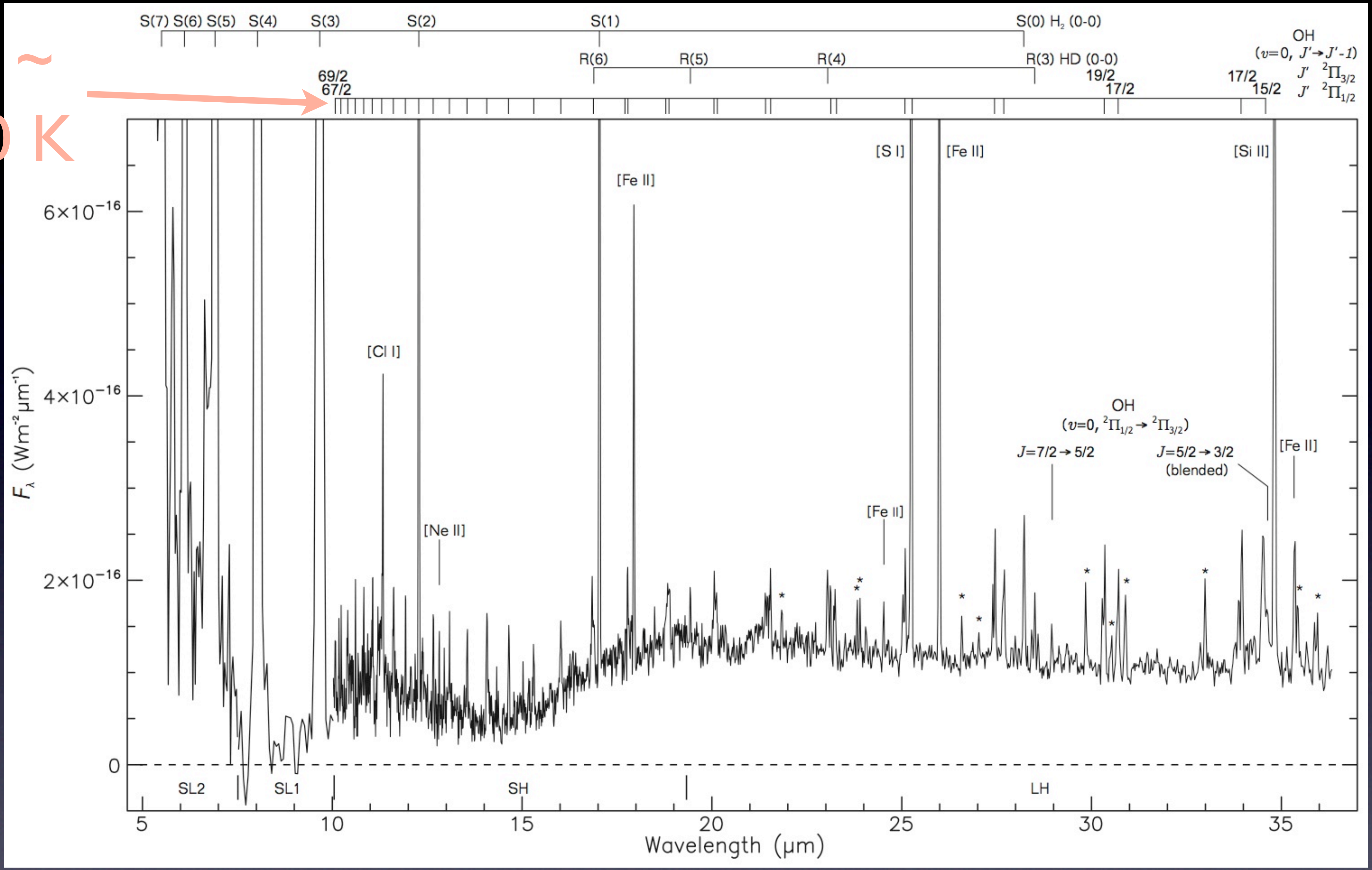
- Observations: typically do not detect hot abundant water
- SWAS, ODIN, and ISO find at least an order of magnitude below expectations (except in a handful of sources)

Water in Shocks

Tappe et al. 2008

HH-211

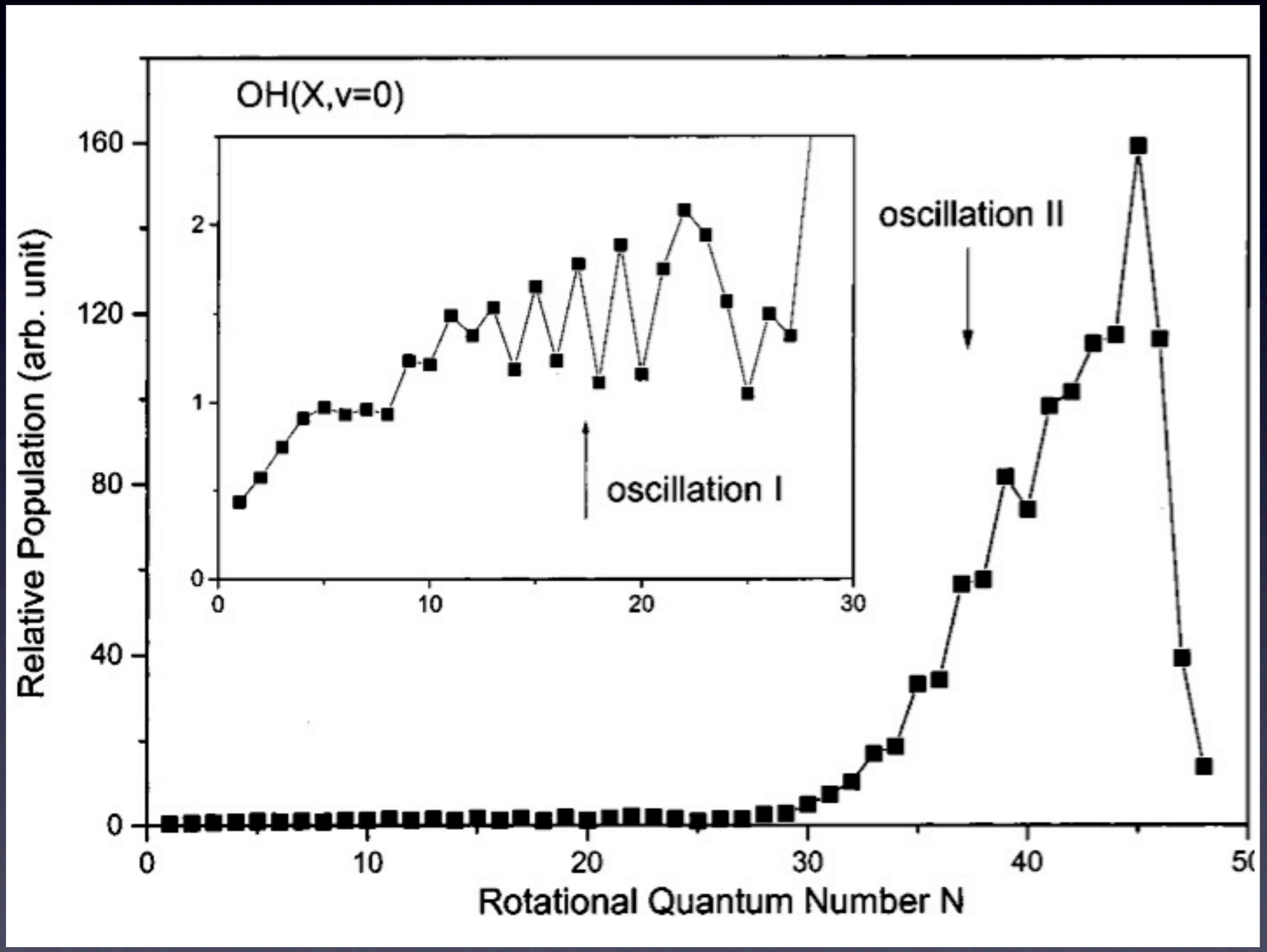
ΔE/k ~ 30000 K



Super-Thermal OH

Water in Shocks - need OH

Rotational State of OH
from $H_2O + h\nu \rightarrow OH + H$

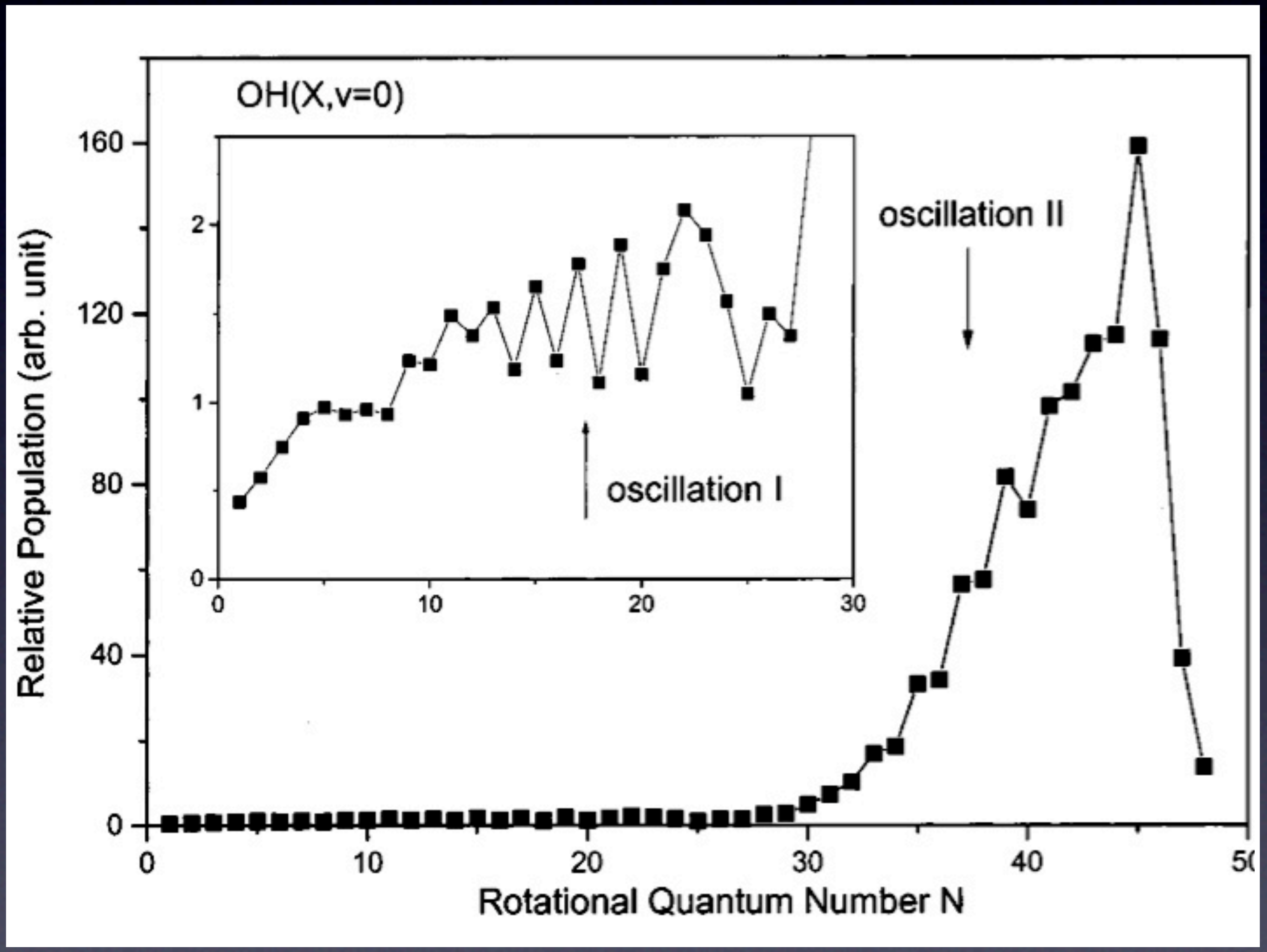


Harich et al. 2000

Water in Shocks - need OH

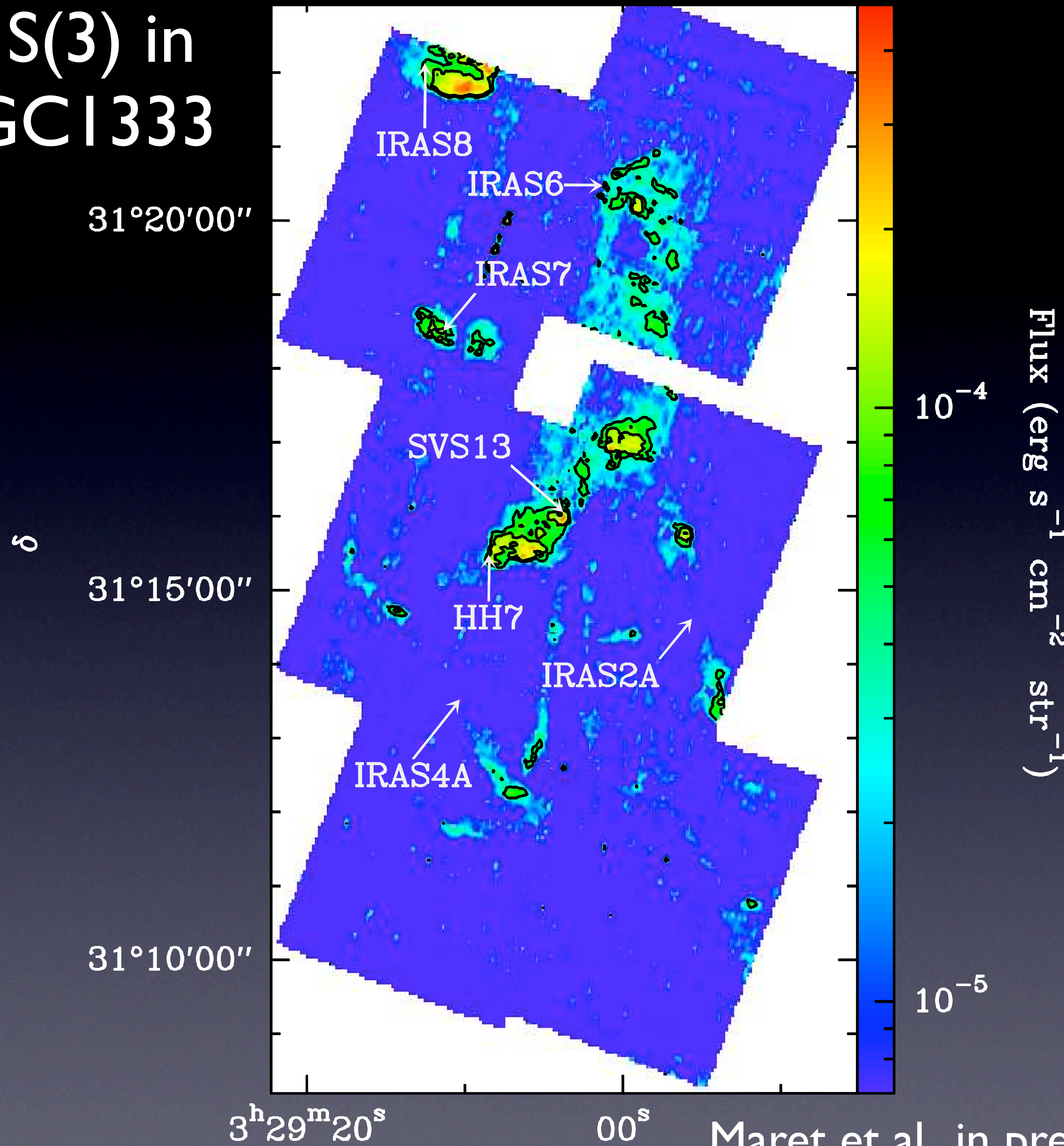
- Near/Mid Term Future
  - ➡ Herschel/SPICA - OH/ H_2O in a range of outflows
  - ➡ SOFIA - spectrally resolved O I -- where is the OH going?
  - ➡ Herschel/SOFIA - [C II] line wings as tracer of UV
  - ➡ JWST - observing OH J > 69/2 (Spitzer SH limit)

Rotational State of OH from $H_2O + h\nu \rightarrow OH + H$



Harich et al. 2000

H_2 S(3) in NGC1333



Maret et al., in prep

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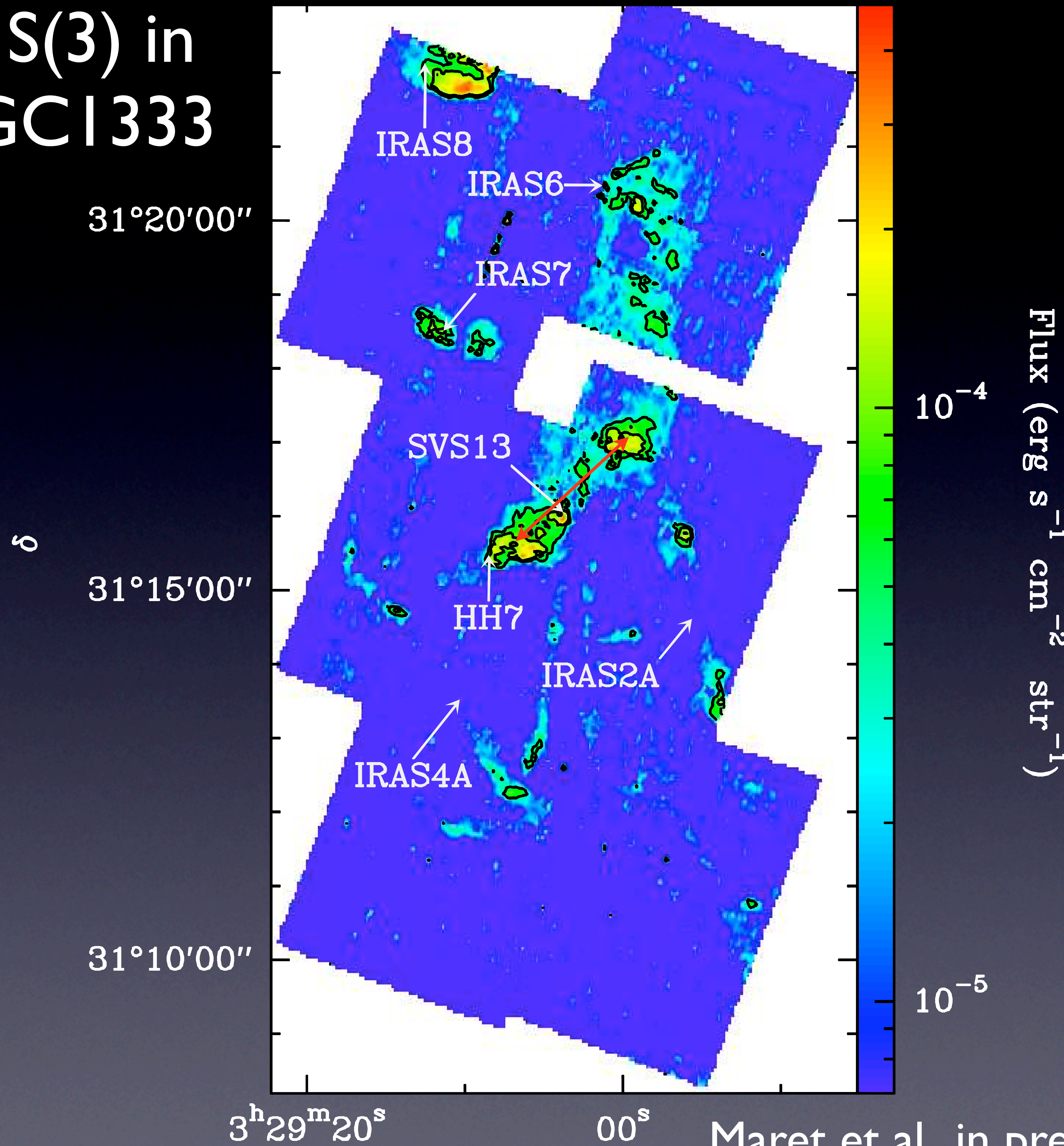

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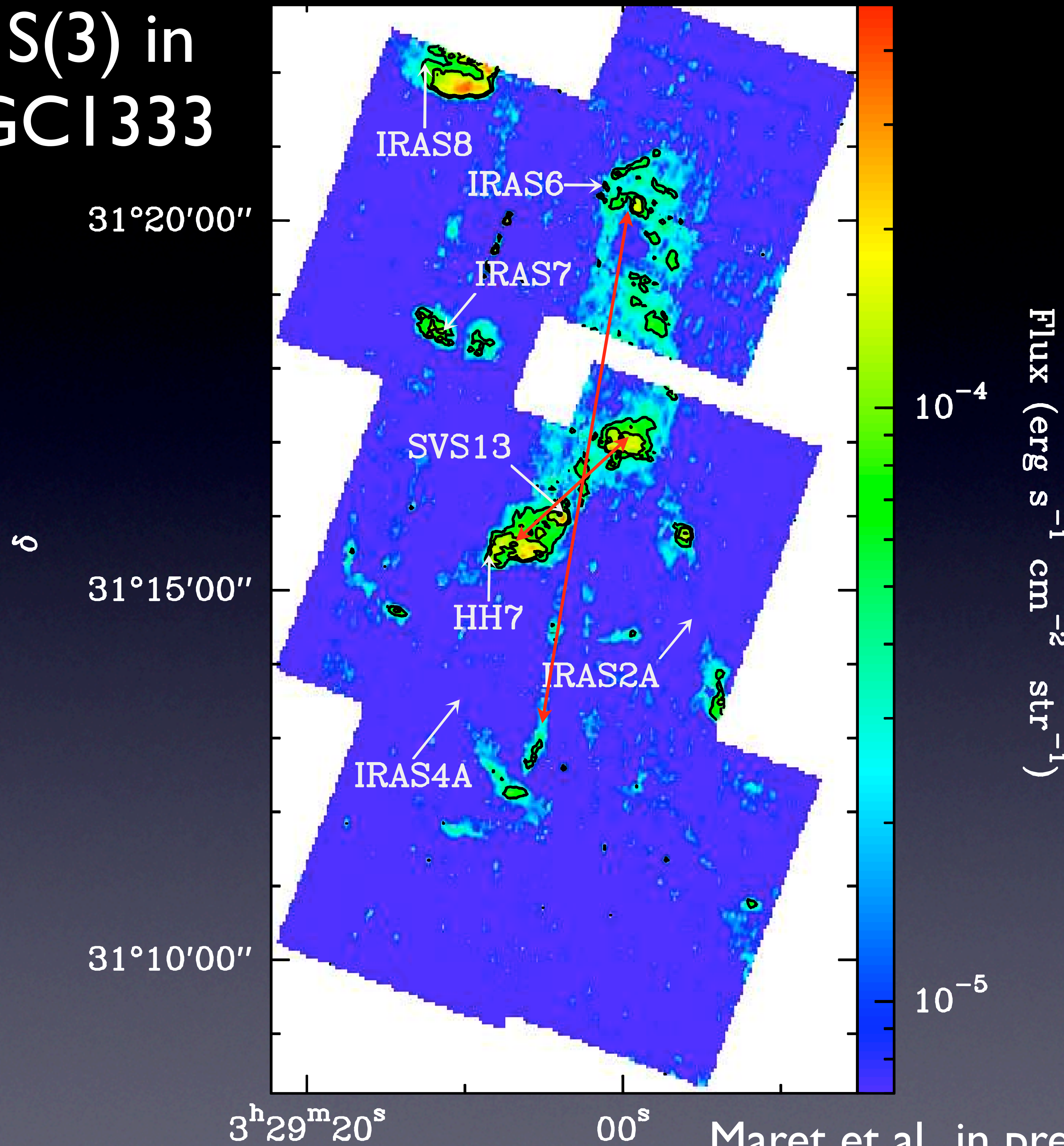

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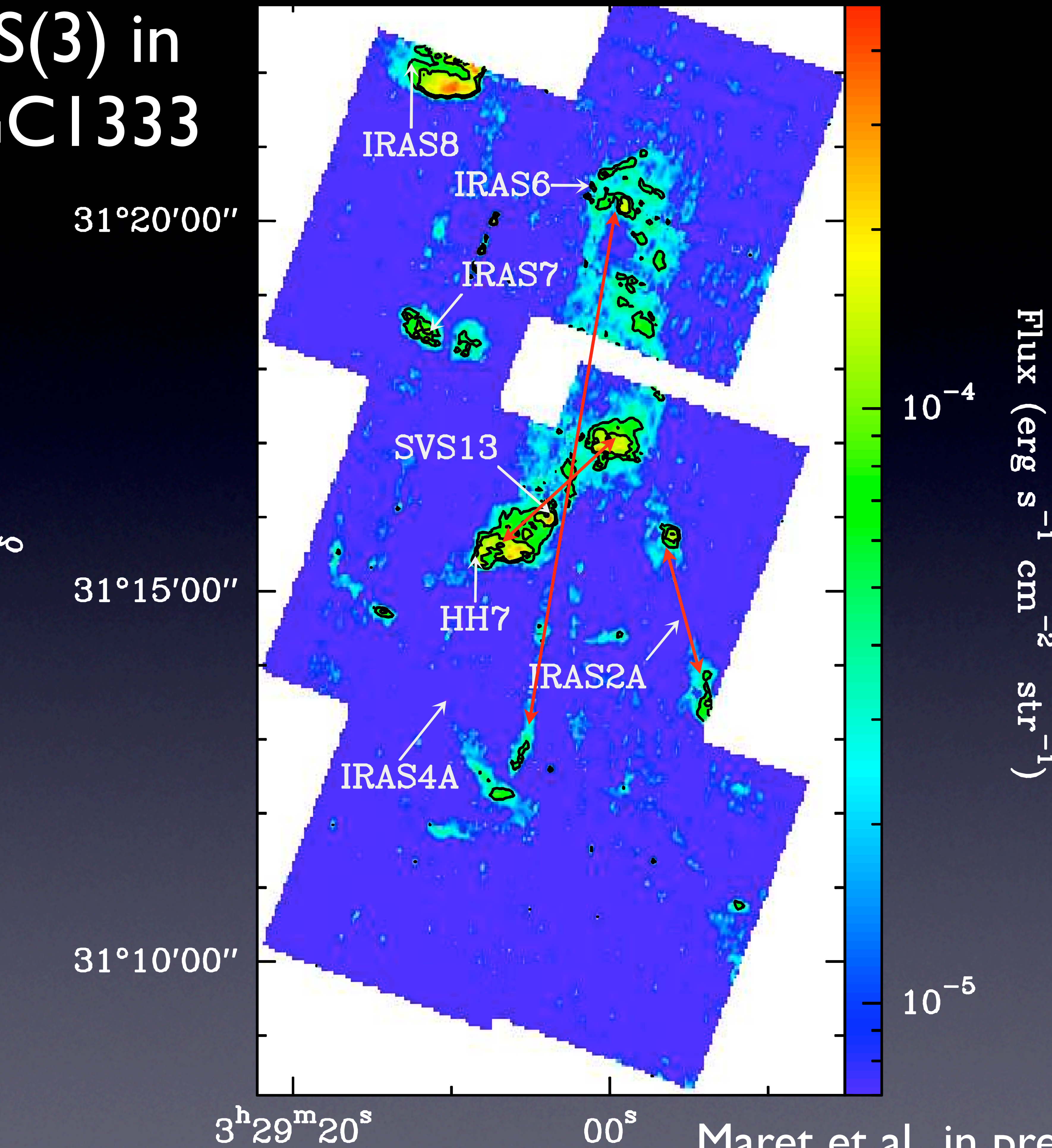

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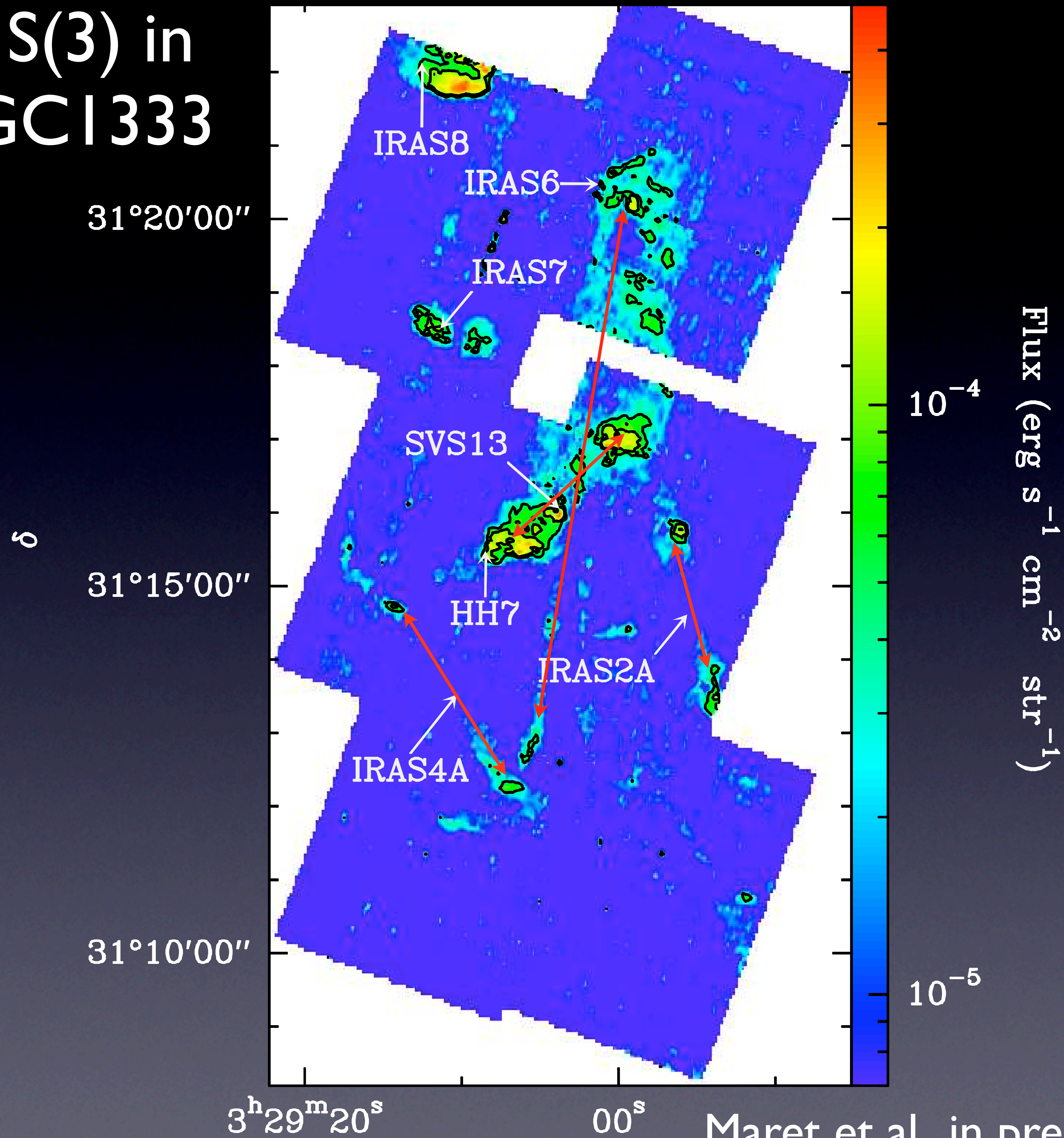

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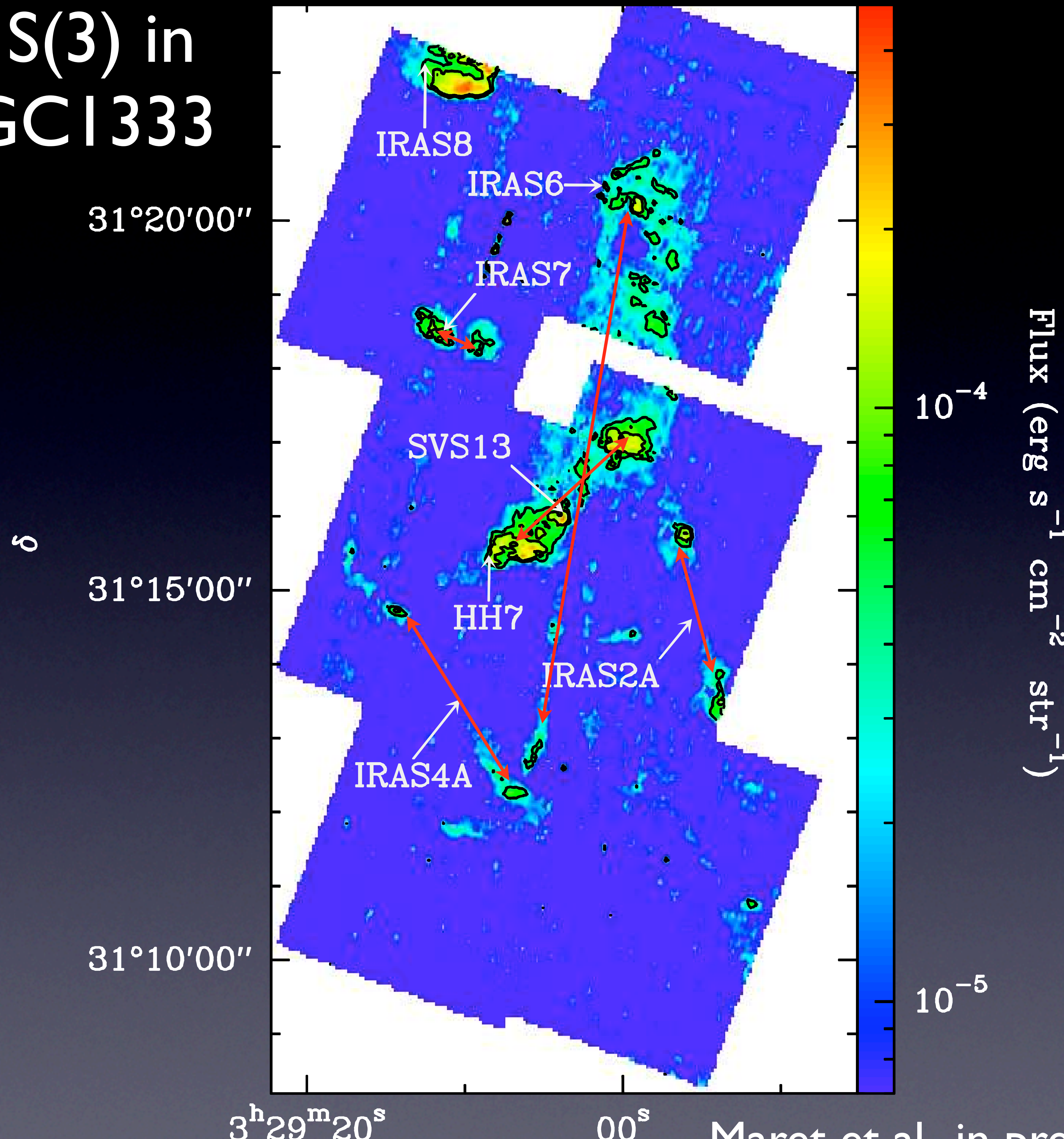
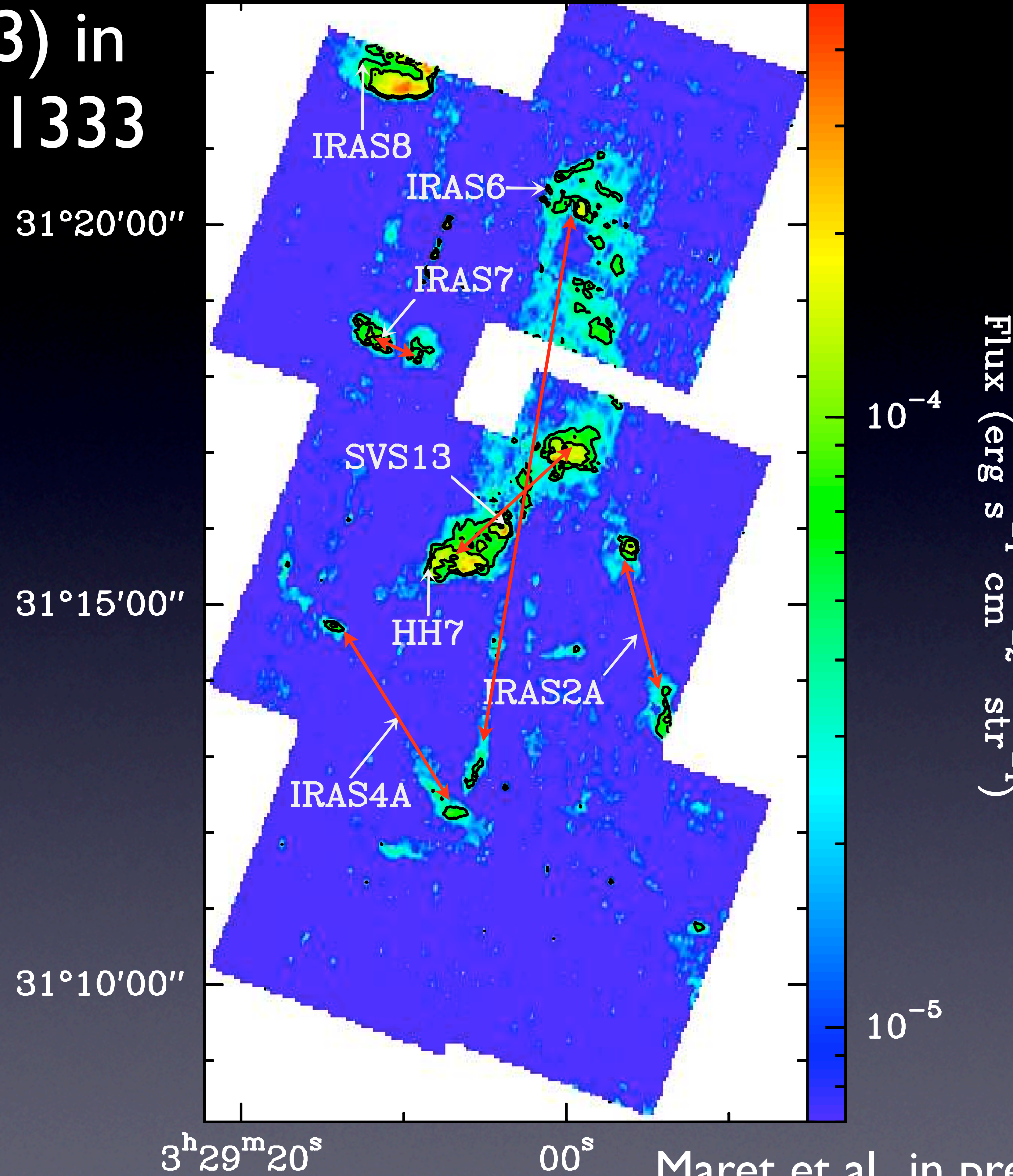


Maret et al., in prep

H_2 S(3) in NGC1333

- ALMA...
- Future for the Far-IR - resolving shocked knots (< 1″ resolution)



Maret et al., in prep

Deuterium In the Galaxy

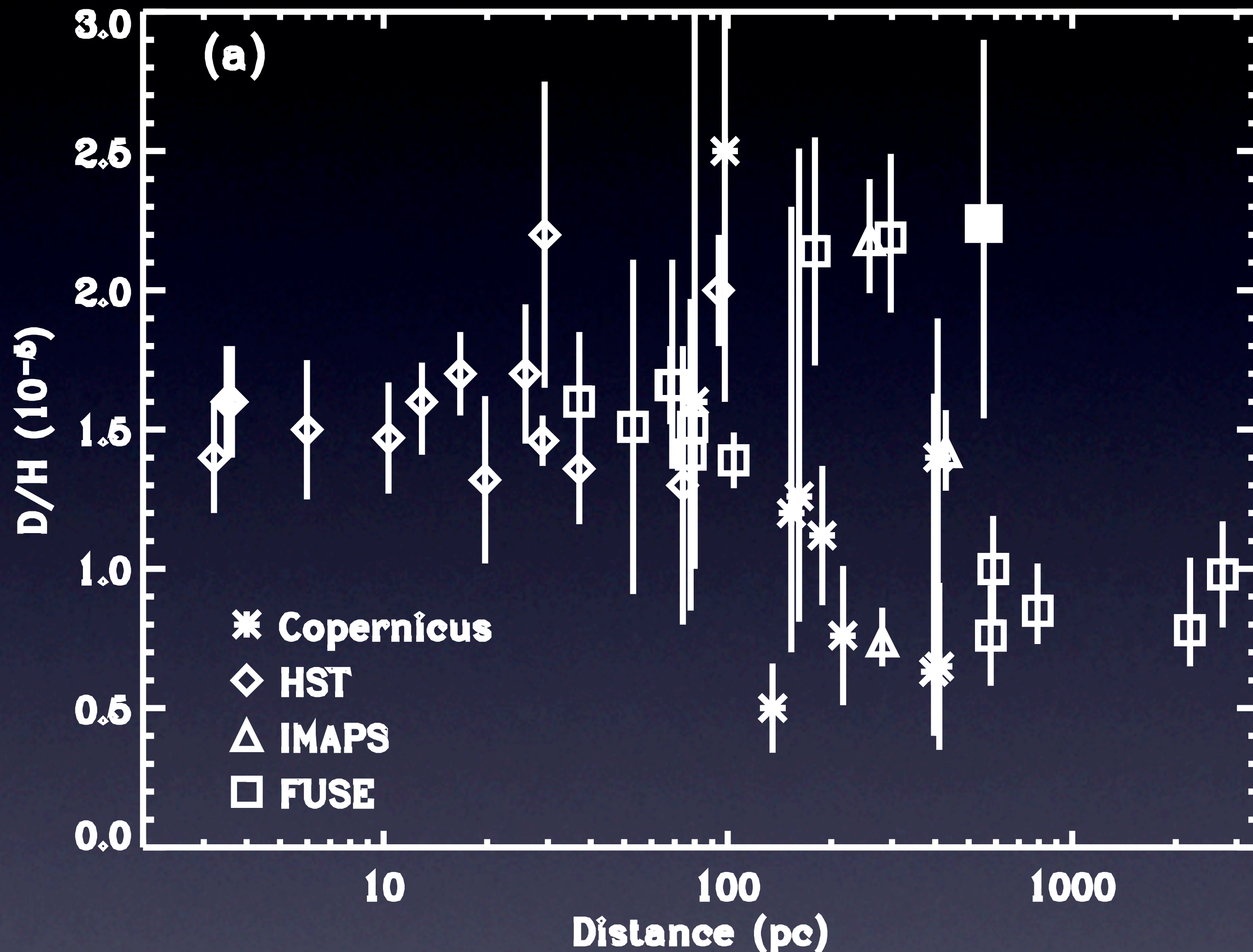
- Important as a relic of the big bang
  - ➡ test of stellar nucleosynthesis
- chemical fractionation occurs at low T -- used as a fossil for past history of physical conditions
  - ➡ holds clues to origins of Earth's water
- ALMA, Herschel, and SOFIA will open this up for numerous species including HDO, DCO^+, DCN, HDCO, NH_2D, NHD_2, ND_3, ...
- Mid and Far-IR offers direct observations of HD pure rotational lines
  - ➡ Complicated by strong (often optically thick) continuum

Deuterium In the Galaxy

- Herschel/SOFIA (in particular GREAT) can extend FUSE results to the center of the Galaxy

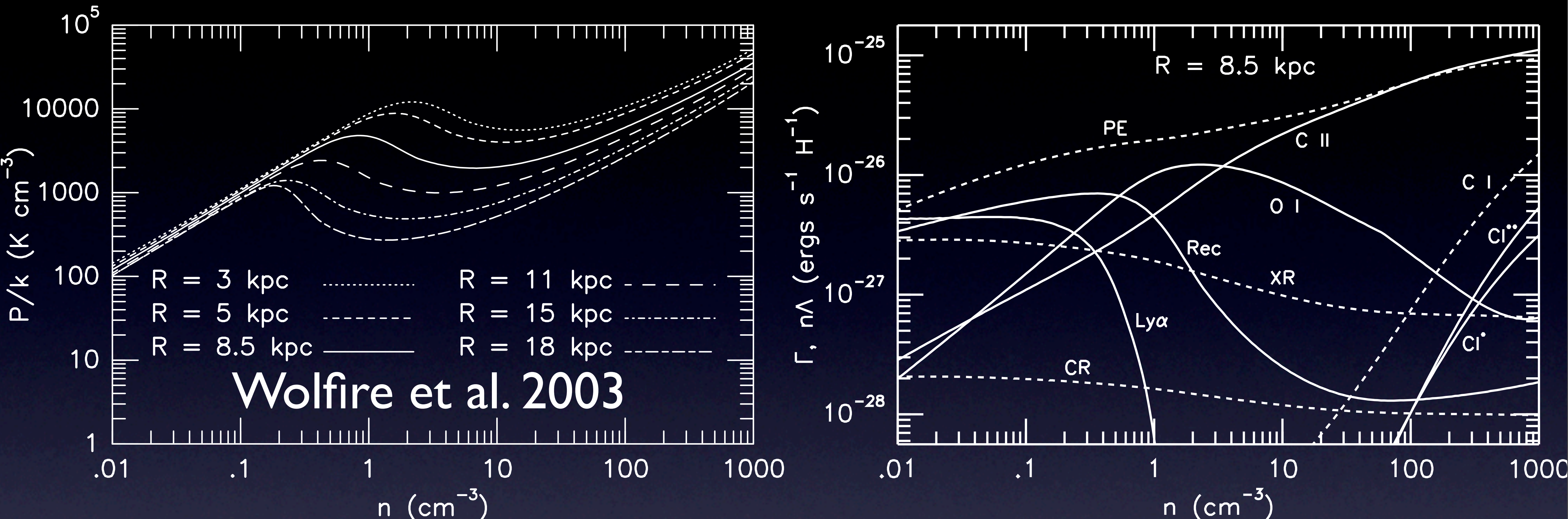
- If we know the HD/H_2 ratio then HD is a direct tracer of gas mass!

➡ does not freeze-out (like CO)

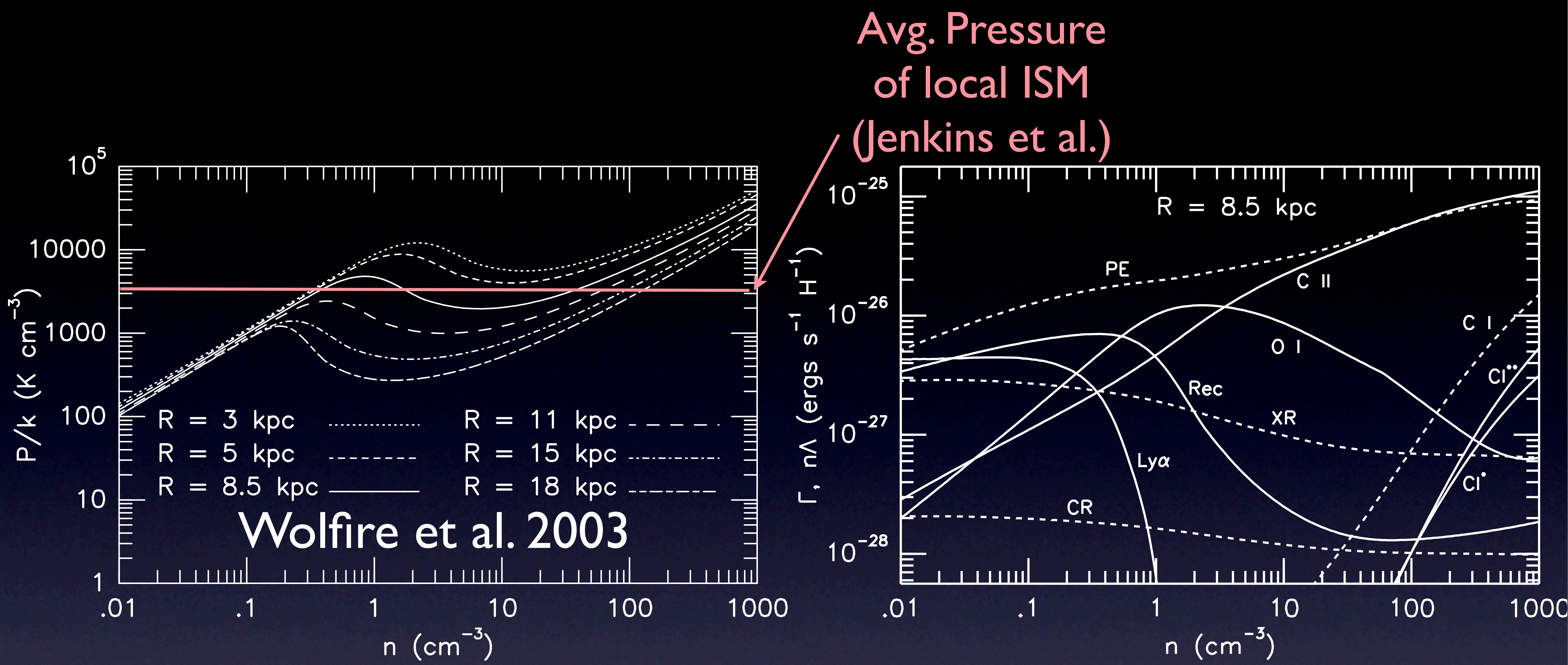


Summary

- In 5 years we will know the far-IR sky much better than we do today - but there will be surprises....
- Obvious part - unexplored scientific terrain requires high resolution imaging (~1″ or less)
- Play to our strengths:
  - ➡ peak of SED (structure, dust temp, polarization)
  - ➡ primary coolants of early phases of cloud/star/planet formation (shocks, finals stages of disk evolution)
  - ➡ water, water, water
  - ➡ extent of interstellar chemistry
  - ➡ main reservoir of deuterium (HD) - tracer of mass
- for ISM science - high spectral resolution is critical



Beginning of Cloud Formation: Atoms



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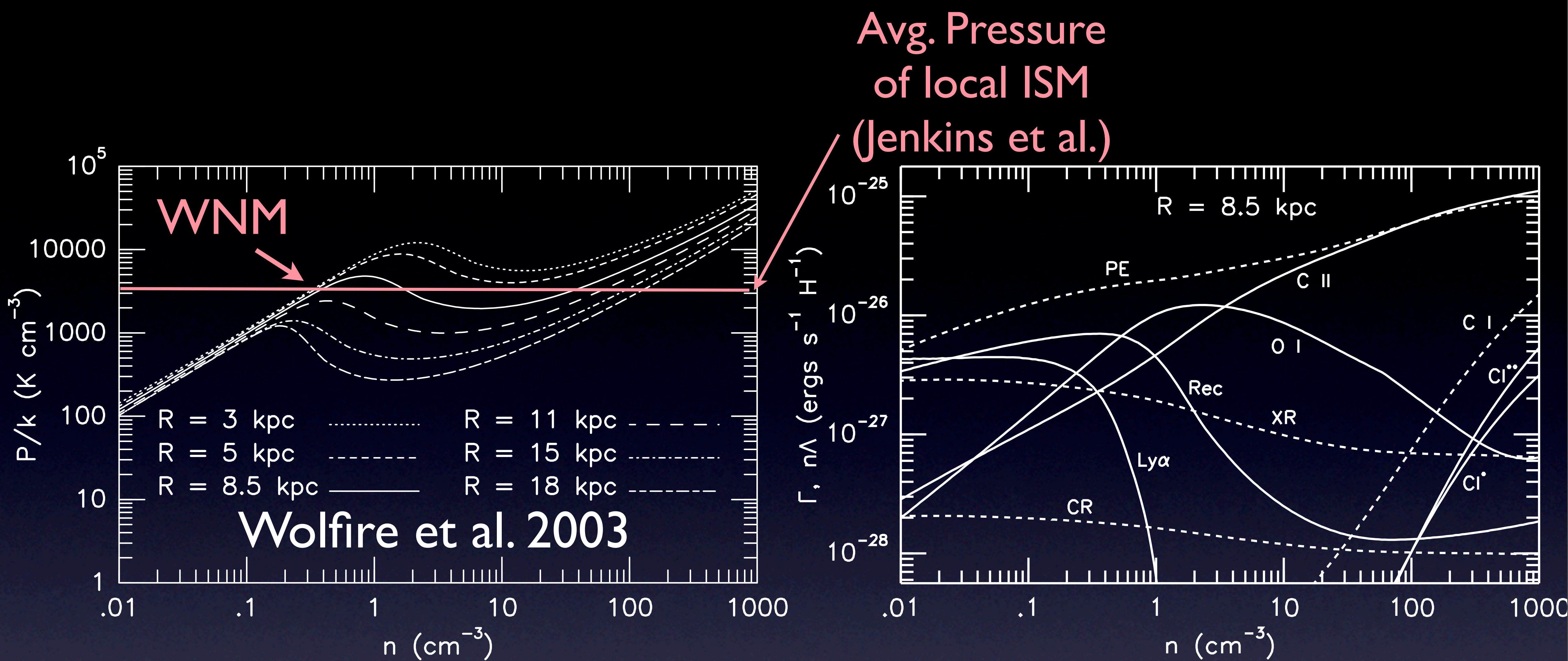

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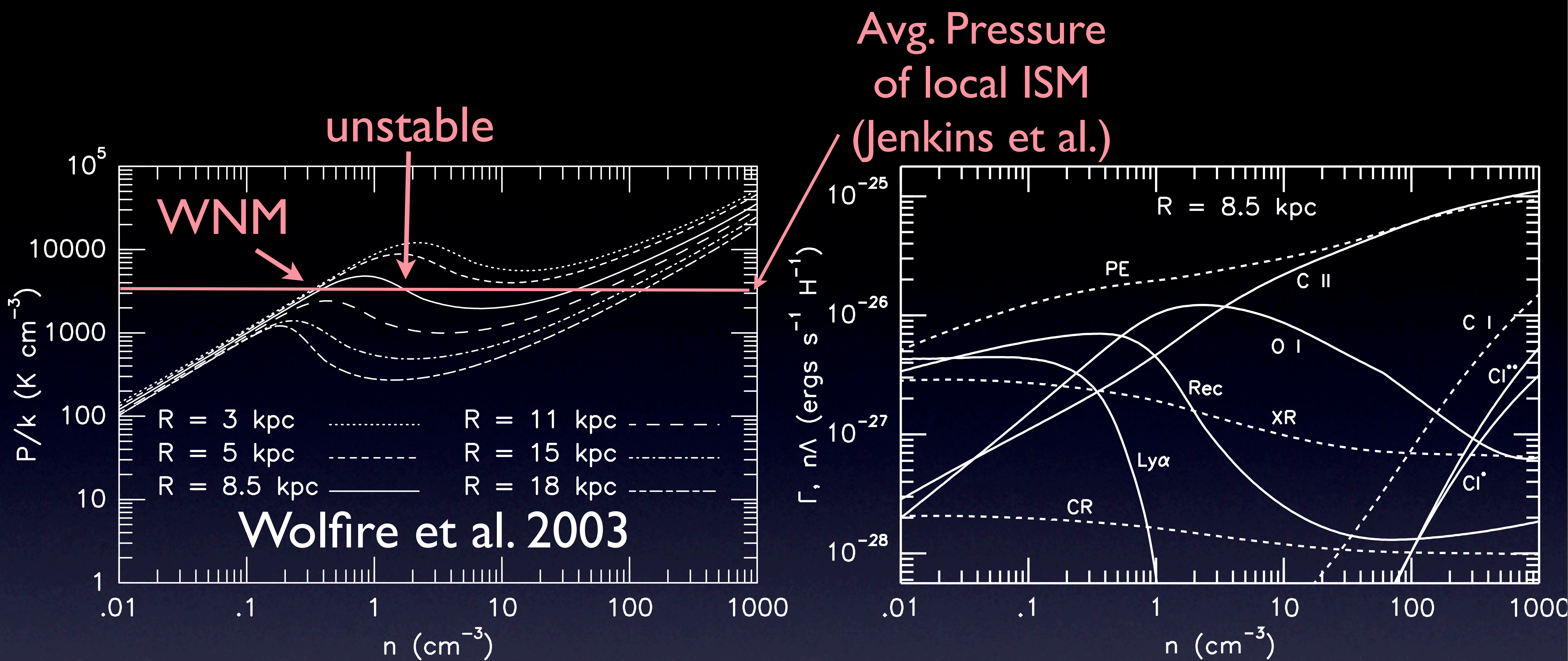

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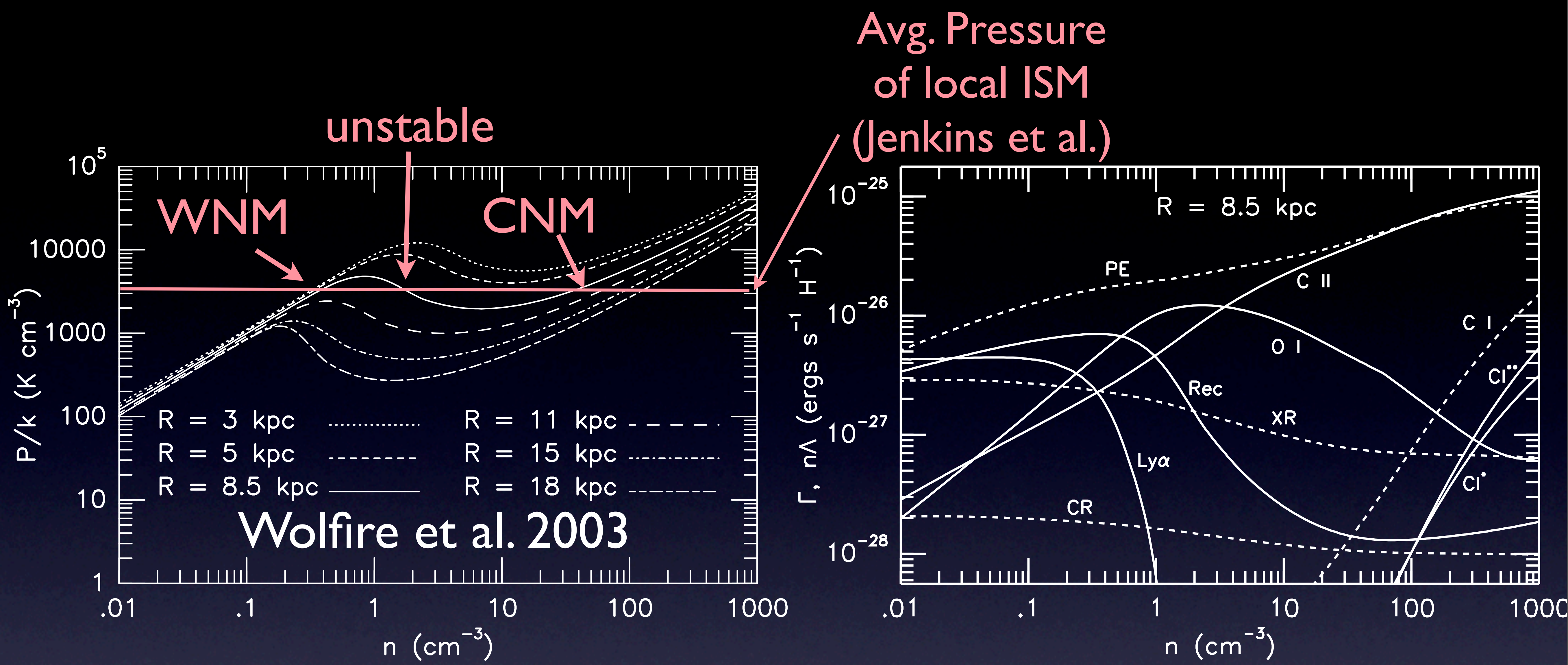

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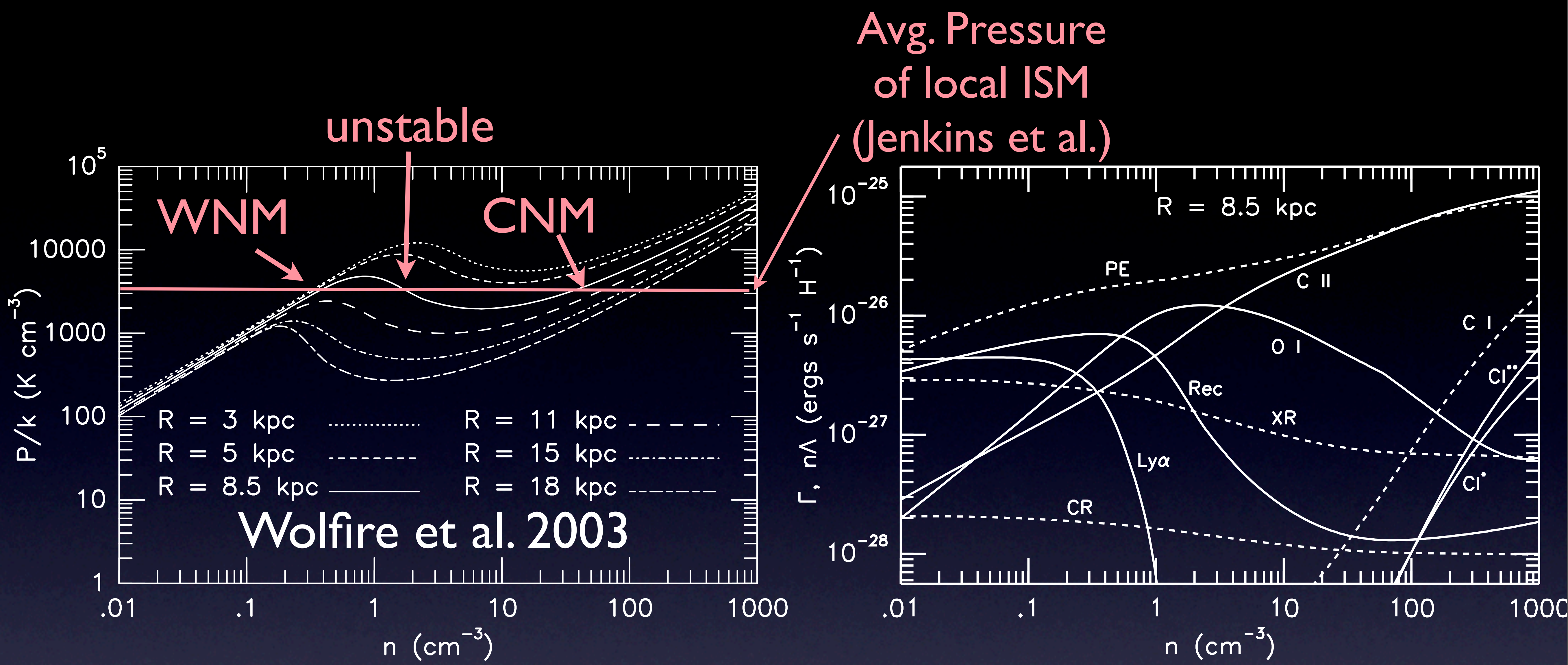

- [C II] 158 μm is dominant coolant of CNM
- Herschel and SOFIA can observe C II with high spectral resolution
- How much C II emits from CNM (use HI)
- Search for H_2 clouds with no CO?

Beginning of Cloud Formation: Atoms

The Beginnings of Star Birth

- Stars older than ~5-10 Myr are unassociated with molecular gas.
- Implies that star formation is fast and is linked to cloud formation
- Star formation must proceed shortly after cloud is born

Table 1
Star forming regions

Region	$< t >$ (Myr)	Molecular gas?
Coalsack	–	yes
Cha III	?	yes
Orion Nebula	1	yes
Taurus	2	yes
Oph	1	yes
Cha I,II	2	yes
Lupus	2	yes
MBM 12A	2	yes
IC 348	1-3	yes
NGC 2264	3	yes
Upper Sco	2-5	no
Sco OB2	5-15	no
TWA	~ 10	no
η Cha	~ 10	no

Hartmann et al. 2001

Chemistry - the limiting factor

- form molecular clouds - need to make molecules
  - ➡ H_2 on grains (limiting factor grain collision timescale - see Goldsmith et al. 2007)

$$\tau_{H_2} \sim 2 \times 10^9 \text{ yr} \left(\frac{T}{10 \text{ K}} \right)^{-0.5} \left(\frac{1 \text{ cm}^{-3}}{n} \right)$$

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Chemistry - the limiting factor

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    ➠shock needed to increase density: spiral arm, supernova, cloud-cloud collision

  - ➡ OR - H_2 is pre-existing (Allen, Pringle) -- this needs to be tested - need sensitive receivers to search for [C II] or [C I] with little H I (other galaxies?)