How to Make a Planet

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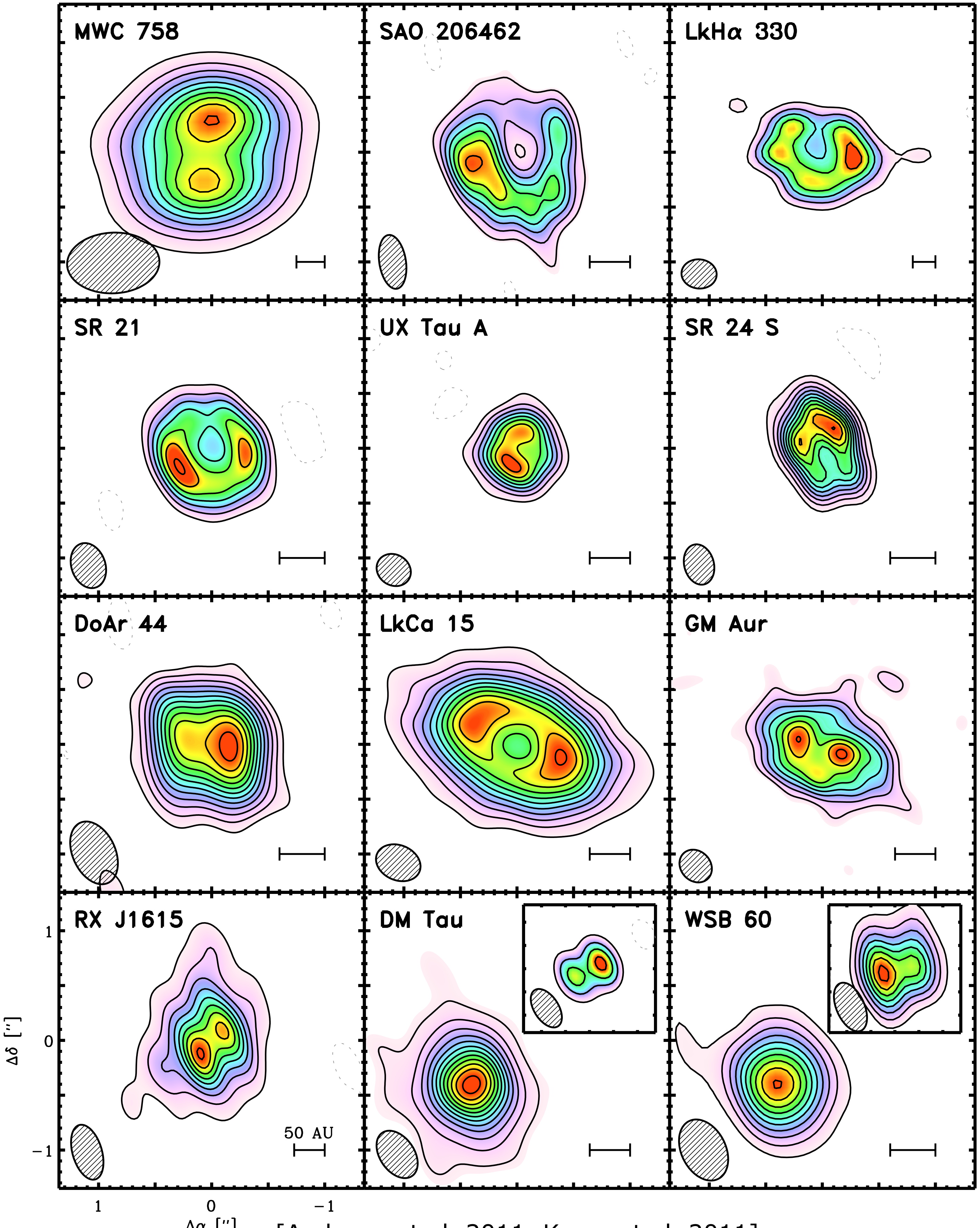
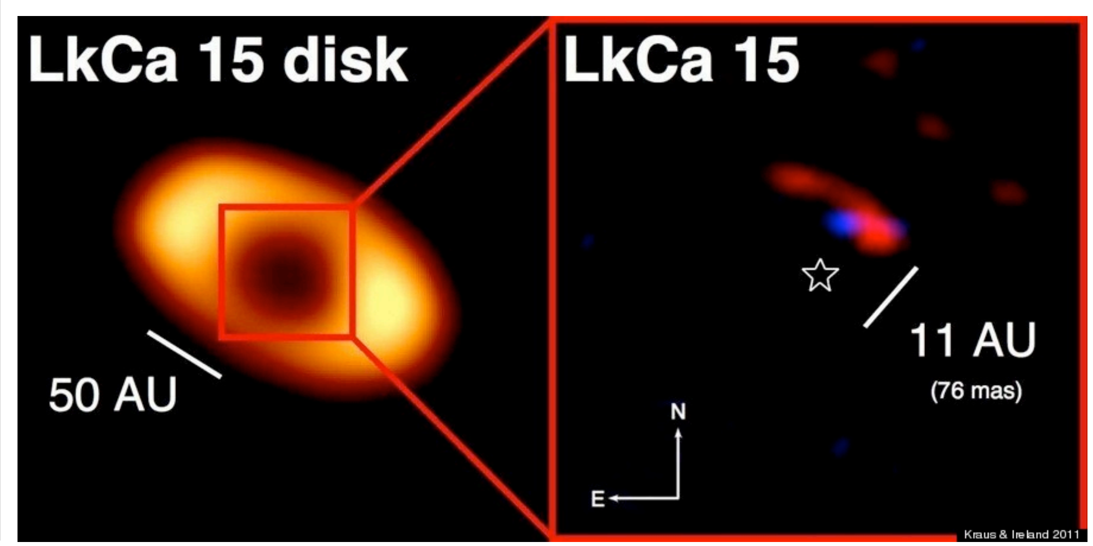
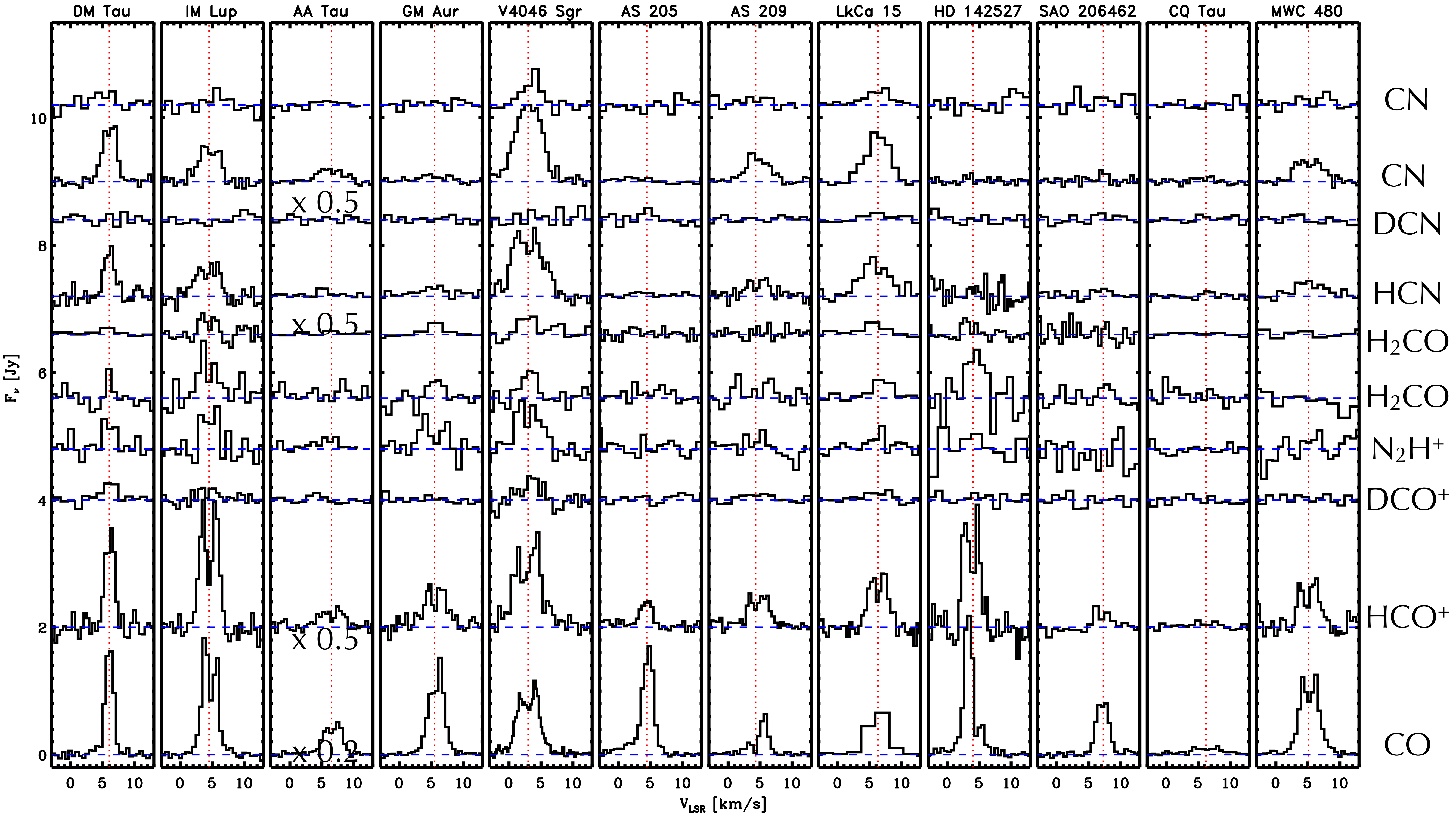
Observations of protoplanetary disks





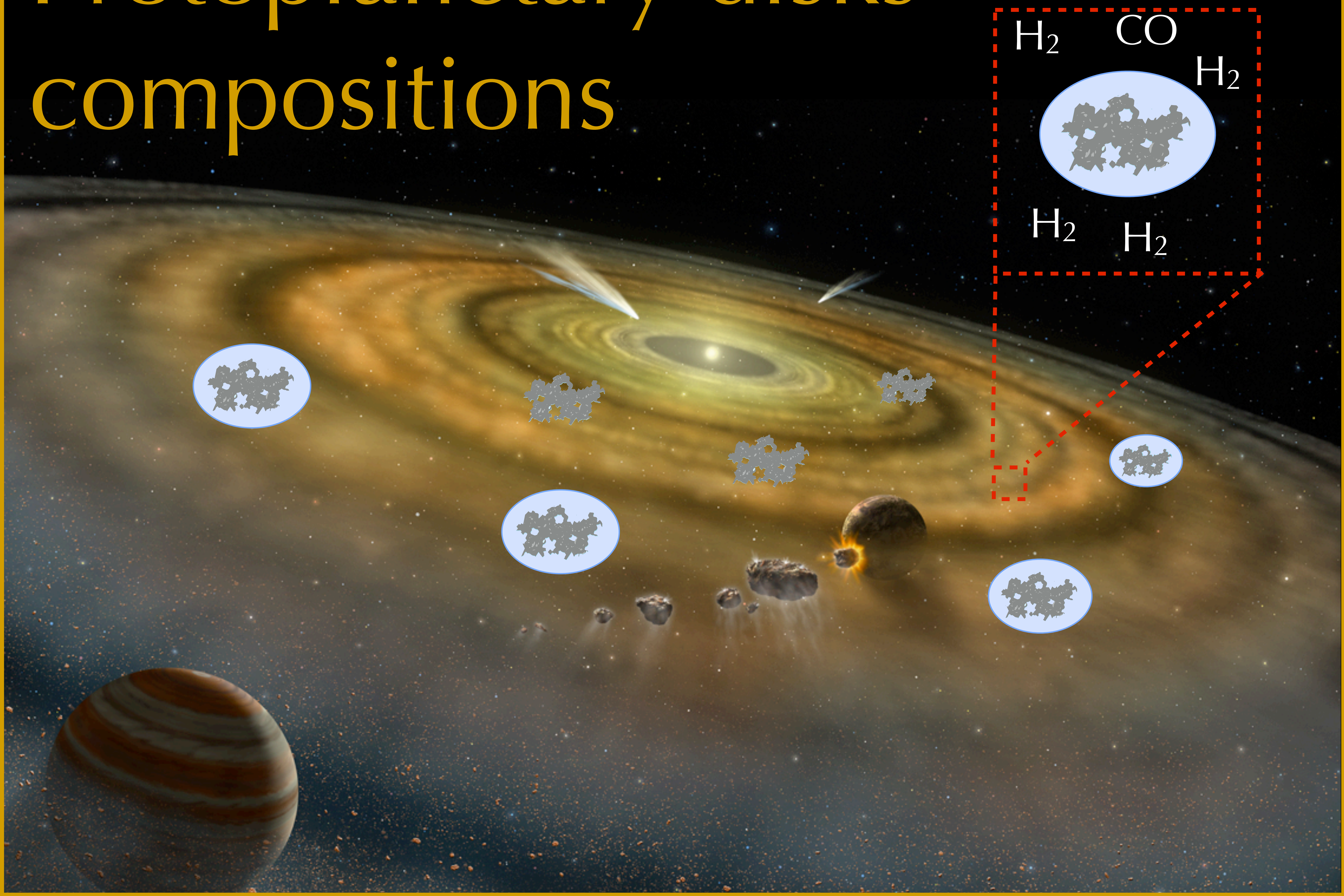
[Andrews et al. 2011, Kraus et al. 2011]

DiSCS: Disk Imaging Survey of Chemistry with SMA



[Öberg et al. 2010a, 2011c]

Protoplanetary disks compositions



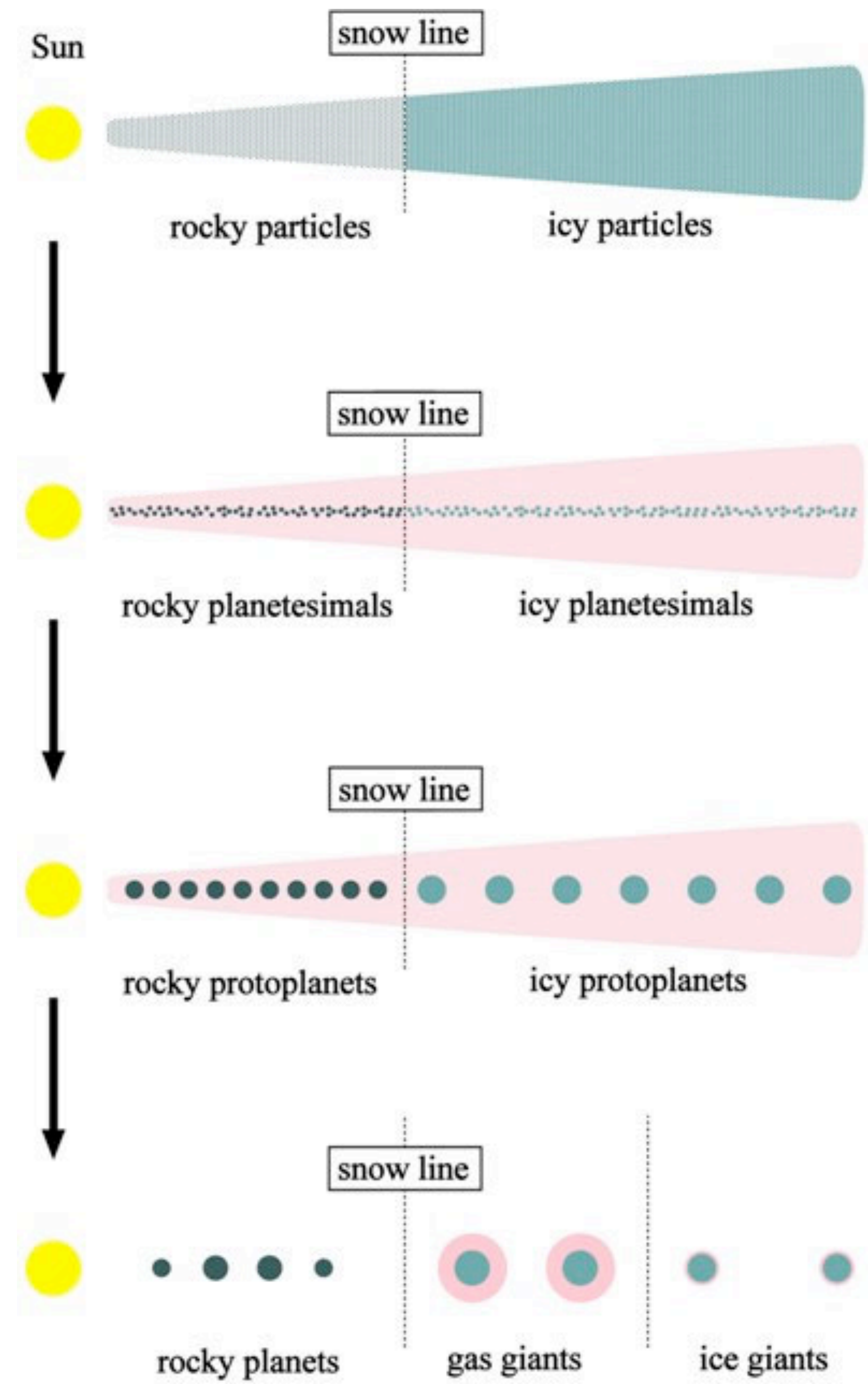
Planet formation through core accretion

Interstellar dust grains coagulate to form cm, m and 1-100 km-size planetesimals

↓

Gravitational focusing results in dust and planetesimal accretion

~1 earth mass accretes slowly from rocky grains: no or limited accretion of volatiles to form rocky planets	~10 earth mass core accretes in less than 1-5 millions years: runaway gas accretion to form gas-giants	core accretes slowly from icy particles: little gas accretion to form ice giants



[Subaru press release image, Honda et al. 2009]

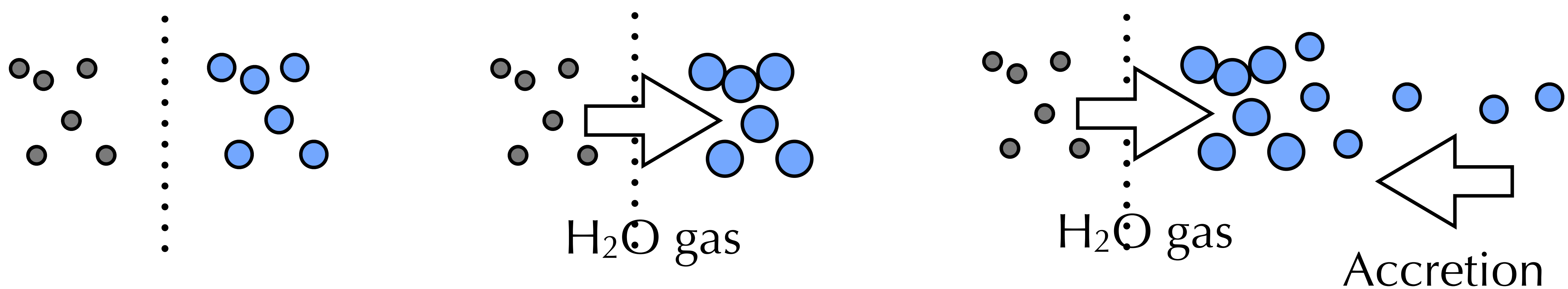
The physical effects of snowlines on planet formation

Icy grains are stickier than bare grains.

Volatile molecules (except for H_2) are ~2-3 times more abundant than silicate grains (1) → dramatic grain column density increases at snowlines + coldfinger effects (2) → enhanced planet formation.

Pressure bumps may even trap material exterior to the snowline (3).

H_2O is the most abundant volatile → planet formation should be the most efficient right outside of the H_2O snowline.

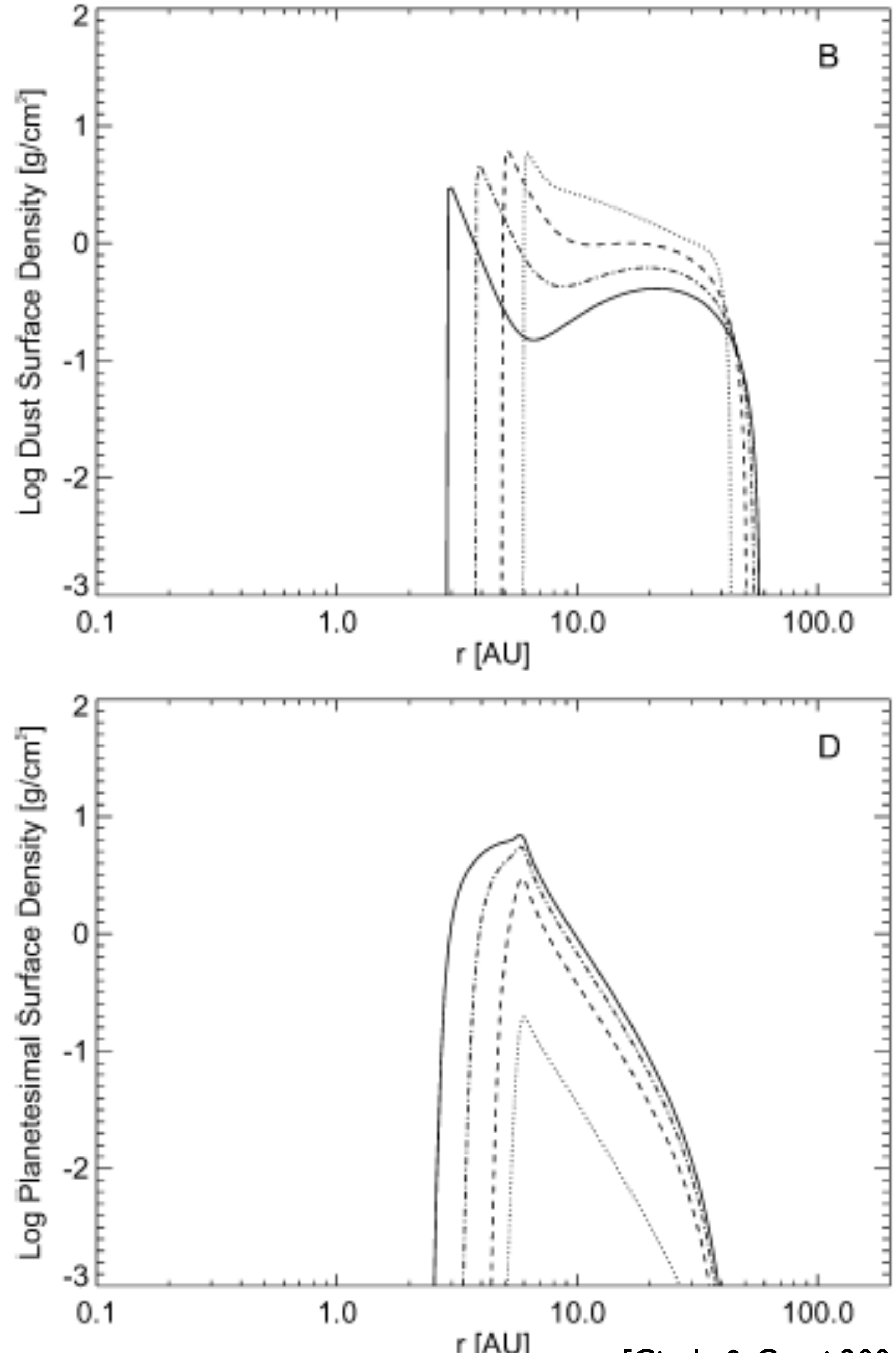


Gas giants should form near snowlines

Simulations reveal steep increase in dust surface density at H_2O snowline.

Planetesimal formation most efficient somewhat exterior to the snowline.

Largest planets, i.e. gas giants, should form there.

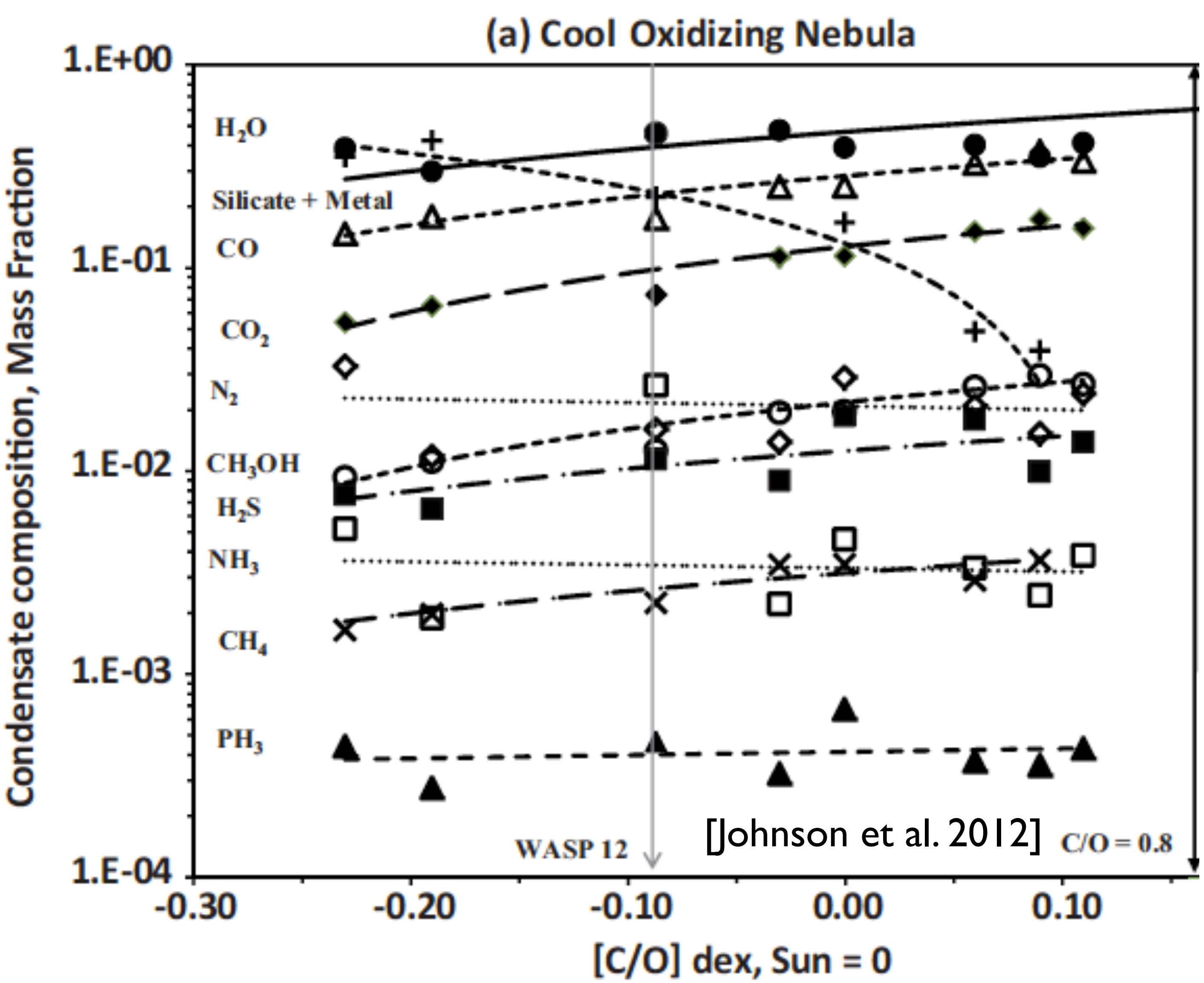


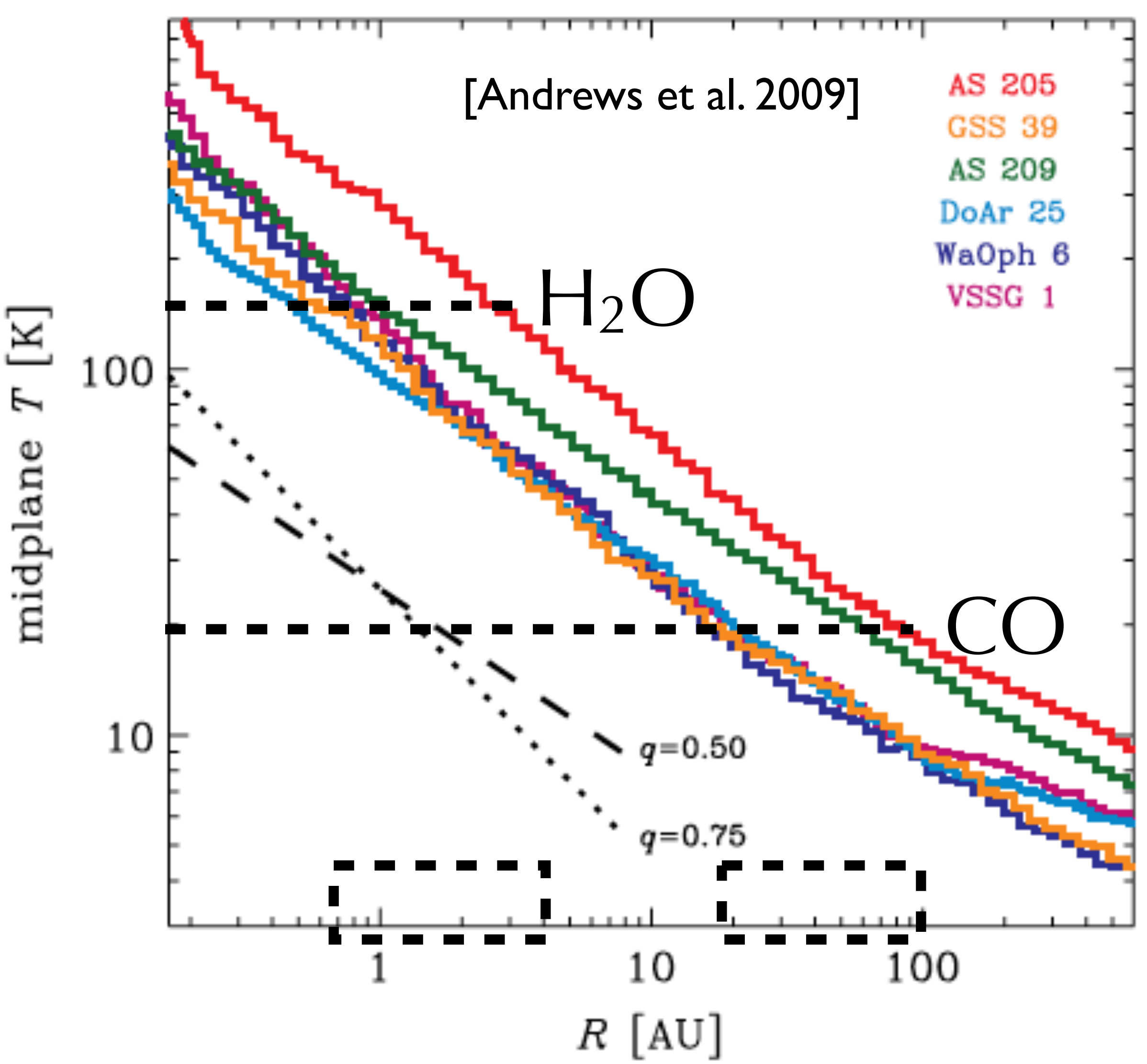
[Ciesla & Cuzzi 2006]

What if H_2O is not the most common volatile?

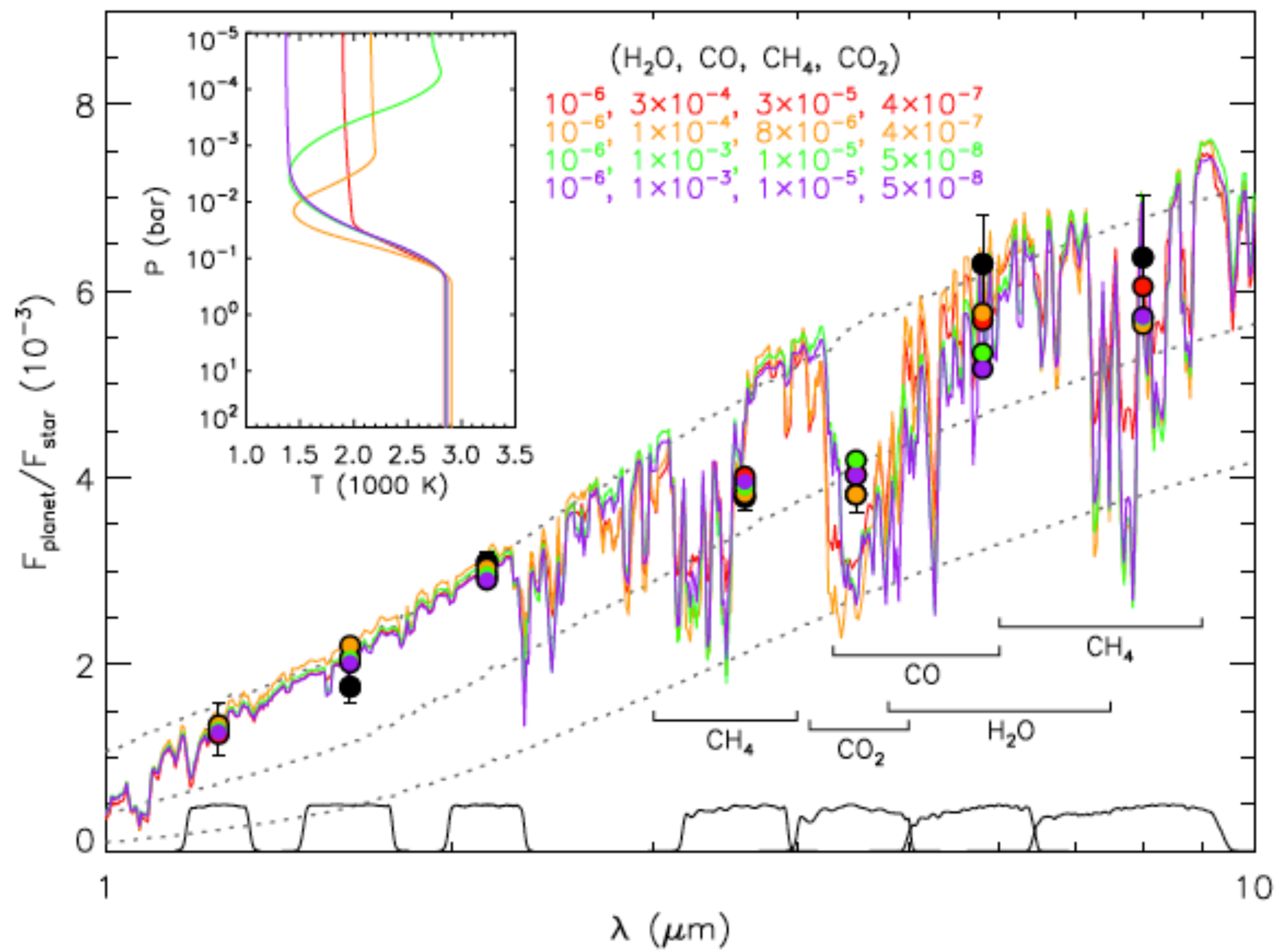
Some stars with exo-planets have stellar C/O ratios larger than in the sun.

In these systems CO and CO_2 may form more important snowlines than H_2O, potentially changing the locations of gas giant formation.

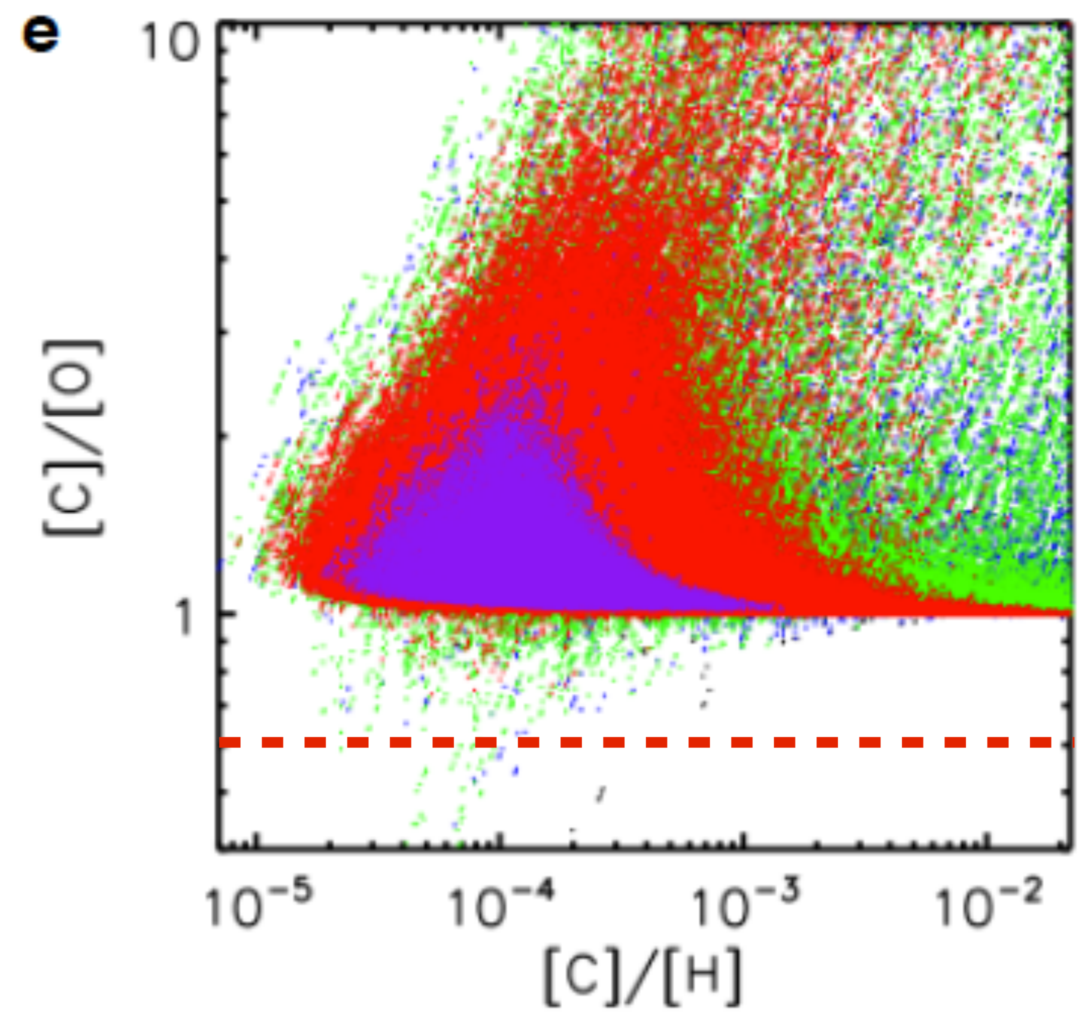




Non-stellar C/O ratios in gas giants



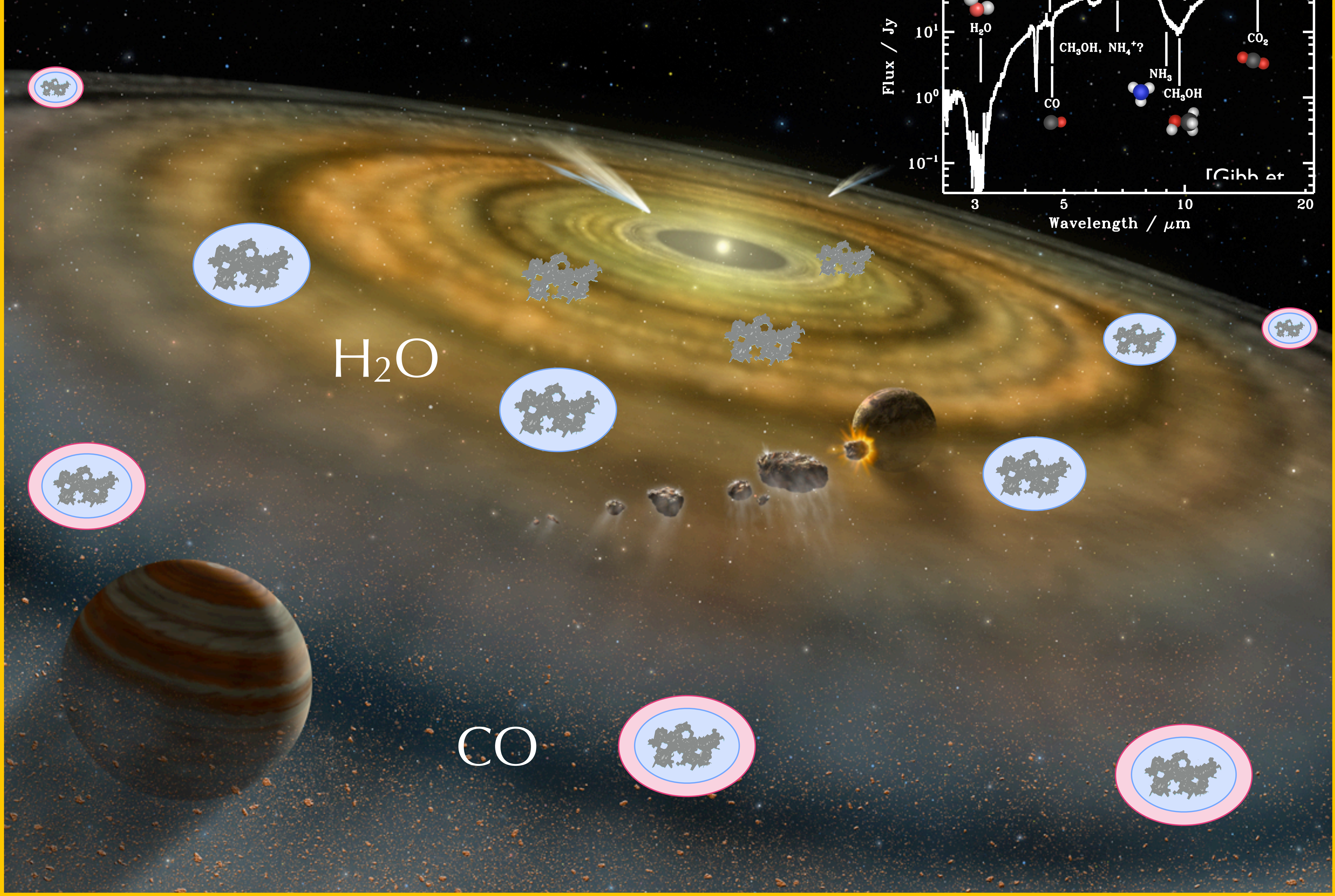
[Madhusudhan et al. 2011]



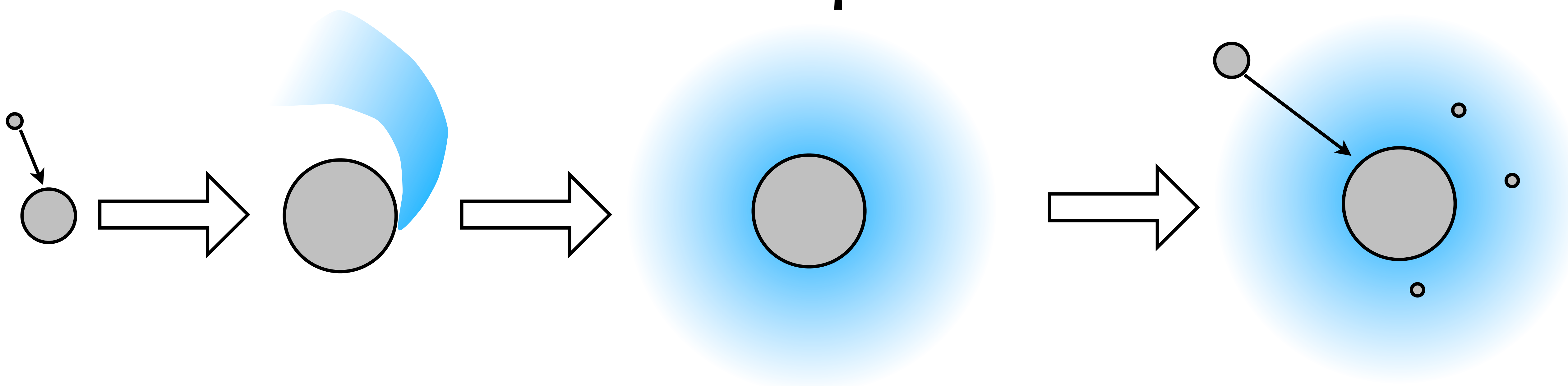
Atmospheric modeling of hot Jupiters reveal elemental deviations from Stellar values.

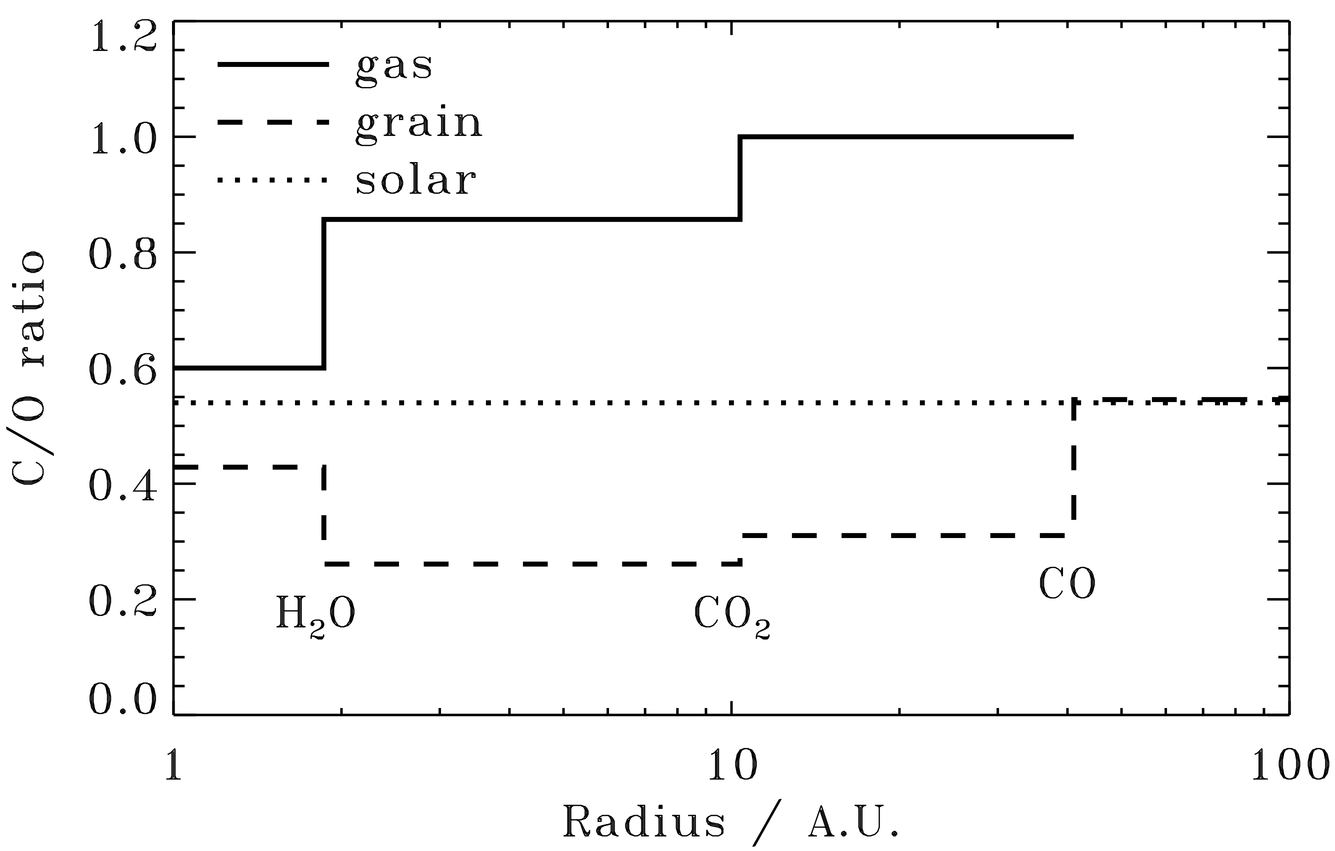
Enhanced C/O has so far been difficult to explain, especially in Wasp-12b where C/H is “normal”.

Disk snowlines



Chemical Effects of Snowlines on Bulk Planet Compositions



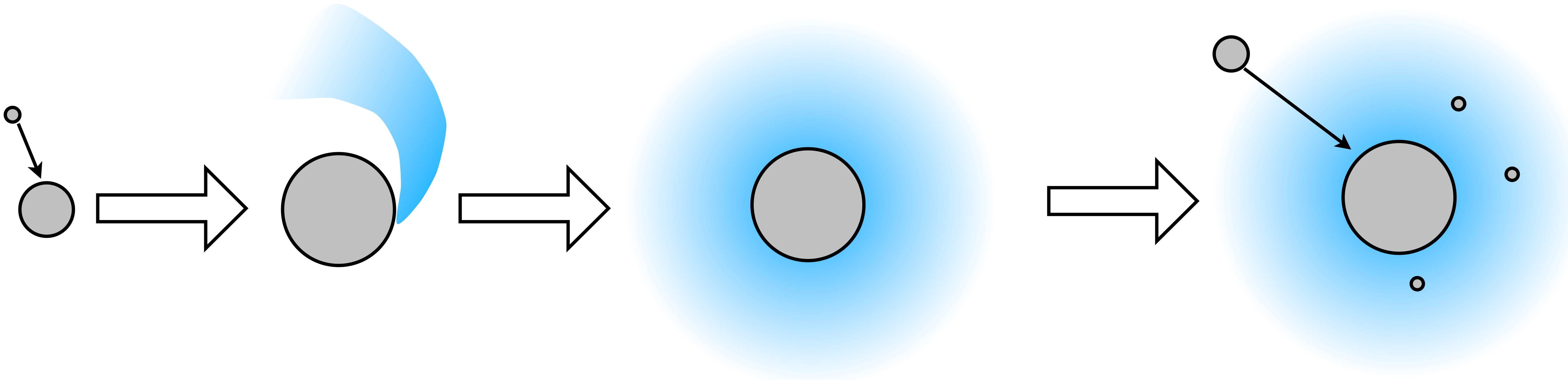


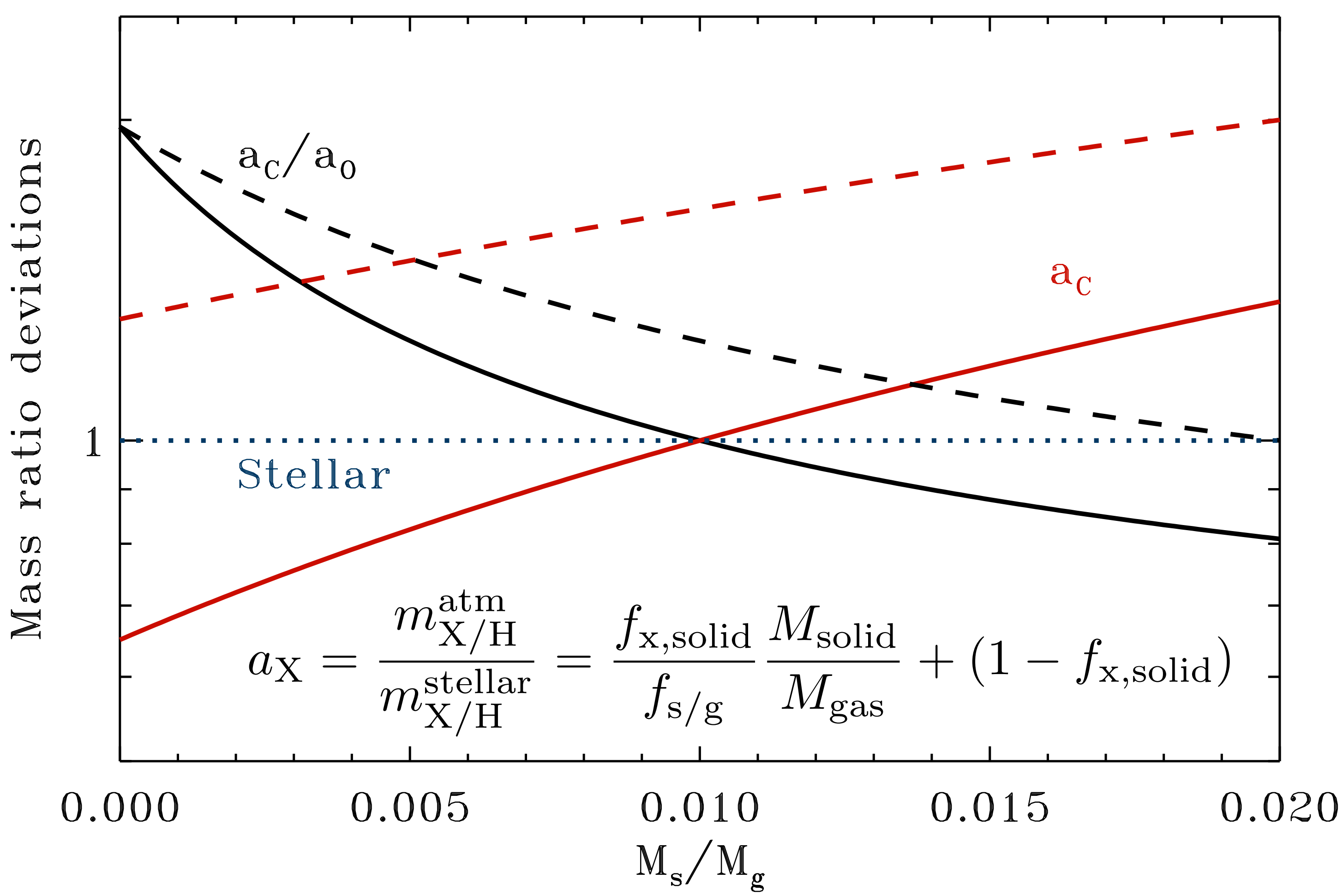
Assuming interstellar molecular abundances, the C/O ratio between the CO_2 and CO snowlines will be ~1.

If a gas giant accretes its core from solids and envelope from gas, its atmosphere may achieve the same ratio assuming now planetesimal pollution or core dredging.

[Öberg et al. 2011d]

Gas Giant C/O Ratios

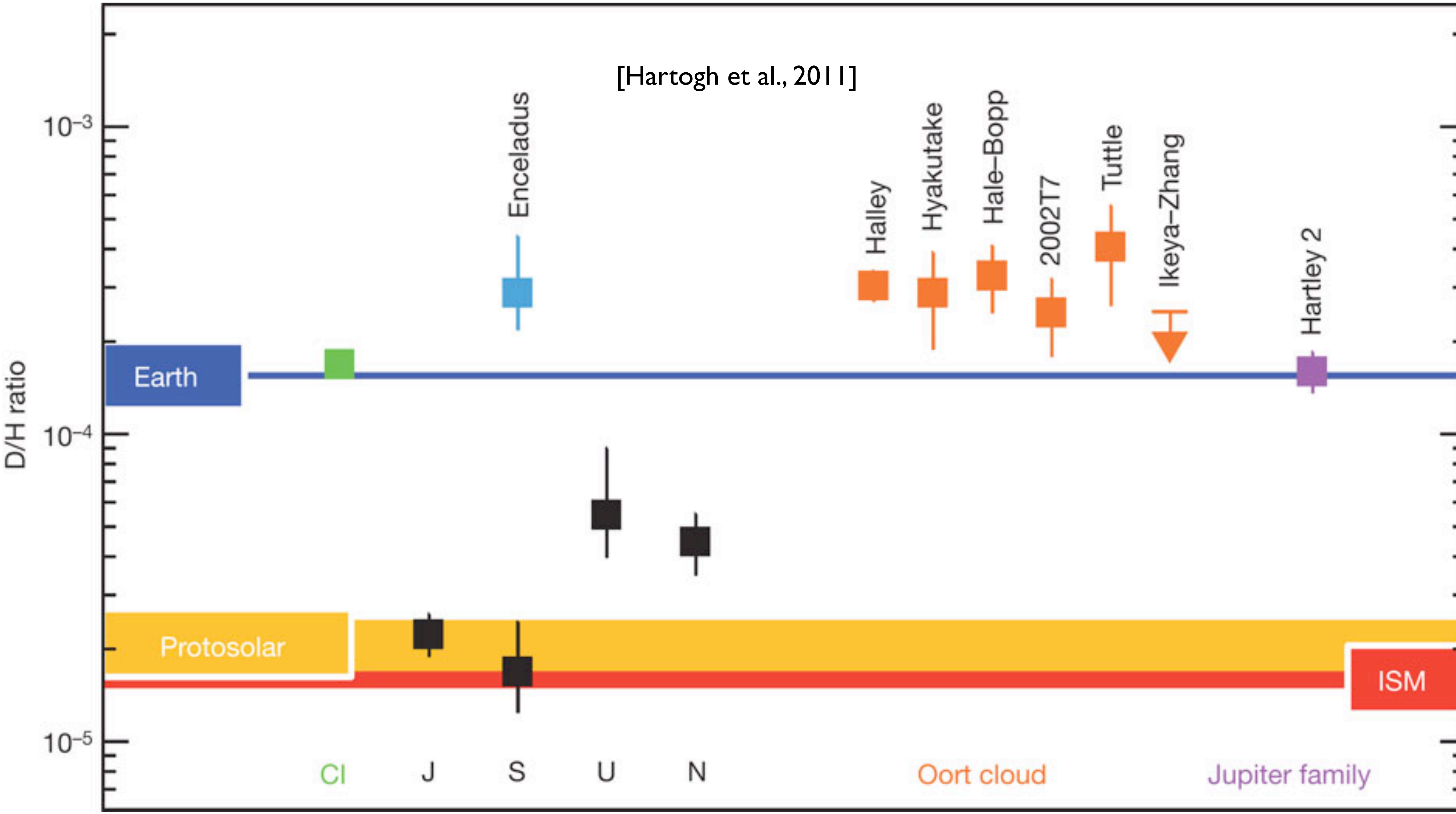




Snow-lines and bulk planet compositions

- Planet core formation is regulated by formation location w.r.t. major condensation front
- The rate of planet core formation with respect to gas dissipation determines which type of planet forms (rocky planet, gas giant, ice giant)
- Gas giant envelope compositions can deviate from stellar compositions because of accretion of gas depleted of certain elements, and because of pollution by certain types of solids.

Delivery of volatiles to Earth from Comets

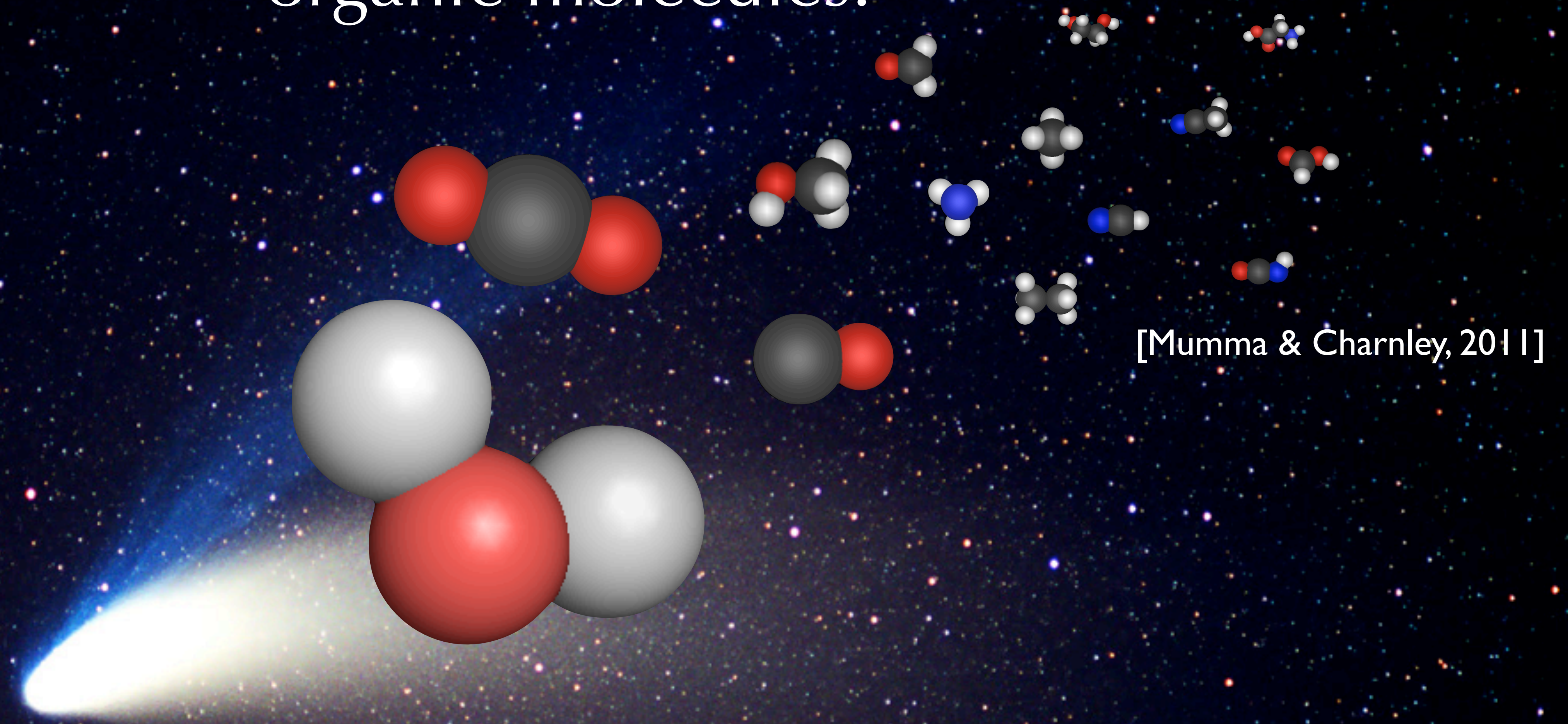


Deuterium enrichment expected at low temperatures because:

$XH + HD \leftrightarrow XD + H_2$ $\Delta H < 0$, but ΔH is "small"

Comet Compositions

Primitive, dirty snowballs; dominated by water, and rich in organic molecules.



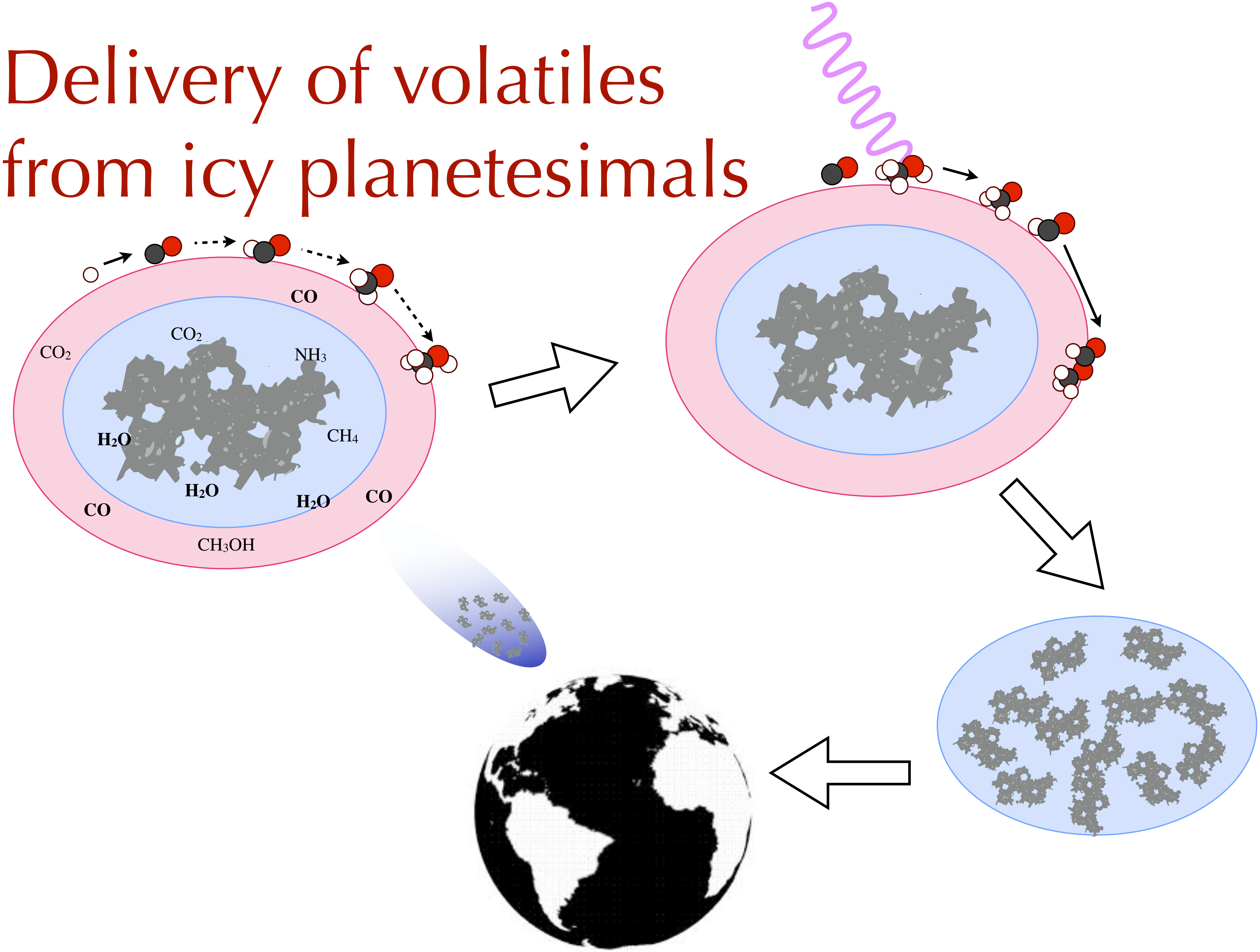
[Mumma & Charnley, 2011]

Templates of volatile-rich planetesimals in the Solar Nebula.

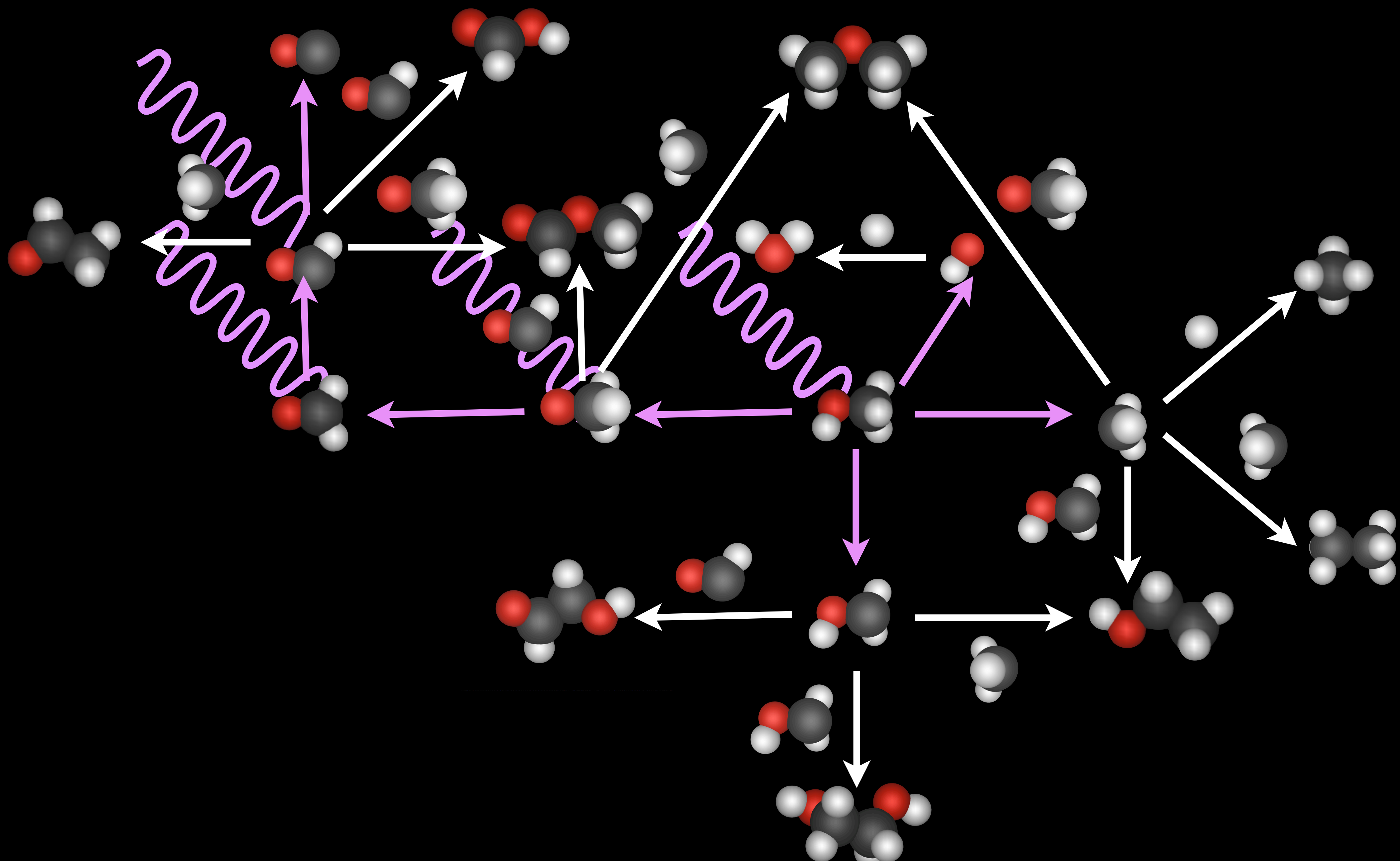
Possible sources of volatiles on inner solar system planets.

Chemically diverse, from organics rich to organics poor.

Delivery of volatiles from icy planetesimals

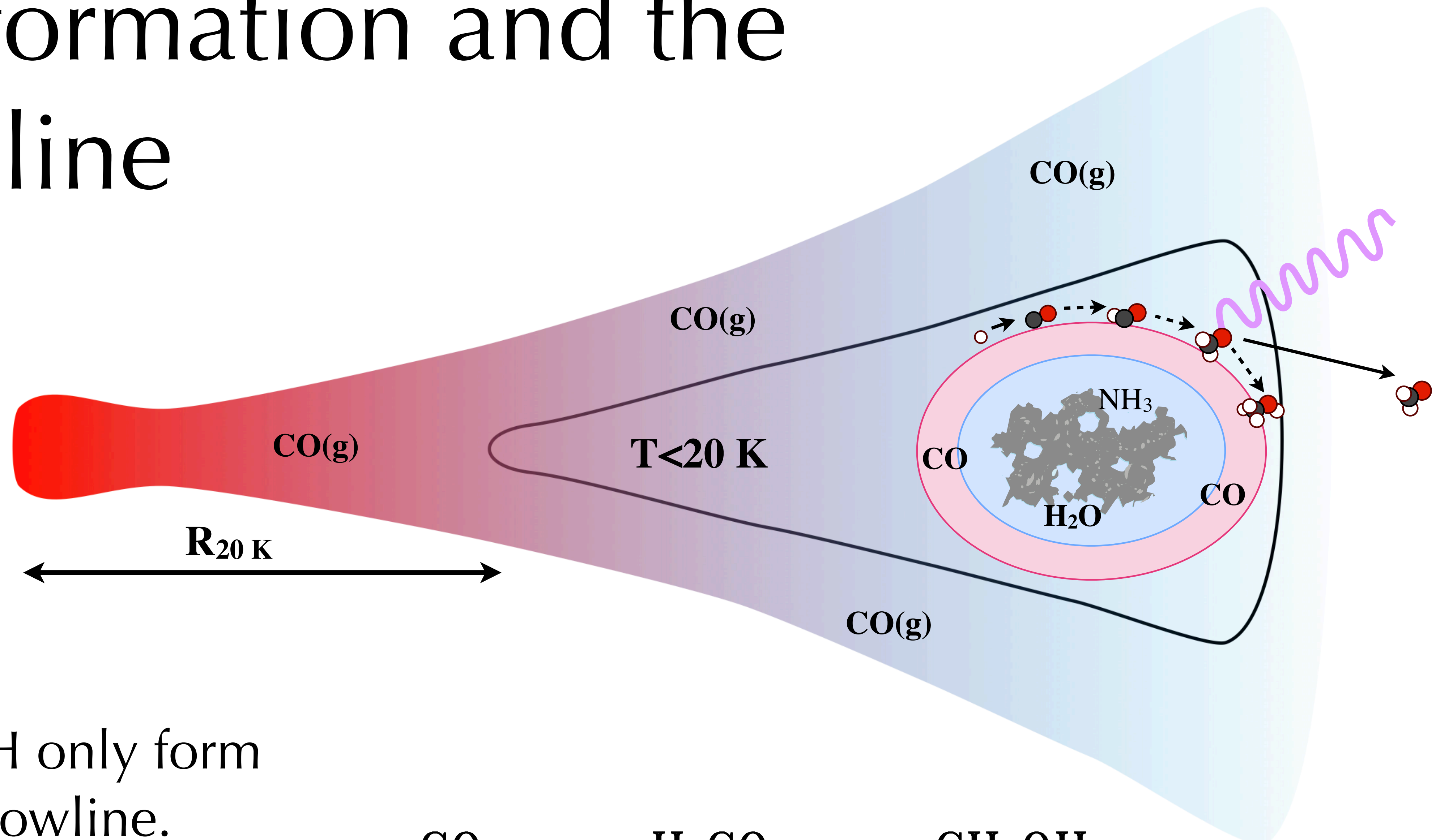


CH_3OH Ice Photochemistry as a Pathway to Prebiotic Molecules



[Öberg et al. 2009d]

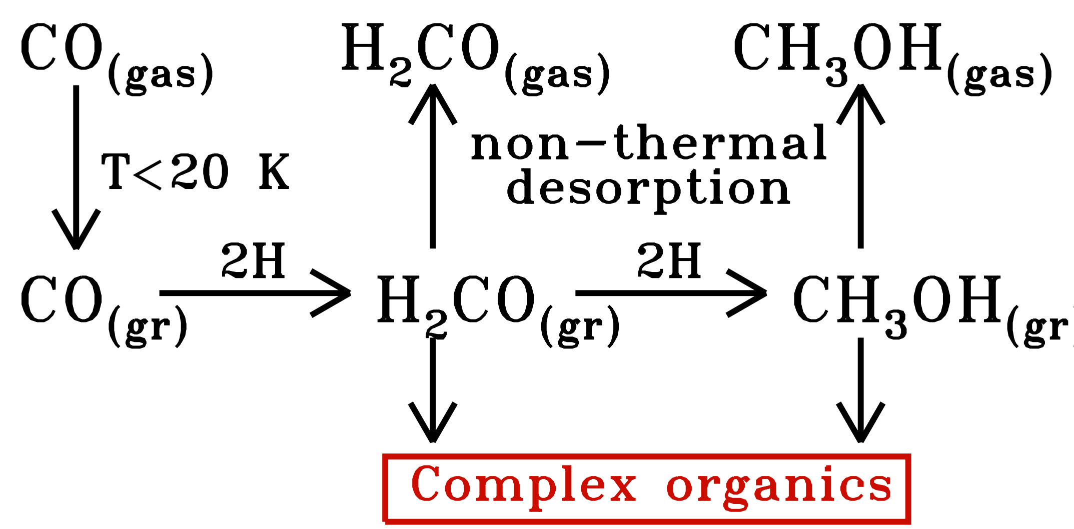
Organic formation and the CO snowline



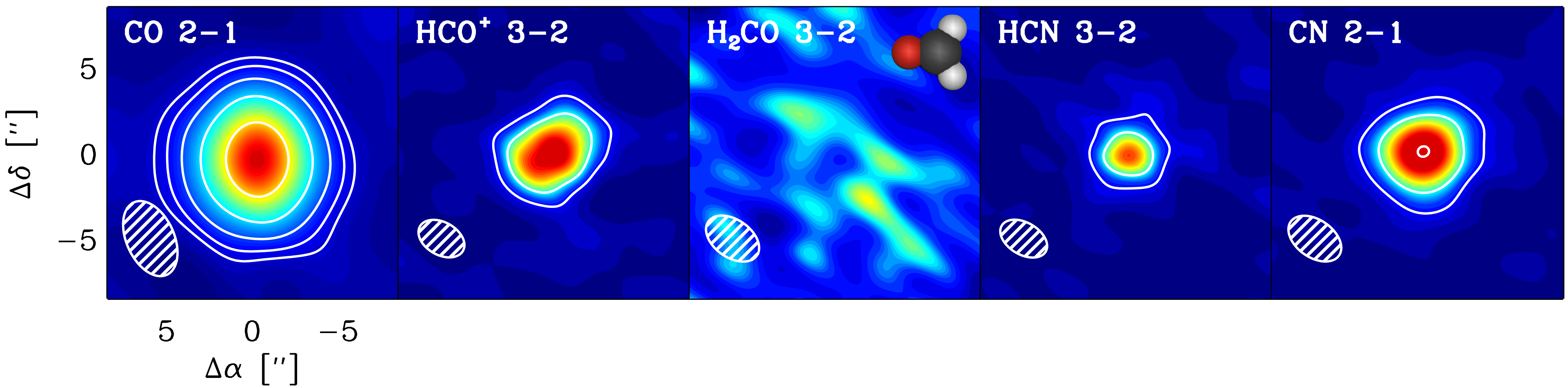
H_2CO and CH_3OH only form beyond the CO snowline.

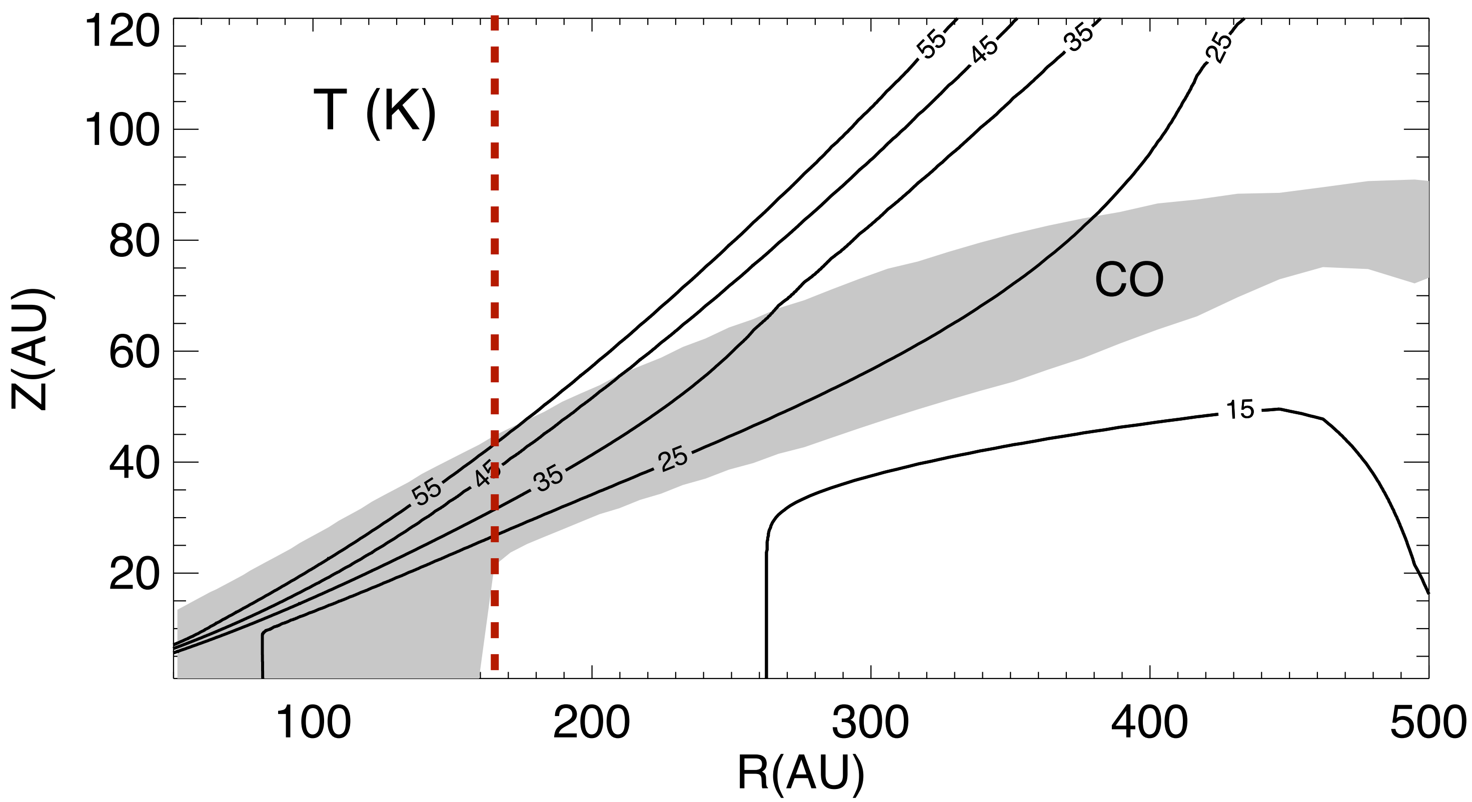
Complex organics dependent on CH_3OH ice chemistry will only form in the outer disk.

Planetestimals need to accrete outer disk material to become rich in prebiotic molecules.



H_2CO and the CO snowline in HD 163296





Multi-transitional CO data (J=2-1, 3-2, 6-5 and four isotopologues) can only be fitted with CO freeze-out outside of 170 AU, corresponding to a freeze-out temperature of ~19 K

Consistent with H_2CO ring radius

H_2CO formation from CO confirmed?

[Qi, d'Alesssio, Öberg et al. 2011, Qi, Öberg et al. 2012 in prep.]

The Role of Snowlines in Shaping Planet Formation

H_2O snowline location key for where rocky planet, gas giant and ice giants form.

The bulk properties of gas giant envelopes depend on CO and H_2O snowlines.

The prebiotic ice chemistry is most efficient outside of the CO snow-line and comets seeding life likely originating in the outer solar system.

Low-mass stars are likely more hospitable to prebiotic chemistry since CO snowlines are closer to the planet-forming zone.