Connecting the Dots…

Between Interior Composition and Outgassing

A Celebration of the Rosetta Mission

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Alas, Knowledge is a Pain

I thought, I knew EVERYTHING,

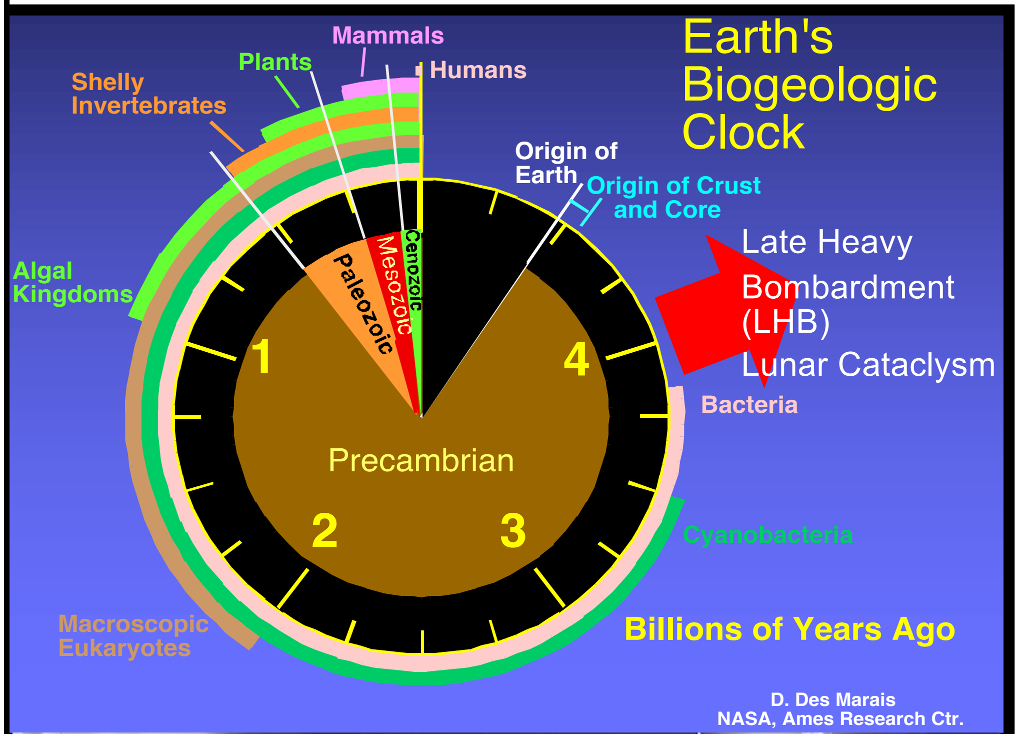
That was Last Night!

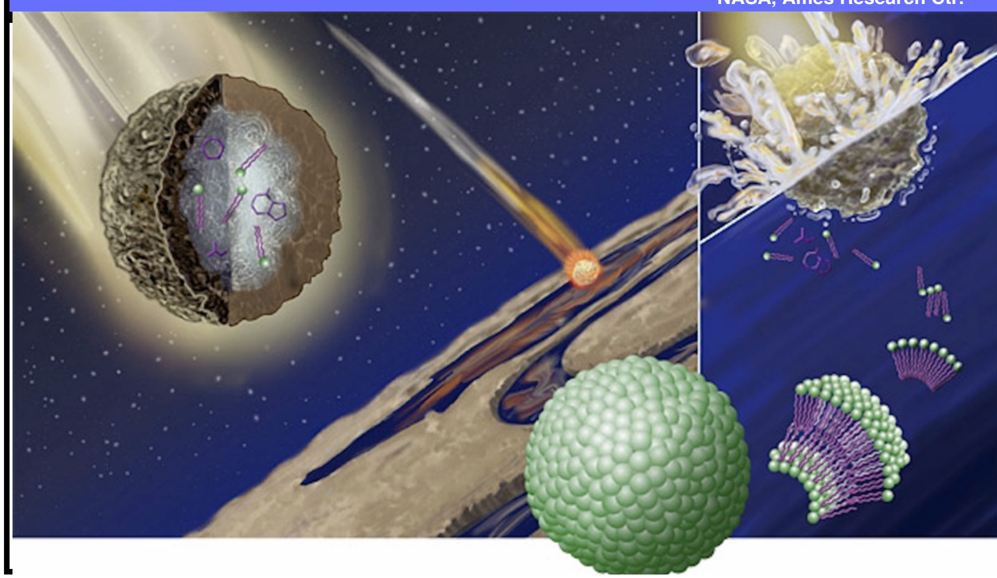
But, as I woke up this Morning,

I am more Confused and Lost!

-Murthy S. Gudipati (May 29, 2018)

Earth, Comets & Asteroids, and Origin of Life





Though my interest in Comets is due to “Potential Prebiotic Molecular Delivery” by Comets to Earth triggering possible ”Origin of Life”, **I would NOT talk about this today.**

The Road is long and the Journey has just began to understand the Origin of Life on Earth!

Comets

- **Genesis:** Molecular Clouds
- **Growth:** Protoplanetary Stage
- **Hibernation:** Kuiper Belt Objects
- **Awakening:** Centaurs
- **Youth:** Short period Comets

Some Comets Die Young!

50 Million Years of Radiation

Dense Molecular Clouds – Formation & Lifetime **~50 Myr** **(10K)**

Protoplanetary Pebbles & Cometesimals – **~50 Myr** **(10 – 130 K)??**

KBO Precursors – Scattered out by Saturn & Jupiter **(Warmer?)**
- Formed where they are now? (**~30 K)**

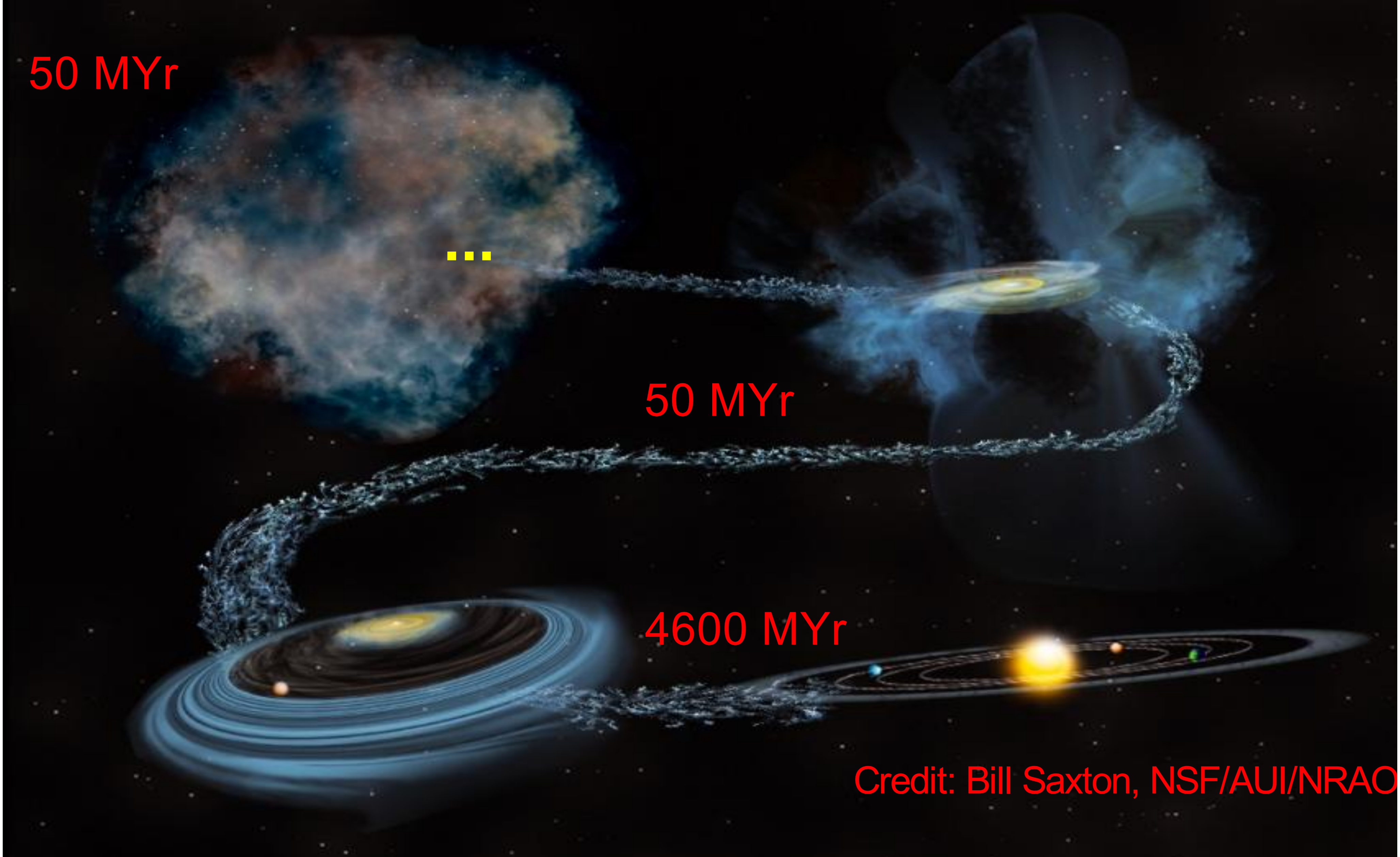
Rest of **4600 Myr** – Hibernation in KBO Region? (~**30 K)**

Centaur – **A few Myrs** **(~50 K – 100 K)**

Short Period Comets – **A few Hundred Years**?? **(120 K – 350 K)**

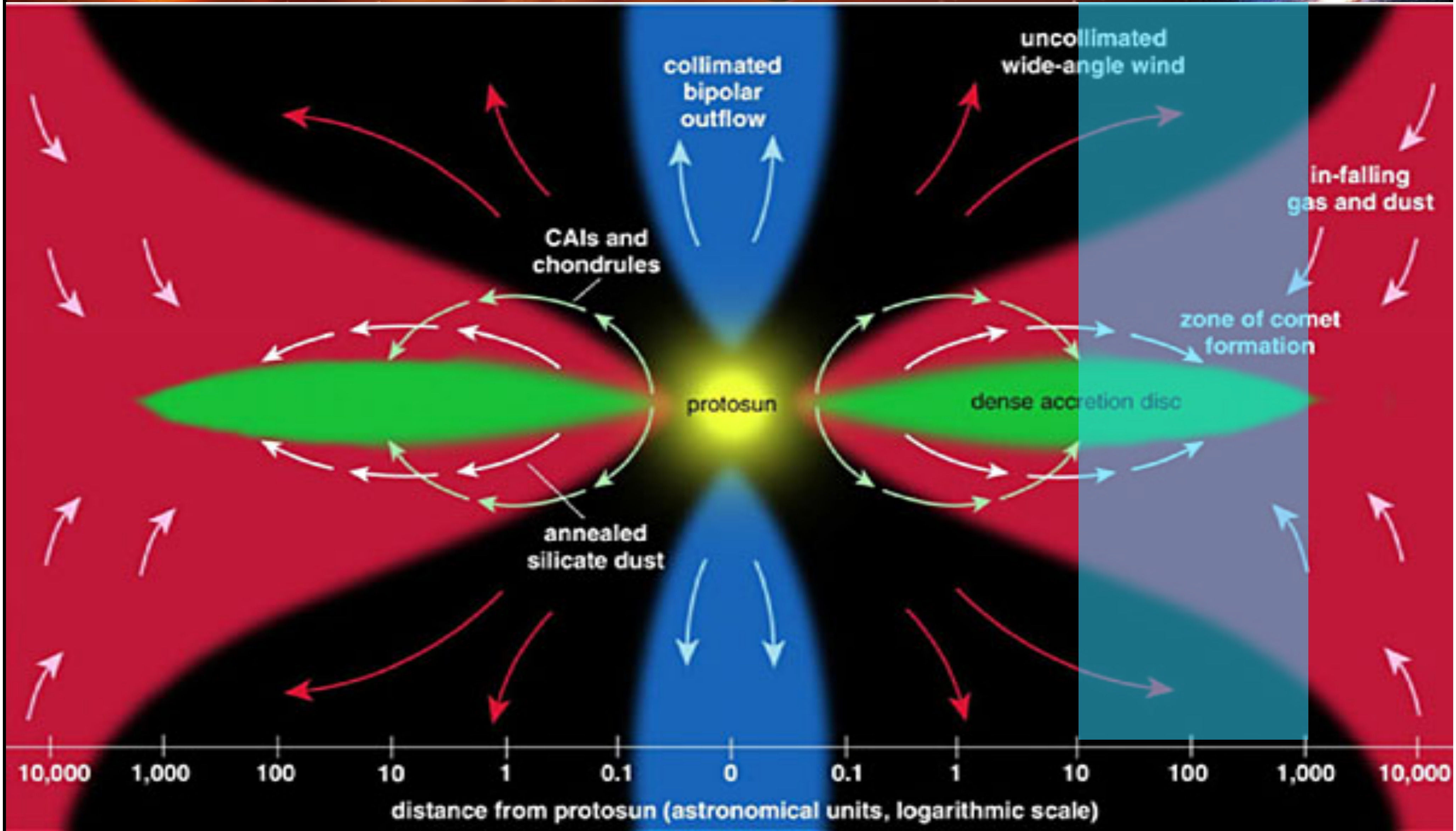
Without Tracers that are "preserved",
The Story is only half-complete!

Tracers Connecting the Dots…



Credit: Bill Saxton, NSF/AUI/NRAO

Protoplanetary Disk is not a Washing Machine
--Kathrin Altwegg

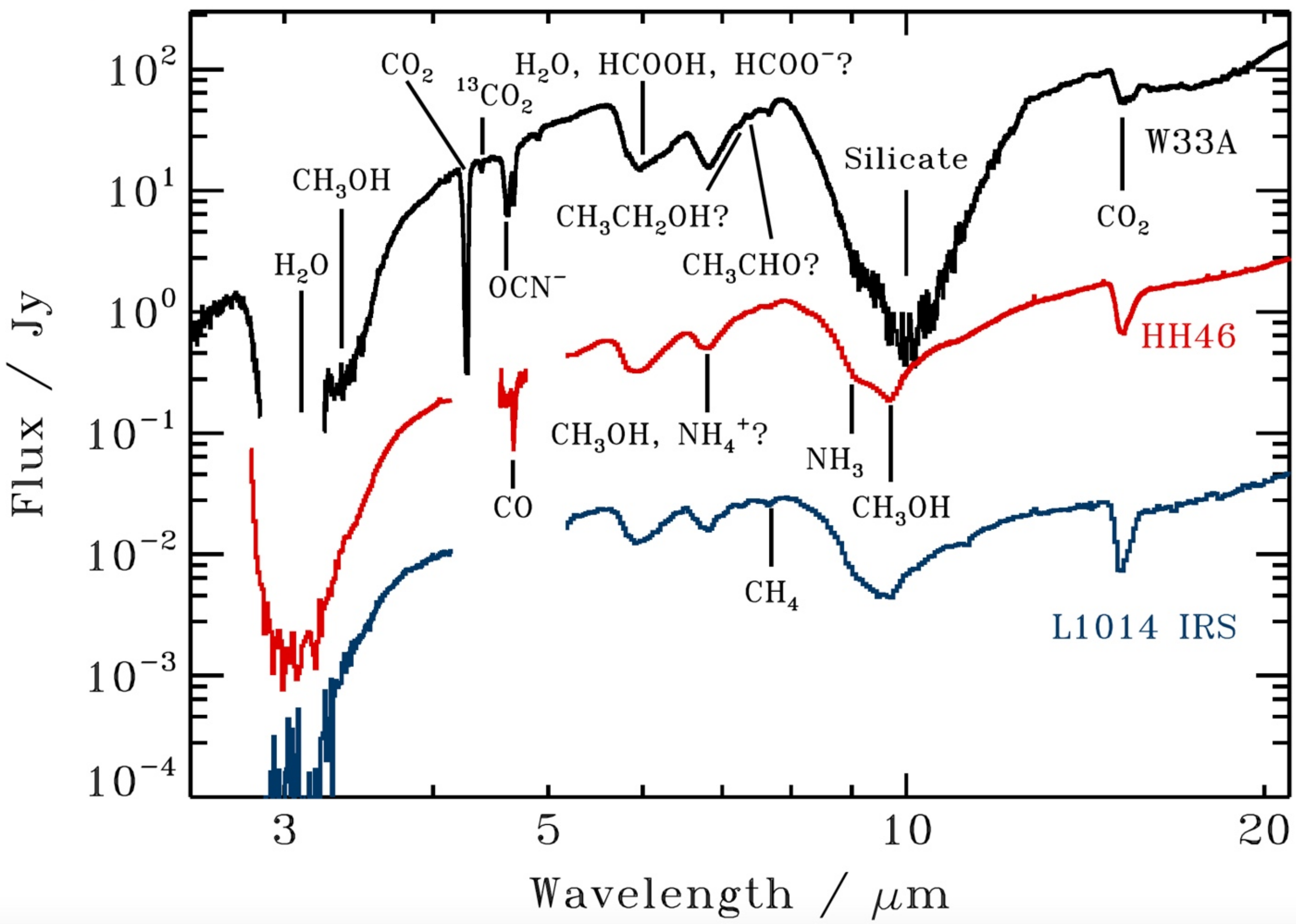


(from Nuth, J. A., 2001, *American Scientist*, v. 89, p.230.)

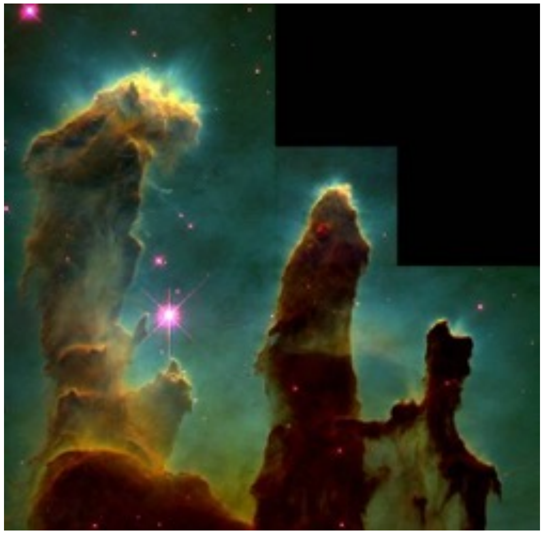
Molecular Clouds towards embedded Stars and Protostars

Amorphous Interstellar Ices

The Astrophysical Journal, 740:109 (16pp), 2011 October 20
Boogert et al.



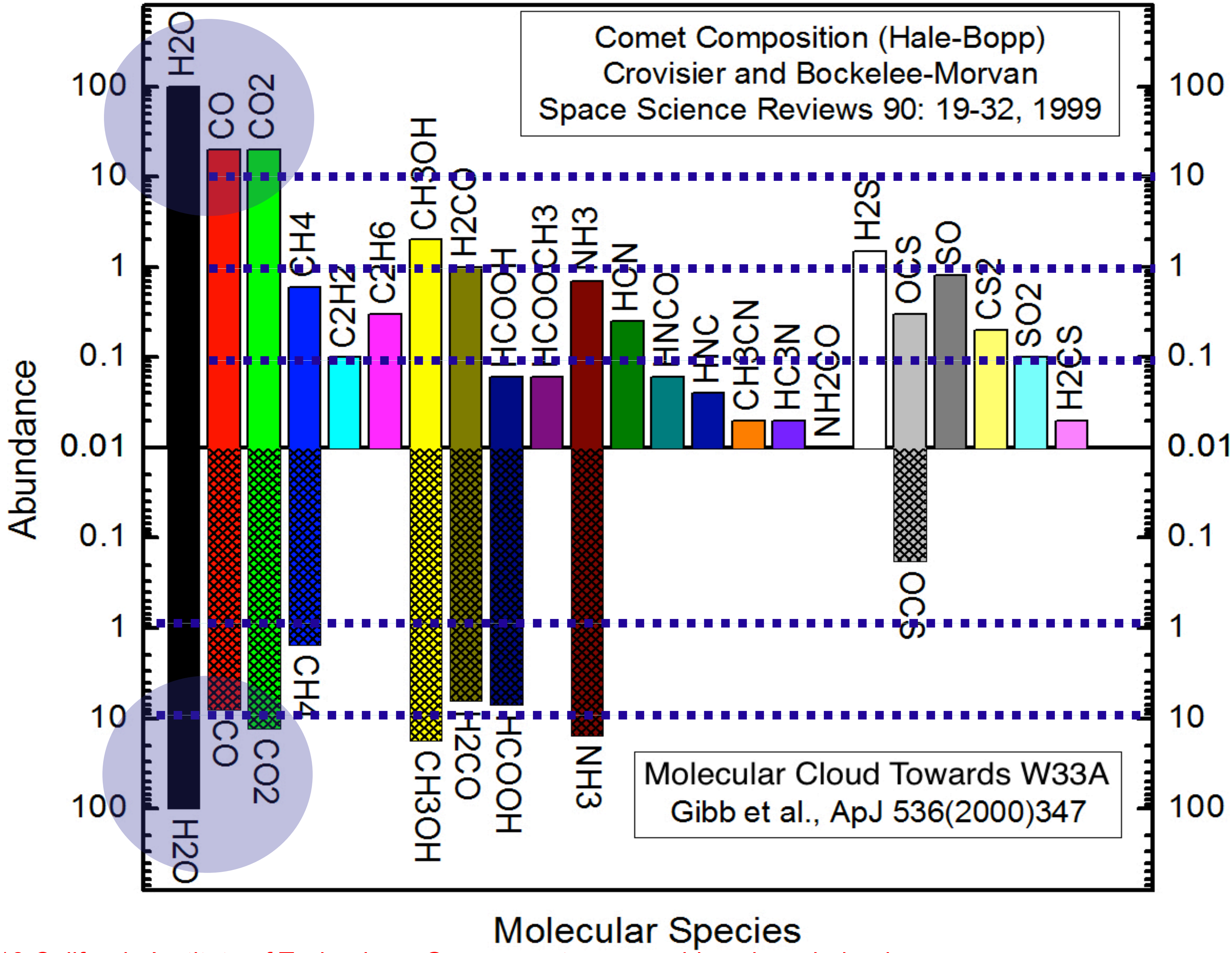
Star-forming Regions / Protostars



Dense Molecular Clouds (The Eagle Nebulae)

Oort Cloud Comets – Similar Composition?

Similar Composition: Oort Cloud Comet(s) and Interstellar Ice Grains

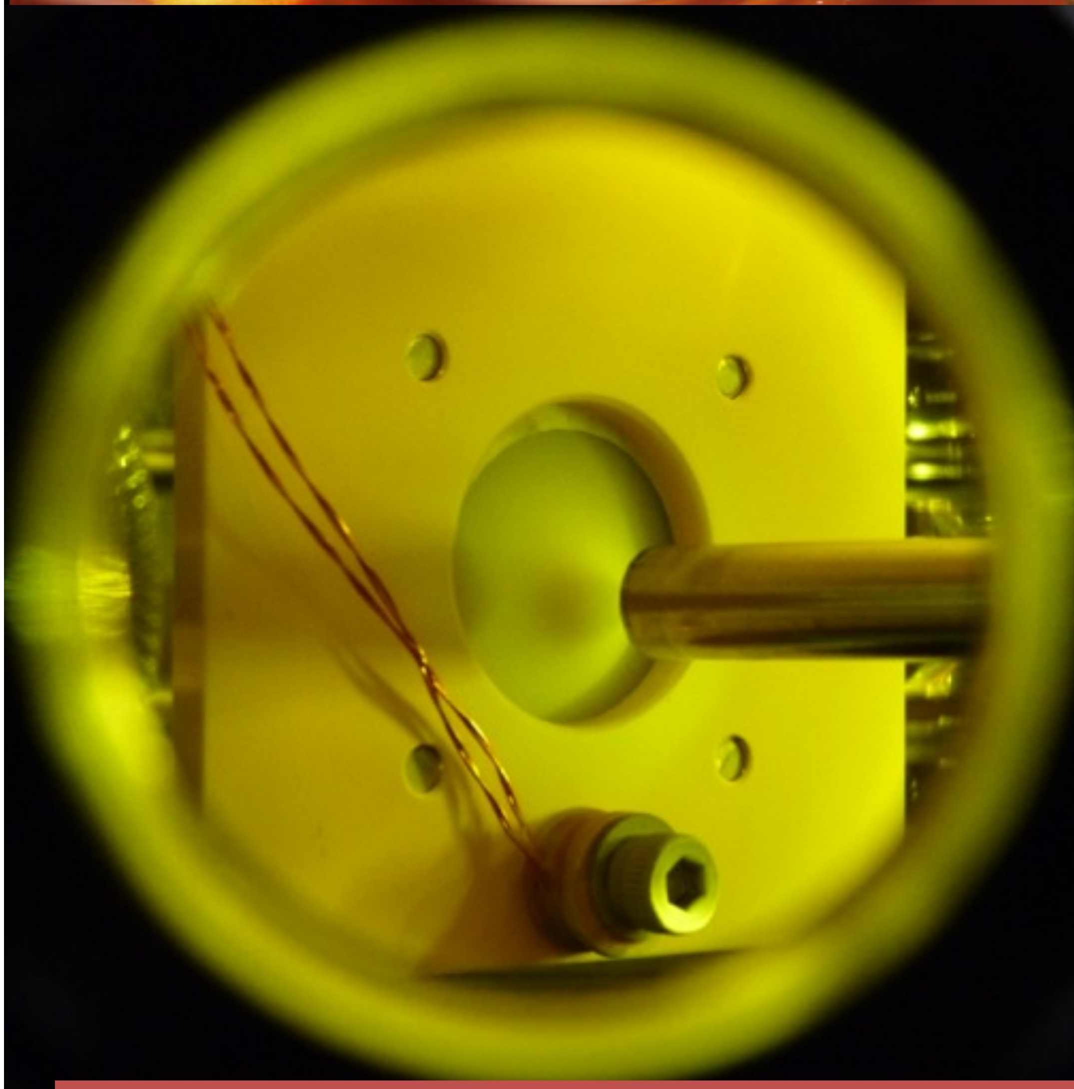


Tracer No. 1 – Amorphous Ice

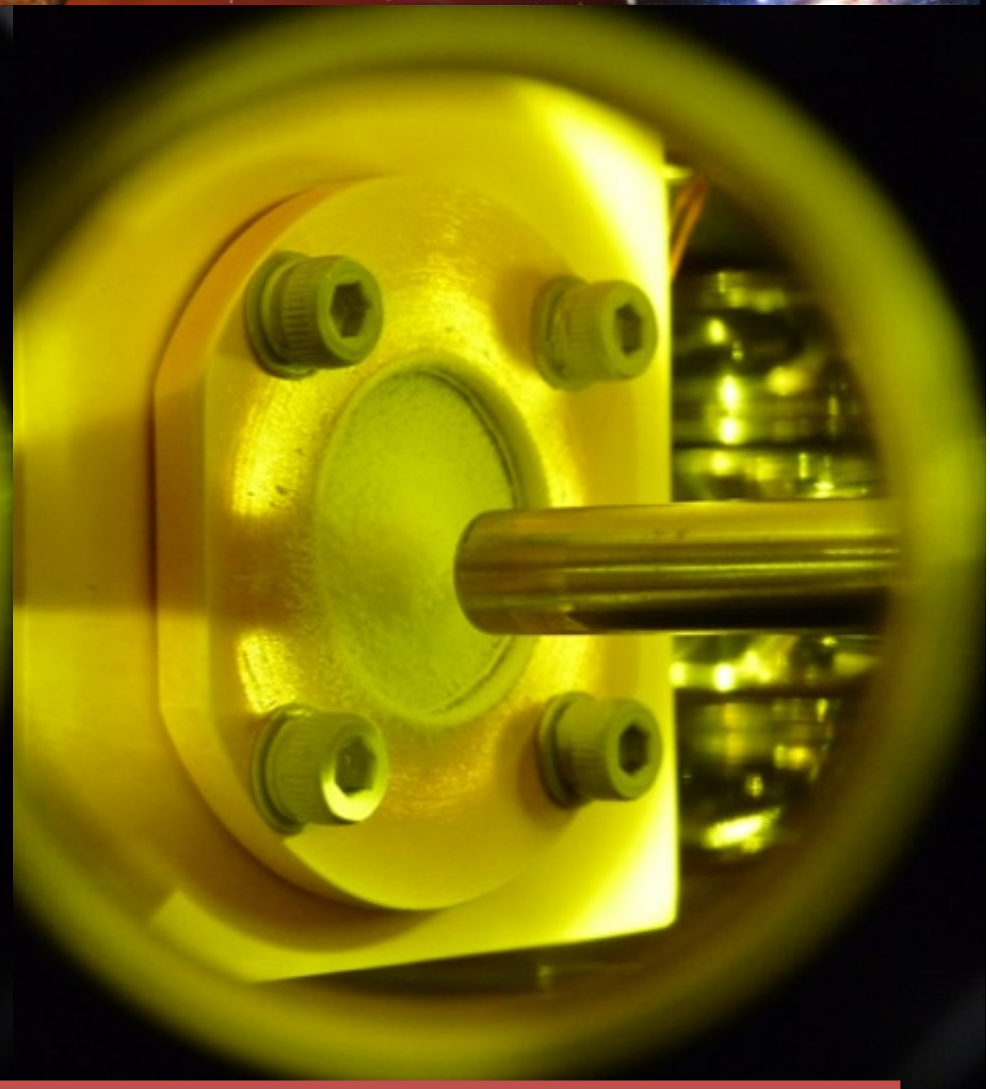
- Interstellar ice grains contain **amorphous water ice**
- We do not know what a comets interior ice phase is: **Amorphous or Crystalline?**
- We need to **“Dig Deep”** to resolve this Key Question. Not, just “Scratch the Surface”.
- **Cliff-Collapses:** We should have seen spectra signatures with VIRTIS, are we prepared for the next Comet Mission to analyze freshly exposed ice from the interior?

This must be done, but perhaps not in my Lifetime!

Macroscopic Amorphous Ices in the Lab: Simulating Interstellar & Comet Ices



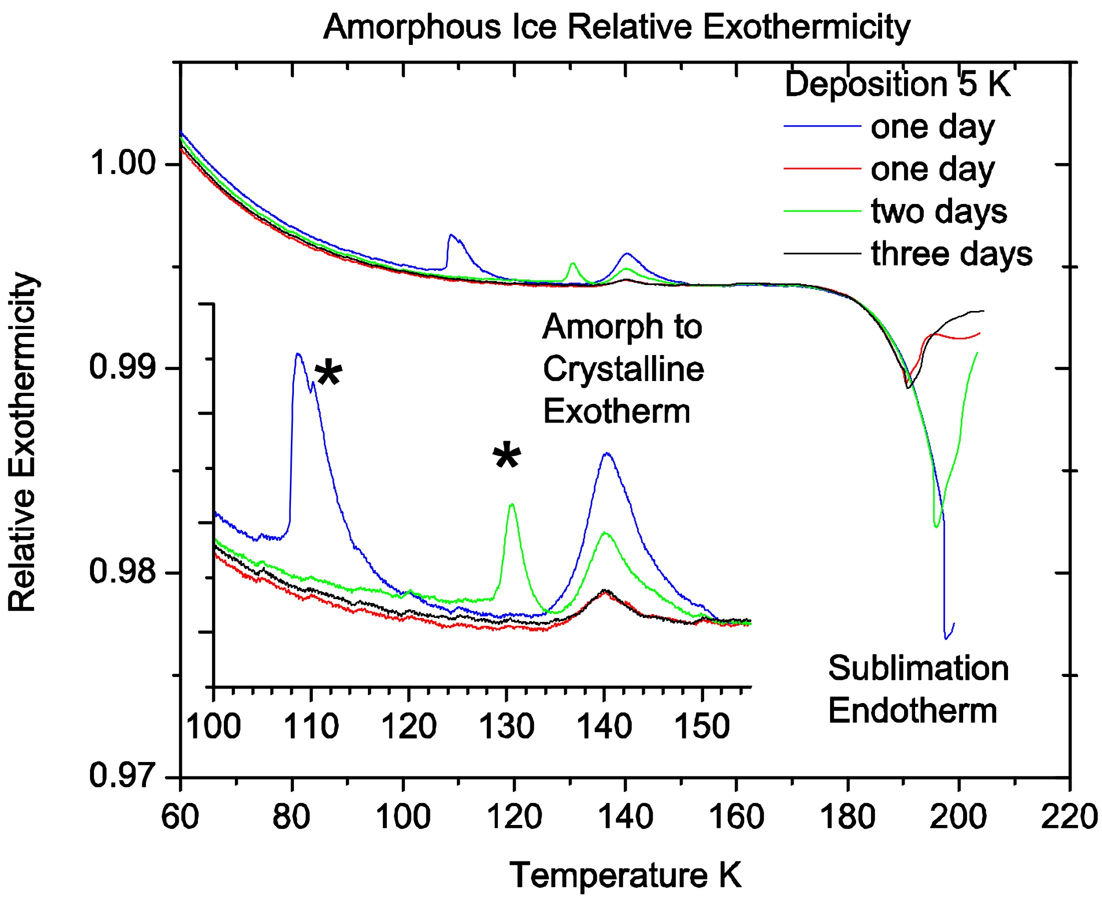
150 K Deposition
(Crystalline)



5 K Deposition
(Amorphous)

Amorphous to Crystalline – Exothermicity

Impurities may change exothermic to endothermic (amorphous to crystalline) transition – to be confirmed in the laboratory



Robert Wagner and Murthy Gudipti (2013) to be published

Kochi & Sirono GRL 28(2001)827

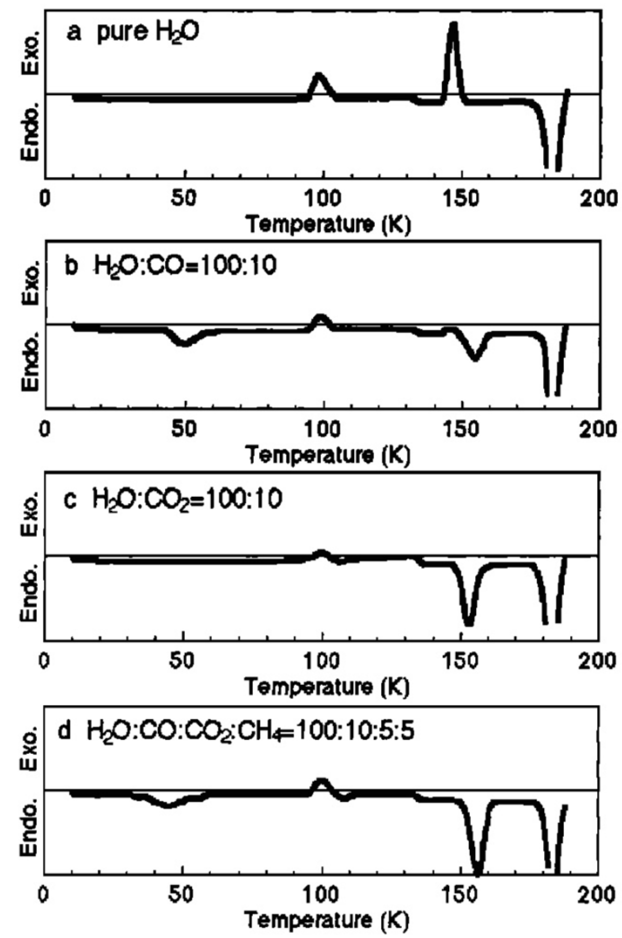


Figure 2. DTA curves of pure (a) and impure (b-d) a-H_2O. Endo., endothermic; Exo., exothermic.

Amorphous Ice in Comets

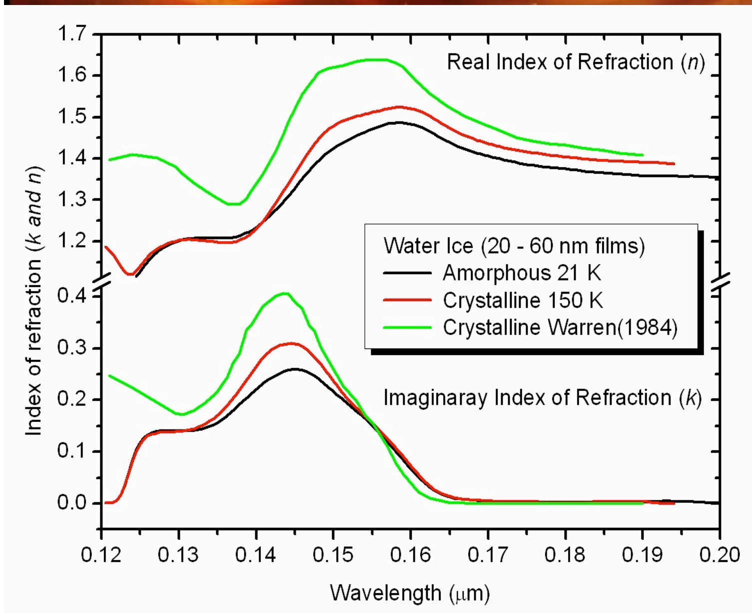
Unless we "Dig Deep" into a Comet And Determine Whether OR NOT It's Interior is made of Amorphous Ice, We haven't fully connected the DOTs…

✔ Amorphous H_2O Ice Excellent Tracer

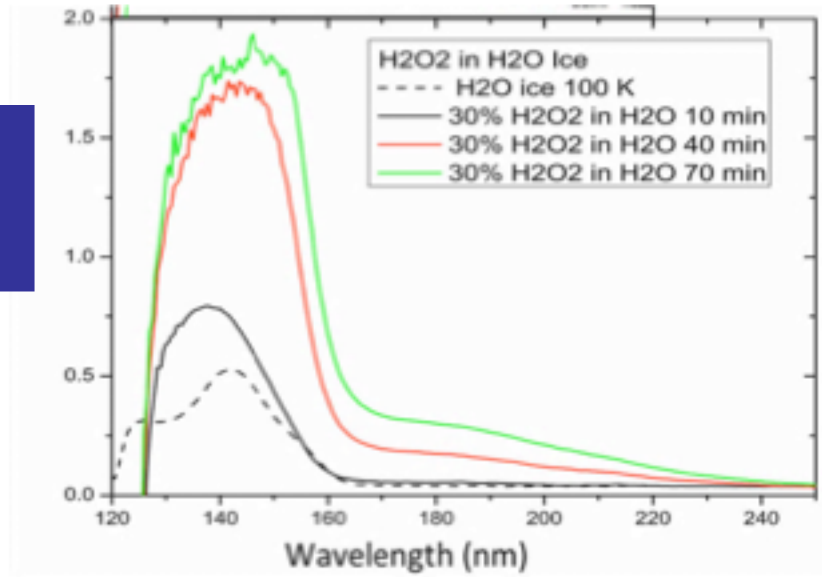
H_2O Ice & Strongly Bound Impurities

NH_3 and H_2O_2 are Strongly Bound with H_2O

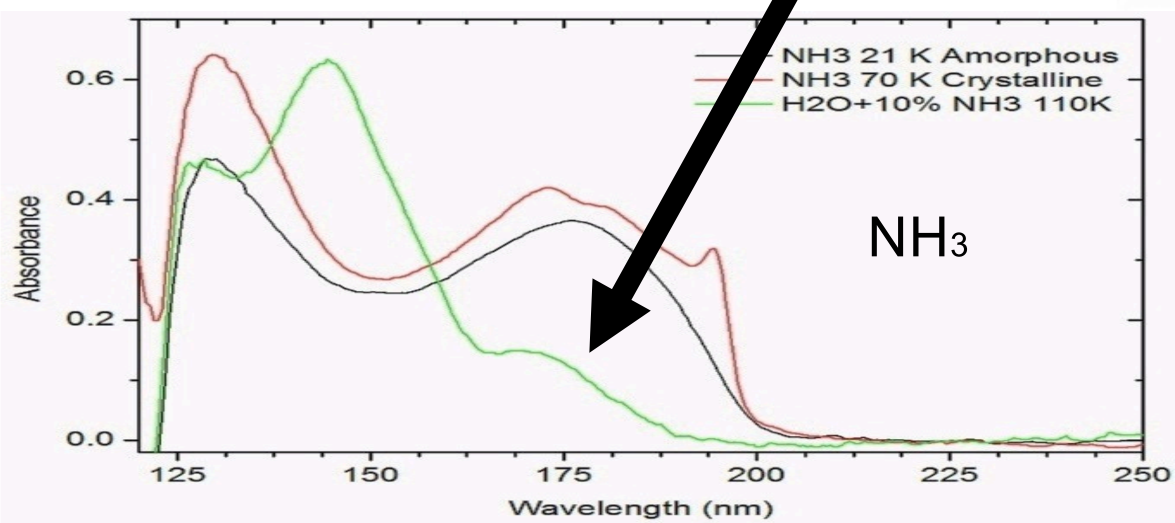
Ice Composition VUV Studies



Strongly Bonded



$30\% H_2O_2$ in H_2O Ice

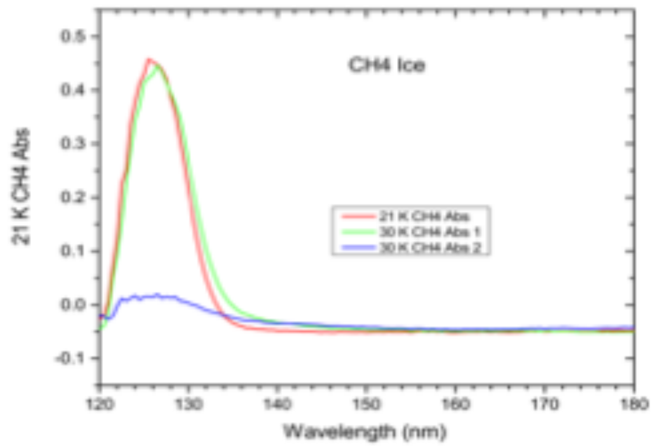


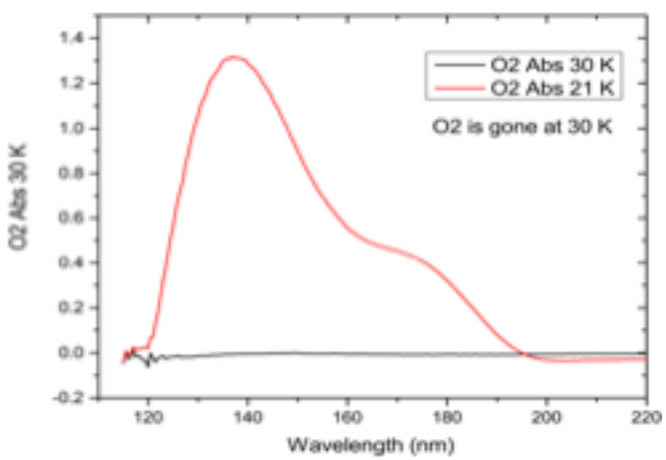
NH_3 binds strongly with H_2O – Not a Good Tracer

H_2O_2 is Photoproduct of H_2O, not a good Tracer

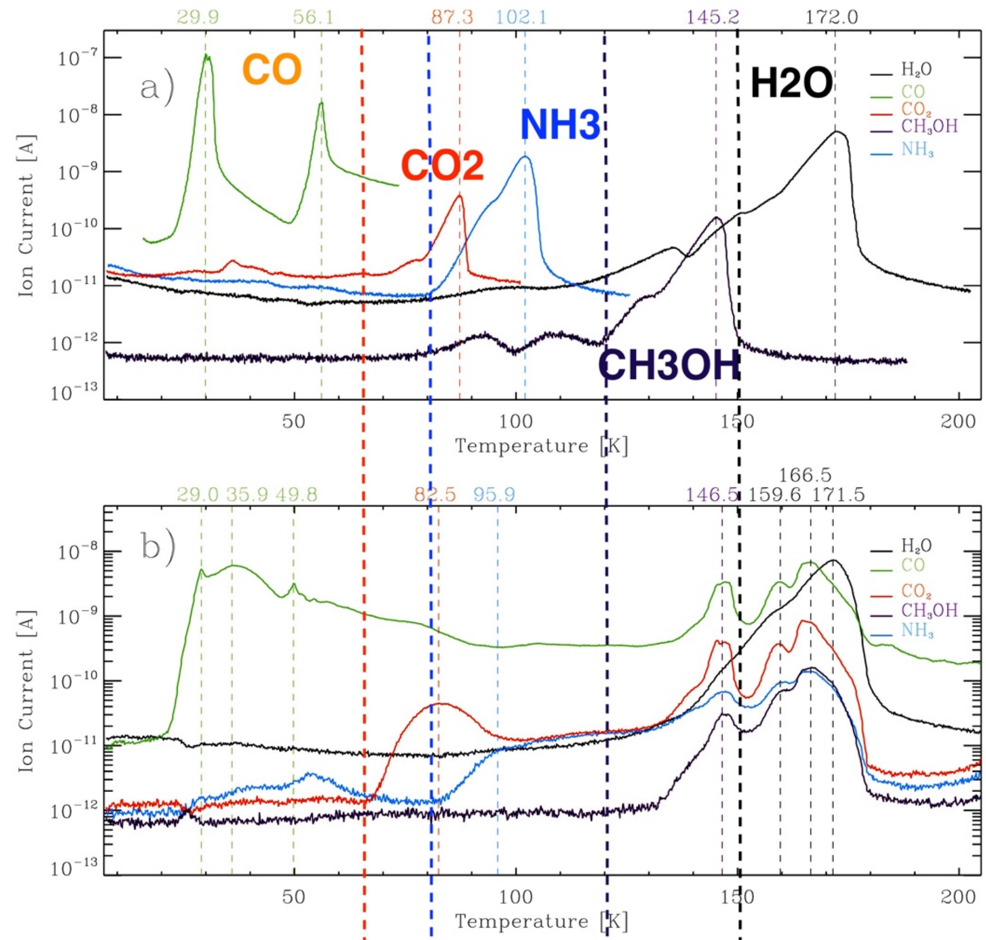
Depletion Temperatures of Volatiles

Crystalline H_2O Ice <160 K; Amorphous H_2O Ice <<80 K
CO_2 Ice <70 K; Super Volatiles ~30 K





Gudipati et al., (NIST, VUV) – to be published



Martin-Domenech et al., *A & A* **2014,** *564*

Trapping of Volatiles in CO_2 Ice

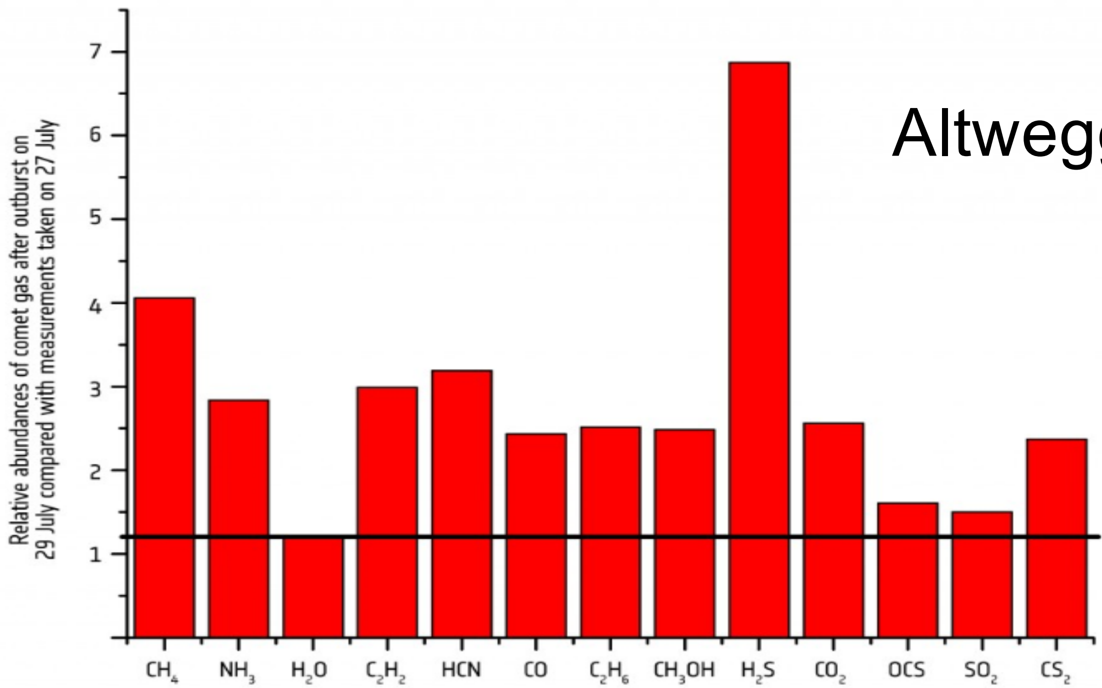
CO_2 is up to 20% of H_2O

Can form Separate CO_2 Ice Domains

Where are the Volatiles Trapped? H_2O-Ice or CO_2-Ice

During Outbursts from Interior CO_2 is accompanied by Volatiles

→ ROSINA MEASUREMENTS OF COMET GAS FOLLOWING OUTBURST



Altwegg et al.,

During an outburst of gas and dust from Comet 67P/Churyumov–Gerasimenko on 29 July 2015, Rosetta's ROSINA instrument detected a change in the composition of gases compared with previous days.
The graph shows the relative abundances of various gases after the outburst, compared with measurements two days earlier (water vapour is indicated by the black line).
Credits: ESA/Rosetta/ROSINA/UBern/ BIRA/LATMOS/LMM/IRAP/MPS/SwRI/TUB/UMich

Trapped vs. Segregated Volatiles

<<1% = Trapped (Depleted Super Volatiles)

1-5% = Trapped (with moderate binding with host) H_2O/NH_3 or H_2O/O_2

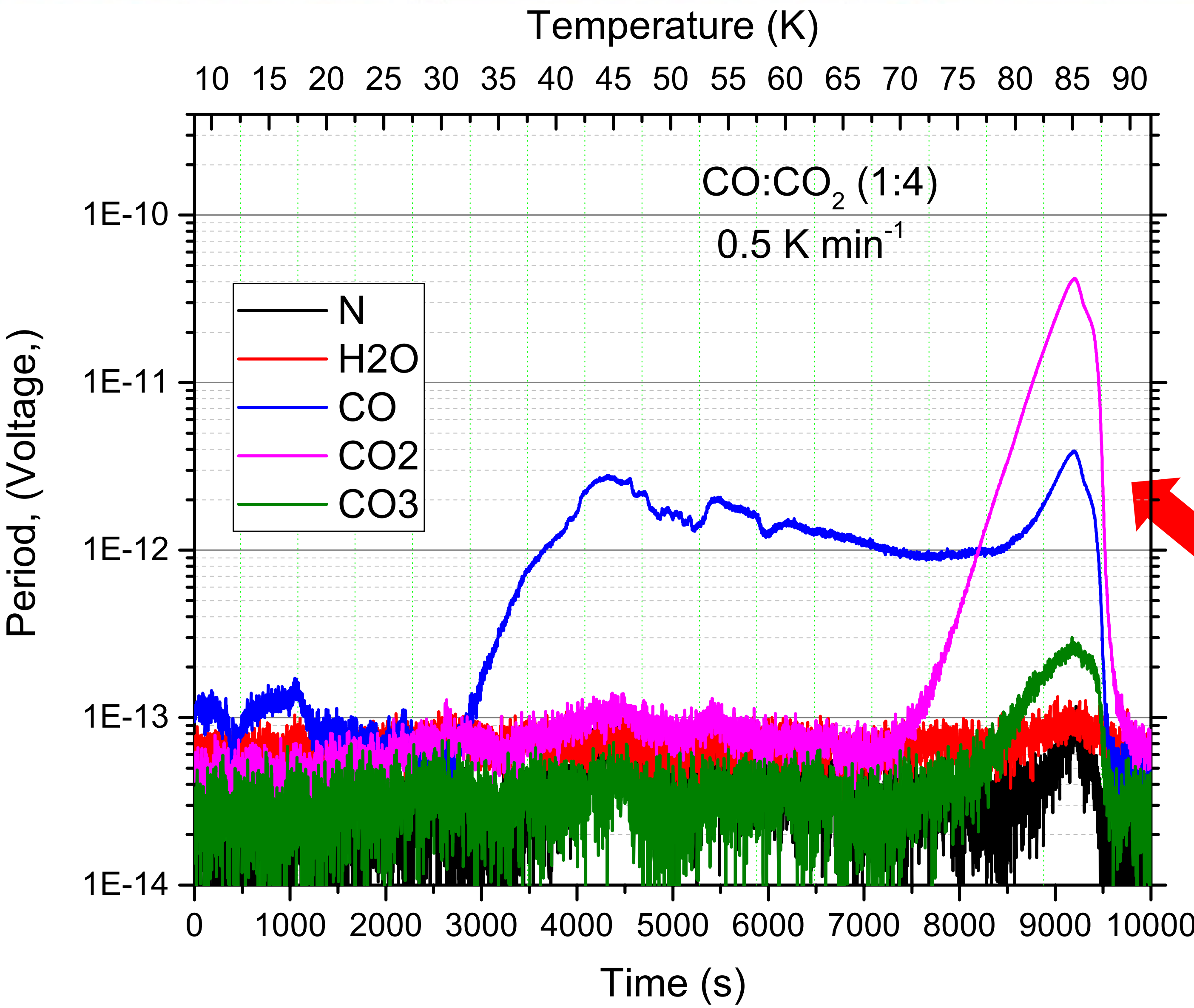
5 – 20 % = Segregation domains (H_2O vs. CO_2)

We conducted New Laboratory Studies to Explore the H_2O vs. CO_2 ices

These are Preliminary Results

Please DO NOT Use or Quote without my Permission

CO in CO_2 Ice

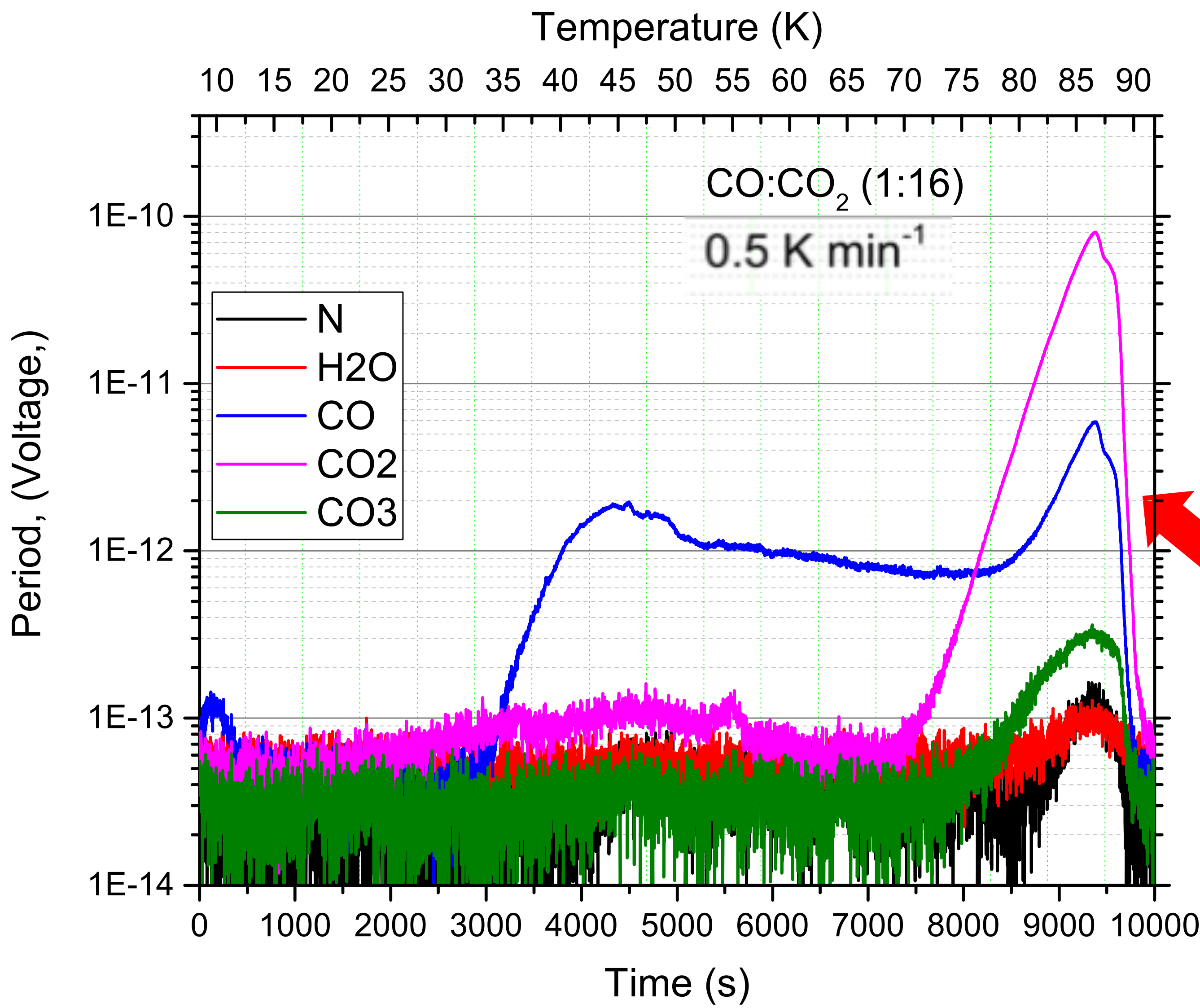


NIST e-impact Ionization of CO_2 gives ~10%CO ~10% O

Pure CO_2 No CO

Murthy Gudipati & Benjamin Fleury – To be Published

CO in CO_2 Ice



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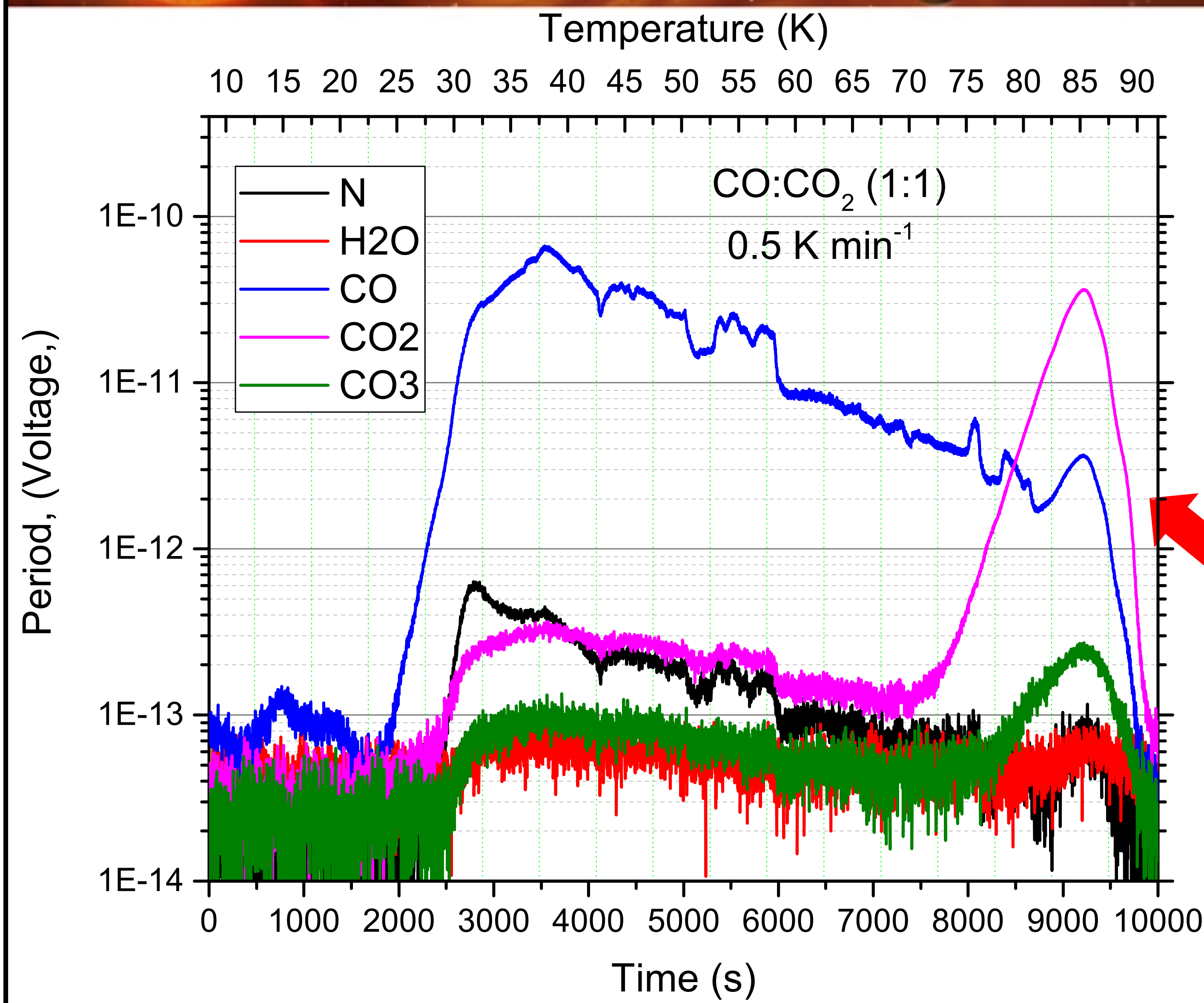

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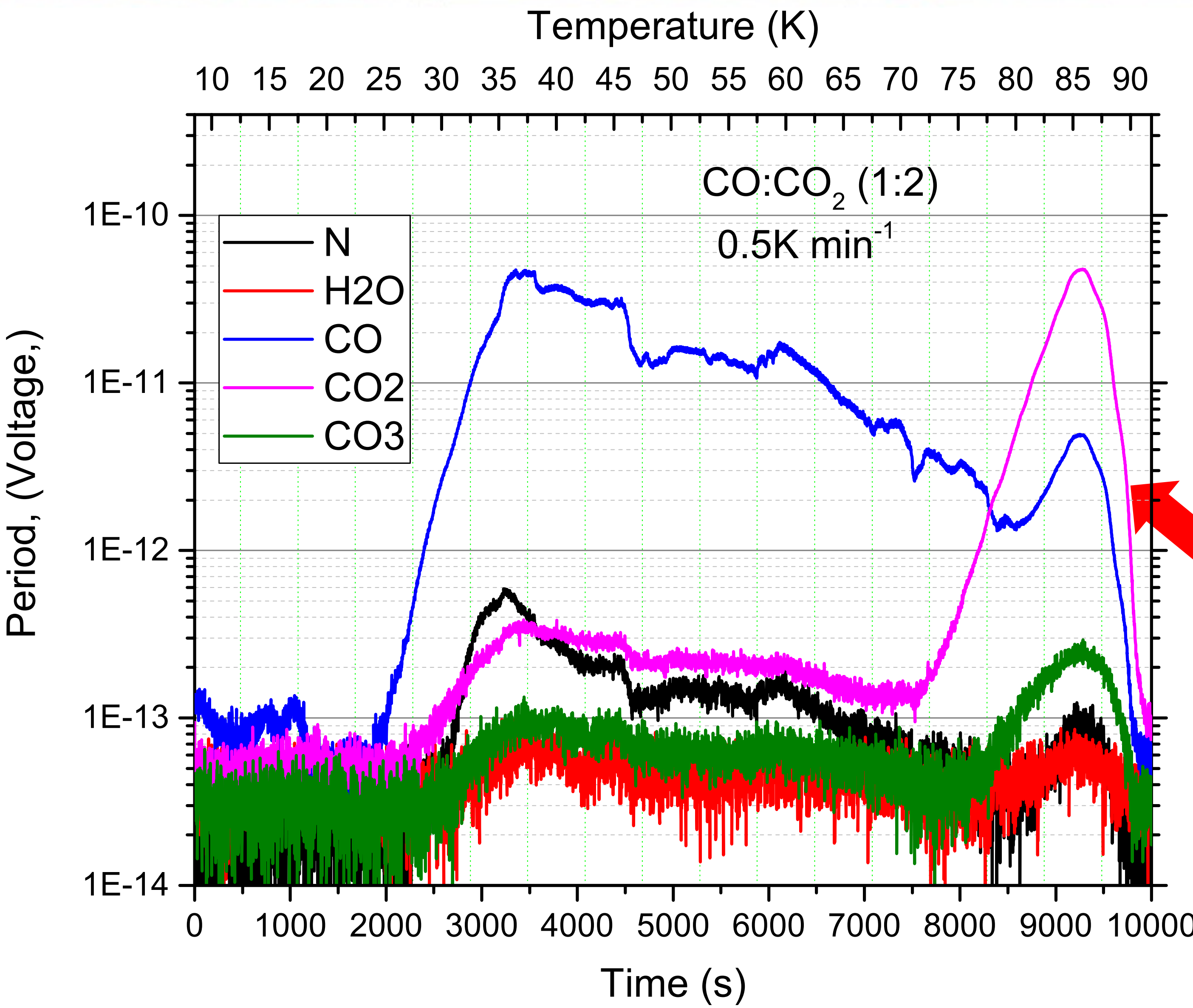

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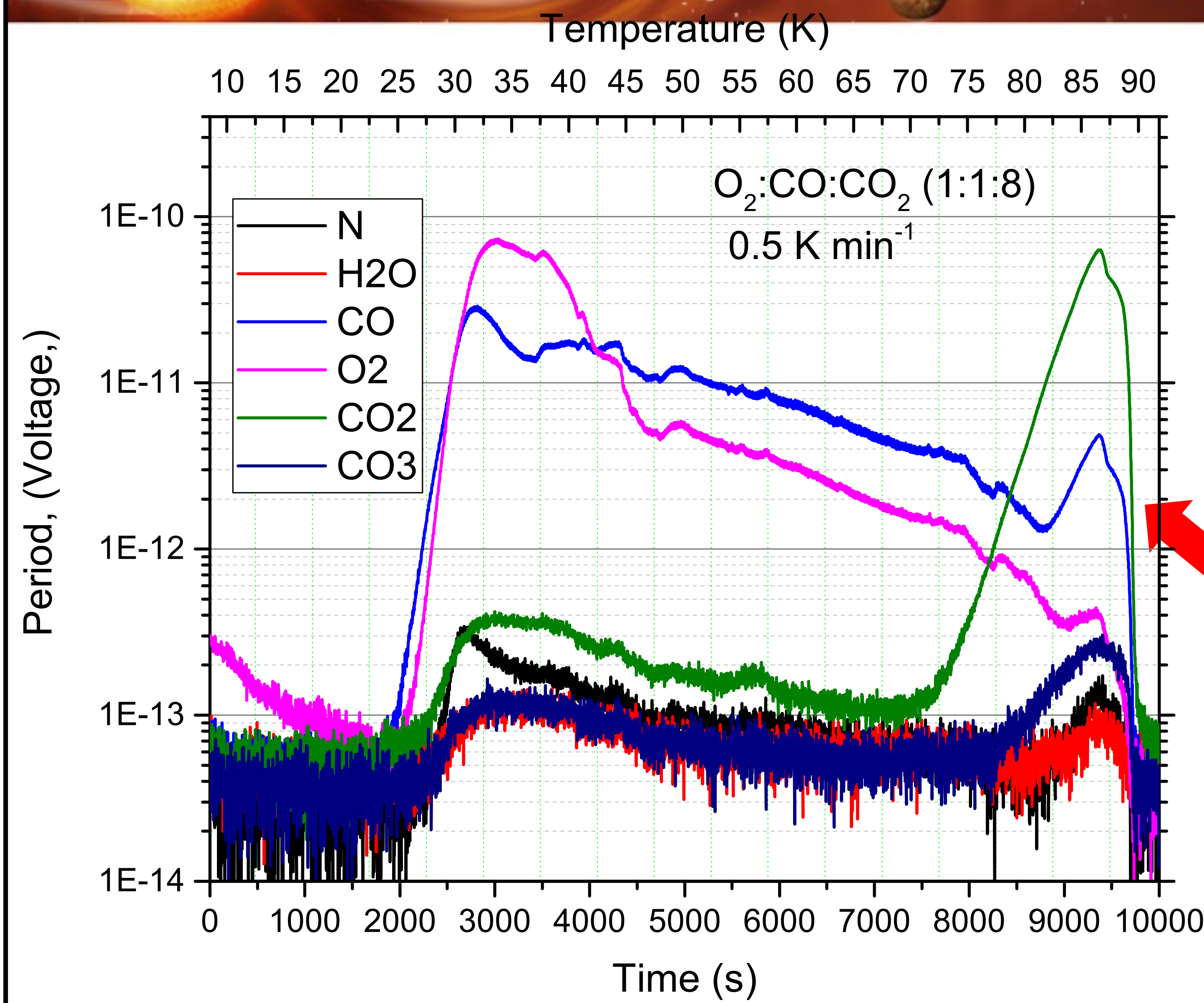
O_2 & CO in CO_2 Ice

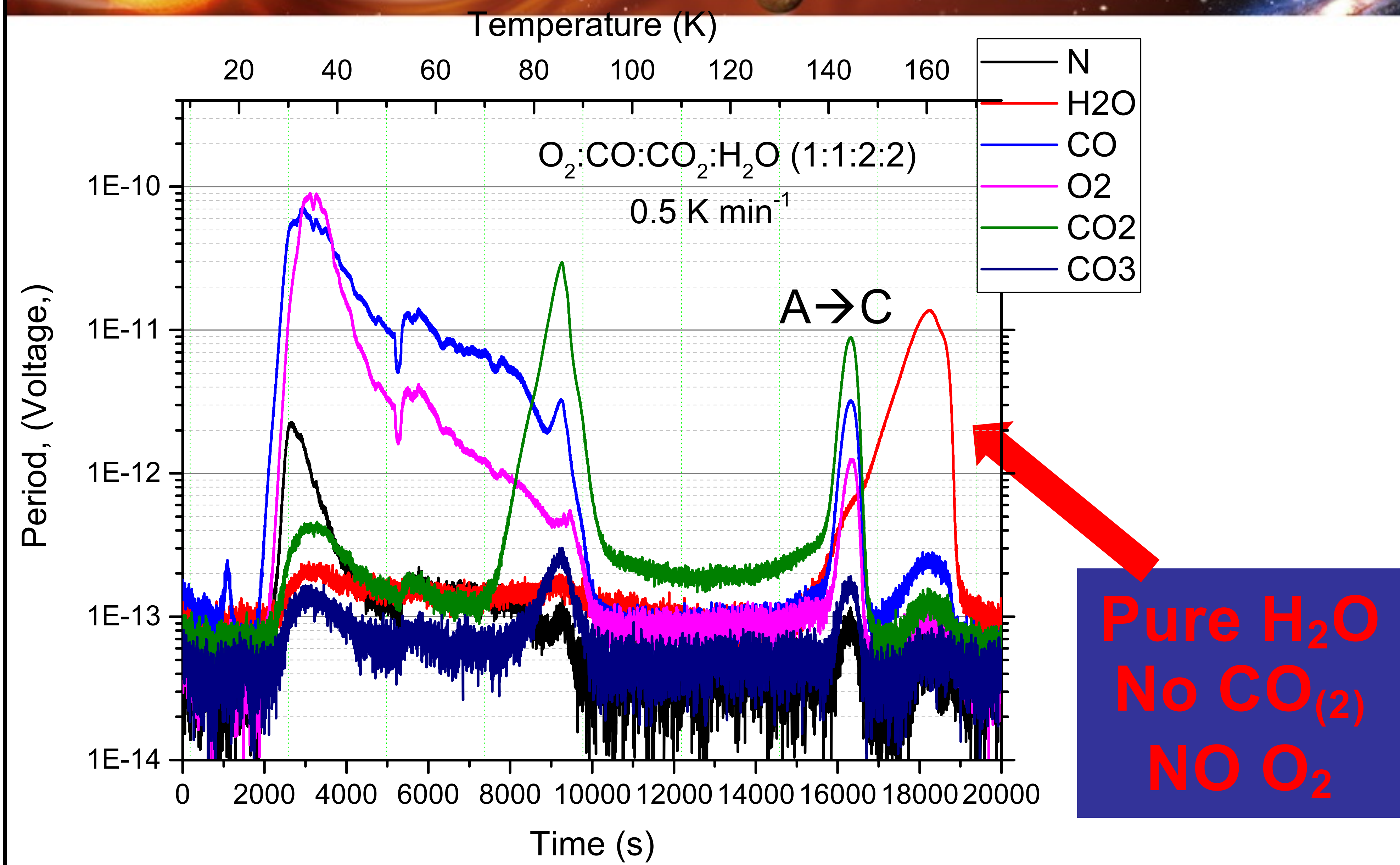


NIST e-impact Ionization of CO_2 gives ~10%CO ~10% O

Pure CO_2 No CO NO O_2

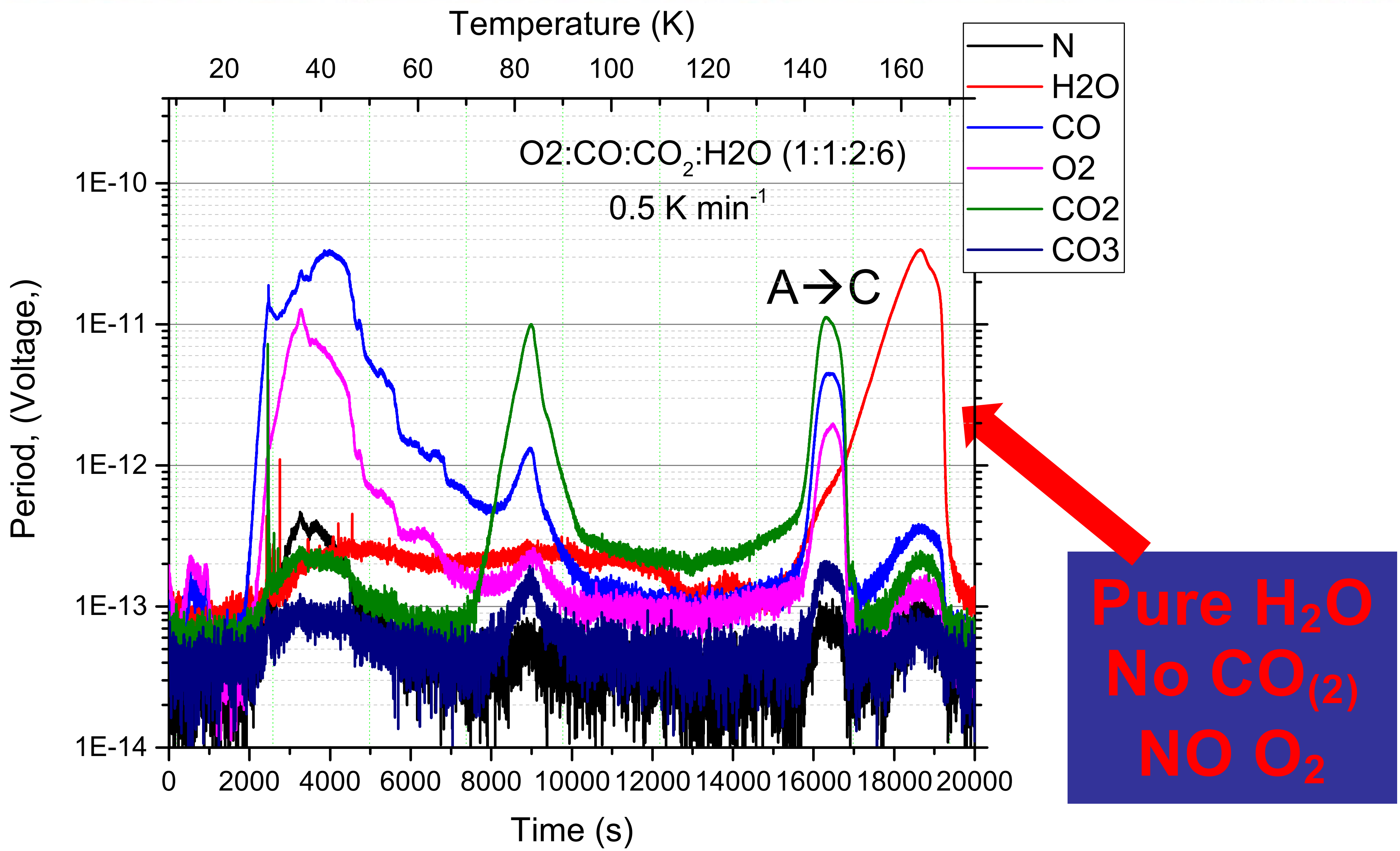
Murthy Gudipati & Benjamin Fleury – To be Published

O_2, CO, & CO_2 in H_2O Ice



Murthy Gudipati & Benjamin Fleury – To be Published

O_2, CO, & CO_2 in H_2O Ice



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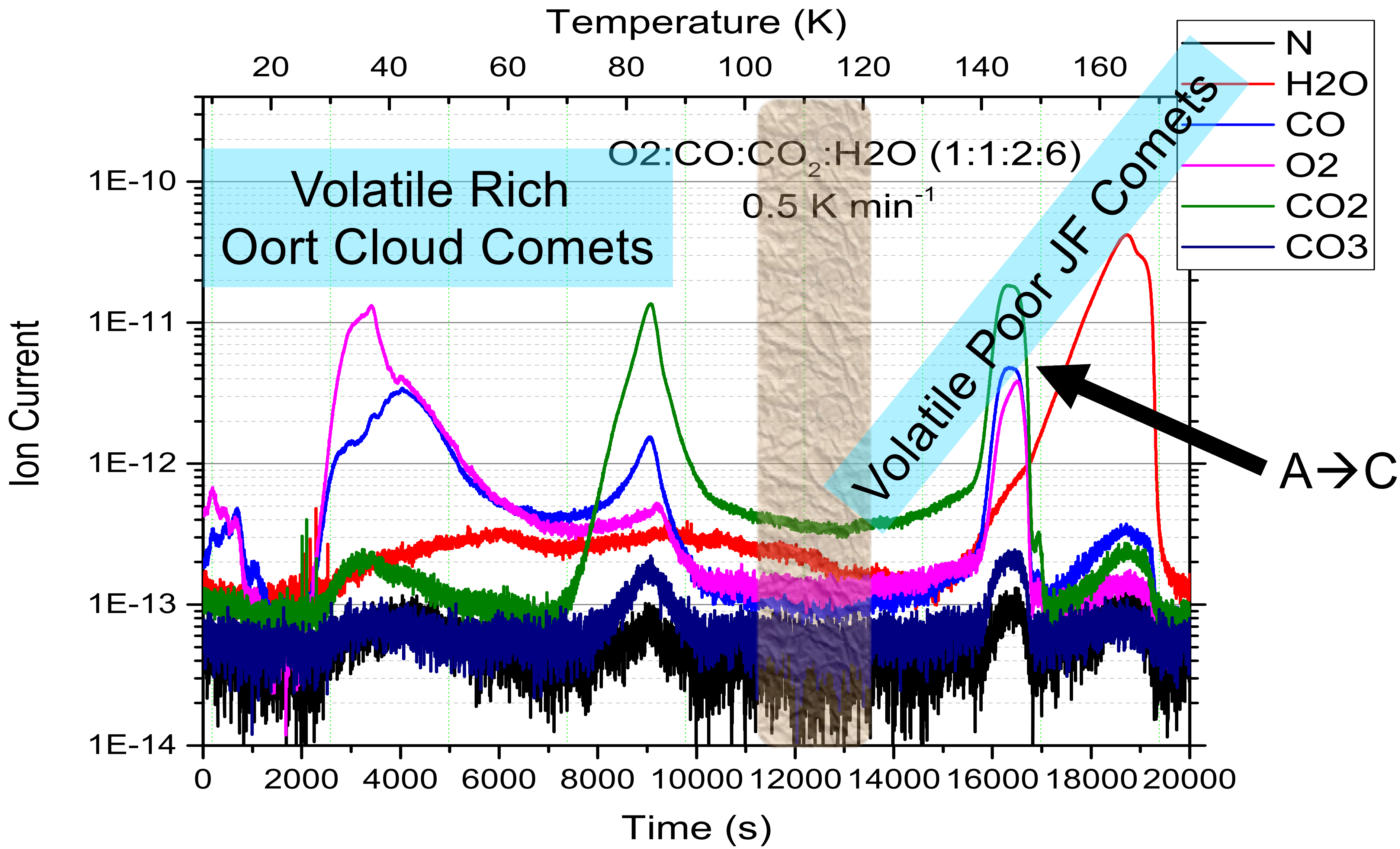
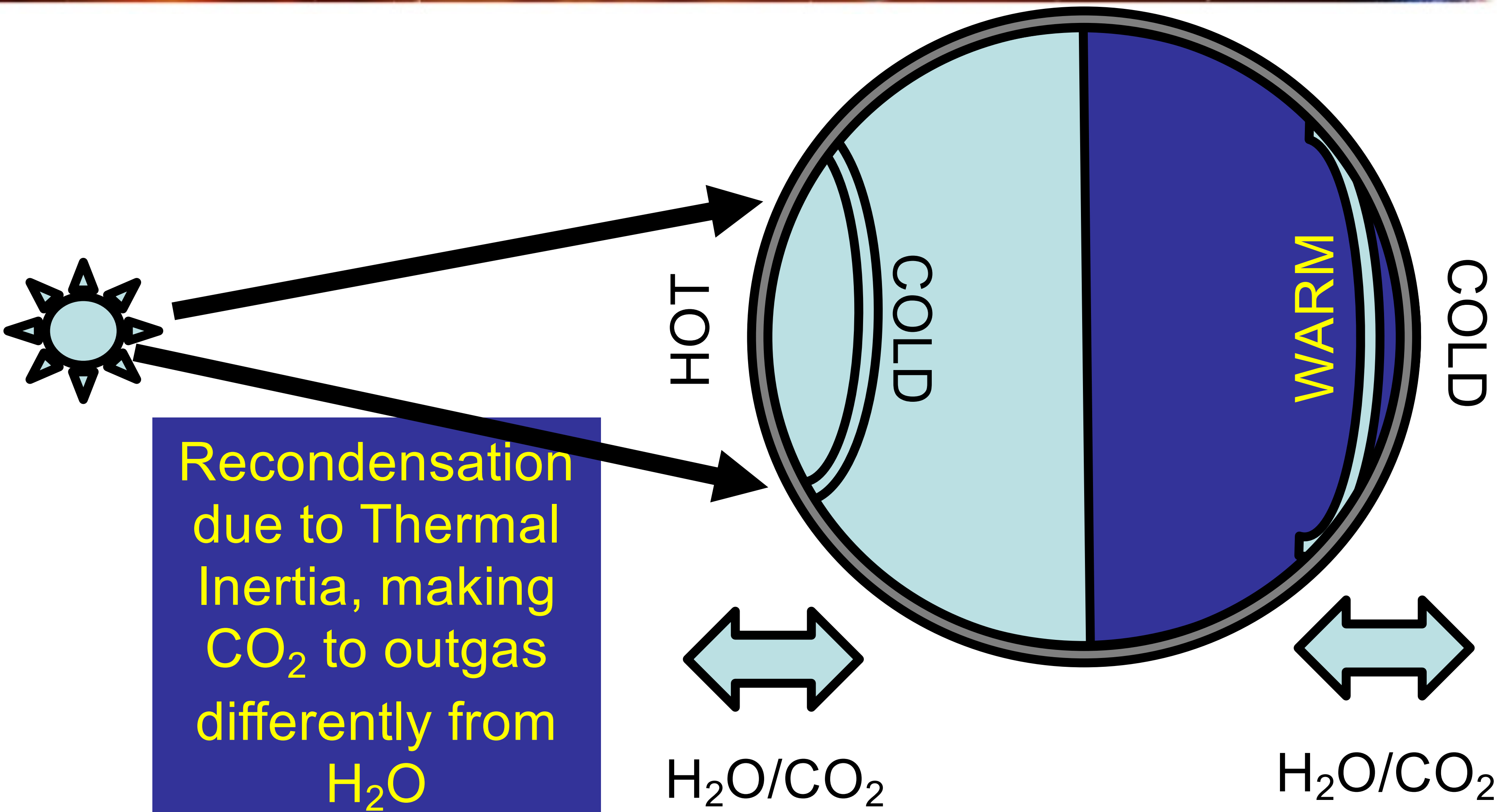
Volatile Depleted vs. Volatile Rich Comets



Murthy Gudipati & Benjamin Fleury – To be Published

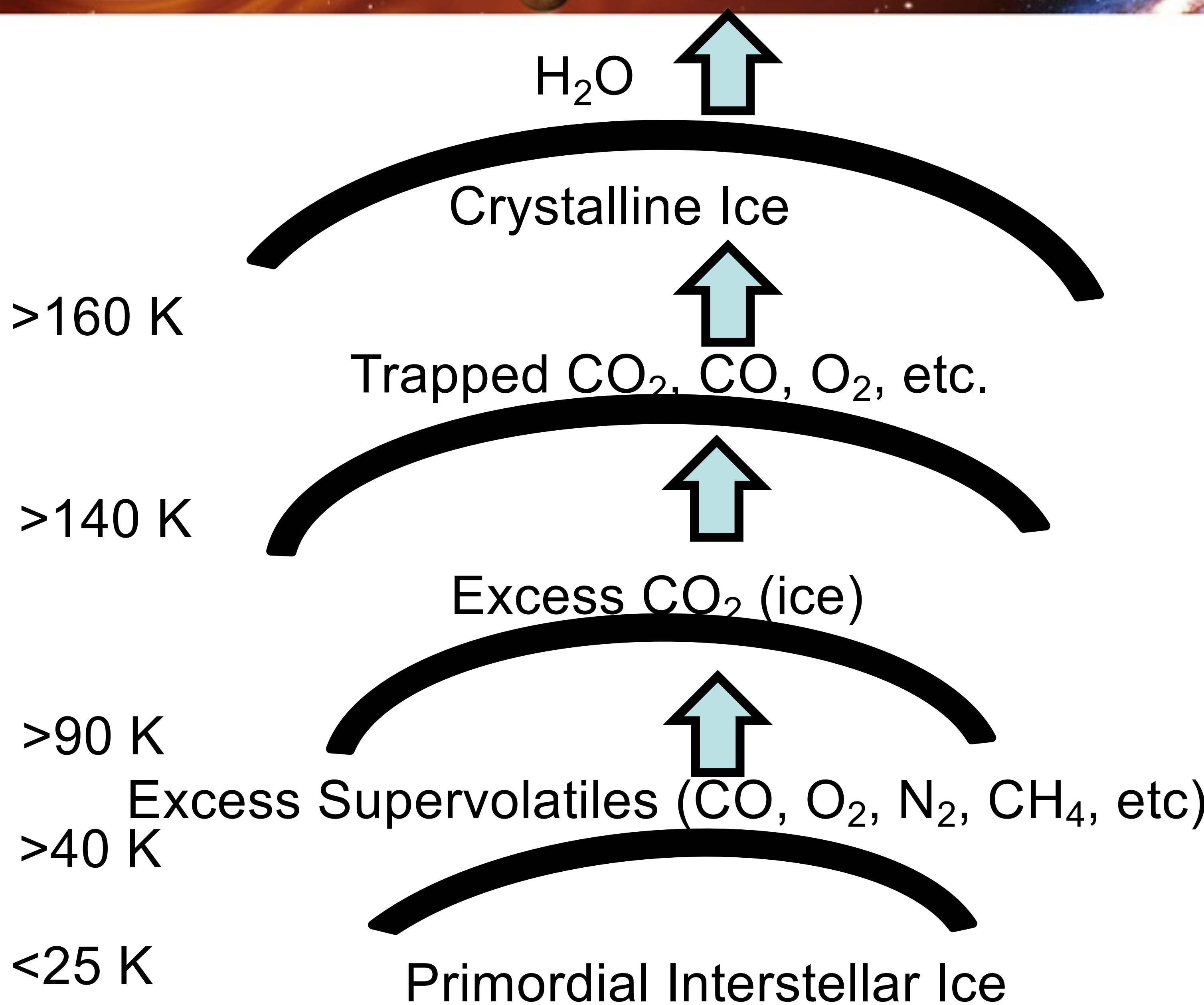
Anti Correlation between H_2O and CO_2



Recondensation due to Thermal Inertia, making CO_2 to outgas differently from H_2O

G. Filacchione et al., Science (2016)
Seasonal exposure of carbon dioxide ice on the nucleus of comet 67P/CG

Thermal Gradients and Volatile Production



Tracers from CO_2 Ice

- CO_2 is the second most abundant molecule (Interstellar & Cometary)
- If CO_2 is >>5%, it starts forming aggregates
- If CO_2 is >>10% it start forming pure ice domains
- Interstellar ice has CO_2 >>10%, hence Pure CO_2 domains must exist in interstellar ice grains.
- CO_2 Amorphous → Crystalline ~40 K

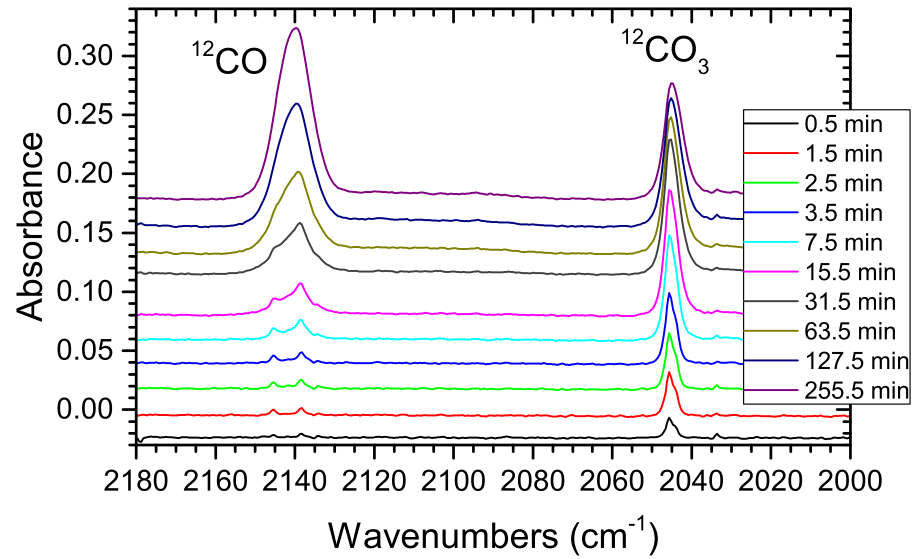
Let's see what is going on with CO_2 Ice

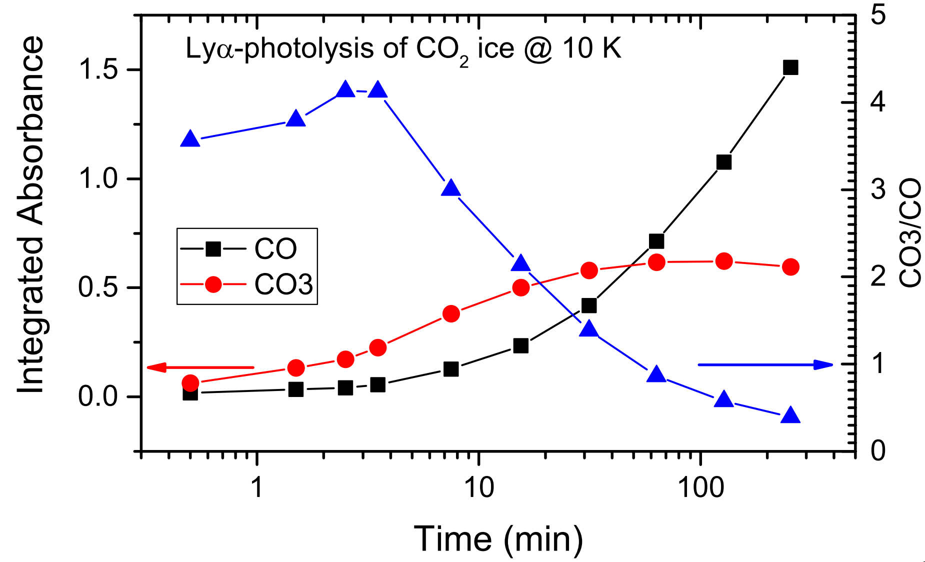
Photochemistry of CO_2/H_2O Ice

Soumya Radhakrishnan, Murthy S. Gudipati, et al. (ApJ in Review)

Pure CO_2 ice Irradiation Yields CO, CO_3, and O_3.

If CO_2 were to exist as pure ice (which it should be at >10% of H_2O) in the Interstellar Ice, then it should have produced CO_3 and we should see CO_3 if Cometary Interior is Primordial.





CO_2/H_2O Mixed Ice

With increasing H_2O content CO_3 and O_3 decrease. Pure CO_2 ice is a must!

More O_2 and O_3 is produced in CO_2 than in H_2O Ice

$CO_2 \rightarrow CO + O$

$CO_2 + O \rightarrow$ **CO3**

$CO_3 \rightarrow CO + O2$

$CO_3 \rightarrow CO_2 + O$

$O + O \rightarrow$ **O_2**

$O_2 + O \rightarrow$ **O_3**

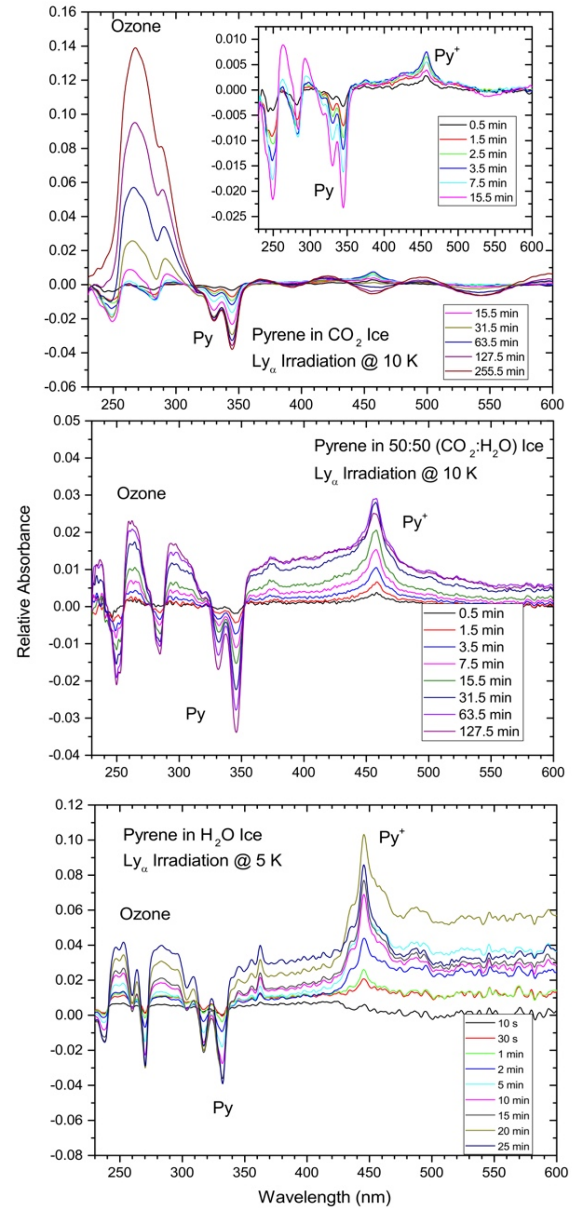
$O_3 \rightarrow O_2 + O$

$H_2O \rightarrow HO + H$

$HO + O \rightarrow$ **HO_2**

$H_2O + O \rightarrow$ **H_2O_2**

$O + O + O \rightarrow O_3$ ✗



CO_3 is a good Tracer

- If Protoplanetary Disk is a Washing Machine, CO3 should be gone!
- We should look for CO3 in Cometary Interior/Outgassing!

✔ **CO_3 is a good TRACER Molecule**
How about O_3??

67P/Churyumov–Gerasimenko is Volatile Poor

- CO_2, CO, and O_2 are expelled from A→C transition ~140 K before H_2O sublimes ~160 K
- O_2 does not come out with H_2O???
- How accurately do we know about outgassing/surface temperature correlation?
- On an average – does this matter?

O_2 – A potential Tracer or NOT?

Murthy Gudipati & Benjamin Fleury – To be Published

Conclusions

Cometary Nucleus of 67P/CG is Depleted in Super Volatiles

Amorphous ice not heated above 120 K can trap volatiles and supervolatiles in small quantities, in agreement with 67P/CG observations.

Tracer Species that lead us all the way to DMCs of ISM:

1) Amorphous Ice
2) CO_3
3) O_2?
4) S_2, D_2O, $^{14}N/^{15}N$, ??

If 67P/CG is a Thermally Processed Nucleus(<120 K) Cometary Interior Ice "MUST BE AMORPHOUS"

Acknowledgments

Thank
You & Rhodes
Co-Workers at JPL/ISL;
Funding: Rosetta (US), JPL, NASA R&A