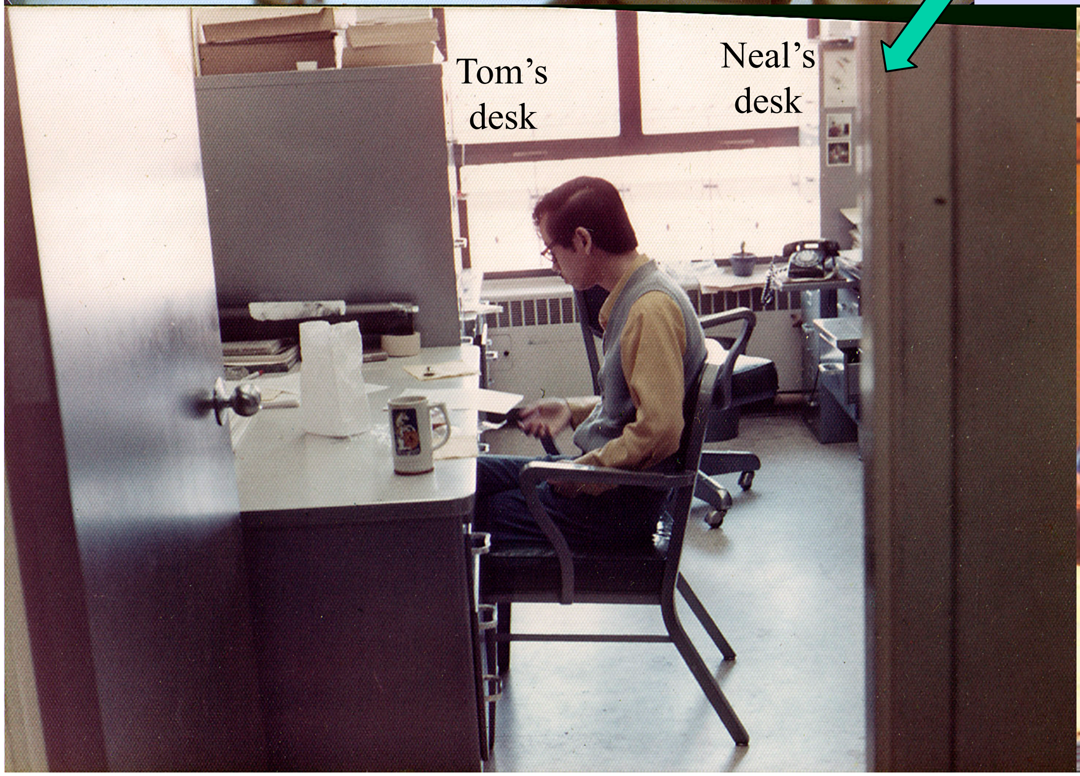
Neal in the 1970s

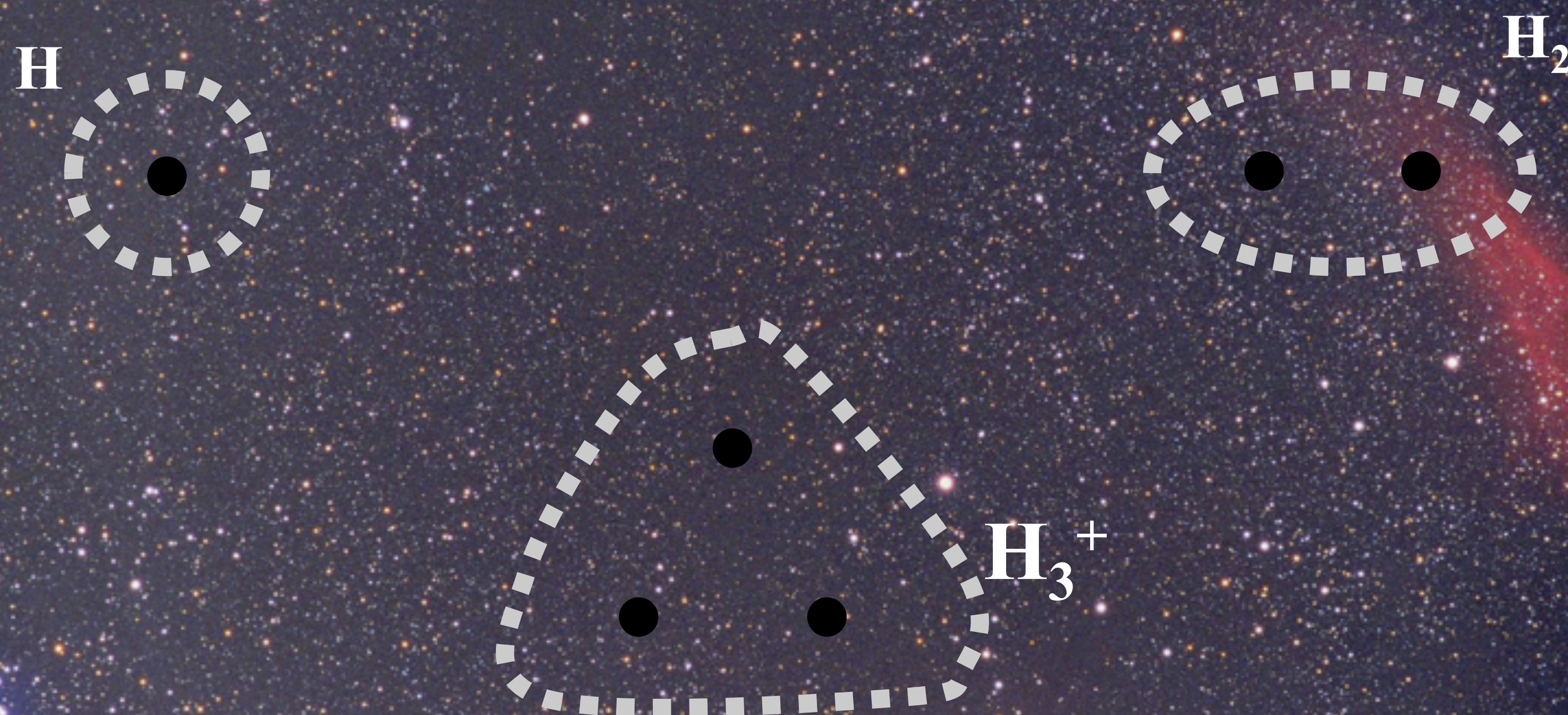
In the Townes library (with Howard Smith, Al Cheung, Mike Chui, ca. 1972)

Our office (ca. 1972)



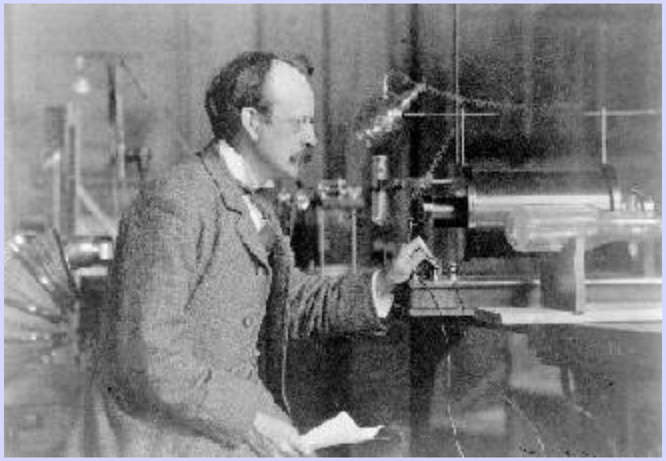
At Townes' 65th birthday (1980; Arno Penzias at left)

THE MOLECULE THAT MAKES MUCH OF NEAL'S AND HIS STUDENTS' RESEARCH POSSIBLE

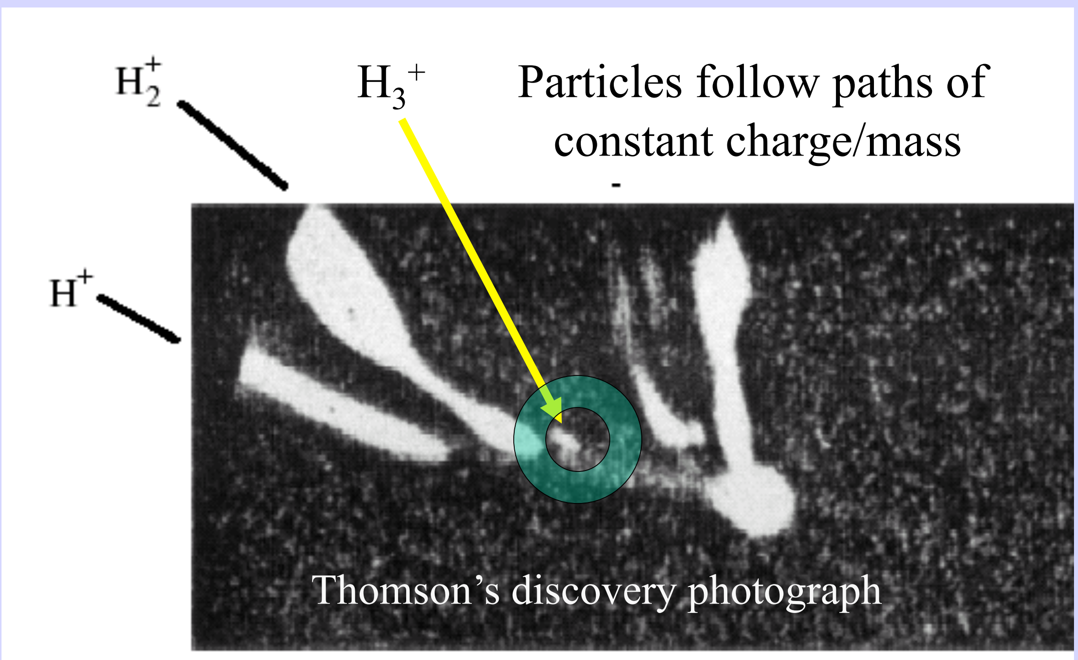


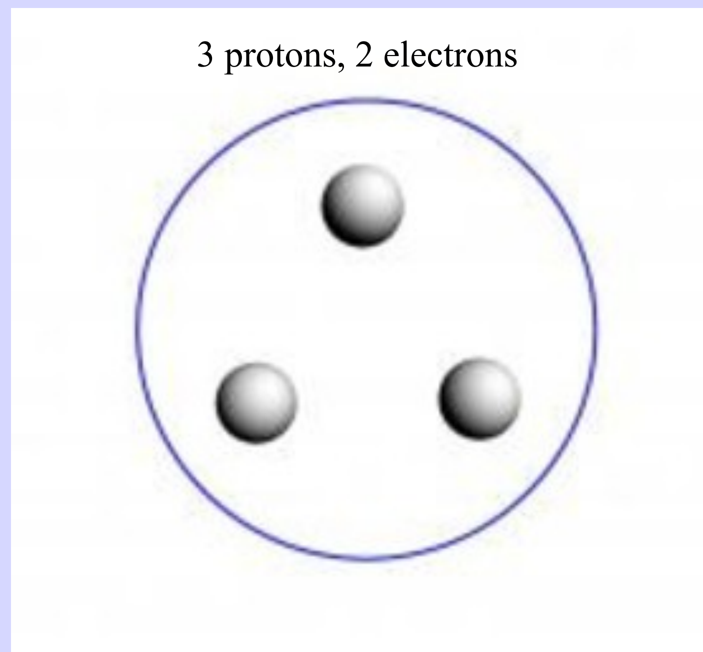
Tom Geballe, Gemini Observatory
Neal Fest, Apr 25-26, 2013

Discovery of H_3^+ in 1911

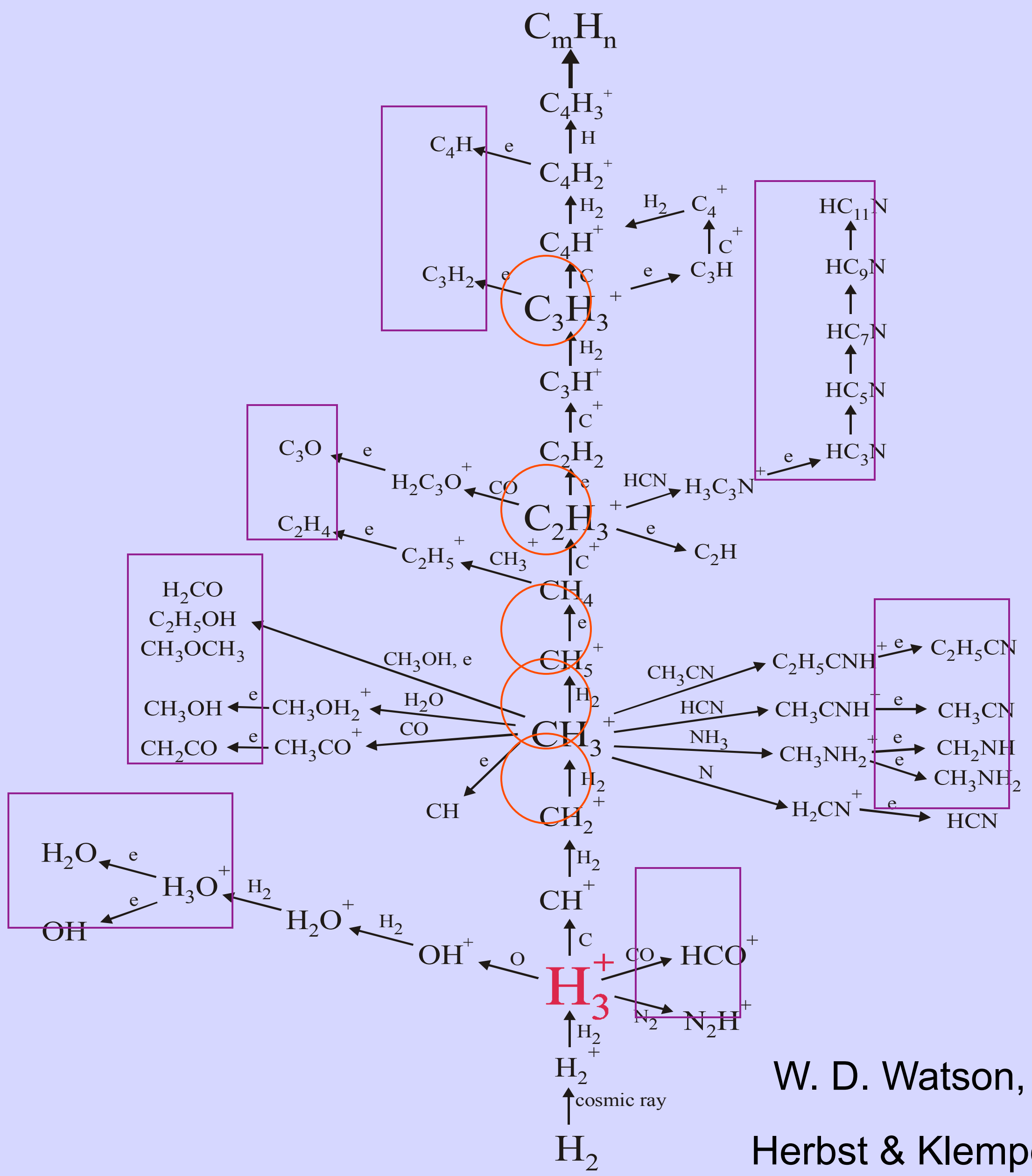


J.J. Thomson (Cambridge) – discoverer of the electron; inventor of the mass spectrometer



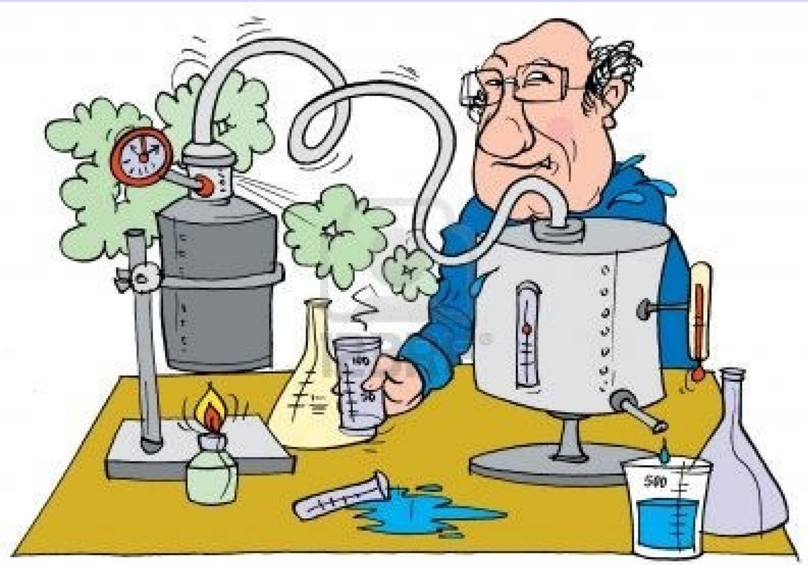


Tree of Interstellar Chemistry



W. D. Watson, ApJ 183, L17 (1973)

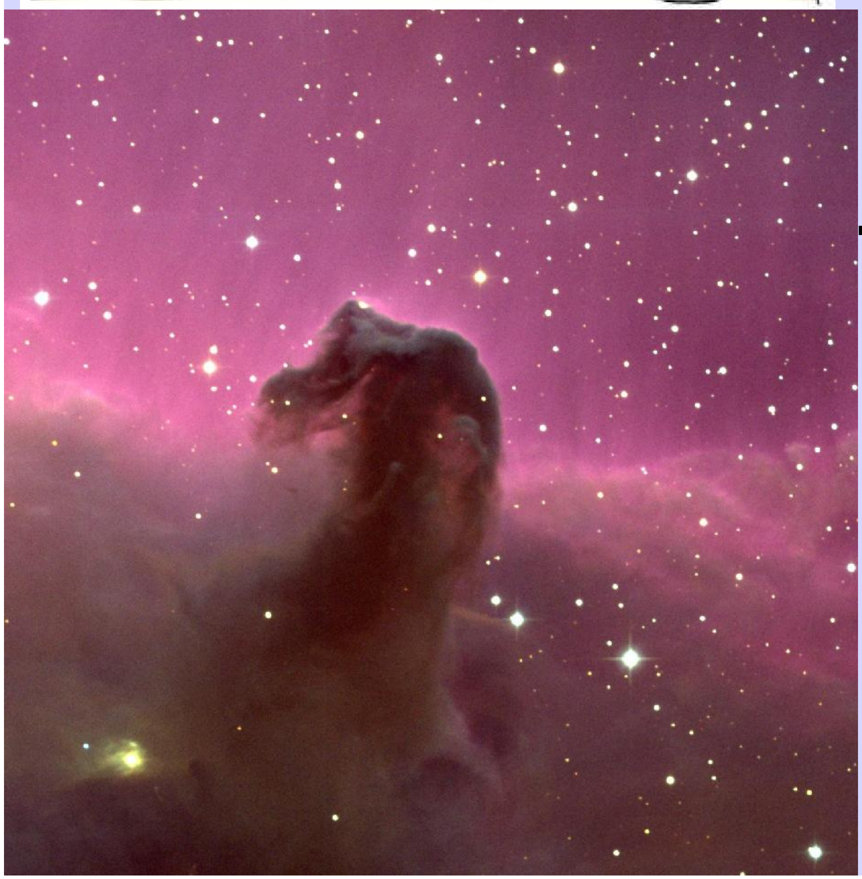
Herbst & Klemperer, ApJ 185, 505 (1973)



Chemistry in the Laboratory:

Molecules electrically neutral, close together and at room temp or warmer.

➔ they get close enough that chemical reactions can occur (overcoming the energy barrier).



Chemistry in Interstellar Clouds:

Molecules neutral and far apart (by lab standards)
Cloud is very cold (~30 K, ~ -400 F)

➔ Molecules rarely bump into one another and at low speed; so no neutral-neutral chemistry can happen.

But

ion-neutral chemistry (esp proton-hop reactions) has no energy barriers and can occur at long range.

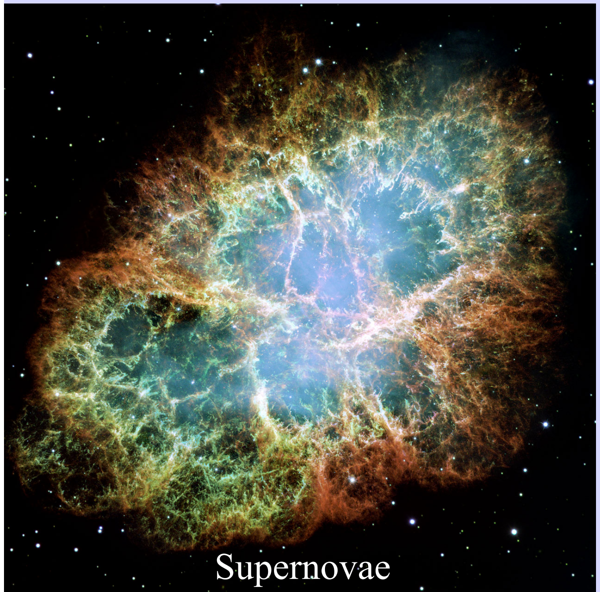
$$H_3^+ + X \rightarrow HX^+ + H_2 \quad (X \neq He, N, O_2)$$
$$HX^+ + Y \rightarrow XY^+ + H \quad (Y \text{ is often } H_2)$$

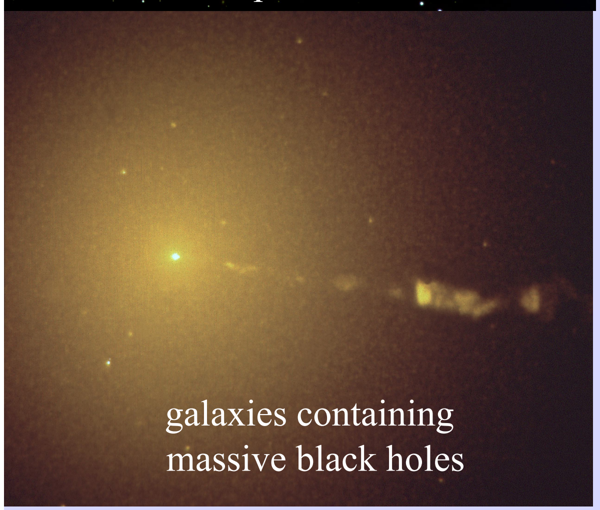
...

$$\text{or } H_3^+ + e \rightarrow H+H+H \text{ or } H_2+H$$

How is H_3^+ created ?

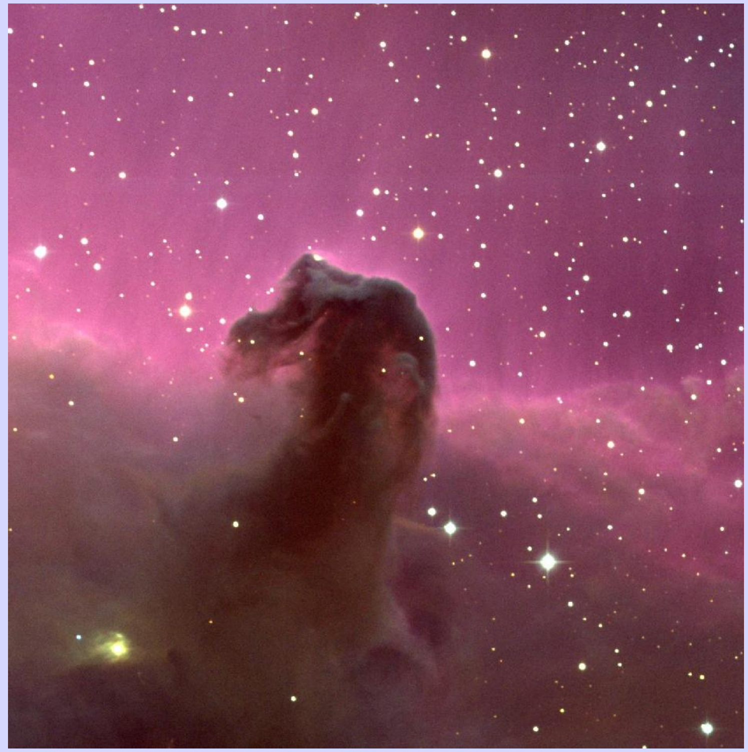
Sources of Cosmic Rays:





CR SED
very uncertain

Interstellar Molecular Cloud
(mostly H_2)



(1) $CR + H_2 \rightarrow H_2^+ + e^- + CR$

cosmic ray ionization rate, ς, ~ 3×10^{-17}/sec (~10^9 yr / H_2)

(10^{40} H_2 molecules ionized per second in a 1$M_{\odot}$ cloud)

(2) $H_2^+ + H_2 \rightarrow H_3^+ + H$ (~1 day)

Steady state (creation rate = destruction rate) $\rightarrow$ $n(H_3^+)$ = const. !!

If ζ is known then $N(H_3^+)$ yields L

History of H_3^+ in astronomy

1961 Must exist in interstellar clouds ($H_2^+ + H_2 \rightarrow H + H_3^+$)

1973 Importance in interstellar chemistry recognized ($H_3^+ + X \rightarrow H_2 + HX^+$)

1980 IR spectrum measured in laboratory; line identifications

1981 First search for interstellar H_3^+

1989 Discovery in Jupiter's aurorae

1993 Found in Uranus & Saturn

1996 Discovery in dense molecular clouds

1997 Discovery in Galactic center

1997 Discovery in diffuse molecular clouds

2001 Extra-galactic H_3^+ (confirmed 2005)

2002 Metastable H_3^+ level populated in the Galactic center (GC)

2003 High value of cosmic ray ionization rate in diffuse clouds

2005 Vast extent of warm rarified H_3^+ - containing gas in the GC

2006+ Continued advances in understanding of cloud environments and the GC

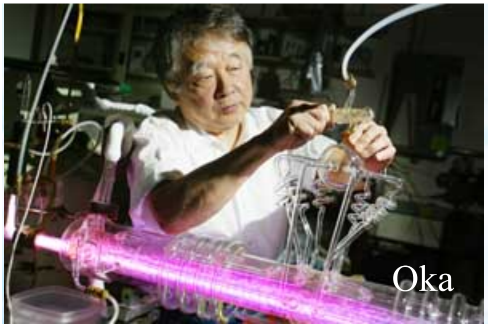
…

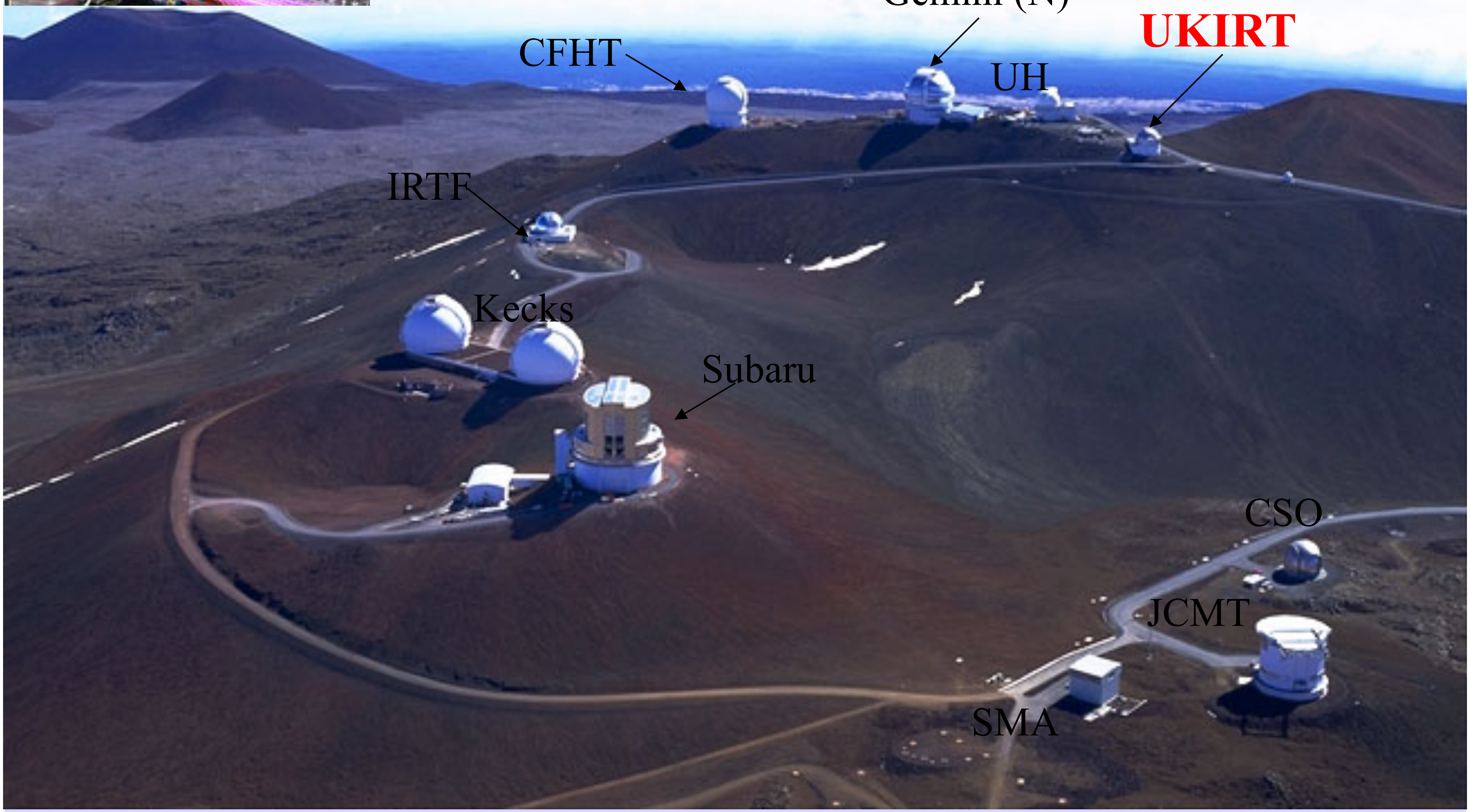
H_3^+ is more than a curiosity and more than just the starting point for interstellar gas phase chemistry.

***It is a unique tool for understanding physical conditions in interstellar space*.**

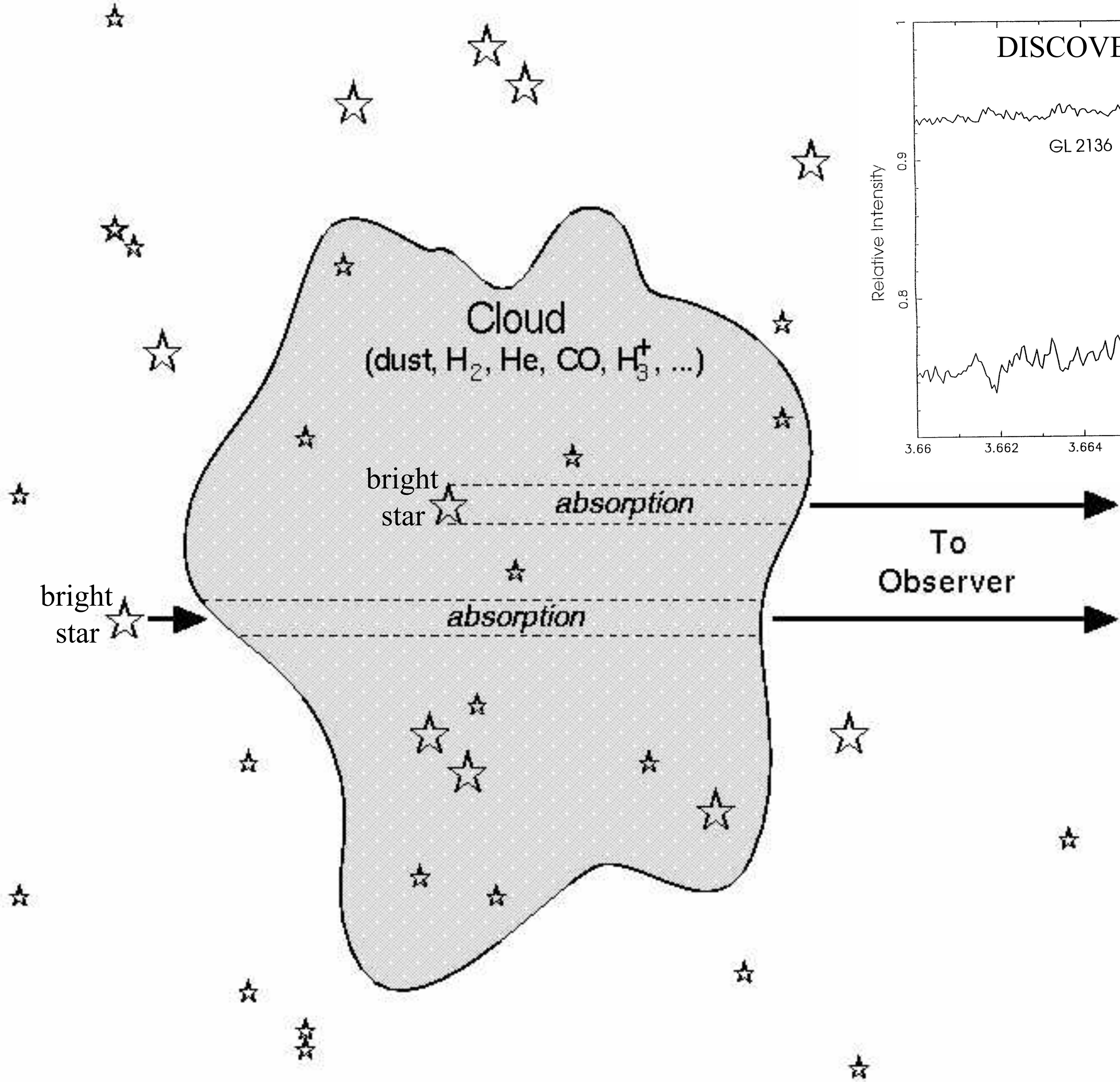
The events of July 11, 1997

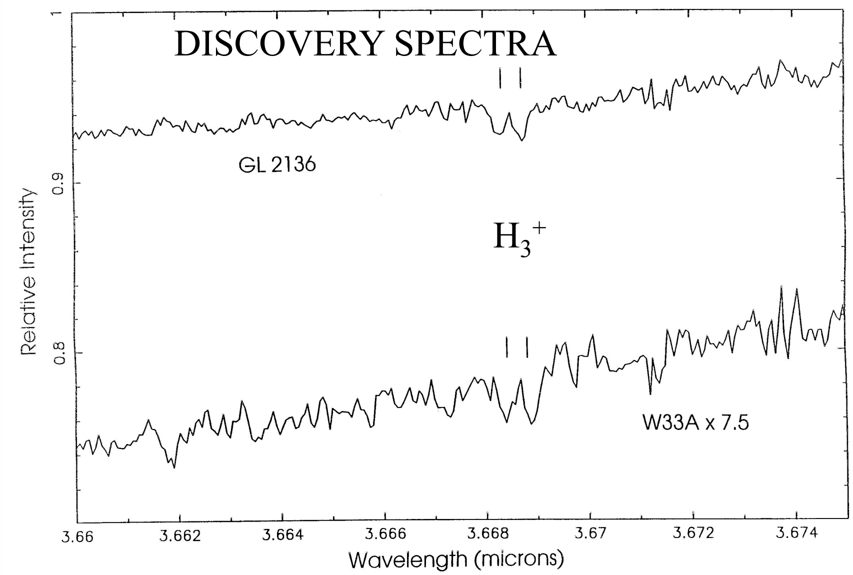
(crucial to our understanding of H_3^+ in the ISM)

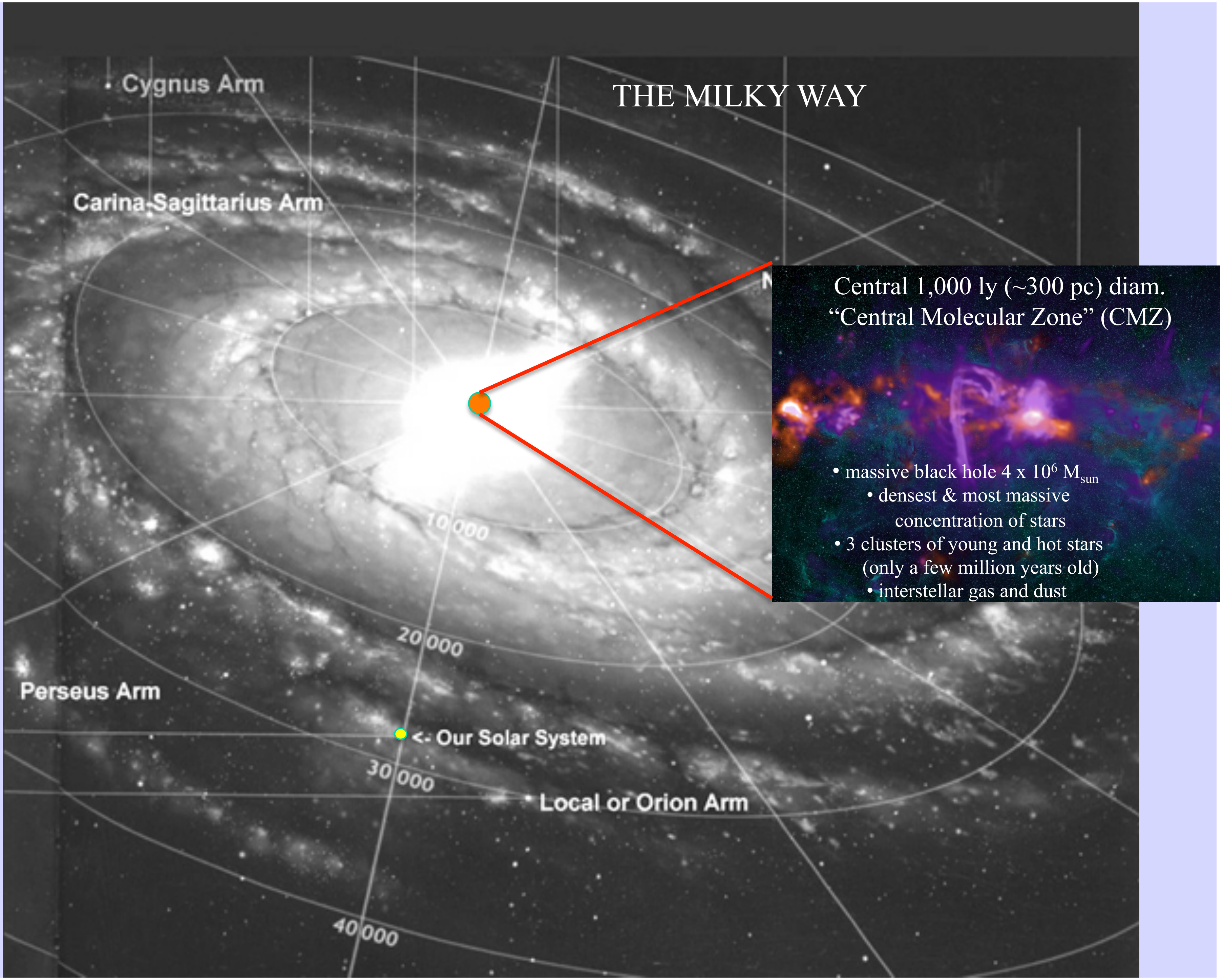




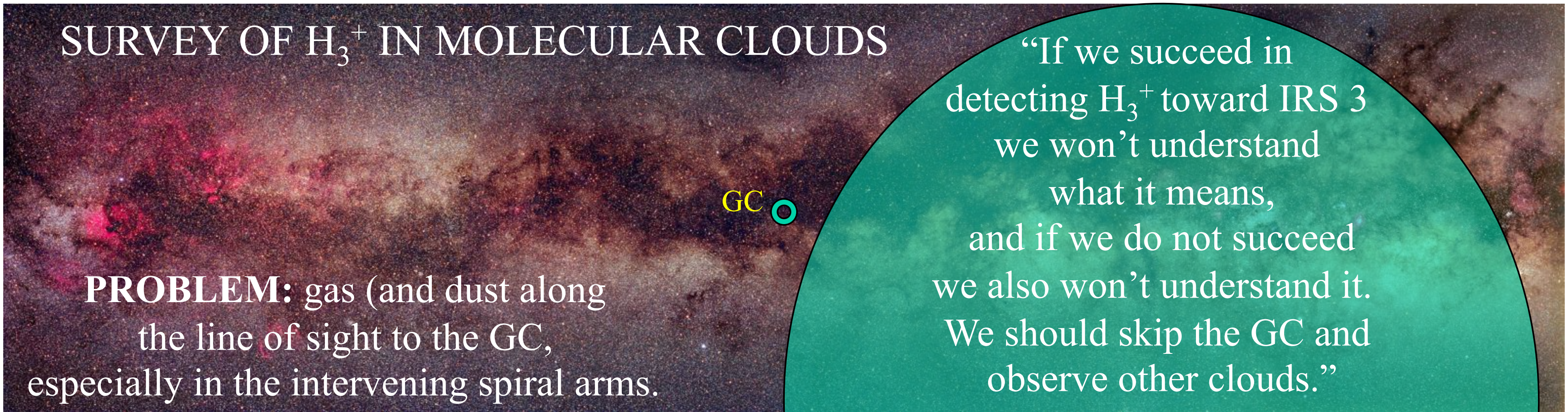
UKIRT - July 15, 1996






THE MILKY WAY
Cygnus Arm
Carina-Sagittarius Arm
Perseus Arm
<- Our Solar System
Local or Orion Arm
10 000
20 000
30 000
40 000
Central 1,000 ly (~300 pc) diam.
"Central Molecular Zone" (CMZ)
• massive black hole 4 x 10^6 M_{sun}
• densest & most massive concentration of stars
• 3 clusters of young and hot stars (only a few million years old)
• interstellar gas and dust

SURVEY OF H_3^+ IN MOLECULAR CLOUDS



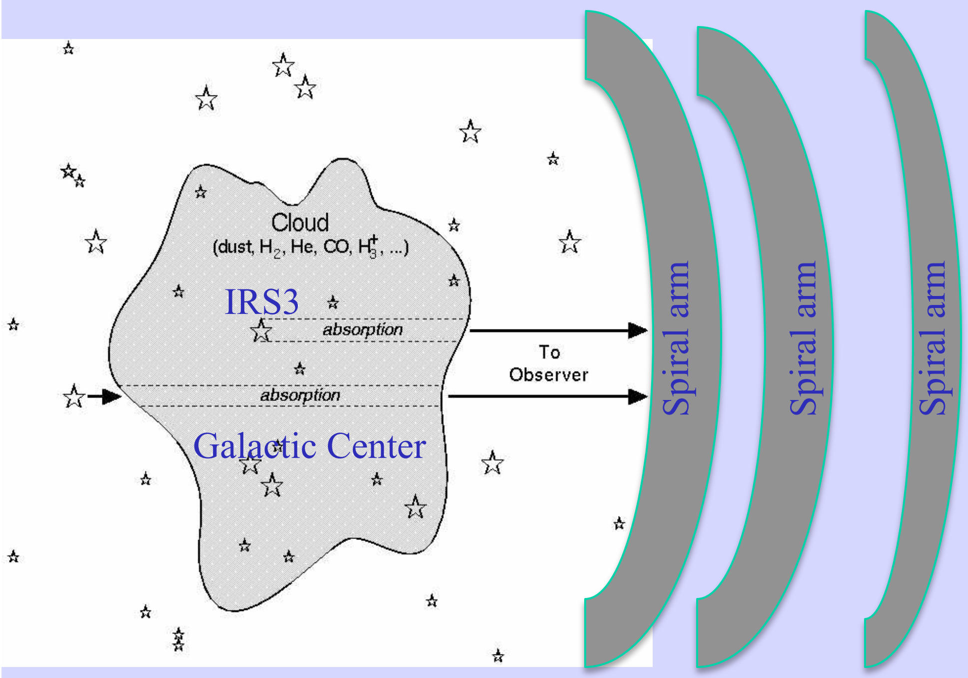
PROBLEM: gas (and dust along the line of sight to the GC, especially in the intervening spiral arms.

"If we succeed in detecting H_3^+ toward IRS 3 we won't understand what it means, and if we do not succeed we also won't understand it. We should skip the GC and observe other clouds."

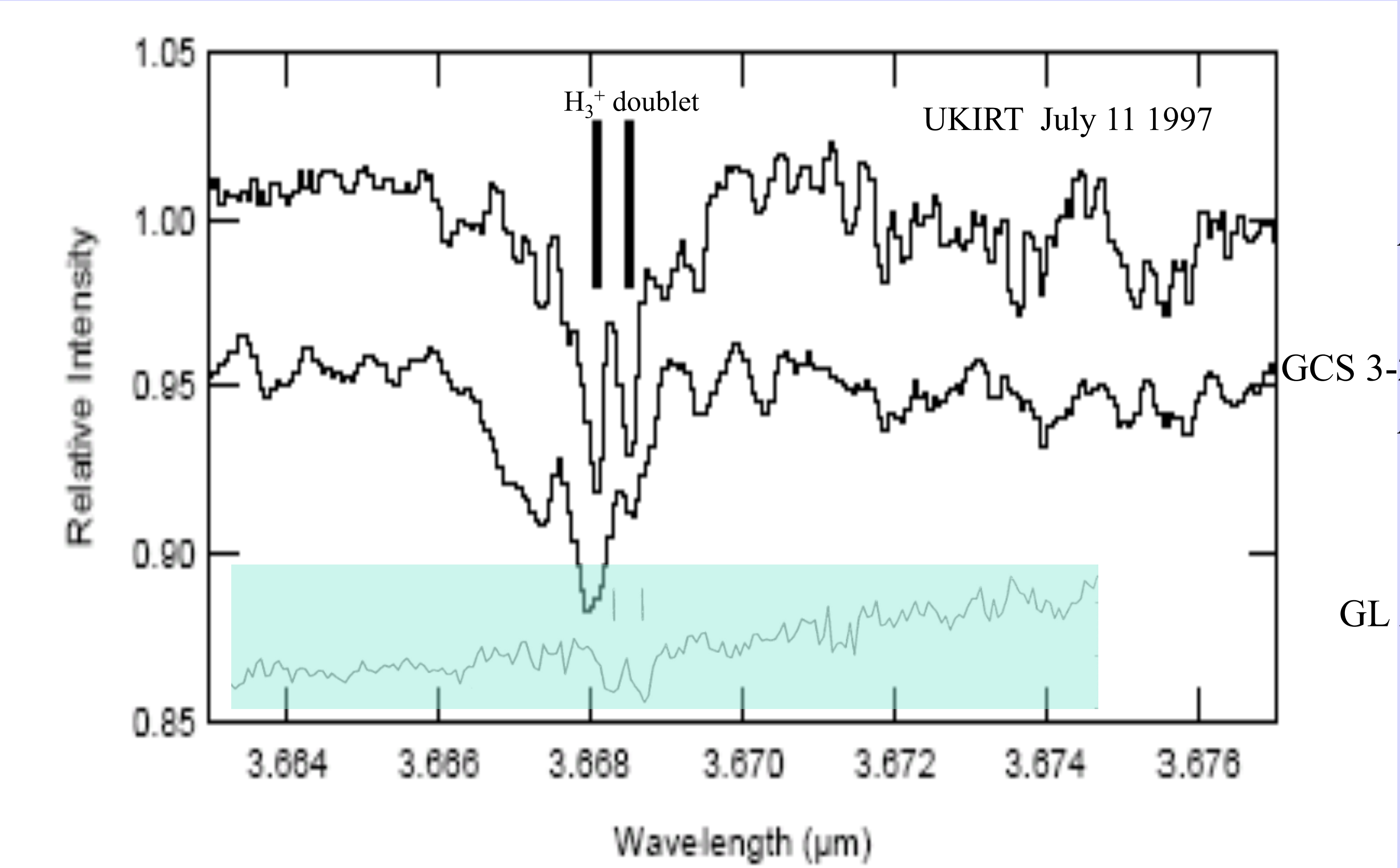
vs.

"Well, it is ***THE GALACTIC CENTER***. We must observe it."

Absorption by H_3^+ in spiral arms and elsewhere will contaminate spectrum of to H_3^+ in the GC.



Discovery of H_3^+ toward GC



GC IRS 3
$A_V = 30$ mag

GCS 3-2 (30 pc from IRS3)
$A_V = 30$ mag

GL 2136, 1996
$A_V = 60$ mag

- ~30X more H_3^+ toward GC than in typical Galactic dense clouds
- But only half as much gas and dust toward GC as toward GL2136

TWO MAIN TYPES OF INTERSTELLAR MOLECULAR CLOUDS IN THE GALAXY

Dense (dark) clouds

• 300 cm^{-3} < n < 100,000 cm^{-3} 0.1-1 pc

• no UV penetrates beyond a thin surface layer (dust abs.)

• interior hydrogen is all in H_2, all carbon is in CO.

• neutral, except tiny fraction (~10^{-9}) ionized by cosmic rays.

This is where interstellar H_3^+ was discovered.

Diffuse clouds

• 10 cm^{-3} < n < 300 cm^{-3} 1-10 pc

• only λ< 916 Å is blocked at surface

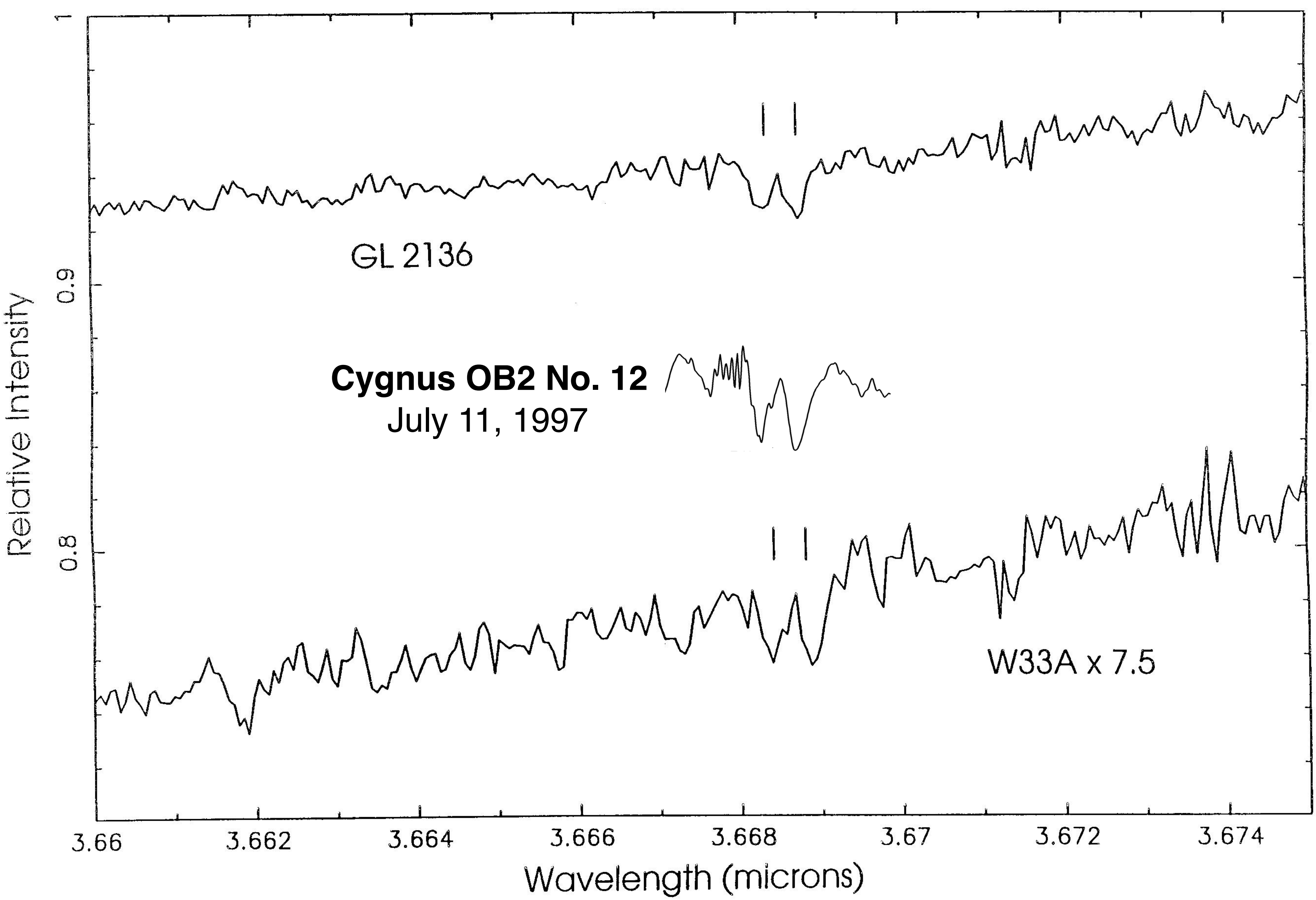
• 99% of C is ionized, only 1% of C in CO

• typically only half of hydrogen is in H_2; half is in atomic

• Lots more electrons (n_e/n_H~10^{-4}) to destroy H_3^+ than in dense cl.

➔ H_3^+ should be much less abundant than in dense clouds.

Try a diffuse cloud just to be sure.



6X less gas, ~100X higher electron density, but same amount of H_3^+ *!*

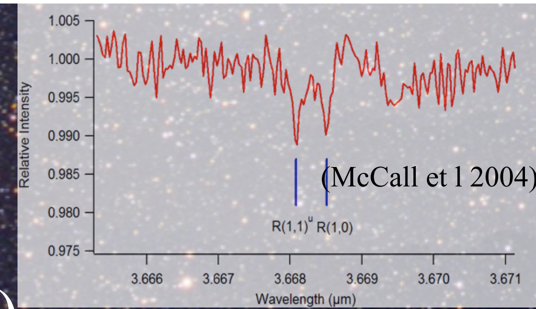
TWO PUZZLES

- How can there be so much H_3^+ in diffuse clouds ?

- Even if H_3^+ is much more abundant in diffuse clouds than we had thought, how could there be such a vast amount of H_3^+ toward and/or in the Galactic center ?

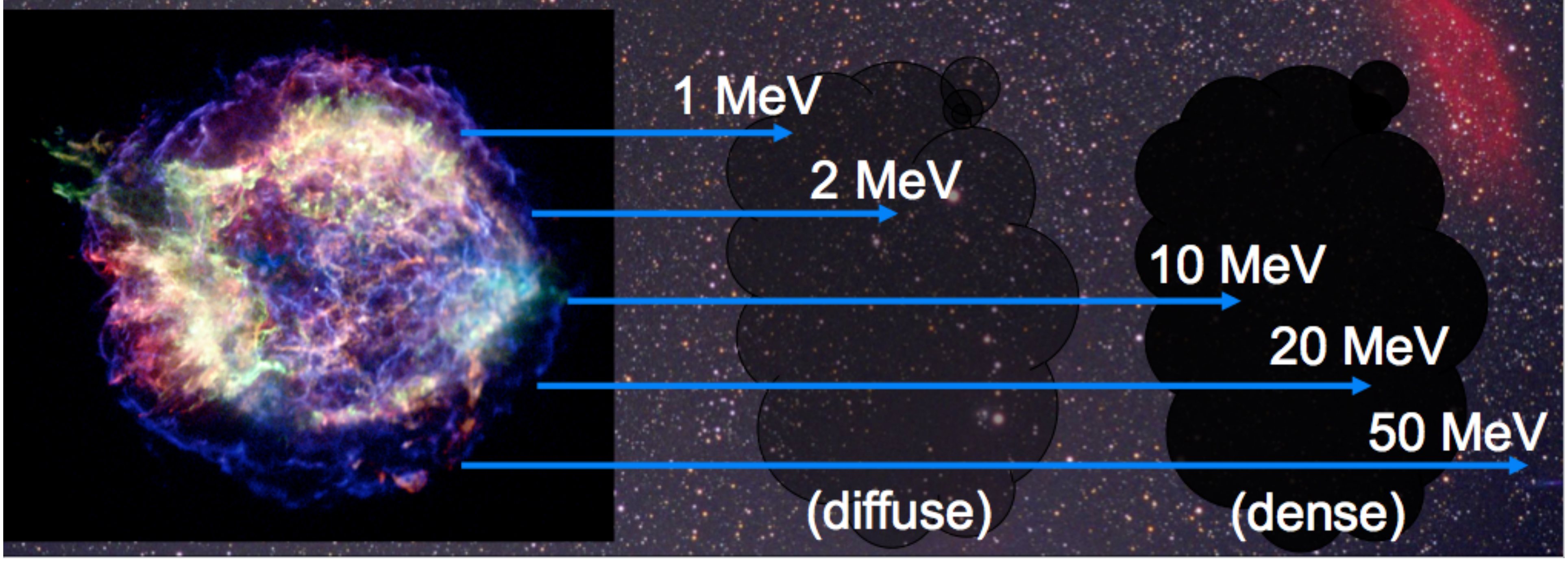
LIKELY ANSWERS (1)

Ben McCall, Nick Indriolo, …



ζ Persei
(A_V=2.8 mag)

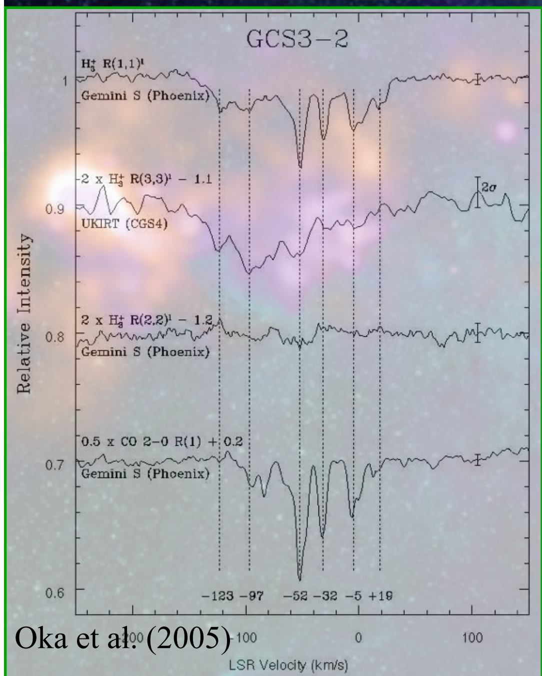
There is a large population of low energy (few MeV) cosmic rays that cannot penetrate beyond the surfaces of dense clouds and thus have little effect on the abundance of H_3^+ inside dense clouds. However, they penetrate diffuse clouds and ionize H_2 inside, resulting in a higher concentration of H_3^+.



LIKELY ANSWERS (2)

Takeshi Oka, Miwa Goto, …

- The cosmic ray flux in the Galactic center is ~100X greater than in dense clouds (because of all of the energetic phenomena (massive black hole, lots of hot stars, supernovae, …).



Oka et al. (2005)

Sgr A

- In addition, a large fraction of the Galactic center region is filled with (*previously undetected*) warm and low density (diffuse) gas.

Inspiring the next generation of scientists …