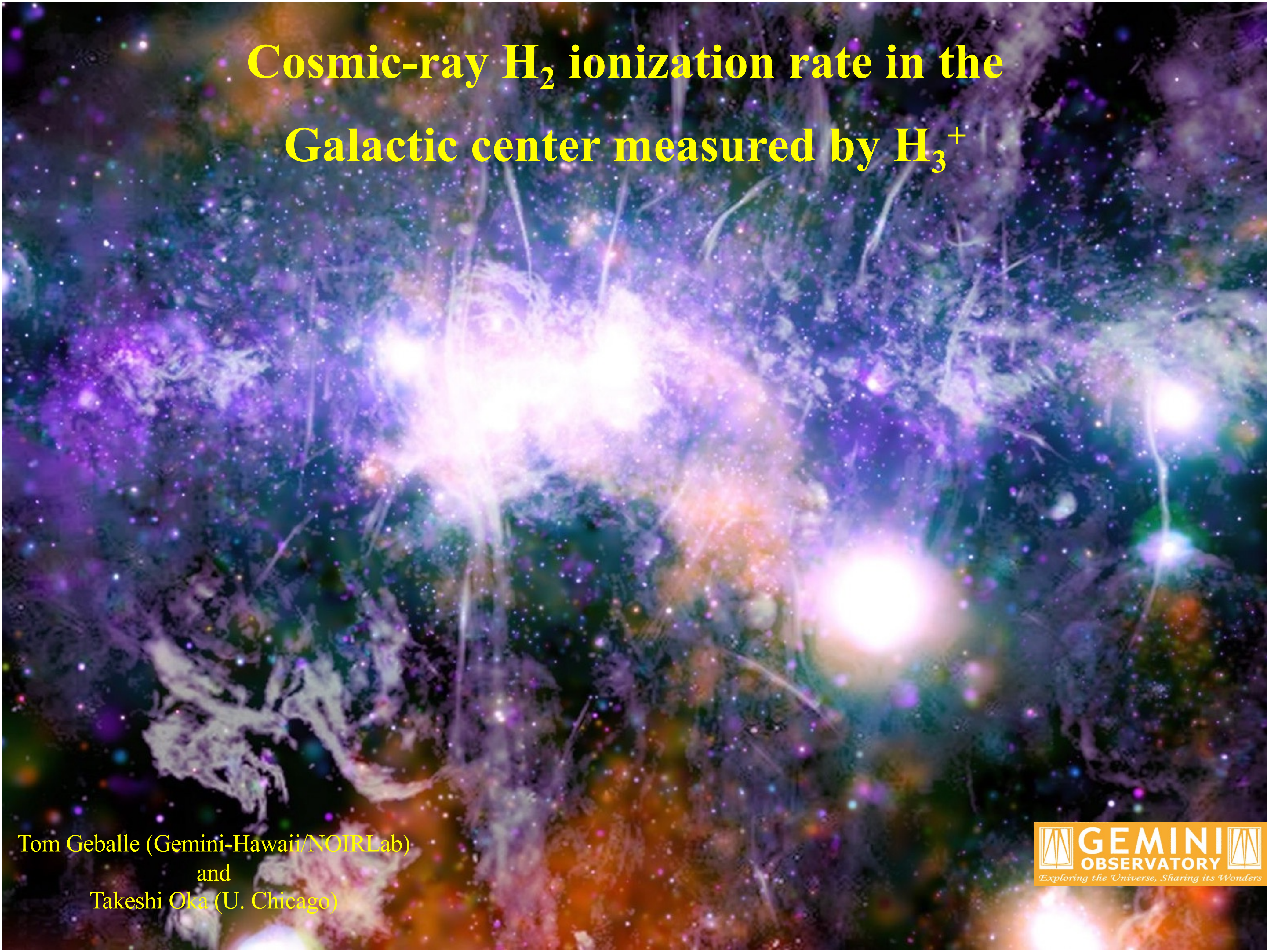
Cosmic-ray H_2 ionization rate in the Galactic center measured by H_3^+



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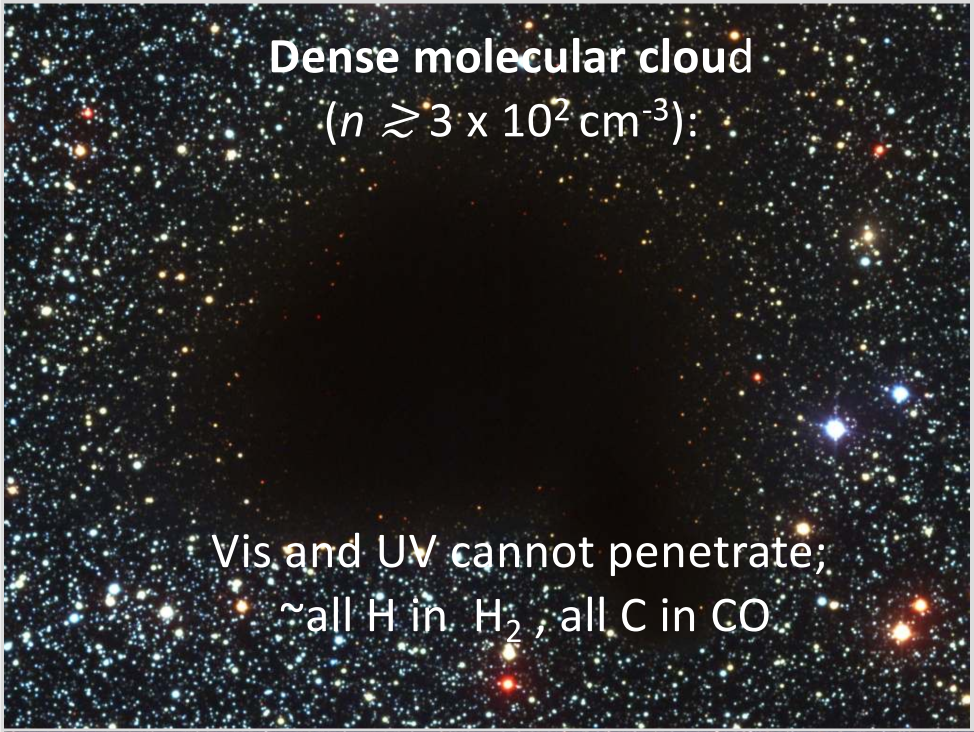
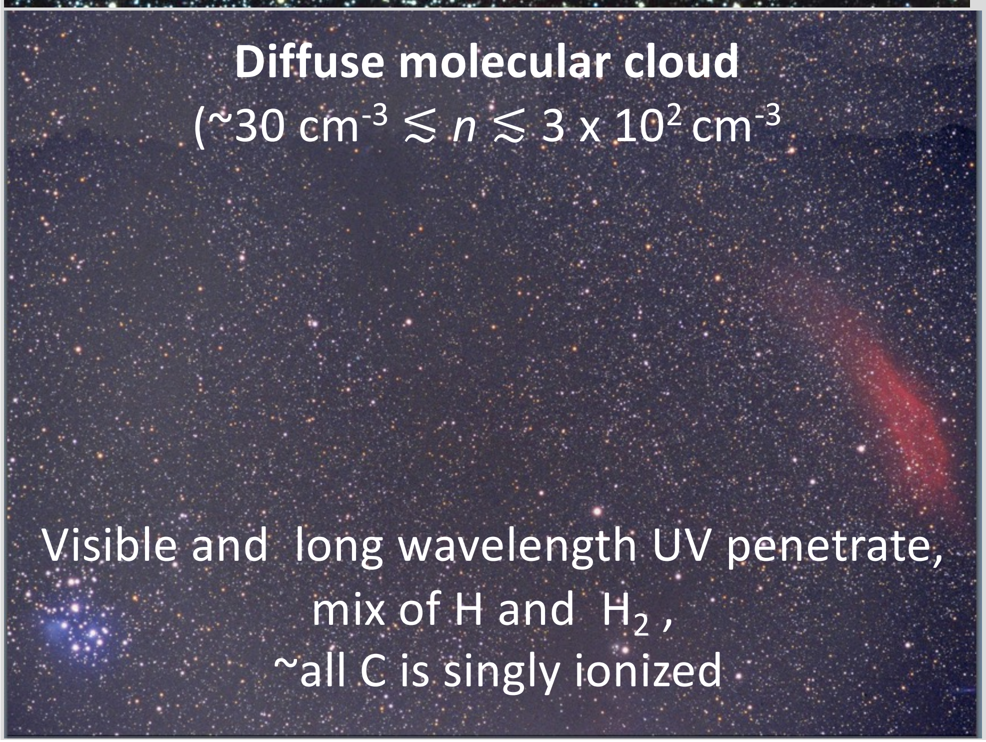
and
Takeshi Oka (U. Chicago)

GEMINI OBSERVATORY
Exploring the Universe, Sharing its Wonders

MOLECULAR CLOUD TYPES IN SPIRAL ARMS:





PRODUCTION OF H_3^+

in dense and diffuse molecular clouds
in spiral arms of the Galaxy:

(1) cr + H_2 ➔ cr + H_2^+ + e

(2) H_2^+ + H_2 ➔ H_3^+ + H

H_3^+ is a direct link to Cosmic-ray ionization rate of H_2, ζ_2

because

(1) is slow ($10^8 - 10^9$ years)

(2) is fast (days – months)

So where hydrogen is fully molecular, production rate of **H_3^+** per unit volume is simply **$\zeta_2\, n(H_2)$**

H_3^+ provides a simple way to determine ζ_2
in spiral arm molecular gas
because
***there is one dominant destruction mechanism for* H_3^+**
in each type of molecular cloud

Dense clouds : $H_3^+ + CO \rightarrow H_2 + HCO^+$

Destruction rate / volume $= k_{CO}\, n(H_3^+)\, n(CO)$

Diffuse clouds : $H_3^+ + e^- \rightarrow H_2 + H$ or $H + H + H$
(most electrons from single ionization of C)

Destruction rate /volume $= k_e\, n(H_3^+)\, n(e^-)$
$\approx k_e\, n(H_3^+)\, n(C)$

(most electrons from single ionization of C)

Steady state in each type of cloud:

$$\zeta_{2dense}\, n(H_2) \approx k_{CO}\, n(H_3^+)\, n(CO)$$

$[CO]/[H_2] \approx 1.5 \times 10^{-4}$ from radio and IR
$k_{CO} \approx 2 \times 10^{-9}$ cm^{-3} s^{-1} at T ~30 K
(Anicich & Huntress 1976)

and

$$\zeta_{2diff}\, n(H_2) \sim k_e\, n(H_3^+)\, n(e^-)$$

for (almost) all H in H_2 ; $n(e^-)/n(H_2) \sim 6 \times 10^{-4}$ $[e^-]=[C]$
$k_e \approx 2 \times 10^{-7}$ cm^{-3} s^{-1} at T ~30 K (McCall et al. 2003)
100X greater than k_{CO}

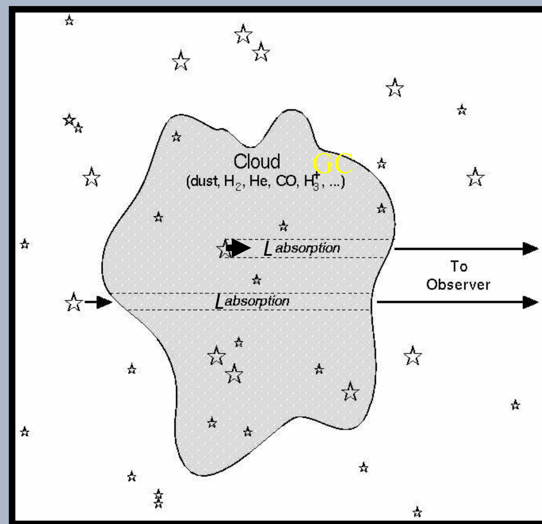
$$\rightarrow\quad n(H_3^+) \approx \zeta_2 \times \text{const.}$$

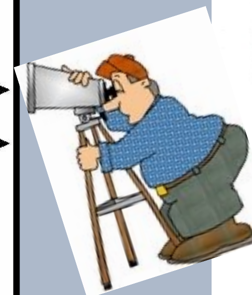
(const. is much smaller for diffuse clouds than for dense clouds)

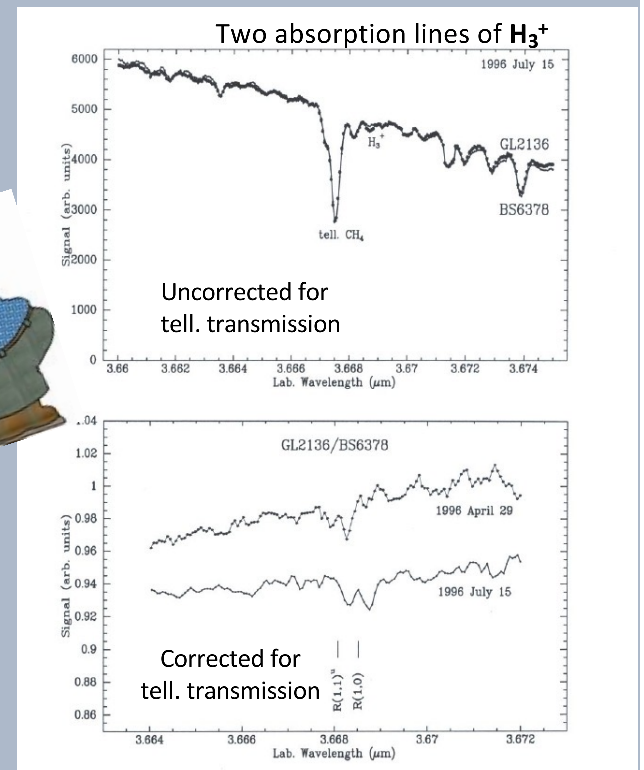
We don't measure $n(H_3^+)$; we measure absorption line strengths, which give column density, $N(H_3^+)$

measured estimated

$$\langle n(H_3^+)\rangle = N(H_3^+) \,/\, L_{cloud}$$







$$\zeta_2 \times L = \text{const.} \times N(H_3^+)$$

two unknowns measured

Estimate of L results in an estimate for ζ_2.

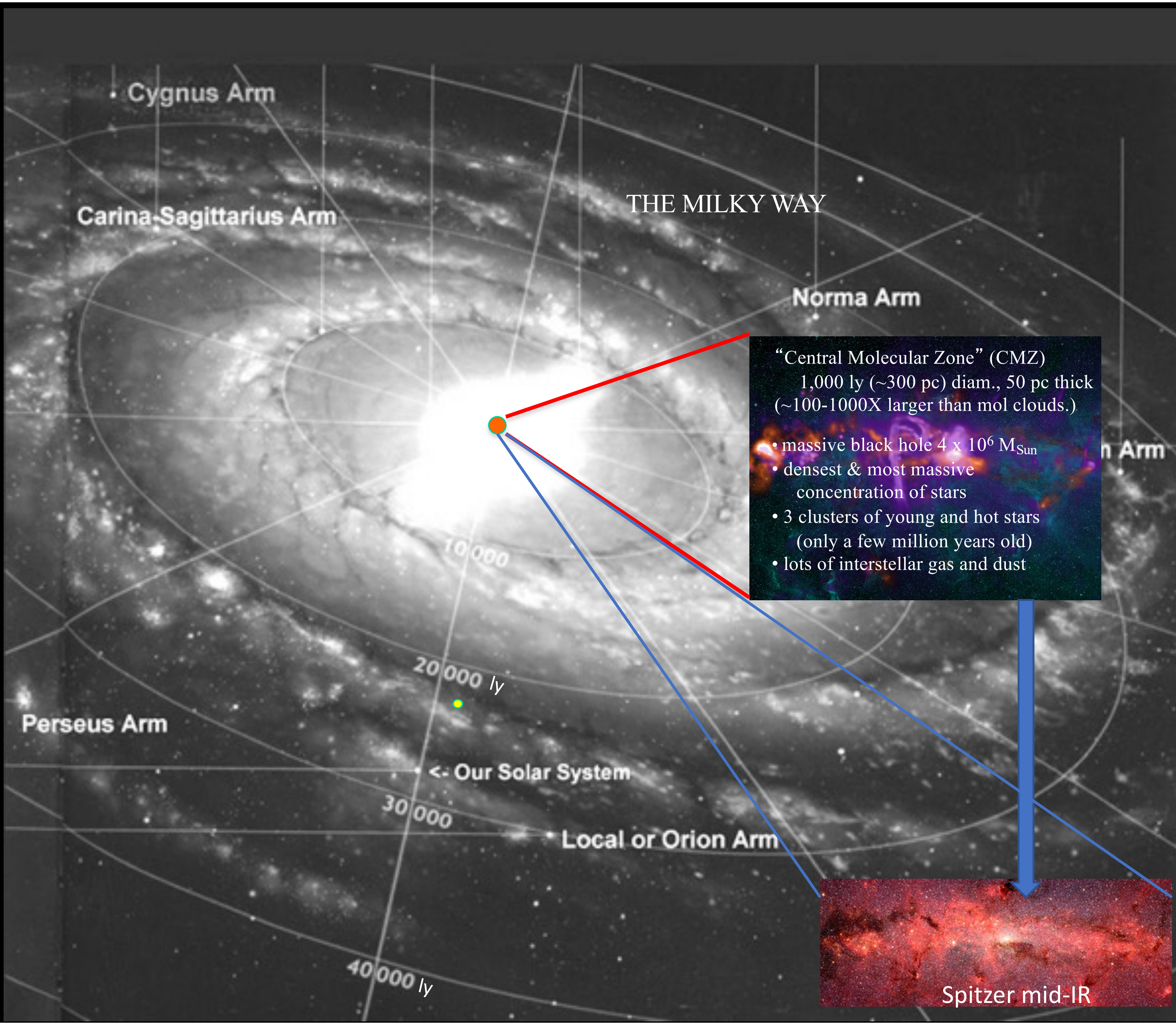
ζ_{2dense} = few × 10^{-17} s^{-1} (as expected**)**

(Geballe & Oka 1996, McCall et al. 1999)

ζ_{2diff} = few × 10^{-16} s^{-1} !

(McCall et al. 2003, Indriolo et al 2007, 2012 Neufeld & Wolfire 2017)

Possible explanation: diffuse clouds largely ionized by low energy cosmic-rays that don't penetrate dense clouds (McCall et al. 2002 Indriolo et al 2007, 2009)



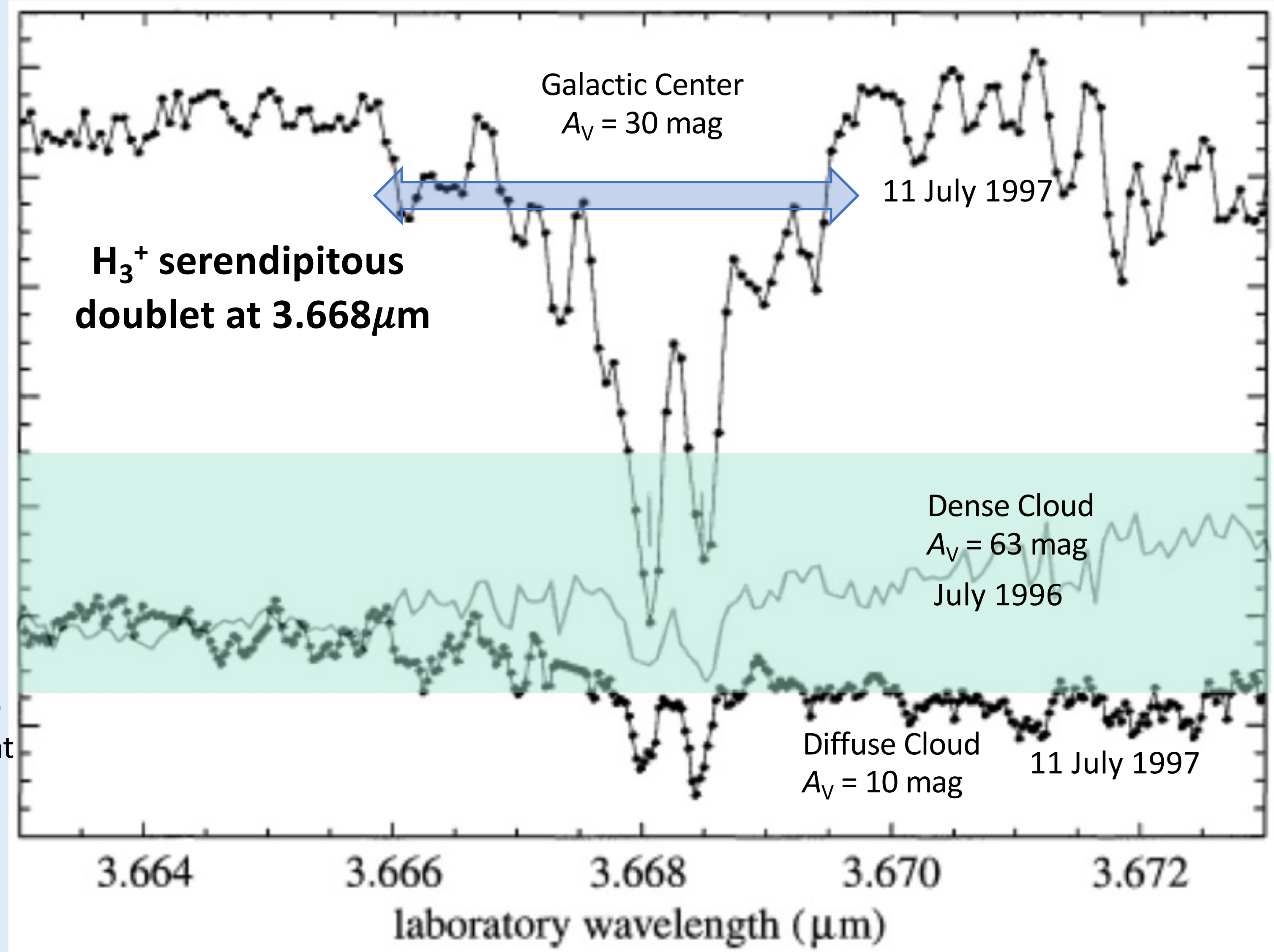
Cygnus Arm
Carina-Sagittarius Arm
THE MILKY WAY
Norma Arm
"Central Molecular Zone" (CMZ)
1,000 ly (~300 pc) diam., 50 pc thick
(~100-1000X larger than mol clouds.)
• massive black hole 4 x 10^6 M_{Sun}
• densest & most massive concentration of stars
• 3 clusters of young and hot stars (only a few million years old)
• lots of interstellar gas and dust
10 000
20 000 ly
Perseus Arm
<- Our Solar System
30 000
Local or Orion Arm
40 000 ly
Spitzer mid-IR

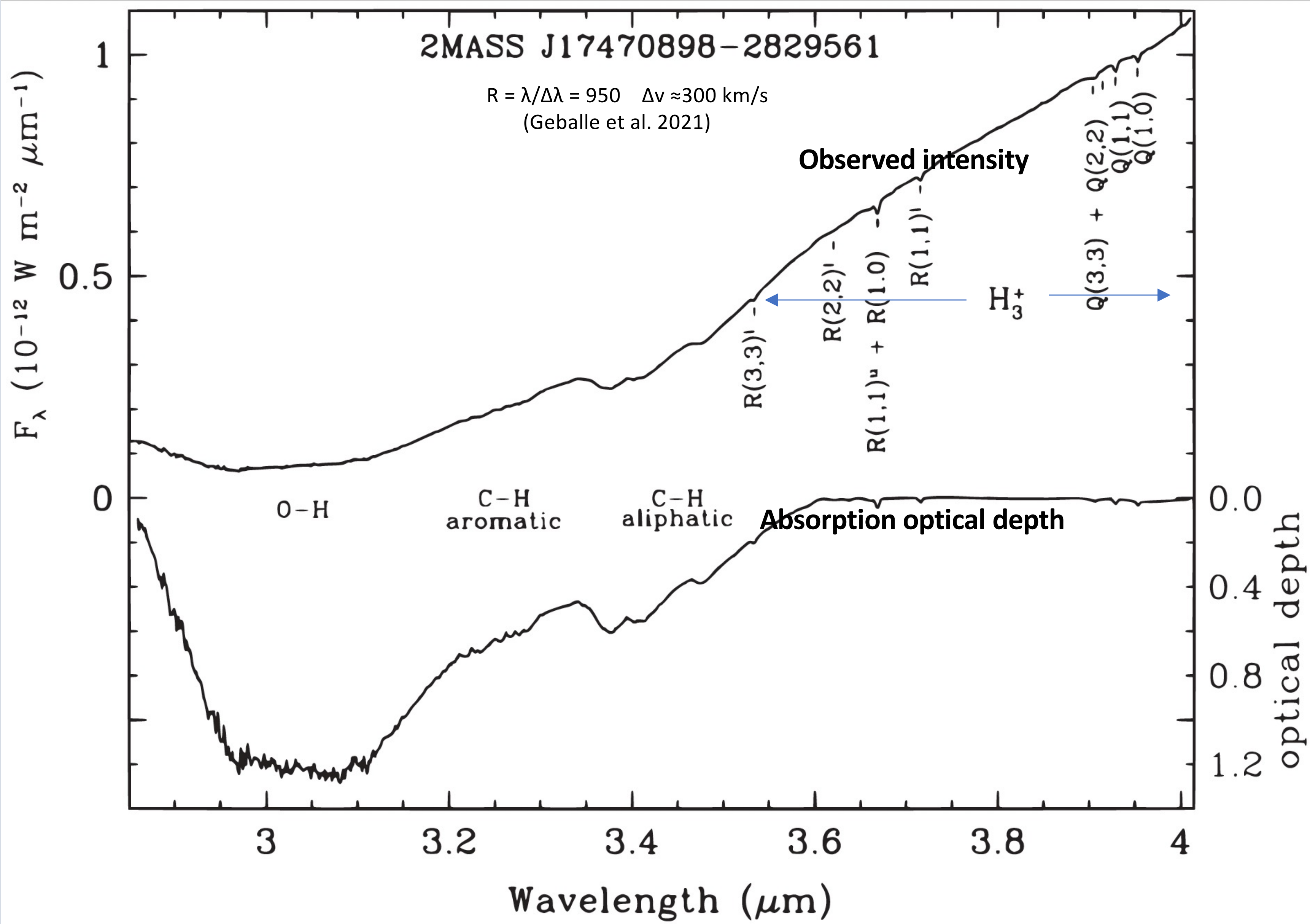
1997: Discovery of huge amount of H_3^+ in the Galactic center

Absorption of H_3^+ toward star in the GC

30X greater than toward dense cloud with twice the amount of gas and obscuring dust

30X greater than toward diffuse cloud with one-third the amount of gas and obscuring dust.

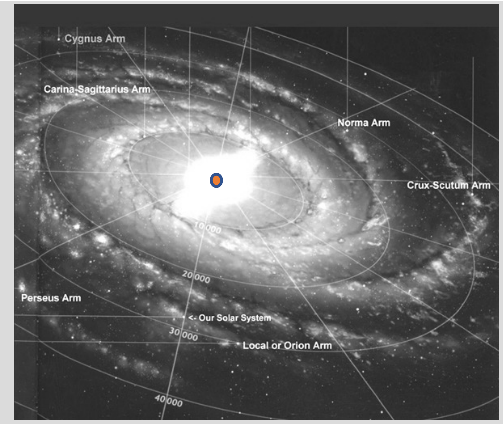




H_3^+ ABSORPTION LINES SEEN ON MANY GC SIGHTLINES

In the 3-4 μm wavelength Interval, the only interstellar spectral features due to gaseous atomic or molecular species that are observed toward objects in the CMZ are due to H_3^+.

WHERE DOES GC H_3^+ ABSORPTION TAKE PLACE ?



8 kpc sightline
3 spiral arms possibly containing cold diffuse and/or dense clouds?
Molecular clouds in the CMZ (what kinds of clouds/densities)?

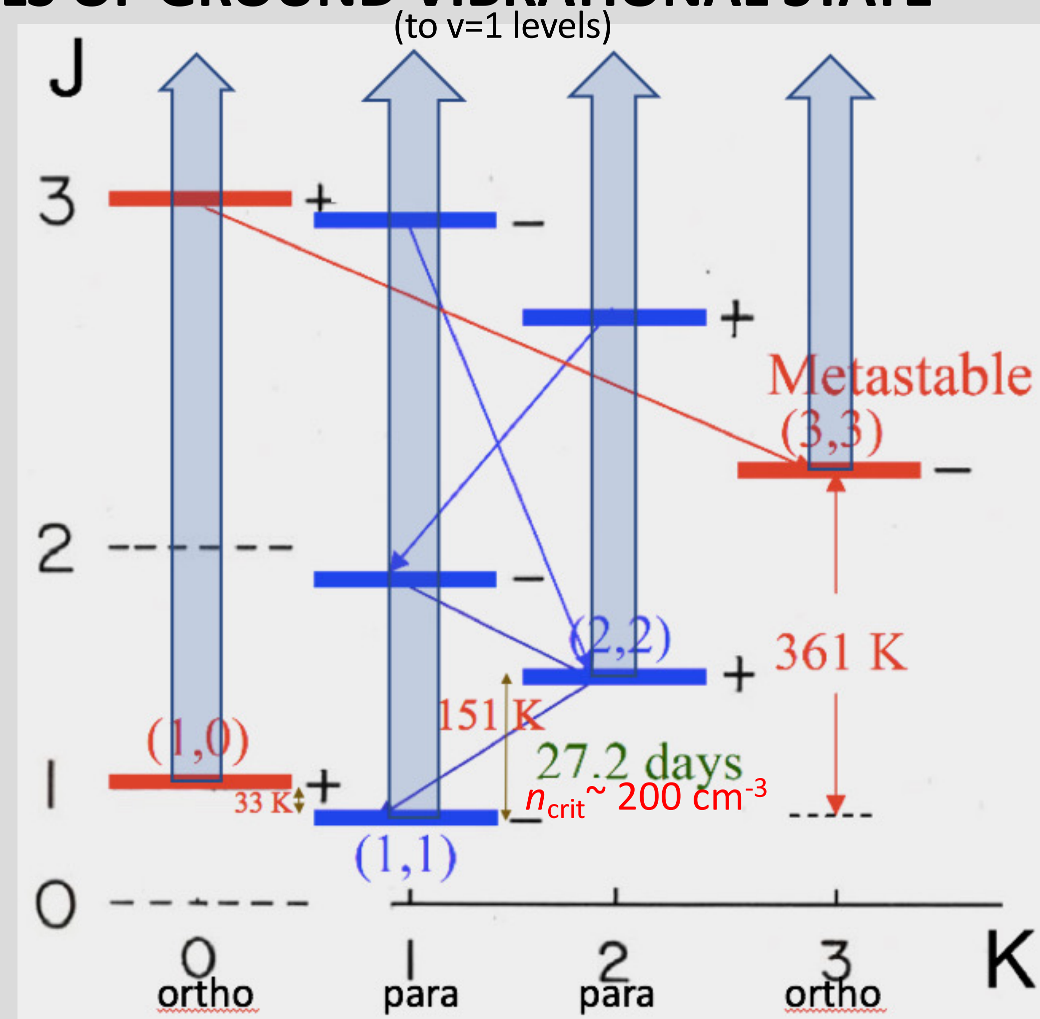
LOW-LYING ROTATIONAL LEVELS OF GROUND VIBRATIONAL STATE

- Energy levels are widely spaced

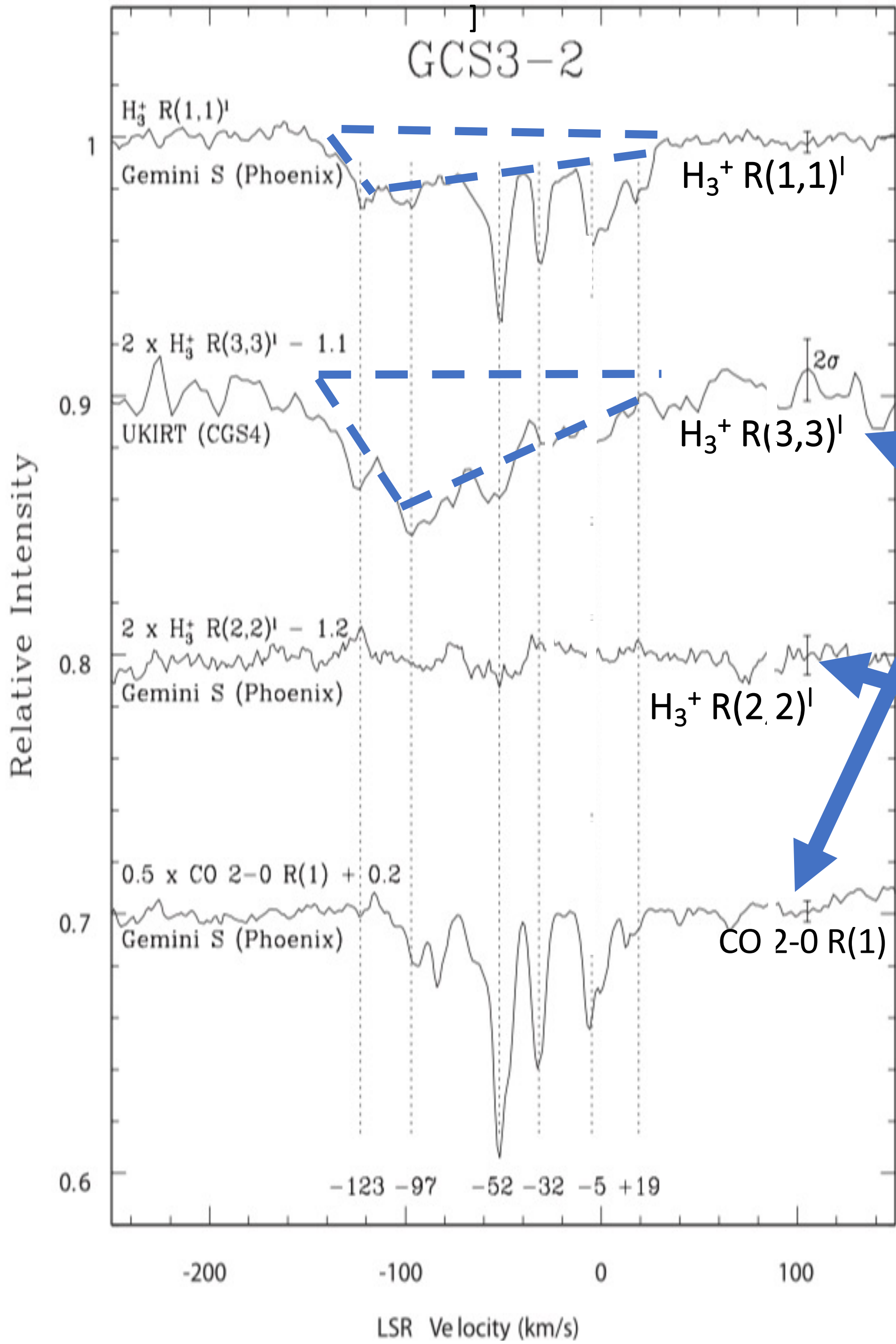
- Absorption lines from (J,K) = (1,0) and (1,1) are the only lines observed in dense and diffuse clouds in Galactic spiral arms

- (2,2) level 151 K above lowest level: not observed in cold gas (spiral arms). (can slowly radiatively decay; n_{crit}~200 cm^{-3}) POTENTIAL DENSITOMETER IN WARM GAS

- (3,3) level 361 K above lowest level: not observable in cold gas (spiral arms). (metastable – **cannot** radiatively decay) THERMOMETER IN WARM GAS



Typical H_3^+ and CO spectra toward central 100 pc of CMZ (Oka et al. 2005)



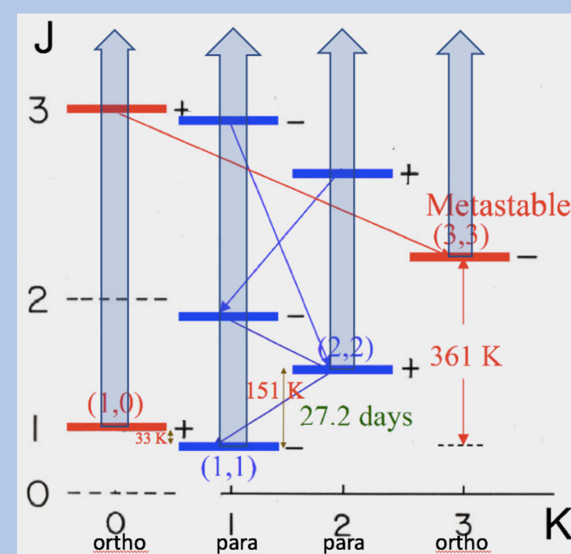
(1) Absorption from low-lying (*J,K*)=(1,1) has both sharp features and *broad absorption at negative velocities*

(2) CO absorption only has sharp features
➔ sharp features from H_3^+ and CO arise in dense gas; velocities match those of 3 spiral arms.

No broad absorption
➔ broad absorption is in diffuse gas

(3) Broad blue-shifted absorption present in line from metastable (3,3) level 360K above (1,1). No sharp absorptions.
➔ high dispersion absorbing gas is warm (~200 K)

(4) No absorption from unstable (2,2) 150 K above (1,1), should see if LTE at 200K
➔ warm gas has $n < 100$ cm^{-3}



CONCLUSIONS FROM OBERVING H_3^+ LINE PROFILES ON ~30 SIGHTLINES INTO THE CMZ (FROM CENTER TO EDGES)

(Oka et al. 2019, 2021)

Gas containing $\mathbf{H_3^+}$:

- Is warm (200K)
- Is low density (< 100 cm-3)
- Has a mass of at least ~ 6 x 10^6 M_{Sun}
- Fills ~2/3 of the CMZ
- Is expanding radially at speeds up to 150 km/s
  from a region close to the very center (Sgr A* ?)
- Is associated with an explosive "event" ~ $1x10^6$ yr ago.
- Will fall back toward the center in the next ~$1x10^6$ yr.

- *Experiences a much more intense cosmic-ray bombardment than clouds in the Galactic arms.*

Spitzer - IR

Earlier estimates of ζ_2 in the CMZ by Oka et al. (2005), Goto et al. (2008) used simple steady-state equation for diffuse clouds and obtained

$$\boldsymbol{\zeta_{2CMZ} = 2\text{-}7 \times 10^{-15}\ s^{-1}}$$

(10X higher than diffuse clouds in Galactic arms)

but

With much higher c-r ionization rate, the simple linear steady-state equation for diffuse clouds is no longer valid.

CONTRASTING APPROACHES

The Meudon analysis (Le Petit et al. 2016) uses a highly sophisticated code taking into account 165 species and 2850 chemical reactions. ***In contrast, here we consider only hydrogen and electrons.****.* - Oka et al. (2019)

WHAT IS DIFFERENT FOR H_3^+ IN THE CMZ ?

Dissociative recombination of H_3^+ on electrons remains
the dominant H_3^+ destruction mechanism.

but harder to produce H_3^+ and more ways to produce electrons:

(1) $f(H_2) < 1$, even in Galactic plane diffuse clouds
(Indriolo et al 2007)
Meudon analysis of CMZ obtained $f(H_2) = 0.6$ ([H_2]/[H} = 0.75)
less H_2 to react with H_2^+ ➔ H_3^+

(2) Charge exch. reaction $H_2^+ + H \rightarrow H_2 + H^+$ competes with $H_2^+ + H_2$ ➔ $H_3^+ + H$
(less H_2^+ to react with H_2 to make H_3^+)

(3) cosmic-ray ionization of both H and H_2
rivals or exceeds e^- from C^+ for $\zeta > 10^{-15}$ s^{-1}
(radiative association (p + e → H > 10^4X slower than $\mathbf{H_3^+}$ + e → $\mathbf{H_2}$ + H or → 3H
(more e^- to destroy H_3^+)

Each of the above processes reduces the abundance of H_3^+,
requiring higher ζ_{2CMZ} than 2005 estimate to produce observed $N(H_3^+)$

Steady state (Oka et al. 2019): $\zeta n_H[f(H_2)]^2 = k_e[(n_C/n_H)_{SV} R n_H + n_e^*] n(H_3^+)$

density of H nuclei — fraction of H atoms in H_2 — electrons from C^+ — C overabunance — electrons from H_2^+ & H^+

"Since n_e is a function of $n(H_3^+)$, which in turn is a complicated function of ζ, it is a hopeless task to solve this equation directly."

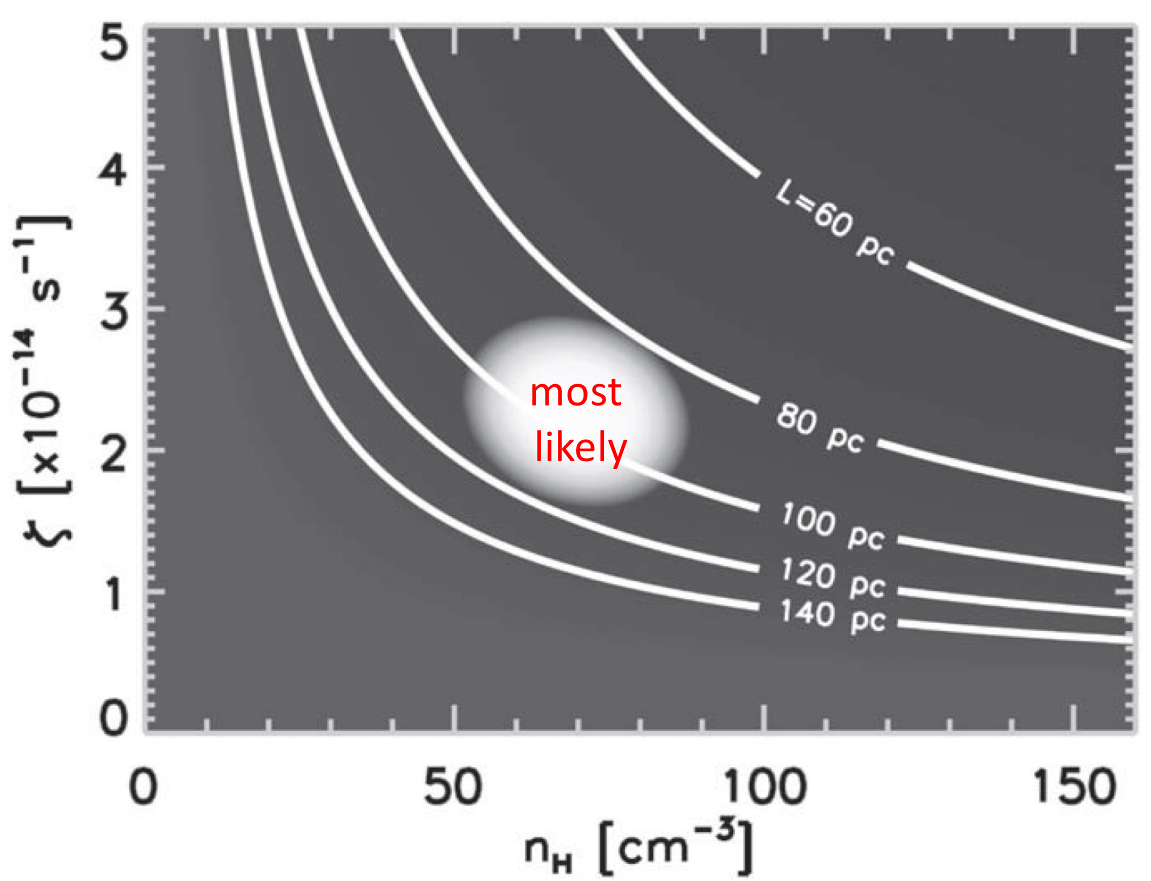
Most likely values of *n* (= *n*(H) + *n*(H_2)) and ζ for the constraints

- $N(H_3^+) = 3 \times 10^{15}$ cm^{-2}
- $n \lesssim 100$ cm^{-3}
- $f(H_2) = 0.6$
- $L \lesssim 150$ pc

***n* ~ 50 cm^{-3}**

(*n*(H_2) ~ 20, *n*(H) ≈ 30)

ζ_{2CMZ} ~ 2 x 10^{-14} s^{-1}



Meudon analysis:

ζ_{2CMZ} = 1-11 x 10^{-14} s^{-1} for $n < 100$ cm^{-3}

ζ_{2cMZ} ~ 100 × ζ_{2diff},

ζ_{2CMZ} ~ 1000 × ζ_{2dense}

STAR FORMATION IN THE GALACTIC CENTER

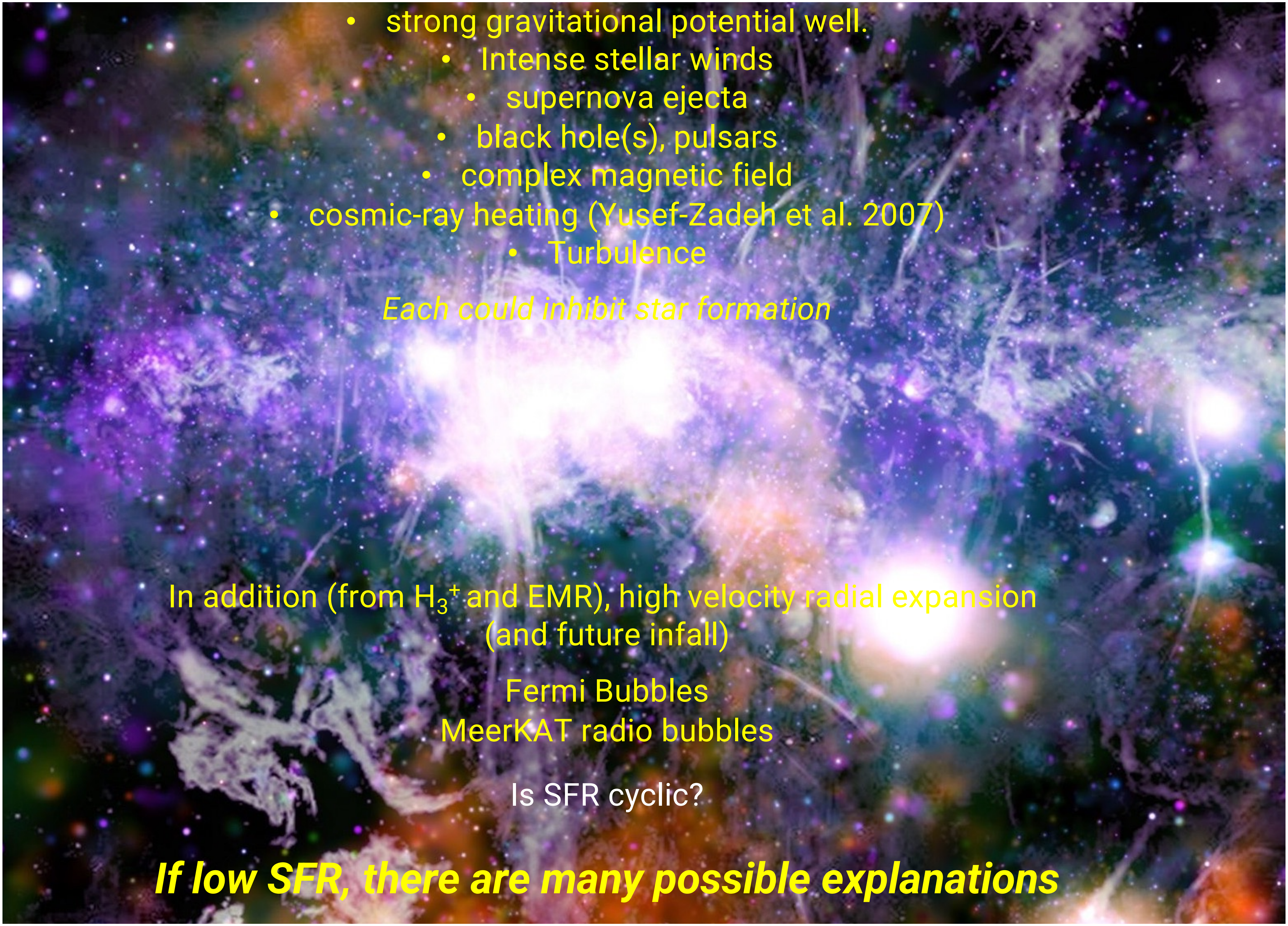
Star Formation “Problem”:

CMZ thought by some to be currently forming stars at ~10% of the rate expected for its amount of dense molecular gas.

(scaled from observed rates in spiral arm dense clouds)

(e.g., Immer et al. 2013, Barnes et al. 2017, Longmore et al. 2013, Hankins et al. 2020)

But see review by Henshaw et al. (2022)

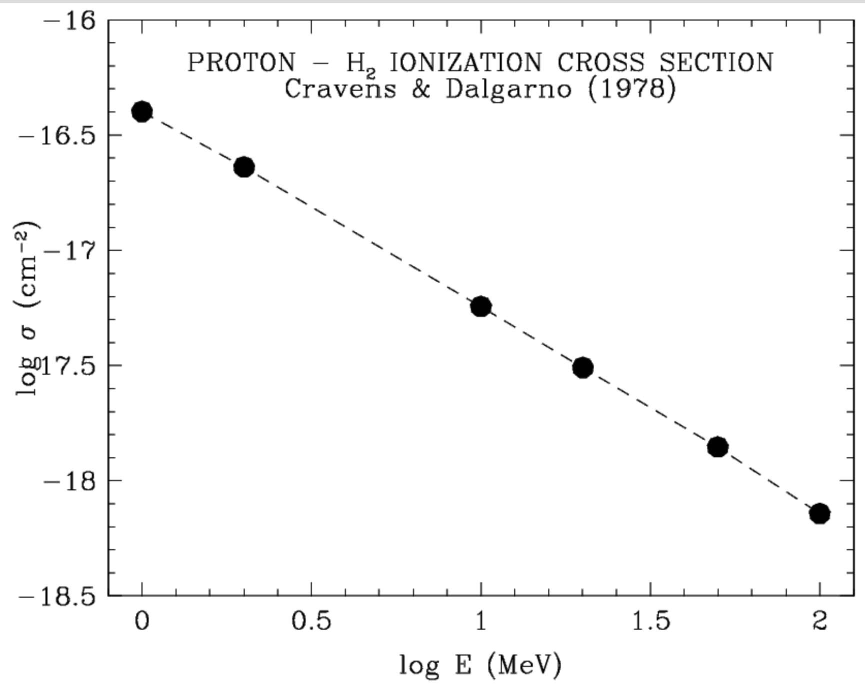


• strong gravitational potential well.
• Intense stellar winds
• supernova ejecta
• black hole(s), pulsars
• complex magnetic field
• cosmic-ray heating (Yusef-Zadeh et al. 2007)
• Turbulence
Each could inhibit star formation
In addition (from H_3^+ and EMR), high velocity radial expansion (and future infall)
Fermi Bubbles
MeerKAT radio bubbles
Is SFR cyclic?
If low SFR, there are many possible explanations

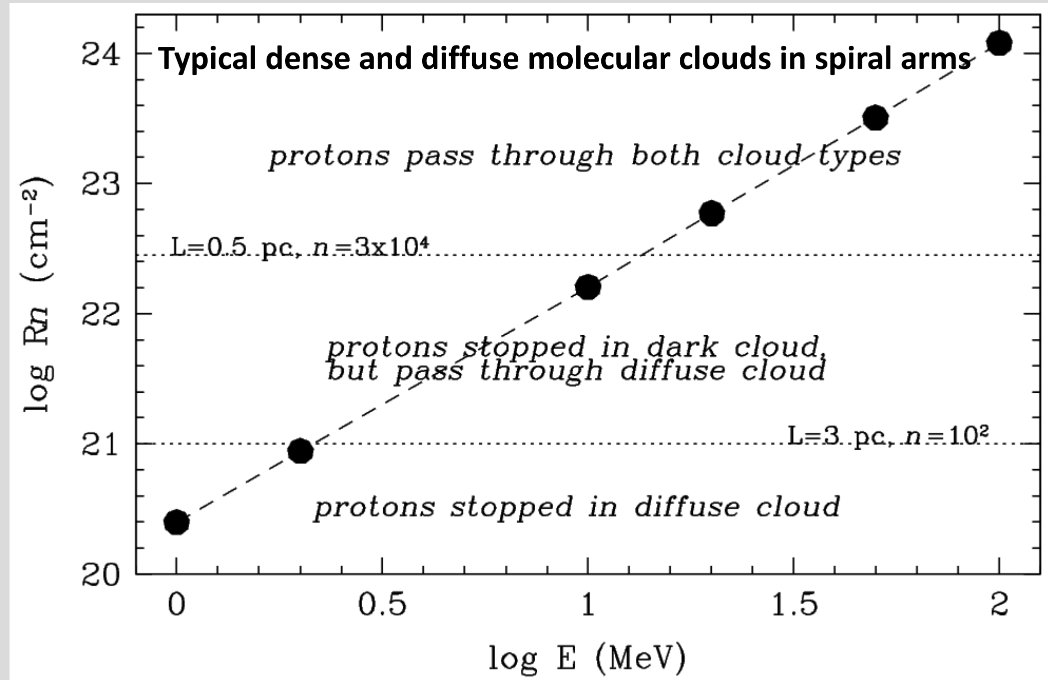
What is the energy spectrum of H_2-ionizing cosmic-rays in the diffuse CMZ?

ζ_2 is result of cosmic-rays with a wide range of energies and ranges

H_2 ionization cross section varies as 1/E



penetration distance proportional to E^2



Progress made in constraining energy spectrum in (small) Galactic diffuse clouds

(e.g., Indriolo et al. 2009)

but CMZ: ~300 pc diameter, ~60 pc thick

Is its c-r spectrum dominated by higher energy cosmic-rays with long penetration distances

or

by many localized sources of lower energy cosmic-rays with short penetration distances?

A Future Challenge