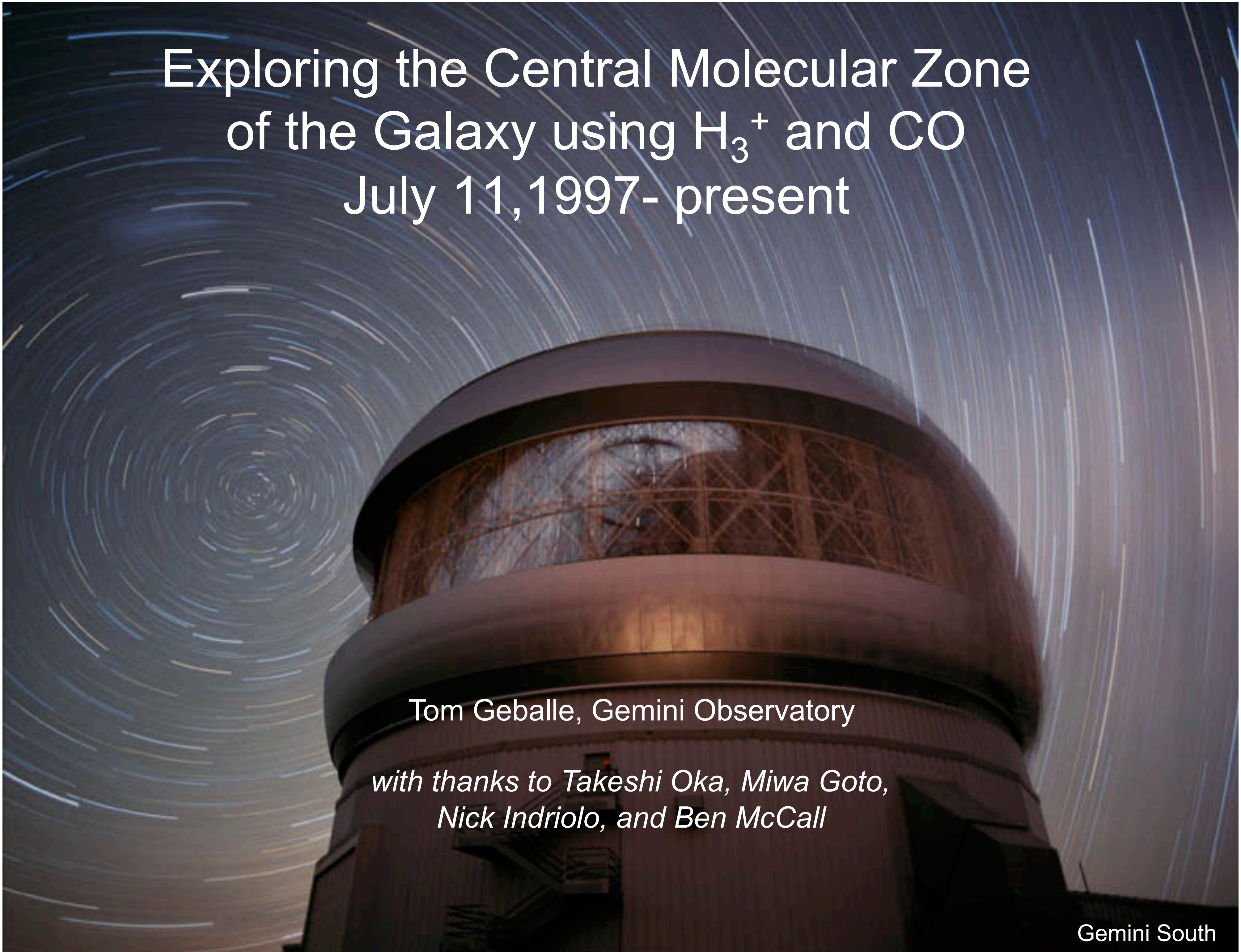
Exploring the Central Molecular Zone of the Galaxy using H_3^+ and CO
July 11,1997- present

Tom Geballe, Gemini Observatory

with thanks to Takeshi Oka, Miwa Goto, Nick Indriolo, and Ben McCall



Gemini South

OUTLINE OF TALK

1. Description of the Galactic center and its Central Molecular Zone

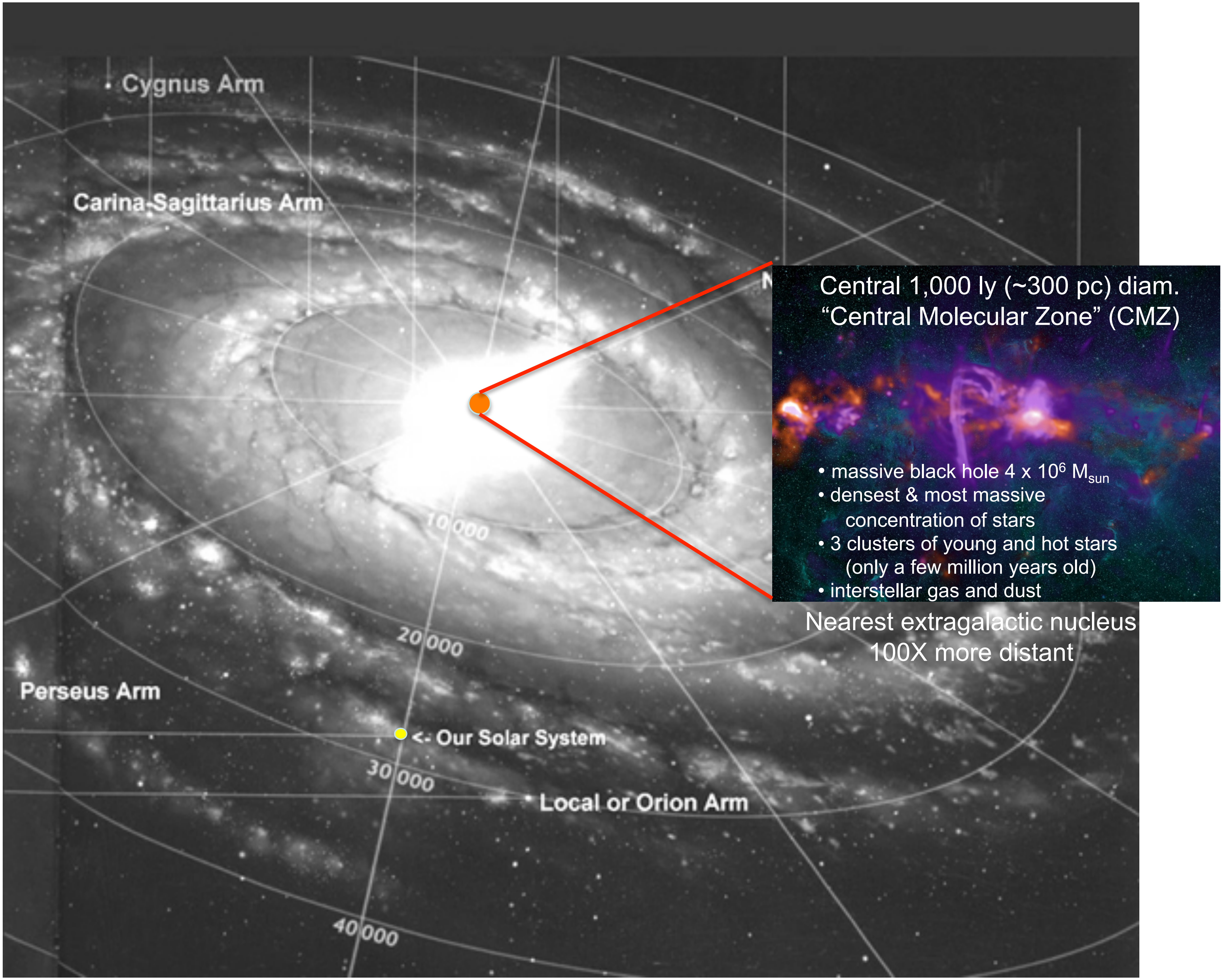
2. Abundances of H_3^+ and CO in “normal” dense and diffuse molecular clouds

3. Unique properties of H_3^+

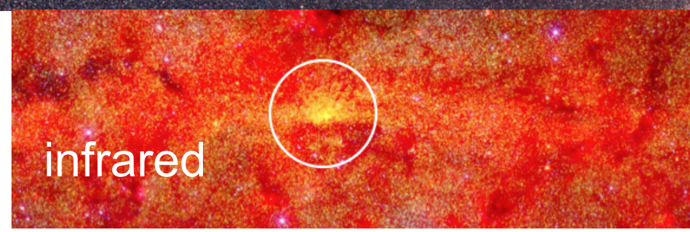
4. Initial GC sightlines: observations and interpretation

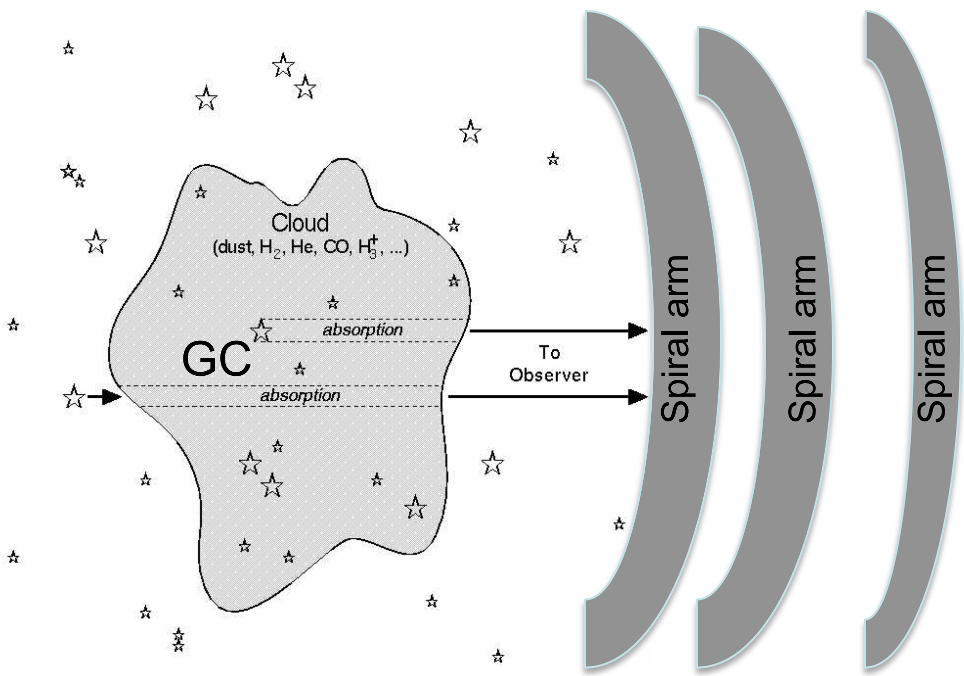
5. New GC sightlines

6. Conclusion



Cygnus Arm
Carina-Sagittarius Arm
10 000
20 000
30 000
40 000
Perseus Arm
<- Our Solar System
Local or Orion Arm
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
Nearest extragalactic nucleus
100X more distant



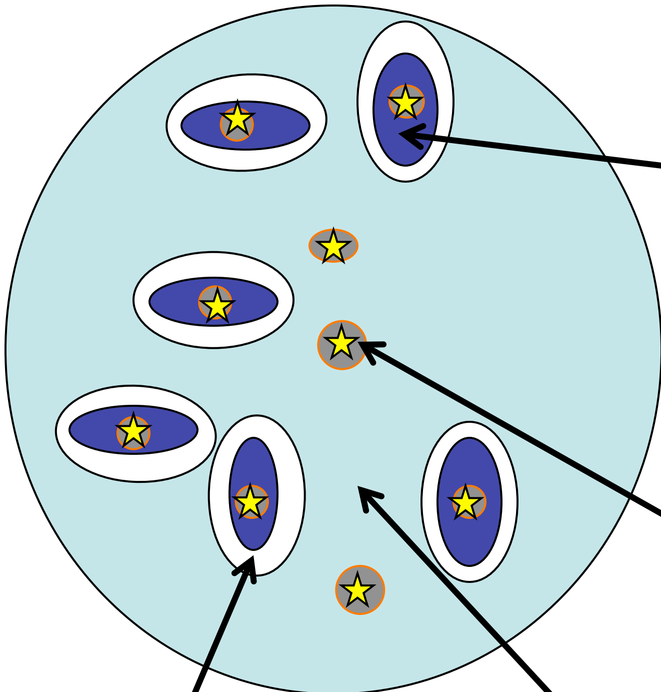


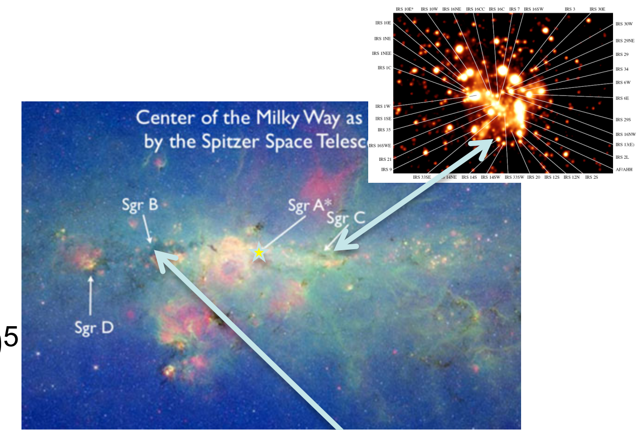
PROBLEM: gas and dust along the line of sight (esp. in the CMZ and in the intervening spiral arms.

(1) Dust produces 30 mag (factor of 10^6) attenuation at visible wavelengths.
Must observe GC in other wavebands.

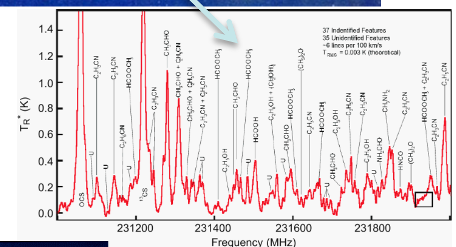
(2) Molecular (CO, H3+, …) absorption lines in spiral arms are superimposed on GC lines.

Gaseous environments in the CMZ ca. 2000
(after Morris & Serabyn 1996; Lazio & Cordes 1998)

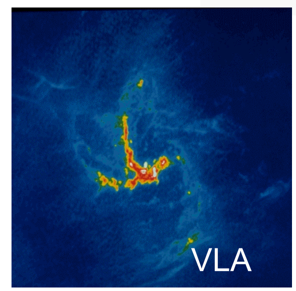




Dense Mol. Clouds
(e.g., Sgr B) n~10^3-10^5
T~100 K, **f ~ 0.1**
The greatest concentration of molecular gas in the Galaxy *(little of it in front of Sgr A* and Central Cluster)*



Ionized gas
T~10^4 K, n~10^3
e.g. Sgr A West
f ~ 0.01



Scattering gas
n~10, T~10^6
f ~ 0.1

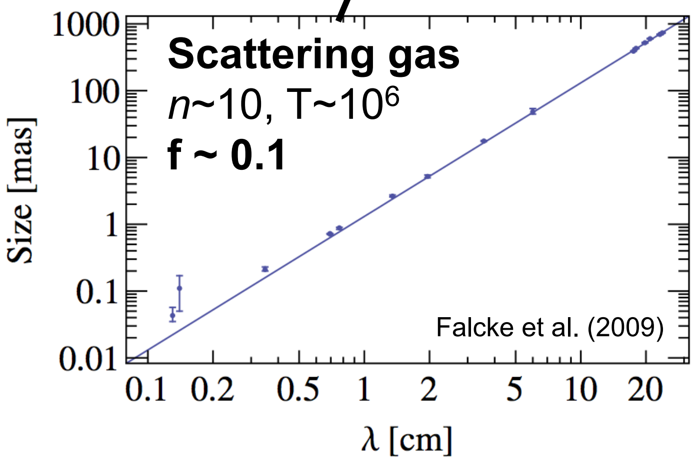
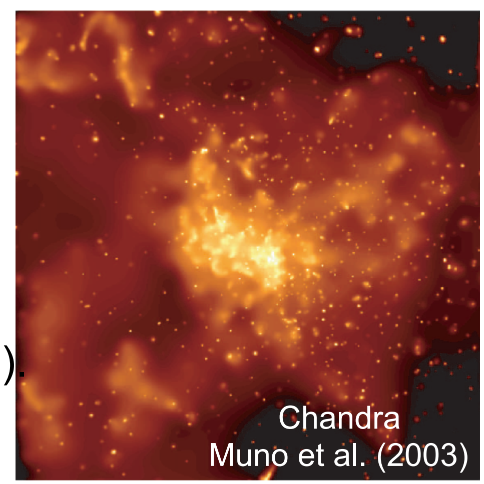
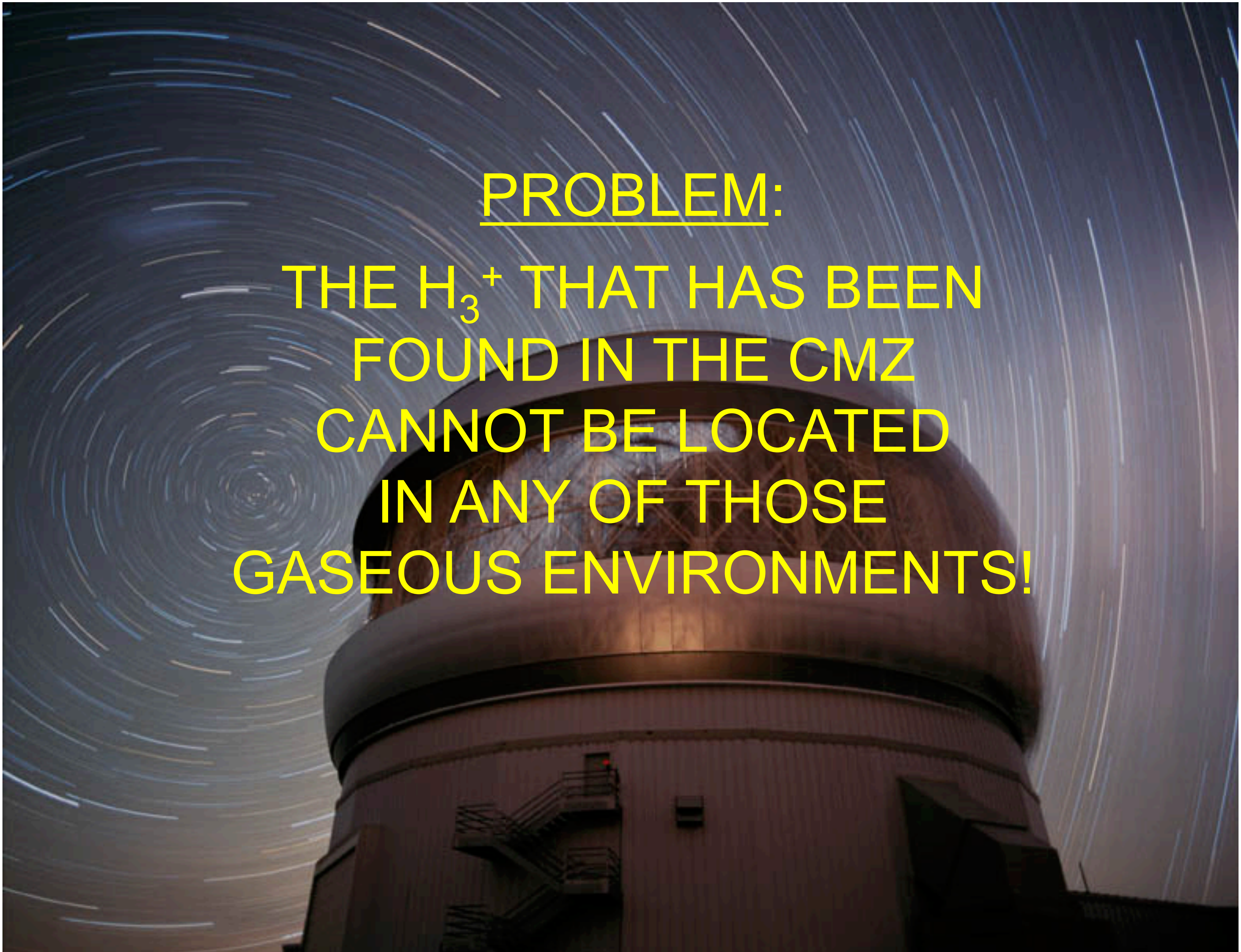


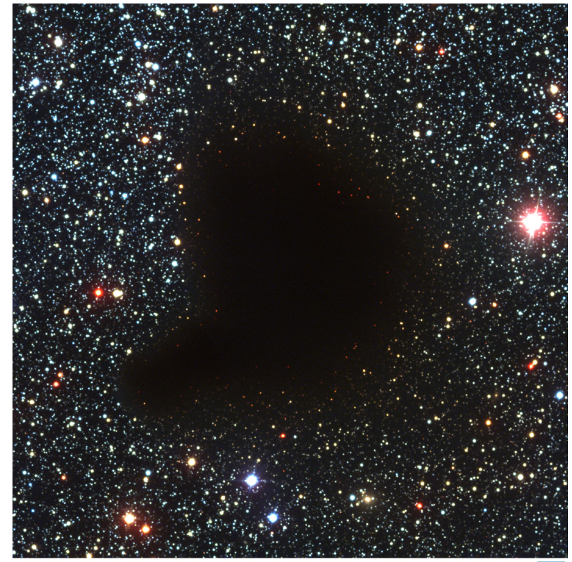
Fig. 1. Measured radio source size (major axis) of Sgr A* as function of observing wavelength in centimeters.

X-ray emitting plasma
(Diffuse X-ray emission seen by 1990s space telescopes
n~0.05, T~$10^{7\text{-}8}$ **K** **f ~ 0.8**
Now known to include diffuse and pointlike sources (Chandra).




PROBLEM:
THE H_3^+ THAT HAS BEEN
FOUND IN THE CMZ
CANNOT BE LOCATED
IN ANY OF THOSE
GASEOUS ENVIRONMENTS!

TWO MAIN TYPES OF INTERSTELLAR MOLECULAR CLOUDS IN THE OUTER GALAXY

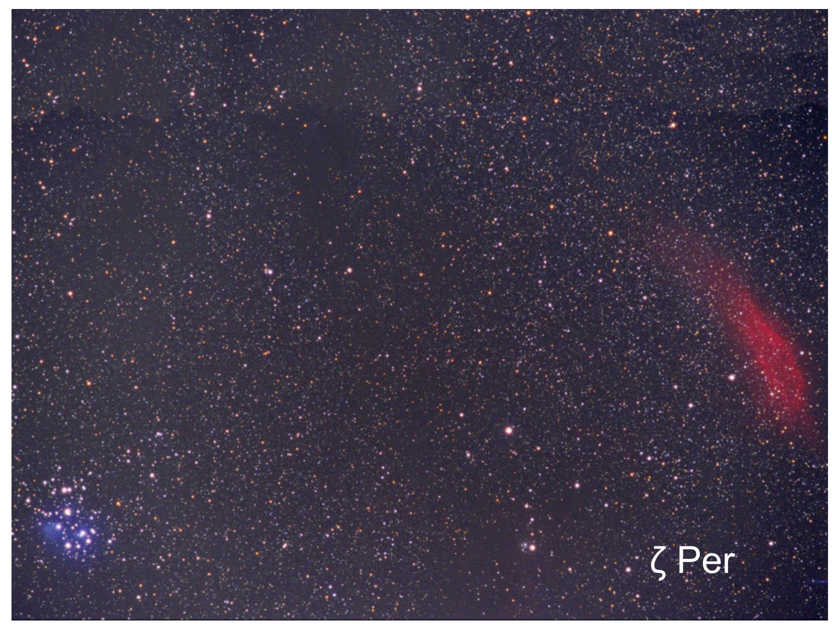


The "Black Cloud" B68
(VLT ANTU + FORS1)

ESO PR Photo 20a/99 (30 April 1999)

Dense (dark) clouds

- 10^3 cm^{-3} < n < 10^5 cm^{-3} 0.1-1 pc
- no UV penetrates beyond a thin surface layer (dust abs.)
- interior H is all in H_2, all C in CO.
- neutral, except small fraction ionized by cosmic rays.
- T ~ 30 K



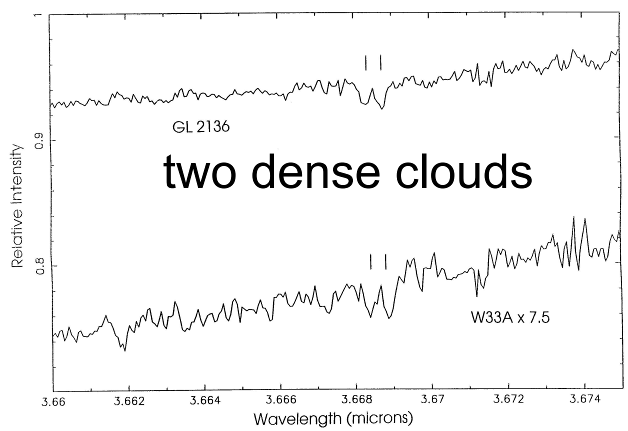
Diffuse clouds

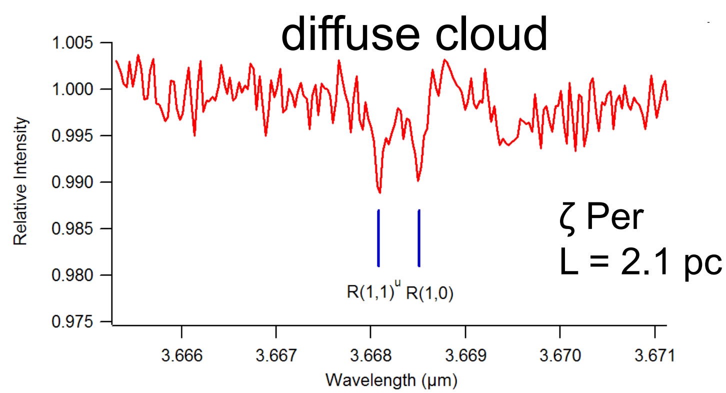
- 10 cm^{-3} < n < 10^3 cm^{-3} 1-10 pc
- only λ< 916 Å is blocked at surface
- 99% of C is ionized, only 1% of C in CO
- typically half of hydrogen is atomic, half is in H_2
- T ~ 60 K

Comparison of H_3^+ number densities and line strengths in typical dense and diffuse clouds in the Galactic plane

	DENSE CLOUDS	DIFFUSE CLOUDS
CREATION RATE	$\boldsymbol{\zeta_{dense}\ n(H_2)}$ $\zeta_{dense} \sim 3 \times 10^{-17}$ sec^{-1} all H in H_2	$\boldsymbol{\zeta_{diff}\ n(H_2)}$ ~10 × ζ_{dense} ~half of H in H_2
DESTRUCTION RATE	$\boldsymbol{k_{CO}\ n(H_3^+)\ n(CO)}$ *~all C in CO* $k_{CO} \sim 2 \times 10^{-9}$ cm^3 sec^{-1}	$\boldsymbol{k_e\ n(H_3^+)\ n(e)}$ *99% of C is ionized; $n(e) \sim n(C^+)$* $k_e \sim 100 \times k_{CO}$
STEADY STATE	$\boldsymbol{n(H_3^+) \sim 1 \times 10^{-4}}$ **cm^{-3}**	$\boldsymbol{n(H_3^+) \sim 1 \times 10^{-5}}$ **cm^{-3}**

Dimensions of diffuse clouds are typically an order of magnitude greater than dense clouds ➔ H_3^+ line strengths in the two cloud types are similar.





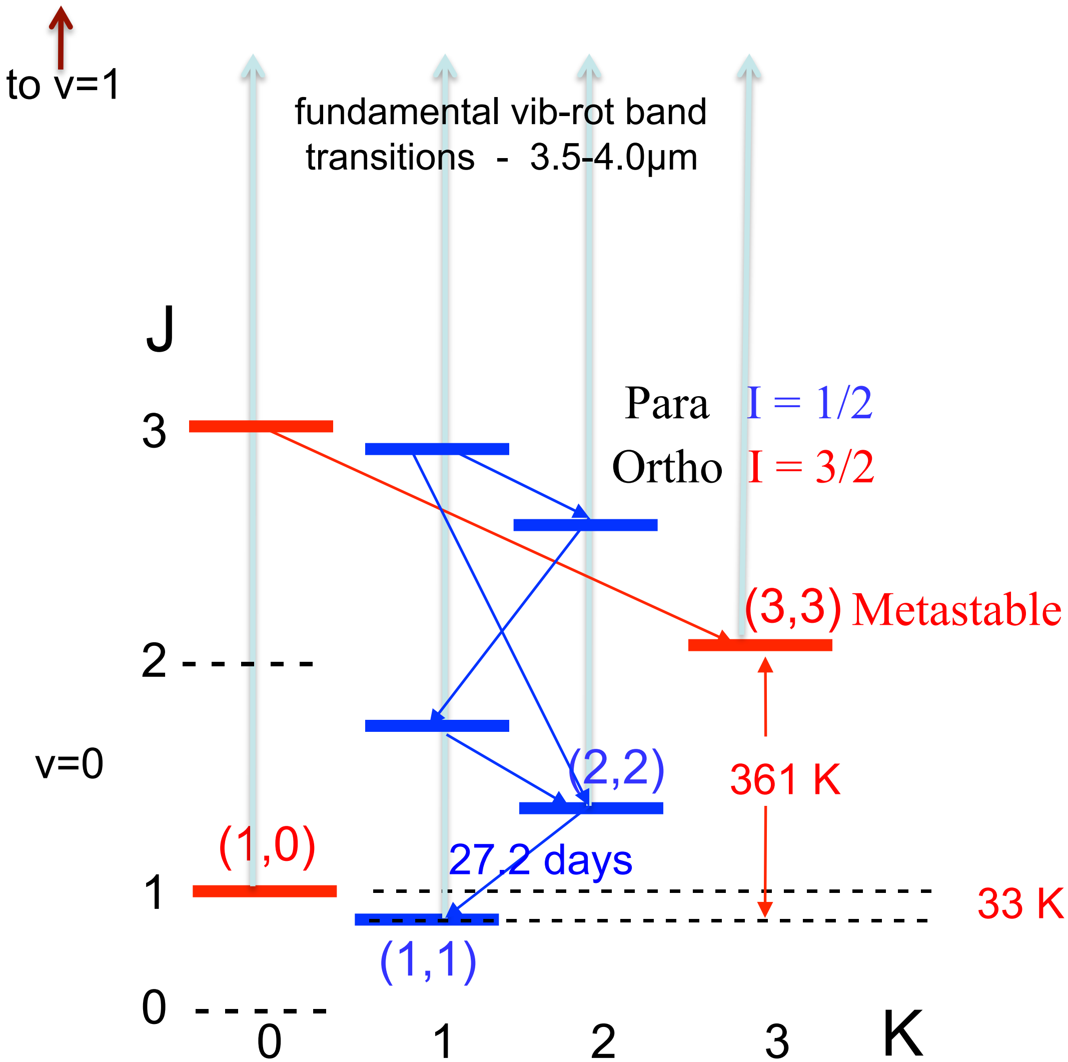
But CO is 100X less abundant in diffuse clouds than dense clouds.

The different behaviors of H_3^+ and CO means that the measuring their relative line strengths is a way to distinguish between cloud environments.

(useful for interpreting the spectra on sightlines to the Galactic center)

N.B. - One has to be careful in the case of CO, to choose appropriate transitions or isotopic species, as the strongest IR bands of $^{12}C^{16}O$ can produce saturated lines, even if most C is atomic (as in diffuse clouds).

H_3^+: a thermometer and a densitometer



Lowest ortho and para levels (1,0) and (1,1) are the only ones populated at typical cloud temperatures

They thermally equilibrate easily via collisions with H_2.

Low temperature thermometer

(with caveats: see McCall's talk)

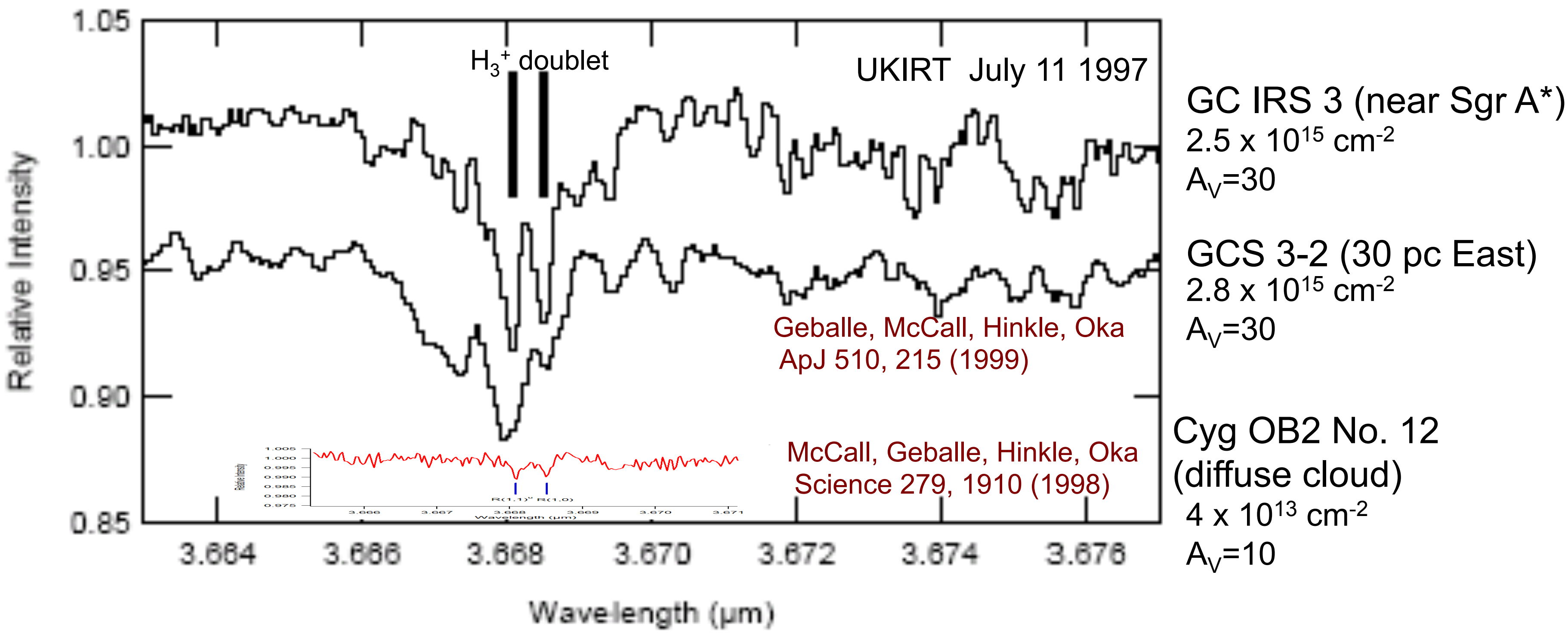
In warm gas metastable (3,3) is populated by collisions.

High temperature thermometer

Einstein A coefficient of (2,2) corrresponds to a critical density of ~200 cm^{-3} at typical cloud temperatures.

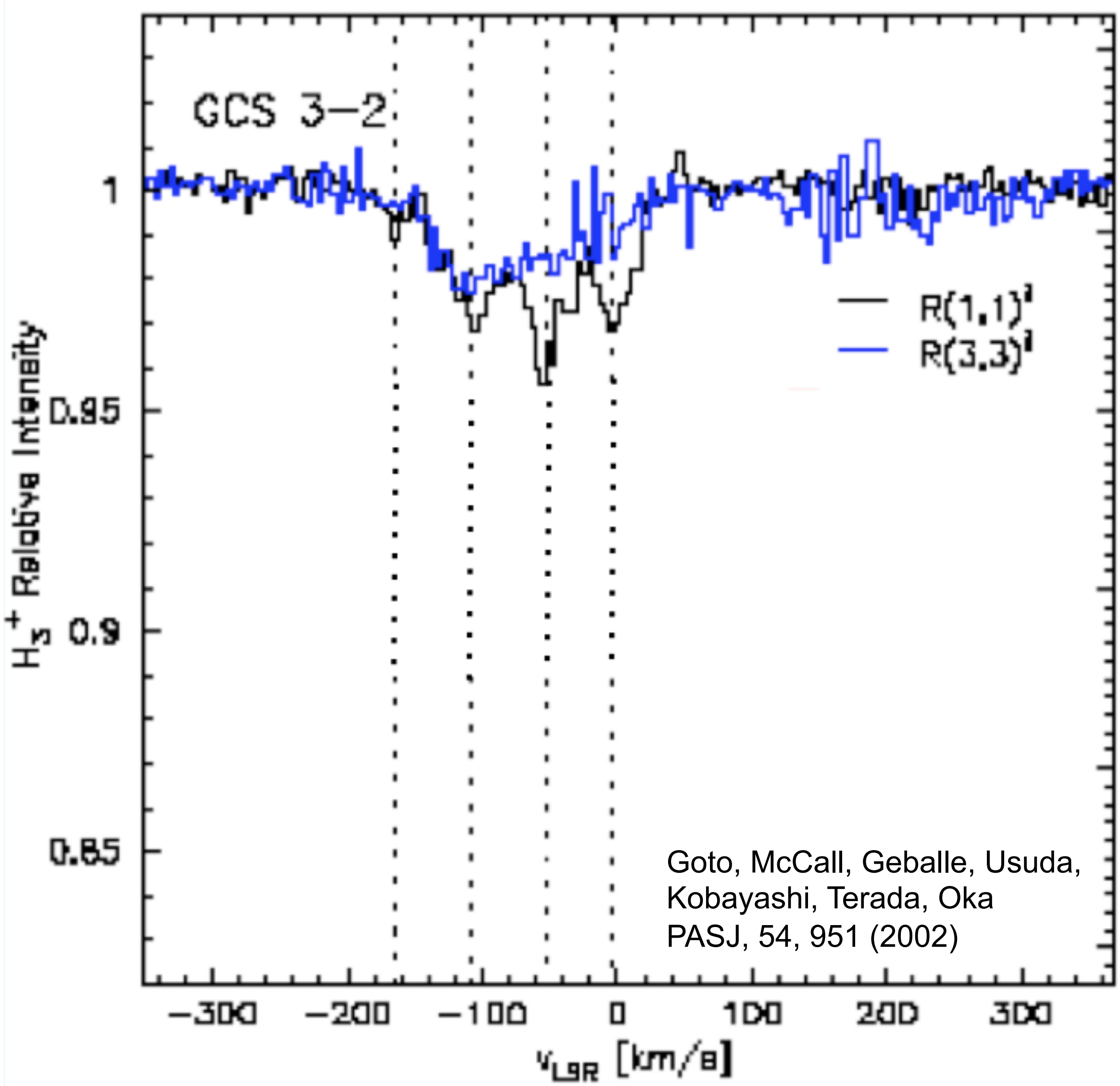
Low density densitometer
if (3,3) is populated

Discovery of H_3^+ toward GC



- 60X and 70X higher column density than typical Galactic diffuse and dense clouds.
- Only 3X higher extinction than toward Cyg OB2 No 12 (diffuse cloud).
- Similar extinction as dense clouds.

Metastable H_3^+



Goto, McCall, Geballe, Usuda,
Kobayashi, Terada, Oka
PASJ, 54, 951 (2002)

Simultaneous multi-line observations from Subaru (GCS3-2 and IRS3)

Detected line from metastable (3,3) level 361 K above lowest level.

Did not detect line from (2,2) unstable level, 250K above lowest level ➔ low density

Full meaning unclear until higher resolution measurements of lines from J=1, 2, and 3.

New spectra of H_3^+ and CO (Gemini South, 2003)

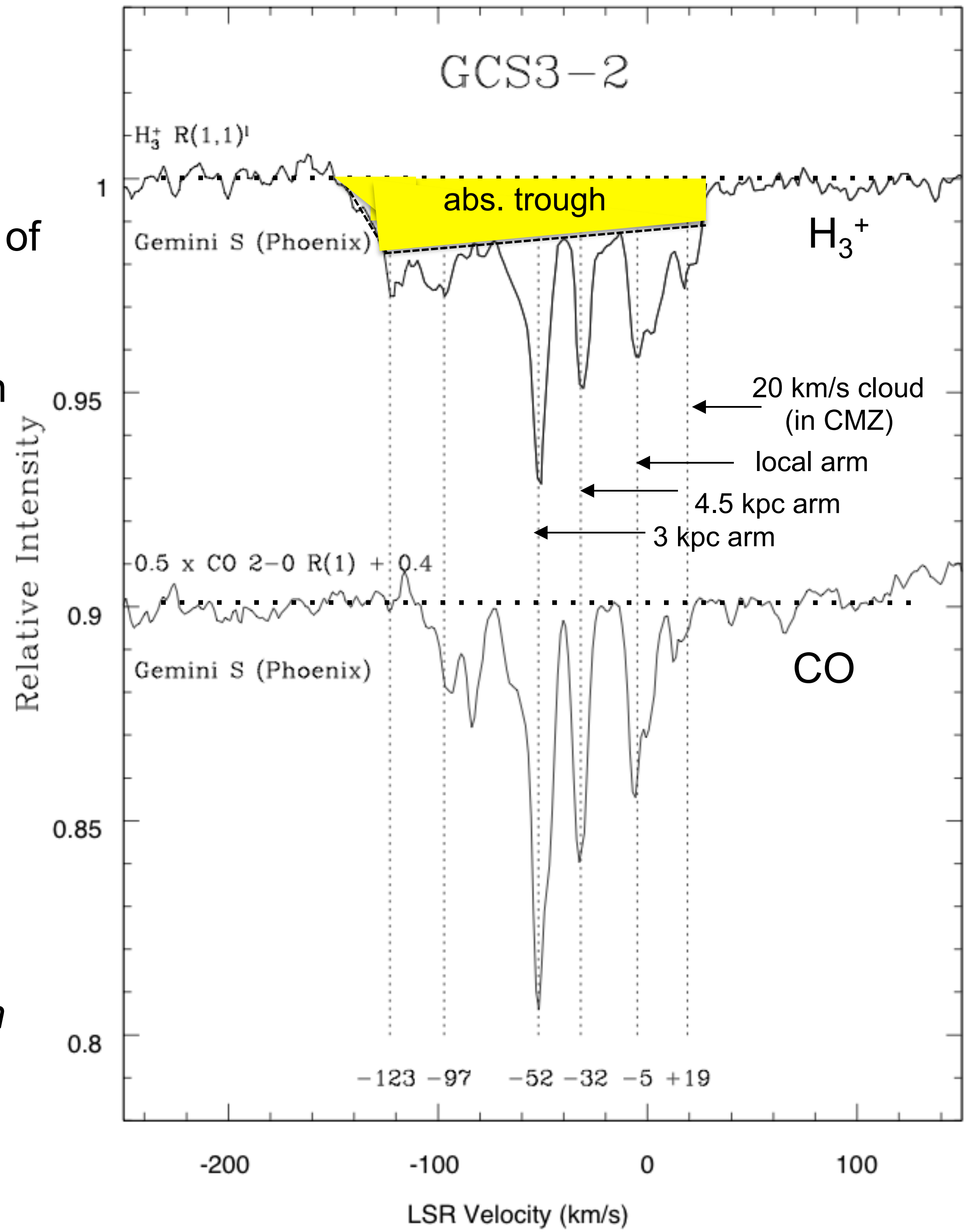
H_3^+ line profiles are a superposition of narrow features at the redshifts of the intervening spiral arms and a ~200 km s-1 wide absorption trough of blueshifted gas.

CO line profiles have only the narrow features.

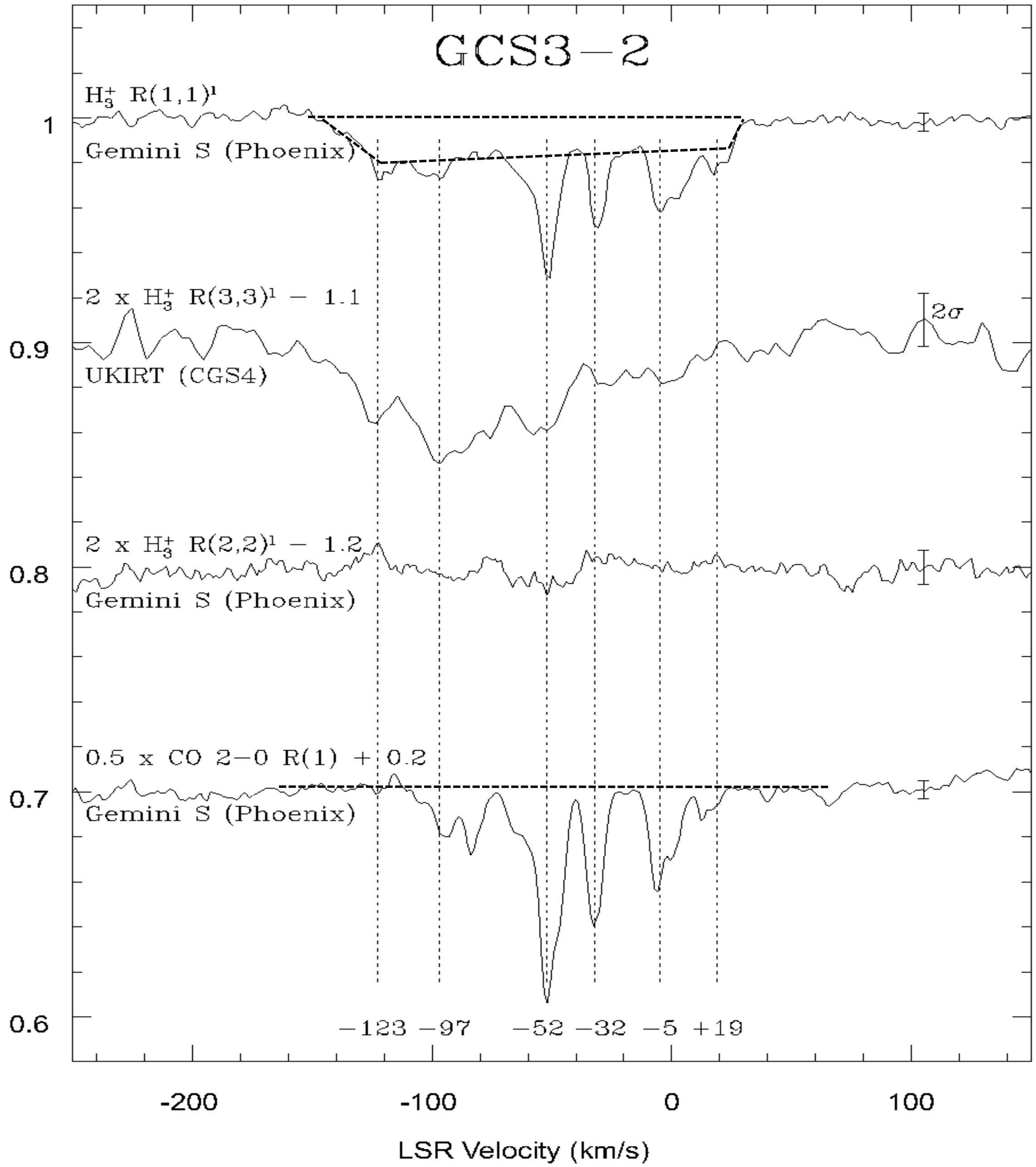
Narrow features originate in dense (and perhaps some diffuse) spiral arm gas.

H_3^+ producing the absorption trough must be in diffuse gas.

Wide velocity range indicates that the diffuse gas is in the CMZ.



Spectra of H_3^+ lines from all three J levels and CO



narrow components plus "trough"

arises in same gas as R(1,1)^l trough comparison ➔ T ~ 250 K

comparison with R(3,3)^l ➔ *trough gas has n* ≤ 100 cm^{-3}

no CO trough
➔trough gas is not dense; more similar to "diffuse" clouds

Oka, Geballe, Goto, Usuda, McCall 2005, *ApJ*, 632, 882

Ionization rate and path length in the CMZ

$N(H_3^+)$ = const. × ζ L

const. includes reaction rates and abundances of H_2, CO (dense), C (diffuse)

Galactic dense clouds:

$N(H_3^+)_{obs} = (1.1 – 5.2) \times 10^{14}\ cm^{-2}$

$\zeta L = (0.6 – 2.3) \times 10^2\ cm\ s^{-1}$

McCall, Geballe, Hinkle, Oka, 1999, *ApJ,* 522, 338

$\zeta = 3 \times 10^{-17}\ s^{-1}$ $L = (0.6 – 2.3)$ pc

Galactic diffuse clouds:

$N(H_3^+)_{obs} = (0.21 – 2.4) \times 10^{14}\ cm^{-2}$ (*~10X larger than initially predicted)*

$\zeta L = (0.4 – 4.4) \times 10^4\ cm\ s^{-1}$ (100X larger than dense clouds)

Indriolo, Geballe, Oka, McCall, 2007, *ApJ,* 671,1736

$\zeta \sim 3 \times 10^{-16}\ s^{-1}$ (~10X higher than in dense clouds), $L = (3 – 30)$ pc

CMZ

$N(H_3^+)_{obs} = (1.8 – 6.1) \times 10^{15}\ cm^{-2}$

Goto, Usuda, Nagata, Geballe, McCall, Indriolo, Suto, Henning, Morong, Oka, 2008, *ApJ,* 688, 306

10X – 100X larger than galactic diffuse clouds

In addition: higher electron density (C more abundant); likely smaller fraction of H in H_2

$\zeta L > 2.0\text{-}6.5) \times 10^5\ cm\ s^{-1}$

Reasonable guesses:

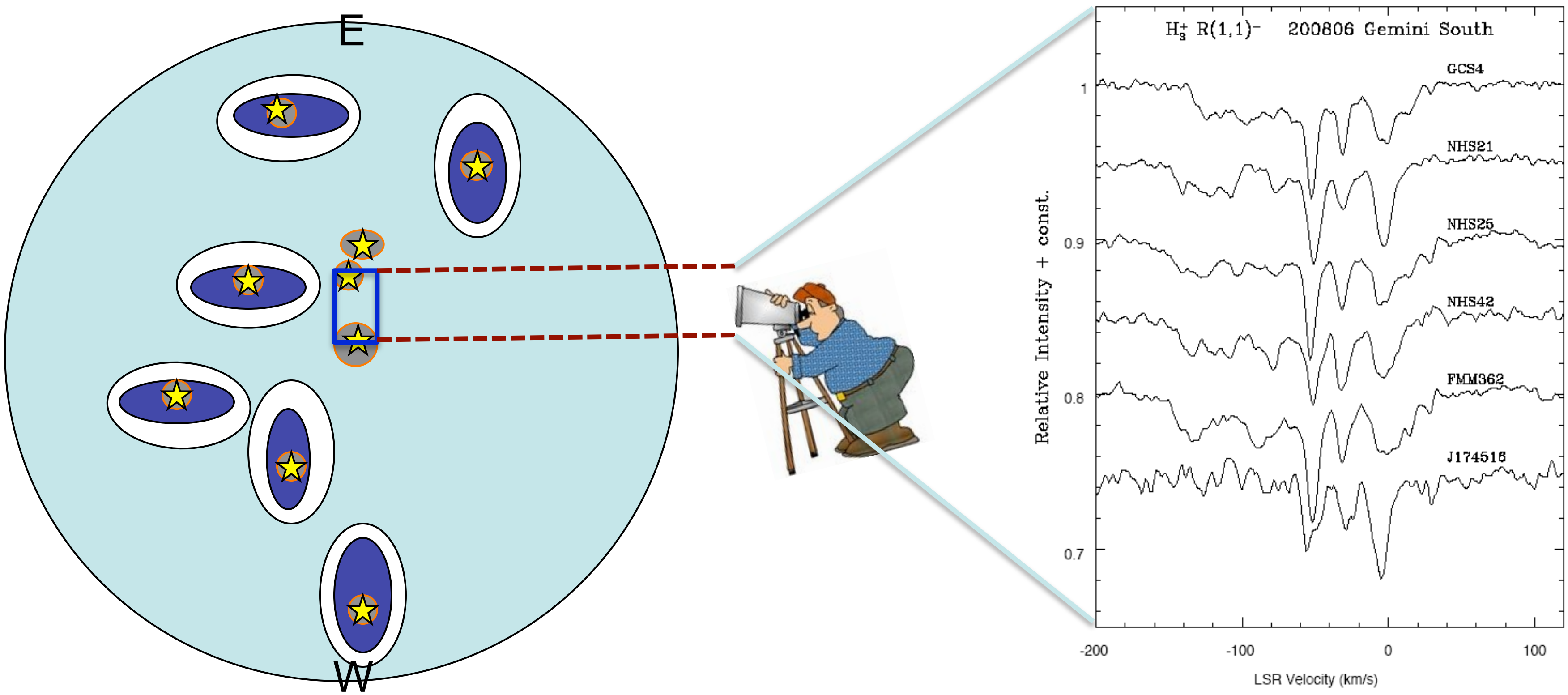
$\zeta \sim 2 \times 10^{-15}\ s^{-1}$ 5X higher than diff. clouds),

$L \sim$ *30-100* pc   100 pc ~ 1/2 the radius of the CMZ

RECENT WORK

1. Refine our understanding of the physical conditions in the known sightlines, and especially those for clouds very close to the center where conditions appear more extreme.
   (Goto's talk on Saturday)

2. Determine the longitudinal extent of the warm diffuse gas in the CMZ



Search for bright, "*smooth-spectrum*" objects in the CMZ
(luminous stars with opaque dust shells)

GLIMPSE Point Source Catalogue - Spitzer Space Telescope
(Ramírez *et al*. 2008, *ApJS*, 175, 147)
Four band photometry: 3.6μm to 8.0μm

2,000,000 stars

[3.6μm] < 7.5 mag (bright enough for spectroscopy of H_3^+

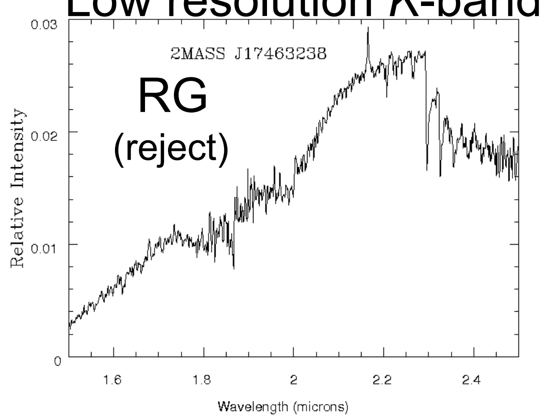
6,000 stars
in CMZ

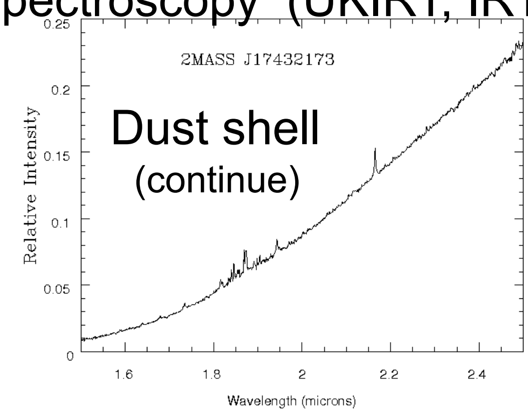
2MASS Catalogue
(Skrutskie *et al*. 2006, *AJ*, 131, 1163)
photometry in *J* (1.25μm), *H* (1.65μm), and *K* (2.2μm) bands

Detected at *K*
J – K < 5 (*high interstellar extinction and/or very cool)*
[3.6] – [8.0] > 2 (*very cool and/or opaque dust shell and/or very high extinction)*
or *K - L* > 1.5

300 stars

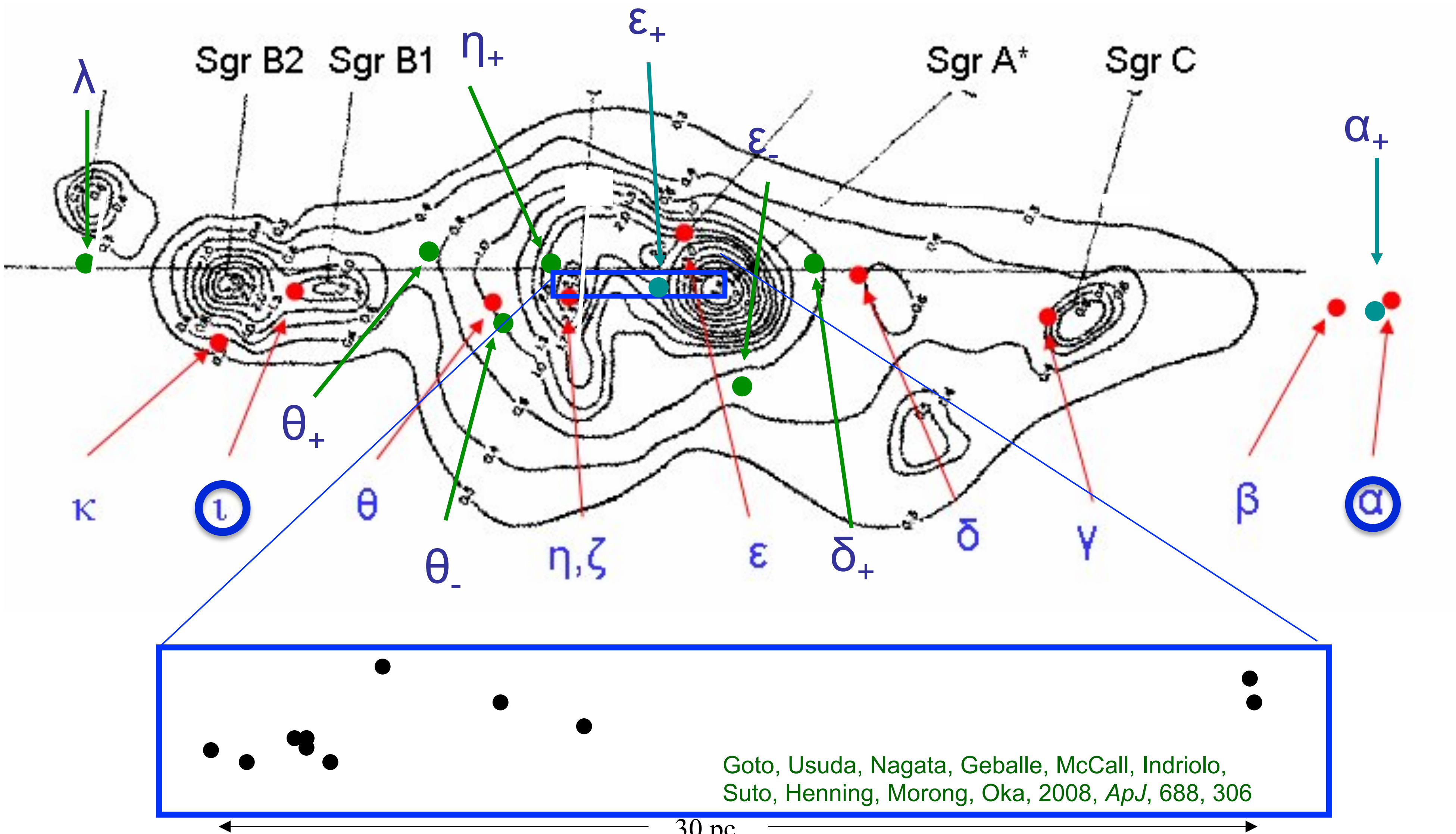
Low resolution *K*-band spectroscopy (UKIRT, IRTF, Gemini)





in progress
~30 stars
out of ~200
some previously known

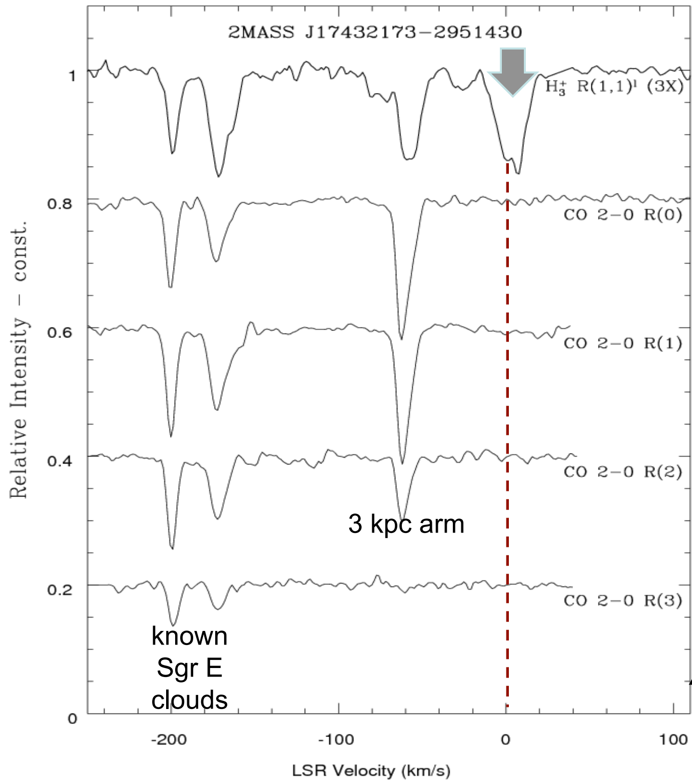
DISTRIBUTION OF NEWLY DISCOVERED SMOOTH-SPECTRUM SOURCES IN CMZ

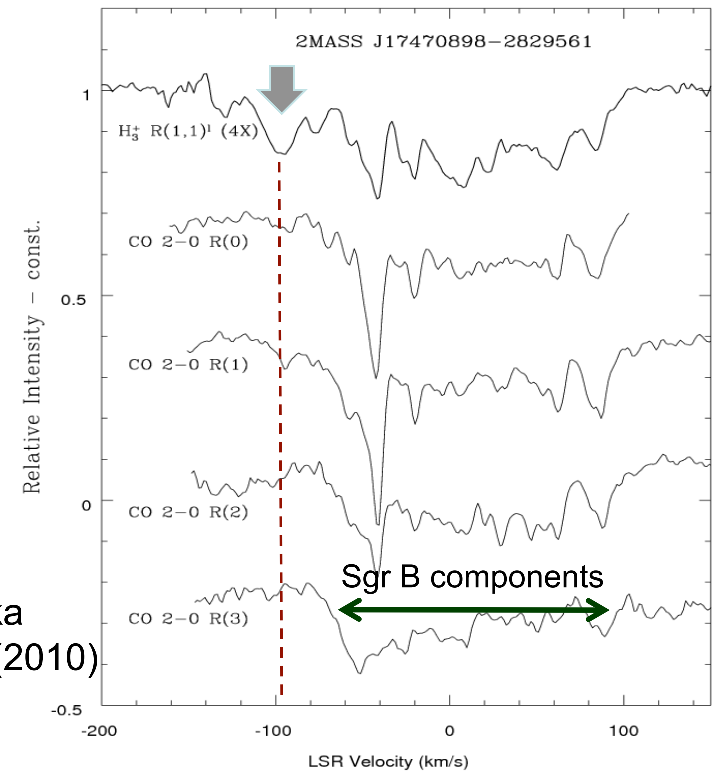


High res. spectroscopy of CO and H_3^+ needed to determine:
(1) location on sightline; (2) properties of absorbing gas
Note locations of α and ι

“alpha”: 140 pc West, 2.7 pc below plane

“iota”: 85 pc East (Sgr B)

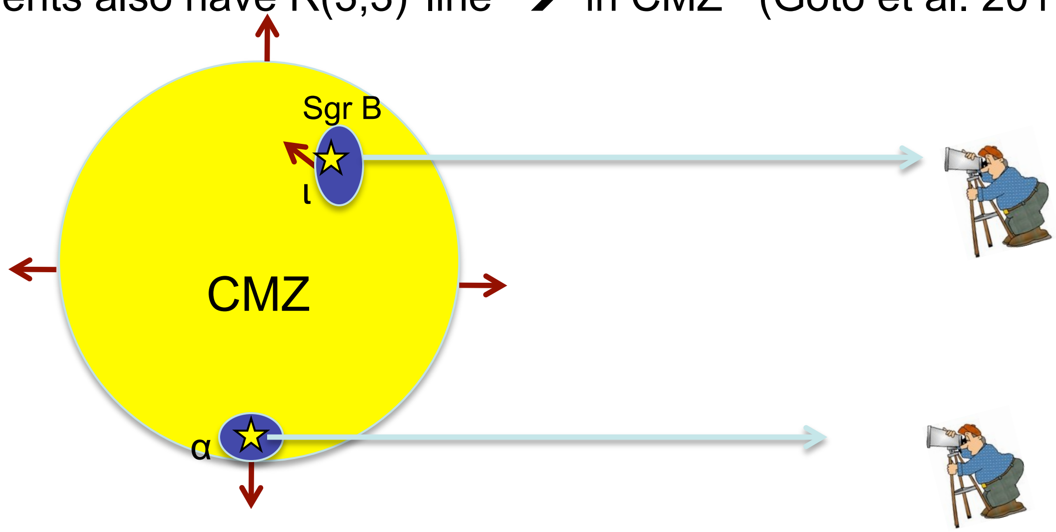




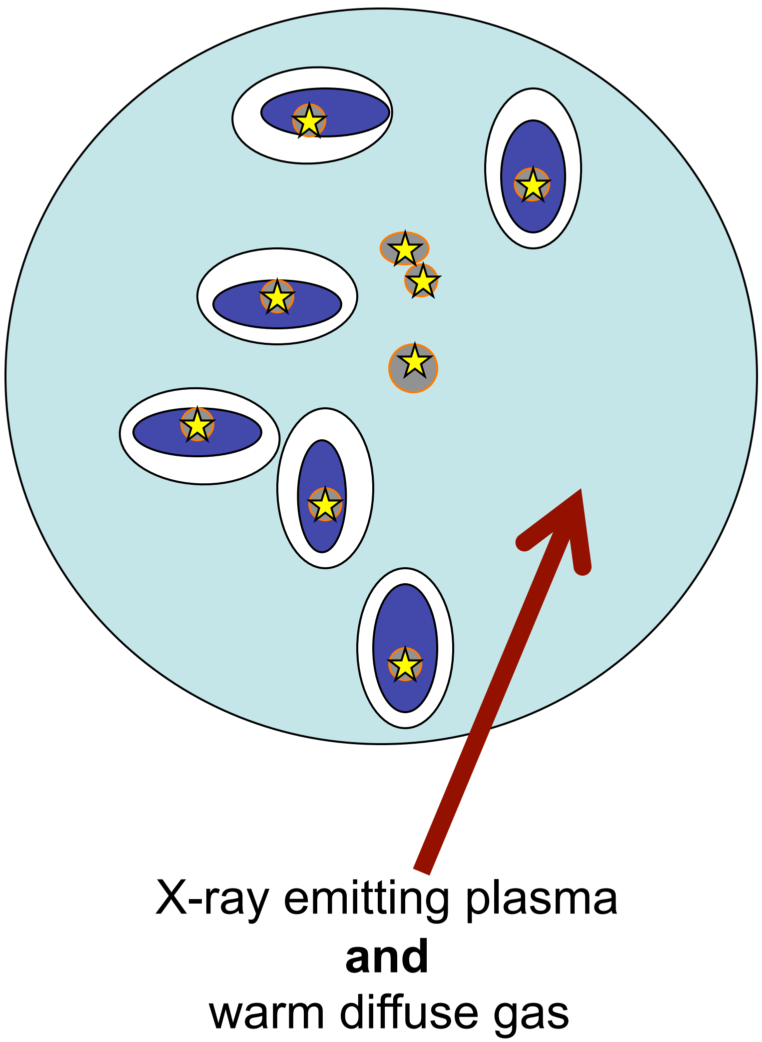
Geballe & Oka
ApJ 709, L70-73 (2010)

diffuse absorption components also have R(3,3)^l line ➔ in CMZ (Goto et al. 2011)

Velocities of warm, diffuse gas toward α and ι are consistent with their locations and outward-moving gas.



CONCLUSION



Based on:

(1) its presence on widely separated sightlines

(2) its presence at a wide range of velocities

(3) its presence on sightlines that do not include CMZ molecular clouds

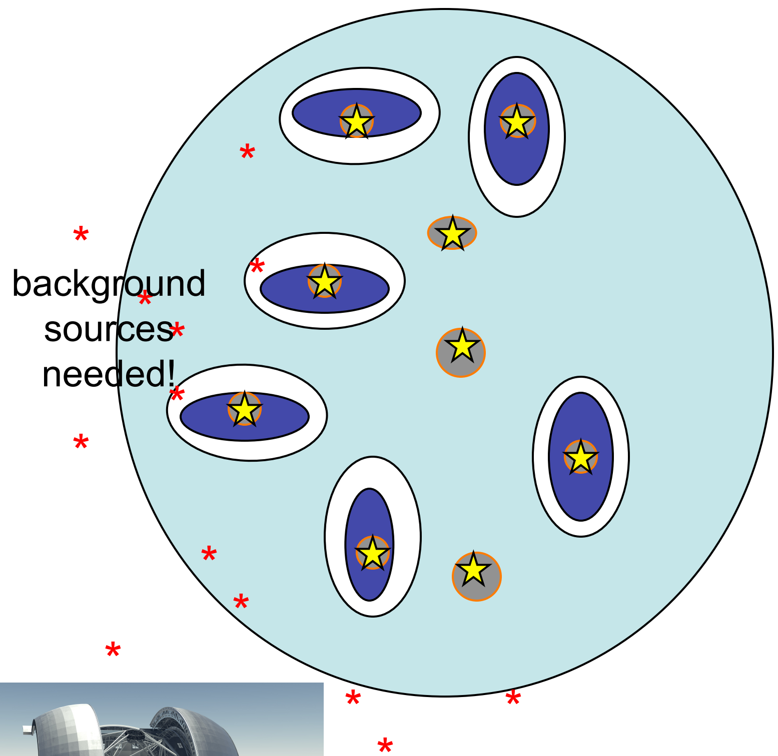
the warm (250 K) and diffuse (~100 cm^{-3}) environment has a significant filling factor in the CMZ along with the other major components (mol. clouds, x-ray plasma, scattering gas).

(Probably shares the large volume previously assigned to the X-ray emitting gas)

QUESTIONS AND FUTURE WORK

1. Pressure balance: Why is the pressure exerted by the diffuse warm gas ($nT \sim 10^4$) significantly less than those of the other major players ($nT \sim 10^{5-7}$) ? Why does it fill such a large fraction of the CMZ?

2. Current H_3^+ data are consistent with a range of expansion velocities; no infall. Is the diffuse gas being ejected or is it responding to the gravitational potential in the nucleus?



Need additional sightlines

- We continue to investigate sightlines toward recently discovered smooth spectrum sources
- We continue to look for new smooth-spectrum sources, esp with longer sightlines passing through the entire CMZ.

(Will need bigger telescopes)