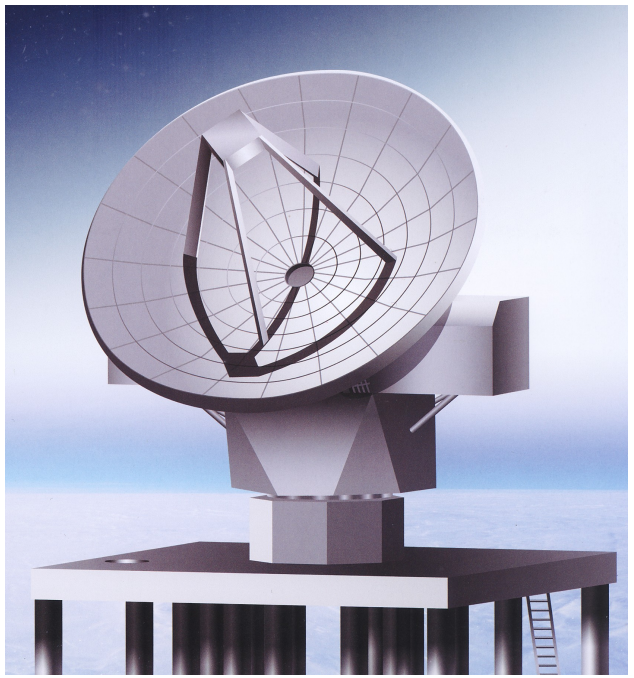
Observations of various atoms and molecules from the Antarctic

Shuro Takano

(College of Engineering, Nihon Univ.)



http://www.px.tsukuba.ac.jp/~nakai/astroobs/antarctica.html

Contents

- Characteristics of the Terahertz region
  - For atoms and molecules
  - Observable species and their nature
- Interesting science cases
  - Our Galactic sources
  - Nearby galaxies
- Summary

•Not familiar frequency region
Only laboratory spectroscopy: ND
•Many Herschel papers!
But further study will be necessary

Characteristics of the Terahertz region

- Of course, higher energy than submm/mm
  - ➢ 1 GHz ➔ 4.79 x 10^{-2} K
    - 500 GHz → 24 K
    - 1000 GHz → 48 K
    - 1500 GHz → 72 K
- Rotational energy levels have much higher energies (energy difference ≈ THz)
  - e.g., CO *J*= 13-12 (1497 GHz) → 503 K (E_{upper})

➔Photons come from relatively high-temperature clouds

Characteristics of the Terahertz region

- Atomic and molecular lines in the THz region
  - High-excitation lines
    - Even for CO
    - Heavy organic molecules: Should be relatively weak
  - Light molecules (→small moment of inertia):

$$B(\text{rotational constant}) \propto \frac{1}{I(\text{moment of inertia})}$$

H_2D^+, HD_2^+, CH, CH^+, NH, OH, OH^+, H_2O, H_2O^+, NH_3,,,

  - Atomic (fine structure) lines : C, N^+, O, …

Typical spectral lines in the THz region

- Hydrogen related
  - H (recombination), H_2D^+, HD_2^+
- Carbon related
  - C, C^+, CH, CH^+, CH_2, …
- Nitrogen related
  - N^+, NH, NH_2, NH_3, …
- Oxygen related
  - O, OH, OH^+, H_2O, H_2O^+ , …

Typical spectral lines in the THz region

- Hydrogen related
  - H (recombination) many

E(upper)

  - H_2D^+ 372.42138 GHz, 1(1, 0)- 1(1, 1), 104.2 K (CDMS)
    1370.08488 GHz, 1(0, 1)- 0(0, 0), 65.8 K
  - HD_2^+ 691.66048 GHz, 1(1, 0)- 1(0, 1), 83.4 K (CDMS)
    1370.05160 GHz, 2(2, 0)- 2(1, 1), 261 K
    1476.60571 GHz, 1(1, 1)- 0(0, 0), 70.9 K

$$\left(\mu m = \frac{300000}{\mathrm{GHz}} \right)$$

Typical spectral lines in the THz region

- Carbon related
  - C 492.16065 GHz, $^3P_1$ - $^3P_0$, 23.6 K (CDMS)
    809.34197 GHz, $^3P_2$ - $^3P_1$, 62.5 K
  - C^+ 1900.53690 GHz, $^2P_{3/2}$ - $^2P_{1/2}$, 91.2 K (CDMS)
    (158 μm)
  - CH 536.76115 GHz etc., N= 1, J=3/2-1/2, F= 2^-- 1^+, 25.8 K
    1470.73960 GHz etc., N= 2, J=3/2-3/2, F= 2^+- 2^-, 96.3 K
    (CDMS)
  - CH^+ 835.13750 GHz, 1- 0, 40.1 K (CDMS)
    1669.28129 GHz, 2- 1, 120 K

Typical spectral lines in the THz region

- Carbon related
  - CH_2 444.82569 GHz etc., 2(1, 2)- 3(0, 3), J= 3- 4, F= 3- 4, 156 K

    581.27527 GHz etc., 5(0, 5)- 4(1, 4), J= 4- 4, F= 4- 4, 336 K

    945.83935 GHz etc., 1(1, 1)- 2(0, 2), J= 2- 3, F= 3- 4, 113 K

    (CDMS)

Typical spectral lines in the THz region

- Nitrogen related
  - N No lines (^4S)
  - N^+ 1461.13141 GHz, $^3P_1$-$^3P_0$ (205 μm)(SLAIM)
    2459.38010 GHz, $^3P_2$-$^3P_1$
  - NH 946.47582 GHz etc., N= 1- 0, J= 0- 1, 45.4 K (JPL)
    974.47861 GHz etc., N= 1- 0, J= 2- 1, 46.8 K
    999.97339 GHz etc., N= 1- 0, J= 1- 1, 48.0 K
  - NH_2 many lines
  - NH_3 572.49816 GHz, 1(0)0s- 0(0)0a, 27.5 K (pure rotation)
    1168.45239 GHz, 2(1)0s- 1(1)0a, 79.3 K (JPL)

Typical spectral lines in the THz region

- Oxygen related
  - O 2060.06800 GHz, $^3P_0$-$^3P_1$, 326 K (JPL) (145 μm)
  - O^+ No lines (^4S)
  - OH 1837.8168 GHz etc., J=3/2-1/2, Ω=1/2,F= 2^+- 1^-, 270 K (JPL)
  - OH^+ 909.15880 GHz, N= 1- 0, J= 0- 1, F=1/2-3/2, 43.6 K
    971.80530 GHz, N= 1- 0, J= 2- 1, F=3/2-1/2, 46.6 K
    1032.9979 GHz, N= 1- 0, J= 1- 1, F=1/2-1/2, 49.6 K
    (CDMS)

Typical spectral lines in the THz region

- Oxygen related
  - H_2O many lines (JPL)
  - H_2O^+ many lines (CDMS)
  - H_3O^+ 307.19241 GHz, 1(1)- 2(1), 0^- - 0^+, 79.5 K (JPL)

    364.79743 GHz, 3(2)- 2(2), 0^+ - 0^-, 140 K

    388.45864 GHz, 3(1)- 2(1), 0^+ - 0^-, 162 K

    396.27241 GHz, 3(0)- 2(0), 0^+ - 0^-, 169 K

    984.71191 GHz, 0(0)- 1(0), 0^- - 0^+, 54.6 K

    1031.29374 GHz, 4(-3)- 3(3), 0^+ - 0^-, 232 K

    1069.82663 GHz, 4(2)- 3(2), 0^+ - 0^-, 269 K

    1092.52314 GHz, 4(1)- 3(1), 0^+ - 0^-, 291 K

Known observational data

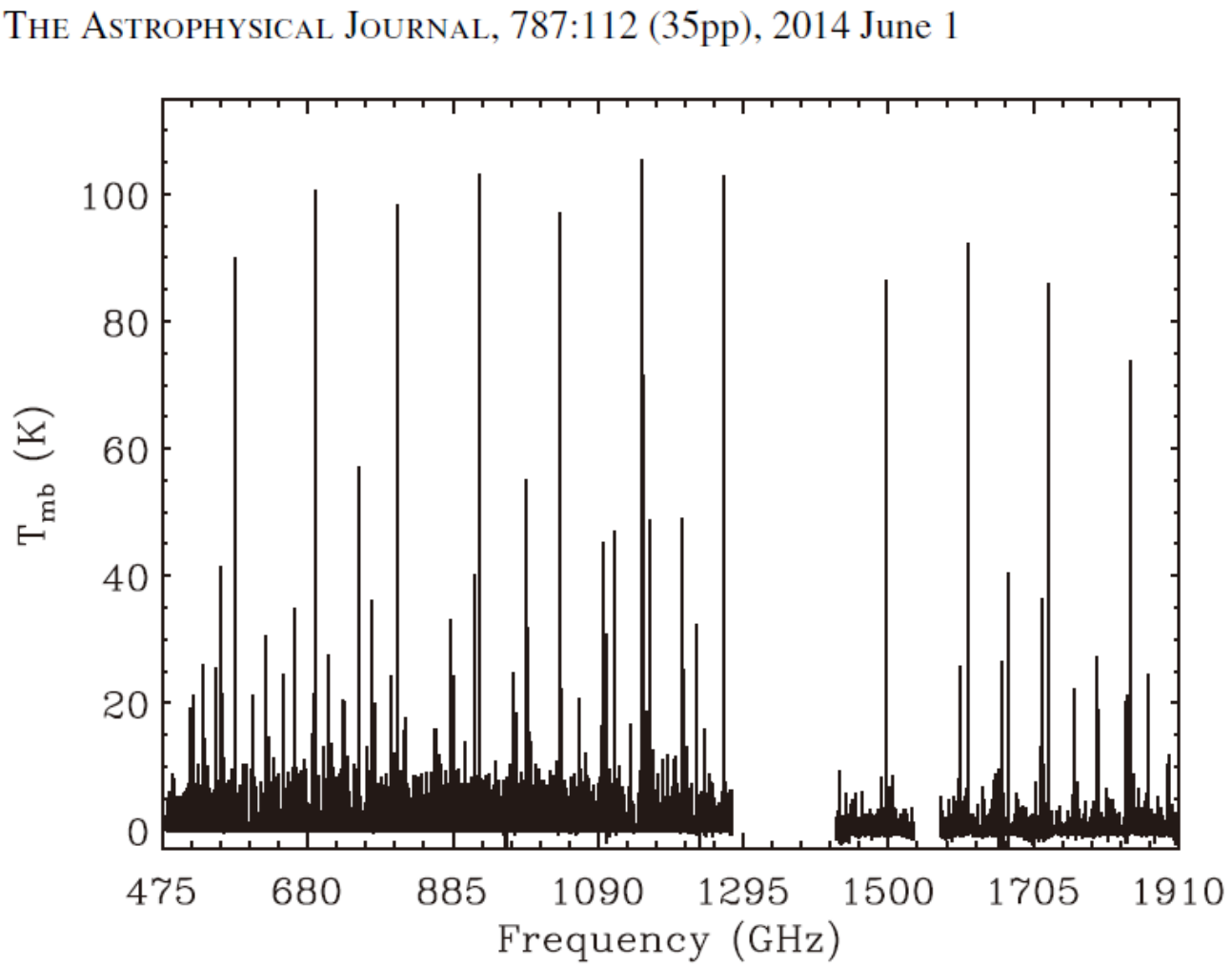
- Lot of Herschel data: Very helpful
  - 3.5 m diameter
  - SPIRE FTS
    - 0.04 cm^{-1} resolution (~1.2 GHz)
  - HIFI (heterodyne)
    - IF 4 GHz width
    - 140 kHz-1.1 MHz resolution

Orion KL seen by Herschel: High freq. resolution with HIFI

Crockett et al. ApJ, 787, 112 (2014)

- 480- 1907 GHz
- 1.1 MHz resolution
- 39 molecules

(79 isotopologues)



Orion KL seen by Herschel: High freq. resolution with HIFI

480-561 GHz

555-637 GHz

626-726 GHz

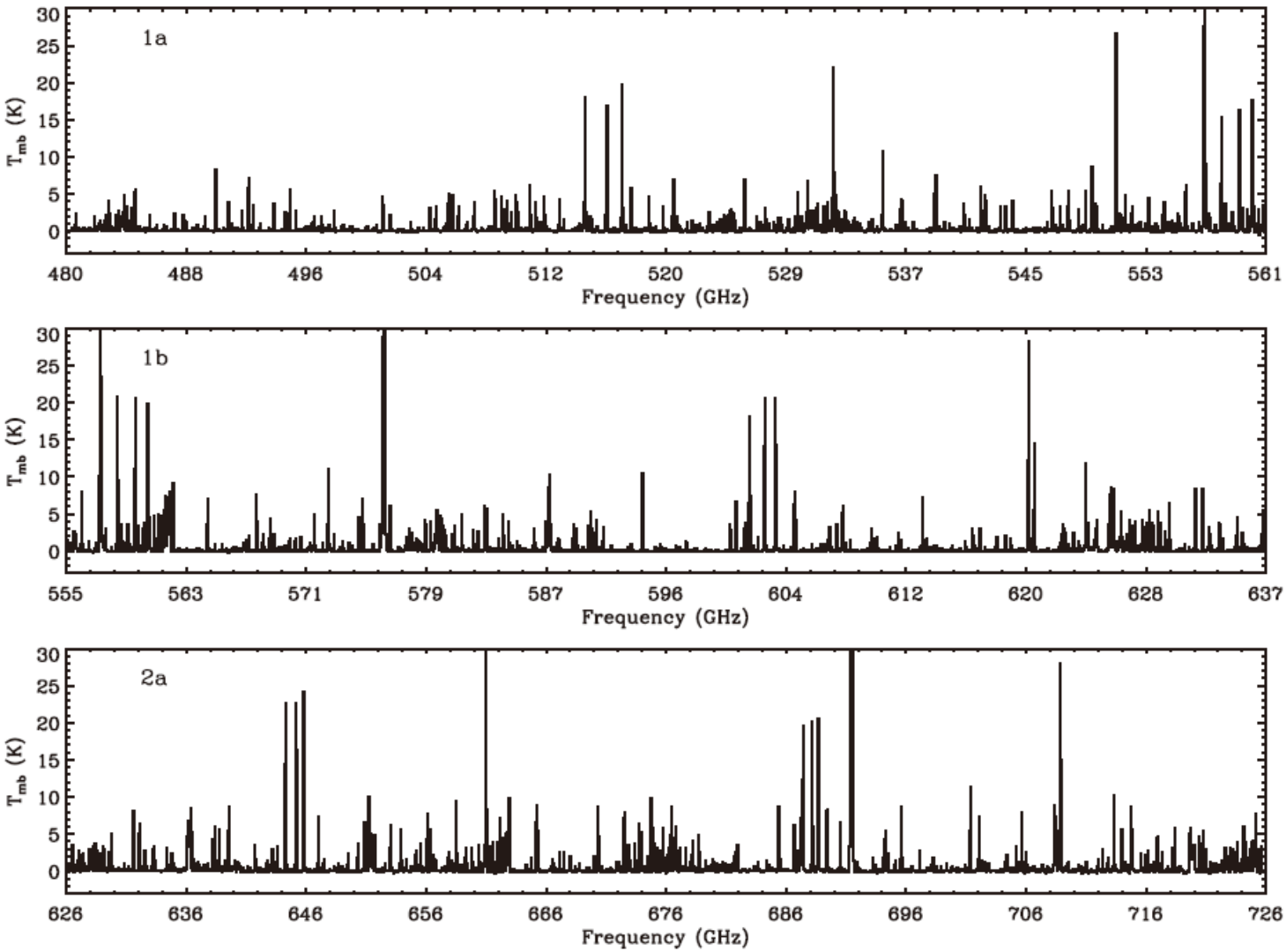


Figure 2. Bands 1a, 1b, and 2a of the HIFI spectral survey toward Orion KL. The data are resampled to a velocity resolution of ~10 km s^{-1} to improve the appe at this scale. Each band is labeled in the upper left corner of each panel.

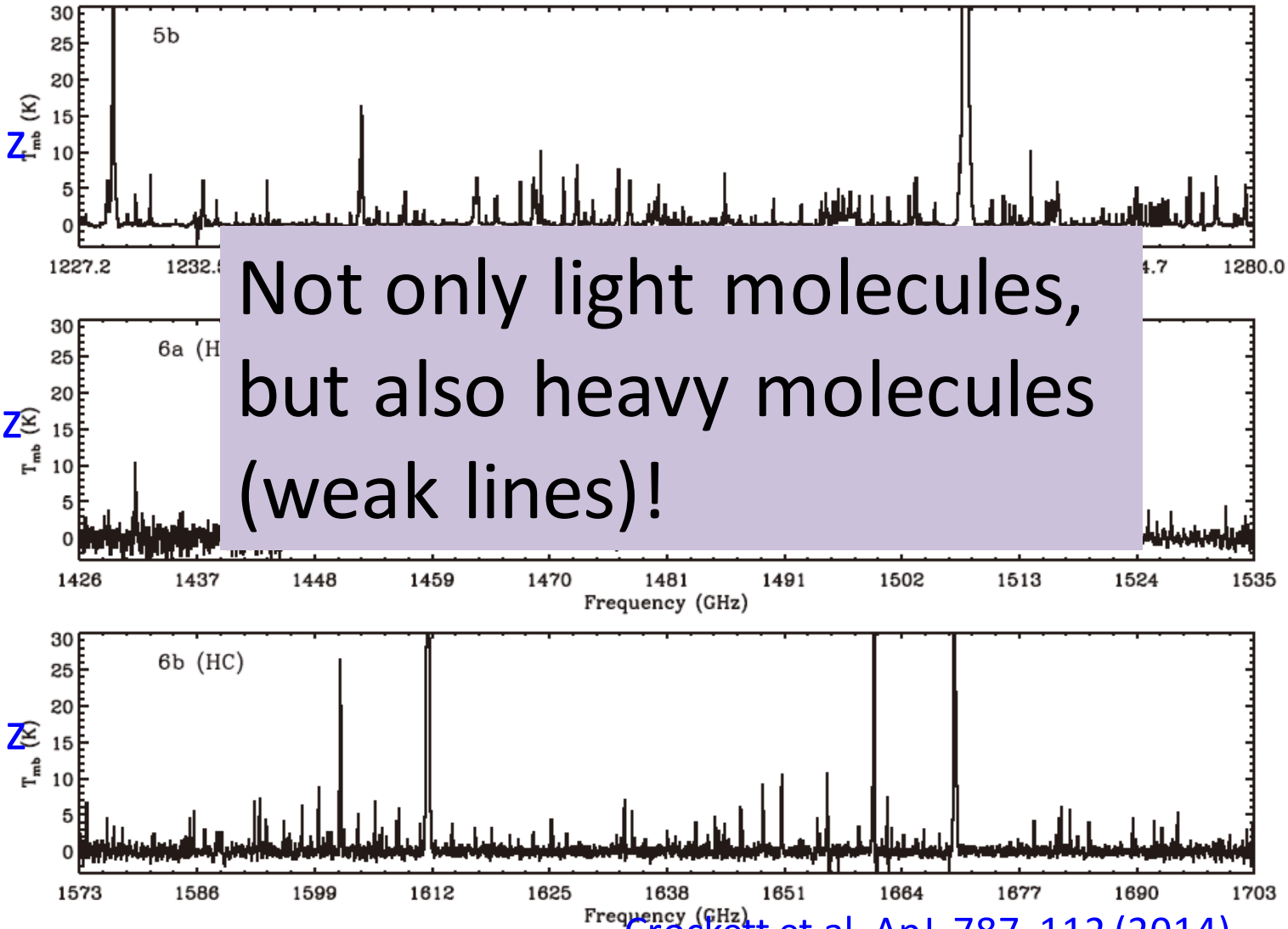
Crockett et al. ApJ, 787, 112 (2014)

Orion KL seen by Herschel: High freq. resolution with HIFI

1227-1280 GHz

1426-1535 GHz

1573-1703 GHz



Not only light molecules, but also heavy molecules (weak lines)!

Crockett et al. ApJ, 787, 112 (2014)

Figure 5. Same as Figure 2, but for bands 5b, 6a, and 6b. The hot core pointing is plotted for band 6.

Orion KL seen by Herschel: High spatial resolution with HIFI

- Predicted number of lines with peak emission >0.1 K
  - LTE, T = 150 K
  - Column density by Comito et al. (2005)
  - Δv = 5 km/s

➔ Larger molecules show significant decrease

➔ But still lot of lines!

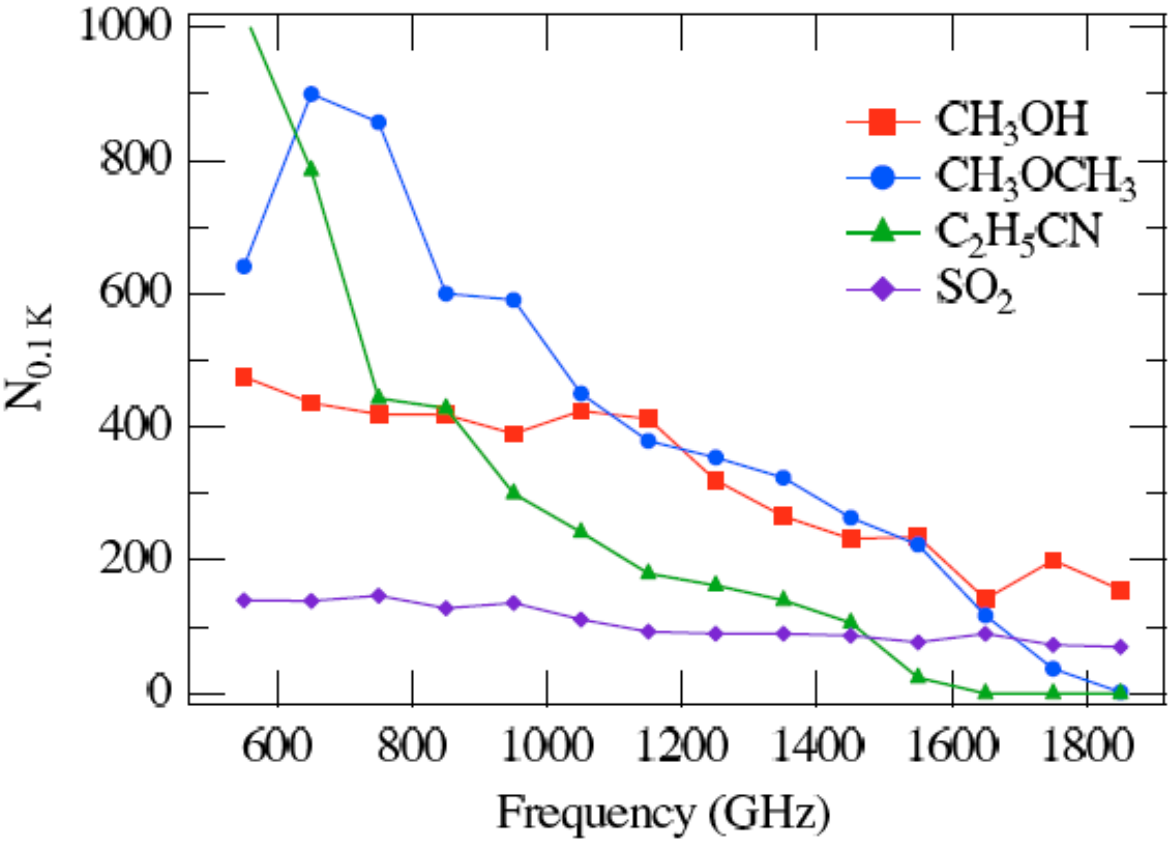


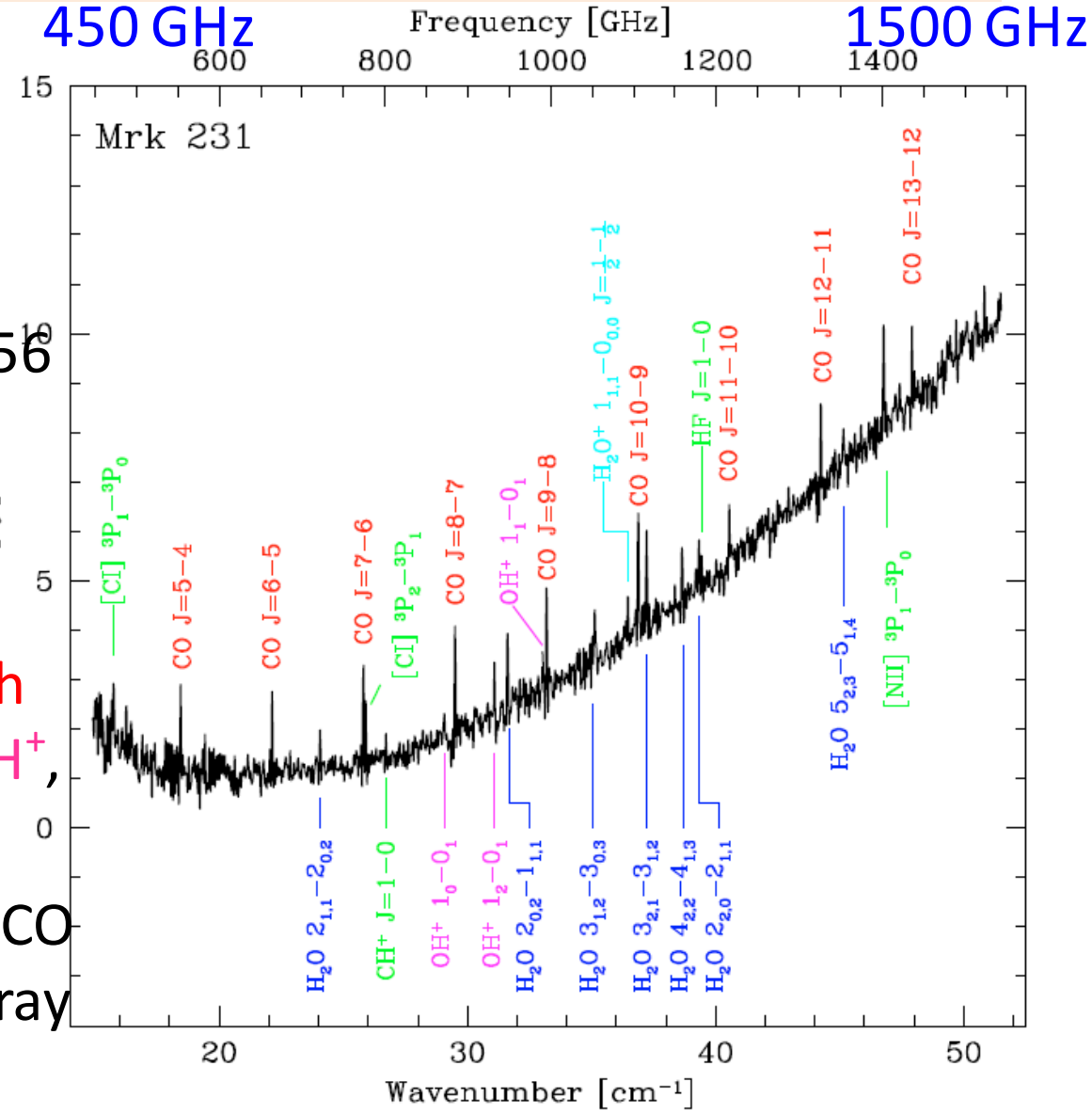
Fig. 3. Predicted number of lines with peak emission >0.1 K based on an LTE model in 100 GHz bins for select "weeds" as a function of frequency.

Crockett et al. A&A 521, L21 (2010)

External galaxies

Herschel SPIRE FTS: Mrk 231

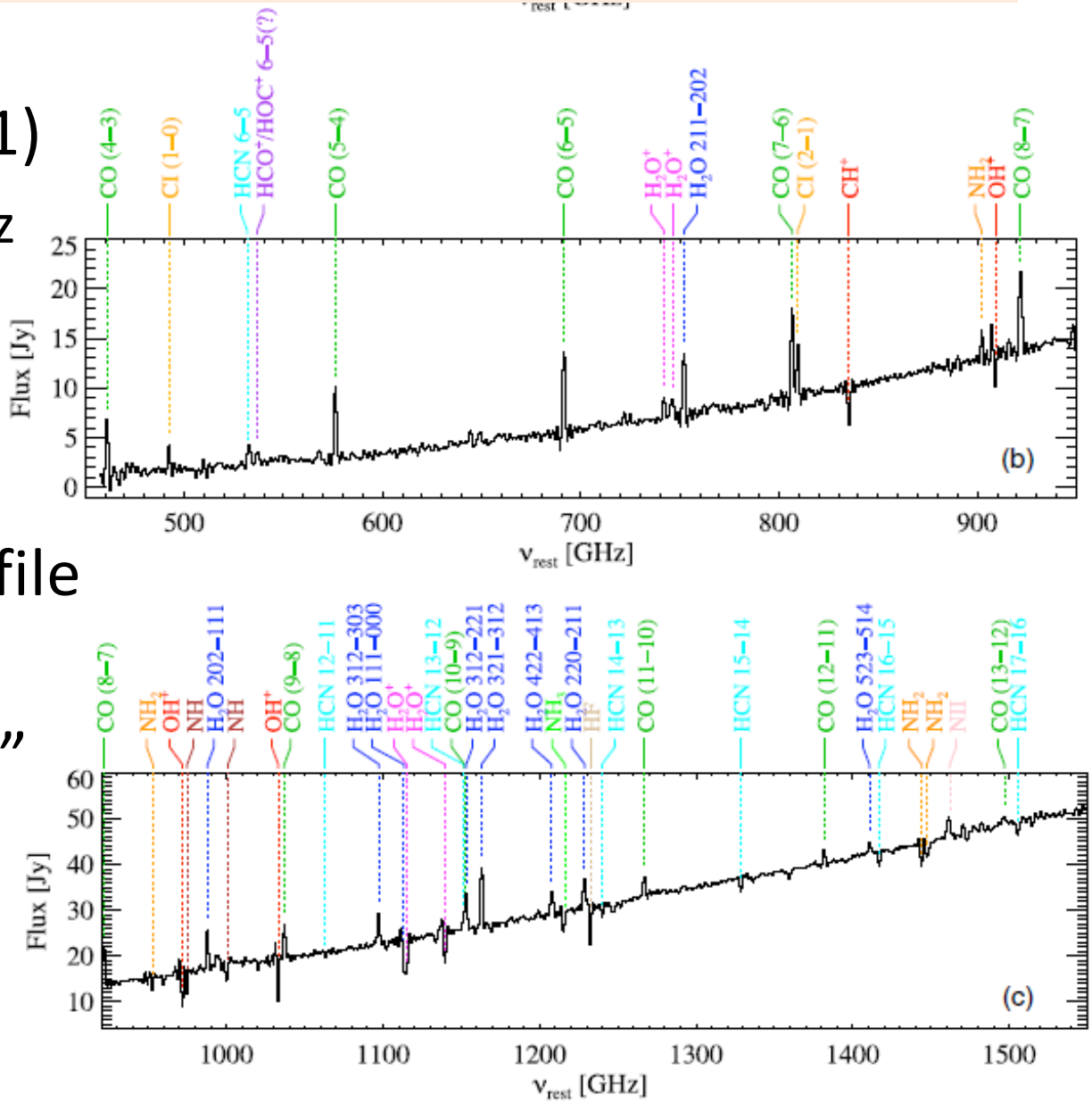
- van der Werf et al. (2010)
  - About 450 - 1500 GHz
  - Beam 17-42” (1” = 0.856 kpc)
  - 0.04 cm^{-1} resolution
  - 25 lines including 6 molecular species (high excitation CO, H_2O^+, OH^+, etc.)
  - H_2O^+, OH^+ : 1/2-1/3 of CO intensities!! ←XDR (X-ray dominated region)



Herschel SPIRE FTS: Arp 220

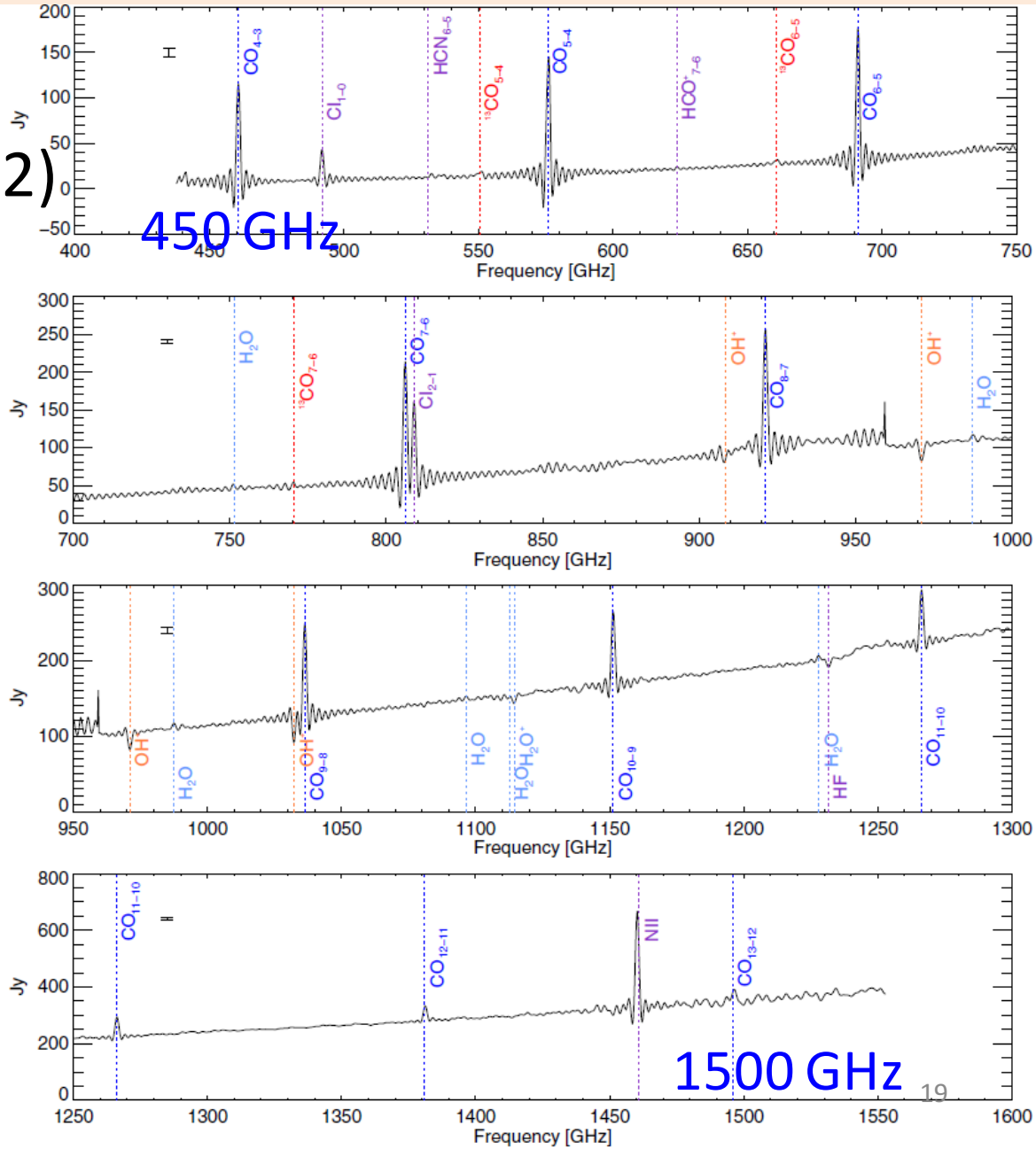
- Rangwara et al. (2011)
  - About 450 - 1500 GHz
  - Beam 17-40”
  - 1.44 GHz resolution
  - H_2O, H_2O^+, OH^+ : Strong P cygni profile → outflow

    “Evidence for AGN” (XDR)



Herschel SPIRE FTS: M 82 (starburst)

- Kamenezky et al. (2012)
  - About 450 - 1500 GHz
  - Beam 19-43”
  - 1.19 GHz resolution
  - H_2O, H_2O^+, OH^+ :
    - Mainly weak absorption
    - PDR + cosmic ray



Science cases in the THz region

- Basic processes of C, N, O reactions
- Deuterium concentration processes
- CH, OH^+, H_2O^+: XDR (X-ray dominated region) tracers?
- CH^+ and shock
- Atoms
  - C (Seta-san's talk)
  - Red-shifted C^+ line
  - N^+
  - Red-shifted O line

Basic gas-phase processes of C, N, O reactions

Carbon network (Red species → THz lines)

$C^+ + H_2$ ----> $CH^+ + H$ (endothermic 4640 K)

----> CH_2^+ (radiative association)

$CH^+ + H_2 \rightarrow CH_2^+ + H$

$CH^+ + e^- \rightarrow C + H$

$CH_2^+ + H_2 \rightarrow CH_3^+ + H$

$CH_2^+ + e^- \rightarrow CH + H$

$CH_3^+ + H_2$ ----> CH_5^+ (radiative association)

$CH_3^+ + e^- \rightarrow CH_2 + H$

$CH_5^+ + e^- \rightarrow$ **CH_4 (methane)** + H

$\rightarrow CH_3 + H_2$

CH_4 can also be produced on grain.

Basic gas-phase processes of C, N, O reactions

Nitrogen network (Red species → THz lines)

$N^+ + H_2$ ----> $NH^+ + H$
(endothermic 209 K, e.g., Marquette et al. 1988)

$NH^+ + H_2 \rightarrow NH_2^+ + H$
$NH^+ + e^- \rightarrow N + H$

$NH_2^+ + H_2 \rightarrow NH_3^+ + H$
$NH_2^+ + e^- \rightarrow NH + H$
$\rightarrow N + H_2$

$NH_3^+ + H_2 \rightarrow NH_4^+ + H$
$NH_3^+ + e^- \rightarrow NH_2 + H$
$\rightarrow NH + H_2$

$NH_4^+ + e^- \rightarrow$ **NH_3 (ammonia)** $+ H$
$\rightarrow NH_2 + H_2$
$\rightarrow NH + H_2 + H$

NH_3 is mainly produced on grain (e.g., Herbst et al. 1987, Hidaka et al. 2011)

Basic gas-phase processes of C, N, O reactions

Oxygen network (Red species → THz lines)

$O^+ + H_2 \rightarrow OH^+ + H$

$OH^+ + H_2 \rightarrow H_2O^+ + H$

$OH^+ + e^- \rightarrow O + H$

$H_2O^+ + H_2 \rightarrow H_3O^+ + H$

$H_2O^+ + e^- \rightarrow OH + H$

$\rightarrow O + H_2$

$H_3O^+ + e^- \rightarrow H_2O$ (water) + H

Observations of these red species: (New species OH^+, H_2O^+)

→Supply basic information

→But, how to estimate excitation temperature?

→Comparison with models with PDR, XDR, cosmic ray, ...

(e.g., Ioppolo et al. 2010)

Processes of deuterium concentration

$H_2 + H_2^+ \rightarrow H_3^+ + H$

$HD + H_3^+ \rightarrow H_2D^+ + H_2$ (230 K exothermic)

$HD + H_2D^+ \rightarrow HD_2^+ + H_2$ (180 K exothermic)

(Vastel et al. 2004)

→ D is introduced to molecules via H_2D^+ and HD_2^+.

- Free from depletion
- But again, difficult to know rotational temperature

Tracers of AGN (Active Galactic Nucleus) (or X-ray dominated region, XDR)?

- HCN/HCO^+ (NMA: Kohno et al. 2001)
- OH^+, H_2O^+ (Herschel)
  - Mrk 231 (van der Verf et al. 2010)

    1/2-1/3 of CO intensities!! ←Very strong

    → XDR (X-ray dominated region)
  - Arp 220 (Rangwala et al. 2011)

    Large column density

    → "Evidence for an AGN"

Tracers of AGN (Active Galactic Nucleus) (or X-ray dominated region, XDR)?

- CH/CO (Herschel: Rangwala et al. 2014)

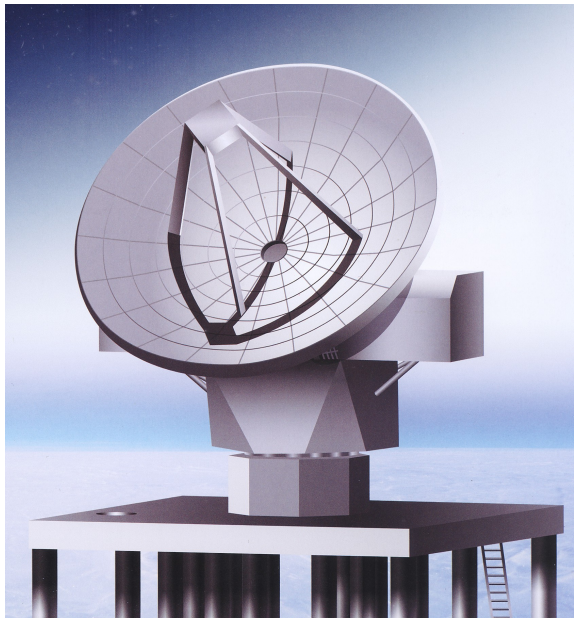
Galaxy	Central nature	CH/CO (abundance ratio)
Arp 220	With AGN?	4.5×10^{-5}
NGC 1068	**AGN**	**1×10^{-4}**
NGC 253	Starburst	2×10^{-5}
M 82	Starburst	2×10^{-5}

Updated XDR model of Malony et al. (1996)

→ The results of NGC 1068 can be explained by an XDR.

Summary

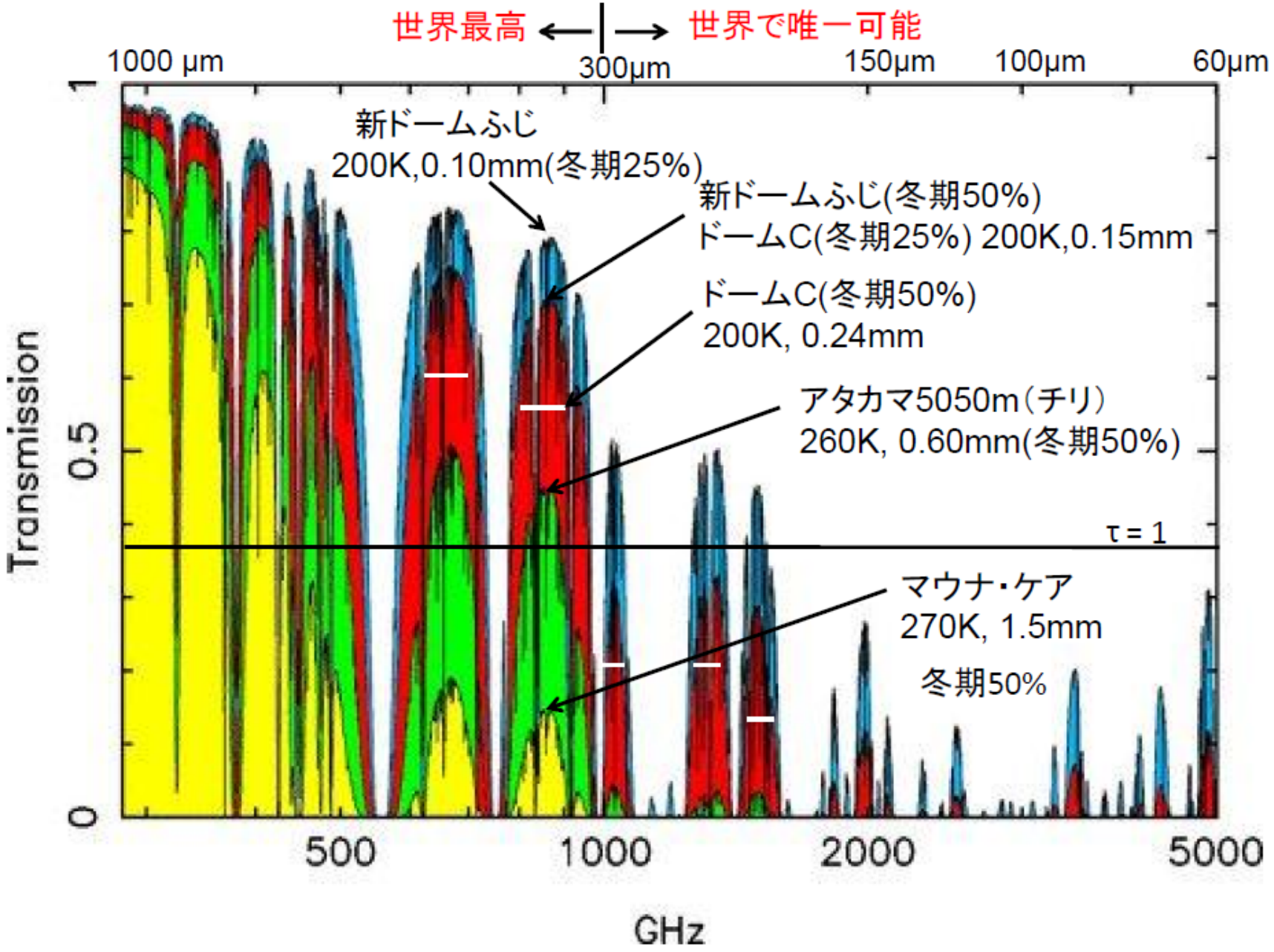
- THz region
  - Relatively high energy phenomena
  - World of mainly atoms and light molecules
    - Still lot of large organic molecular lines (our Galaxy)
    - But still new species expected (e.g., OH^+ and H_2O^+, ...)
- Science cases
  - Basic chemical network
  - Deuterium concentration
  - Tracers of AGN (XDR)
  - Tracers of shocks
  - Atomic diffuse phase



http://www.px.tsukuba.ac.jp/~nakai/astroobs/antarctica.html

Additional slides

大気透過率（H.Yang, et al. 2010 PASP 122, 490 ）



http://www.px.tsukuba.ac.jp/~nakai/astroobs/pdf/transmission.pdf

Introduction: Molecules in space

- About 190 species in interstellar space and circumstellar envelopes of late-type stars

- About ~60 species in external galaxies!
  (CDMS: Univ. Cologne)

  "Detection of extragalactic argonium, ArH^+, toward PKS 1830−211" (with ALMA cycle 2)

  Müller et al. A&A 582, L4 (2015)

CH^+: Tracer of strong shock?

$C^+ + H_2 \rightarrow CH^+ + H$ (endothermic 4640 K, e.g., Rangwala et al. 2014)

But the abundance is large

- C-shocks?
- Turbulence
- H_2 vibrationally excited?

(e.g., Falgarone et al. 2010)