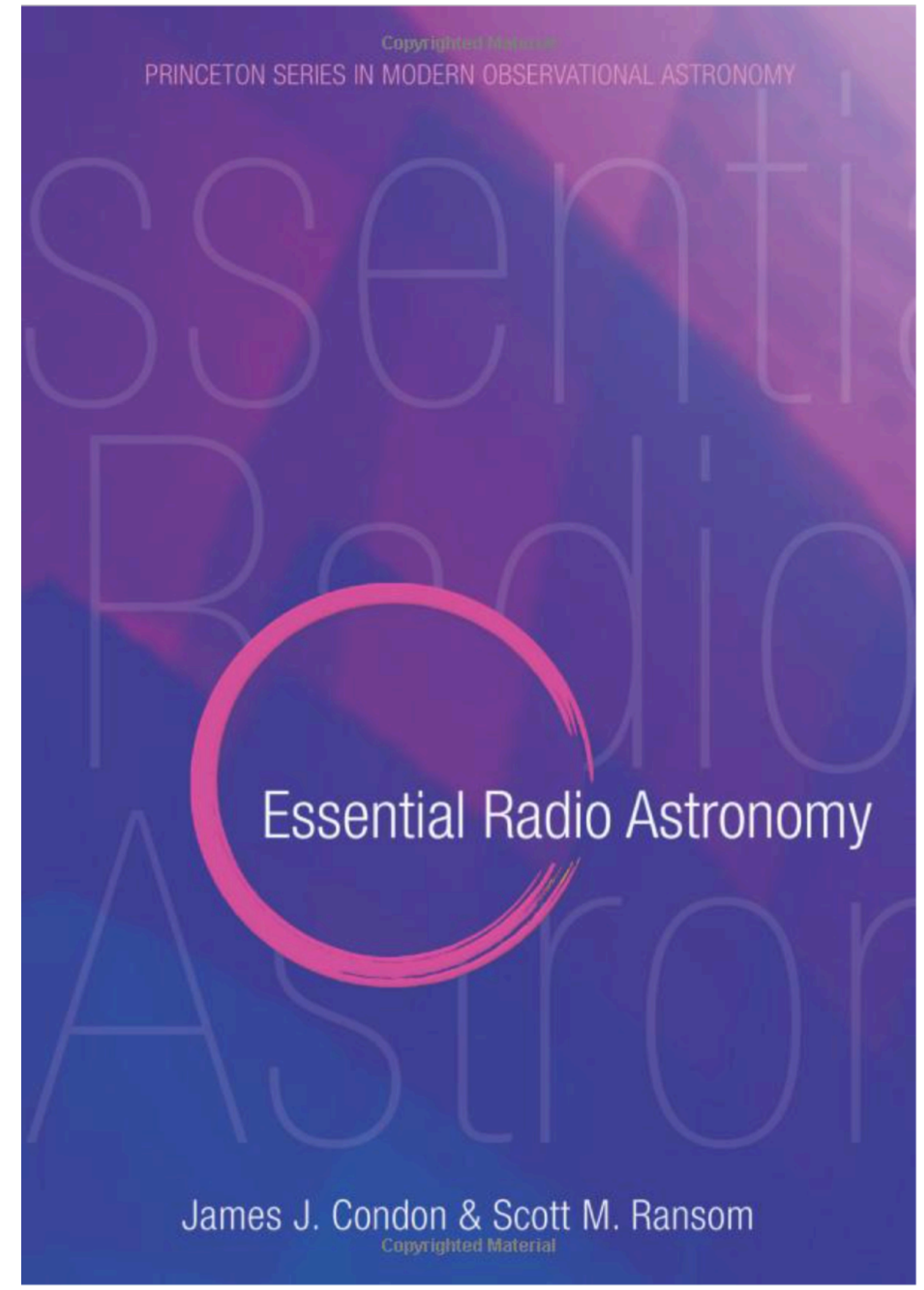
Introduction to Radio/sub-mm Astronomy

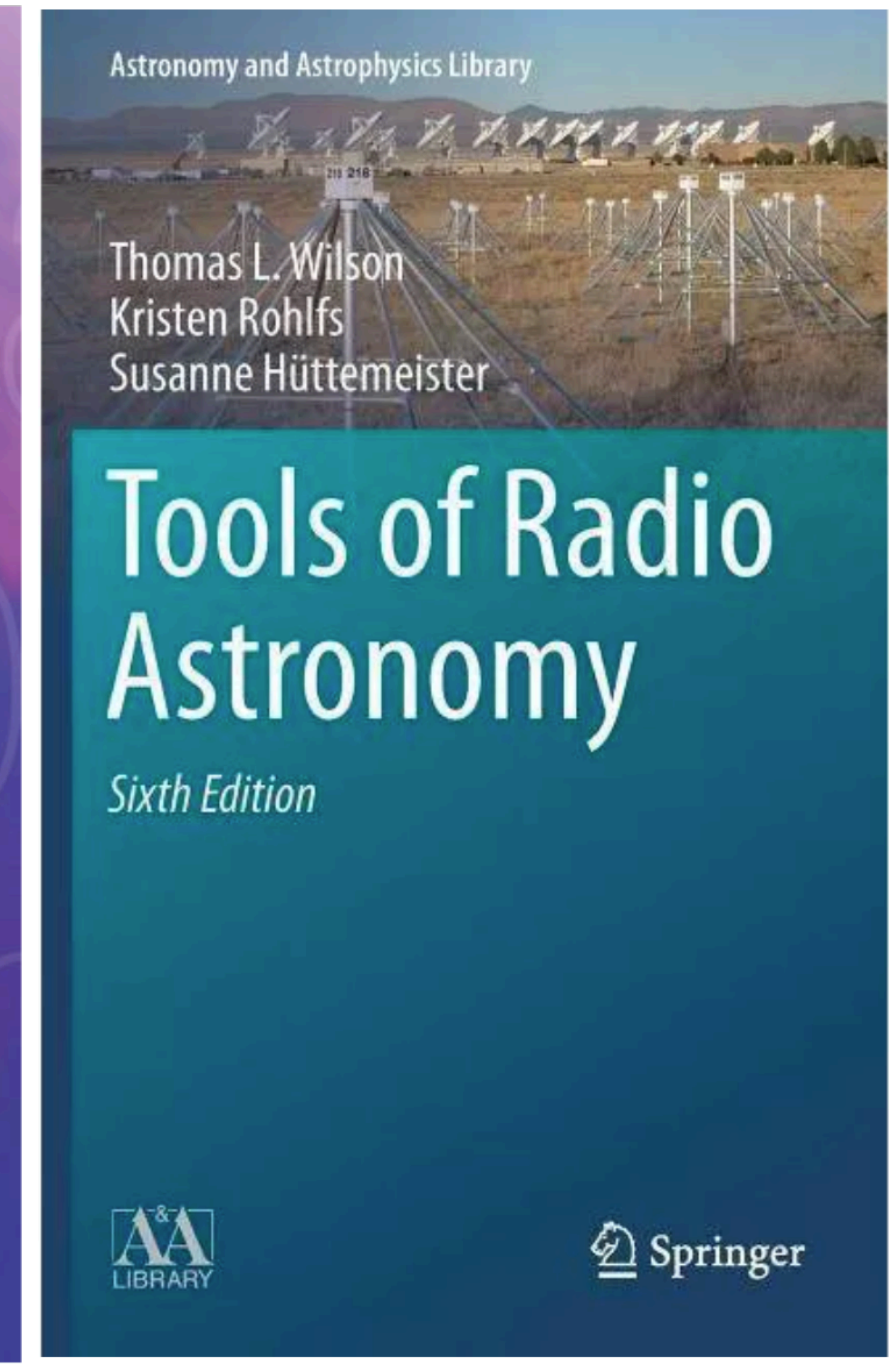
Xue-Jian Jiang (蒋雪健)

Dec. 01, 2020

Literature

- *Essential Radio Astronomy*
  https://science.nrao.edu/opportunities/courses/era
- *Tools of Radio Astronomy*





Summer schools (slides available)

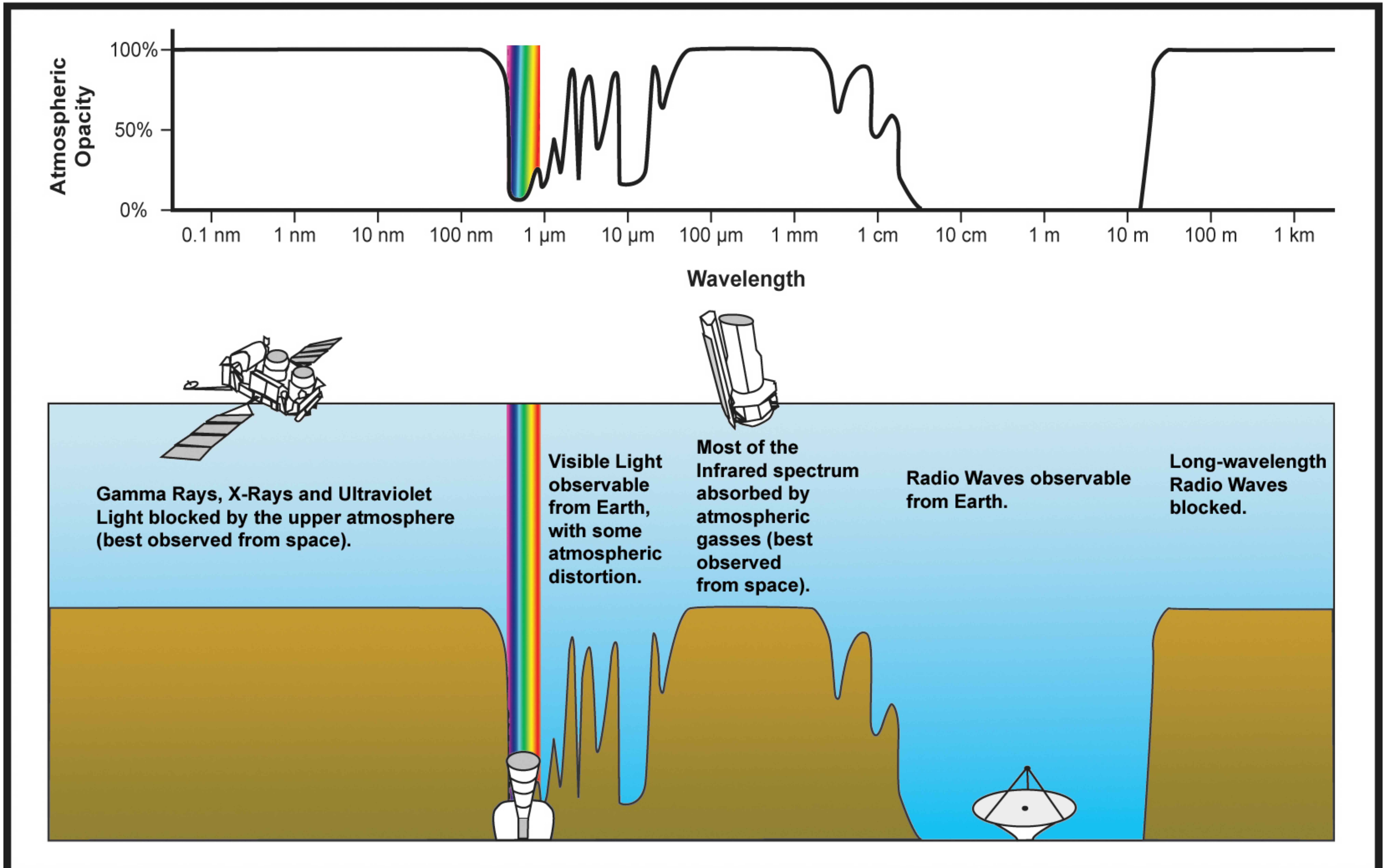
- NRAO: https://science.nrao.edu/science/meetings/2015/summer-schools
- IRAM: https://publicwiki.iram.es/SummerSchools
- ASIAA: https://events.asiaa.sinica.edu.tw/school/20160815/program.php

This presentation have used materials from different literature, please click on texts with underline for links.

Questions

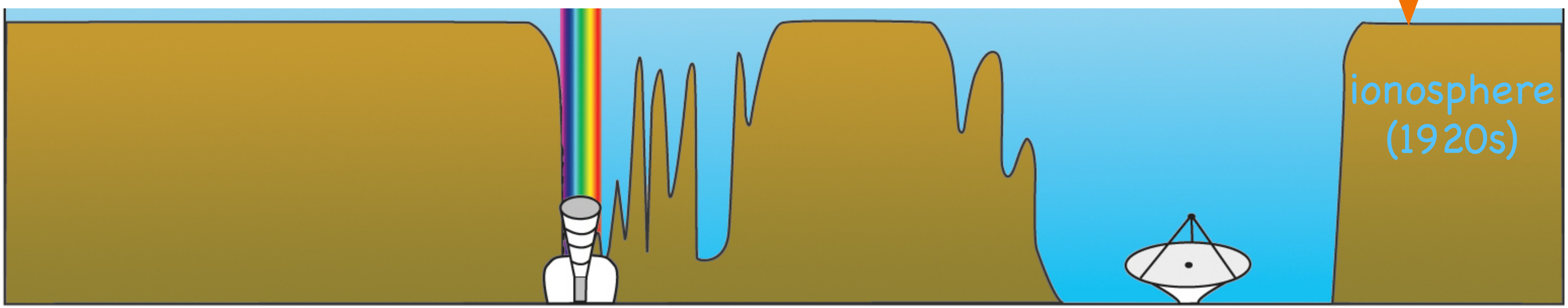
- What is the radio/submm atmosphere window?
- What is special about the radio/submm band?
- What astrophysical process produce radio/submm signal?
- How to do radio/submm observations?

The Radio Window
ν ~ 10 MHz to 1 THz



History of Radio Astronomy

- Unsuccessful attempts to find solar radio signal: 1890, 1896, 1900… (freq. too low)
- Existence of the ionosphere demonstrated in 1920s
- Solar radio signal finally detected in 1942 by a radar station



See: History of Radio Astronomy - NASA
History of Radio Astronomy a previous talk by Harriet Parsons

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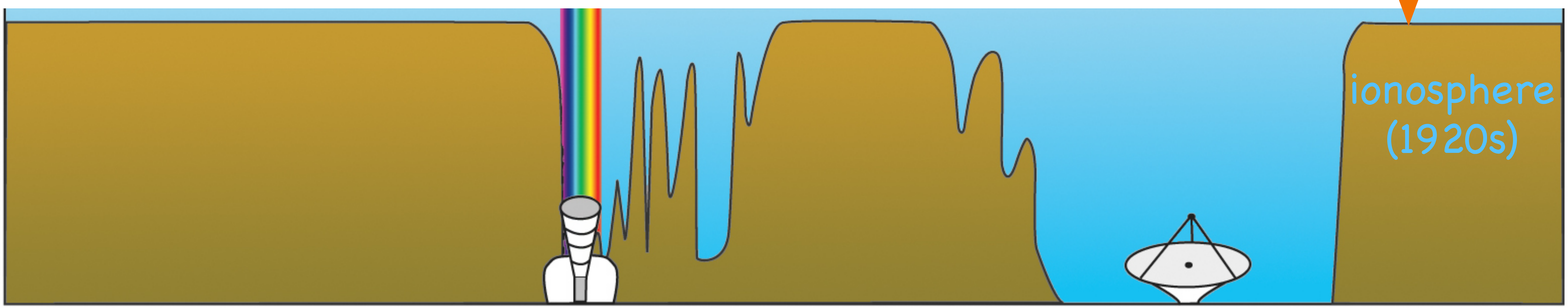

- Problem: Noise interfering with short-wave radio communication
- Discovery: "clouds of 'cosmic dust' in that direction…" (Milky Way)
  — **Karl Jansky 1932**

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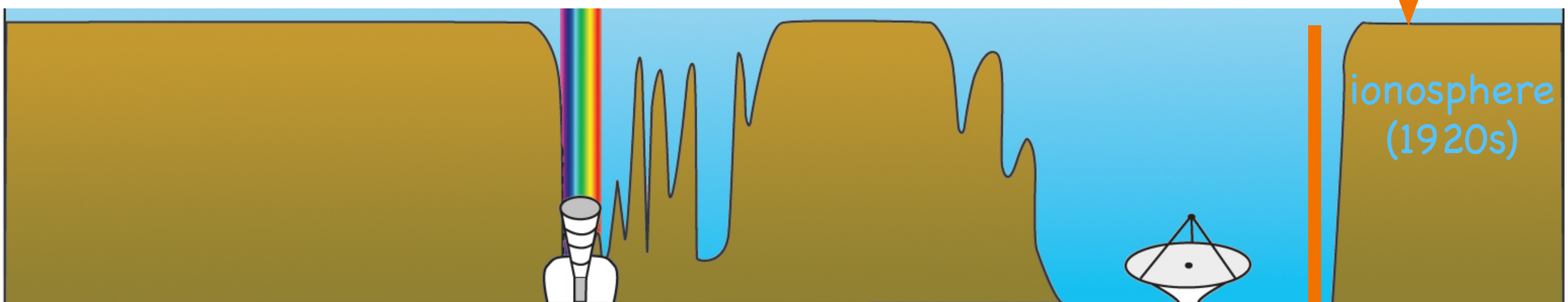

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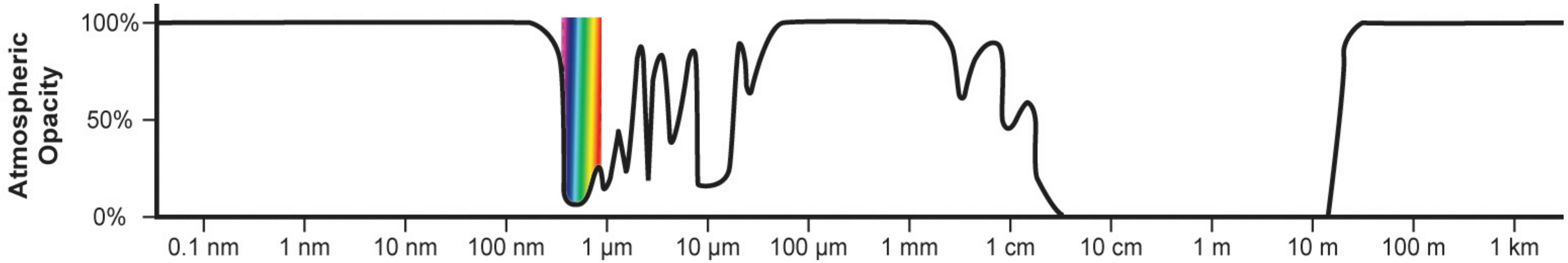
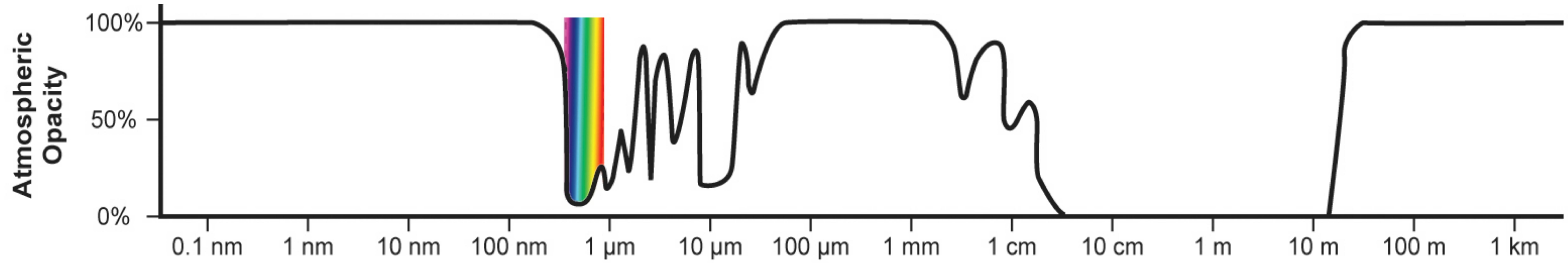
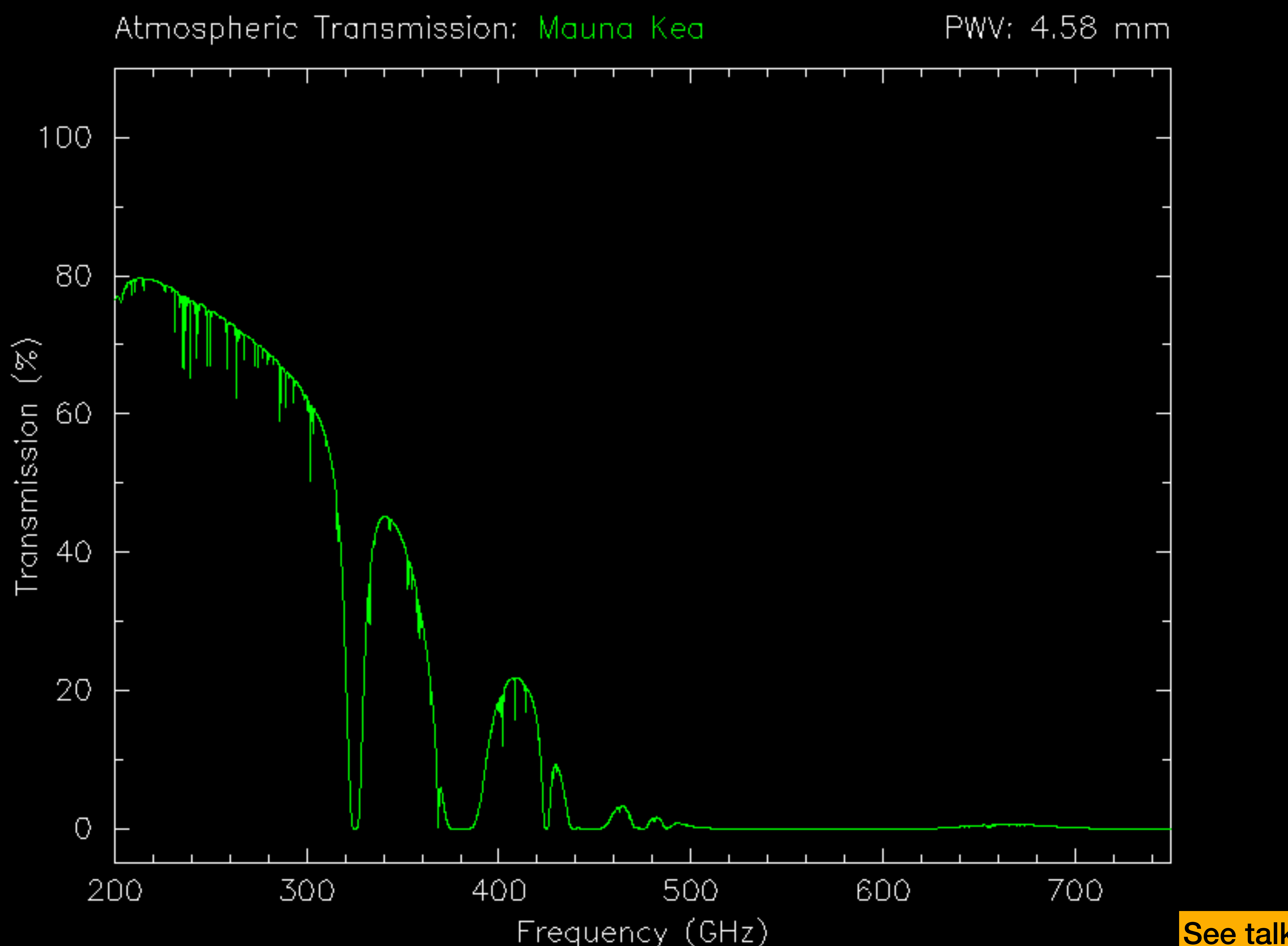


Maunakea: The best site for sub-mm observations in the Northern hemisphere


Atmospheric Opacity
100%
50%
0%
0.1 nm
1 nm
10 nm
100 nm
1 µm
10 µm
100 µm
1 mm
1 cm
10 cm
1 m
10 m
100 m
1 km

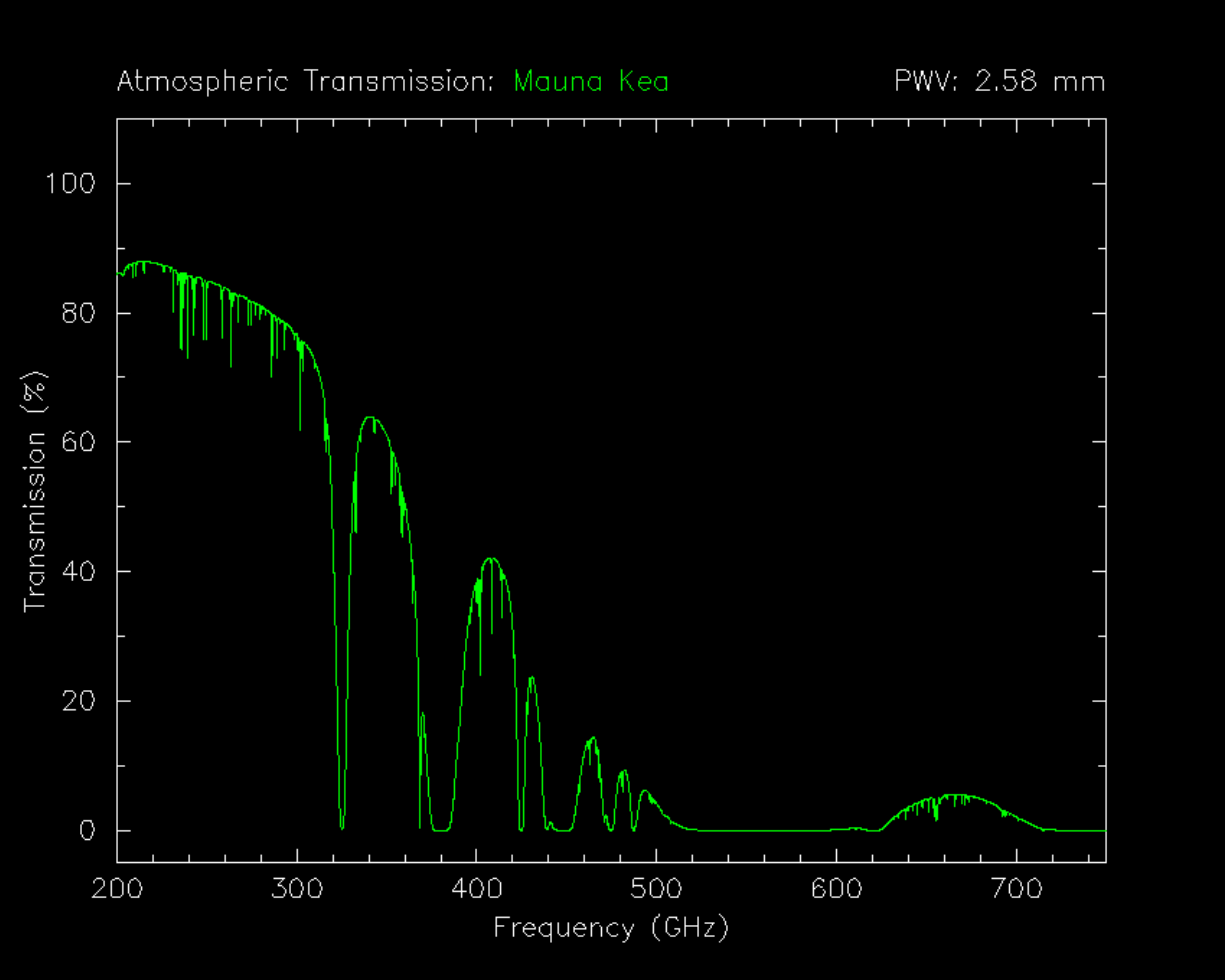

Maunakea: The best site for sub-mm observations in the Northern hemisphere

CSO, JCMT, SMA

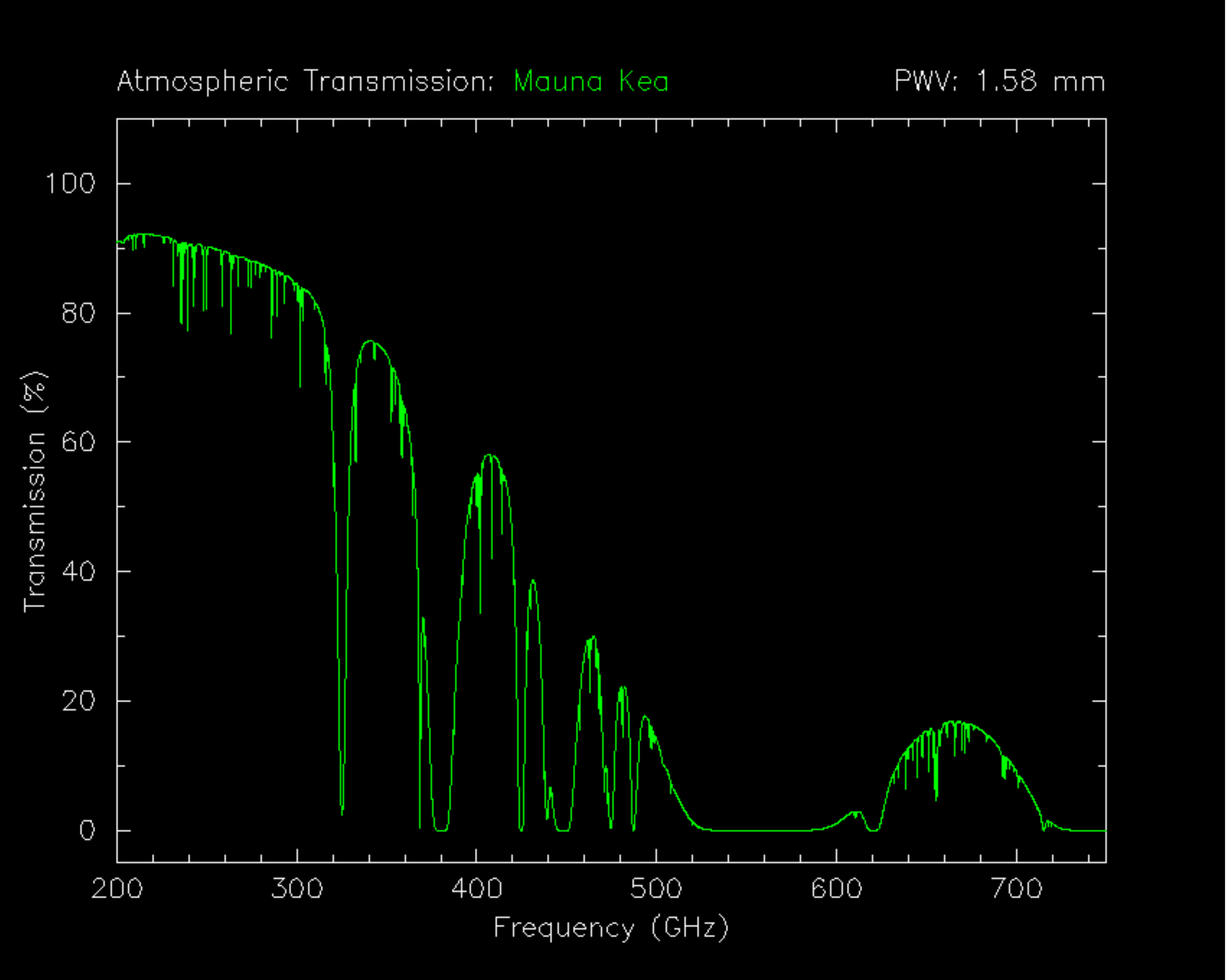


PWV ~ 4.58 mm
Band 4/5 Boundary

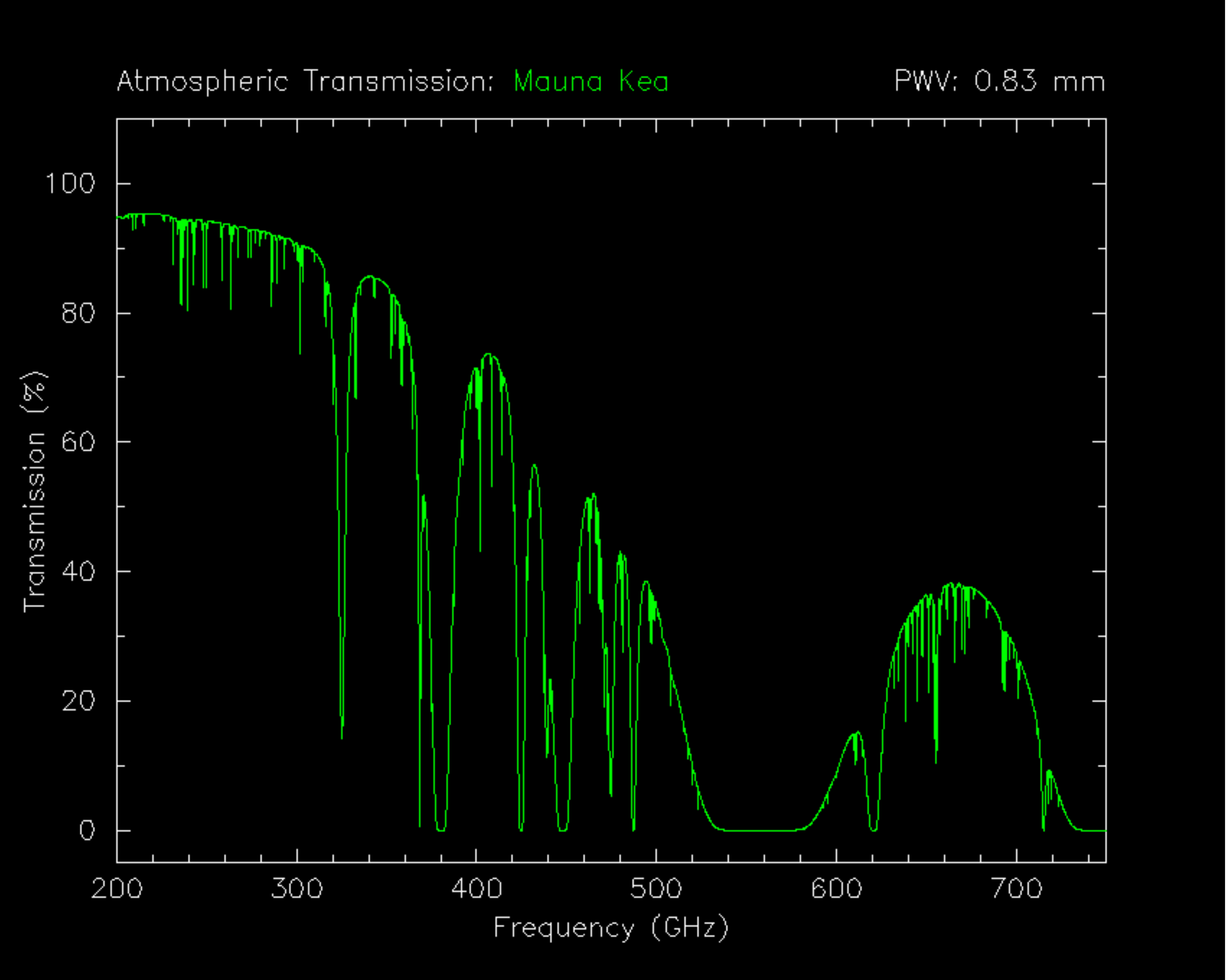
See talk “band-5 proposals”



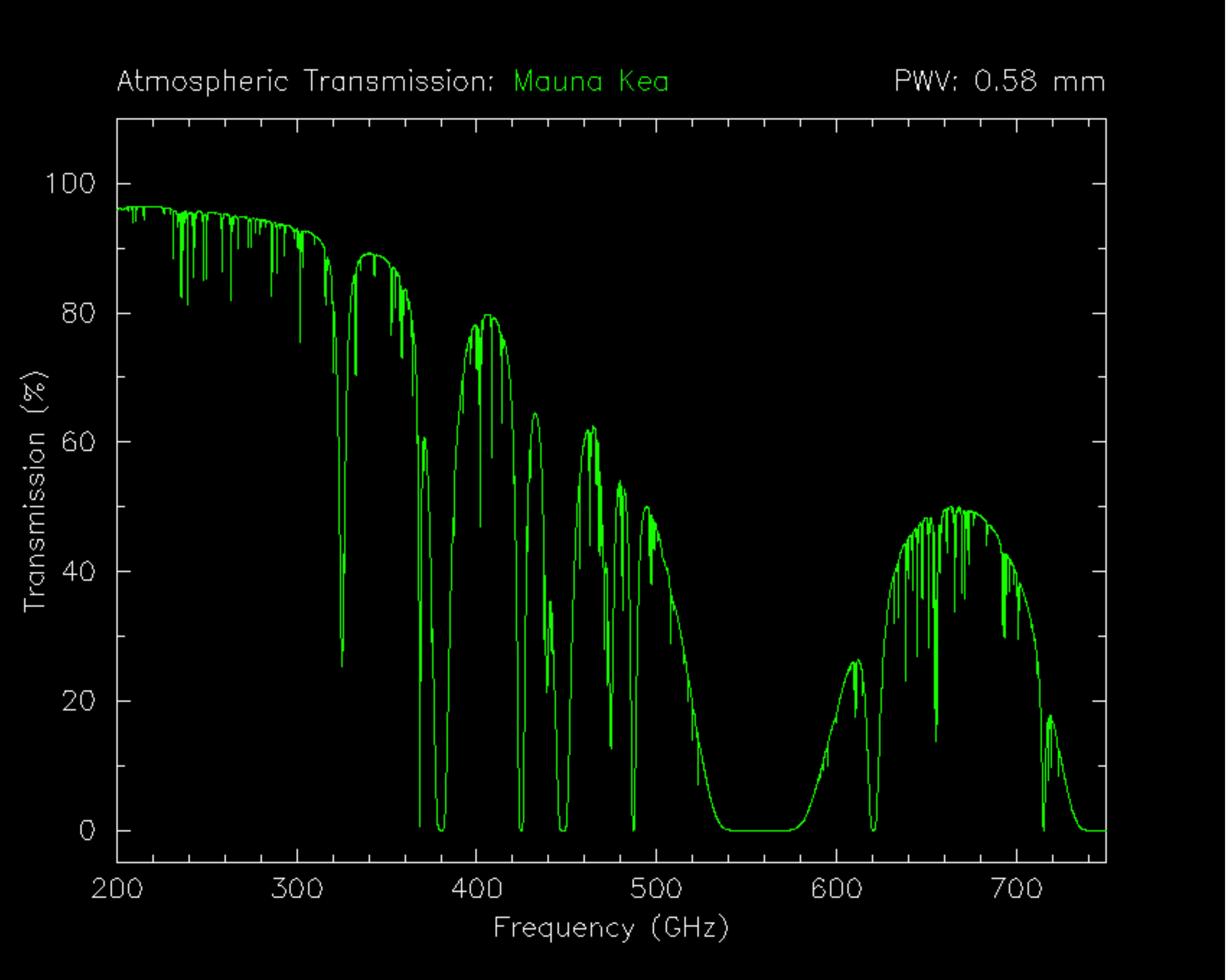
PWV ~ 2.58 mm
Band 3/4 Boundary



PWV ~ 1.58 mm
Band 2/3
Boundary

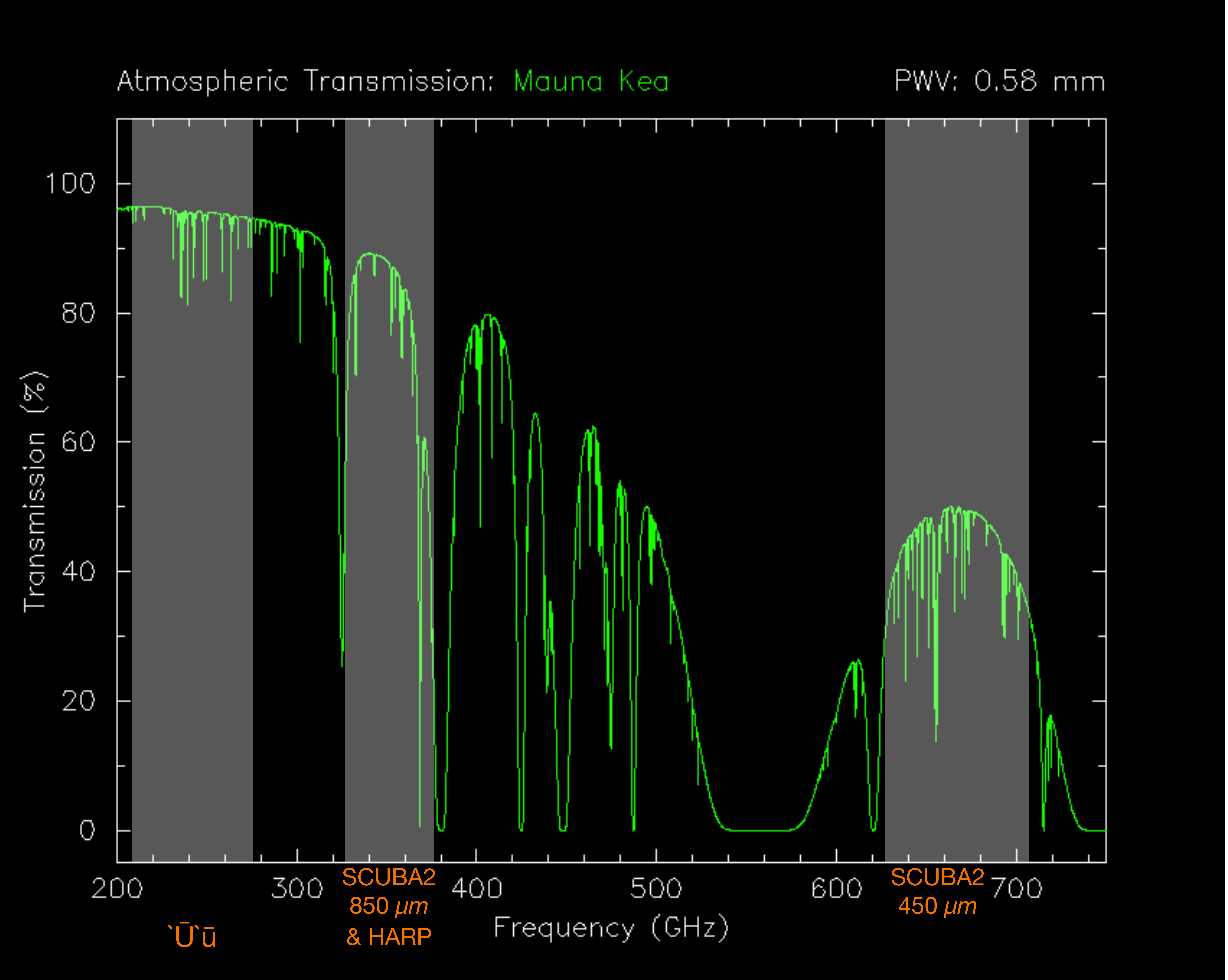


PWV ~ 0.83 mm
Band 1/2
Boundary



PWV ~ 0.58 mm
Band 1
Boundary

High freq. requires better weather!



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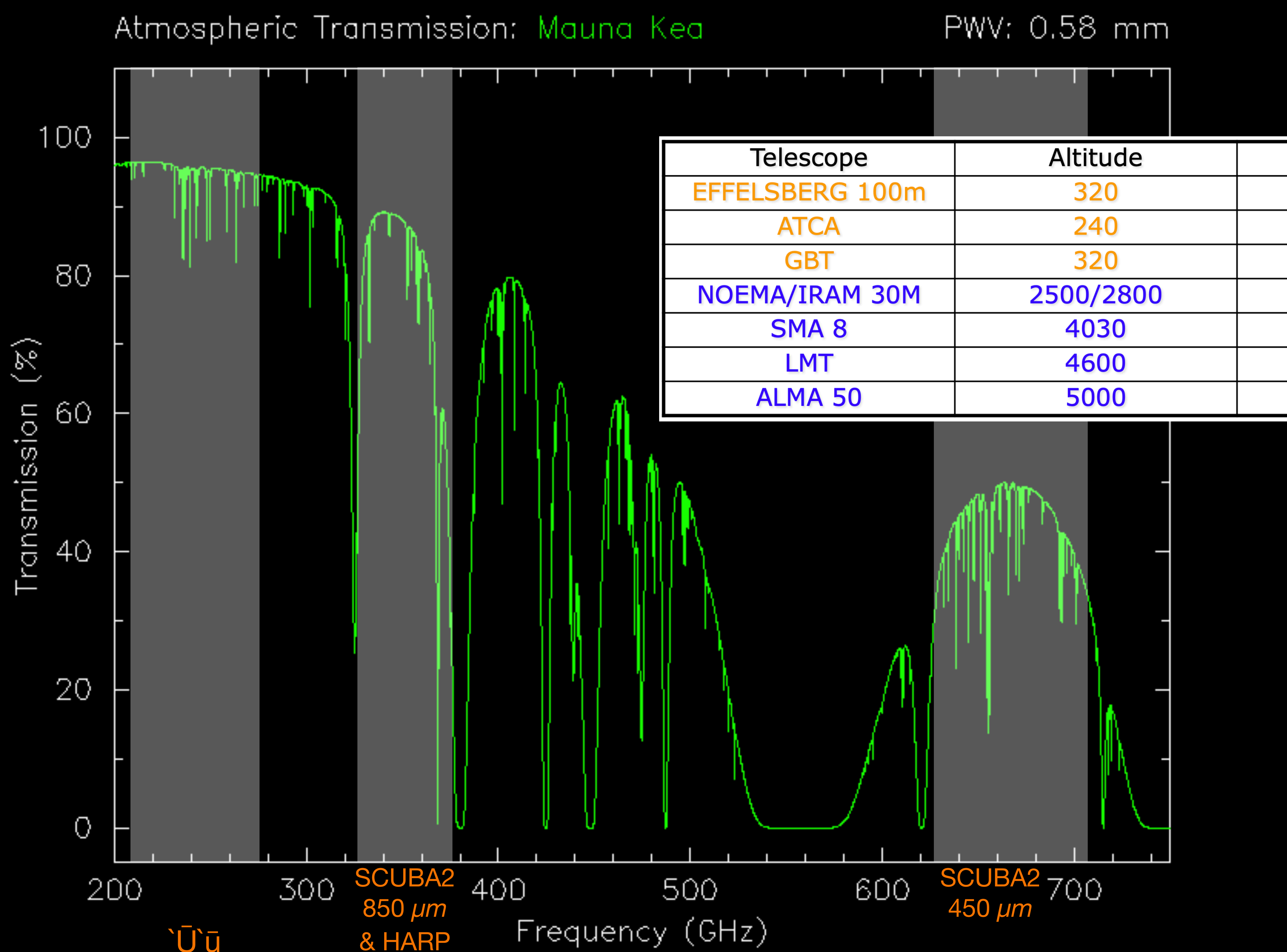

Telescope	Altitude	Frequencies
EFFELSBERG 100m	320	<90 GHz
ATCA	240	<105 GHz
GBT	320	<115 GHz
NOEMA/IRAM 30M	2500/2800	< 380 GHz
SMA 8	4030	<700 GHz
LMT	4600	<350 GHz
ALMA 50	5000	<1000 GHz

PWV ~ 0.58 mm
Band 1
Boundary

High freq. requires better weather!

Questions

- **What is the radio/submm atmosphere window?**
  — a very broad and transparent observing window
- What is special about the radio/submm band?
- What is the astrophysical source of radio/submm signal?
- How to do radio/submm observations?

Questions

- What is the radio/submm atmosphere window?
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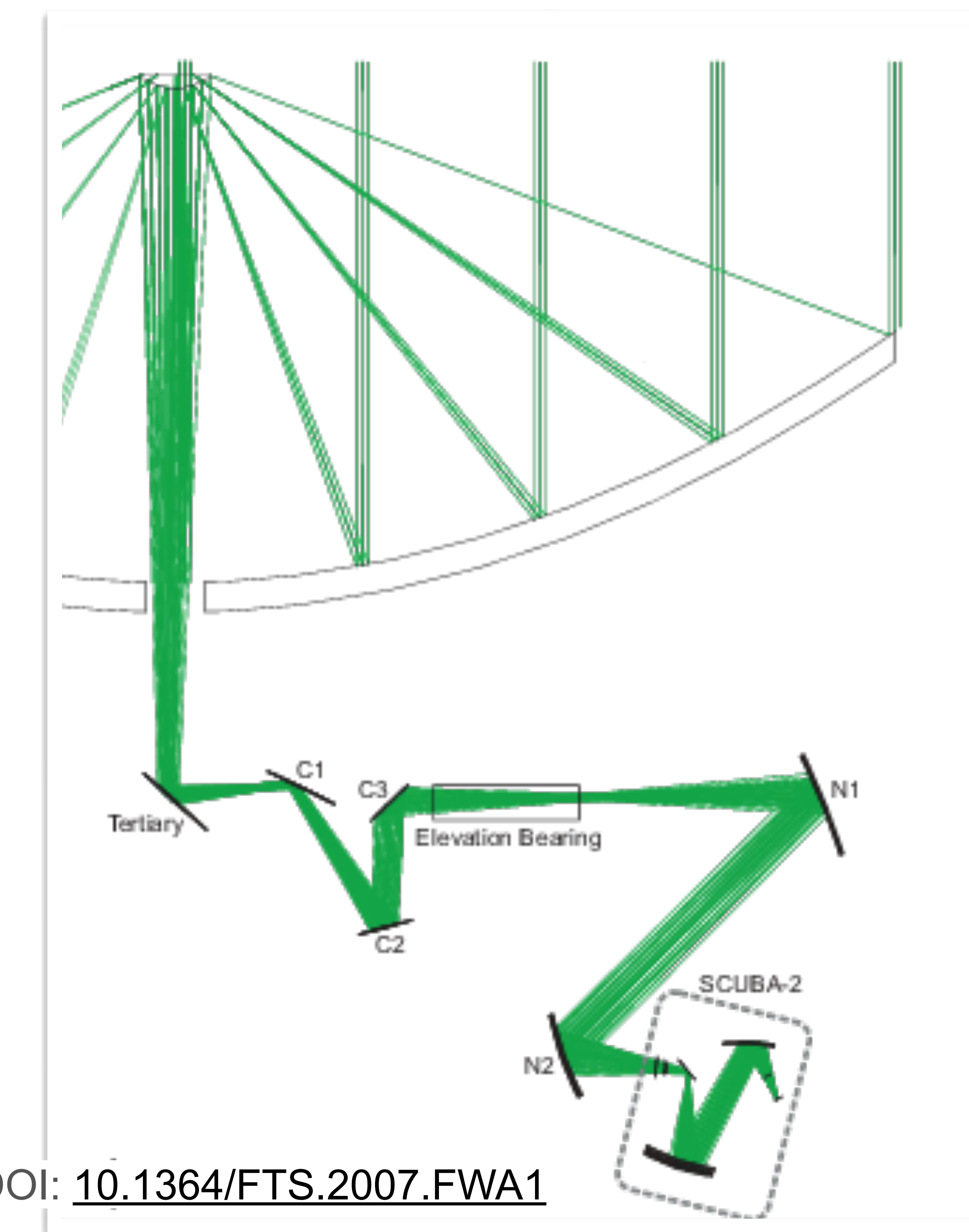
- **What is special about the radio/submm band?**
- What astrophysical process produce radio/submm signal?
- How to do radio/submm observations?

Sub-mm vs. Visual Wavelength Astronomy
- Similarities

- Still uses curved reflecting surfaces, classical optical paths, etc. "Light" still generally treated as waves (c.f. X-ray astronomy). Still need to characterize focus, pointing, etc.
- Types of observations essentially same:
  - Continuum
  - Spectral line
  - Polarization
  - Timing / variability
  - Combinations of some / all of the above



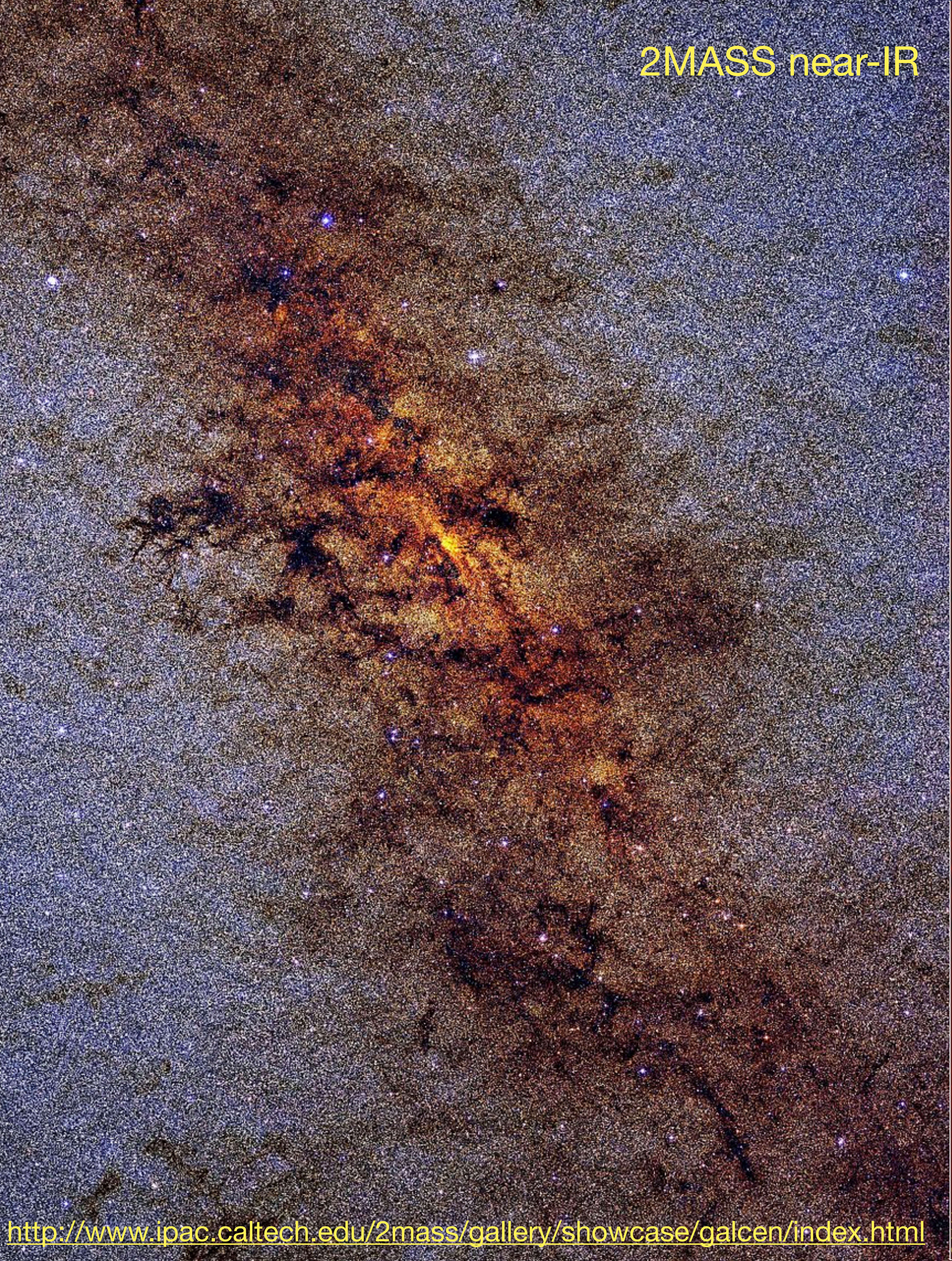
DOI: 10.1364/FTS.2007.FWA1

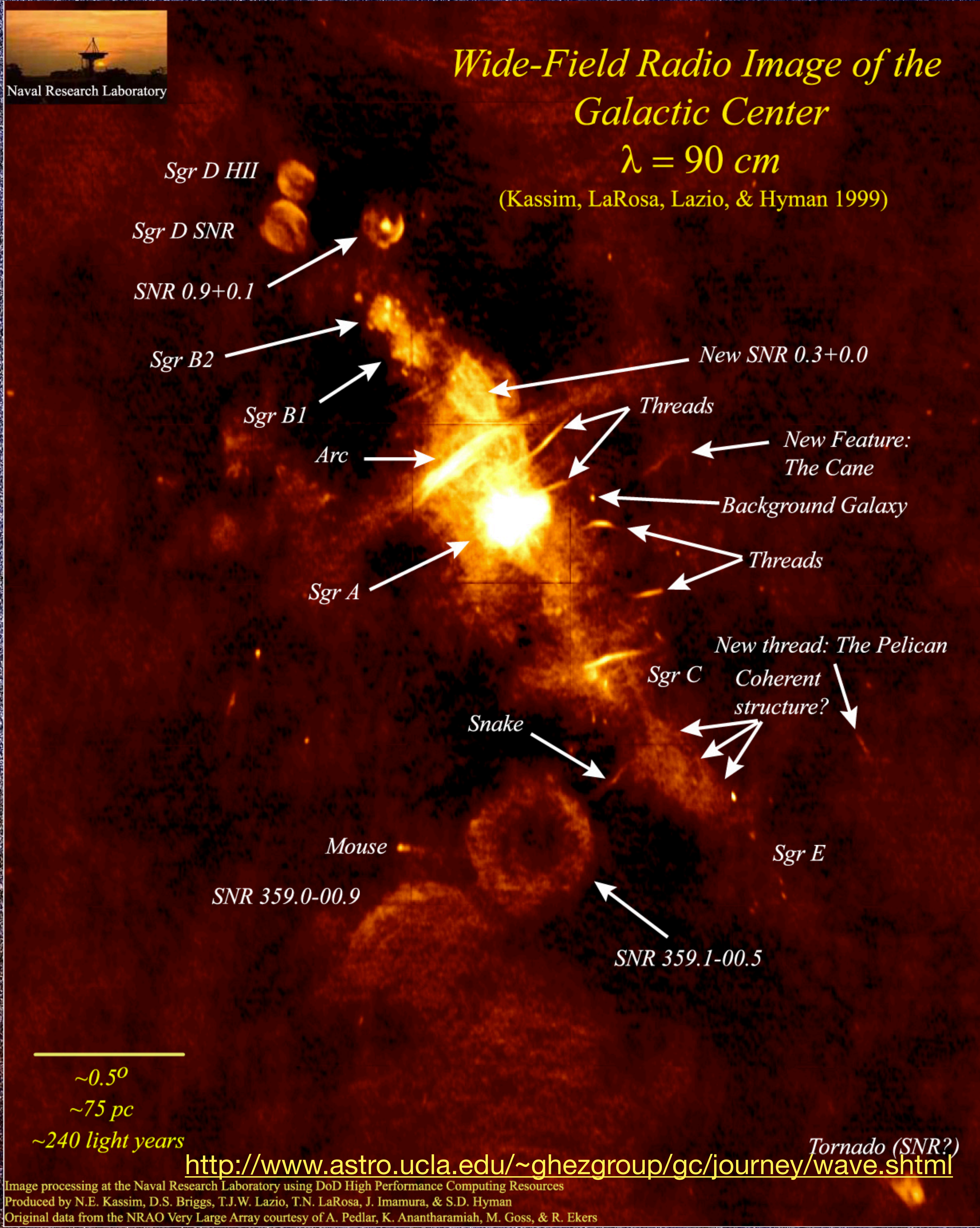
Sub-mm vs. Visual Wavelength Astronomy
- Differences

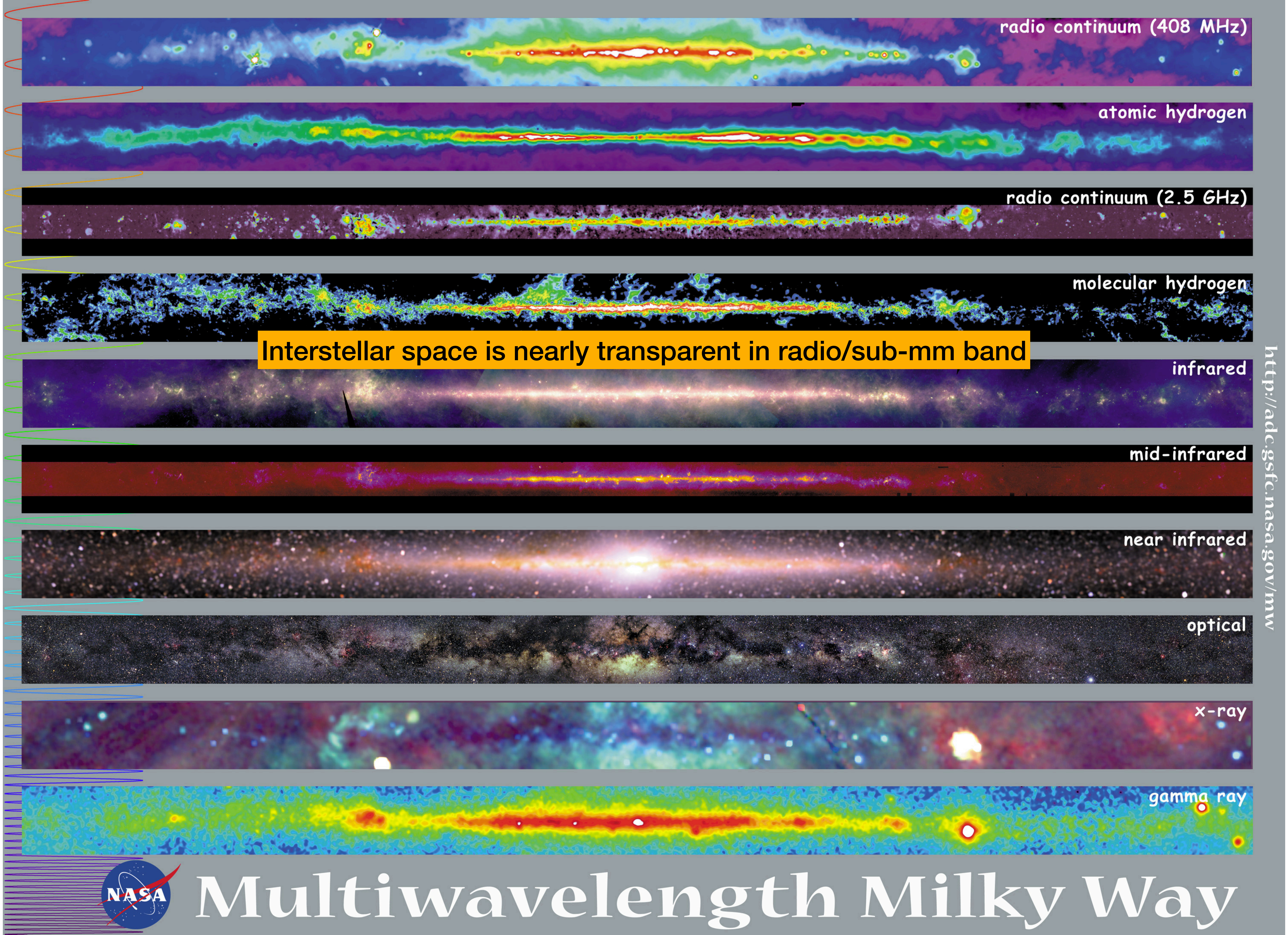
- Probes different environments (e.g. diffuse gas/dust vs. starlight)
- Due to wavelength (frequency) range covered, necessitates use of strange mixture of instrument technologies from radio & infrared astronomy
- Because of this, many (but not all…) concepts & terminology (e.g. beam, T_A^*) derive from radio astronomy
- Example: preserve phase -> interferometry

The Radio Sky

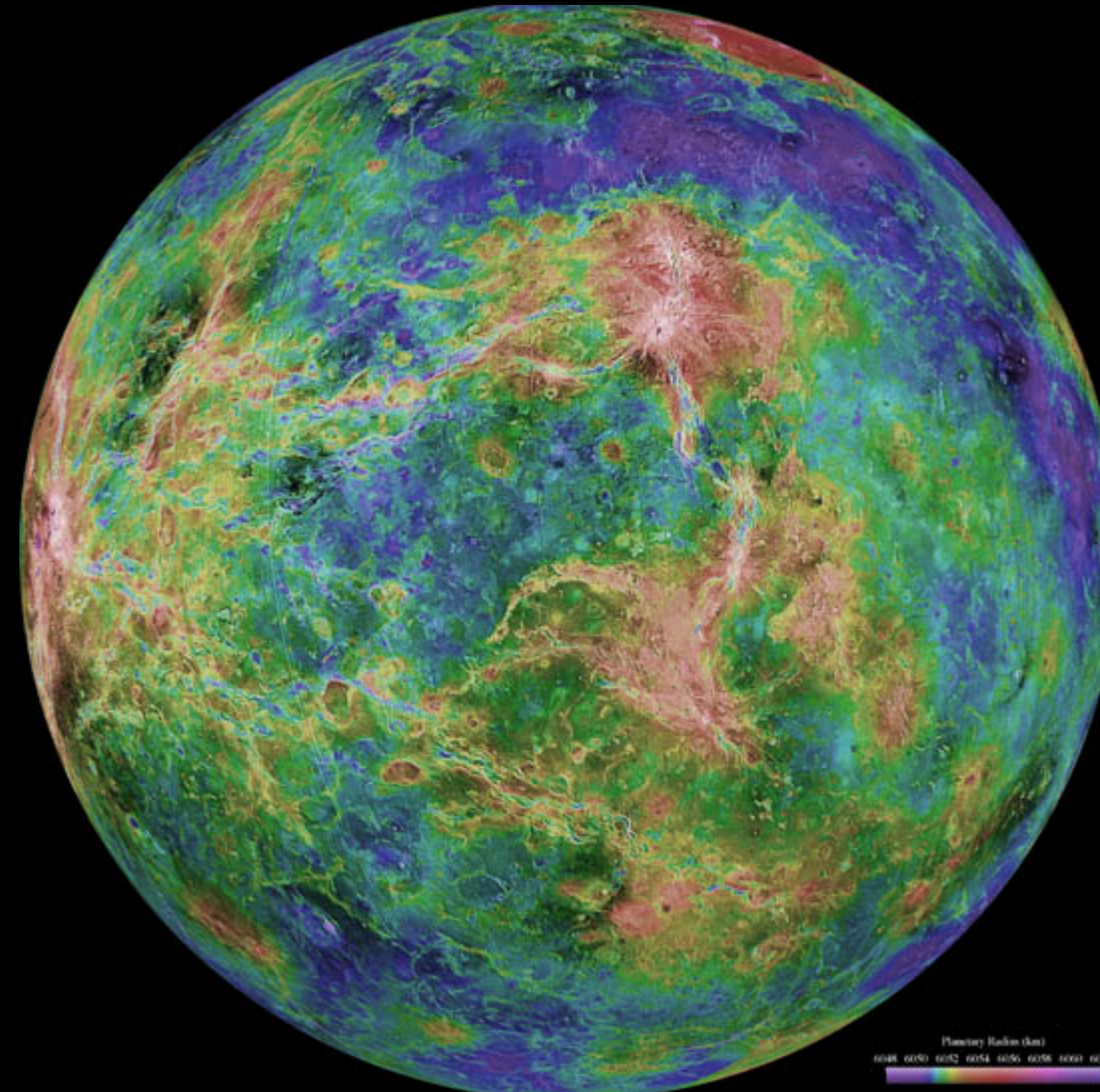
Both Day and Night


2MASS near-IR
http://www.ipac.caltech.edu/2mass/gallery/showcase/galcen/index.html


Naval Research Laboratory
Wide-Field Radio Image of the Galactic Center
λ = 90 cm
(Kassim, LaRosa, Lazio, & Hyman 1999)
Sgr D HII
Sgr D SNR
SNR 0.9+0.1
Sgr B2
Sgr B1
New SNR 0.3+0.0
Threads
New Feature: The Cane
Arc
Background Galaxy
Threads
Sgr A
New thread: The Pelican
Sgr C
Coherent structure?
Snake
Mouse
Sgr E
SNR 359.0-00.9
SNR 359.1-00.5
~0.5°
~75 pc
~240 light years
Tornado (SNR?)
http://www.astro.ucla.edu/~ghezgroup/gc/journey/wave.shtml
Image processing at the Naval Research Laboratory using DoD High Performance Computing Resources
Produced by N.E. Kassim, D.S. Briggs, T.J.W. Lazio, T.N. LaRosa, J. Imamura, & S.D. Hyman
Original data from the NRAO Very Large Array courtesy of A. Pedlar, K. Anantharamiah, M. Goss, & R. Ekers

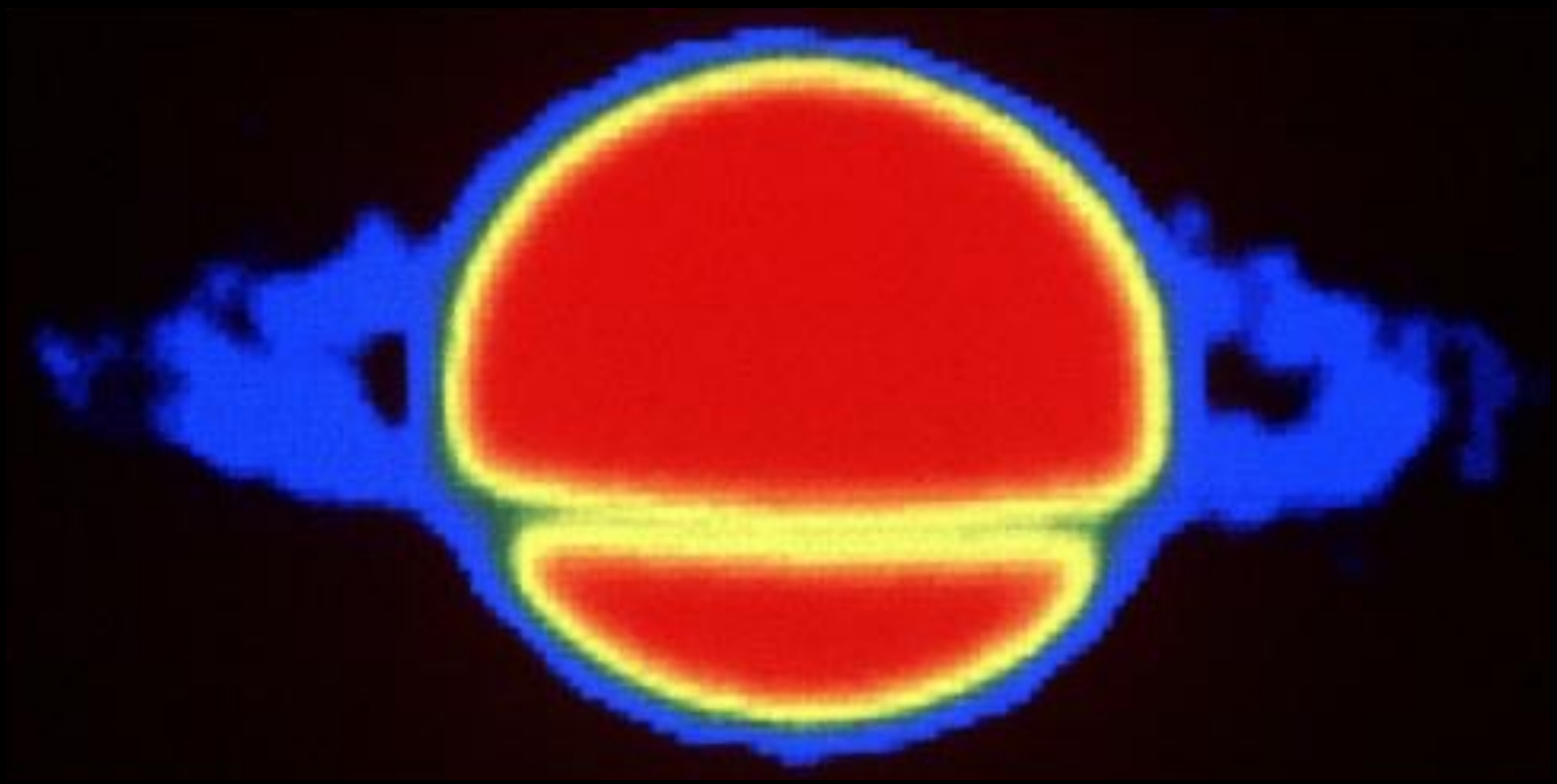


radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
Interstellar space is nearly transparent in radio/sub-mm band
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way



Magellan/Arecibo radar image of Venus

NRAO/AUI/NSF

https://public.nrao.edu/gallery/saturn-in-radio-waves/
NRAO/AUI/NSF

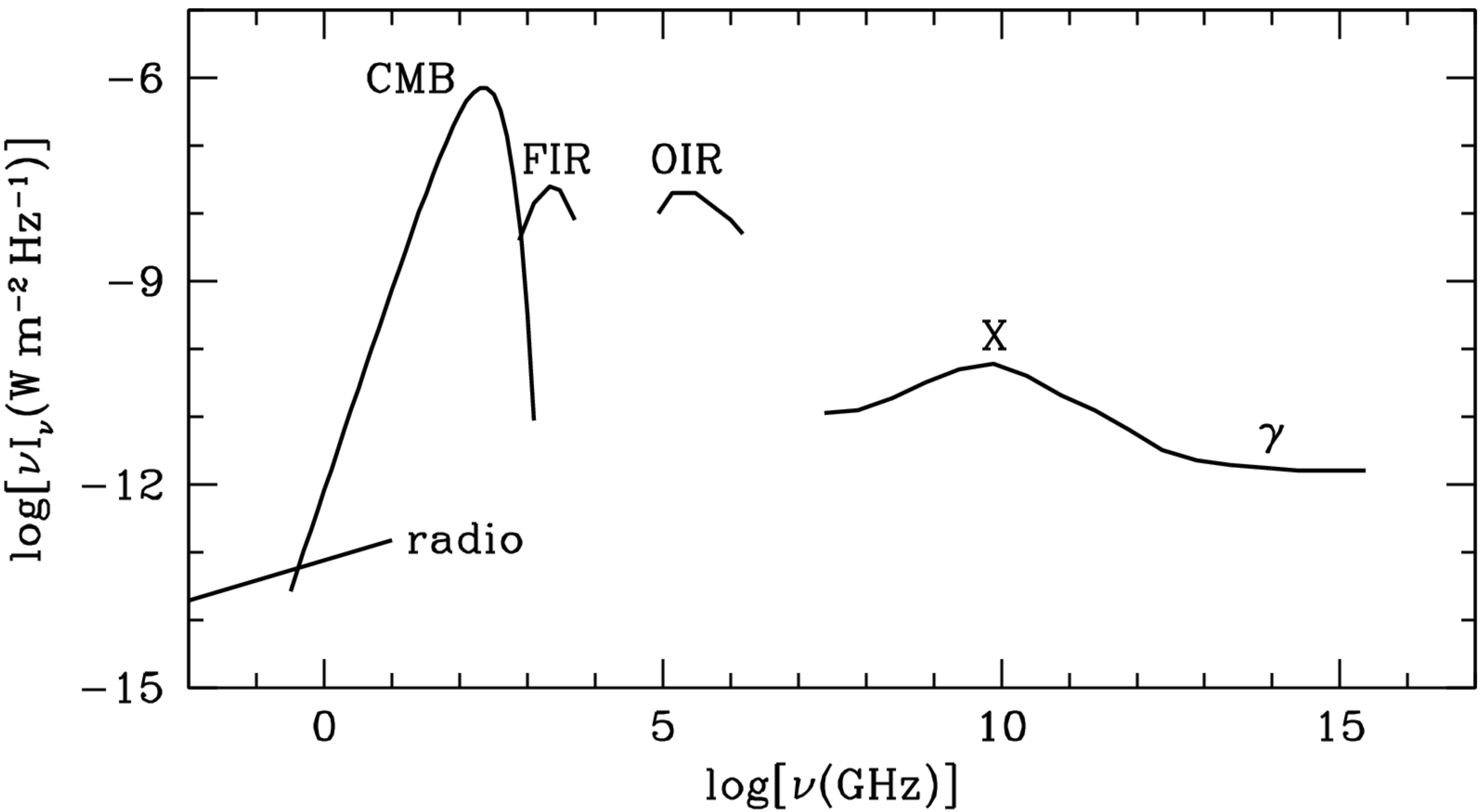
What is special about long wavelengths?

More specific

- The dusty interstellar medium (ISM) is nearly transparent ($\lambda >> D_{dust}$)
- Cold sources emit most photons at low frequency
  - ~mm photons are very abundant in the spectrum of the universe
  - Abundant cold dust/atomic/molecular emission in (sub)mm band
- Easy to observe high-redshift galaxies in sub-mm

~mm photons are very abundant in the spectrum of the universe

The electromagnetic spectrum of the universe



Spectral line forest in molecular cloud (~230 GHz)

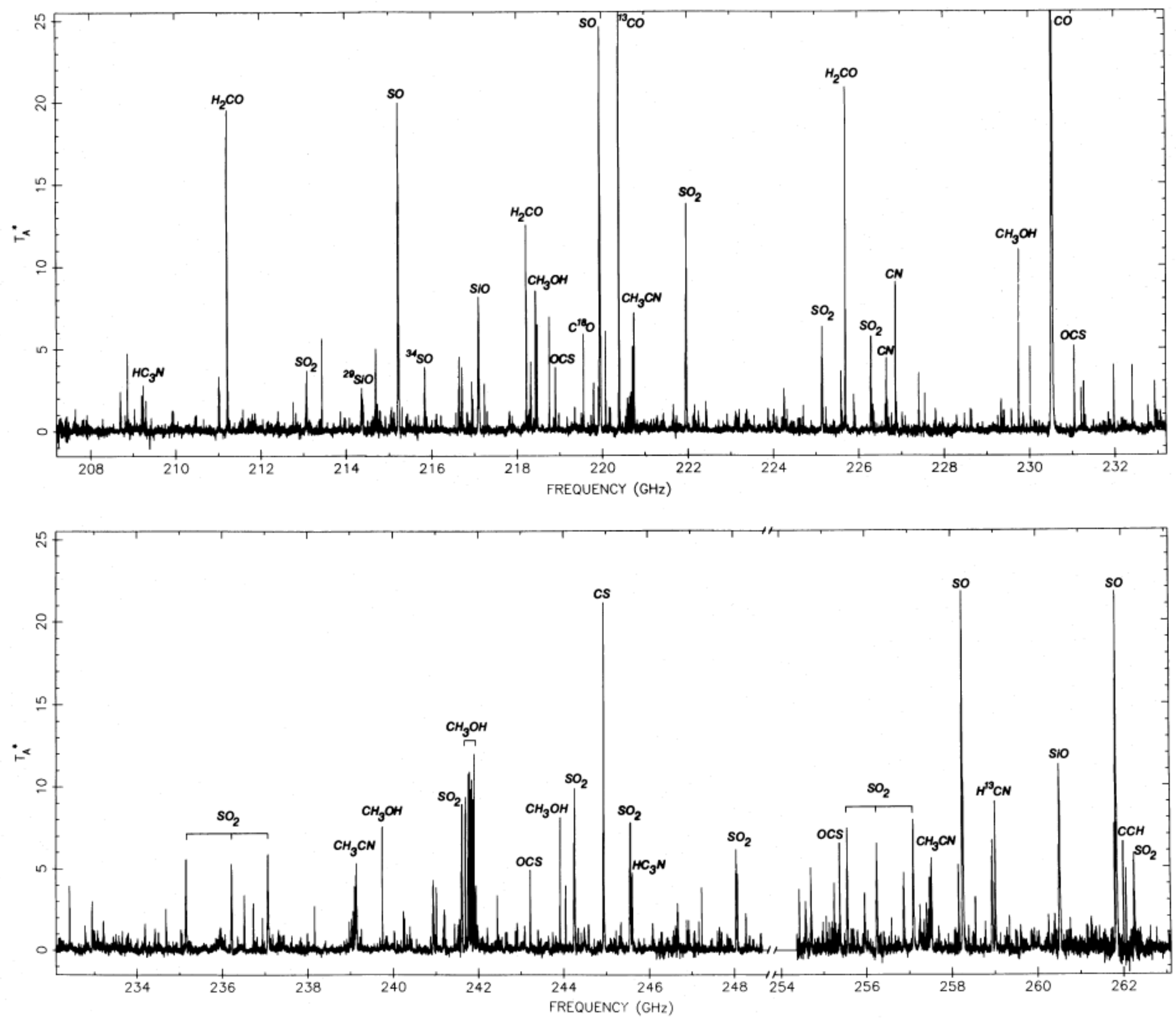


FIG. 1.—Compressed view of the OVRO spectral line survey of OMC-1

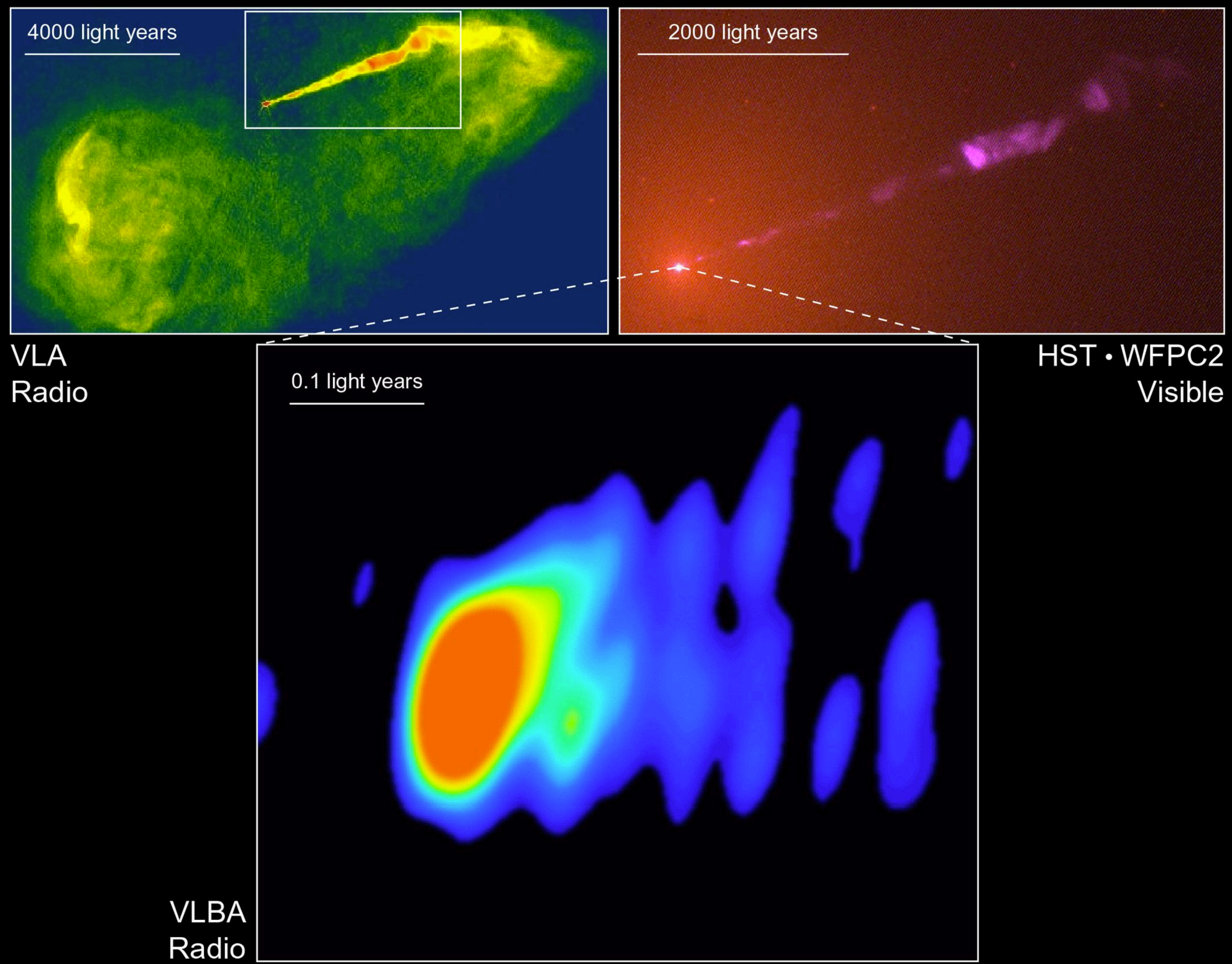
What is special about long wavelengths?

<u>Discoveries</u>: It revealed a “parallel universe”

- The violent universe of SMBHs (Quasar)
- Emission from cool interstellar gas (HI, OH, CO)
- The cosmic microwave background (CMB)
- Neutron stars (Pulsar)
- Cosmological evolution
- Nonthermal radiation
- Aperture Synthesis (interferometry)
- Maser
- ……

- Radio astronomy is no longer a separate and distinct field, it is part of multi-wavelength astronomy.
- Retains unique astronomical and technical features

Galaxy M87



NASA, NRAO and J. Biretta (STScI) • STScI-PRC99-43

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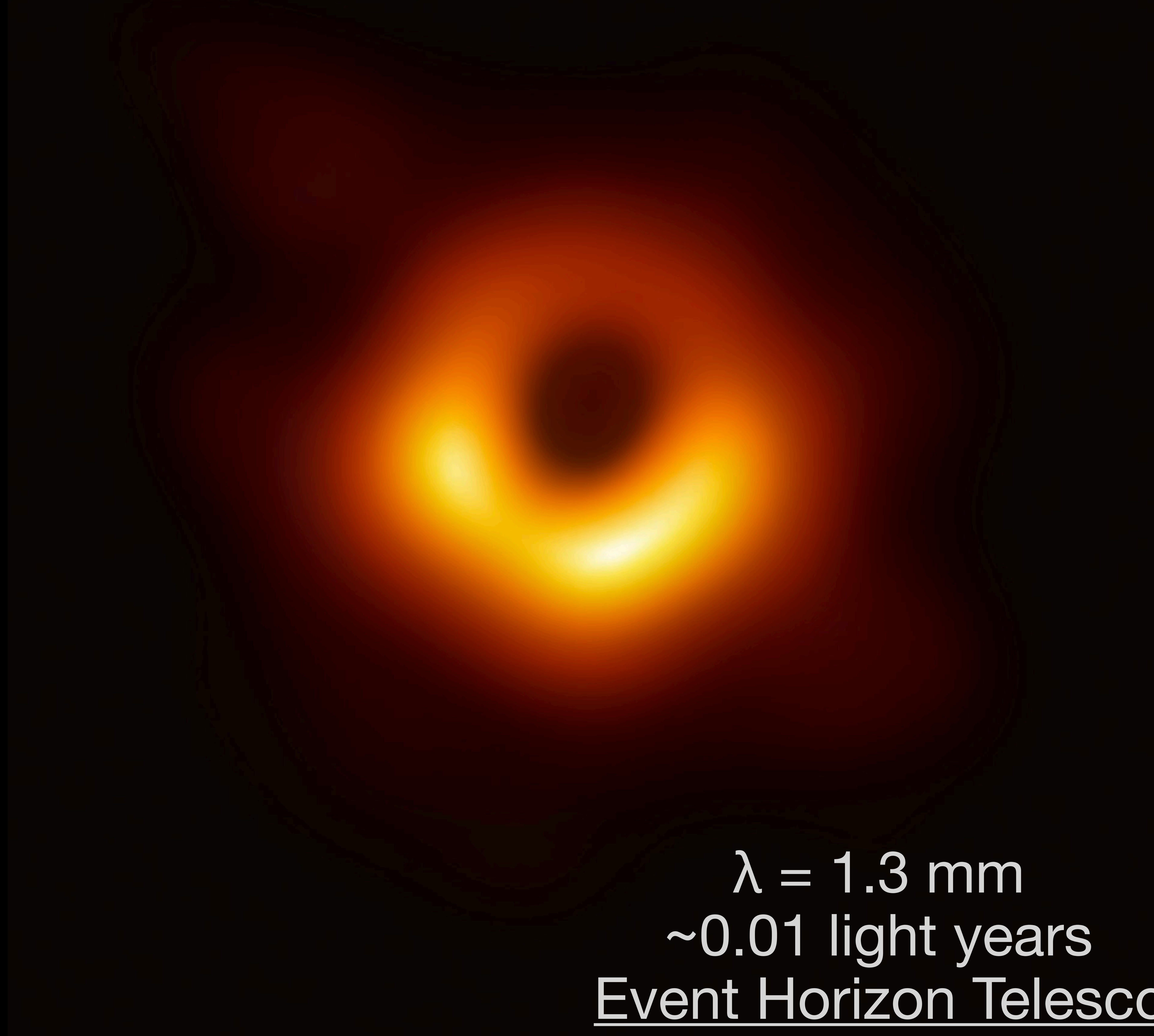

λ = 1.3 mm
~0.01 light years
Event Horizon Telescope

Some sub-mm Telescopes

- 1964: Haystack 37-m tel. (λ>6mm)
- 1965: Green Bank 140ft telescope (λ>6mm)
- 1969: Kitt Peak 36'/12m telescope (λ>1mm)
- 1970: Effelsberg 100m telescope (λ>3mm)
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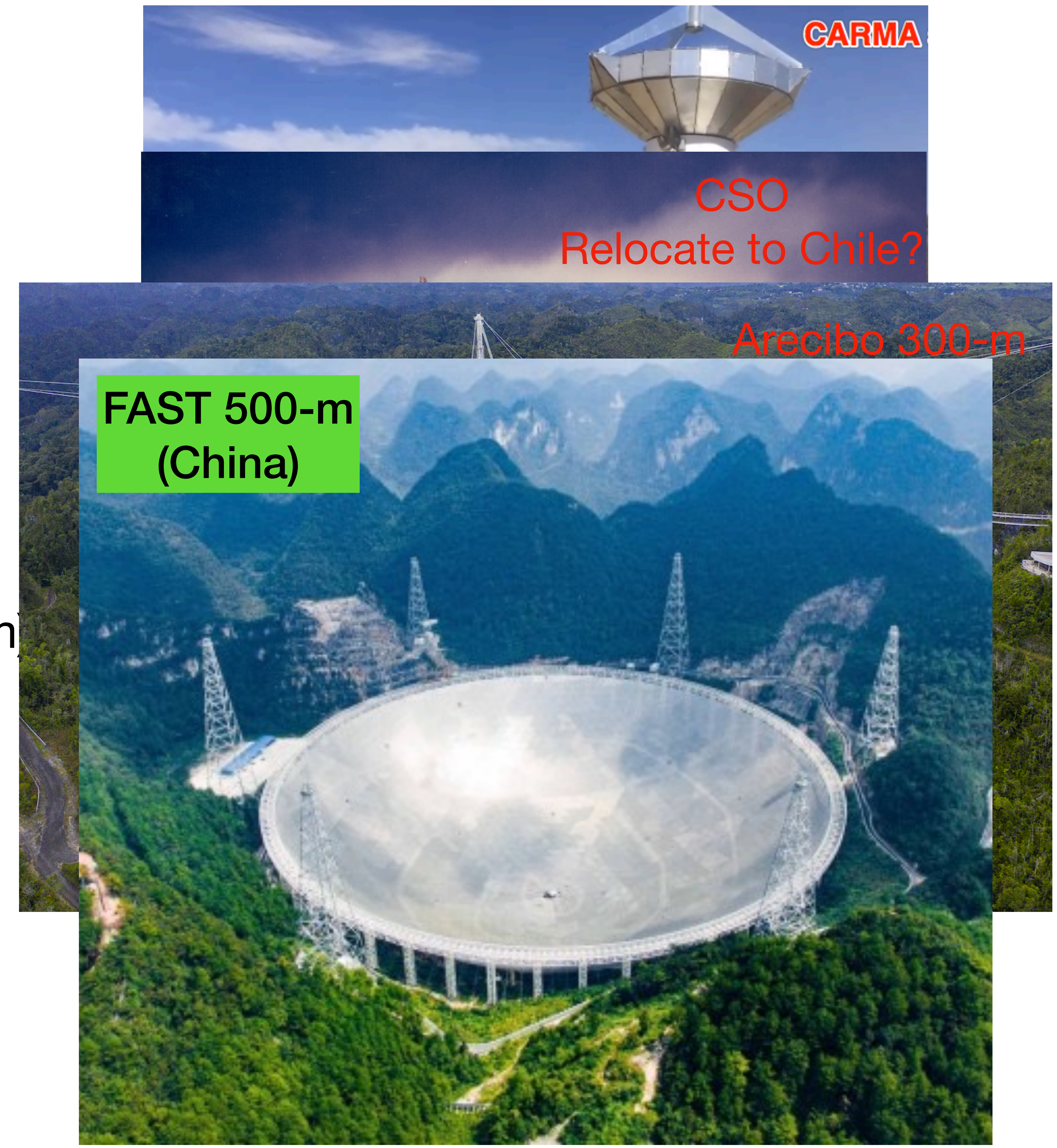

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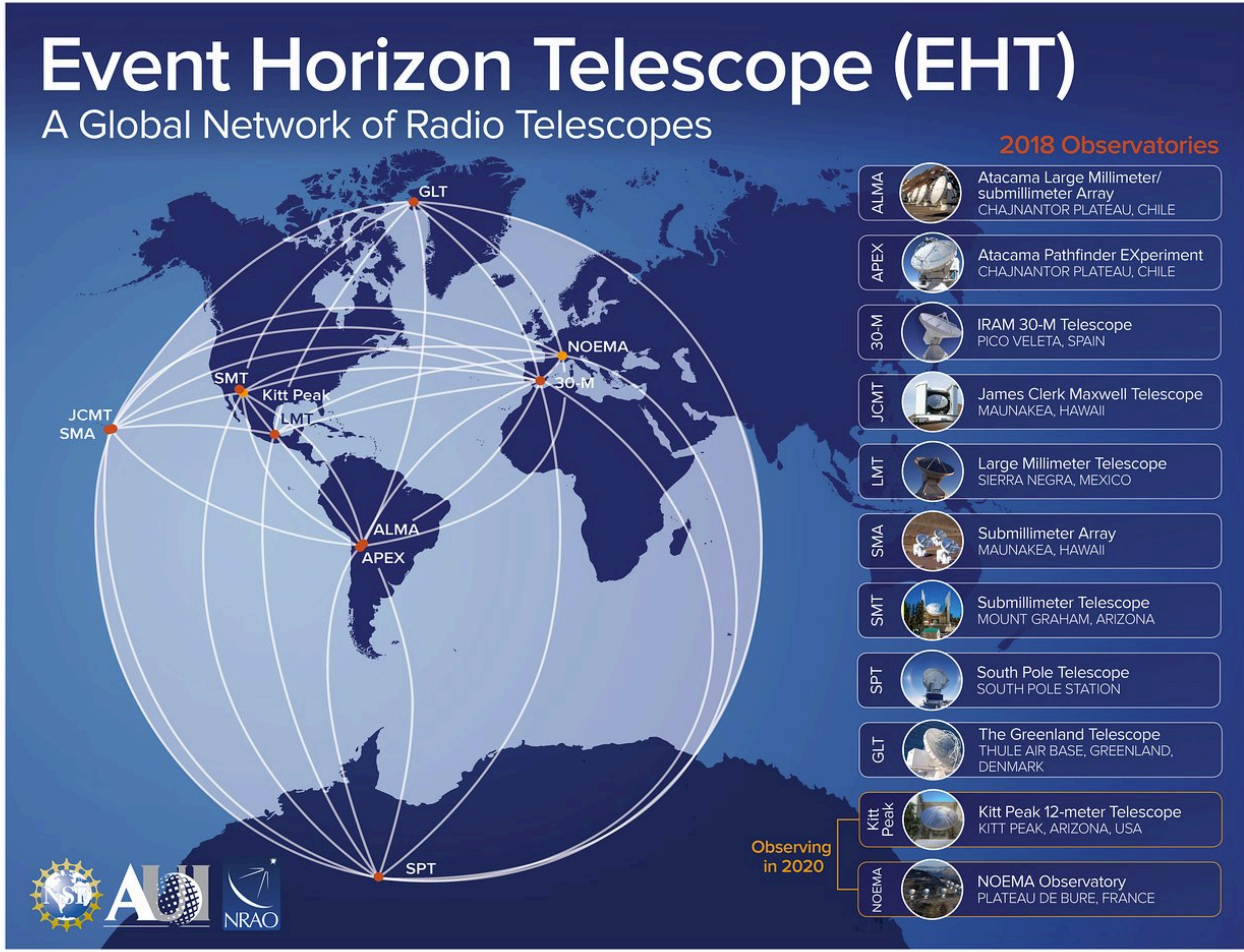
- FUTURE?

Telescopes evolve!

Telescopes evolve!

- More in low freq:
  LOFAR
  SKA (ASKAP, MeerKAT)
  JVLA
  …



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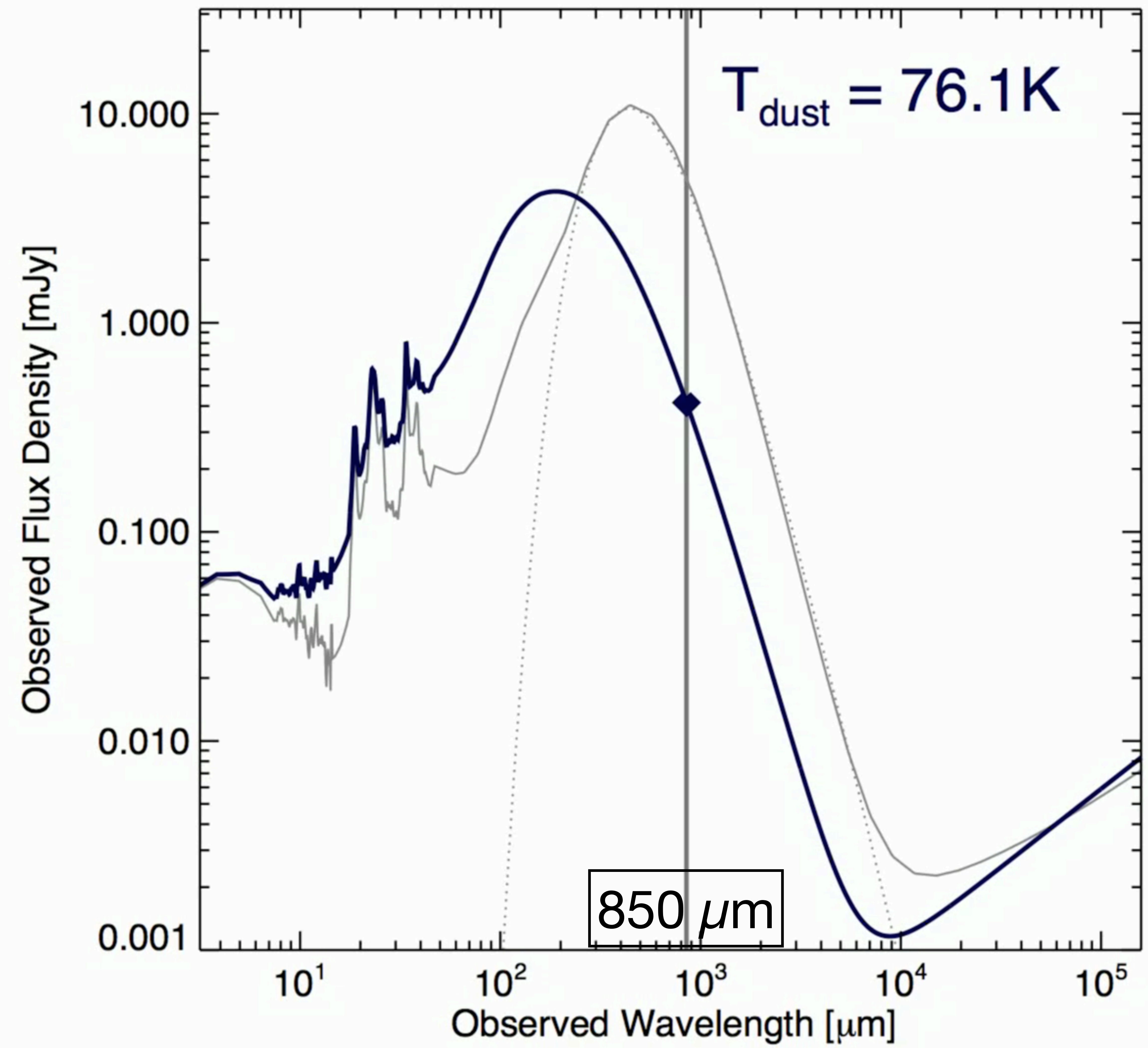
Radio Emission Mechanisms

Thermal emission - continuum

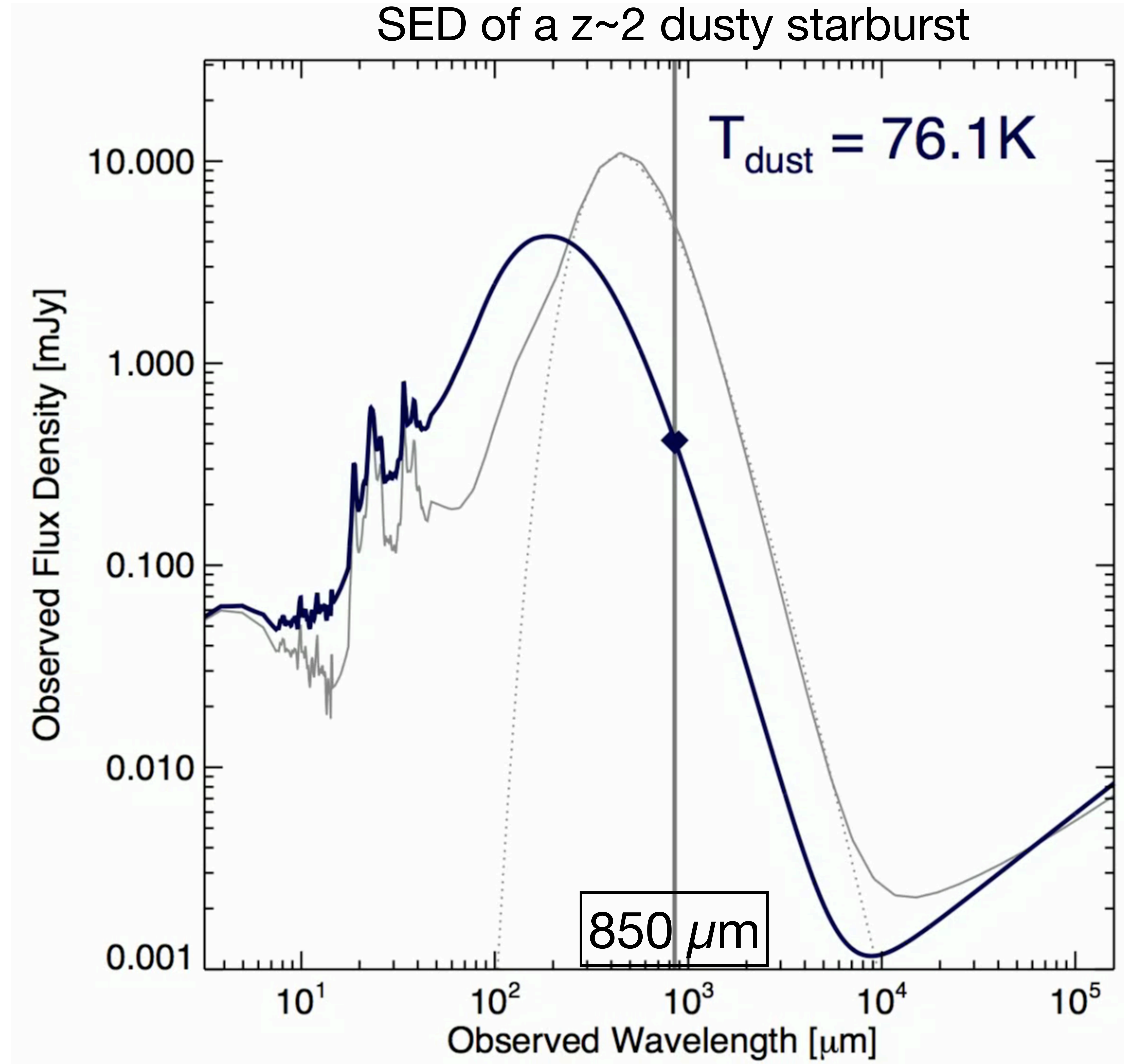


CAITLIN M. CASEY

Radio Emission Mechanisms

Thermal emission - continuum

- Red lava - hot enough to radiate at visible wavelengths!
- Colder things still glow, but at longer wavelengths / lower frequencies, including in the sub-mm



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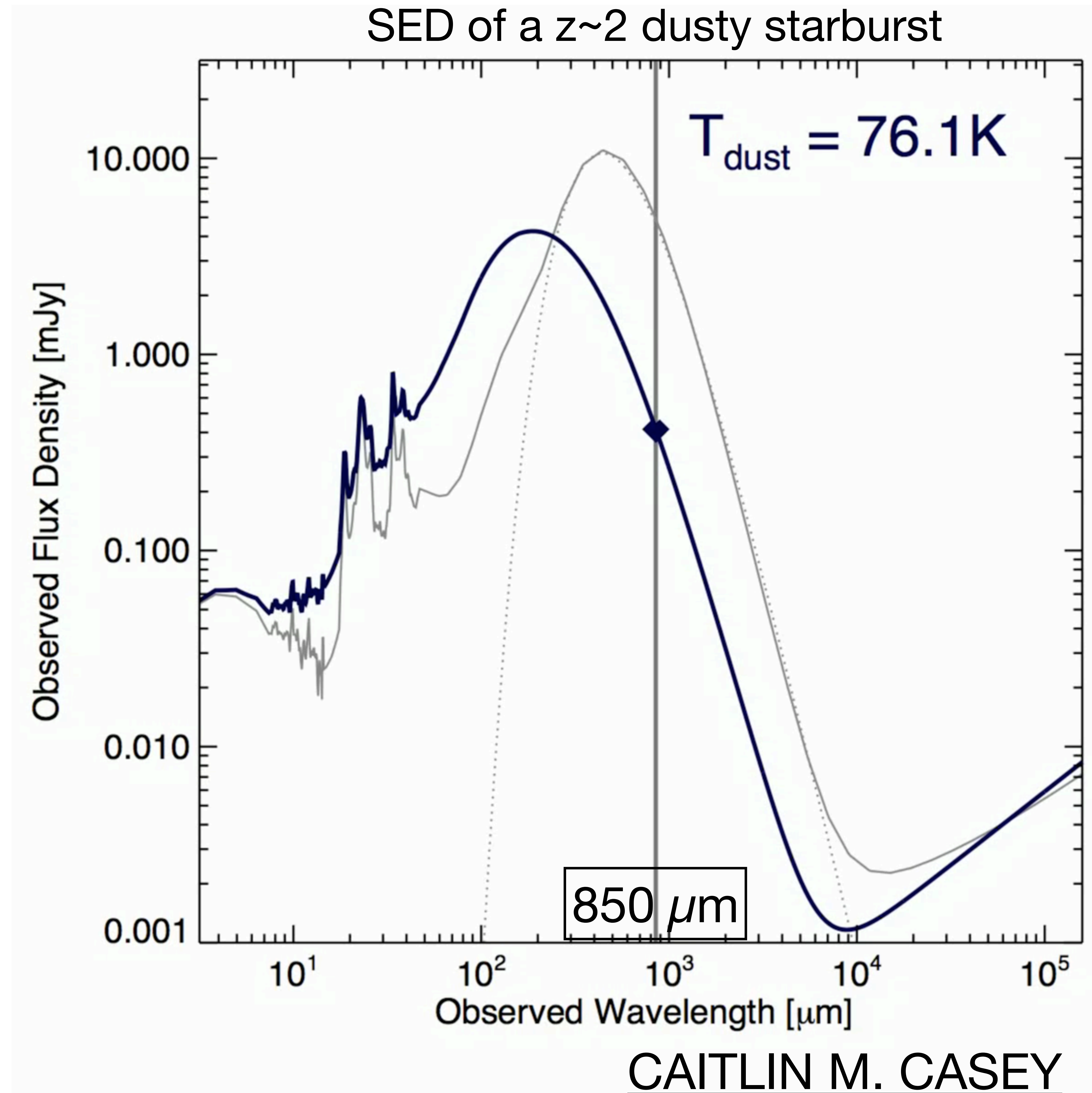
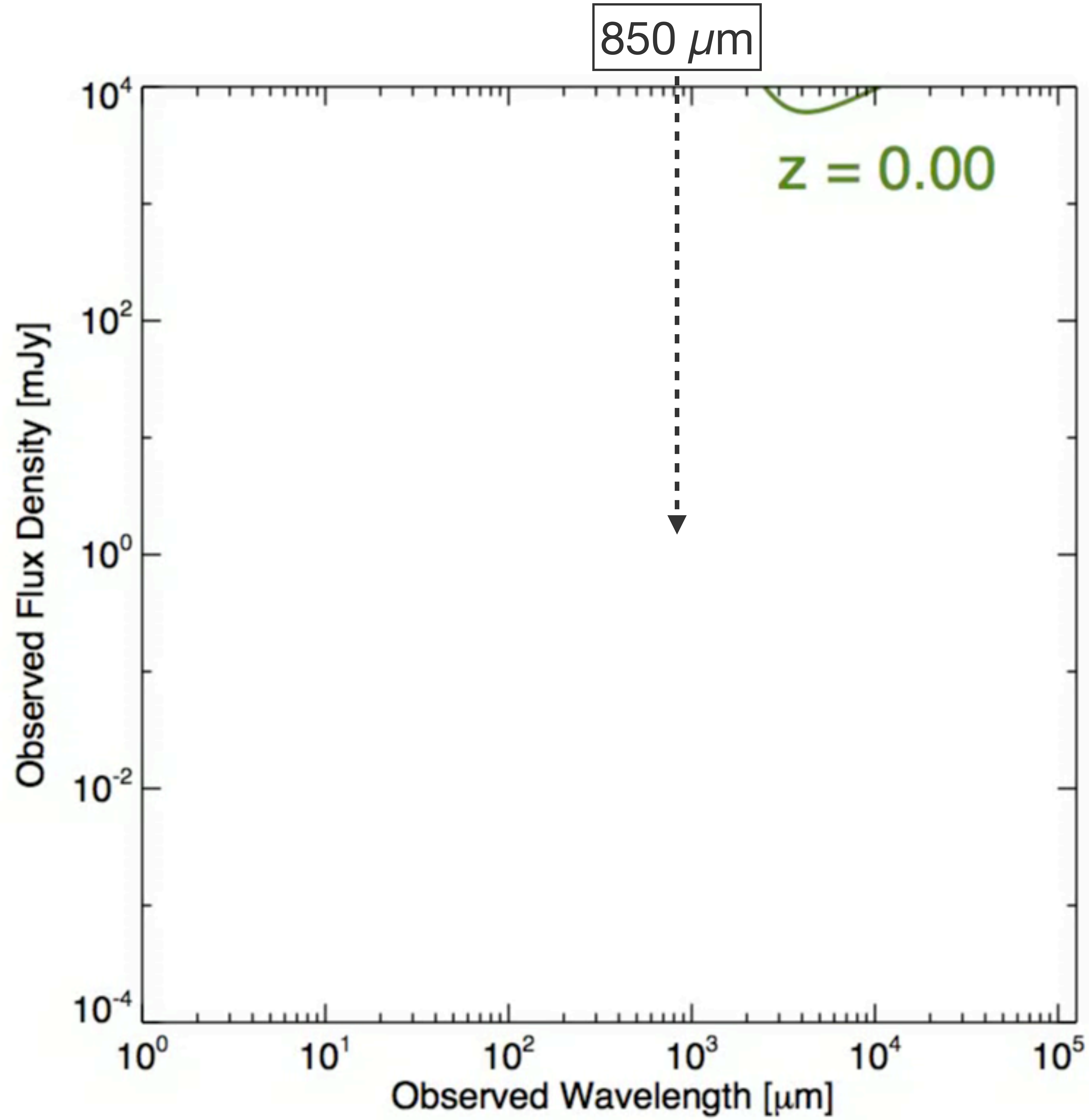


Radio Emission Mechanisms

Easy to observe high-z galaxies in sub-mm (negative k-correction)



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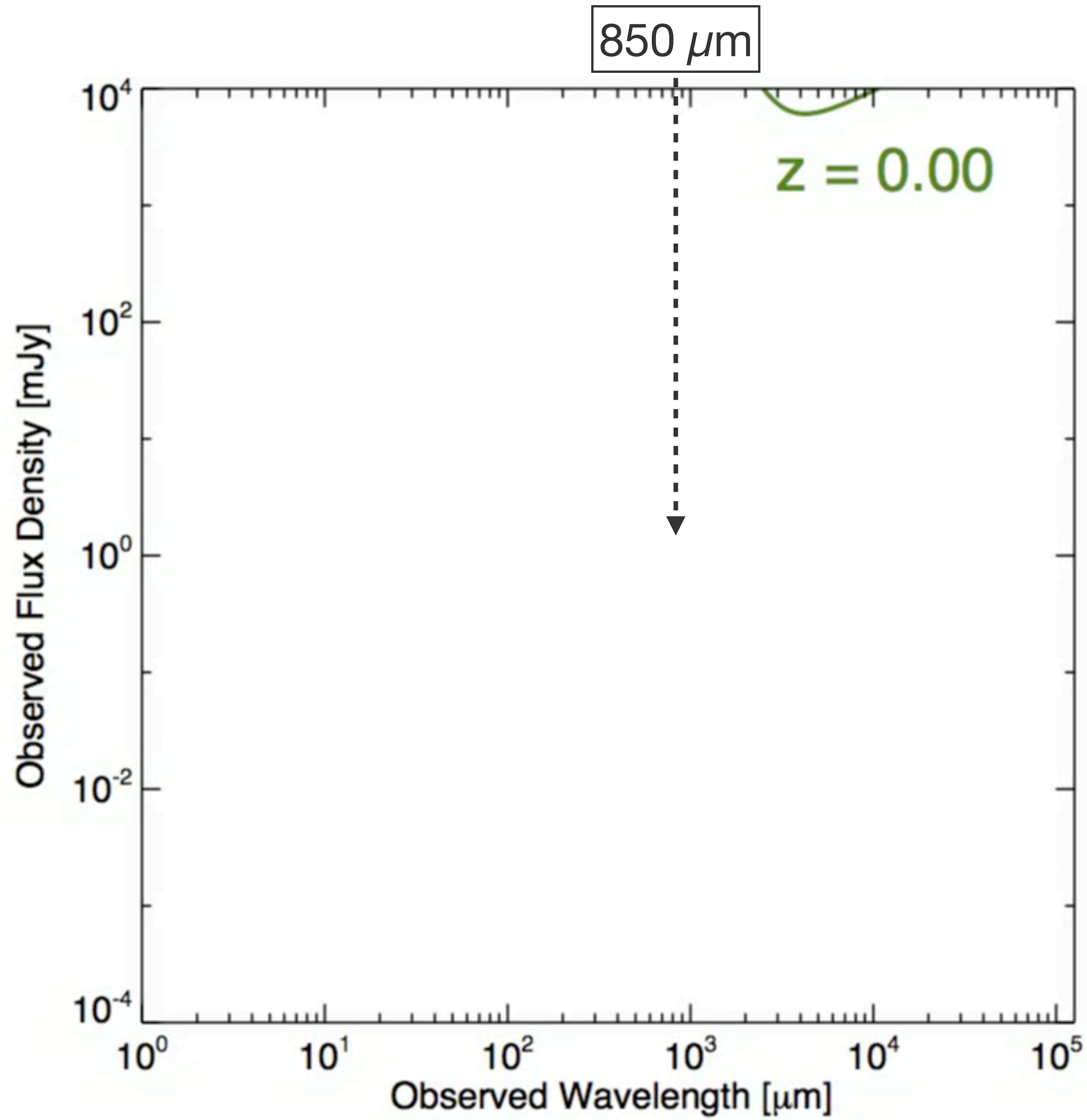

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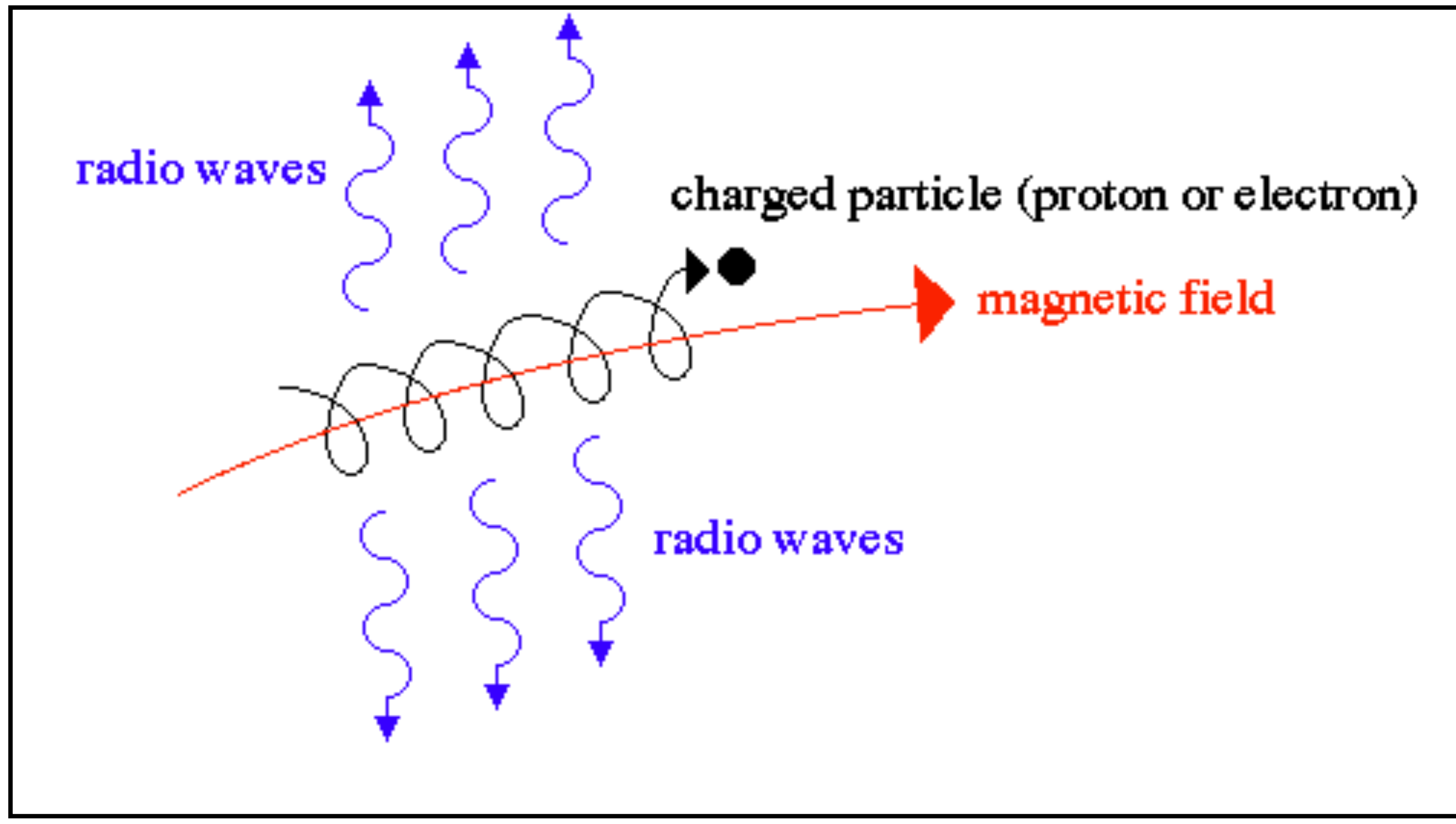
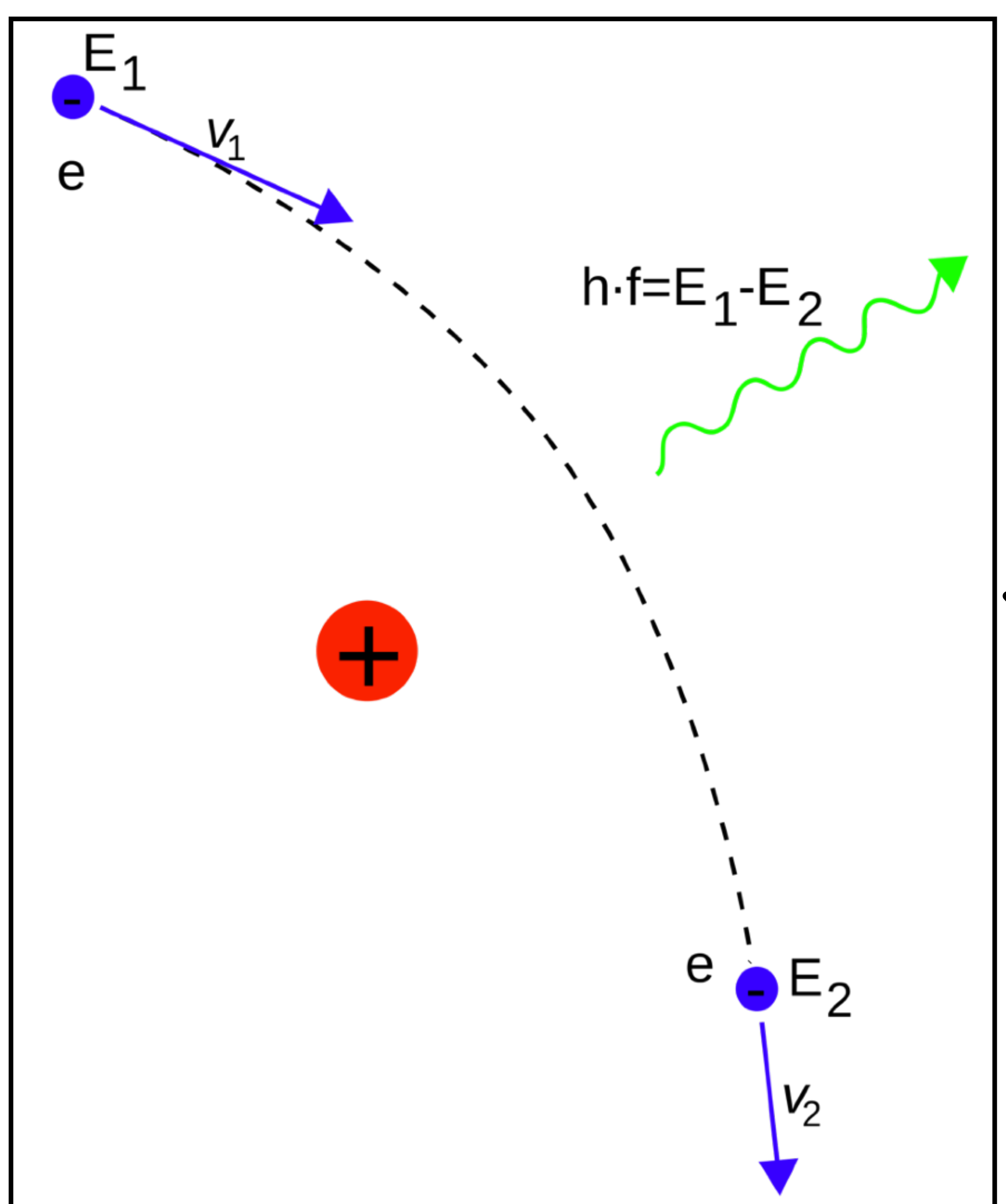
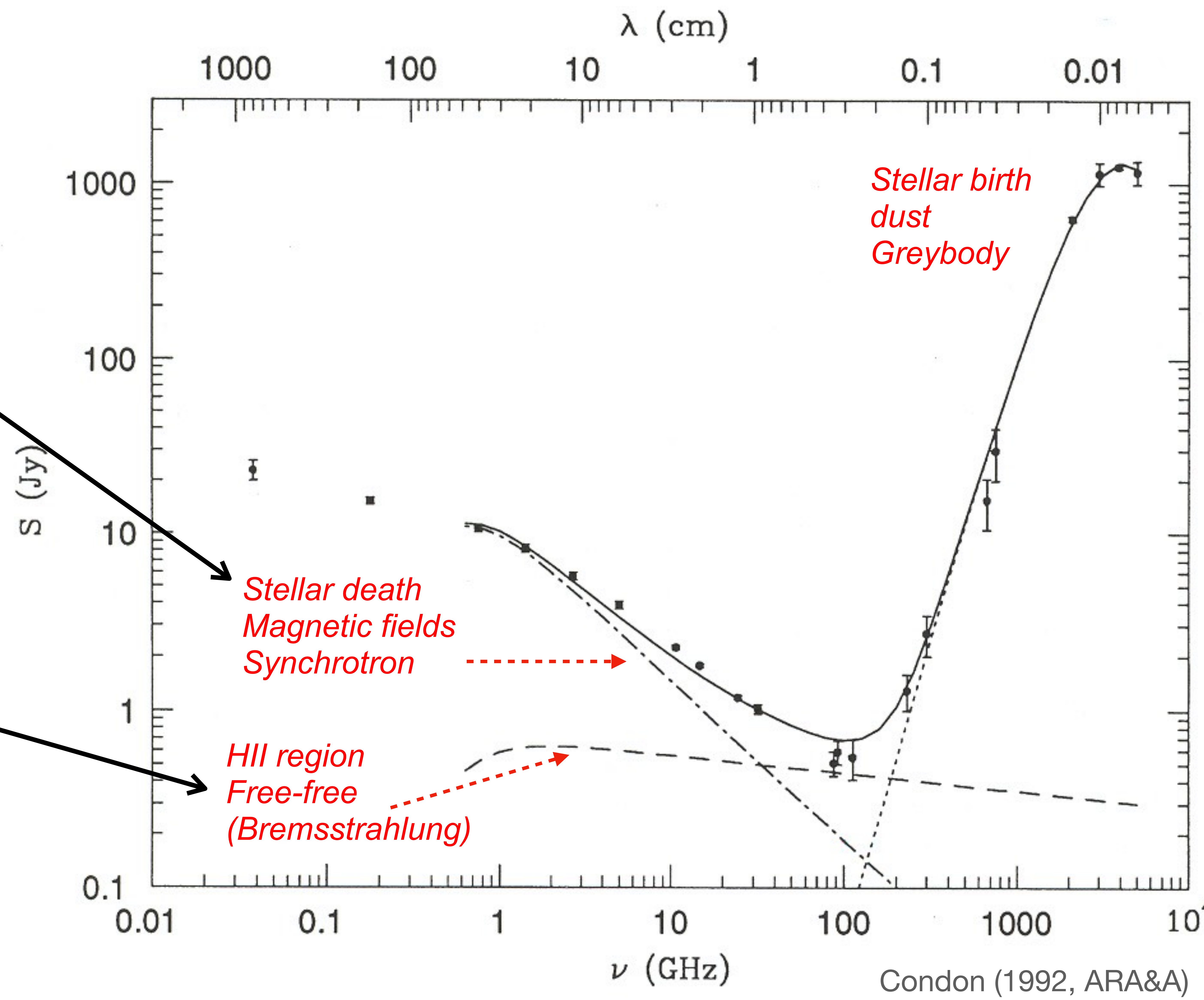
Radio Emission Mechanisms

Greybody, free-free & Synchrotron

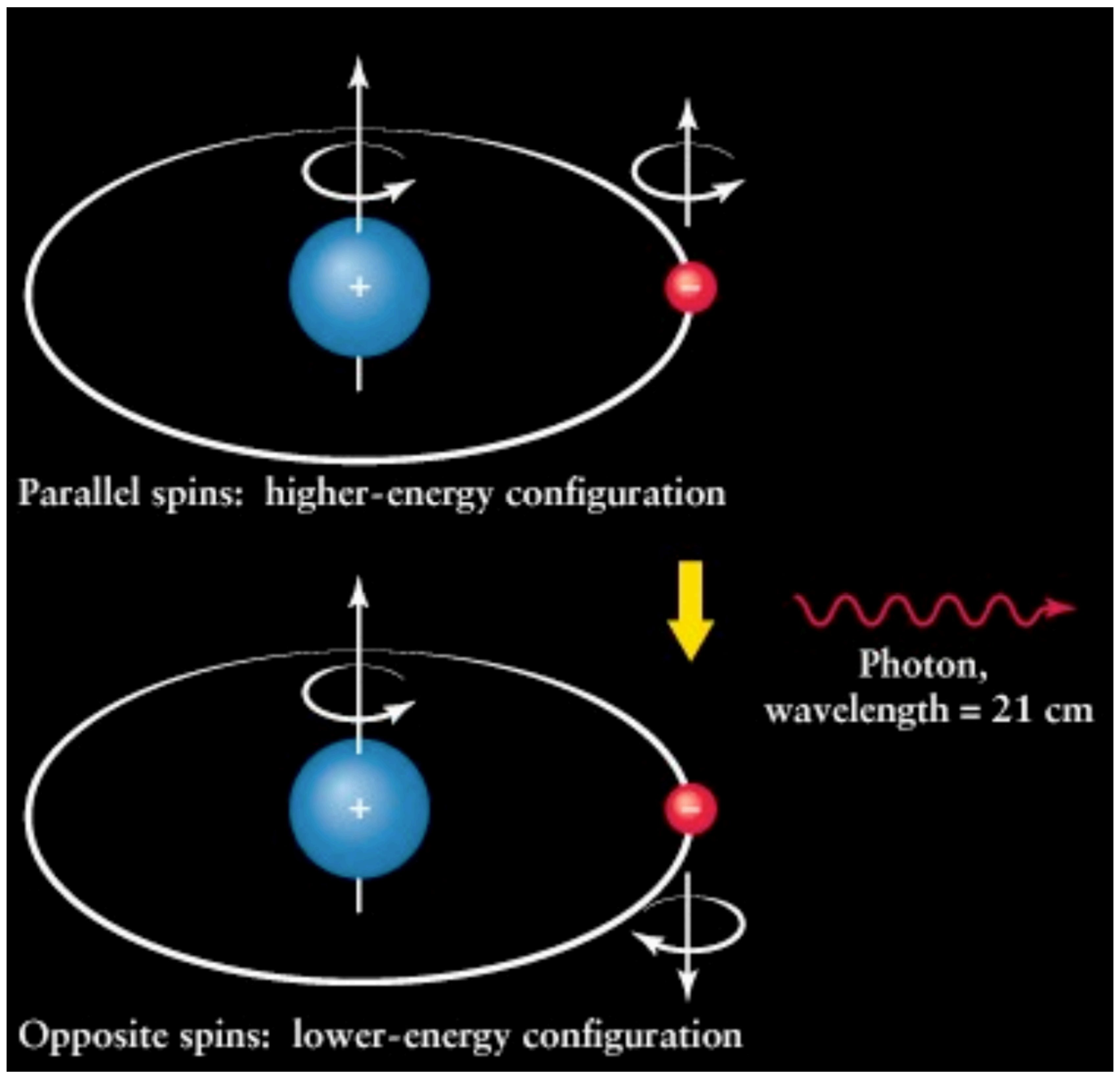


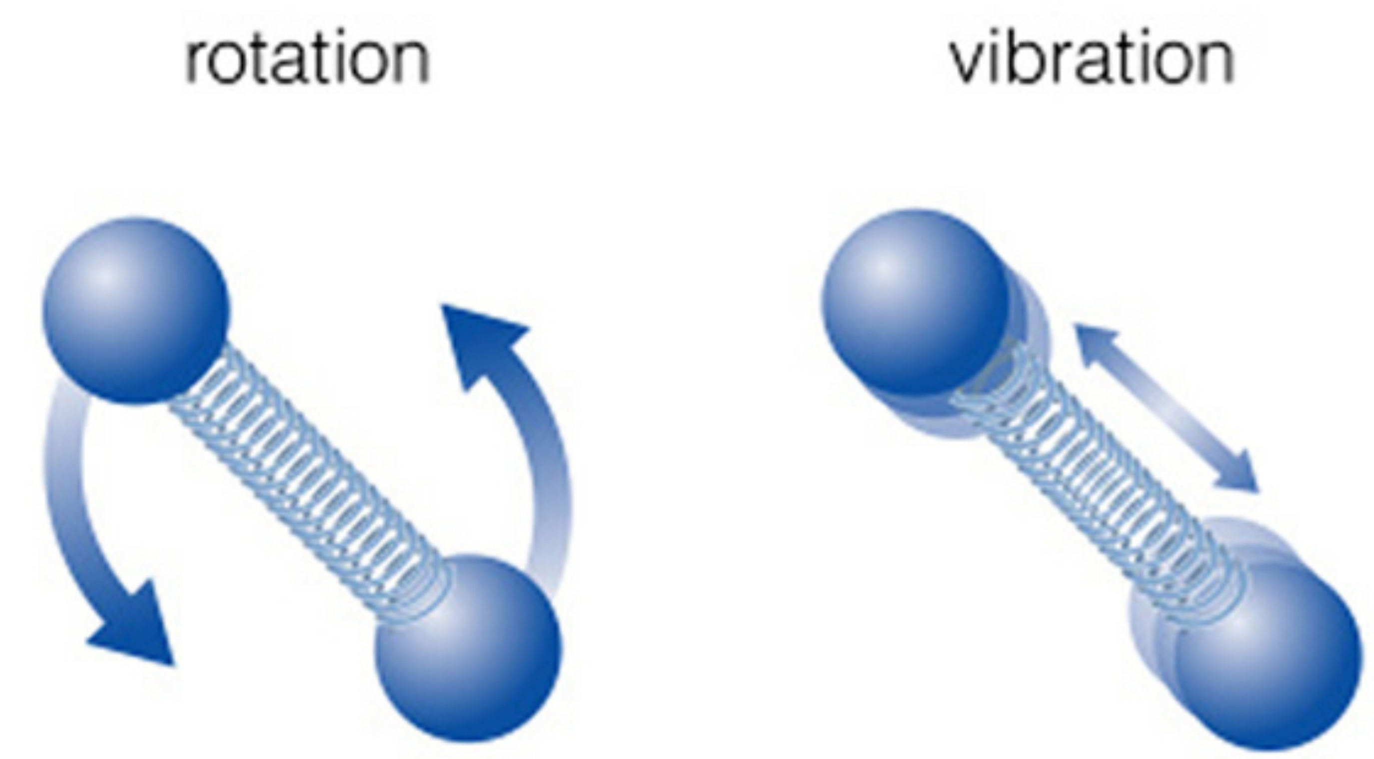




Radio Emission Mechanisms

Spectral line emission

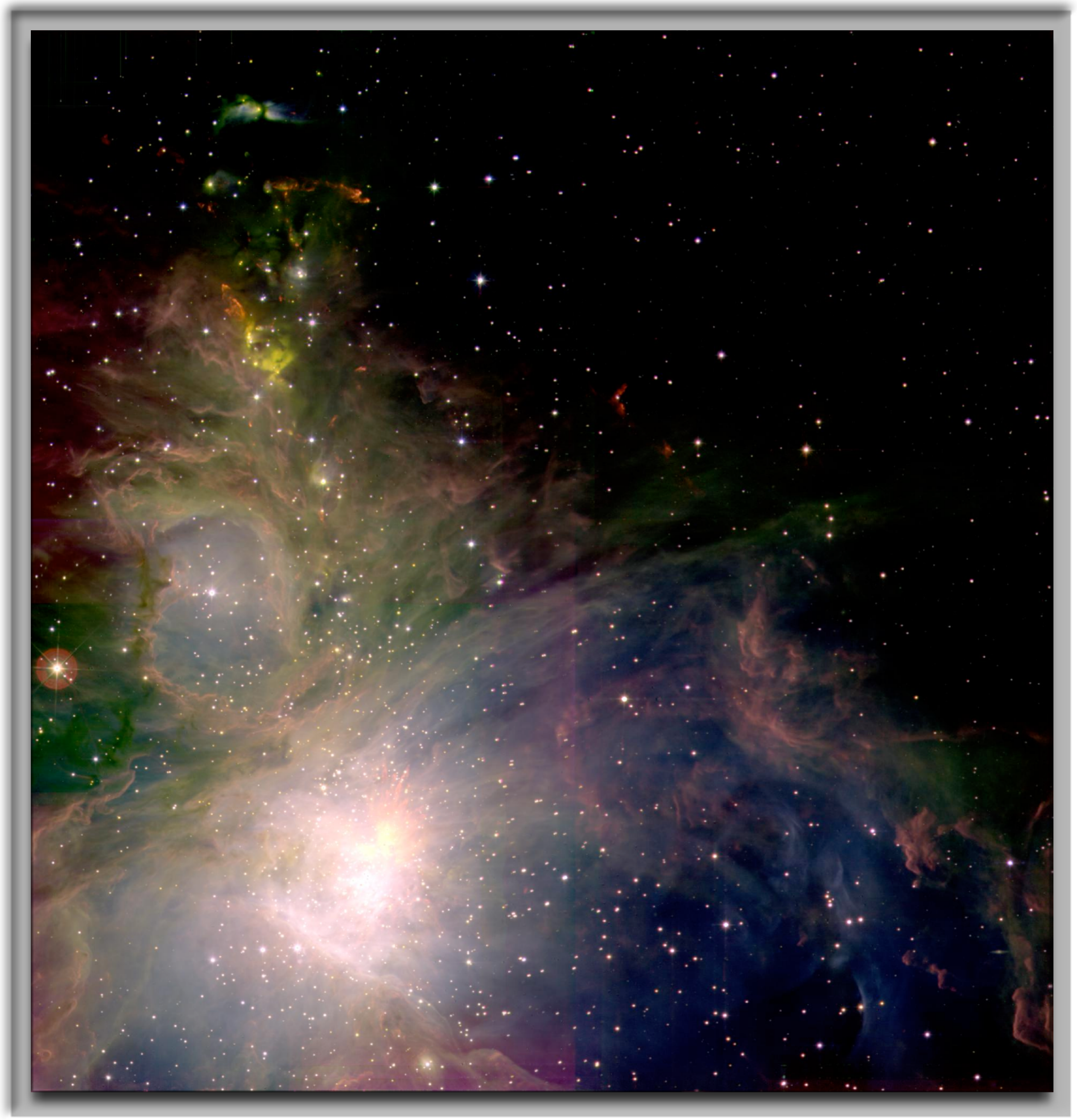




Molecular Lines CO, CS, H_20, SiO, etc.

- gas physical conditions (n, T)
- kinematics (Doppler Effect)

Continuum/spectral lines trace Different phases of ISM



UKIRT / WFCAM

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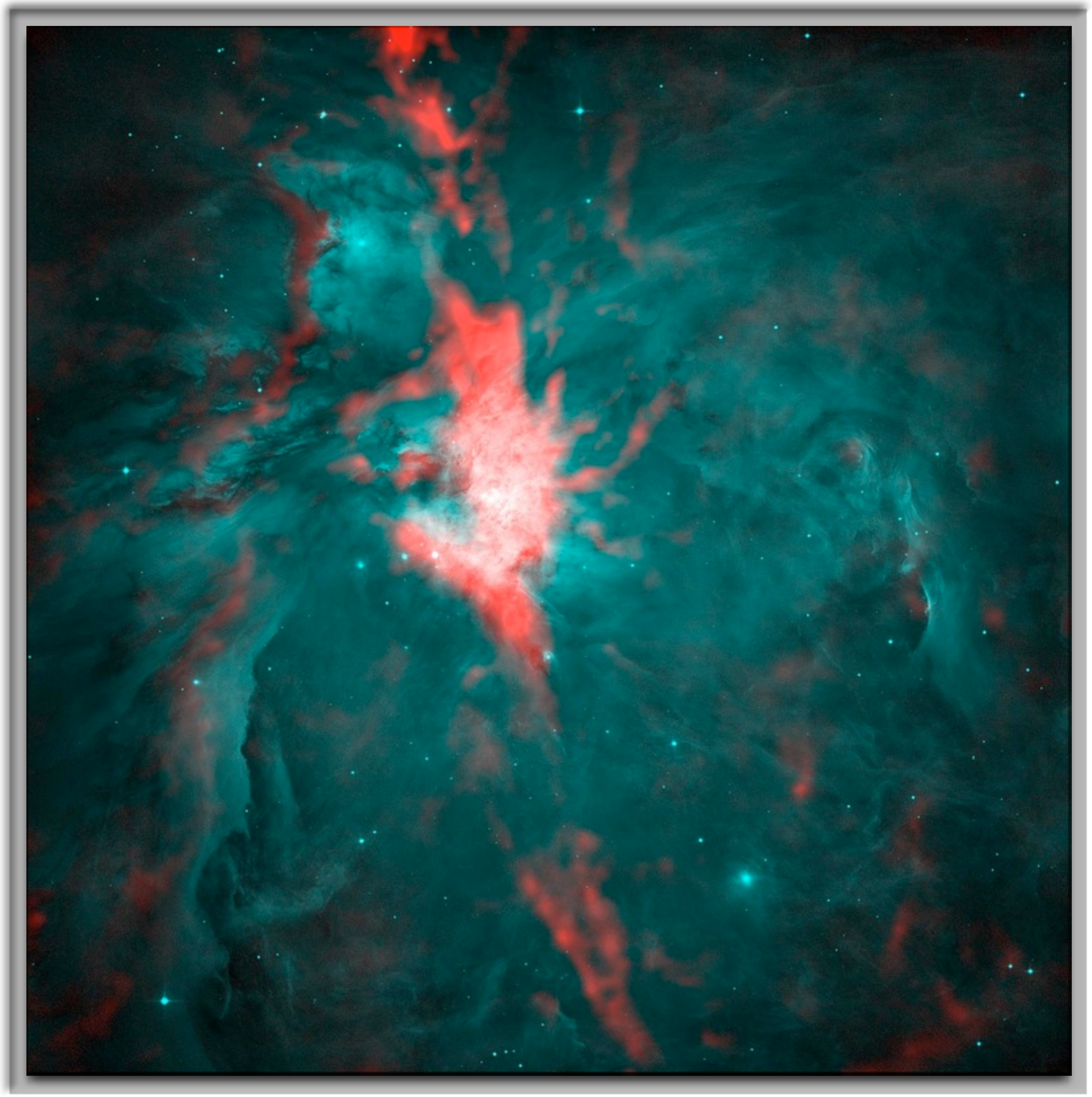
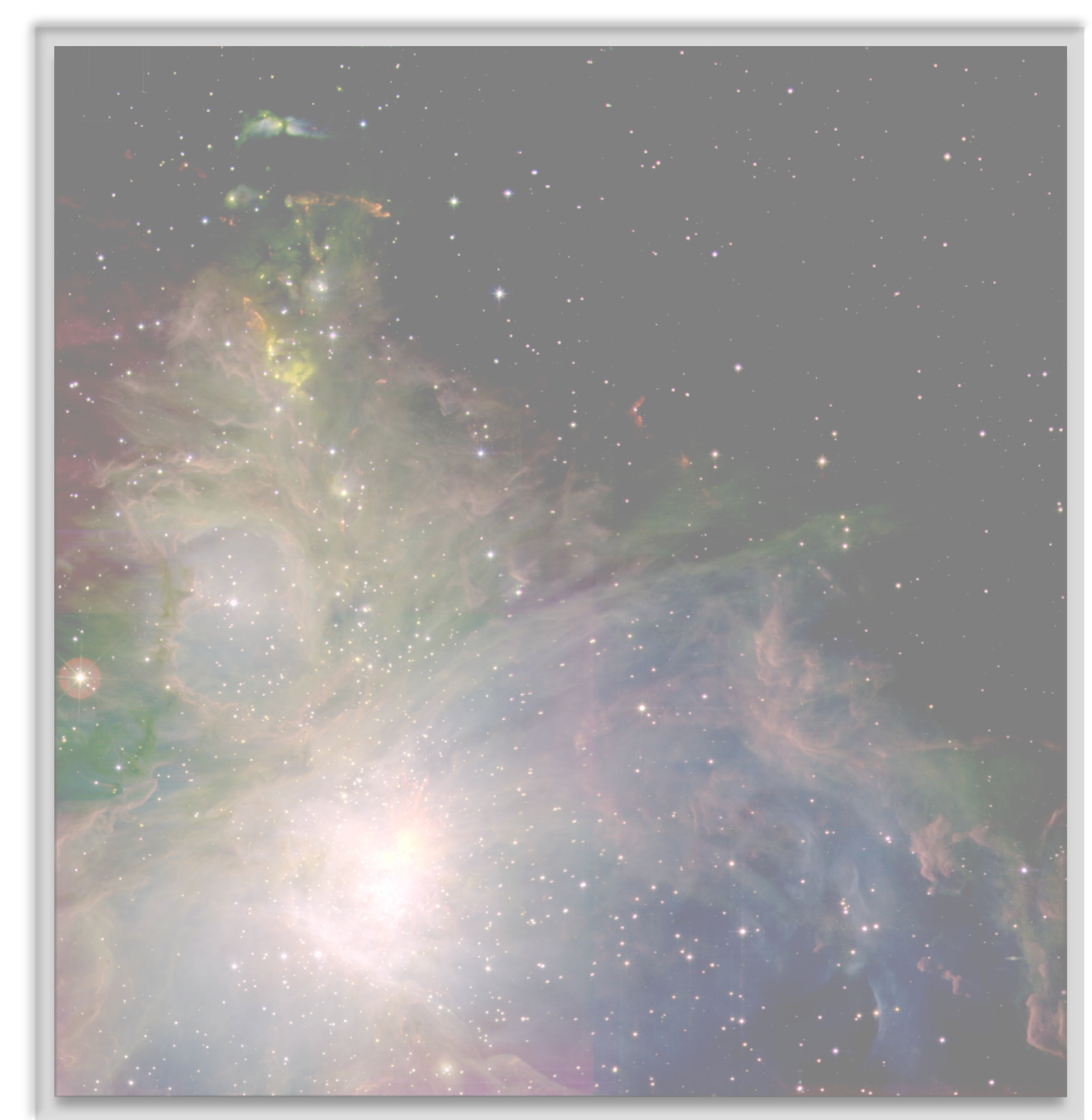


JCMT / SCUBA-2



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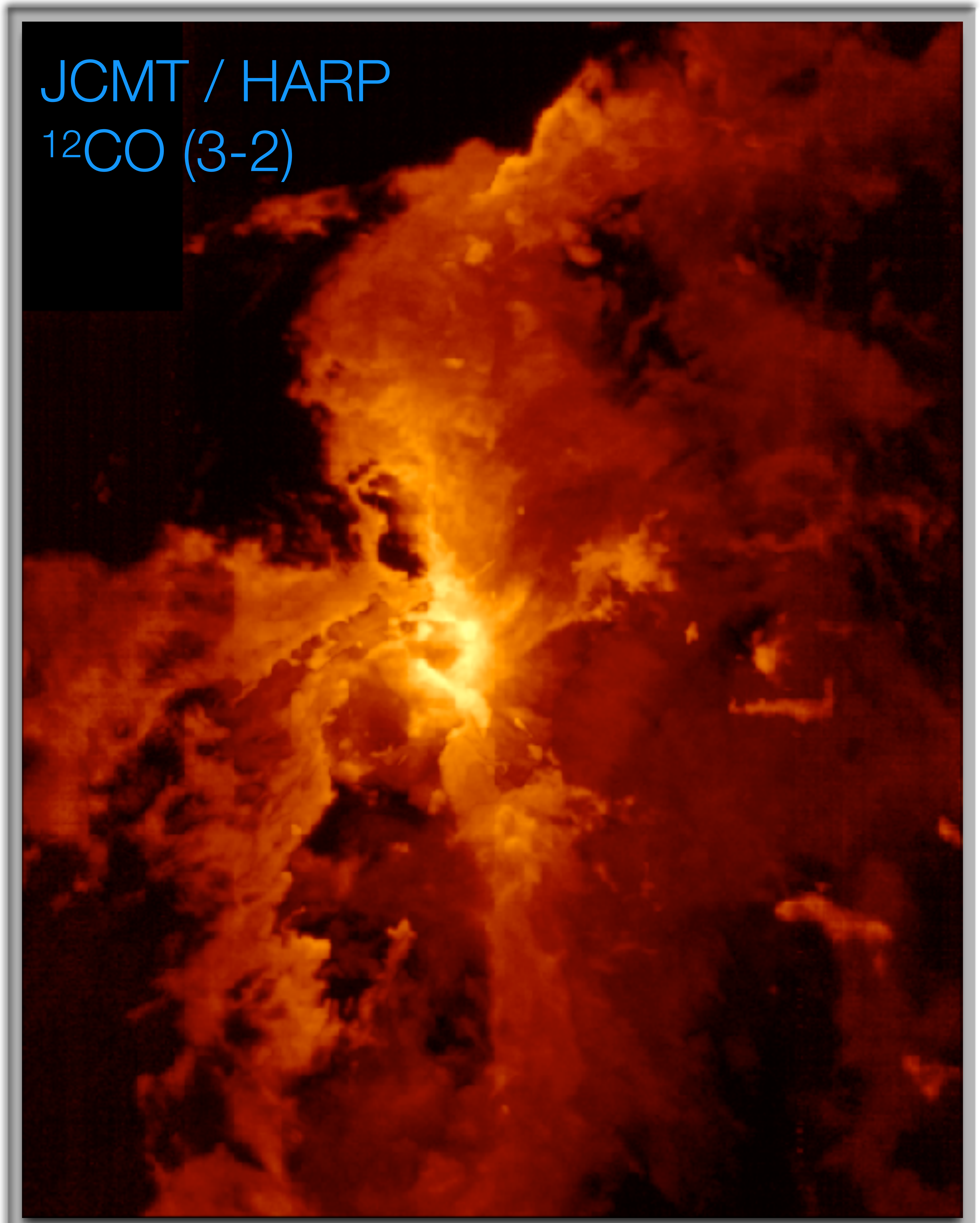

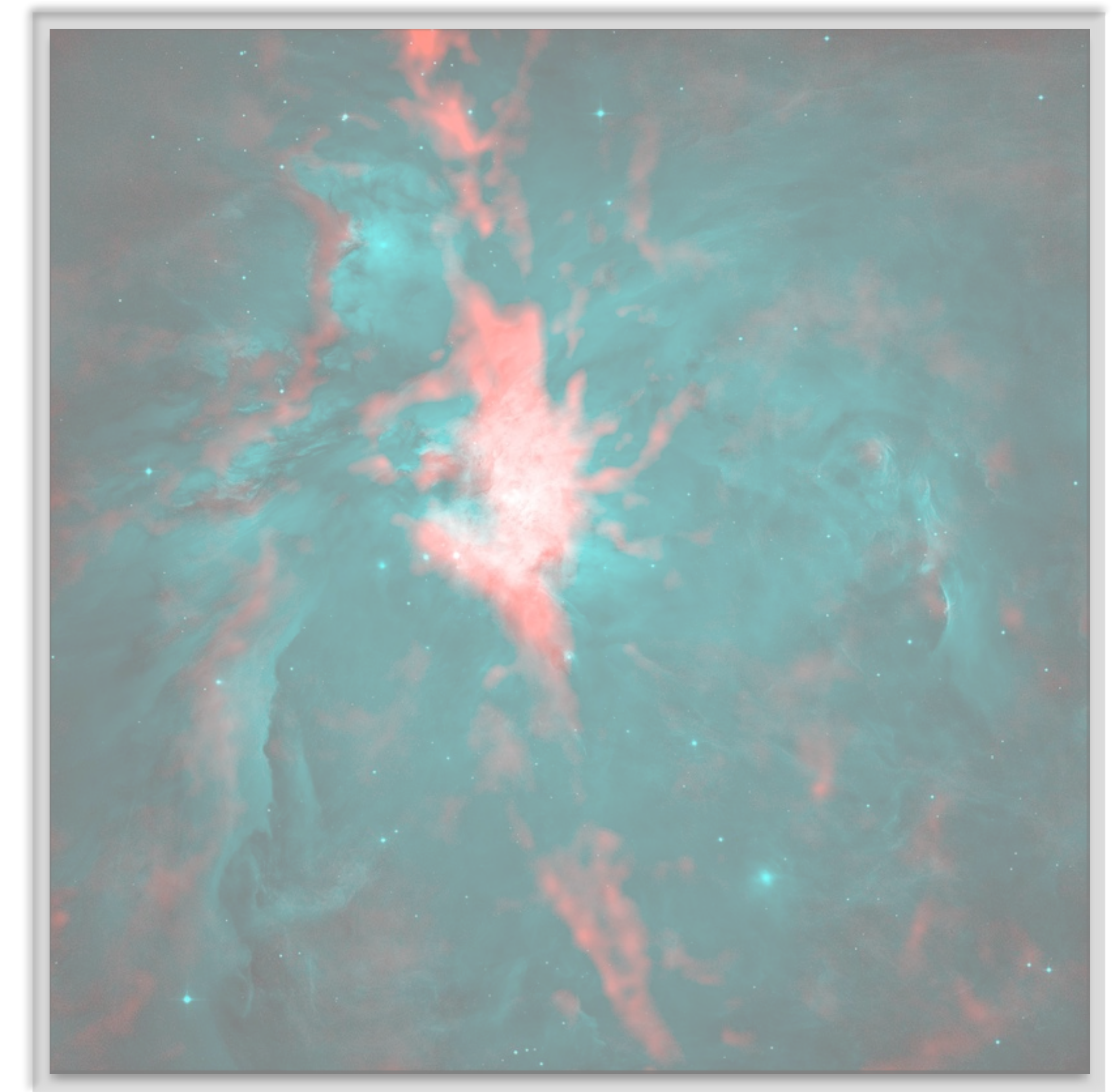

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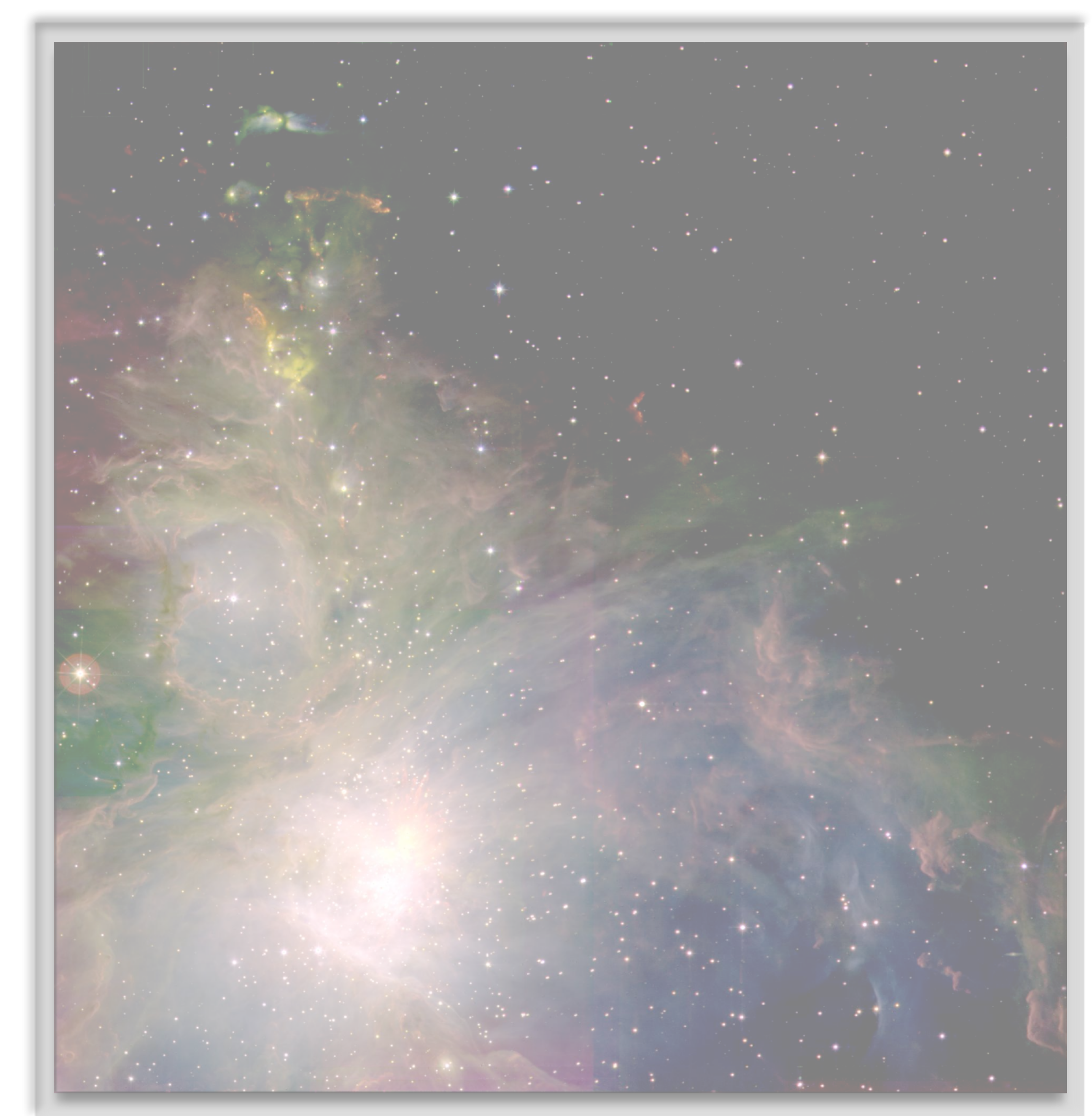

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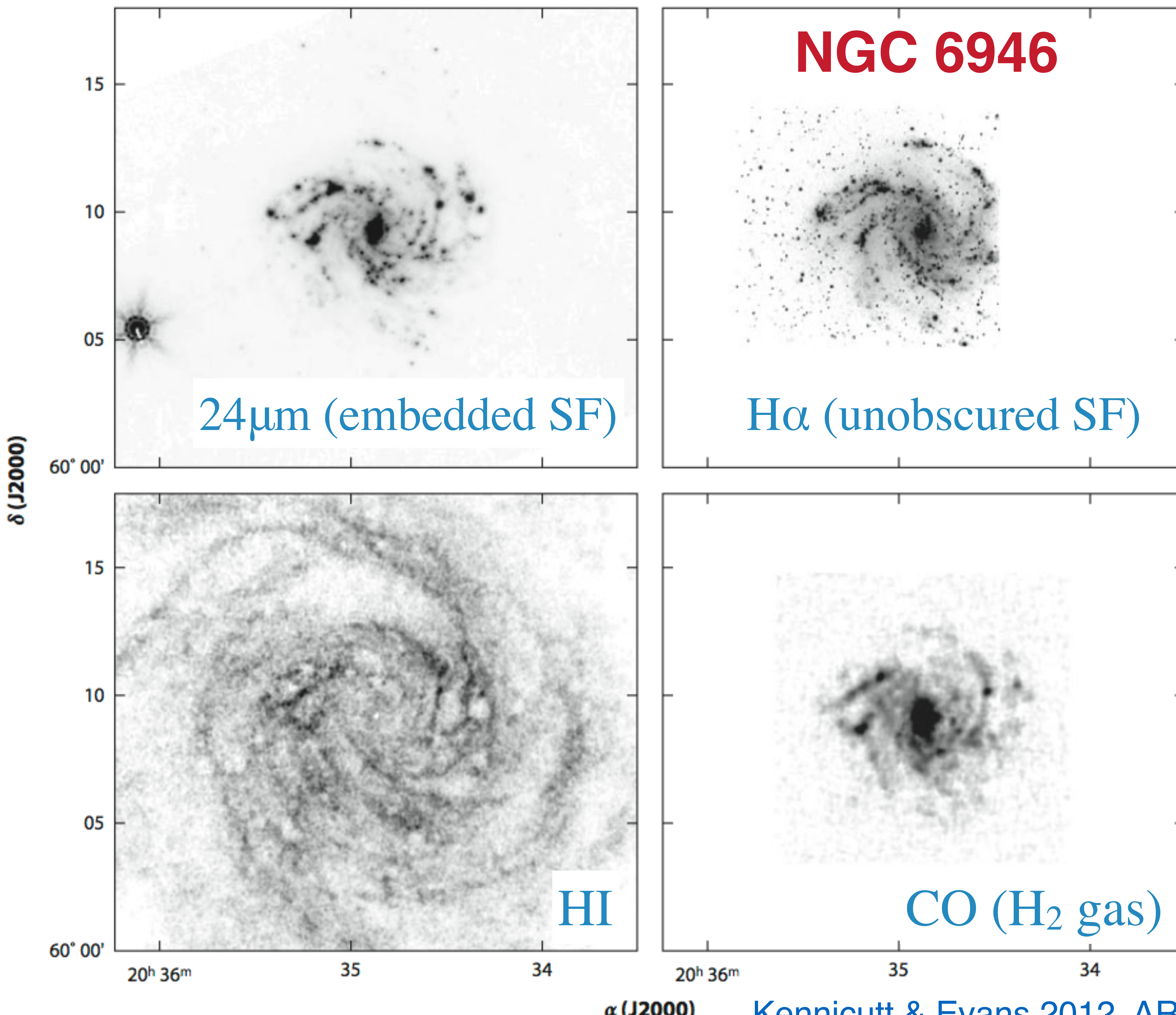


Kennicutt & Evans 2012, ARAA

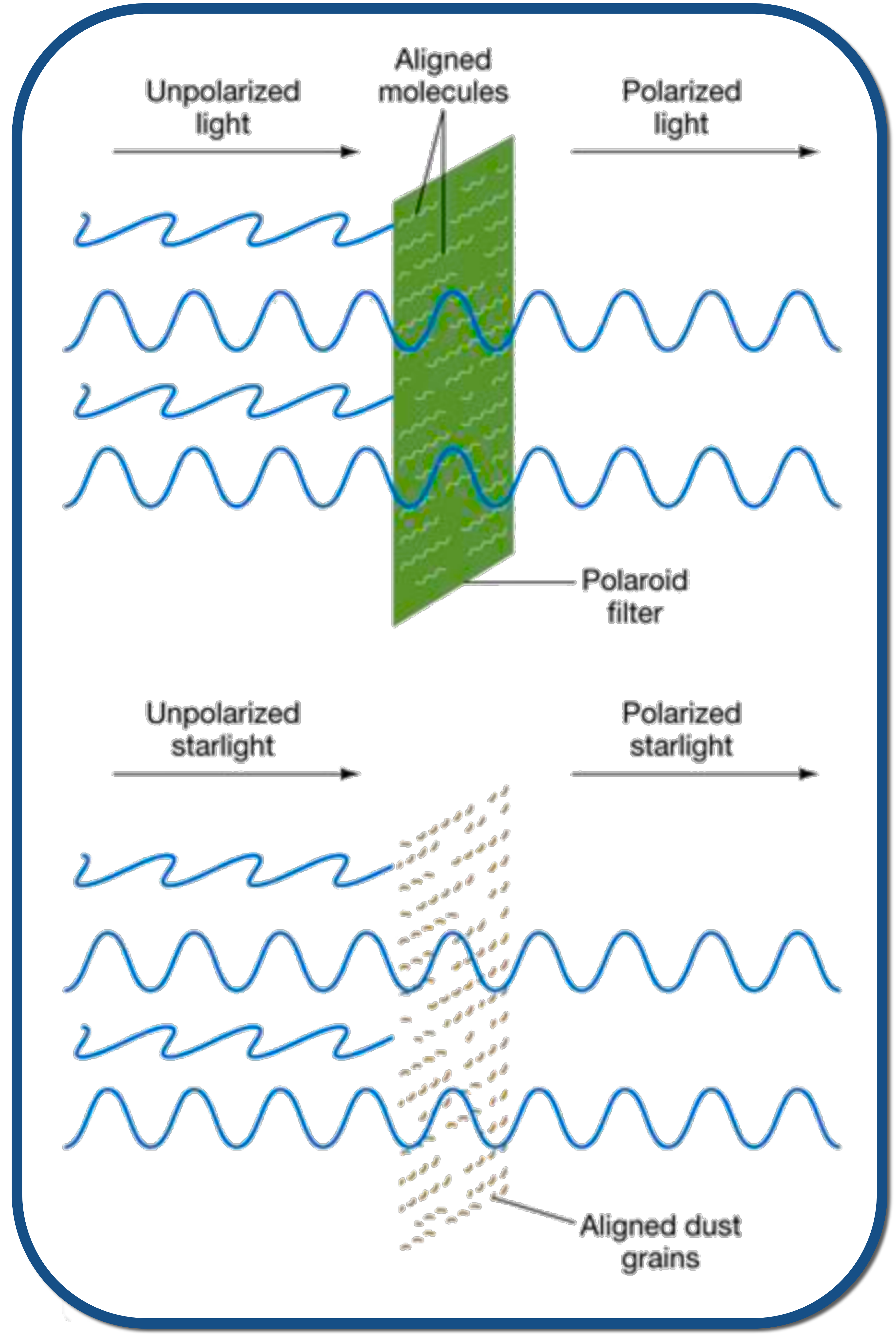
Radio Emission Mechanisms

Polarization

Magnetic Fields Align Non-Spherical Dust Grains…

By looking at polarized light, we can “see” magnetic fields!

True in visible, IR, sub-mm, etc.



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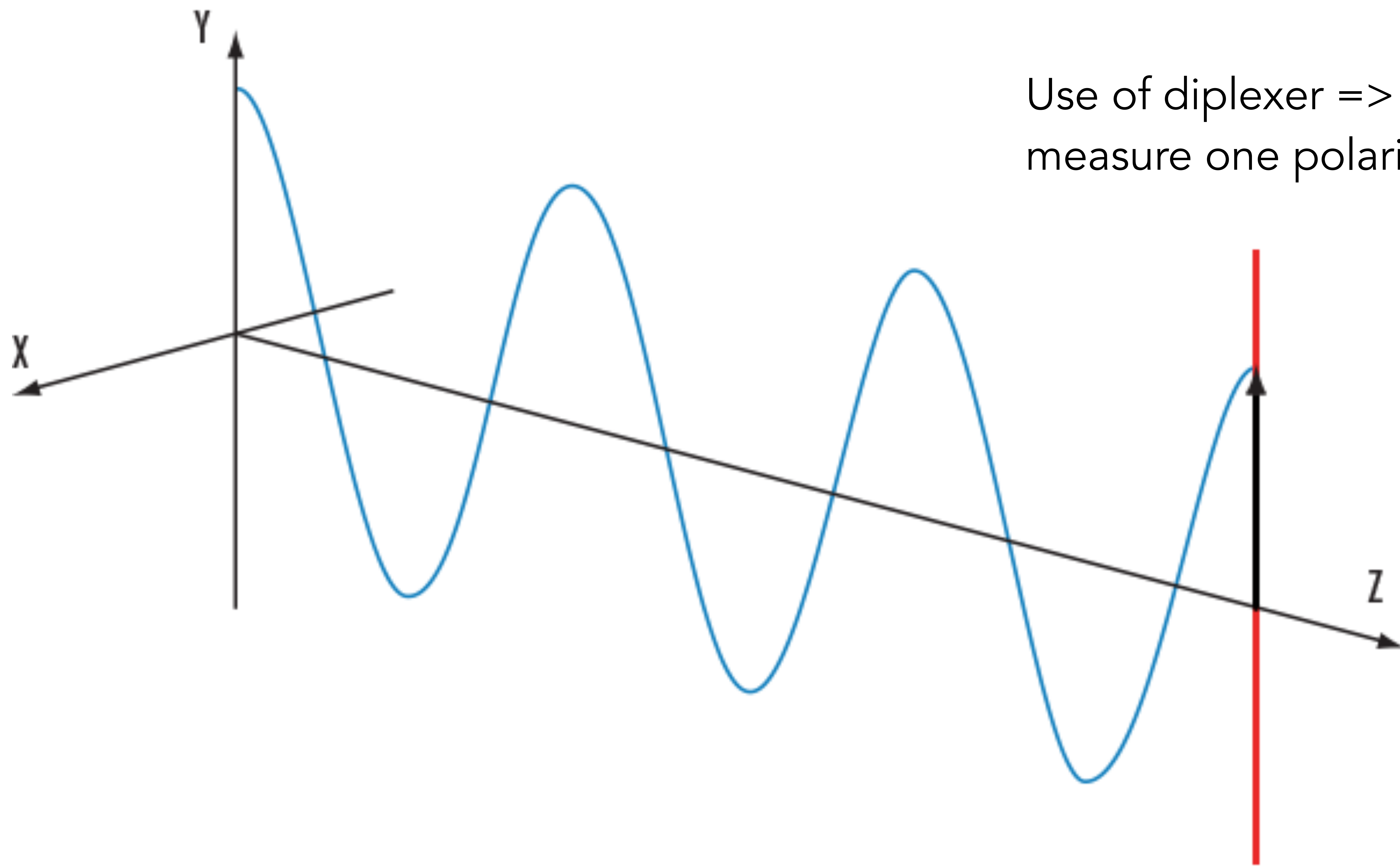

Use of diplexer => we only measure one polarization

https://www.edmundoptics.com/resources/application-notes/optics/introduction-to-polarization/

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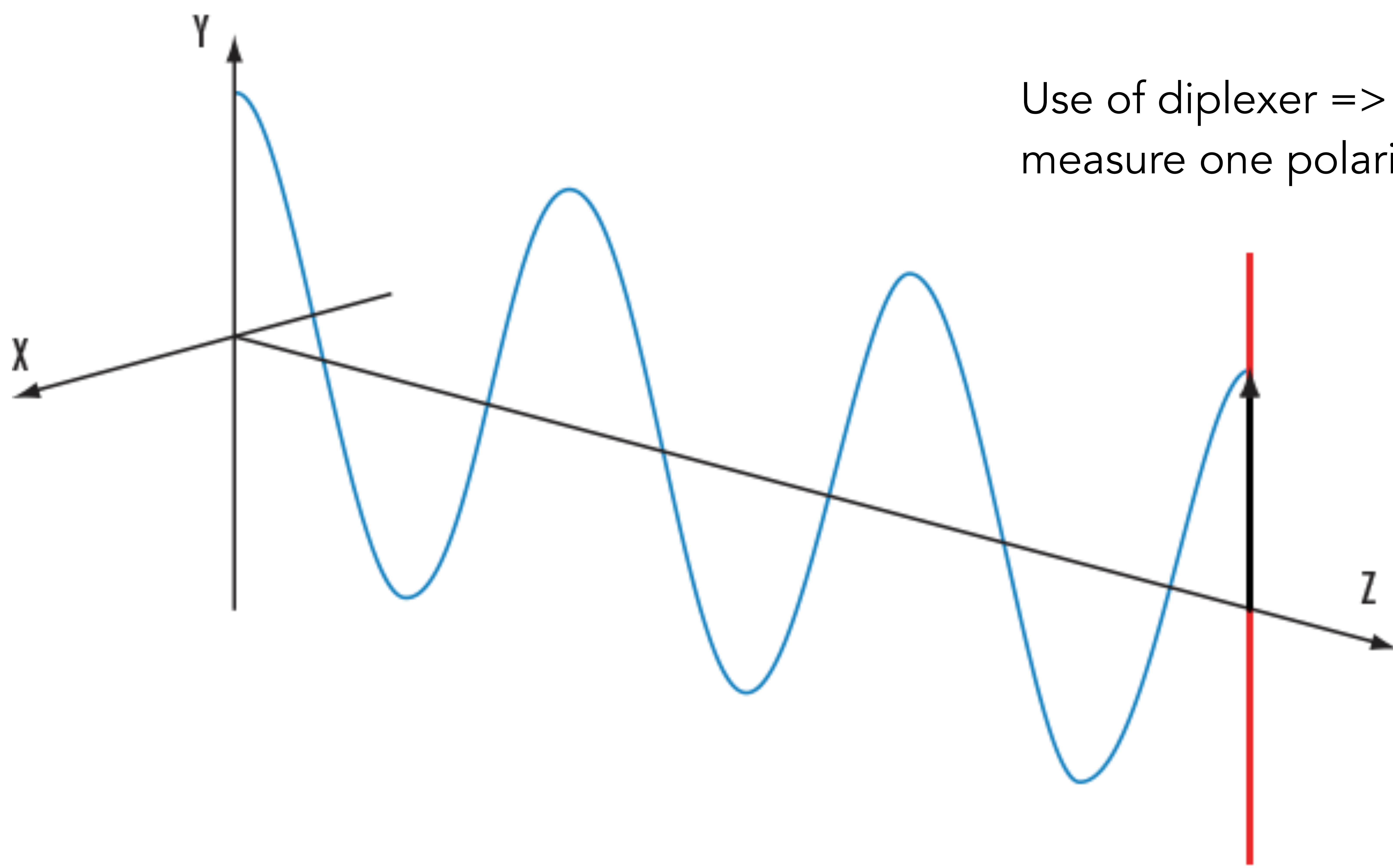

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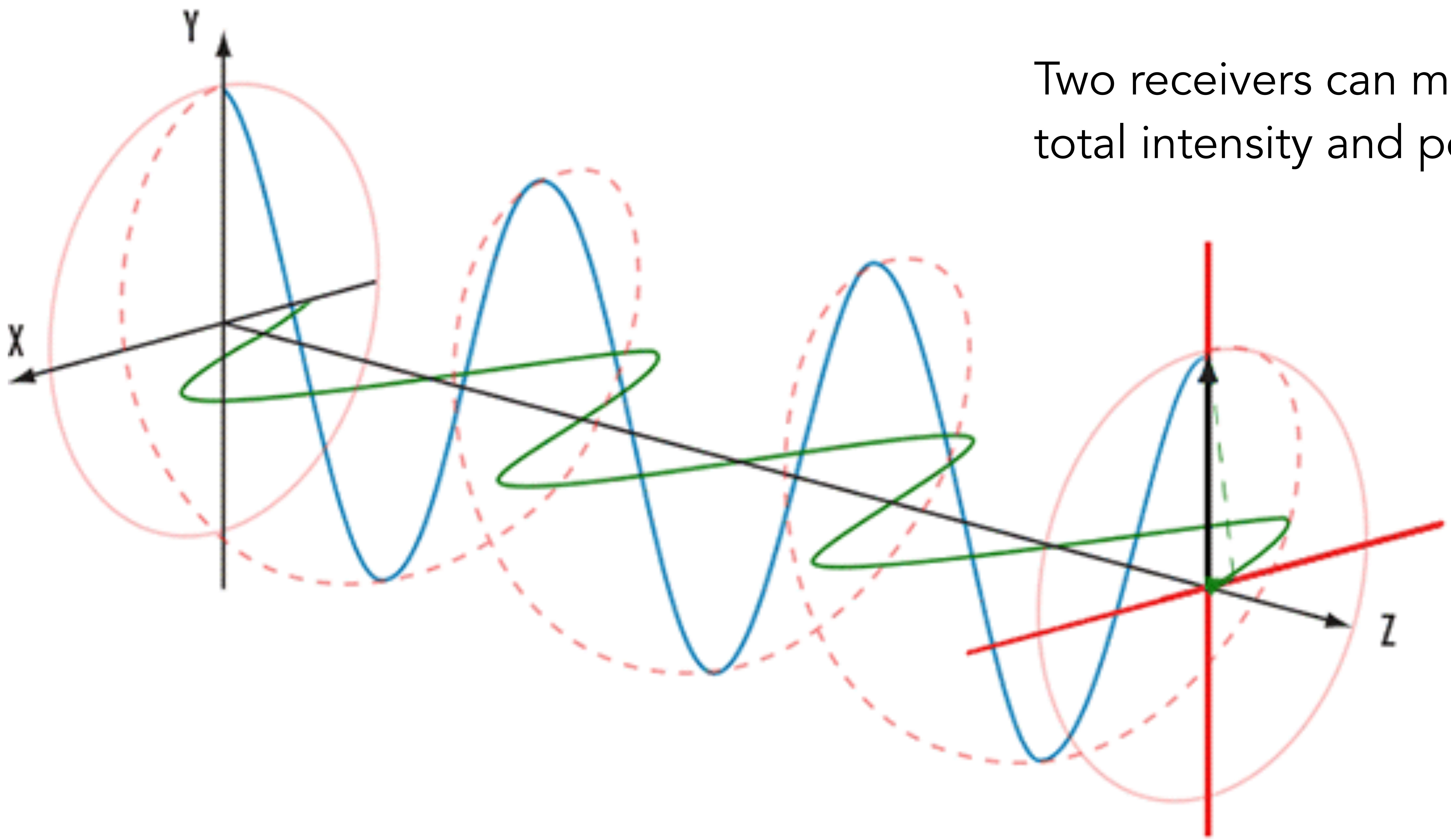

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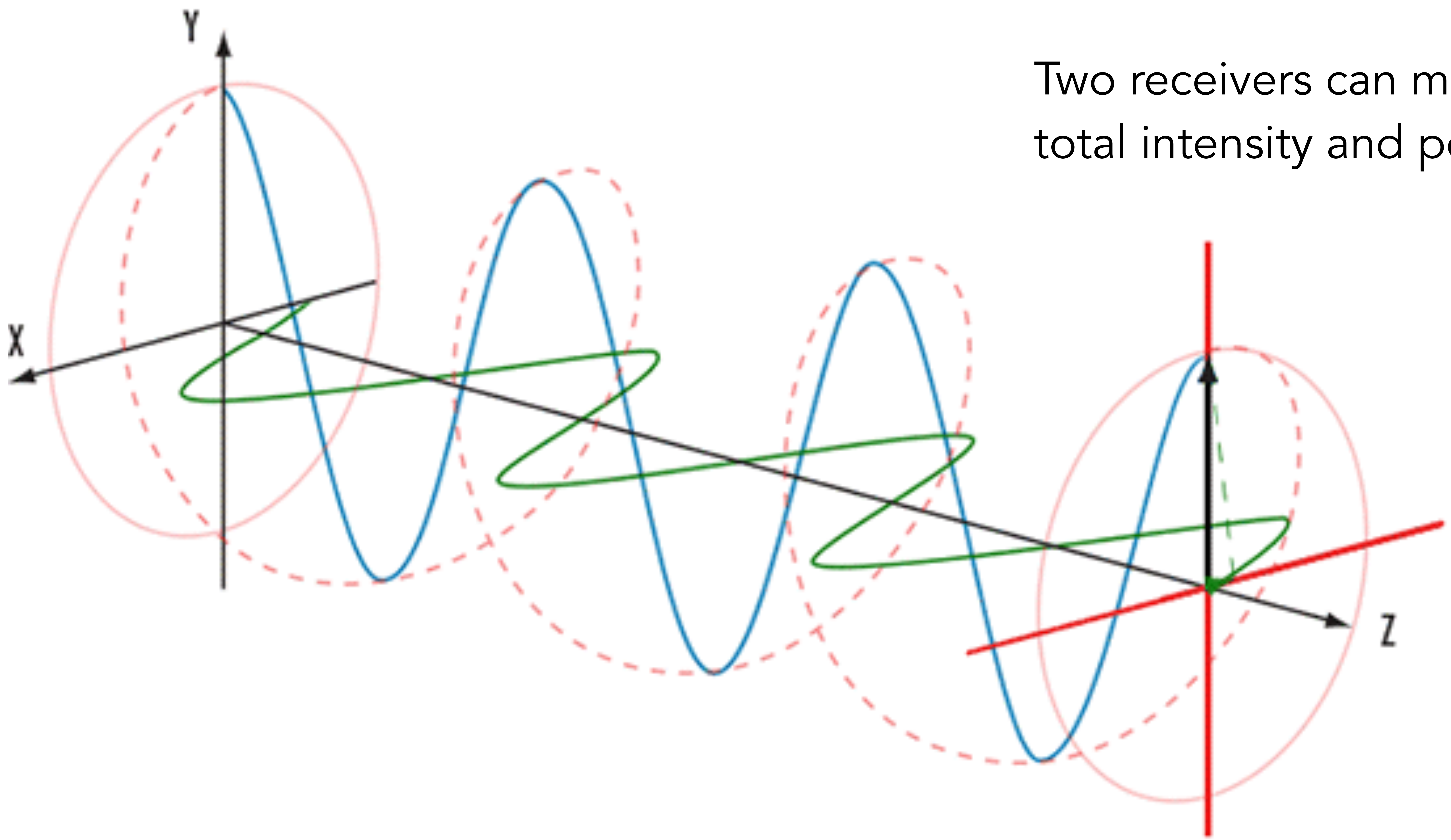

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Radio Emission Mechanisms

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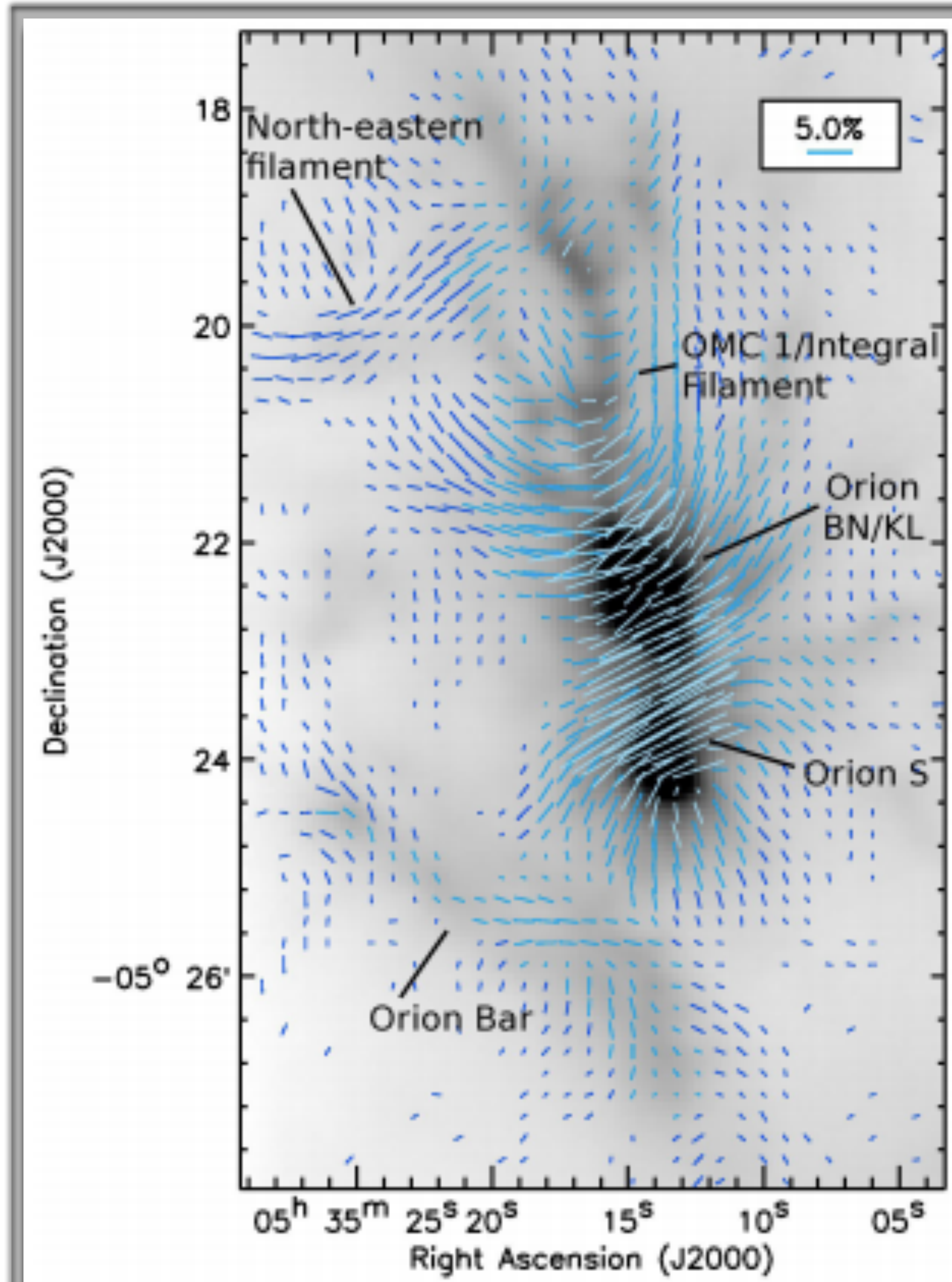
And yes: it works!



SCUBA-2 / POL-2

Credit: BISTRO Large Program Consortium

Questions

- What is the radio/submm atmosphere window?
  — a very broad and transparent observing window

- What is special about the radio/submm band?
  — It revealed a "parallel universe"

- **What astrophysical process produce radio/submm signal?**
  — free-free, dust, atomic/molecular lines …
  — temperature, density, magnetic field …
  — see talk "JCMT Science"

- How to do radio/submm observations?

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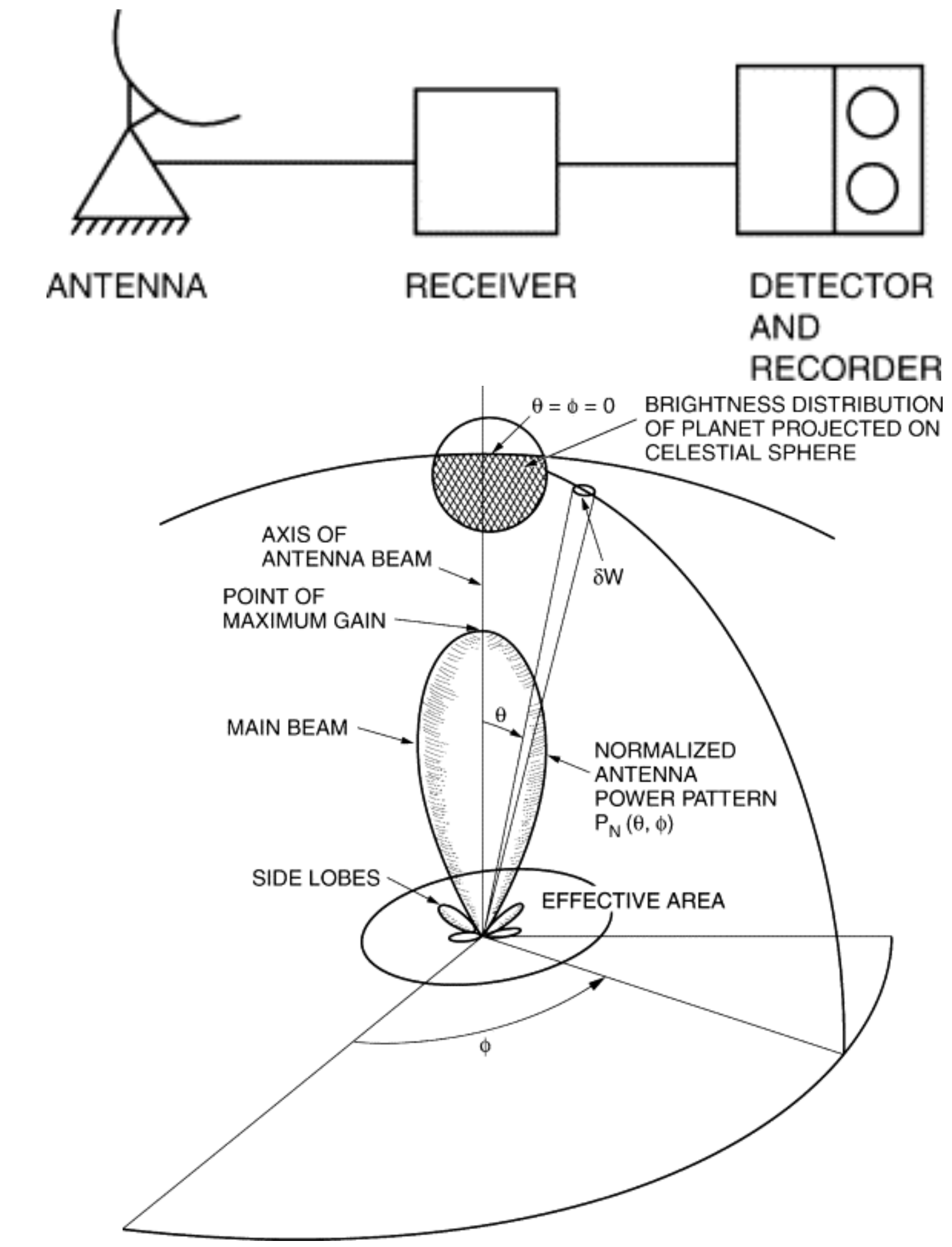
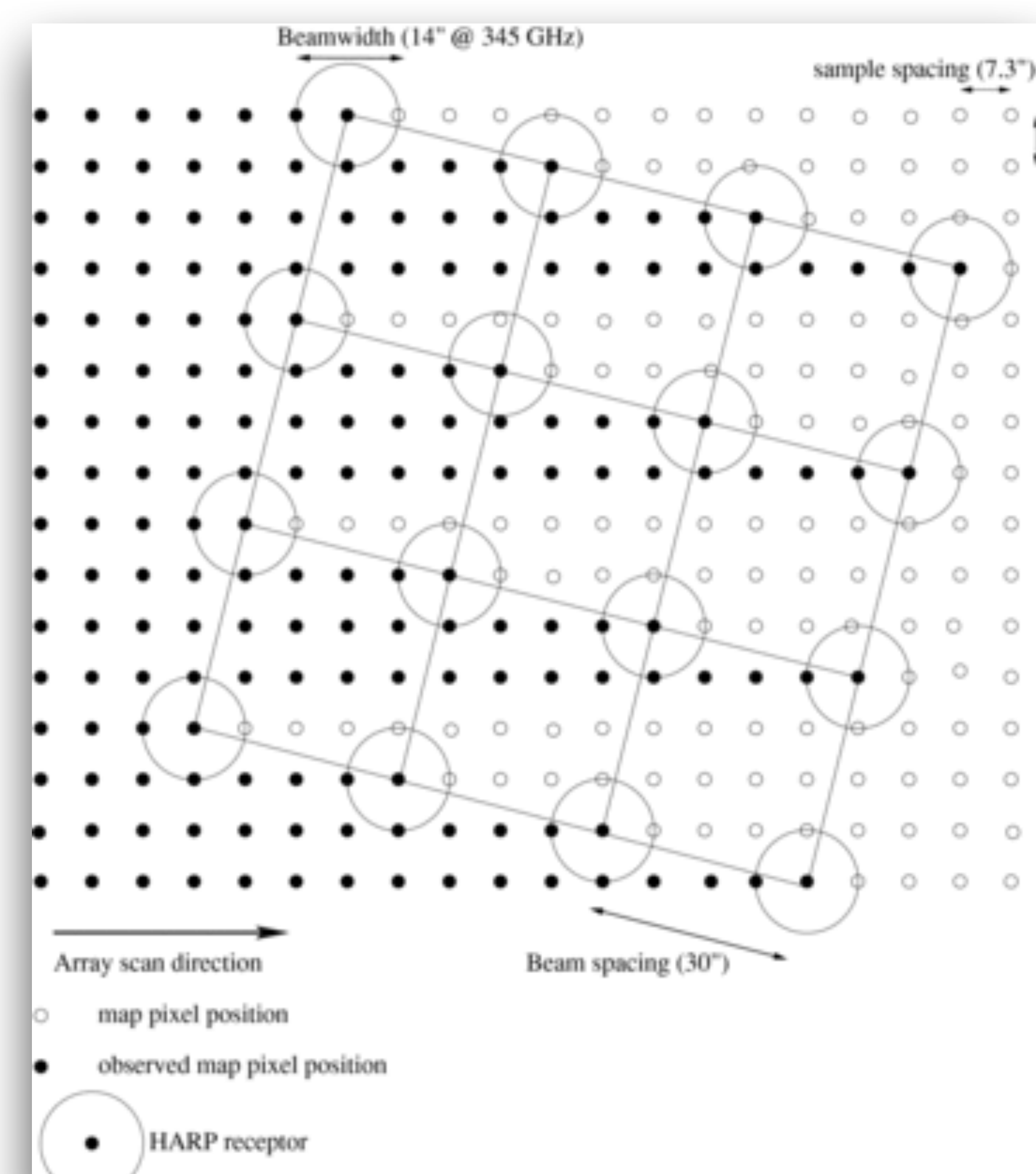
How to do radio/submm observations?

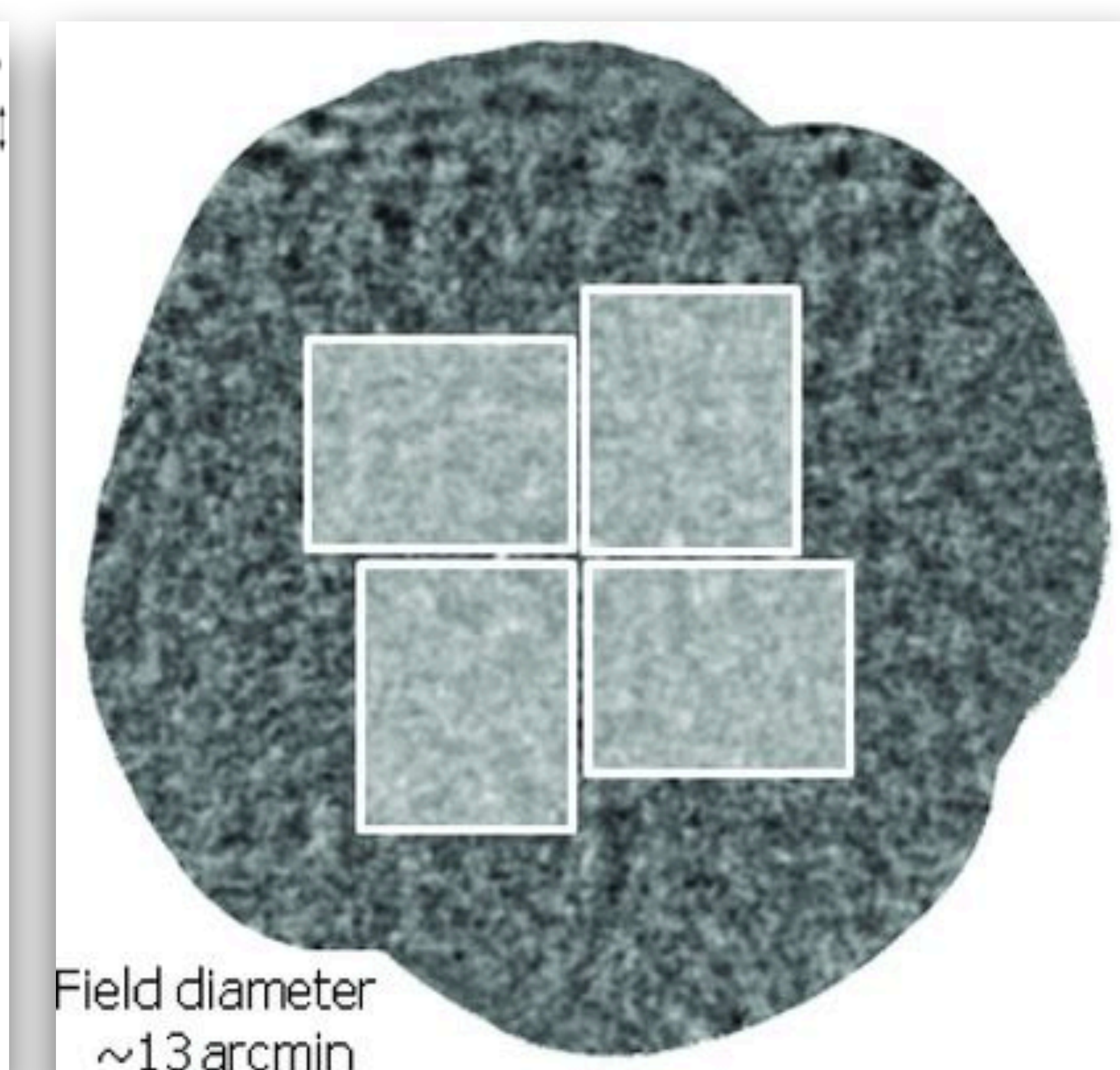
Some Definitions

- T_b and T_{mb} (see talk "Heterodyne calibration")
- Antenna temperature T_A
- System temperature T_{sys}
- Sensitivity and Noise
- Intensity and Flux
- Observing Modes and Switching Modes
- Spectral resolution
- Angular resolution (Beam size, confusion)
- FOV …





HARP obs modes



SCUBA-2 obs modes

How to do (sub)mm spectral line observations with the JCMT?

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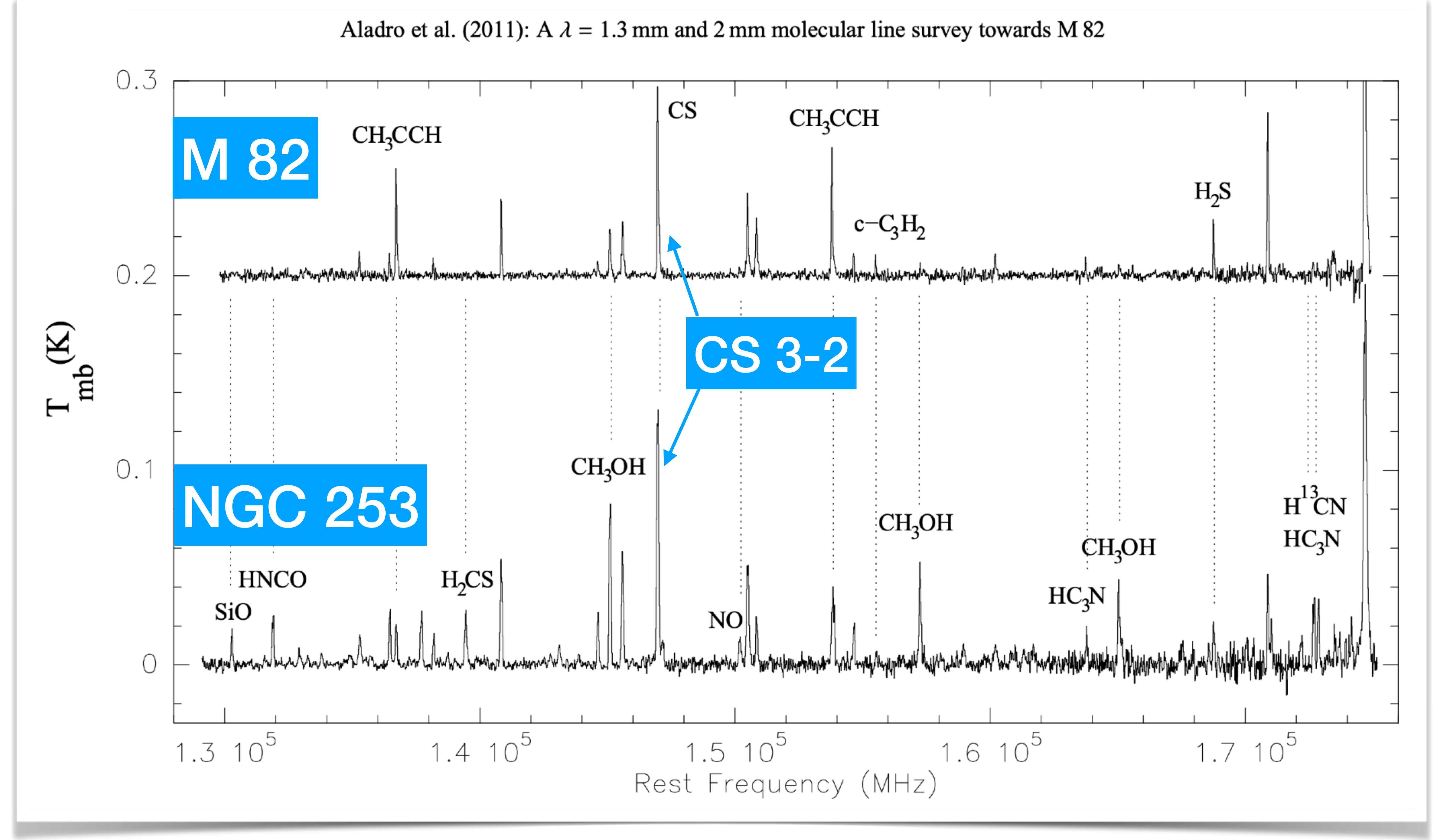

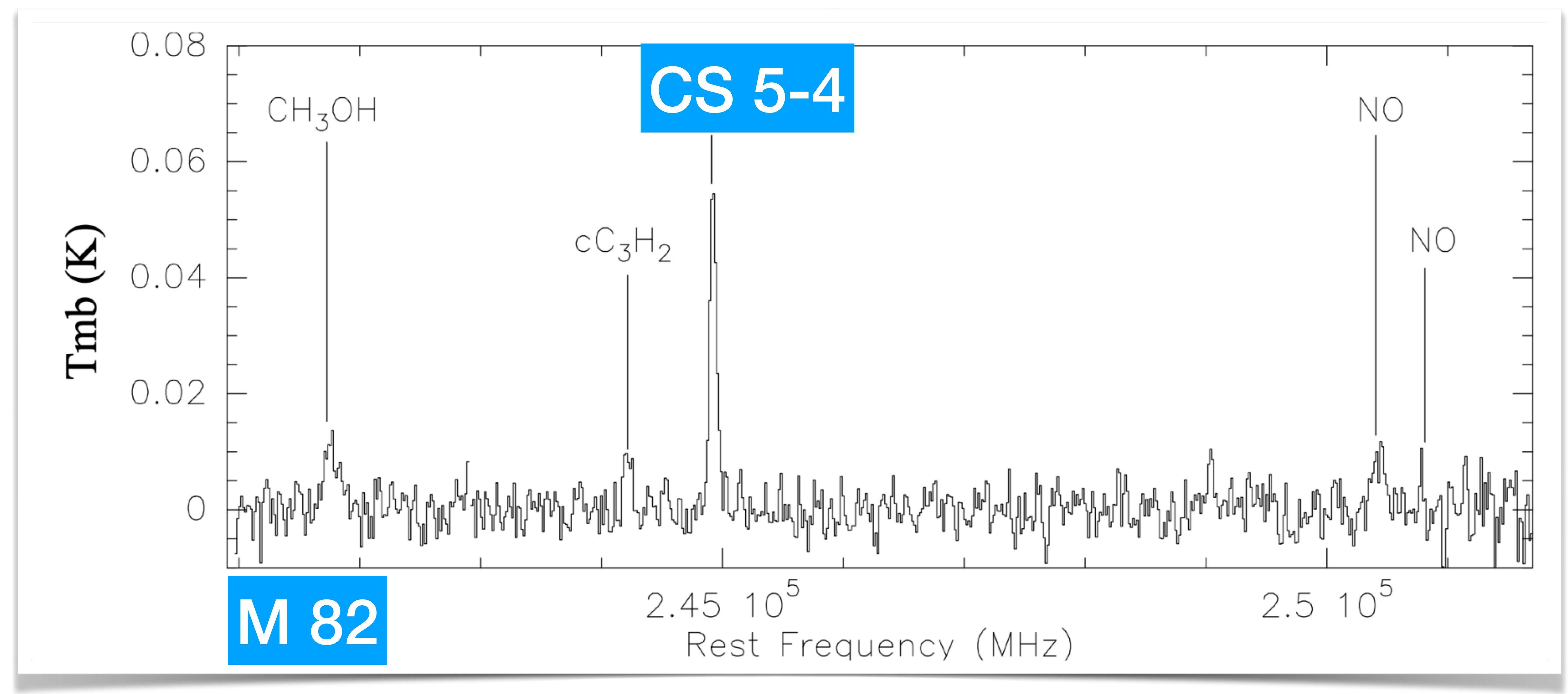

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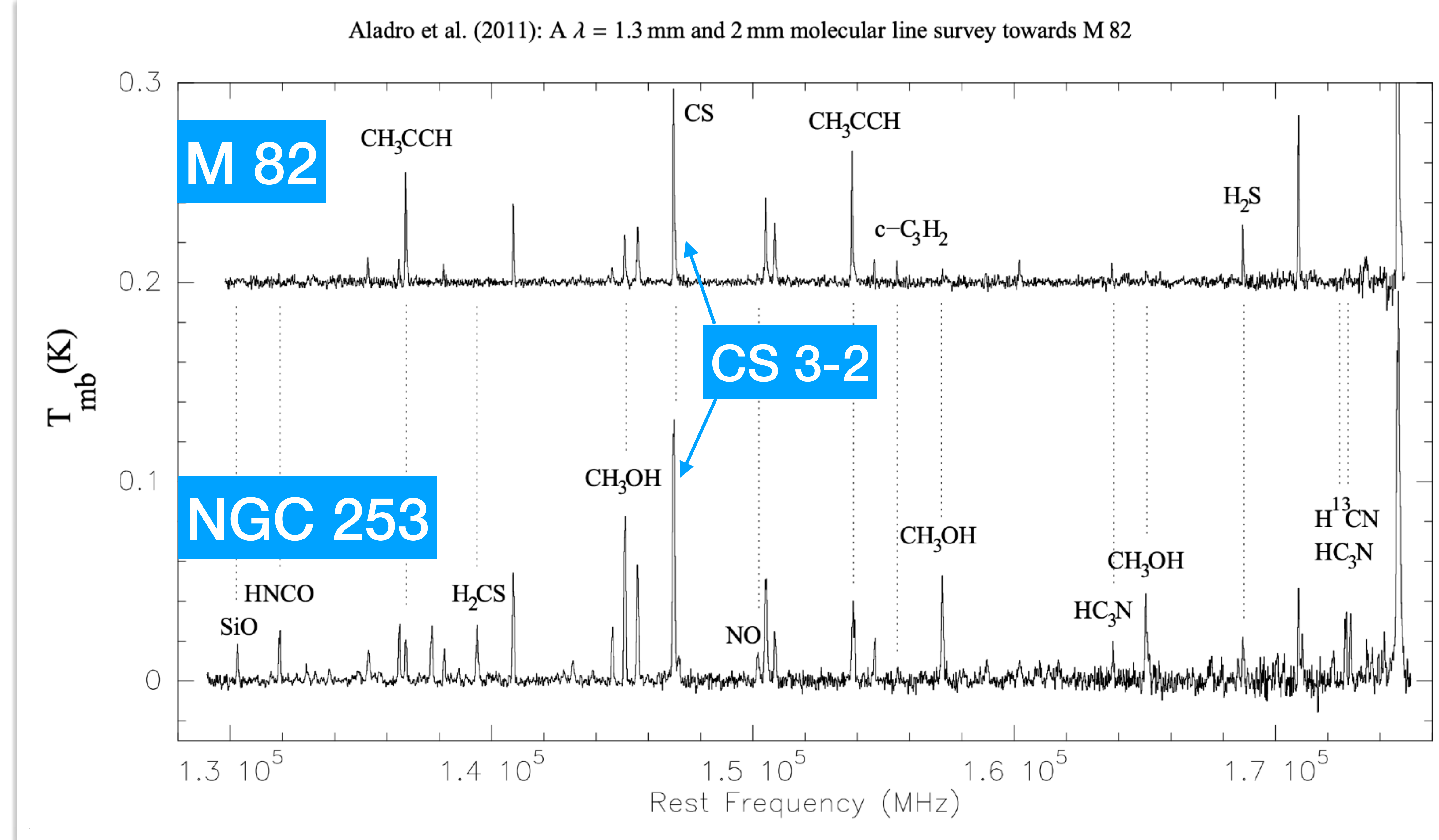

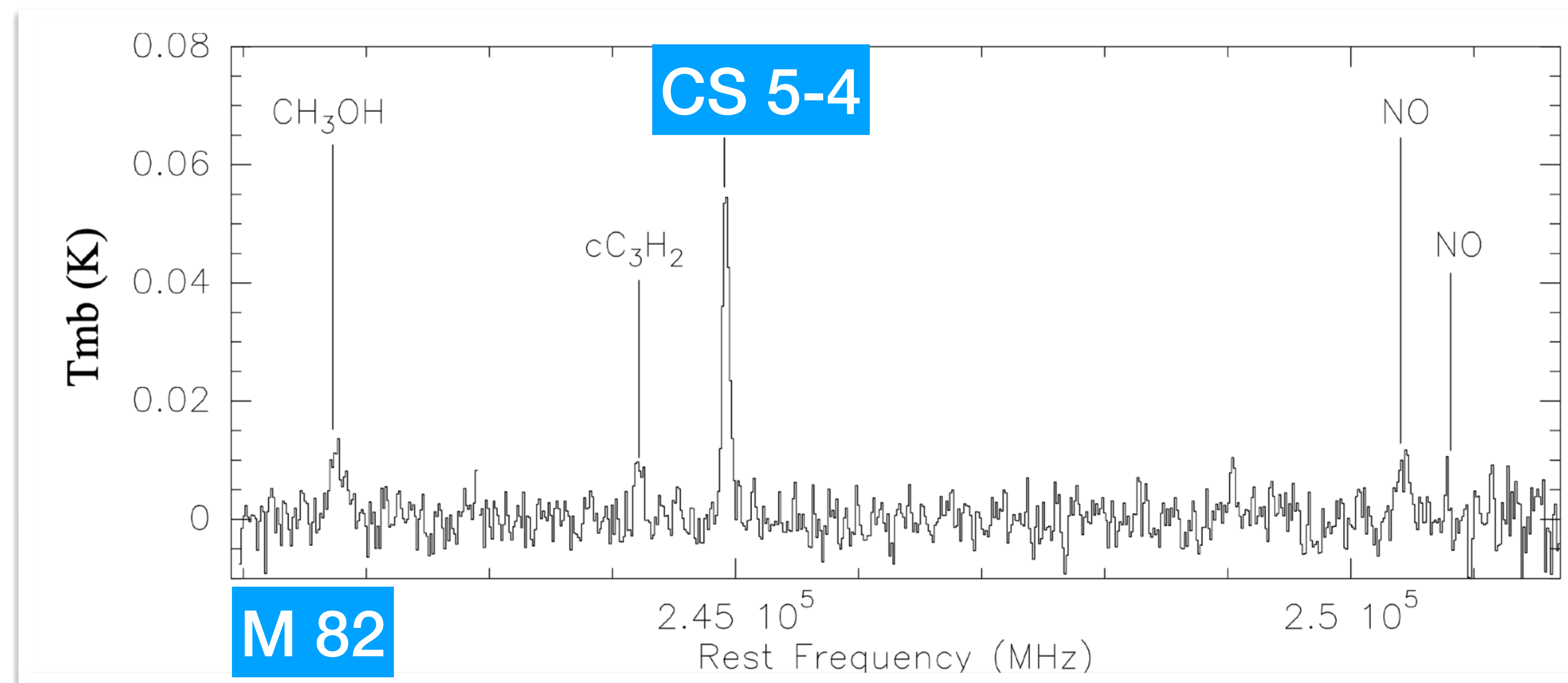

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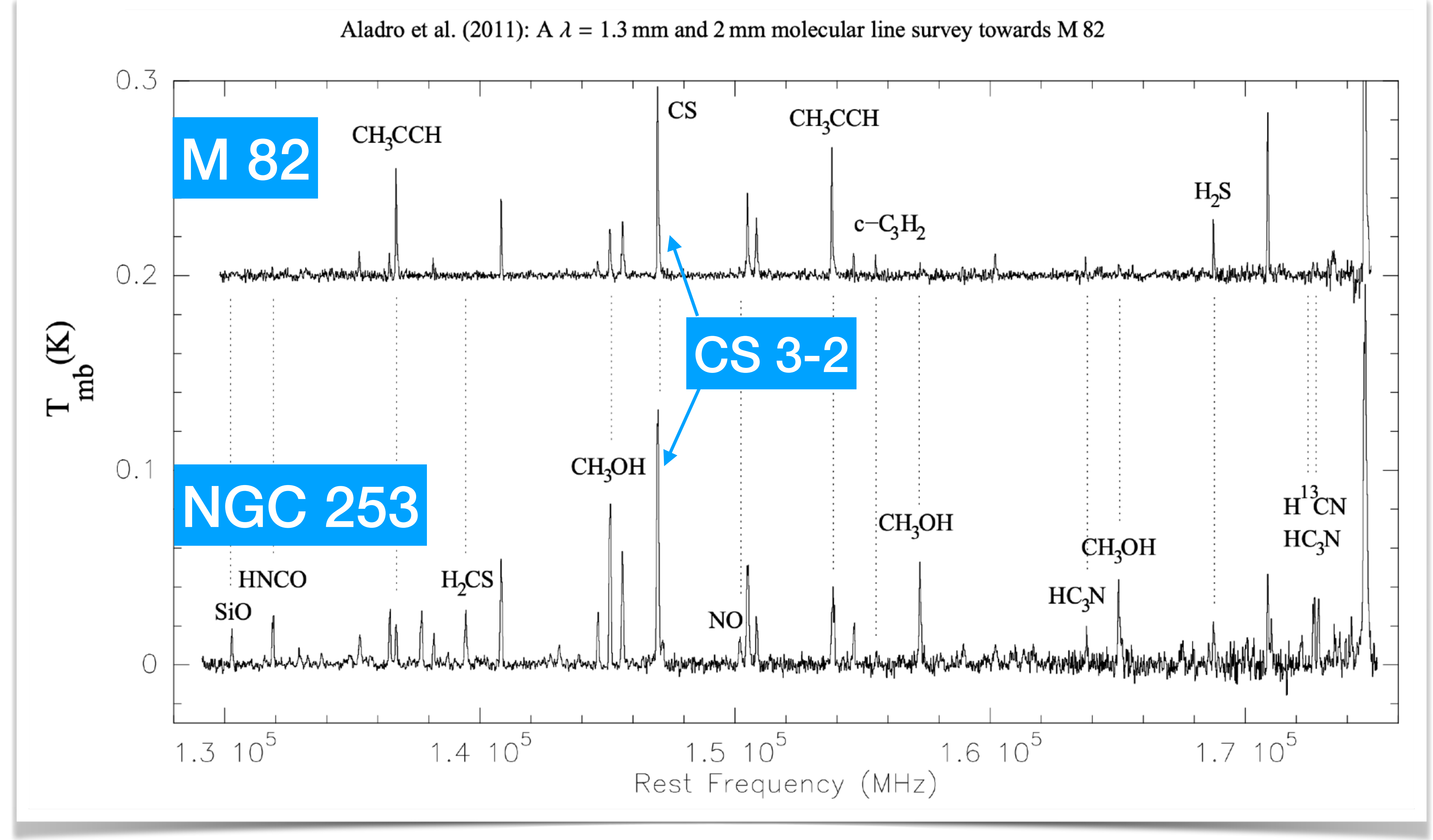

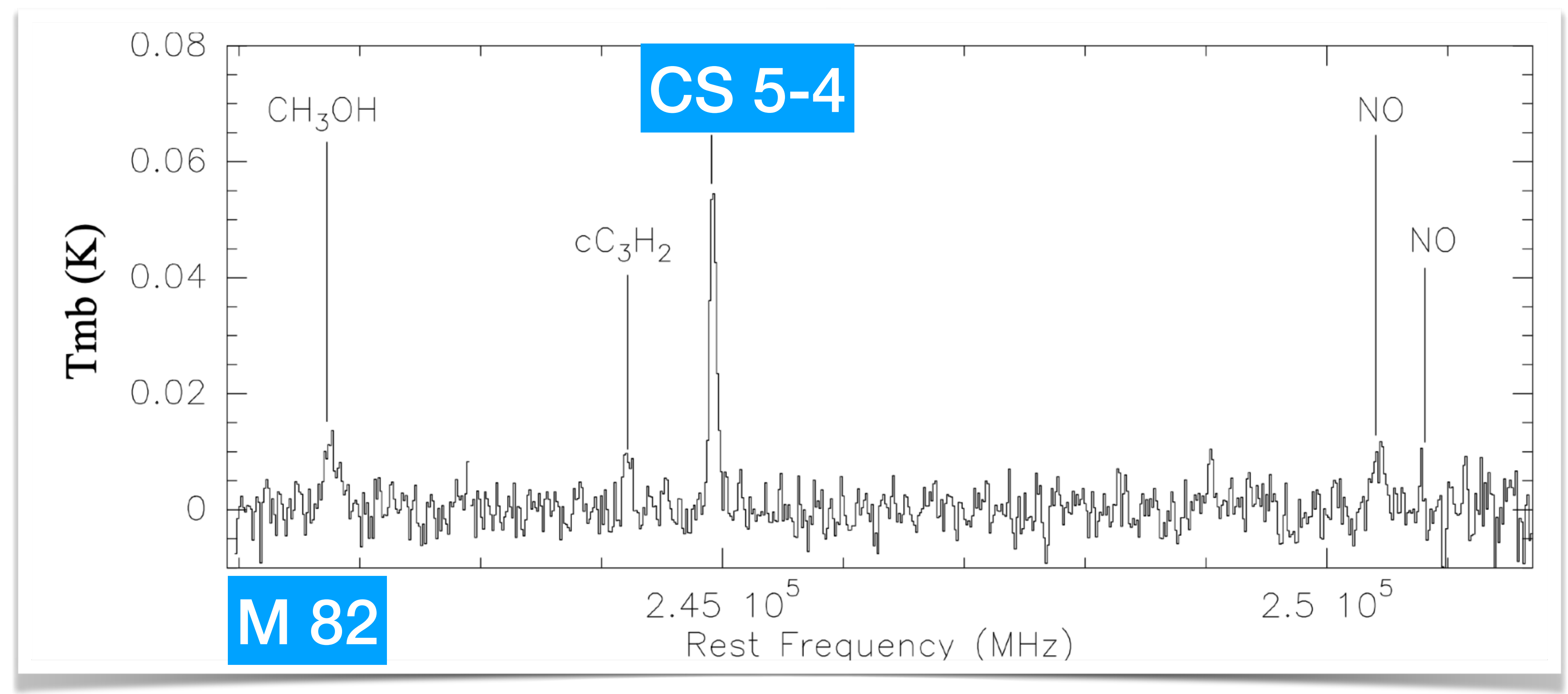

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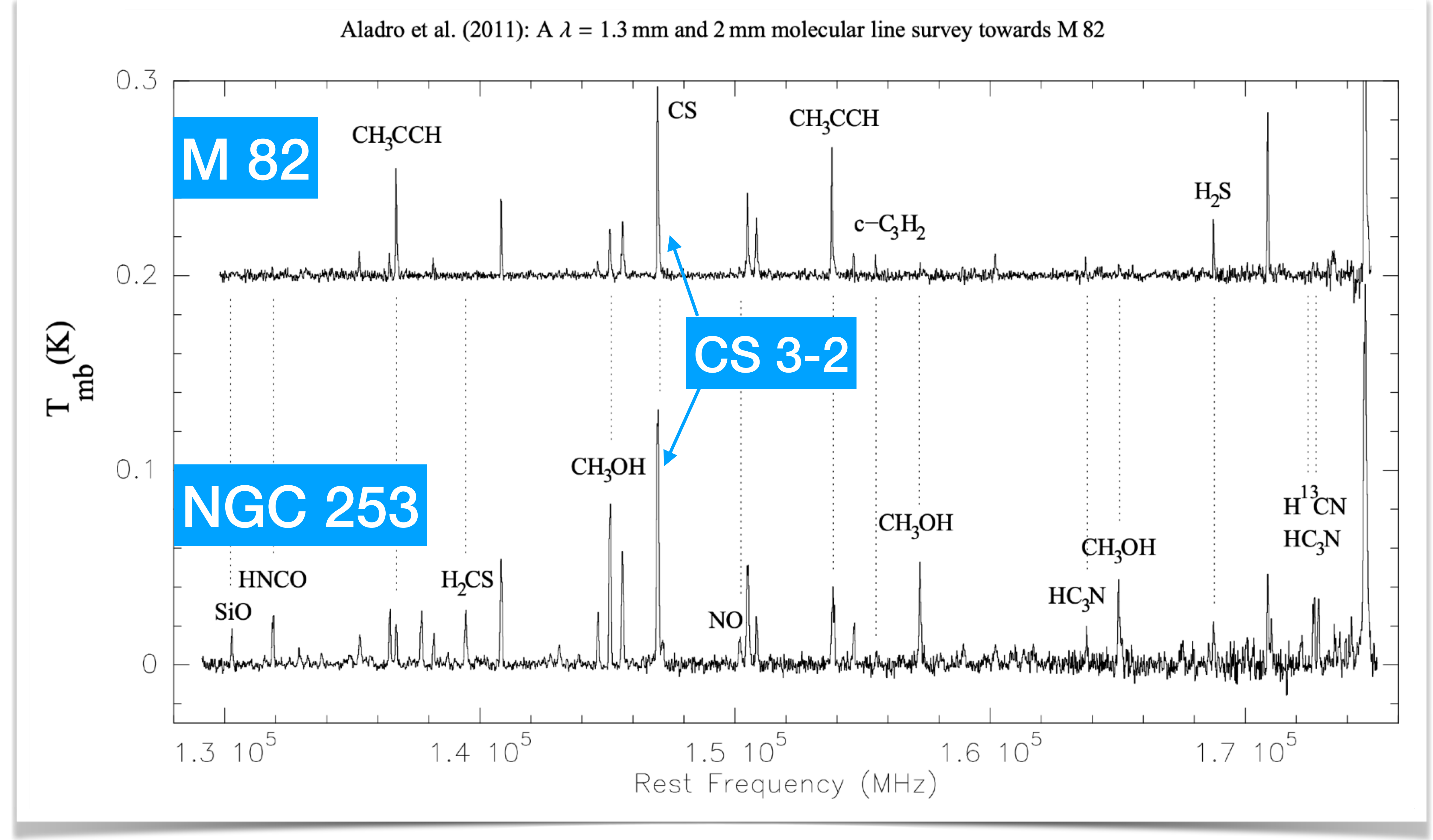

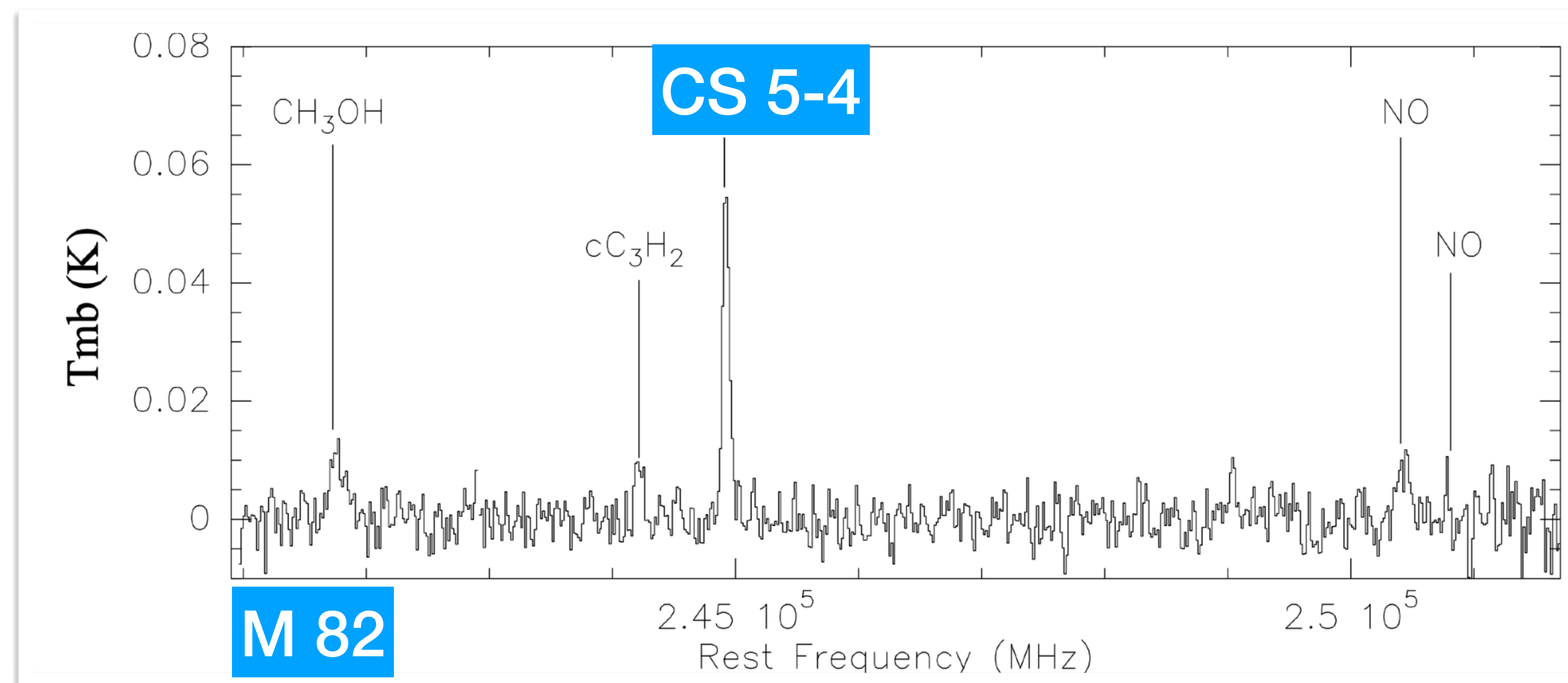

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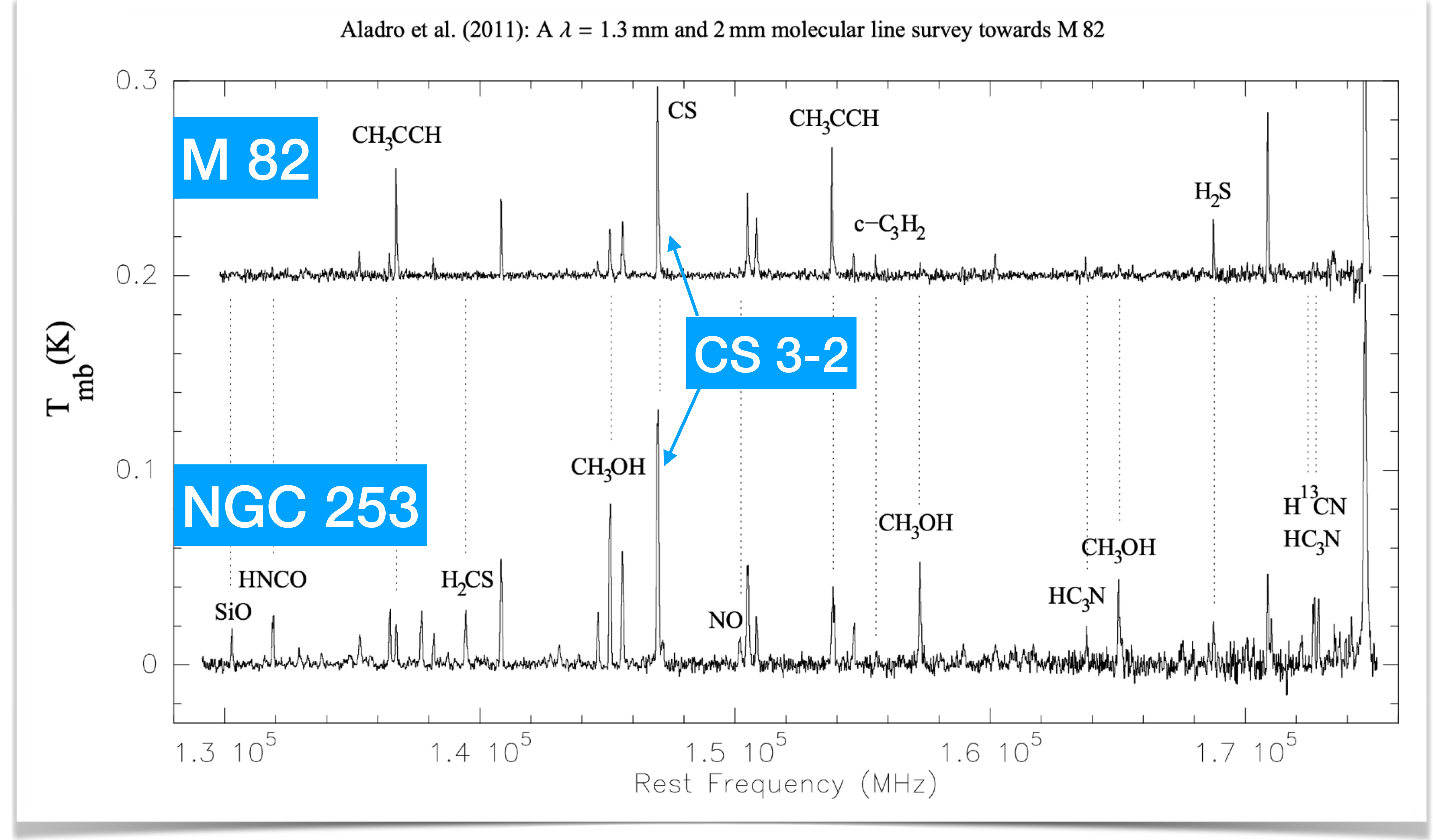

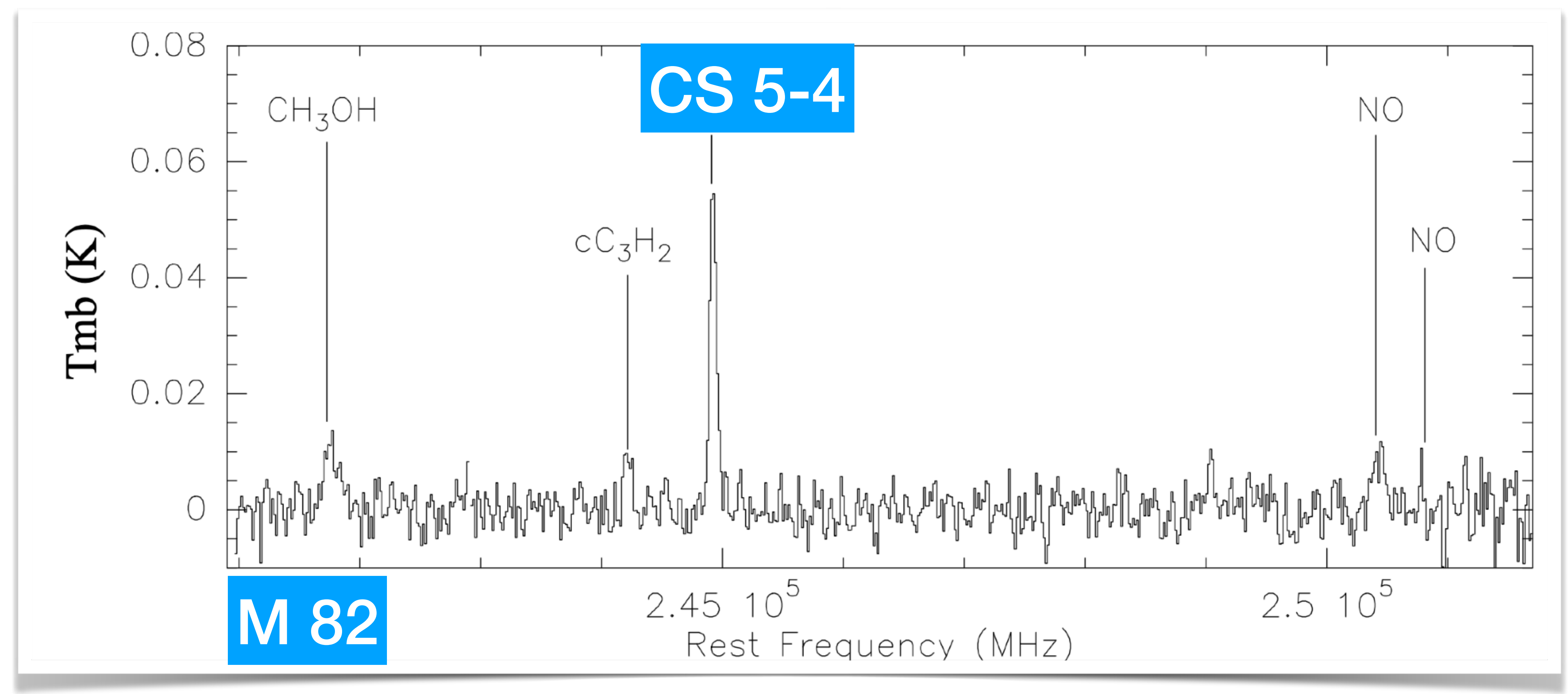

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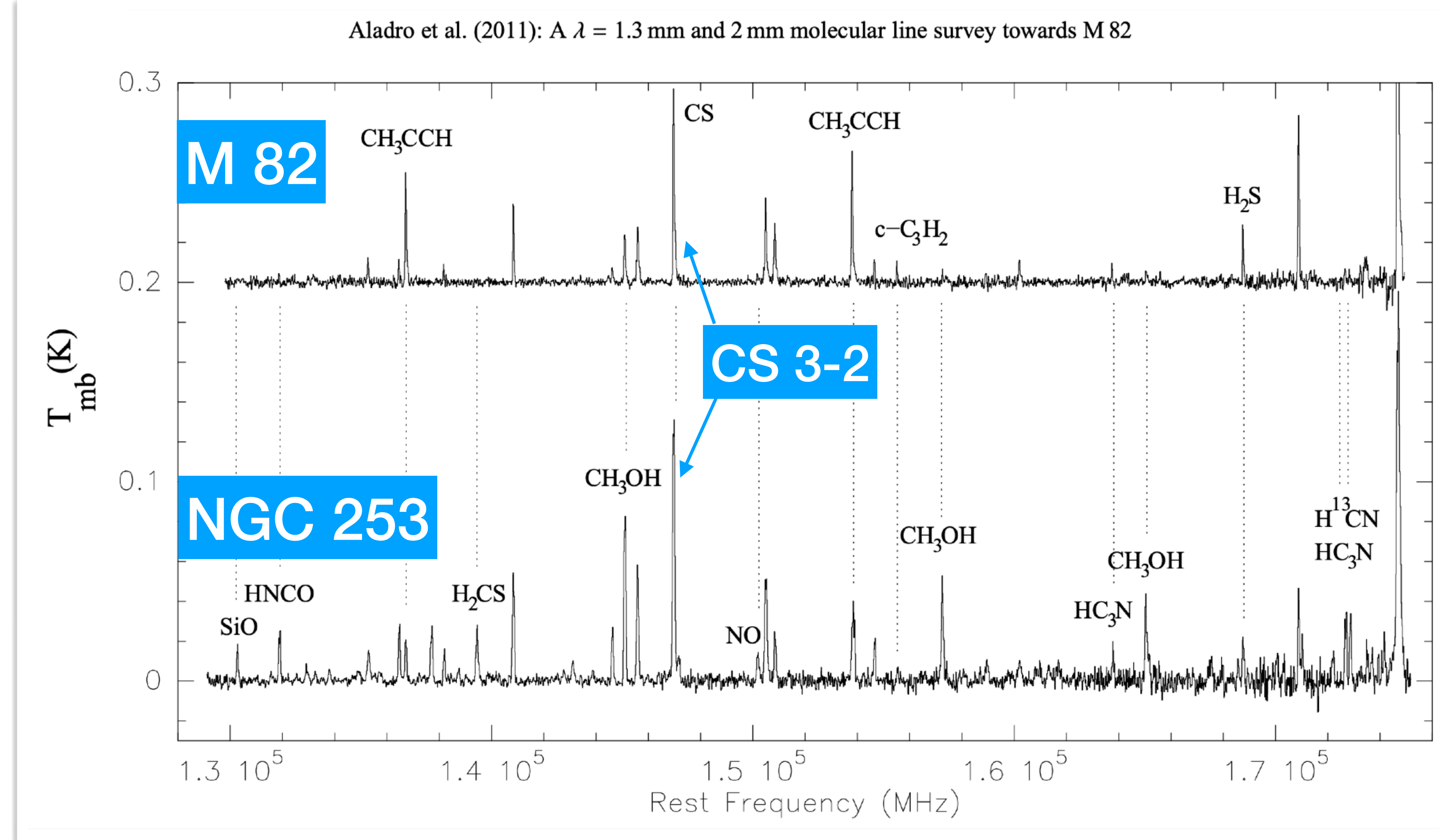

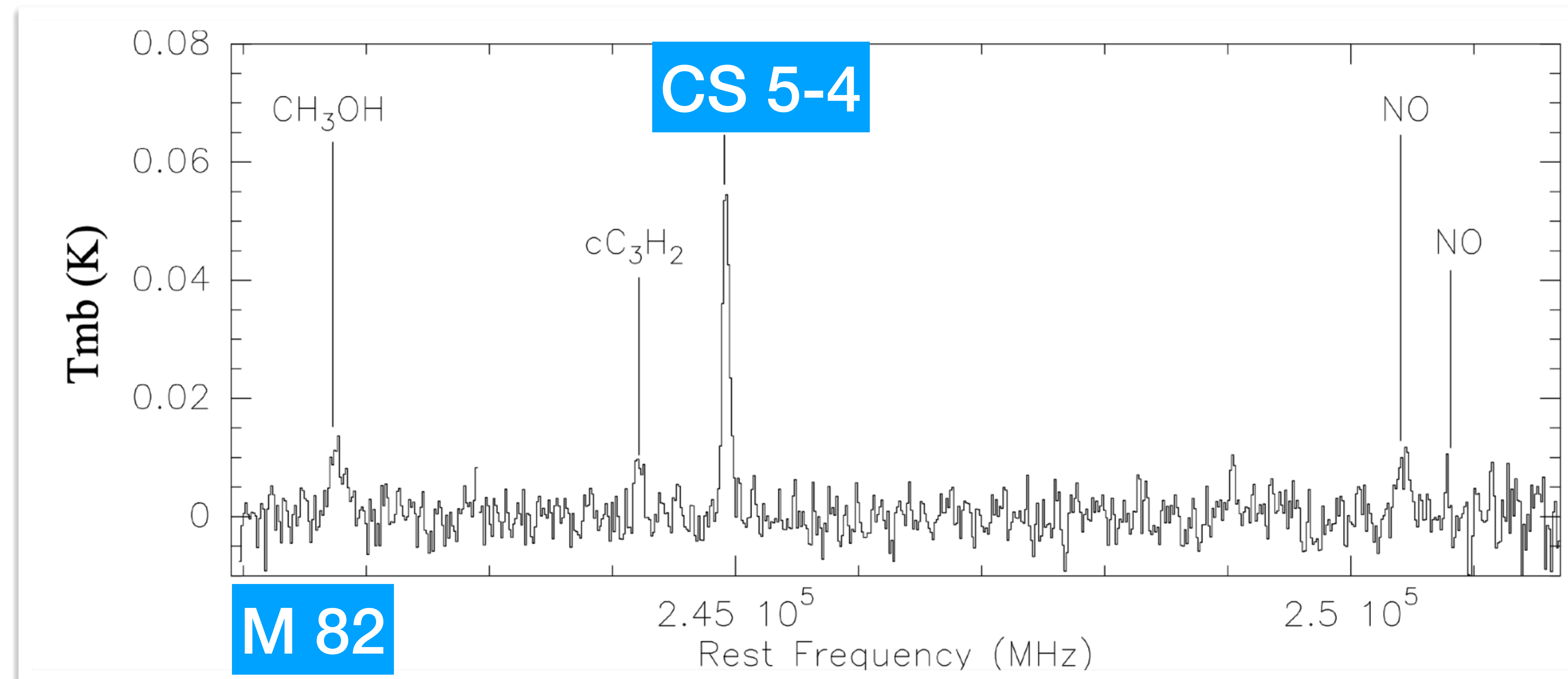

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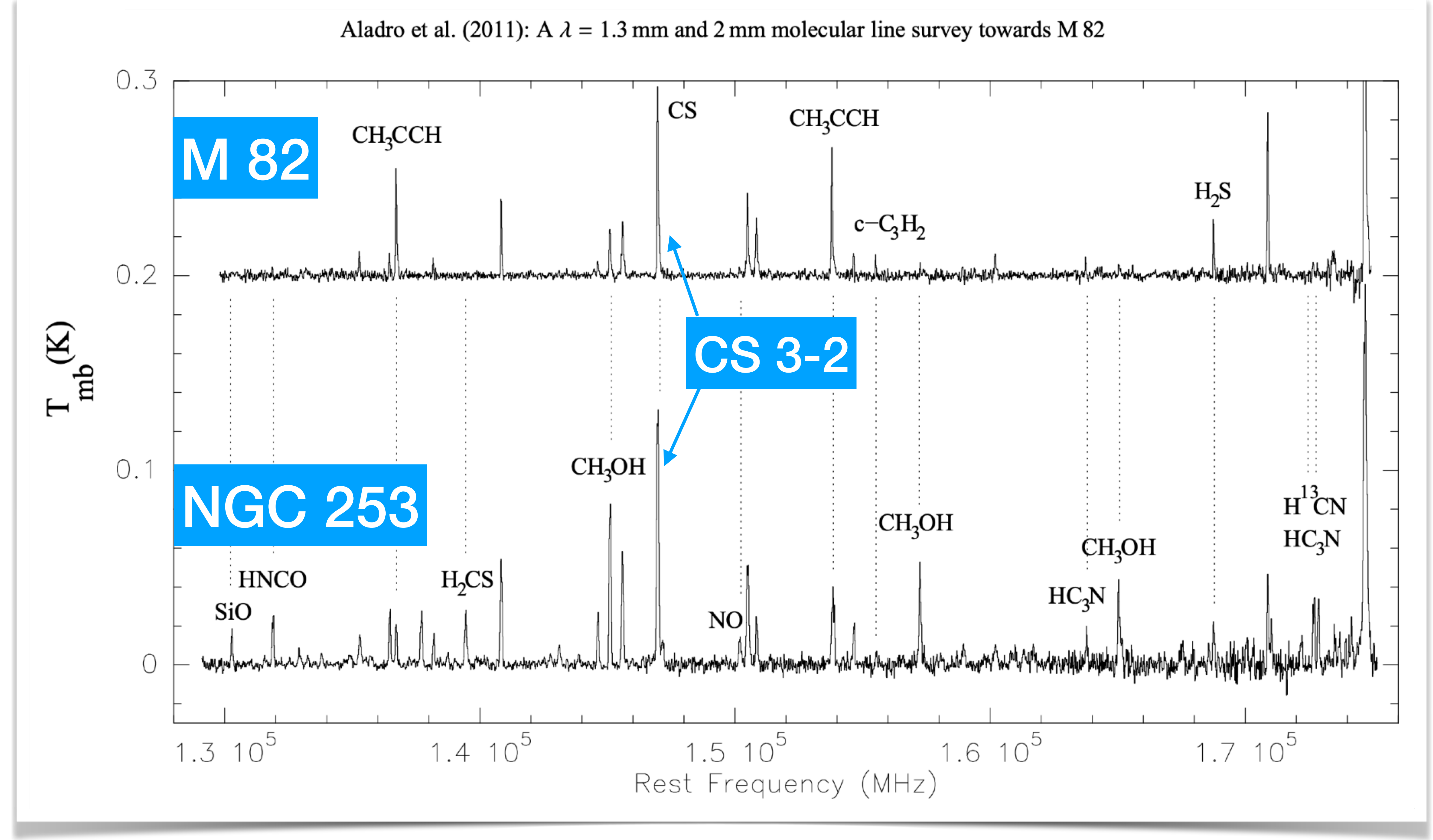

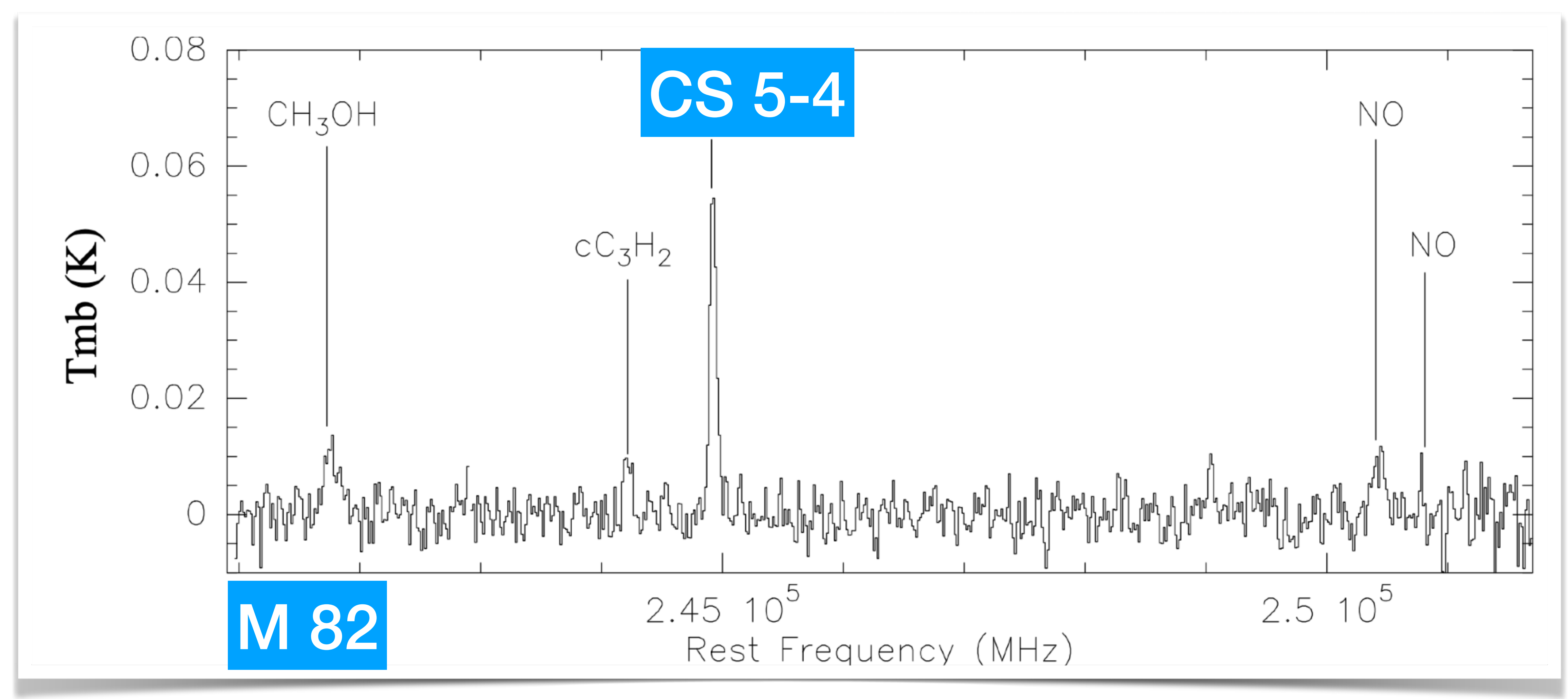

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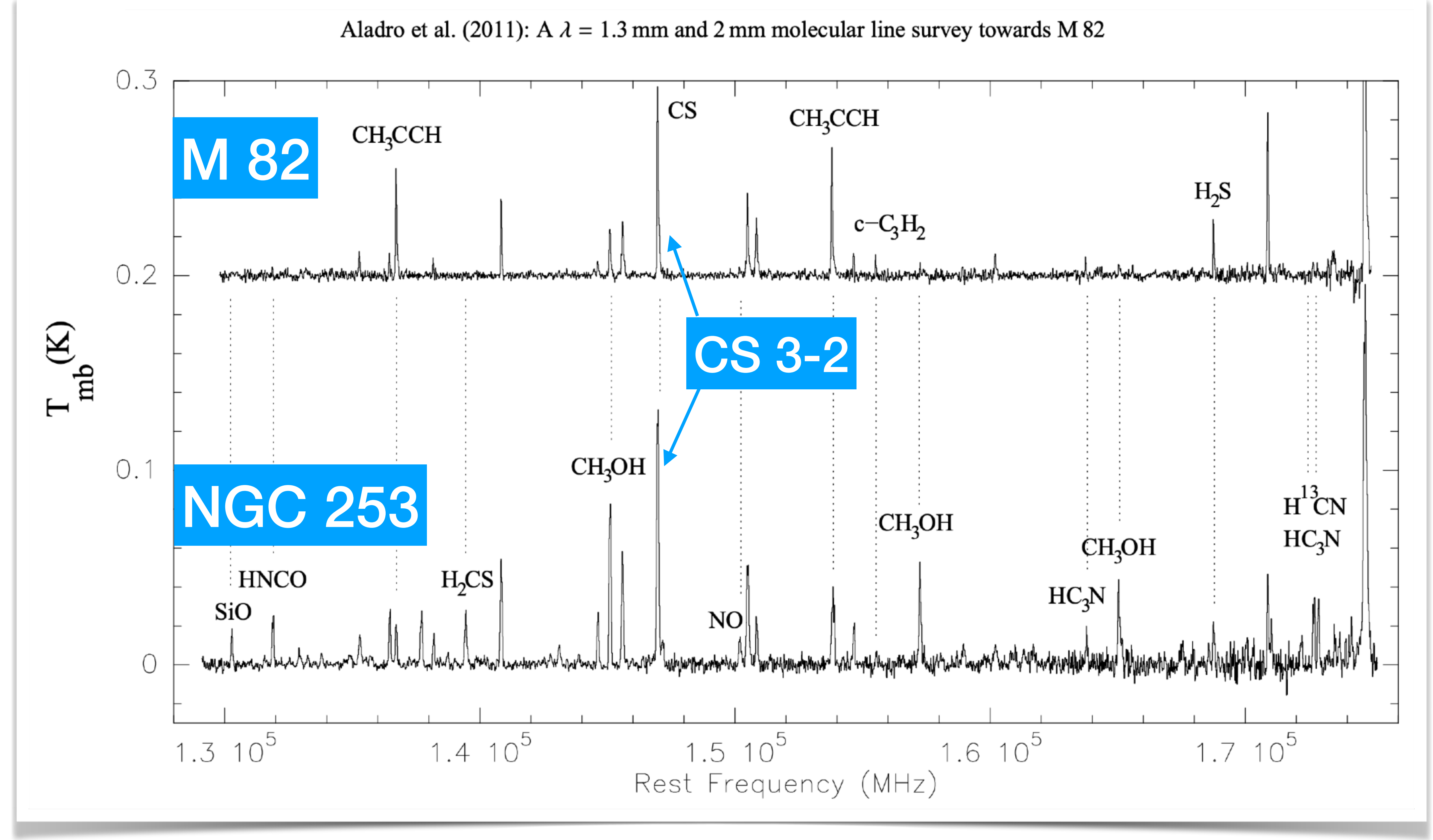

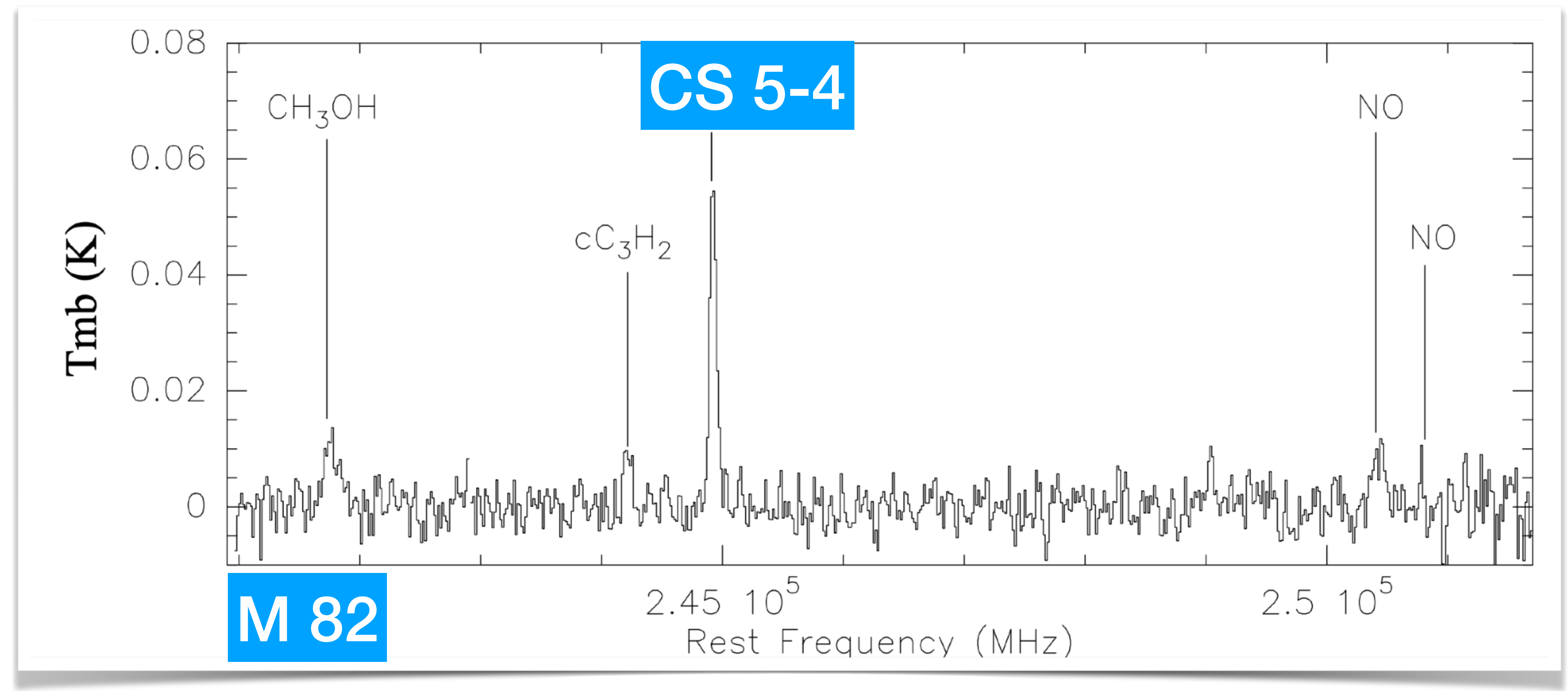

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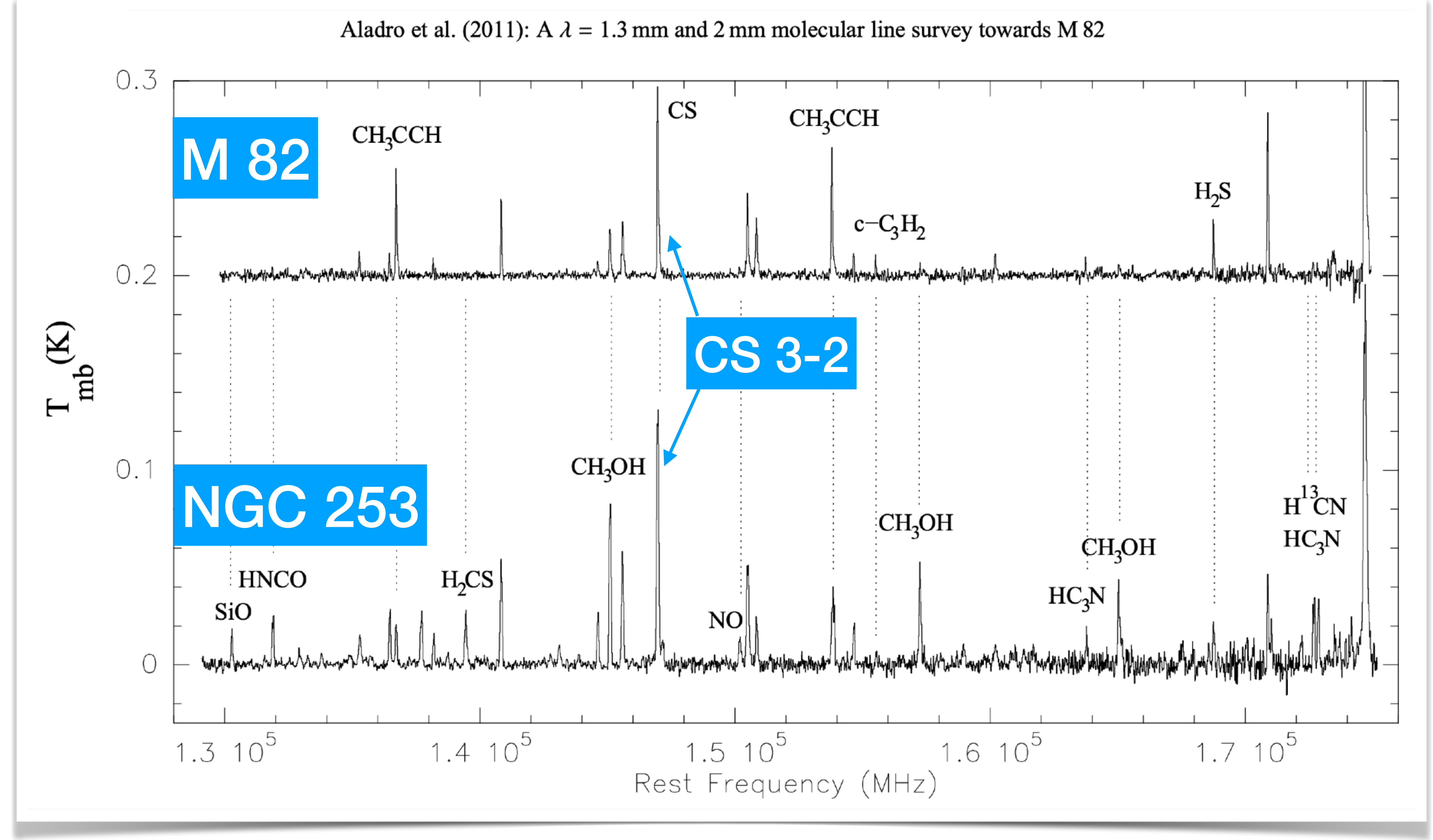

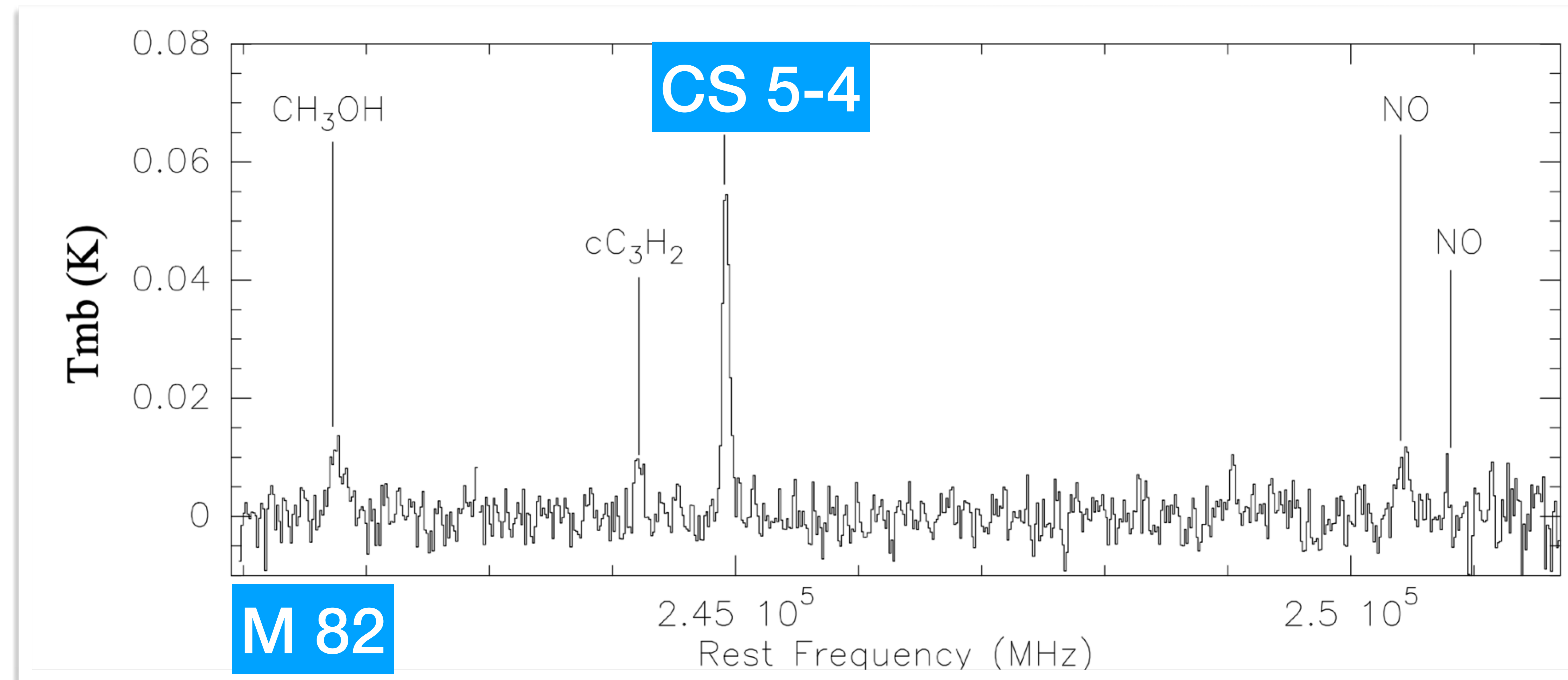

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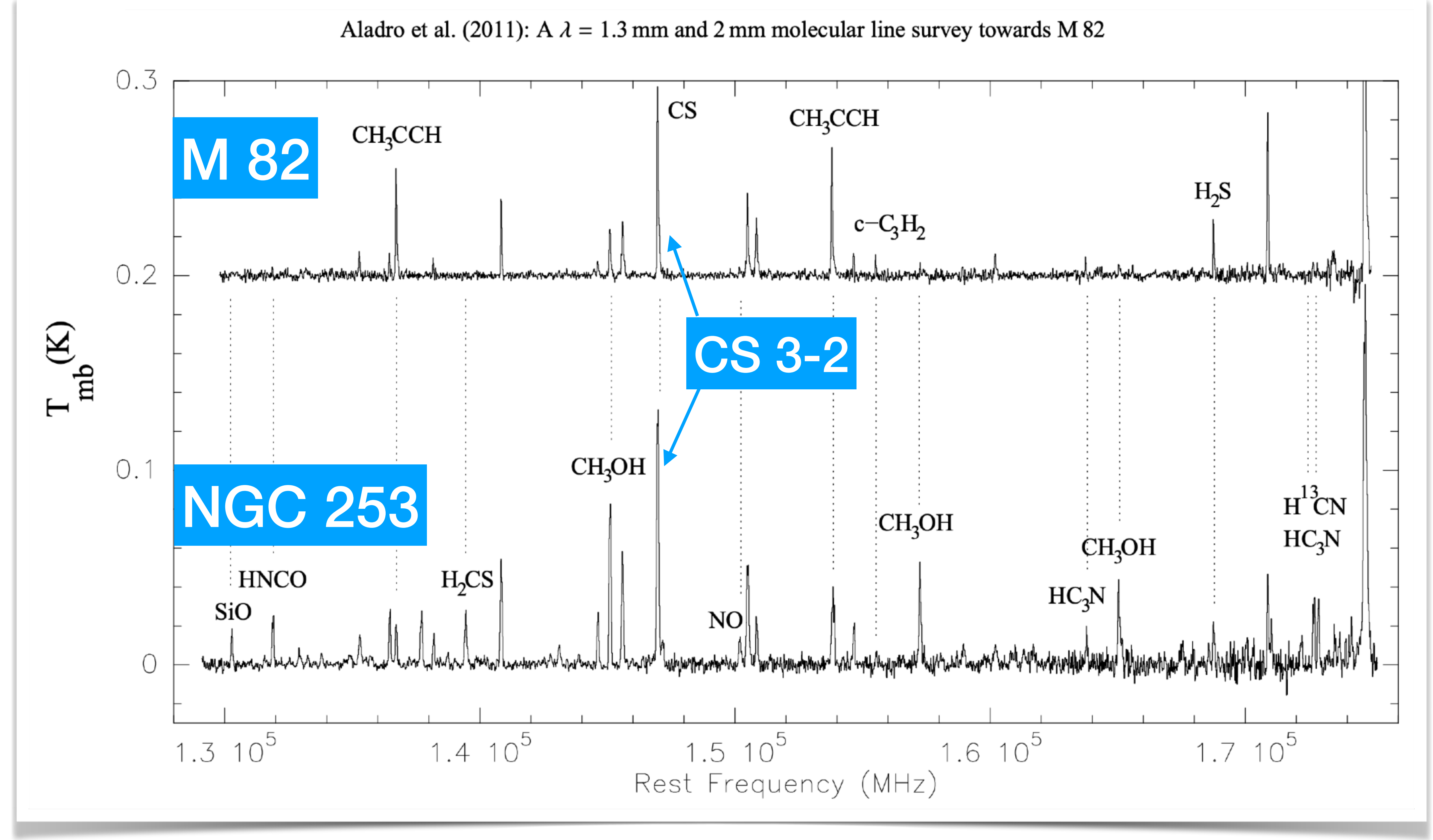

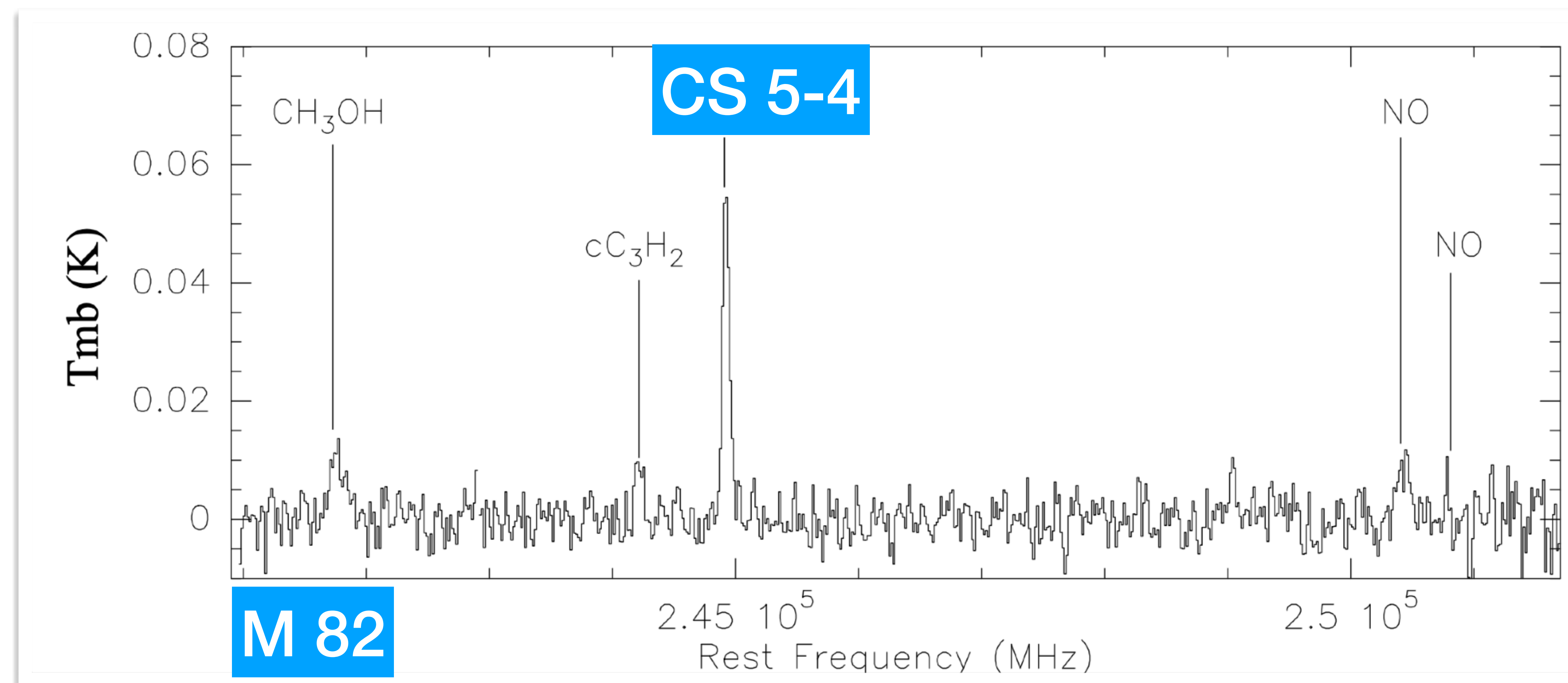

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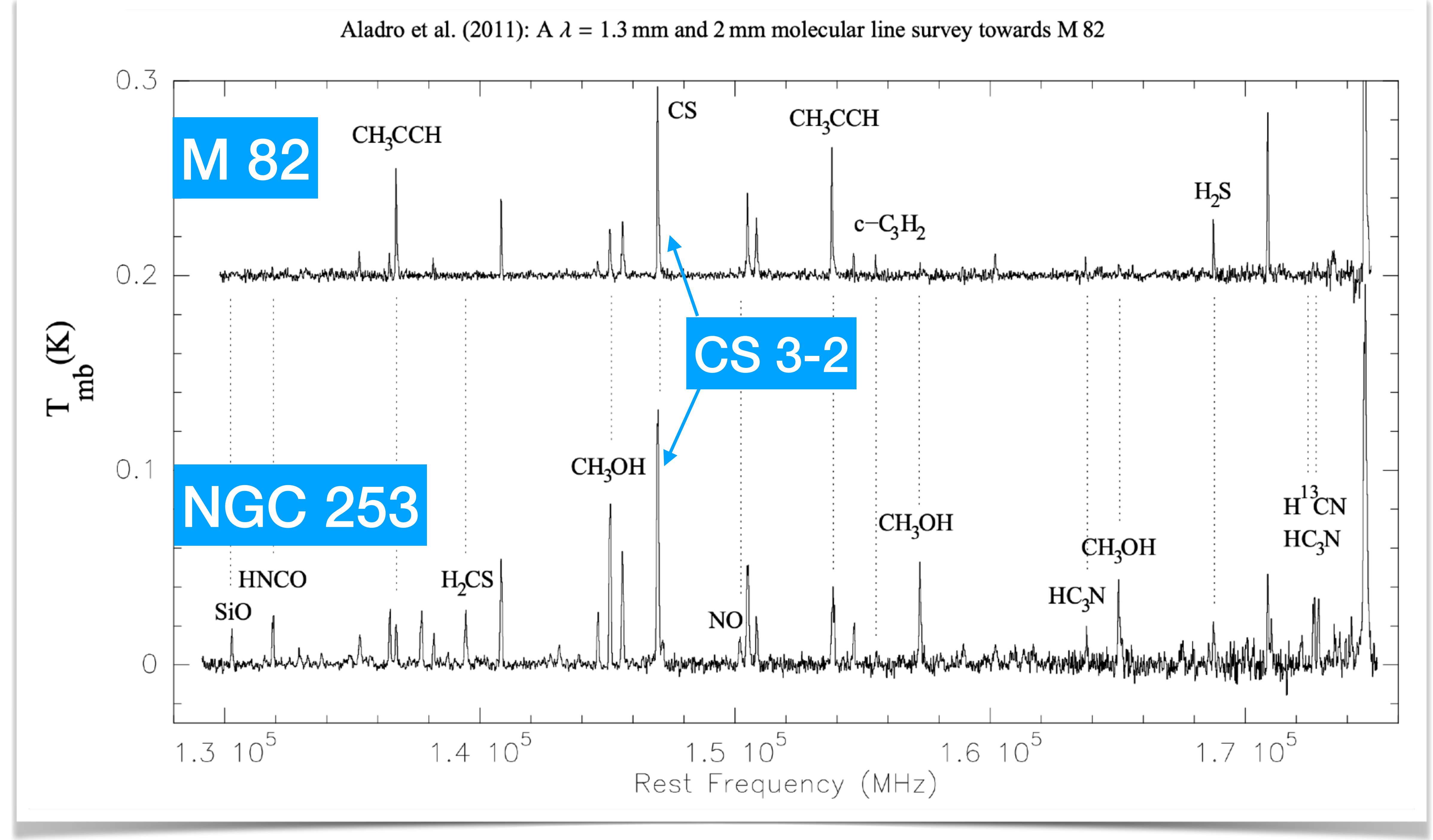

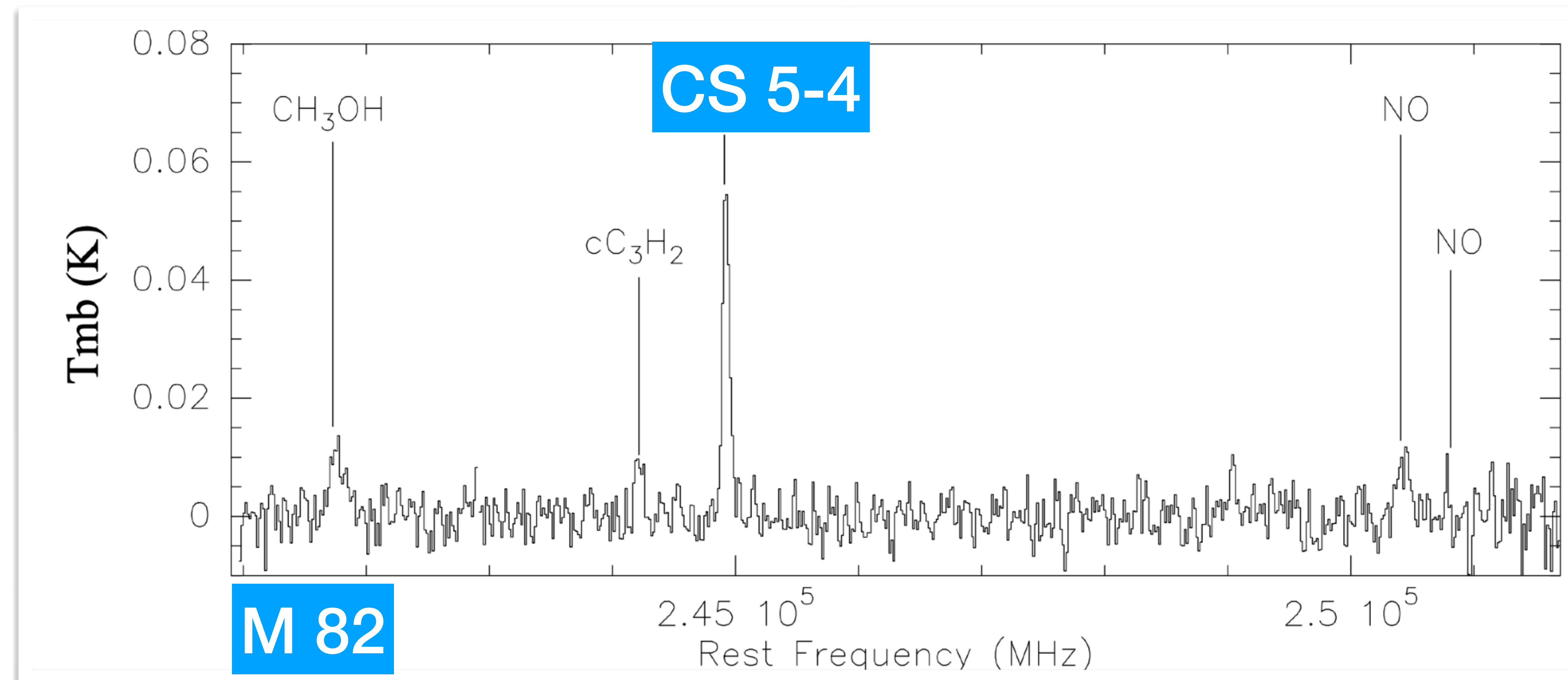

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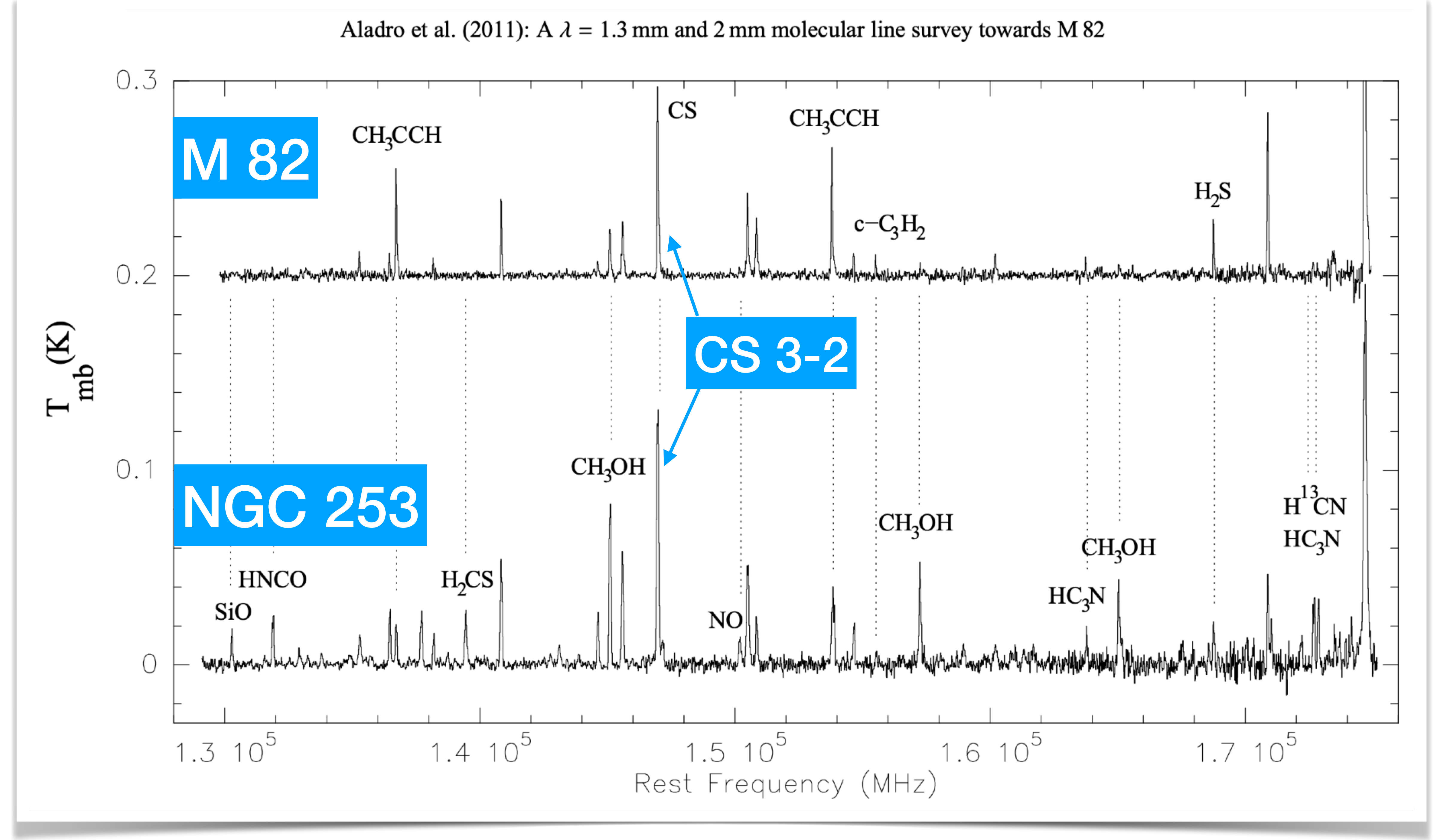

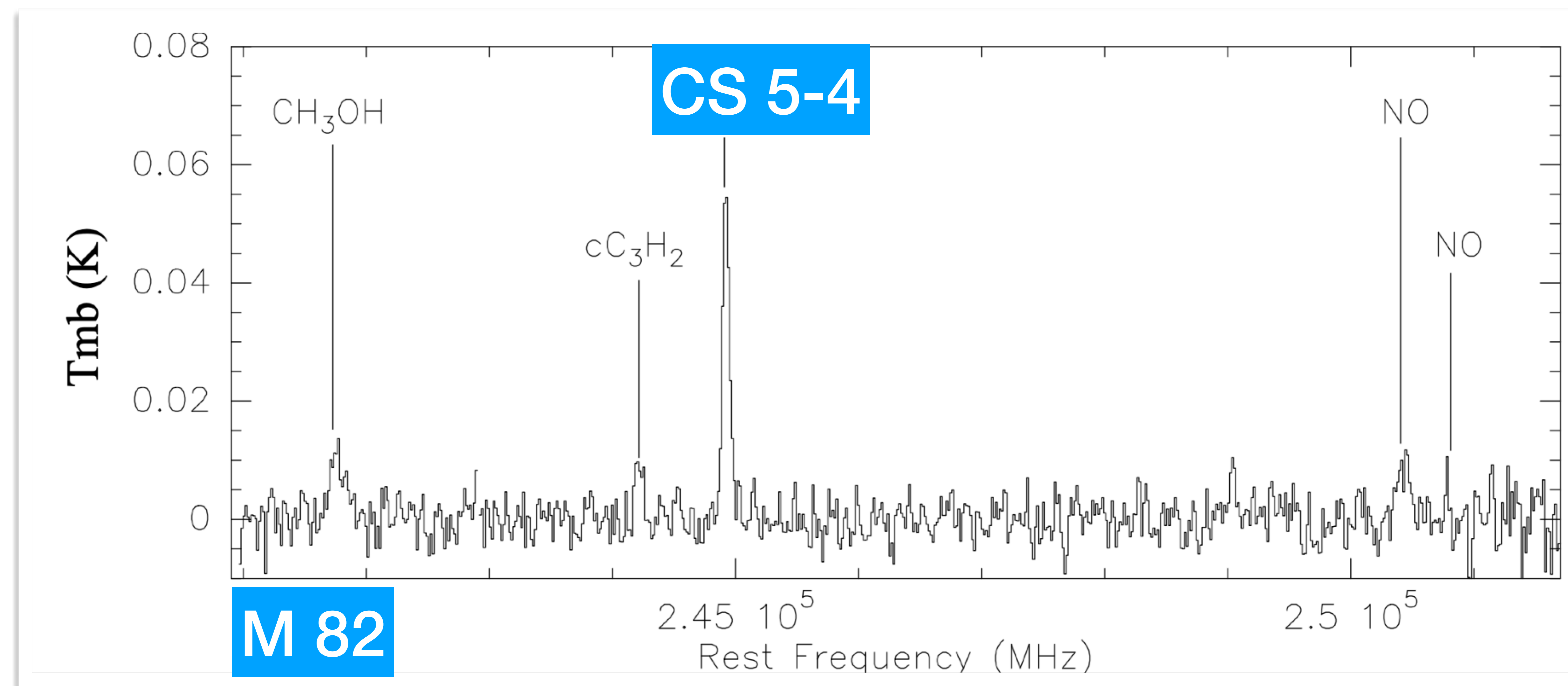

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Proposal & Science talk

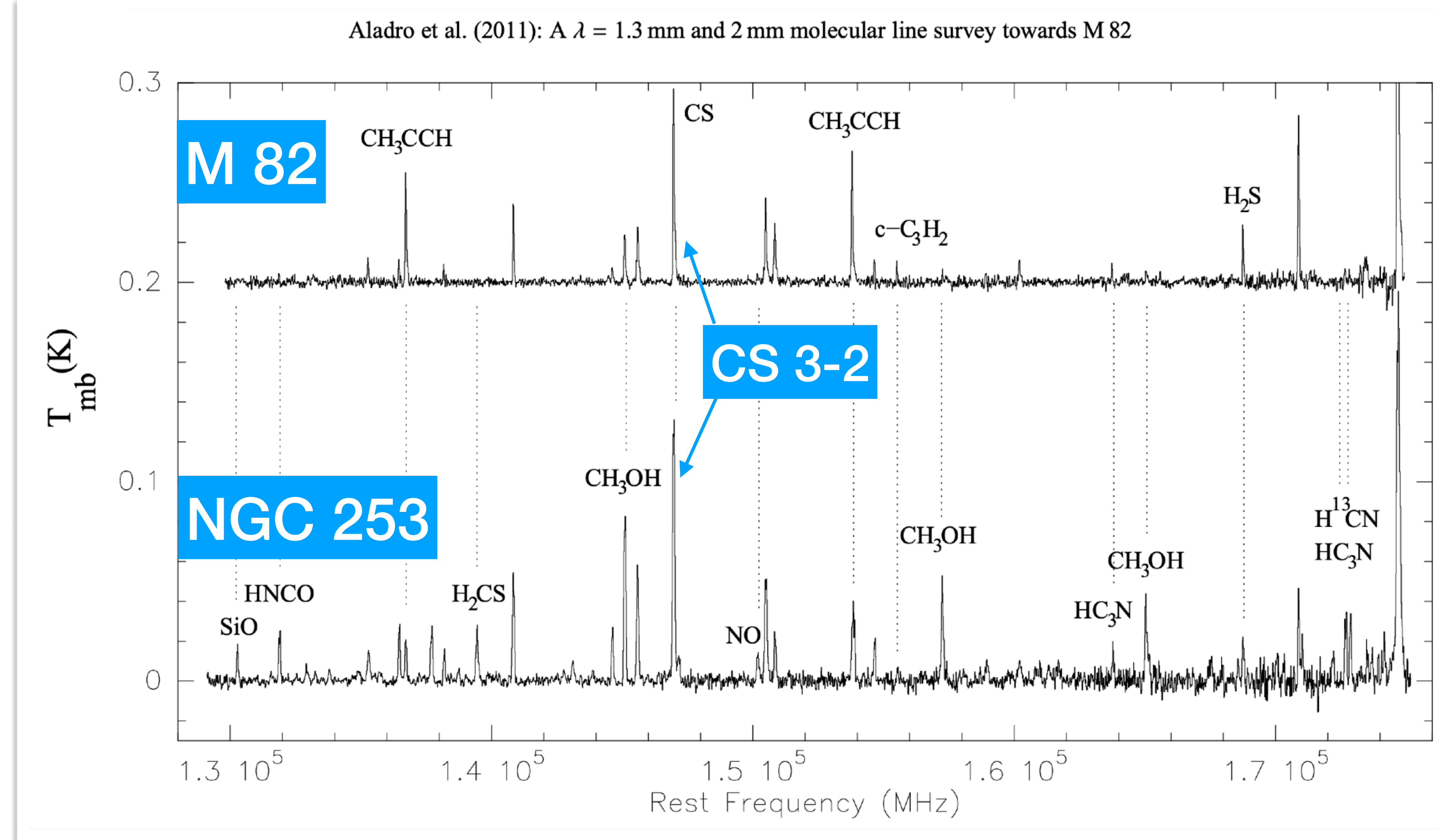
Calibration

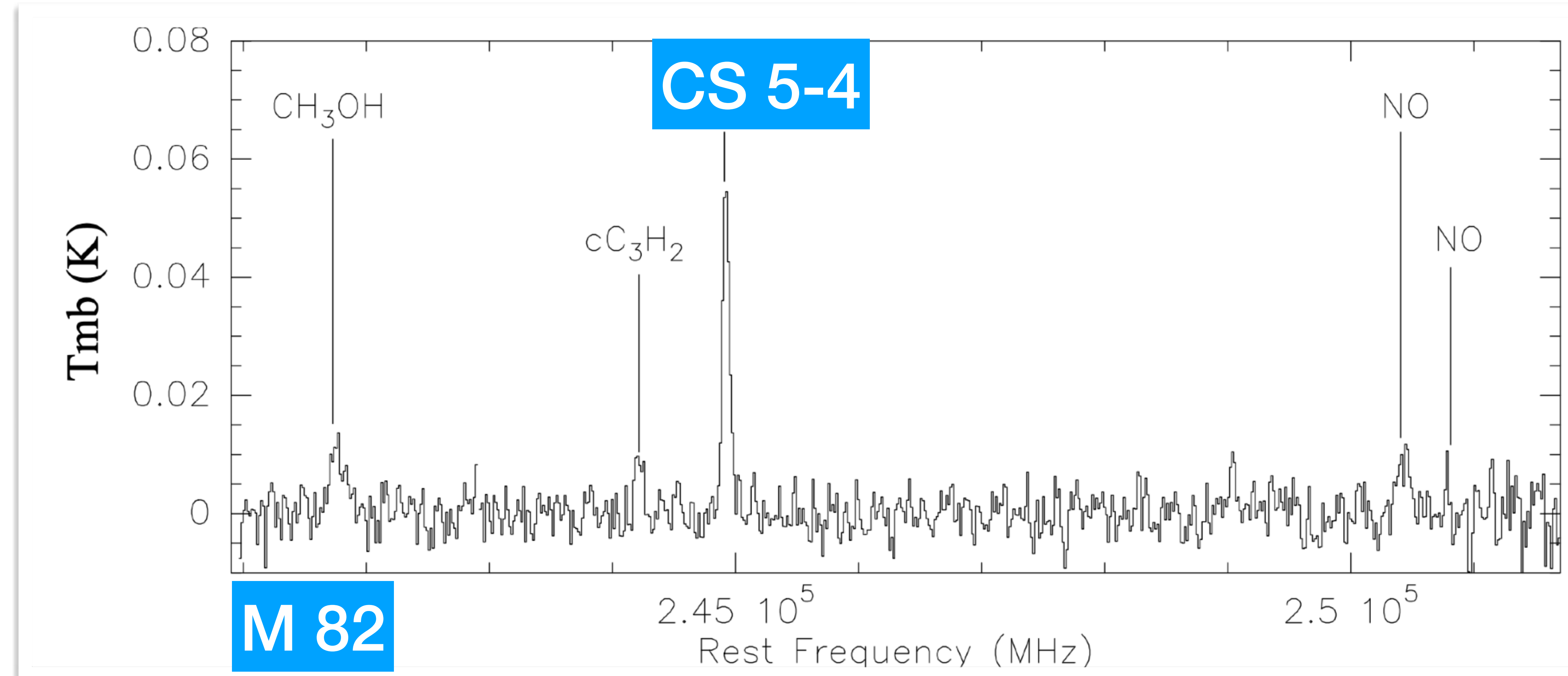
ITC

Intro to JCMT

Observing Tool

Starlink





Please refer to other talks & tutorials!

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  — see talk “JCMT Science”
- **How to do radio/sub-mm observations?**
  — understand the telescope and go for your science!

Goal

- Only a brief introduction
- to recognize when radio/submm observations might help solve an astrophysical problem, and to design, propose, and analyze radio/ submm observations.