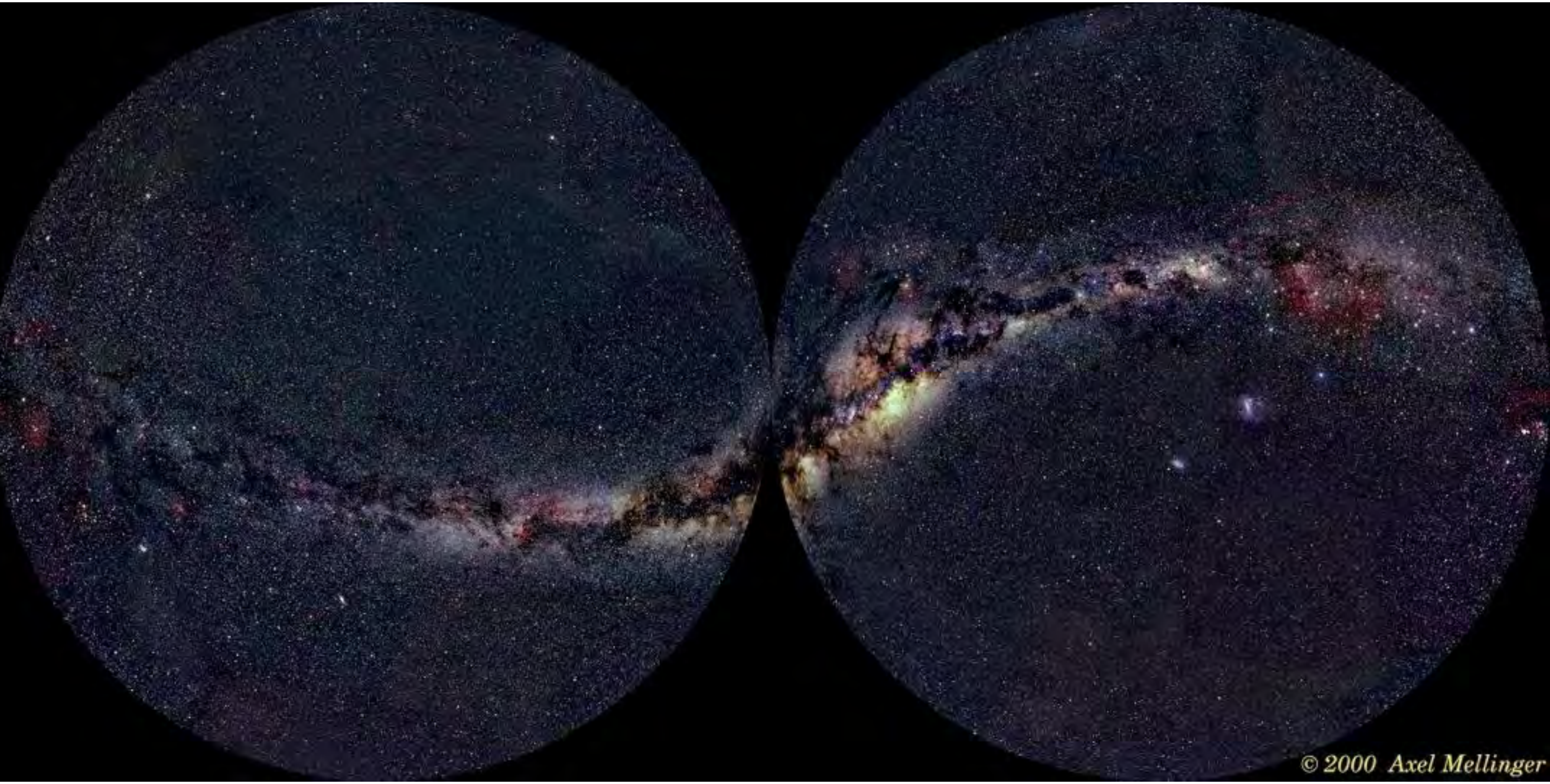
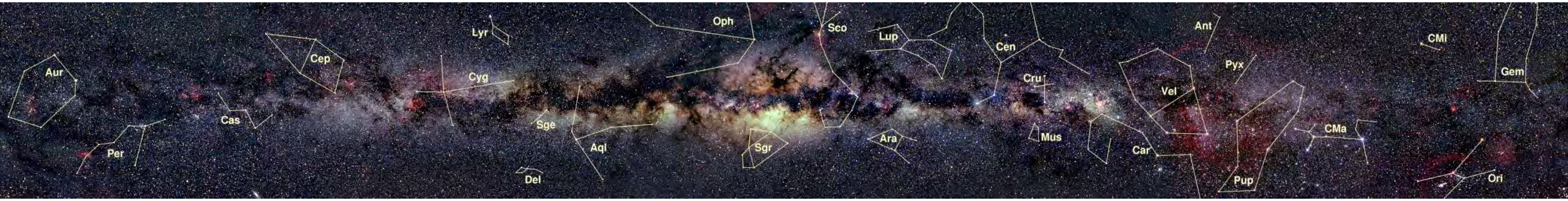
ALMA:
The Cool Side of the Universe

Leonardo Testi – ESO/INAF

ALMA
Joys and tribulations in building a transformational observatory


© 2000 Axel Mellinger


Aur
Per
Cas
Cep
Lyr
Cyg
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Oph
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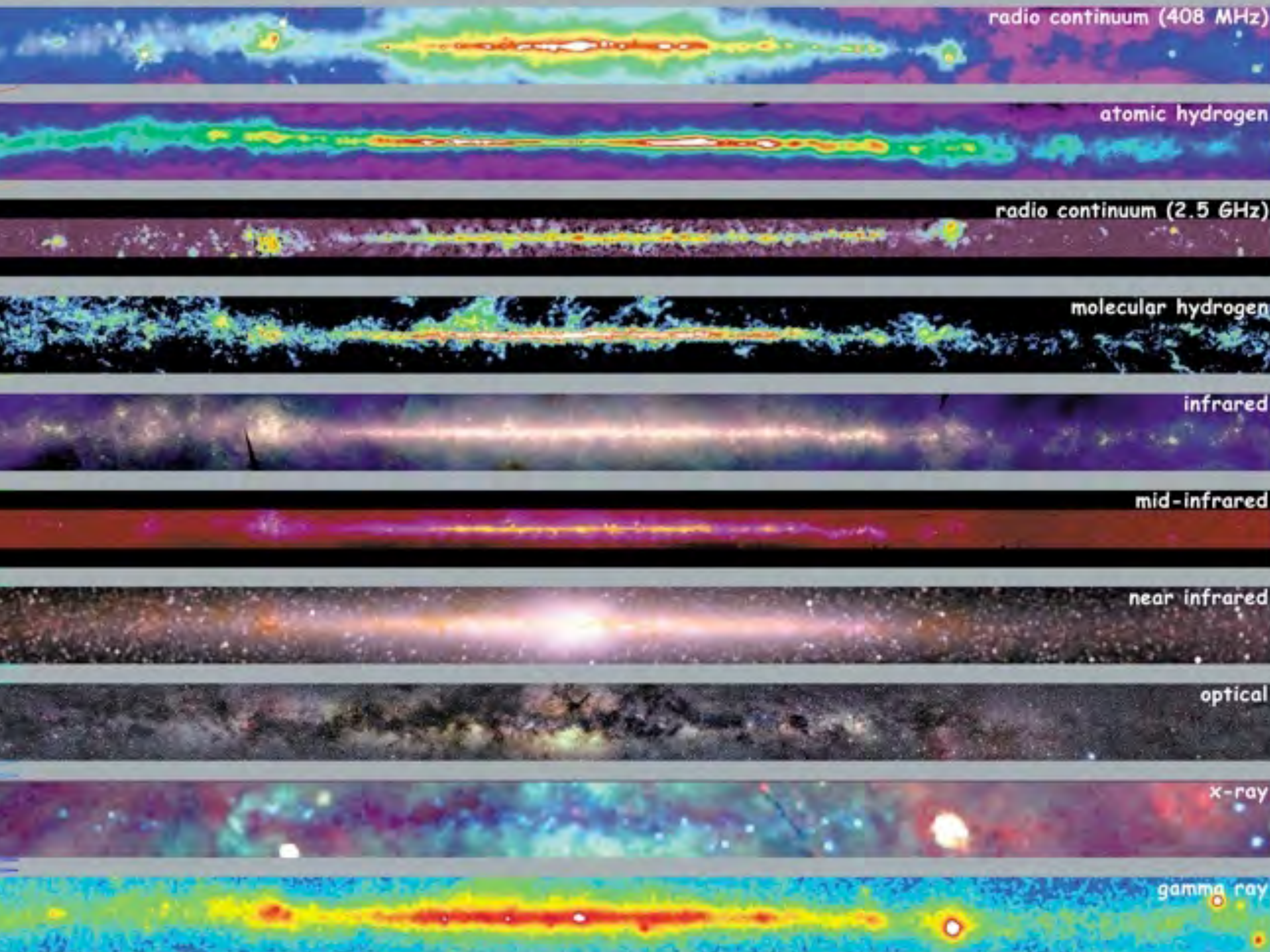
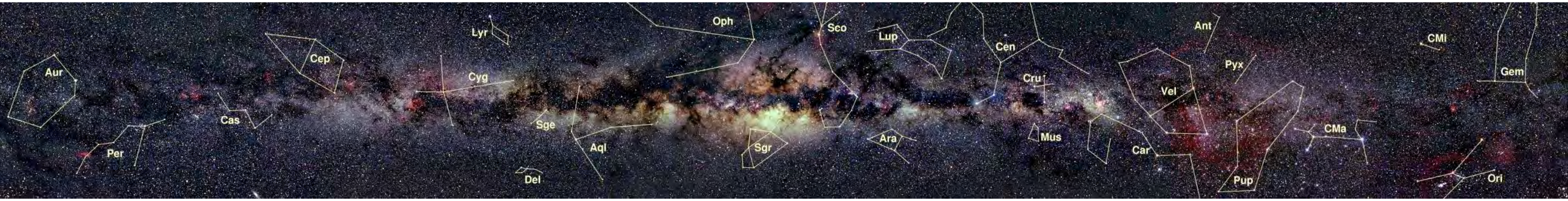
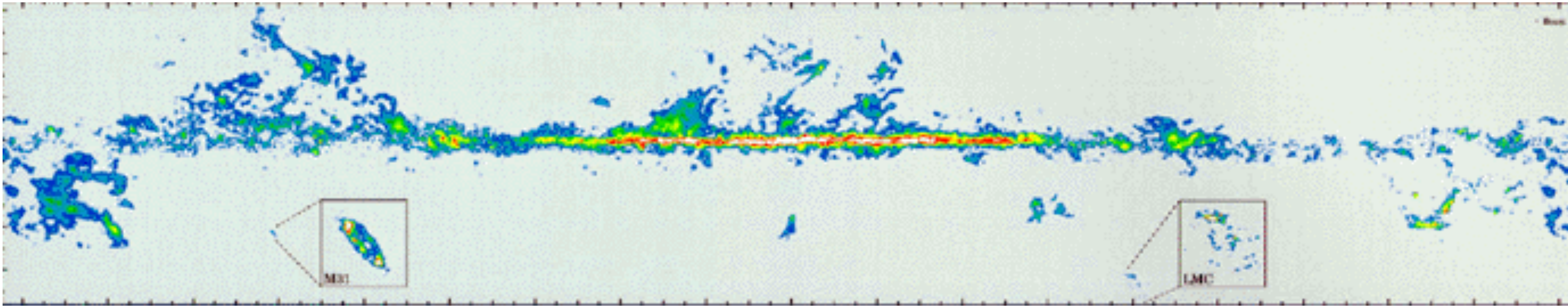
CMa
CMi
Gem
Ori


radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray

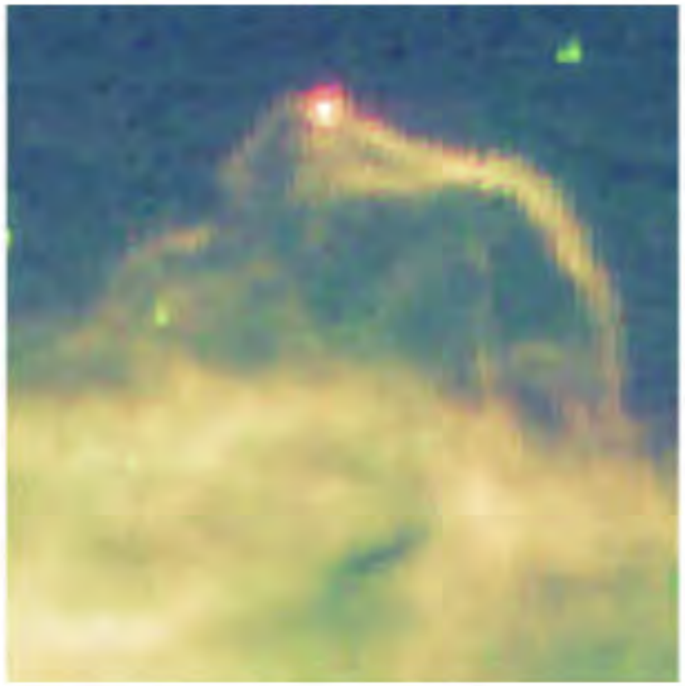
Molecular clouds and star formation



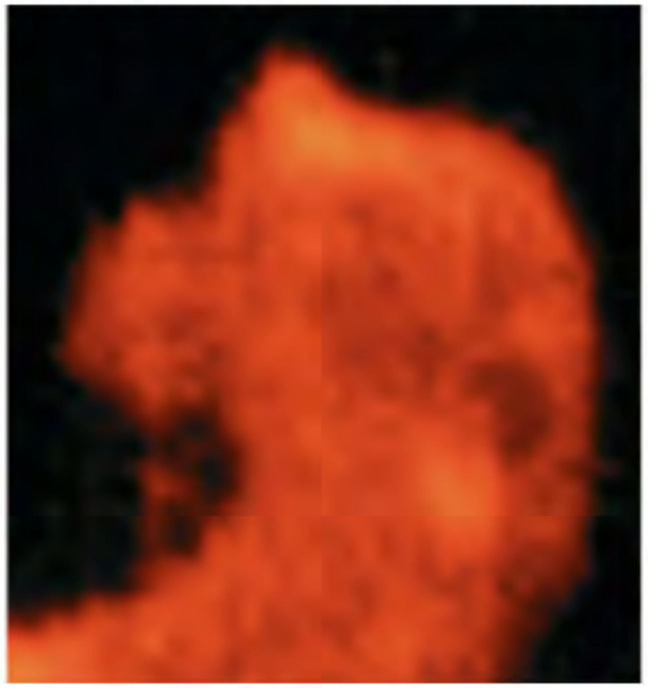


Optical (ESO)

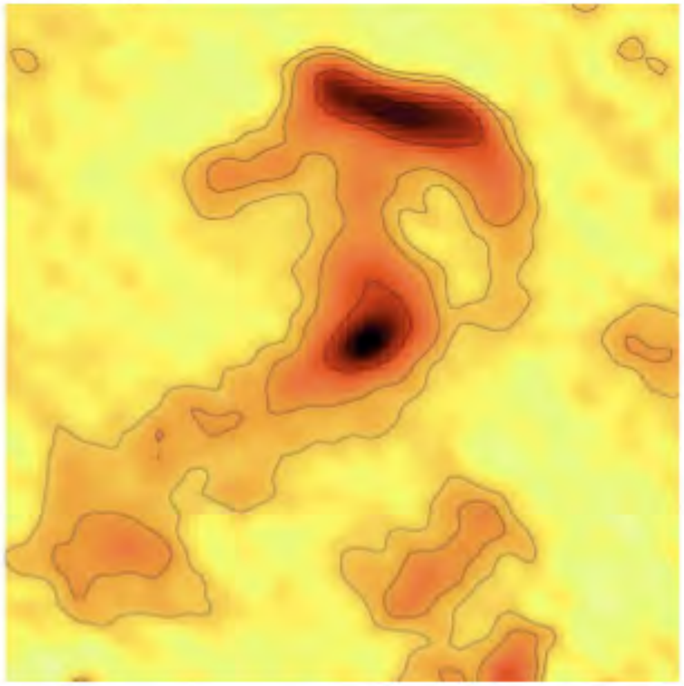
Infrared (ESA/ISO/ISOCAM)



Radio CO 3-2 Line (CSO)

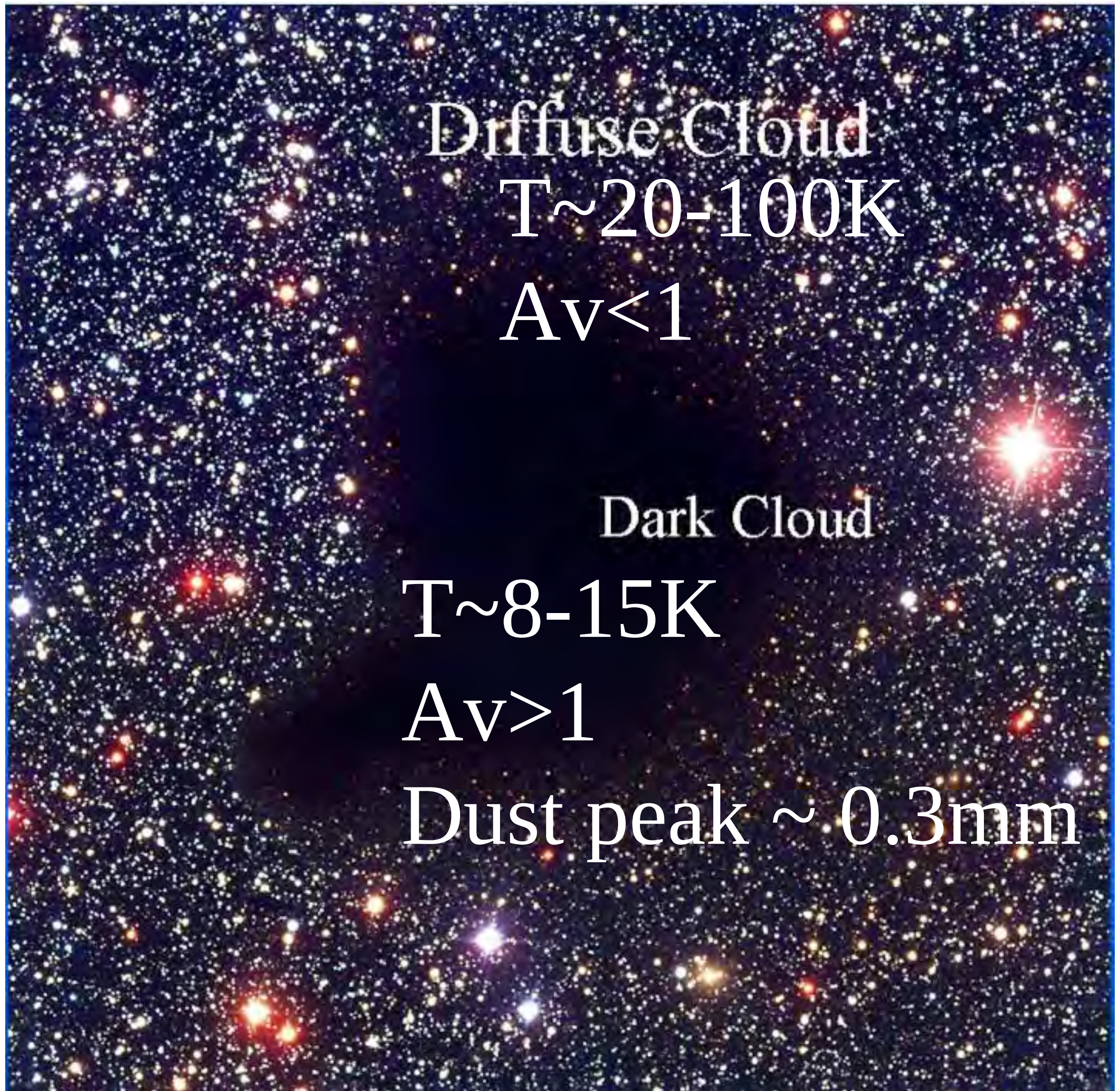


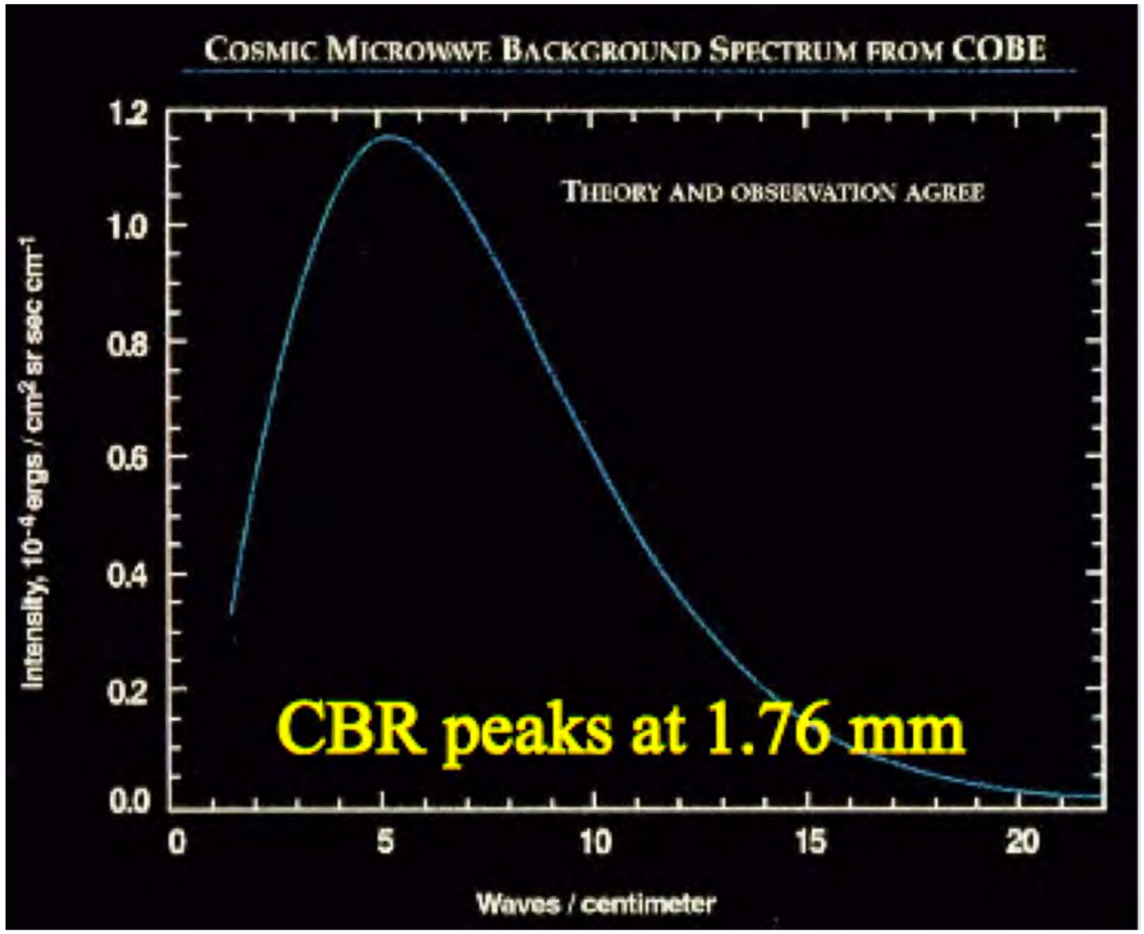
Submm (APEX)



Millimeter wavelengths: thermal continuum

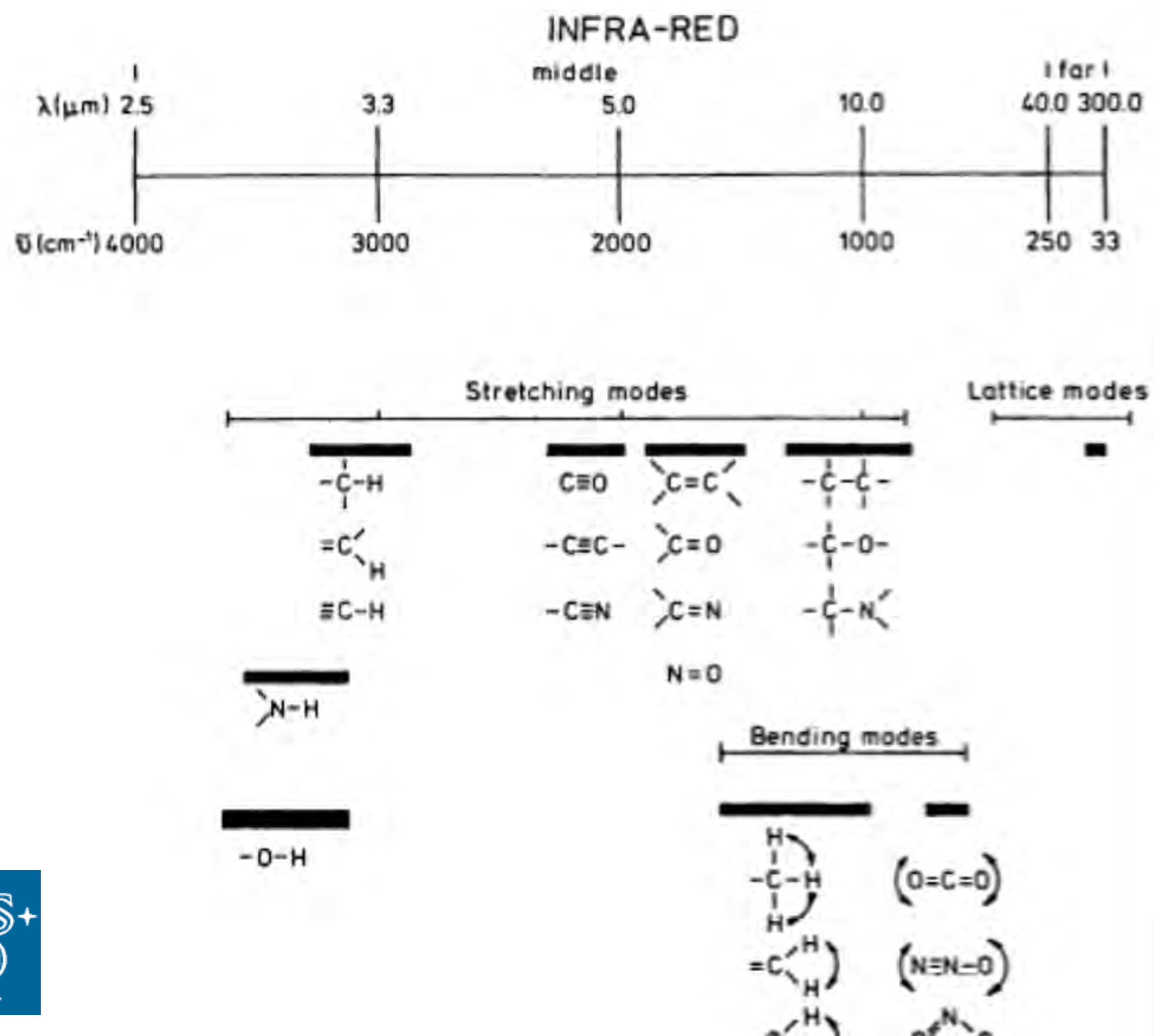
- Thermal emission:
  - near-IR & visible: hot matter 1000K-100000K
  - Far-IR & millimeter: cold matter 3K-100K
  - BB: λ_m=hc/3kT~0.5/T mm   Dust: λ_m=hc/(3+β)kT~0.3/T mm

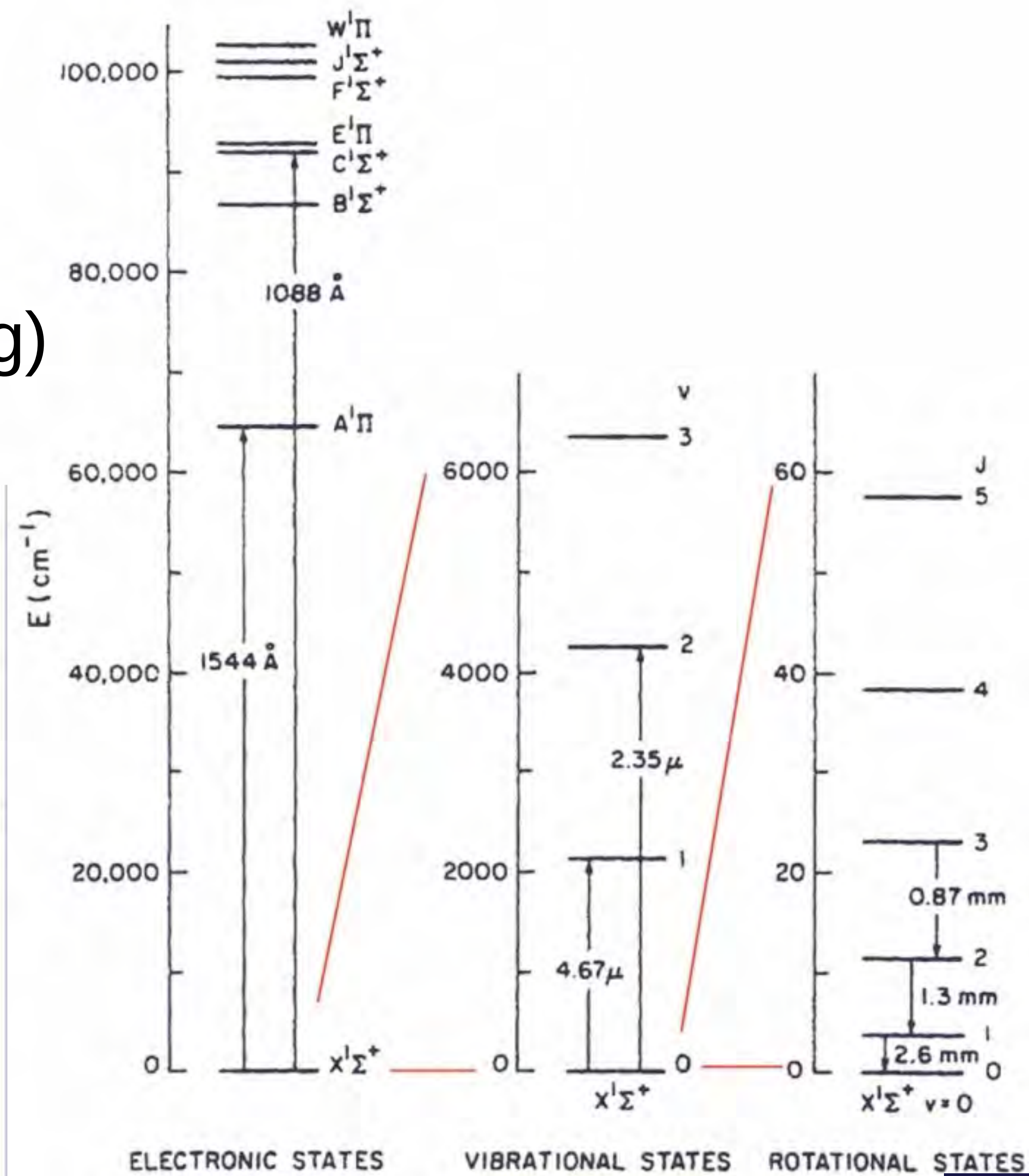




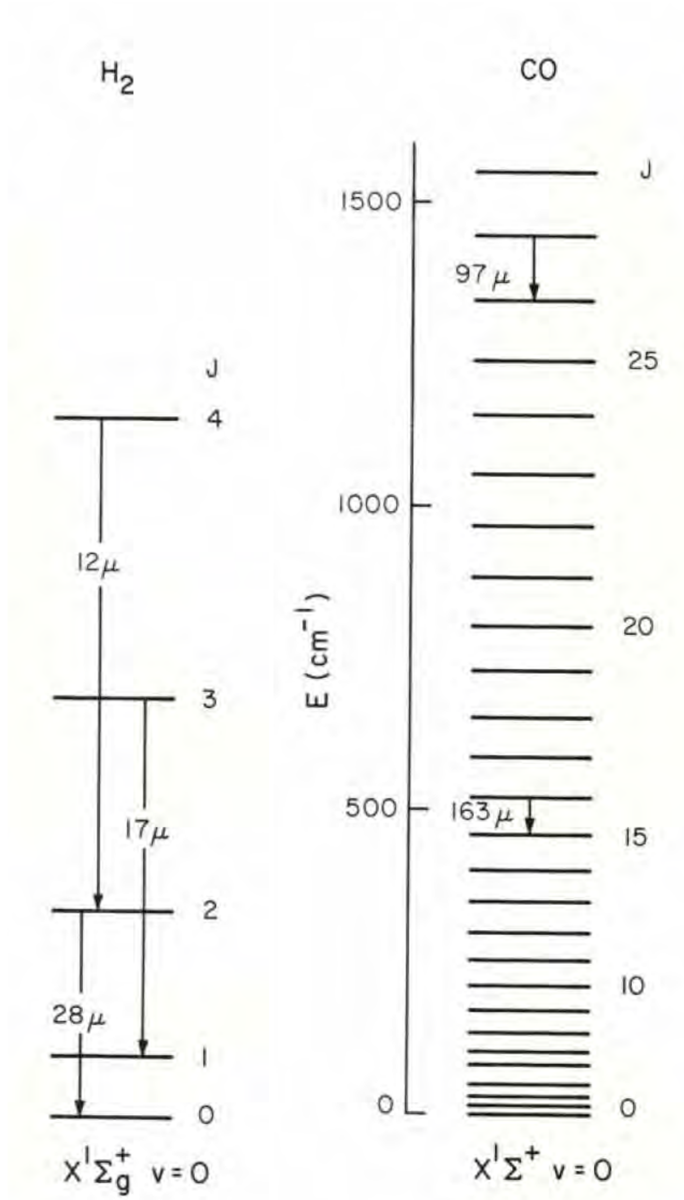
Molecular line emission

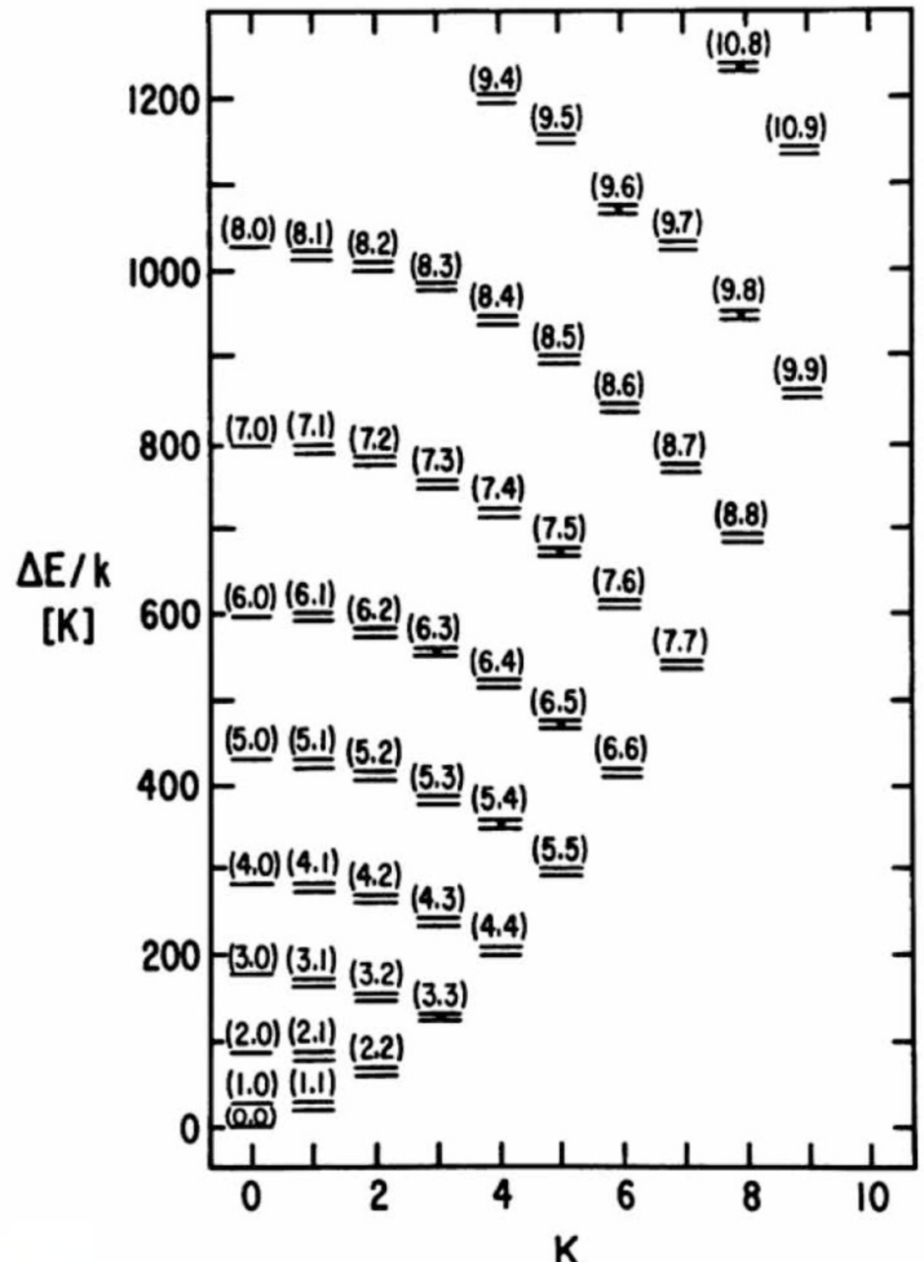
- Molecular lines:
  - Rotation
  - Vib (Stretching and Bending)
  - Electronic

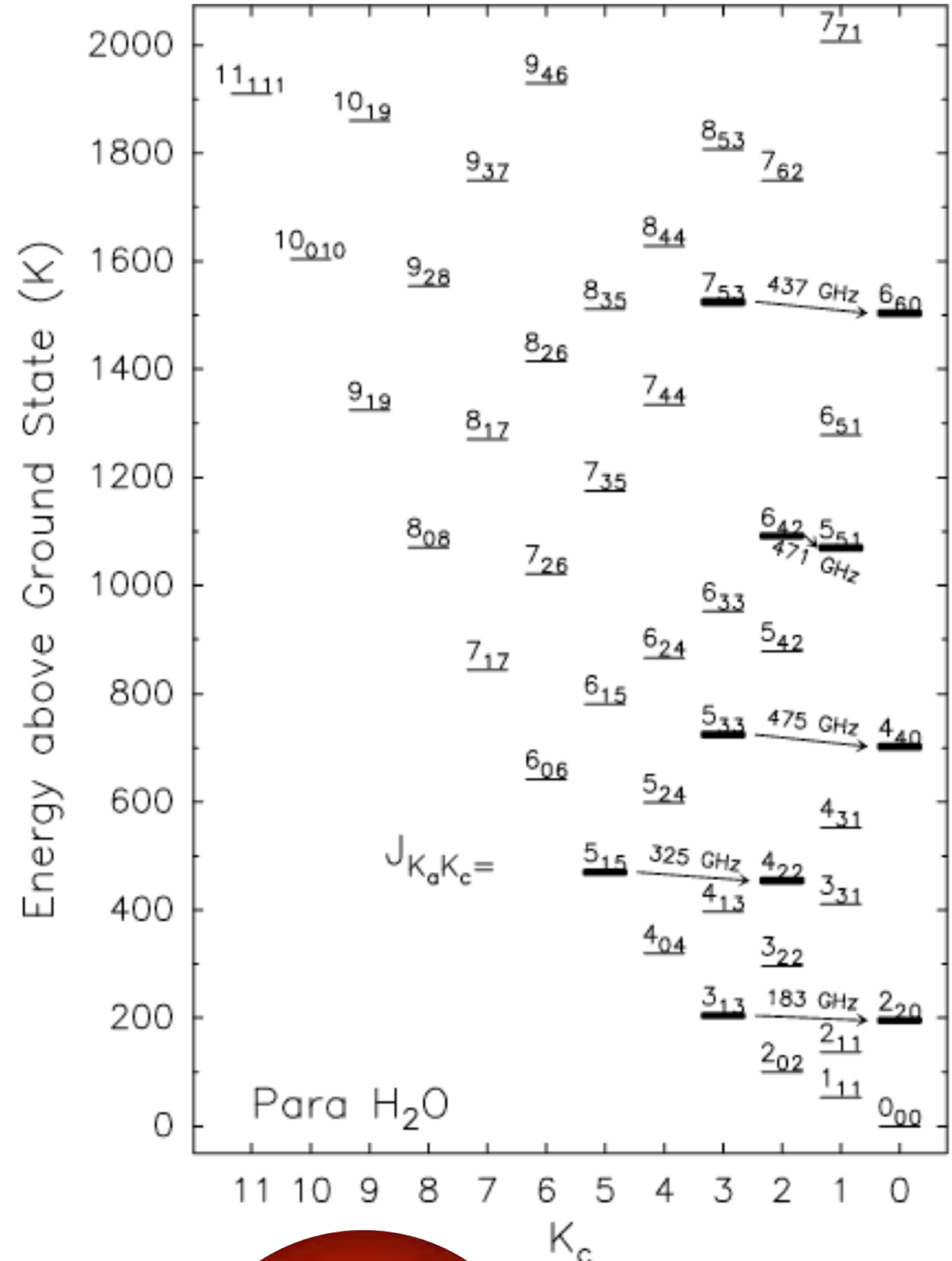


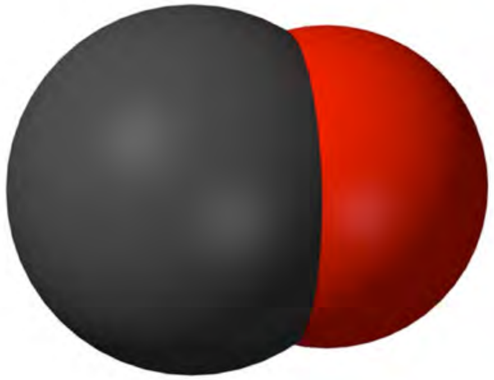


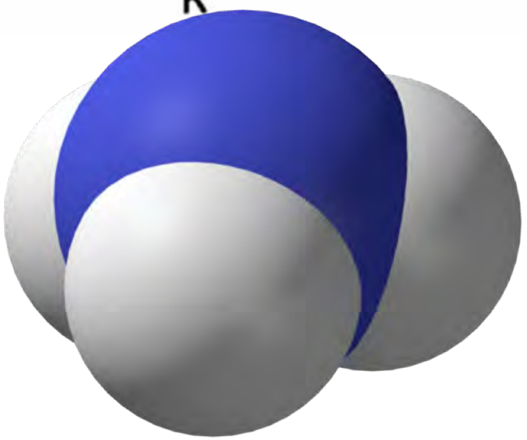
Examples of simple Astrophysically relevant molecules

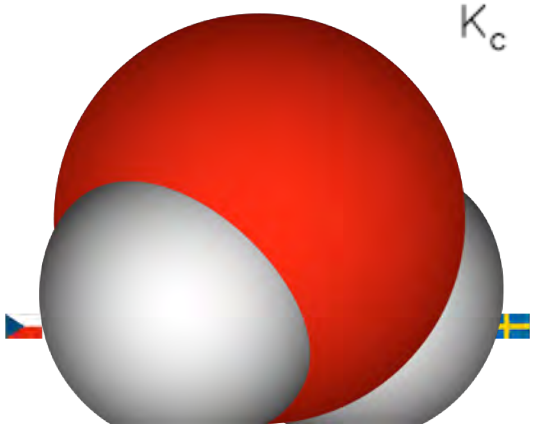


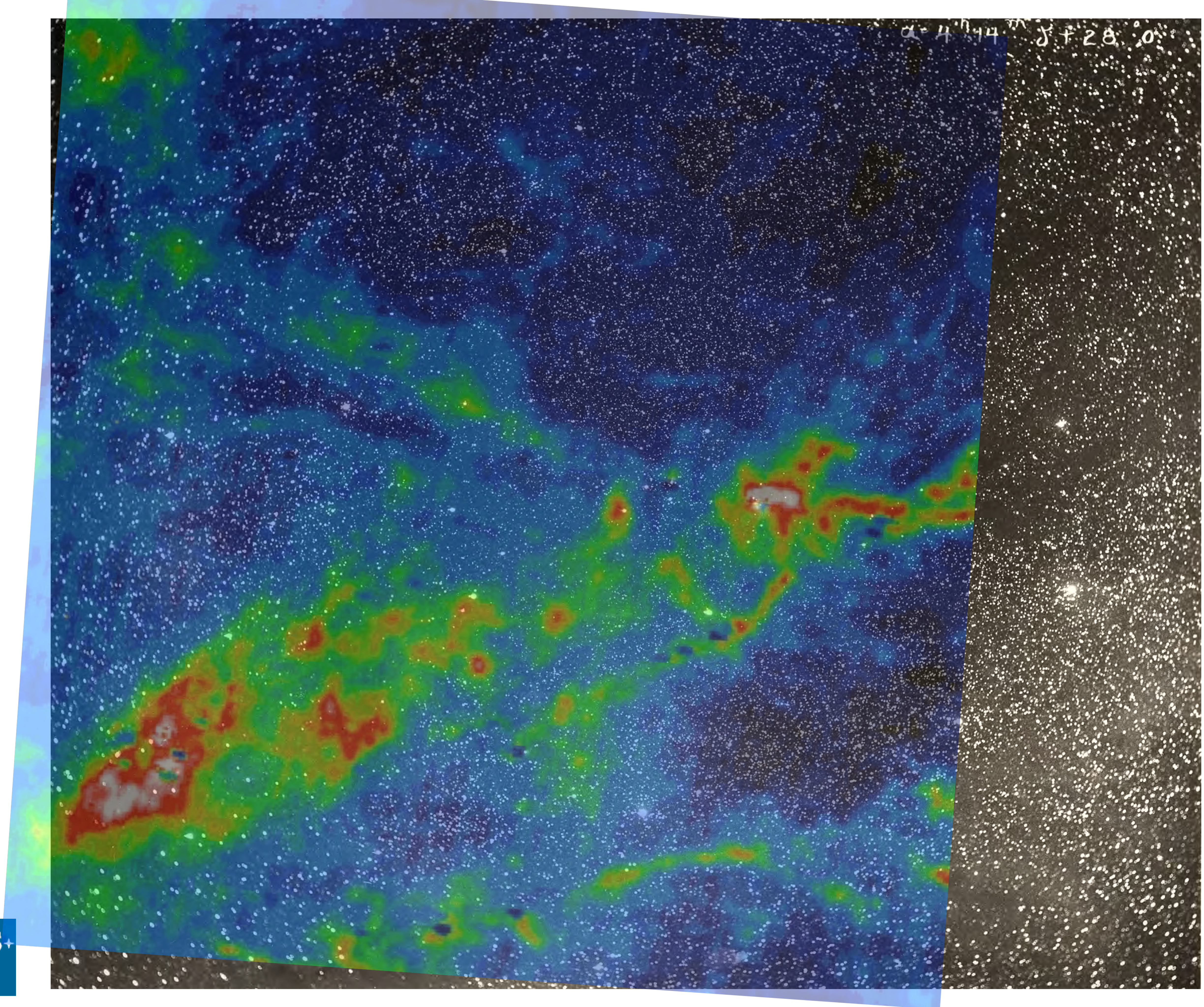






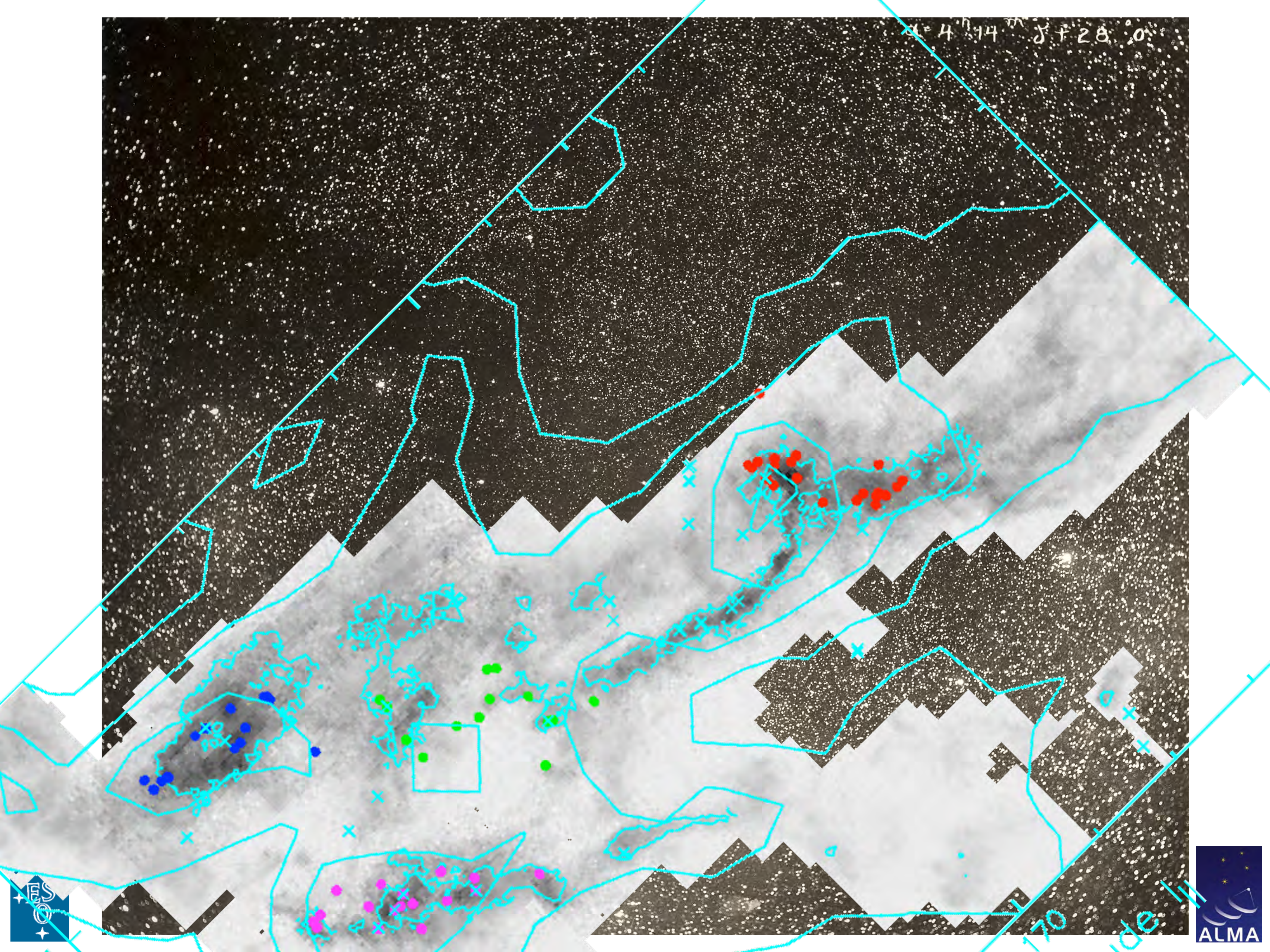






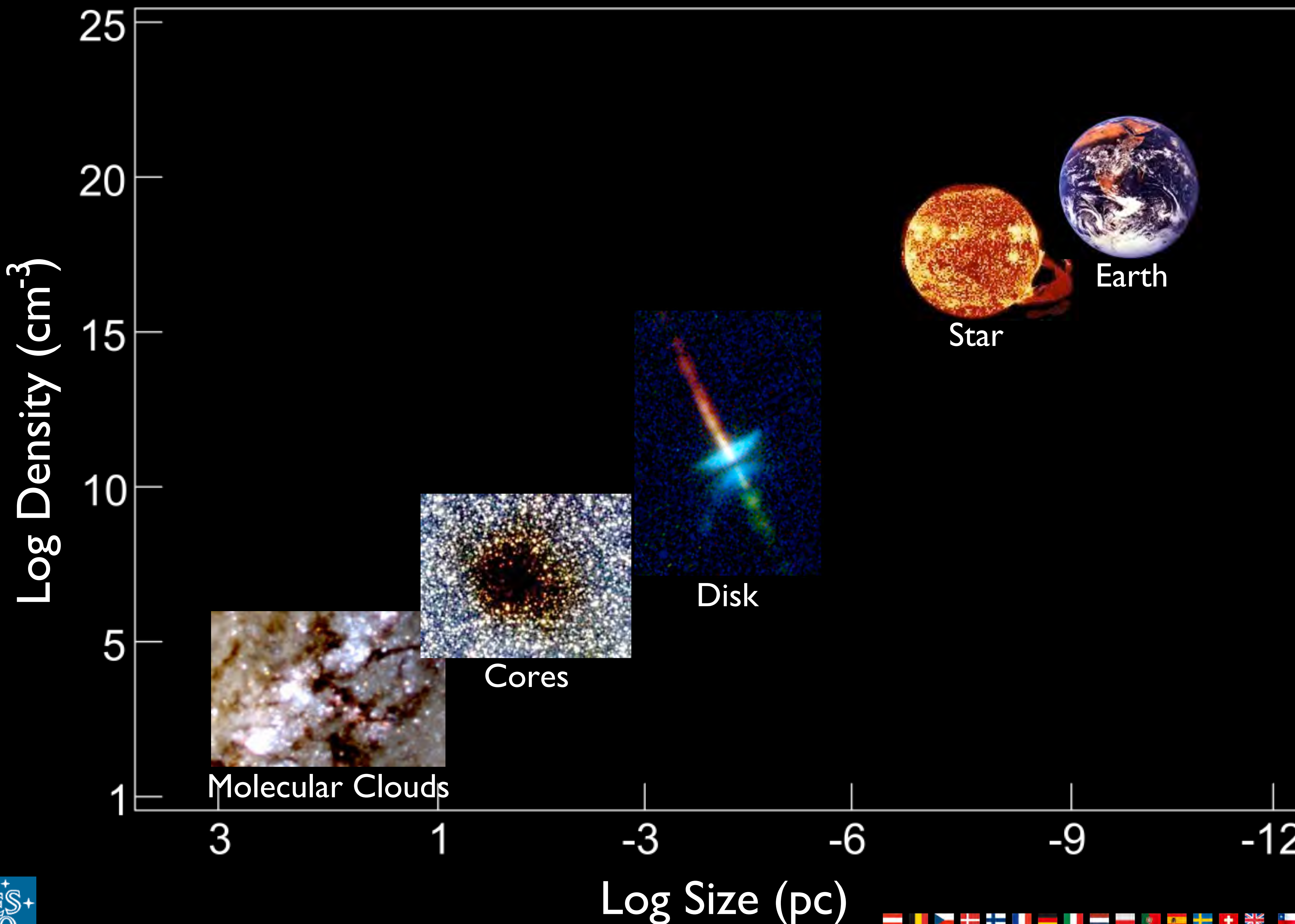
ESO

ALMA

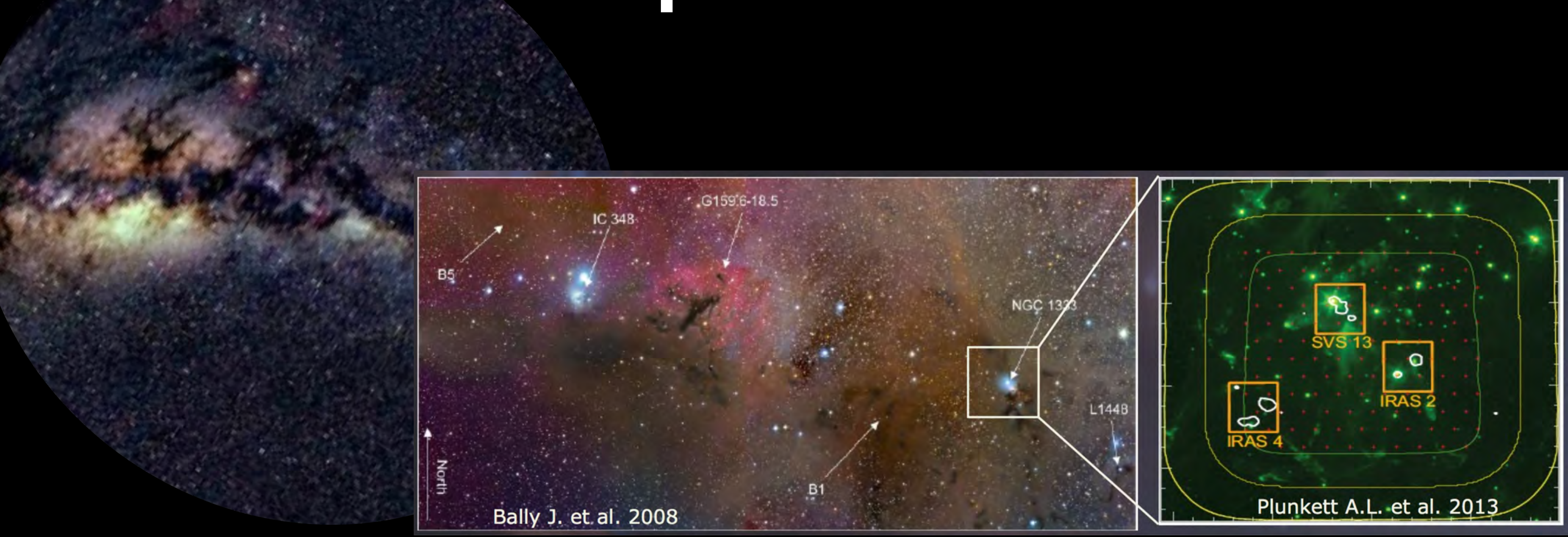


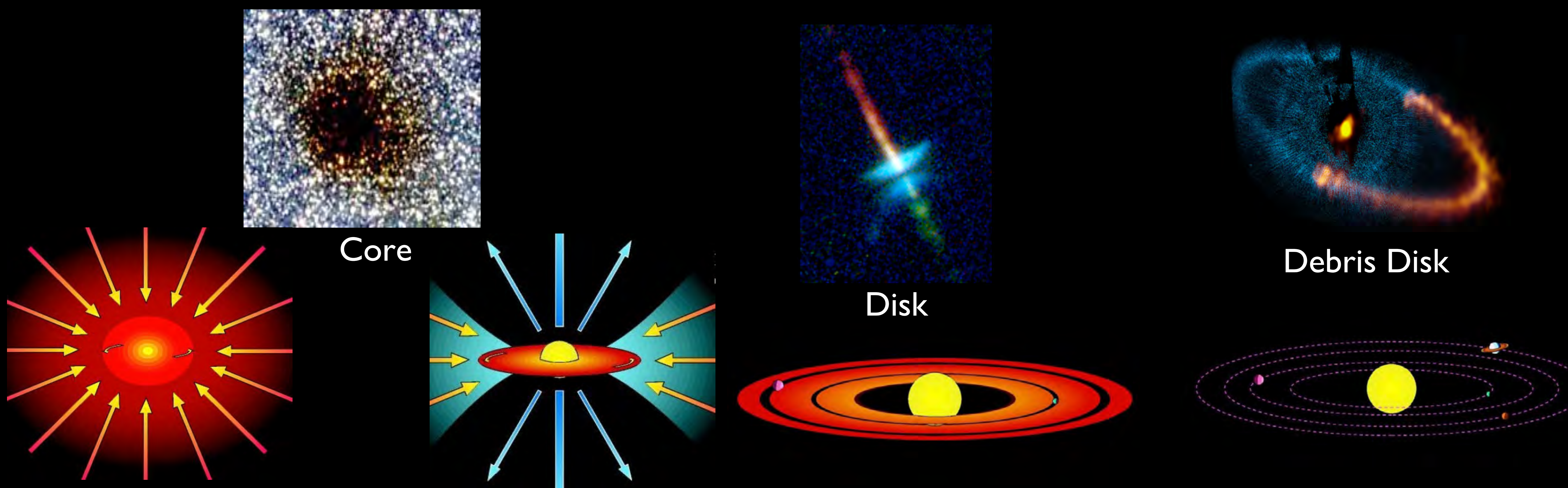
ESO
ALMA

From clouds to stars and planets

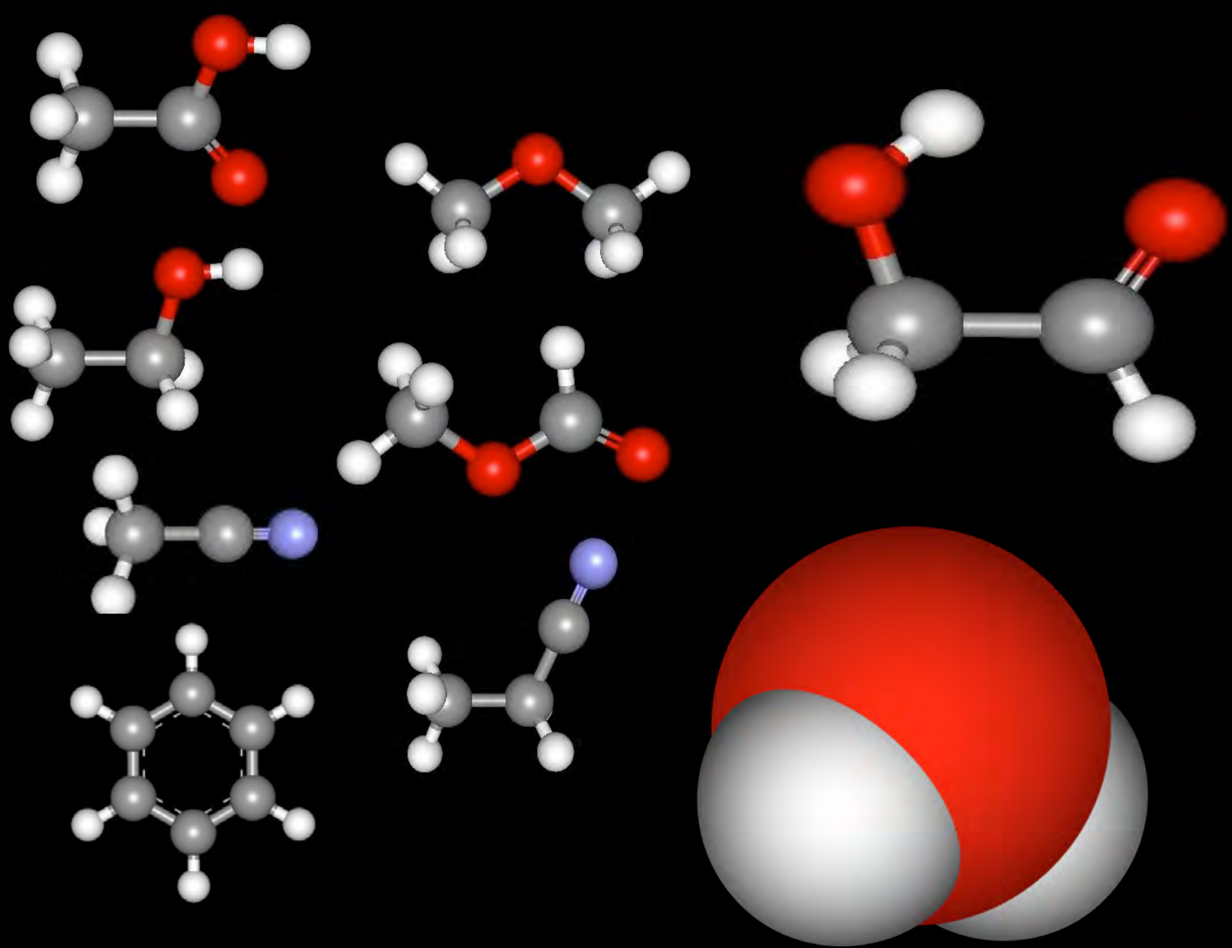


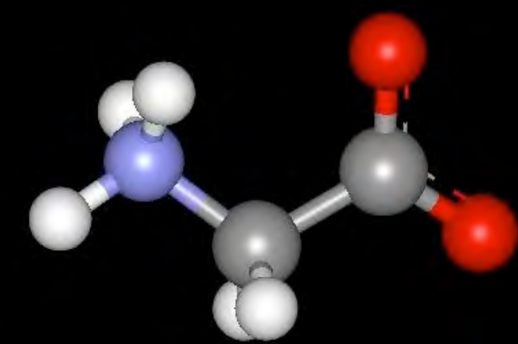
Star and planet formation



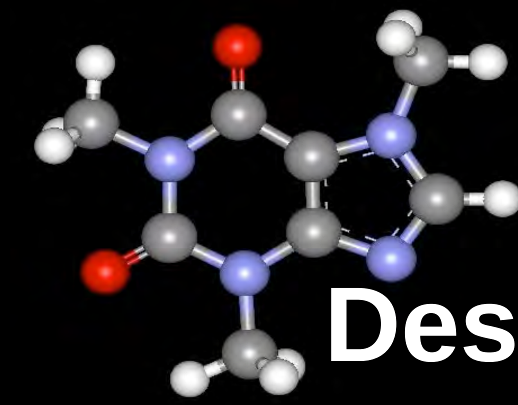


How to build habitable planets



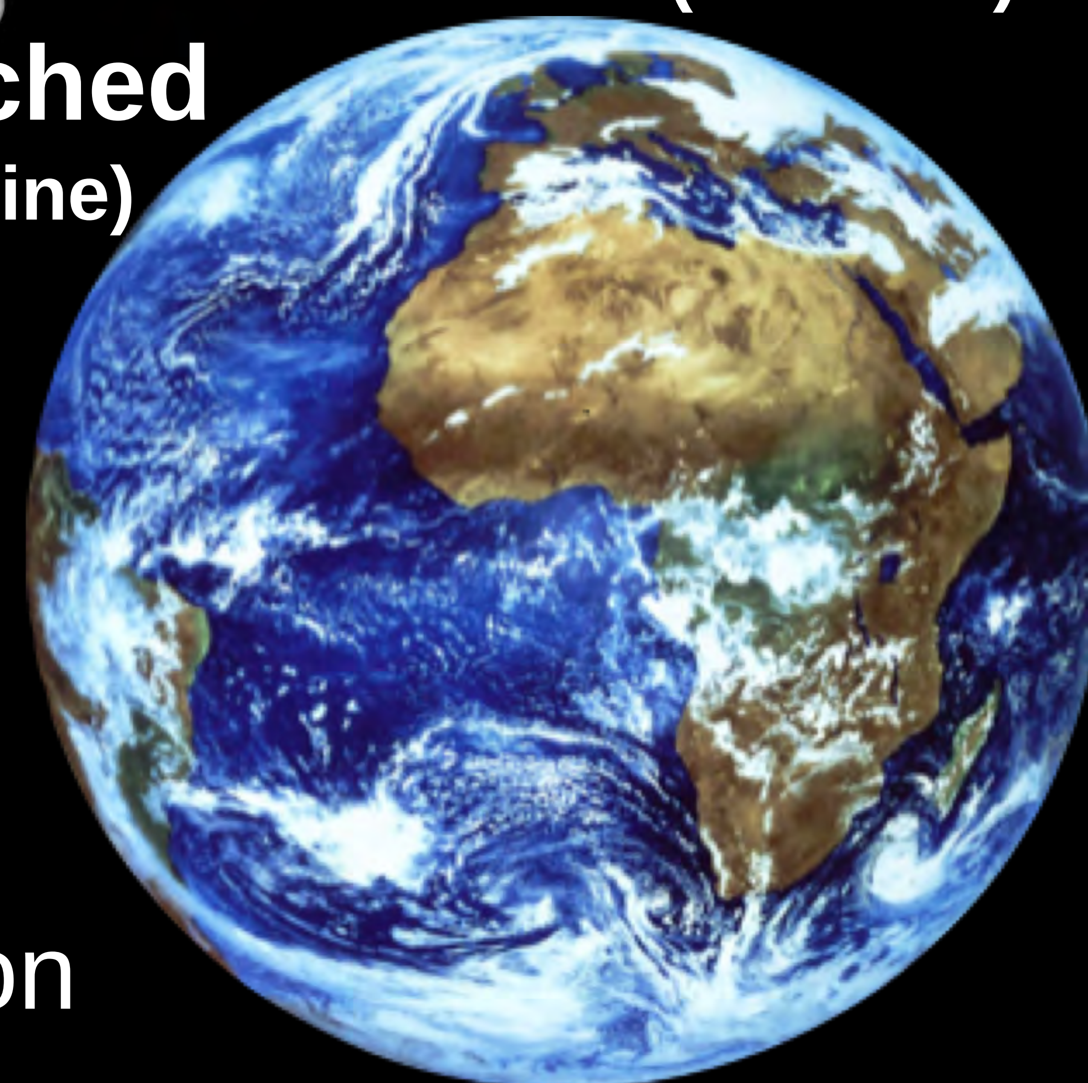


Searched
(Glycine)



Desired
(Caffeine)

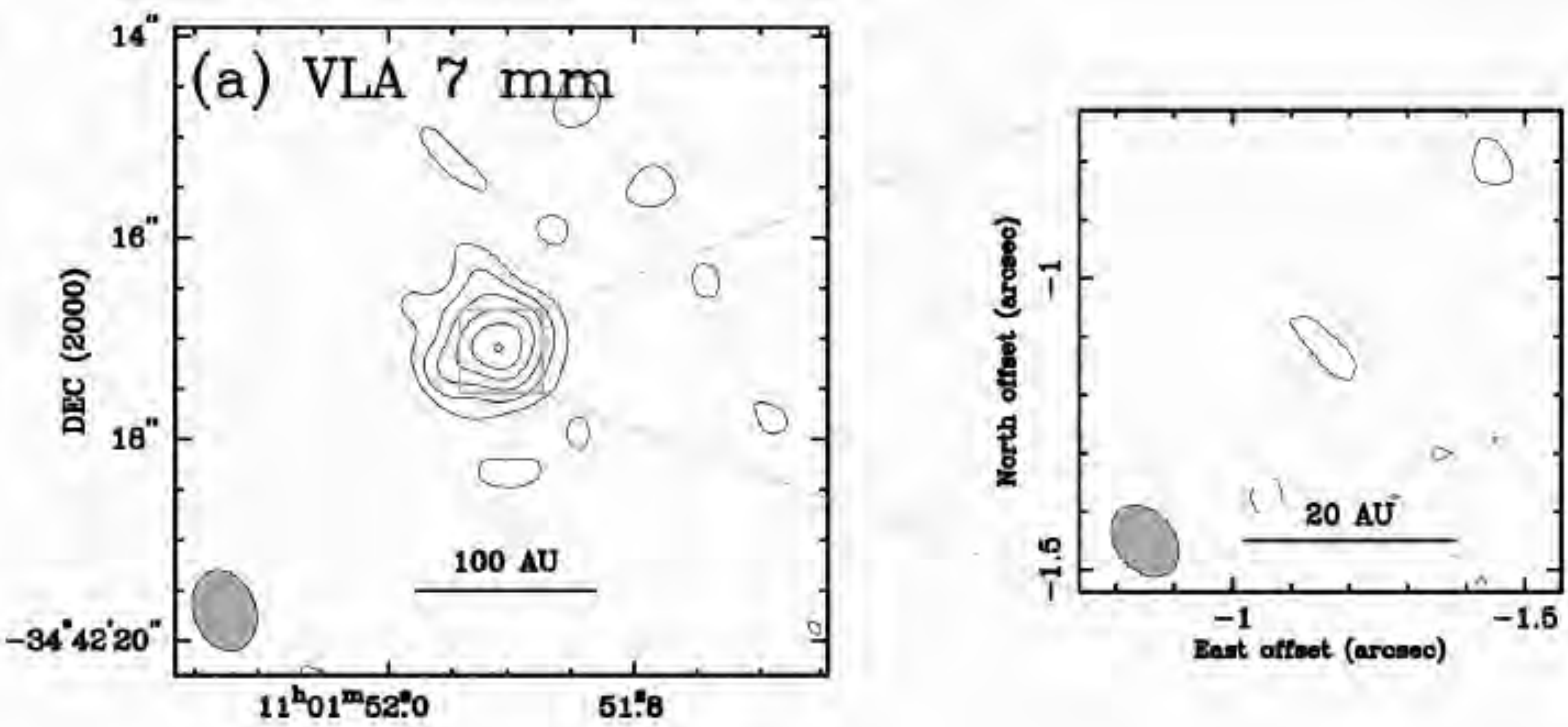
Observed in ISM and protostars



Recipe:

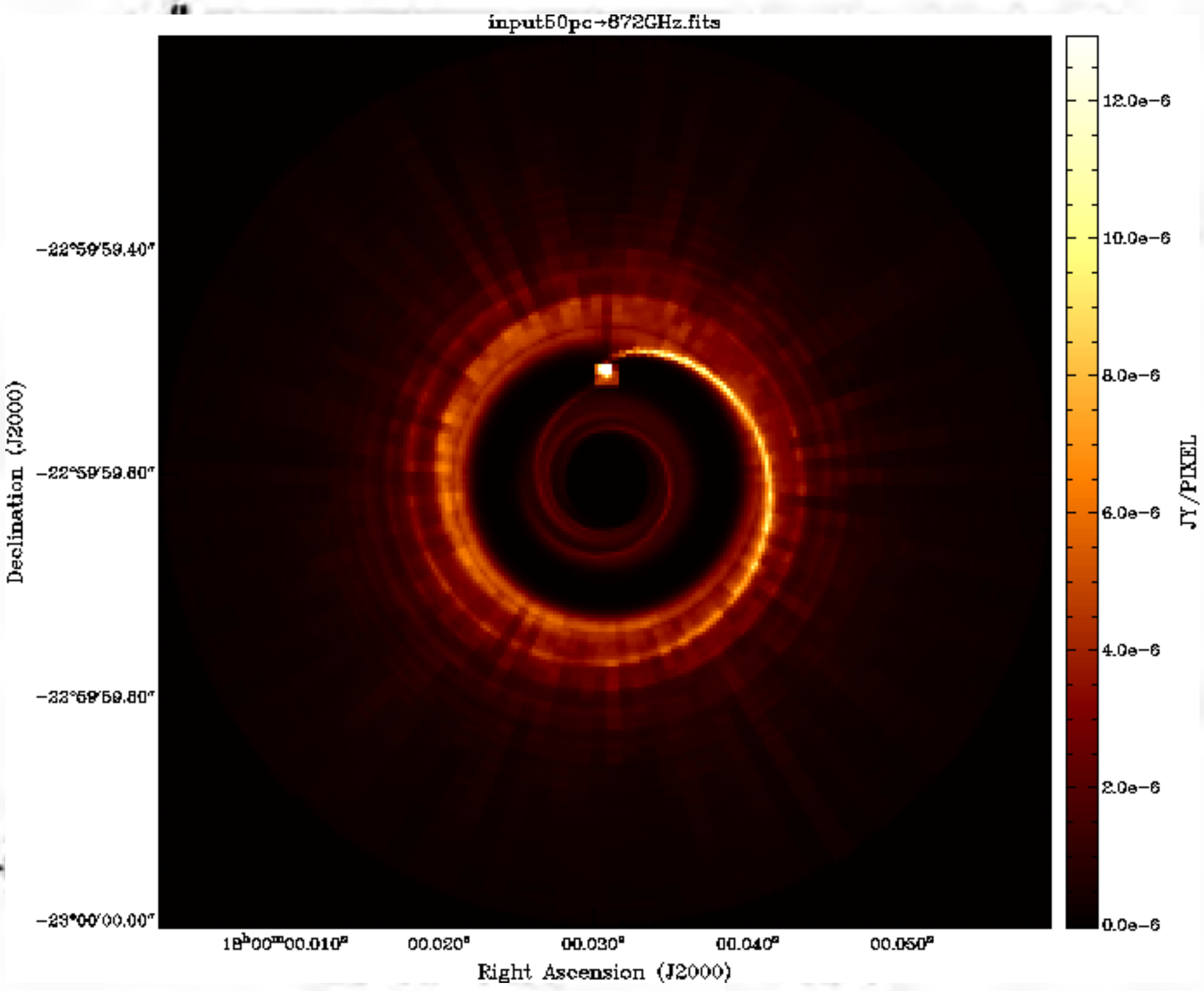
- Assemble Eath-like planets
- Place them at the right location
- Deploy pre-biotic material

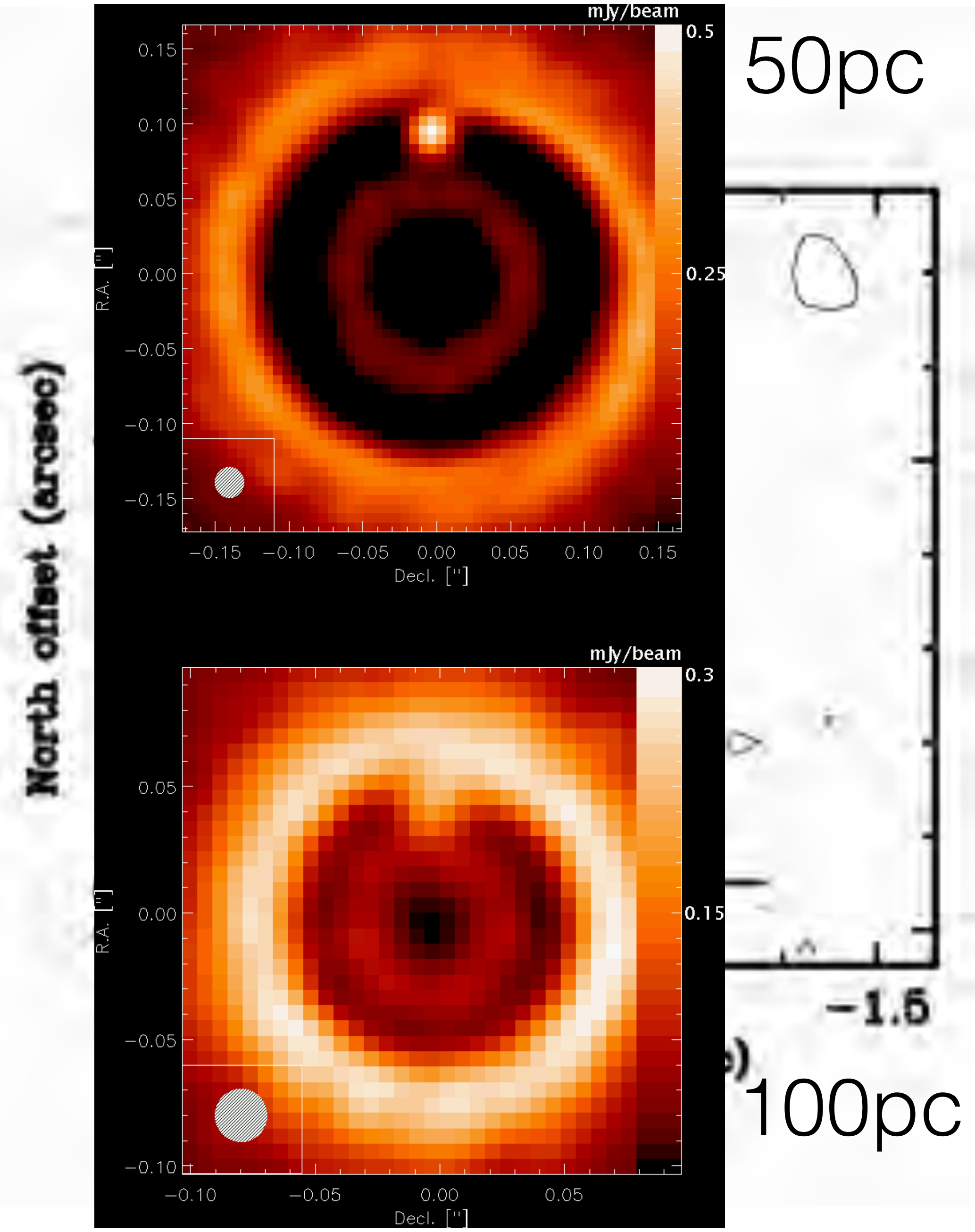
Disks and Planet Formation



- TW Hya - Closest known protoplanetary disk (50pc)
- Possible evidence of ongoing planet formation

Disks and Planet Formation



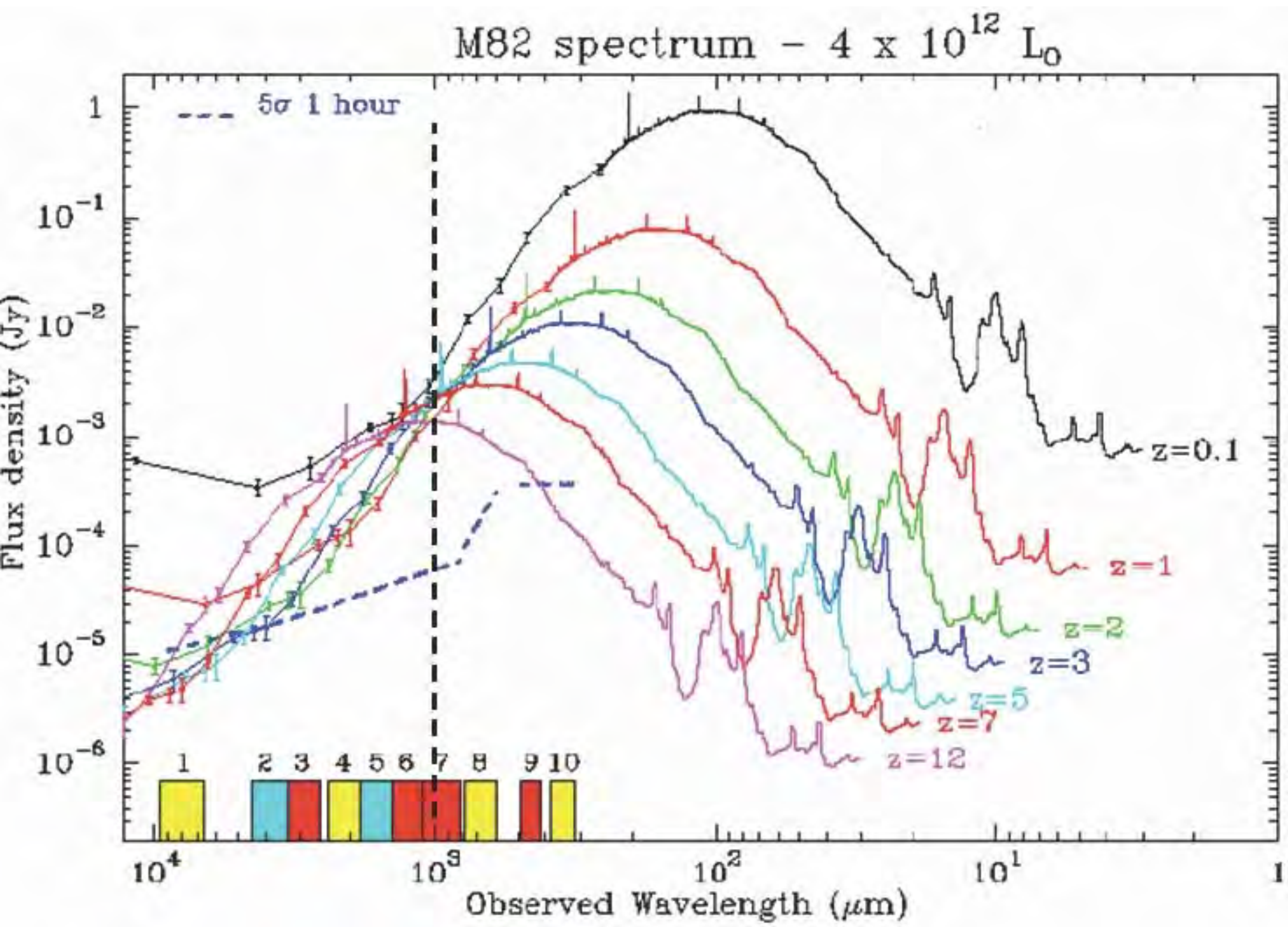


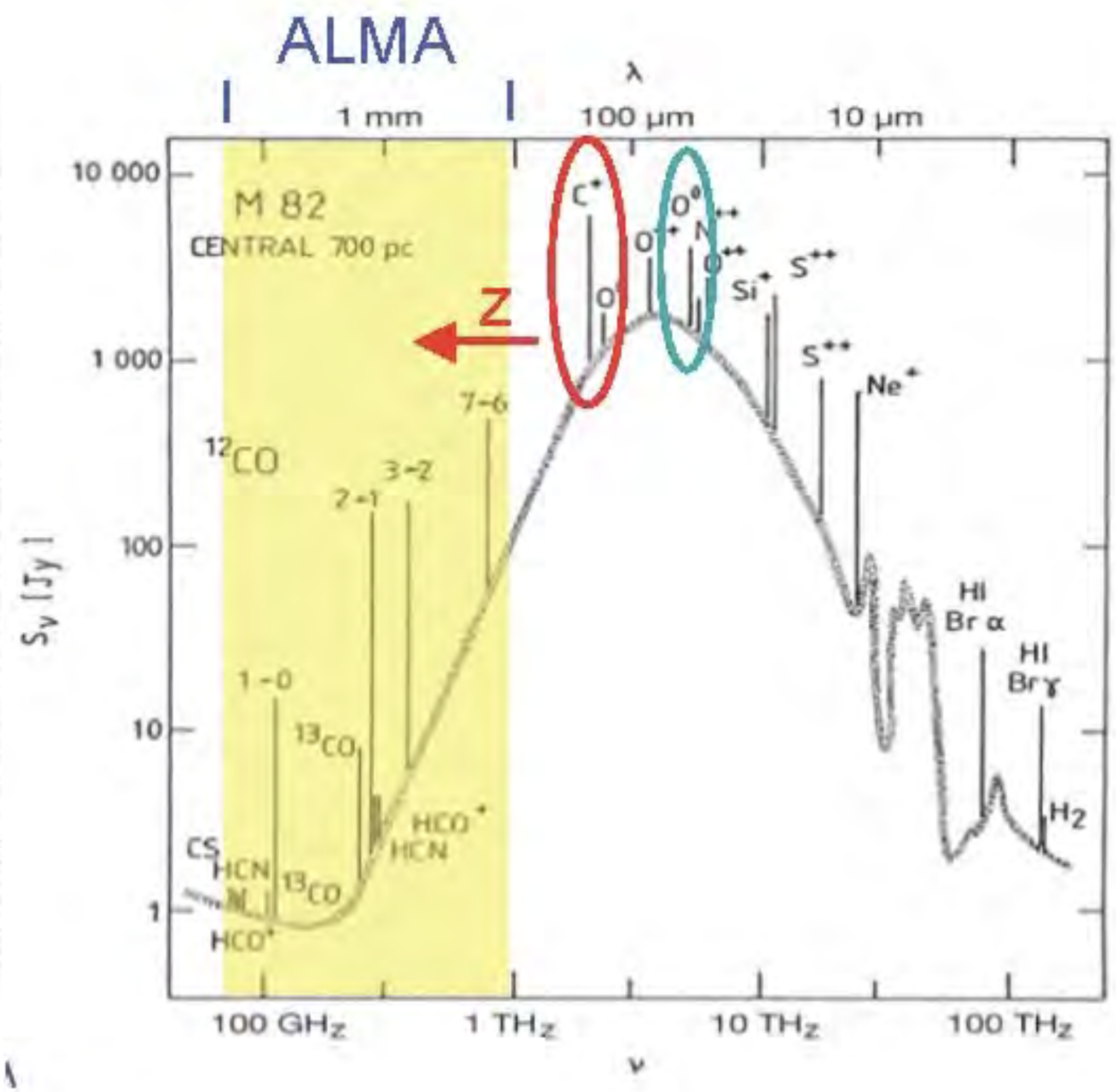
50pc

100pc

- Simulations of giant protoplanets in circumstellar disks
- ALMA 650GHz Y1 8h
- NB. 50 & 100pc distance! (though experiment even with ALMA)

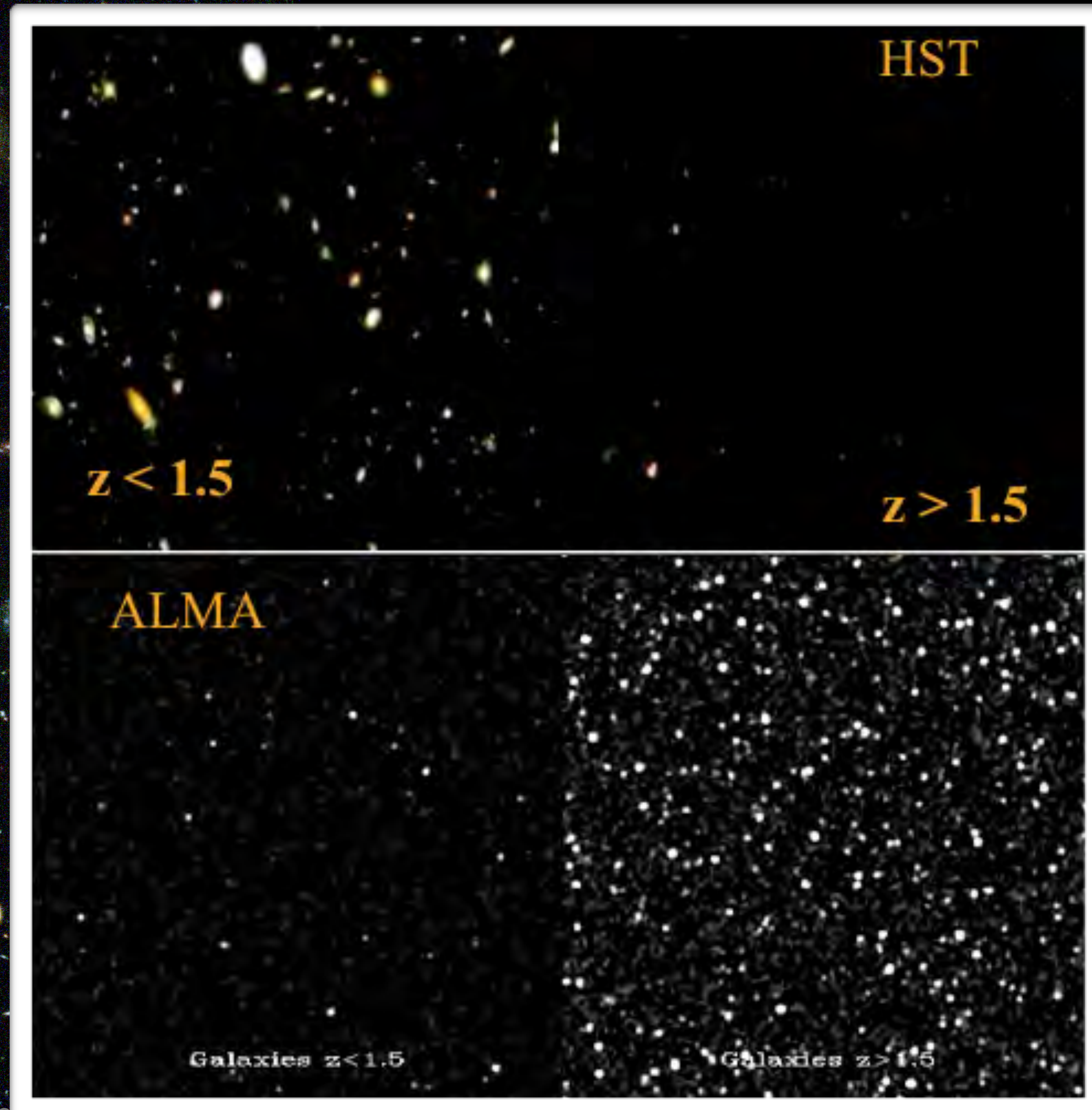
History of Galaxies



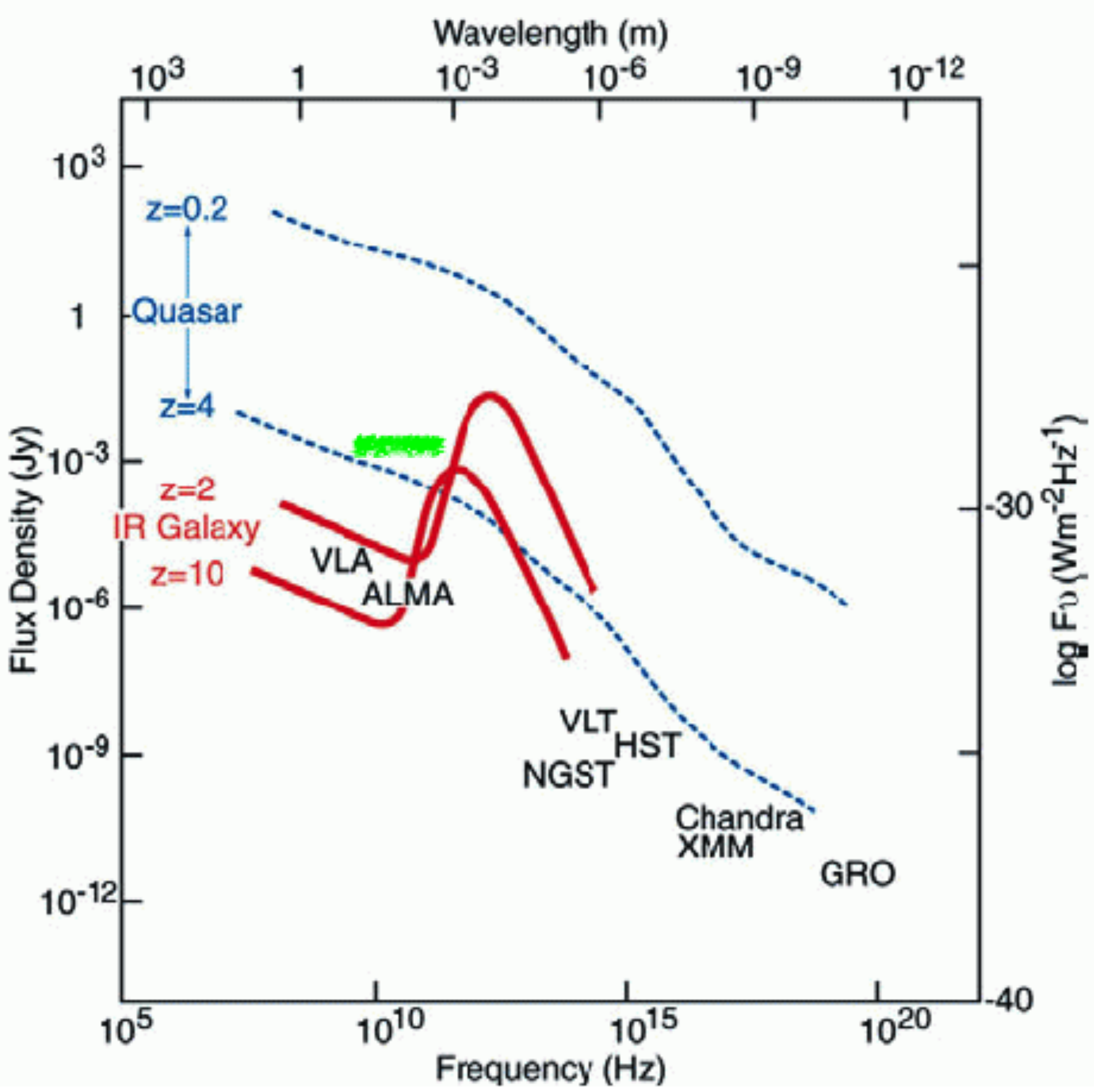


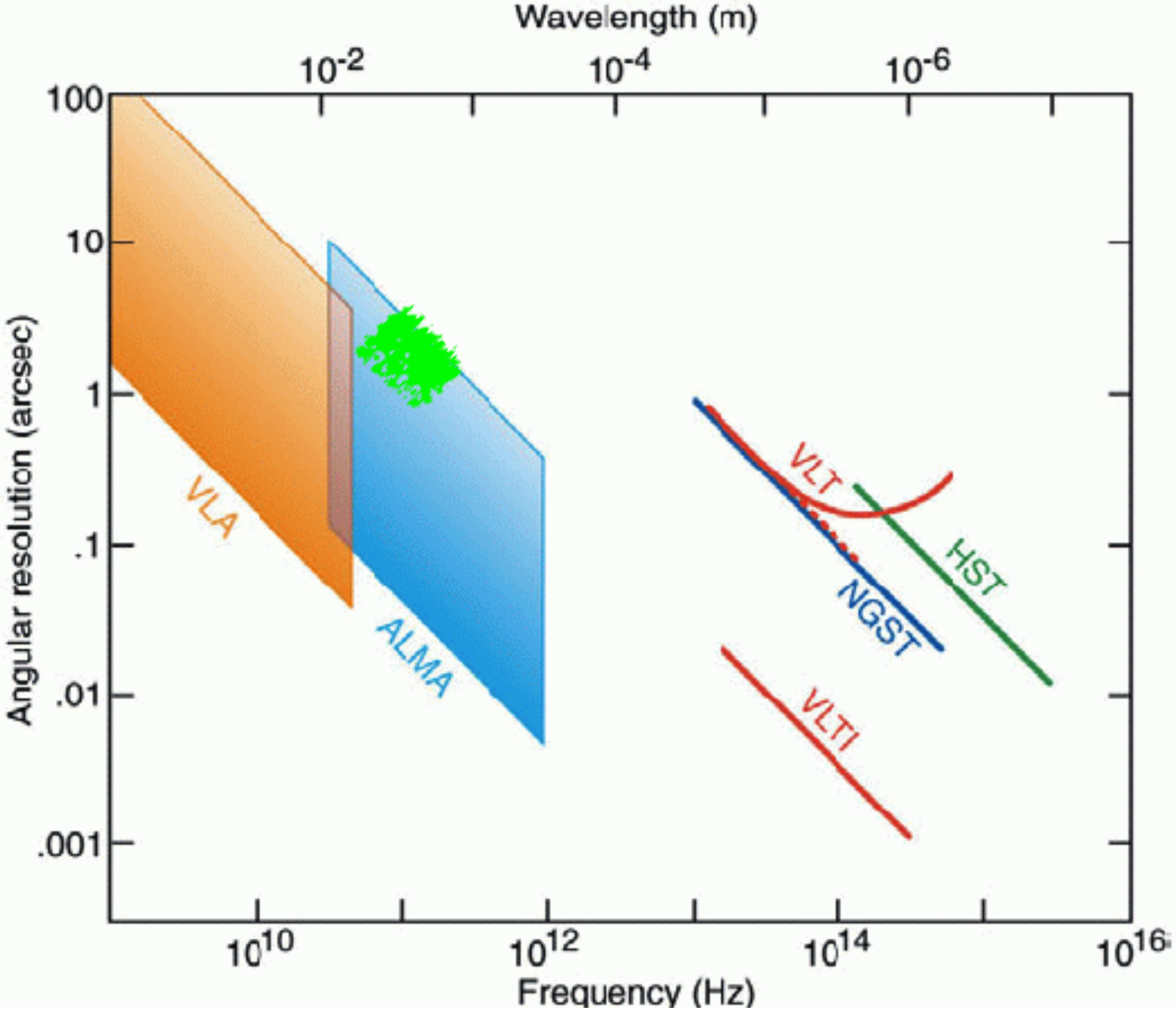
- Measuring redshift and the properties of the ISM in the early Universe using CO, [CII] or [OI]

The Early Universe



(Sub)mm facilities of the 1990s





Coming together for ALMA

LSA

(1988)

MMA

(1982)

LMA

(1983)

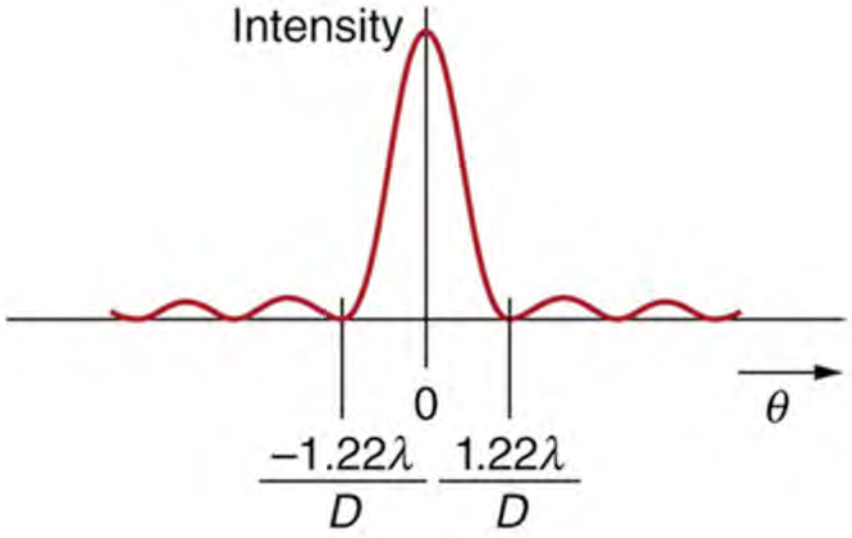
ALMA

ATACAMA LARGE MILLIMETER ARRAY

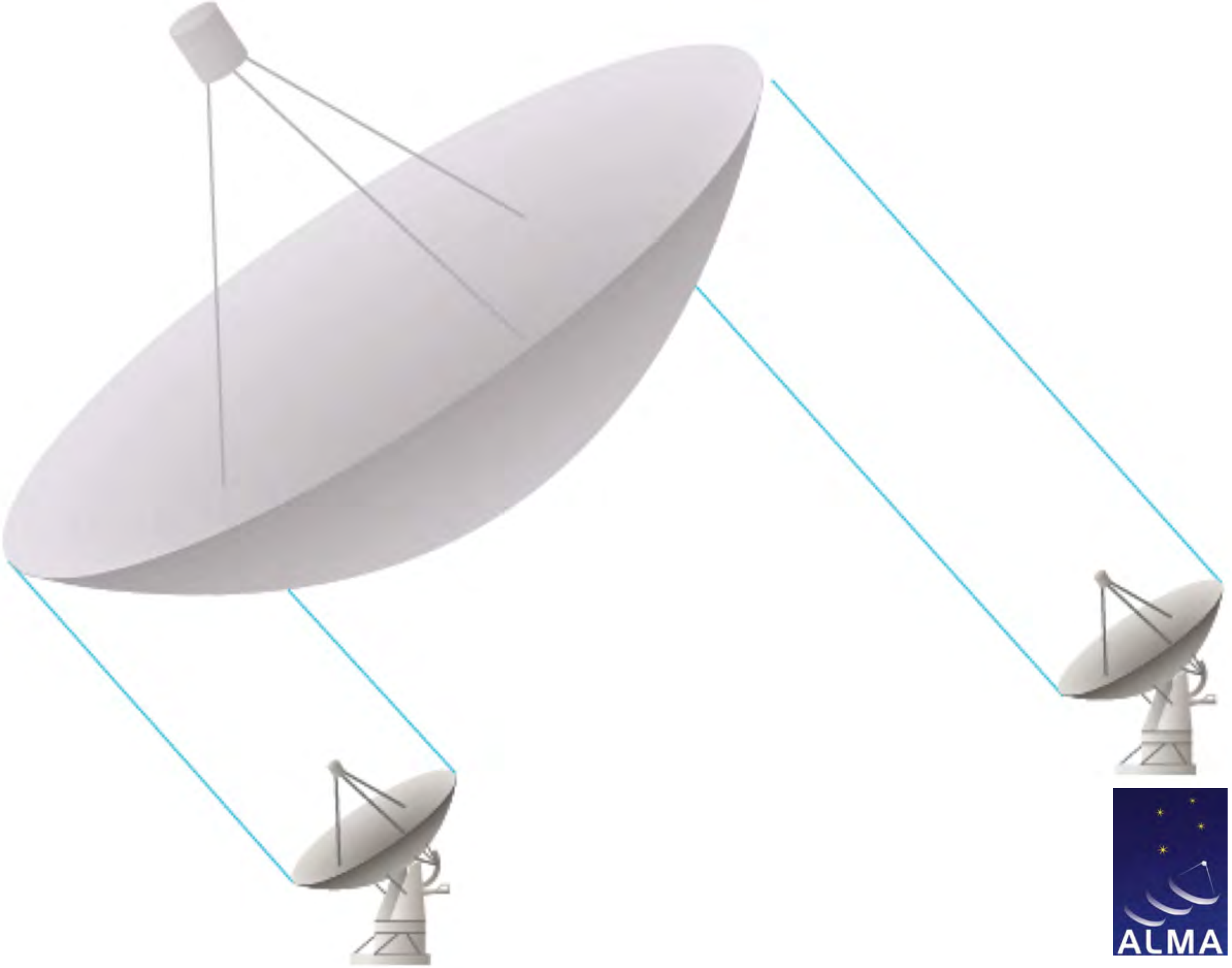
ALMA

Angular resolution

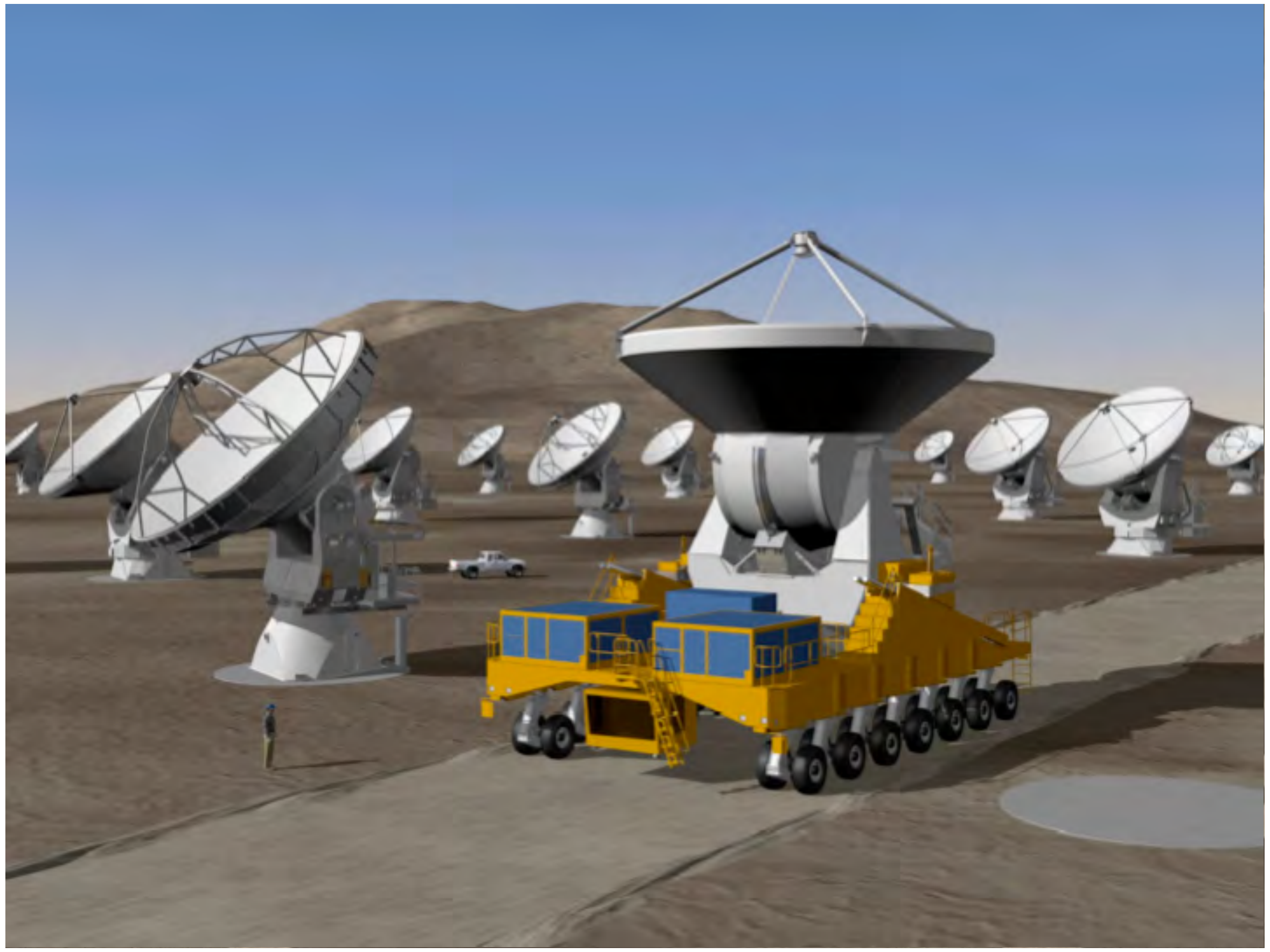
- Diffraction limit: ~1.22*lambda/D => 1mm/30m~8”
- 8” > 1000 AU @ 140pc (Sun-Neptune ~ 30AU)
- Sun-Jupiter ~ 5AU => 0.035” => >~7km @1mm
- Sun-Earth = 1AU => 0.007” => ~17km @0.5mm



(a)

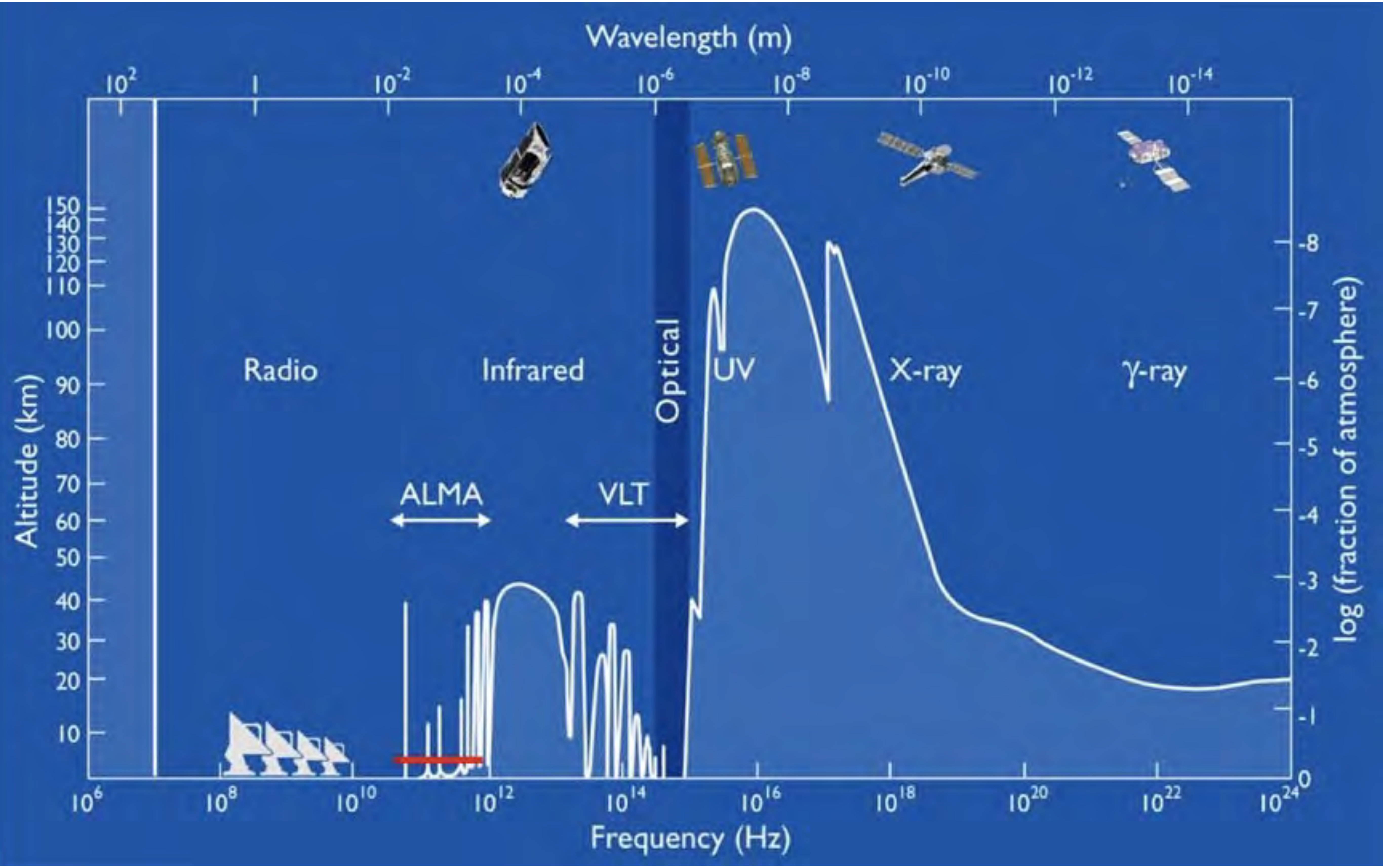


Atacama Large Millimeter Array



- At least 50x12m Antennas
- Frequency range 30-1000 GHz (0.3-10mm)
- 16km max baseline (<10mas)
- ALMA Compact Array (4x12m and 12x7m)

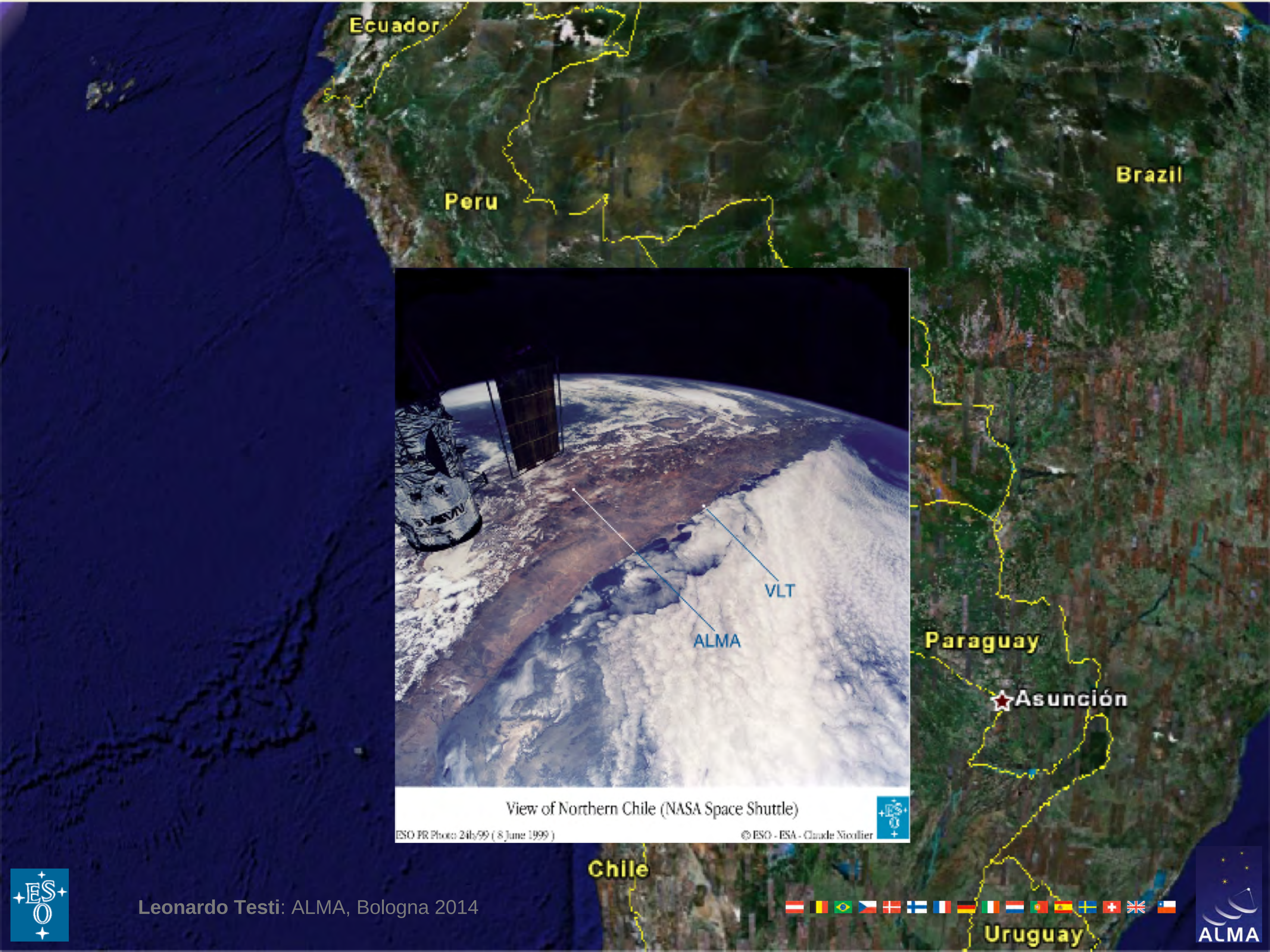
1. **Detect and map CO and [C II] in a Milky Way galaxy at z=3 in less than 24 hours of observation**
2. **Map dust emission and gas kinematics in protoplanetary disks**
3. **Provide high fidelity imaging in the (sub)millimeter at 0.1 arcsec resolution**



Wavelength (m)
10^2
1
10^-2
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
Altitude (km)
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
Radio
Infrared
Optical
UV
X-ray
γ-ray
ALMA
VLT
log (fraction of atmosphere)
-8
-7
-6
-5
-4
-3
-2
-1
0
10^6
10^8
10^10
10^12
10^14
10^16
10^18
10^20
10^22
10^24
Frequency (Hz)

ESO

ALMA



View of Northern Chile (NASA Space Shuttle)

ESO PR Photo 24b/99 (8 June 1999)

© ESO - ESA - Claude Nicollier

San Pedro de Atacama,
Atacama Desert, Chile

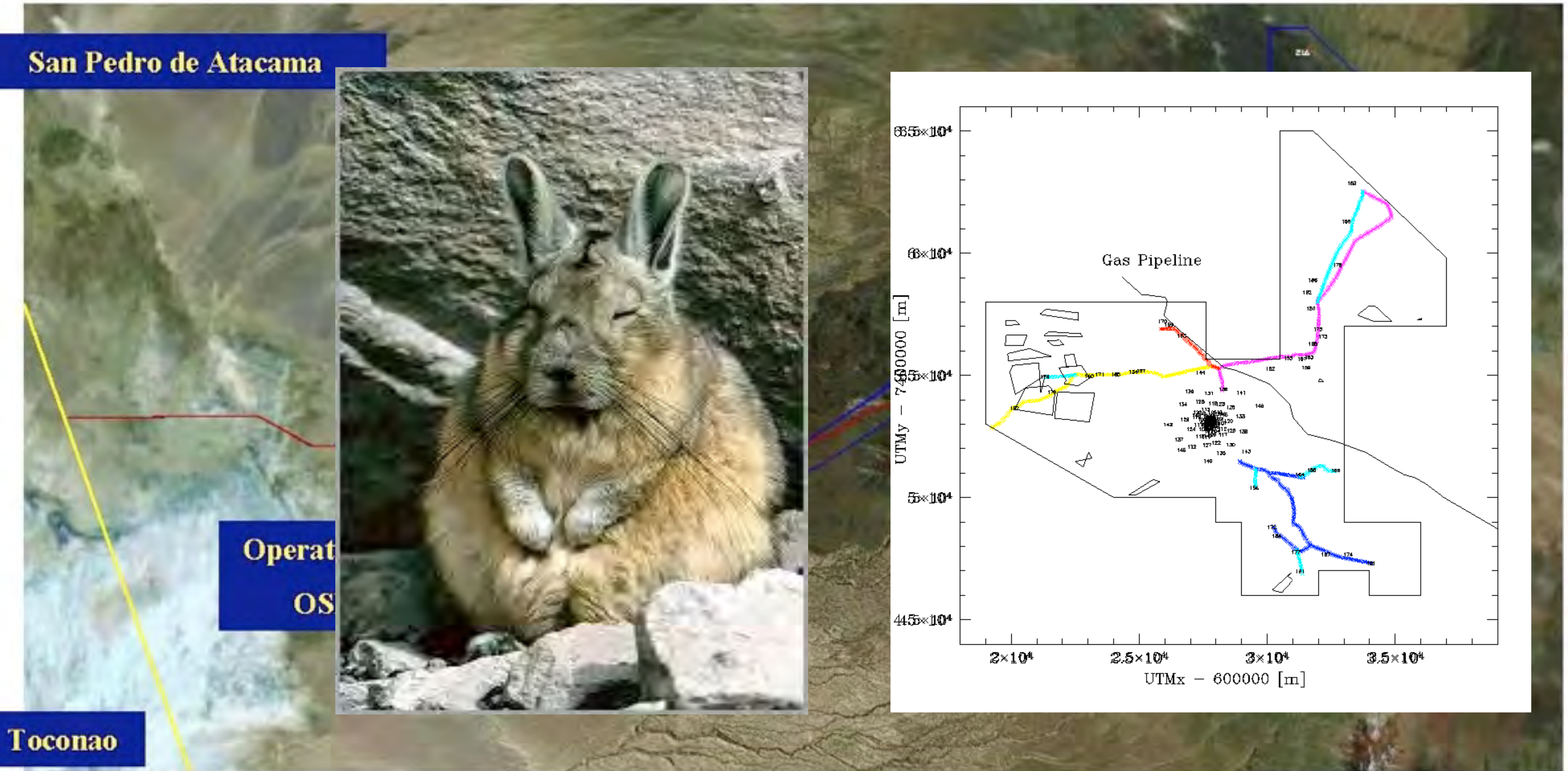




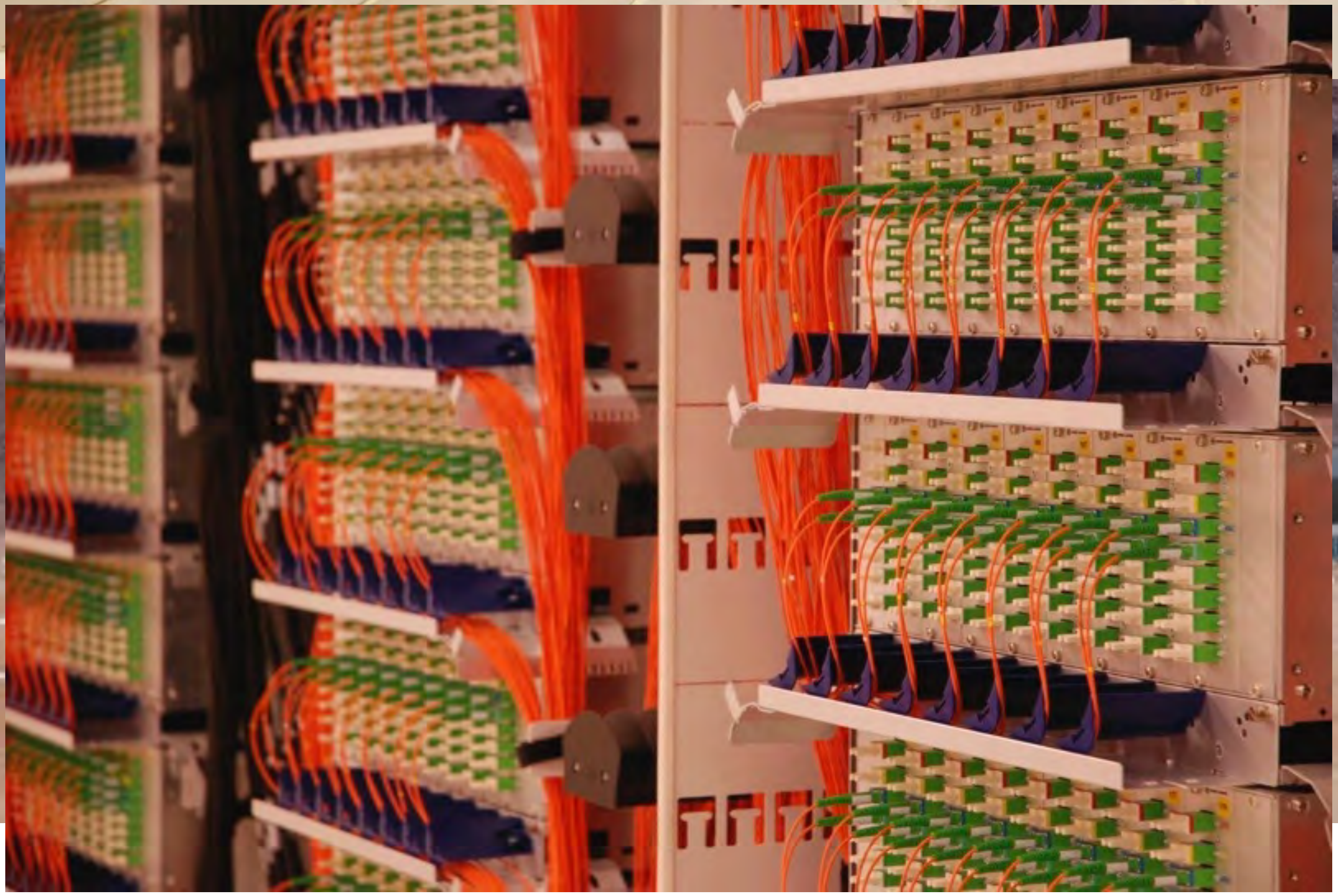


Altiplano Chajnantor

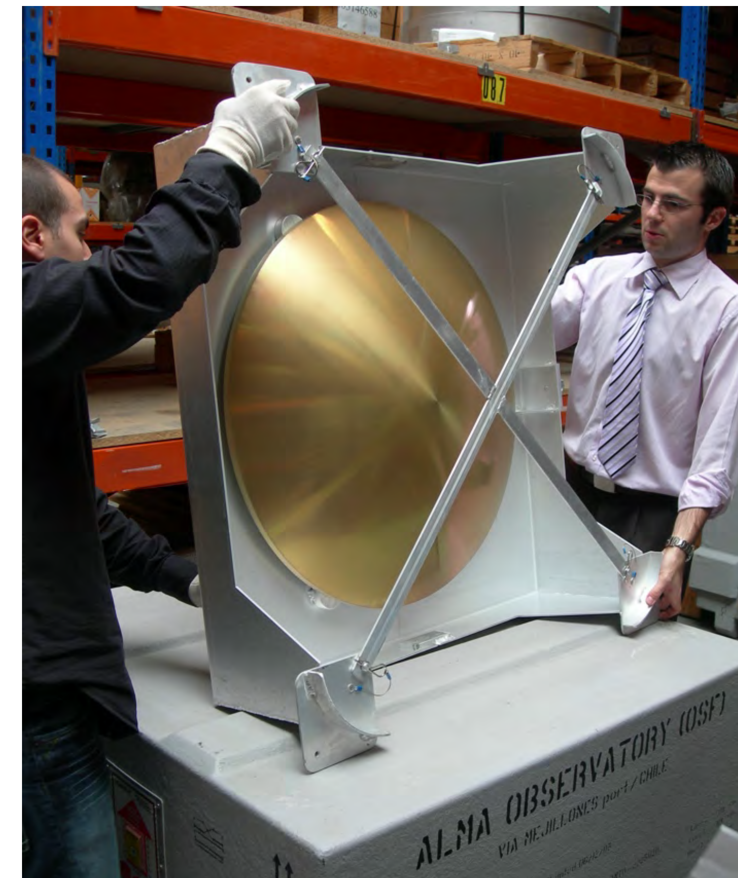
ALMA Science Advisory Committee 2001


San Pedro de Atacama
Toconao
Gas Pipeline
6.5×10^4
6×10^4
5.5×10^4
5×10^4
4.5×10^4
UTMy − 7400000 [m]
2×10^4
2.5×10^4
3×10^4
3.5×10^4
UTMx − 600000 [m]

Array Operations Site – 5000 m







ALMA OBSERVATORY (OSF)











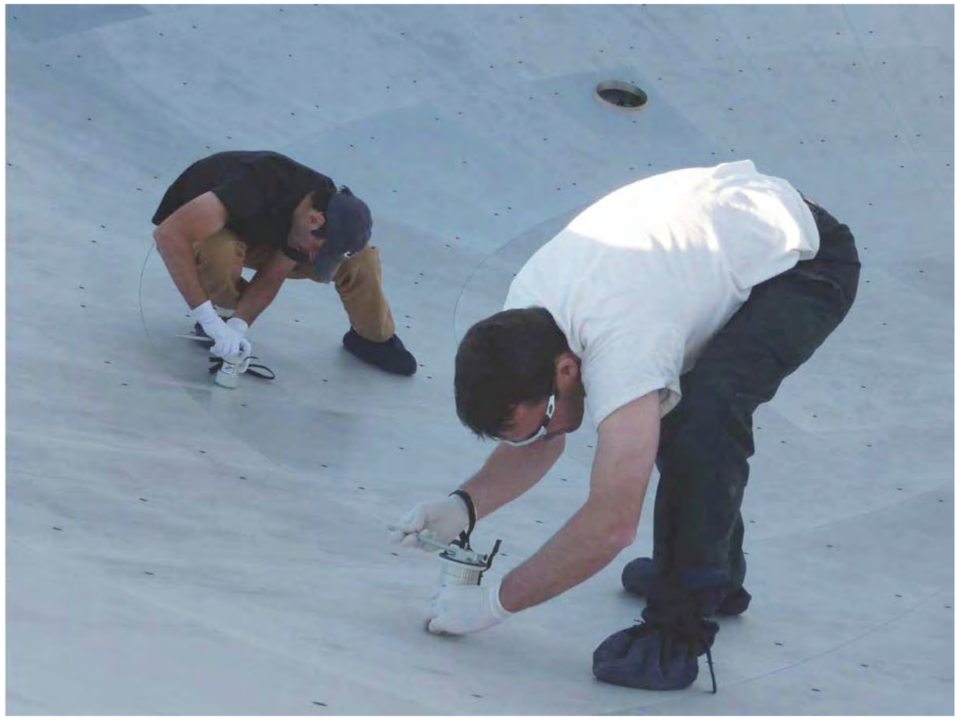
Vertex #1 – April 2007

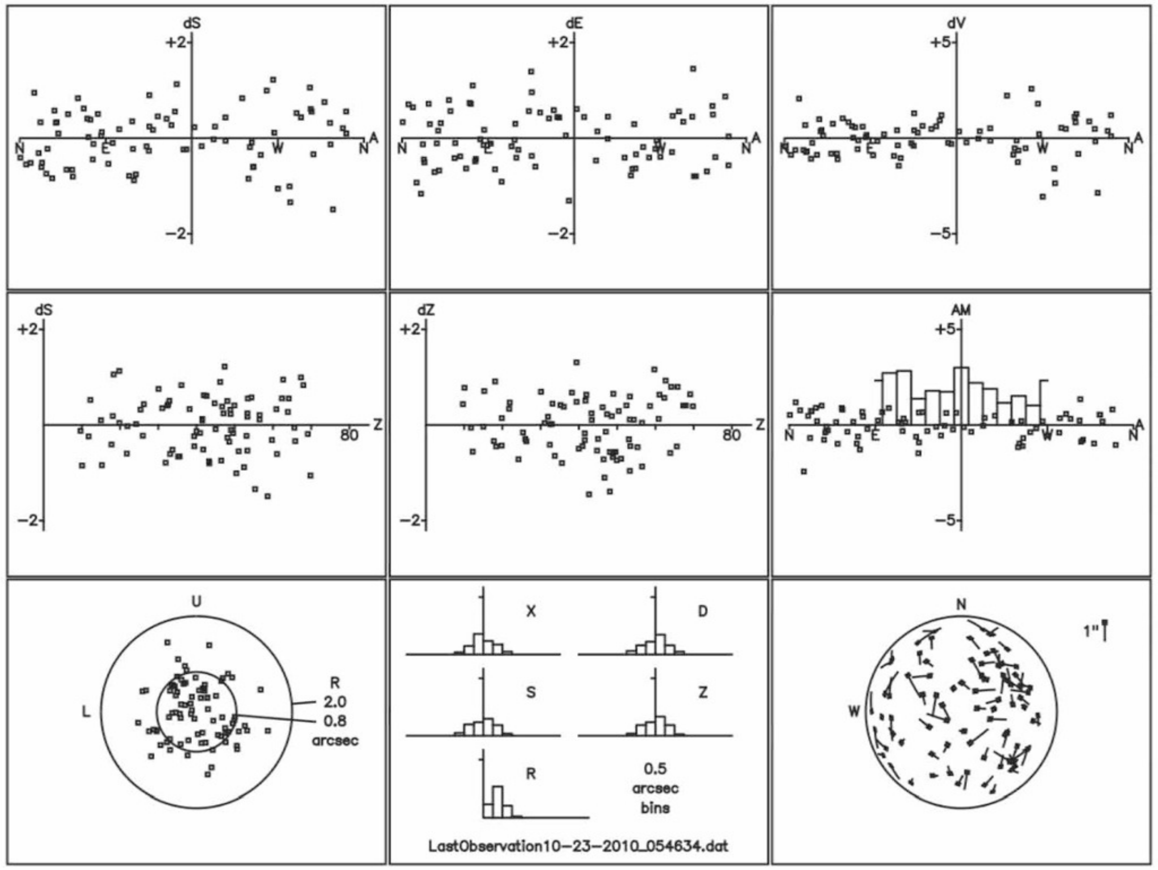

Operations Support Facility – 2900m

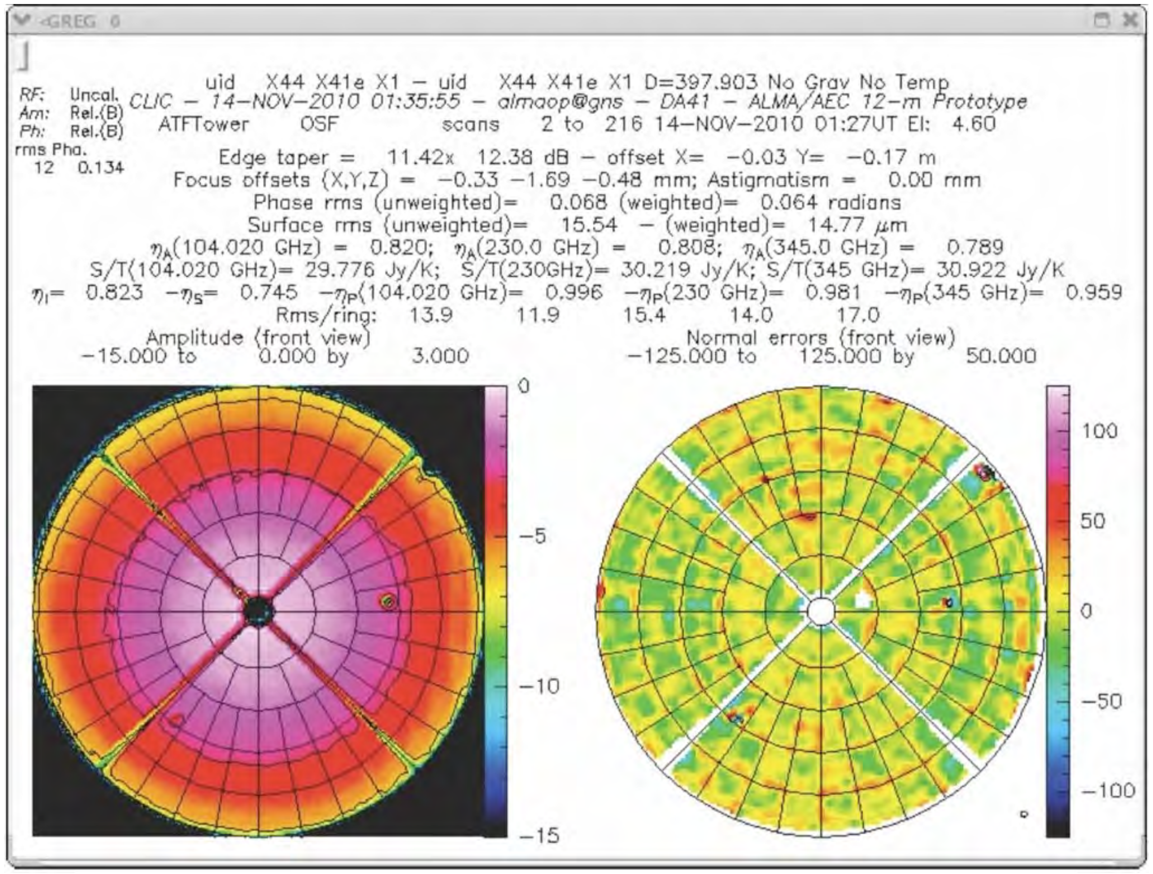
Lascar – April + October 2006

Antenna performances

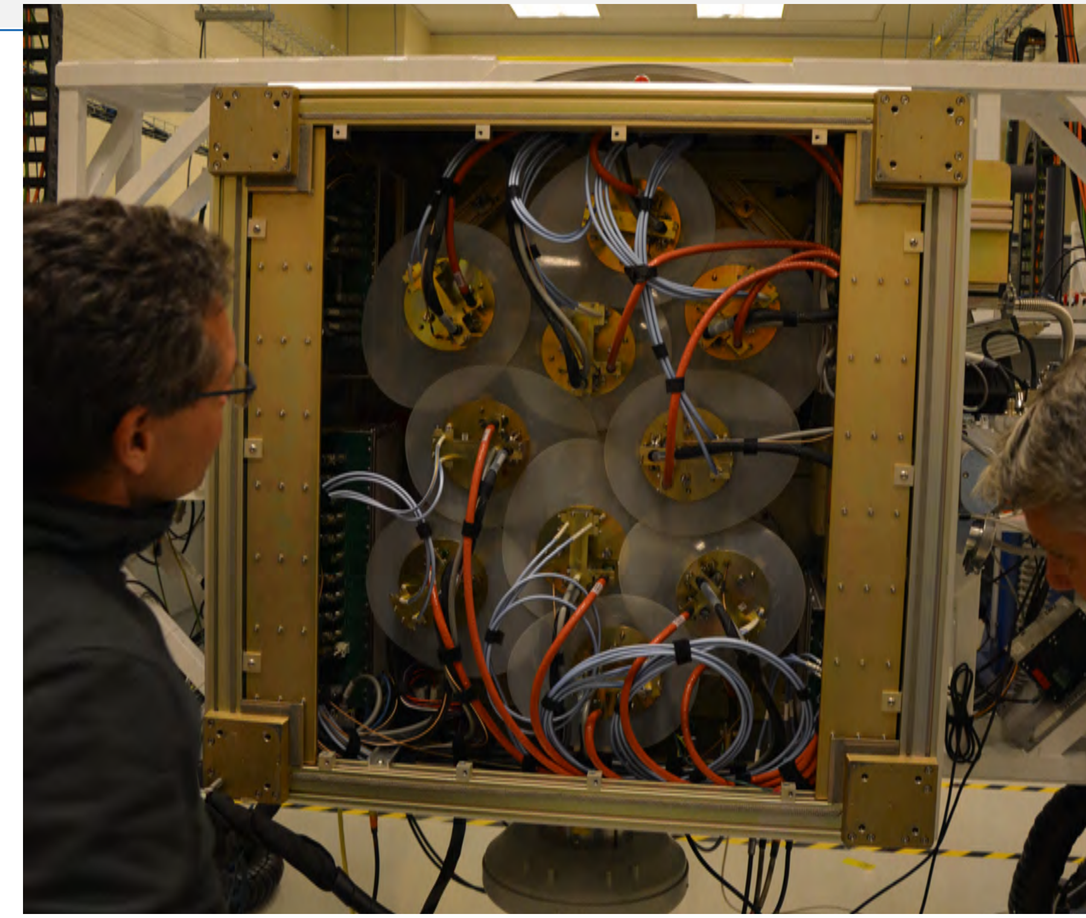
- Excellent dynamical and optical performances of all antenna types
- Good results for very stringent potinting tests (well within specs)
- Excellent results from surface setting

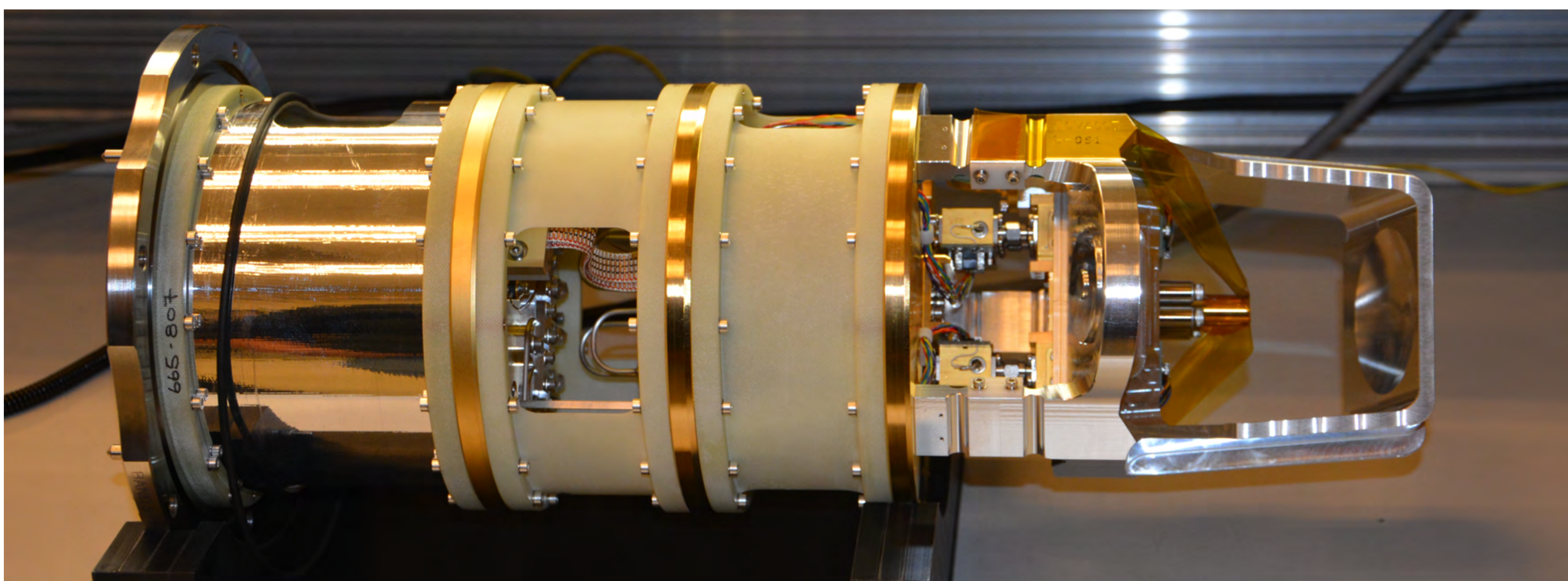






The best receivers ever built

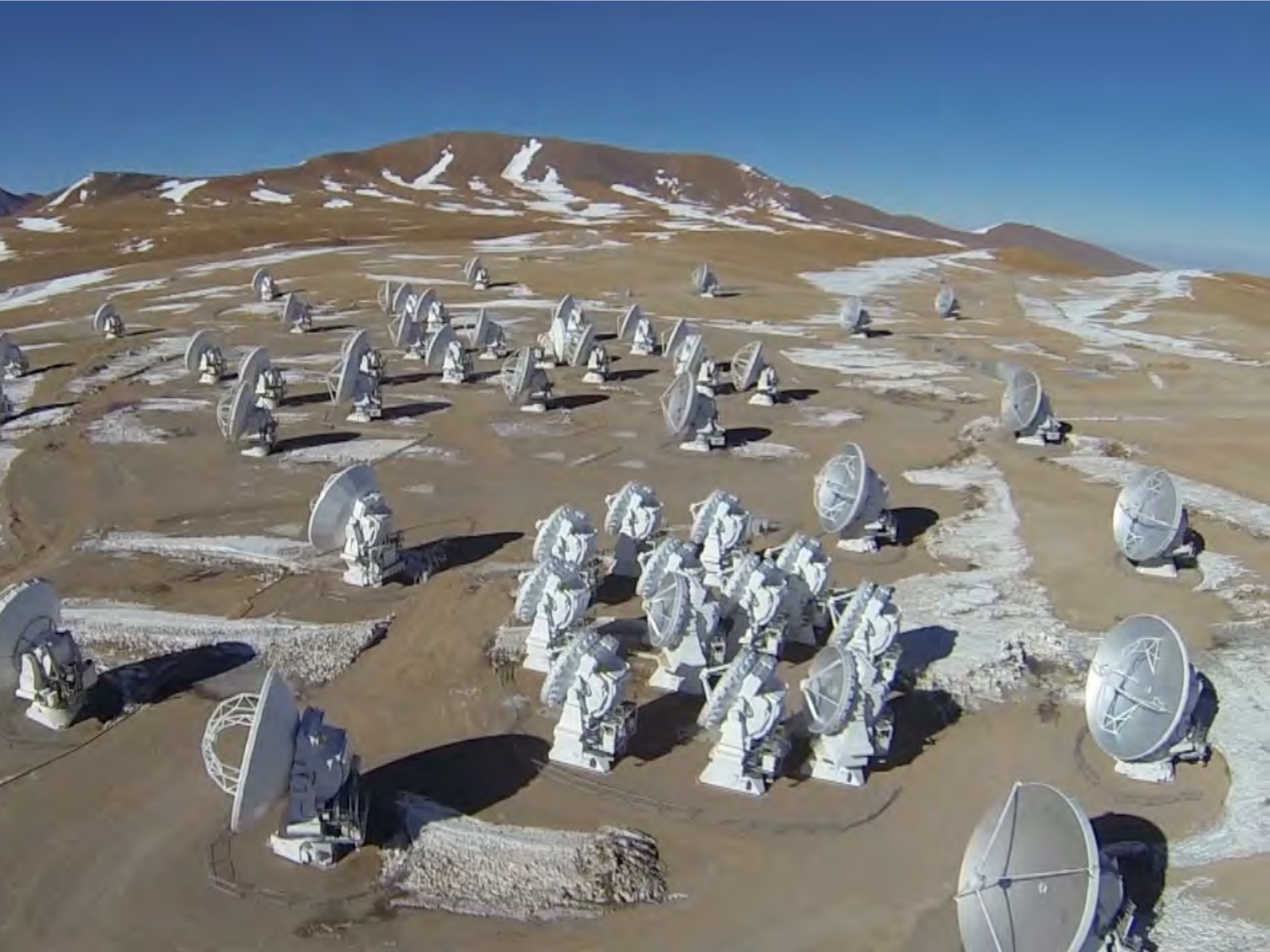




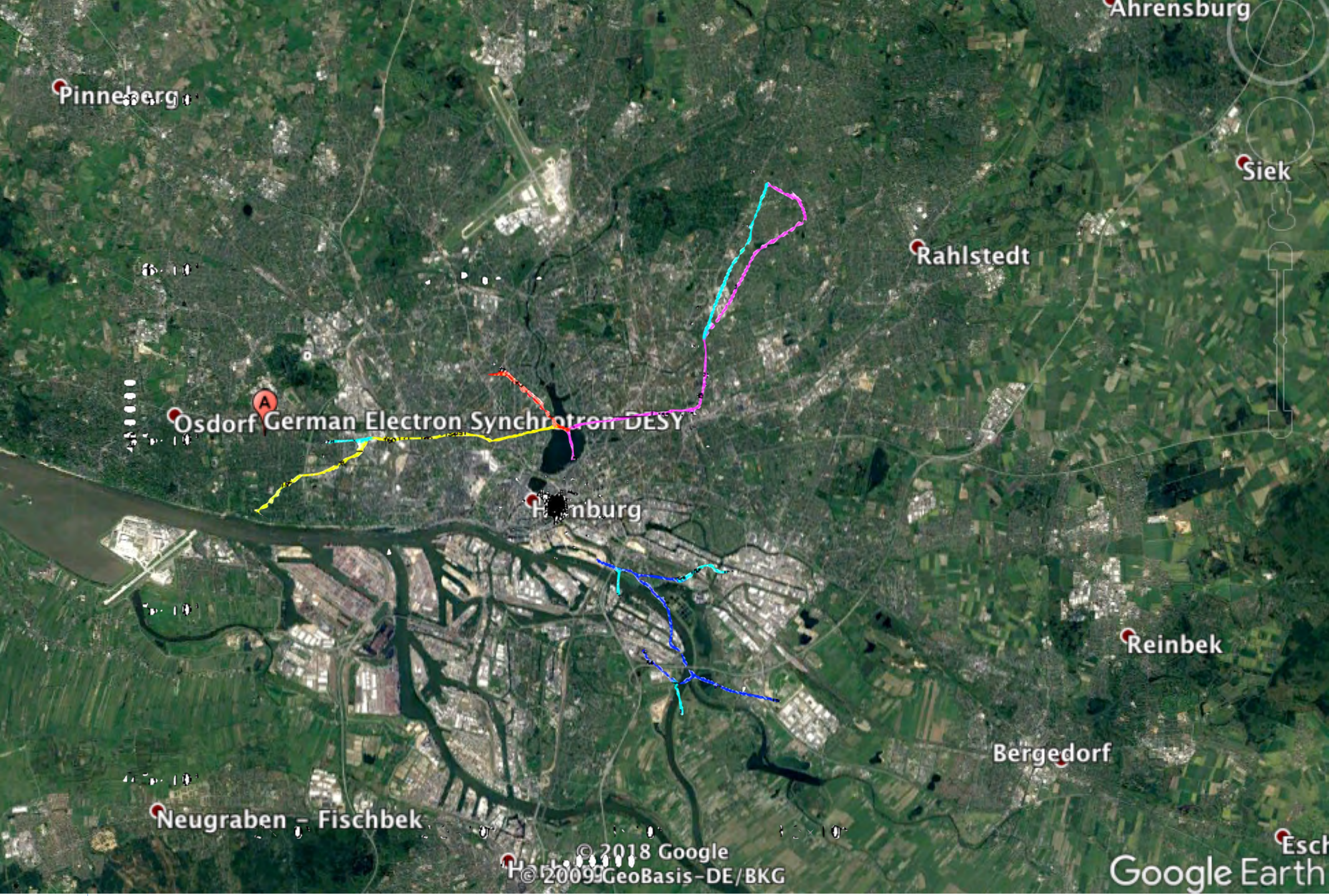

Otto
ALMA
ESO
SCHEUERLE


Otto

First antenna at 5000m

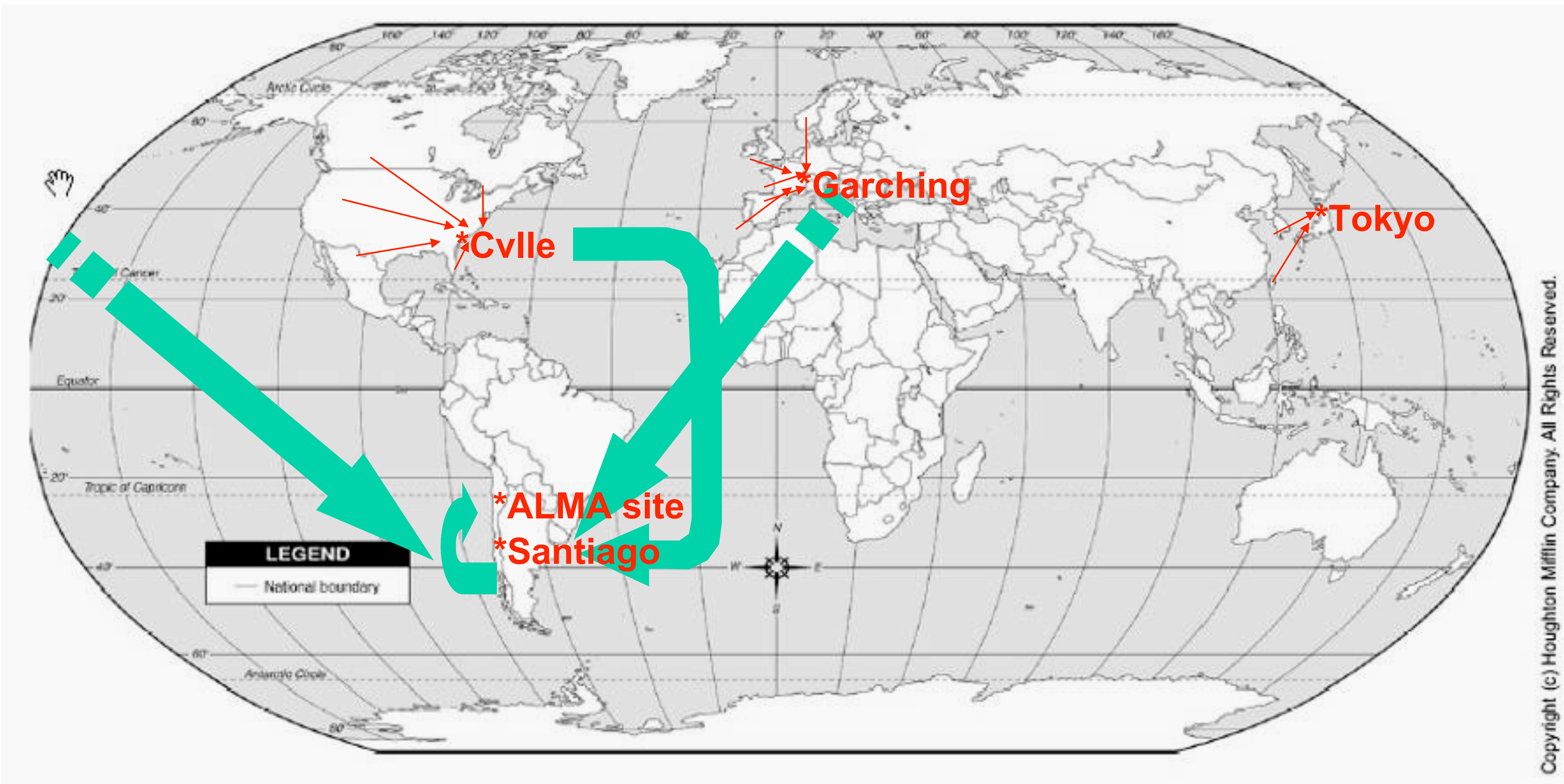


ALMA Compact Configuration



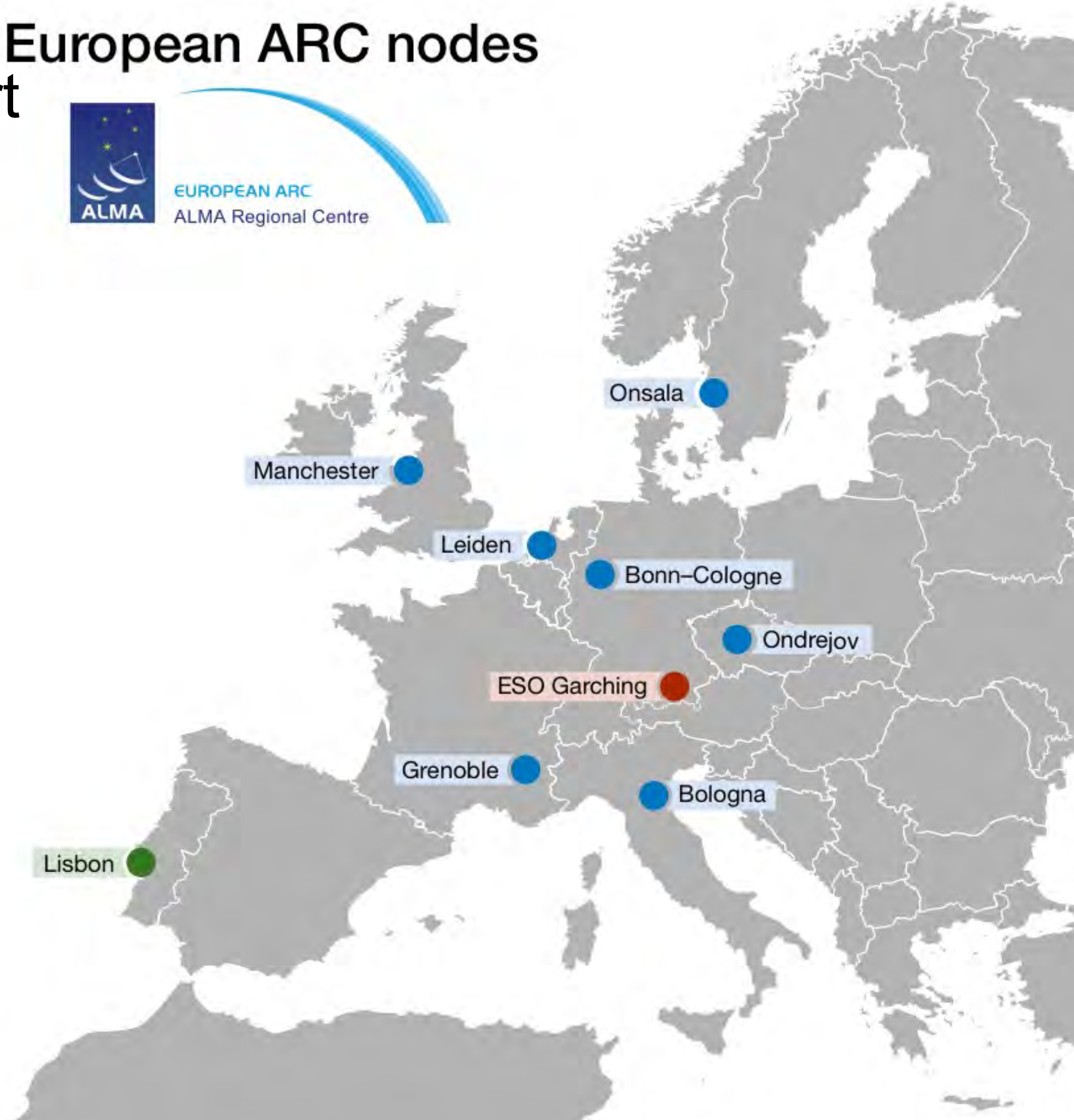
ALMA Exteded Array

ALMA Science Operations sites
OSF, Santiago and the ARCs



ALMA Regional Centre Nodes

- **Distributed user support**
  - ➢ 7 ARC nodes
  - ➢ 1 Centre of Expertise
  - ➢ Central coordination at ESO
- **Support for proposal preparation**
  - ➢ Feasibility and simulations
  - ➢ Tutorials and workshops
- **Data processing**
  - ➢ Execution and checking of the data calibration and imaging pipelines
  - ➢ Quality Assurance – Level 2
  - ➢ Data delivery to users
- **Data Archive**
  - ➢ Archive maintenance and operation
  - ➢ Support for Archive research
  - ➢ Archive reprocessing

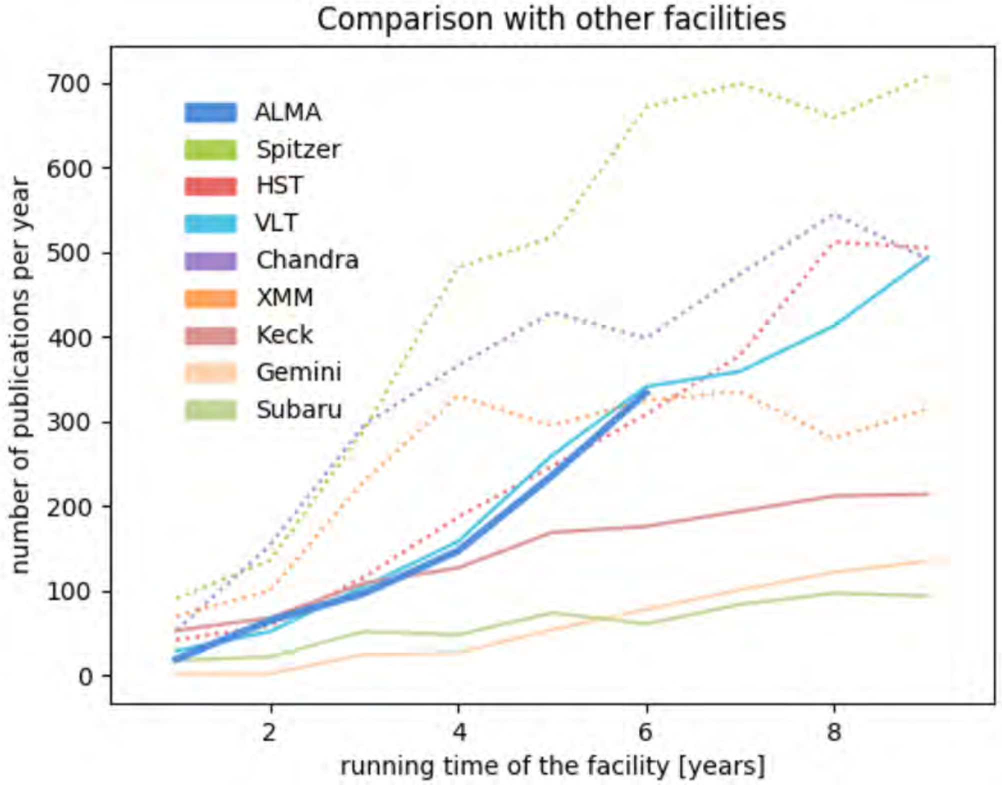


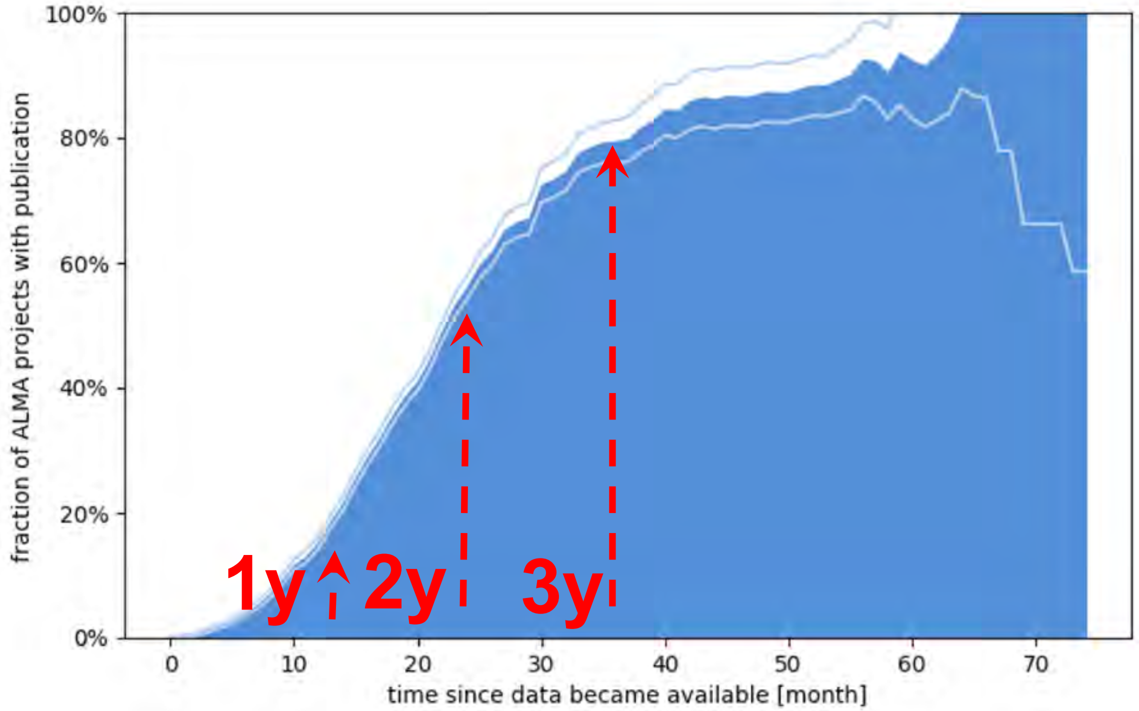
EU ARC Network workforce

ALMA Science Programme

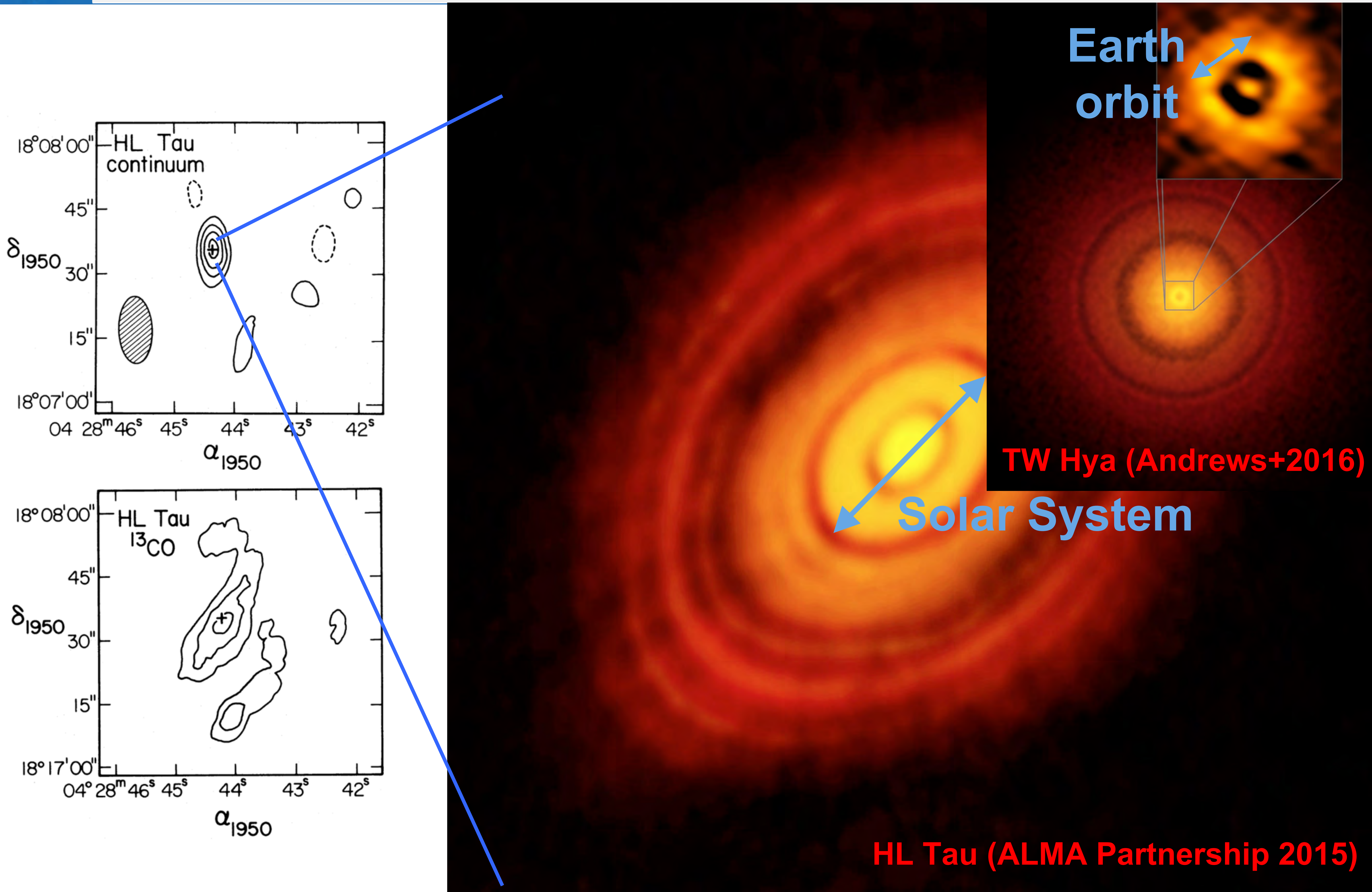
- **ALMA from Early to Full Science C0-C5**
  - ➢ 30-90% of the total number of antennas
  - ➢ Maximum separation 400m -> 16km
  - ➢ Marvelous science machine
- **Enormous pressure to use ALMA worldwide**
  - ➢ Requests for 9 times the available time
  - ➢ Top 8% science projects selected (ESO)
  - ➢ Peer review system
- **An ALMA Cycle**
  - ➢ 1700 proposals, severl 100s in high pri.
  - ➢ Fast science turnaround

Comparison with other facilities

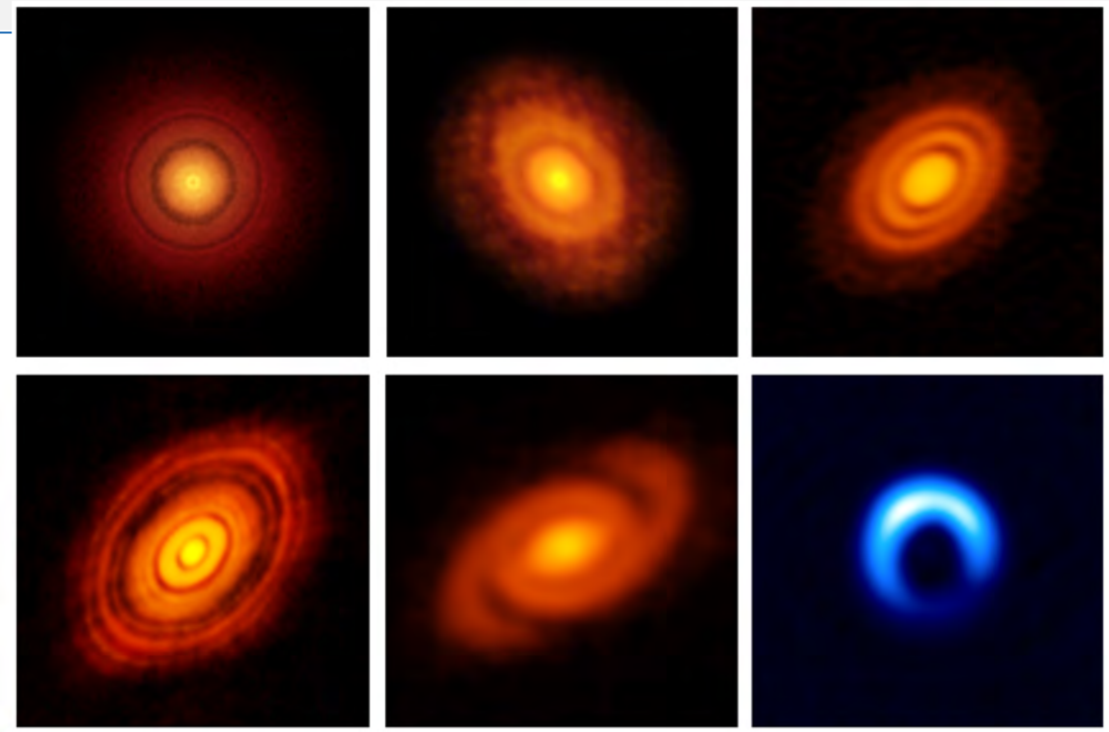


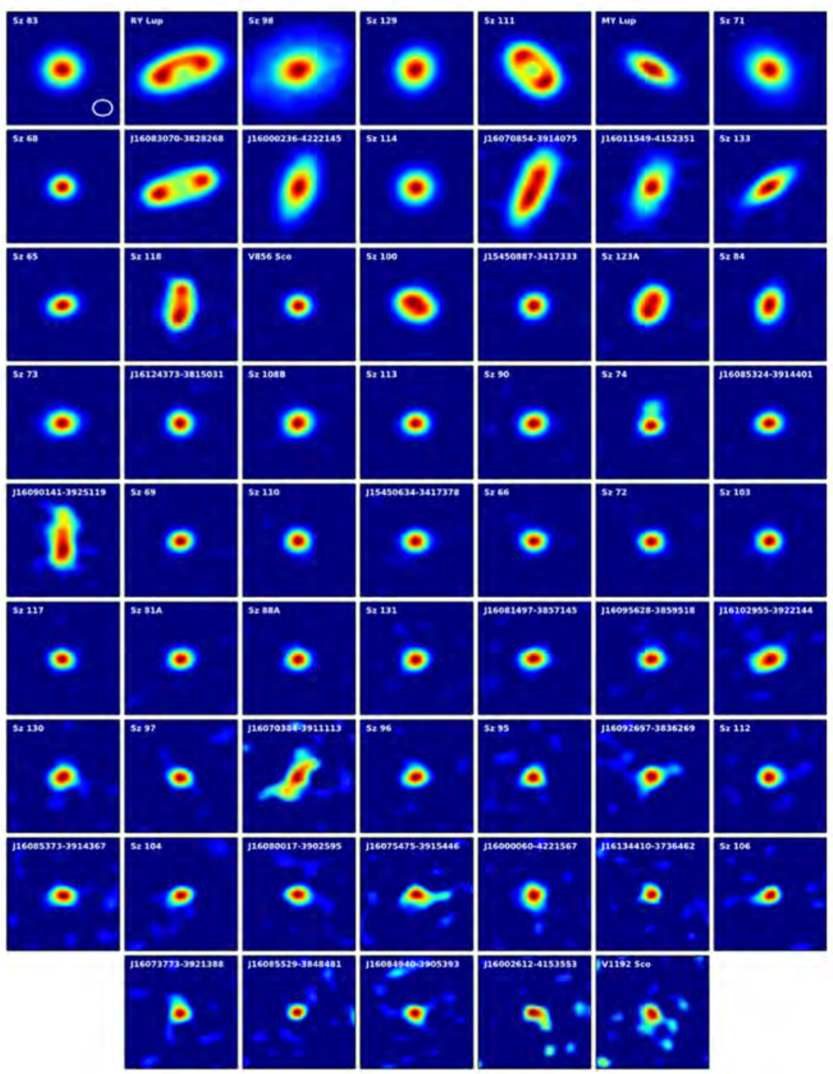


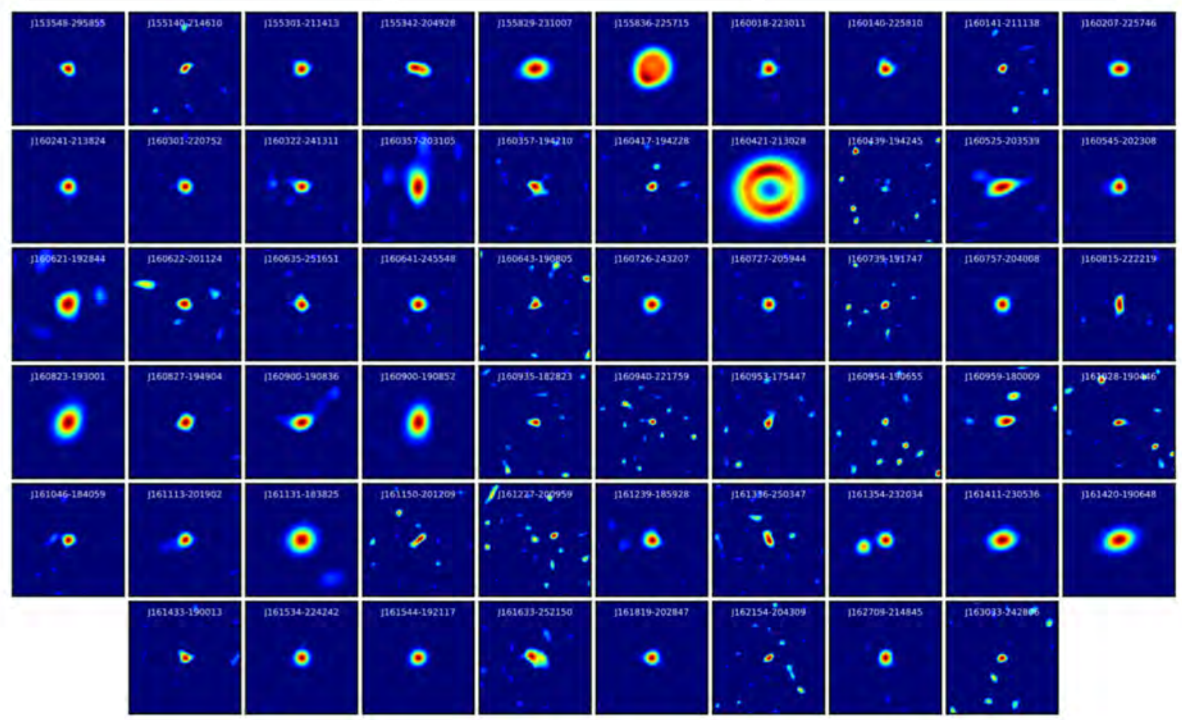
The ALMA Revolutions

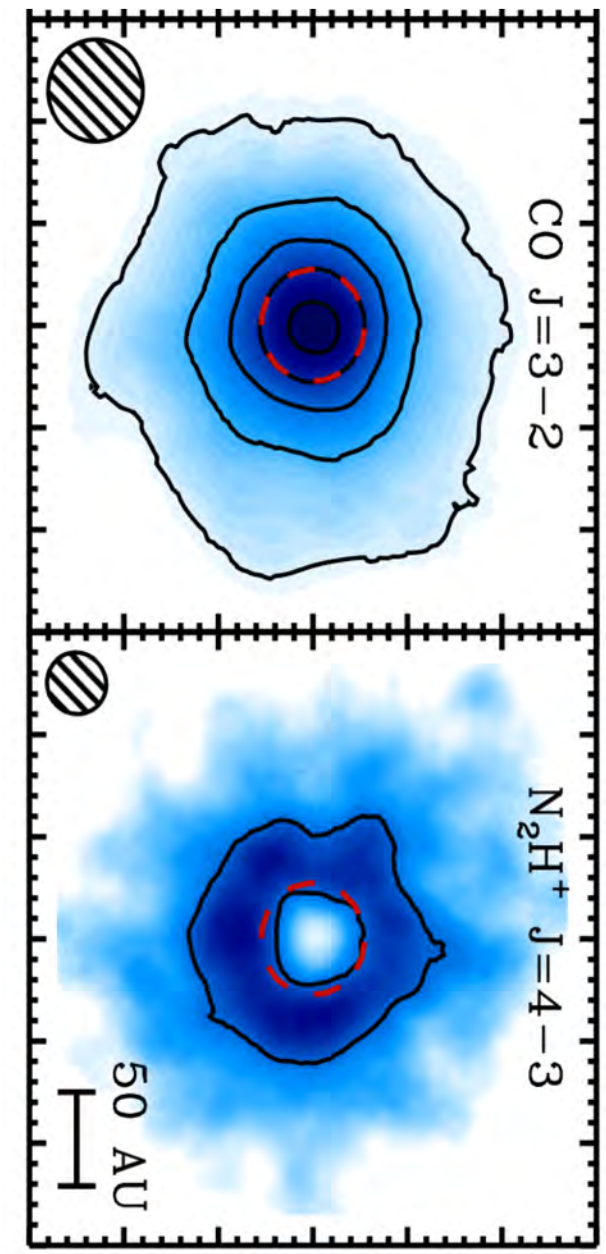


Planet forming disks





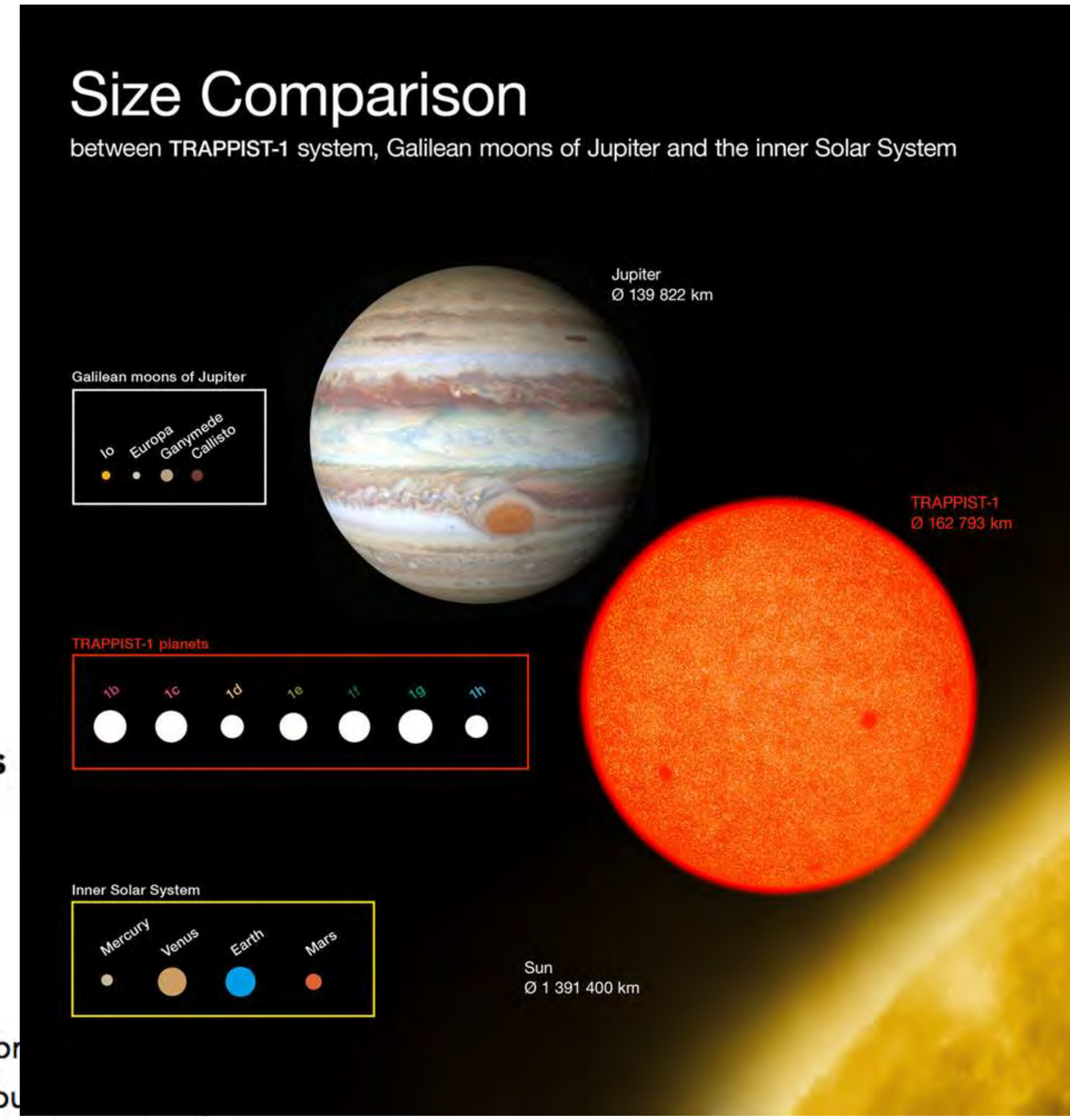




- Gaps, holes and asymmetries: the trademarks of planets
- Disk gas content: mass and chemical composition

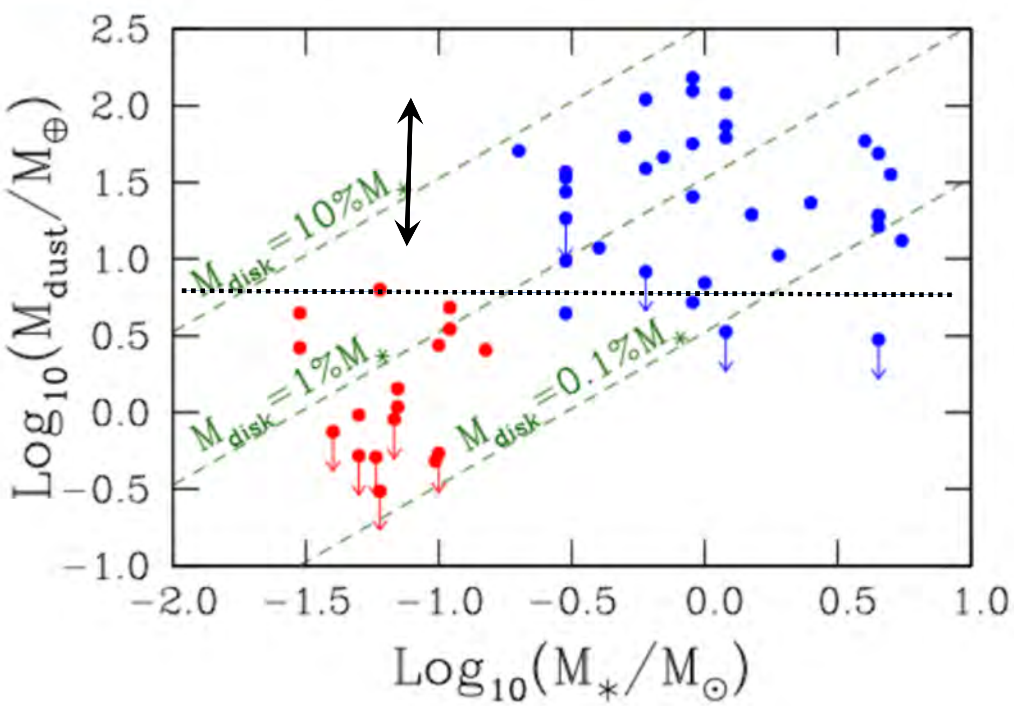
Forming the TRAPPIST-1 system

- Young Brown Dwarf disks
  - Where is the material to form TRAPPIST-1?
  - Planet formation much faster than we think or TRAPPIST-1 unreasonably rare…



Science Highlights - Possible Disk Truncation in Ophiuchus Brown Dwarfs

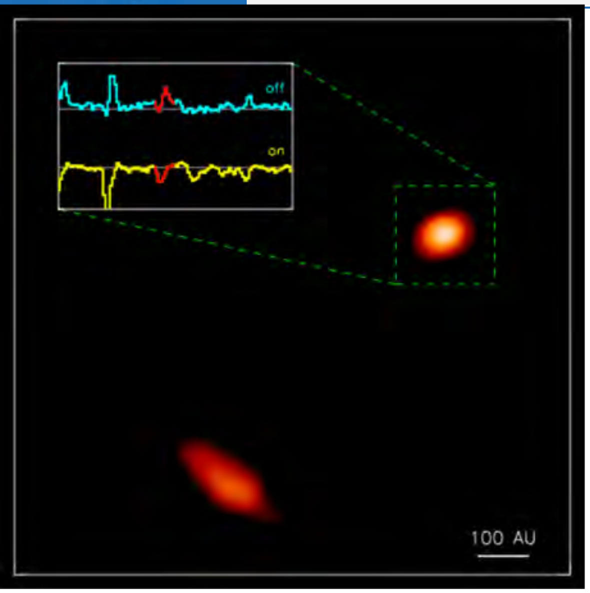
by Portal Admin — last modified Feb 02, 2017 01:37 PM



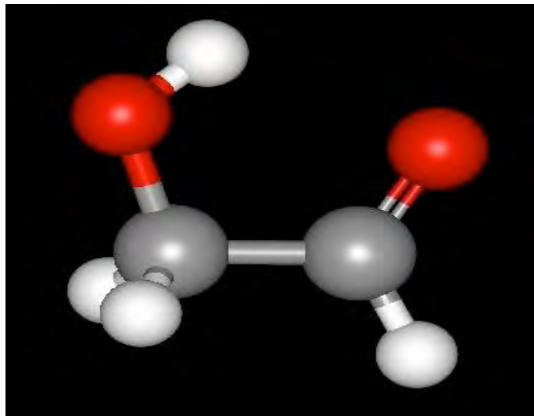
The sensitivity, resolution
properties of the cold ou
understanding the formation of their cei
recent Astronomy & Astrophysics paper,
an unbiased sample of spectroscopically

Full Summary...

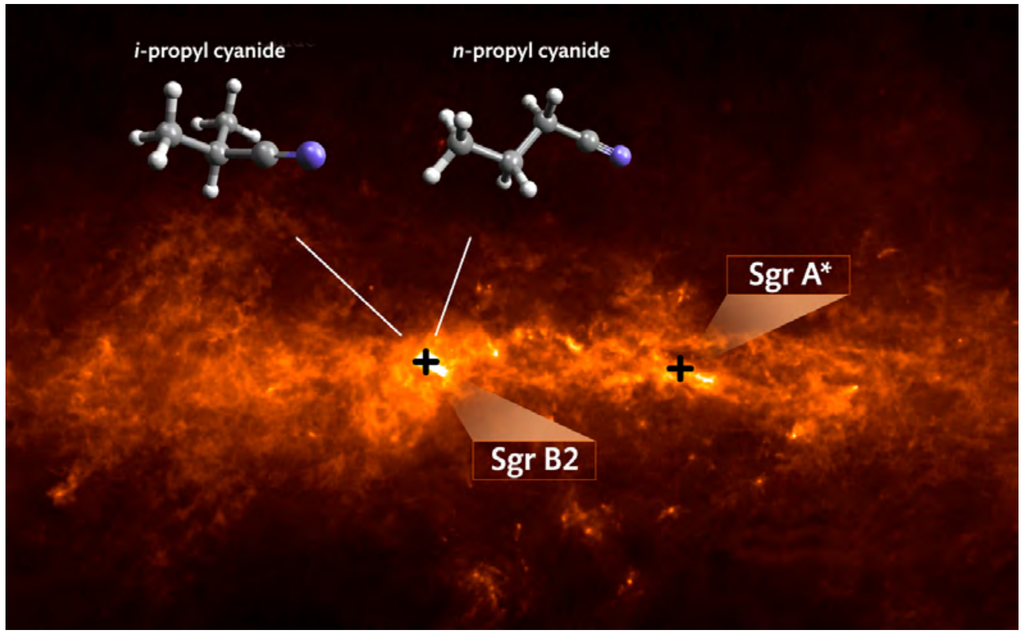
Complex organic molecules

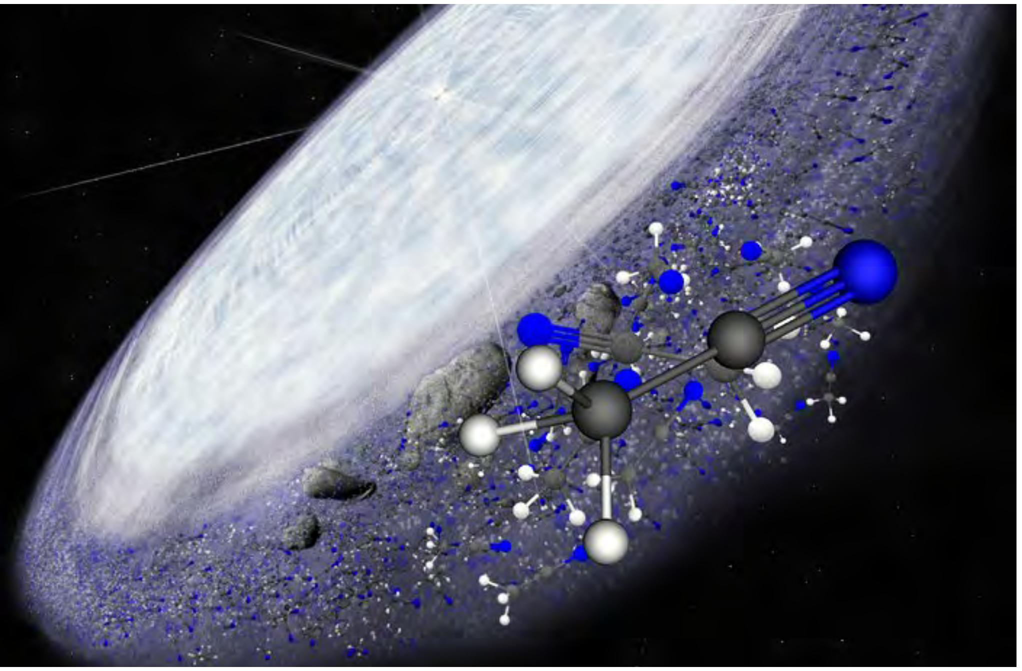


- 2012 ALMA Science Verification:
  - First detection on simple sugar in young Solar System analog



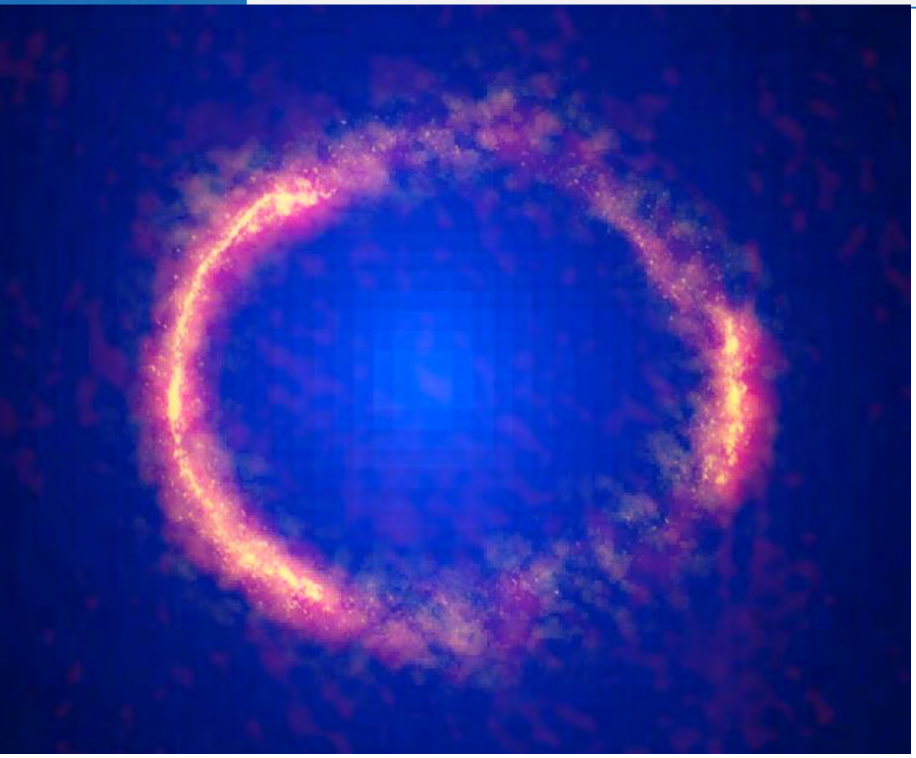
- 2013 ALMA Line Survey:
  - First detection of branched molecule in the interstellar medium

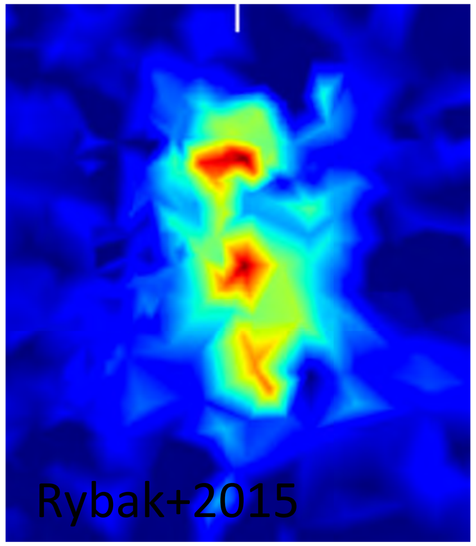


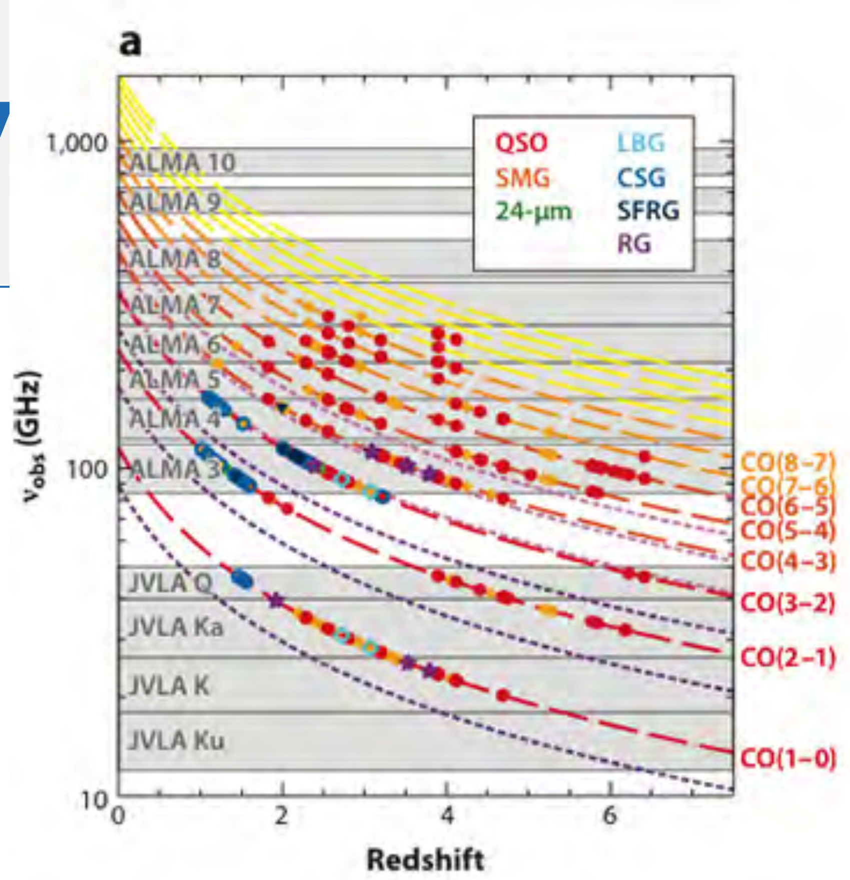


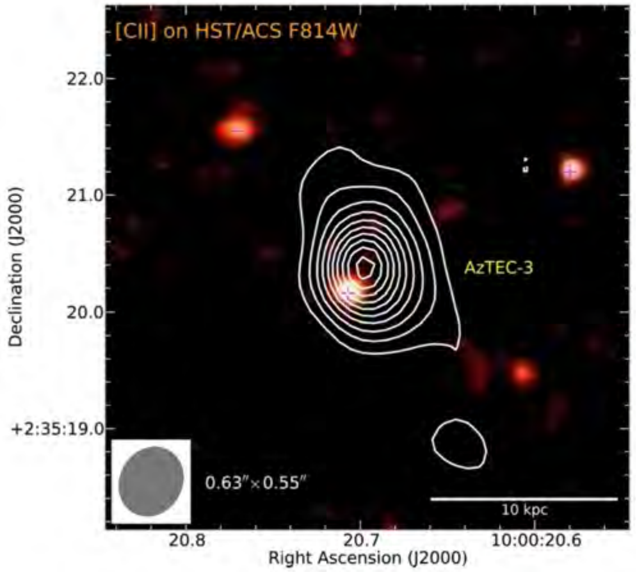
- 2014-2017 Protoplanetary disks:
  - Complex organic molecules in planet forming environments

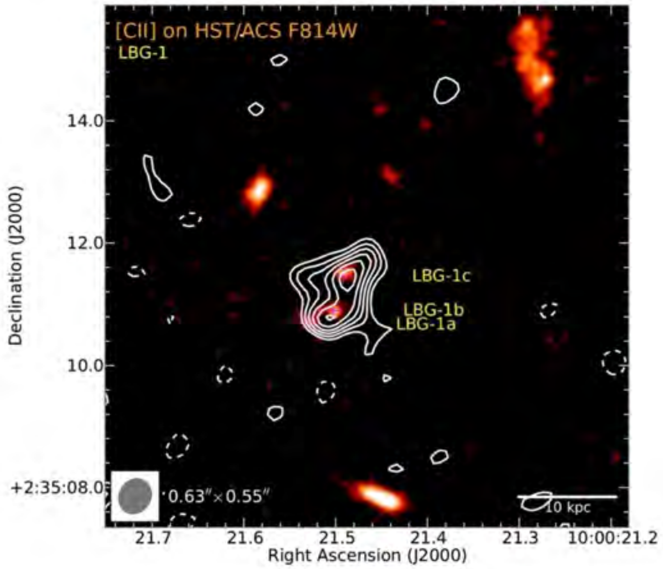
The high-z Univ

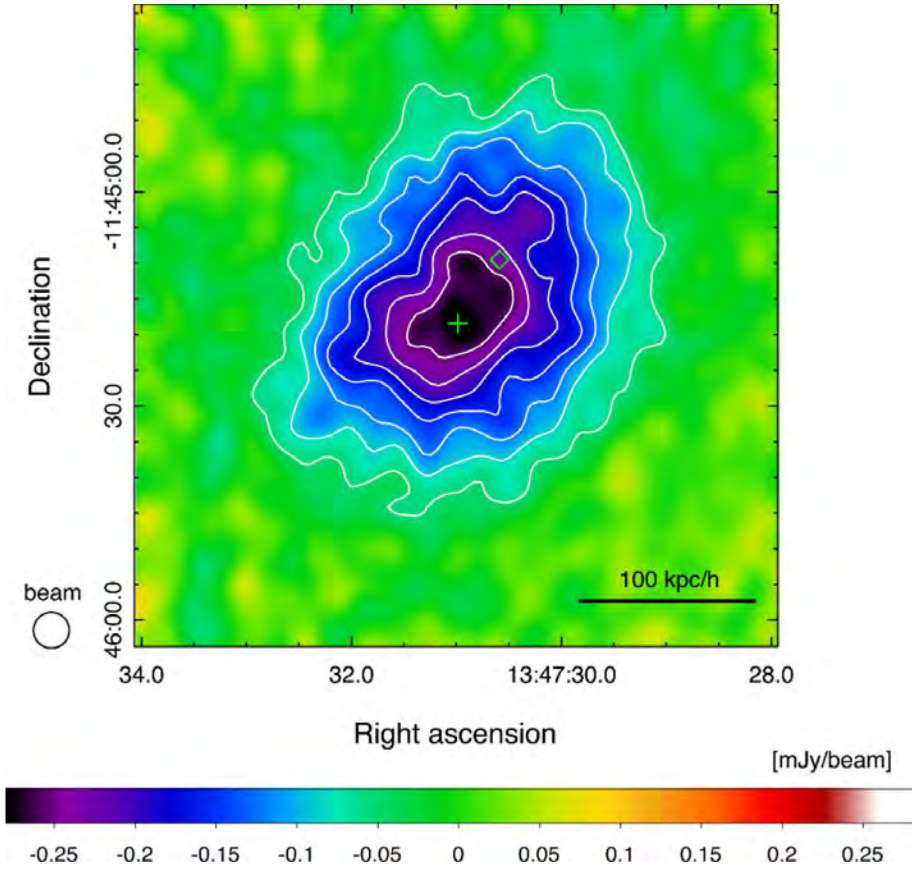






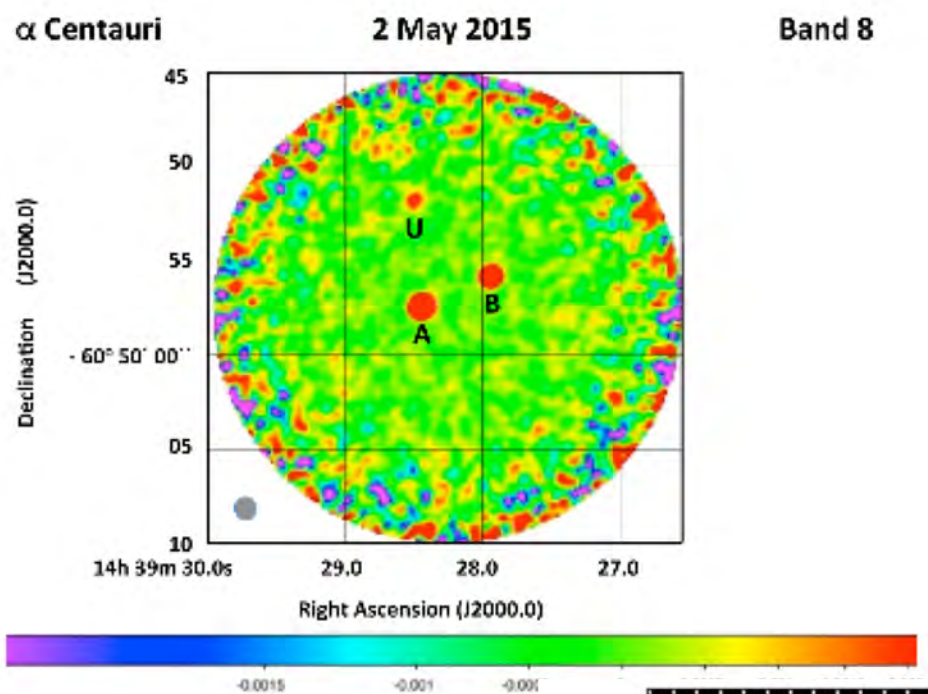


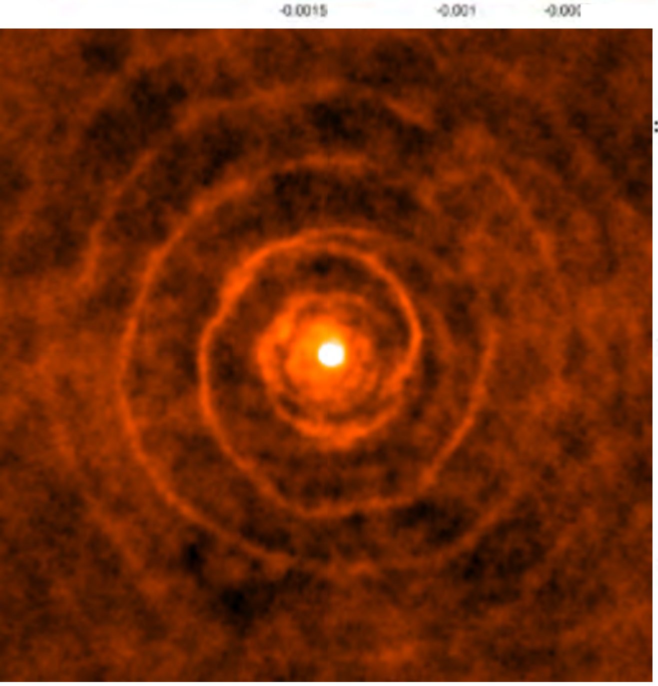


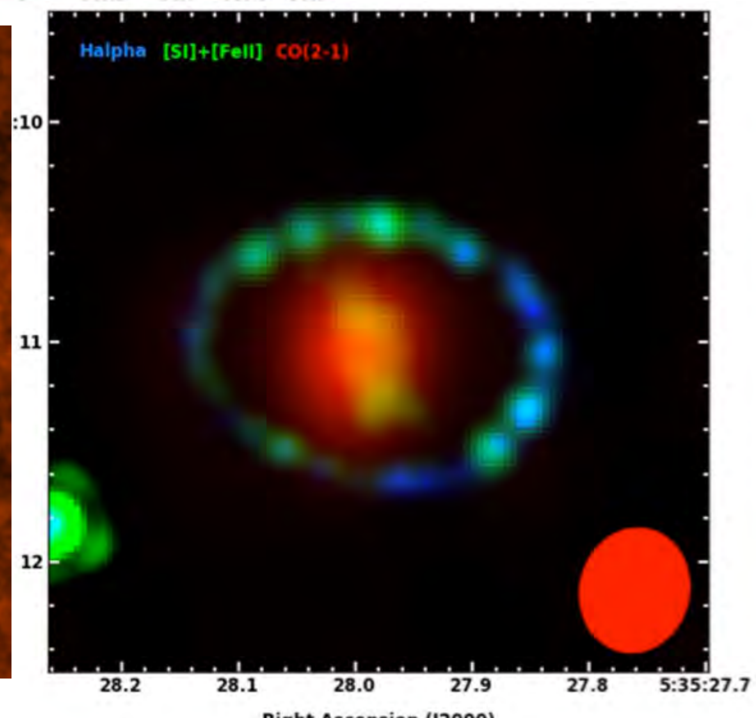


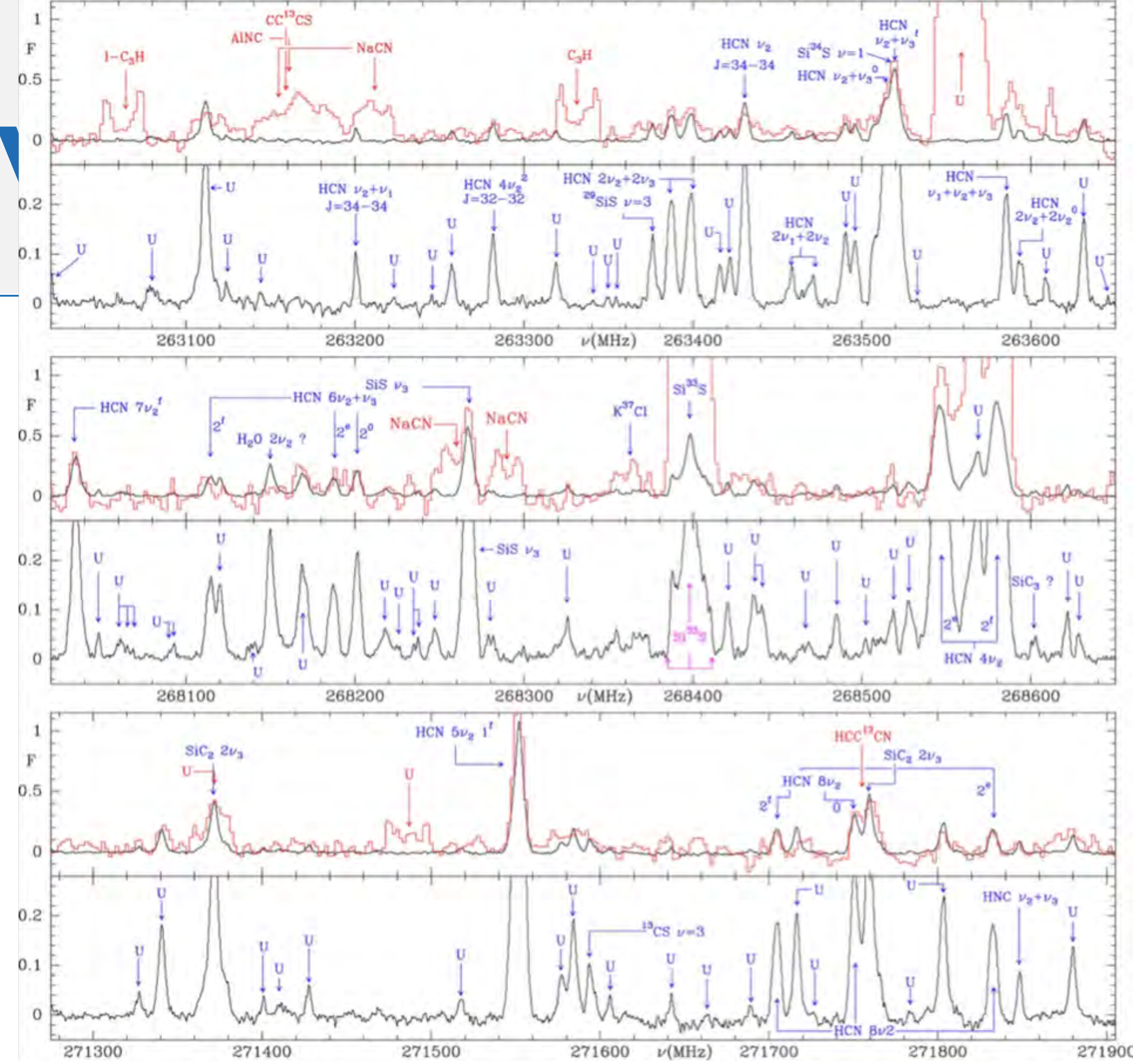
- Lensed star forming galaxies
- Atomic and molecular gas at high-z, the SZ effect

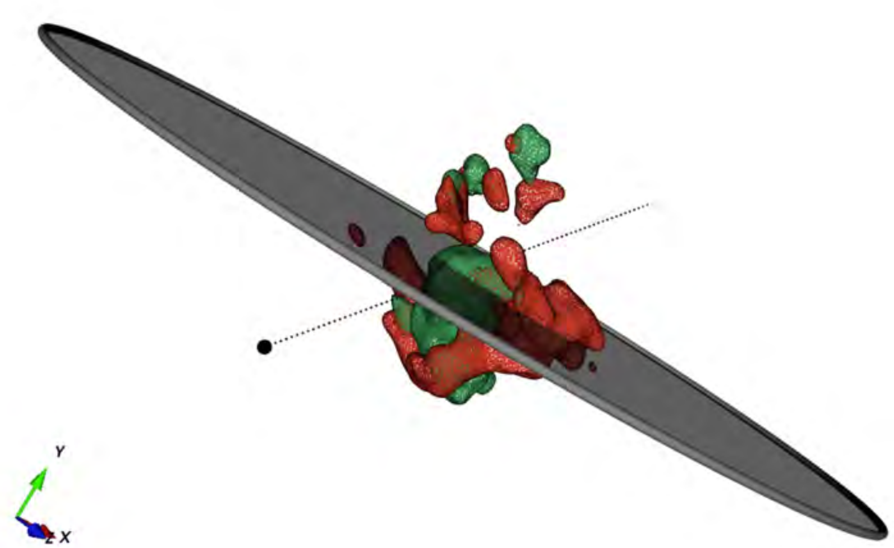
Stellar ev





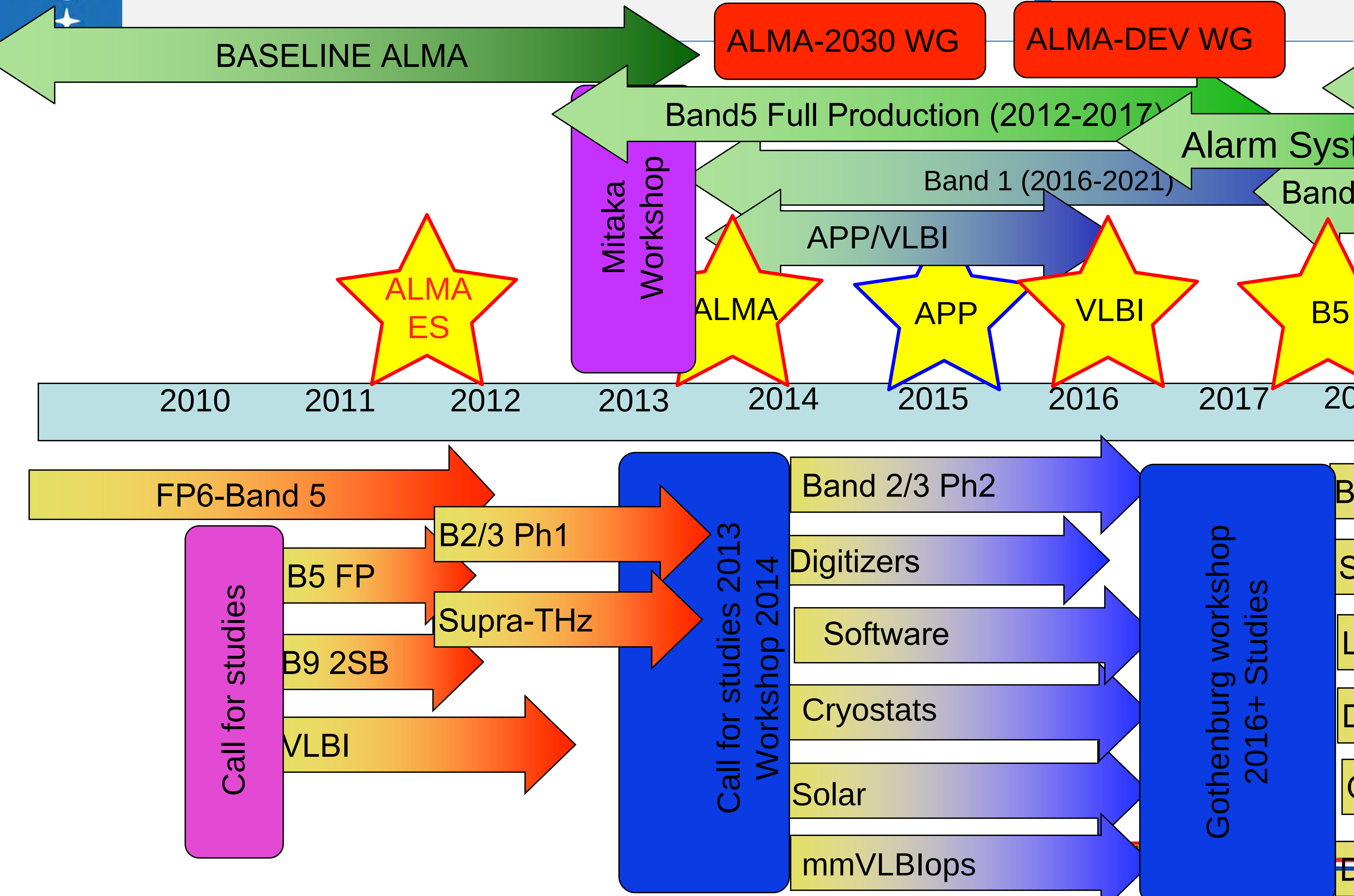




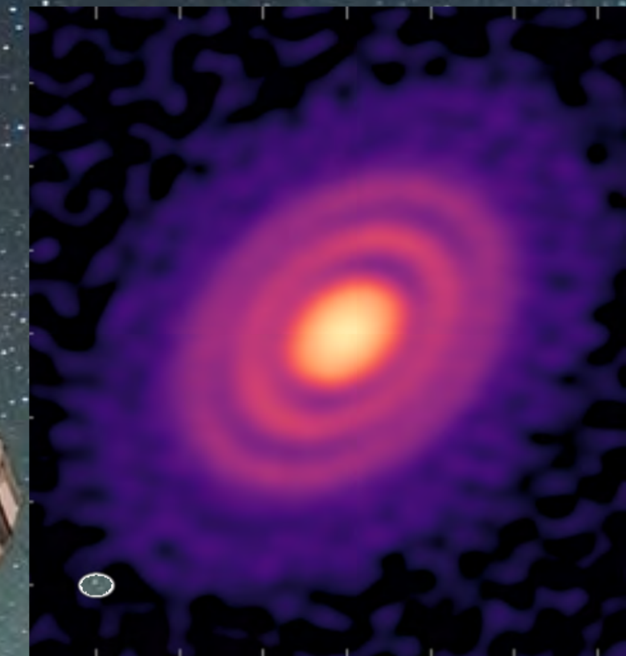


- The alpha-Cen system, SN 1987A
- Mass loss from AGBs, chemical richness

Timeline Summary

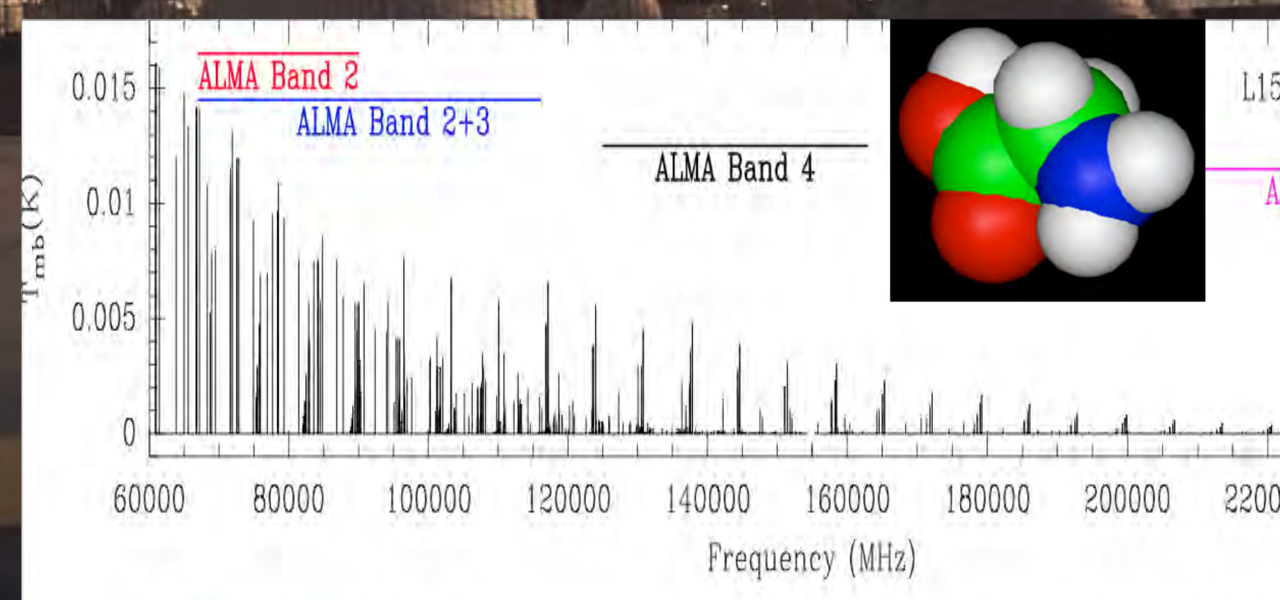


Long Term Science Vision

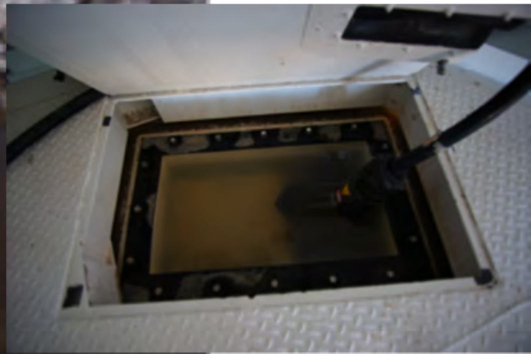


ALMA Science in 2030

- Earth formation region
- Astrobiology
- Early Universe/Cosmology



Joys of open air telescopes



Power cable repair – Feb 2018

Summary

- Building ALMA was challenging, but very rewarding
  - Dream high, avoid to draw compromises that will result in "designing out" future expansion
  - Do not underestimate the "easy" stuff
- Operating a facility for external users is very different than running your own experiment
  - Watch for the "post office clerk" syndrome
- Long term planning for development is key
  - To keep the facility state of the art
  - To motivate and retain top-level staff
- Modern astrophysics requires multi-wavelength, multi-messenger approach

...while flying to ALMA…