An Overview of ALMA

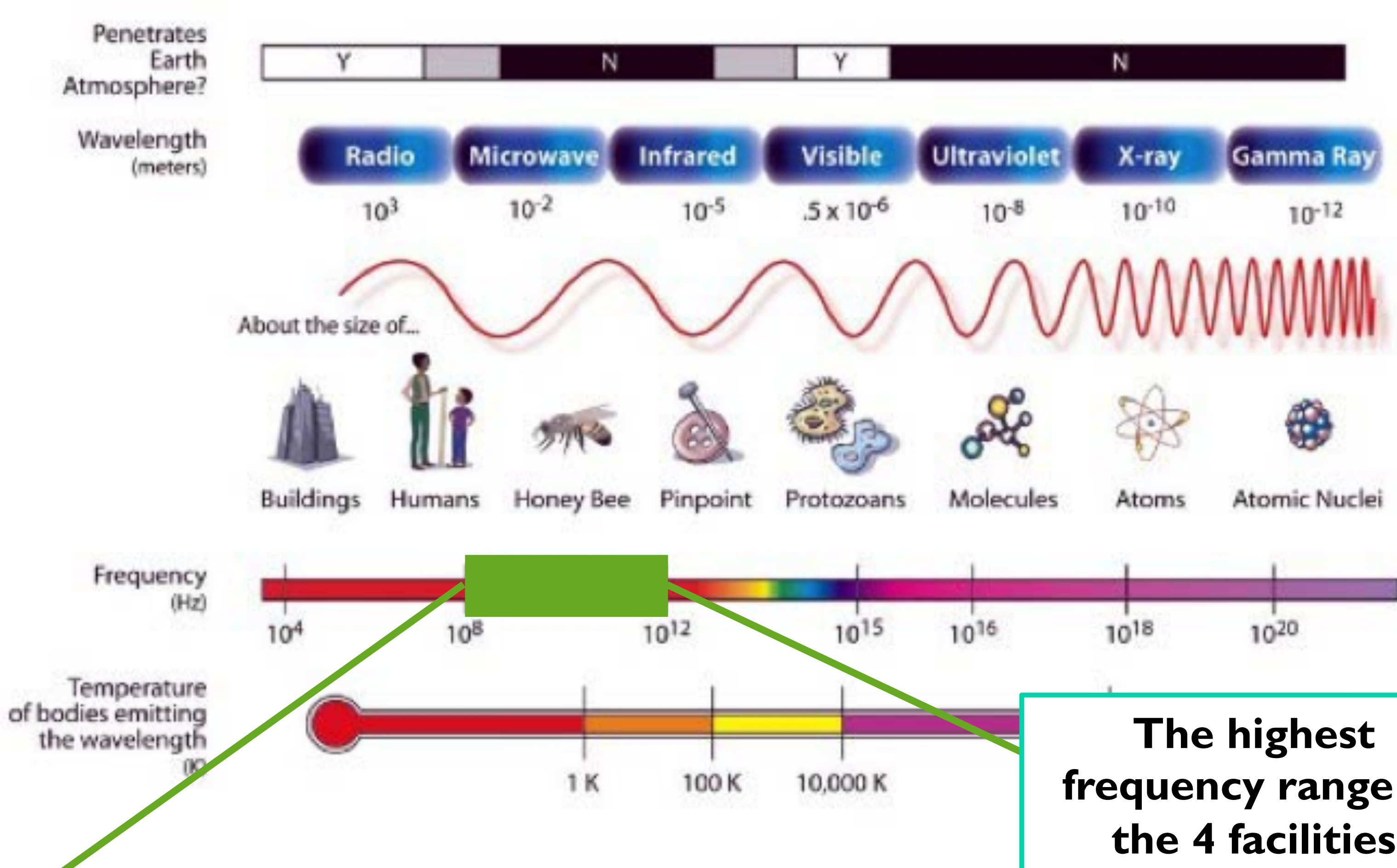
Current capabilities, some science cases, and considerations for high-frequency observing

Laura Pérez & NAASC Staff

Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

NRAO:
One Observatory, Four Facilities

Atacama Large Millimeter/submillimeter Array:
a 66-antenna array in Chile



The highest frequency range of the 4 facilities

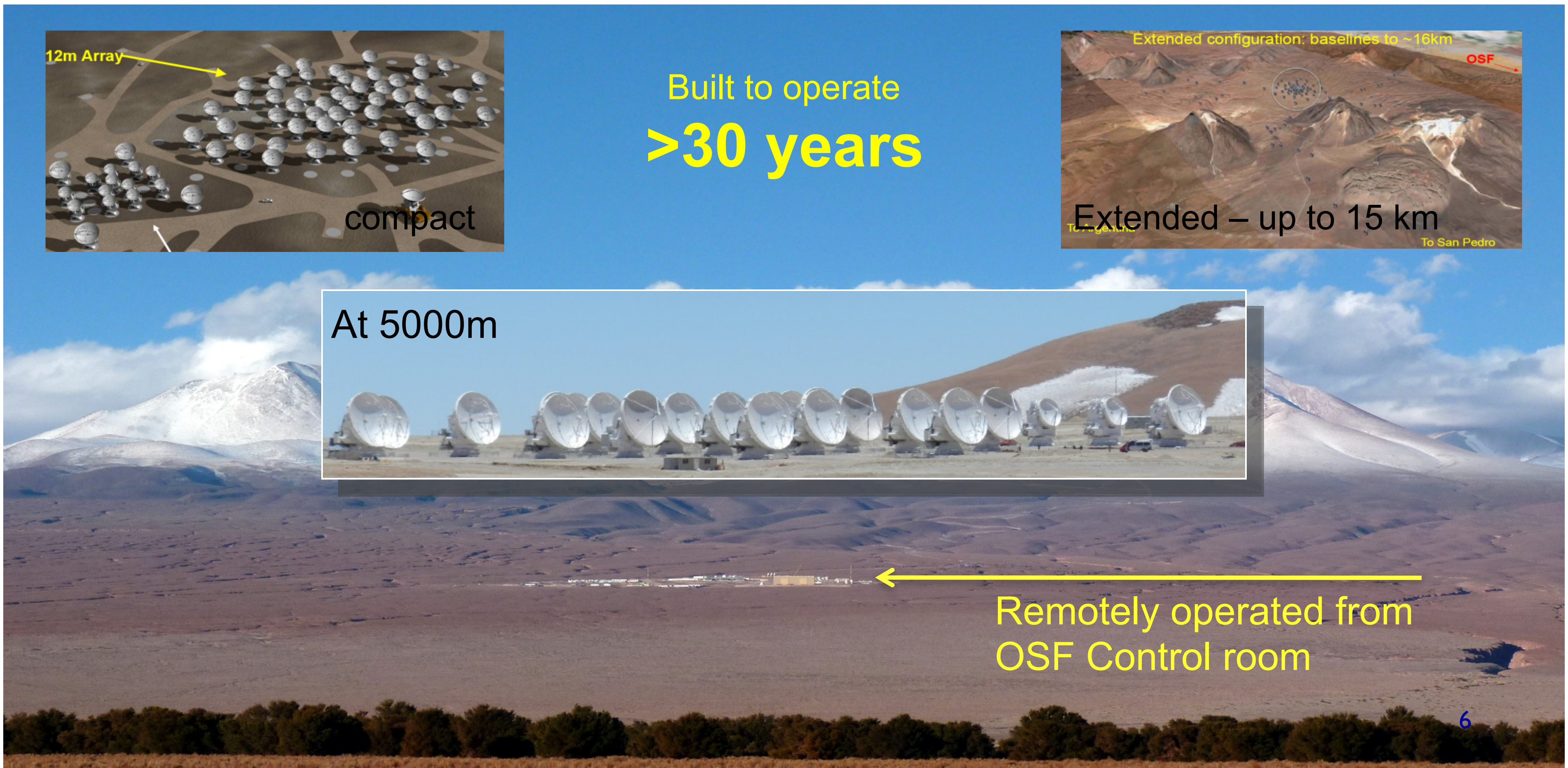

Palomar Observatory
5,600 FT
Kitt Peak Observatory
6,900 FT
Very Large Array
7,000 FT
Keck Observatory
14,000 FT
ALMA Observatory
16,500 FT
The highest altitude of the 4 facilities

ALMA Overview

- A global partnership to deliver a revolutionary millimeter/submillimeter telescope array
    - North America (US, Canada, Taiwan)
    - Europe (ESO)
    - East Asia (Japan,Taiwan)
    - In collaboration with Chile
- 5000 m (16,500 ft) site in Chilean Atacama desert
- 66 telescopes in full operation
    - Main Array: 50 x 12m antennas
    - Total Power Array: 4 x 12m antennas
    - Atacama Compact Array (ACA): 12 x 7m antennas

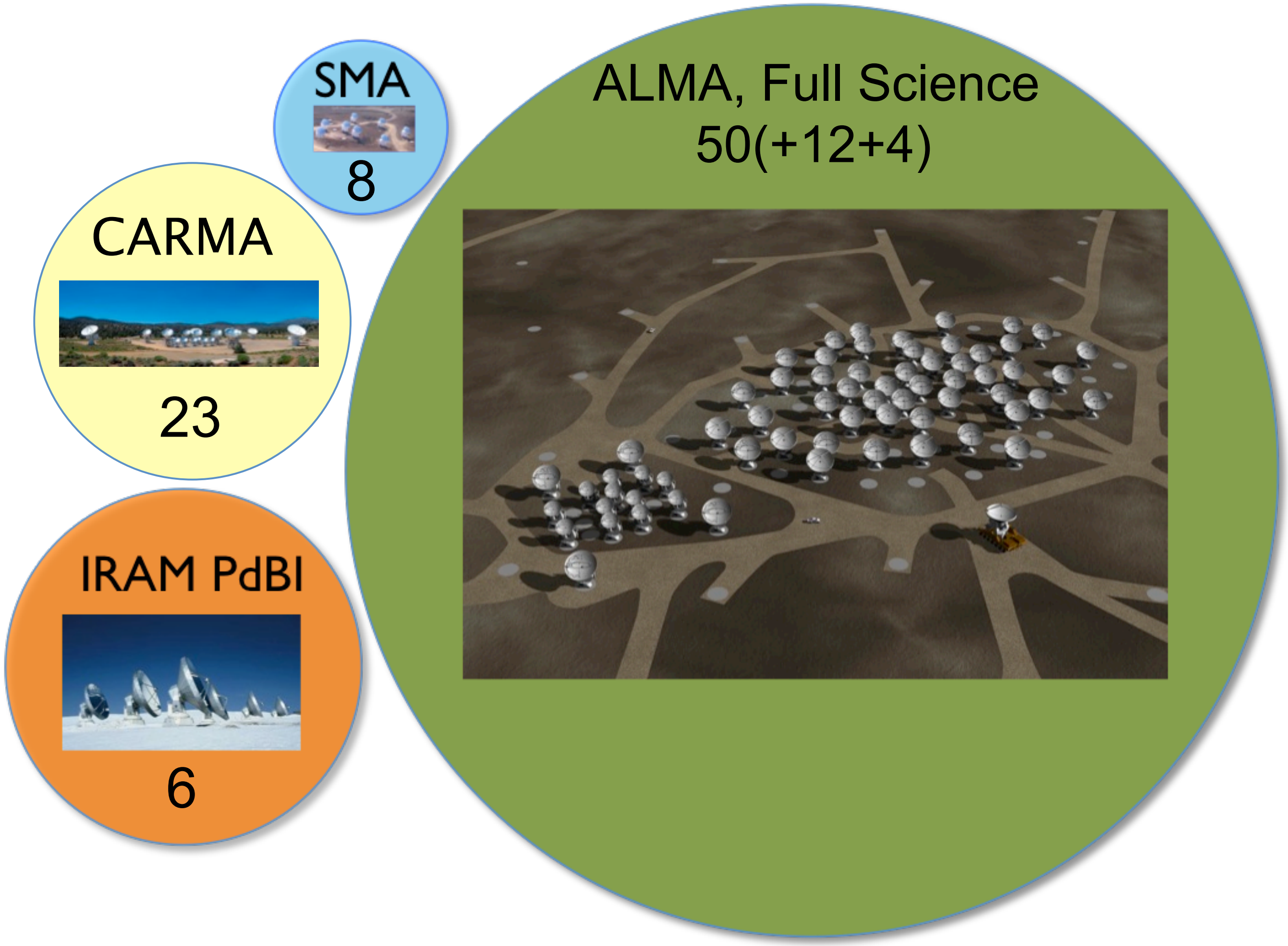
ALMA Overview

- ALMA is capable of doing **aperture synthesis** and **total power** observing
- Operating over the entire *accessible* **mm and sub-mm wavelength range**



Unprecedented Sensitivity

Collecting Area
~ sensitivity



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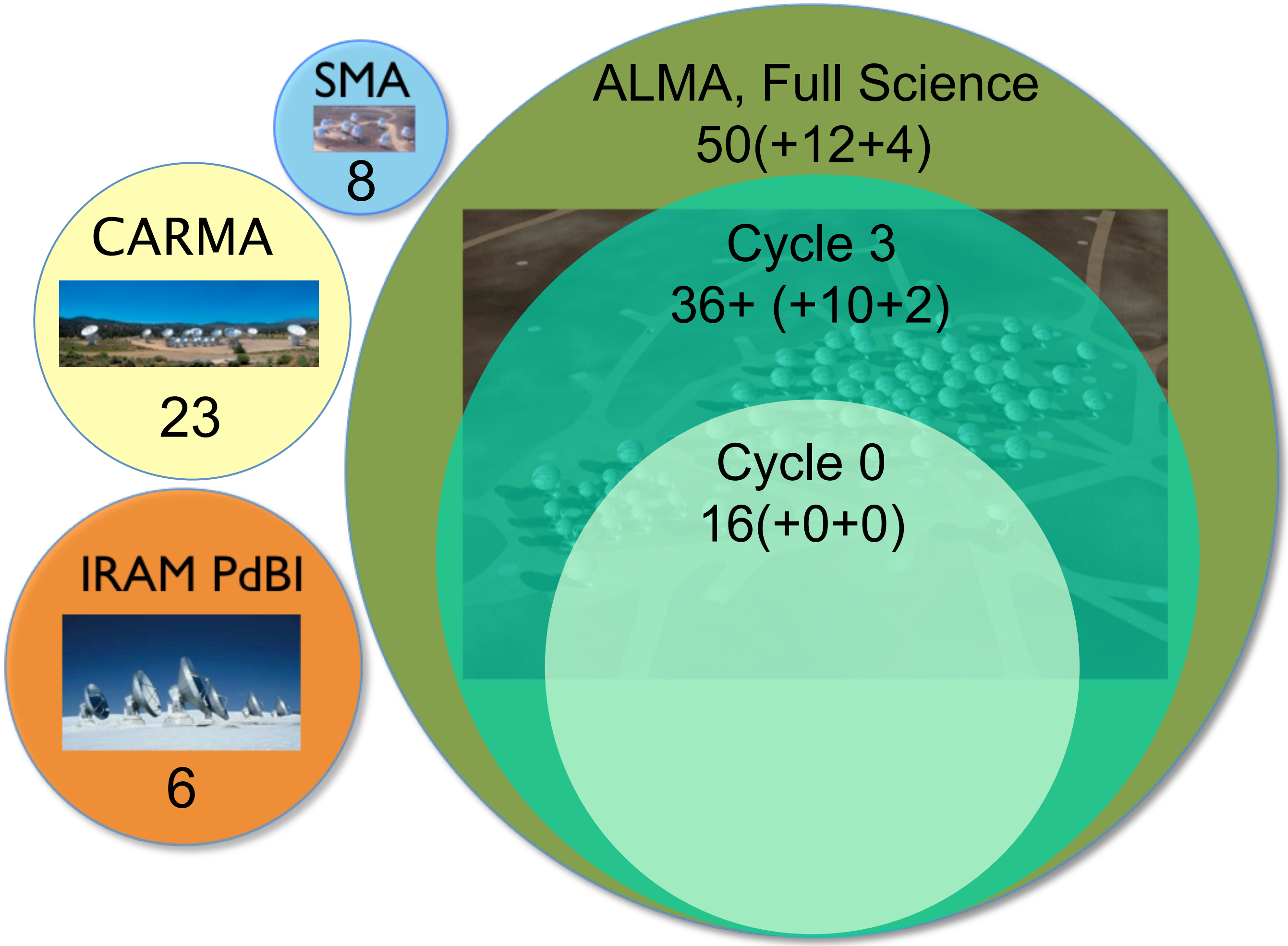
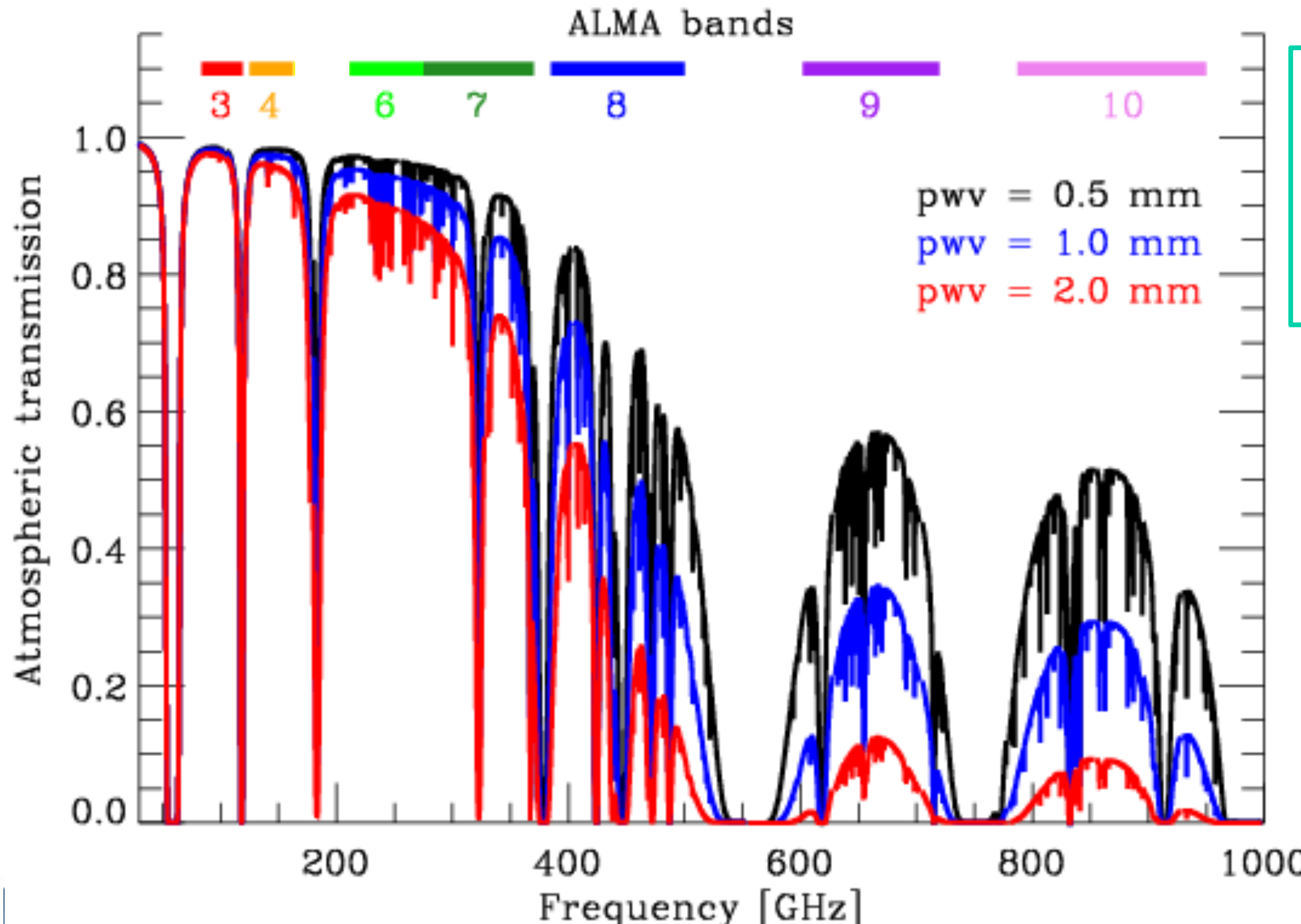


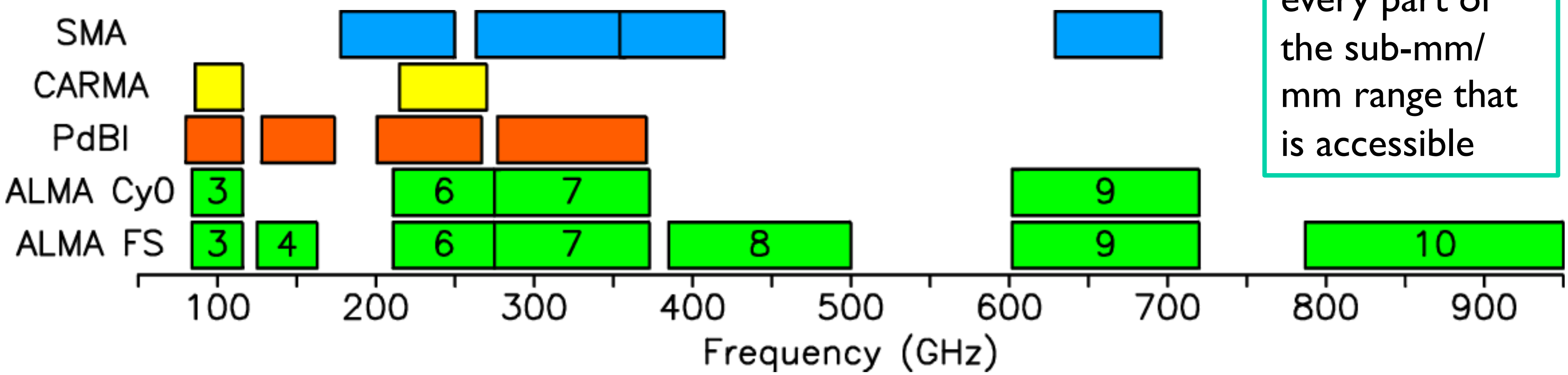
Current status:
All 66 antennas have been **accepted**

Unprecedented Spectral Coverage



Coverage of every part of the sub-mm/mm range that is accessible

Unprecedented Spectral Coverage



Coverage of every part of the sub-mm/ mm range that is accessible

Current status:

Receiver bands installed on all antennas

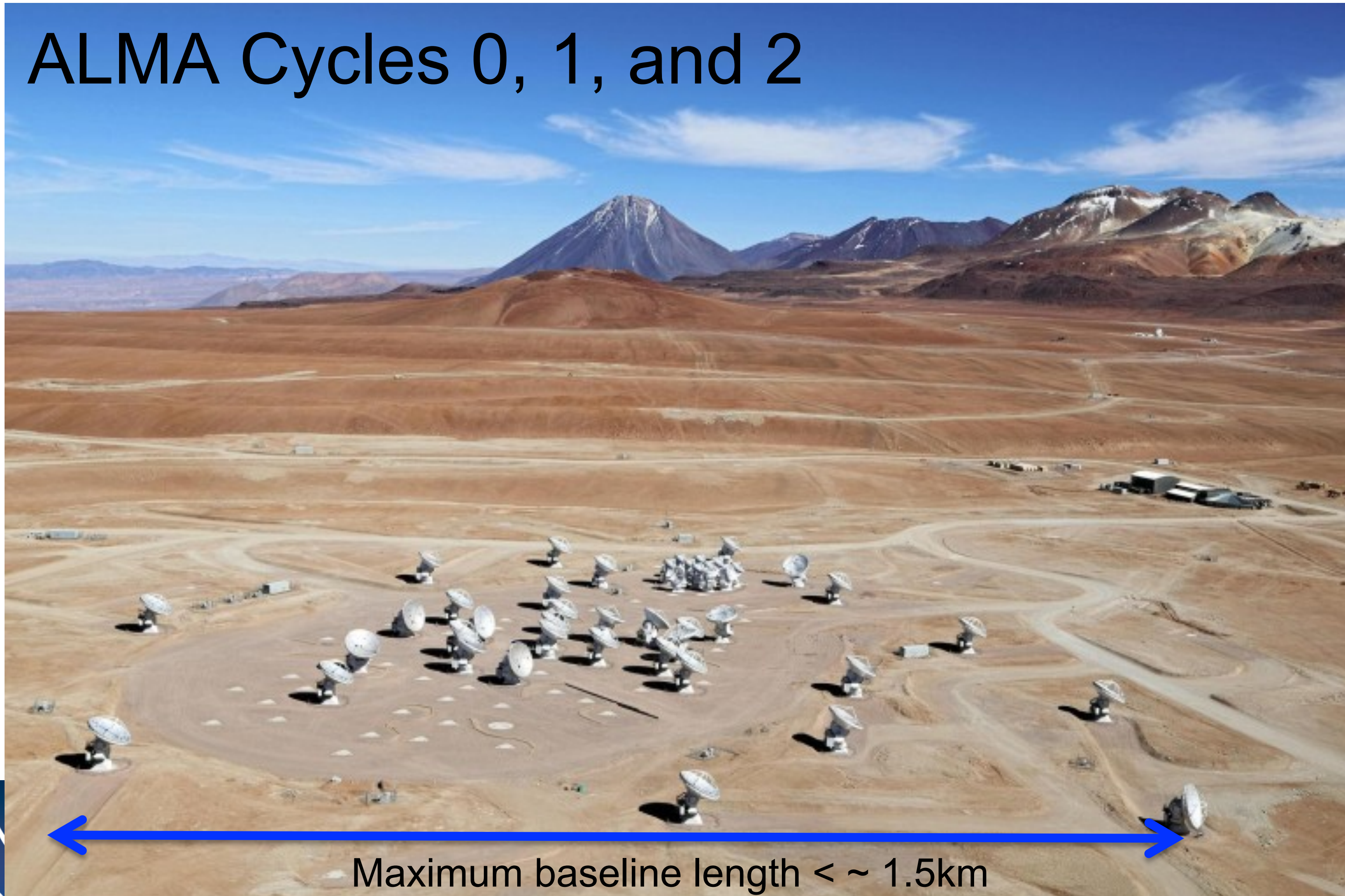
- Band 3, 3mm (84-116 GHz)
- Band 6, 1mm (211-275 GHz)
- Band 7, 850 μm (275-370 GHz)
- Band 9, 450 μm (602-720 GHz)

Receiver bands partially installed or undergoing verification

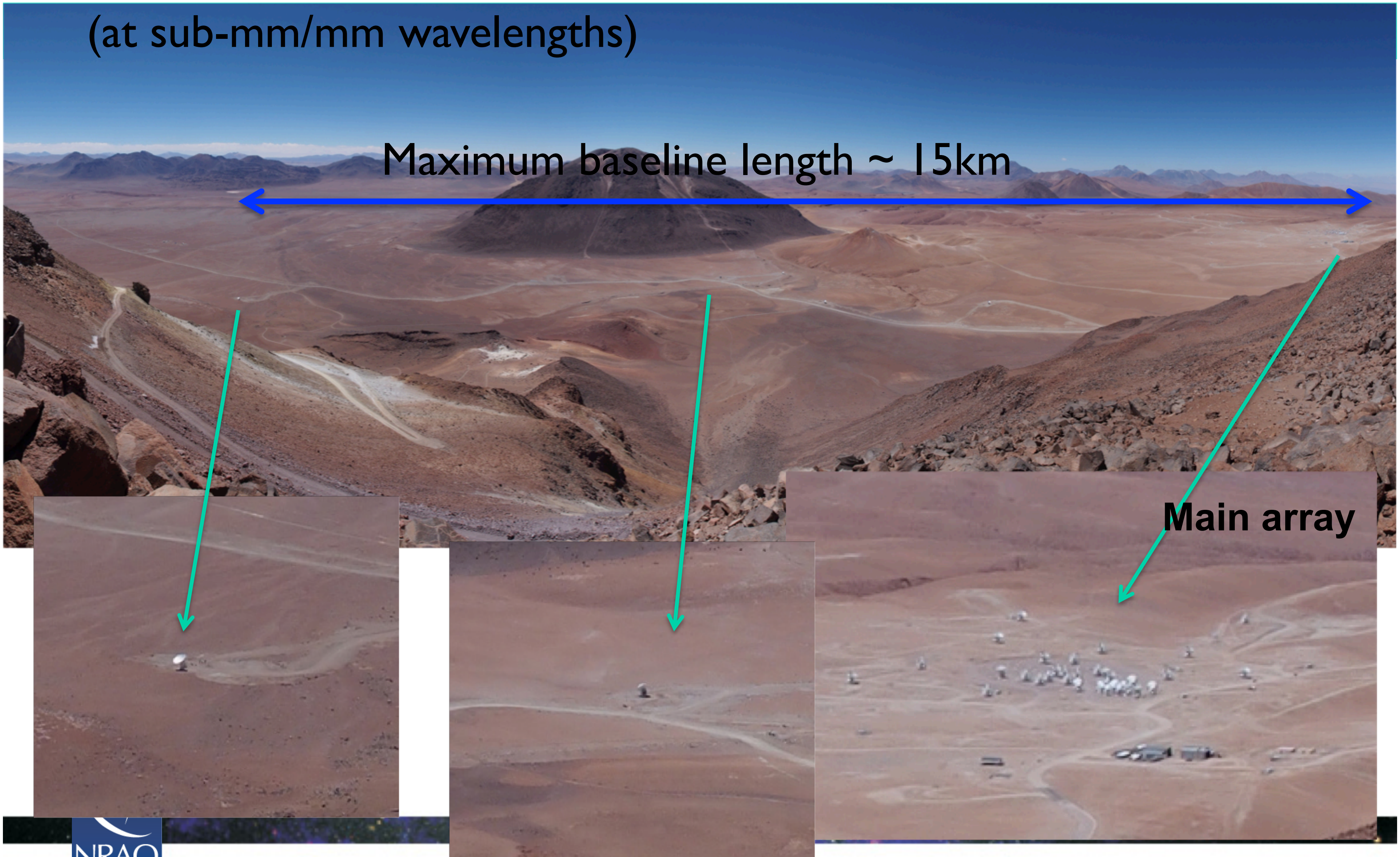
- Band 4, 2mm (125-163 GHz) 56/66
- Band 8, 650 μm (385-500 GHz) 53/66
- Band 10, 350 μm (787-950 GHz) 43/66

Unprecedented Baseline Coverage

(at sub-mm/mm wavelengths)



Unprecedented Baseline Coverage




The combination of these 3 factors:
Sensitivity + Spectral Coverage + Imaging Capabilities
allows for transformational science!

Summary of Current Capabilities

ALMA Cycle 2 currently ongoing, Cycle 3 begins October 2015

- At least 36x12m antennas in the main array, and 10x7m antennas (for short baselines) and 2x12m antennas (for making single-dish maps) in the Morita-san Array (ACA)
- Receiver bands 3, 4, 6, 7, 8, 9, & 10
- Long Baselines: 10 km for Bands 3, 4, 6; 5 km for Band 7; 2 km for the rest
- Both single-field interferometry and mosaics
- Spectral-line observations with all Arrays and continuum observations with the 12m Array and the 7m Array (except in Bands 9 and 10)
- Polarization at PI-specified frequencies (on-axis, continuum in Bands 3, 6 and 7 - no ACA, no mosaics, no spectral line, no circular polarization)
- Mixed correlator modes (both high and low frequency resolution in the same observation)

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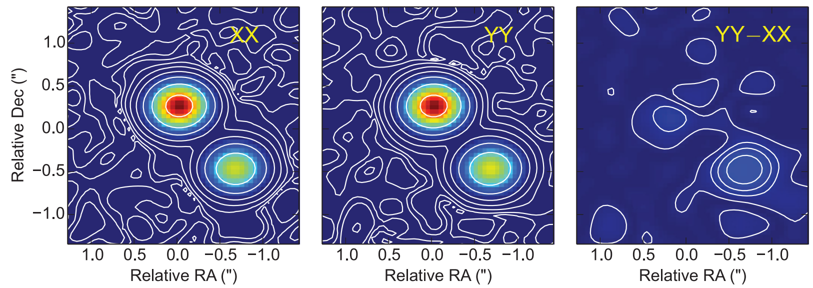
Let’s look at some recent science cases!

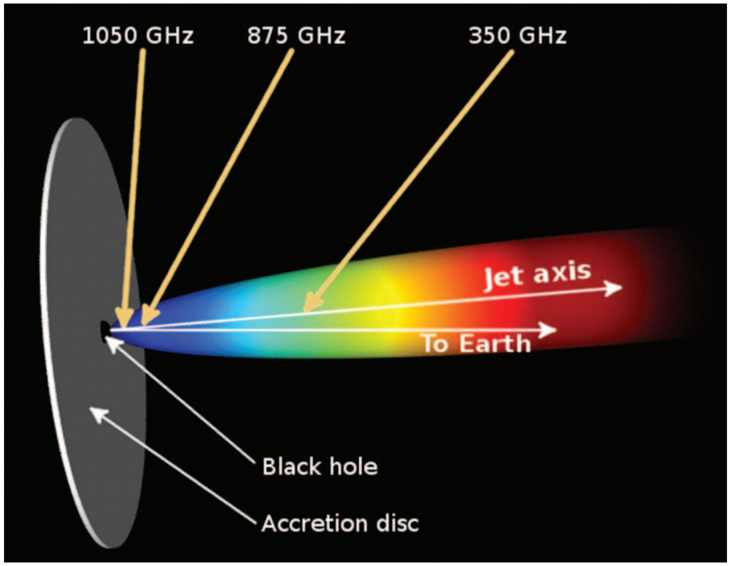
The Magnetic Field at the jet-base of a SMBH

Martí-Vidal et al. (2015, *Science*)

- Lensed AGN at z=2.5 (PKS 1830-211)
- ALMA observations at 100, 250, and 350 GHz detected polarization signal
- Amount of Faraday Rotation (RM) proportional to B strength and n_e along the line of sight
- **First time measurements allow for estimation of B very close to jet base**
- Magnetic fields of at least ~10 Gauss on 0.01 pc scales are required to account for large RM measured

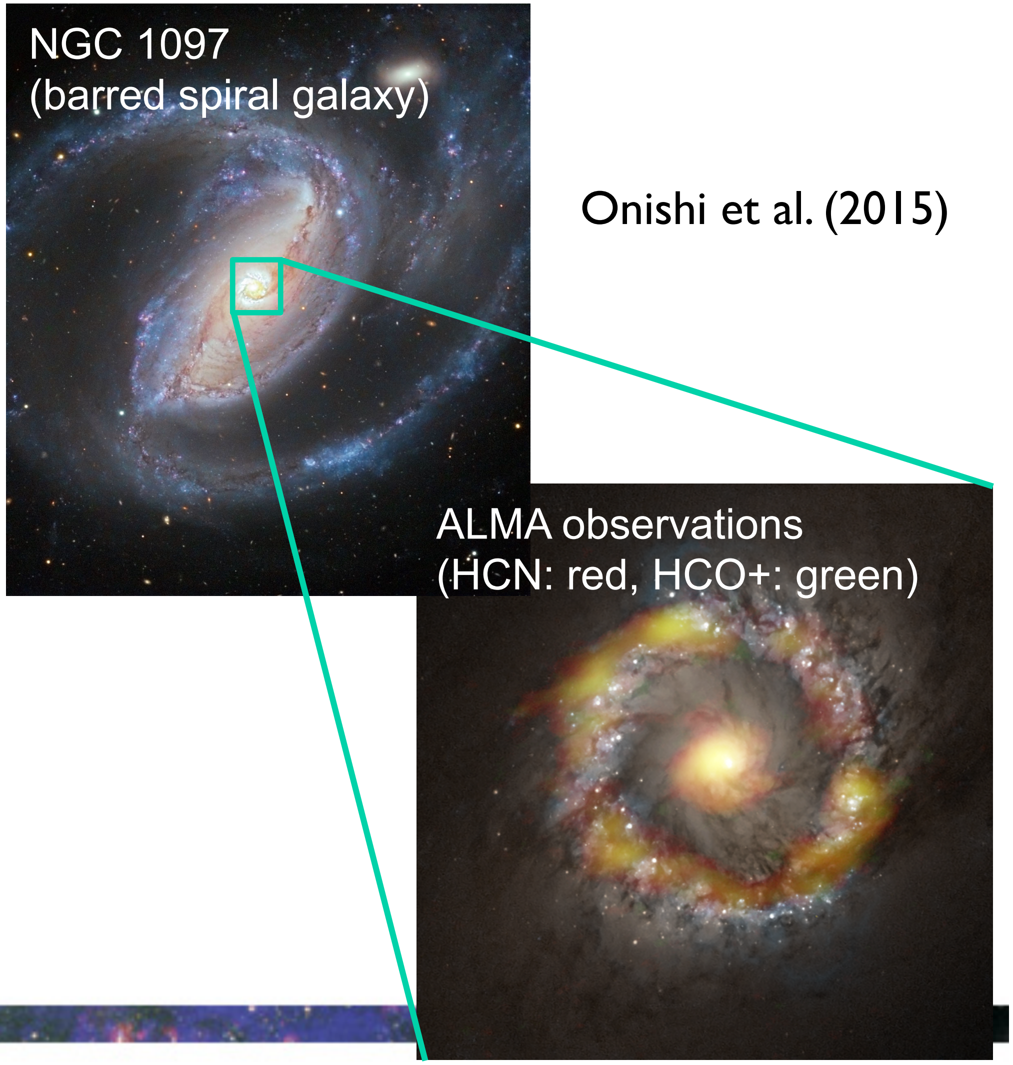
ALMA image of gravitationally lensed AGN





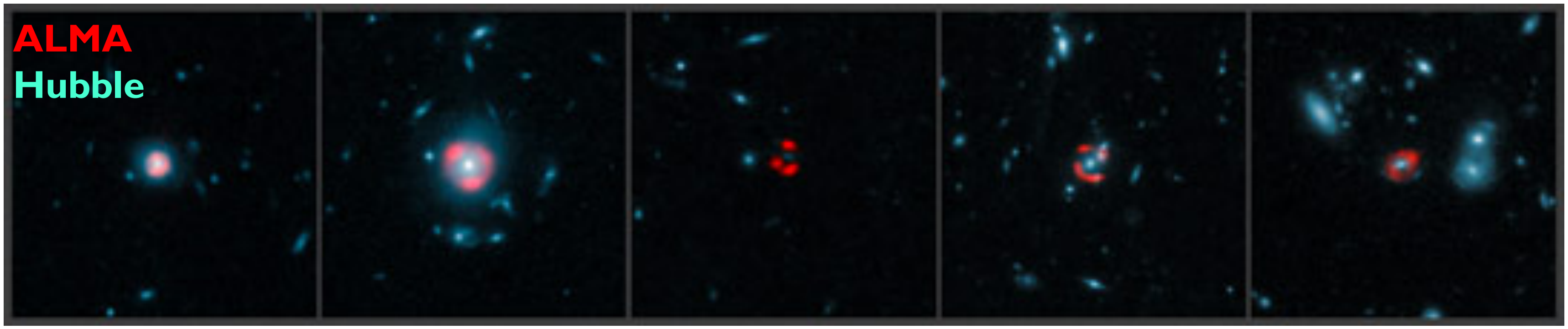
Precise measurements of central BH mass in a barred spiral galaxy

- BH mass measurements fundamental for constraining galaxy evolution models
- Other techniques are difficult for more common galaxies
- ALMA spectral line observations (HCN, HCO+) to **constrain distribution and kinematics of molecular gas near BH**
- SMBH mass ~1.4 x 10^8 Msun
- Potential for the future: large samples (only 2hrs for this observation)

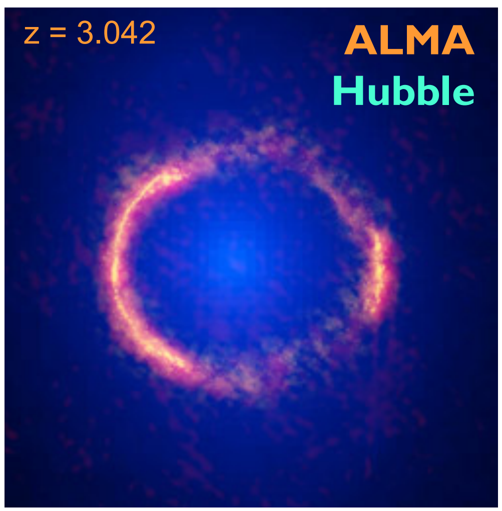


Onishi et al. (2015)

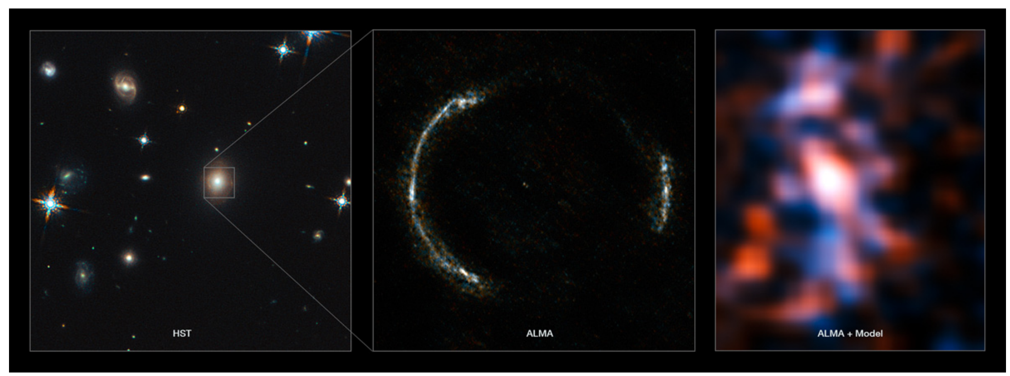
Sub-mm galaxies: strongly lensed star-forming galaxies at high redshift



Viera et al. (2013, Nature), Hezaveh et al. (2013)

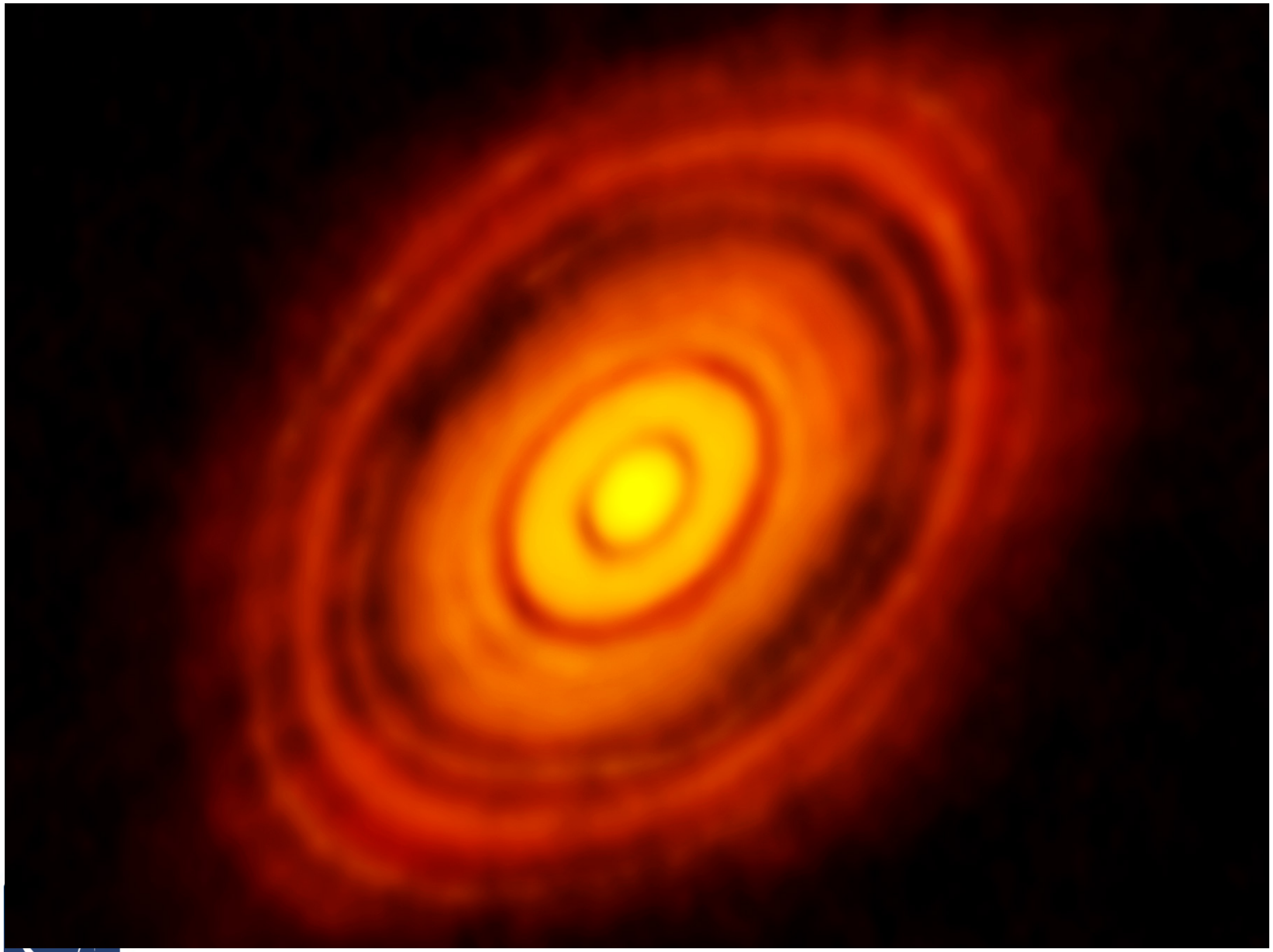


ALMA Partnership, Vlahakis, et al. (2015)



Swinbank et al. (2015)

Rings and Gaps in the Disk surrounding the young star HL Tau

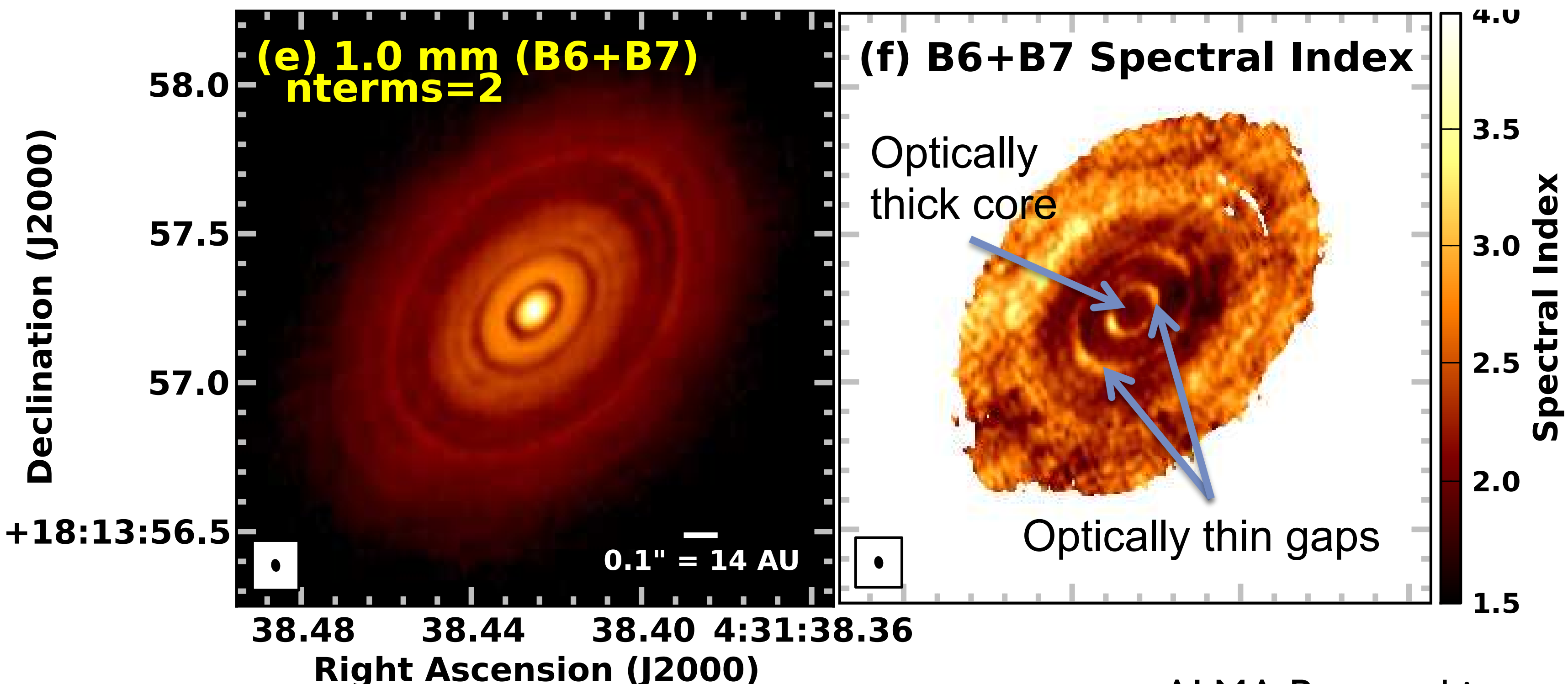


ALMA Partnership, Brogan, et al. (2015)

Rings and Gaps in the Disk surrounding the young star HL Tau

Highest fidelity HLTau image

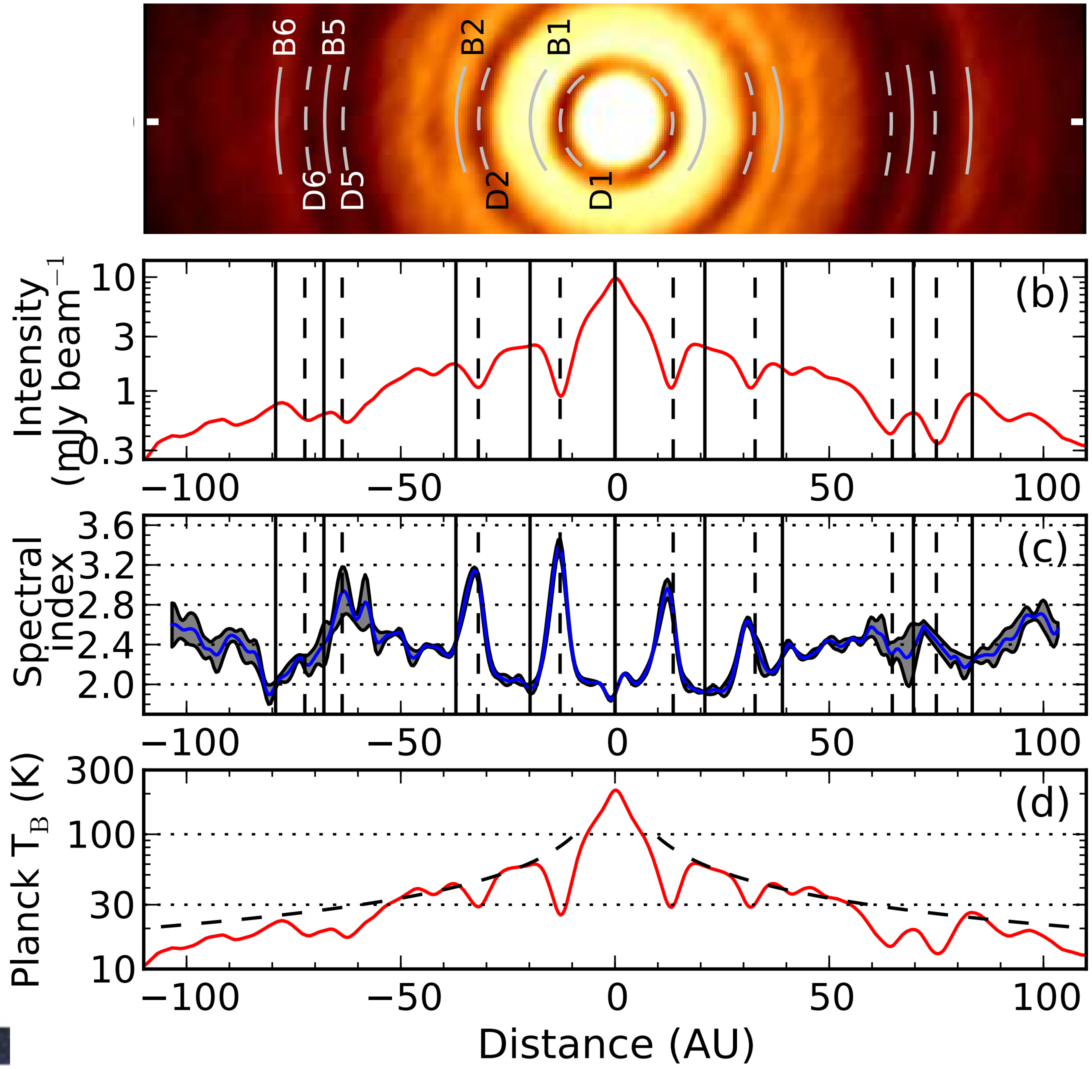
Spectral index map



ALMA Partnership,
Brogan, et al. (2015)

The HL Tau disk and its rings

Disk deprojection done with best-fit inclination and PA



ALMA Partnership, Brogan, et al. (2015)

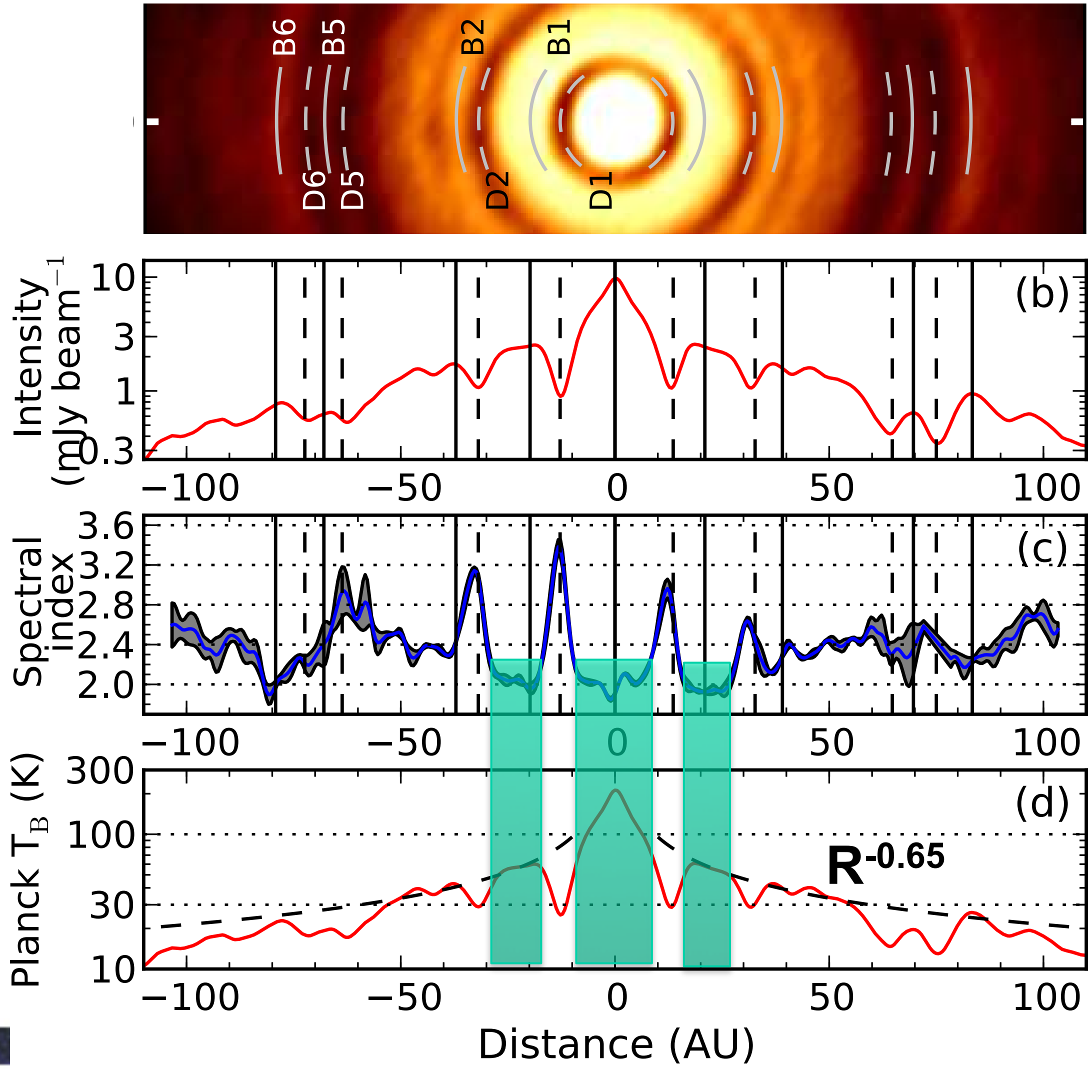
Intensity Radial cut

Spectral index Radial cut

Brightness Temperature Radial cut

Temperature constrained where τ>1

Temperature profile in between accreting/flat disk (-0.75) and flared disk (-0.5)



ALMA Partnership, Brogan, et al. (2015)

Intensity Radial cut

Spectral index Radial cut

Brightness Temperature Radial cut

Optically thick emission (α ~2)

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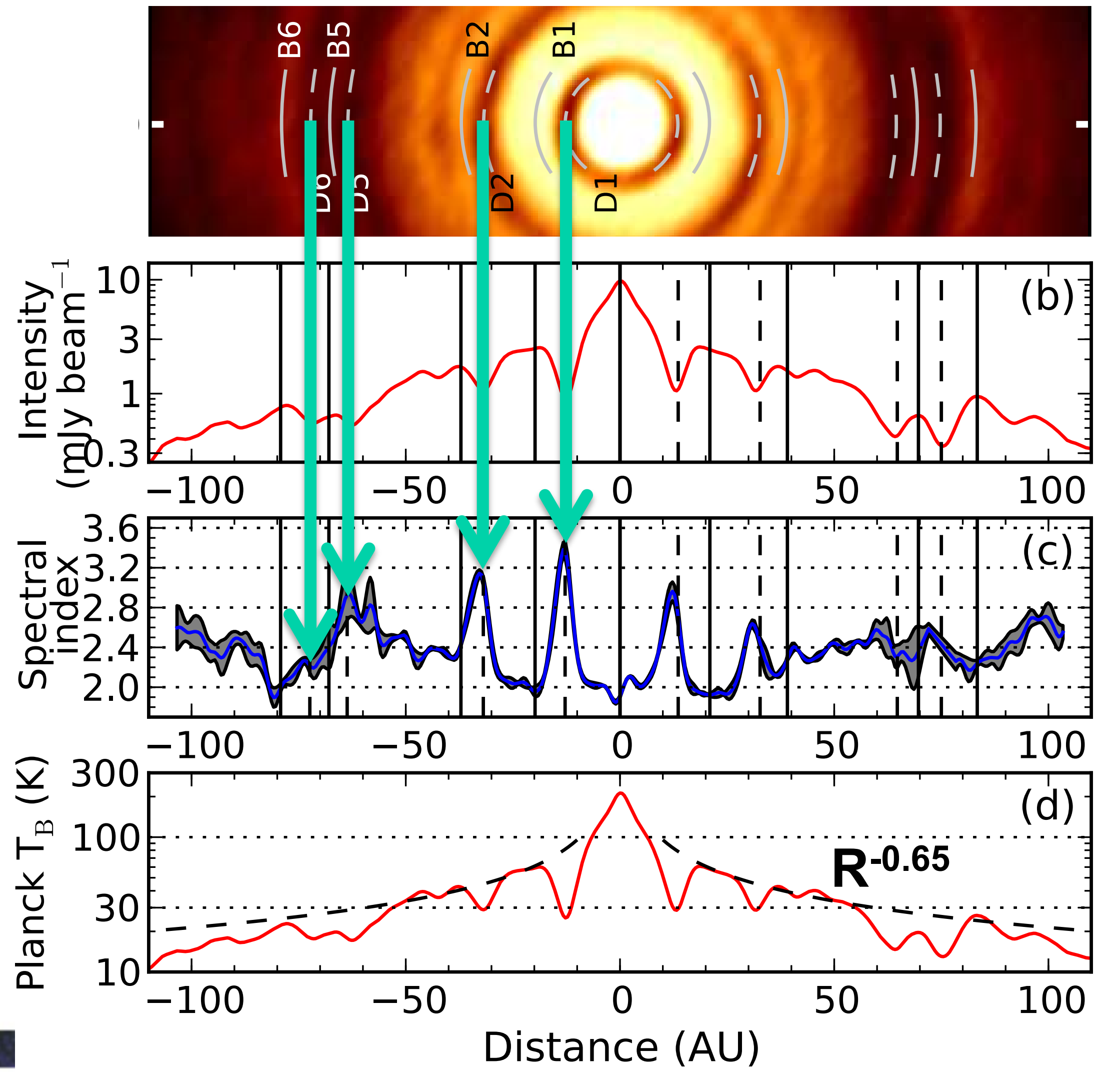
Radial variations of the spectral index

We find $\beta \sim 0.8 \rightarrow 0.3$, consistent with some amount of grain growth and evolution



ALMA Partnership, Brogan, et al. (2015)

Intensity Radial cut

Spectral index Radial cut

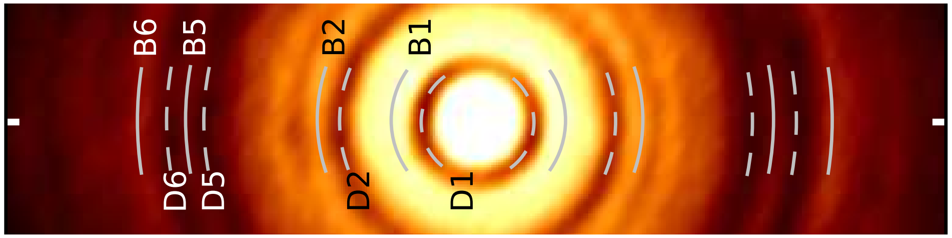
Brightness Temperature Radial cut

Spectral index in gap decreases with radius

Tantalizing evidence for planet-formation origin of rings and gaps

- At rings: high Tb & low spectral index → optical depth is high!
- At gaps: low Tb & high spectral index → optical depth is low!
  - *Dust opacity and/or column density decrease in gaps*
- Centers of rings/gaps offset from disk "center" → *not circular!*
- Magnitude of center offset increases with radius → *increasing eccentricity of orbits?*
- Several of these rings appear to be near *resonances*

D1:D2:D3:D4 ~ 1:4:6:8
D2:B1 ~ 2:1
D2:B6 ~ 1:4



ALMA Partnership, Brogan, et al. (2015)

Now onto some further considerations when observing at sub-mm/mm…

Interferometric data calibration steps

A priori calibrations (baseline, focus, etc.)

Water Vapour Radiometry (WVR) calibration

System Temperature (Tsys) calibration

Flux calibration

Bandpass calibration

Gain calibration

Examine data, flag/repeat if necessary

Self-calibration

Apply calibration to science target

Imaging

Fundamentals discussed in R. Perley's talk

Calibration steps discussed in A. Wootten's talk

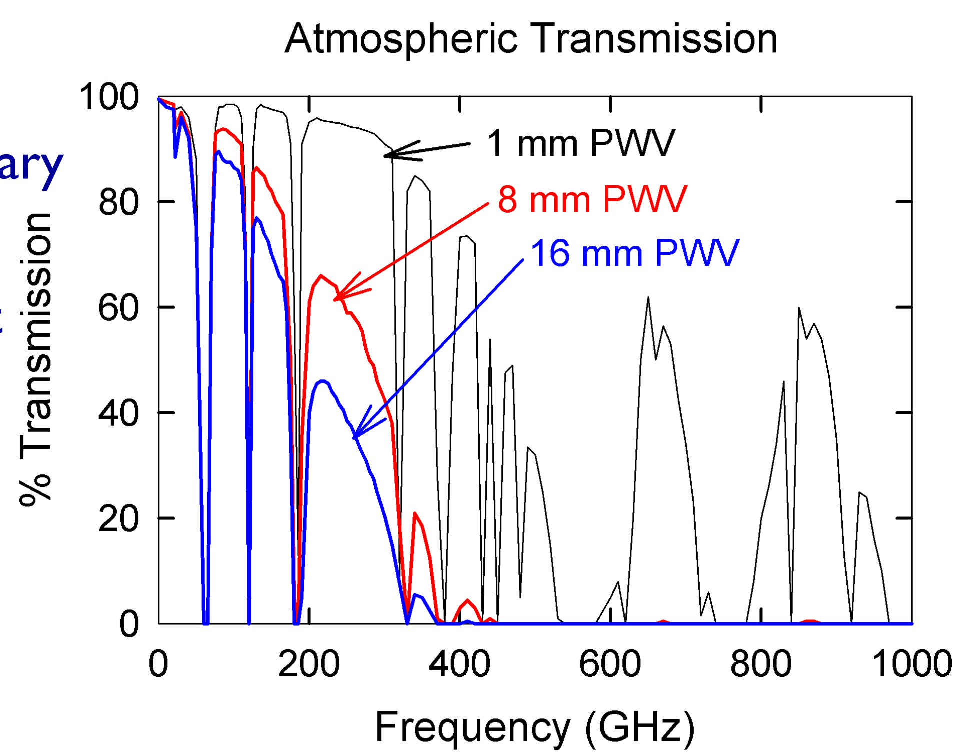
Imaging discussed in A. Moullet's talk

However, there are some *additional steps* to consider when dealing with high frequency (i.e. sub-mm/mm) observations (To be further discussed in C. Brogan's talk)

Interferometric data calibration steps

A priori calibrations (baseline, focus, etc.)
Water Vapour Radiometry (WVR) calibration
System Temperature (Tsys) calibration
Flux calibration
Bandpass calibration
Gain calibration
Examine data, flag/repeat if necessary
Self-calibration
Apply calibration to science target
Imaging

High frequency observations (i.e. sub-mm/mm) can be significantly affected by the atmosphere!



System Sensitivity: characterized by T_{sys}

The system sensitivity drops exponentially (!!!) as opacity increases

$$S / N = T_{source} / (T_{noise}\, e^{\tau})$$
$$T_{sys} = T_{noise}\, e^{\tau} \approx T_{atm}(e^{\tau} - 1) + T_{rx} e^{\tau}$$

Typical optical depth at 230 GHz:

$\tau_{225} = 0.15 = 3$ mm PWV (zenith) → at elevation = 30° ⇒ $\tau_{225} = 0.3$

$T_{sys} = (T_{atm}(1-e^{-\tau}) + T_{rx})\, e^{\tau} = (77 + 75)1.35 \sim 200$ K

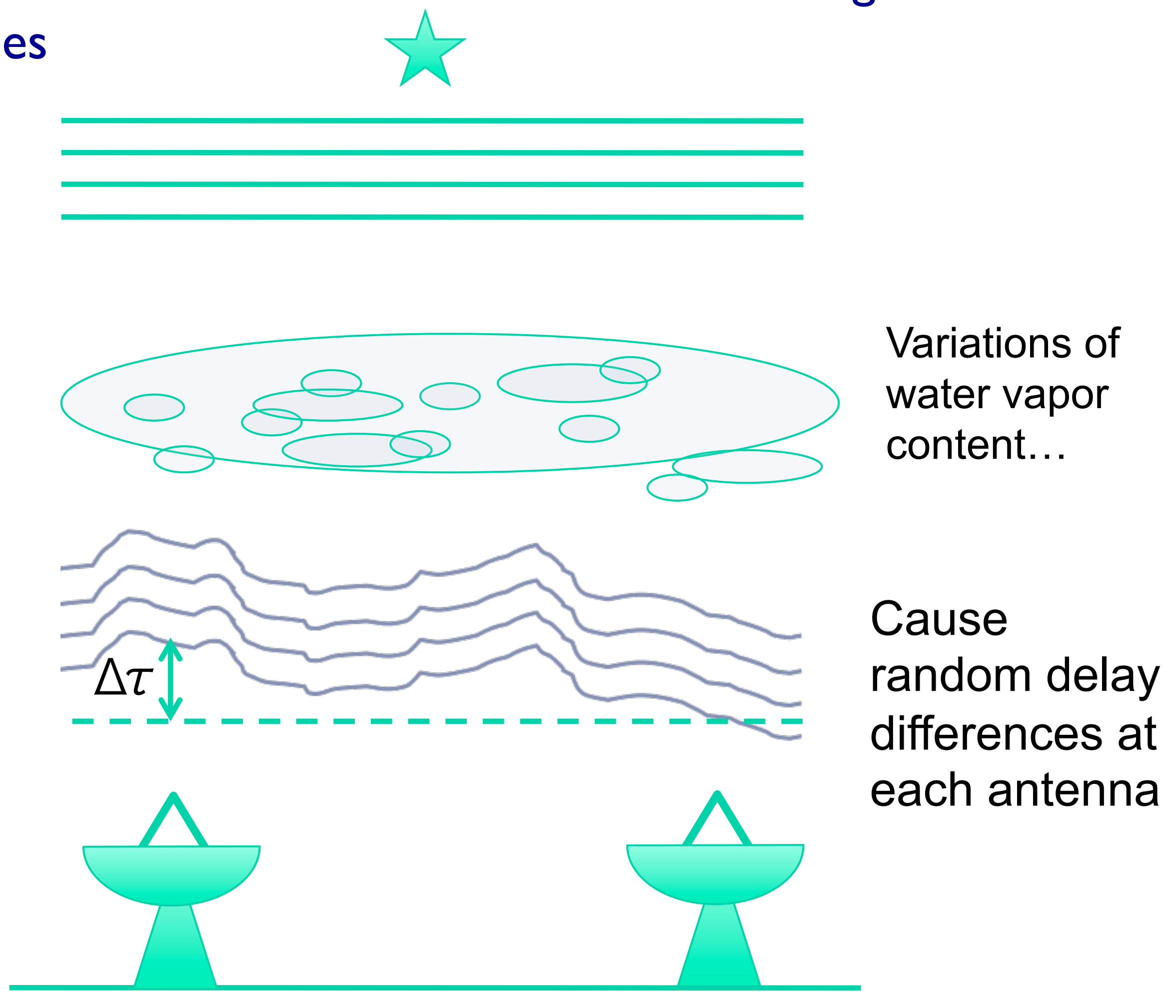
assuming $T_{atm} = 300$ K and $T_{rx} = 75$ K

⇨ Atmosphere adds considerably to T_{sys}

⇨ Since the opacity can change rapidly, T_{sys} must be measured often

Atmospheric phase fluctuations

Our ability to obtain high angular resolution images is hindered by *atmospheric phase fluctuations*, which distort the "flat" wavefront arriving from distant astronomical sources

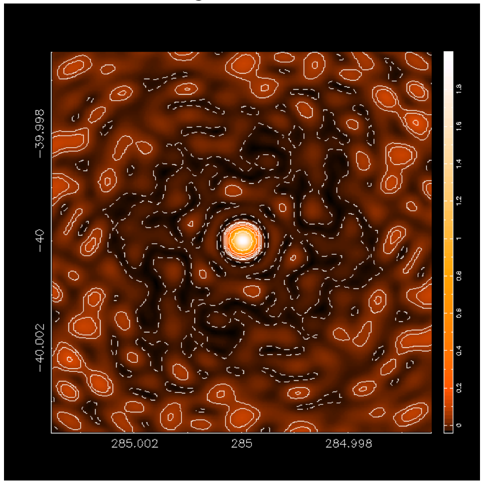


$$\Delta\phi = 2\pi \cdot \nu \cdot \Delta\tau$$

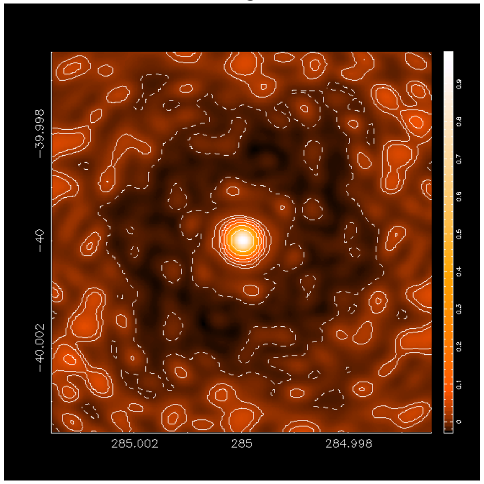
Net effect: Phase fluctuations corrupt the observed visibility data

- Reduce angular resolution of observations
  - → Introducing "radio seeing"
- Reduce sensitivity of observations

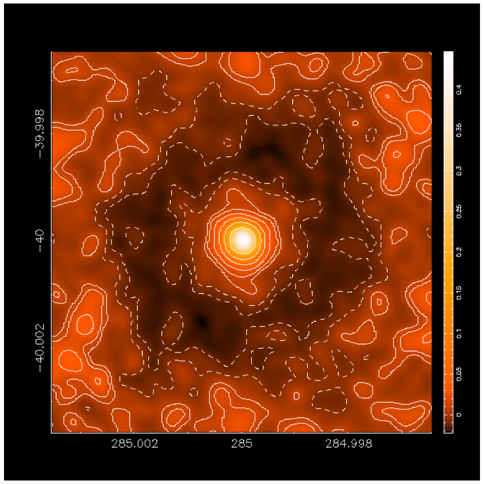
2 Jy peak



0.98 Jy peak



0.45 Jy peak



Increasing magnitude of atmospheric phase fluctuations

http://www.mrao.cam.ac.uk/projects/alma/fp6/index.html

Net effect: Phase fluctuations corrupt the observed visibility data

Reduce angular resolution of observations

→ Introducing "radio seeing"

Reduce sensitivity of observations

⇨ Atmosphere adds considerably to phase errors on the visibilities

⇨ Since the pwv fluctuations can change rapidly, its magnitude must be measured often in order to correct for it.

Interferometric data calibration steps

A priori calibrations (baseline, focus, etc.)

Water Vapour Radiometry (WVR) calibration

System Temperature (Tsys) calibration

Flux calibration

Bandpass calibration

Gain calibration

Examine data, flag/repeat if necessary

Self-calibration

Apply calibration to science target

Imaging

High frequency observations can be significantly affected by the atmosphere!

Several different techniques used to correct for atmospheric effects.

These advanced topics will be covered in C. Brogan's Talk

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ALMA

Go use ALMA!

For more info:

https://almascience.nrao.edu/

The Atacama Large Millimeter/submillimeter Array (ALMA), an international astronomy facility, is a partnership of Europe, North America and East Asia in cooperation with the Republic of Chile. ALMA is funded in Europe by the European Organization for Astronomical Research in the Southern Hemisphere (ESO), in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC) and the National Science Council of Taiwan (NSC), and in East Asia by the National Institutes of Natural Sciences (NINS) of Japan in cooperation with the Academia Sinica (AS) in Taiwan. ALMA construction and operations are led on behalf of Europe by ESO, on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI), and on behalf of East Asia by the National Astronomical Observatory of Japan (NAOJ). The Joint ALMA Observatory (JAO) provides the unified leadership and management of the construction and operation of ALMA.

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