ALMA: From Our Solar System To The Galactic Centre

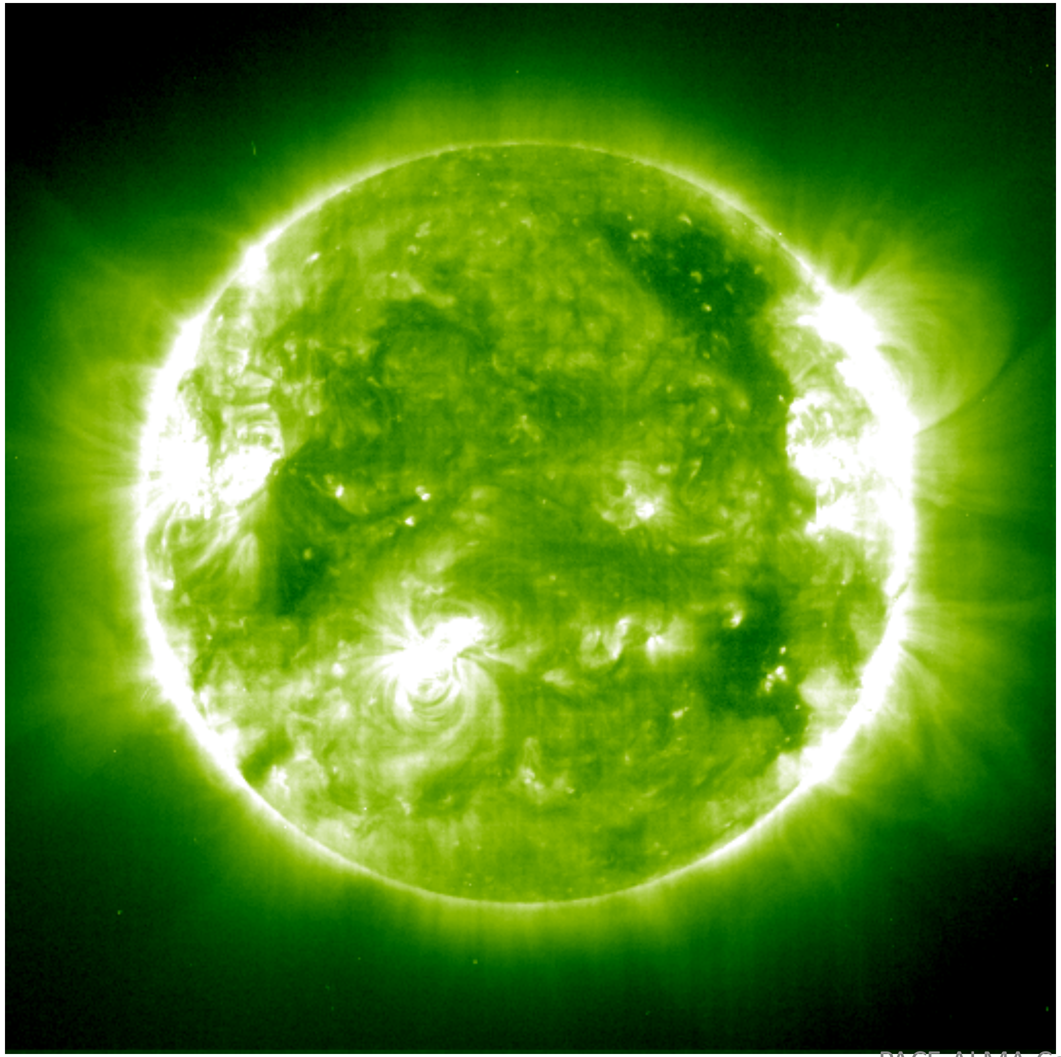
Liz Humphreys (ESO)

EUROPEAN ARC
ALMA Regional Centre

- Solar System
- Exoplanets
- Star Formation
- Astrochemistry
- Stars
- Galactic Centre

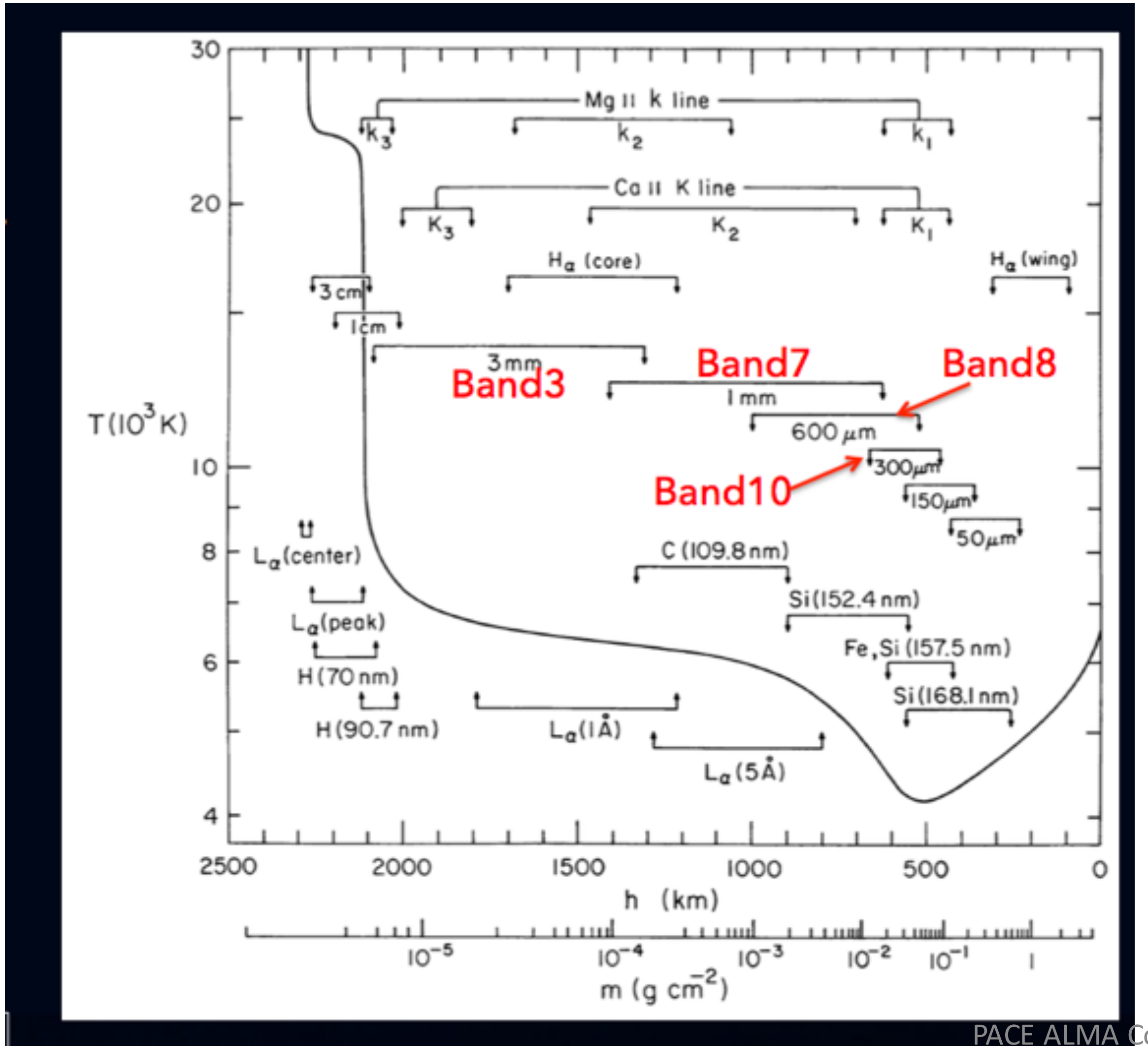
Solar System Objects

The Sun



- The structure of the quiet solar atmosphere
- Coronal holes (where vast solar winds originate because of diverging magnetic fields)
- Solar active regions
- Active and quiescent filaments
- Energetic phenomena like filament eruptions and flares

What is observed with ALMA: no flare



Vernazza, Avrett, & Loeser (1981)

- mm/submm emission is thermal continuum from tau=1 layer
  - i.e. ALMA probes the radio photosphere
- Models indicate that for ALMA this is located in the lower chromosphere

Resource: Masumi Shimojo et al.

What is observed with ALMA: with a flare

- The gyro-synchotron emission at 86 GHz (Band 3) needs electrons with energy over 1MeV
- Higher frequency needs higher energy electrons
- Thermal emission from the high temperature and density of the flare cannot be neglected
- Determine thermal/non-thermal from the spectrum

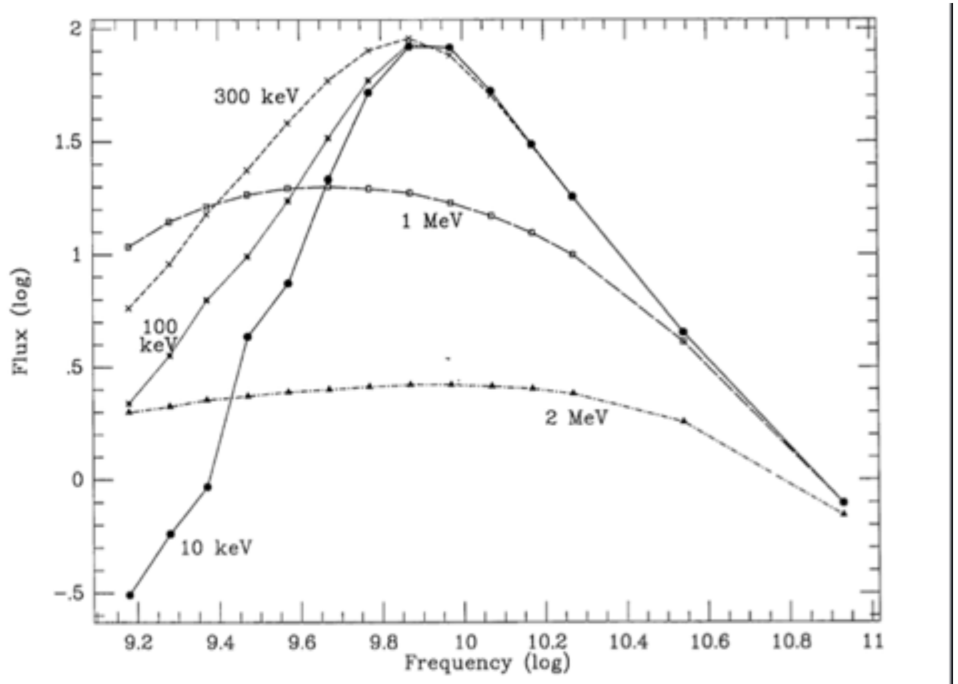
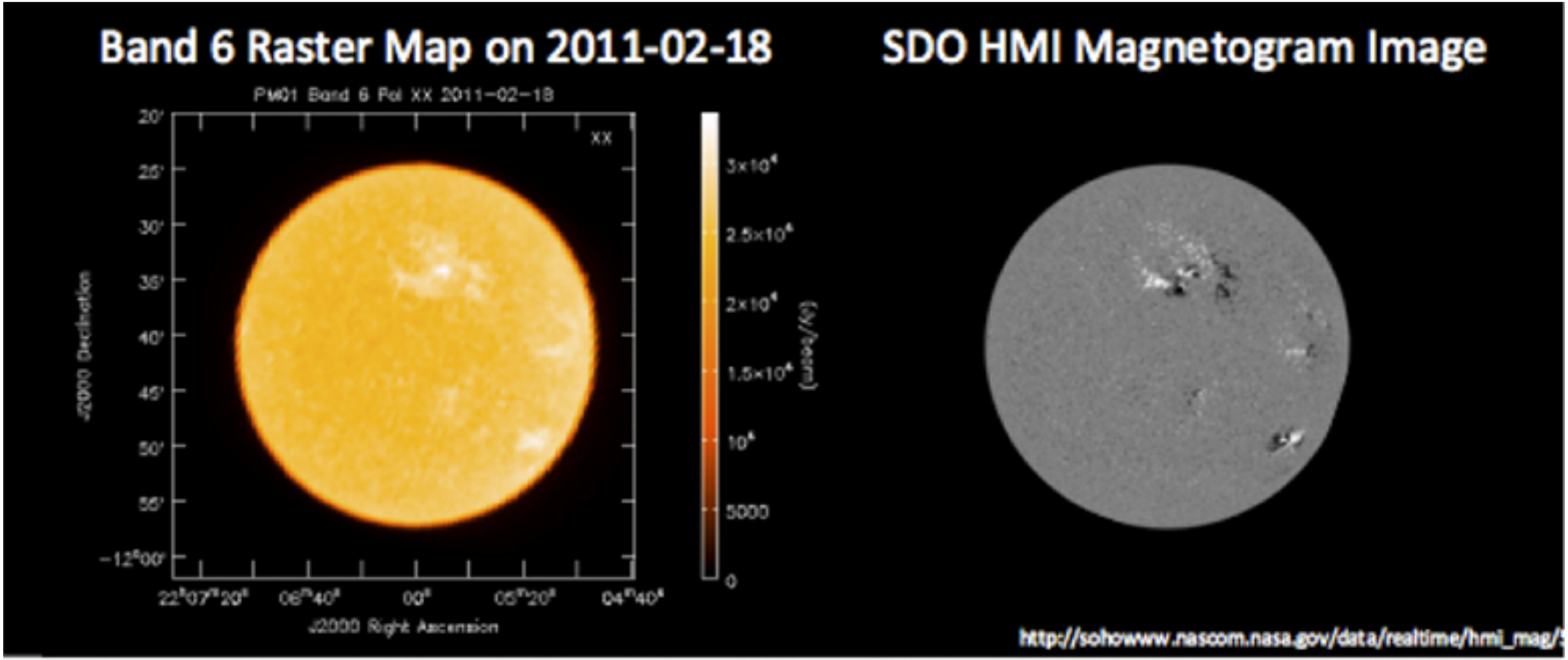


Fig. 1. A plot of nonthermal gyrosynchrotron flux spectra as a function of frequency for different values of the low-energy cutoff. The spectral index is 4, the magnetic field 300 G, the high-energy cutoff is 10 MeV and the angle between the line of sight and the magnetic field is 45°. The flux scale is in s.f.u. (the same values for the source dimensions were used in all cases); the logarithm of the flux is plotted. The curves are labelled according to the low-energy cutoff. The actual values of the frequency plotted are 1.5, 1.89, 2.37, 2.98, 3.75, 4.72, 5.93, 7.46, 9.38, 11.79, 14.82, 18.54, 35.0, and 86.0 GHz.

White and Kundu (1992)

Solar Chromosphere



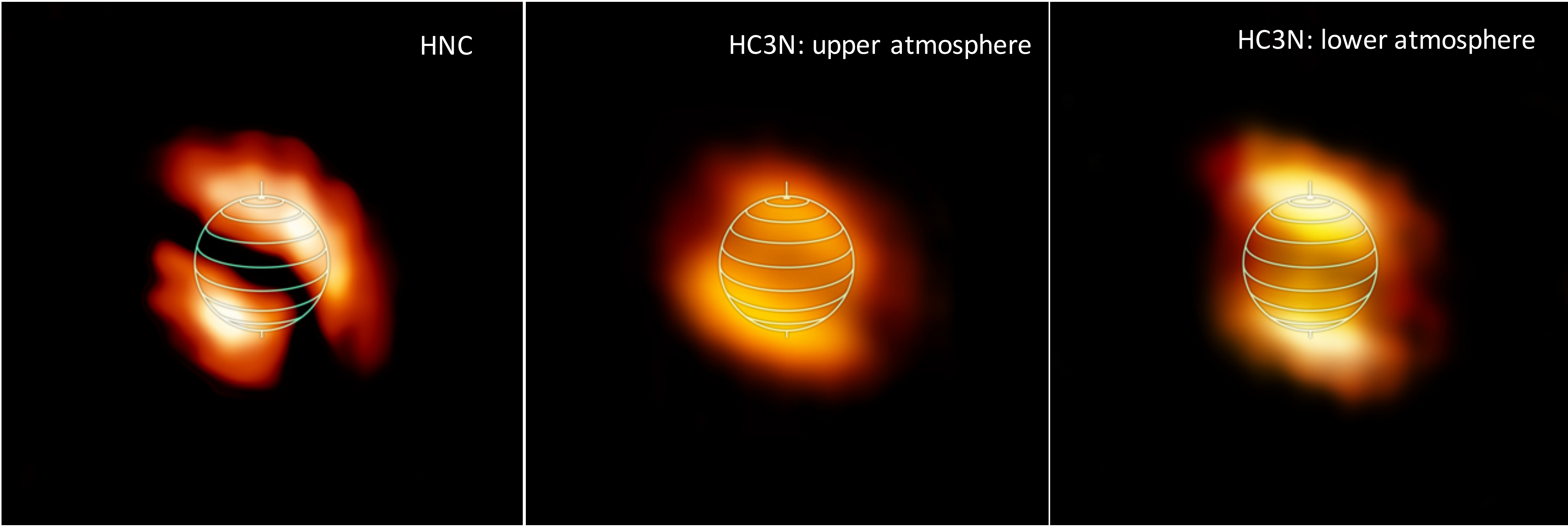
Imaged through a high level of atmospheric water vapor
substituting the effect of a solar filter

Planetary Atmospheres & Surfaces

- Composition:
  - vertical distribution of species
  - search for new species
- Thermal structure: P(T)
- Dynamics: winds
- 3D mapping and monitoring: seasonal variations
- ALMA high angular and spectral resolution crucial

Constraints on the origin and formation of planets and the formation of the solar system

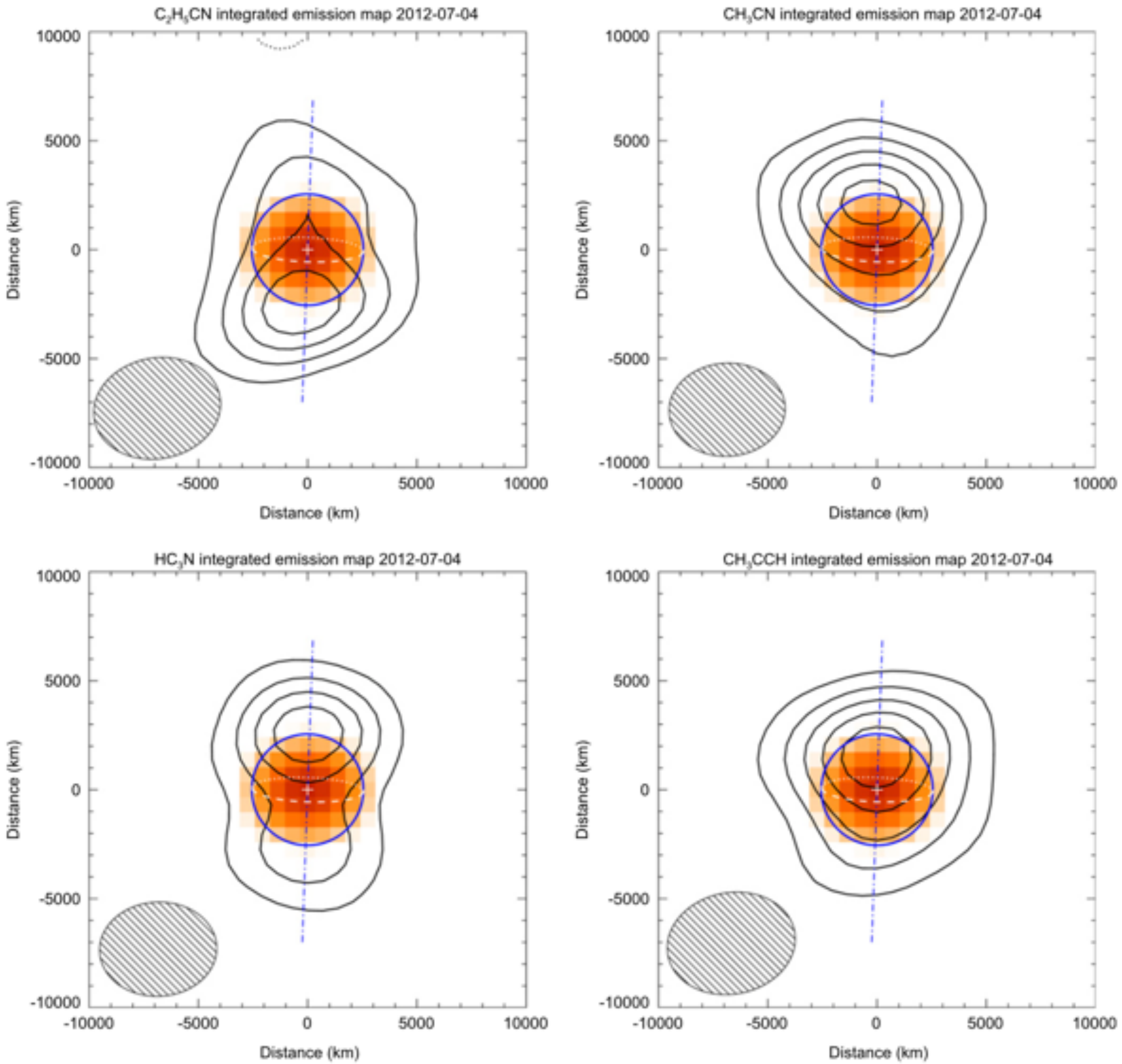
Organic molecules on Titan



Not known yet how these enhanced pockets form – effects tied to Saturn's magnetic field?

Cordiner et al. (2014): 3-minute snapshot

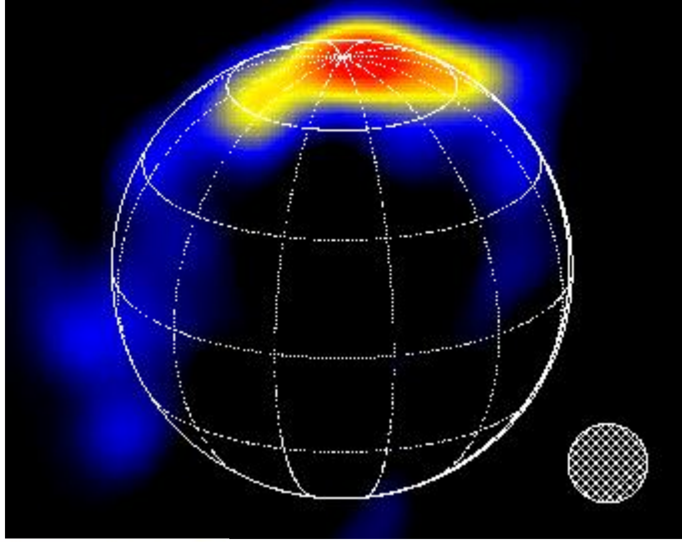
Ethyl Cyanide: ALMA

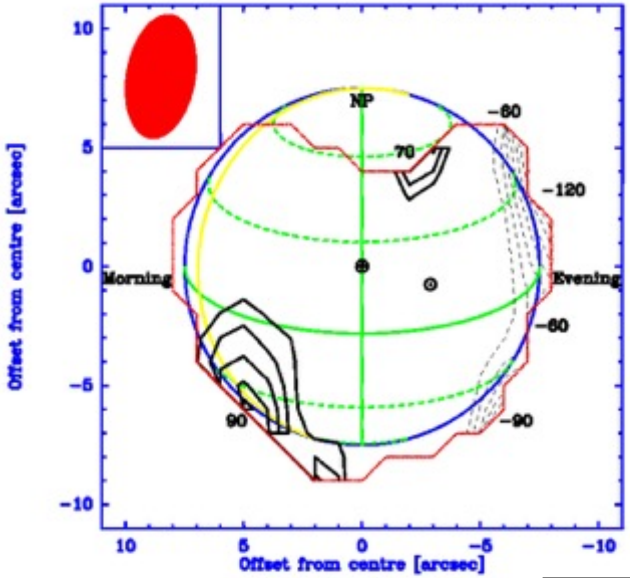


Mars Water Cycle

OVRO HDO 226 GHz

(Gurwell)





Mars Wind CO
Observations
IRAM PdB
Moreno

Pluto - Triton
HST: separation 0.9”

Mapping Planets with ALMA

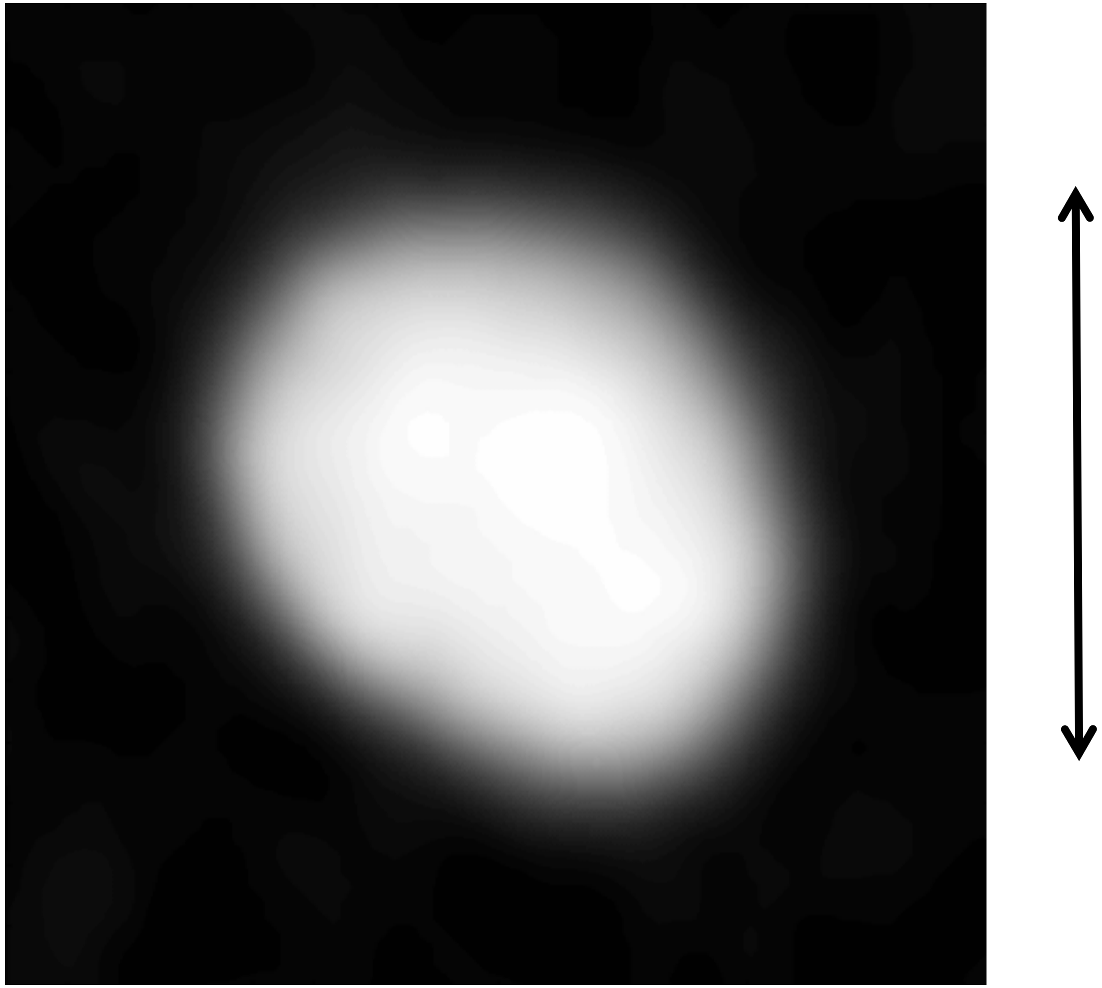
Apparent diameters

Mercury	5-12''
Venus	10-65
Mars	4-26
Jupiter	30-50
Saturn	15-21
Uranus	3-4
Neptune	2

Ceres	0.4-0.7''
Io	0.8-1.3
Titan	0.6-0.9
Pluto	0.1
TNO	0.04
Comet nucleus	0.001-0.01
Comet Coma	60

Asteroids

Juno

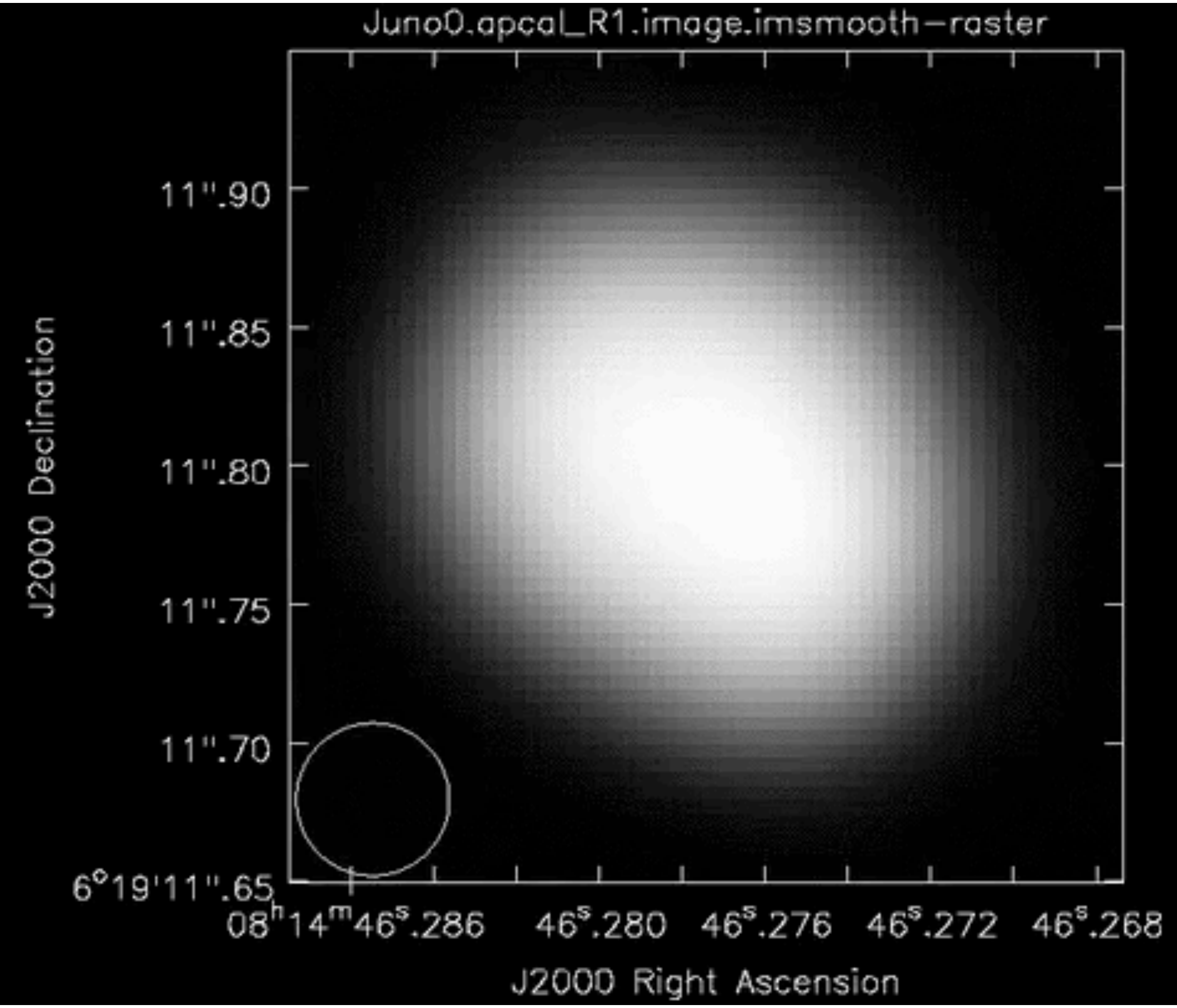


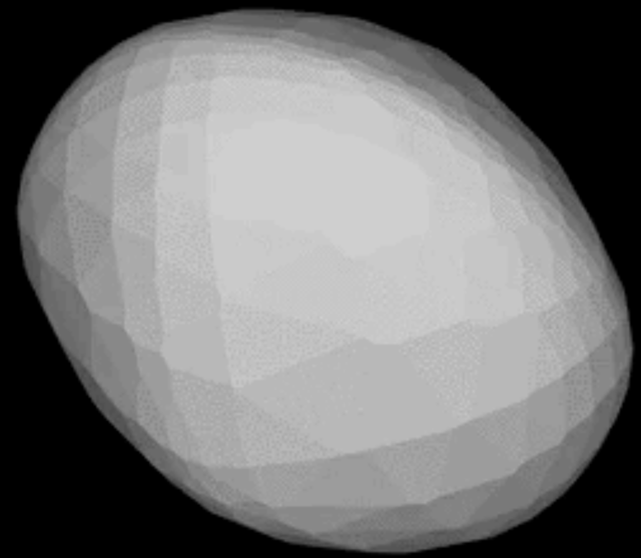
Angular resolution 50 mas or 60 km

Measure asteroid shape, position, rotational period

ALMA Partnership, Hunter et al., 2015

(Left) ALMA long baselines Science Verification images of the asteroid Juno at 50milliarcsec angular resolution. (Right) Thermal model of the asteroid surface.

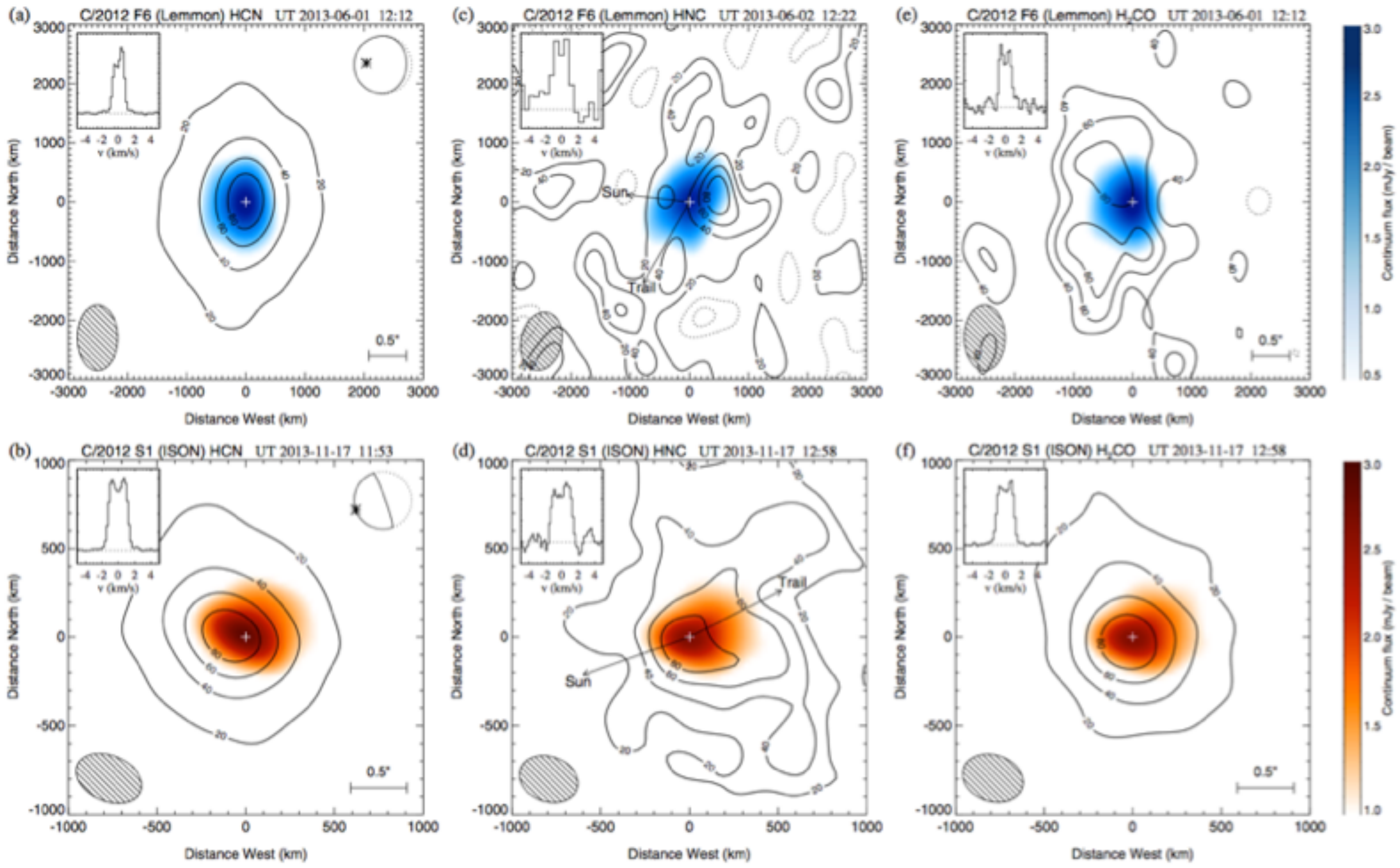




Chemical Investigation of Comets

Lemmon Heliocentric Distance 1.5 AU

ISON Heliocentric Distance 0.5 AU



Photolysis/thermal degradation by solar radiation field

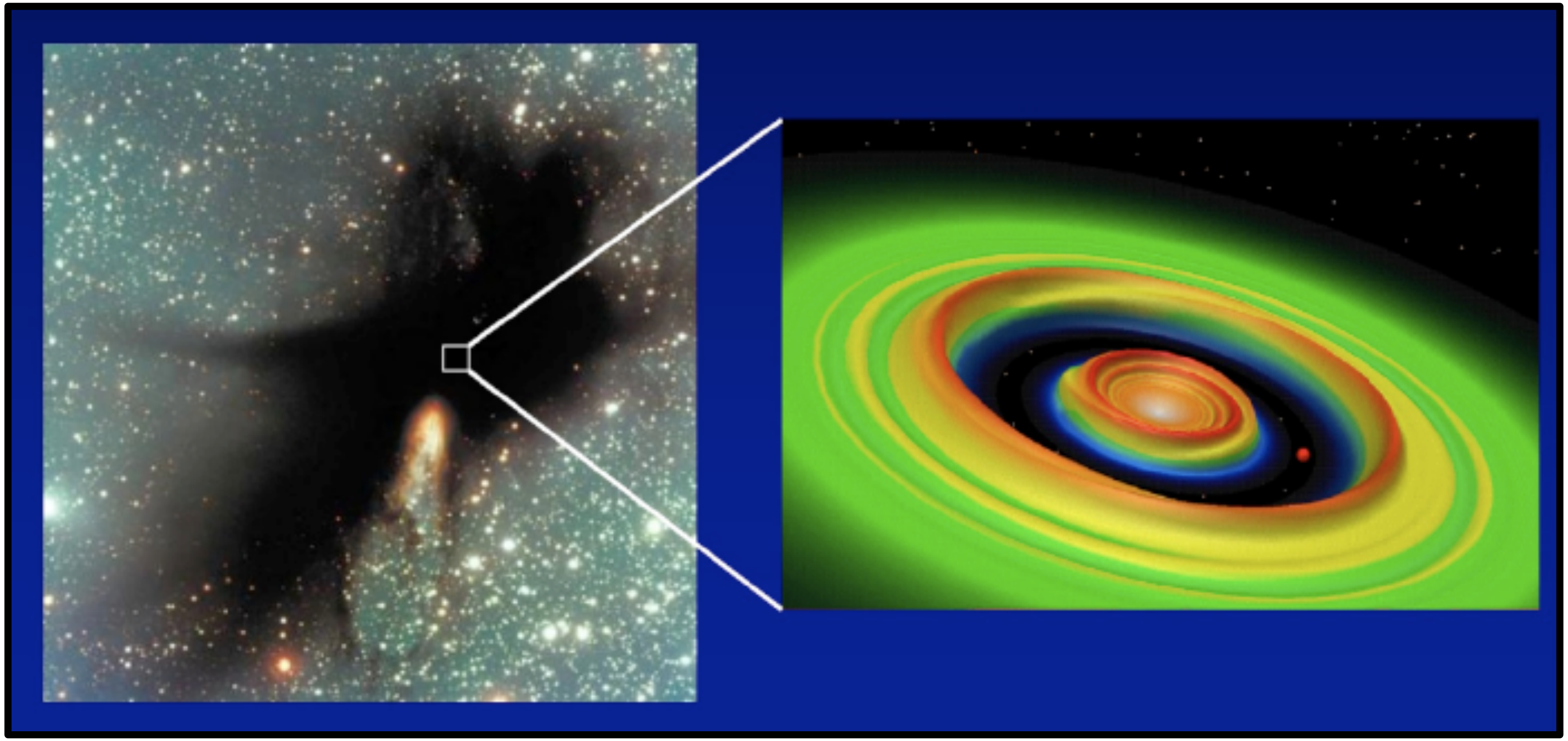
ALMA Exoplanets

ALMA exoplanets

- ALMA can detect planetary systems at all evolutionary phases
- Discovery methods:
  - direct detection
  - stellar wobble
  - radial velocity
- Characterisation methods:
  - direct detection
  - transmission spectrum
  - formation conditions in protoplanetary disks

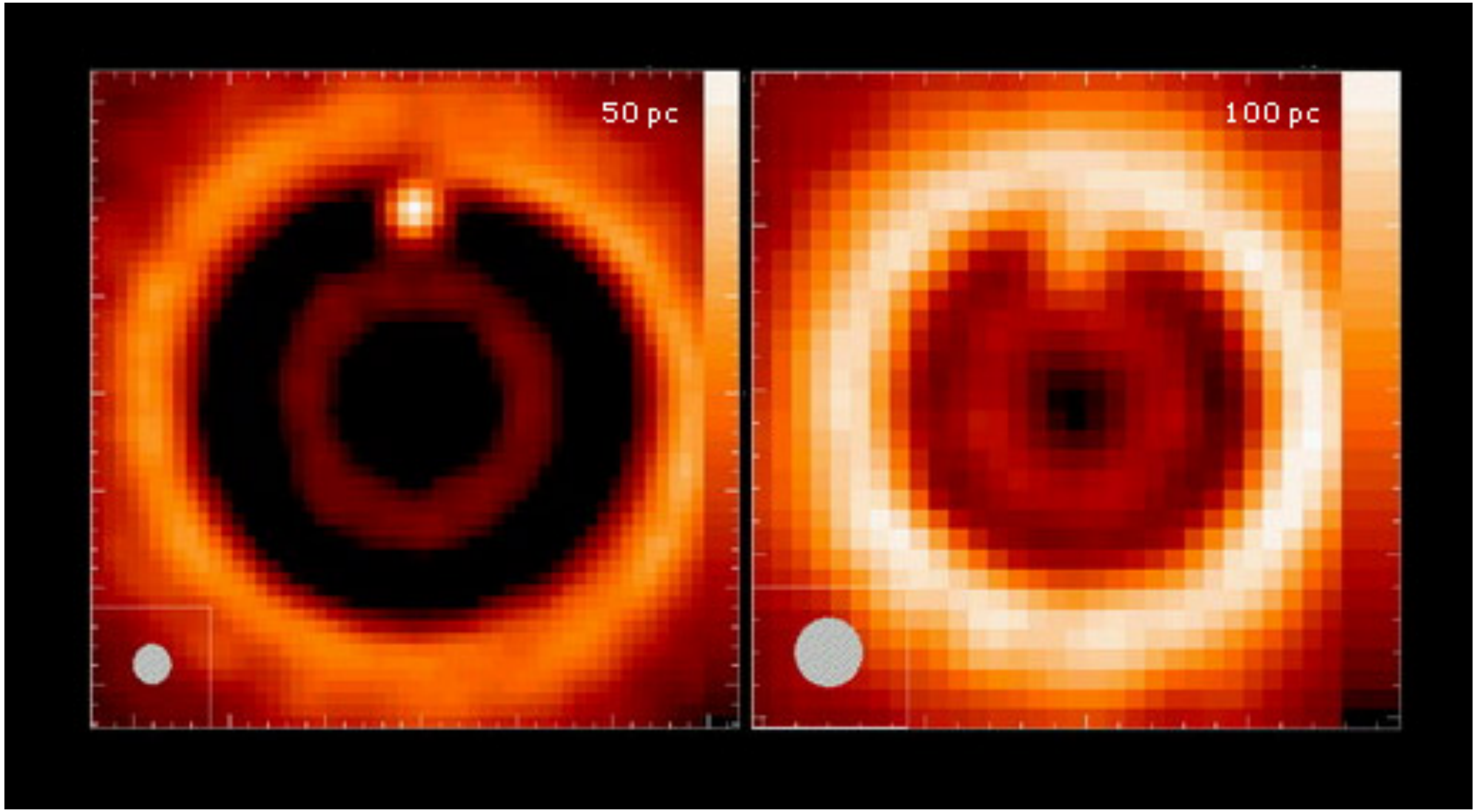
[Slide: H. Messias]

ALMA Key Science Driver

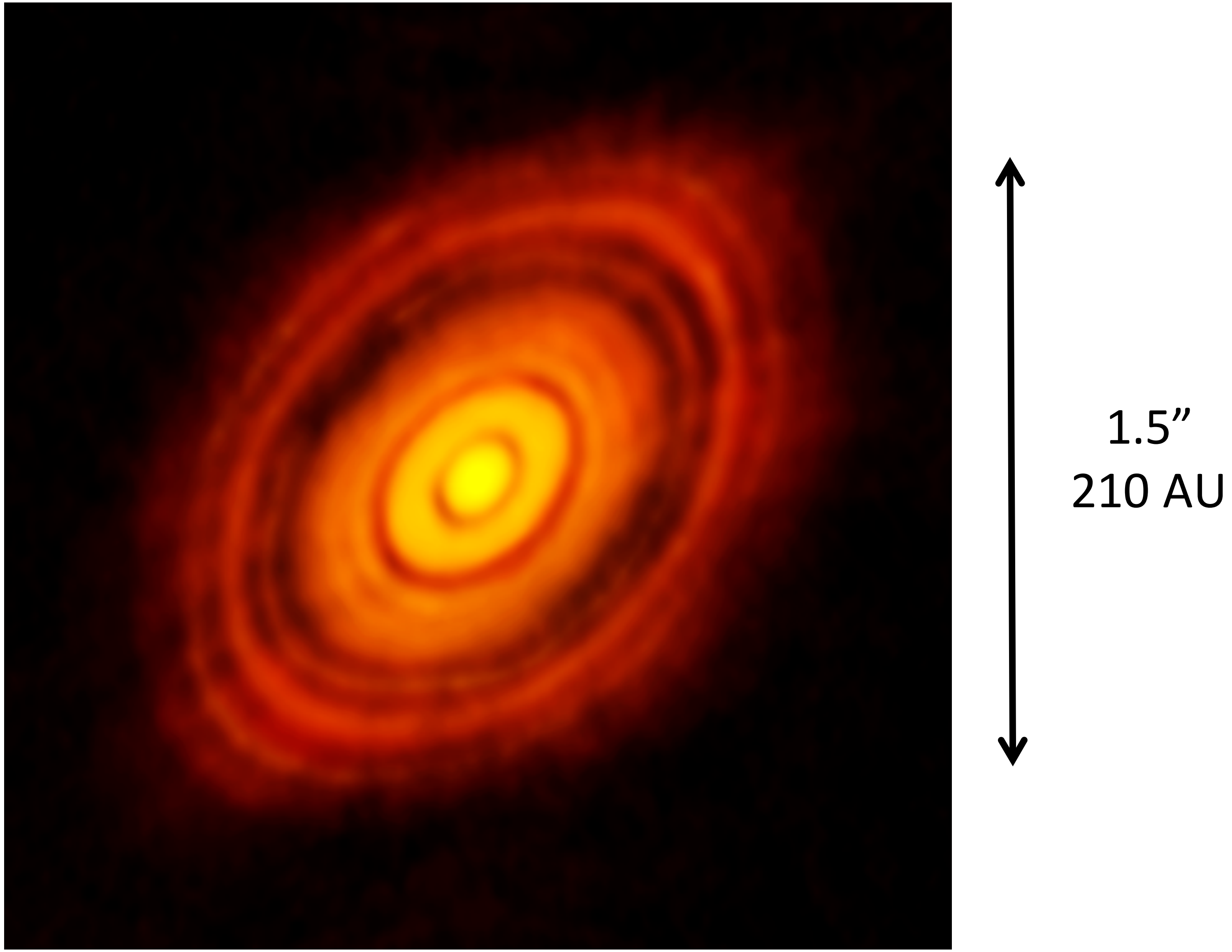


Imaging exoplanet formation

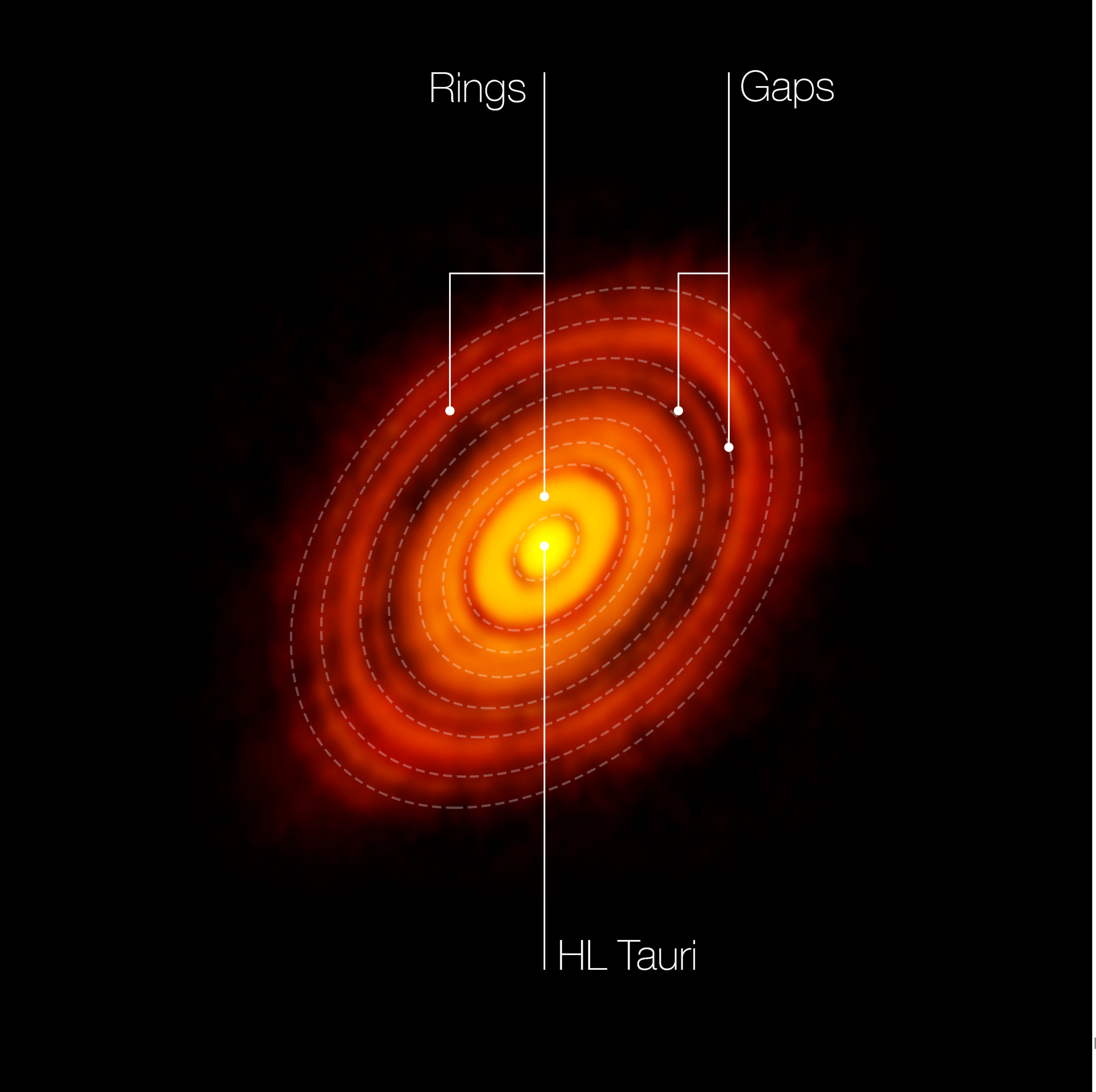
Simulations



Wolf (2005)



Protoplanetary disk HL Tau

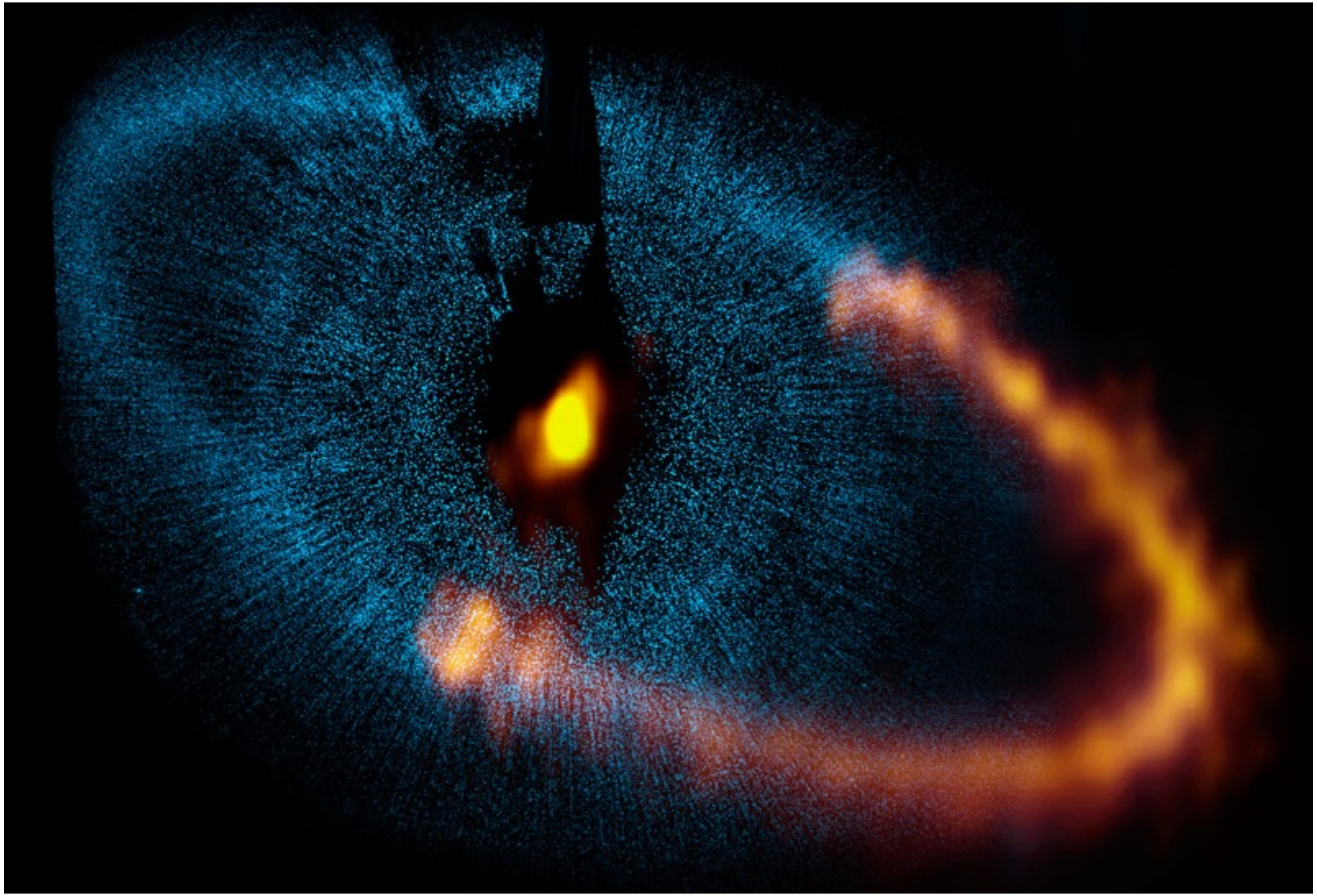


- Planet-forming gaps
- System believed to be ~1 Myr
- Too young to be forming sufficiently large planets in theoretical models

Planet-formation process faster than previously thought?

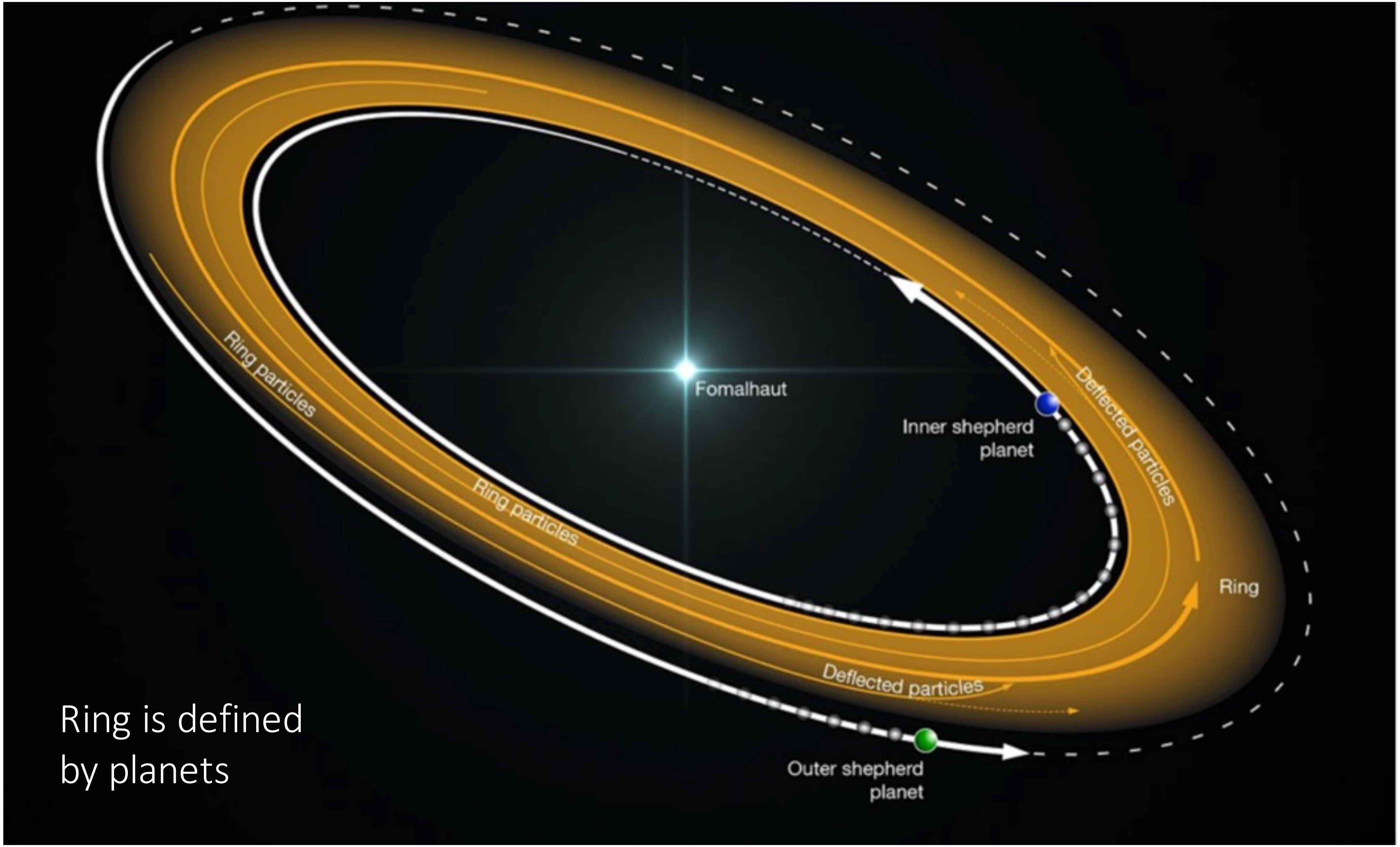
Debris disk: Fomalhaut

Dust ring is
16 AU
across



Fomalhault at 350GHz with ALMA (red) with HST optical image (blue)

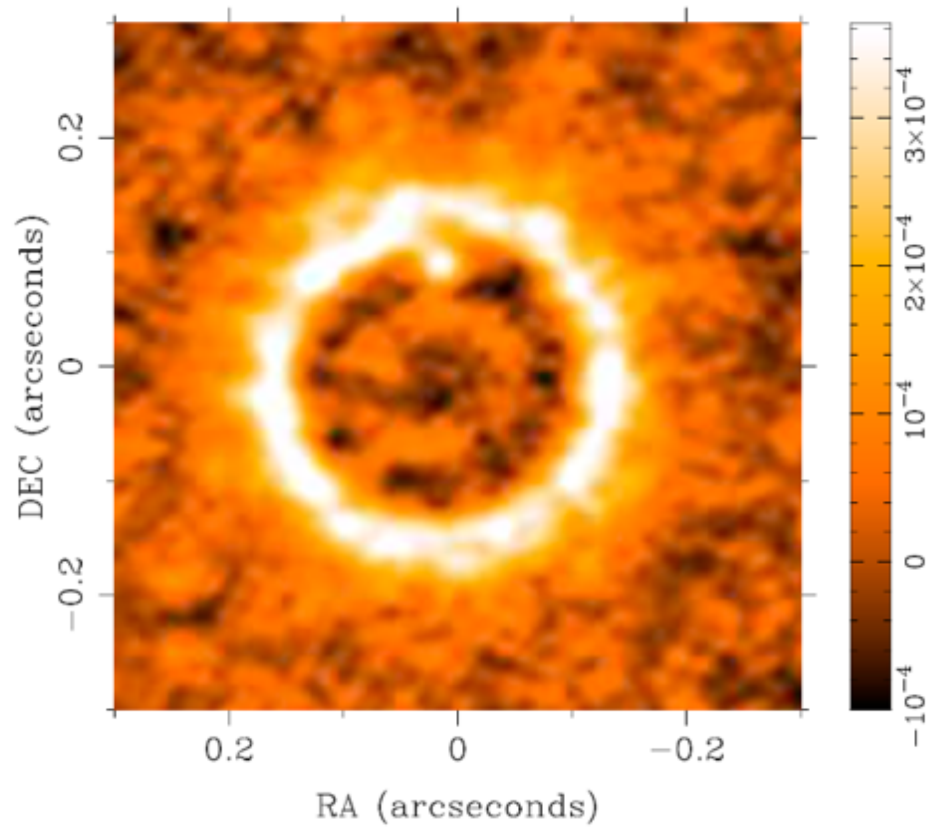
ALMA (ESO/NAOJ/NRAO)/Aaron Boley et al. (2012)



Ring is defined by planets

Direct detection

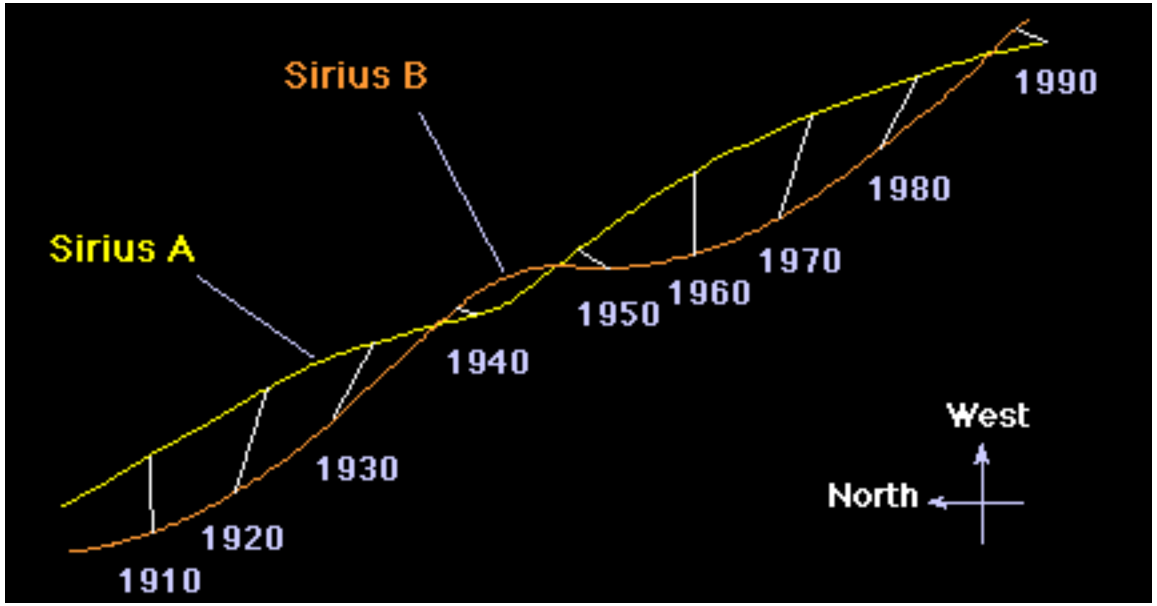
- Direct detection of gaseous, giant planets
- From exoplanets.eu list, based on measured and expected properties:
  - there are about 80 1< $M_{jupiter}$ <10 planets at < 100pc which ALMA can detect in less than 2hr in Cycle4
- Issues
  - dynamic range
    - emission from planet must be distinguishable from that of star
  - limited spatial resolution



[Slide: H. Messias]

Stellar Wobble

- Planet around star will induce a small wobble in the star
- Issues:
  - ALMA absolute astrometry
- Historical example – Sirius B first discovered via its induced wobble in Sirius A
- See Butler et al. (2007, "Observing extrasolar planetary systems with ALMA"), M. Bryan et al. (2016, arXiv:1601.07595)

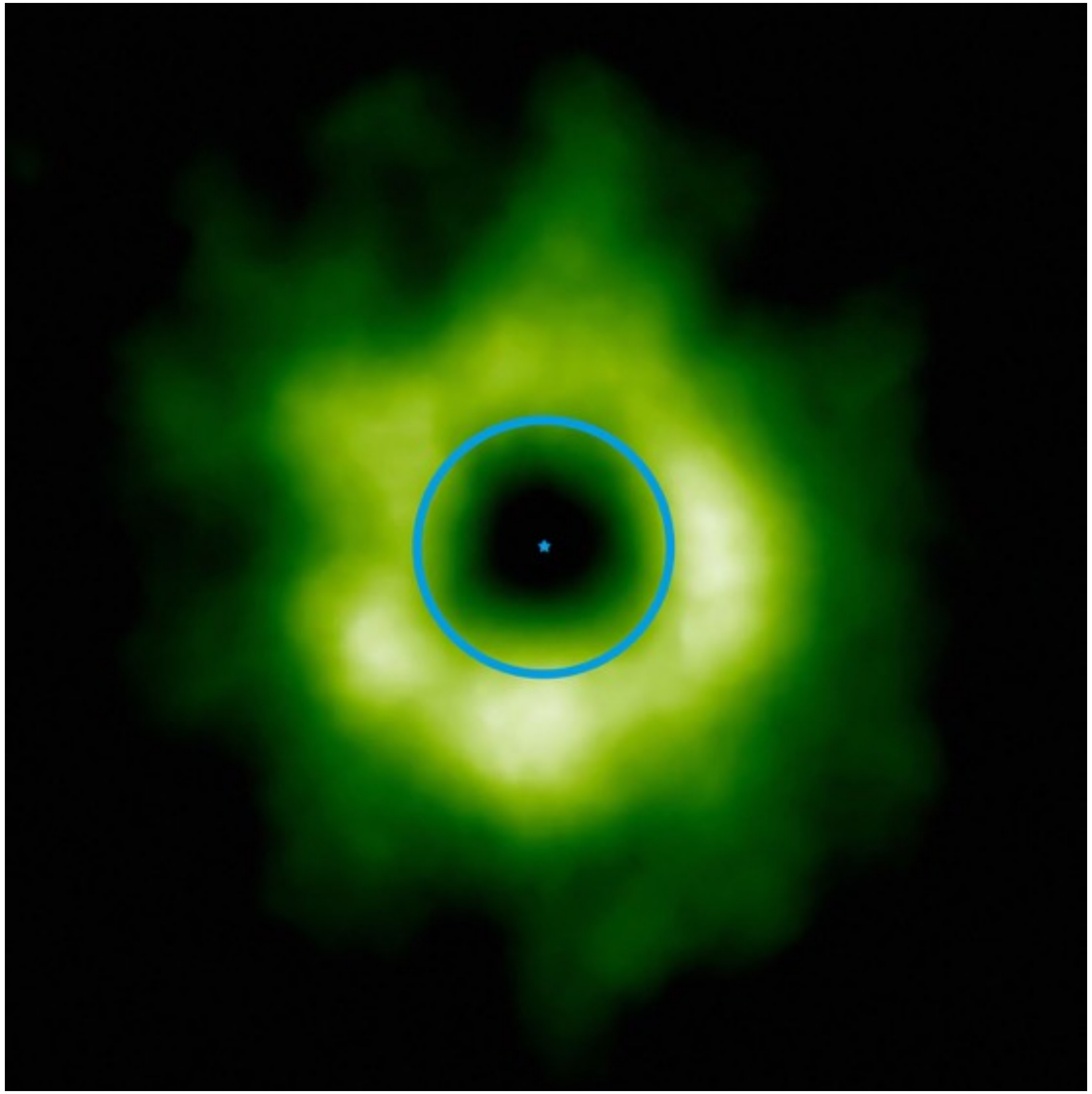


Up to about 10 arcseconds

ALMA has the potential to detect the stellar wobble of hundreds of stars

[Slide: H. Messias]

Snow line in TW Hydrae



Issues –

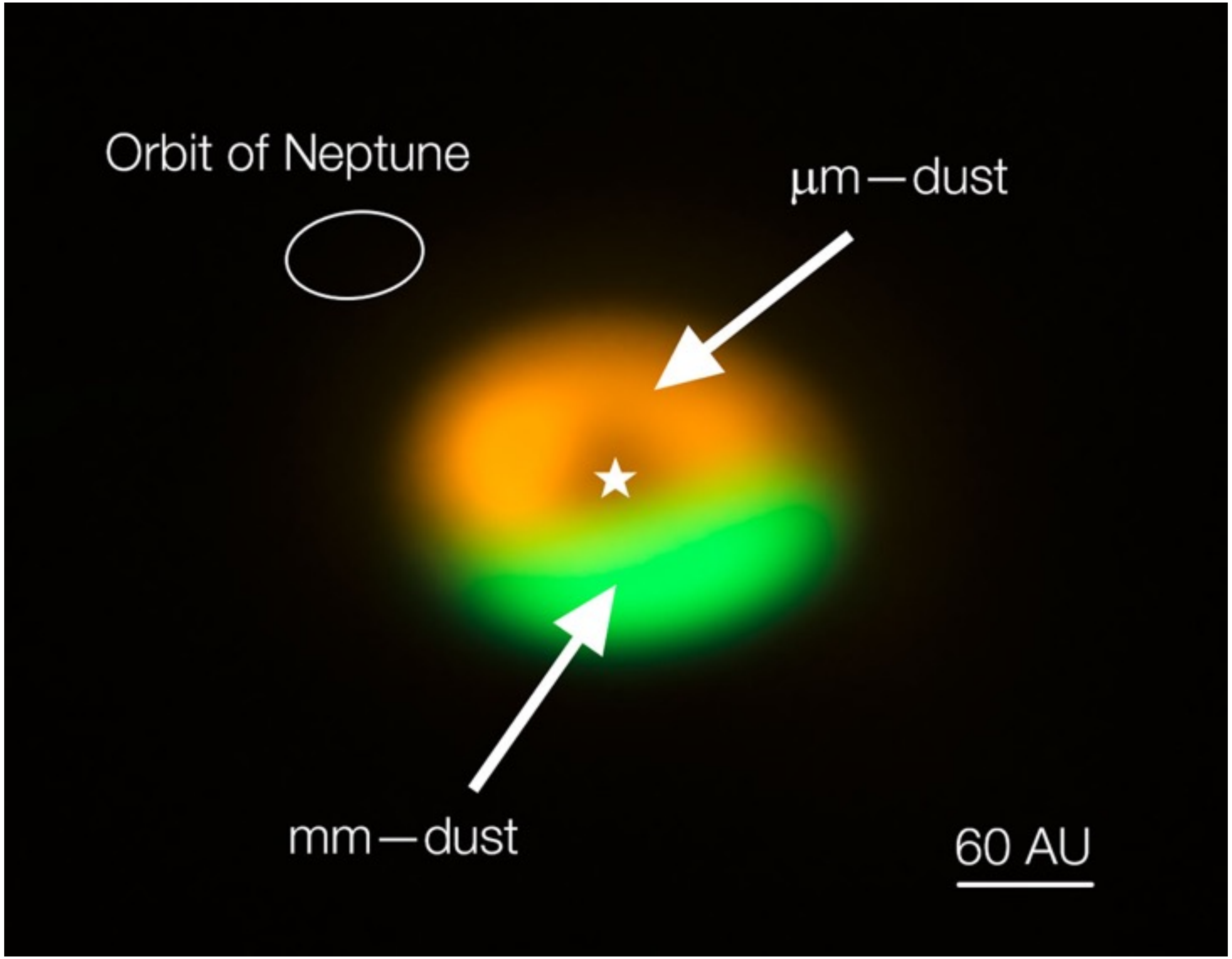
- target selection
- integration time
- angular resolution

Formation Conditions in Disks

N2H+ image of TW Hydrae disk. Radius ~30AU

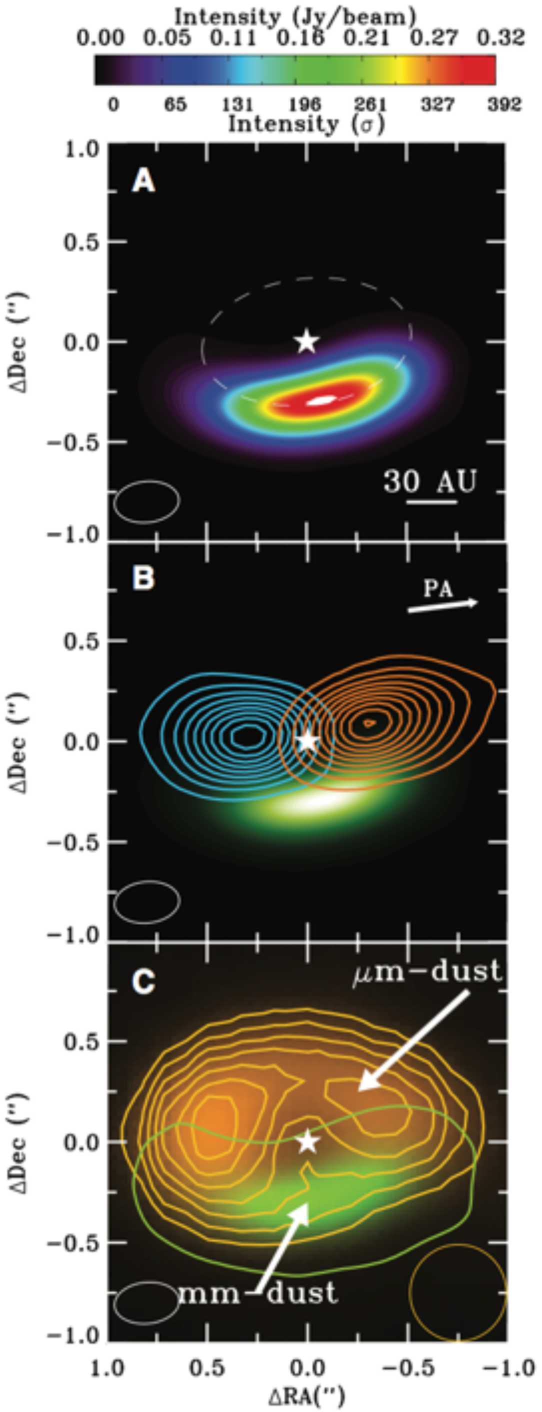
Chunhua et al. 2013, Science, 341, 630

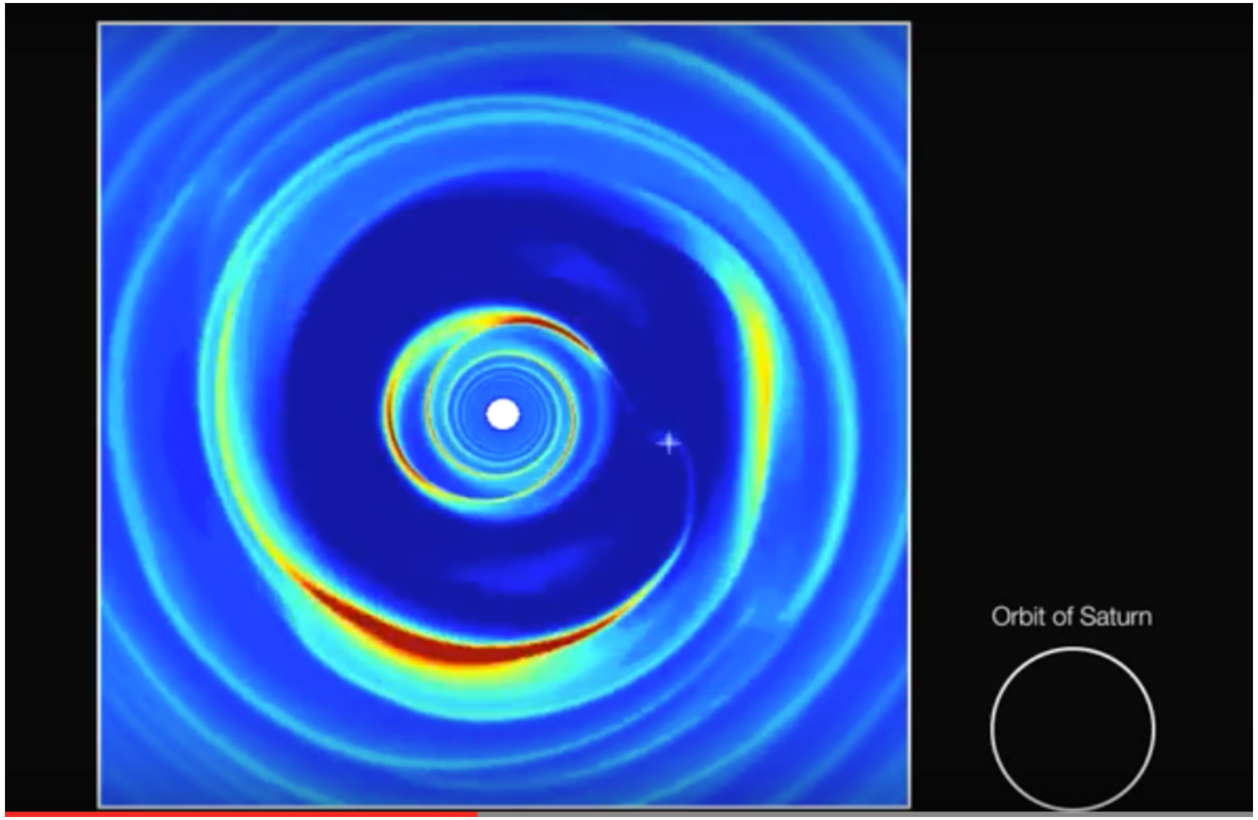
[Slide: H. Messias]



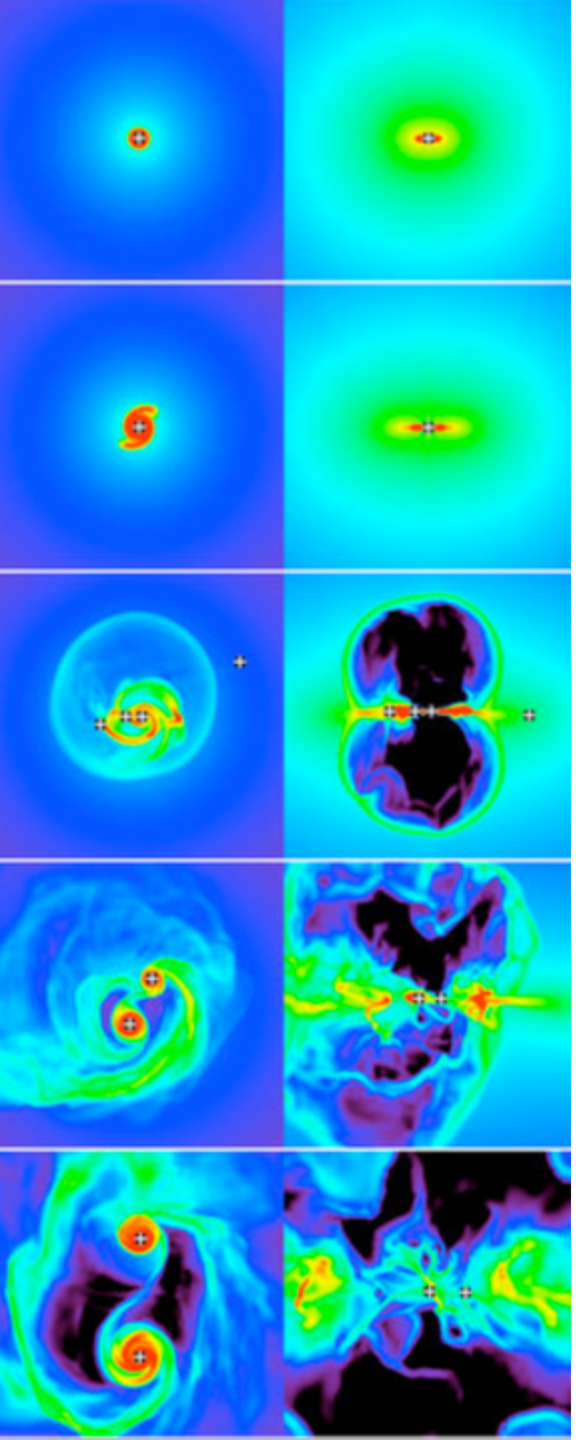
Dust traps in protoplanetary disks

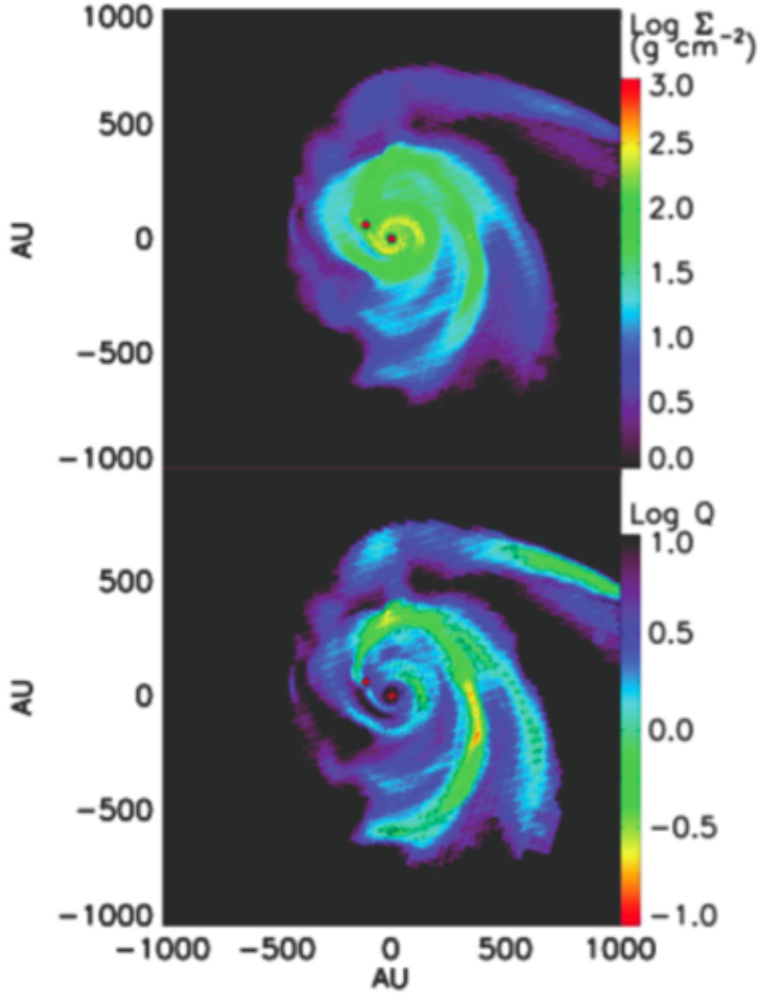
Oph-IRS48, Orange is micron sized dust from VLT/VISIR observations, green is mm sized dust from ALMA





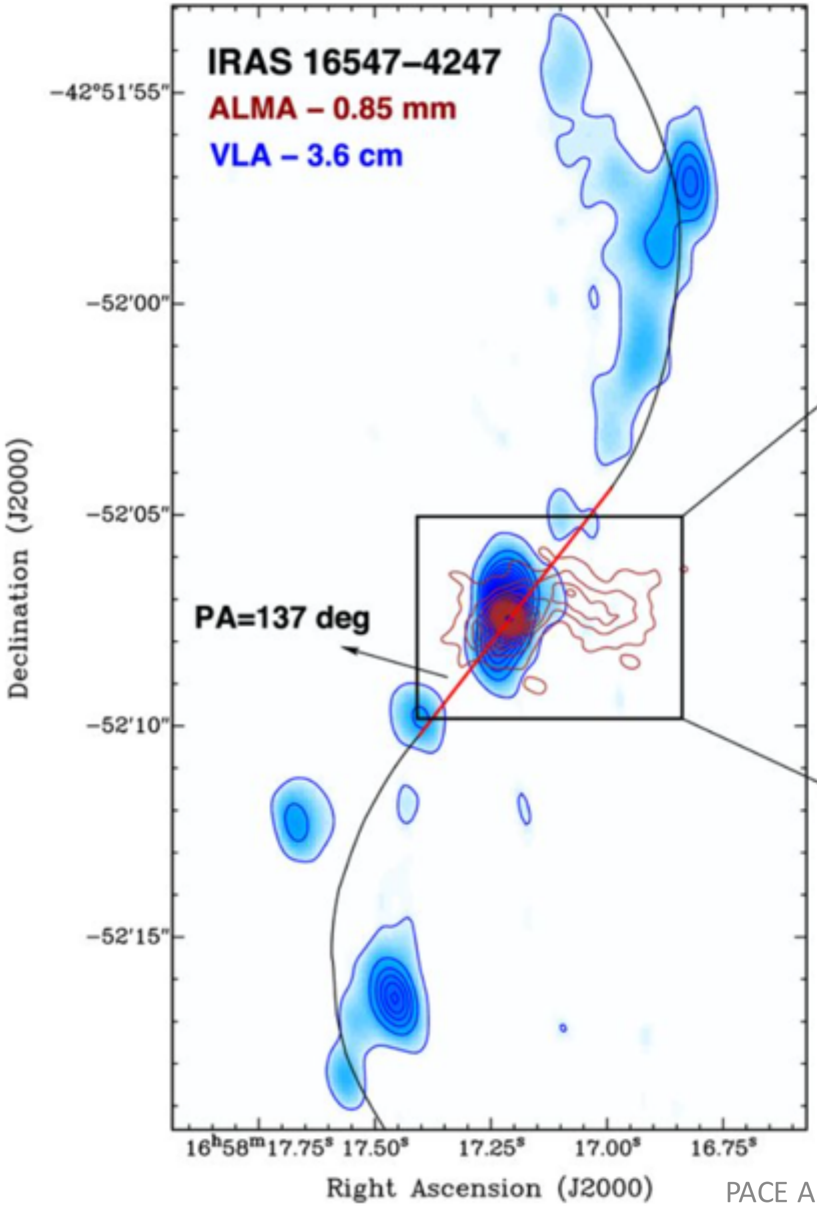
Simulations show how a vortex forms at the outer edge of the planetary gap. This can trap mm-size particles over million year timescales



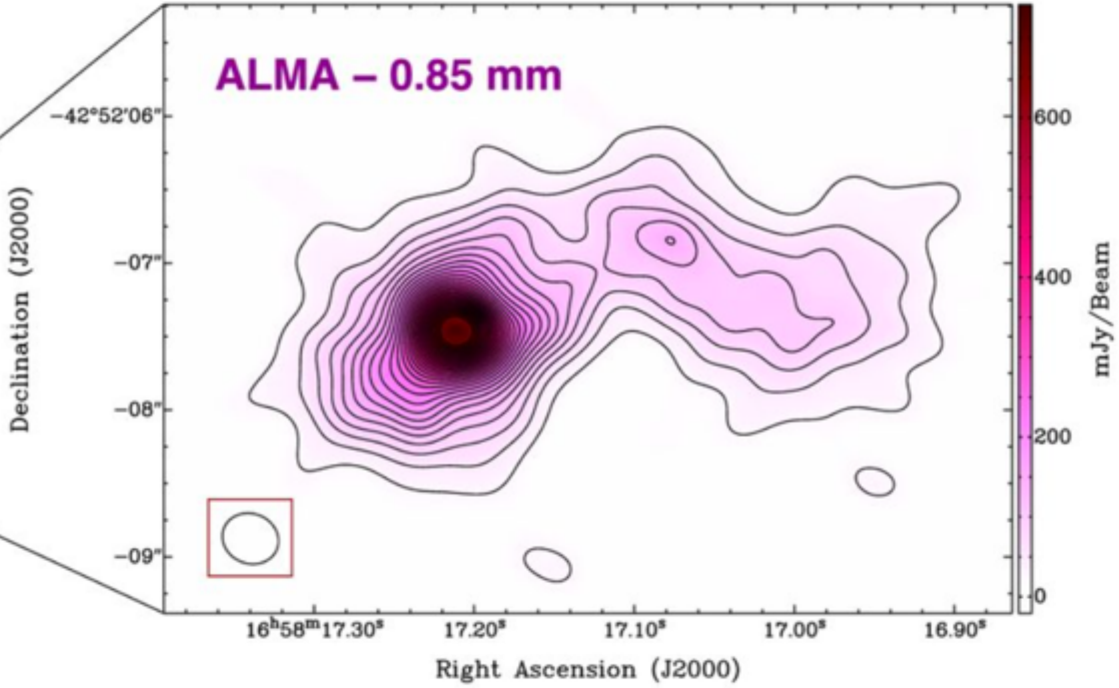


Star Formation

Disks around massive stars **IRAS 16547- ALMA**

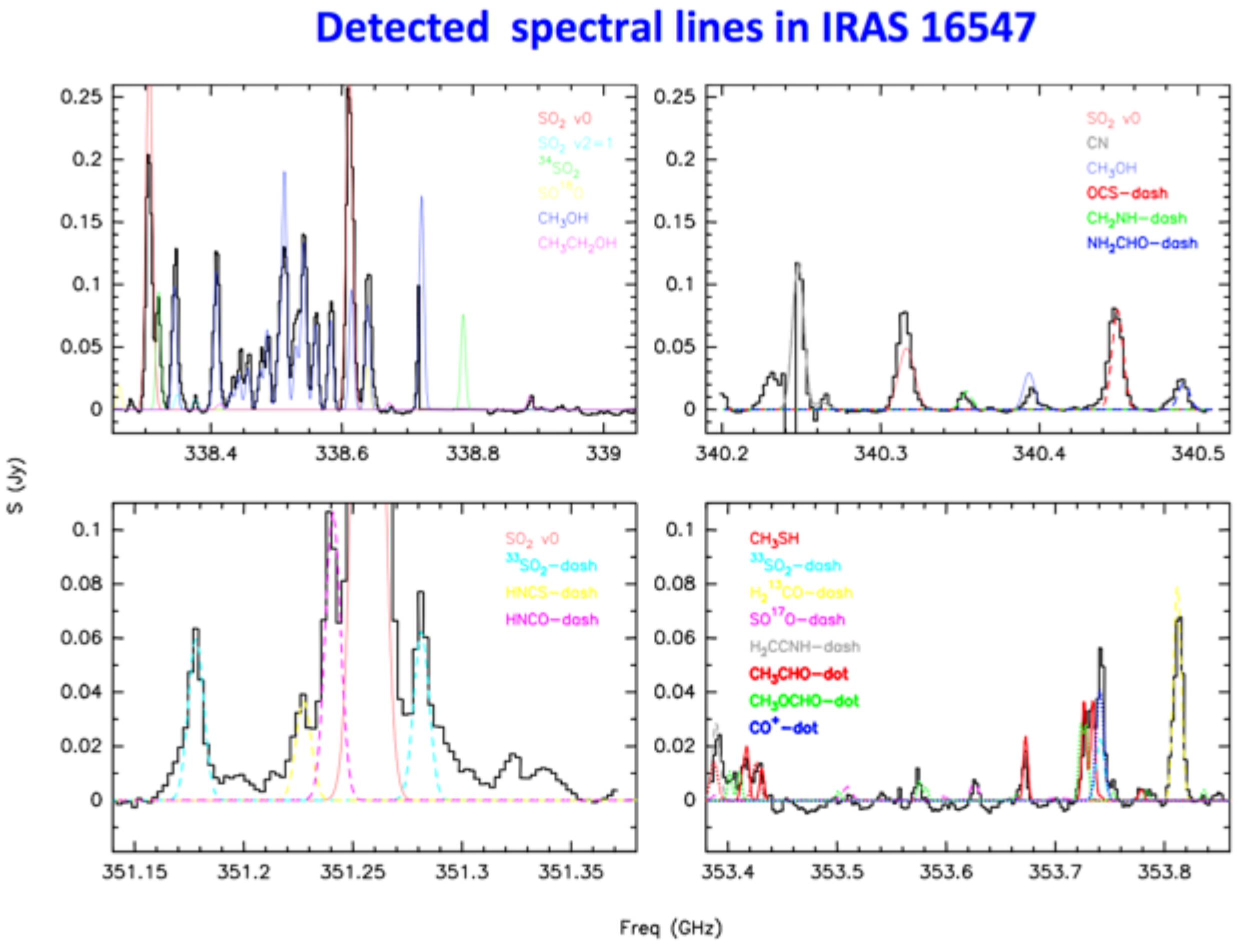


O-type protostar

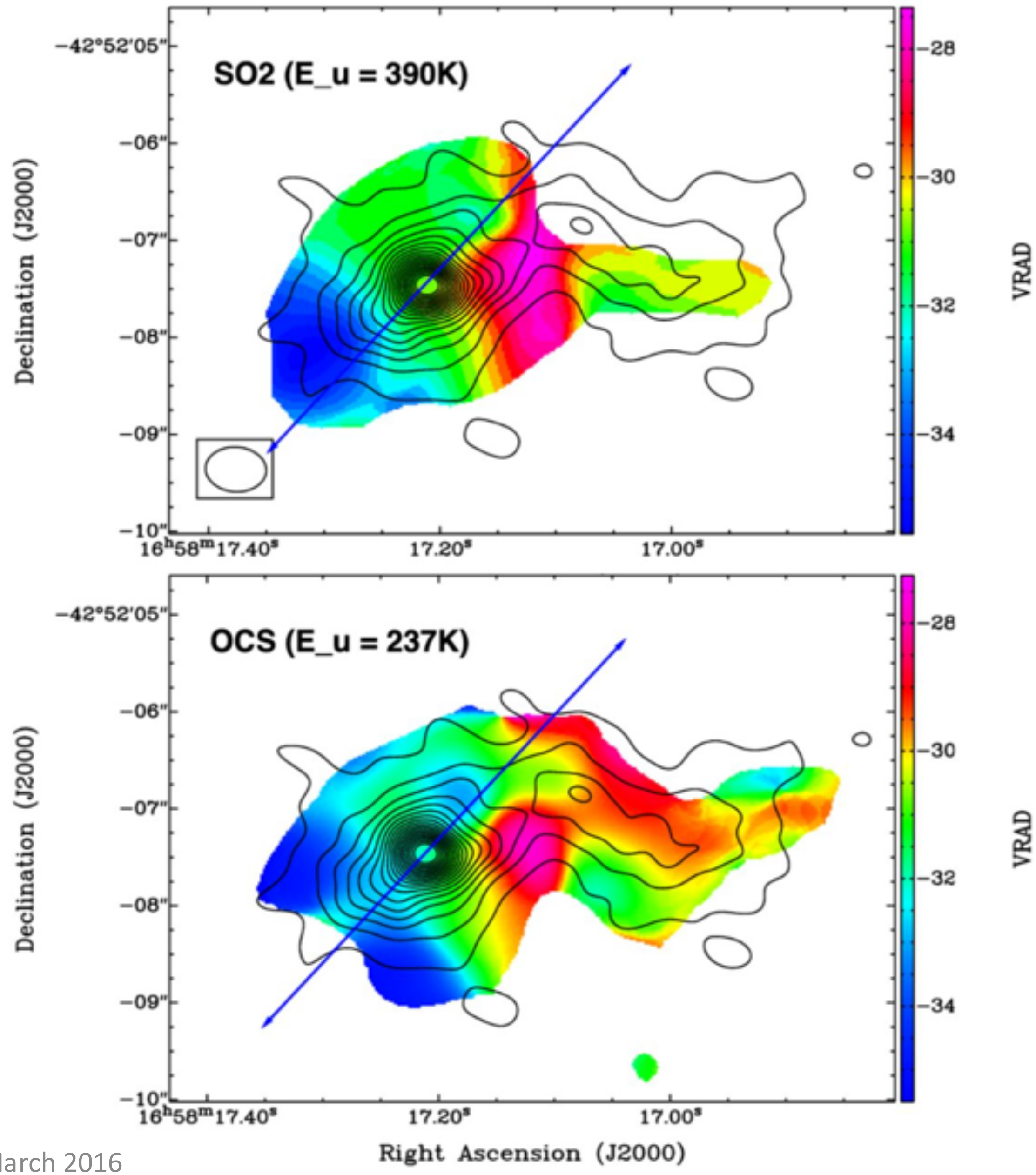


Zapata et al. (2015)

Disk Chemistry and Dynamics



SO_2 / OCS -- ALMA

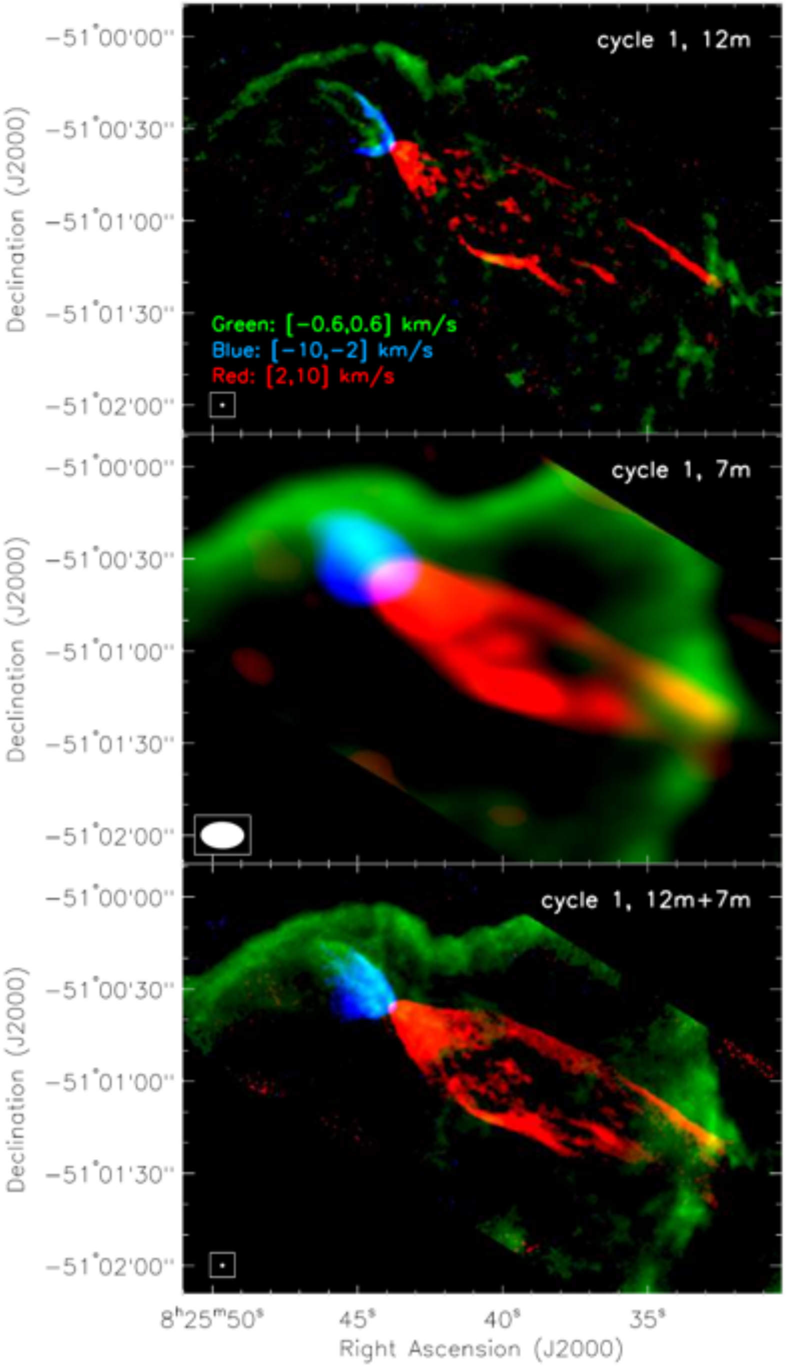


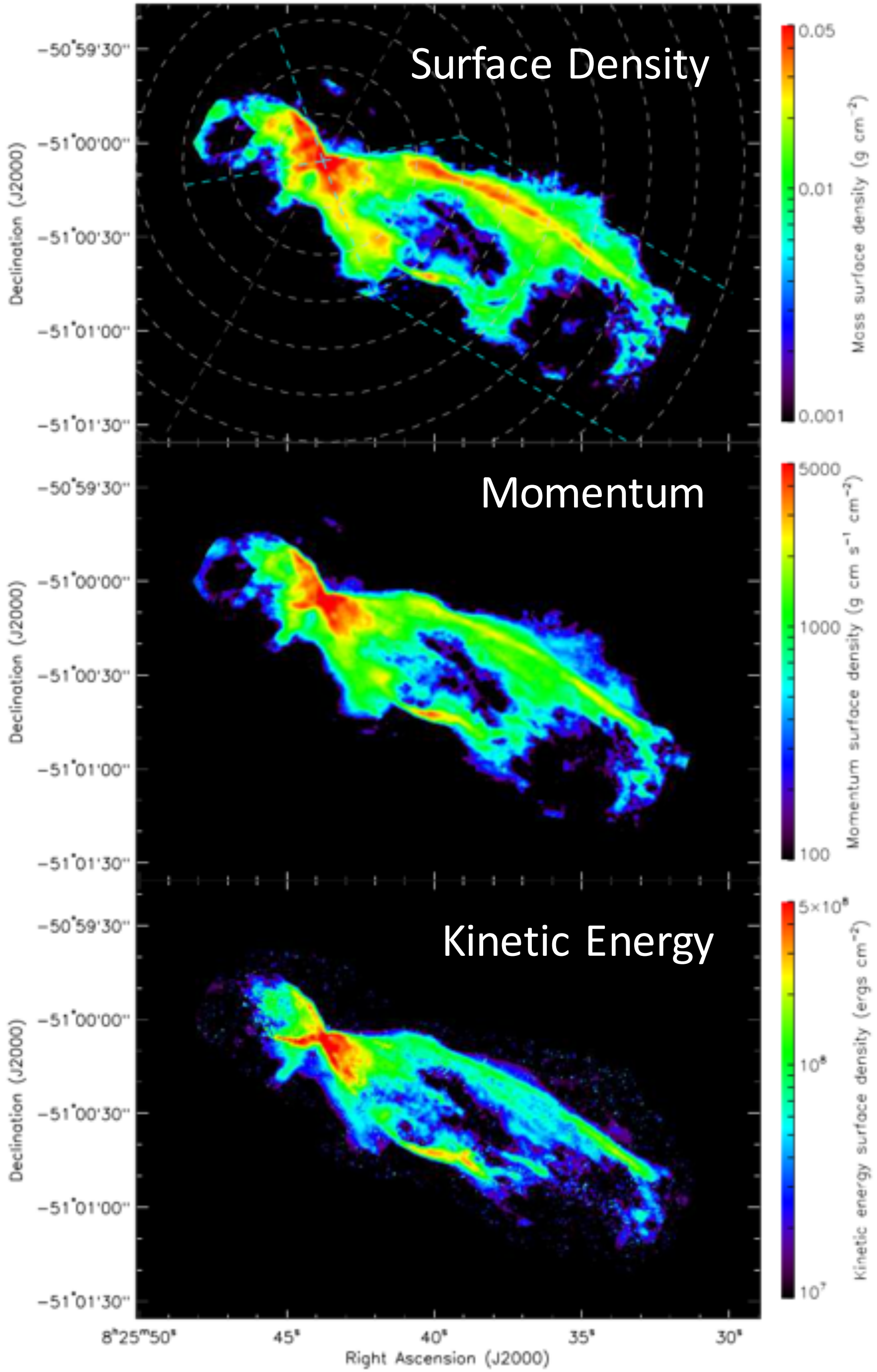
Outflow Properties

HH46/47

Zhang et al. (2016)

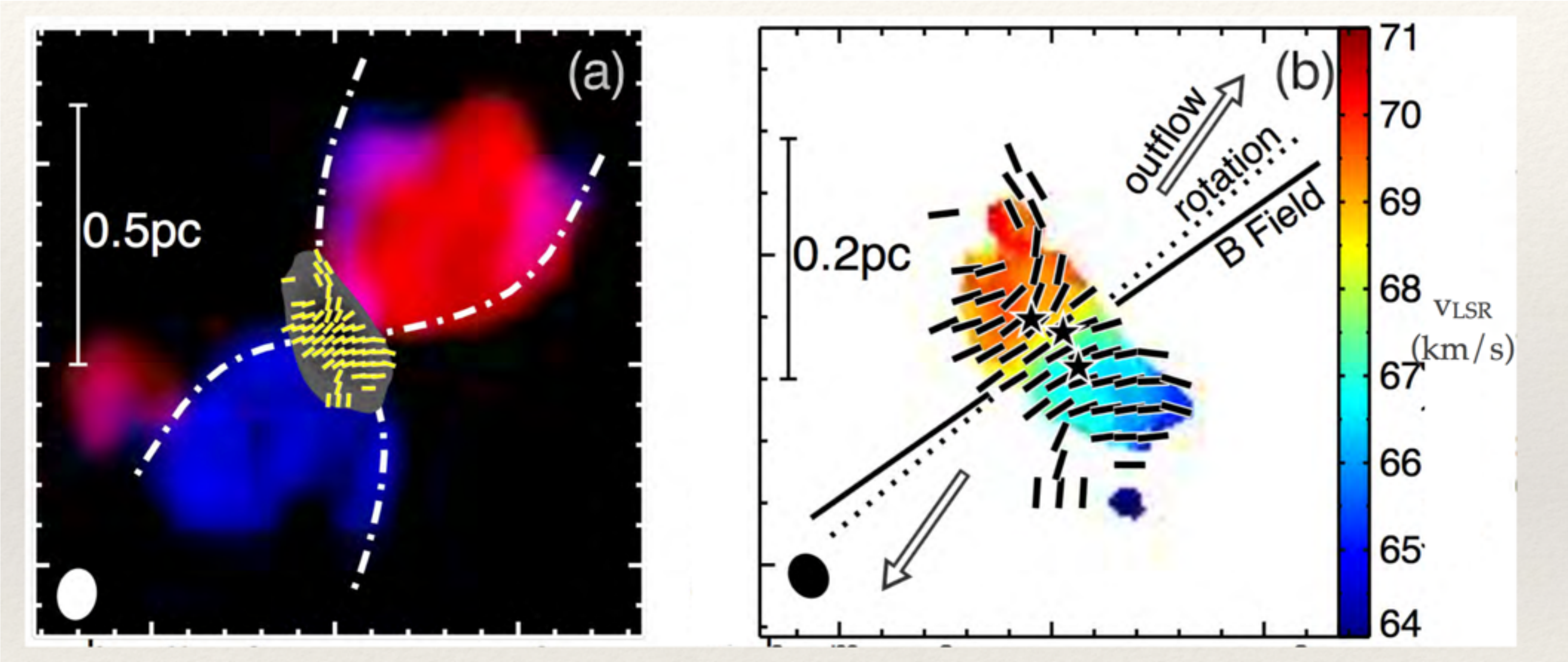
Outflow cavity wall composed of multiple shells entrained in a series of jet bow-shock events





Magnetic Fields: Continuum

SMA observations of massive core G240.31+0.07

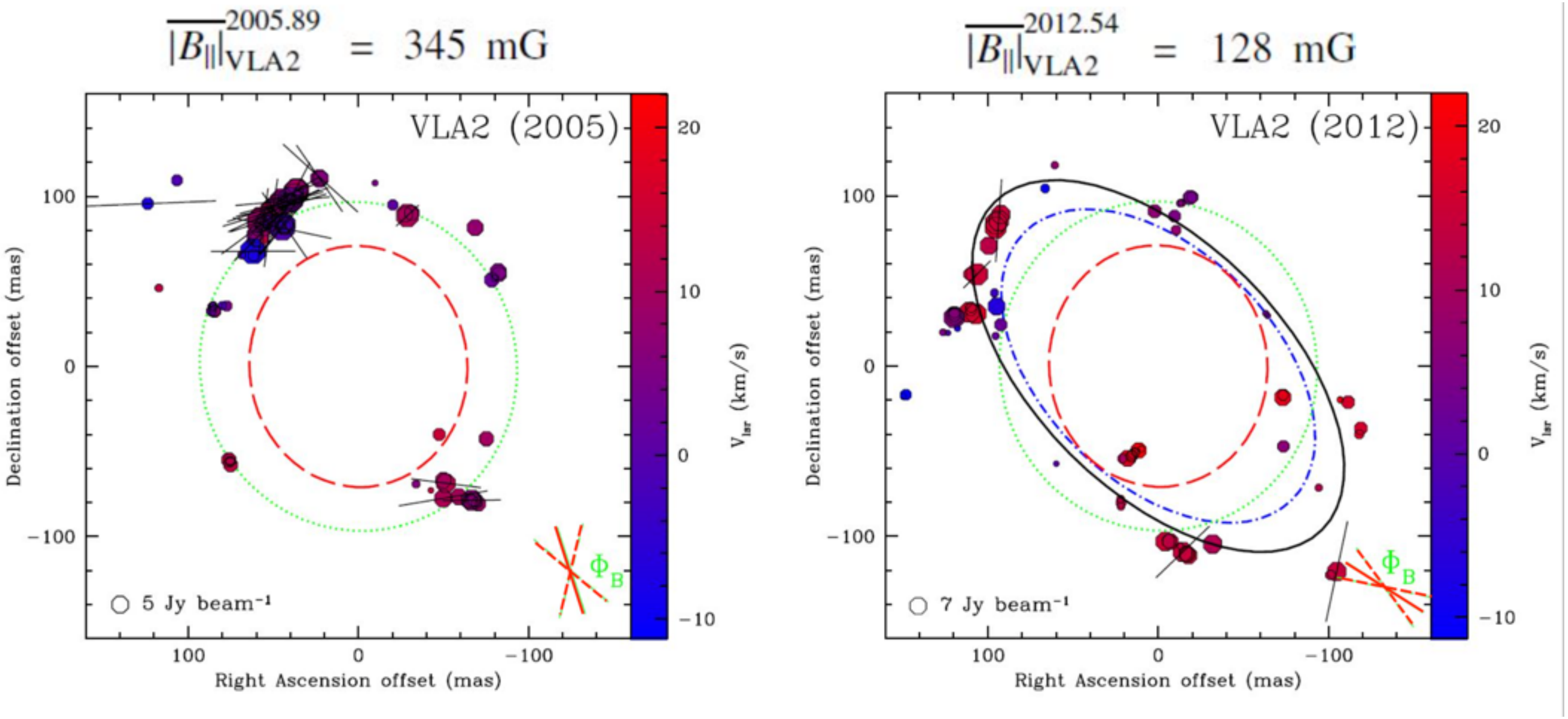


Qiu et al. 2009, 2014

D=5.3 kpc; L≈ 3x10^4 Lsun; M≈125 Msun
A well aligned case: bipolar outflow, magnetic field and rotation axes. Evidence of magnetic braking

Magnetic Fields: Spectral Line

New at Cycle 4



Surcis et al.

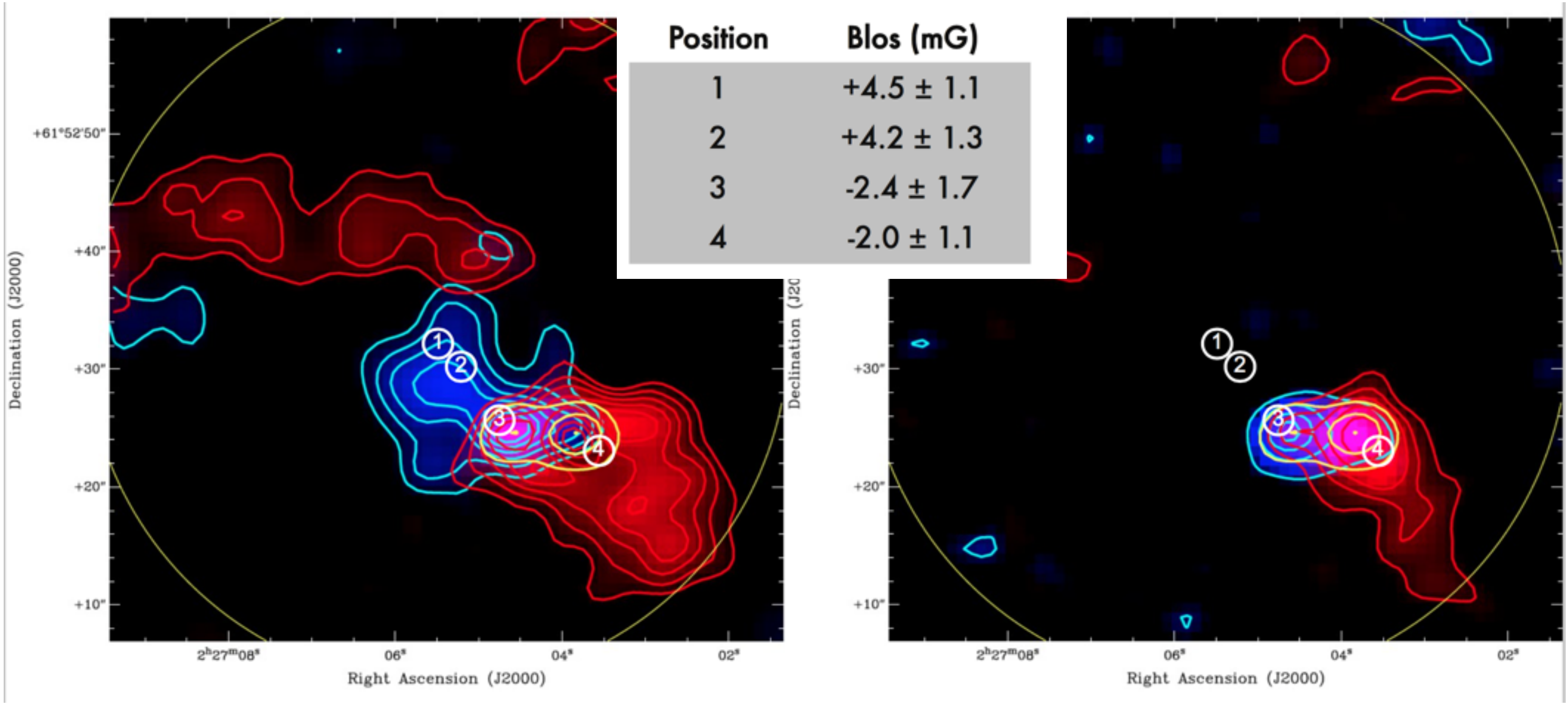
Magnetic field changes in W49N. Using masers and VLBI.
Masers occur throughout the ALMA bands

CARMA 226 GHz

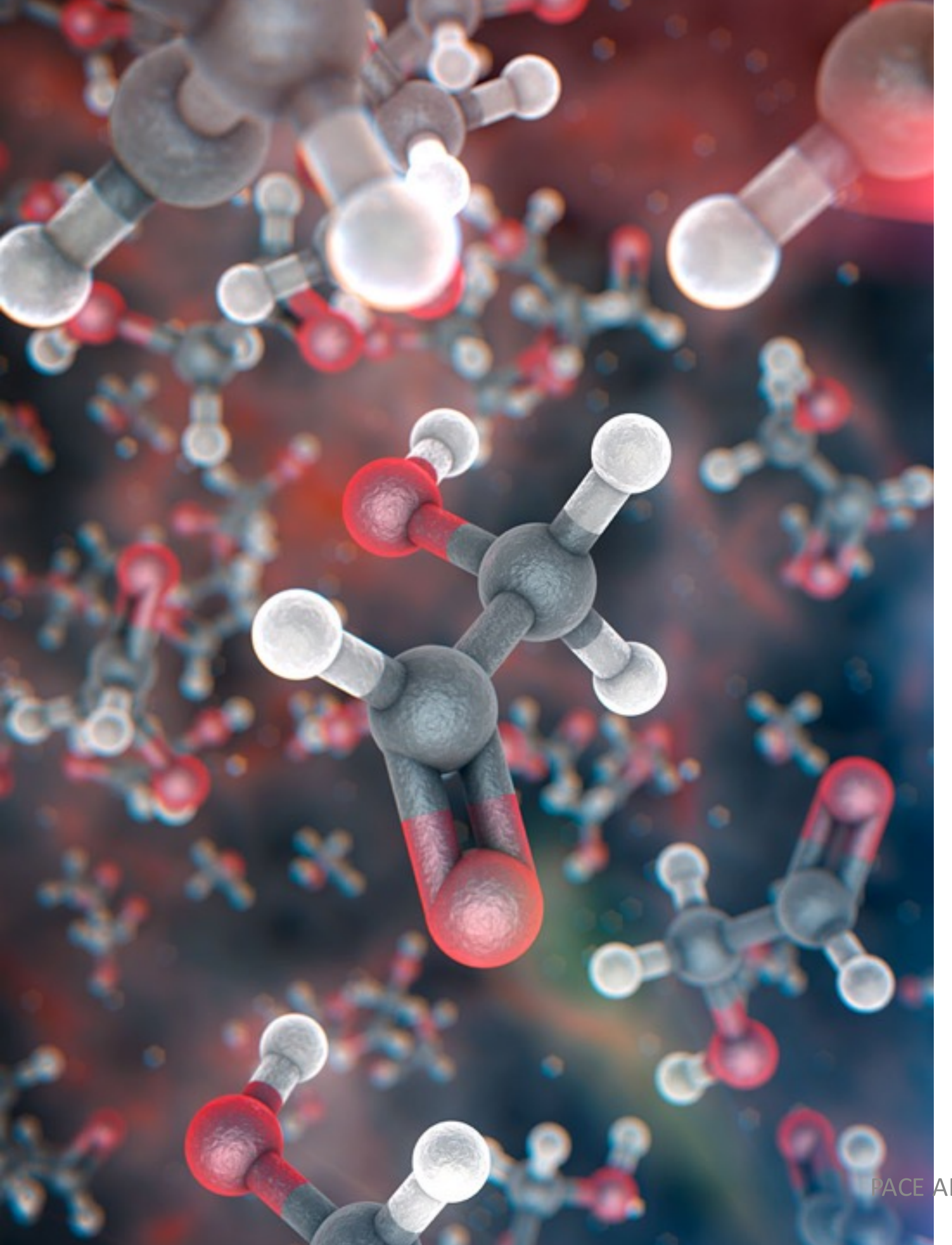
Magnetic Fields: Spectral Line

Manuel Fernandez Lopez

Position	Blos (mG)
1	+4.5 ± 1.1
2	+4.2 ± 1.3
3	-2.4 ± 1.7
4	-2.0 ± 1.1

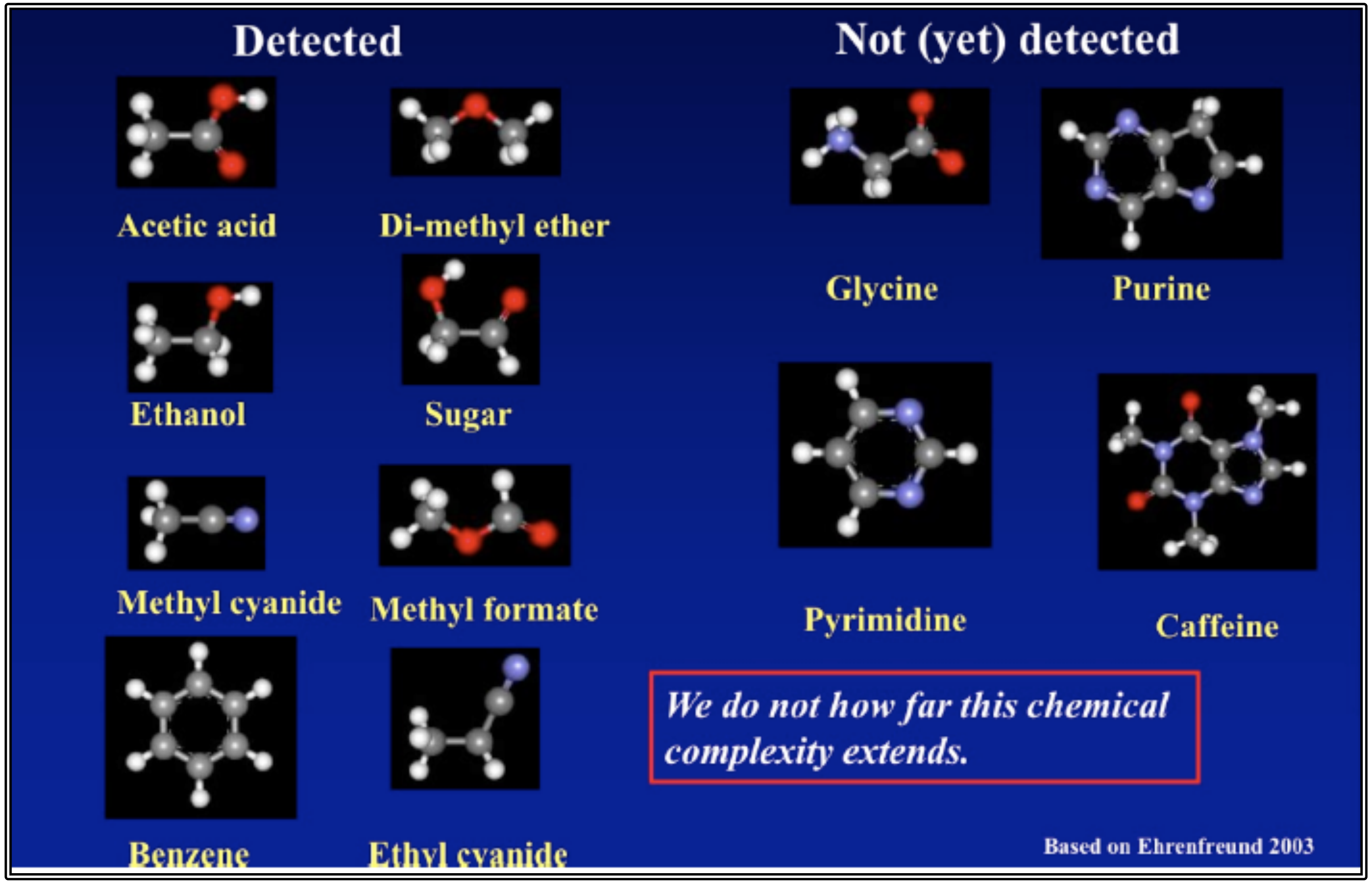


Zeeman effect observed in CN(2-1) low velocity and high velocity gas



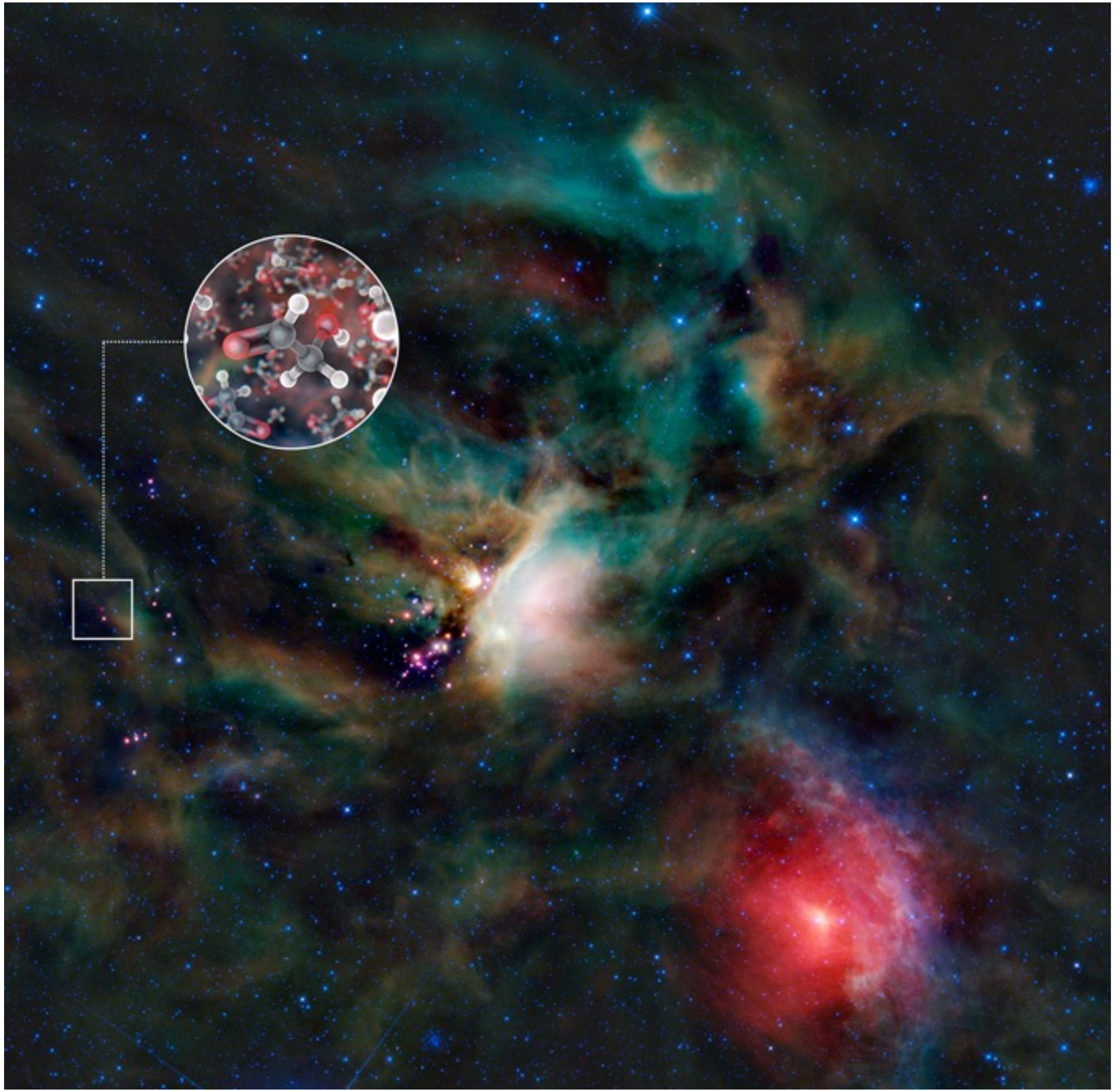
Astrochemistry

ALMA Key Science Driver

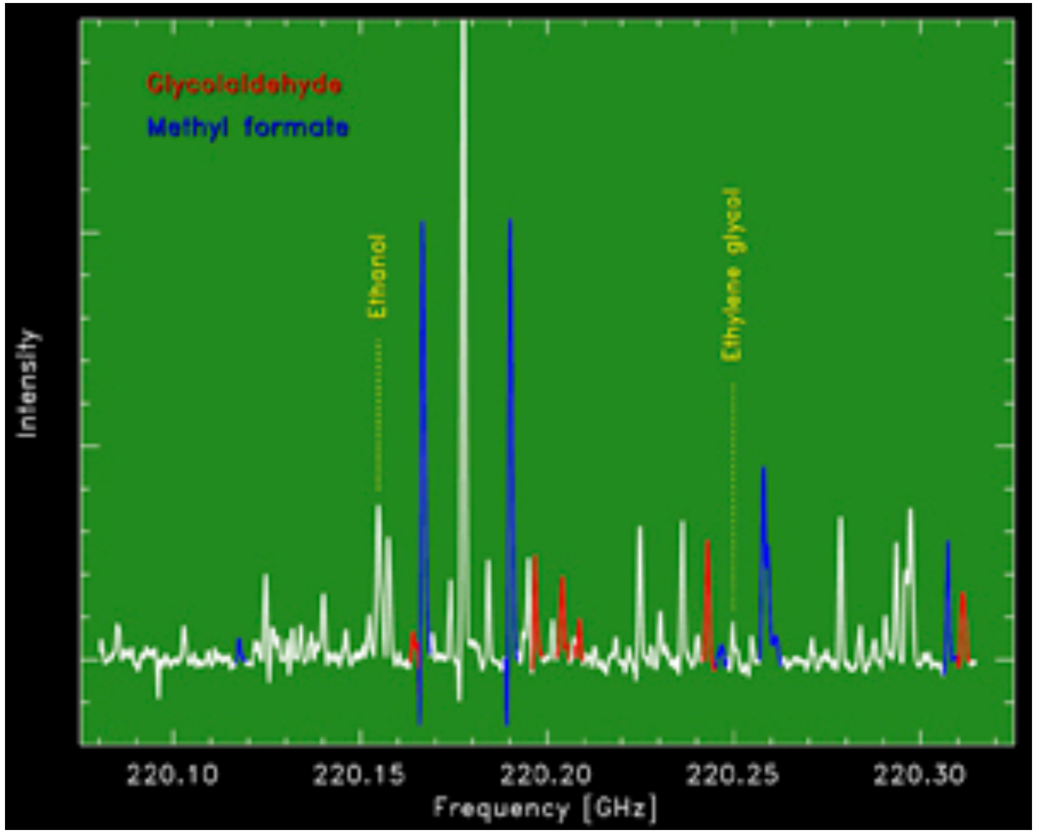


Searching for complex organic chemistry

Precursor of RNA detected in protoplanetary disk

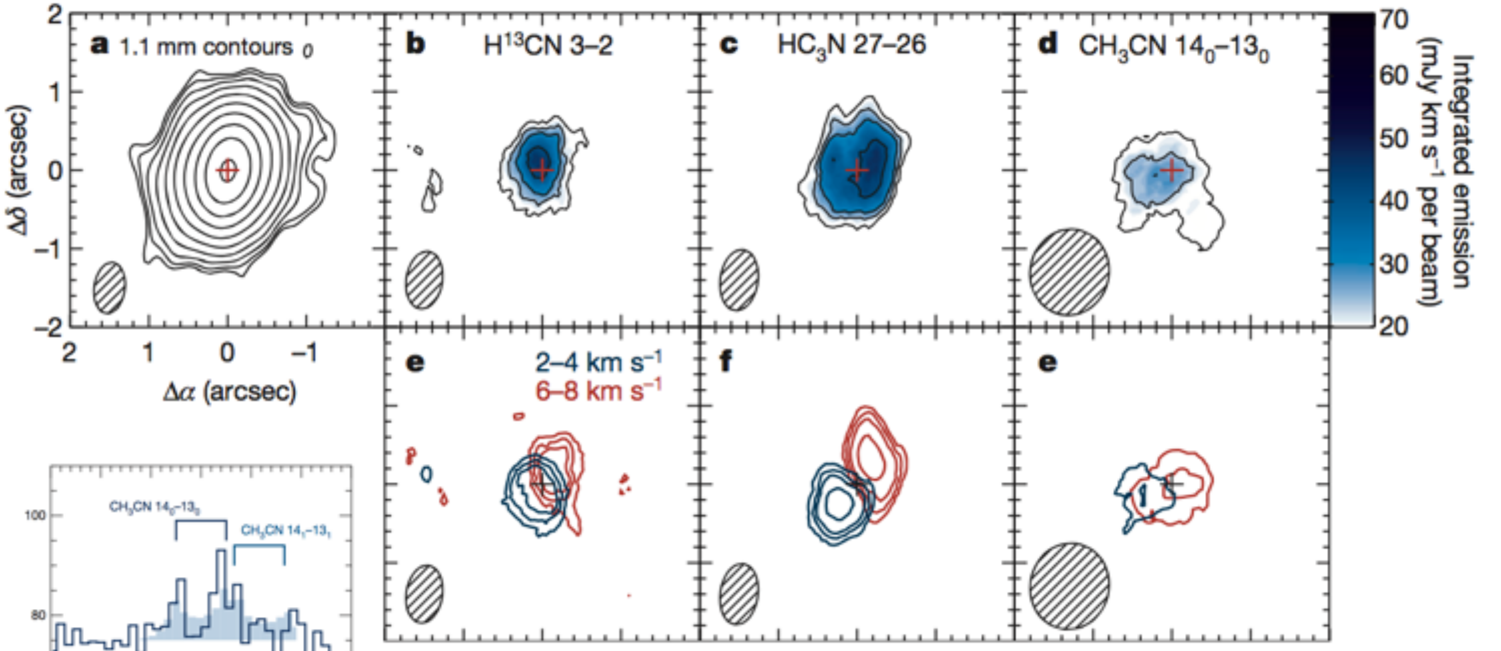


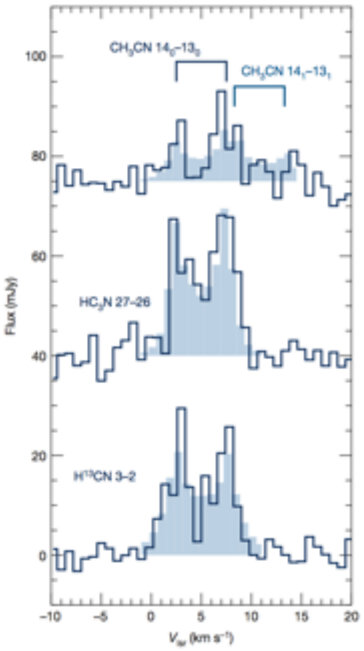
Rho Ophiuchi ALMA (ESO/NAOJ/NRAO)/Jes Jorgensen et al. (2012)



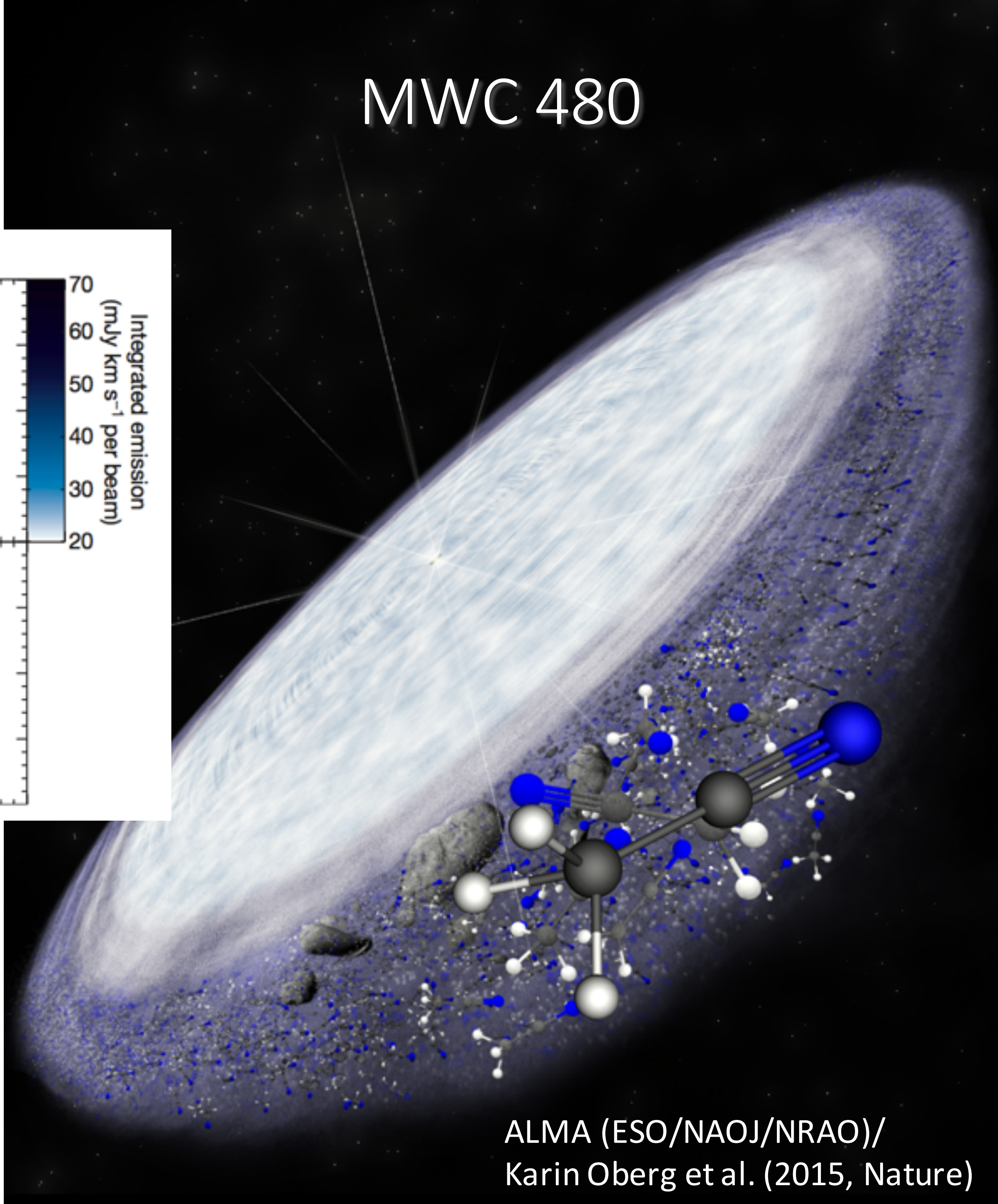
Class 0 protostellar binary
IRAS 16293-2422

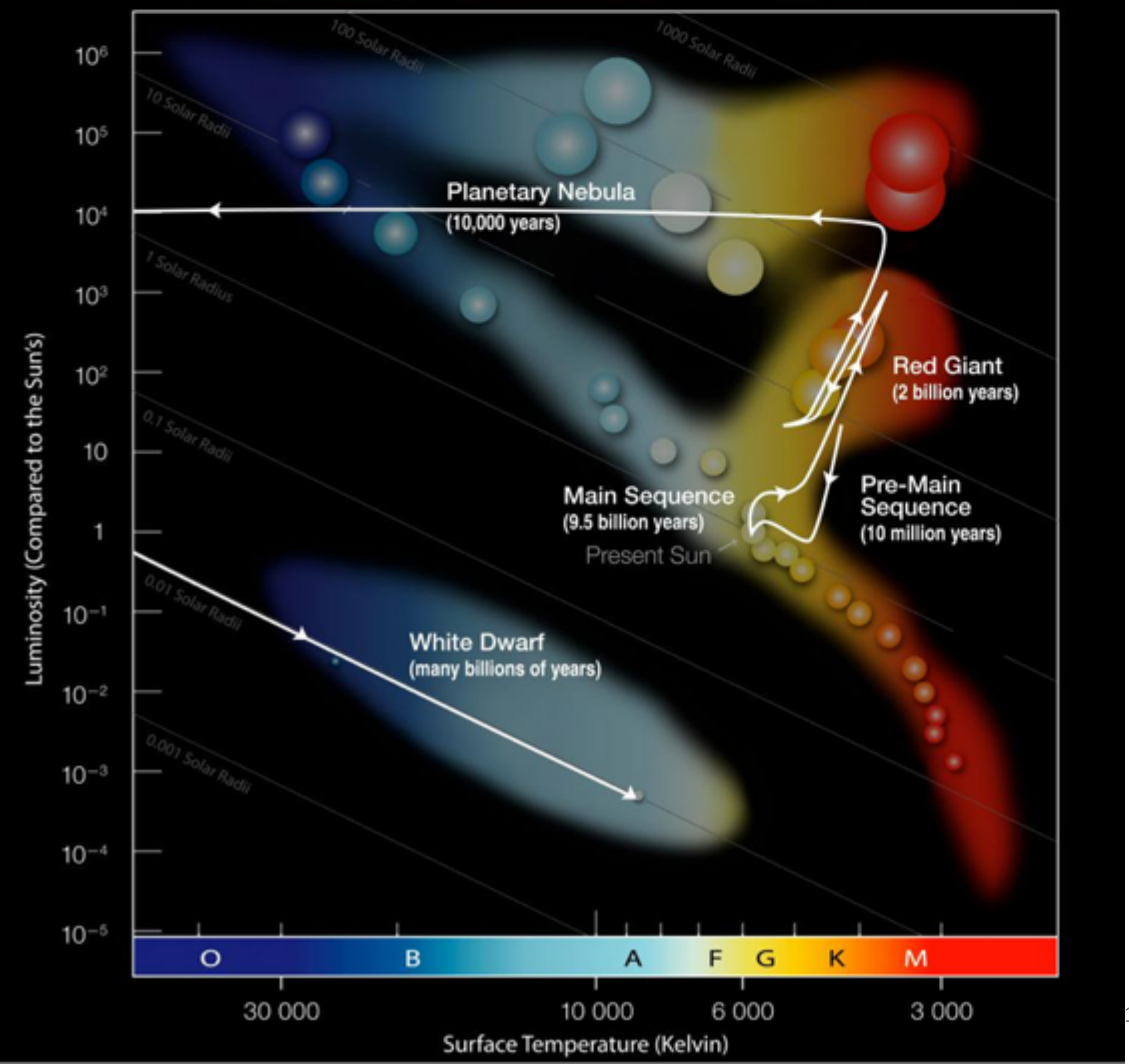
Comet-like chemistry in protoplanetary disk





MWC 480
Herbig Ae star
Mass ~ 1.8 Msolar
Distance 140 pc

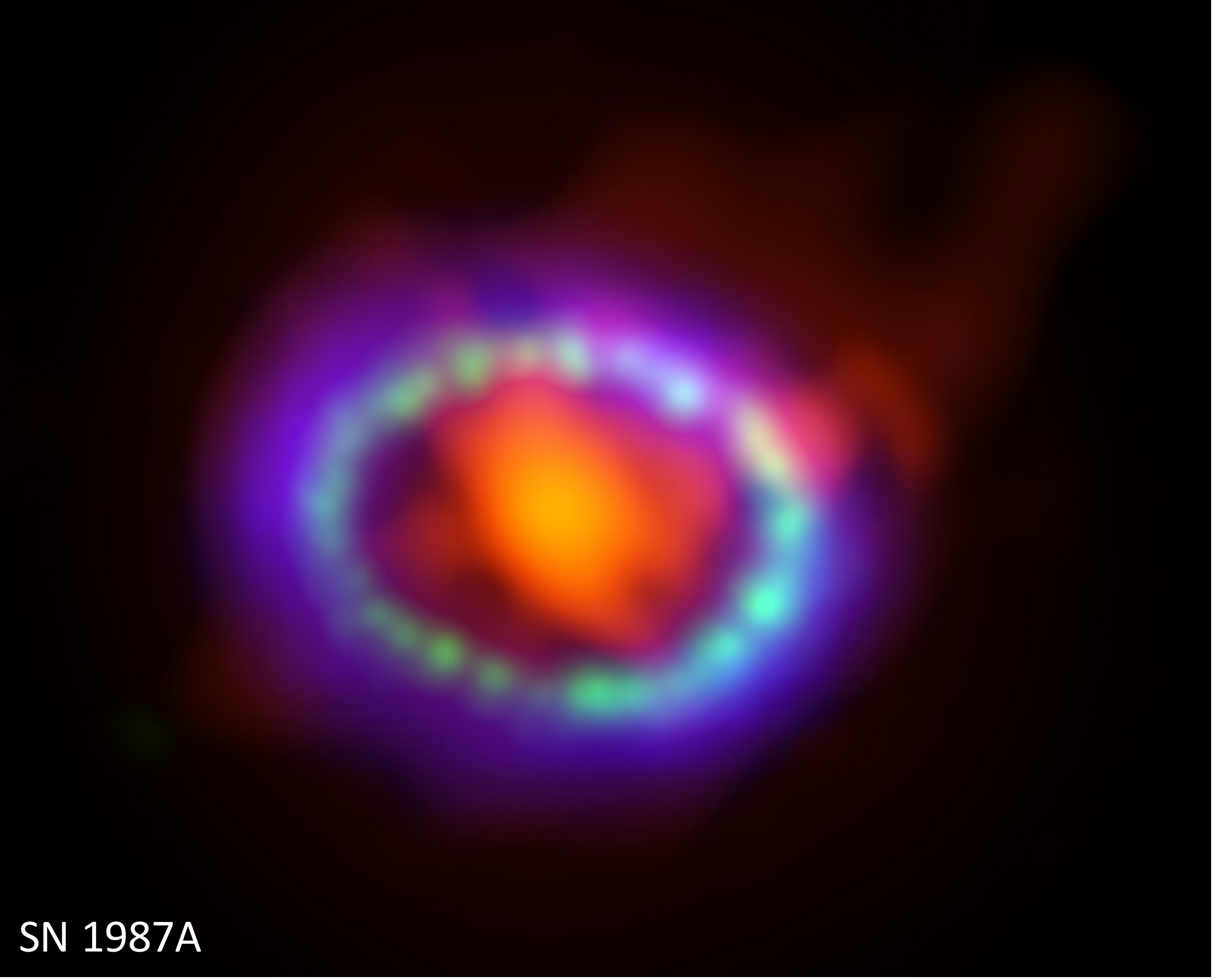




Luminosity (Compared to the Sun's)
10⁶
10⁵
10⁴
10³
10²
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
100 Solar Radii
1000 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radii
0.01 Solar Radii
0.001 Solar Radii
Planetary Nebula
(10,000 years)
Red Giant
(2 billion years)
Main Sequence
(9.5 billion years)
Present Sun
Pre-Main
Sequence
(10 million years)
White Dwarf
(many billions of years)
O
B
A
F
G
K
M
30 000
10 000
6 000
3 000
Surface Temperature (Kelvin)

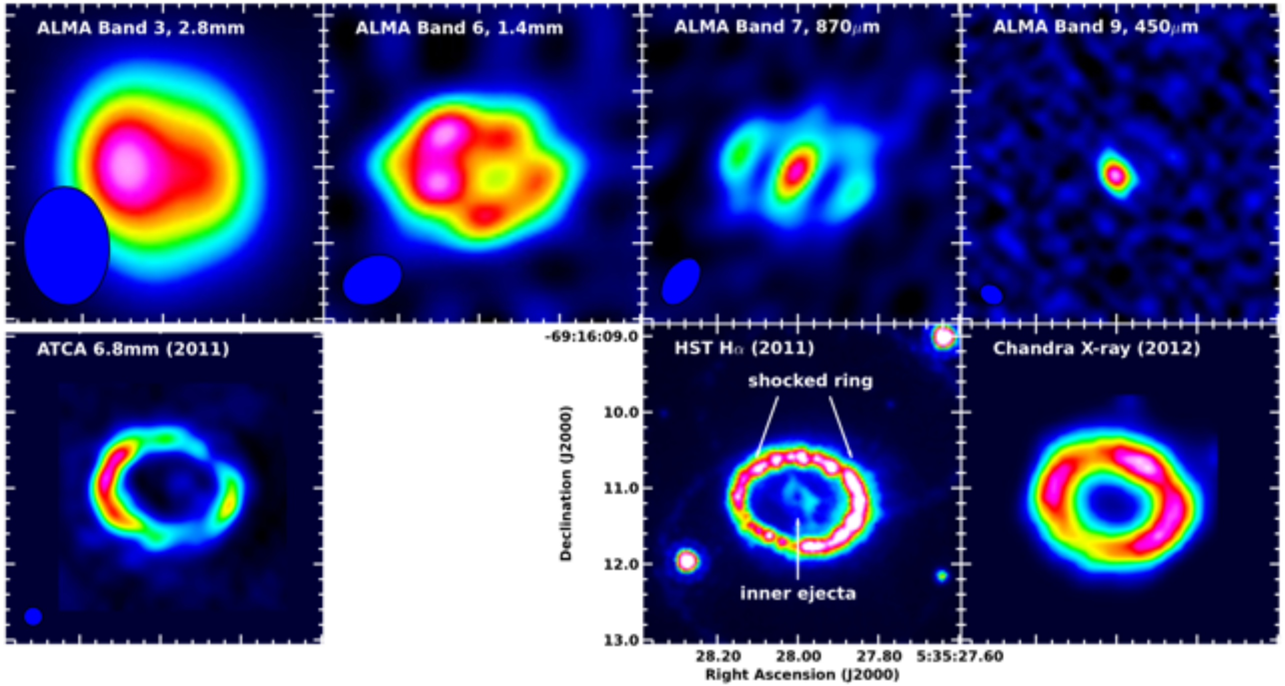
Stars

Supernovae



Indebetouw et al. (2014)

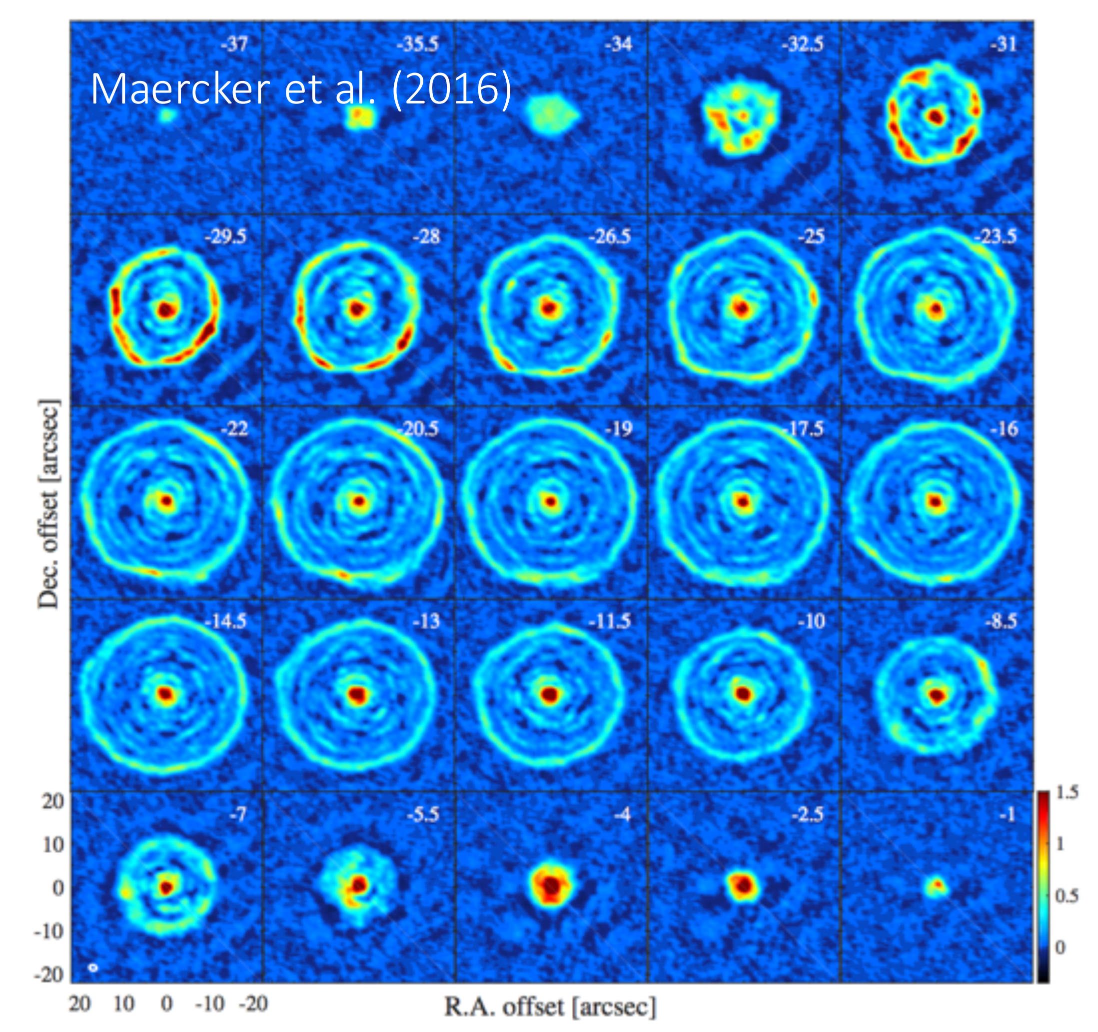
ALMA data (in red) shows newly formed dust in the center of the remnant.
HST (in green) and Chandra (in blue) show the expanding shockwave.



Rebound shock may later destroy
Significant proportion of the dust

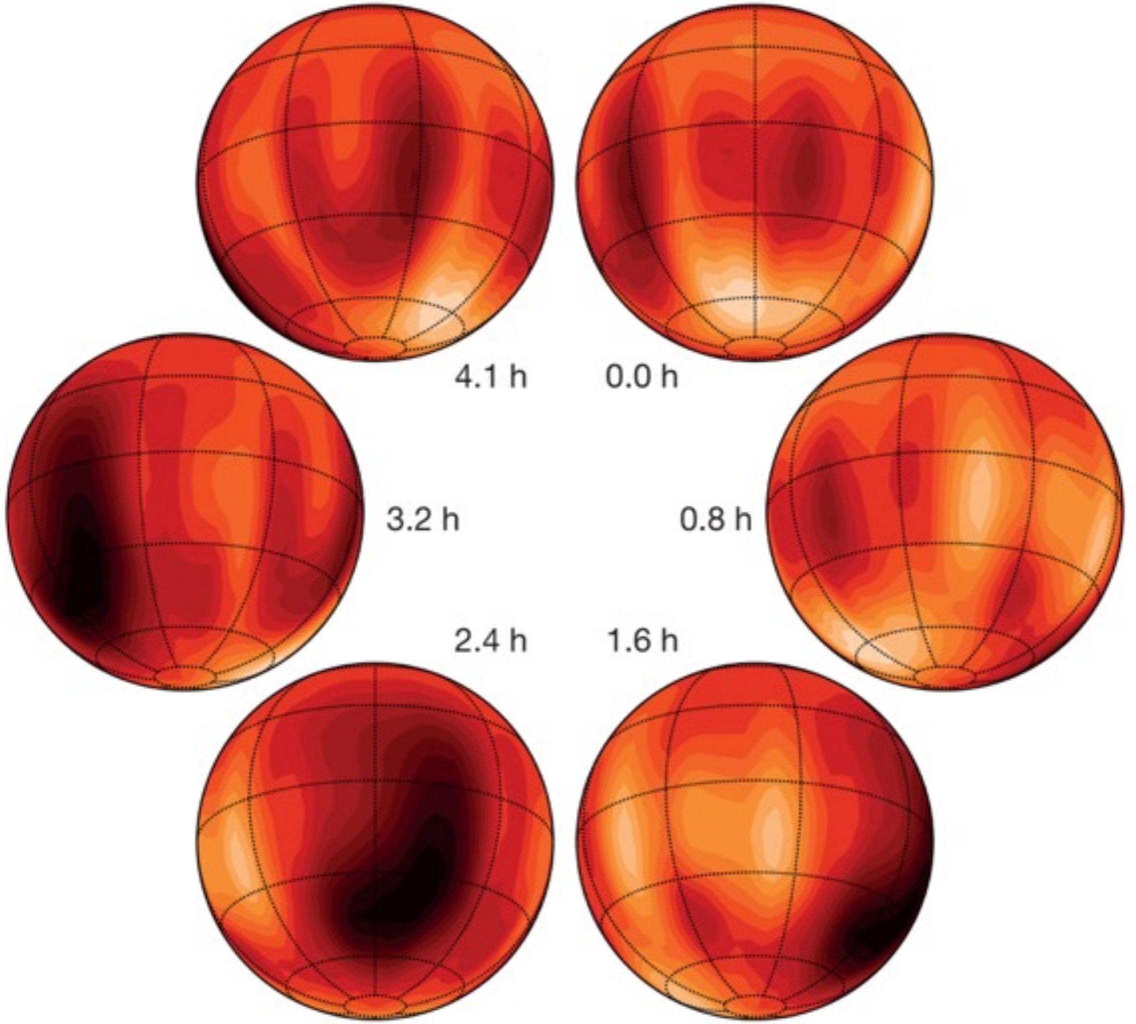
AGB Stars: R Sculptoris

ALMA (ESO/NAOJ/NRAO/Matthias Maercker et al. (2012, Nature)



Total mass lost since last thermal pulse factor x4 higher than models. However immediately following thermal pulse sharp decline in mass loss rate

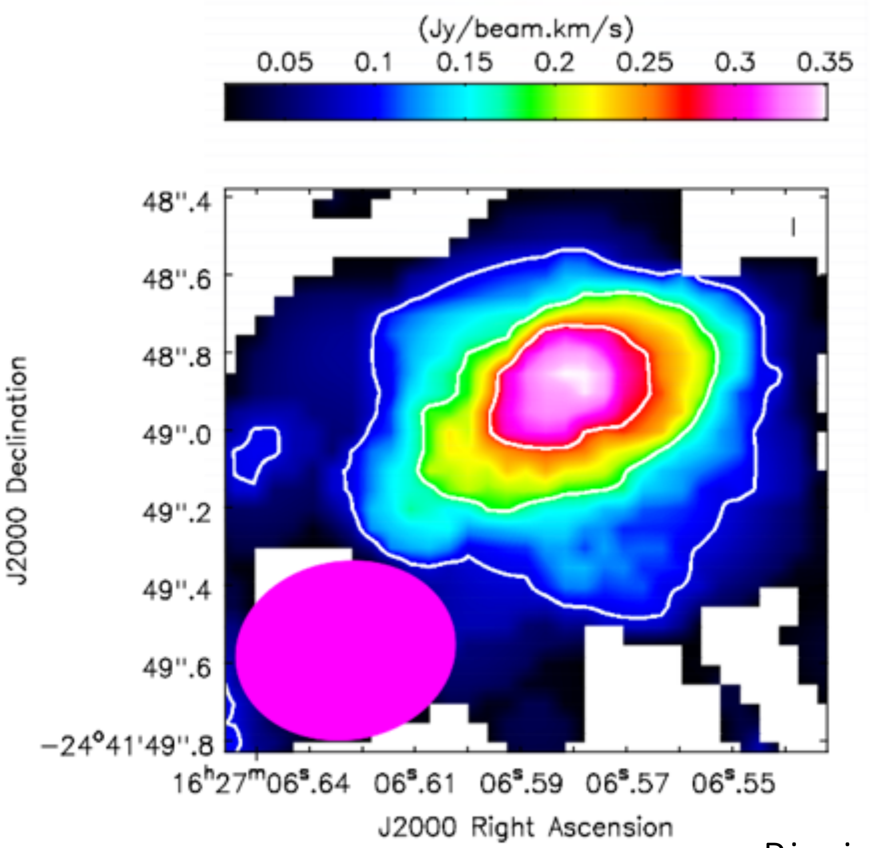
Brown Dwarfs



Substellar bodies more massive than planets but not massive enough to initiate sustained hydrogen fusion that powers self-luminous stars

Luhmann 16B VLT, Crossfield et al. (Nature, 2014)

Variation of dust opacity with frequency in ALMA bands suggests the presence of mm-size dust grains - can rocky planets form?

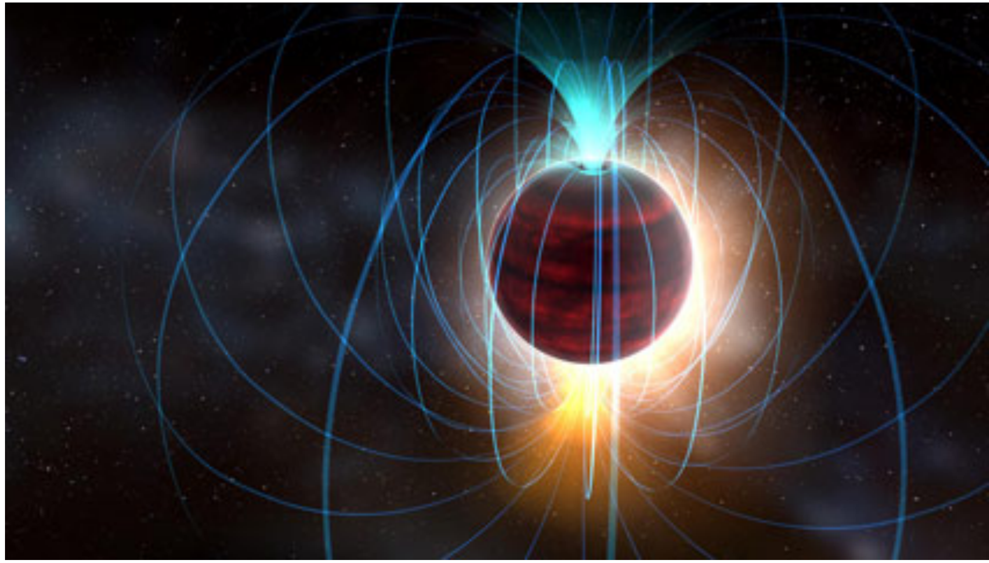


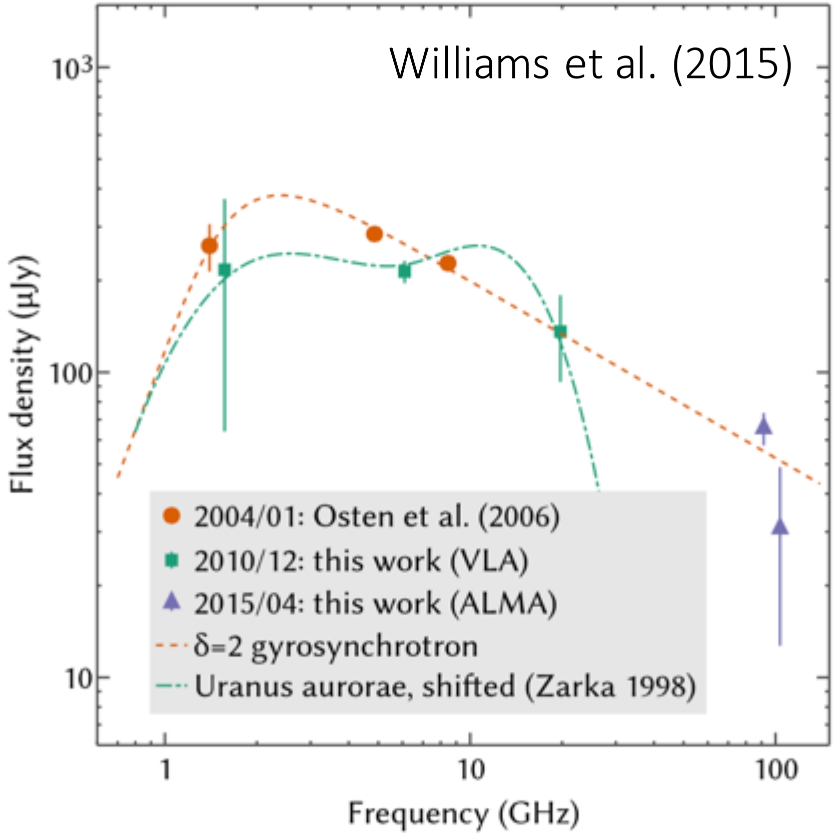
Ricci et al. (2013)

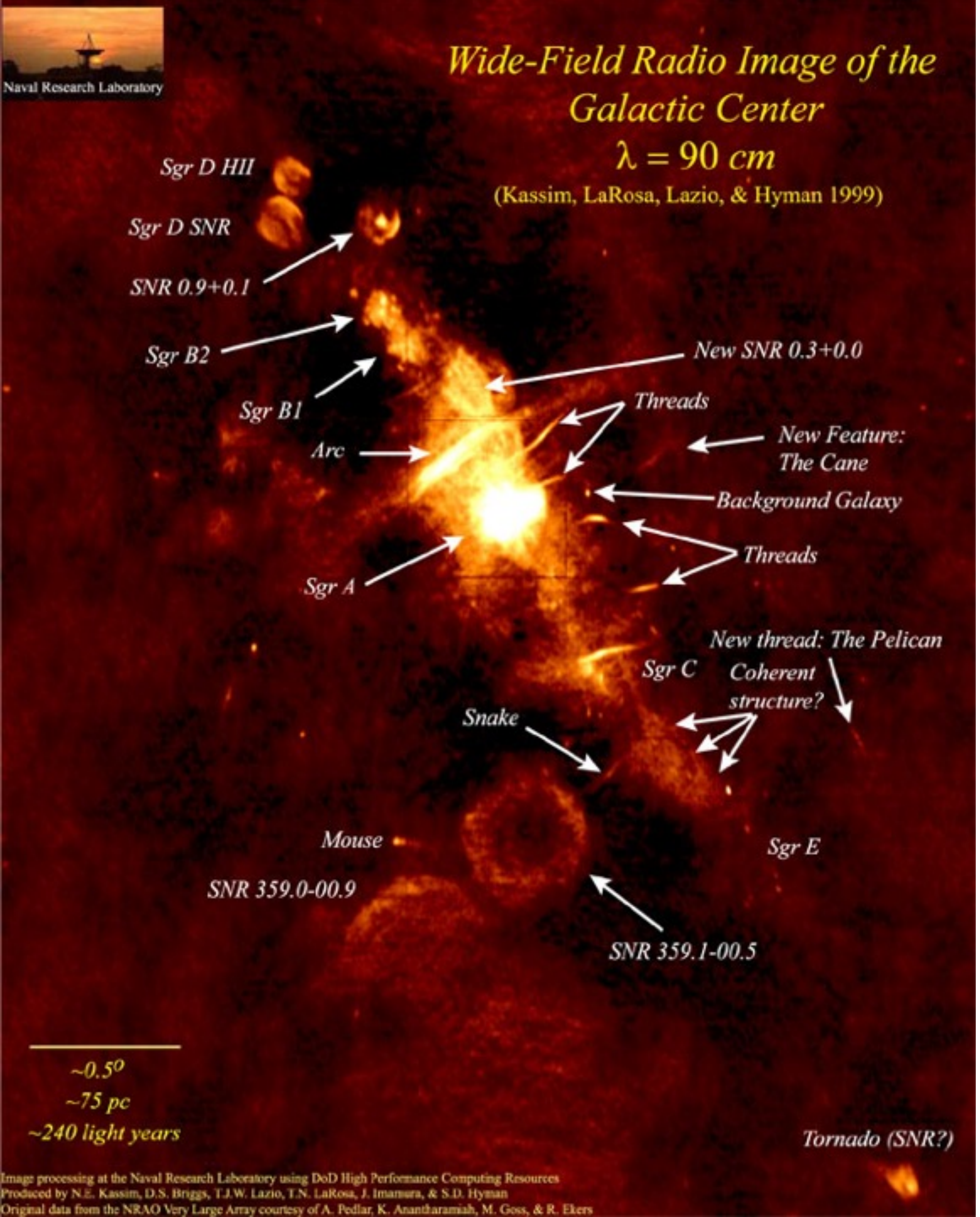
Red Dwarfs

- Low-mass main sequence stars
- TVLM 513-46546
- Distance ~ 12 pc
- Rotation period = 2 hours
- Surface magnetic field ~ 3 kG
- ALMA: first ultracool dwarf detected in the mm

Flare-like synchrotron emission from magnetic activity detected. Could indicate red dwarfs are not good candidates for hosting habitable planets. Because they are so cool a planet would have to orbit very close to have liquid water, putting it right in the path of these flares.

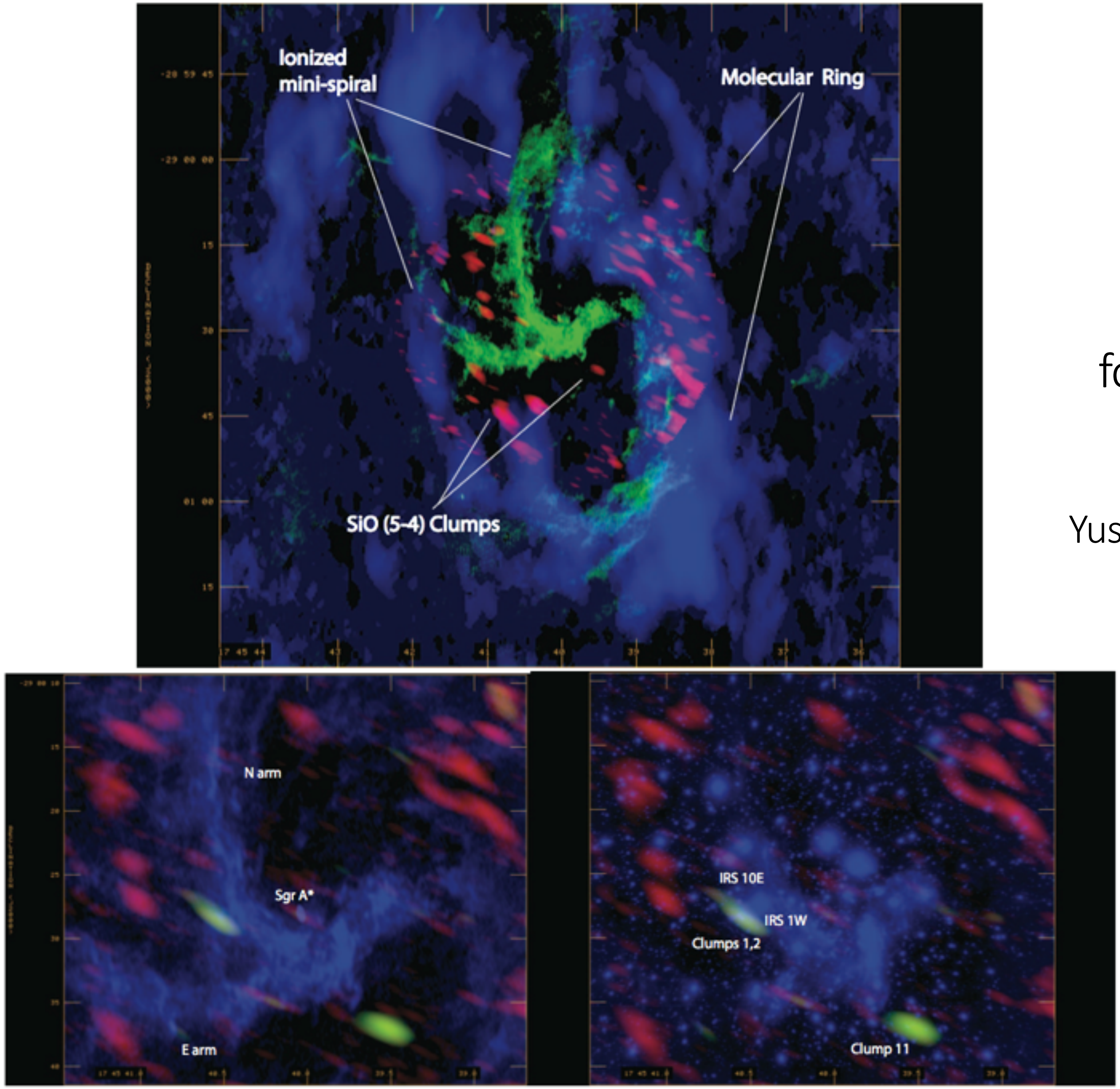






Galactic Centre

Galactic Centre



SiO clumps in a zone forbidden for star formation!

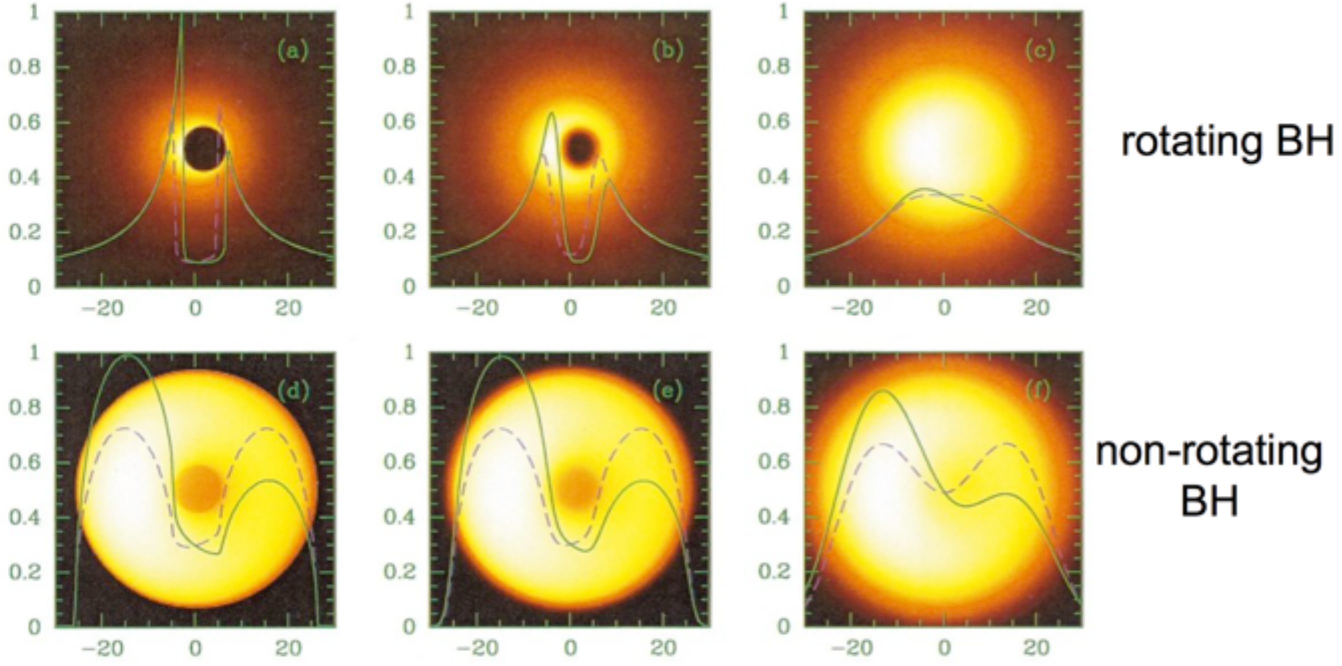
Yusef-Zadeh et al. (2013)

Galactic Centre

- 11 SiO(5-4) clumps within 0.6pc of Sgr A*, interior to the 2pc circumnuclear molecular ring
- Three clumps closest to SgrA* display the largest central velocities and dispersions at ~150 km/s
- Remaining clumps trace the mini spiral and have small line widths (18-56 km/s)
- SiO clumps are interpreted as high mass protostellar clumps associated with outflows

Detecting the shadow of a black hole

A "picture" of the Galactic Center Black Hole taken with ALMA + mm VLBI



Simulations
Falcke+2000

230 GHz VLBI Stations

Future EHT

Image credit: New Times, 9 June 201

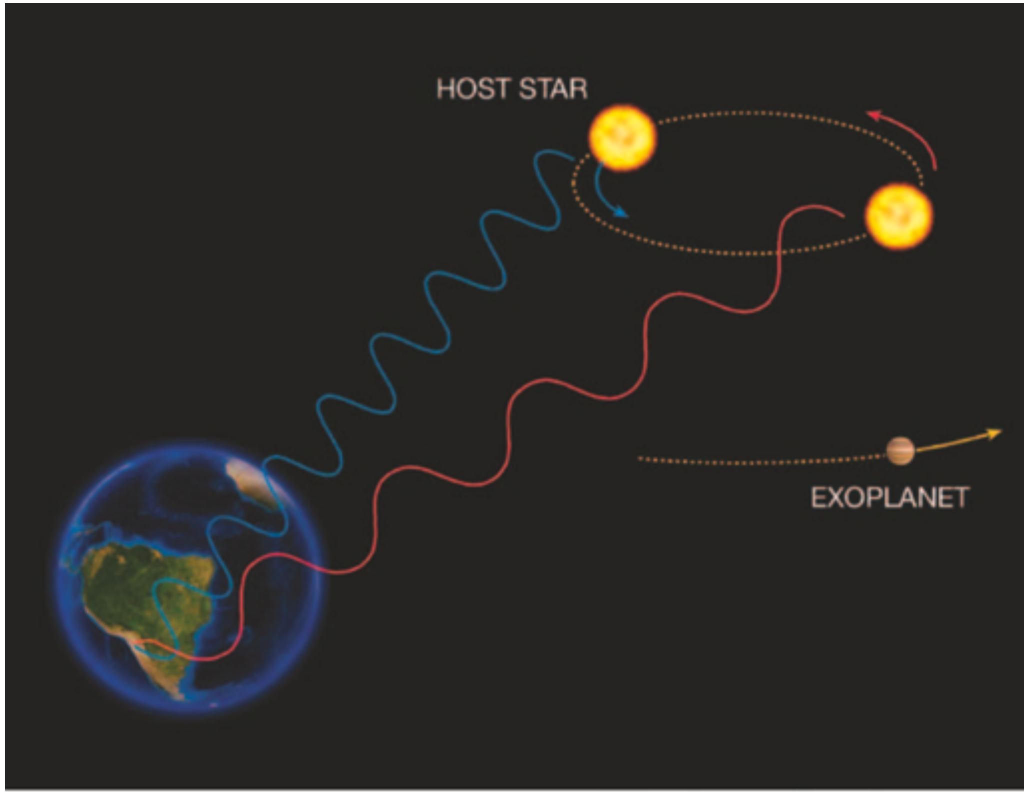
New at Cycle 4

ALMA in mmVLBI

Thank you and good luck!

Radial velocity

- Planet around star will induce a periodic blue/redshift in the spectrum of the star
- ALMA at high-frequencies can achieve 3m/s
- Issues:
  - stellar brightness and atmospheric chemical content (better success in dwarf stars?)
  - bandpass calibration
  - Earth atmosphere absorption



[Slide: H. Messias]

Transmission spectrum

- Transiting planet atmosphere will leave an absorption imprint in the stellar continuum
- Issues –
  - bandpass calibration
  - chemical species vs Earth atmospheric absorption vs Earth-exoplanet relative velocity

[Slide: H. Messias]