# “Cradle of Life” summary

## ngVLA Science Working Group 1



**Chat Hull**

Jansky Fellow — Harvard-Smithsonian Center for Astrophysics
National Radio Astronomy Observatory


4 January 2016

ngVLA workshop
AAS 227th meeting
Kissimmee, Fla.

# “Cradle of Life” contributors

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Doug Johnstone (NRC)
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John Tobin (Leiden)
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**Co-chairs:**
Andrea Isella (Rice)
Chat Hull (Harvard/NRAO)
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**Fearless leaders:**
Chris Carilli
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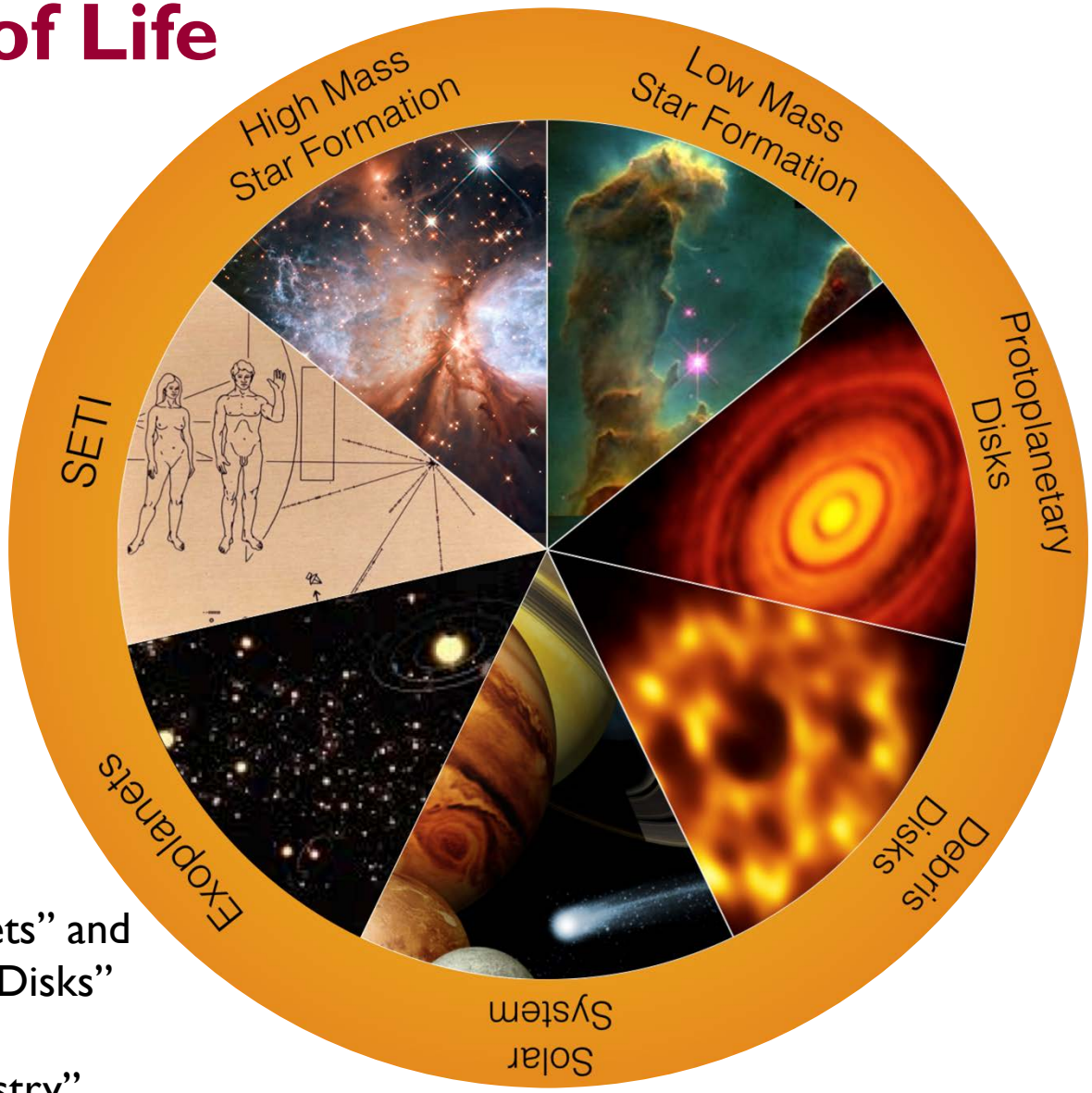
# Wheel of Life




Merged "Exoplanets" and "Protoplanetary Disks"

Added "Chemistry"

Credit: Andrea Isella, 2015 ngVLA Workshop

# Outline

- **Optical depth**
  - Planet formation
  - Chemistry
  - Multiplicity/fragmentation/IMF
- **Debris disks**
- **Jets & outflows**
- **Chemistry**
  - Ammonia, complex organics
  - Chasing the water snow line
- **Polarization**
- **Time domain**
  - SETI
  - Orbiting material
- **Solar System**
  - Pluto, asteroids, Jupiter, and more

Other CoL speakers

# Optical depth

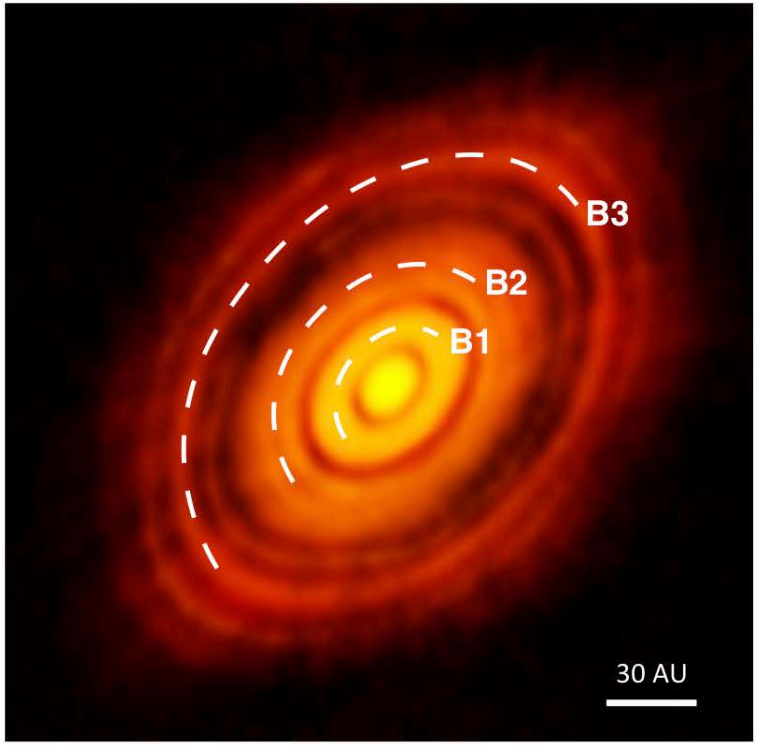
# ALMA

Photo credit: C. Hull

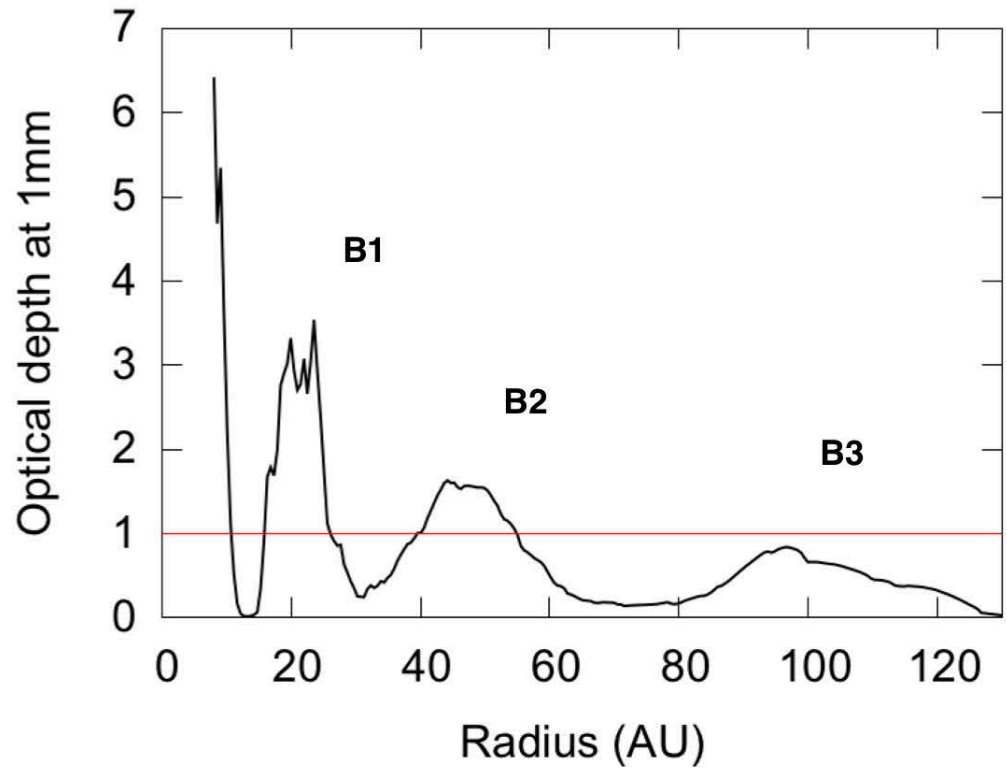
# Optical depth – planet-forming regions

Isella

## Inner rings in HL Tau disk are optically thick



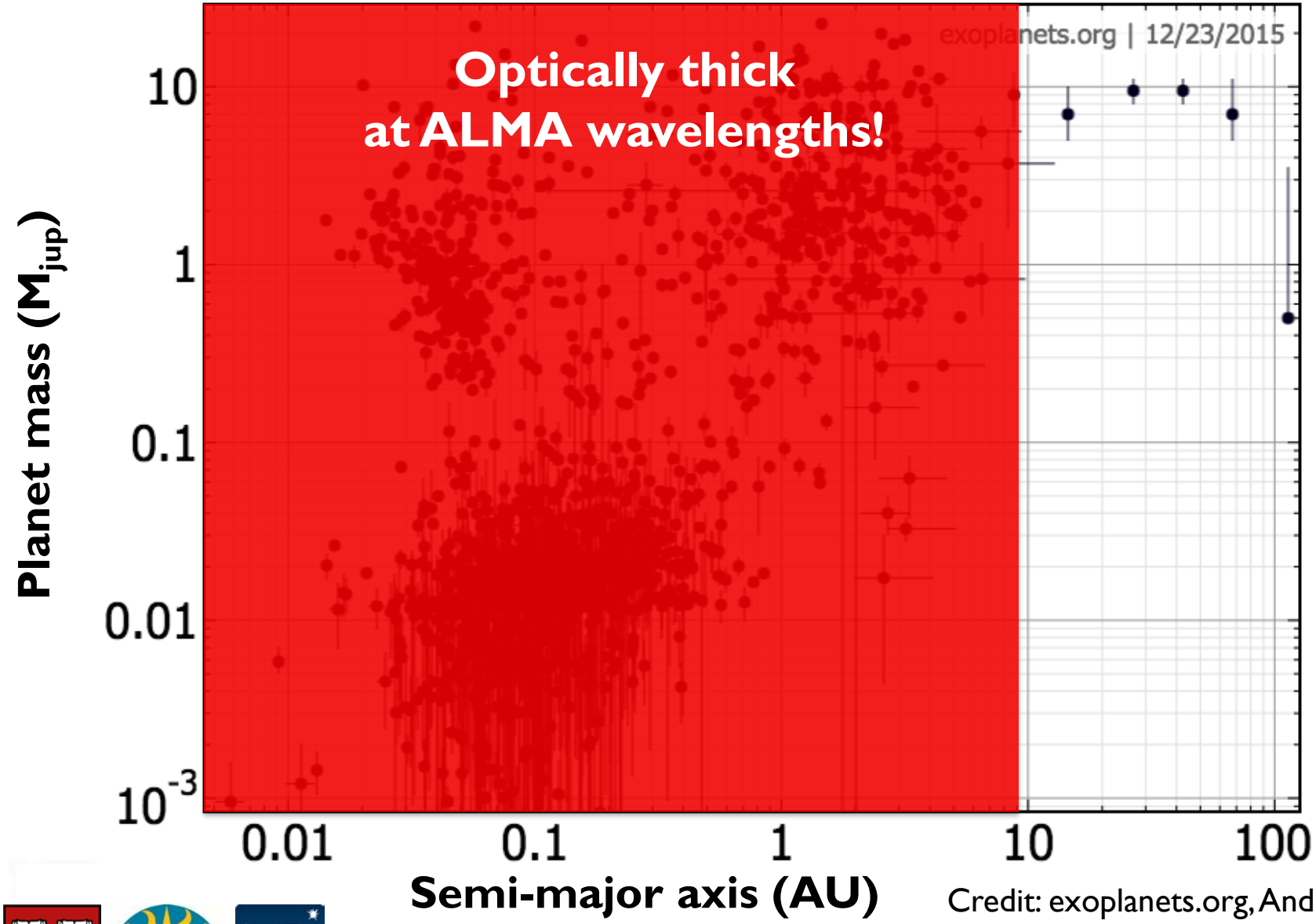

ALMA Partnership 2015




Jin+2016 (in press)

# Optical depth

Isella, Tobin, Rodriguez

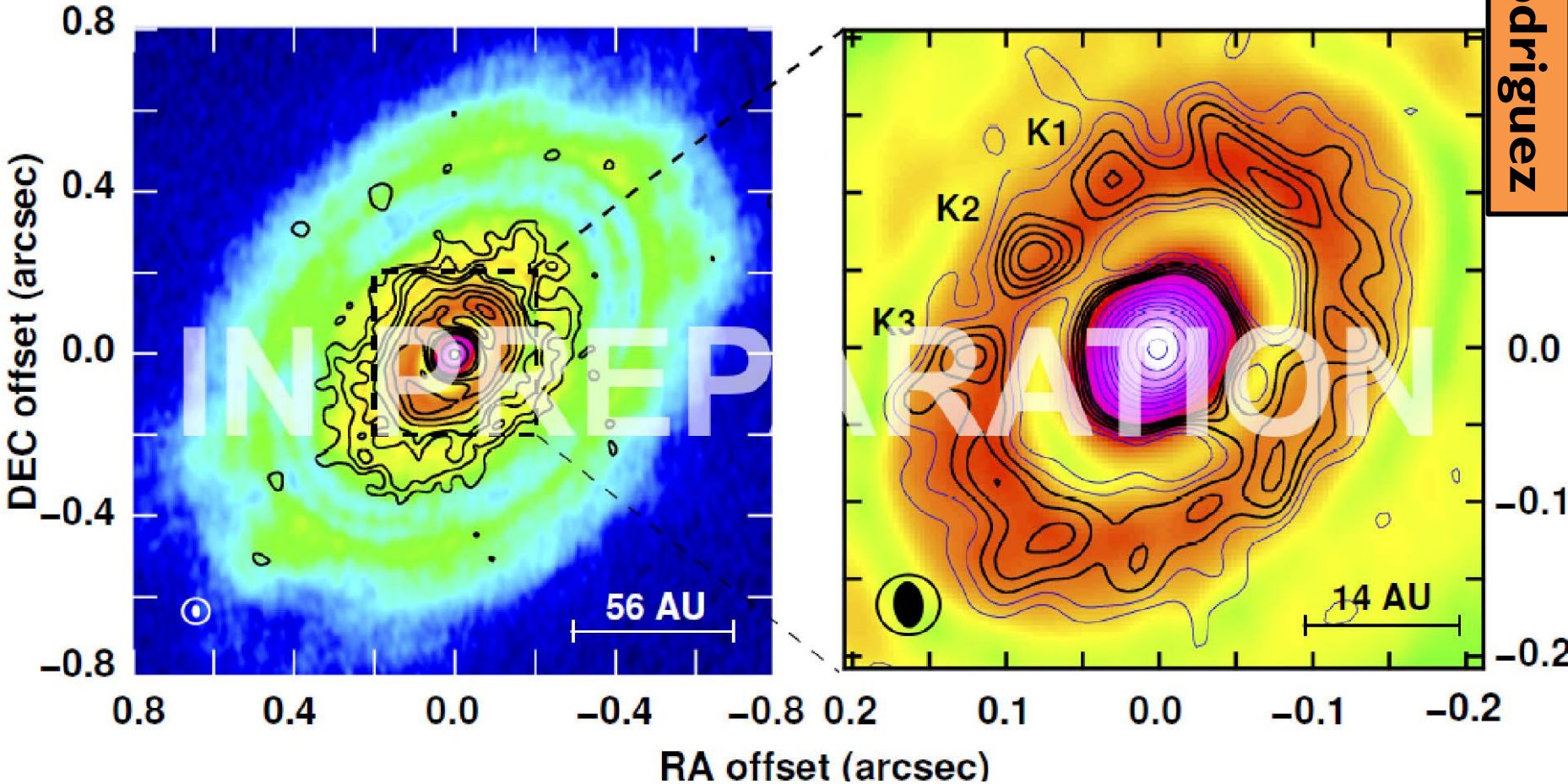



Credit: exoplanets.org, Andrea Isella

# Optical depth – planet-forming regions

Isella, Rodriguez

Deep (~15 hr) 7mm VLA observations of HL Tau

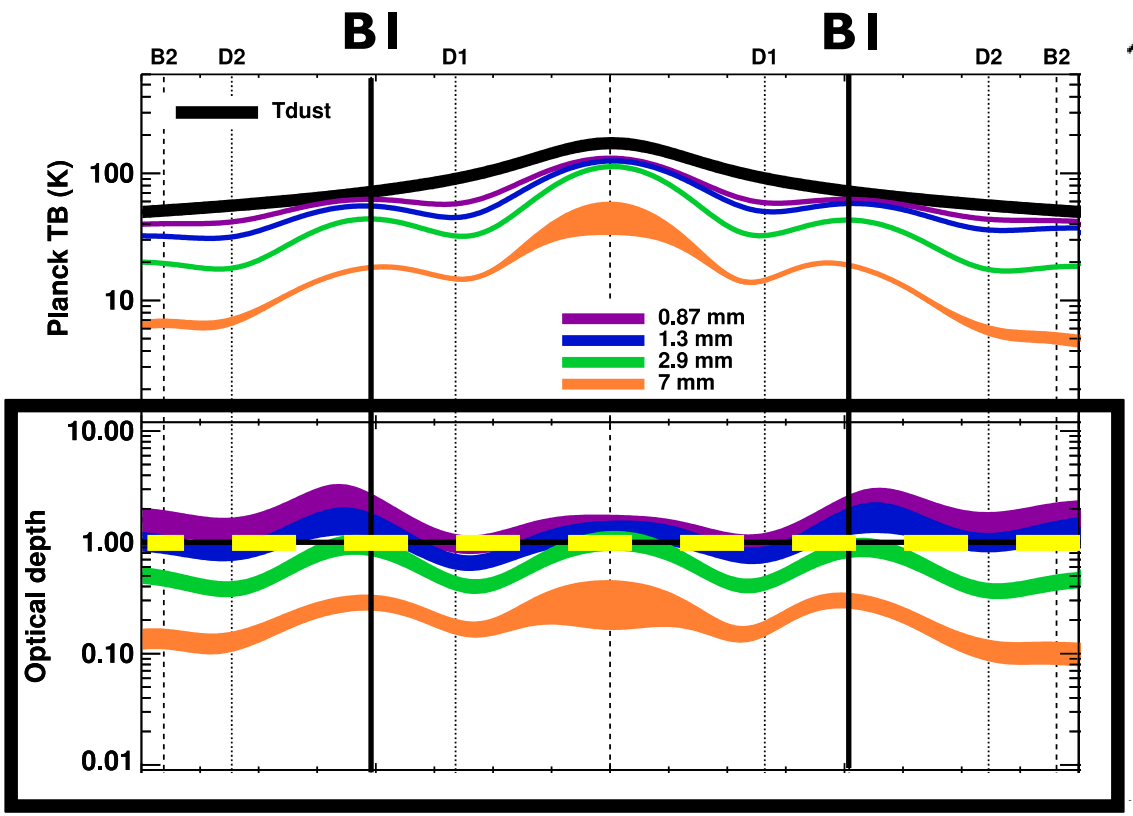


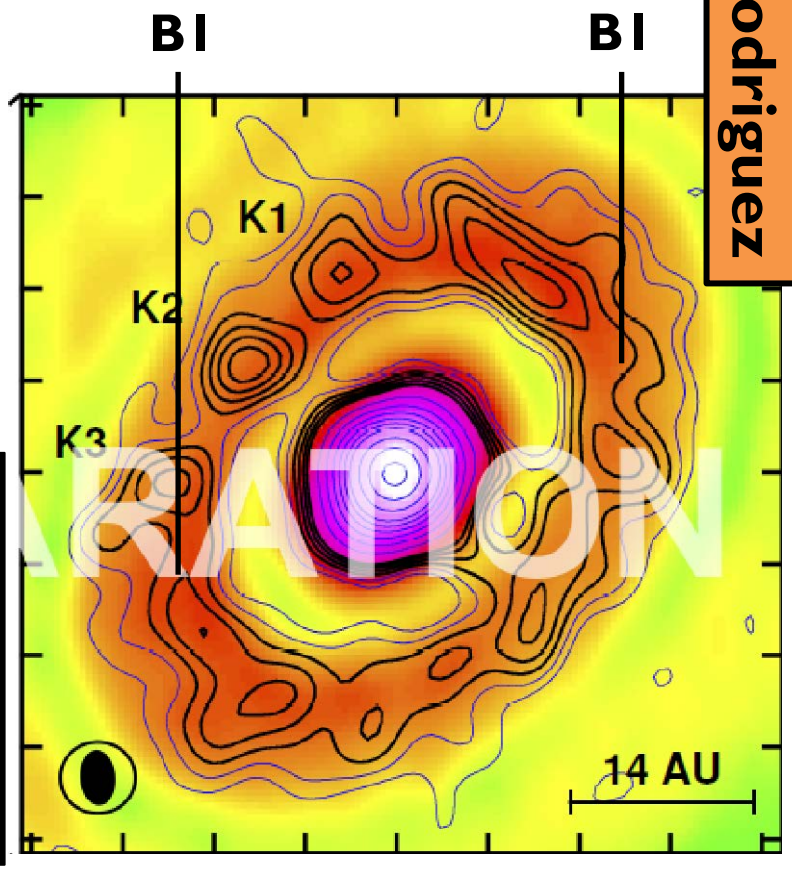

Credit: Carrasco-González+2016 (in prep)

# Optical depth – planet-forming regions

Isella, Rodriguez

Rings are optically thin at 7mm!



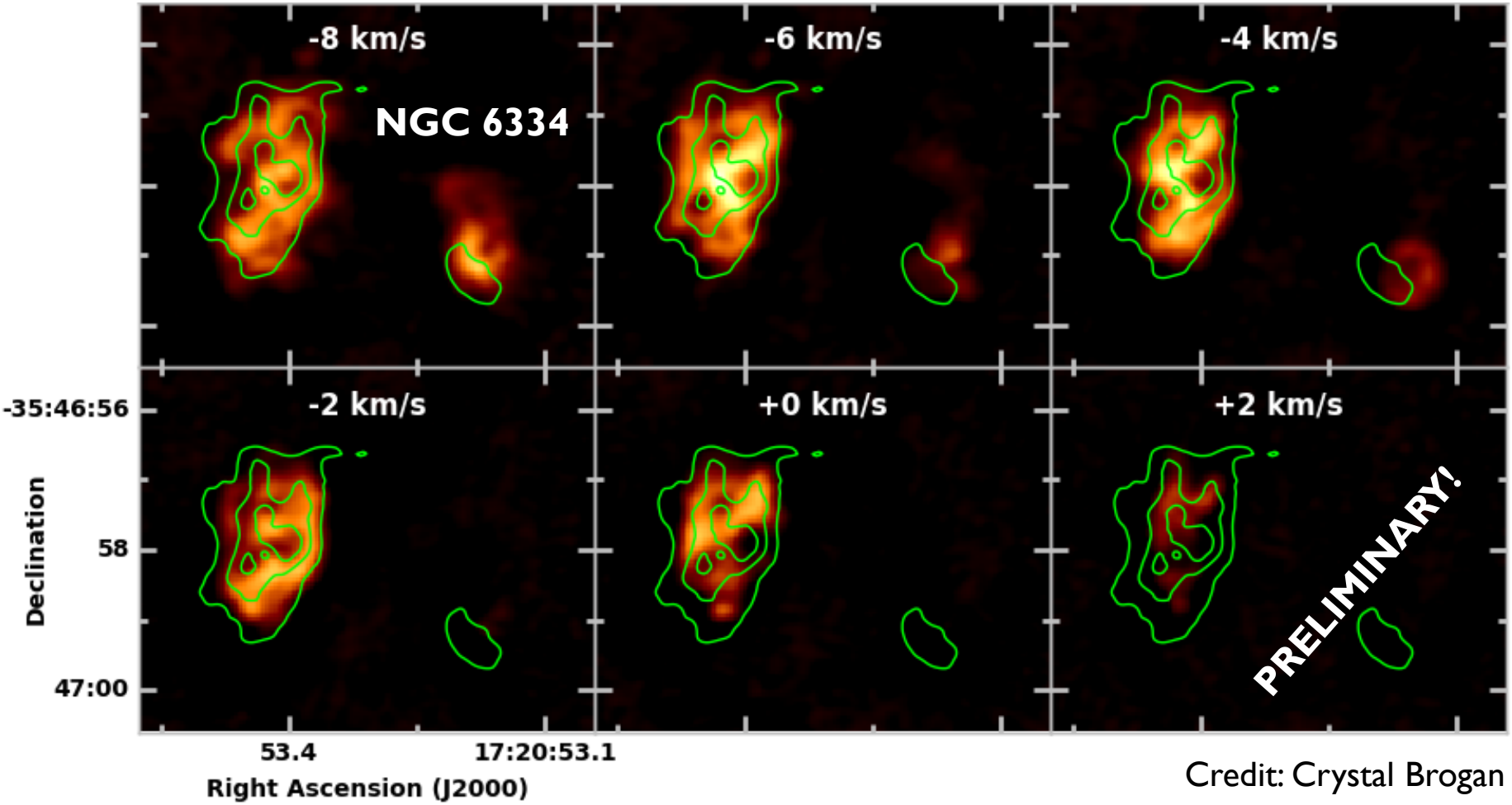




Need higher resolution and sensitivity to resolve rocky-planet-forming region (inner ~10 AU)

Credit: Carrasco-González+2016 (in prep)

# Optical depth – chemistry

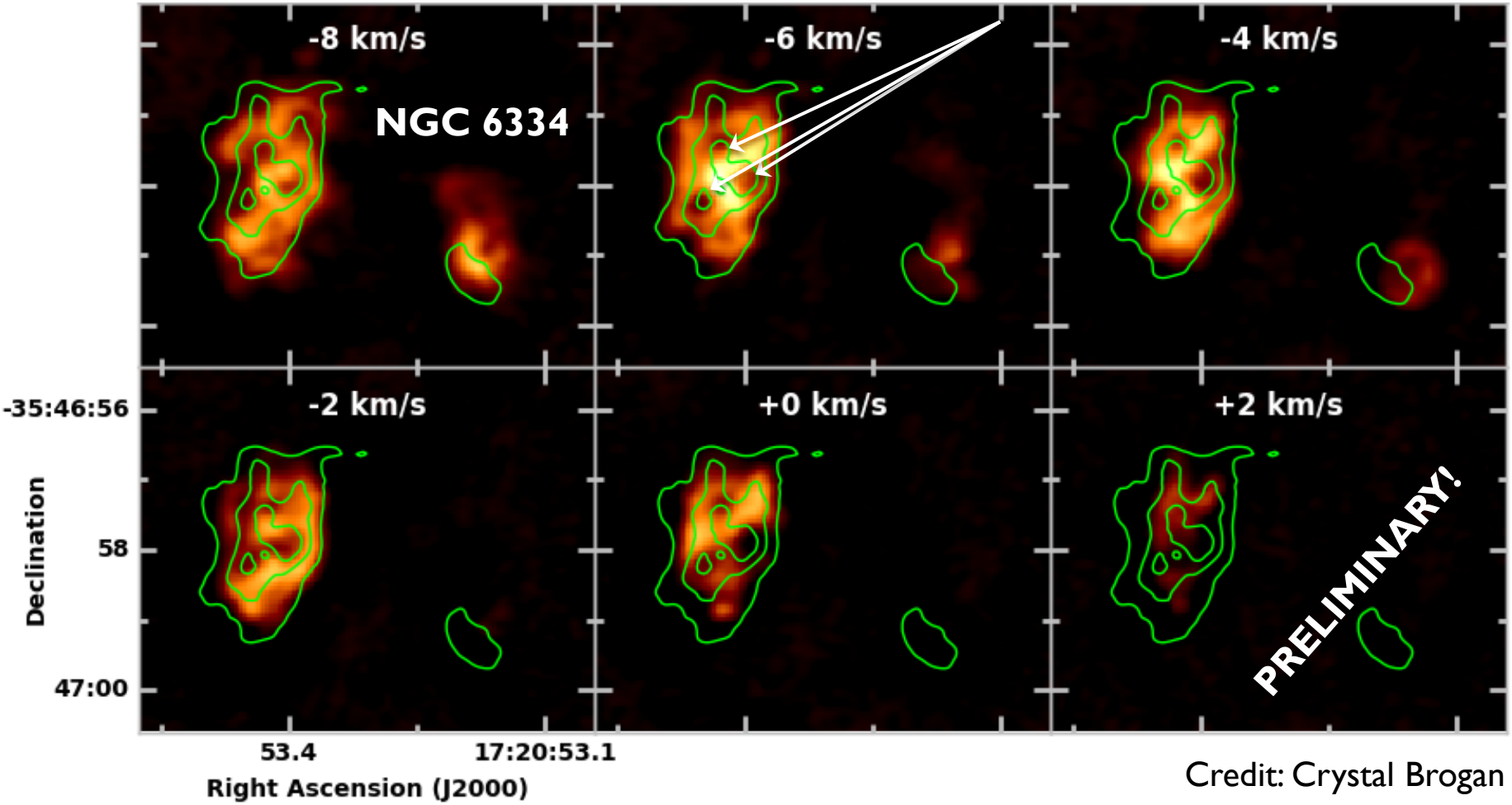
$CH_3CN$ (colorscale) and dust (contours) in a massive protocluster




Credit: Crystal Brogan

# Optical depth – chemistry

Line emission obscured by optically thick continuum?

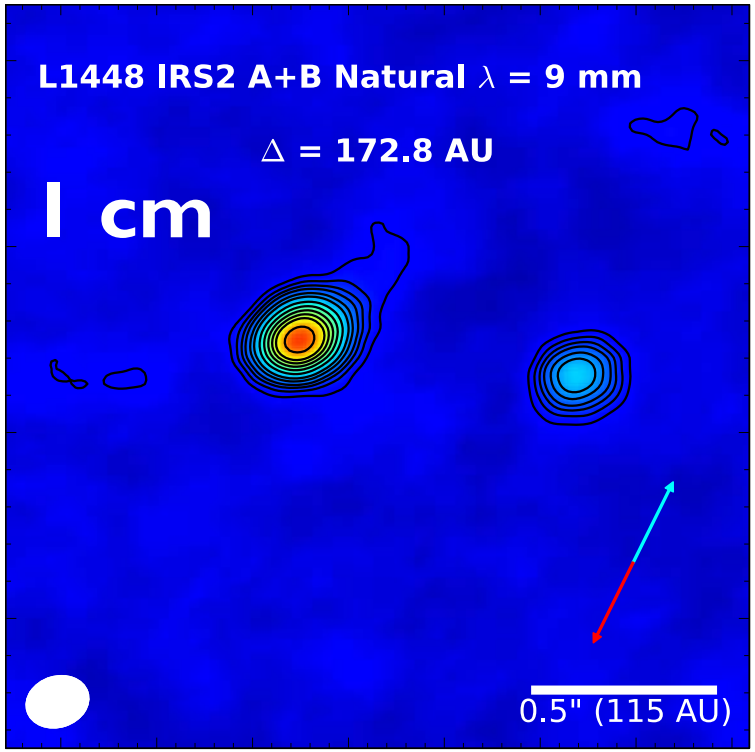



Credit: Crystal Brogan

# Optical depth & free-free – multiples

Tobin

Binary may be obscured by optically thick dust emission




ngVLA Memo #6, "Cradle of Life," 2015; Credit: John Tobin

# Optical depth & free-free – multiples

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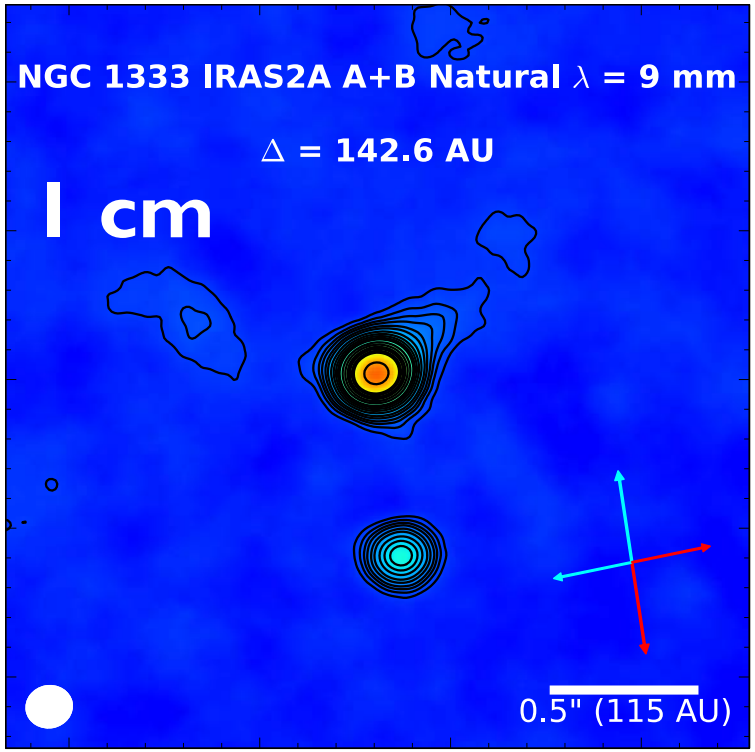
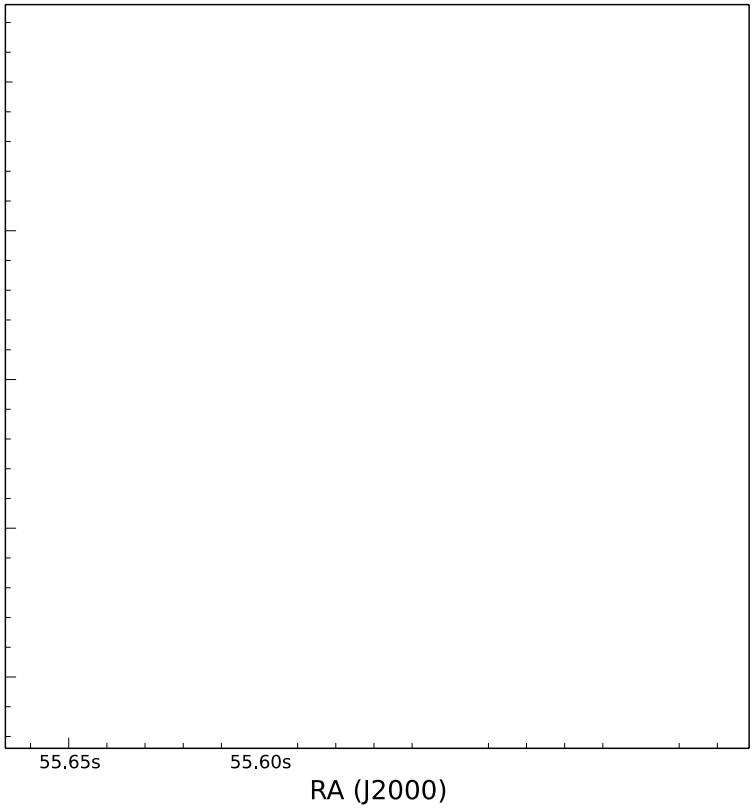


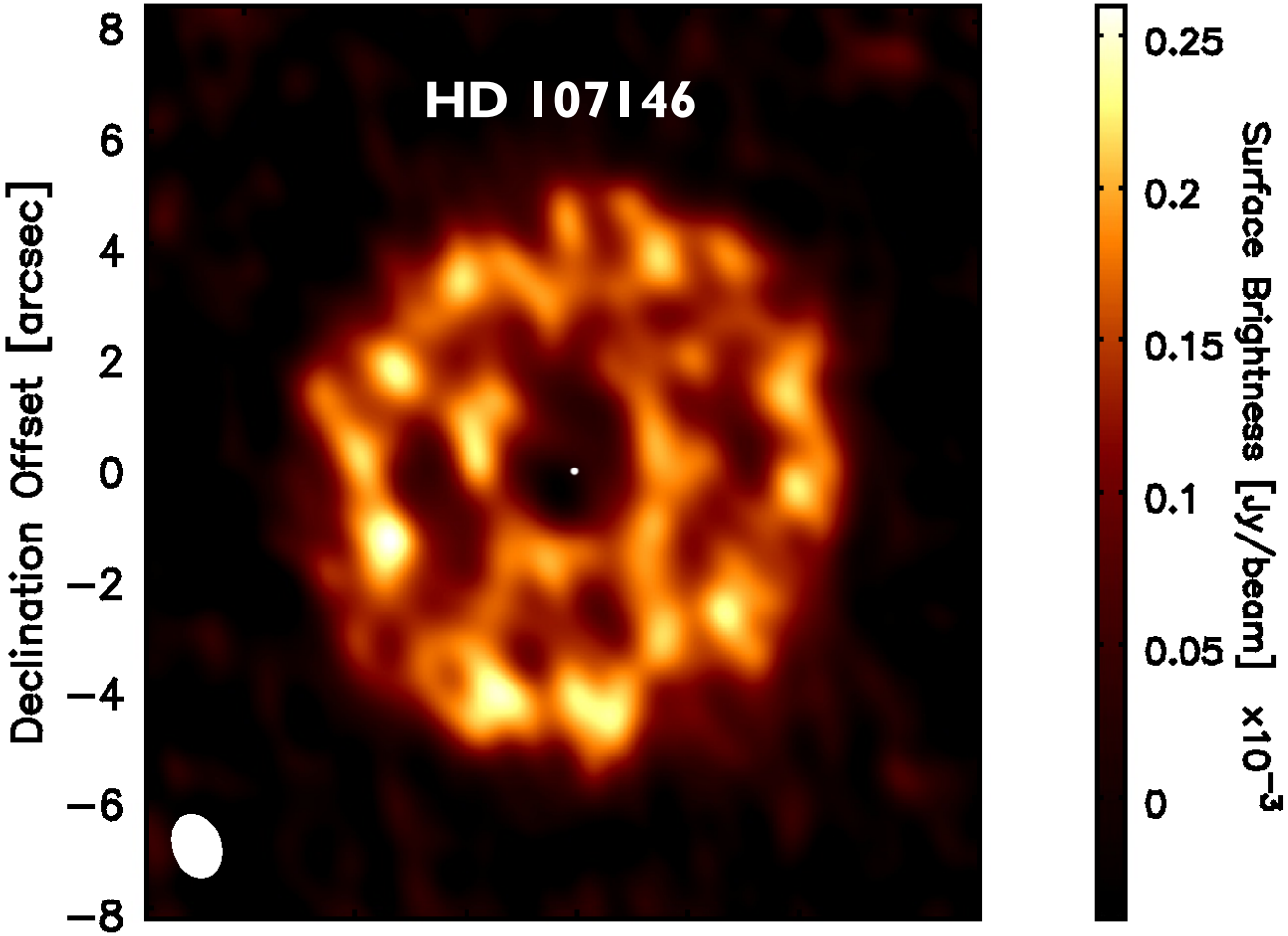

ngVLA Memo #6, "Cradle of Life," 2015; Credit: John Tobin

# Debris disks

# Debris disks – collisional models

Wilner

ngVLA will probe larger grains at high sensitivity, allowing tests of collisional models




Ricci+2014

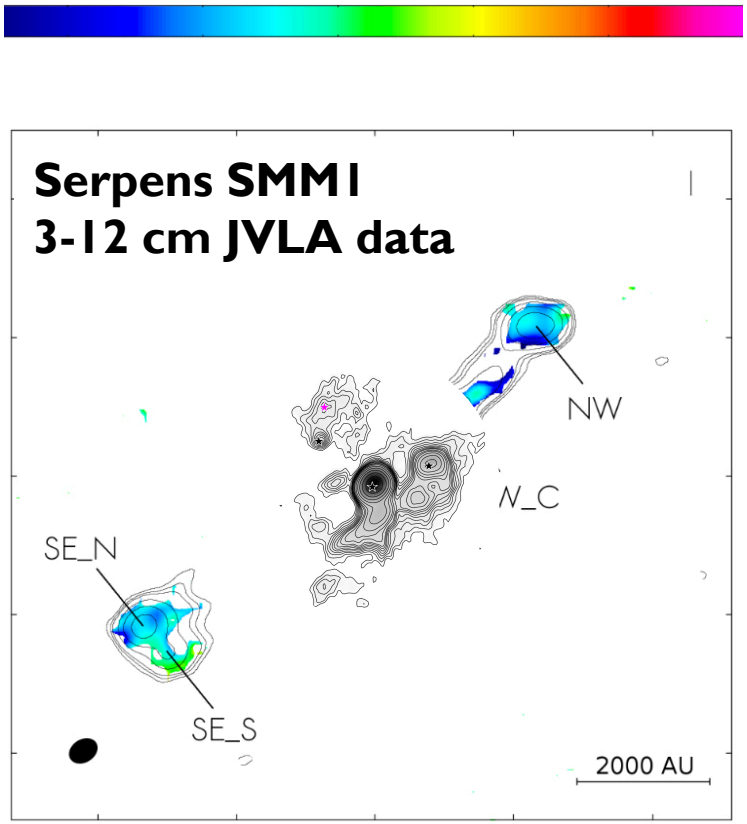
# Jets & Outflows

# Jets & outflows

Rodriguez

Spectral index

-0.4 0 0.4



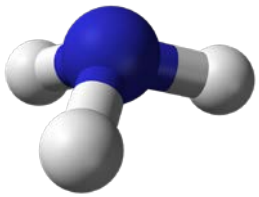

Rodriguez-Kamenetzky et al. (2016)
Overlay: **Hull**+2016, in prep

Higher **sensitivity** & **angular resolution** will open doors:

- Acceleration and collimation mechanisms
- Binarity and multiplicity
- Time-series follow-up of discrete ejecta (for plane-of-sky velocity)
- Radio recombination lines (for radial velocity)
- Relativistic electron populations (core of jet is usually thermal, but lobes can be non-thermal – see left)
- Larger sample of sources is needed to understand correlations of radio emission with (1) age, (2) bolometric luminosity, and (3) jet momentum

# Chemistry

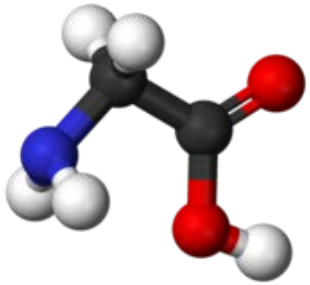
# Chemistry – chemical census in disks



**Ammonia (NH3)**

**Snow lines**

**"Complex" organic molecules**



Ammonia: newenergyandfuel.com
Snow: images.clipartpanda.com
Glycine: images-mediawiki-sites.thefullwiki.org

# Chemistry – chemical census in disks

- **$NH_3$** : the most important N-bearing molecule
  - Critical thermometer!

- Probing the $NH_3$ (and thus $H_2O$) **snow lines**

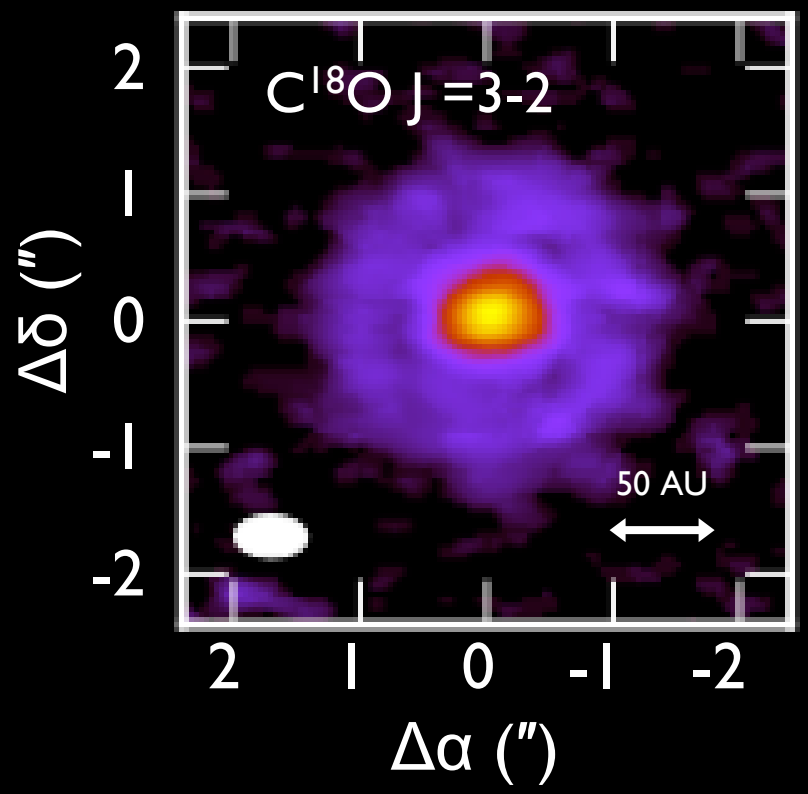
- Very **complex organic molecules**
  - E.g., glycine
  - Less line crowding at centimeter wavelengths
  - Performing census of complex material present where planets form

- Observe **volatiles** in regions optically thick at ALMA wavelengths

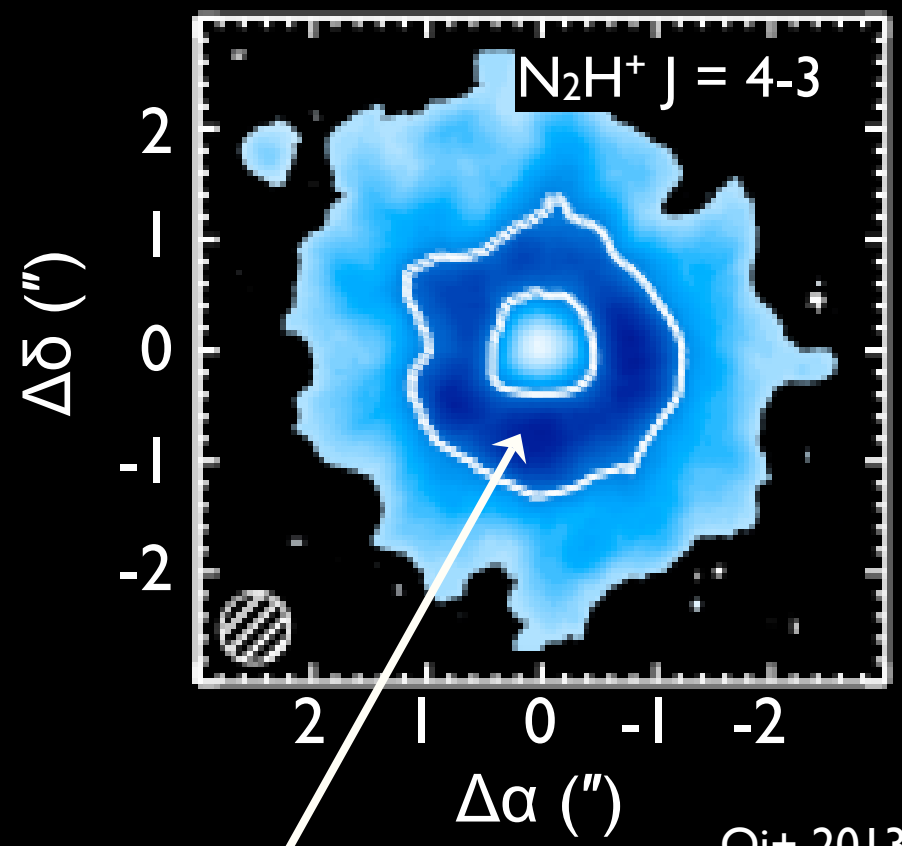
- Can observe lower-temperature lines to probe **ice-phase chemistry**

# TW Hya CO snow line

$N_2H^+ + CO \Rightarrow N_2 + HCO^+$




Schwarz+ 2015, in prep.




Qi+ 2013

**Need the ngVLA to probe $NH_3$ inside the CO snow line**

Slide credit: Ted Bergin

# Chemistry – chasing the $H_2O$ snow line

**Location**

- Close to the star ($T_{dust}$ ~ 200 K)
- Inner 1–3 AU

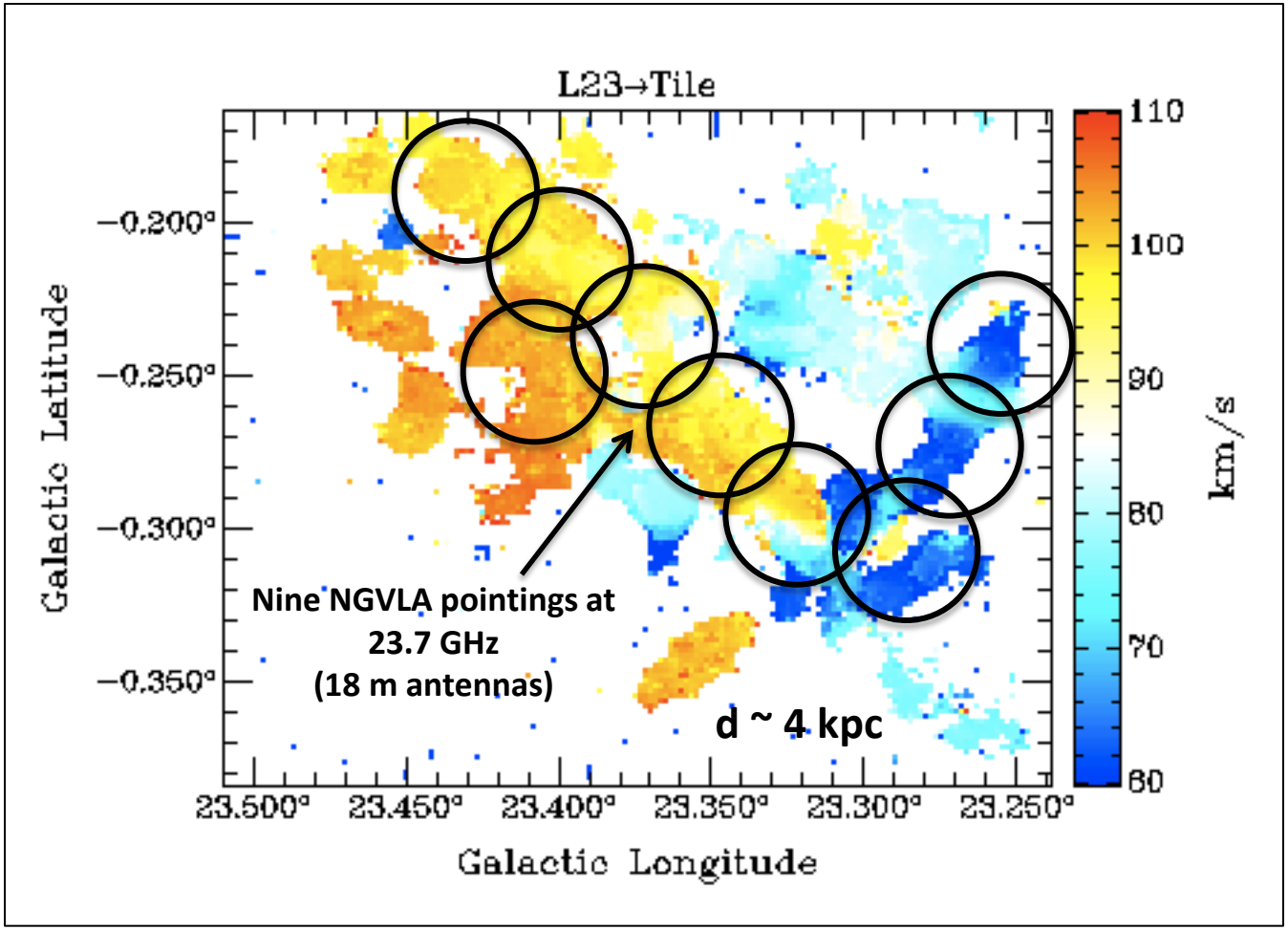
**Method**

- Probe with **$NH_3$** transitions!
- Ammonia and water evaporate under the same conditions

# Chemistry – $NH_3$ in star-forming filaments

Di Francesco

## $NH_3$ first moment map of L23 field




Courtesy: T. Hogge, J. Jackson; slide: J. Di Francesco

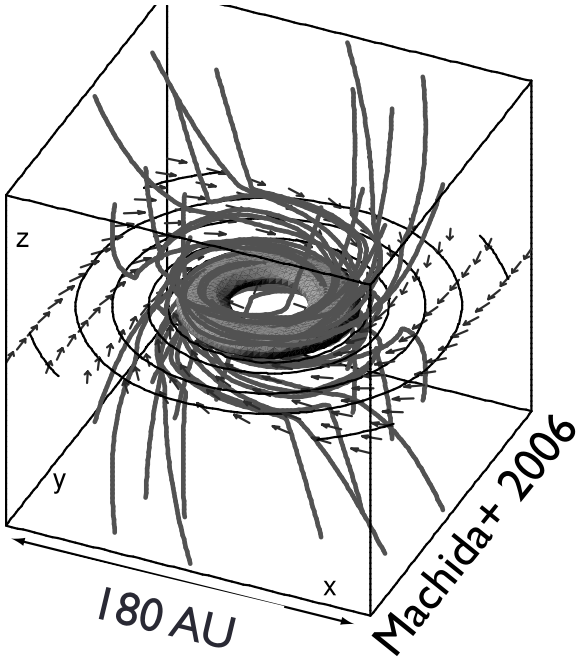
# Polarization

# Polarization – B-fields on ~100 AU scales?

1 pc

0.1 pc

?

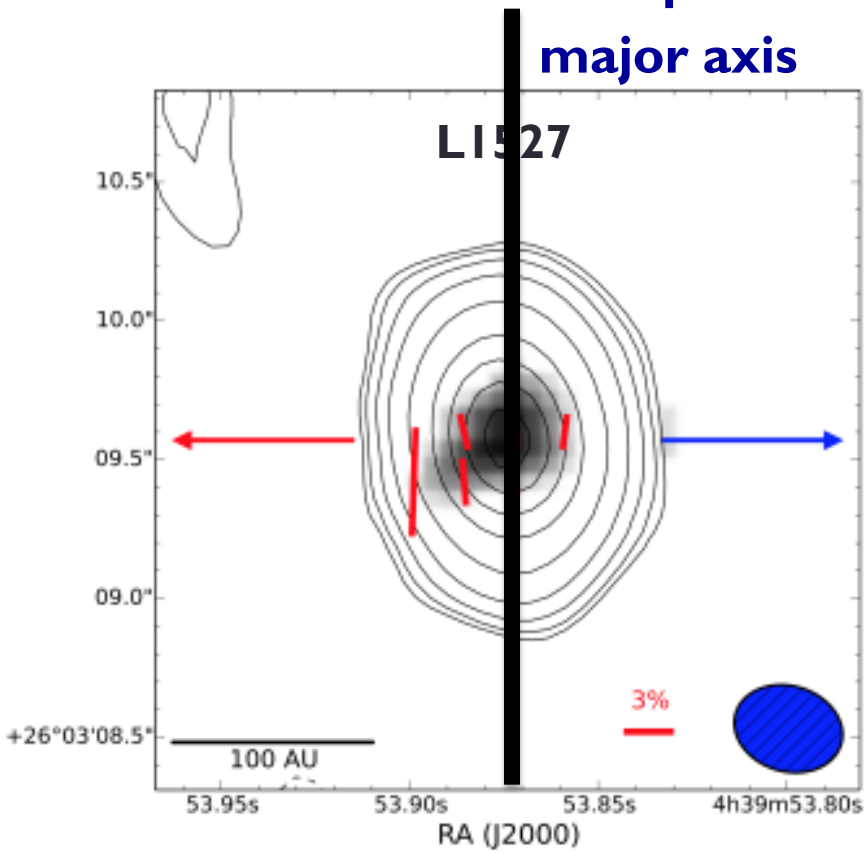



**1000 AU**

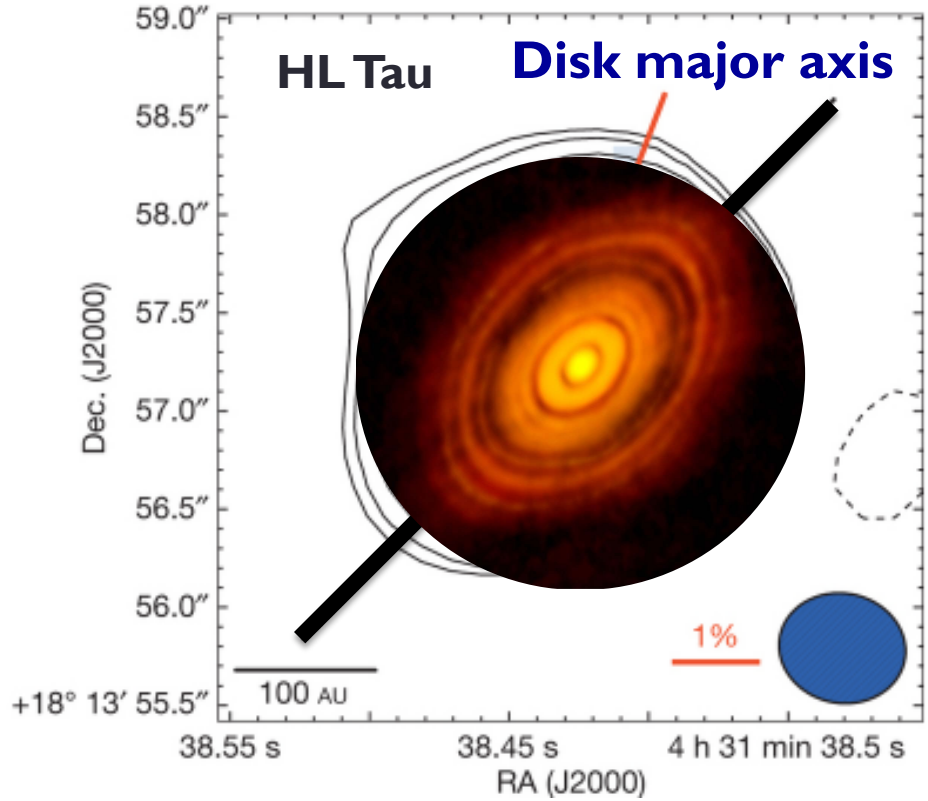
**100 AU**

CARMA/SMA +
ALMA/ngVLA

# Polarization – B-fields on ~100 AU scales?




Segura-Cox+2015

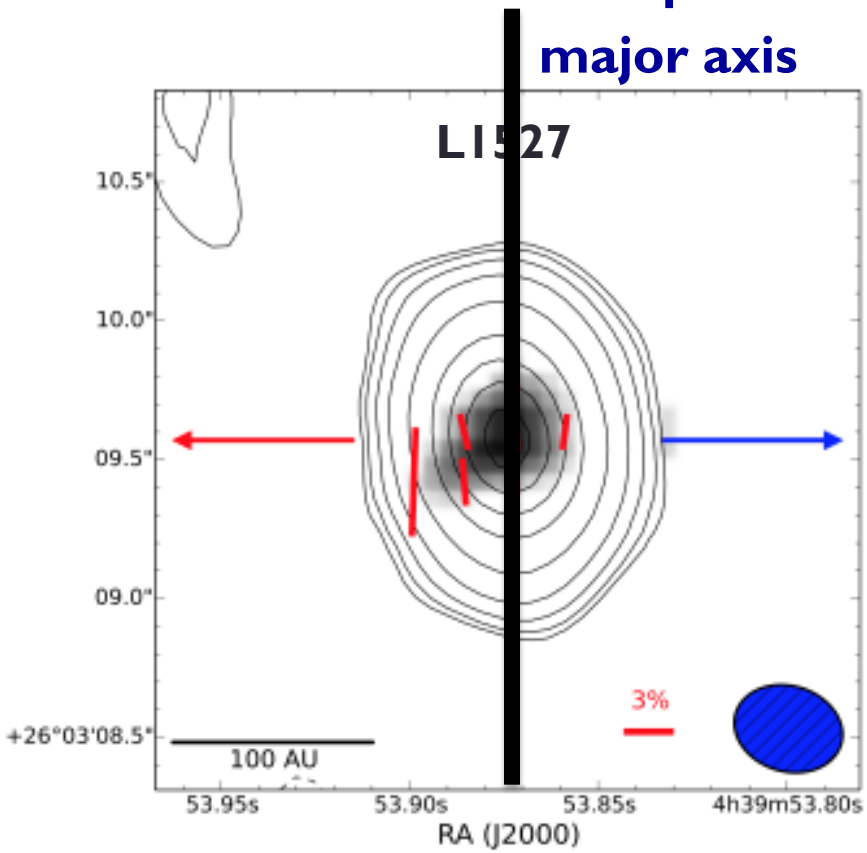



Stephens+2014

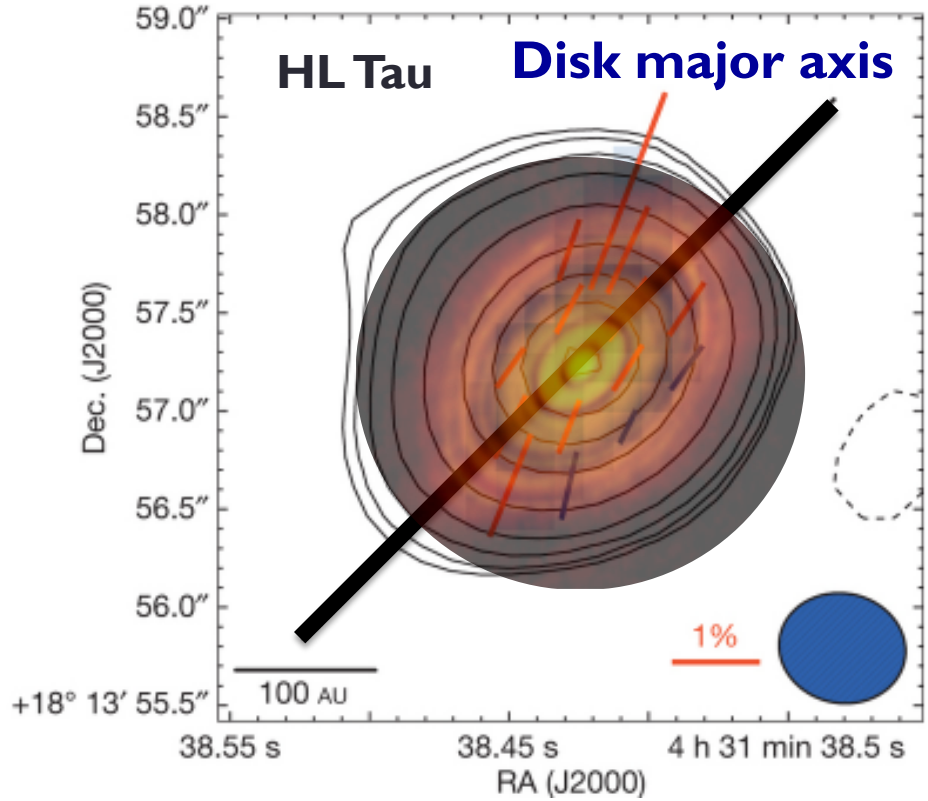
Overlay: ALMA Collaboration 2015

B-fields appear to be predominantly **toroidal**

# Polarization – B-fields on ~100 AU scales?




Segura-Cox+2015




Stephens+2014

Overlay: ALMA Collaboration 2015

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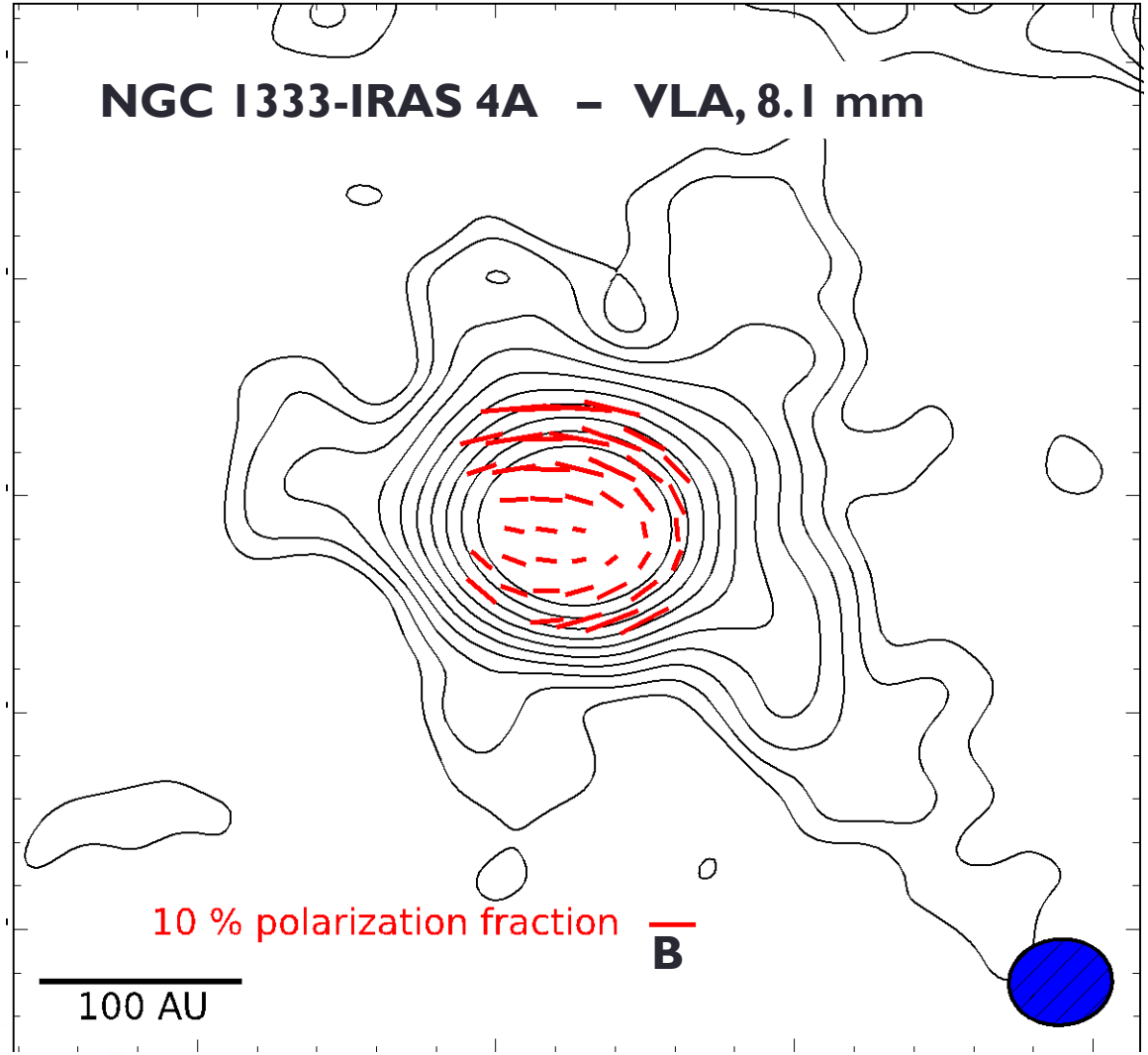
# Polarization – B-fields

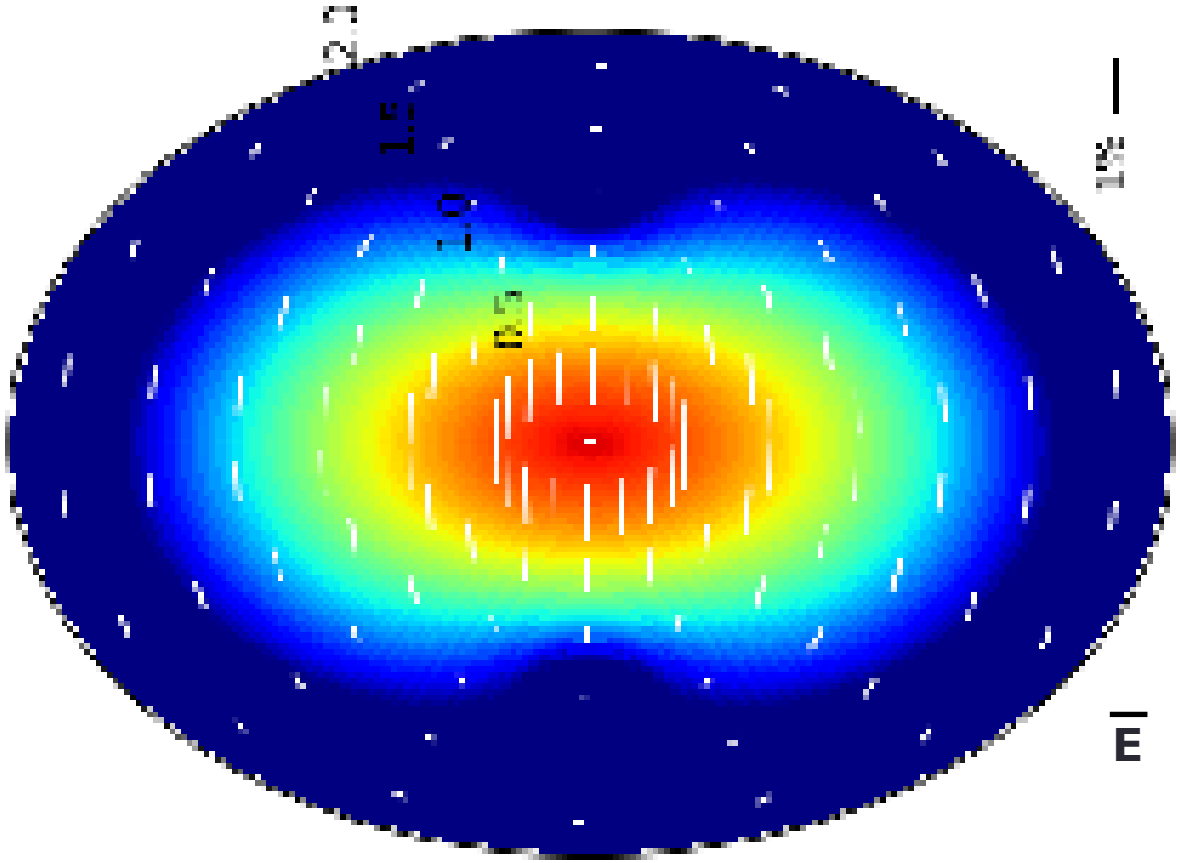



Cox+2015

- Larger grains
- High resolution
- Low optical depth

# Polarization – mm-wave scattering?

High optical depth at high resolution could lead to polarization from scattering instead of from dust-grain alignment

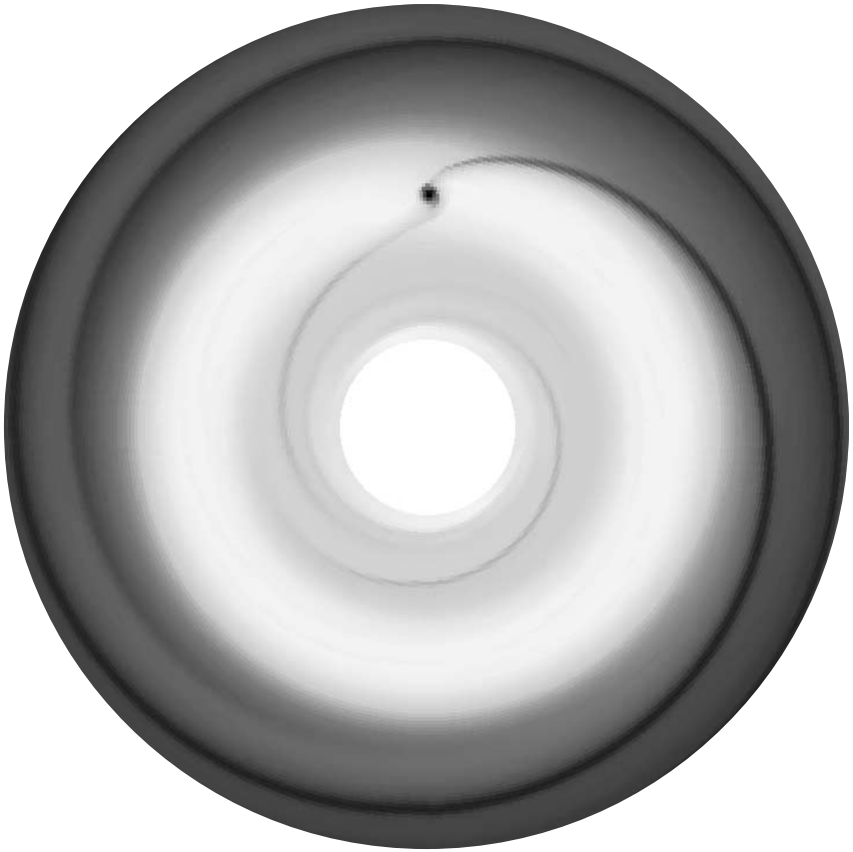



Yang+2015
See also Kataoka 2015a, 2015b

# Time Domain

# Time domain – planet-forming regions

The ngVLA could potentially make **time-lapse movies** of orbiting material in the planet-forming regions of disks



Wolf & D'Angelo 2005

# Time domain – SETI

## Emission mechanisms

- Light sails (left)
- Interplanetary radar
- Long-range aircraft radar
- High-power TV & radio

Guillochon & Loeb 2015

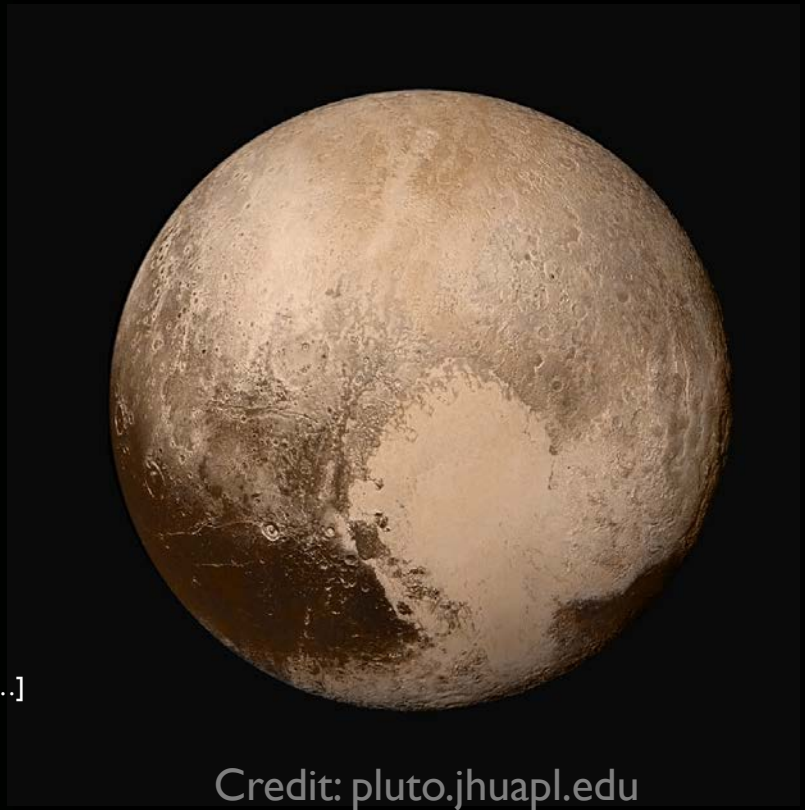
# Solar System

# Solar system – Pluto & Ceres

CERES ♀

[not to scale…]

PLUTO

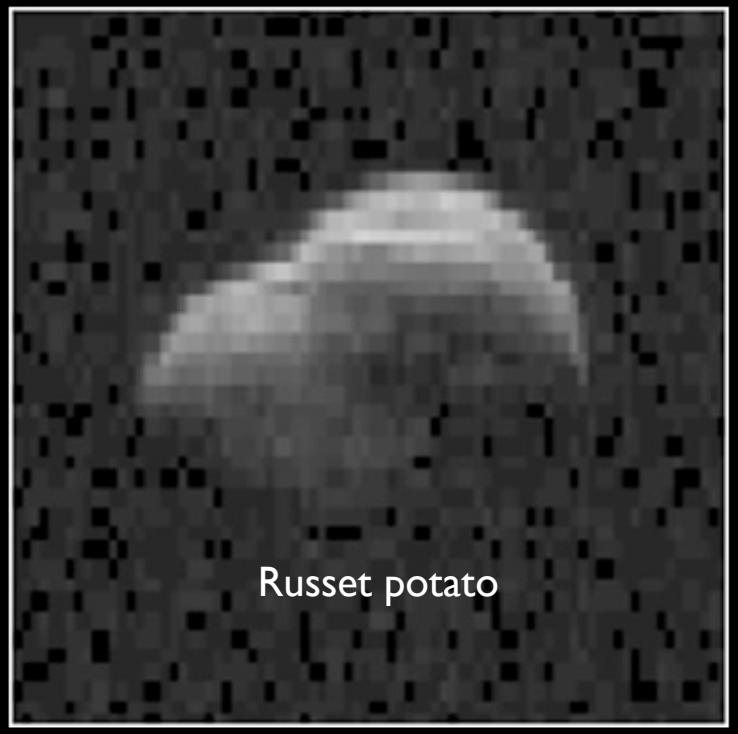


Credit: space-facts.com/ceres-pluto-dwarf-planet-gifs

Credit: pluto.jhuapl.edu

New images show evidence of active processes.
Need to understand the subsurface temperature!

# Solar system – asteroid 1998 WT24




2001


2015

Credit: JPL/NASA

Improvements from 2001 → 2015: greater BW & using GBT as receiver. ngVLA is the next step.

# Solar system – Jupiter with the VLA

*"…VLA maps of Jupiter look very much like HST maps of Jupiter…"*

—Imke de Pater

# Summary

## TOPICS & PHENOMENA

Optical depth, debris disks, jets & outflows, chemistry, polarization, time domain, Solar System…

## ngVLA white papers

Overview: 2015 arXiv 1510.06438
**Cradle of Life: 2015 arXiv 1510.06444**
Galaxy Assembly through Cosmic Time: 2015 arXiv 1510.06411
Time Domain, Fundamental Physics, and Cosmology: 2015 arXiv 1510.06432
"Galaxy Ecosystems": The Matter Cycle in and around Galaxies: 2015 arXiv 1510.06431

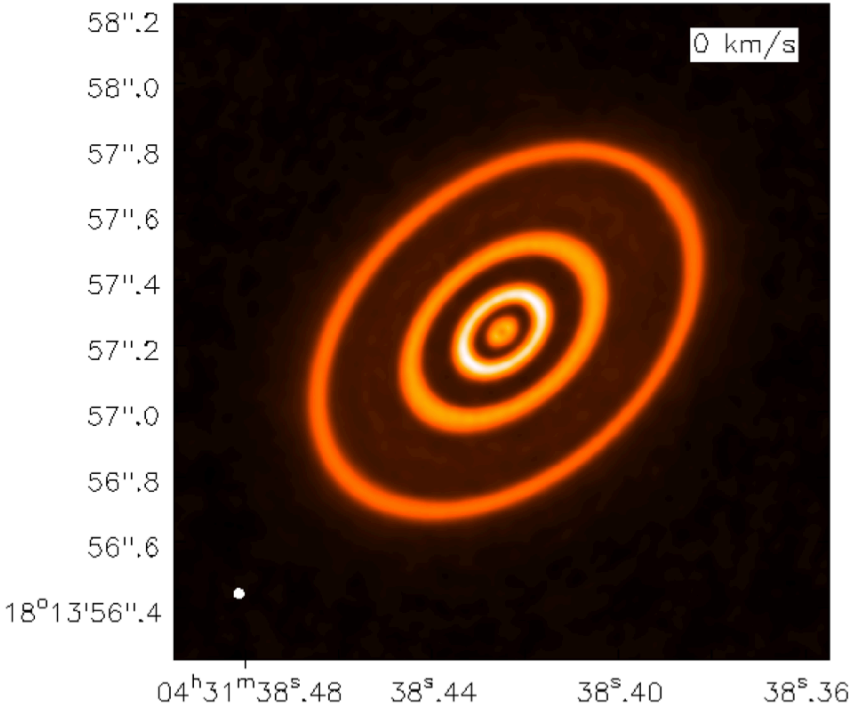
## ngVLA Memo Series

library.nrao.edu/ngvla.shtml

# Fin

# Optical depth – planet-forming regions

Isella



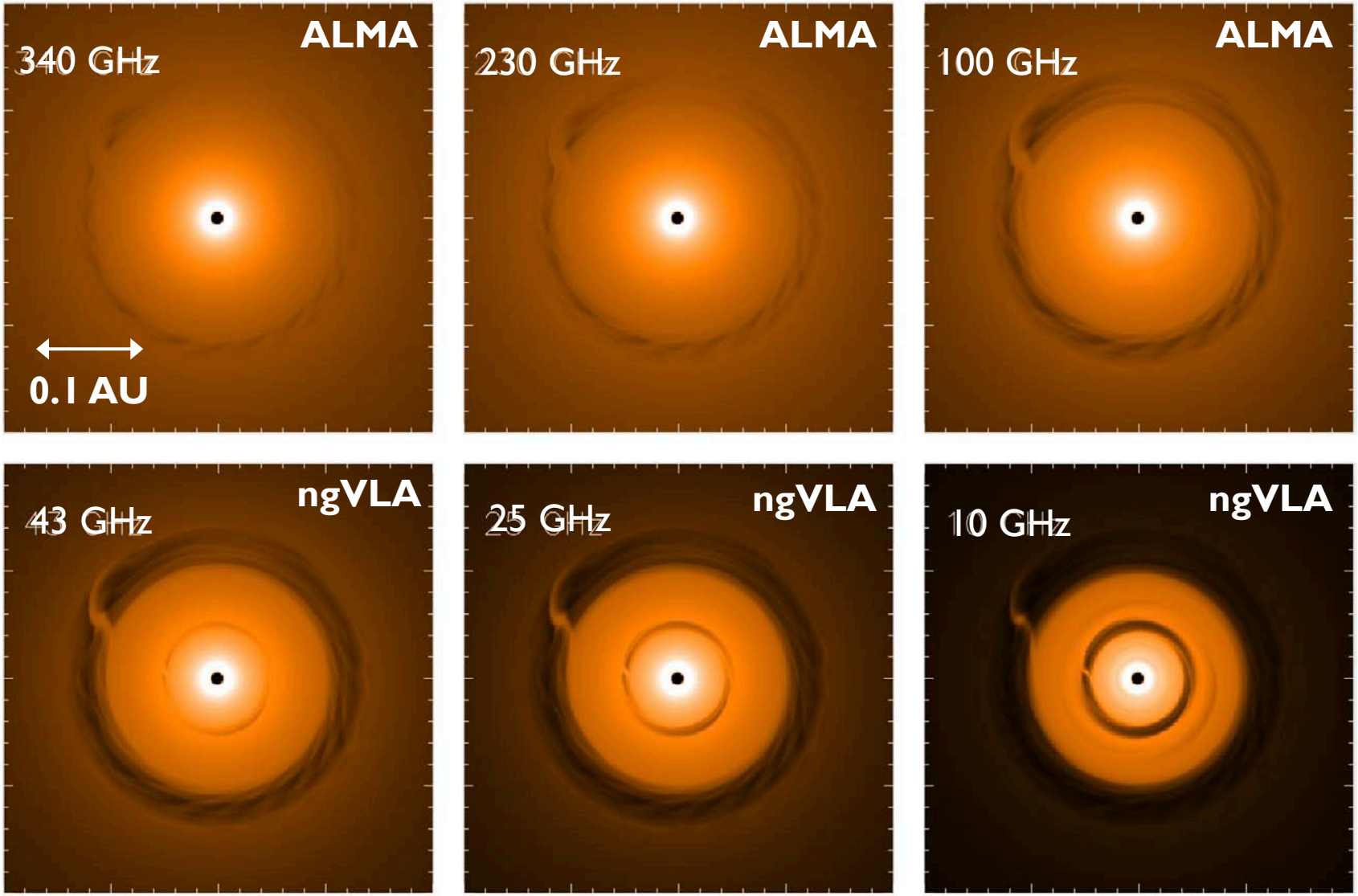

**Simulated observation (noise is included) at the wavelength of 1 cm. Angular resolution 0.025".**

Jin et al. (2016, ApJ submitted)

Credit: Andrea Isella

# Optical depth – planet-forming regions

Isella




ngVLA Memo #6, "Cradle of Life," 2015; Credit: Andrea Isella, Chris Carilli