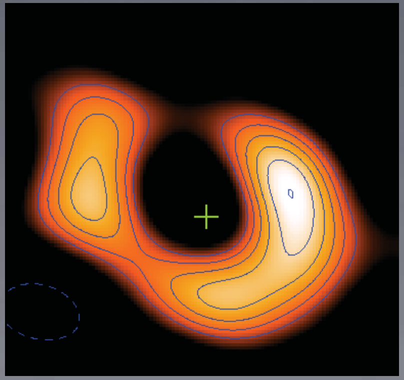
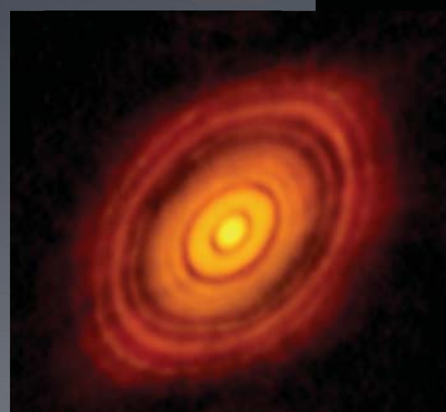



Outstanding problems in (star and) planet formation

Gregory J. Herczeg (沈雷歌)
KIAA/PKU

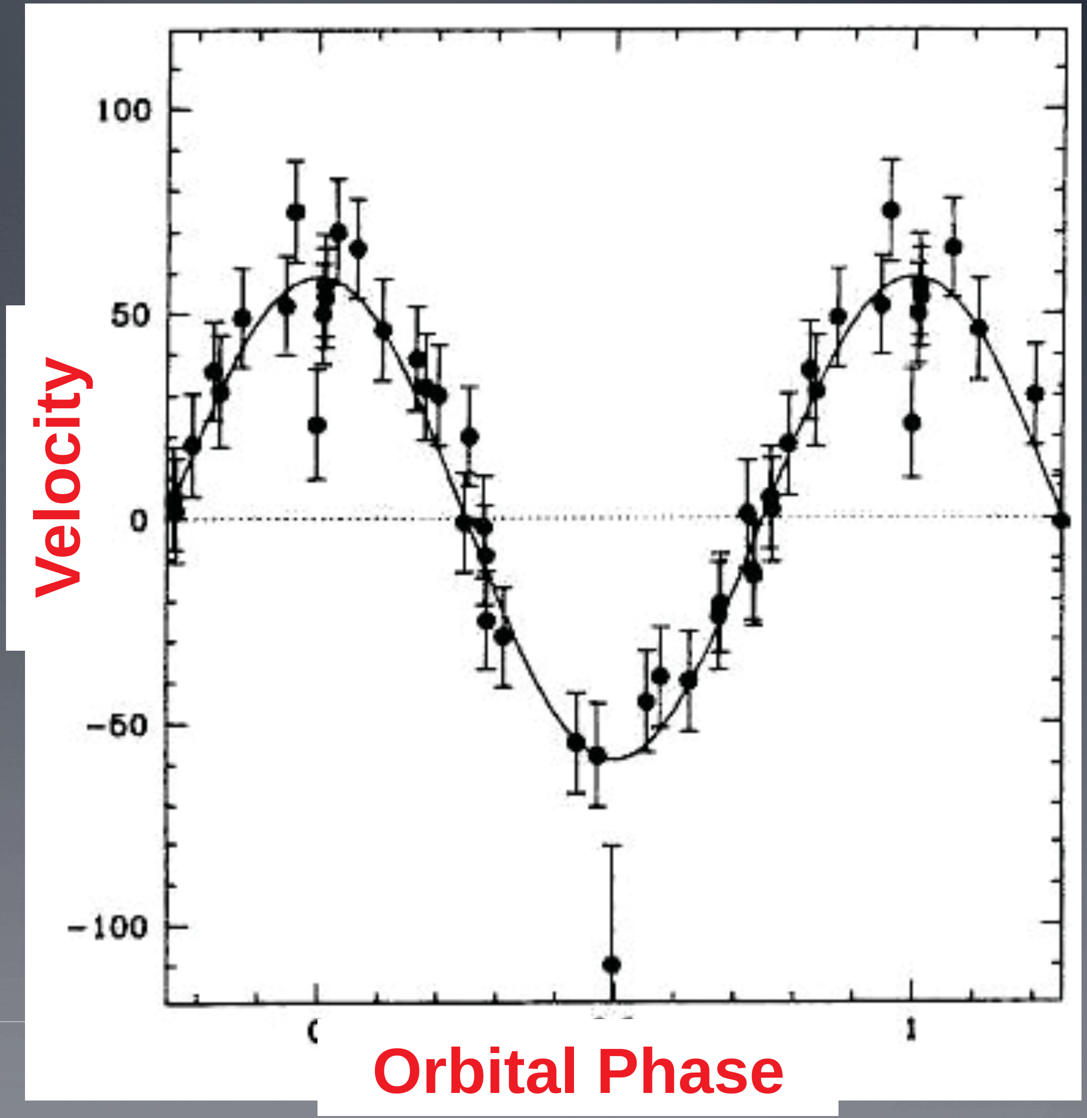




The last astrophysical step of our origins

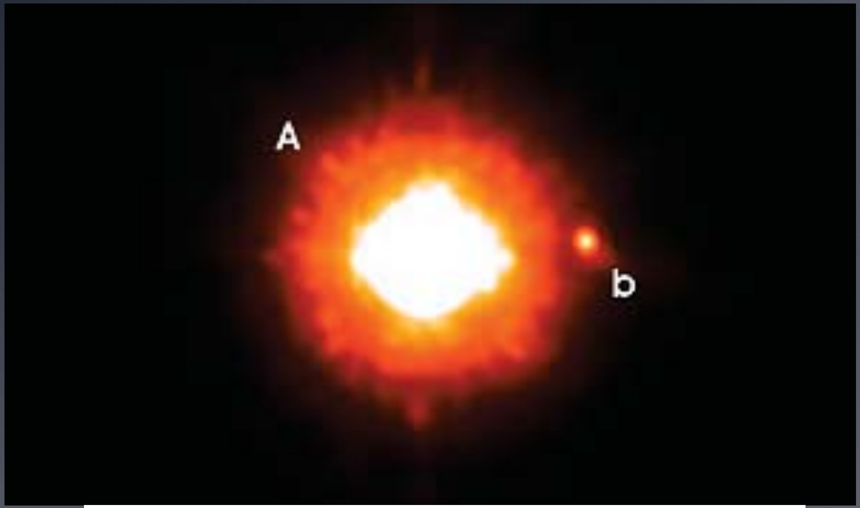


Planet detection methods

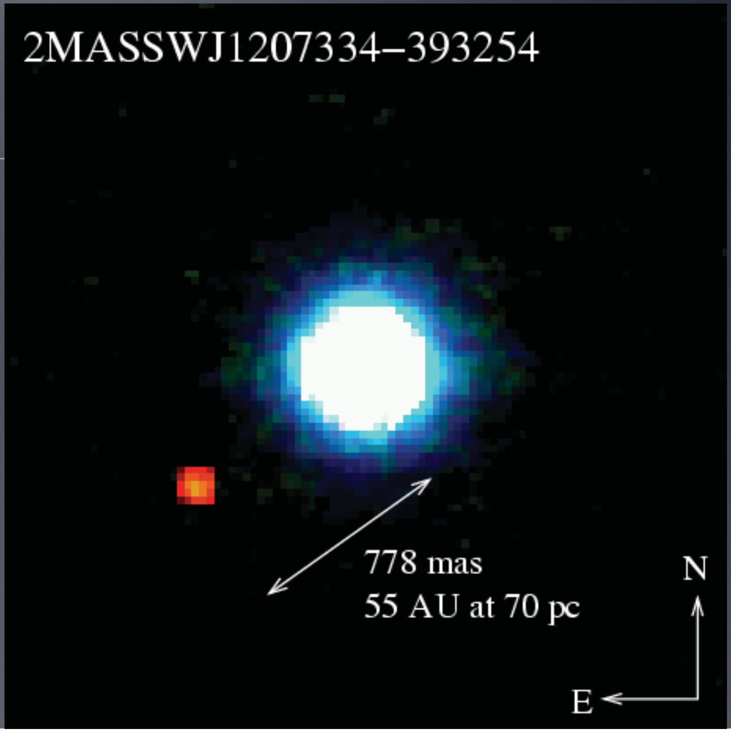
- Radial Velocity (eg Mayor et al.)
  - HARPS on 3.6m European telescope
- Planet transits – Kepler
- Direct detection – Marois et al.
  - Difficult
- Gravitational microlensing



First detections of planet-mass objects



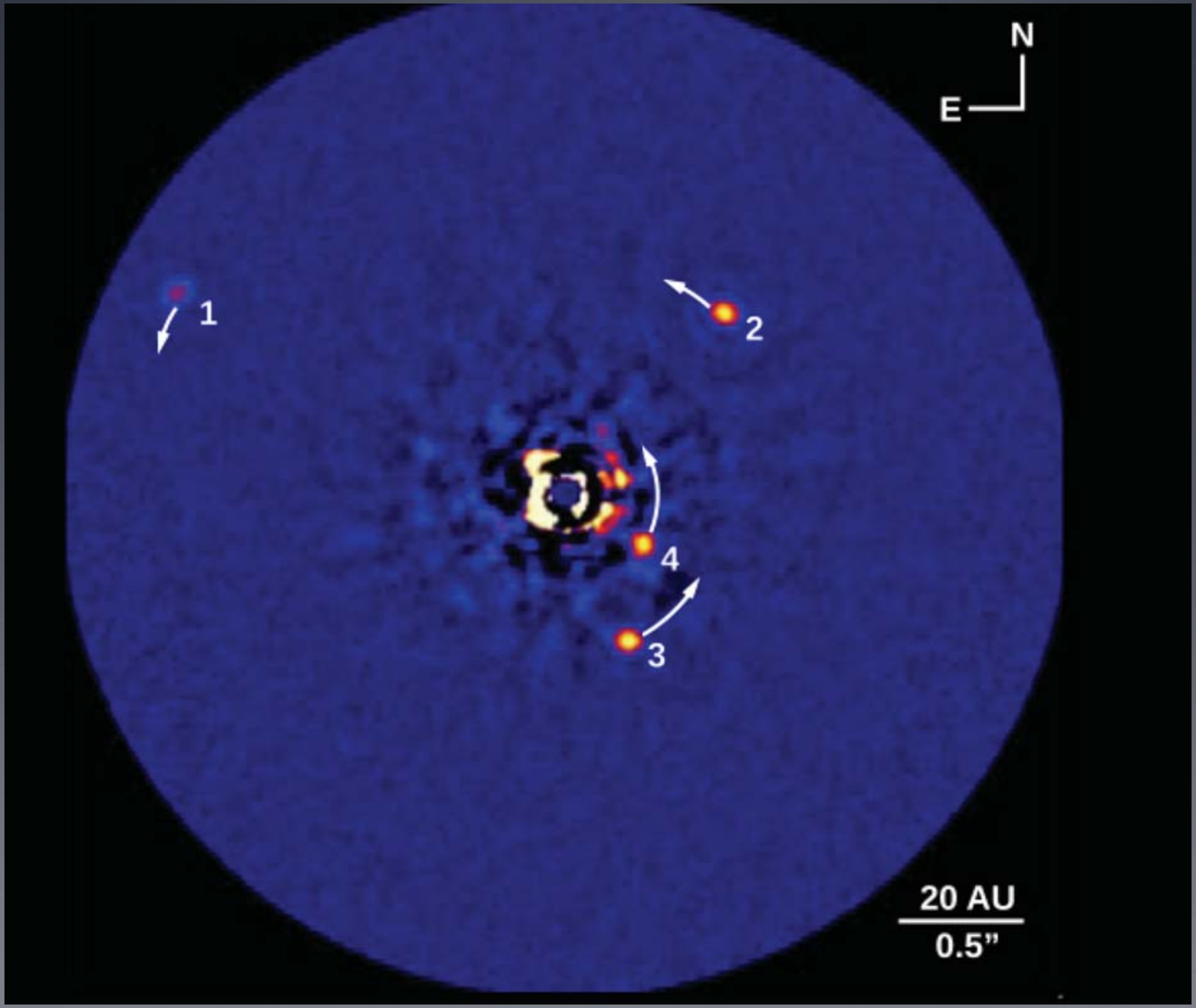
GQ Lup b: Guenther+2005
110 AU separation



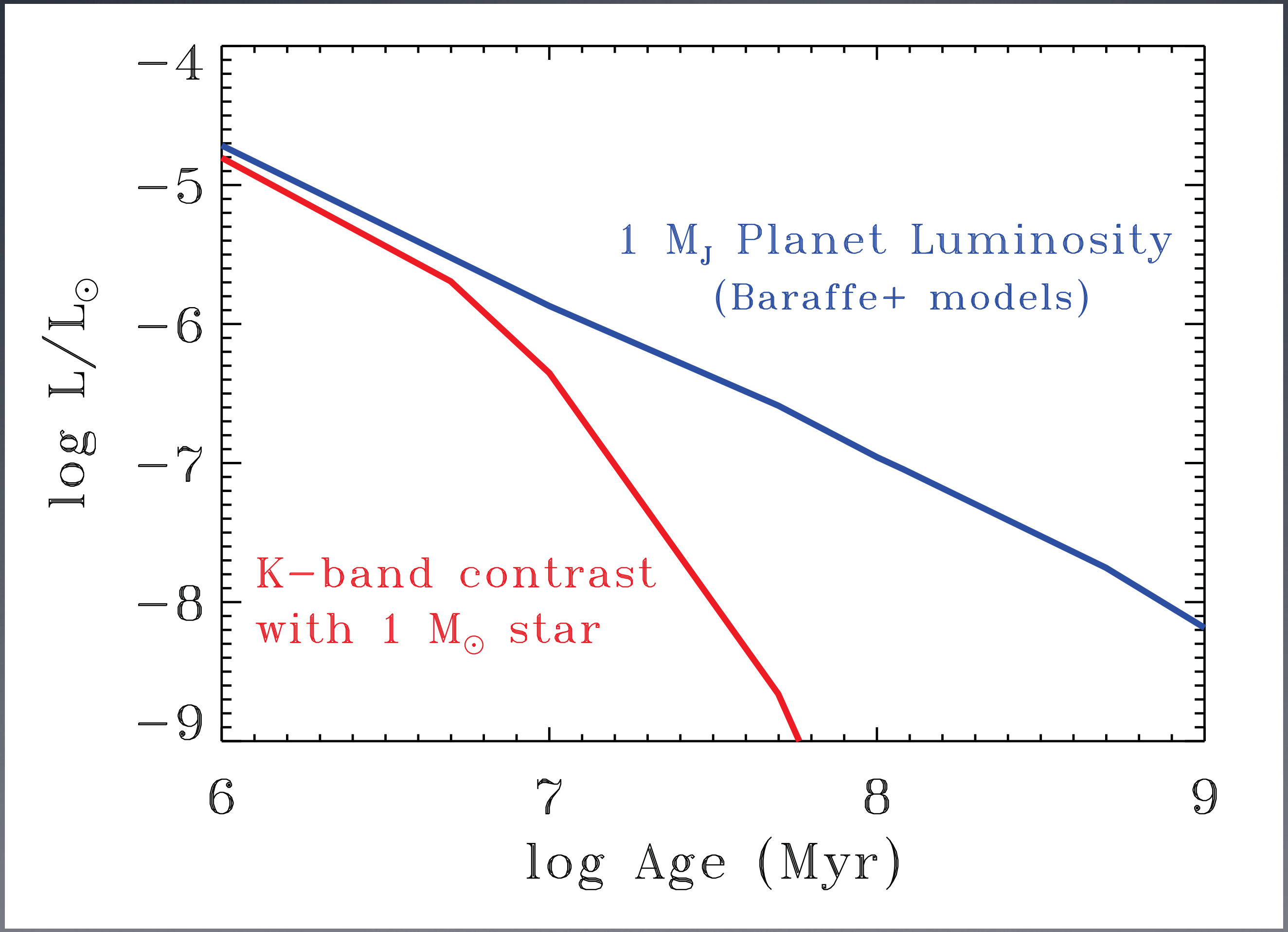
2M1207b: Chauvin+2005
primary is BD, 50 AU separation

Formation of wide binaries: wide separation may indicate binary fragmentation; scattering or disk gravitational instability also possible

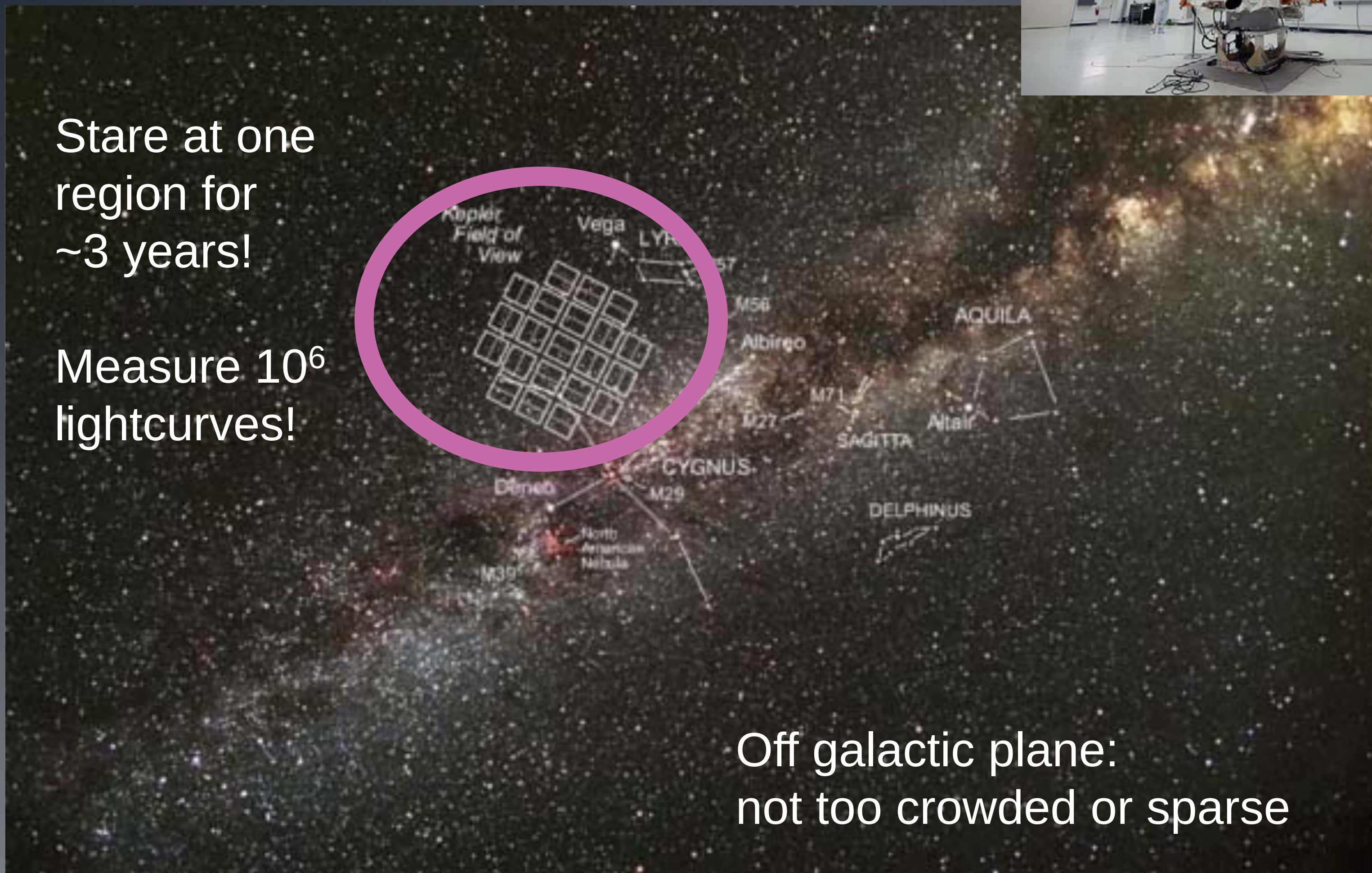
Direct Imaging: requires coronagraph to block out the star (similar to eclipse)



Young planets are bright (so targets/detections are all young)



Kepler Strategy

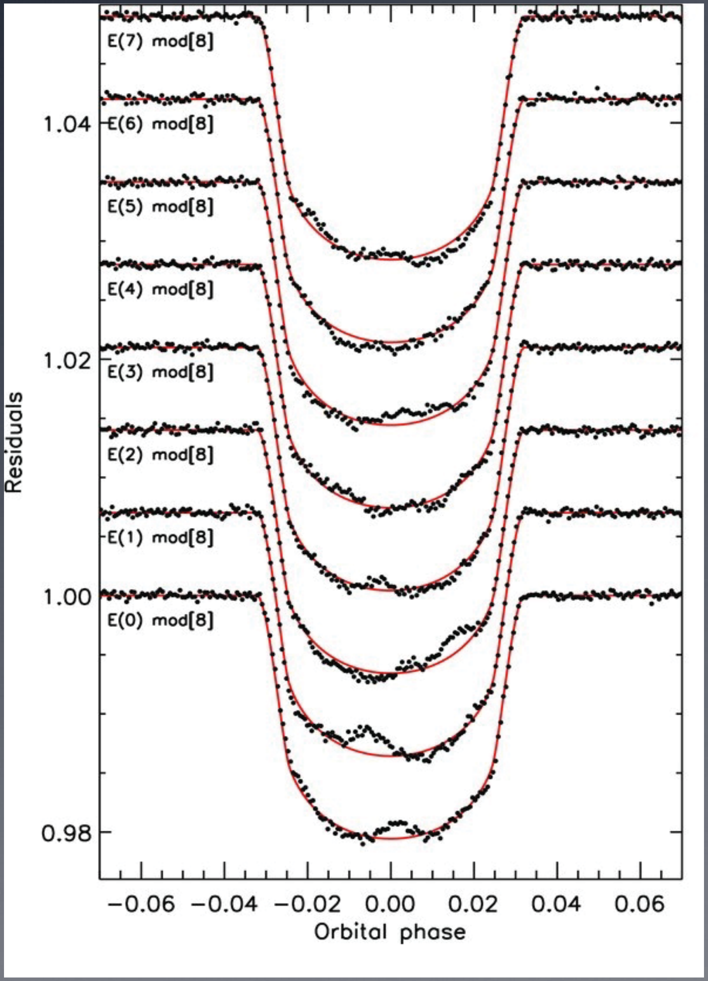


Stare at one region for ~3 years!

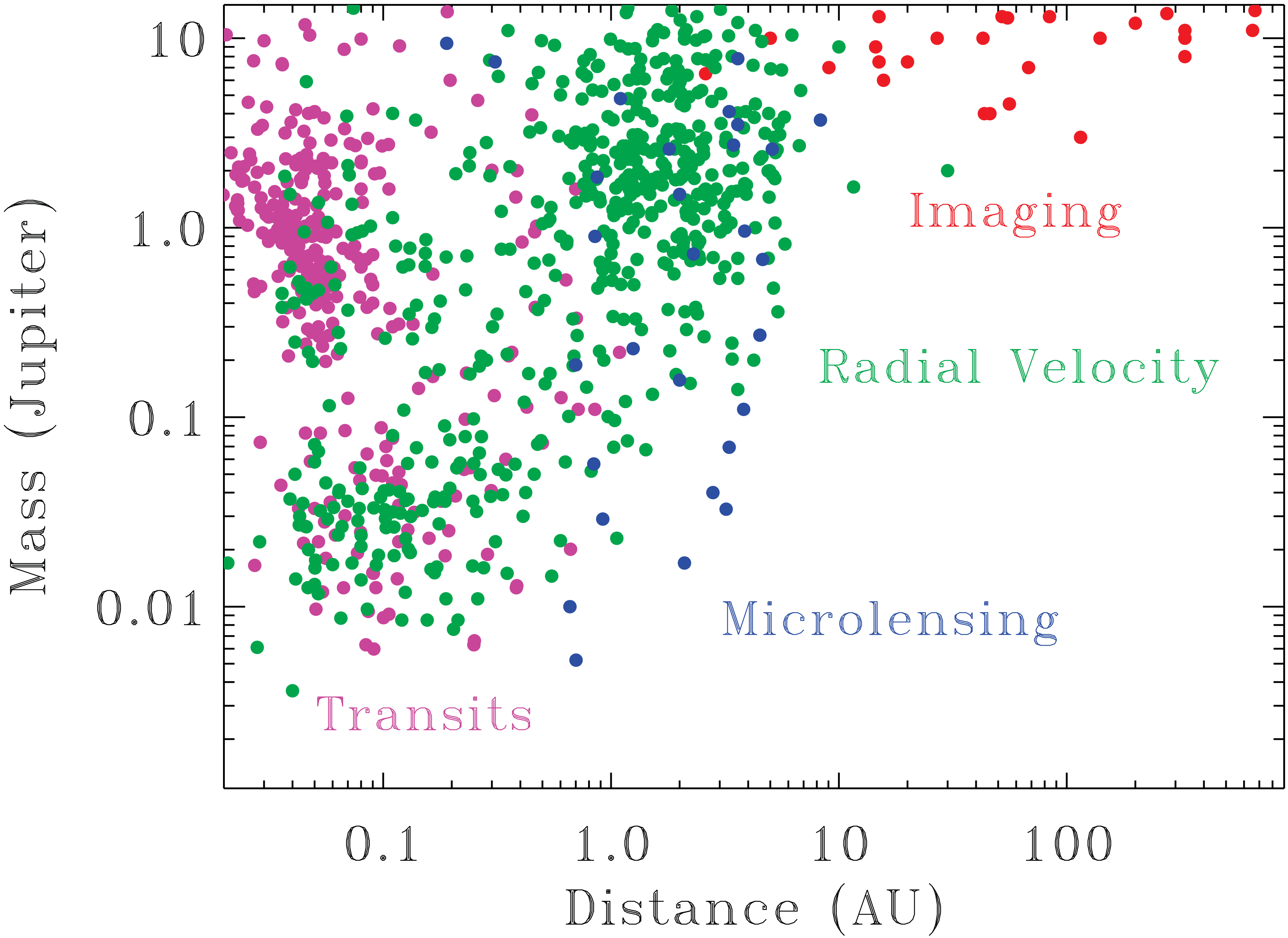
Measure 10^6 lightcurves!

Off galactic plane: not too crowded or sparse

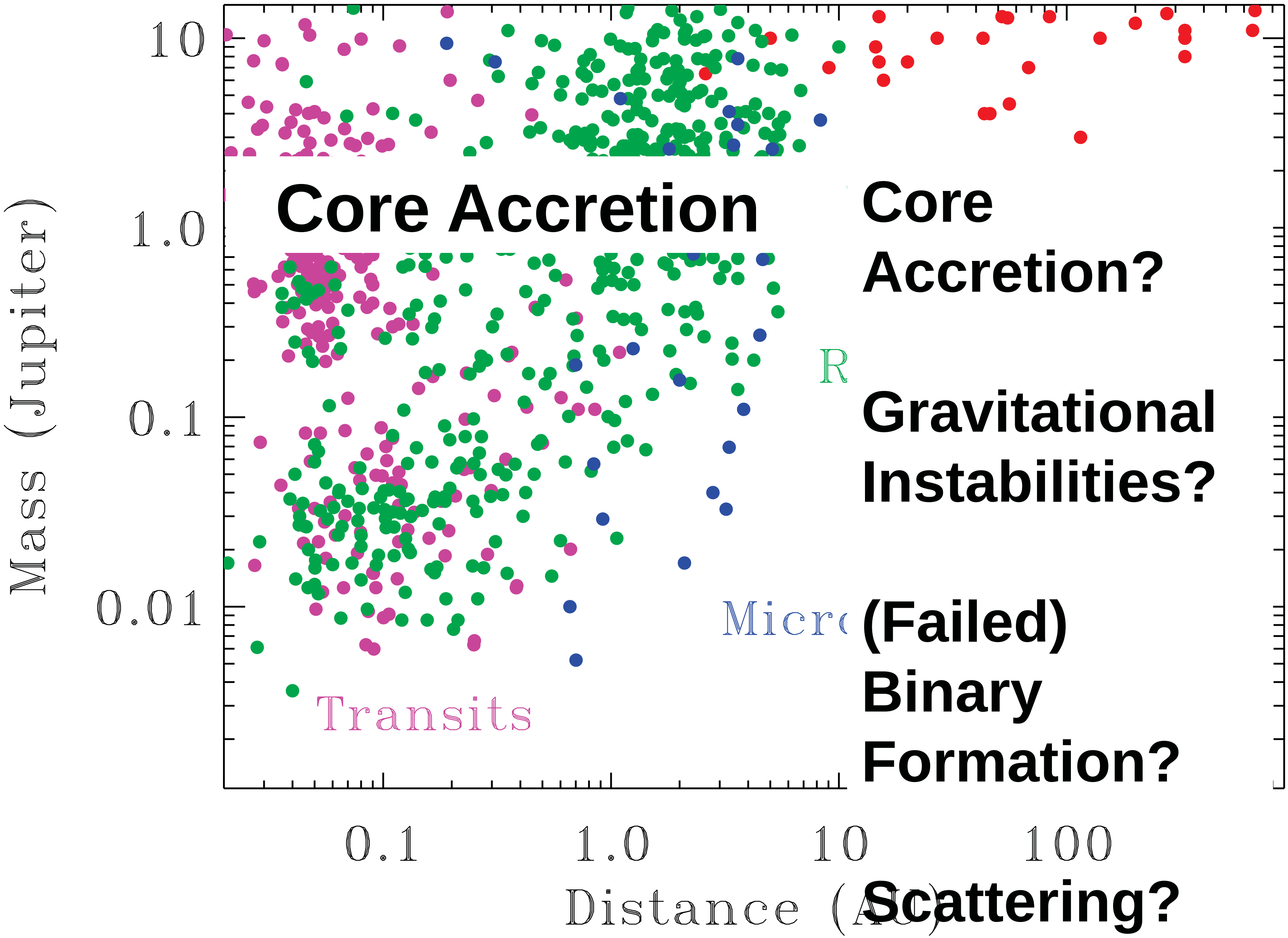
Kepler lightcurve
(Desert et al. 2011)



- Over 2000 planet candidates
  - Need ground-based follow-up confirmation
- Very high precision photometry (part per million)
- Look for moons, rings?
- Atmospheric composition!



Mass (Jupiter)
10
1.0
0.1
0.01
Imaging
Radial Velocity
Microlensing
Transits
0.1
1.0
10
100
Distance (AU)



Core Accretion

Core Accretion?

Gravitational Instabilities?

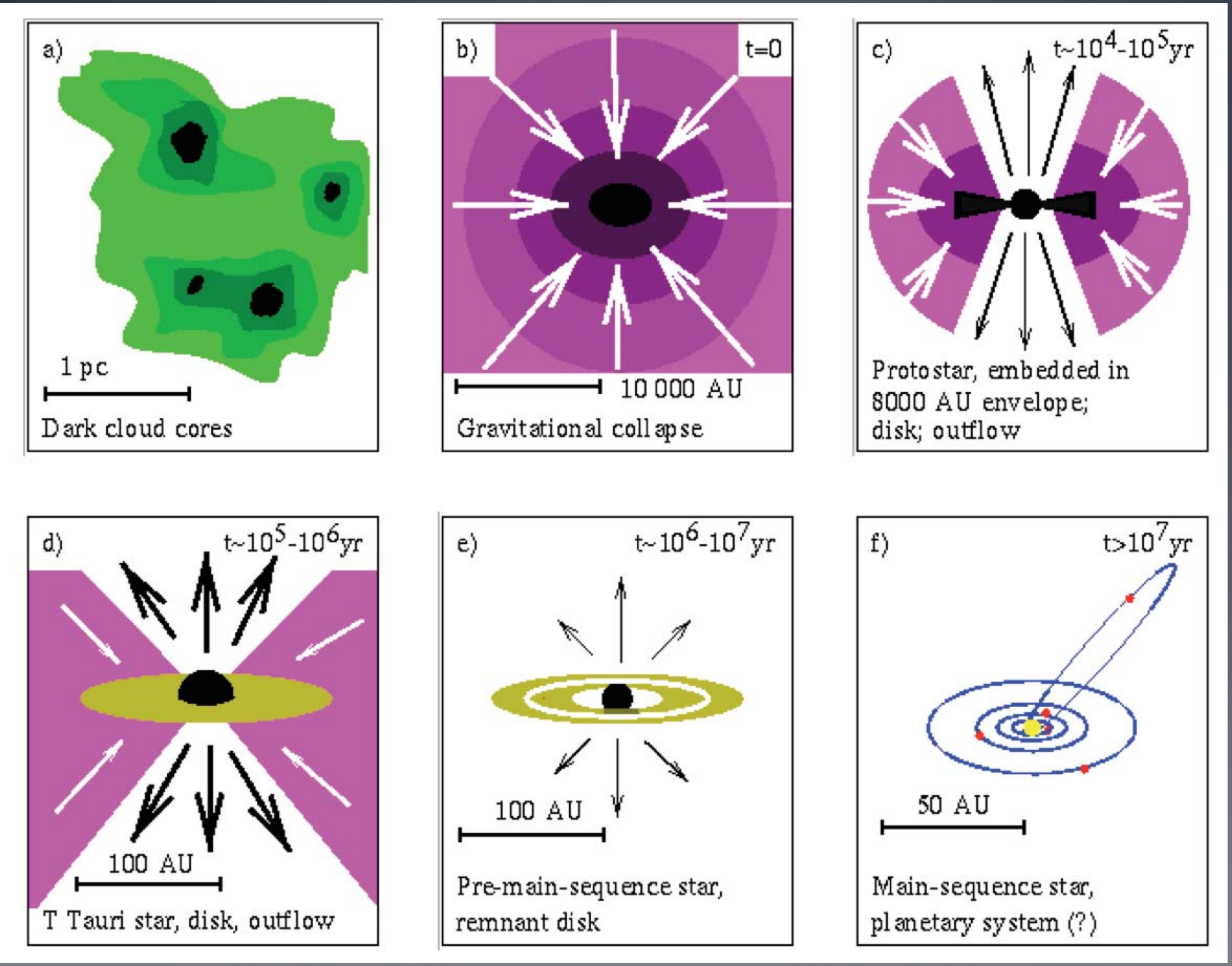
(Failed) Binary Formation?

Scattering?

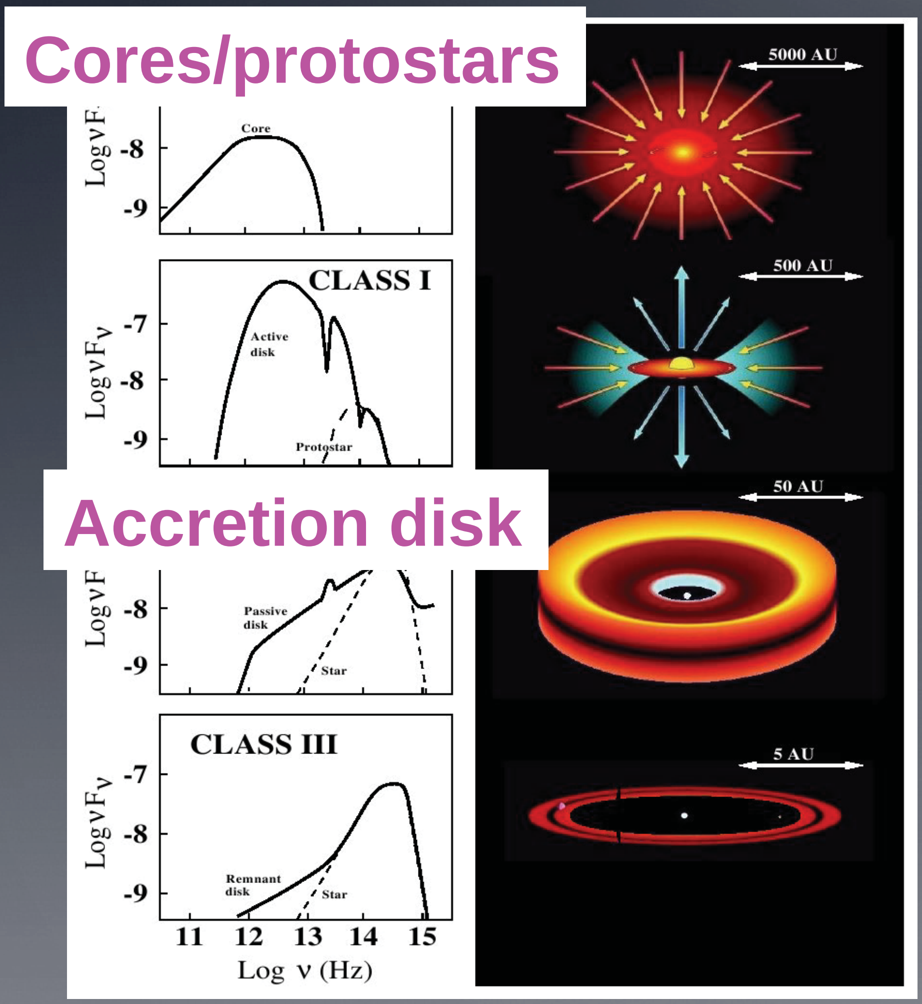
From interstellar clouds to planetary systems

Stars forming in molecular cloud

Evolution from clouds to planetary systems



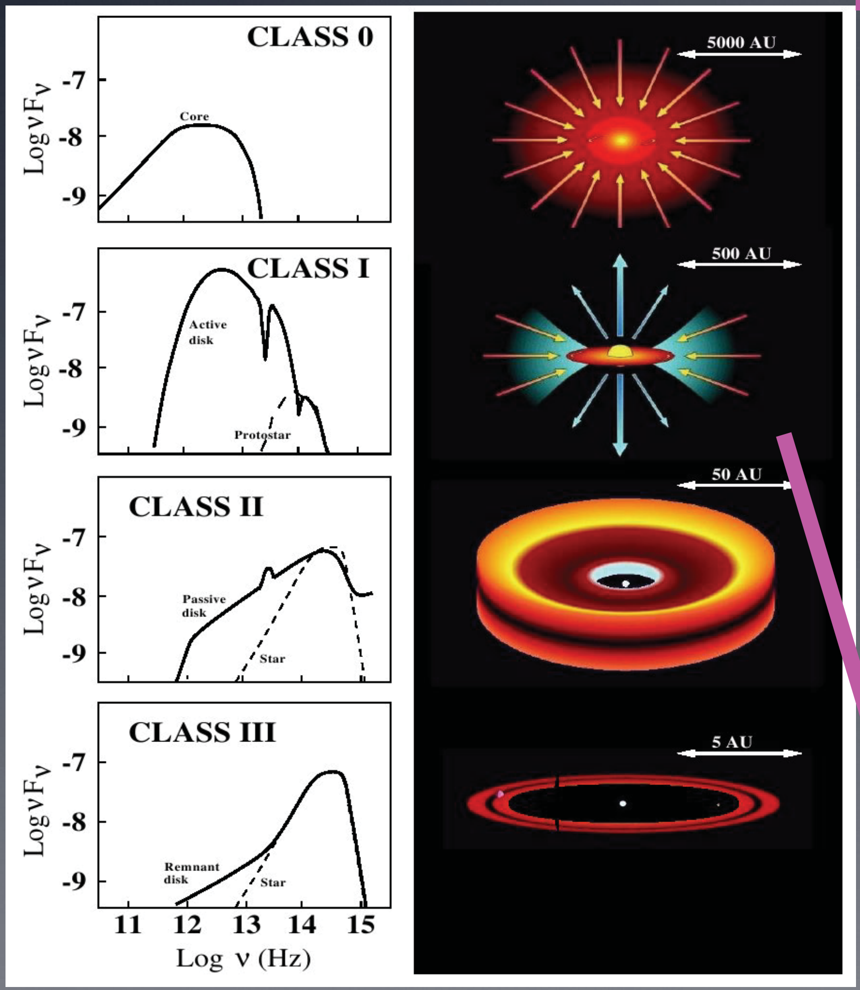
Pre-main sequence stellar evolution
Star forms inside an envelope

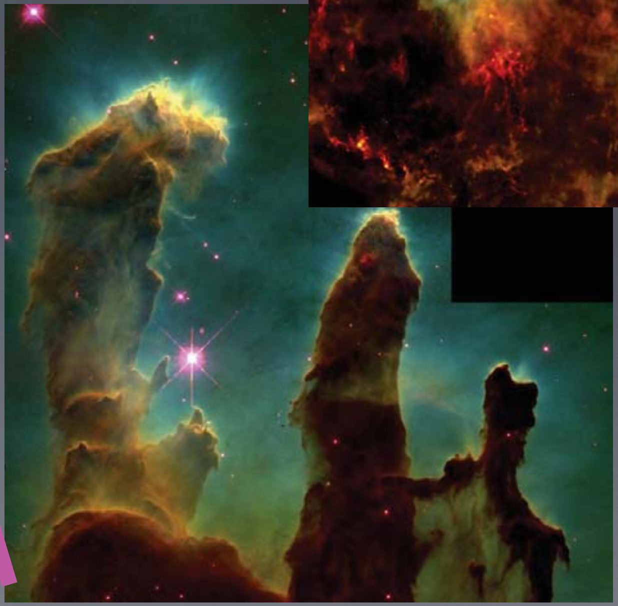


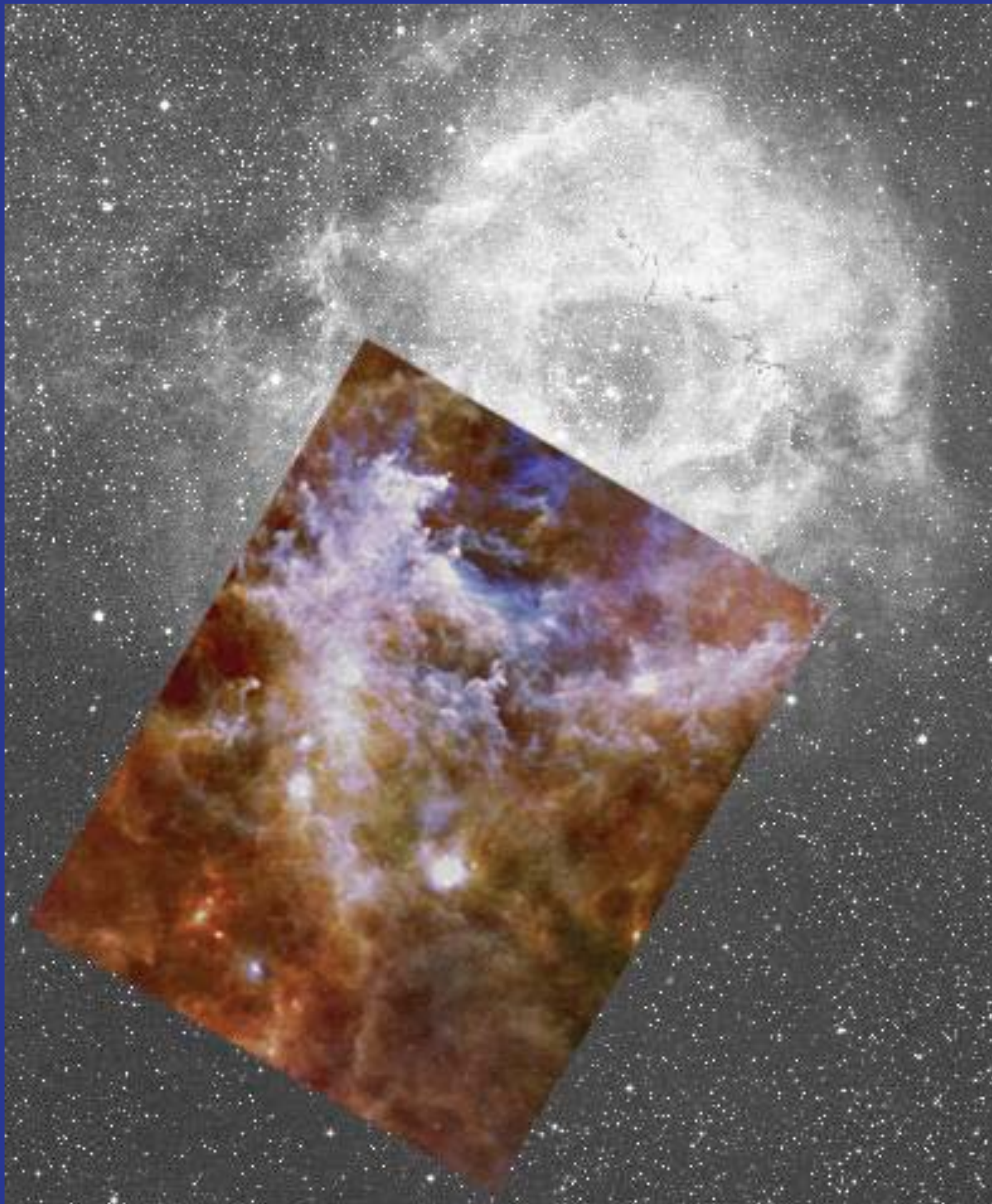
Young protostars surrounded by dust

Luminosity absorbed and re-radiated at long wavelengths

Pre-main sequence stellar evolution
Star forms inside an envelope



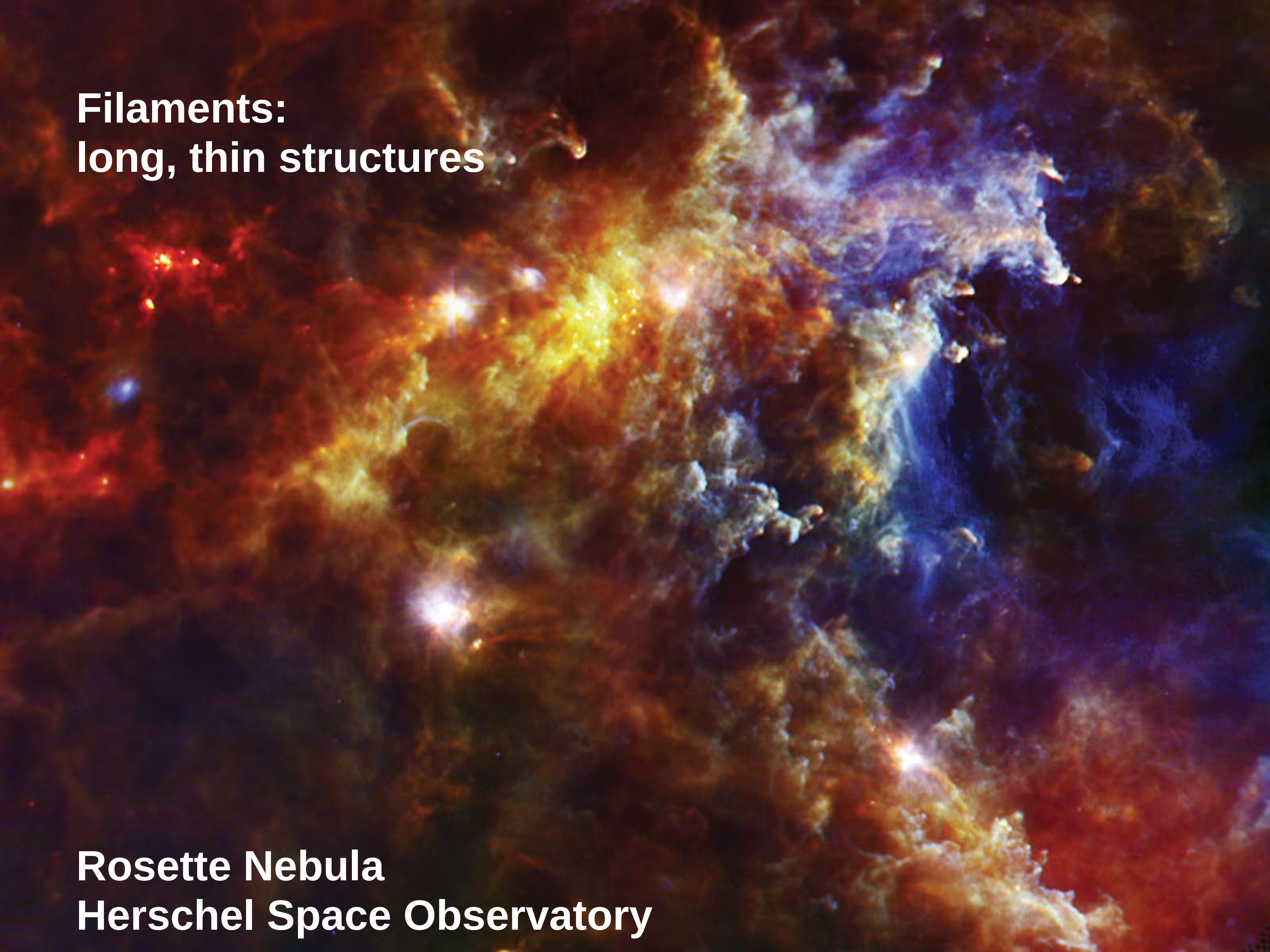




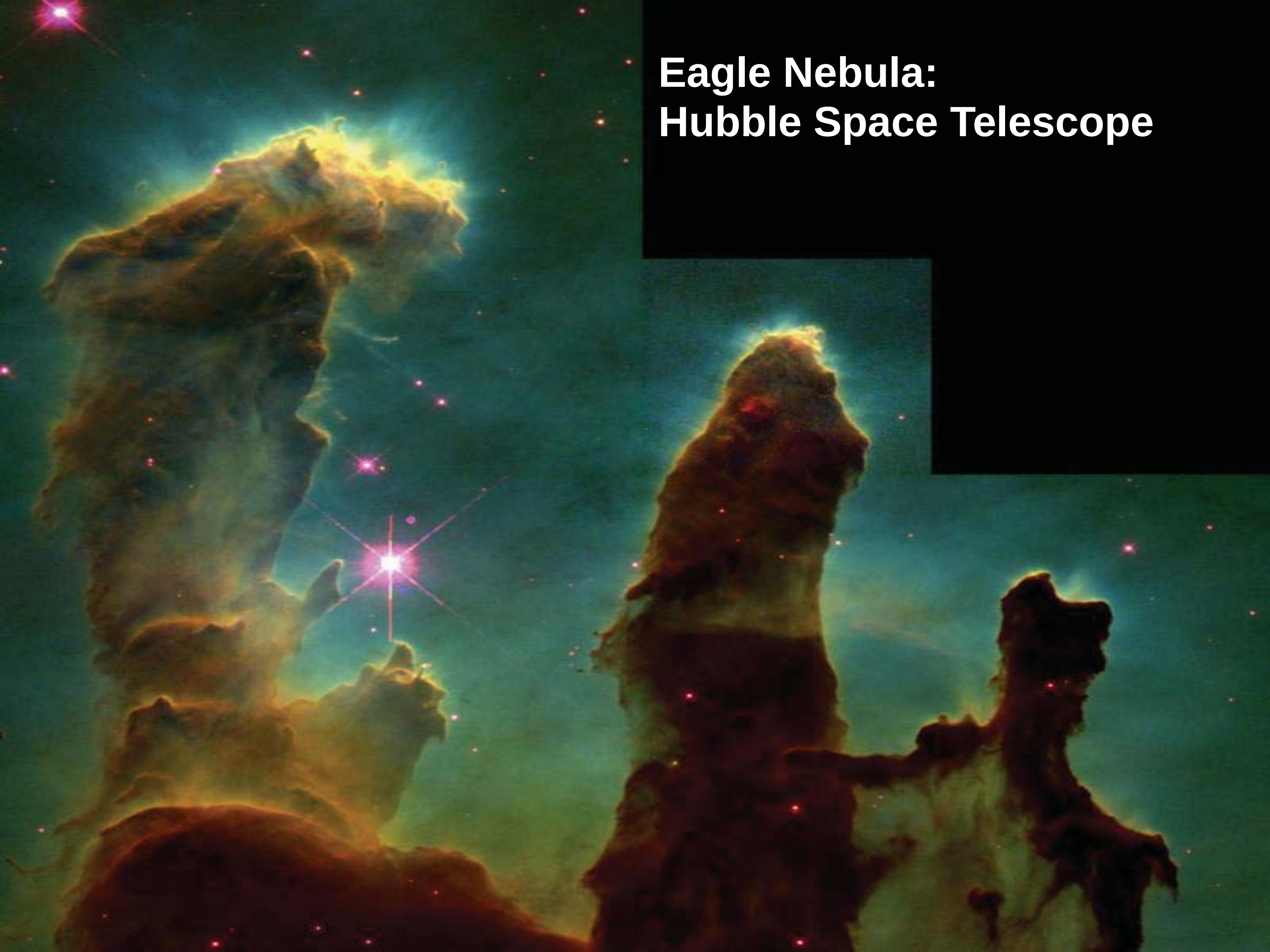
Rosette Nebula

Schneider et al. 2010

H-alpha (black/white) +
far-IR (colors, from Herschel
Space Observatory)


Filaments:
long, thin structures
Rosette Nebula
Herschel Space Observatory

Eagle Nebula:
Hubble Space Telescope



"Pillars" and "Mountains" of Star Formation

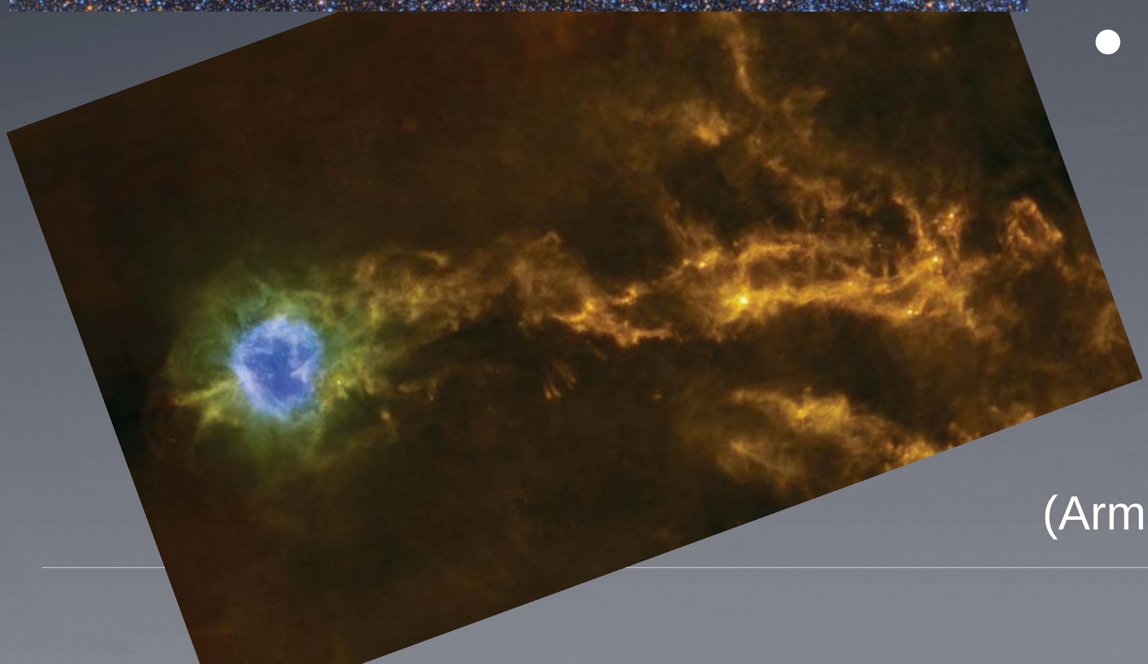
NASA / JPL-Caltech / L. Allen (Harvard-Smithsonian CfA)

Spitzer Space Telescope • IRAC

Inset: Hubble Space Telescope

ssc2005-23b

Eta Carina Cluster, Hubble Space Telescope



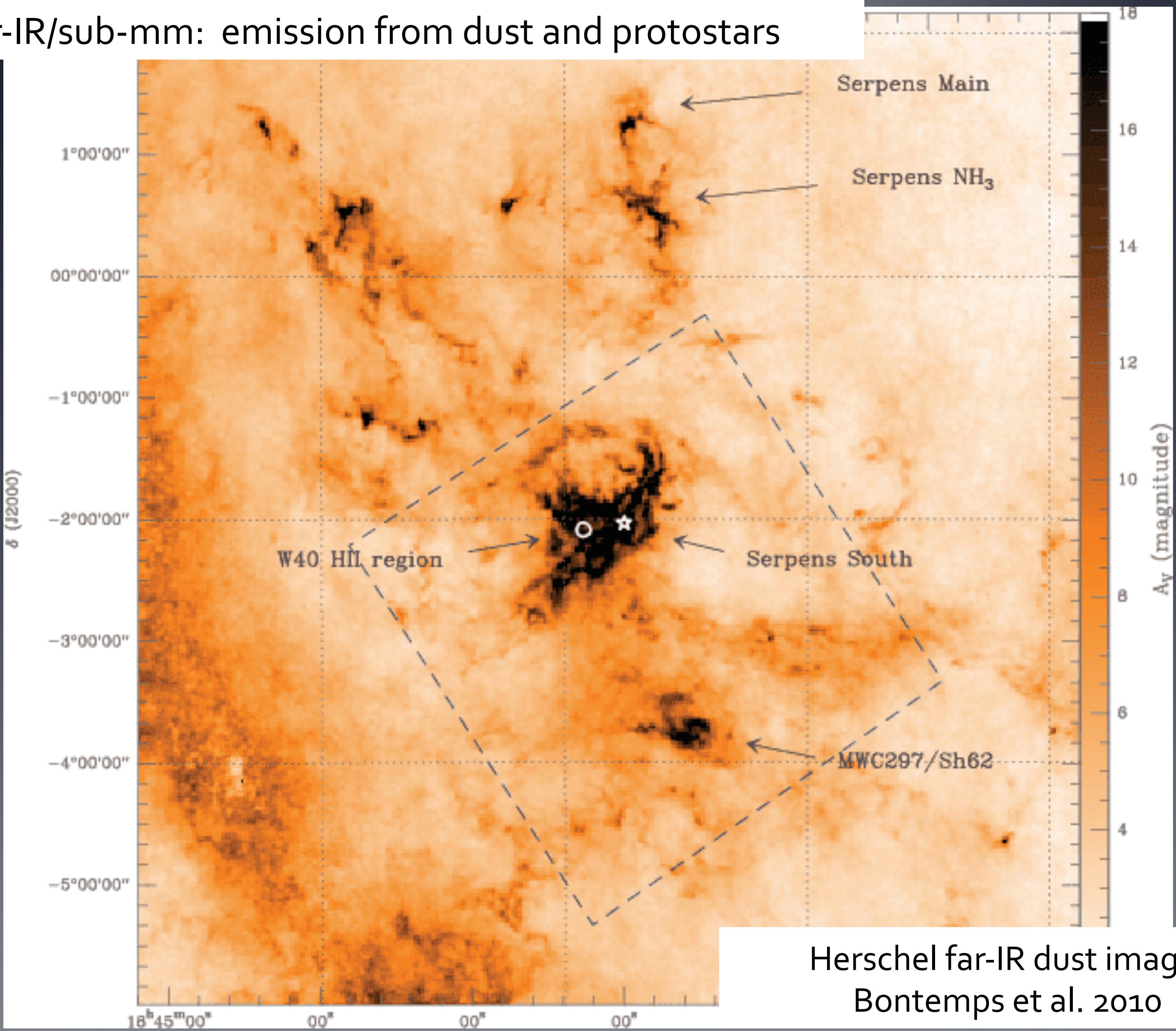
Cocoon Nebula

- Optical:
  - dark lanes where dust
  - H-alpha at nebula
- Herschel:
  - warm dust at nebula
  - dust lanes appear bright

(Armazounian et al. 2011)

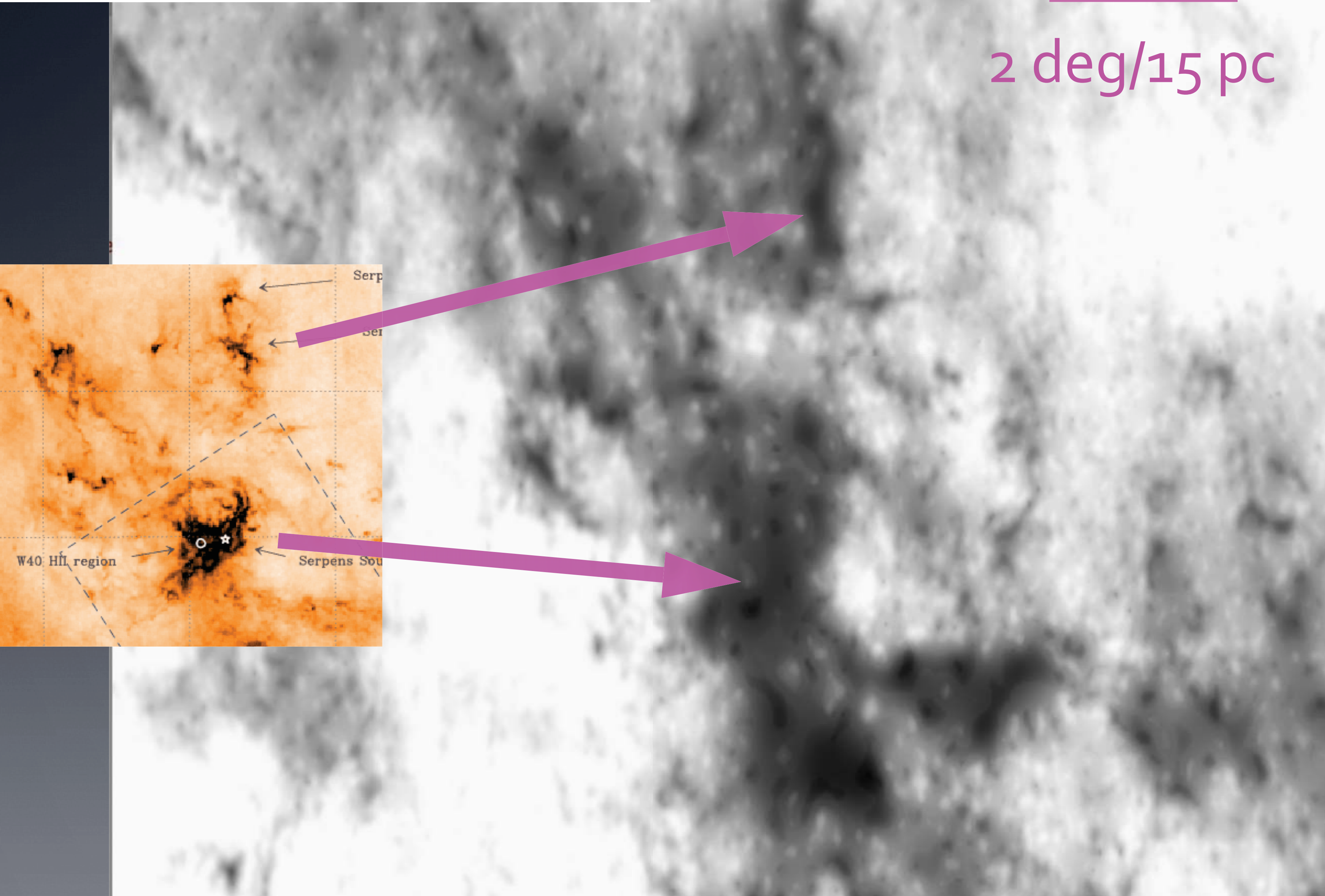
Serpens star-forming region
Courtesy Adam Block via APOD

Far-IR/sub-mm: emission from dust and protostars



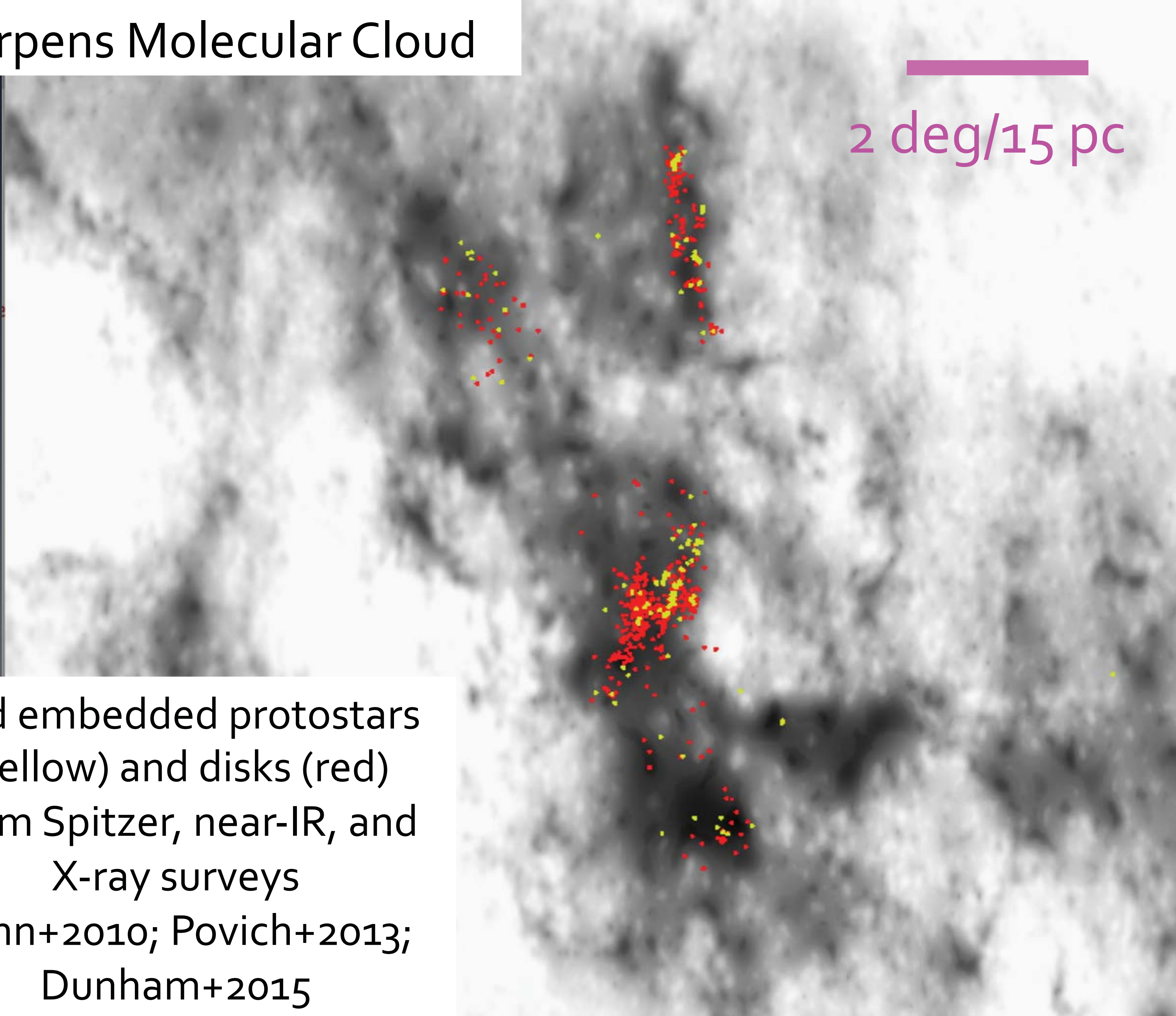
Herschel far-IR dust image,
Bontemps et al. 2010

Serpens Molecular Cloud



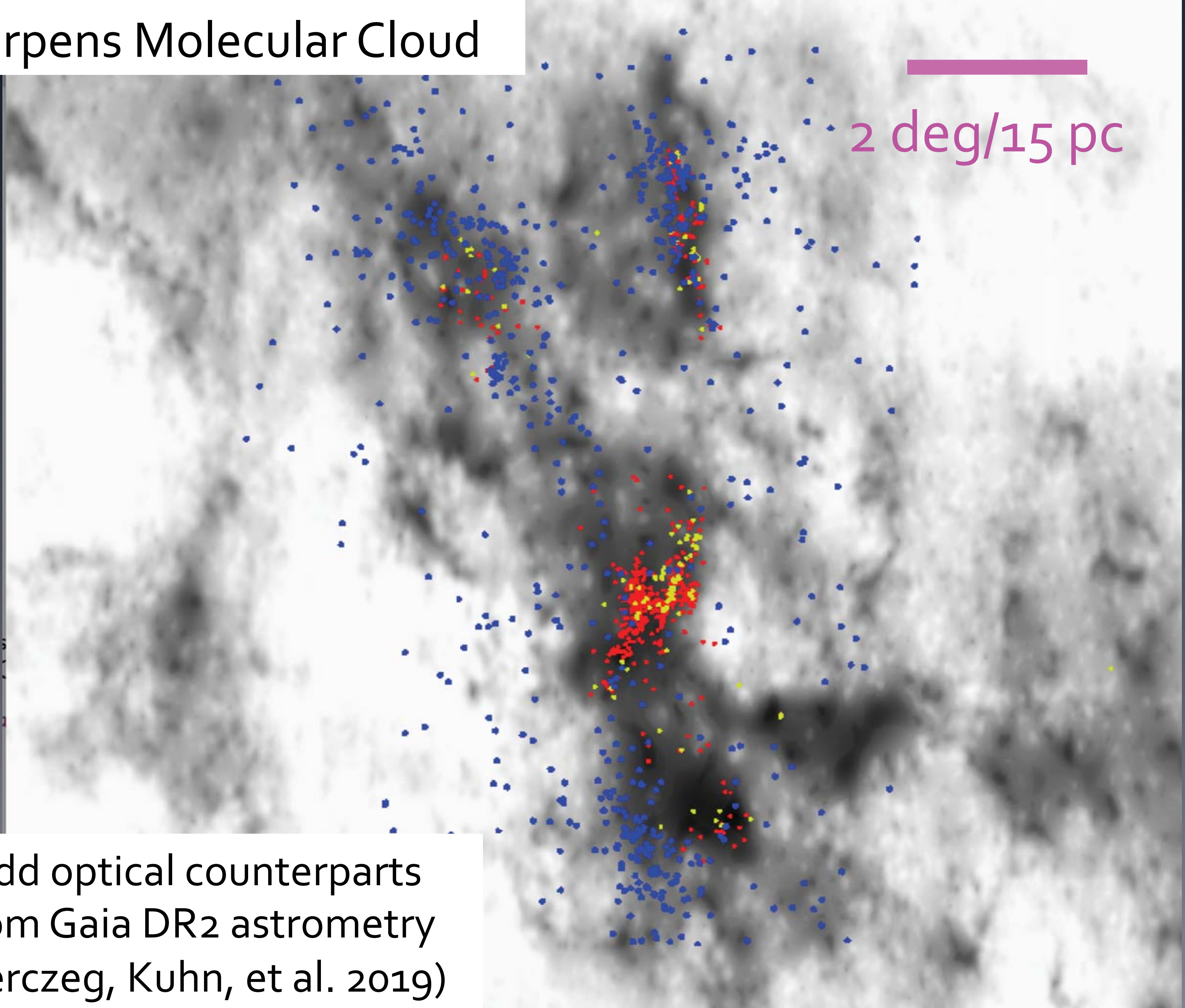
Cambresy 2003 extinction map

Serpens Molecular Cloud



Add embedded protostars (yellow) and disks (red) from Spitzer, near-IR, and X-ray surveys
Kuhn+2010; Povich+2013; Dunham+2015

Serpens Molecular Cloud

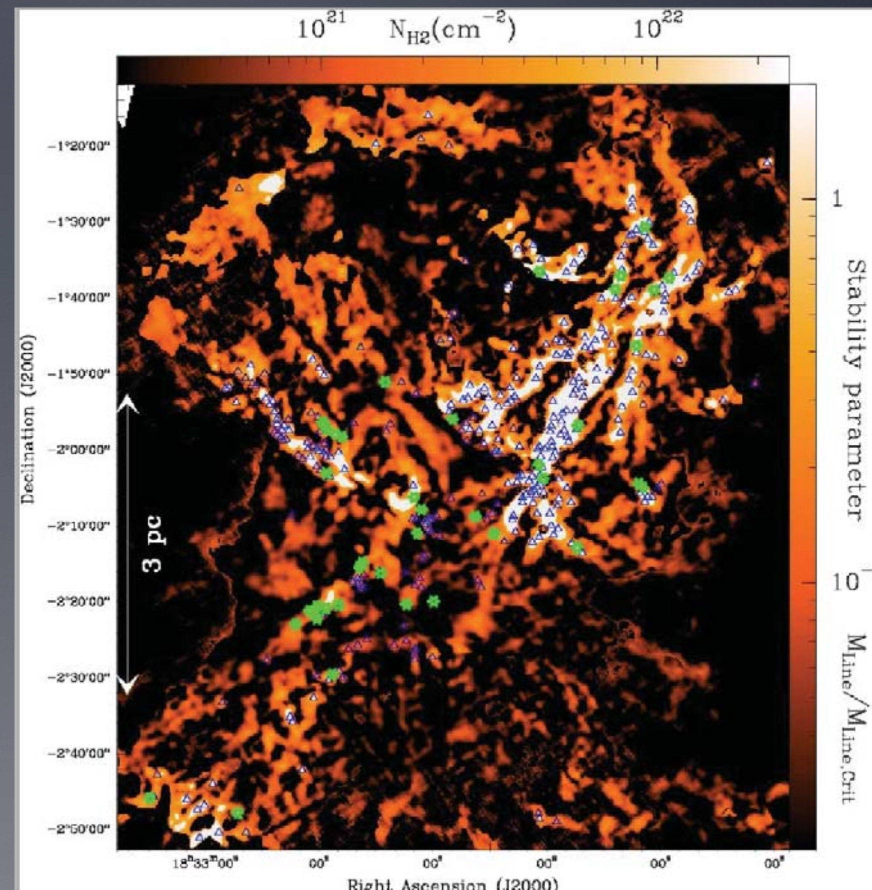


Add optical counterparts from Gaia DR2 astrometry (Herczeg, Kuhn, et al. 2019)

Molecular clouds are filamentary

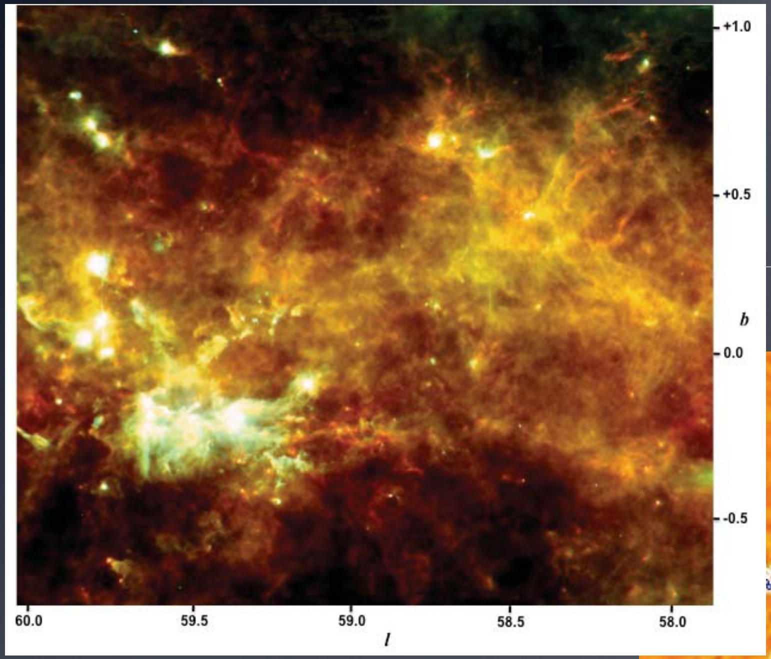
(Arzoumanian, André, et al. 2011)

- All filaments: 0.1 pc across
- Cores (green dots) form in filaments
- Suggests turbulence organizes cold ISM

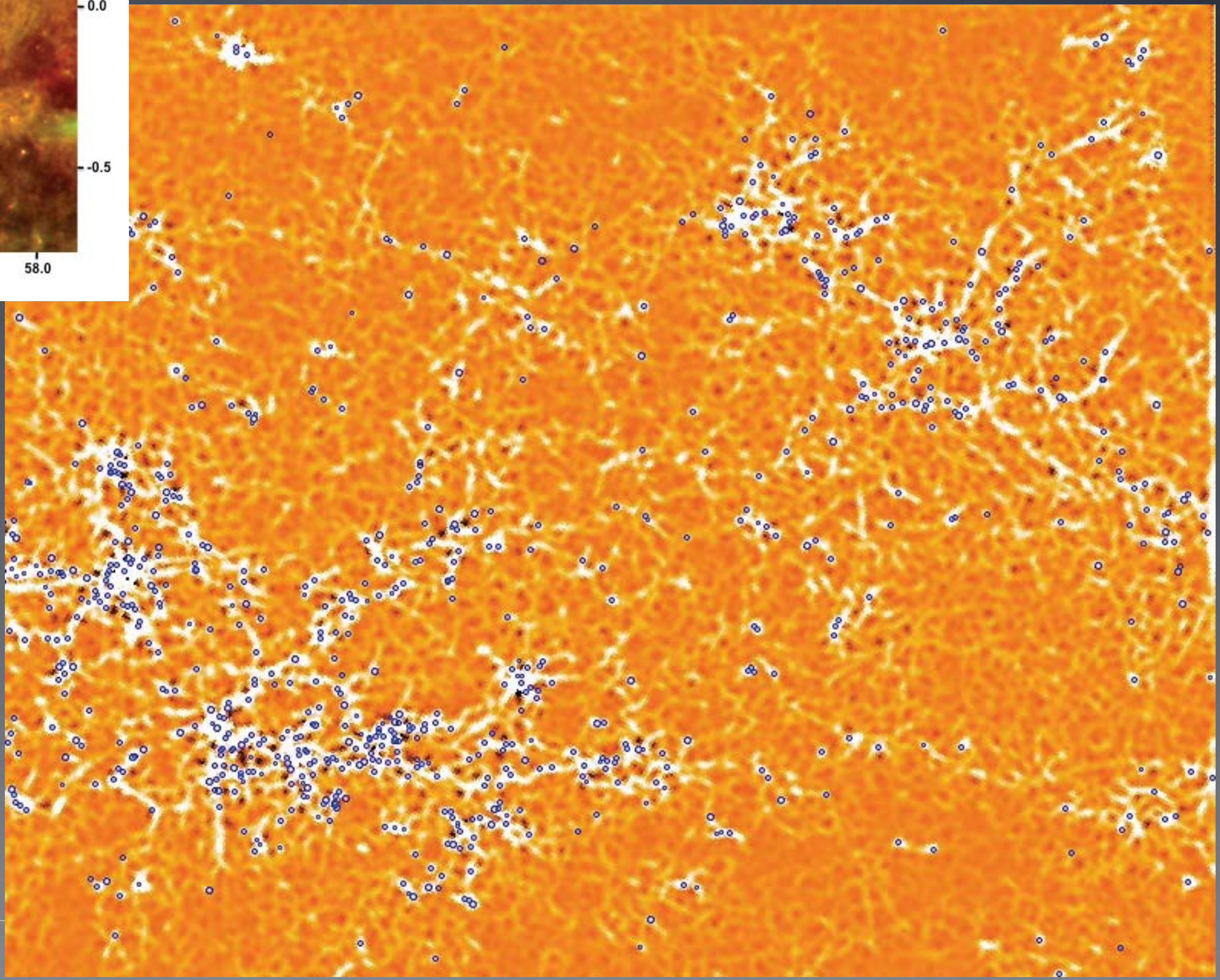


Density-transformed map from left

Filamentary Star Formation

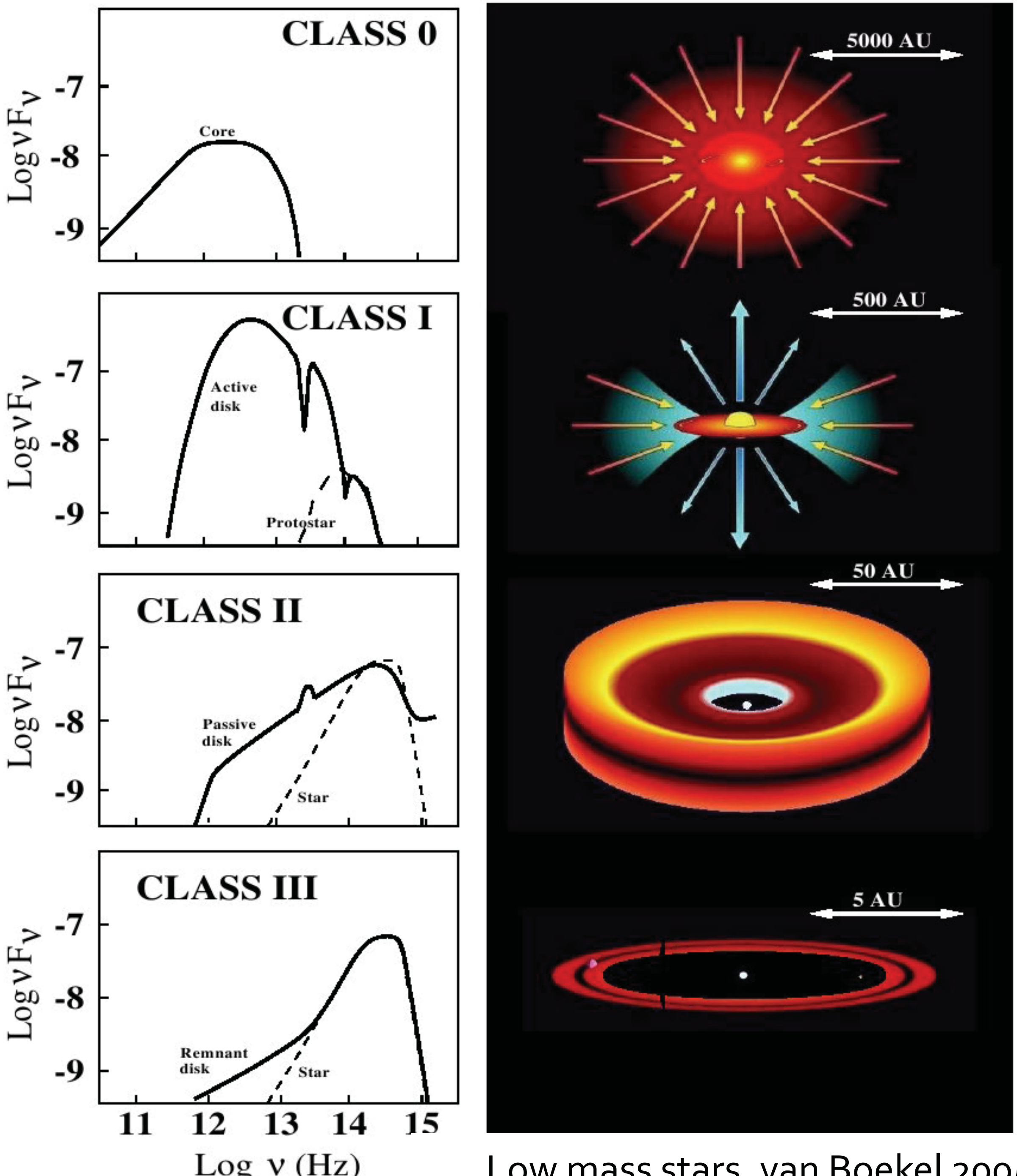


Density-transformed map from left



Molinari et al. 2010

Cores (dots here) only along filaments (high extinction)

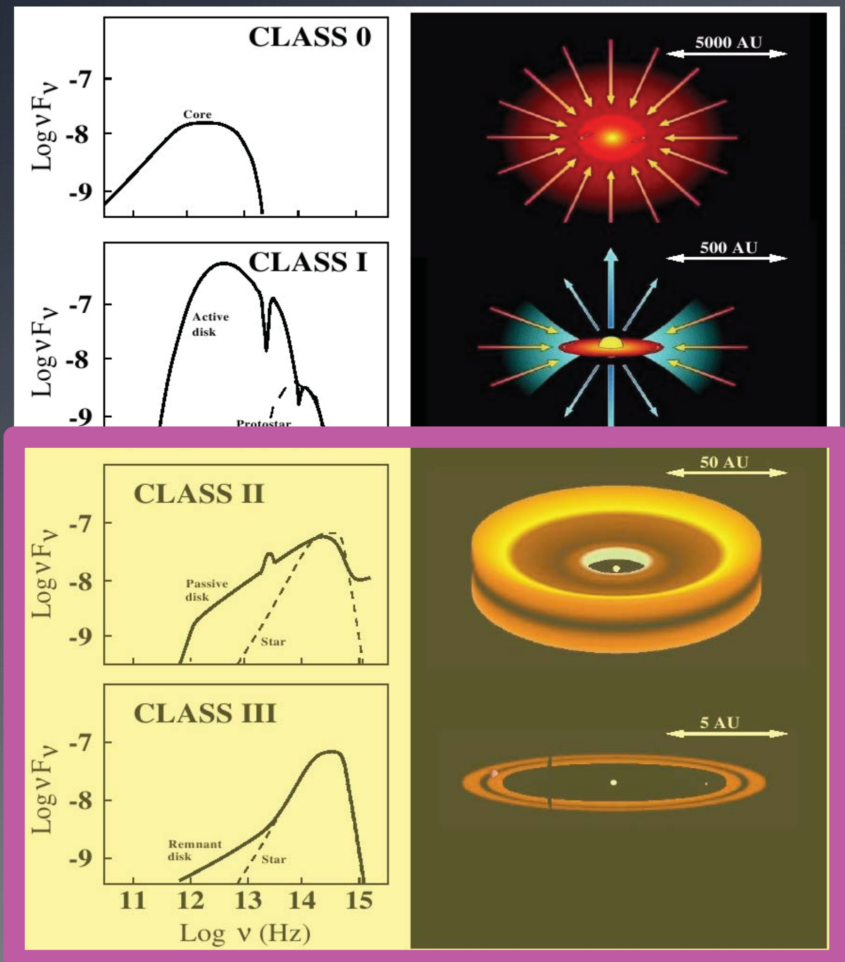


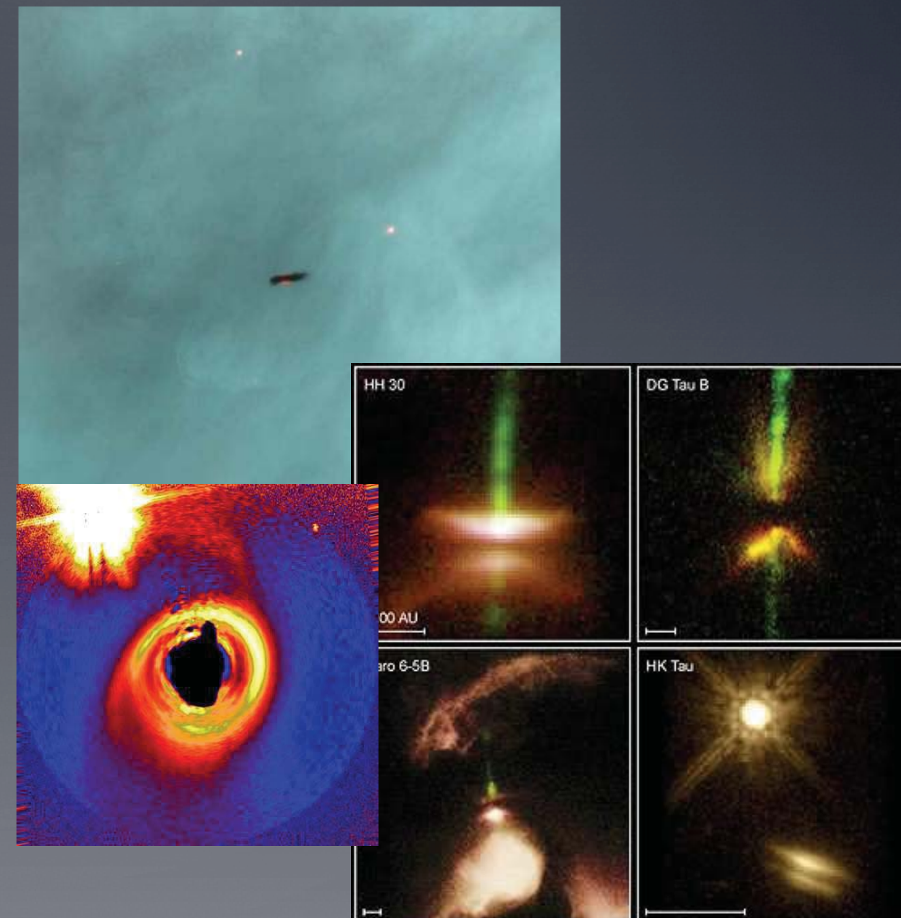
Low mass stars, van Boekel 2005

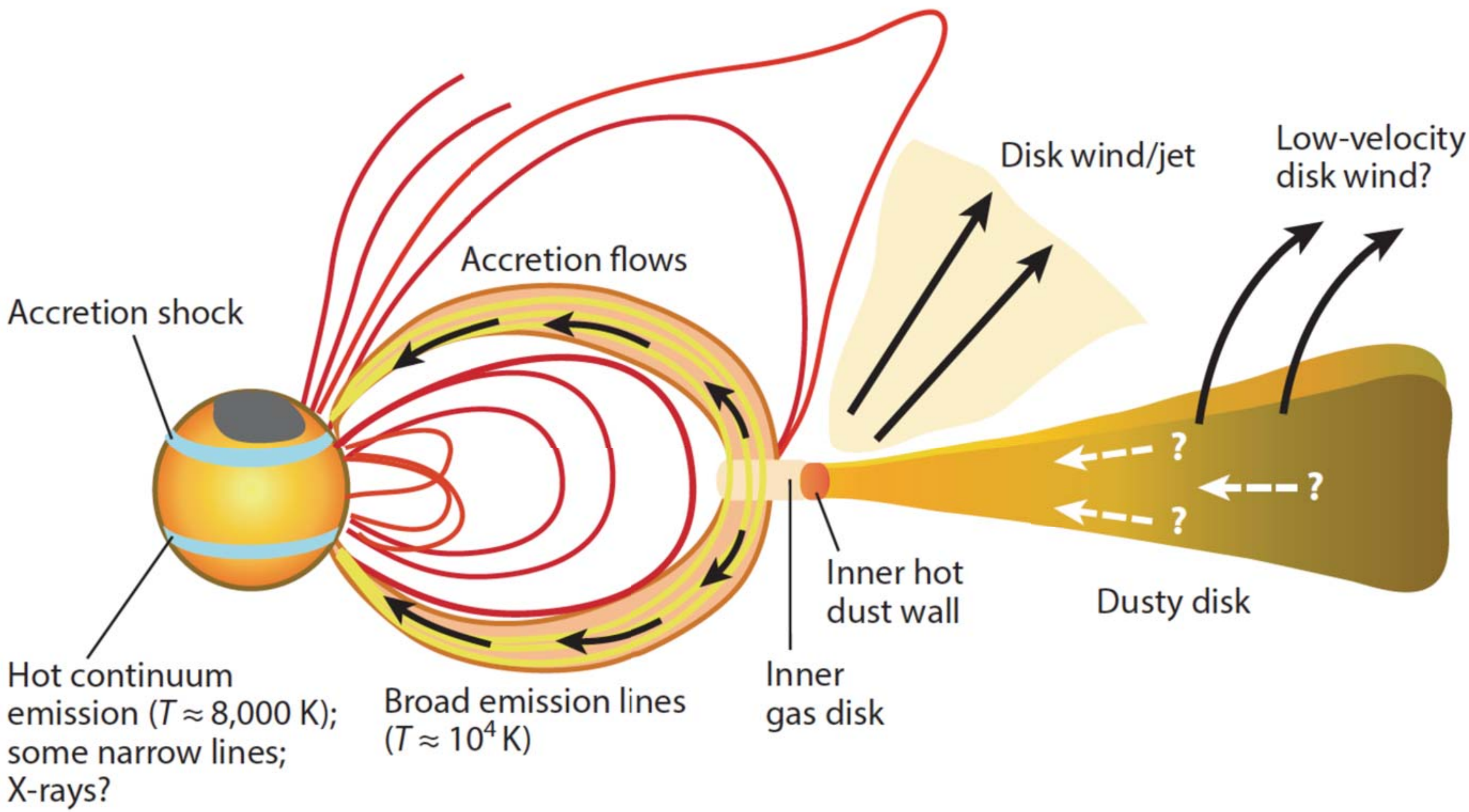
Protostars:
~few 10^5 yr
Stellar growth

Disks
~few 10^6 yr
Planet formation

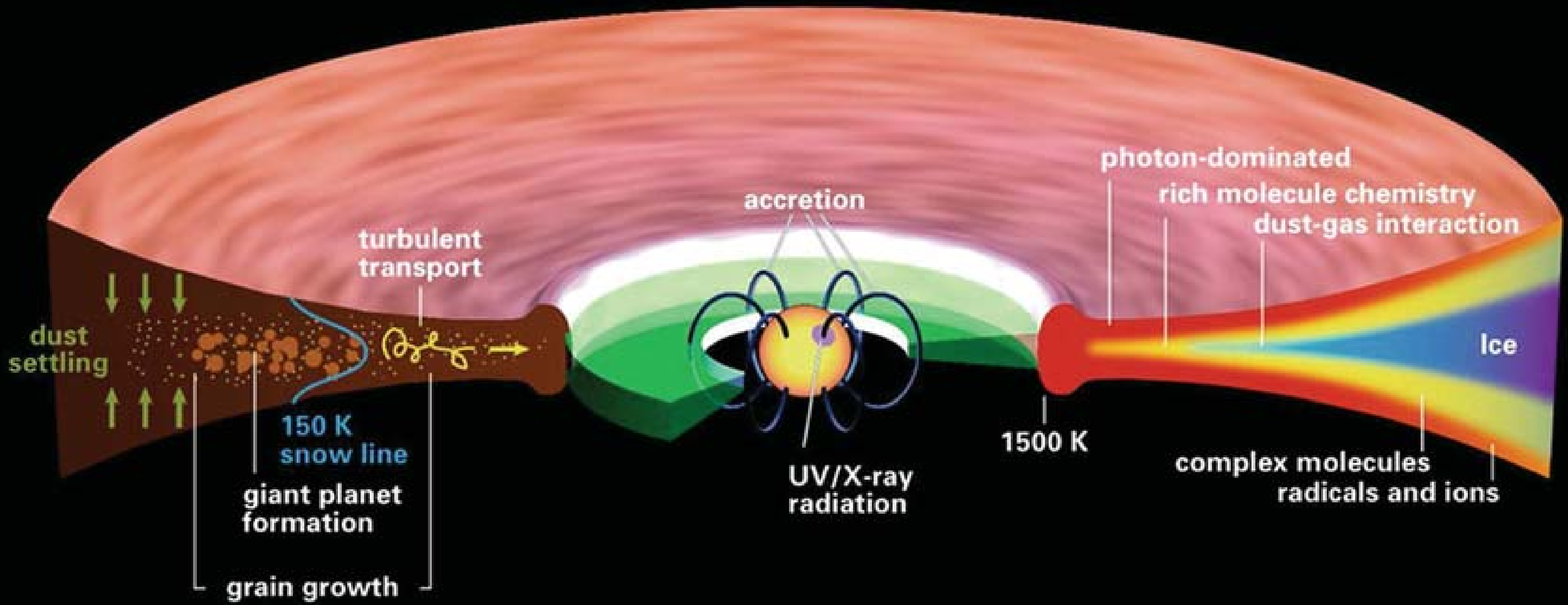
Class II/classical T Tauri star:
Protoplanetary disks, envelope has disappeared







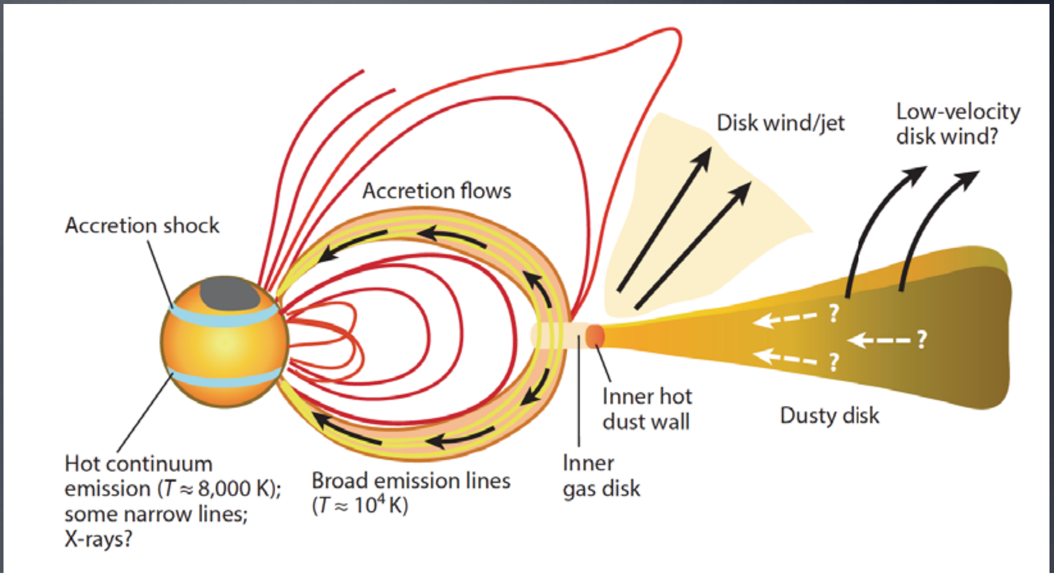
Hartmann, Herczeg, & Calvet, ARAA



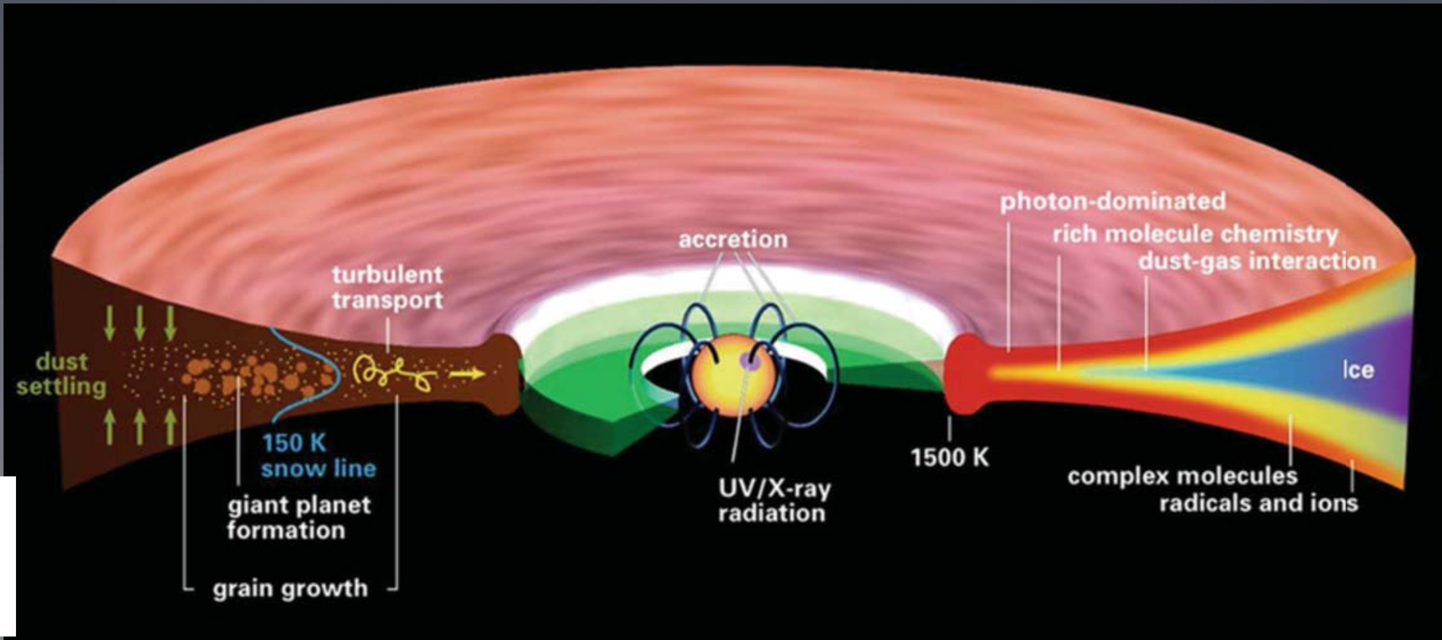
Henning & Semenov (2013)

Disk evolution processes

- Star-disk accretion
- Disk winds (e.g., Fang+2018)
- Photoevaporation
- Grain growth/drift



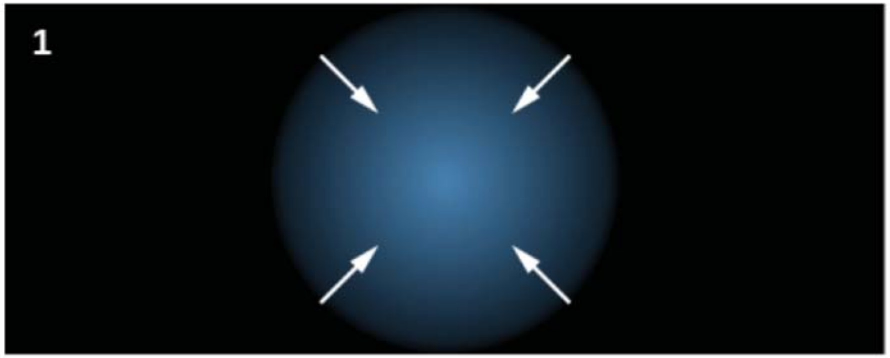
Hartmann, Herczeg, & Calvet, ARAA



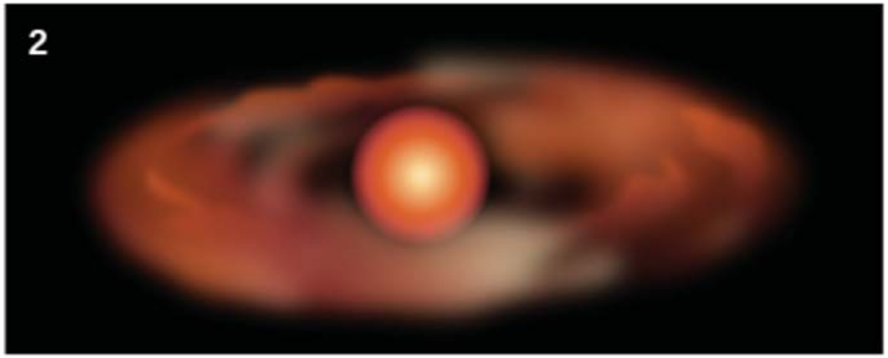
Henning & Semenov (2013)

Planet Formation

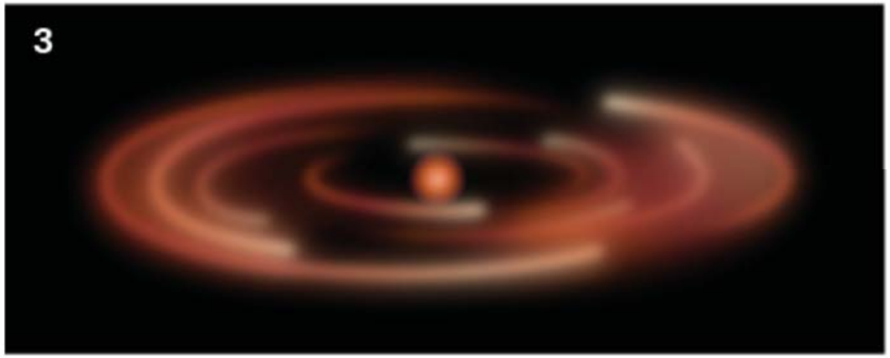
(last step in star formation, last class)



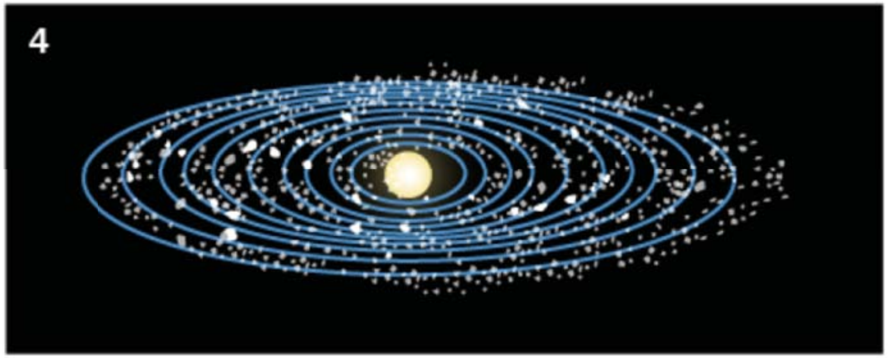
The solar nebula contracts.



As the nebula shrinks, its motion causes it to flatten.



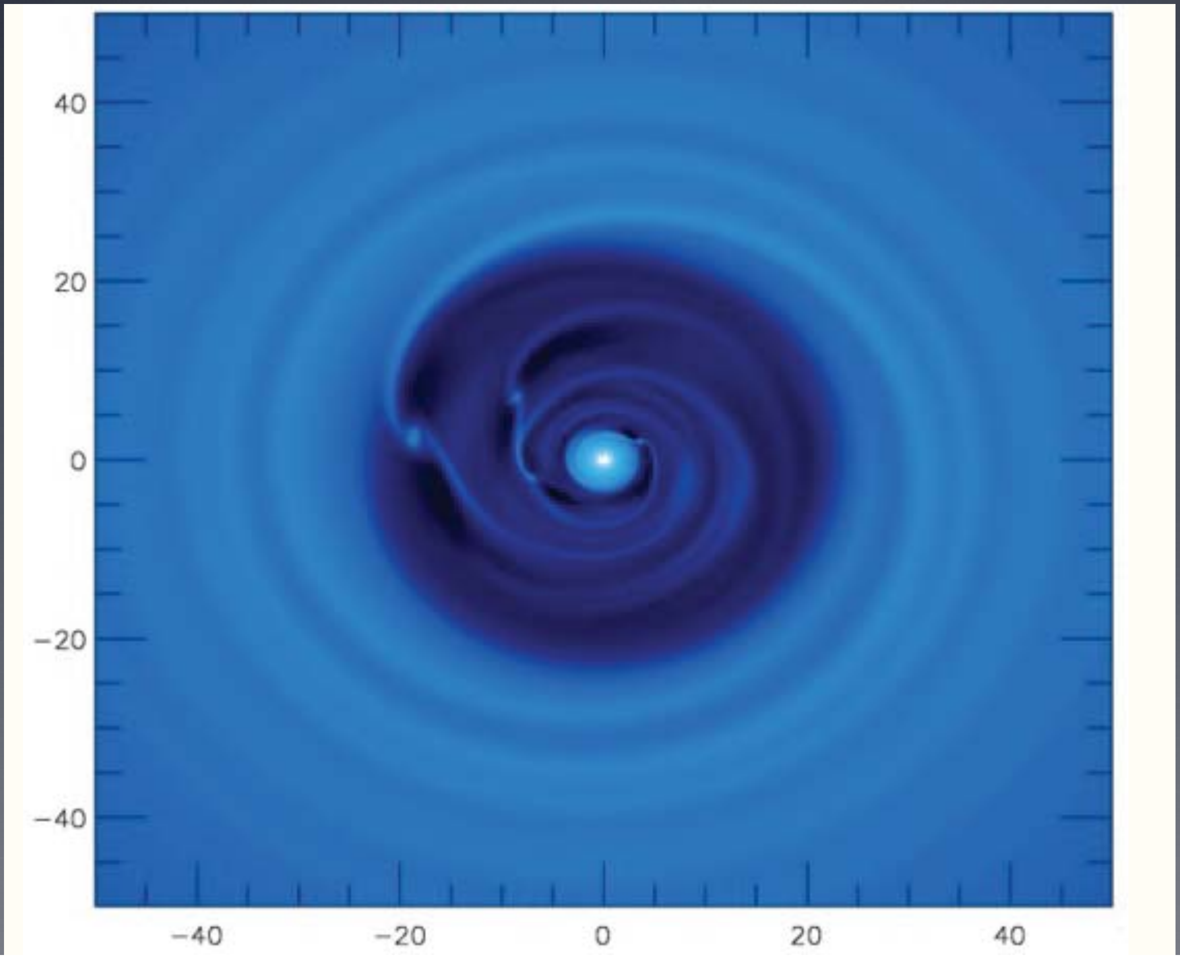
The nebula is a disk of matter with a concentration near the center.



Formation of the protosun. Solid particles condense as the nebula cools, giving rise to the planetesimals, which are the building blocks of the planets.

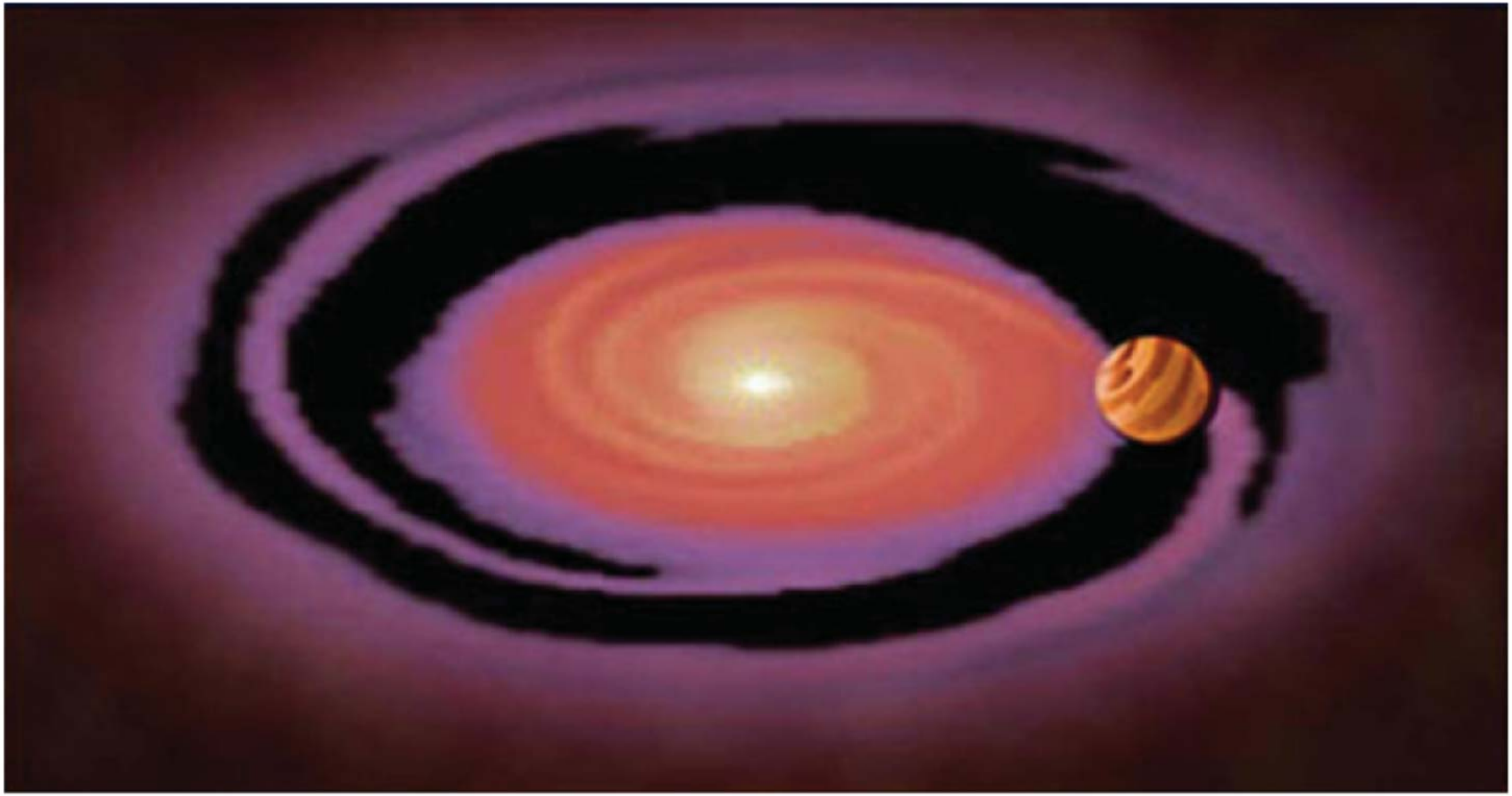
How would a forming planet affect a disk?

(e.g., Zhu+2011)

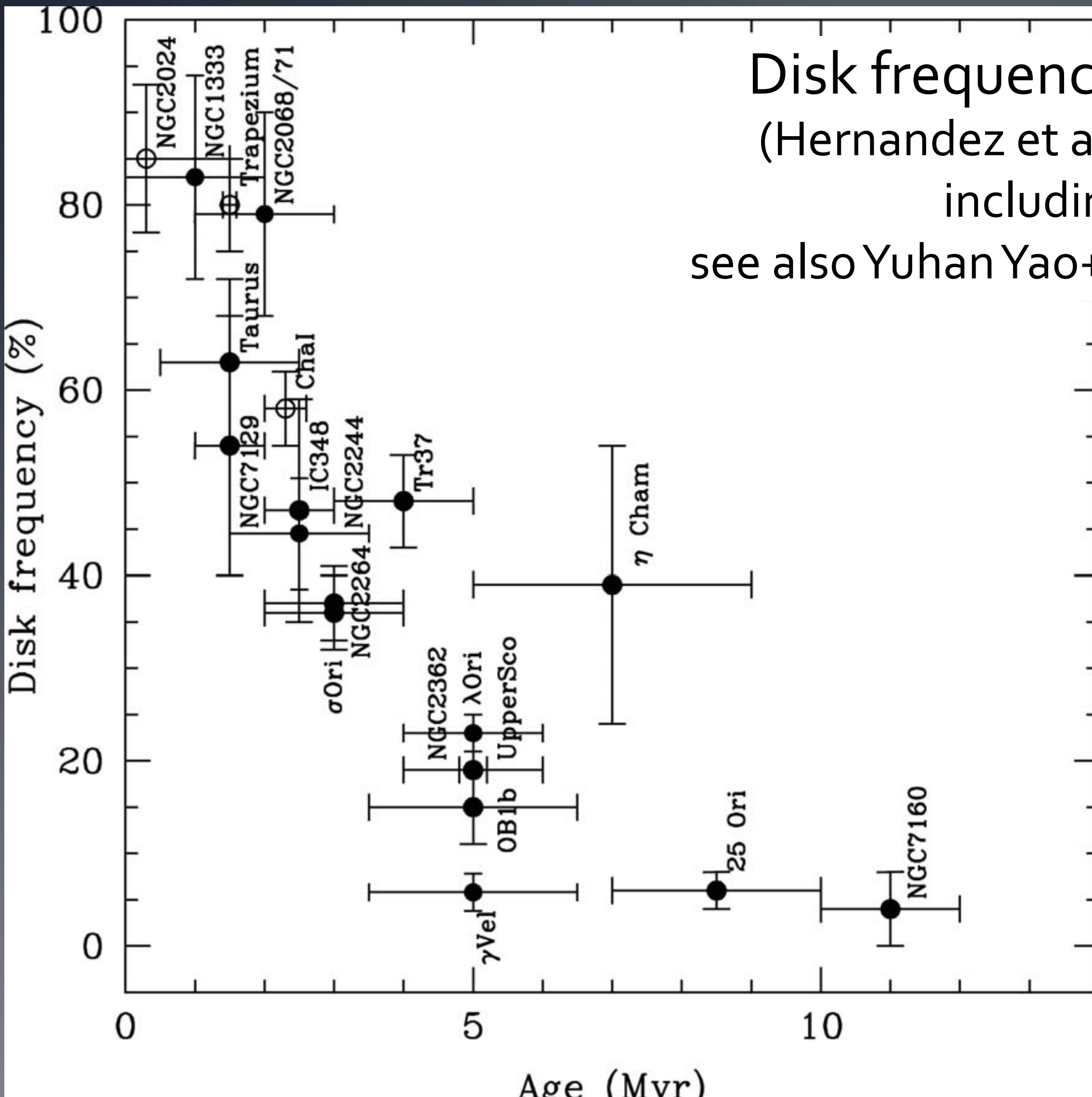


Gaps in disks: first proposed by Lin & Papaloizou 1986

Planets should form in disk and carve a gap

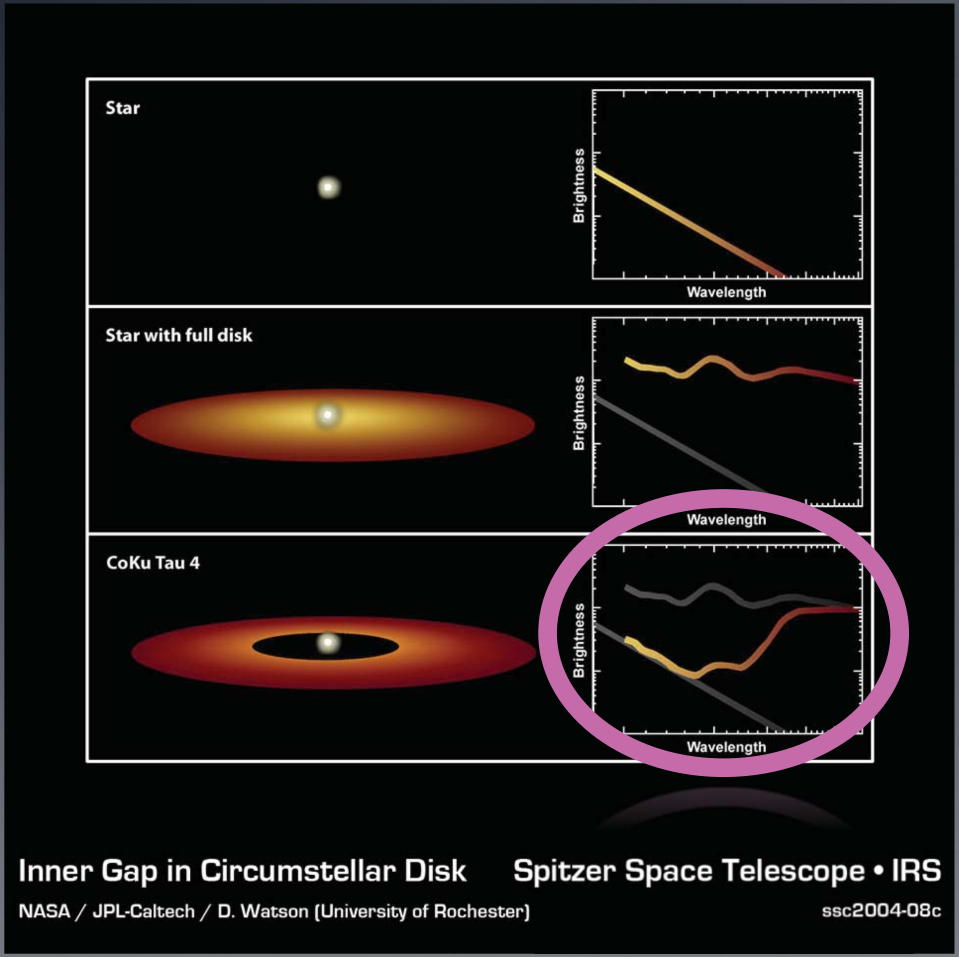


Dust and gas disk timescales:
planet formation must occur within ~3 Myr



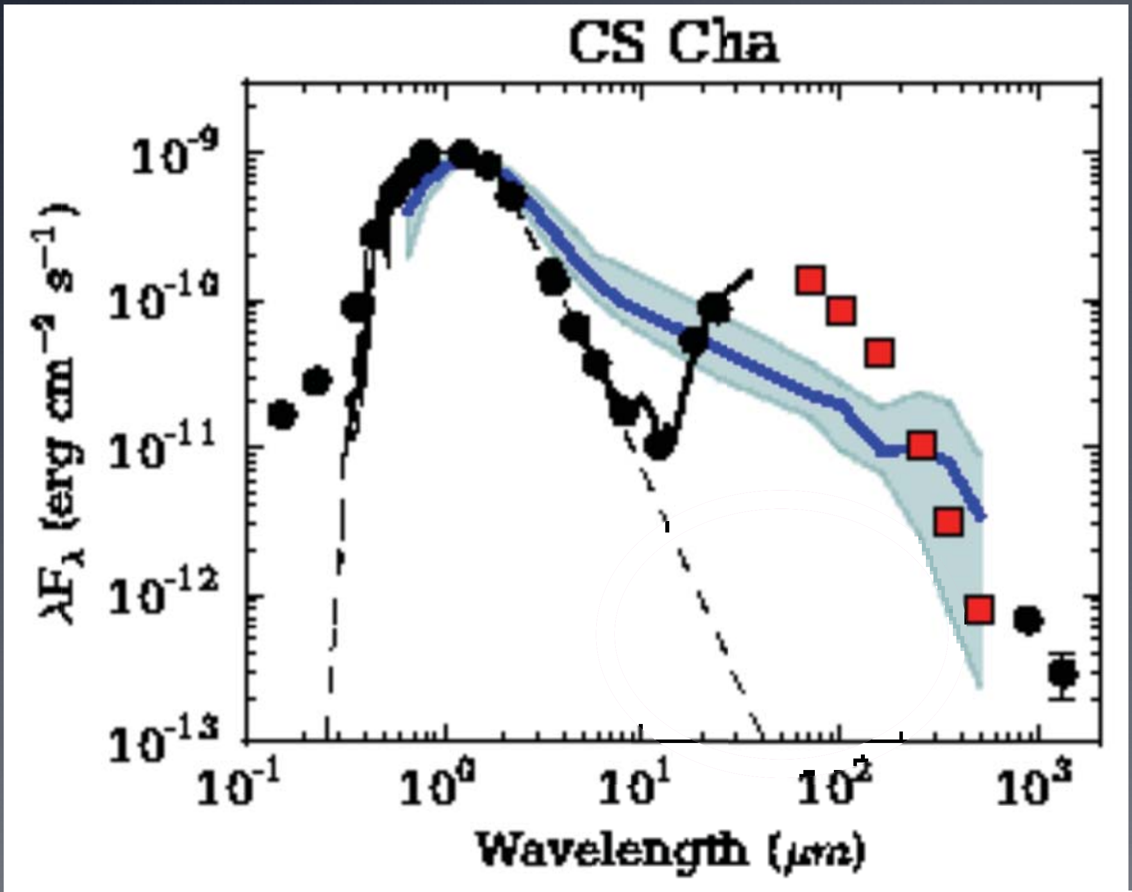
Disk frequency in different clusters
(Hernandez et al. 2008 and many others,
including Haisch+2001;
see also Yuhan Yao+2018 for mass dependence)

Do disks show evidence of planet formation?



- Transition disks:
  - Inner holes in their dust distribution
  - Usually found with near/mid-IR spectra obtained with Spitzer

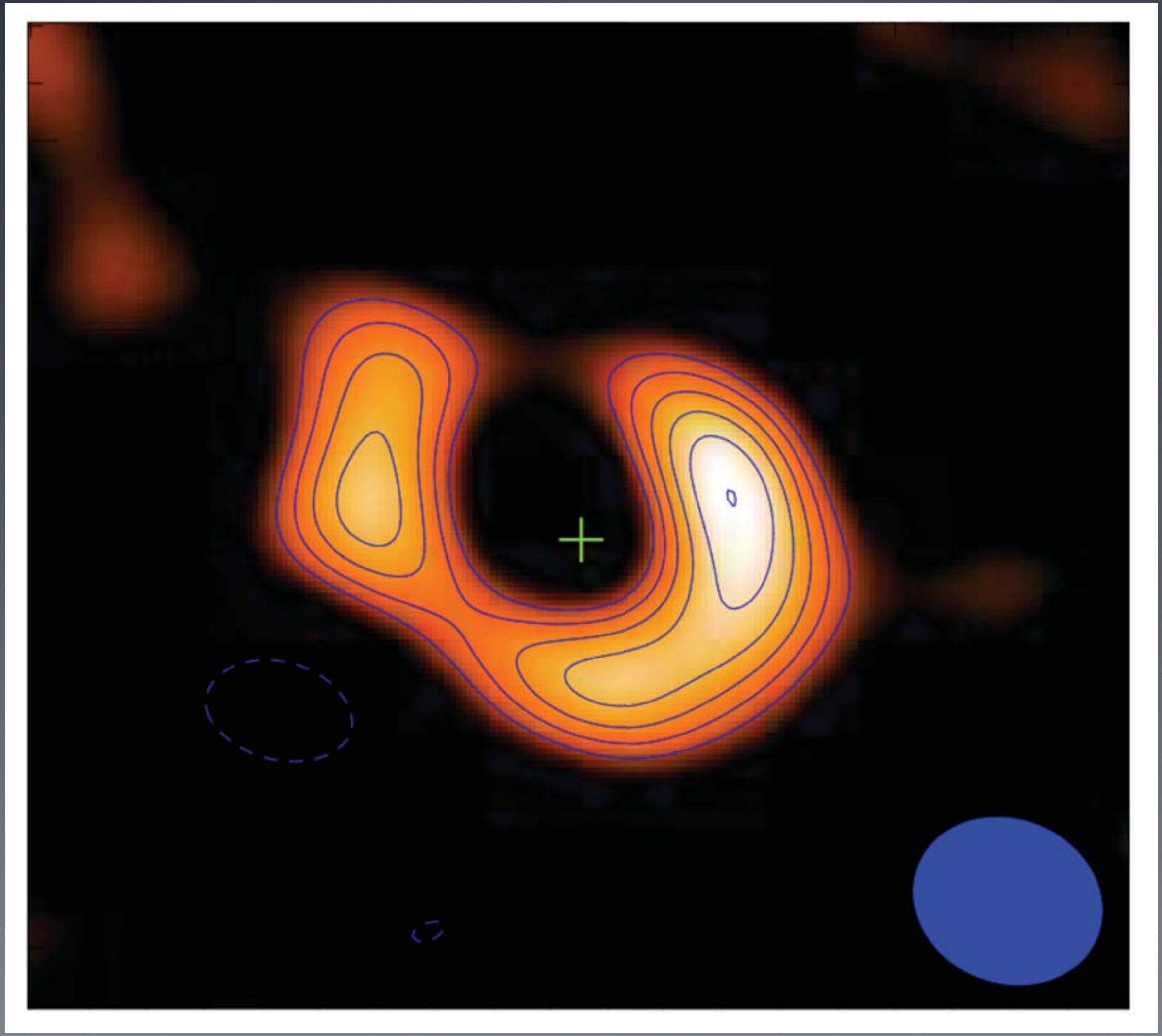
Do disks show evidence of planet formation?



Espaillat+2007; see also, eg Strom+1989, Calvet +2002, D'Alessio+2005, Kim+2009, Merin+2010

- Transition disks:
  - Inner holes in their dust distribution
  - Usually found with near/mid-IR spectra obtained with Spitzer

Confirmation of large inner holes in mm-dust
(Brown et al. 2008)



Atacama Large Millimeter Array (ALMA)

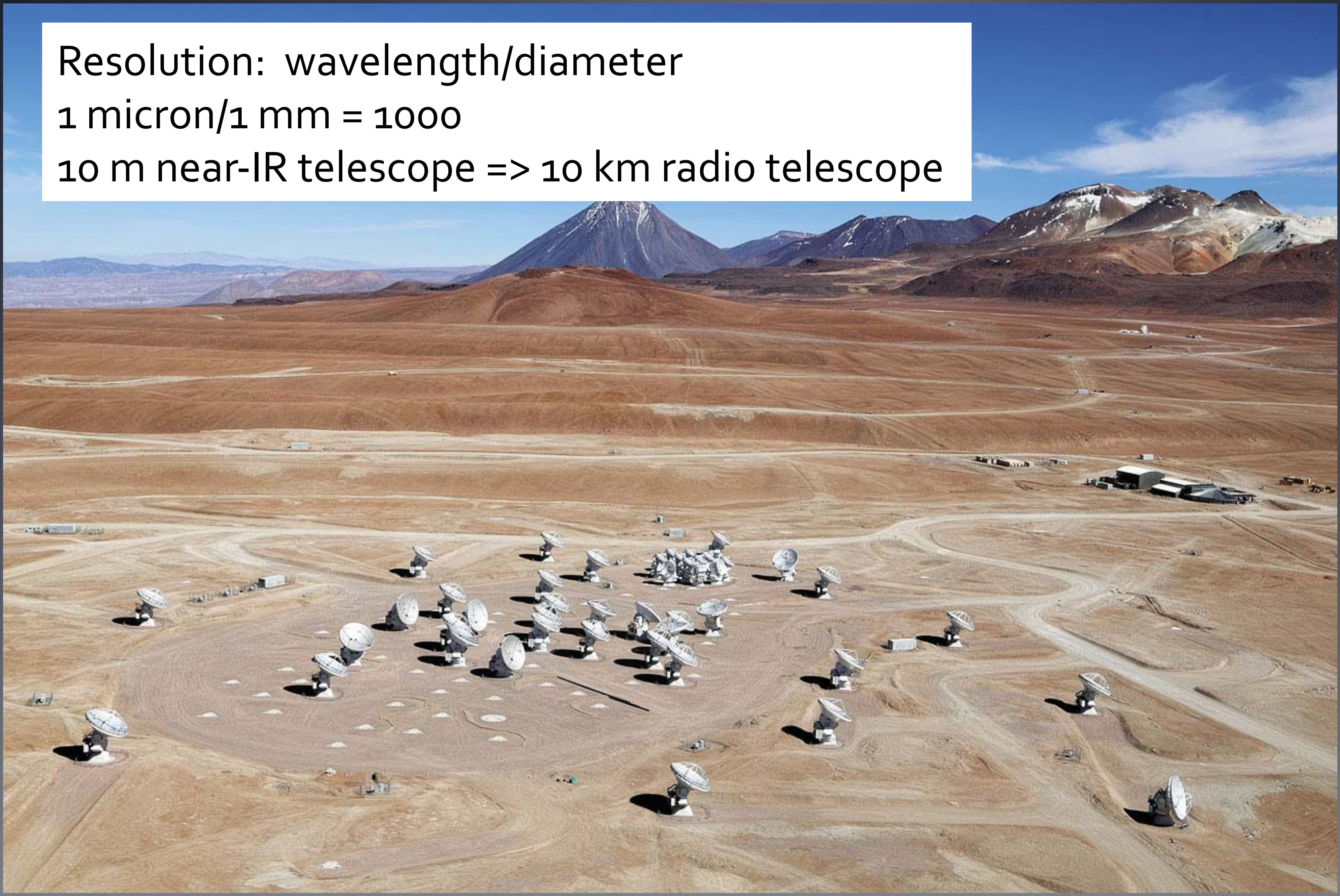
Sub-mm interferometer, 5000m high plateau in Chile

Atacama Large Millimeter Array (ALMA)

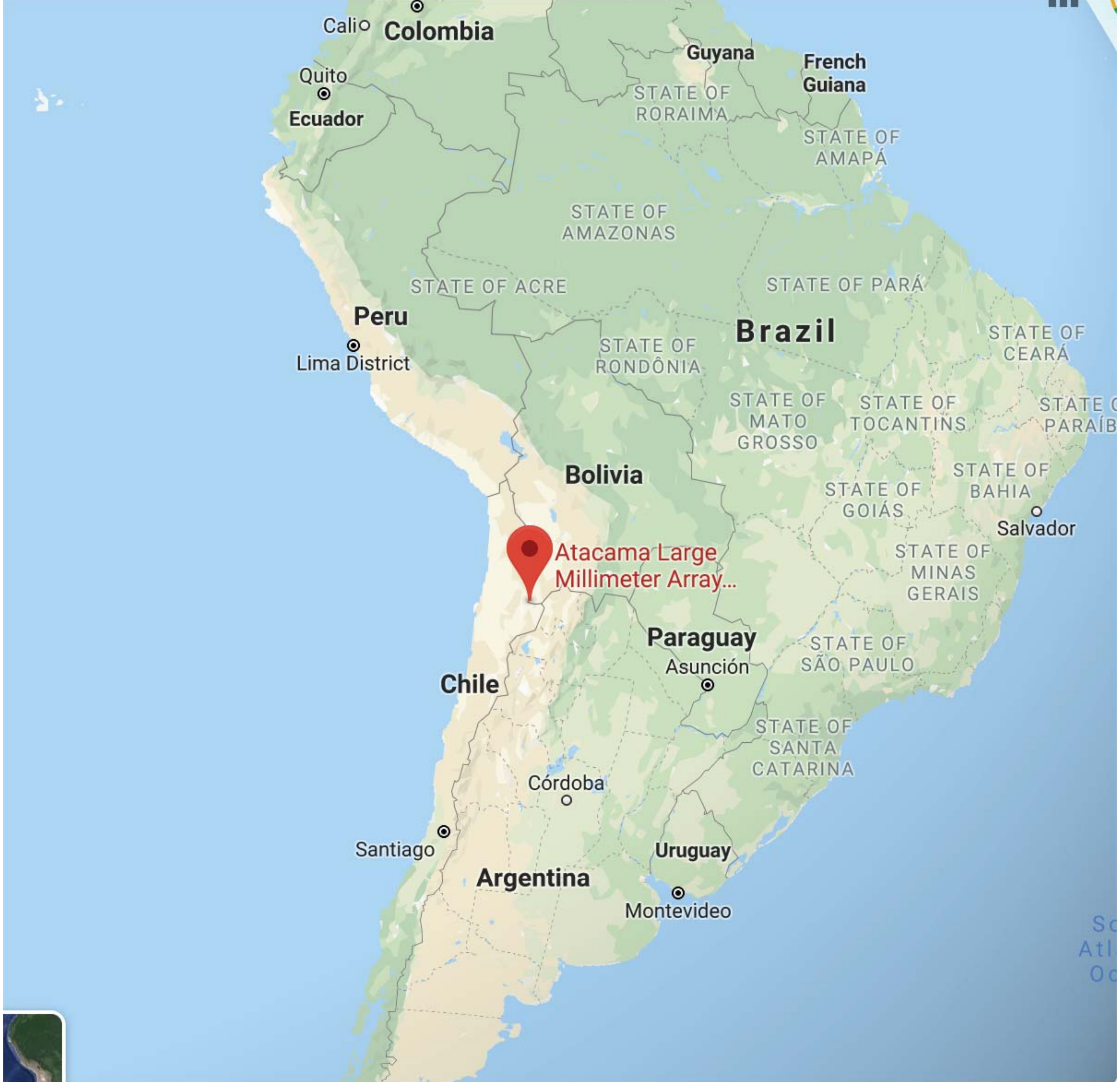
Resolution: wavelength/diameter

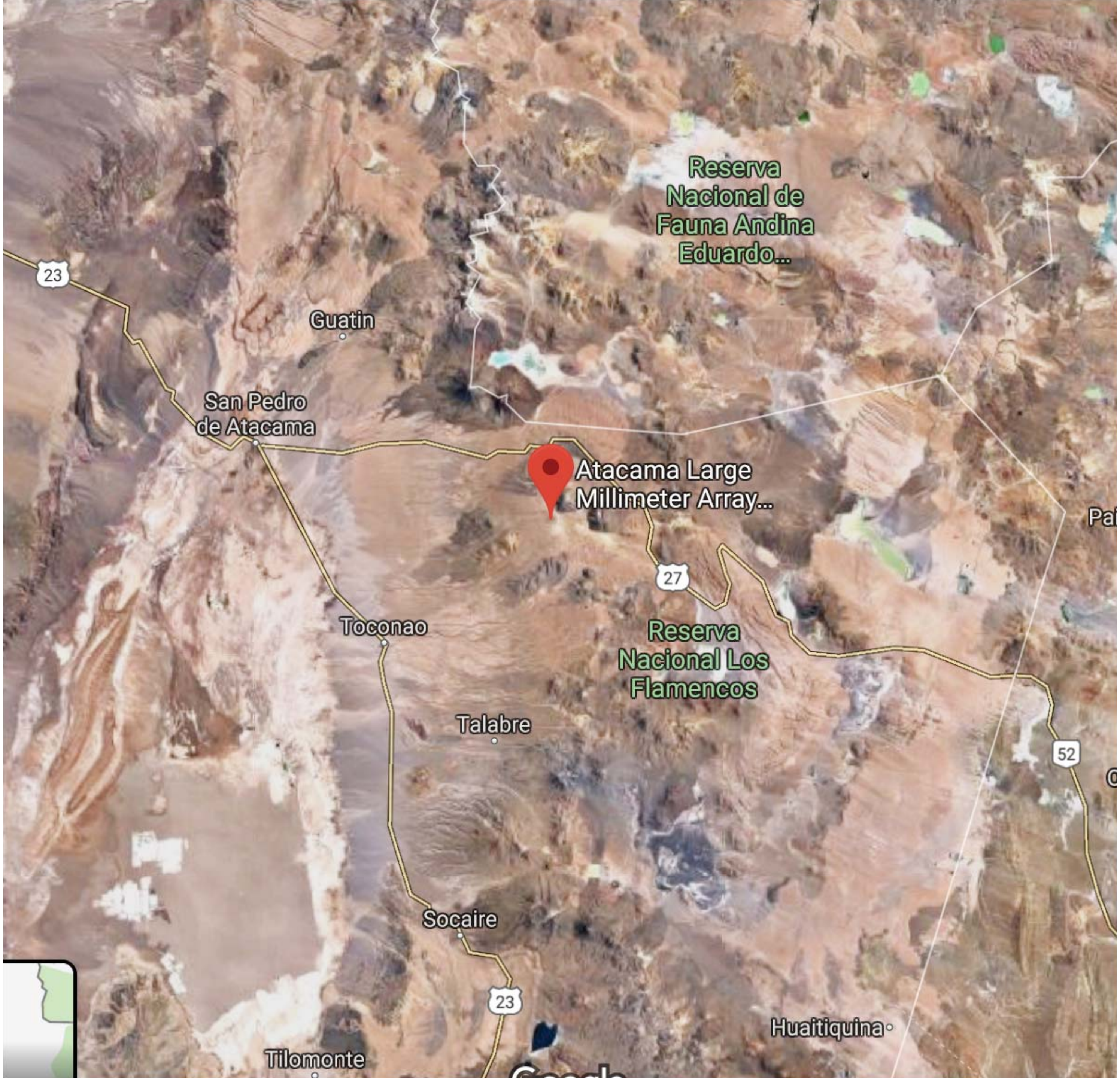
1 micron/1 mm = 1000

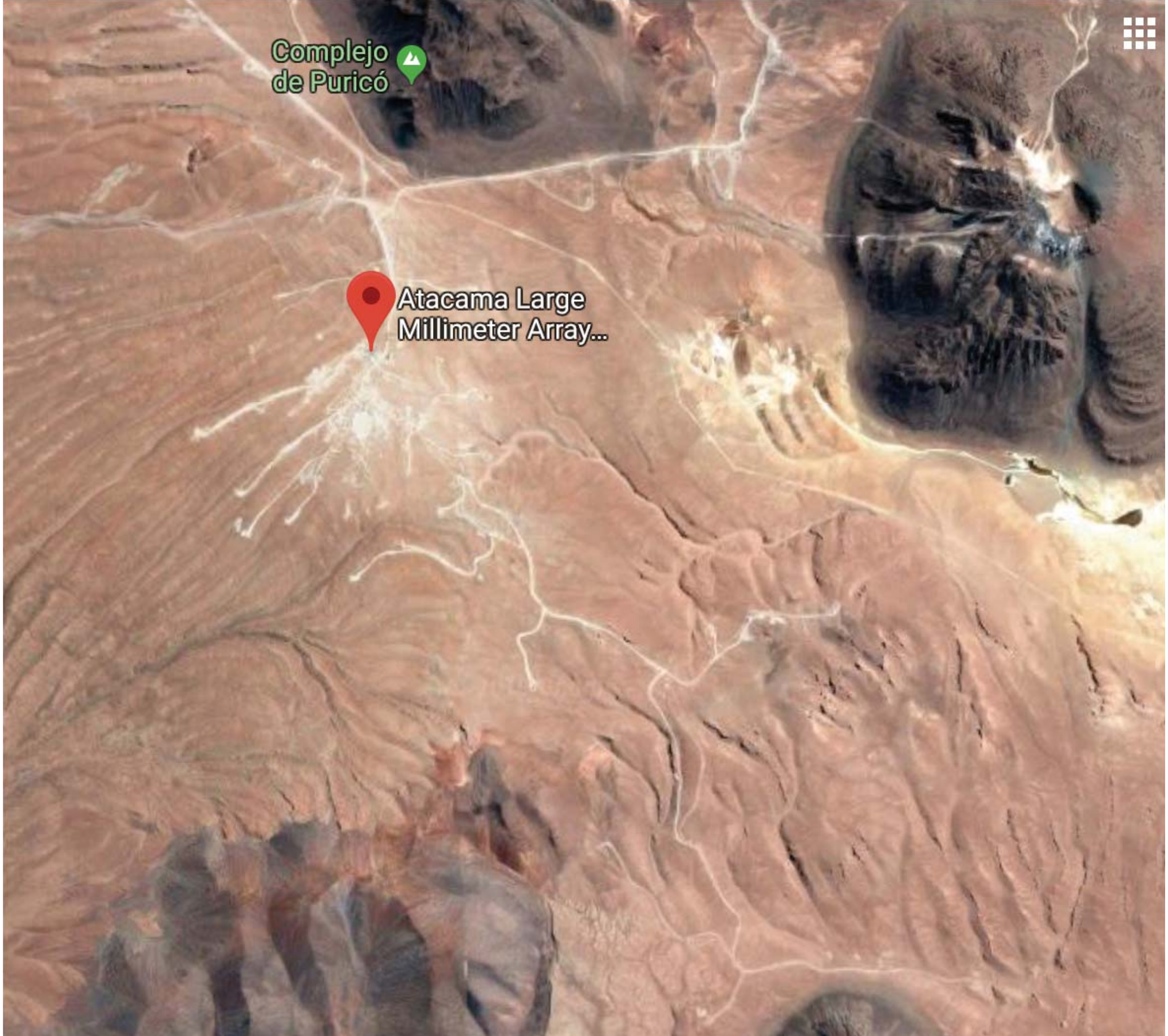
10 m near-IR telescope => 10 km radio telescope

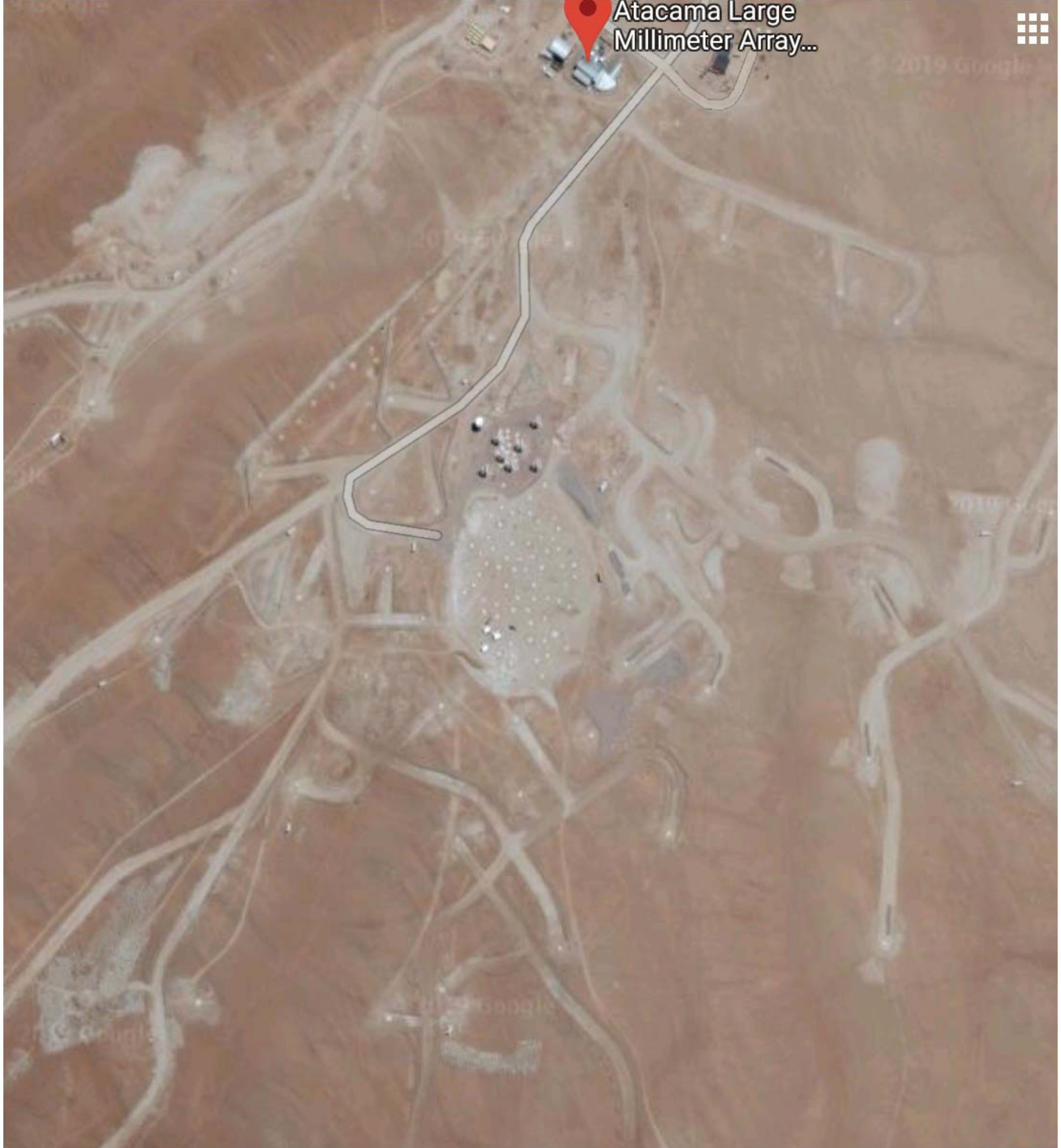


Sub-mm interferometer, 5000m high plateau in Chile


Cali
Colombia
Guyana
French Guiana
Quito
Ecuador
STATE OF RORAIMA
STATE OF AMAPÁ
STATE OF AMAZONAS
STATE OF ACRE
STATE OF PARÁ
Peru
Lima District
Brazil
STATE OF RONDÔNIA
STATE OF CEARÁ
STATE OF MATO GROSSO
STATE OF TOCANTINS
Bolivia
STATE OF BAHIA
STATE OF GOIÁS
Salvador
Atacama Large Millimeter Array...
STATE OF MINAS GERAIS
Paraguay
STATE OF SÃO PAULO
Asunción
Chile
STATE OF SANTA CATARINA
Córdoba
Santiago
Uruguay
Argentina
Montevideo


Reserva Nacional de Fauna Andina Eduardo...
23
Guatin
San Pedro de Atacama
Atacama Large Millimeter Array...
27
Toconao
Reserva Nacional Los Flamencos
Talabre
52
Socaire
23
Huaitiquina
Tilomonte


Complejo
de Puricó
Atacama Large
Millimeter Array...


Atacama Large
Millimeter Array...

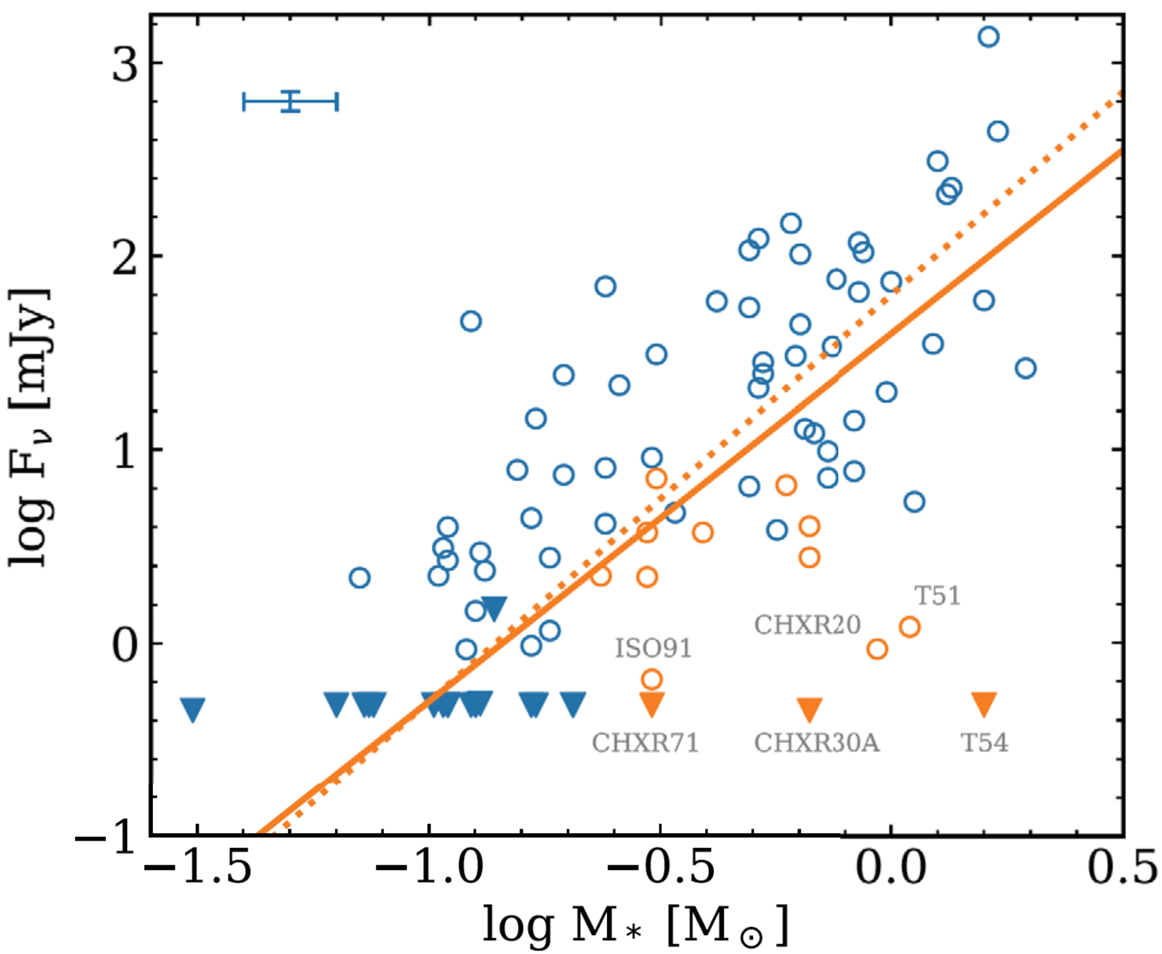
ALMA Observations

- (sub)-mm: cold universe! (usually)

- Continuum emission: mm-sized dust grains (with uncertainty)
- Gas emission lines: can be spectrally resolved
  - Usually molecular; CO is most common
  - Rotational lines from low excitation levels

- Maps in both dust and gas!

Complete surveys of disk flux (mass)



e.g., Ansdell+2016; Pascucci +2016; Barenfeld+2016; see also Miotello+2017; Long +2017 for CO flux

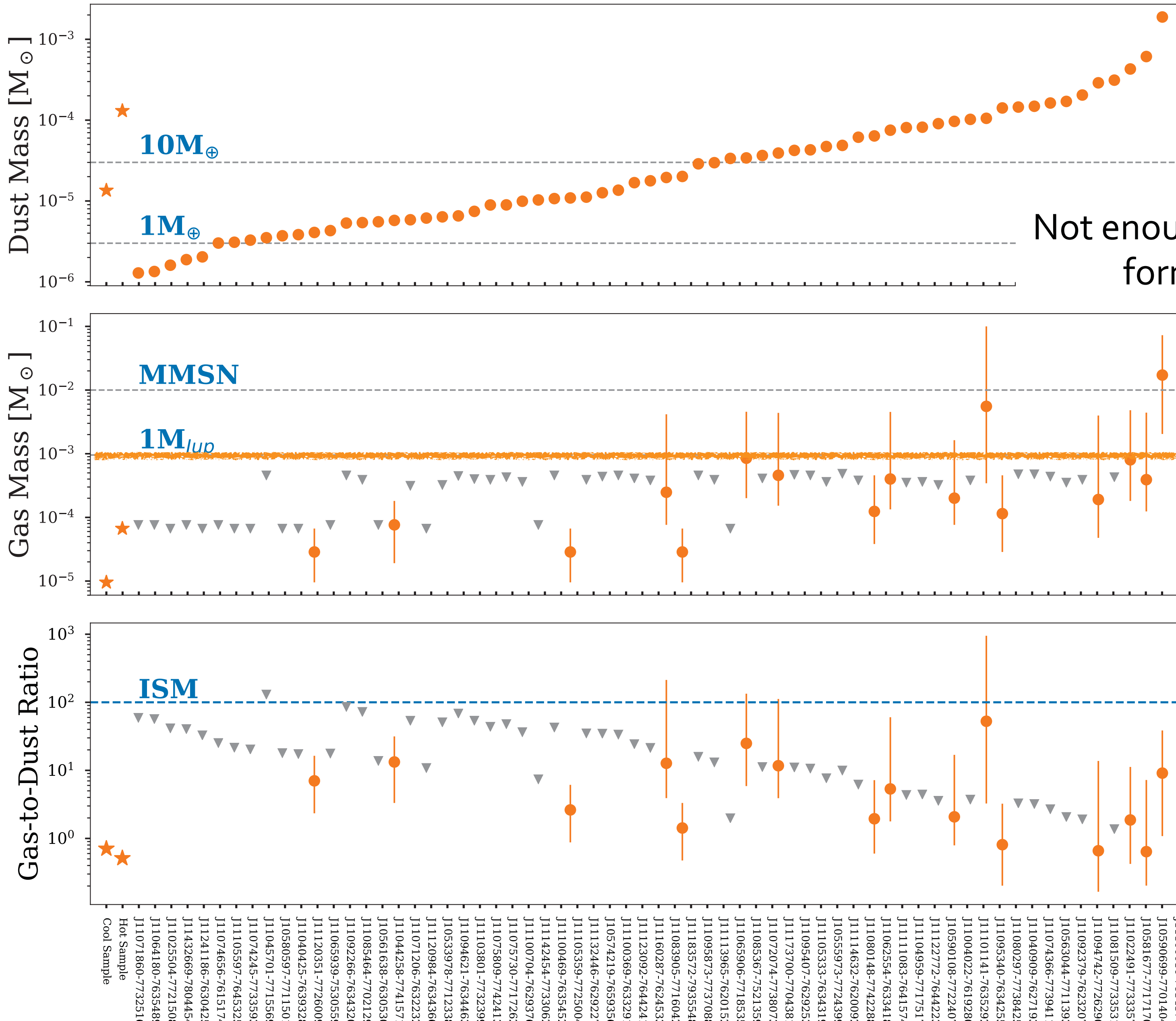
From Long+2018a

Cha I : 2 Myr-old star-forming region

Dust Mass

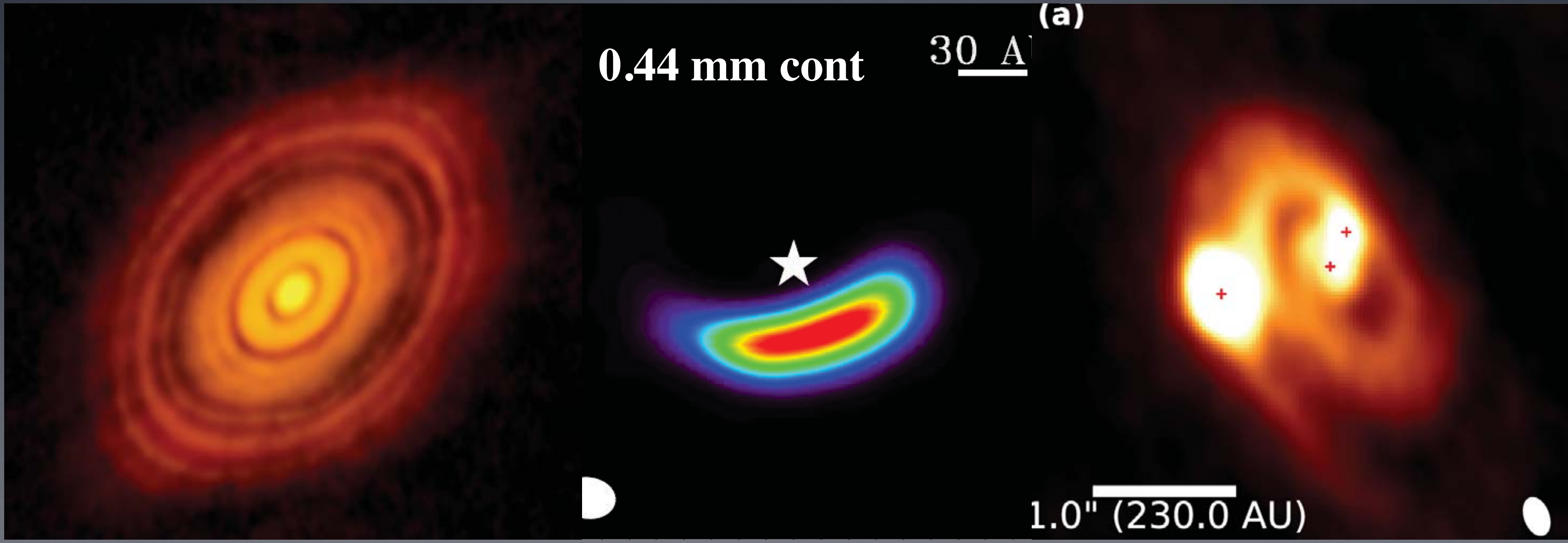
Gas Mass

ratio



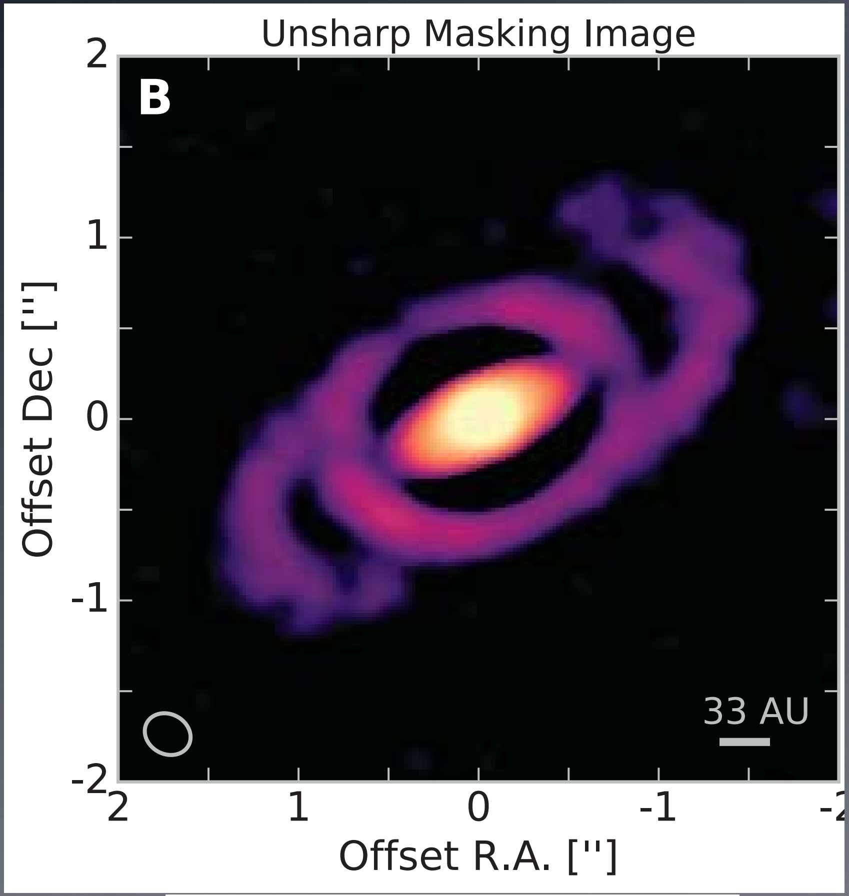
Not enough mass lef
form planets

The ALMA revolution:
Dust structures in protoplanetary disks

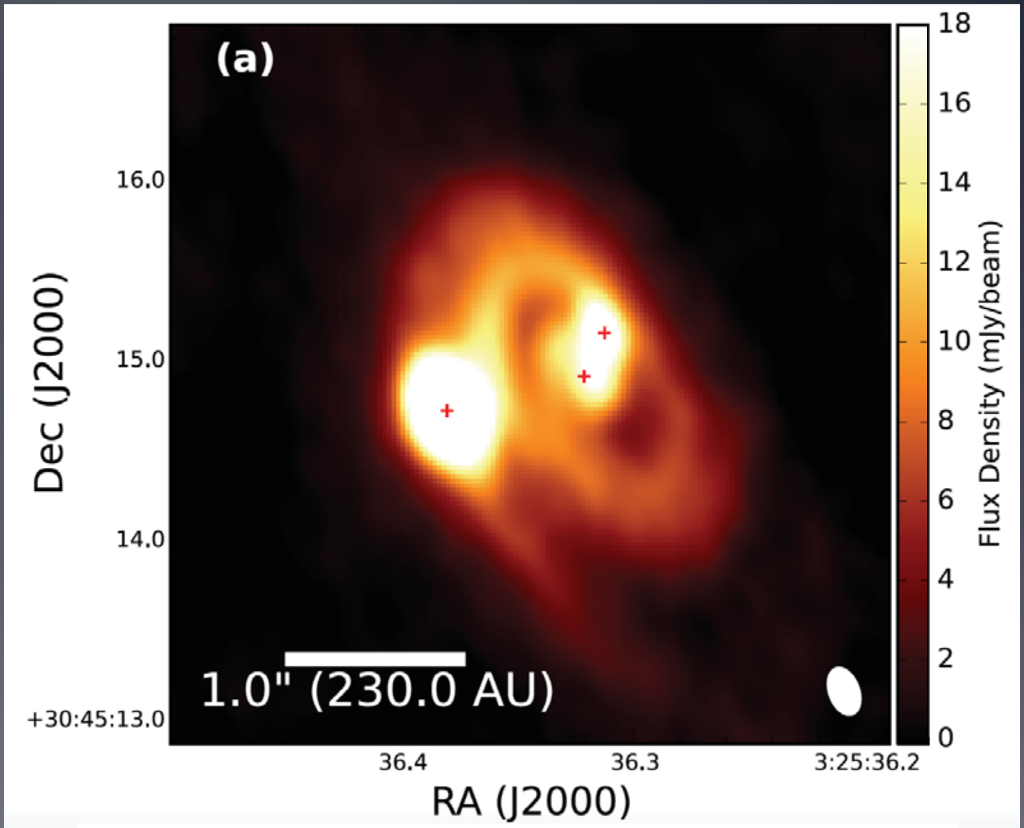


Radial drift: dust flows to pressure maxima

Spirals in young protoplanetary disks



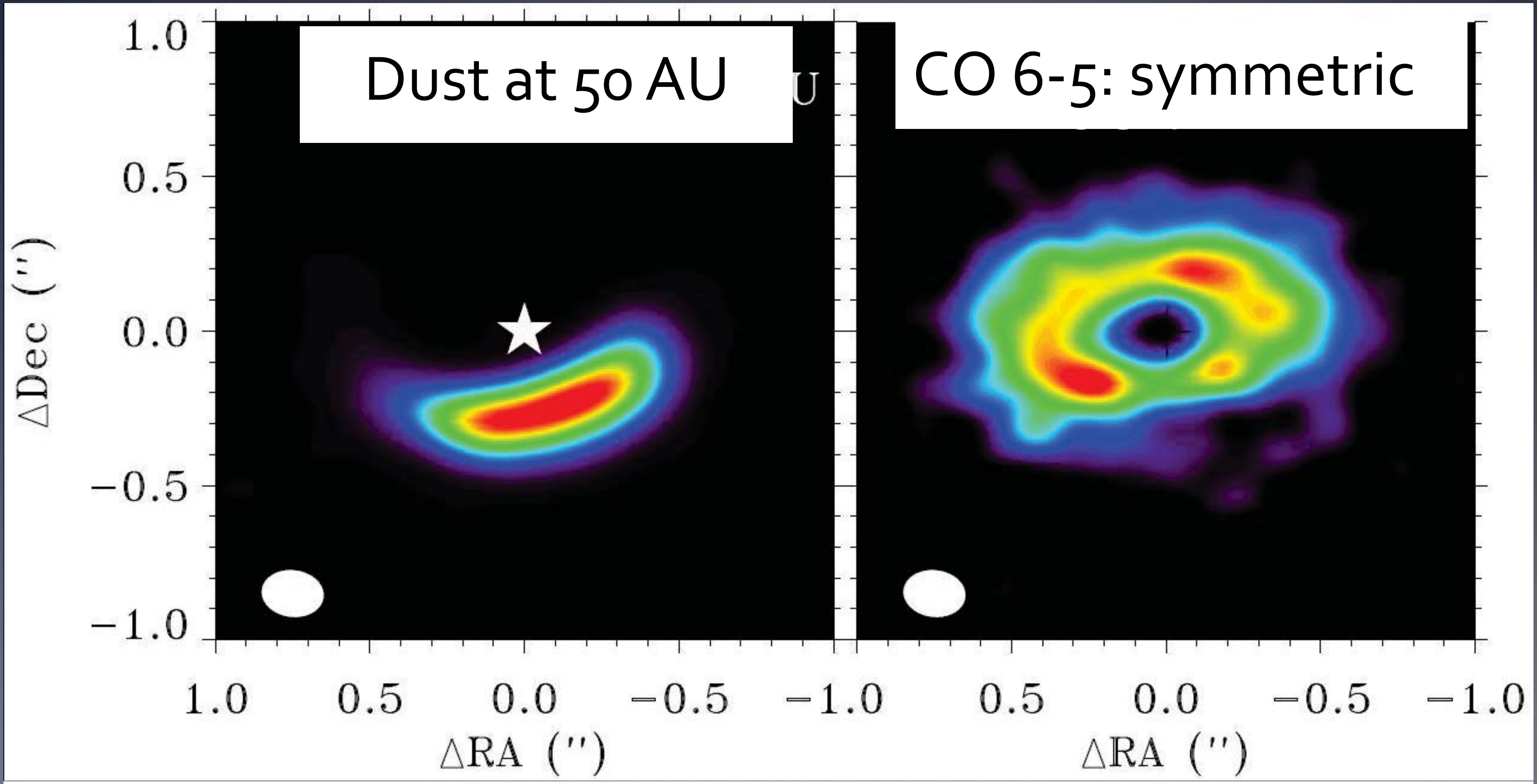
spiral density waves (Perez+2016)



Binary formation in young, gravitationally unstable disk (Tobin+2016)

Dust trap in a transition disks

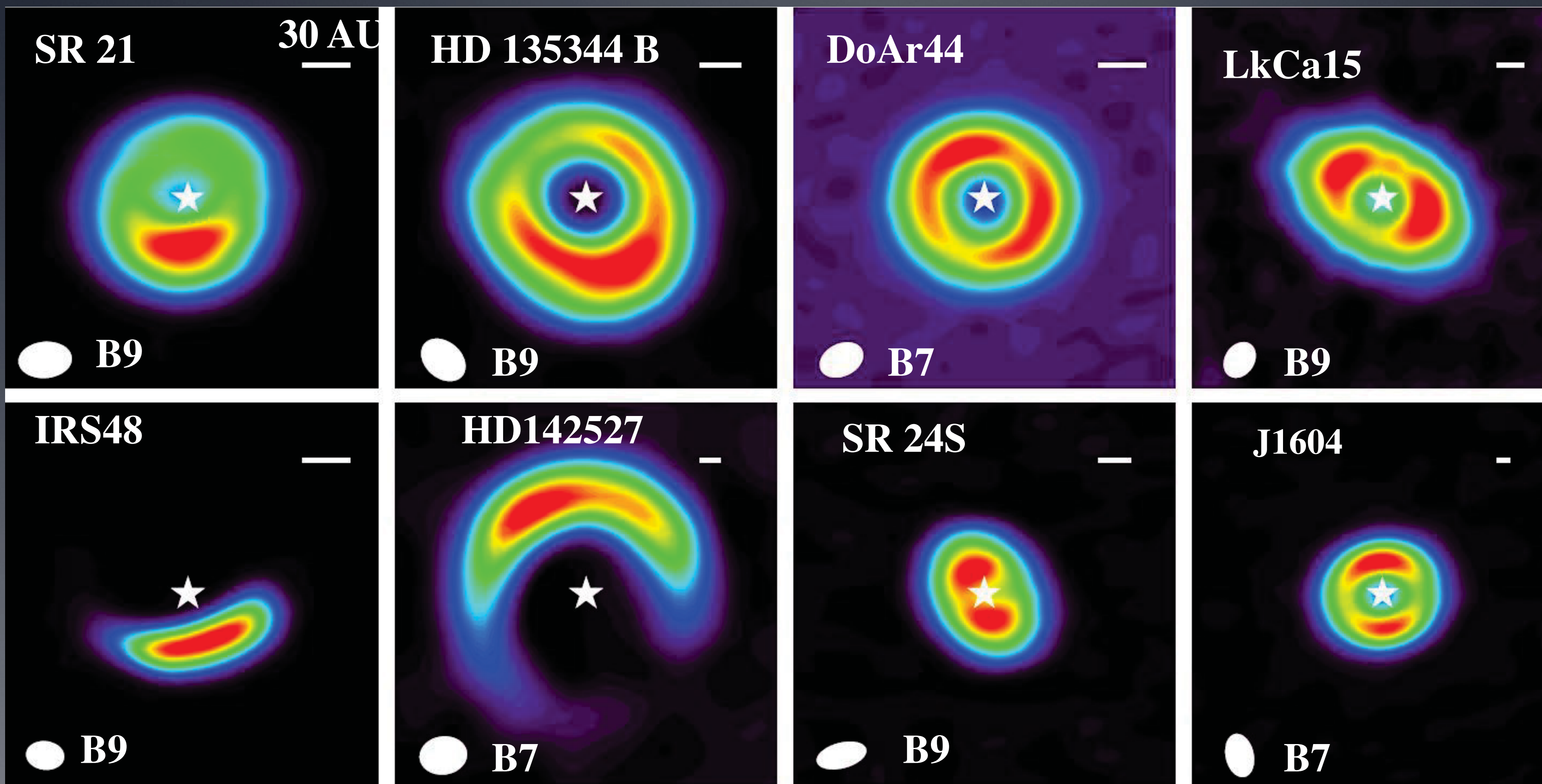
(van der Marel+2013, 2015)



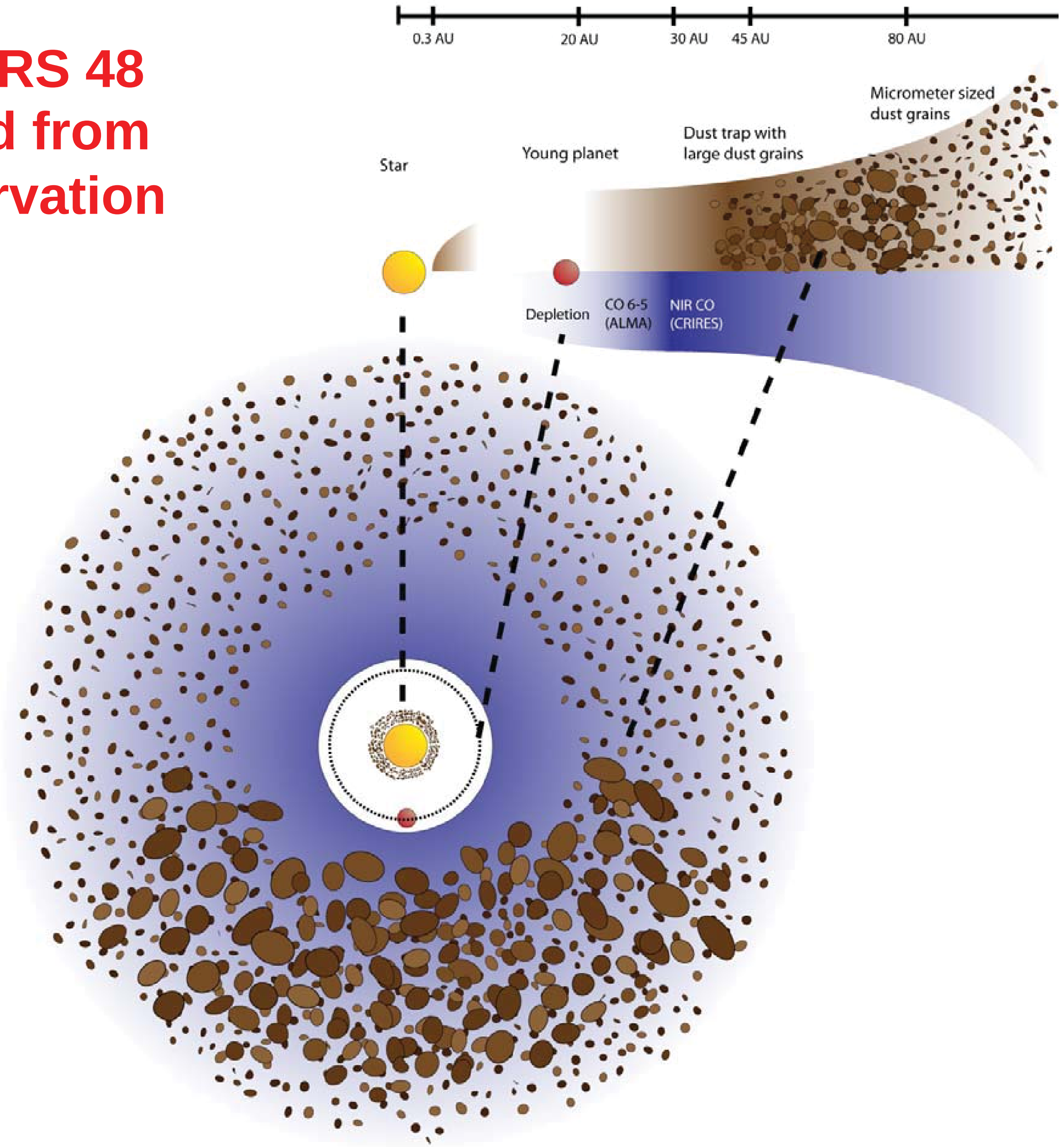
Planet inside hole: Vortex? Comet/KBO factory?

Dust traps with ALMA

(e.g., van der Marel+2015; Pinilla+2015)

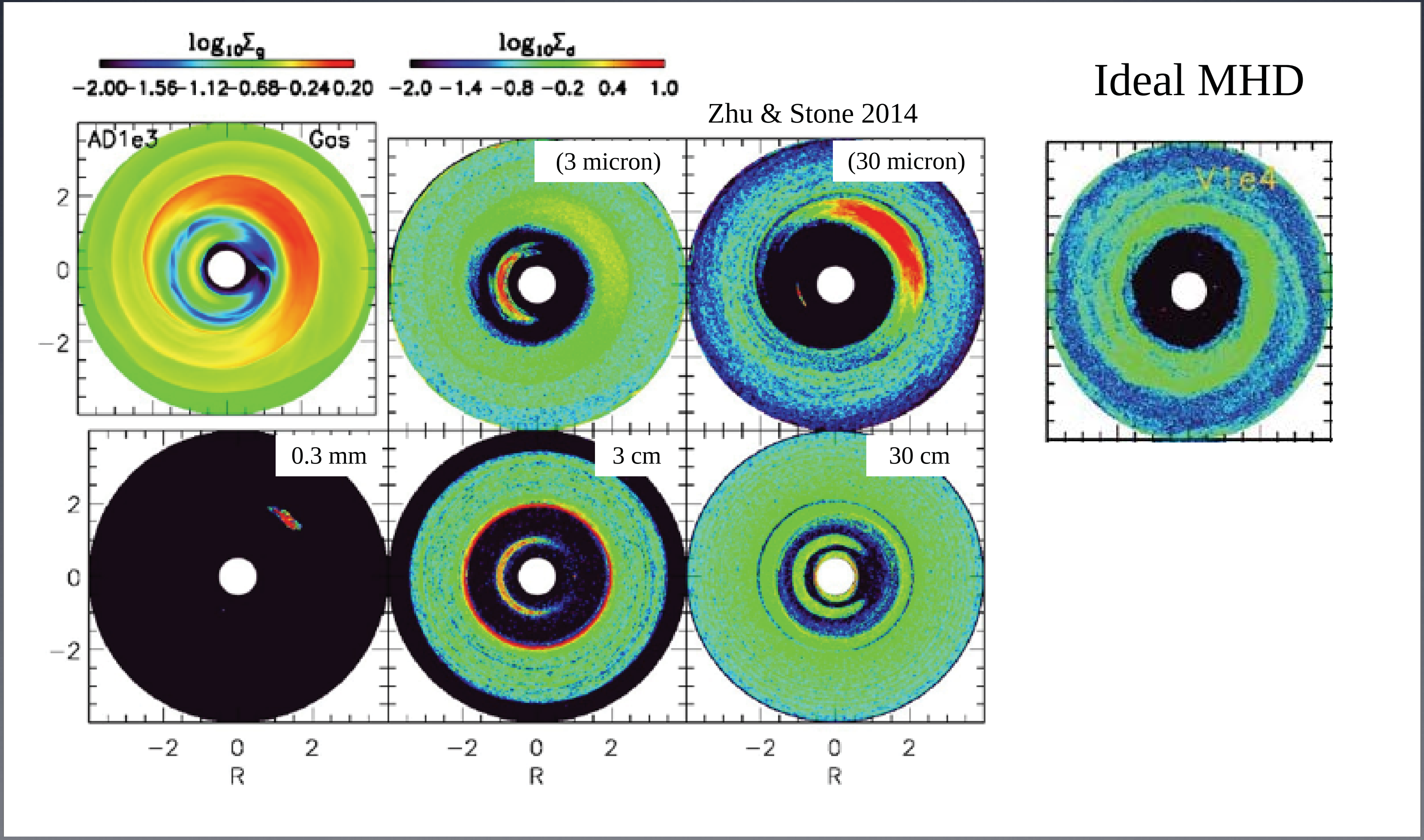


Cartoon of IRS 48 disk inferred from ALMA observation



Simulating dust traps

Zhu & Stone (2014)

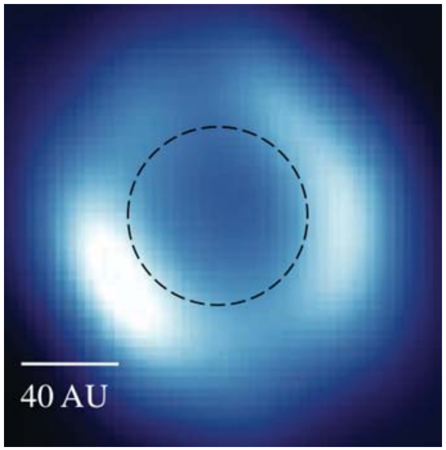


Decoupling of mm-sized, micron-sized

Dong et al. 2012, slide prepared by Ruobing Dong

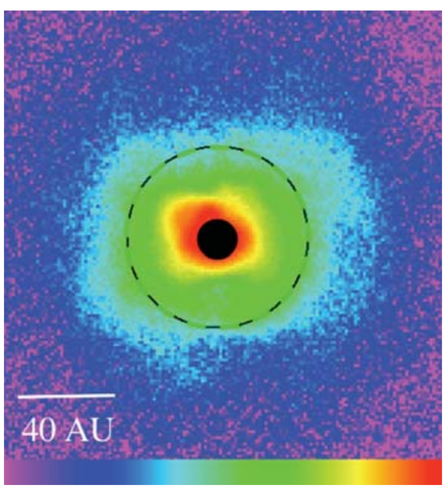
SR 21, SMA 0.88 mm Image

Andrews et al. 2011, Williams & Cieza 2011

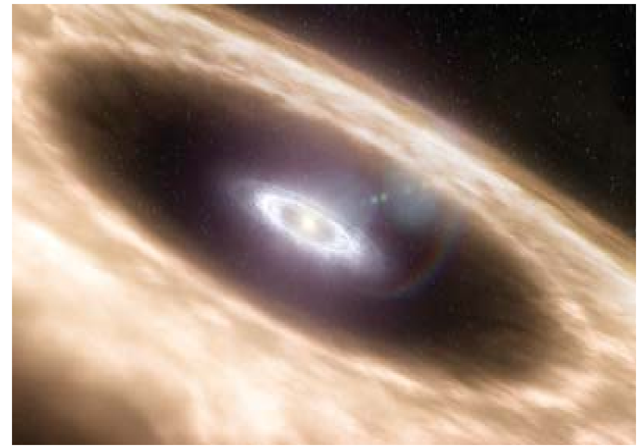


SR 21, Subaru H-band Image

Follette et al. 2013

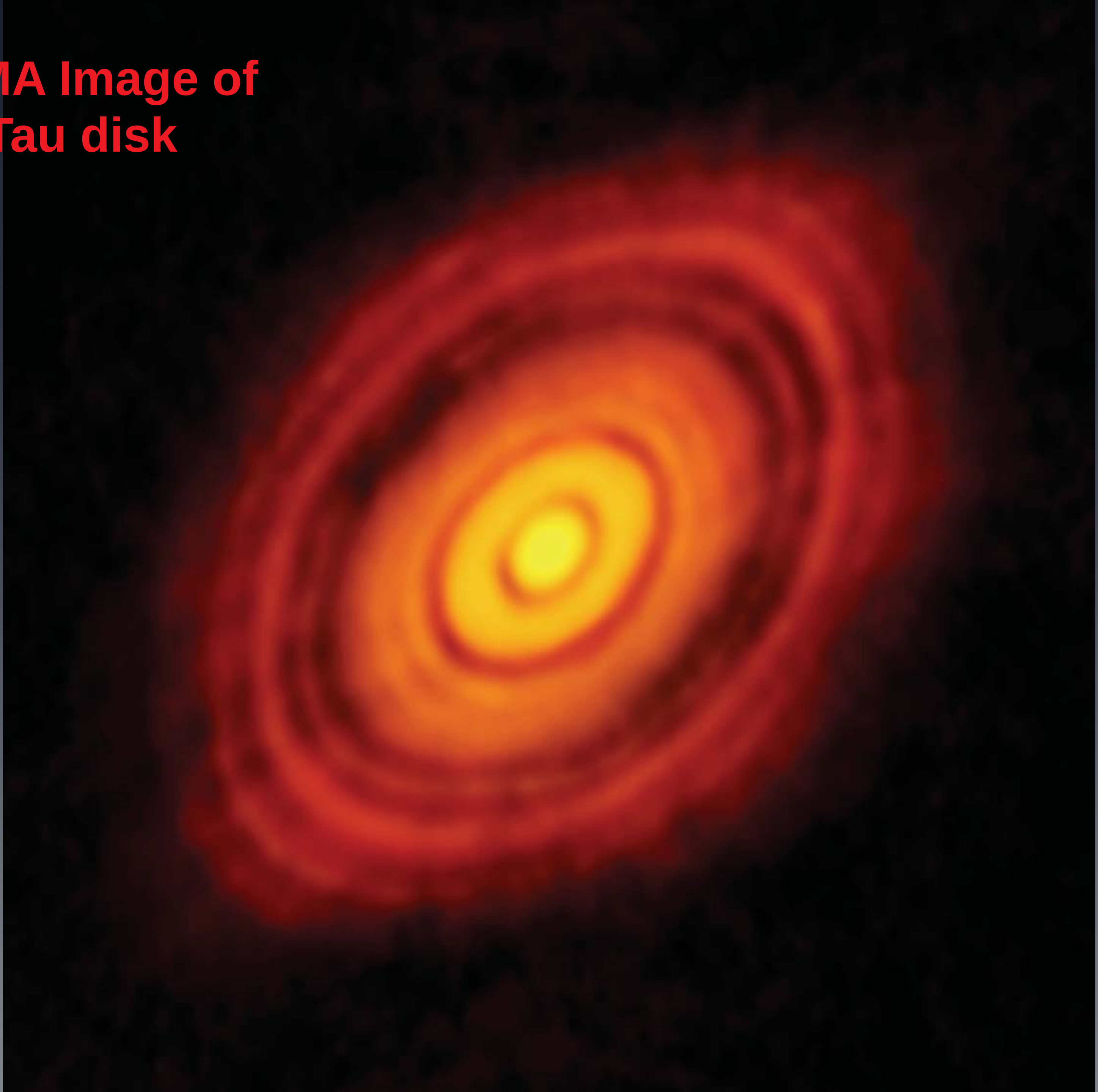


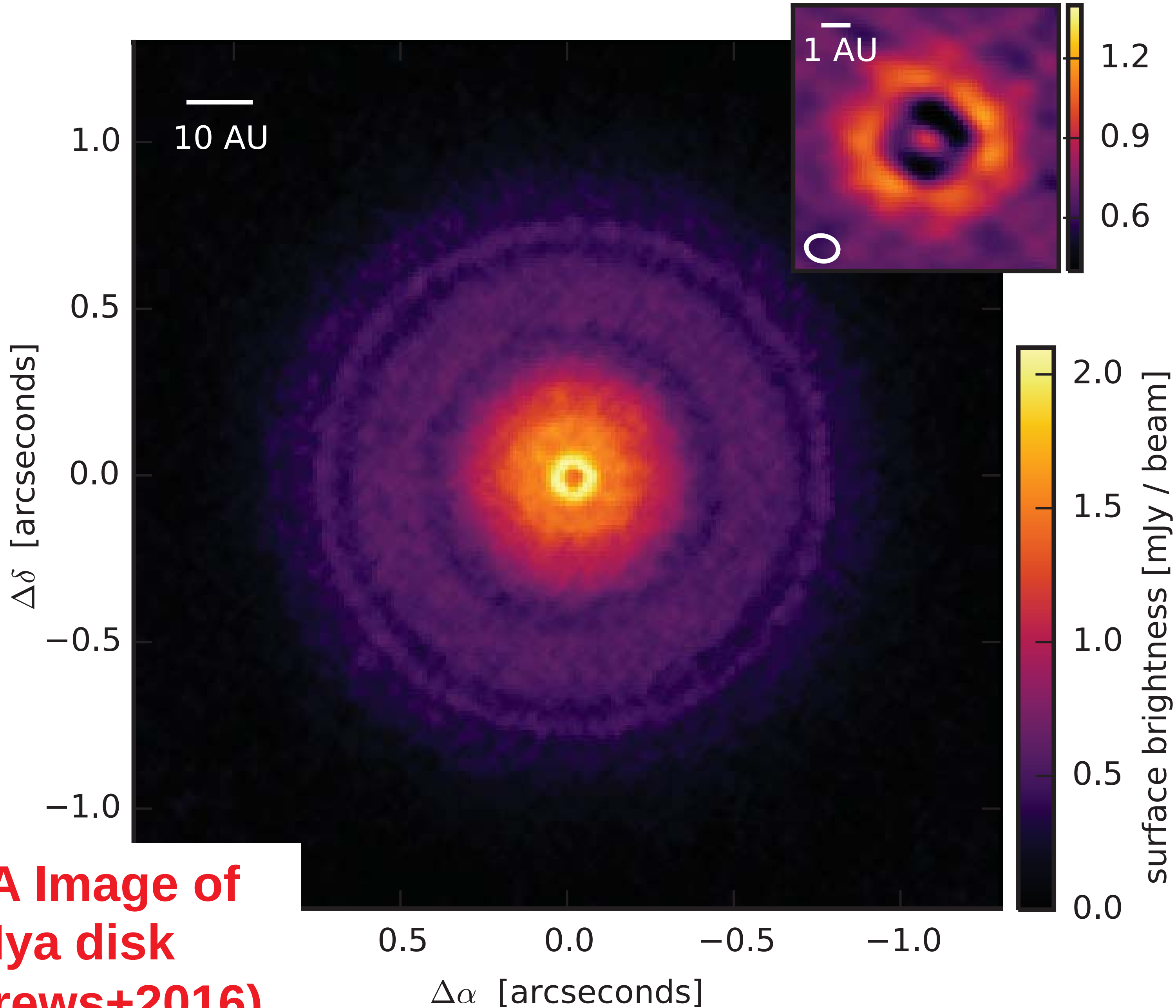
~mm-sized grains



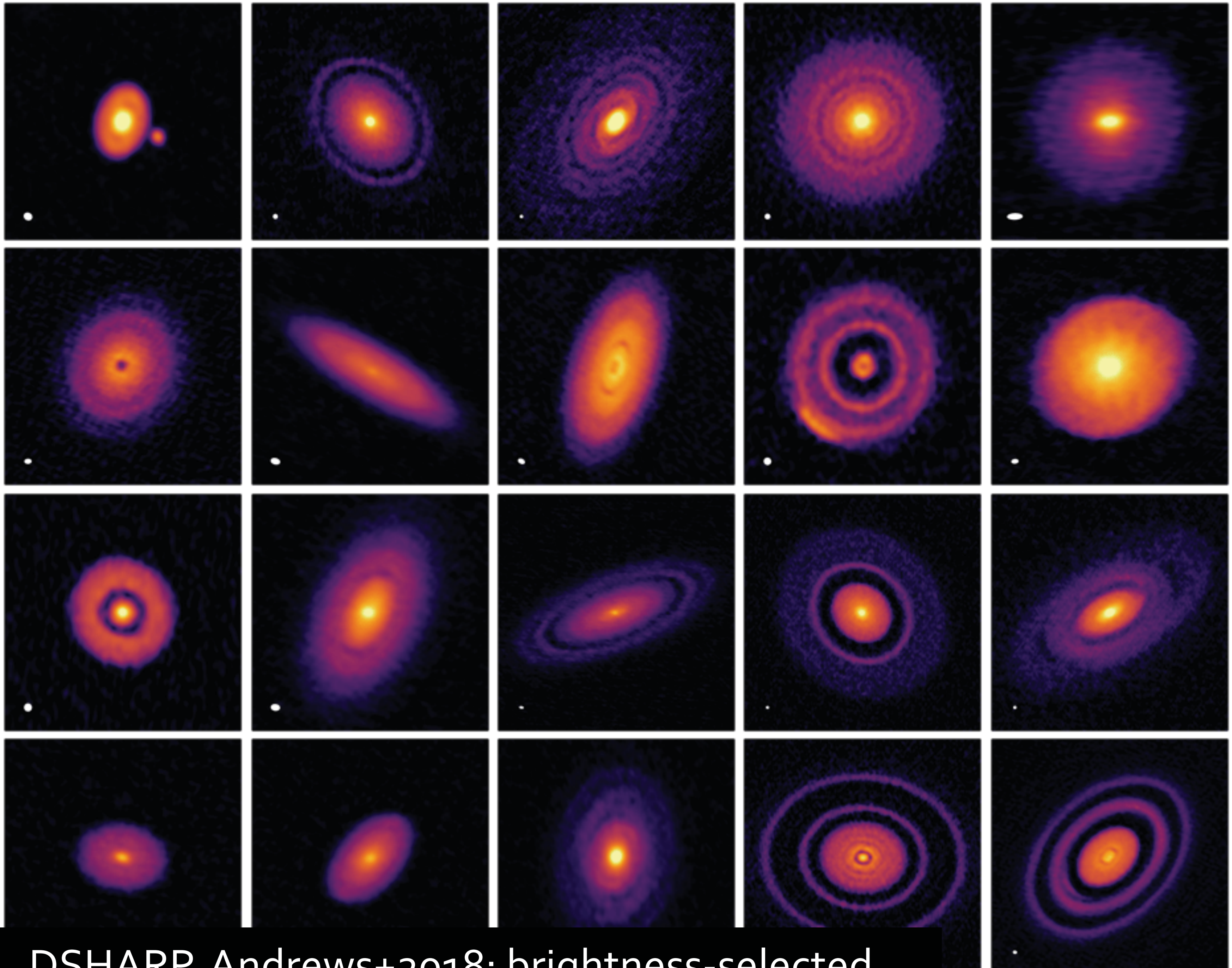
~sub-micron-sized grains

ALMA Image of HL Tau disk





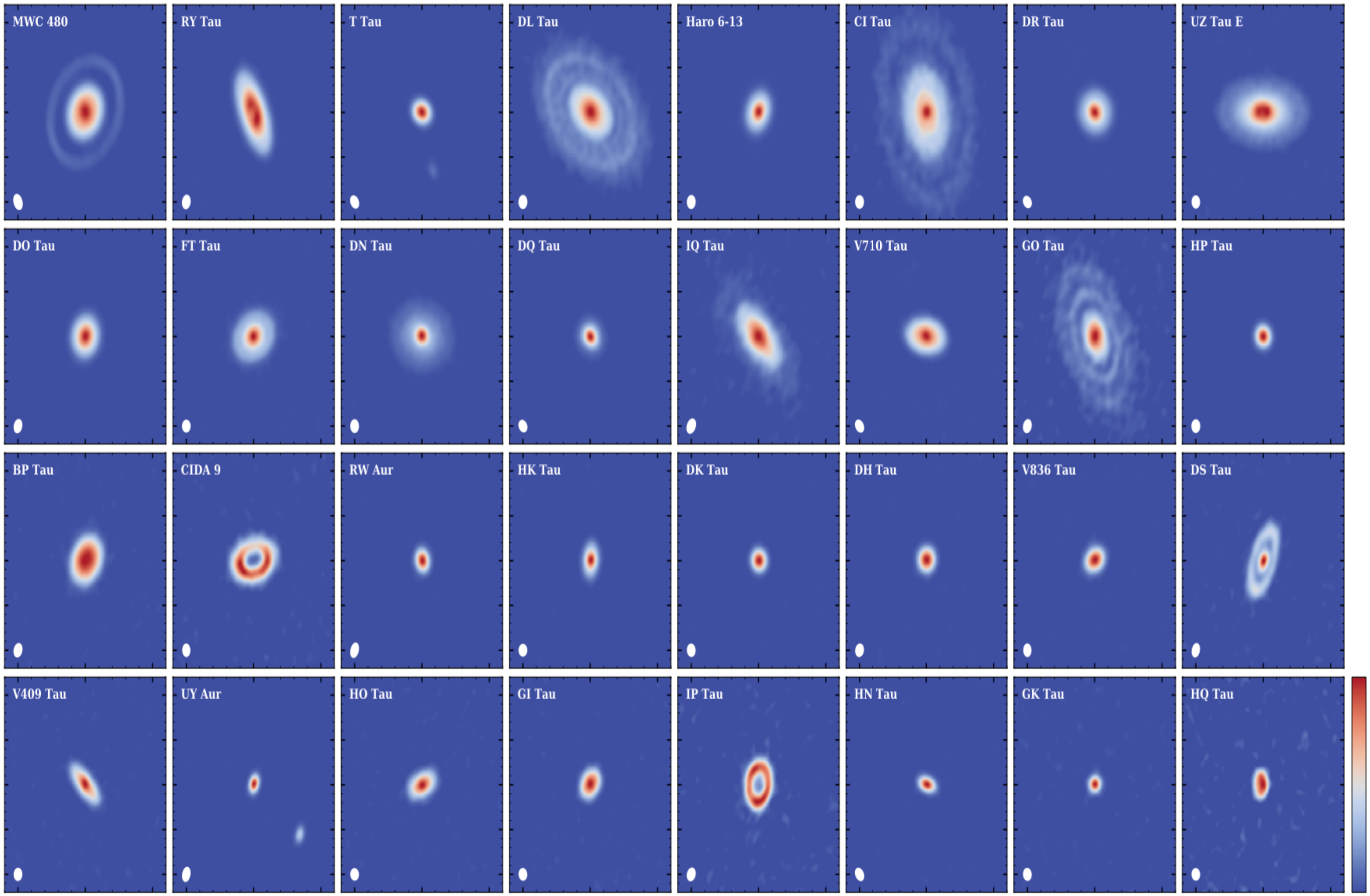
ALMA Image of TW Hya disk (Andrews+2016)



DSHARP, Andrews+2018: brightness-selected

Unbiased-ish ALMA survey of Taurus disks (0.1"/14 AU)

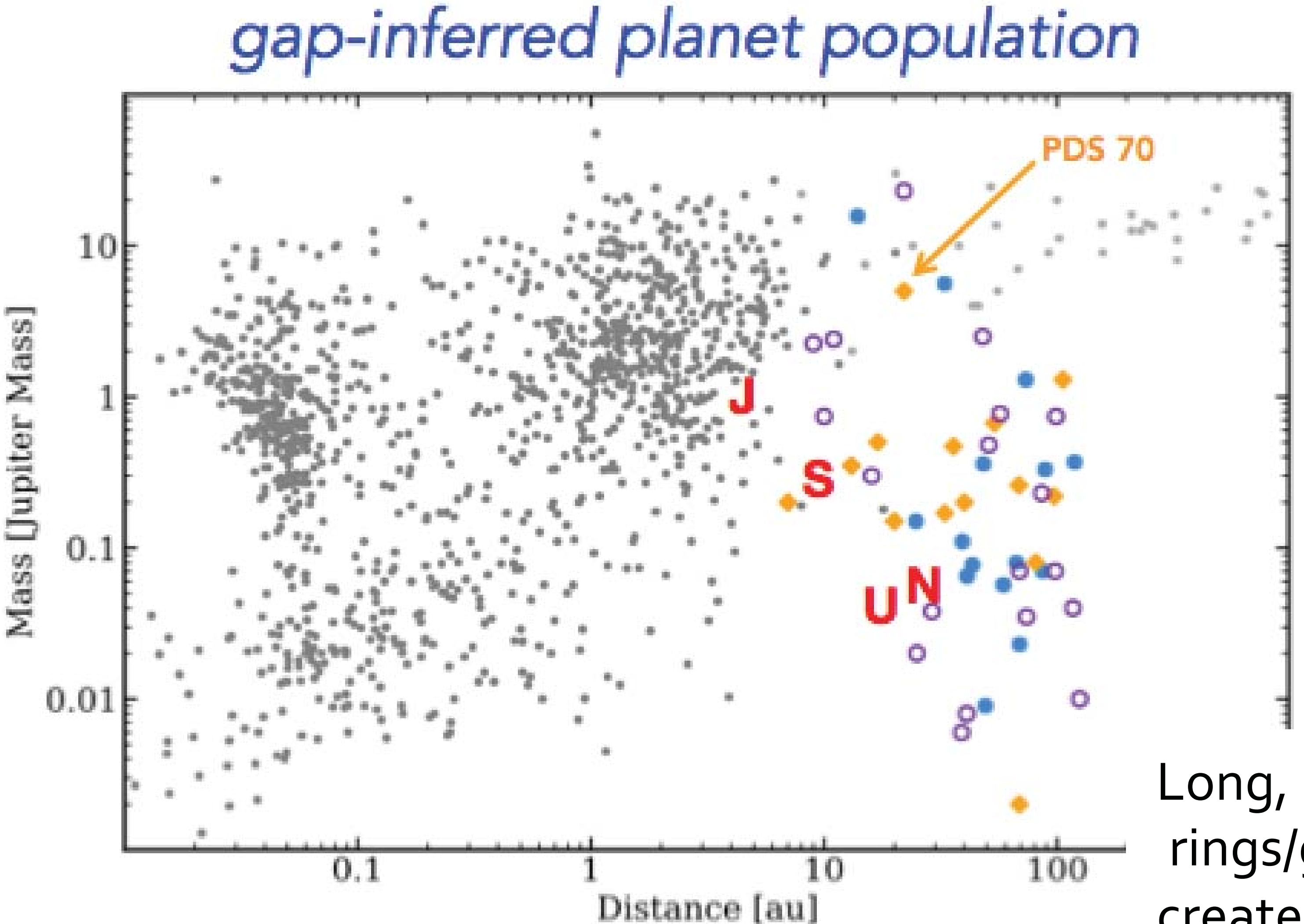
Long et al. 2018/2019, Yao Liu et al. 2018; Lodato+2019, Manara et al. 2019; includes Herczeg (PI), Pinilla, Harsono, Ragusa, Dipierro, Tazzari, Salyk, and ~10 others



2.4" (350 AU) on each side

What if the gaps are carved by young planets?

(Lodato et al. 2019)

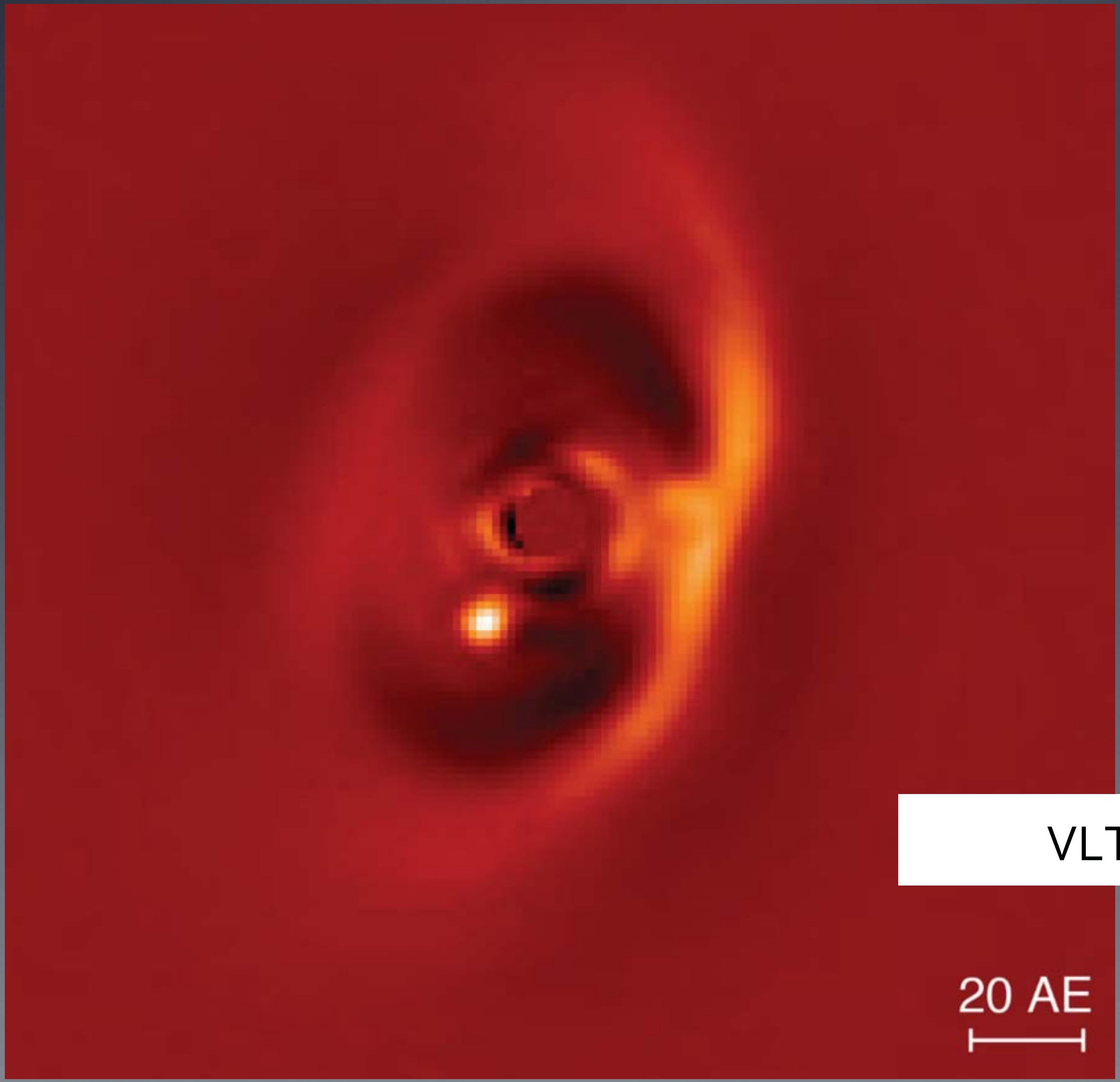


Long, Pinilla+2018: rings/gaps are not created by ice lines

Zhang+2018 (DSHARP); Bae+2018 (archival)

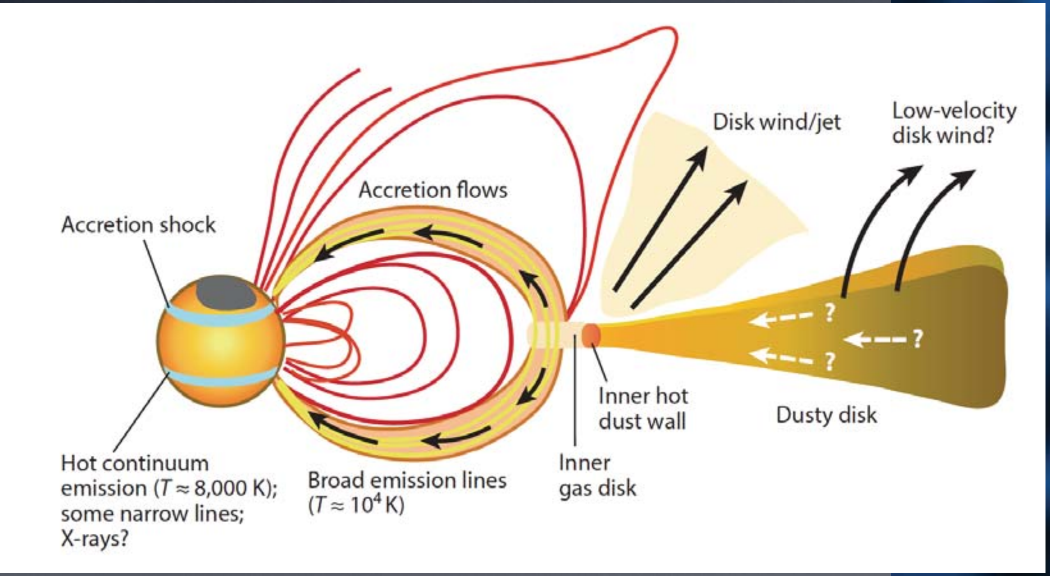
Planet(s) in a disk around the star PDS 70!

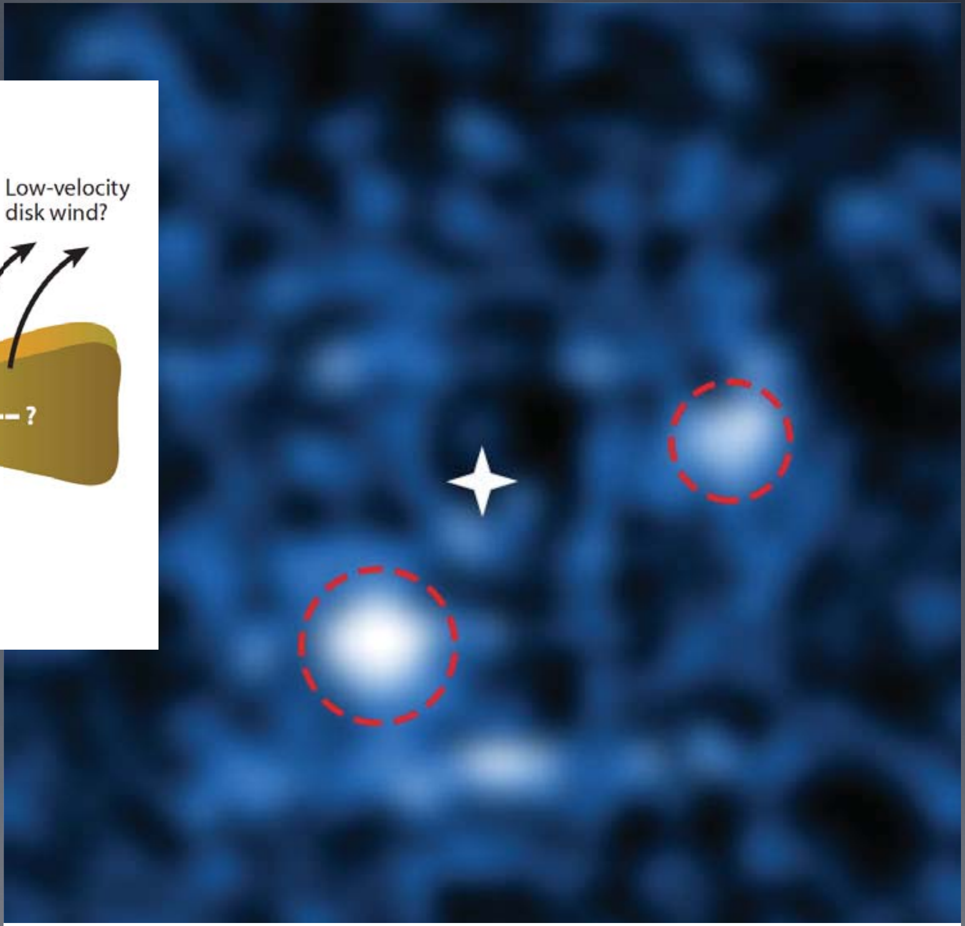
(Keppler et al. 2018)



VLT/Sphere

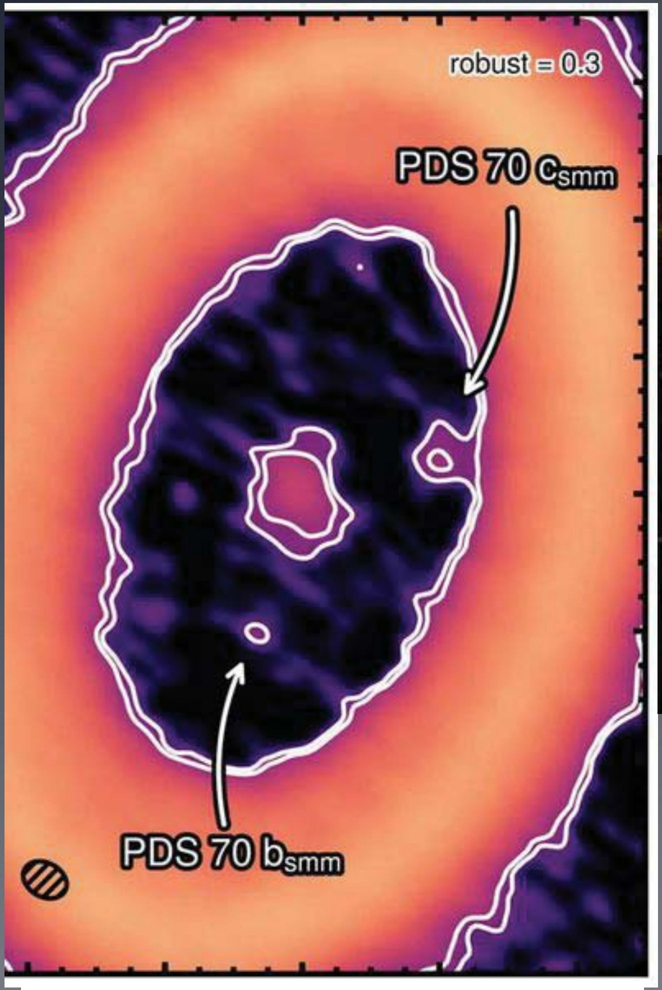
Proto-lunar disks around PDS 70bc?



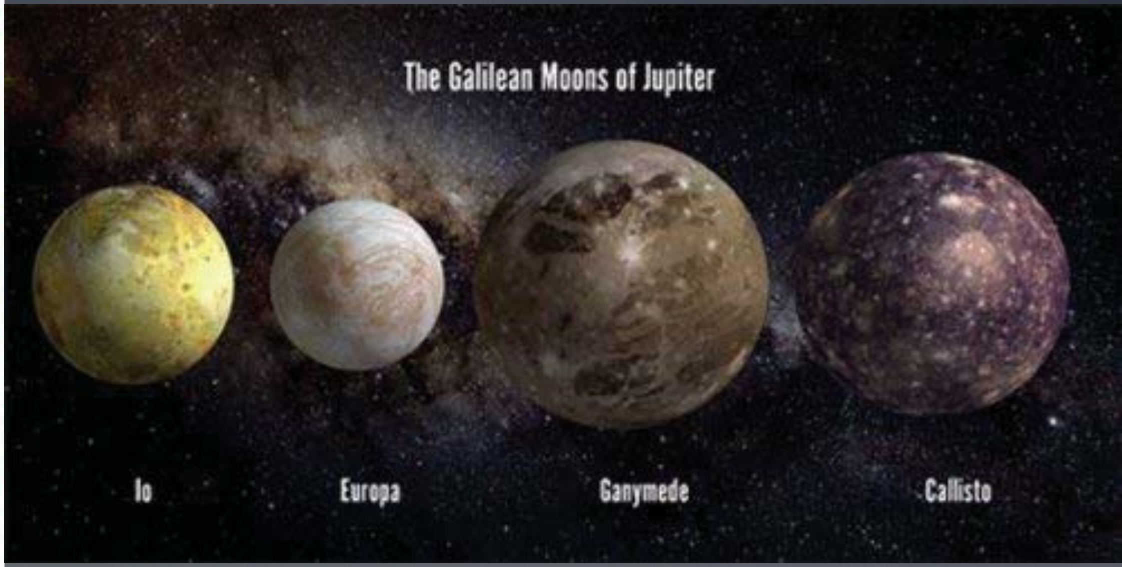


MUSE/H-alpha accretion, Haffert+2019
See also, eg., Bowler+2013; Zhou, Herczeg, et al. 2014; Wagner+2019

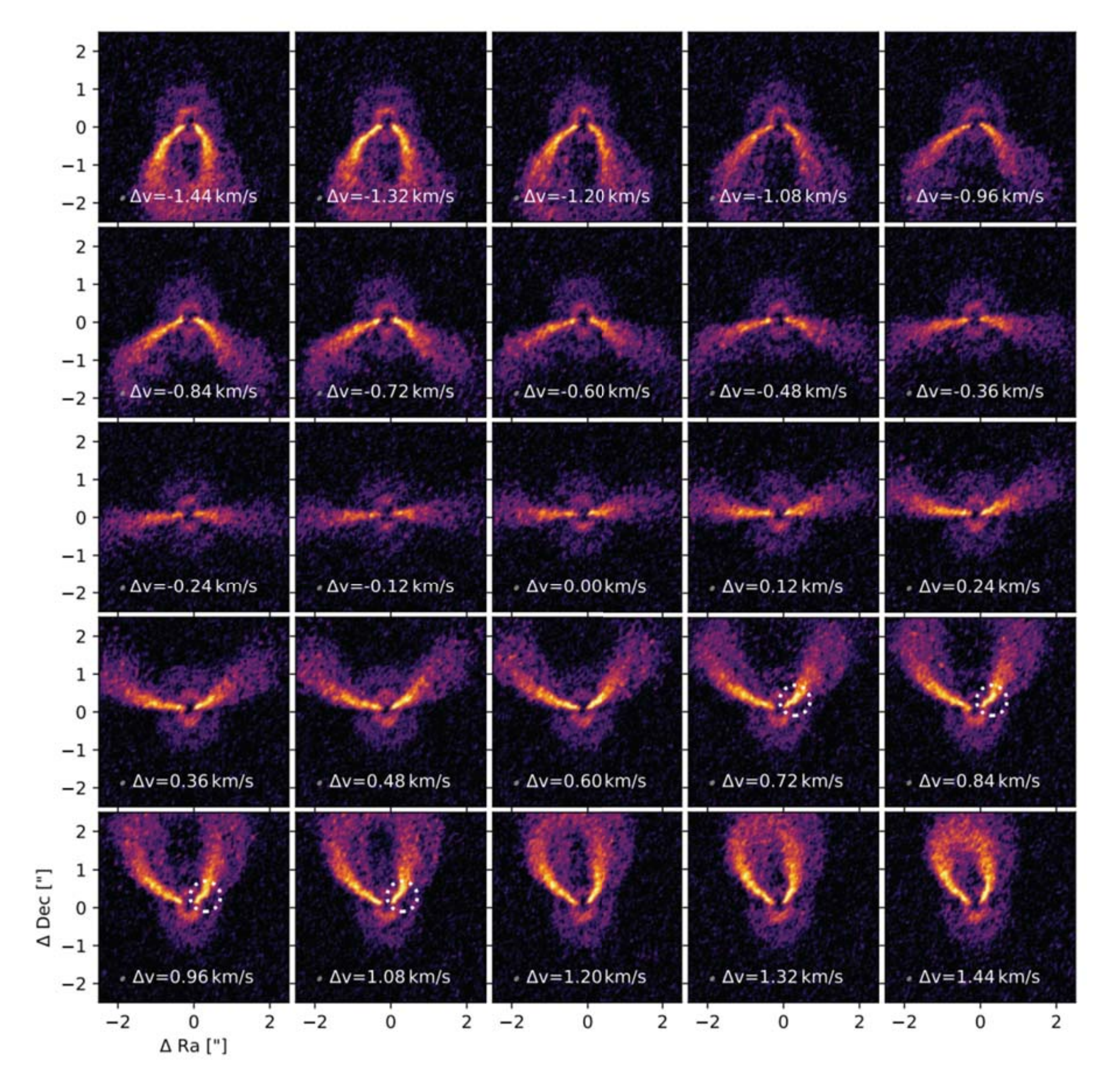
Proto-lunar disks around PDS 70bc?

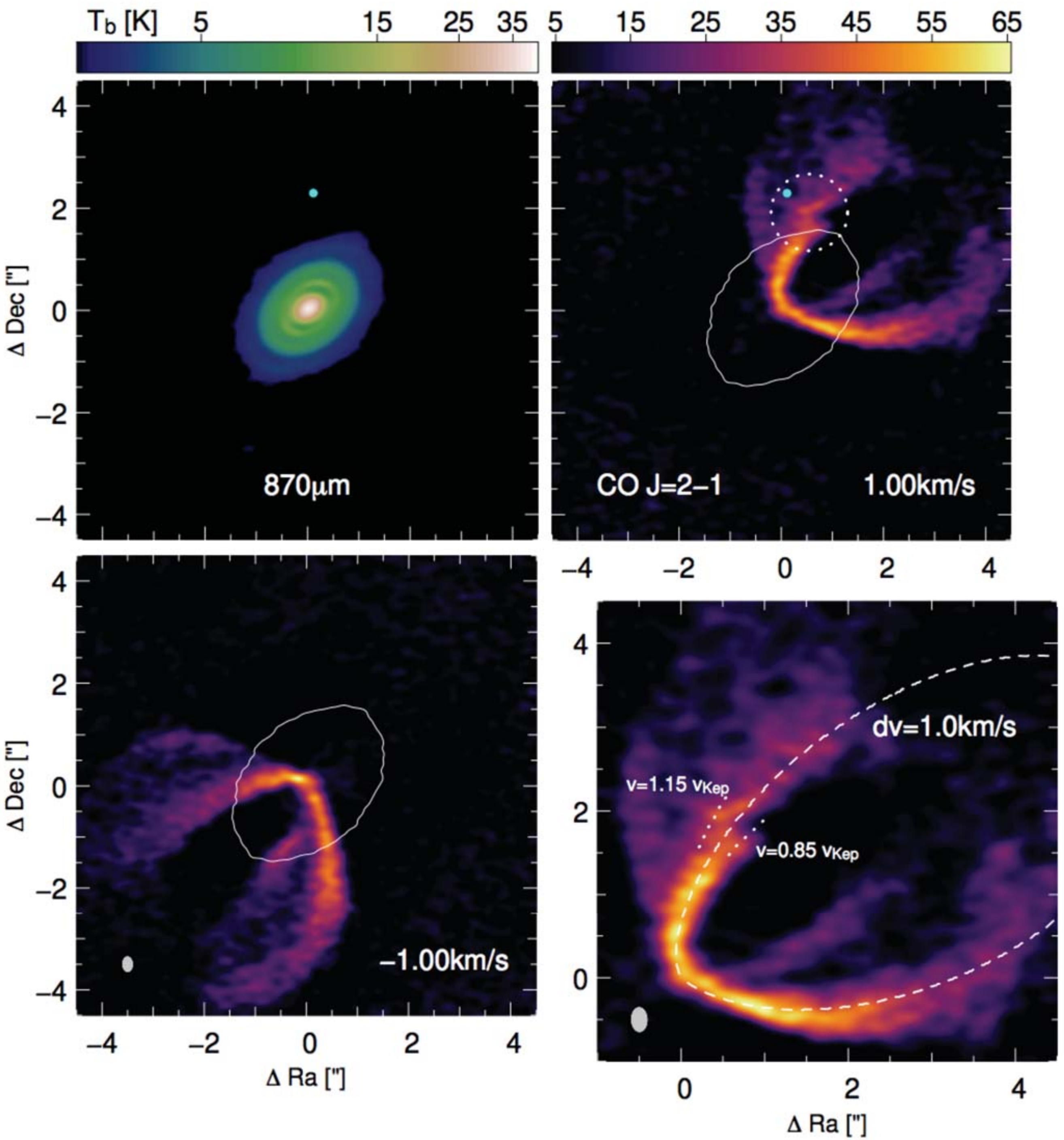


ALMA/dust, Isella+2019

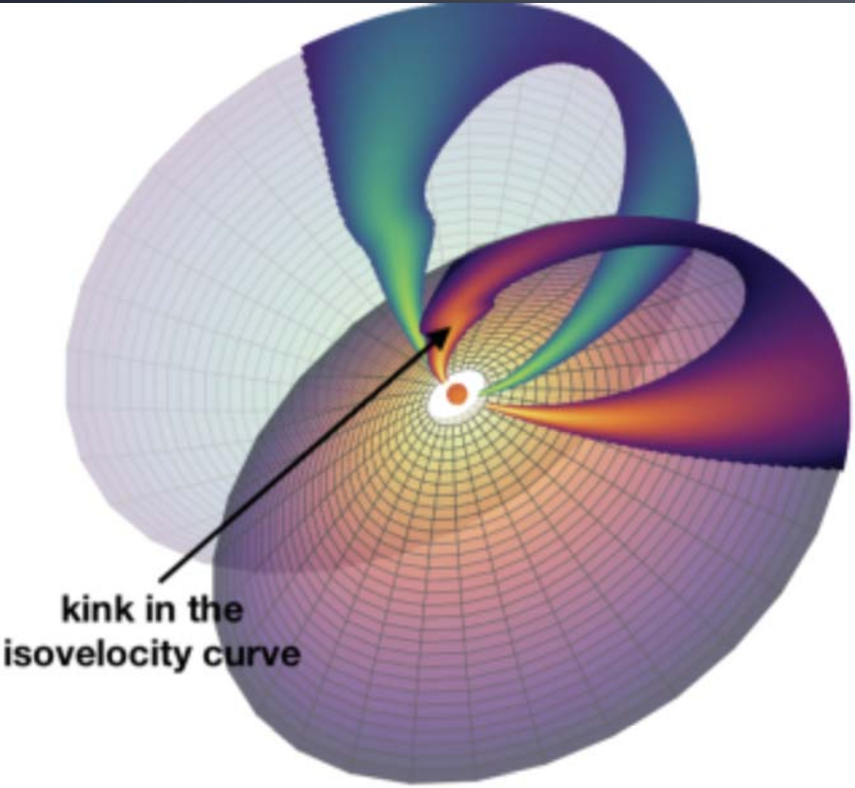


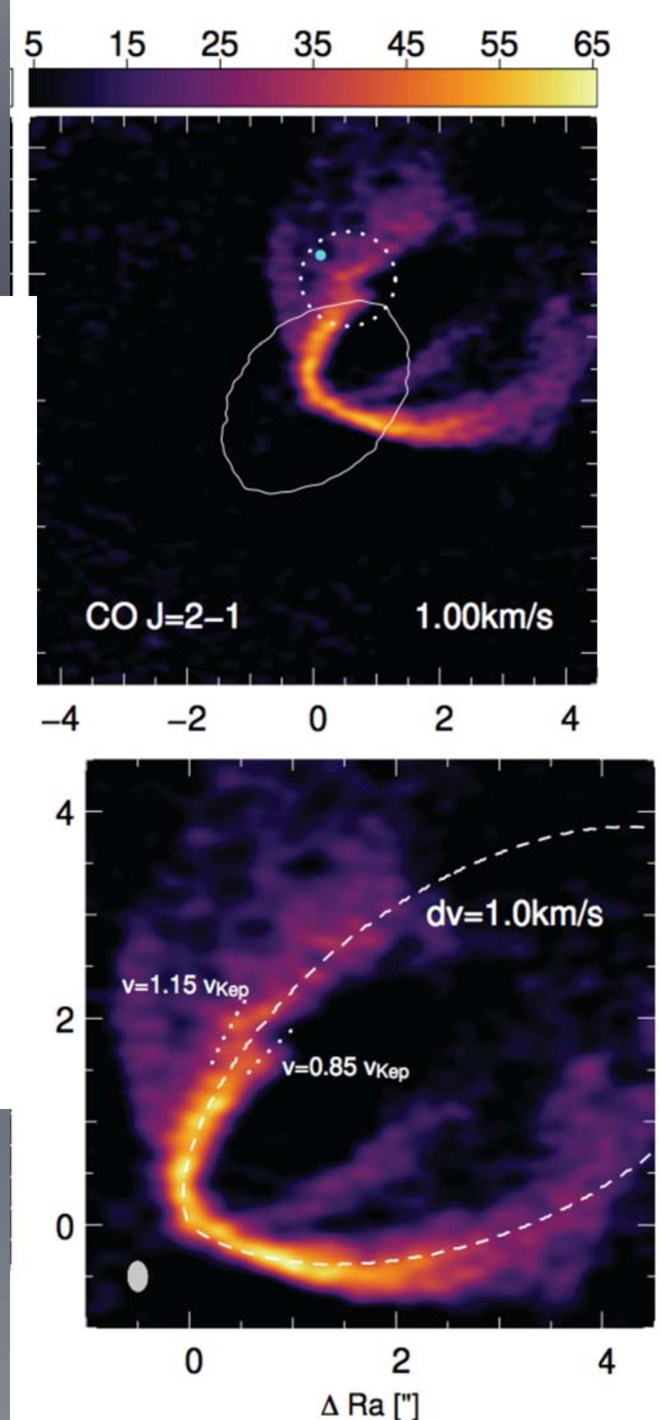
CO channel maps: maps at different velocities of an emission line

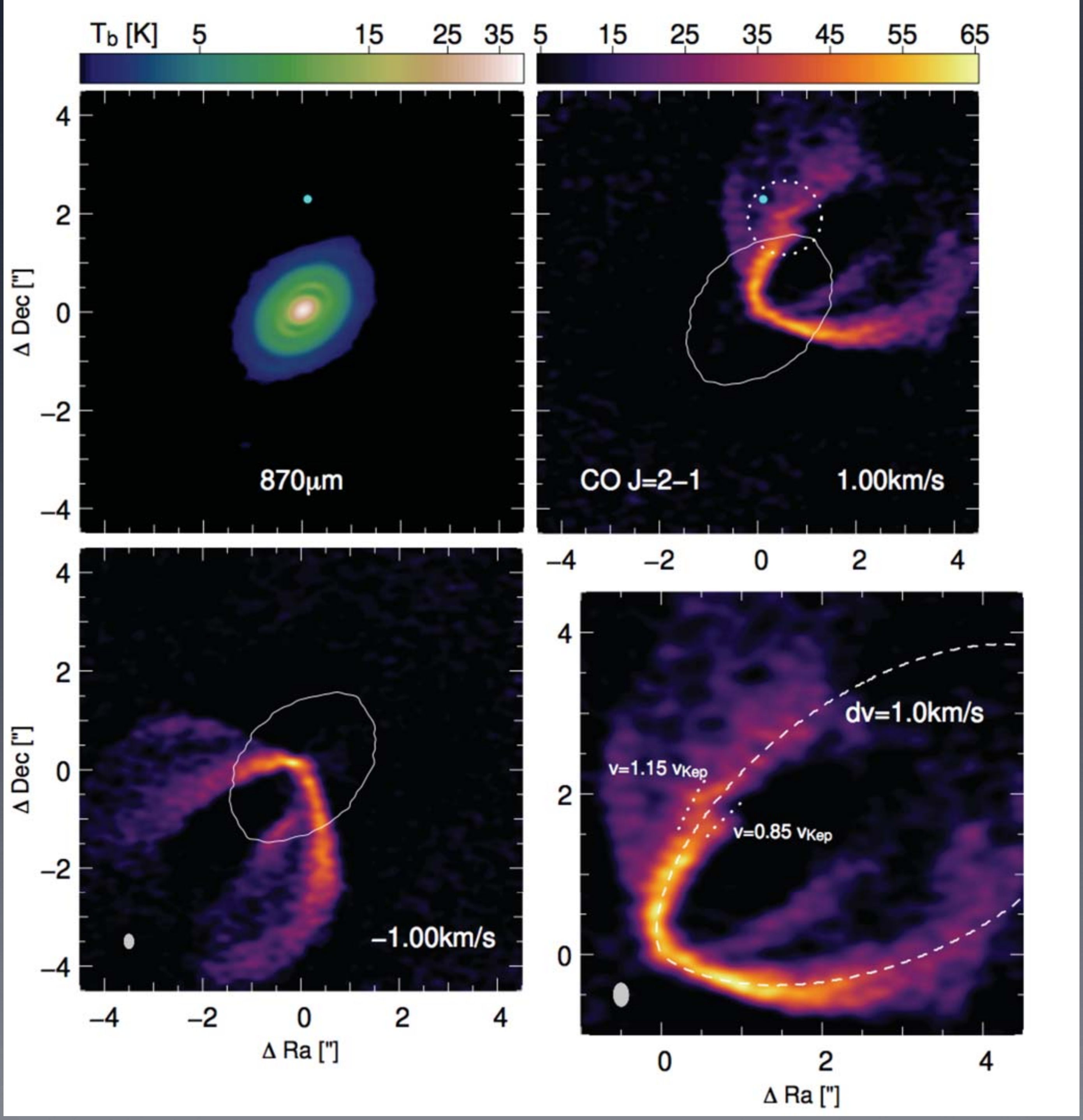




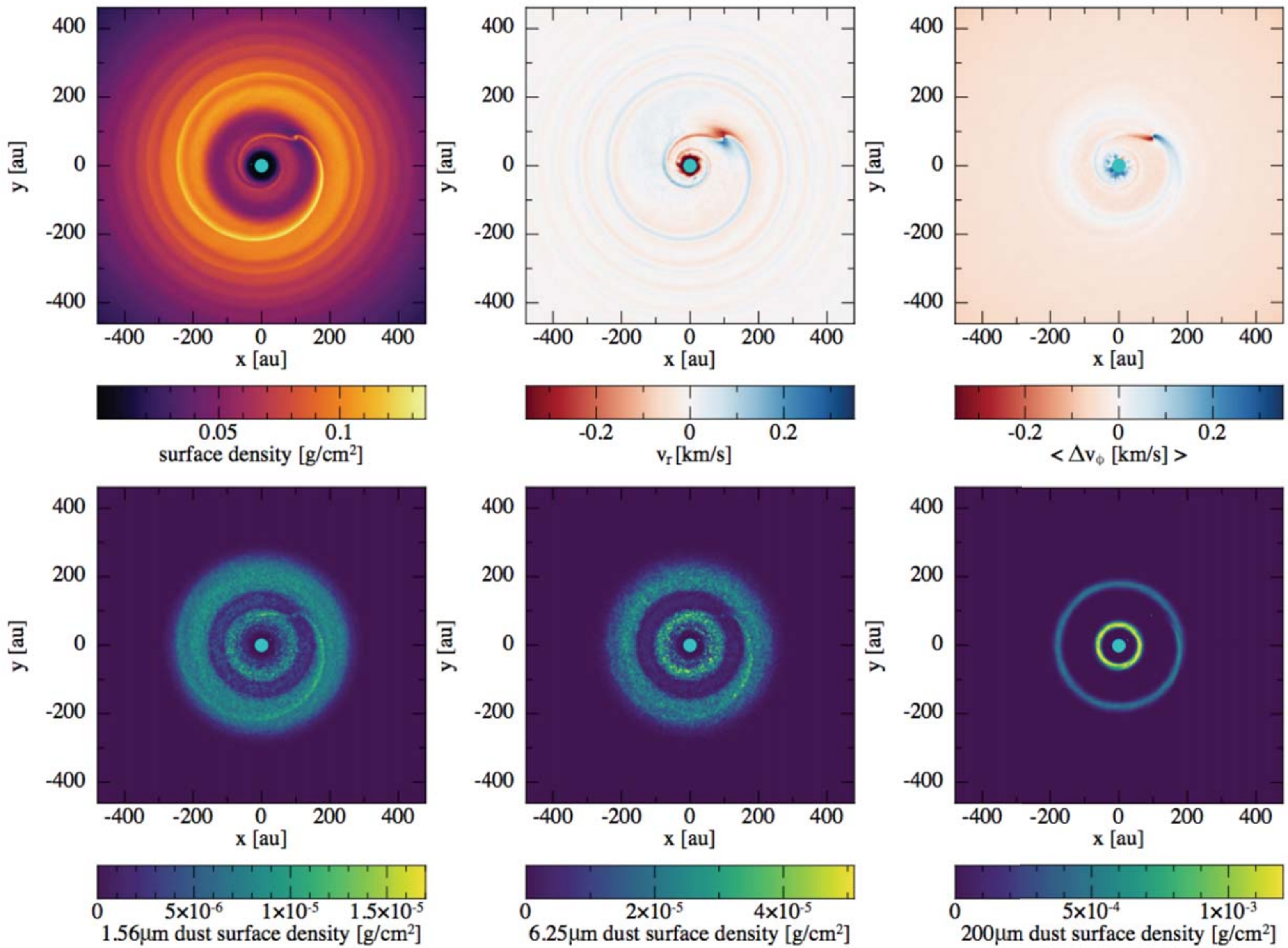
Tb [K] 5 15 25 35
5 15 25 35 45 55 65
870μm
CO J=2−1
1.00km/s
−1.00km/s
dv=1.0km/s
v=1.15 vKep
v=0.85 vKep
Δ Dec ["]
Δ Ra ["]


kink in the
isovelocity curve


5 15 25 35 45 55 65
CO J=2−1
1.00km/s
dv=1.0km/s
v=1.15 vKep
v=0.85 vKep
Δ Ra ["]



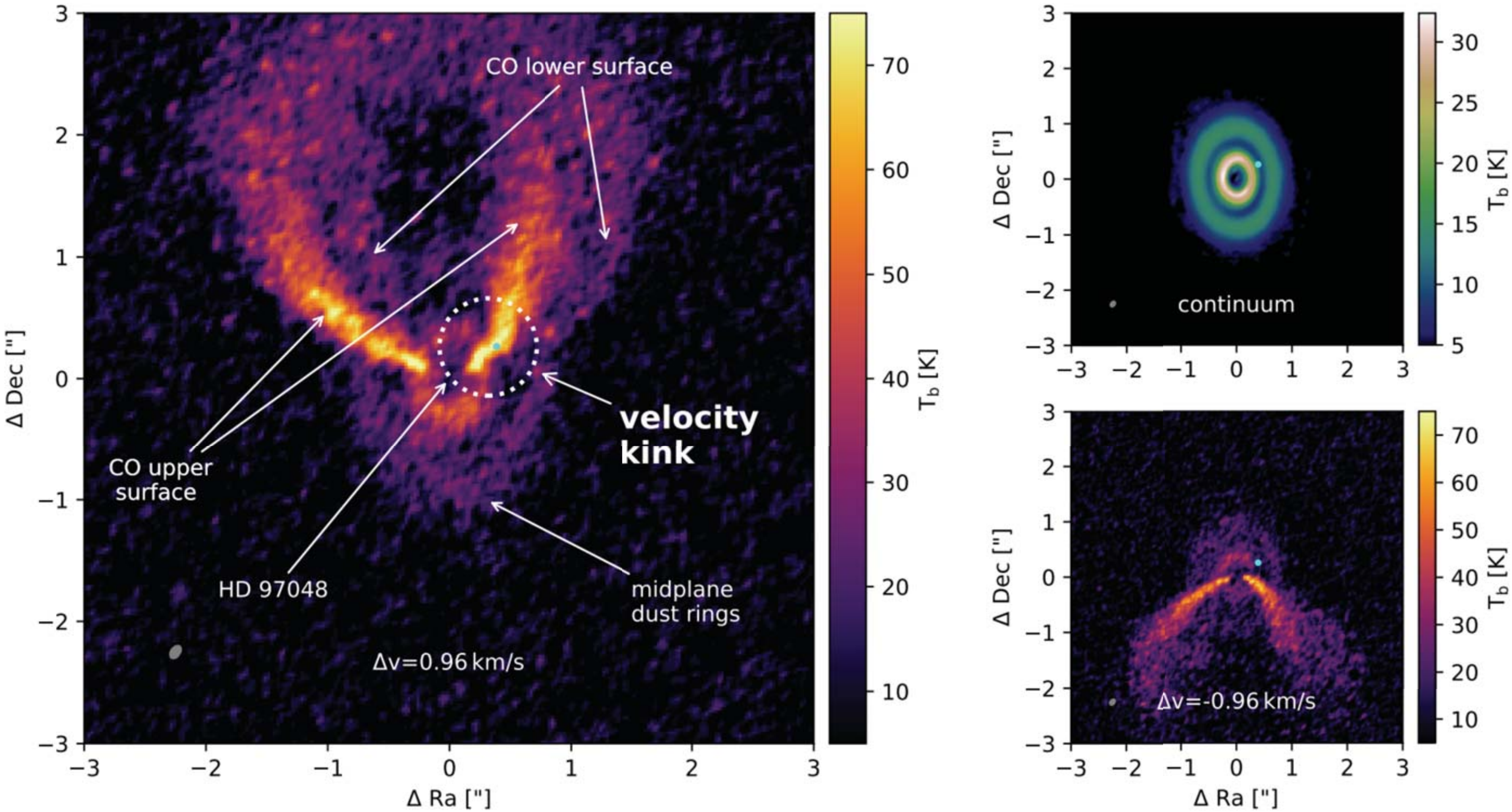
Tb [K]
5
15
25
35
5
15
25
35
45
55
65
870μm
CO J=2−1
1.00km/s
−1.00km/s
dv=1.0km/s
v=1.15 vKep
v=0.85 vKep
Δ Dec ["]
Δ Ra ["]



400
200
0
-200
-400
y [au]
-400 -200 0 200 400
x [au]
0.05 0.1
surface density [g/cm^2]
-0.2 0 0.2
v_r [km/s]
-0.2 0 0.2
$< \Delta v_\phi$ [km/s] $>$
0 5×10^{-6} 1×10^{-5} 1.5×10^{-5}
1.56μm dust surface density [g/cm^2]
0 2×10^{-5} 4×10^{-5}
6.25μm dust surface density [g/cm^2]
0 5×10^{-4} 1×10^{-3}
200μm dust surface density [g/cm^2]

Planet from kink in CO channel maps!

Pinte et al. 2018/2019; see also Teague+2018



Planet introduces spiral wave; location consistent with gap

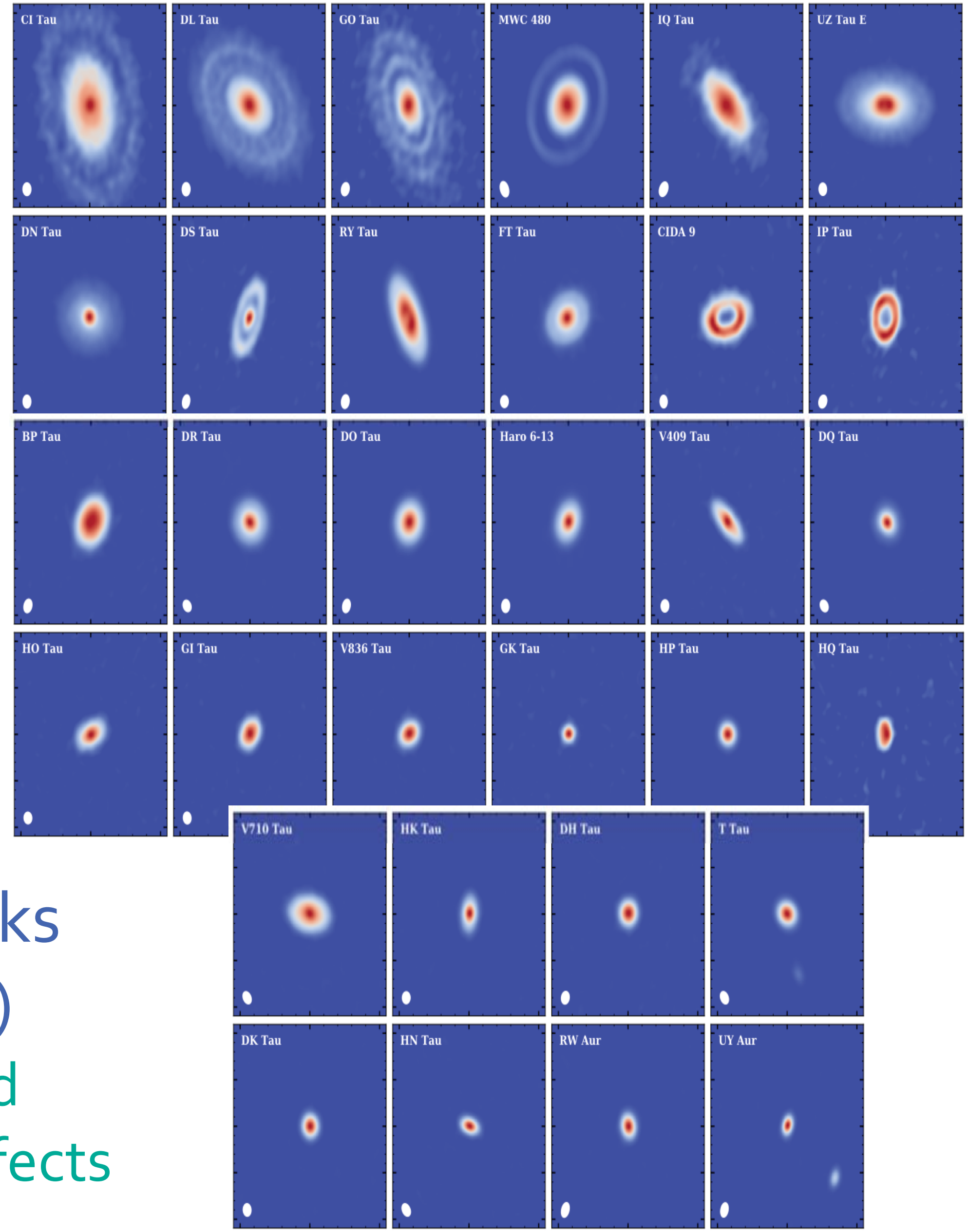
Unbiased survey of Taurus disks (Long et al. 2018/2019)

12 large disks with substructures

12 smooth (?), compact disks (~20-40 AU; not fainter)

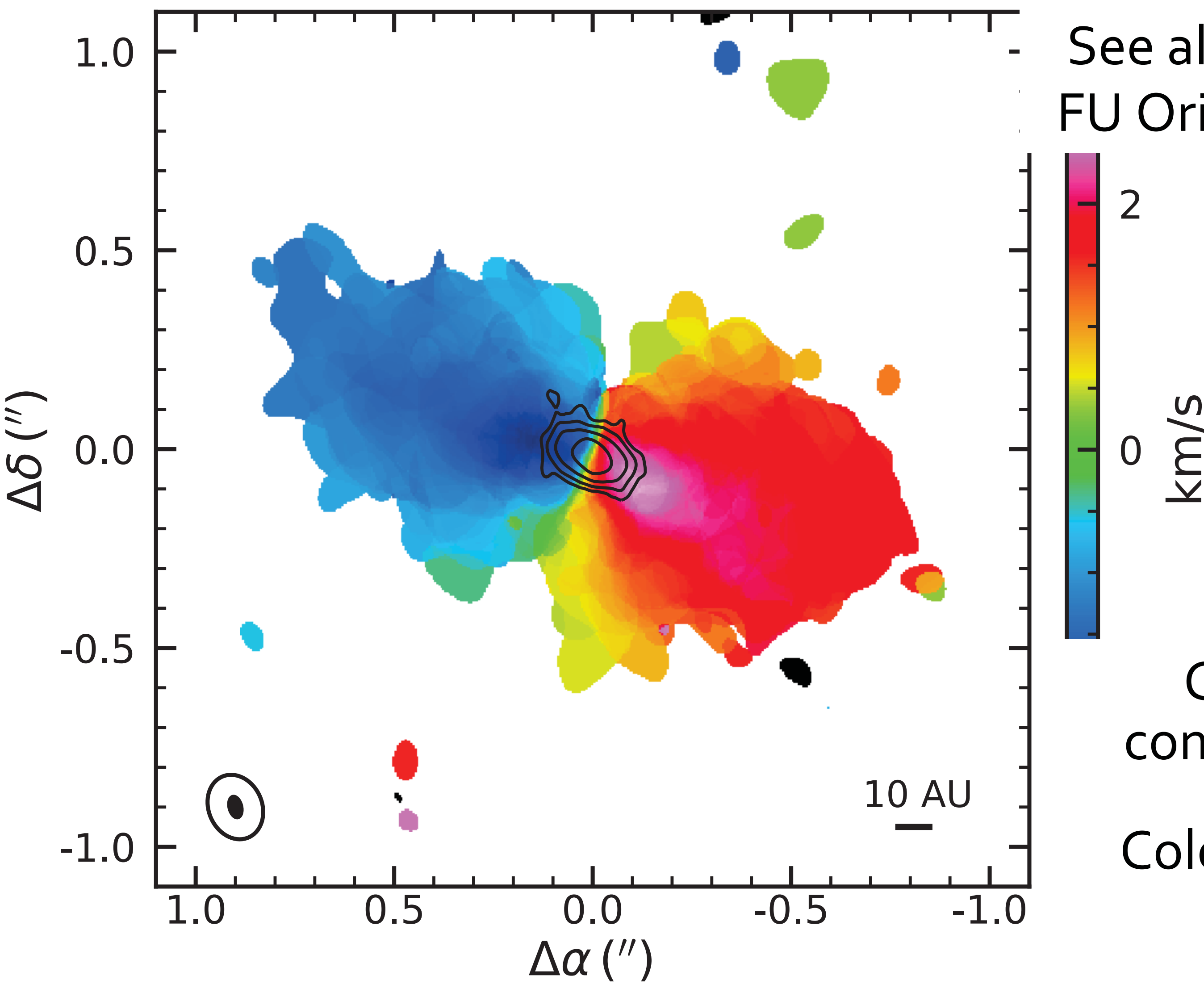
Truncated: smooth disks in binaries (0.7″ — 4″)

See also Akeson+2019 and Barenfeld+2019 for binary effects



Small dust disks: efficient radial drift for CX Tau?

(Facchini et al. 2019)



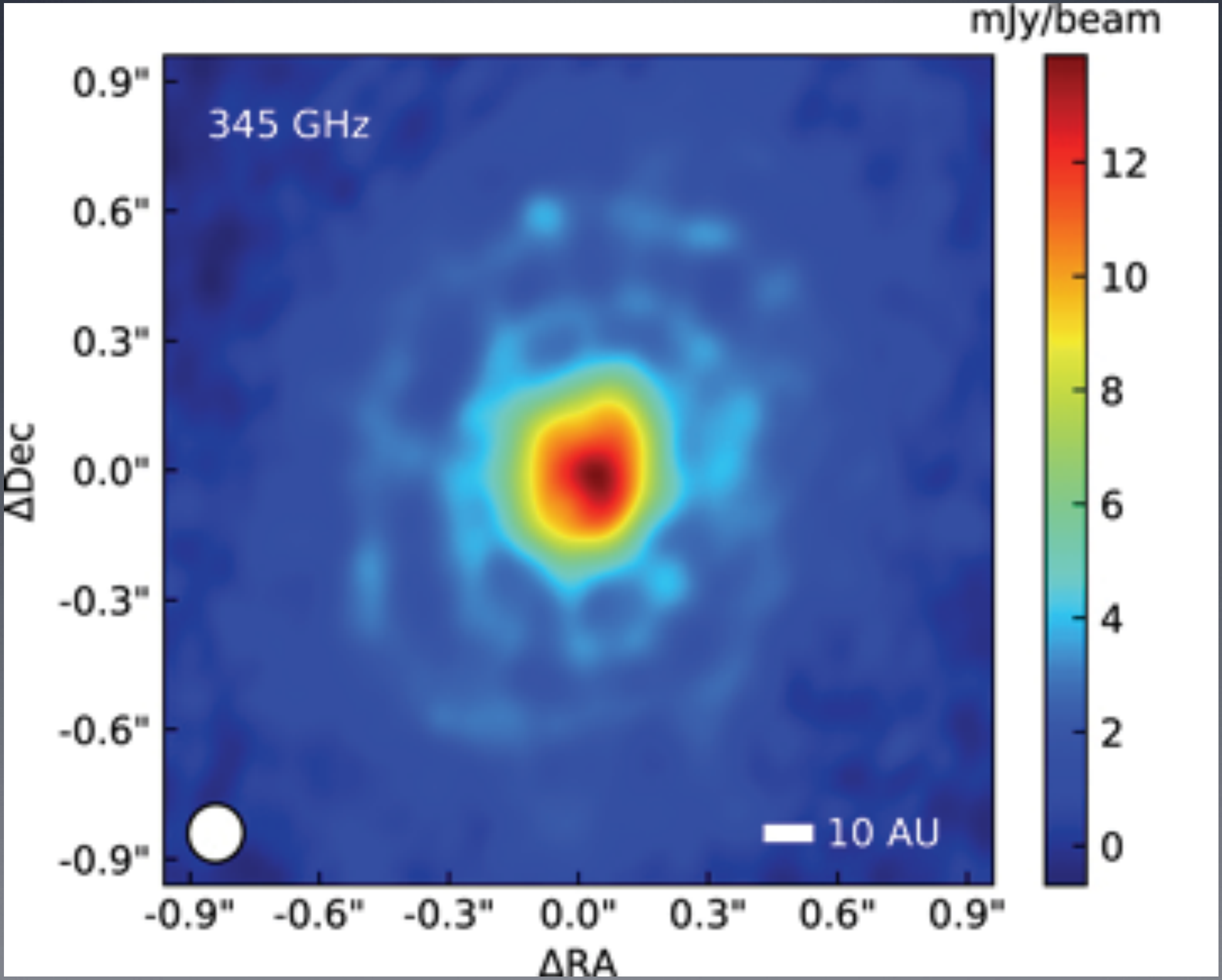
See also, Baobab Liu: FU Ori dust disk is ~10 AU

Contours: mm-continuum emission

Colors: CO emission

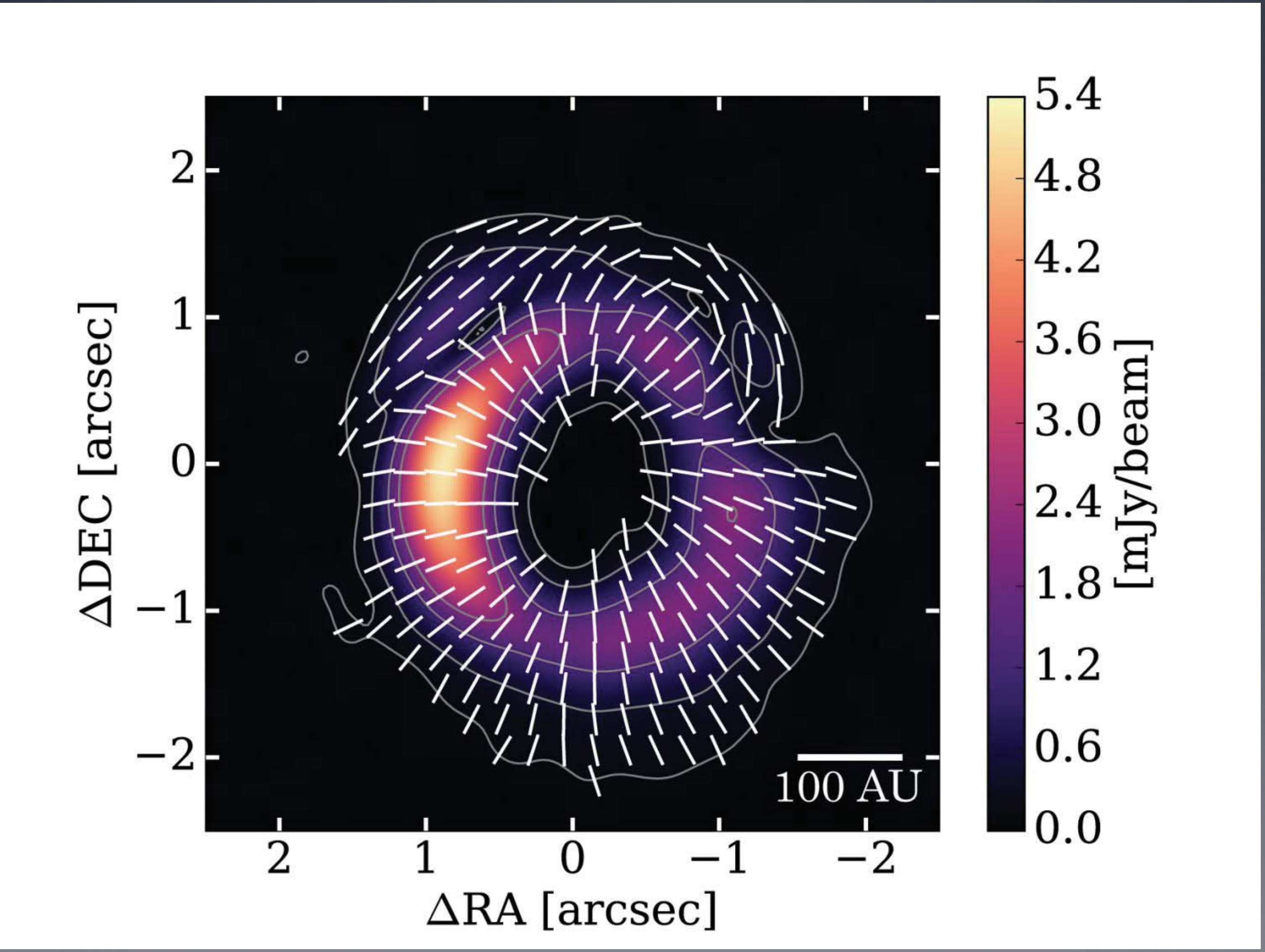
Disks and substructures form at young ages

Tobin+2018; see also Jørgensen+



Polarization: scattering important, maximum grain size of 100 microns?

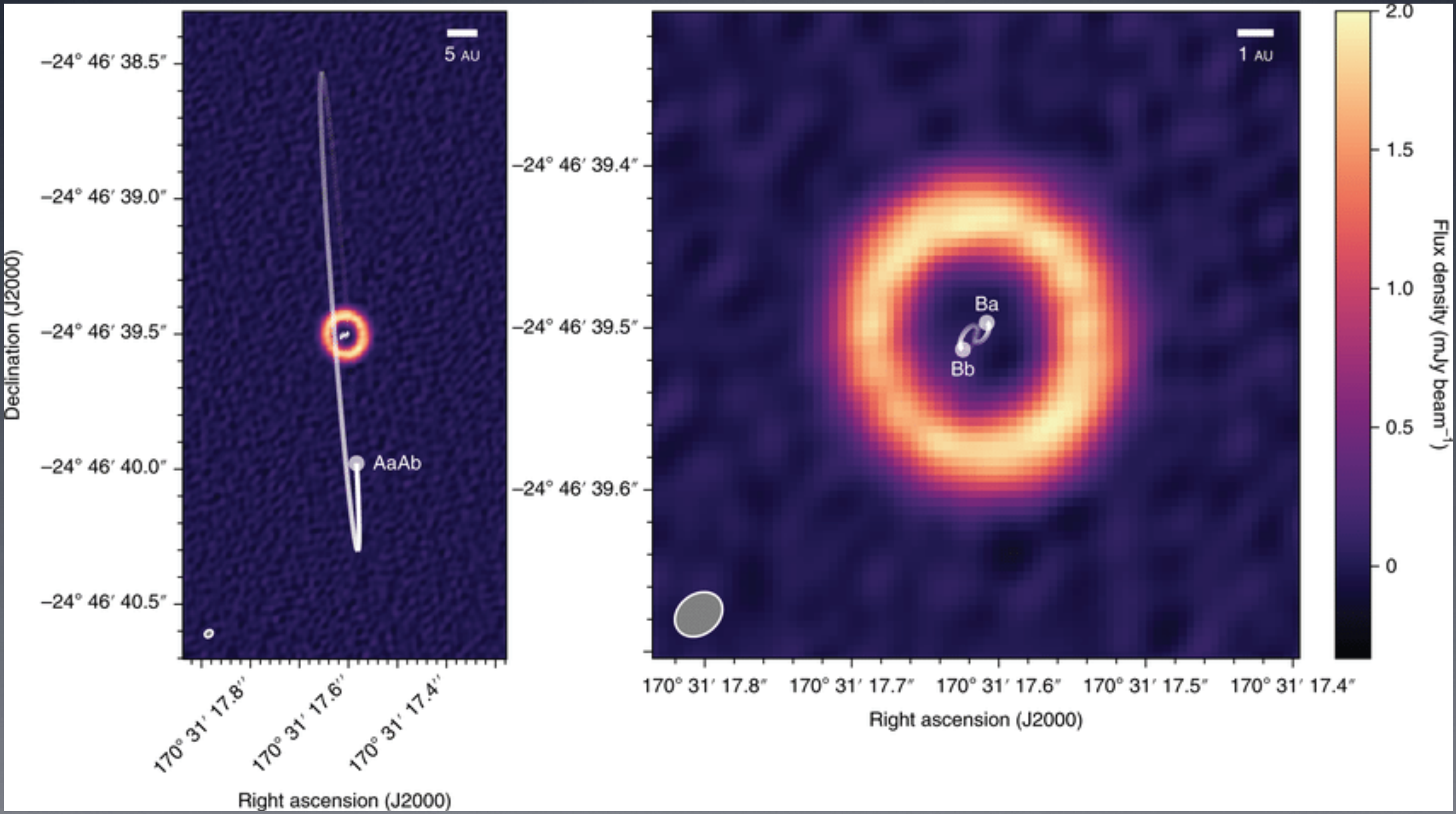
Kataoka+2015; would radically change disk masses



Weird disk around the binary of HD 98800N

binary in a quadruple system, disk+binary not coplanar

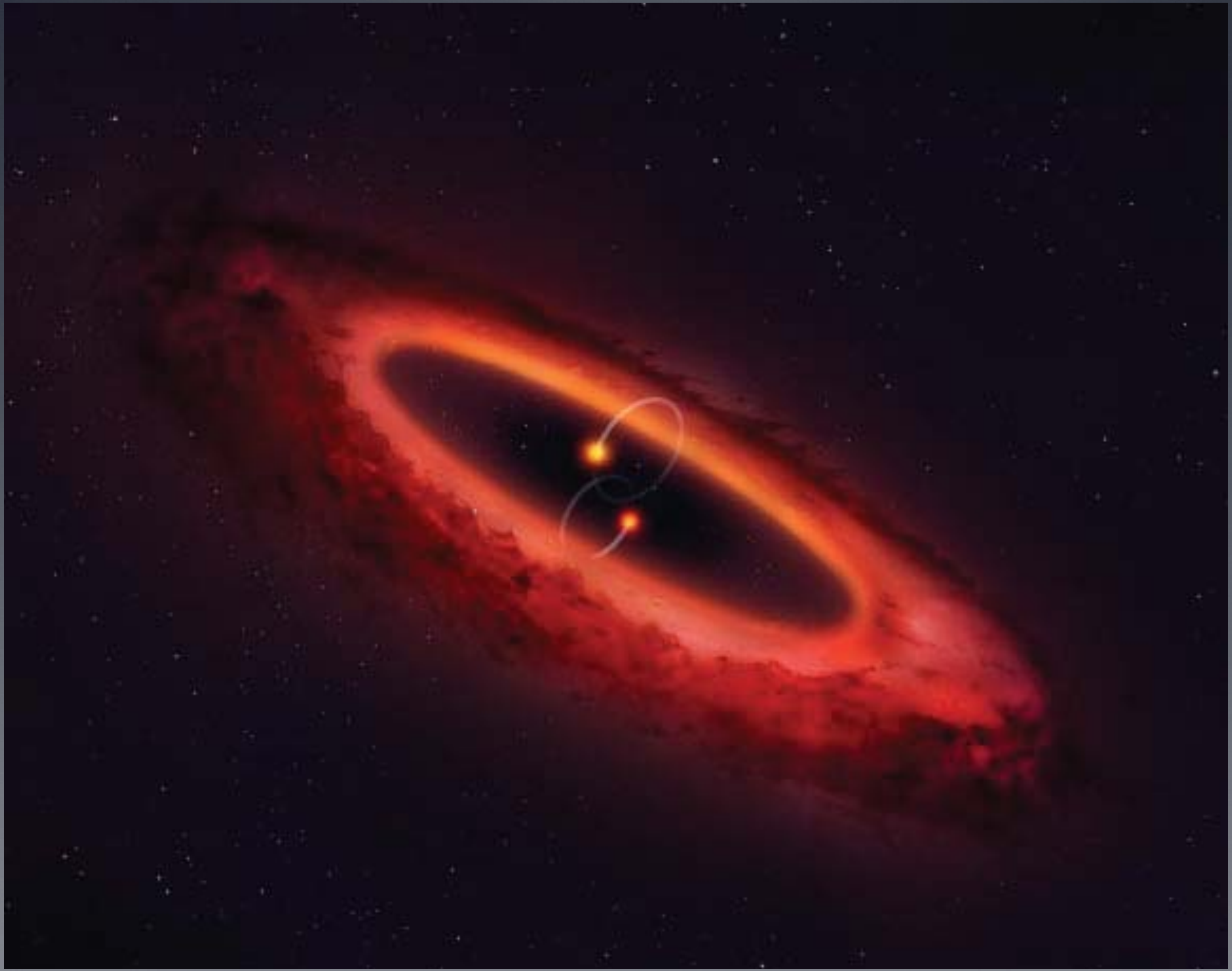
Kennedy+2018



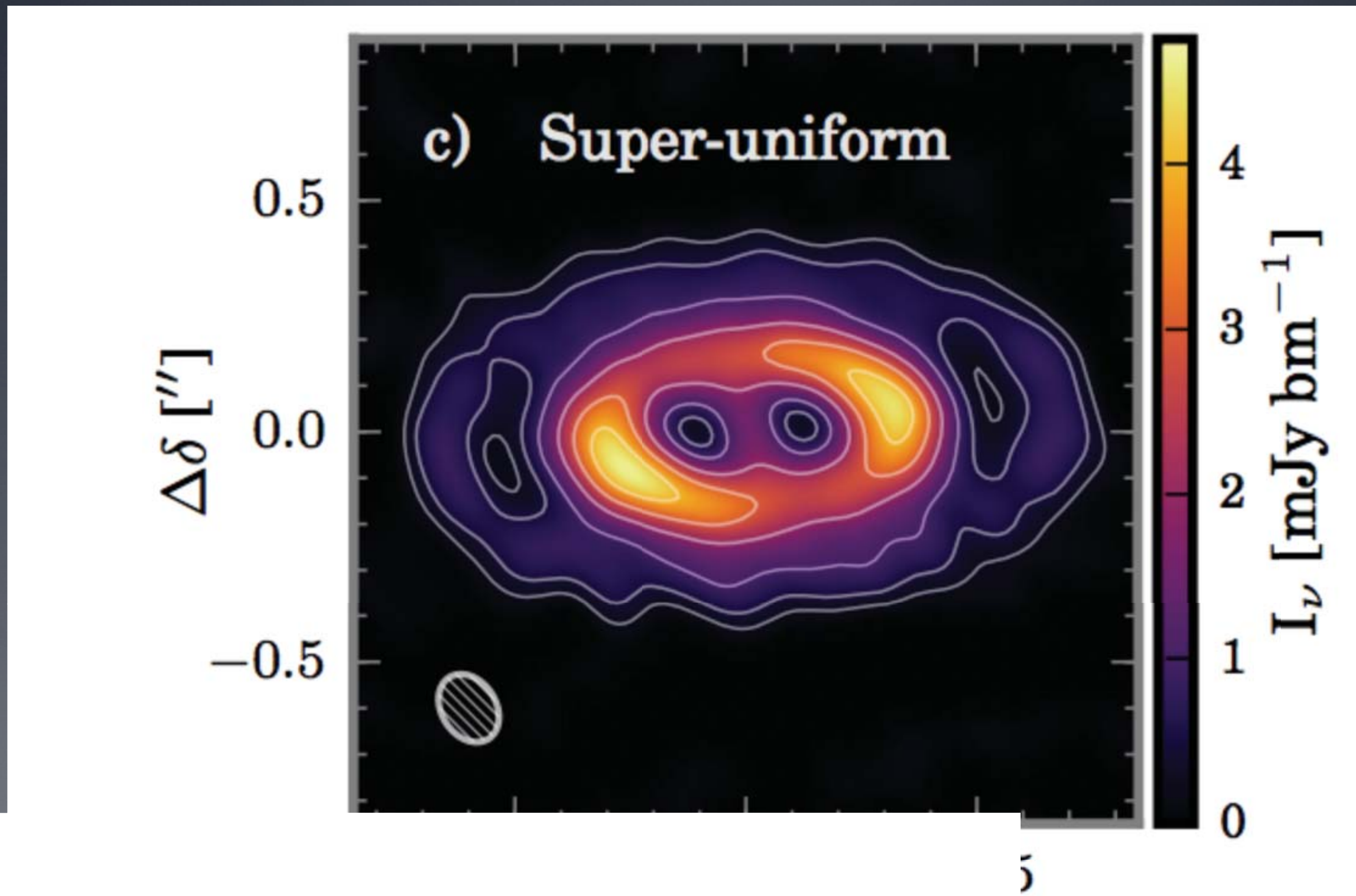
Weird disk around the binary of HD 98800N

binary in a quadruple system, disk+binary not coplanar

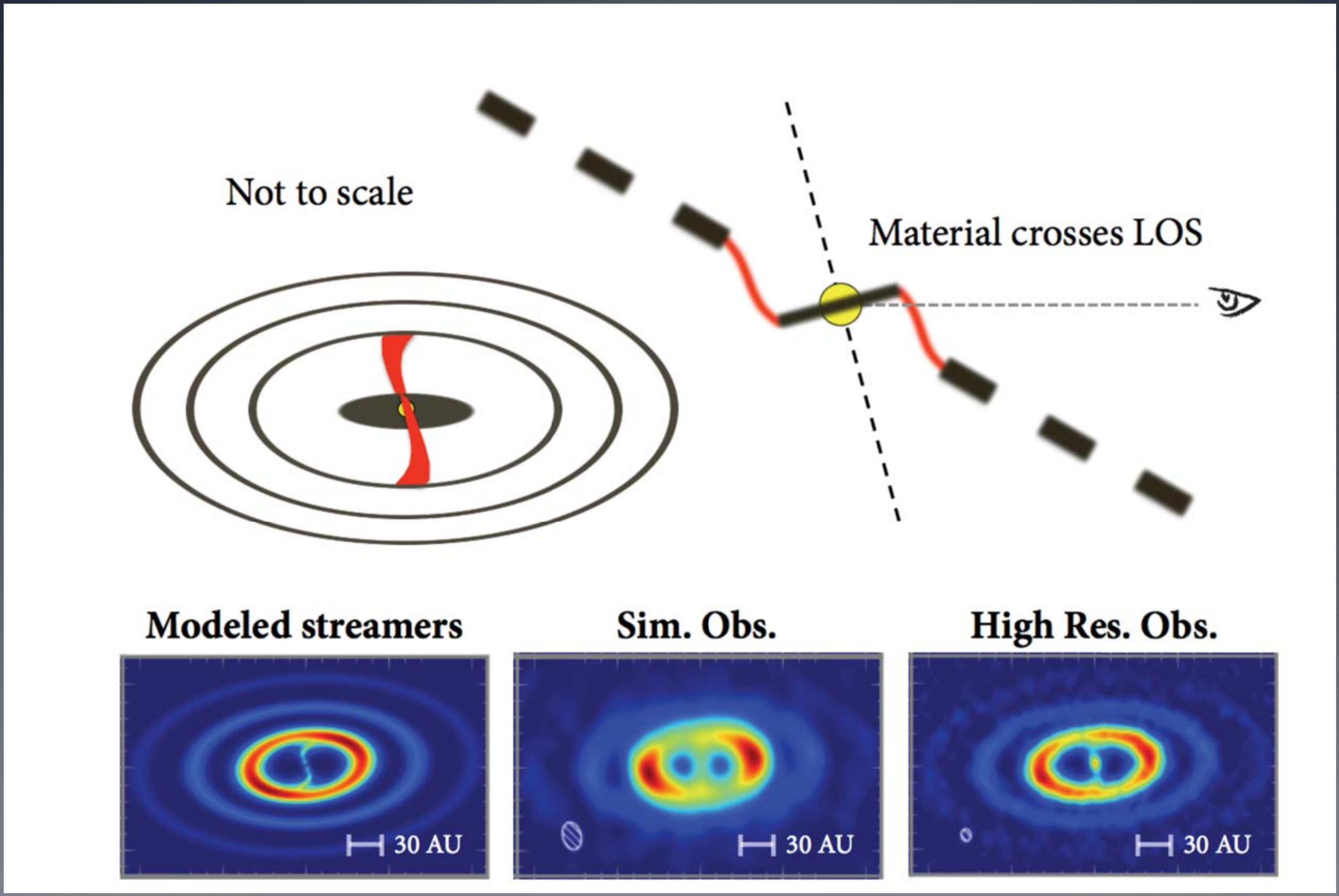
Kennedy+2018



Warped disk (Loomis+): different inclination versus radius



Warped disk (Loomis+): Mass flows between radii



Spitzer-IRS H2O lines (soon JWST!)
Carr & Najita (2007) and Salyk+(2007)