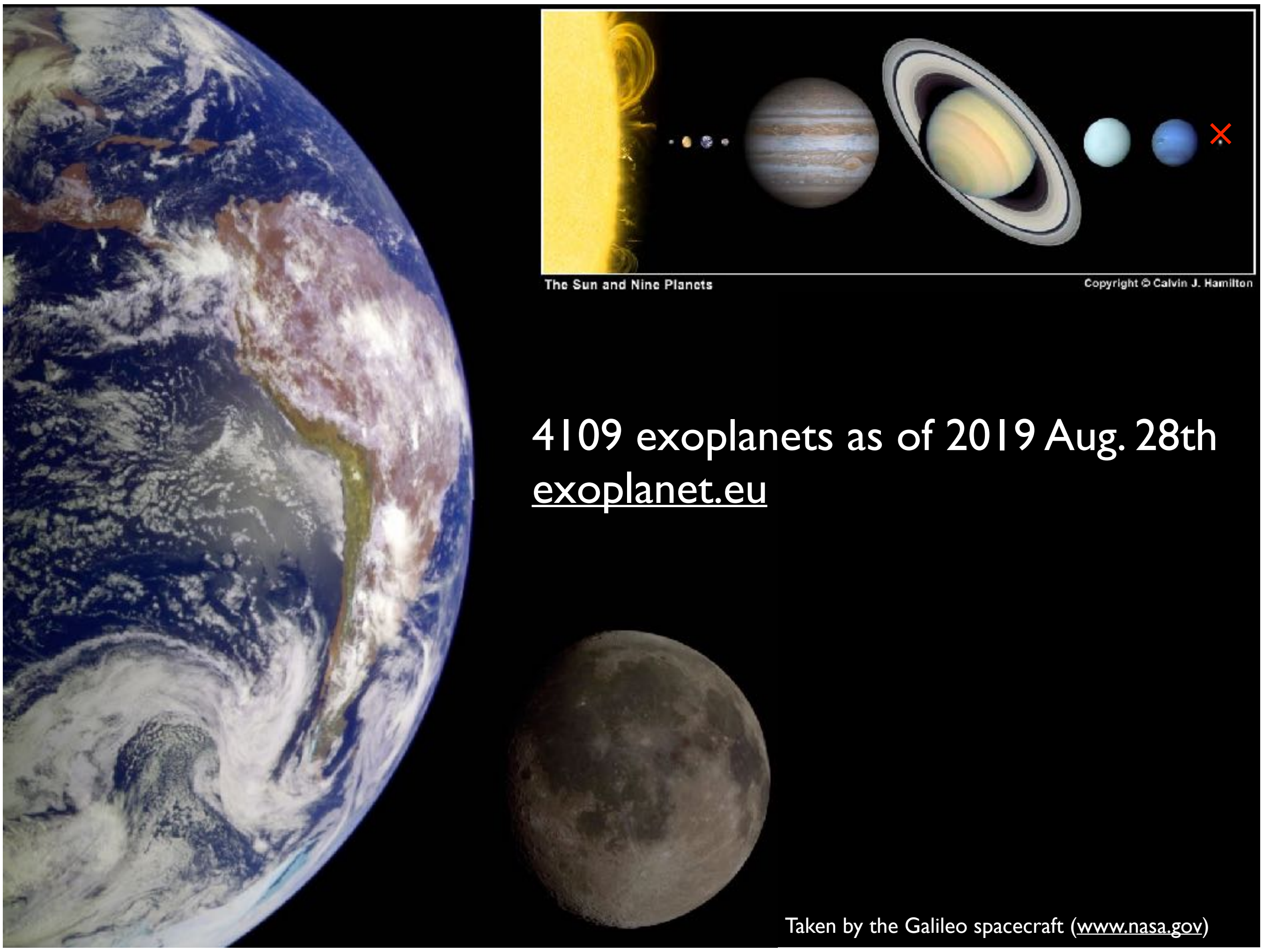
원시성 원반

2019.08.27 — 08.29
서울대학교 평창캠퍼스
2019 전파 여름학교

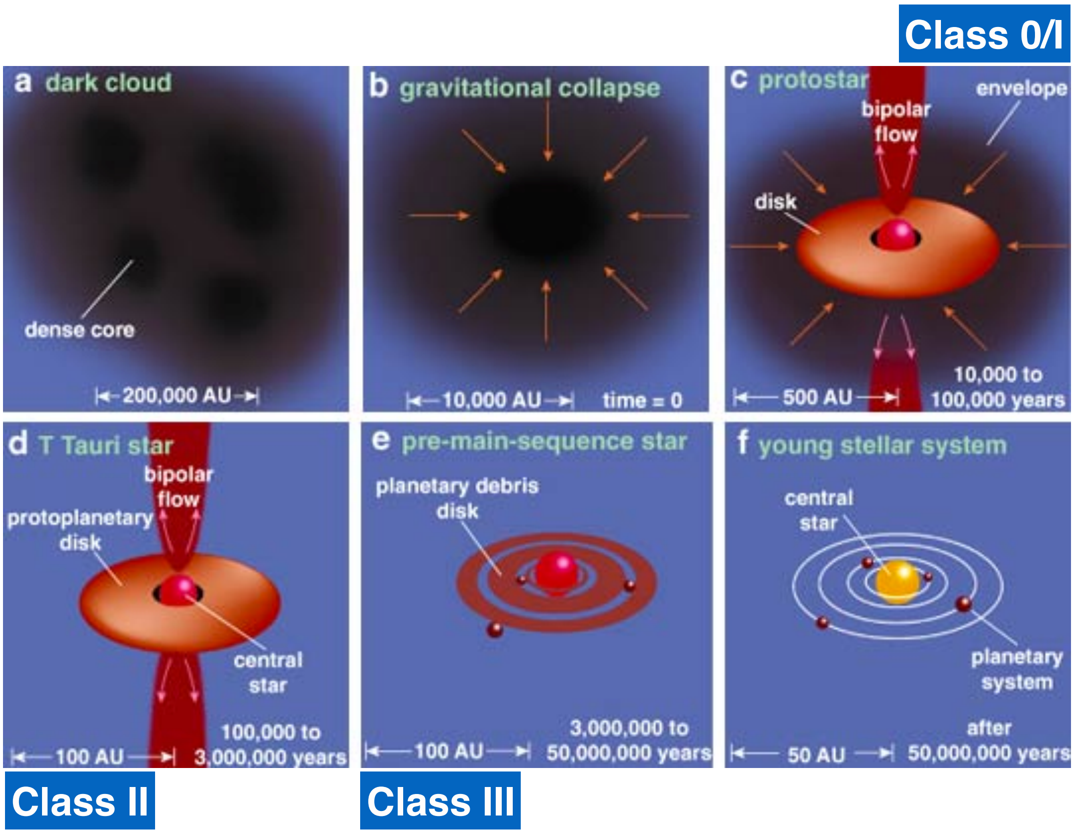
권우진
Woojin Kwon



Atacama Large Millimeter/submillimeter Array

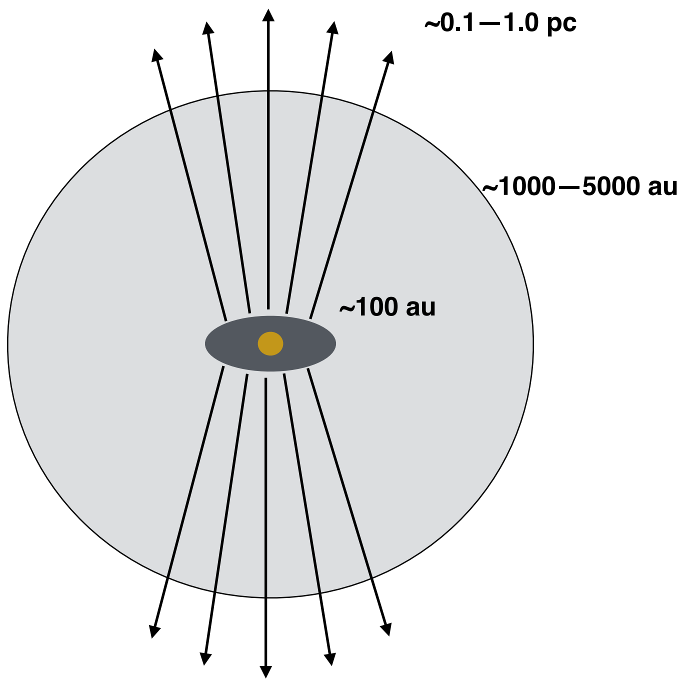
- The largest ground-based astronomical facility
- 50 12-m, 12 7-m, 4 12-m = 66 antennas
- ~5000 m in altitude, Chajnantor plateau, Chile
- East Asia, Europe, North America, & Chile

Star & Planet Formation



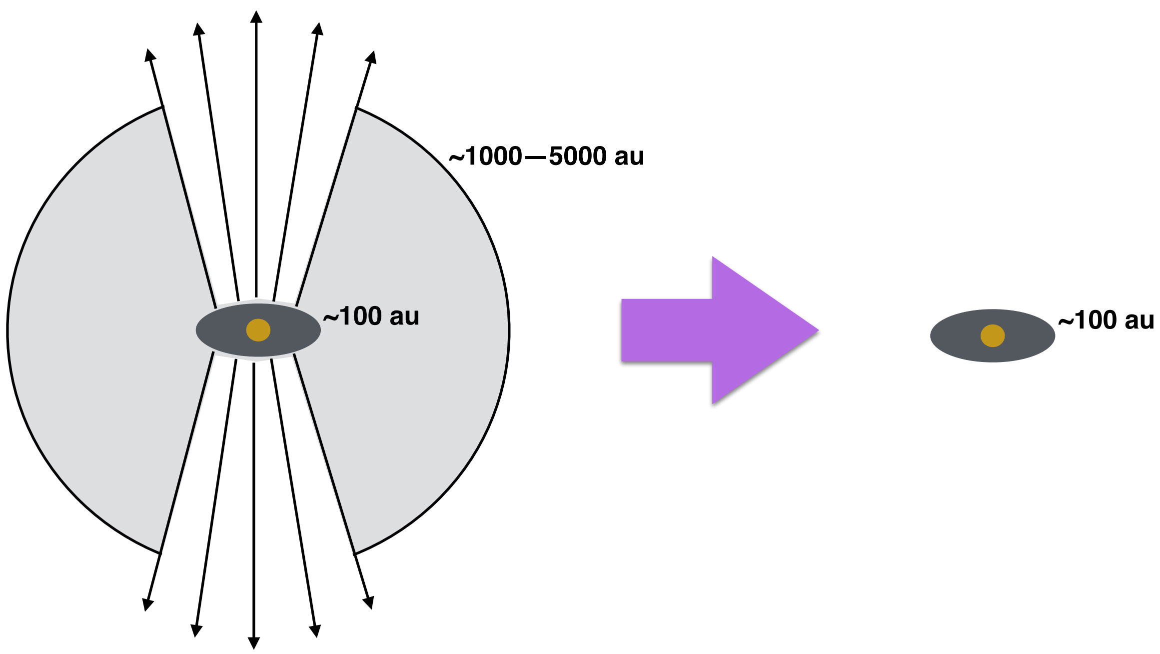
YSO components

- Protostar
- Envelope
- Bipolar outflow
- Disk



Class 0/I to Class II/III

Timescales ~1 Myr

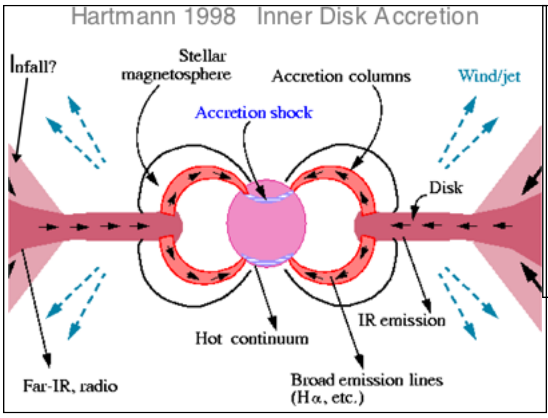


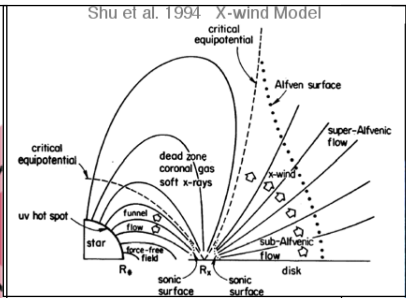
Accretion & Outflow

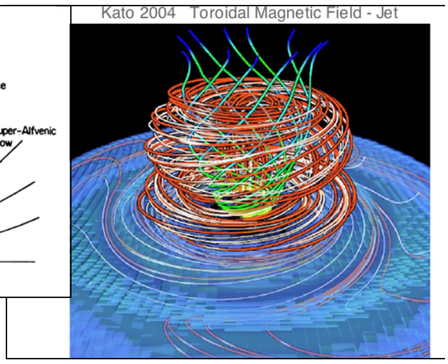
- **Two main activities during star formation**

- Accretion
  “Static” outer envelope, infalling inner envelope, accretion disk

- Bipolar outflow
  rotation disk & magnetic fields (magnetocentrifugal models)

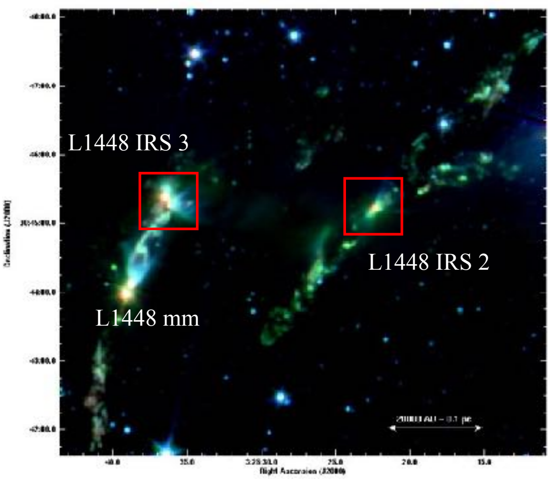


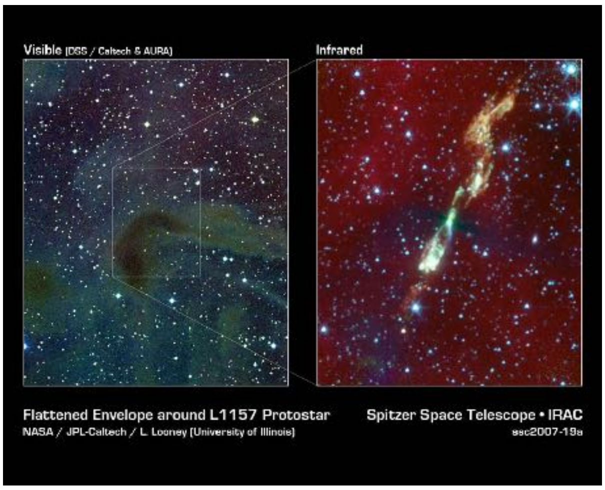




Class 0 YSOs

- Massive envelope, strong bipolar outflow



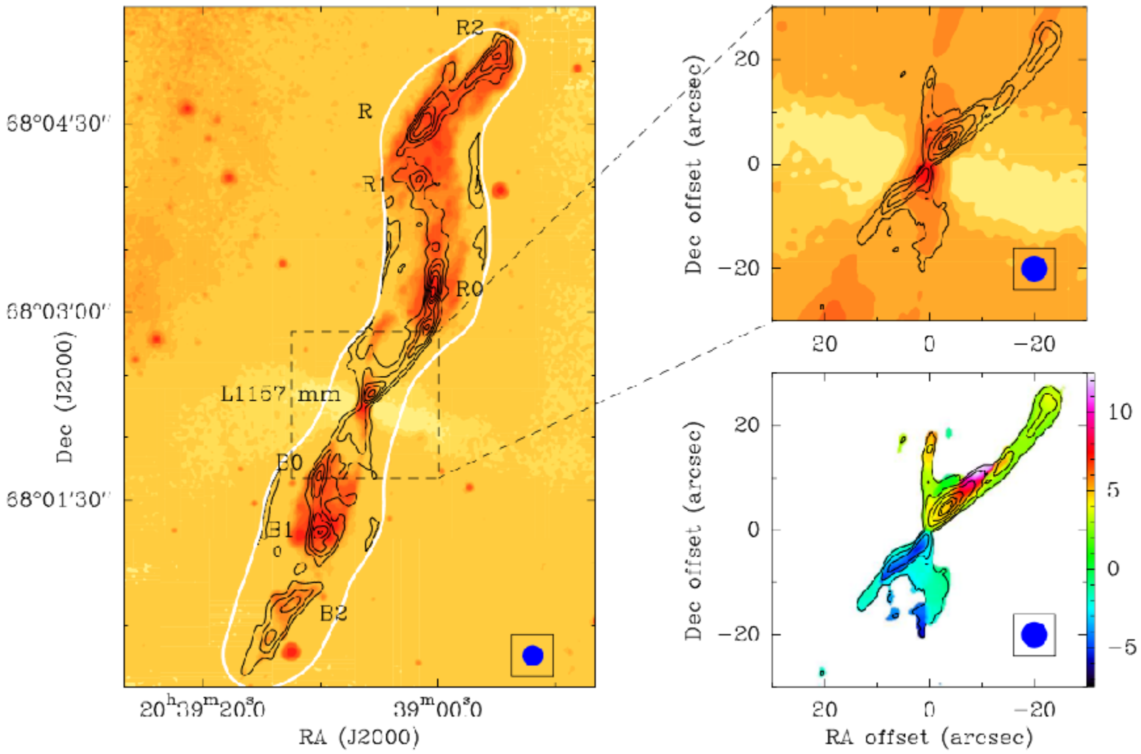


Tobin et al. (+Kwon) 2007

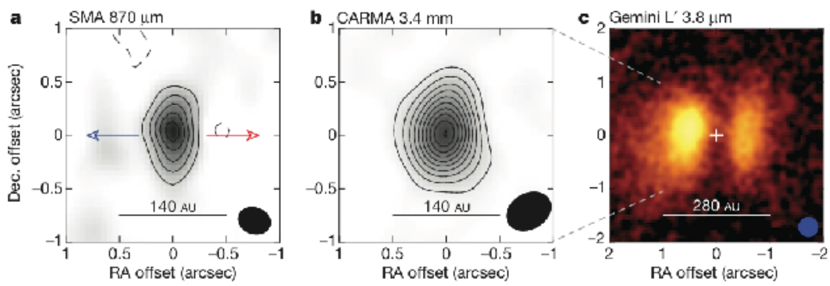
Looney, Tobin, & Kwon 2007

Bipolar outflows

Kwon et al. 2015

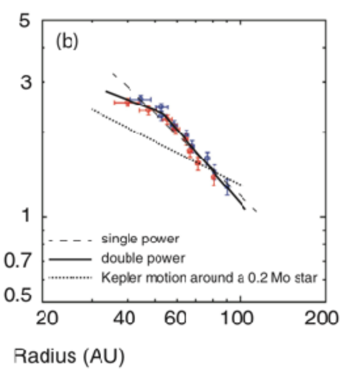


- Class 0 YSO disks: L1527, VLA1623A, HH 212

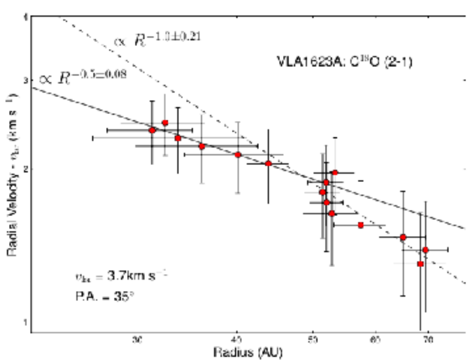


L1527
(SMA, CARMA)
Tobin et al. 2012

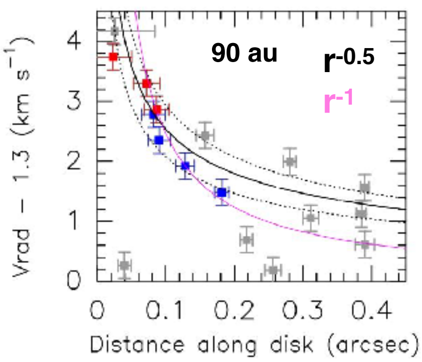
L1527 Ohashi et al. 2014



VLA1623A Murillo et al. 2013



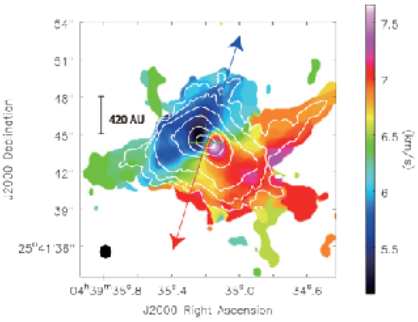
HH 212 Codella et al. 2014

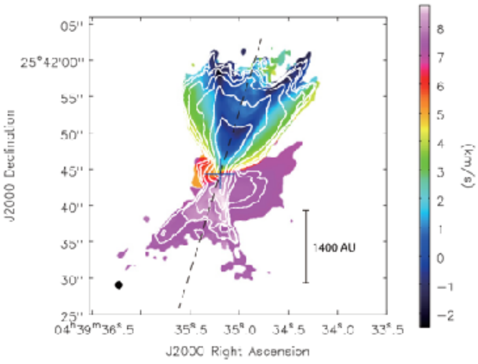


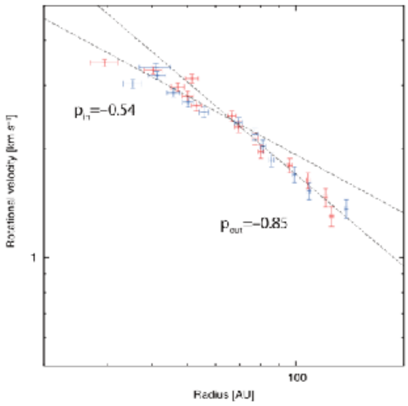
Class I YSOs

Bipolar Outflow & Disk

- **TMC-1A** (d~140 pc) Aso et al. 2015
- ALMA (cycle 0)
  Band 6: cont., CO, $C^{18}O$
  resolution~1”
- Bipolar outflow and infalling/rotating disk

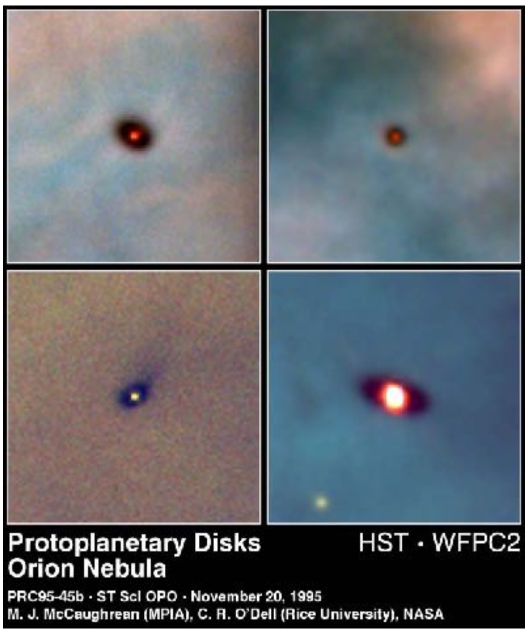




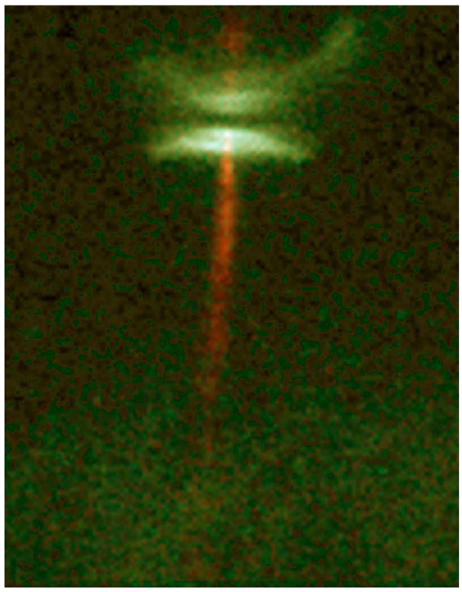


Class II YSOs

Protoplanetary Disks

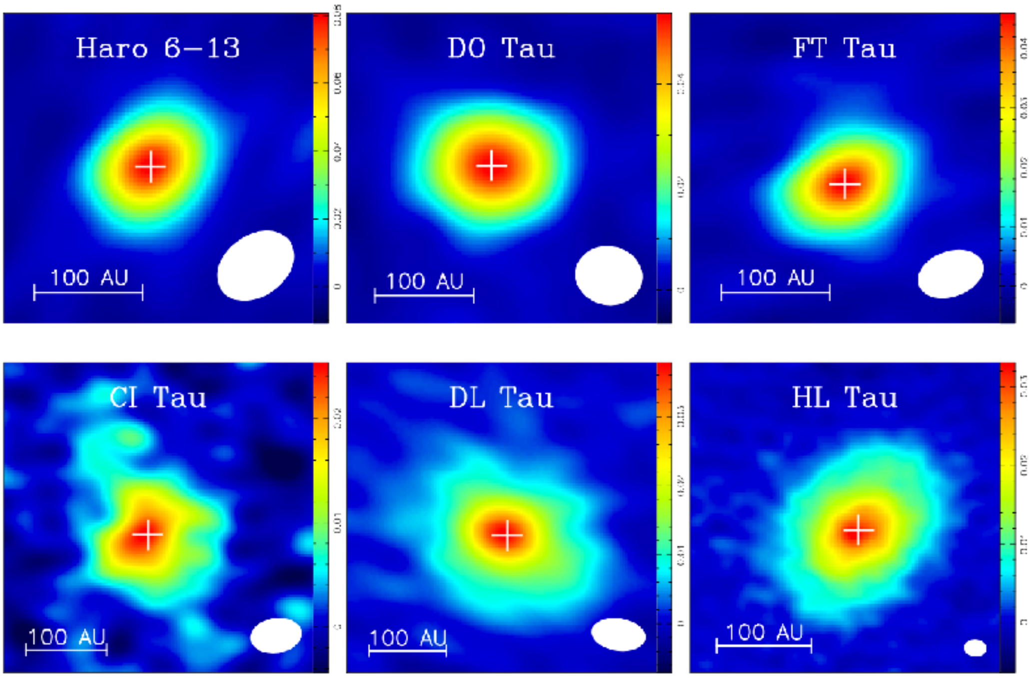


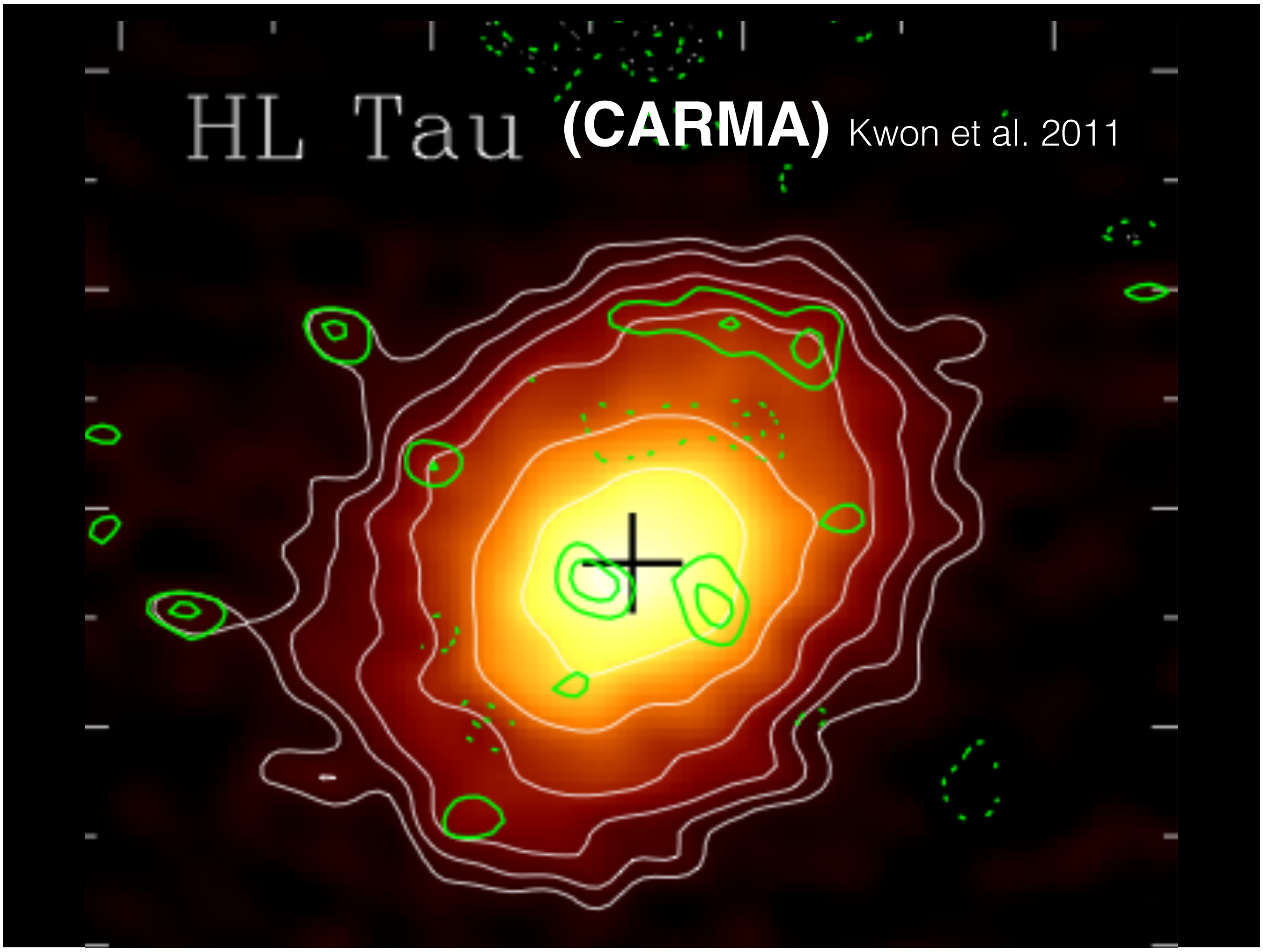
Burrows et al. 1995 HH 30



Disks in 1 mm continuum

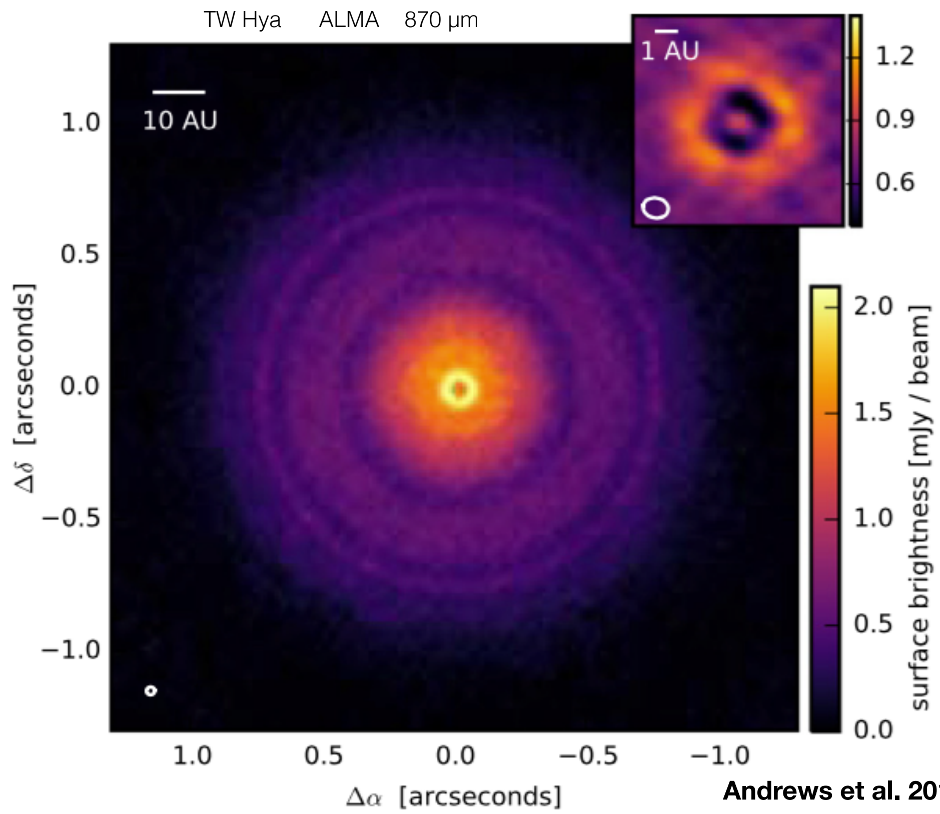
Kwon et al. 2015





HL Tau (ALMA)

Protoplanetary disks TW Hya (d~54 pc)

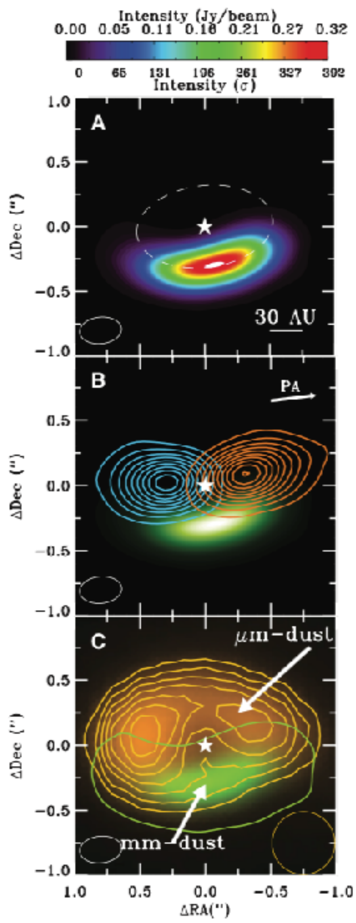


Andrews et al. 2016

Radial drift and trap of large grains in protoplanetary disks

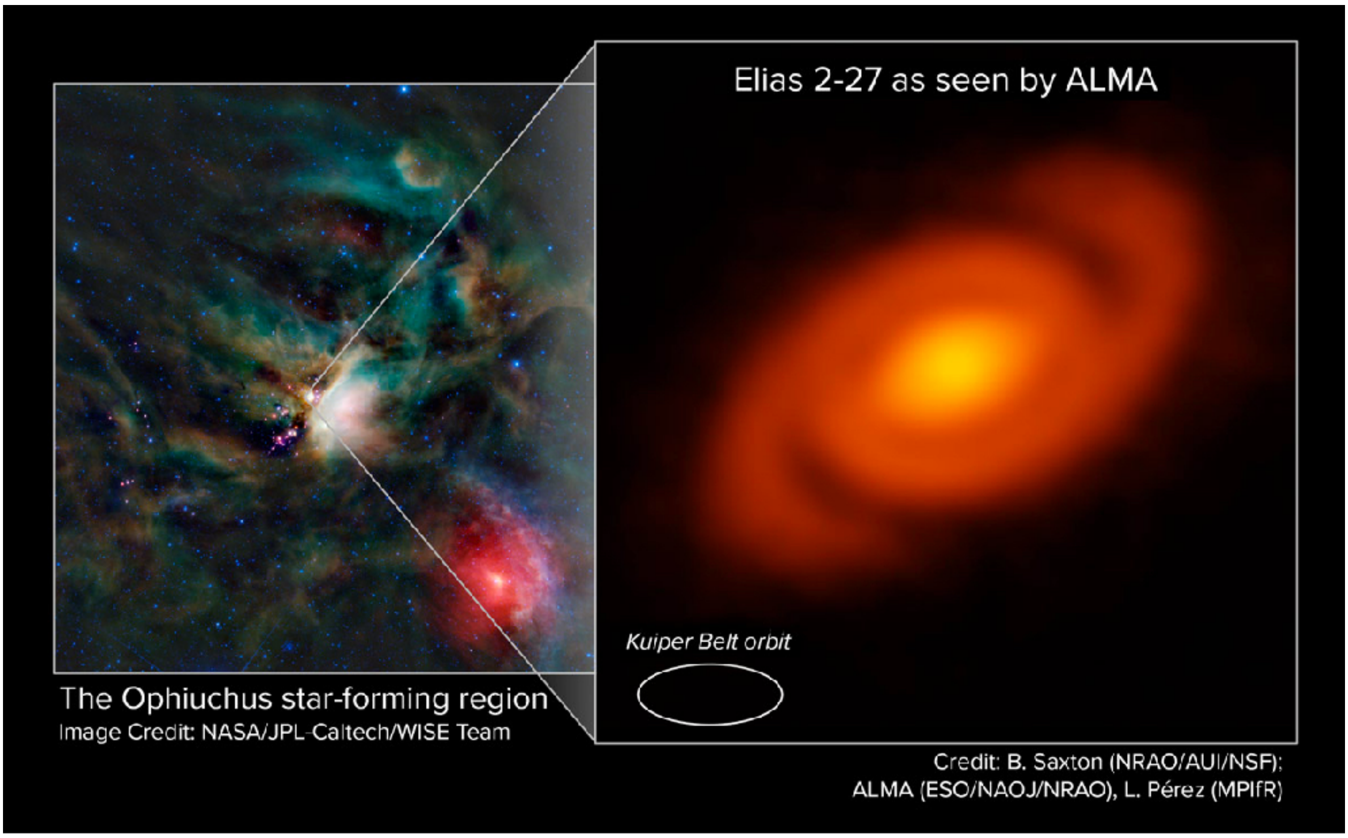
- A Major Asymmetric Dust Trap in a Transition Disk
- Van der Marel et al. 2013, Science
- Oph IRS 48 (d ~ 120 pc)
- 0.44 mm (685 GHz, Band 9) continuum, CO 6-5
  0.32”x0.21”
  VLT 18.7 μm emission

$$\frac{v_{\rm rot}^2}{r} = \frac{GM_\star r}{(r^2+z^2)^{3/2}} + \frac{1}{\rho_{\rm gas}}\frac{\partial P}{\partial r}$$



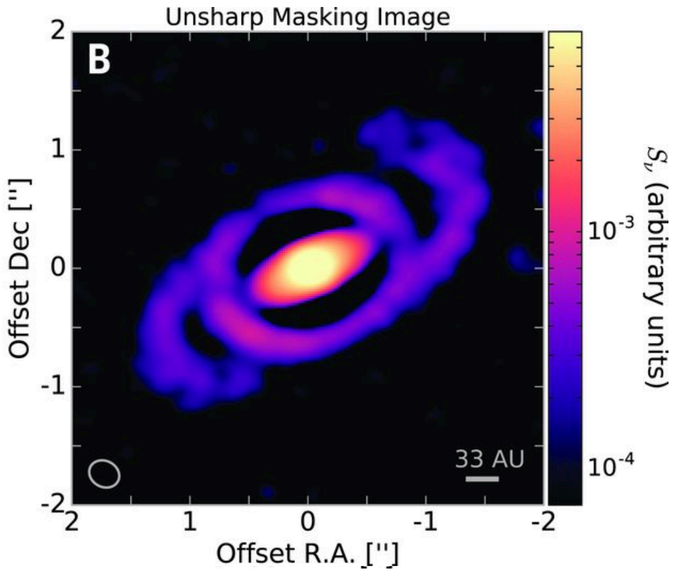
Elias 2-27

Perez et al. (+Kwon) 2016
ALMA (1.3 mm)



Spiral structures in Elias 2-27

- Perez et al. (+ Kwon) 2016, Science
- Elias 2-27
  ρ-Ophiuchus star-forming complex
  d~139 pc
  Class II YSO
  $M_* \sim 0.5$—$0.6\ M_\odot$
  $M_{disk} \sim 0.04$—$0.14\ M_\odot$
  $\dot{M}_{acc} \sim 8\times10^{-8}\ M_\odot$/year
- Observations
  44 antennas, 12.5 min on target
  1.3 mm (Band 6), 0.26”x0.22”
  CO, 13CO, C18O
- First detection of spirals down to mid-plane
  A ring gap around 70 au in radius
  Optical depth: τ = 0.1 at 100 au, τ = 0.02 at 300 au
- Neither planet-disk interaction nor GI explains the spiral and the ring gap.

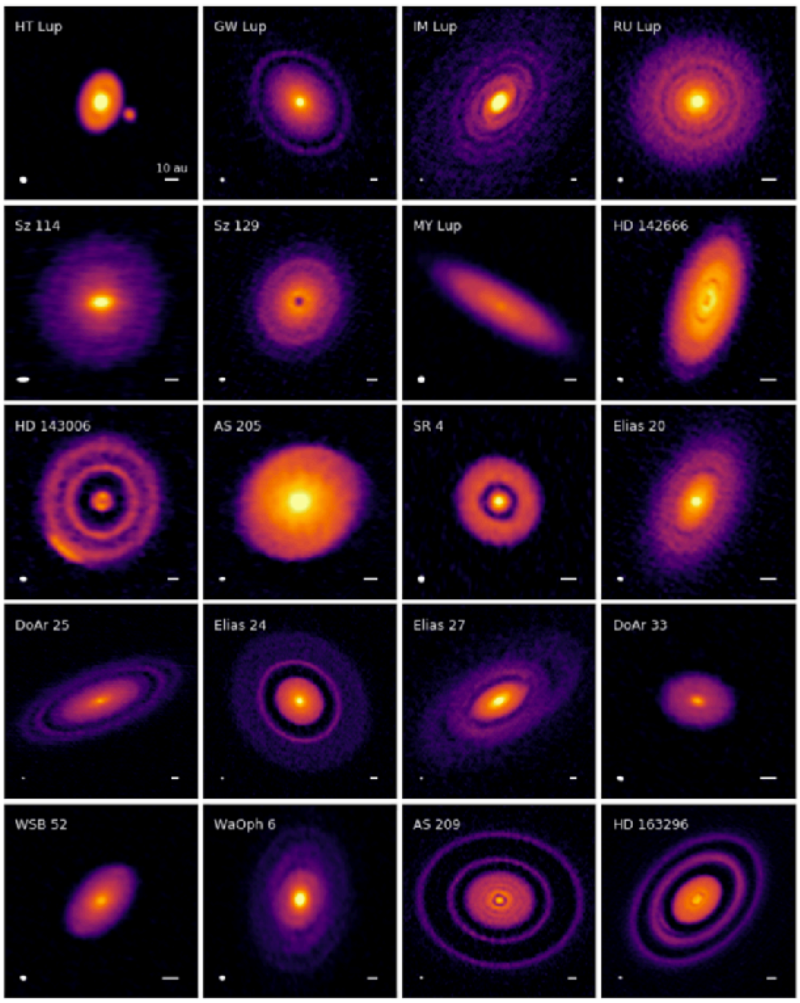


DSHARP

Disk
Substructures at
High
Angular
Resolution
Project

Sean Andrews et al. 2018:
10 ApJL papers,
posted at astro-ph
on Dec. 12, 2018

0.035” (5 au scales)
Band 6



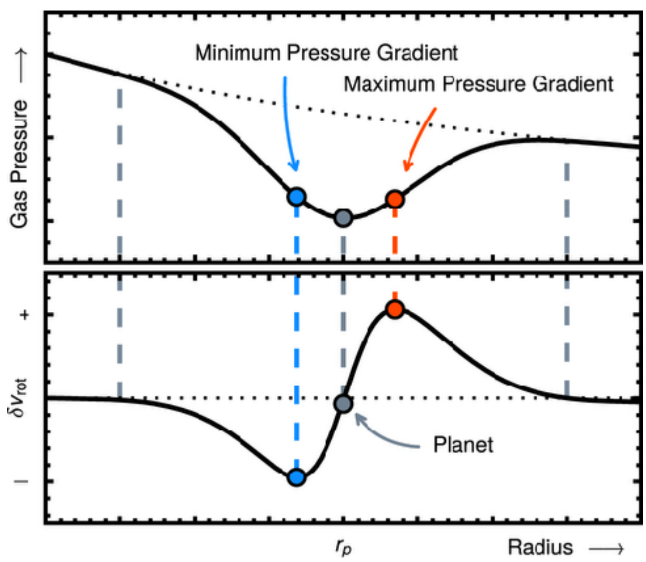
Planets in substructures? What creates substructures?

- Planets
  => Gas pressure changes expected
  Lin & Papaloizou 1980, Bae et al. 2016, 2017, 2018, Bae & Zhu 2018a,b

- Changes in particle properties
  => No gas pressure changes expected
  Zhang et al. 2015, Okuzumi et al. 2016

From Jaehan Bae's slides

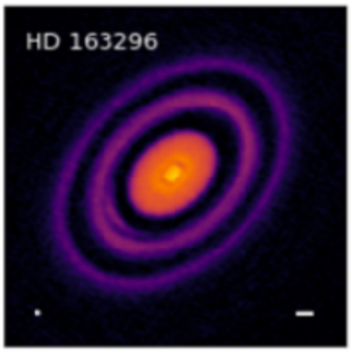
Velocity gradient revealing existence of planets

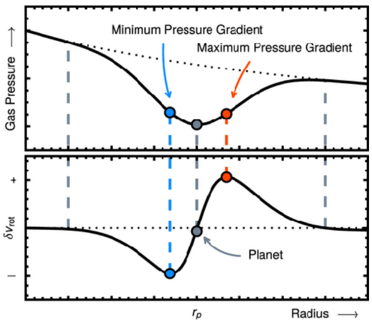


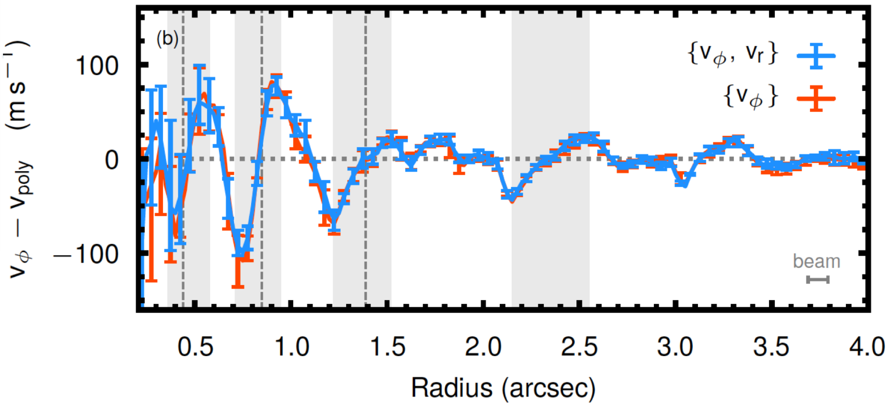
Teague, Bae et al. 2018

$$\frac{v_{\rm rot}^2}{r} = \frac{GM_\star r}{(r^2+z^2)^{3/2}} + \frac{1}{\rho_{\rm gas}}\frac{\partial P}{\partial r}$$

HD 163296 disk





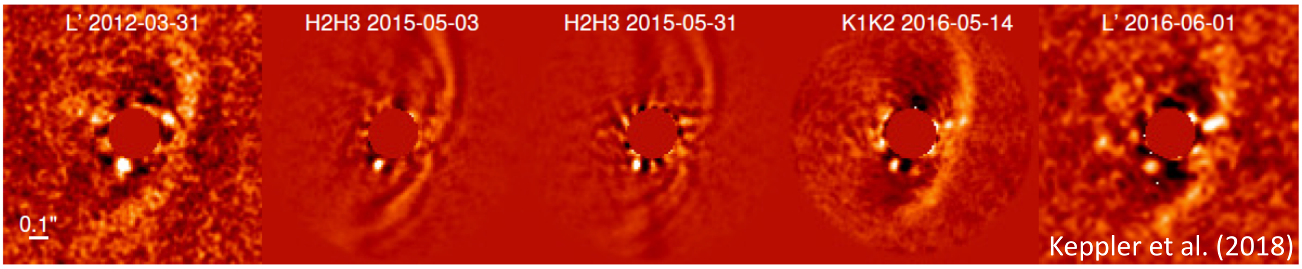


Teague, Bae et al. 2018
Teague, Bae & Bergin (Nature, accepted)

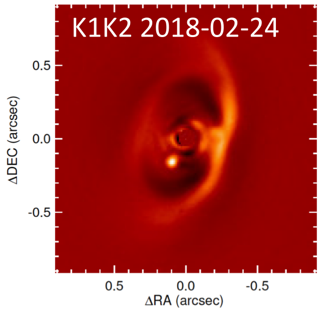
PDS 70

- Direct detection of proto-planets
  - Accretion onto planet (e.g., Hα)
  - **Circumplanetary disk**
- K7 star in the Upper Centaurus Lupus association (d ~ 113 pc, Gaia DR2)
- 0.8 M⊙
- 5 Myr old

Discovery of a planetary companion PDS 70b

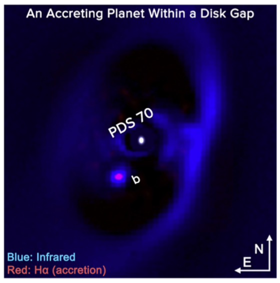


Gemini/NICI | VLT/SPHERE | VLT/SPHERE | VLT/SPHERE | VLT/Naco



VLT/SPHERE
2.5 hour integration

Müller et al. (2018)



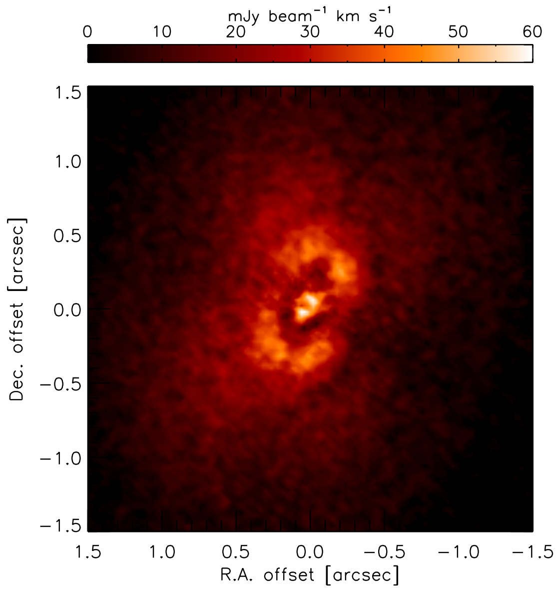
$\dot{M}_{PDS70b} = 10^{-8\pm1}\ M_{Jup}/yr$

Wagner et al. (2018)

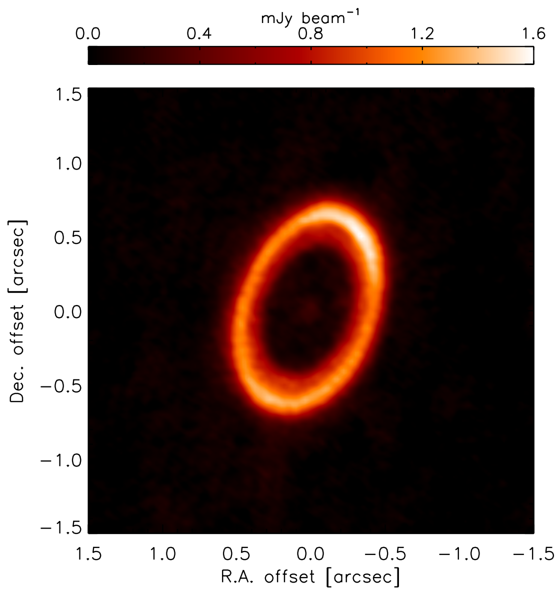
From Jaehan Bae's slides

ALMA observations

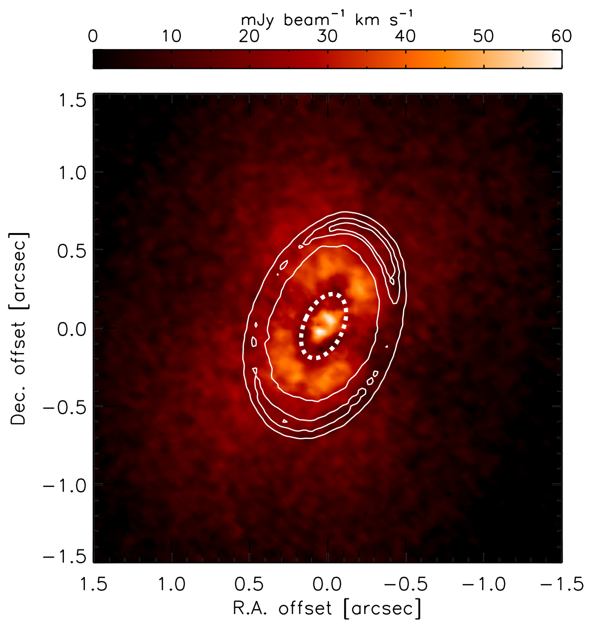
^{12}CO 3-2 integrated intensity (moment 0)



350 GHz (855 μm) continuum



Keppler, Teague, Bae et al. (2019)



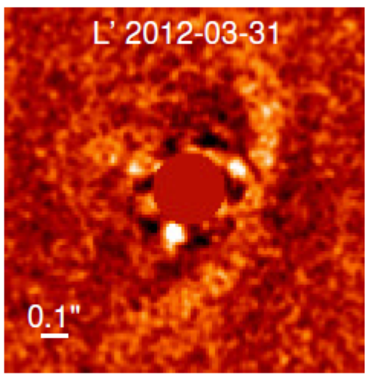
- A gap in CO is detected along PDS 70b's orbit.
- The continuum ring blocks CO emission from the far side of the disk.
- There is non-negligible CO emission between PDS 70b's orbit and the continuum ring.

In Keppler, Teague, Bae et al. (2019):

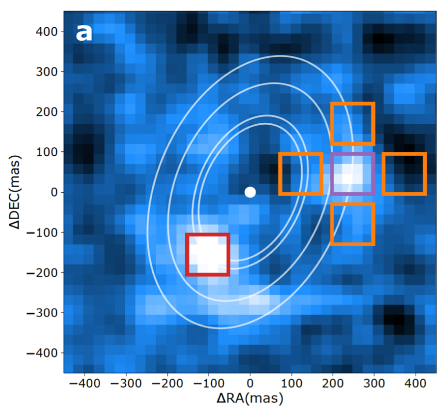
"We find that even a planet with a mass of 10 M_{Jup} may not be sufficient to explain the extent of the wide gap and an additional low-mass companion may be needed to account for the observed disk morphology."

And…

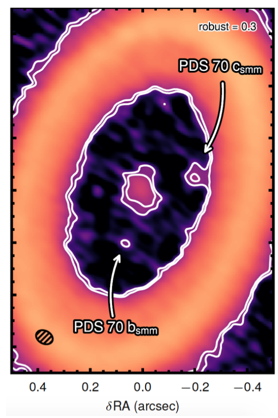
- It turned out that there's an additional planetary-mass companion within the cavity!



L' band (3.5 μm) scattered light
Keppler et al. (2018)



Hα (6563Å)
Haffert et al. (2019)

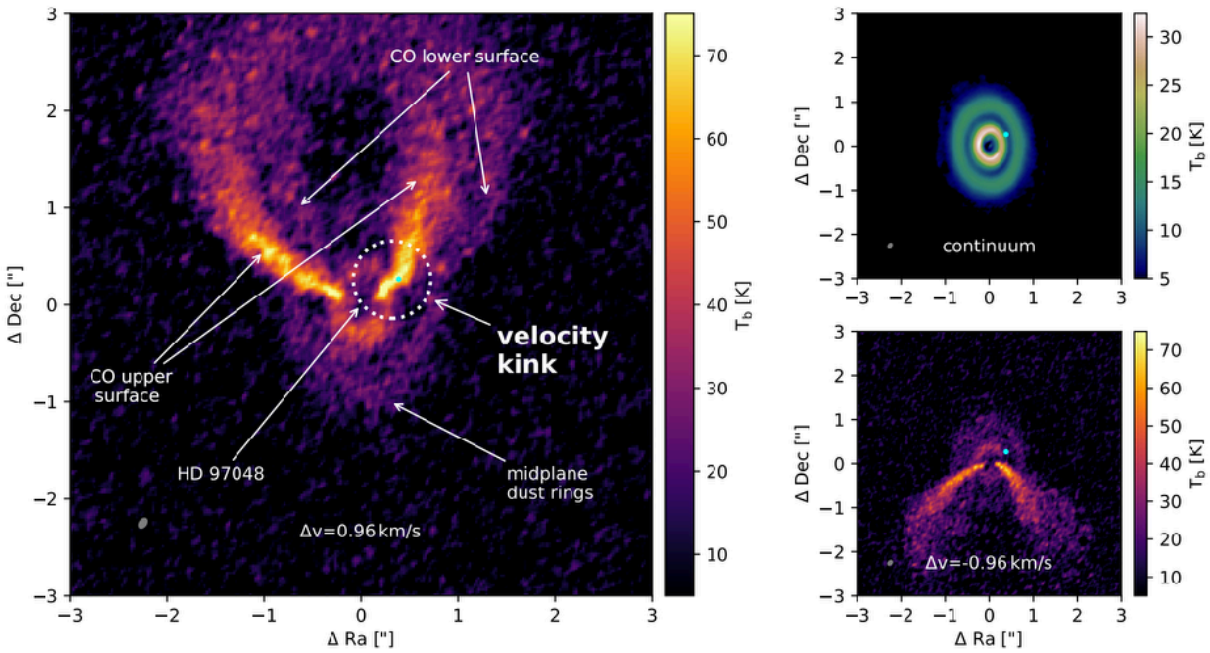


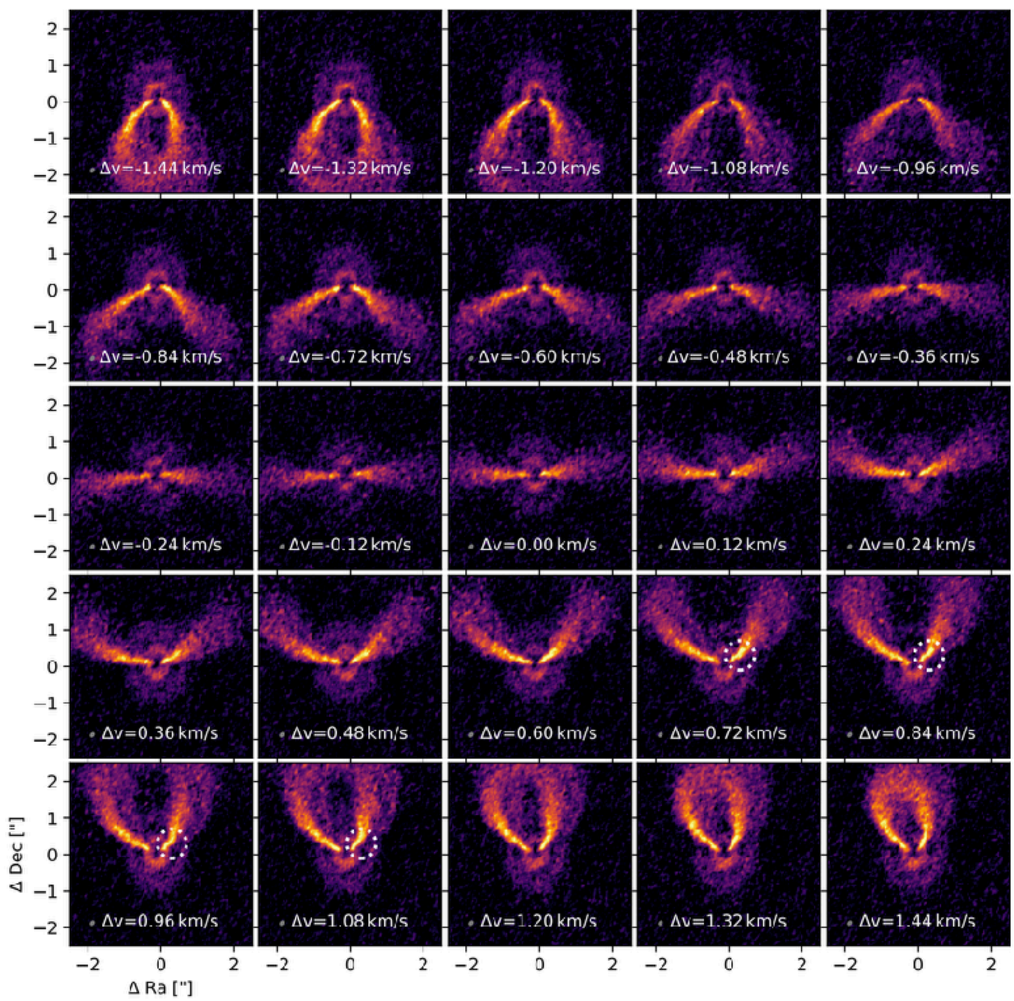
sub-mm continuum (855 μm)
Isella et al. (2019)

From Jaehan Bae's slides

Velocity Kink in HD 97048

- ALMA 13CO 3-2, θ~0.1”, Pinte et al. 2019

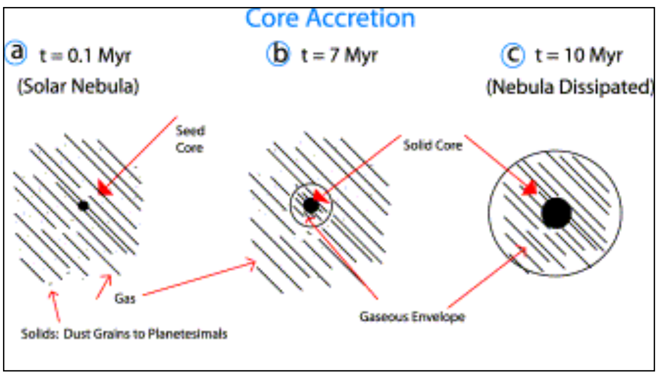




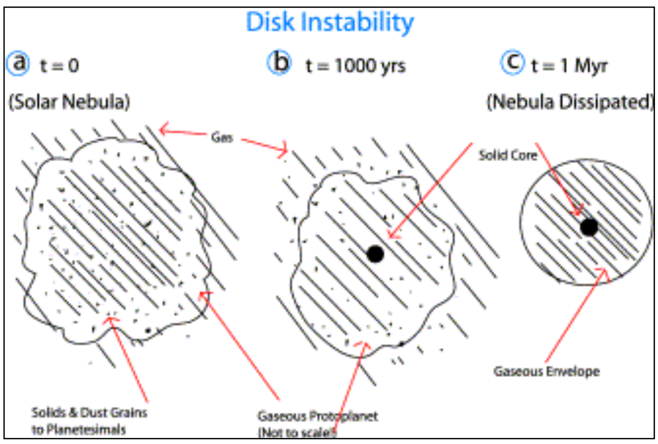
Proto-planet formation

Giant planet formation

- Core accretion vs. disk instability?



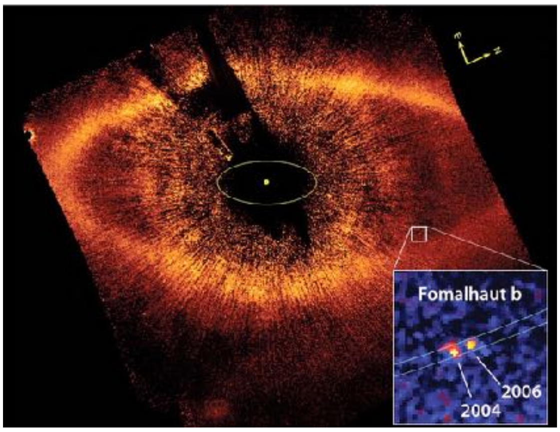
Formation of gas and ice giant planets, A.P. Boss 2002

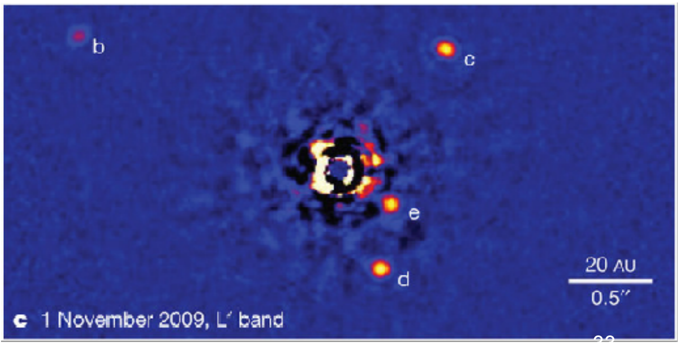


Giant planet formation

- Core accretion vs. disk instability?
- Fomalhaut b : a few M_J at 119 AU Kalas et al. 2008
- HR 8799 Marois et al. 2008, 2010

  5-13 M_J at 15, 24, 38, and 68 AU

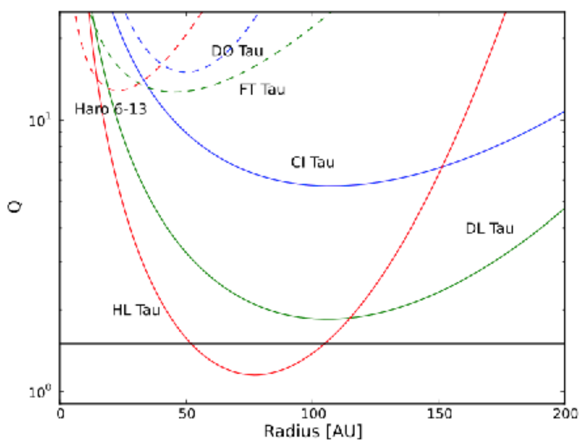


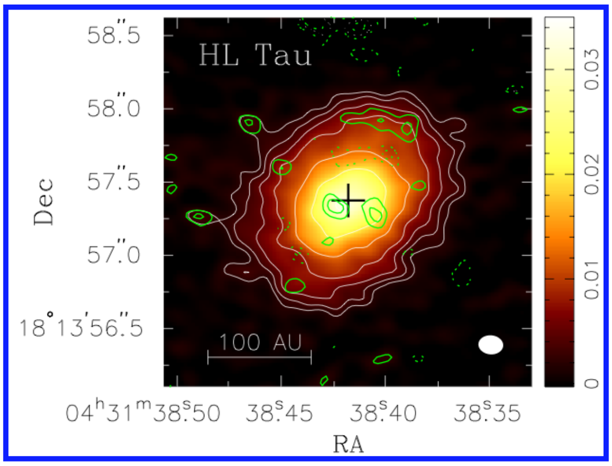


Gravitationally unstable outer region

- Toomre $Q = c_s\Omega / \pi G\Sigma \sim M_* / M_{disk}$
- HL Tau

  Toomre Q < 1.5 in 50 AU < R < 100 AU Kwon et al. 2011, 2015





A Short Story of Magnetic Fields & Polarizations in YSOs

Early disk formation vs. B

Segura-cox+Kwon et al. 2015

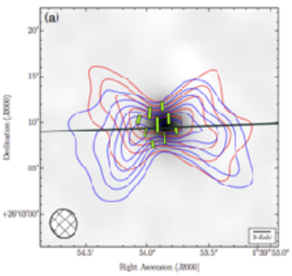
cf. Non-ideal MHD effects, density profiles (e.g., Machida et al. 2011, 2014)

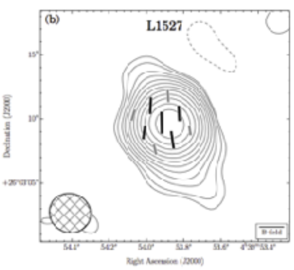
L1527, VLA1623A Ohashi et al. 2014 Murillo et al. 2013

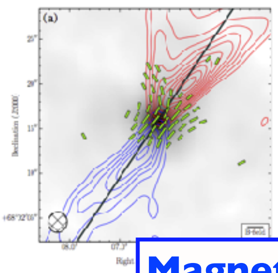
Large disk ~ 100 AU

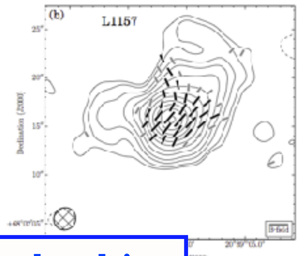
L1157, B335 Yen et al. 2015

No disk > 15 AU





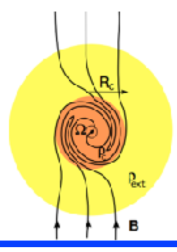


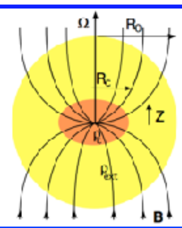


Hull+Kwon et al. 2014

Magnetic braking

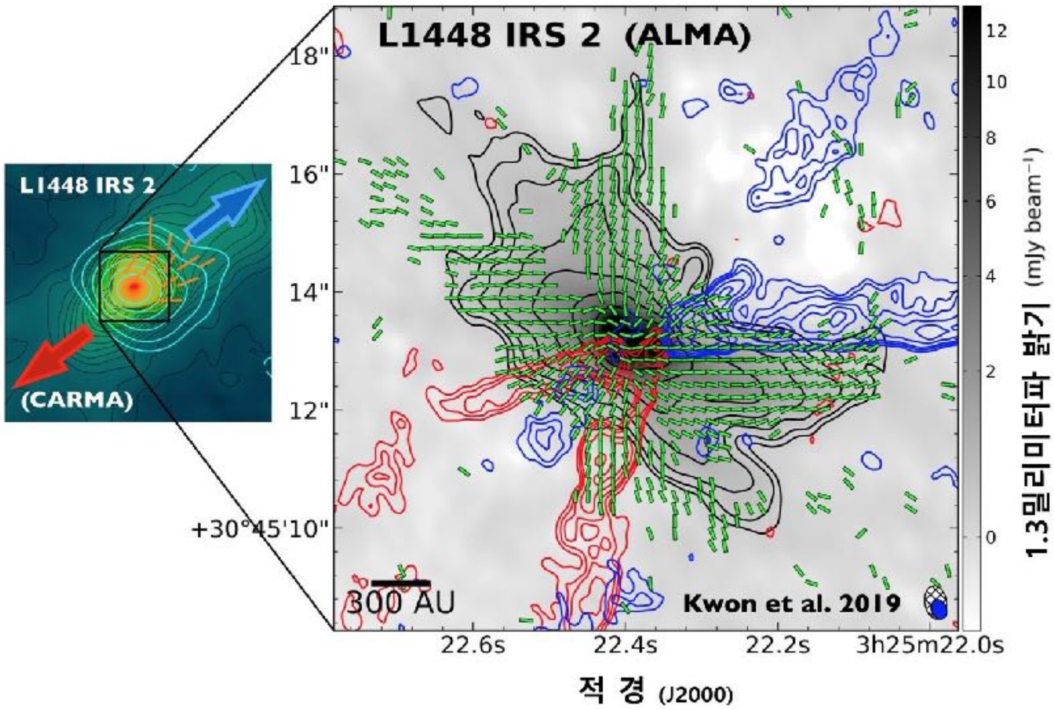
Joos et al. 2012





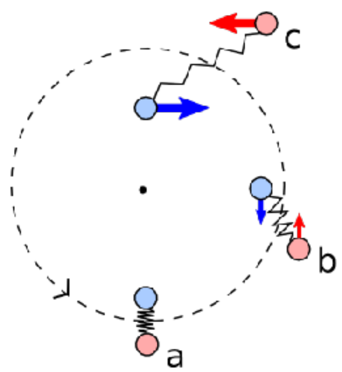
Early disk formation

in B-fields aligned to outflow



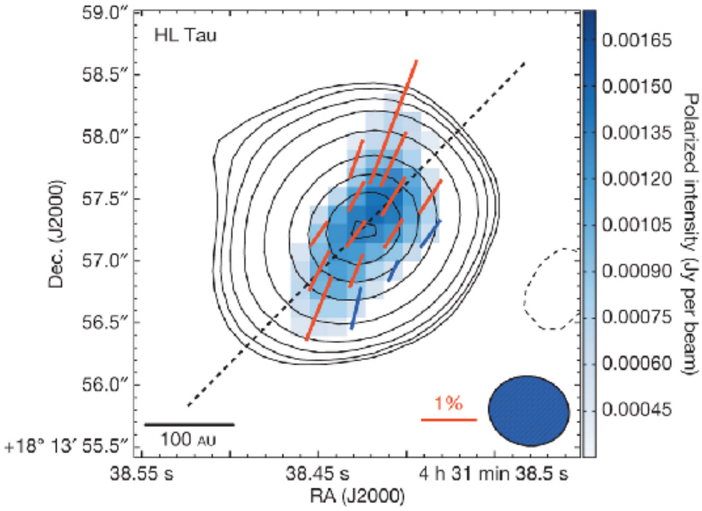
Magnetic fields in protoplanetary disks
Magneto-rotational instability?

- MRI: accretion mechanism at later stages of YSOs
- Required conditions
  Rotational velocity decreases outward
  Toroidal magnetic fields



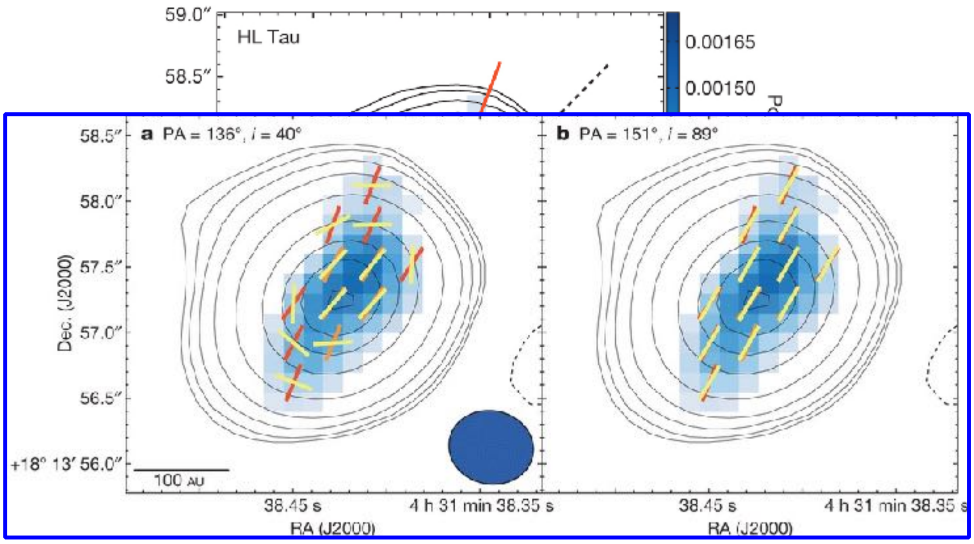
First resolved “magnetic fields” in HL Tau

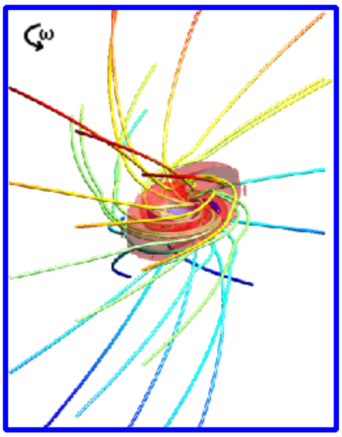
- Stephens et al. (+Kwon) 2014, Nature
- CARMA, polarimetric obs at 1.3 mm, up to 0.5’’
- Toroidal fields dominant (magneto-rotational instability), but not a simple toroidal field



First resolved “magnetic fields” in HL Tau

- Stephens et al. (+Kwon) 2014, Nature
- CARMA, polarimetric obs at 1.3 mm, up to 0.5’’
- Toroidal fields dominant (magneto-rotational instability), but not a simple toroidal field



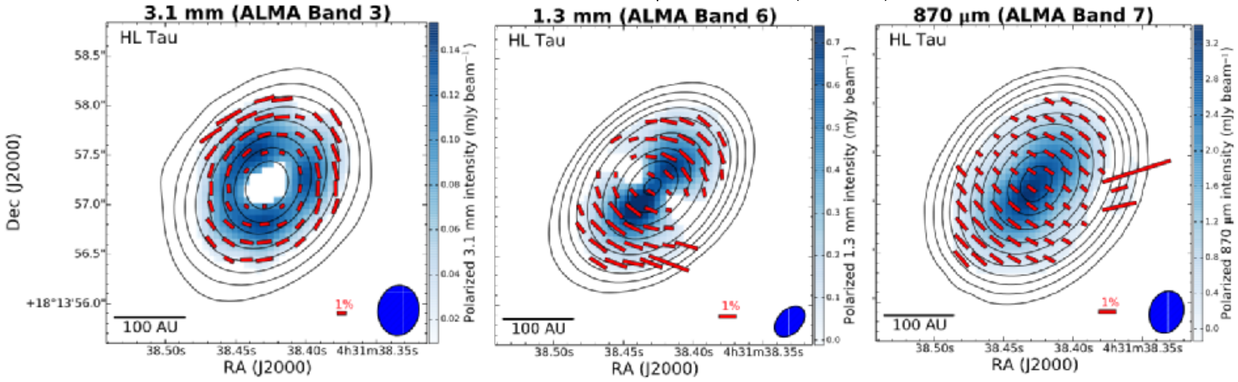


Various Polarization Mechanisms

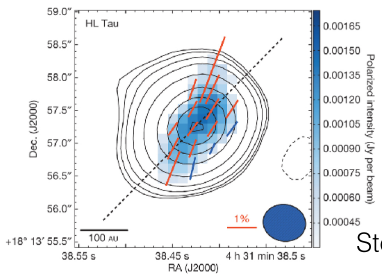
in Protoplanetary disks

Magnetically aligned dust grains => various mechanisms

Kataoka et al. 2017, Stephens et al.(+Kwon) 2017



Radiation alignment



Self-scattering

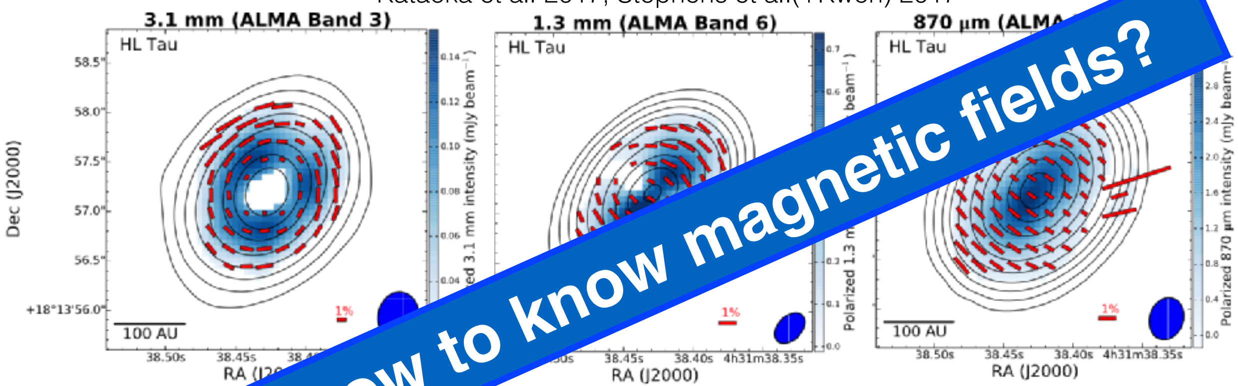
Stephens et al.(+Kwon) 2014

Various Polarization Mechanisms

in Protoplanetary disks

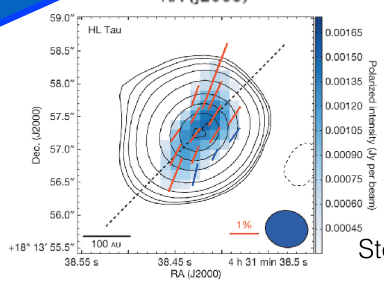
Magnetically aligned dust grains => various mechanisms

Kataoka et al. 2017, Stephens et al.(+Kwon) 2017



Then, how to know magnetic fields?

Radiation alignment

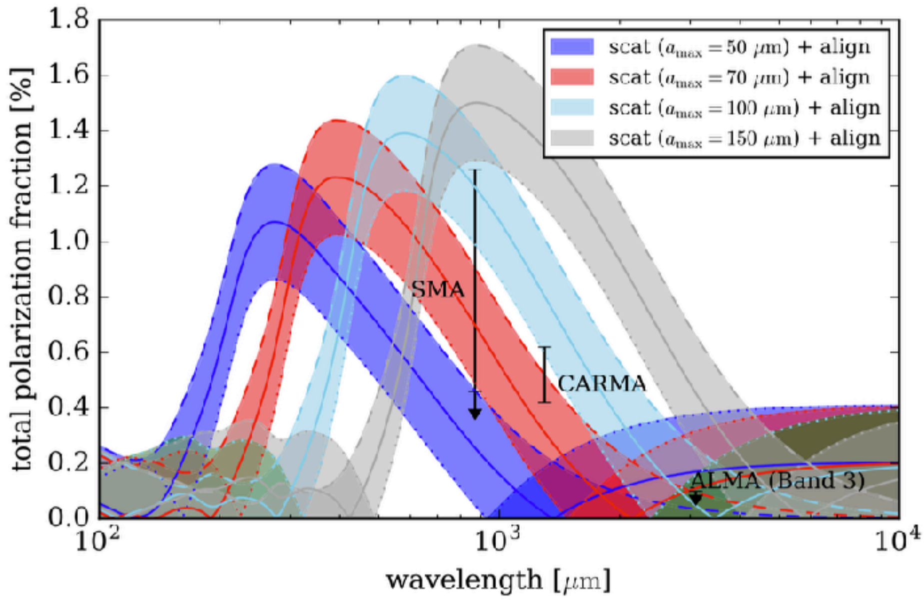


Self-scattering

Stephens et al.(+Kwon) 2014

Grain sizes constrained by polarizations

- Polarizations of HL Tau (Kataoka et al. 2017)



Summary

- Young stellar objects
  Class 0, I, II, III
- Substructures of protoplanetary disks
- Planet formation features
  - rotational velocity gradients
  - circumplanetary disks
  - velocity kink
- Planet formation scenarios
  - core-accretion
  - gravitational instability
- Magnetic fields & polarizations in YSOs