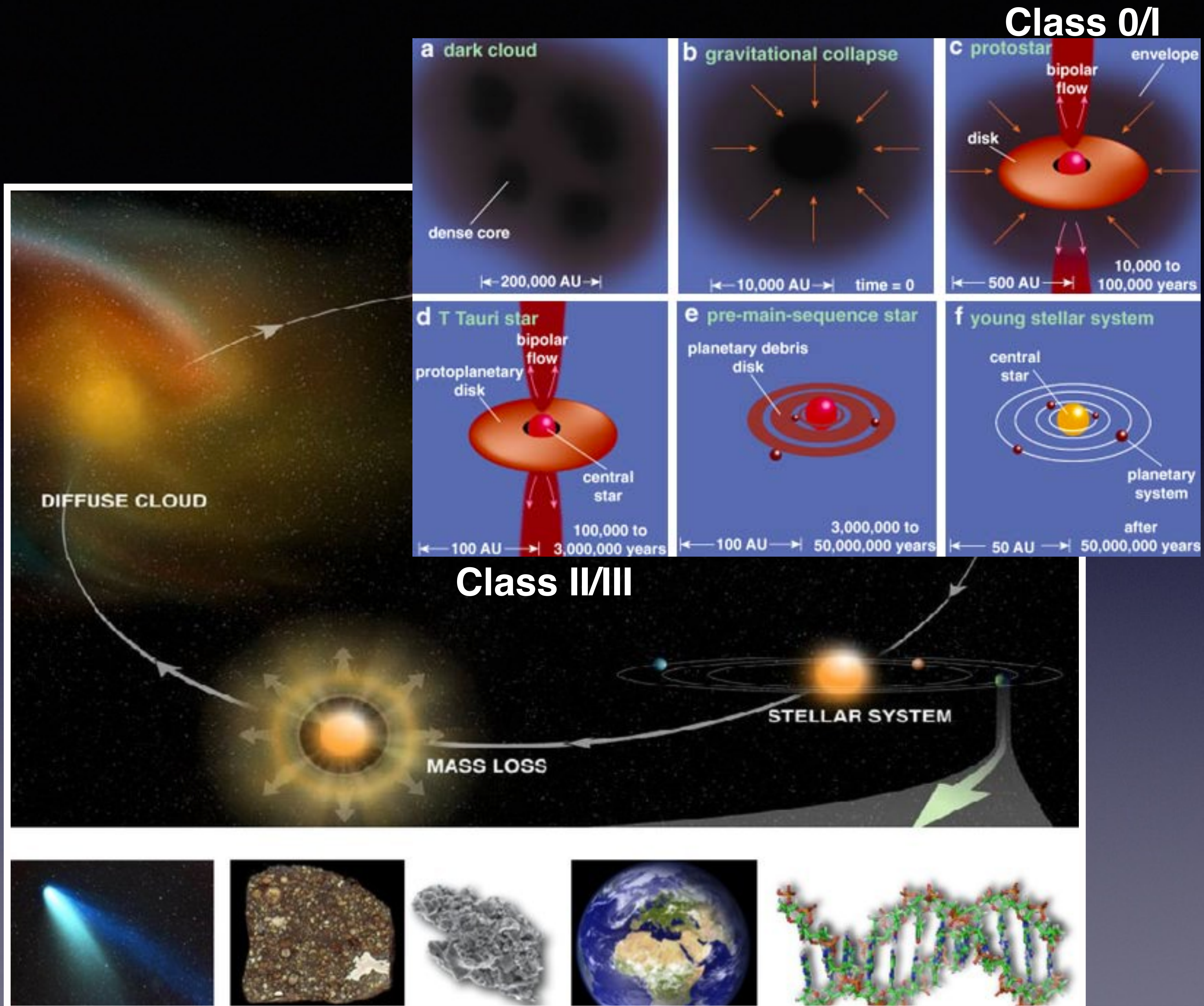
ALMA Science Cases with our Galaxy

SNU Town hall meeting for ALMA Cycle 5
2016 March 23
Woojin Kwon

- 1201 refereed articles (ADS) with “ALMA” in abstracts, as of 3/21/2016
- 618 publications at www.almascience.org
- Array sciences: relatively compact structures!


Class 0/I
a dark cloud
dense core
200,000 AU
b gravitational collapse
10,000 AU
time = 0
c protostar
bipolar flow
envelope
disk
500 AU
10,000 to 100,000 years
d T Tauri star
bipolar flow
protoplanetary disk
central star
100 AU
100,000 to 3,000,000 years
e pre-main-sequence star
planetary debris disk
100 AU
3,000,000 to 50,000,000 years
f young stellar system
central star
planetary system
50 AU
after 50,000,000 years
Class II/III
DIFFUSE CLOUD
STELLAR SYSTEM
MASS LOSS

- Cases in ALMA primer
  1. Protoplanetary disks
  2. Magnetic fields
  3. Evolved stars
  4. Asteroid 3 Juno
- Solar objects: Asteroid 3 Juno
- Evolved stars: R Sculptors, AFGL 3068
- Young stellar objects: many cases

Science Cases in ALMA primer

Level one science aims

I. The ability to detect spectral line emission from C^+ in a normal galaxy like the Milky Way at a redshift of $z = 3$, in less than 24 hours of observation.

II. The ability to image gas kinematics in a solar-mass protostellar/protoplanetary disk at a distance of 150 pc (roughly, the distance of the star-forming clouds in Ophiuchus or Corona Australis), enabling one to study the physical, chemical, and magnetic field structure of the disk and detect the tidal gaps created by planets undergoing formation.

III. The ability to provide precise images at an angular resolution of 0.1′′. Here the term "precise image" means an accurate representation of the sky brightness at all points where the brightness is greater than 0.1% of the peak image brightness. This requirement applies to all sources visible to ALMA that transit at an elevation greater than 20 degrees.

1. Multi-wavelength Continuum Survey of Protostellar Disks in Ophiuchus

- Science goals: evolution of protostellar disks
- Method: dust properties based on SED
- Targets: 6 Class II YSOs in Ophiuchus MC (d~125 pc)

Observation design (cycle4)

- Receivers: Bands 3, 4, 6, 7, 8, 9, 10
  (98, 145, 233, 344, 405, 679, 869 GHz)
- Angular resolution (LAS): 0.4'' (2'')
  e.g., 100 AU disks = 0.8'' at 125 pc of Oph MC
- Sensitivity:
  0.019, 0.043, 0.11, 0.24, 0.34, 0.94, 1.54 mJy/beam
  e.g., 0.01 $M_{\odot}$, 20 K, typical opacity, 125 pc
  detect 3 beam size disk, edges ~ 10% of the peak
- Target time (36 main array antennas)
  26 min, 6.6 min, 1.2 min, 47 sec, 1.5 min, 3.3 min, 7.2 min

Observation design (cycle5)

- Receivers: Bands 3, 5, 7, 9
  (98, 203, 344, 679 GHz)

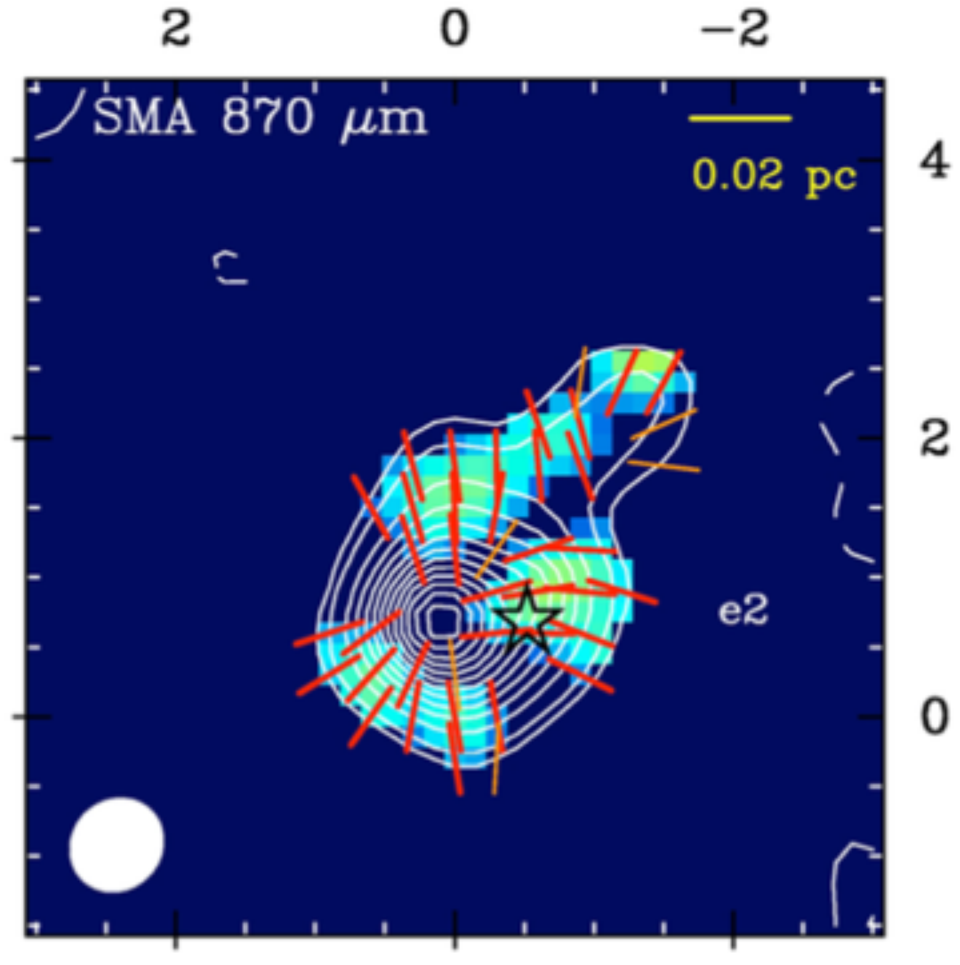
- **Angular resolution (LAS)**: 0.4'' (2'')
  e.g., 100 AU disks = 0.8'' at 125 pc of Oph MC

- **Sensitivity**:
  0.019, 0.074, 0.24, 0.94 mJy/beam
  e.g., 0.01 $M_{\odot}$, 20 K, typical opacity, 125 pc
  detect 3 beam size disk, edges ~ 10% of the peak

- Target time (43 main array antennas, 7.5 GHz bandwidth)
  23 min, 2.5 min, 41 sec, 2.4 min

2. Dust Polarization and Magnetic Fields in Star Forming Clouds

- Science goals: magnetic field effects at thermal Jeans-length scales
- Method: dust polarization
- Targets: W51 e2 (d~7 kpc)



Ya-Wen Tang et al. 2009

Observation design

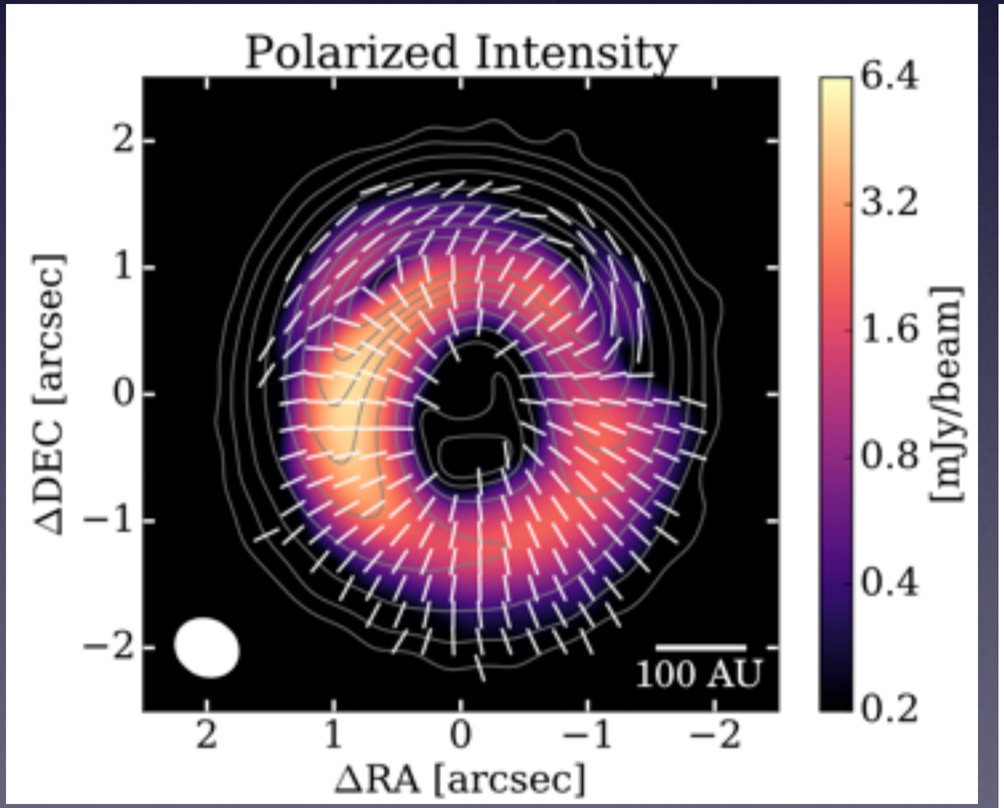
- Receivers: Band 7 (343 GHz)
  highest sensitivity to polarized dust emission
- Angular resolution (LAS): 0.2'' (0.8'')
  thermal Jeans length scale 1400 AU at 7 kpc => 0.2''
  core size => 0.8''
- Sensitivity: 100 μJy/beam
  flux 9.3 Jy over 0.8''
  9.3 Jy / 16 beams = 0.6 Jy/beam
  1% polarization => ~6 mJy/beam, so 60σ detection
- Target time: 5 min but 3 hours requested
  for sufficient parallactic angle coverage

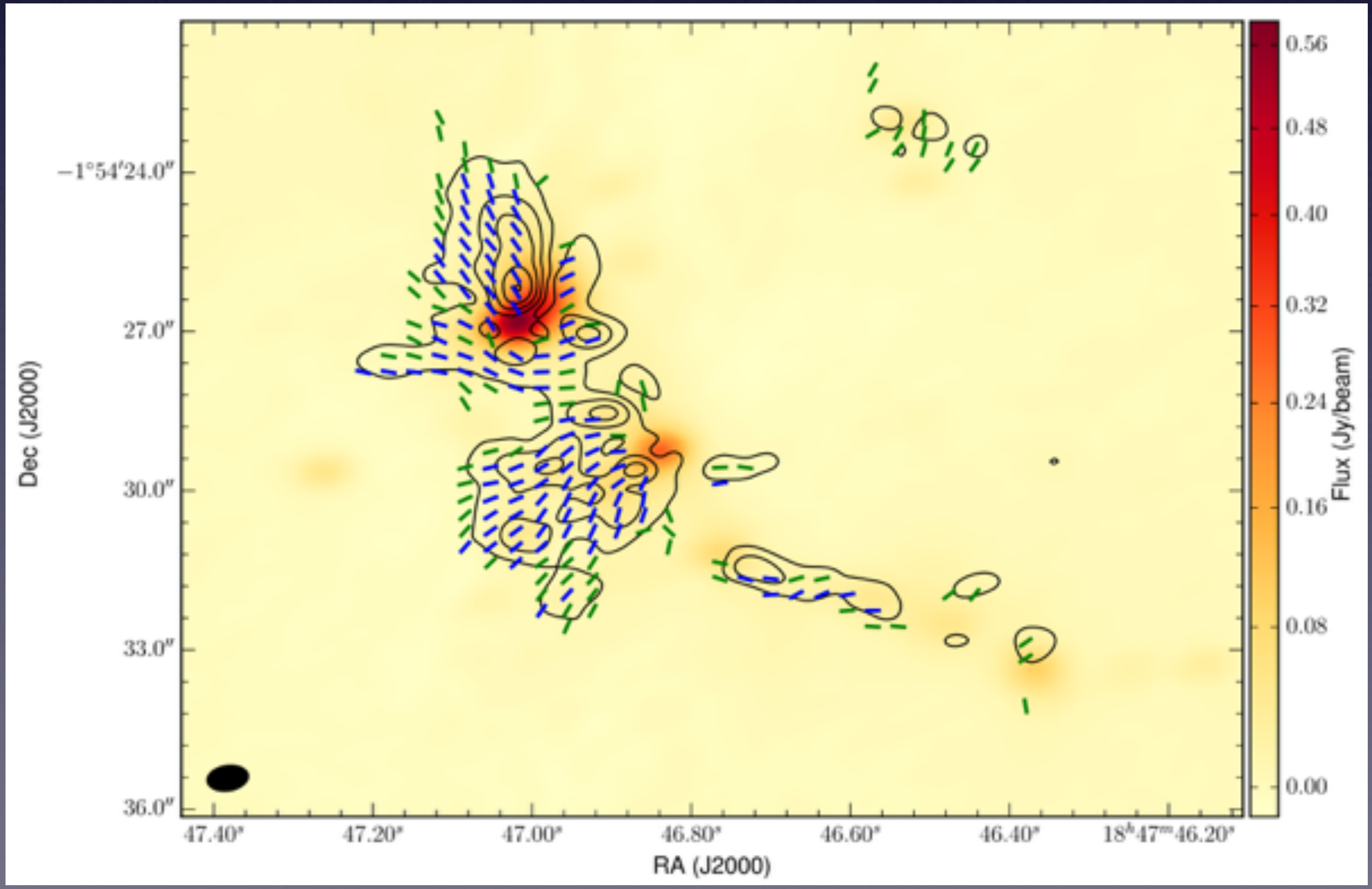
ALMA polarimetric observations

ALMA started to show the results!

Herbig Ae star **HD 142527**
Kataoka et al. 2016
Band 7

High mass star forming clump
W43-MM1 (B-vectors)
Cortes et al. 2016
Band 6

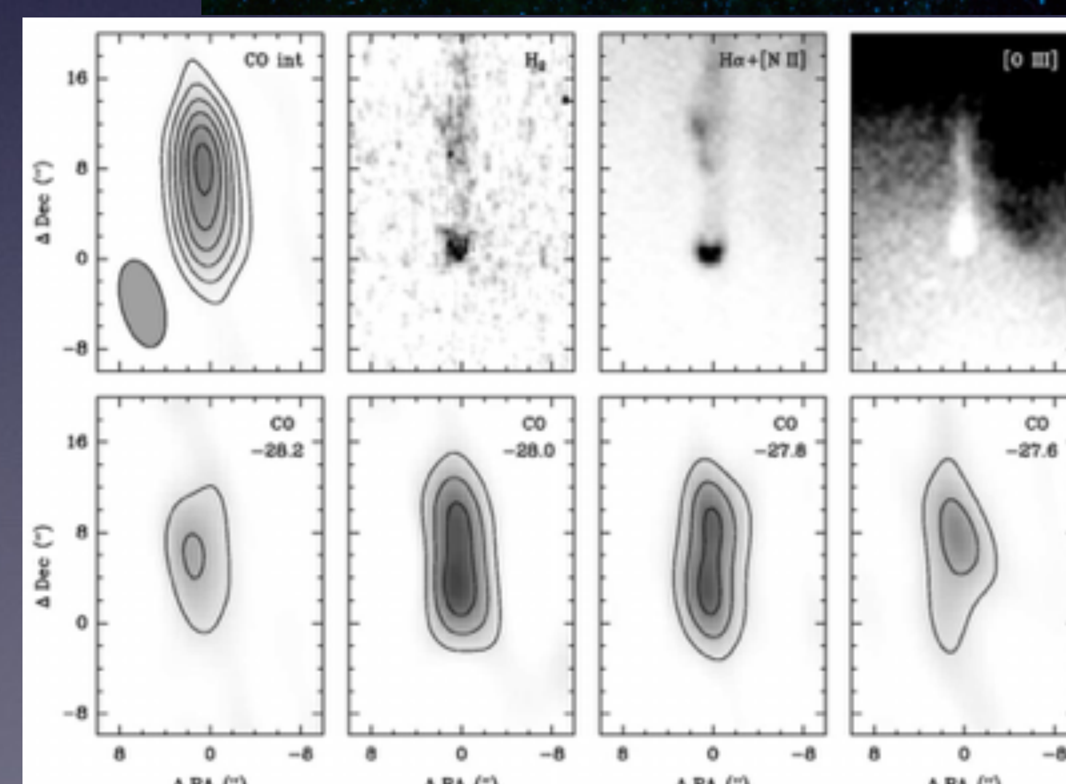




3. Observing Molecular Gas in a Planetary Nebula

- Science goals: physical processes that created the nebulae, origin of tiny clumps (windswept, photo-evaporating, or shadowing?)
- Method: map the structure of molecular gas in a Planetary Nebula
- Targets: Helix Nebula thousands of small (< 1''), dense ($n \sim 10^5$ cm^{-3}), quiescent ($\Delta V < 1$ km/s), and faint ($T_A^* < 5$ K) clumps slowly evaporating in the radiation field of the central white dwarf
  Huggins et al. 2002

Spitzer Space Telescope



Huggins et al. 2002 PdBI

Observation design

- Receivers: CO 2-1 in Band 6 (230.538 GHz)
- Angular resolution (LAS): 0.3'' (1'')
  10x10 better than previous studies (~3'') => 0.3''
  fragmentation scale => ~1''
- Mosaic required: Helix (diameter~25')
  (primary beam~27'' => roughly 7500 pointings)
  one pointing each SE and NW of the nebula
- Spectral resolution: expected line profiles (~0.8 km/s fwhm)
  117 MHz bandwidth mode and spectral averaging factor 4
  0.158 km/s resolution
- Sensitivity: peak < 5 K
  0.5 K, moderate sensitivity (S/N~5) for bright Helix Nebula fragments
- Observation time: 3.9 hours to reach 0.5 K in 0.16 km/s, including overheads
  two positions => 7.8 hours

4. Continuum High Resolution Imaging of the Asteroid 3 Juno

- Science goals: T distribution, regolith thickness and composition
- Method: observe at 1.3 mm continuum over time for rotational period and 3D shape as well
- Targets: Asteroid 3 Juno

Observation design

- Receivers: Band 6 (233 GHz)

- Angular resolution (LAS): 0.020'' (0.17'')
  near-IR + modeling: Juno ~ 240 km
  8 beams => ~29 km resolution (20 mas at 1.97 AU)
  Target size 0.17'' < Max. Recoverable Scale 0.34'' of the configuration

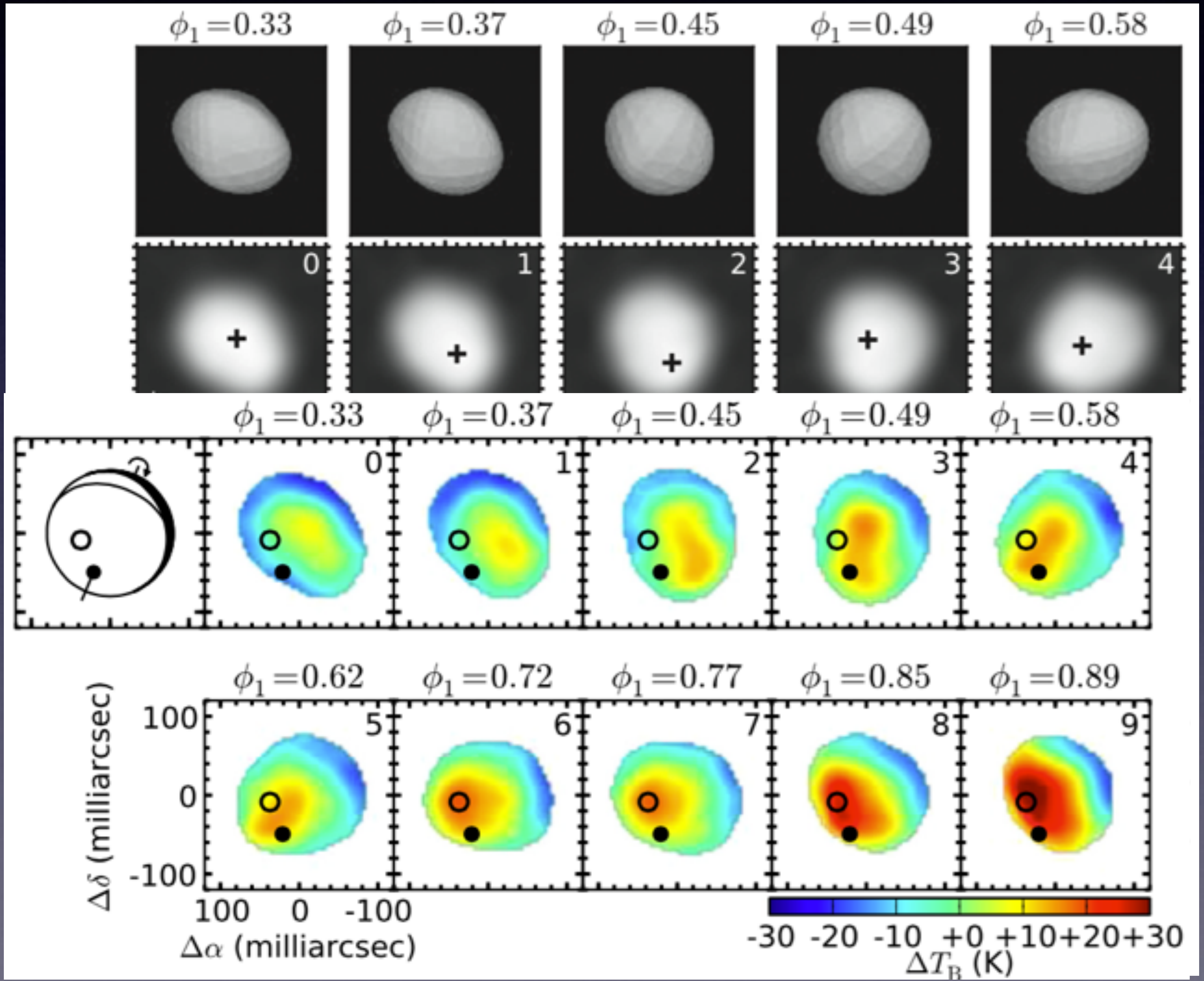
- Sensitivity: 0.038 mJy/beam
  flux 240 mJy at 250 GHz
  240 mJy/64 beams = 3.8 mJy/beam, 100σ detection

- Observation time:
  12 min on-source time (dual pol, 7.5 GHz bandwidth, 43 antennas)
  33 min including overheads
  more than 10 times observations (cf. Juno's rotation P ~ 7.2 hours)

Science Cases using ALMA

Solar Objects: Asteroid 3 Juno

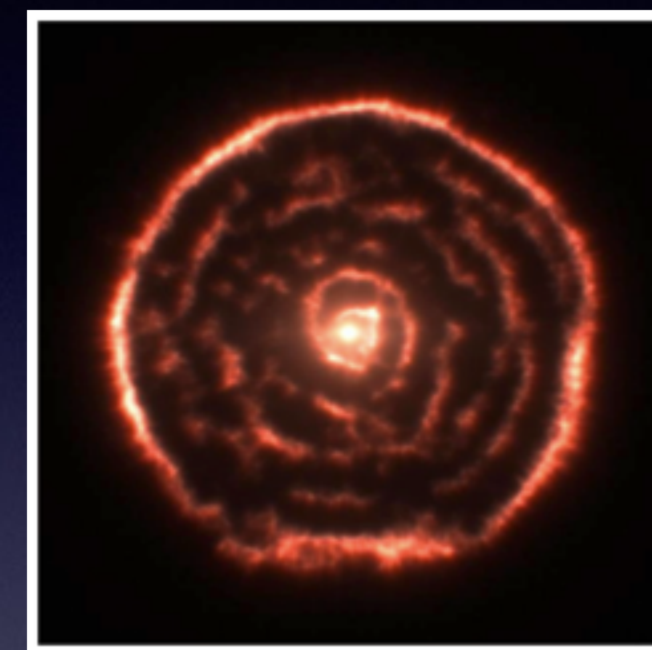
- One of the long-baseline campaign data sets ALMA partnership et al. 2015
- Angular resolution: 0.042''
- 1.3 mm continuum DAMIT models
- Results:
  - consistency between models and data
  - warmest parts correlated to afternoon areas in images 0-5
  - crater in images 6-7 subsolar points?



ALMA partnership et al. 2015

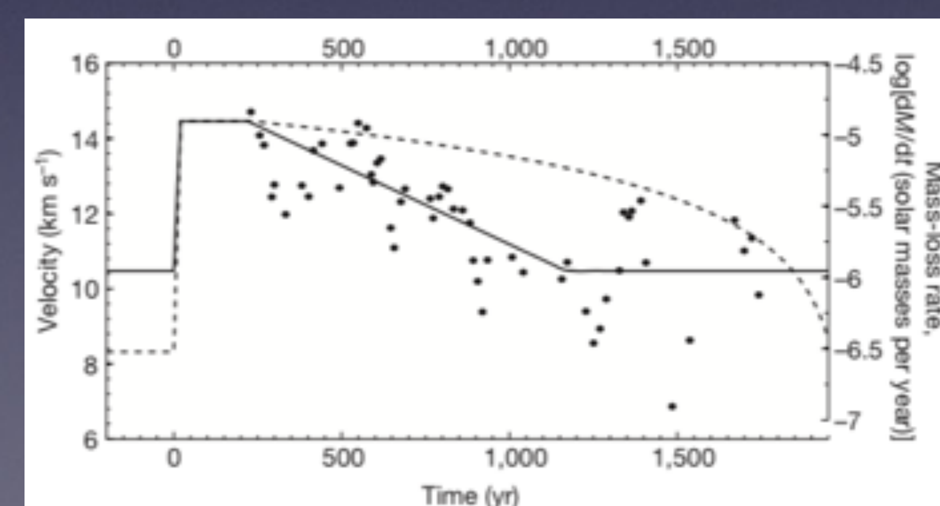
Evolved Stars: R Sculptors

- Unexpectedly large mass loss during the thermal pulse cycle of the red giant star R Sculptors
Maercker et al. 2012 Nature



- Timescales and mass-loss properties during and after a thermal pulse determining lifetime of asymptotic giant branch and amount of elements returned

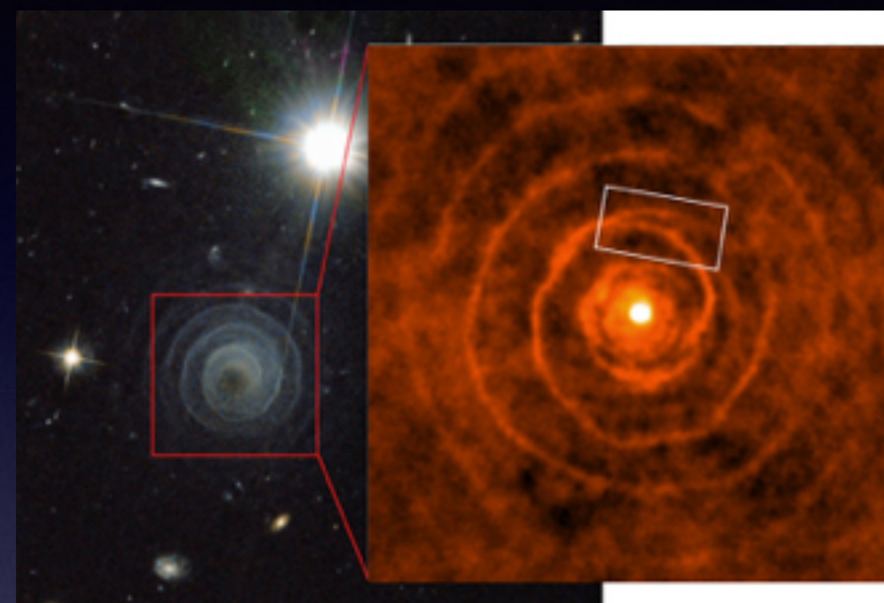
- ALMA cycle 0 observations:
CO 3-2 (345 GHz)
angular resolution of 1.3''

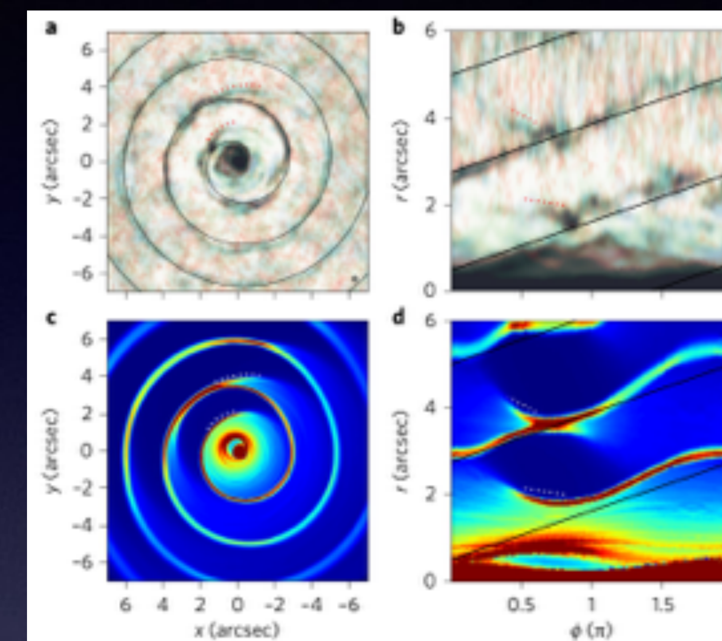


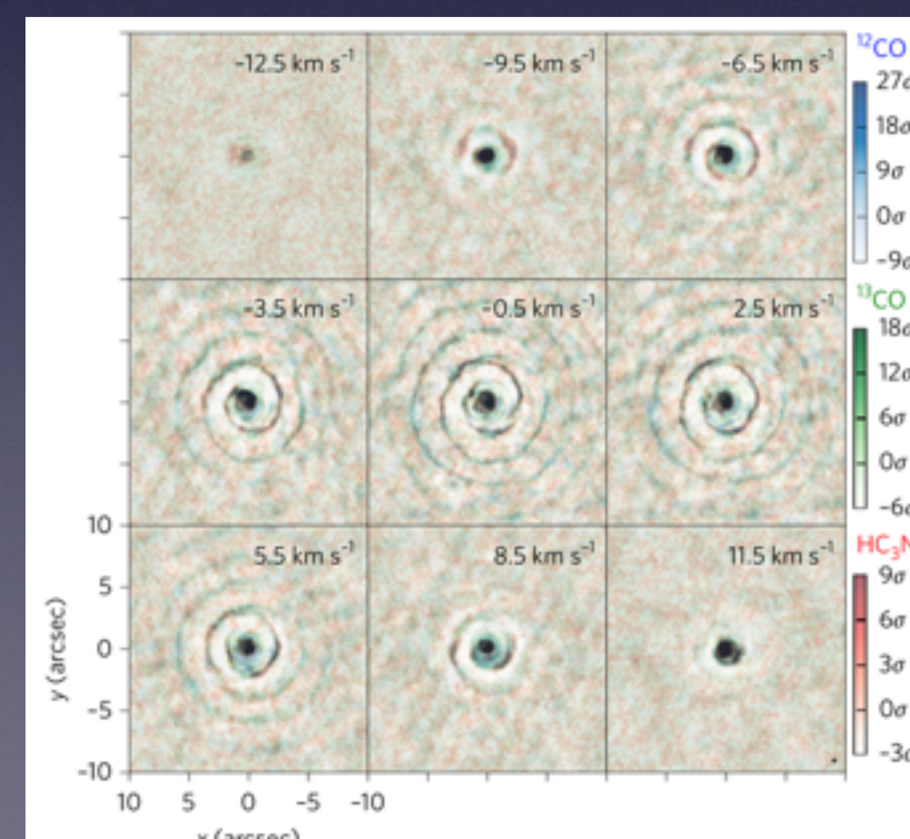
- Binary system <= spiral shell structure
200 year lasting thermal pulse, 1800 years ago
30 times higher mass-loss rate during the pulse
(mass-loss ~ 3×10^{-3} $M_\odot$, 3 times more mass than previously thought)

Preplanetary nebula (AGB) AFGL 3068

- Kim et al. 2017
- Observations
  Band 6
  CO, ^{13}CO, HC_3N
  ~0.3 arcsec
- HST spiral pattern
  —> binary in circular orbit
  ALMA with bifurcation
  —> binary in highly eccentric orbit (e~0.8)



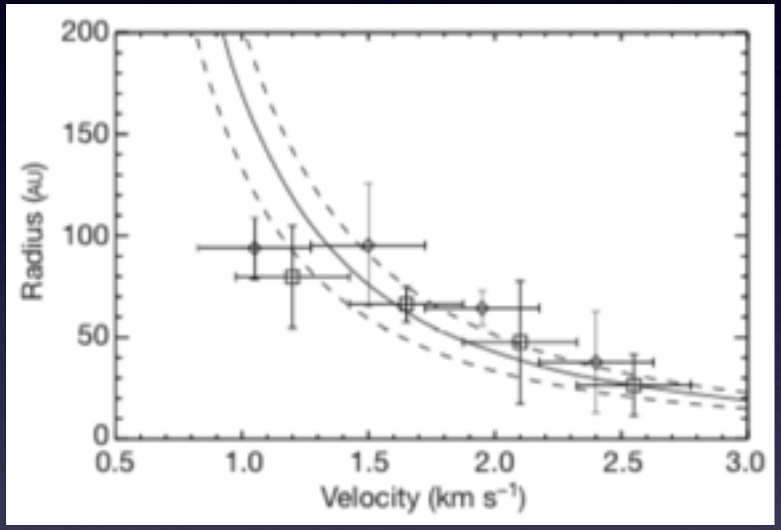


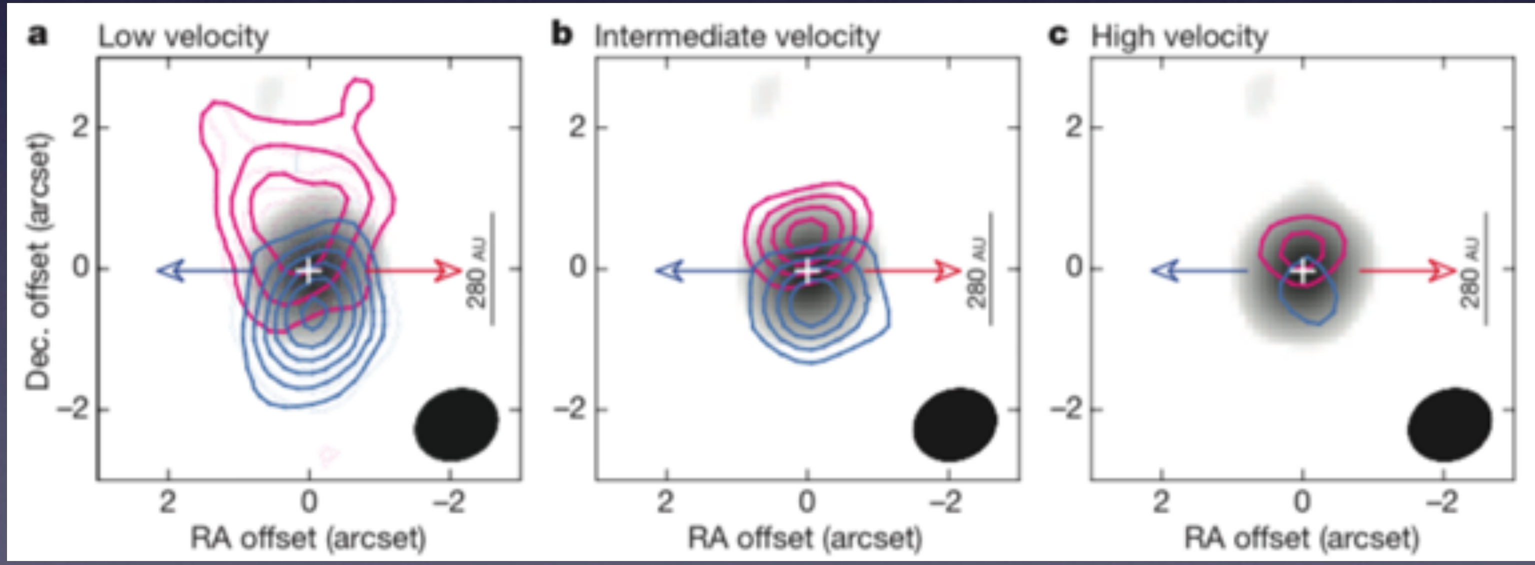


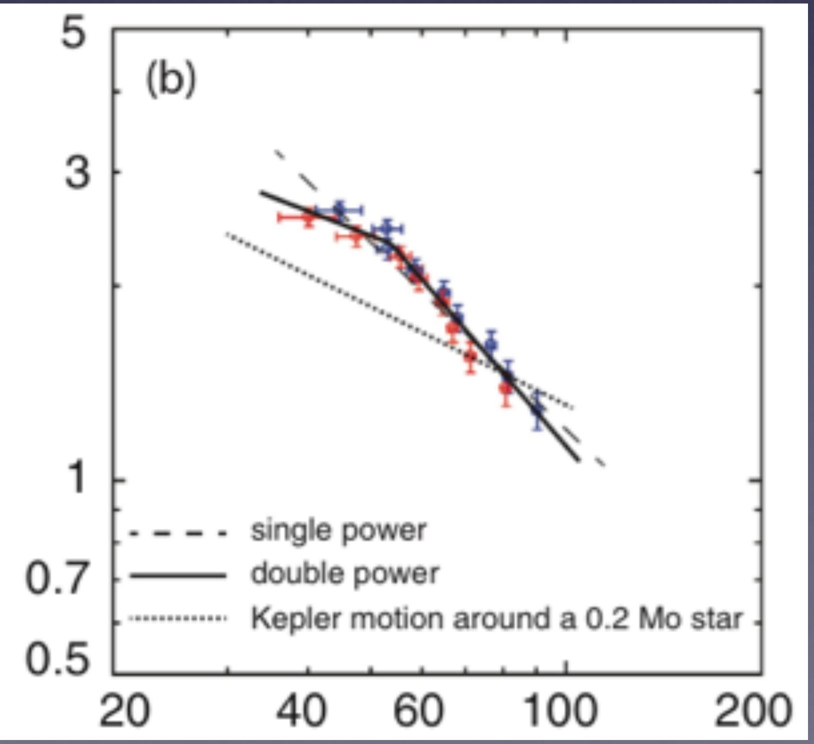
Circumstellar disks of Class 0 YSOs

- L1527
  Taurus MC (d~140 pc)
  CARMA (SMA): ^{13}CO, 1.0''
  ALMA: $C^{18}O$, 0.7'', 0.17 km/s

Tobin et al. 2012, Nature

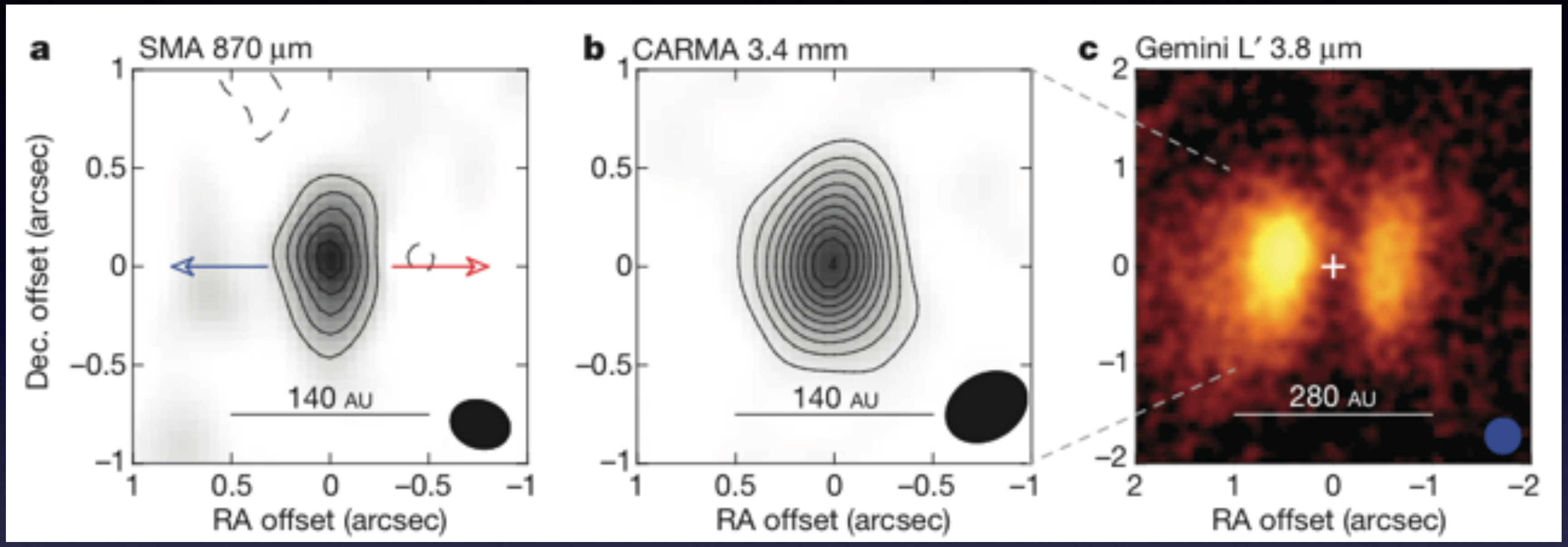






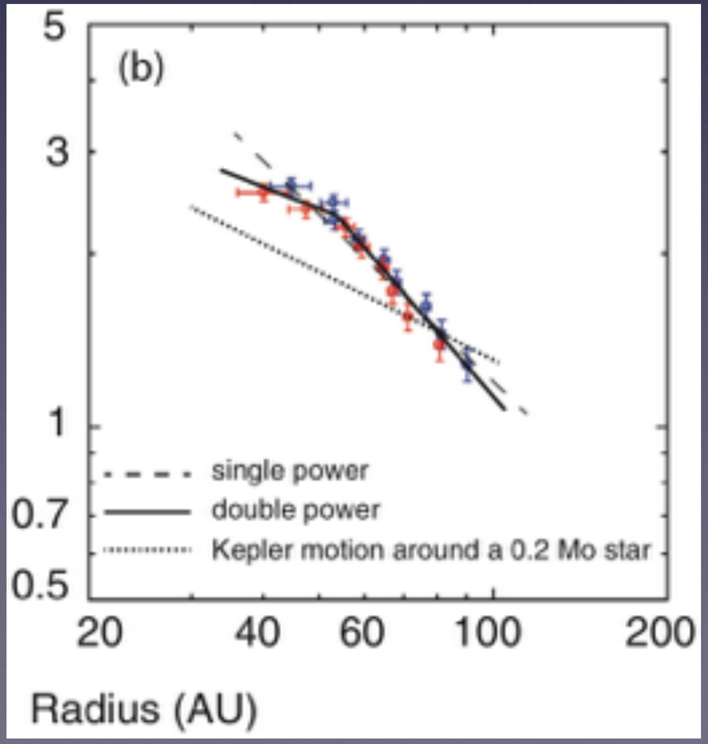
Ohashi et al. 2014

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

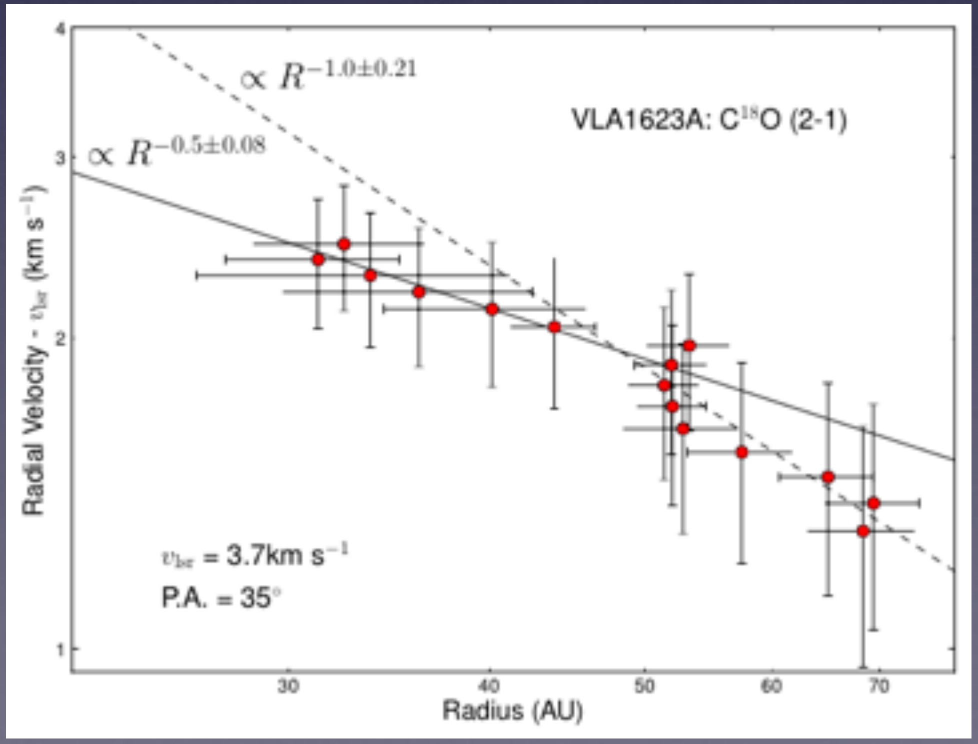


L1527
(SMA, CARMA)
Tobin et al. 2012

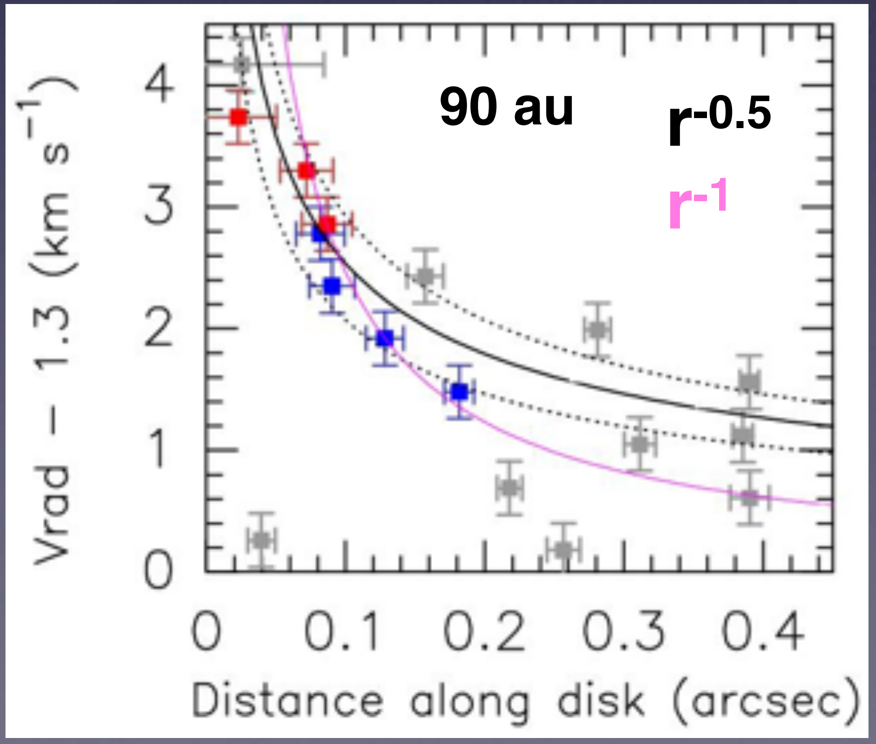
L1527 Ohashi et al. 2014



VLA1623A Murillo et al. 2013

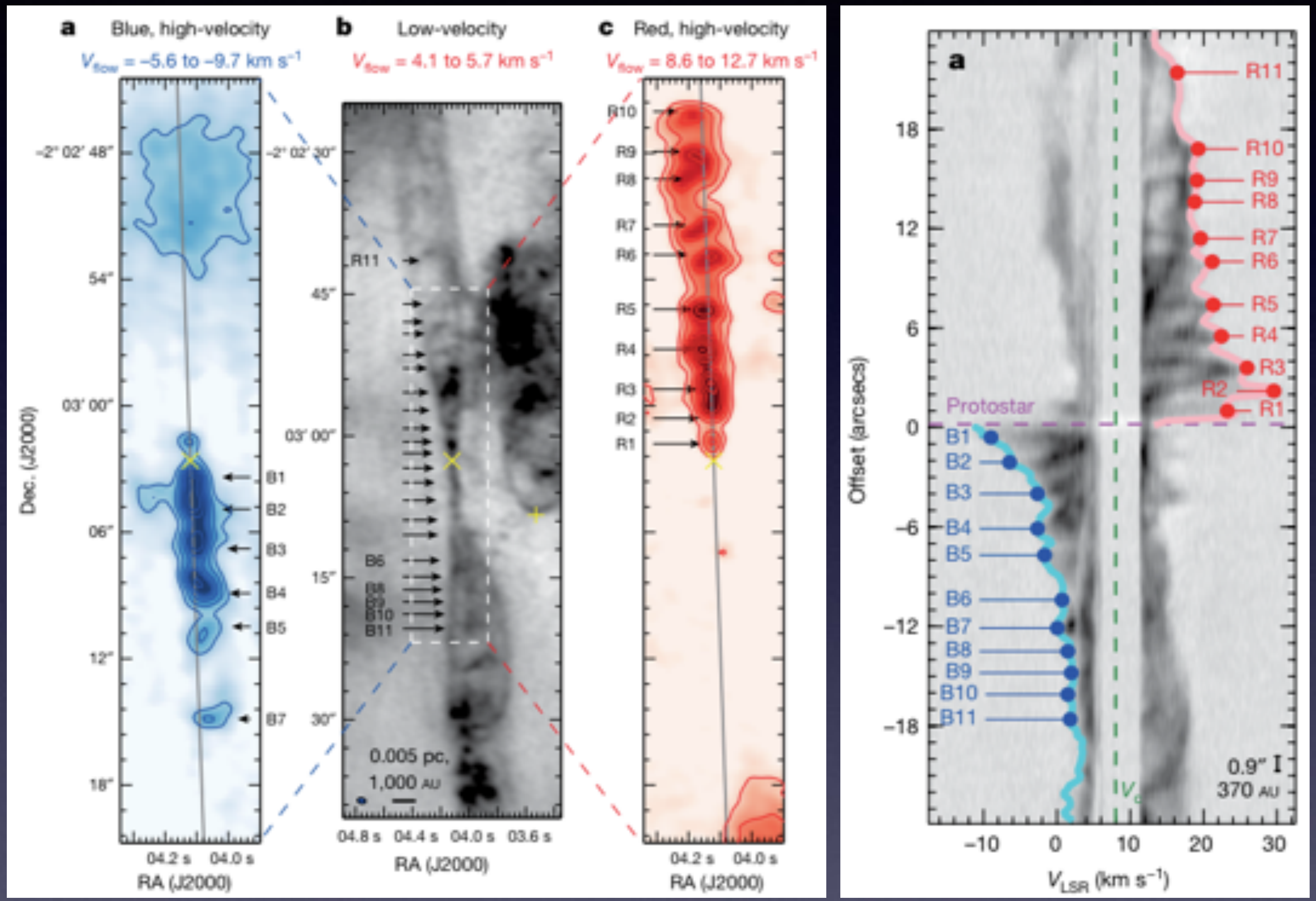


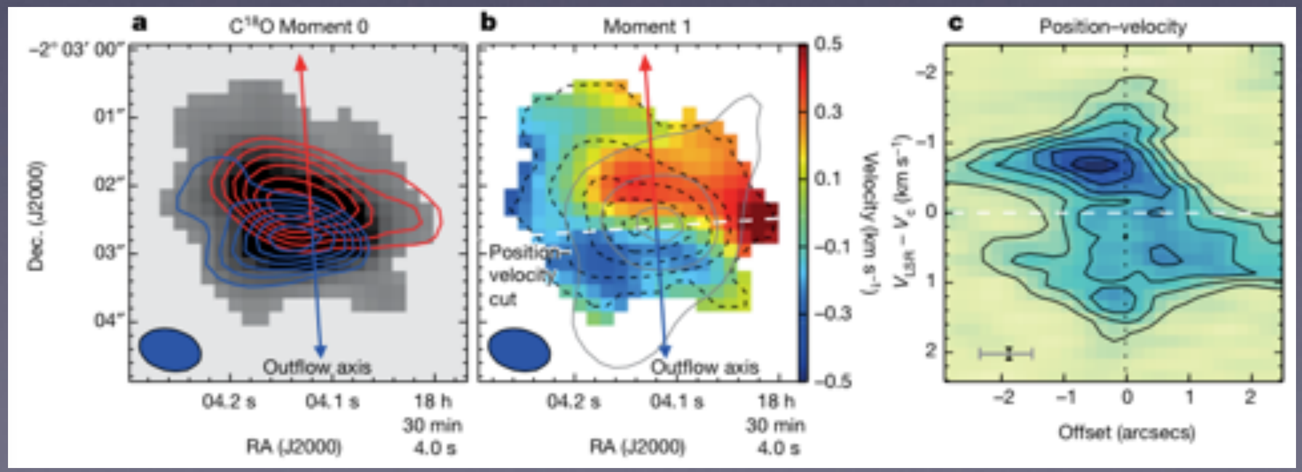
HH 212 Codella et al. 2014



Class 0 YSOs: Bipolar Outflow & Disk

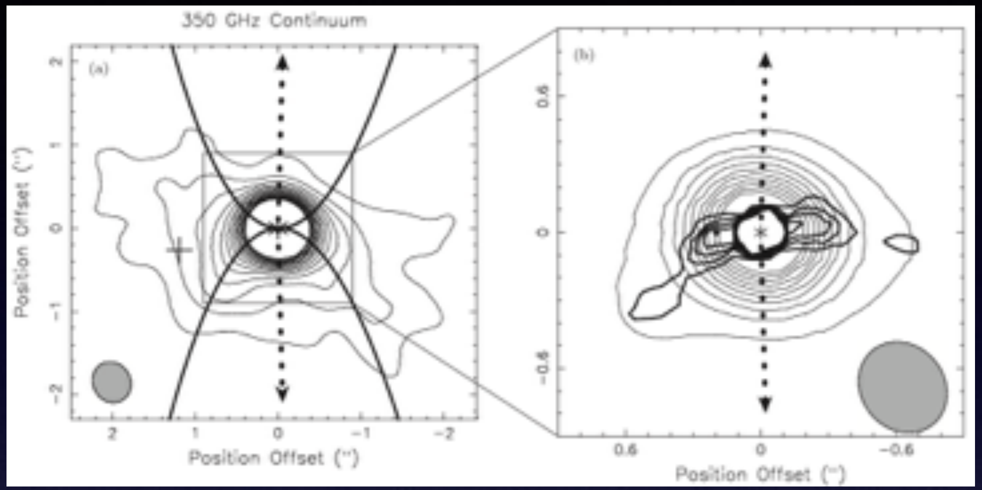
- Episodic outflow events
  Plunkett et al. 2015, Nature
- CARMA-7 (Class 0 YSO) in Serpens South (415 pc)
  0.9''
  CO 2-1, (^{13}CO), C^{18}O
- clumpy CO emission => episodic ejection
- slow-down jet-entrained material and/or intrinsically variable ejections
- "Keplerian rotating disk"?





Class 0 YSOs: Bipolar Outflow & Disk

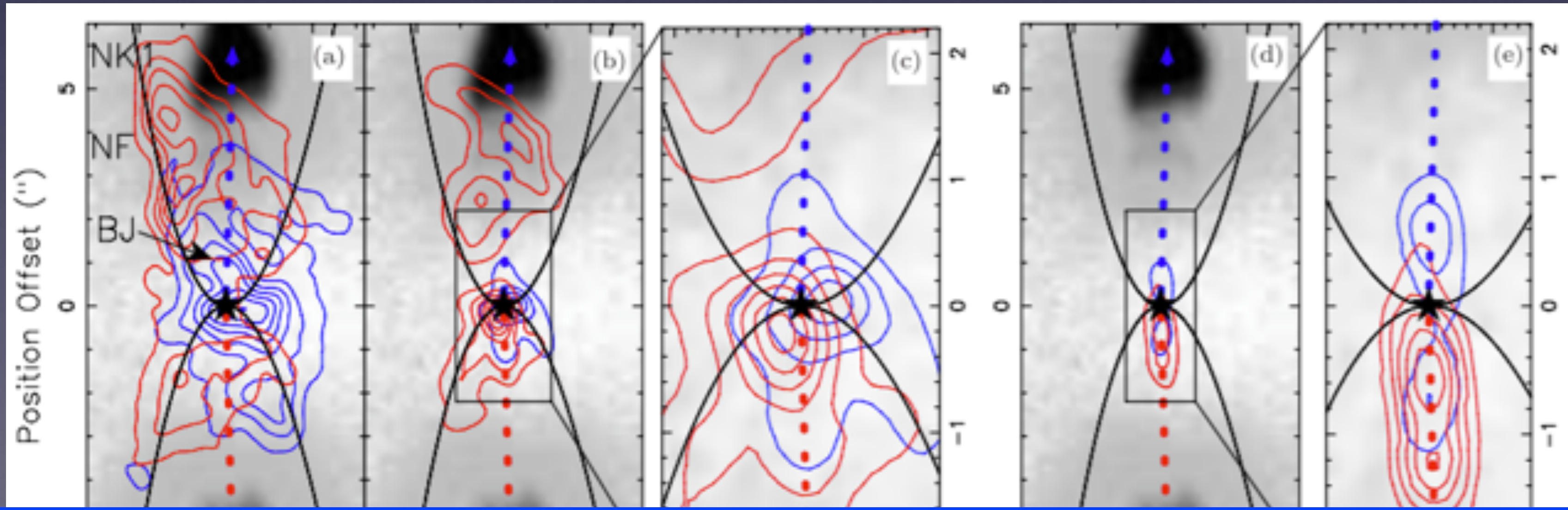
- **HH212** (Class 0 YSO, 400 pc)
  Chin-Fei Lee et al. 2014
- angular resolution ~ 0.4''
  350 GHz continuum, HCO^+ 4-3



> 120 kλ, clean comp.

- Flattened envelope and compact disk in continuum
  Infalling envelope, rotating disk in HCO^+ (Keplerian?)

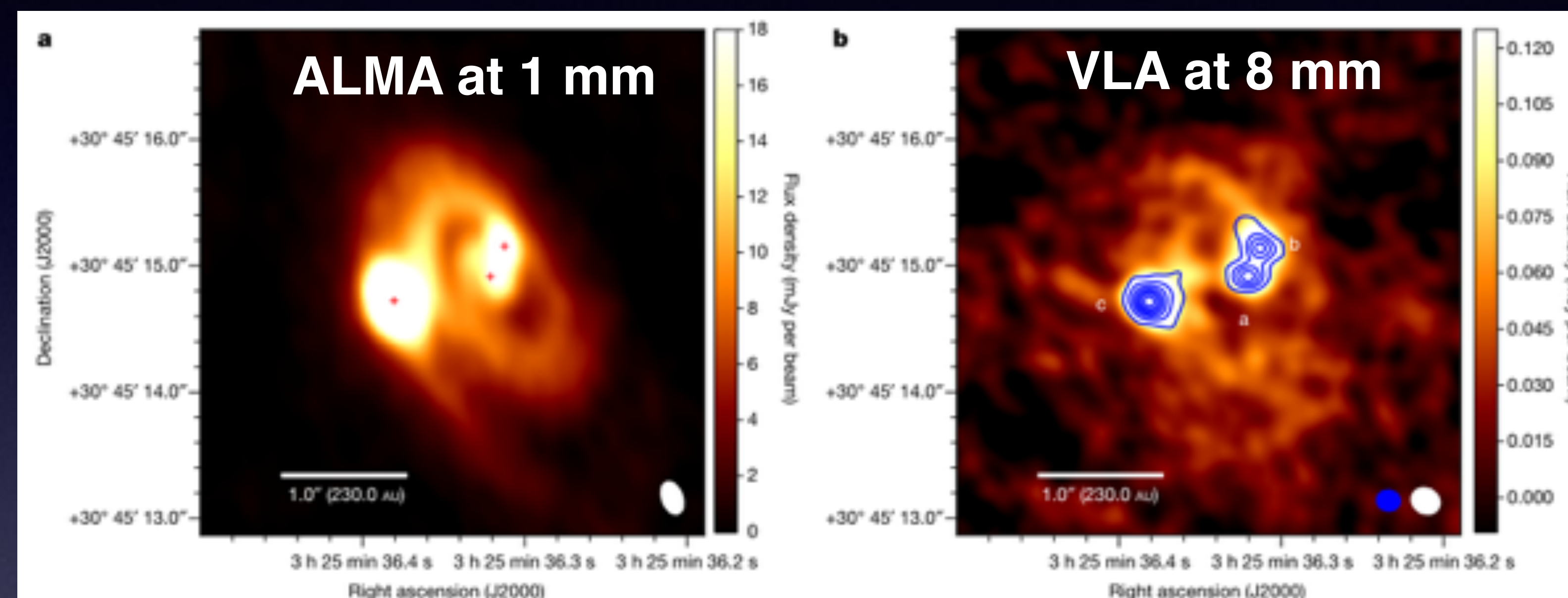
$|V_{off}| < 1$ km/s (1 km/s, 2 km/s) (2 km/s, 3 km/s)

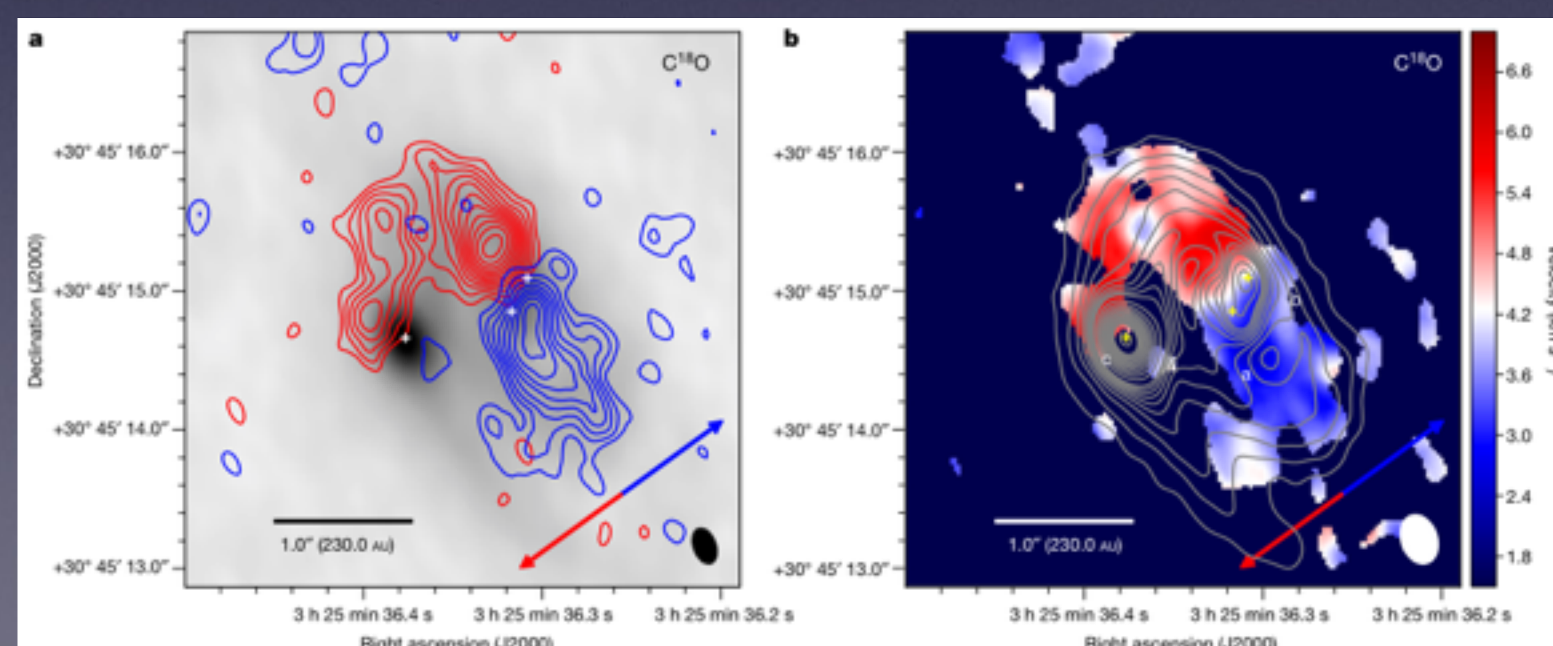


Chin-Fei Lee's talk: The edge-on disk ("Hamburger") has been revealed by recent ALMA observations at a resolution of 0.02''.

Class 0 YSO multiple system L1448 IRS 3B

- Tobin et al. 2016, Nature
- Angular resolution ~ 0.2”
  Band 6
  Continuum, $C^{18}O$
- a+b ~ 1 M⊙ ($C^{18}O$ data)
  c ≳ 0.085 M⊙ (dust emission)
  c is formed by gravitational instability in the disk





1.25–4.0 km/s
5.5–7.0 km/s
continuum

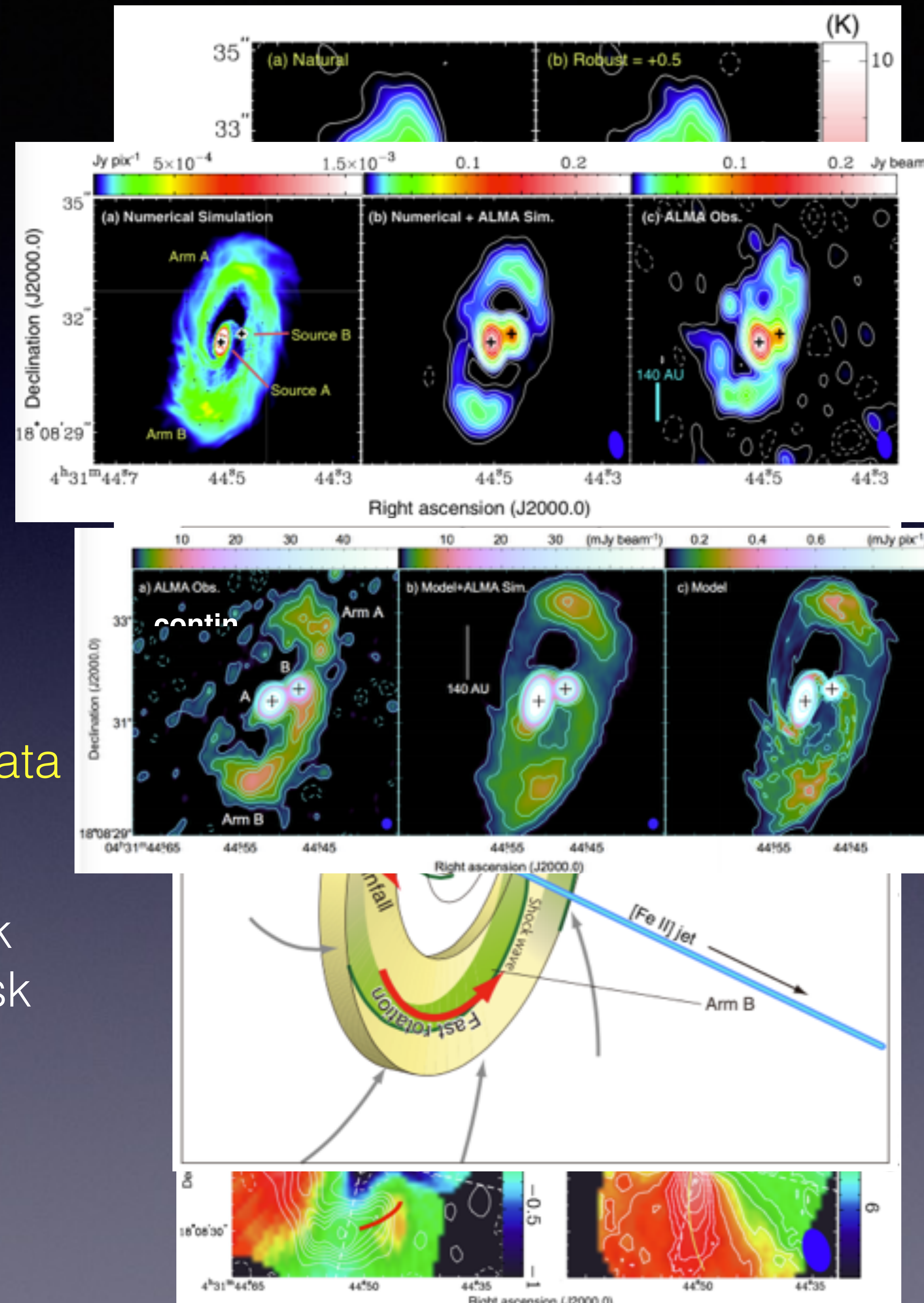
Class I Binary System

- L1551 NE
  Takakuwa et al. 2014

- Observations
  - 0.9 mm continuum, $C^{18}O$ 3-2, ^{13}CO
  - Angular resolution up to 0.36''
  - 1.6 times higher resolution, 6 times higher sensitivity than previous SMA data

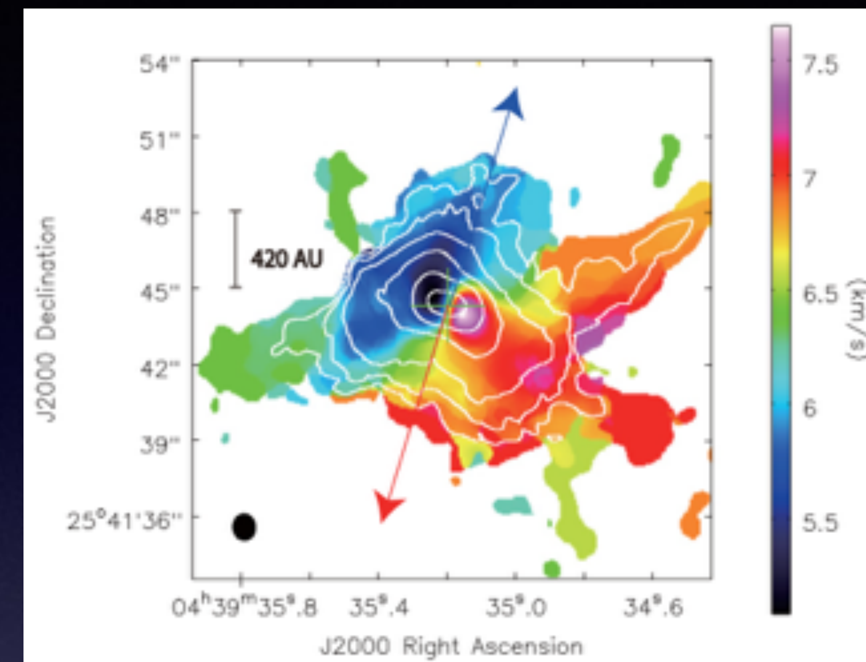
- Results:
  - circumstellar disks, circumbinary disk
  - Keplerian rotation of circumbinary disk
  - infalling gas motion

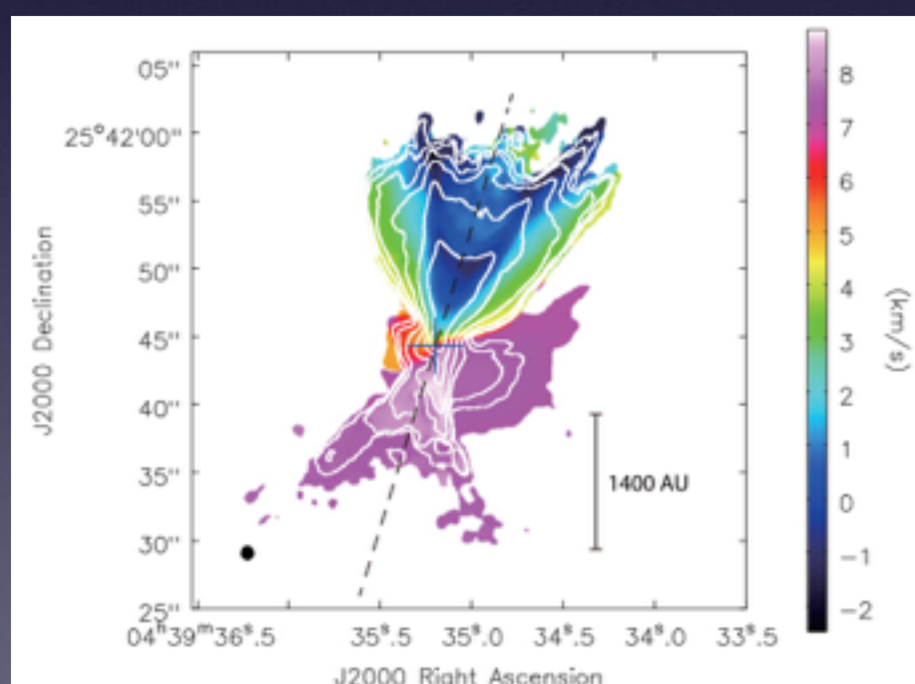
- Updated paper: Takakuwa et al. 2017
  ~0.2''
  cont. $C^{18}O$, ^{13}CO, SO, CS

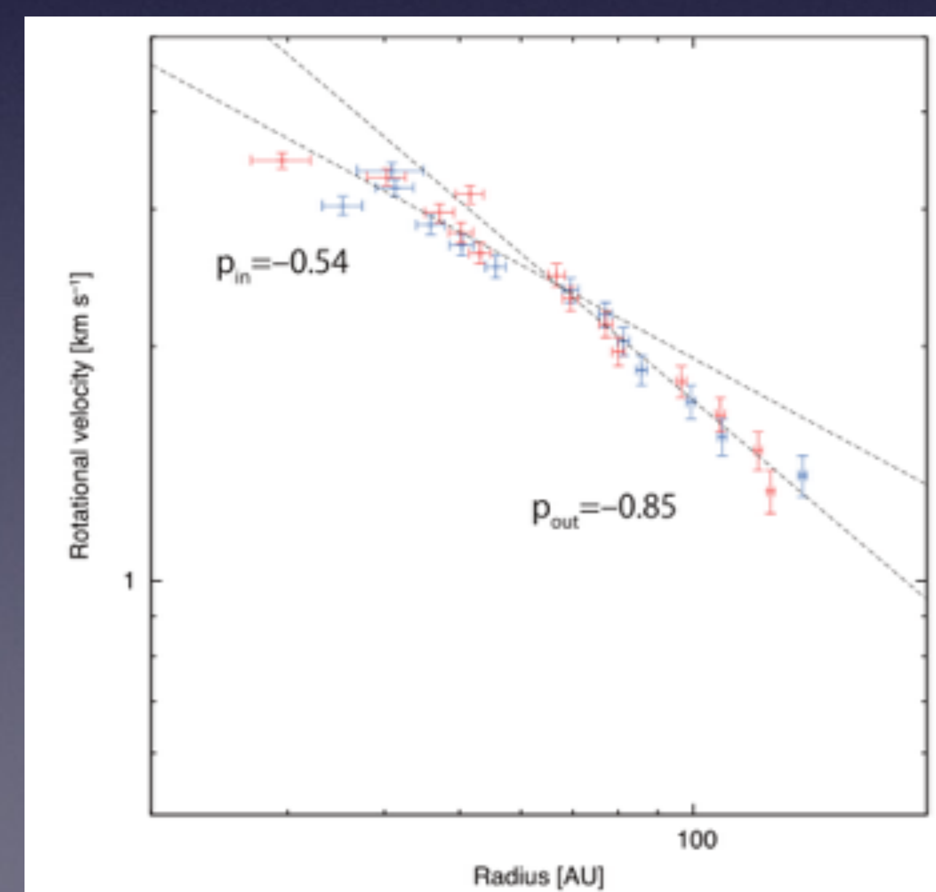


Class I YSOs: Bipolar Outflow & Disk

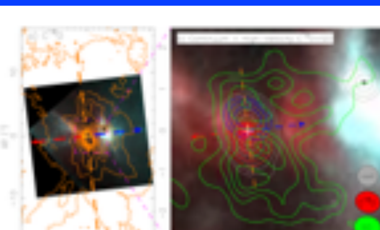
- **TMC-1A** (d~140 pc)   Aso et al. 2015
- ALMA (cycle 0)
  Band 6: cont., CO, $C^{18}O$
  resolution~1”
- Bipolar outflow and infalling/rotating disk





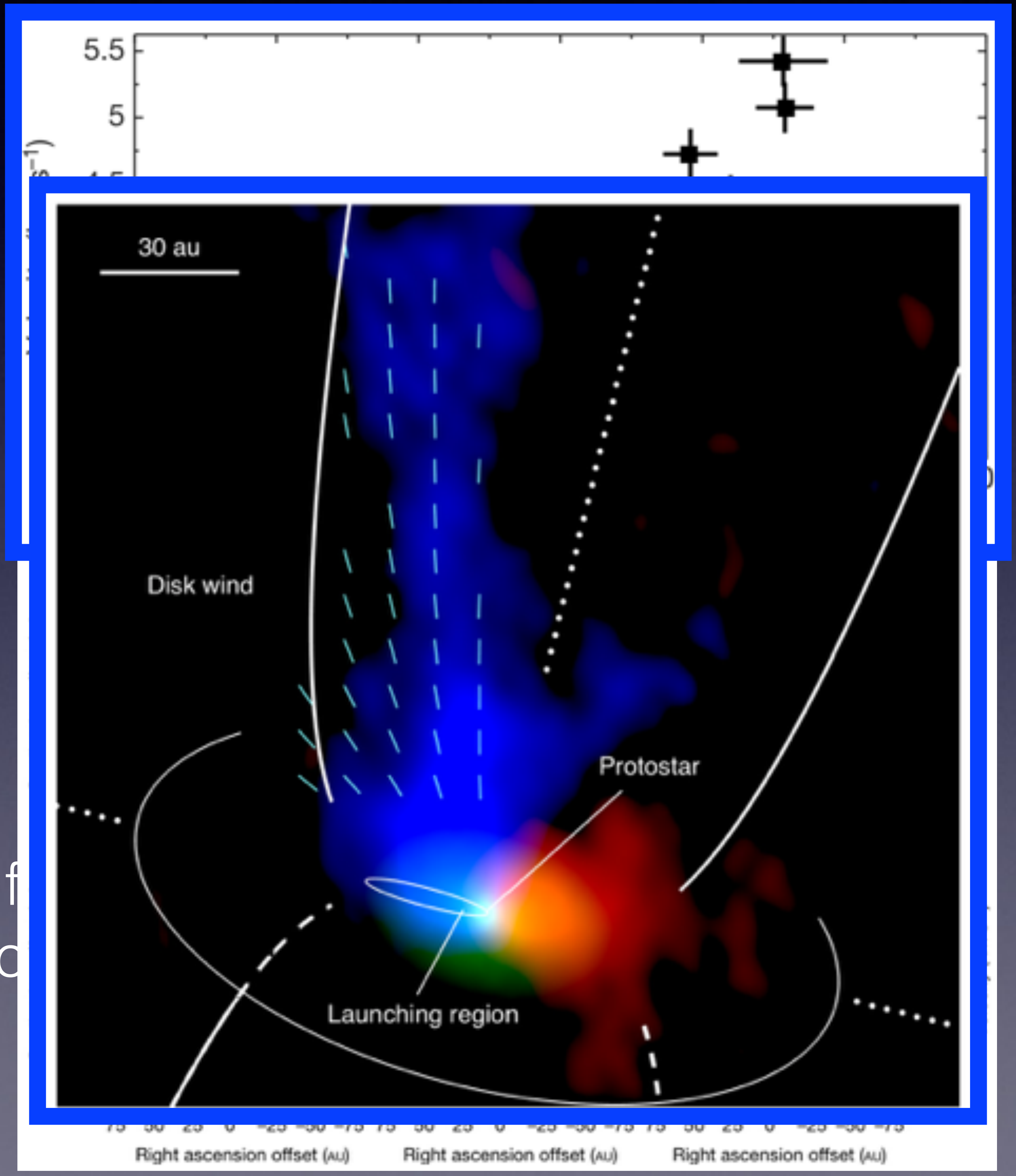


Another example of Class I:
HH111   Lee et al. 2016



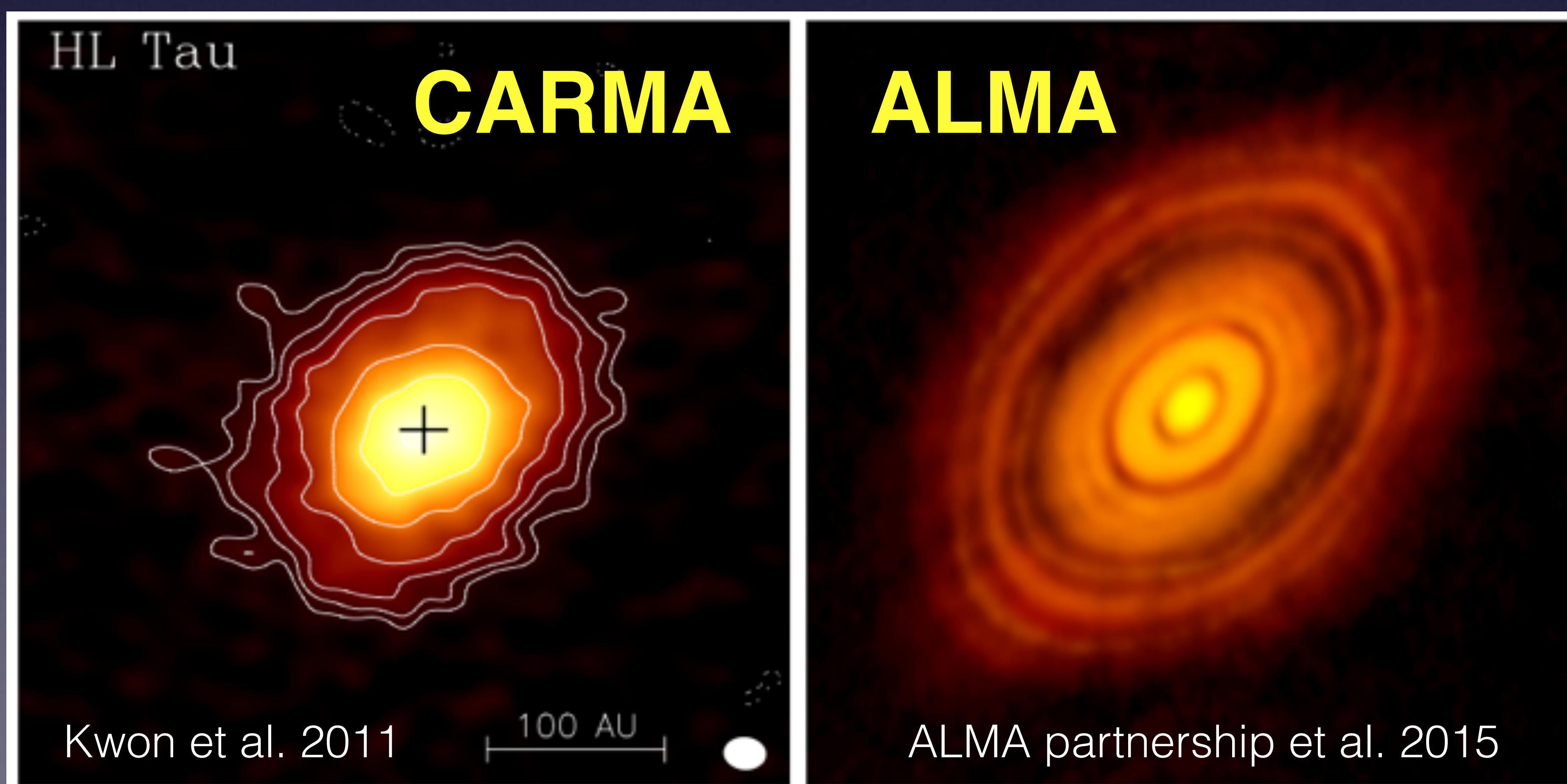
Protostellar outflow driven by an extended disk wind

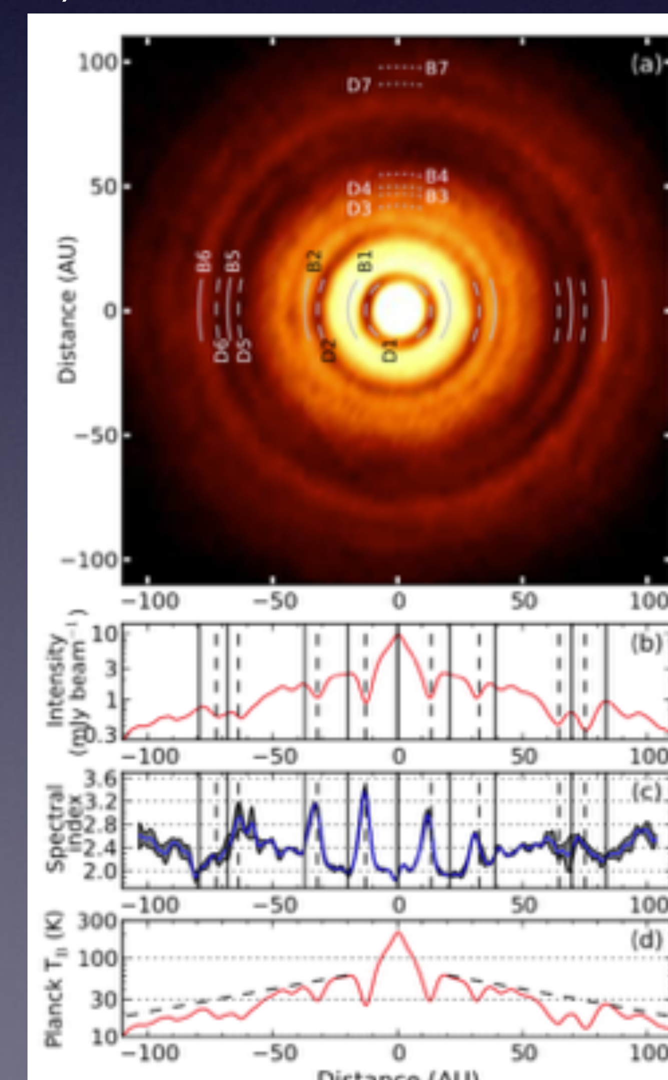
- Per Bjerkeli et al. 2016 Nature
- TMC1A
  Class I in the Taurus MC (d=140
  Keplerian rotation disk r~60-100
  M_{*}~0.5 $M_{\odot}$, M_{disk}~0.05 $M_{\odot}$
- ALMA observations
  CO, ^{13}CO, $C^{18}O$ J=2-1
  6 au resolution (~0.05 arc-sec)
- "TMC1A CO outflow is launched f
  substantially displaced from the c



Protoplanetary disks: HL Tau

- ALMA Partnership et al. 2015
- Bands 3, 6, 7 (102, 233, 344 GHz) continuum
- Angular resolution: up to 0.02''
- Flat disk, 7 bright and dark rings, grain properties, 1.3 $M_{\odot}$ (HCO^{+})

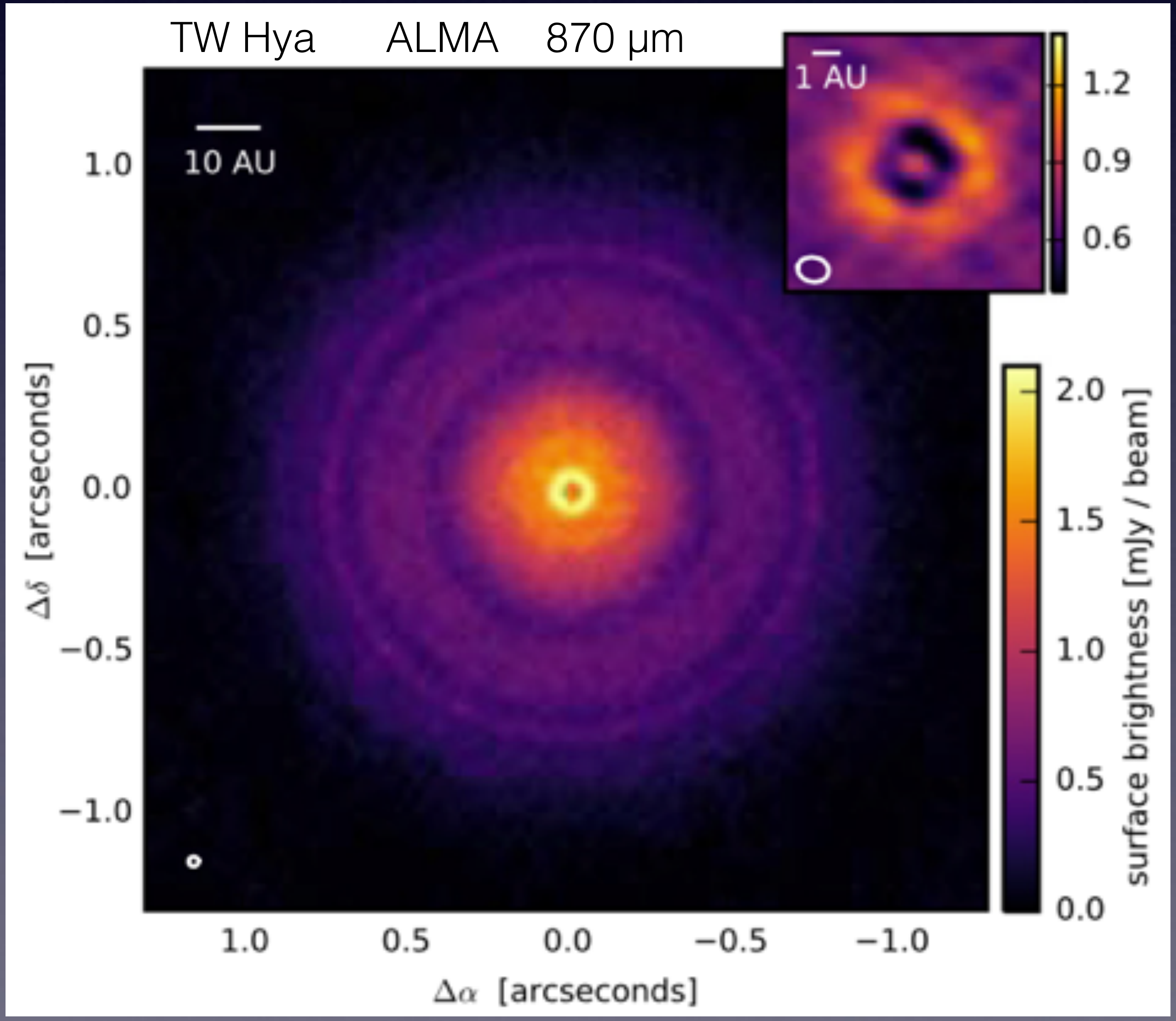


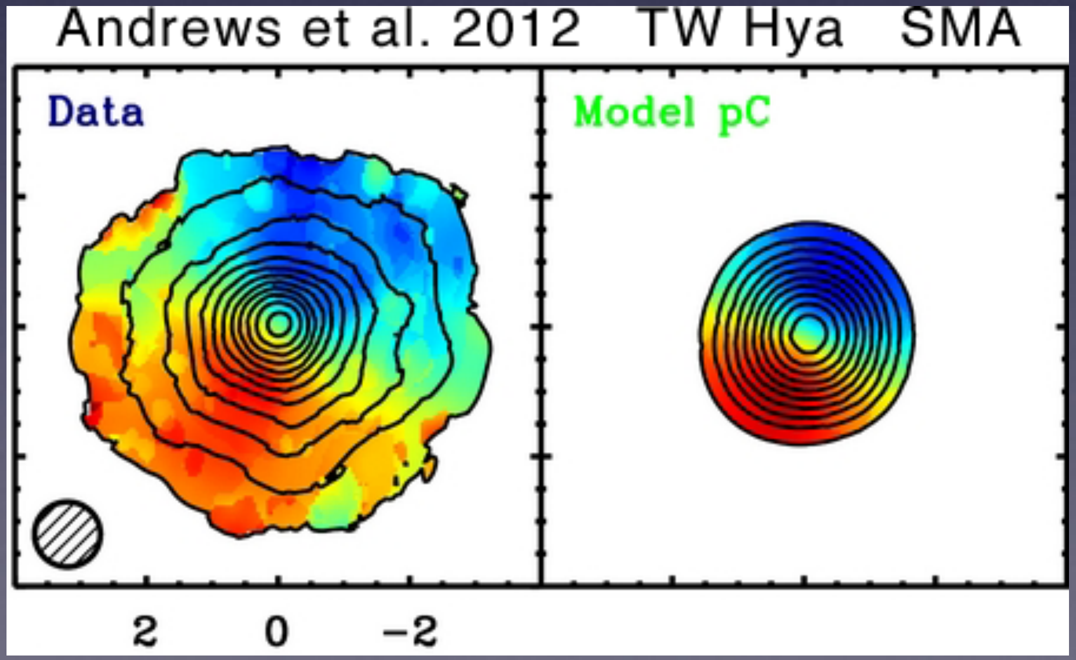


Protoplanetary disks (ALMA)

- TW Hya (d~54 pc)
- 24 x 18 mas beam at 345.9 GHz (867 micron)
- Dark rings centered at 1, 22, 37, 43 au
- Magnetic, chemical, dynamical origins

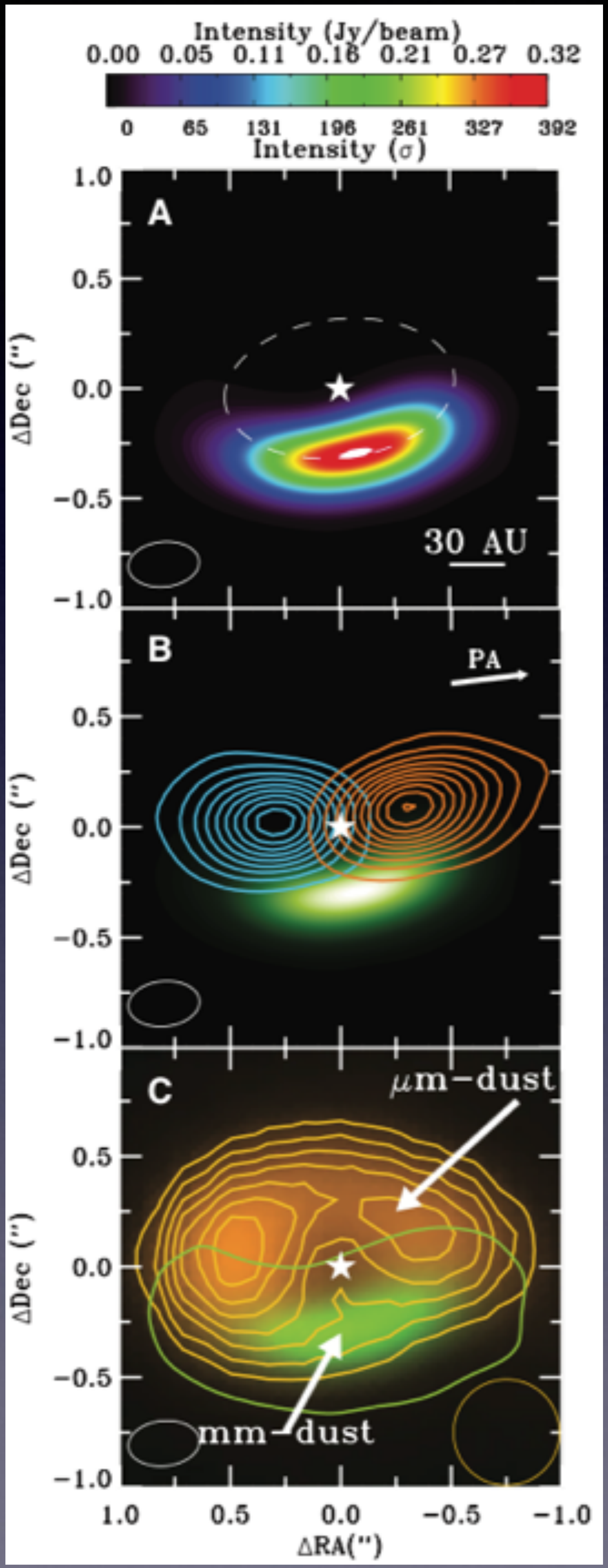
Andrews et al. 2016





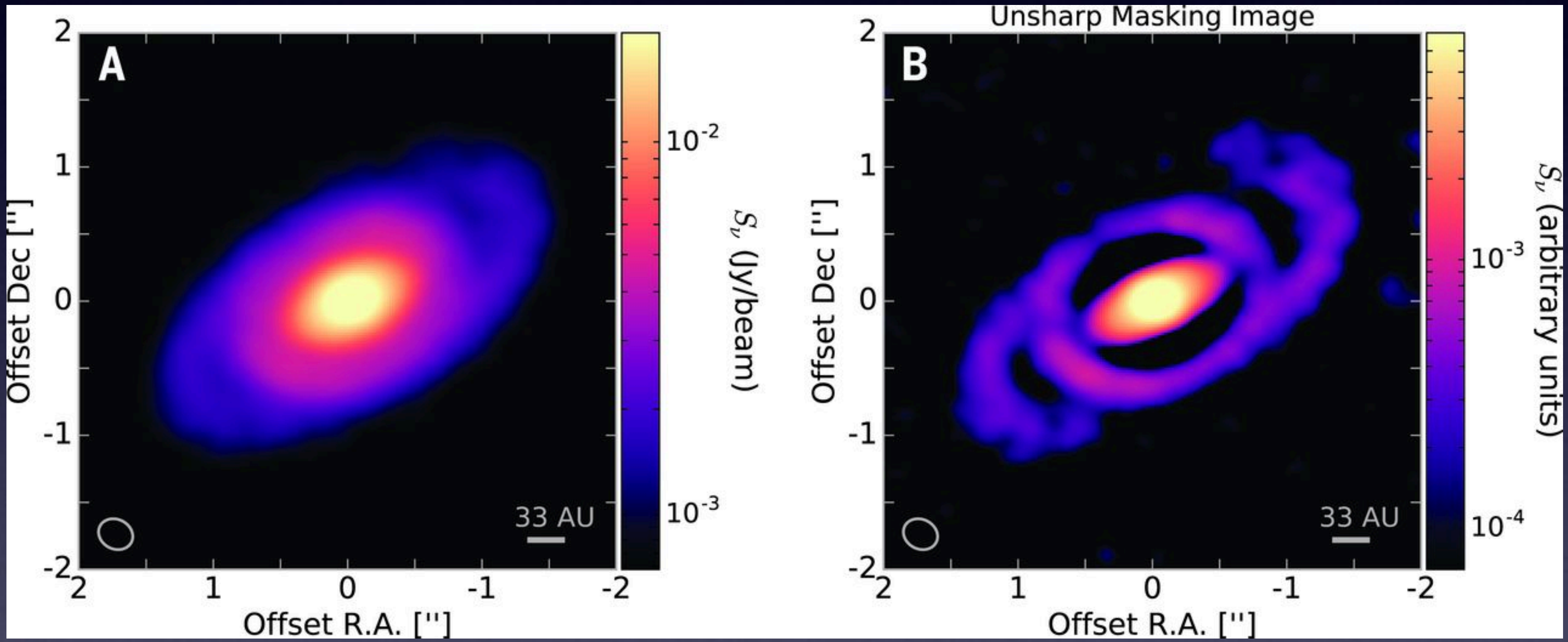
Protoplanetary disks

- 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



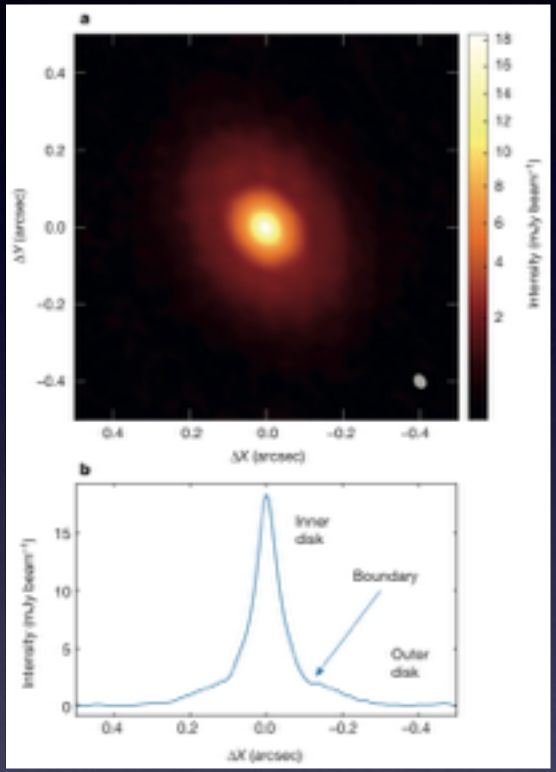
Spiral structures in Elias 2-27

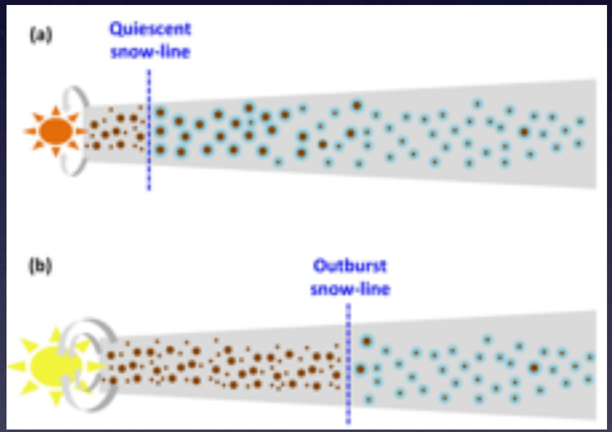
- Perez et al. 2016, Science
- Elias 2-27
  ρ-Ophiuchus star-forming complex
  d~139 pc
  Class II YSO
  $M_* \sim 0.5$—$0.6\ M_\odot$
  $M_{disk} \sim 0.04$—$0.14\ M_\odot$
  $\dot{M}_{acc} \sim 8\times10^{-8}\ M_\odot$/year
- Observations
  44 antennas, 12.5 min on target
  1.3 mm (Band 6), 0.26”x0.22”
  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.



"Imaging" the water snow-line during a protostellar outburst

- Cieza et al. 2016 Nature
- V883 Ori
  ~414 pc
  M_{*}~1.3 $M_{\odot}$, M_{disk}>0.3 $M_{\odot}$
- Observations
  Band 6: continuum, CO, 13CO, C18O
  0.03 arcsec (12 au)





- An abrupt change in optical depth around 42 au (water snow-line)
  r < 42 au: efficient dust grain fragmentation due to $V_{fragment}$~1 m/s
  r > 42 au: quick growth to centimeter size grains due to V_{f}~10 m/s
- Earlier stage than HL Tau disk
  Planet formation (e.g., boundary of rocky and gaseous planets) should take into account dynamical snow-line caused by episodic accretion

Debris disks

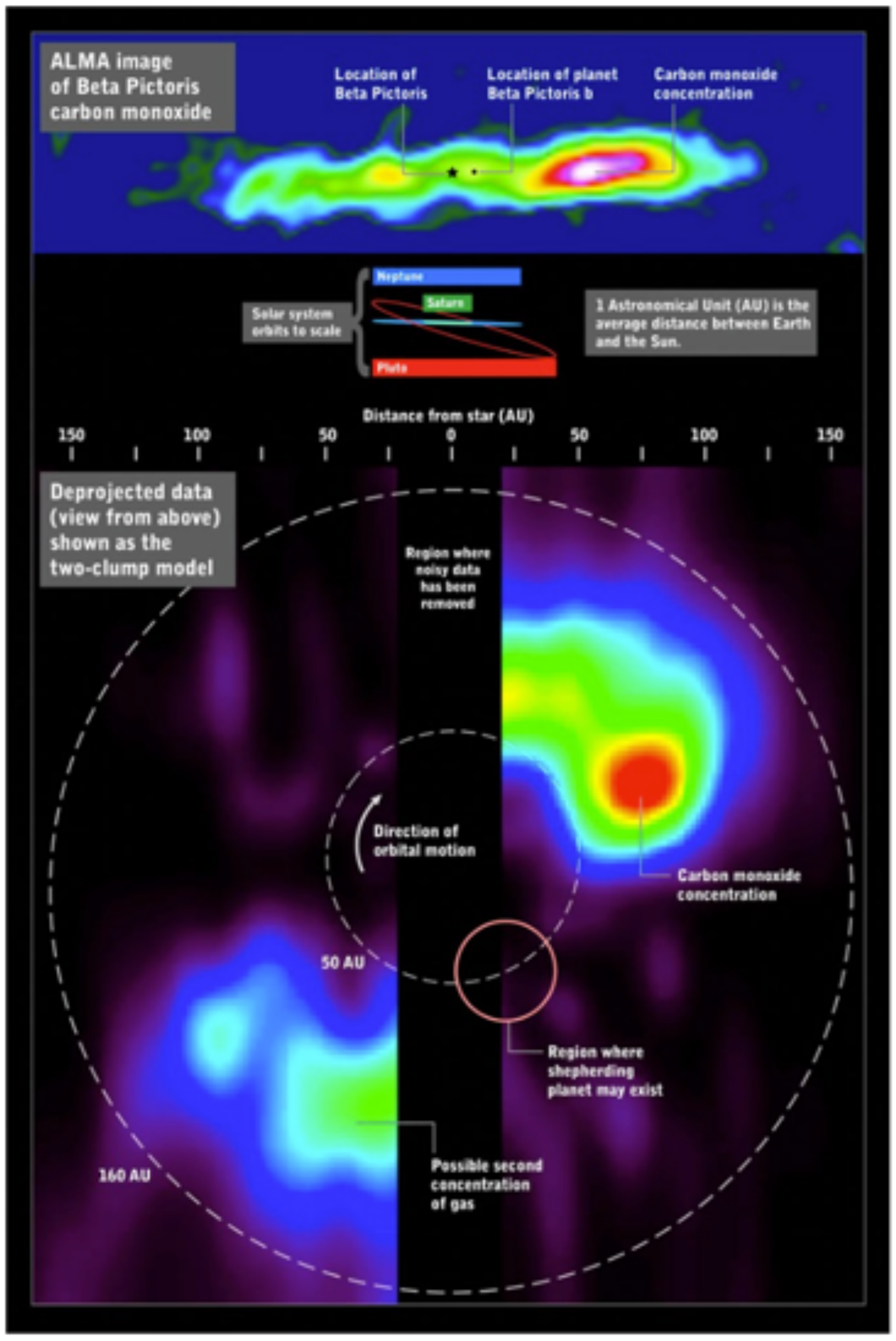
- Dent et al. 2014, Science

- β Pictoris (d ~ 19.44 pc)
  edge-on debris disk,
  infalling comets at a few AU from the star,
  a massive planet at ~10 AU,
  atomic gas out to ~300 AU

- ALMA observations
  870 μm continuum, CO 3-2
  0.6'' (12 AU)

- CO photodissociation timescale in the unshielded outer disk (by UV photons of ISM)
  ~ 120 years << 600 year orbital period at 85 AU
  => CO must be continuously replenished at ~1.4×10^{18} kg/yr

- Photodesorption can't explain the amount.
  => planetesimal collisions trapped in resonances by a outward migrating planet or
  => a recent collision of ~Mars mass



Conclusions

- Unprecedented, highest angular resolution AND sensitivity at (sub)mm wavelengths
- Excellent image fidelity
- Want to study small structures (< 5’’) at (sub)mm
  => (sub)mm arrays (e.g., ALMA, ALMA ACA, SMA, NOEMA)
  And need a high sensitivity
  => **ALMA!!!**