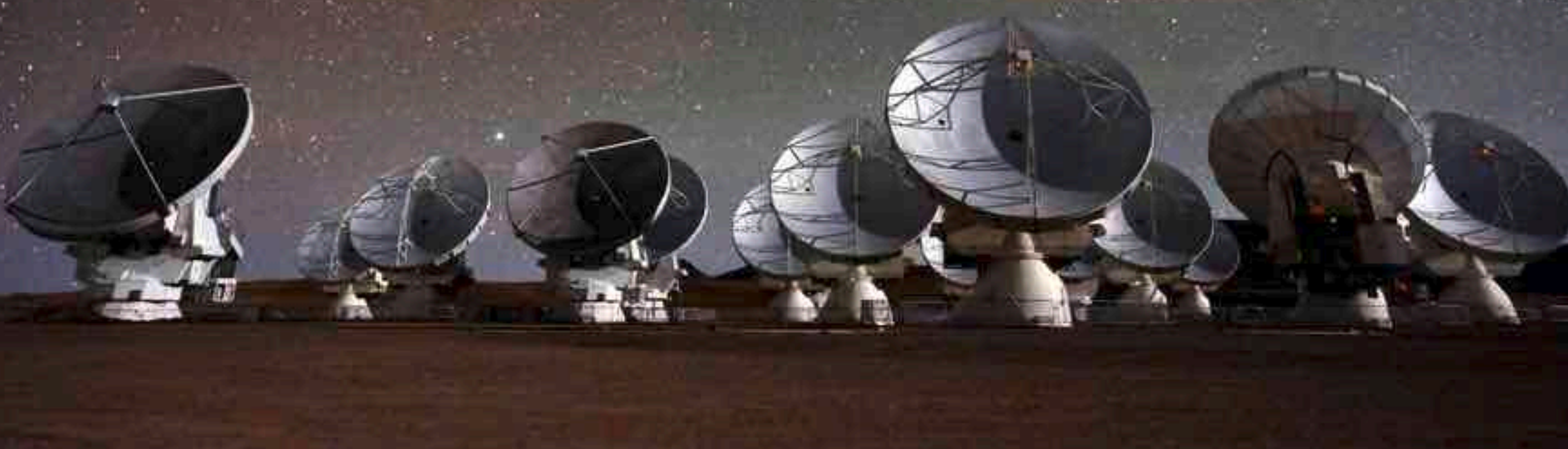
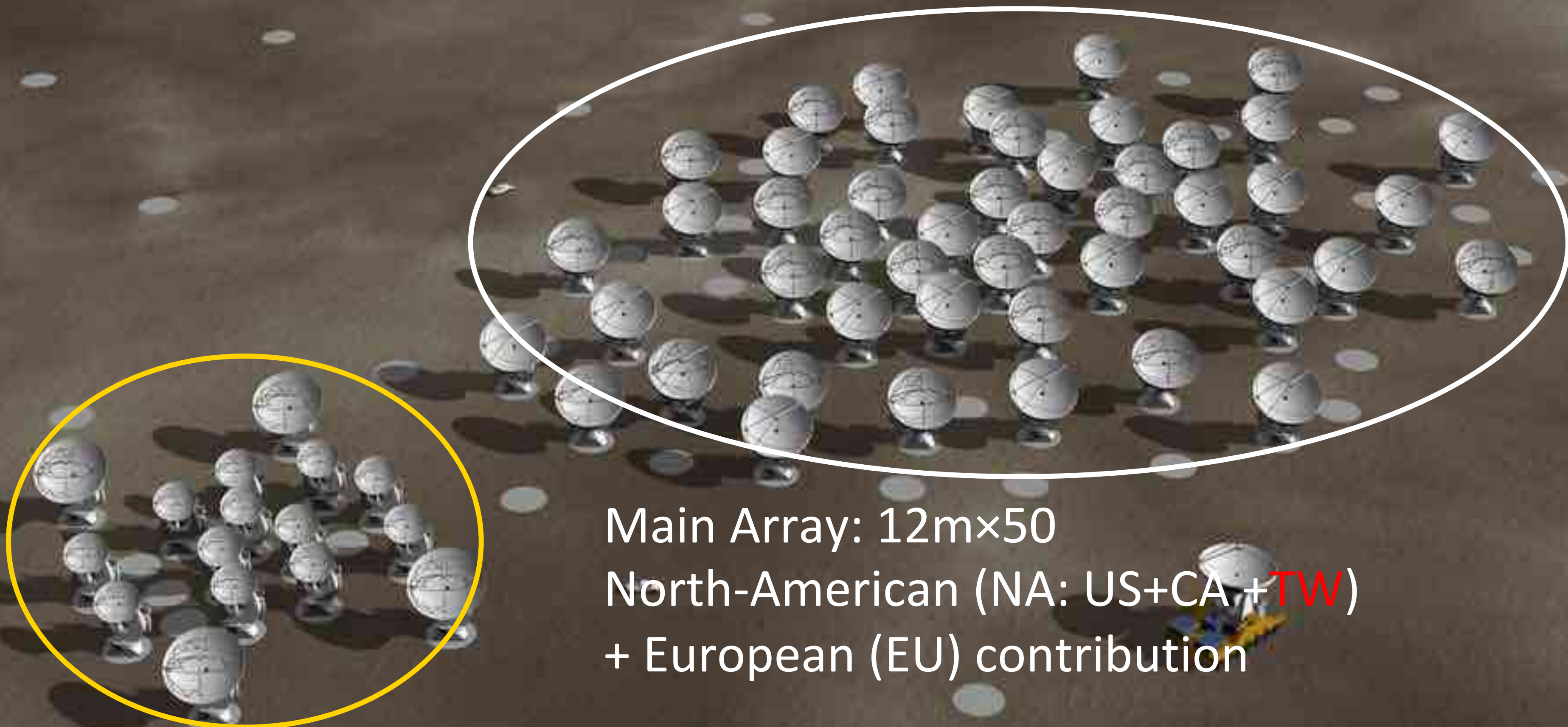
Unveiling The Early Processes of Star Formation With ALMA

Chin-Fei Lee (2020 Nov 24)



ALMA = Atacama Large Millimeter/submillimeter Array

Largest array telescope ever built. Inaugurated on 2013-03-13



Main Array: 12m×50

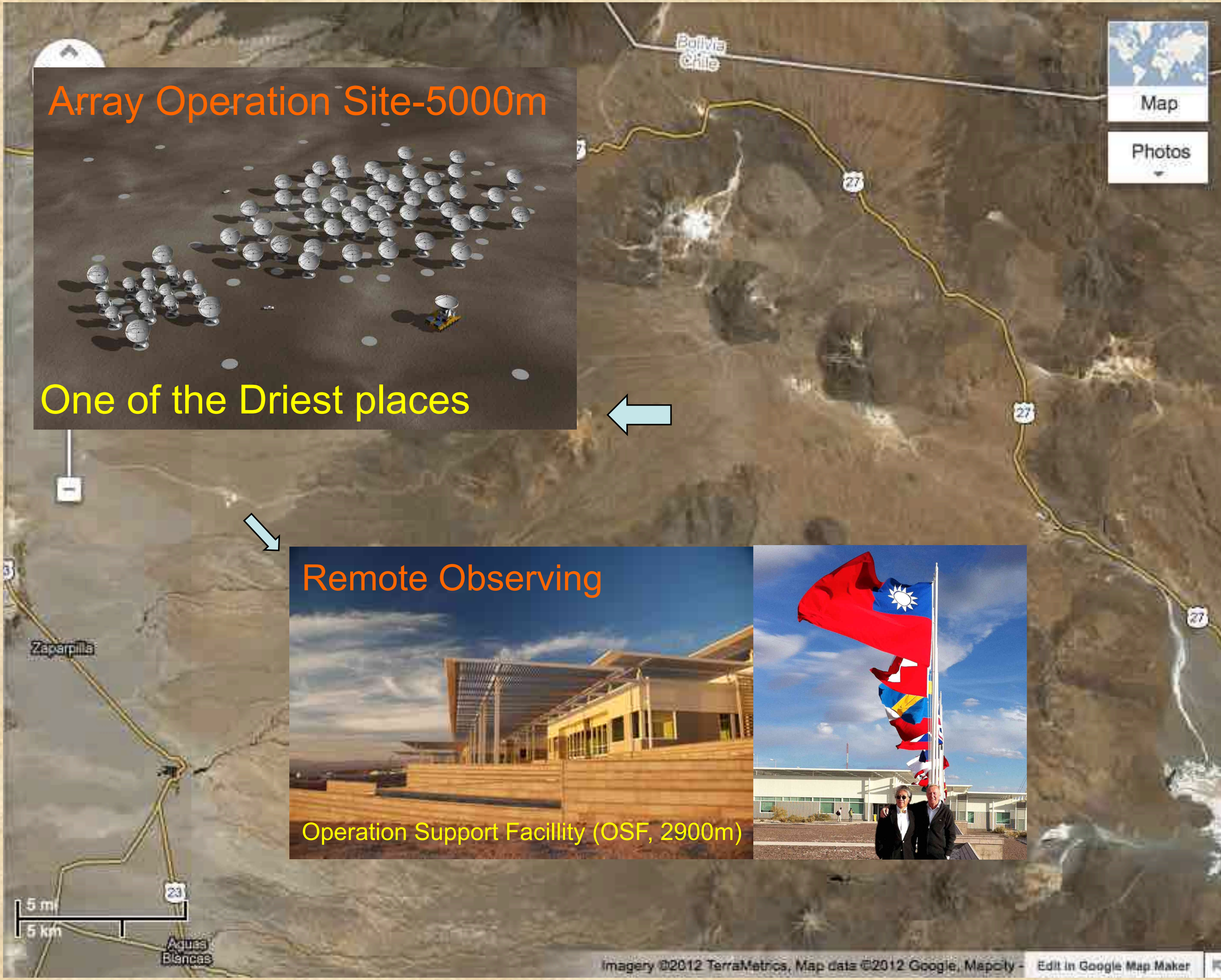
North-American (NA: US+CA+TW)

+ European (EU) contribution

Atacama Compact Array (ACA): 12m×4 + 7m×12

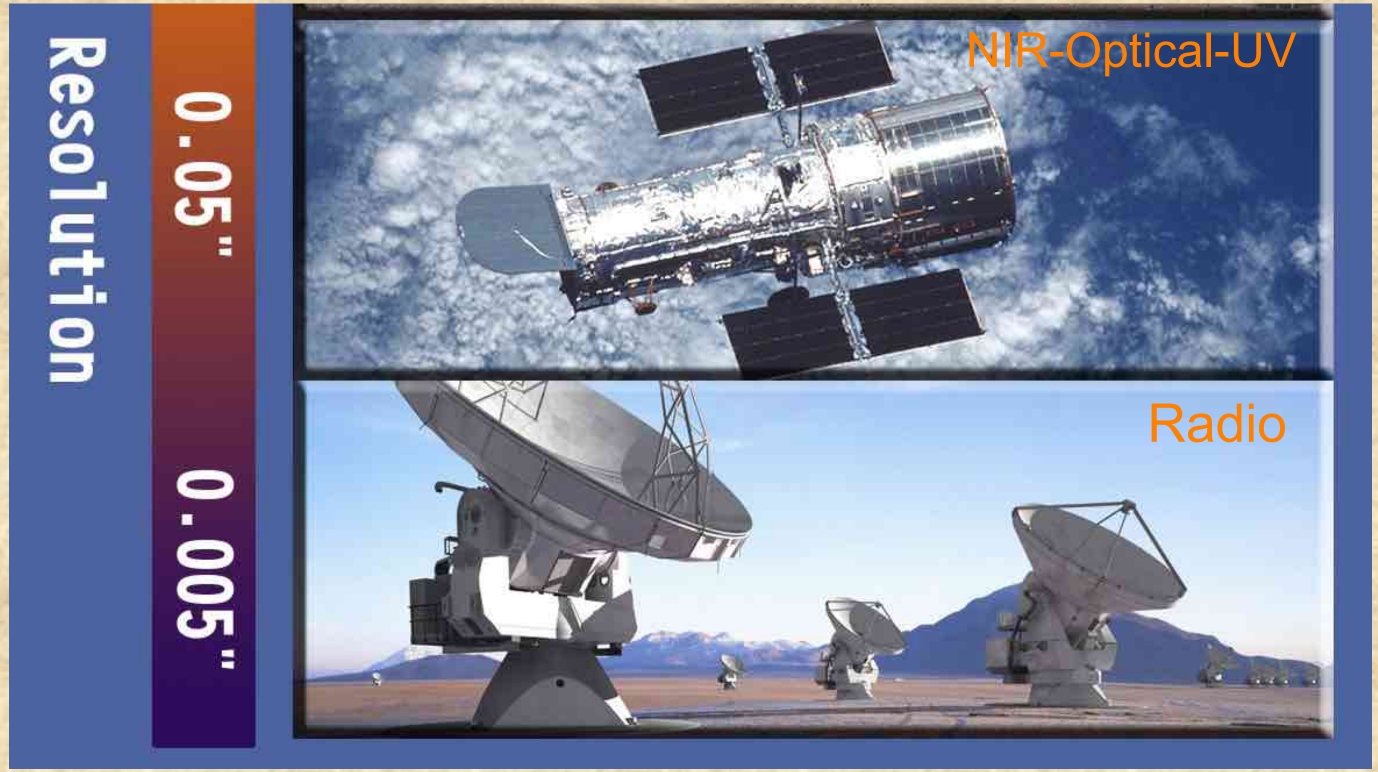
East-Asian (EA: JP+TW+KR) contribution

=>TW has open access to EA and NA times by proposals!!


Array Operation Site-5000m
One of the Driest places
Remote Observing
Operation Support Facillity (OSF, 2900m)
Bolivia
Chile
Map
Photos
27
Zaparpilla
23
5 mi
5 km
Aguas Blancas
Imagery ©2012 TerraMetrics, Map data ©2012 Google, Mapcity -
Edit in Google Map Maker

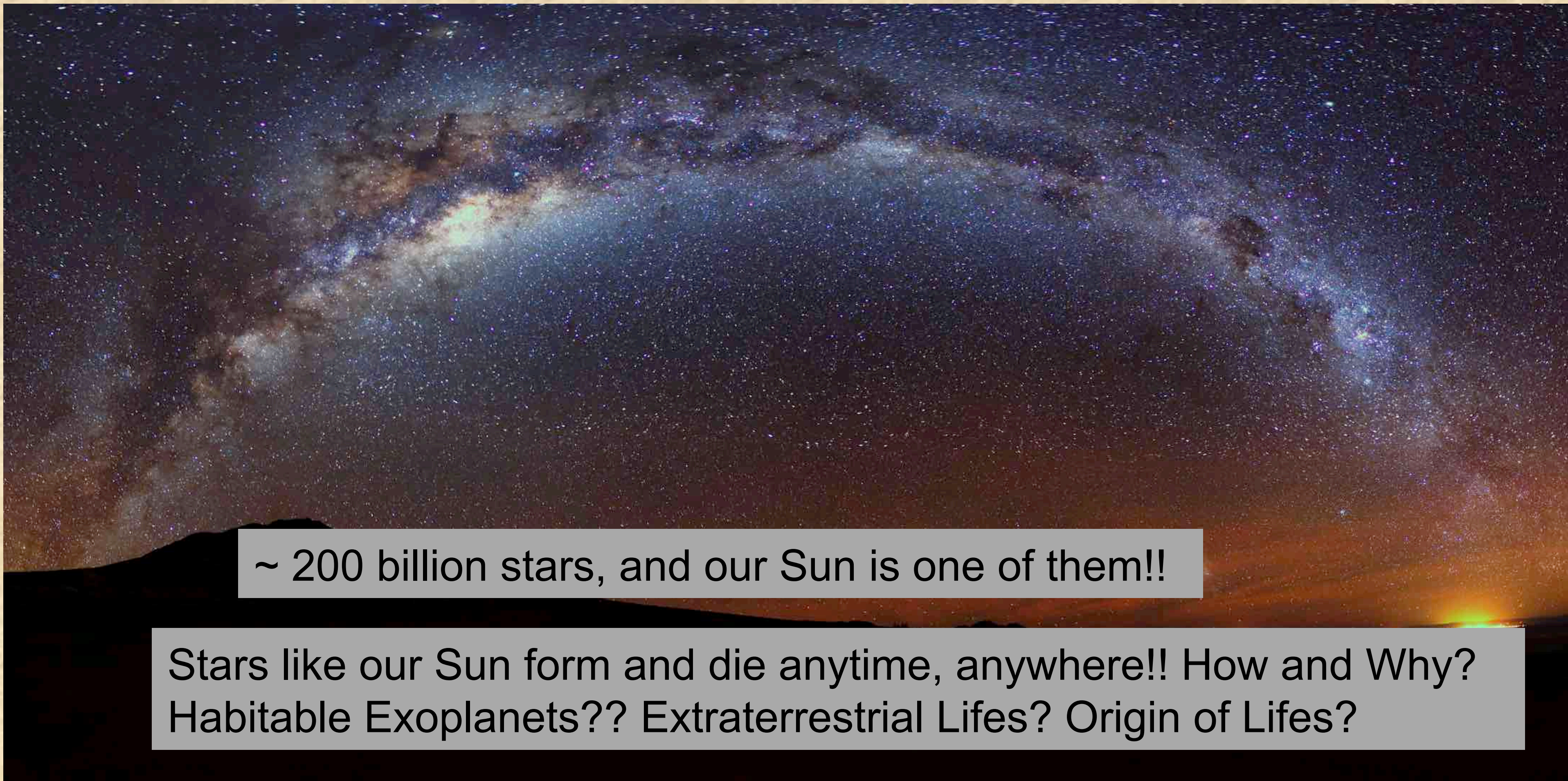
Birdview of ALMA

ALMA vs. Hubble Space Telescope




中研院天文所

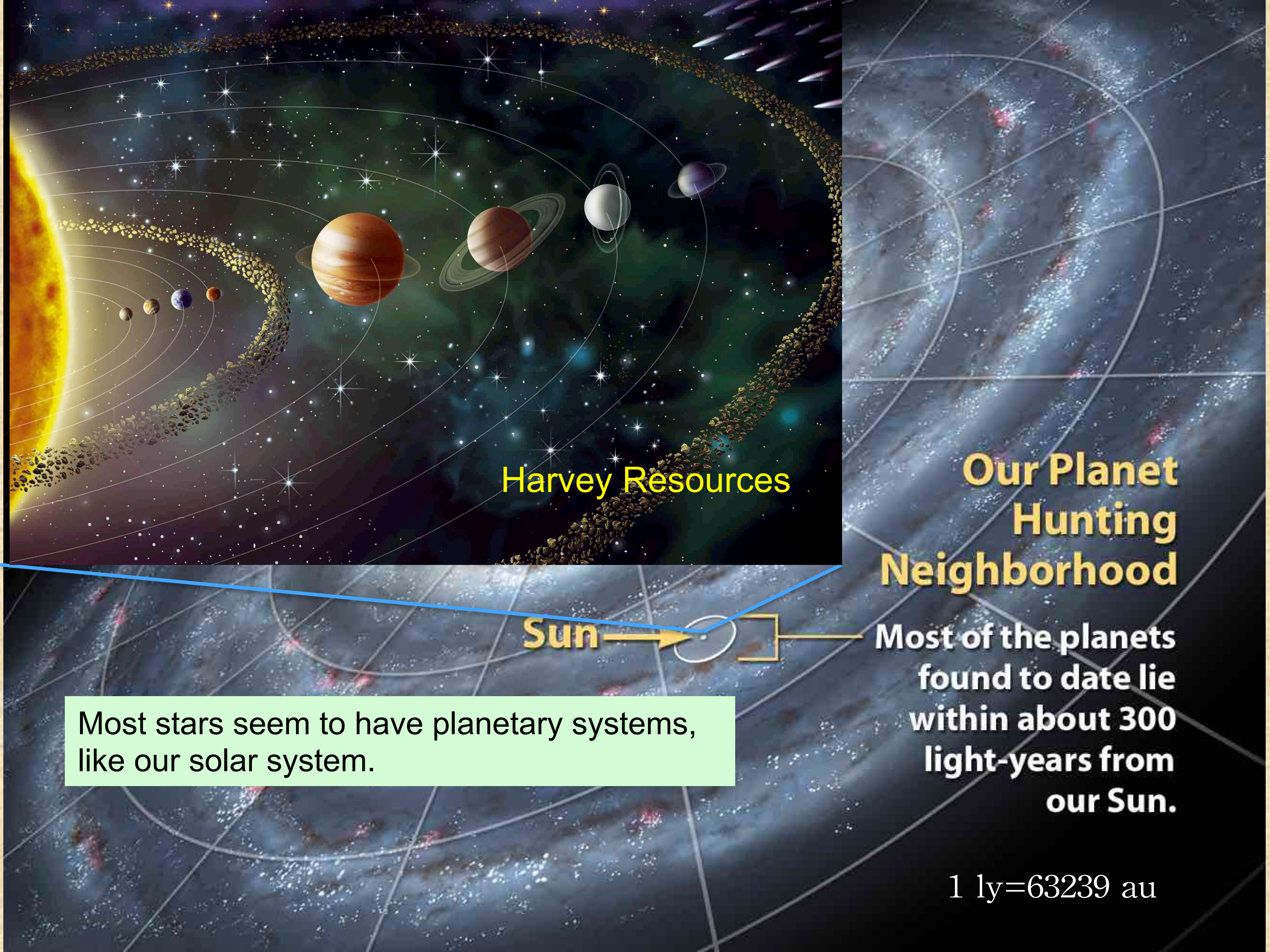
The Milky Way viewed at Atacama



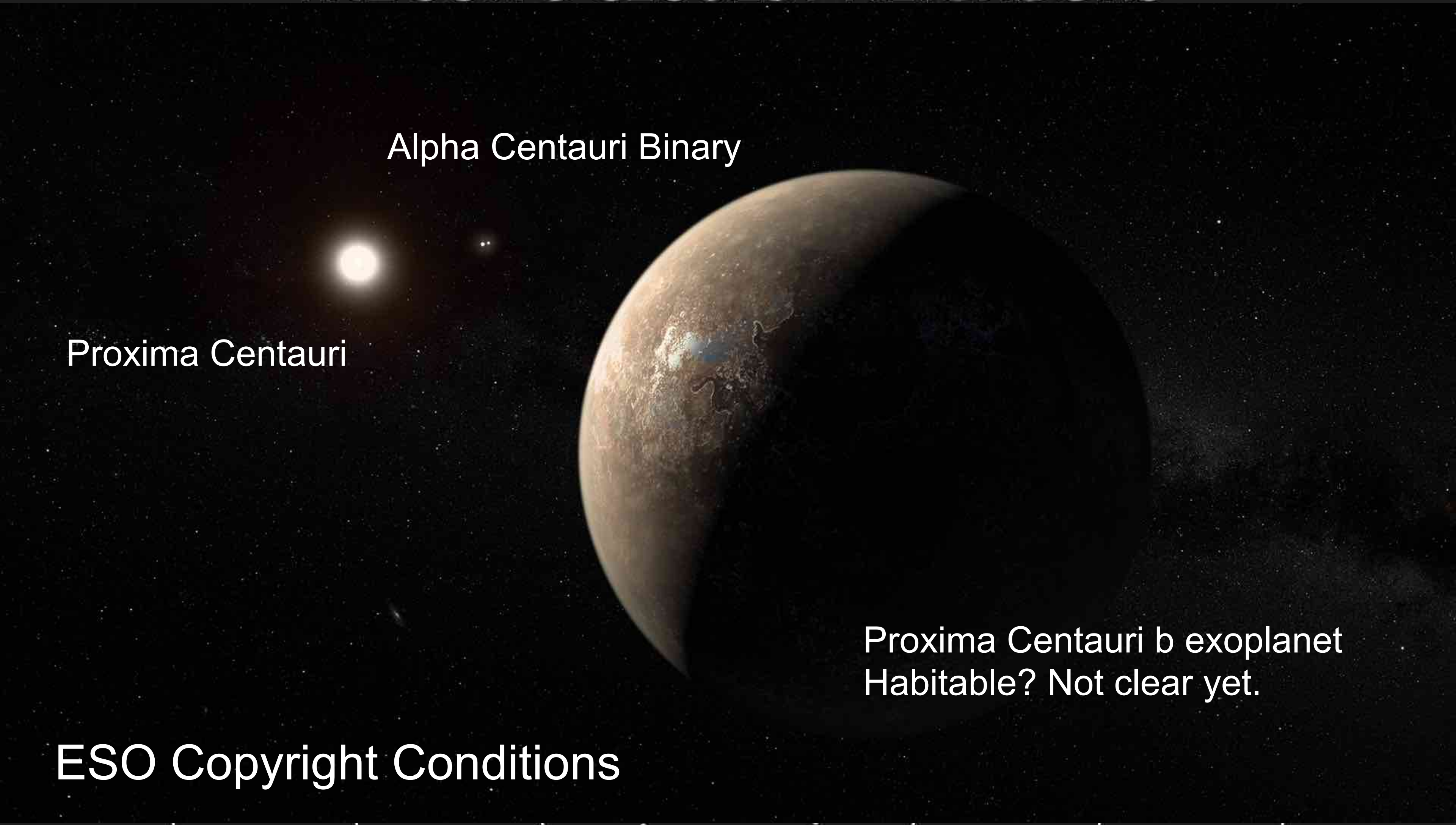
~ 200 billion stars, and our Sun is one of them!!

Stars like our Sun form and die anytime, anywhere!! How and Why?
Habitable Exoplanets?? Extraterrestrial Lifes? Origin of Lifes?

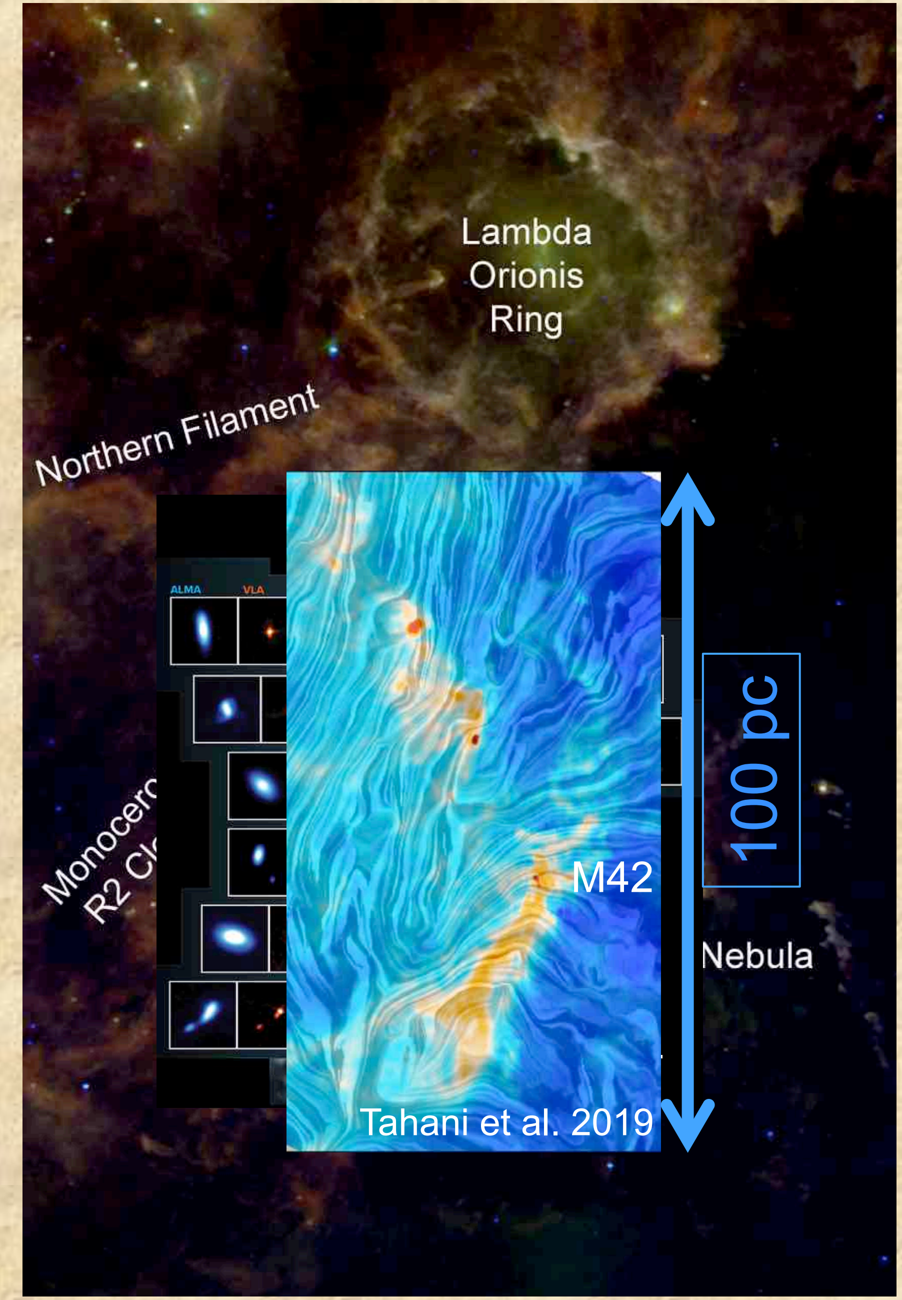
Credit：ALMA


Harvey Resources
Our Planet Hunting Neighborhood
Sun
Most of the planets found to date lie within about 300 light-years from our Sun.
Most stars seem to have planetary systems, like our solar system.
1 ly=63239 au

THE SUN'S CLOSEST NEIGHBORS

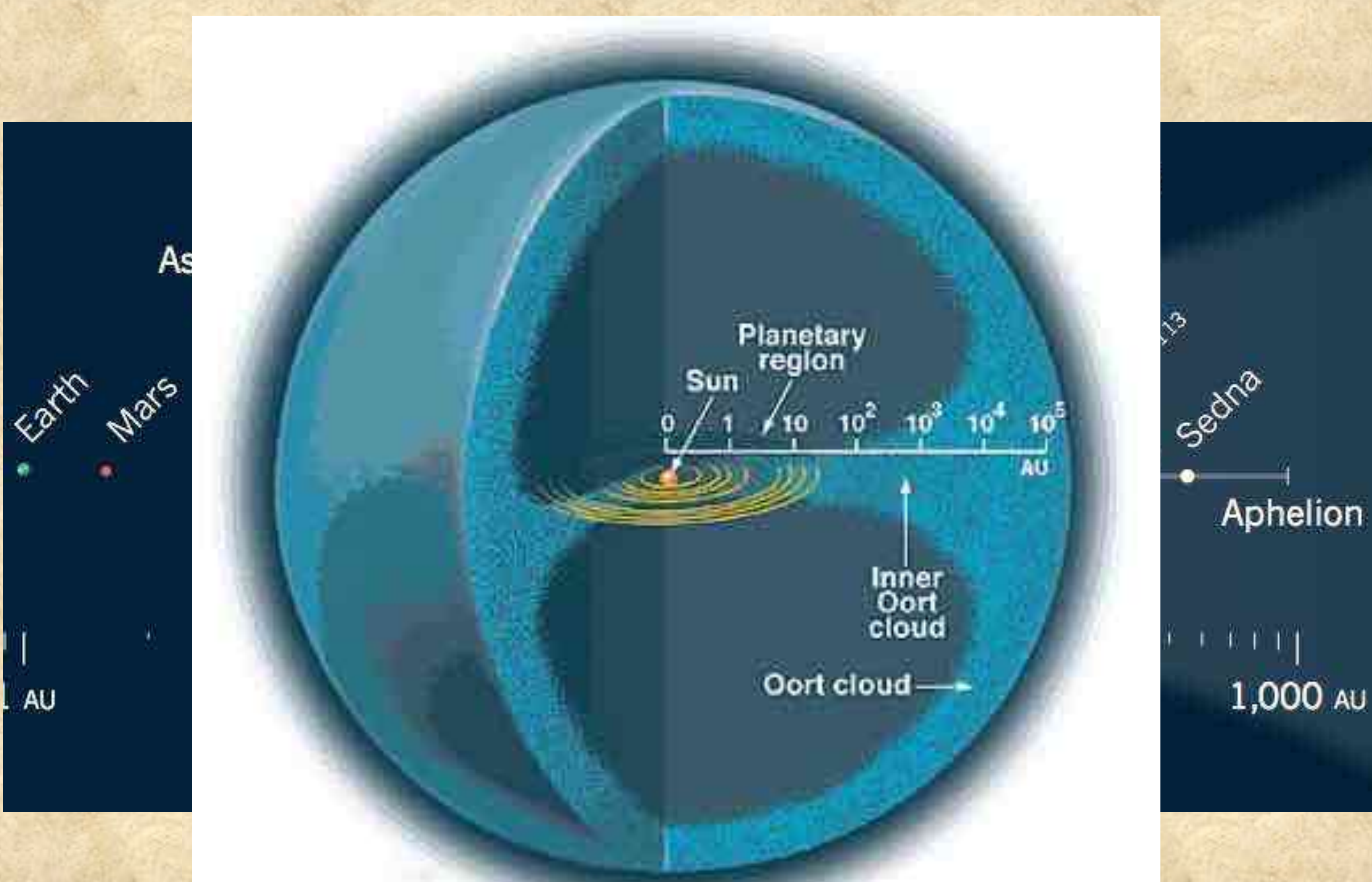


Orion Constellation



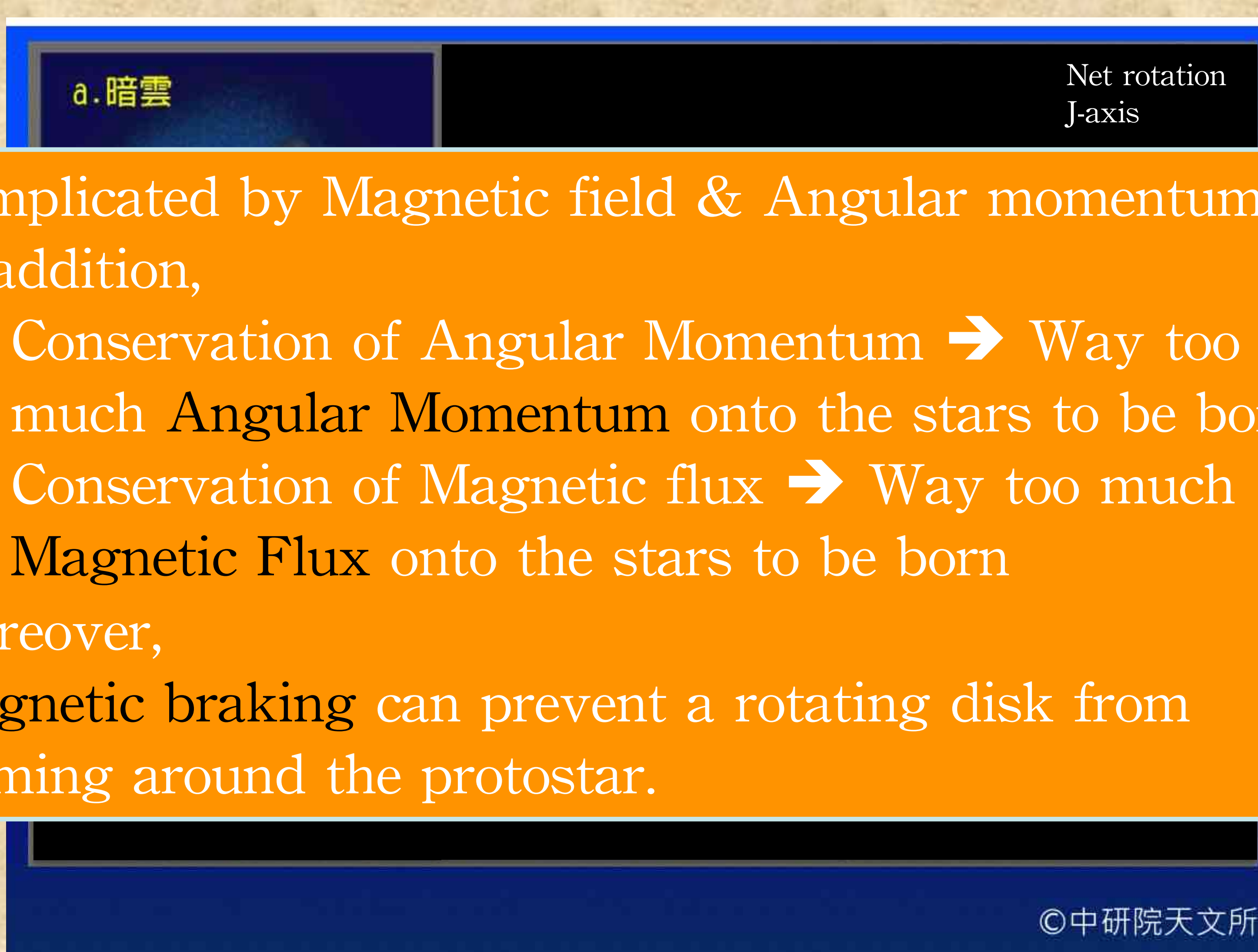
1 pc=3.26 ly
=206265 au

Solar System enclosed in a large Oort Cloud?



10^5 au~0.5 pc~1.6 ly?

Star and Planet Formation Process



Complicated by Magnetic field & Angular momentum.

In addition,

1. Conservation of Angular Momentum ➔ Way too much **Angular Momentum** onto the stars to be born
2. Conservation of Magnetic flux ➔ Way too much **Magnetic Flux** onto the stars to be born

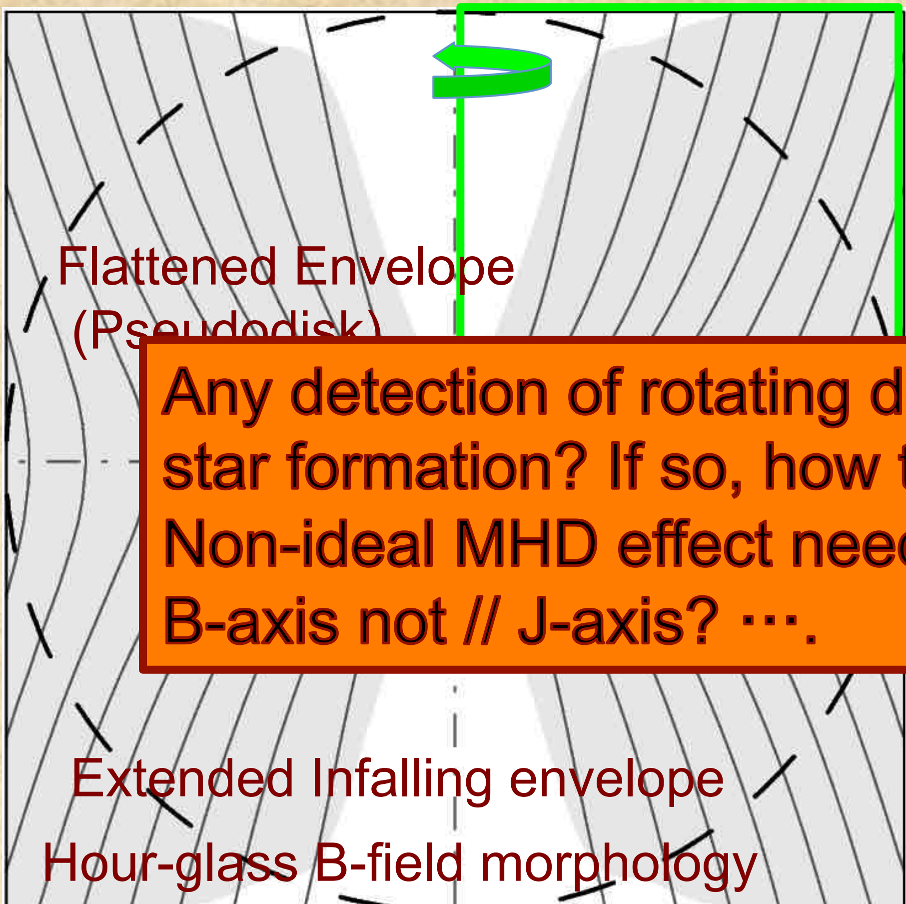
Moreover,

Magnetic braking can prevent a rotating disk from forming around the protostar.

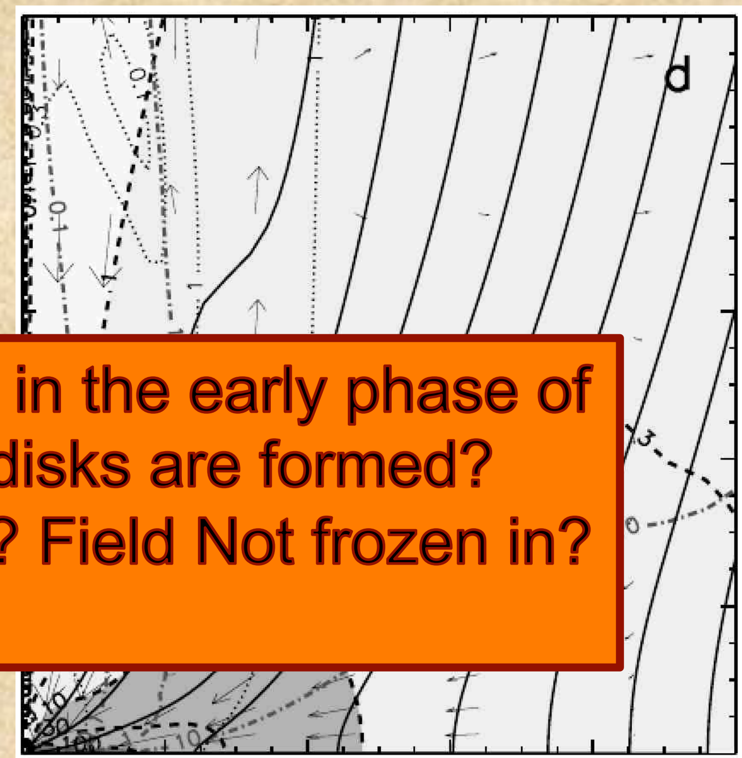
Magnetic Braking Catastrohe (MBC)

Collapse of Magnetized Rotating Core

(B-axis // J-axis, Ideal MHD, field frozen in material)



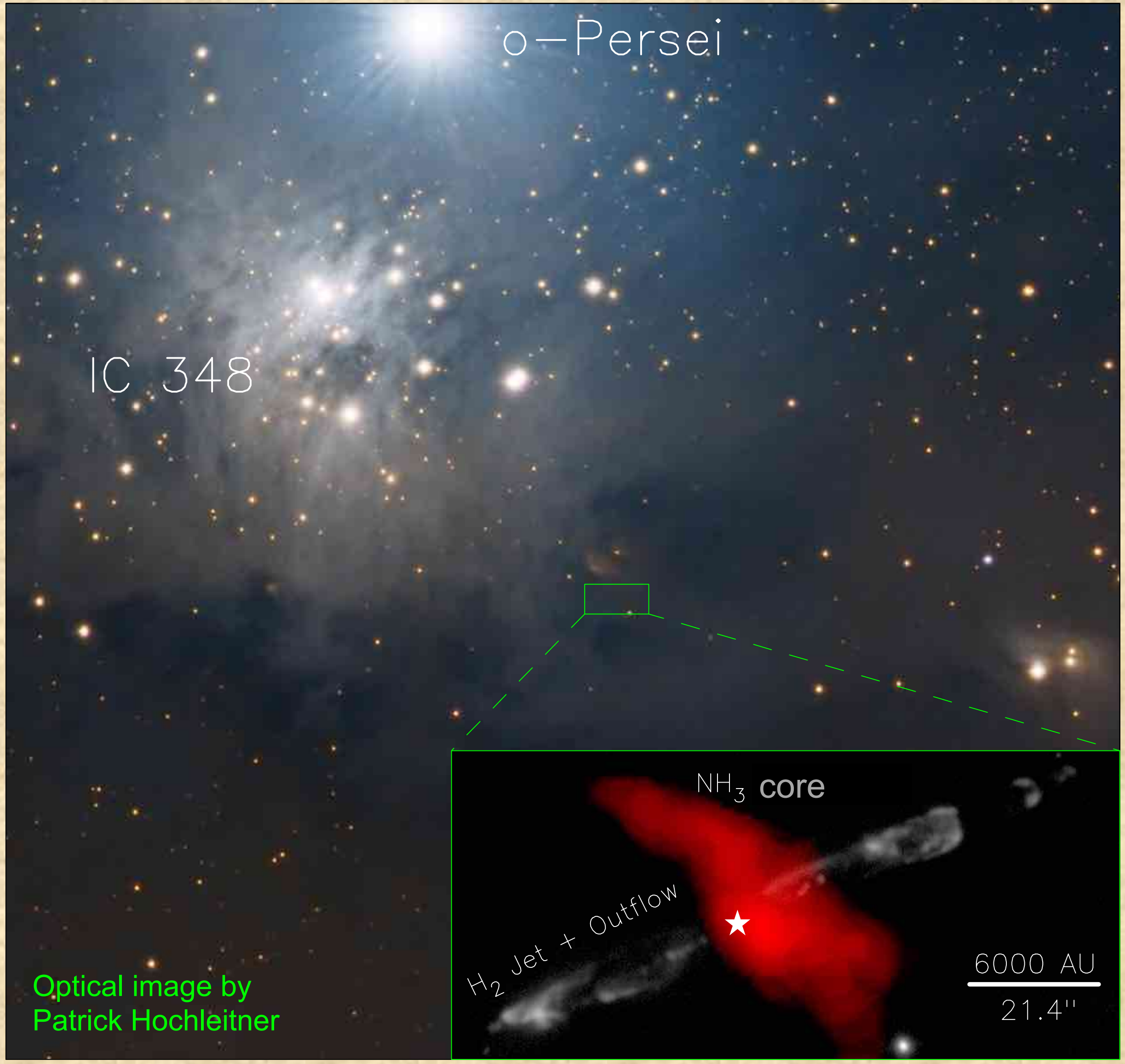
Any detection of rotating disks in the early phase of star formation? If so, how the disks are formed? Non-ideal MHD effect needed? Field Not frozen in? B-axis not // J-axis? ⋯.



Allen et al. 2003

No rotating disk formed inside Flattened Envelope➔Magnetic Braking Catastrohe (MBC)

HH 211 star-forming region @1000 ly in Perseus Cloud



Hirano et al. 2006

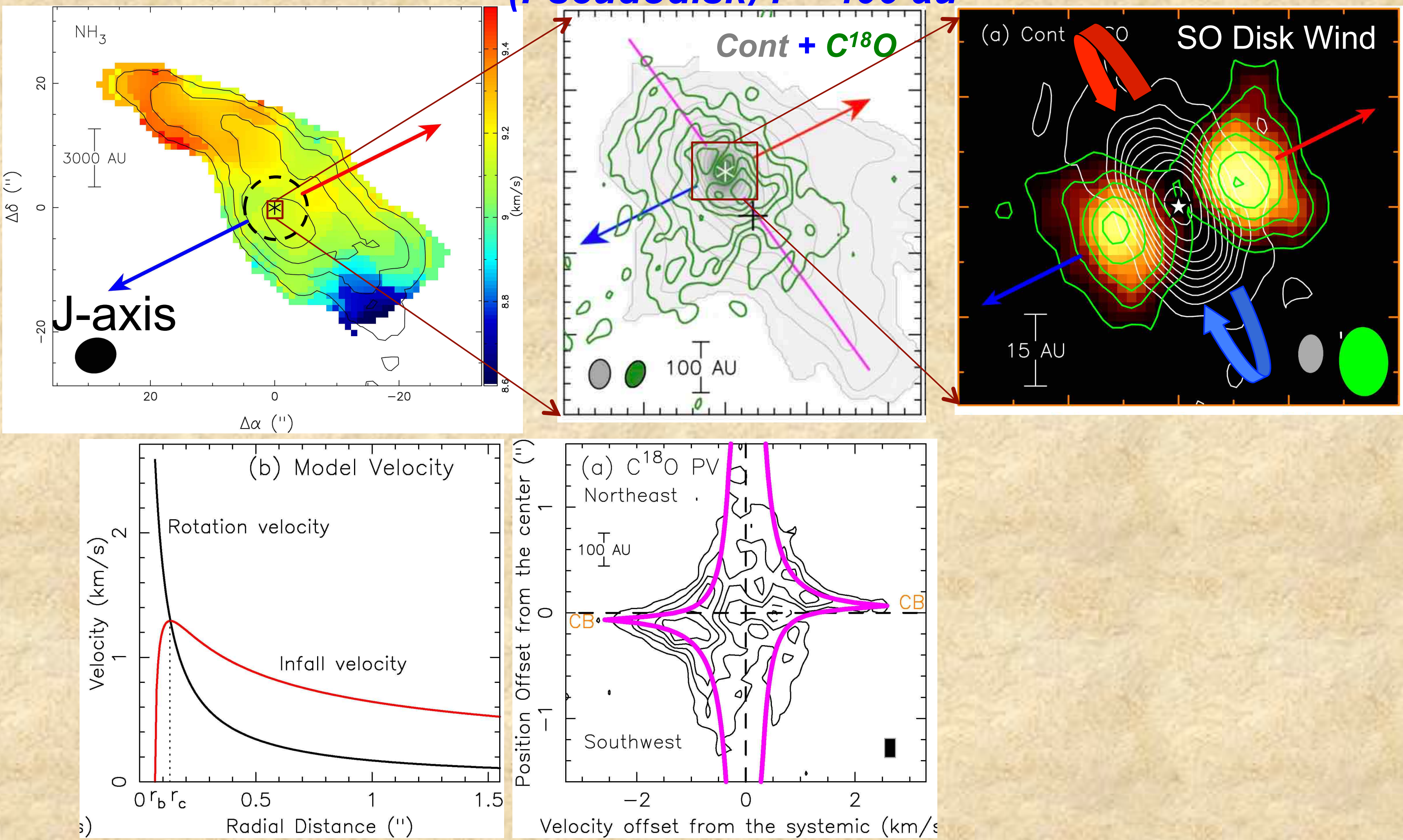
Wiseman et al. 2001

Age~10^4 yr, Luminosity~ 3.6 Lsun, $M_\star$~ 0.08 Msun

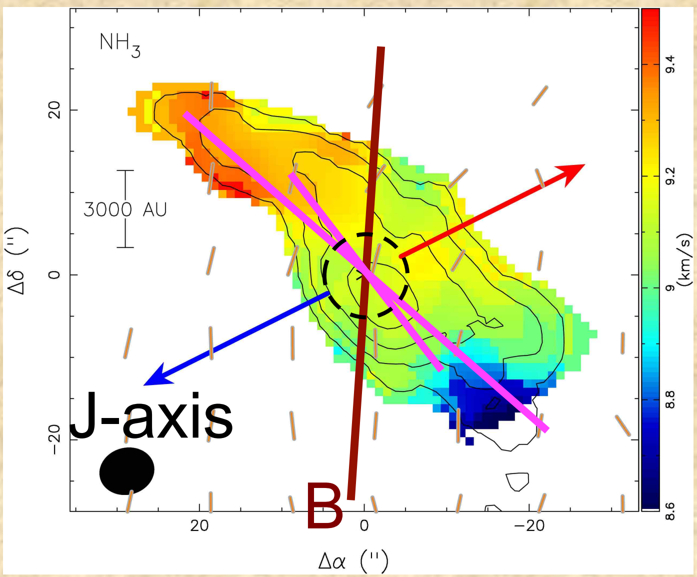
NH_3 Core is rotating (r ~ 0.05 pc)

Gravitational collapsing+Rotating $C^{18}O$ Envelope (Pseudodisk) r ~ 400 au

Rotating Disk found! r_D ~15 au ➔ $M_\star$ ~ 0.08 $M_\odot$



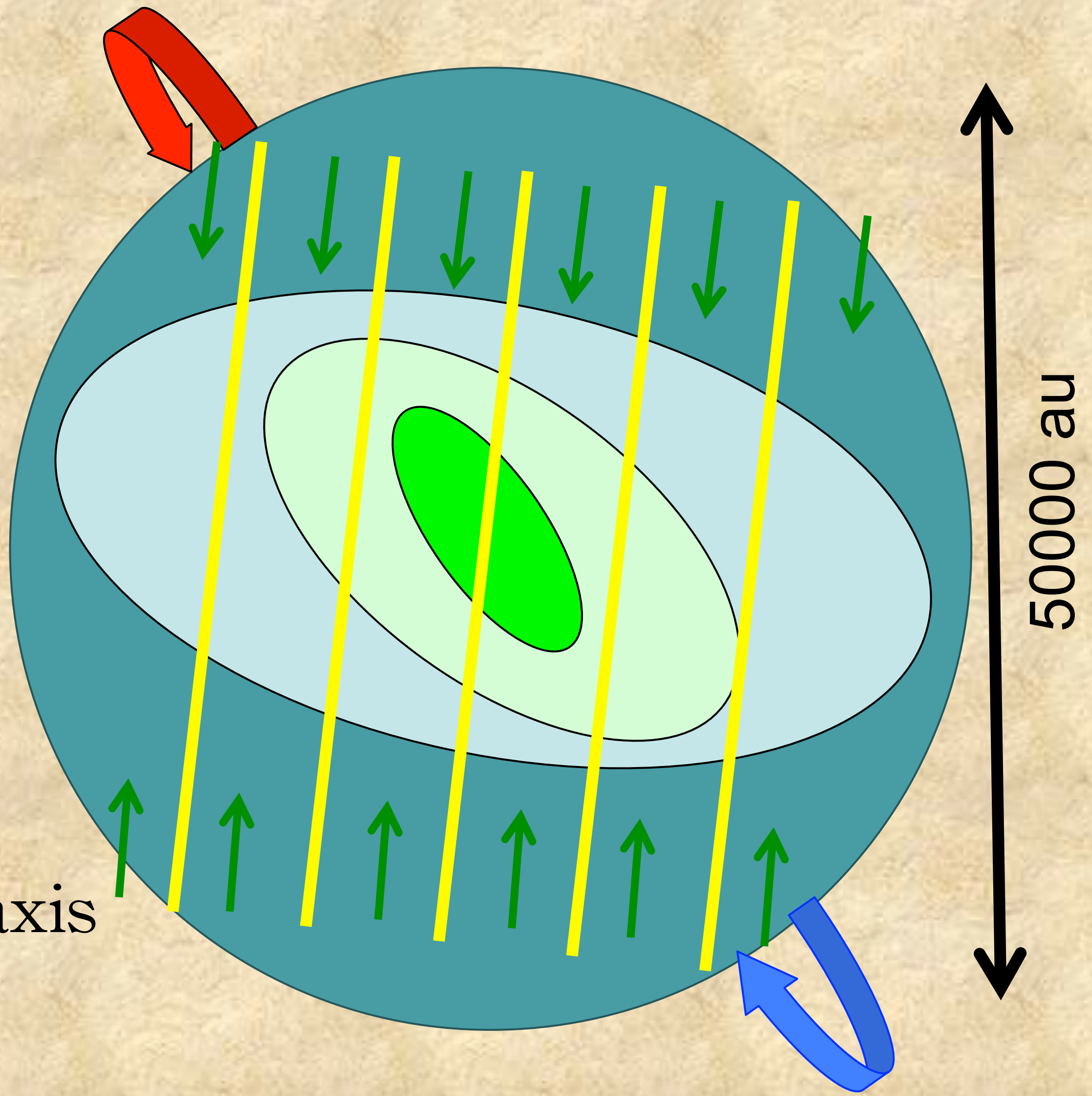
NH_3 *Core* Flattened!!



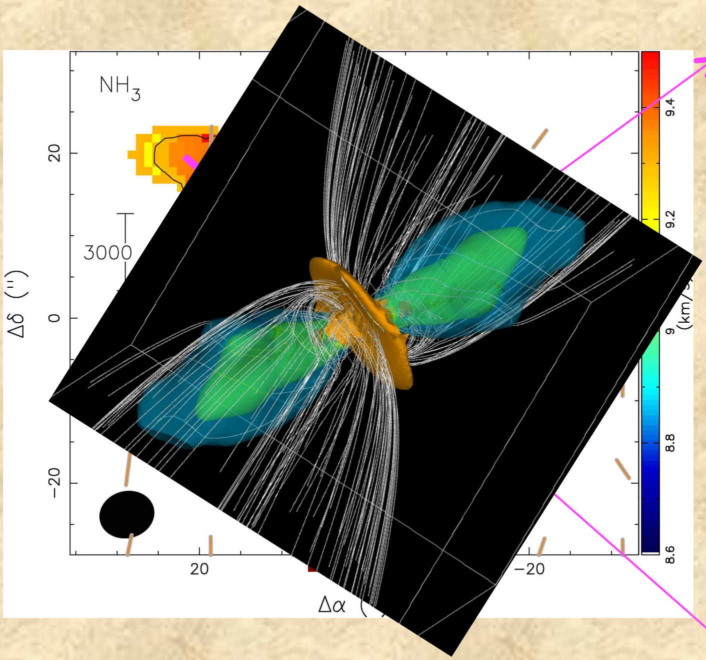
Matthews et al. 2009

Misalignment betw.
B-axis and (Rotation) J-axis

Initial Structure

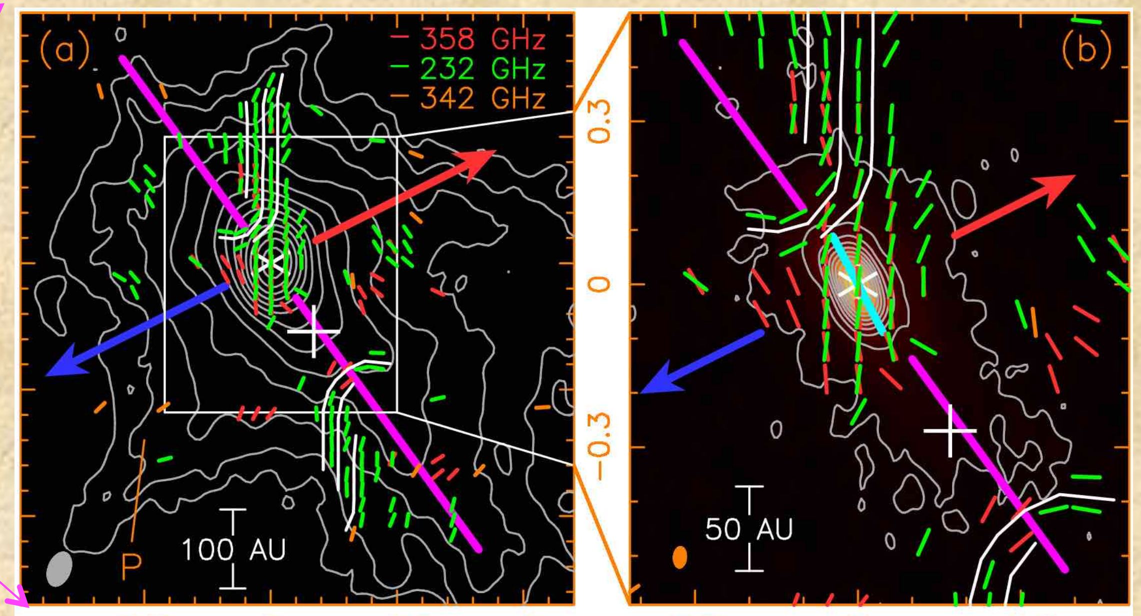


Rotating Core



Matthews et al. 2009

B-field in inner region (pseudodisk) from ALMA dust polarization at 230/345 GHz

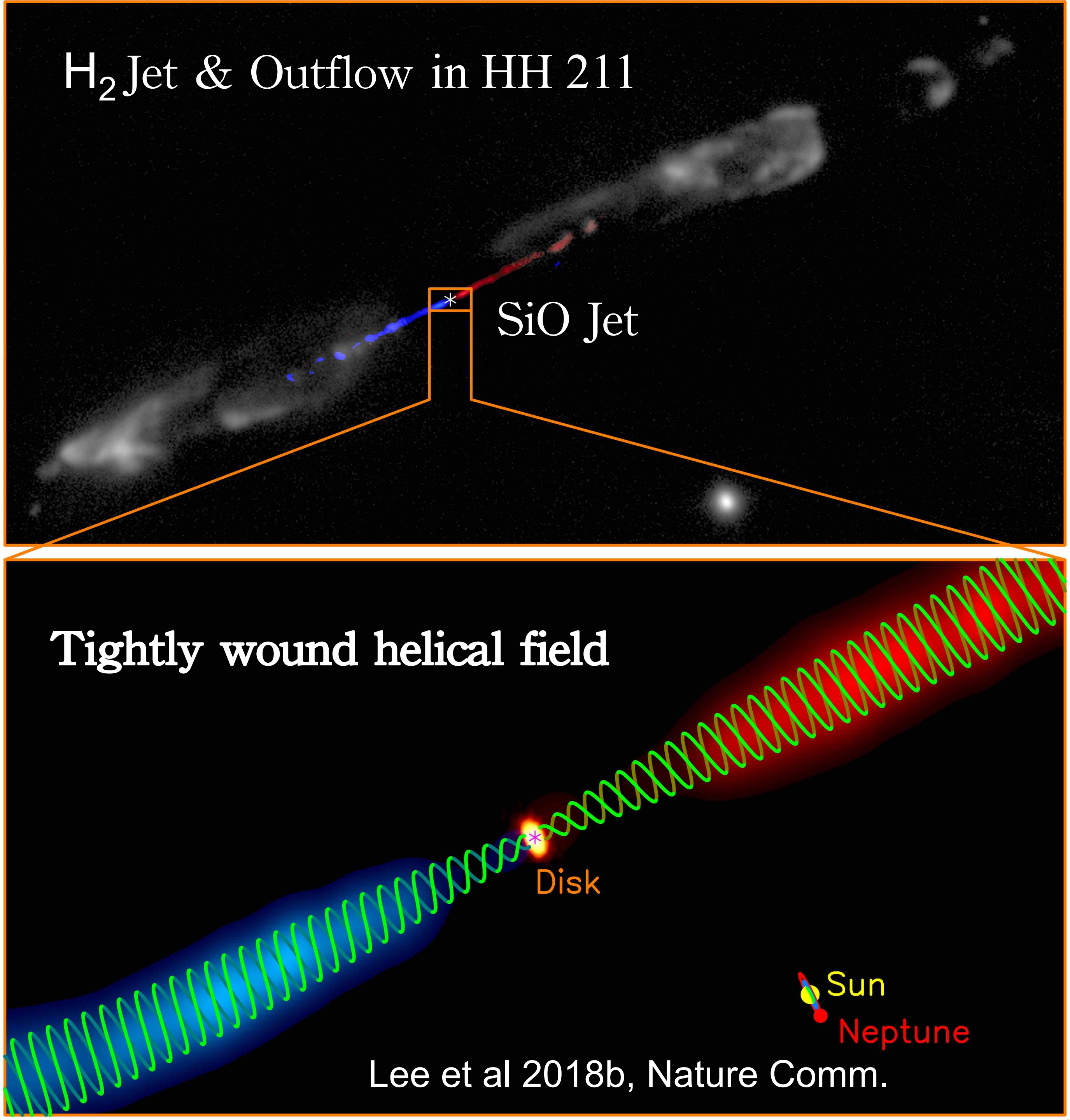


1. Misalignment betw core & pseudodisk & disk
2. Field guided infall forming Pseudodisk!

3. Pseudodisk has a pinched field morphology due to gravitational infall mainly along equatorial plane and a toroidal field produced by rotation!

B_ϕ ~ 7.8 mG at r ~ 100 au

4. Disk field?? Unresolved!

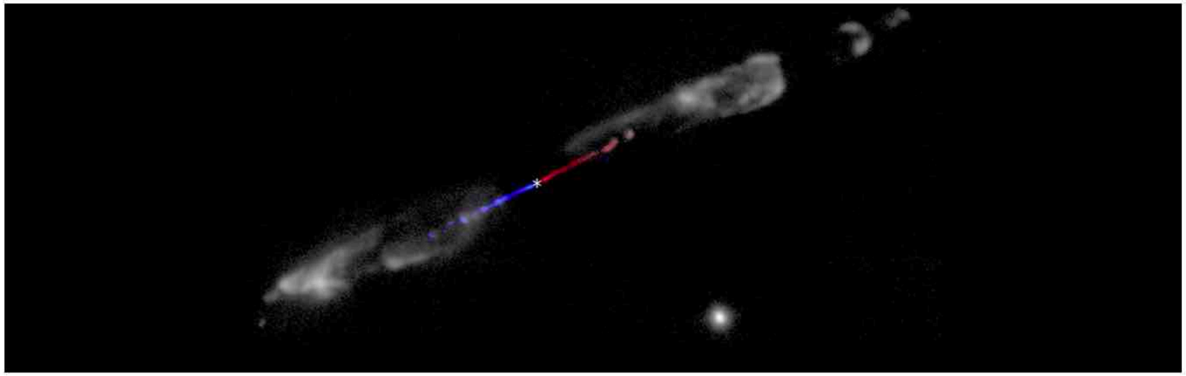


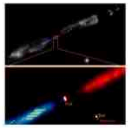
H2 Jet & Outflow in HH 211
SiO Jet
Tightly wound helical field
Disk
Sun
Neptune
Lee et al 2018b, Nature Comm.

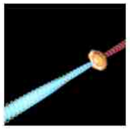
Magnetic fields found in a Jet from a Baby Star

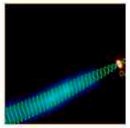
28 November, 2018

Scientific Paper









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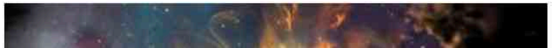
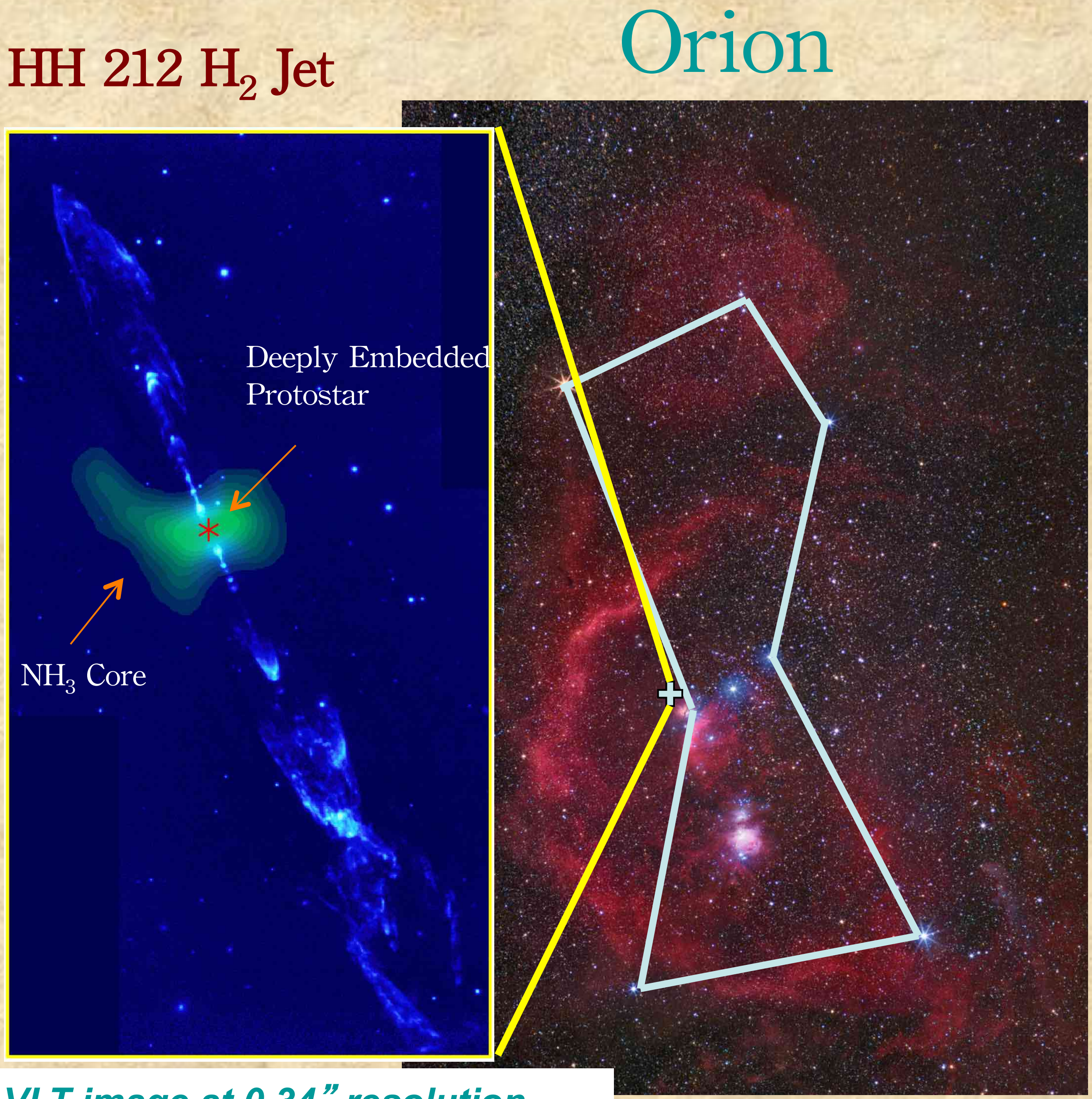


An international research team led by Chin-Fei Lee in the Academia Sinica Institute of

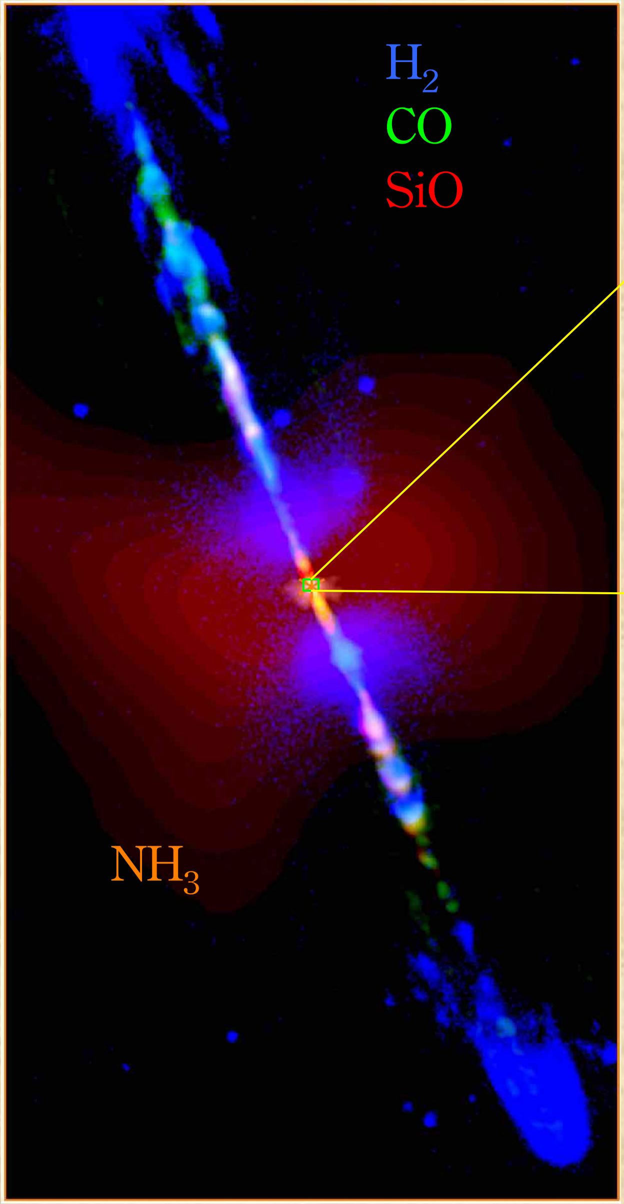
Age ~ 5×10^4 yrs,

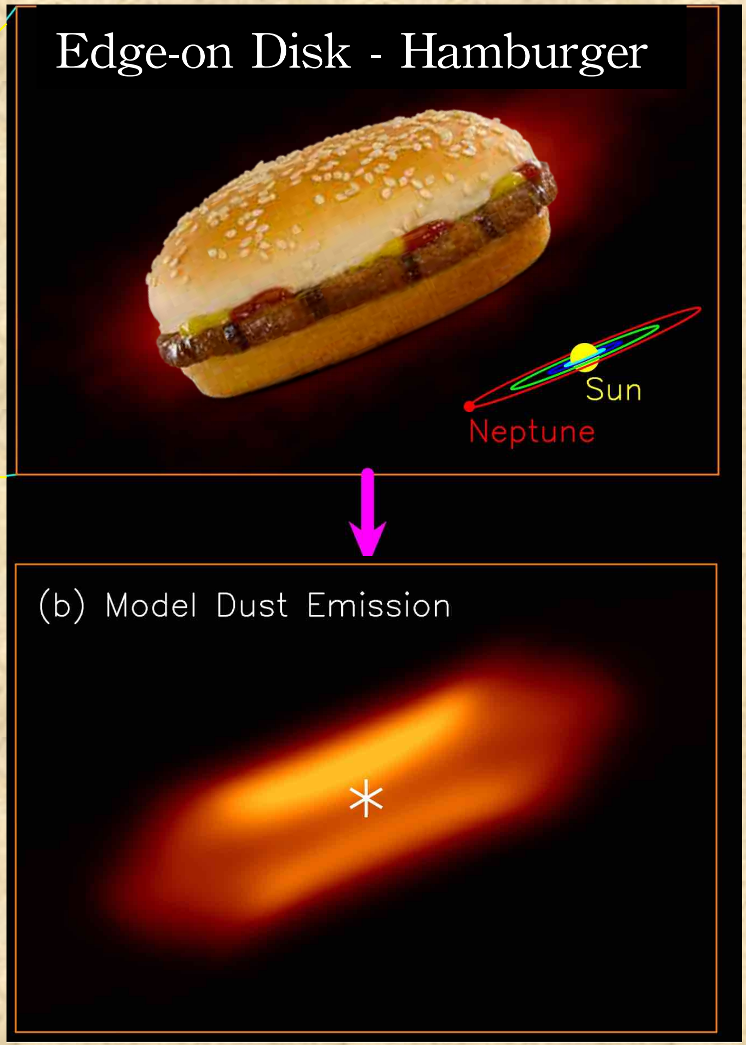
$M_\star$ ~ 0.25 M_{sun}!!



VLT image at 0.34" resolution
McCaughrean et al. 2002

Disk found with ALMA 345GHz @0.02"(8au) resolution! $r_D \sim 45$ au



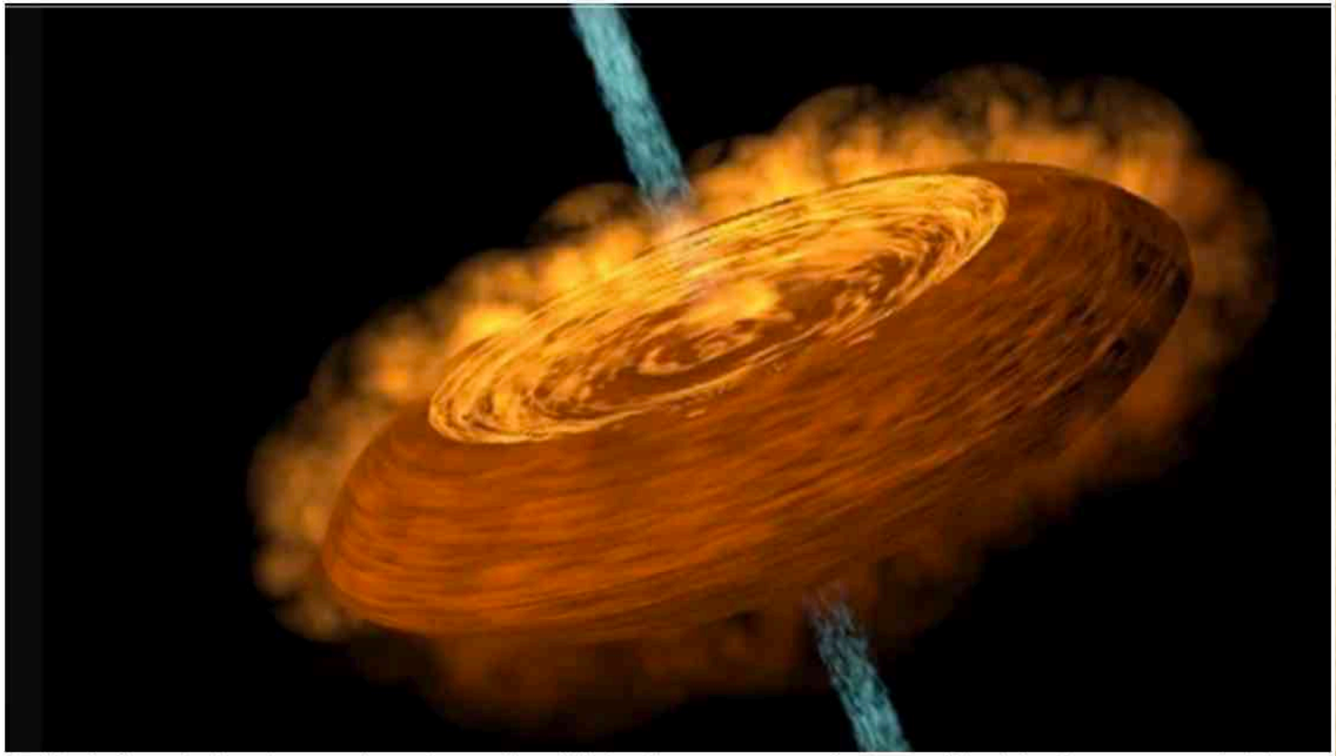


Lee et al. 2017a, Science Advances

CBS NEWS NEWS SHOWS VIDEO MORE

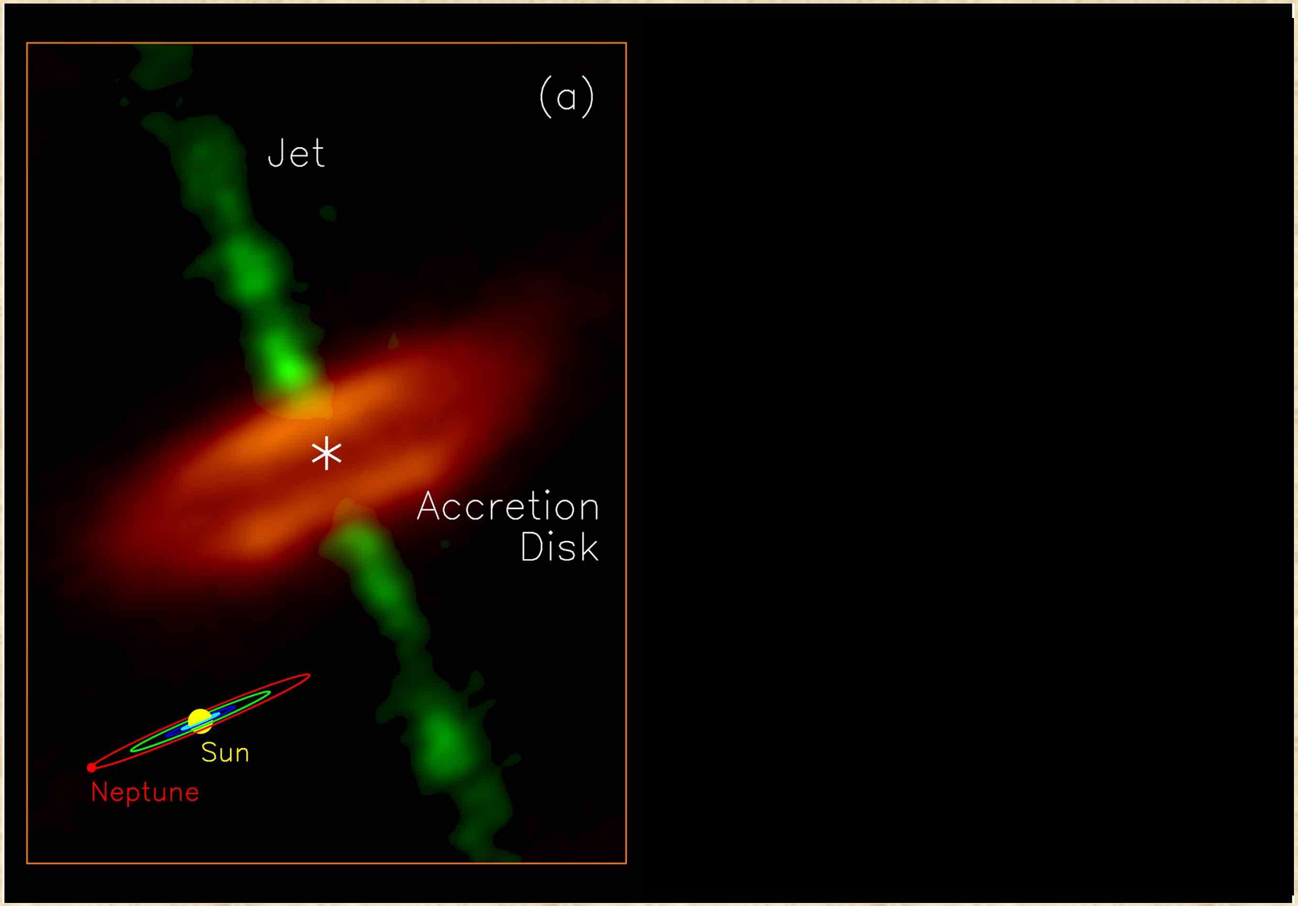
By HANNEKE WEITERING / SPACE.COM / April 20, 2017, 4:14 PM

"Space hamburger" spotted in astronomical first



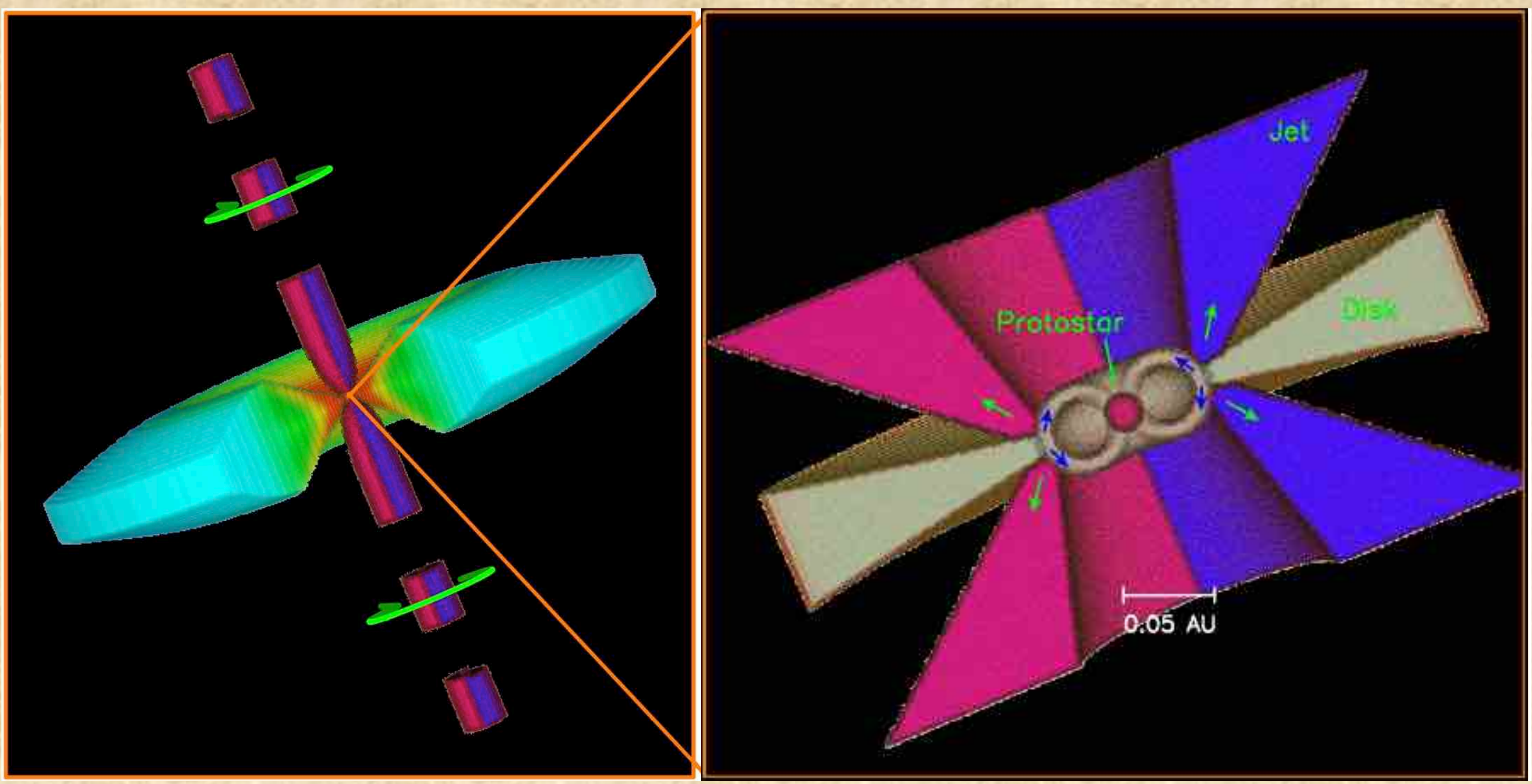
An illustration of a hamburger-shaped accretion disk feeding a young protostar, and the jets of gaseous material ejected from the young star's north and south poles. / YIN-CHIH TSAI/ASIAA

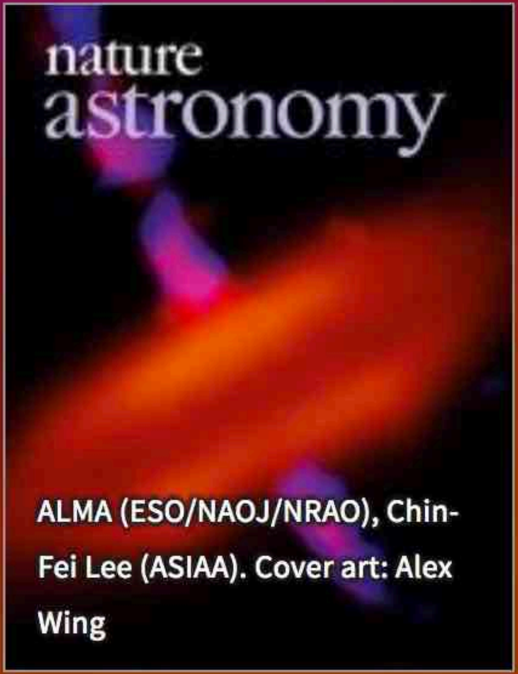
Innermost SiO Jet within 100 au: Jet rotation



Jet rotates the same way as the disk, carrying L from the disk
Measured Specific Angular Momentum ≤ 10 au km/s!
➔Launching Radius ≤ 0.05 au as in X-wind (Lee et al. 2017)

Accretion and Ejection Processes





ALMA (ESO/NAOJ/NRAO), Chin-Fei Lee (ASIAA). Cover art: Alex Wing

Volume 1 Issue 7

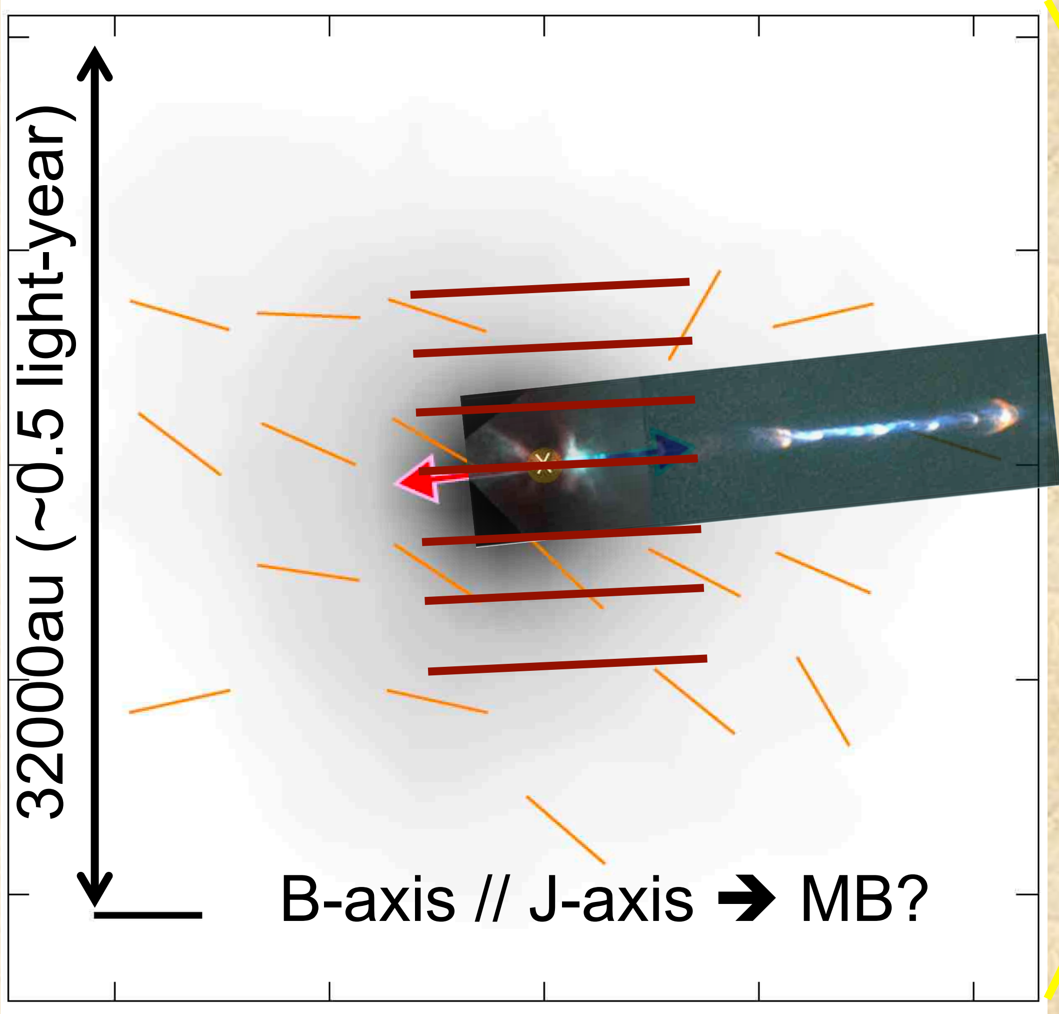
Spinning bullets from a young gun

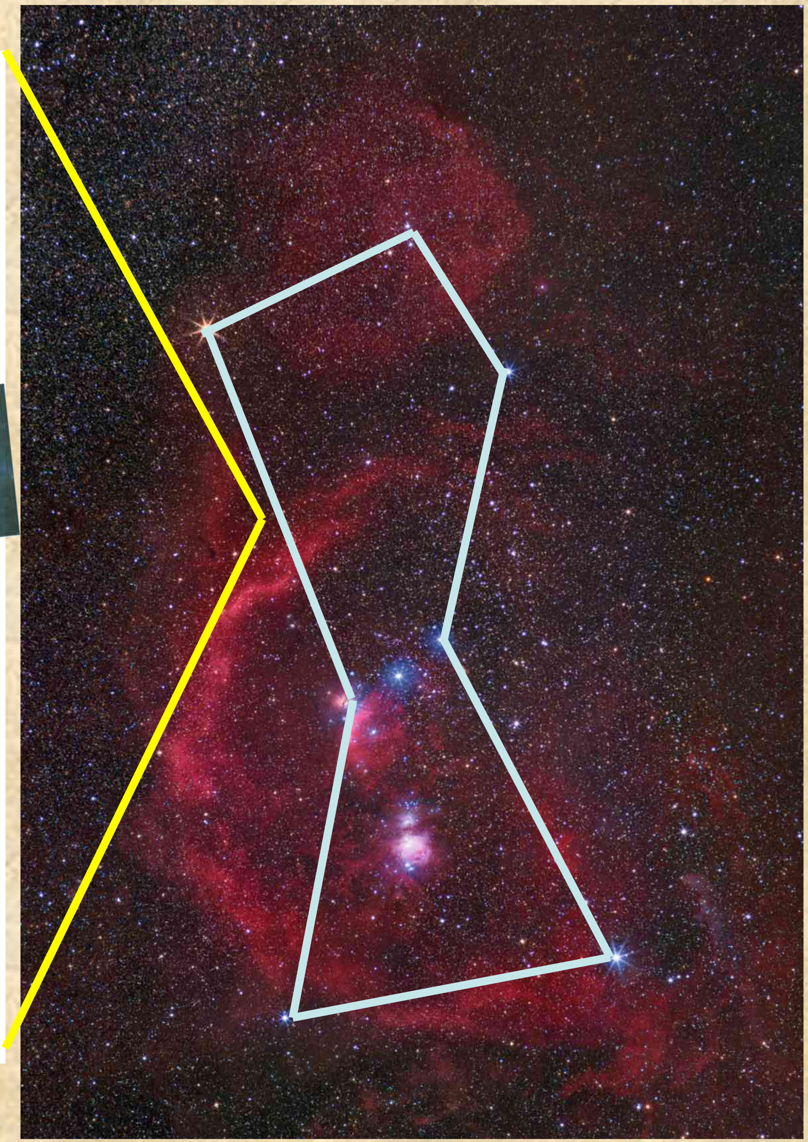
Observations of a narrow, high-velocity jet launched from the innermost regions of a protostar/disk system reveal the presence of spinning clumps of material within the jet. This putative rotation implies that the jet removes angular momentum from the disk, thus allowing disk material to accrete onto the central protostar.

See Lee *et al.* **1**, 0152 (2017).

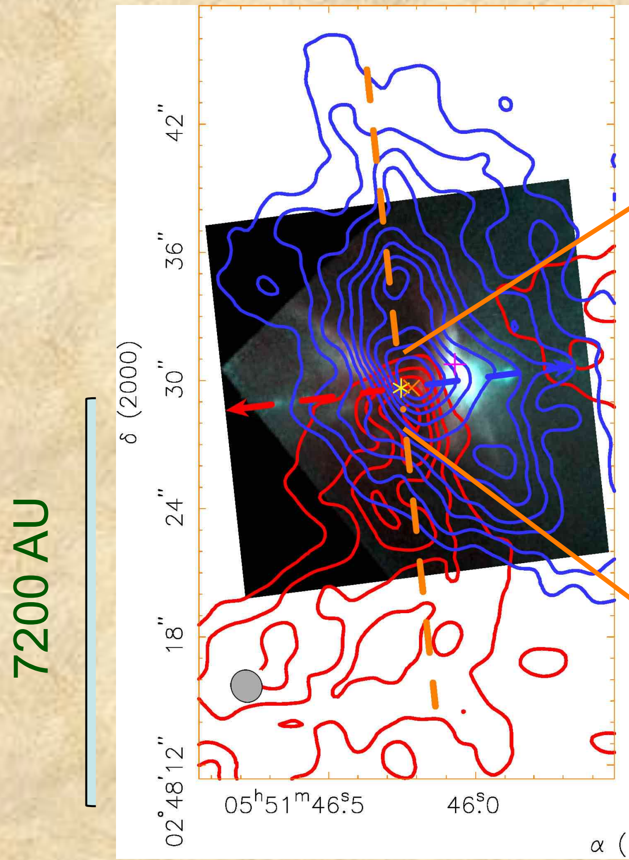
HH 111 @ 0.5 Myrs, $M_{\star}$ ~ 1.5 Ms

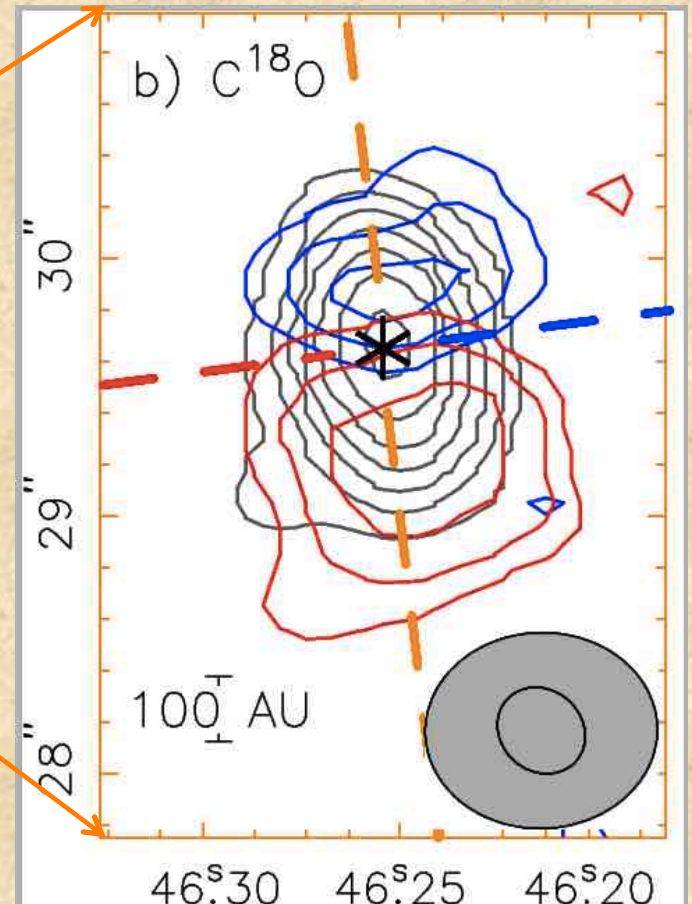
Orion Constellation





Gaseous Envelope in $C^{18}O$ J=2-1 (Lee 2010, 2011)





(1) Extended Perpendicular to the jet

(2) Rotating-collapsing inner core

(3) Mass ~ 0.3 Ms

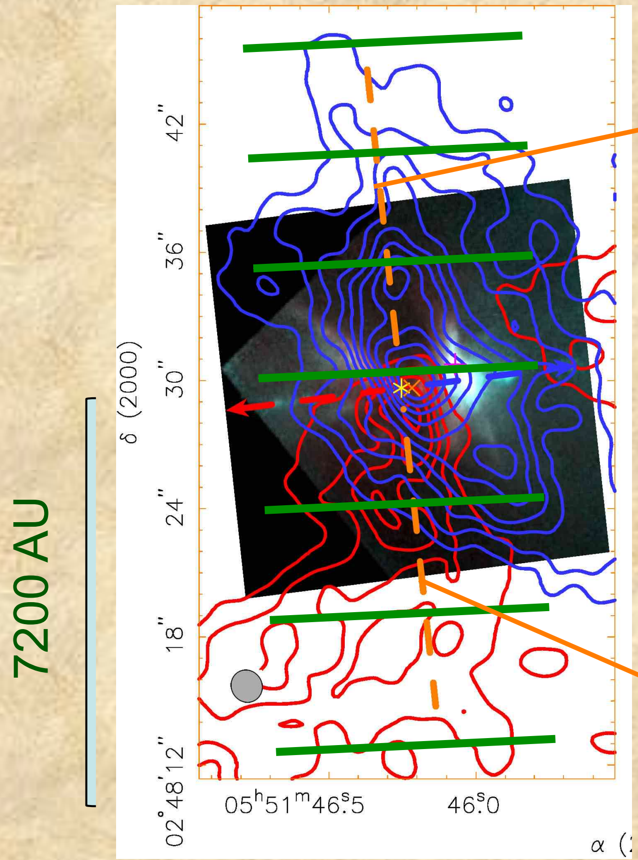
(4) Infall rate ~ 4.3e-6 Ms yr

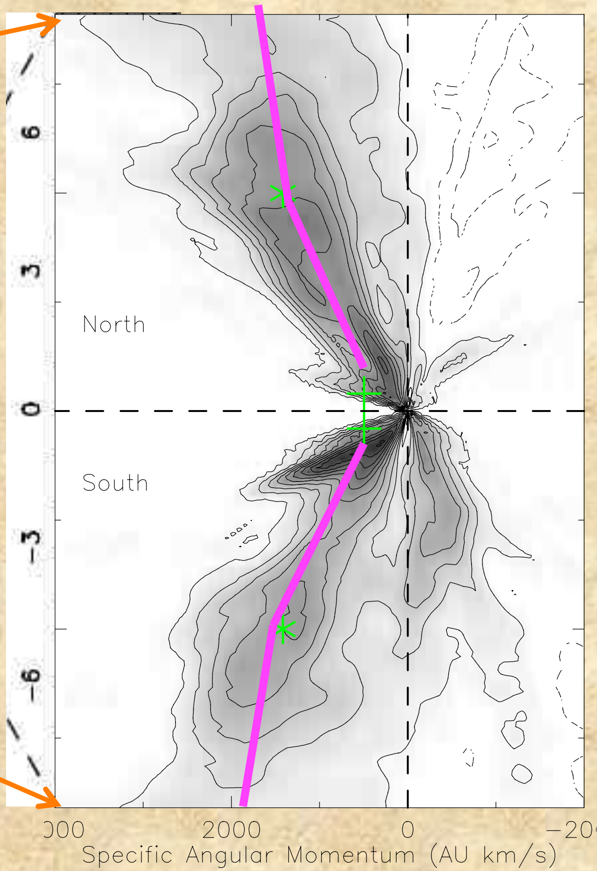
Keplerian rotating disk r_D ~160au!!

➔ $M_\star$ ~ 1.5 Msun

➔ Age ~ 0.5 Myr old

Gaseous Envelope in $C^{18}O$ J=2-1 (Lee 2010, 2011)





(1) Extended Perpendicular to the jet

(2) Rotating-collapsing inner core

(3) Mass ~ 0.3 Ms

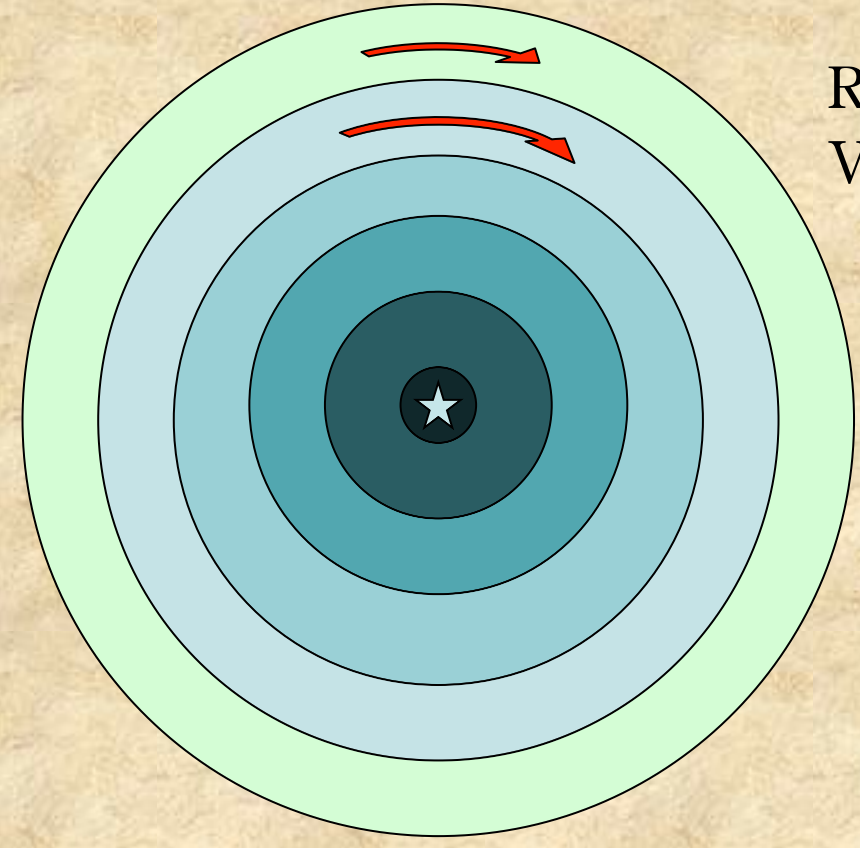
(4) Infall rate ~ 4.3e-6 Ms yr

Lost of angular momentum at 2000 AU (5”) results in a small disk. Magnetic Braking (MB)? (Lee 2010, 2016)

First spiral arms detected in active accretion phase because of ALMA unprecedented resolution!!!

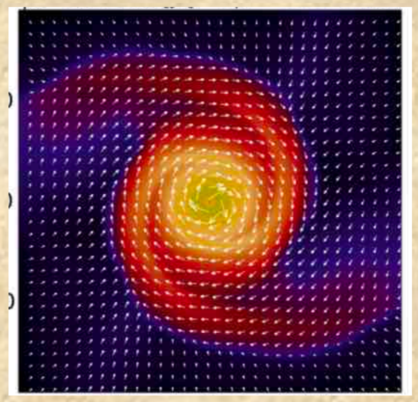
Lee et al. 2020, Nature Astronomy

Keplerian Rotating Accretion Disk



Rotation Velocity

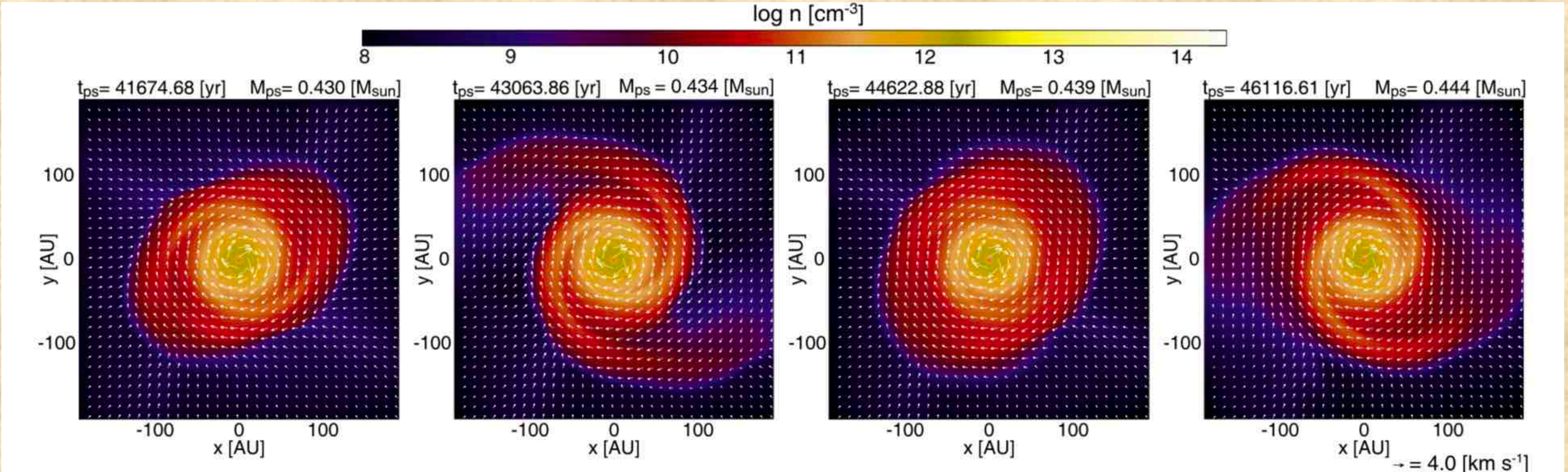
Vrot = (GM/R)^(1/2)

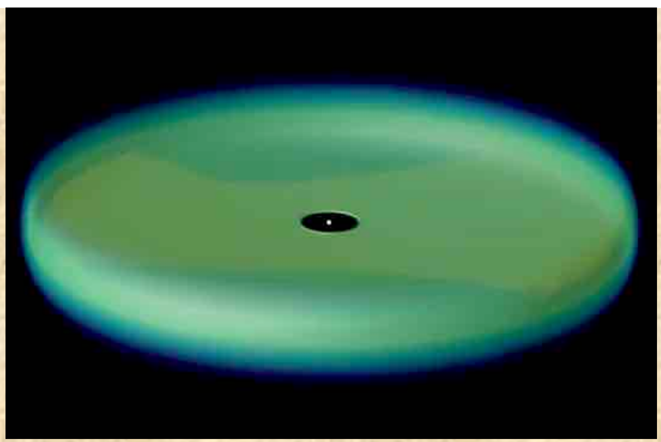


L = R x Vrot = (G M R)^(1/2) ➔ smaller @ smaller radius

➔ need to transport L away or outward, but how?

Spirals Repeatedly Formed by Gravitational Instability sustained by envelope accretion



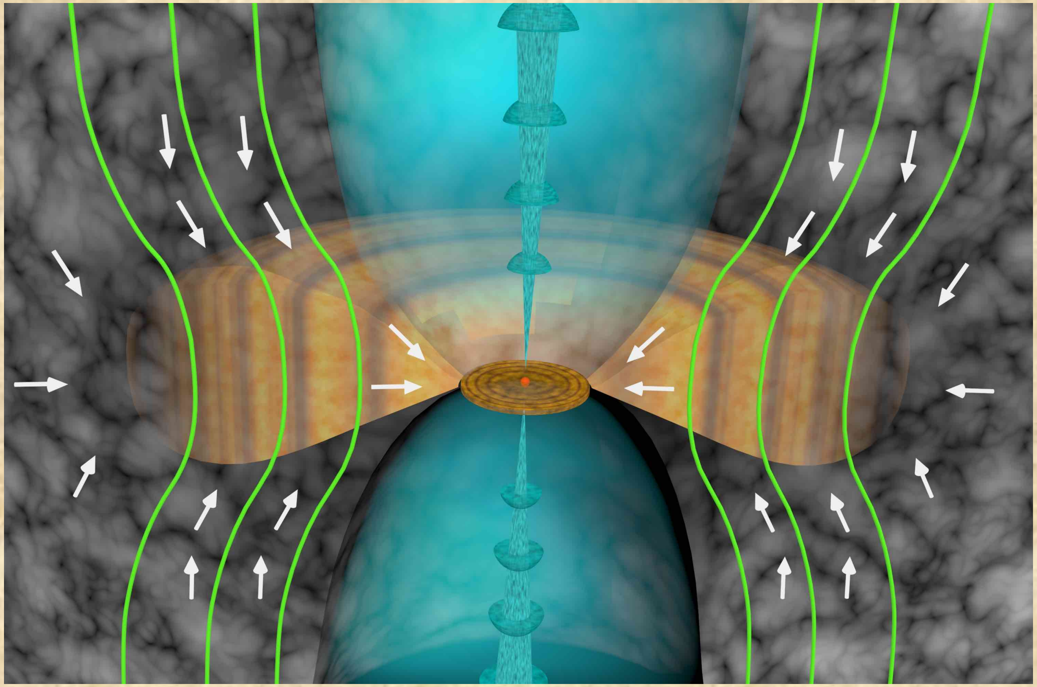


Tomida et al. 2017

Gravitational Torque can transport angular momentum outwards.

➔ Material can accrete and fall inwards.
➔ Solution to the long-standing angular momentum problem in disk accretion.

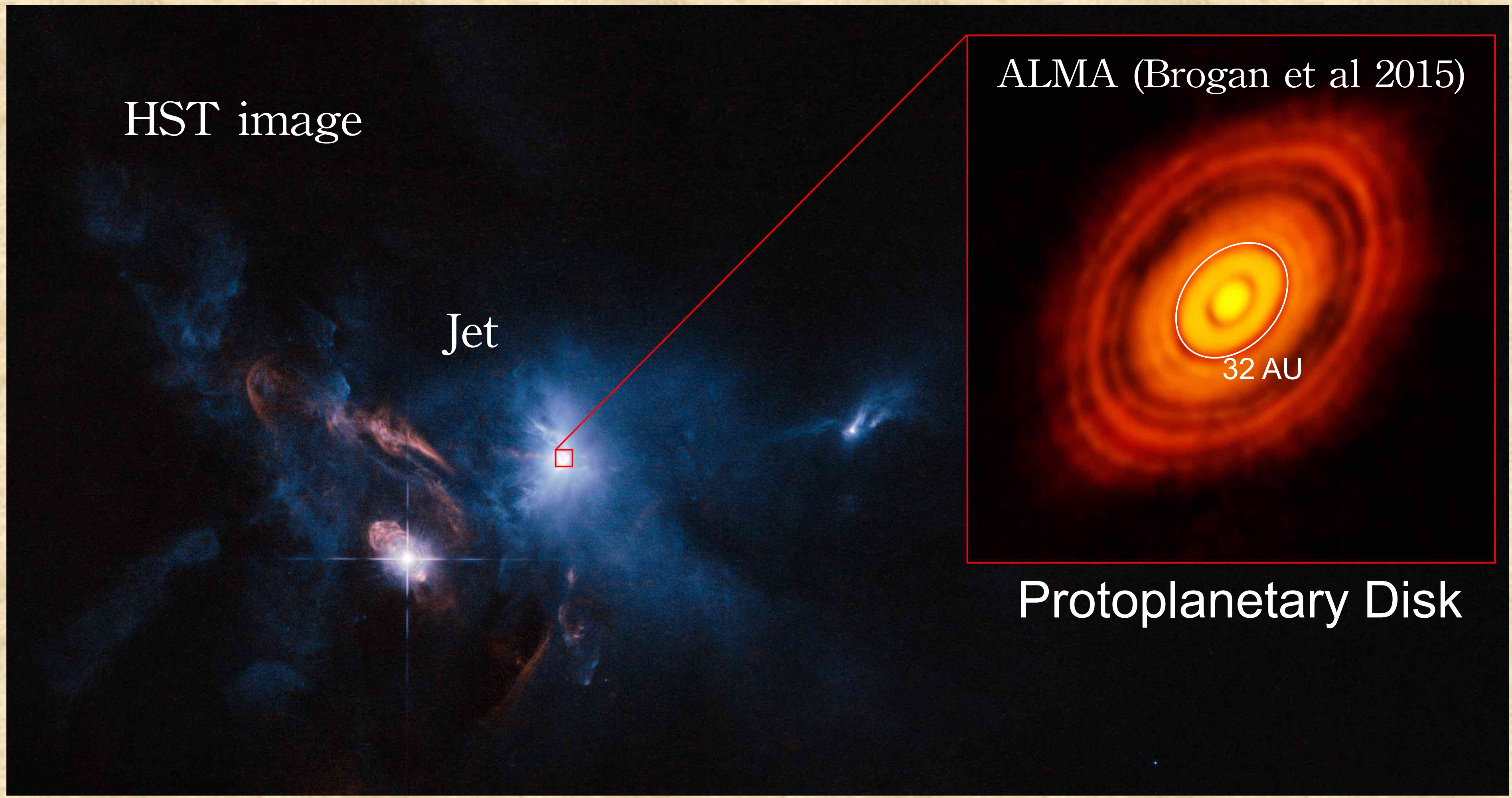
Formation Process of a Solar System like our own



1. Infall guided by magnetic field, forming flattened envelope
2. Keplerian disk formed in flattened env. feeding protostar
3. Magnetic braking may reduce the disk size, if J // B-axis
4. Jet magnetized, launched from the innermost edge of disk.
5. GI induces spiral arms transporting L inside Keplerian disk.
   Disk Wind carrying away L from the disk? MRI turbulence?

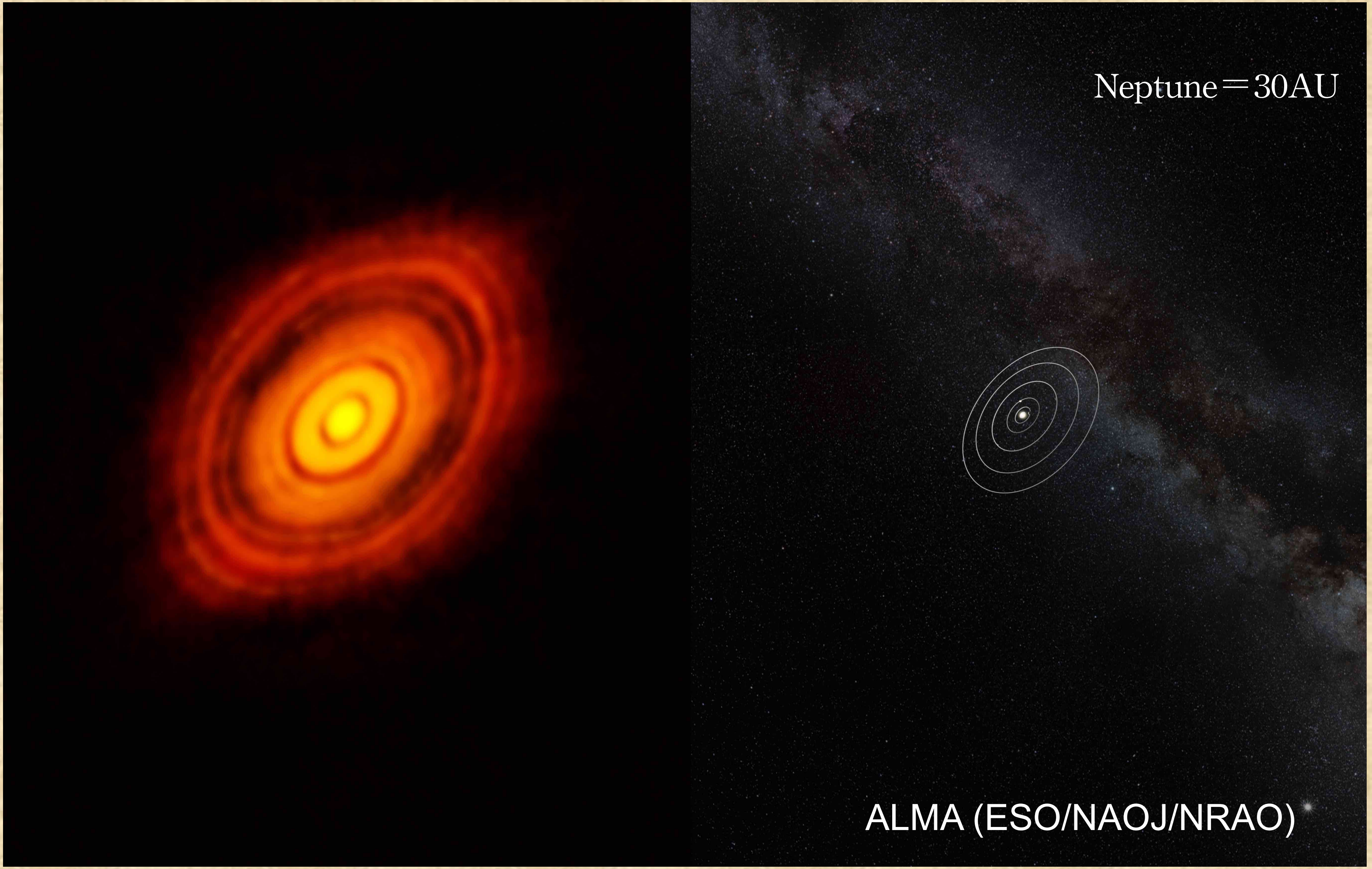
Disk & Jet in the Early Phase of Star Formation

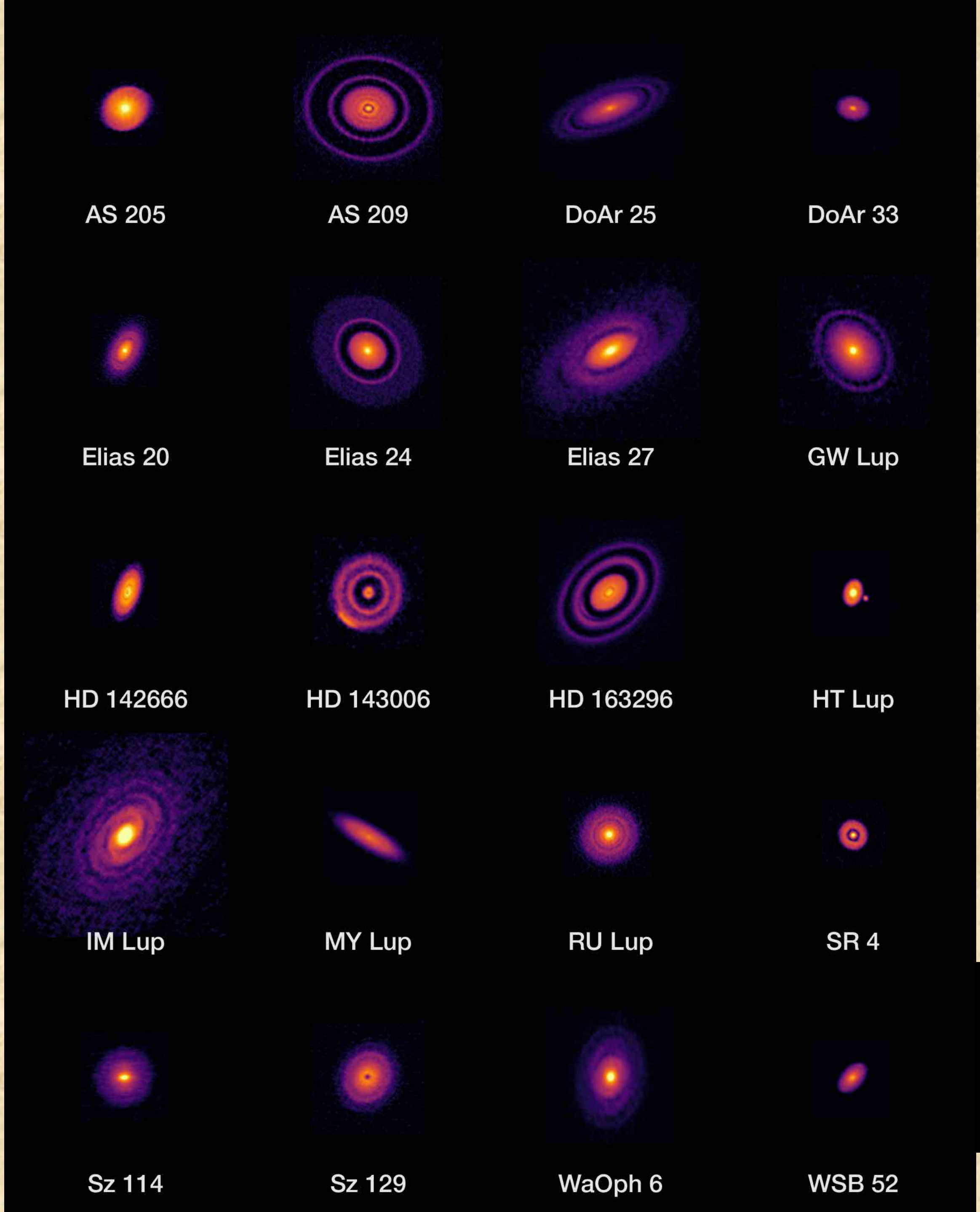
HL Tau @ ~ 1 Myr with $M_\star \sim 2\ M_\odot$



ALMA (ESO/NAOJ/NRAO), ESA/Hubble and NASA

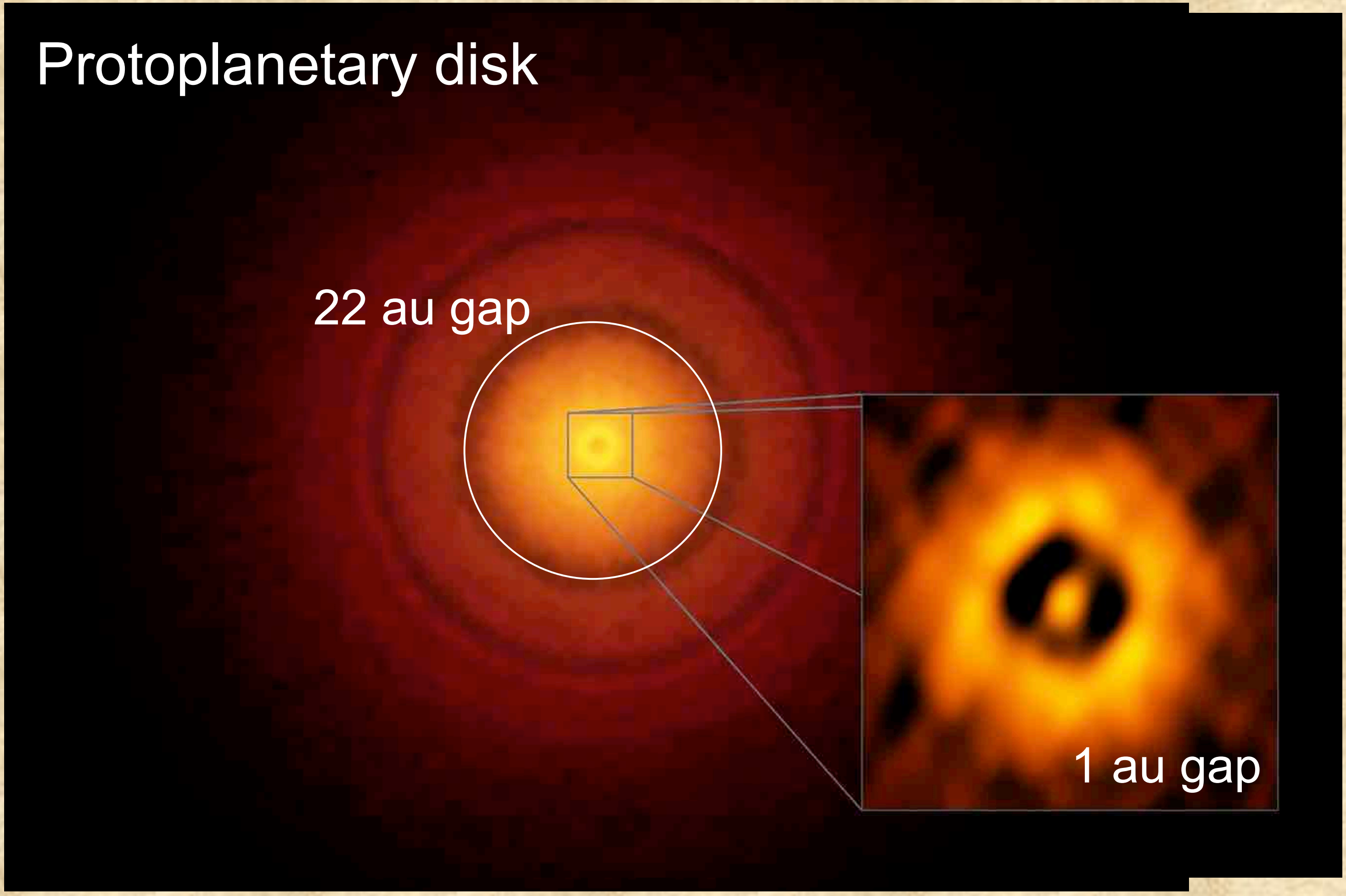
HL Tau Protoplanetary Disk vs Solar System





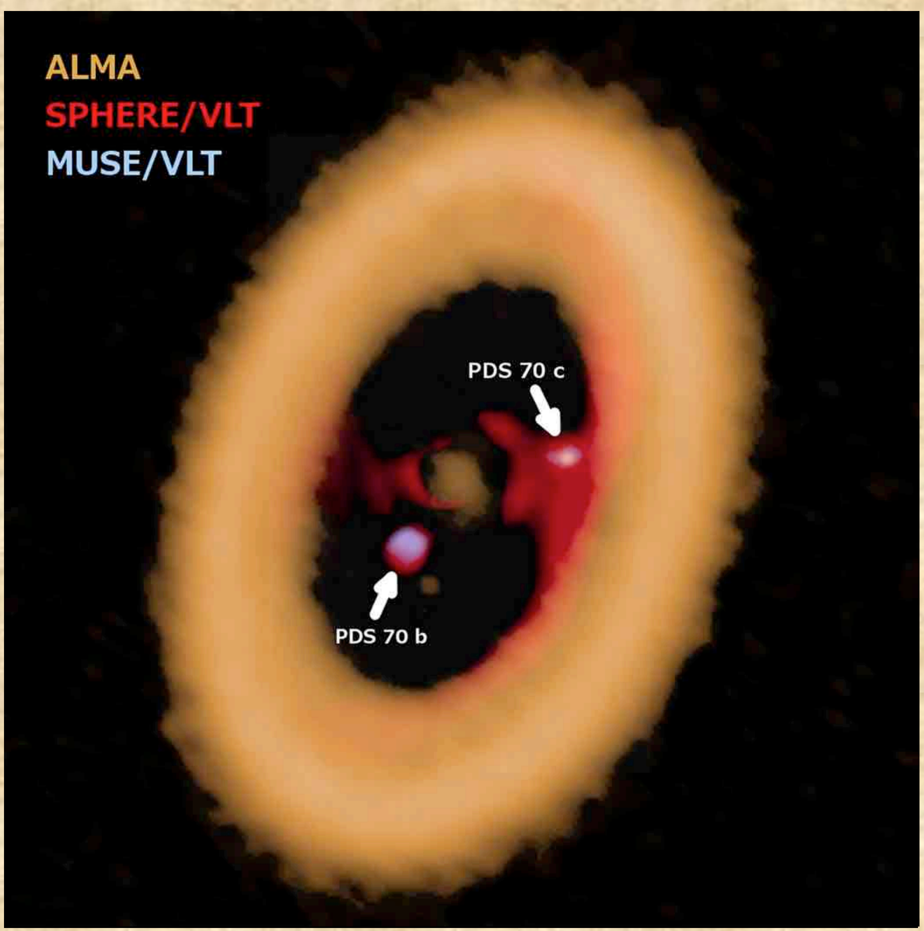
ALMA (ESO/ NAOJ/ NRAO)Andrews et al.; N. Lira

TW Hydrae @ 10 Myr with $M_\star \sim 0.55\ M_\odot$



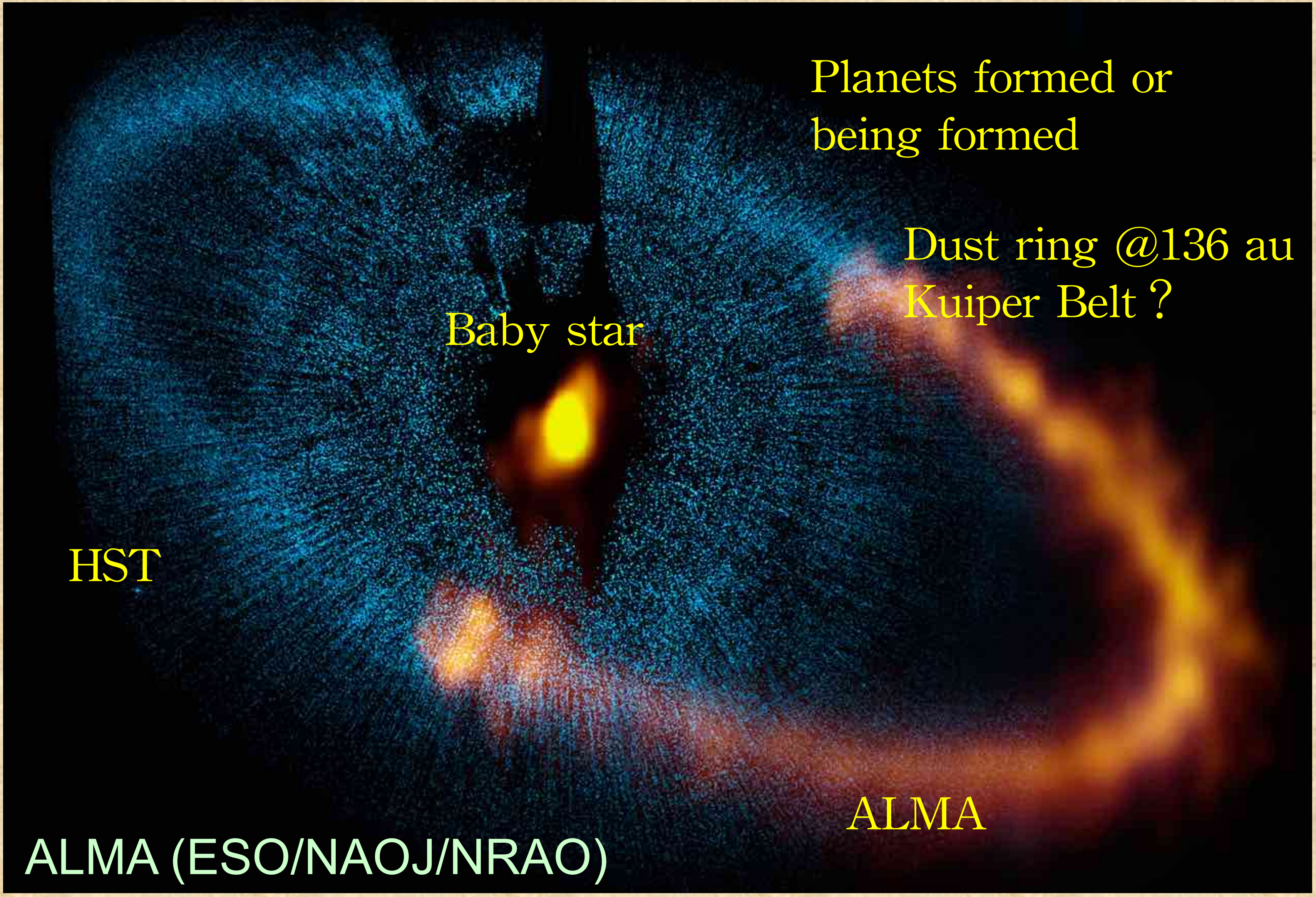
S. Andrews (CfA), B. Saxton (NRAO)   ALMA (ESO/NAOJ/NRAO)

PLANET FORMATION- PDS 70



ALMA (ESO/NAOJ/NRAO), ESA/Hubble and NASA/Andrea Isella et al

Fomalhaut Debris Disk @0.44 Byrs w. $M_\star$ 1.9$M_\odot$



Solar System @ ~ 4.6 Byrs

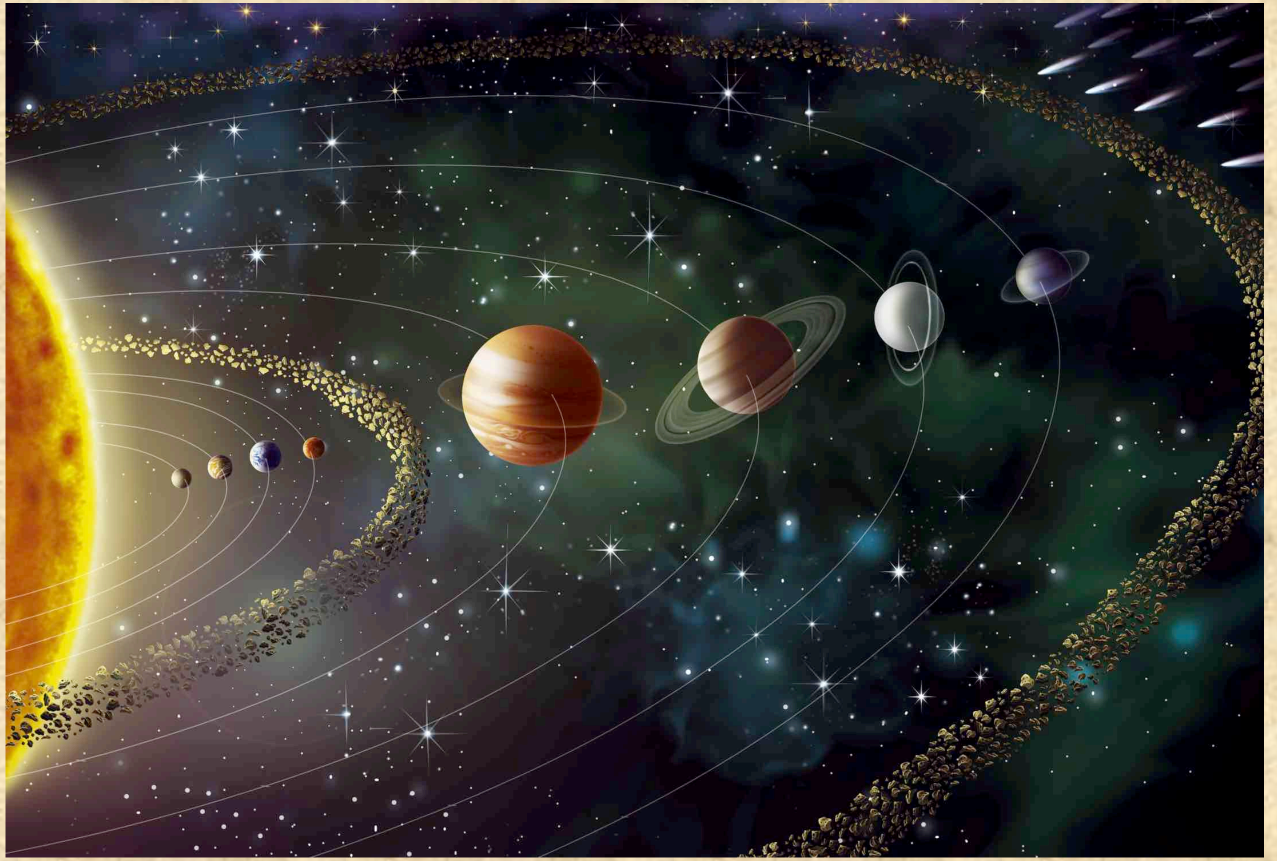
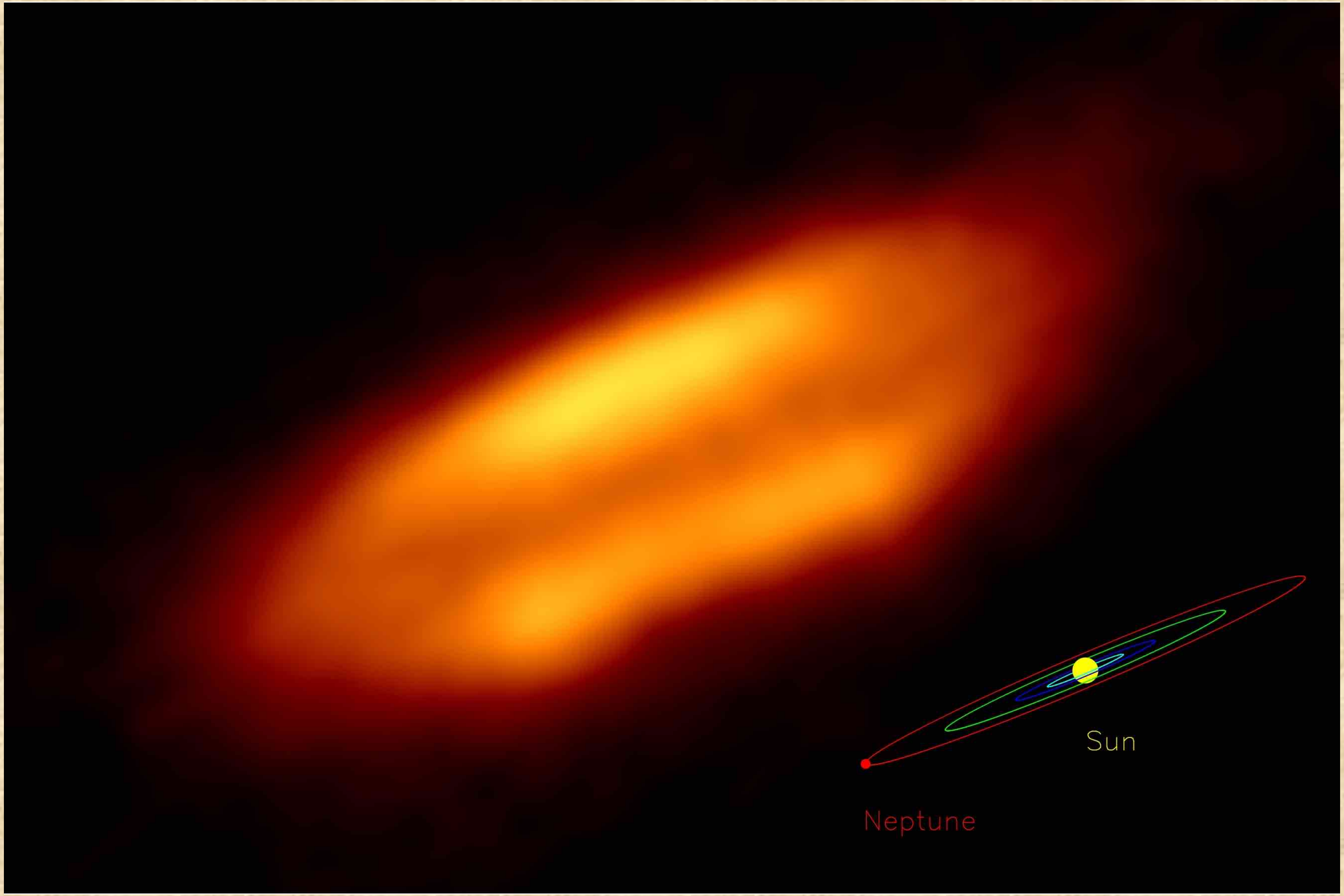


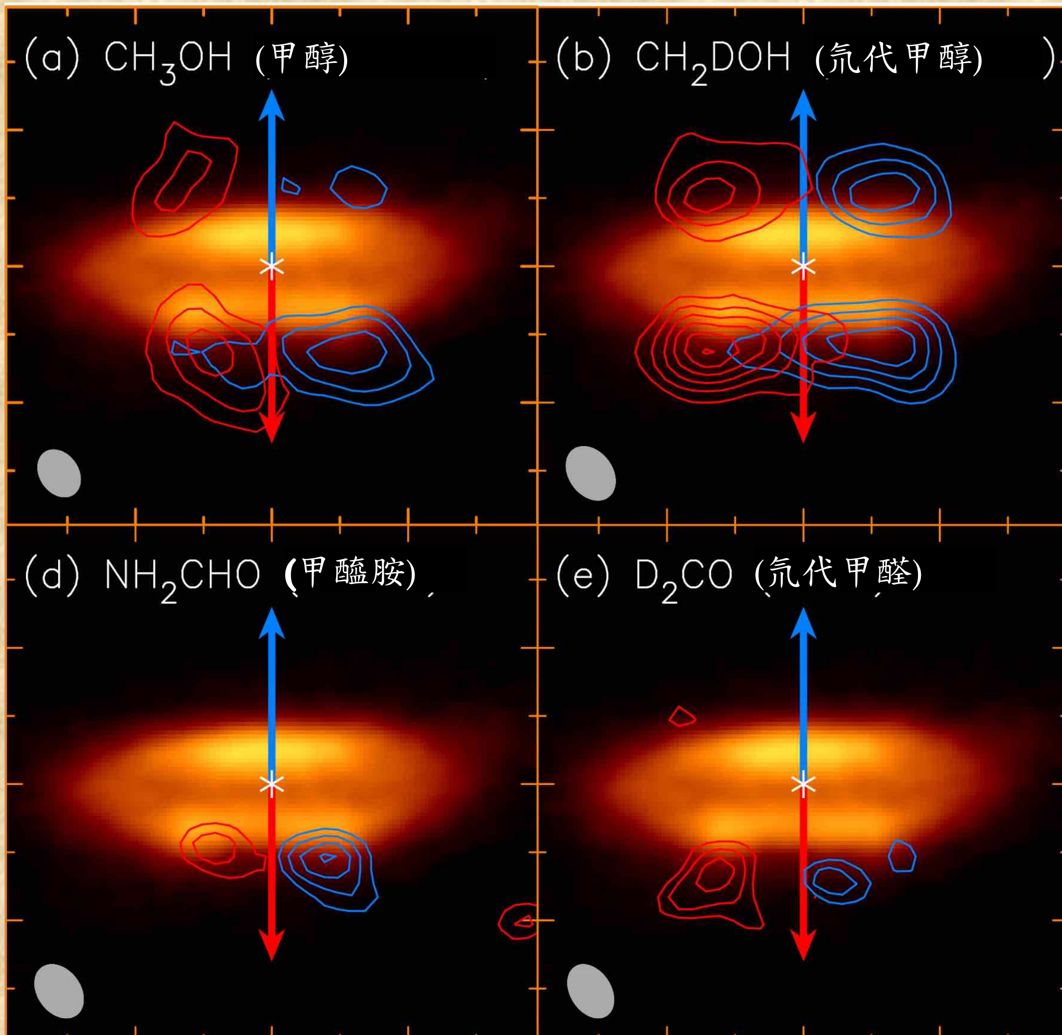
Image Credit: Harvey Resources

Simulations of Planet Formation

Any life building blocks in Hamburger ?



Complex Organic Molecules (COMs) found in Disk Atms



Keplerian Rotation
➔ $M_\star$ ~ 0.25 Msun

Lee et al. 2017b

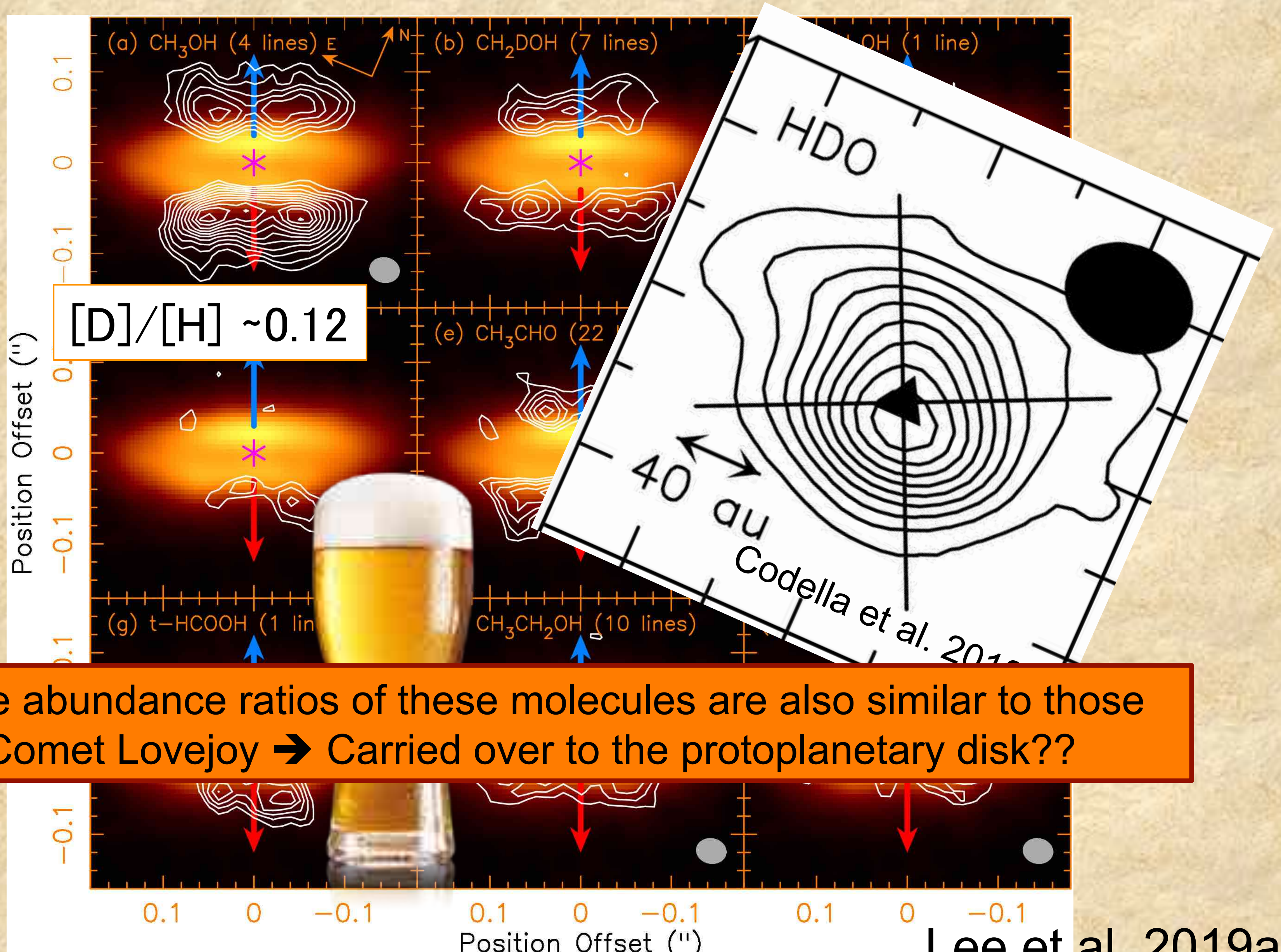
Star-forming disks contain complex molecules early on. Credit: ASIAA/Jung-Shan Chang

ASTRONOMY AND ASTROPHYSICS · 10 July 2017

Organic molecules spotted in star-forming disk

Life's building blocks seen around young would-be star.

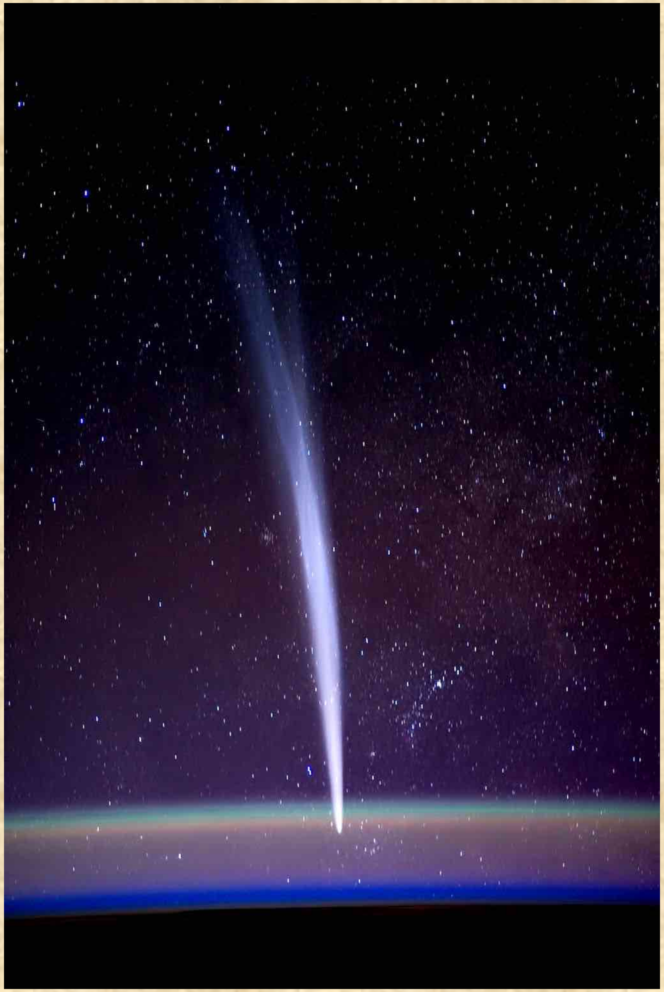
More COMs found in Disk Atmosphere



The abundance ratios of these molecules are also similar to those in Comet Lovejoy ➔ Carried over to the protoplanetary disk??

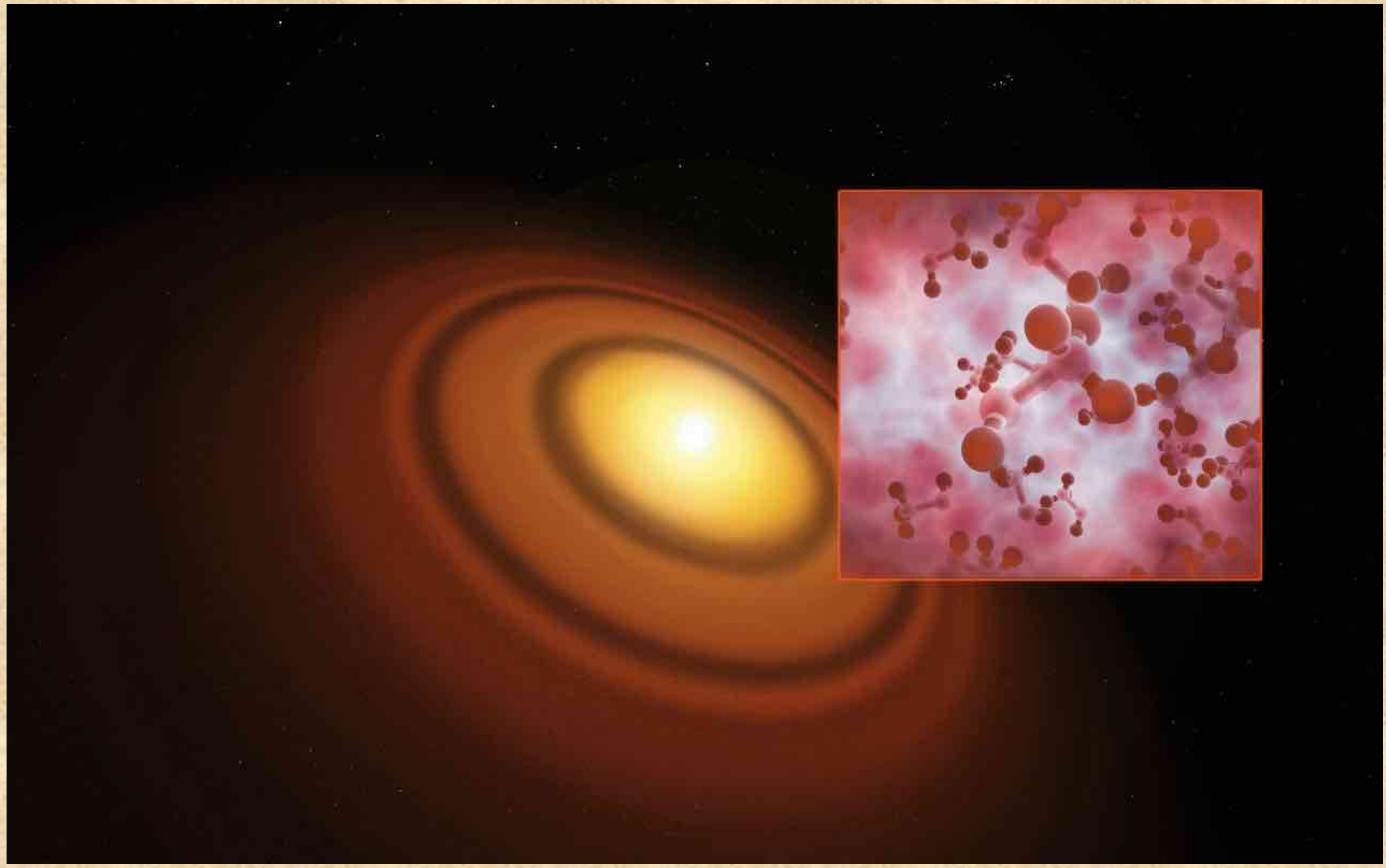
Lee et al. 2019a

A photo of Comet Lovejoy taken from National Space Station on 2011/12/21



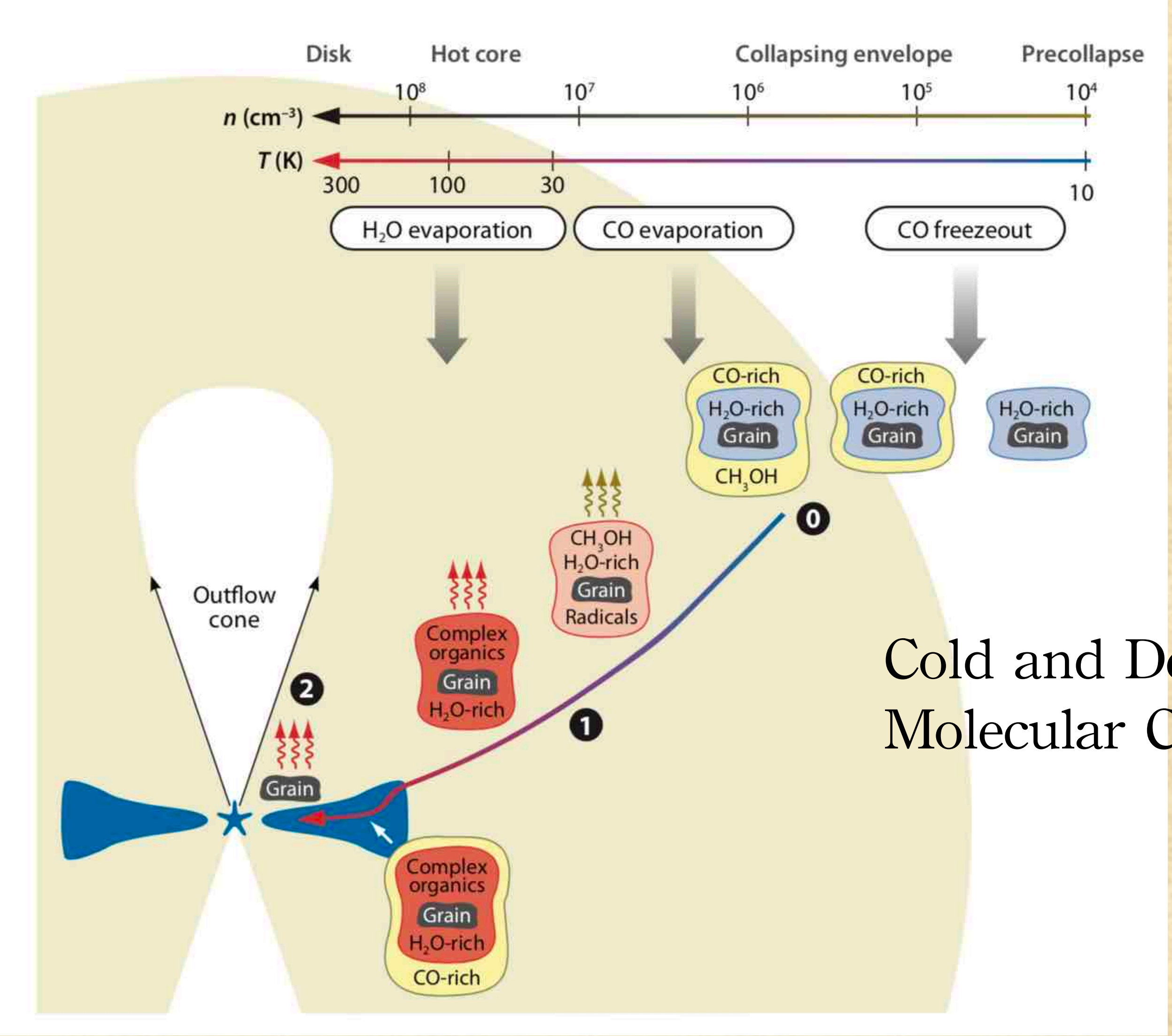
It was first discovered by an Australian amateur astronomer Lovejoy on 2011/11/27. It is a periodic comet.

Methanol甲醇also found in TW Hydrae protoplanetary disk



Catherine Walsh ALMA (ESO/NAOJ/NRAO)

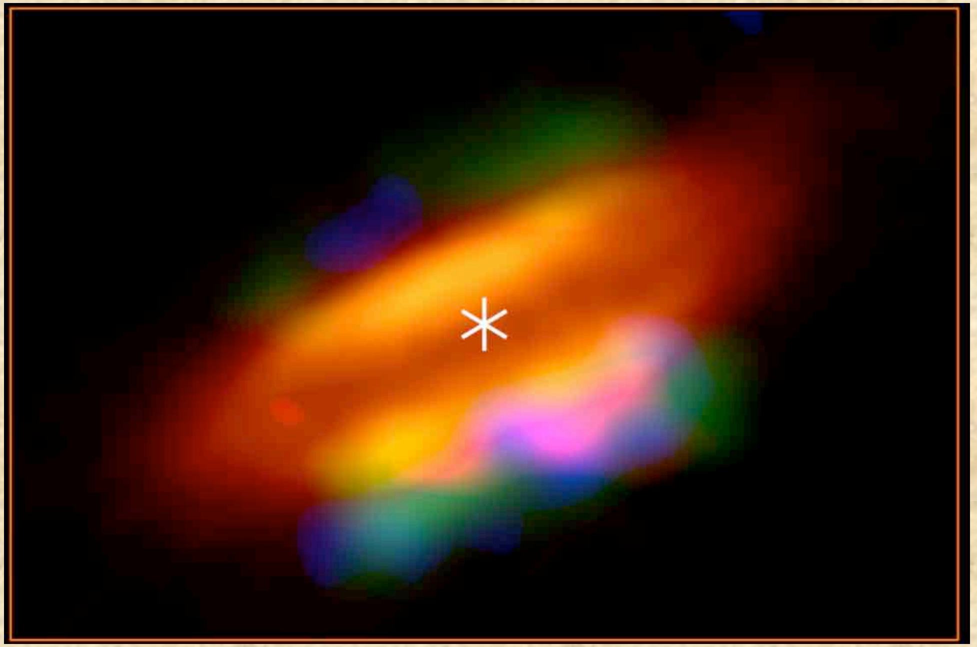
How do COMs form and appear on accretion and protoplanetary disks?



Cold and Dense Molecular Core

Herbst & van Dishoeck 2009

Complex Organic Molecules (COMs)



- ➔ Amino acids
- ➔ Aliens ?