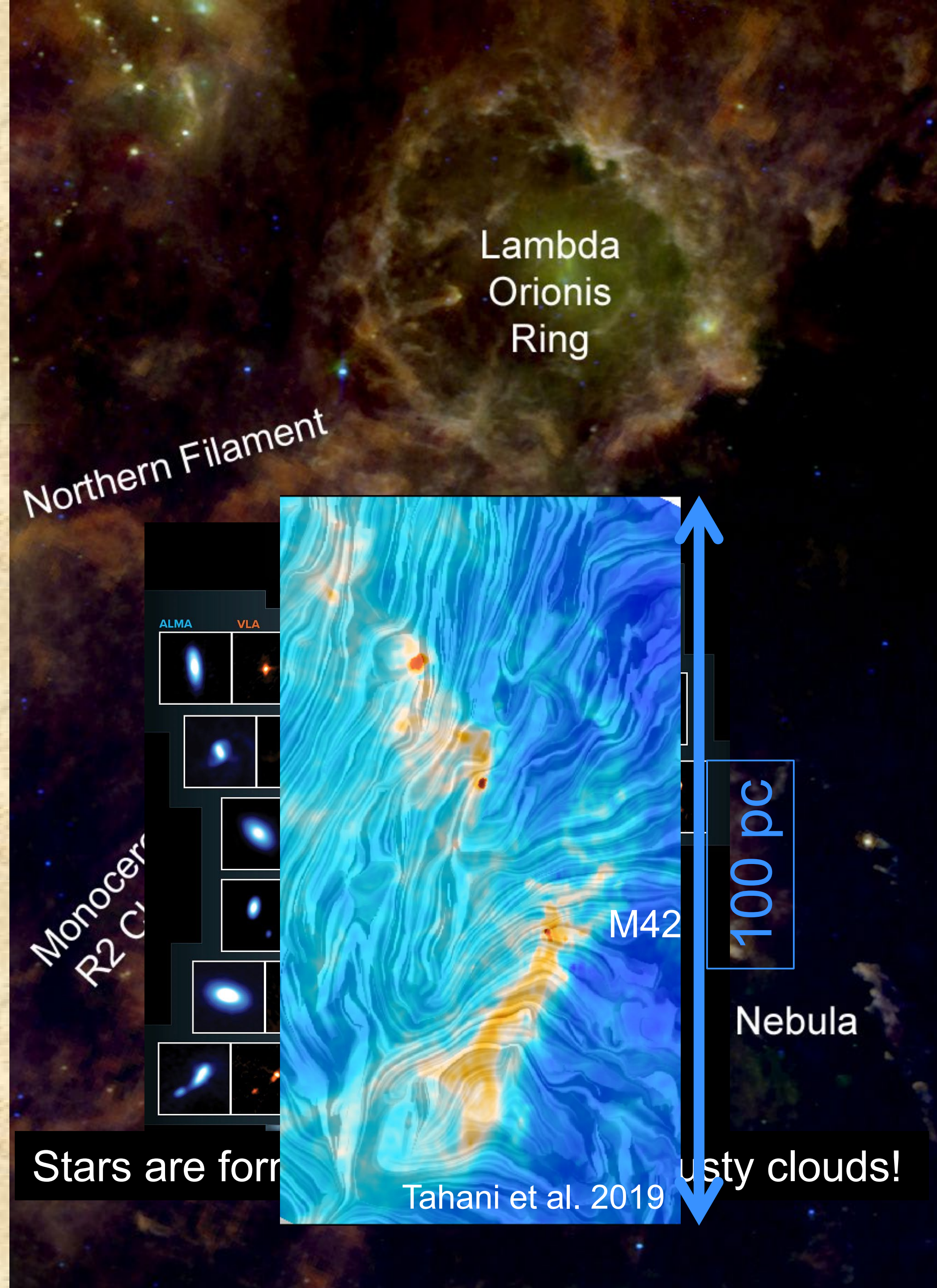
Formation of the Disks and Jets in The Early Phase of Star Formation

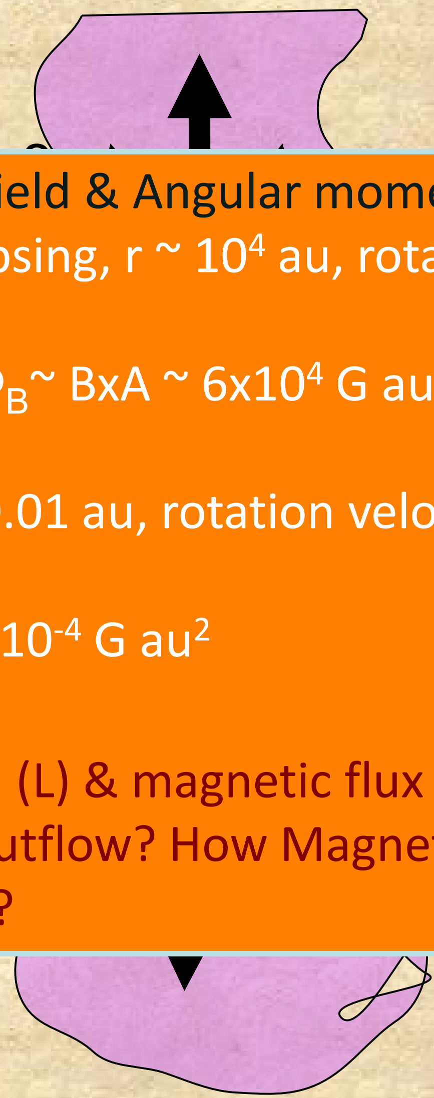
Chin-Fei Lee (2022 Dec 16)

Orion Constellation



1 pc=3.26 ly
=206265 au

Formation Process of Sunlike Stars



0.1 pc (~20000 au), 1-2 $M_\odot$

Complicated by Magnetic field & Angular momentum:

Prestellar cores to be collapsing, $r \sim 10^4$ au, rotation velocity $v_\varphi \sim 0.1$ km/s, magnetic field $B \sim 0.2$ mG

➔ $L \sim r\, v_\varphi \sim 10^3$ au km/s, $\Phi_B \sim B \times A \sim 6\times10^4$ G au^2

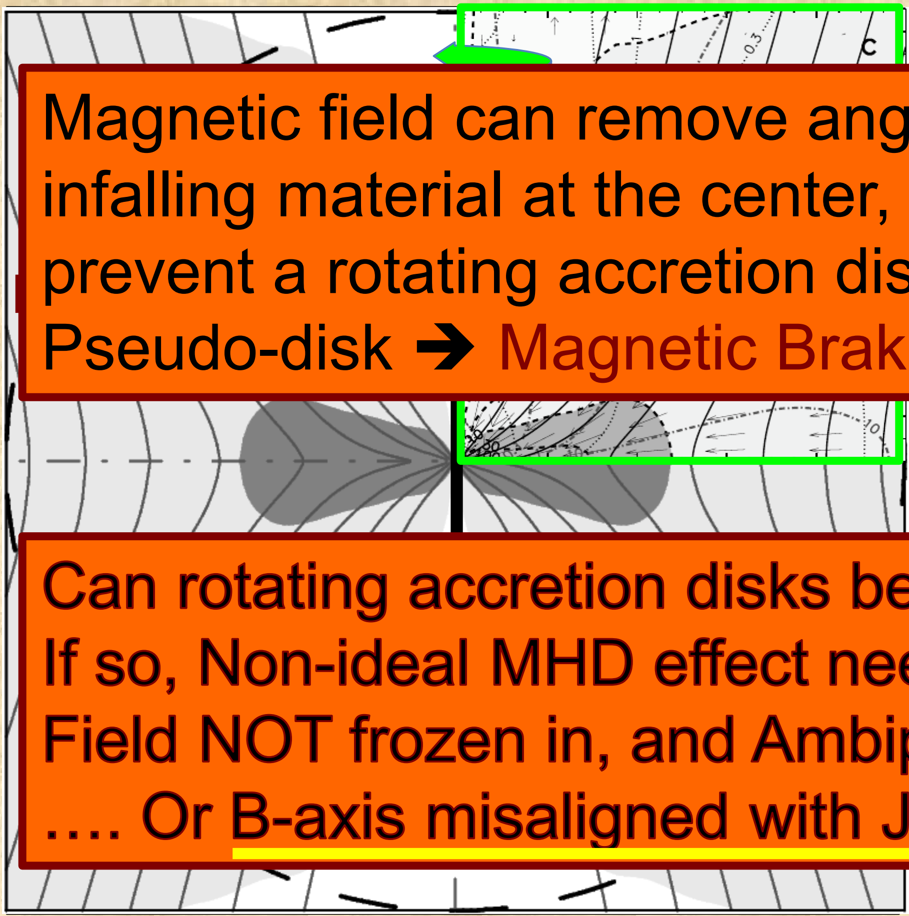
In the stars to be born, $r \sim 0.01$ au, rotation velocity $v_\varphi \sim 10$ km/s, magnetic field $B \sim 1$ G

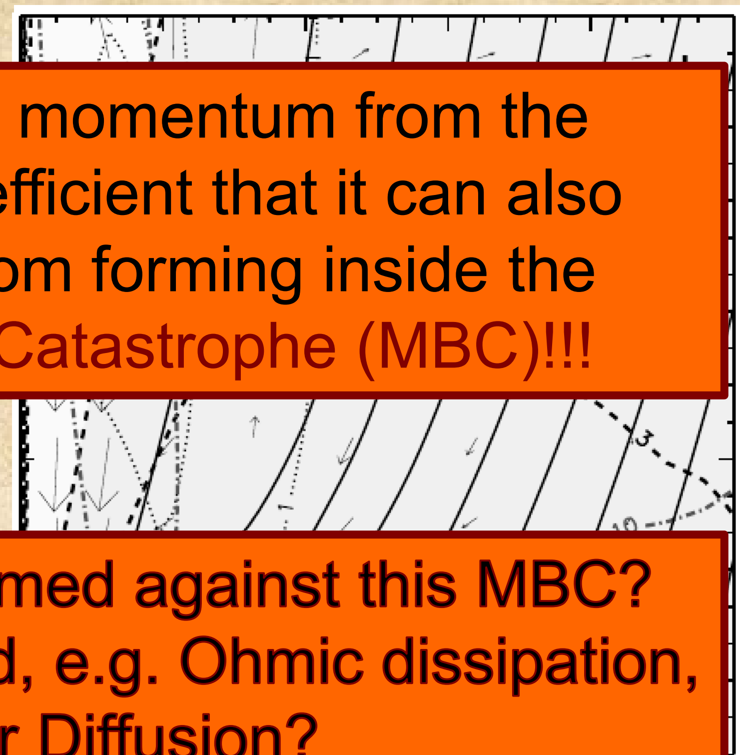
➔ $L \sim 0.1$ au km/s, $\Phi_B \sim 3\times10^{-4}$ G au^2

Where angular momentum (L) & magnetic flux (Φ_B) go? Stay in Core and Envelope? Going to Disk/Outflow? How Magnetic field and angular momentum affect star forming process?

Modified from Kate Pattle

Inside-out Collapse of Magnetized and Rotating Prestellar Core (Ideal MHD, field frozen in material)



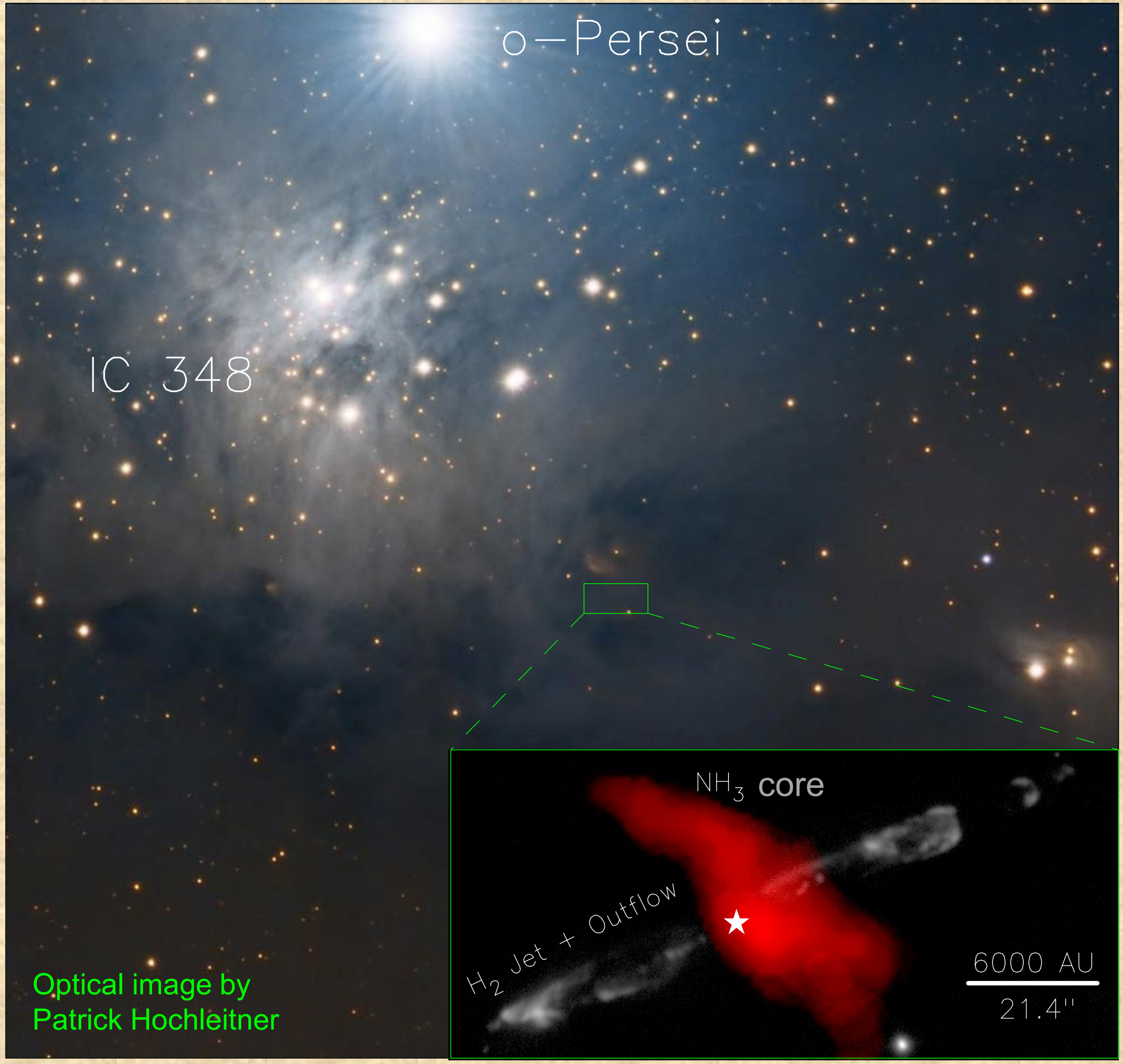


Magnetic field can remove angular momentum from the infalling material at the center, so efficient that it can also prevent a rotating accretion disk from forming inside the Pseudo-disk ➔ Magnetic Braking Catastrophe (MBC)!!!

Can rotating accretion disks be formed against this MBC? If so, Non-ideal MHD effect needed, e.g. Ohmic dissipation, Field NOT frozen in, and Ambipolar Diffusion?
…. Or B-axis misaligned with J-axis?

Evolution is self-similar

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



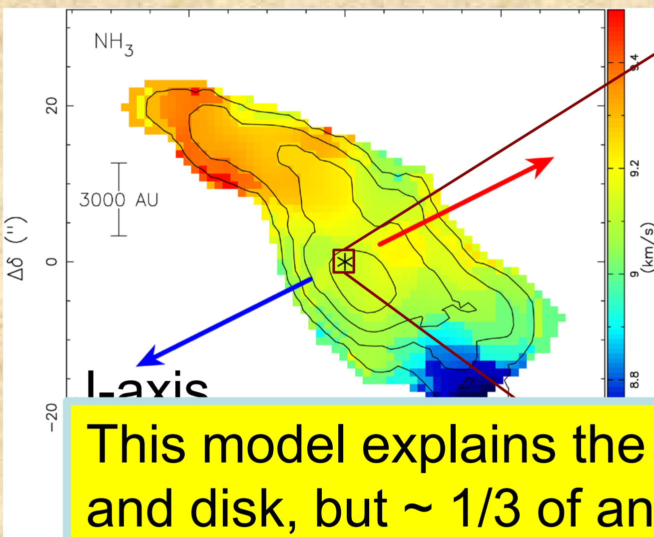
Hirano et al. 2006

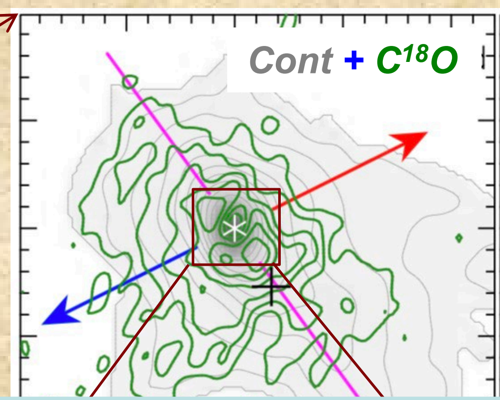
Wiseman et al. 2001

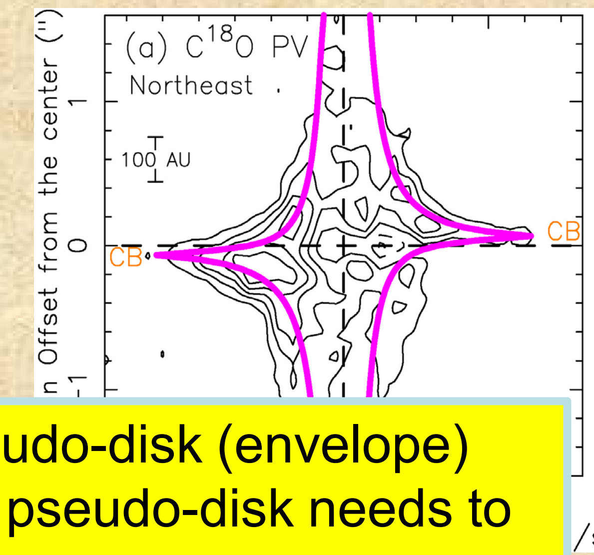
Age~2x10^4 yr, Luminosity~ 3.6 Lsun, $M_{\star}$<~ 0.08 Msun

Rotating NH_3 Core (r ~ 0.05 pc or 10^4 au)

Pseudo-Disk: r ~ 400 au (infall > rotation)

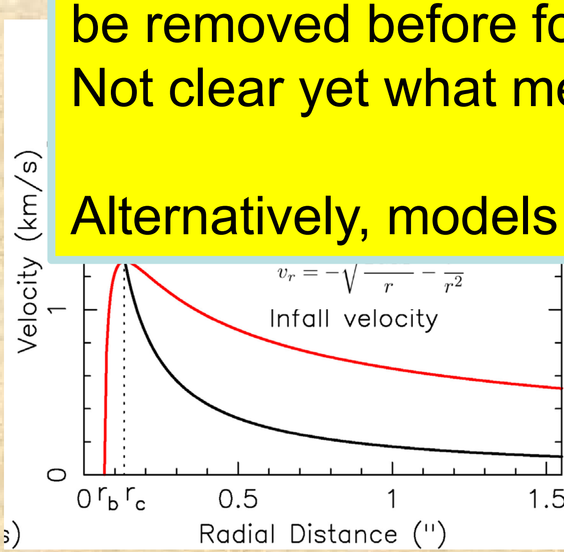


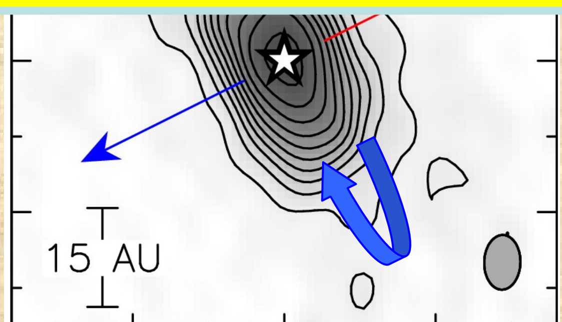


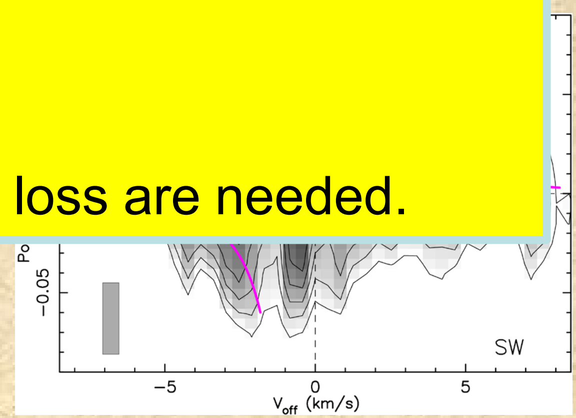


This model explains the observations of the pseudo-disk (envelope) and disk, but ~ 1/3 of angular momentum of the pseudo-disk needs to be removed before forming the disk!
Not clear yet what mechanism can do it!

Alternatively, models without angular momentum loss are needed.

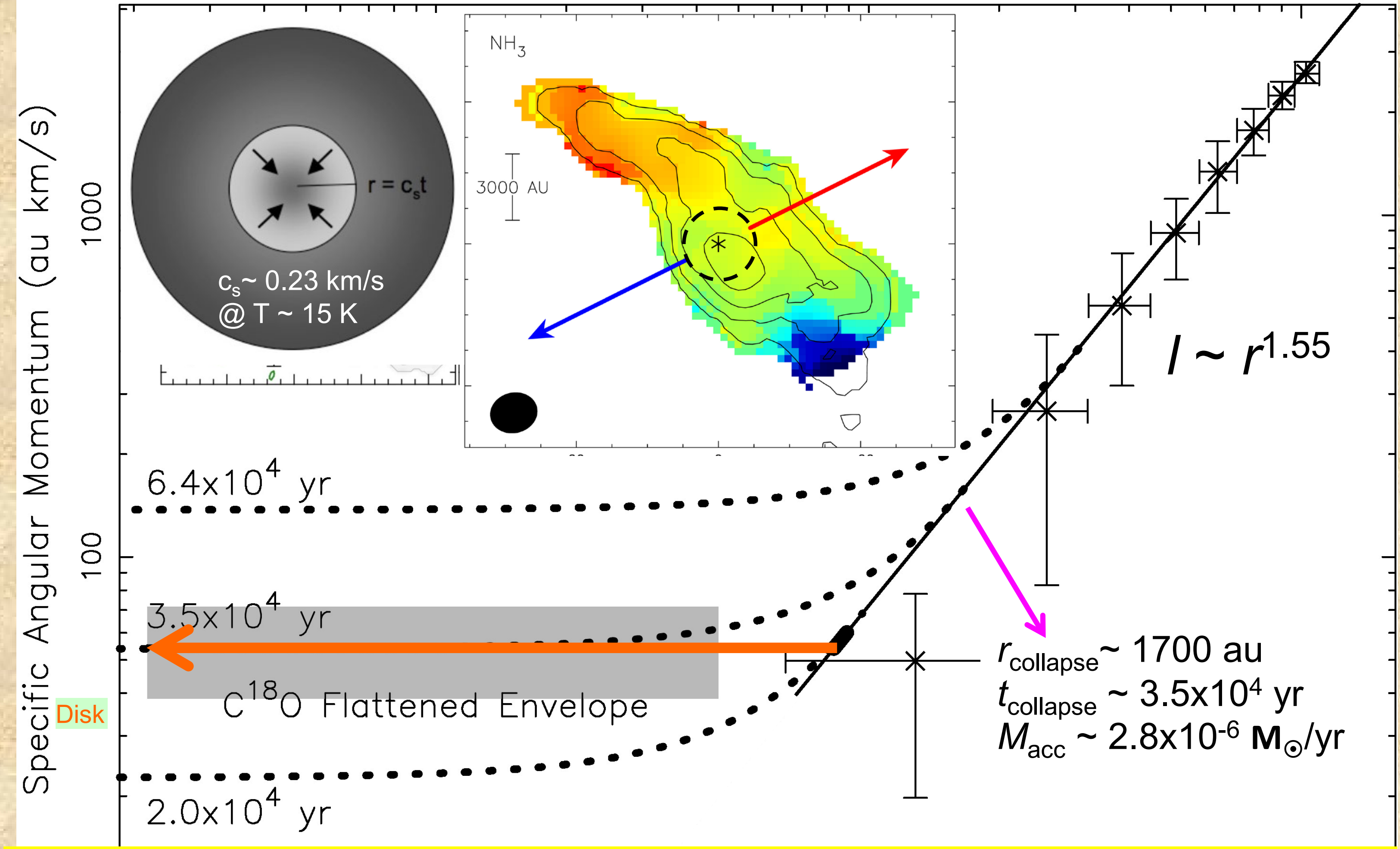




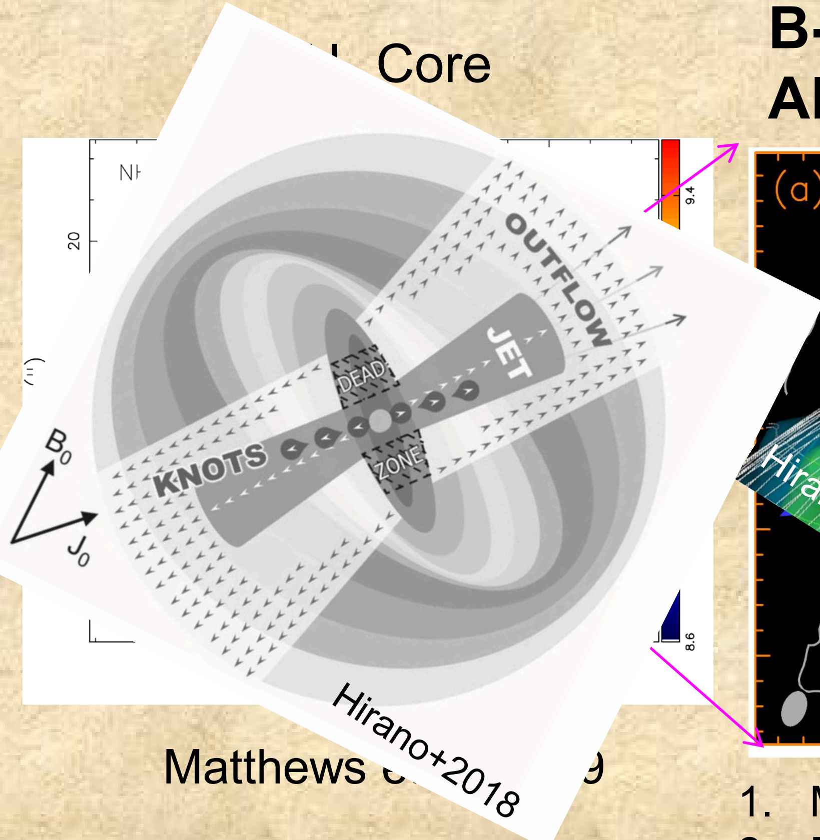


- ~ Kep. Rot. disk r_D~20au
- l ~ 38 au km/s at disk edge
- $M_\star + M_d$~ 0.08 $M_\odot$

Angular Momentum Distribution
Inside-out Collapse & collapsing Radius

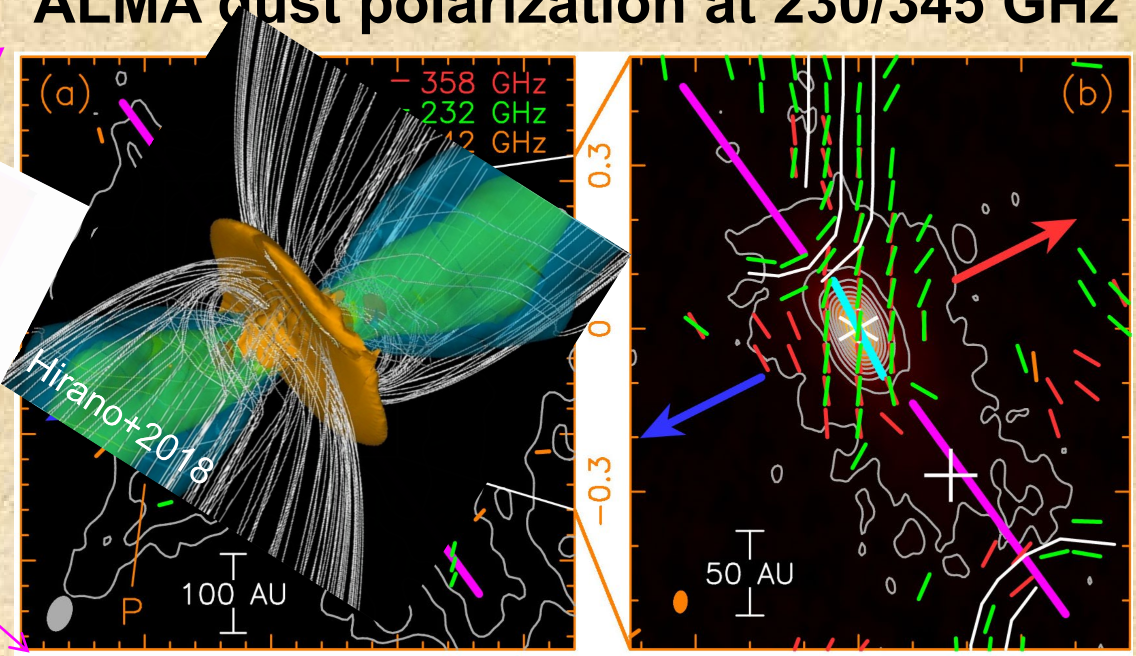


It seems that no loss of angular momentum from the core to the pseudo-disk at this early phase.



Matthews

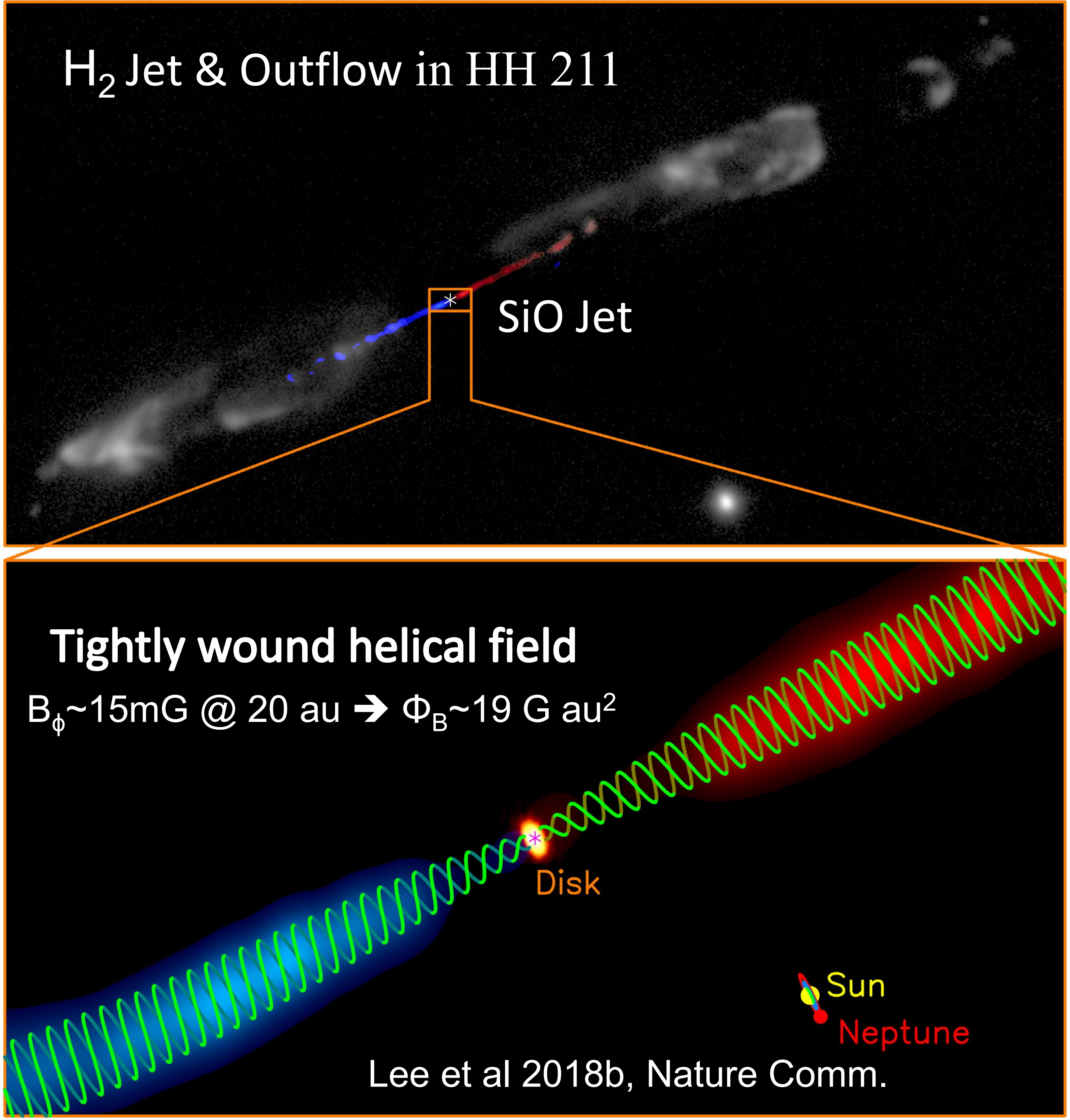
B-field in pseudodisk mapped by ALMA dust polarization at 230/345 GHz



Misalignment betw. B-axis and J-axis

1. Misalignment betw core & pseudodisk & disk
2. Field guided infall forming the 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 ➔ Φ_B ~ 245 G au^2 within 100 au

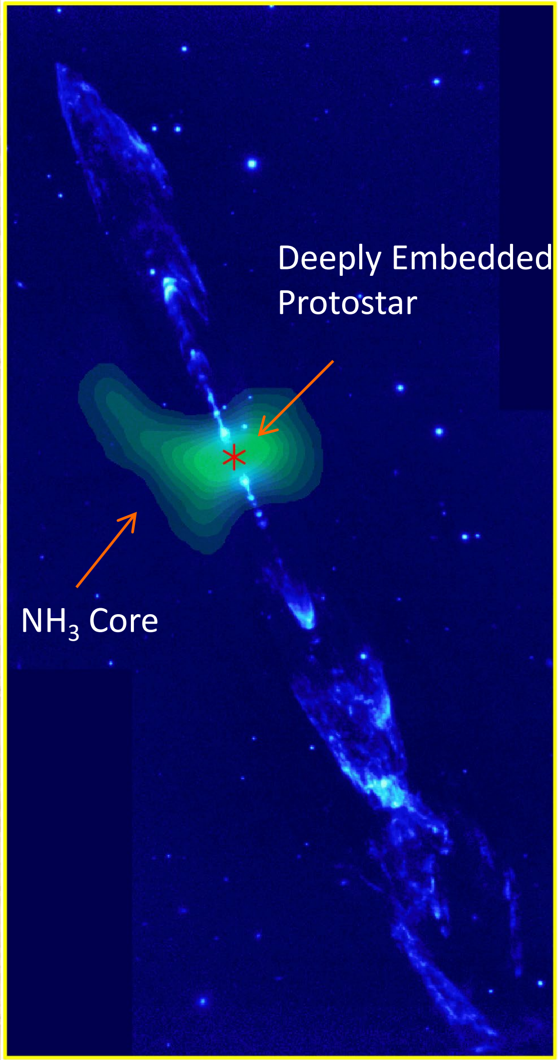
If magnetic flux is conserved, expected Φ_B ~ 450 G au^2 ➔ significant Φ_B still carried inward by infalling material ➔ Angular momentum and Φ_B problem needs to be further solved in the (near) disk scale.



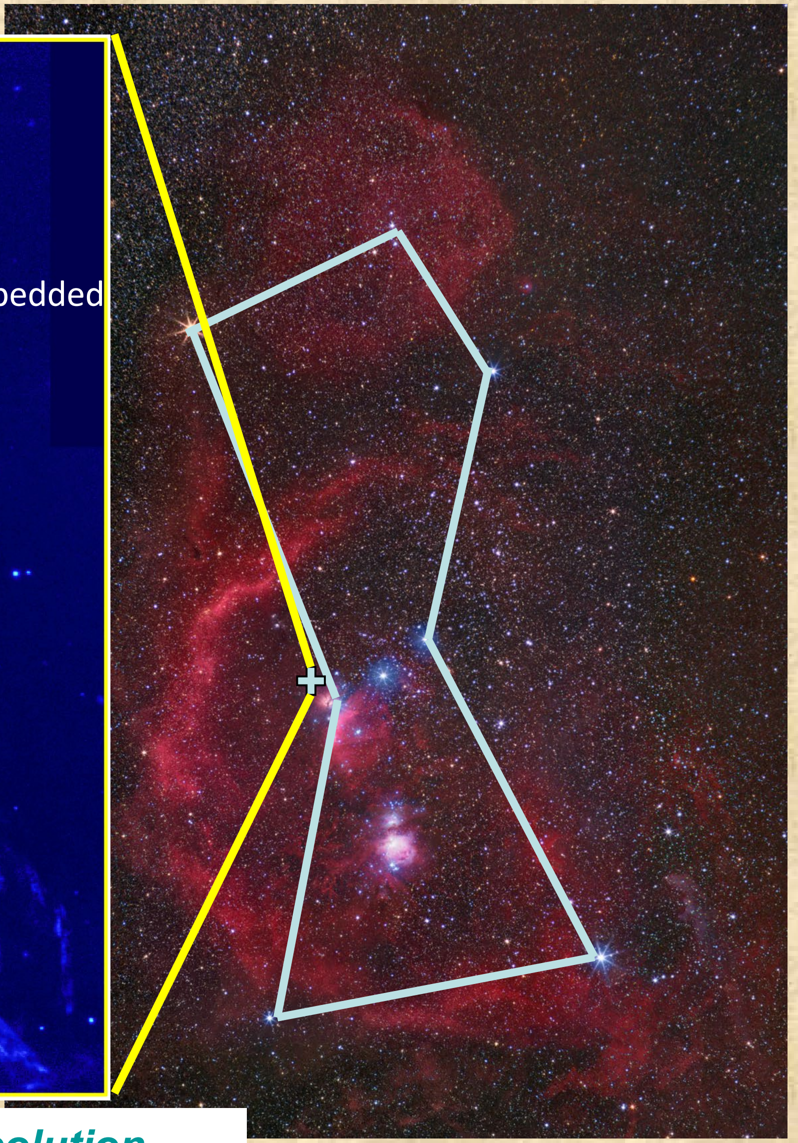
H_2 Jet & Outflow in HH 211
SiO Jet
Tightly wound helical field
B_ϕ~15mG @ 20 au ➔ Φ_B~19 G au^2
Disk
Sun
Neptune
Lee et al 2018b, Nature Comm.

Age ~ 5×10^4 yrs, $M_\star$ ~ 0.20 $M_\odot$

HH 212 H_2 Jet

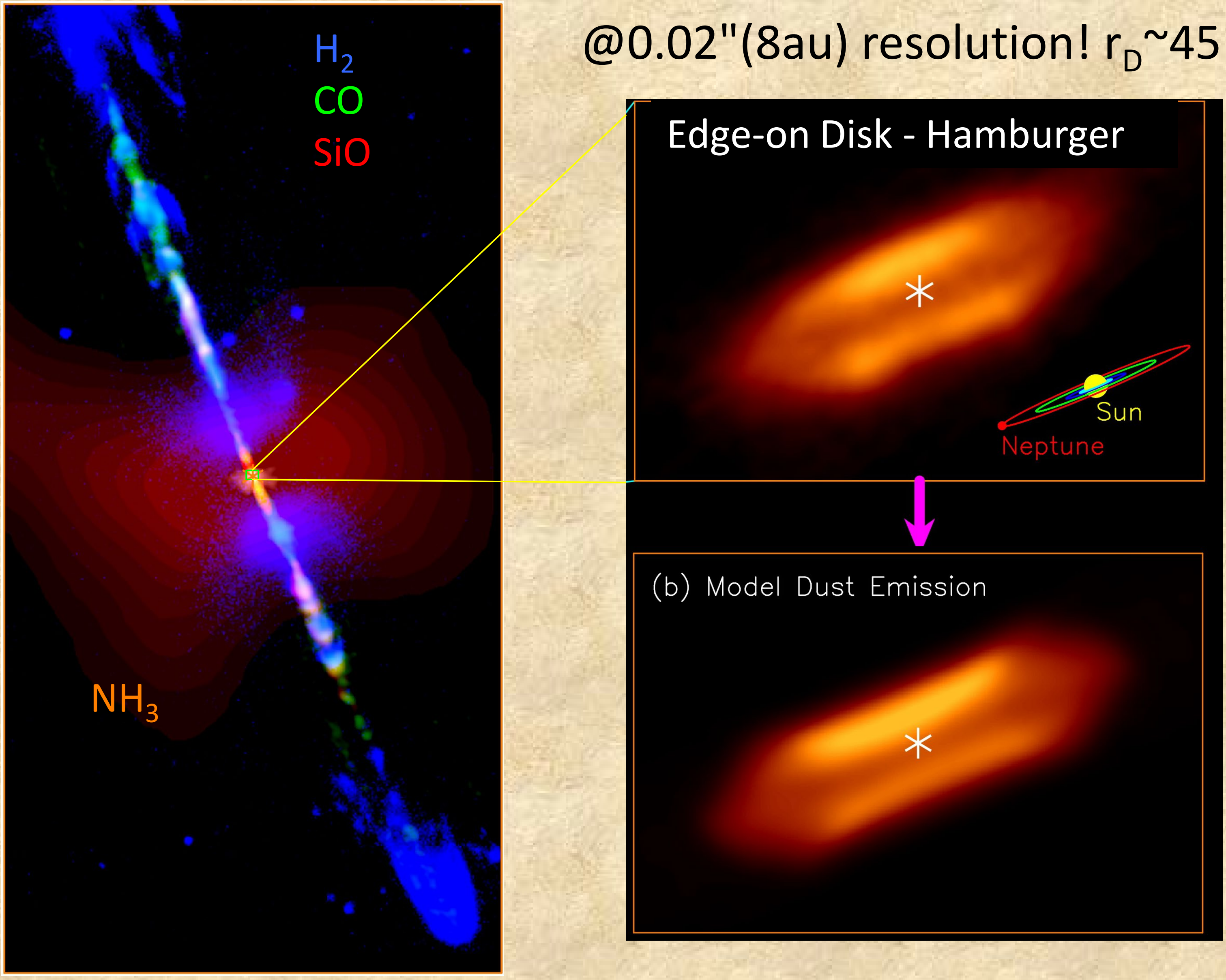


Orion



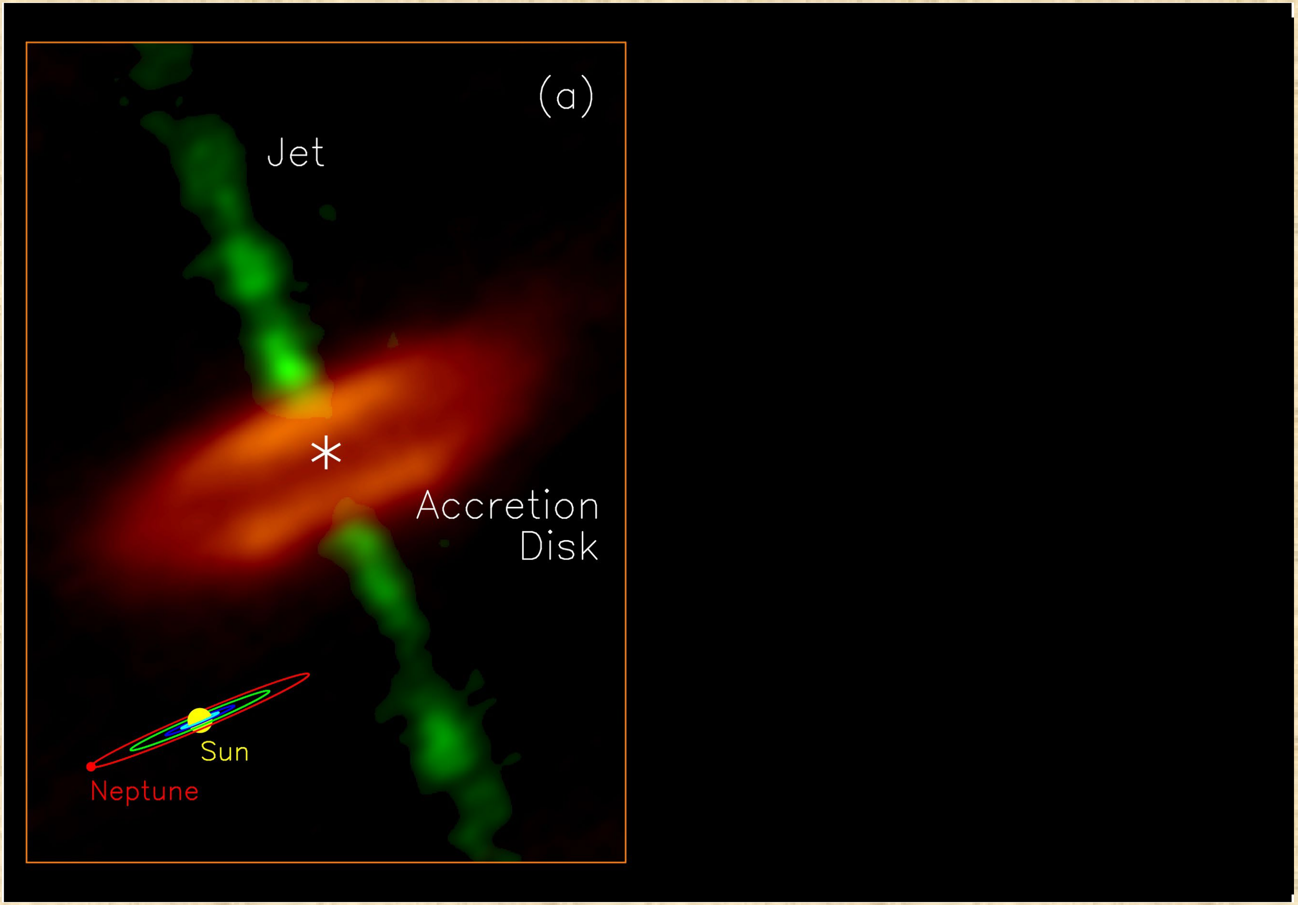
VLT image at 0.34" resolution
McCaughrean et al. 2002

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



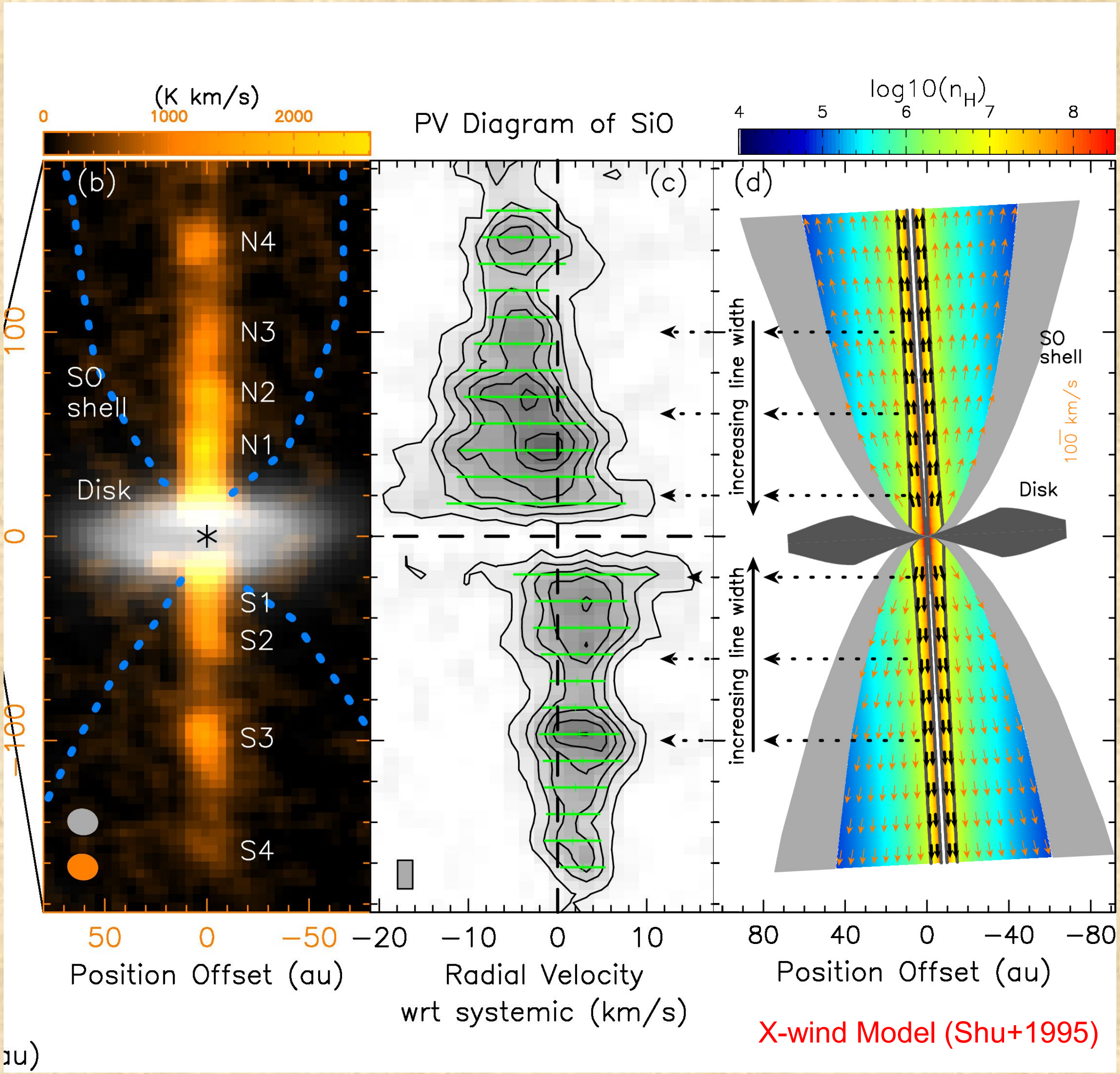
Lee et al. 2017a, Science Advances

Innermost SiO Jet within 100 au: Jet rotation

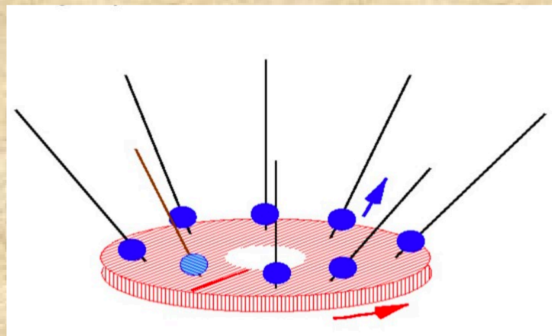


Jet rotates the same way as the disk, carrying L from the disk
Measured Specific Angular Momentum ≤ 10 au km/s! ➔Launching Radius ≤ 0.05 au as in X-wind (Lee+2017 Nature Astronomy)

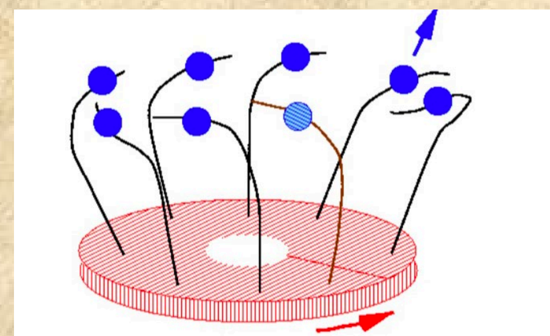
Innermost SiO Jet within 100 au: Radial Expansion



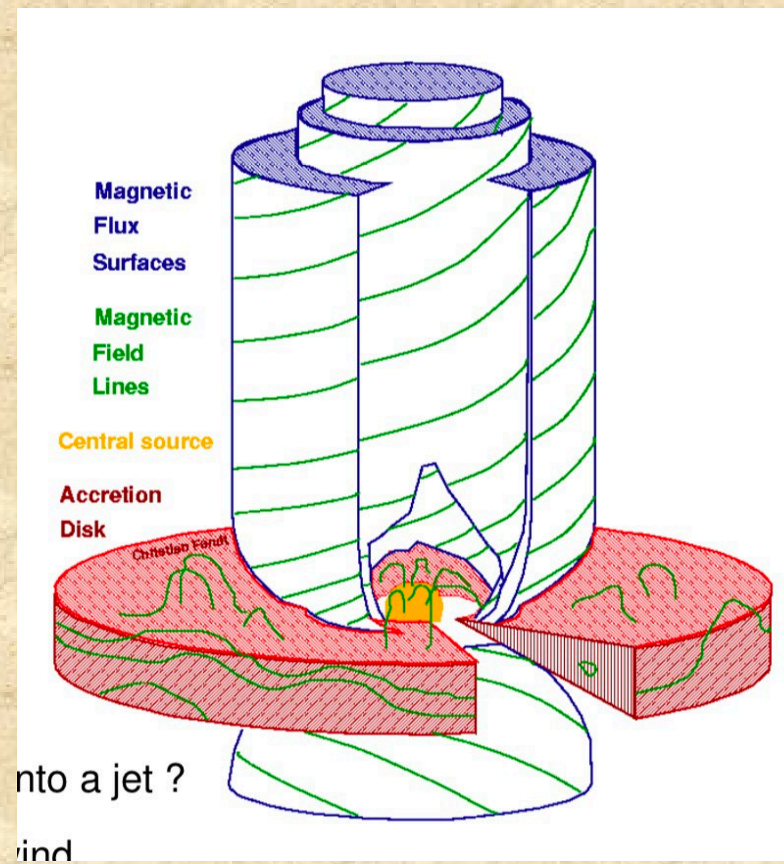
Ejection and Collimation Processes



Disk Material swung out by Magneto-Centrifugal force



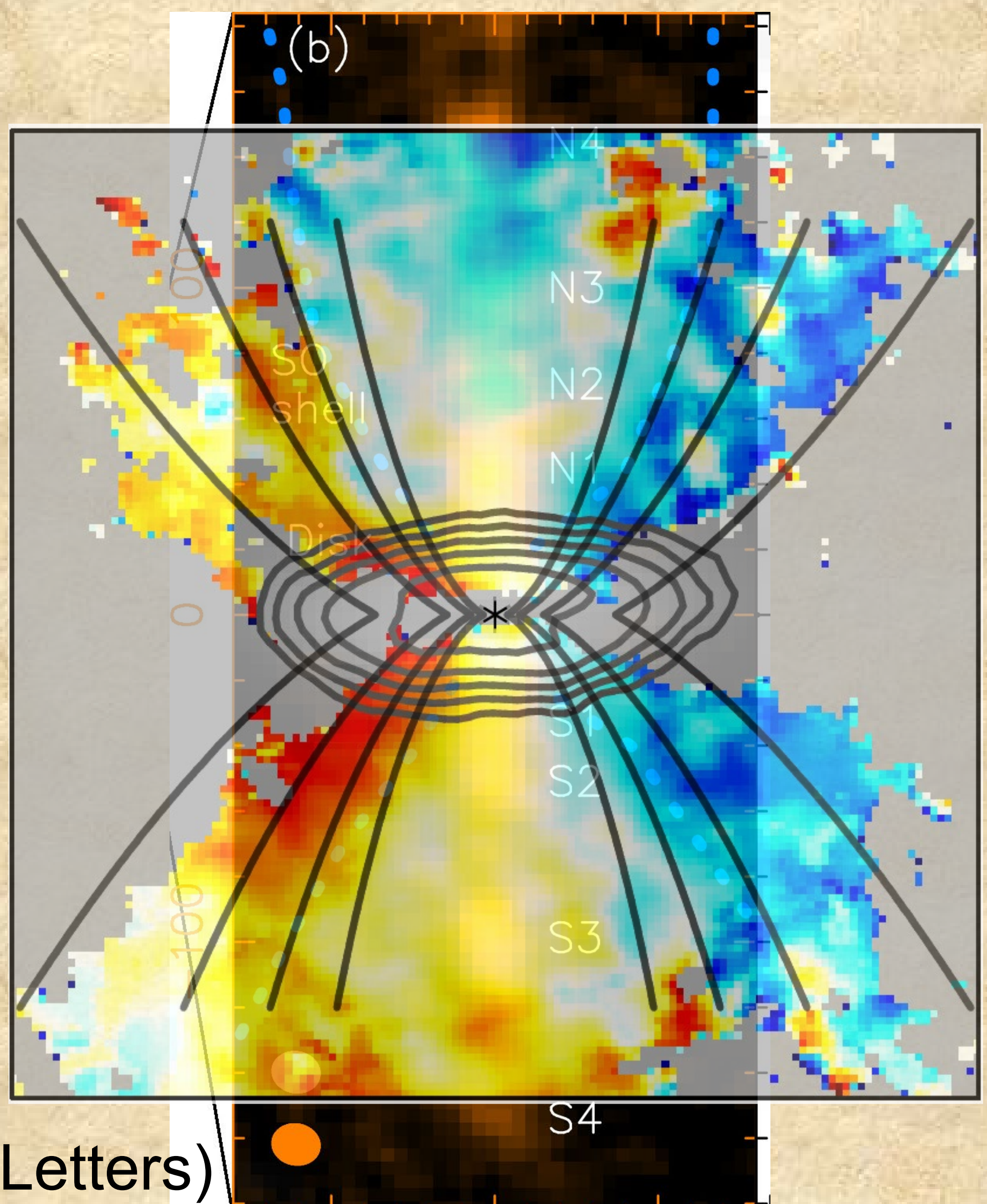
Poloidal field bent to toroidal field by the inertia of jet material



Jet material collimated by the toroida field (Lorentz force)

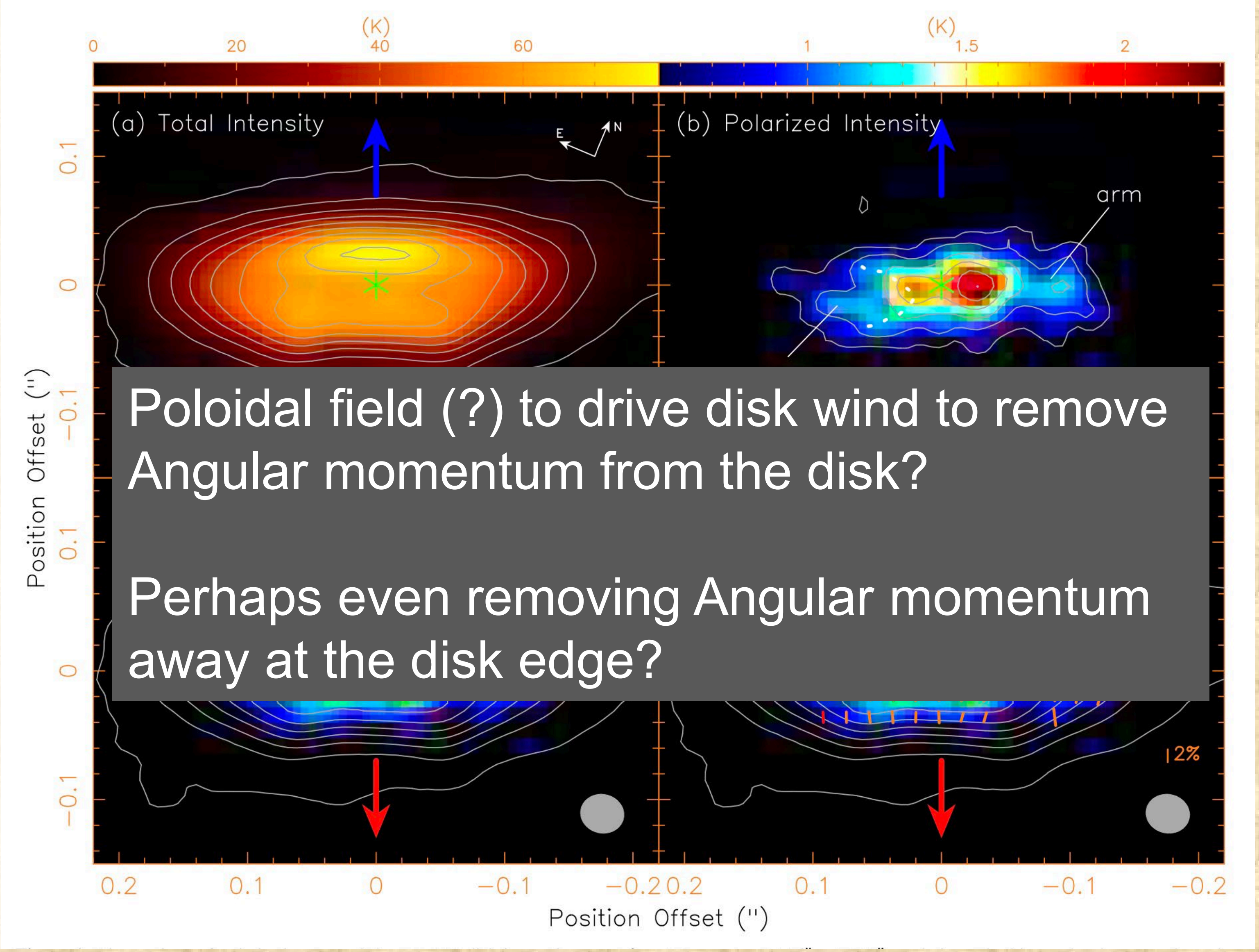
Adopted from C. Fendt

SO shells within 100 au: Magnetized Disk Wind



(Lee+2021, ApJ Letters)

350 GHz Dust Polarization Observations of the HH 212 Disk

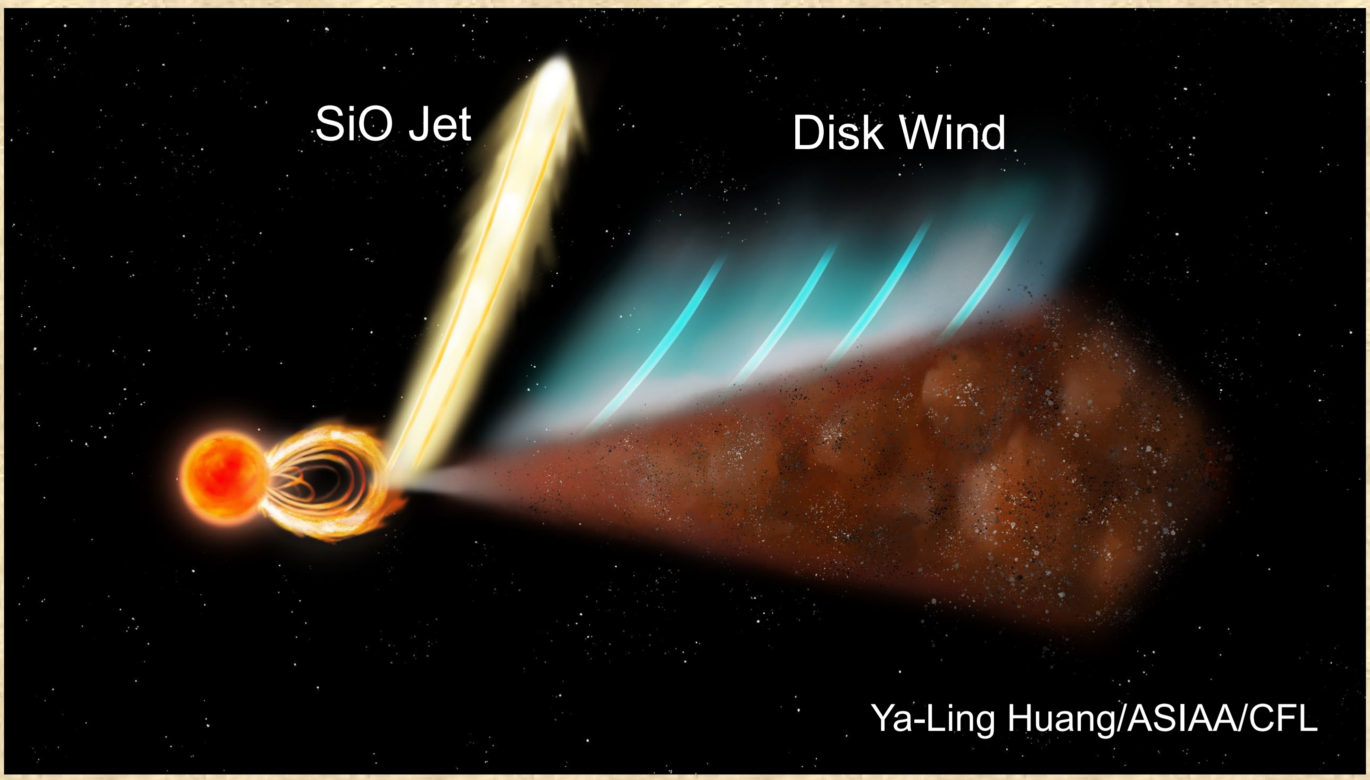


Poloidal field (?) to drive disk wind to remove Angular momentum from the disk?

Perhaps even removing Angular momentum away at the disk edge?

Lee+2021

Accretion and Ejection Processes



Disk is spinning @ Keplerian rotation, so do the field lines

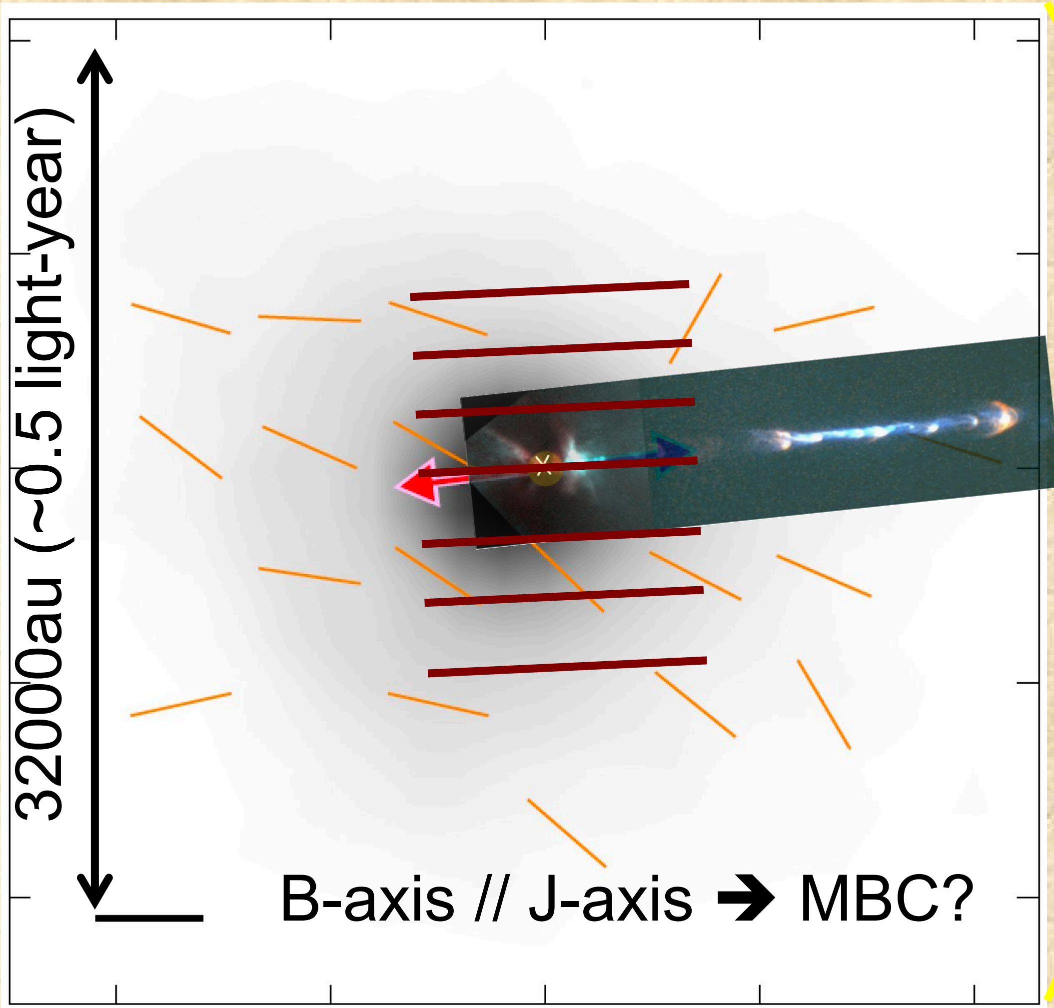
➔ disk materials are flung out along the field lines by magneto-centrifugal force with $v_w \sim \text{sqrt}(2J\text{-}3)v_\phi$ where J ~ 3-5

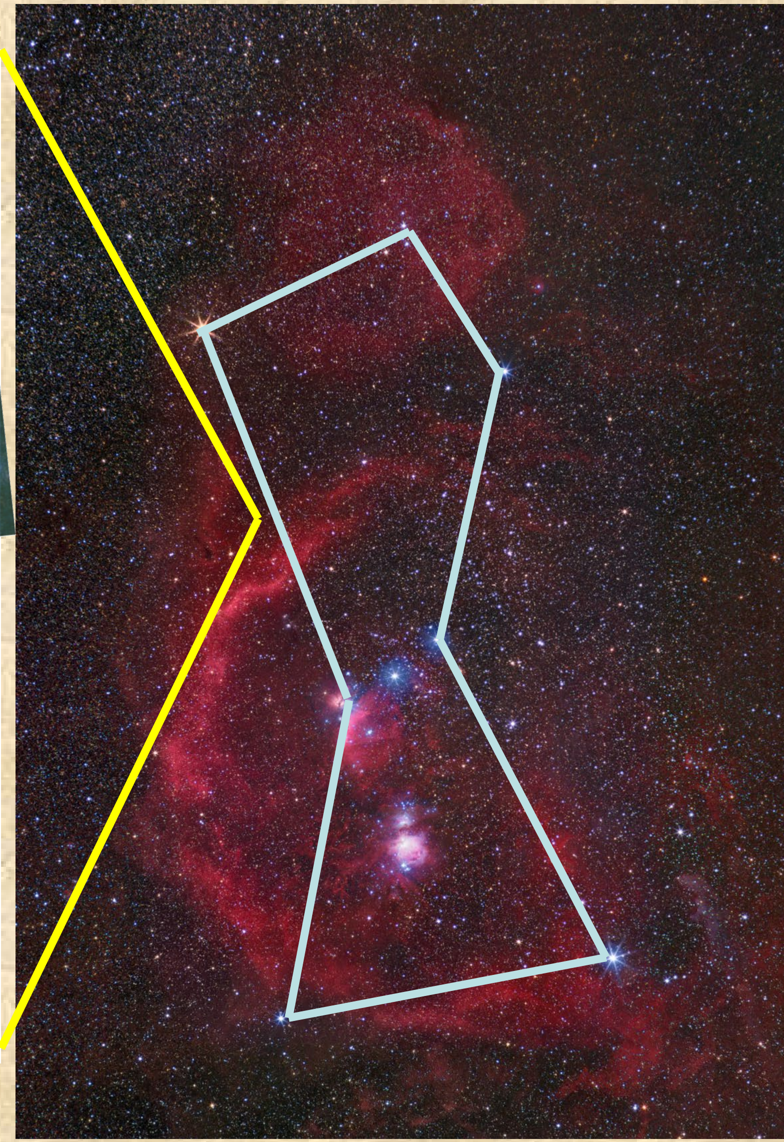
➔ Jet from dust-free zone, while disk wind from outer dusty zone

➔ Removing angular momentum and magnetic flux from the disk

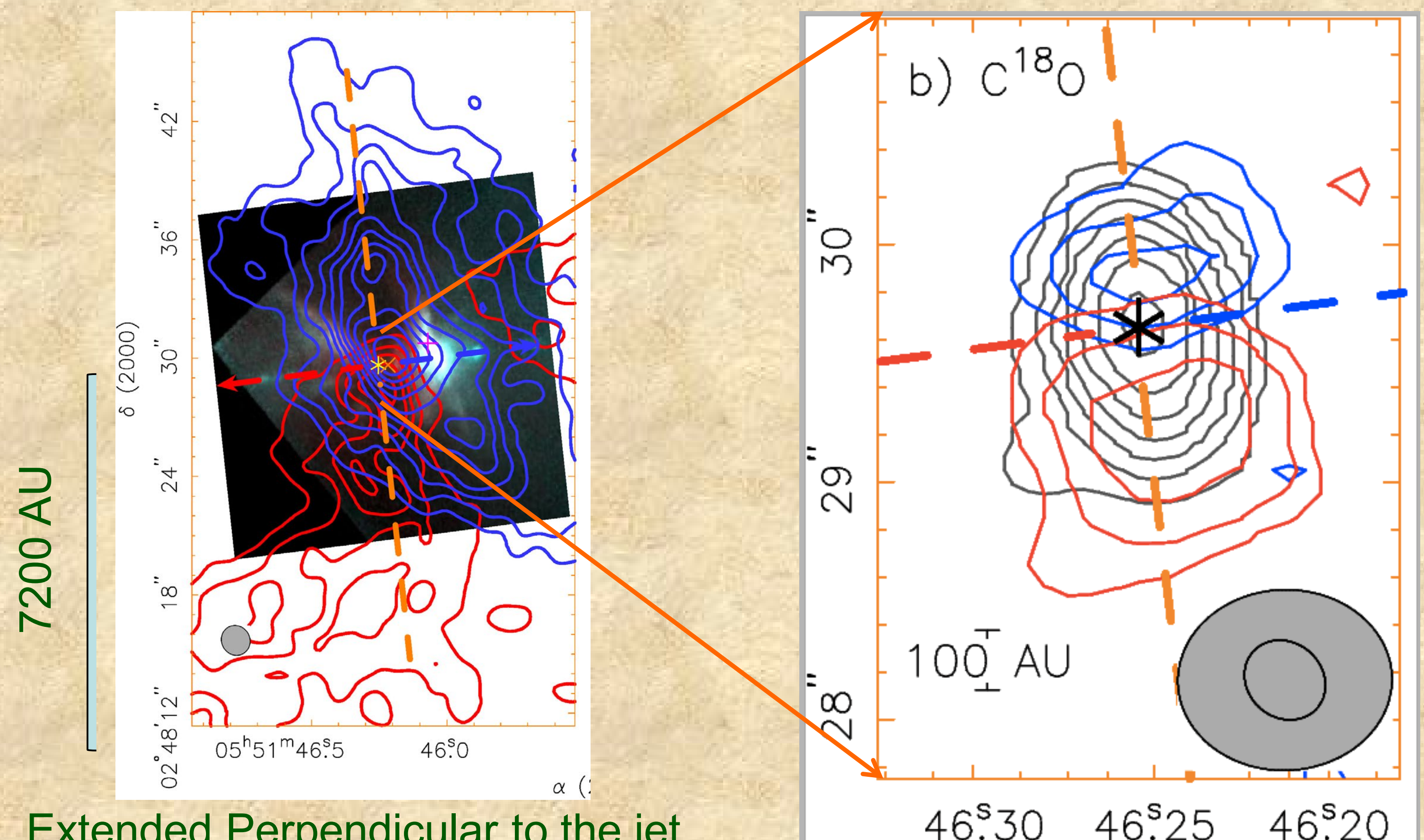
HH 111 @ 0.5 Myrs, $M_{\star} \sim 1.8\ M_{\odot}$

Orion Constellation





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



(1) Extended Perpendicular to the jet

(2) Rotating-collapsing inner Envelope

(3) Envelope Mass ~ 0.3 $M_\odot$

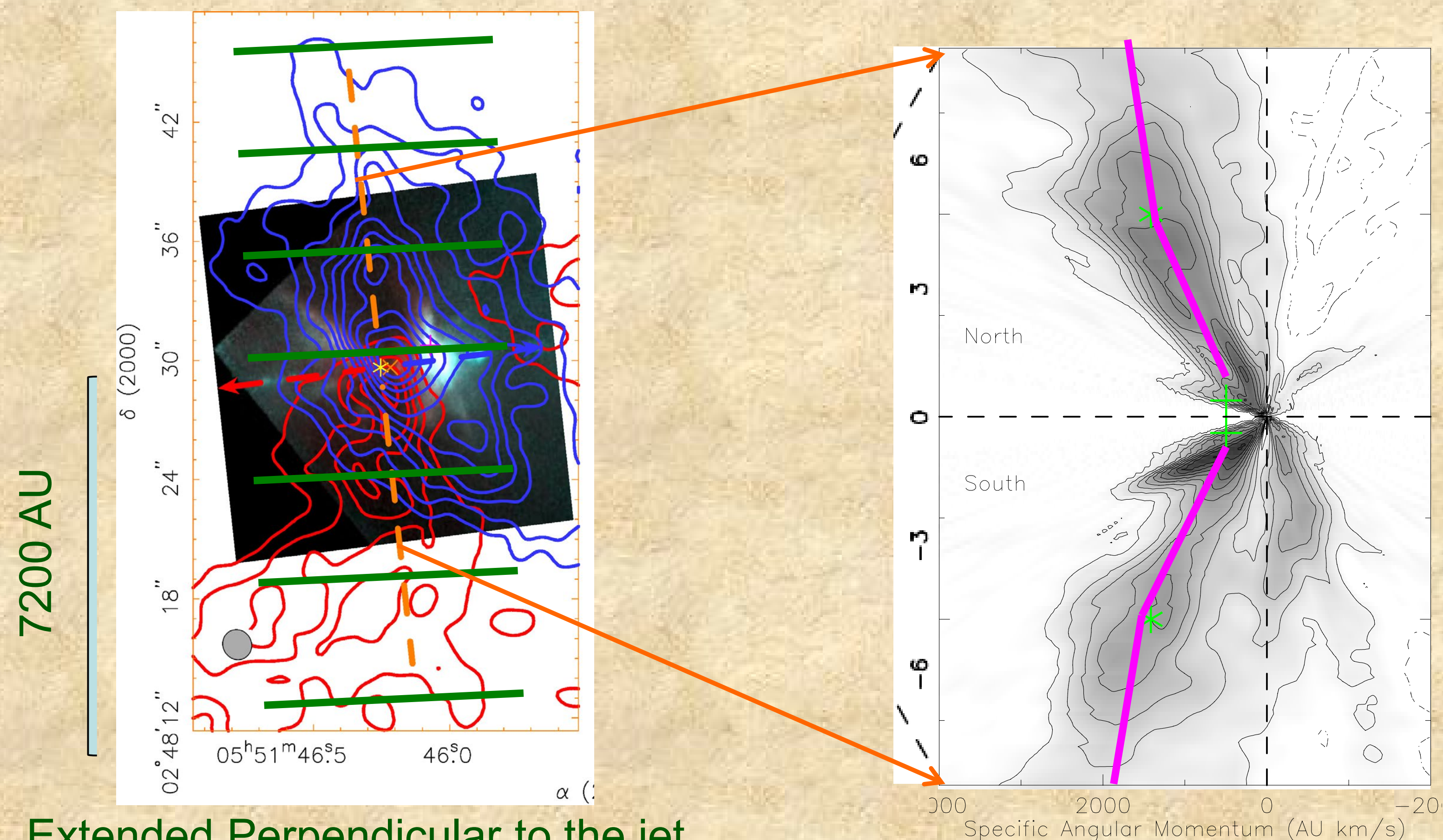
(4) Infall rate ~ 4.3e-6 $M_\odot$/yr

Keplerian rotating disk r_D ~ 200au!!

➔ $M_\star$ ~ 1.8 $M_\odot$

➔ 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 Envelope

(3) Envelope Mass ~ 0.3 $M_\odot$

(4) Infall rate ~ 4.3e-6 $M_\odot$/yr

Lost of angular momentum at 2000 AU (5") results in a small disk.

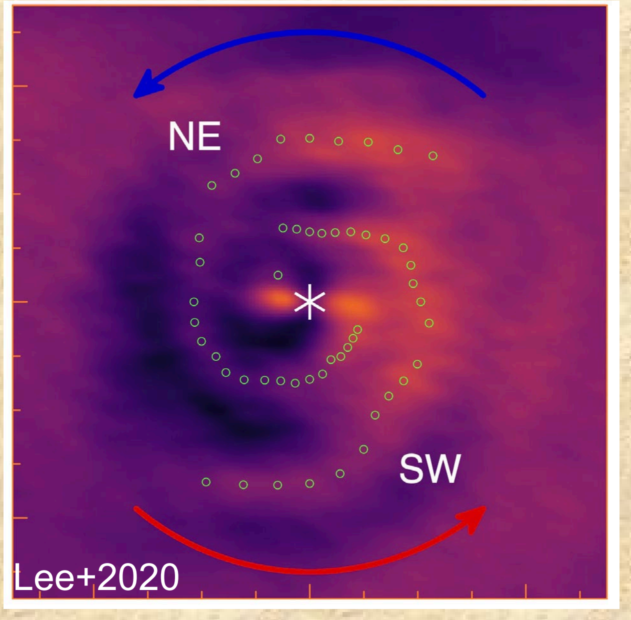
Magnetic Braking (MB) in late phase? (Lee 2010, 2016)

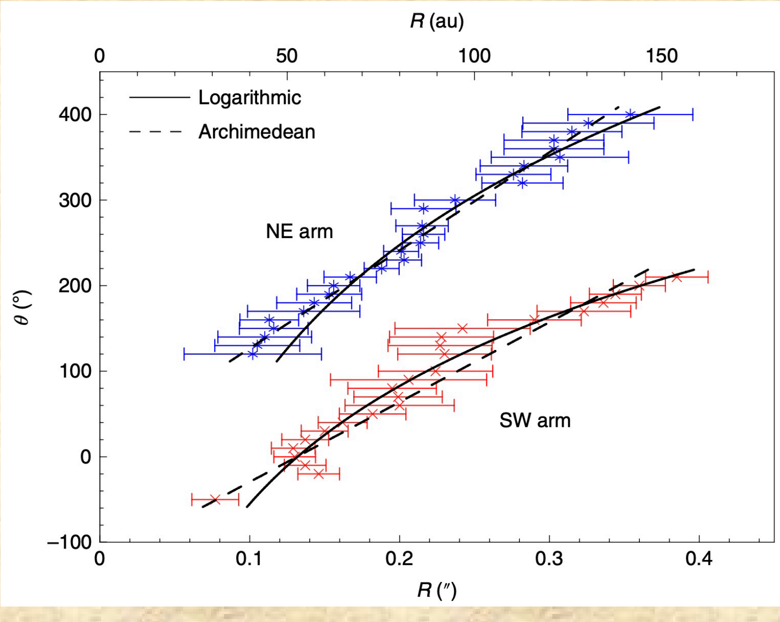
HH 111 @ 0.5 Myrs, $M_\star \sim 1.8\ M_\odot$

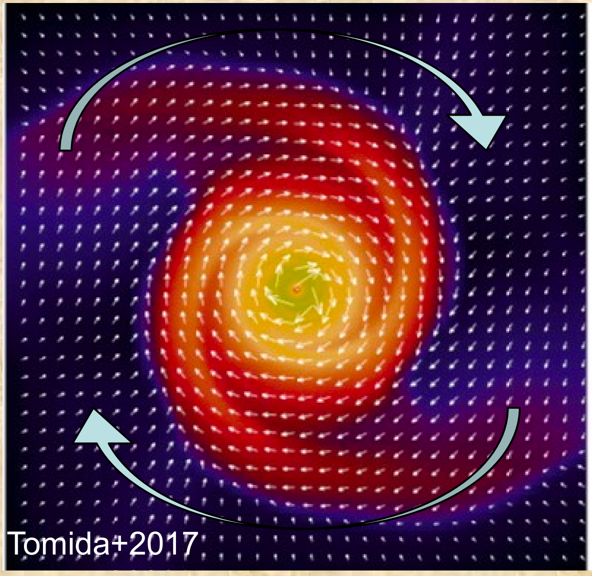
First spiral arms detected in active accretion phase because of ALMA unprecedented resolution!!!

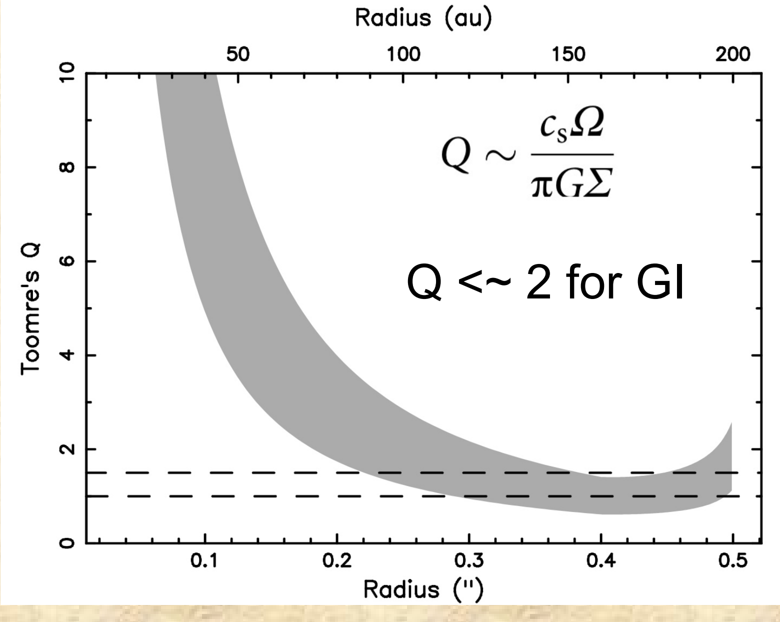
Lee et al. 2020, Nature Astronomy

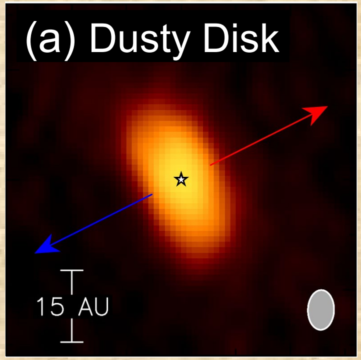
Trailing Spirals Triggered by Gravitational Instability (GI)



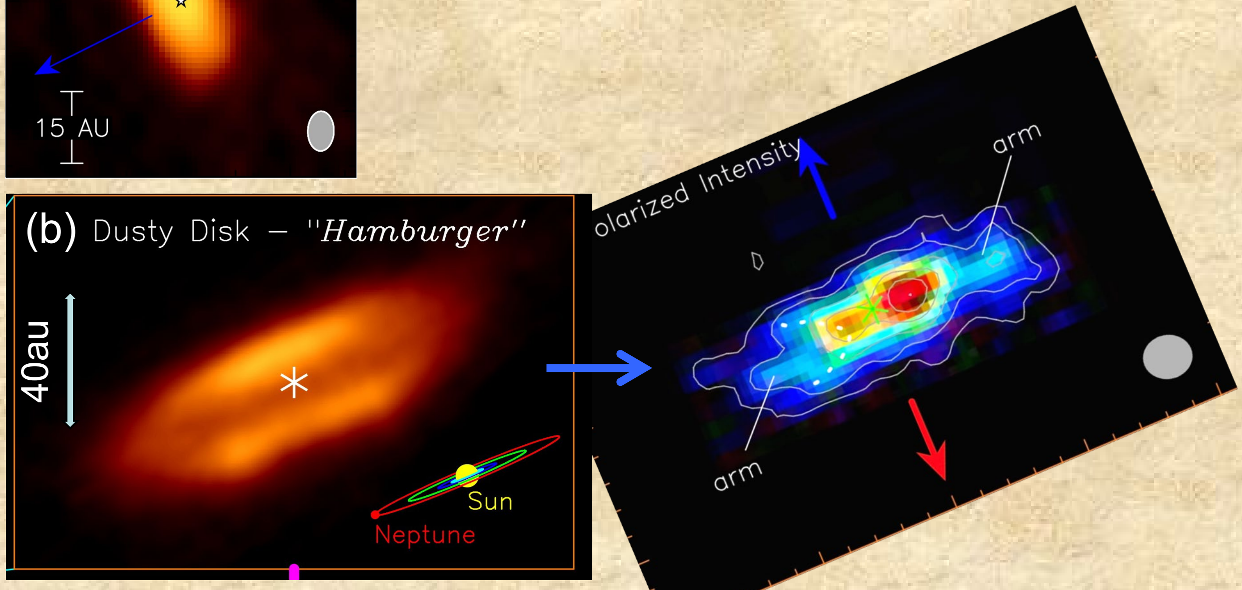




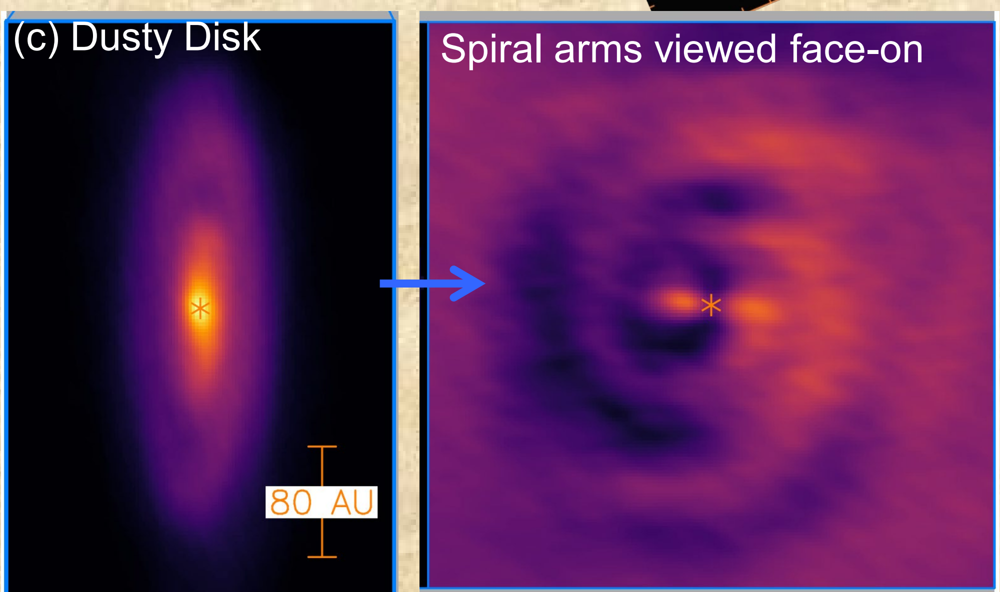




HH 211: Youngest disk detected, but unresolved in vertical direction.

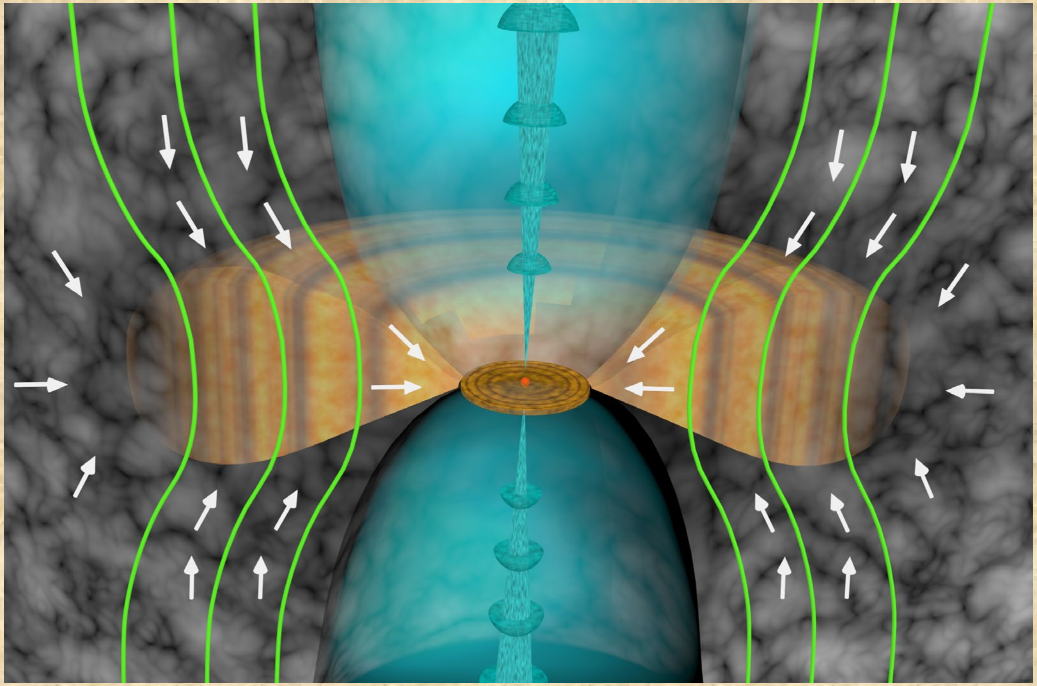


HH 212: First Dark Lane detected in submm, uveiling the vertical structure & spirals in midplane (?)



HH 111: First Spiral Arms detected in active accretion phase likely induced by Gravitational Instability

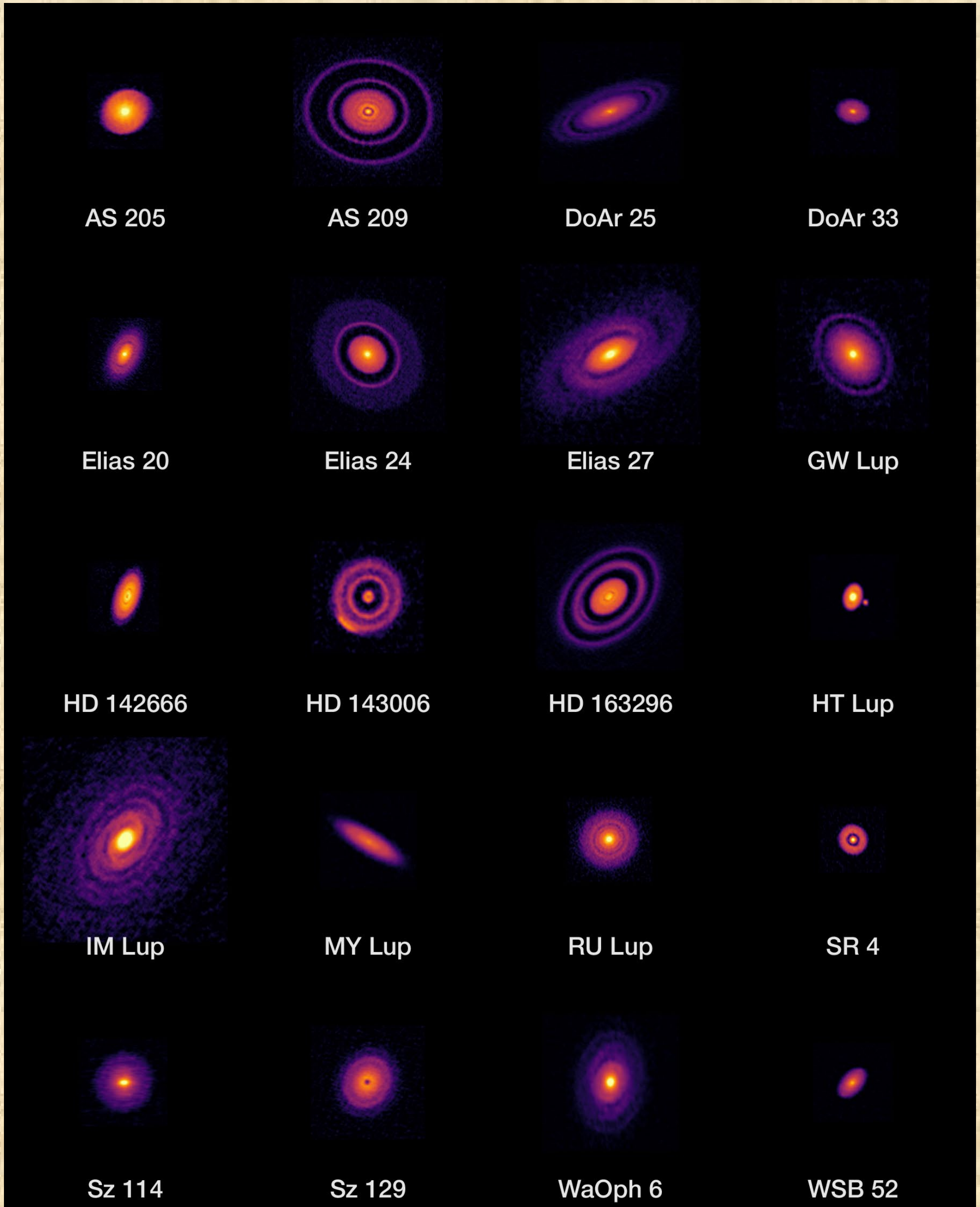
Formation Process of a Solar System like our own



1. Infall guided by magnetic field, forming flattened envelope
2. Keplerian disk formed (due to L) in flattened env. feeding protostar
3. MB is not as efficient if J-axis is misaligned with B-axis
4. Jet magnetized & rotating, launched from the innermost edge of disk.
5. GI ➔ spirals transporting L within the Keplerian disk & away (?) from it.
6. Magnetized Disk Wind carrying L & B away from the disk?

Disk & Jet in the Early Phase of Star Formation

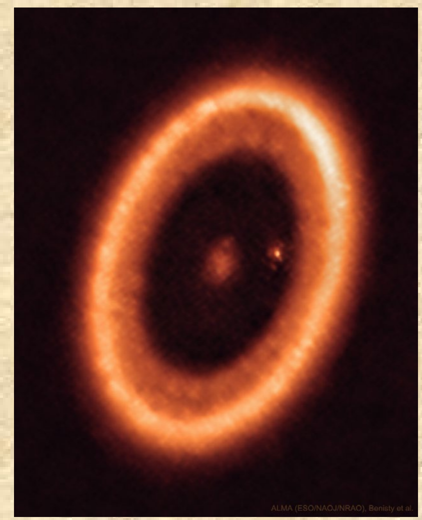
Protoplanetary Disks



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

PLANET FORMATION

PDS 70



ALMA (ESO/NAOJ/NRAO); M. Benisty et al.