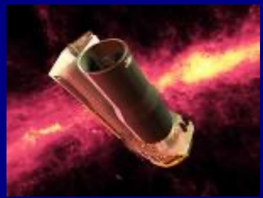
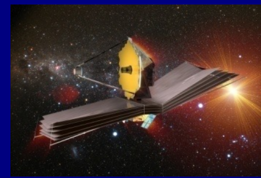
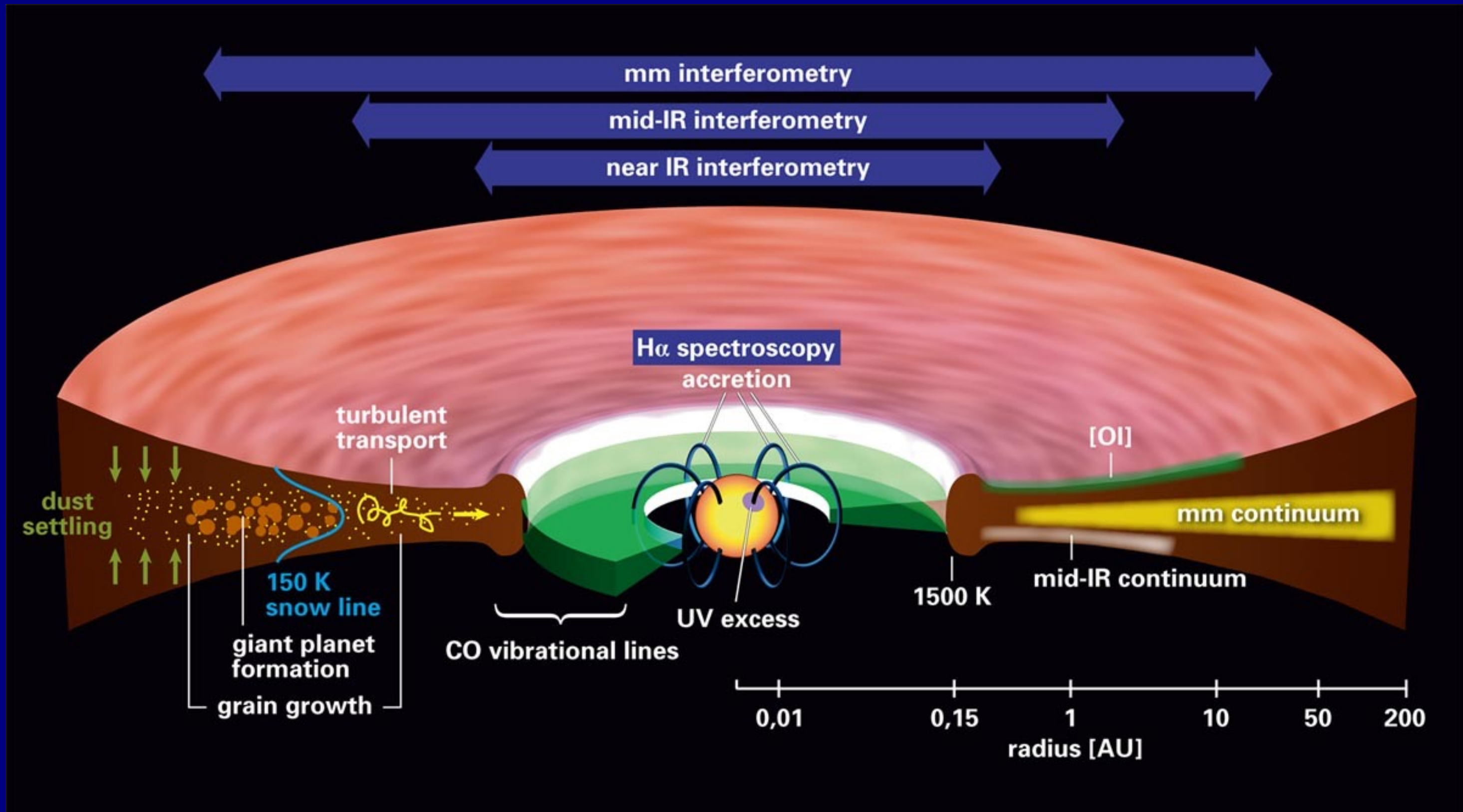


Protoplanetary Gas Disks II



Small Structures – Low Mass – Low line/continuum ratio



Summary – Last Lecture

- Matter falling from $\theta = \pi/2$ (angle from rotation axis) falls to maximum „centrifgual" radius: $R_c = \Omega^2 r_0^4/G M \sim t^3$ (Inside-out collapse solution – Shu)

- Dust opacity – function of frequency: $\kappa(\nu) \sim \nu^\beta$; $\tau(\nu)$ has same functional dependence

  Near-IR wavelengths - disk is optically thick: νS_ν provides information about $T(r)$

  Millimetre wavelengths - disk is optically thin: νS_ν provides information about $\kappa(\nu)$

- Remember (isothermal): Optically thick - $S_\nu = B_\nu(\nu, T)$ (Flux given by Planck function)
  Optically thin - $S_\nu = \tau(\nu) B_\nu(\nu, T)$ (Flux also given by mass)

- In the near-IR: Observation of scattered light (polarized) from µm-sized grains (adaptive optics)
- In the submm/mm: Thermal dust emission from millimetre-sized grains (pebbles)

- CO observations: Keplerian velocity profiles and temperature distributions

- JWST – molecular emission from the inner disks (water, …)

Protoplanetary Gas Disks II – Accretion Disks

No solid body rotation, but a shear flow → Viscous forces. This has two consequences:

(1) Mass transport inward, angular momentum transport outward

Solar system: Sun has 99% of mass, but less than 2% of the angular momentum

(2) Heating of the (very inner) disk

Die Rotation kosmischer Gasmassen

Von Carl Friedrich von Weizsäcker

Aus dem Max-Planck-Institut für Physik, Göttingen

(Z. Naturforschg. 3a, 524—539 [1948]; eingegangen am 7. Juli 1948)

Original idea: C.F. von Weizsäcker (1944, 1948)
Solution of angular momentum problem related to formation of solar system
1948: *Rotation kosmischer Gasmassen*

General solution of equations by R. Lüst on the occasion of the 50th birthday of W. Heisenberg

Rediscovery: Cataclysmic variables (Lynden Bell & Pringle 1974)
Quasars (Lynden-Bell 1969)

For a thin accretion disk the equations of mass conservation and angular momentum result in a diffusion equation for the surface density Σ.

$\delta\Sigma/\delta t = 3/R\ \delta/\delta R\ [R^{1/2}\ \delta/\delta R\ (\nu\ \Sigma\ R^{1/2})\ ]$ – Basic equation for viscous disk evolution

Ansatz for viscosity $\nu = \alpha\ c_s\ H$ (Shakura & Sunyaev 1973, for black holes)

What is the reason for the viscosity:

a) Molecular viscosity – much too small
b) α represents viscosity of a turbulent flow (α-disk models)

But what is the origin of „turbulence“ in the flow (no hydrodynamical instability revealed in isothermal disk with Keplerian flow)

Possible solution: Fully ionized medium → magnetic field acts on fluid → magneto-rotational instability (MRI) - Balbus & Hawley (1981)

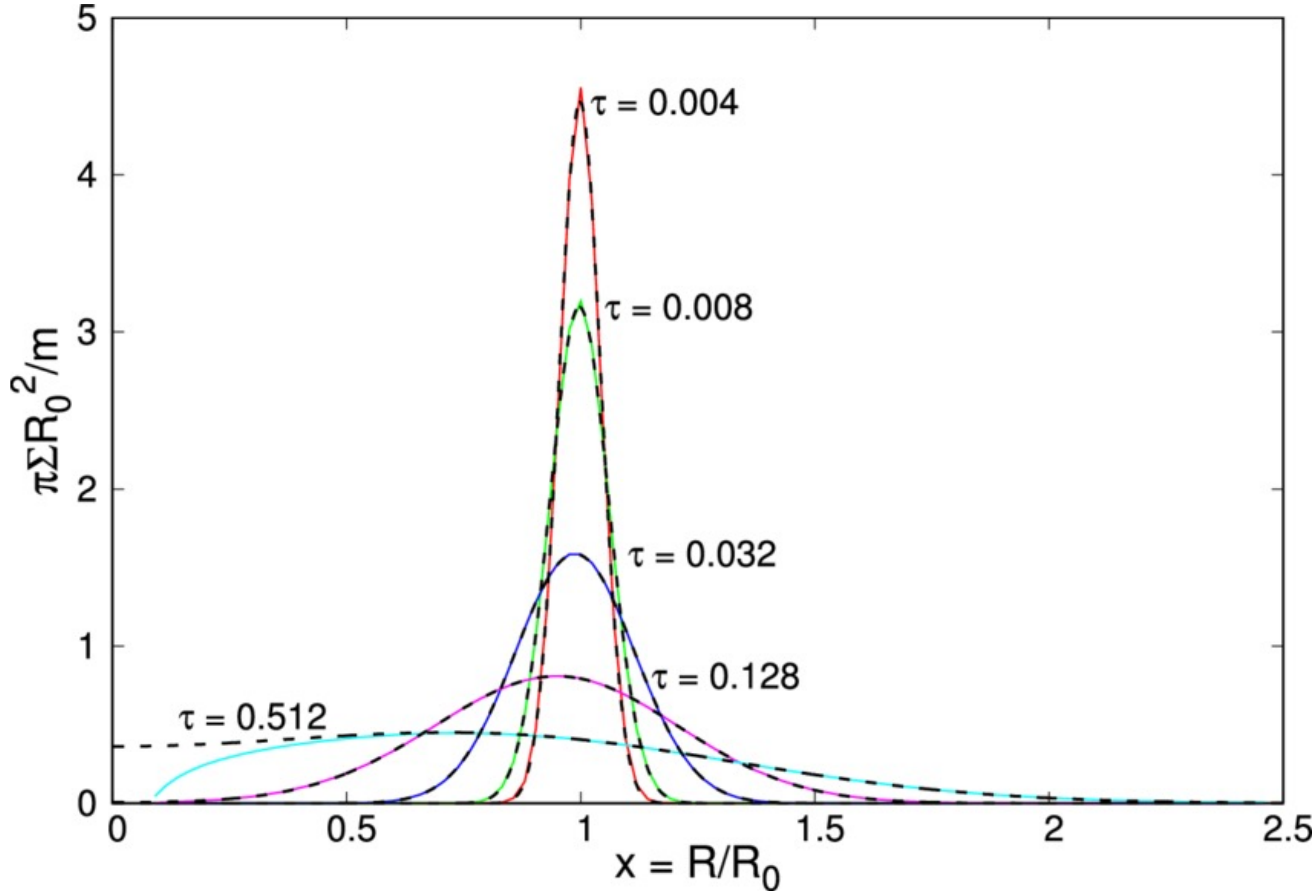
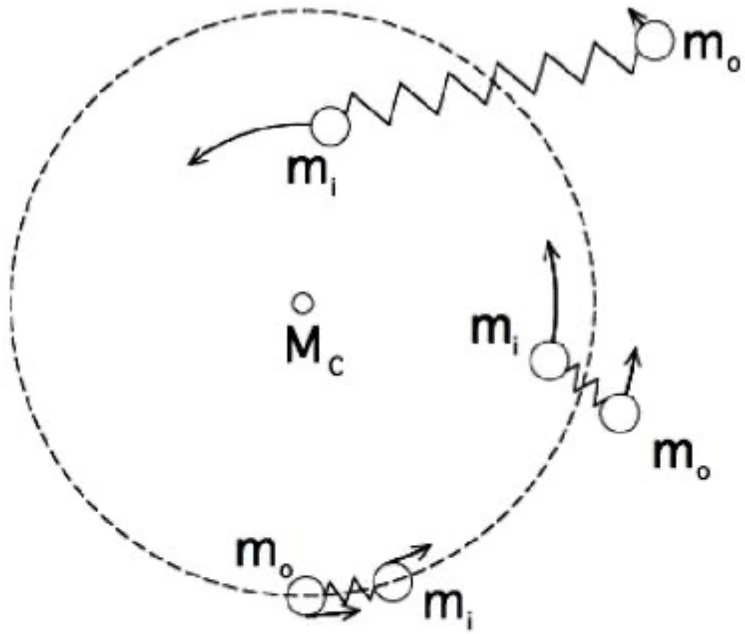


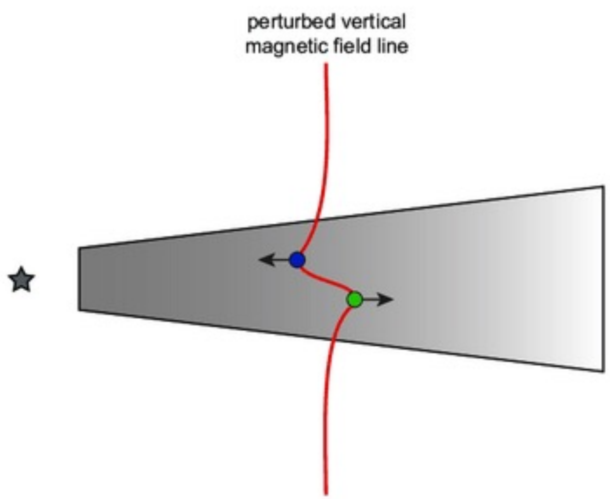
Figure from Pringle

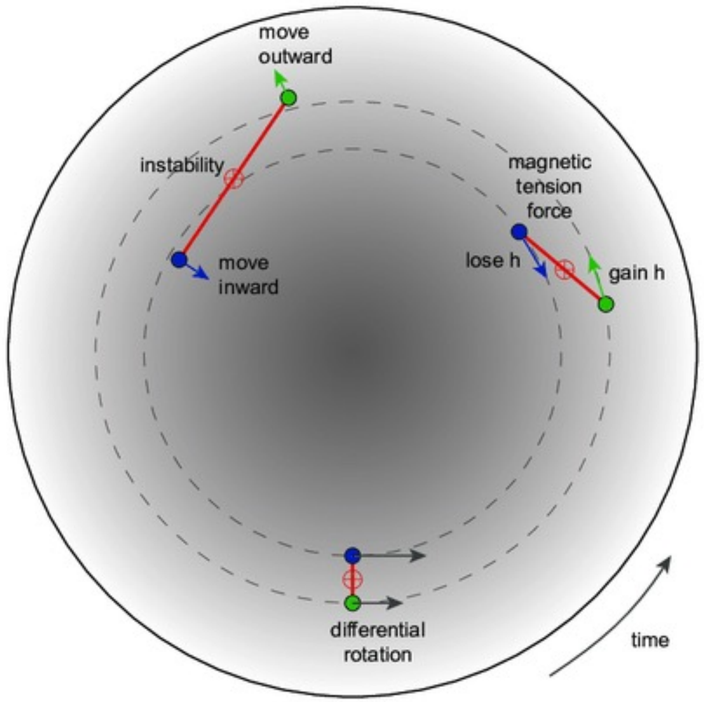


Magnetic fields bind fluid elements as they would be connected by a spring

Inner element orbits faster than outer element, but angular momentum of lower orbit is smaller than that of higher orbit → „Spring“ → Will pull back on m_i and drag m_o forward;
m_i loses angular momentum → gets faster
m_o gains angular momentum → gets slower

Remember: It is the magnetic field!





In ideal MHD simulations: α between 10^{-3} and 10^{-4}

However, limited ionization degree and non-ideal MHD effects
(Hall effect, ambipolar diffusion, Ohmic dissipation)

Non-ideal MHD effects

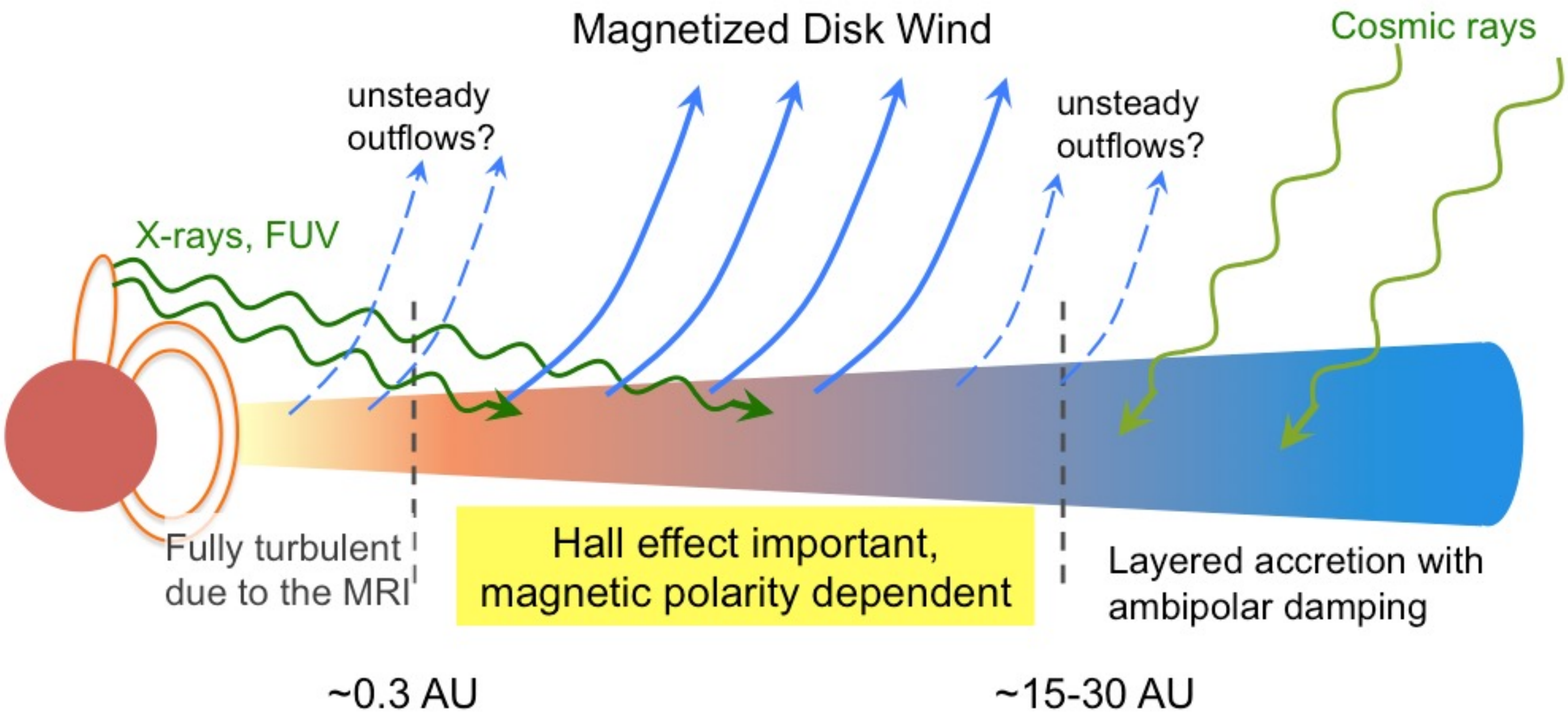
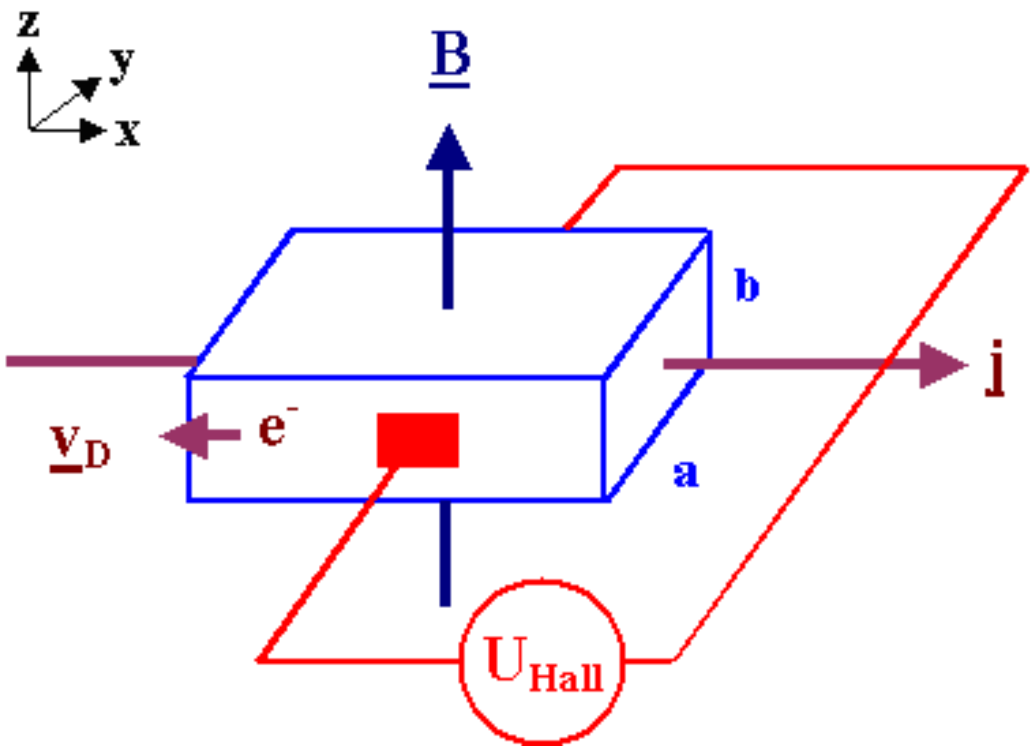
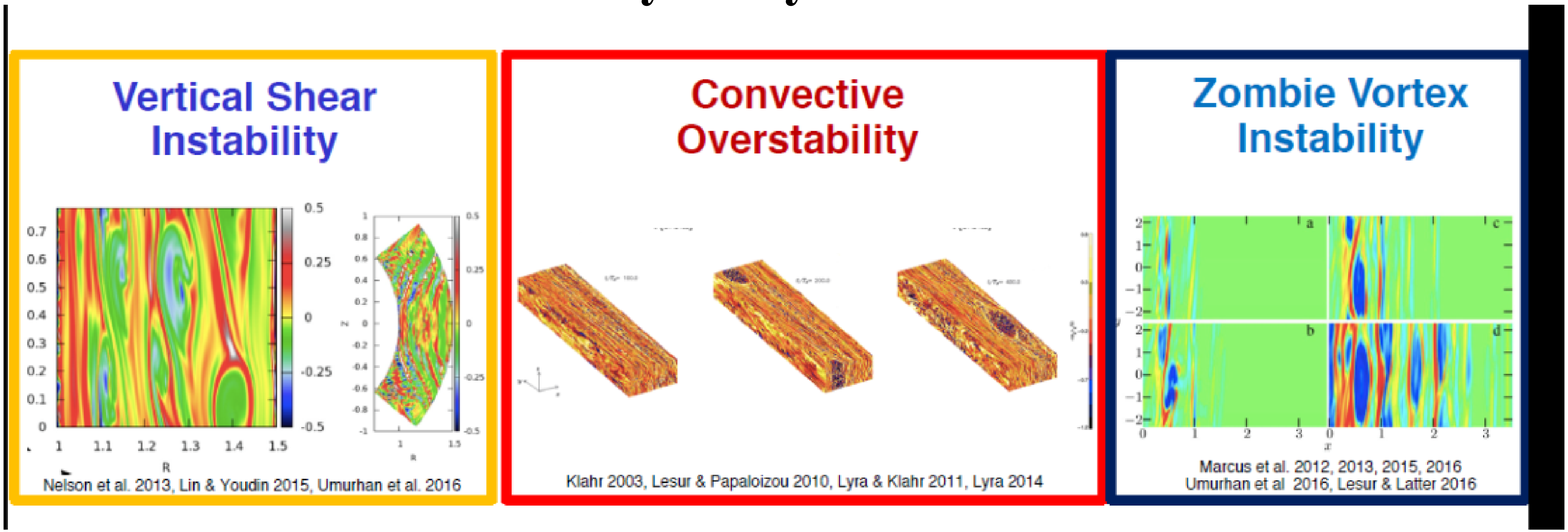


Figure from Bai

Remember: Hall Effect



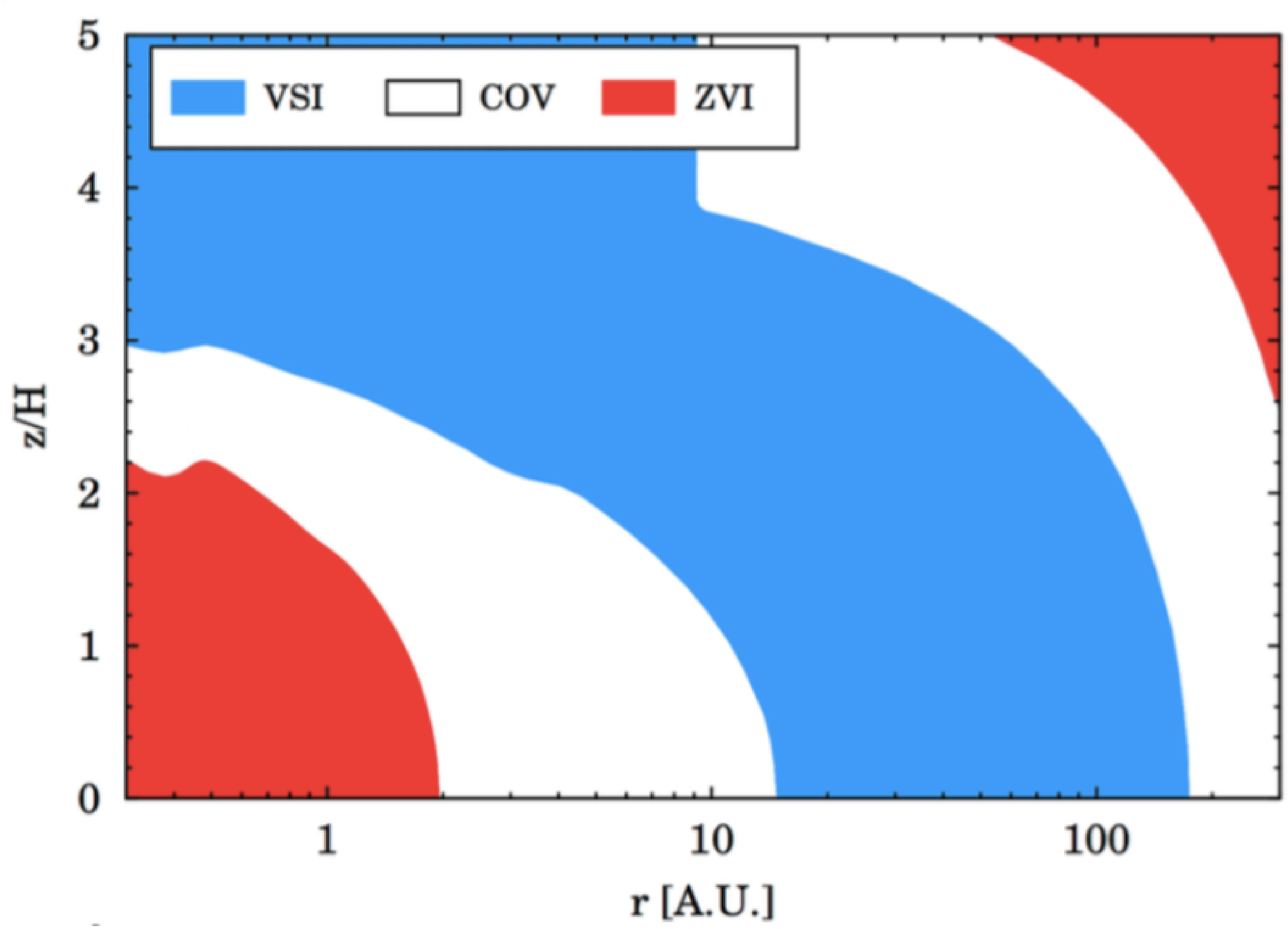
Thermal – Hydrodynamical Instabilities



Compilation from W. Lyra

- Convective overstability (Radial entropy gradient, finite cooling time)
- Zombie vortex instability (Cascade of baroclinic critical layers)
- Vertical shear instability (Vertical shear motion)

  α is mostly below 10^{-3}



Malygin 2016

Alternative: Outflows and Disk winds; Gravitational instability in massive disks (spirals)

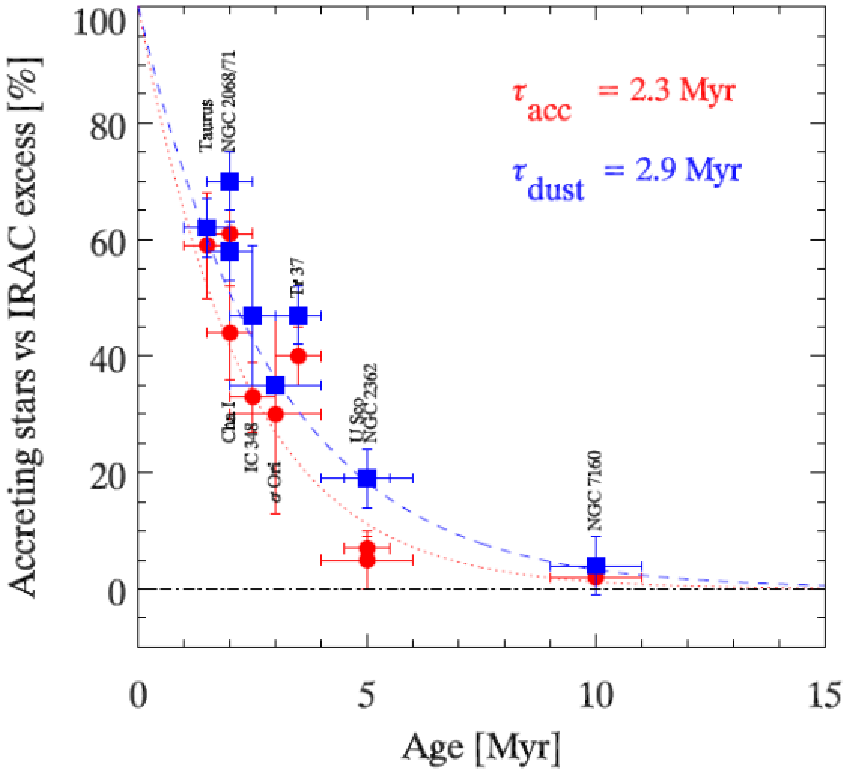
Steady-state geometrically thin accretion disk

- Pressure of gas not important → motion in disk plane
- $dM/dt = 2\pi R \Sigma (-v_R) = \text{const.}$

Some simple considerations:

(1) Centrifugal force = Gravitational force (momentum equation)
Cylindrical polar coordinates (R, φ, z)
Central point mass M_{star} should dominated (disk masses much smaller)
$v_\varphi^2/R = G M_{star}/R^2 \rightarrow \omega = (G M_{star}/R^3)^{1/2}$
Keplerian disk: $d\omega/dR \neq 0$ (shear flow)

(2) Number of accreting objects decays wih time; this is very similar to dust evolution

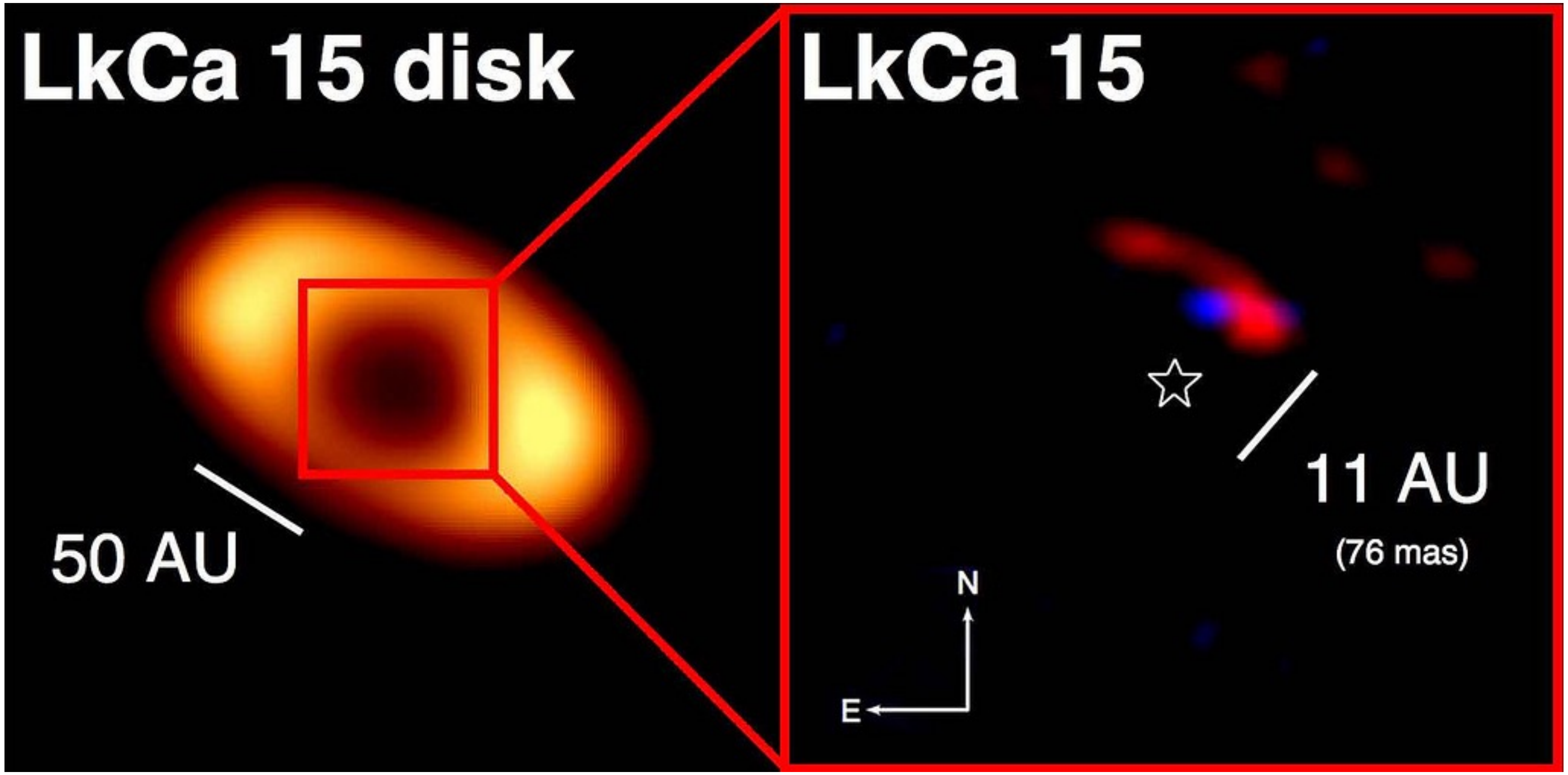


Time dependence of accretion rate and infrared access (Fedele et al. 2009)

(3) $dM/dt \sim M_{star}^2$ (difficult to understand from accretion theory)

(4) Special disk: „Transition“ disks – large inner gaps
(Stellar/planetary companions, photoevaporation, opacity gaps)

Example for a Transition Disk



Adam Kraus und Michael Ireland, von NASA Blueshift bei flickr eingestellt unter Creative Commons, Attribution 2.0 Generic (CC BY 2.0)

Left: λ = 850 µm (Andrews et al. 2011), Right: λ=2.1 µm (blue; K‘ band), 3.7 µm (red, L band)

Energy considerations lead to temperature distribution:

Energy dissipated from potential energy when mass M flows through Δ R:

$dE/dt \sim dM/dt \;\; G\, M_{star}/2\, R \;\; \Delta R/R$

In the thin disk approximation: Energy will be emitted locally through the disk suface

$dE/dt \sim 4\, \pi\, R\, \Delta R\, \sigma\, T_{eff}^4$ (Area: $\pi\, R^2$; diff.: $2\pi\, R\, \Delta R$, to 2 sides → factor 2)

(optically thick case of a geometrically thin disk)

$T_{eff}^4 \sim G\, M_{star}\, dM/dt\, R^{-3}$ → $T_{eff} \sim R^{-3/4}$

(Note: Passively heated flat disk $T \sim R^{-3/4}$; if $L_{star} > G\, M_{star}\, dM/dt/R_{star}$; $T_{dust} \sim R^{-1/2}$)

Complete calculation (selection of inner boundary conditions)
(Pringle, J.: 1981, ARAA, 19, 137)

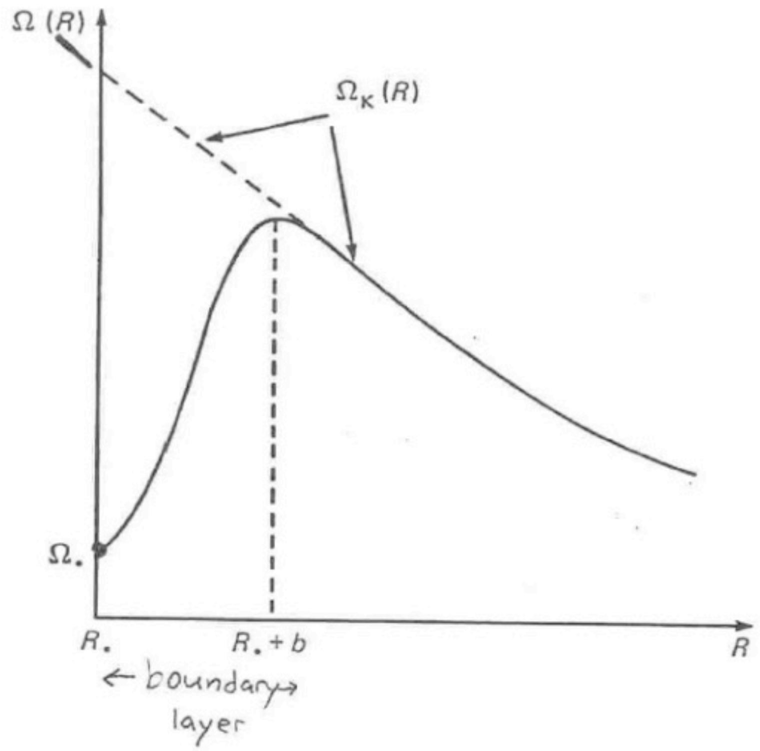
$T_{eff}^4 = 3\ G\ M_{star}\ dM/dt\ /8\ \pi\ \sigma\ R^3\ [1 - (R_{star}/R)^{1/2}]$ with R_{star} inner boundary of the disk

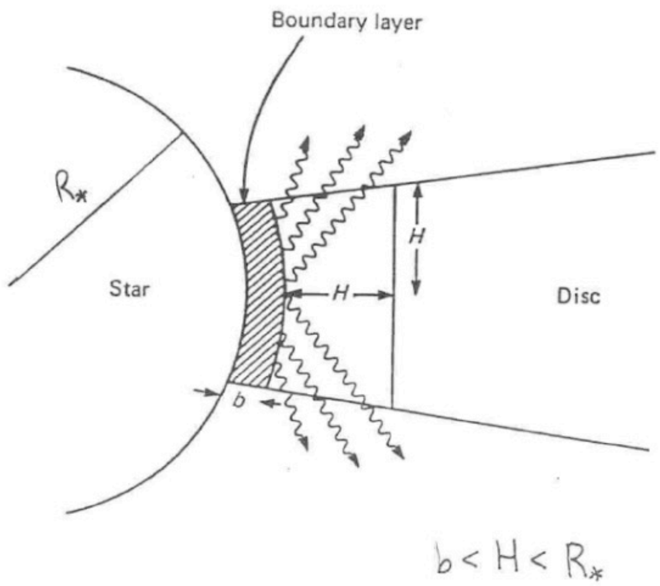
Full luminosity of the disk

$L_{disk} = \int_{Rstar}^{\infty} \sigma\ T_{eff}^4\ 4\pi\ R\ dR = G\ M_{star}\ dM/dt\ /2\ R_{star}$

- Only half of the potential energy will be emitted from disks
- Disk is only half of the story; the same amount of energy will come from the boundary layer where the disk material comes to rest

Energy will be emitted in thin hot boundary layer (much hotter than disk)
T ~ 7.000 to 10.000 K → UV radiation

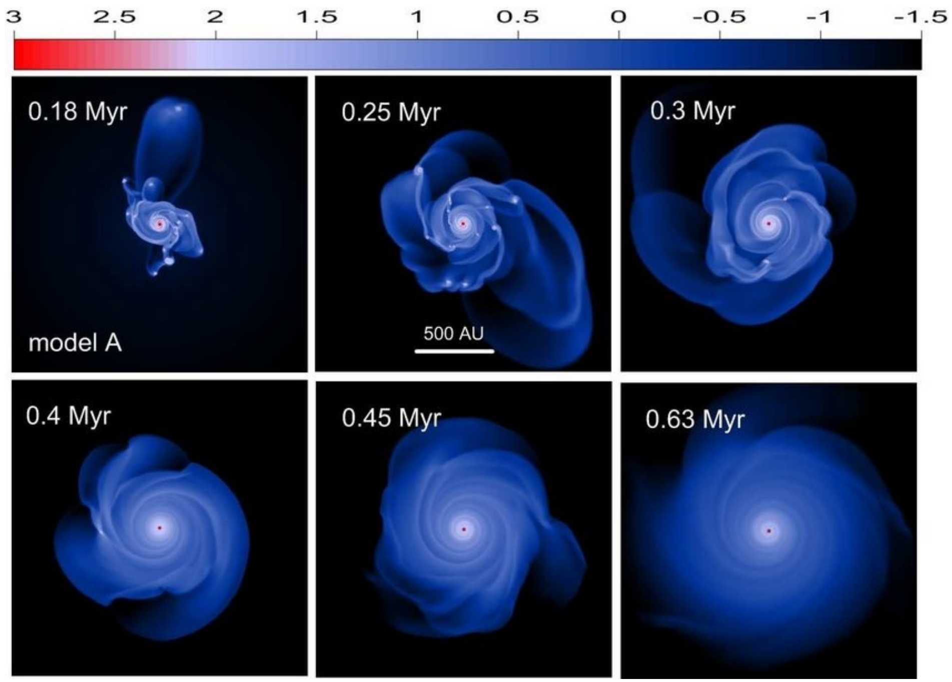




How to trace the gas in the inner disk regions?

- In „dusty“ part → H_2 emission would only trace surface layer
- NIR and MIR lines of vibrationally excited CO trace gas < 1000 K

Disks around massive young stellar objects



Vorobyov & Pavlyuchenkov (2017)

- Radiation pressure problem during formation of massive stars → Disks should be an important ingredient of circumstellar environments of massive YSO
- Observational challenges

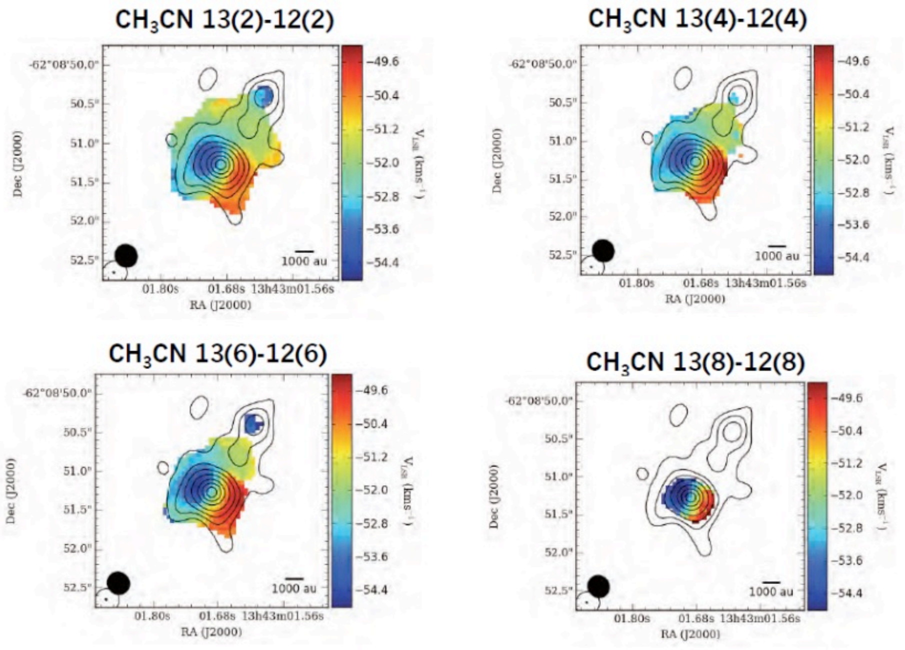
a) Still deeply embedded, on averag large distances, clustered environment → Confusion
b) (Sub)millimeter or IR interferometry important to distentangle the spatial confusion
c) Right spectral line tracers difficult to identify; Discrimination between envelope and disk emission

Disks around massive young stellar objects

- Often large rotation structures (tori) detected in molecular line tracers
- Disks around B-type stars clearly identified (AFGL 490, IRAS 20126+4104)
- Best example for disks around massive star is AFGL 4176 ($L = 10^5\ L_{sun}$)

CH_3CN J=13-12 K-line (indication of Keplerian velocity)

1.2mm dust continuum emission: Mass ~ 8 M_{sun})



Contours: continuum

Resolution: 0.30 x 0.28" or 1260 x 1180 AU

K. Johnston)