Gravitational Instabilities in Protoplanetary Disks

Speaker:
Wenhua(Wendy) Ju
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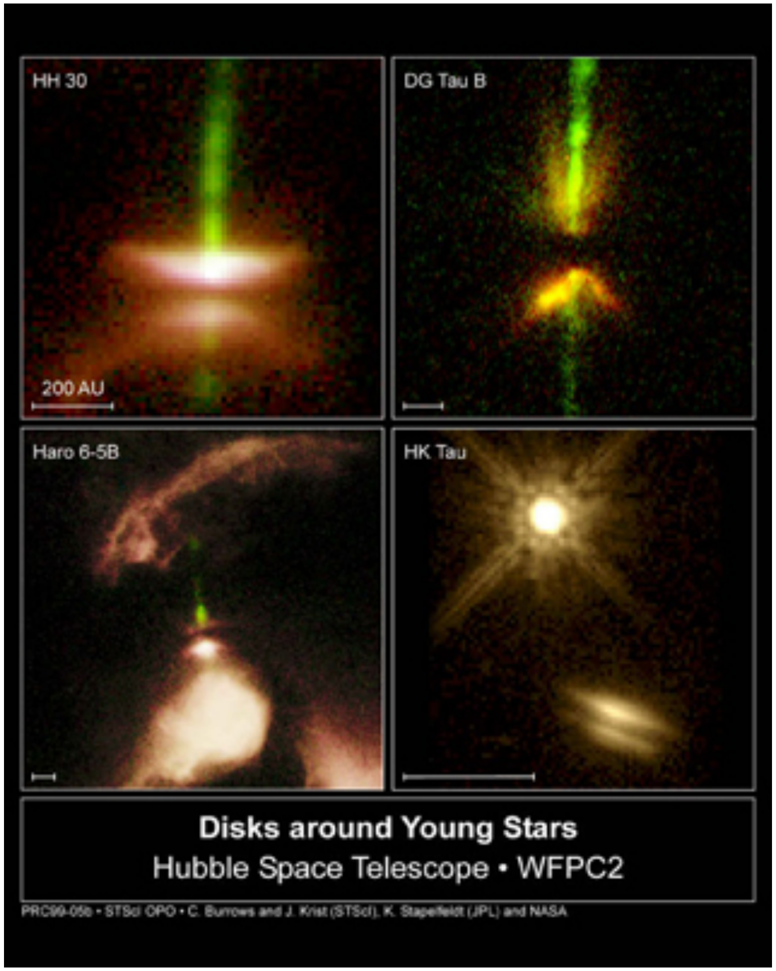
Outline

- Motivation of studying Gravitational Instabilites (GI) in protoplanetary disks
- Gravitoturbulence and locality of GI
- Fragmentation of disks due to GI
- FU Orionis outbursts and models of disk evolution

Motivation – Protoplanetary Disks



Credit: C. Burrows and J.Krist(STScI), K.Stapelfeldt(JPL) and NASA

- Accretion disks are required:
  - Observation(Infrared and sub-mm)
  - Dynamical role in star formation: accretion
  - Site of planet formation

Properties of Protoplanetary Disks

- Masses: $10^{-3} – 10^{-1}$ M_{sun} in gas
- Sizes: 100 – 1000 AU
- Lifetimes: $10^6 – 10^7$ yr
- Temperature: cold, ~ several 100 K
- Thickness: H/R ~ 0.03 – 0.05
- Opacity: τ ~ $10^3 – 10^4$ (at 1 AU in optical, mainly due to dust)
- Very low ionization fraction: MRI couldn't work in "dead zones"

Motivation – Gravitational Instability(GI)

- Alternative source of angular momentum transport in cold disks (Lin & Pringle 1987; Armitage, Livio & Pringle 2001).
  - Locally: gravitational turbulence → "viscosity"
  - Globally: bar structures, spiral arm structures
- Giant Planet Formation:
  - Limit of time:

    giant planets have to be formed within several million years from

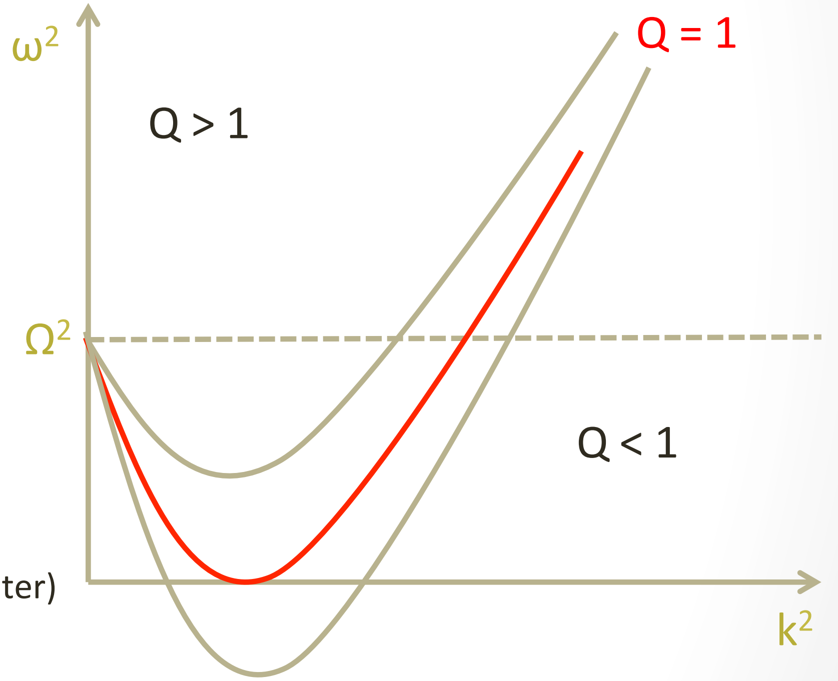
    the star forming event
  - Difficulty with current planet formation theory(i.e. core instability models, (Ida & Lin 2004; Rafikov 2010)
  - Giant planets might have formed by Gravitational Instability(disk fragmentation, Boss 2000).

When does GI work?

- Dispersion relation for density waves in gas disks in WKB limit(Binney & Tremaine 1987):

$$\omega^2 = c_{\rm s}^2 k^2 - 2\pi G\Sigma|k| + \kappa^2$$

- Similar to Jeans Instability:
  - Gravity ⟷ Pressure + F_{centri}
  - Small wavelengths: P
  - Long wavelengths: Fcentri
  - Intermediate: GI



- GI occurs when:
  - 1. $\omega^2 < 0$
  - 2. $Q \equiv \frac{c_s\Omega}{\pi G\Sigma} < Q_{\rm crit} \simeq 1$ (Toomre Parameter)
  - 3. $M_{\rm disk} \gtrsim \frac{H}{r} M_*$
  - 4. $\dot{M} \gtrsim \frac{3\alpha c_s^3}{G} = 7.1 \times 10^{-4}\alpha\left(\frac{c_s}{1\ {\rm km\ s^{-1}}}\right)^3 M_\odot\ {\rm yr}^{-1}$

$$\dot{M} = 3\pi\alpha c_s^2\,\Sigma/\Omega$$

Pre-assumption for 4: No external torques, no heating from external illumination .

Thermal processes are important to GI

$$\boxed{Q \equiv \frac{c_s \Omega}{\pi G \Sigma} < Q_{\mathrm{crit}} \simeq 1}$$

- Timescales:
  - Change of Σ: accretion timescale ~ $(r/H)^2(\alpha\Omega)^{-1}$
  - Cooling or heating: thermal timescale ~$(\alpha\Omega)^{-1}$
  - $r/H \gg 1$

Final Fate for GI Unstable Disks

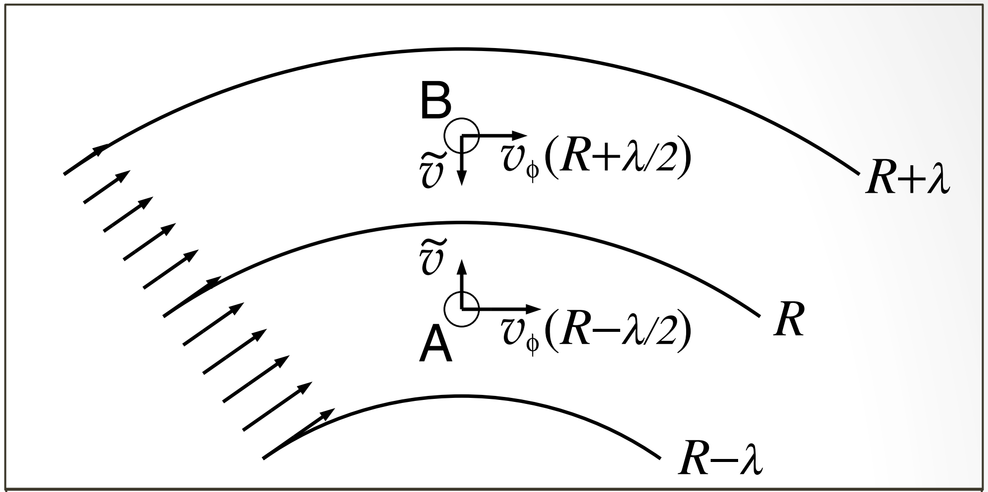
- Quasi-steady, long-lived state:
  - Gravitational turbulences transport angular momentum out
  - Marginally stable $Q \sim Q_{0.}$
  - Self-regulated state cooling ~ heating by GI

- Rapid fragmentation:
  - If cooling is much more efficient than heating
  - Formation of massive planets or substellar objects (Boss 1997).

- Bursts of accretion (FU Ori bursts):
  - If temperature becomes high enough to trigger MRI

1.GI as a specific form of “viscosity”: Controversy about locality of GI

Locality



Exchange of fluid blobs in differentially rotating flow(Frank et al. 2002).

- Evolution of viscous disks:

$$\frac{\partial\Sigma}{\partial t} = \frac{3}{R}\frac{\partial}{\partial R}\left[R^{1/2}\frac{\partial}{\partial R}\left(\nu\Sigma R^{1/2}\right)\right]$$

$$\nu \sim \lambda\tilde{v}$$

- α-prescription:

$\nu = \alpha c_{\rm s} H$ (Shakura and Sunyaev, 1973)

Lin & Pringle, 1987:
Self-gravity could be treated as local, gravitoturbulent process, and thus could be described in a modified viscous α framework.

Balbus & Papaloizou, 1999:
Self-gravitating disks could only be described as local process when the pattern speed Ω_p matches the local angular velocity Ω. Otherwise, the energy equation cannot be put into the form of a diffusion equation as required in local viscous scenario.

Locality

- Gravitoturbulence:
  - Local Thermal Equilibrium:

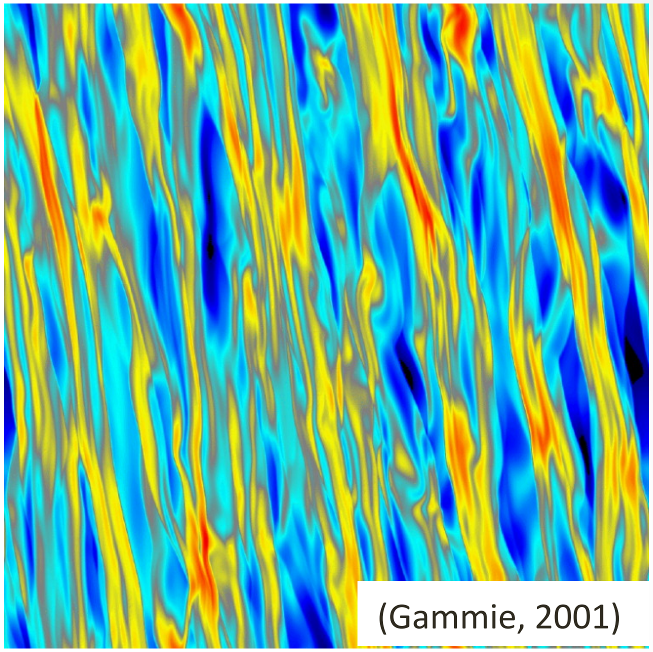
$$\alpha = \frac{4}{9\gamma(\gamma-1)}\frac{1}{t_{\mathrm{cool}}\Omega}$$

  - Assuming opacity to be power law of midplane temperature:

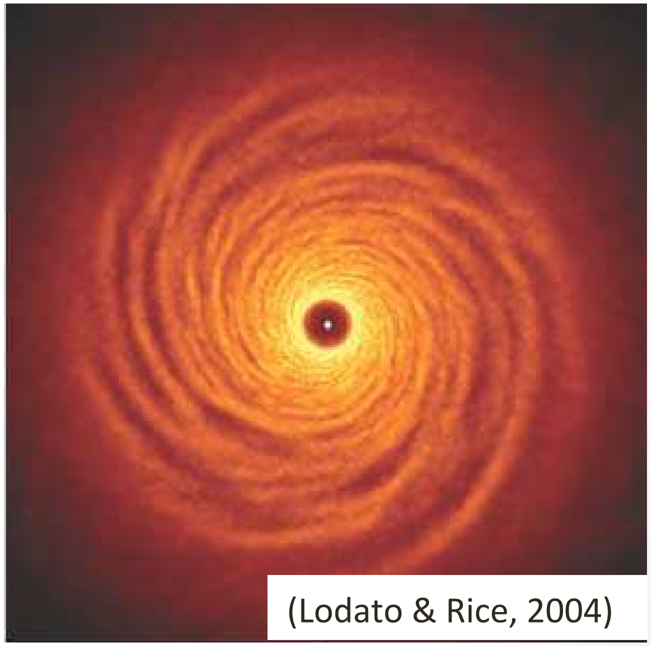
$$\alpha \sim \frac{\sigma}{\kappa_0}\left(\frac{\mu m_p}{\gamma k_B}\right)^{4-\beta}(Q_0\pi G)^{6-2\beta}\Sigma^{4-2\beta}\Omega^{2\beta-7}$$

(Levin 2007)

- Locality is proved when:
  - $M_{\mathrm{disk}} / M_* < 0.25$ (Lodato&Rice 2004)
  - $M_{\mathrm{disk}} / M_* = 0.1$, departure is 10% (Cossin, Lodato & Clarke, 2009)
  - $M_{\mathrm{disk}} / M_* < 0.5$ (including radiative transfer, Forgan et al. 2010)



(Gammie, 2001)

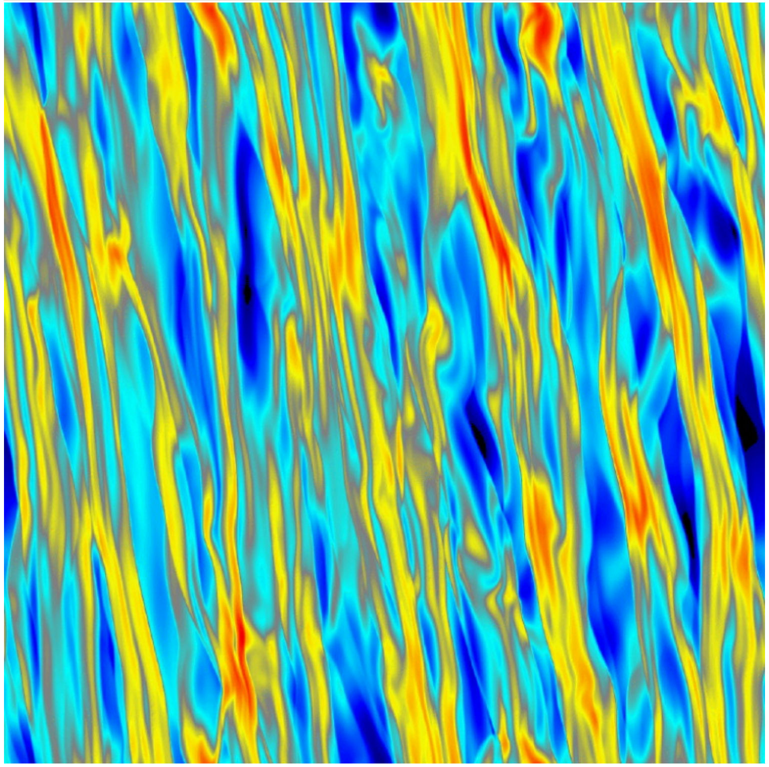


(Lodato & Rice, 2004)

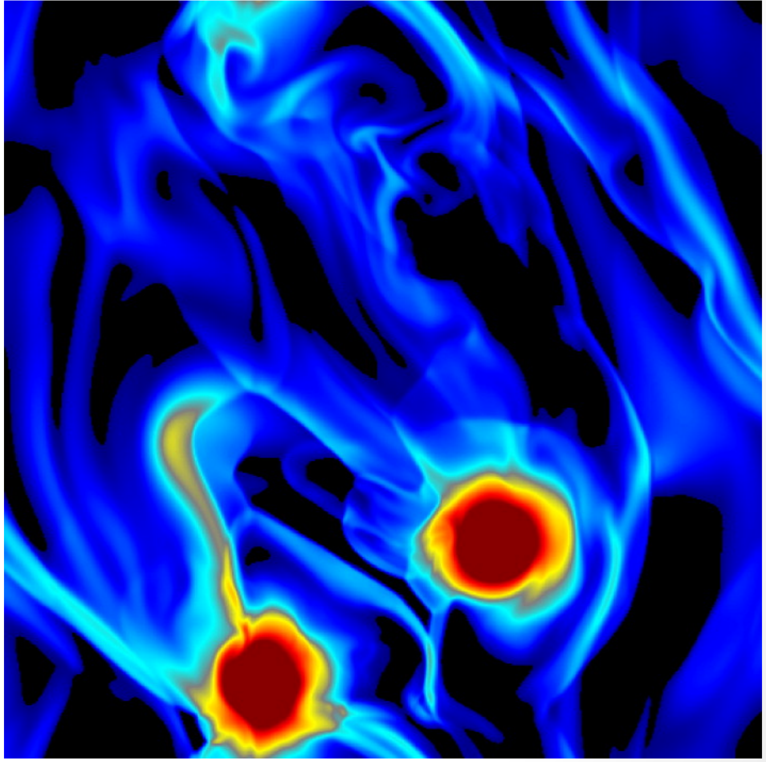
2. Fragmentation due to GI

Disk Fragmentation

2D hydrodynamic simulation by Gammie 2001:
Disks will fragment when $t_{cool} \leq 3\ \Omega^{-1}$



$t_{cool} = 50\ \Omega^{-1}$, no fragmentation



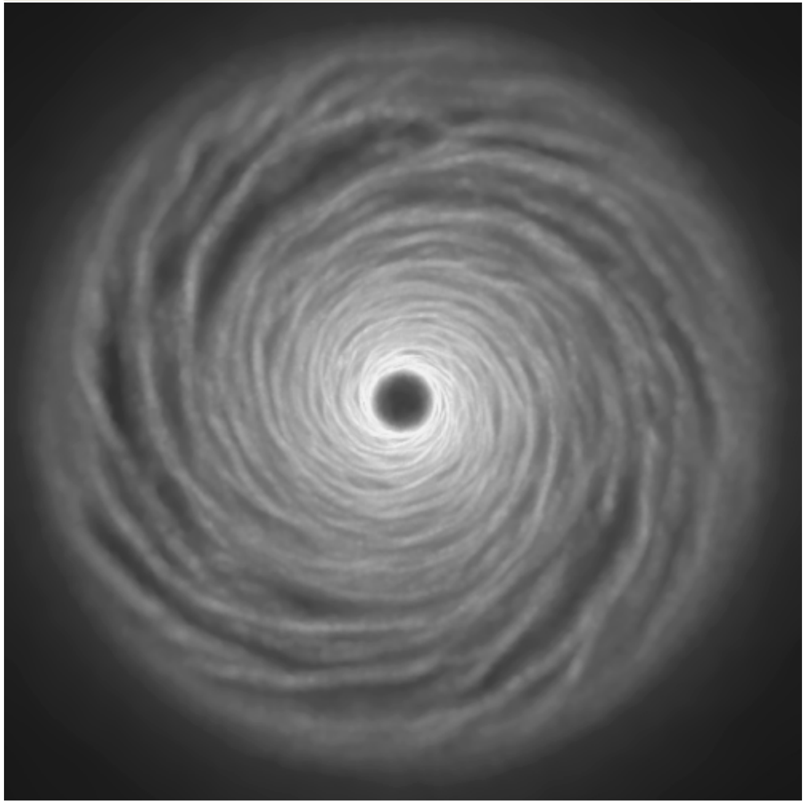
$t_{cool} = 2\ \Omega^{-1}$, fragmentation

Disk Fragmentation

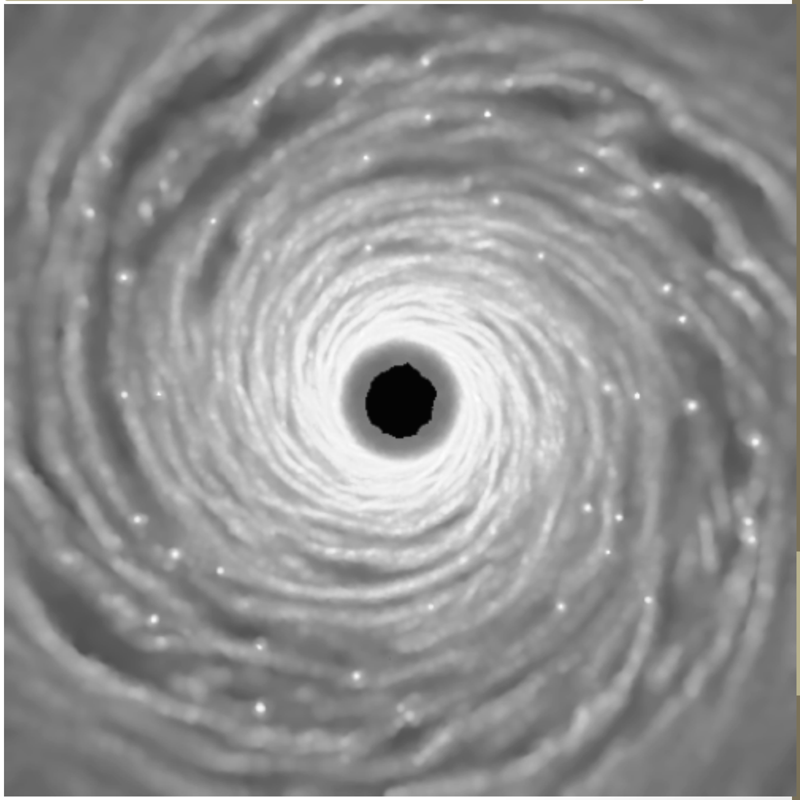
3D hydrodynamic simulation by Rice et al. 2003:

Disks will fragment when $t_{cool} \leq 5\ \Omega^{-1}$

$t_{cool} = 5\ \Omega^{-1}$, no fragmentation



$t_{cool} = 3\ \Omega^{-1}$, fragmentation



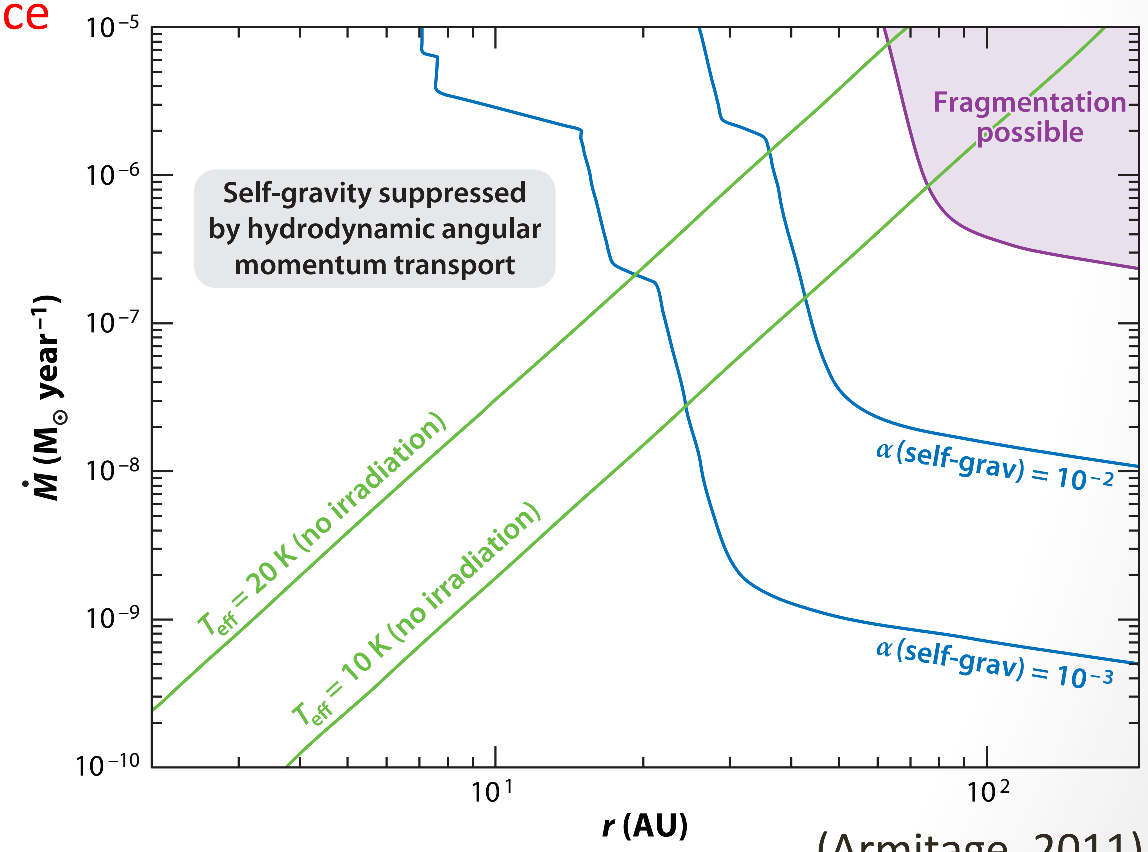
Disk Fragmentation

$$\alpha = \frac{4}{9\gamma(\gamma-1)}\frac{1}{t_{\mathrm{cool}}\Omega}$$

$$\dot{M} \gtrsim \frac{3\alpha c_s^3}{G}$$

- If:
  - there's no irradiation from central star;
  - angular momentum transport is totally dominated by gravitoturbulence
- Then:

1.around a 1 $M_\odot$ star,
2.self-gravity acts as a local process whose efficiency is set by the requirement of thermal equilibrium (Clarke 2009, Rafikov 2009).
3.The opacity includes contributions from water ice, amorphous carbon, silicates, and graphite



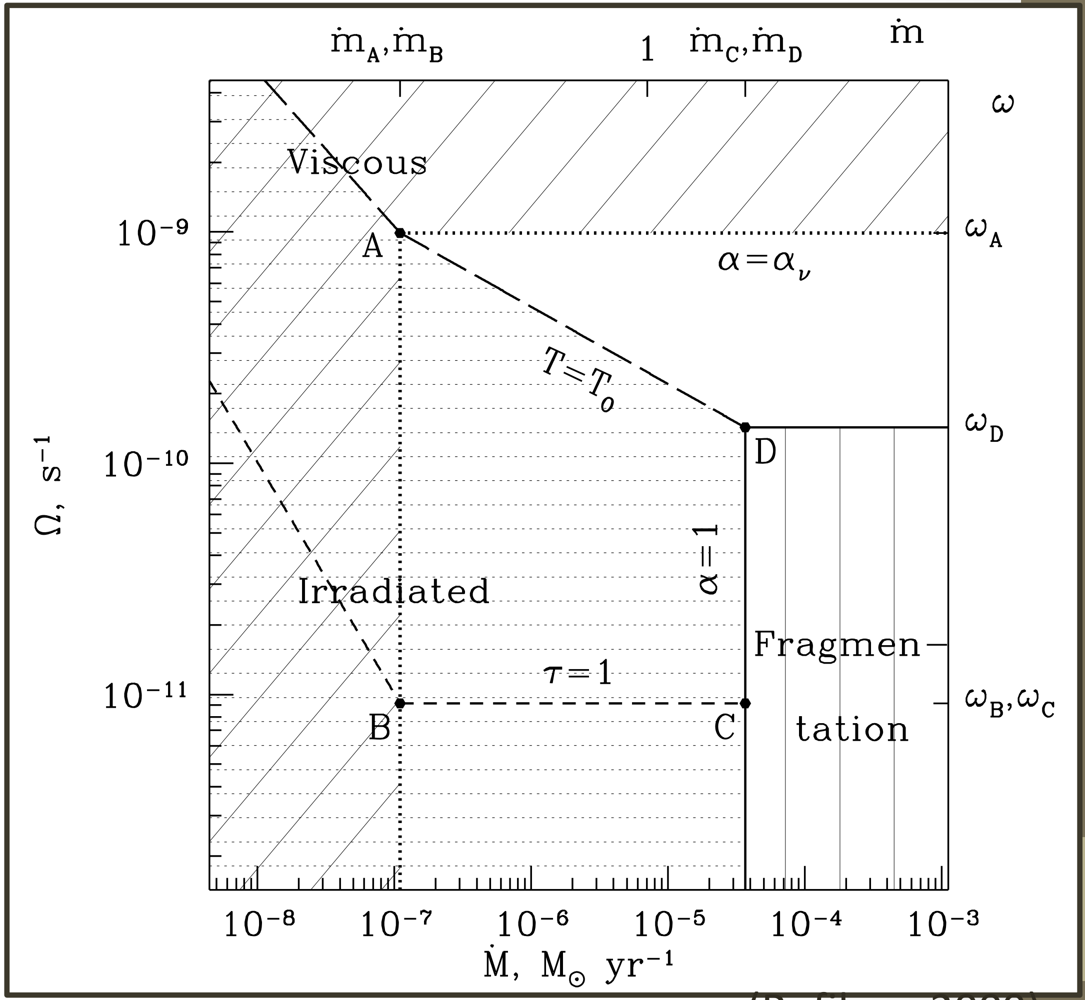
(Armitage, 2011)

Disk Fragmentation

- Two caveats:
    - Background viscosity: if background viscosity dominates, then the disk might be gravitationally stable;
    - Stellar irradiation: external heating source keeps the disk gravitationally stable

Disk Fragmentation

- Background viscosity:
  - $\alpha_\nu = 0.003$
- Strong stellar irradiation :
  - $T_0 = 35\text{K}$ due to irradiation, spatially constant
- Opacity:
  - $\kappa = \kappa_0 T^2$



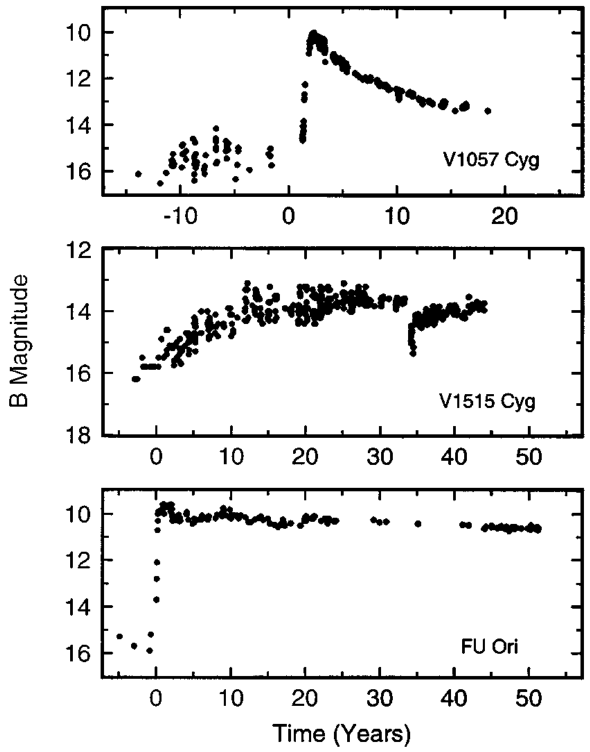
(Rofikov, 2009)

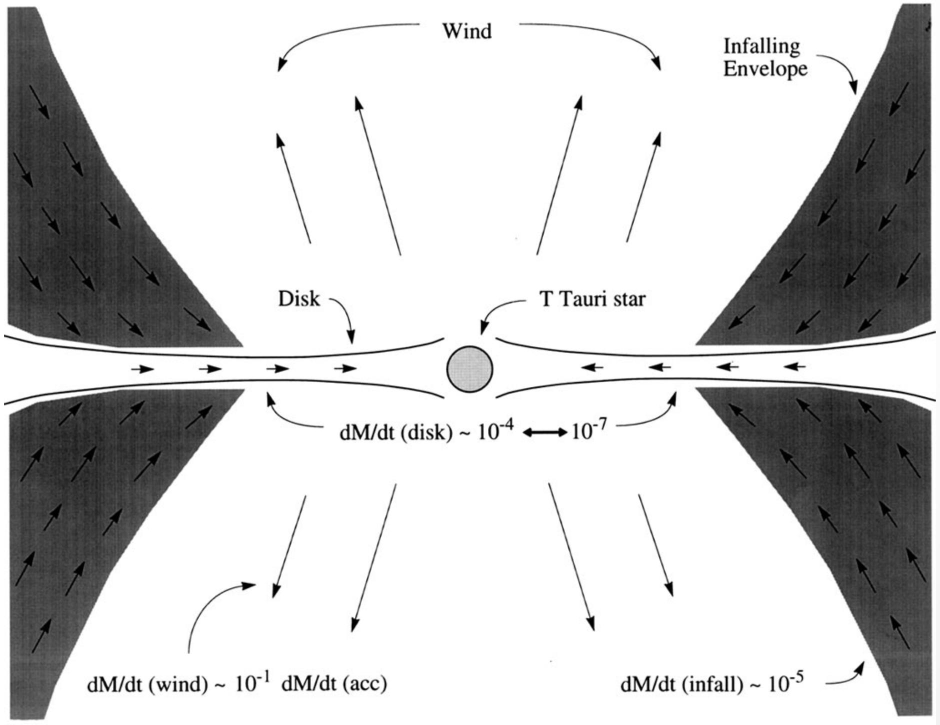
3. Disk Evolution & FU Orionis Bursts

Phenomena

- Luminosity problem of protostars(Kenyon et al. 1990):

  Typical bolometric luminosity << infall rate
- FU Orions outbursts(Hartmann & Kenyon 1996)



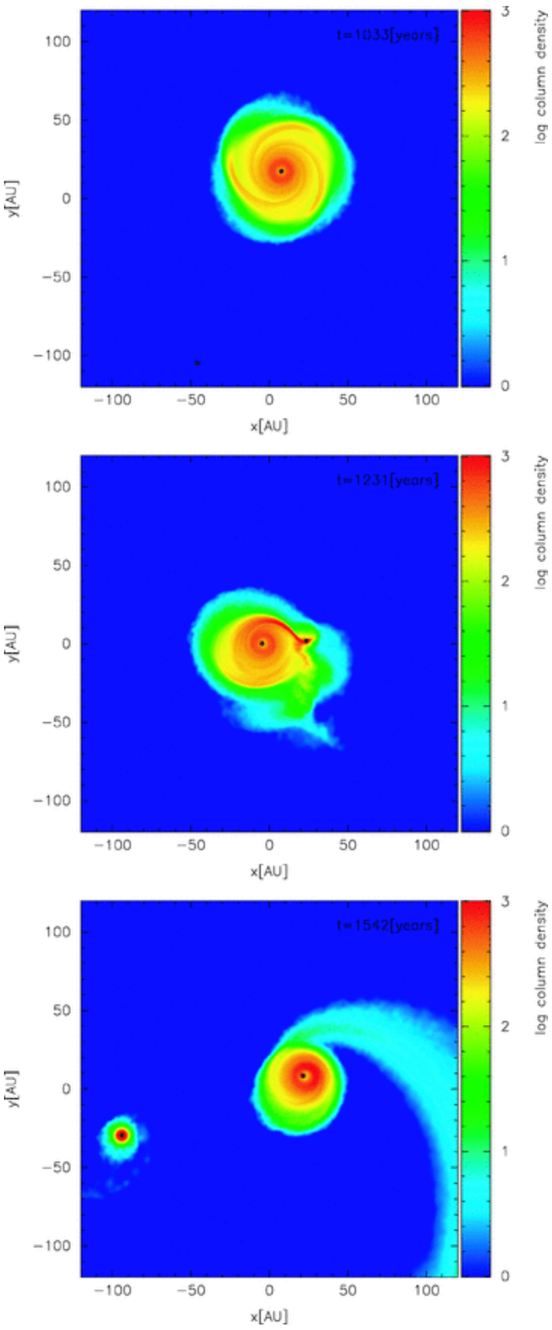


Models of Disk Evolution

- Rapid matter addition to the disk
  - Perturbations from companions.(Bonnell & Bastien 1992; Forgan & Rice 2010)
  - Inspiral of clumps formed in outer self-gravitating region of the disk.(Vorobyov & Basu 2005, 2010)

(Forgan & Rice 2010)

(Vorobyov & Basu 2010)


t=1033[years]
t=1231[years]
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y[AU]
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100
50
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log column density
3
2
1
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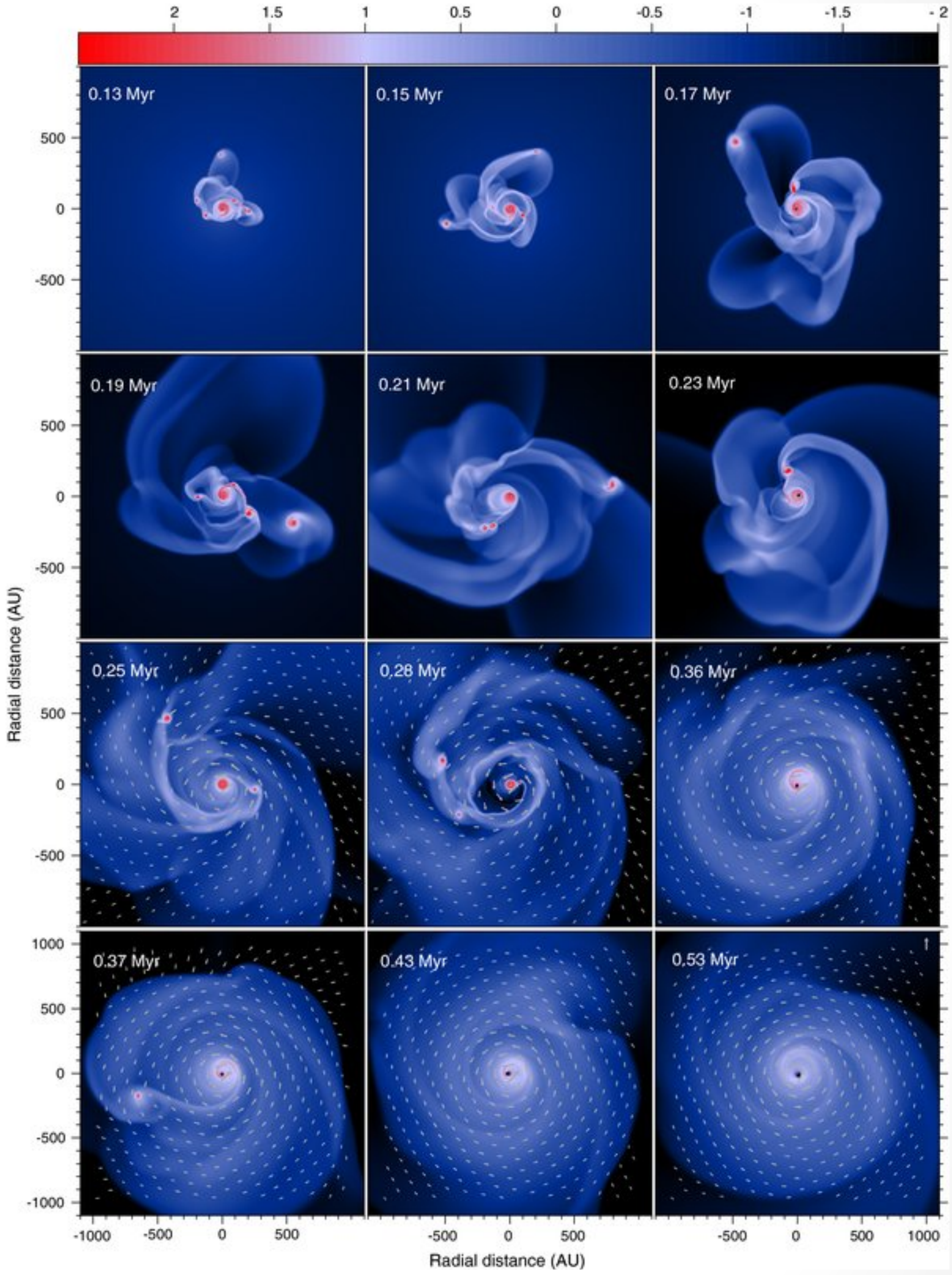
2
1.5
1
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0
-0.5
-1
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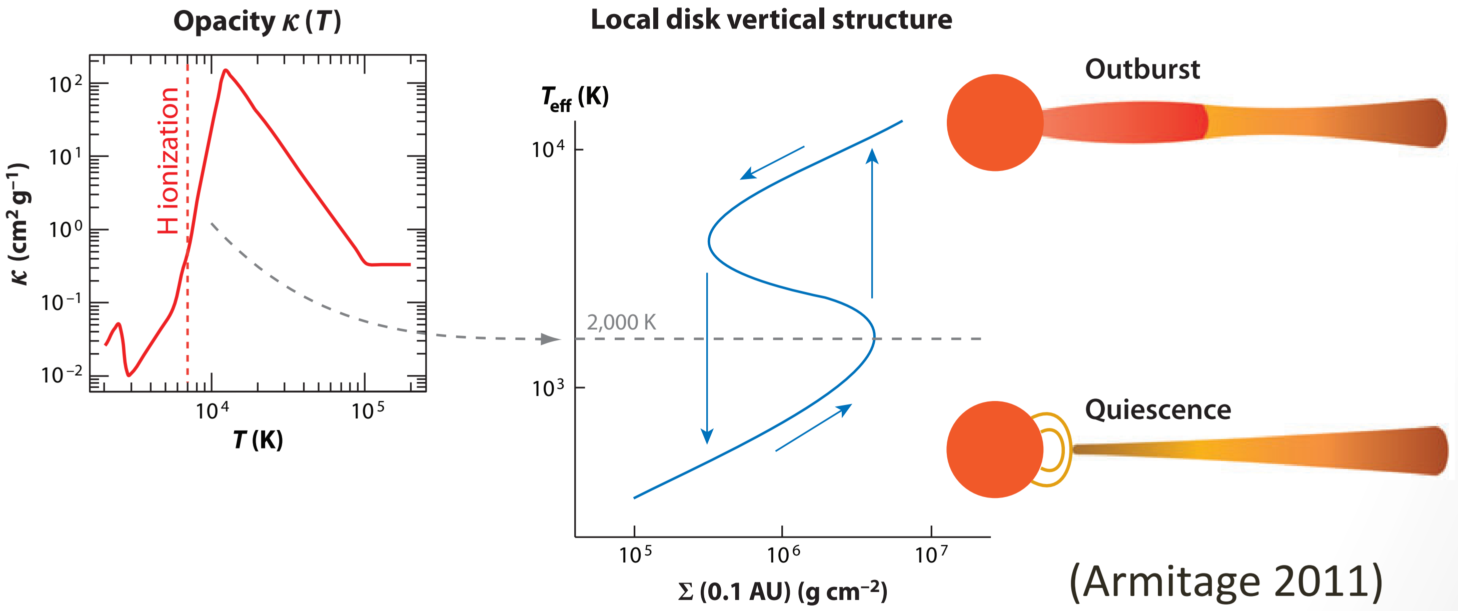
0.13 Myr
0.15 Myr
0.17 Myr
0.19 Myr
0.21 Myr
0.23 Myr
0.25 Myr
0.28 Myr
0.36 Myr
0.37 Myr
0.43 Myr
0.53 Myr
Radial distance (AU)
Radial distance (AU)
1000
500
0
-500
-1000

Models of Disk Evolution

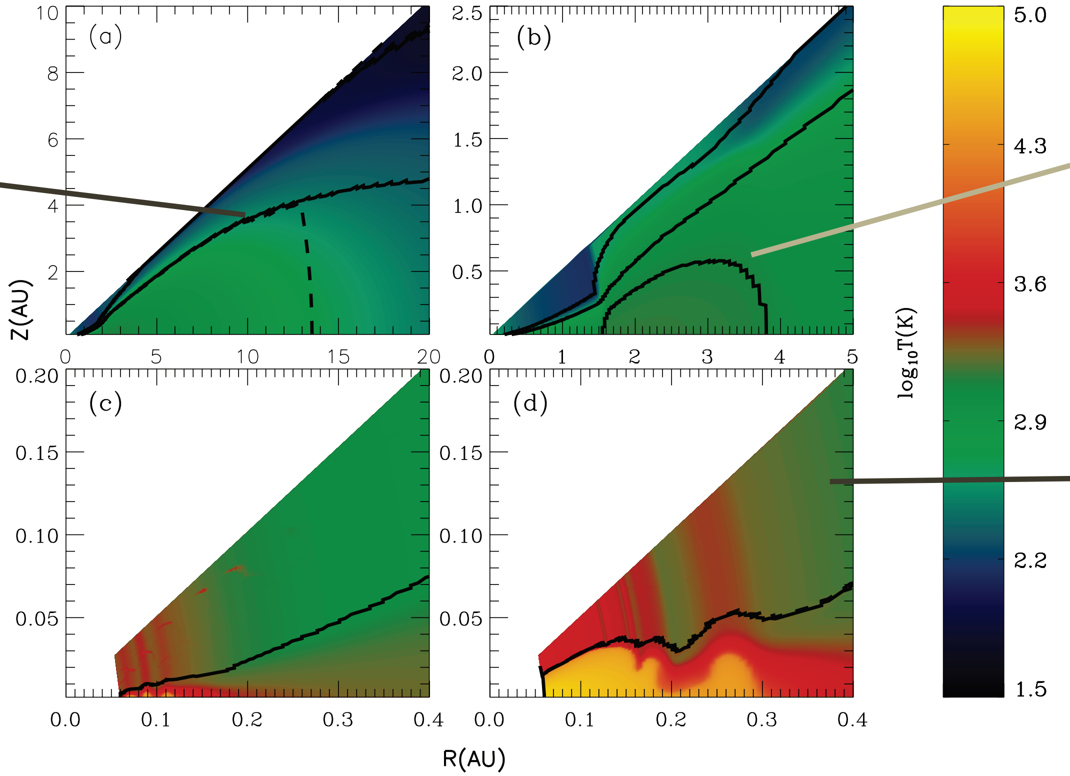
- Thermal Insabilities (TI, Bell & Lin 1994):
  - Opacity of the disk changes rapidly at T ~ 10^4 K due to ionization of hydrogen.
  - Problem: only works if angular momentum is extremely inefficient(α~10^{-3} – 10^{-4}).



(Armitage 2011)

Models of Disk Evolution

- Association with MRI:
  - Dead zone at r ~ 1 AU, where angular momentum transport is low in the midplane, and where materials pile up and heat up;
  - MRI triggered at T_M ~ 1200K (Zhu et al. 2009), rapid accretion



α= 0.025

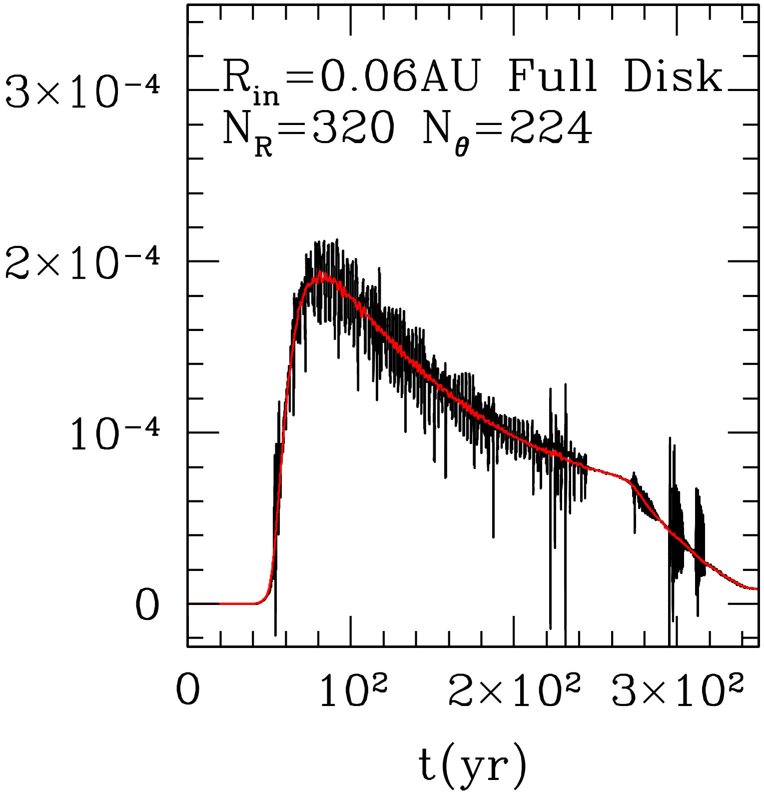
α= 0.1

Lasts 100yr at 2×10^{-4} M_{sun}/yr

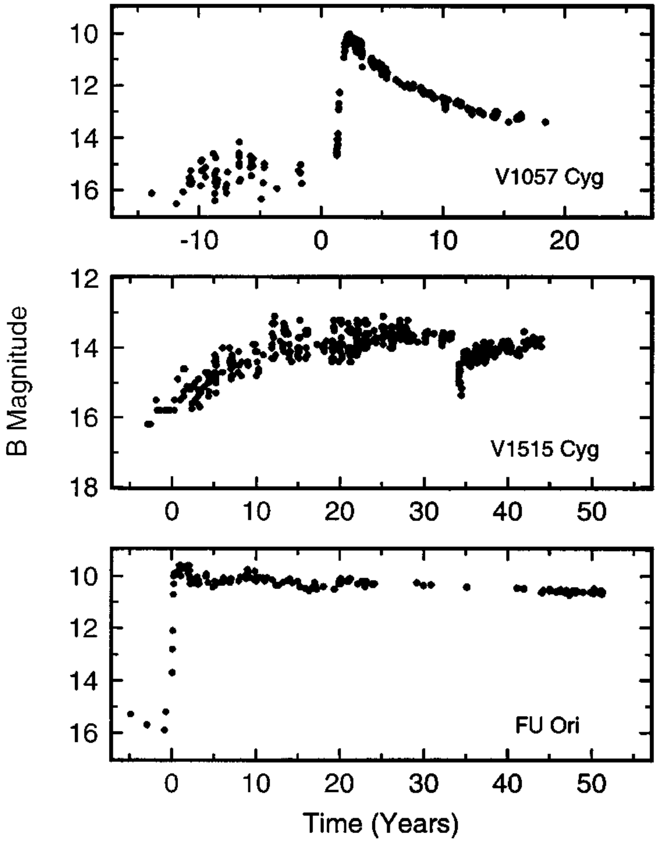
(Zhu et al. 2009)

Models of Disk Evolution

2D simulation (Zhu et al. 2009):

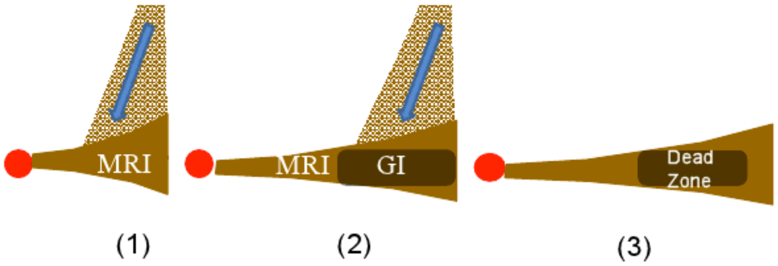


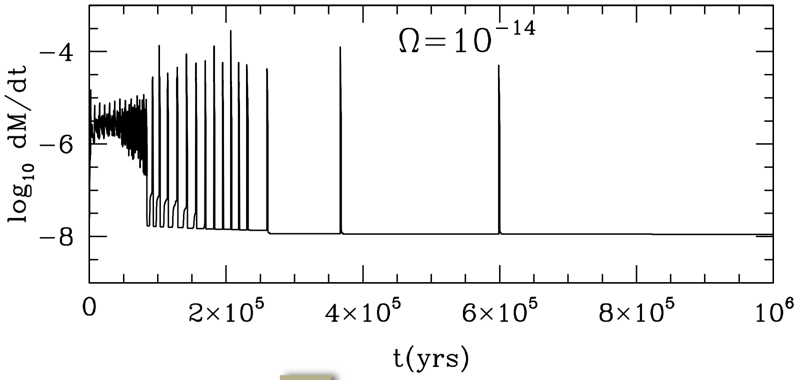
Observed FU Ori (Hartmann & Kenyon 1996):

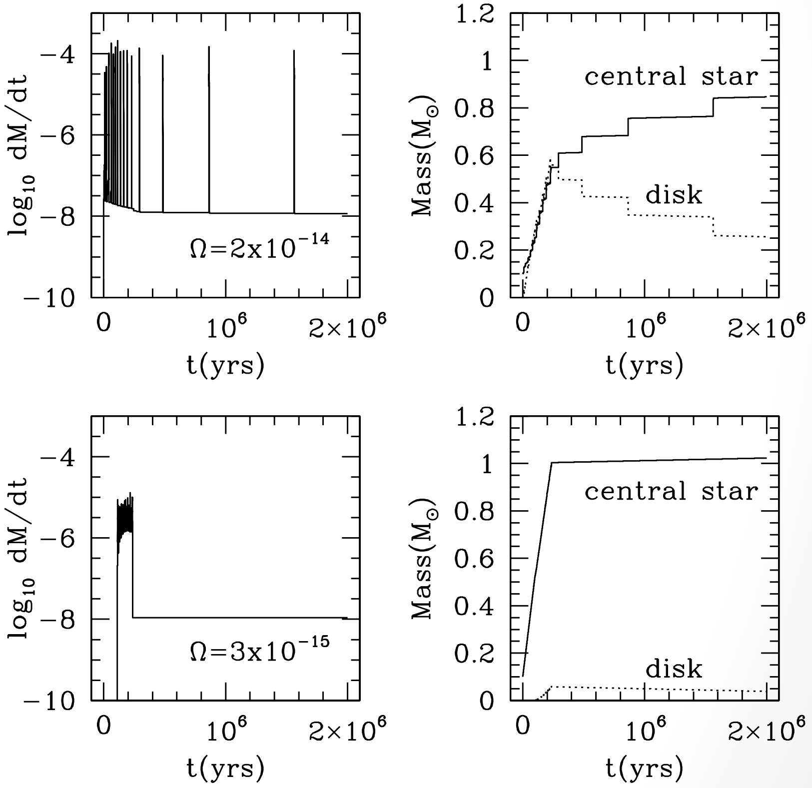


Long-term evolution

- Layered accretion with infall (Zhu, Hartmann & Gammie, 2010):







Solves the luminosity problem!

Conclusions

- Gravitational instability could be common and so important to protoplanetary disks
- Locality of gravitational instability is plausible in low-mass disks
- Gravitational instability results in two outcomes depending on the cooling time:
  - Gravitoturbulence (steady angular momentum transport)
  - Fragmentation
- Irradiation and background viscosity constrain regimes where GI works:
  - Irradiation stabilizes disks against fragmentation at low mass accretion rates
  - Background viscosity could dominate angular momentum transport and stabilize the disk
- Heating up due to GI could trigger MRI and produce bursts of accretion, which explains FU Ori outbursts.

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