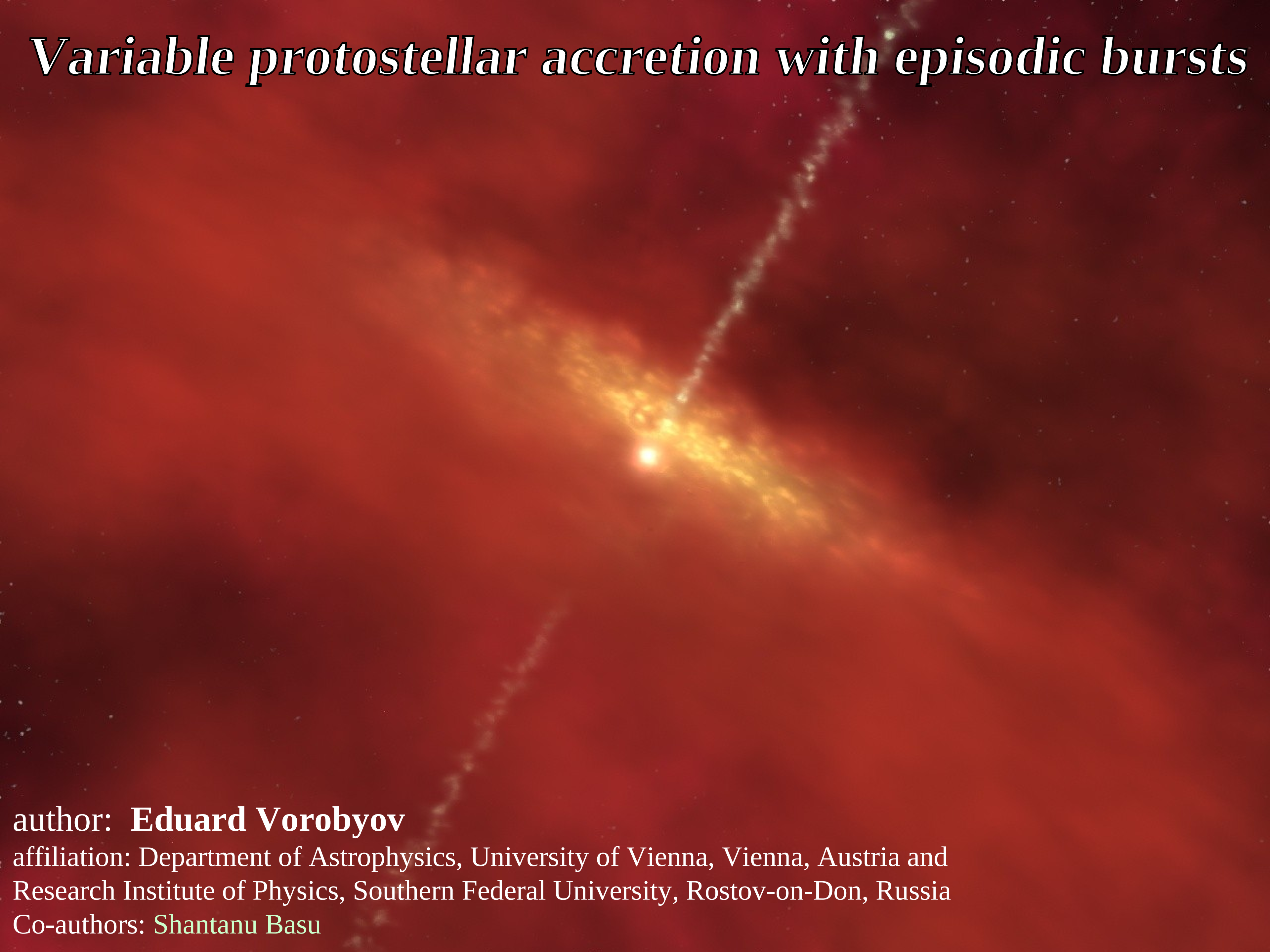

Variable protostellar accretion with episodic bursts

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OUTLINE

1. Failure of the classic spherical accretion models

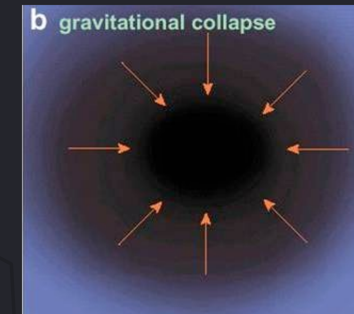
2. Episodic accretion bursts in the disk fragmentation model

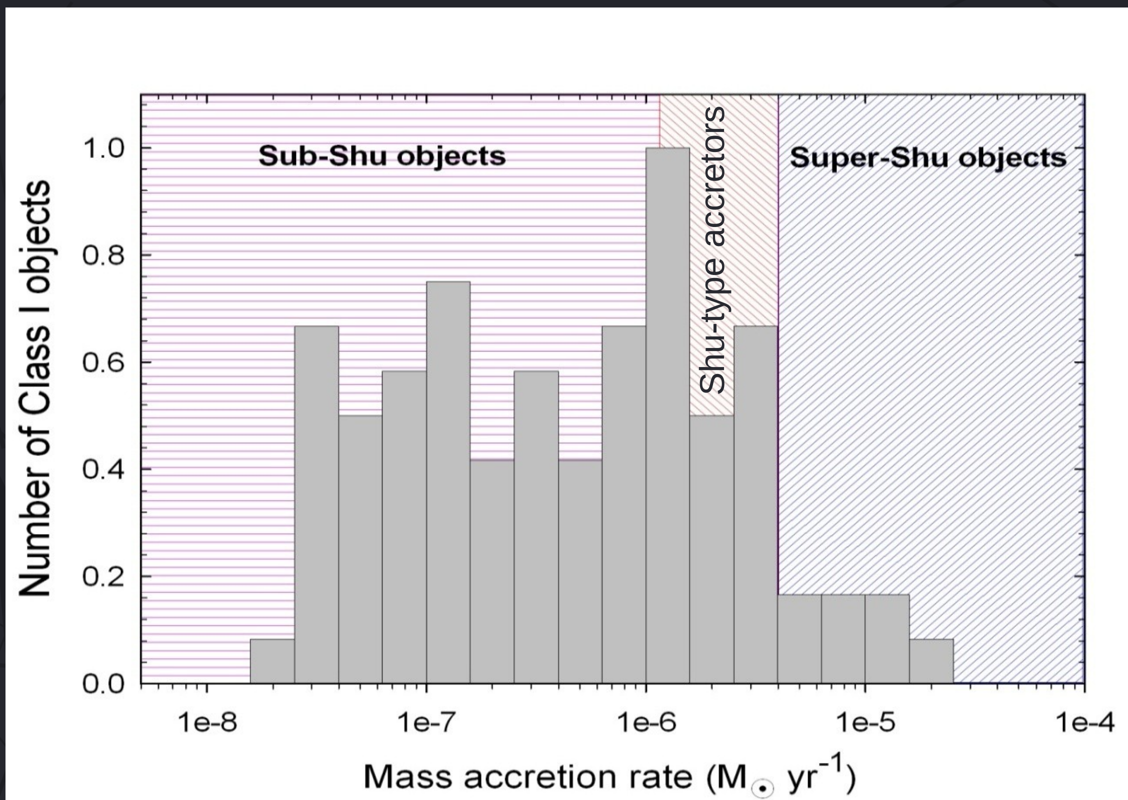
- Accretion variability in gravitationally unstable disks

Failure of the classic spherical collapse model

Mass accretion rate onto the star in the standard model of spherical collapse (Shu 1977)

$$\dot{M}_{Shu} \approx \frac{c_s^{\,3}}{G} \approx (1-4)\times10^{-6} \quad M_{\odot}\,yr^{-1}, \ \text{for } T = 10 - 20\ K$$





Histogram presents inferred accretion rates in young embedded sources (Perseus, Serpens, and Ophiuchus Enoch et al. 2009)

55% – $\dot{M} < 10^{-6}$ $M_{\odot}\,yr^{-1}$

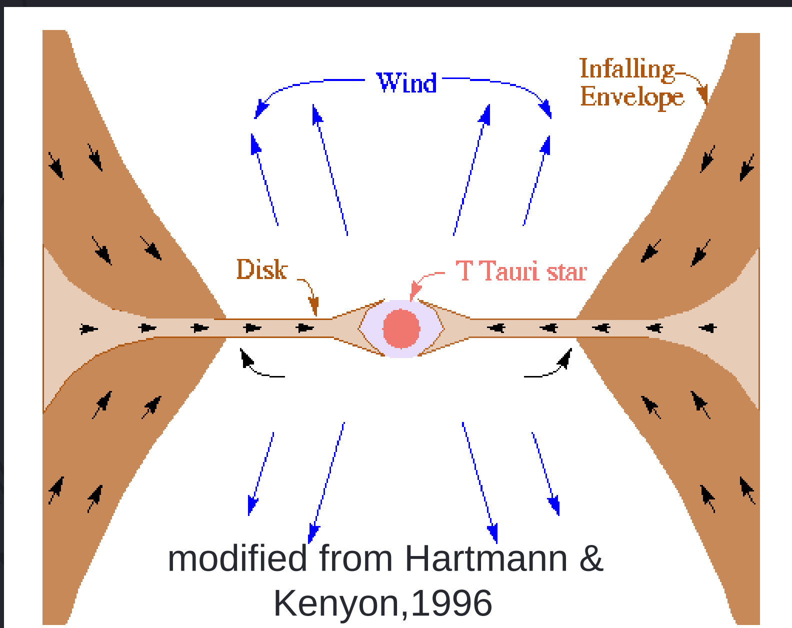
5% – $\dot{M} > 10^{-5}$ $M_{\odot}\,yr^{-1}$

Key features of young star-forming regions – wide spread in accretion rates (~ 3 orders of magnitude).

Stars do NOT accrete at a rate predicted by simple spherical collapse models.

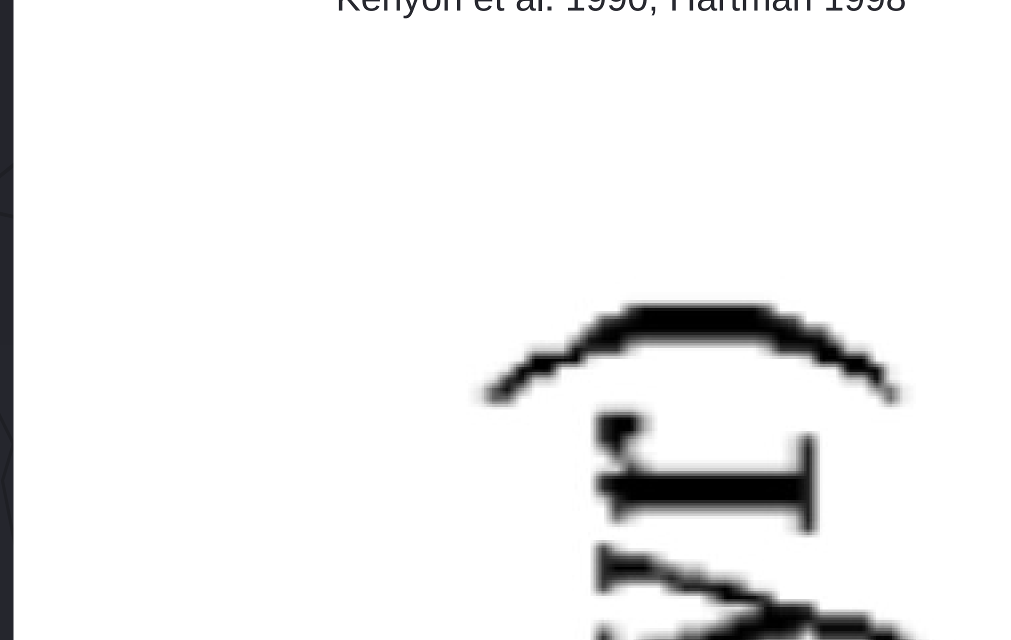
Variable accretion with episodic bursts

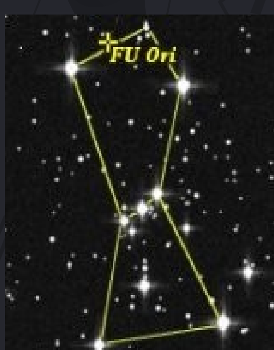
Infalling material from a collapsing core accumulates in a protostellar disk and is driven onto a protostar in a series of short-lived (<100-200 yr) accretion bursts. The quiescent periods between the bursts (10^3-10^4 yr) are characterized by low-rate accretion.



modified from Hartmann & Kenyon,1996

Kenyon et al. 1990, Hartmann 1998





FU Orionis is a prototype example

Before 1937 – was 16th mag star, but increased by over 6 mag (factor of ~ 250 in luminosity) in one year. Currently flickering around 9.5 mag

How significant are the bursts?

(Updated from Hartmann & Kenyon, 1996, ARAA, 34, 207)

FUors are **rarely** seen…
but they are common events!

Within 1 kpc of the Sun:

- 8 FUors since 1936 → Fuors frequency is 0.1 yr^{-1}
- Average star formation rate 0.02 yr^{-1} (Miller & Scalo 1979, ApJS, 41, 513)
- FUors occur at several times the rate of star formation; averaging multiple bursts per star

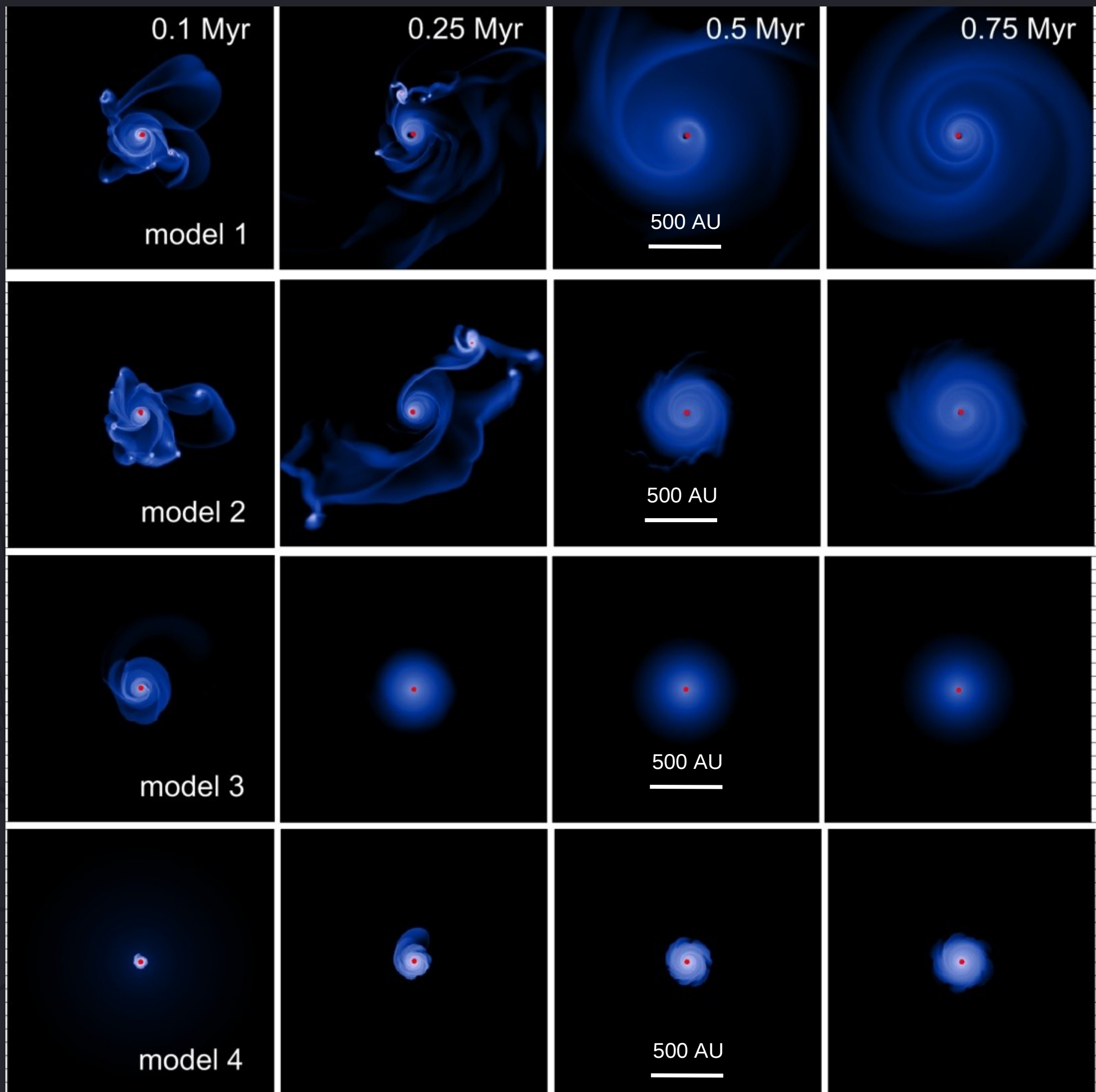
Adopted from PPVI

Mechanisms responsible for episodic bursts

Several mechanisms that can produce episodic bursts include:

- viscous-thermal instabilities in the inner disk (Lin & Papaloizou 1986),
- thermal instabilities induced by density perturbations due to a massive planet in the disk (Lodato & Clarke 2004),
- tidal effects from close encounters in binary systems or stellar clusters (Bonnell & Bastien1992; Reipurth & Asprin 2004; Pfalzner et al. 2008).
- combination of gravitational instability and the triggering of the magnetorotational instability (Armitage et al. 2001; Zhu et al. 2010)
- accretion of dense gaseous clumps in a gravitationally unstable disk (Vorobyov & Basu 2006, 2010, 2015; Machida et al. 2011)

Long-term evolution of self-gravitating circumstellar disks



$M_{core} = 1.1\ M_{\odot};\ \beta = 0.88\%$

$M_{core} = 1.5\ M_{\odot};\ \beta = 0.88\%$

Fragmenting disks

$M_{core} = 0.3\ M_{\odot};\ \beta = 0.88\%$

$M_{core} = 1.1\ M_{\odot};\ \beta = 0.14\%$

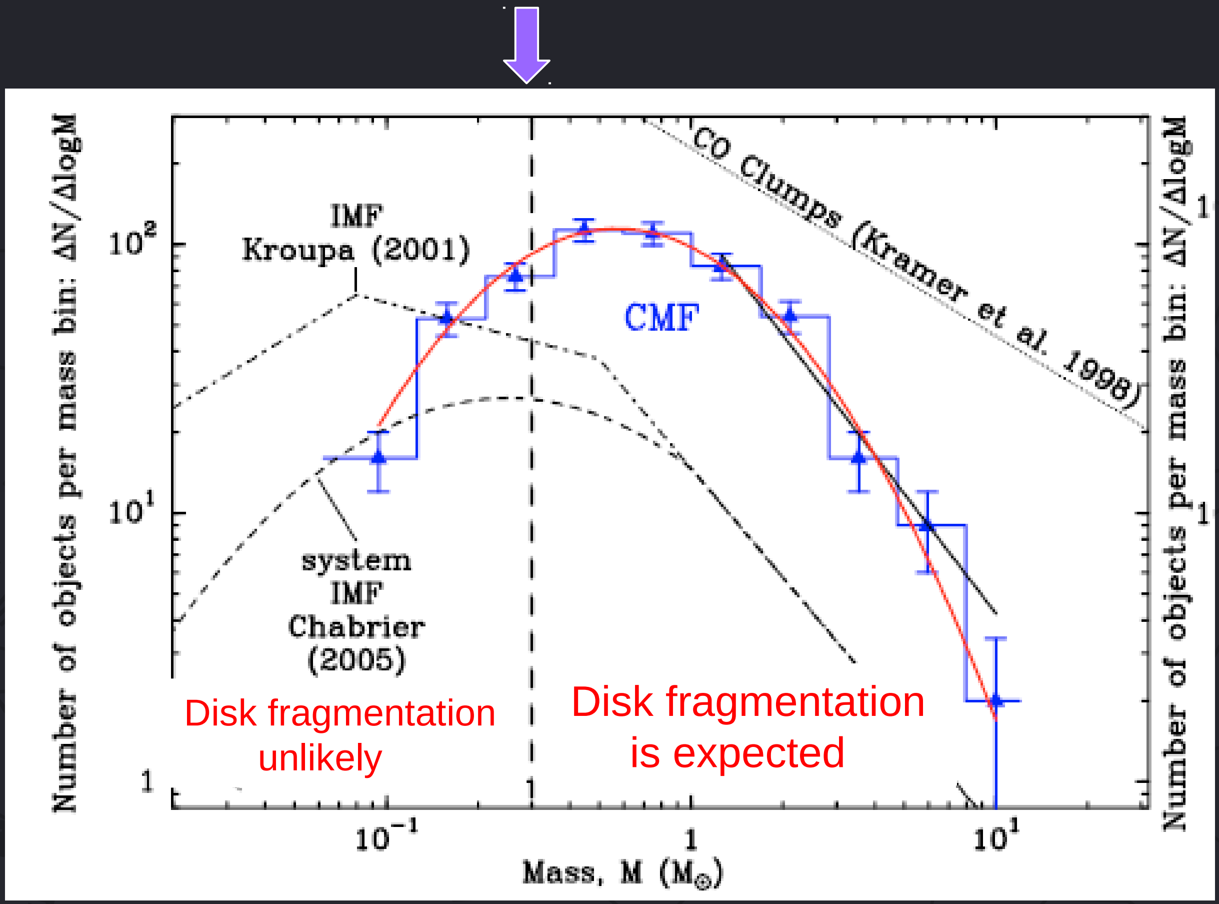
Non-fragmenting disks

Key result: evolution of protostellar disks depends crucially on the initial mass and angular momentum of parental pre-stellar cores. There is little dependence on the core shape

(Vorobyov & Basu 2015, ApJ, 805, 115)

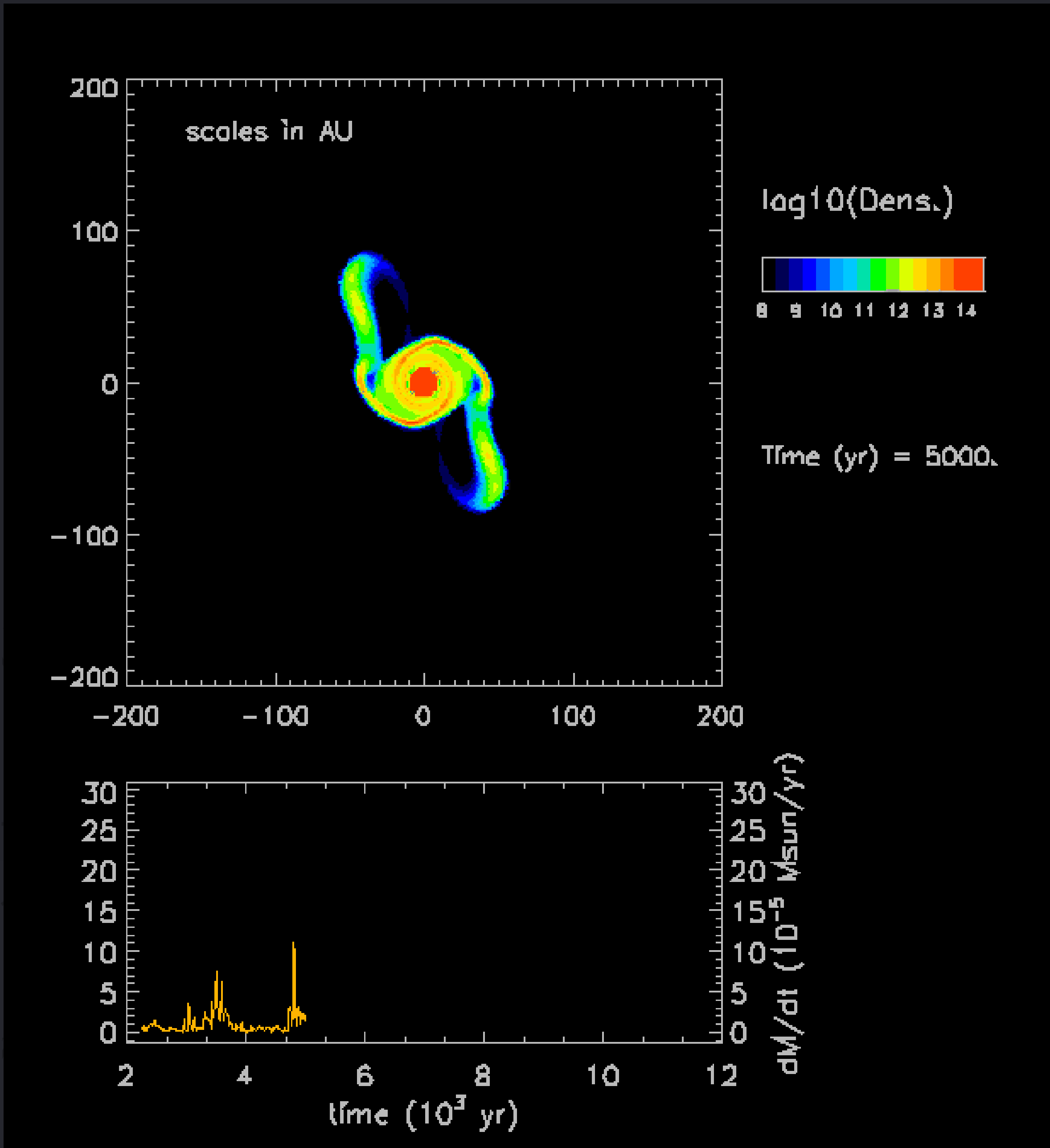
Initial core mass function in the Aquila region (Andre et al. 2010)

Critical core mass
0.3 M



Depending on the distribution of beta-parameter,
about 40-70% of cores are likely to produce fragmenting disks!

Migration of fragments onto the protostar and the burst mode of accretion



Initial core mass = 1.0 M_{sun}

β = 0.8%

Face-on view of the disk

Black regions – infalling envelope (off scale)

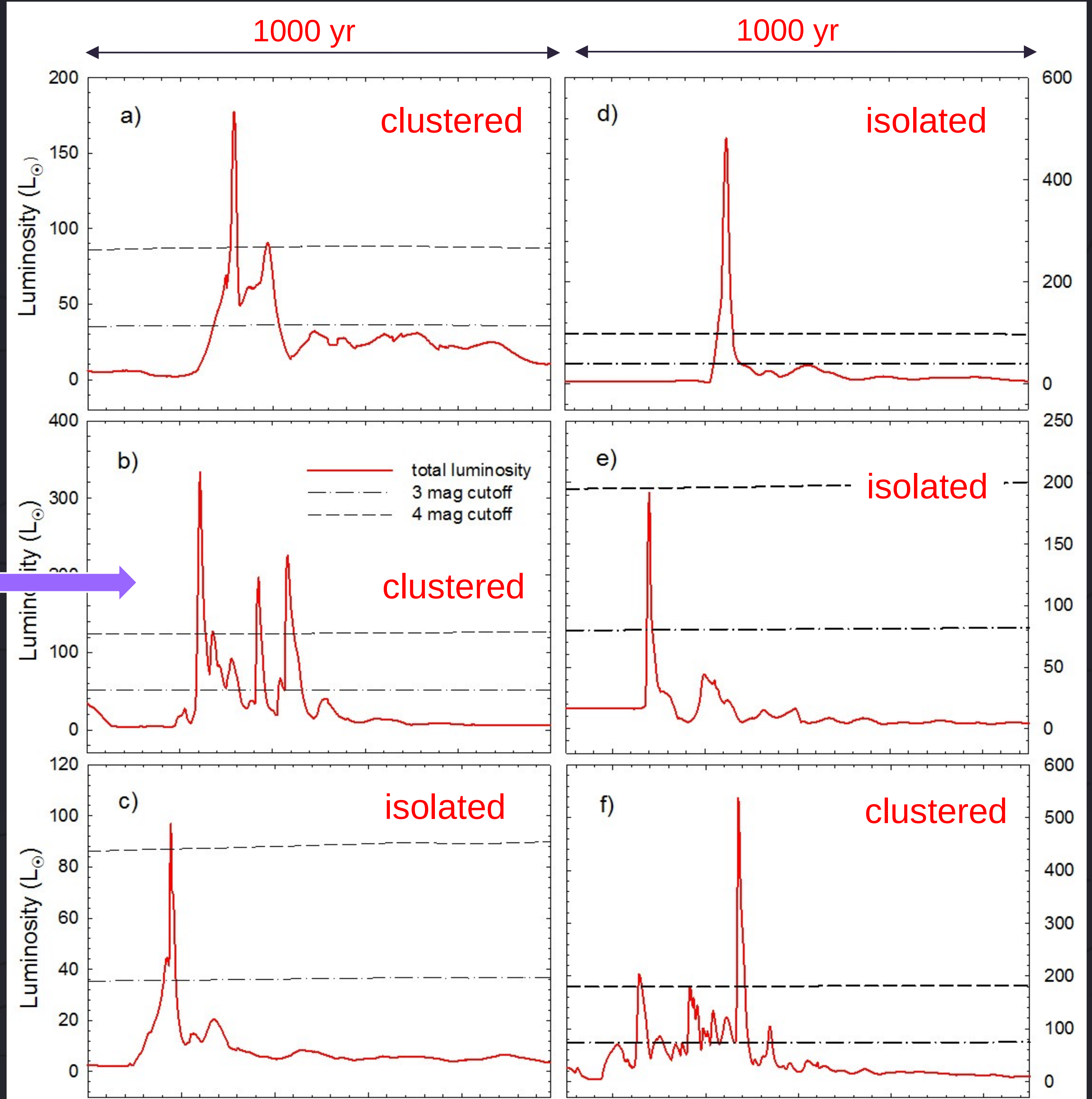
Mass accretion rate at 5 AU

$10^{-5}\ M_{\odot}$ / year

Vorobyov & Basu (2006, 2010)

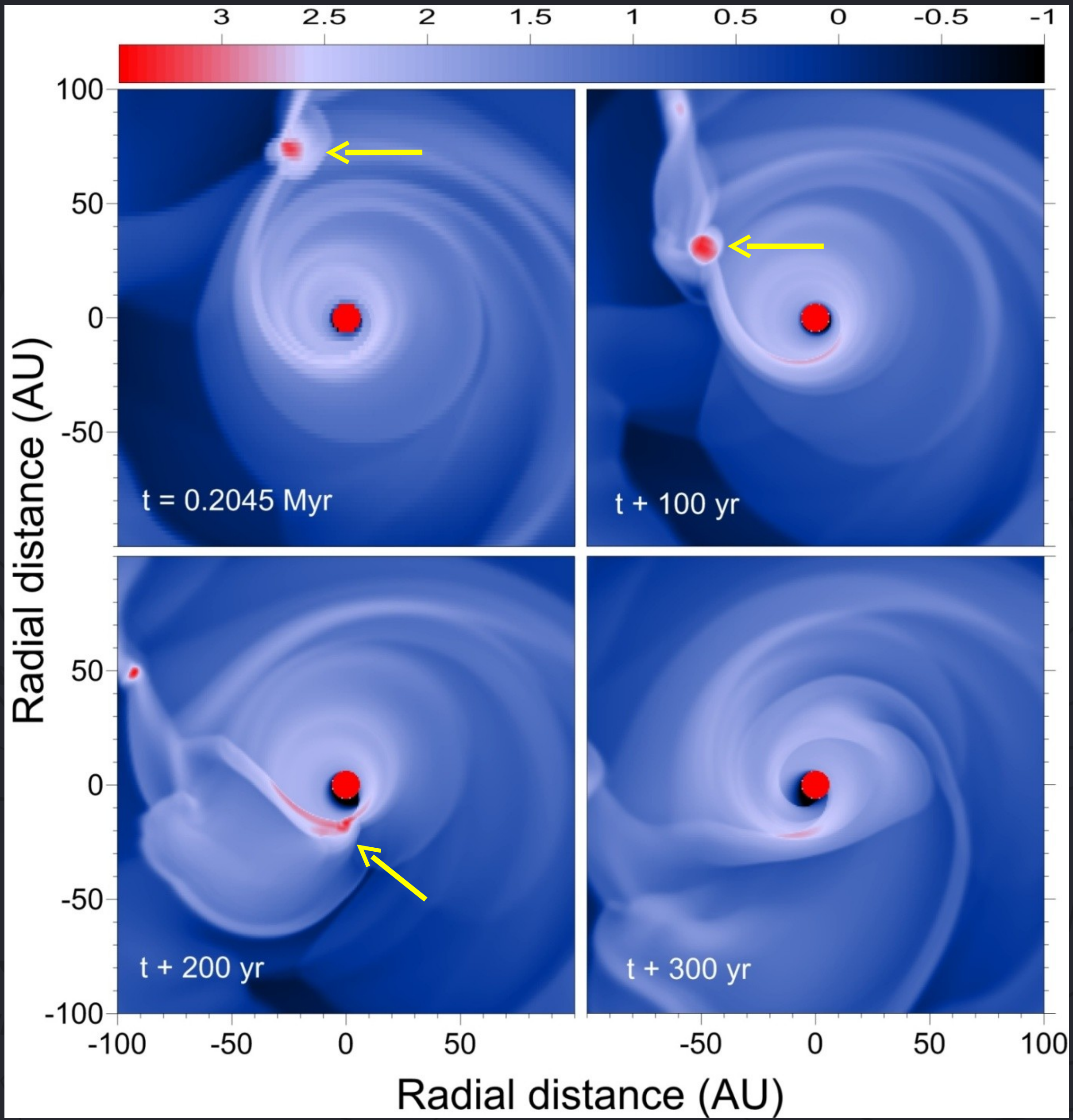
Isolated vs. clustered bursts – zooming in onto individual bursts

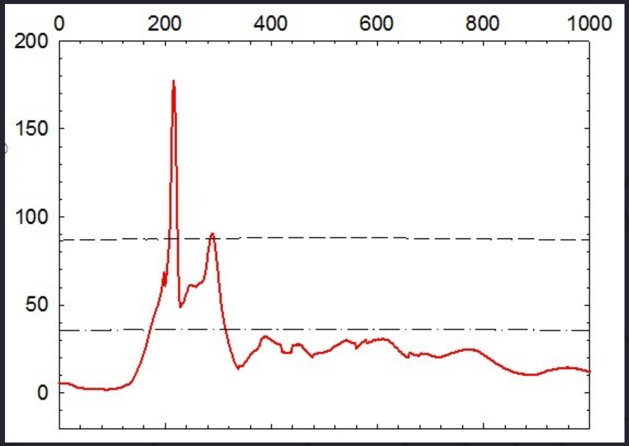
one primary burst
and
a few lesser bursts after
every 100-200 yr



(Vorobyov & Basu 2015, ApJ)

Tidal disruption of a fragment on approach to the star





Fragments can be tidally disrupted when approaching the star, giving rise to a series of closely packed bursts

Fragments that withstand the disruptive influence of tidal torques produce isolated bursts

Properties of the bursts in the disk fragmentation model (Vorobyov & Basu 2015)

Model	$N_{\rm bst}$	$M_{\rm bst}^{\rm tot}$ (%)	$t_{\rm bst}^{\rm tot}$ (%)	$L_{\rm max}/L_{\rm min}/L_{\rm mean}$ ($L_{\odot}$)	$\dot{M}_{\rm max}/\dot{M}_{\rm min}/\dot{M}_{\rm mean}$ ($10^{-4}\ M_{\odot}\ {\rm yr}^{-1}$)	$t_{\rm bst}^{\rm max}/t_{\rm bst}^{\rm min}/t_{\rm bst}^{\rm mean}$ (yr)	$t_{\rm qst}^{\rm max}/t_{\rm qst}^{\rm min}/t_{\rm qst}^{\rm mean}$ (10^{4} yr)
					4-mag cutoff		
1	10	3.8	0.035	357/87/208	2.4/0.78/1.4	48/12/25	10/1.6/4.7
2	13	18.6	0.06	3042/77/846	20/0.8/5.3	78/10/36	15/0.36/4.4
5	3	1.3	0.02	620/403/500	1.2/0.92/1.0	82/18/41	–
7	3	2.0	0.04	227/115/157	2.6/0.9/1.5	64/36/47	–
					FUors (observations)		
	26	–	–	525/10/200	10/0.01/1.9	80/4/20	–

Isolated bursts:

Total number per system – 3 -13 **(about 5-10)**

Burst duration – [10 – 80] yr **(4 – 80 yr)**

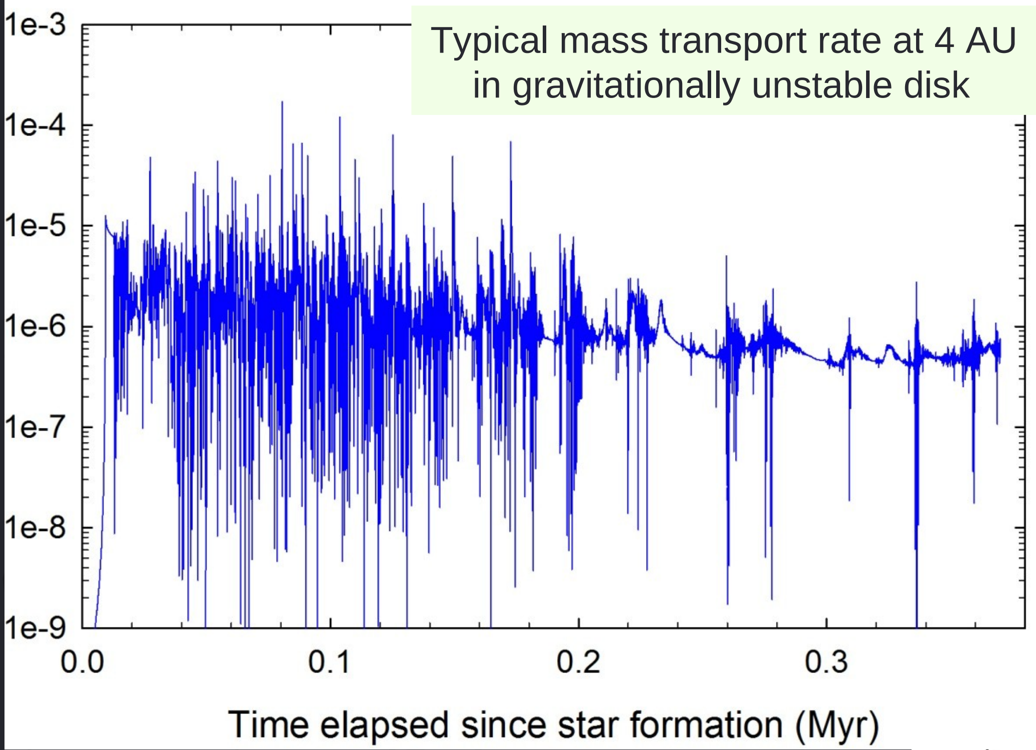
Duration of quiescent phase – [3.6*10^{3} -1.5*10^{5}] yr

Accretion rate – [8*10^{-5} - 2*10^{-3}] $M_{\odot}$ yr^{-1} **(10^{-6} – 10^{-3} $M_{\odot}$ yr^{-1})**

Clustered bursts:

Duration between the bursts – a few hundred years

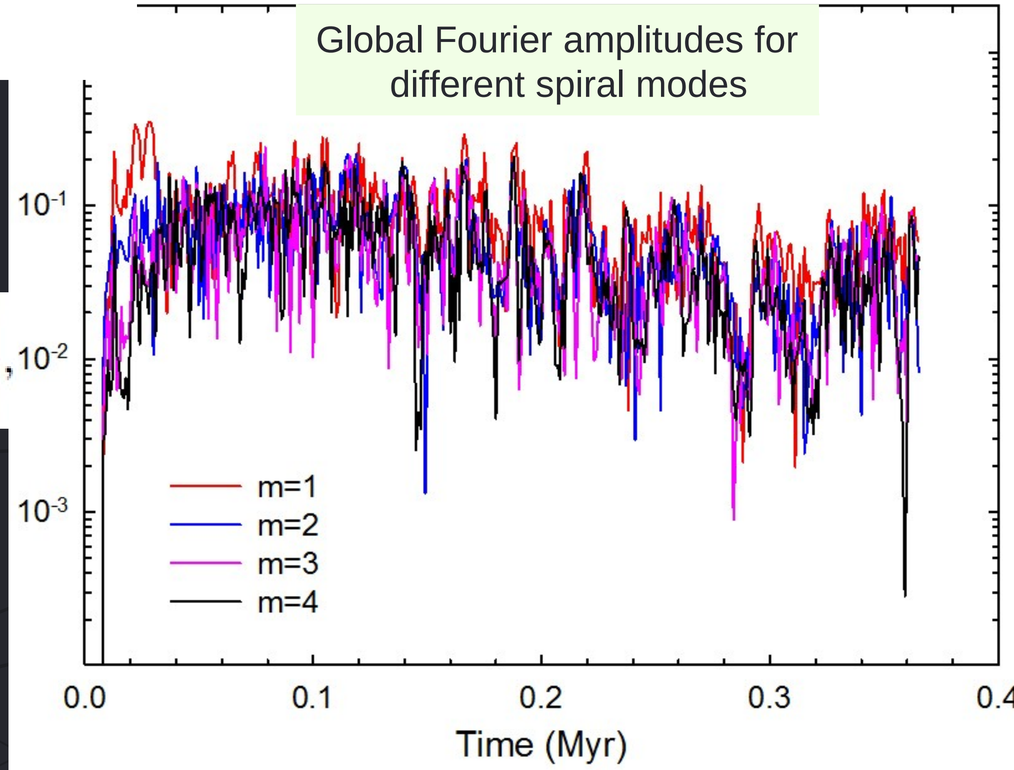
Number of bursts - a few



GFA can be regarded as a measure of non-axisymmetric density perturbations in the disk.

C_2 = 0.1 means that the amplitude of a two-armed spiral relative to the underlying axysimmetric disk is 10%

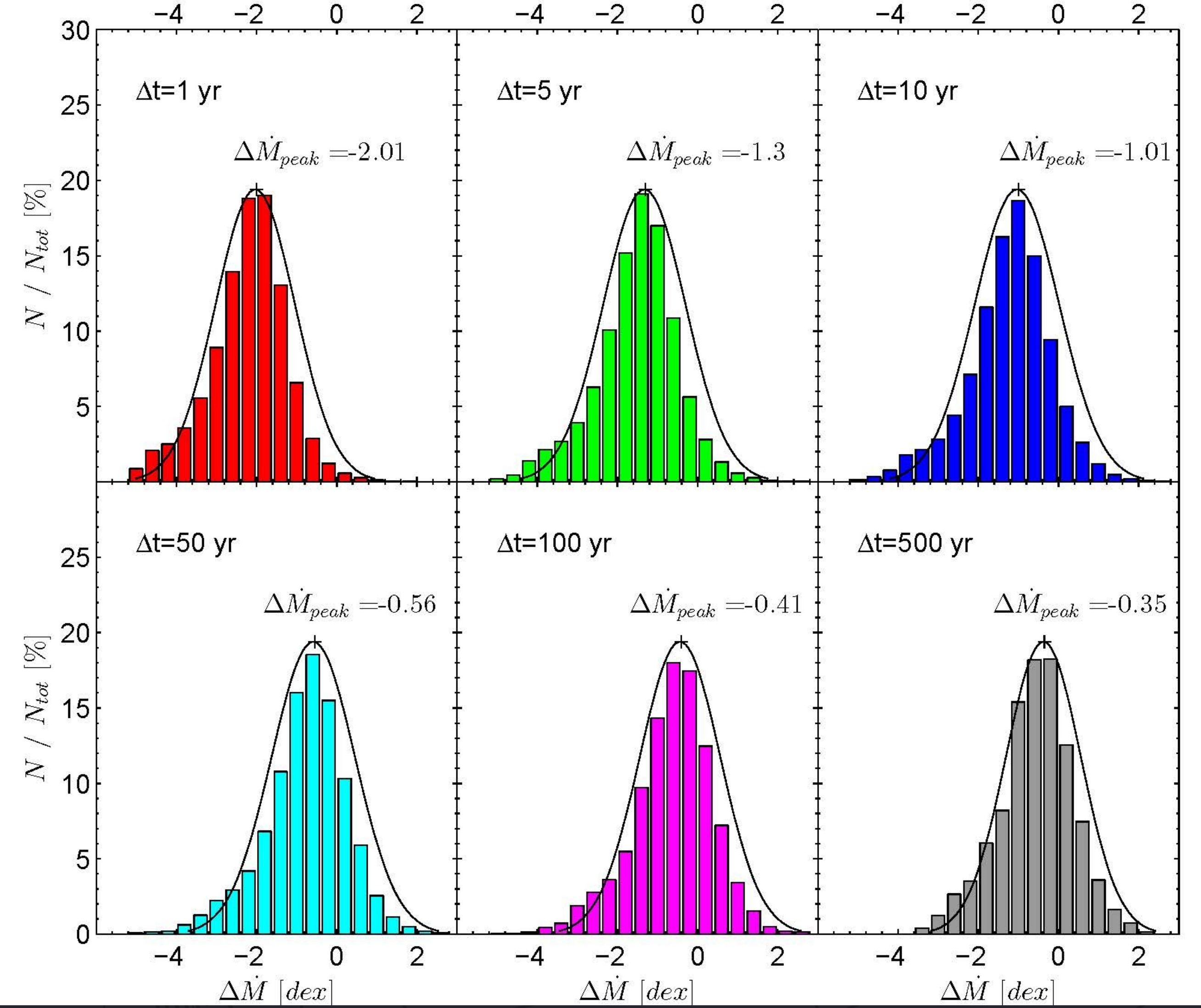
$$C_m(t) = \frac{1}{M_{disk}} \left| \int_0^{2\pi} \int_{R_{sc}}^{R_{disc}} \Sigma(r, \phi, t)\, e^{im\phi} r\, dr\, d\phi \right|,$$



Non-linear interaction between time-varying spiral modes produces highly variable transport rates?

$$\Delta \dot{M} = \log \frac{|\dot{M}(t+\Delta t) - \dot{M}(t)|}{\min[\dot{M}(t+\Delta t), \dot{M}(t)]}$$

Relative amplitude in mass transport rate at 4 AU



Can variability at AU scales influence / feed stellar variability?

1) Relative amplitude increases with increasing time sampling Δt
2) Significant spread around the peak value (several orders of magnitude)

Key conclusions

- Inward migration of clumps in gravitationally unstable disks produce luminosity outbursts with properties similar to FUors.

- Clump-triggered bursts have a wide range in properties, featuring isolated and clustered events with burst durations from 10 to 80 yr and quiescent periods from a few 100 yr to 10^5 yr.

- Mass transport rates at a few AU are intrinsically variable. Relative amplitude increases with increasing time sampling.

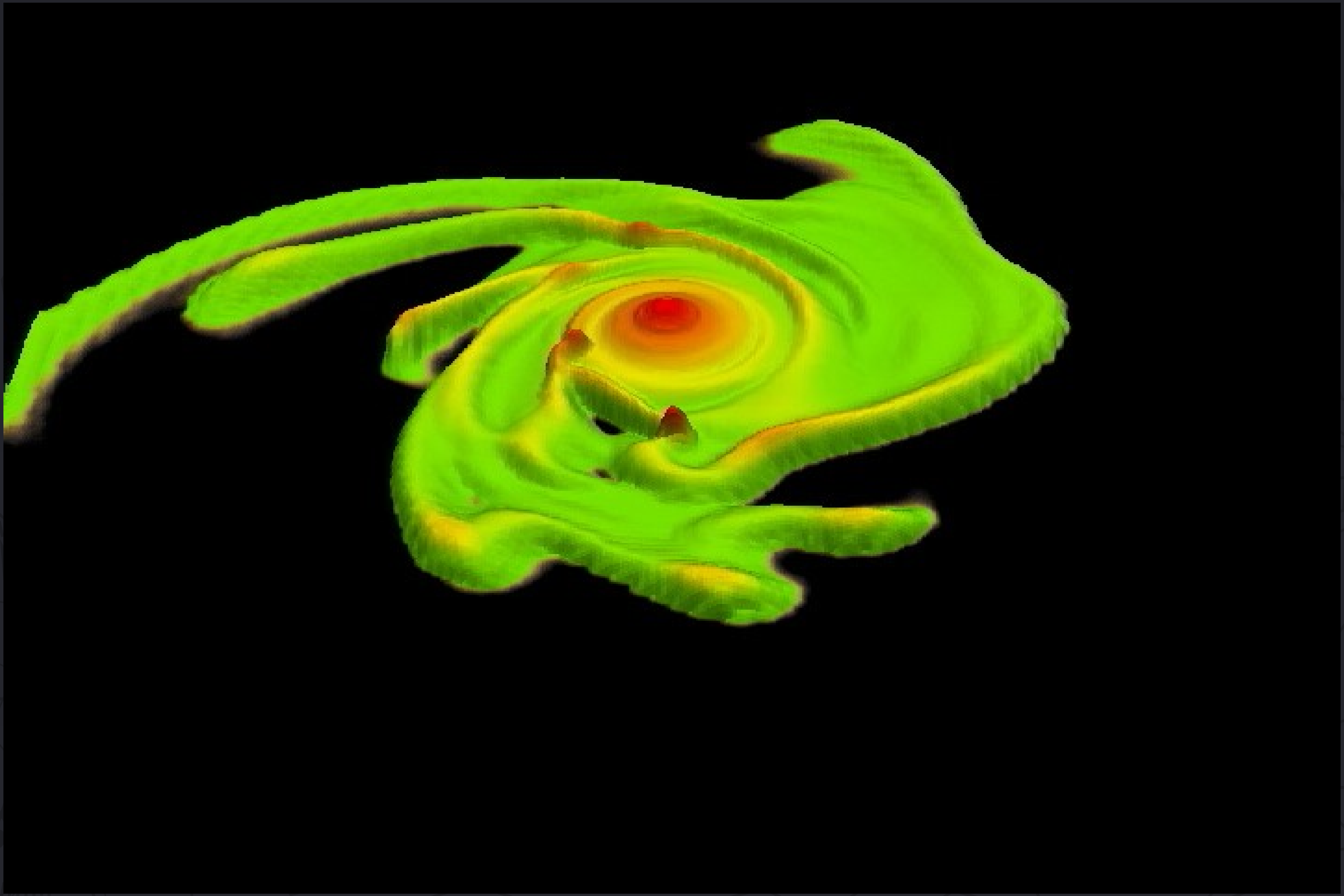
Open questions:

- How does variable accretion affect the jets/outflows (knots)?

- How variability at several AU is linked to stellar variability?

Numerical simulations have been performed on the VSC-2, SHARCNET and ACEnet clusters

3D view on the burst phenomenon

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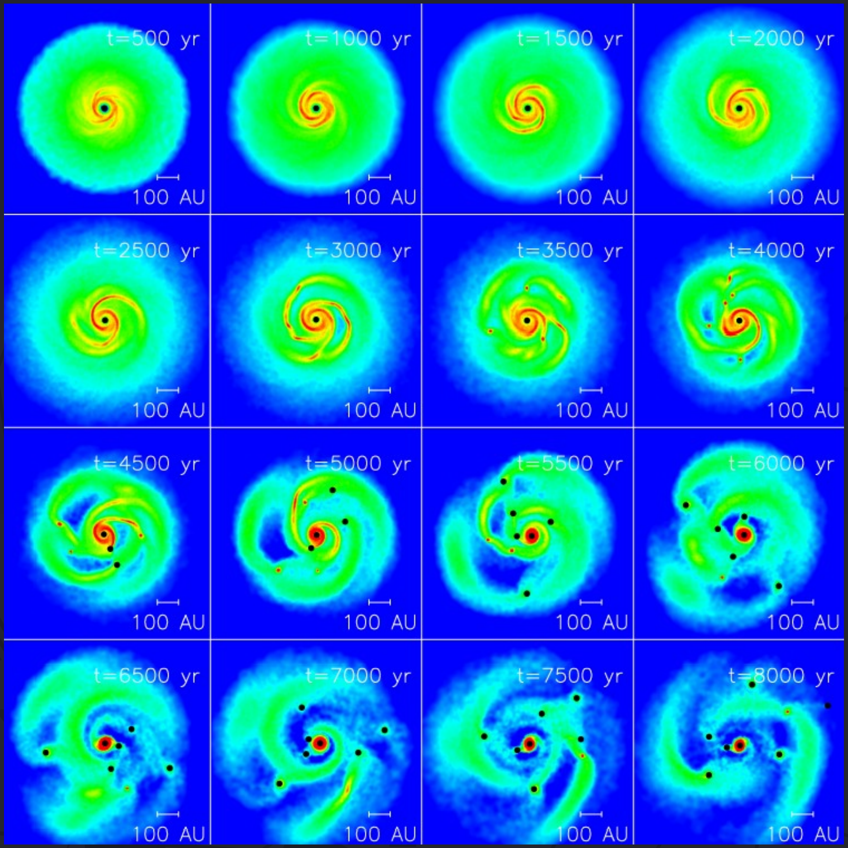
Variable accretion with episodic bursts.
A new paradigm?

Gravitational fragmentation and inward migration of fragments onto the protostar

(Vorobyov & Basu 2005, ApJL; Vorobyov & Basu 2006, 2010, ApJ)

Gravitational fragmentation of protostellar disks

Stamatellos & Whitworth (2009 MNRAS)



Various numerical and theoretical studies[1] of protostellar disks have shown that under favorable initial configurations and in the absence of magnetic fields, disk fragmentation is a robust phenomenon.

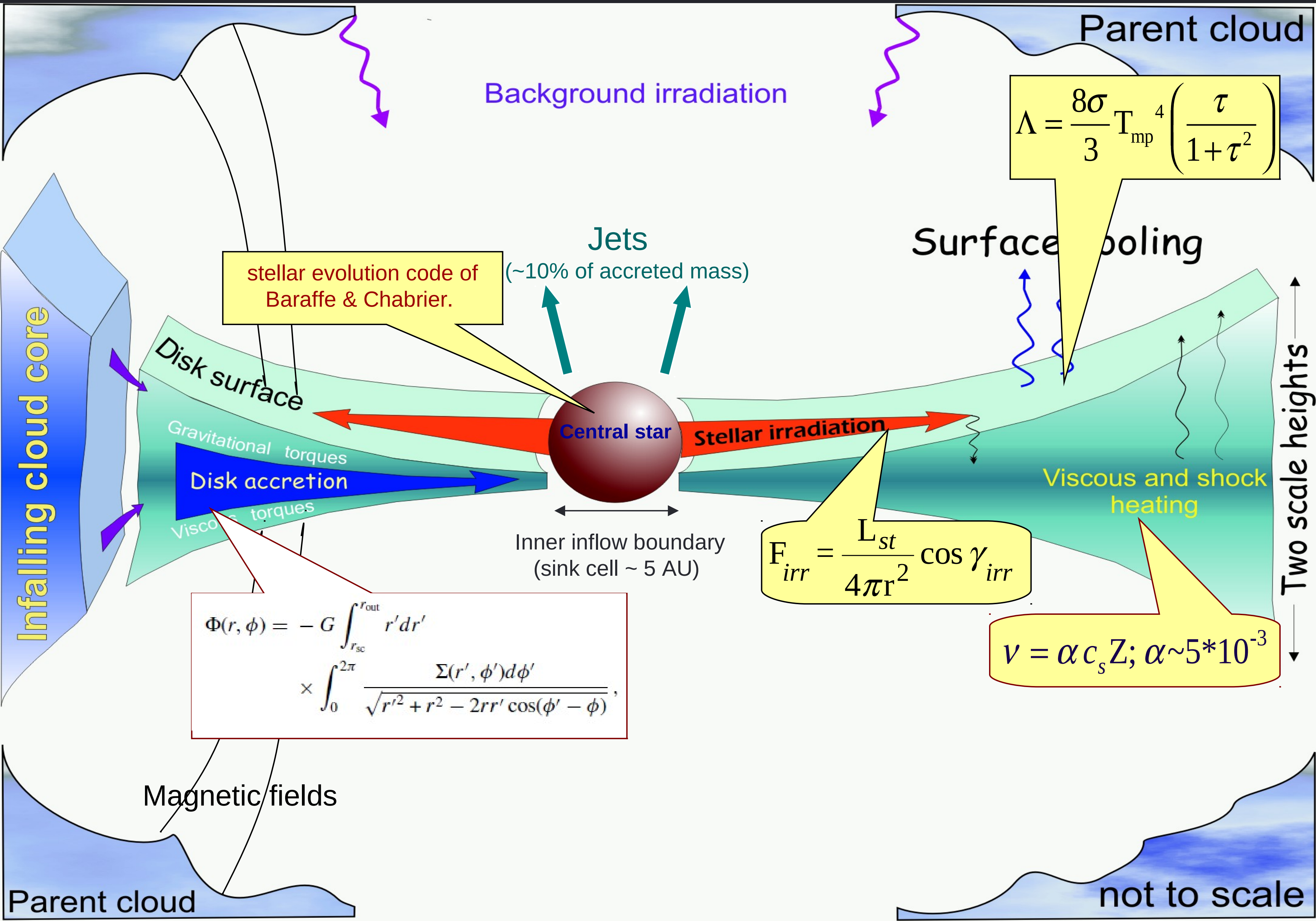
Prerequisites for disk fragmentation:

- relatively massive disks (> 10% that of the star)
- sufficiently large size (> 50 AU)
- sufficiently fast disk cooling ($\Omega * t_{cool} < 3 - 5$)

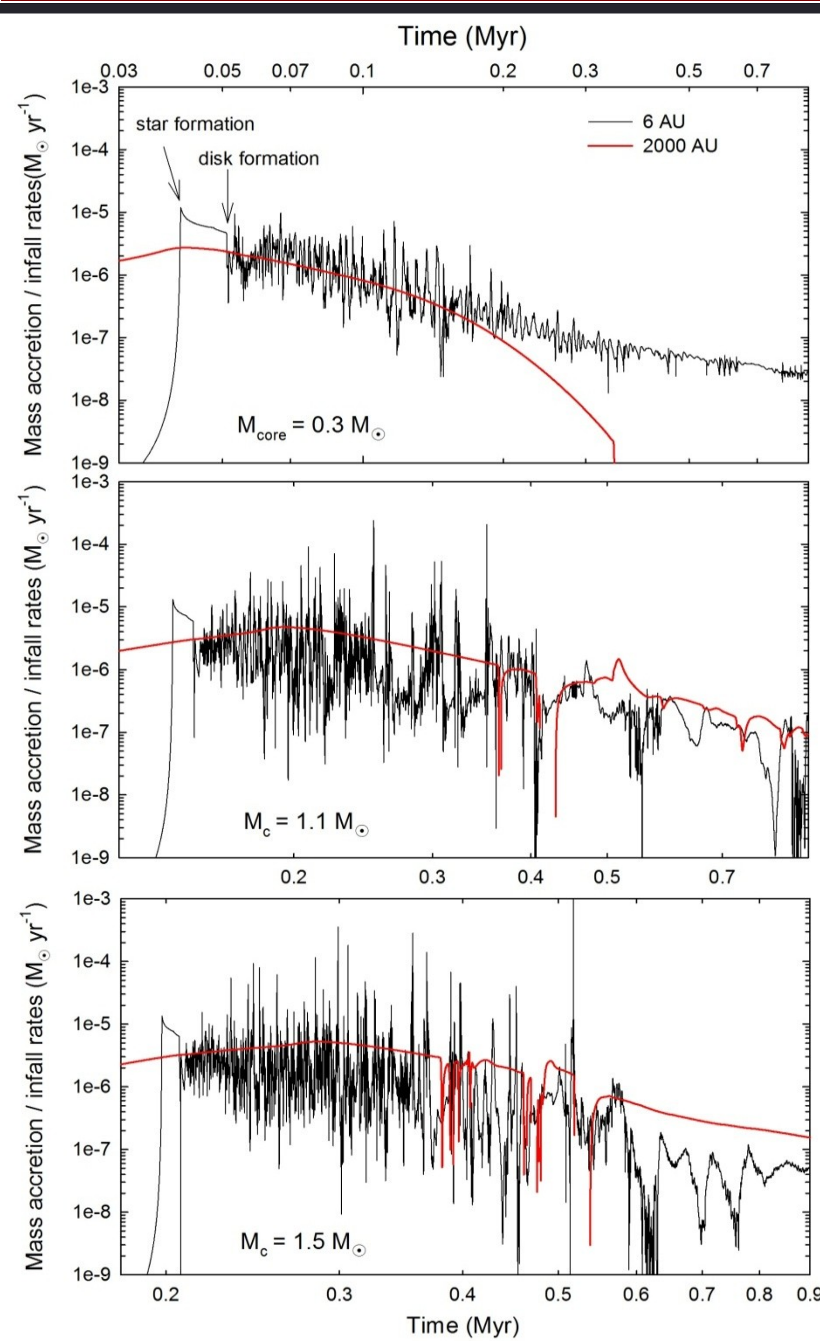
[1] References : Stamatellos, Whitworth, Kroupa, Inutsuka, Gammie, Bate, Boss, Machida, Zhu, Durisen, Nayakshin, Mayer, Wadsley, Kratter, Krumholz, Klein, Hayfield, Lodato, Clarke, Goodwin, Thies, Vorobyov, Basu and many others)

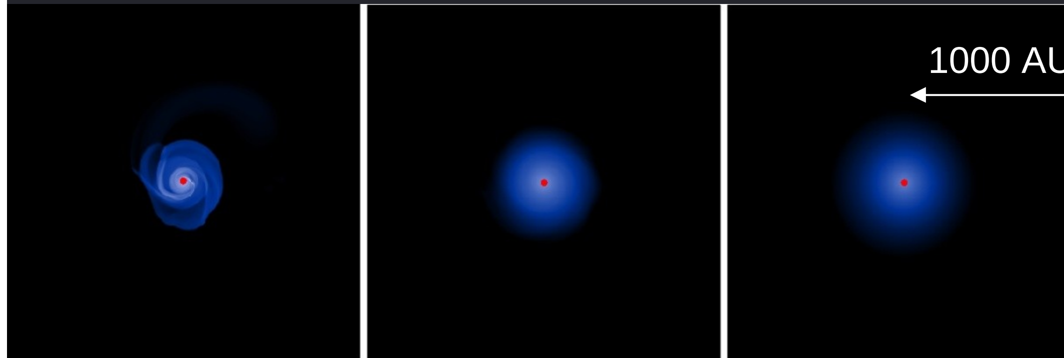
Major question: fragments can form in the disk, but can they survive?

Model of an accreting protostar and protostellar disk

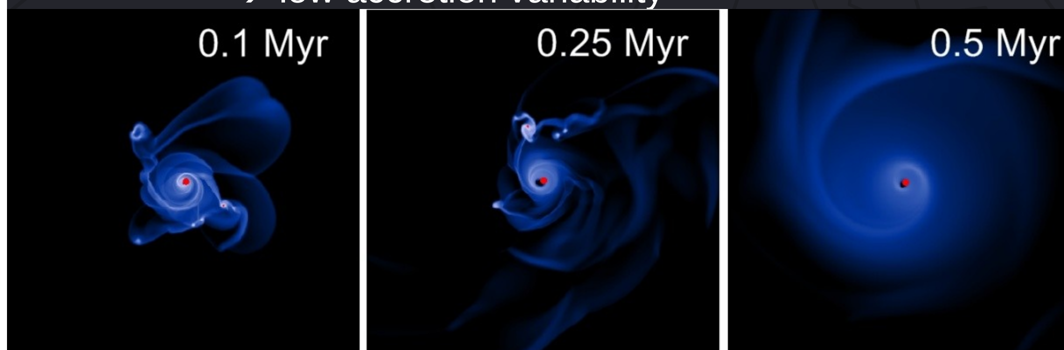


Accretion and infall rates in models with different core masses





Weak gravitational instability, no disk fragmentation →
→ low accretion variability



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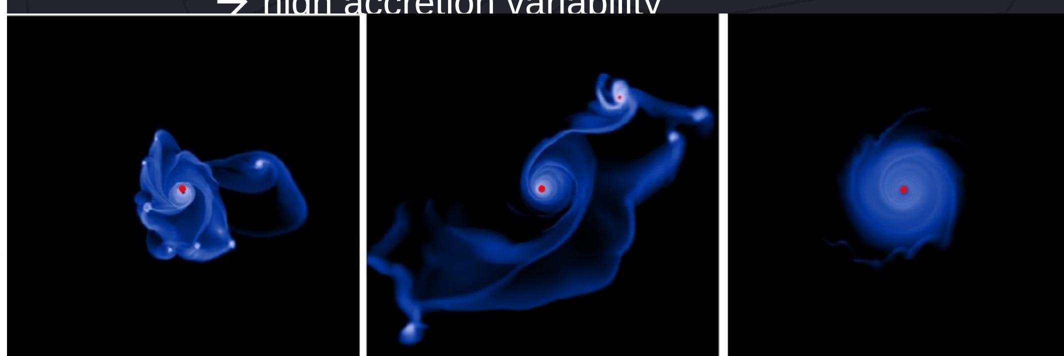

Key result: gravitational instability and fragmentation are responsible for accretion variations and bursts

How significant are the bursts?

(Updated from Hartmann & Kenyon, 1996, ARAA, 34, 207)

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Within 1 kpc of the Sun:

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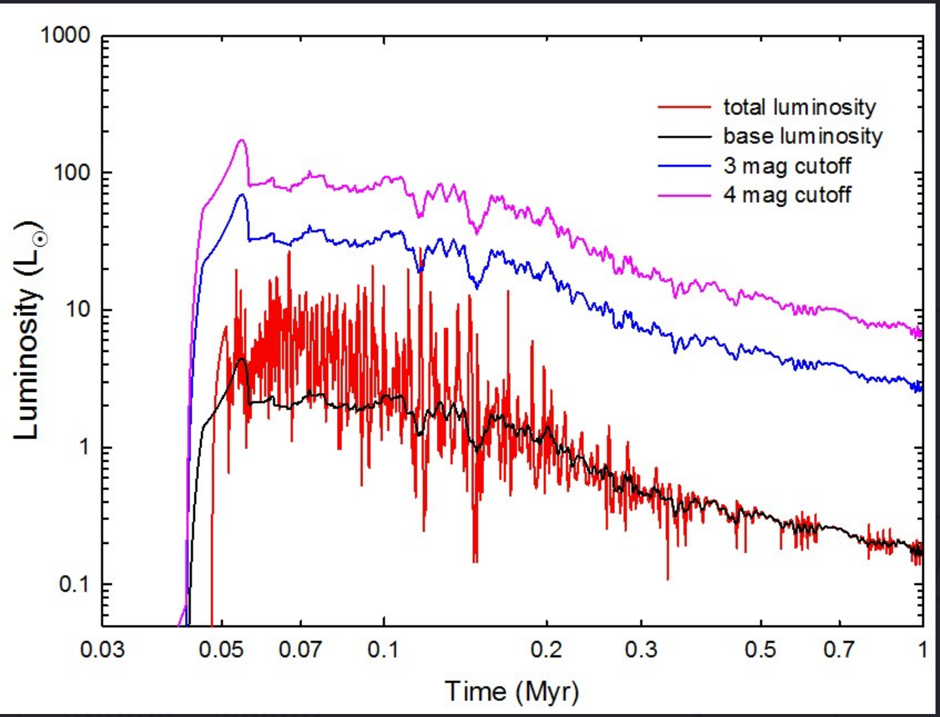
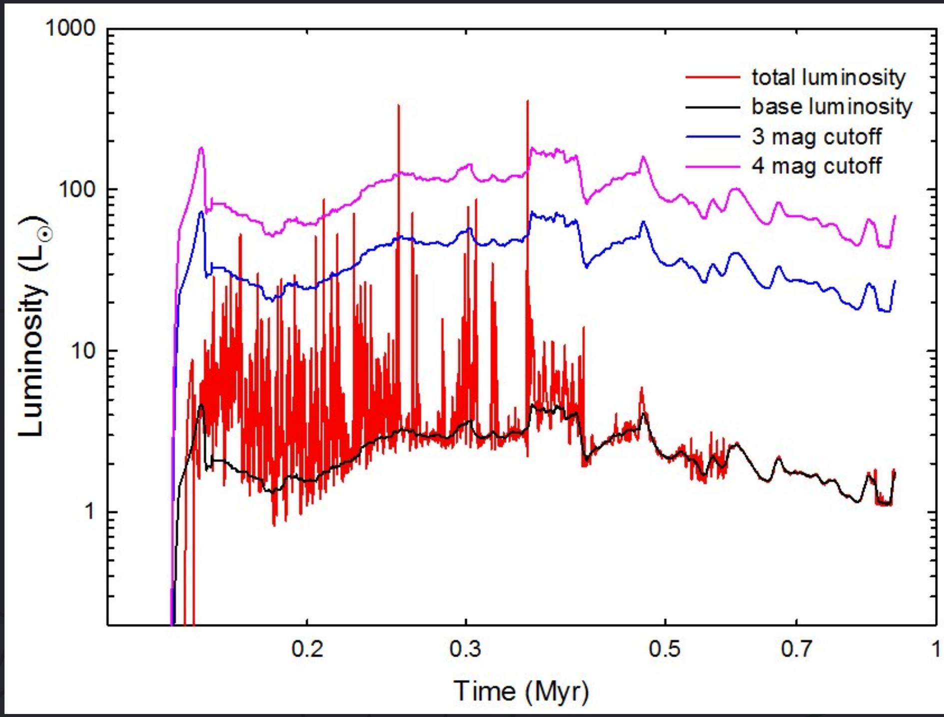
- FUors occur at several times the rate of star formation; implying multiple bursts per star

Adopted from PPVI presentation
“Episodic accretion in young stars”

Properties of the bursts

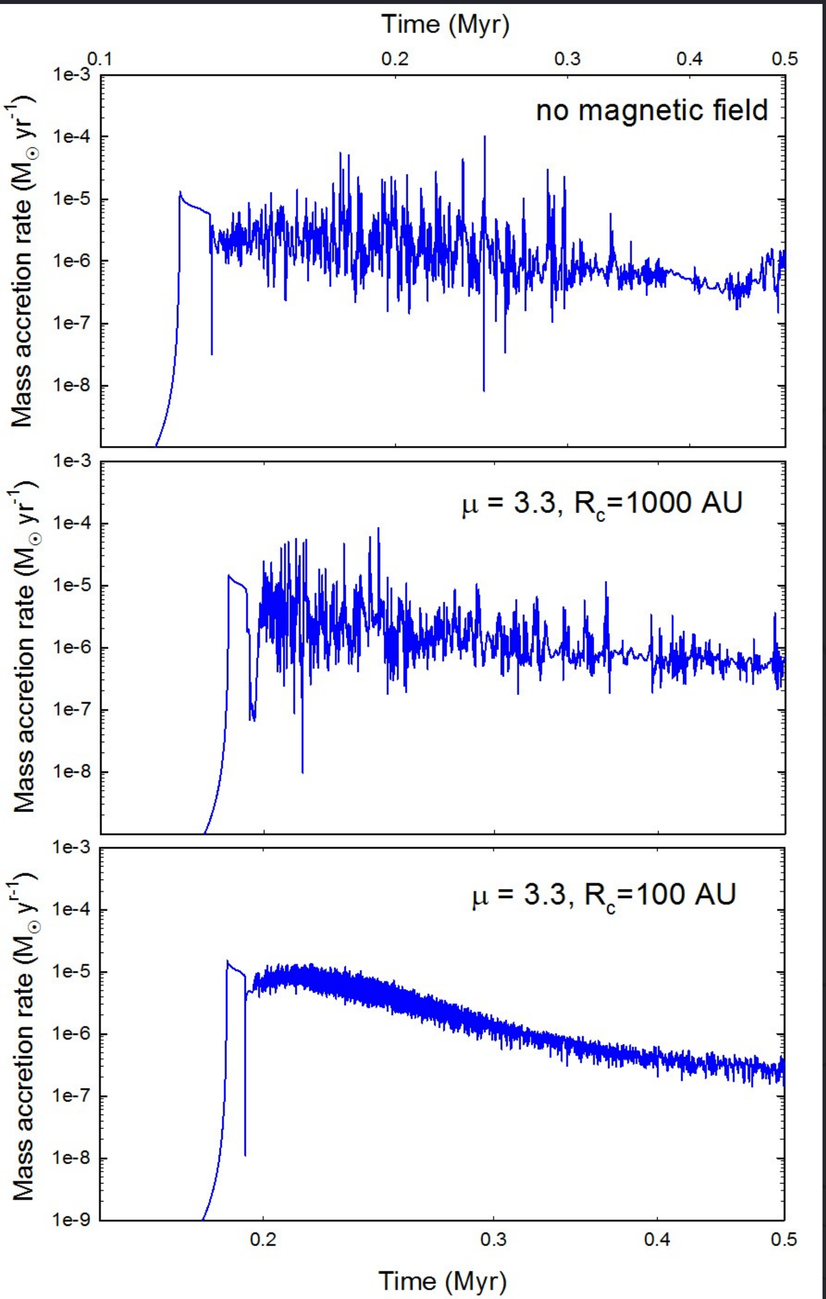




Base luminosity – photospheric luminosity plus accretion luminosity with dot{M} ≤ 10^{-6} $M_{\odot}$ yr^{-1}

Core mass	N_{burst} (4 mag cutoff)	Accreted mass (relative to total mass)	Time spent in bursts (relative to total time)	N_{burst} (3 mag cutoff)	Accreted mass (relative to total mass)	Time spent in bursts (relative to total time)
0.3 Msun	0	0	0	2	0.8%	0.026%
1.1 Msun	5	2.4%	0.016%	17	7.4%	0.12%

The effect of magnetic field



Ideal MHD plus a toy model for magnetic braking

$$\dot{L}_{\rm mb} = \frac{\Sigma r^2 \left(\Omega(r) - \Omega_{\rm c}(r)\right)}{t_{\rm mb}},$$

The rate of loss of angular momentum via magnetic braking

$$t_{\rm mb} = \frac{R_{\rm c}}{v_{\rm A}},$$

Characteristic time of magnetic braking

Implications of variable accretion

Variable accretion with episodic bursts

- star
  - Variable mass and energy deposition
    - radius, chemistry, total luminosity, position on the HR diagram
- Disk / envelope
  - Quiescent periods
    - Decrease in temperature
      - disk stability, chemistry, condensation of volatiles
  - Luminosity bursts
    - Increase in temperature (~ fact. 2 – 3)
      - disk stability, chemistry, evaporation of ices, CAI, crystalline silicates

Baraffe et al. 2009, 2012; Baraffe & Chabrier 2010; Vorobyov et al. 2013, Stamatellos et al. 2012; Dunham & Vorobyov 2012; Km et al. 2012