Variable accretion with episodic bursts

author: **Eduard Vorobyov**

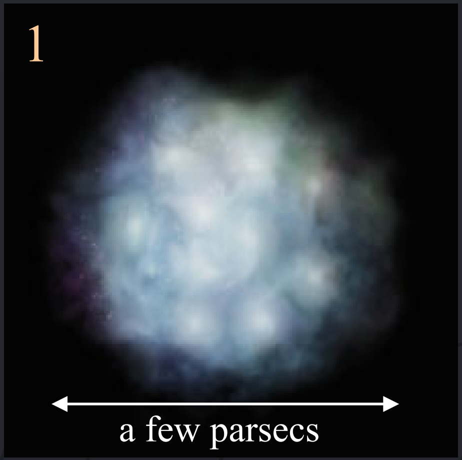
affiliation: Department of Astrophysics, University of Vienna, Vienna, Austria and
Research Institute of Physics, Southern Federal University, Rostov-on-Don, Russia

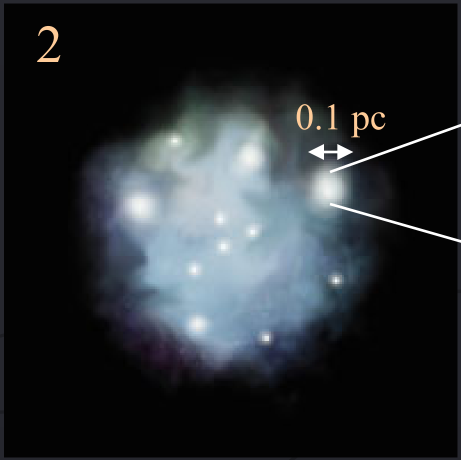
Co-authors: Shantanu Basu, Michael Dunham, Isabelle Baraffe, Gilles Chabrier

OUTLINE

1. Failure of the classic spherical accretion models (e.g. Shu 1977)
2. Variable accretion with episodic bursts - a new paradigm?
3. Accretion in gravitationally unstable disks.

Five main stages of low-mass star formation





t = 1 - 2 Myr

3

Pre-stellar phase

~ 0.1 pc

a few x 10^4 yr

Embedded phase

4

a few x 10^5 yr

Planet formation phase

5

a few x 10^6 yr

Most of the stellar mass is accreted during
a short-lived embedded phase, we know this for sure

But we do not know the past accretion history …
Accretion rates were constant? Declining? Time-varying?

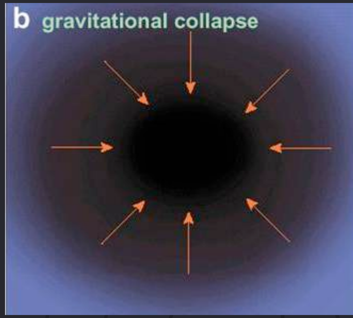
Stellar evolution, disk dynamics and chemistry, dust and ice composition
may depend on the past accretion history!

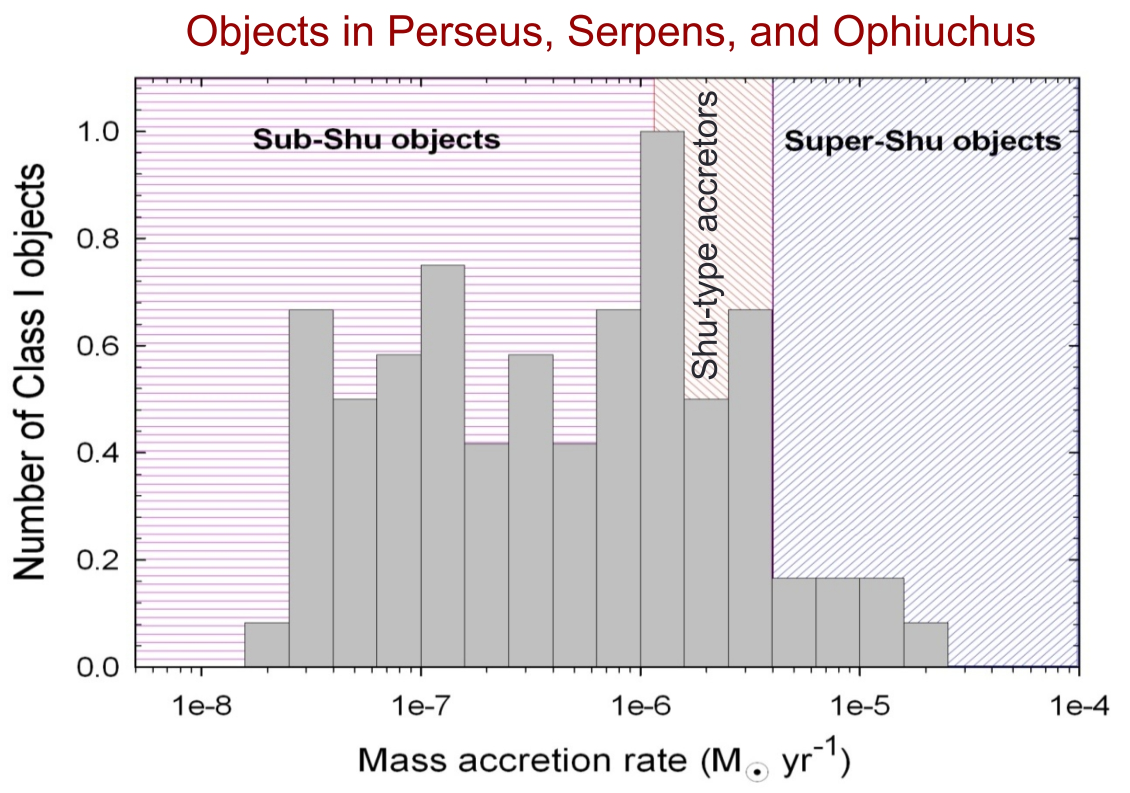
Mass accretion rates

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

[illegible]

$M_\odot\ yr^{-1}$, for T = 10 – 20 K




Objects in Perseus, Serpens, and Ophiuchus

[illegible]

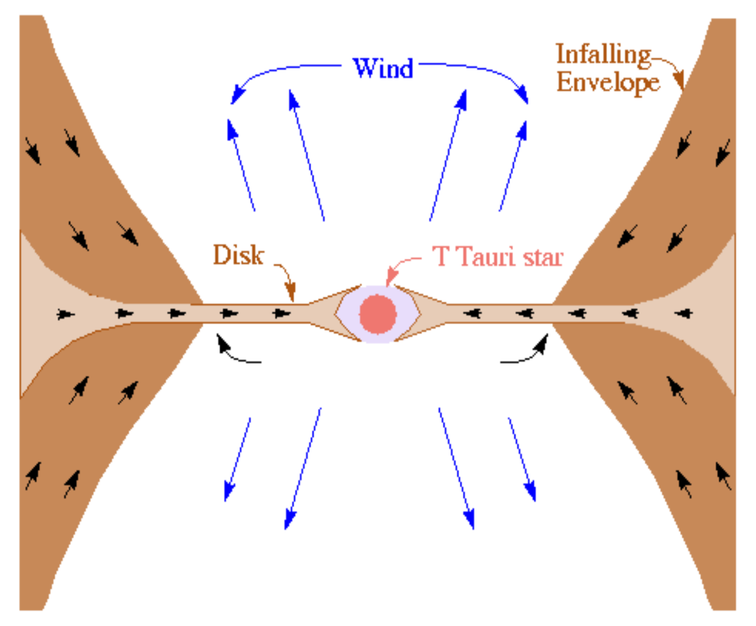
55% – $M_\odot\ yr^{-1}$

5% – $M_\odot\ yr^{-1}$

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

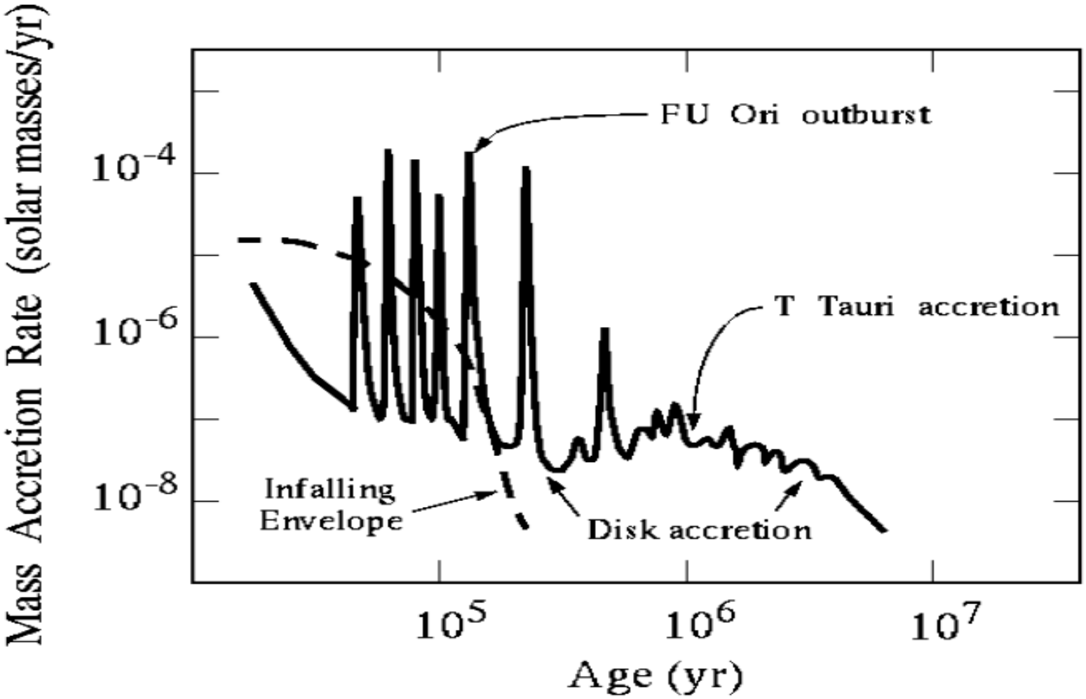
Variable accretion with episodic bursts

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.

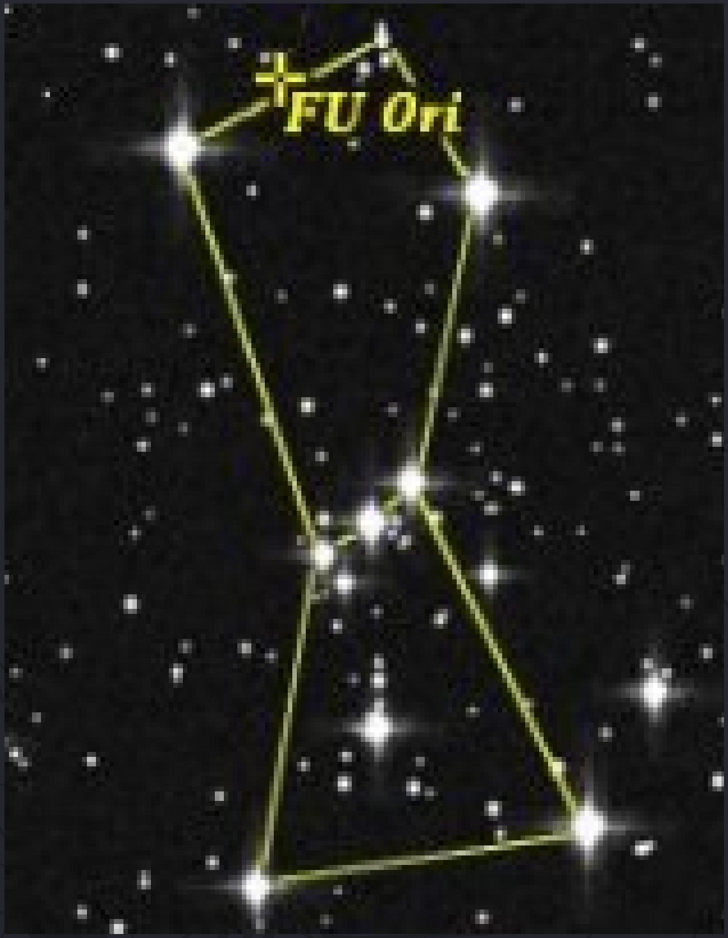


modified from Hartmann & Kenyon,1996

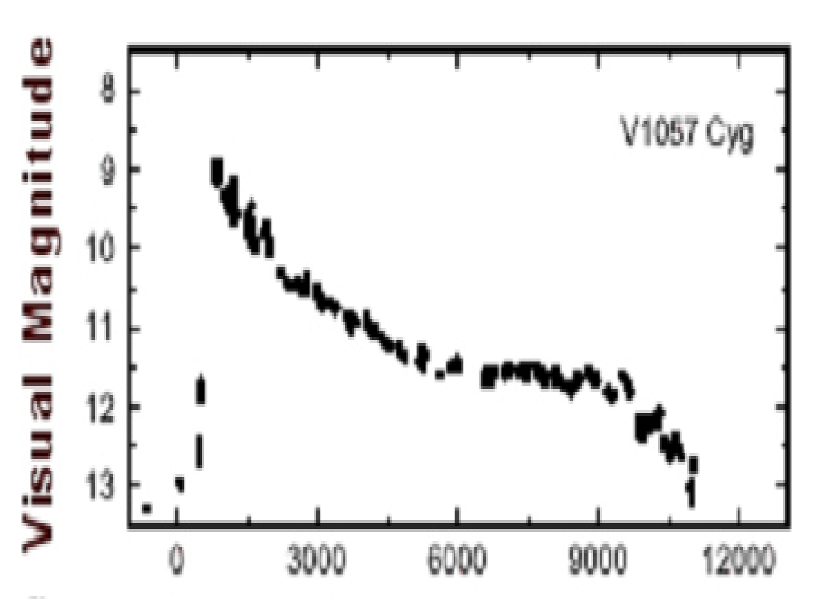
Kenyon et al. 1990; Hartman 1998



FU Orionis eruptions



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



35 yr

A sharp increase in luminosity of FUors is thought to be caused by accretion bursts

Variable accretion with episodic bursts.
A new paradigm?

Mechanisms responsible for episodic bursts

Several mechanisms that can produce episodic bursts include:

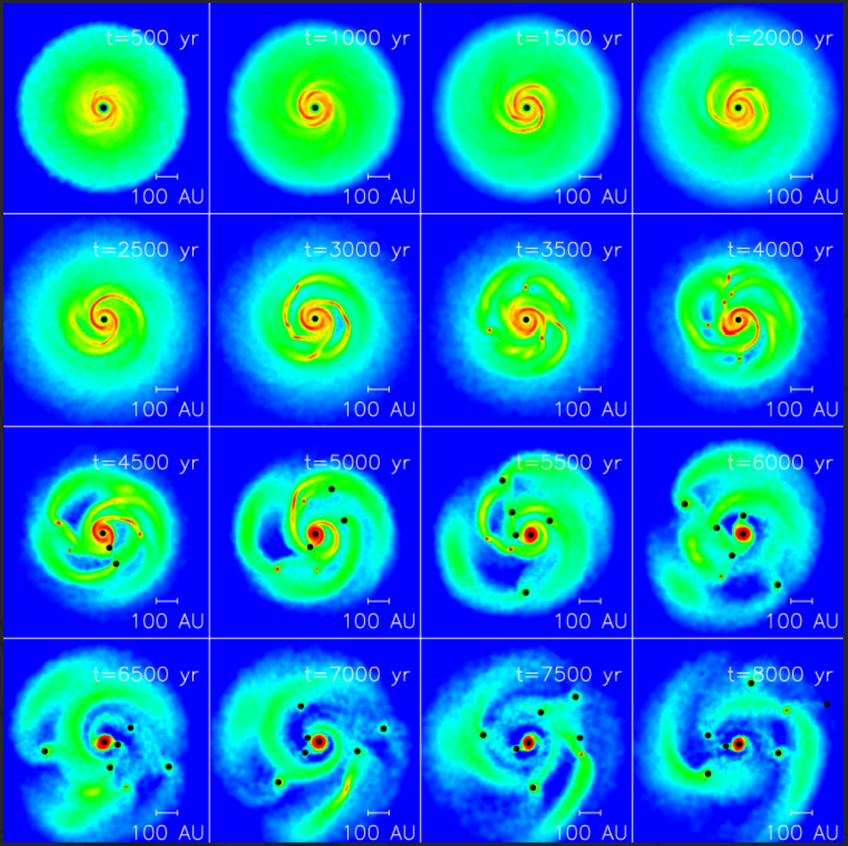
- viscous-thermal instabilities in the inner disk (Lin & Papaloizou 1986),
- thermal instabilities induced by density perturbations due to a massive planet in the disk (Lodato & Clarke 2004),
- tidal effects from close encounters in binary systems or stellar clusters (Bonnell & Bastien1992; Reipurth & 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 fragmenting disk (Vorobyov & Basu 2005, 2006, 2010; Machida et al. 2011)

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.

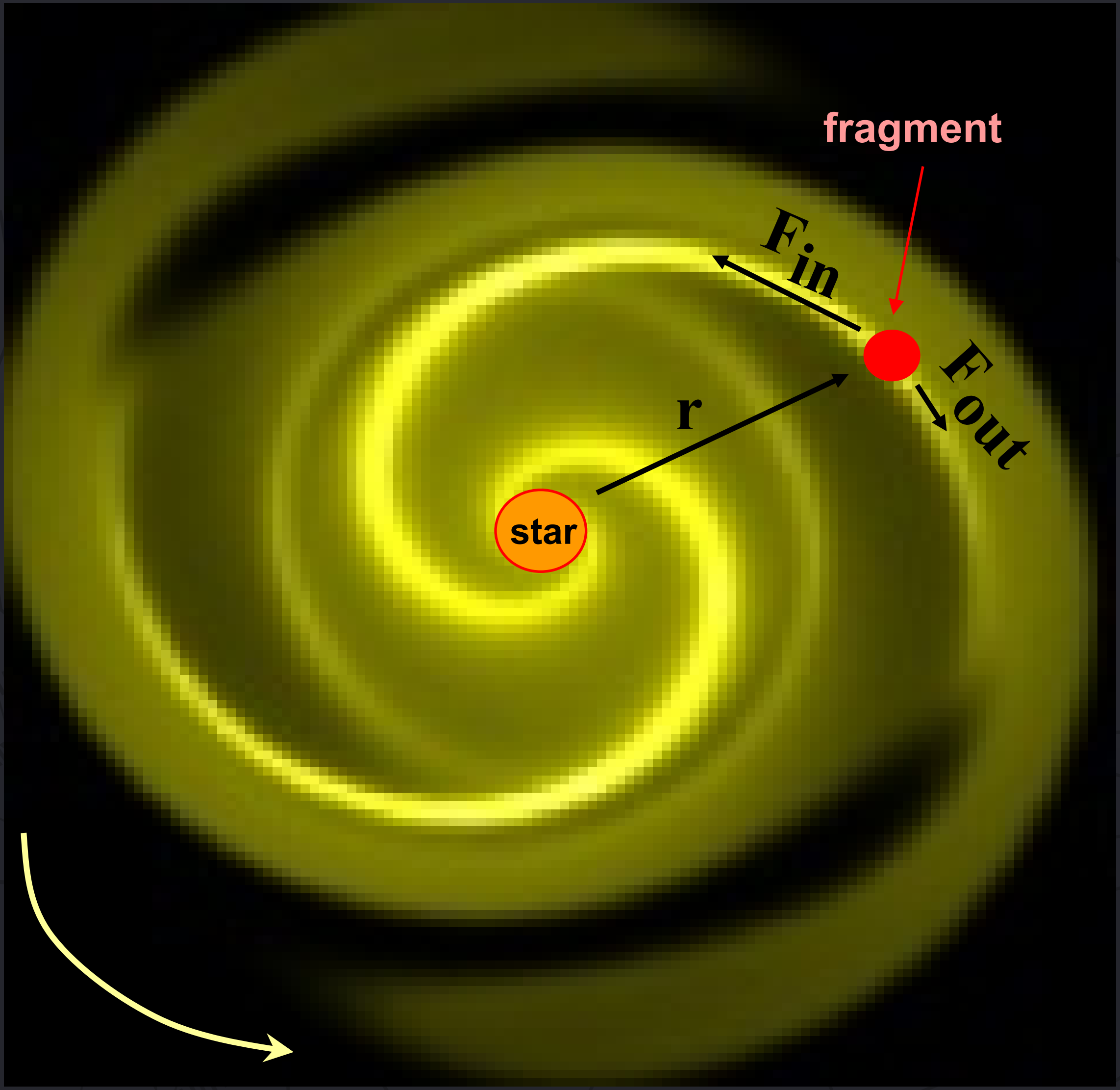
Prerequisites for disk fragmentation:

- 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?

Inward vigration of fragments in protostellar disks



$$\Gamma_{in} = \mathbf{r} \times \mathbf{F}_{in} > 0$$

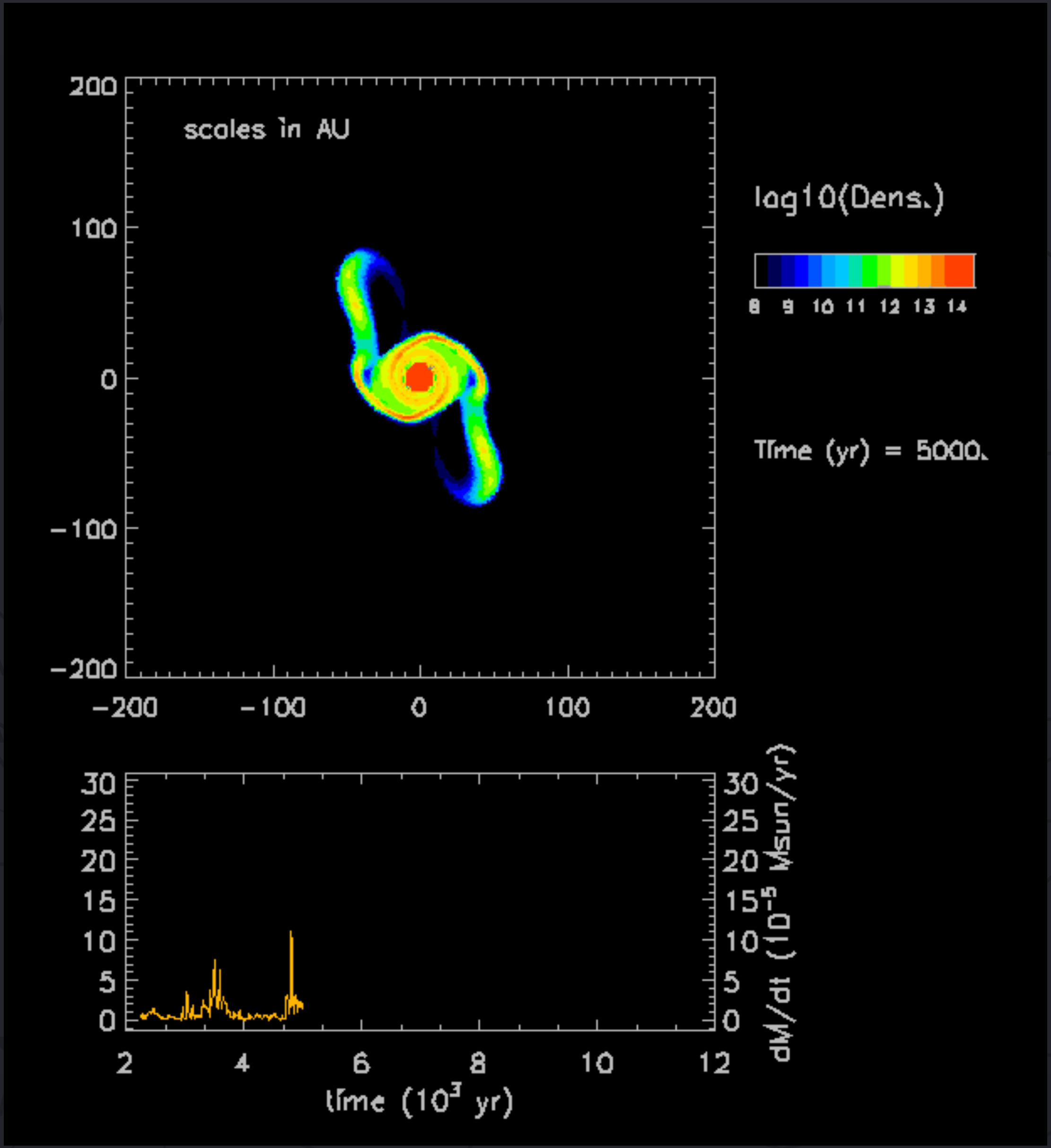
$$\Gamma_{out} = \mathbf{r} \times \mathbf{F}_{out} < 0$$

Fragments may stay at quasi-stable orbits for as long as $\Gamma_{in} > \mathrm{abs}(\Gamma_{out})$

In the embedded phase this inequality almost always breaks due to
1)continuing disk growth via accretion from the infalling envelope.
2)sub-Keplerian velocity of the accreted material

Key result: most fragments forming in the disk migrate onto the star

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



Initial core mass = 1.0 M_{sun}

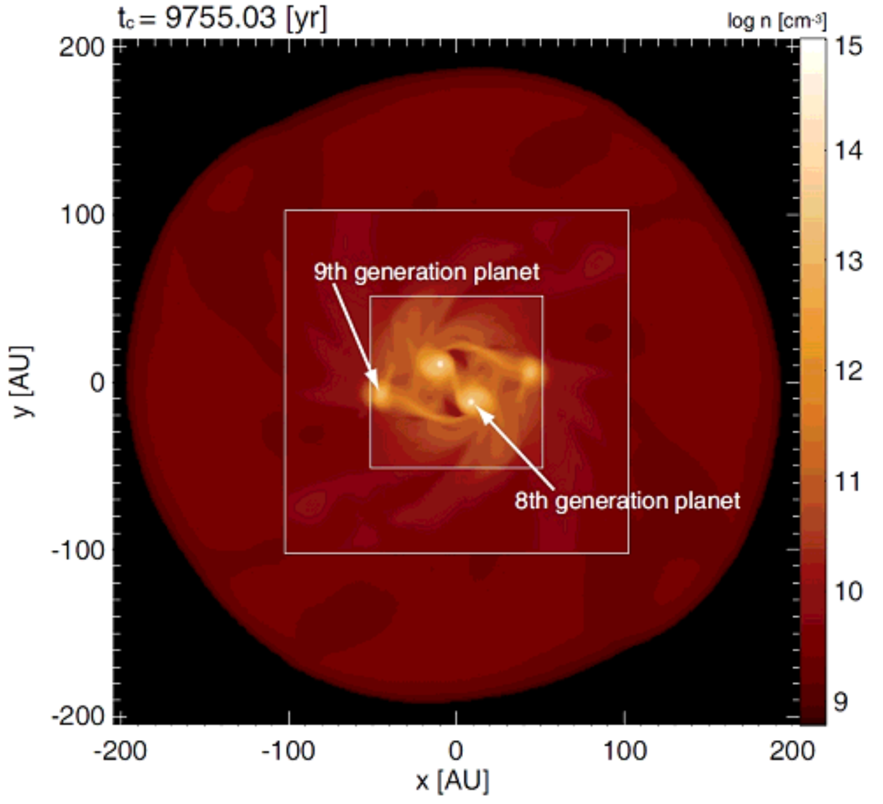
Face-on view of the disk
Black regions – infalling envelope
(off scale)

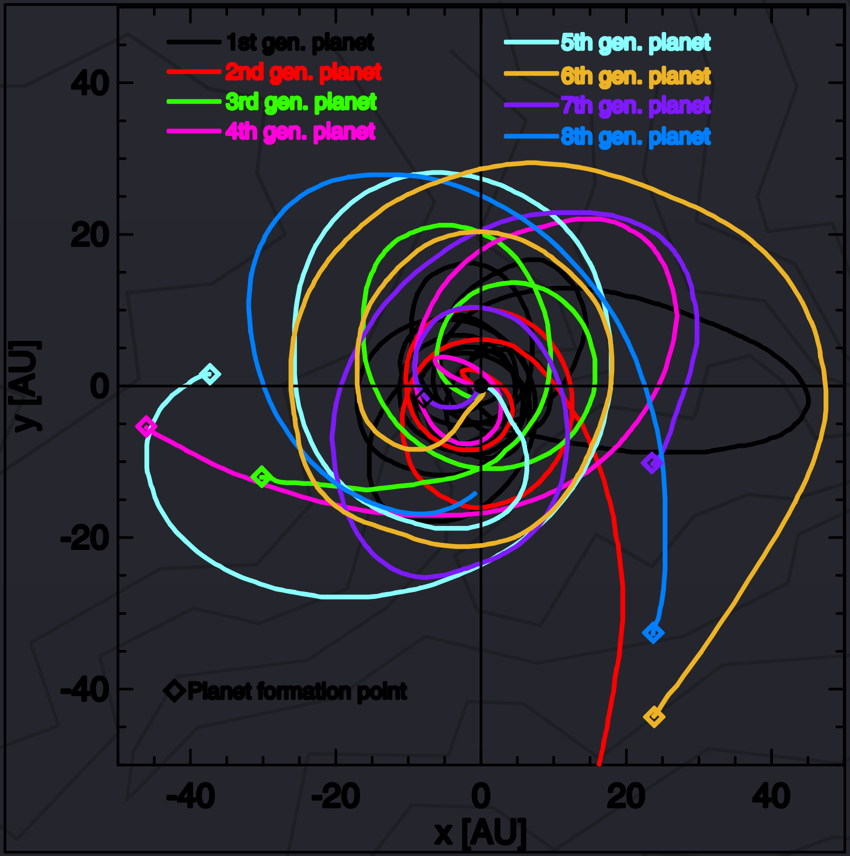
Mass accretion rate at 5 AU
10^{-5} $M_\odot$ / year

Vorobyov & Basu (2006, 2010)

Migrating fragments in full 3D simulations

Full 3D numerical hydrodynamics simulations starting from pre-stellar cores but limited in time scope (≤ 10^5 yr)

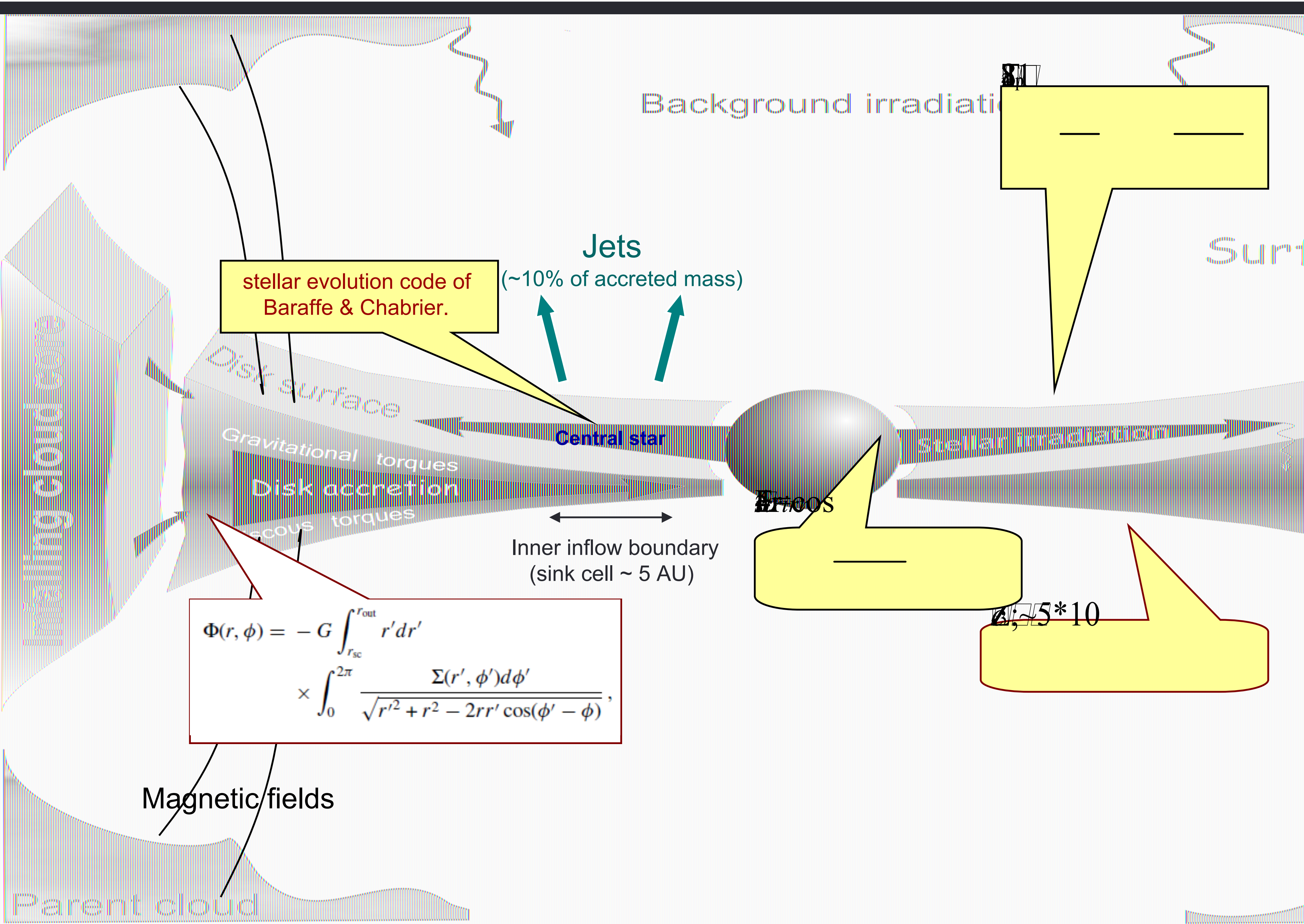




Machida, Inutsuka, Matsumoto 2011, ApJ, 729, 42

See also Zhu et al. (2012)

Model of an accreting protostar and protostellar disk



stellar evolution code of Baraffe & Chabrier.

Jets
(~10% of accreted mass)

Inner inflow boundary
(sink cell ~ 5 AU)

$$\Phi(r,\phi) = -G\int_{r_{sc}}^{r_{out}} r'dr' \times \int_0^{2\pi} \frac{\Sigma(r',\phi')d\phi'}{\sqrt{r'^2+r^2-2rr'\cos(\phi'-\phi)}},$$

Magnetic fields

Numerical hydrodynamics equations in the thin-disk approximation (r,ϕ)

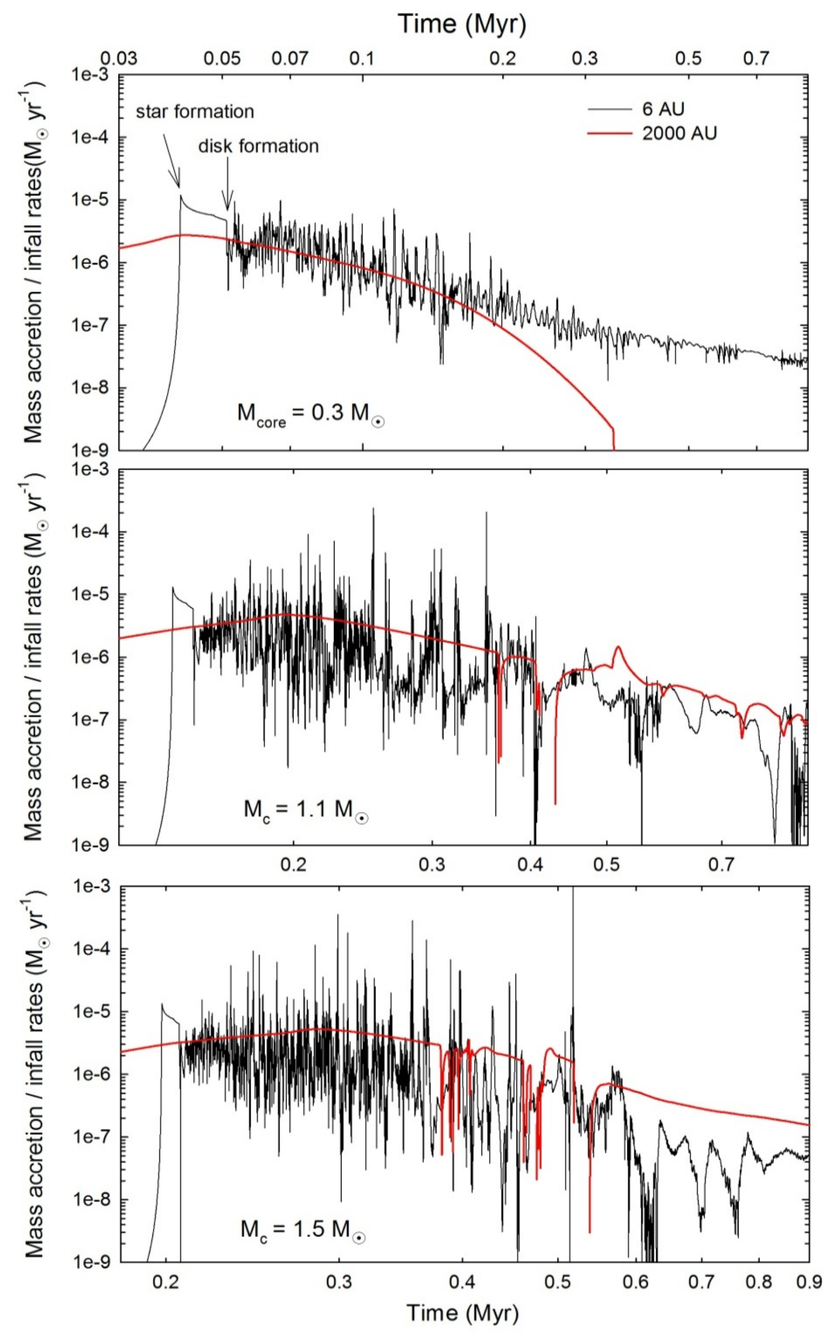
main equations

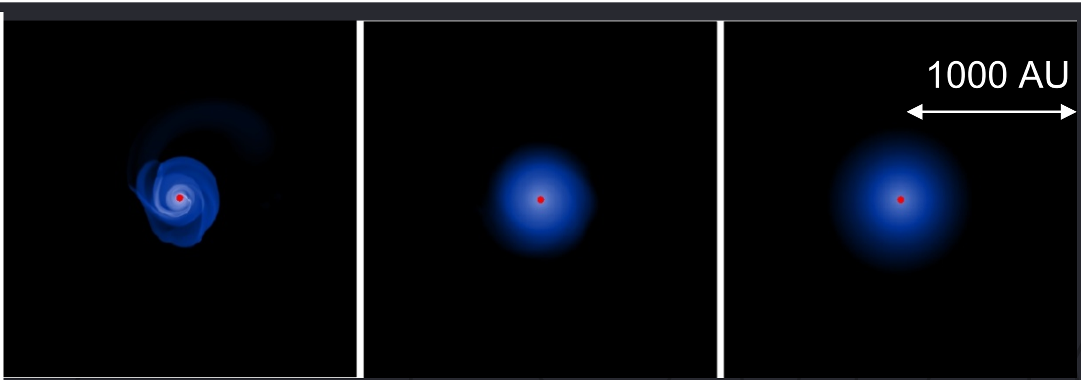
[illegible]

complementary equations

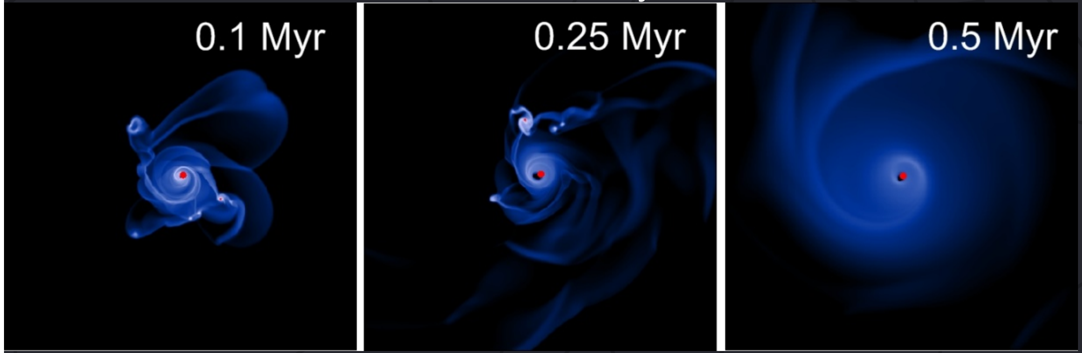
[illegible]

Accretion and infall rates in models with different core masses





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



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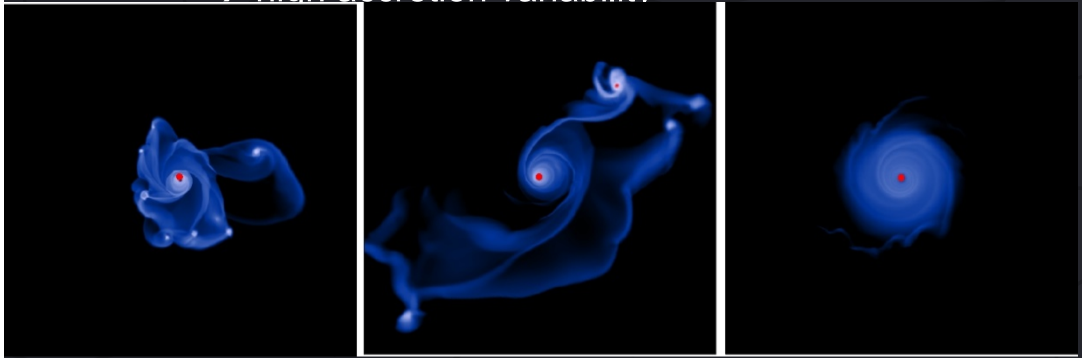


Key result: gravitational instability and fragmentation are responsible for accretion variations and bursts

How significant are the bursts?

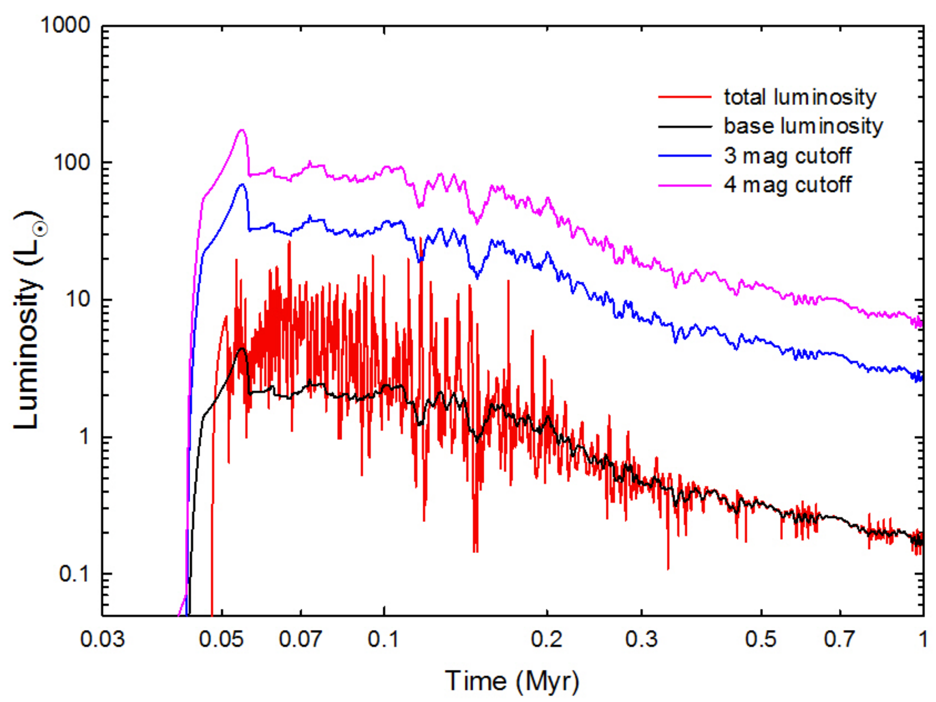
FUors are **rarely** seen…
but they are common events!

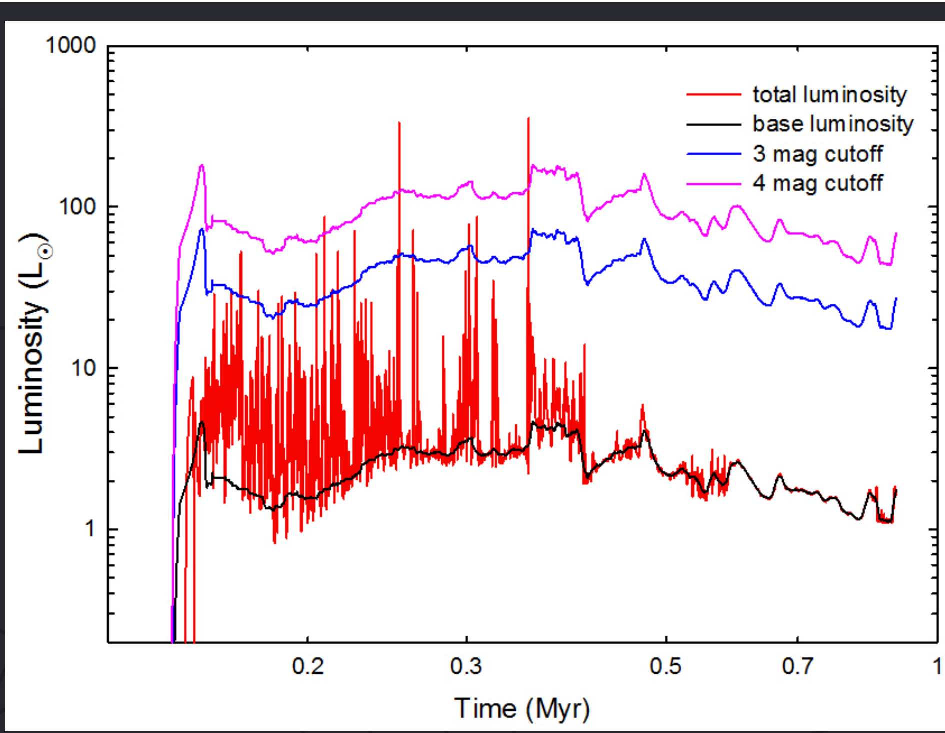
Within 1 kpc of the Sun:

- 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; implying multiple bursts per star

Adopted from PPVI presentation
“Episodic accretion in young stars”

Properties of the bursts

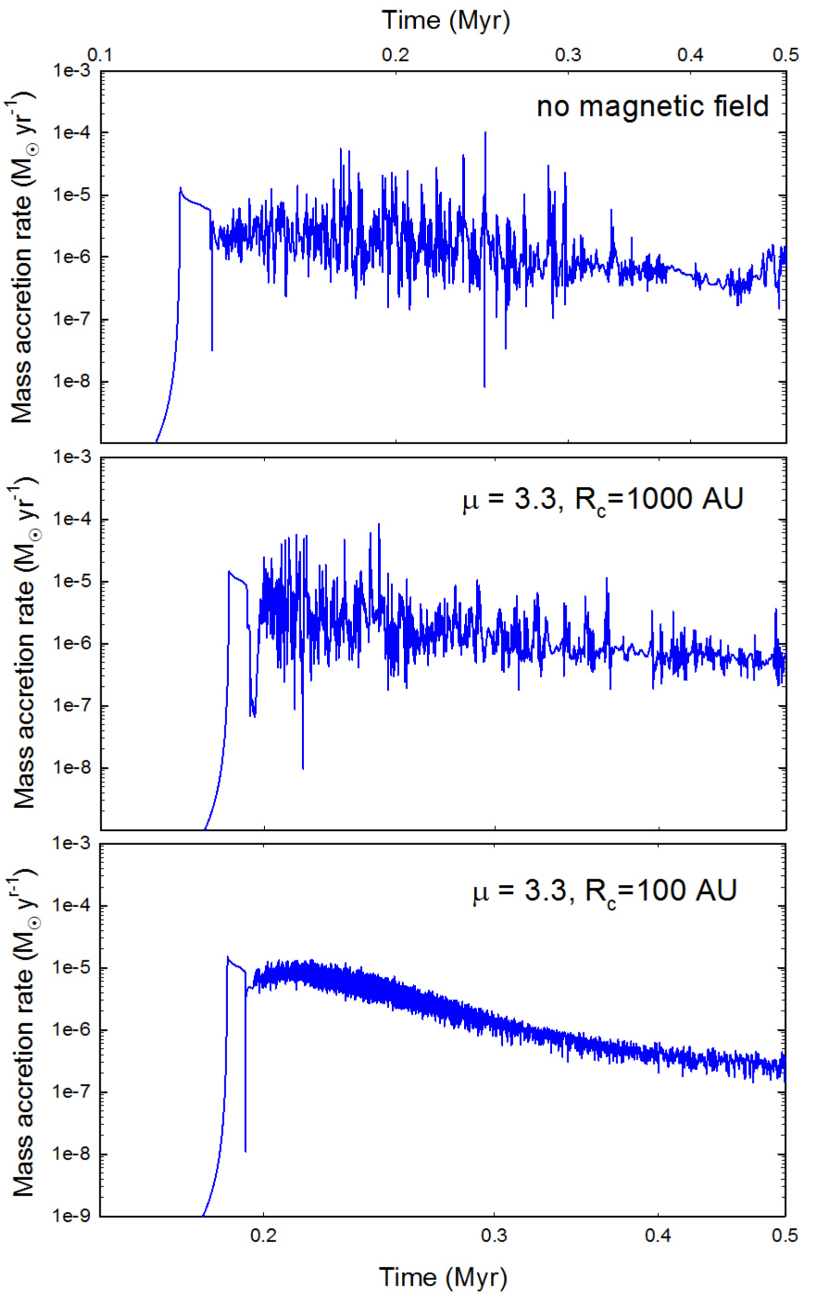




Base luminosity – photospheric luminosity plus accretion luminosity with dot{M} ≤ 10^{-6} $M_{\odot}$ yr^{-1}

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%
1.5 Msun	9	16%	0.36%	20	25%	2.6%

The effect of magnetic field



Ideal MHD plus a toy model for magnetic braking

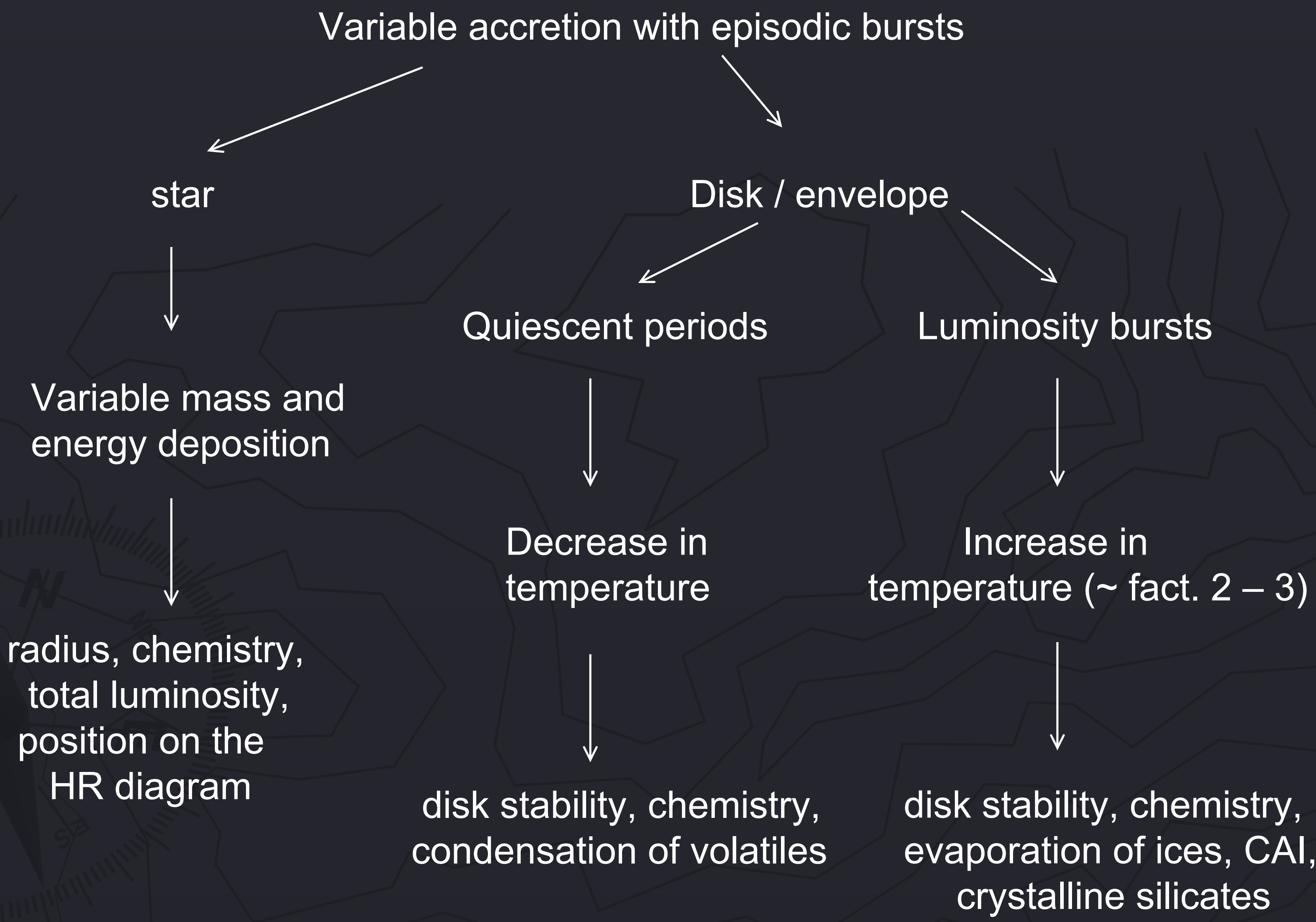
$$\dot{L}_{\rm mb} = \frac{\Sigma r^2 \left(\Omega(r) - \Omega_{\rm c}(r)\right)}{t_{\rm mb}},$$

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

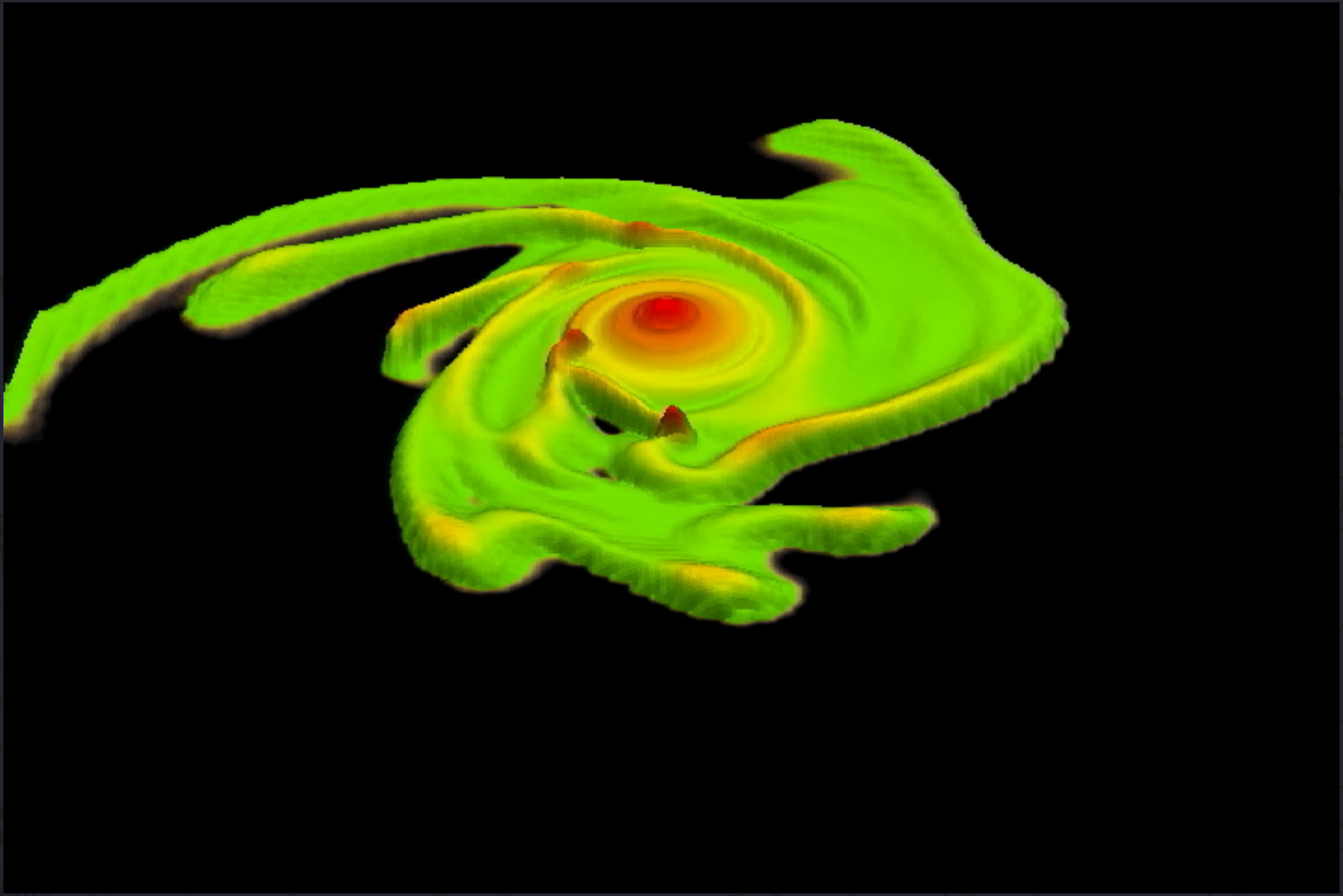
Luminosity bursts

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

3D view on the burst phenomenon



Key results for the disk instability model

- Accretion rates at several AU appear to be intrinsically variable in the embedded phase of disk evolution thanks to disk gravitational instability and fragmentation.

- When the disk fragments, most of the fragments are torqued onto the star via gravitational interaction with spiral arms, producing strong luminosity outbursts.

- The luminosity outbursts can have significant impact on both the host star and the disk/envelope

Open questions:

- Can magnetic fields kill accretion variability and bursts once and for all?

- How does variable accretion affect the properties of the stars (internal structure, spin, cold vs. hot accretion)?

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

- Is the fragment migration mechanism universal for astrophysical disks?

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