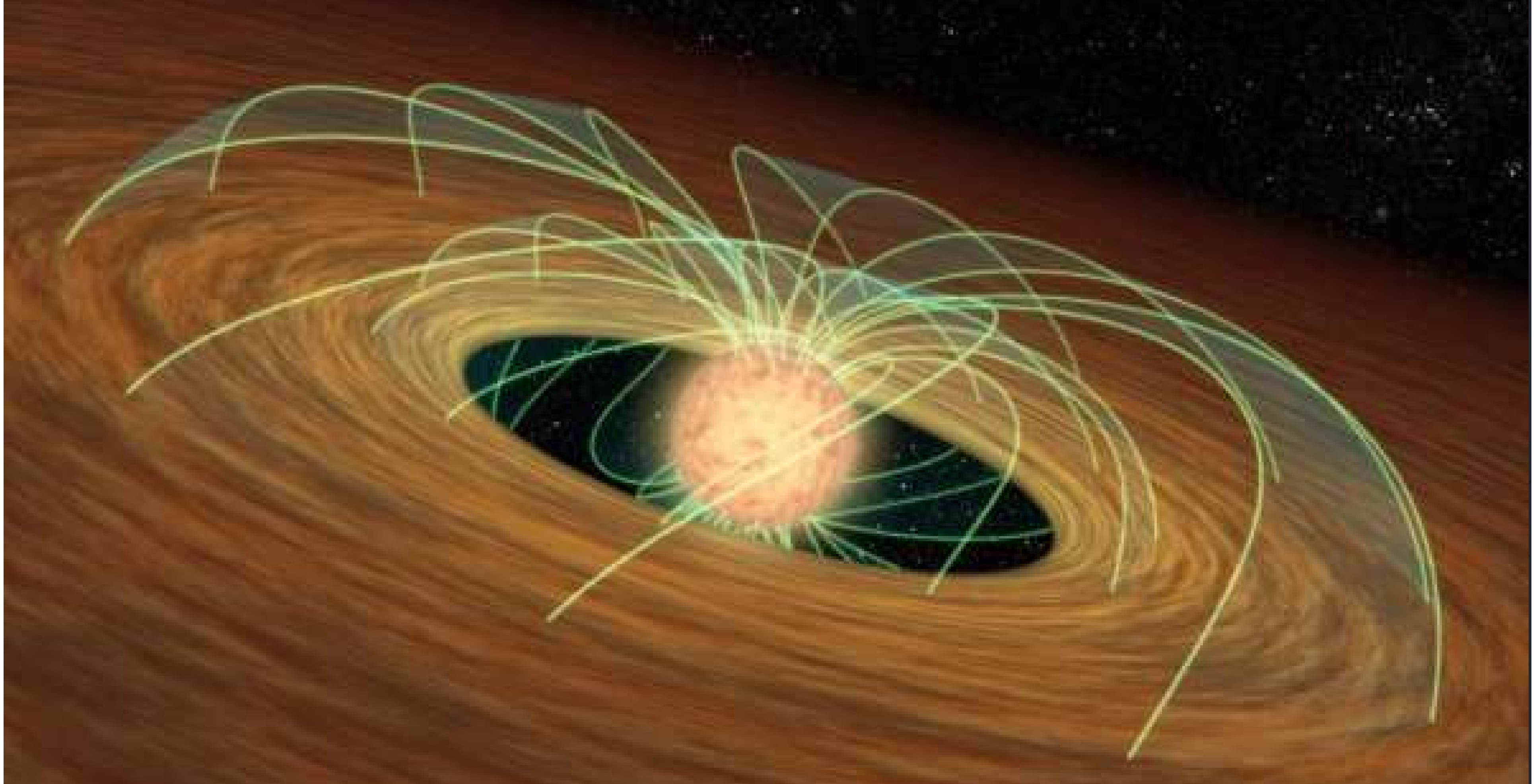
Accretion bursts and their effect on the pre-main-sequence stellar evolution

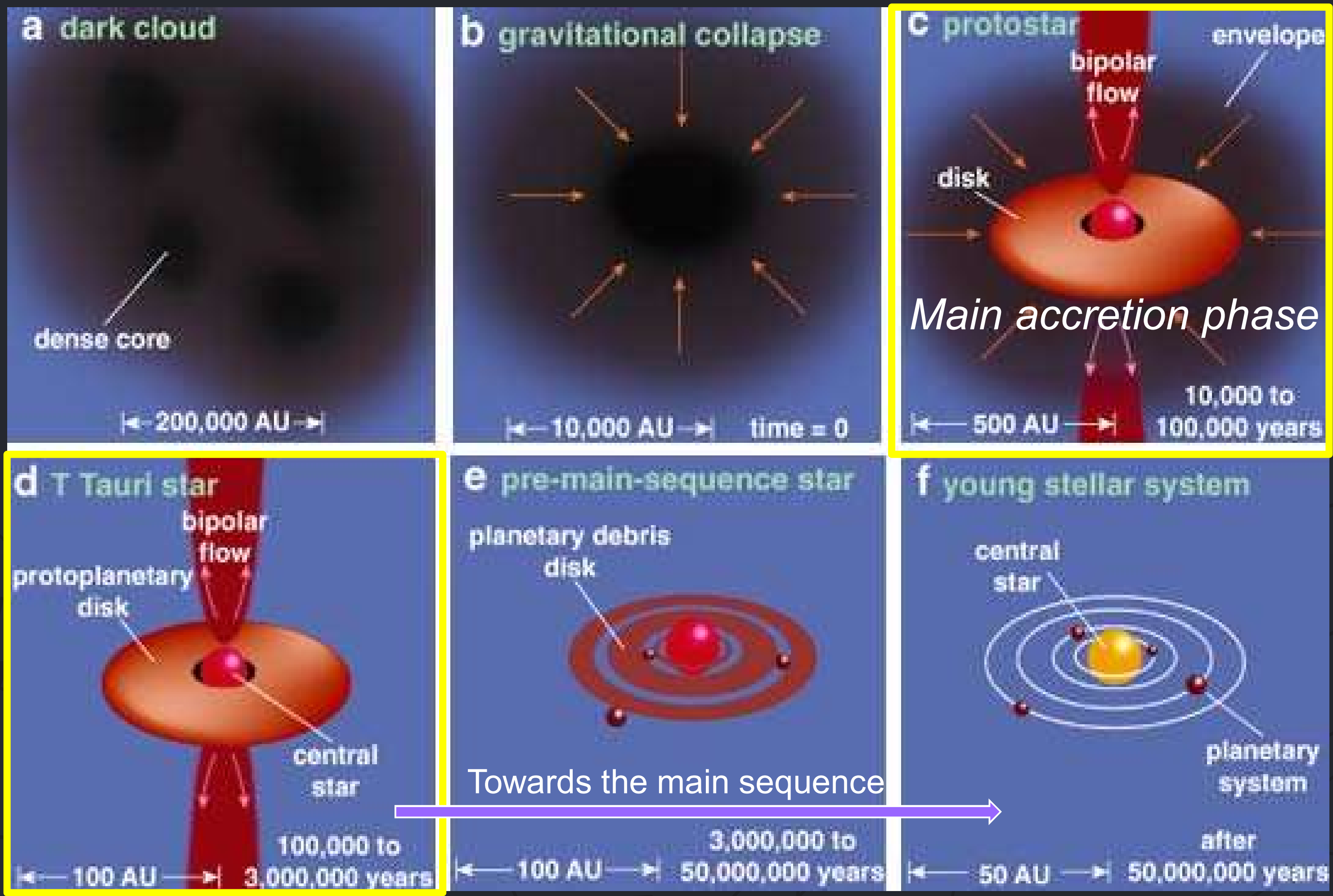


author: **Eduard Vorobyov**

co-authors: **Vardan Elbakyan, Takashi Hosokawa, Manuel Guedel, Harold Yorke**

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

Formation pathway for a planetary system around a solar-mass star



Protostellar accretion starts from the formation of the protostellar seed and ends with the dissipation of the circumstellar disk

Duration of accretion – a few Myr – a small fraction of the total pre-main-sequence lifetime

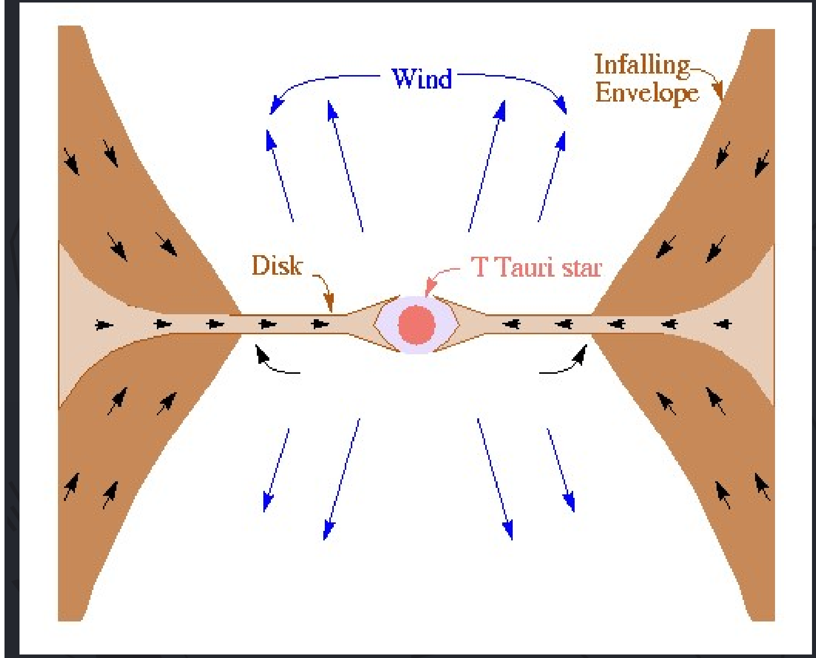
What is the character of mass accretion on protostars?

1) **Steady or steadily declining with time** (historically most popular scenario)

2) **Variable with episodic bursts** (motivated by discovery of FU-Orionis-type eruptive stars)

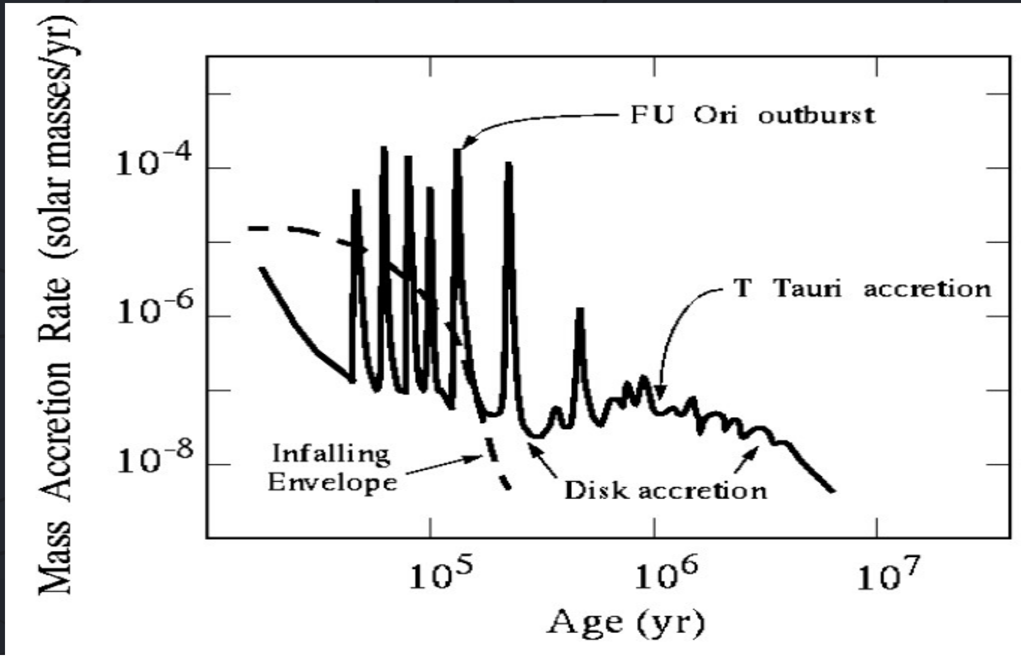
Variable accretion with episodic bursts

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



Mechanisms responsible for episodic bursts

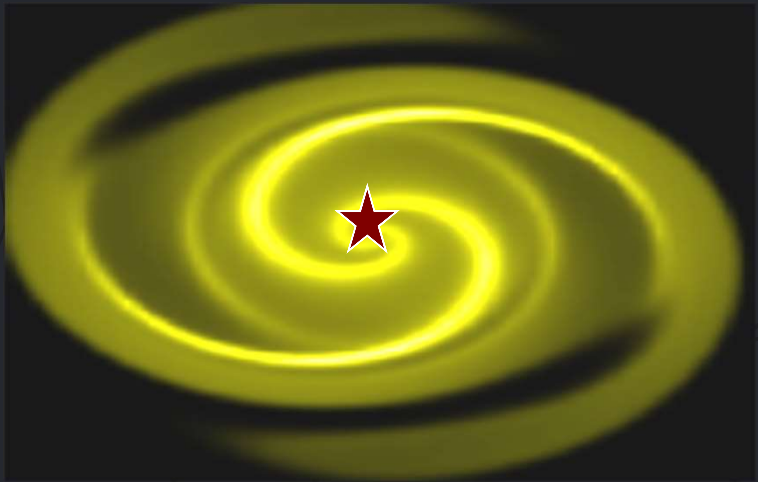
- Thermo-viscous instabilities in the inner disk (Lin & Papaloizou 1986, Bell & Lin 1994),
- tidal effects from close encounters in binary systems or stellar clusters (Bonnell & Bastien1992; Pfalzner et al. 2008, Forgan & Rice 2010).
- The magnetorotational instability (Armitage et al. 2001; Zhu et al. 2010, Bae et al. 2013, 2014)
- accretion of dense gaseous clumps in a gravitationally unstable disk (Vorobyov & Basu 2005, 2006, 2010, 2015; Machida et al. 2011)
- Outbursts due to planet-disk mass exchange (Lodato & Clarke 2004, Nayakshin & Lodato 2012)

All models involve somehow or other **the circumstellar disks**

Disk fragmentation and migration of gaseous clumps on the star

(Vorobyov & Basu 2005, 2015; Zhao et al. 2018; Meyer et al. 2017; Vorobyov & Elbakyan 2018)

The gravitational instability (Safronov 1960, Toomre 1964)

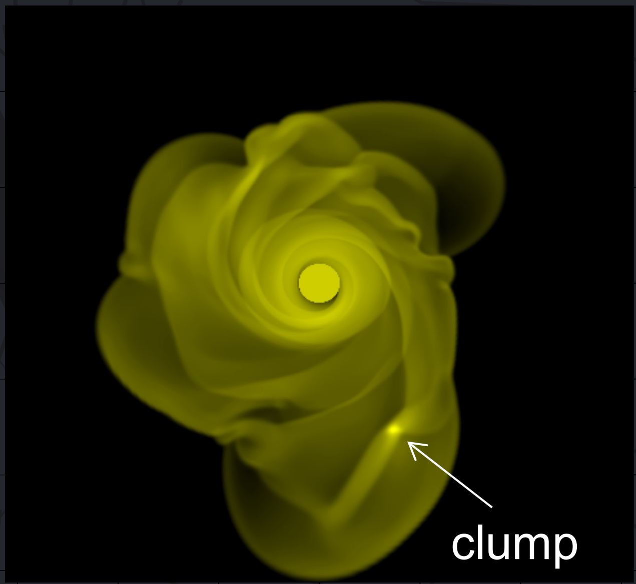


sound speed

epicycle frequency

$$Q = \frac{c_s\, k}{\pi\, G\, \Sigma} < 1.5\text{-}2.0$$

gas surface density

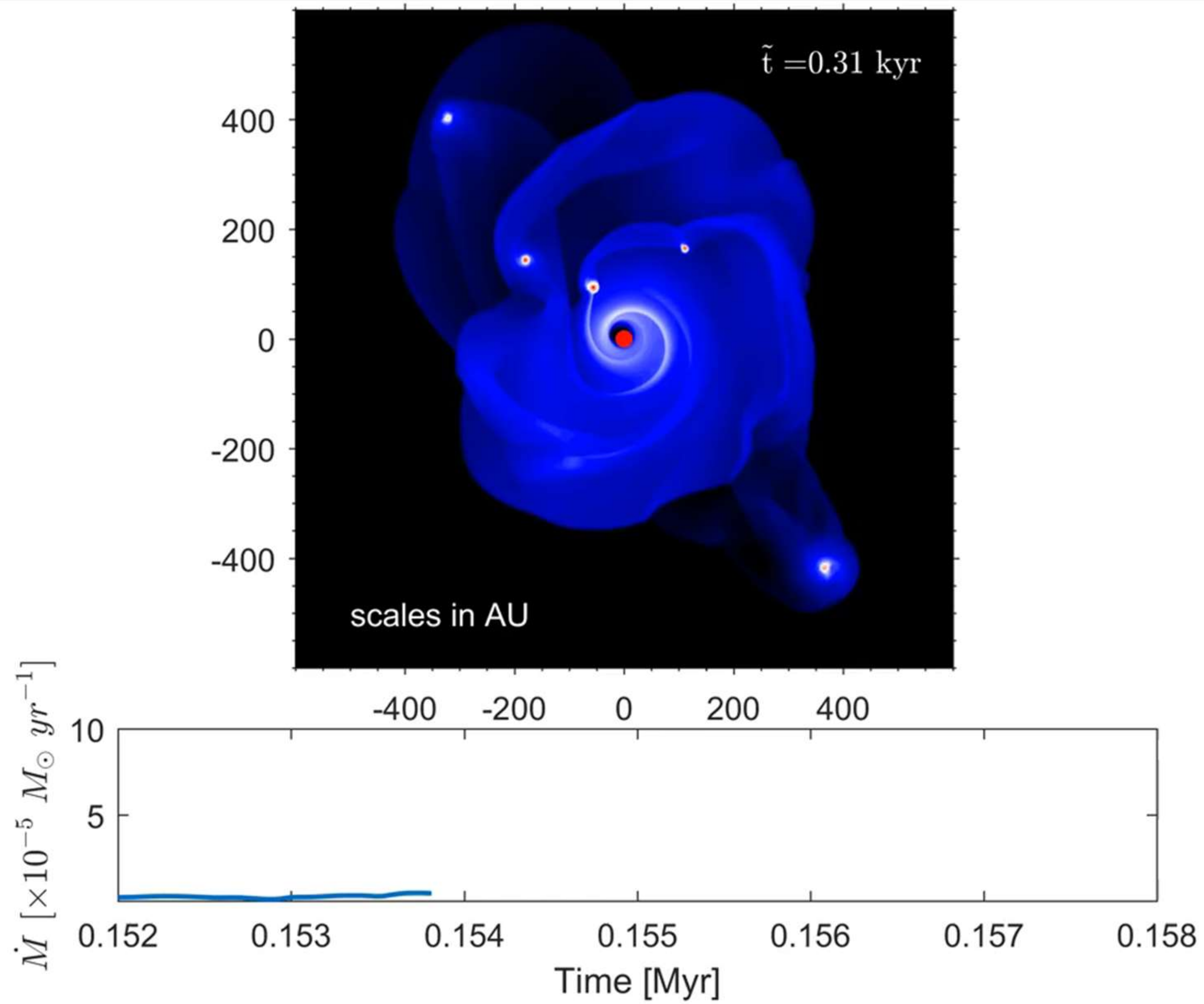


Unstable disk can further fragment if

$$t_{cool}\Omega < \frac{2\,\pi}{\sqrt{1-Q^2}} \quad \text{and } Q < 1$$

Meyer et al. 2018

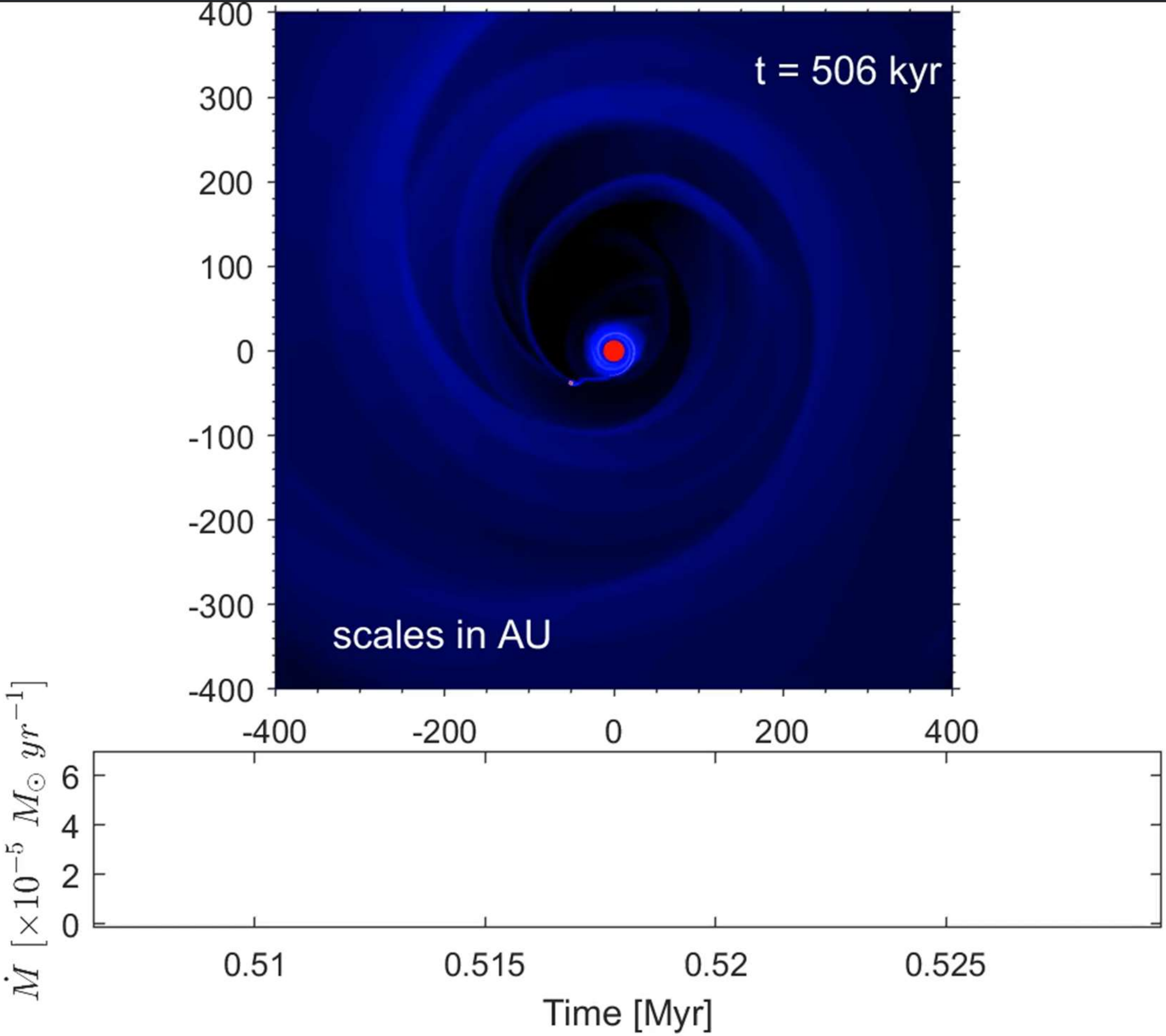
Tidal truncation of migrating clumps and accretion bursts
(Vorobyov & Elbakyan 2018)



Gas surface density

Mass accretion rate

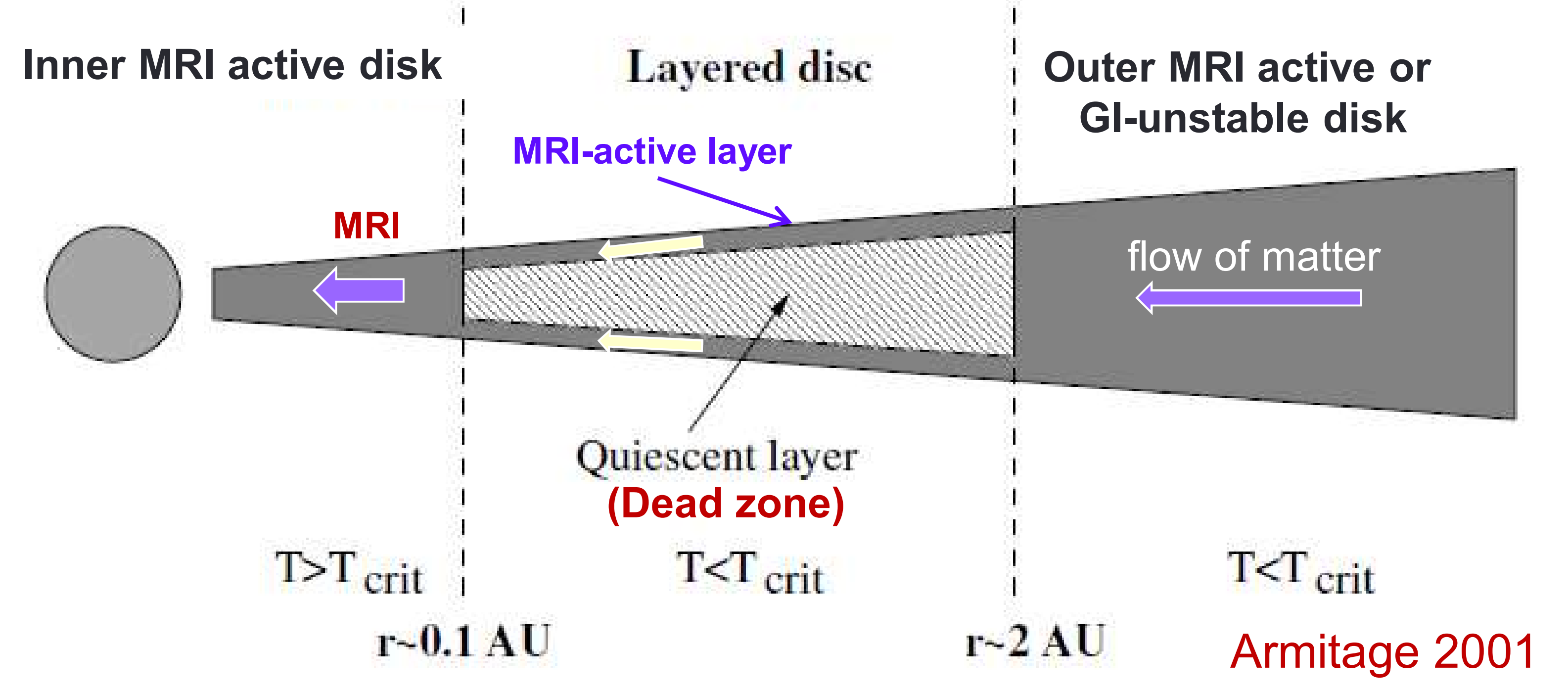
A giant protoplanet losing its diffuse atmosphere



Magnetorotational-instability-induced bursts

(Armitage 2001. Zhu et al. 2009, 2010, Martin & Lubow 2011, Bae et al. 2013, 2014)

The basic idea is to assume that a dead zone with reduced mass transport exists at a few AU. Such a dead zone is potentially unstable, since if gas temperature becomes greater than T_{crit}~1200-1500 K, the onset of the MRI would be able to maintain a high accretion state until much of the mass has been accreted.

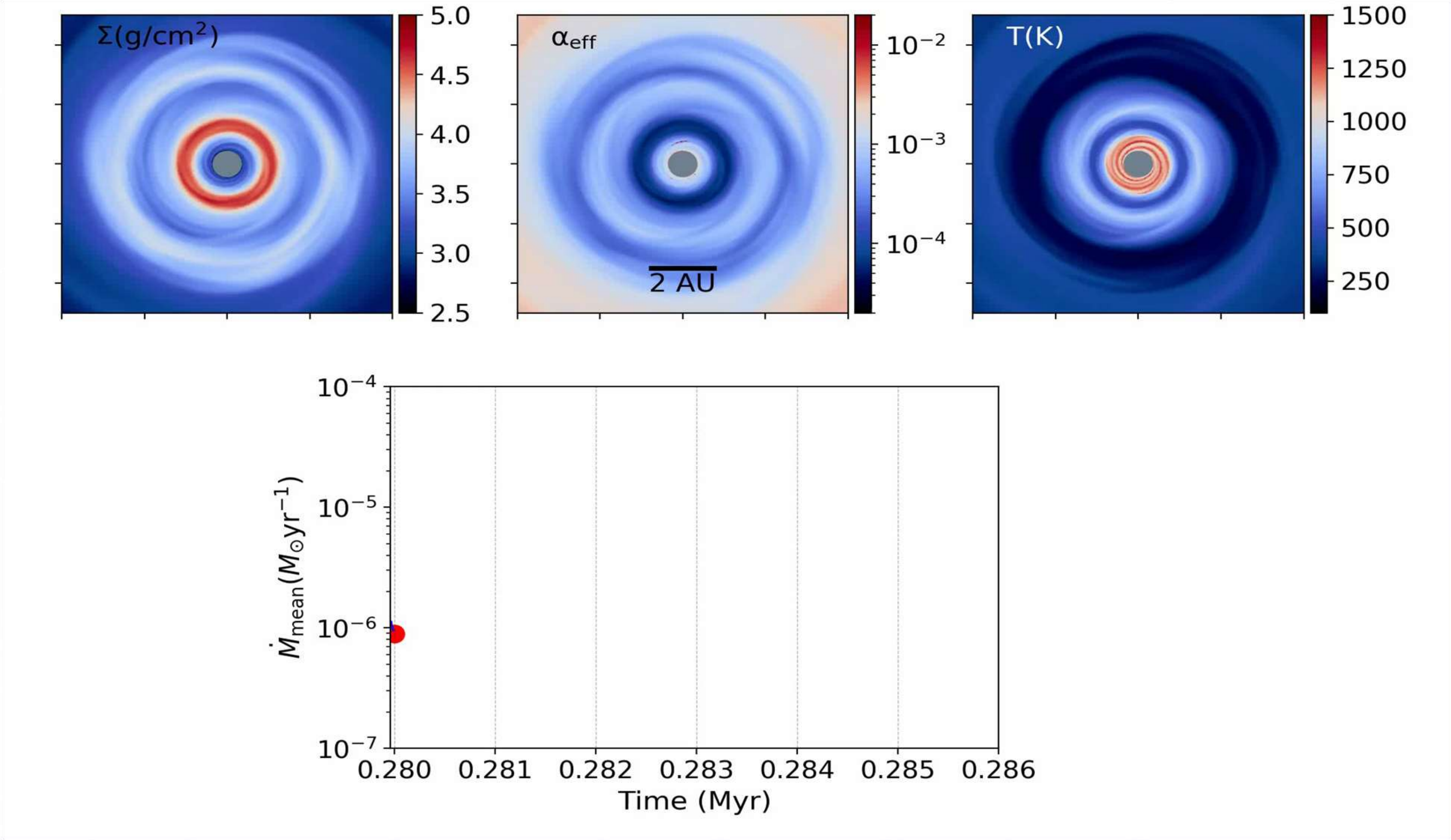


MRI-active disks are characterized by the viscous α-parameter, $\sim 10^{-2}$

MRI-dead disks are characterized by $\alpha \sim 10^{-4}$

An MRI-triggered burst in the inner disk
(Kadam, Vorobyov, et al. 2019)

Gas surface density | alpha-parameter | gas temperature



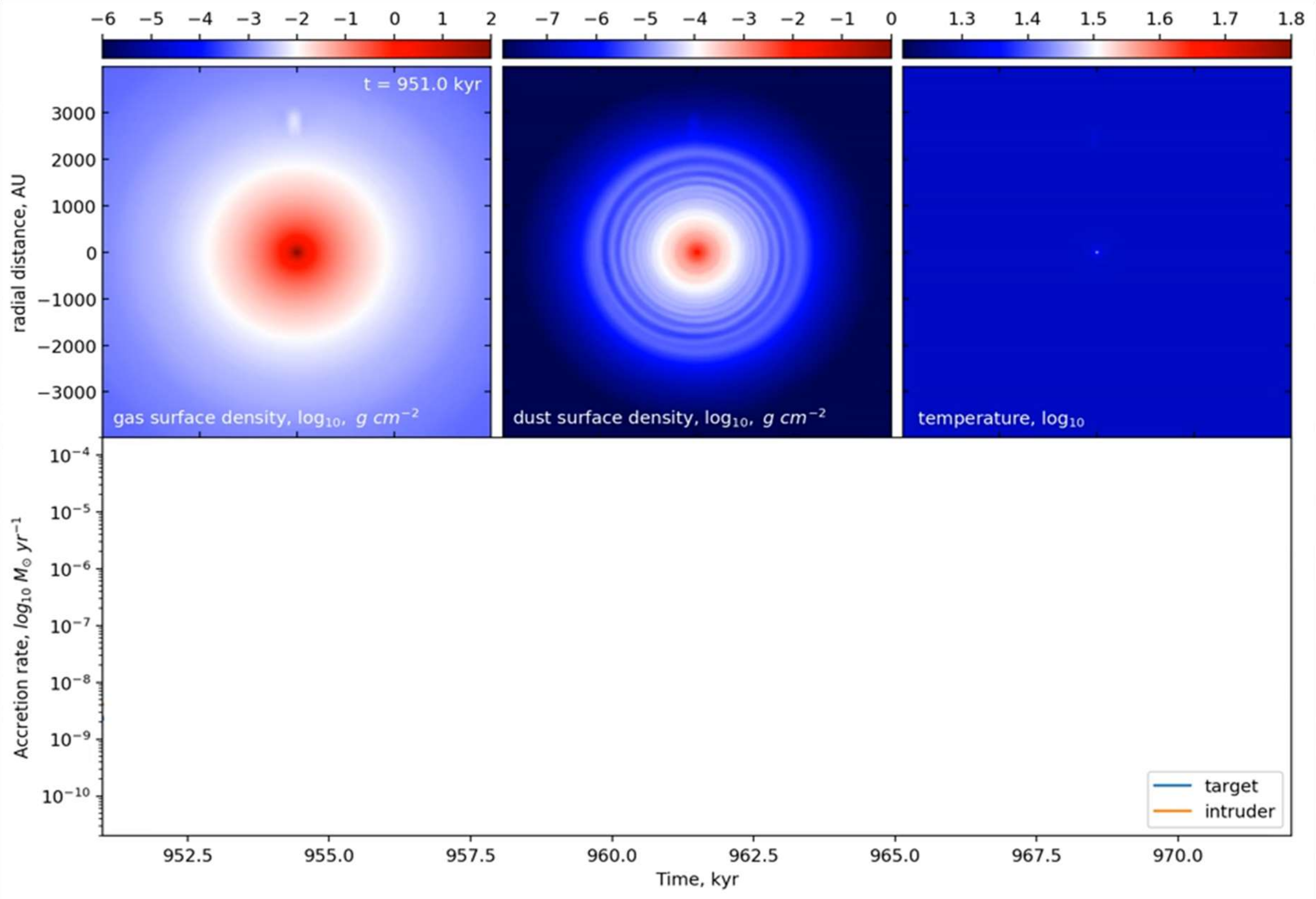
Accretion bursts triggered by close encounters

(Bonnell & Bastean 1992, Pfalzner 2008, Vorobyov et al. 2019)

gas density

dust density

gas temperature

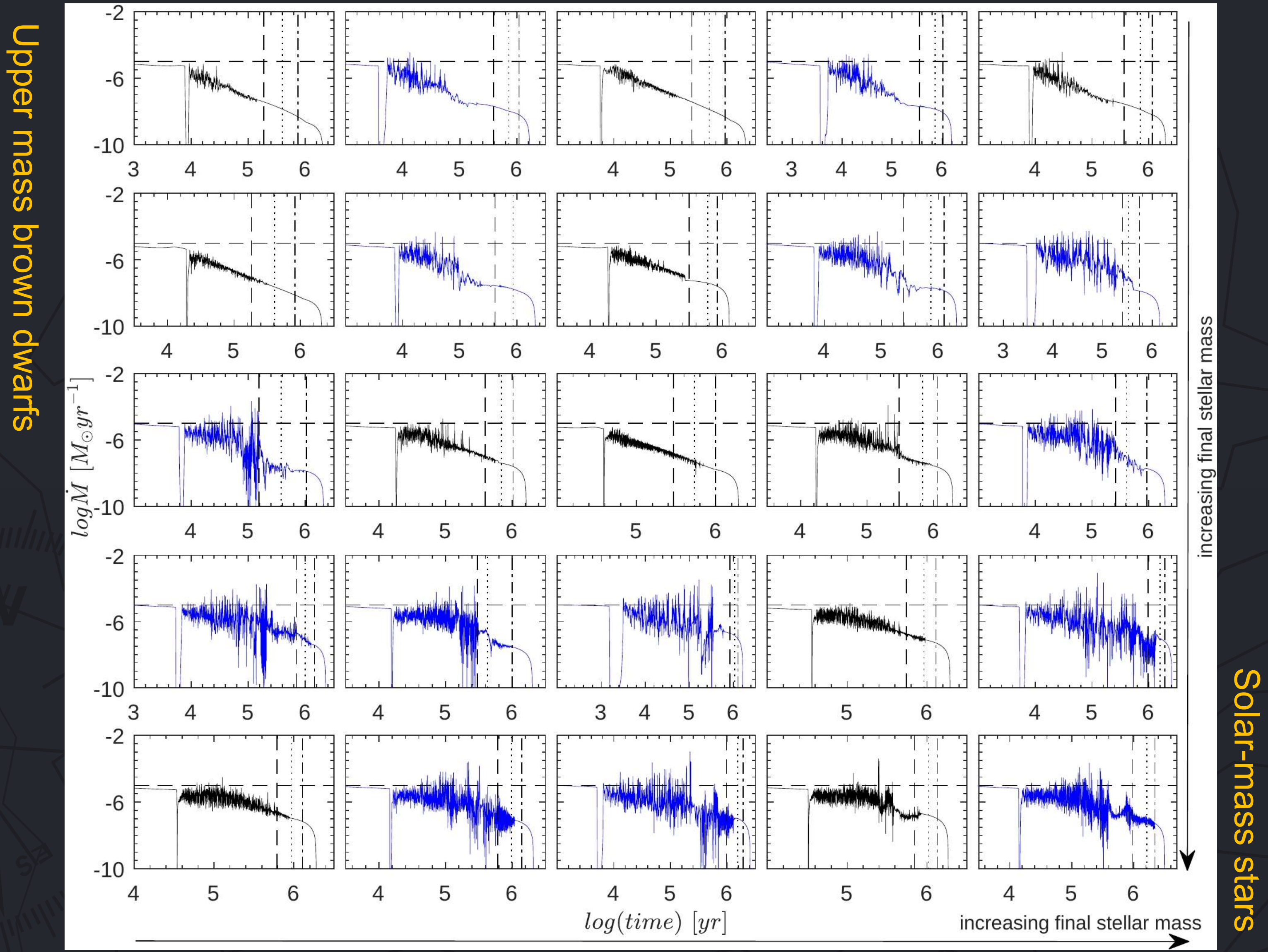


Stellar excursions caused by the bursts

(Elbakyan et al. 2019)

Accretion rates from hydrodynamic models of disk evolution (Vorobyov & Basu 2015):

Upper mass brown dwarfs



Solar-mass stars

both quasi-steady and strongly variable accretion can be realized

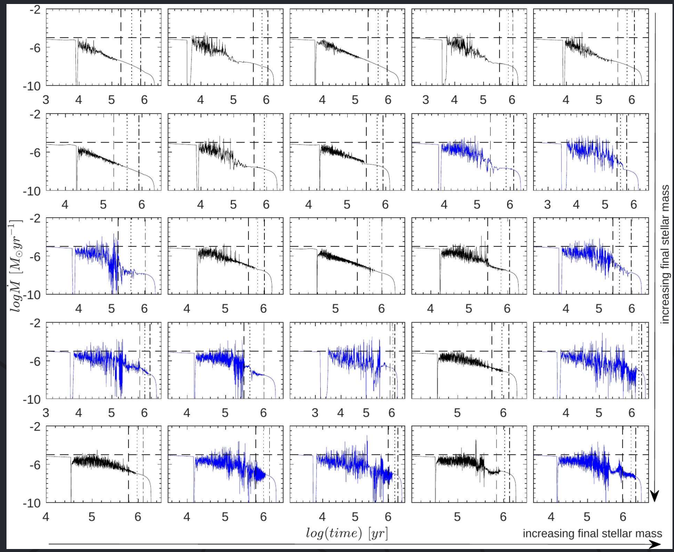
Accretion rate histories from disk models
(Vorobyov & Basu 2015)

⇩

1D STELLAR code
(Yorke & Bodenheimer 2008; Hosokawa et al. 2011)

⇩

Stellar evolution tracks
(L_{phot}, L_{accr}, T_{eff})



Initial stellar seed parameters: mass = 5 $M_{Jupiter}$; radius = 3 $R_{Jupiter}$

Final stellar masses: from 0.04 M_{sun} to 1.3 M_{sun}

Stellar ages: from the protostellar seed formation to 25 Myr

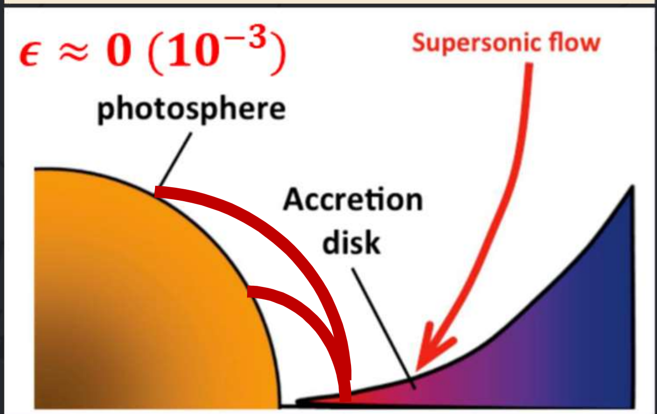
Note that accretion occurred only during the initial 2-3 Myr
and was set to zero at later times

$$E_{accr} = \epsilon \, \frac{1}{2} \frac{G \, M_* \dot{M}}{R_*}$$

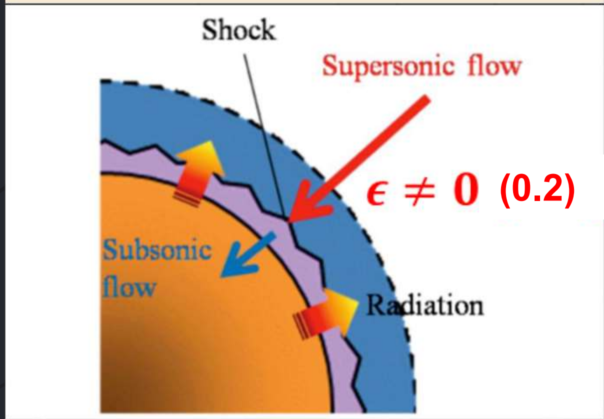
accretion energy absorbed by the star (per unit time)

ϵ — the thermal efficiency of accretion

cold accretion



hot accretion

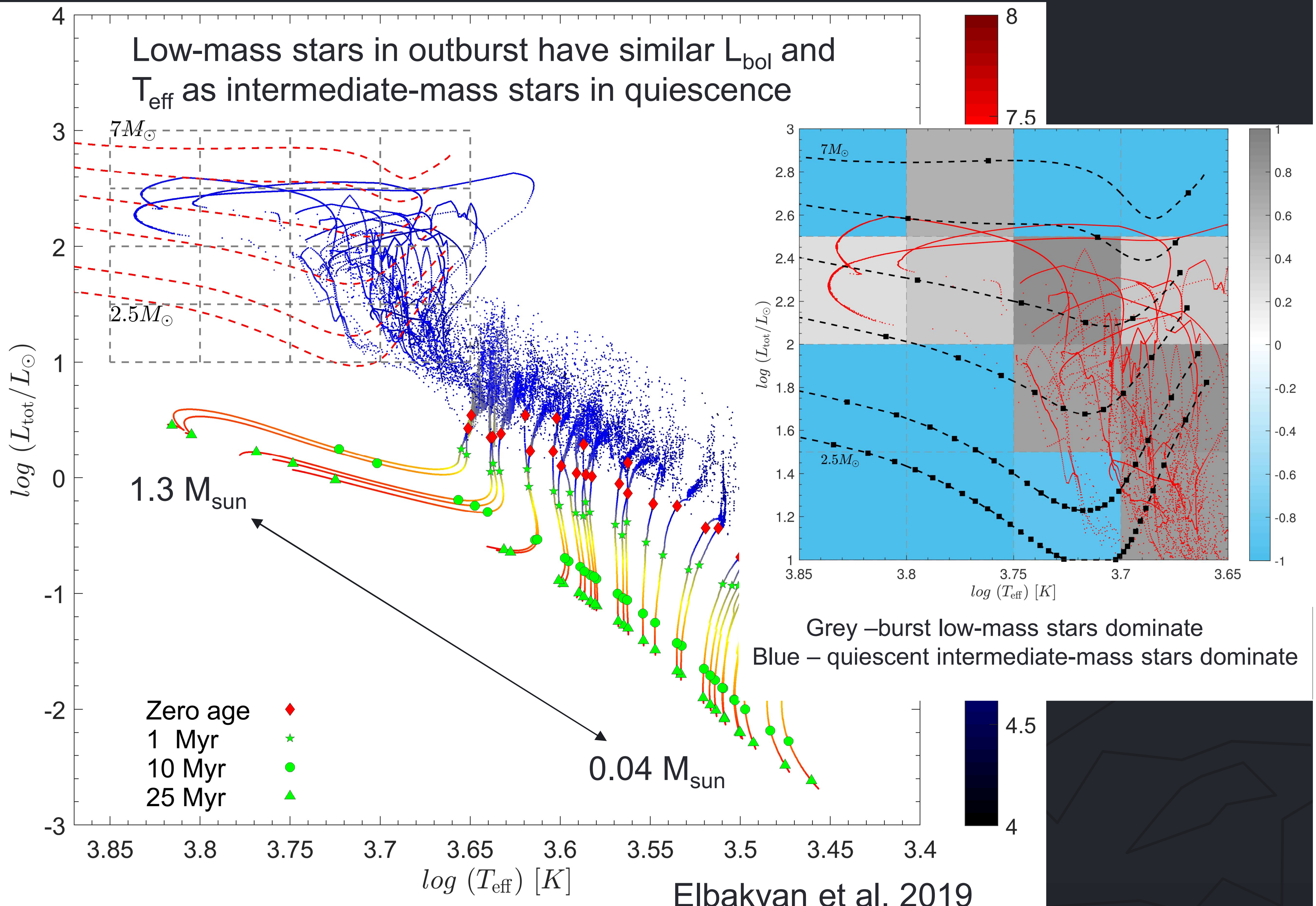


hybrid accretion (Baraffe et al. 2012)

$$\epsilon = 10^{-3} \;\; if \;\; \dot{M} < \dot{M}_{crit} \quad and \quad \epsilon = 0.2 \;\; if \;\; \dot{M} > \dot{M}_{crit}$$

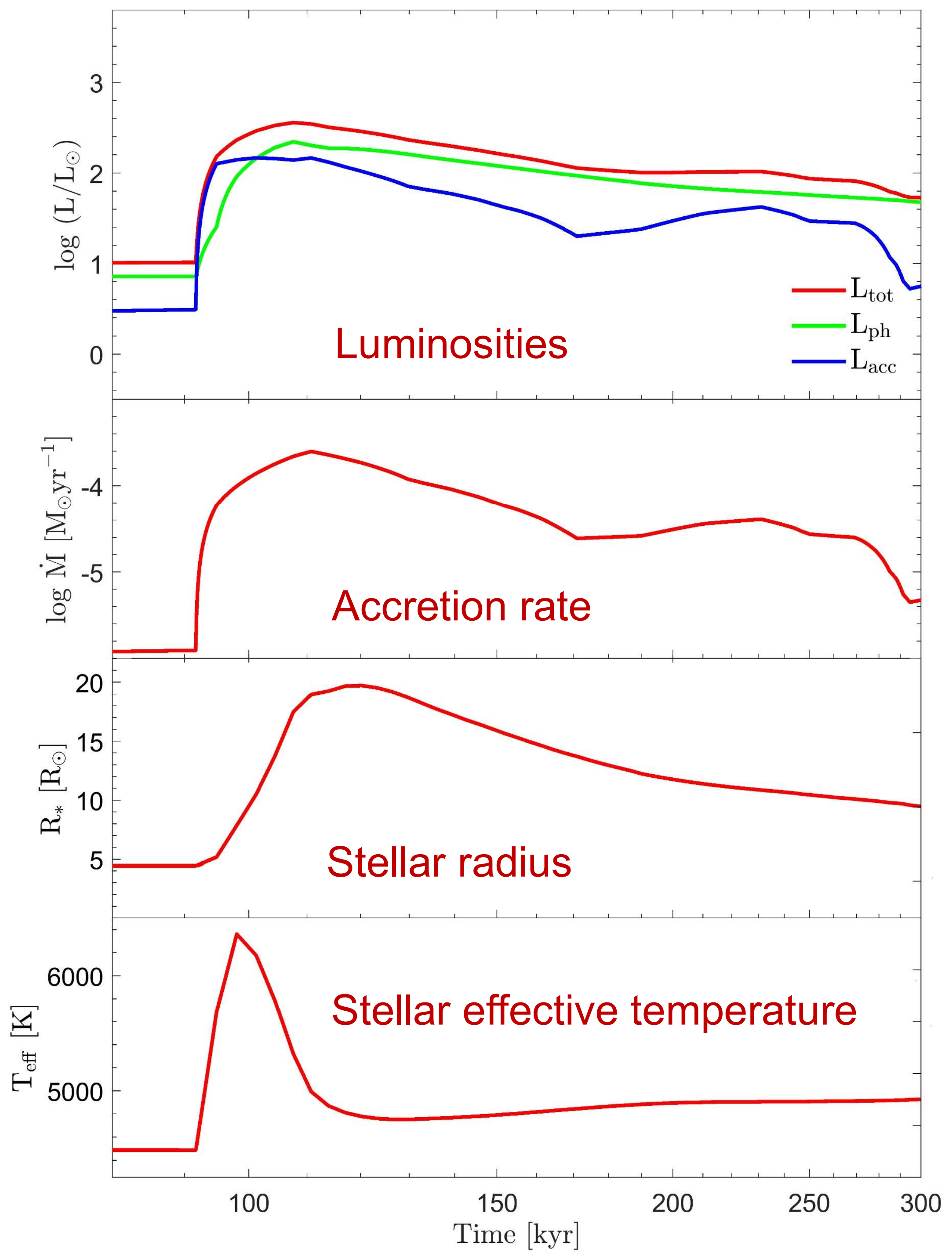
$\dot{M}_{crit} = 10^{-5} \, M_{sun} \, yr^{-1}$ - lower limit on FU-Orionis-type bursts

Stellar evolution tracks on the HR diagram for hybrid accretion



Grey –burst low-mass stars dominate
Blue – quiescent intermediate-mass stars dominate

Elbakyan et al. 2019



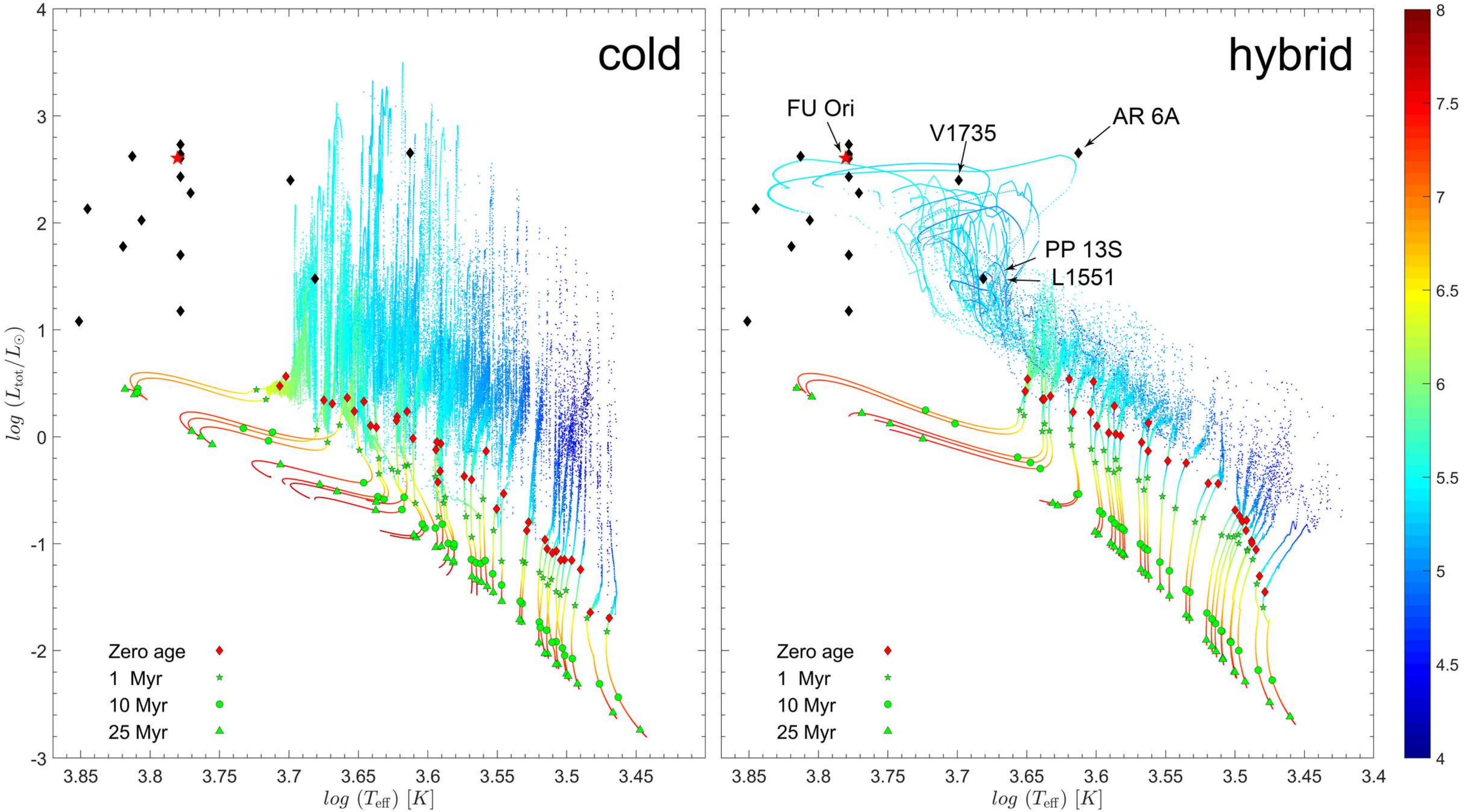
Accretion luminosity dominates in the early stages of the outburst

Photospheric luminosity dominates in the late stages of the outburst

The star bloats by a factor of several and gradually returns to the pre-busts state

The effective temperatures sharply increases and drops back

Comparison of stellar excursions with known FUors from Gramajo et al. 2014



The comparison with known FUors is inconclusive: both cold and hybrid accretion can match FUors, but hybrid accretion does it better

Problems with determination of pre-main-sequence stellar ages

(Vorobyov et al. 2019)

Two approaches in studying the pre-main-sequence stellar evolution

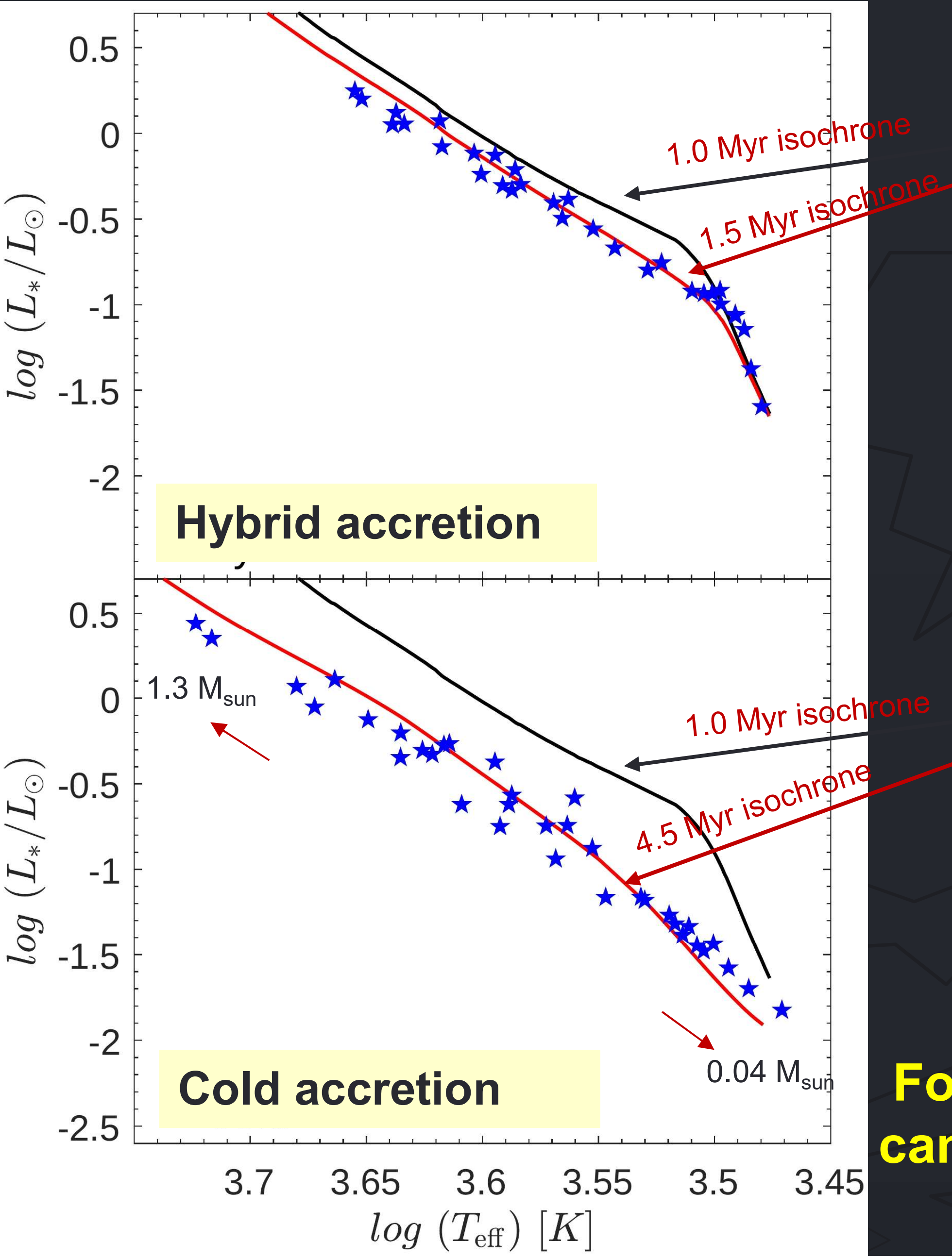
1) **Non-accreting models** – a star is born with a FIXED (final) mass and its evolution is followed until it reaches the zero-age main sequence.

2) **Accreting models** – a star is formed starting from a small seed (a few Jupiter masses), gains its final mass by accretion from a surrounding disk and then its evolution is followed until it reaches the zero-age main sequence.

Non-accretion models are a popular means of determining the ages and masses of pre-main-sequence stars

Accreting models suffer from uncertainties in the history of mass accretion and from uncertainties in the thermal efficiency of accretion

Age mismatch between accreting models and non-accreting isochrones



Black and red lines – 1.0 Myr and 1.5 Myr non-accreting isochrones

Blue stars – 1.0 Myr old accreting objects

Black and red lines – 1.0 Myr and 4.5 Myr non-accreting isochrones

For cold accretion, 1.0-Myr-old objects can be falsely identified as 4.5-Myr-old! A notable scatter also exists

Key results

- There exists several mechanisms that can explain the FU Orionis-type luminosity outbursts equally well. The work is underway to distinguish between the burst mechanisms based on the disk structure and kinematics.

- Low-mass stars in outburst exhibit excursions to the part of the HR diagram that is normally occupied by intermediate-mass stars in quiescence. This may cause confusion when calculating the IMF in young star-forming clusters.

- The amount of accreted energy is a poorly constrained parameter from both observations and theory, but its importance can not be underestimated.

- Age estimates of young stars based on the isochrones derived from NON-accretion stellar evolution models may be misleading. Strong age overestimate is likely for the case of cold accretion

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