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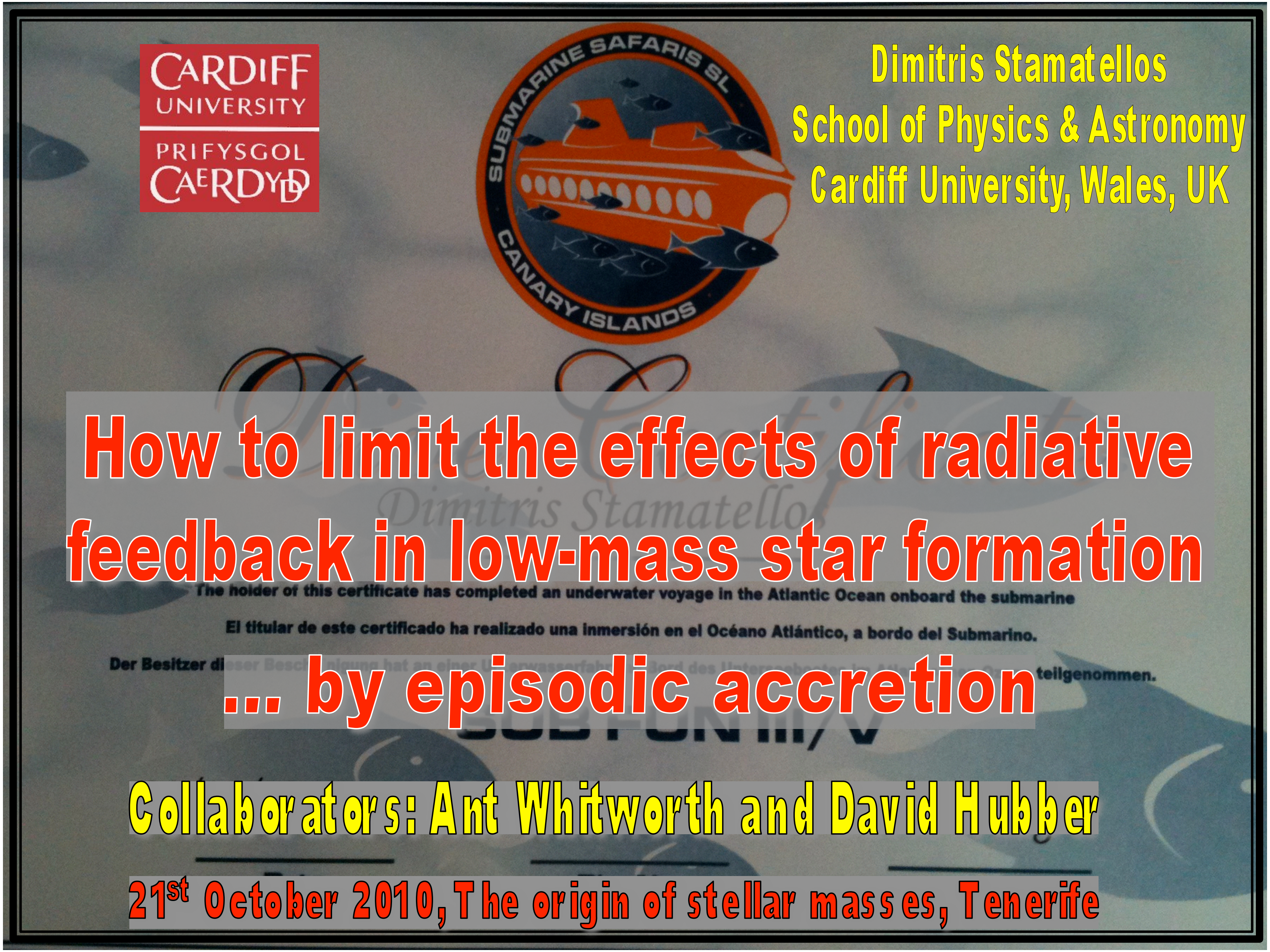
# How to limit the effects of radiative feedback in low-mass star formation

## ... by episodic accretion

Collaborators: Ant Whitworth and David Hubber

21st October 2010, The origin of stellar masses, Tenerife



SUBMARINE SAFARIS SL
CANARY ISLANDS

Dimitris Stamatellos

The holder of this certificate has completed an underwater voyage in the Atlantic Ocean onboard the submarine

El titular de este certificado ha realizado una inmersión en el Océano Atlántico, a bordo del Submarino.

Der Besitzer dieser Besc[illegible] hat an einer U[illegible]erwasserfahr[illegible] Bord des Unterseebootes [illegible] teilgenommen.

SUB FUN III/V

# Brown dwarf and low-mass star formation by disc fragmentation

- The theory of gravoturbulent collapse (1 core → 1 star) of molecular clouds (e.g. Chabrier) has two major drawbacks in the low-mass regime

  (i) difficult to explain the formation of low-mass binaries (e.g. see poster by Reggiani)

  (ii) gravitationally bound brown dwarf-mass cores have not been observed

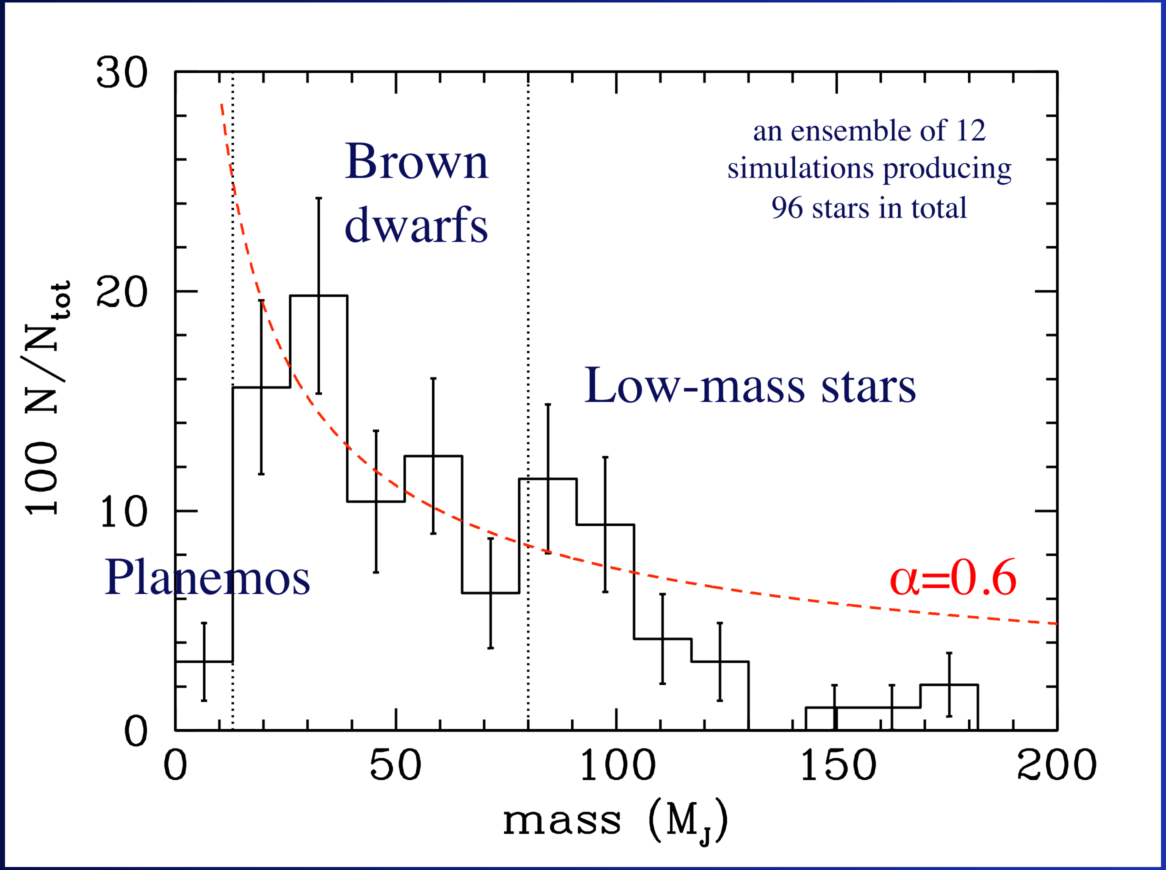
- Other theories are needed for the formation of low-mass stars and brown dwarfs: ejection of protostellar embryos (Clarke et al. 2003, Bate et al. 2003), disc fragmentation (Bate et al. 2003, Stamatellos et al. 2007)

# Brown dwarf and low-mass star formation by disc fragmentation

- The shape the low-mass end of the IMF
- The brown dwarf desert
- The binary statistics of brown dwarfs
- The formation of planetary-mass free-floating objects

Stamatellos & Whitworth 2009, MNRAS

# The low-mass IMF



$\Delta N/\Delta M \sim M^{-\alpha}$

**Pleiades: α=0.6±0.11**

(Moraux et al. 2003)

**σ Orionis: α=0.6±0.20**

(Caballero et al. 2007)

***This is not an IMF.***
***It represents the mass spectrum of only one formation mechanism (for one set of initial conditions).***

Stamatellos & Whitworth 2009, MNRAS

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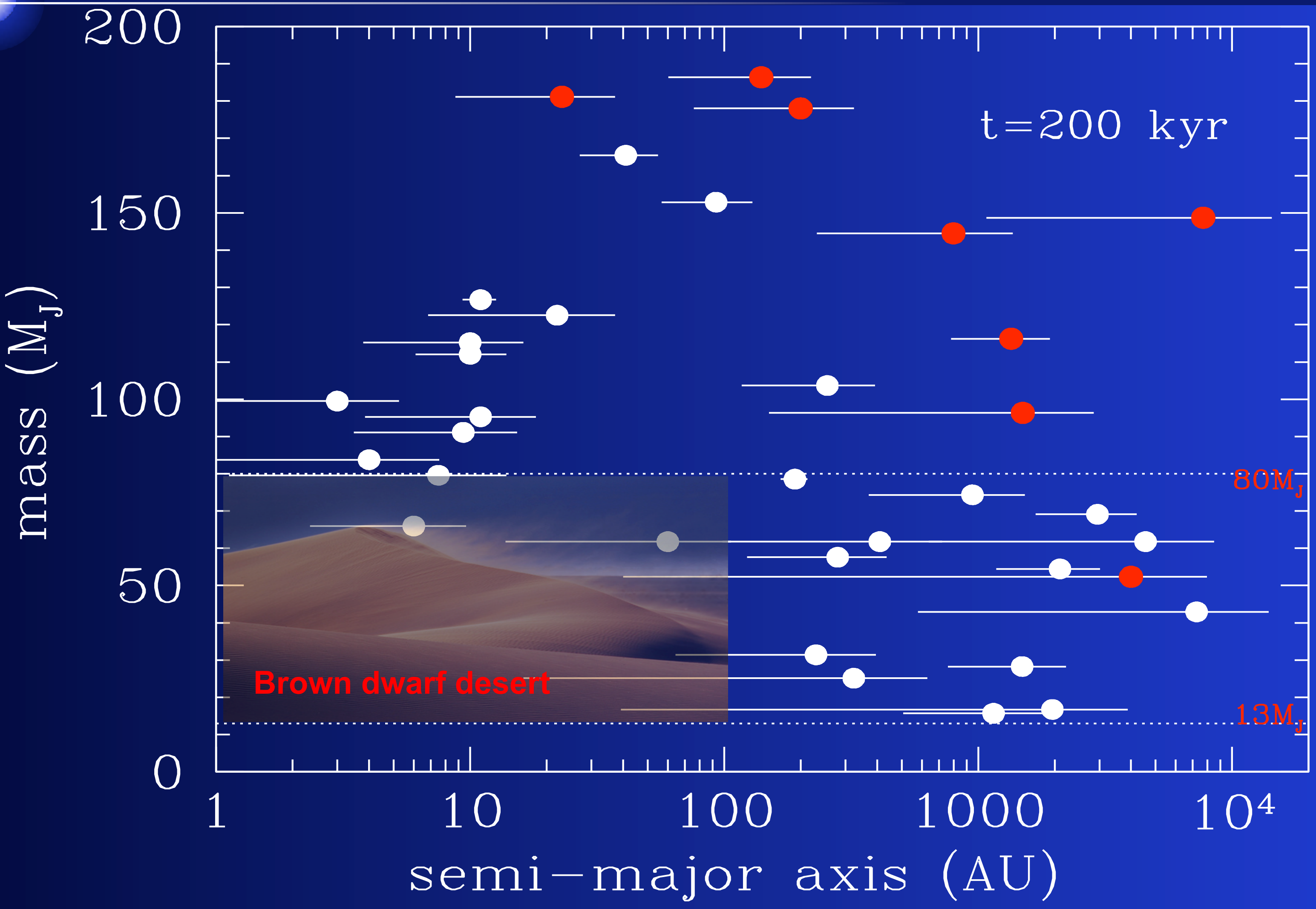
# The brown dwarf desert



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- The shape the low-mass end of the IMF
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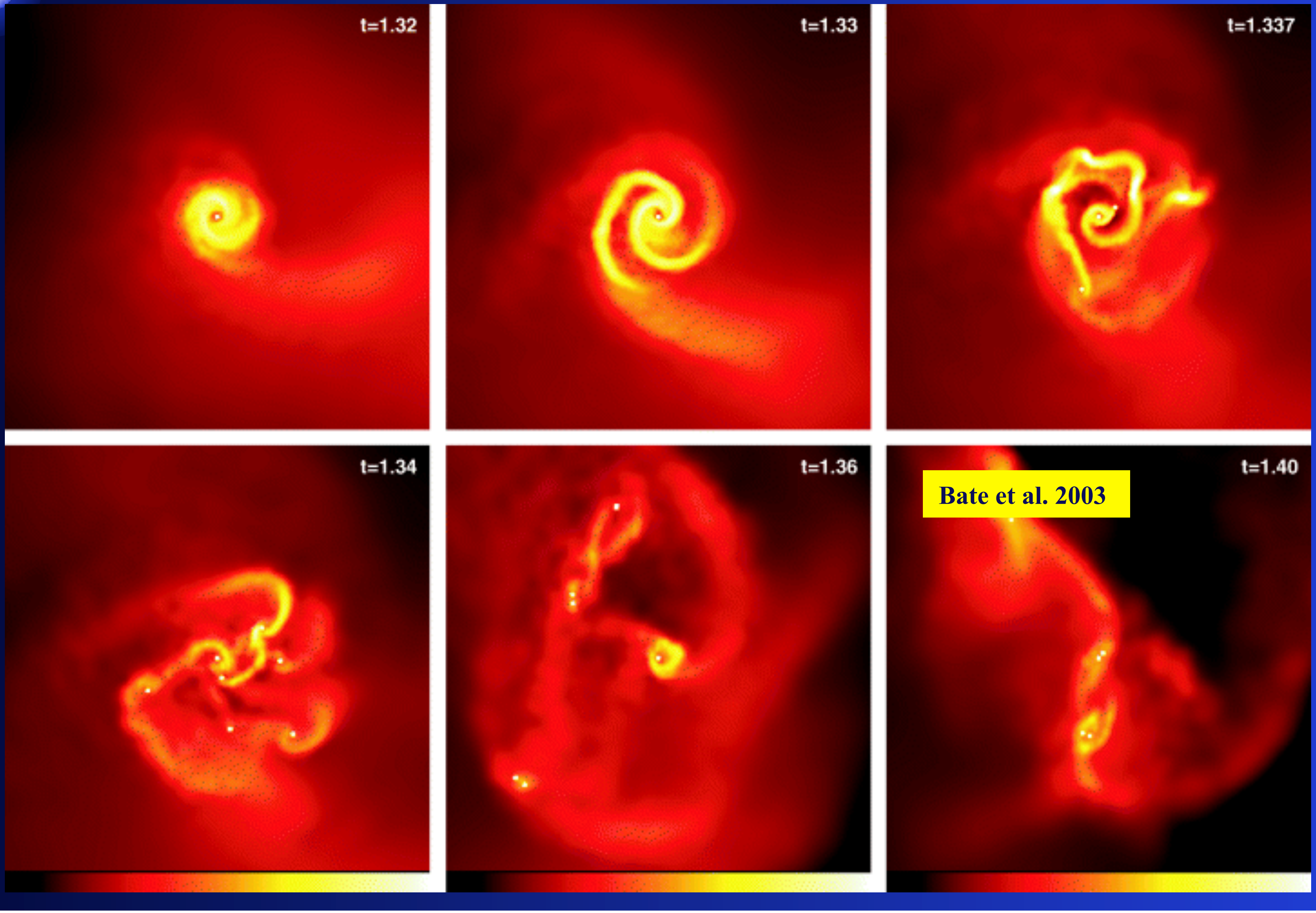
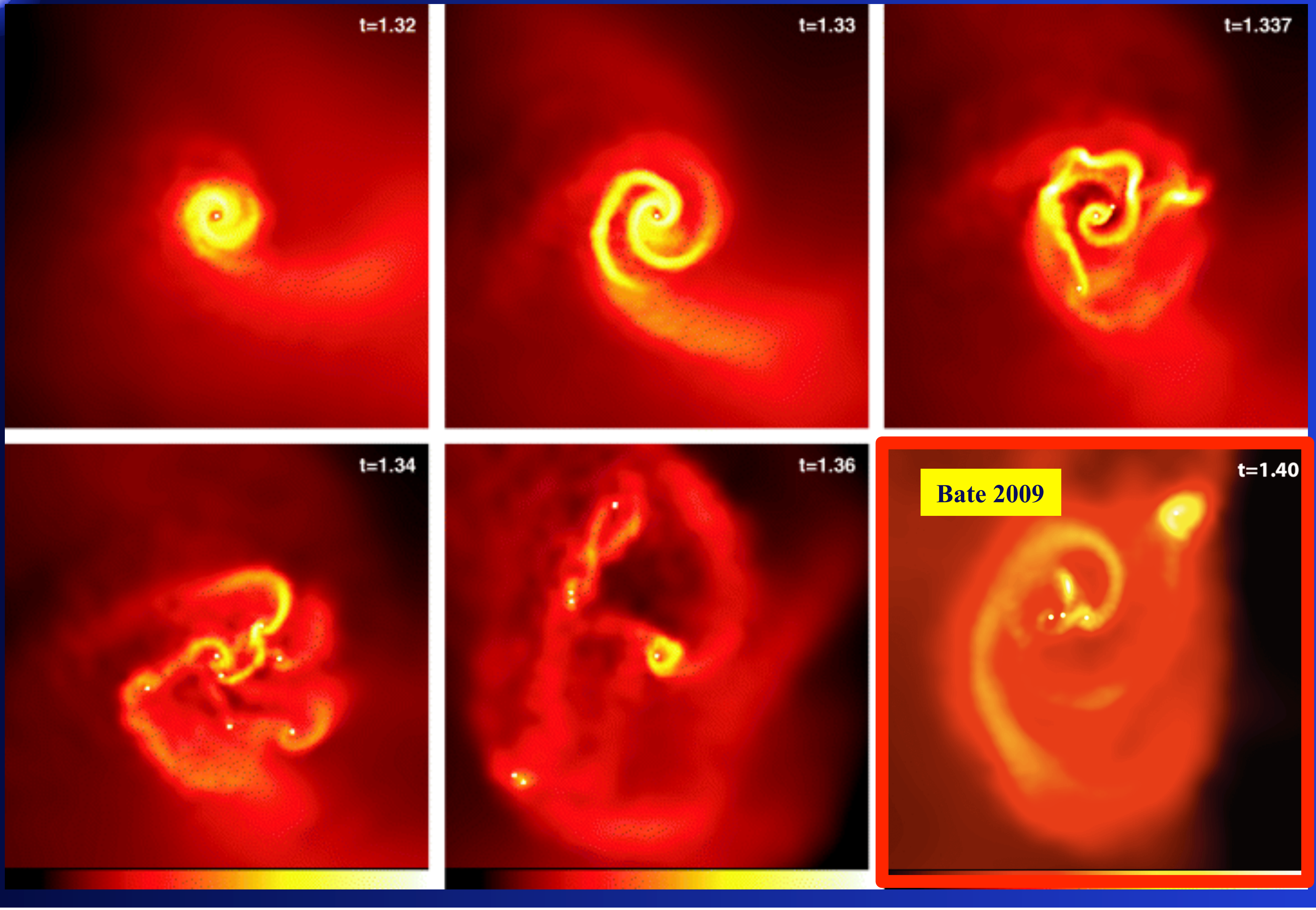
Stamatellos & Whitworth 2009, MNRAS

# Radiative feedback suppresses the formation of low-mass stars and brown dwarfs



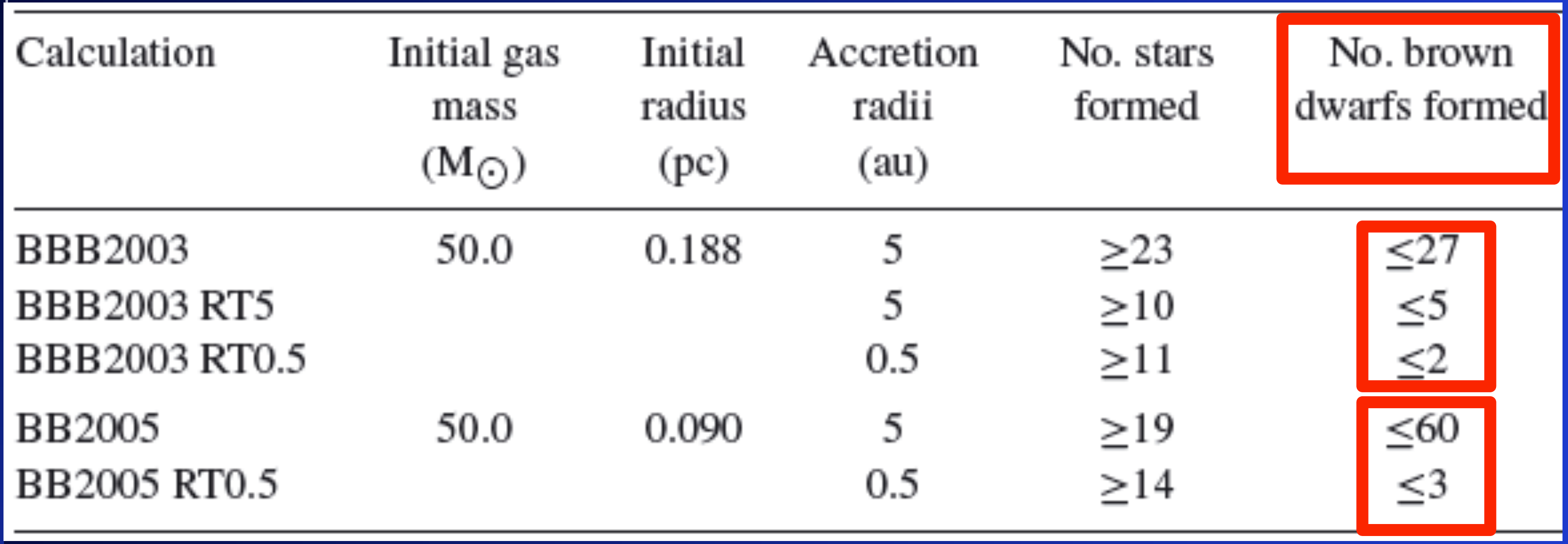
Bate et al. 2003

# Radiative feedback suppresses the formation of low-mass stars and brown dwarfs



# Radiative feedback suppresses the formation of low-mass stars and brown dwarfs

## Bate 2009 vs Bate et al. 2003

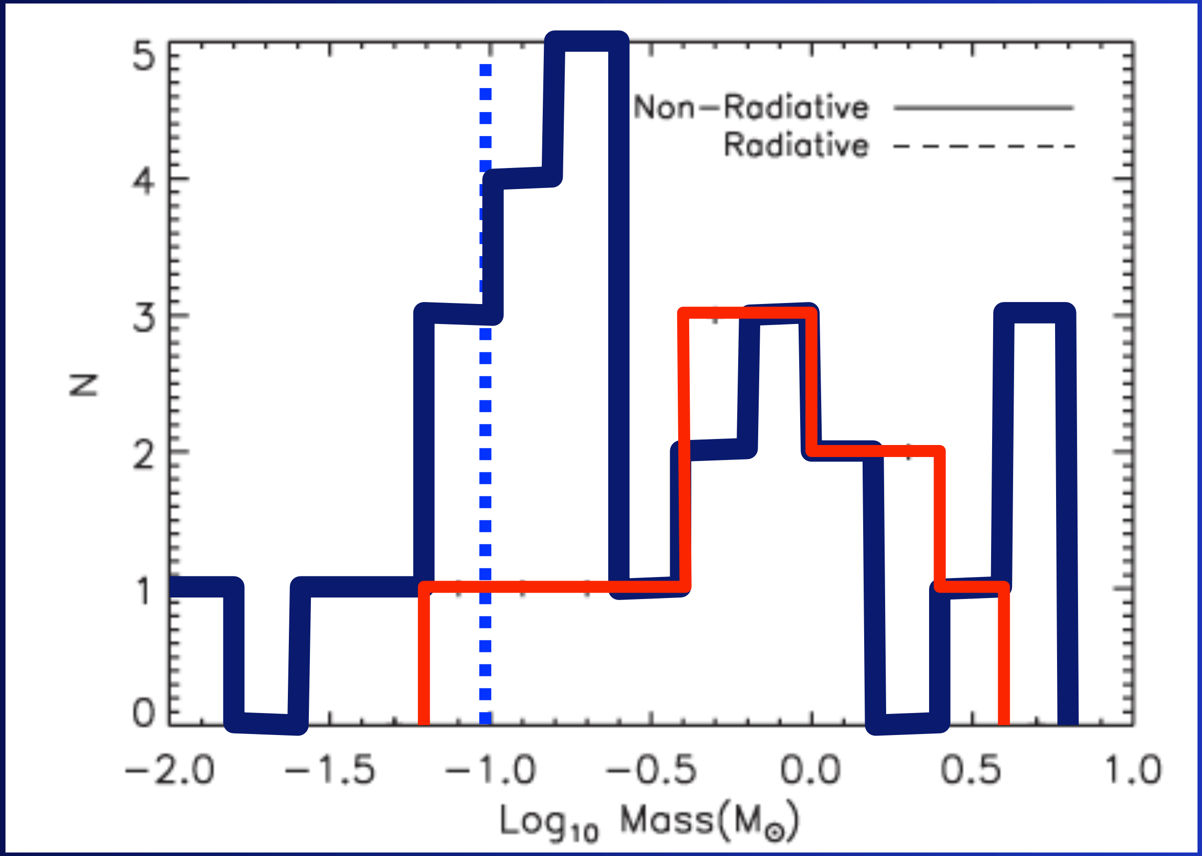


| Calculation | Initial gas mass ($M_\odot$) | Initial radius (pc) | Accretion radii (au) | No. stars formed | No. brown dwarfs formed |
|---|---|---|---|---|---|
| BBB2003 | 50.0 | 0.188 | 5 | ≥23 | ≤27 |
| BBB2003 RT5 | | | 5 | ≥10 | ≤5 |
| BBB2003 RT0.5 | | | 0.5 | ≥11 | ≤2 |
| BB2005 | 50.0 | 0.090 | 5 | ≥19 | ≤60 |
| BB2005 RT0.5 | | | 0.5 | ≥14 | ≤3 |

**Most of the radiative feedback from protostars is ignored but its effect is already dramatic !**

# Radiative feedback suppresses the formation of low-mass stars and brown dwarfs

- Offner et al. 2009: Full radiative feedback is included



- Almost no brown dwarfs form at all ➔ something is missing

# The importance of radiative feedback from protostars

## Simulation I:

**Radiative feedback is included down to the sink radius (1AU)**

[similar to Bate's simulations – most of radiative feedback missing]

**Initial conditions: turbulent cloud core**

$$M = 5.4 M_\odot \qquad N_{\rm SPH} = 10^6 \text{ particles}$$

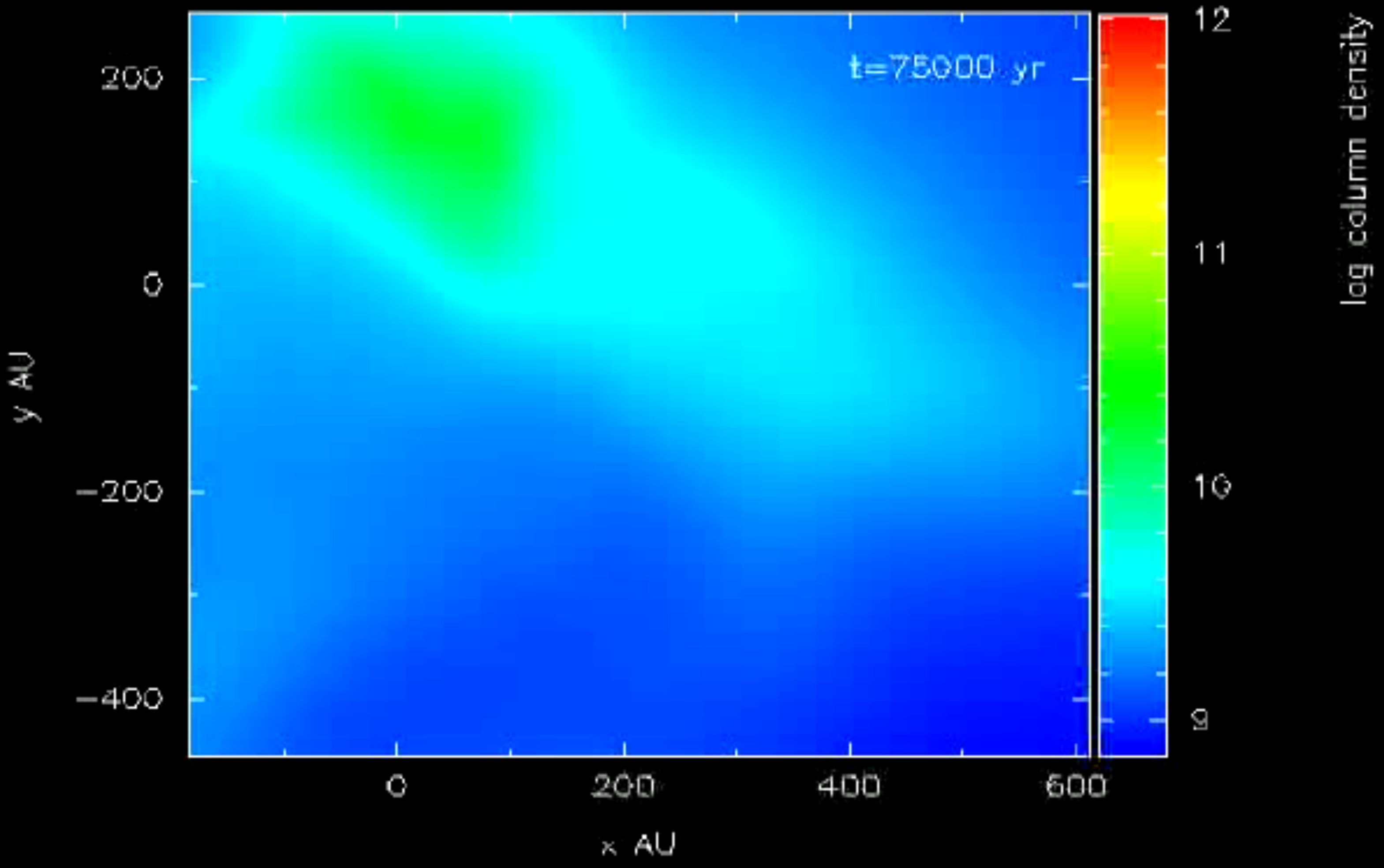
$$\rho(r) = \frac{\rho_{\rm kernel}}{(1 + (r/R_{\rm kernel})^2)^2}$$

$$R_{\rm KERNEL} = 5000 \text{ AU}$$

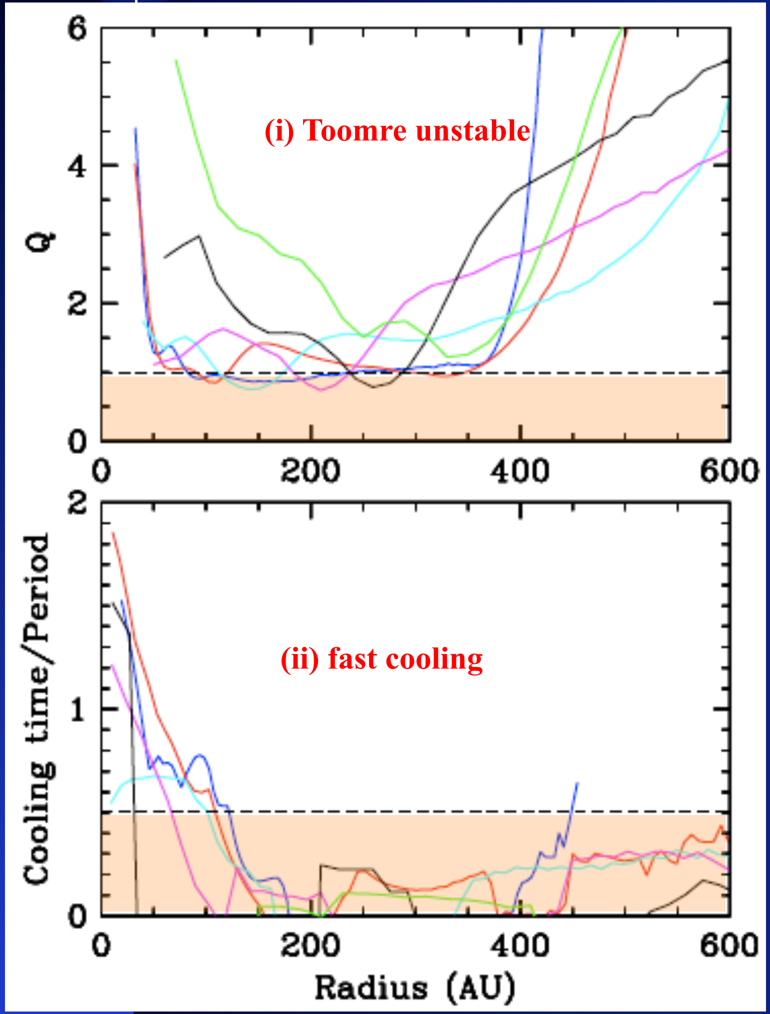
$$\rho_{\rm KERNEL} = 3 \times 10^{-18} \text{ g cm}^{-3}$$

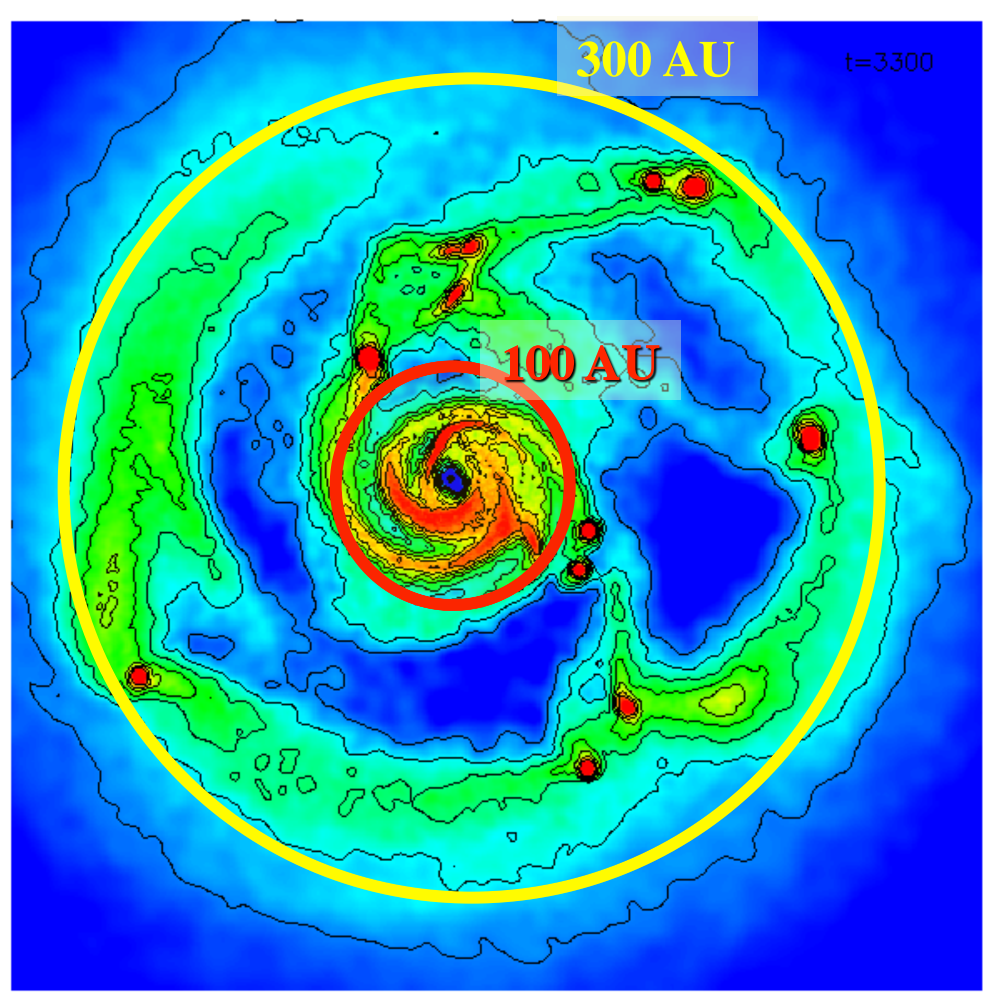
$$R_{\rm CORE} = 50\,000 \text{ AU}$$

- SPH code SEREN by David Hubber et al. (2010), submitted
- Diffusion method of Stamatellos et al. (2007)


t=75000 yr
200
0
−200
−400
y AU
0
200
400
600
x AU
12
11
10
9
log column density

# Disc fragmentation criteria





# The importance of radiative feedback from protostars

## Simulation II:

**Radiative feedback from protostars is fully included**

**Continuous radiative feedback**

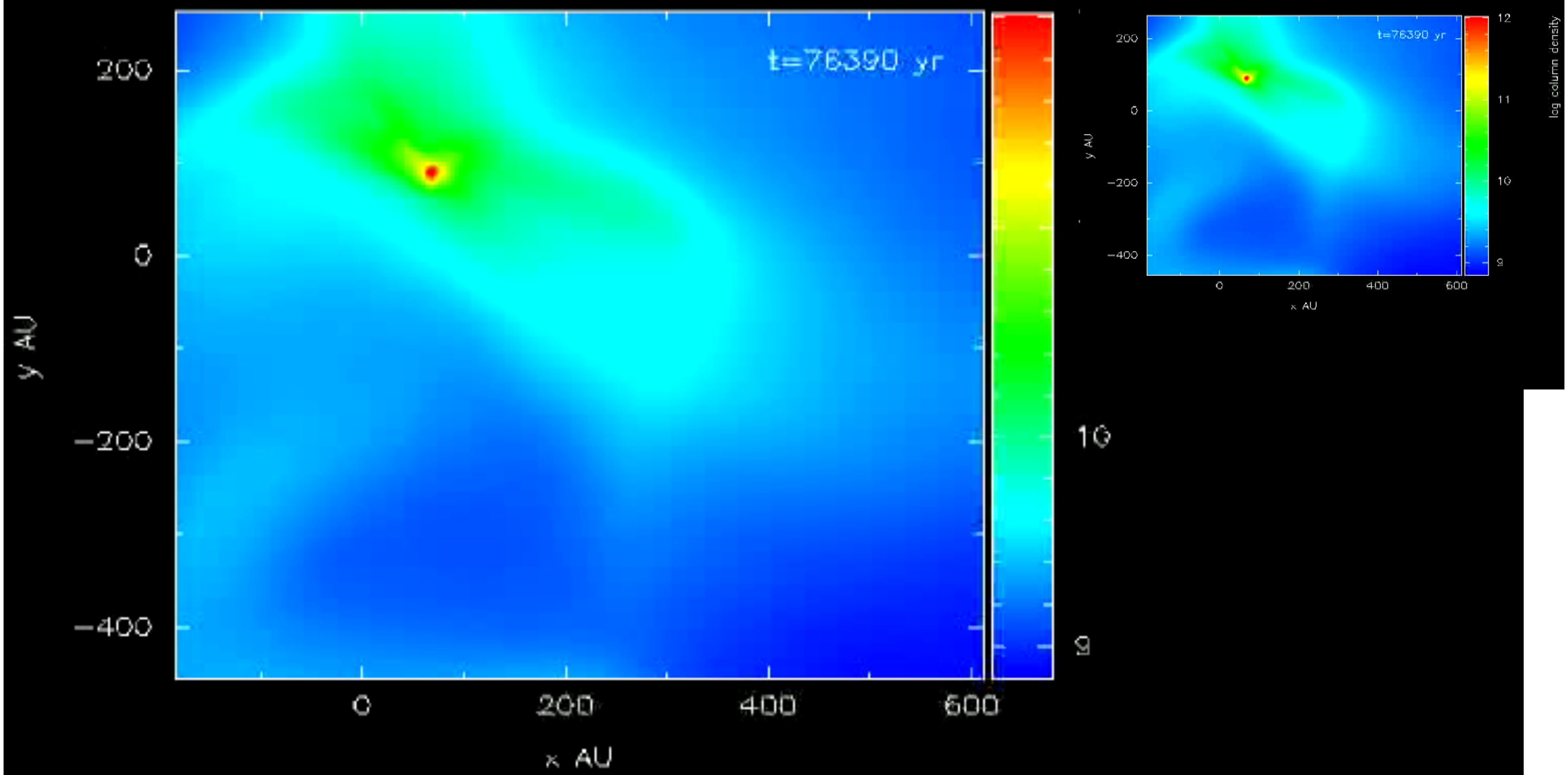
[similar to Offner, Krumholz, Klein  simulations]

$$L_\star = \left(\frac{M_\star}{\mathrm{M}_\odot}\right)^3 \mathrm{L}_\odot + f_\mathrm{rad}\,\frac{GM_\star \dot{M}_\star}{R_\star}\left(1 - \frac{R_\star}{2R_\mathrm{sink}}\right)$$

$f_\mathrm{rad} = 0.75$ The fraction of the accretion energy that is radiated away

Background heating

$$T_\mathrm{o}^4(\boldsymbol{r}) = (10\,\mathrm{K})^4 + \sum_\star \left\{\frac{L_\star}{16\pi\sigma_\mathrm{SB}\,|\boldsymbol{r} - \boldsymbol{r}_\star|^2}\right\}$$


t=76390 yr
200
0
y AU
−200
−400
0
200
400
600
x AU
10
9
t=76390 yr
200
0
y AU
−200
−400
0
200
400
600
x AU
12
11
10
9
log column density

# Accretion is episodic: FU Ori's

- FU Ori-type stars

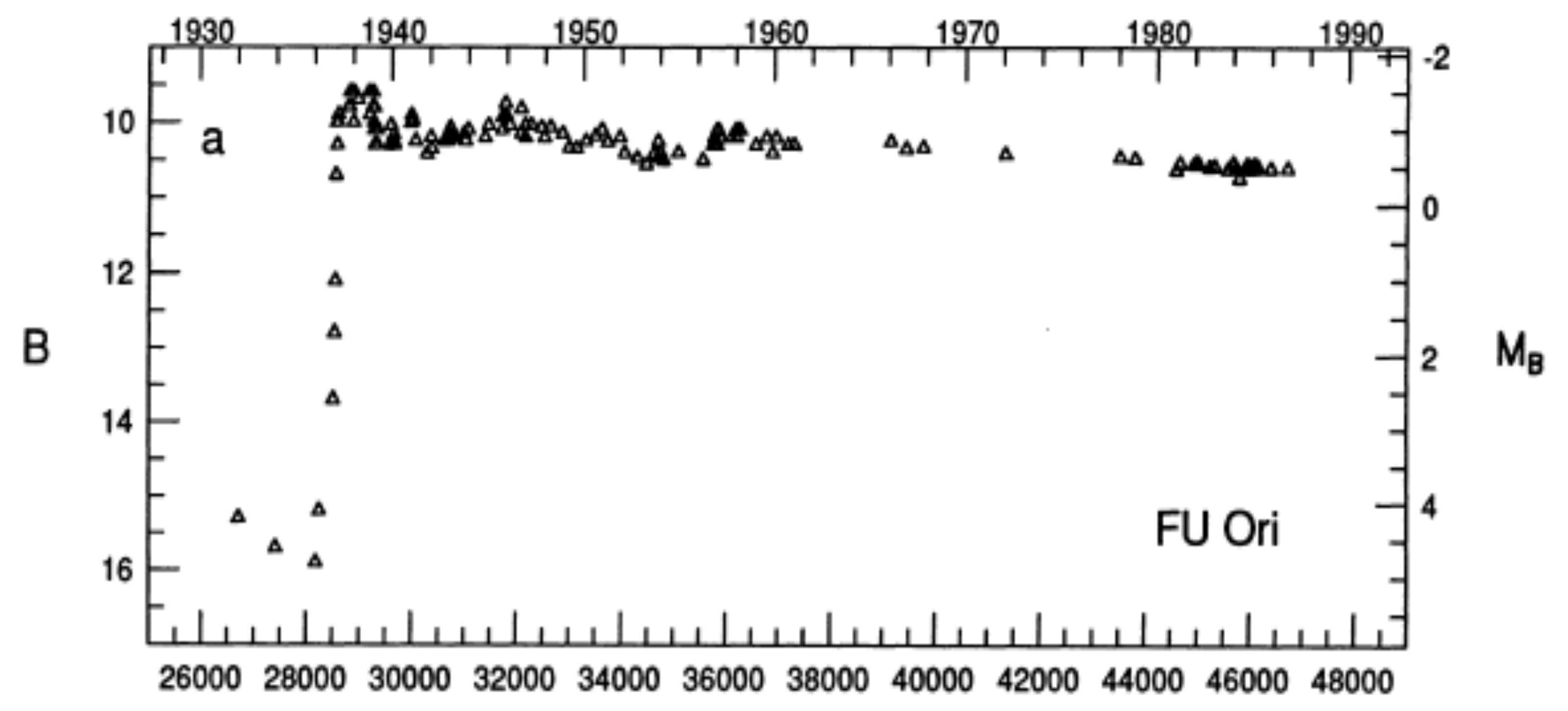
Hartmann & Kenyon 1996, ARAA

rise time: 1-10 yr

duration: 10s to a few 100s yr

Accretion rate: a few$10^{-4}$ $M_\odot$/yr

Mass: 0.01-0.1 $M_\odot$/event



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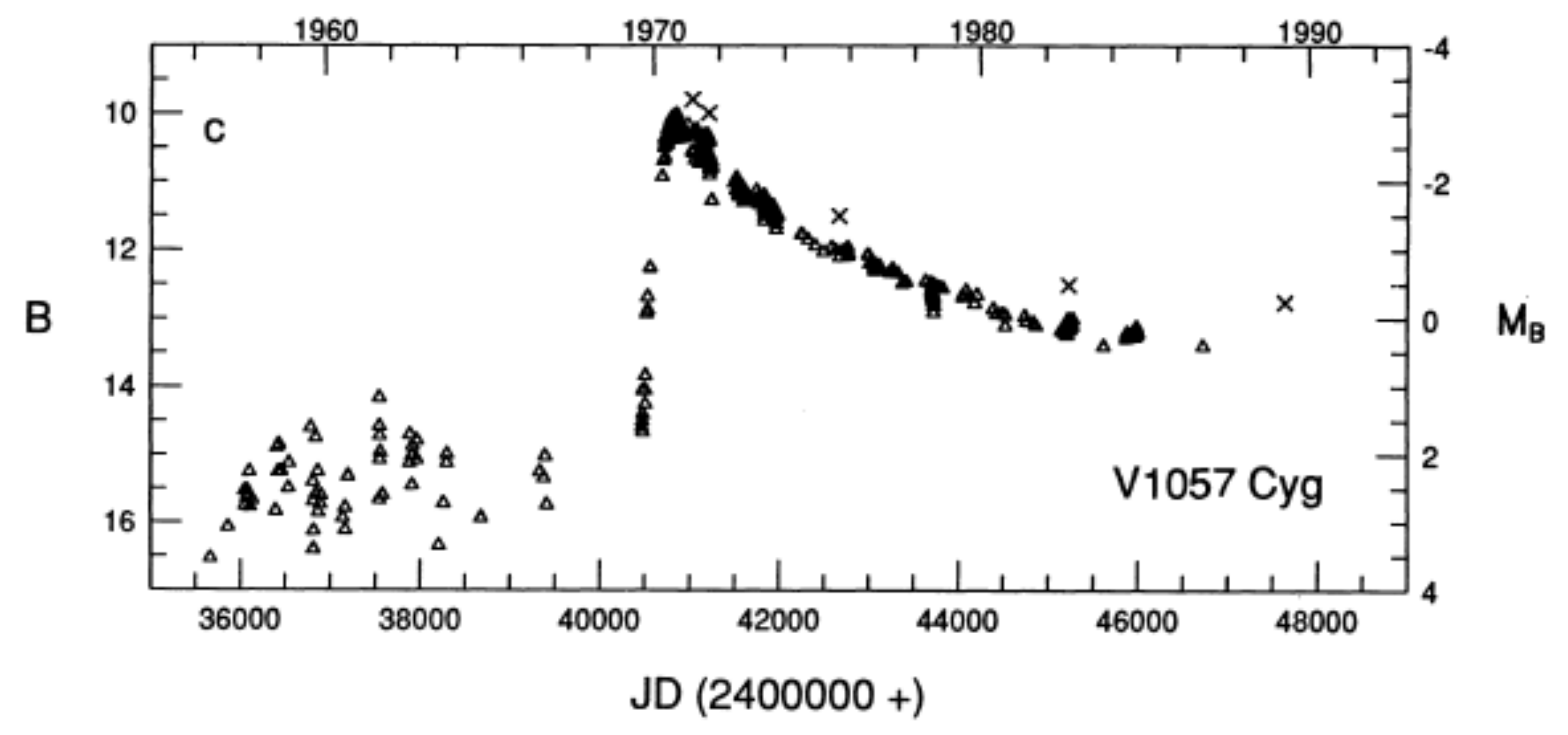
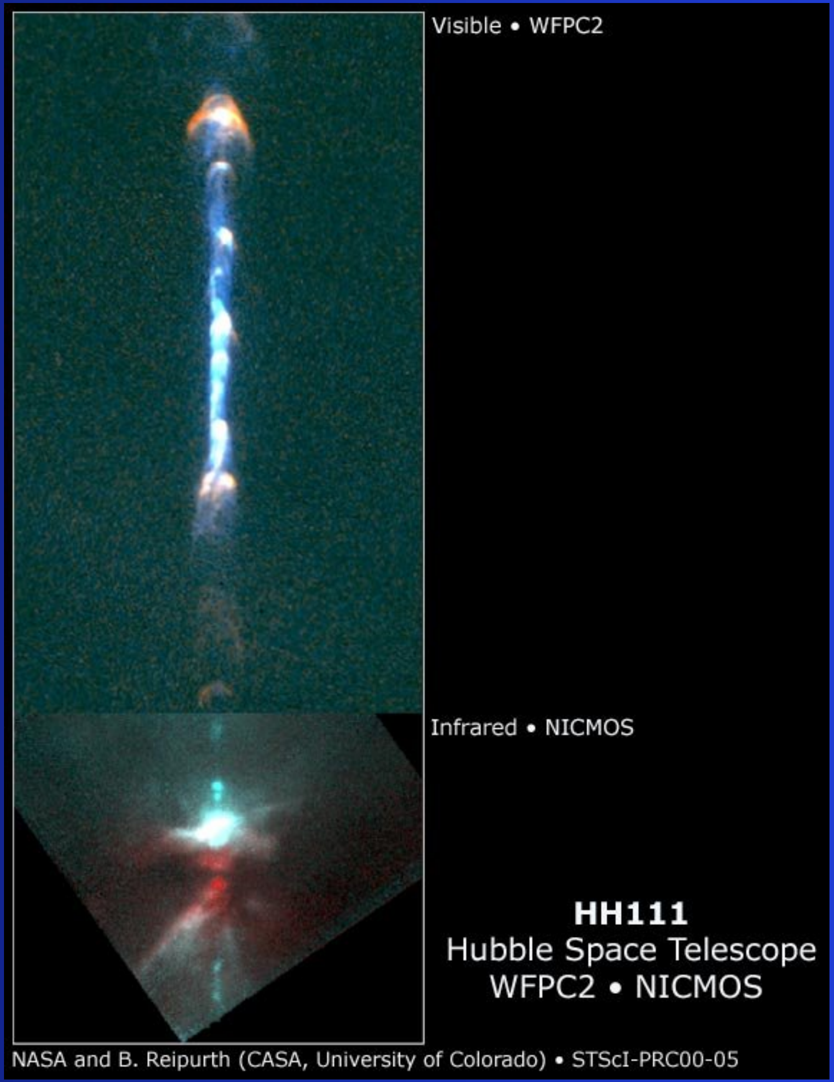


# Accretion is episodic: Herbig-Haro objects

- Episodic accretion onto a protostar results in episodic ejection of material.

Reipurth Nature 340 ,42–45(1989)



NASA and B. Reipurth (CASA, University of Colorado) • STScI-PRC00-05

# Accretion is episodic: the luminosity problem

- The luminosities of protostars are not high enough (Kenyon et al. 1990; Evans et al. 2009; talk by Erin Kryukova earlier today)

$$0.5\mathrm{M}_\odot/10^5\mathrm{yr} \rightarrow \dot{M} = 5\times10^{-6}M_\odot\mathrm{yr}^{-1} \rightarrow L = \frac{GM\dot{M}}{R_\star} \approx 25L_\odot$$

- FU Ori type outbursts may happen for all protostars providing a solution to the luminosity problem :the luminosity is very high only during short events

# The case for episodic accretion

- Thermal instability (Bell & Lin 1994)
- Binary companion (Bonnell & Bastien)
- Gravitational instabilities (Vorobyov & Basu 2005, 2006)
- Planet "blocking" (Lodato & Clarke 2004)

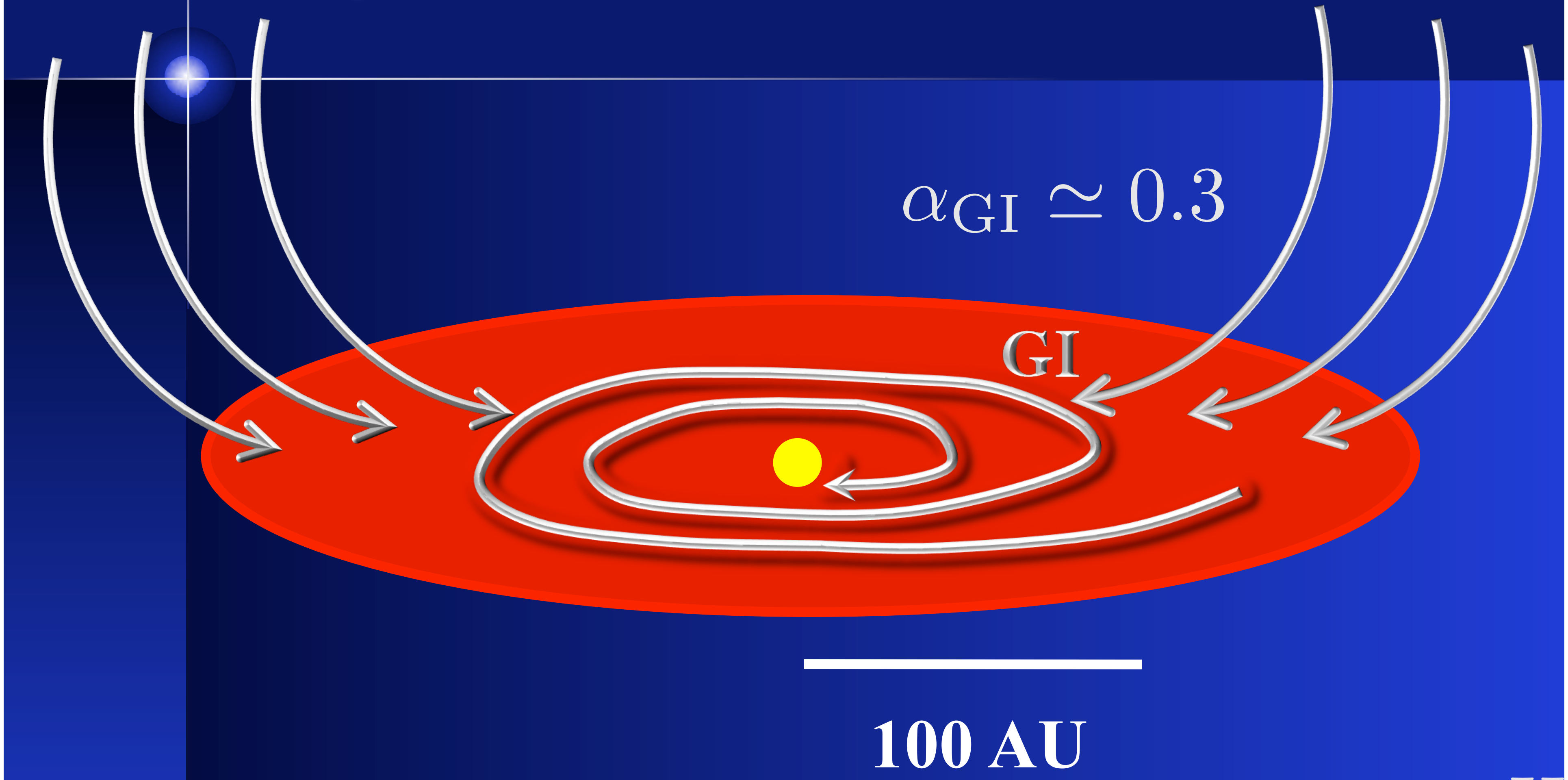
- Zhu, Hartmann et al. 2008-2010: The combined effect of different angular momentum transfer efficiencies of the gravitational instability (GI) and magneto-rotational instability (MRI).

GI: works better >10 AU from the star

MRI: works better at <1 AU

MRI is initiated when **$T_M$>1400 K** in the inner disc region and the outburst starts. Stops when temperarture drops again.

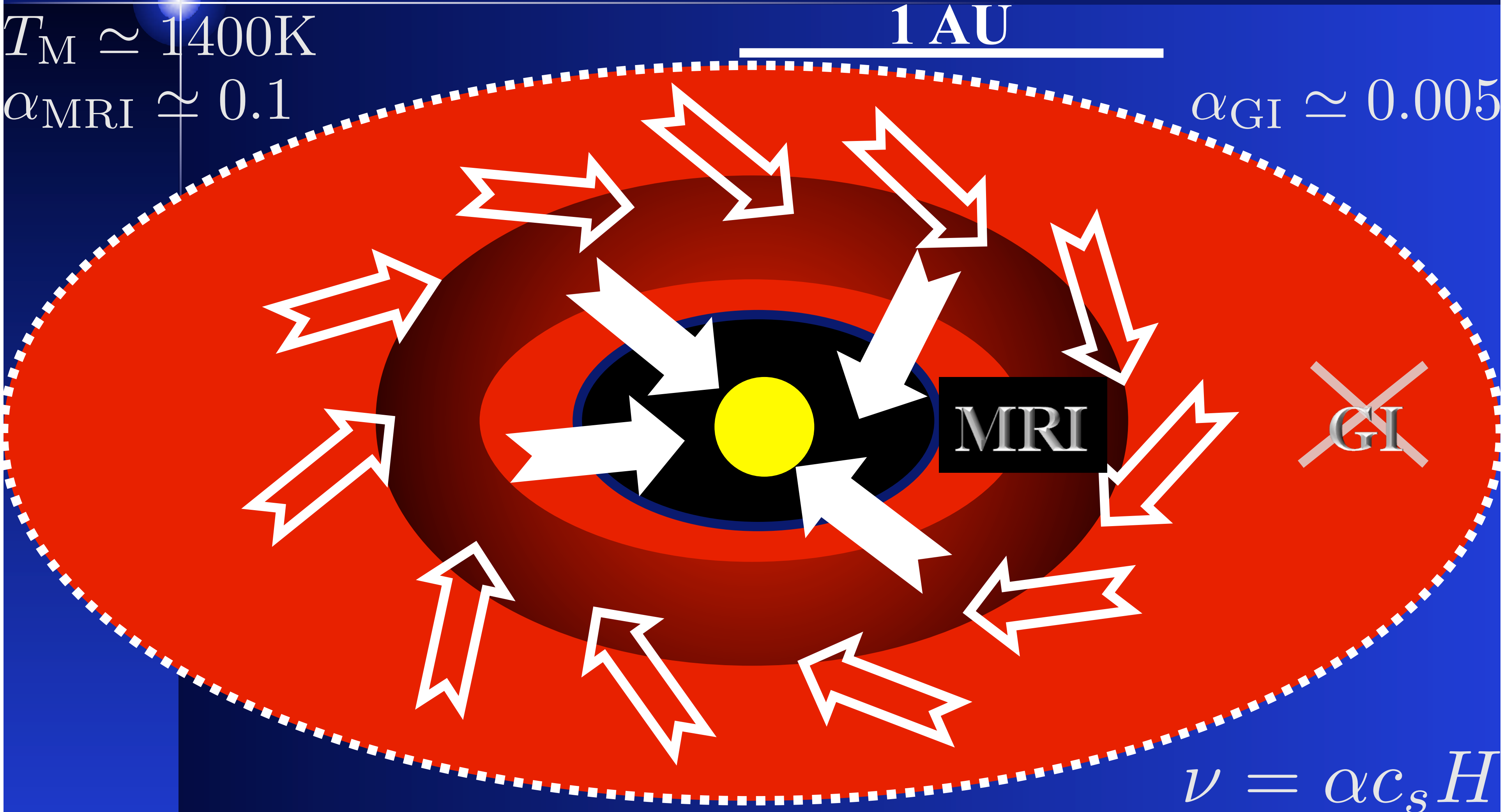
# Episodic accretion: GI vs MRI



$\alpha_{\mathrm{GI}} \simeq 0.3$

$\nu = \alpha c_s H$

# Episodic accretion: GI vs MRI



$T_{\rm M} \simeq 1400{\rm K}$

$\alpha_{\rm MRI} \simeq 0.1$

1 AU

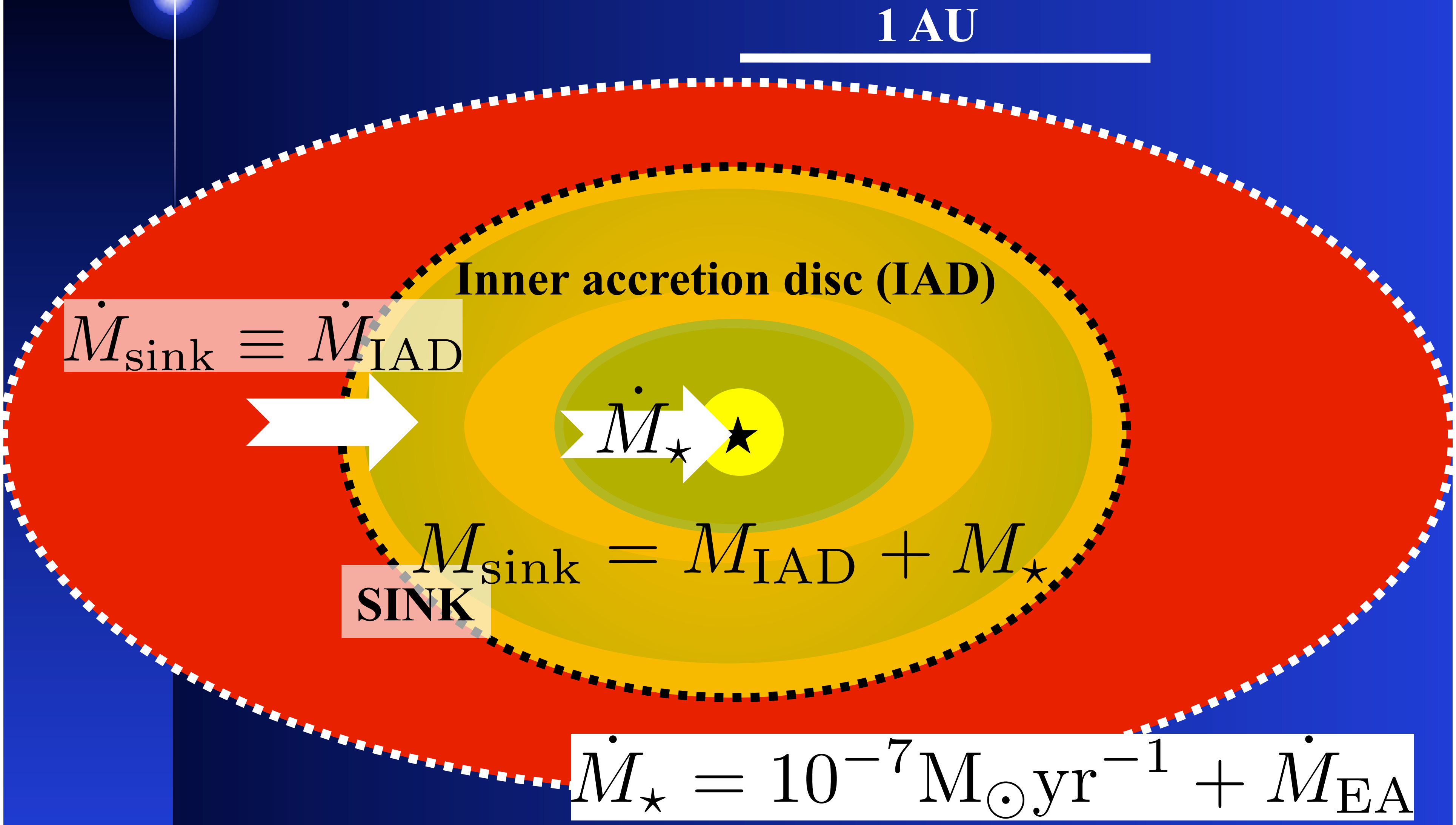
$\alpha_{\rm GI} \simeq 0.005$

MRI

~~GI~~

$\nu = \alpha c_s H$

# A phenomenological model of episodic accretion



1 AU

**Inner accretion disc (IAD)**

$$\dot{M}_{\rm sink} \equiv \dot{M}_{\rm IAD}$$

$$\dot{M}_\star$$

$$M_{\rm sink} = M_{\rm IAD} + M_\star$$

**SINK**

$$\dot{M}_\star = 10^{-7}{\rm M}_\odot{\rm yr}^{-1} + \dot{M}_{\rm EA}$$

# A phenomenological model of episodic accretion

Episodic accretion is initiated when

$$M_{\mathrm{IAD}} \geqslant M_{\mathrm{MRI}} \quad (T_M = 1400\ \mathrm{K})$$

$$M_{\mathrm{MRI}} \simeq 0.13\,\mathrm{M}_{\odot} \left(\frac{M_{\star}}{0.2\,\mathrm{M}_{\odot}}\right)^{2/3} \left(\frac{\dot{M}_{\mathrm{IAD}}}{10^{-5}\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}}\right)^{1/9}$$

Duration of an episodic accretion event

$$\Delta t_{\mathrm{MRI}} \simeq 0.25\,\mathrm{kyr} \left(\frac{\alpha_{\mathrm{MRI}}}{0.1}\right)^{-1} \left(\frac{M_{\mathrm{MRI}}}{0.13\,\mathrm{M}_{\odot}}\right)$$

Zhu et al. 2010a

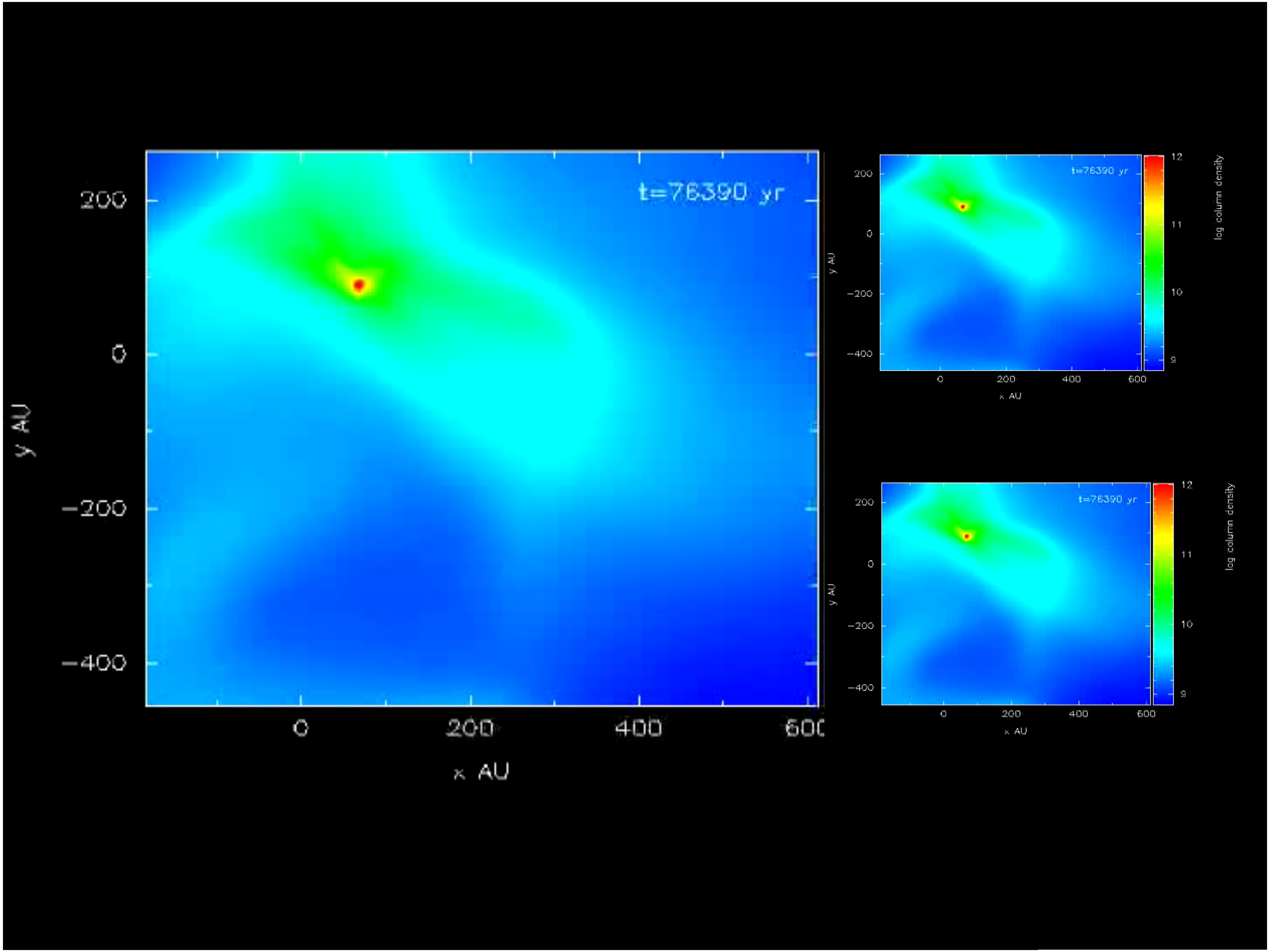
$$\dot{M}_{\star,\mathrm{EA}} = \frac{M_{\mathrm{MRI}}}{\Delta t_{\mathrm{MRI}}}\, e^{-\frac{(t-t_0)}{\Delta t_{\mathrm{MRI}}}}\,, \quad t_0 < t < t_0 + \Delta t_{\mathrm{MRI}}$$

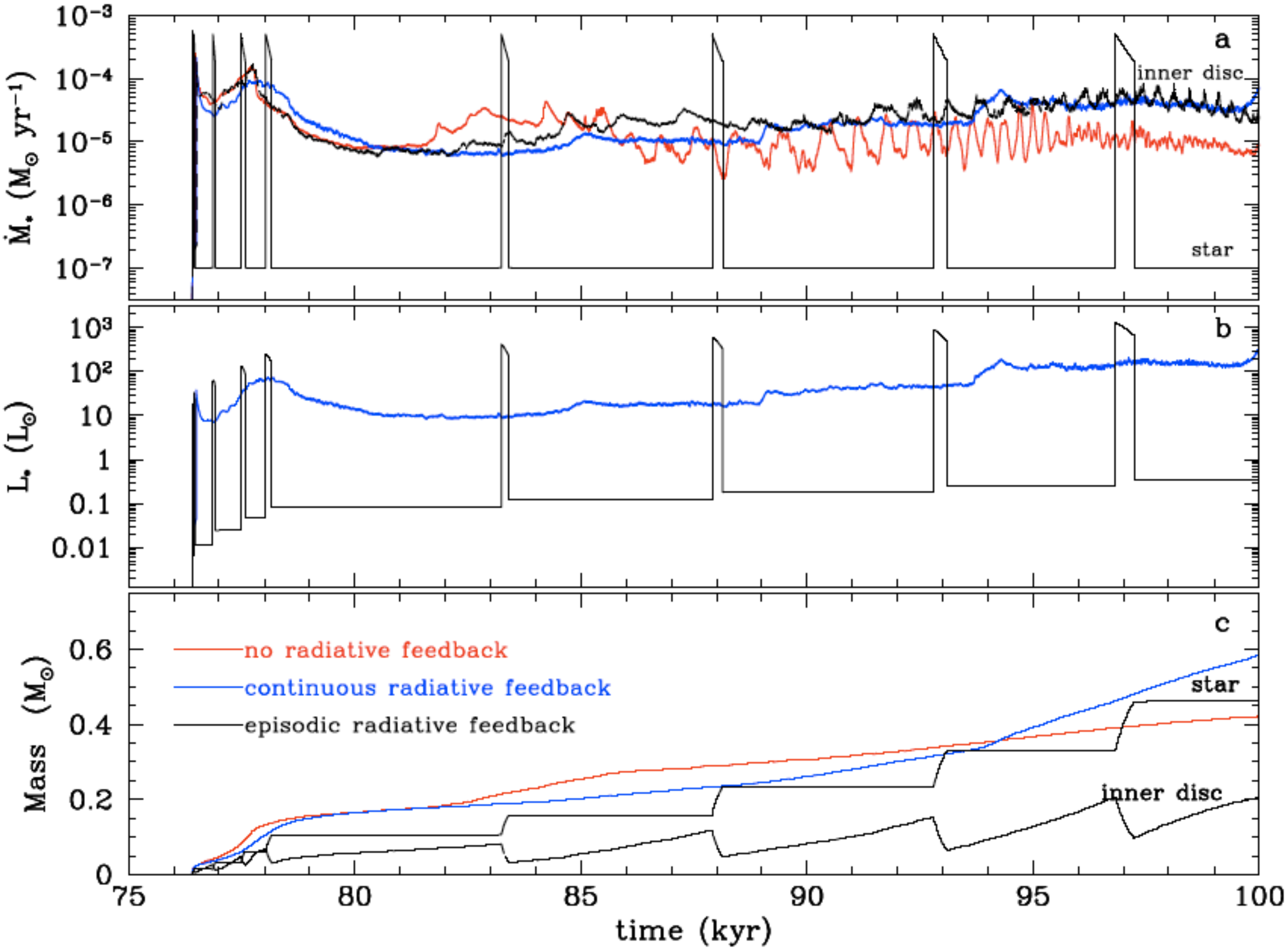
# The importance of radiative feedback from protostars

## Simulation III:

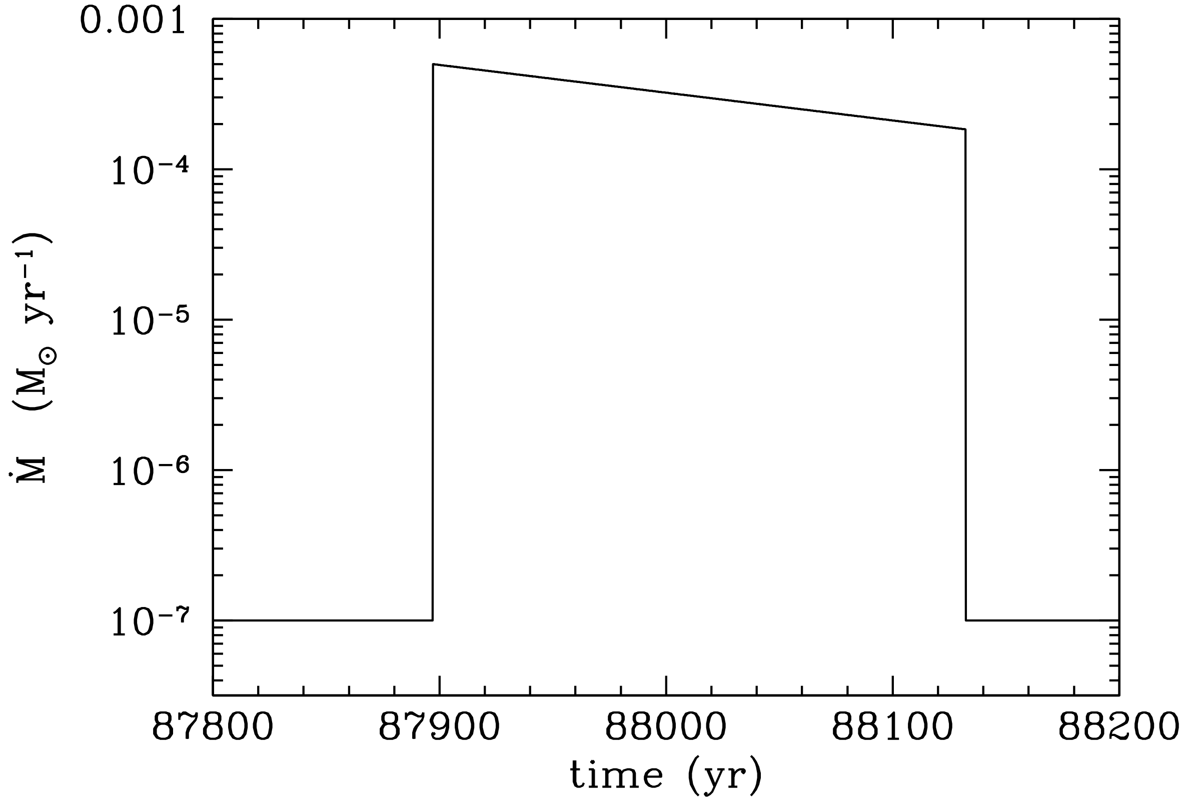
Radiative feedback from protostars is fully included;

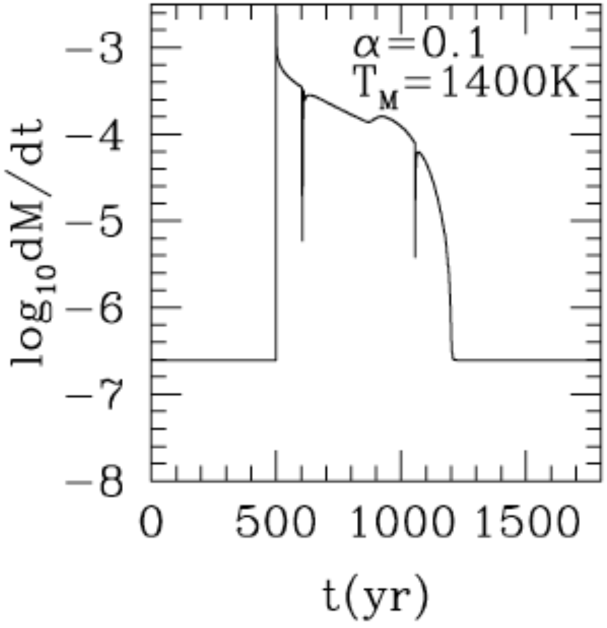
the radiative feedback is not continuous but episodic


t=76390 yr
200
0
−200
−400
y AU
0
200
400
600
x AU
t=76390 yr
200
0
−200
−400
y AU
0
200
400
600
x AU
12
11
10
9
log column density
t=76390 yr
200
0
−200
−400
y AU
0
200
400
600
x AU
12
11
10
9
log column density

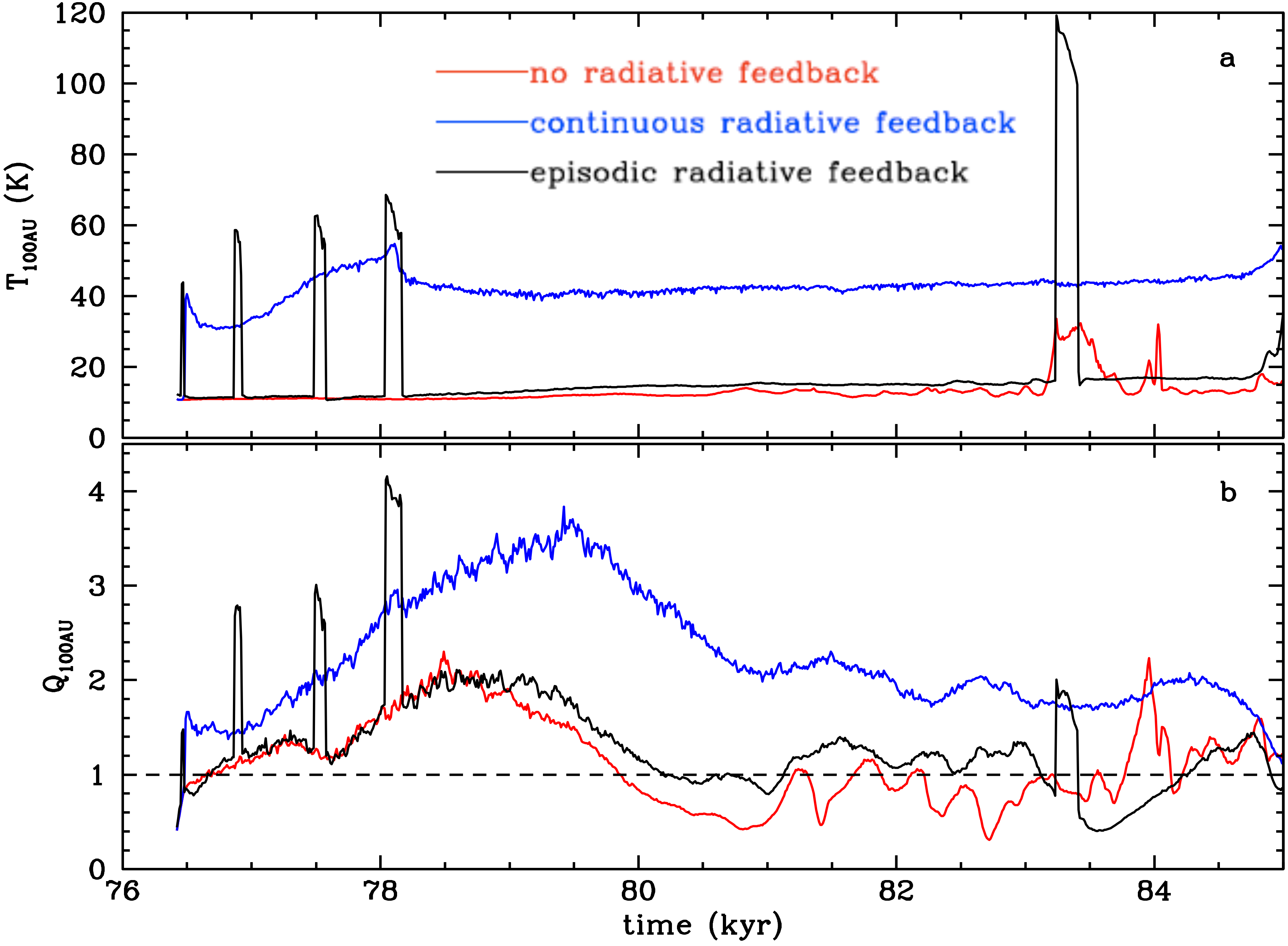

a
inner disc
star
$\dot{M}_*$ ($M_\odot$ yr$^{-1}$)
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
b
$L_*$ ($L_\odot$)
$10^3$
$10^2$
10
1
0.1
0.01
c
no radiative feedback
continuous radiative feedback
episodic radiative feedback
star
inner disc
Mass ($M_\odot$)
0.6
0.4
0.2
0
75
80
85
90
95
100
time (kyr)

# Example of an outburst



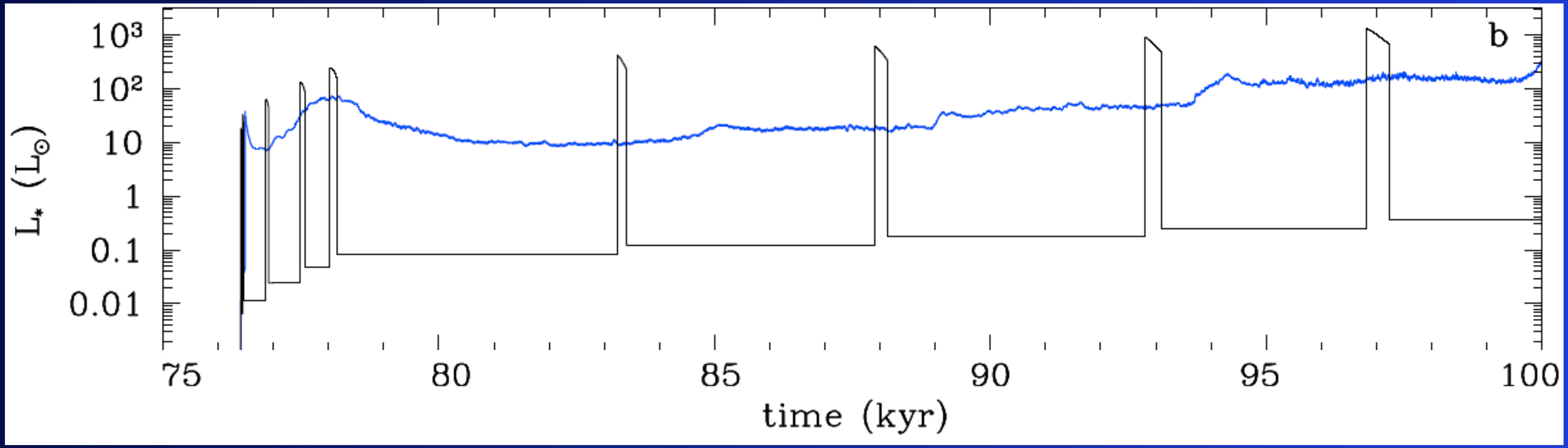


Zhu et al. 2010a


120
100
80
60
40
20
0
$T_{100AU}$ (K)
a
no radiative feedback
continuous radiative feedback
episodic radiative feedback
4
3
2
1
0
$Q_{100AU}$
b
76
78
80
82
84
time (kyr)

- **The importance of radiative feedback depends on**
  - duration of outburst ($\Delta t_{MRI}$)
  - how often an outburst happens ($T_{EA}$)

$\Delta t_{MRI} << T_{EA}$



**Duration of episodic accretion event**

$$\Delta t_{\rm MRI} \simeq 0.25\,{\rm kyr}\, \left(\frac{\alpha_{\rm MRI}}{0.1}\right)^{-1} \left(\frac{M_{\rm MRI}}{0.13\,{\rm M}_\odot}\right)$$

**Time interval between successive episodic accretion events**

$$T_{\rm EA} \simeq 13\,{\rm kyr}\, \left(\frac{M_\star}{0.2\,{\rm M}_\odot}\right)^{2/3} \left(\frac{\dot{M}_{\rm IAD}}{10^{-5}\,{\rm M}_\odot\,{\rm yr}^{-1}}\right)^{-8/9}$$

# Concluding remarks

- Episodic radiative feedback (due to episodic accretion) limits considerably the effects of the protostellar luminosity

- Disc fragmentation is still possible; discs fragment to form low-mass stars, brown dwarfs and planetary-mass objects

- The frequency of episodic accretion events may regulate low-mass star formation in different environments.