

# Protostellar/PMS Mass Infall and the Luminosity Problem

(Padoan, Haugbølle, & Nordlund 2014, arXiv:1407.1445)

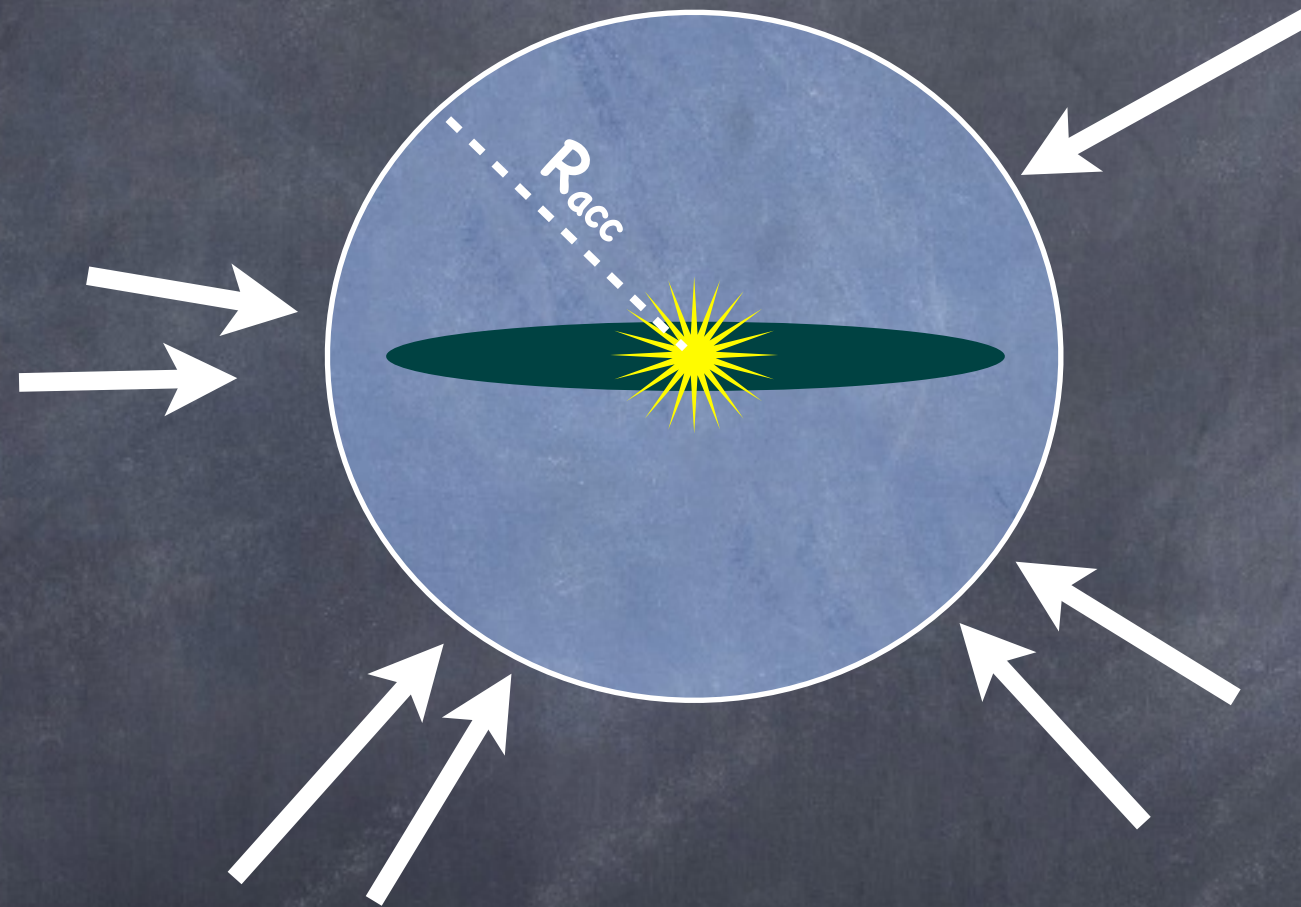
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# Mass Infall

Mass infall onto the star+disk system, measured within a sphere of size  $R_{\text{acc}} \geq R_{\text{disk}}$



NOT the 'internal' accretion from the disk to the star

INFALL: simulated (PS and PMS) - not observed

ACCRETION: observed (only PMS) - not simulated



# Why do we study mass-infall?

- It brings in the stellar mass and may be much more complex than in spherical collapse models.
- It may be strong during most of the planet-formation epoch.
- It may control the disk evolution and the internal accretion, even during non-embedded phases.
- It is easier to simulate than disk accretion, if large scales are computed self-consistently.



# The Plan

- Simulate a large star-forming region, without resolving disks, for over 3 Myr
- Measure the infall rates on sink particles
- Compare infall rates with observed accretion rate of pre-main-sequence (PMS) stars
- Assume infall rates are good proxy of accretion rate also for young protostars
- Predict luminosity of protostars and compare with observed luminosity
- Learn about origin of protostellar luminosity and formation timescale of individual stars



# The Simulation

- Periodic box, random driving, isothermal E.O.S.
- MHD, self-gravity, sink particles
- $\alpha_{\text{vir}} = 0.9$ ;  $M_s = 10$ ;  $M_a = 5$
- $L_{\text{box}} = 4 \text{ pc}$ ;  $n = 800 \text{ cm}^{-3}$ ;  $T = 10 \text{ K}$ ;  $B_0 = 7 \mu \text{ G}$ ;  
 $M = 3000 M_{\odot}$
- $256^3 + 6$  AMR levels:  $dx = 50 \text{ AU}$



Huge range of scales ( $1.6e4$ ), but still designed to avoid resolving protostellar disks.

## Sink formation:

- Sink formed above  $n=10^8 \text{ cm}^{-3}$  (IMF complete to  $0.03 M_{\odot}$ )
- Accretion above  $n=100 \text{ cm}^{-3}$  ( $dM/dt$  detected to  $10^{14} M_{\odot}/\text{yr}$ )
- Accretion sphere with  $R_{\text{acc}}=8dx=400 \text{ AU}$  (external accretion)
- Closest allowed neighbor sink at  $R_{\text{excl}}=16dx=800 \text{ AU}$
- N-body code for sink interactions/binaries
- Up to  $SFE=0.16$  and 1300 sinks



# Importance of the integration time:

- To fully populate the Salpeter range of the IMF
- To follow the infall/accretion during PMS (non-embedded class II and III sources)

Before gravity: many  $t_{\text{dyn}}$  to relax the turbulence

After gravity:  $3 t_{\text{dyn}} = 3 t_{\text{ff}} = \underline{3.2 \text{ Myr}}$



# Comparison with previous state-of-the-art simulations

Bate (2012–2014) – HD:

0.4 pc,  $500 M_{\odot}$ ,  $t_{\text{final}} = 0.09$  Myr (183 stars)

Krumholz et al. (2012) – HD:

0.46 pc,  $1000 M_{\odot}$ ,  $t_{\text{final}} = 0.02$  Myr (158 stars)

Myers et al. (2014) – MHD:

0.46 pc,  $1000 M_{\odot}$ ,  $t_{\text{final}} = 0.05$  Myr (92 stars)

This work, Padoan et al. (2014) – MHD:

4.0 pc,  $3100 M_{\odot}$ ,  $t_{\text{final}} = 3.2$  Myr (1300 stars)

- 10 times larger size
- 35–160 times longer integration time
- 7–14 times more stars



Very realistic density field and velocity power spectrum with correct MHD slope down to the sonic scale.

**X projection**

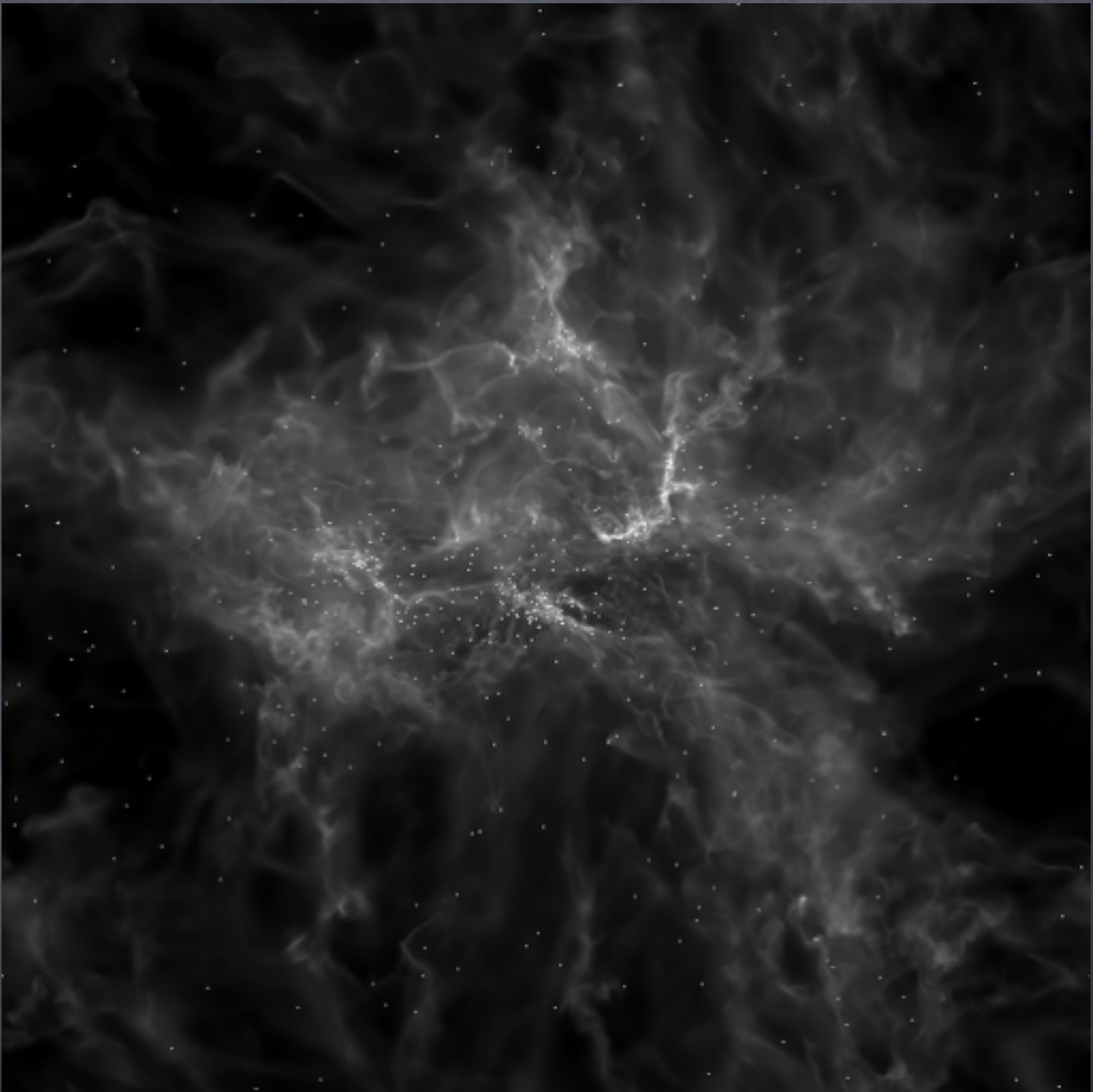
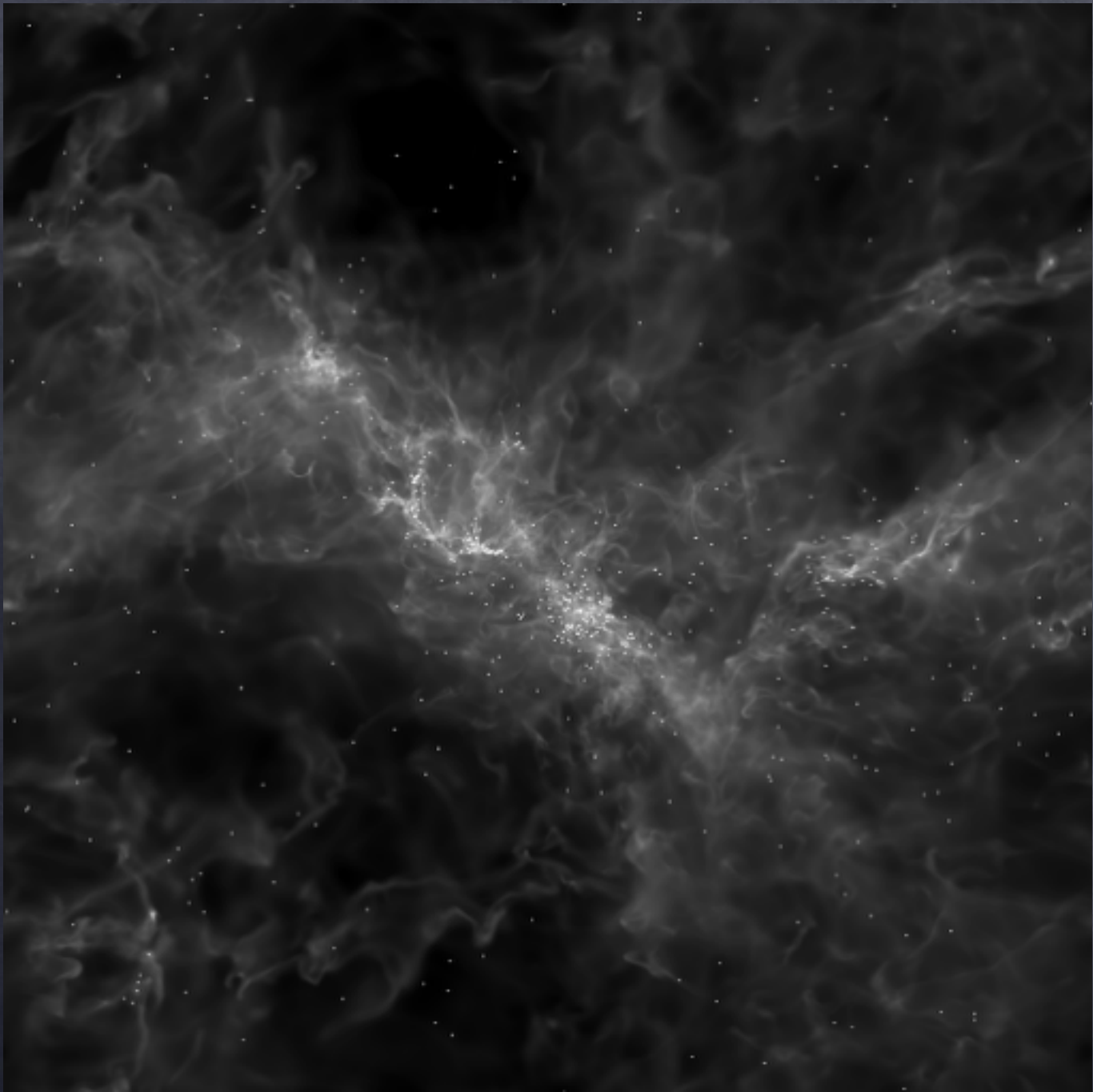
**y projection**

**1 pc**



Evolution during 3.2 Myr, from 1 to 1,300 stars







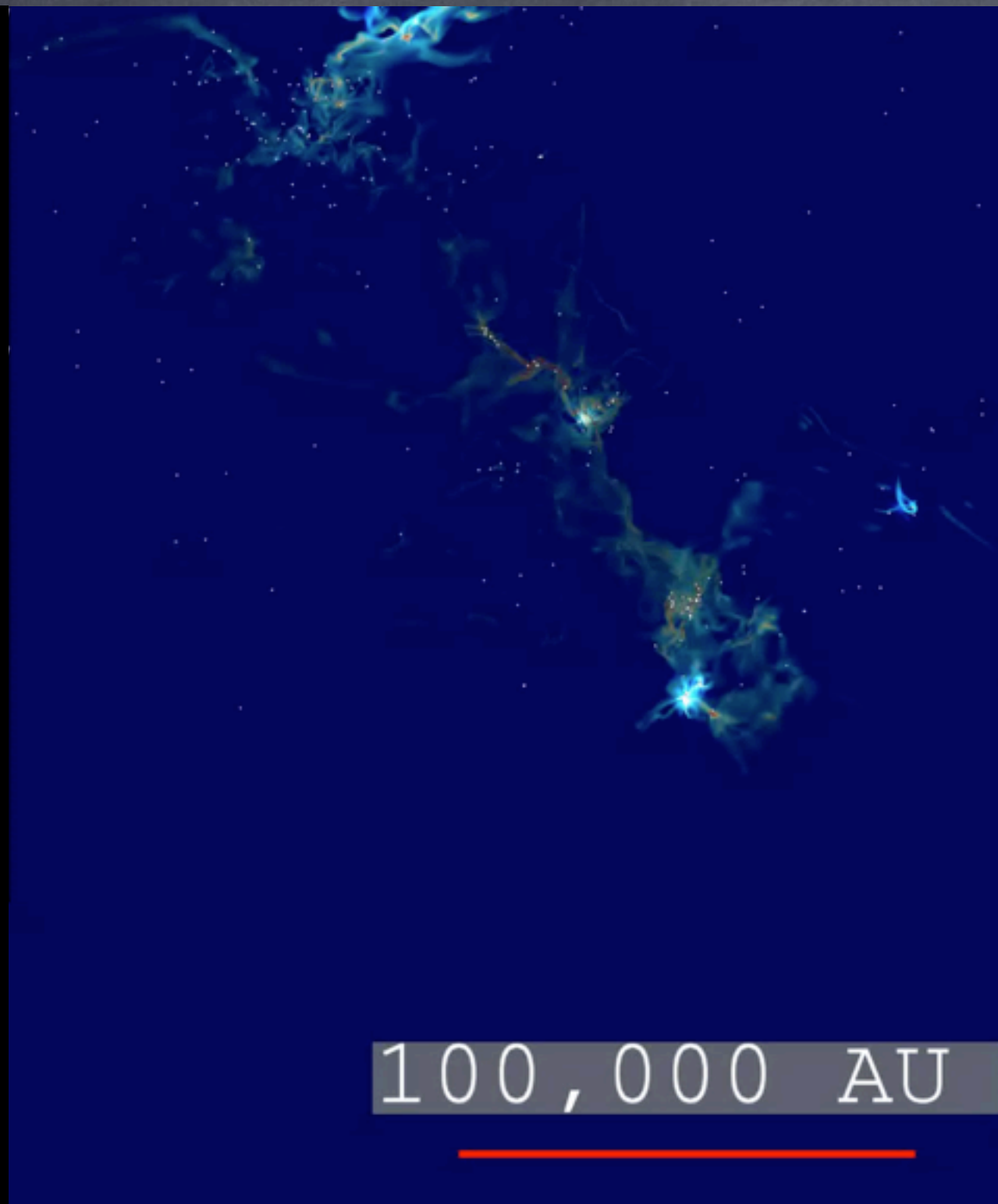
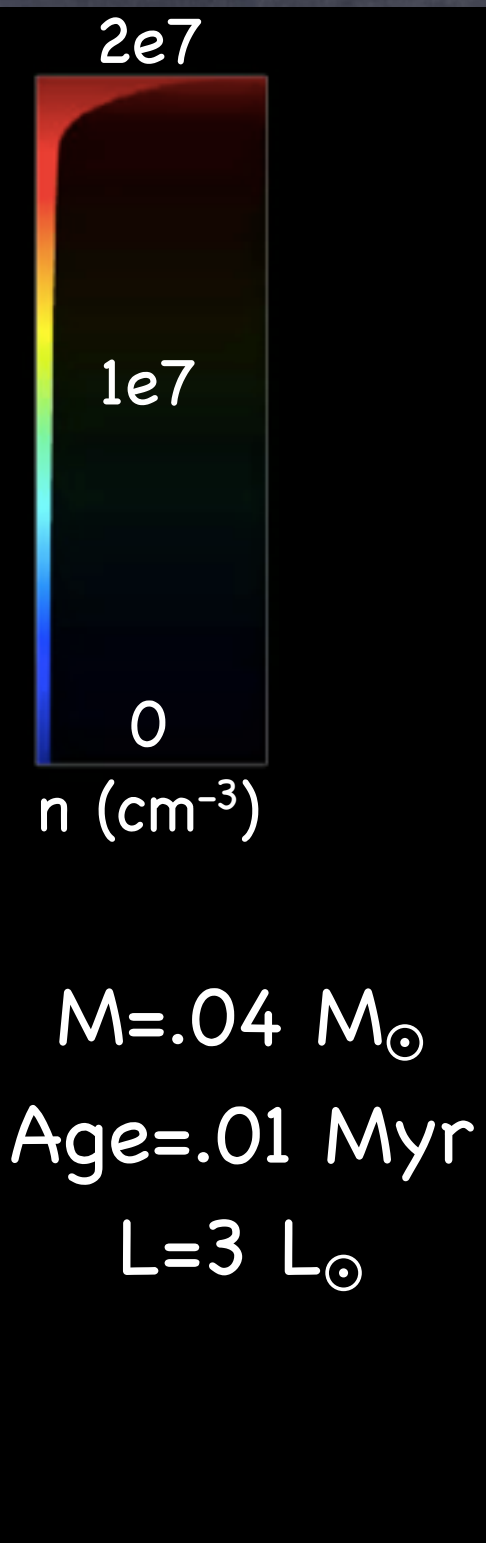
Moving from density projection to 3D rendering and gradually zooming in one can see that:

- The structure is truly filamentary in 3D.
- It remains filamentary down to the smallest scales of mass infall.
- The small-scale filaments are integral part of the large scale structure

Very different from isolated spherical cores



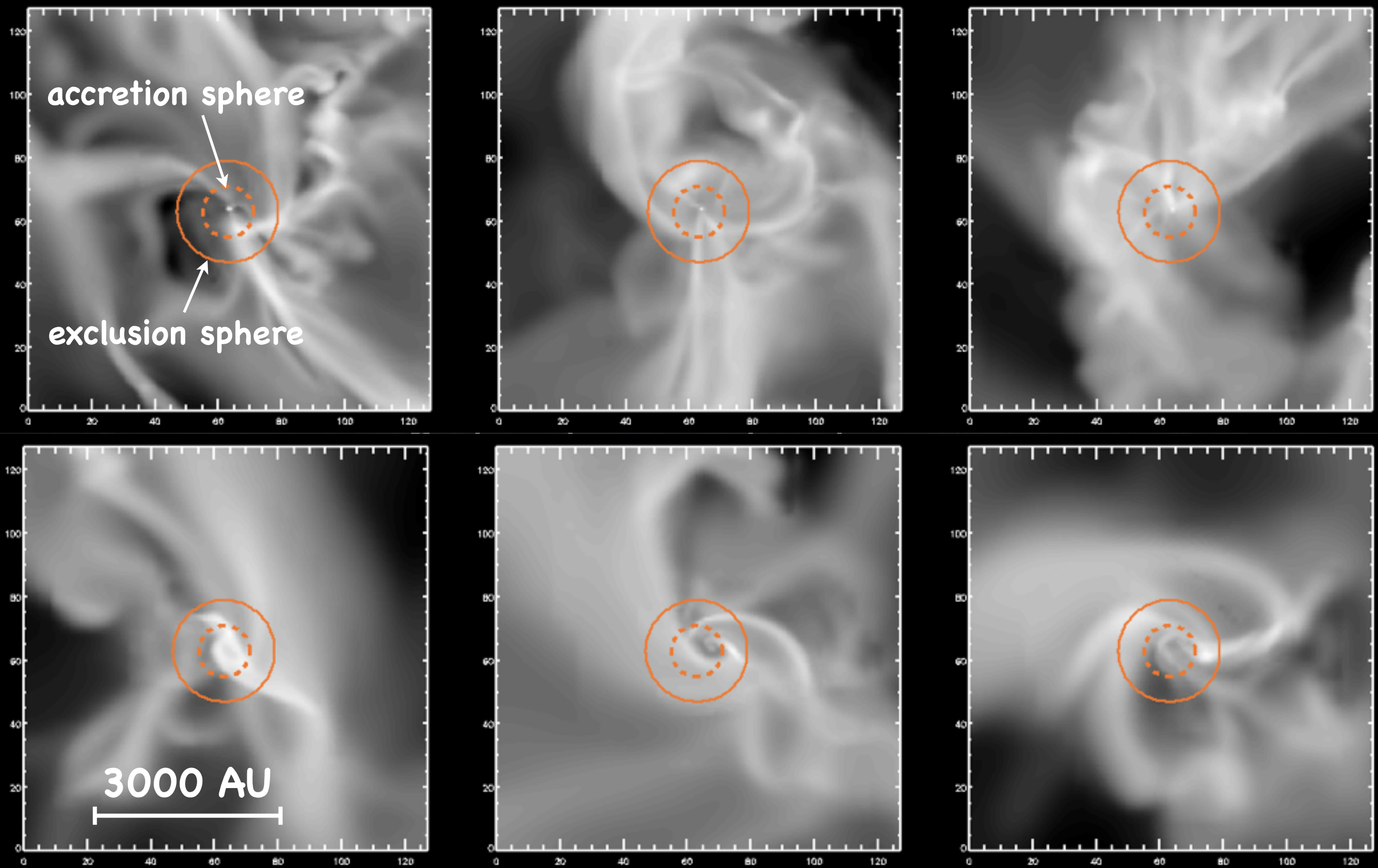
# Example of structure around a newly-formed sink:



by Tim Sandstrom  
NASA/Ames

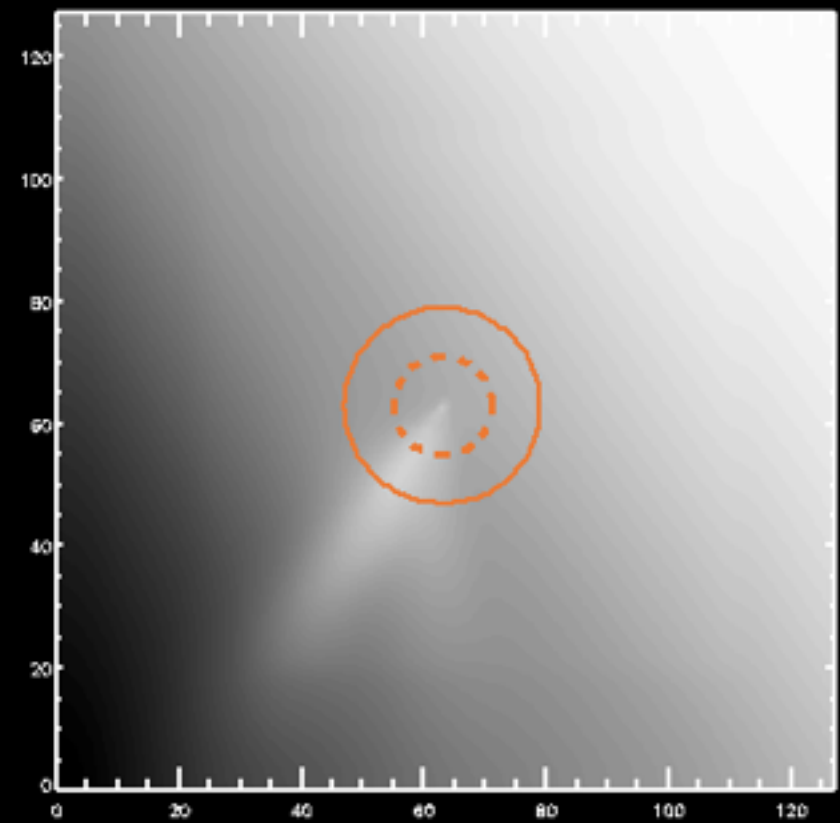
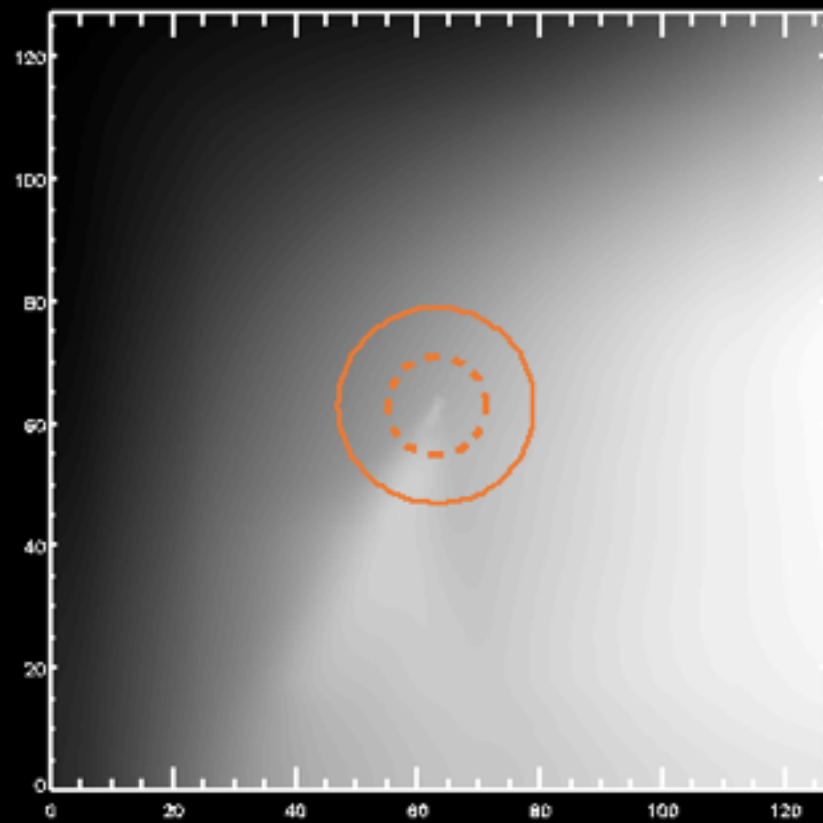
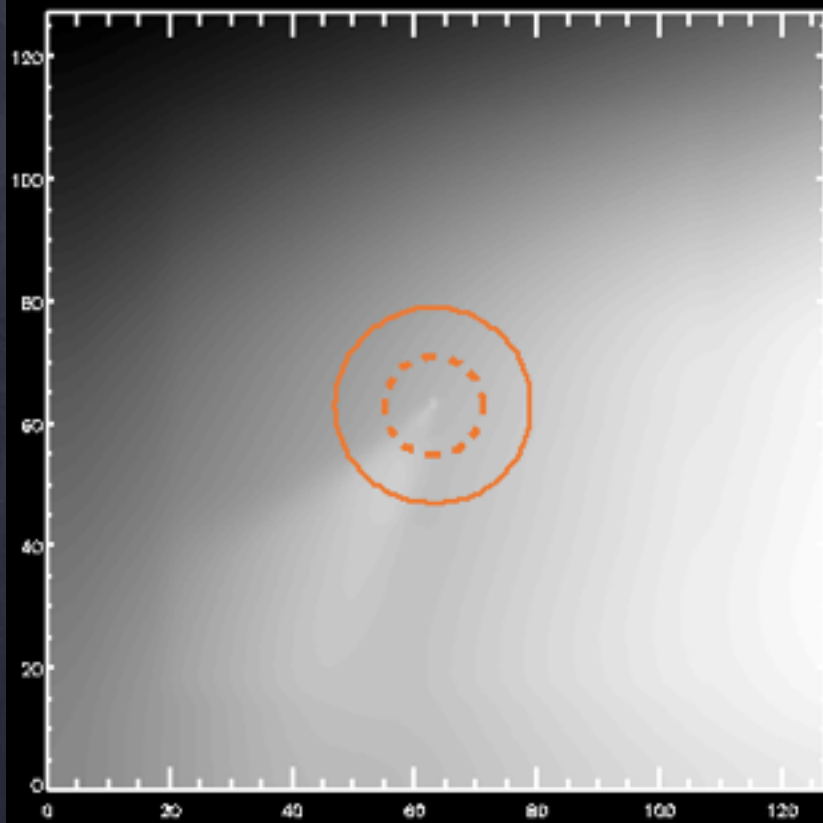


# The early infall is highly filamentary





The late infall is Bondi-Hoyle like

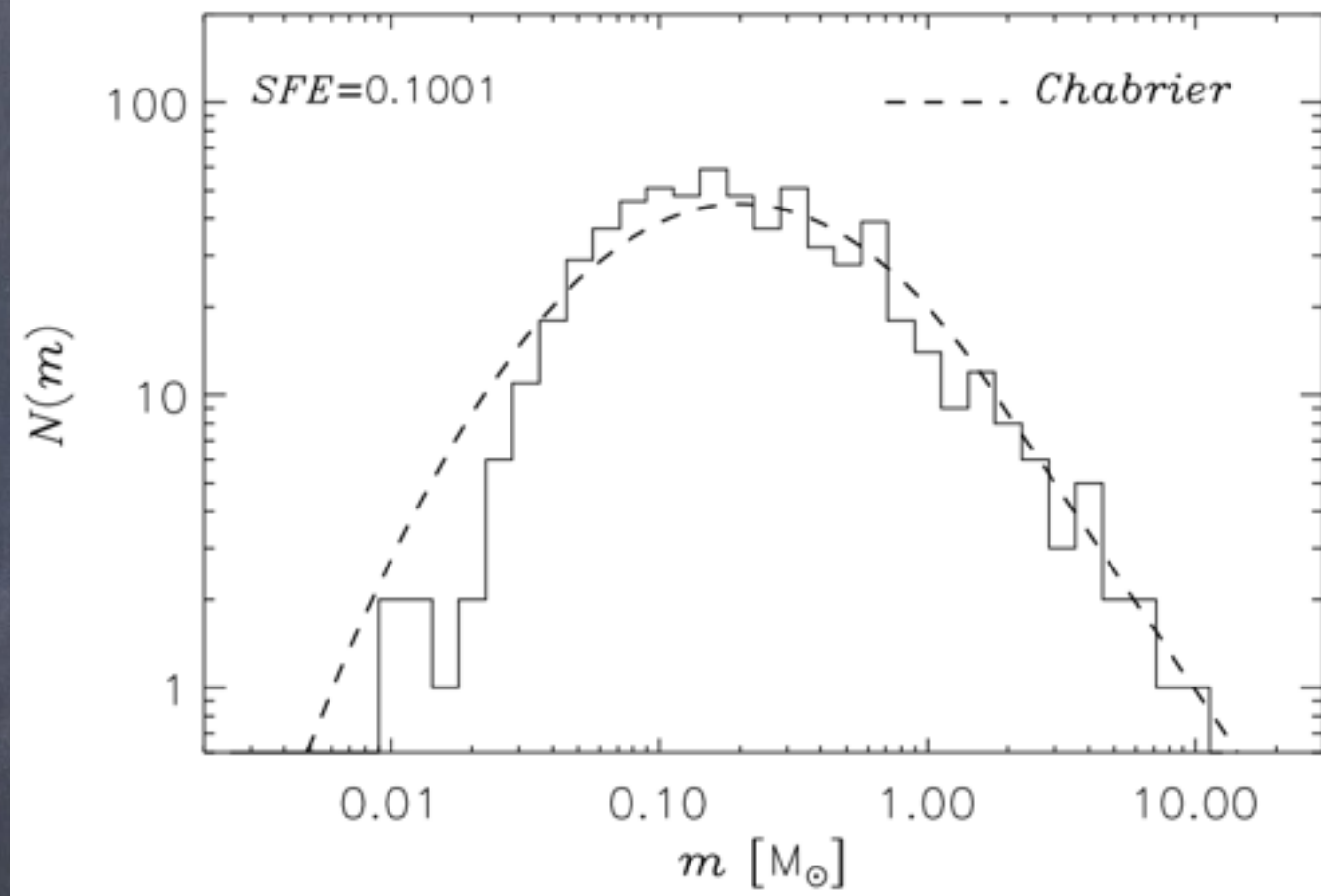
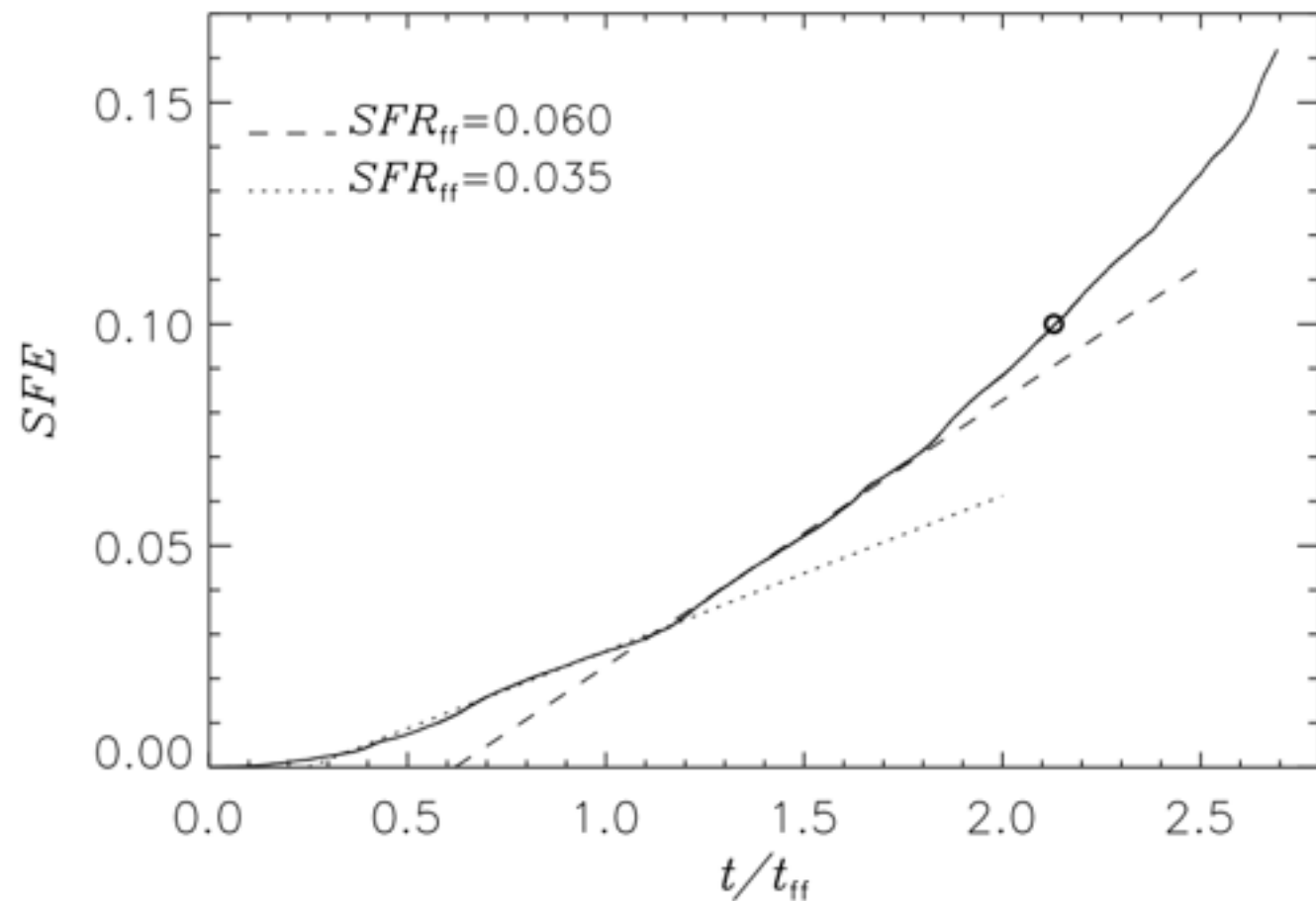




# SFR and IMF

$SFR_{ff} = 0.035$  for more than one free-fall time of the mean density

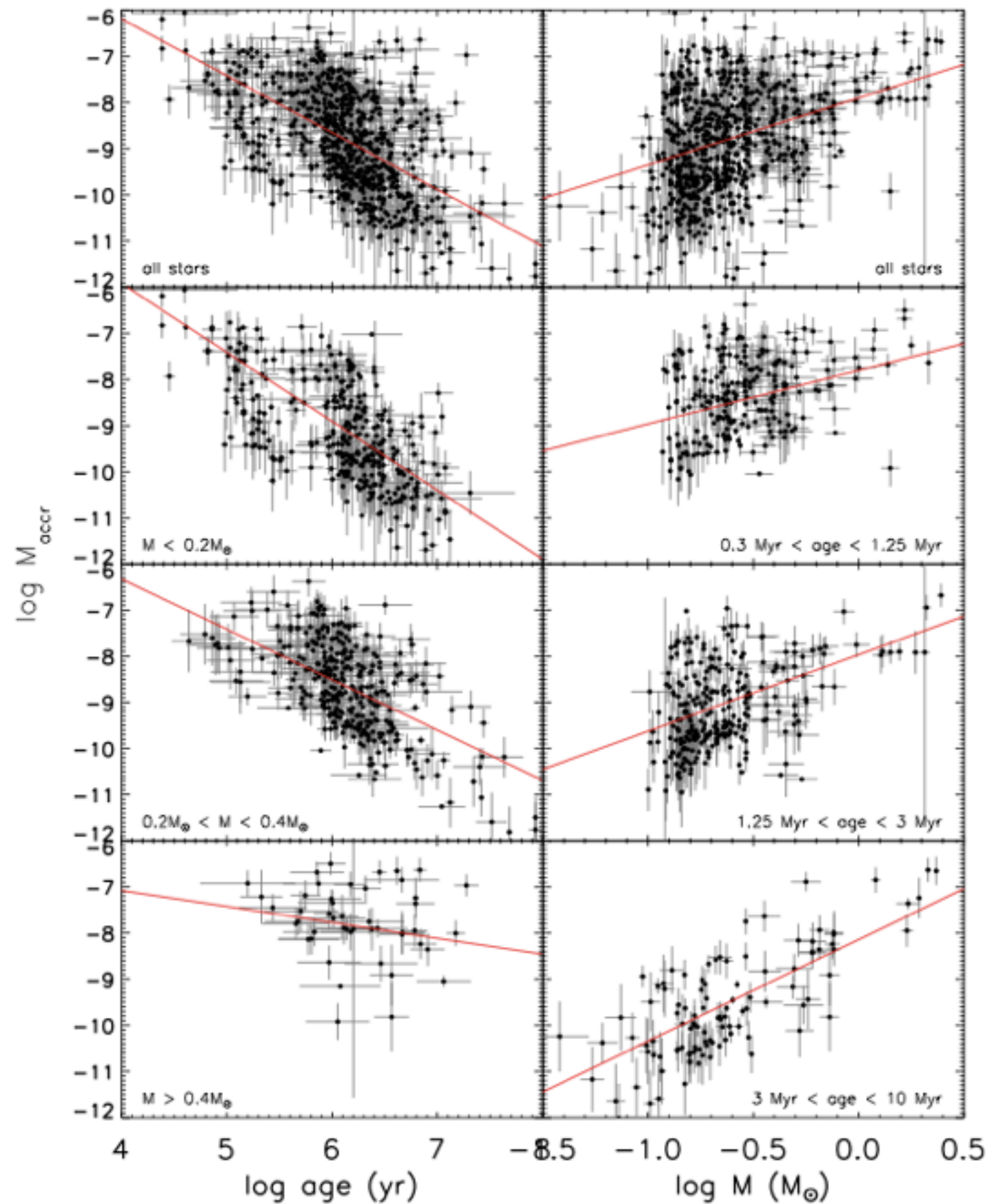
Chabrier IMF complete to  $0.03 M_{\odot}$ , including a full Salpeter range



Very realistic star formation, ideal to study the long-term evolution of the protostellar infall on a large sample

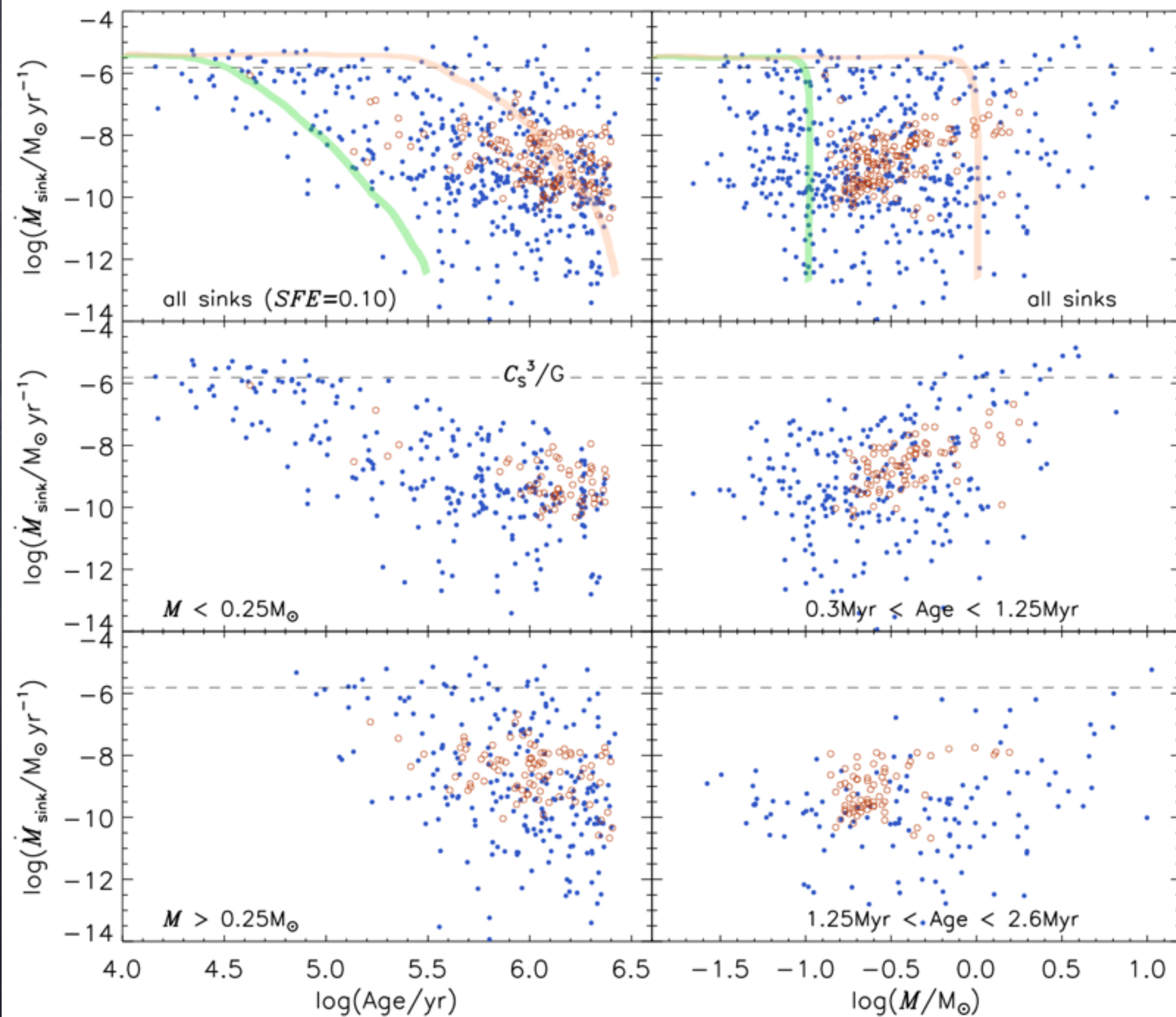


# The ONC sample (Manara et al. 2012)



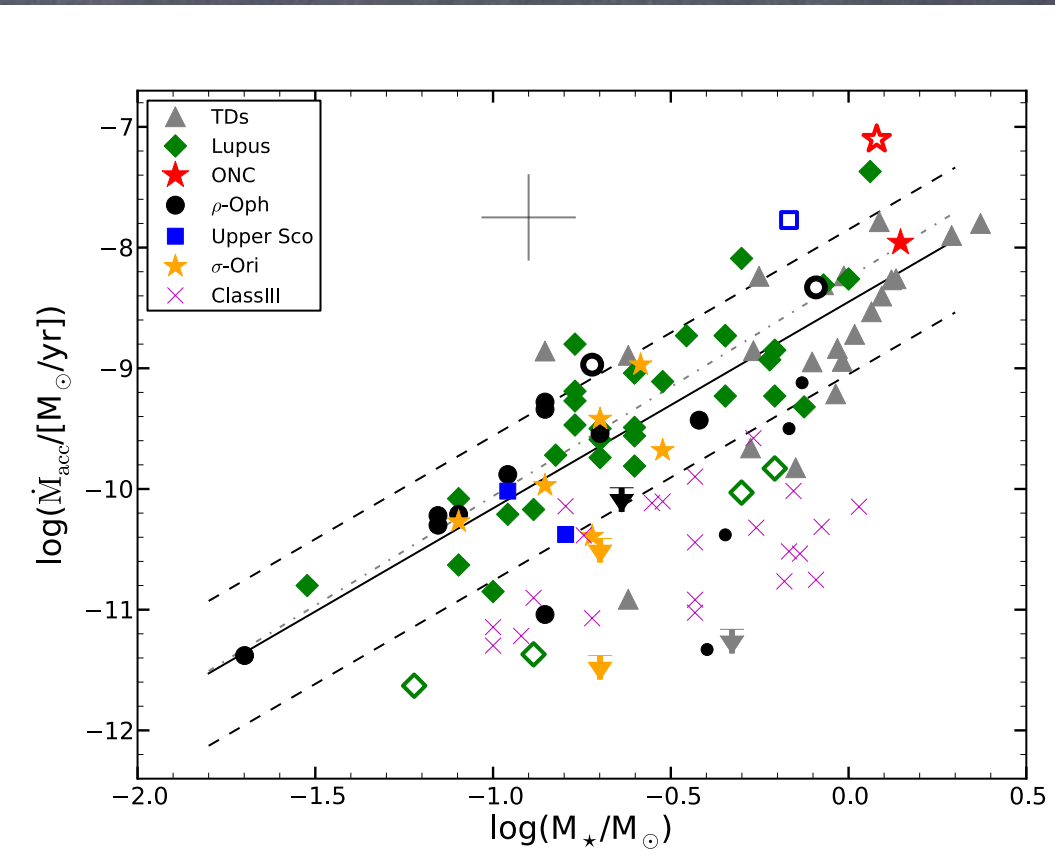
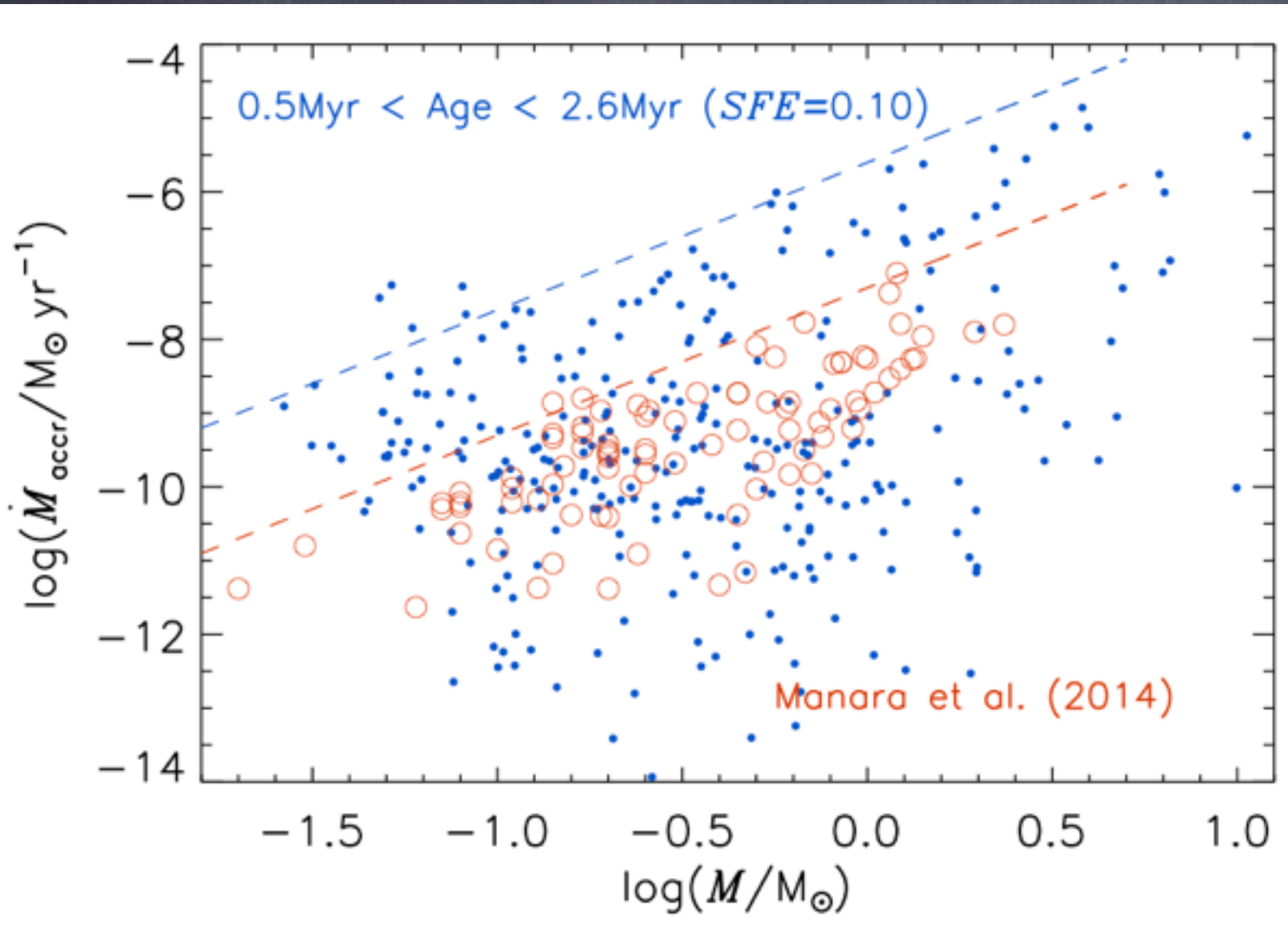


# Simulation at 2.6 Myr: Infall rate $\sim$ observed accretion rate





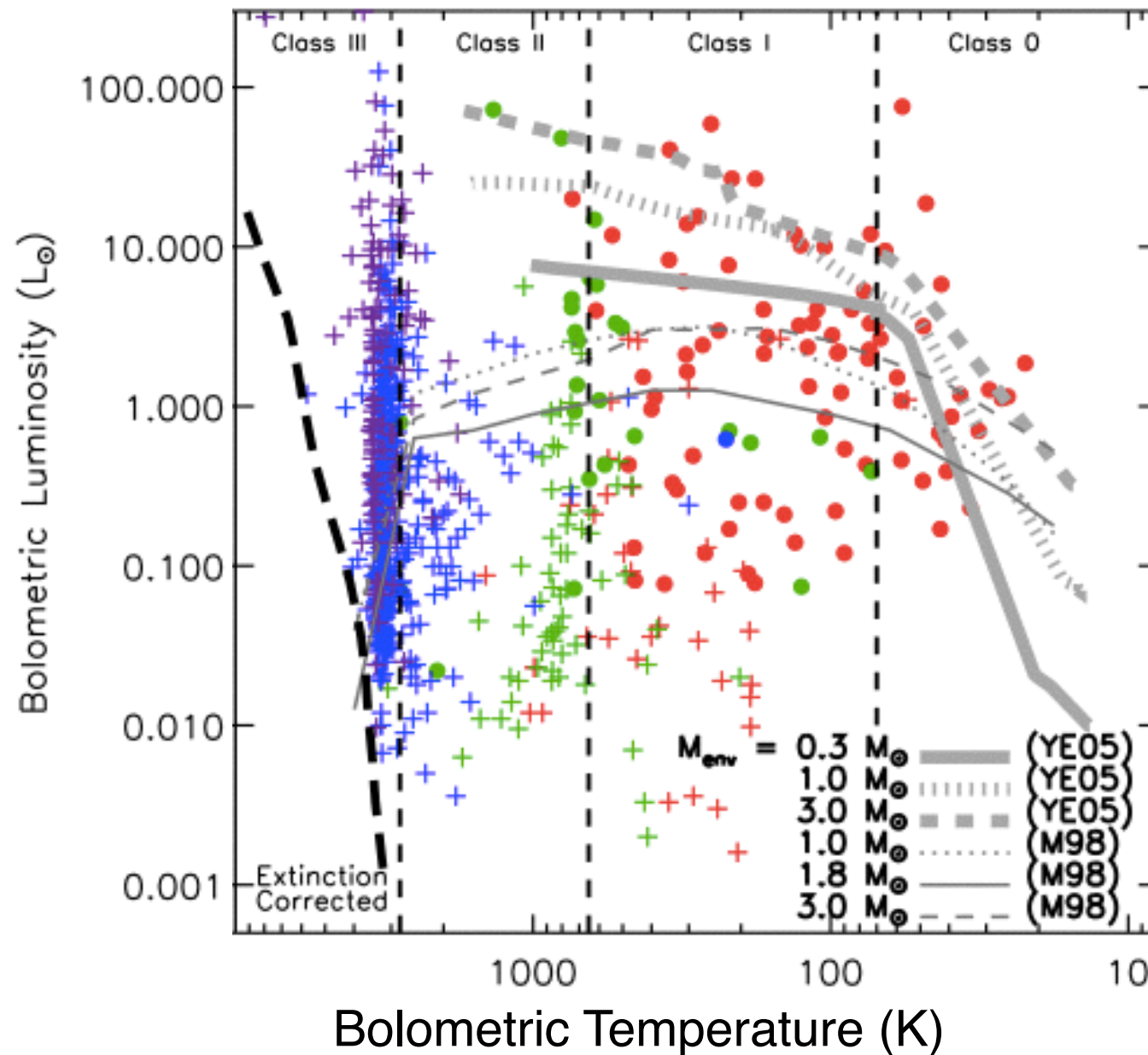
The upper envelope is sensitive to age, but it should be higher than that for the observed accretion rates, because some stars are still embedded even after 0.5 Myr, and because of energy losses between infall and accretion.



Observational sample  
(Manara et al. 2014)

# The Luminosity 'Problem'

Protostars from the c2d project (Evans et al. 2009)



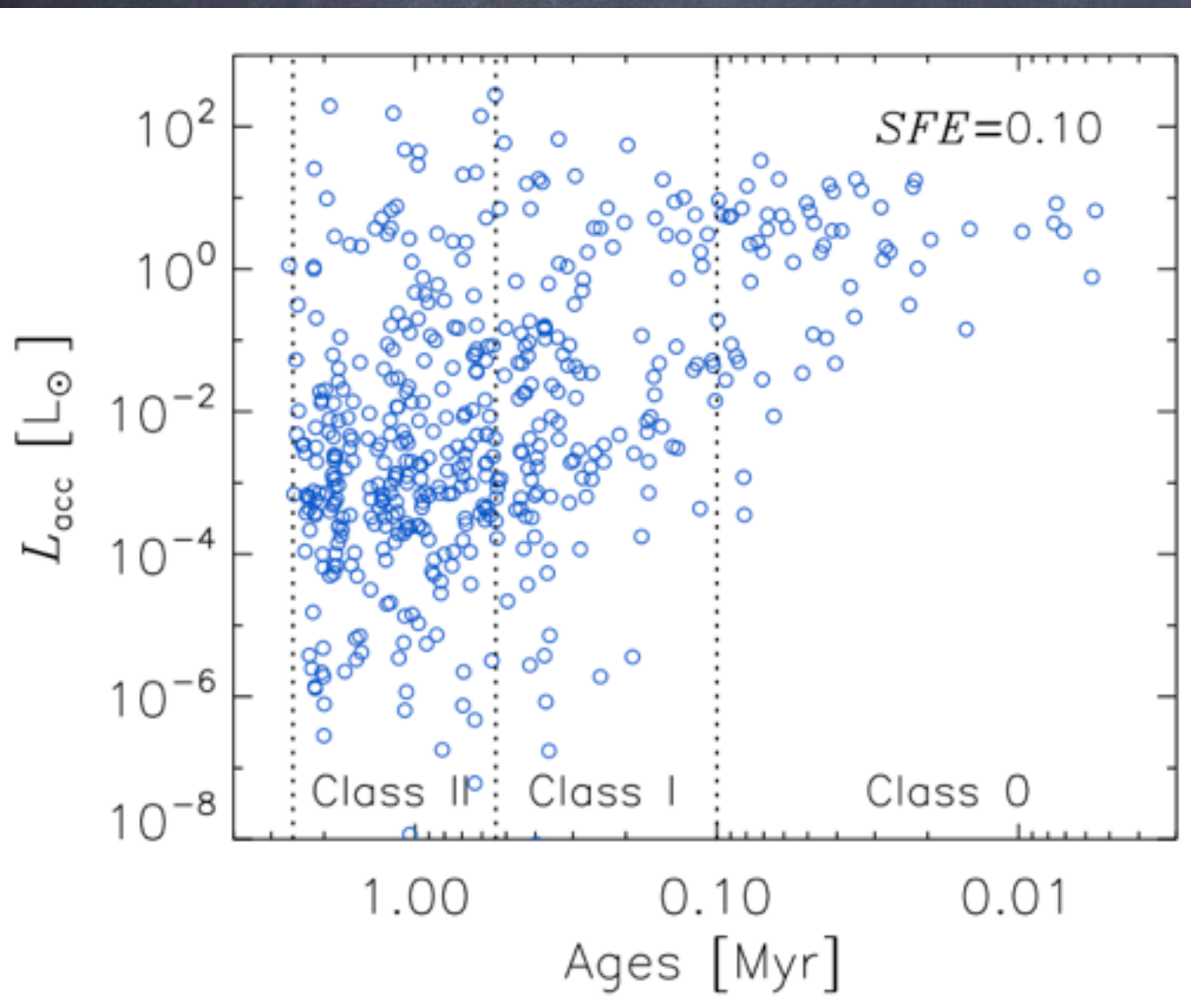
The bolometric luminosities of protostars with detected sub-mm envelope (filled circles) span three orders of magnitude ( $0.1 \lesssim L_{\odot} \lesssim 100$ ); without detected envelopes, five orders of magnitudes ( $0.001 \lesssim L_{\odot} \lesssim 100$ ).



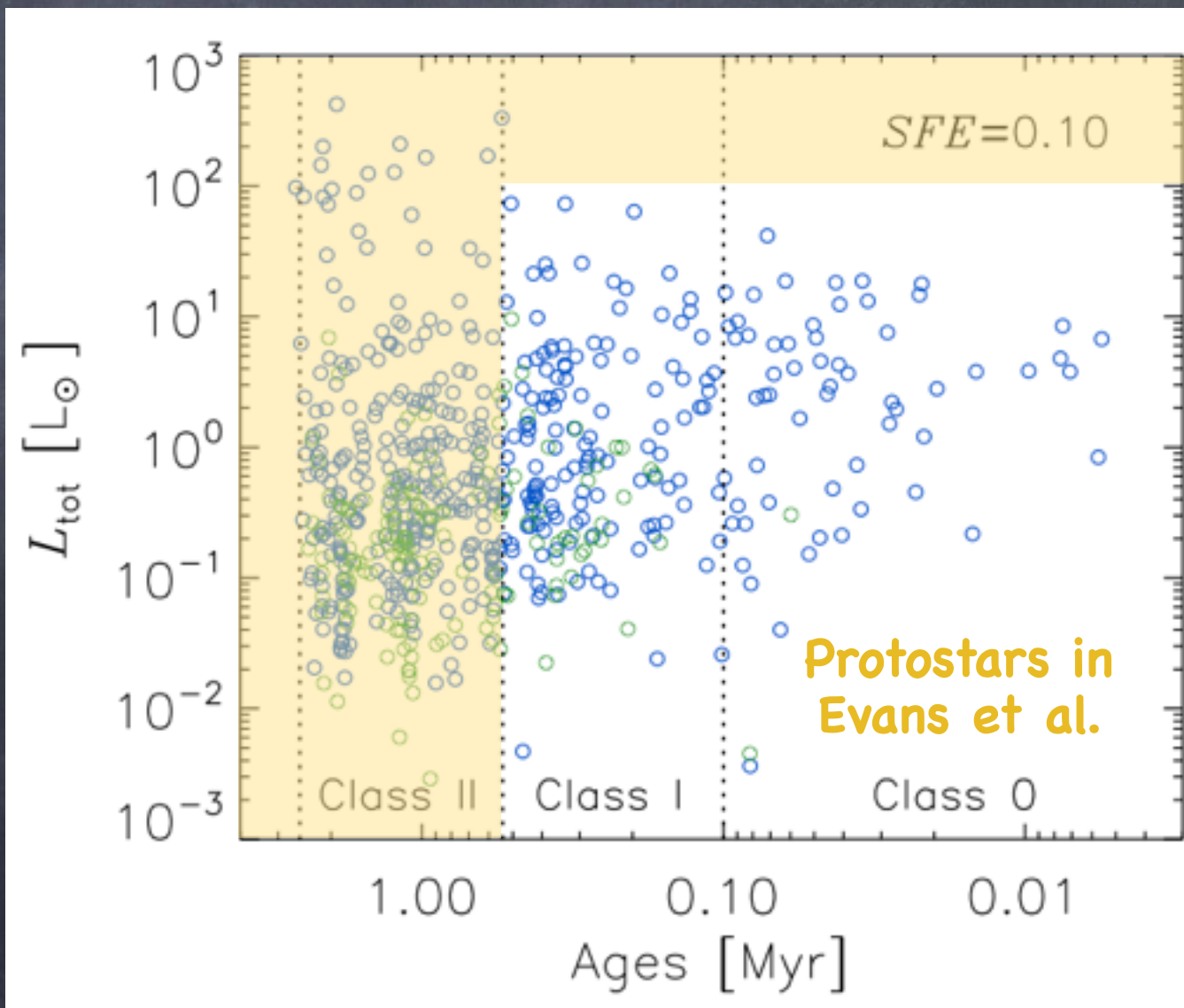
# The Luminosity 'Problem'

Given the realistic comparison of the infall rates with the observed accretion rates of older PMS stars, we now estimate the accretion luminosity of protostars assuming the infall rate is equal to the accretion rate.

accretion luminosity

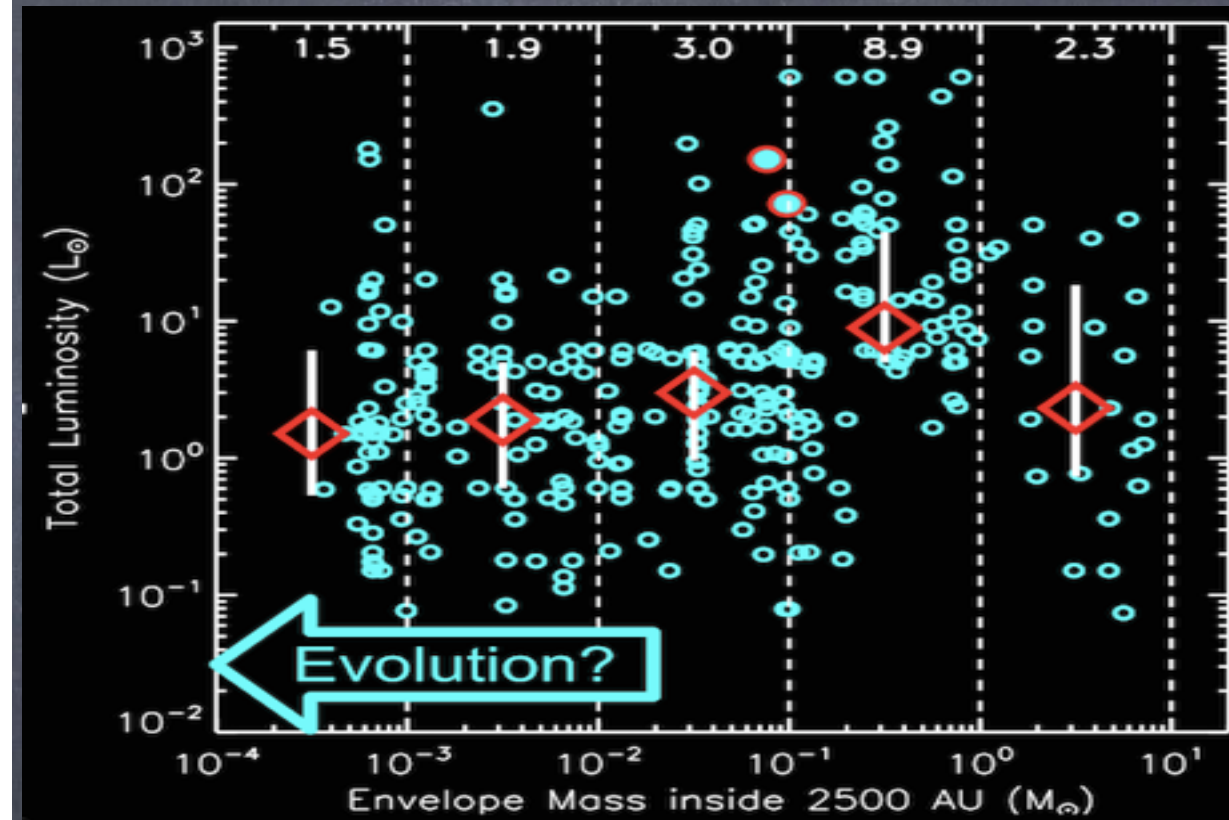
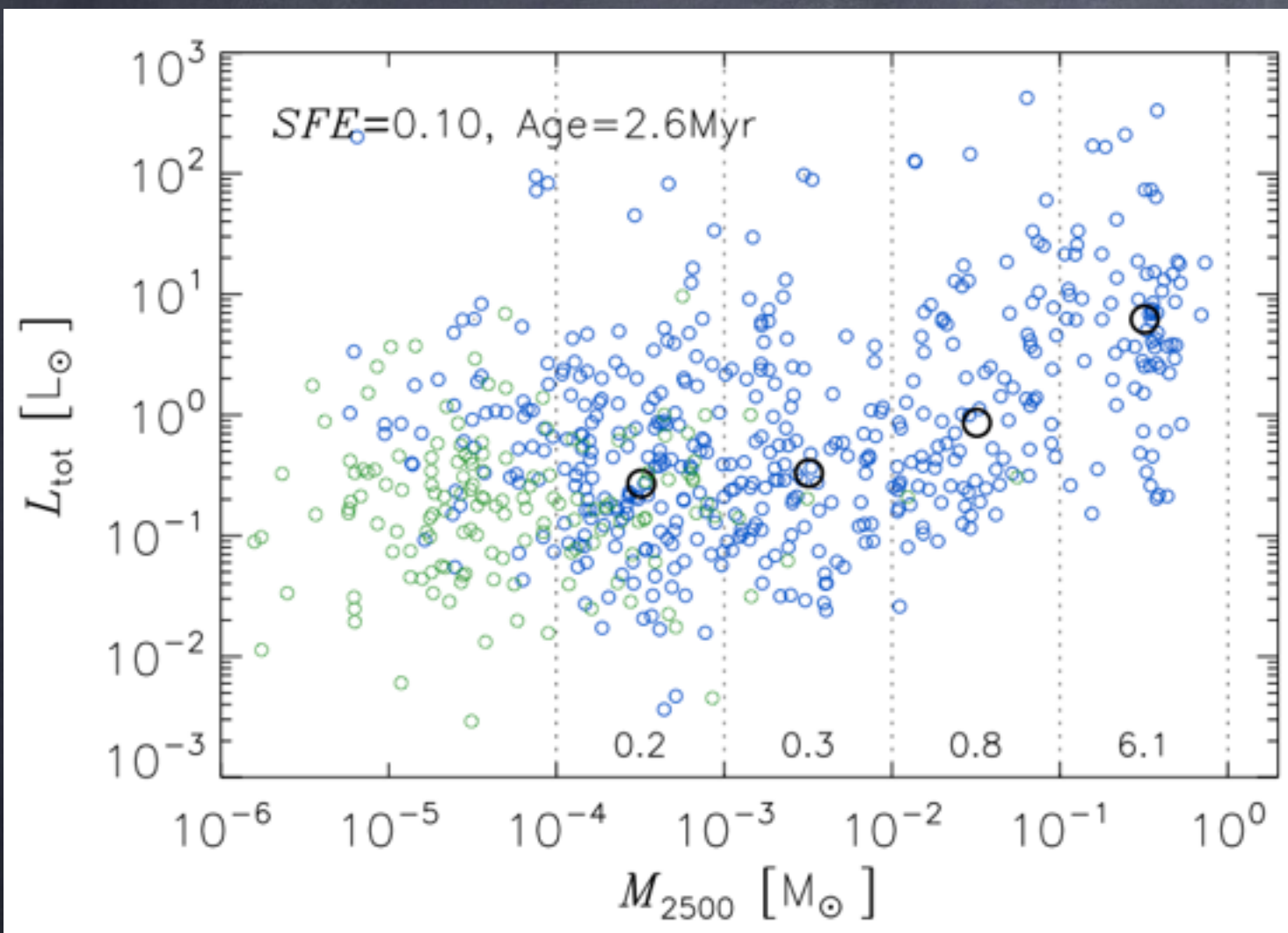


accretion+star+envelope





We can avoid the spectral index classification (which depends on complex disk physics and geometry), and instead use the envelope mass, as in the Herschel Orion Protostar Survey (HOPS, Manoj et al. 2013; Fisher et al. 2013; Stutz et al. 2013)

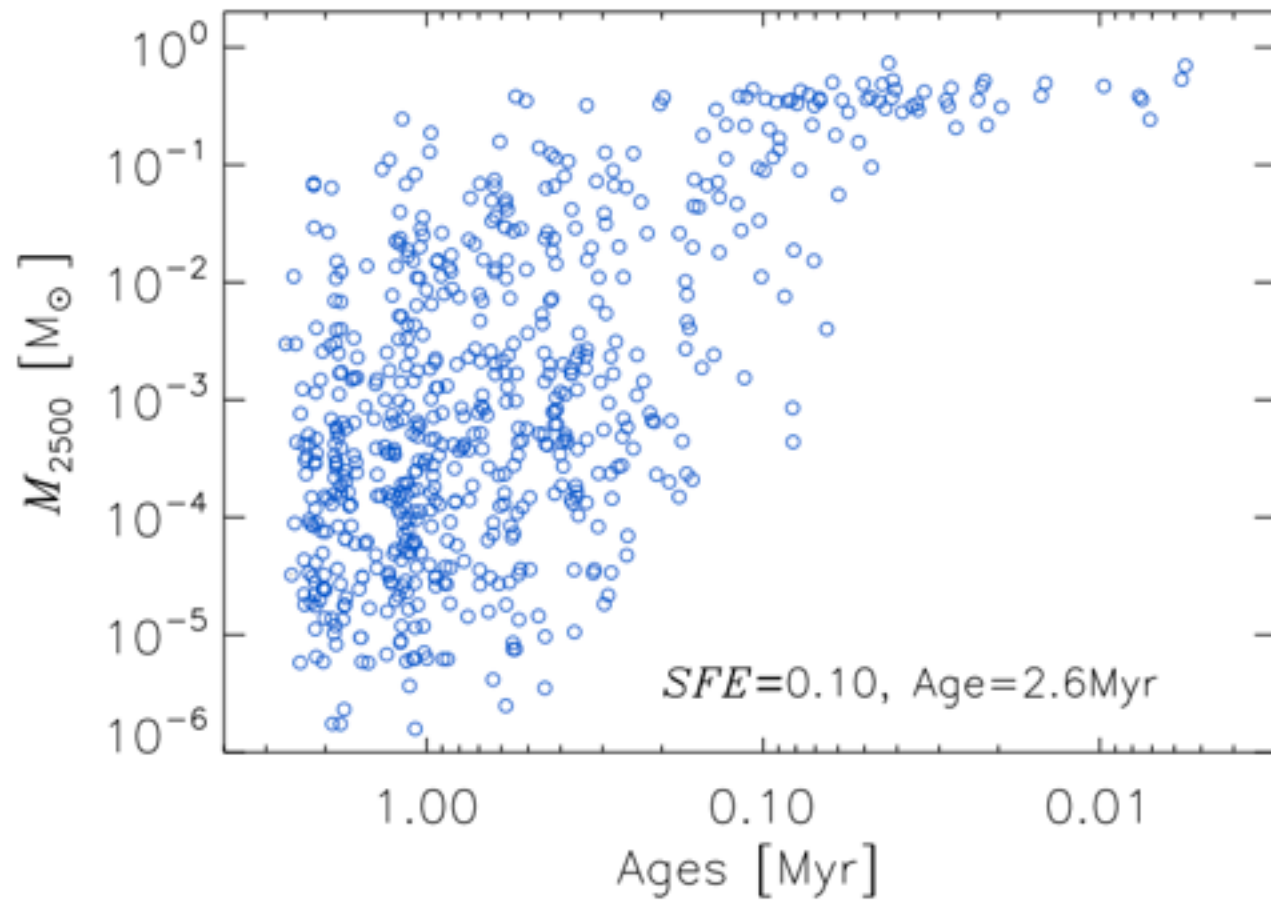


Herschel's protostars in Orion  
(Fisher et al. 2014)

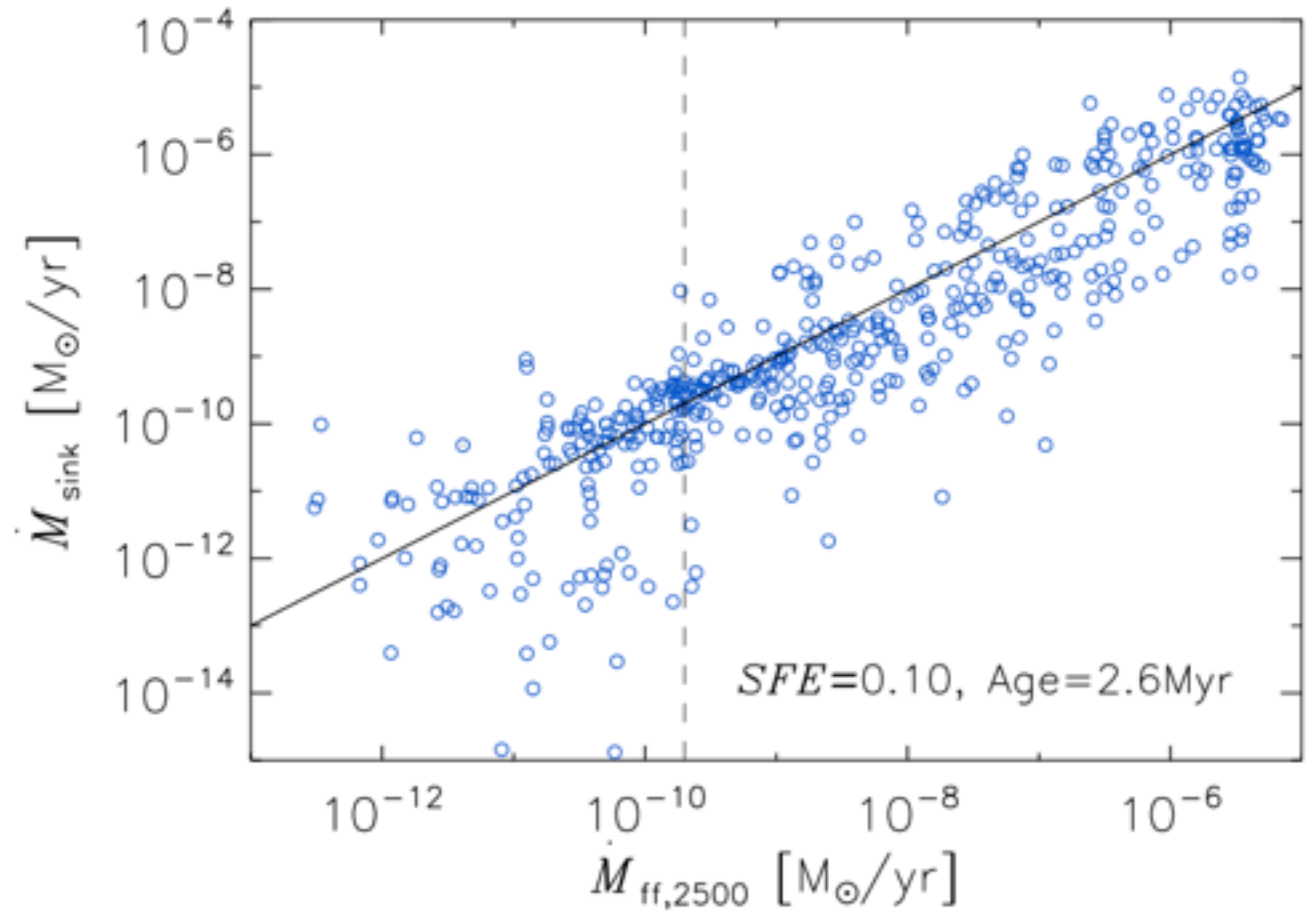
However, this is still a rather poor indicator of age.



Loose relation between  $M_{2500}$  and age (as between spectral index and age)



Approximate correlation of  $M_{2500}$  free-fall time and mass infall rate



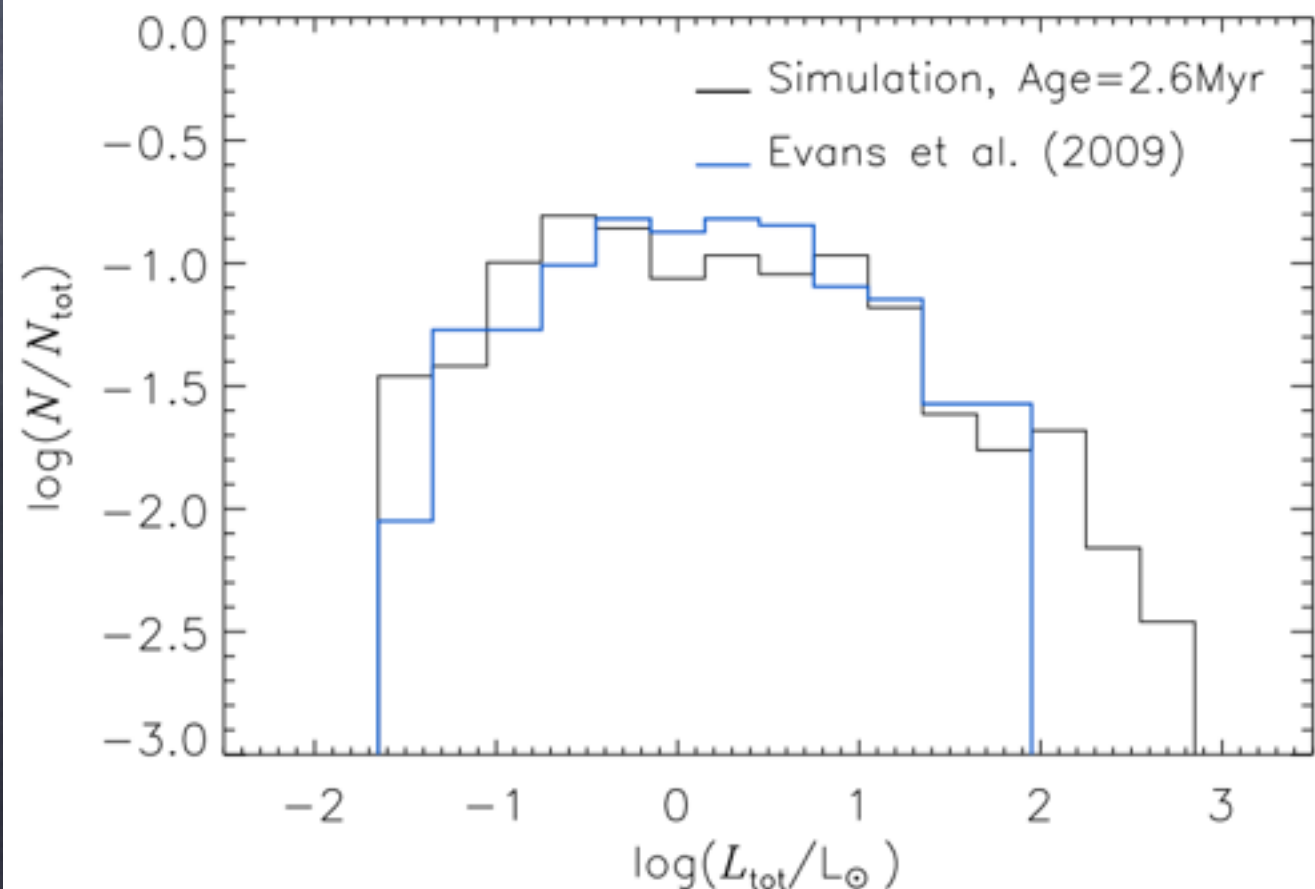
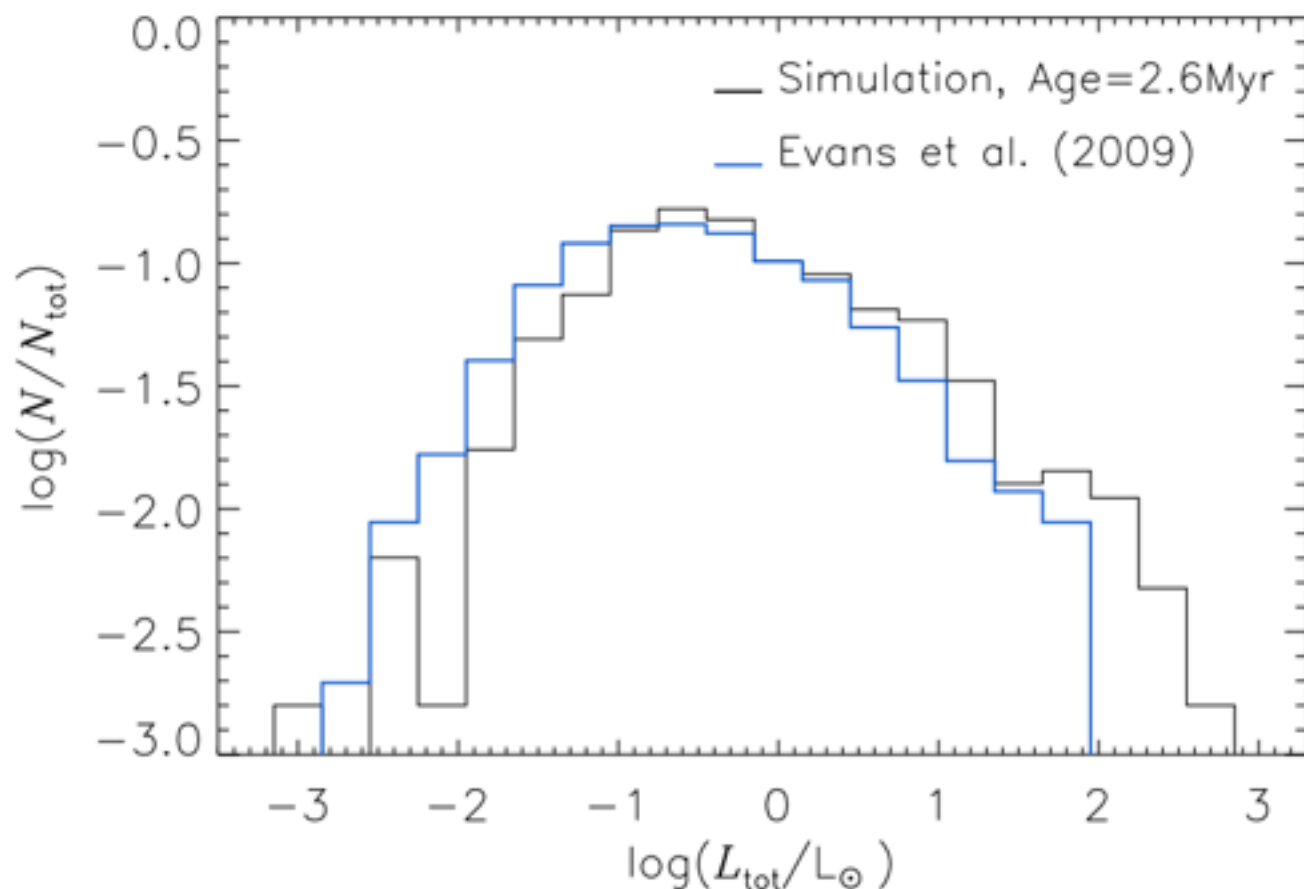


# The Protostellar Luminosity Function

Only a qualitative comparison, because we are not tailoring the simulation to any specific star-forming region.

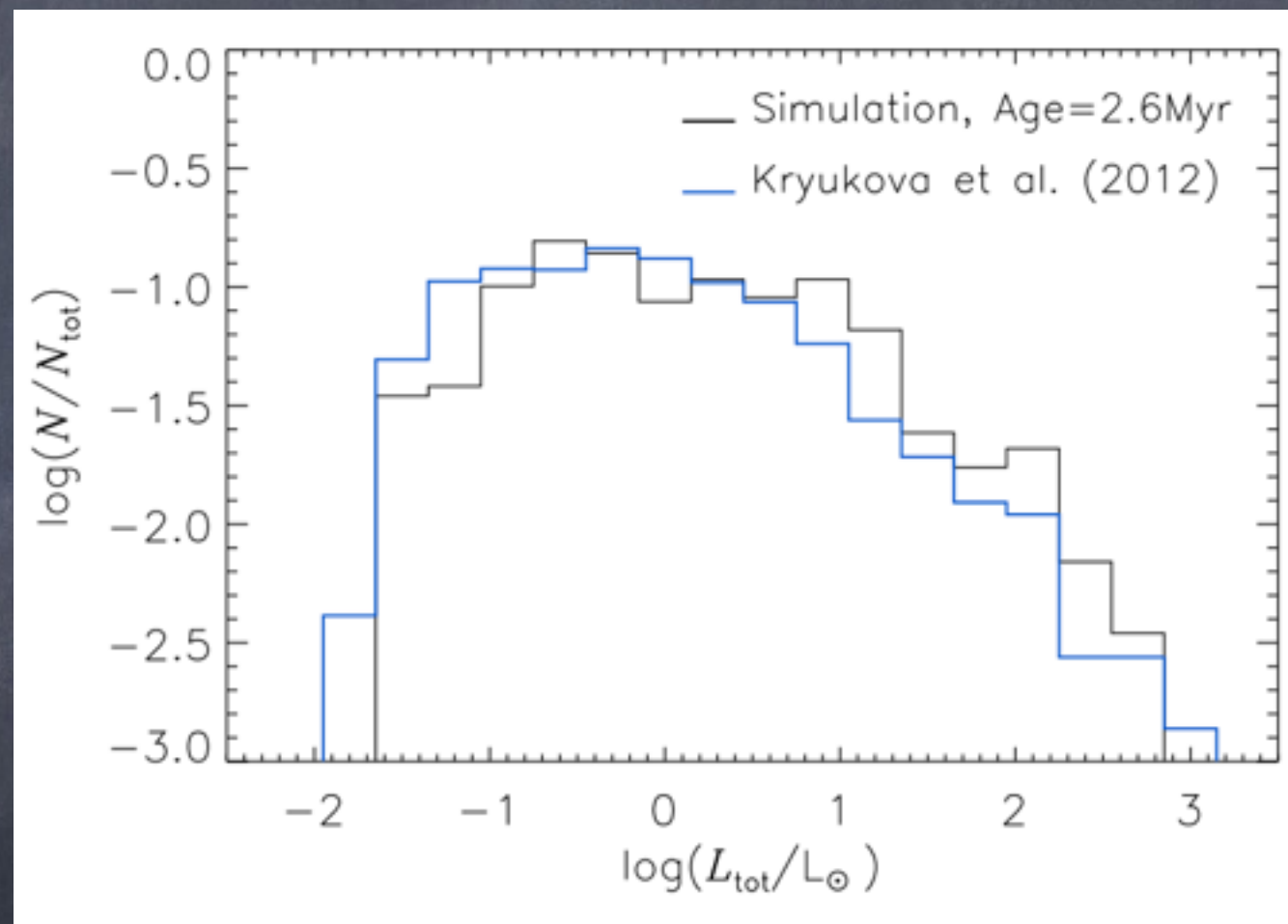
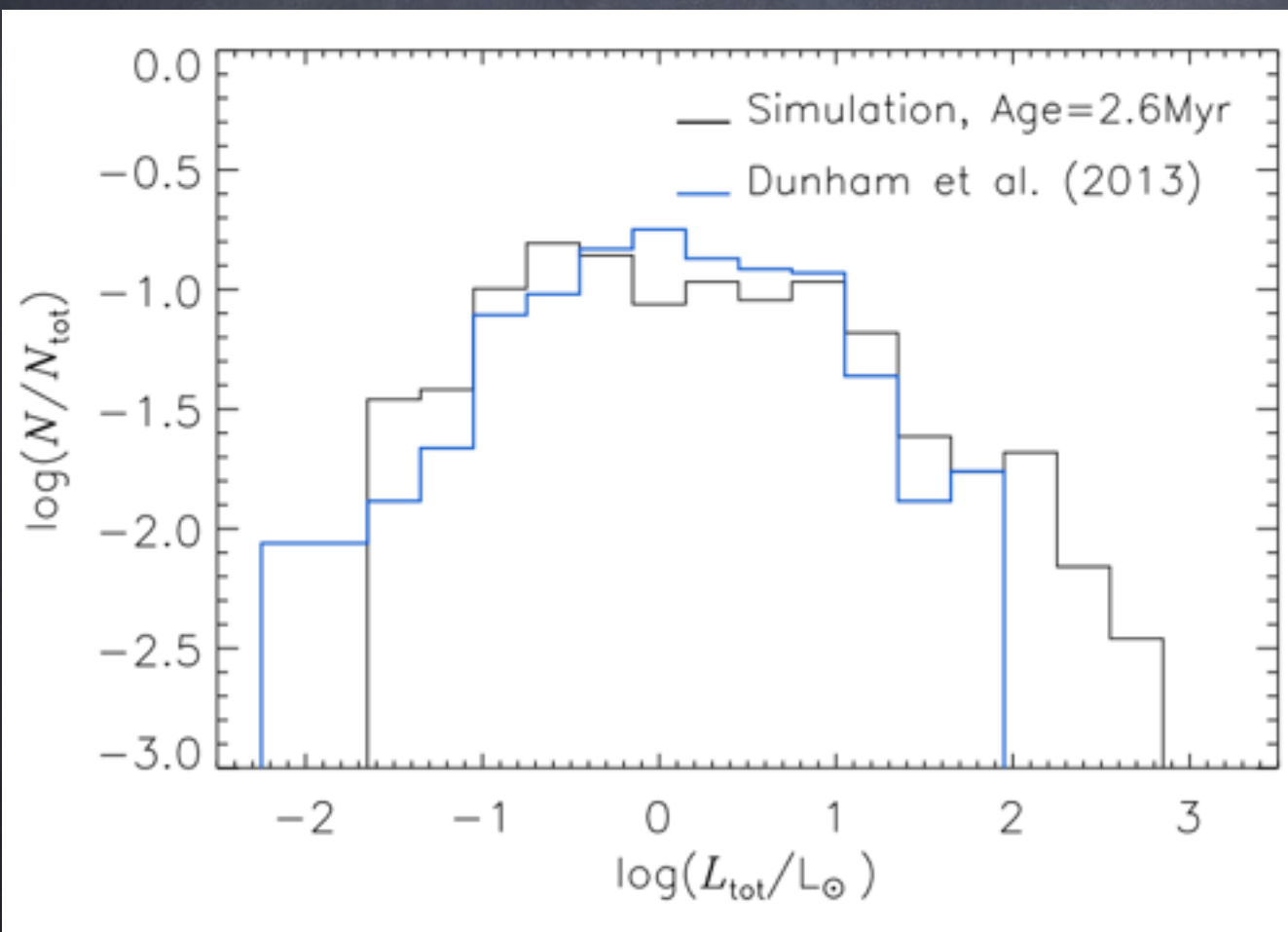
Evans et al.'s full sample (class 0 to III), 1024 source from different regions (blue), compared with our 631 sinks found at  $t=2.6$  Myr (black). Useful to compare the underlying IMFs: We lack BDs and have more massive stars than in the c2d sample. Both LFs peak around  $0.2 L_{\odot}$

Evans et al.'s sub-sample with detected envelopes (class 0 and I), 110 sources (blue), compared with our 288 sinks with  $M_{2500} > 0.001 M_{\odot}$  at  $t=2.6$  Myr (black). Similar PLFs, apart from a few more massive protostars in the simulation (11 sinks  $> 4 M_{\odot}$ )



Dunham et al. (2013) extended the c2D sample from 112 to 230 protostars, but 100 of the new sources lacks sub-mm detections, so their total luminosity is underestimated by a factor of 2.6 on average (could be up to 10). The low luminosity tail of the PLF is very uncertain

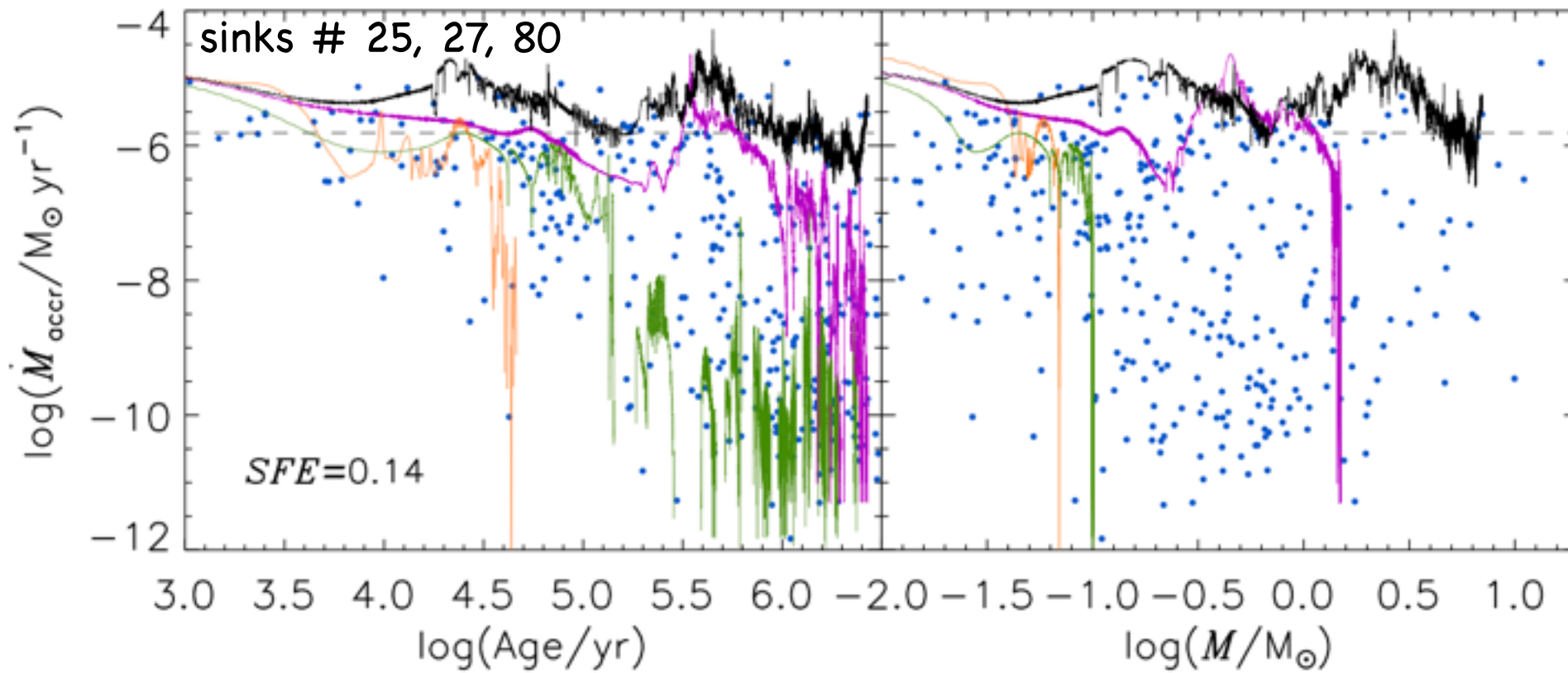
Kryukova et al. (2012) 728 Spitzer sources, from both low-mass and high-mass star-forming regions (no sub-mm data, but correction to extrapolate the bolometric luminosity). Now that more massive protostars are included, the match with our PLF is much improved.



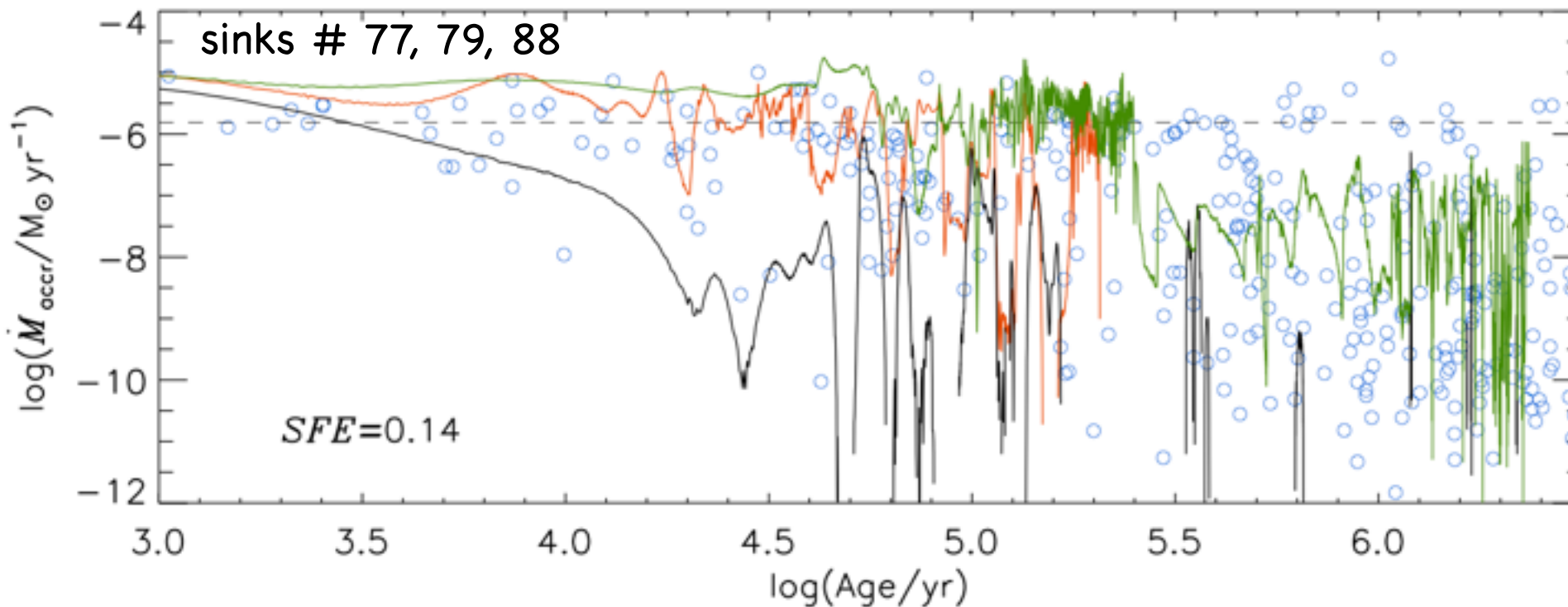
- The PLF, like the underlying IMF, has region-to-region variations.
- Do not take seriously the low-luminosity tail of the PLF.
- **Good qualitative match between sink PLF and observed PLF.**



# The explanation of the luminosity scatter:



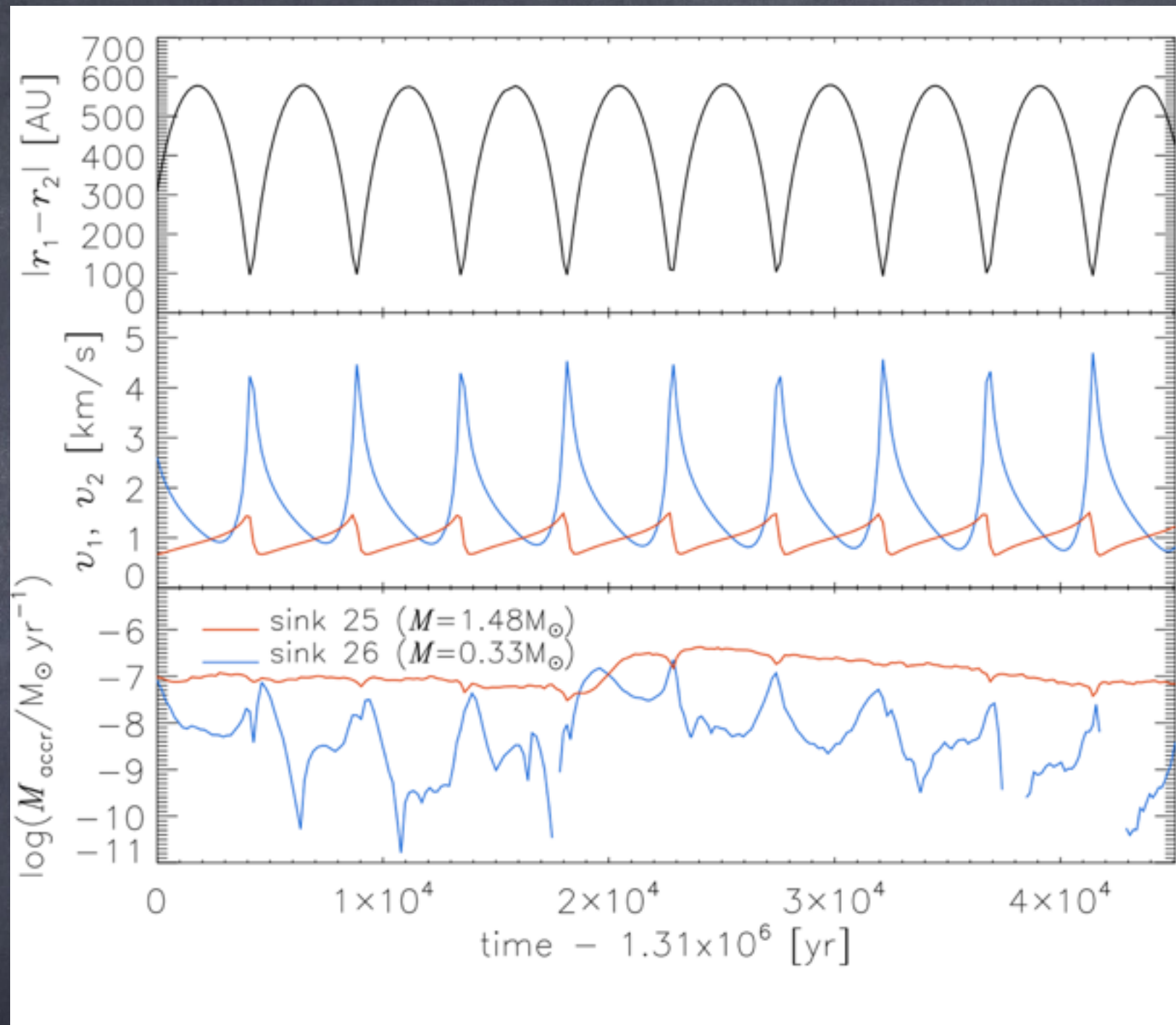
1. Stars of either different or equal final mass can follow very different tracks of infall versus time.



2. Individual stars, (especially binaries, but also single stars) have tracks of infall versus time with huge oscillations.



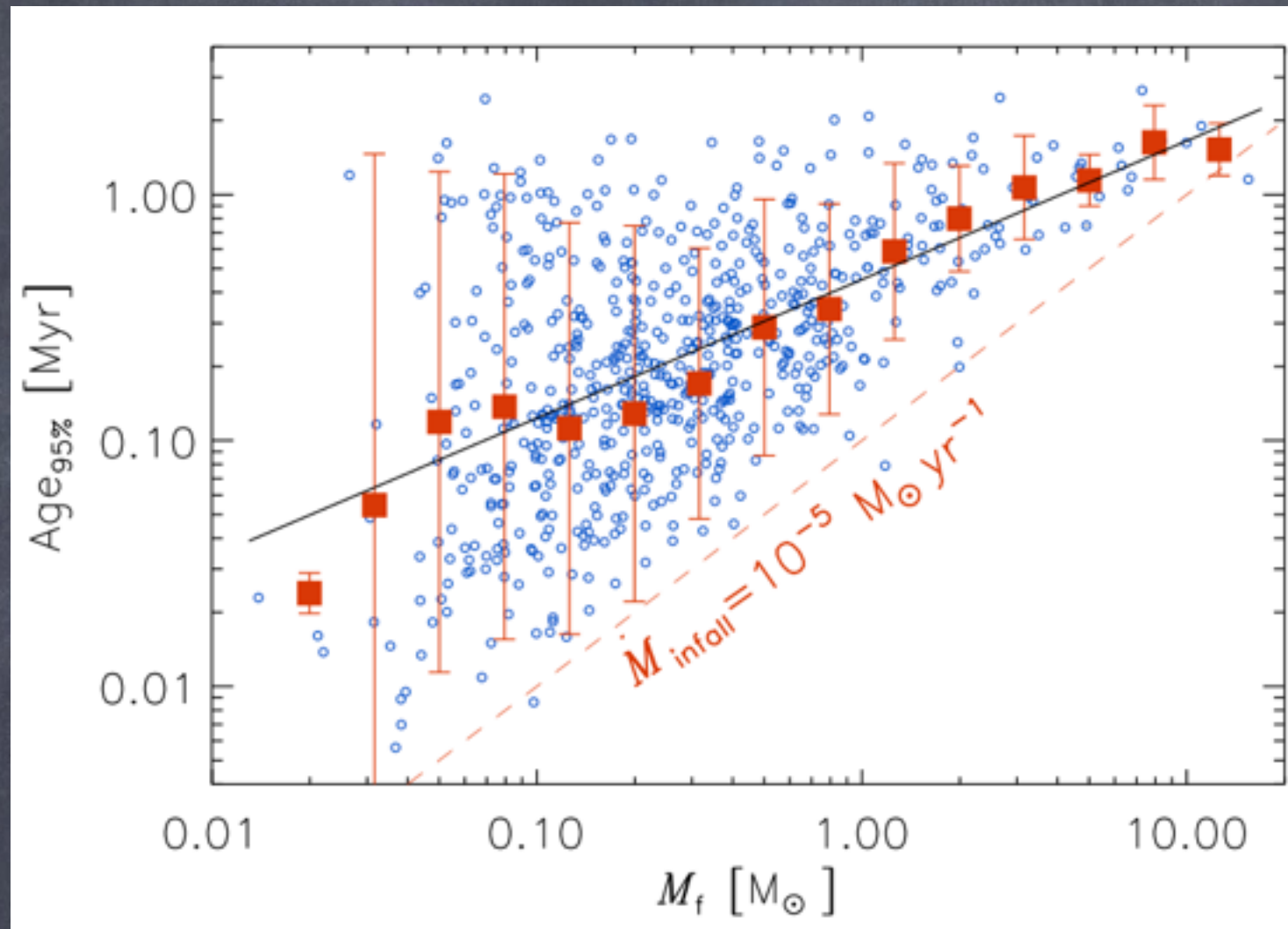
# Protostellar/PMS Binaries



The infall rate of the secondary grows by 2–3 orders of magnitude at the approximate time of the periastro, becoming comparable to the infall rate of the primary.



What is the characteristic timescale to form a star, and how does it scale with final mass?



$$\text{Age}_{95\%} = 0.45 \text{ Myr} (M_f/M_\odot)^{0.56}$$

This applies to typical molecular clouds (Larson scaling relations). The coefficient could be smaller or larger than 0.45 Myr in regions that deviates significantly from Larson relations.

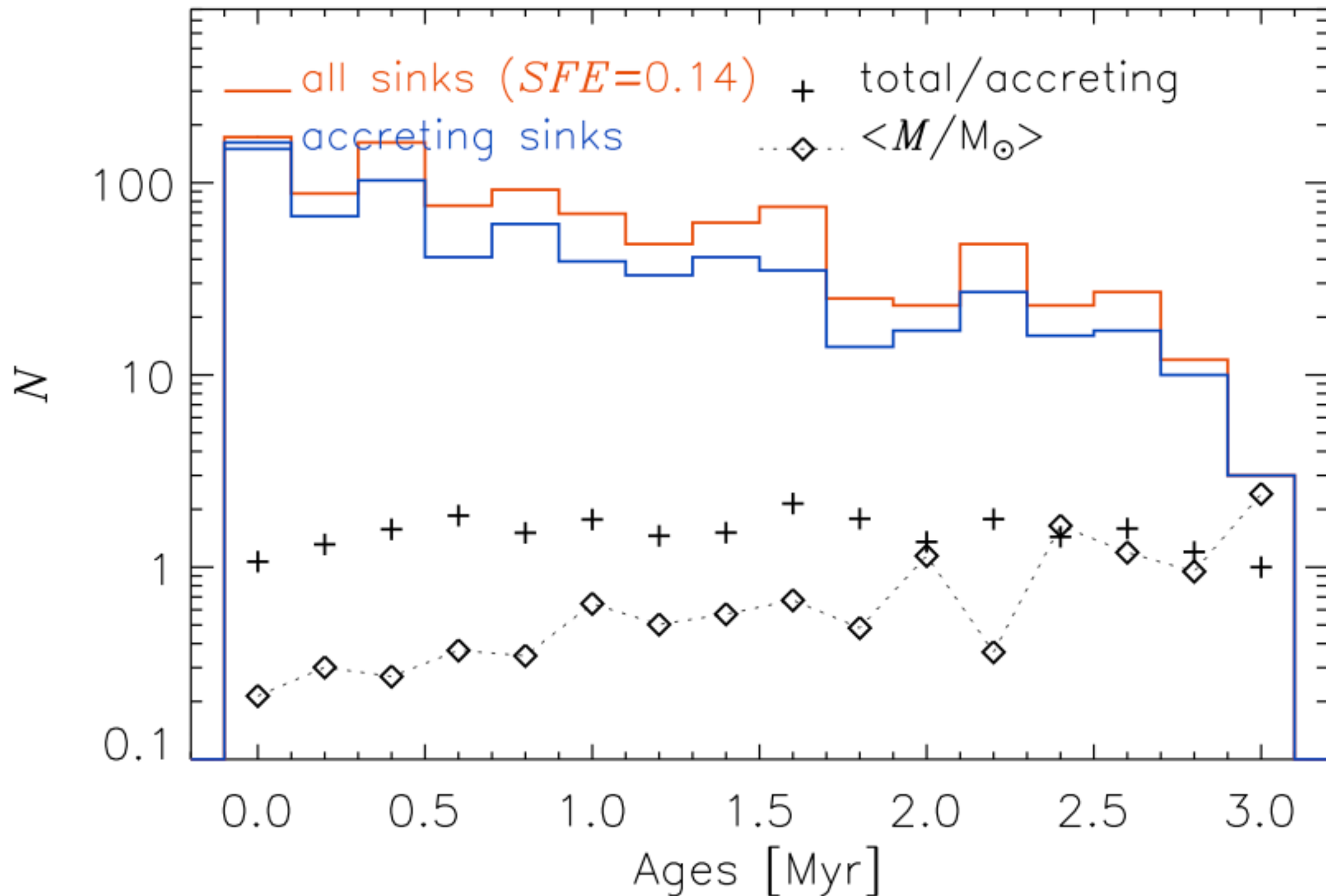


# Conclusions

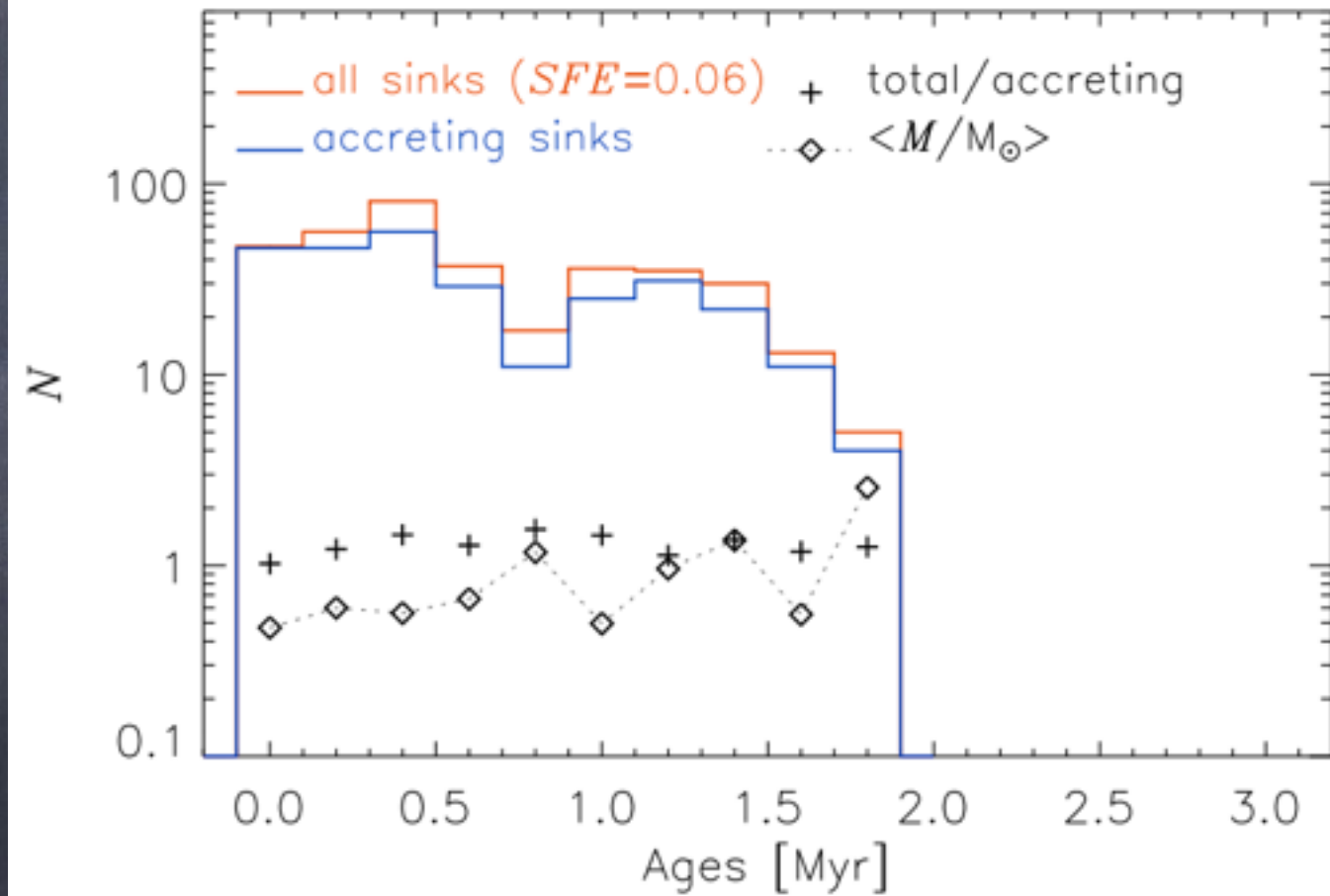
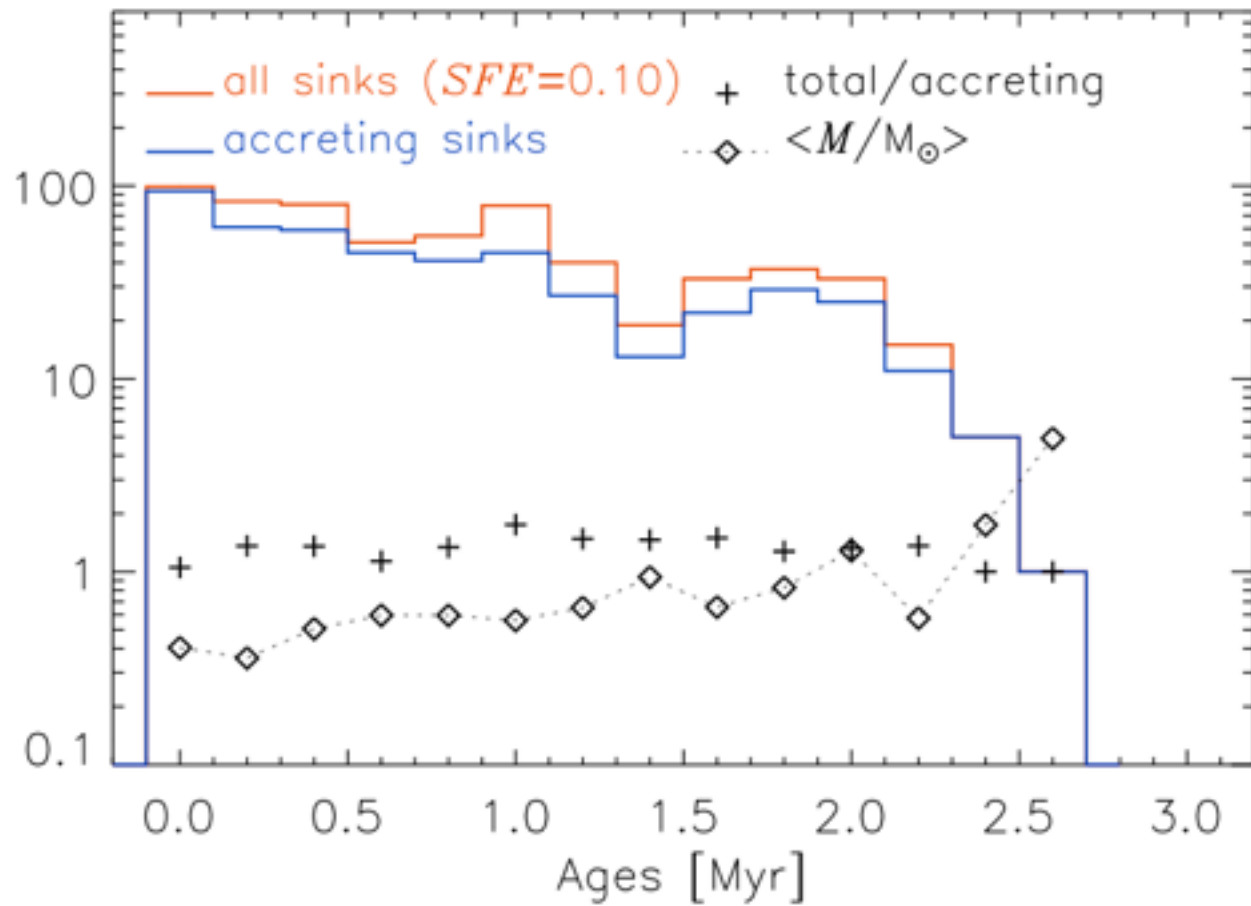
- Mass infall controls the accretion rate of both protostars and PMS stars.
- The luminosity problem is solved when realistic protostellar initial and boundary conditions (and their statistical distributions) are adopted (large-scale simulation), under the reasonable assumption that the mass infall controls the protostellar accretion rate.
- The observed large scatter of protostellar luminosities is due both to star-to-star differences in the time evolution of the infall rate and to large fluctuations of the infall of individual stars (especially during binary or multiple interactions).



Is external accretion really important, or am I  
hiding a large fraction of non-accreting stars?  
Most stars are accreting

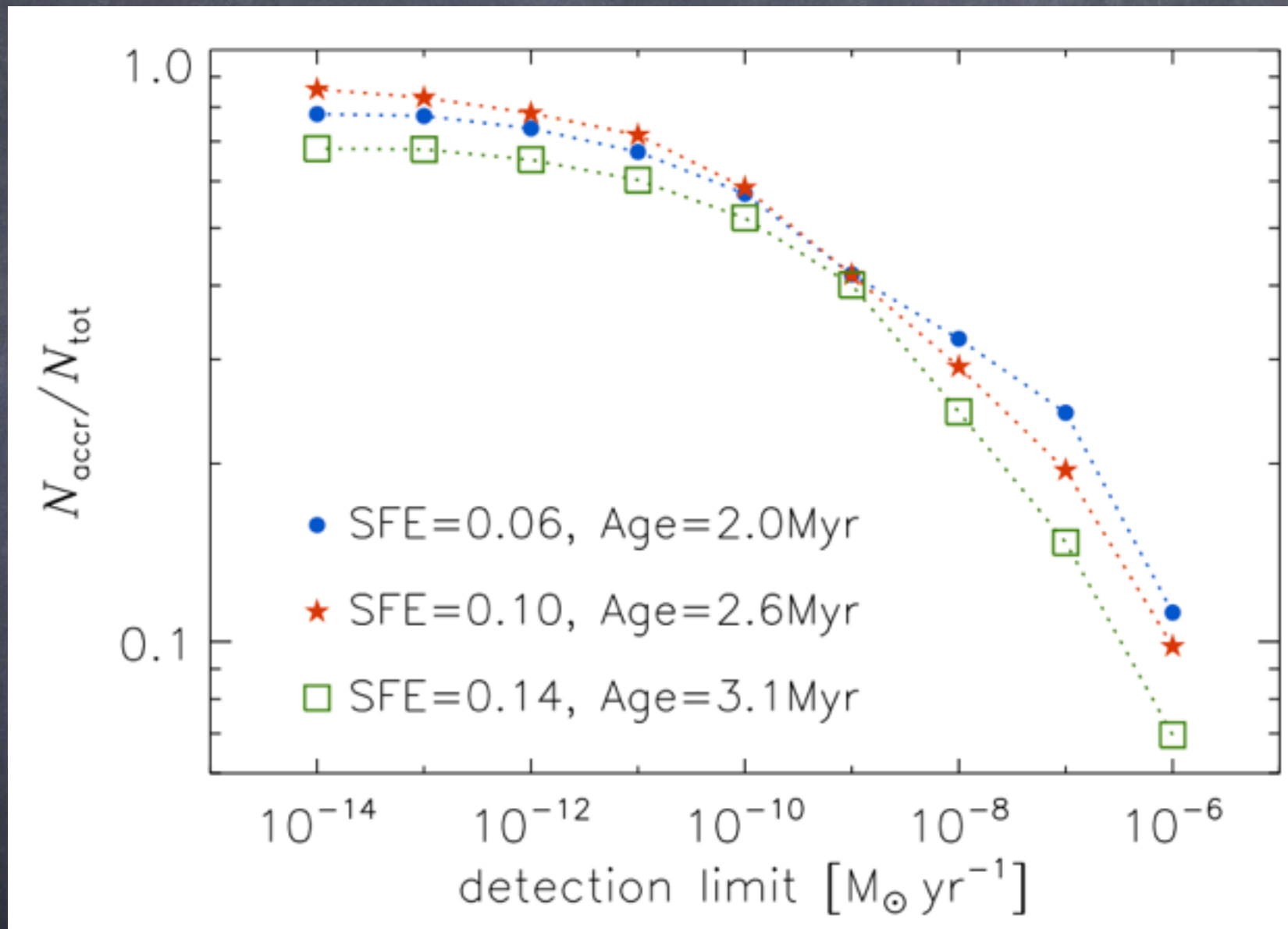


# Not much age dependence





Cumulative fraction including non-detections:  
Can it be done for real star-forming regions?



External accretion can account  
for all (internally) accreting stars.