Increasing SFR in Hierarchically Collapsing Molecular Clouds, and their Cluster Structure

Enrique Vázquez-Semadeni
Instituto de Radioastronomía y Astrofísica, UNAM

UNIVERSIDAD NACIONAL AUTONOMA DE MEXICO

IRyA

Collaborators:

CRyA UNAM:

Javier Ballesteros-Paredes.

Gilberto Gómez

Pedro Colín

Graduate student:

Vianey Camacho

ABROAD:

Alejandro González-Samaniego (UC Irvine)

Manuel Zamora-Avilés (U. Michigan)

- This talk:
  - Palla & Stahler’s accelerating star formation
  - Cloud assembly and hierarchical collapse.
  - Evolution of the SFR.
  - Resulting cluster structure features.

THE ASTROPHYSICAL JOURNAL, 540:255–270, 2000 September 1

ACCELERATING STAR FORMATION IN CLUSTERS AND ASSOCIATIONS

FRANCESCO PALLA[1] AND STEVEN W. STAHLER[2]

Received 1999 November 29; accepted 2000 April 7

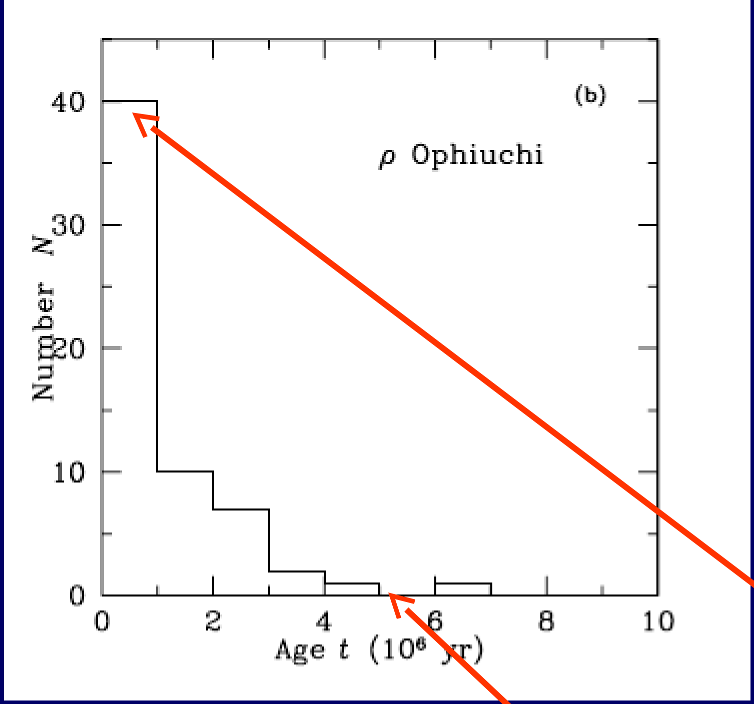
ABSTRACT

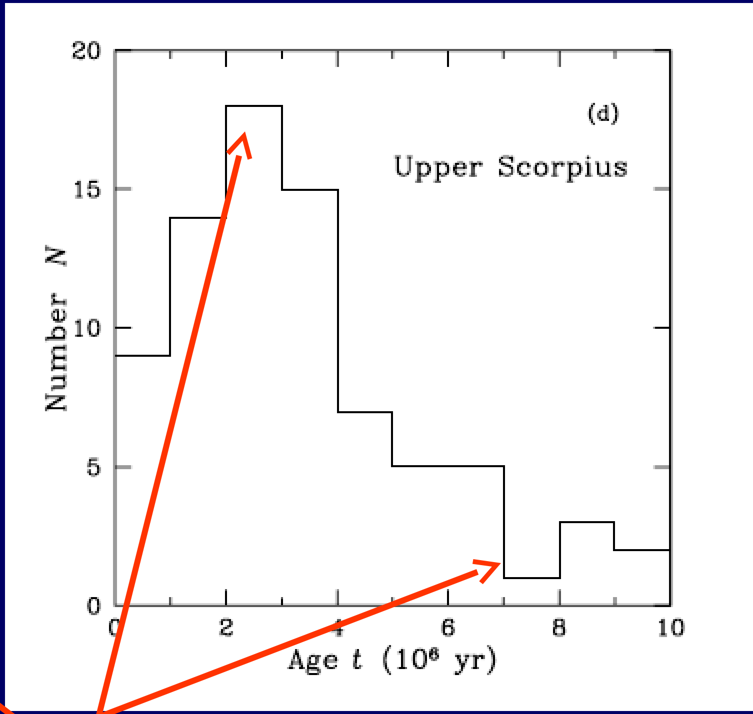
We use our own, recently developed pre–main-sequence evolutionary tracks to investigate the star formation histories of relatively nearby associations and clusters. We first employ published luminosities and effective temperatures to place the known members of each region in the H-R diagram. We then construct age histograms detailing that region's history. The groups studied include Taurus-Auriga, Lupus, Chamaeleon, ρ Ophiuchi, Upper Scorpius, IC 348, and NGC 2264. This study is the first to analyze a large number of star-forming regions with the same set of theoretical tracks.

Our investigation corroborates and extends our previous results on the Orion Nebula Cluster. In all cases, we find that star formation began at a relatively low level some 10^7 yr in the past and has more recently undergone a steep acceleration. This acceleration, which lasts several million years, is usually continuing through the present epoch. The one clear exception is the OB association Upper Scorpius, where the formation rate climbed upward, peaked, and has now died off. Significantly, this is also the only region of our list that has been largely stripped of molecular gas.

The acceleration represents a true physical phenomenon that cannot be explained away by incompleteness of the samples; nor is the pattern of stellar births significantly affected by observational errors or the presence of unresolved binaries. We speculate that increasing star formation activity arises from contraction of the parent cloud. Despite the short timescale for acceleration, the cloud is likely to evolve quasi-statically. Star formation itself appears to be a critical phenomenon, occurring only in locations exceeding some threshold density. The cloud's contraction must reverse itself, and the remnant gas dissipate, in less than 10^7 yr, even for aggregates containing no massive stars. In this case, molecular outflows from the stars themselves presumably accomplish the task, but the actual dispersal mechanism is still unclear.

Subject headings: open clusters and associations: individual (Chamaeleon; IC 348; Lupus; NGC 2264; Orion Nebula Cluster; ρ Ophiuchi; Taurus-Auriga; Upper Scorpius) — stars: evolution — stars: formation — stars: pre–main-sequence





- Most stars seem to form over short SF burst.
  - But with tail of older objects.
- No room for accelerating SF in models for SFR based on clouds in equilibrium, and SF controlled by stationary turbulent parameters (e.g., Krumholz & McKee 05; Padoan & Nordlund 11; Hennebelle & Chabrier 11).
  - … which give stationary SFR, reported as SFE per free-fall time.

THE ASTROPHYSICAL JOURNAL, 527:285–297, 1999 December 10

TURBULENT FLOW–DRIVEN MOLECULAR CLOUD FORMATION: A SOLUTION TO THE POST–T TAURI PROBLEM?

JAVIER BALLESTEROS-PAREDES,[1,2] LEE HARTMANN,[2] AND ENRIQUE VÁZQUEZ-SEMADENI[1]
Received 1999 April 19; accepted 1999 July 21

ABSTRACT

We suggest that molecular clouds can be formed on short timescales by compressions from large scale streams in the interstellar medium (ISM). In particular, we argue that in the Taurus-Auriga complex, with filaments of 10–20 × 2–5 pc, most have been formed by H I flows in $\lesssim$3 Myr, explaining the absence of post–T Tauri stars in the region with ages $\gtrsim$3 Myr. Observations in the 21 cm line of the H I "halos" around the Taurus molecular gas show many features (broad asymmetric profiles, velocity shifts of H I relative to ^{12}CO) predicted by our MHD numerical simulations, in which large-scale H I streams collide to produce dense filamentary structures. This rapid evolution is possible because the H I flows producing and disrupting the cloud have much higher velocities (5–10 km s^{-1}) than are present in the molecular gas resulting from the colliding flows. The simulations suggest that such flows can occur from the global ISM turbulence without requiring a single triggering event such as a supernova explosion.

Subject headings: ISM: clouds — ISM: evolution — stars: formation — stars: pre–main-sequence — turbulence

- Discrepancy!
  - For some time, LH thought old stars were due to contamination from field stars...

I. CLOUD ASSEMBLY

- How do dense clouds form? (before any cloud collisions may happen…)

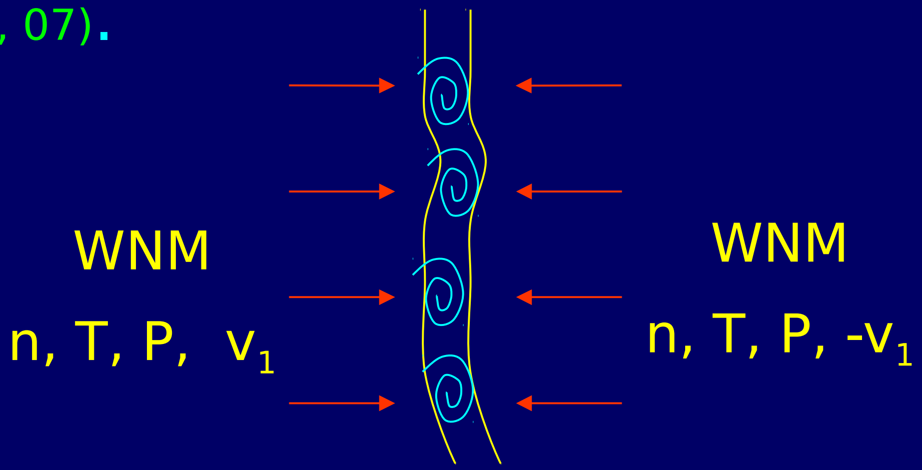
- From the continuity equation, the formation of dense regions in a compressible medium requires the ***convergence*** of material toward the concentration point:

$$\frac{d\rho}{dt} \equiv \frac{\partial \rho}{\partial t} + u \cdot \nabla \rho = - \rho \nabla \cdot u$$

⇒ Dense, cold clouds ***must*** form by ***converging flows***

(In general; not a particular type of setup)

- Converging flows in the WNM induce a phase transition to the CNM (Hennebelle & Pérault 99; Ballesteros-Paredes+99; Koyama & Inutsuka 02; Heitsch+05,06; Vázquez-Semadeni+06, 07).



  - Clouds are most often born as moderately-supersonic atomic sheets (VS+06, ApJ, 643, 245; compare to Heiles & Troland 2003).
    - Cloud boundaries are phase transition fronts, not isolating walls (Vázquez-Semadeni+06; Bannerjee+09).
    - Clouds's mass grows

– The CNM clouds quickly become ***strongly*** Jeans unstable because, upon the WNM → CNM transition:

$\rho \rightarrow 10^2 \rho, \quad T \rightarrow 10^{-2} T$

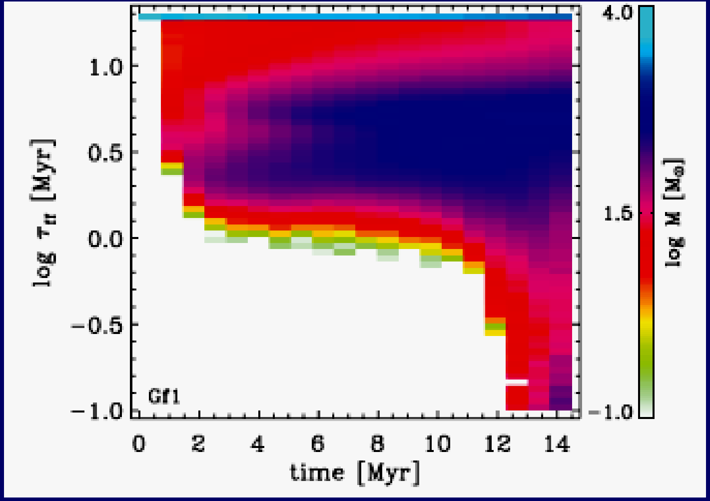
⇒ Jeans mass, $M_J \sim \rho^{-1/2} T^{3/2}$, drops by ~ 10^4 upon warm-cold transition (Gómez & VS 2014, ApJ, 791, 124).

– Jeans mass drops from ~10^7 to ~10^3 M_{sun}.

– The turbulence is moderately supersonic (M_s ~ a few; Koyama & Inutsuka 02; Audit & Hennebelle 05; Heitsch+05; Banerjee+09).

⇒***The collapse starts at the cloud scale.***

- Global collapse of turbulent, non-spherical medium is *hierarchical...* (Vázquez-Semadeni+09, ApJ, 707, 1023).
  - Turbulence produces a distribution of (nonlinear) density fluctuations of various sizes and amplitudes.
    - Implies a distribution of free-fall times. Small-scale, high-density fluctuations have shorter free-fall times (Heitsch & Hartmann 08) than the large-scale, low-density fluctuations that contain them.



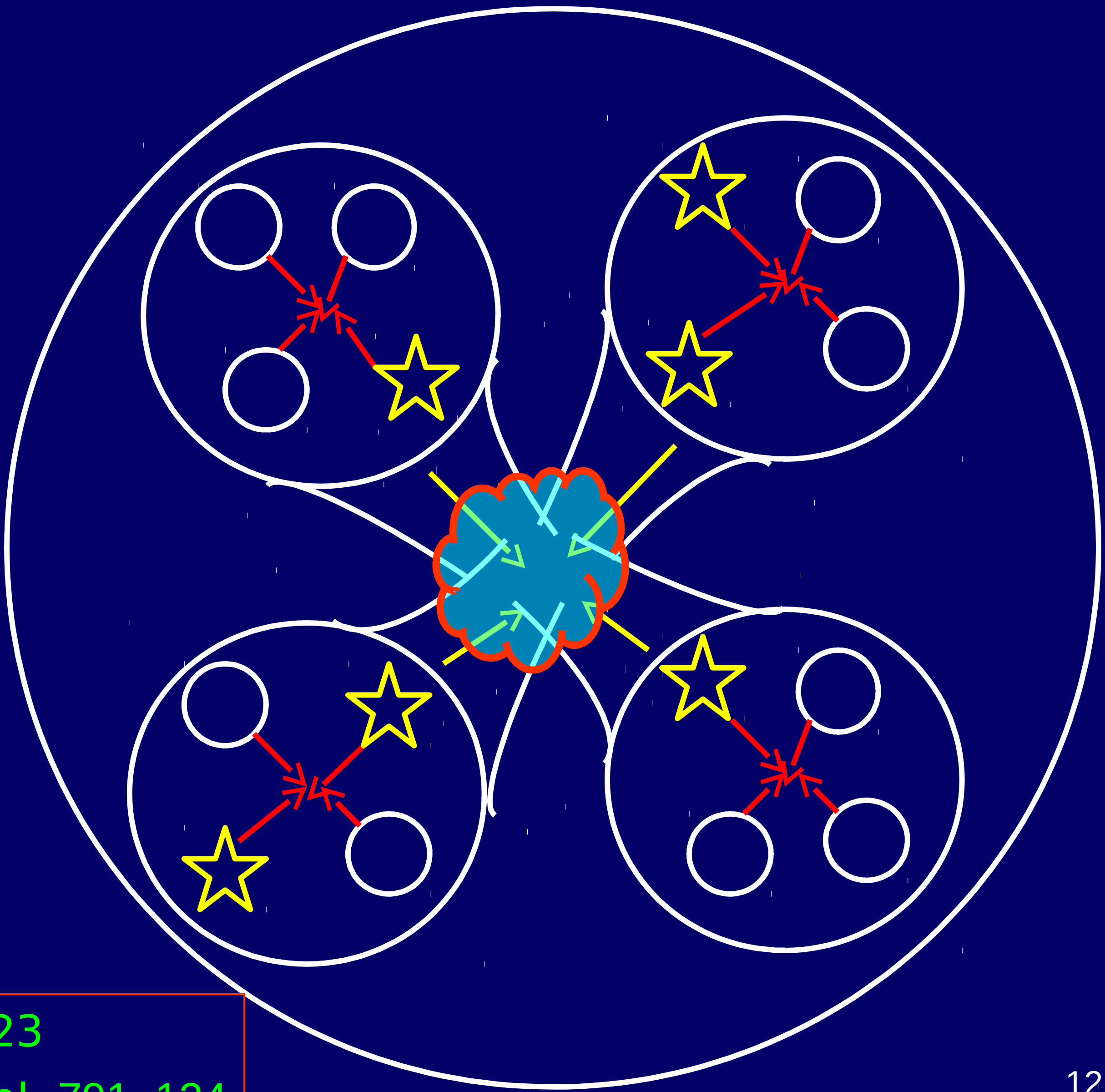
Heitsch & Hartmann 08

 A distribution of Jeans masses (see also Padoan & Nordlund 02).

Small-scale collapses are part of large-scale ones.

Small-scale objects collapse first because of their higher densities.

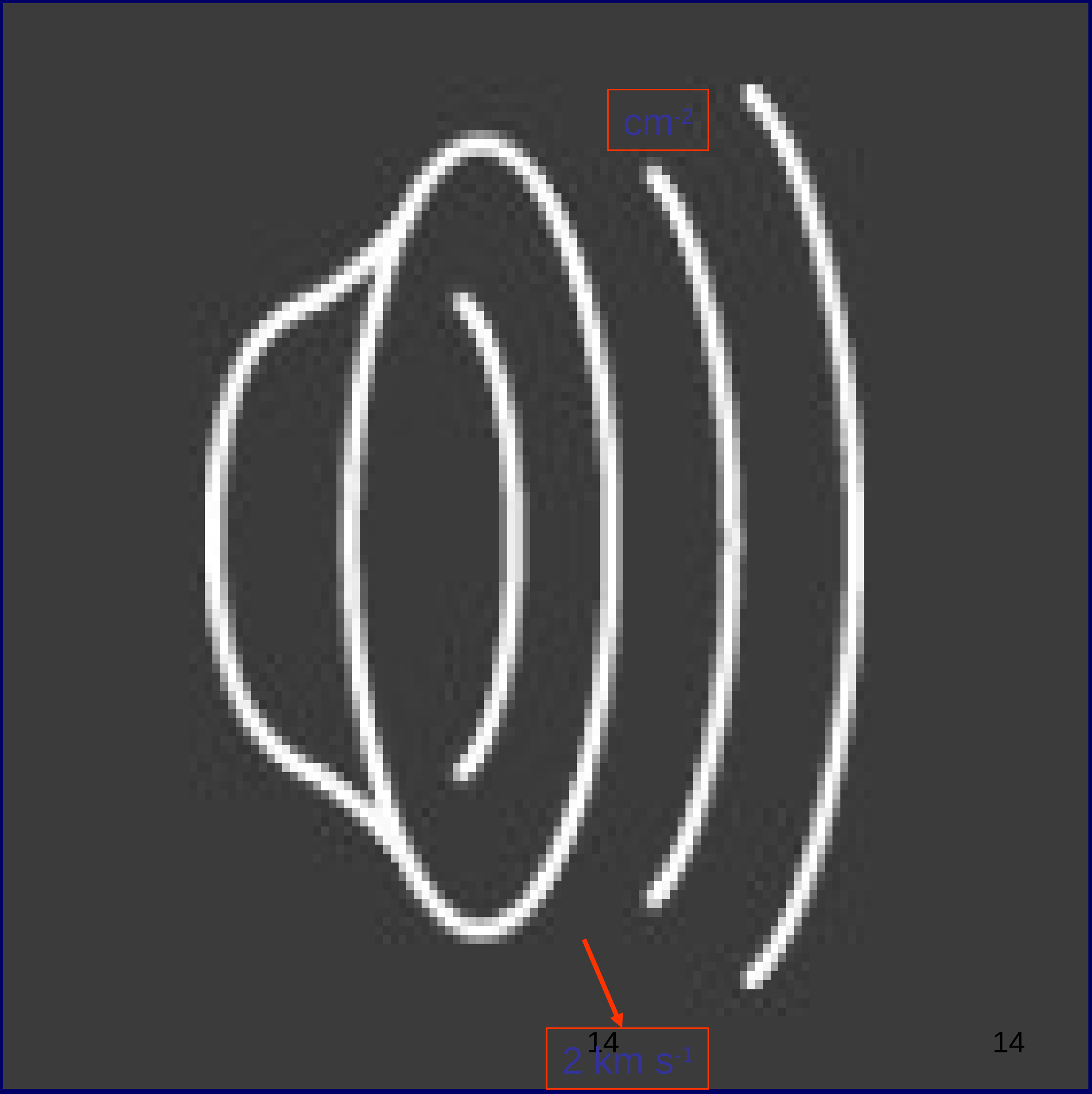
Similar to Hoyle's (1953) fragmentation, but with nonlinear fluctuations and filament formation.



VS+2009, ApJ, 707, 1023

Gómez & VS, 2014, ApJ, 791, 124

- Consequences of multi-Jeans, nearly pressureless collapse:
  - Formation of filaments as ***gas funnels toward cores*** (not equilibrium structures) (Gómez & VS 14, ApJ, 791, 124).



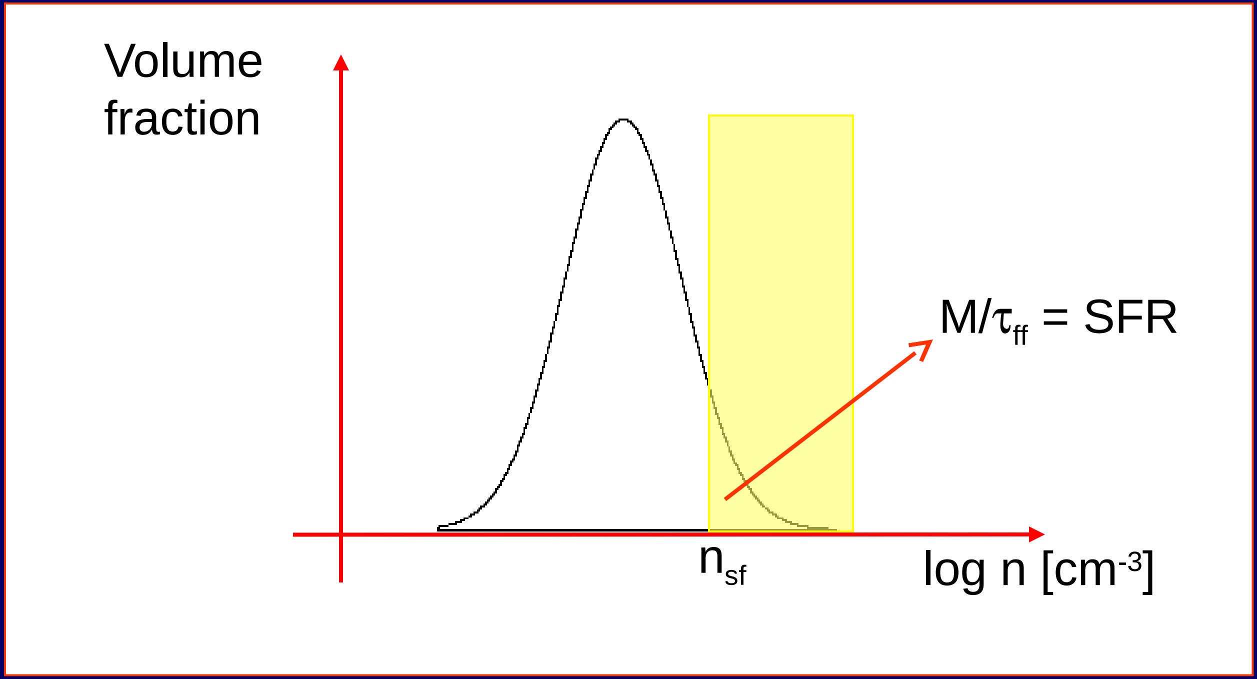
Gómez & VS 2014,
ApJ, 791, 124

- Consequences of multi-Jeans, nearly pressureless collapse:
  - Formation of filaments as ***gas funnels toward cores*** (not equilibrium structures) (Gómez & VS 14, ApJ, 791, 124).
  - SF accelerates! (Zamora-Avilés et al., 2012, ApJ, 751, 77; ZA & VS 2014, ApJ, 793, 84)

AN ANALYTICAL MODEL FOR THE EVOLUTION OF THE SFR

Zamora-Avilés et al., 2012, ApJ, 751, 77;
ZA & VS 2014, ApJ, 793, 84

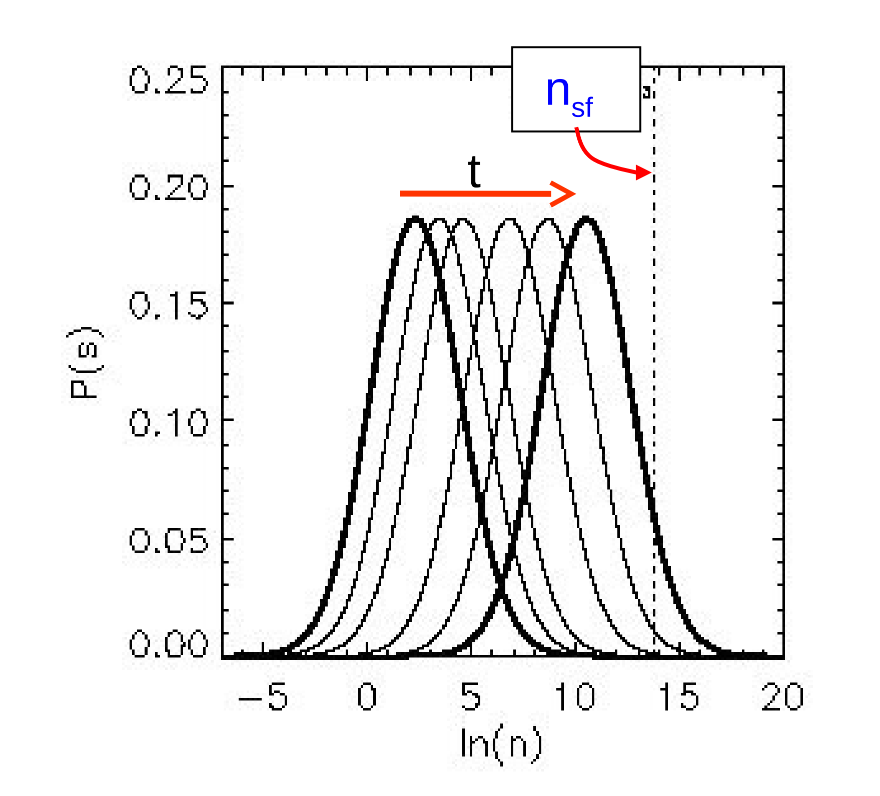
- Most analytical models for the SFR in molecular clouds (e.g., Krumholz & McKee 2005; Padoan & Nordlund 2011; Hennebelle & Chabrier 2011) are *stationary*. They:
  - Assume a lognormal density PDF (Vázquez-Semadeni 1994):



  - Assume SFR is given by mass fraction above some n_{sf} divided by characteristic timescale.
    - Models differ in choice of n_{sf} and timescale (Federrath & Klessen 12).
    - Typically predict SFR_{ff} (actually, SFE per free-fall time).

A simple ***analytical, evolutionary*** model: (Zamora-Avilés et al., 2012, ApJ, 751, 77; ZA & VS 2014, ApJ, 793, 84)

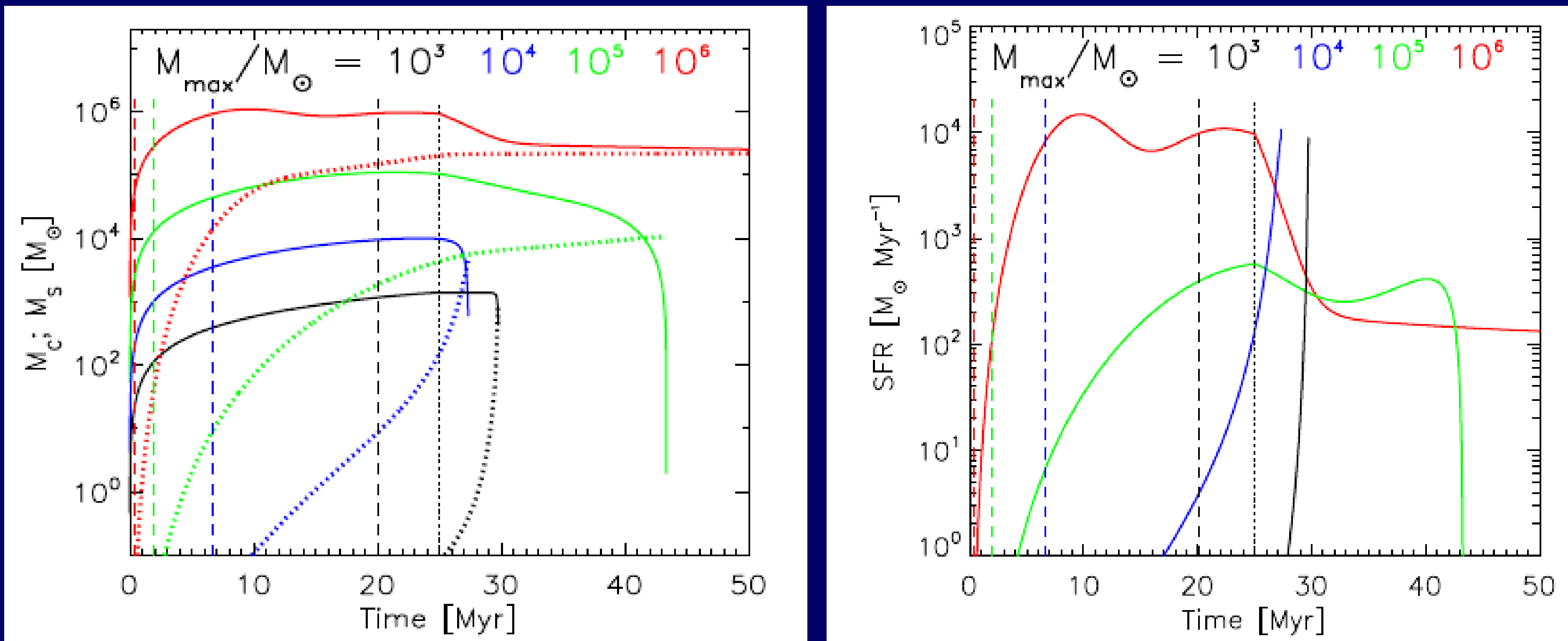
- Including:
  - Accretion onto cloud (mass growth).
  - ***Global gravitational contraction*** (variation of density PDF) .



Implication: SFR must increase with time

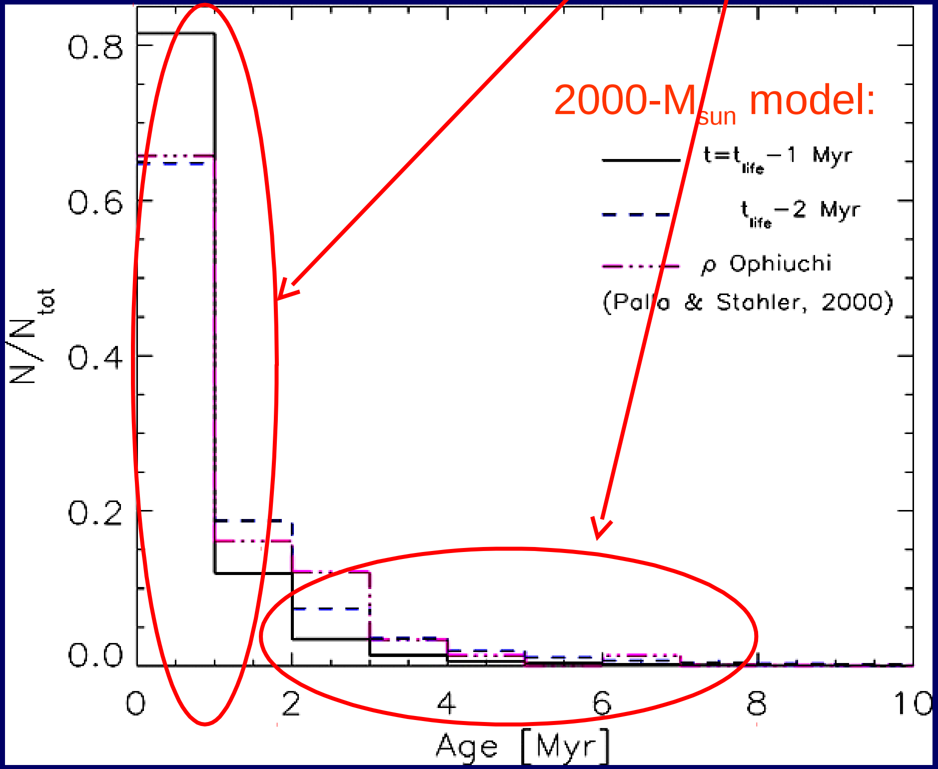
- Next:
  - Assume IMF, compute number of massive stars.
  - Compute rate of mass ionization by massive stars in cloud (Franco+94).
  - Follow evolution of cloud’s mass, size, density and SFR.
  - Main controlling parameter is ***total cloud mass***
    - (for CNM initial conditions).

SFR evolves (increases, then comes back down, or shuts off):



Zamora-Aviles & VS 2014, ApJ, 793, 84

- Because SF accelerates, stellar population of an evolved star-forming region consists of:
  - Older, scarce component formed by early, low-mass, low-SFR, and
  - Younger, more abundant component formed at later, massive, high-SFR burst.

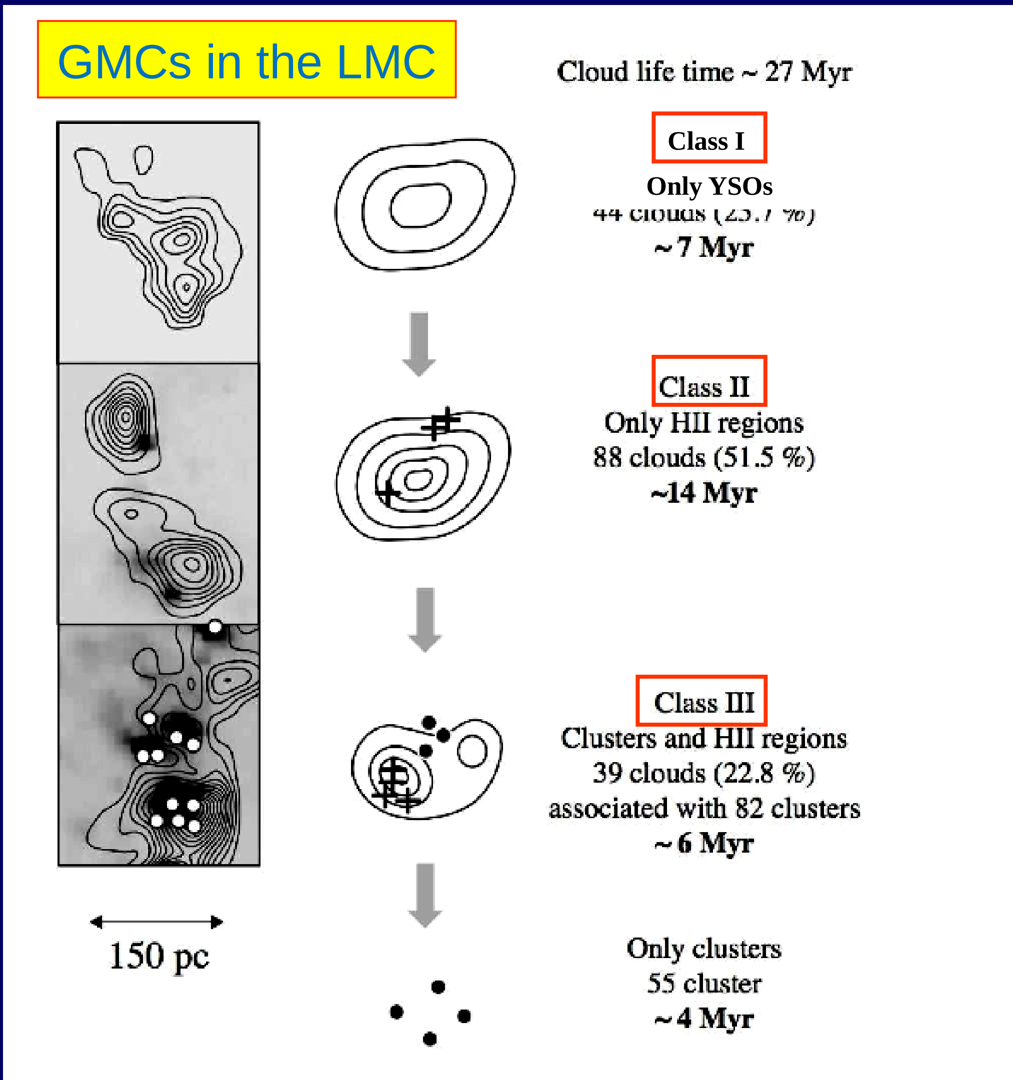


Consistent with age histograms in embedded clusters by Palla & Stahler 1999, 2000.

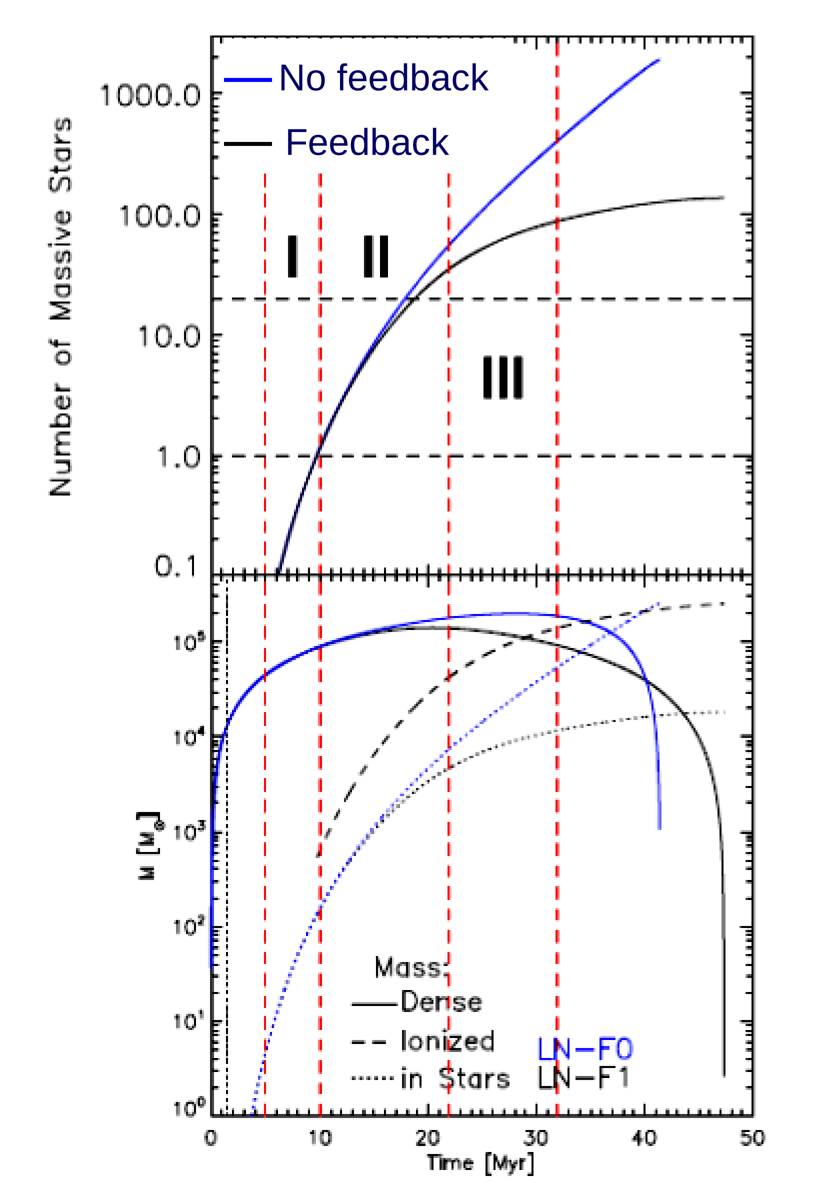
Analytical model by Zamora-Avilés+12, ApJ, 751, 77

– Evolution of GMCs' stellar population ($M \sim 10^5\ M_{sun}$):

Model



Kawamura+2009



Zamora-Avilés+2012

- Consequences of multi-Jeans, nearly pressureless collapse:
  - Formation of filaments as ***gas funnels toward cores*** (not equilibrium structures) (Gómez & VS 14, ApJ, 791, 124).
  - SF accelerates! (Zamora-Avilés et al., 2012, ApJ, 751, 77; ZA & VS 2014, ApJ, 793, 84)
  - Cluster structural properties (VS+17, MNRAS, 467, 1313).
    - Age and mass radial gradients (compare to, e.g., Povich+16).
    - Fractal structure.

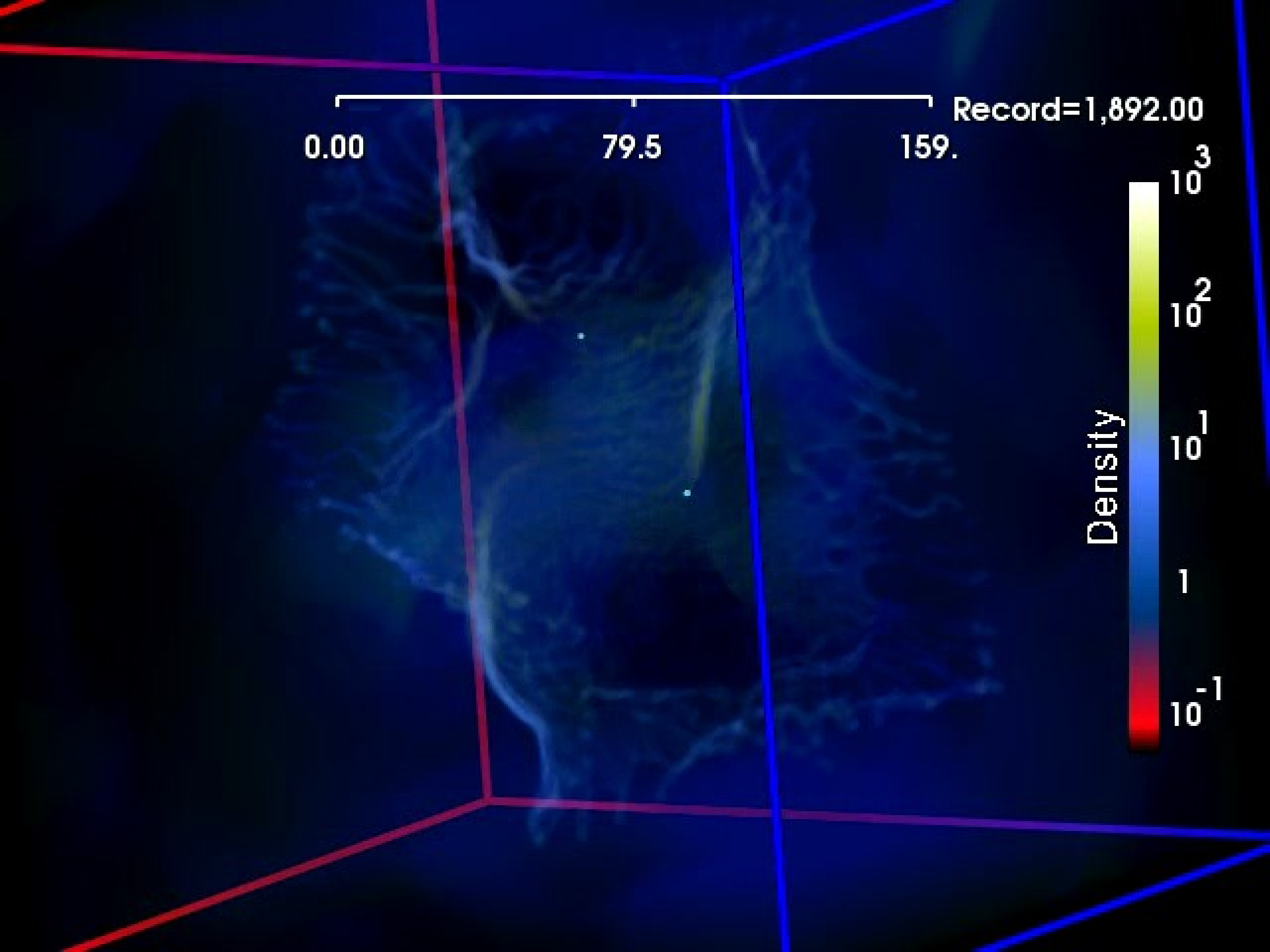
Numerical simulations (Colín+2013, MNRAS, 435, 1701; Vázquez-Semadeni+17, MNRAS, 467, 1313)

- Simulations of cloud formation including radiative feedback and a realistic IMF (imposed).

  - ART AMR code.
    - Box size: 256 pc
    - Colliding flow simulation at 5.9 km s^{-1} plus 30% turbulent fluctuations
    - Maximum resolution: 0.06 pc.

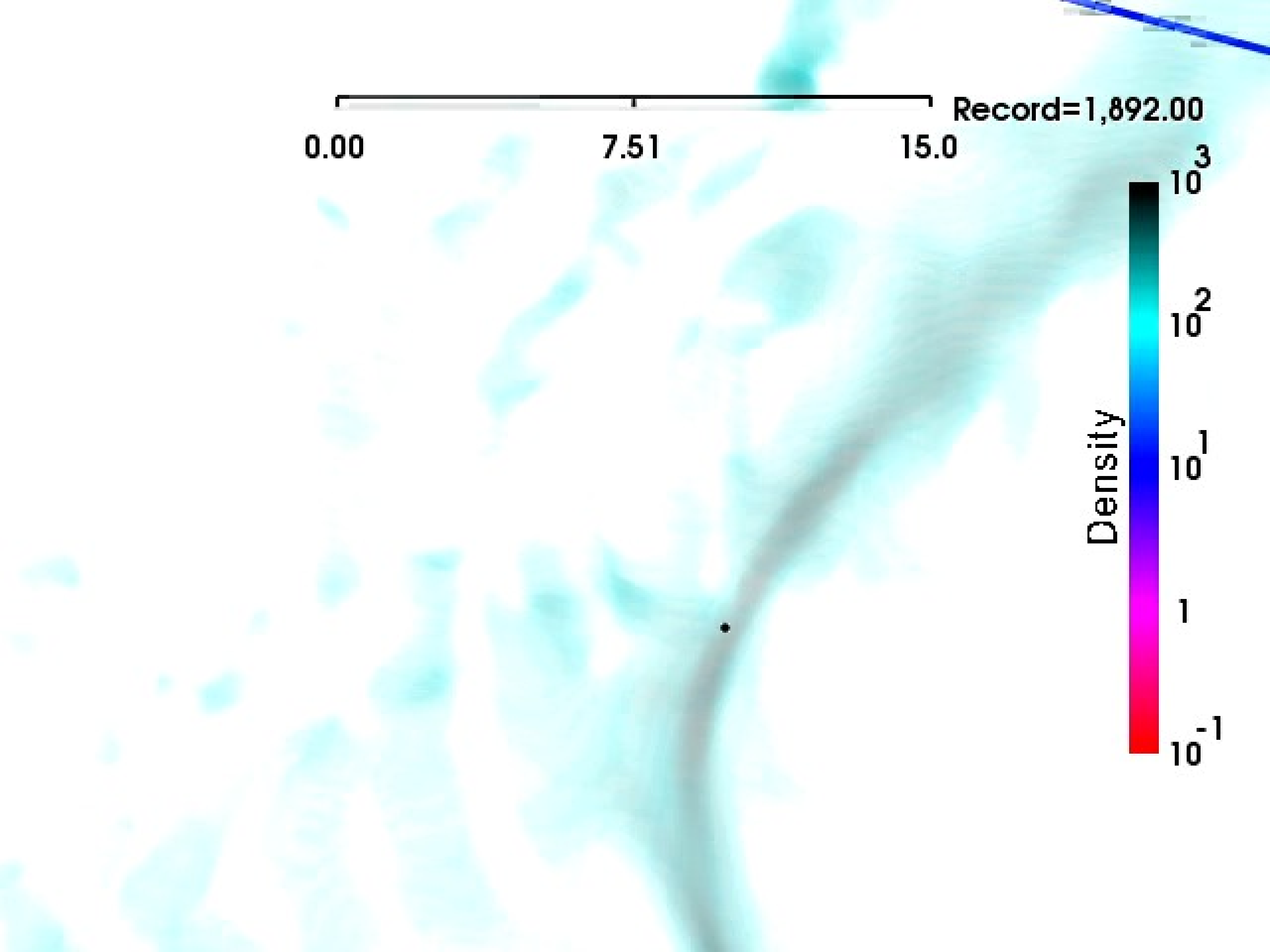
  - IMF imposed by probabilistic SF scheme.
    - A roughly Salpeter-like IMF

  - A “PMRT” (“poor man’s radiative transfer”) scheme.
    - Simplified radiative transfer method.
    - Each “star” radiates according to its own mass.



Record=1,892.00
0.00
79.5
159.
Density
10^3
10^2
10^1
1
10^-1

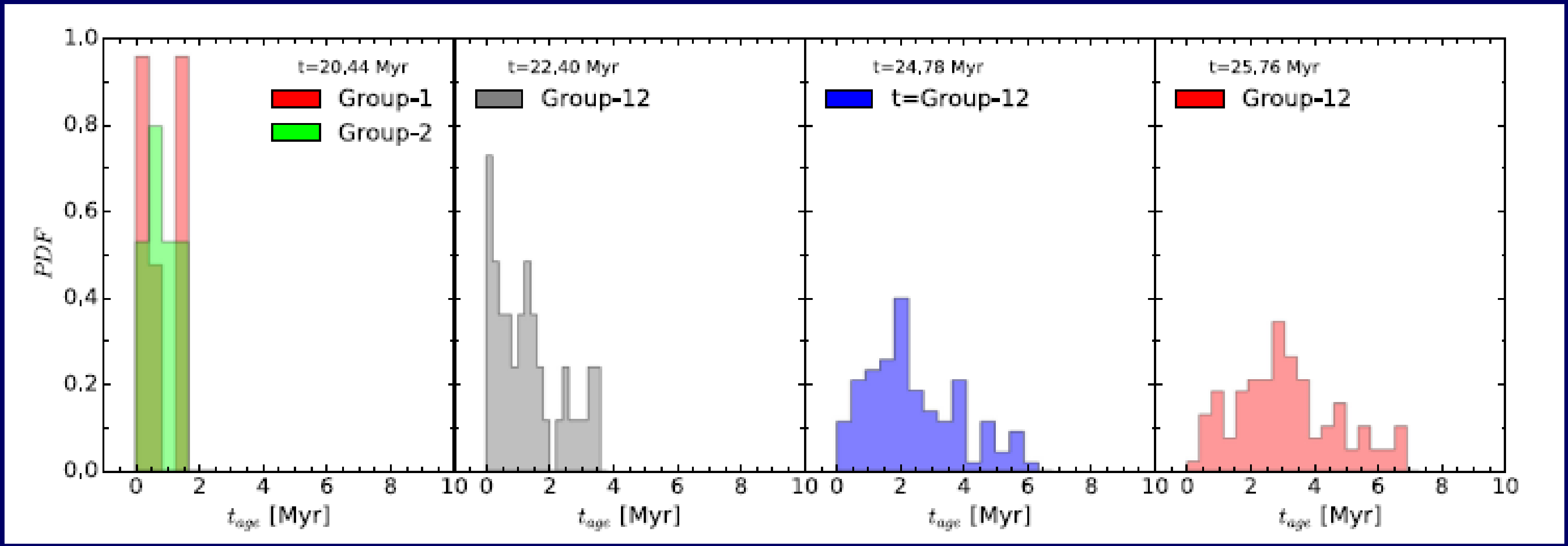
“Cluster 2”



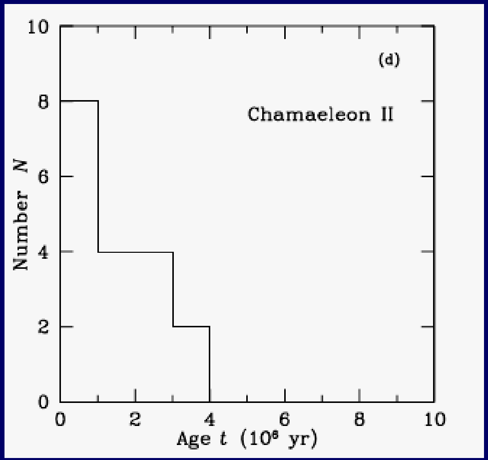
Record=1,892.00
0.00
7.51
15.0
Density
10^3
10^2
10^1
1
10^{-1}

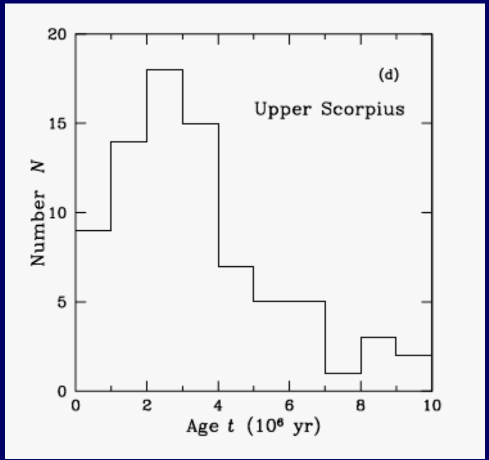
1. SFR increases by collapse, then decreases by feedback.

- Stellar age histograms peak at a certain age (VS+17, MNRAS, 467, 1313).

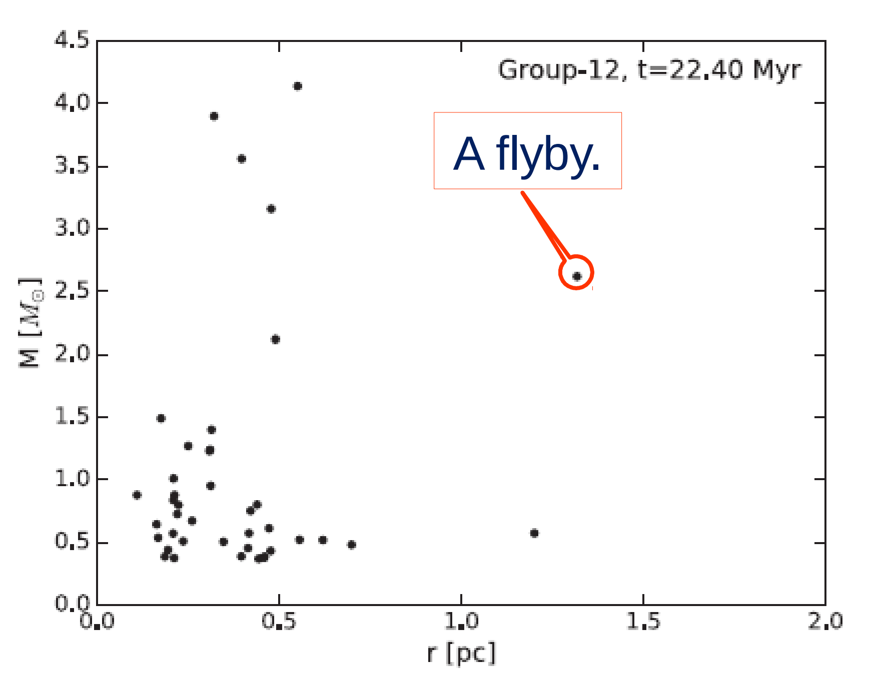


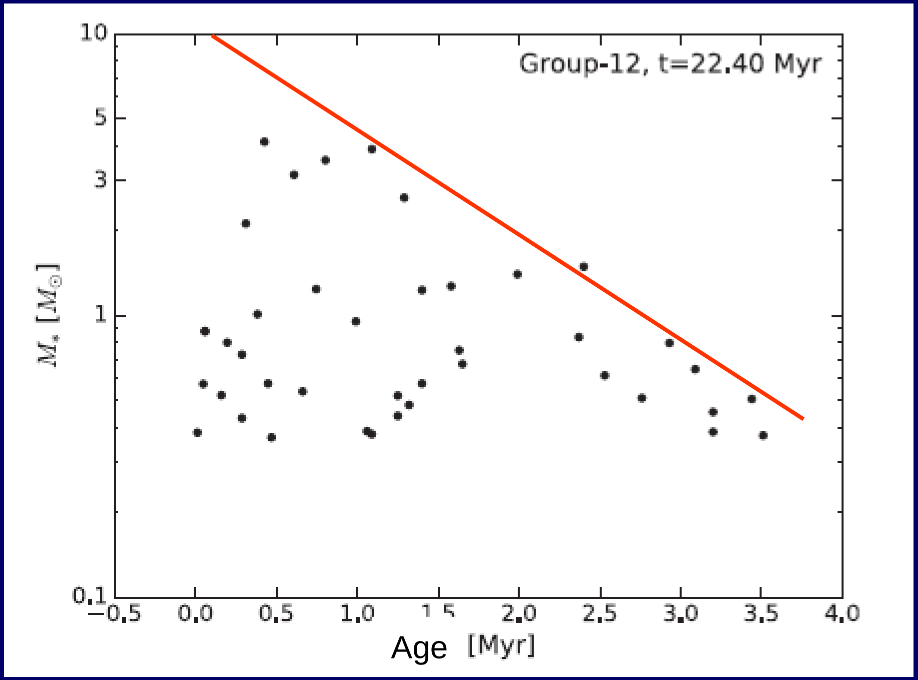
Compare to observed embedded cluster age histograms (e.g., Palla & Stahler 2000).

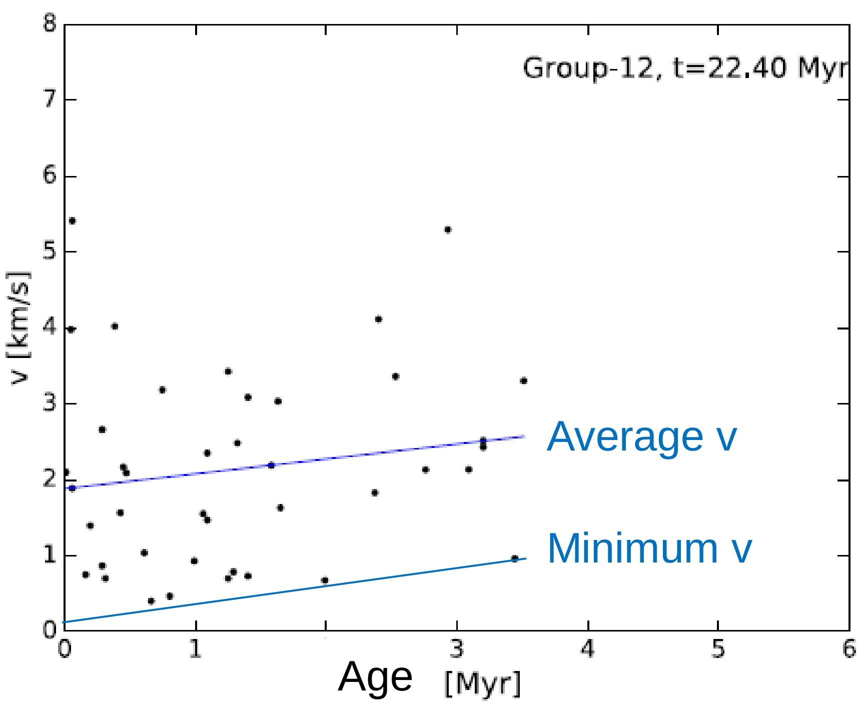


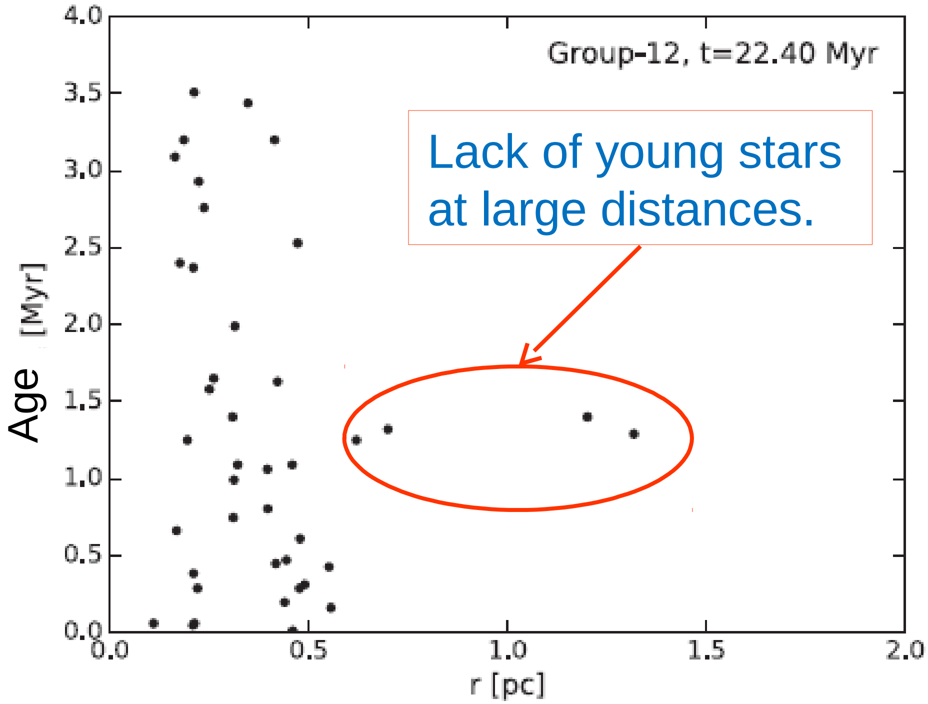


2. Correlations and gradients:
- Mass-age.
- Age-velocity.
- Age gradient.





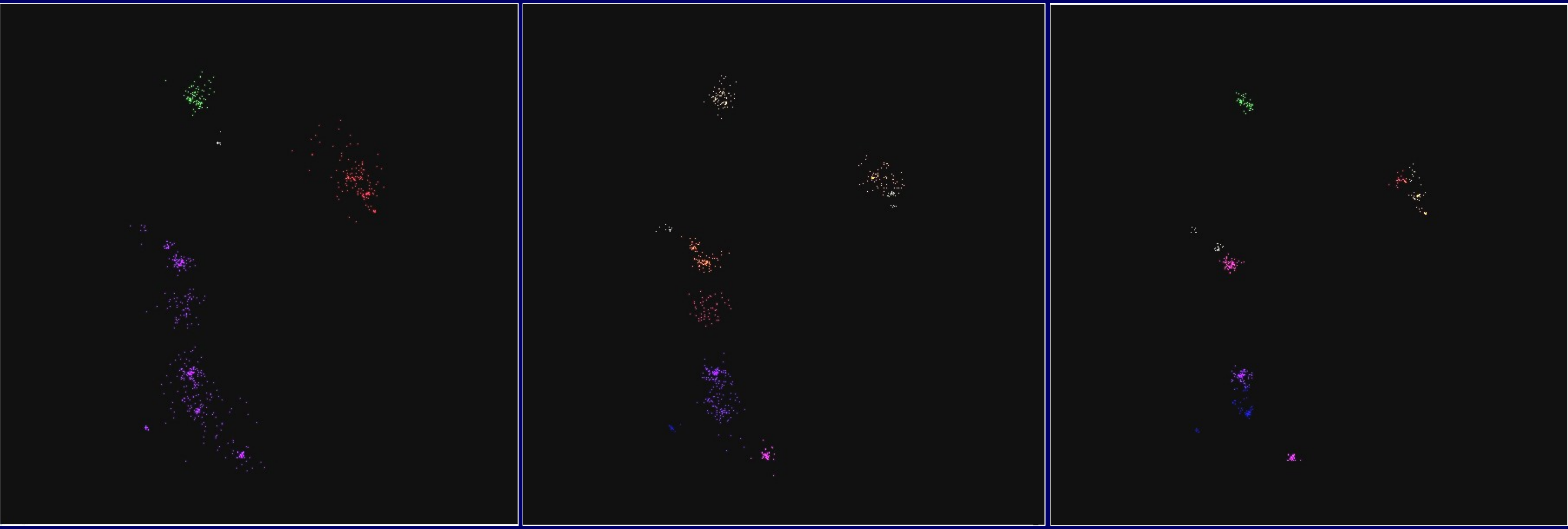

Group-12, t=22.40 Myr
v [km/s]
Age [Myr]
Average v
Minimum v


Group-12, t=22.40 Myr
Lack of young stars at large distances.
Age [Myr]
r [pc]

3. Self-similar, fractal cluster structure:

- Cluster consists of groups, which consist of subgroups, etc.
- Compare to talk by Simon Portegies Zwart.

Applying a friends-of-friends algorithm at t=30 Myr:



Linking parameter = 2 — 4 groups

Linking parameter = 1 — 9 groups

Linking parameter = 0.5 — 13 groups

VI. CONCLUSIONS

- Gravitational collapse likely to star at the cloud scale.

- Global collapse of star-forming molecular clouds implies:
  - Filaments form spontaneously.
  - SF accelerates due to collapse,
    - then decays due to feedback.

  - Collapse is hierarchical (collapses within collapses):
  - Clusters are born with:
    - Fractal (hierarchiical, self-similar) structure.
    - Radial age gradients.
    - Age-mass correlations (massive stars form at peak of SFR).