The imprint of global hierarchical cloud collapse and stellar feedback on early star cluster evolution

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IRyA

Stellar clusters

Most of the stars form in massive star forming regions ***(Lada & Lada 2003)*****,**

but their structural properties still require and adequate theoretical understanding:

i) The existence of a mass segregation in clusters
(Hillenbrand & Hartmann, 1998)

ii) The distribution of protostellar separations
(Bressert+2010)

iii)The likely existence of an age gradient in clusters
(Kuhn, Getman & Feigelson, 2015a)

iv)The apparent deficit of OB stars in some infrared dark clouds
(Povich+2016)

Stellar clusters

Some current advances:

i) Most massive stars form in-situ at the cluster centres, rather than sinking there through dynamical interactions in the cluster itself ***(Kirk, Offner & Redmond, 2014)***

ii) By comparing multiwavelength observations with numerical simulations, that clusters form by mergers of "subclusters" structures ***(Kuhn+2015b)***

iii)Observationally, the presence of subunits of different ages in the clusters has been pointed out by ***(Rivera-Gálvez+2015, Pecaut & Mamajek, 2016)***

iv) Kinematical properties of young stellar forming regions can be explained by a global gravitational collapsing model (no feedback included!) ***(Kuznetsova, Hartmann & Ballesteros-Paredes, 2018)***

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Is there a theoretical scenario within which these structural properties could be explained in a self-consistent form?

The scenario: Global Hierarchical Collapse (GHC), Vazquez-Semadeni+09, +19

Molecular Cloud Formation (solar neighbourhood conditions):

By compression-triggered phase transition WNM → CNM
Koyama & Inutsuka 2004; Audit & Hennebelle 2005; Heitsch+2005; Vázquez-Semadeni+06

Global Collapse:

Jeans mass drops precipitously ($x10^4$) by cooling compression and cloud begins to collapse (*Vázquez-Semadeni+07, Gomez&VS14*)

Multi-scale Collapse:

Small-scale collapses within and falling into larger-scale ones.

Star formation:

As clouds collapses star formation rate increases,
Massive star-forming regions consist of mergers of low-mass regions.

The scenario: (GHC) in our numerical simulations

Simulations of cloud formation and evolution with OB star ionizing heating feedback and crude radiative transfer ***(Colín+2013, MNRAS, 435, 1701)***

✓ ART AMR+Hydro code ***(Kravtsov+2003)***

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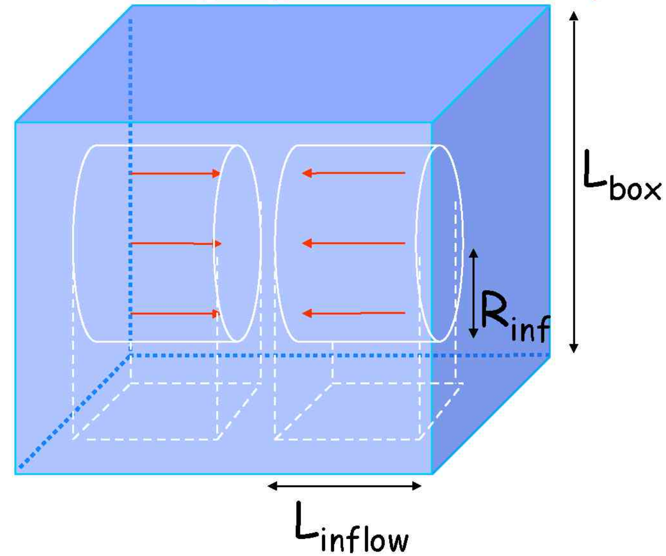
Continuity equation
(mass conservation)

$$\frac{d\rho}{dt} = -\rho\nabla\cdot u$$

- ✓ Initial low-amplitude turbulence velocity fluctuations

Converging inflow setup



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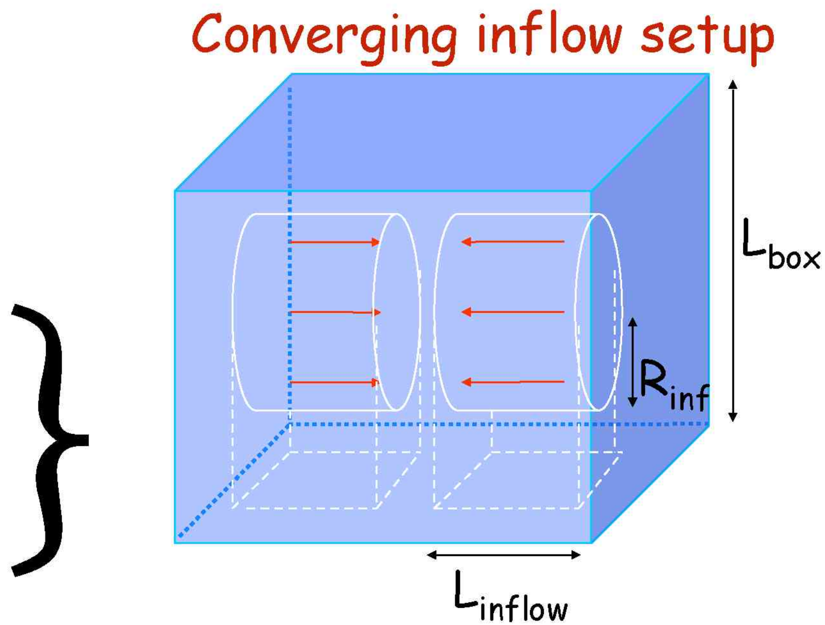
- ✓ A probabilistic SF algorithm: if n_{SF} is reached, create a stellar particle with probability p: *the longer it takes to form a stellar particle in a collapsing site, the more massive the particle will be.*



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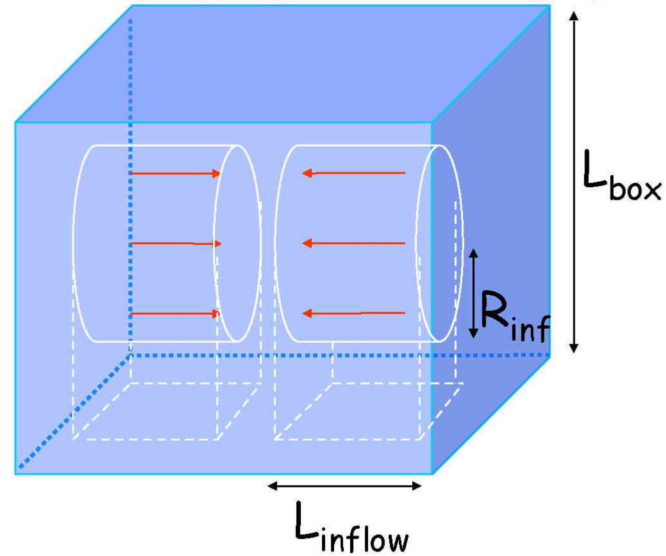

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Thus, our SF prescription is such that *stellar particles in our simulations are formed with masses of individual stars:*

populating the MF at the relevant scales to implement a prescription for feedback from massive stars.

Numerical Simulations:

ART Code

$L_{box} = 256$ pc

$n_0 = 1$ cm^{-3} $T_0 = 5000$ K

max. resolution: 4096^3

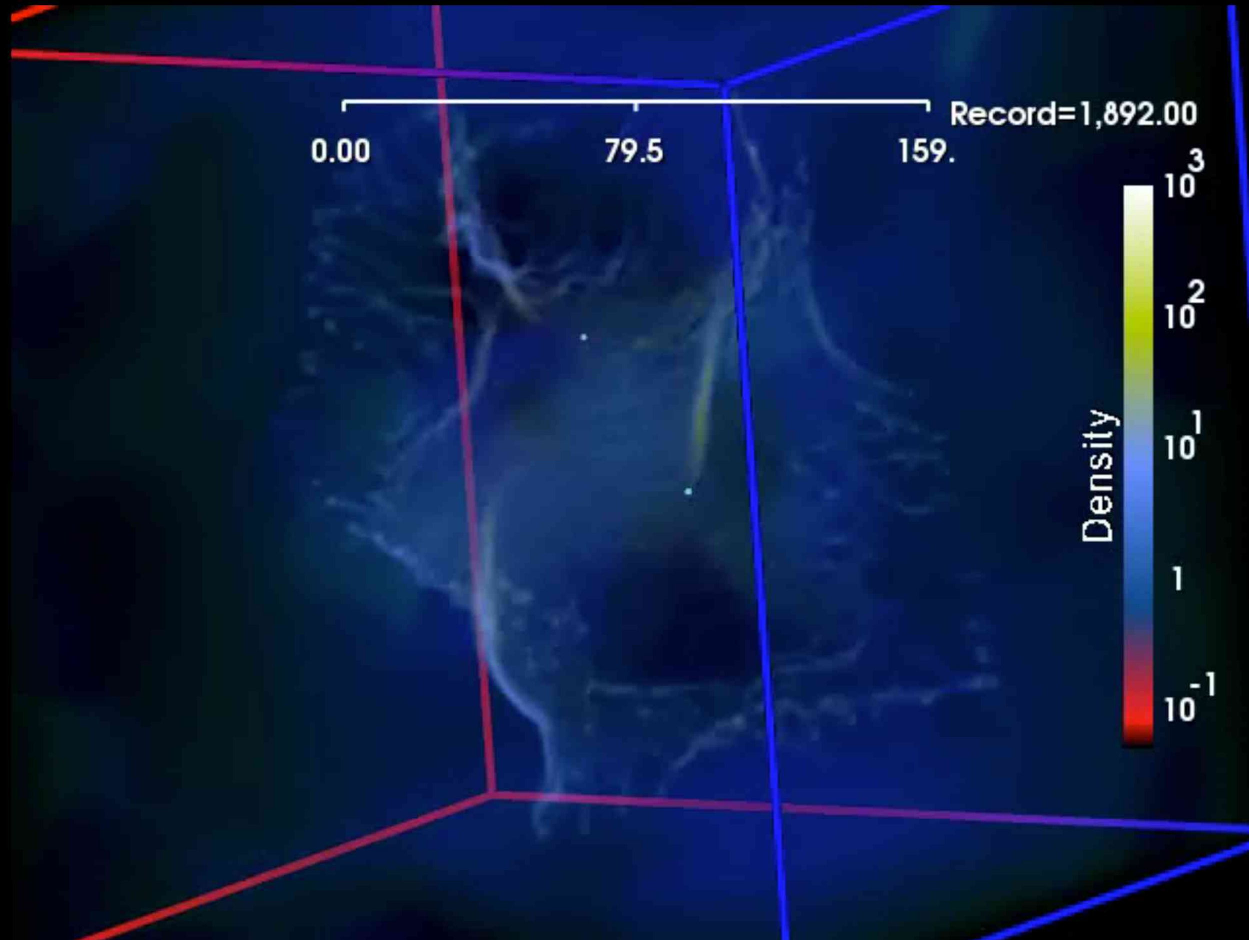
min. cell size ~ 0.06 pc

~ 13 000 au

$n_{SF} = 9.2 \times 10^4$ cm^{-3}

(0.78 $M_\odot$ @ level 5)

SP min. mass = 0.39 $M_\odot$

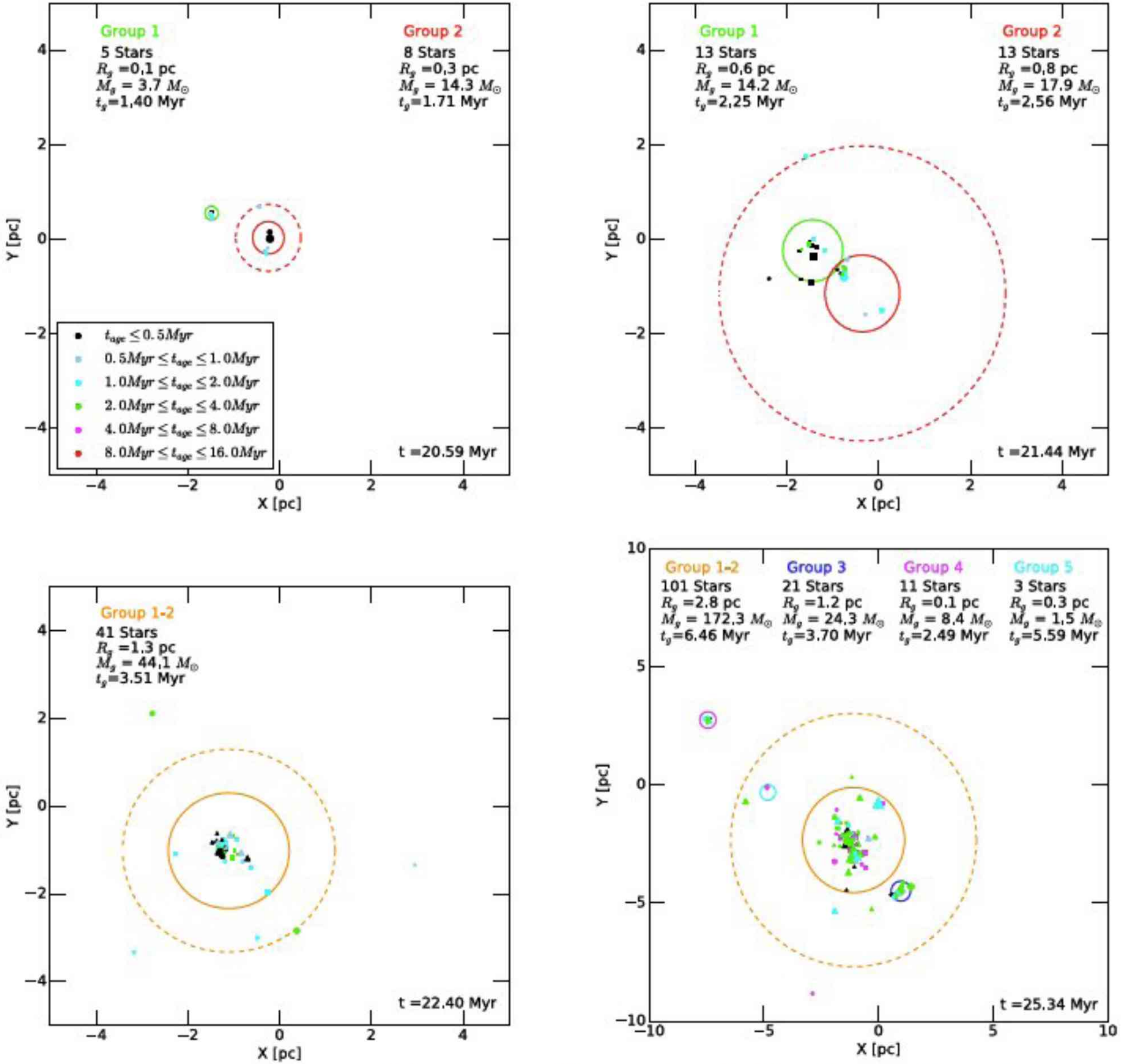


Our aim:

to study the impact of the cloud structure and the feedback on the assembly and early evolution of Stellar Clusters.

Vazquez-Semadeni, E., González-Samaniego, A. Colín, P. (MNRAS, 2017)

Results: *hierarchical star cluster assembly*



Stellar cluster formed by mergers and engulfing

Massive stars reside in the centres

and

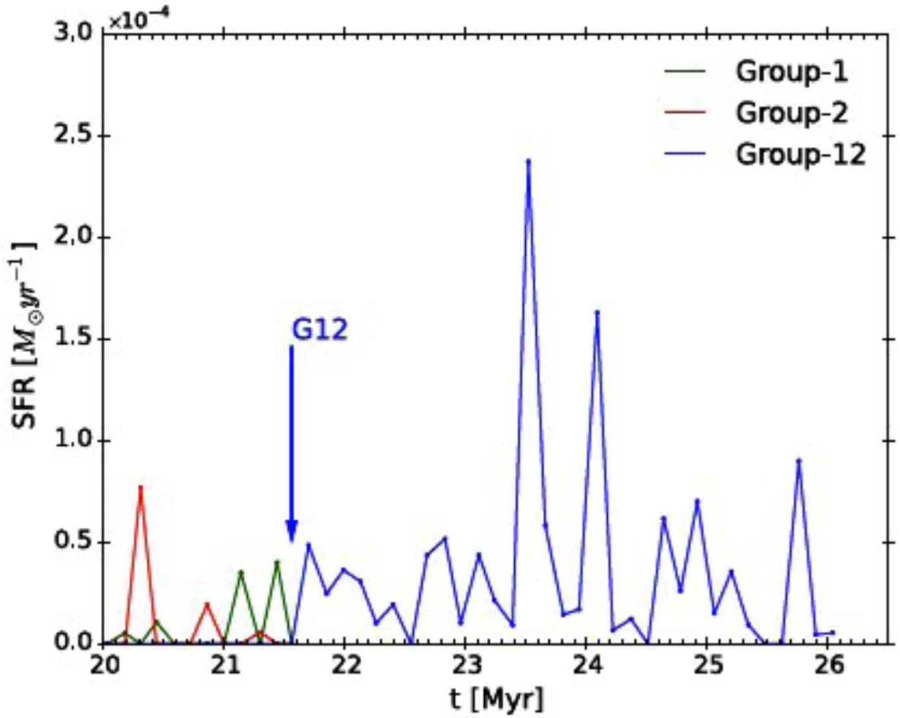
Different age sub-structures within the stellar clusters

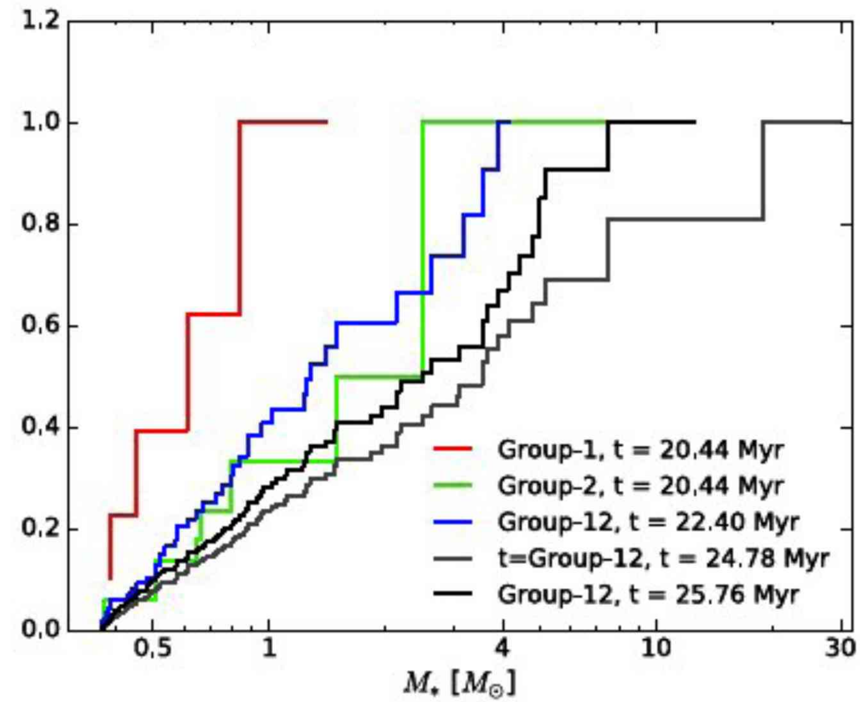
Vazquez-Semadeni, E., González-Samaniego, A. Colín, P. (MNRAS, 2017)

Results: Star formation rate and delayed massive-star formation

The star formation rate increases over time!

Massive stars do not appear until the accretion rate and the SFR are large!





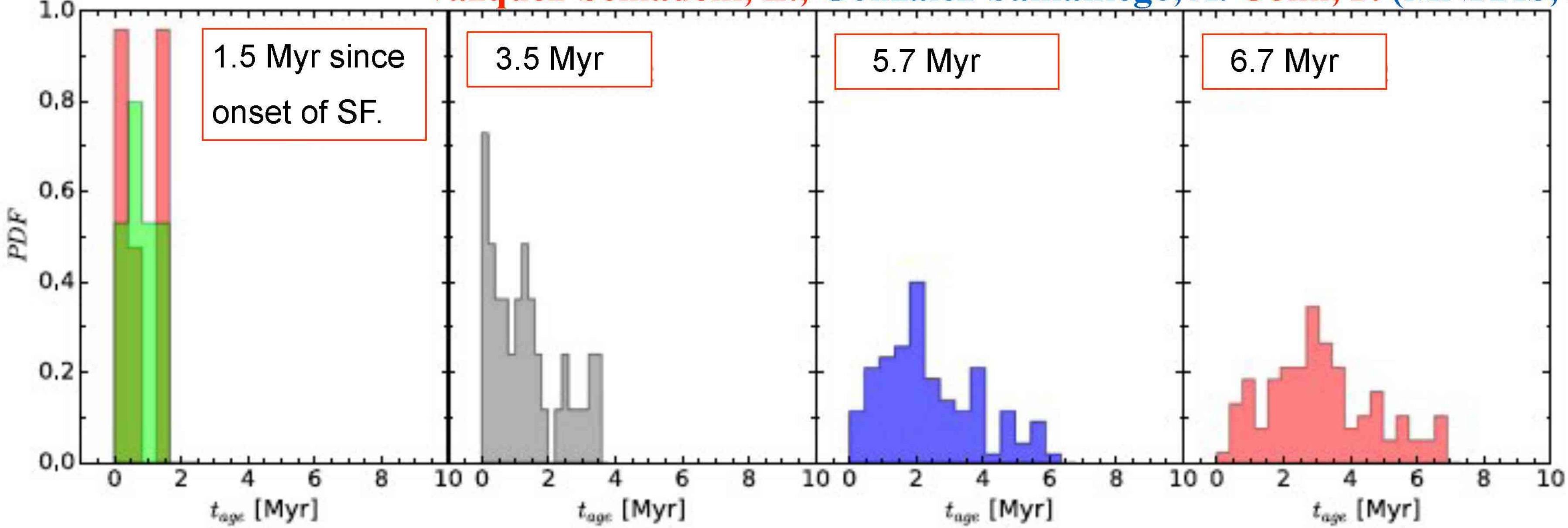
Massive star formation is delayed

Vazquez-Semadeni, E., González-Samaniego, A. Colín, P. (MNRAS, 2017)

Results: age histograms

- Stellar age histograms peak at a certain age:

Vazquez-Semadeni, E., González-Samaniego, A. Colín, P. (MNRAS, 2017)



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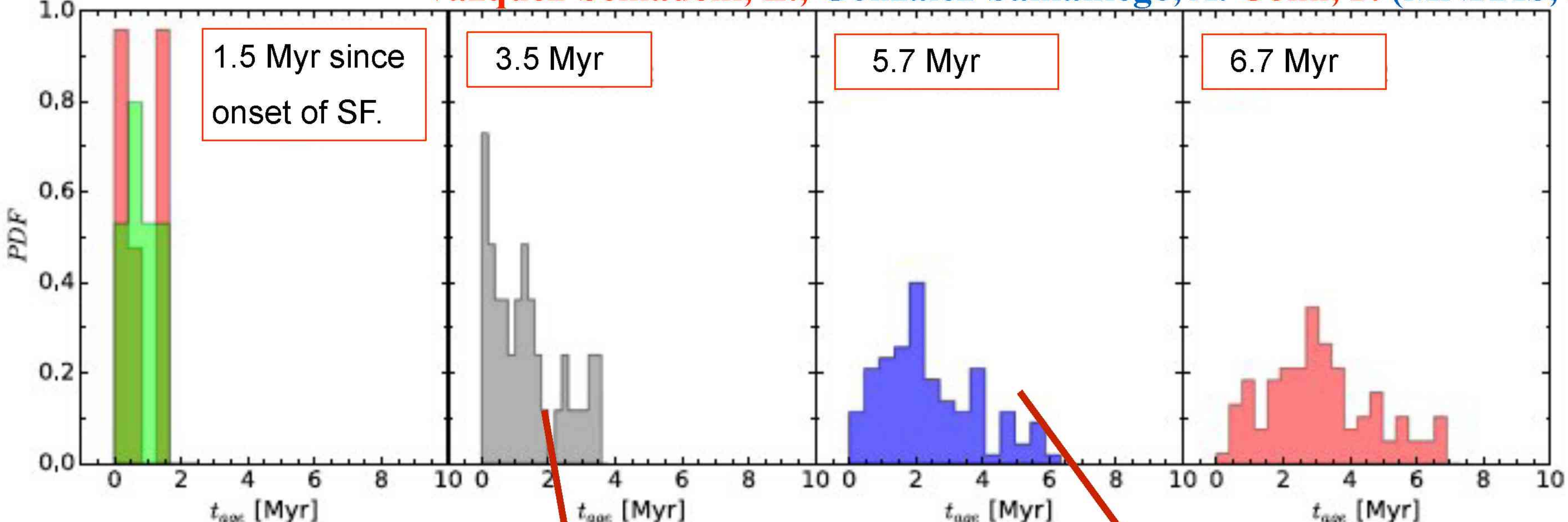
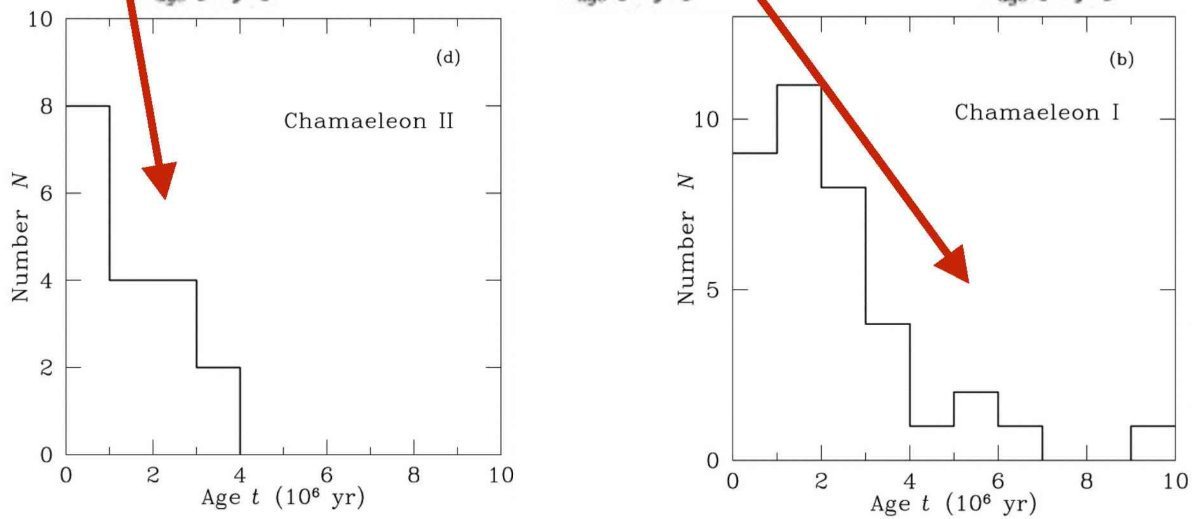


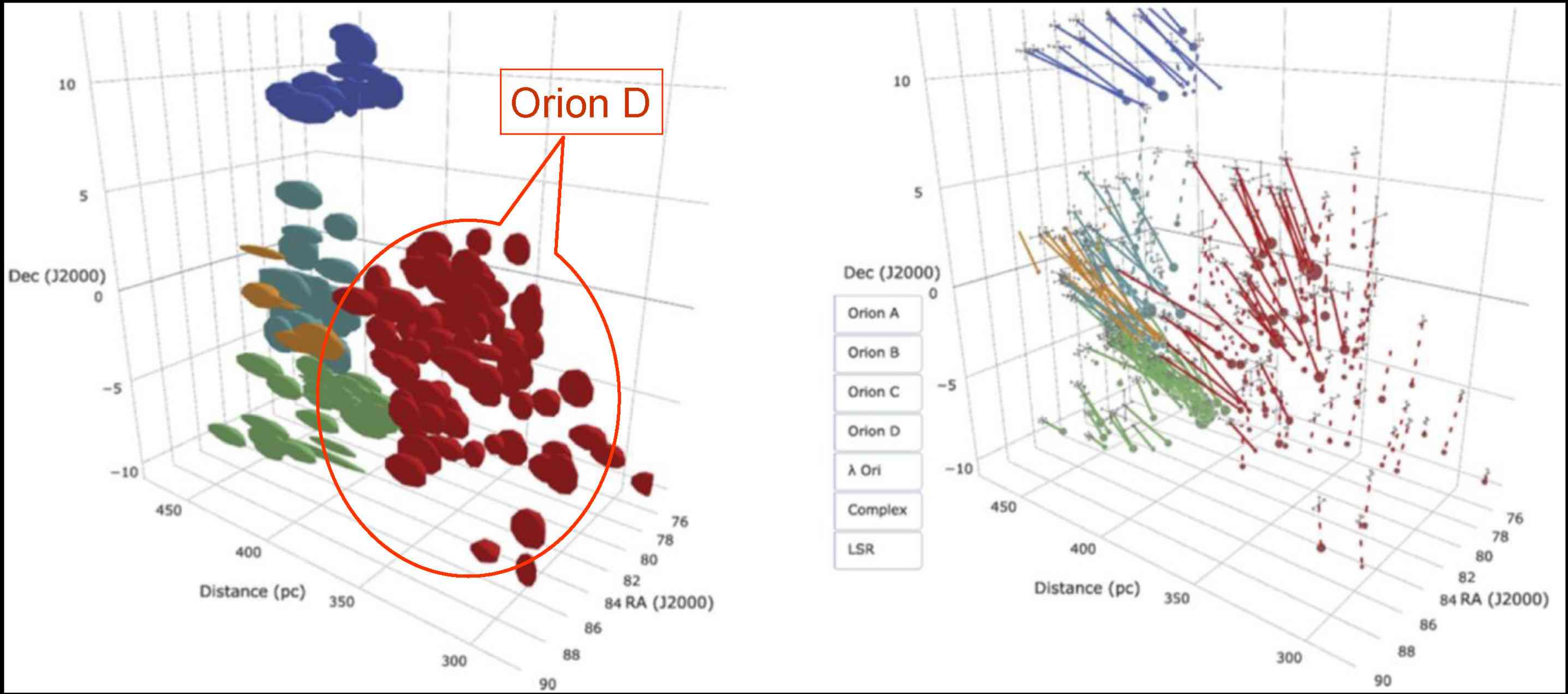
Similar to embedded stellar clusters age histograms (e.g., Palla & Stahler 2000; ApJ 540 255)



Comparison with observations (González-Samaniego+19, in prep.):

- Kounkel+18 (AJ, 156, 84): spectroscopic and astrometric study of Orion.
- Discussed 5 star-forming regions: Orion A, B, C, D and λ Ori.
- Process on simulation stars:

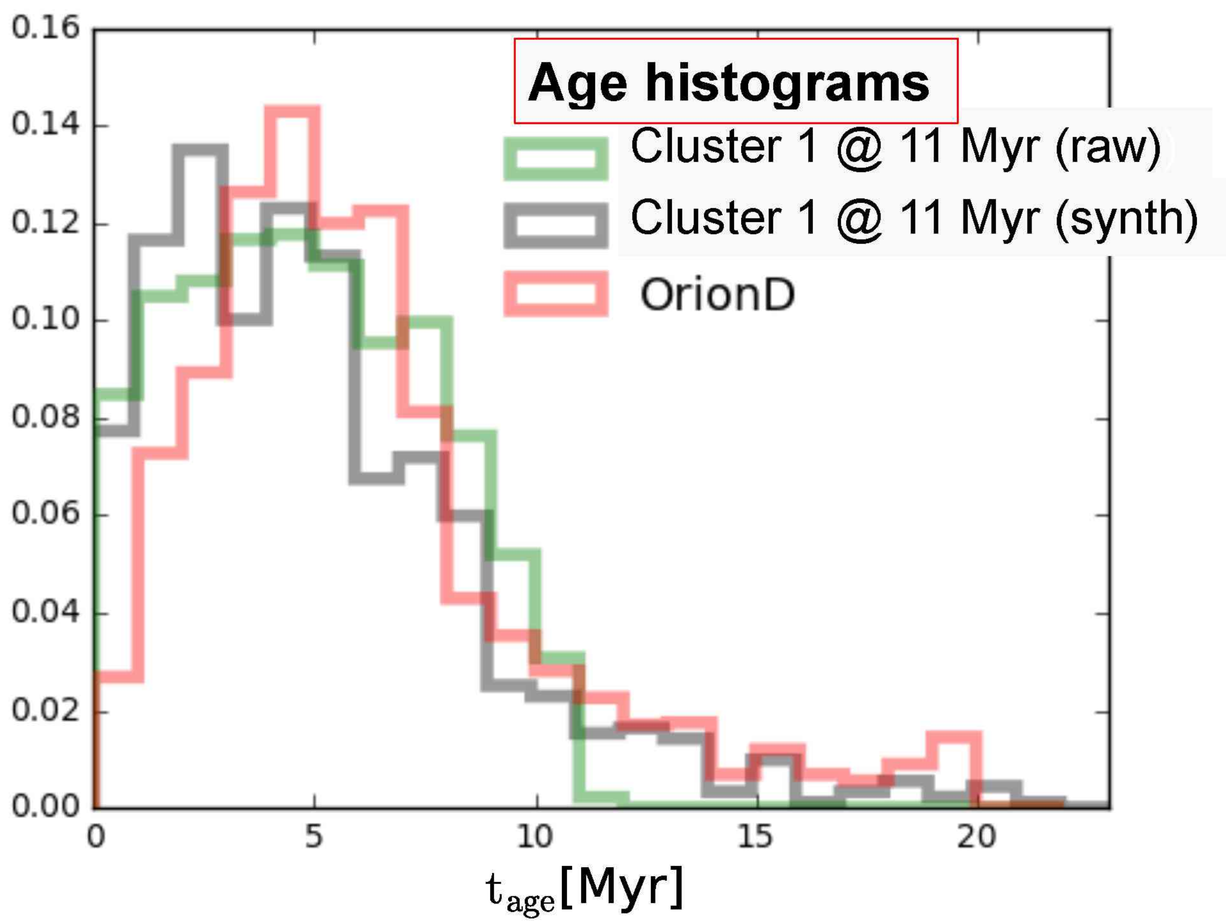
  (age,mass) → (color,magnitude) → place in HR diagram → synthetic (age,mass)



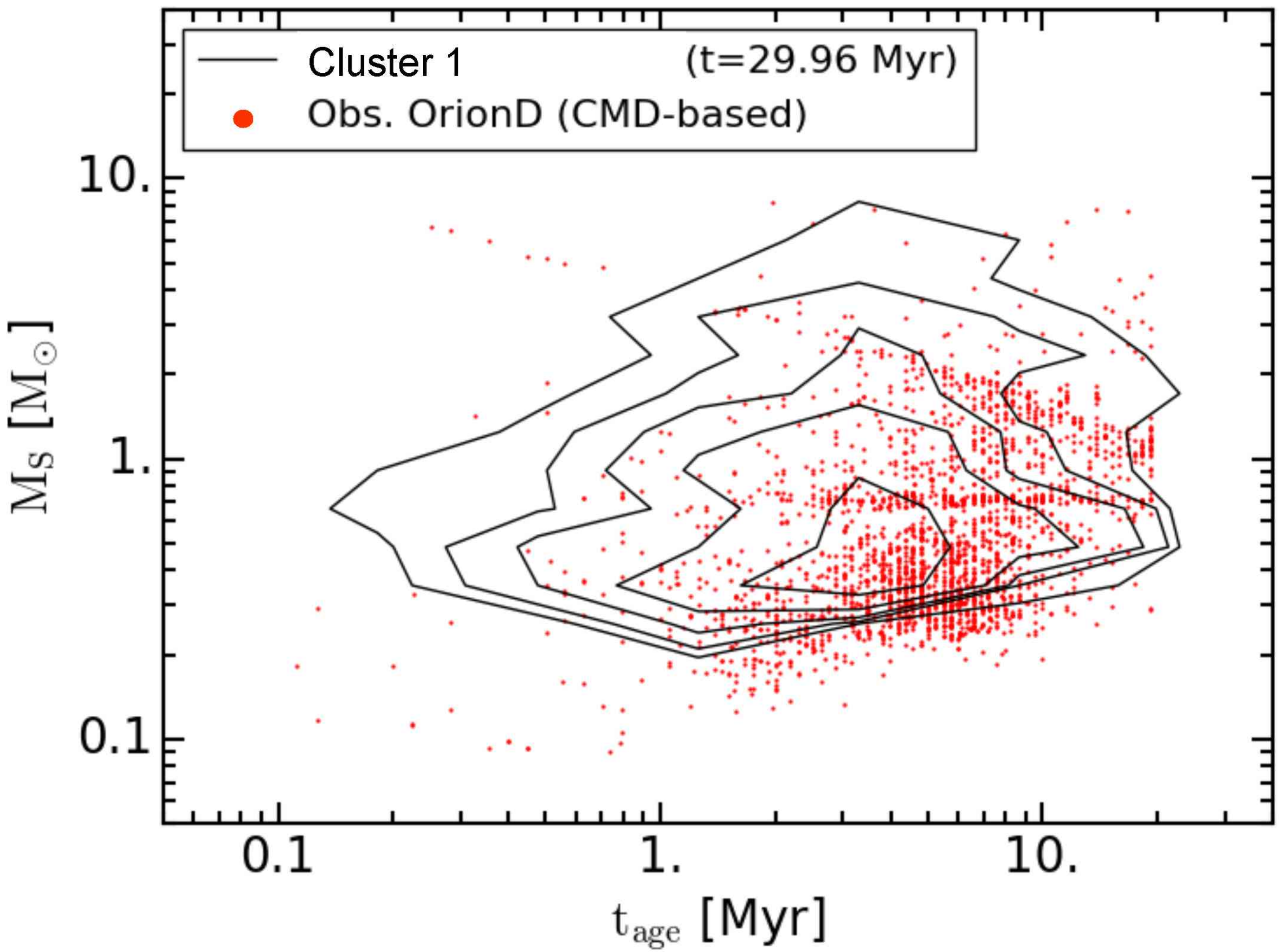
The APOGEE-2 Survey of the Orion Star-forming Complex. II. Six-dimensional Structure
Kounkel et al., 2018 AJ 156 84

Results: age histograms (synthetic vs observed)

Synthetic and observed age histograms for Cluster 1 (11 Myr after the formation of its first star) and Orion D from **Kounkel +18. (González-Samaniego+19, in prep.)**

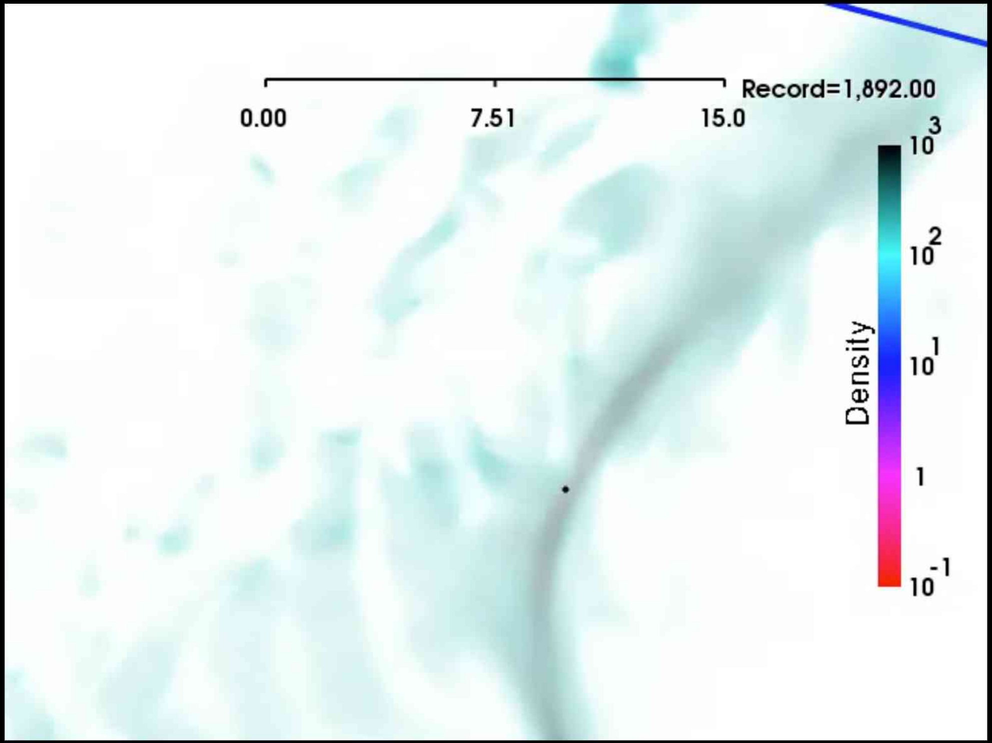


- ***Orion D observations vs Synthetic observations (simulations)***



Feedback changes everything!

Without Feedback



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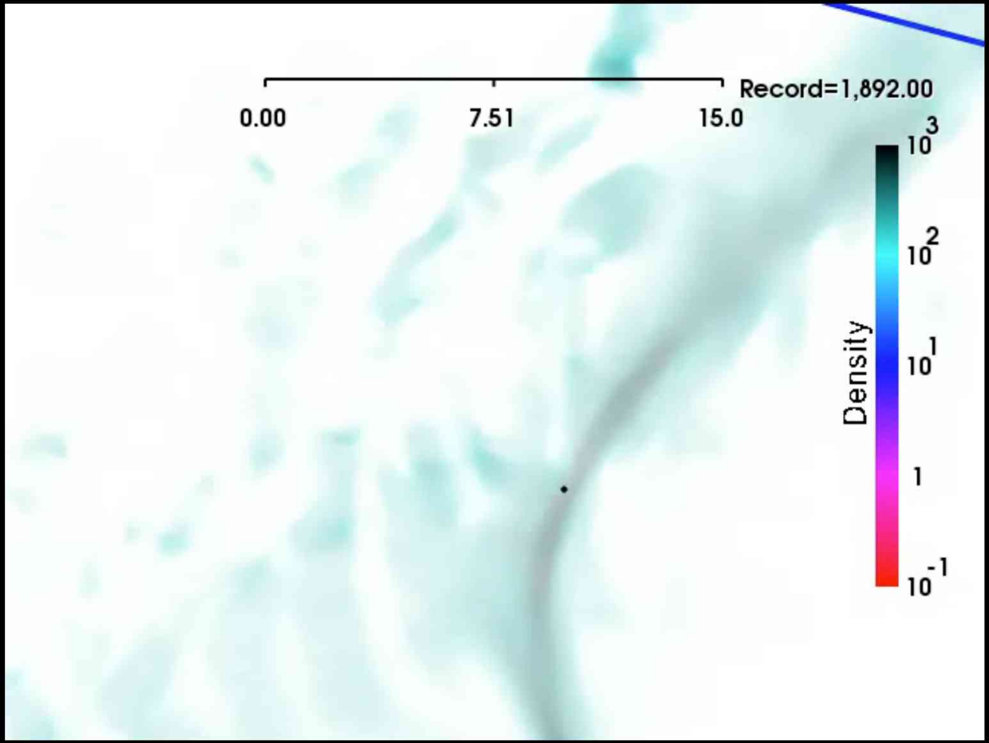
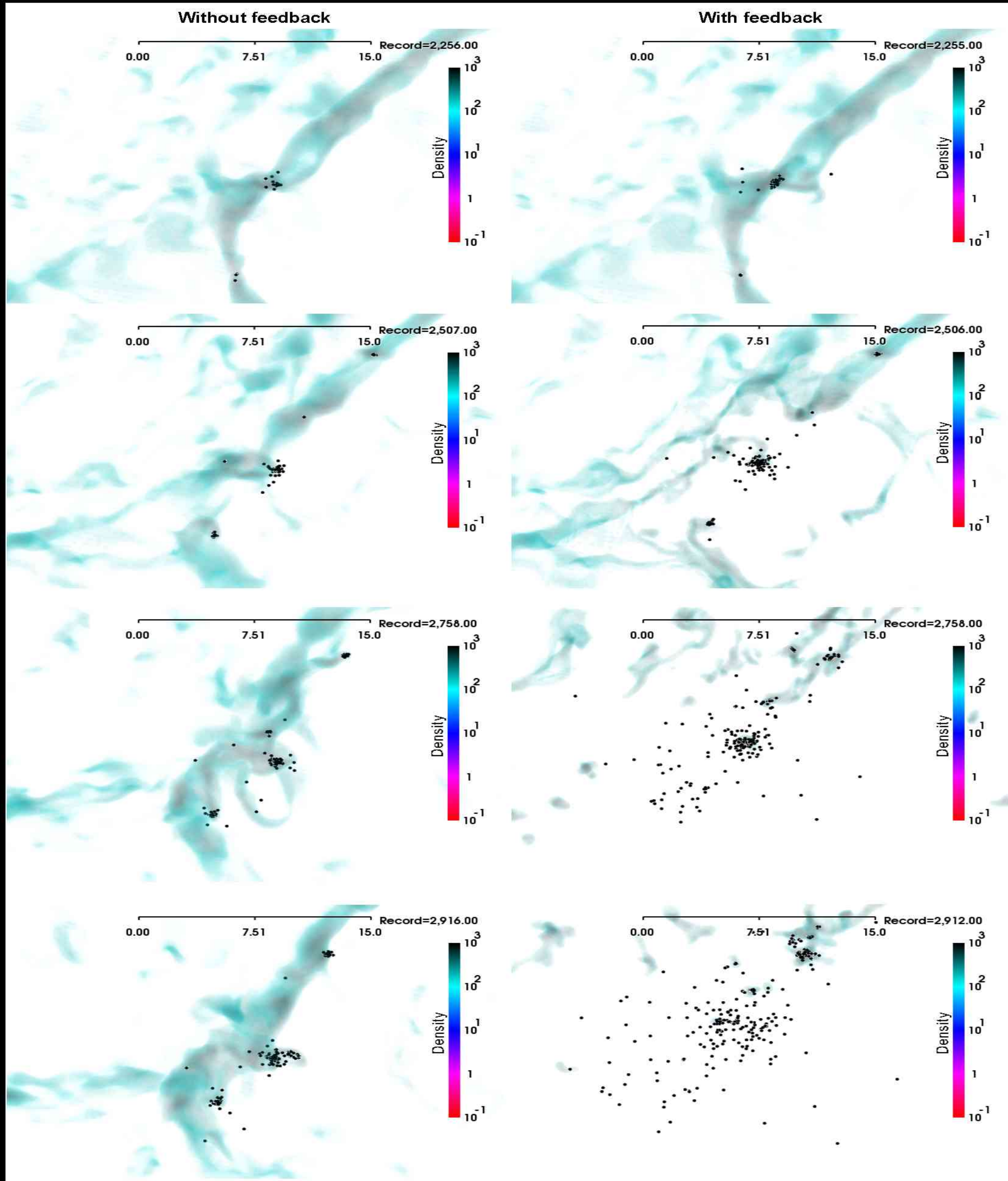


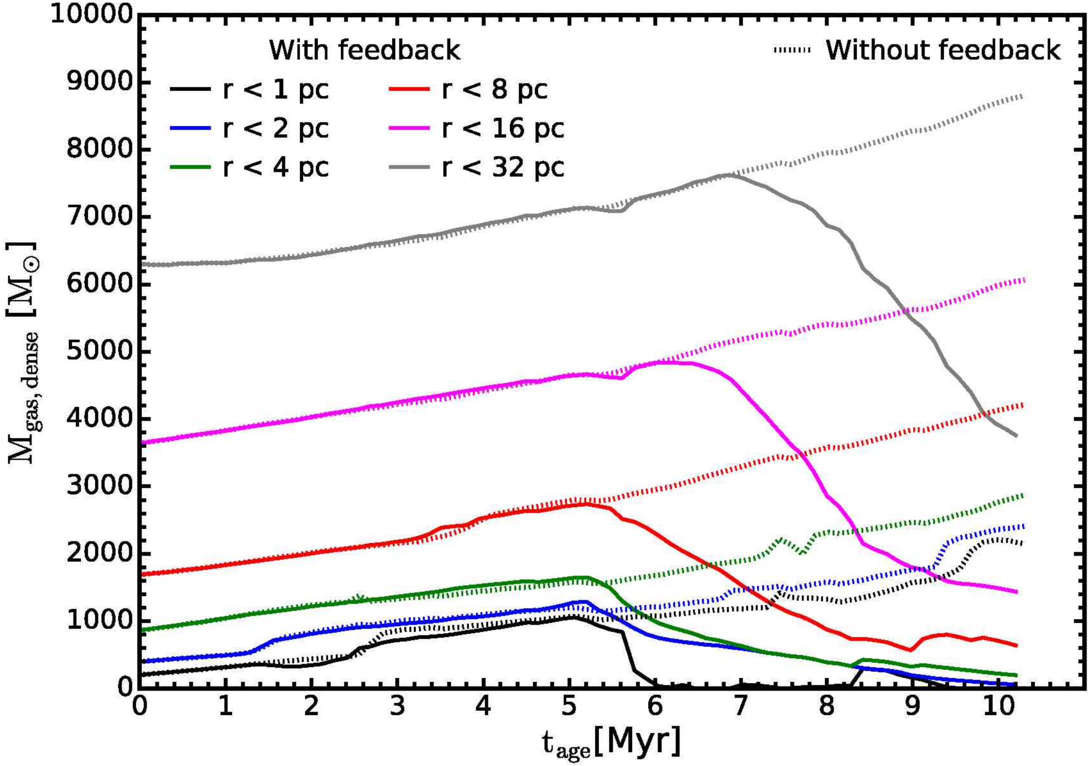
González-Samaniego, A. & Vázquez-Semadeni (In prep.)



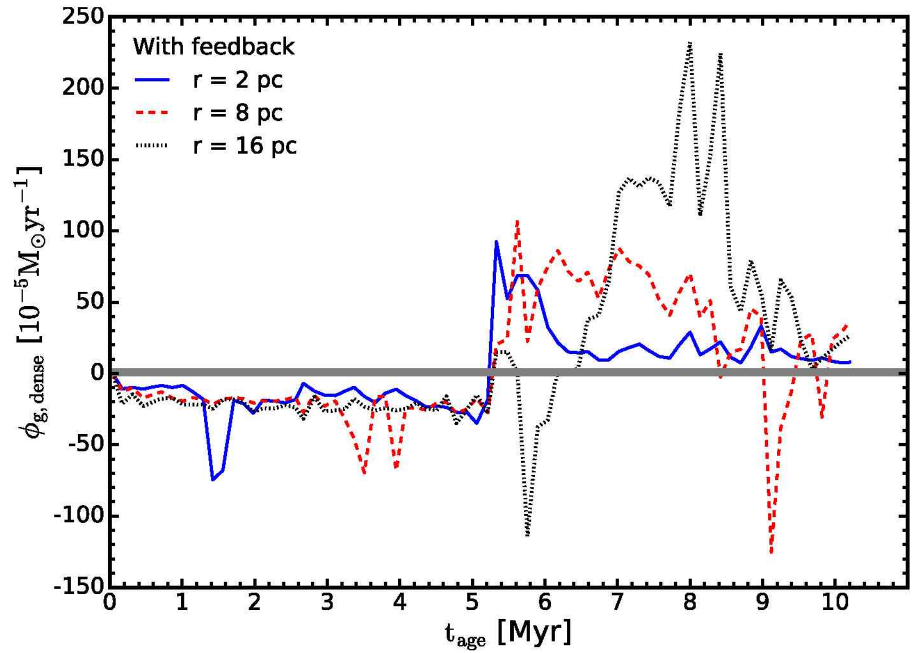
- Clouds effectively (semi-locally) destroyed.
- Qualitatively consistent with observations of gas dispersal around clusters.

Feedback vs not feedback

Dense gas dispersed

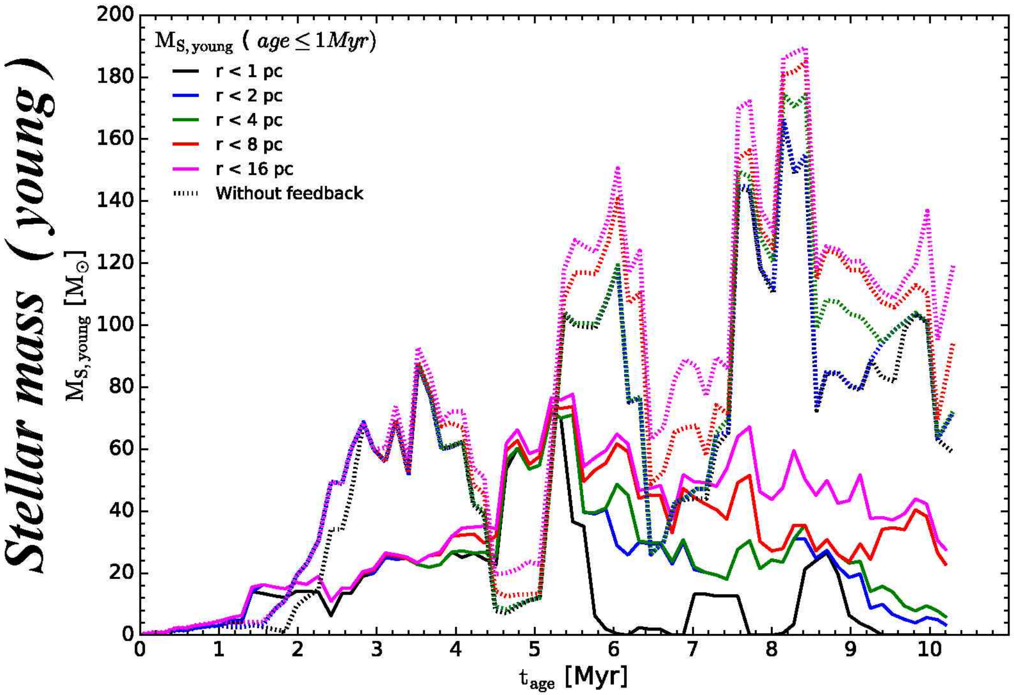


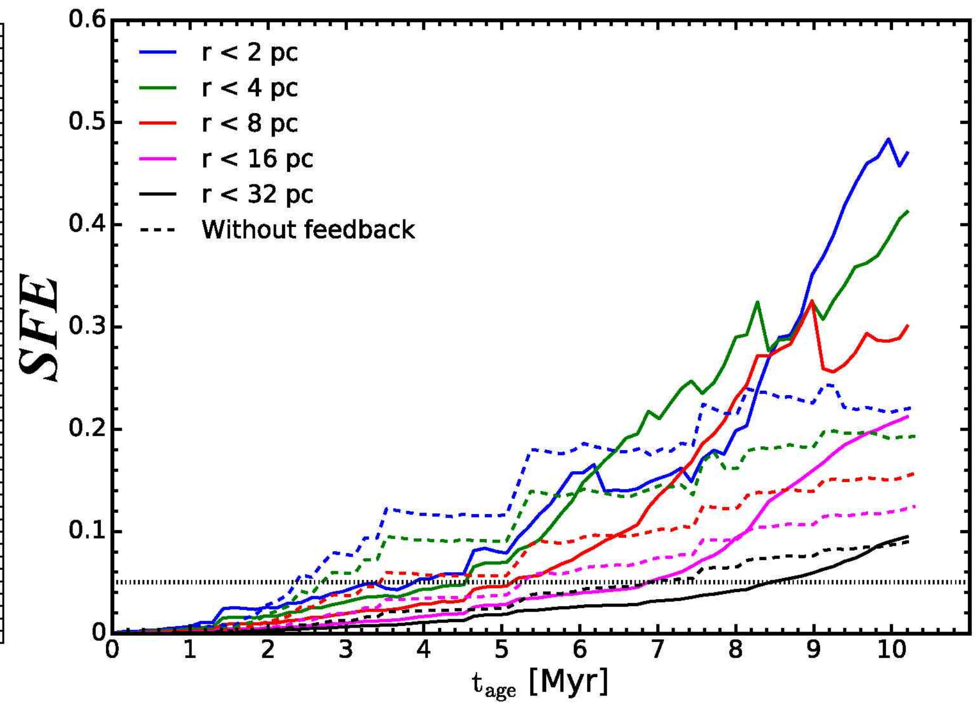
Net flux of dense gas reversed



- ***Stellar mass assembly***

$$\mathrm{SFE} = \frac{M_*}{M_* + M_{gas}}$$





Feedback regulating SFR and SFE;

It destroys MCs when only ~10% has been used in forming stars.

Conclusions:

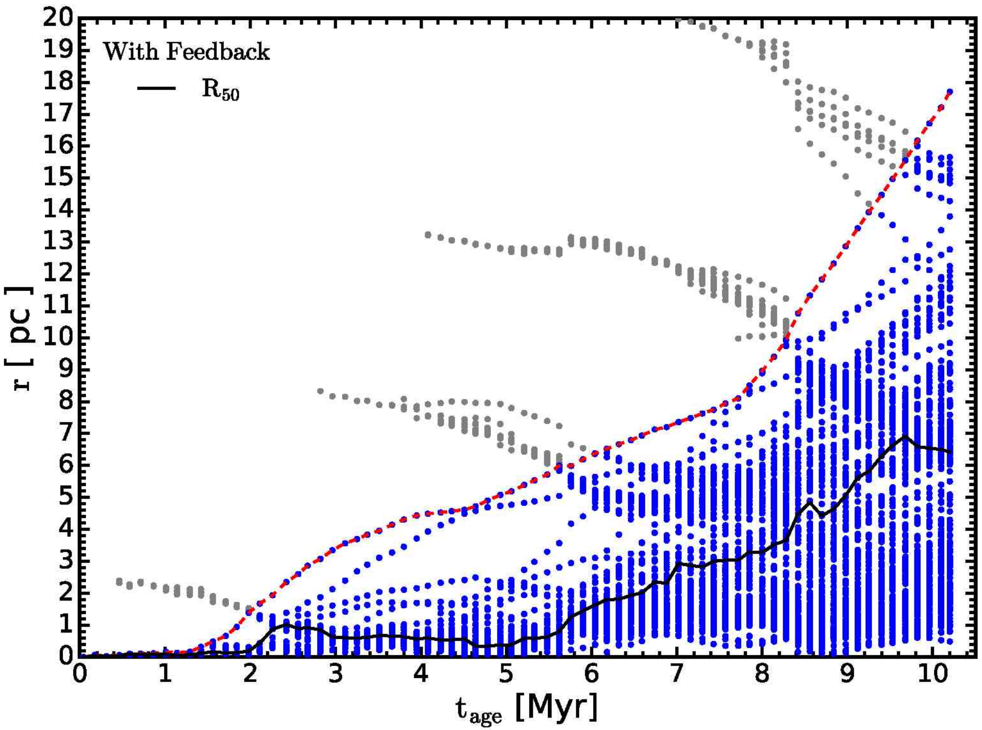
We presented numerical simulations of Stellar Clusters formed within collapsing MCs. (GHC). We showed that under this scenario:

- *The collapse is hierarchical* because it consist of small-scale collapses within larger scale ones.
- The small-scale collapses consist of clumps that are embedded in the filaments and falling on to the large scale centres.
- This process leads to a structure, in which each unit is formed of smaller-scales subunits that approach each other and may merge.
- Massive stars only form once the local SFR is large enough to sample the IMF up to high masses: *massive stars tend to appear late in the evolution of the MC* and only in the central massive clump.
- Imprint of cloud structure creates radial mass and age gradients, and characteristic age-mass 2D distribution (similar to that of Orion D).
- *Feedback from ionizing stars* destroys (at least locally) the MCs: qualitatively consistent with observations of gas dispersal around clusters (*Leisawitz+1989; Mayya+2012*)
- *Stellar feedback regulates SFR* by dispersing dense gas and cutting filamentary supply when only ~10% has been used in forming stars.

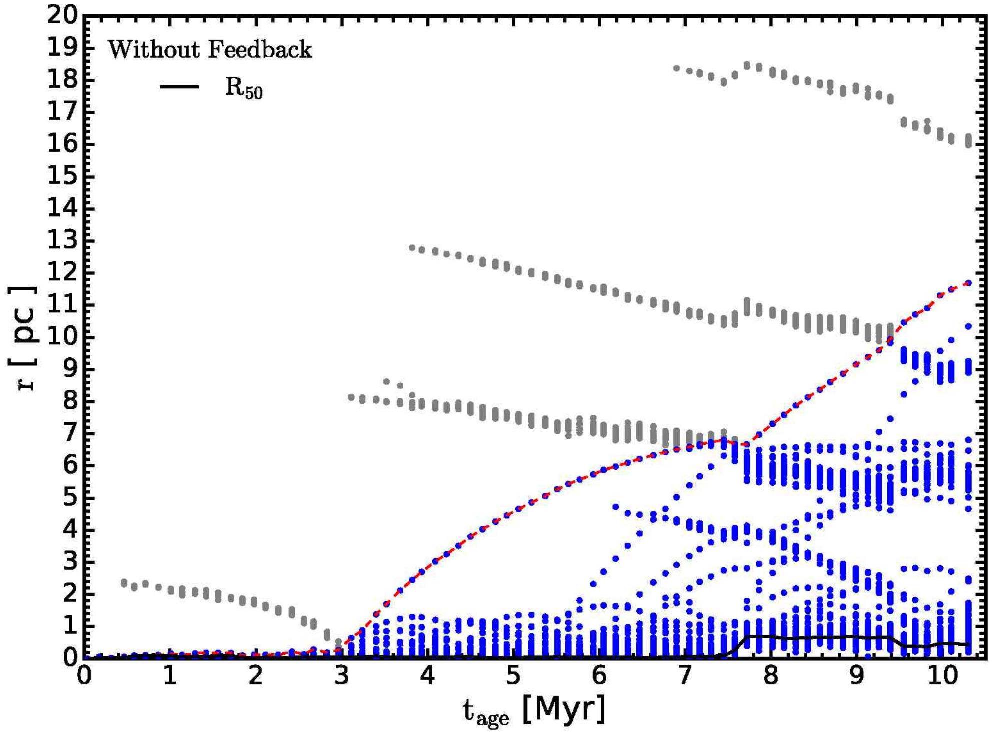
Thanks!

Results: González-Samaniego+2019 (to be submitted)

- *With Stellar feedback*



- *Without Stellar feedback*



Stellar feedback affects stellar distribution in clusters!

Results: hierarchical star cluster assembly

Hierarchical collapse of cloud implies several properties of cluster:

Hierarchical-collapse structure of cloud imprinted on cluster structure.

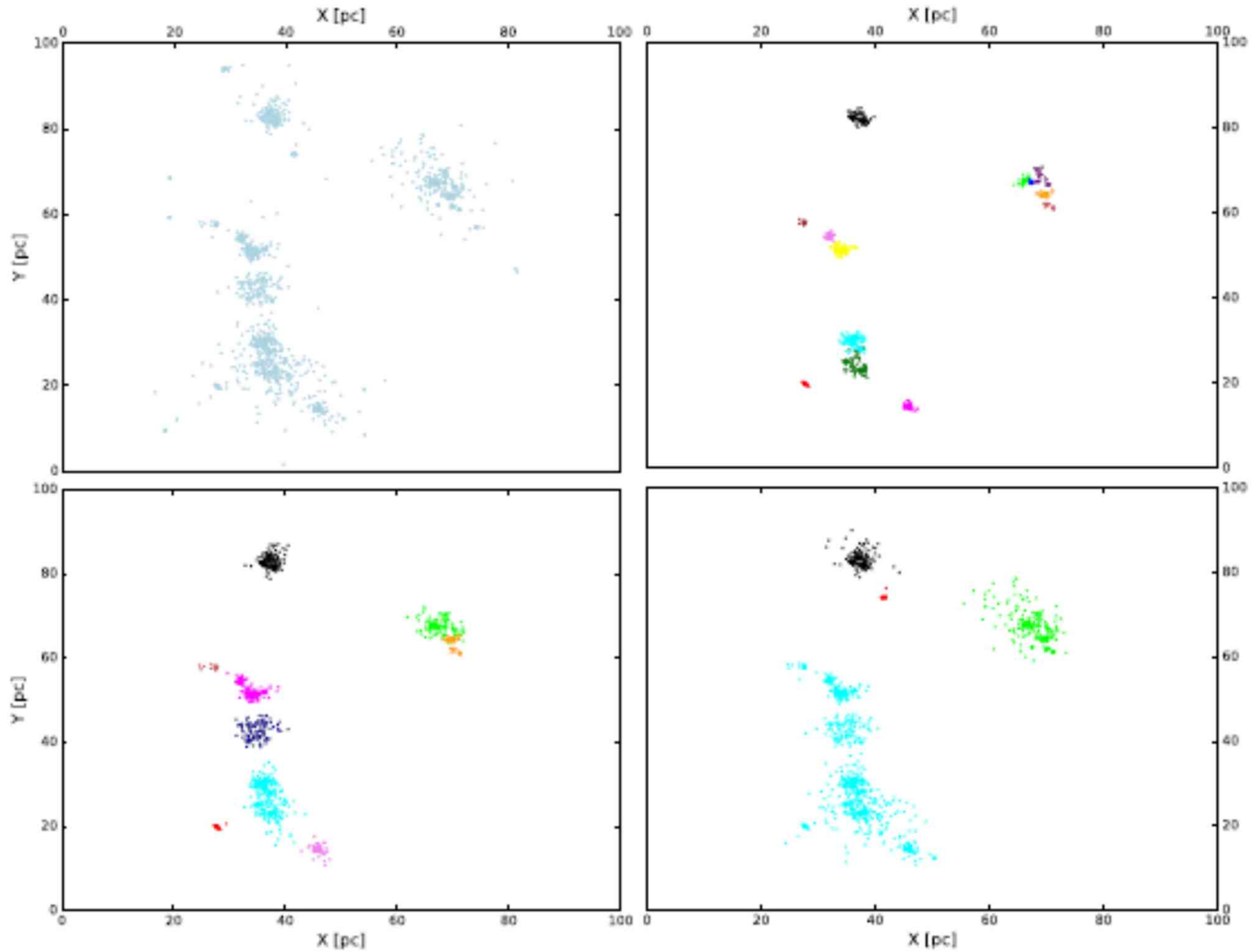
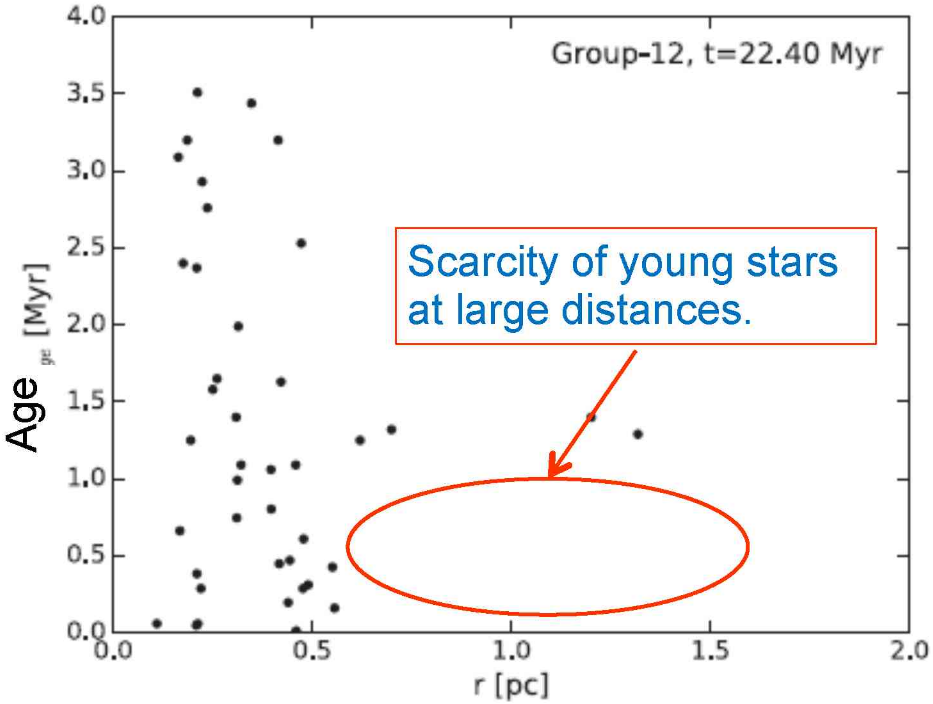


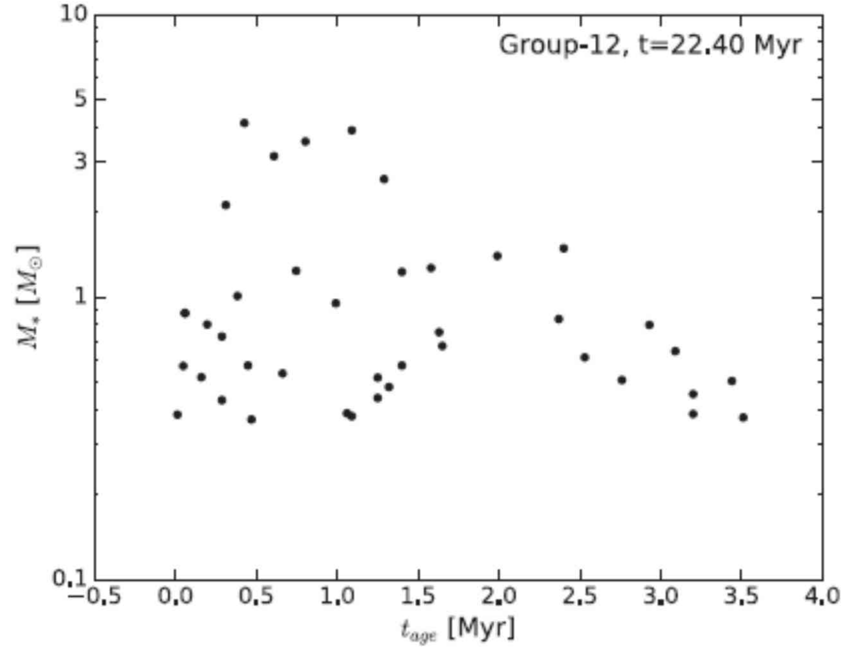
Figure 12. Groups identified by the FOF algorithm in Cluster 2 at time $t = 29.96$ Myr varying the 'linking parameter' ℓ of the algorithm, which determines the distance out to which neighbours are searched. Top left: all stars in the cluster. Top right: $\ell = 0.5$. Bottom left: $\ell = 1$. Bottom right: $\ell = 2$.

Vazquez-Semadeni, E., González-Samaniego, A. Colín, P. (MNRAS, 2017)

Results: *hierarchical star cluster assembly*



Mass-age relation



The Astrophysical Journal, 787:109 (11pp), 2014 June 1 doi:10.1088/0004-637X/

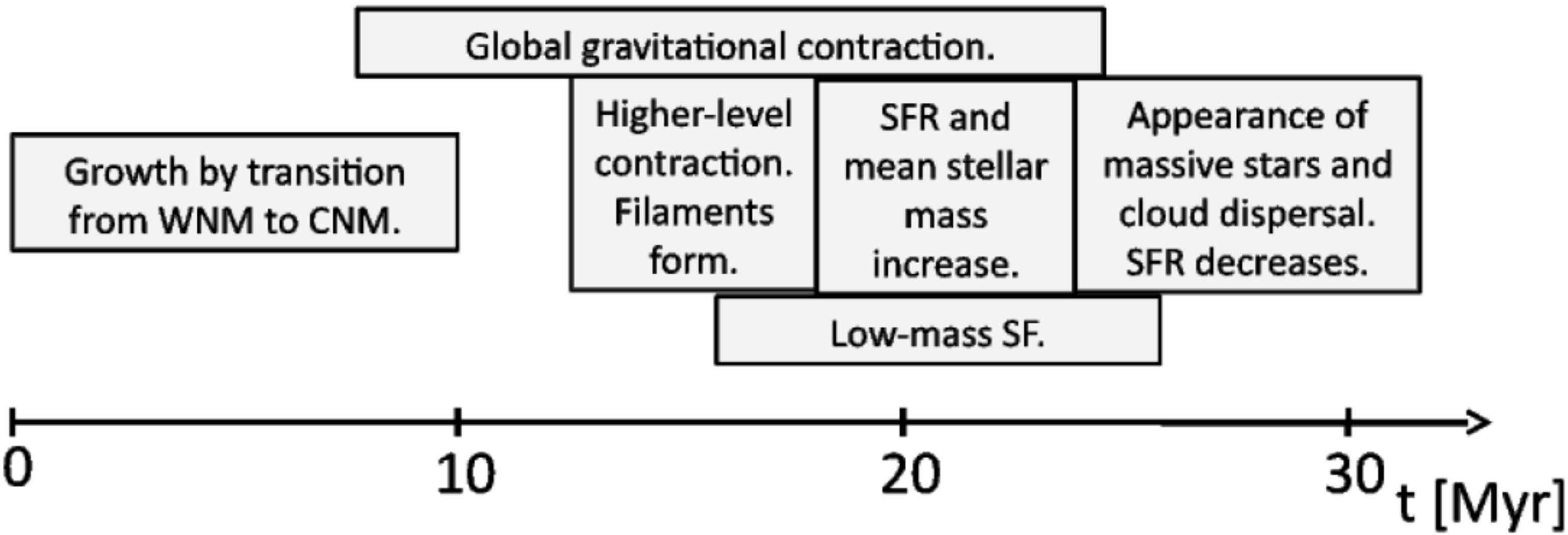
CORE–HALO AGE GRADIENTS AND STAR FORMATION IN THE ORION NEBULA AND NGC 2024 YOUNG STELLAR CLUSTERS

Konstantin V. Getman, Eric D. Feigelson, and Michael A. Kuhn
Department of Astronomy and Astrophysics, 525 Davey Laboratory, Pennsylvania State University, University Park, PA 16802, USA
Received 2013 November 19; accepted 2014 March 11; published 2014 May 9

We find core–halo age gradients in both the NGC 2024 cluster and ONC: PMS stars in cluster cores appear younger and thus were formed later than PMS stars in cluster peripheries. These findings are further supported by the spatial

Vazquez-Semadeni, E., González-Samaniego, A. Colín, P. (MNRAS, 2017)

The Scenario: Global Hierarchical Collapse (GHC), Vazquez-Semadeni+09



Vazquez-Semadeni et al. (2019)