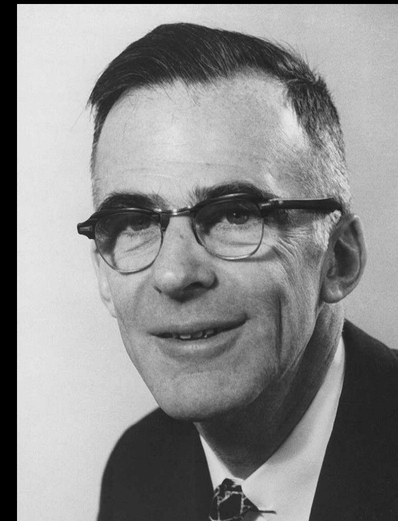
Michela Mapelli

Few good reasons to get bored of star clusters

Bologna, May 4 2017

A glorious past:

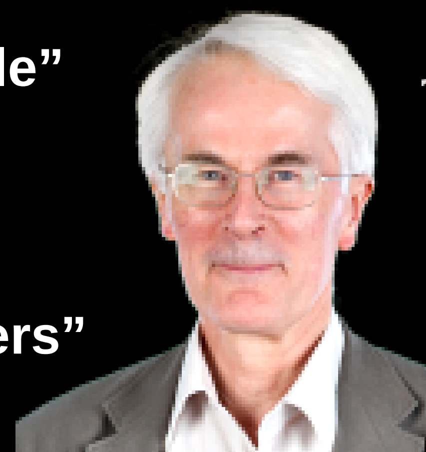


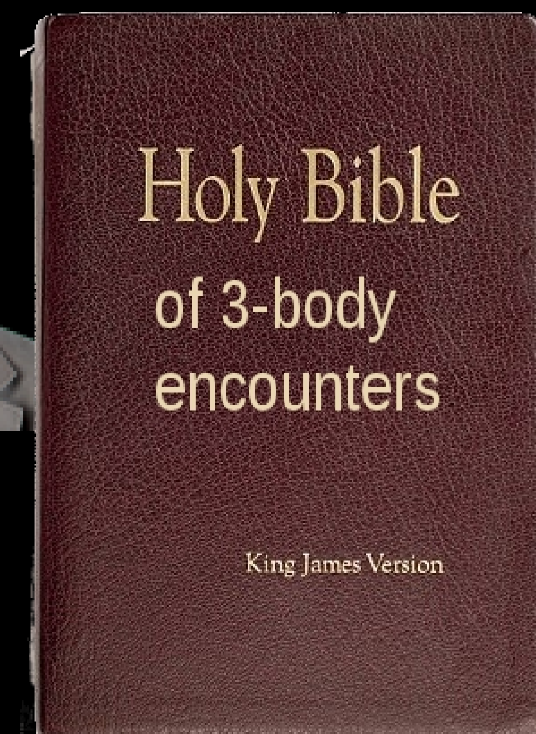
1969: Lyman Spitzer publishes his study on equipartition and instabilities

1971: Michel Hénon publishes his algorithm for simulating star clusters with Monte Carlo method (still used today).

Tons of Monte Carlo simulations since then....

1975: Douglas Heggie publishes the "Bible" of binary evolution in star clusters.





1988: Lyman Spitzer publishes "Dynamical Evolution of Globular Clusters"

Everything clear since then?????

TALK IS OVER...

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Bologna, May 4 2017

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MERAC

OSSERVATORIO ASTRONOMICO DI PADOVA
INAF ISTITUTO NAZIONALE DI ASTROFISICA

NOT
Few good reasons to get bored of star clusters

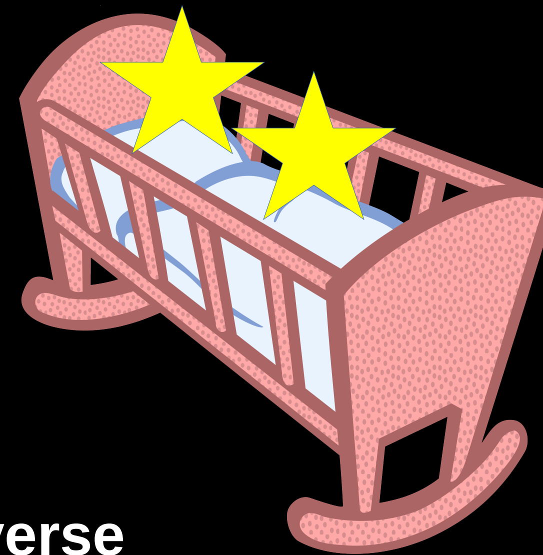
COLLABORATORS: Mario Spera, Nicola Giacobbo, Ugo N. Di Carlo, Alessandro A. Trani, Elisa Bortolas, Alessandro Ballone, Sandro Bressan, Giacomo Beccari, Germano Sacco, Rob Jeffries

Bologna, May 4 2017

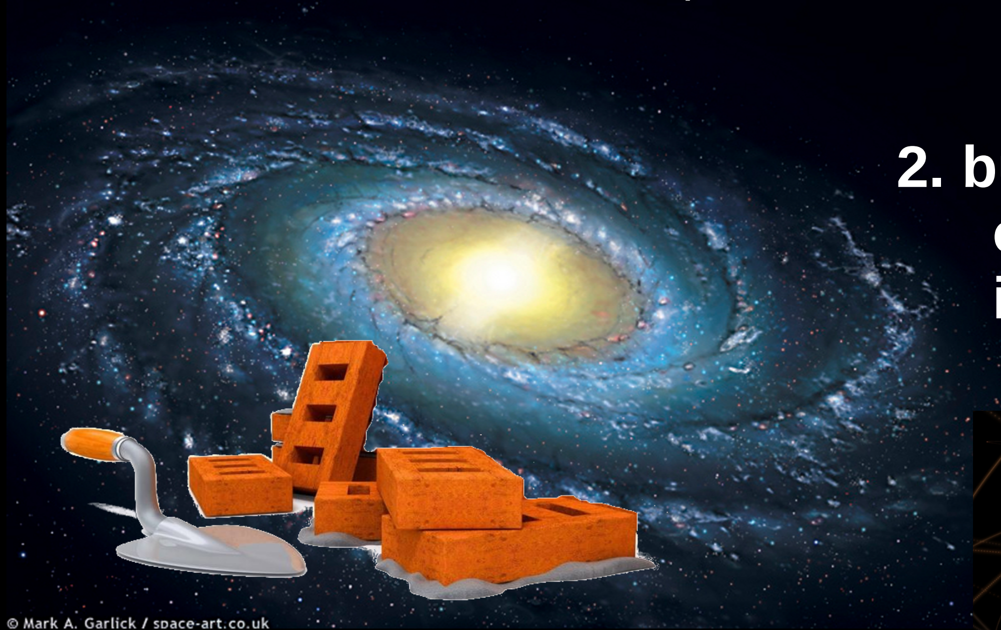
OUTLINE

1. Star clusters as collisional systems
2. State-of-the art simulations
3. Runaway collisions
4. Spitzer's instability
5. The key role of GAS
6. Conclusions

Three good reasons to study star clusters:

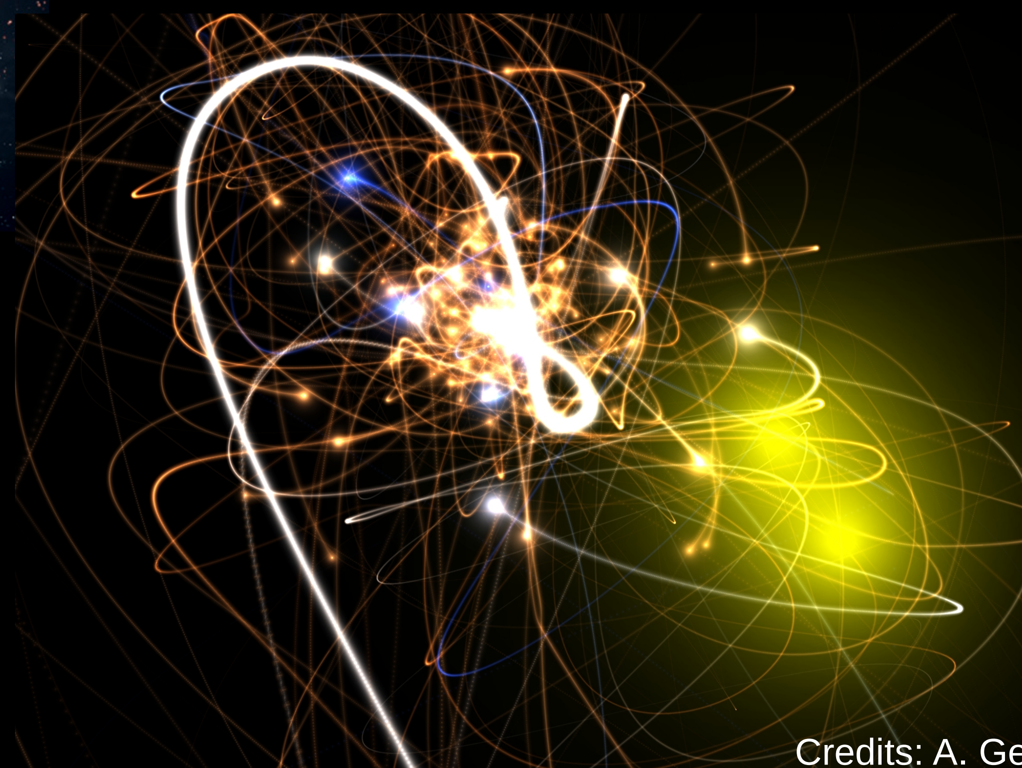


1. cradle of stars (especially massive stars)
   Lada & Lada 2003; Weidner & Kroupa 2006



2. building blocks
   of galaxies
   in the local Universe

3. unique place for dynamics:
   only place where
   stellar collisions are likely



Credits: A. Geller

1. Star clusters as collisional systems

Two-body relaxation timescale:

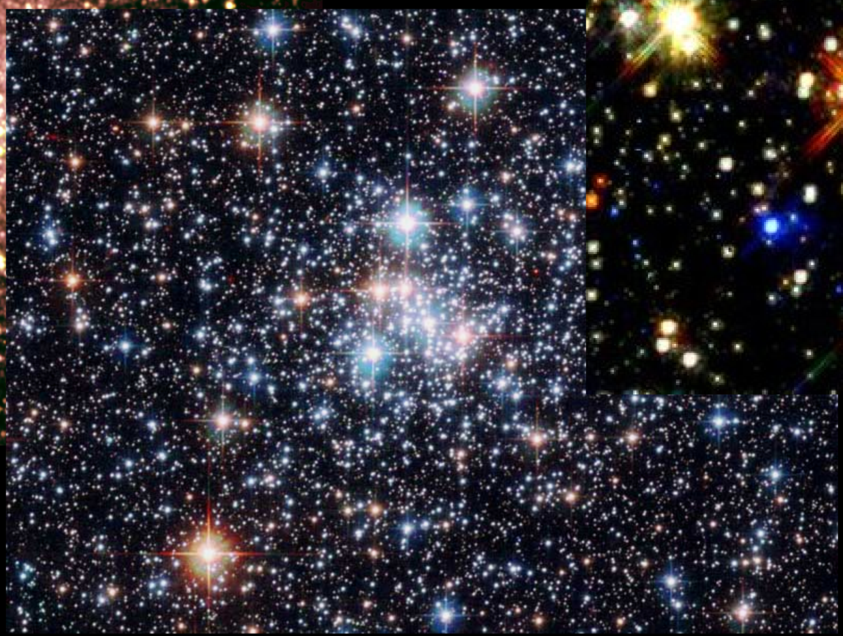
$$t_{\rm rlx} \sim 20\,{\rm Myr}\left(\frac{\sigma}{10\,{\rm km\,s^{-1}}}\right)^3\left(\frac{1\,{\rm M_\odot}}{m}\right)\left(\frac{10^5\,{\rm M_\odot\,pc^{-3}}}{\rho}\right)$$

Spitzer & Hart 1971

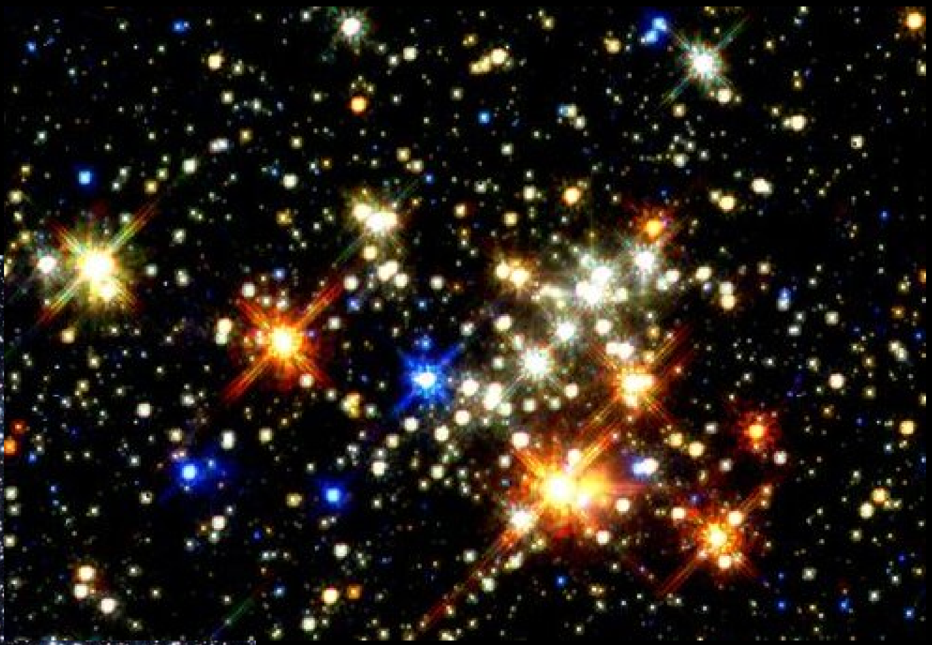
A system is collisional if $t_{\rm rlx}$ < lifetime

Evolution of collisional systems DRIVEN by two-body encounters

47Tuc by SALT



NGC290 by HST



Quintuplet by HST

1. Star clusters as collisional systems

PROCESSES IN COLLISIONAL SYSTEMS:

- MASS SEGREGATION

- RUNAWAY COLLISIONS

- EQUIPARTITION – SPITZER'S INSTABILITY

- CLOSE ENCOUNTERS BETWEEN SINGLE STARS AND BINARIES

- CORE COLLAPSE

2. Techniques to simulate star clusters

DIRECT-SUMMATION N-BODY SIMULATIONS
(resolve star-star interactions)

→ solve Newton's equation directly

$$\ddot{\vec{r}}_i = -G \sum_{j\neq i} m_j \frac{\vec{r}_i - \vec{r}_j}{\left|\vec{r}_i - \vec{r}_j\right|^3}$$

computationally expensive
(scale with N^2)

GPUs saved us (since ~2007)

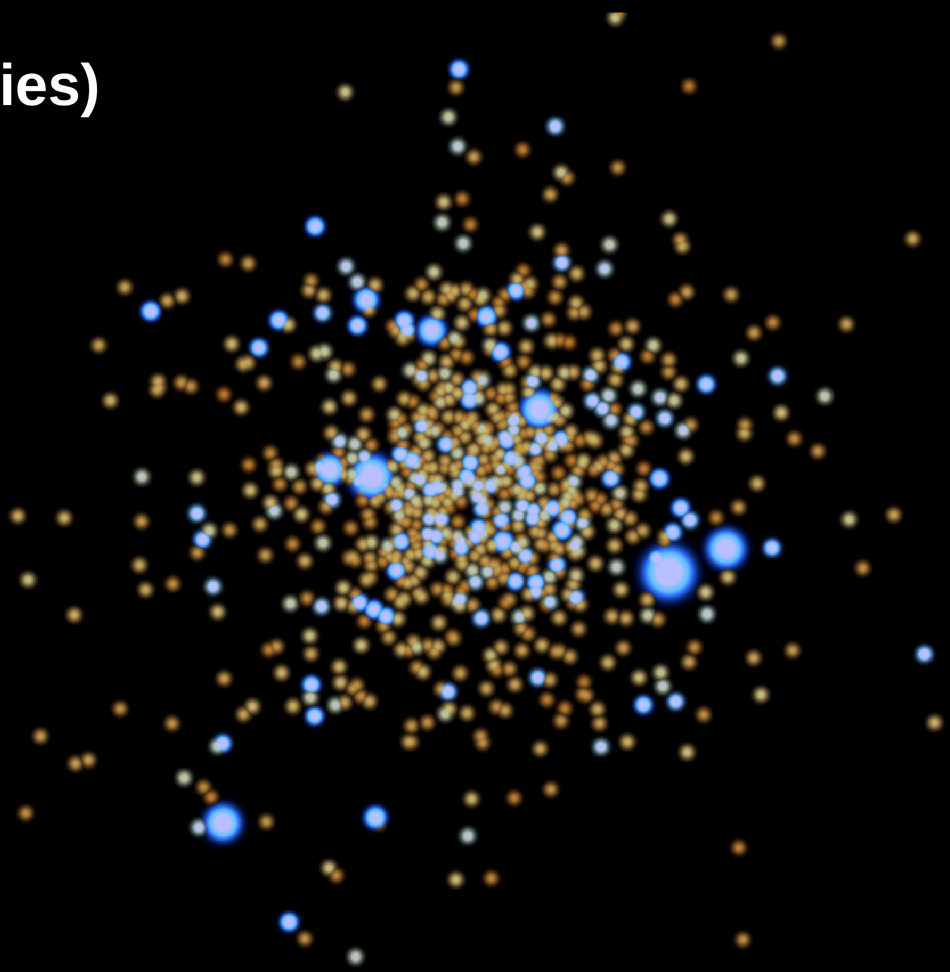
2. Techniques to simulate star clusters

DIRECT-SUMMATION N-BODY SIMULATIONS
(resolve star-star interactions)

+

POPULATION SYNTHESIS RECIPES
(evolve single stars and binaries)

- single stellar evolution
- wind mass transfer
- Roche lobe mass transfer
- common envelope
- tidal evolution
- magnetic braking
- orbital evolution
- recipes for supernova explosion
- recipes for remnant formation



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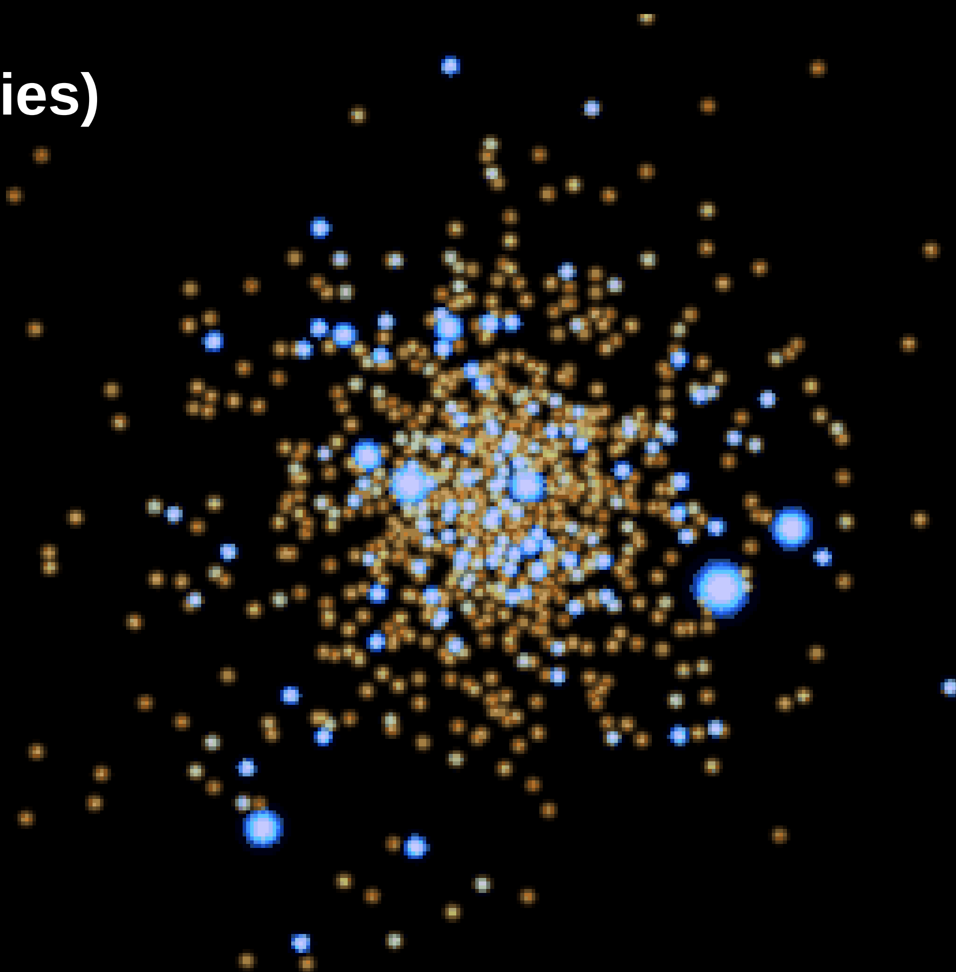
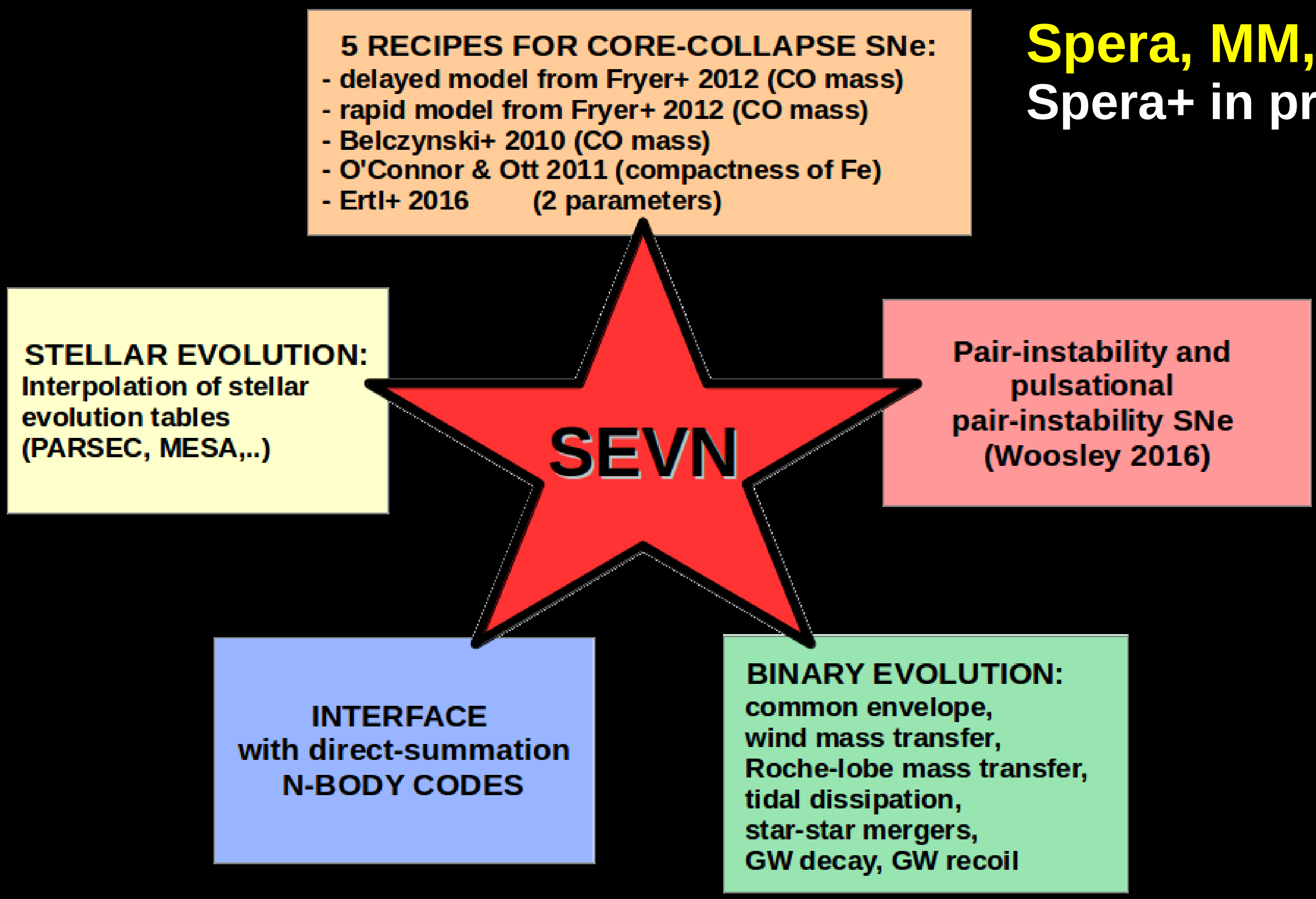


2. Techniques to simulate star clusters

SEVN (Stellar Evolution for N-body codes)

- metallicity-dependent stellar evolution (Bressan+ 2012)
- stellar remnant formation (Fryer+ 2012,Ertl+ 2016)
- open source: http://web.pd.astro.it/mapelli/group.html

Spera, MM, Bressan 2015
Spera+ in prep.

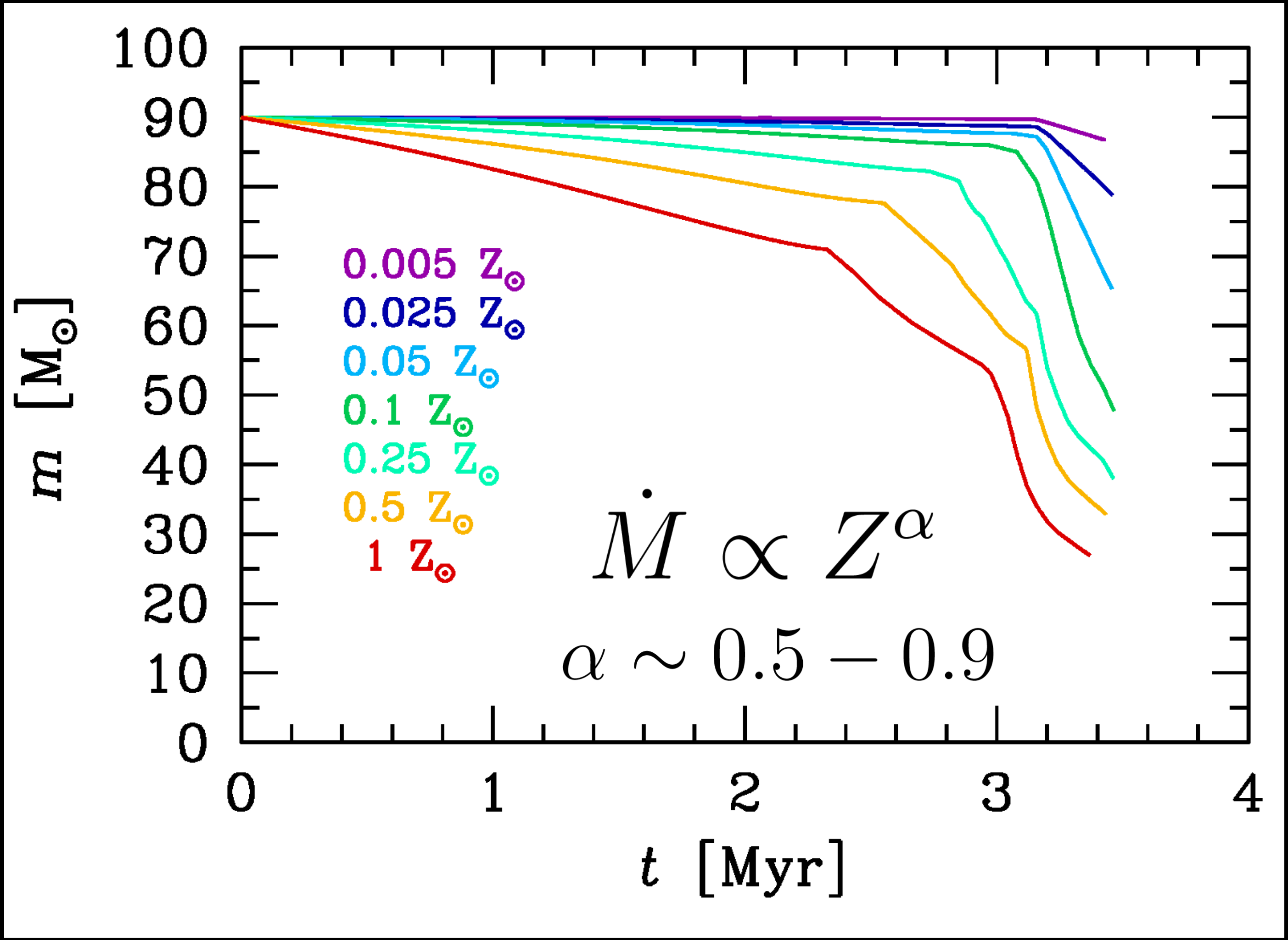


2. Techniques to simulate star clusters

SEVN (Stellar Evolution for N-body codes)

Massive stars (>30 Msun) might lose >50% mass by winds

(Vink+ 2001, 2005, 2016; Bressan+ 2012; Tang, Bressan+ 2014; Chen, Bressan+ 2015)

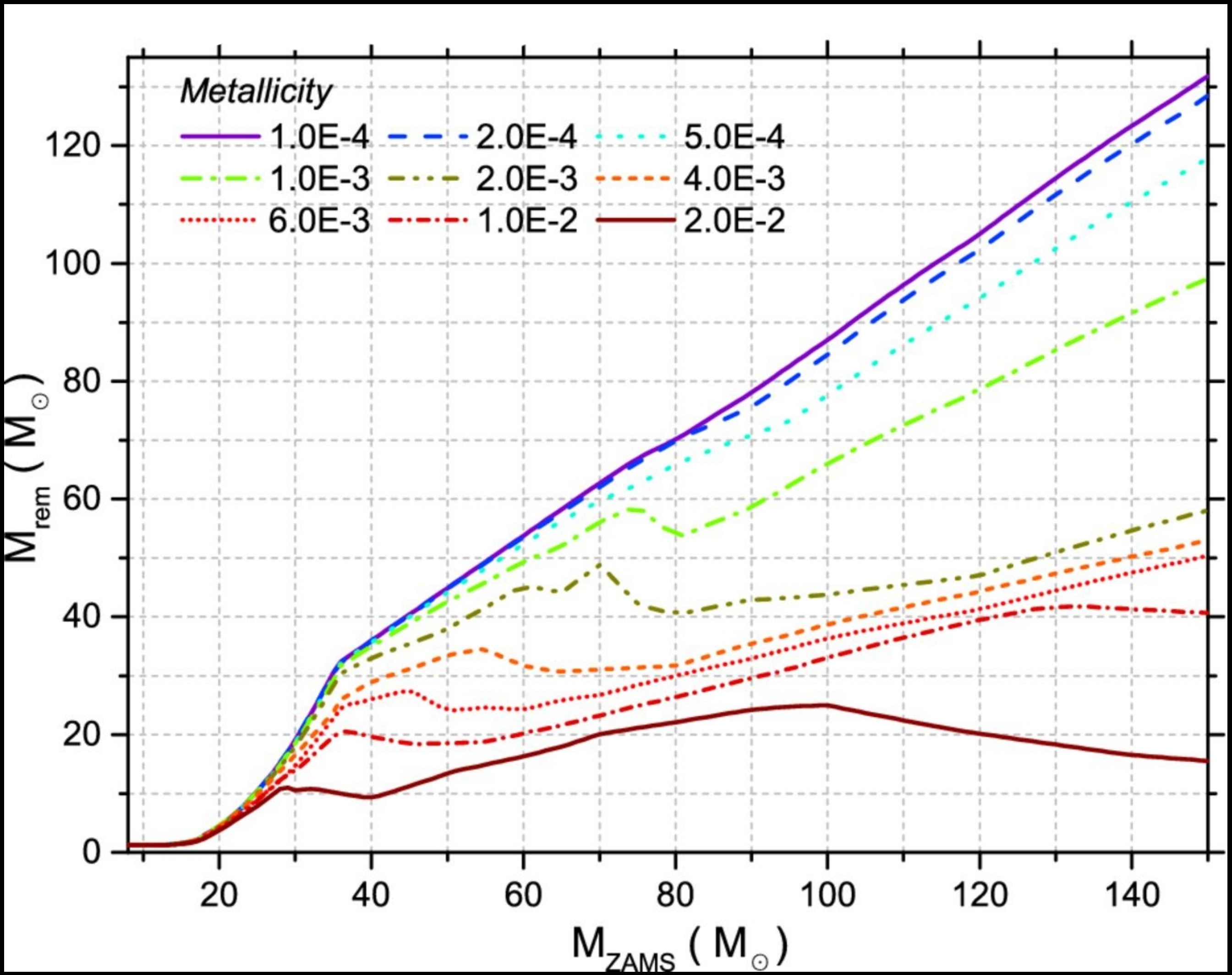


METAL-POOR STARS LOSE LESS MASS THAN METAL-RICH STARS

THIS AFFECTS MASS OF THE REMNANT (regardless of the SN model)

SEVN (Stellar Evolution for N-body codes)

Mass of remnant as a function of ZAMS mass and metallicity



Remnant mass in SEVN code

MM+ 2009, 2010, 2013
Spera, MM & Bressan 2015

Spera, Giacobbo & MM 2016

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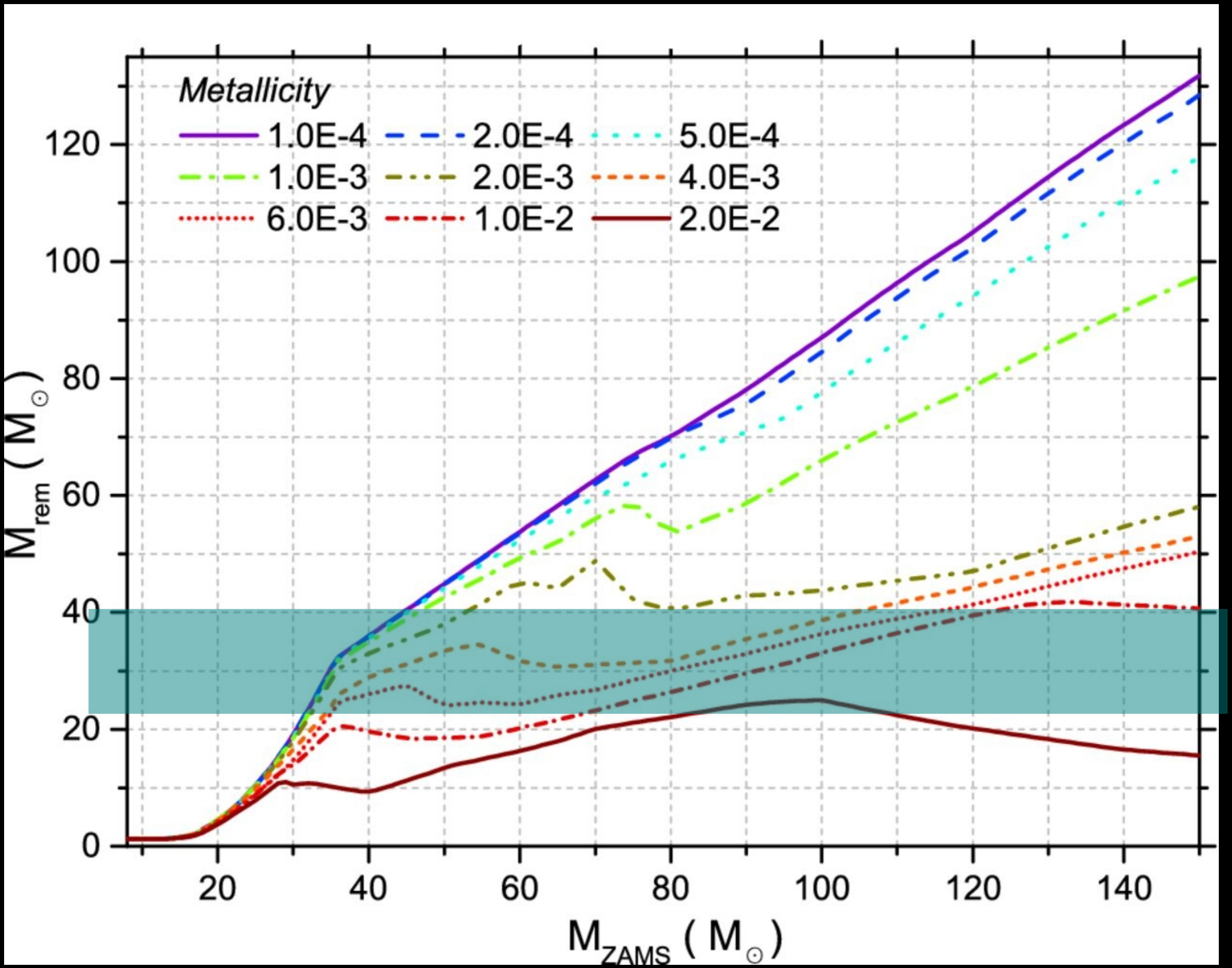

Remnant mass in SEVN code

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Spera, MM & Bressan 2015

Spera, Giacobbo & MM 2016

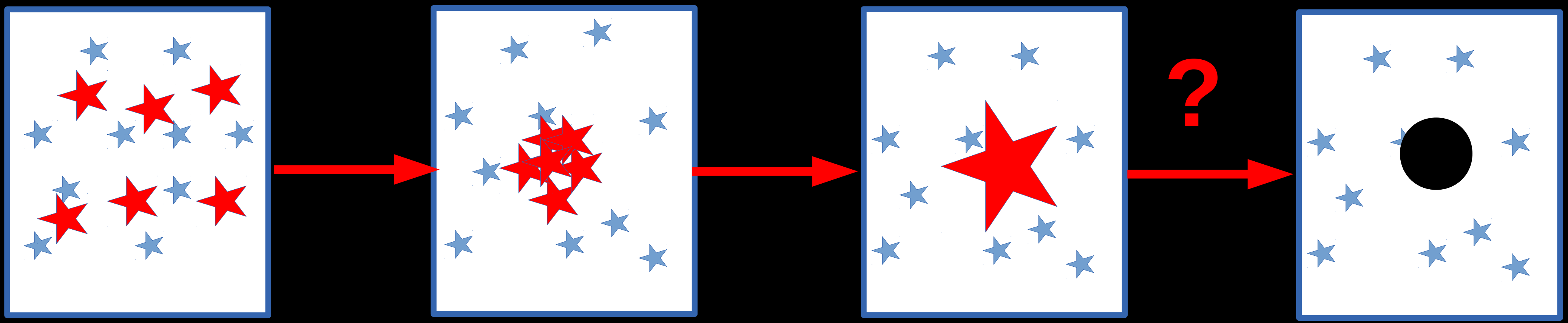
3. Runaway collisions

Most popular dynamical scenario to form intermediate-mass black holes (IMBHs, 100 – 10'000 Msun)

Mass segregation fast in young star clusters:

$$t_{\rm DF}(25M_\odot) \sim 2{\rm Myr}\left(\frac{t_{\rm rlx}}{50{\rm Myr}}\right) < t_{\rm SN}$$

Massive stars segregate to the centre where collide with each other



Massive super-star forms and possibly collapses to IMBH

What is the final mass of the collision product?

Colgate 1967; Sanders 1970; Portegies Zwart+ 1999, 2002, 2004; Gurkan+ 2004; Freitag+ 2006; Giersz+ 2015, and many many others

3. Runaway collisions

Massive stars (>30 Msun) might lose >50% mass by winds

(Vink+ 2001, 2005, 2016; Bressan+ 2012; Tang, Bressan+ 2014; Chen, Bressan+ 2015)

Mass loss affects:

1 - the probability that the merger product undergoes more collisions and grows in mass

→ **less collisions if the merger product loses mass: important to include winds in the N-body simulation**

2 - the possibility that the remnant is massive

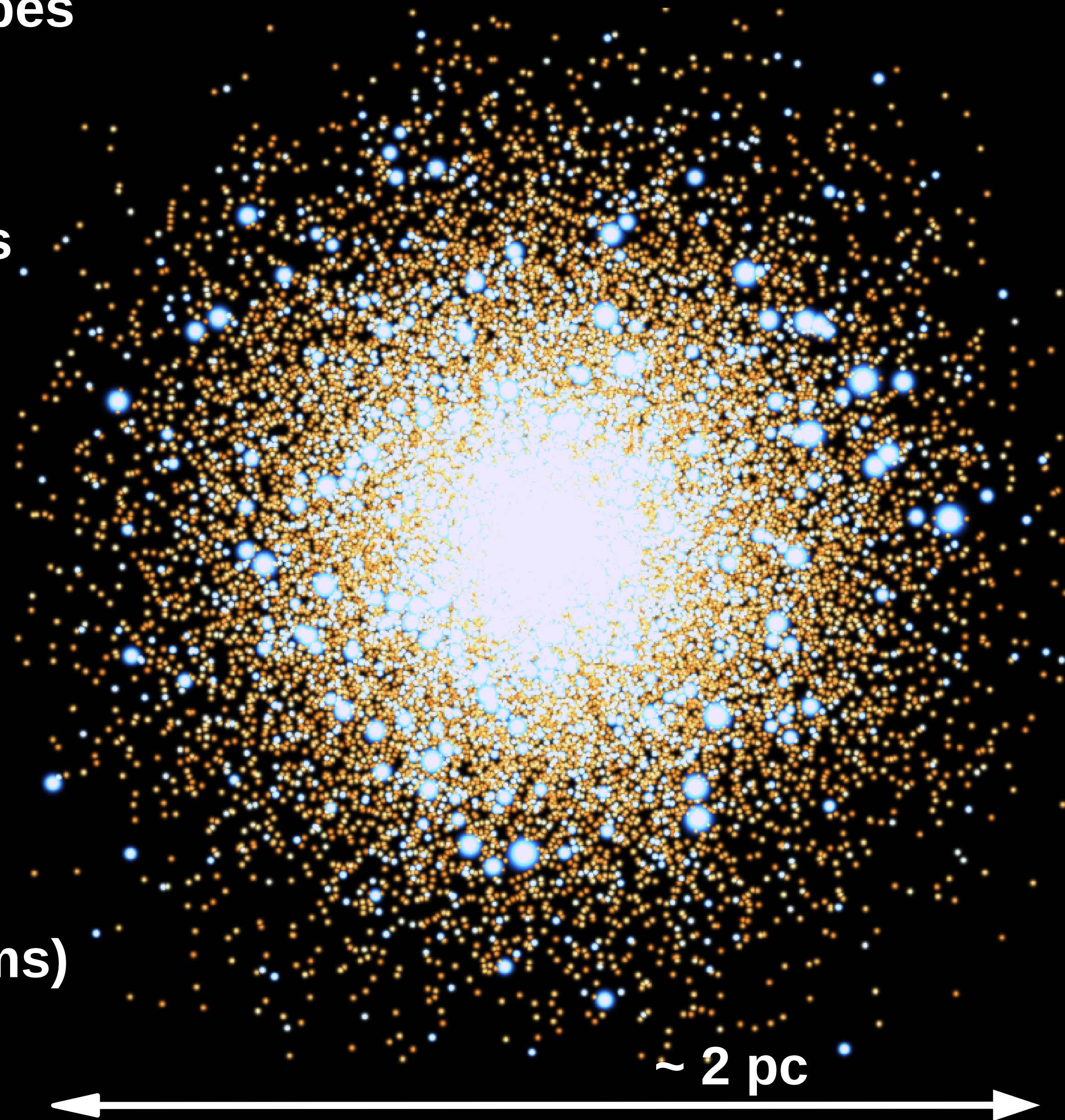
→ **BH mass depends on the pre-supernova (SN) mass**

3. Runaway collisions

AIM:
Simulate the runaway collision with stellar winds and SN recipes

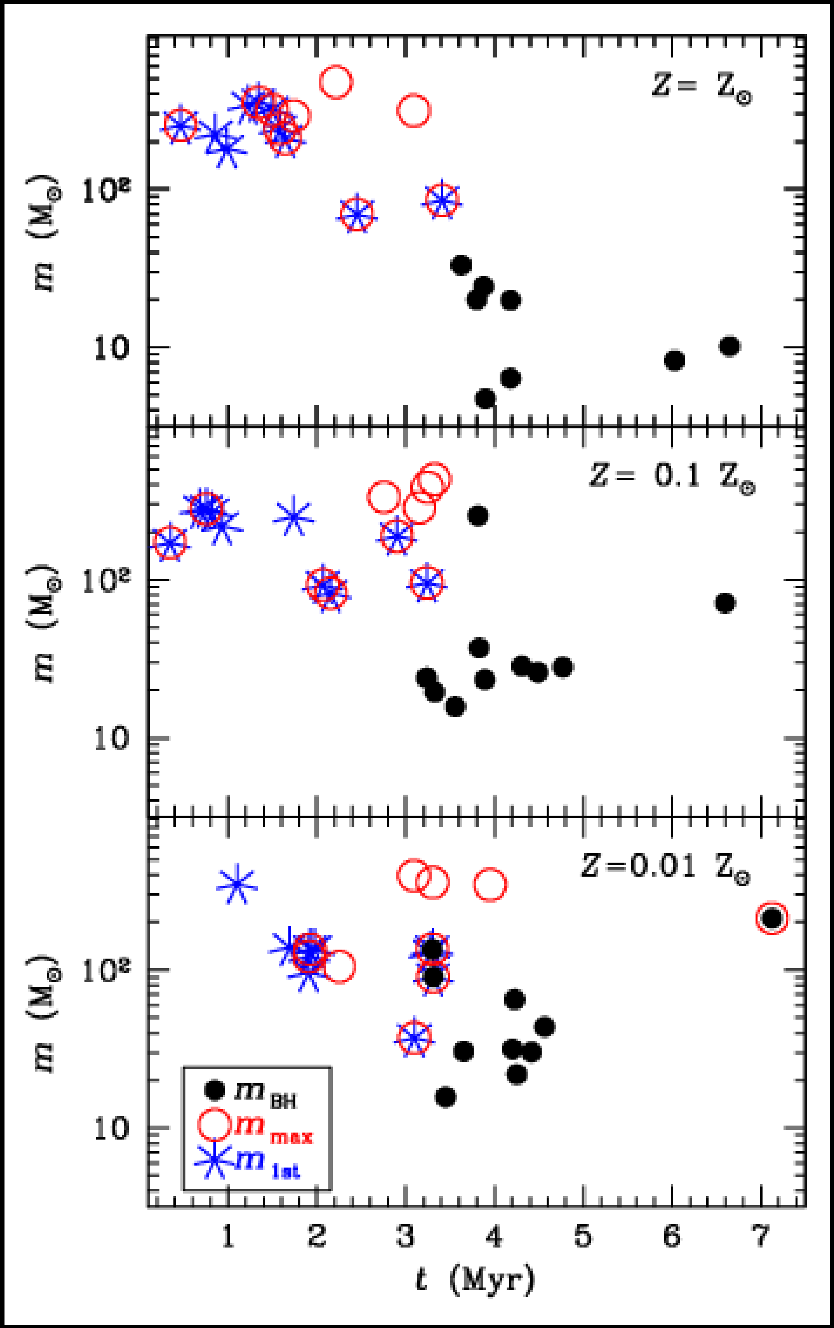
SIMULATION GRID:

- 30 star clusters with 10^5 stars
  - 10 at Z = 0.01 Zsun,
  - 10 at Z = 0.1 Zsun,
  - 10 at Z = Zsun
- King (1966), $W_0 = 9$,
  $r_c = 0.05$ pc,
  $r_h \sim r_{vir} \sim 1$ pc
- Kroupa IMF
(total mass : 6.5×10^4 Msun)
- no primordial binaries
(lower limit for merging systems)



MM 2016

3. Runaway collisions



MM 2016

Mass of runaway collision product accounting for metallicity:

*** maximum mass up to 500 Msun**

*** 1/10 BH in the IMBH regime (>100 Msun) at Z = 0.01 – 0.1 Zsun**

NO IMBHs from runaway collisions at SOLAR METALLICITY!

*** CAVEAT 1: uncertainties in the evolution of very massive stars**

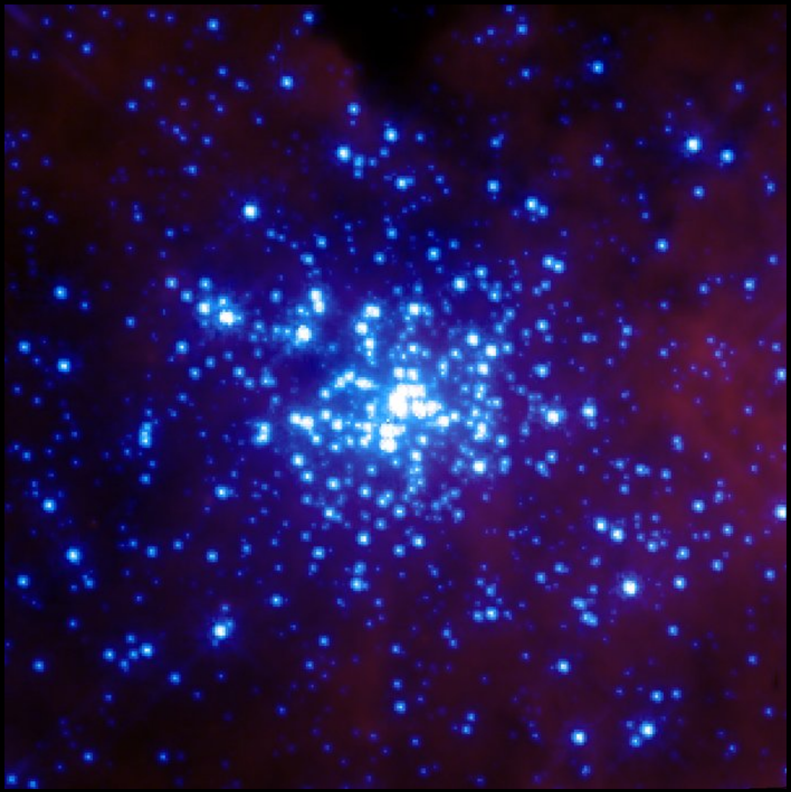
*** CAVEAT 2: uncertainties in mass-loss during/after collisions**

3. Runaway collisions

RUNAWAY COLLISION SCENARIO VS OBSERVATIONS:

1. VERY MASSIVE STARS (>100 Msun) ONLY IN DENSE STAR CLUSTER even at solar metallicity

Crowther+ 2010, 2016; Vink+ 2015



2. IMBHs AT LOW METALLICITY

?????

PREDICTION TO BE CHECKED WITH LIGO – VIRGO AND LISA

4. Equipartition and Spitzer's Instability

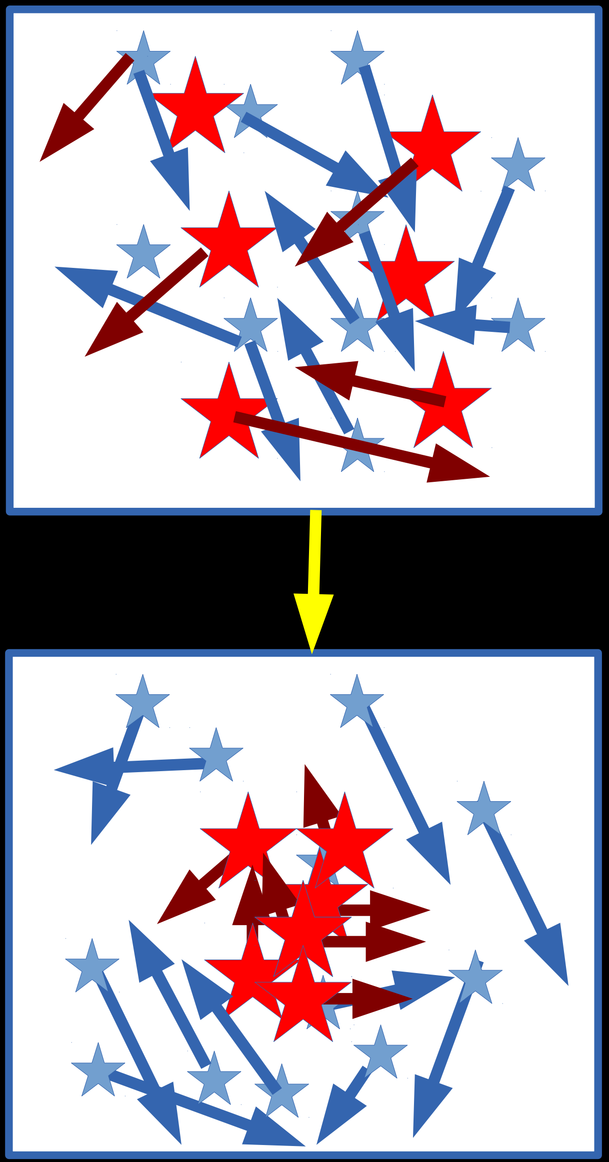
In GAS systems at thermal equilibrium, energy is shared EQUALLY by all particles (Boltzmann 1876)

**→ for analogy with gas,
in a two-body relaxed star system**

$$m_i v_i^2 \sim m_j v_j^2$$

$$\rightarrow v(m)\ \mu\ m^{-0.5}$$

More massive stars transfer kinetic energy to light stars and slow down



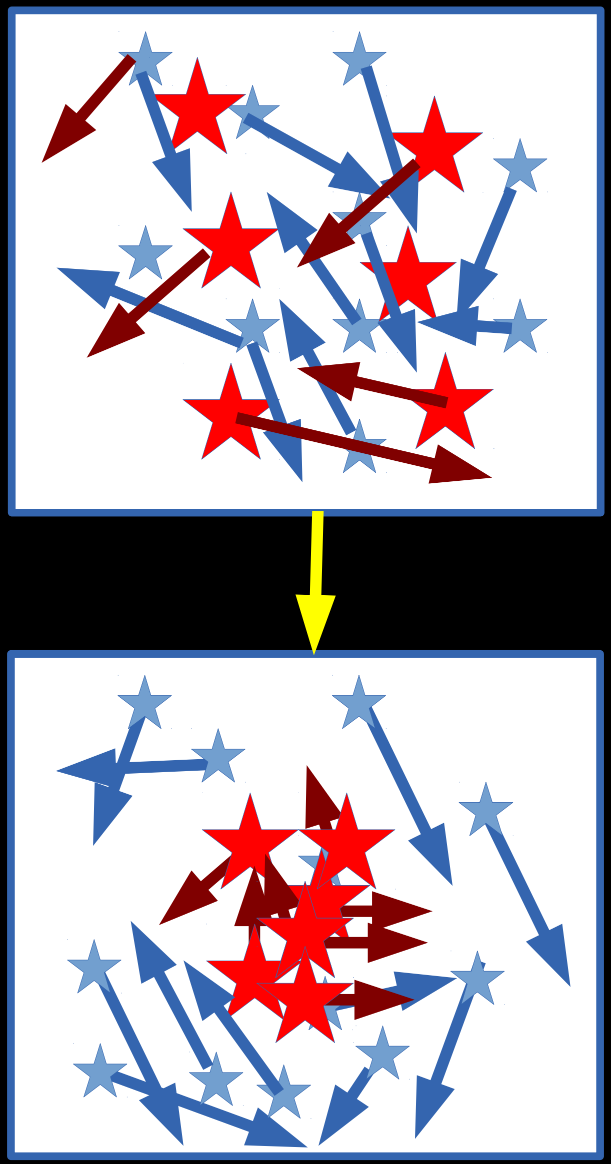
4. Equipartition and Spitzer's Instability

But theorists predict cases when equipartition CANNOT be reached

Spitzer (1969): In an idealized system of 2 masses m_1 and m_2 ($m_2 >> m_1$, $M_i = \Sigma\, m_i$), equipartition cannot be reached if

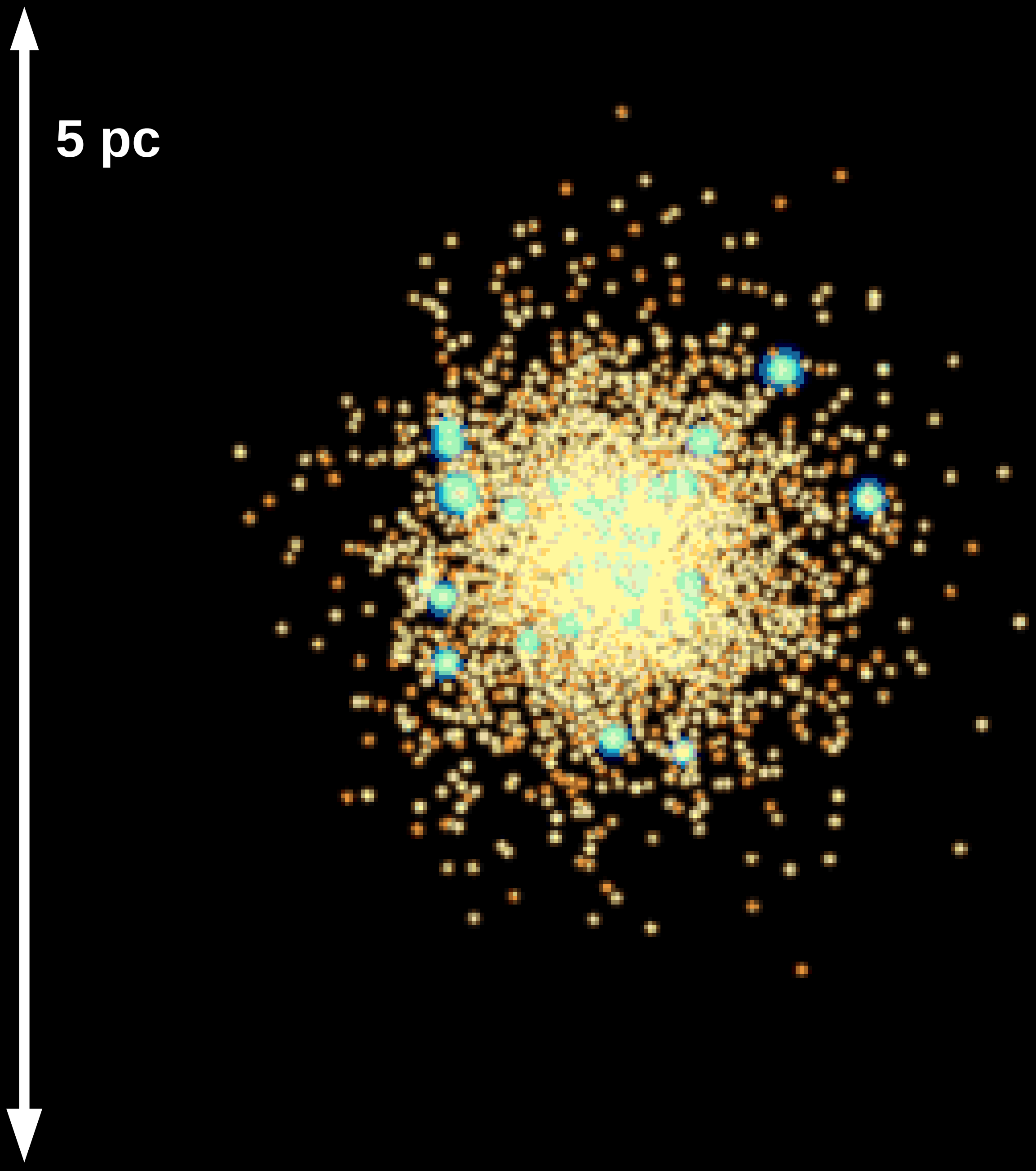
$$M_2 > 0.16\, M_1\, (m_2/m_1)^{3/2}$$

MASSIVE STARS DYNAMICALLY DECOUPLE FROM LIGHT STARS: the velocity dispersion of massive stars grows (Spitzer's instability)



(Bonnell & Davies 1998; Allison+ 2009; Portegies Zwart+ 2010)

How common is Spitzer's instability?



- 400 N-body simulations of open clusters
N ~ 6000
M ~ 3900 $M_\odot$
R_{vir} ~ 1 pc

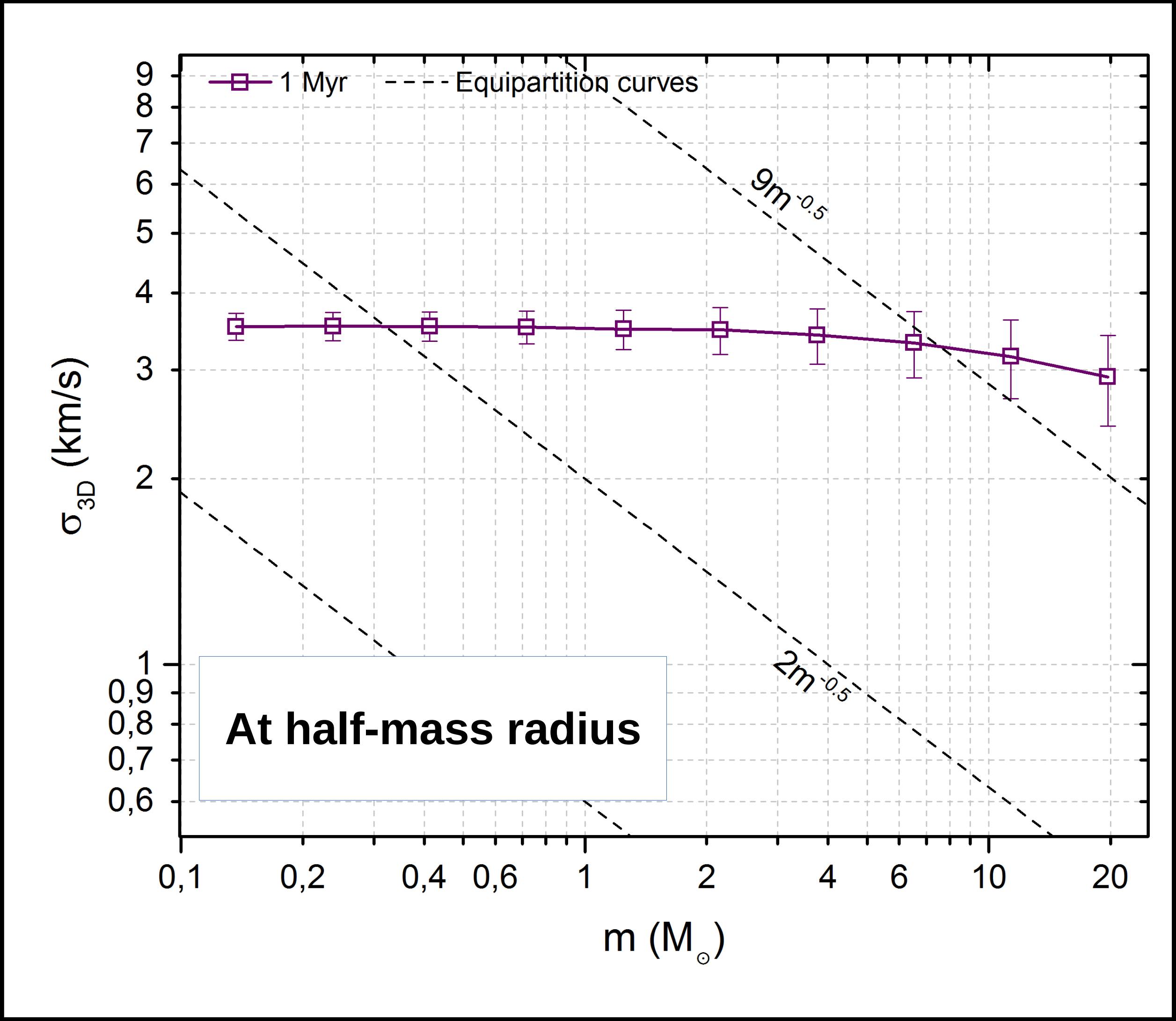
- Realistic IMF (Kroupa 2001)

- stellar evolution
- Milky Way tidal field
- King model or 'clumpy' model

Spera, MM & Jeffries 2016

4. Equipartition and Spitzer's instability

How common is Spitzer's instability?



Star clusters try to reach equipartition but never attain it in steady state:

- initially flat sigma profile

Spera, MM & Jeffries 2016

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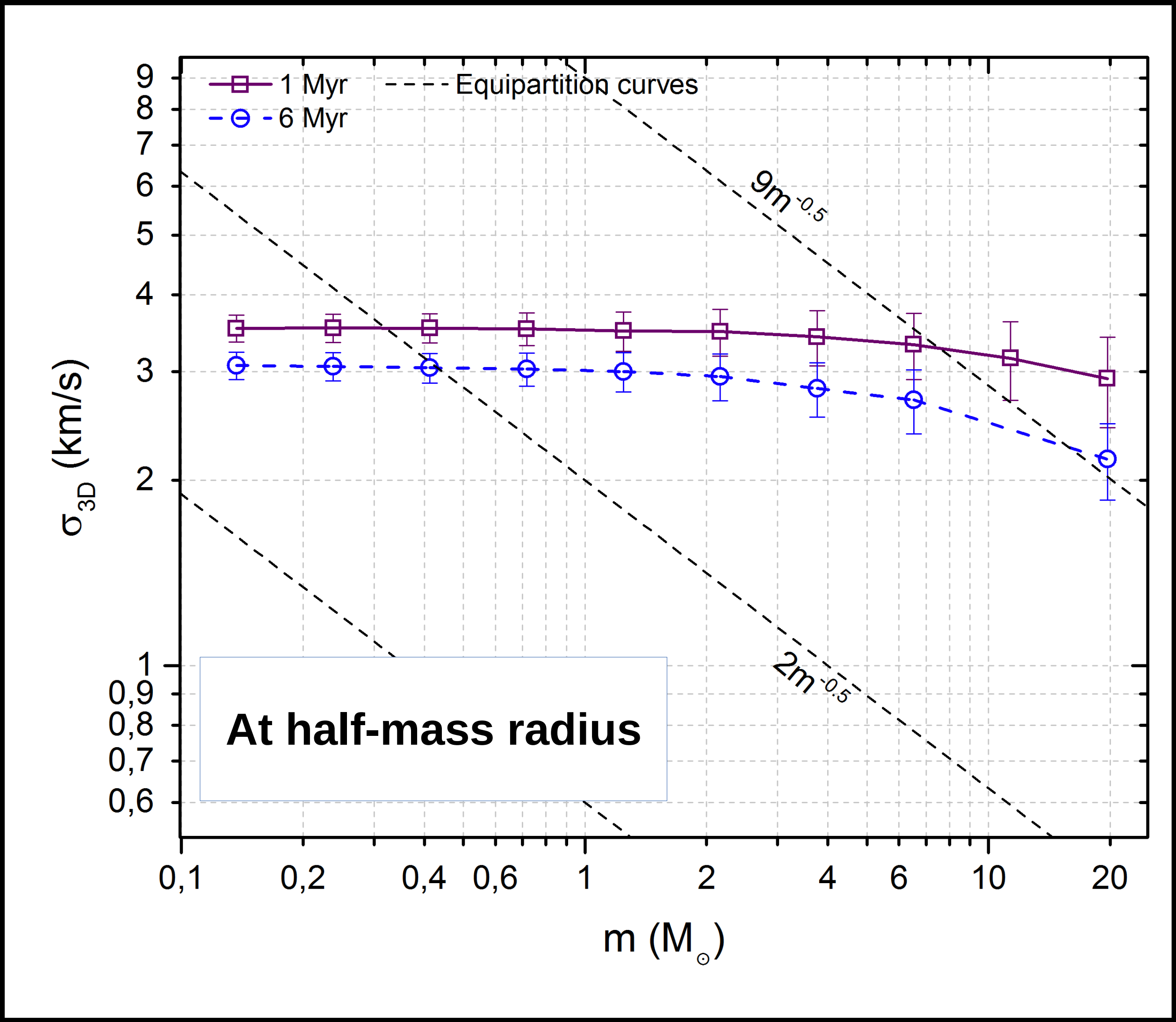

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Spera, MM & Jeffries 2016

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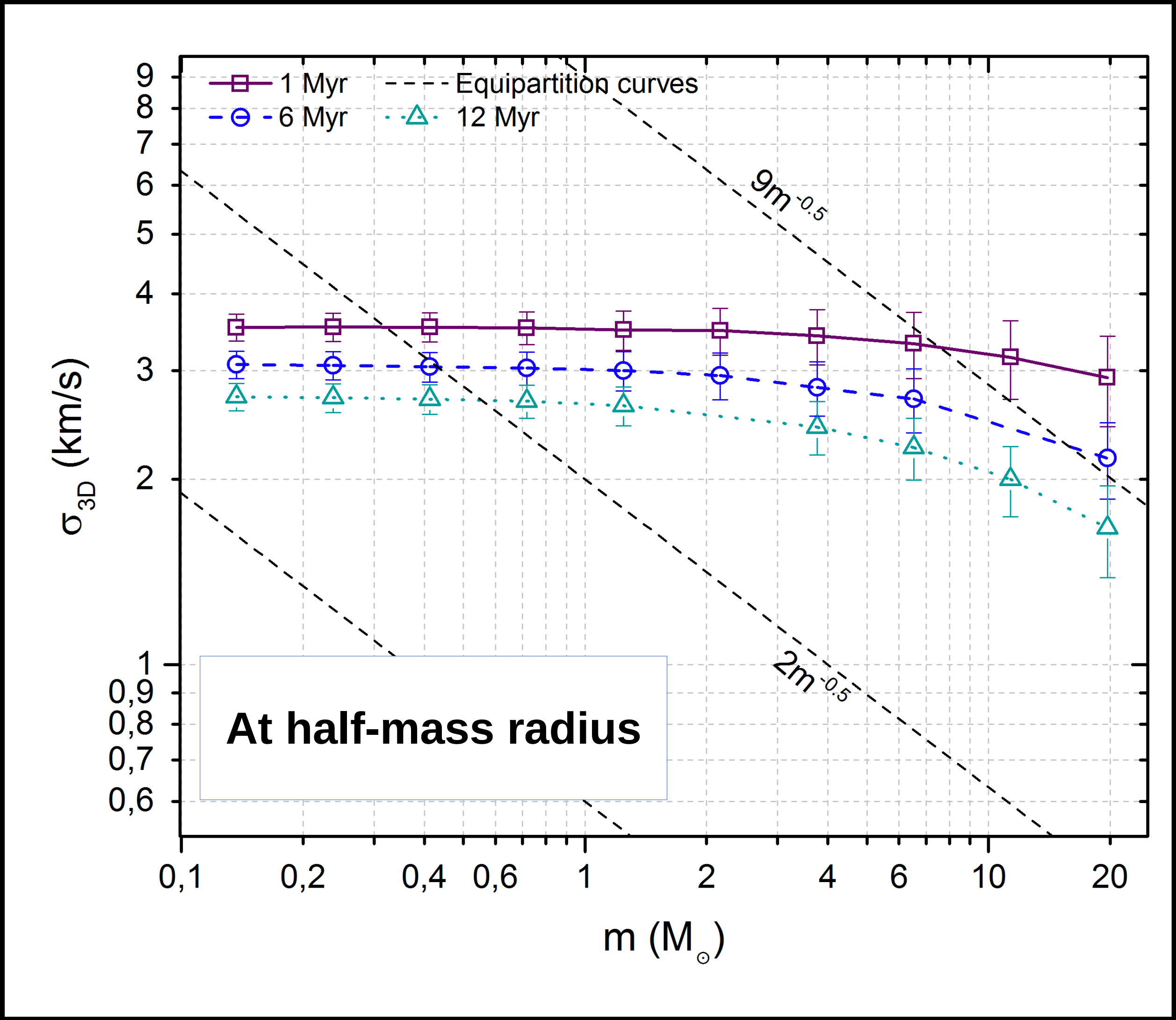

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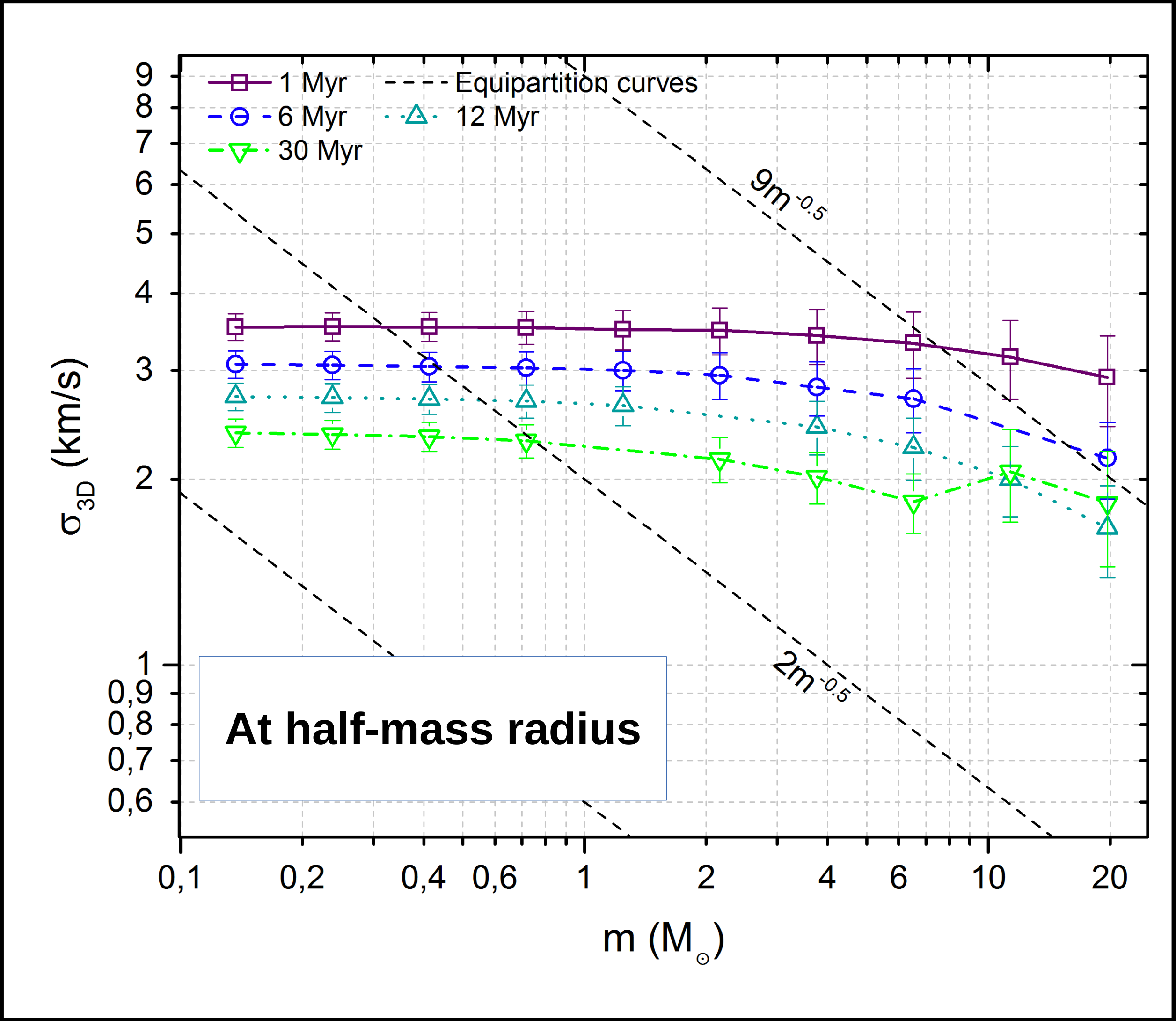

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- **high mass stars become hotter**

Spera, MM & Jeffries 2016

4. Equipartition and Spitzer's instability

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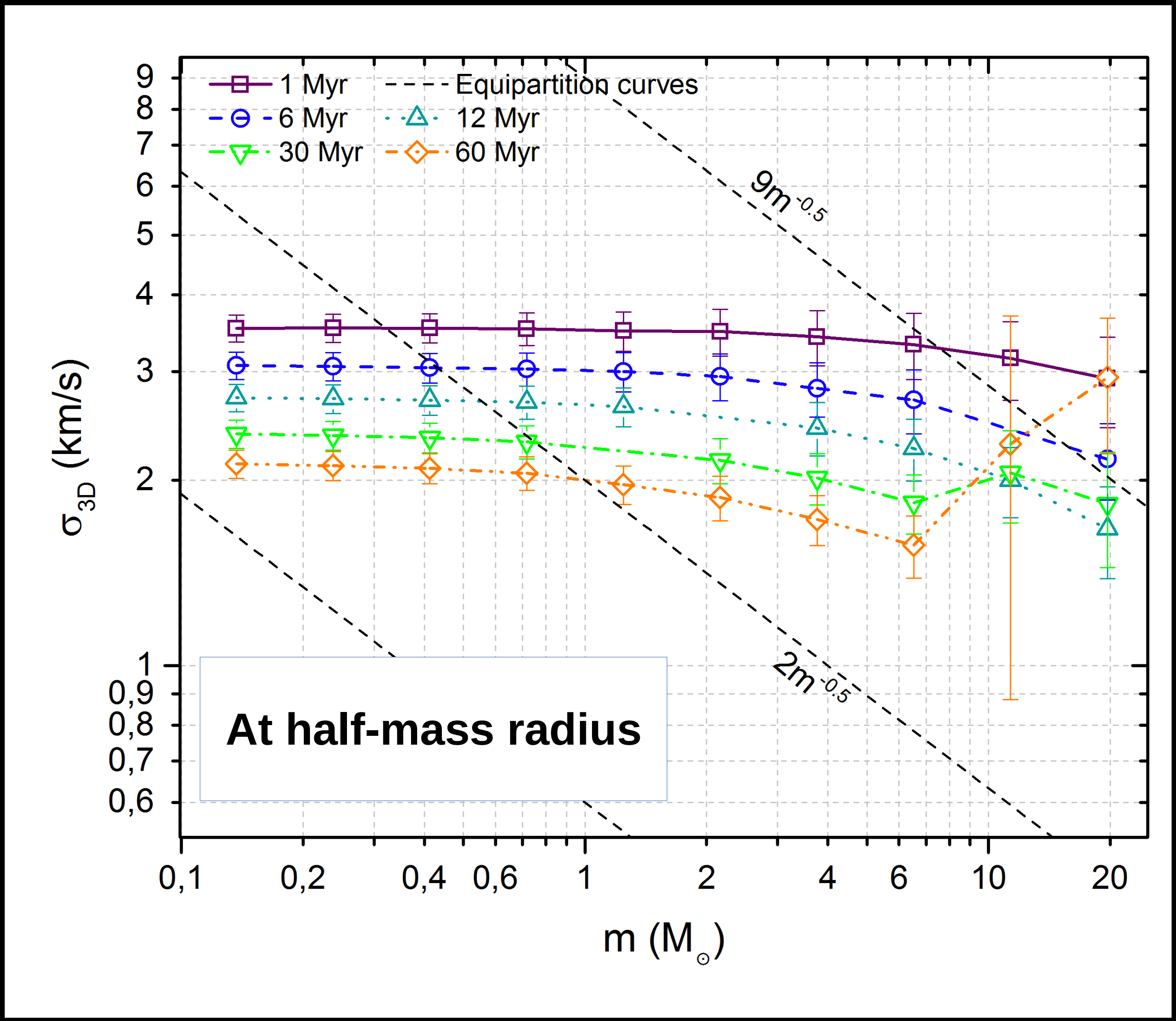

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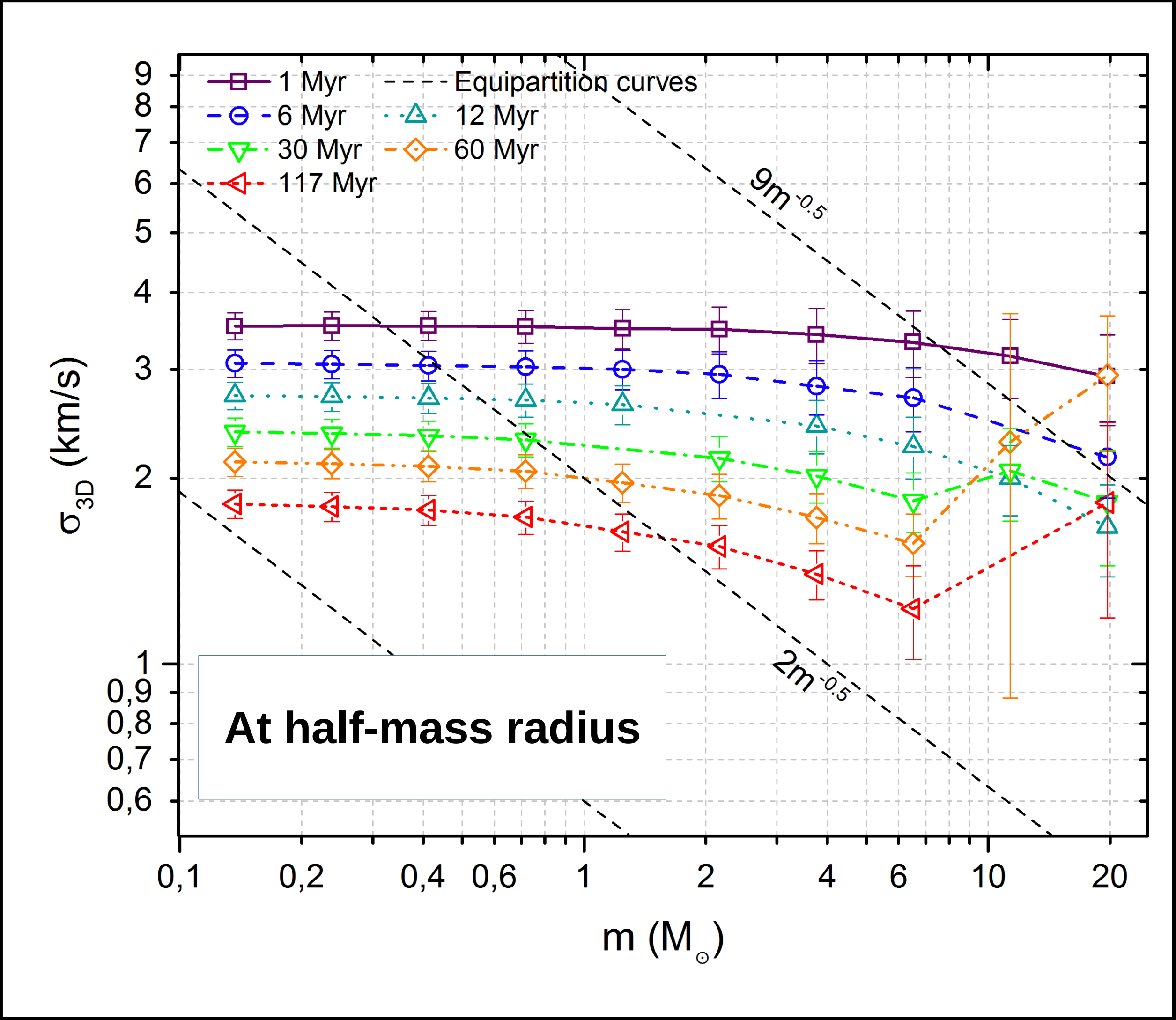

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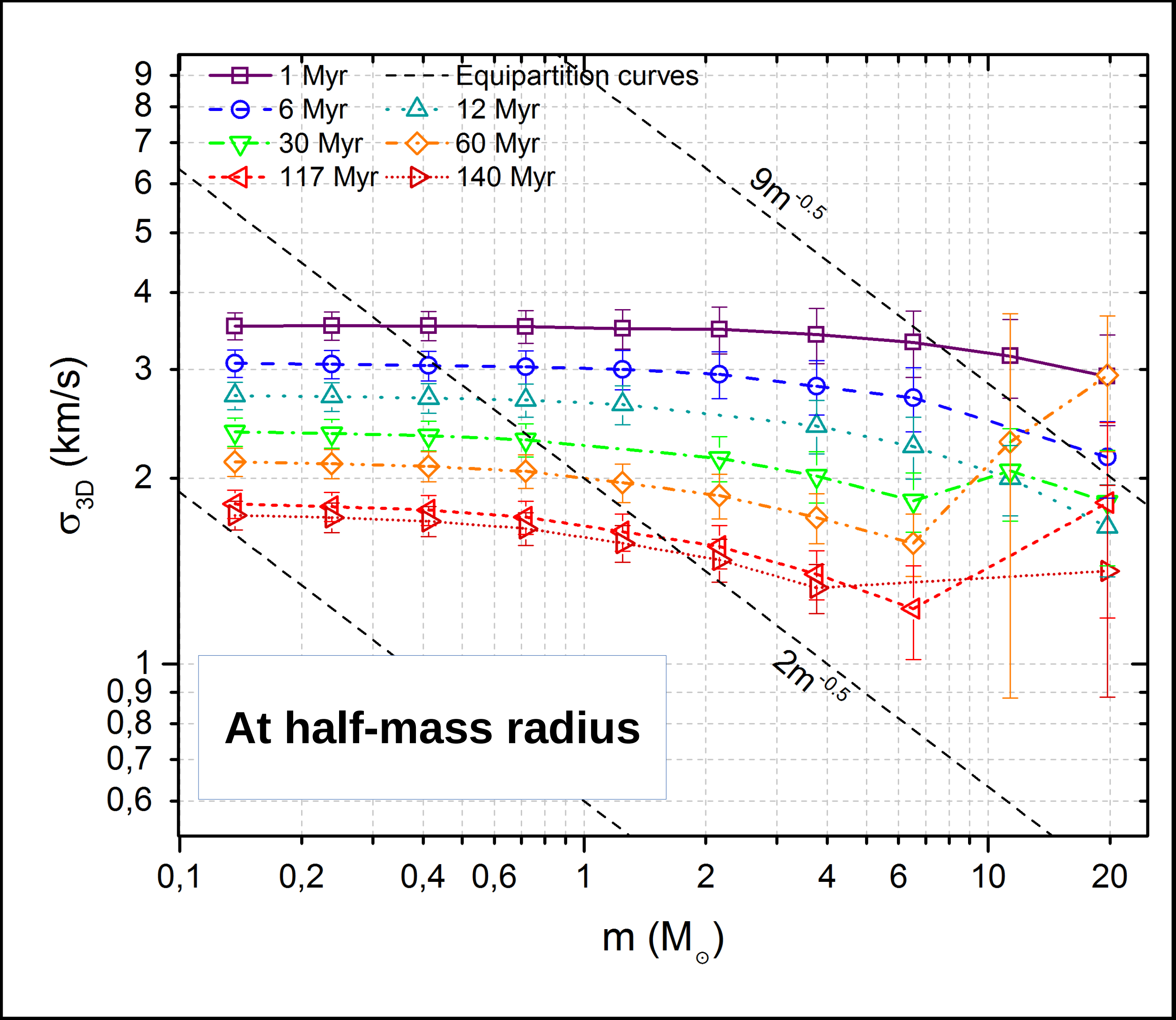

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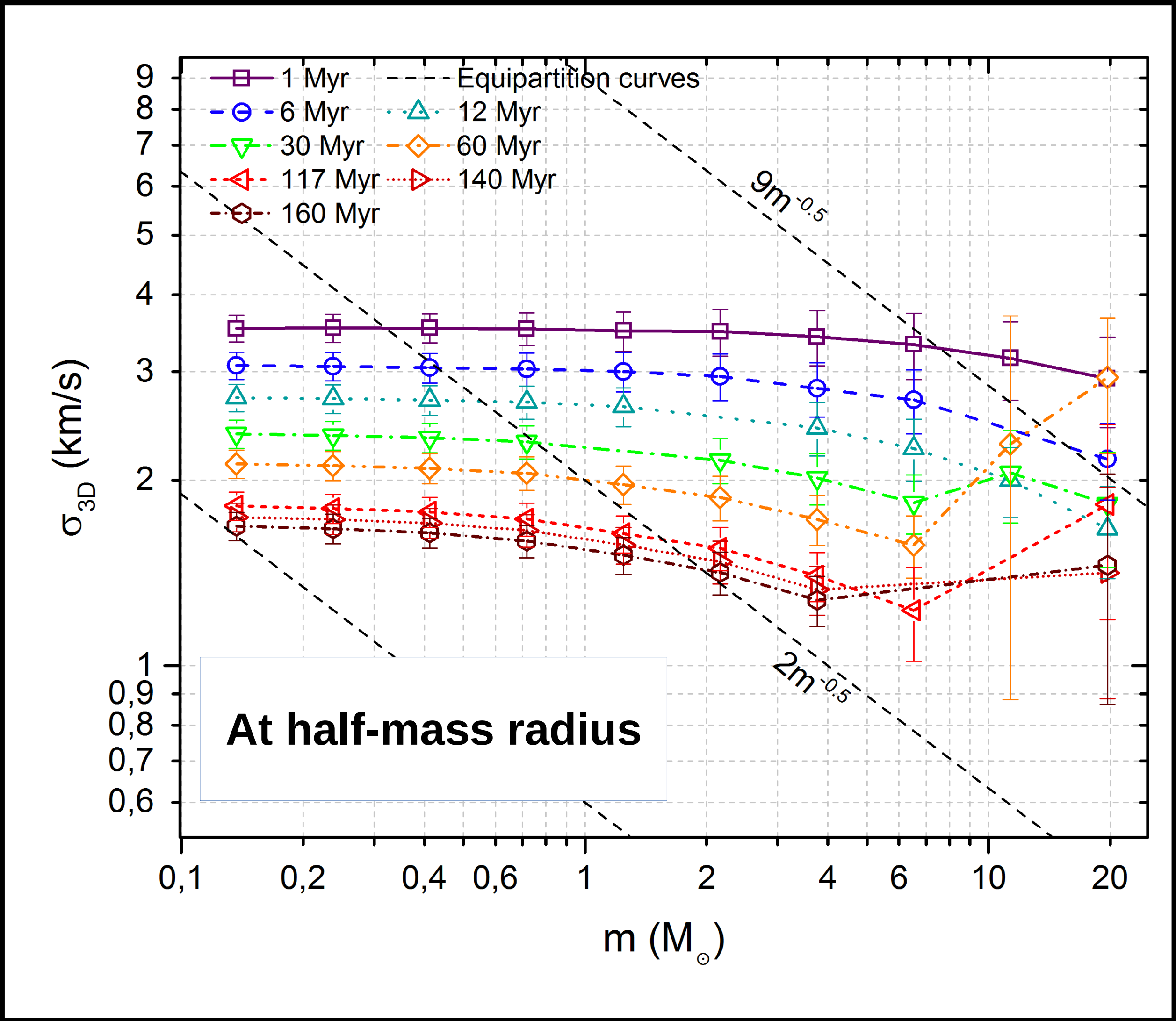

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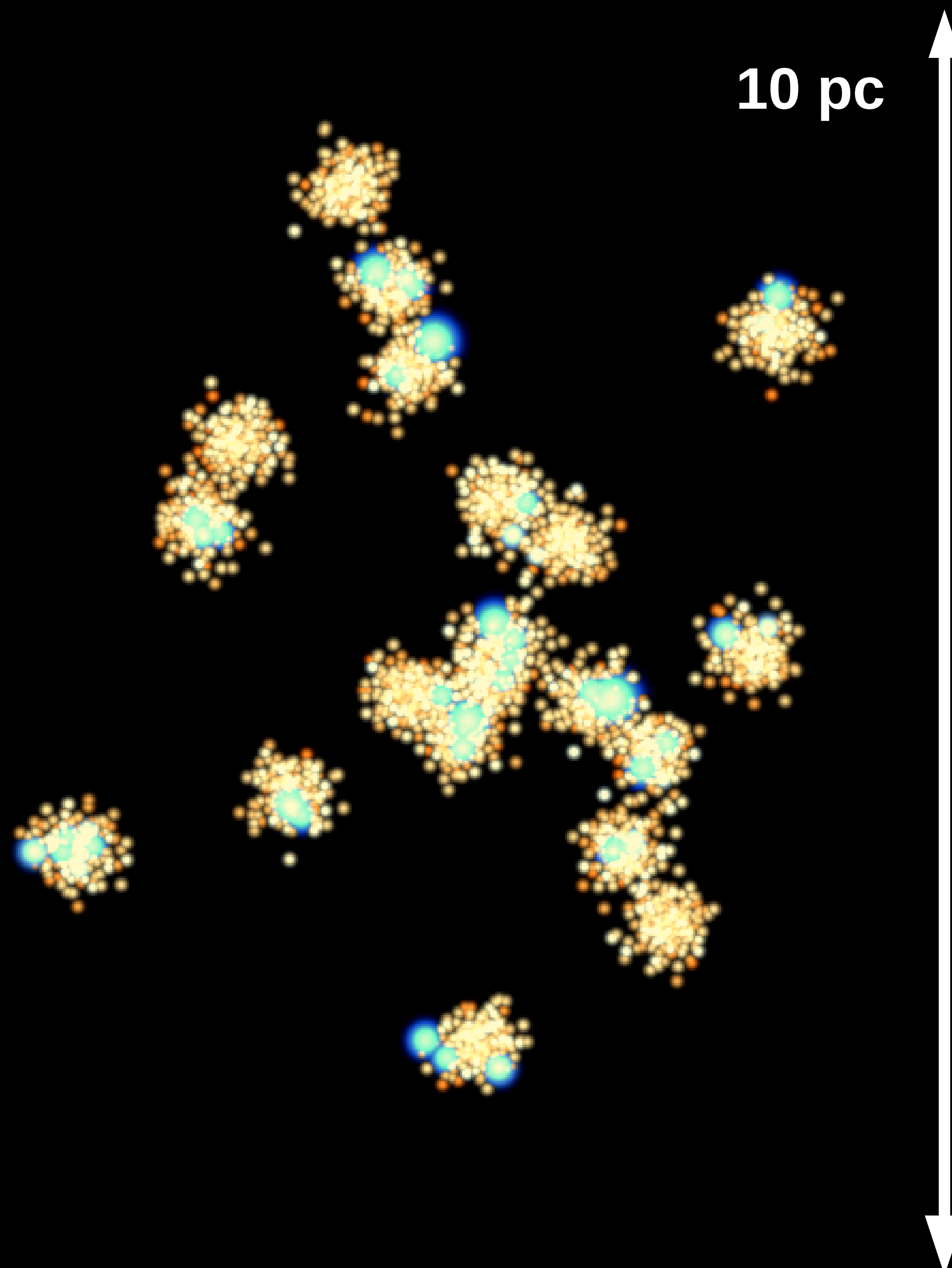
BEHAVIOUR EXPECTED FROM SPITZER INSTABILITY

Spera, MM & Jeffries 2016

What about non-virial and non-King models?

Merger of clumps (20 clumps at rest) equivalent to SUB-VIRIAL initial conditions



Spera, MM & Jeffries 2016

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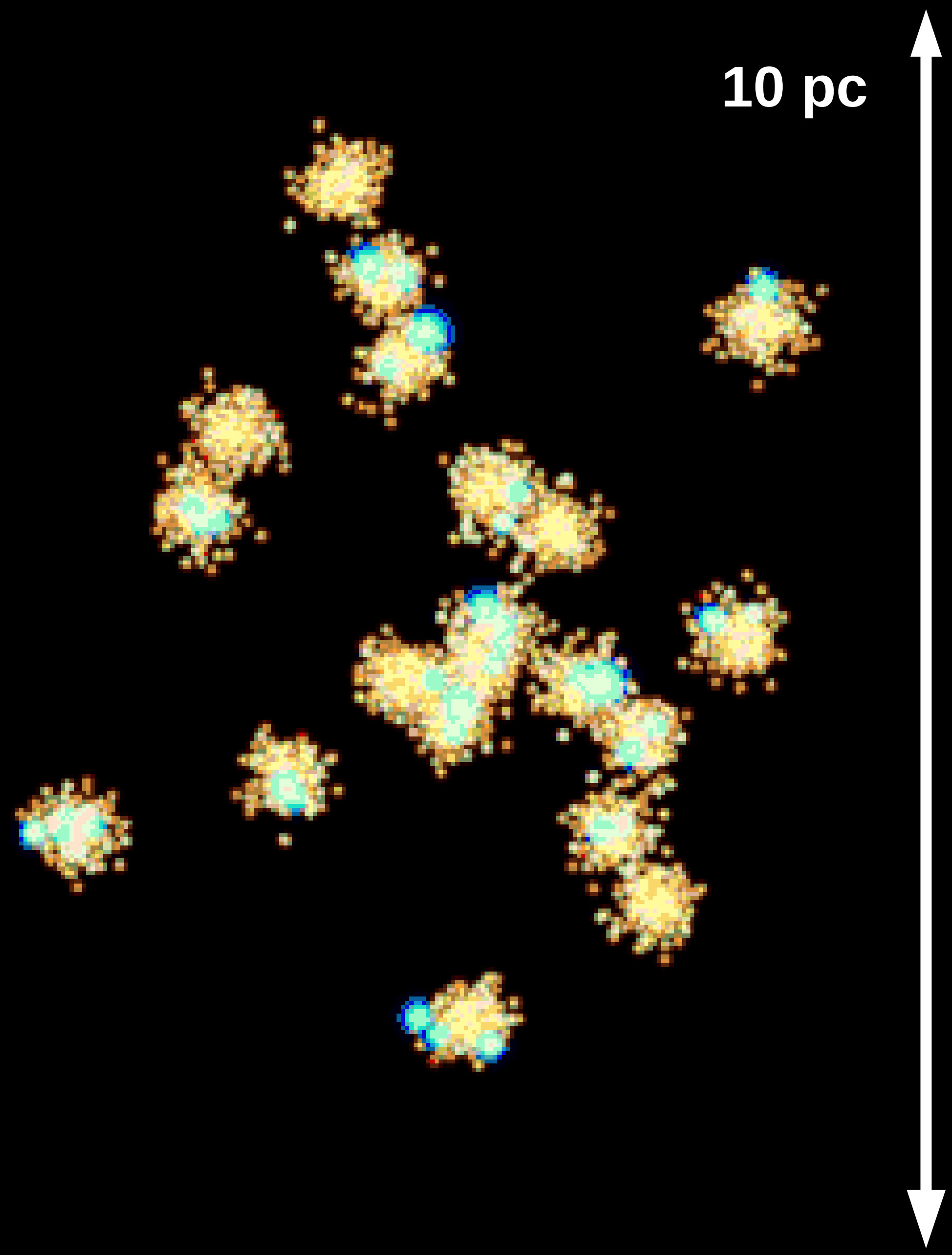

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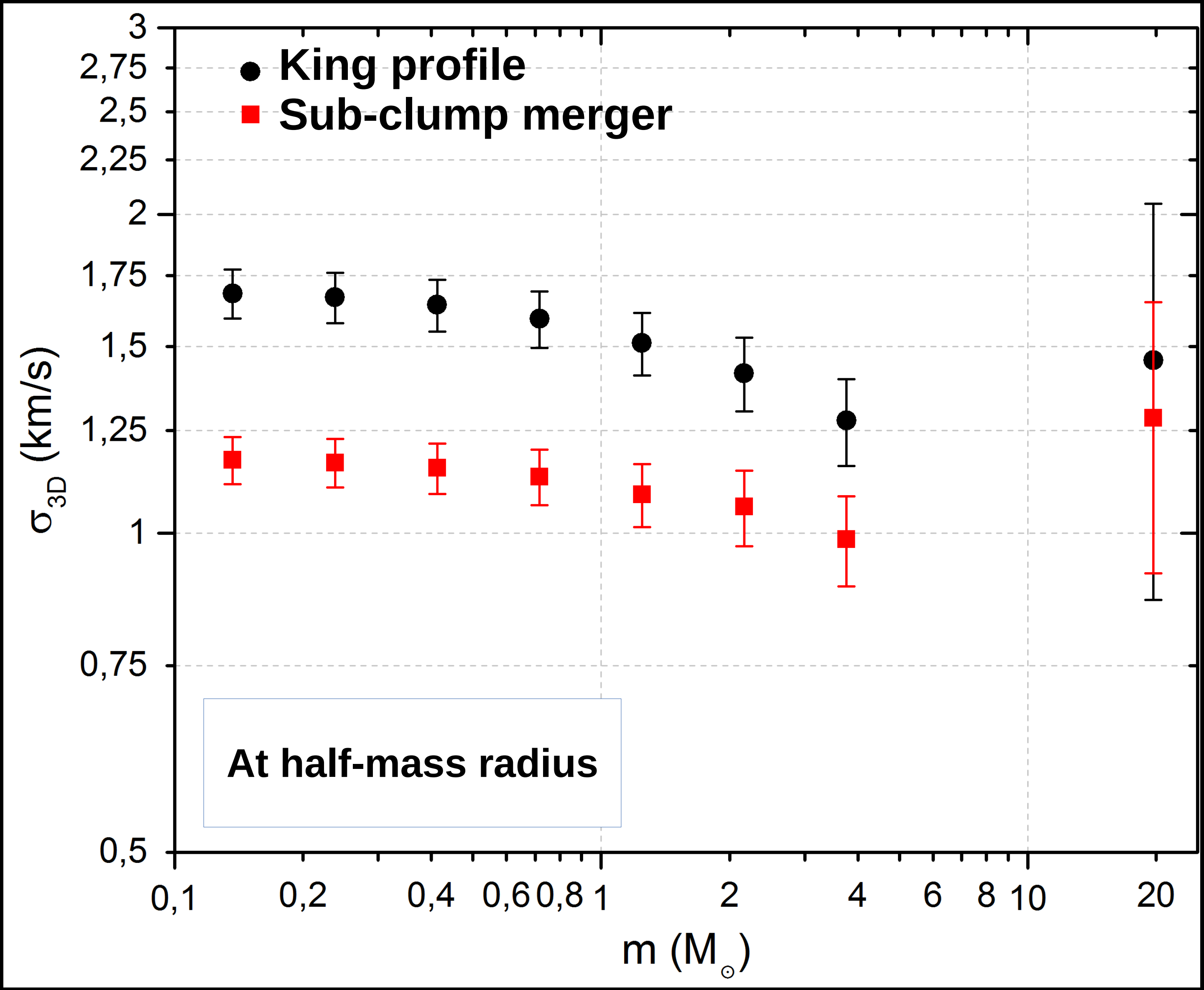

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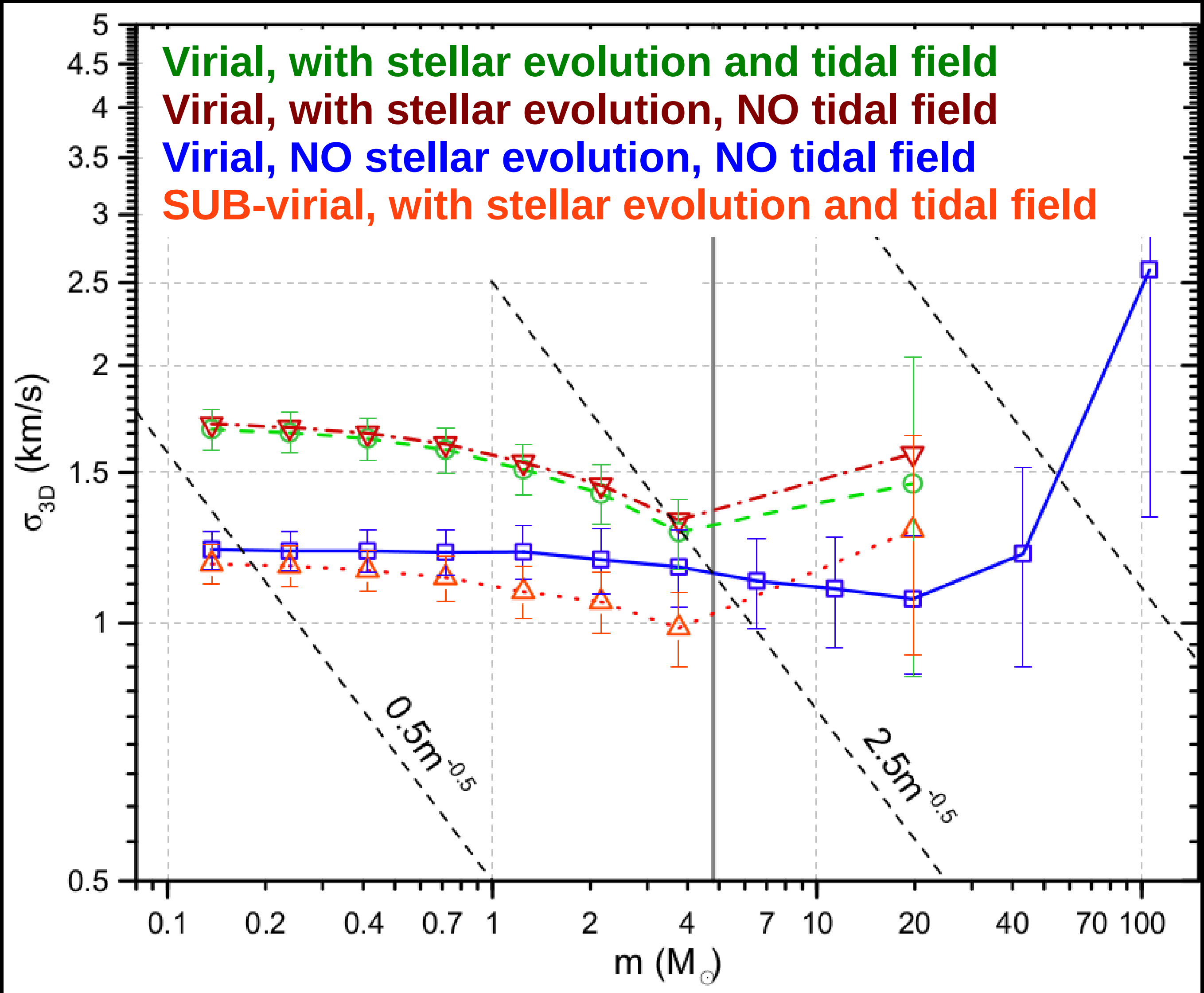


Spitzer's instability is very common

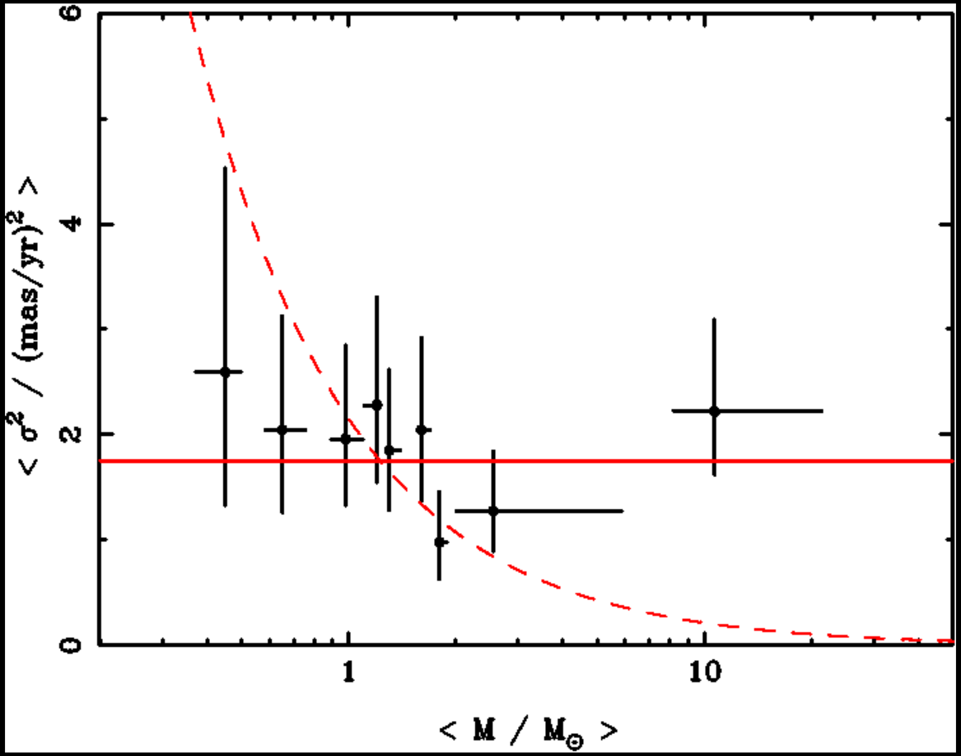
Spera, MM & Jeffries 2016 (see also Trenti & van der Marel 2013; Bianchini+ 2016; Parker+ 2016; Vesperini+ 2016)

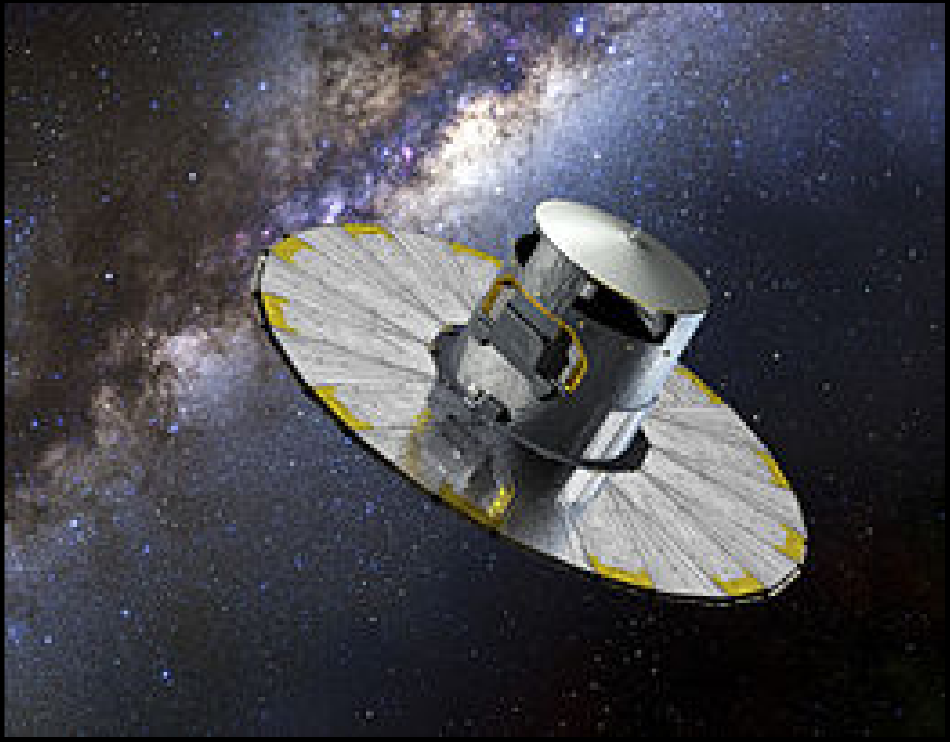
4. Equipartition and Spitzer's instability

Spitzer's instability is very common

Published observations so far:
OB Vela association
proper motion study
by Wright+ 2016

(based on Omega 2000 @
Calar Alto 3.5 m in 2011
+ MegaCam @ CFHT in 2012-2013)





Something Gaia &
the follow-up surveys
(Gaia-ESO) can look for

5. The key role of GAS

Most dynamical simulations of star clusters

- spherical systems (king, plummer)
- already in virial equilibrium (with some exception)
- stars appear in the main sequence
- NO GAS !!!!

5. The key role of GAS

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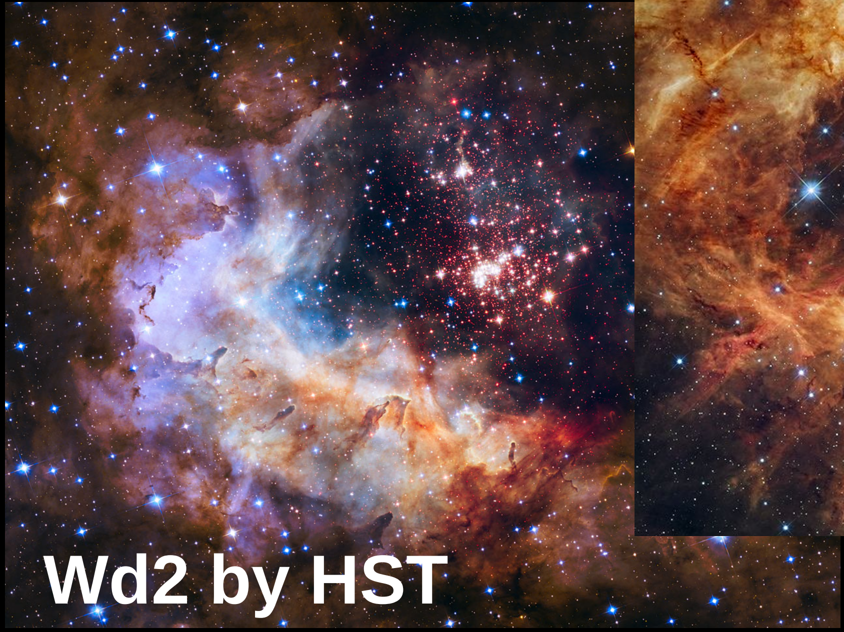
NGC3603 by HST



Wd2 by HST

R136 by HST

5. The key role of GAS

Most dynamical simulations of star clusters

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- **stars appear in the main sequence**
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Everything I have said so far might be wrong....

5. The key role of GAS

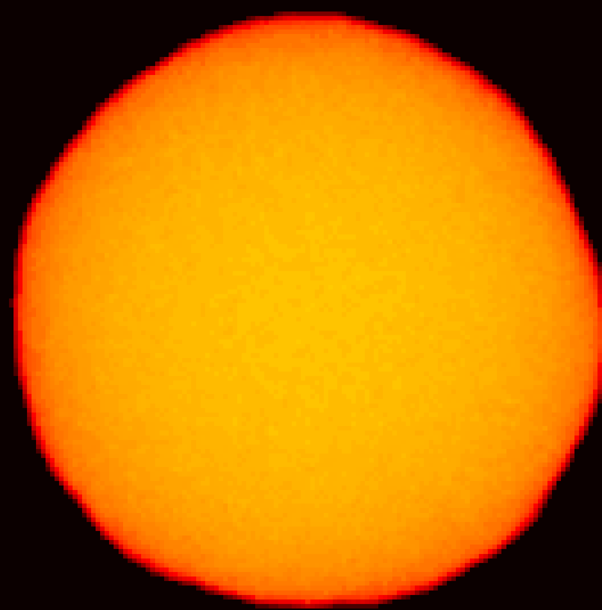
PhD comics' philosophy helps...

BACK TO WORK! WE CAN DO BETTER THAN THIS

5. The key role of GAS

5. The key role of GAS

Simulations of star cluster dynamics starting from gas hydrodynamics



* Turbulence supported molecular clouds

* $10^{3\text{-}5}$ M⊙

* equilibrium chemistry

* cooling and heating with Planck & Rosseland opacity tables (D'Alessio+ 2001, Boley 2009)

* protostars modelled as sink particles

AIM: To produce self-consistent initial conditions for star clusters

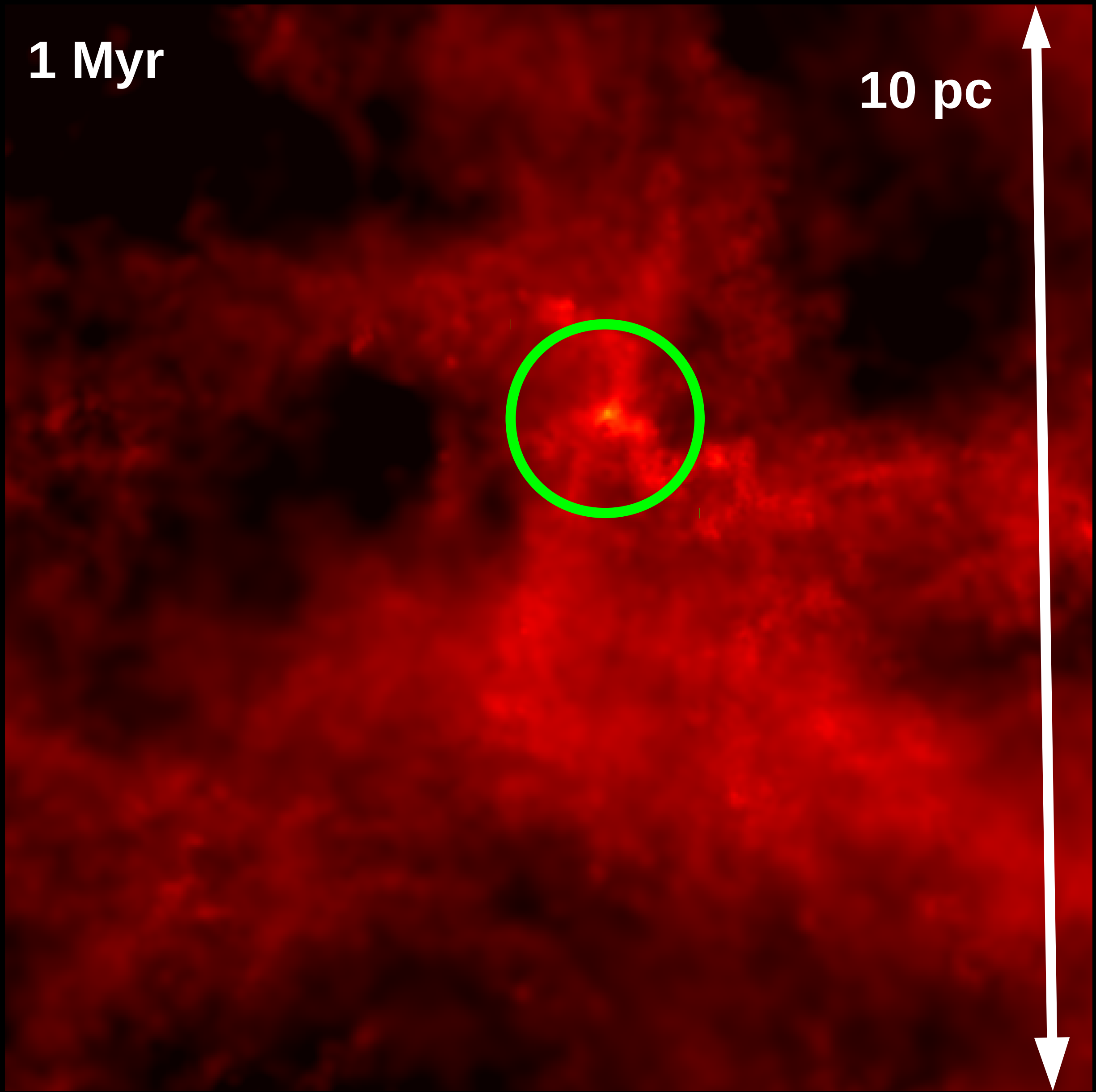
MM 2017

5. The key role of GAS

Star clusters form from hierarchical assembly of gas clumps

Zoom of molecular cloud simulation

At 1 Myr the first star cluster forms



5. The key role of GAS

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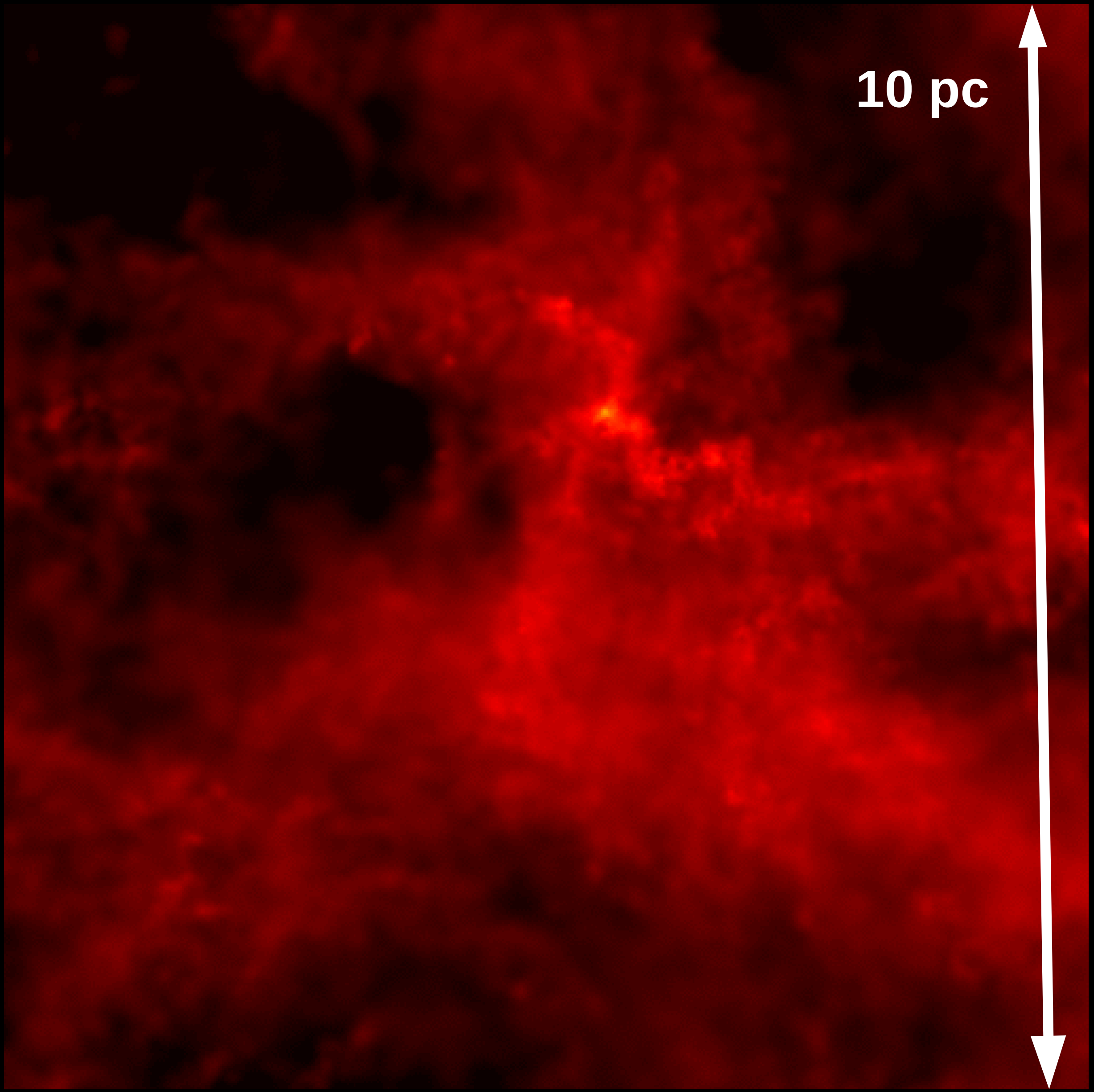
Zoom of molecular cloud simulation

At 1 Myr the first star cluster forms

Then accretes other sub-clusters



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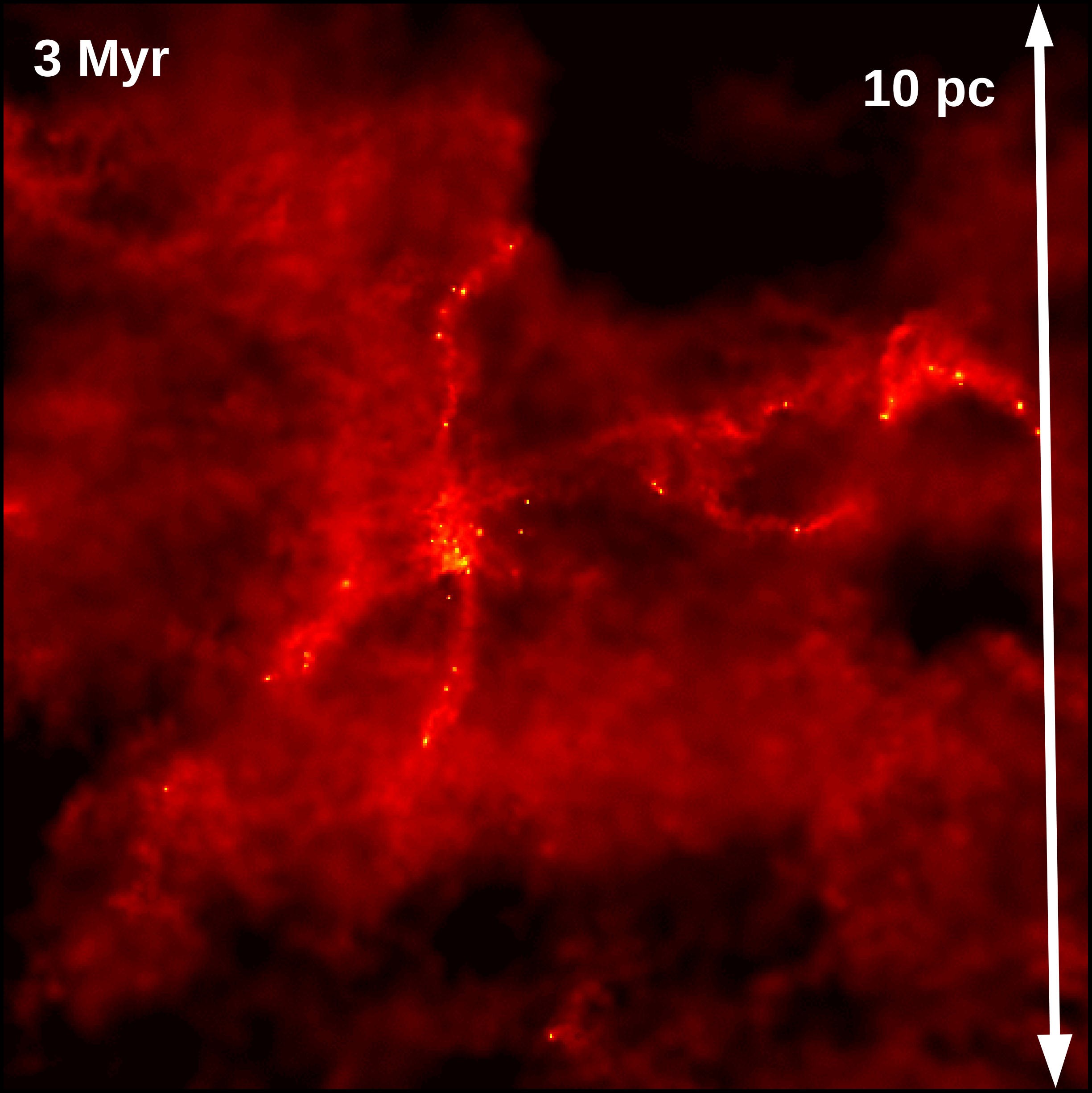

5. The key role of GAS

Star clusters form from hierarchical assembly of gas clumps

Zoom of molecular cloud simulation

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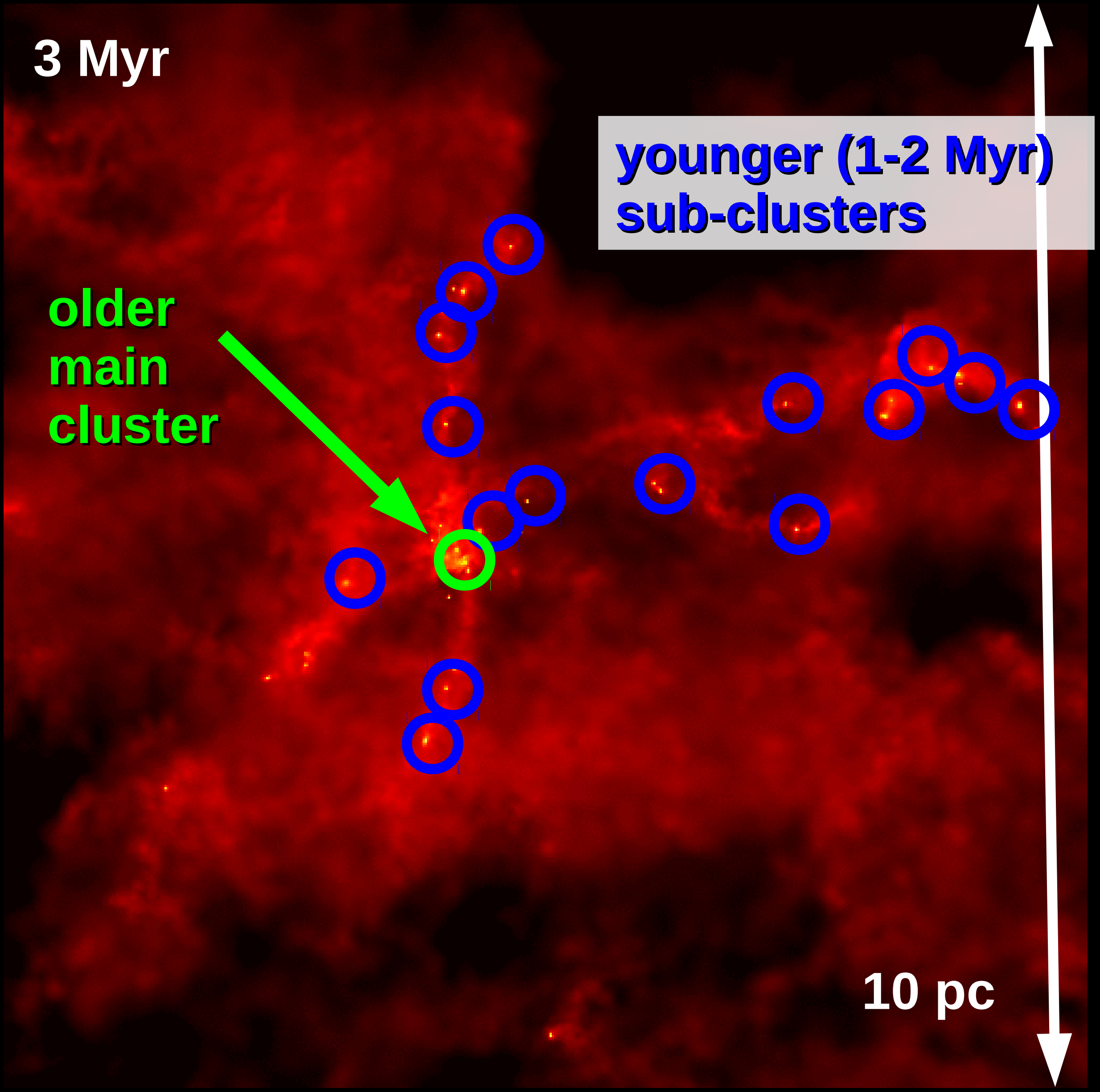
Then accretes other sub-clusters

TORQUES IMPRINT ANGULAR MOMENTUM IN THE GAS

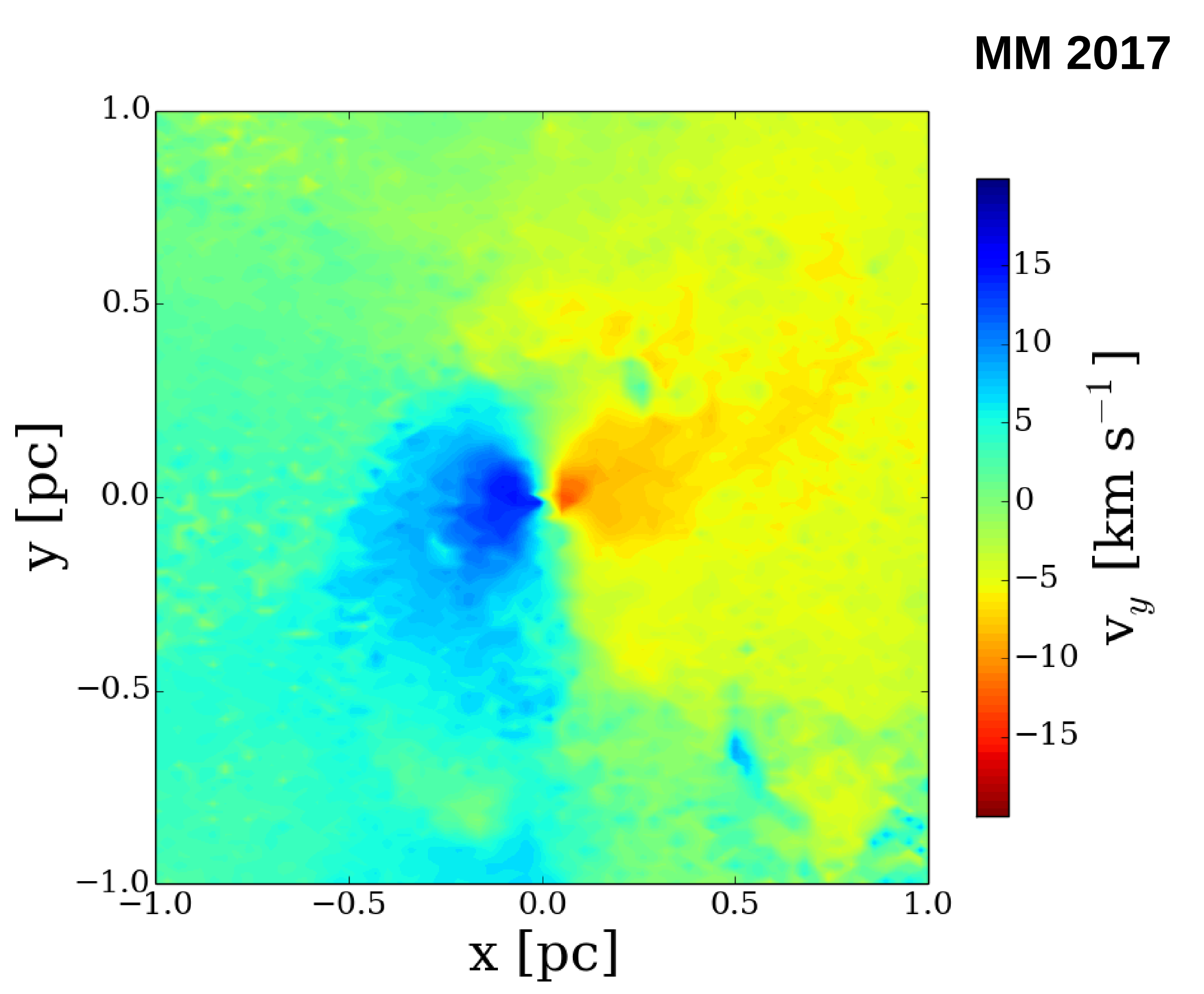


5. The key role of GAS

Star clusters form from hierarchical assembly of gas clumps

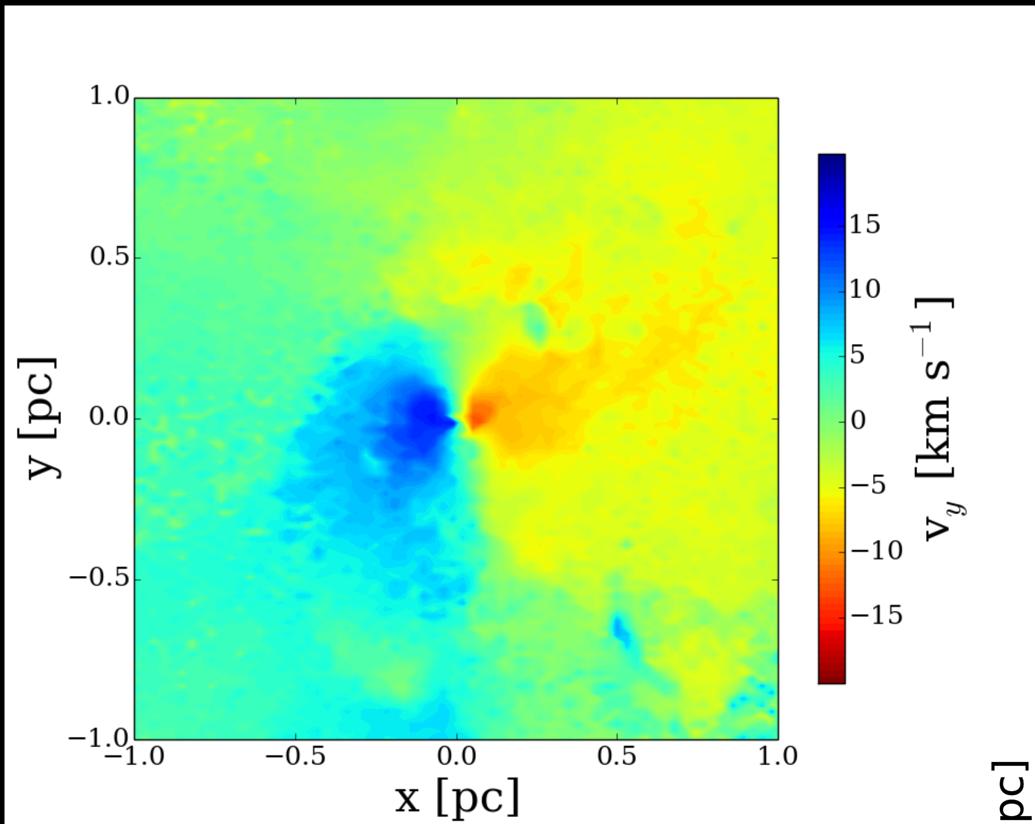
TORQUES IMPRINT ANGULAR MOMENTUM IN THE GAS

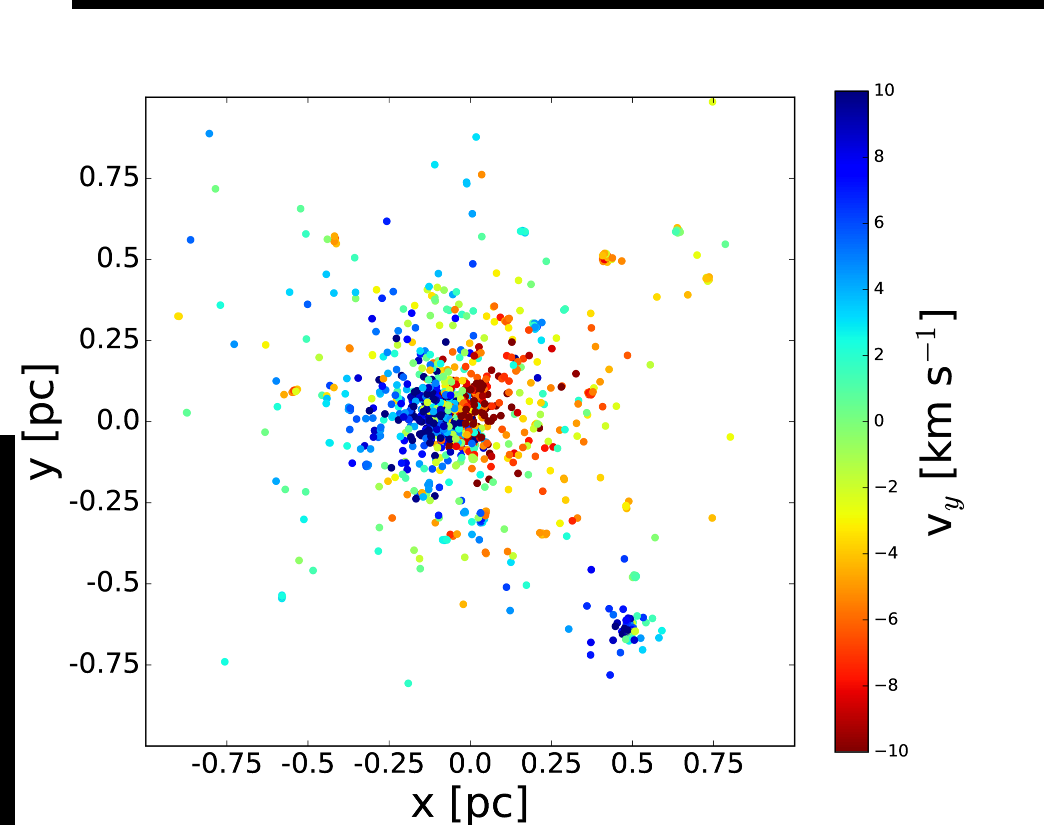
GAS ROTATES



5. The key role of GAS

STARS INHERIT ROTATION SIGNATURE OF GAS

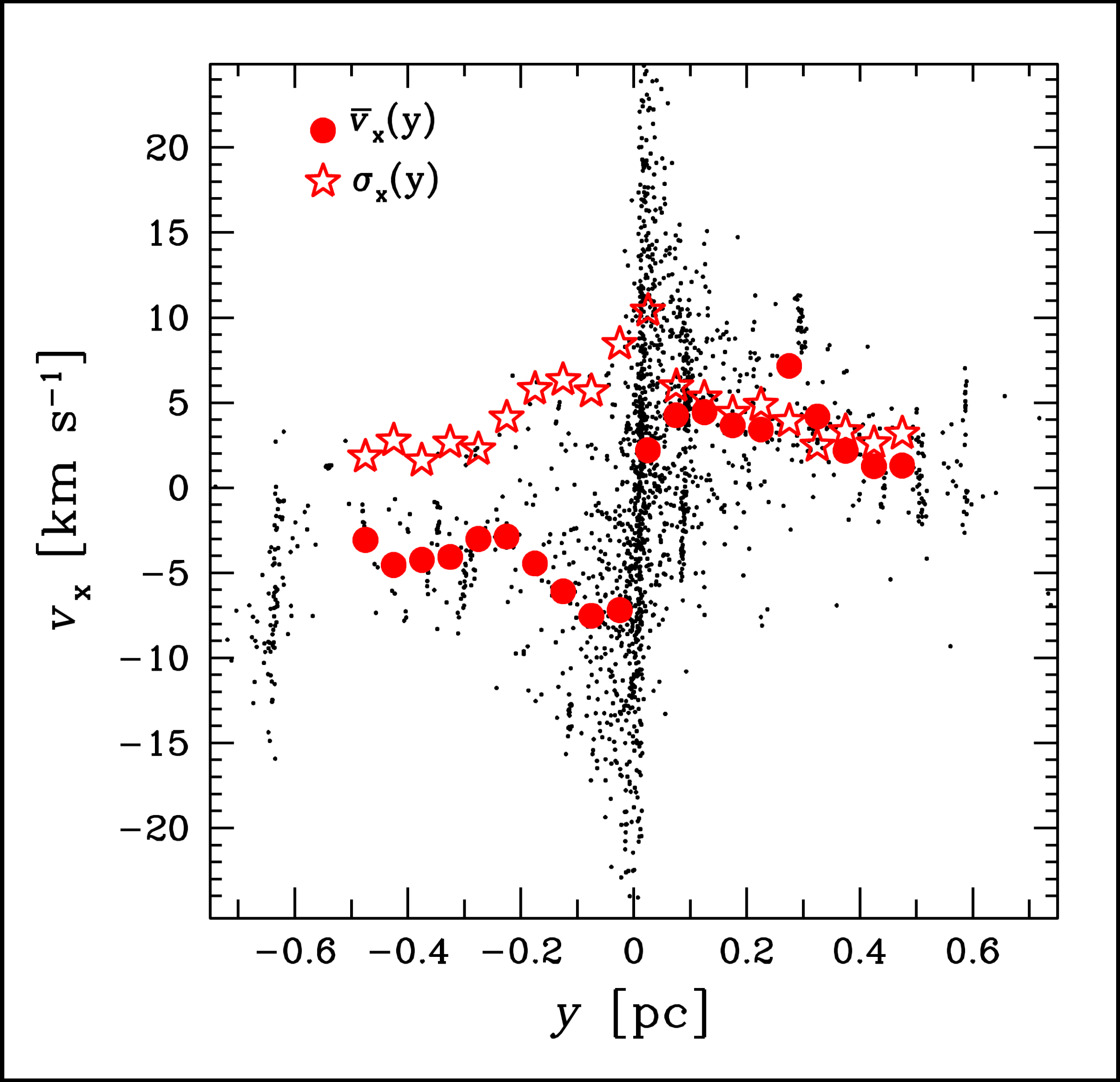




MM 2017

5. The key role of GAS

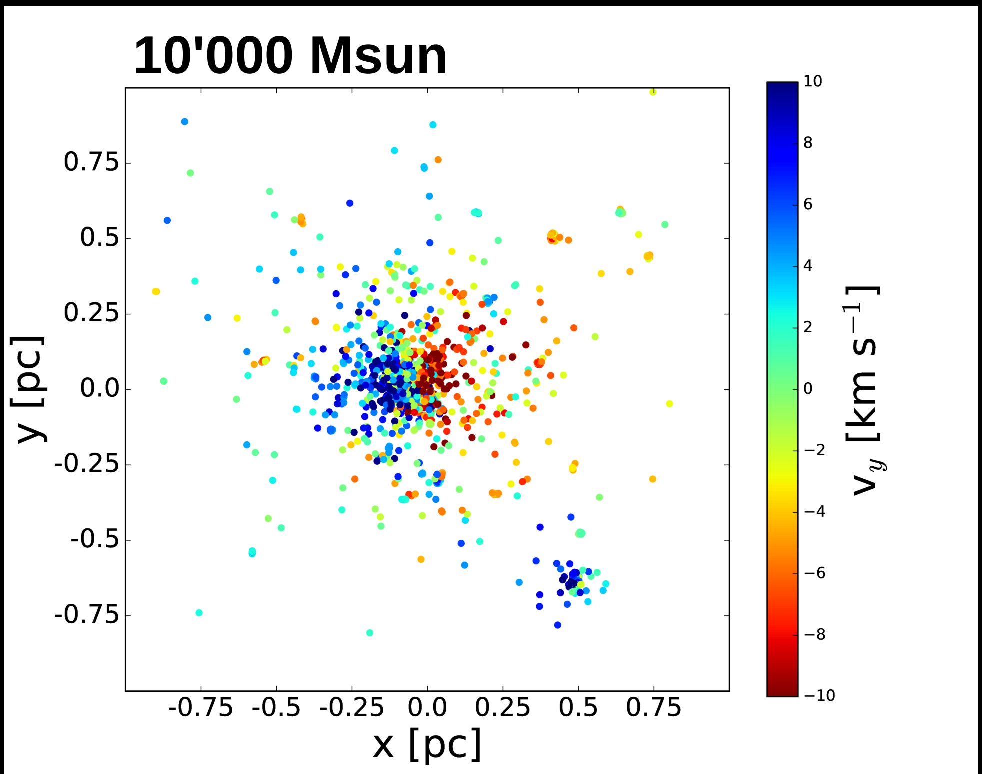
STARS INHERIT ROTATION SIGNATURE OF GAS

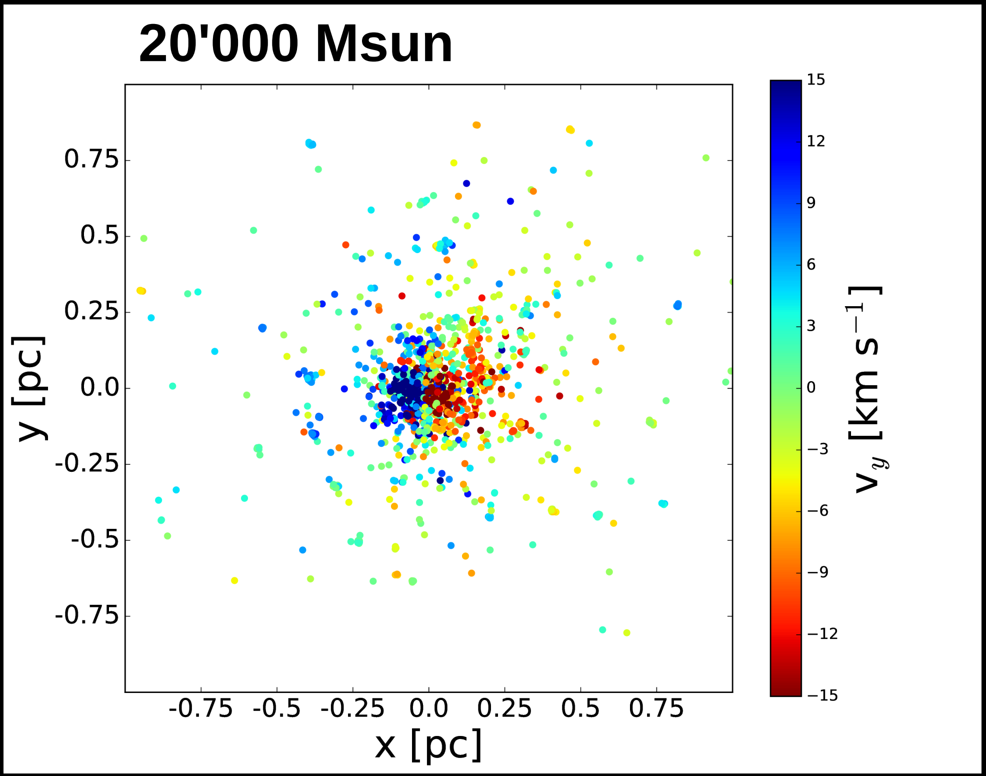


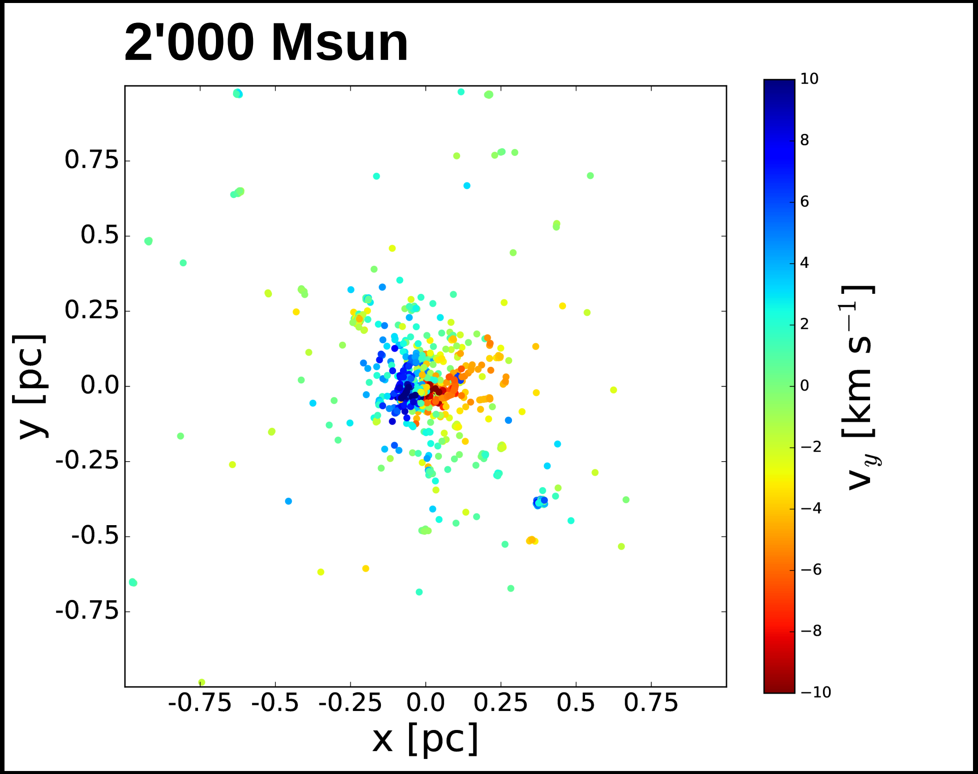
MM 2017

5. The key role of GAS

Rotation seems to be ubiquitous in simulated star clusters with mass ≥ 1'000 Msun







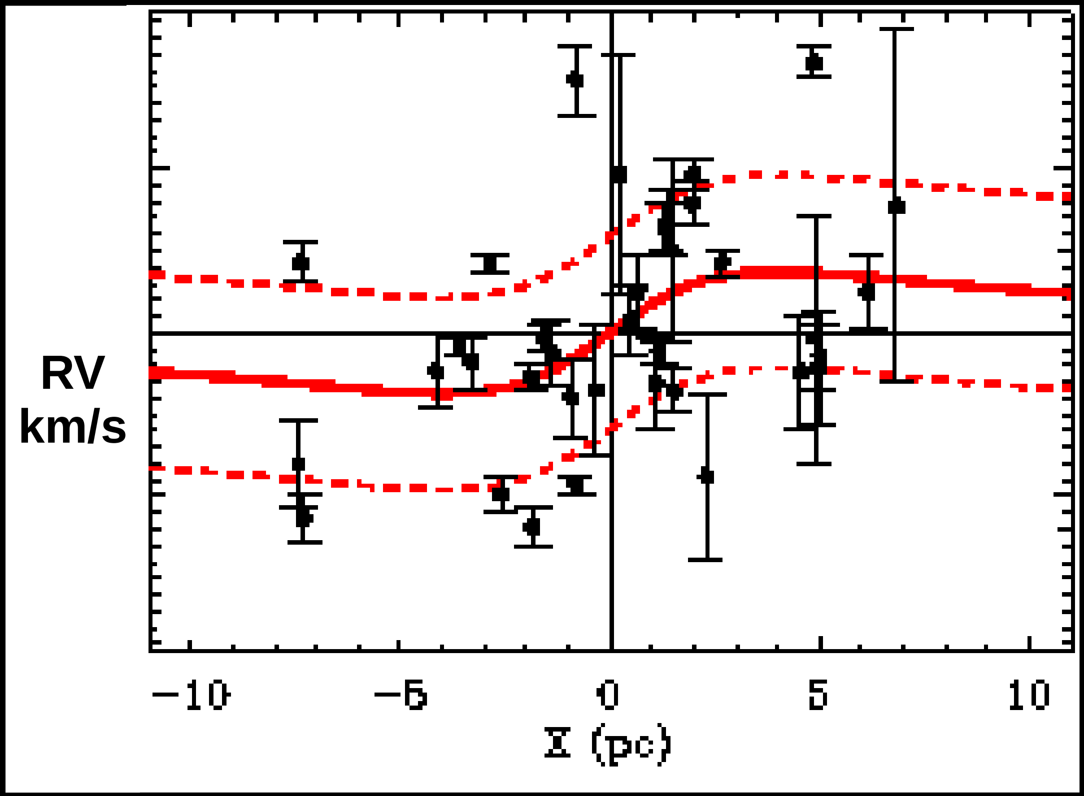
WORK IN PROGRESS:

Impact of rotation on mass segregation, core collapse...

MM 2017

5. The key role of GAS

Do we observe rotation signatures in young star clusters?



R136 in Large magellanic clouds (Hénault-Brunet et al. 2012)

- only 36 stars
- overly difficult to observe with sufficient precision (binaries!)
- only few massive star clusters in vicinity

5. The key role of GAS

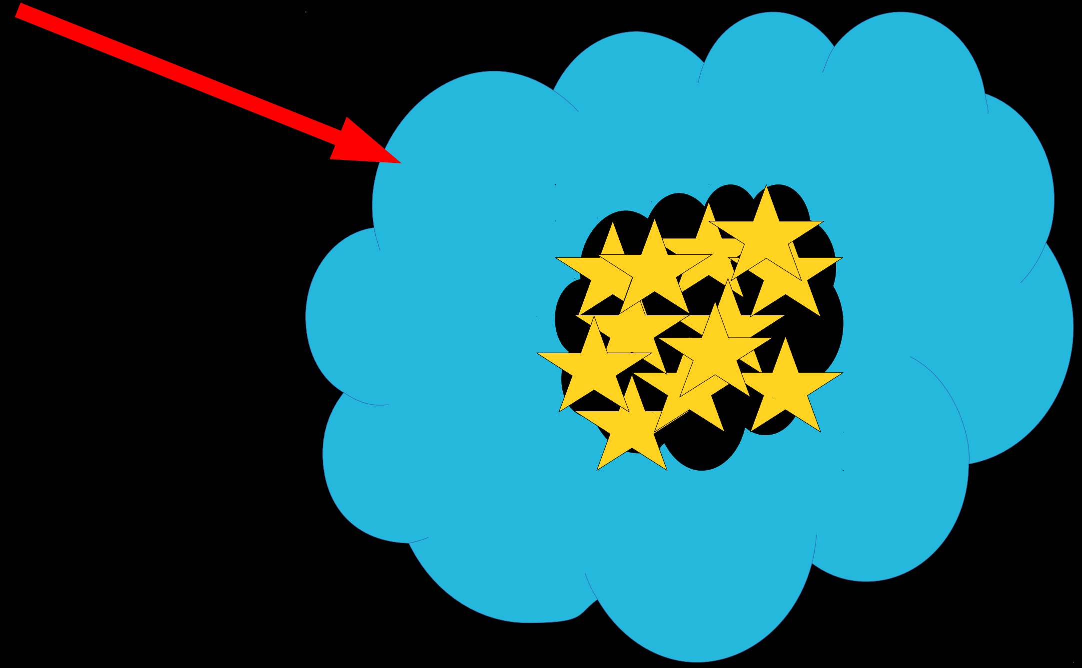
How long does the rotation signature last?

Two-body encounters expected to remove rotation

Central two-body relaxation timescale ~ 1 Myr

Check with DIRECT-SUMMATION SIMULATION:

- models two-body encounters properly
- does not model GAS



HYDRO SIM

5. The key role of GAS

How long does the rotation signature last?

Two-body encounters expected to remove rotation

Central two-body relaxation timescale ~ 1 Myr

Check with DIRECT-SUMMATION SIMULATION:
- **models two-body encounters properly**
- **does not model GAS**

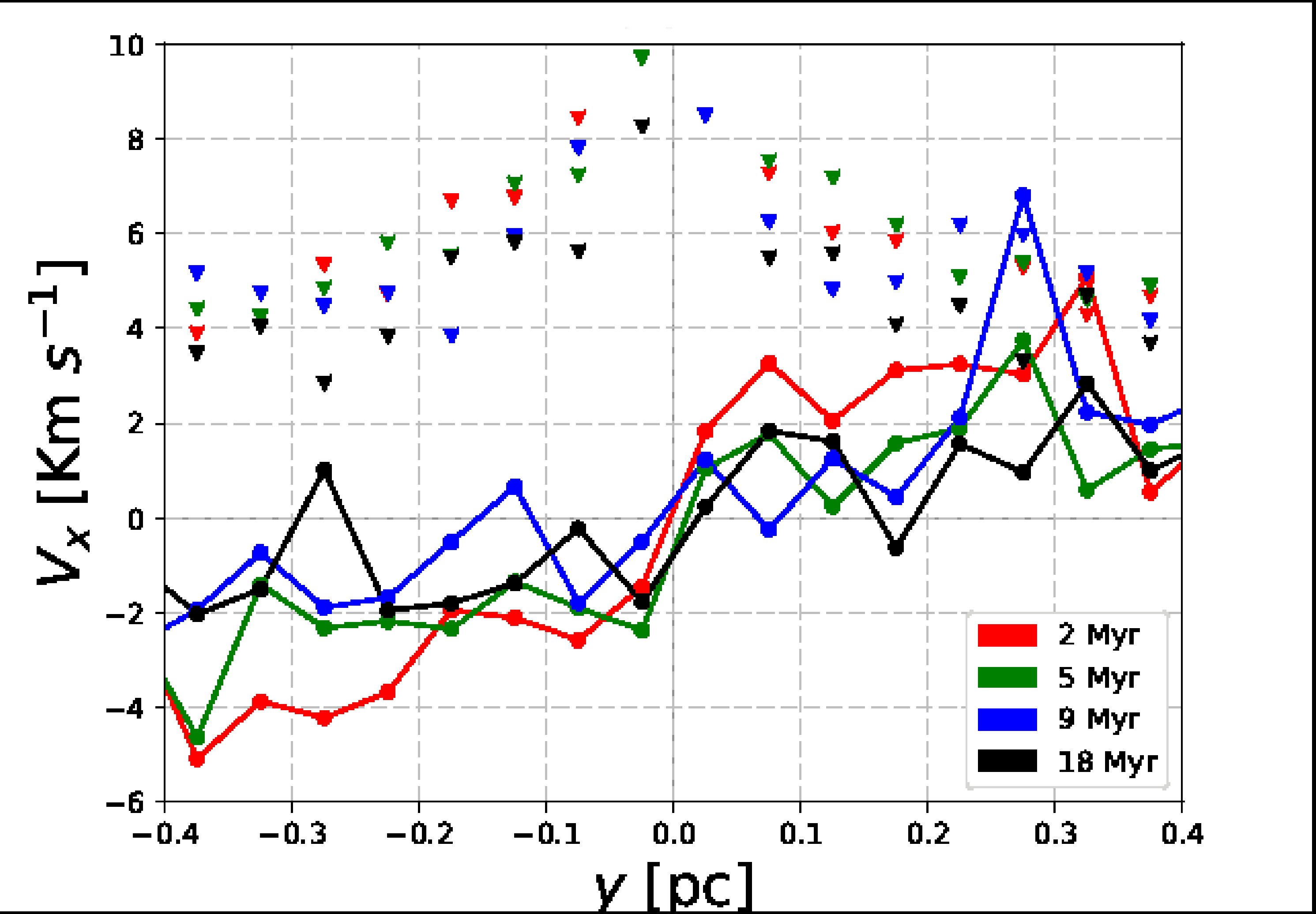
→ after 2 dynamical times
gas is REMOVED completely
“by hand” (like supernova feedback..)

and star cluster re-simulated
with direct-summation code

Direct N-body SIMULATION

5. The key role of GAS

How long does the rotation signature last?

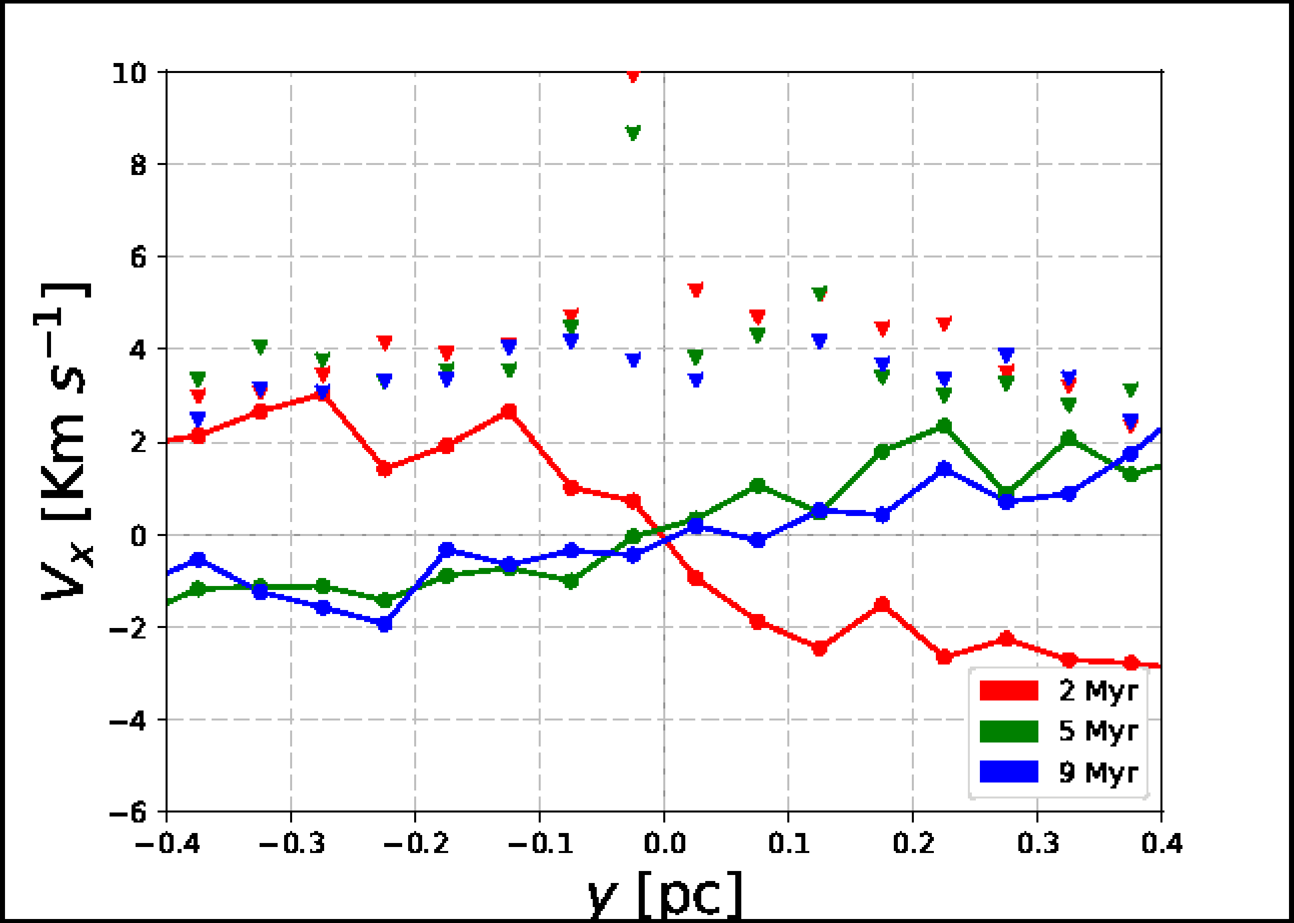


* Rotation decreases but less fast than expected

Di Carlo, MM, in prep.

5. The key role of GAS

How long does the rotation signature last?

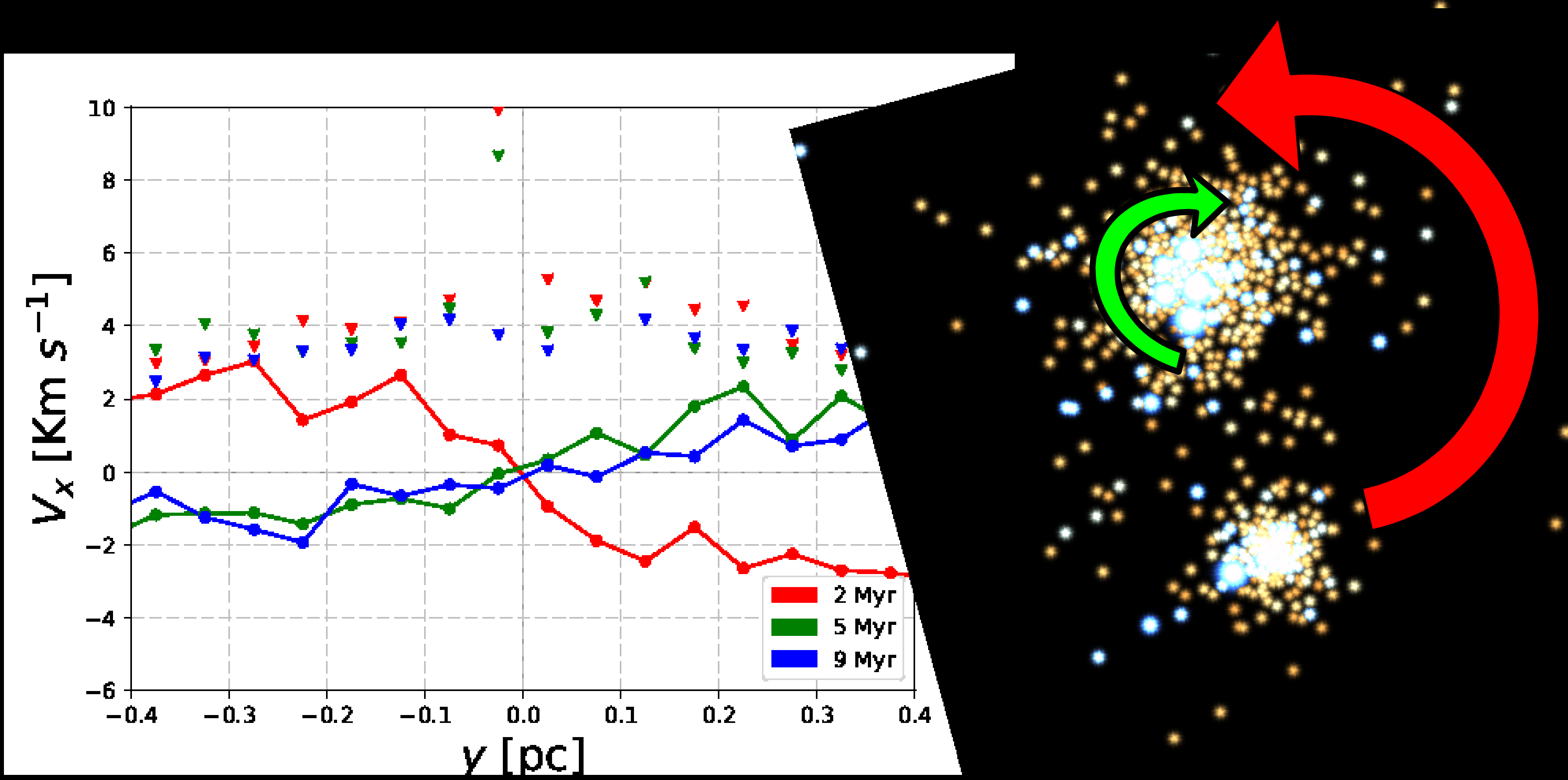


* In one cluster it even changes direction
WHY?

Di Carlo, MM, in prep.

5. The key role of GAS

How long does the rotation signature last?



* In one cluster it even changes direction

WHY? merger of an additional sub-cluster With opposite orbital angular momentum

Di Carlo, MM, in prep.

OUR TEAM:

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Enrico Montanari

6. Conclusions

– Star clusters are site of intense dynamical processes

– Direct N-body simulations + stellar evolution are an invaluable tool (SEVN, Spera, MM & Bressan 2015)

– Runaway collisions may lead to formation of IMBHs only in metal-poor clusters (MM 2016)

– Equipartition is not reached in most cases and Spitzer's instability develops (Spera, MM & Jeffries 2016)

– BUT our star cluster models might be UNREALISTIC: we need to account for gas

– Hydro-simulations show that rotation is common in the early stages of star cluster evolution (MM 2017)

– More interplay between hydro and dynamics in future! (Di Carlo, MM, in prep.)

Thank You!

6. Main refs to our work

MM 2016: http://adsabs.harvard.edu/abs/2016MNRAS.459.3432M

Spera, MM, Bressan 2015:
http://adsabs.harvard.edu/abs/2015MNRAS.451.4086S

Spera, MM, Jeffries 2016:
http://adsabs.harvard.edu/abs/2016MNRAS.460..317S

MM 2013:
http://adsabs.harvard.edu/abs/2013MNRAS.429.2298M

MM & Zampieri 2014:
http://adsabs.harvard.edu/abs/2014ApJ...794....7M

Ziosi+ 2014:
http://adsabs.harvard.edu/abs/2014MNRAS.441.3703Z

Kimpson+ 2016:
http://adsabs.harvard.edu/abs/2016MNRAS.463.2443K

MM 2017:
http://adsabs.harvard.edu/abs/2017MNRAS.467.3255M