Simulations of star clusters in evolving galaxies

from infant to old

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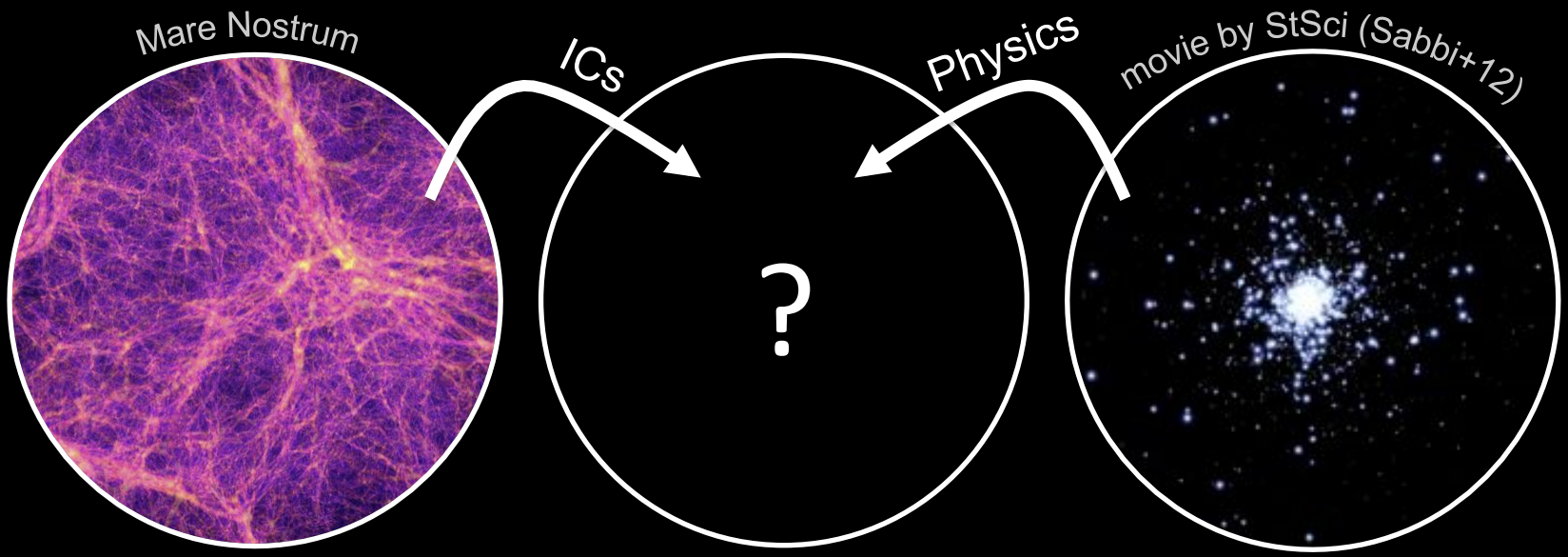
Simulations of Galaxy and Star Cluster Formation



good ← Initial conditions → bad

density fluctuations (cosmology)
relaxed systems (galaxies)

spherical symmetry ...

cf. Alison Sills' talk yesterday

bad ← Physics → good

poor resolution,
sub-grid recipes

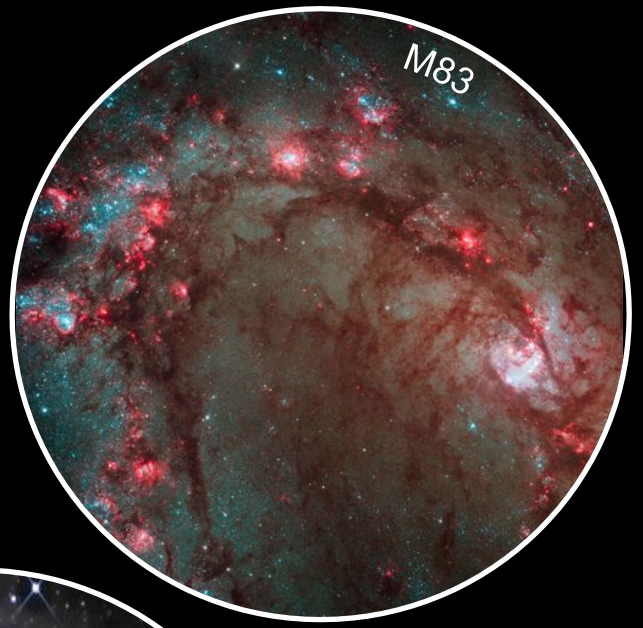
accurate treatment
high precision

WHY SHOULD WE CARE ABOUT THE (GALACTIC) ENVIRONMENT?

Galaxies have an influence on star clusters

- formation
  - stars form in clusters
  - under specific conditions

    regions (e.g. spirals)
    events (e.g. mergers)



- dissolution
  - tidal stripping

Evolving environment

- mass growth (e.g. cold flows)
- mergers
- intrinsic evolution

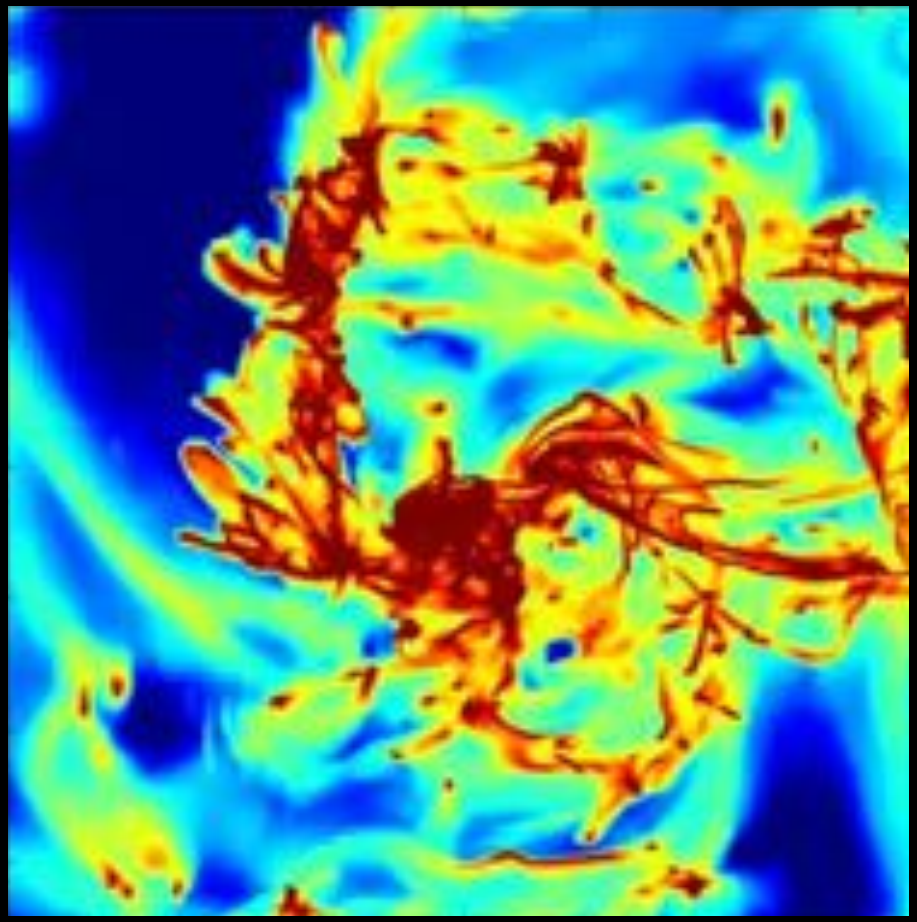
  formation, destruction of thick / thin disk, bulge, bar, spiral ...

EXAMPLE: CLUMPY DISK

Bournaud, Perret, Renaud et al. (2014)
see also Agertz et al. (2009)

Milky Way progenitor at z~2

high gas fraction (50%)
→ violent disk instabilities



Simulation:

- AMR (RAMSES), 3D, Hydro + Gravity (gas+stars+DM)
- 4 pc resolution over $(35\ \mathrm{kpc})^3$
- Star formation + feedback (HII, radiative pressure, SNe)

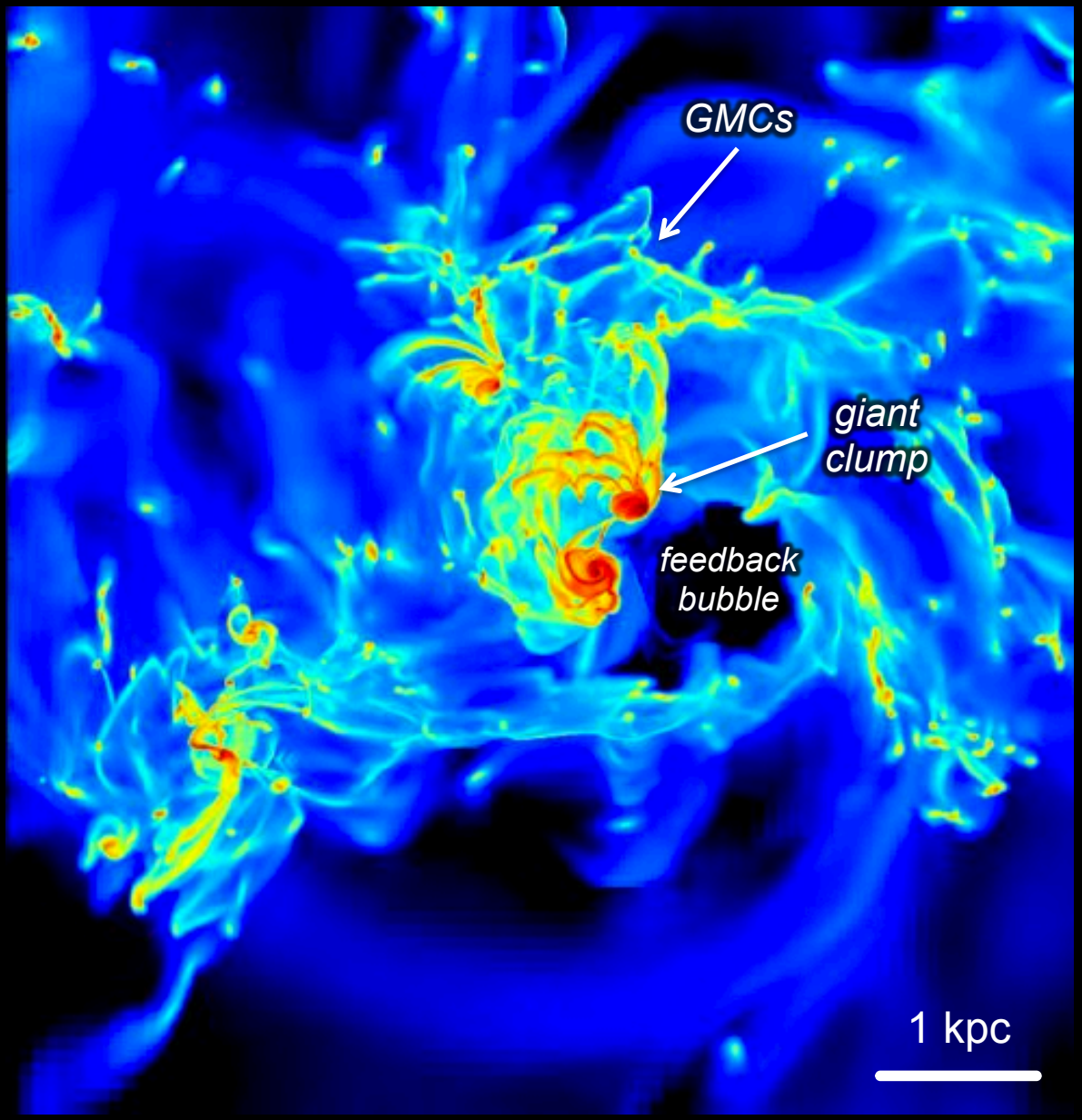
Formation of Massive Clumps in the Disk

Giant clumps
($10^{8\text{-}9} M_\odot$)

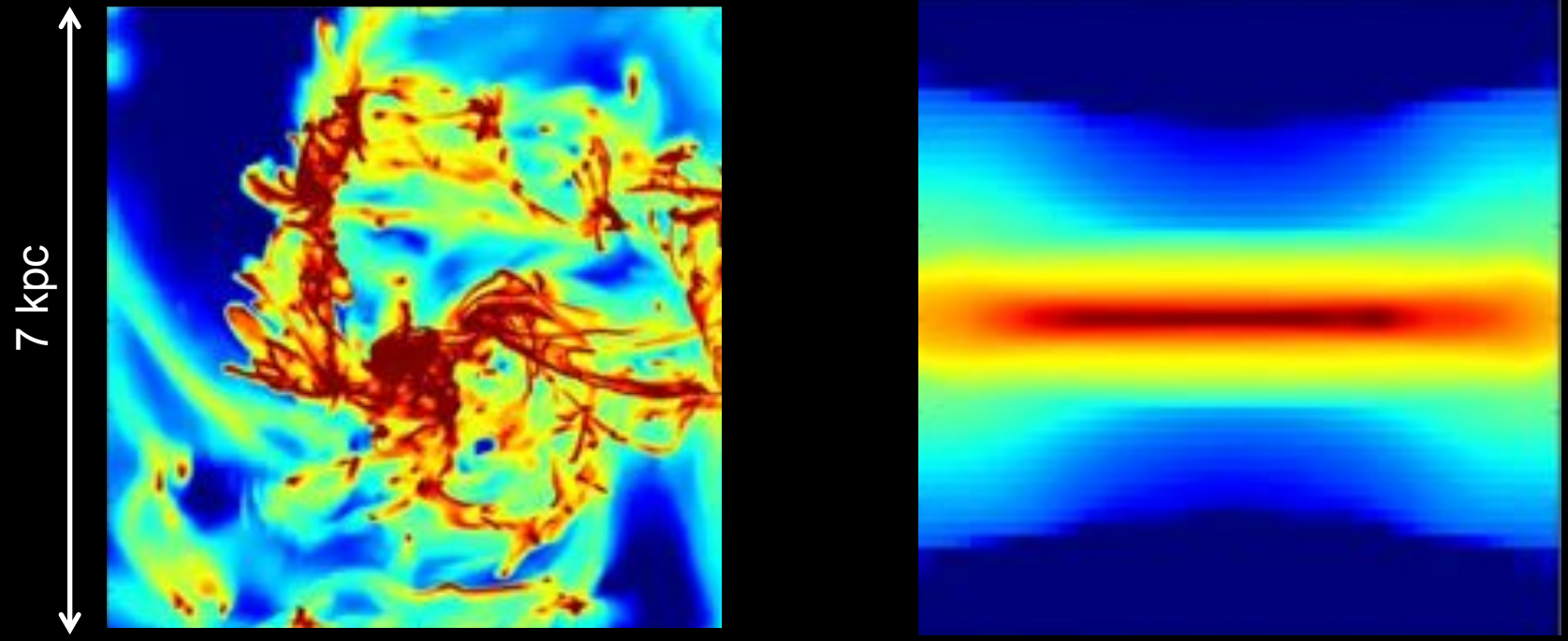
Giant molecular clouds
($10^{5\text{-}7} M_\odot$)

intense star formation:
up to 5 $M_\odot$/yr in giant clumps

→ Formation of massive clusters in the disk



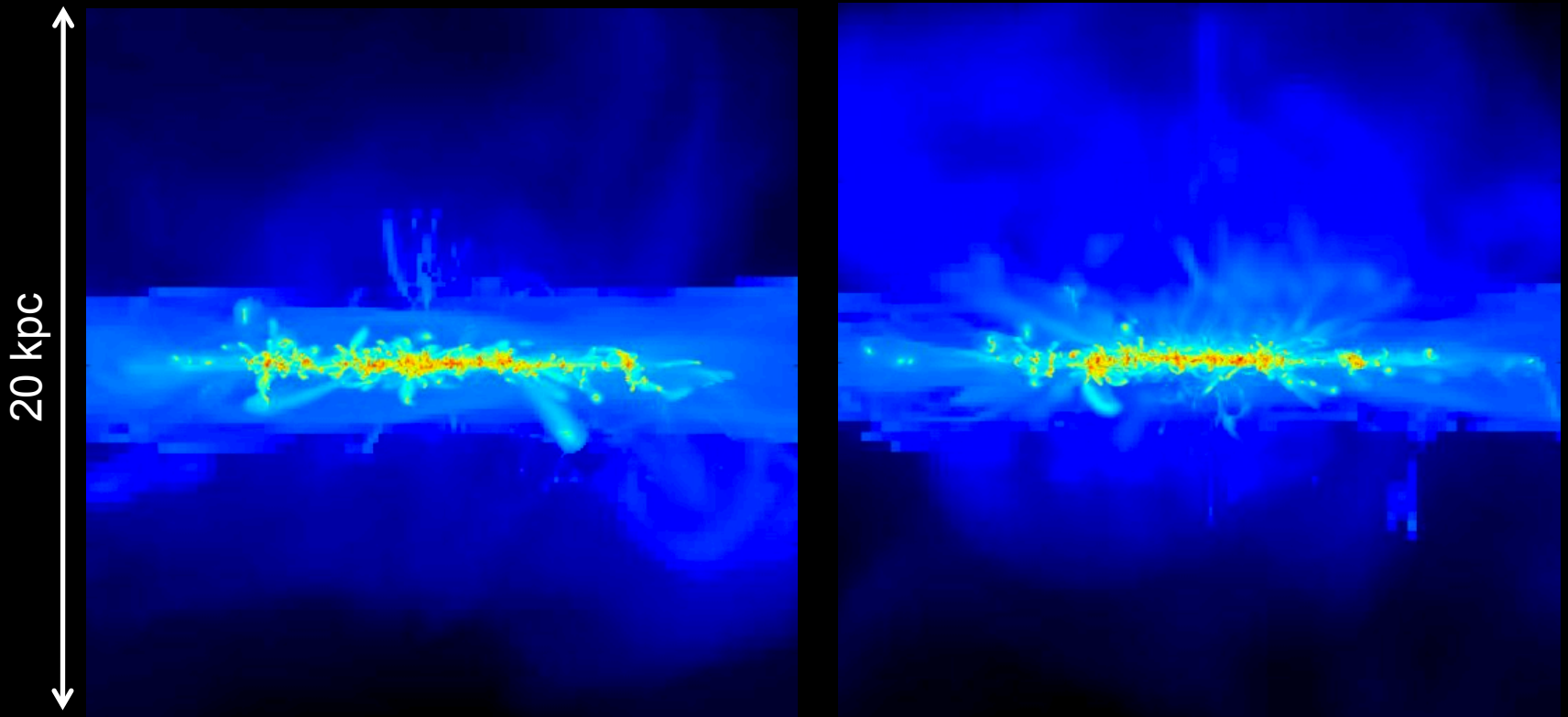
VERTICAL STRUCTURE



high SFR (50 $M_{\odot}$/yr over the galaxy)
→ strong stellar feedback

Disk Thickening

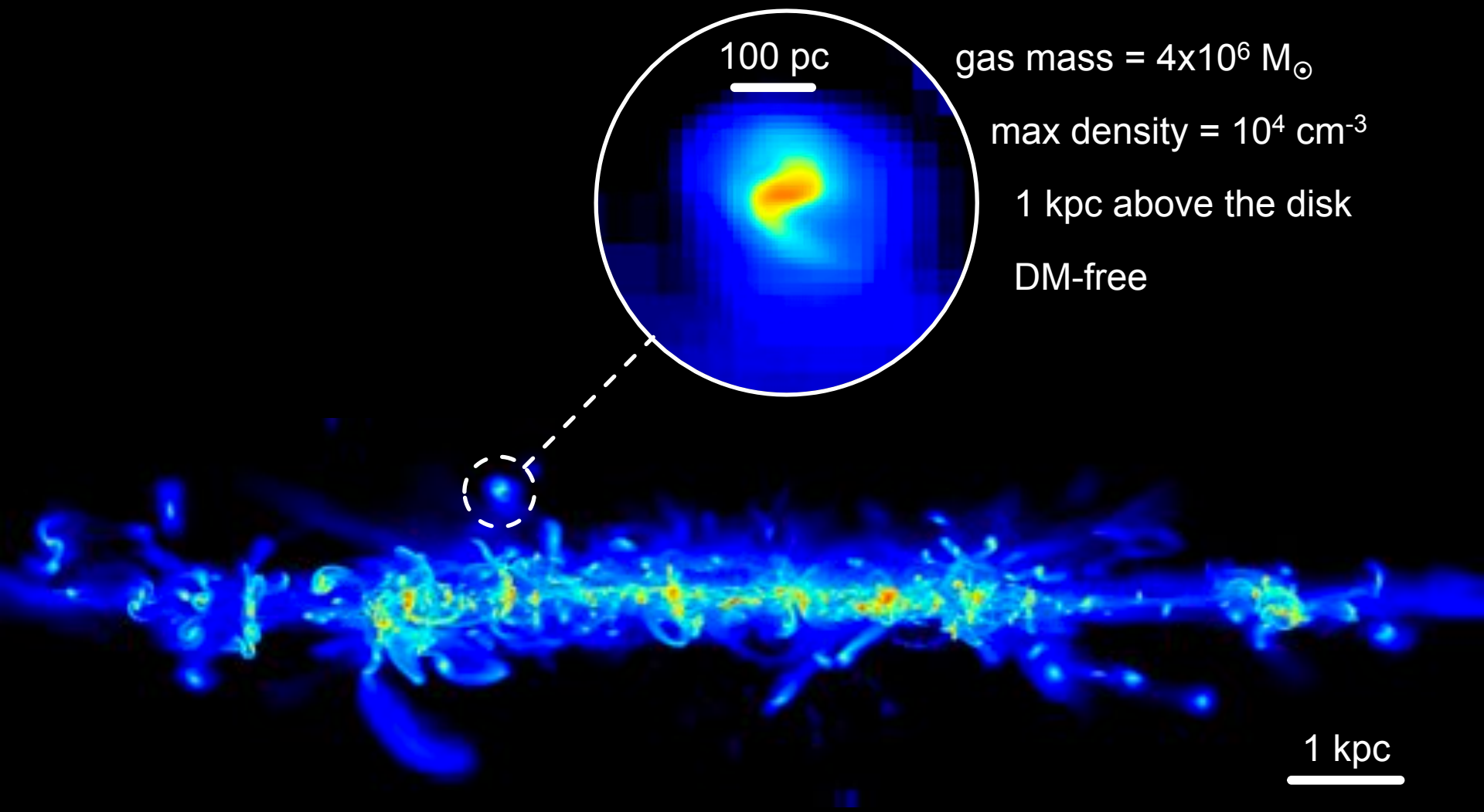
Renaud et al. (in prep.)



15 Myr later

Ejection of mostly diffuse, warm gas, but ...

EJECTION OF GMCS



Already several cases in one snapshot

→ off-disk GC formation?

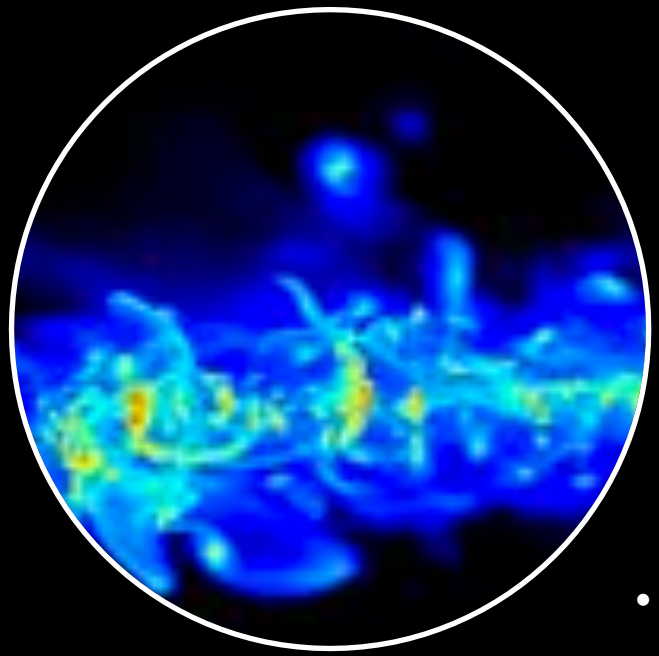
Early formation of Massive Clusters

- accretion and stripping form dwarf satellites

  but GCs in the MW halo are too metal rich

  Larsen et al. (2014)

- in the disk (massive clumps)
- in a thicker structure



Two clusters in the tidal streams of a dwarf galaxy orbiting a DM halo
(simulation by J. Peñarrubia)

- remnants of super-star clusters formed in mergers

YET ANOTHER SIMULATION OF THE ANTENNAE

THE ANTENNAE

Renaud et al. (in prep.)
(simulation used in Renaud et al. 2014)

gas

new stars

2 kpc

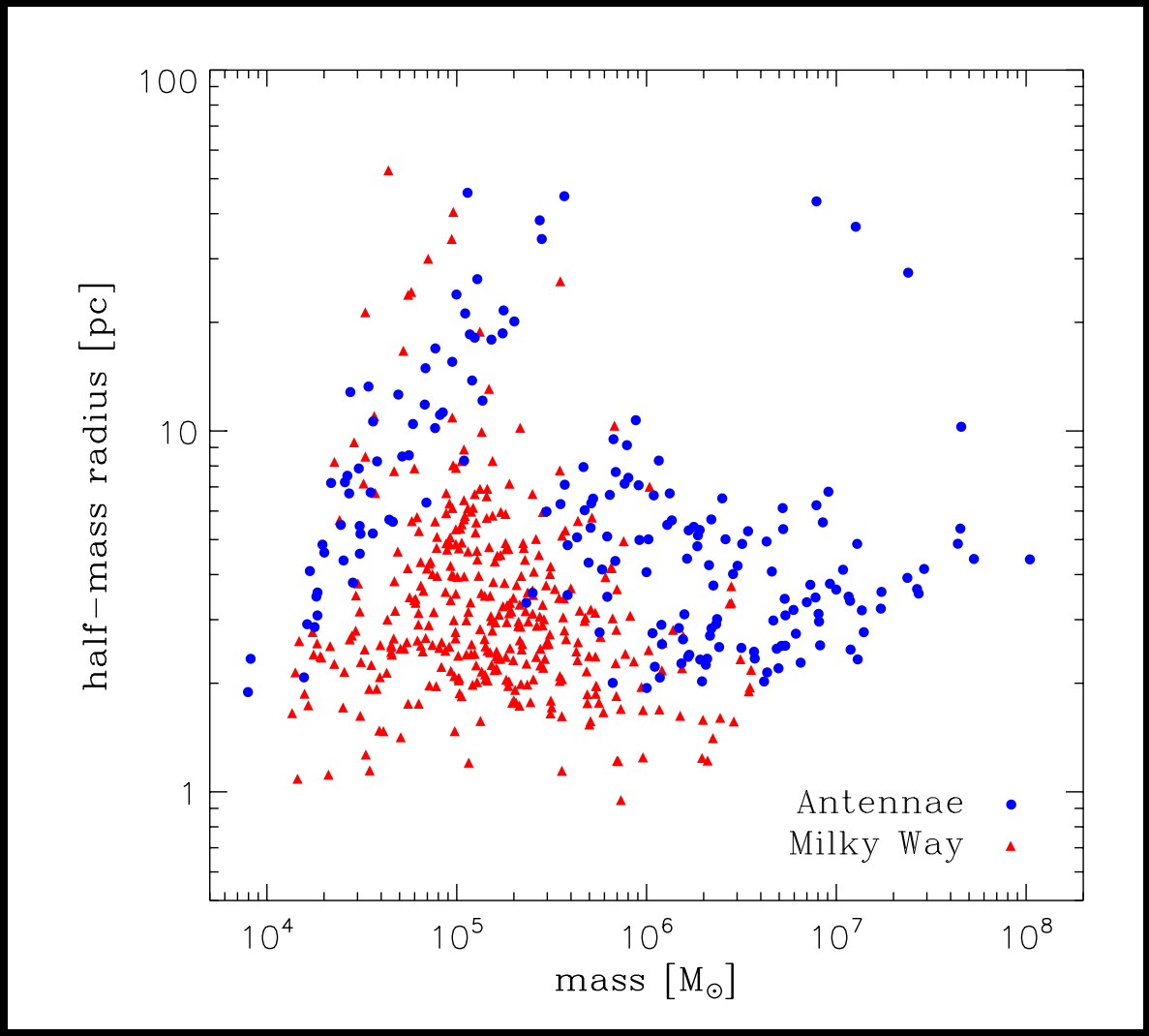
Ask me about the physics of starbursts!

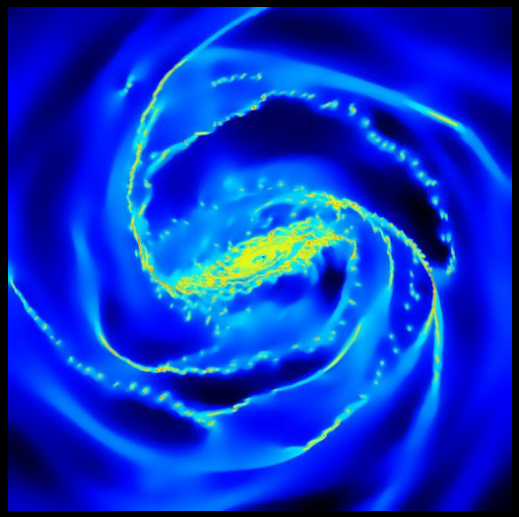
Simulation: same as before but 1 pc resolution over (200 kpc)

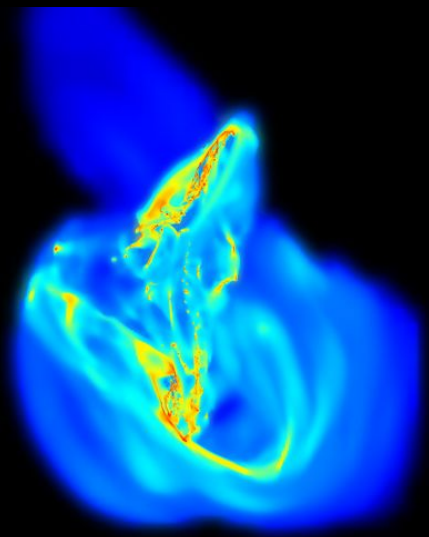
FORMATION OF SSCs

Comparison with a (sub-parsec resolution) Milky Way simulation

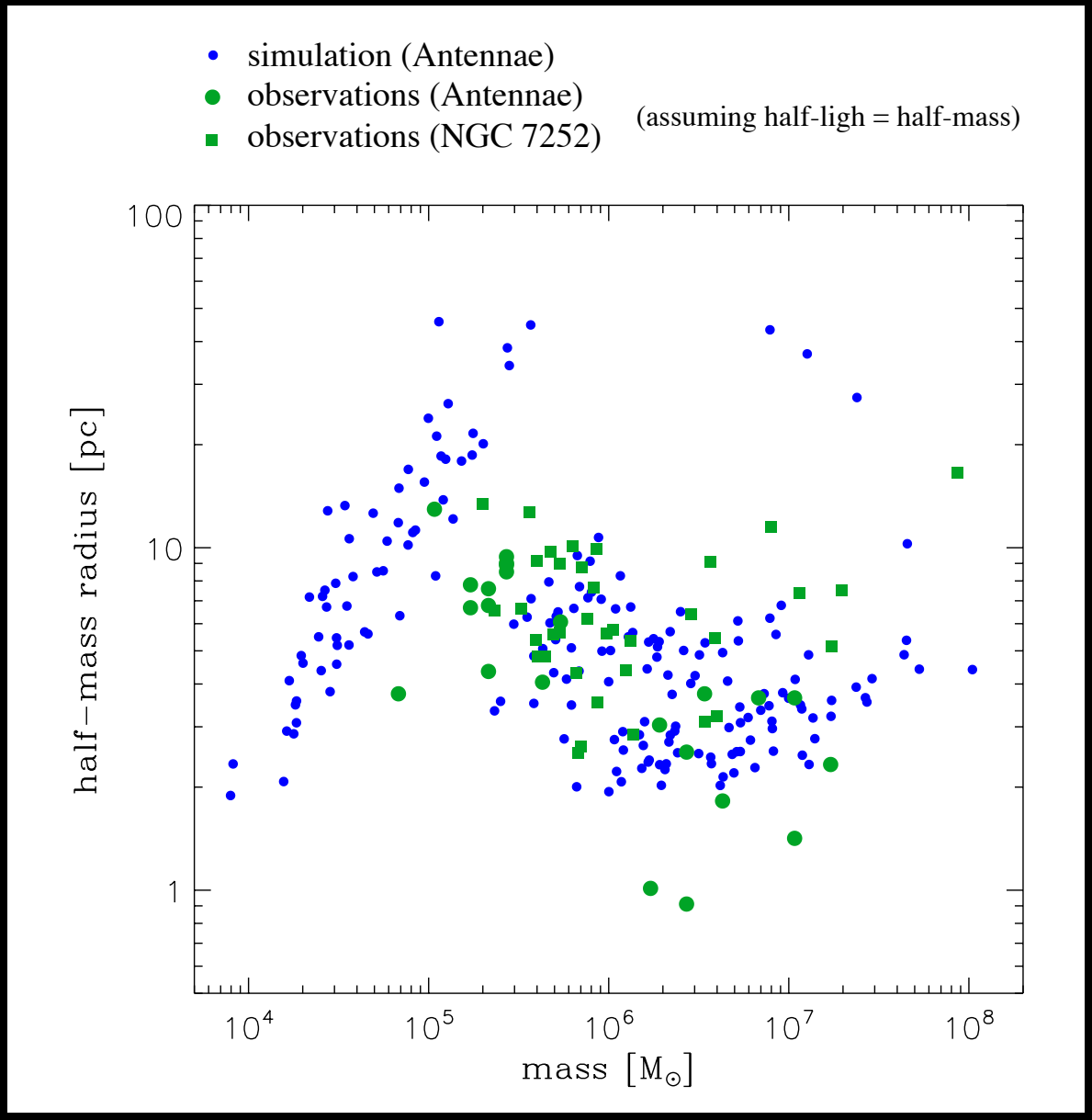
Renaud et al. (2013)







Comparison with Observations of YSCs



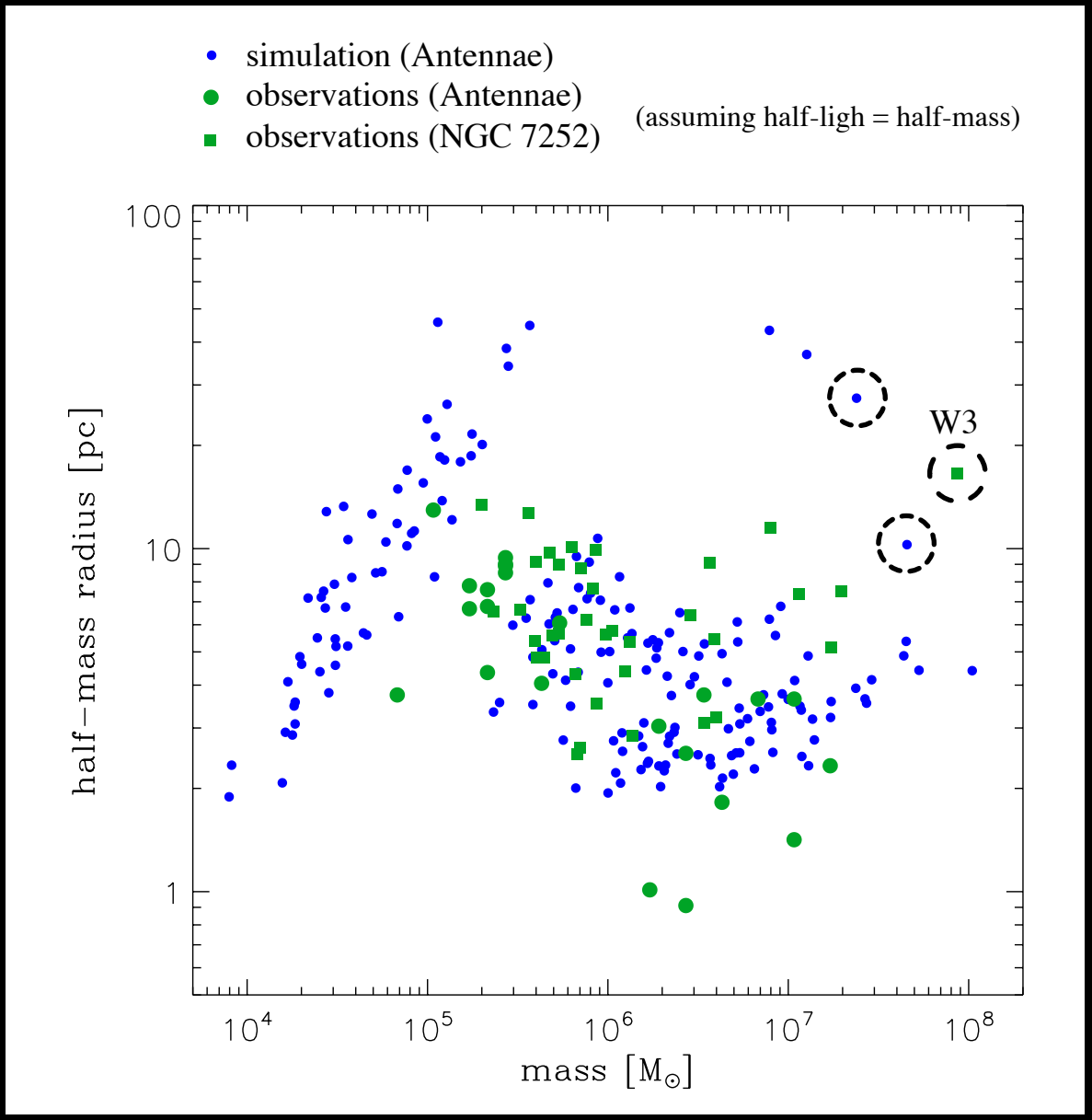
in the Antennae

Mengel et al. (2008)
Bastian et al. (2009)

in NGC 7252

Bastian et al. (2013)

W3



- compact (4 pc) all its life
- but fly through the center of the merger and get extended

- massive cloud
- forms at 4 kpc
- 1.5 $M_\odot$/yr for 30 Myr

No hierarchical sub-clouds

Fellhauer & Kroupa (2005)
Bonnell et al. (2003)

Survival of Clusters

Several ways to form (massive) star clusters early

At least some have to survive to be detected today

Internal effets:

- gas expulsion
- secular evaporation (fueled by two-body relaxation)

External effets:

- tidal stripping
- collisions (?)

Star Clusters in Time-dependent Tidal Fields

In the inertial ref. frame:

$$\frac{\mathrm{d}^2\mathbf{r}}{\mathrm{d}t^2} = -\nabla\phi_{\mathrm{c}}(\mathbf{r}) + \mathbf{T}(\mathbf{r})\mathbf{r} + \nabla\phi_{\mathrm{G}}(\mathbf{0})$$

from a star cluster simulation

from a galaxy simulation

tidal tensor:

$$\mathrm{T}^{ij} = -\frac{\partial^2\phi_{\mathrm{G}}}{\partial x^i \partial x^j}$$

Tides

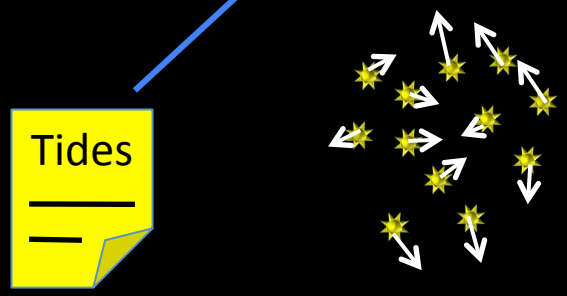
Renaud, Gieles & Boily (RGB), 2011

For comparable approaches, see also
Rieder et al. (2013)
Brockamp et al. (2014)

ADDING THE "TT" TO NBODY6

N-body simulation of the cluster: Nbody6 Aarseth 2003, Nitadori & Aarseth 2012

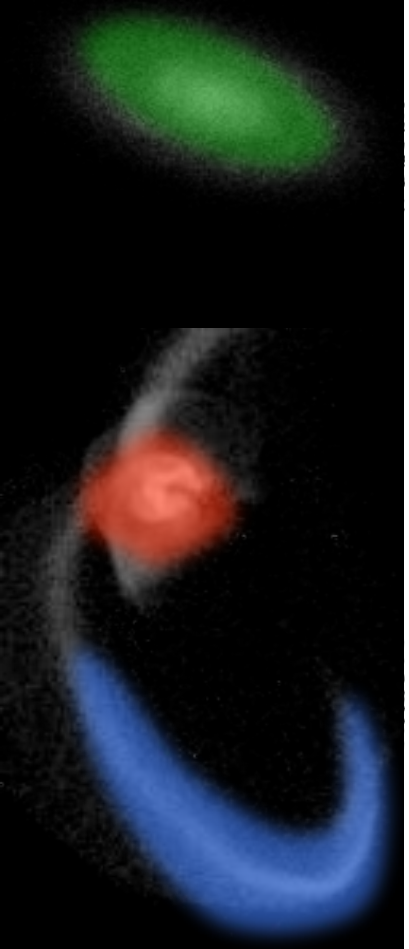
$$\frac{\mathrm{d}^2\mathbf{r}}{\mathrm{d}t^2} = -\nabla\phi_\mathrm{c}(\mathbf{r}) + \mathbf{T}(\mathbf{r})\cdot\mathbf{r}$$

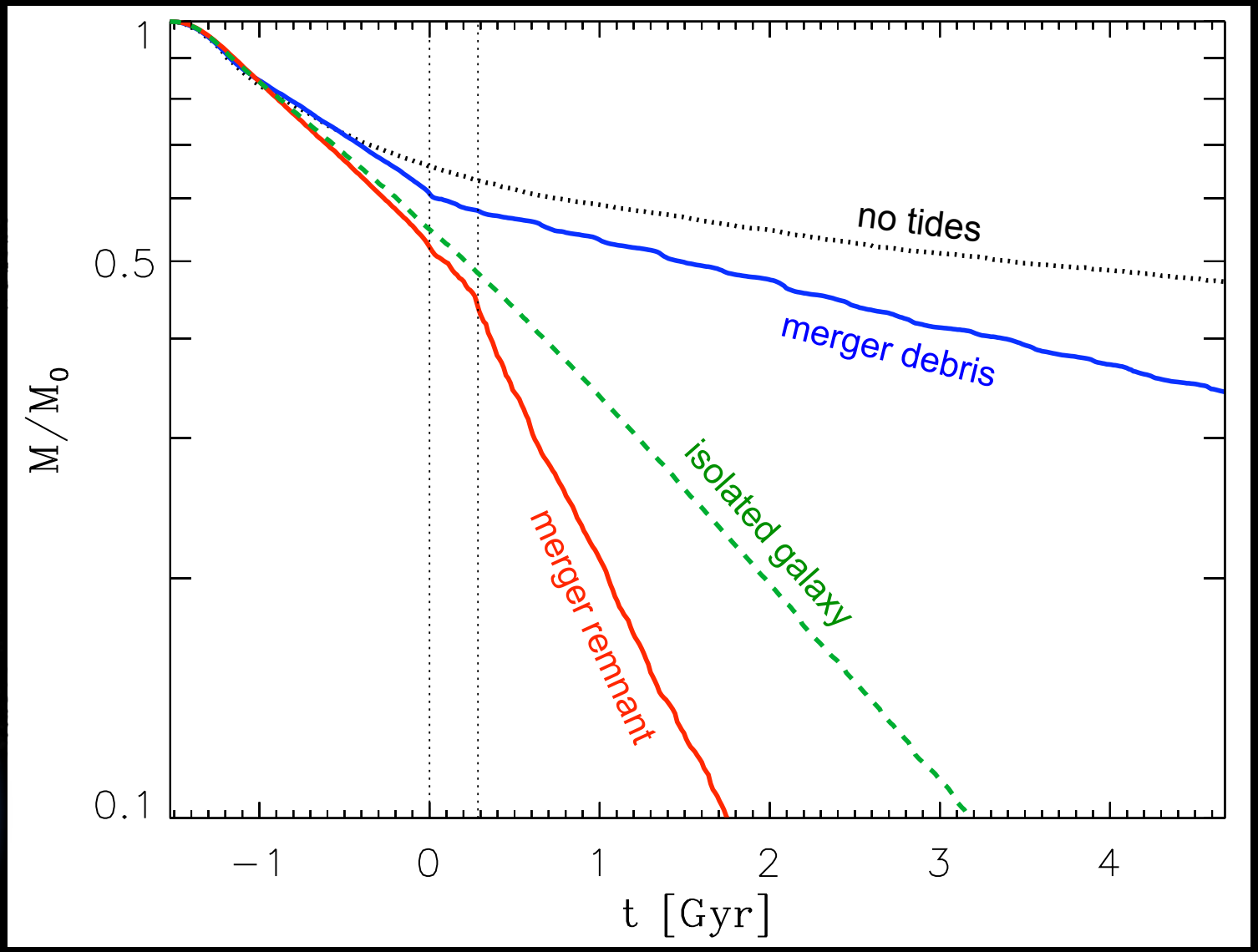


Sum of the internal and external forces: Nbody6tt

available online (google it!)

Population of Orbits and Star Clusters





~ 700 Nbody simulations

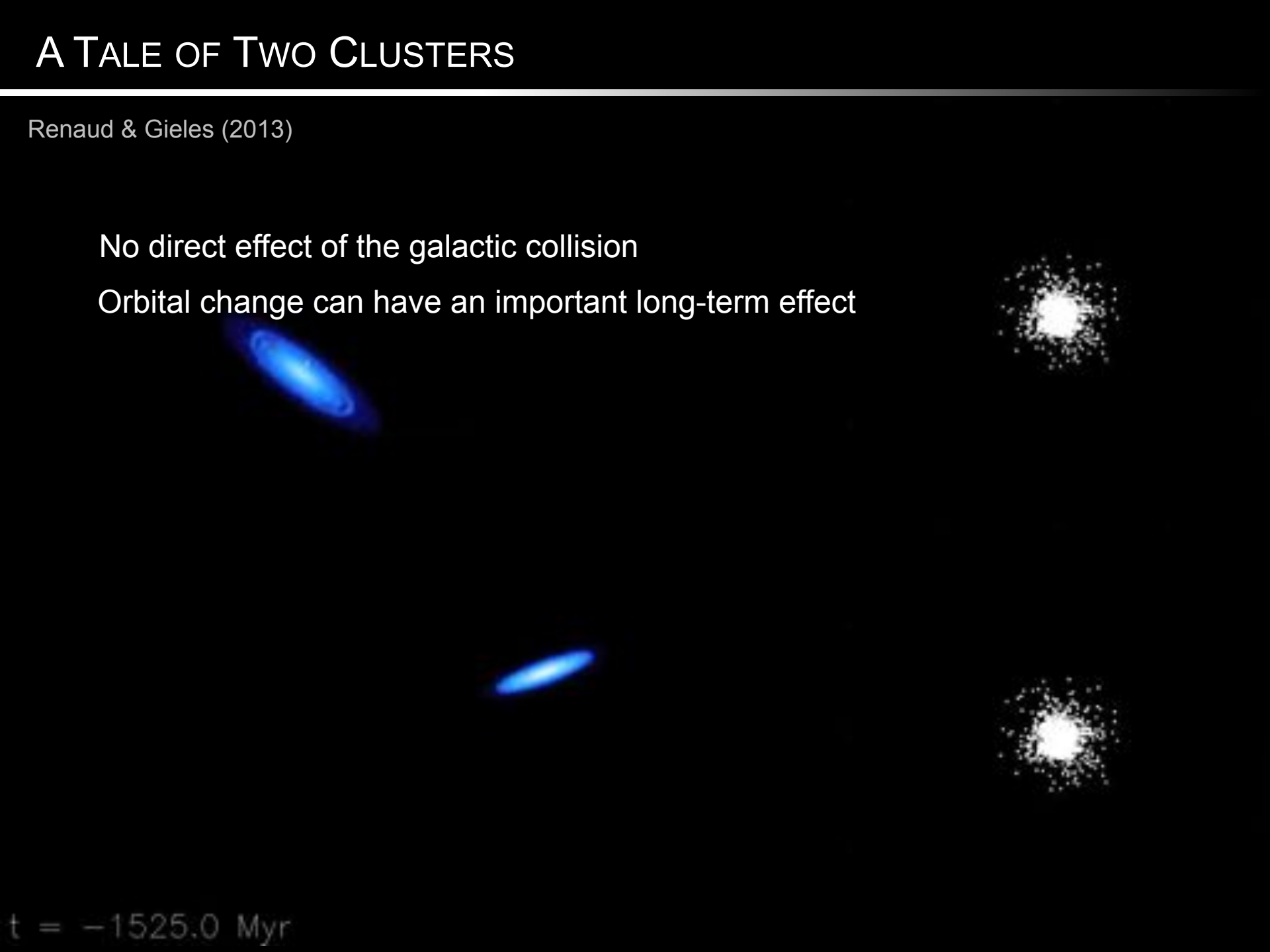
Renaud & Gieles (2013)

A Tale of Two Clusters

Renaud & Gieles (2013)

No direct effect of the galactic collision

Orbital change can have an important long-term effect



SUMMARY

Role of the galactic environment on (massive) star clusters

- Early formation in massive gas clumps (Clumpy disks)
- Early formation in thick disk / halo (via feedback)
- Early AND continuous formation of SSCs in mergers
- Survival to mergers: indirect effet (via orbital change)