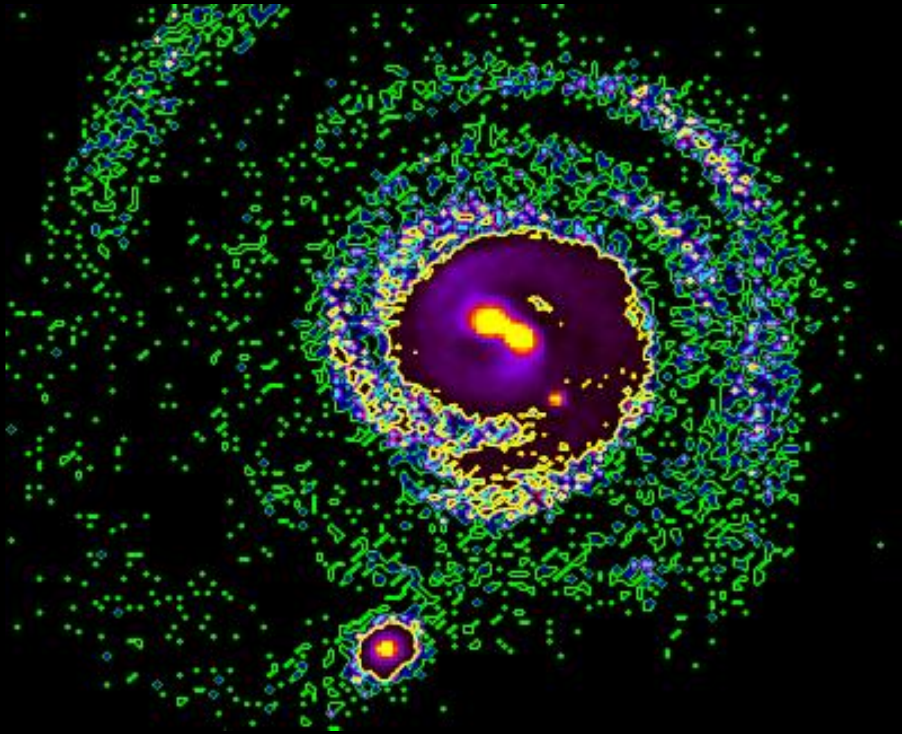
# The MEGaN project: investigating the evolution of galactic nuclei and their environment



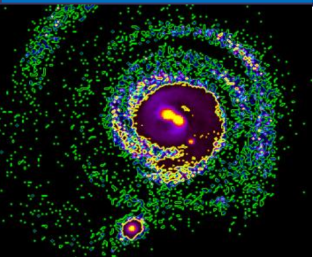
Stellar aggregates over mass and spatial scale

*Physikzentrum Bad Honnef*

*Decemeber 5-9, 2016*

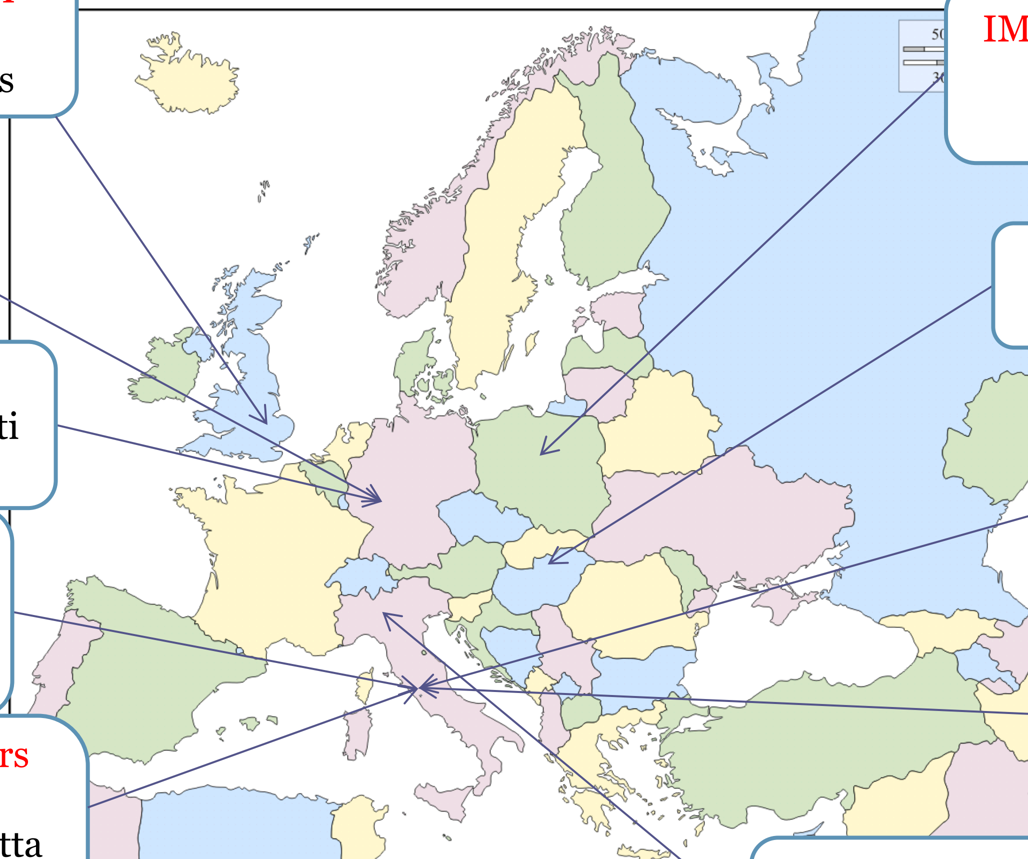
*Manuel Arca Sedda*

*Università di Roma – Sapienza*



# The MEGaN project: modelling the evolution of galactic nuclei

funded by the University of Rome Sapienza through the grant 52/2015



**IMBH-SMBH interactions**
A. Gualandris

**SMBHB evolution**
R. Spurzem
P. Berczik

**Nuclear Clusters**
A. Mastrobuono-Battisti
I. Georgiev

**Nuclear and star clusters, galaxies and SMBHs**
R. Capuzzo-Dolcetta

**Dense star clusters and stellar BHs**
R. Capuzzo-Dolcetta
G. Fragione
S. Rastello
I. Tosta e Melo

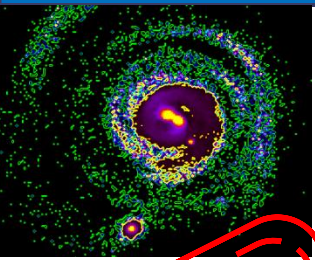
**IMBH/BH sub. formation**
M. Giersz
A. Askar

**BHs and BHBs evolution**
B. Kocsis

**Galaxy clusters and SMBH interactions**
M. Donnari
M. Merafina

**Star clusters evolution**
M. Montuori

**TDEs and dwarf galaxies**
M. Colpi
M. Dotti

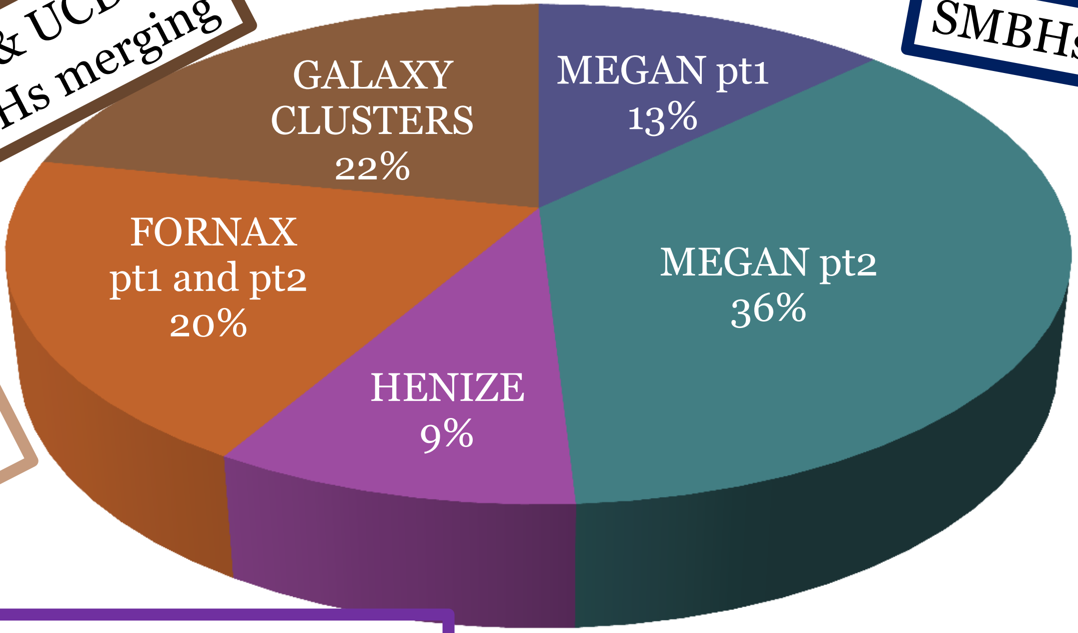


# The MEGaN project: modelling the evolution of galactic nuclei

funded by the University of Rome Sapienza through the grant 52/2015

See Poster of Martina Donnari

**GPU usage: 109028 hours**
**Tot. No. sim. = 23**



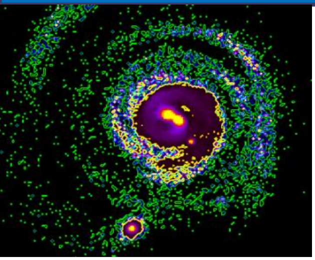

BCGs & UCDs
SMBHs merging

SMBHs + GCs

GCs+IMBHs+
SMBHs+GN

Dwarf Sphs
NCs
SMBHs
Dark Matter

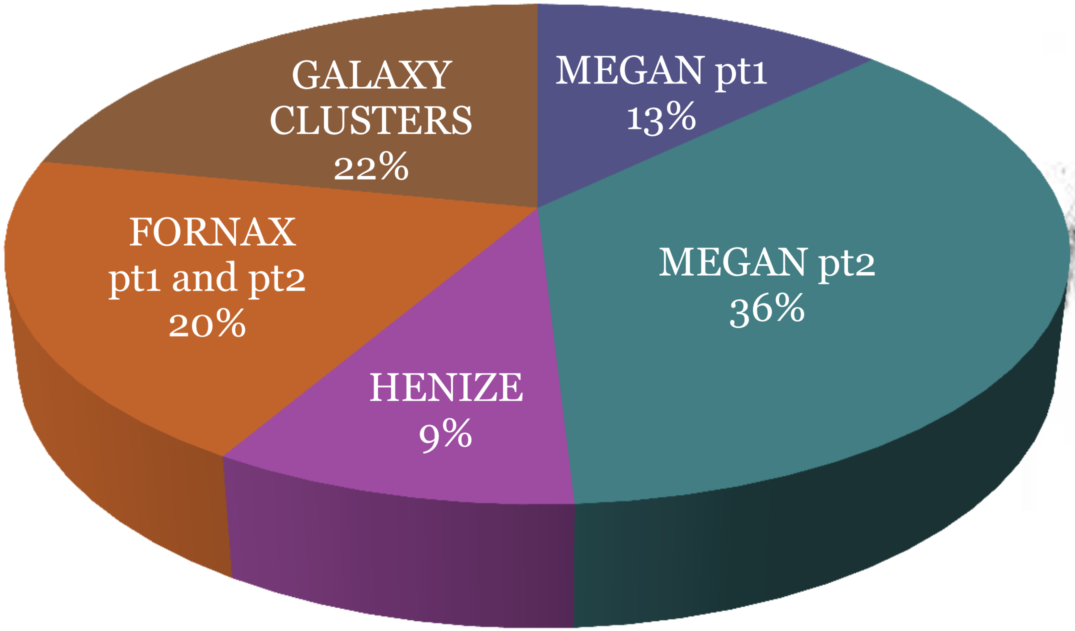
NCs and NSDs formation in starburst galaxies
SMBH pre-existence

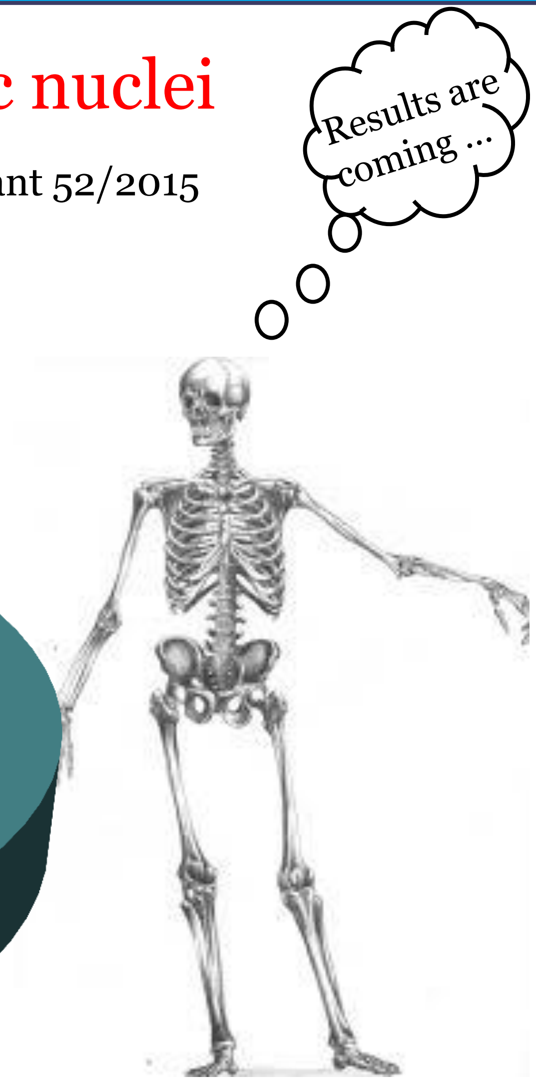


# The MEGaN project: modelling the evolution of galactic nuclei

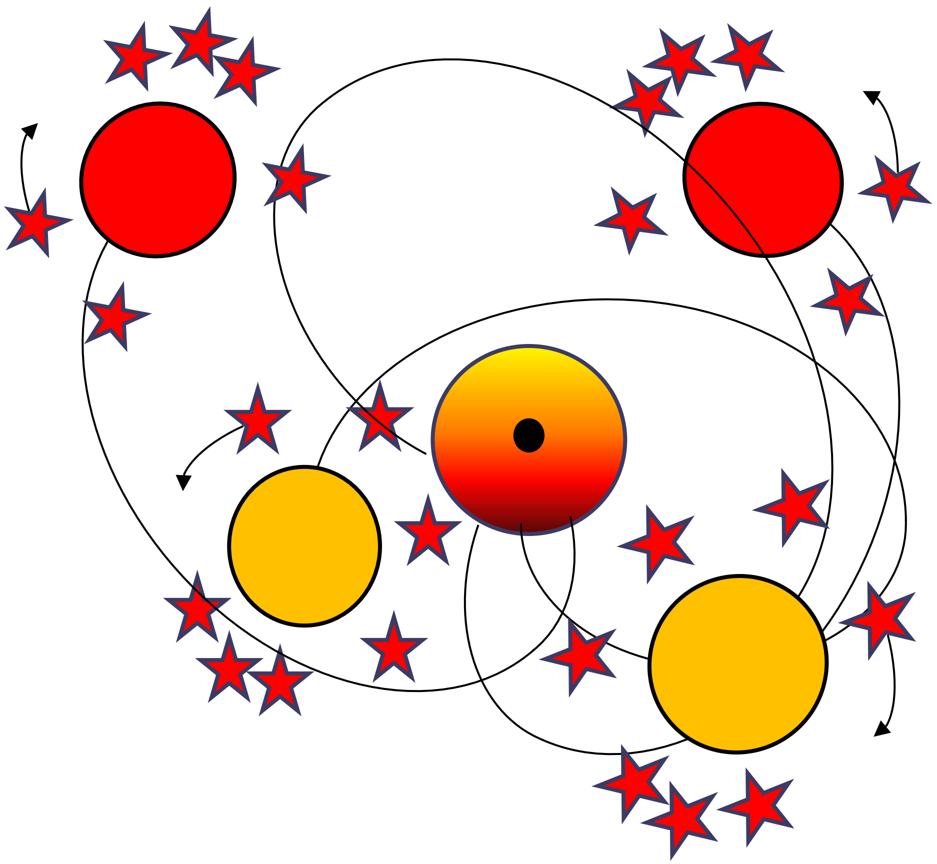
funded by the University of Rome Sapienza through the grant 52/2015

**1 CPU usage → >10 yrs.**

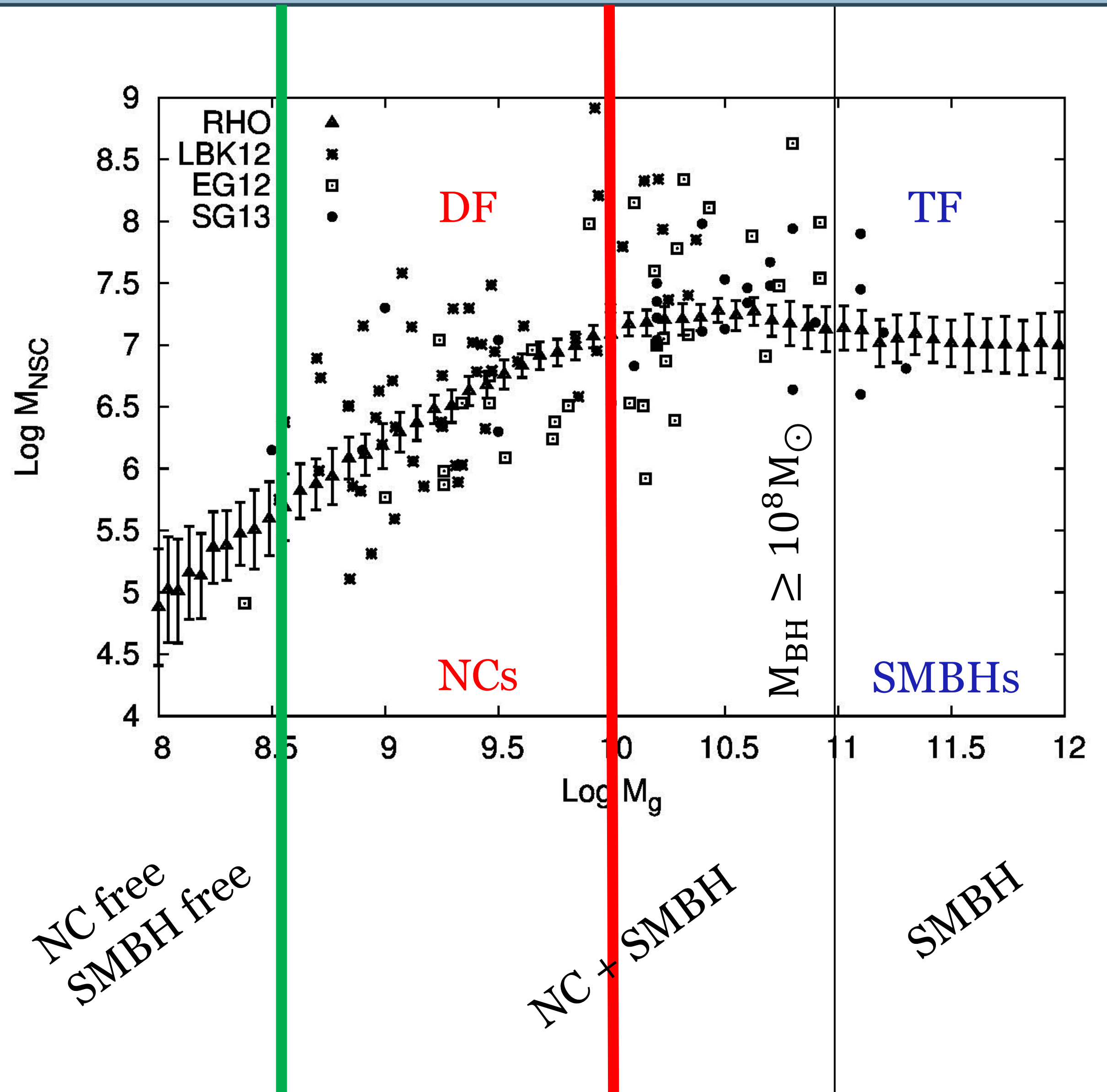


# NCs and SMBHs



# NCs and SMBHs: star clusters infall scenario




✓ Dynamical Friction + Tidal Forces

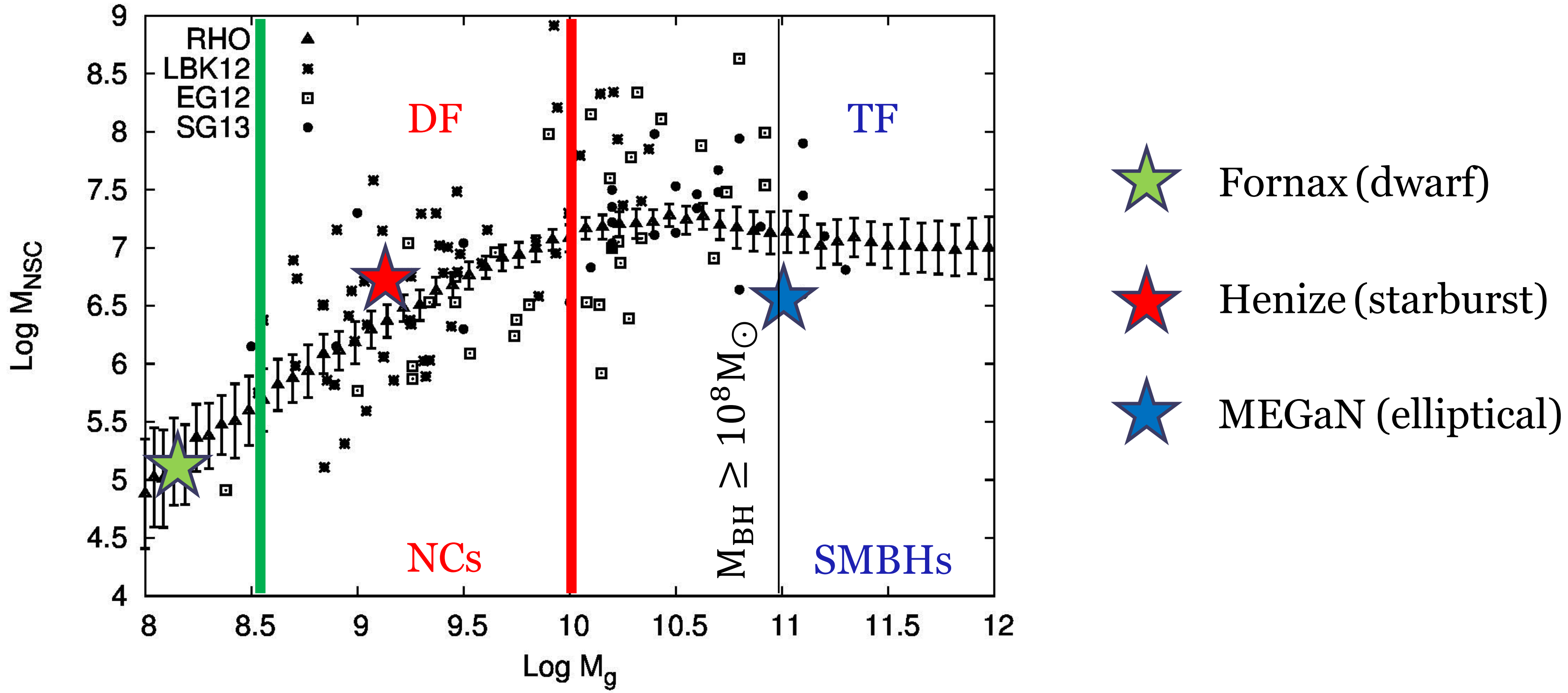
**Arca Sedda M., Capuzzo-Dolcetta R., 2014, MNRAS, 444, 3738-3755c**

Antonini F., 2013, ApJ, 763, 62

Gnedin O., Ostriker J., Tremaine S., 2014, ApJ, 785, 71

See Poster of Iara Tosta e Melo

# NCs and SMBHs: star clusters infall scenario





Arca Sedda & Capuzzo-Dolcetta, 2016, MNRAS, 461, p.4335-4342

Arca-Sedda et al., 2015, Apj, 806, 220

Arca-Sedda et al., 2016, MNRAS, 456, 2457

Arca Sedda & Capuzzo-Dolcetta, 2017, MNRAS,464, 3060

Arca-Sedda & Capuzzo-Dolcetta, in prep.

Arca-Sedda & Capuzzo-Dolcetta, in prep.

# NCs and SMBHs: star clusters infall scenario

**DF**

- ✓ Dearth of NCs and/or SMBHs in dwarf spheroidals;
- ✓ Acquire informations about dSph formation history;
- ✓ Formation of NCs in starburst galaxies;
- ✓ Formation of rotating NSD in middle-weight galaxies;

$M_{BH} \geq 10^8 M_\odot$

**TF**

- ✓ Dearth of NCs in massive galaxies hosting very massive SMBHs;
- ✓ Computational challenge;
- ✓ Strong dynamical feedback from the central SMBH can:
  - ✓ enhance TDEs,
  - ✓ produce HVSs,
  - ✓ force stellar BHBs to merge,
  - ✓ enhance IMBH-SMBH collisions


Arca Sedda & Capuzzo-Dolcetta, 2016, MNRAS, 461, p.4335-4342

Arca Sedda & Capuzzo-Dolcetta, 2017, MNRAS,464, 3060

Arca-Sedda et al., 2015, Apj, 806, 220

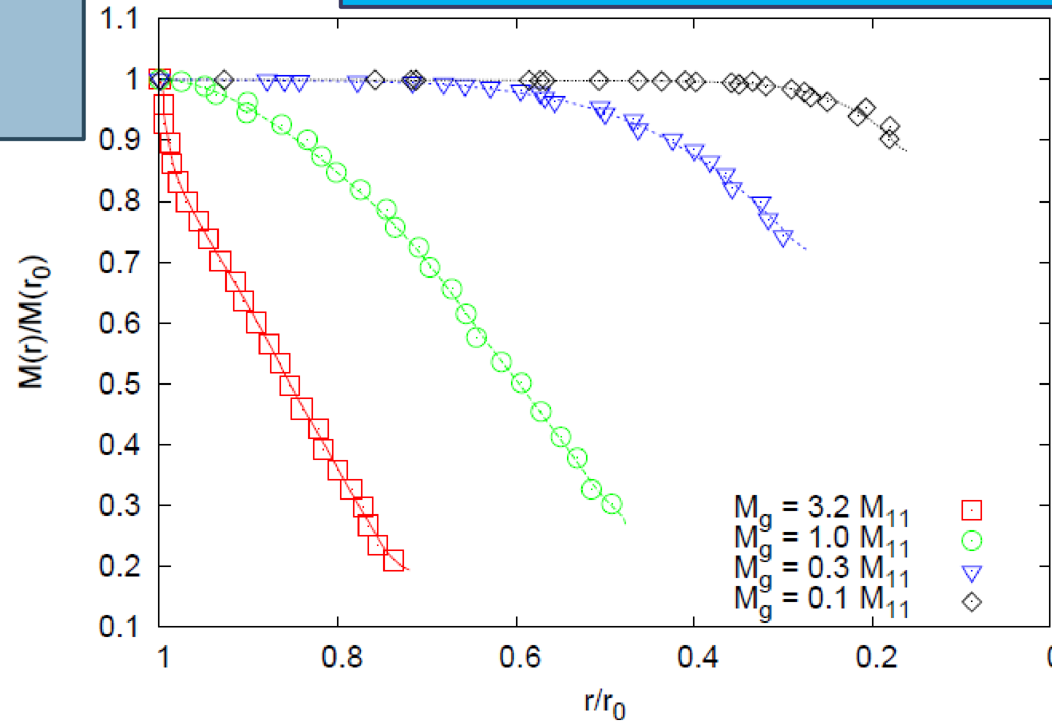
Arca-Sedda et al., 2016, MNRAS, 456, 2457

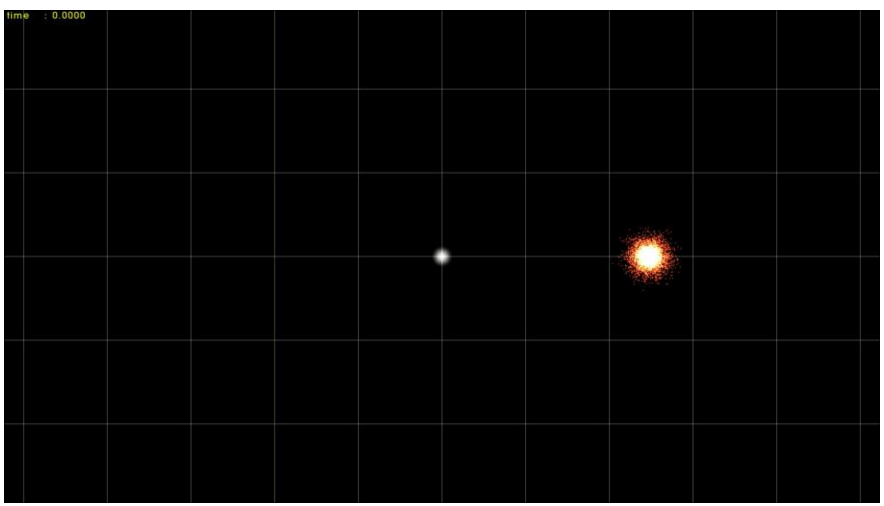
Arca-Sedda & Capuzzo-Dolcetta, in prep.

# The role of SMBHs on the formation of a NC

- ✓ Dynamical friction (DF): clusters transfer some of its orbital energy to field stars, thus moving on even smaller orbits and reaching, eventually, the galactic centre;

- ✓ Tidal forces (TF): tidal forces exerted from the galactic background and/or the central SMBH can disrupt the star clusters as they move on their orbits.





[10] Arca-Sedda et al., 2016, MNRAS, 456, 2457

# The MEGaN simulation: N-body modelling of a massive galactic nucleus

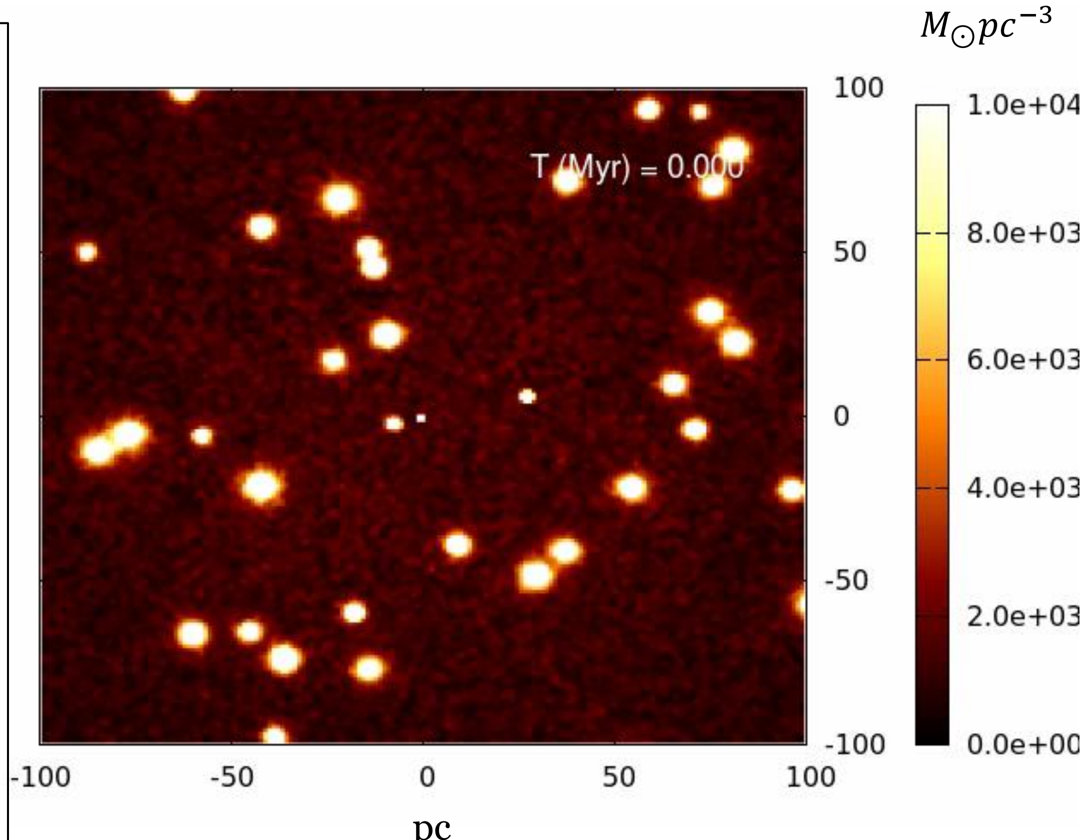
THE MEGaN simulation

- central SMBH mass
  $M_{SMBH} = 10^8 \ M_{\odot}$;

- host galaxy mass:
  $M_g = 10^{11} M_{\odot}$,
  density profile inner slope:
  $\gamma = 0.1$;

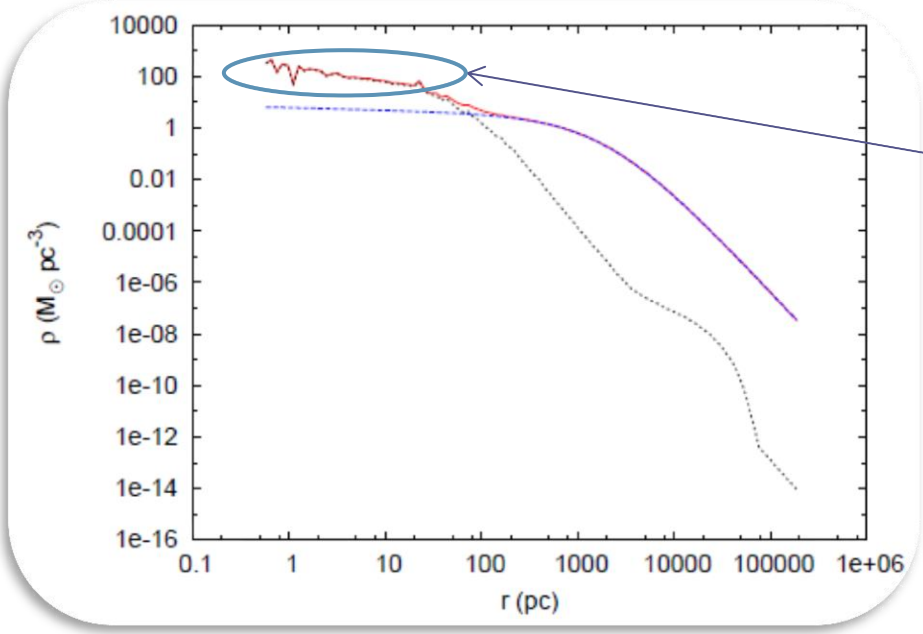
- GCs: No = 42
  masses in the range
  $(0.3 - 2) \times 10^6 M_{\odot}$;

- Total No. of particles > 1M;
- Individual particle mass $10^2 M_{\odot}$ .

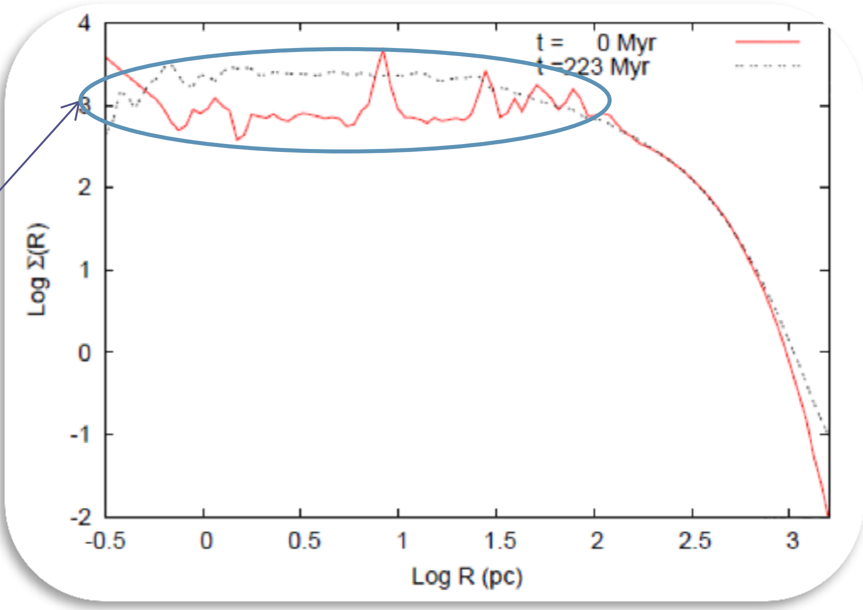


# THE MEGaN simulation: results (1/4)

## Does a nuclear cluster form?



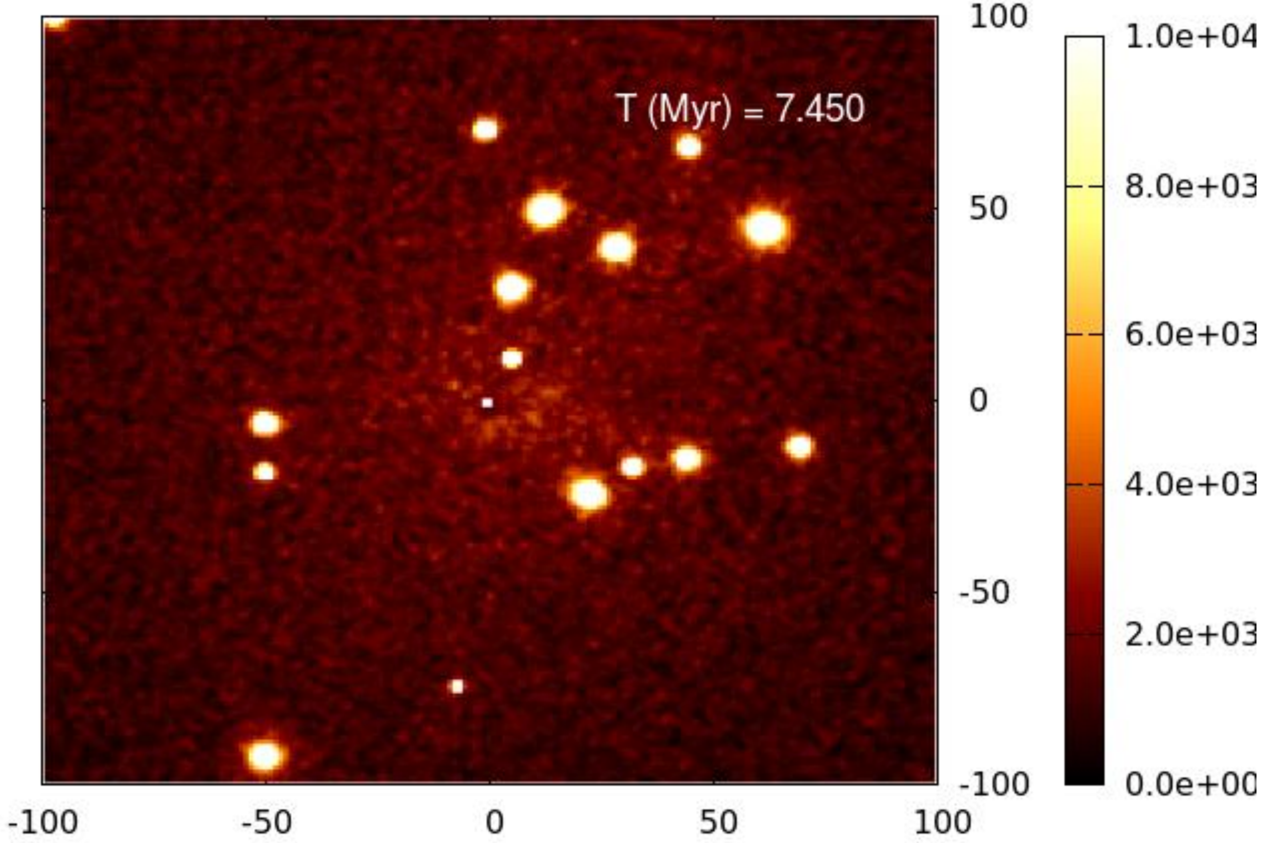

The spatial mass profile seems to highlight the presence of a nucleus that extends over 100 pc (it is not a NC), but ....




... the projected one does not! We do not have any 'observational' evidence of a NC!

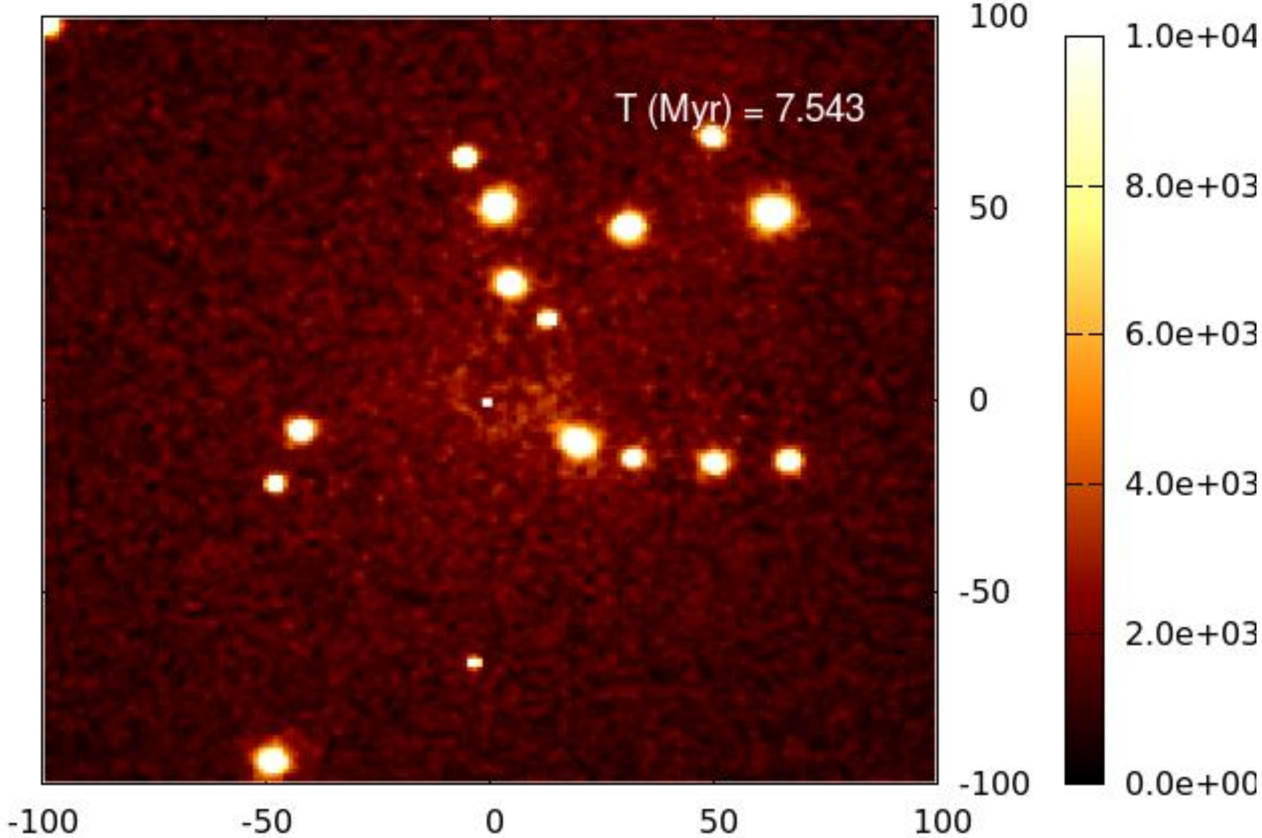
# THE MEGaN simulation: results (2/4)

## Formation of high-velocity stars



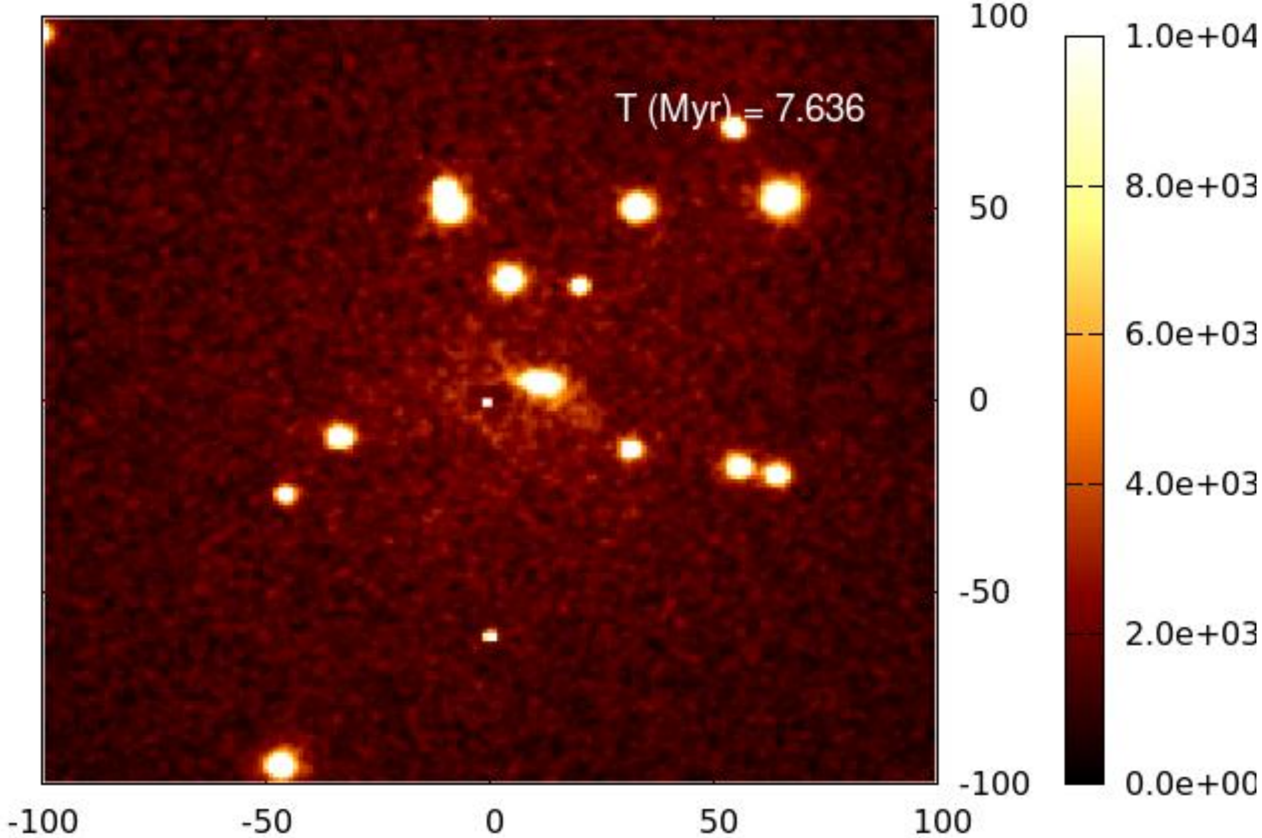
# THE MEGaN simulation: results (2/4)

## Formation of high-velocity stars



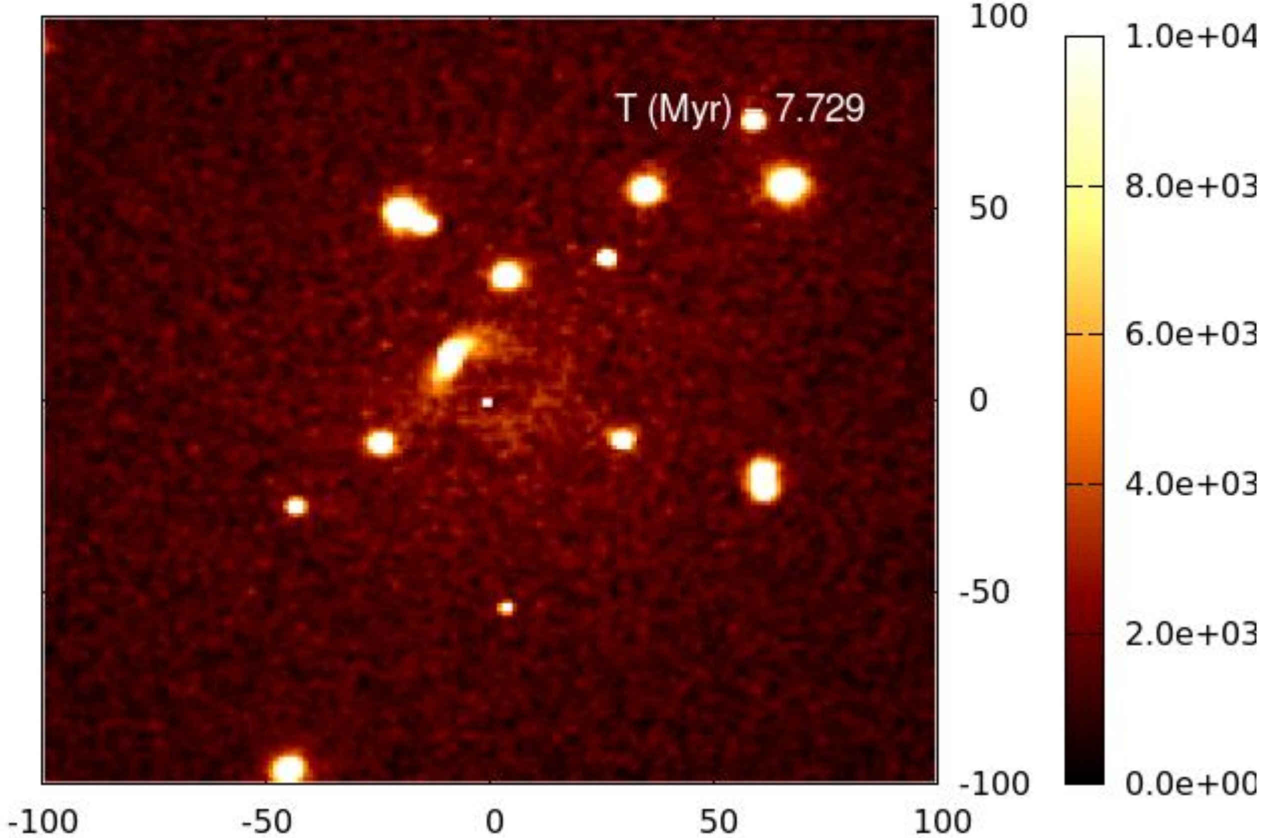
# THE MEGaN simulation: results (2/4)

## Formation of high-velocity stars



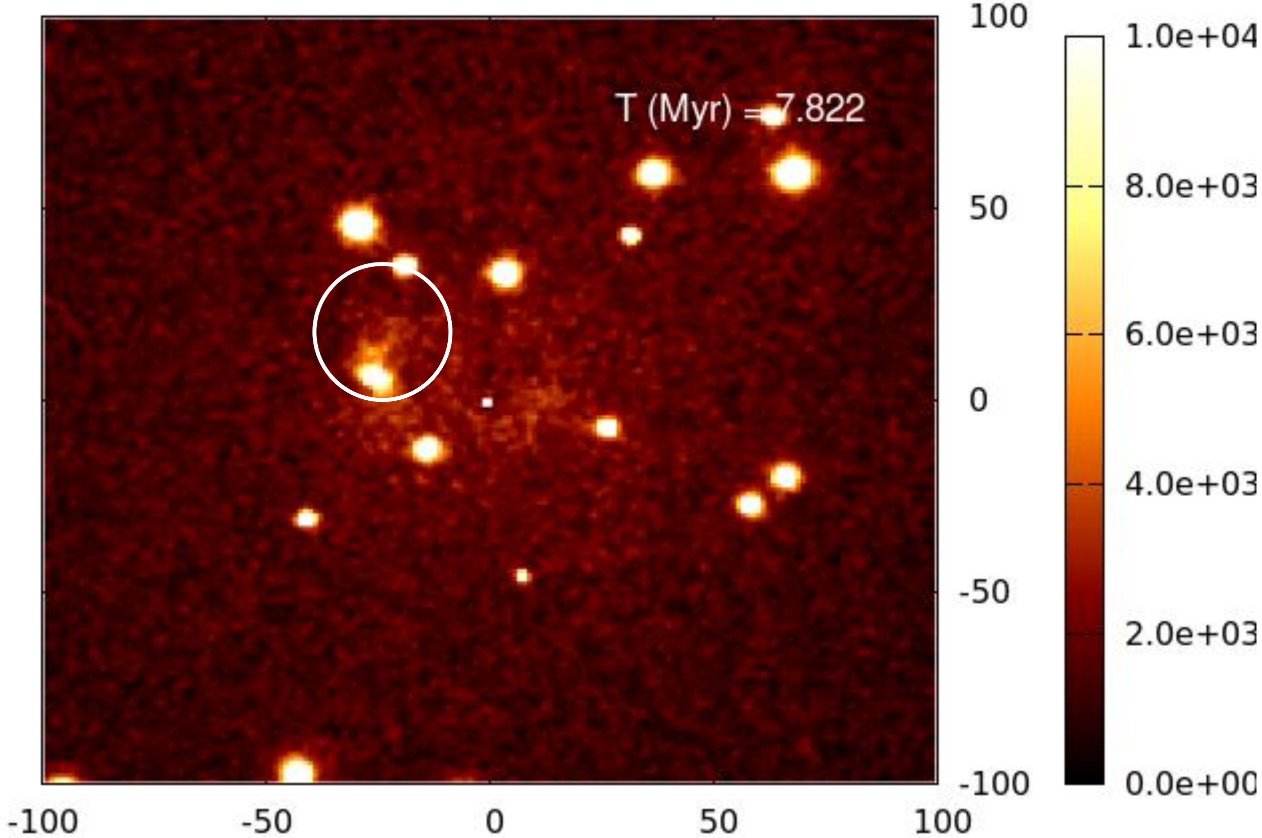
# THE MEGaN simulation: results (2/4)

## Formation of high-velocity stars



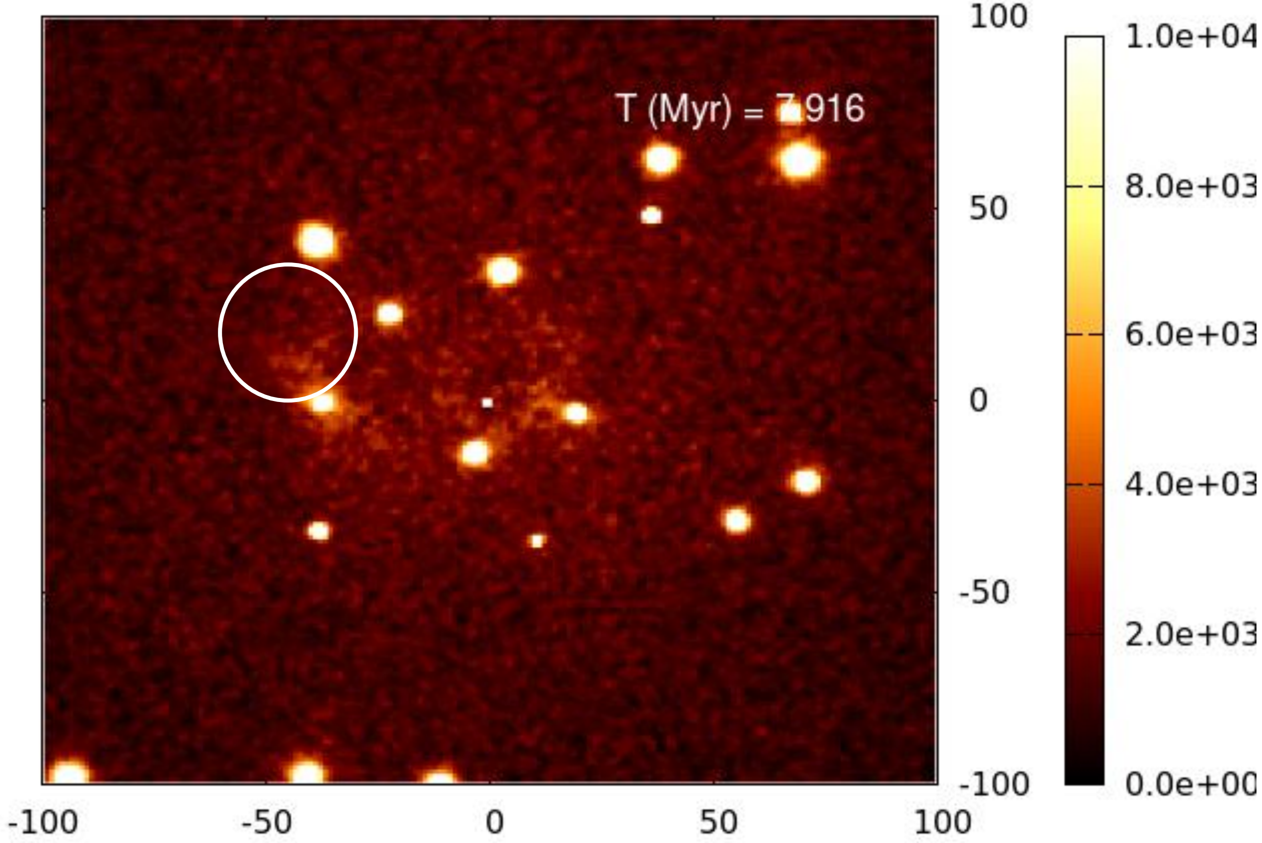
# THE MEGaN simulation: results (2/4)

## Formation of high-velocity stars



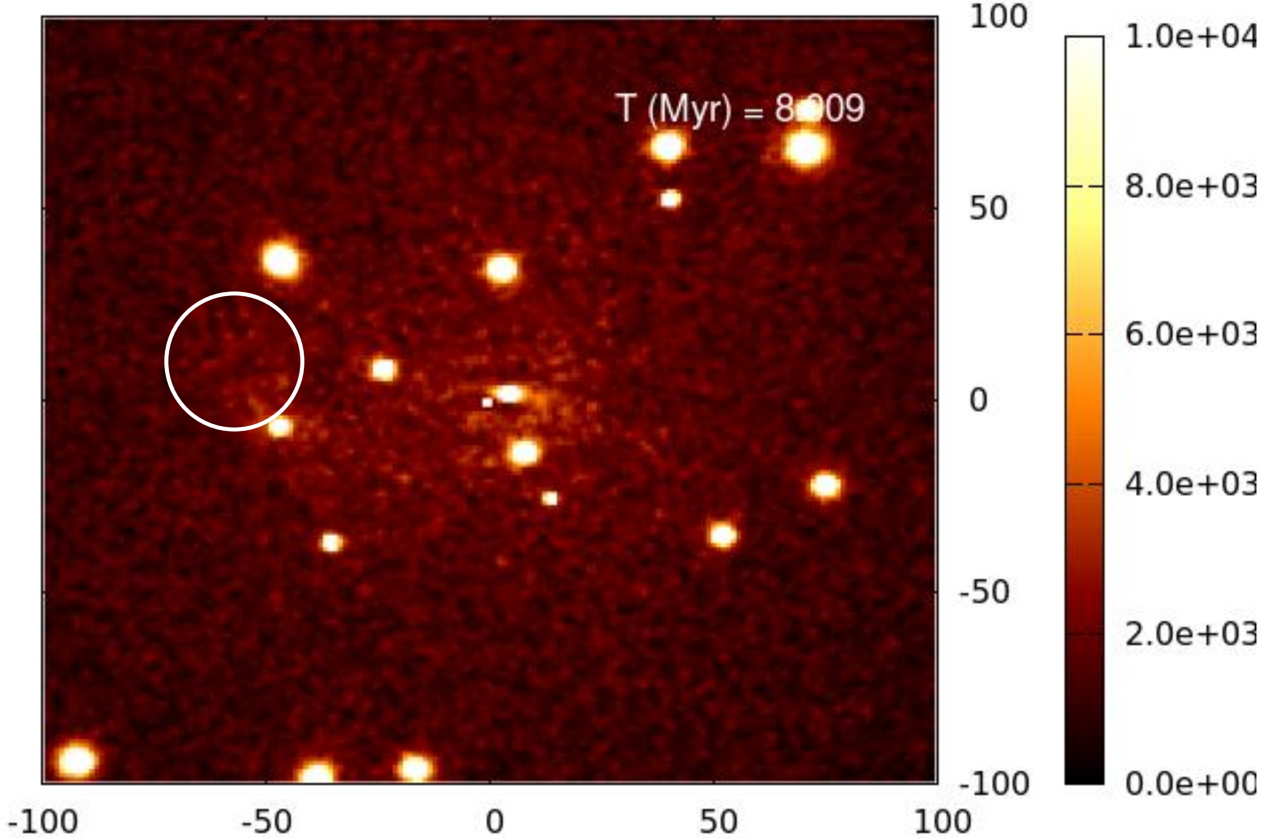
# THE MEGaN simulation: results (2/4)

## Formation of high-velocity stars



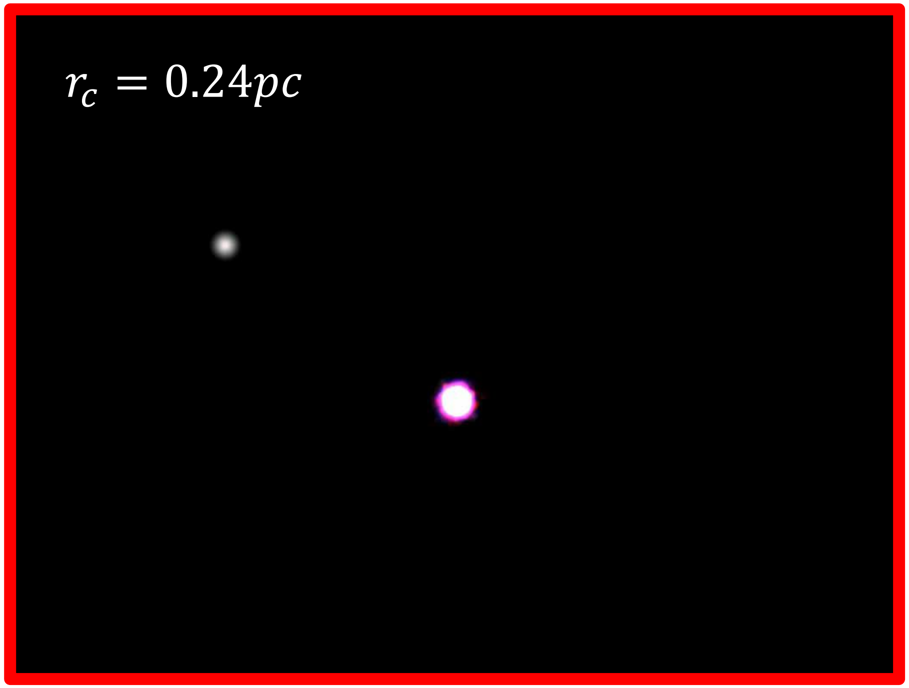
# THE MEGaN simulation: results (2/4)

## Formation of high-velocity stars

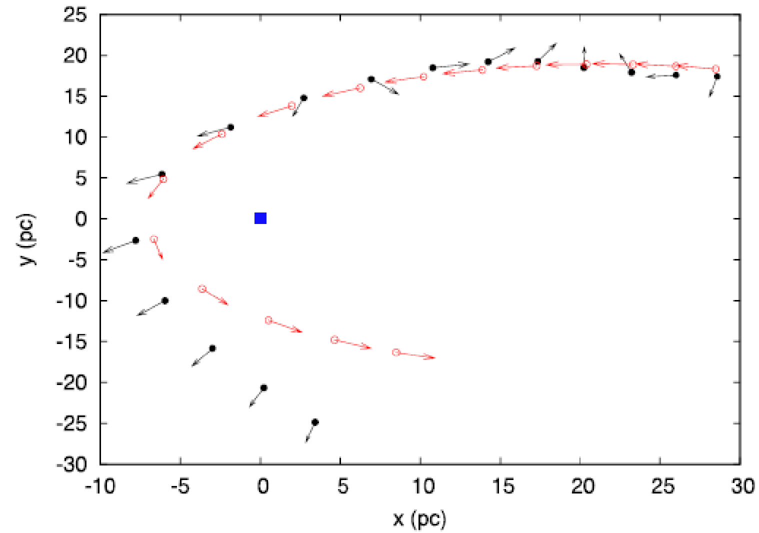


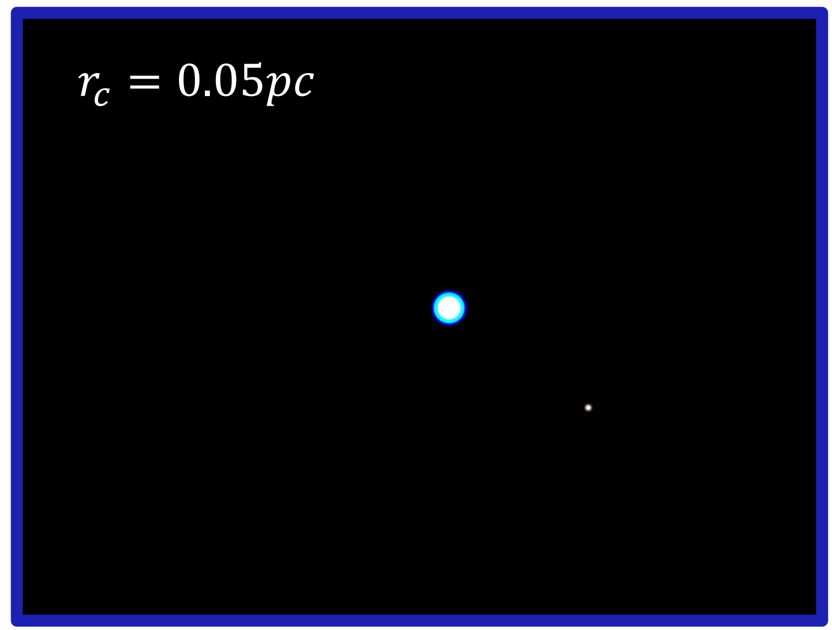
# THE MEGaN simulation: results (2/4)

## Formation of high-velocity stars




100pc



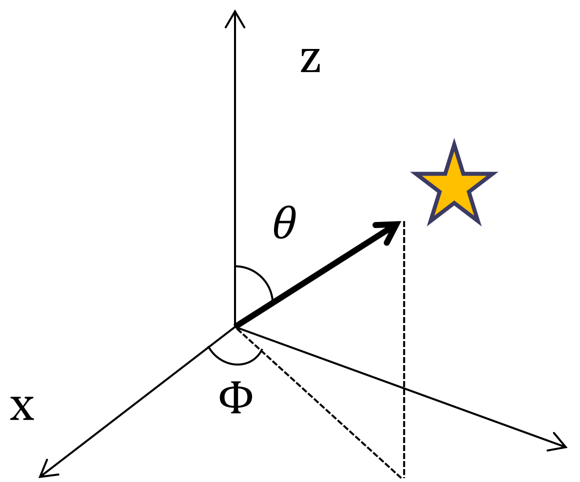



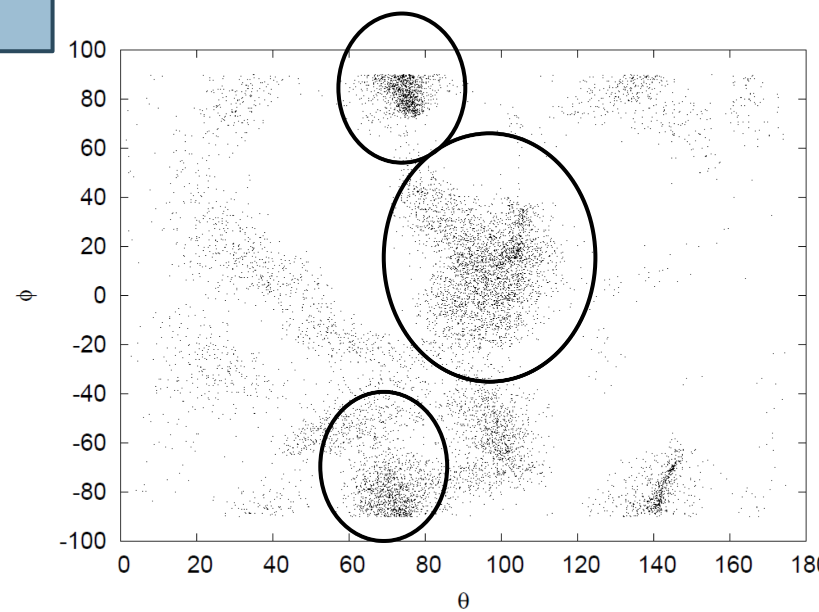

Arca-Sedda et al., 2016, MNRAS, 456, 2457

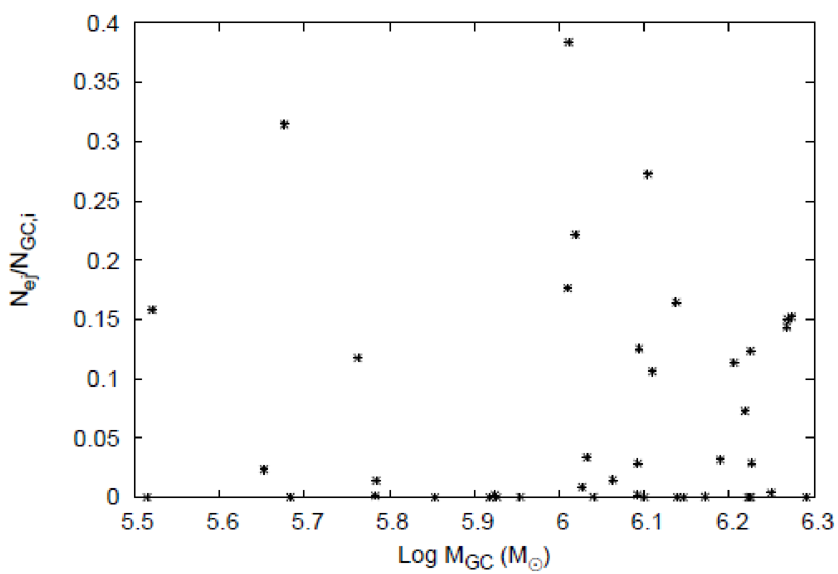
Capuzzo-Dolcetta and Fragione, 2015, MNRAS, 454, 2677

# THE MEGaN simulation: results (2/4)

## Formation of high-velocity stars



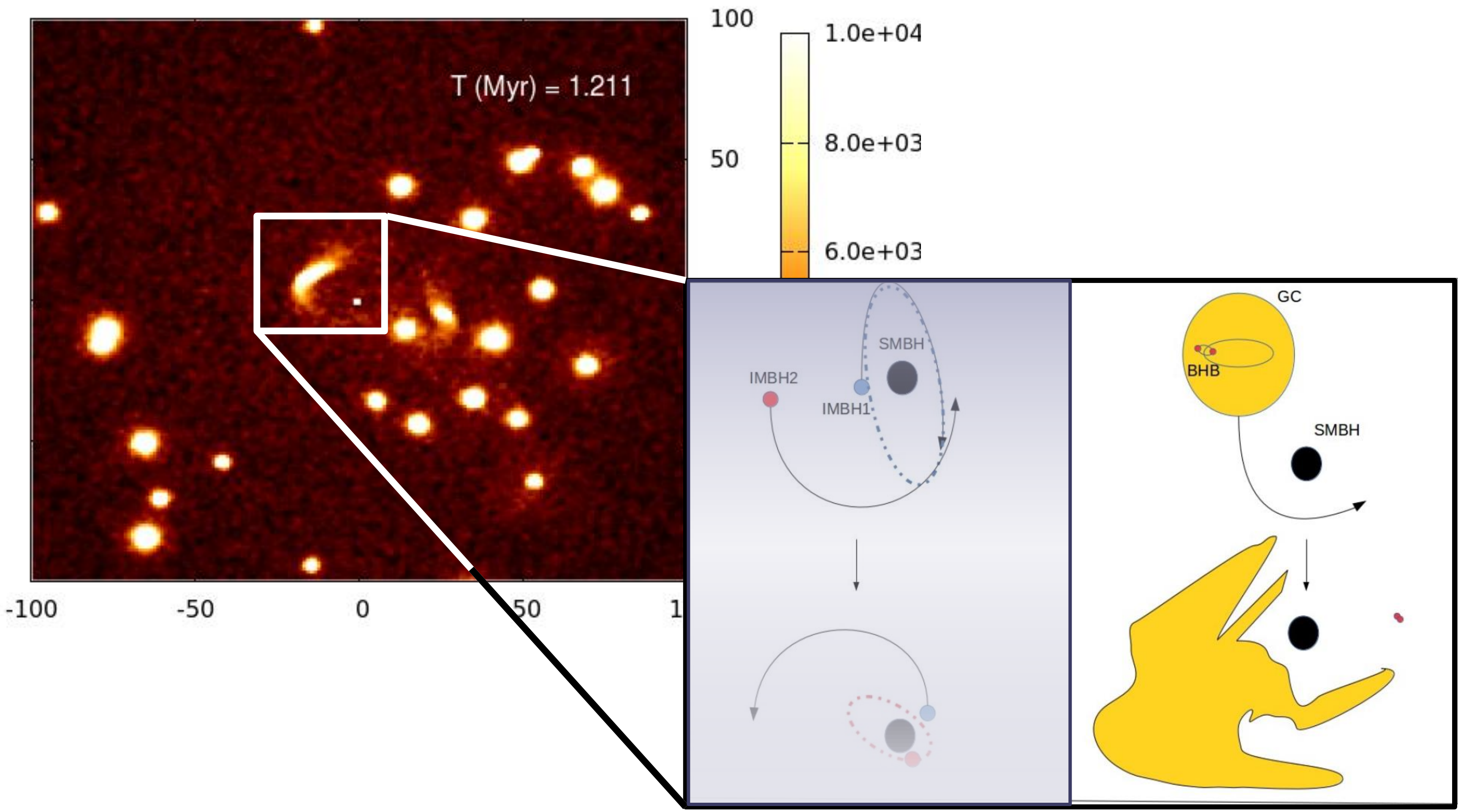




- **2%** of the total GCS stars are ejected with $v_{ej} \simeq 140 - 500 km/s$;
- 0.02% with $v_{ej} > 1500 km/s$ .

- Assuming a Kroupa IMF ($\langle m \rangle = 0.62\ M_{\odot}$) we estimate
  $\simeq 10^2$ **HVSs** with $v_{ej} > 1500\ km\ s^{-1}$
  $\simeq 10^4$ with $v_{ej} \geq 200\ km\ s^{-1}$

# THE MEGaN simulation: results (3/4)

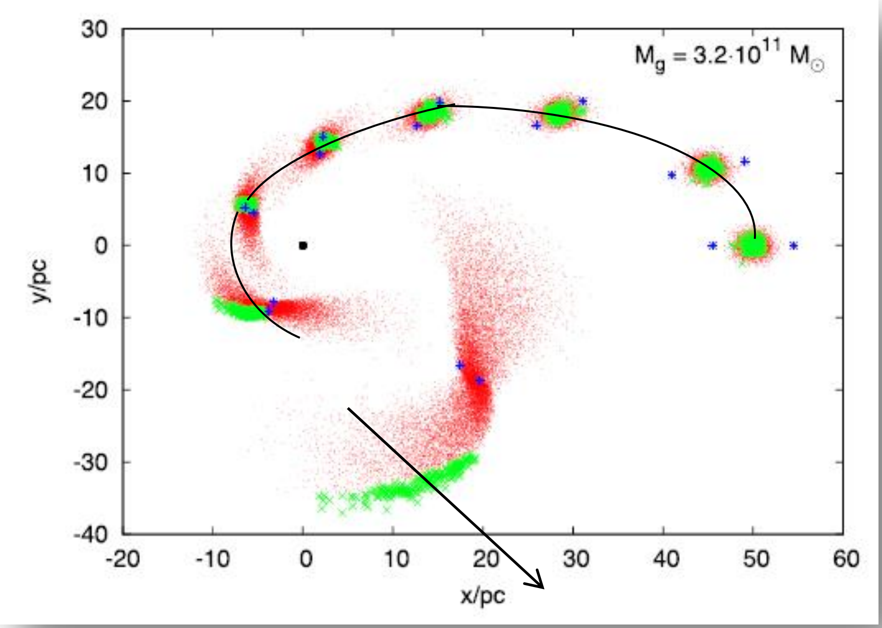
## Production of coalescing stellar black hole binaries (BHBs)

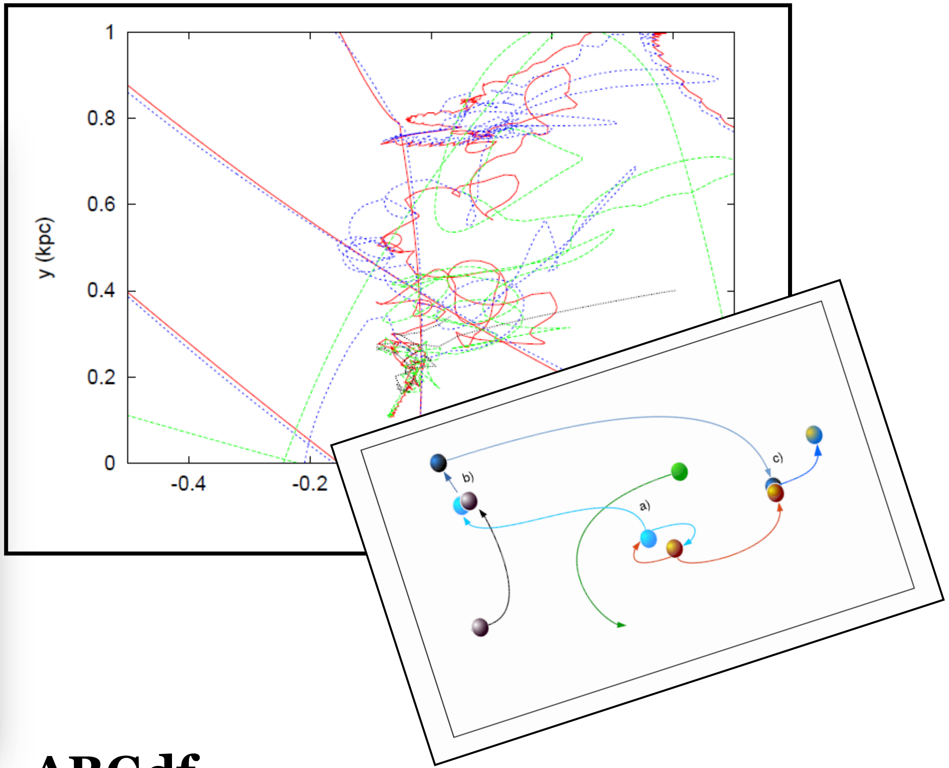


# THE MEGaN simulation: results (3/4)

## Production of coalescing stellar black hole binaries (BHBs)

Numerical approach: HiGPUs + ARGdf




### HiGPUs

Capuzzo-Dolcetta R., Spera M. and Punzo D., 2013, JCP, 236, p. 580-593

- ✓ **Highly parallel**
- ✓ **Direct N-body**

### ARGdf

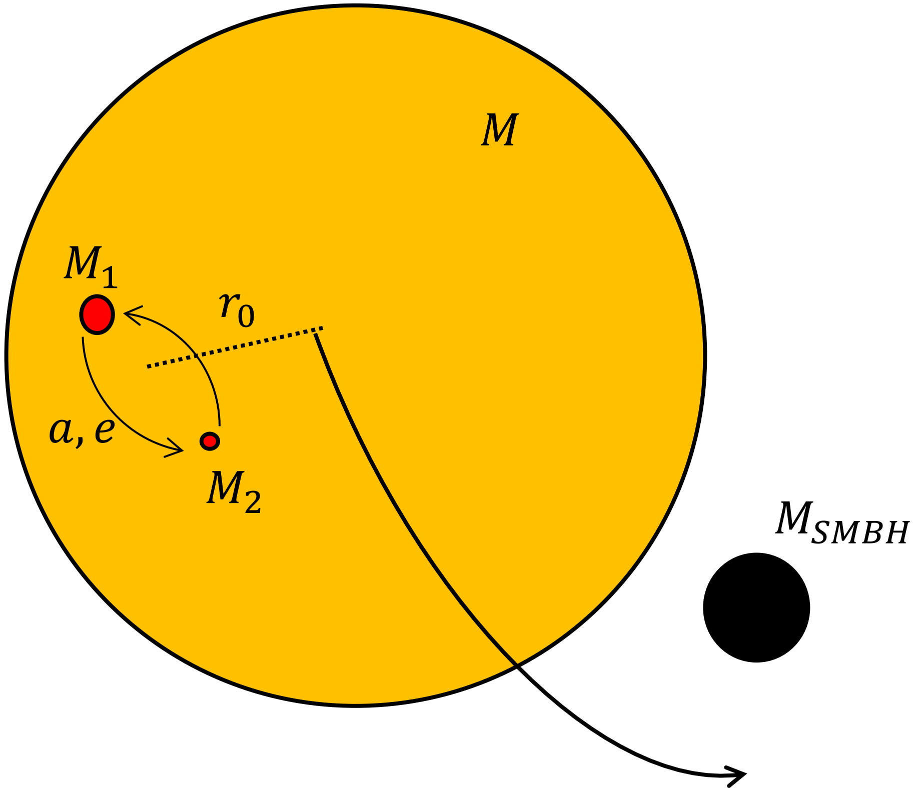
**New implementation of the version developed by:**
Mikkola S. and Merritt D. 2008, AJ, 135 (6), pp. 2398-2405

- ✓ **Algorithmic regularization**
- ✓ **PPN terms**
- ✓ **Dynamical friction**
- ✓ **External potential**

# THE MEGaN simulation: results (3/4)

## Production of coalescing stellar black hole binaries (BHBs)

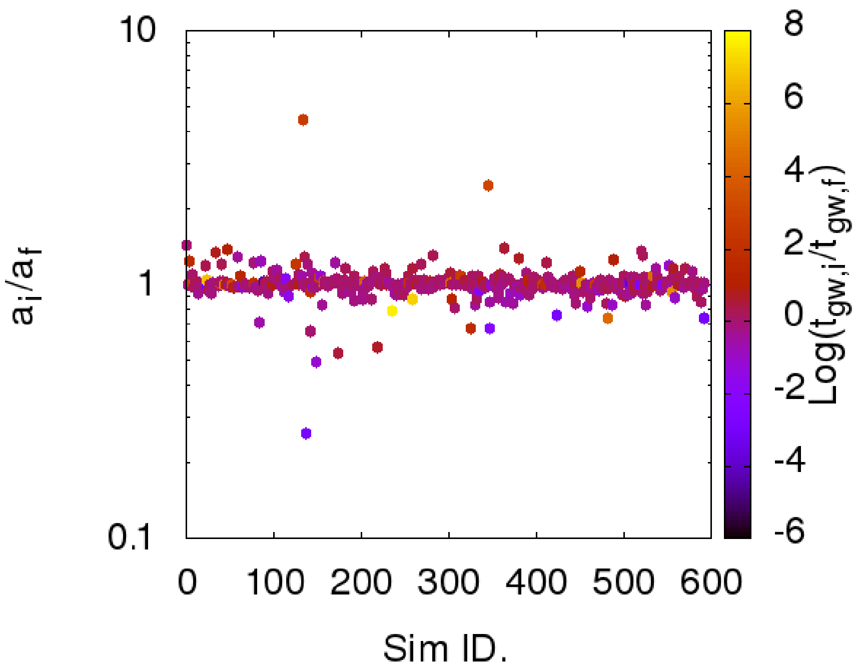
- $M = 1.8 \times 10^6 M_\odot$
- $M_1 = 30\ M_\odot$ $\quad M_2 = 20\ M_\odot$
- $P(a)da \propto a^{-1}$
- $a_M = 10^{-4} pc$
- $a_m = 100(R_{s1} + R_{s2})$
- $P(e)de \propto 2ede$
- $r_0 = 0.2 - 2\ pc$
- $\rho(r) = \rho_D(r)$

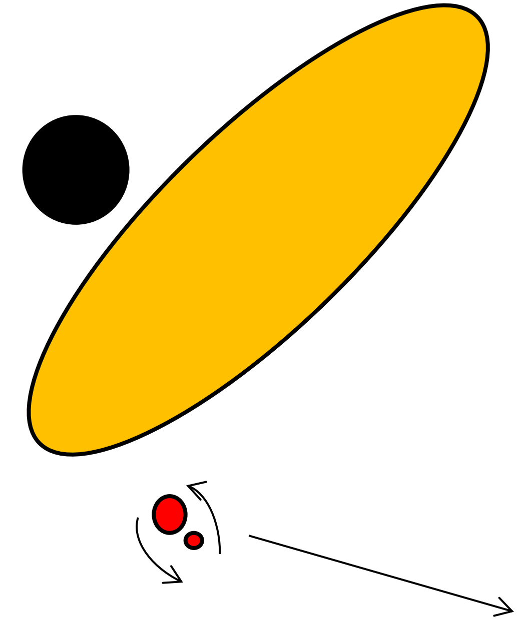


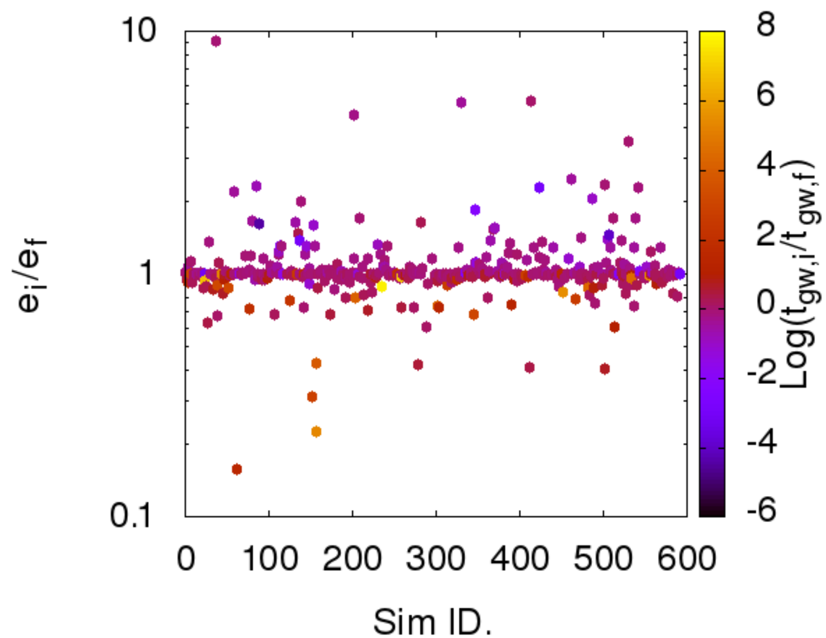

$$t_{gw} = \frac{5}{256} \frac{c^5 a^4 (1 - e^2)^{7/2}}{G^3 M_1 M_2 (M_1 + M_2)} = 9.6 Gyr \left( \frac{a}{10^{-6} pc} \right)^4 (1 - \mathrm{e})^{7/2}$$

# THE MEGaN simulation: results (3/4)

## Production of coalescing stellar black hole binaries (BHBs)





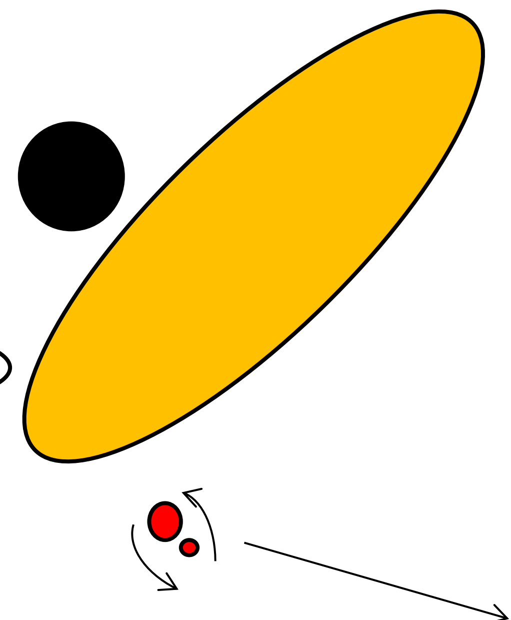
# THE MEGaN simulation: results (3/4)

## Production of coalescing stellar black hole binaries (BHBs)

$$t_{gw} = \frac{5}{256}\frac{c^5 a^4 (1-e^2)^{7/2}}{G^3 M_1 M_2 (M_1+M_2)} = 9.6Gyr\left(\frac{a}{10^{-6}pc}\right)^4 (1-\mathrm{e})^{7/2}$$

BHB breaks → i-th BH ejected; j-th BH bounded to the SMBH

BHB ejected → wandering BHB; eccentricity → coalescence



**1.5% of the cases studied**

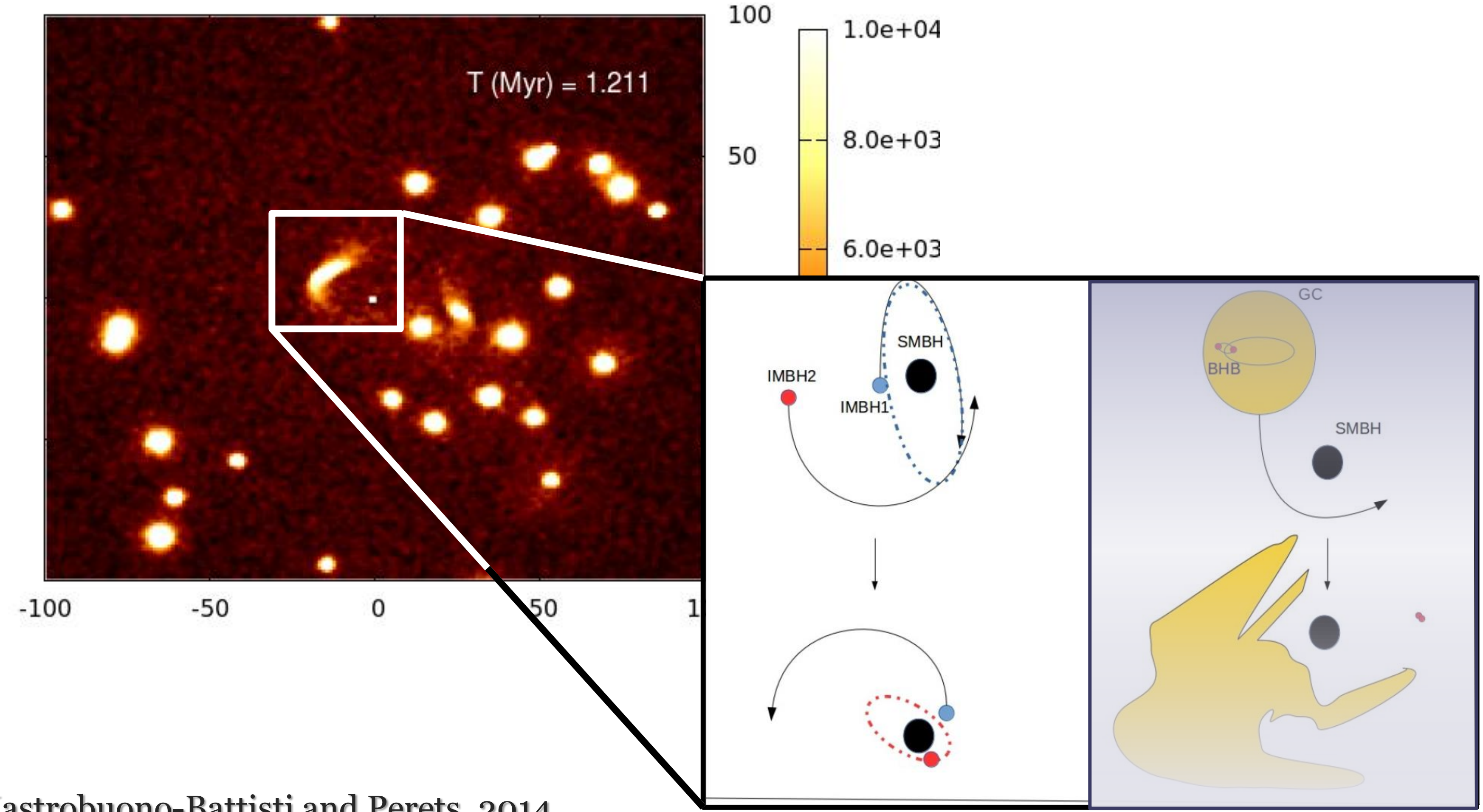
$$N_{events} = n_{bin} N_* N_{GC} \eta_{orb} P_{gw}$$

$n_{bin} = 10\%$ (?)
$\eta_{orb} = 1\% - 50\%$ (?)
$N_{GC} = 1$ (?)

→ $N_{events} = 30 - 1500$ (*per GC*)

# THE MEGaN simulation: results (4/4)

## Implications for IMBHs and SMBHs interactions

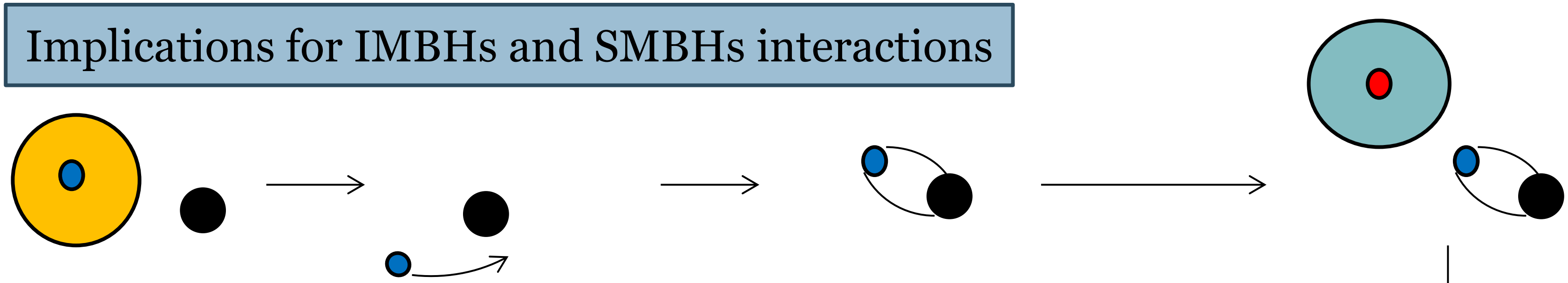


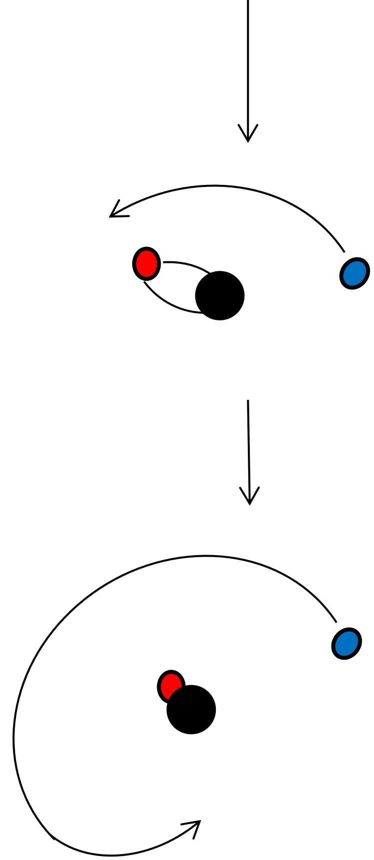

Mastrobuono-Battisti and Perets, 2014, Apj, 796, 60

Arca Sedda and Gualandris, in prep.

# THE MEGaN simulation: results (4/4)

## Implications for IMBHs and SMBHs interactions





1. a GC infalls, it contains an IMBH, decay time $t_{df} \propto M^{-0.67}$;
2. the GC disrupts, the IMBH orbitally decay over a time-scale $t_{df} \propto M_{IMBH}^{-0.67}$. An IMBH-SMBH binary (ISBHB) form;
3. a second GC infalls and disrupts;
4. its IMBH will orbitally decay toward the ISBHB;
5. possibly, a swap leads to the formation of a hard ISBHB

# THE MEGaN simulation: results (4/4)

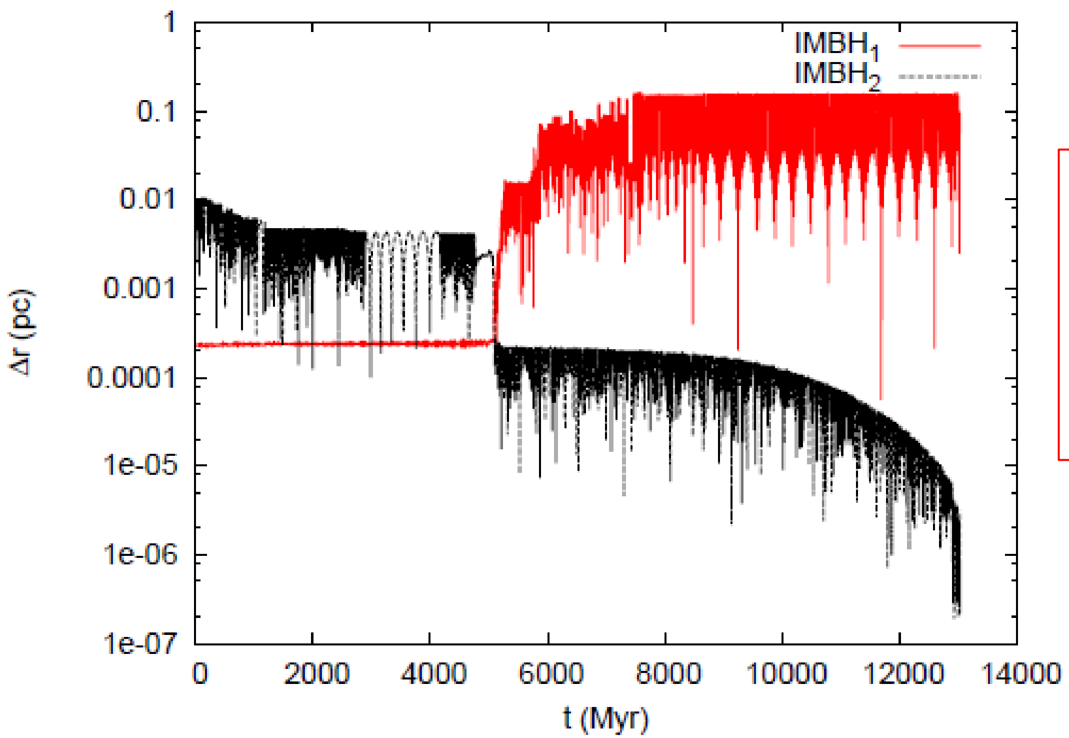
## Implications for IMBHs and SMBHs interactions

$$M_1 = 1.97 \times 10^6 M_\odot \rightarrow M_{ibh1} = 1.12 \times 10^4 M_\odot$$

$$M_2 = 1.86 \times 10^6 M_\odot \rightarrow M_{ibh2} = 1.06 \times 10^4 M_\odot$$

$$\frac{M_{ibh}}{M_{sbh}} \simeq 10^{-4}$$

Are they EMRIs (or at least IMRIs)?




25%: Coalescence within a Hubble time

10%: Coalescence within 100 Myr

# Conclusions