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Simulating the cradle of stars

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OUTLINE:

1 – Star clusters: the cradle of stars

2 – 'DRY' STAR CLUSTERS:

2.1 Star clusters with GPUs
2.2 N-star: our new stellar evolution tool for N-body
2.3 Some applications of our direct-summation
N-body models: BHs (FIRB 2012)
Gaia Eso Survey clusters

3 –'WET' STAR CLUSTERS:

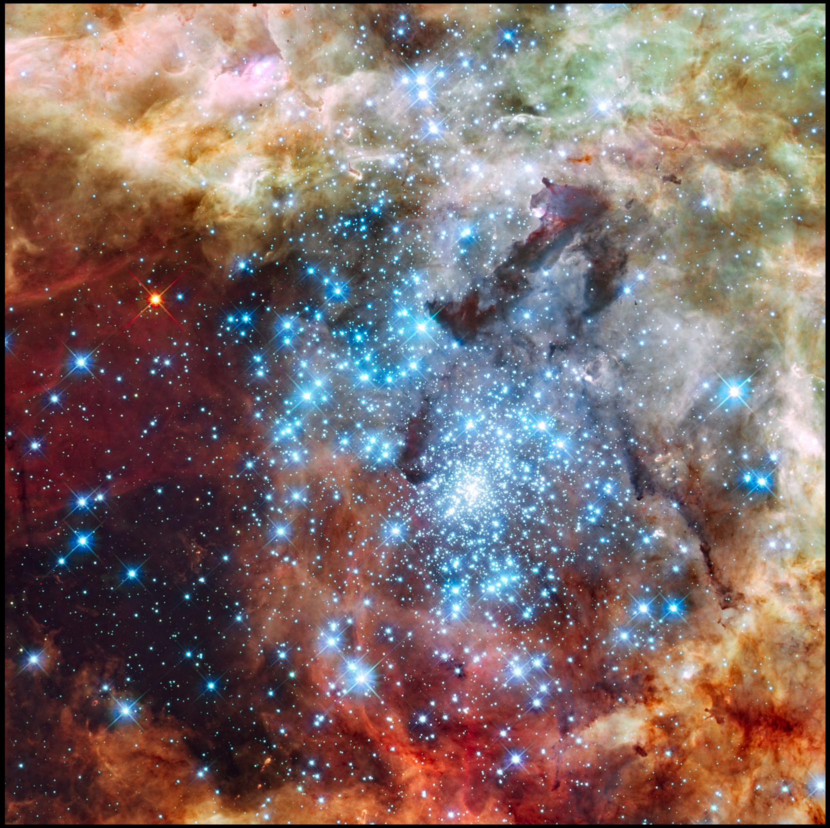
2.1 Studying molecular cloud fragmentation
2.2 SF in the Galactic centre

4– Conclusions

1– Star clusters: the cradle of stars

STAR CLUSTERS (SCs): self-gravitating systems of stars (10^3-7)

R136 in 30 Doradus, HST



Most stars (~80%) form in SCs
(Lada & Lada 2003; Portegies Zwart et al. 2010)

If we do not understand SCs, we cannot shed light on

- how stars form

- how stars evolve

- how galaxies build up

SCs are a CORNERSTONE for ASTROPHYSICS!

But SC formation/evolution still barely understood

1– Star clusters: the cradle of stars

Interesting for both dynamics and stellar evolution

DYNAMICS:

collisional systems (2-body relaxation time scale < lifetime) have exciting dynamical evolution (runaway collapse of the core, gravothermal oscillations, 3body and multiple encounters)

STELLAR EVOLUTION:

Dynamics strictly connected with stellar evolution (mass loss by massive stars, formation of remnants, formation of stellar exotica)

SIMULATIONS of SCs versus COSMOLOGICAL SIMULATIONS:

In SCs we MUST and we CAN RESOLVE SINGLE STARS

→ each particle is a single star with
mass, radius, luminosity, temperature and metallicity

→ we must resolve CLOSE gravitational encounters between stars

GAS:

For very young SCs we should include parent molecular gas

'DRY' STAR CLUSTERS (no gas)

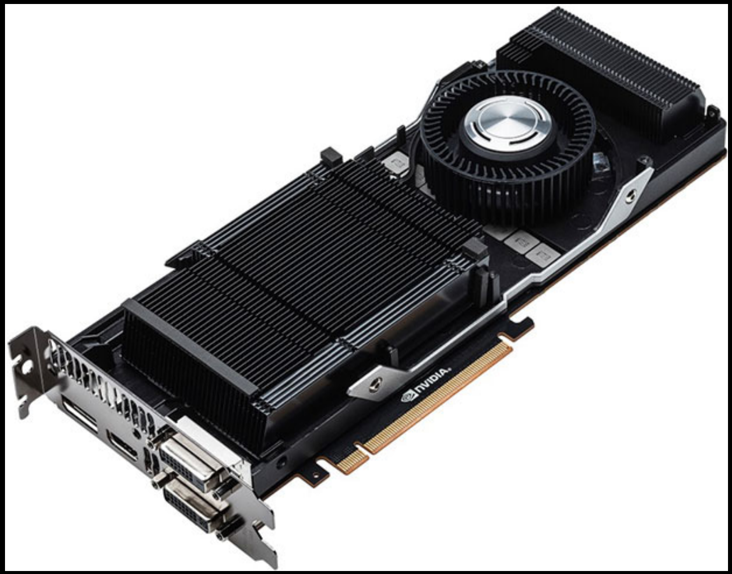
2.1– Star clusters with GPUs

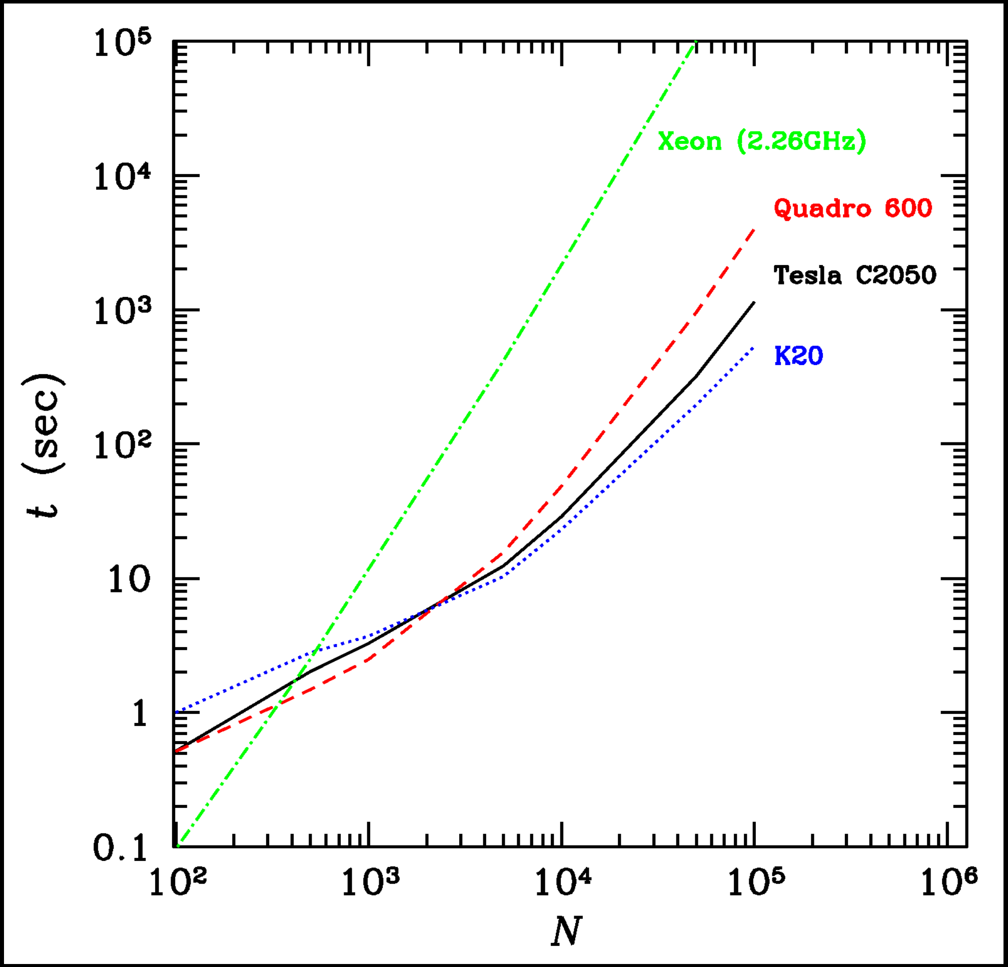
Direct-summation N-body codes

*** solve Newton force directly with high accuracy → O(N^2)**

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

*** usage of GPUs is very important!**



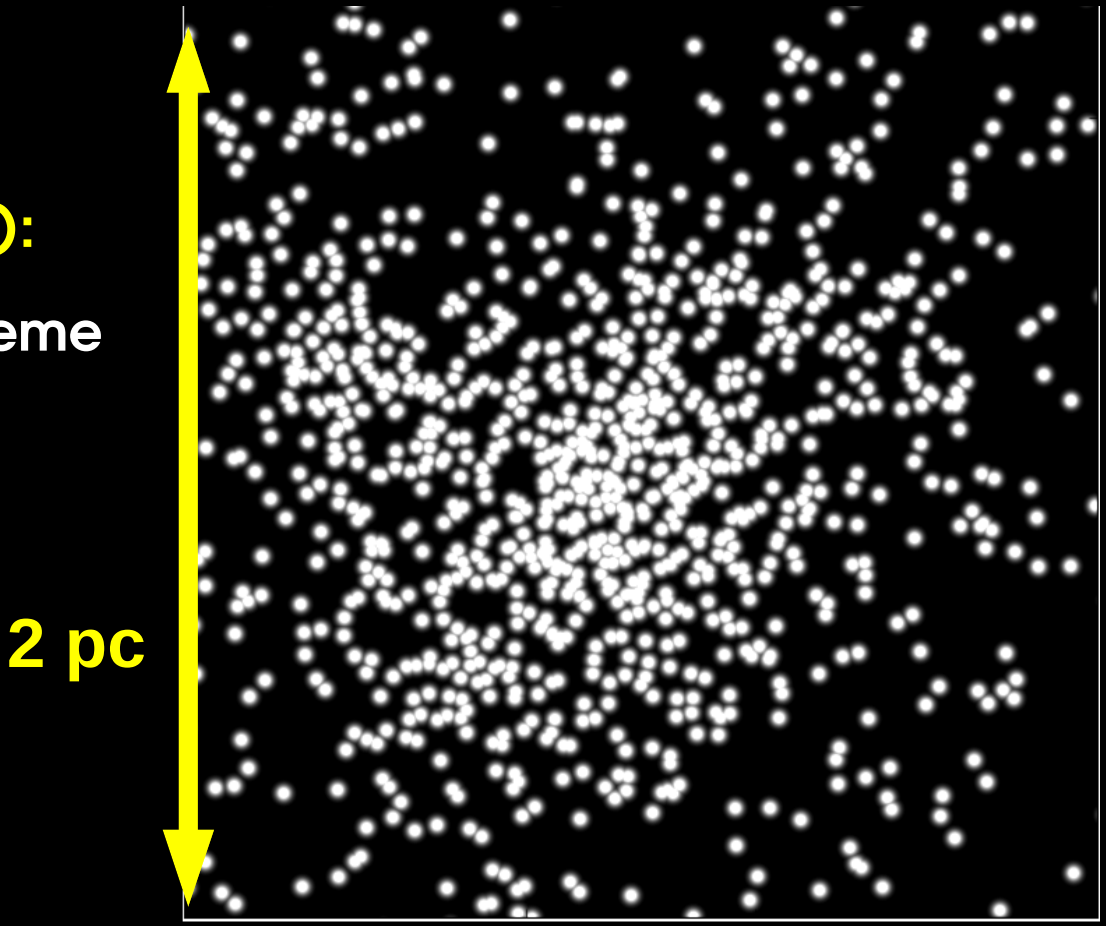


STARLAB public
software environment (Portegies Zwart et al. 2001)
in our version (MM et al. 2013)
with the SAPPORO library for running on GPUs (Gaburov et al. 2009)

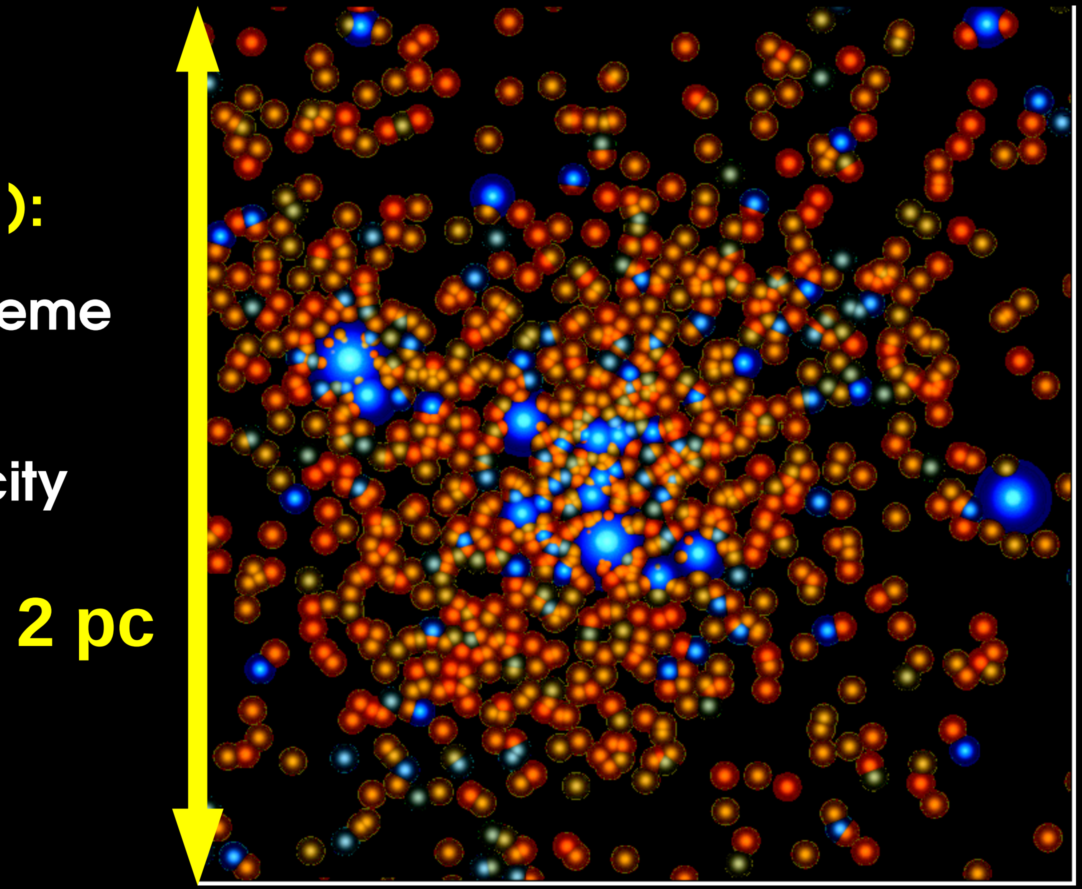
2.1– Star clusters with GPUs

STARLAB (Portegies Zwart+2001):

- Hermite predictor-corrector scheme for dynamics



2.1– Star clusters with GPUs



STARLAB (Portegies Zwart+2001):

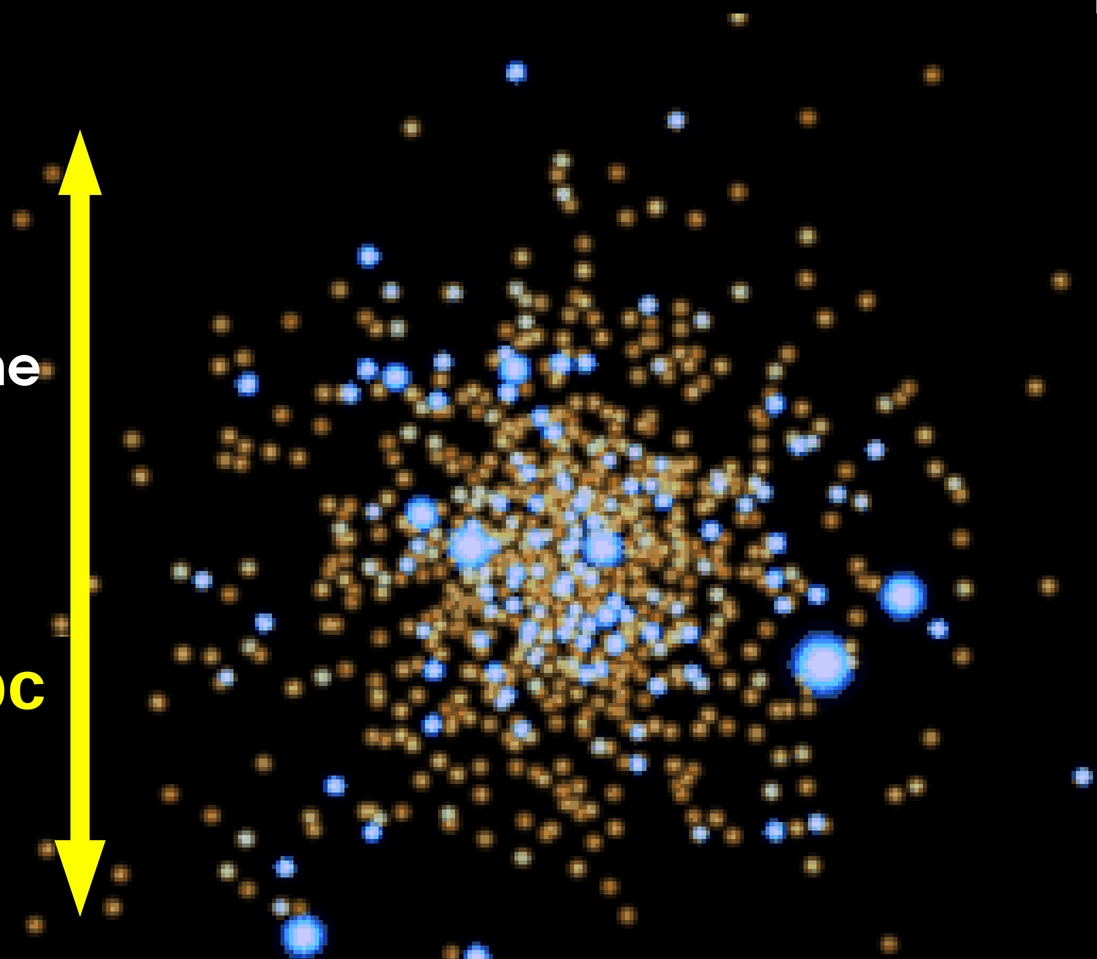
- Hermite predictor-corrector scheme for dynamics
- stellar evolution at solar metallicity

OUR VERSION OF STARLAB (MM+ 2013) INCLUDES

- METALLICITY DEPENDENCE of STELLAR EVOLUTION (Hurley+ 2000)
- METALLICITY DEPENDENT STELLAR WINDS for main sequence and Wolf-Rayet stars (Vink+ 2001; Vink & de Koter 2005)
- METALLICITY-DEPENDENT RECIPES for supernovae and BH mass (Mapelli+ 2009; Belczynski et al. 2010)

STARLAB code (Portegies Zwart+ 2001), MM+ 2013 stellar evolution tools; MM+ visualization tool

2.1– Star clusters with GPUs



1 pc

STARLAB (Portegies Zwart+2001):

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2.2 N-star: our new stellar evolution tool

A major upgrade of stellar evolution recipes is under way!!

WHAT IS NEW?

1-STELLAR EVOLUTION with PARSEC (Bressan et al. 2012): new stellar evolution

2- VERSATILE: reads interpolating tables, you can choose your preferred stellar evolution model!

3- dramatic differences for MASSIVE stellar evolution

4- METALLICITY-DEPENDENT RECIPES for supernovae and BH mass (Mapelli+ 2009; Belczynski et al. 2010; Spera, MM & Bressan, in prep)

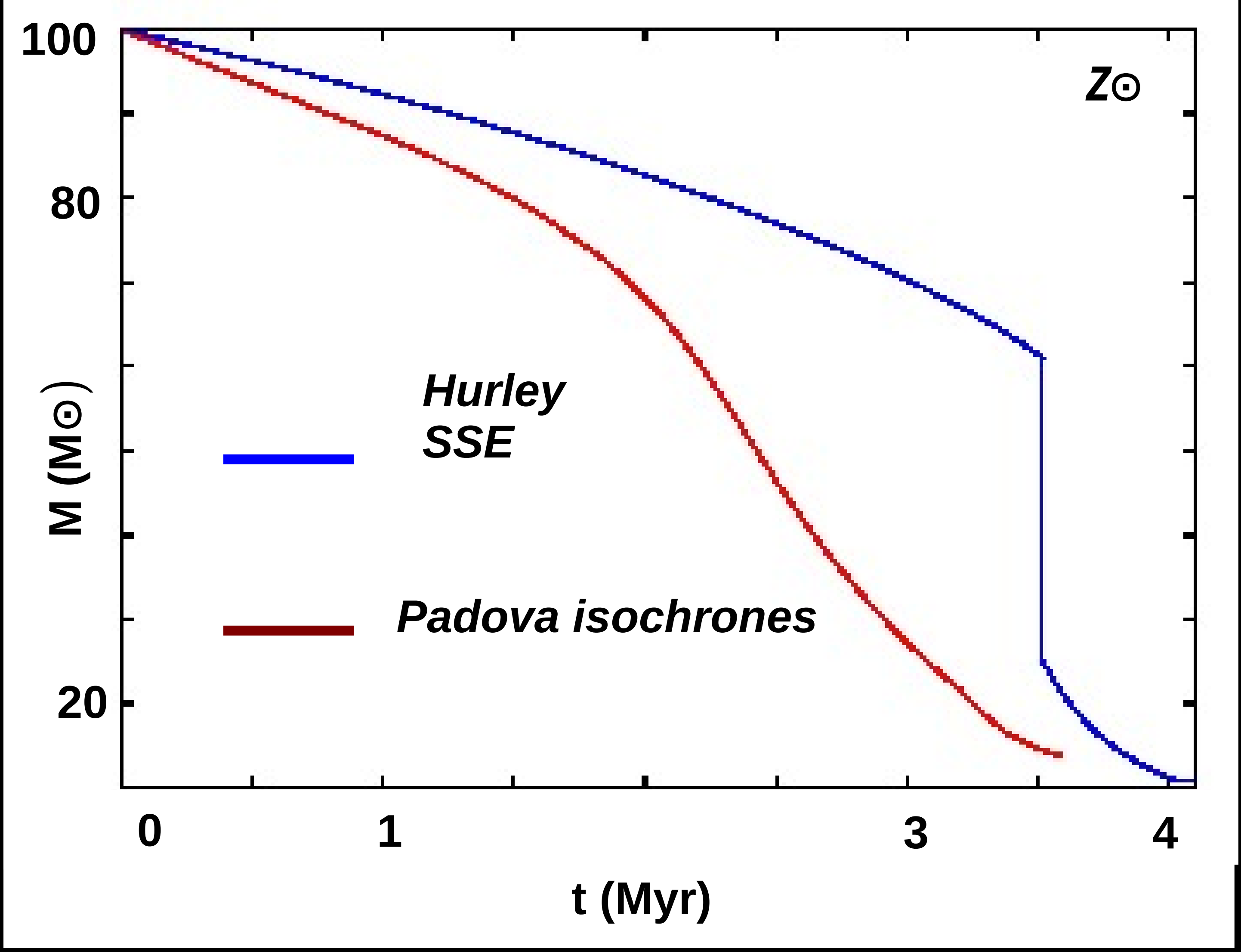
5- We add pre-main sequence stars

6- Does not need GPUs (it is fast vs N-body) but works together with N-body codes (STARLAB, HiGPUs) using GPUs

2.2 N-star: our new stellar evolution tool

WHAT IS NEW?

3- dramatic differences for MASSIVE stellar evolution



2.2 N-star: our new stellar evolution tool

We will publicly release
the code as soon as tested
(expected date: spring 2015)

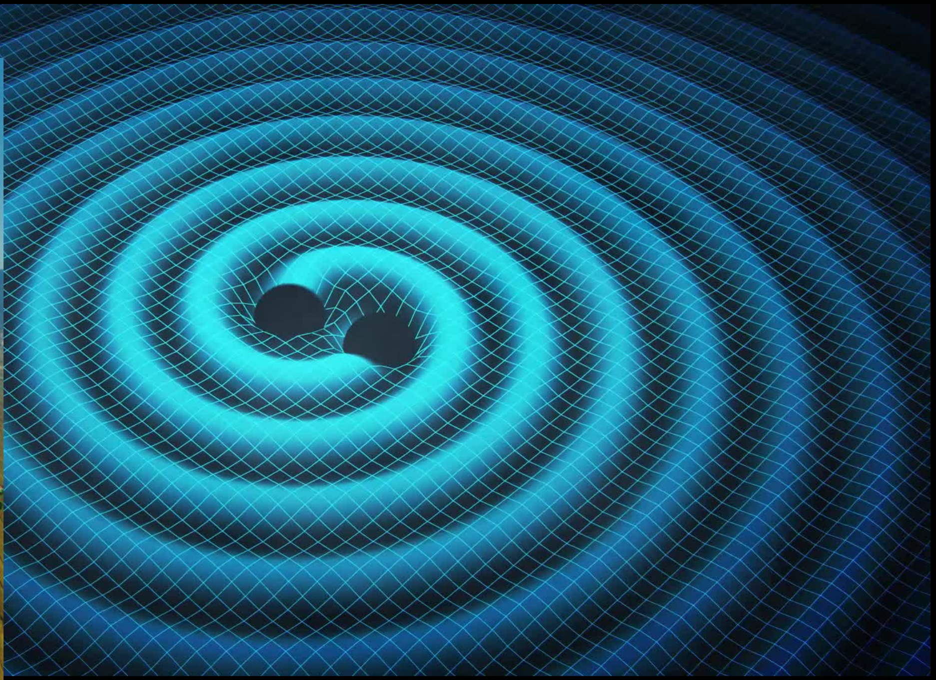
Optimized for HiGPUs
(Capuzzo Dolcetta, Spera, Punzo 2013)
and for STARLAB (Portegies Zwart+ 2001)

We will include it in the AMUSE
package (Pelupessy+ 2012)

2.3– Some applications of our models: (1) BHs

Young star clusters are RESERVOIRS of black holes (BHs) and BH binaries

BH-BH MERGERS are IMPORTANT SOURCES of GRAVITATIONAL WAVES (GWs)
in the ADVANCED LIGO/VIRGO FREQUENCY RANGE (10-10^4 Hz)



→ IMPORTANT TO ESTIMATE THE DEMOGRAPHICS OF BH BINARIES IN SCs

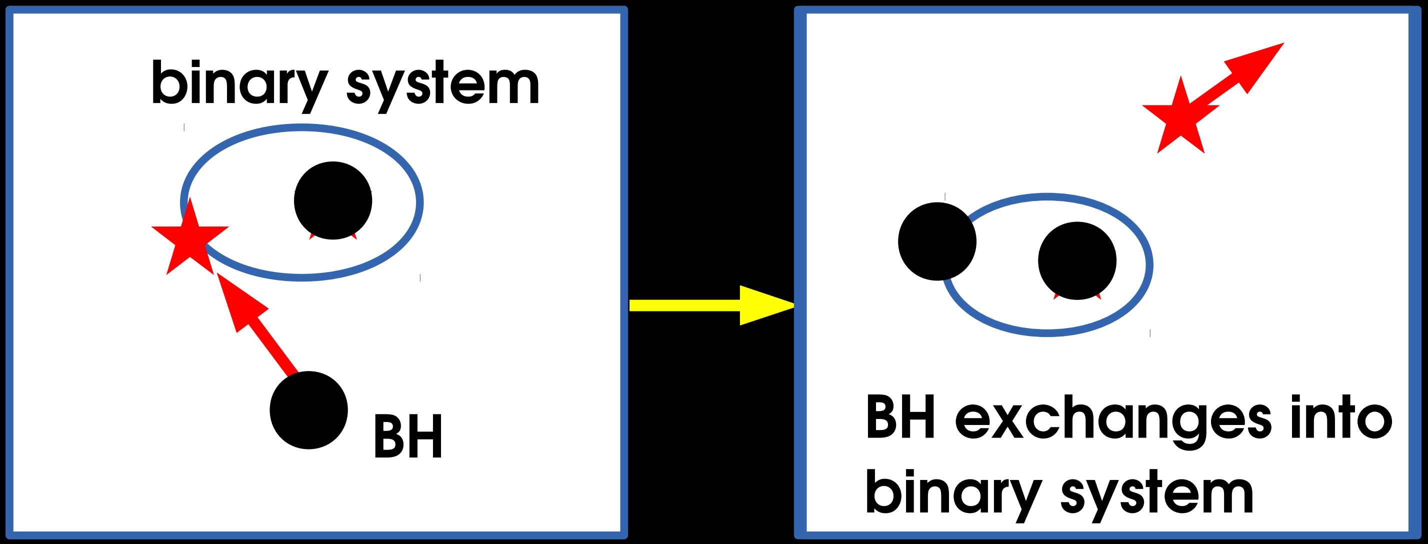
MAIN AIM of our recently funded FIRB 2012 project (Italian excellence grant for young researchers, 958k EUR)

2.3– Some applications of our models: (1) BHs

Star clusters are a DENSE environment→ close encounters between stars and binary systems are frequent

THE BINARY CAN EXCHANGE COMPANION

EXCHANGE PROBABILITY MAXIMUM FOR MASSIVE OBJECTS



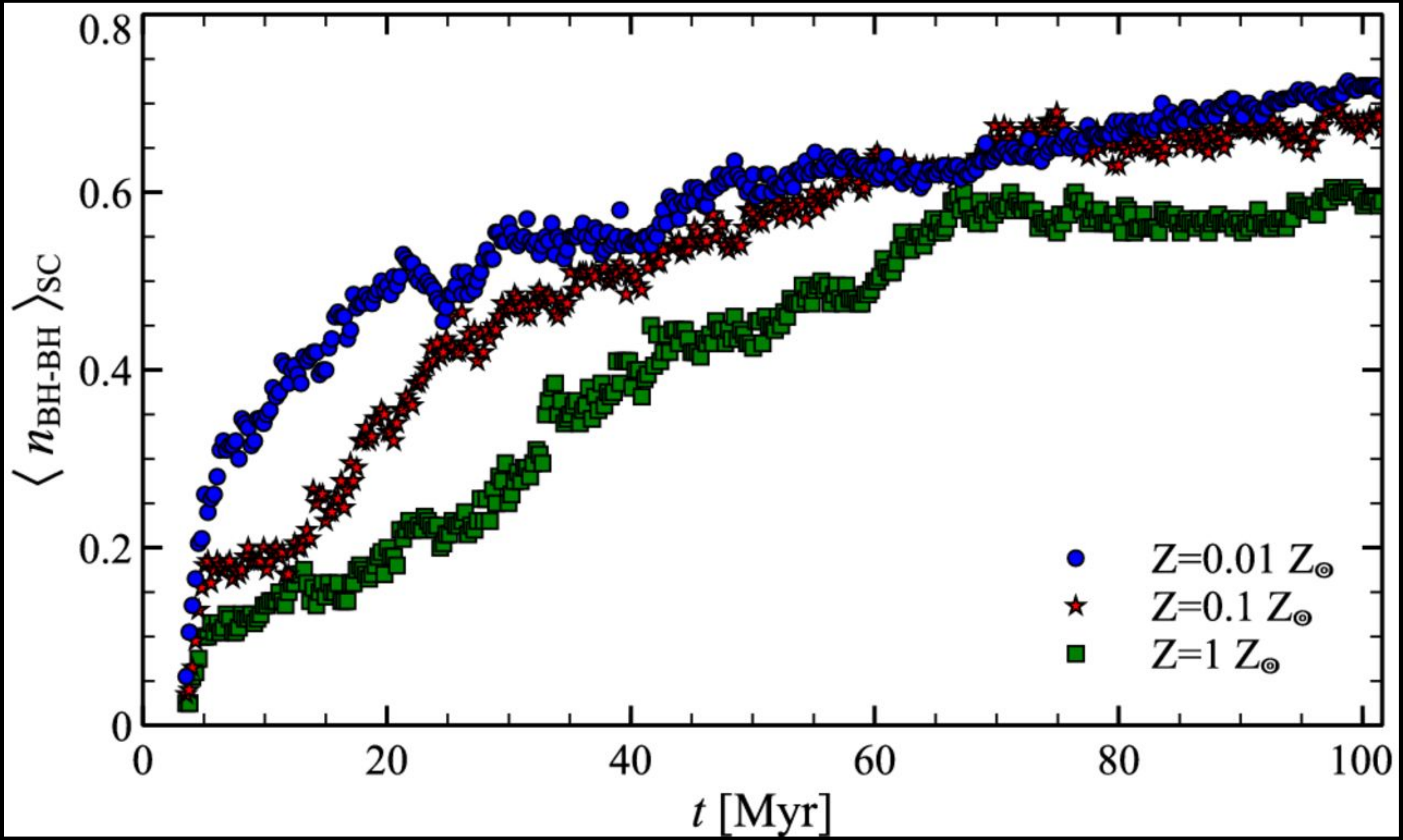
EXCHANGES ENHANCE THE FORMATION OF BH-BH BINARIES:

97% of BH-BH binaries form from EXCHANGE IN OUR SIMULATIONS (MM+ 2013; ZIOSI, MM+ 2014; MM & ZAMPIERI 2014)

--> IMPORTANCE FOR PREDICTING GRAVITATIONAL WAVES

2.3– Some applications of our models: (1) BHs

BH-BH COALESCENCE TIMESCALE (Ziosi, MM et al. 2014)
for a simulated grid of 600 young SCs with different metallicity



Number of BH-BH per SC as function of time (Ziosi, MM et al. 2014)

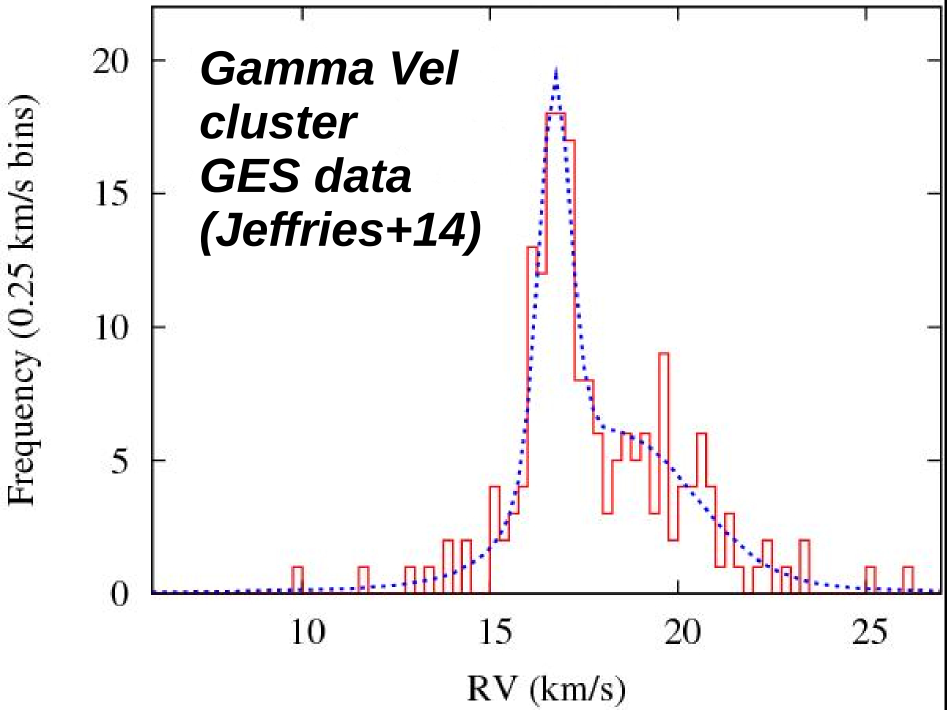
<u>SIMULATIONS RUN on GPU clusters EURORA and PLX @ CINECA</u>

2.3– Some applications of our models: (2) SC interactions

Gaia ESO survey (GES, PIs Gilmore & Randich): optical spectroscopic survey @ VLT to study radial velocity and chemistry of 10^5 stars (2011 – now). Complementary to Gaia

GES+GAIA offers a 7+ parameter space (x, y, z, vx, vy, vz, metallicity)

~100 young star clusters and OB associations



Gamma Velorum cluster:
Young (5-10 Myr)
Nearby (350 pc)
Marginally bound SC

COMPLEX KINEMATICS WITH TWO DIFFERENT POPULATIONS:

How to explain it?

WE PROPOSE TWO SUB-CLUSTERS BORN FROM THE SAME CLOUD

2.3– Some applications of our models: (2) SC interactions

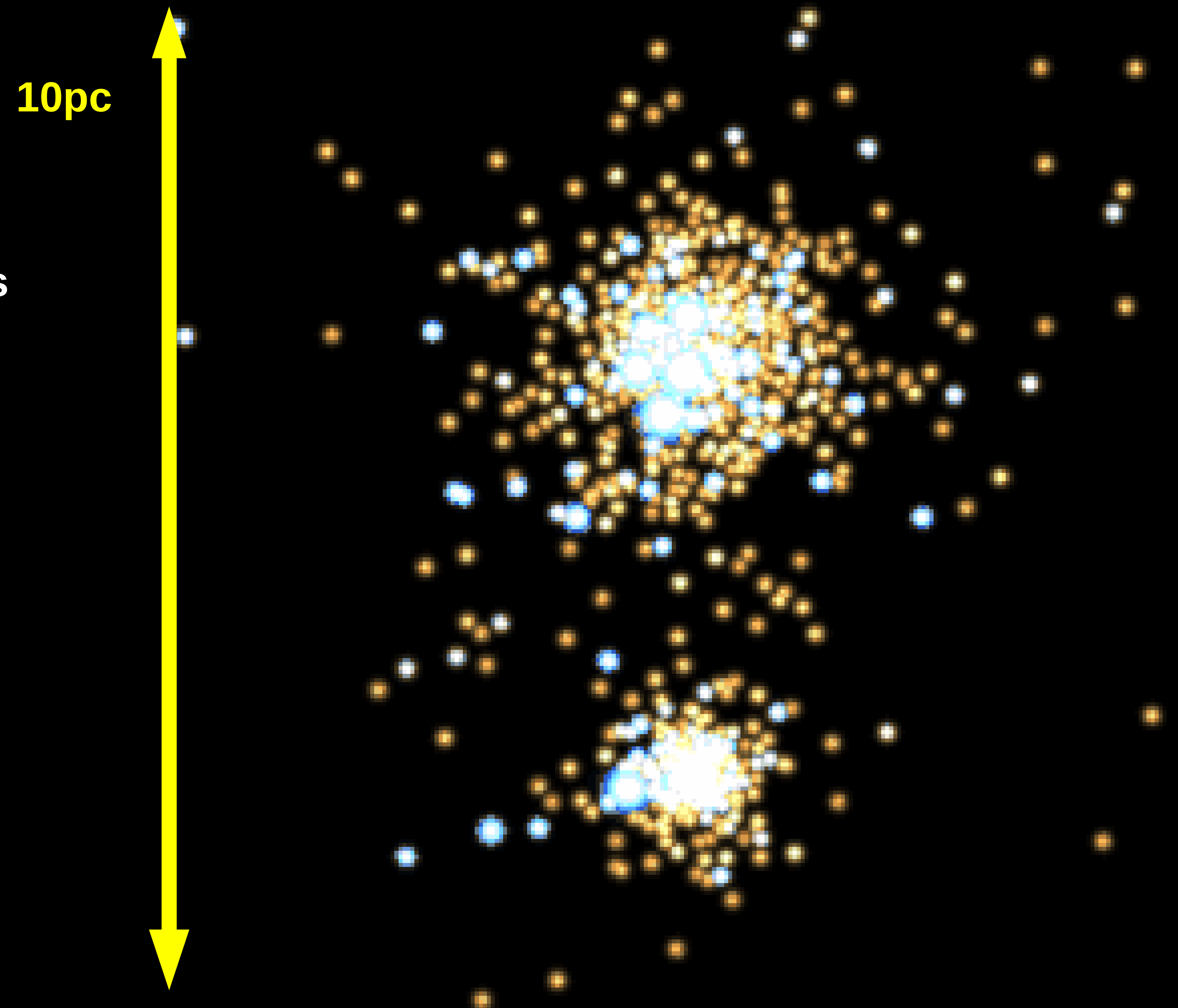
SIMULATION OF INTERACTION BETWEEN 2 SUB-CLUSTERS

Clusters modelled as Plummer spheres

M1=800 Msun
M2=500 Msun

SMALL CLUSTER Is NOT VIRIAL (Q=4.5)

Time =0 → 5.4 Myr



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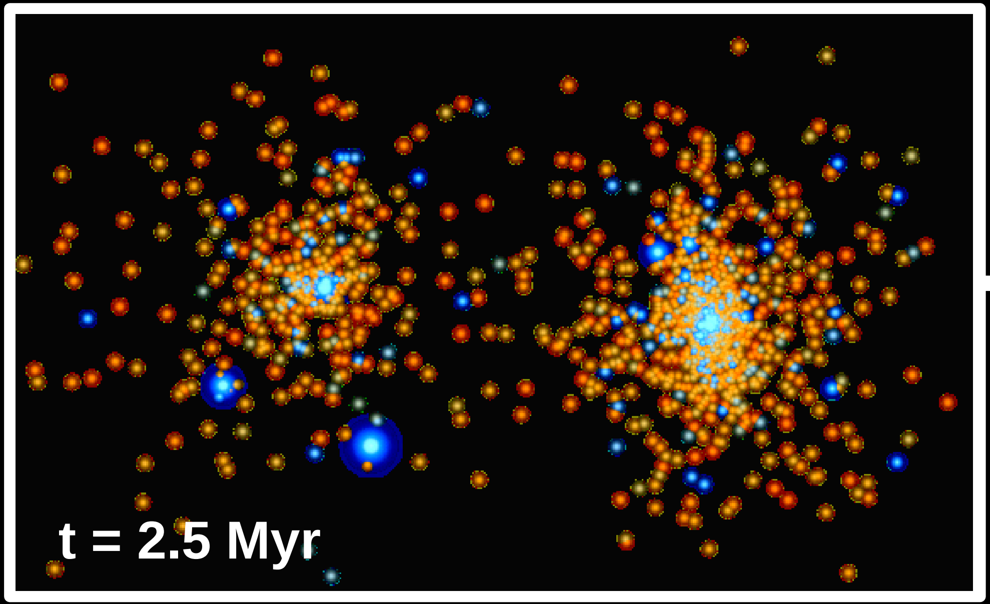
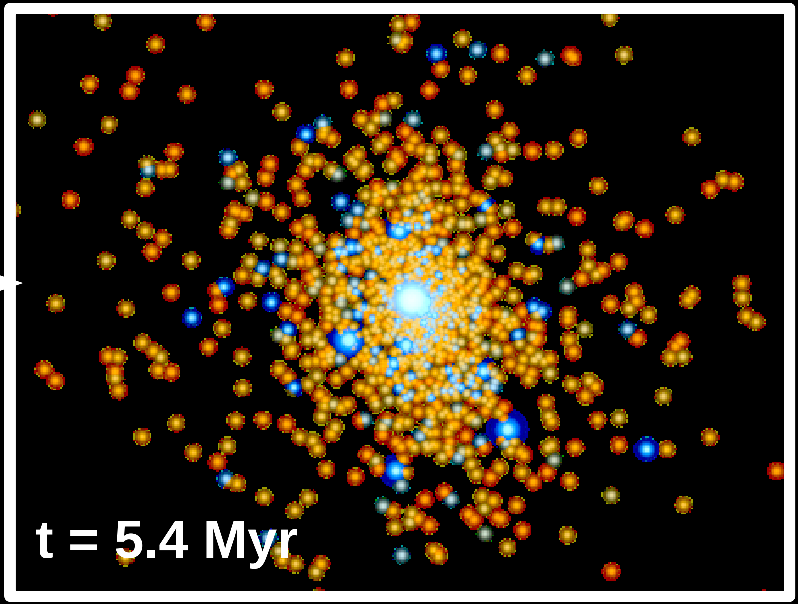
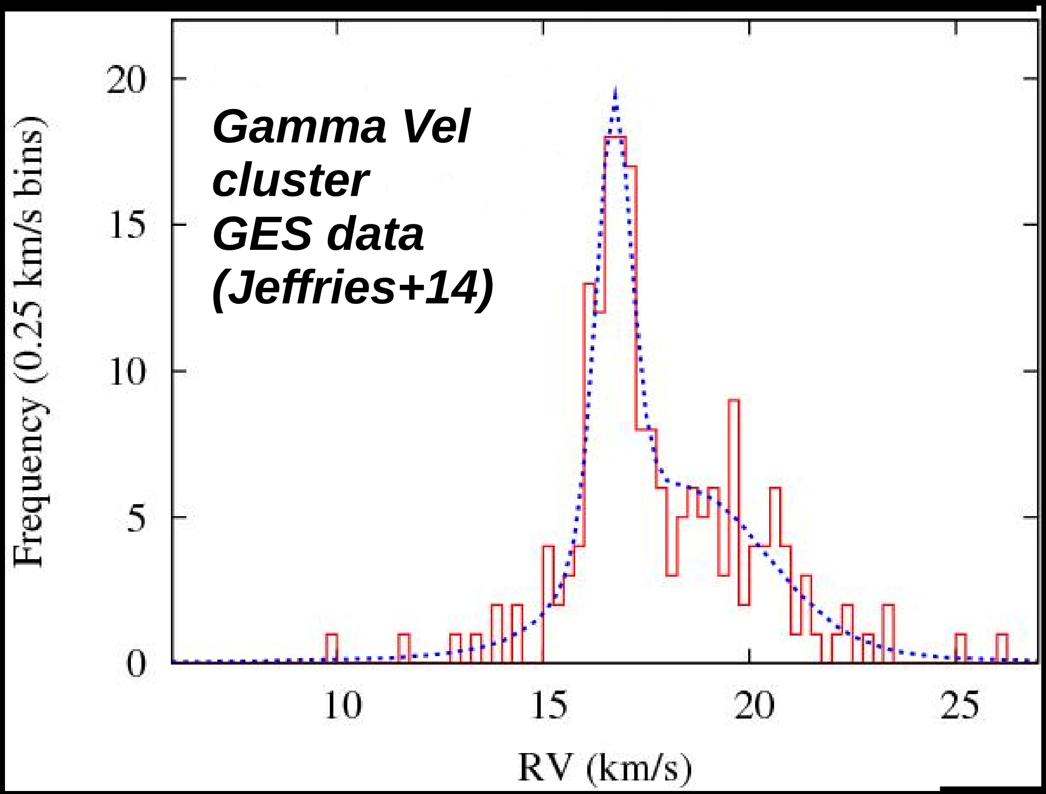
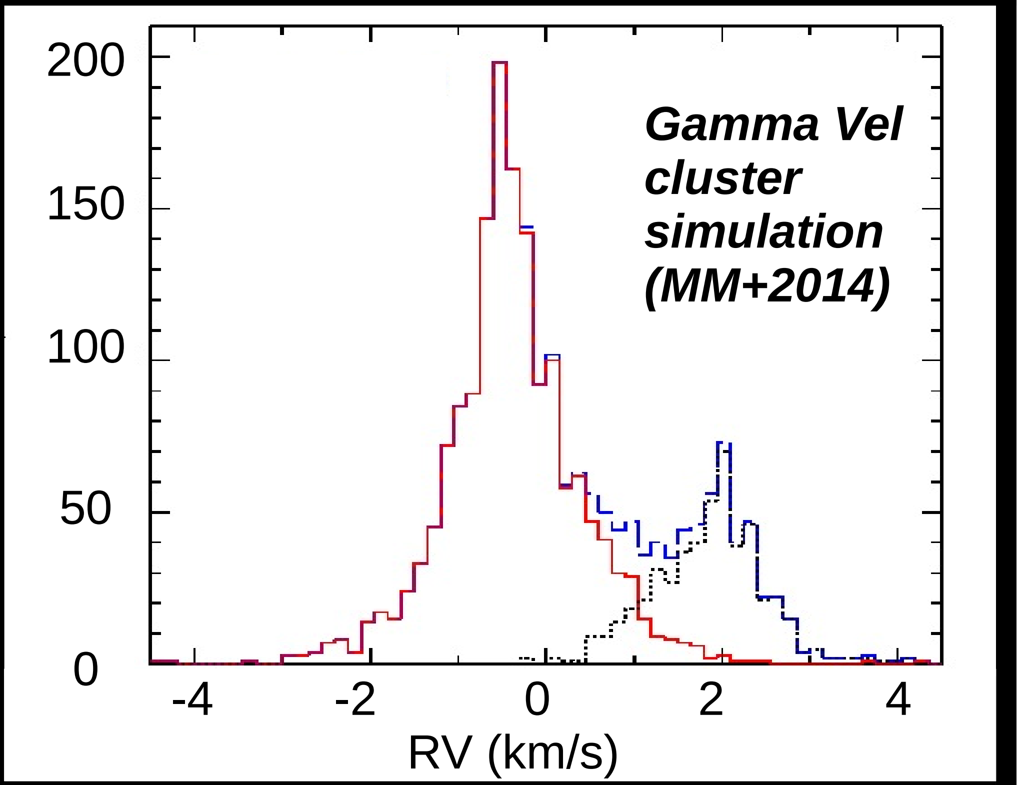






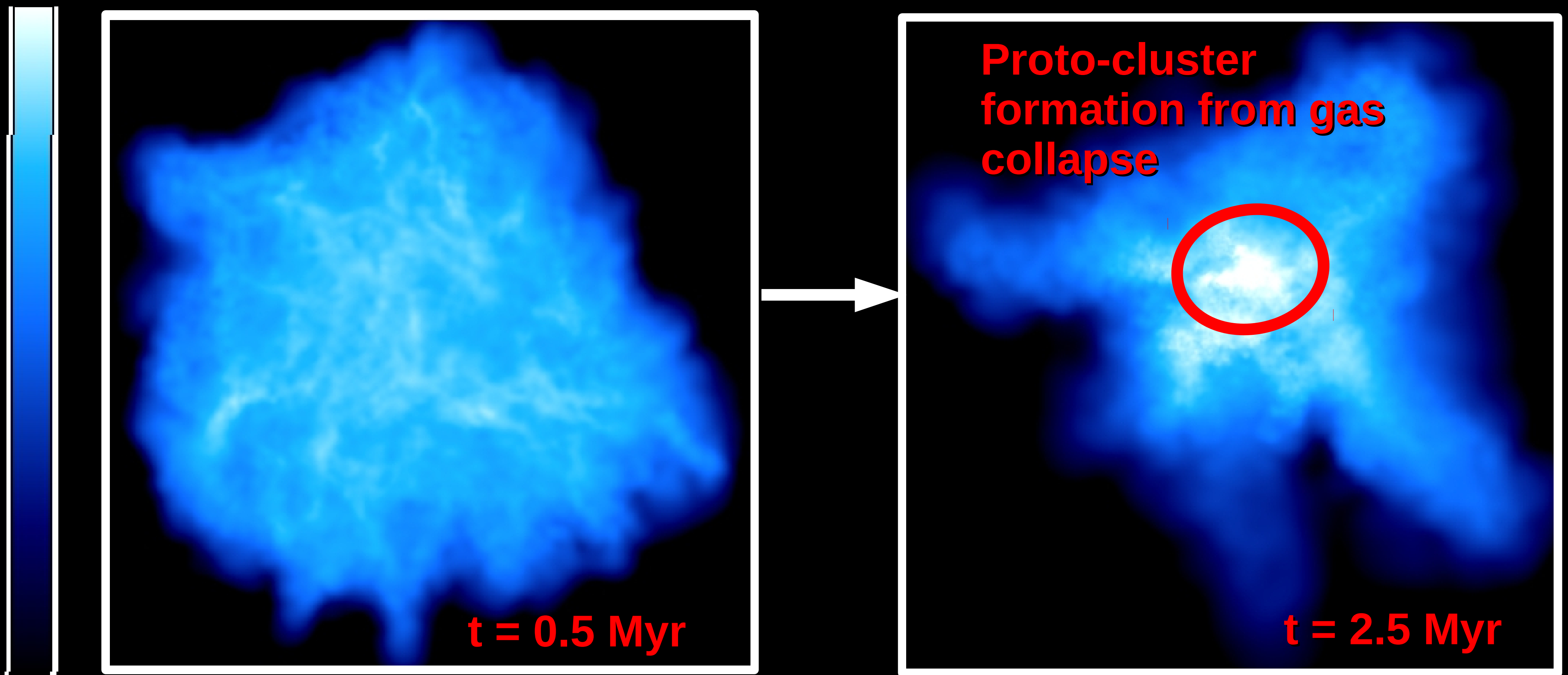


'WET' STAR CLUSTERS (gas)

5– Studying molecular clouds with SPH

add gas component to study formation of SC
from molecular clouds and evaporation of gas

SPH simulation of a turbulent molecular cloud



MM & Tristen Hayfield

5– Studying molecular clouds with SPH

SPH simulation of a turbulent molecular cloud

Cloud radius: 10pc
Mass: 10^4 Msun
Temperature: 100 K
Particle M: 0.04 Msun

Turbulence supported

Turbulence generated as Larson 1981
Marginally bound

N-body SPH gasoline (Wadsley+ 2004)

Rosseland+Planck opacities

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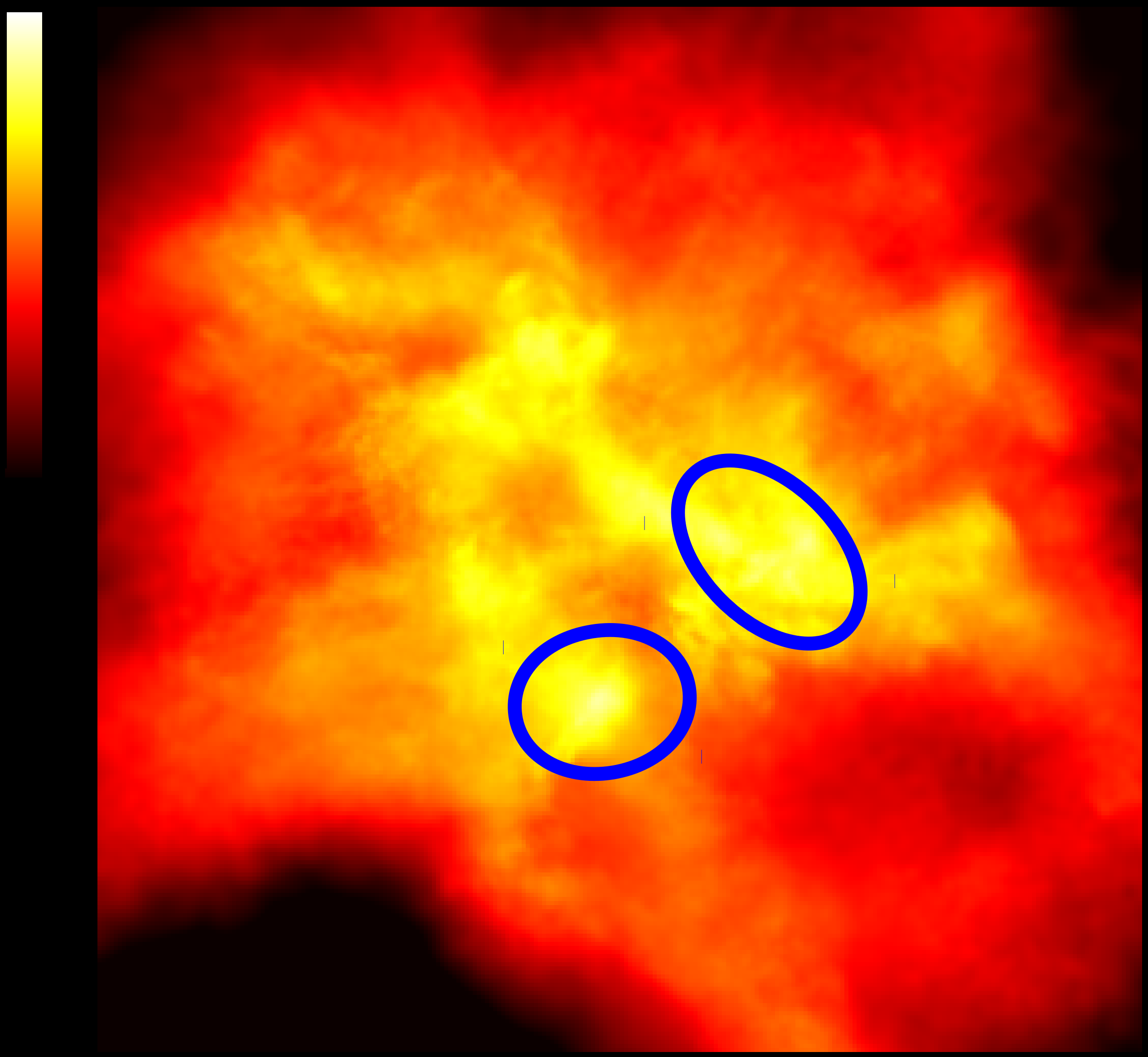


5– Studying SF in the Galactic centre with SPH

There is a SC also in
OUR Galactic centre (GC)

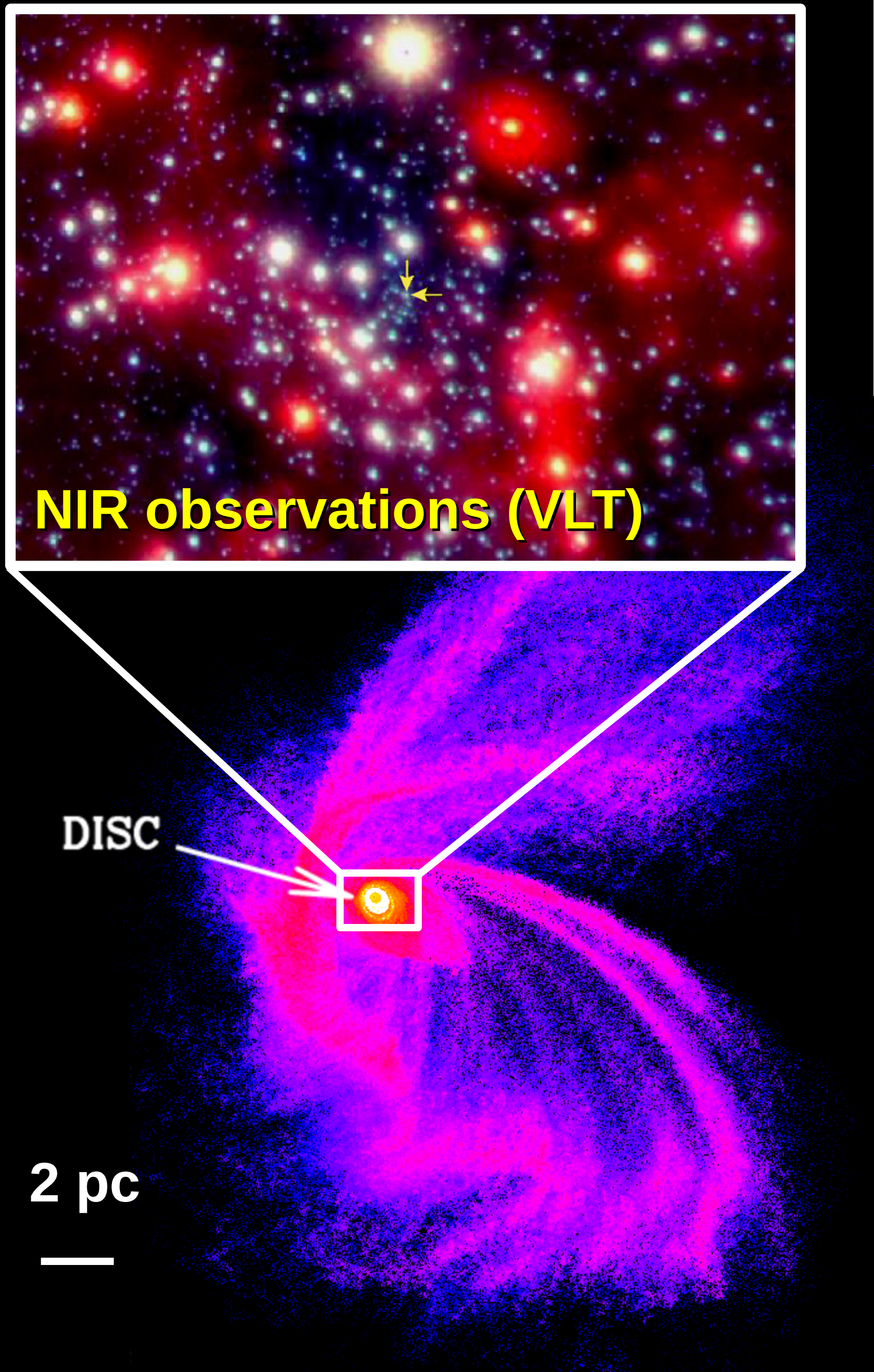
The formation of this SC is
different from that of other SCs:

- the GC hosts a 4x10^6 M⊙ supermassive black hole (SMBH)

- the SMBH exerts a tidal shear that disrupts molecular clouds

stars can form in a gas disc, born from the disruption of a molecular cloud
(MM+ 2012, 2013; Gualandris+ 2012)

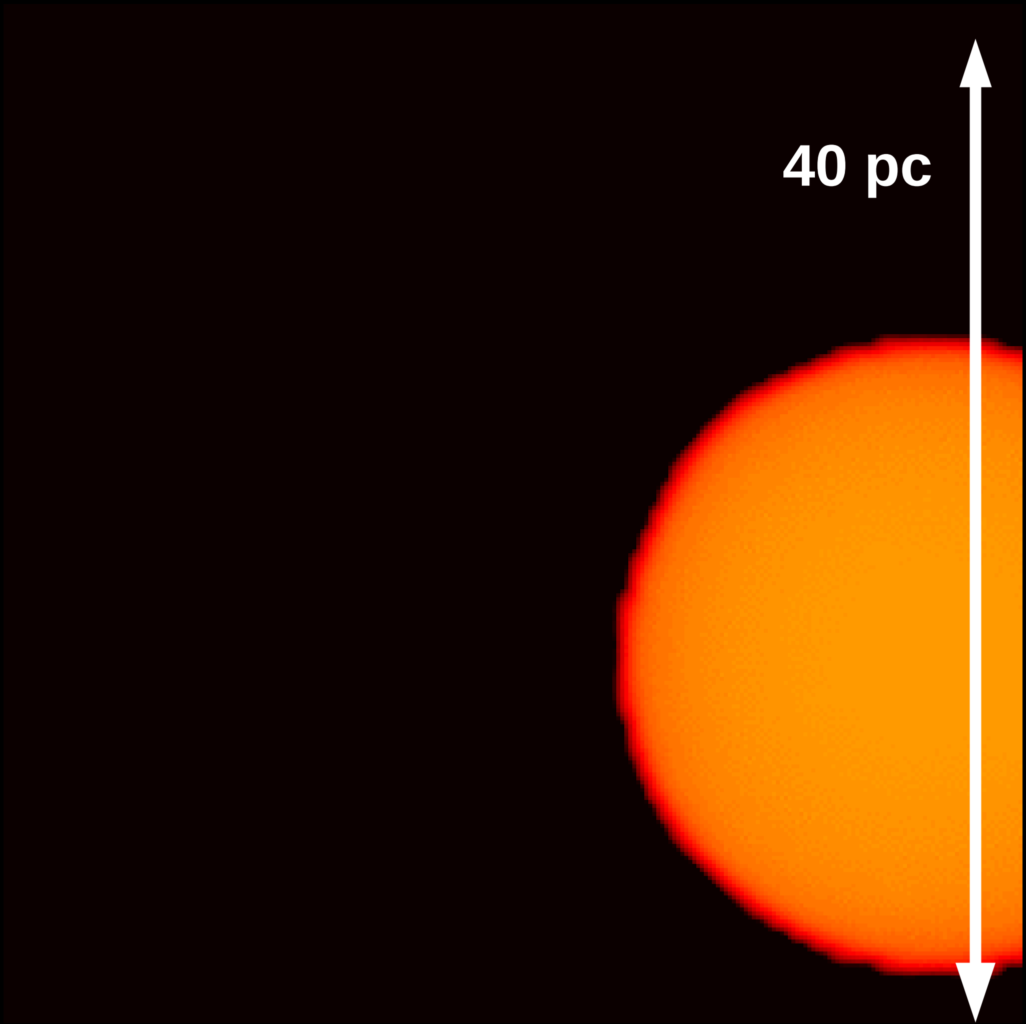
SIMULATION of SC FORMATION
INCLUDING PARENT GAS



5– Studying SF in the Galactic centre with SPH

N-body SPH

- Molecular cloud model is turbulence supported and marginally bound
- SMBH is SINK PARTICLE
- protostars form from fragmentation in the disc



2.3 M CPU hours at Fermi BGQ CINECA for the StarSMBH project (PI Mapelli)

5– Conclusions and future

* SCs as building blocks of galaxies

* DRY star clusters (dynamics+stellar evolution):
  GPUs are a MUST for astrophysical COLLISIONAL systems and high-precision dynamics

  We present a NEW TOOL for STELLAR EVOLUTION in combination with GPU-OPTIMIZED N-BODY CODES
  - VERSATILE
  - most accurate recipes for massive stars
  - most accurate recipes for BH formation

* WET star clusters (GAS):
  It is essential to investigate the formation of SCs from molecular clouds

  WORK IN PROGRESS: including hydrodynamic of GAS in our N-body+stellar evolution simulations of SC formation (AMUSE)

MY YOUNG COLLABORATORS

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PhD student

Dr. Mario Spera
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Brunetto M. Ziosi,
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THANKS