# Close encounters, inspirals and mergers: the link between globular and nuclear star clusters


## Alessandra Mastrobuono-Battisti

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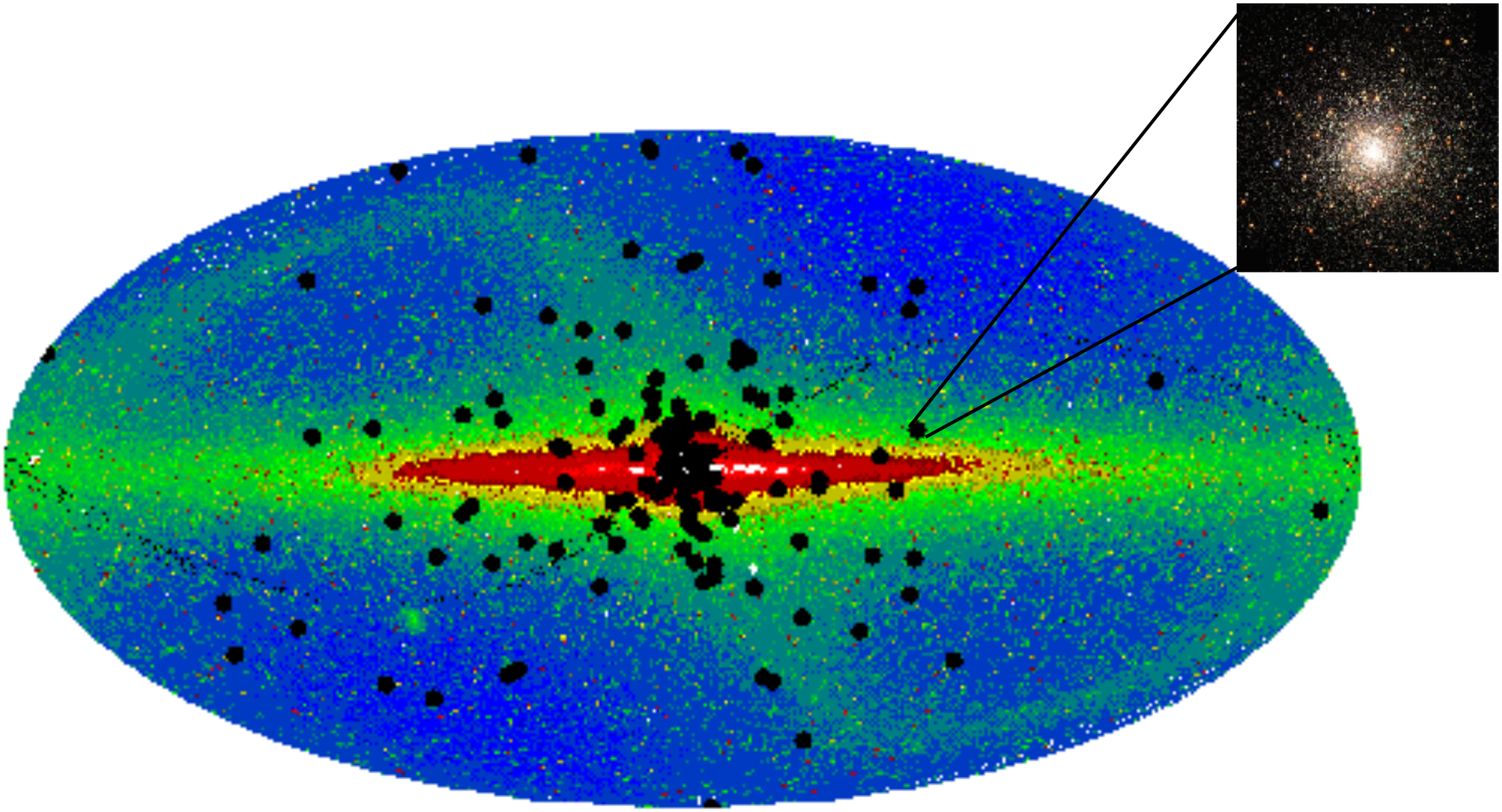
Hagai Perets (Technion)

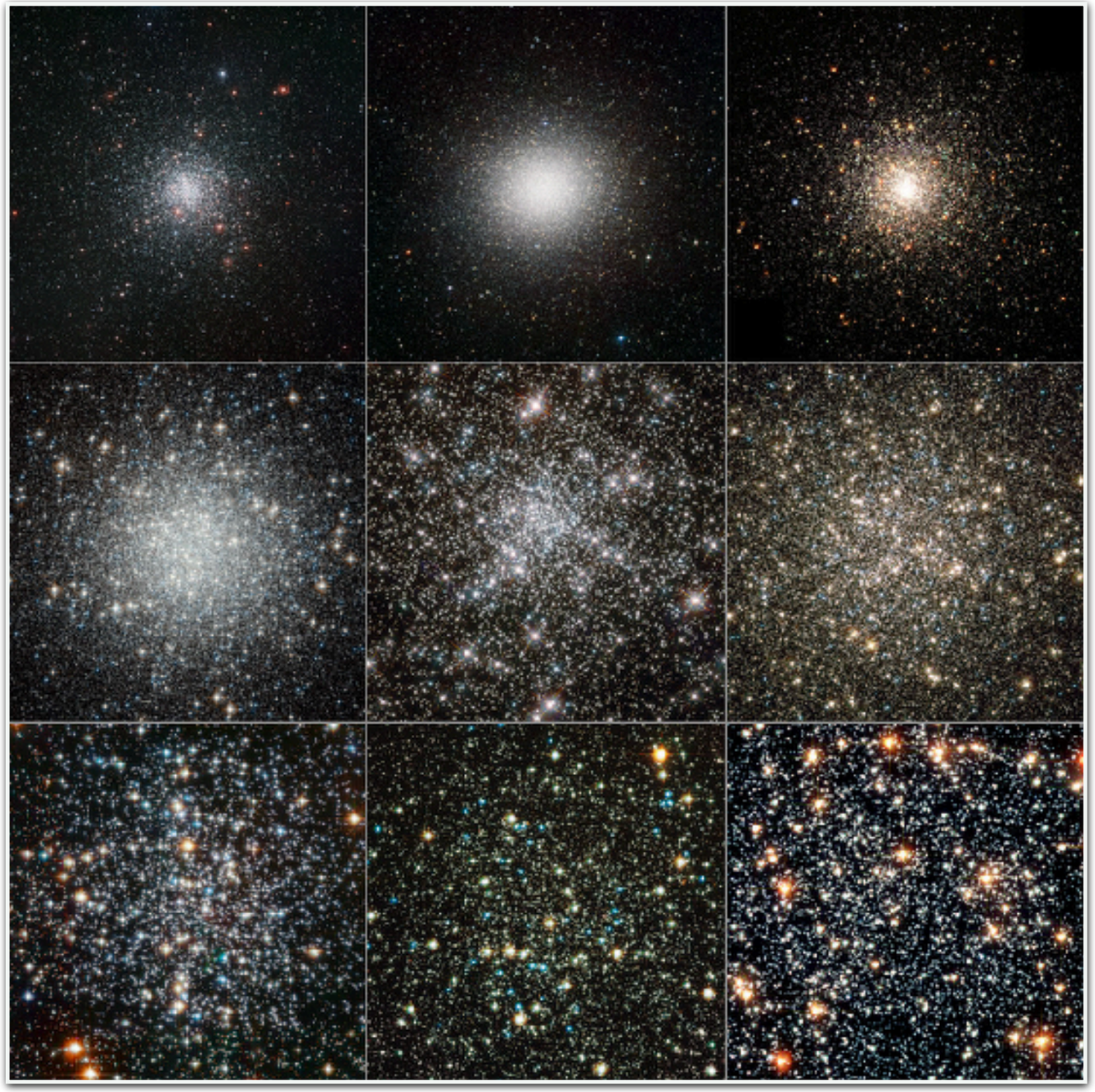

**Nice, 05.03.2019**

# There are about 200 globular clusters in the Milky Way



The positions of the 146 known Galactic globular clusters (from Bill Harris's compilation ) on top of the COBE FIRAS 2.2 micron map of the Galaxy. Image credit:  Brian Chaboye.

# Globular clusters are the oldest stellar systems in our Galaxy



$r_h$<10pc

$N_{stars}$~$10^5$-$10^6$;

M ≤ few × $10^6$ $M_\odot$

Age ~11-13 Gyr

**Top row:** Messier 4 (ESO), Omega Centauri (ESO), Messier 80 (Hubble)
**Middle row:** Messier 53 (Hubble), NGC 6752 (Hubble), Messier 13 (Hubble)
**Bottom row:** Messier 4 (Hubble), NGC 288 (Hubble), 47 Tucanae (Hubble)

# Globular clusters evolve in the Galaxy and trace its assembly history

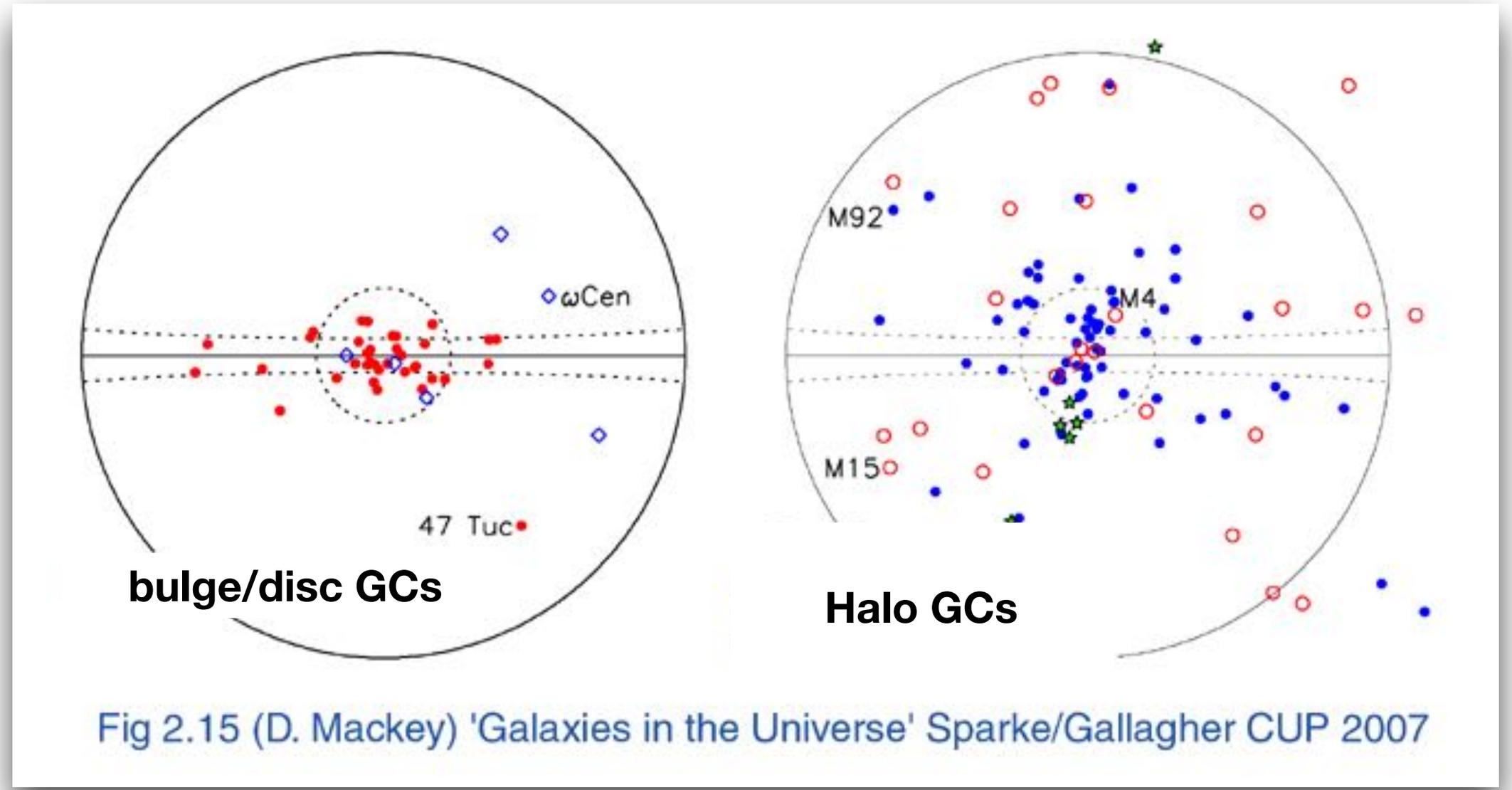



Fig 2.15 (D. Mackey) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

see Brodie & Strader, 2006

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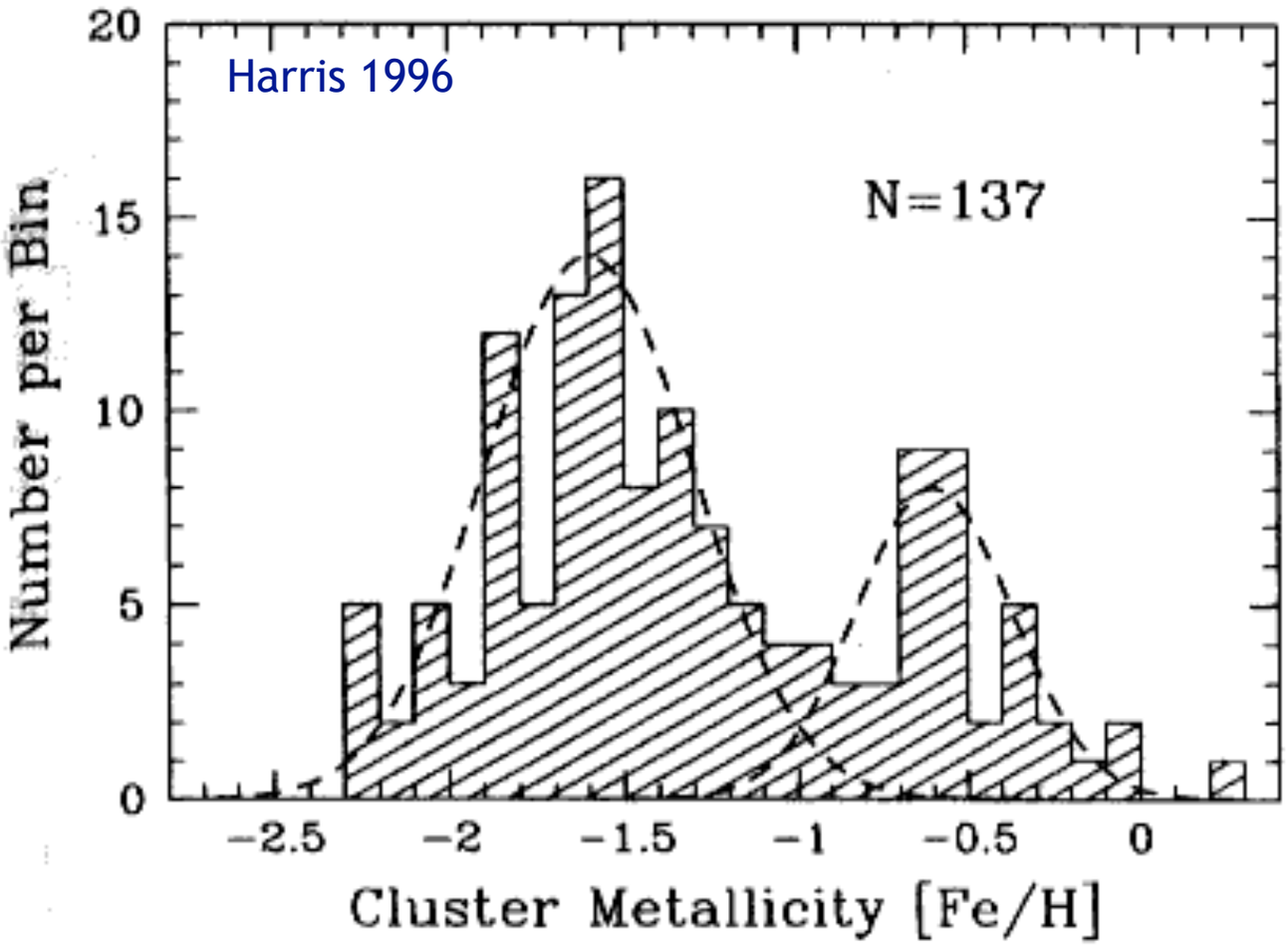


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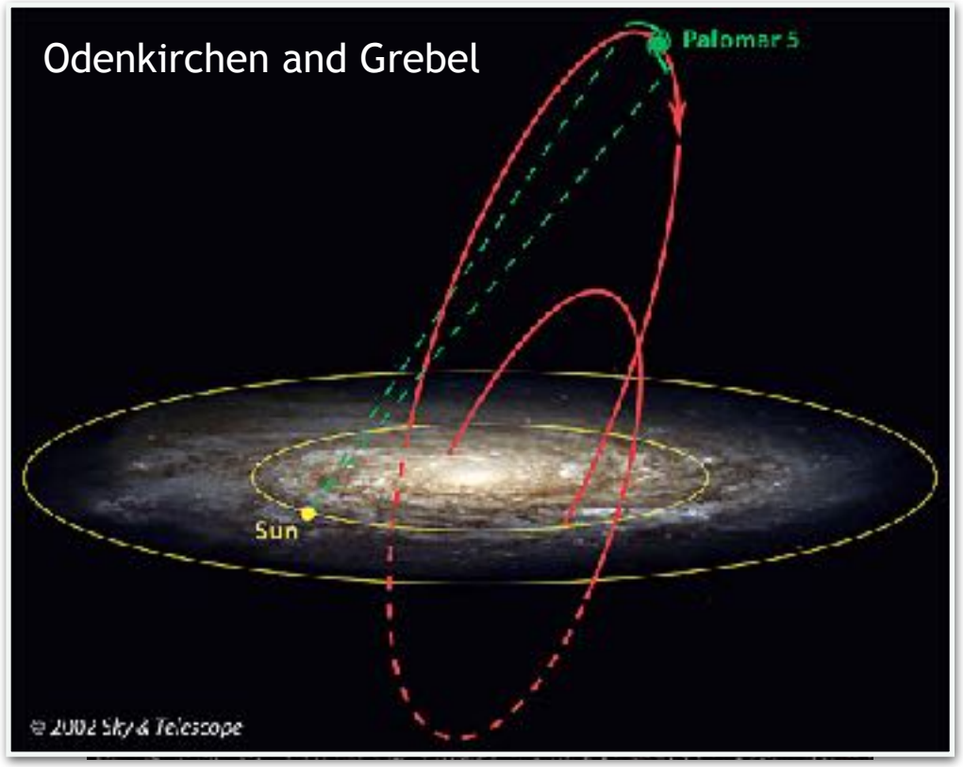

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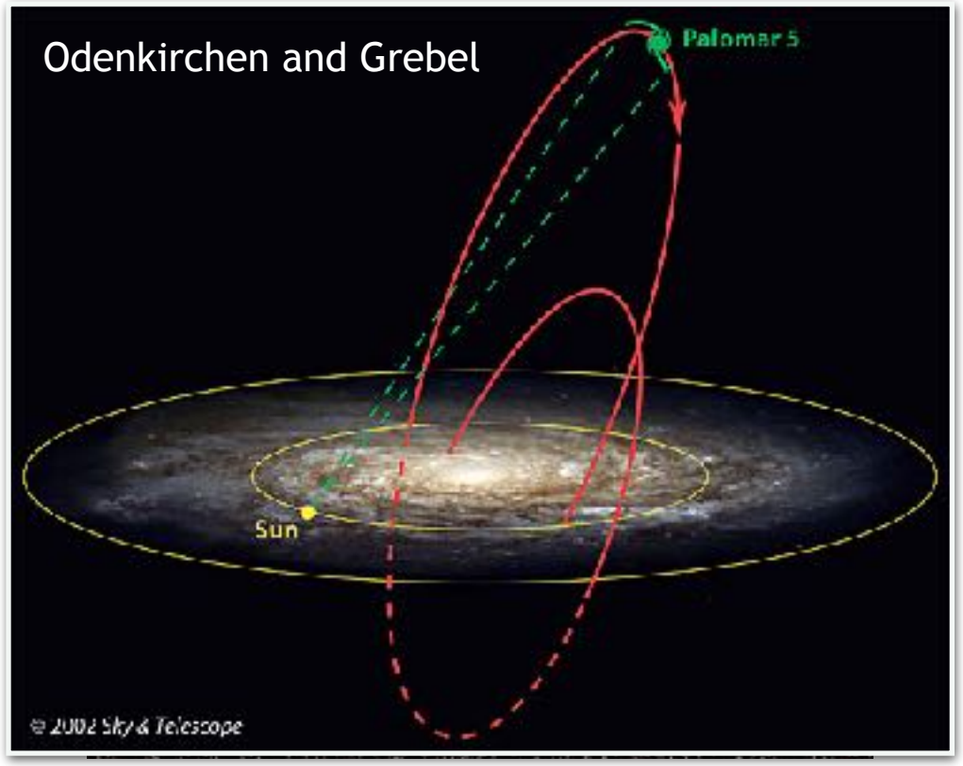


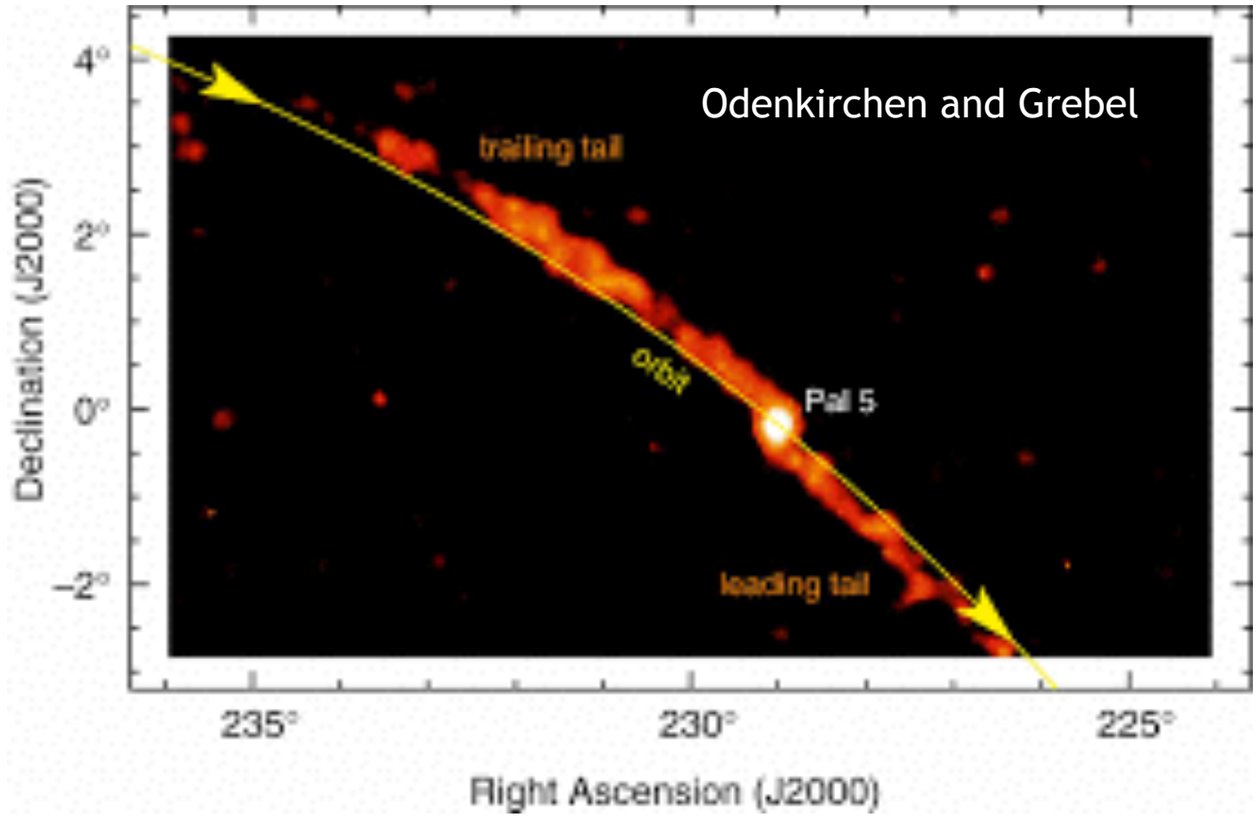

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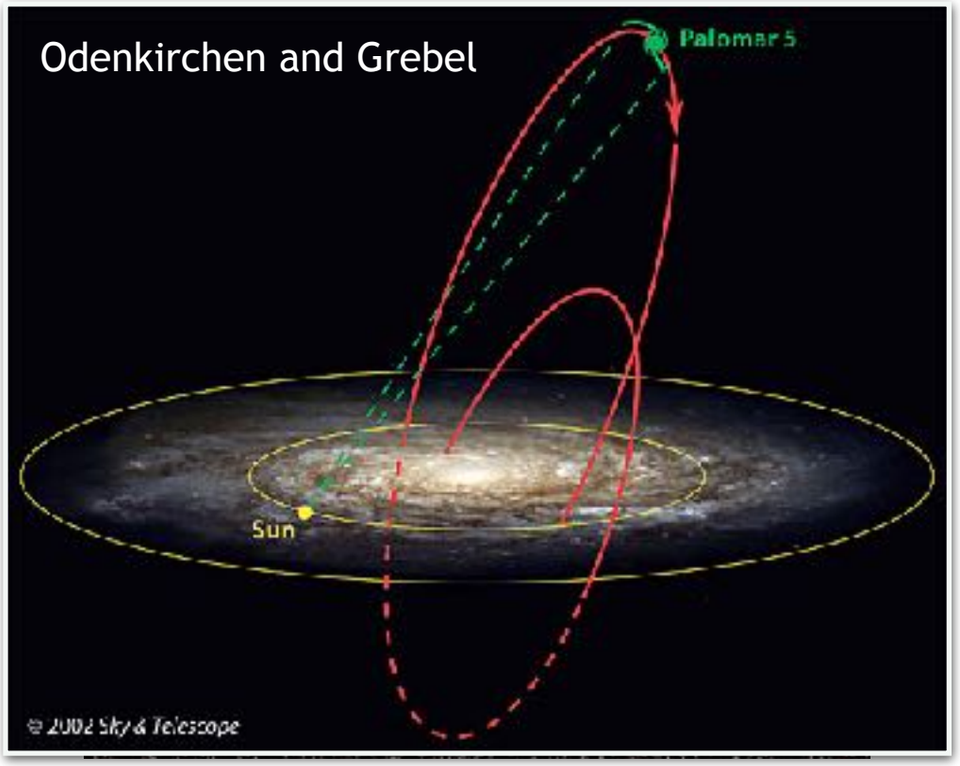


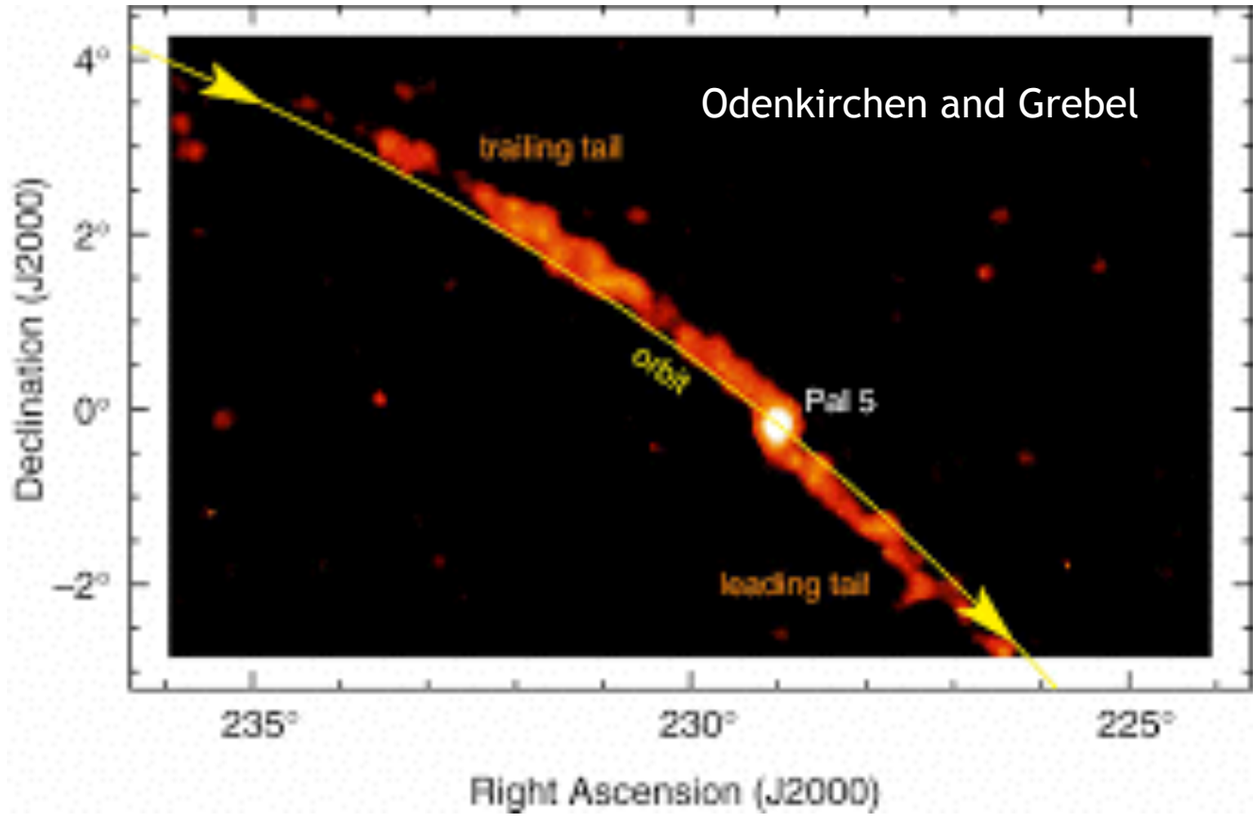


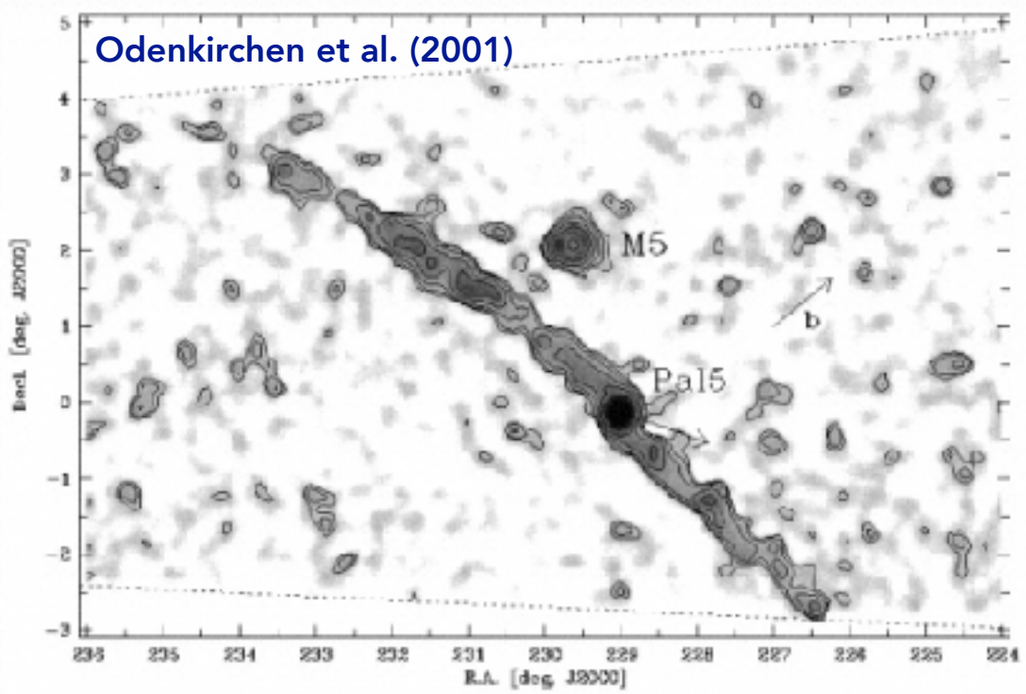

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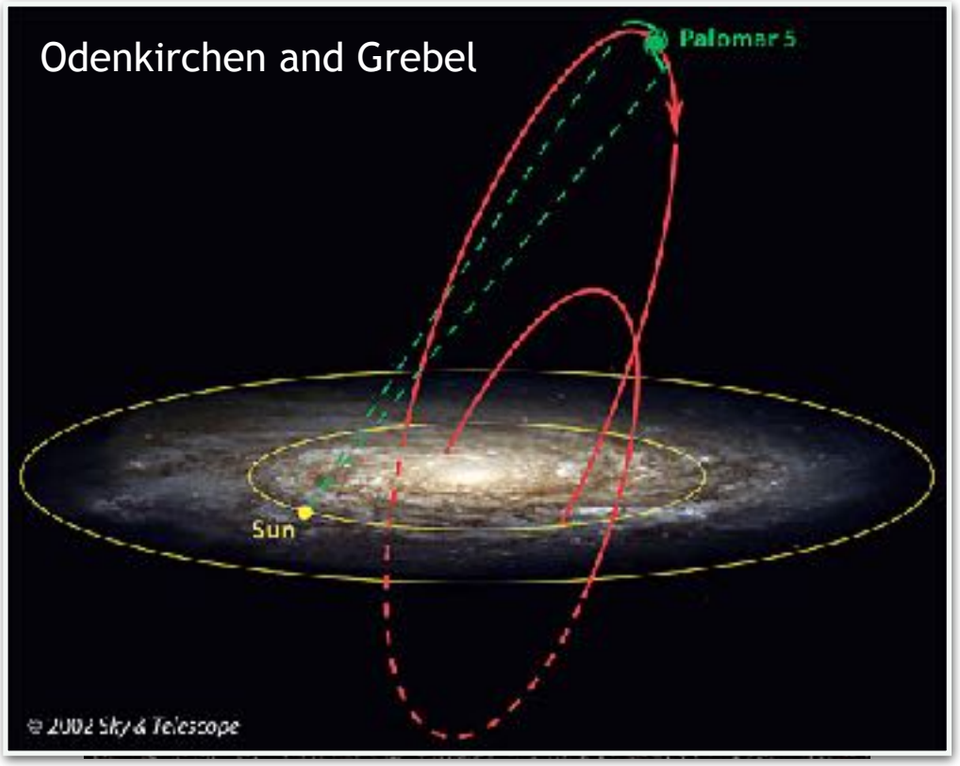


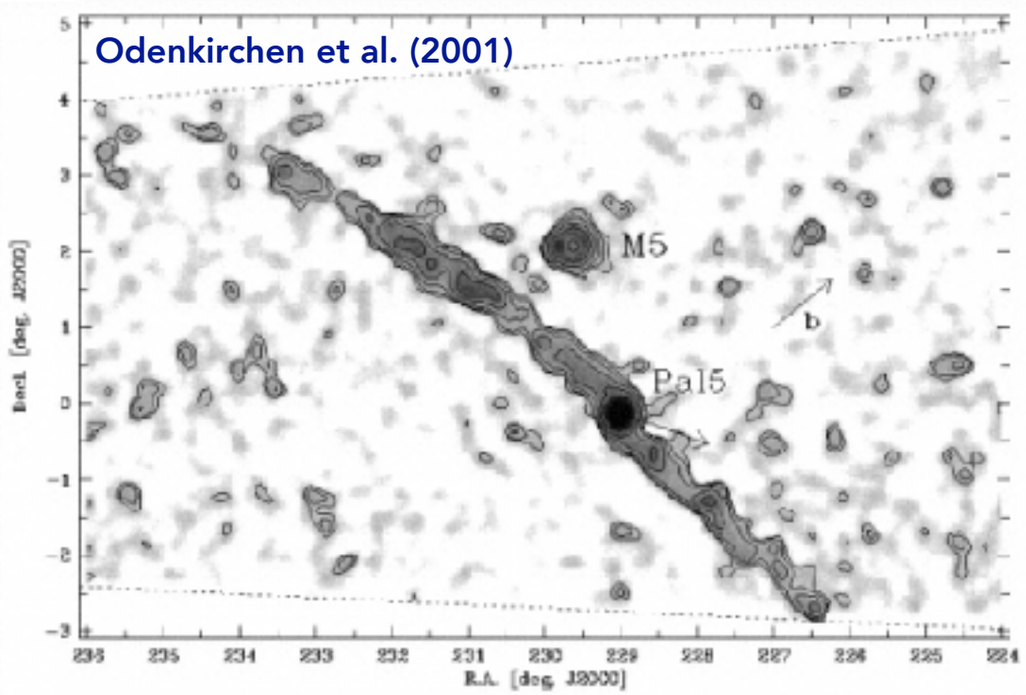


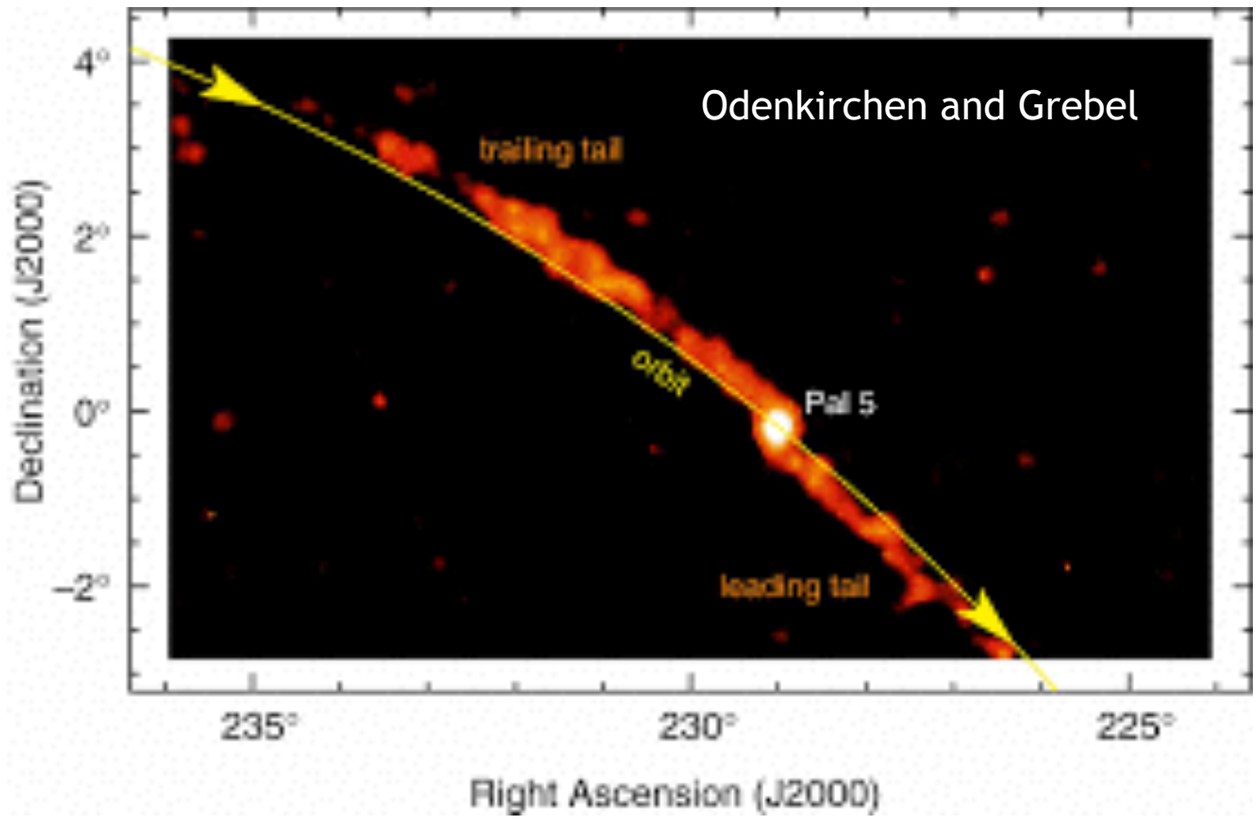


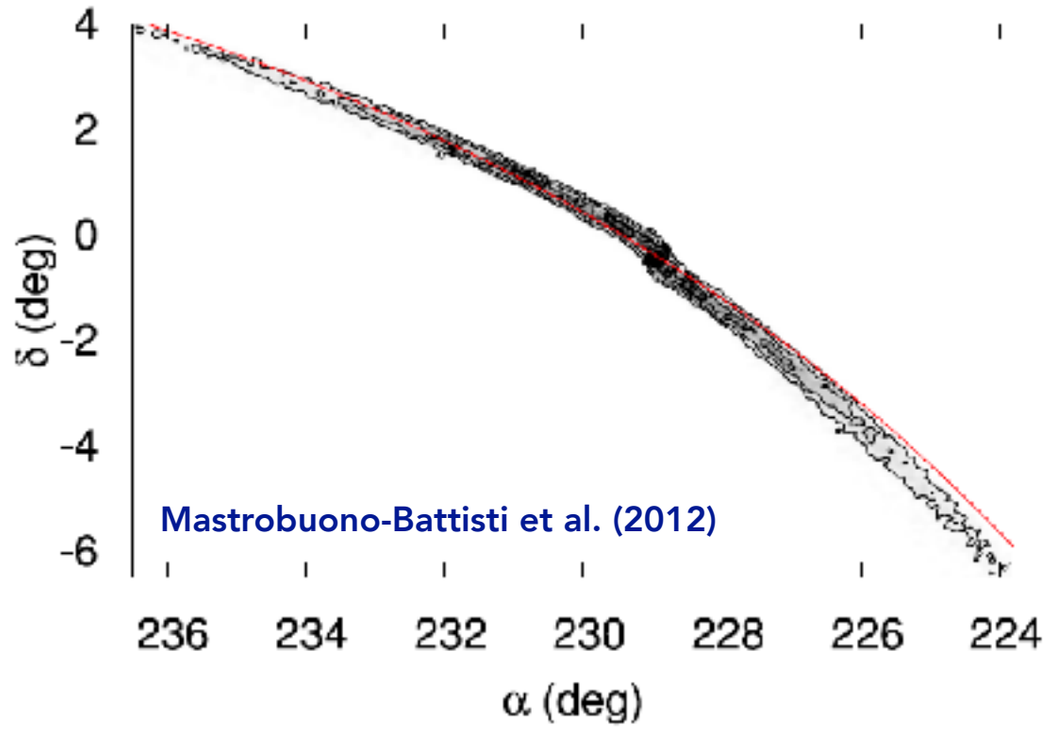

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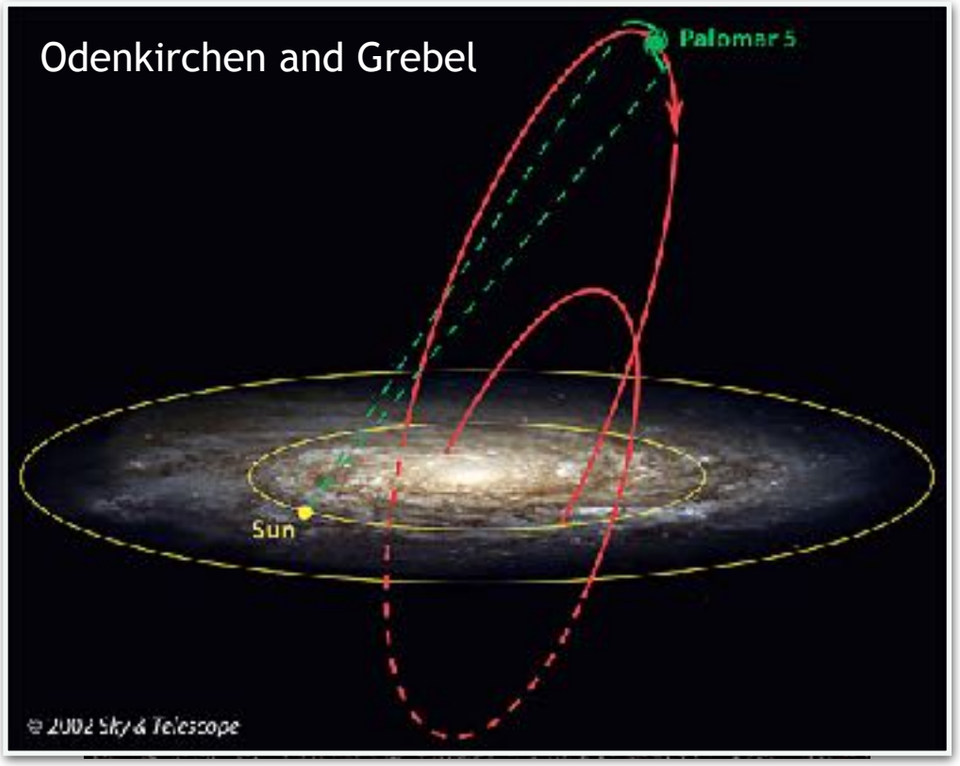


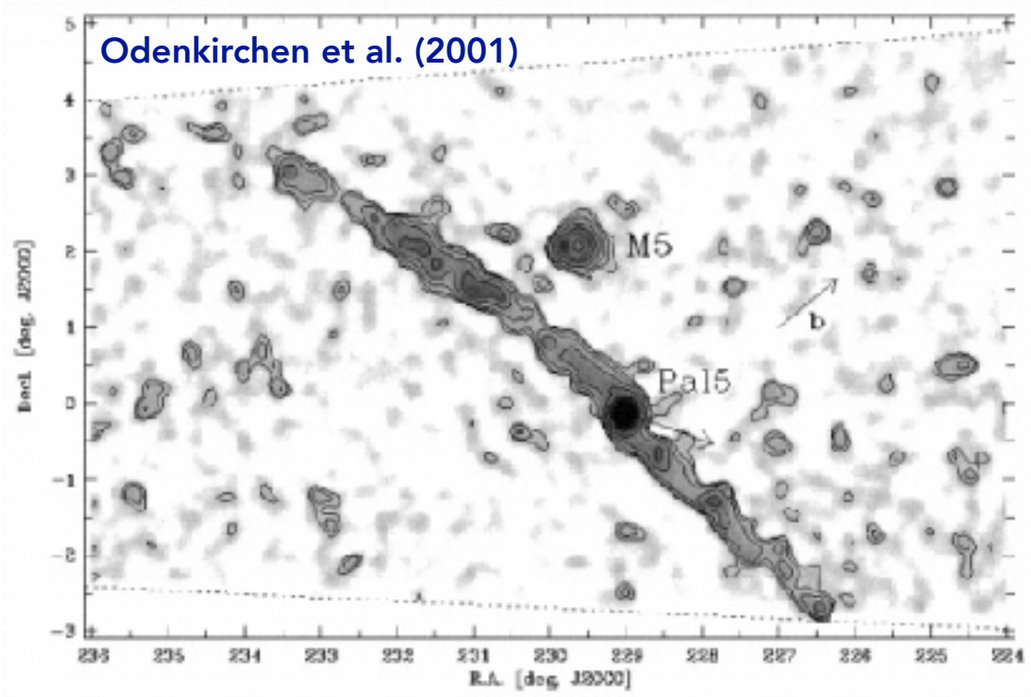


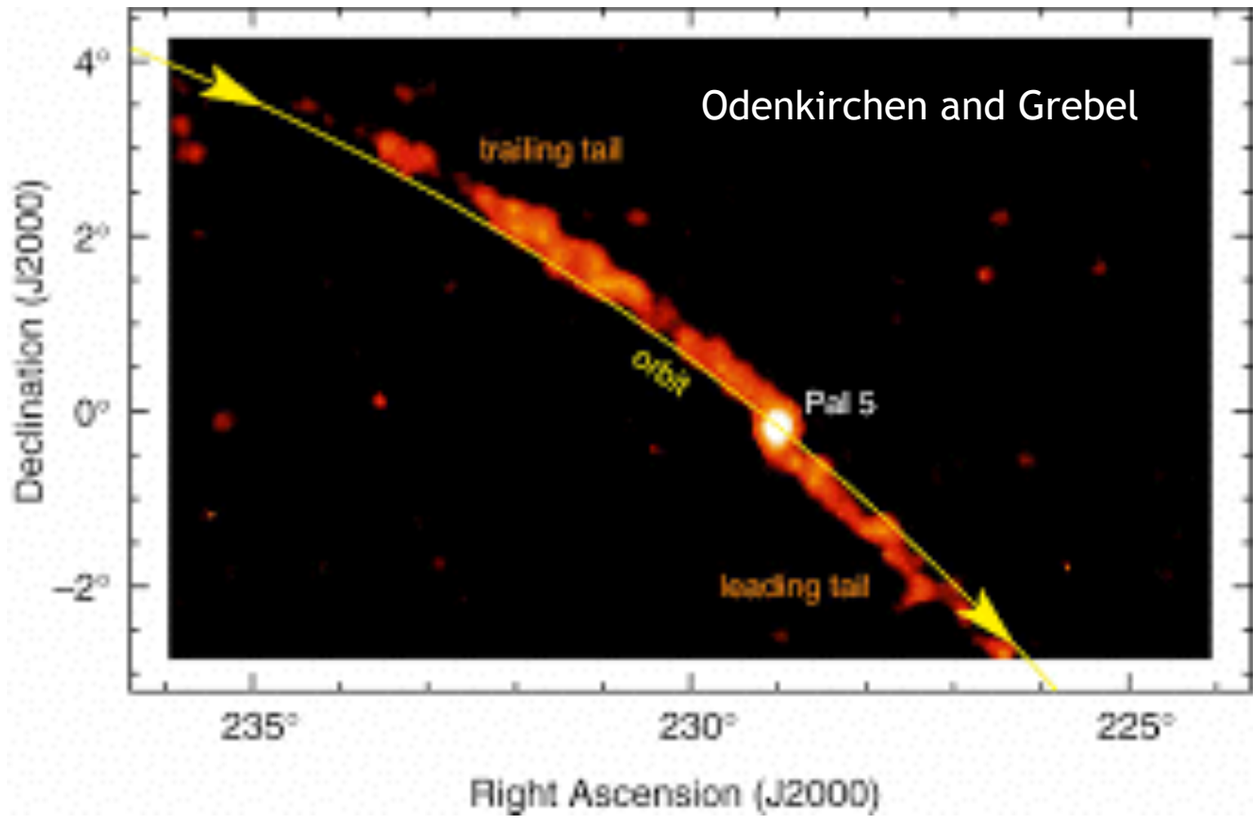


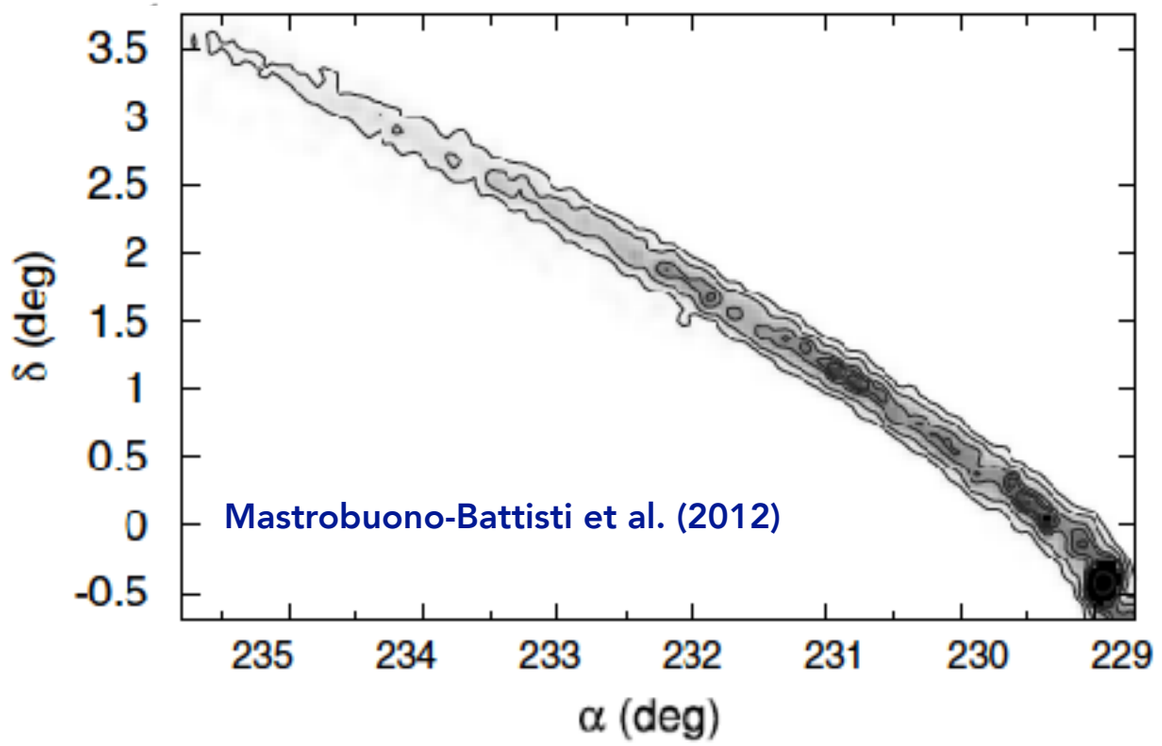

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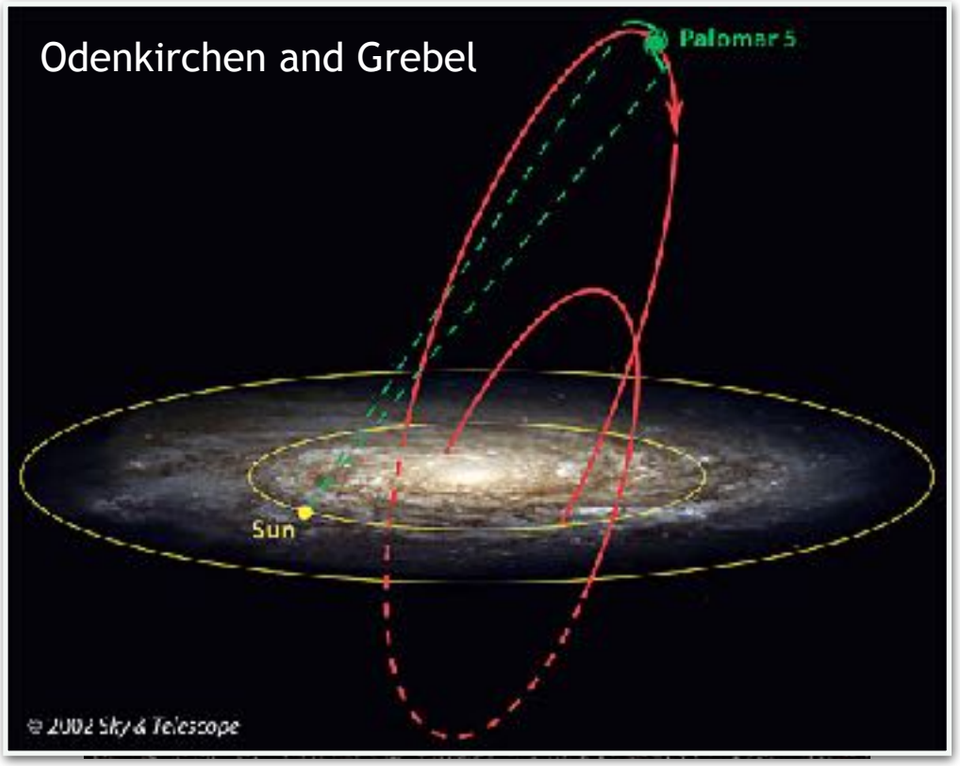


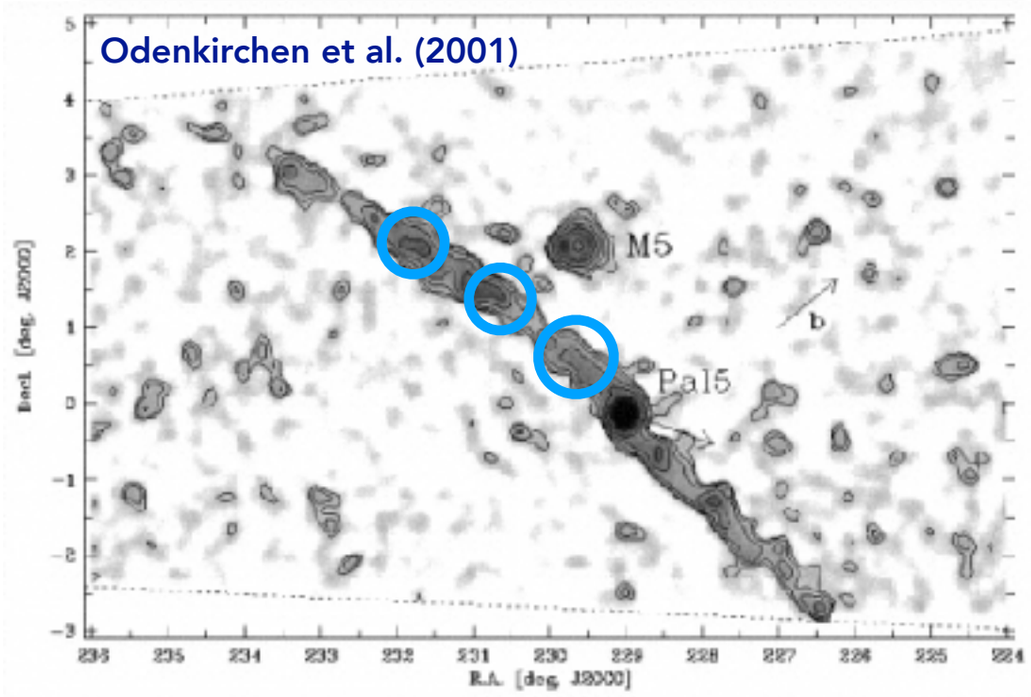


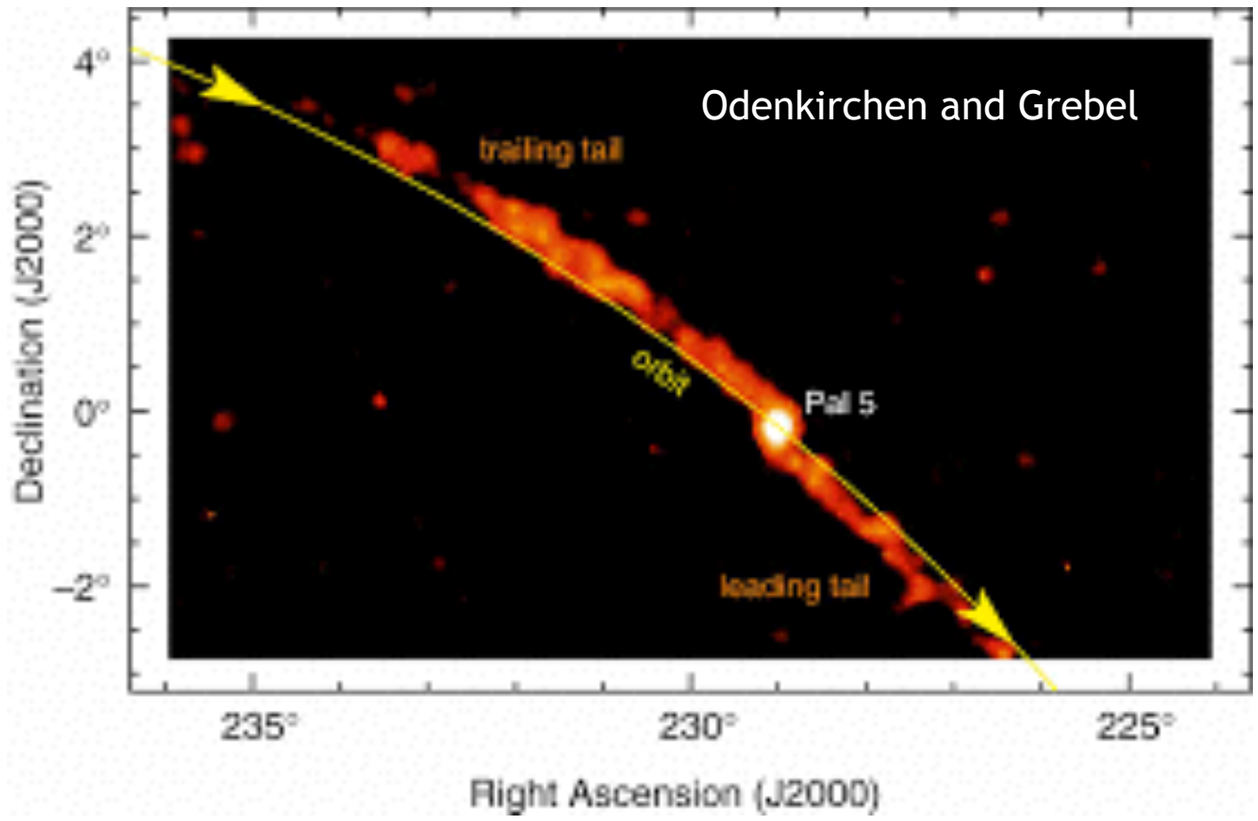


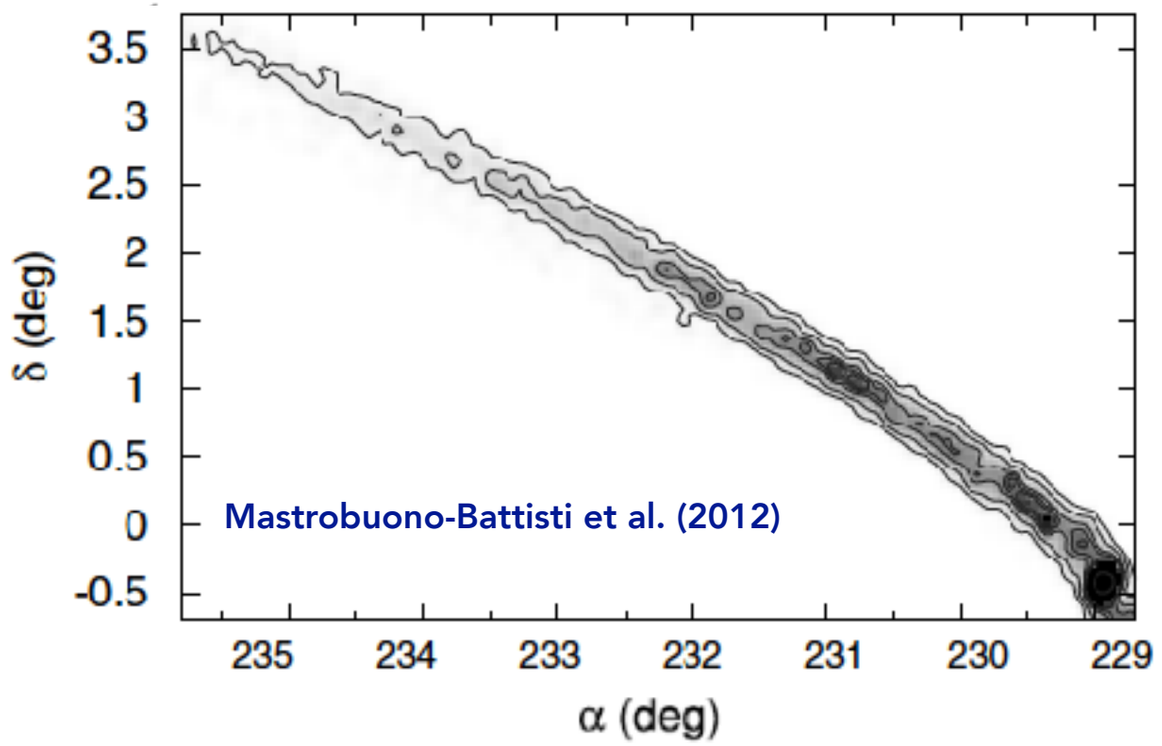

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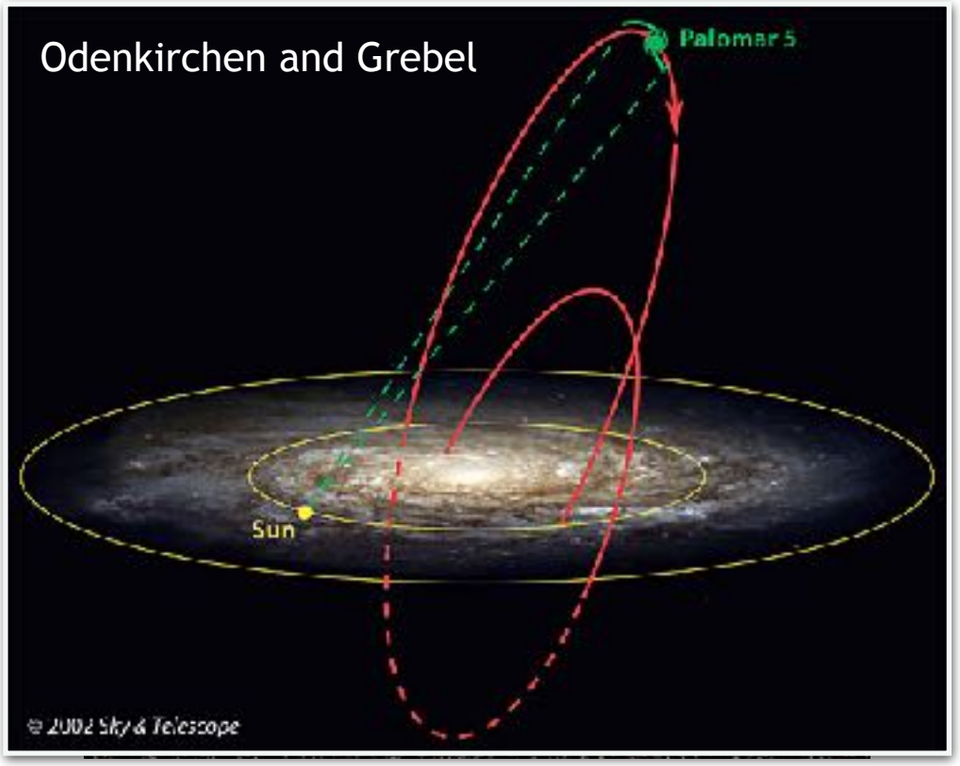
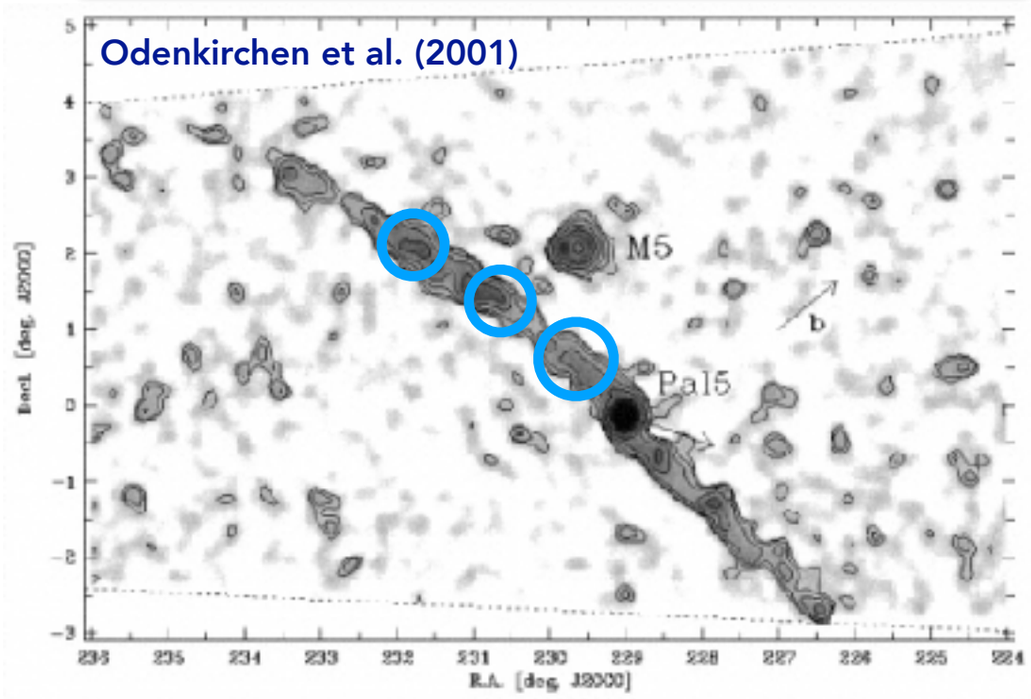
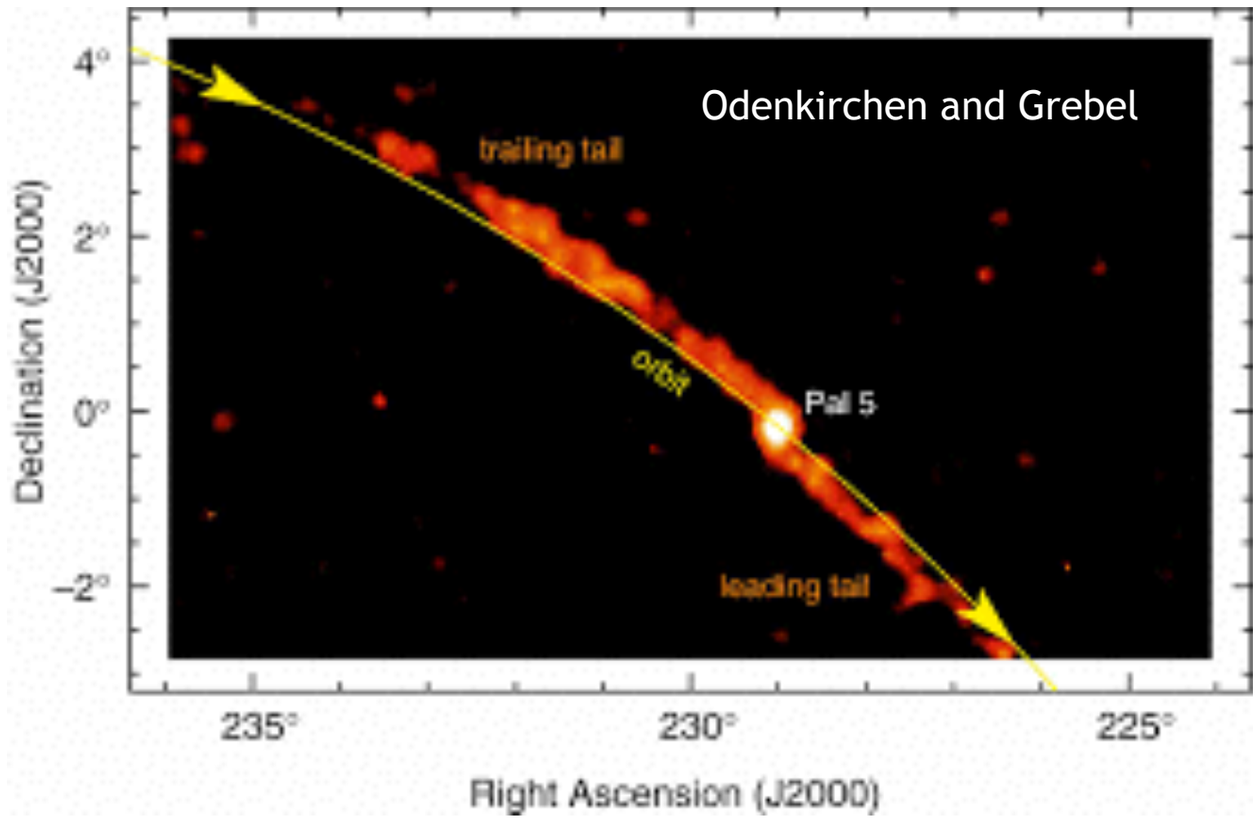
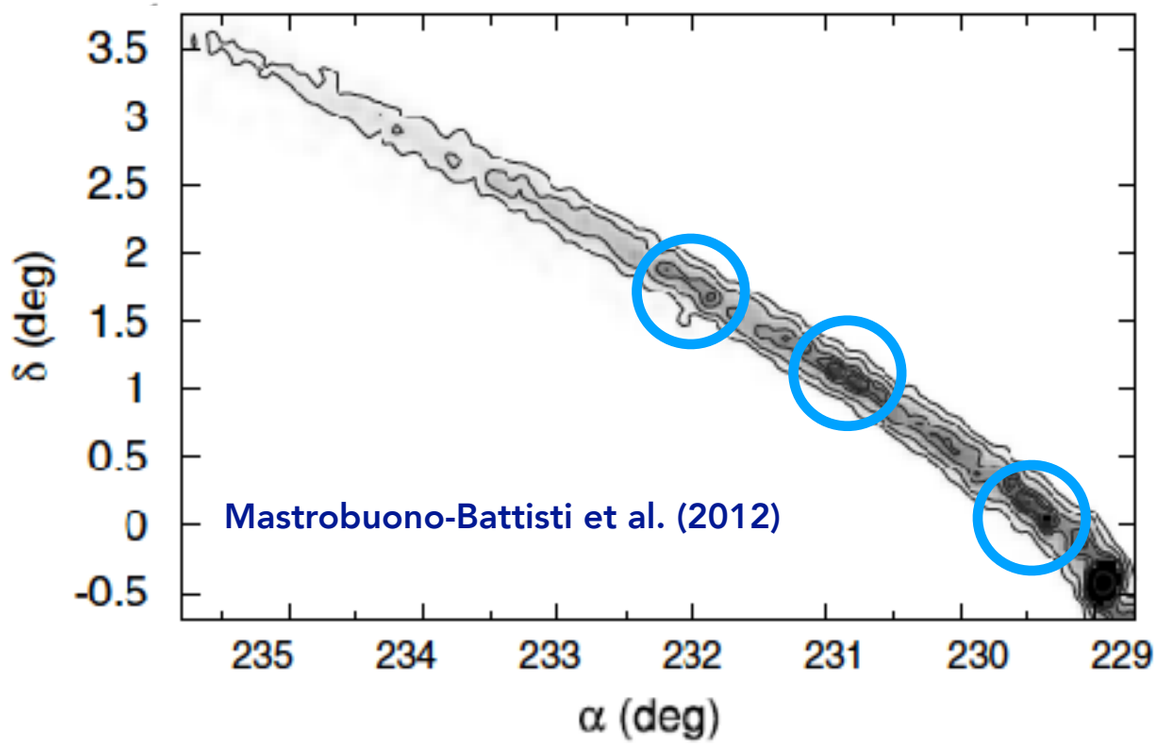
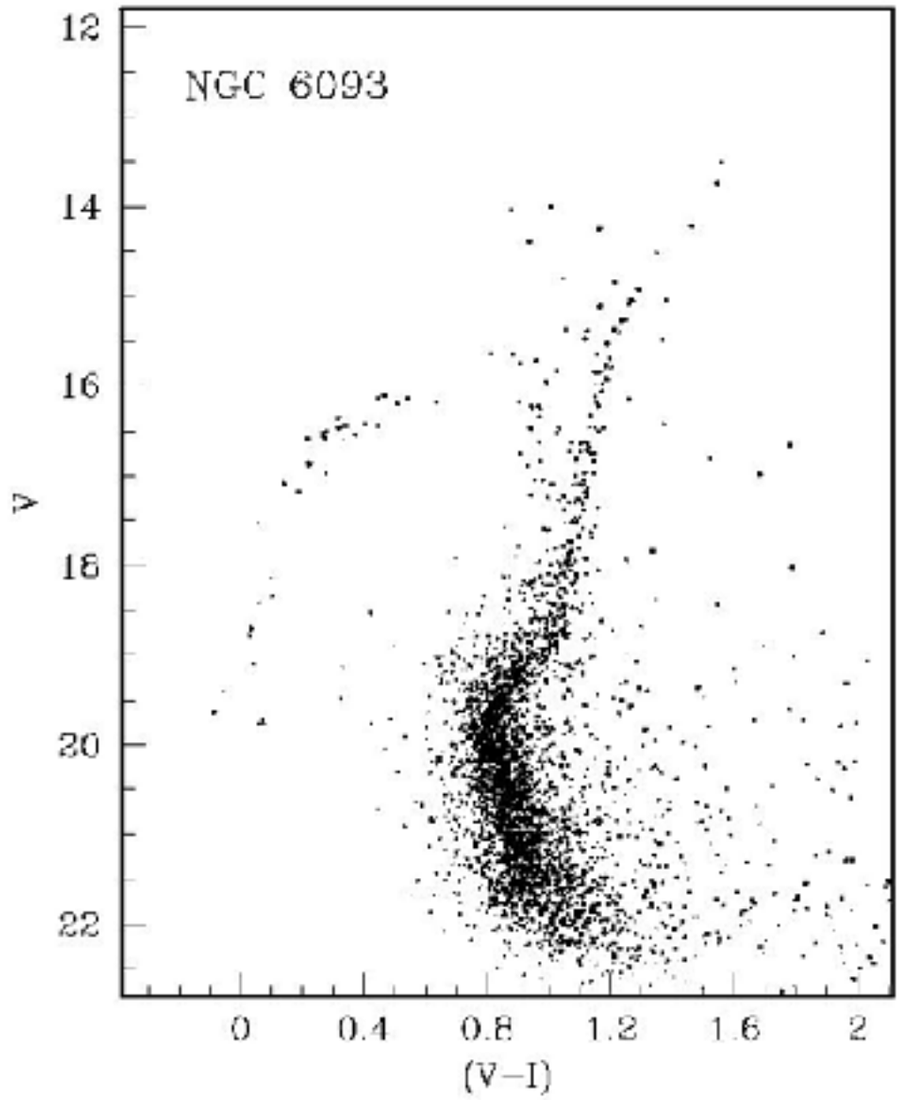


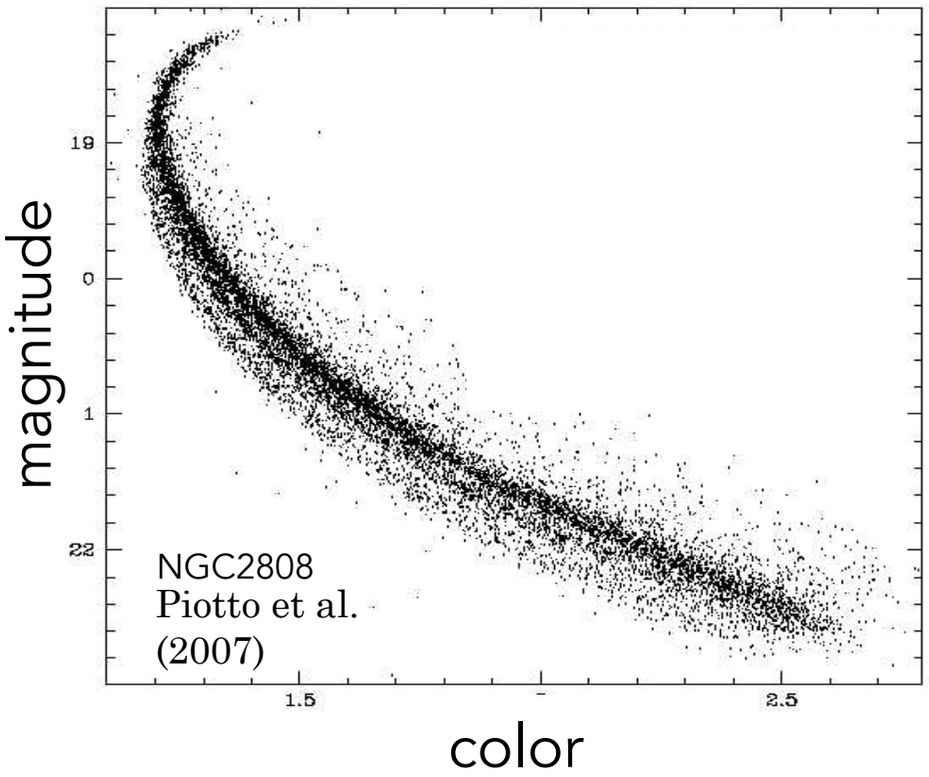
# Globular clusters were  for long considered single stellar populations




http://groups.dfa.unipd.it/ESPG/GC.html

However, **GCs** host **multiple stellar populations** (e.g. Bedin et al. 2004, Gratton et al. 2004, Piotto et al. 2007, Piotto 2009, Di Criscienzo et al 2011, Milone et al. 2011, Gratton et al. 2012).

# Globular clusters had a complex star formation, that is not yet fully understood




Gratton et al. 2004; Carretta et al. 2007; Kayser et al. 2008; Carretta et al. 2009, 2010; Pancino et al. 2010; Milone et al. 2010, 2012, 2013; Gratton et al. 2012; Carretta 2015

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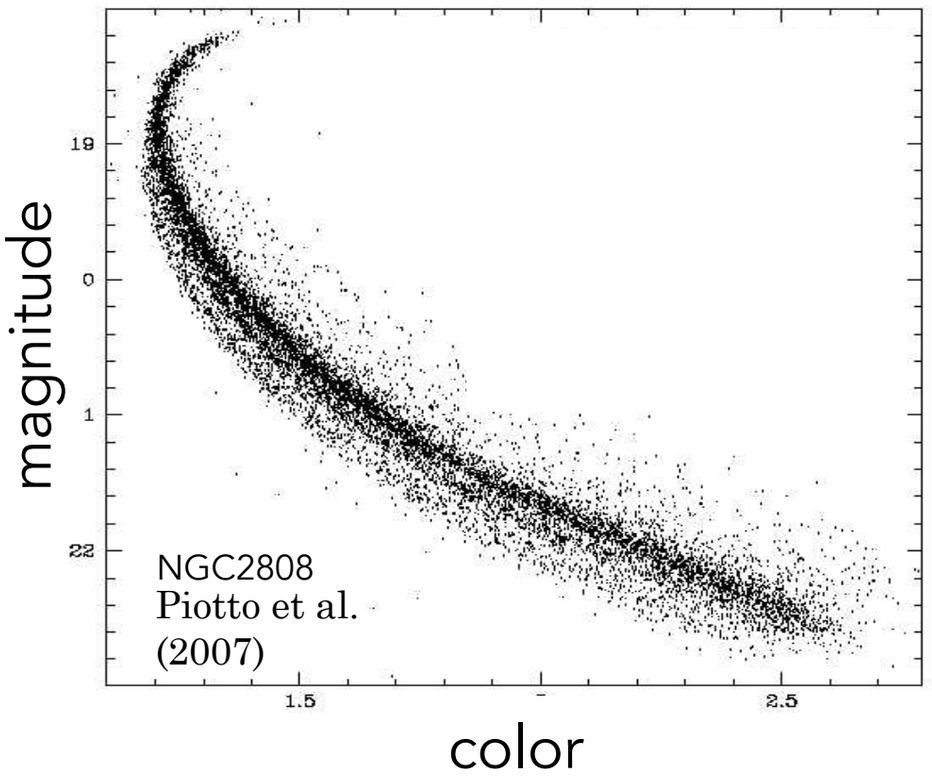


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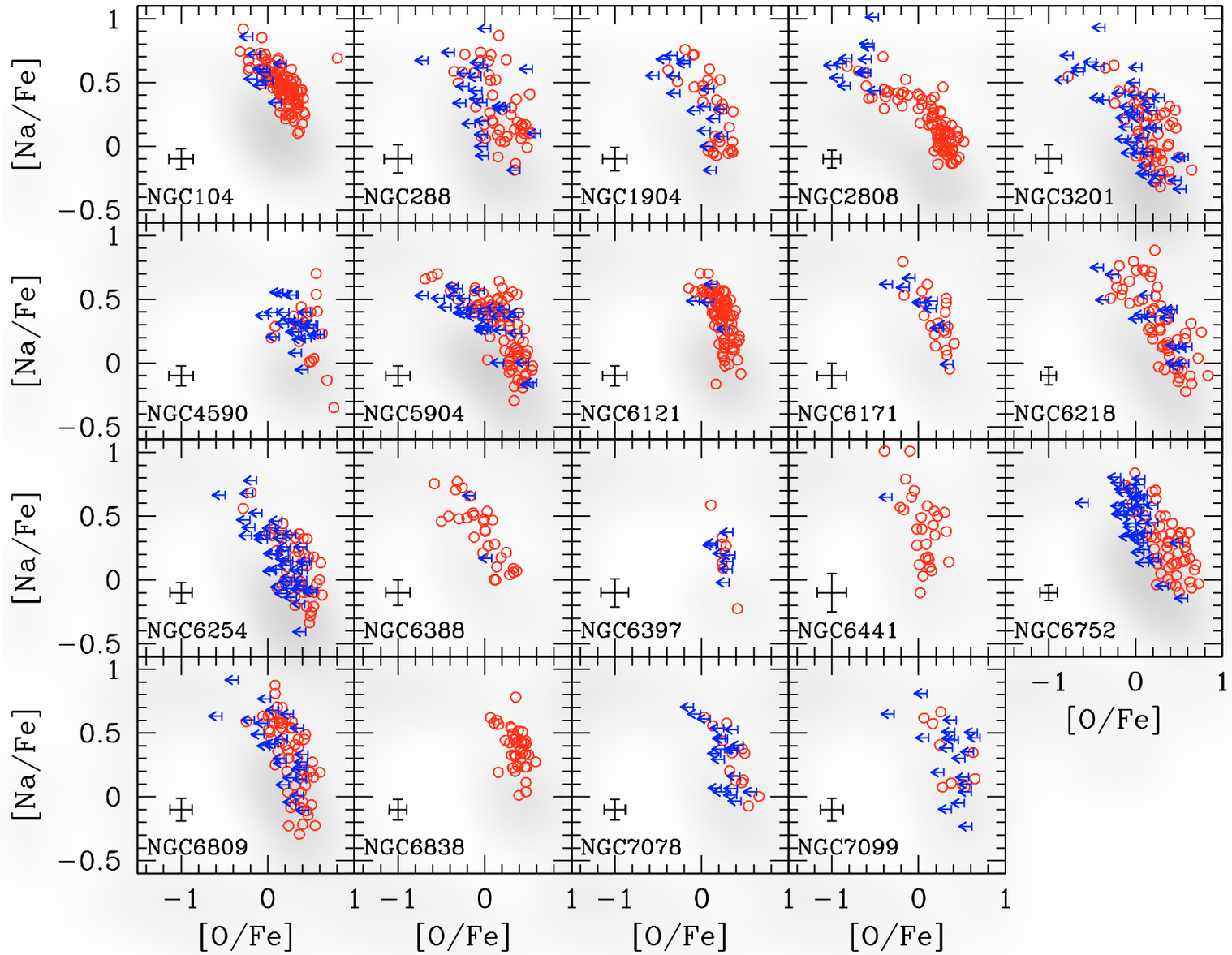

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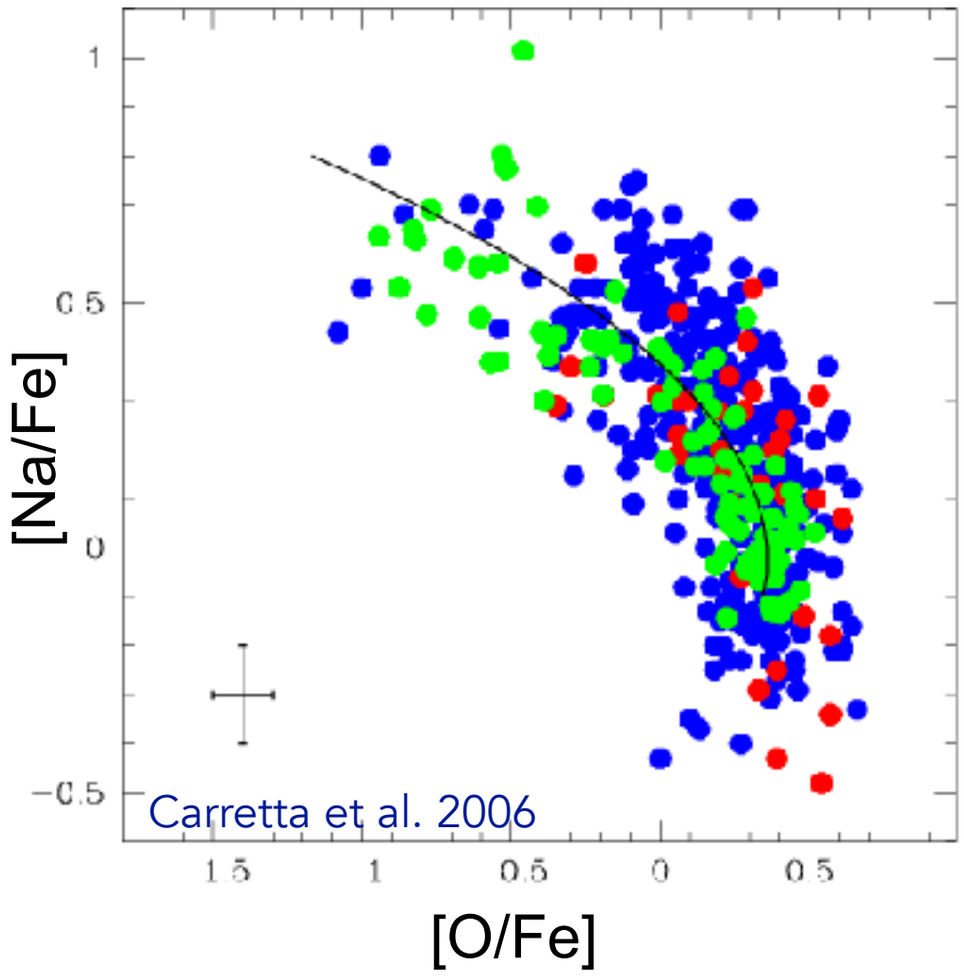


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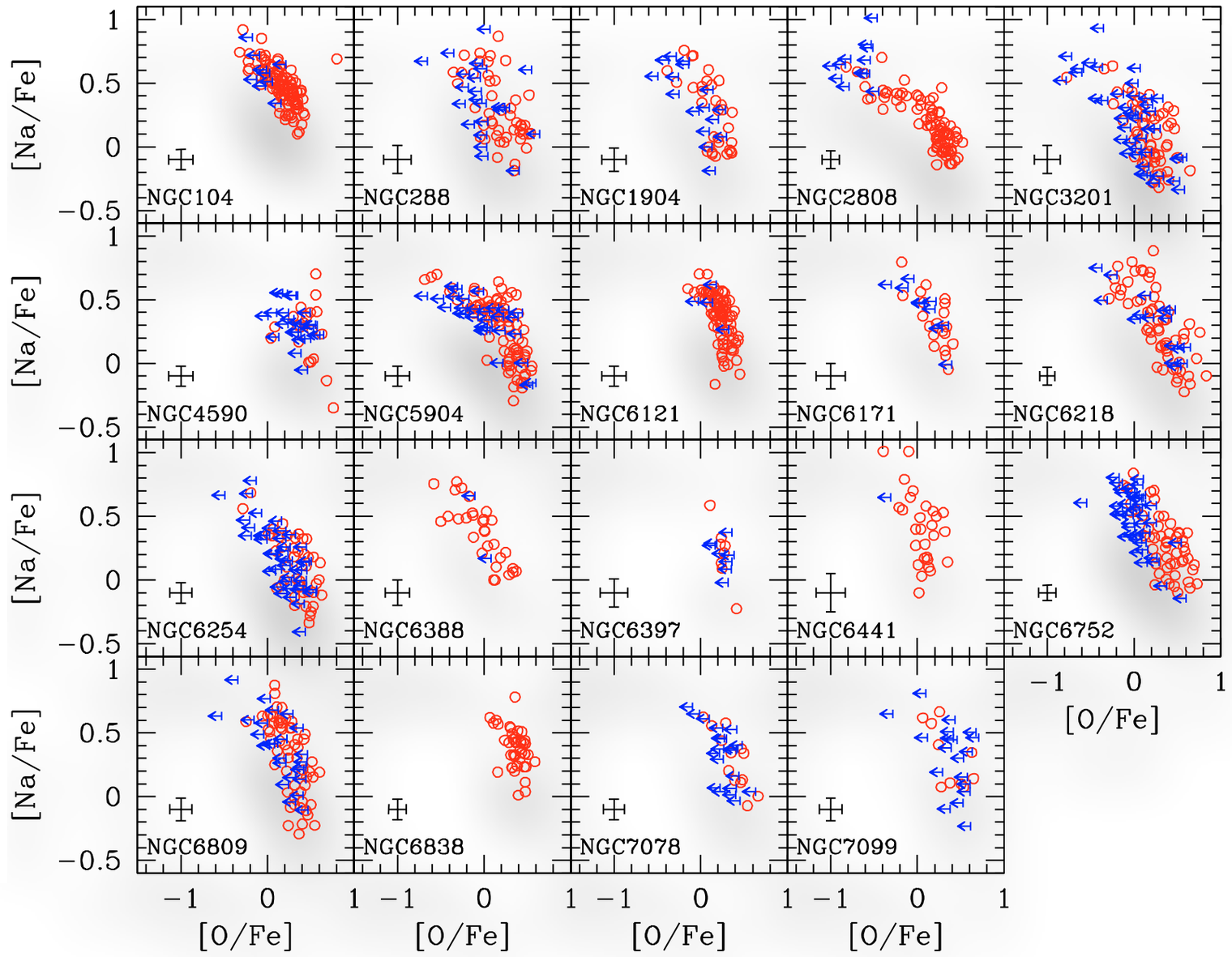

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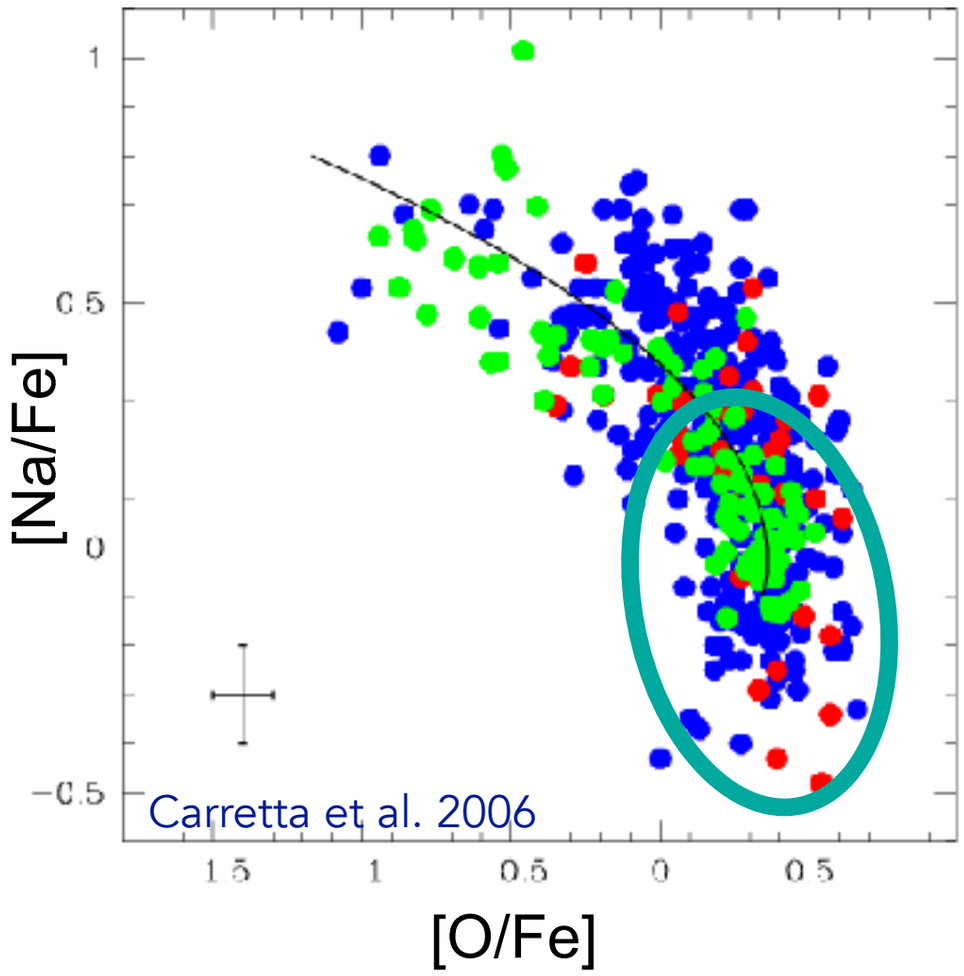


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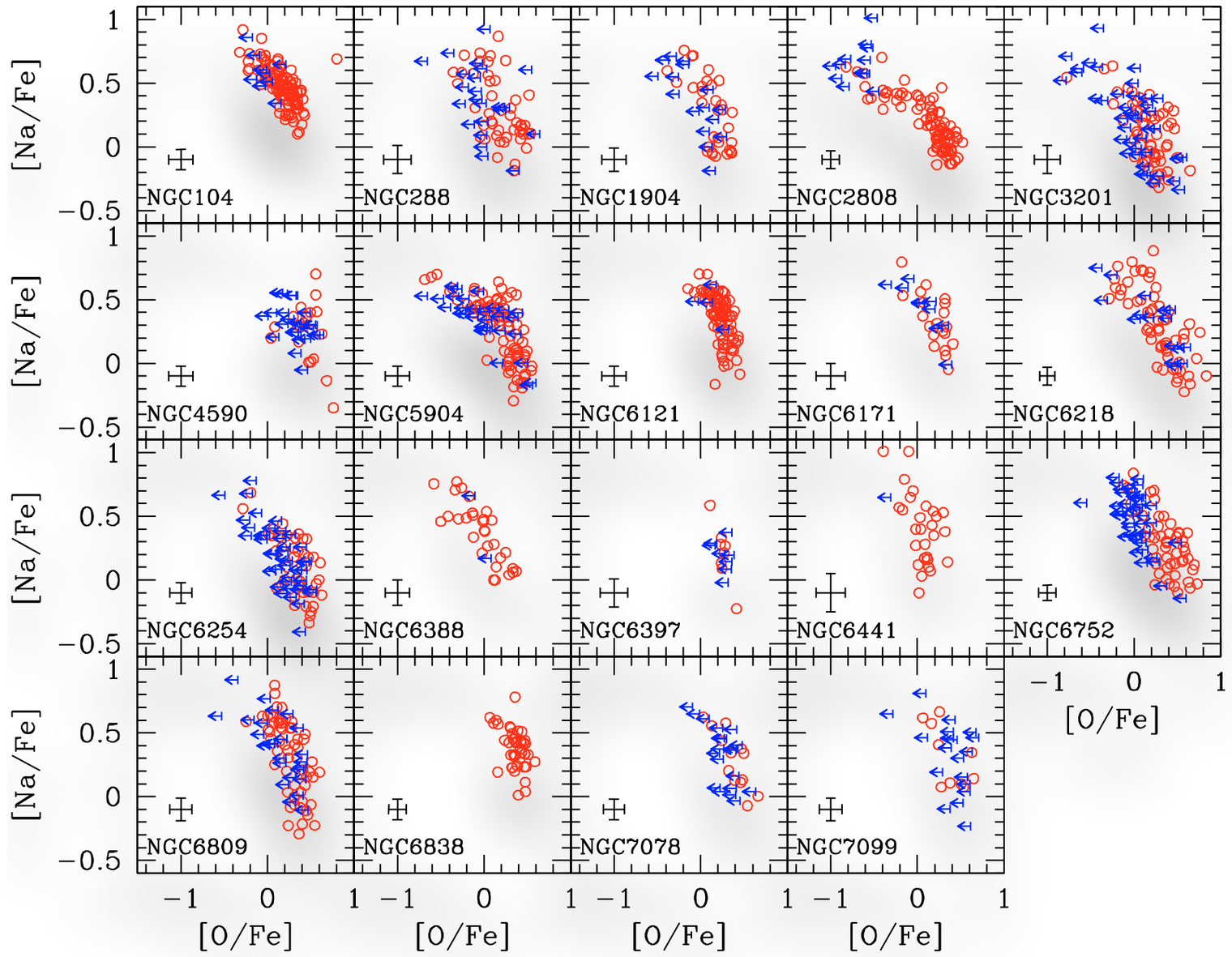

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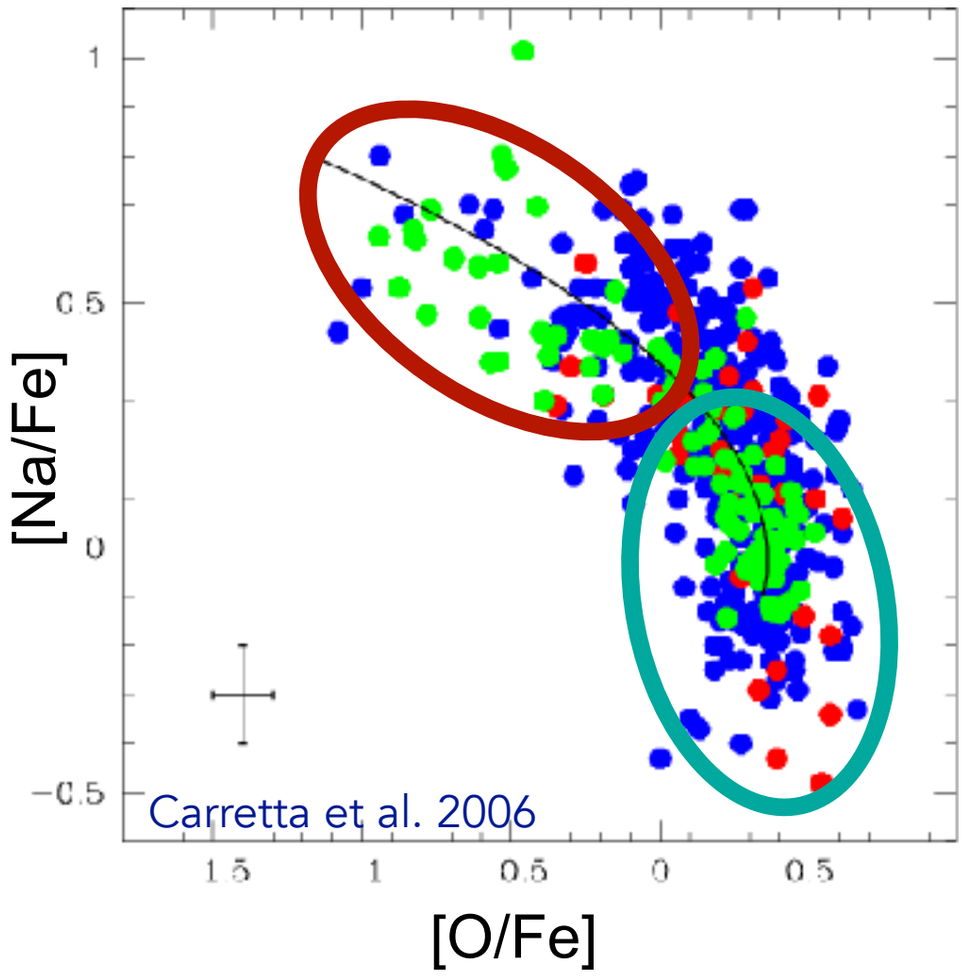


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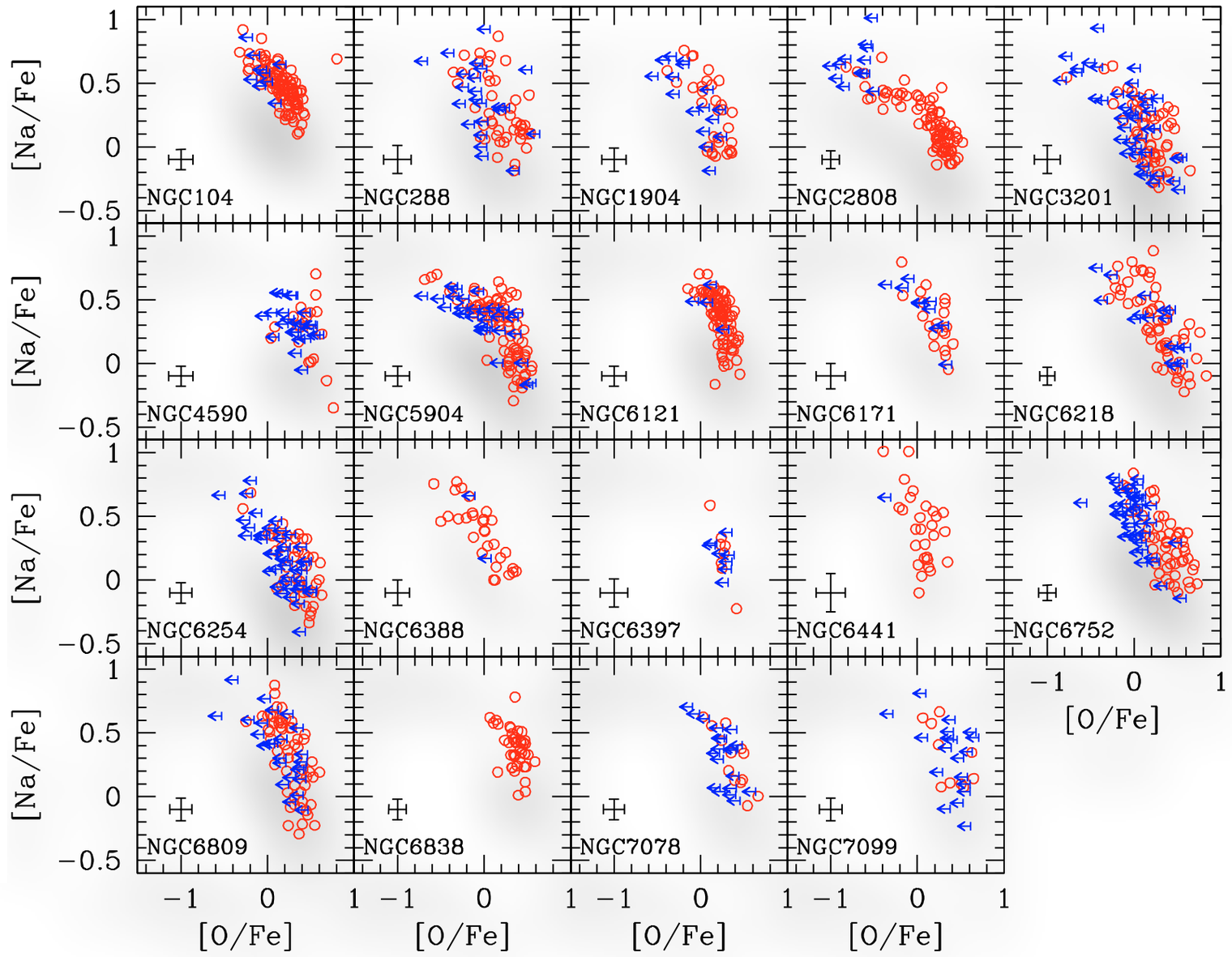

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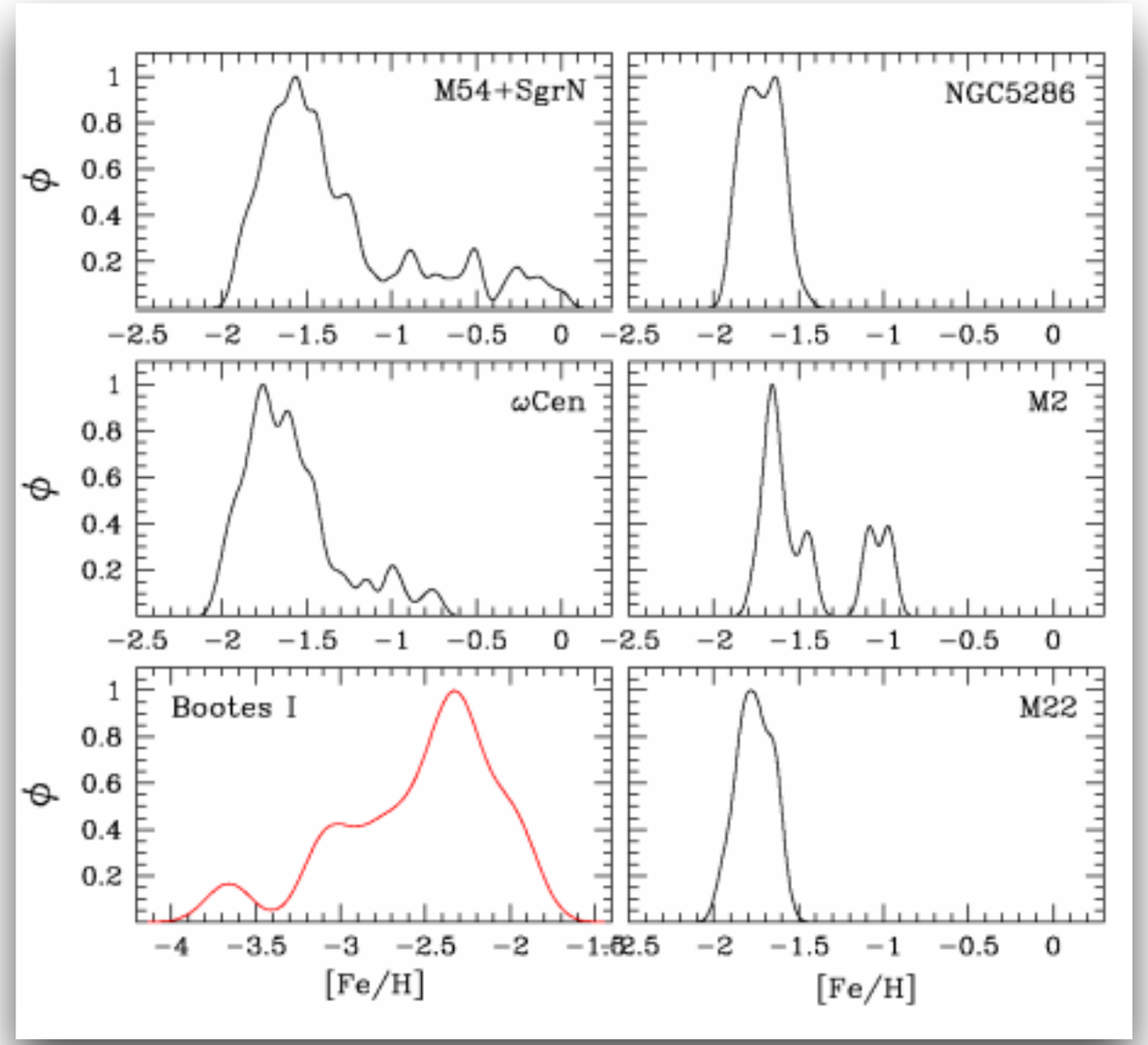


**Marino et al. 2015, 2018**

Norris & Da Costa 1995, ; Smith et al. 2000; Johnson & Pilachowski 2010; Marino et al. 2011; Yong et al. 2014; Johnson et al. 2015; Marino et al. 2015; Da Costa 2016; Johnson et al. 2017, 2018.

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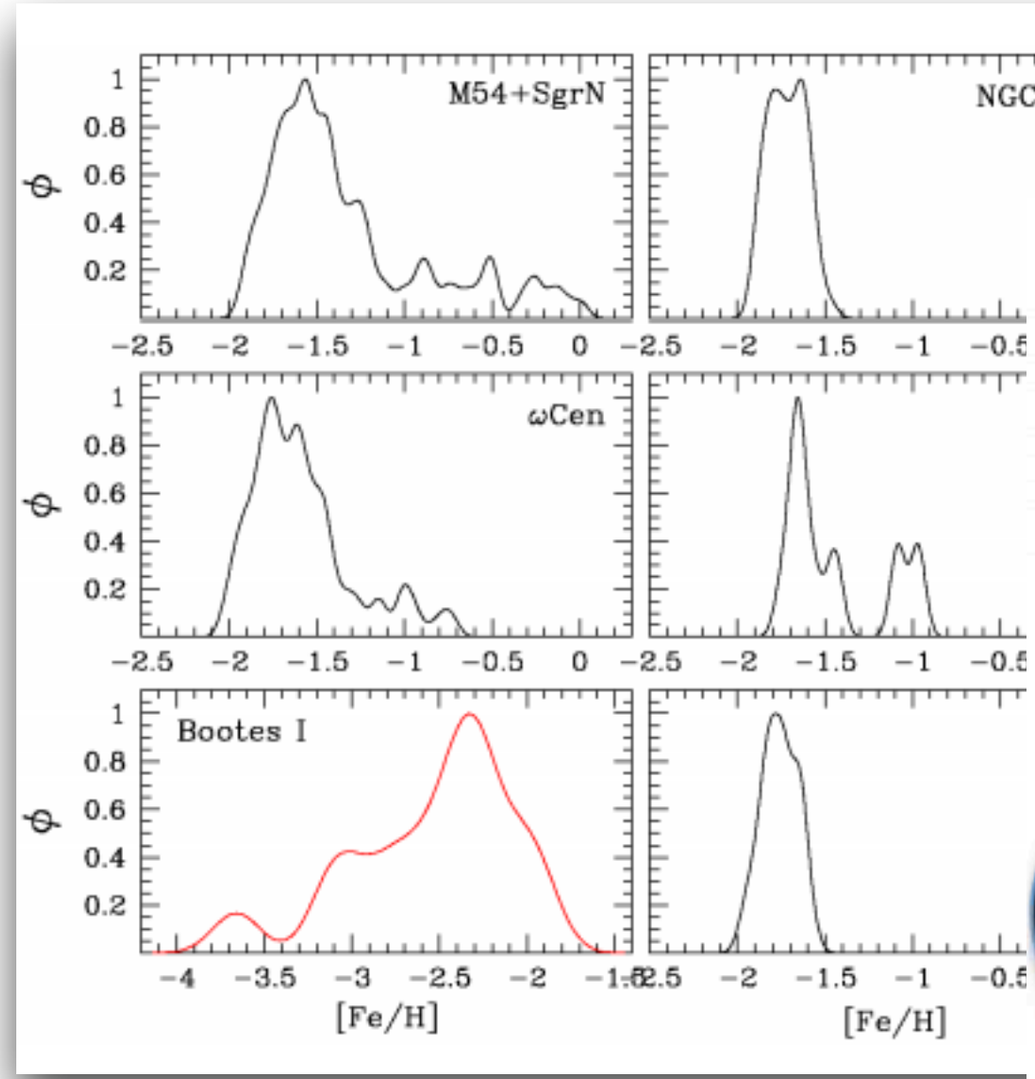


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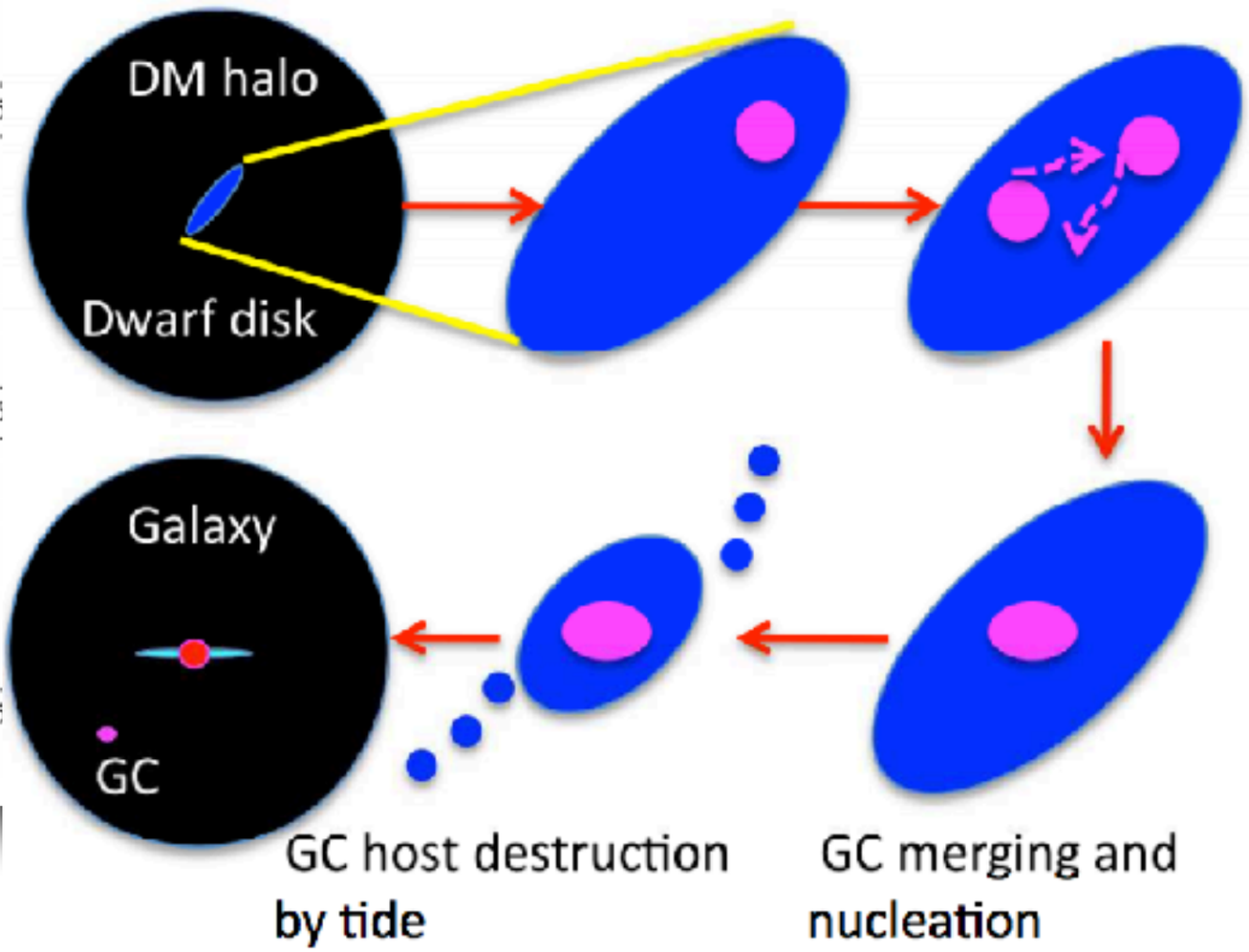


**Gavagnin et al. 2016; Bekki & Tsujimoto 2016**

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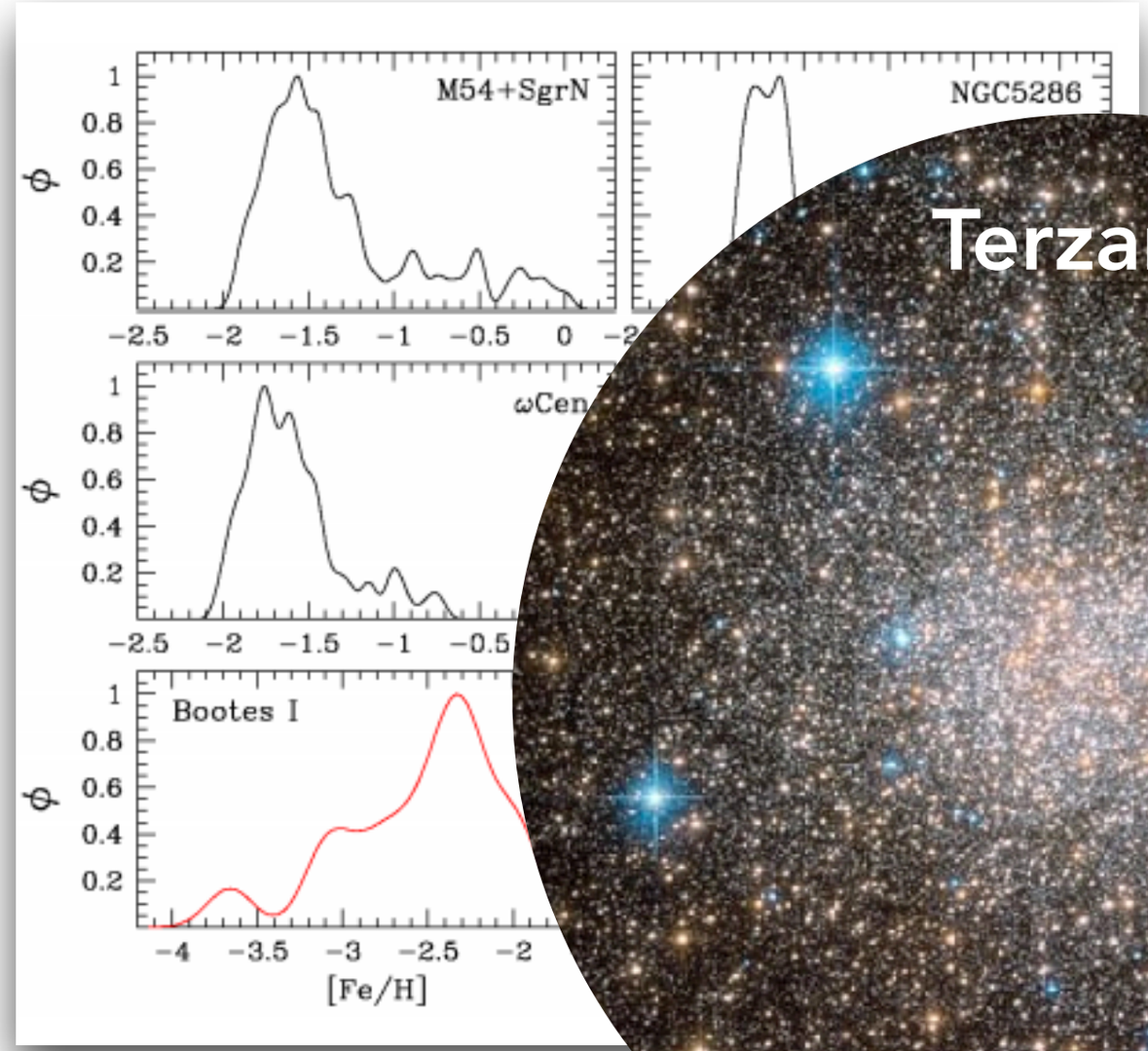





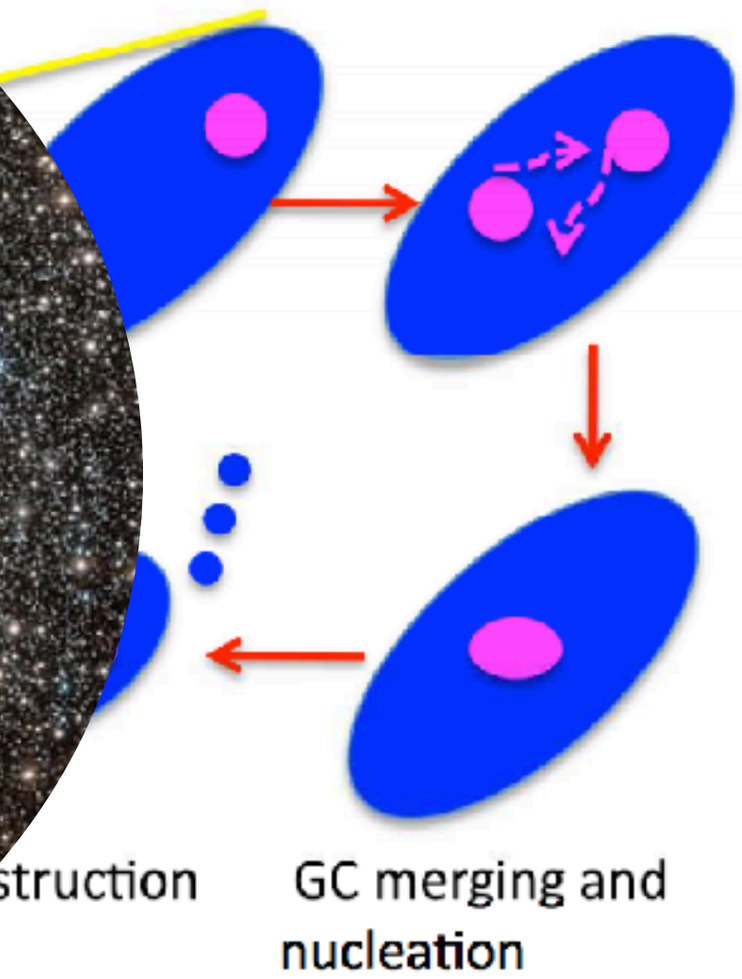


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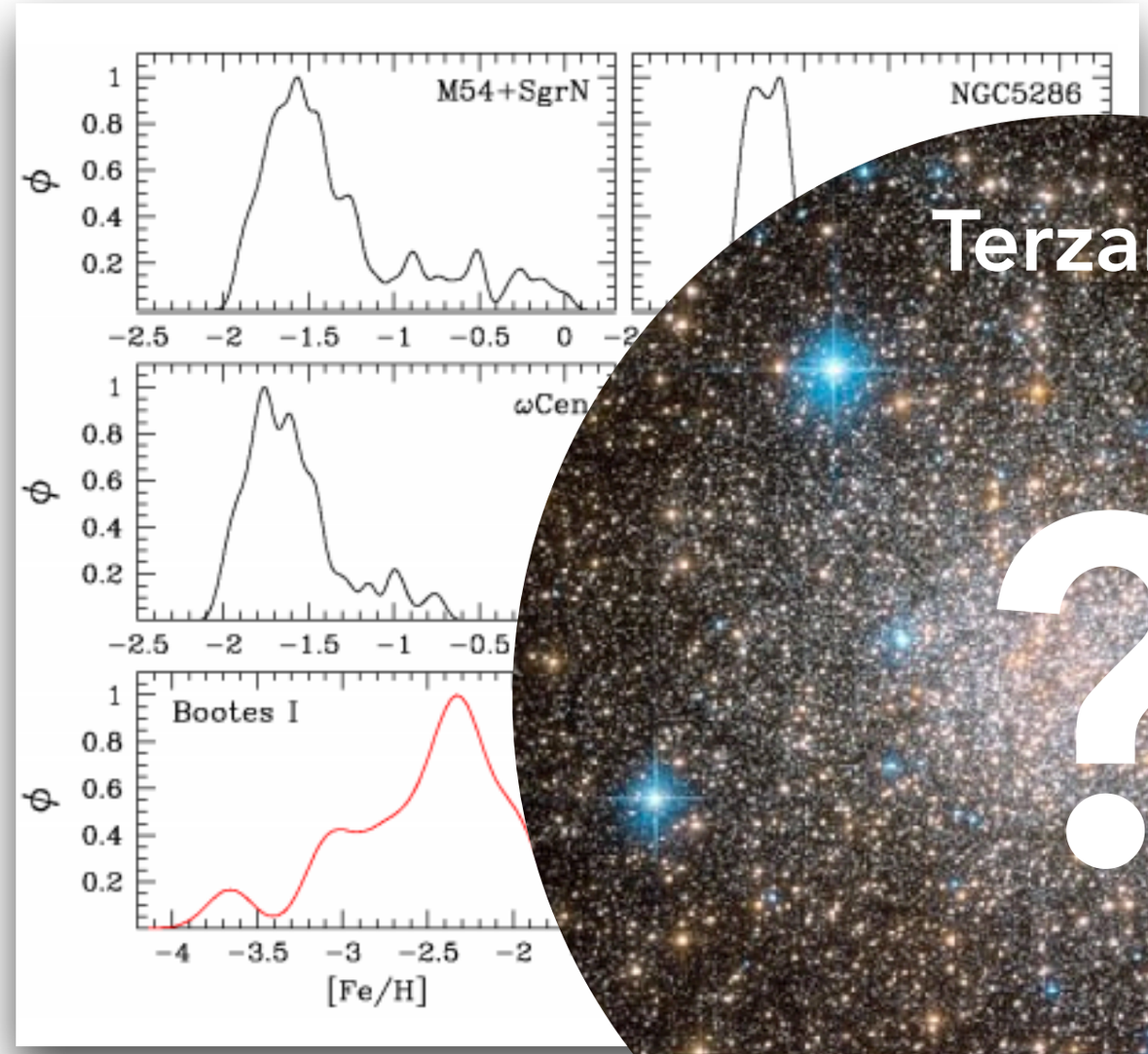


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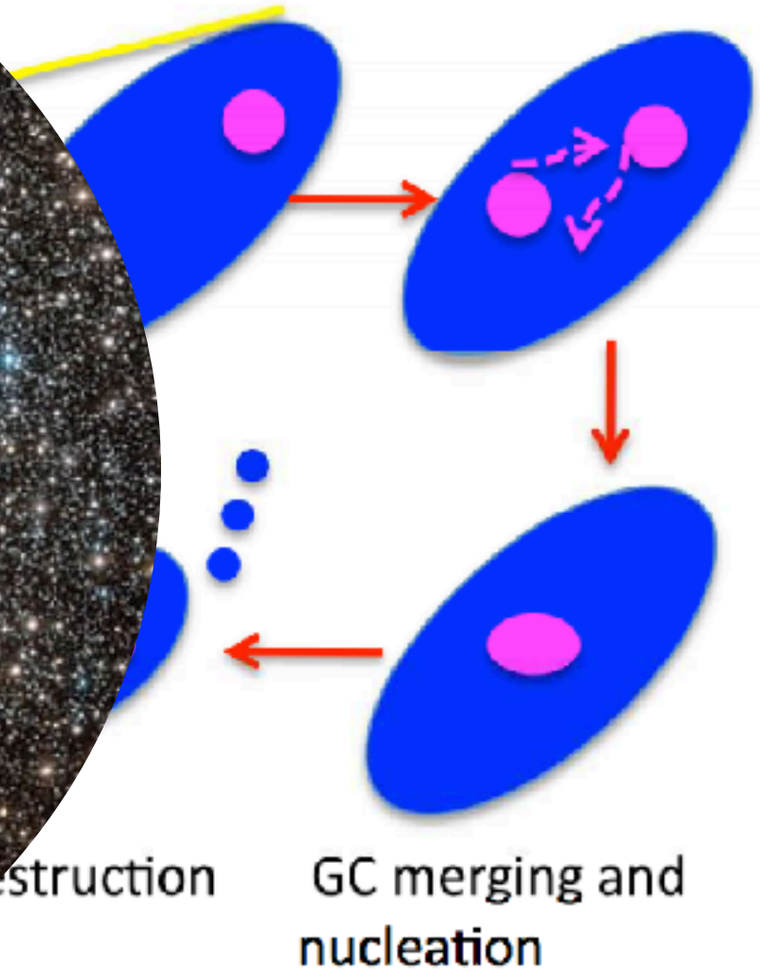


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# Disc globular clusters have an interesting life

$$\lambda = \frac{1}{n\Sigma}, \quad r = \nu/\lambda$$

$$R = N_{GC} r = N_{GC}^2 \nu \Sigma / V.$$

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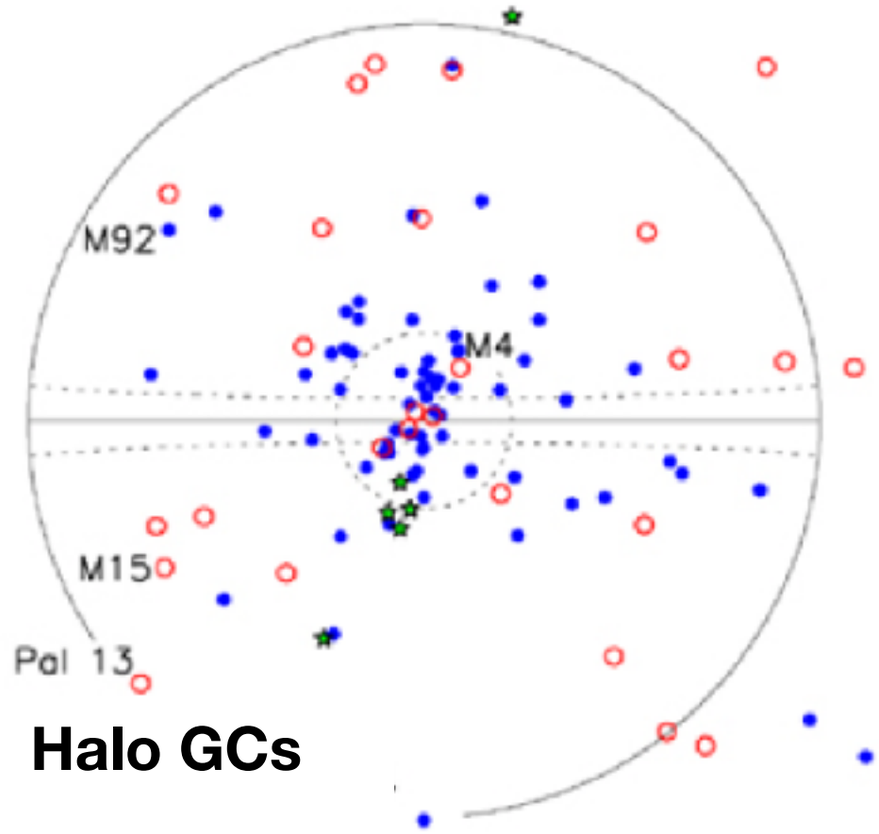


**Halo GCs**

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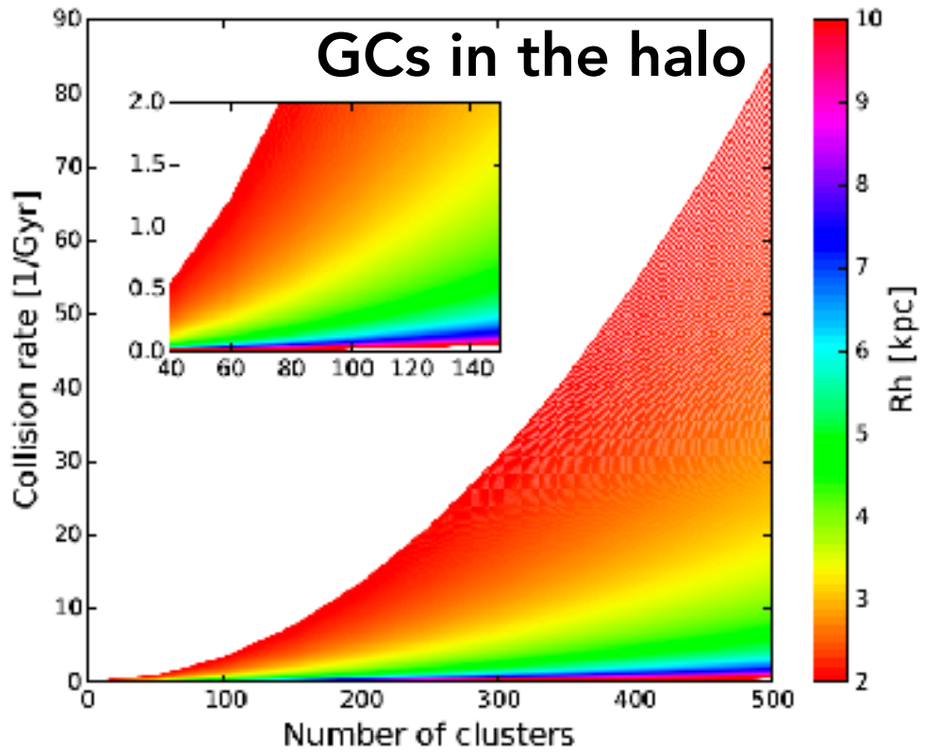


Khoperskov, Mastrobuono-Battisti et al., 2018

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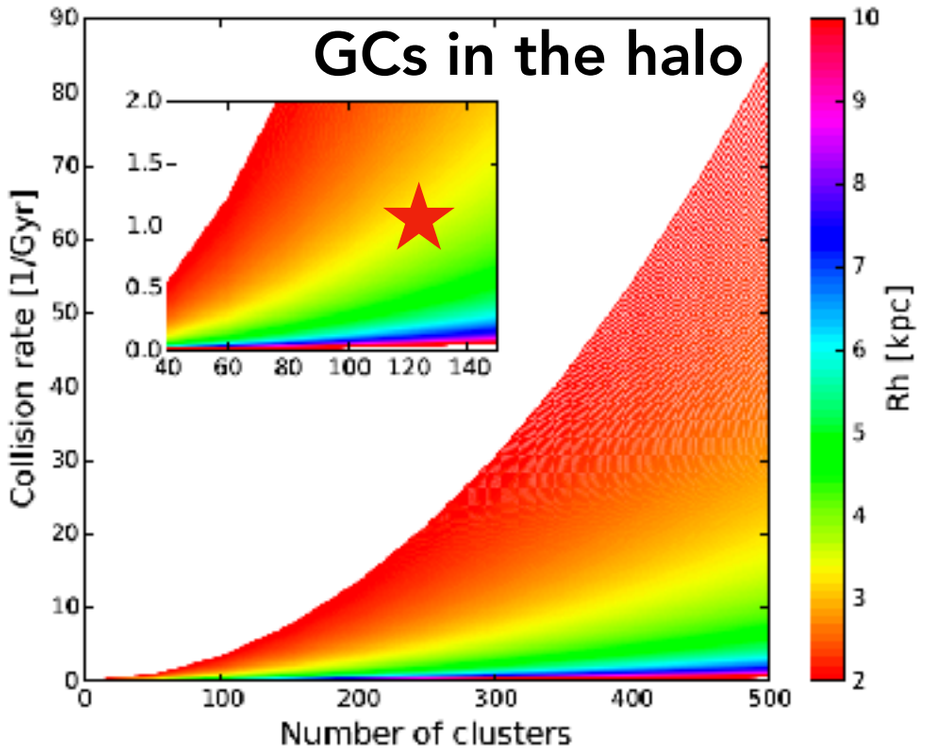


Khoperskov, Mastrobuono-Battisti et al., 2018

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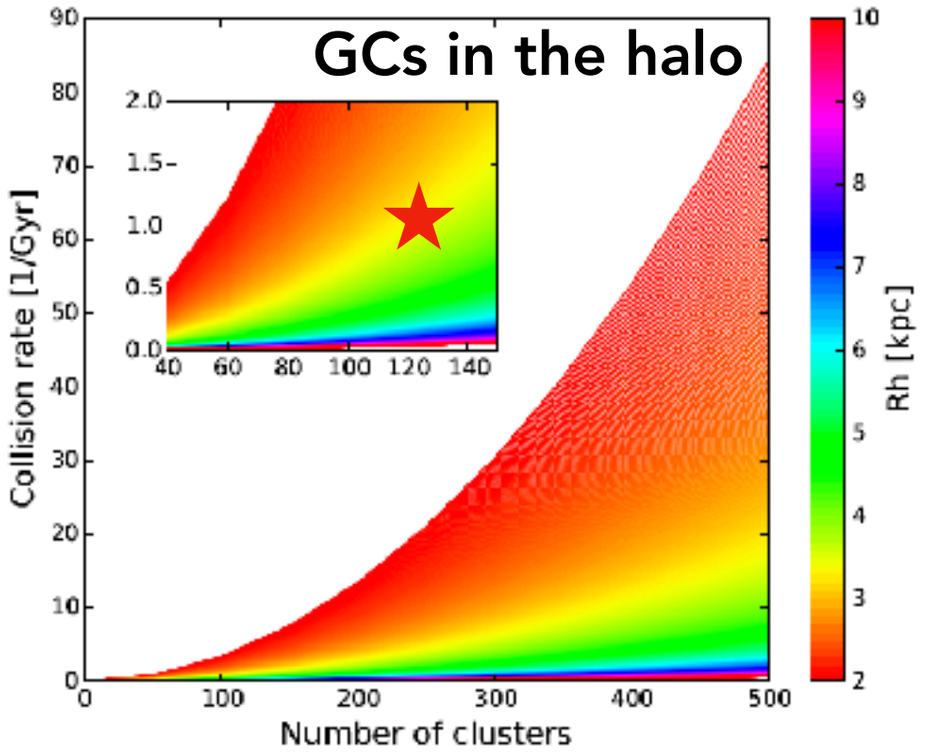


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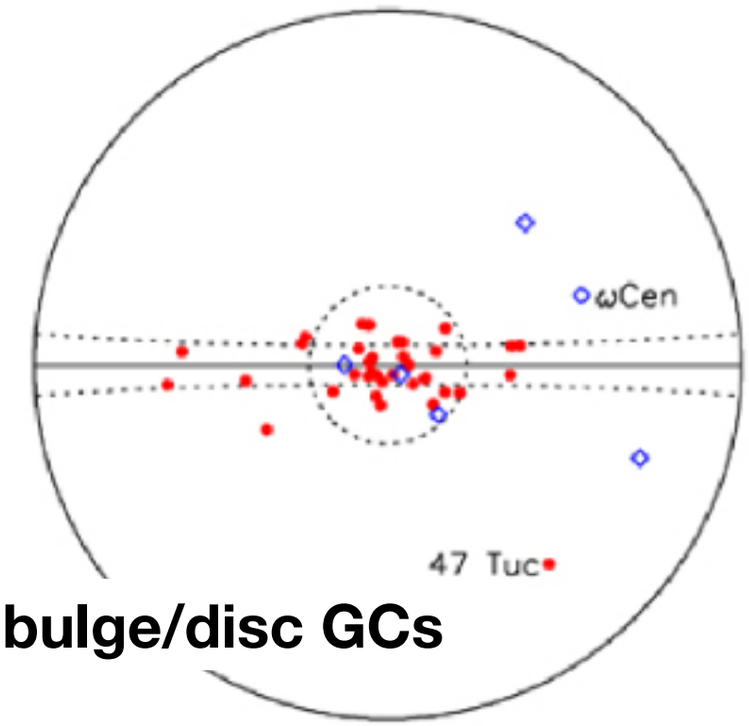


**bulge/disc GCs**

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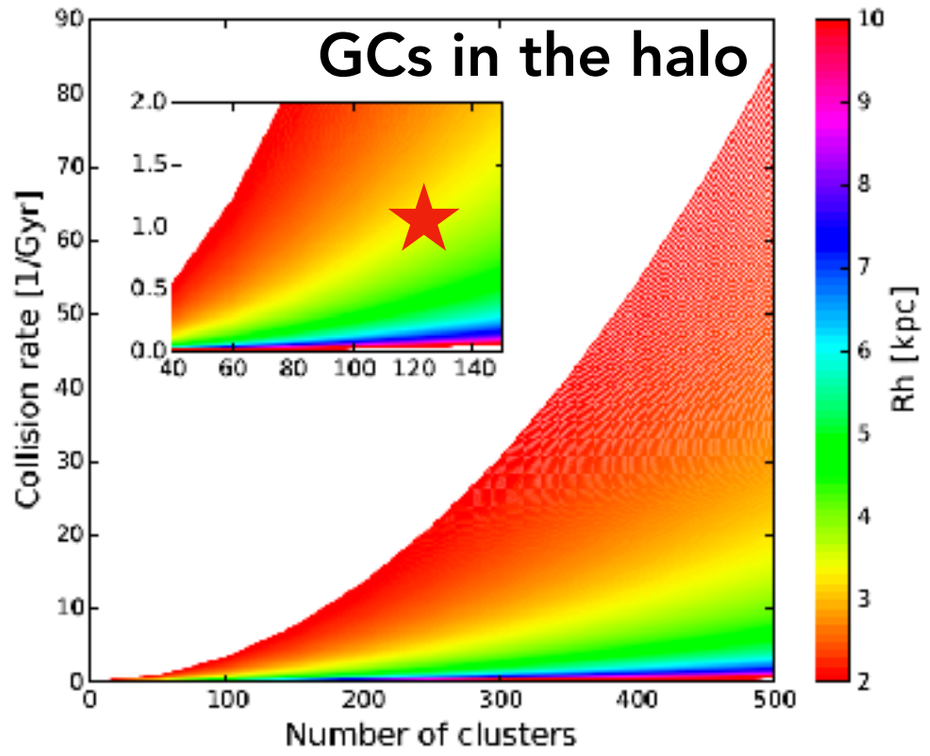
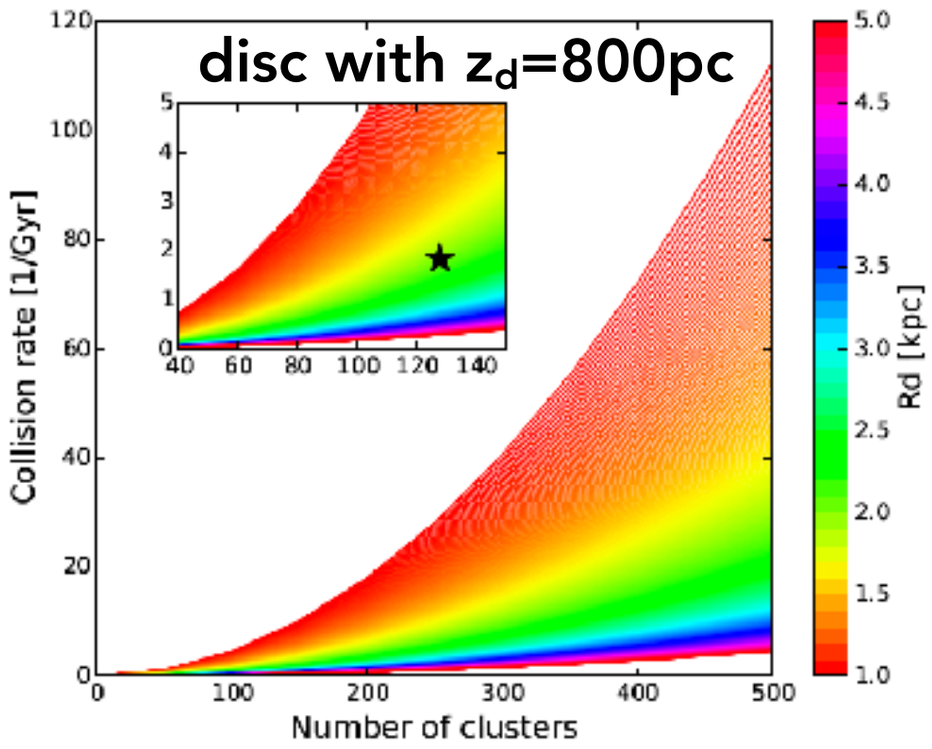
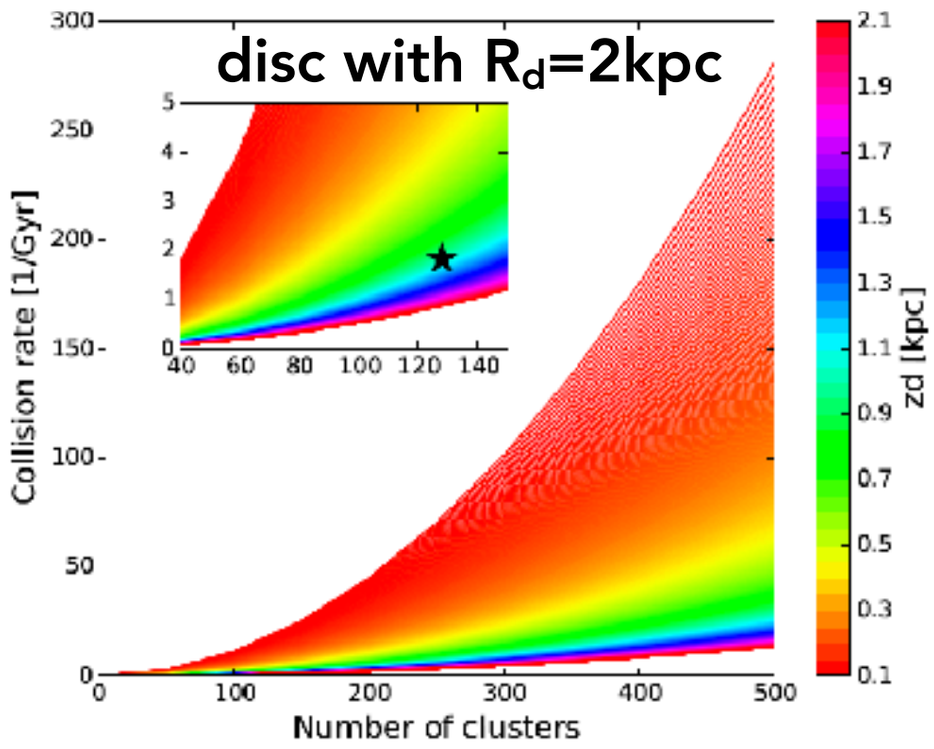
$$R = N_{GC} r = N_{GC}^2 \nu \Sigma / V.$$

Overall collision rate

100 km/s




Khoperskov, Mastrobuono-Battisti et al., 2018

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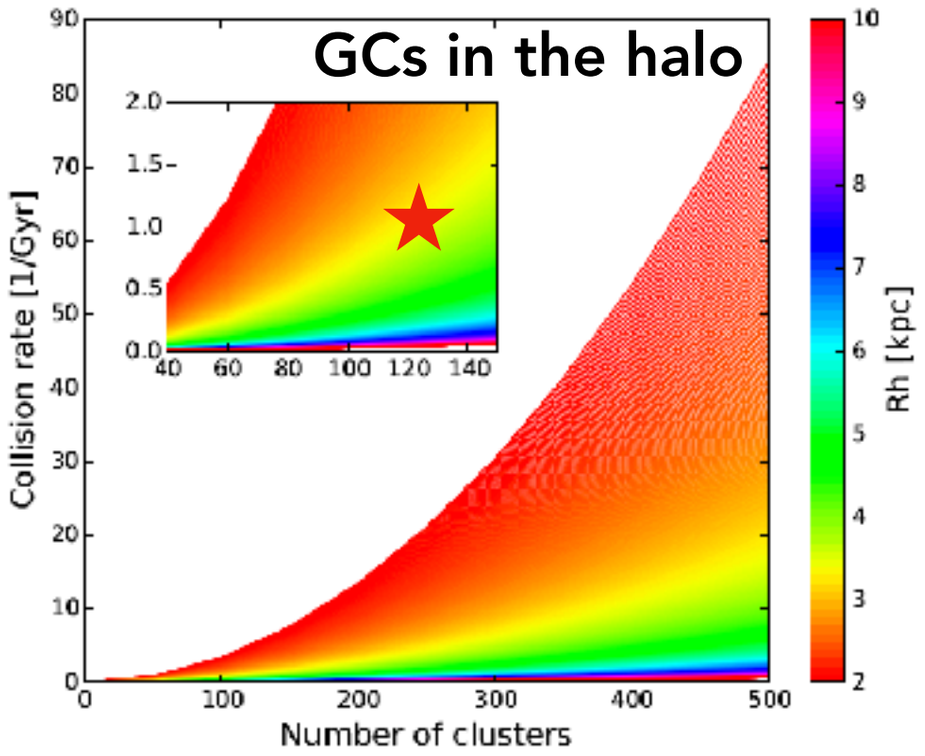


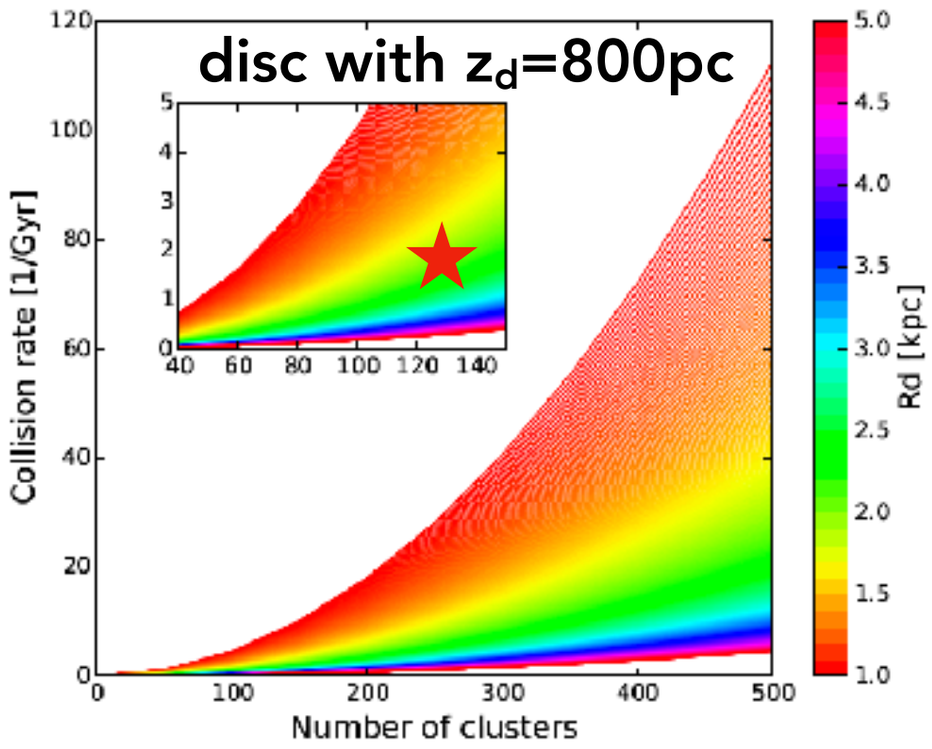


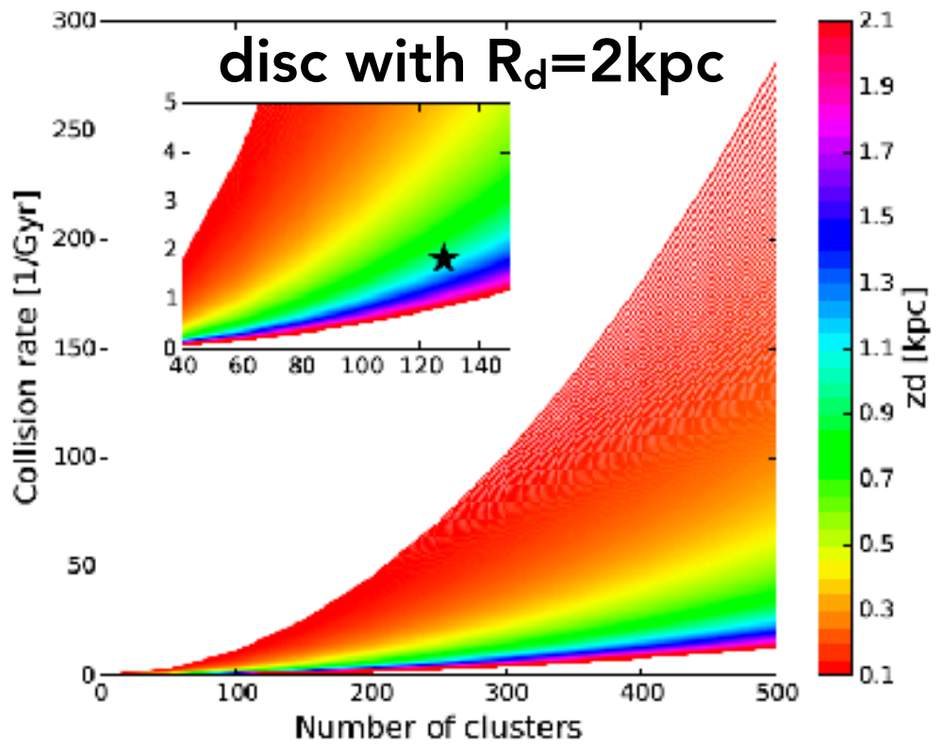


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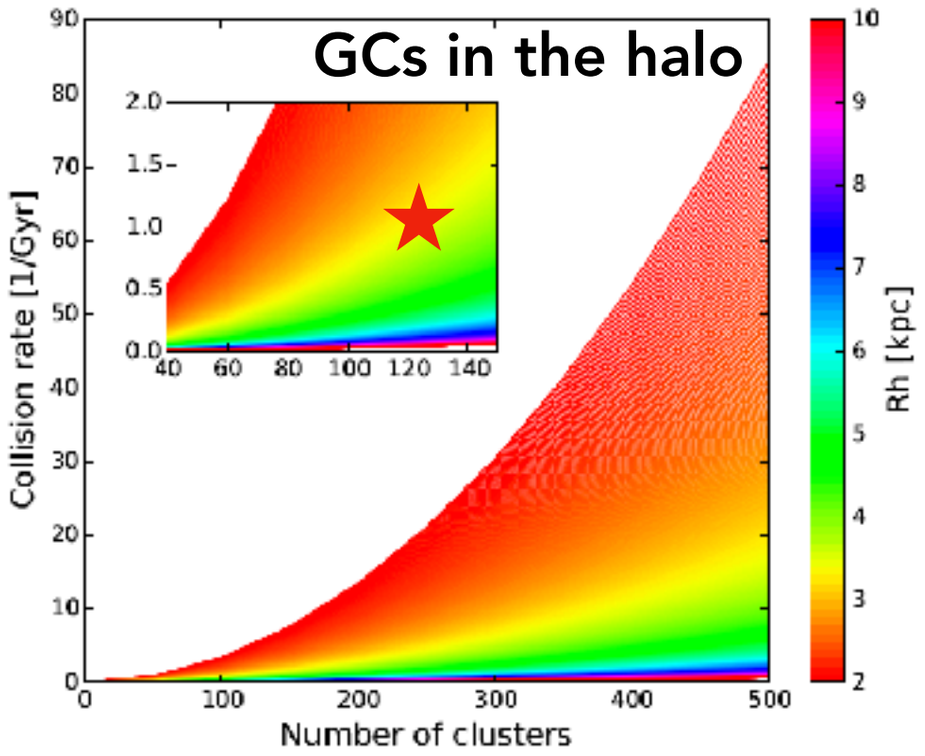


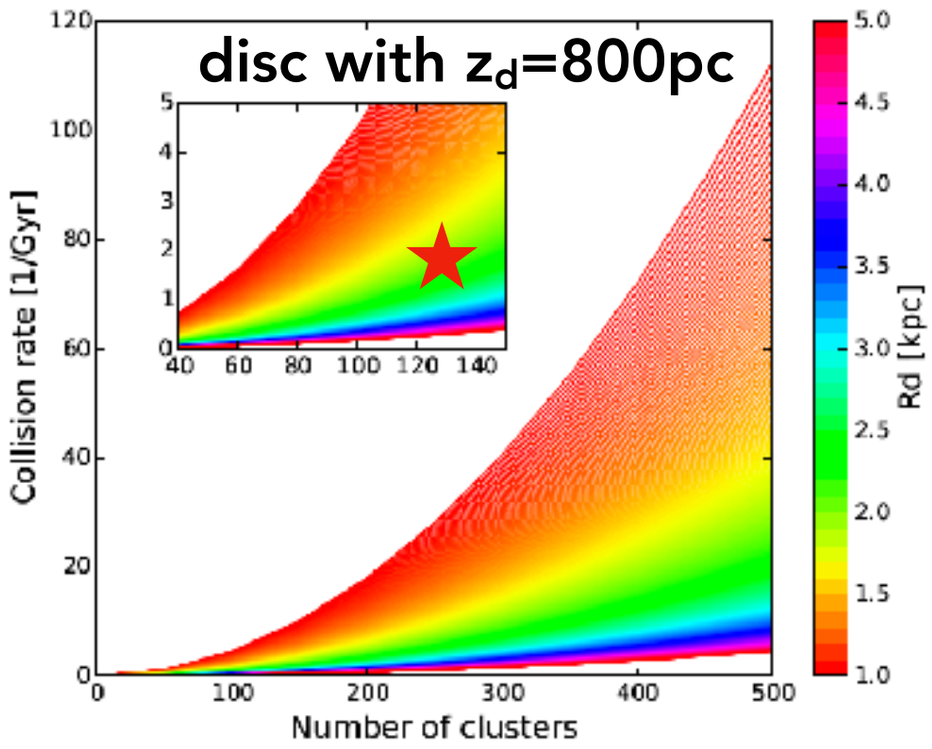


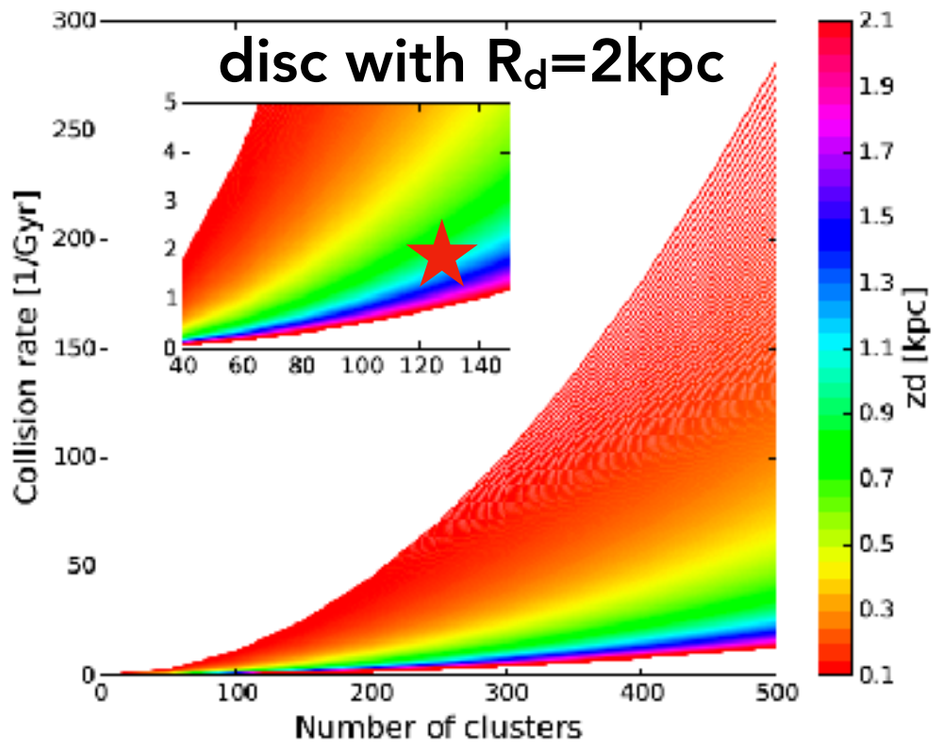


Khoperskov, Mastrobuono-Battisti et al., 2018

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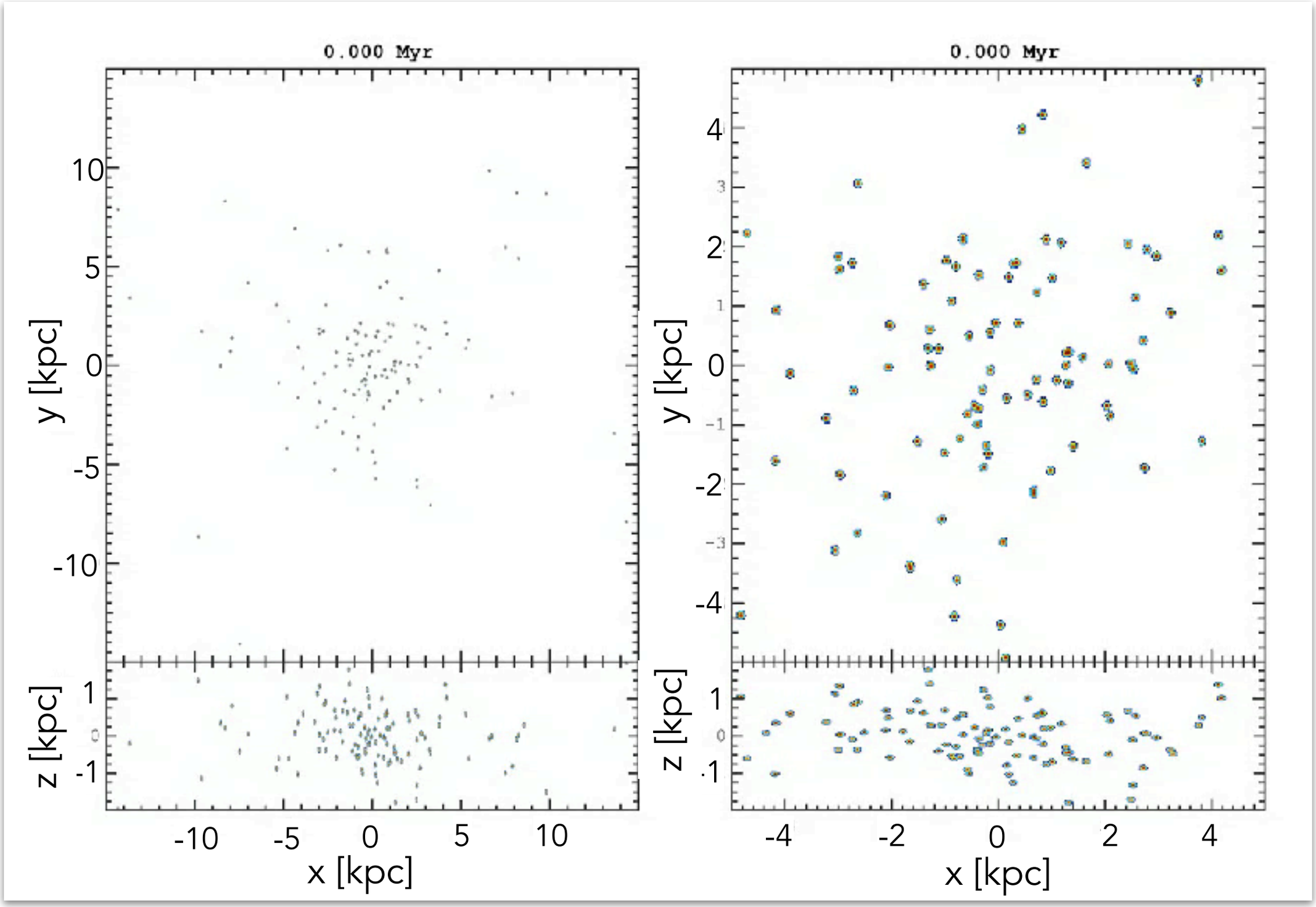
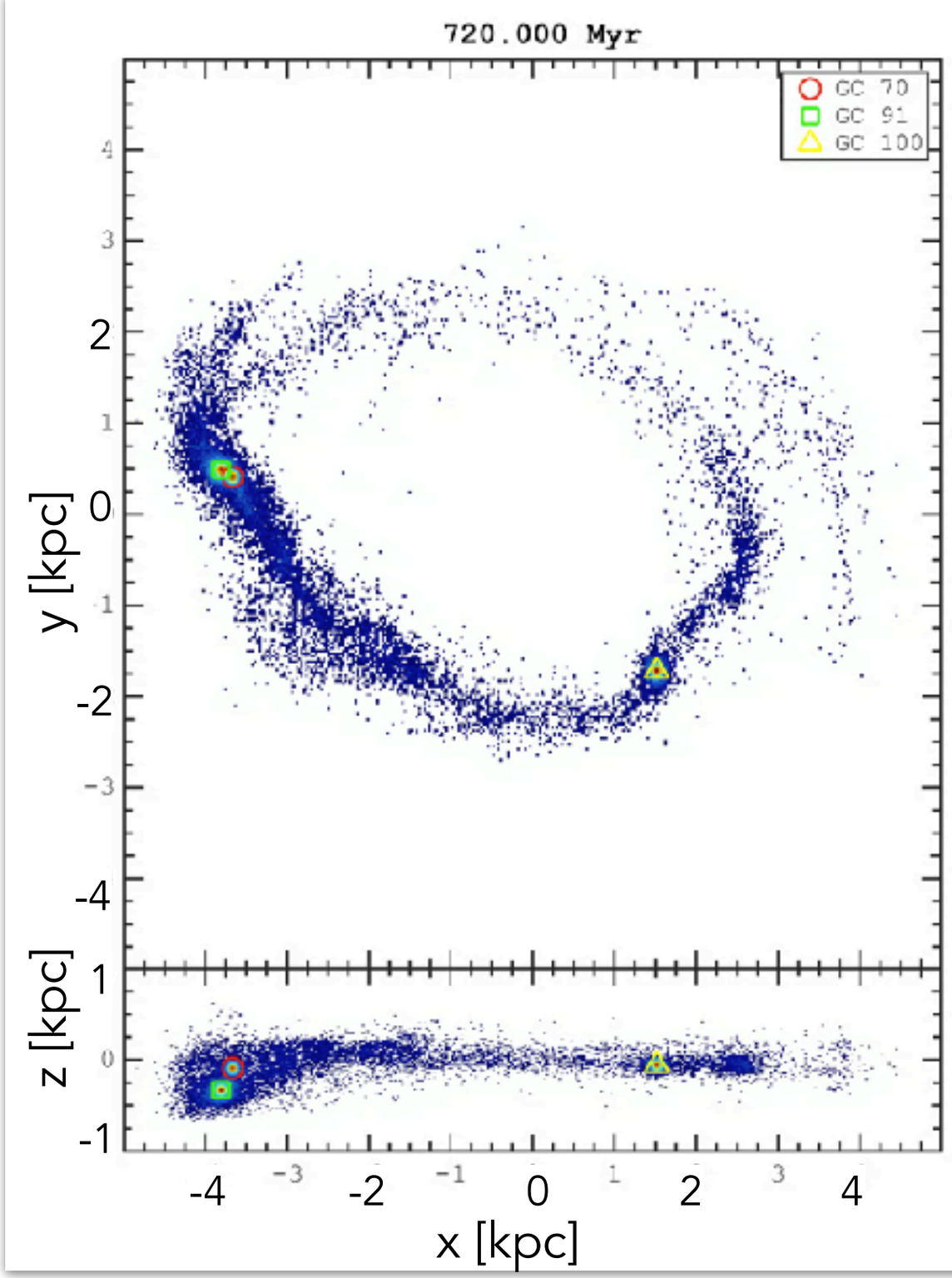
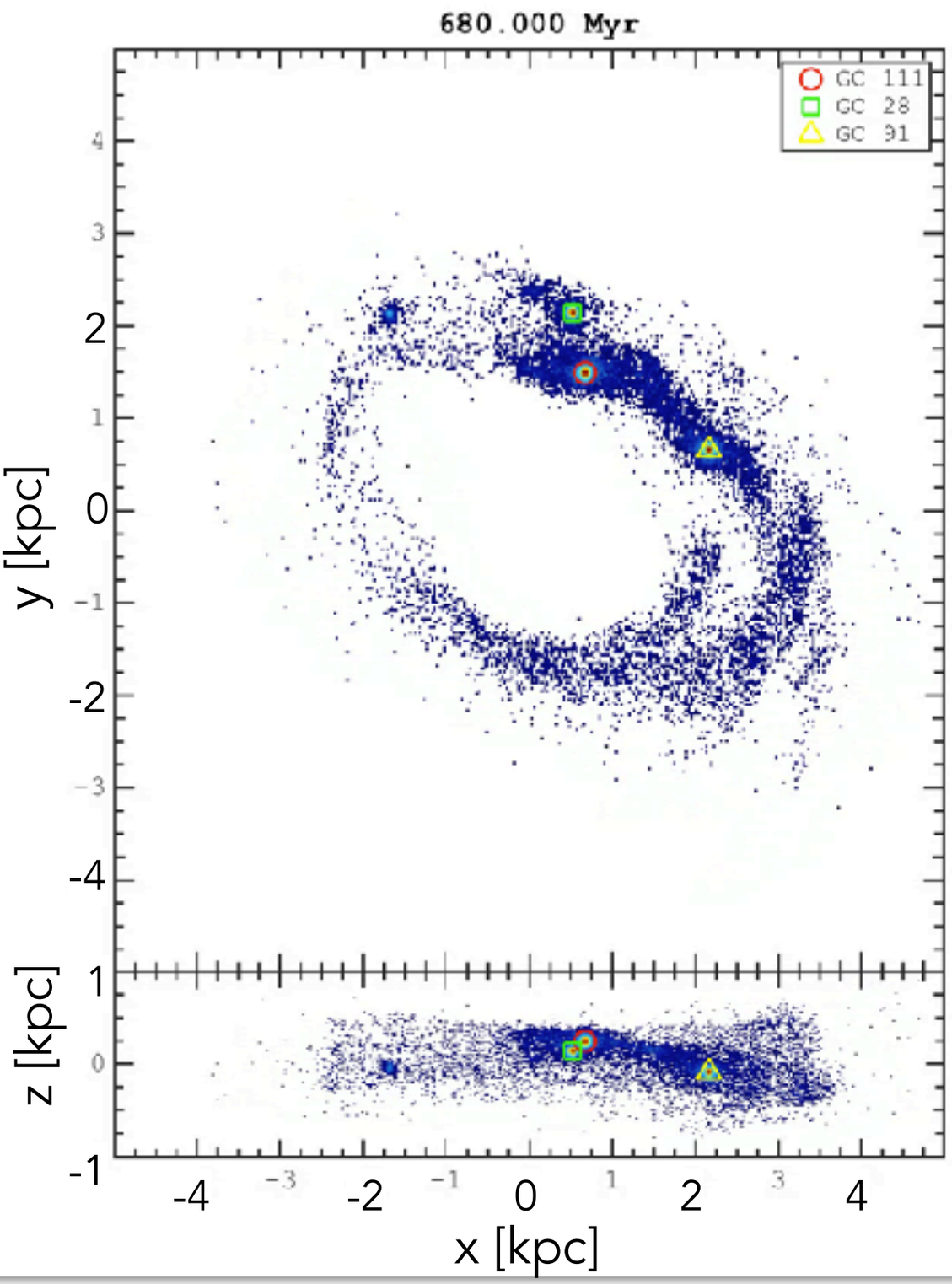



Renaud et al. 2017, Gavagnin et al. 2016, Bekki & Tsujimoto 2016

**Khoperskov, Mastrobuono-Battisti et al., 2018**

# They can contaminate each other and/or merge

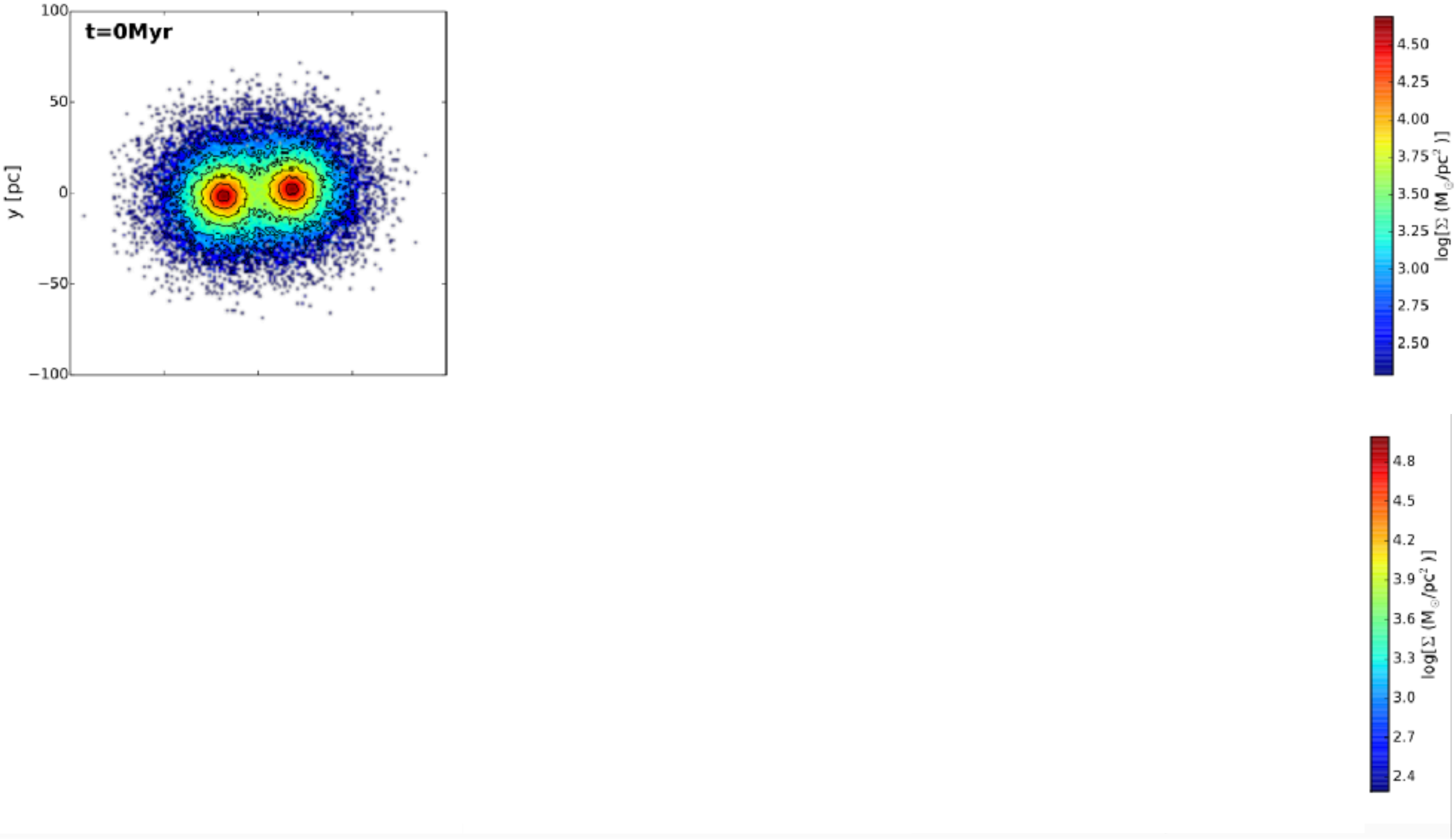



Khoperskov, Mastrobuono-Battisti et al., 2018

# We followed the long term evolution of the merger product

Mastrobuono-Battisti, Khoperskov, Di Matteo & Haywood, 2019



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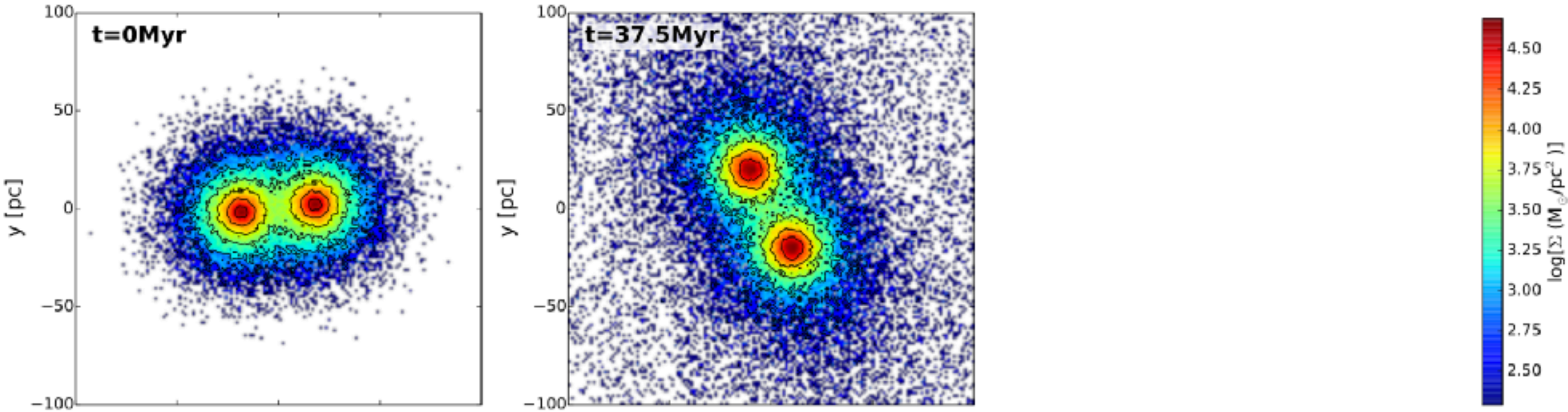

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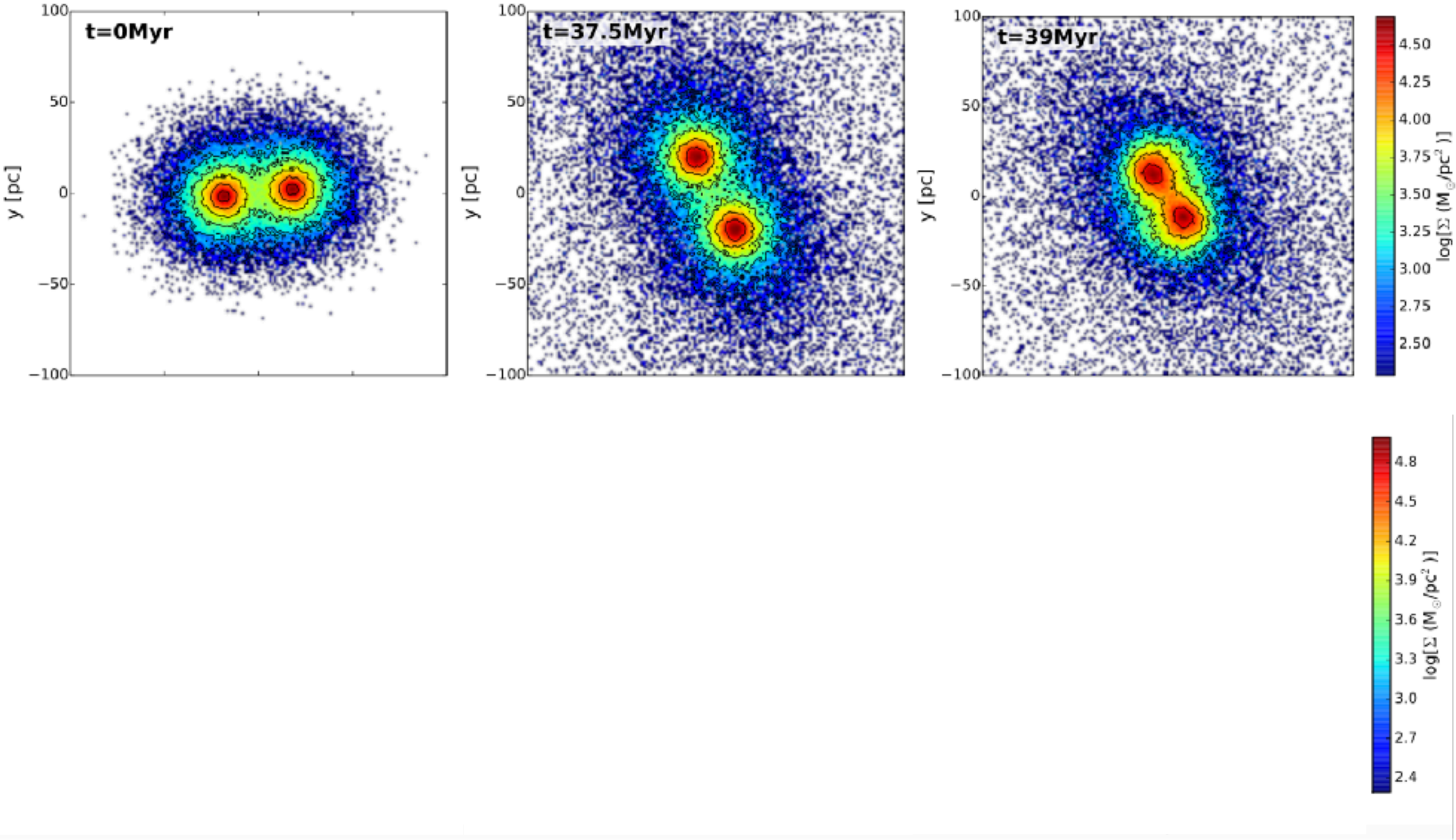

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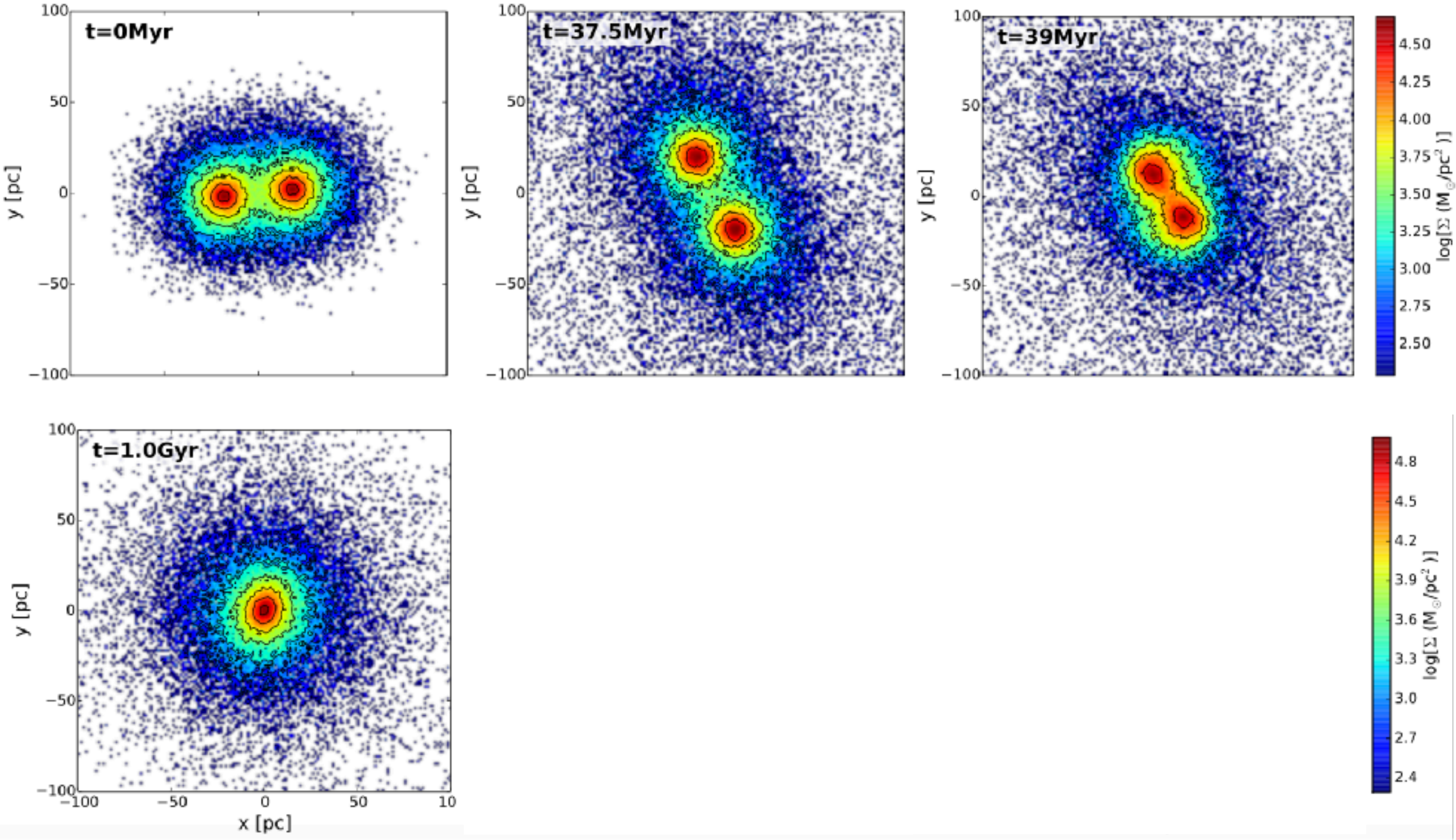

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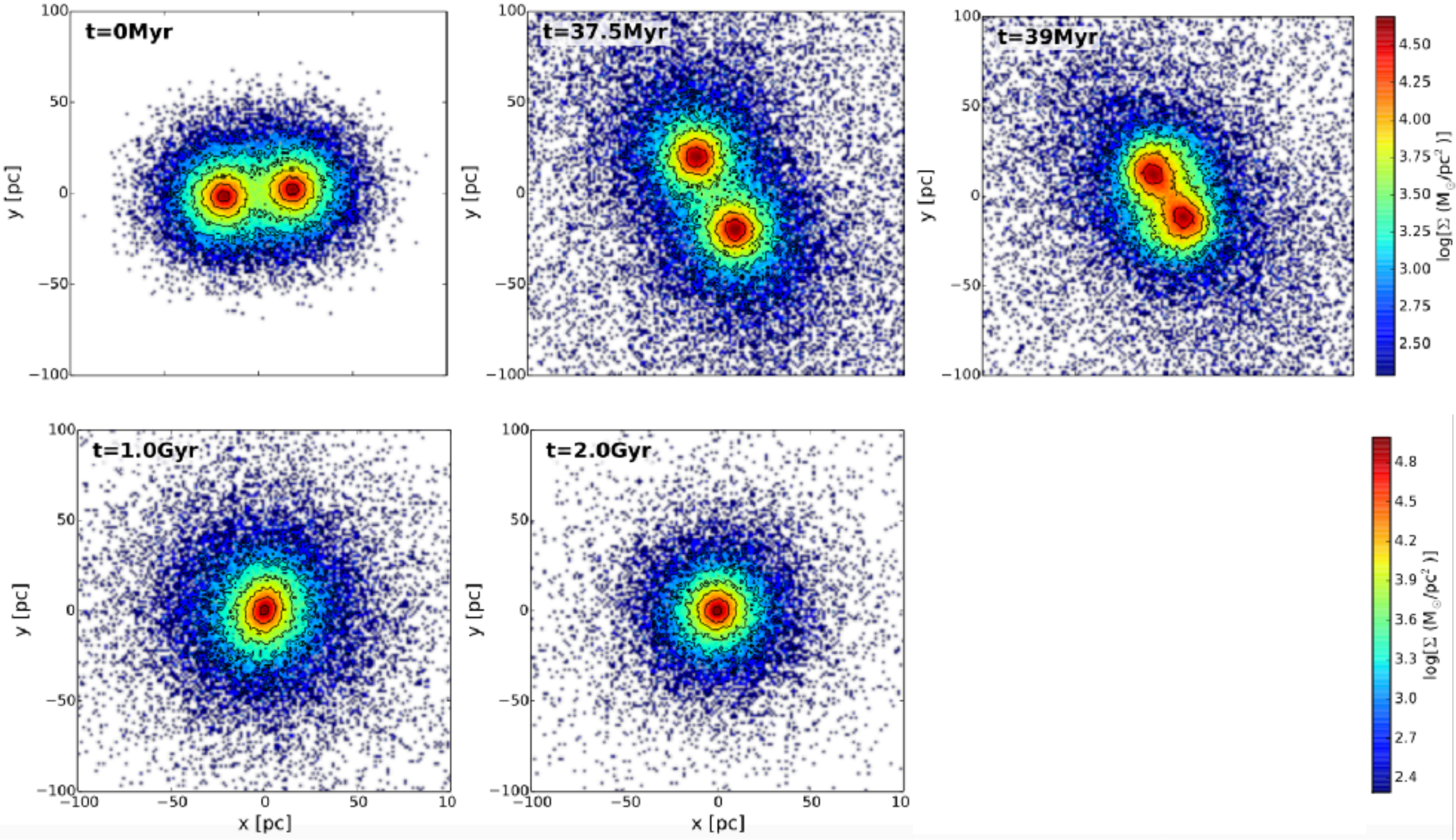

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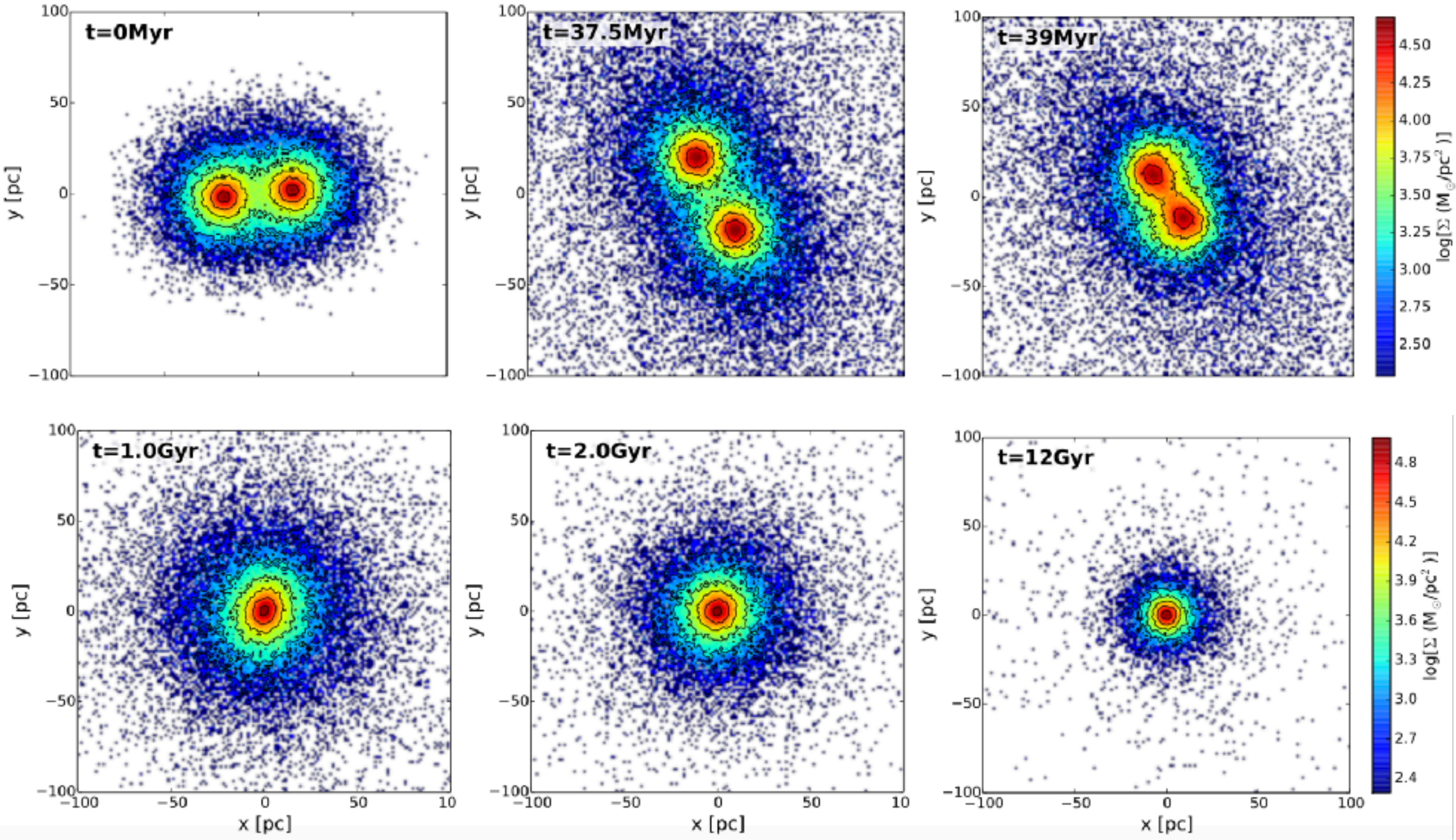

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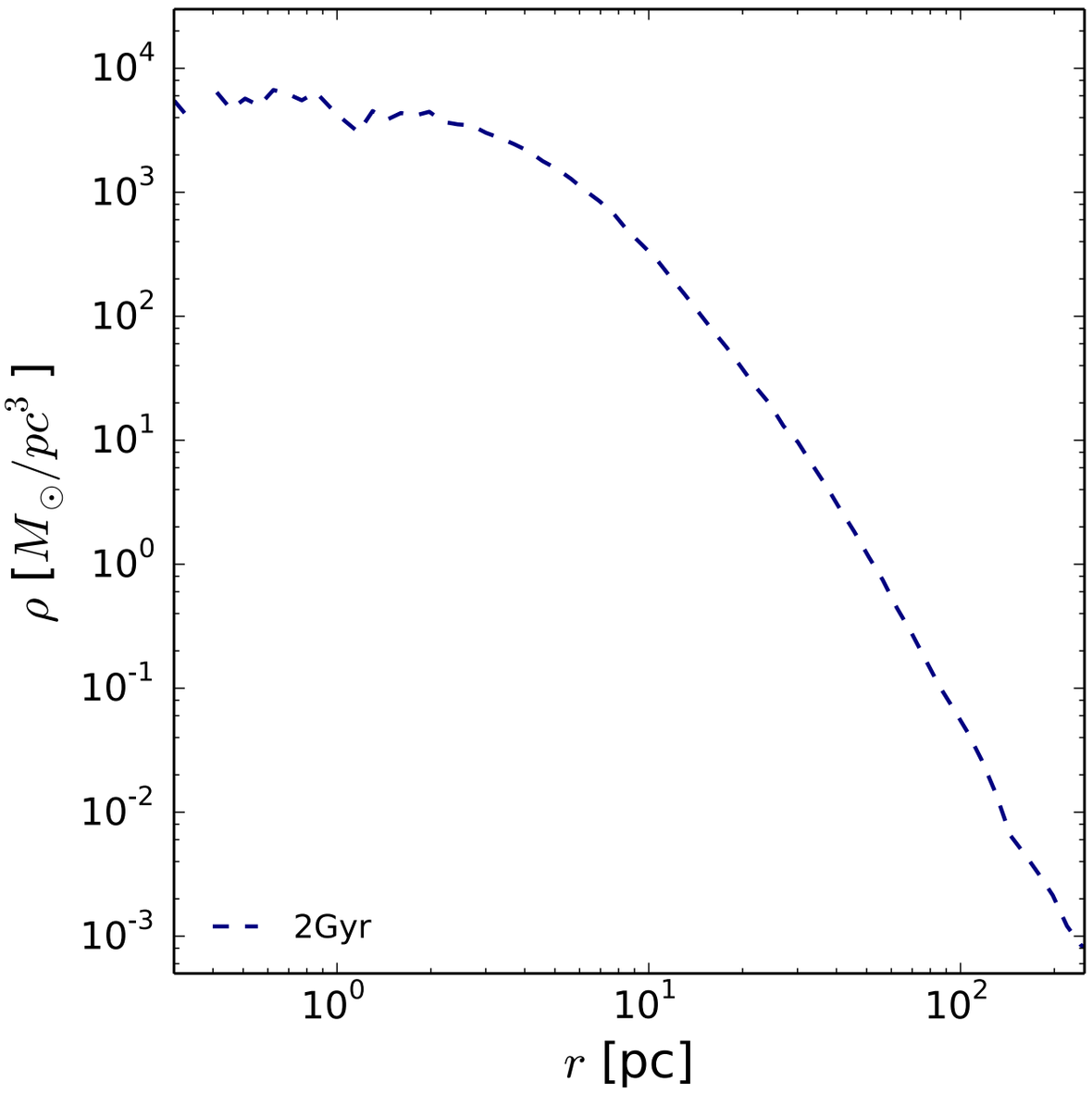


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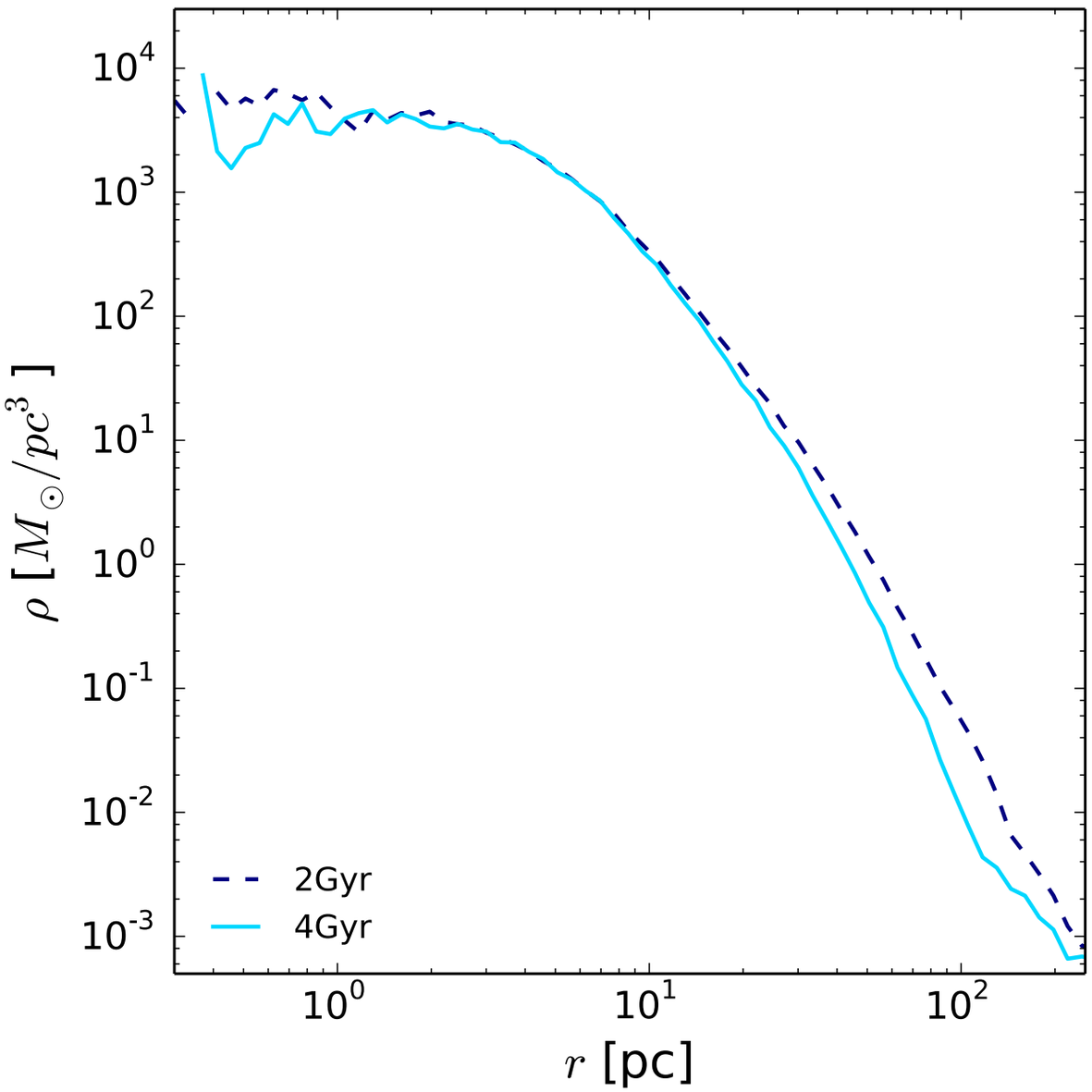


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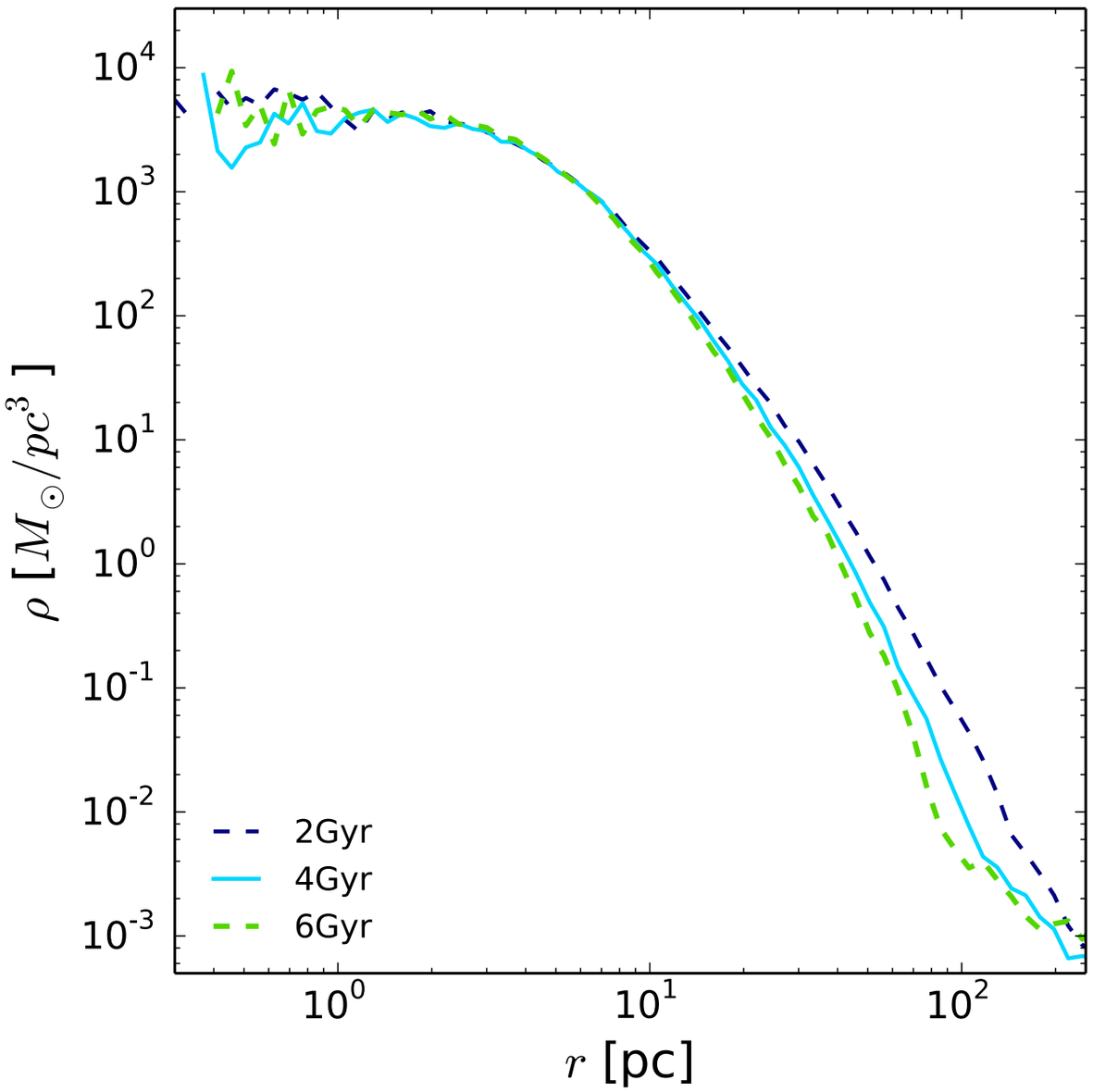


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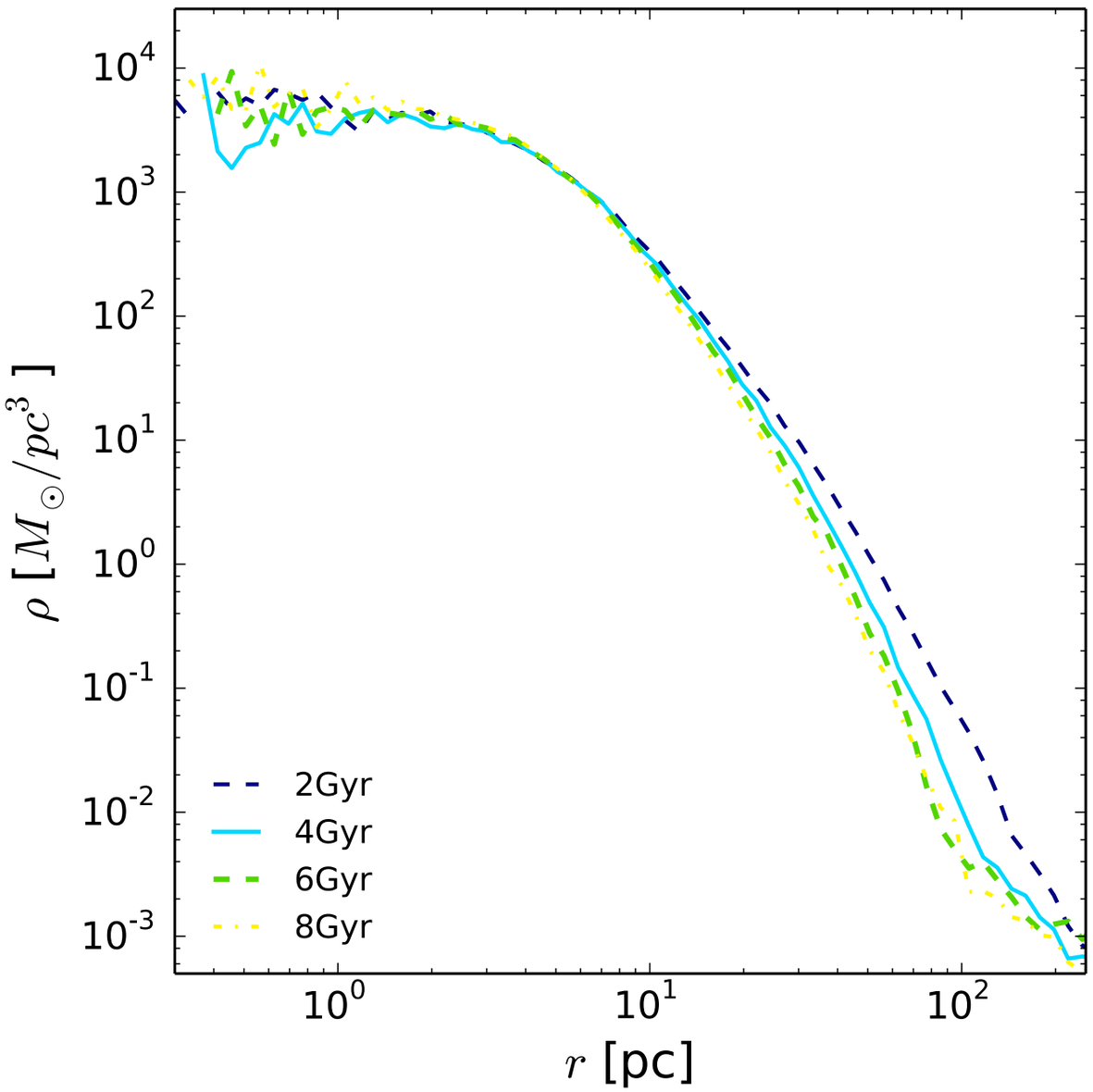


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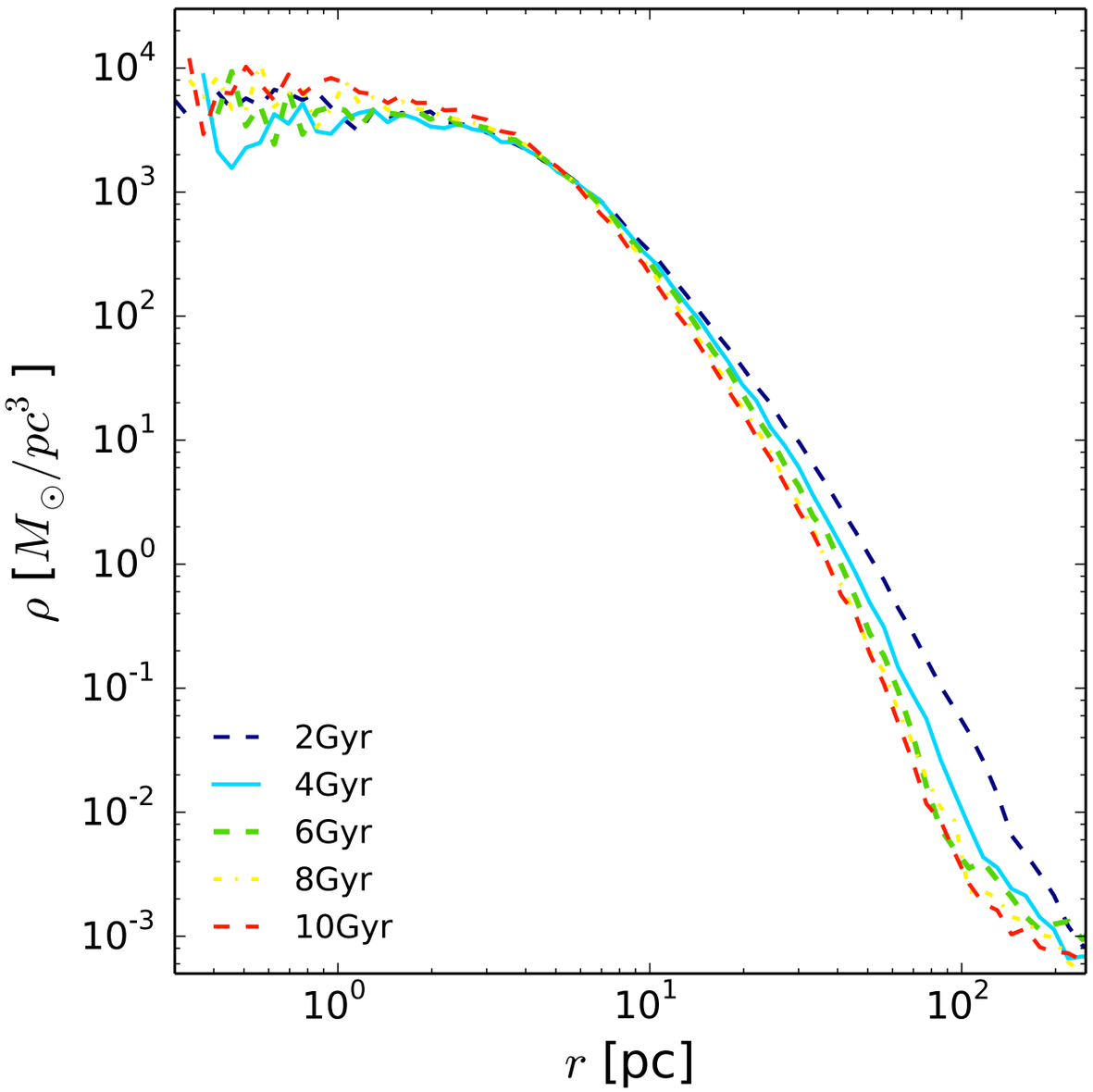


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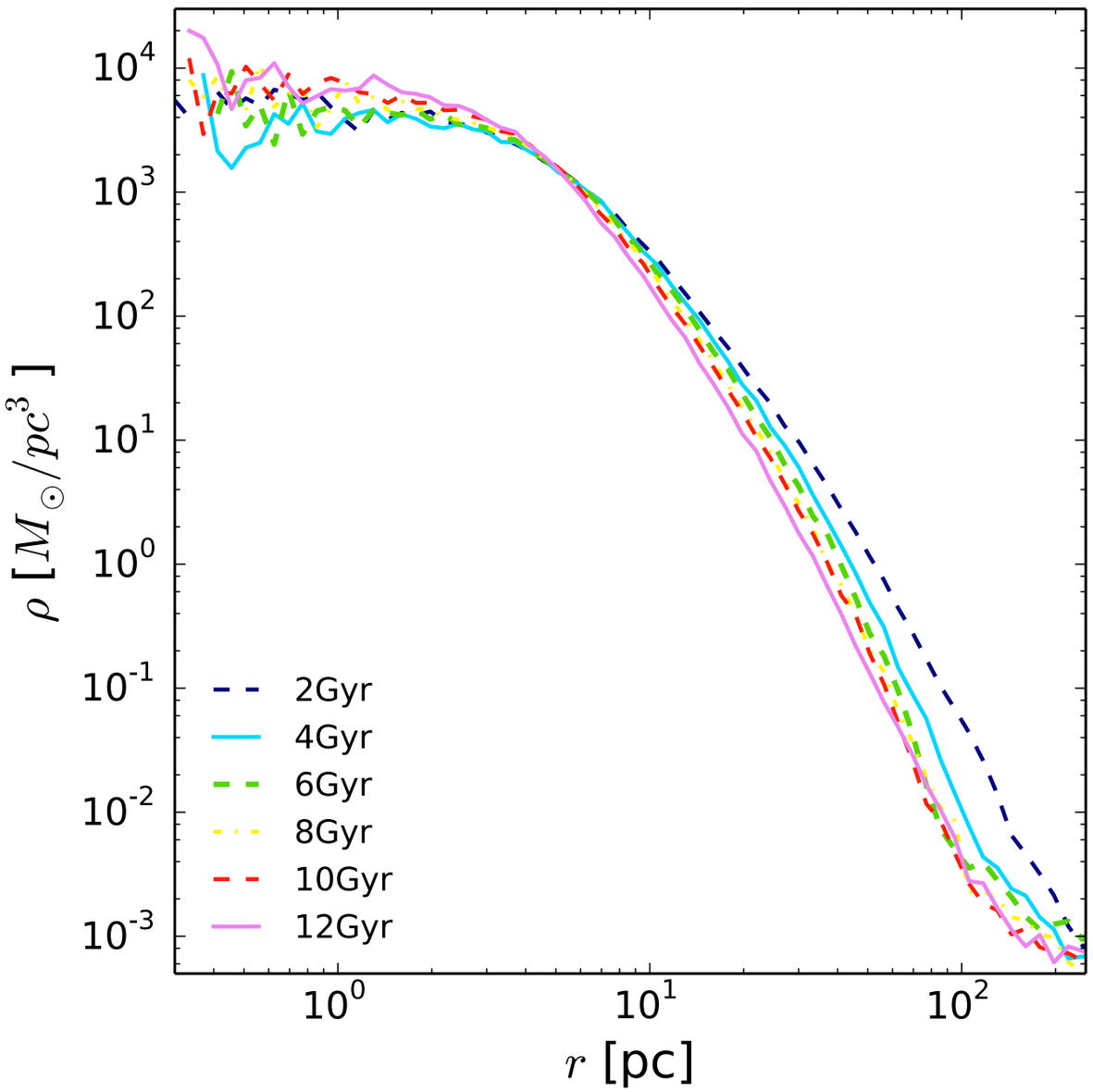


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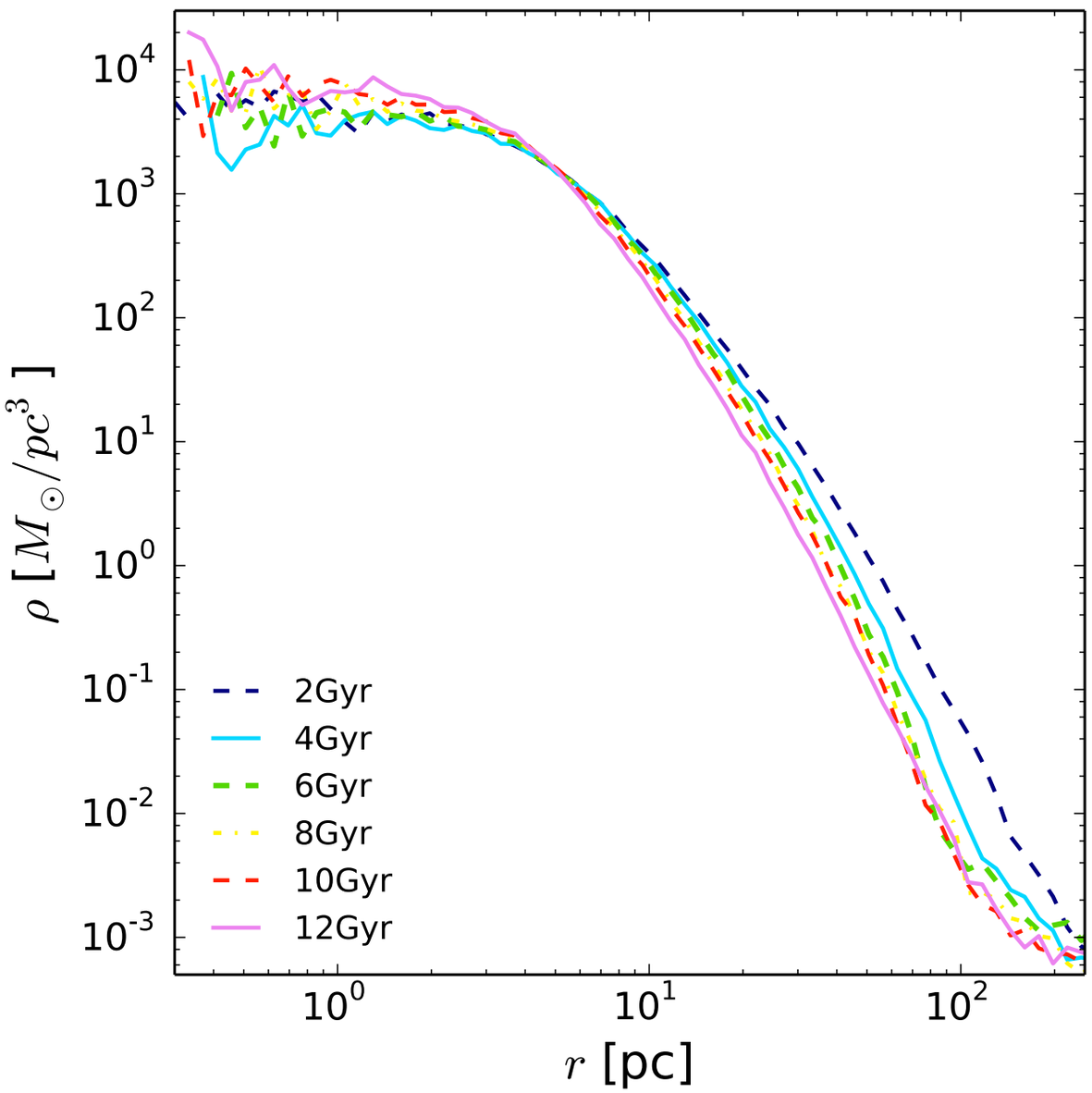


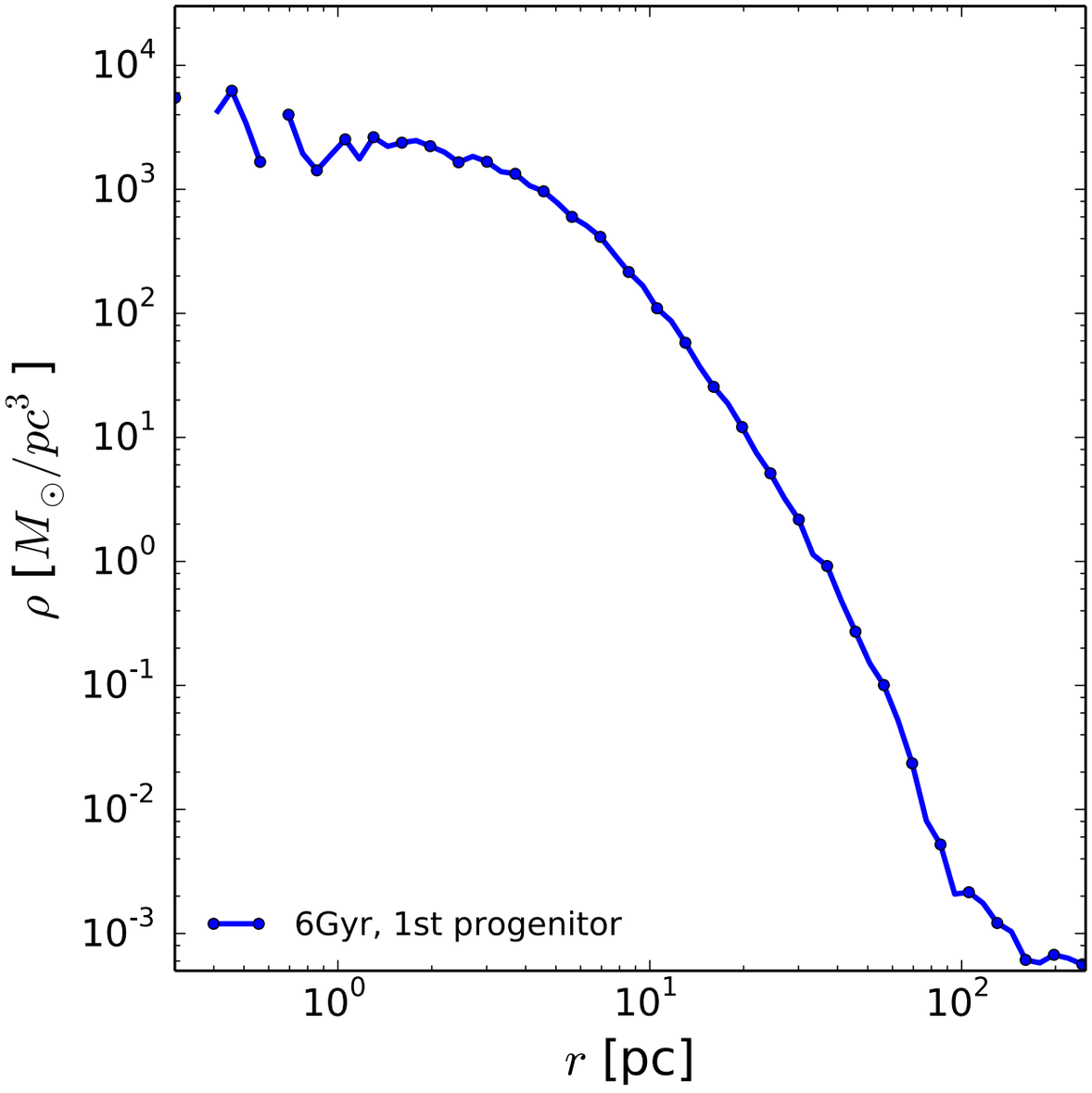


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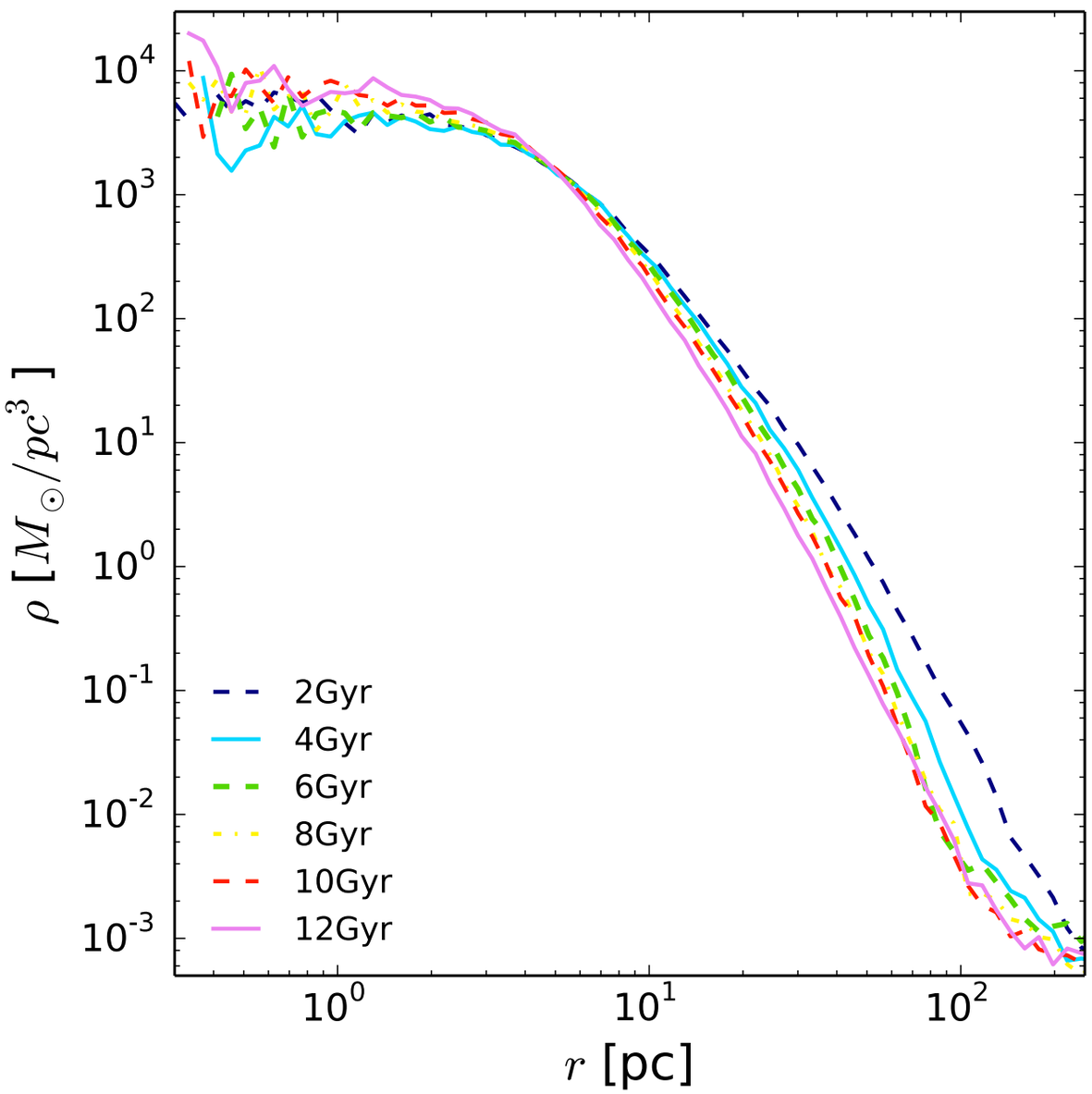


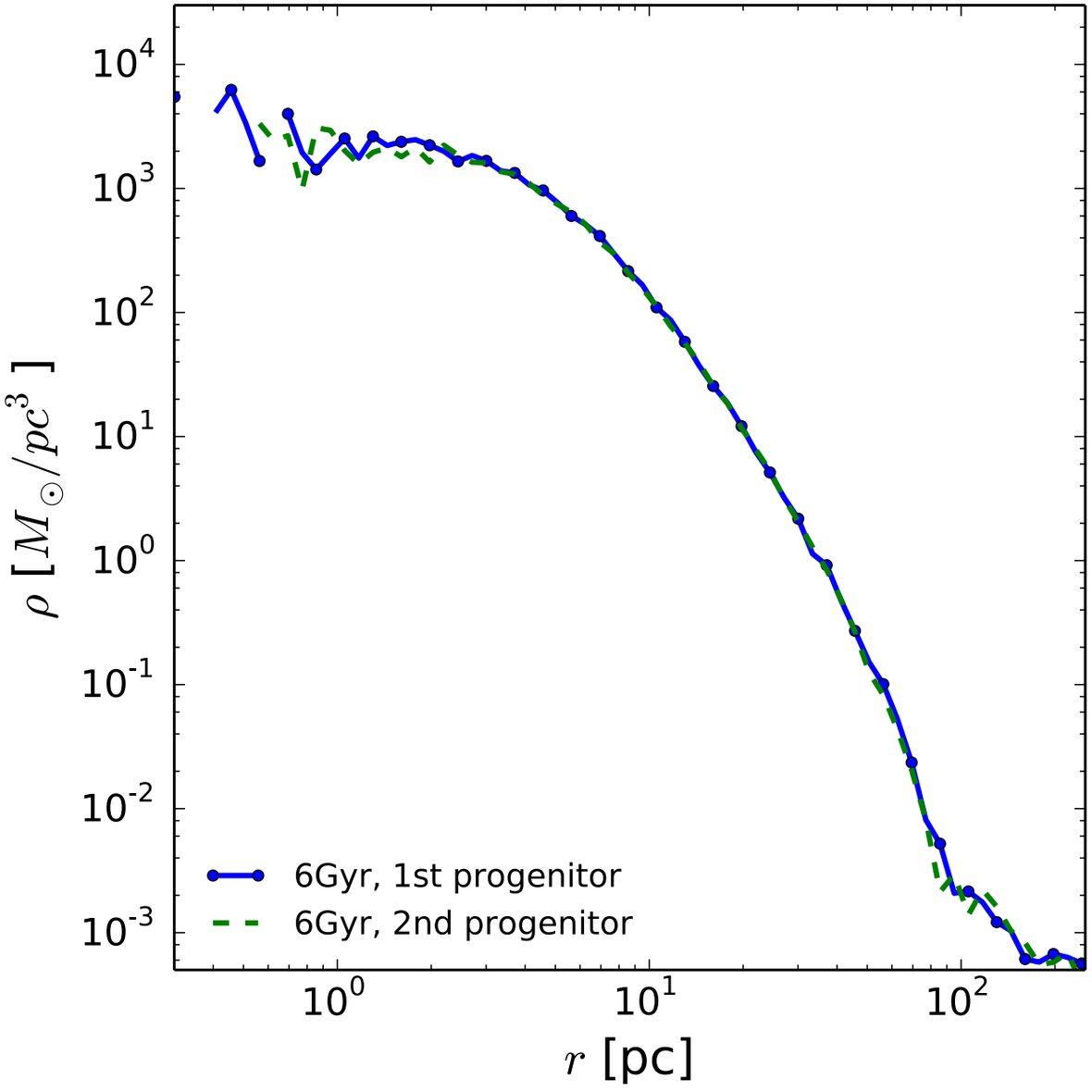


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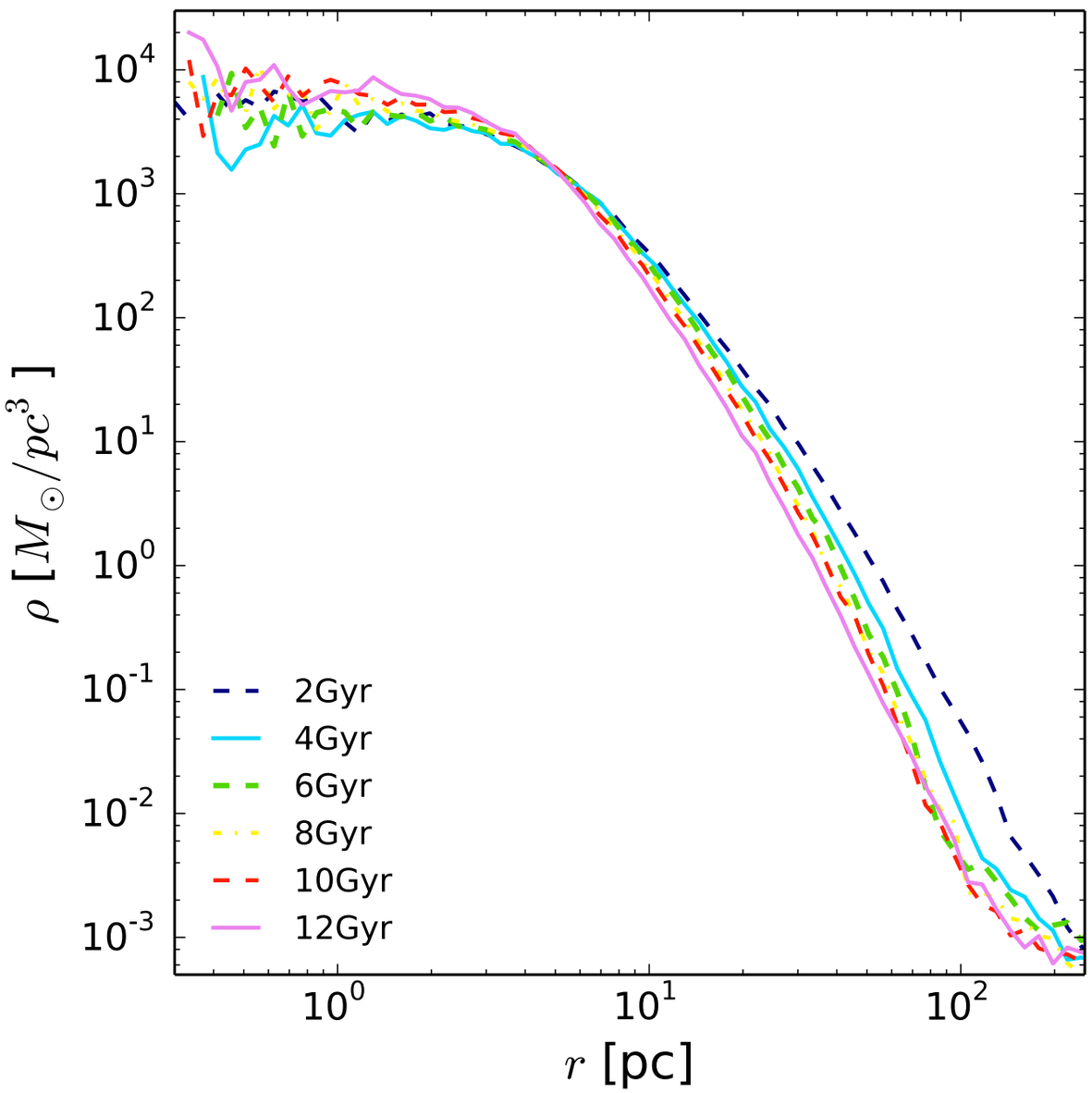


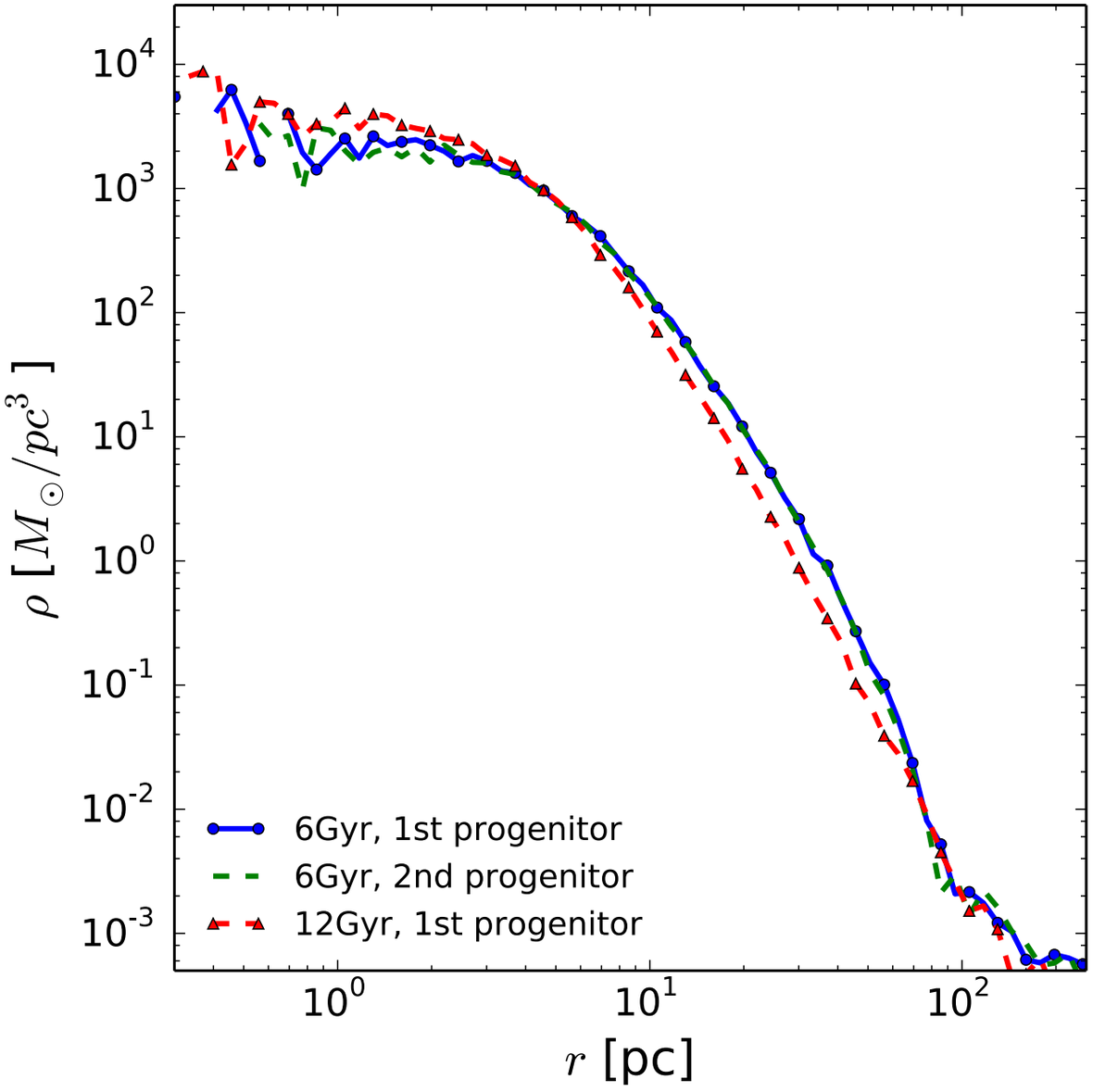


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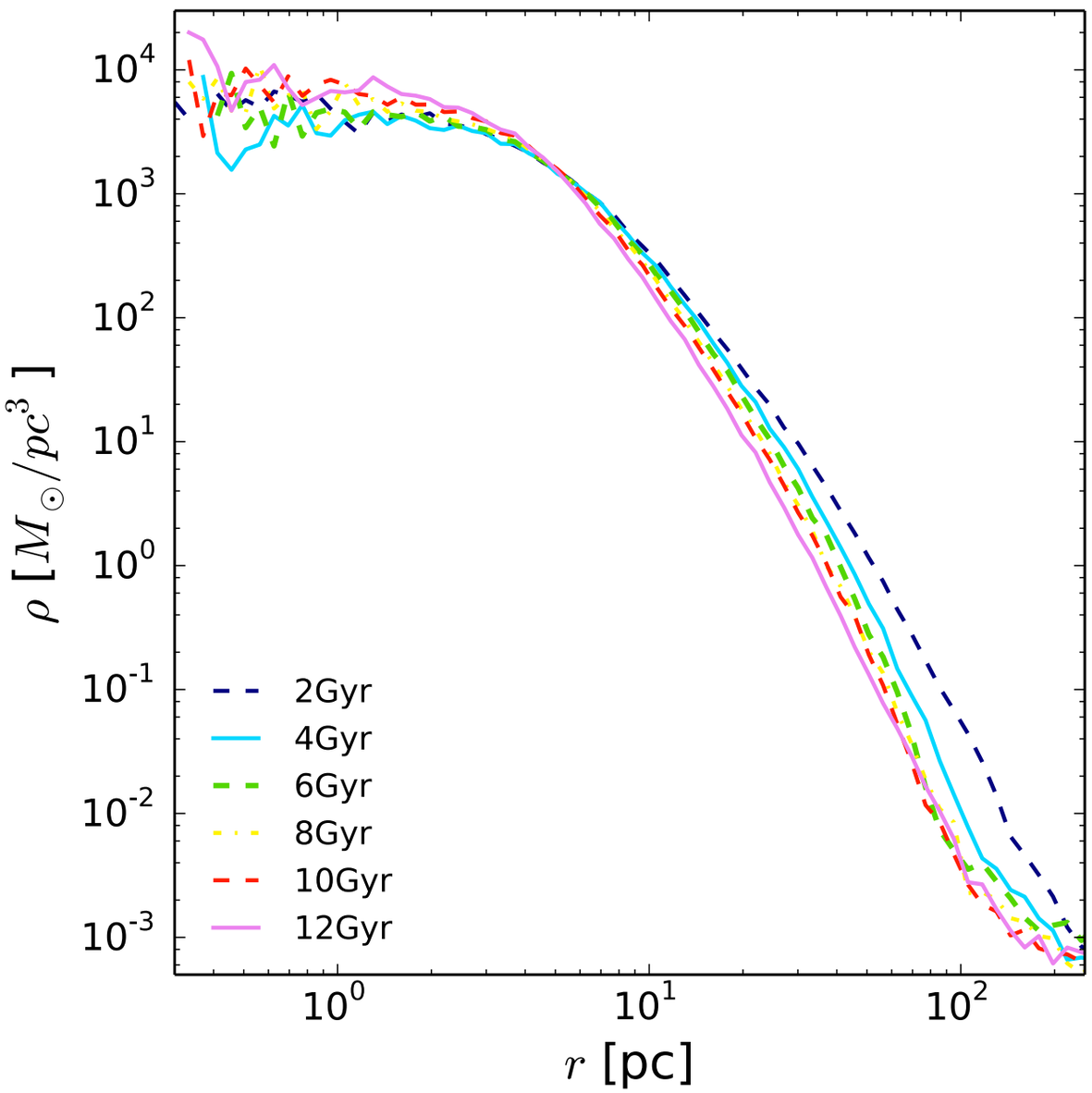


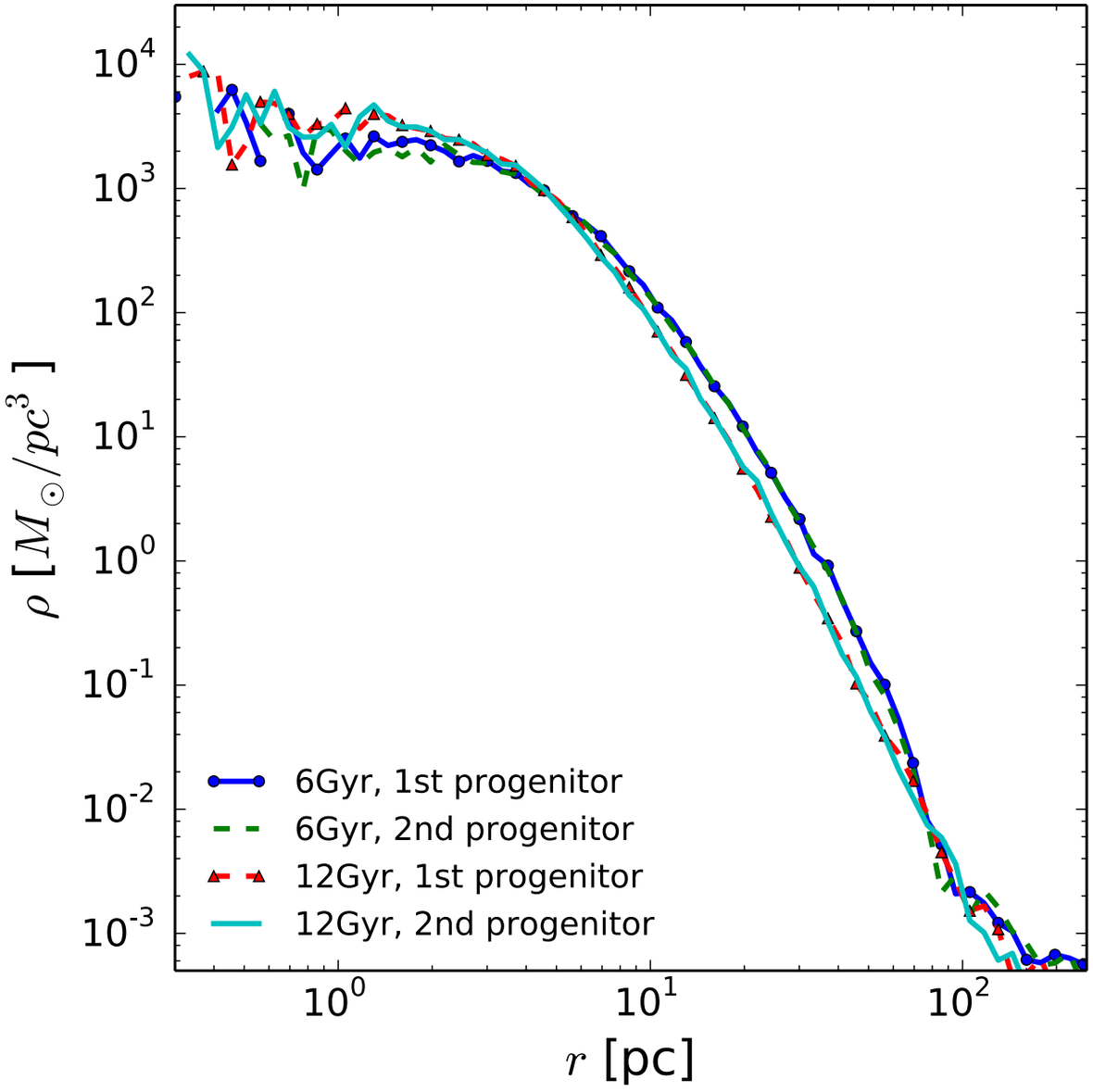


**Mastrobuono-Battisti et al., 2019**

# The impact between clusters with different densities can lead to a different result

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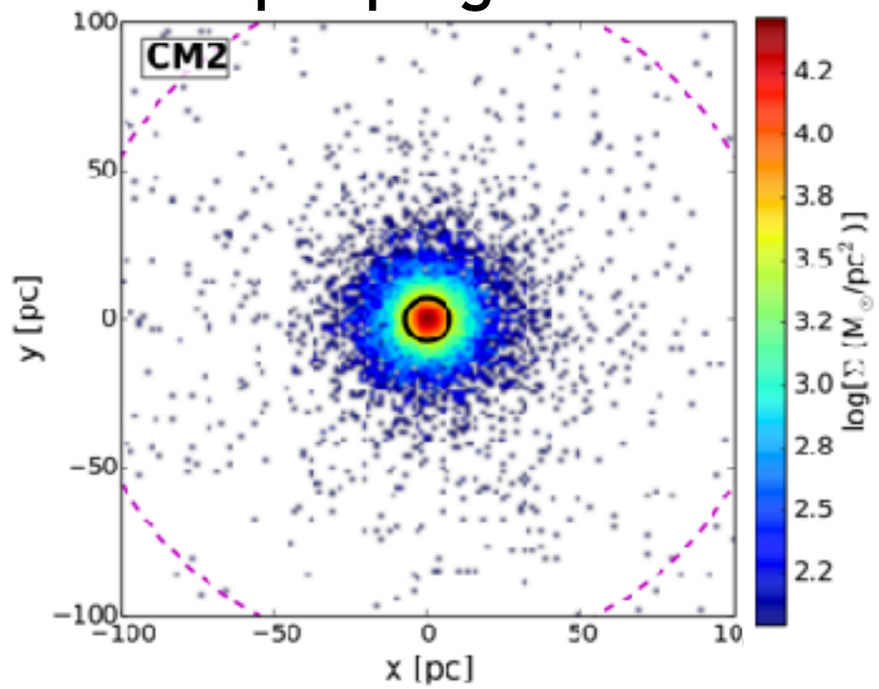

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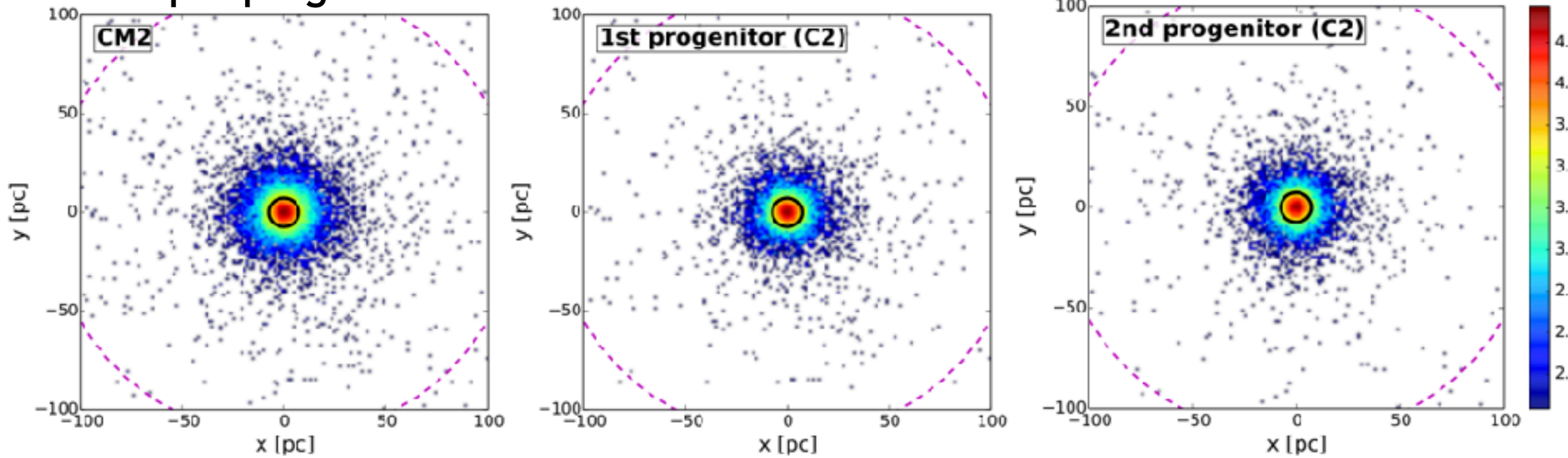

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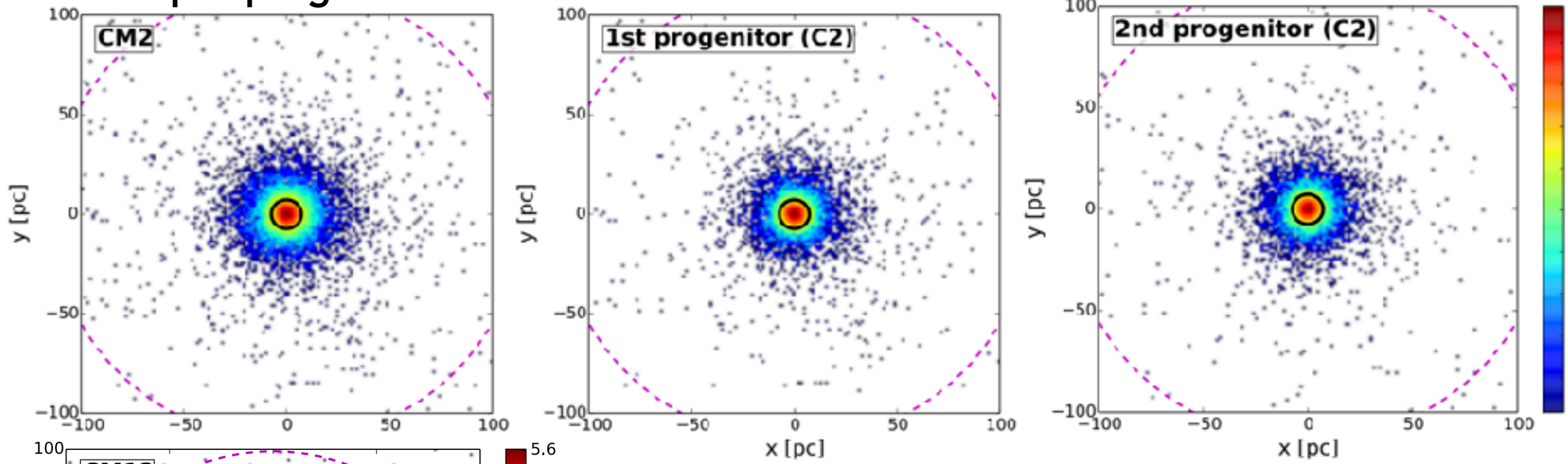


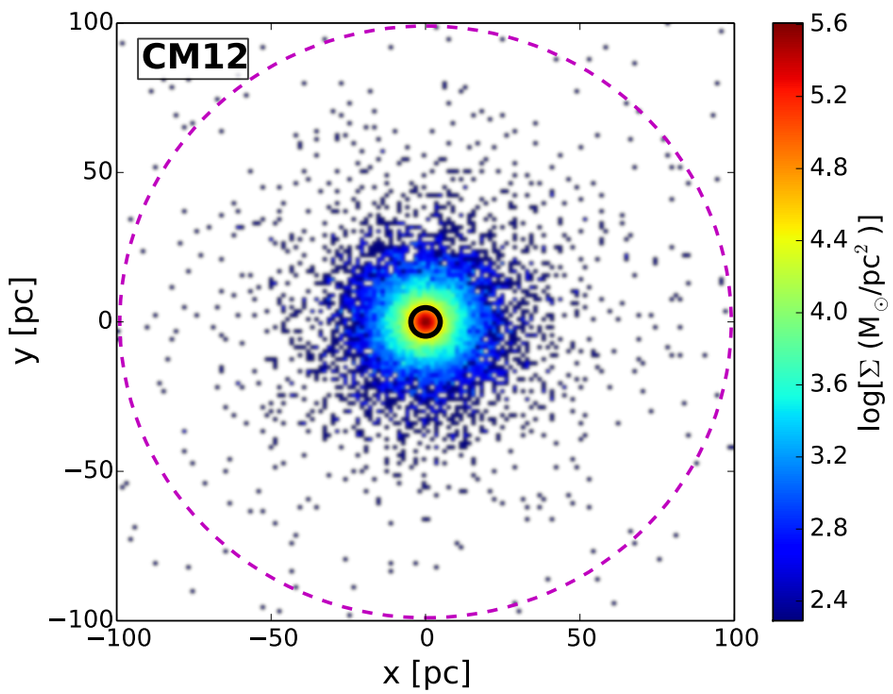


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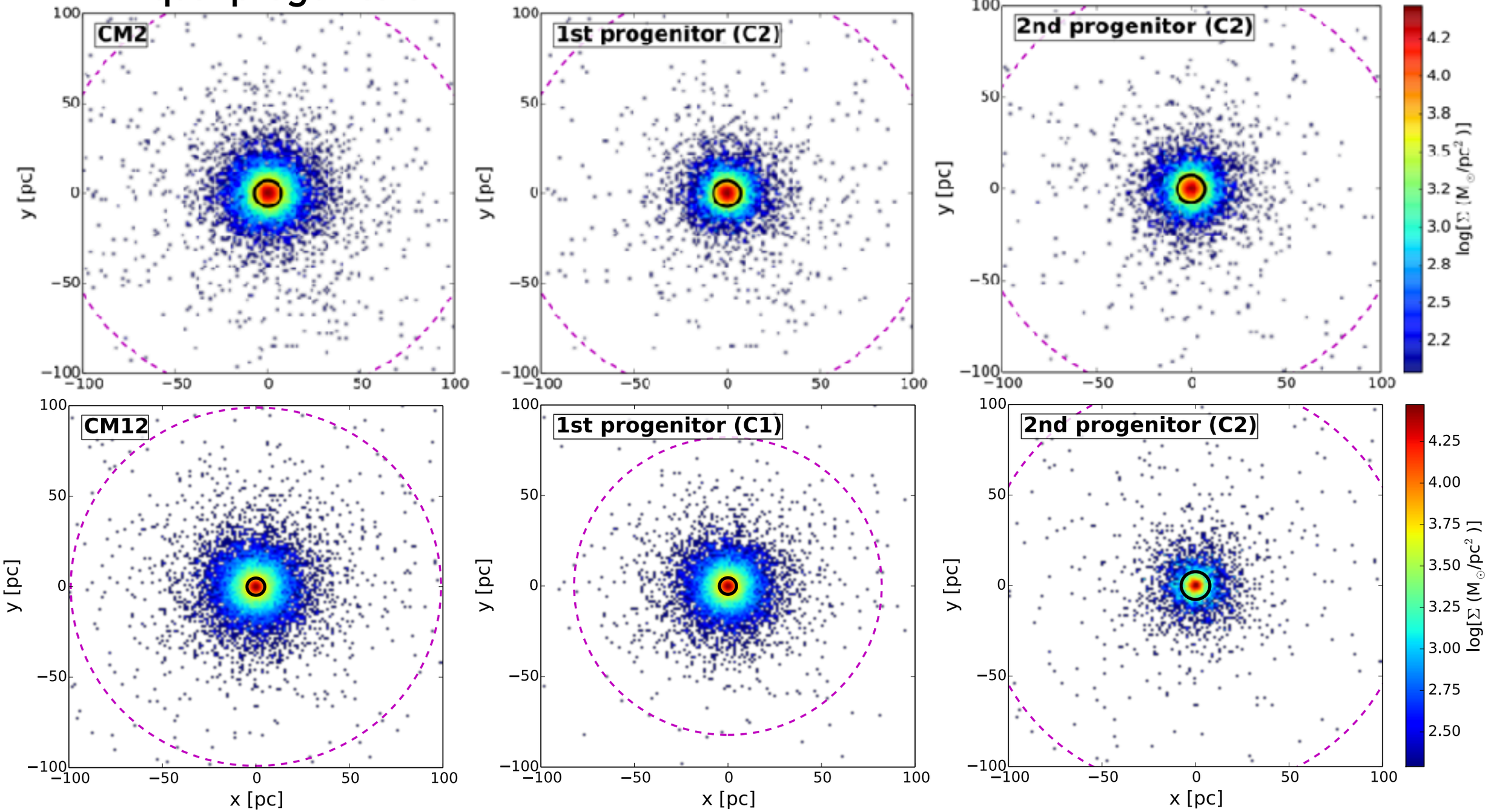


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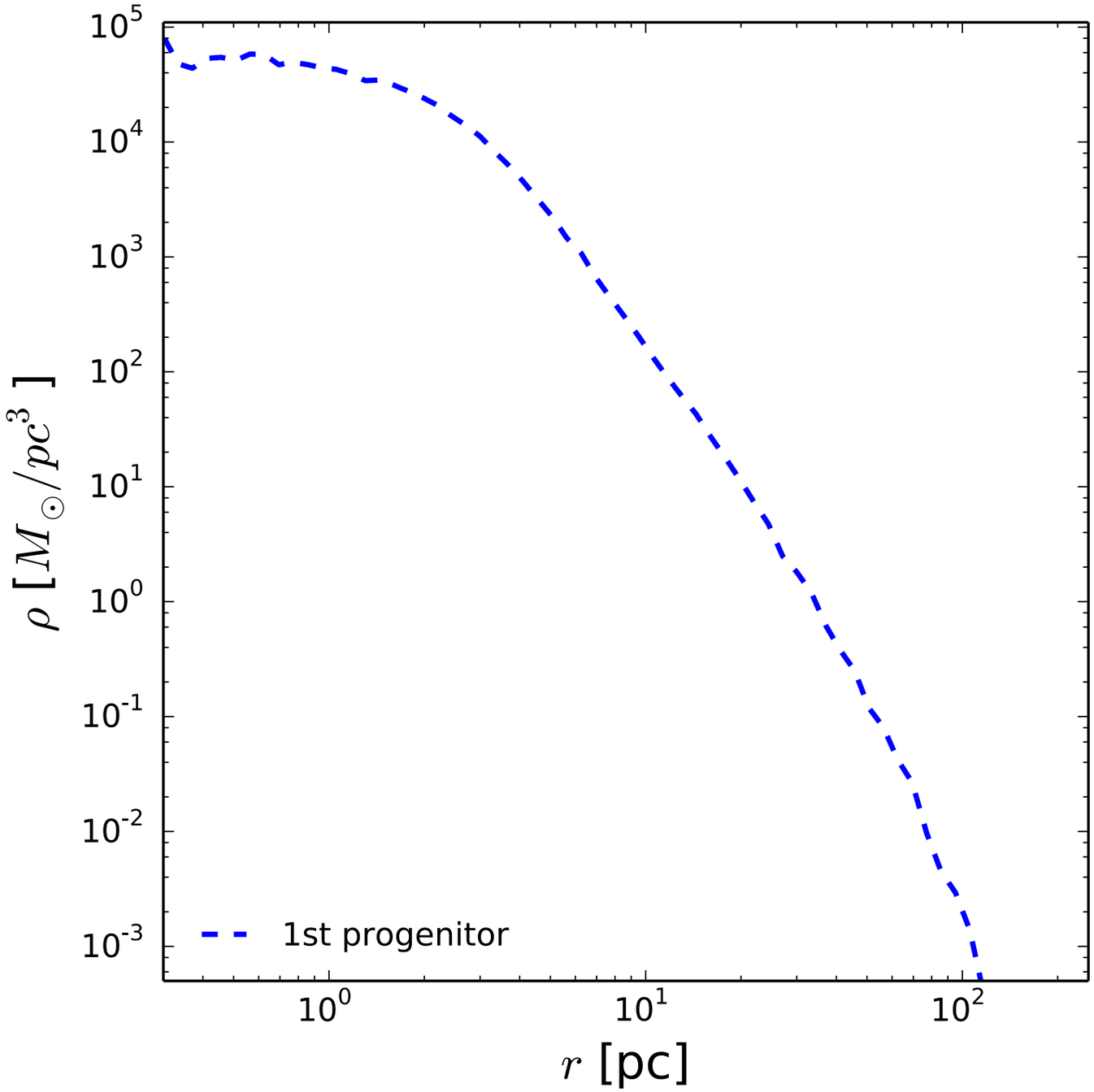

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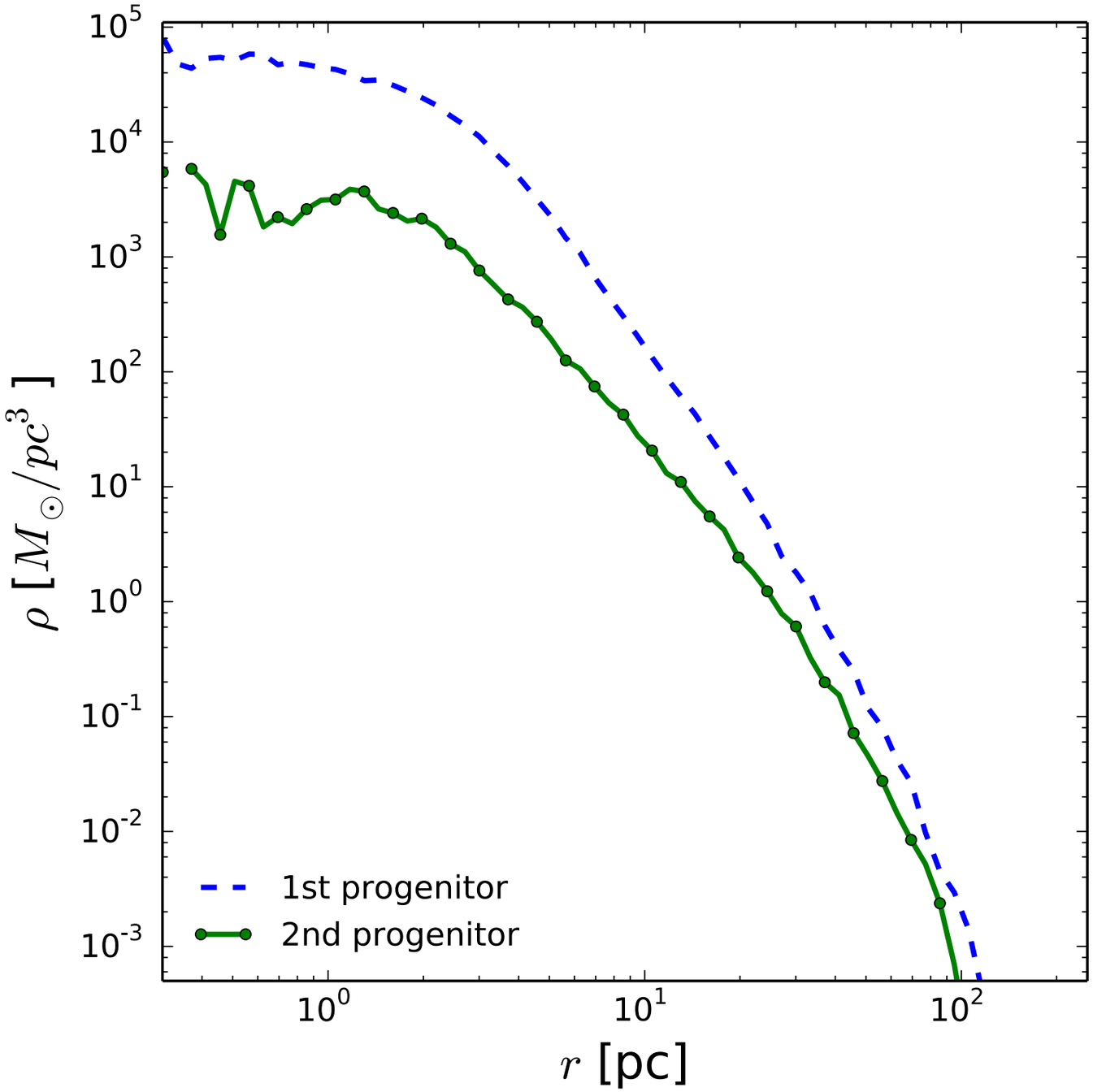

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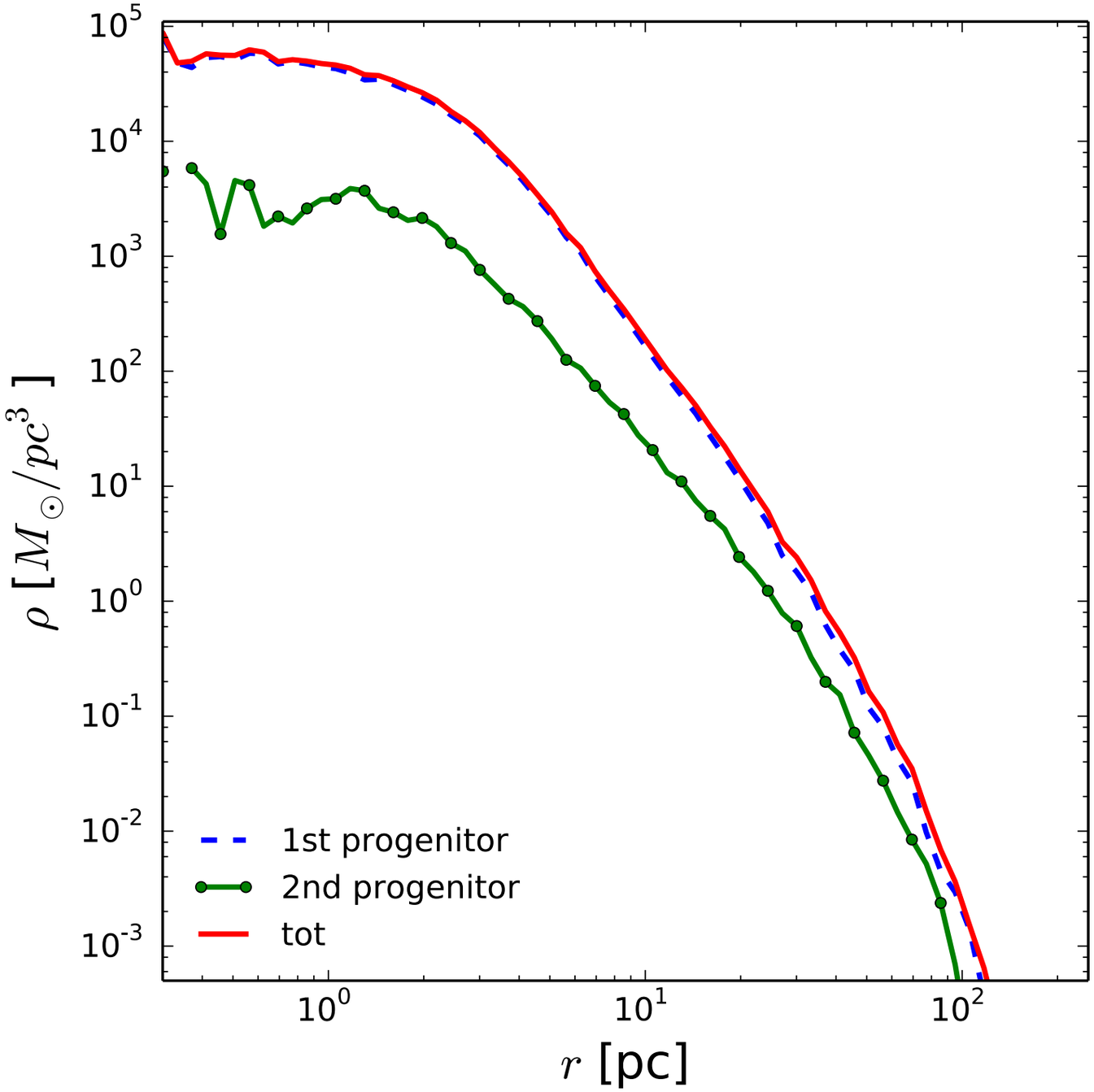

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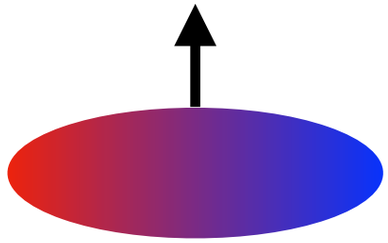
cluster seen edge-on



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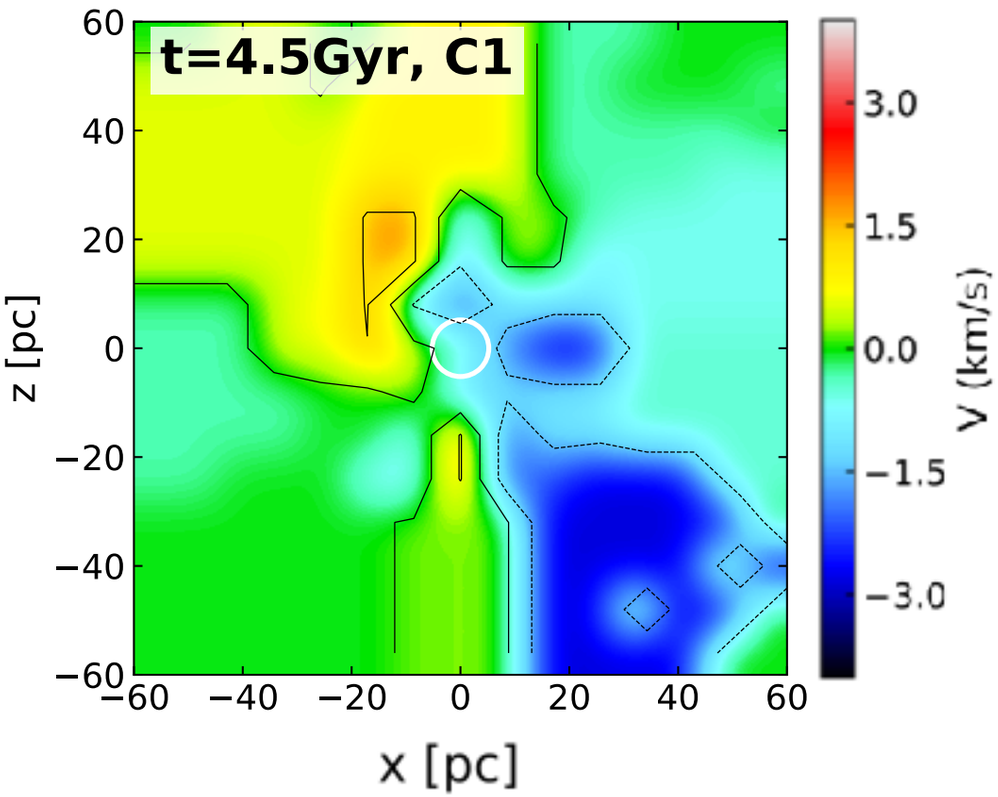

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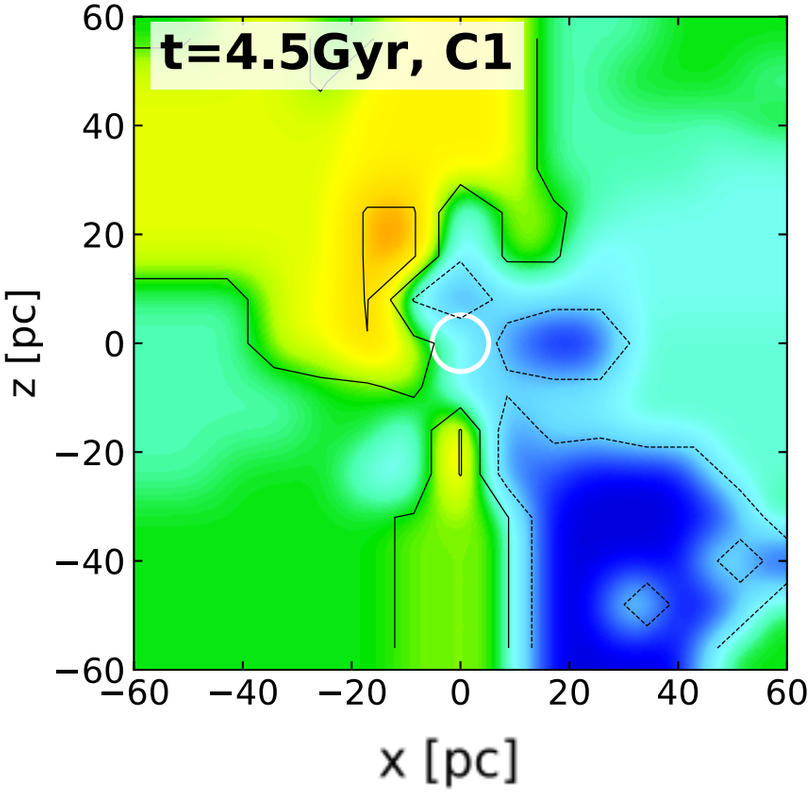


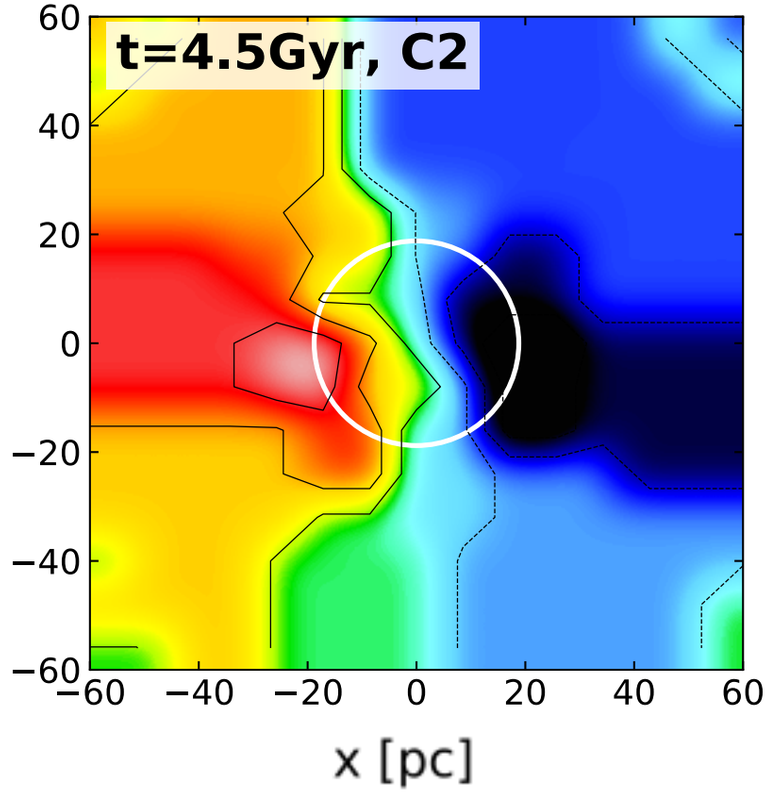

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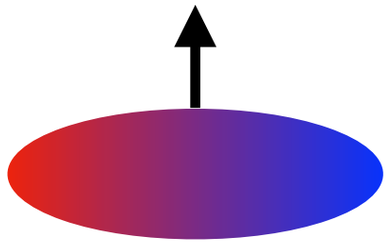


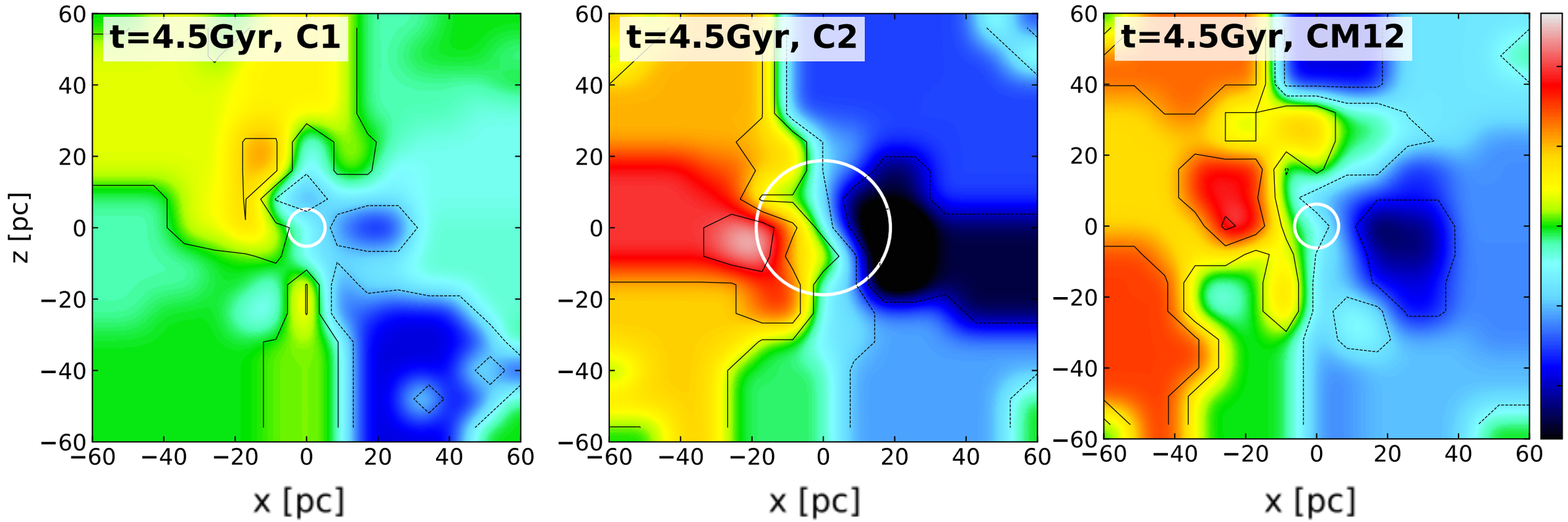

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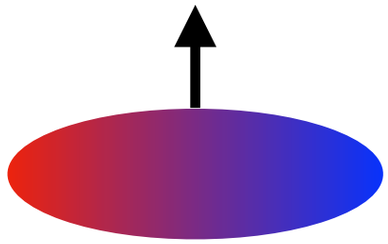


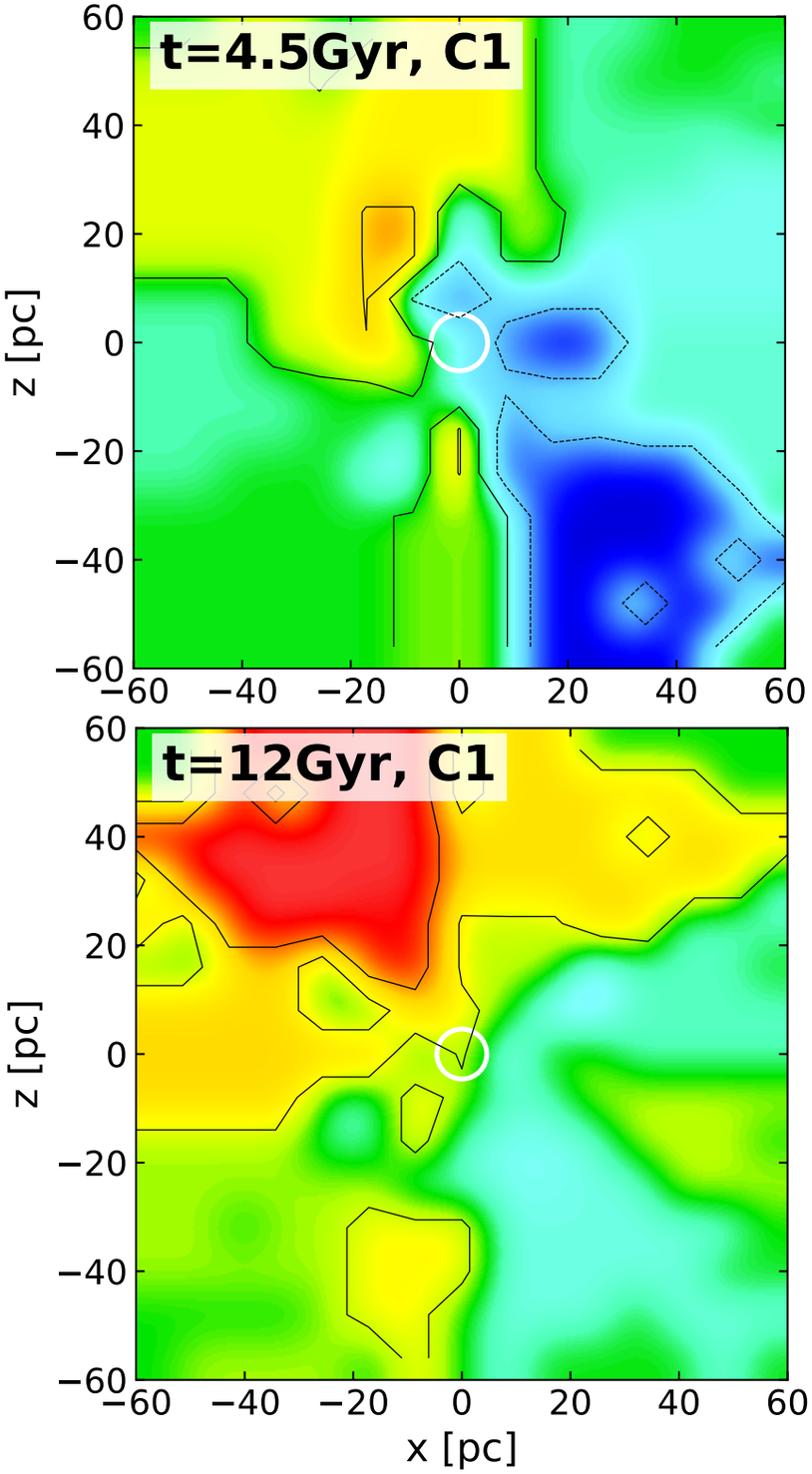

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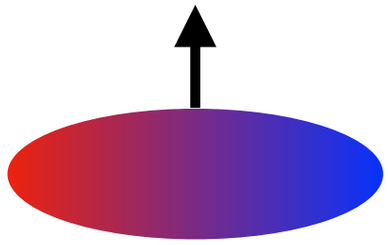


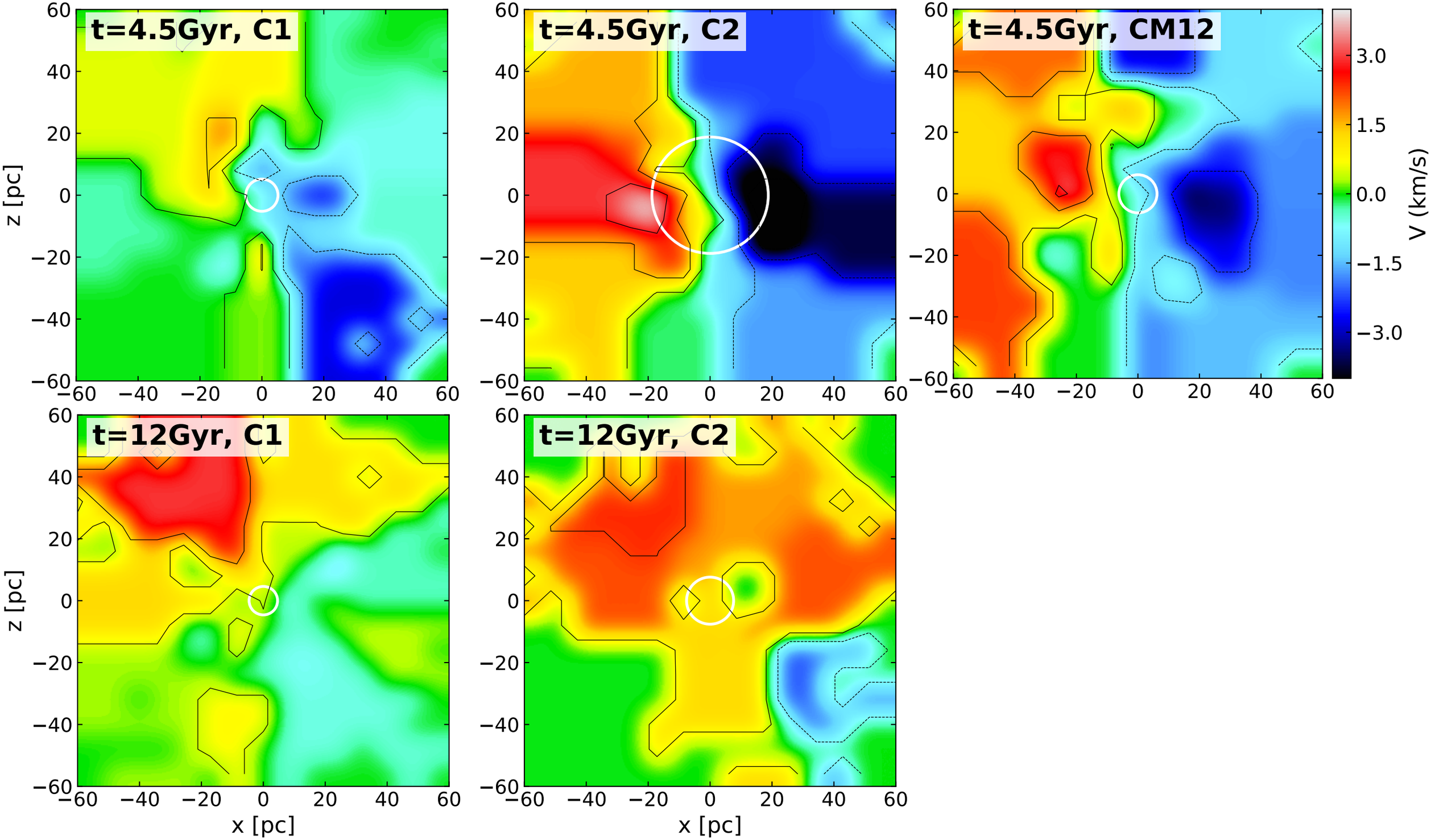

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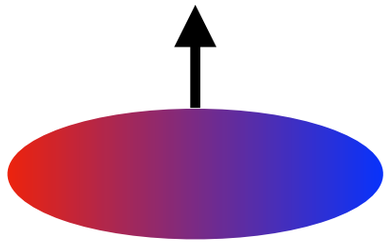


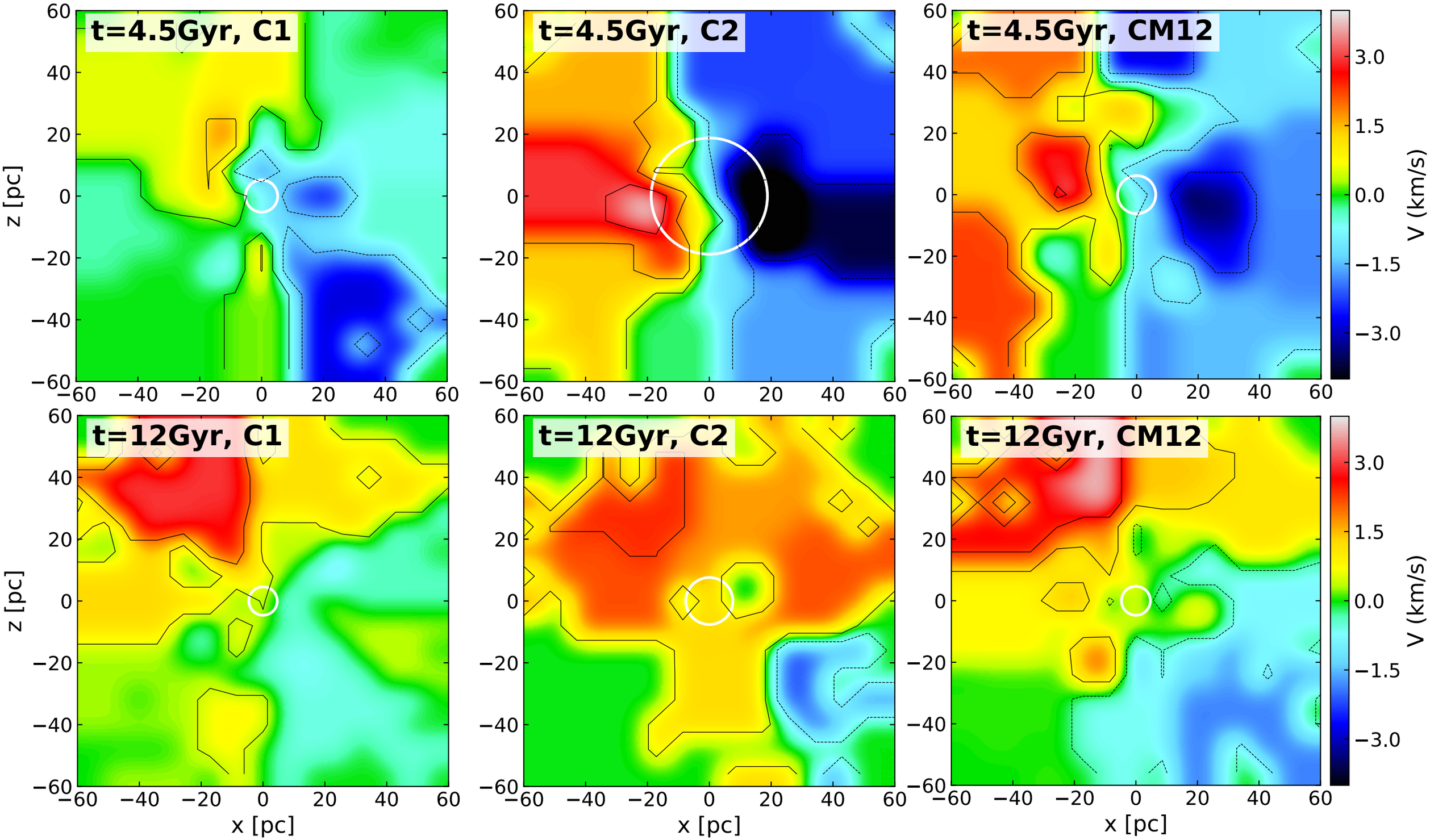

# The mass lost after the merger could be substantial and is in the Galactic disc

Mastrobuono-Battisti et al., 2019

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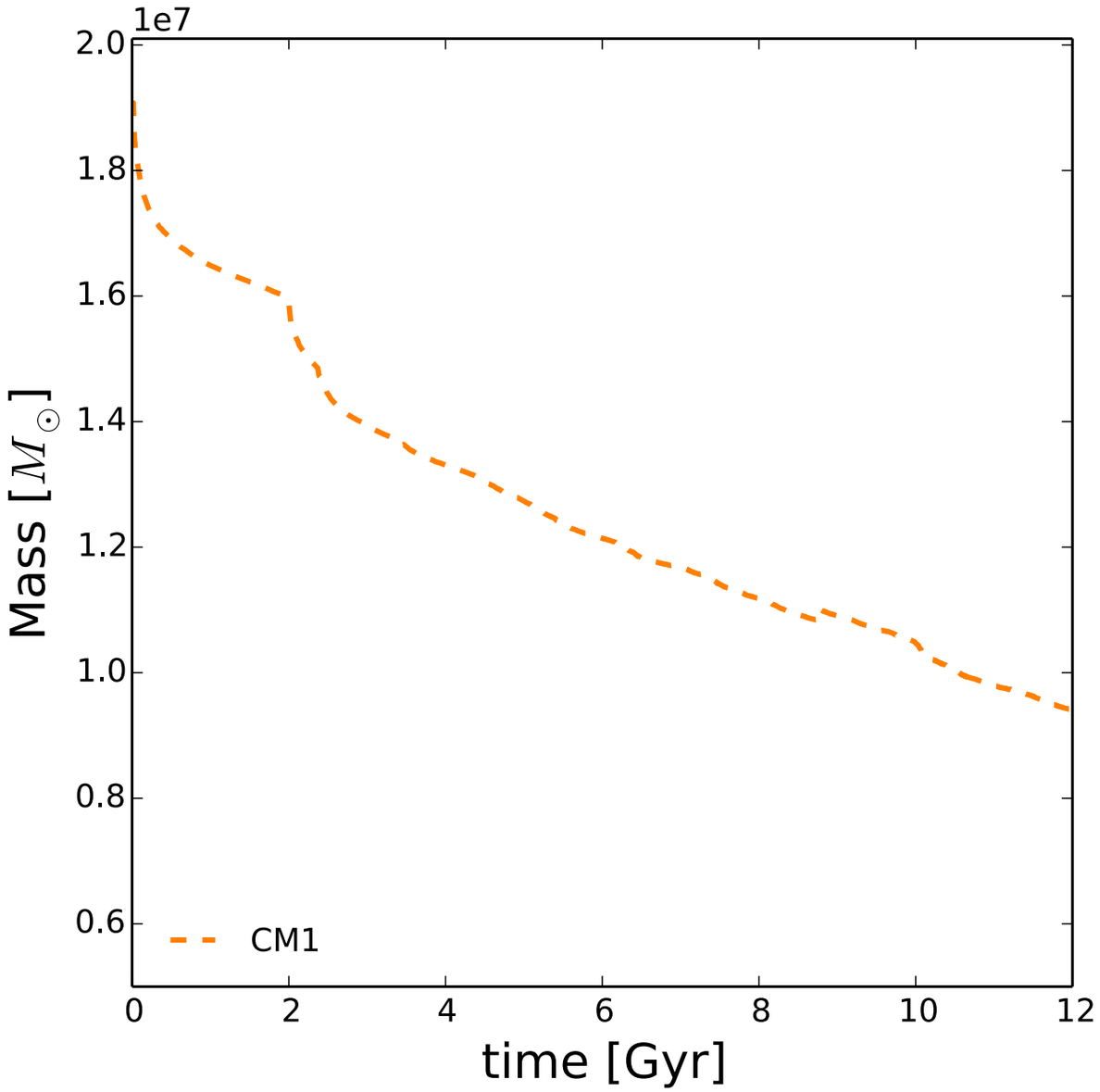


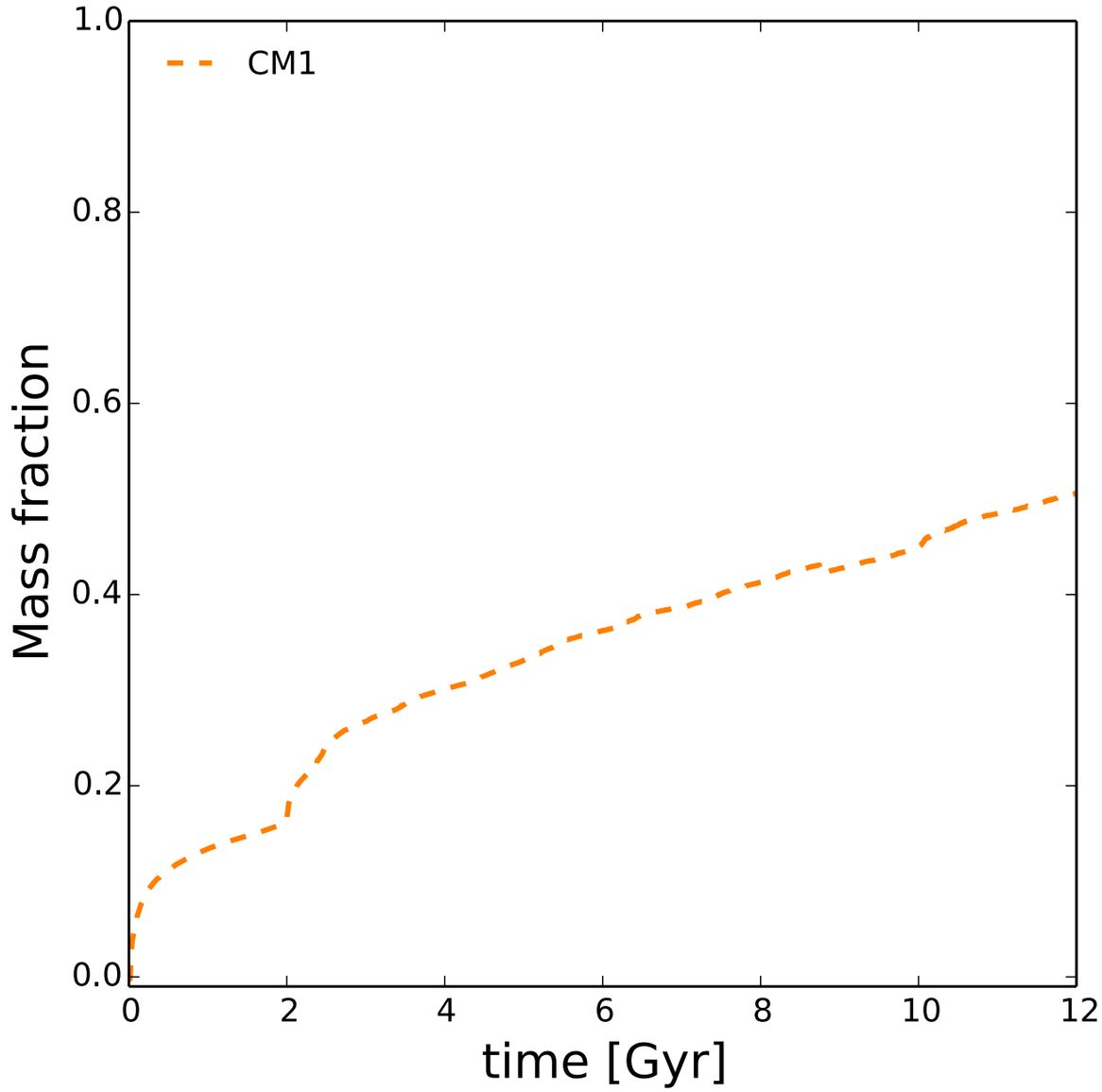


Mastrobuono-Battisti et al., 2019

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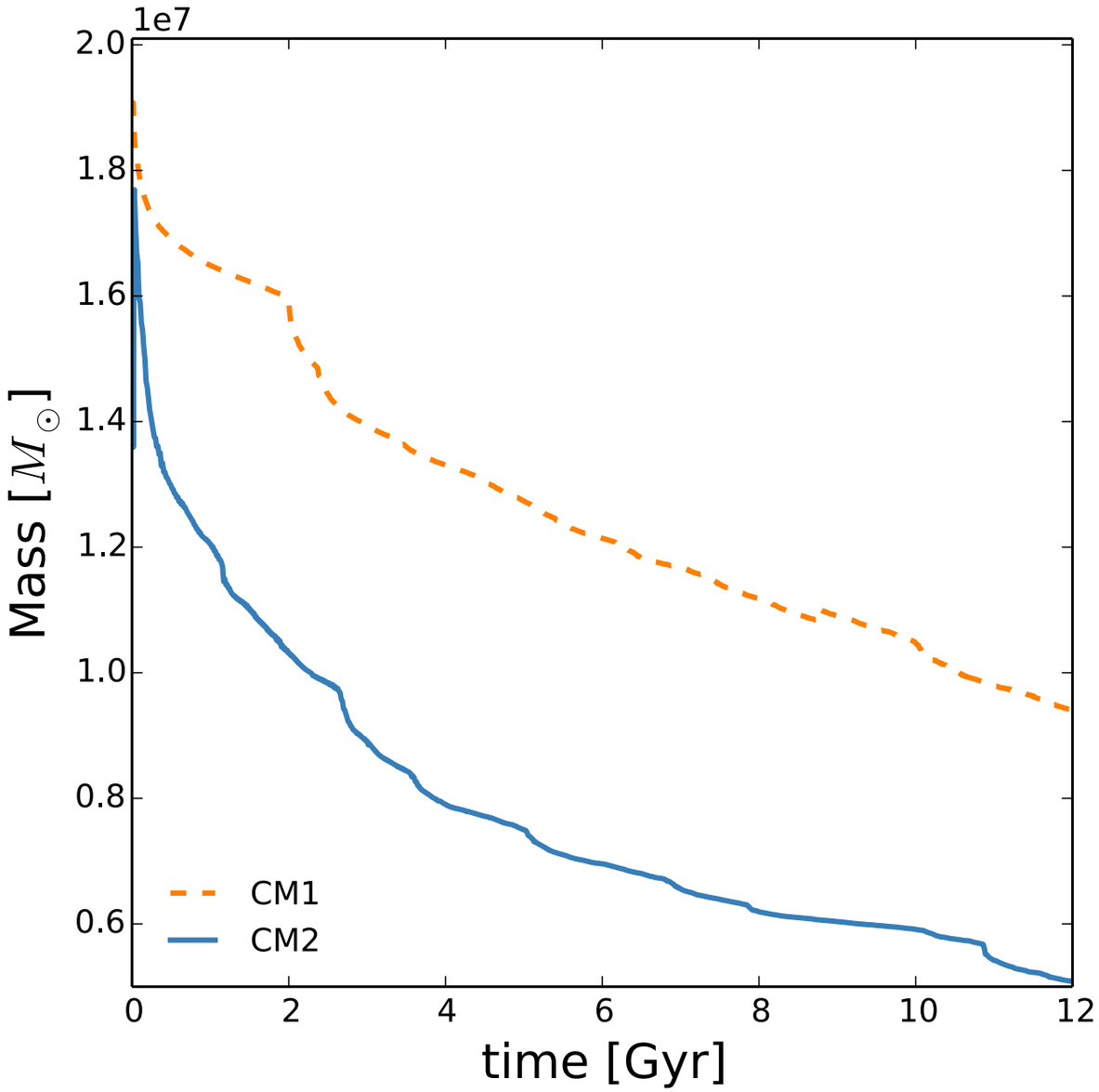


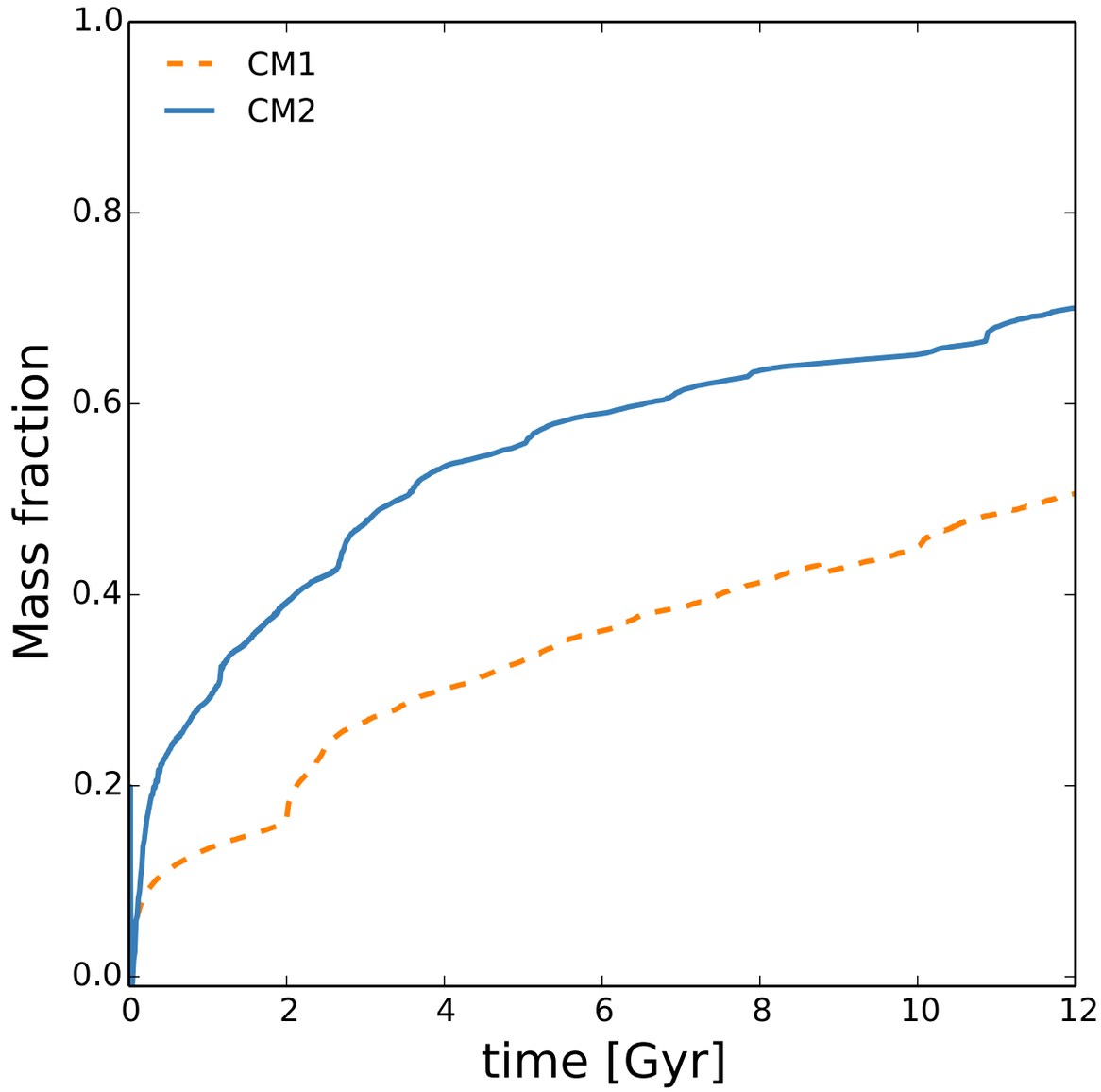


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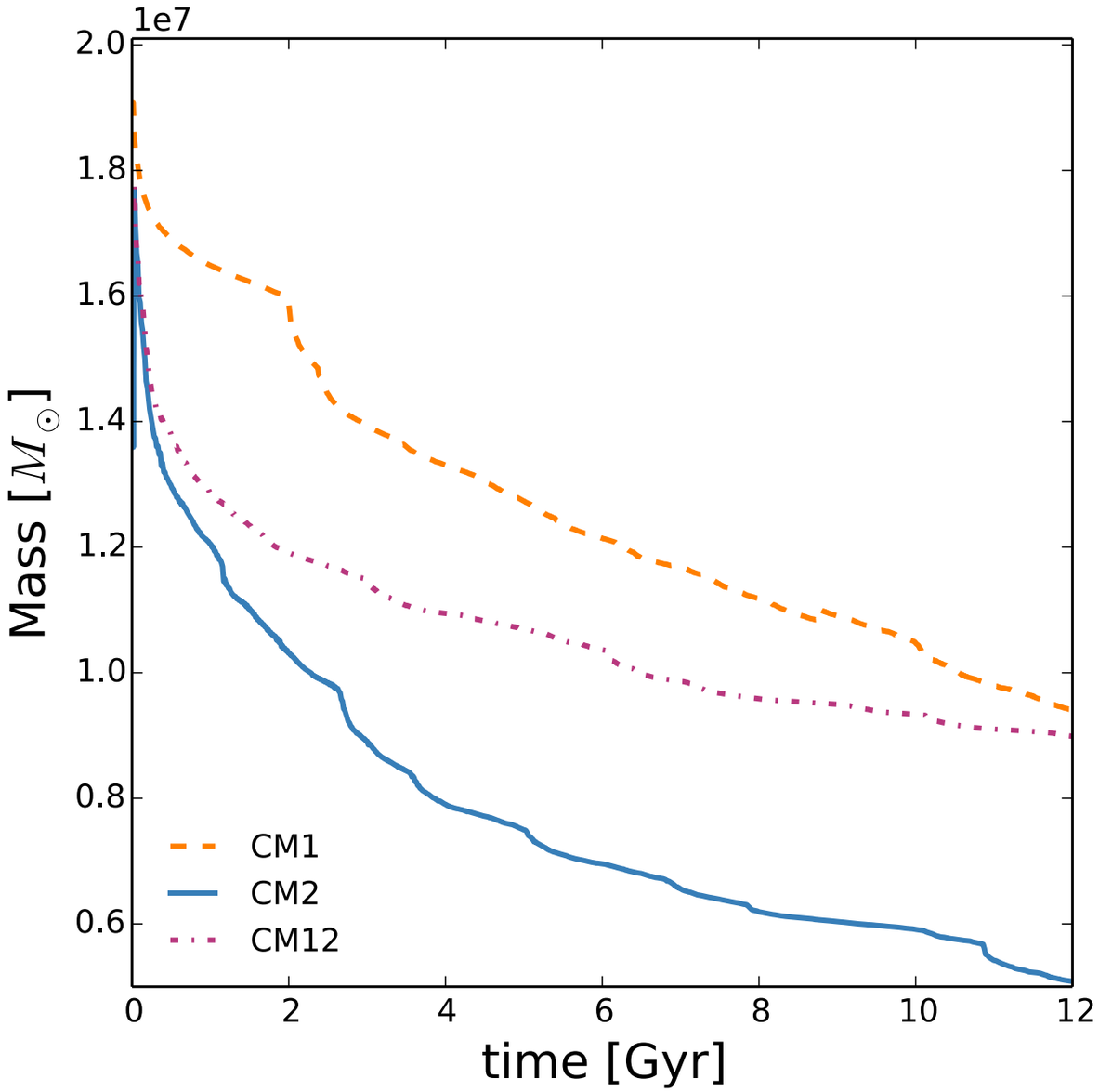


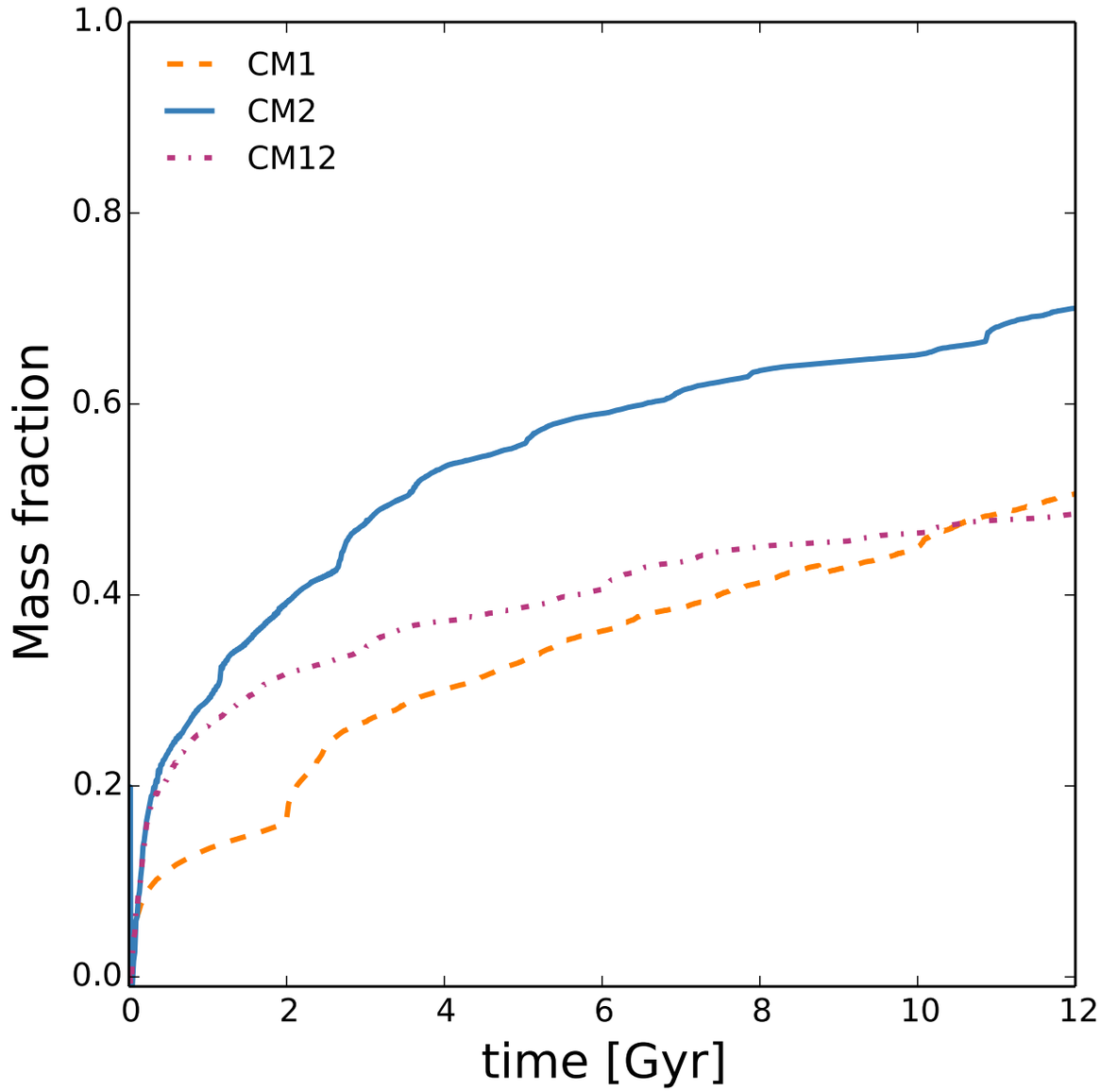


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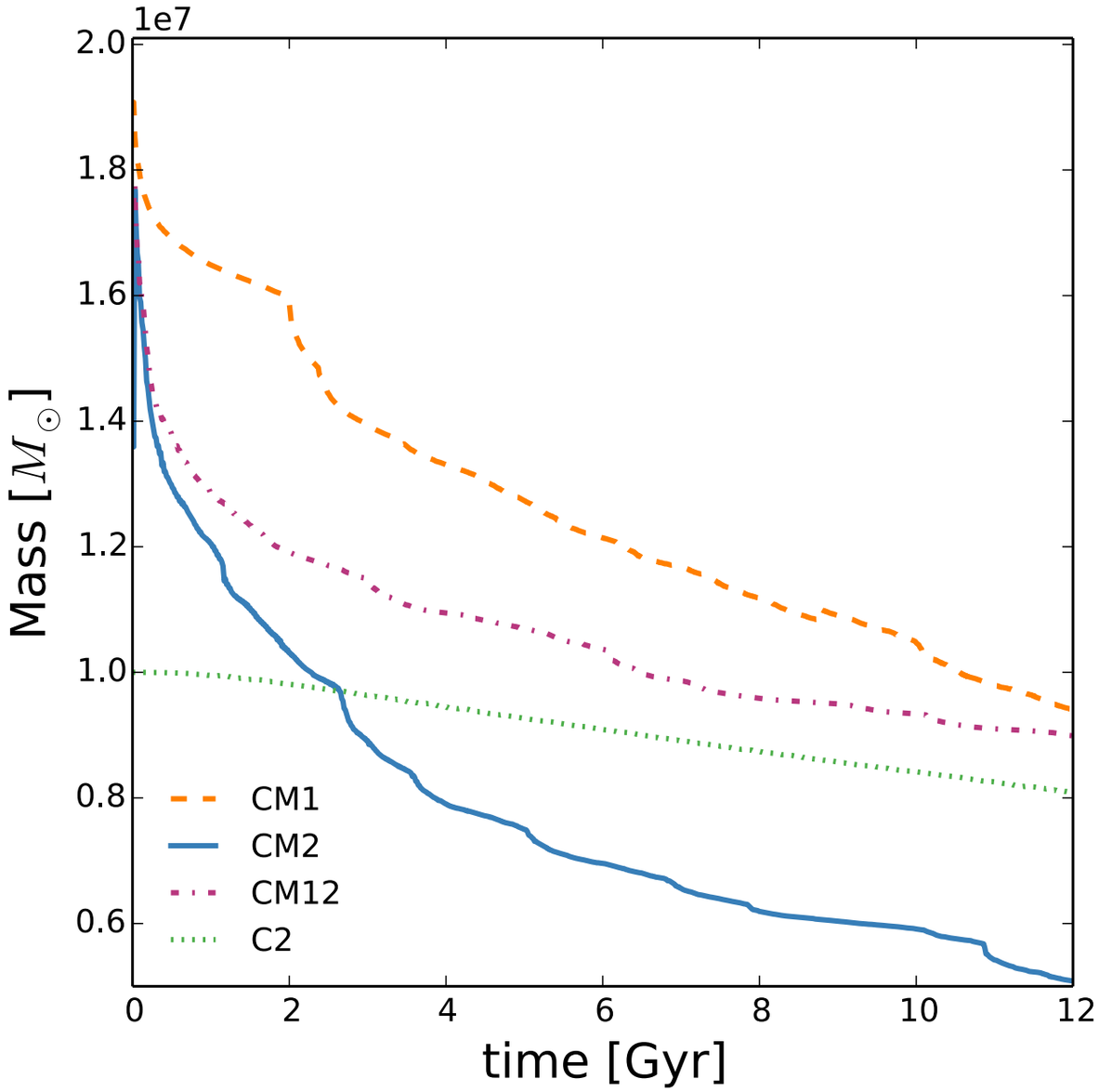


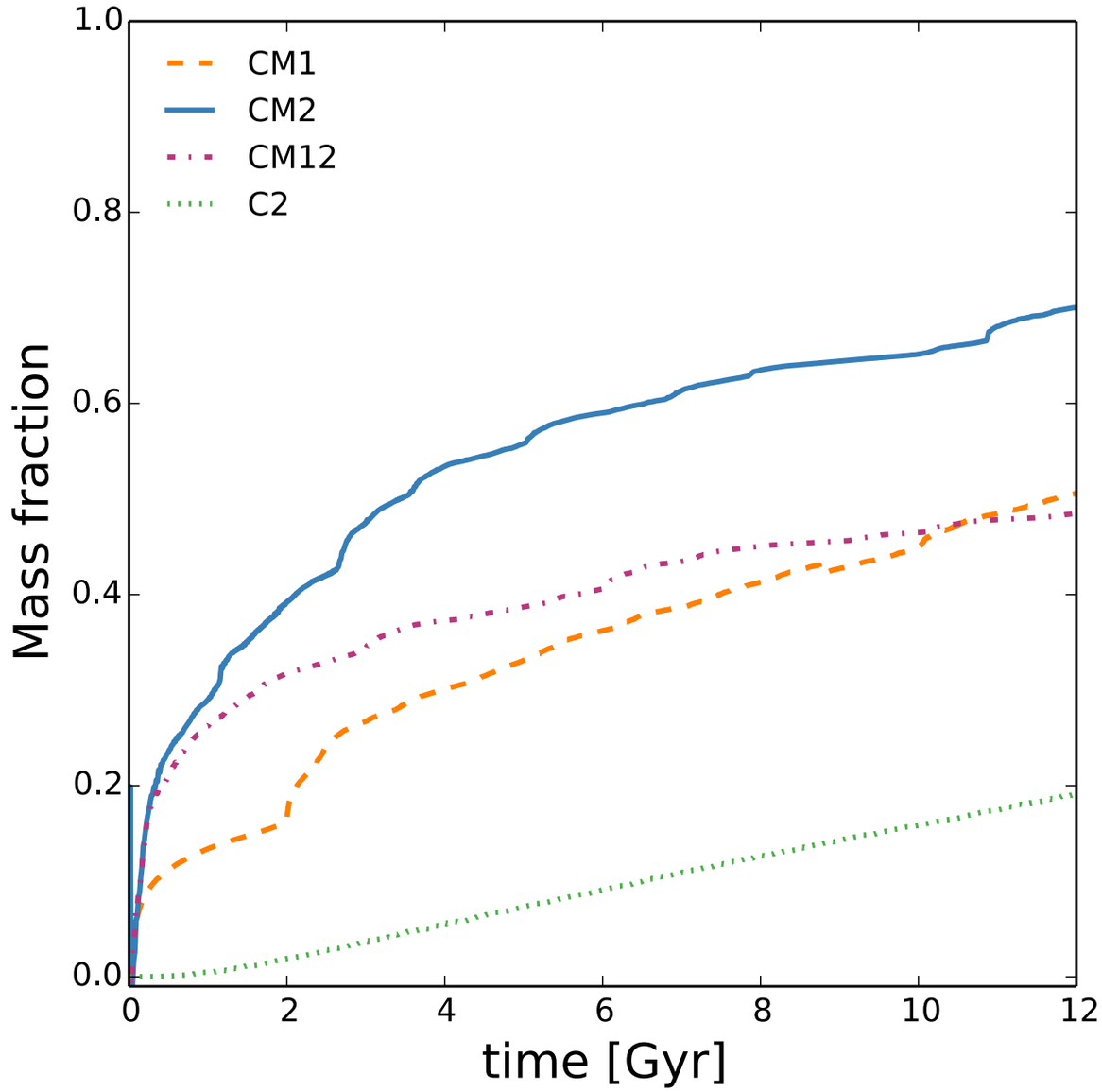


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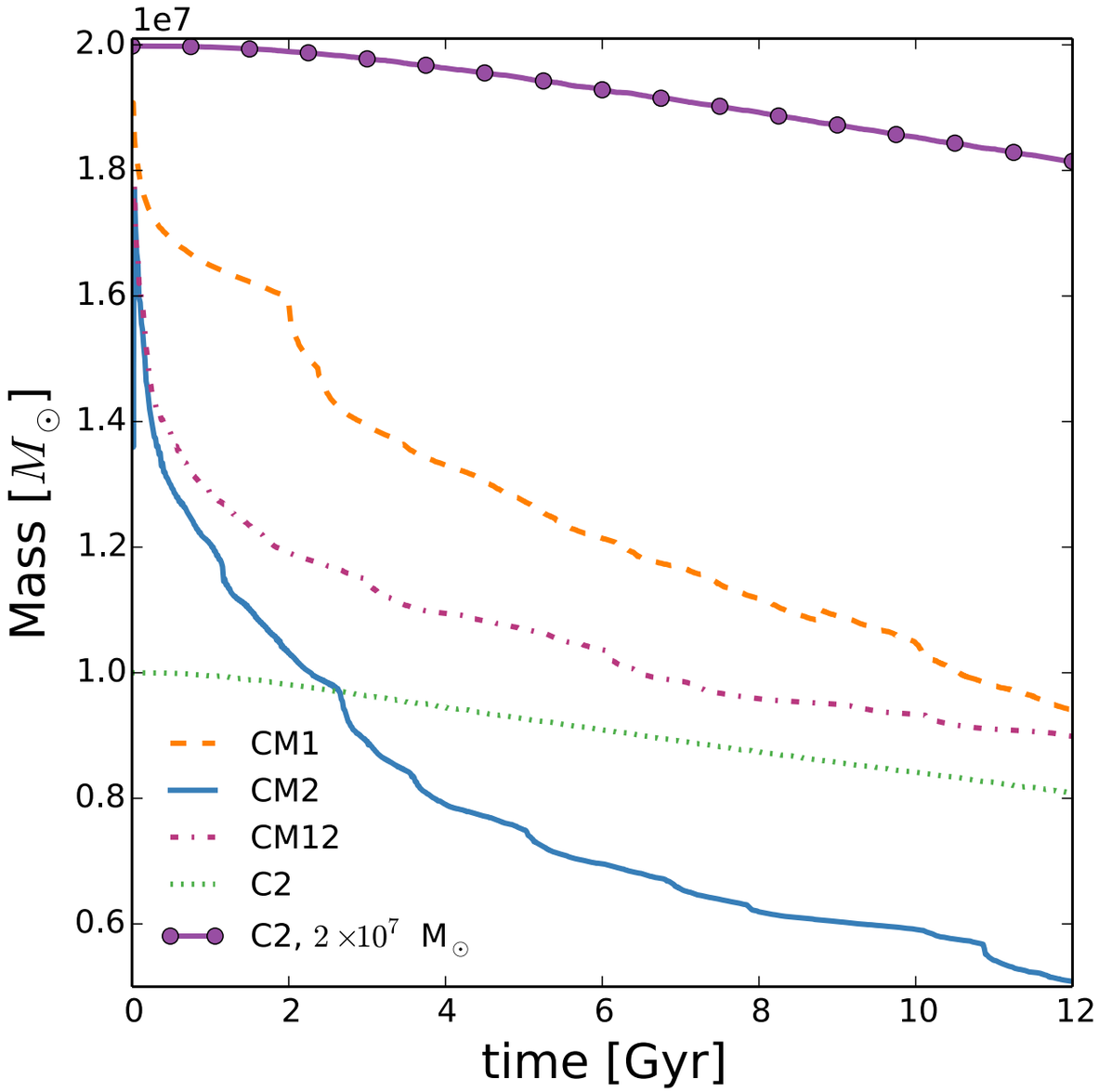


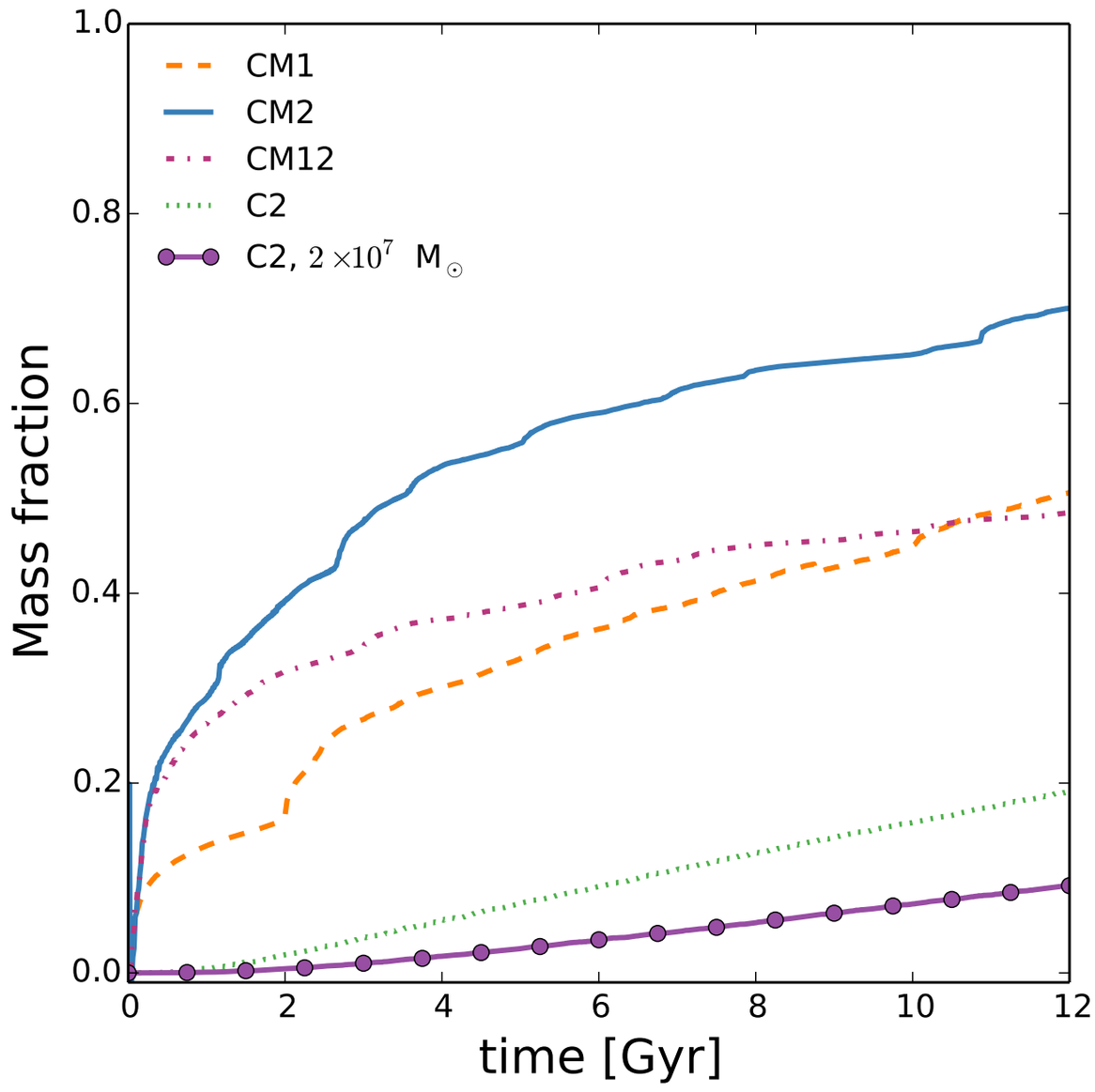


Mastrobuono-Battisti et al., 2019

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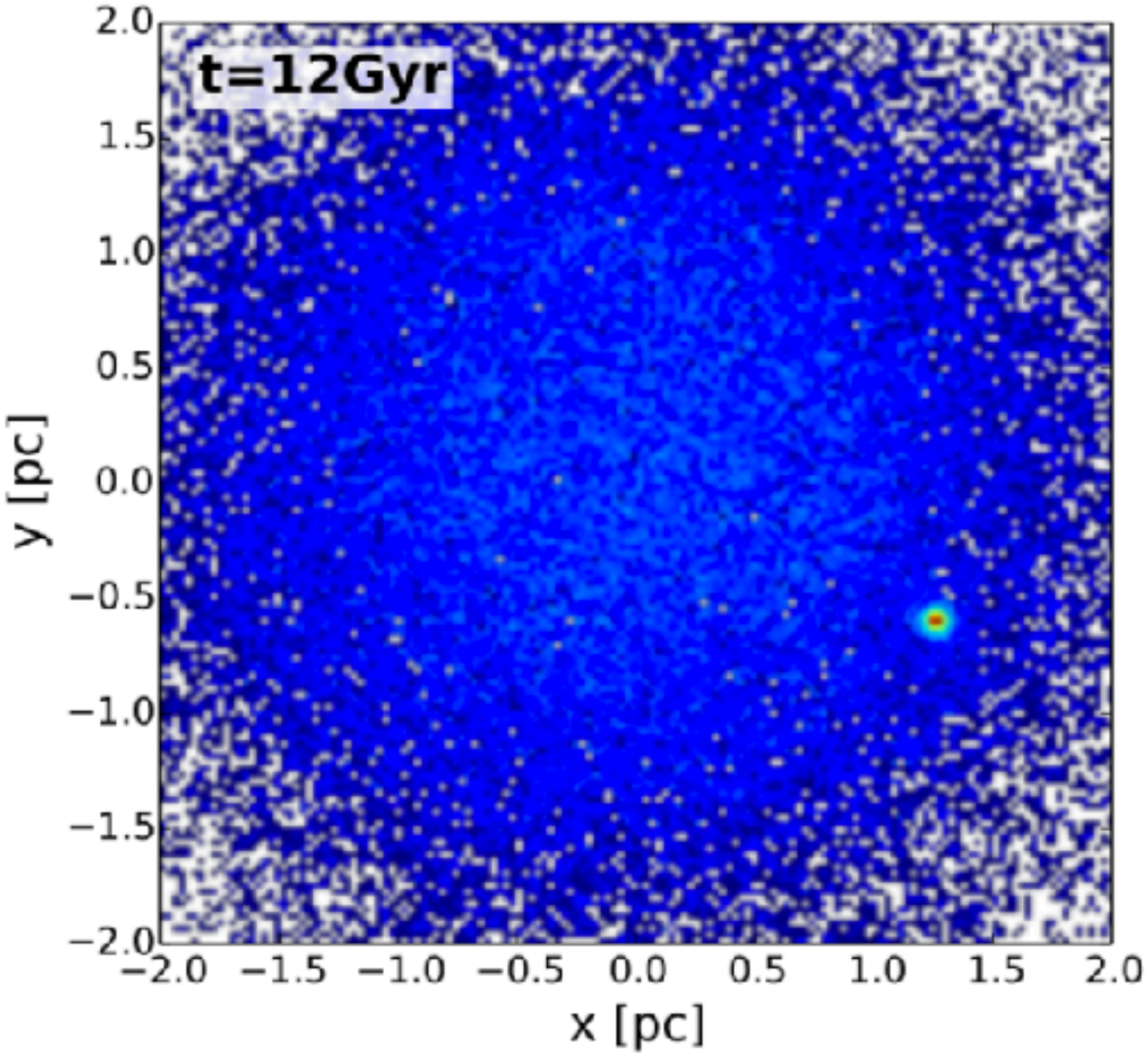
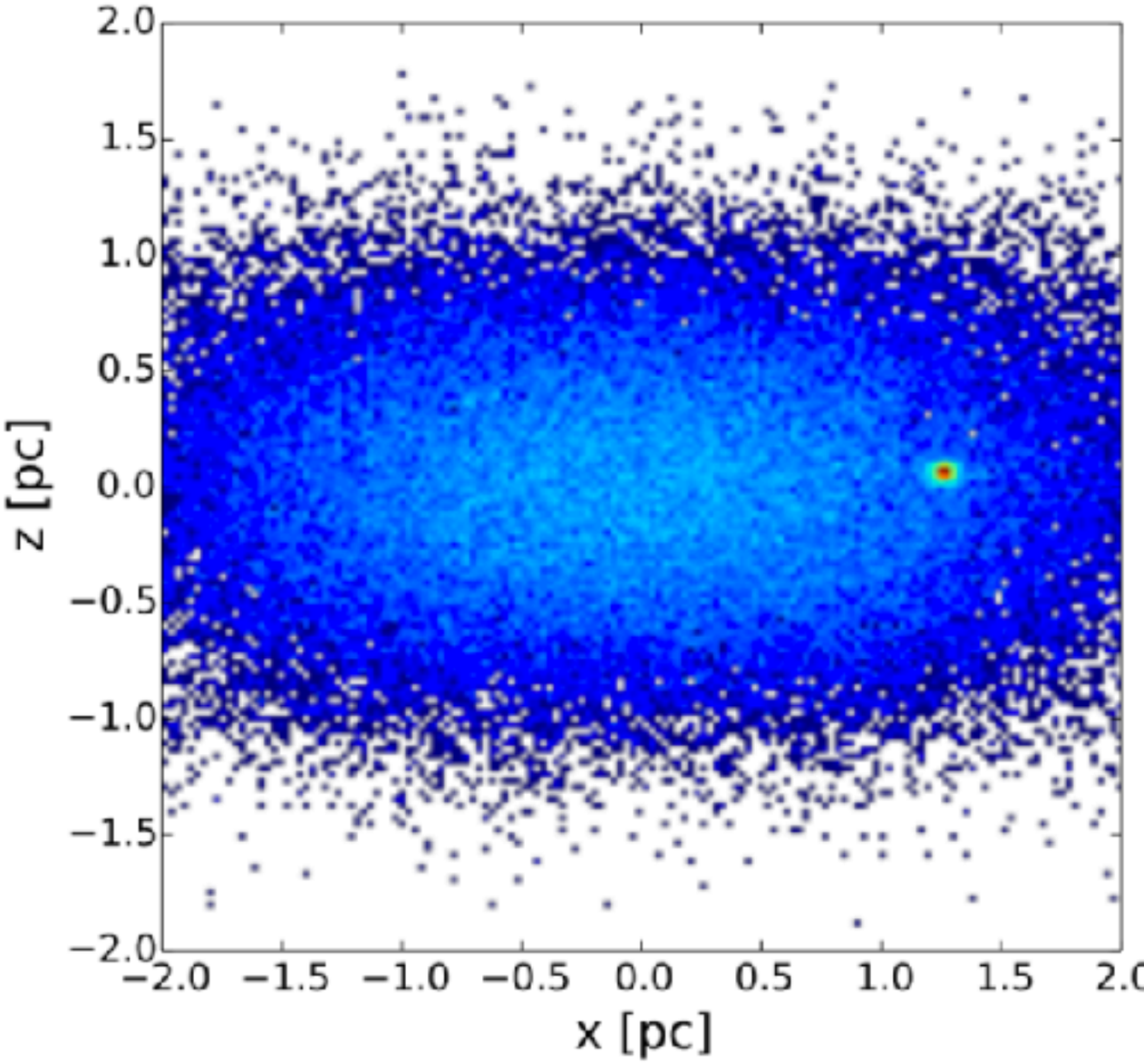
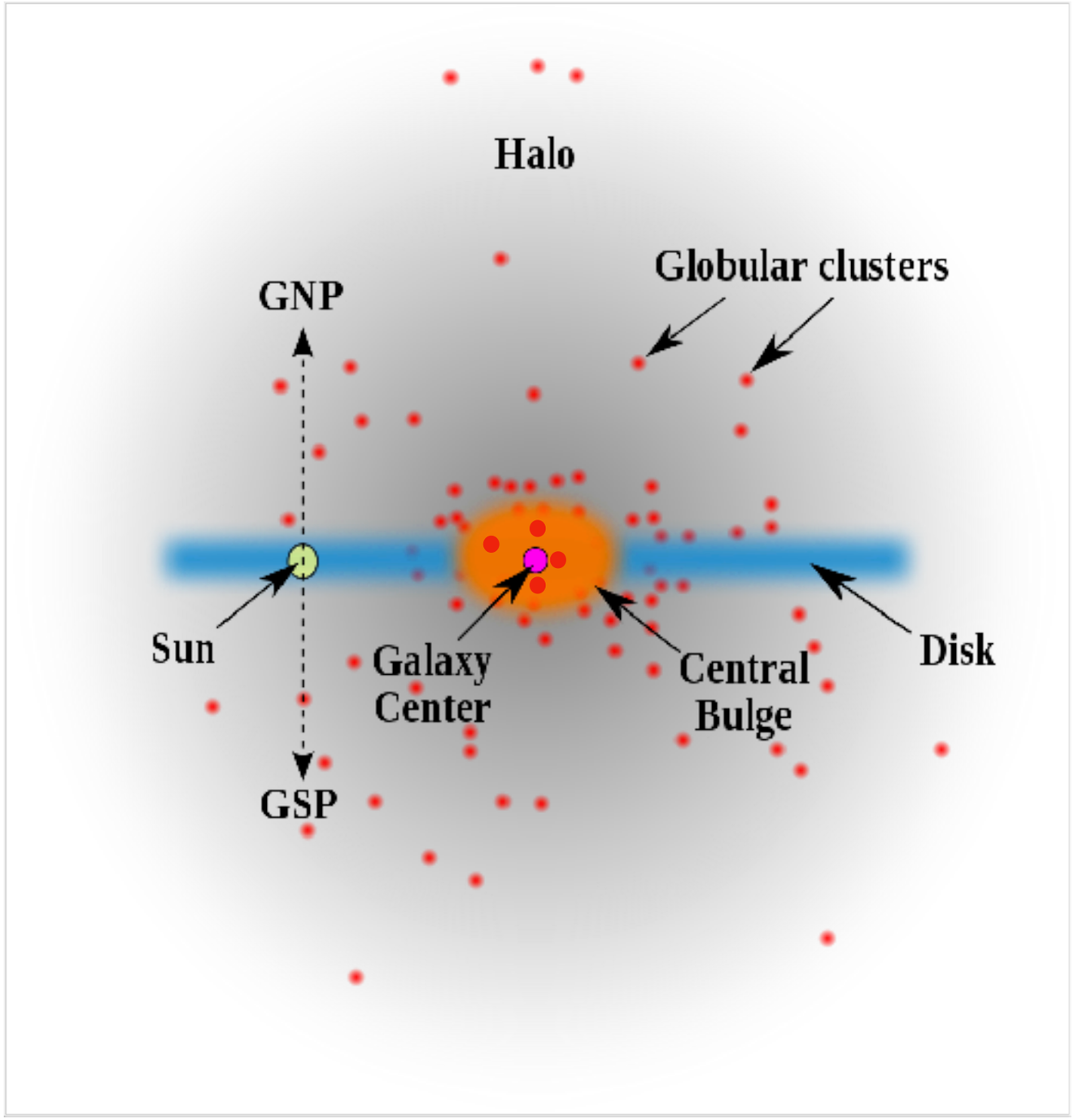



Mastrobuono-Battisti et al., 2019

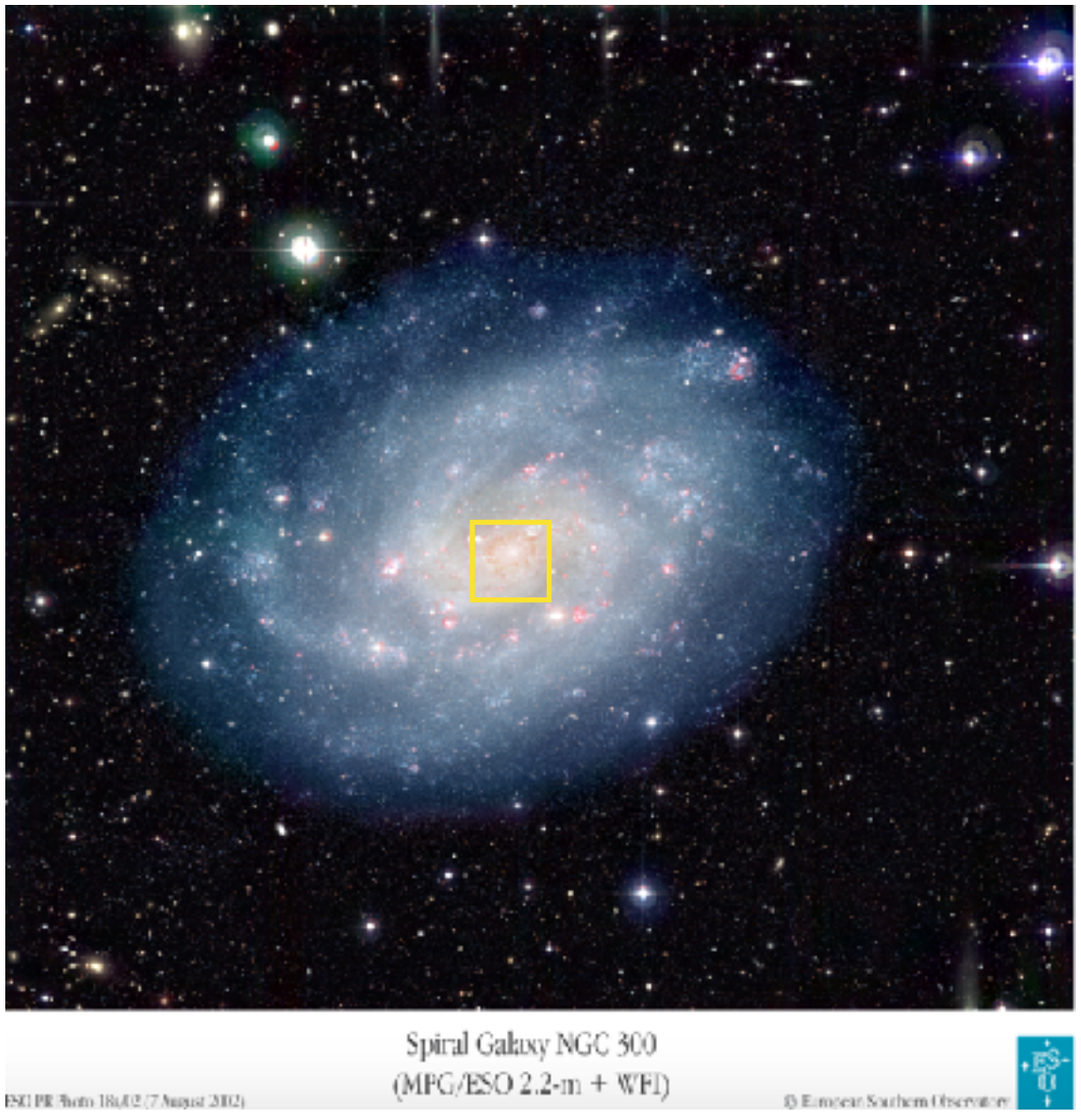
# Massive and dense globular clusters can survive and decay towards the Galactic centre




➡ Could globular clusters contribute to the build-up of the Galactic nucleus?

➡ What is the link between stars in globular clusters, in the bulge and in the Galactic nucleus?

# Galactic centres often host a massive and luminous nuclear star cluster




Neumayer et al 2011, Carollo et al. 1998, Matthews et al. 1999, Böker et al. 2002, 2003, 2004, Böker 2010, Côte et al. 2006

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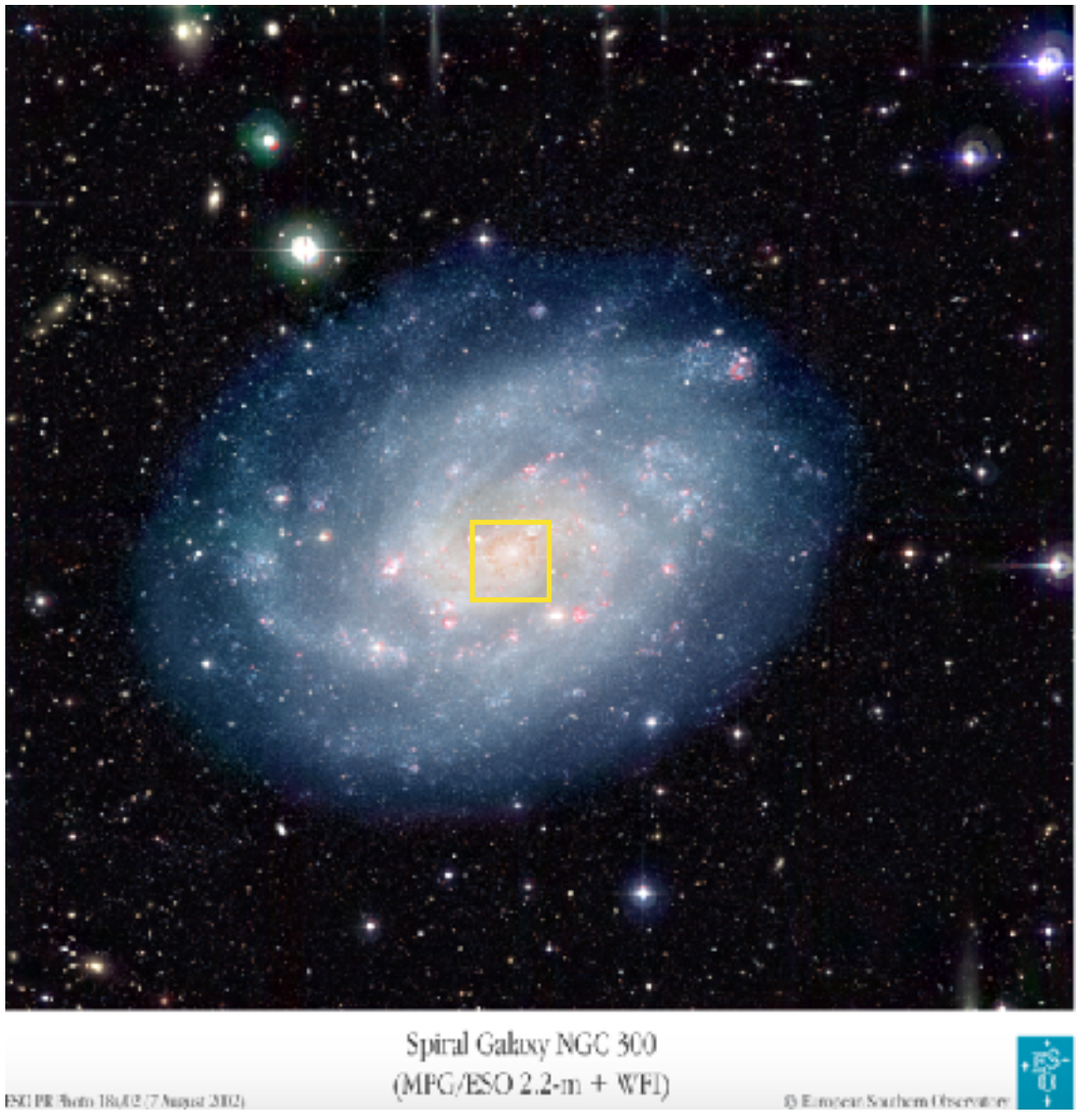



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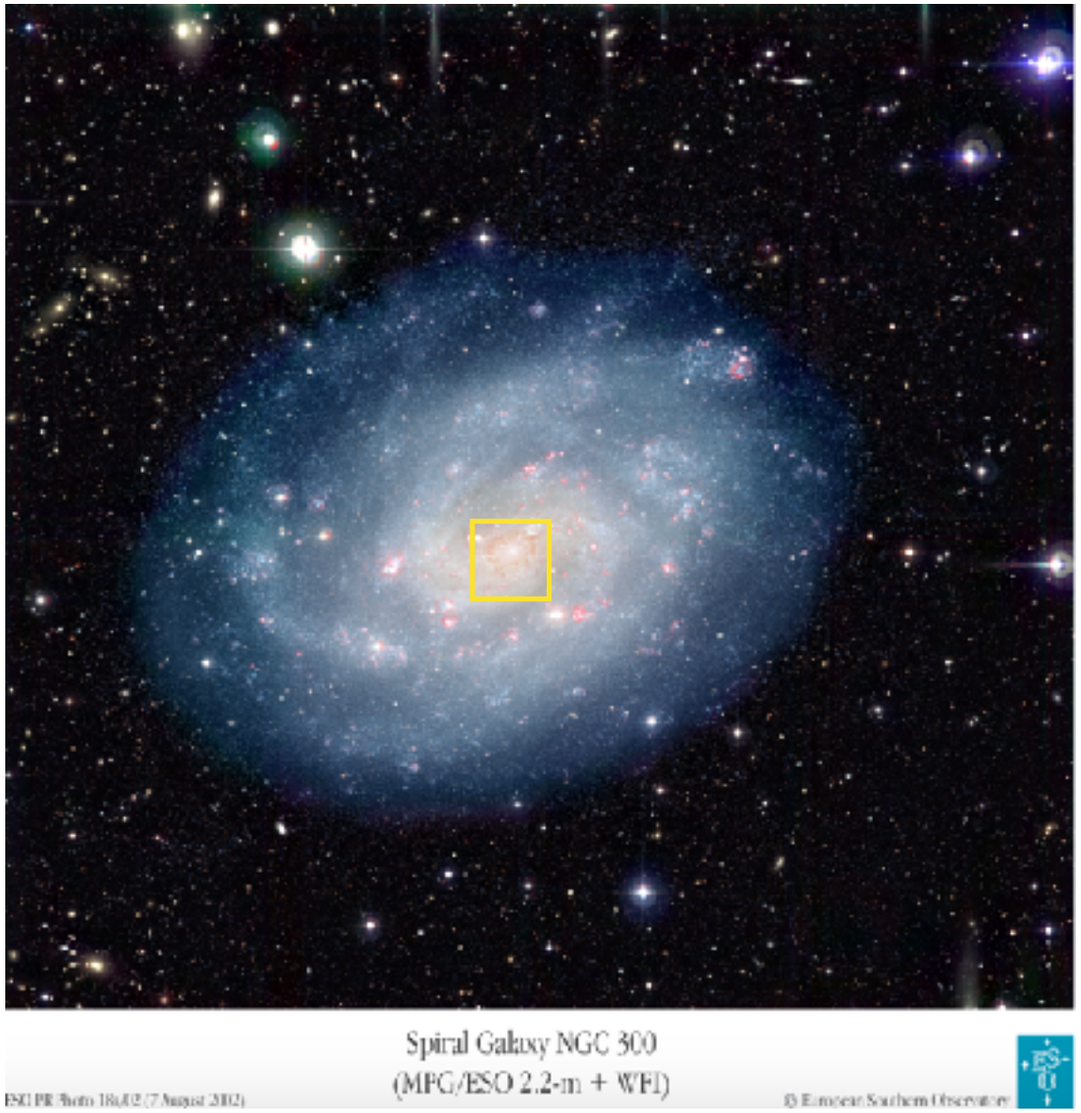



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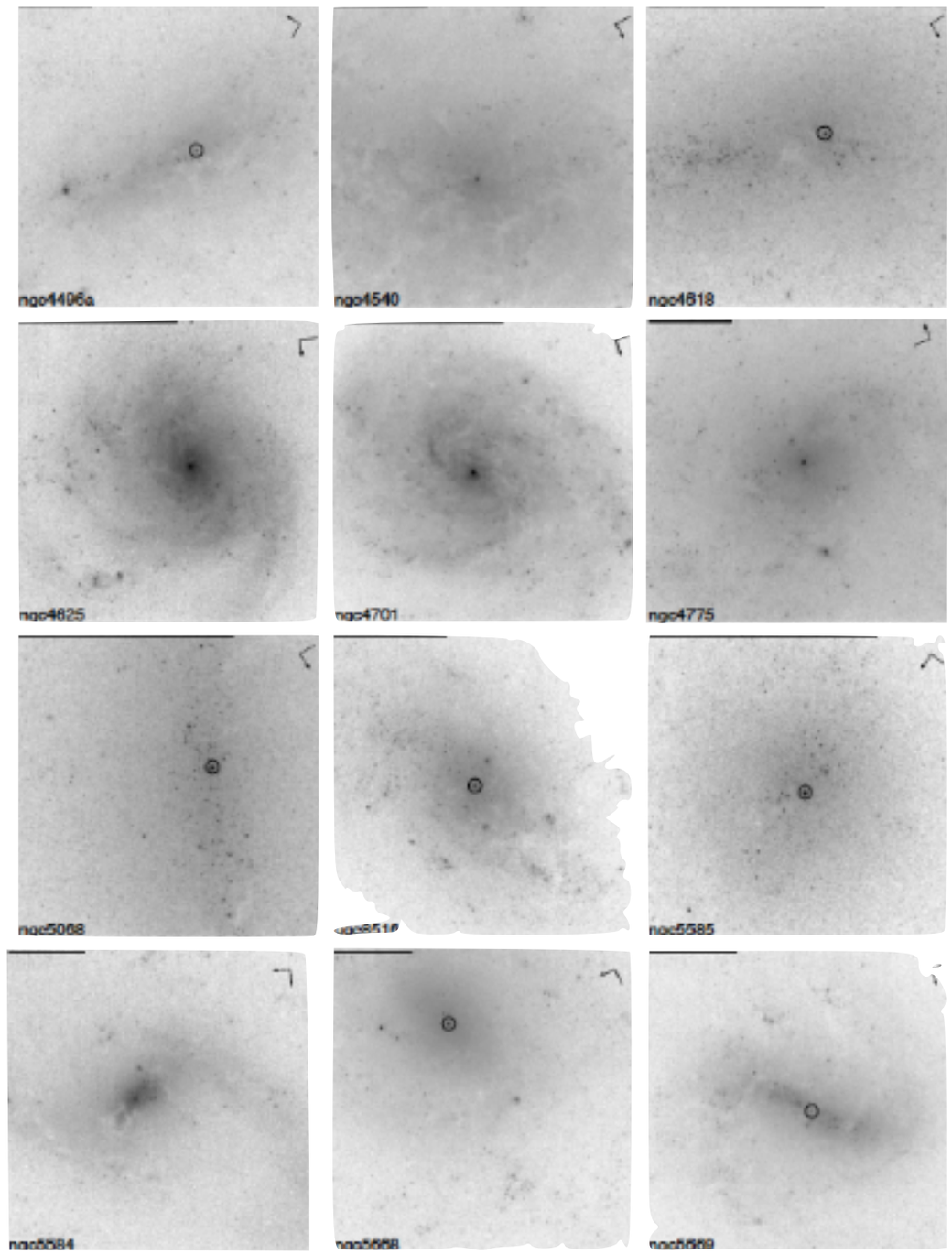
# Nuclear Star Clusters (NSCs) are observed at the centre of most galaxies




**Very common:**

>77% late types
>66% early types
} lower limits!

(Böker+ 2002, Côté+ 2006, Georgiev+ 2014)

Böker+ 2002, 2004; Carollo+ 2002; Coté+ 2006; Balcells+ 2007; Georgiev & Böker 2014; den Brok+ 2014

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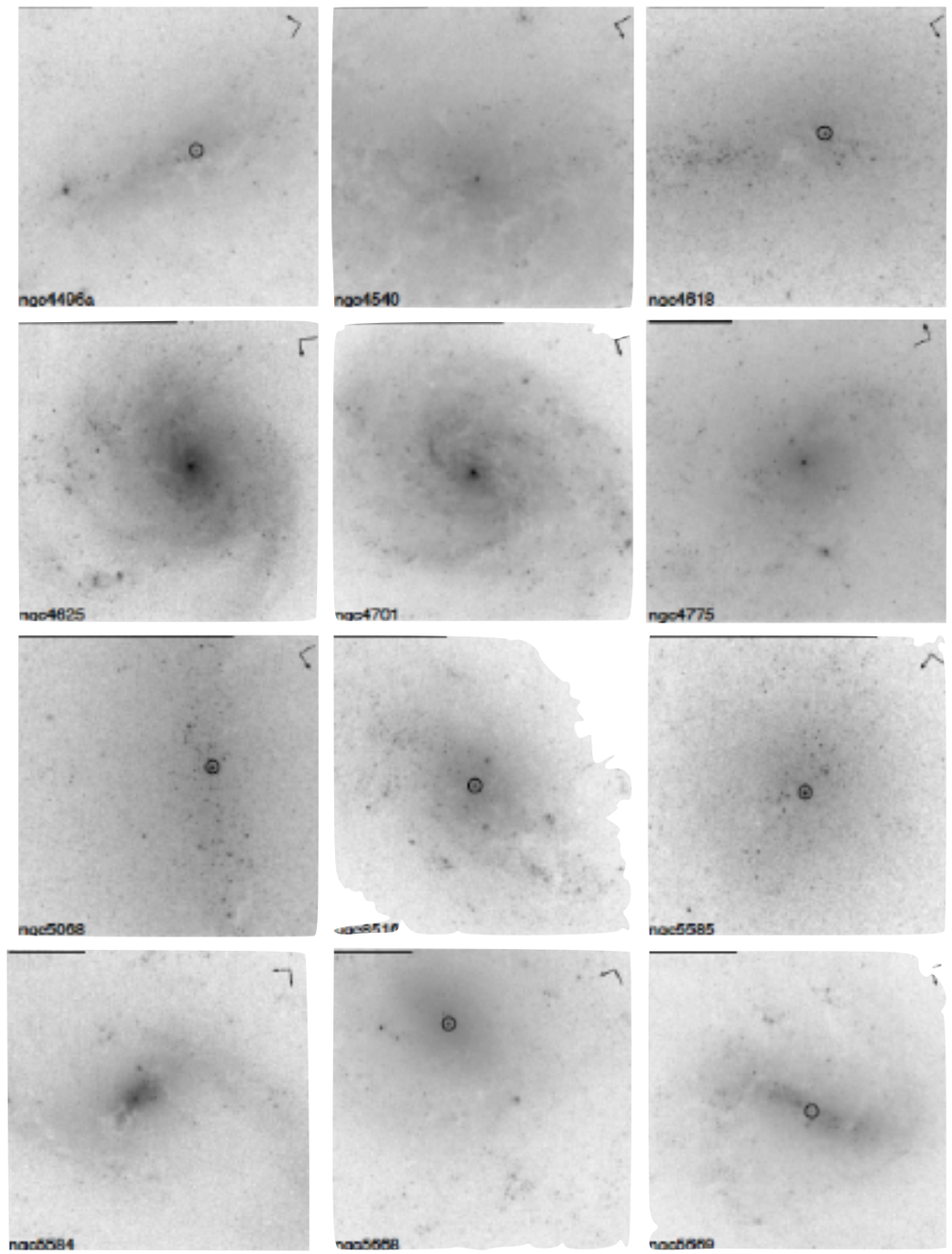


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**Very compact:**

$$R_{eff} \sim 2 - 5pc$$

**Very massive:**

$$M \sim 10^6 - 10^7 M_\odot$$

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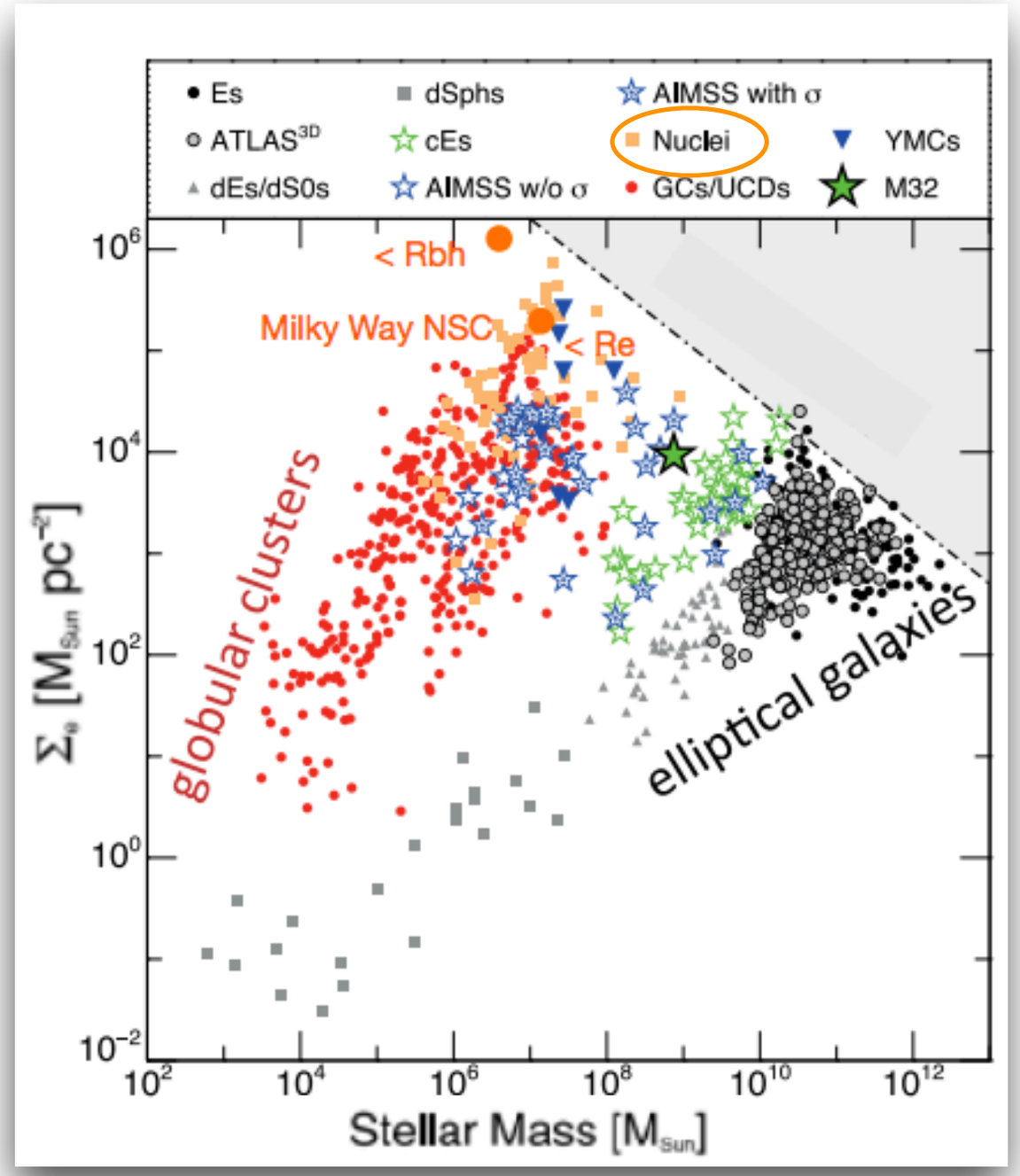
# … and they are the densest clusters in the Universe

Norris et al. 2014



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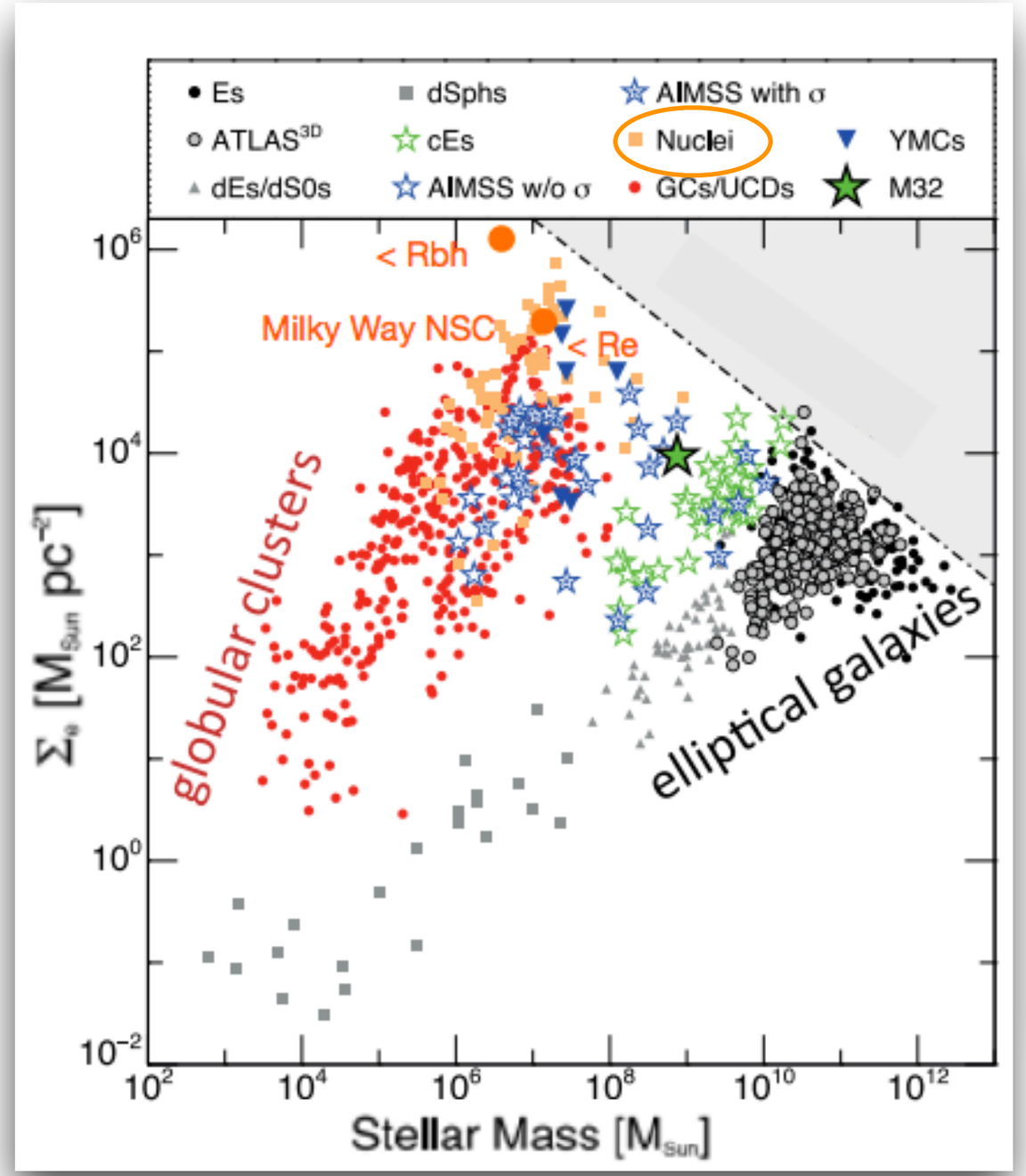
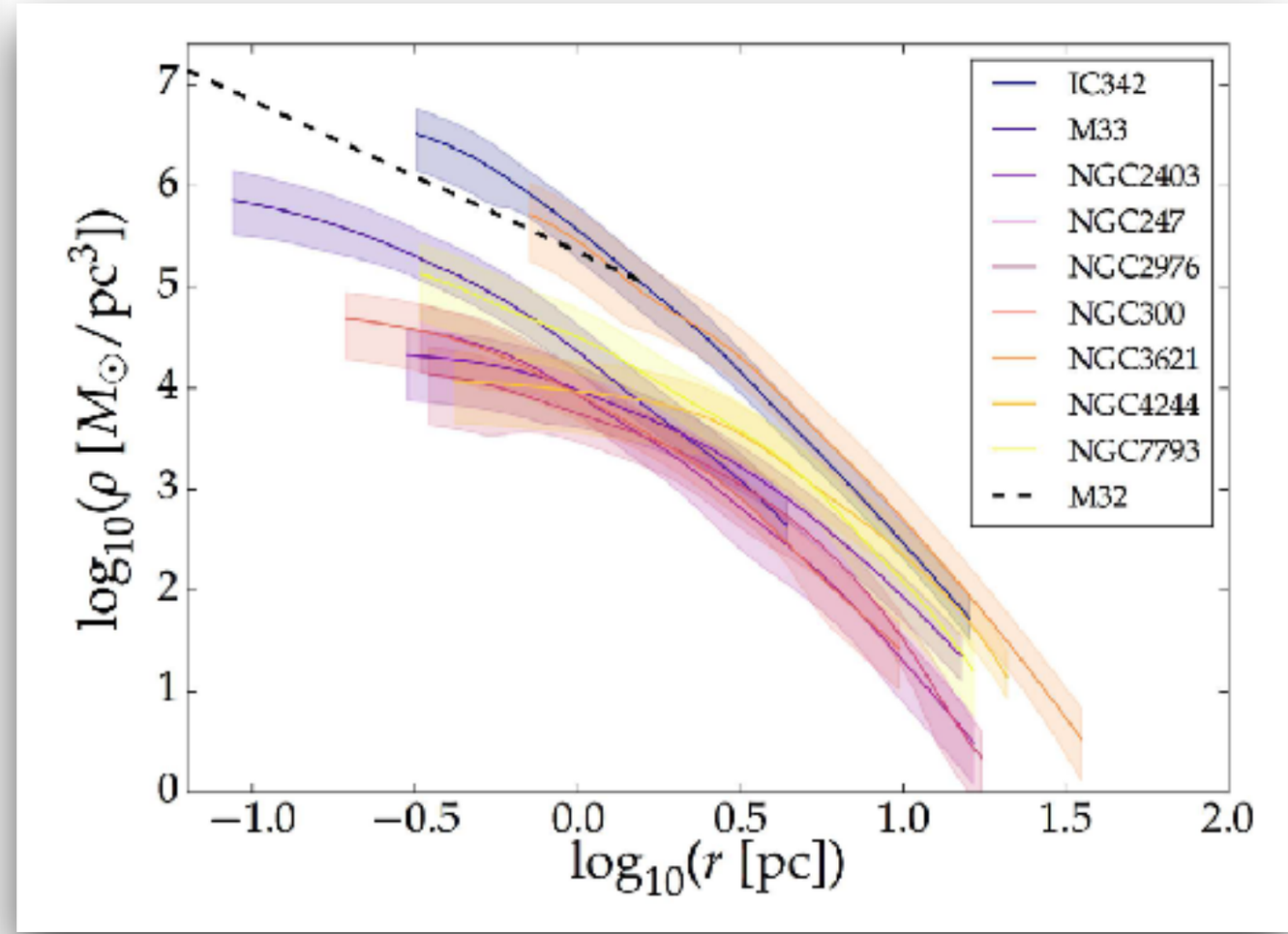
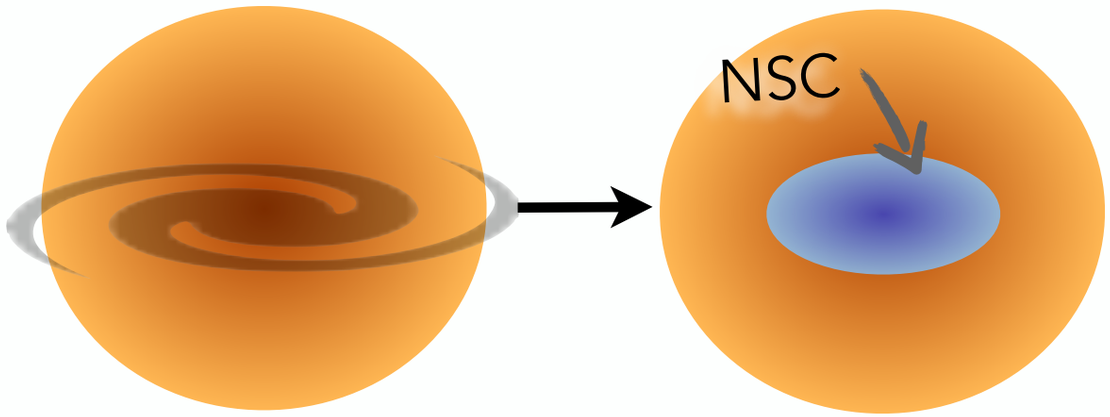



Carson et al. 2016

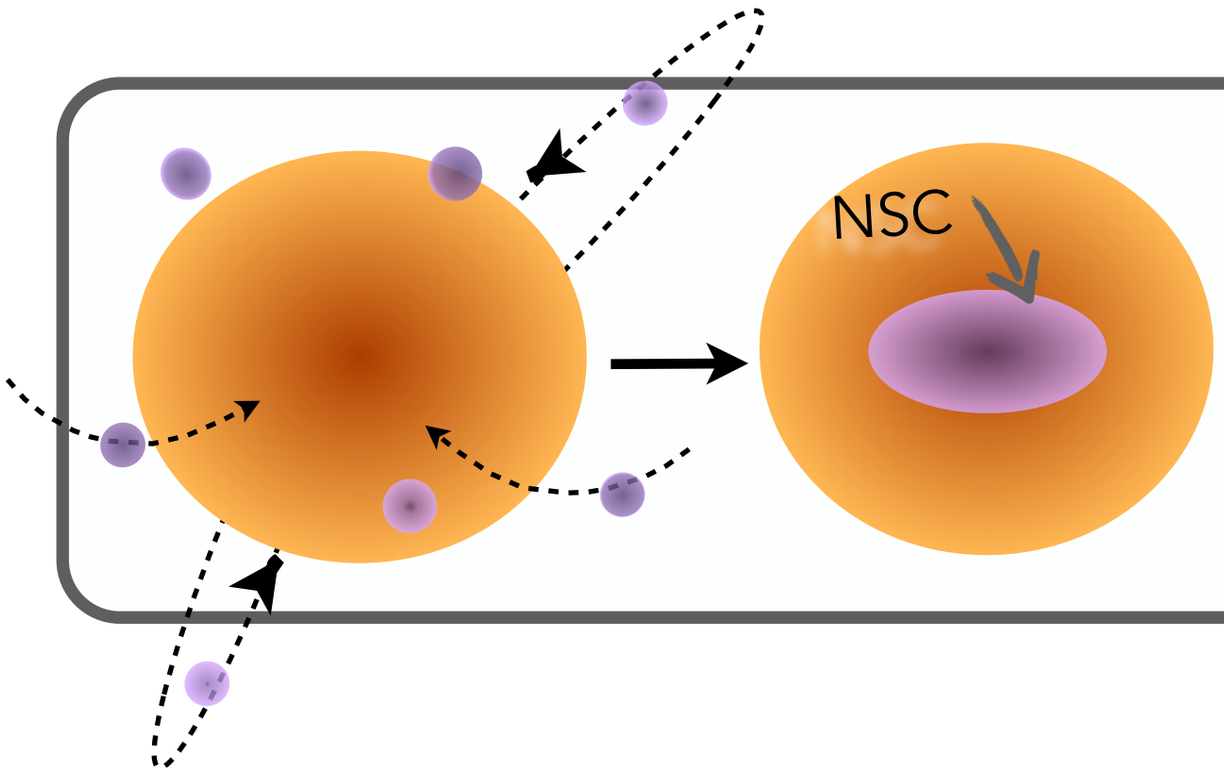


# NSCs form through cluster infall and/or in-situ star formation




**Gas accretion and in situ star formation**

(Loose+ 1982, Milosavljevic+ 2004, Pflamm-Altenburg+ 2009,...)




**Accretion & merger of star clusters**

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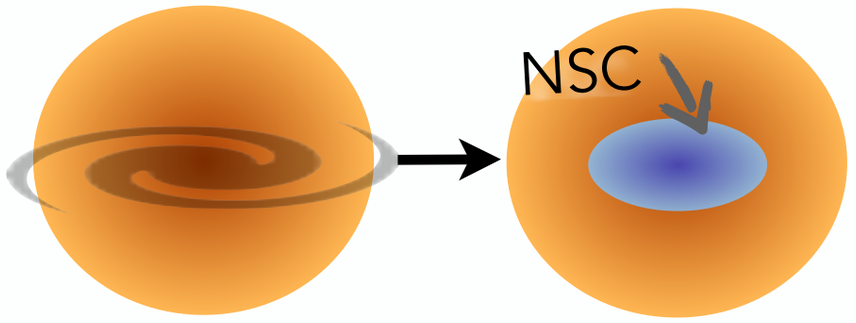


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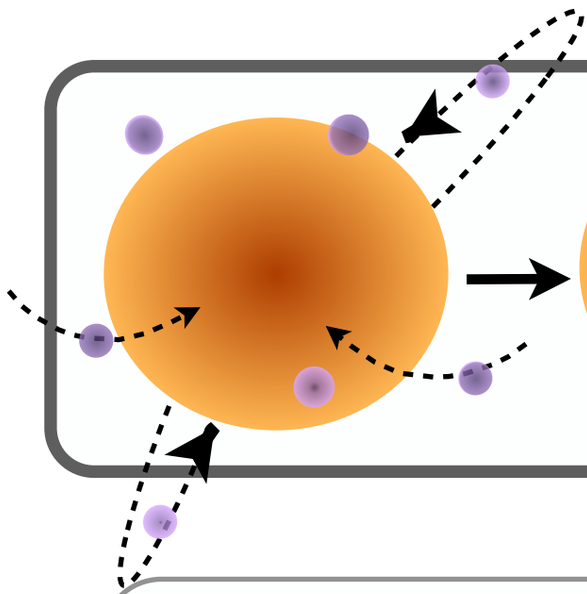


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Both mechanisms could work together

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Which is the **dominant** one?

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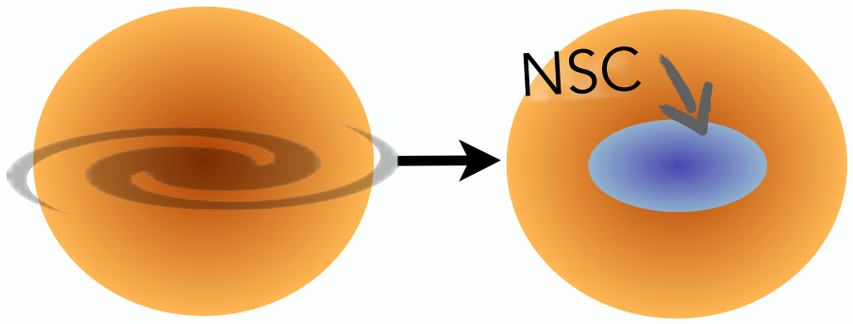


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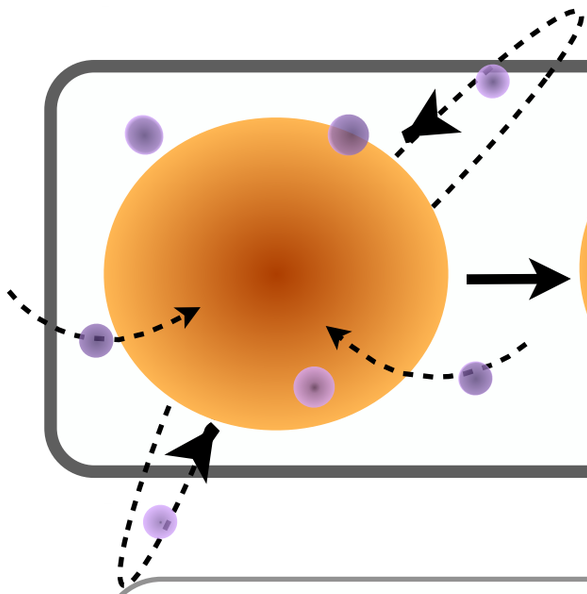
**Stellar populations:**

Range of metallicities

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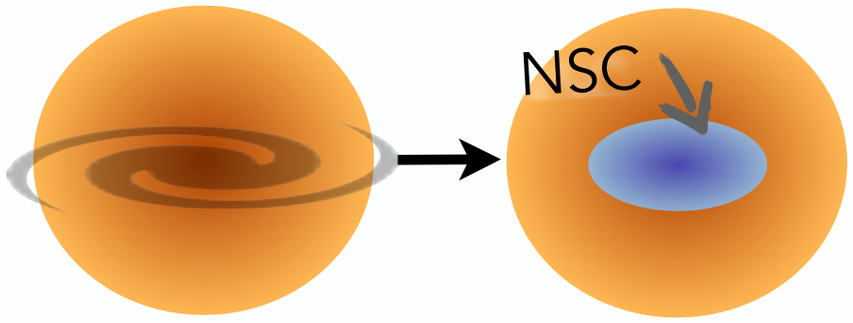


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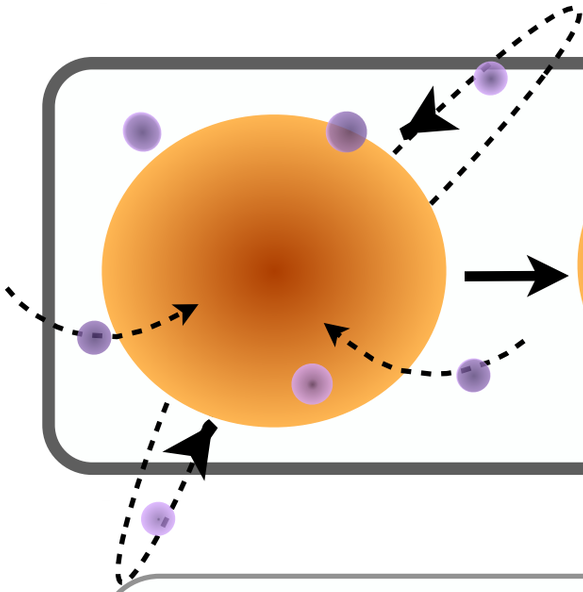


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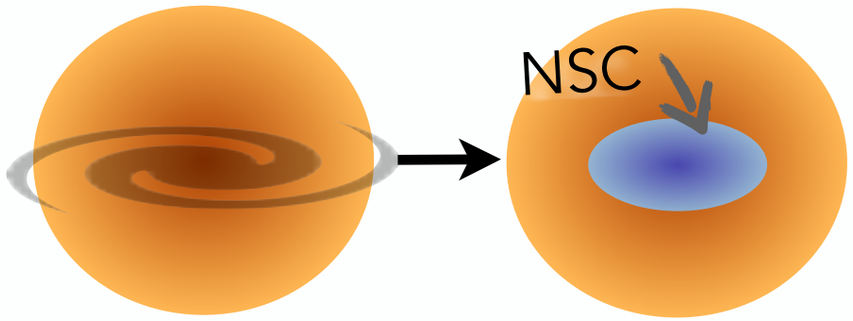


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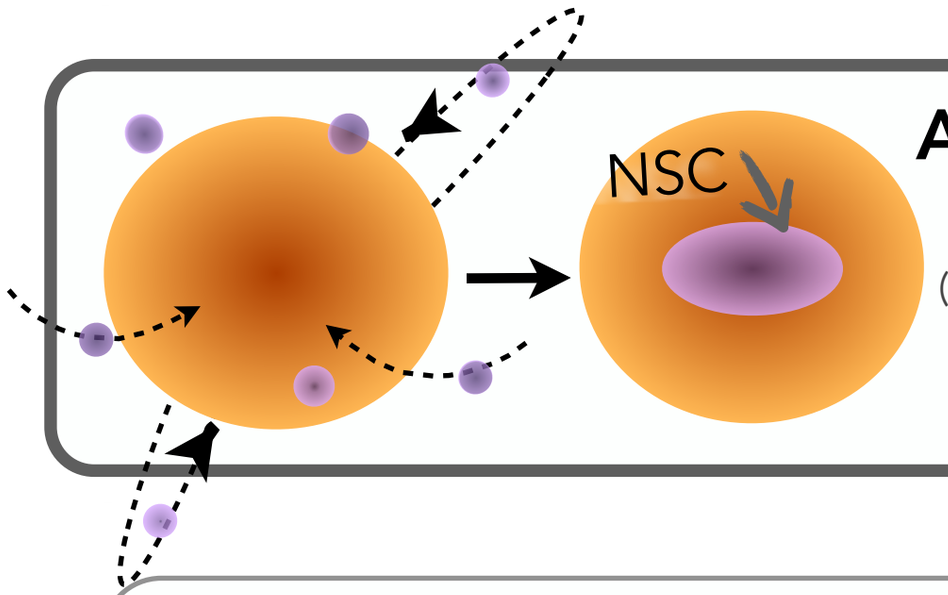


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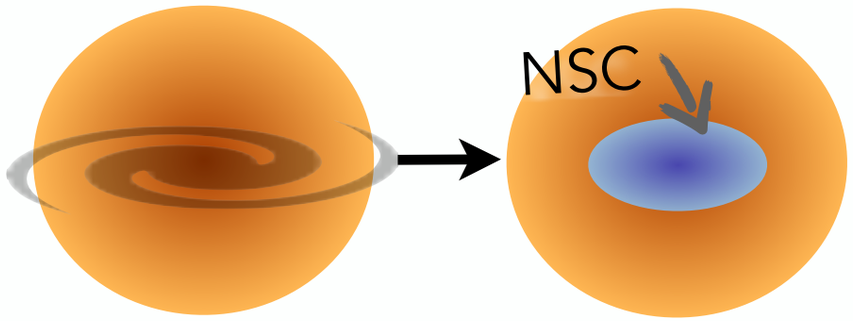


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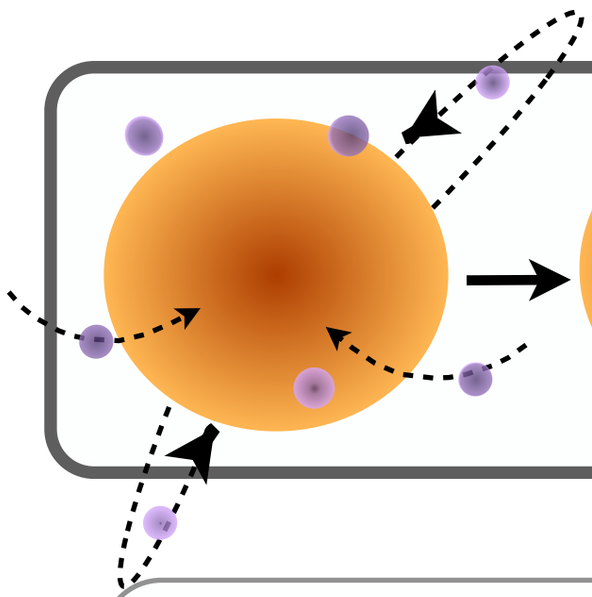


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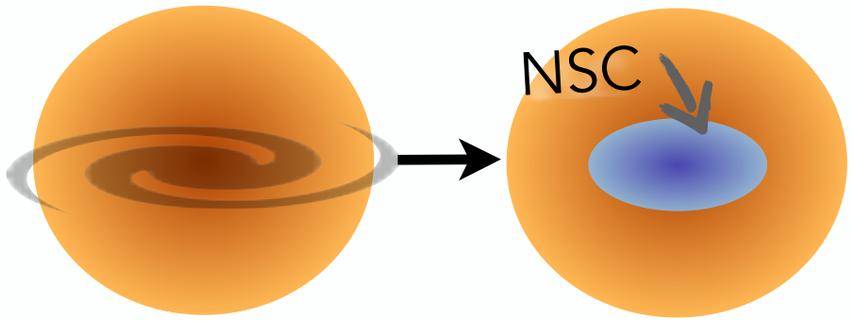


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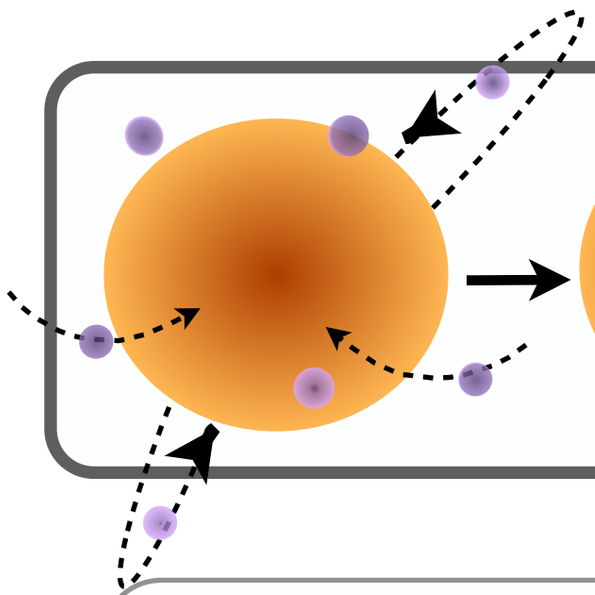


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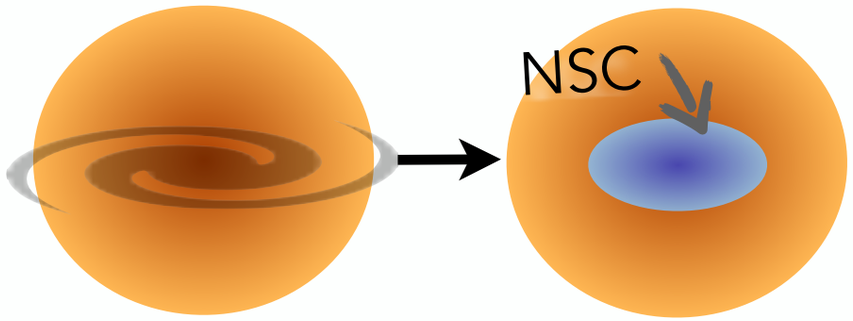


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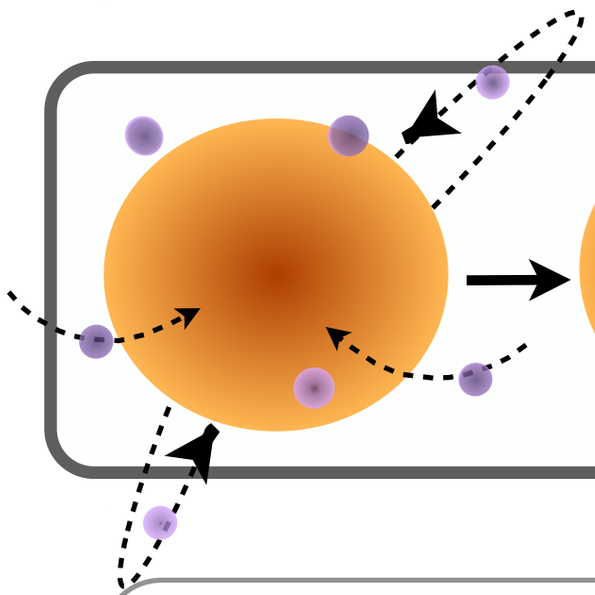


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# The Milky Way has a NSC hosting a central Massive Black Hole

Alessandra Mastrobuono-Battisti MPIA, Heidelberg

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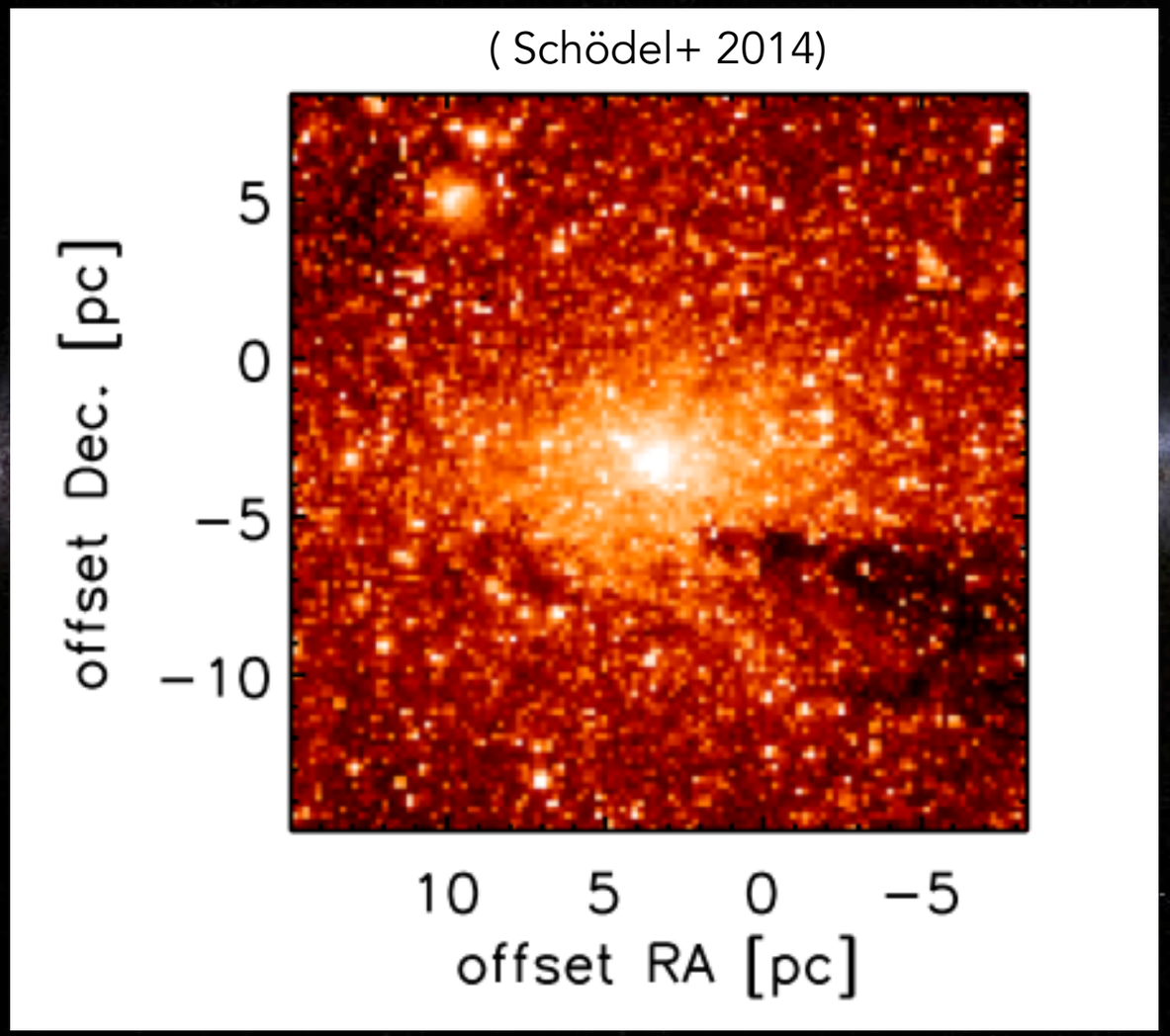

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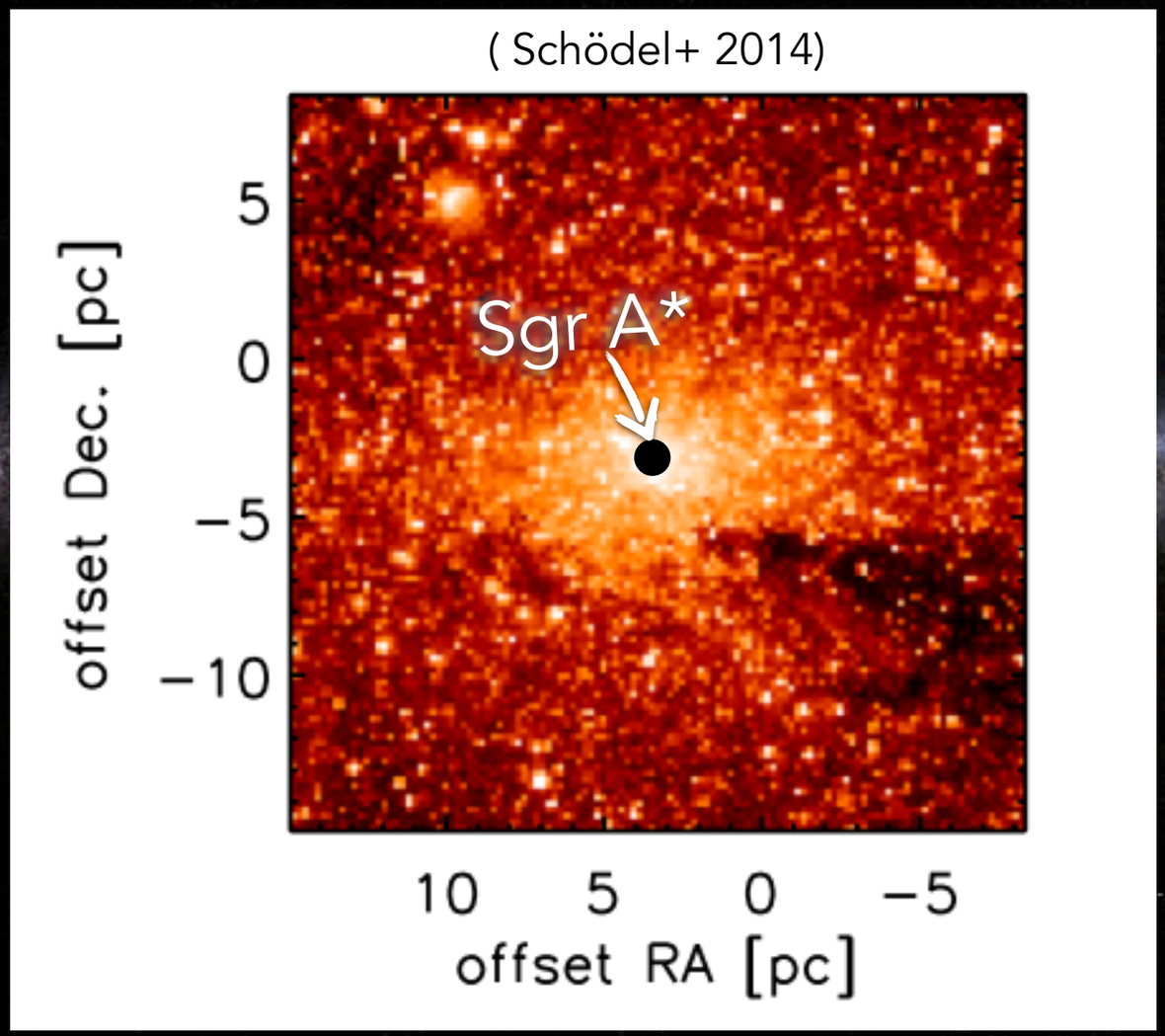

# We modelled NSC formation from cluster infalls using *N*-body simulations

Credit: Sassa Tsatsi

Antonini, Capuzzo-Dolcetta, **Mastrobuono-Battisti** & Merritt, 2012 ApJ; Perets & **Mastrobuono-Battisti**, 2014, ApJ; **Mastrobuono-Battisti**, Perets & Loeb, 2014, ApJ; Tsatsi, **Mastrobuono-Battisti** et al., 2017, MNRAS. See also Hartmann et al., 2011.

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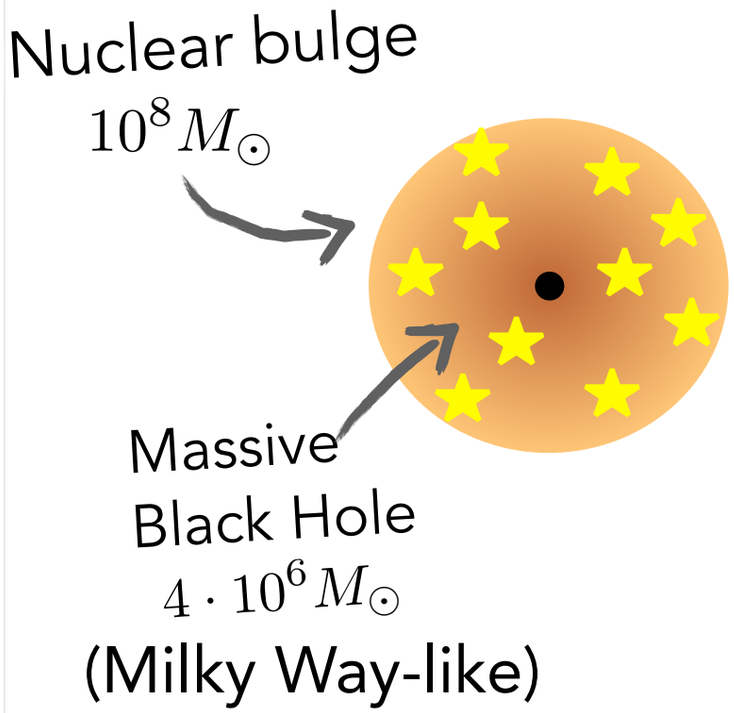


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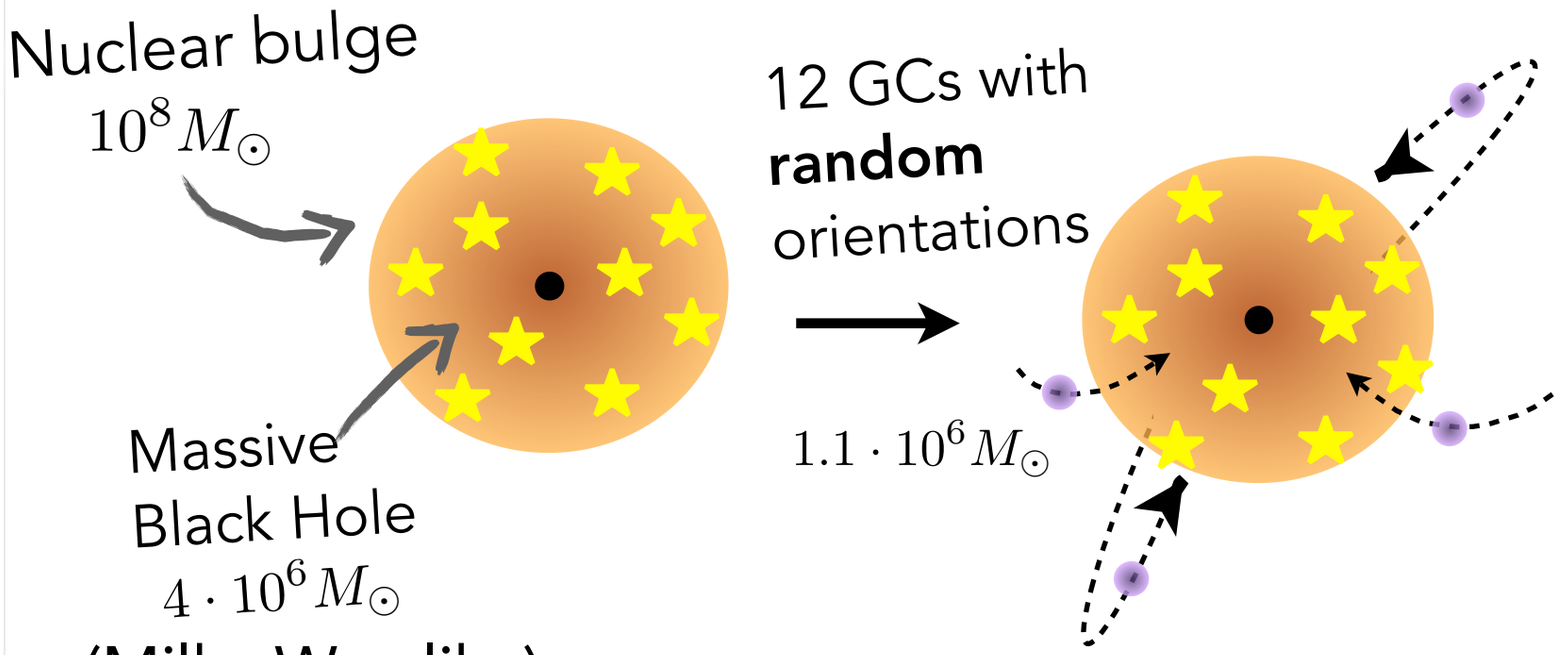
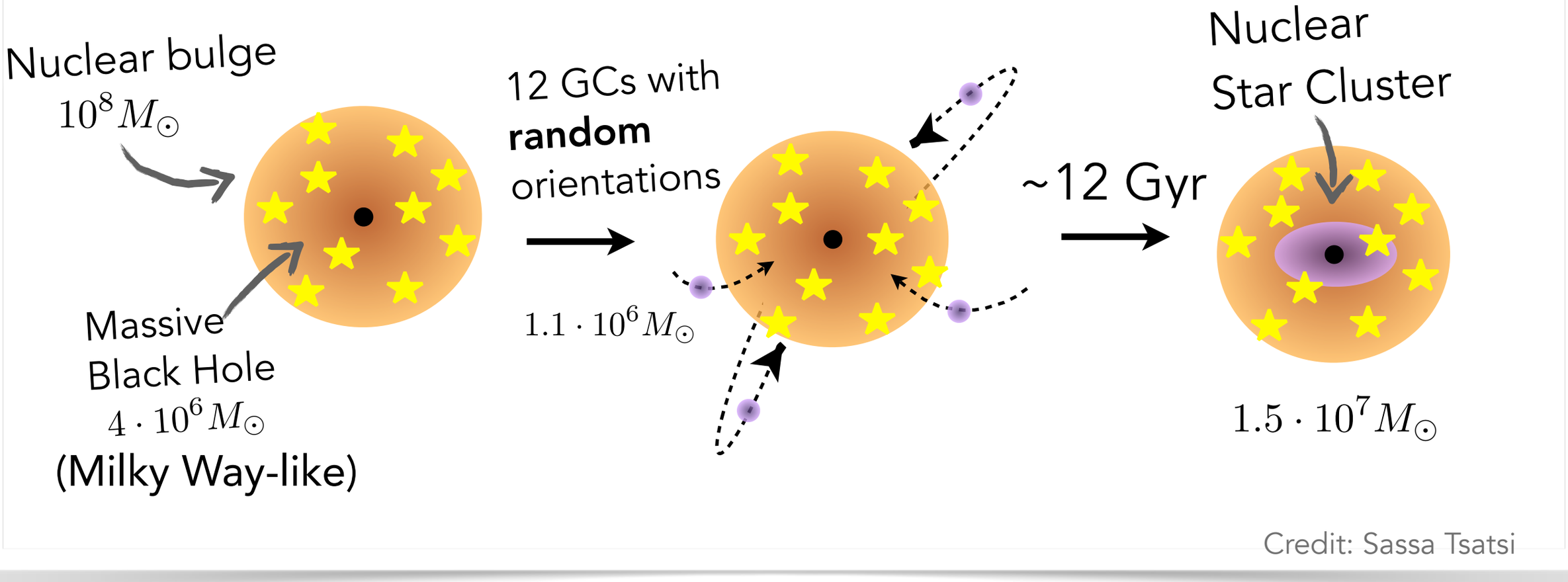



Credit: Sassa Tsatsi

Antonini, Capuzzo-Dolcetta, **Mastrobuono-Battisti** & Merritt, 2012 ApJ; Perets & **Mastrobuono-Battisti**, 2014, ApJ; **Mastrobuono-Battisti**, Perets & Loeb, 2014, ApJ; Tsatsi, **Mastrobuono-Battisti** et al., 2017, MNRAS. See also Hartmann et al., 2011.

# We modelled NSC formation from cluster infalls using *N*-body simulations

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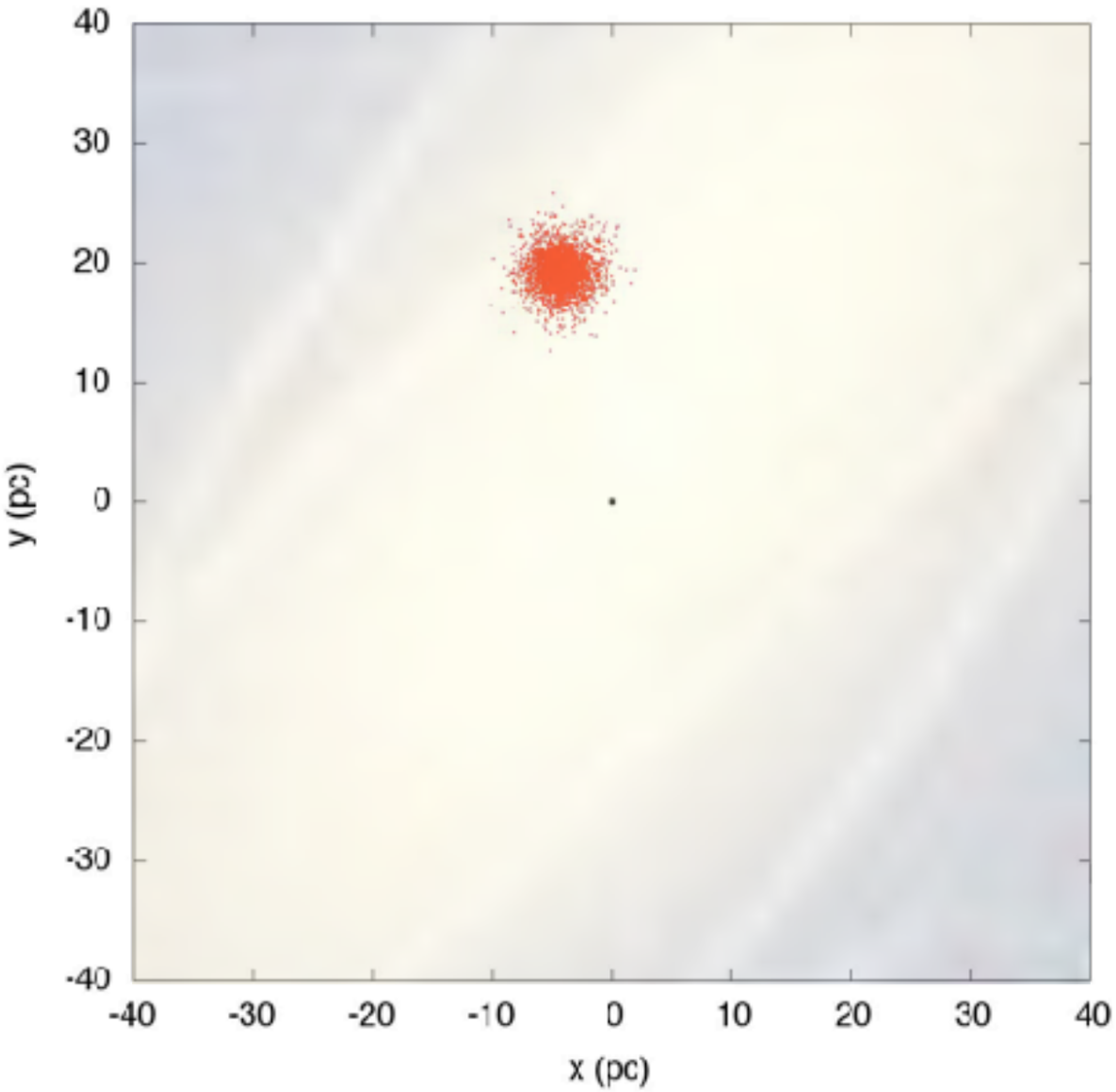


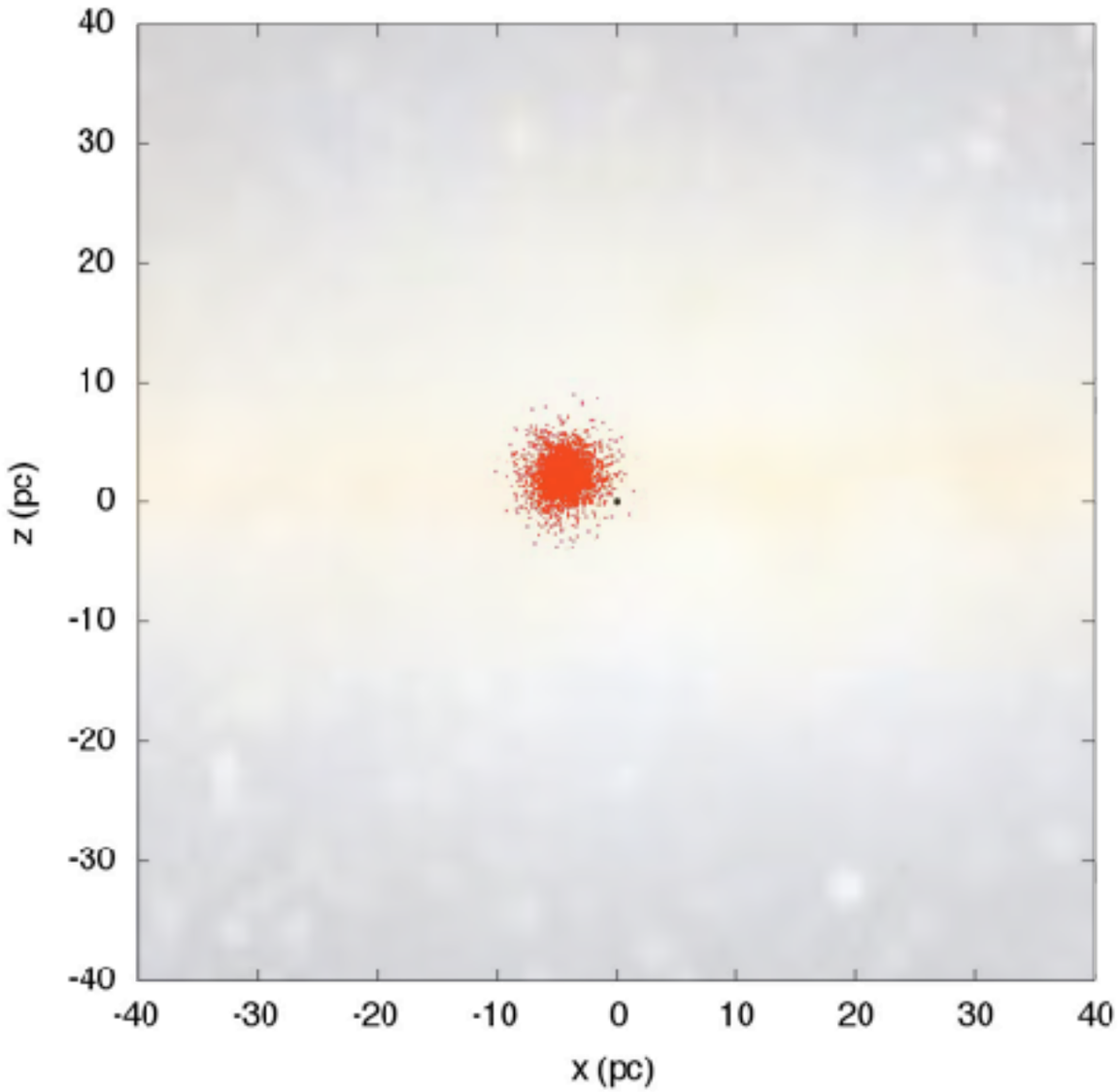

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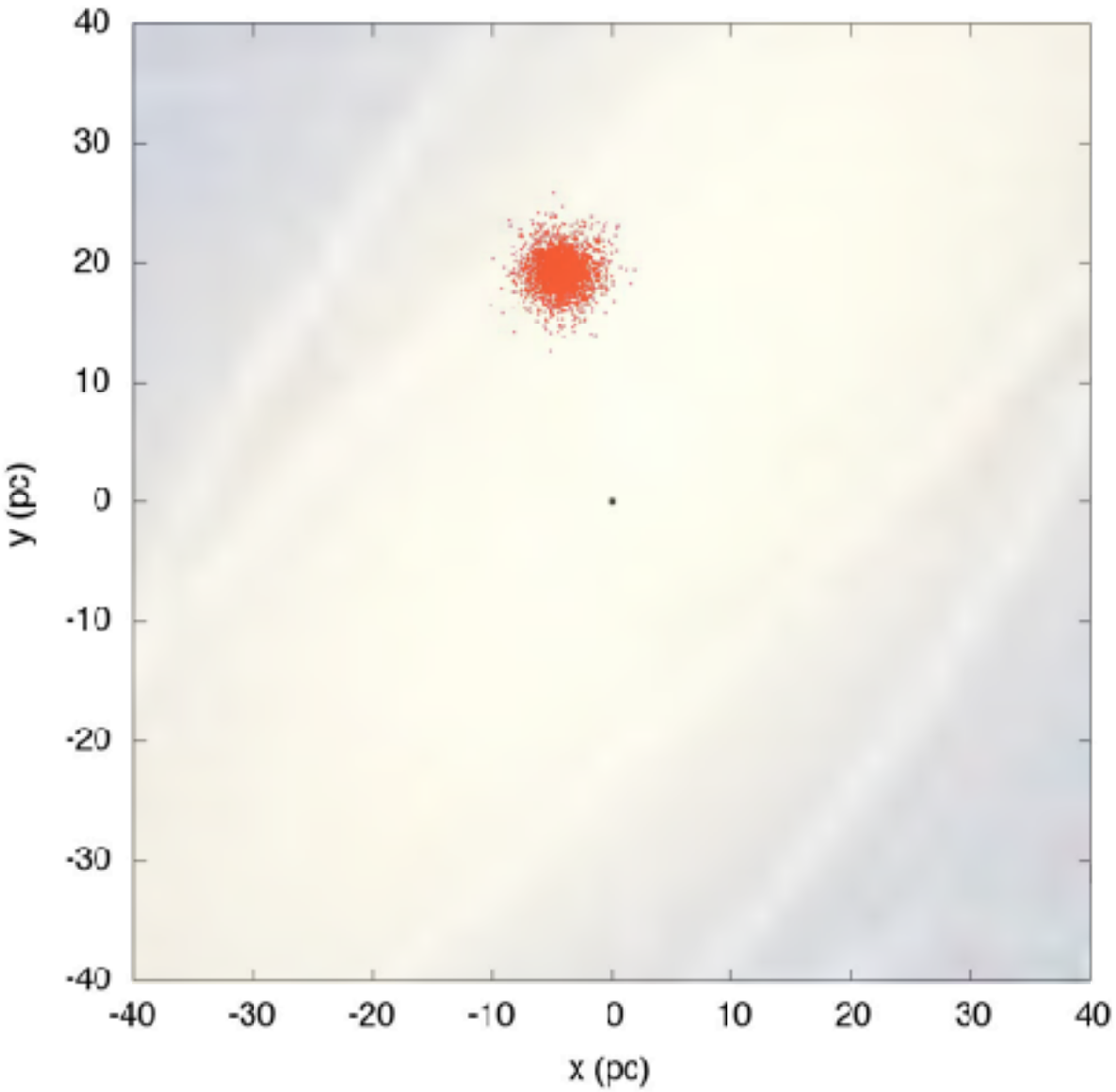
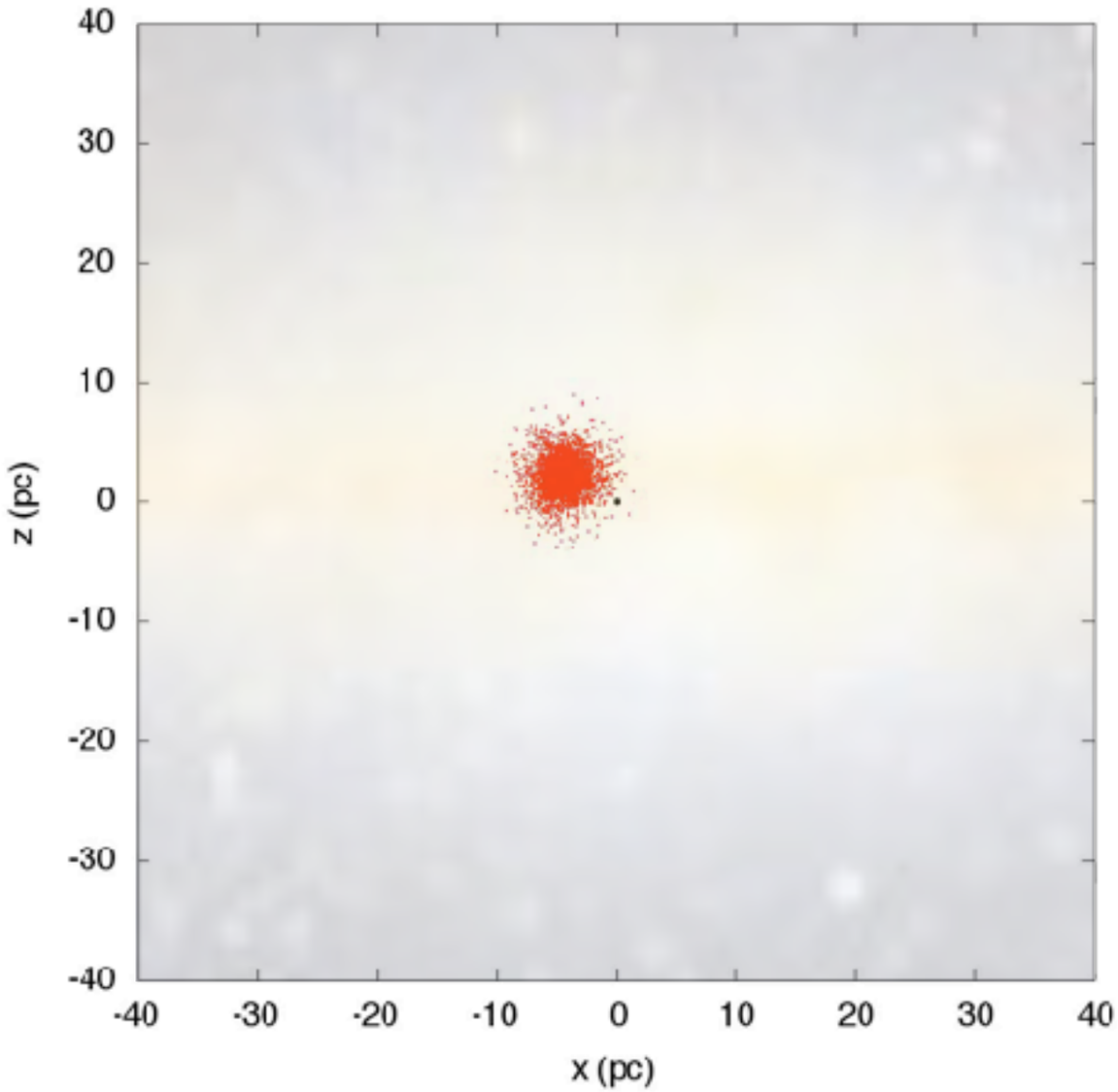
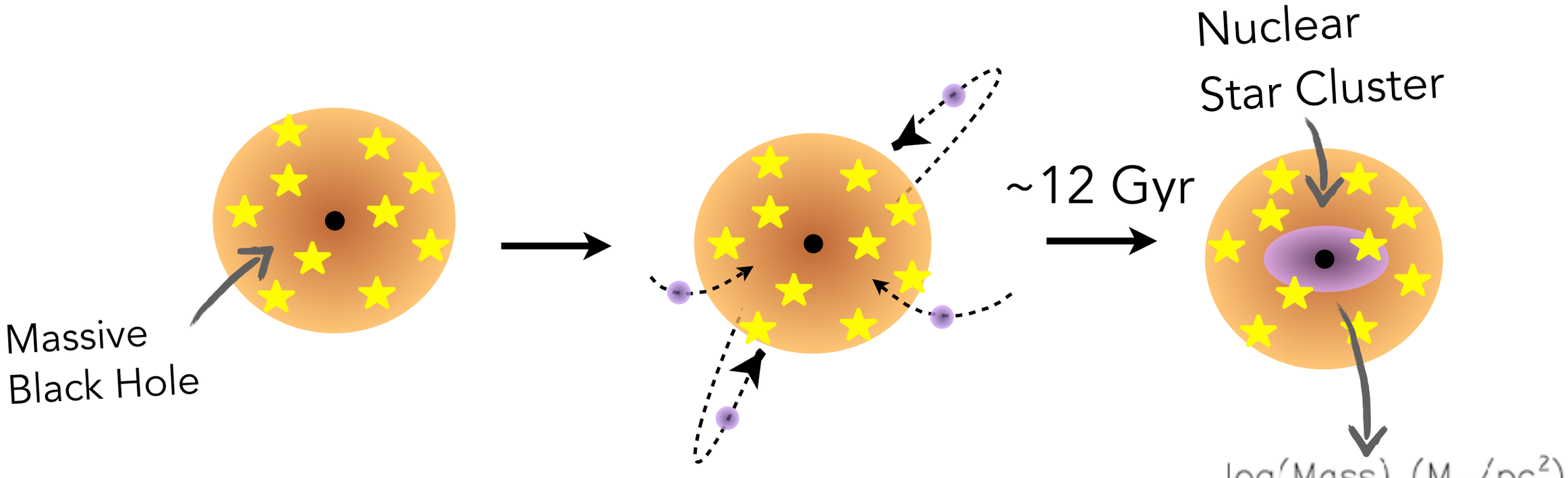


# The simulated NSC is very similar to the MW one




similar to MW NSC mass $\sim 2 \cdot 10^7 M_\odot$ (Schödel+ 2014)

similar BH mass $\sim 4 \cdot 10^6 M_\odot$ (Ghez+ 2008)

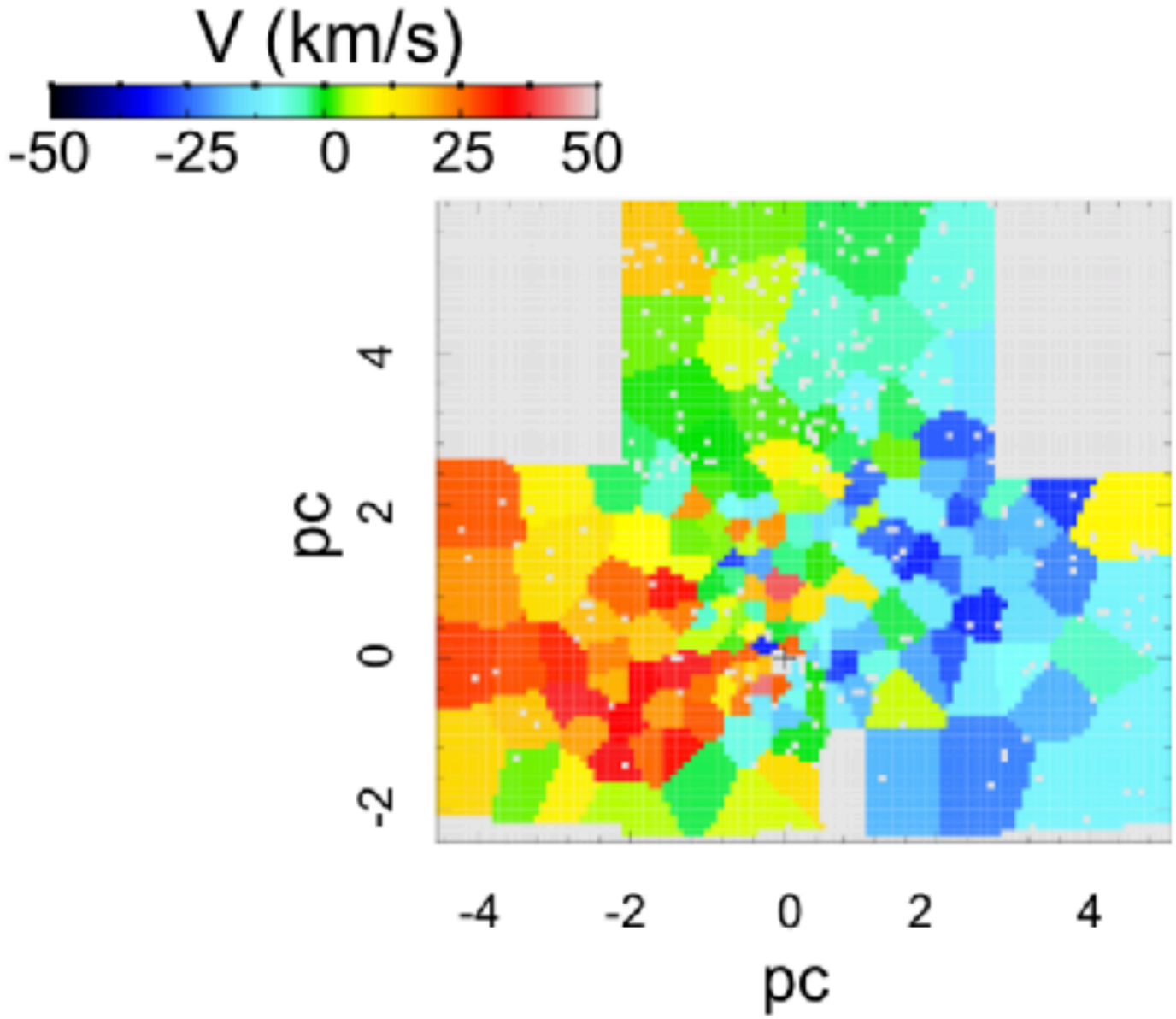
similar flattening q~0.7 (Schödel+ 2014)

similar density profile (Schödel+ 2014)

similar tangential anisotropy β~ -0.1 (Meritt+ 2010)

**Antonini et al. 2012; Tsatsi, Mastrobuono-Battisti et al., 2017**

# The simulated NSC is rotating as much as the observed one

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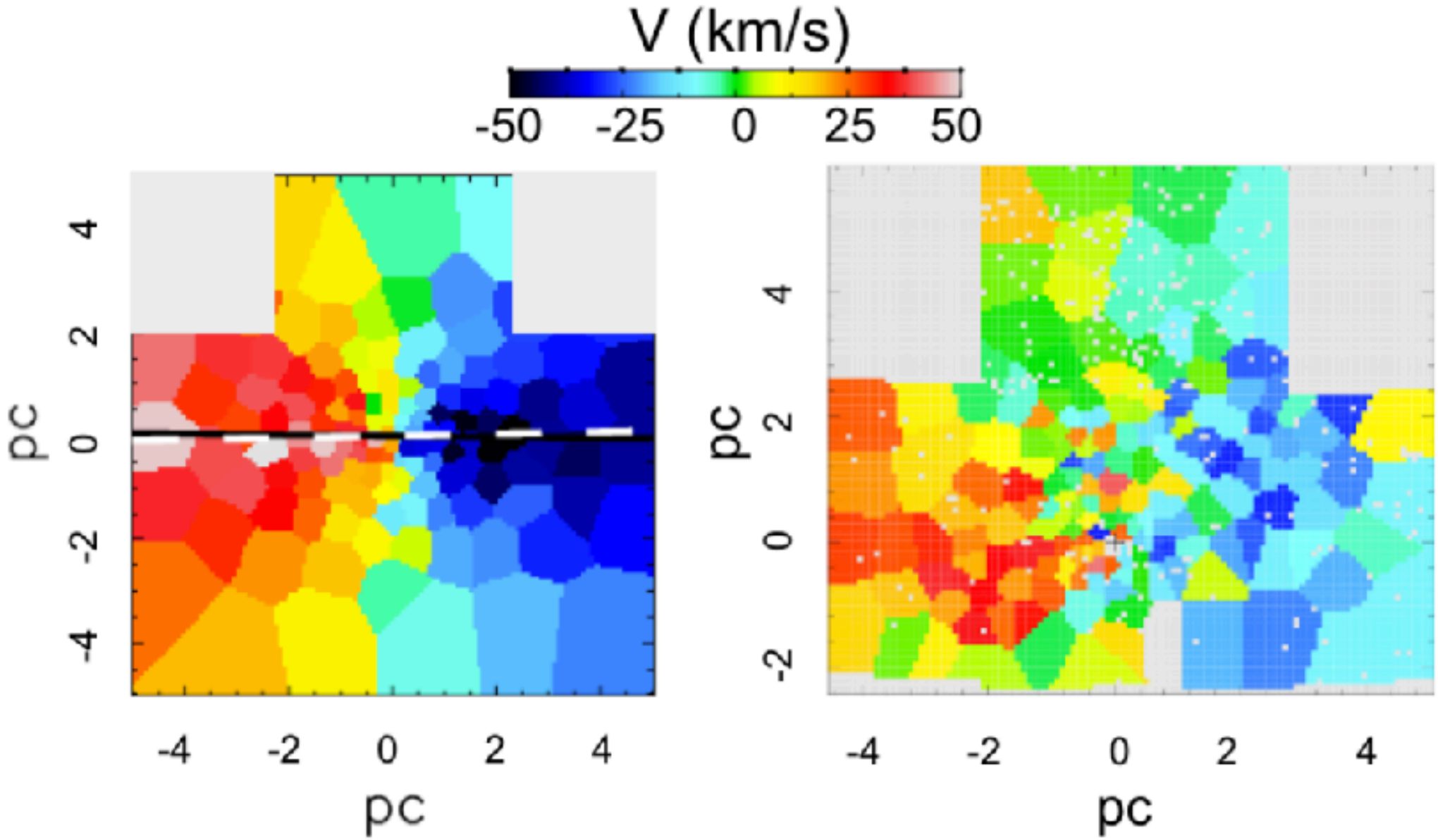
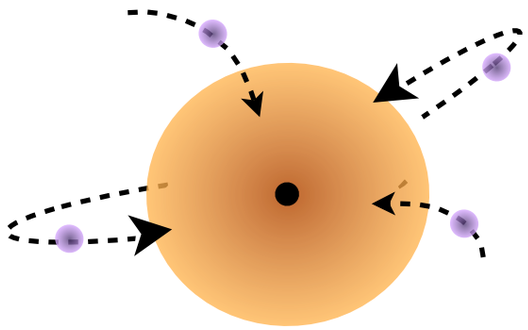
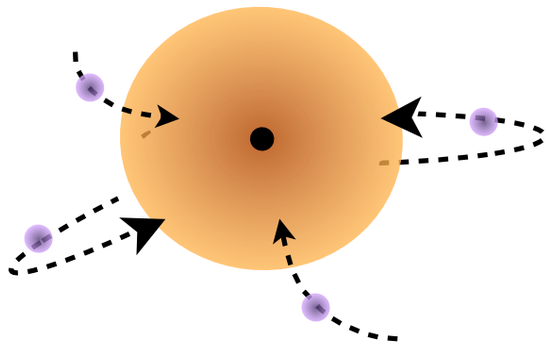



Tsatsi, Mastrobuono-Battisti et al., 2017; Feldmeier et al. 2014

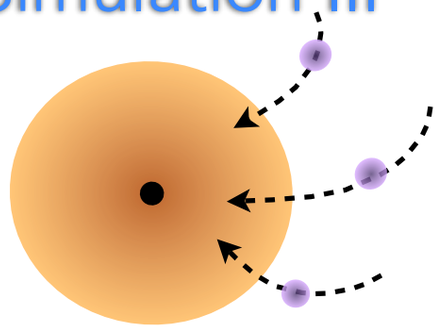
Simulation I



Simulation II



Simulation III



Tsatsi, Mastrobuono-Battisti et al., 2017

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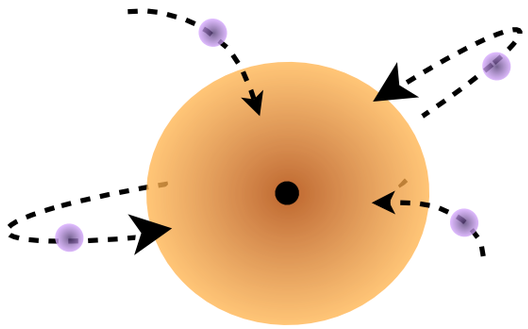

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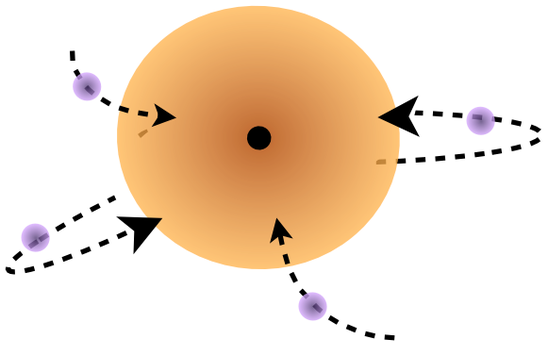

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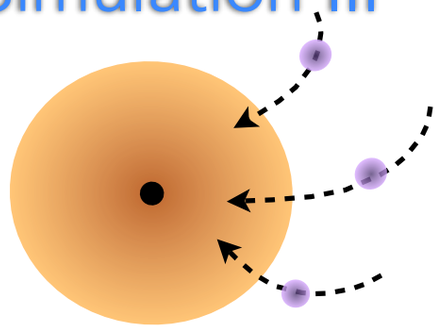

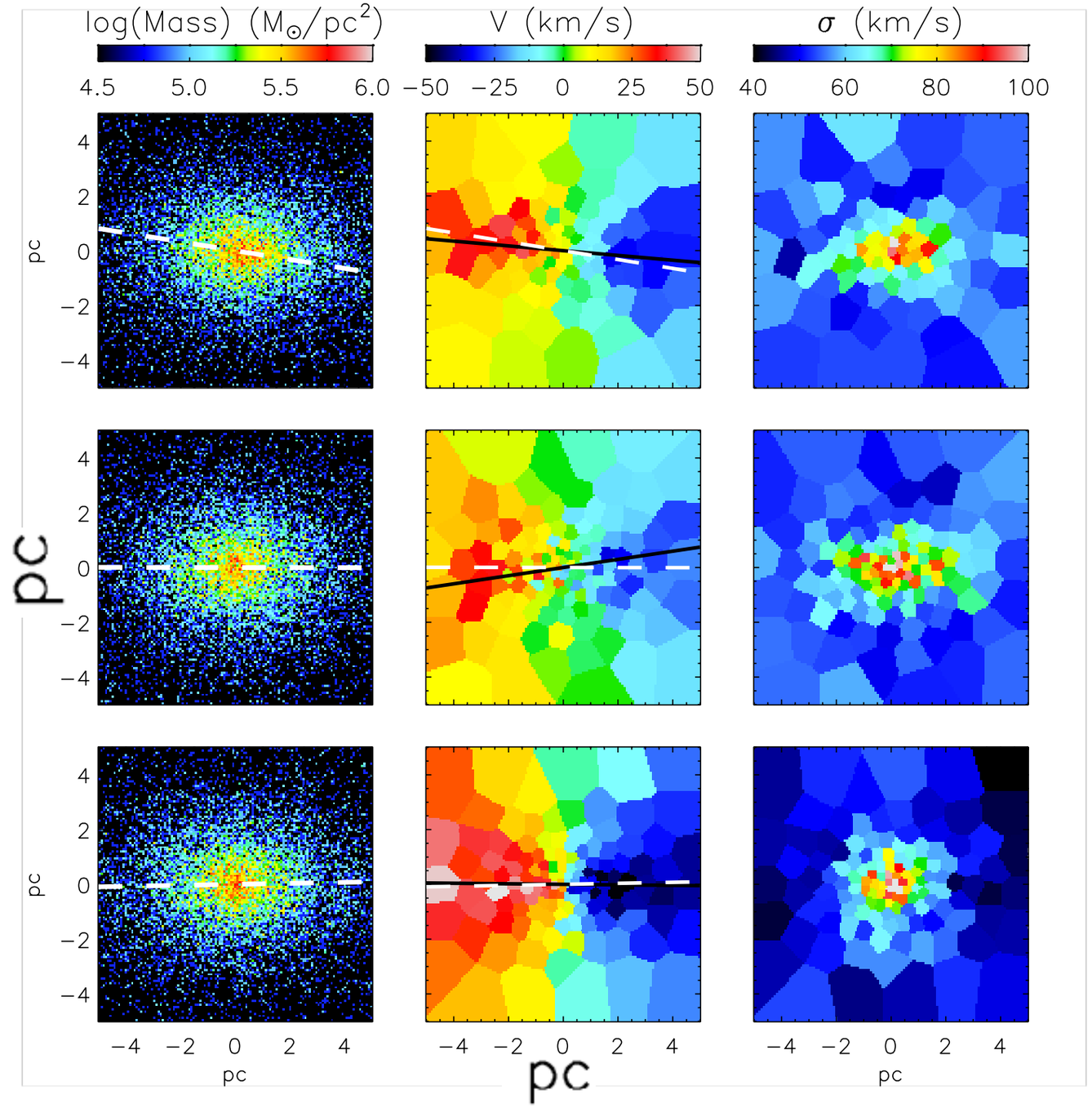


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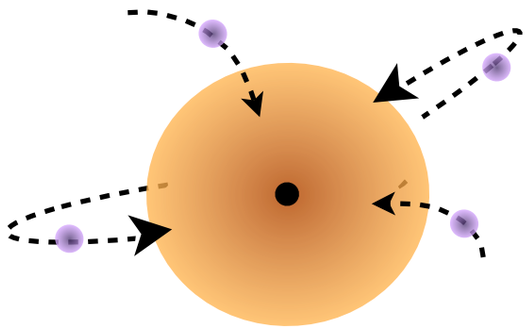

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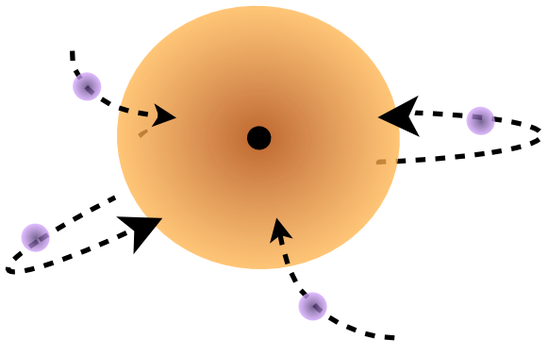

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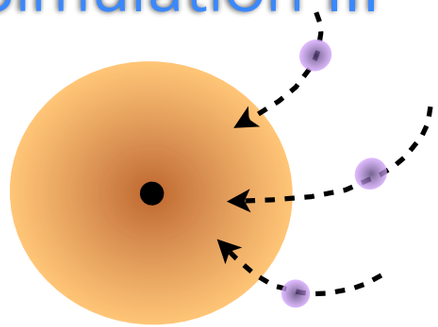

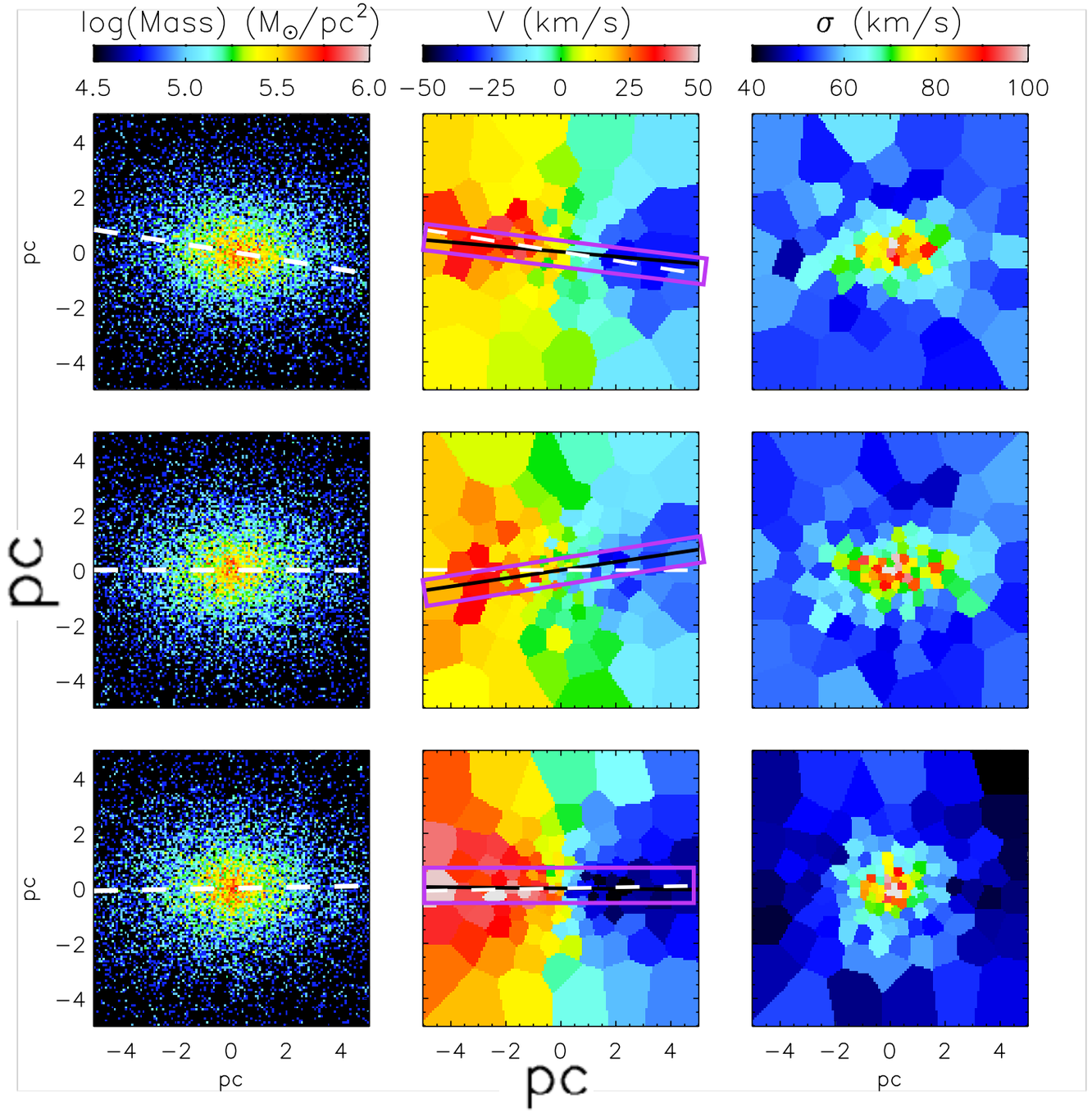


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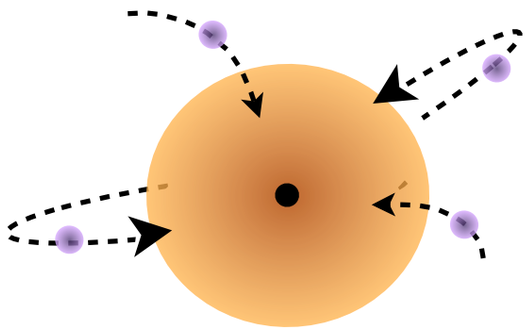

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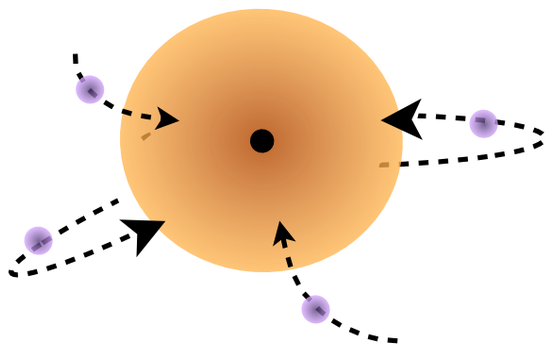

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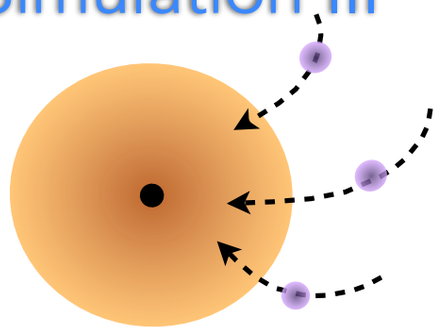

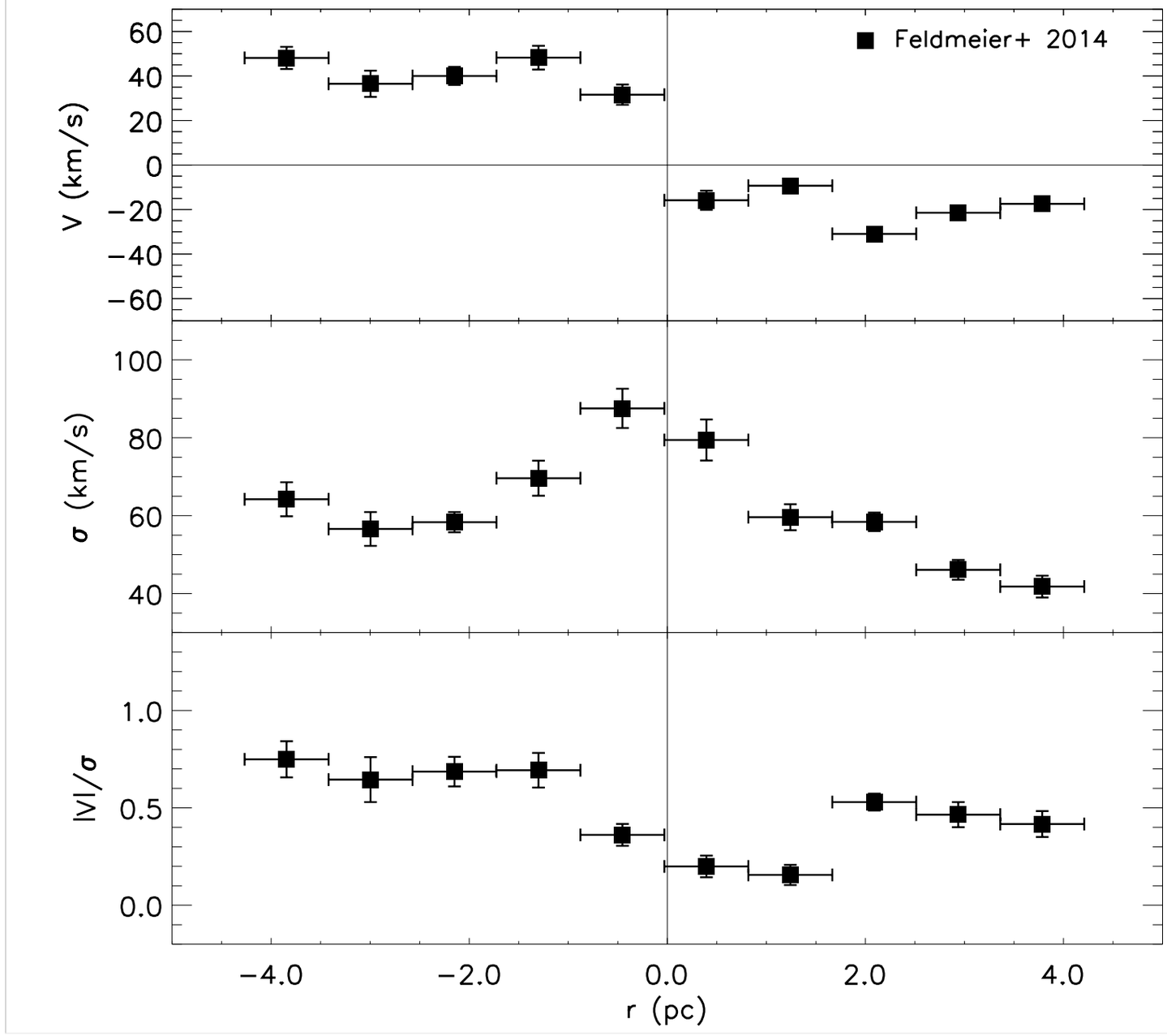


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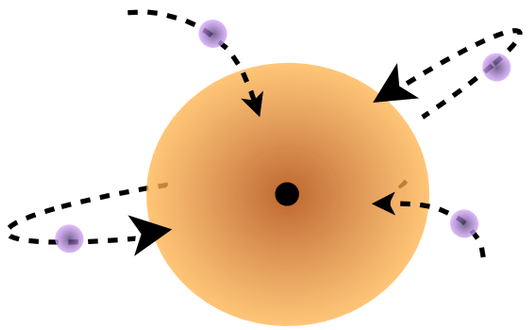

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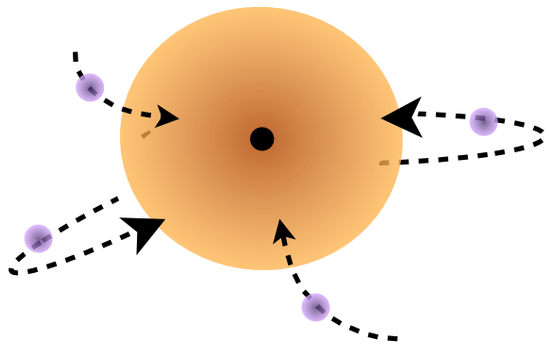

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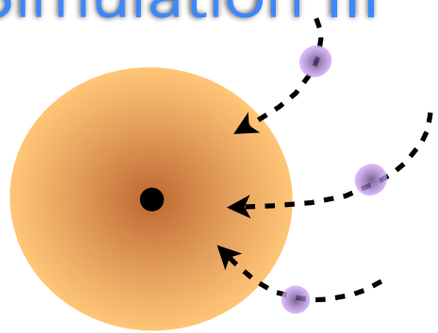

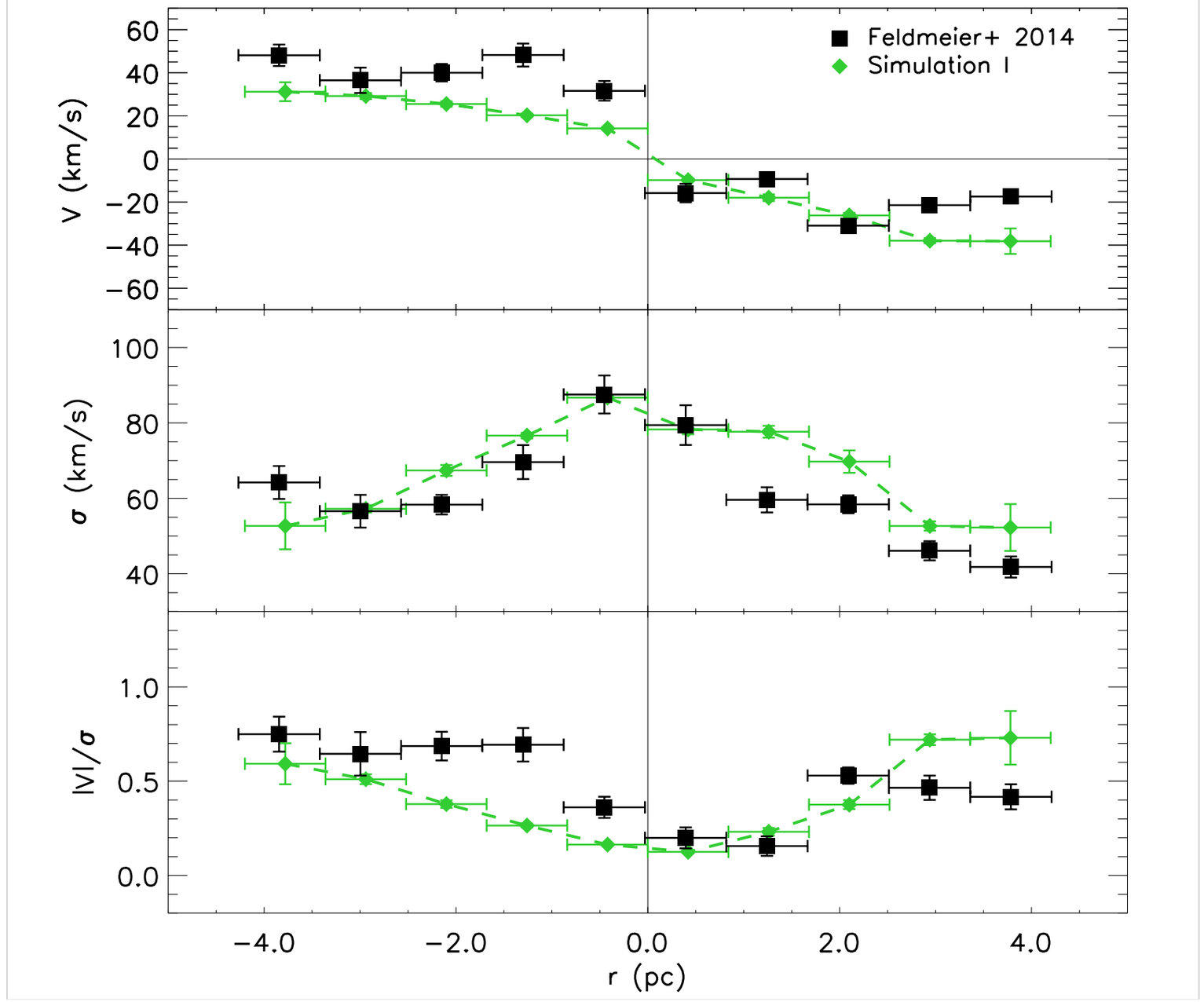


Tsatsi, Mastrobuono-Battisti et al., 2017

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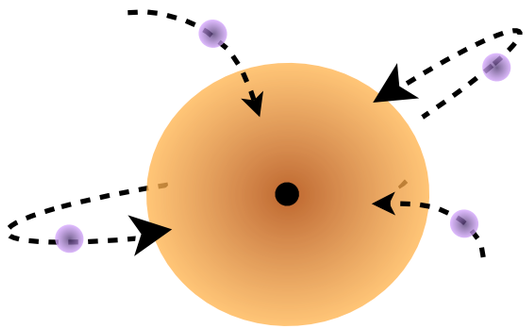

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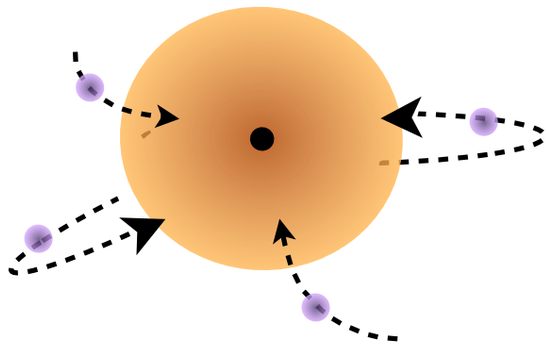

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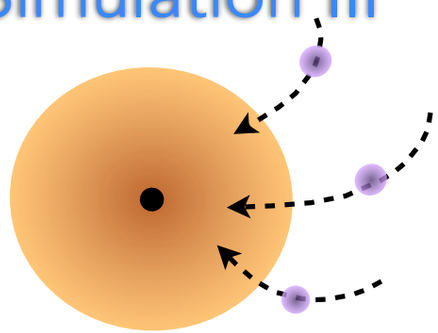

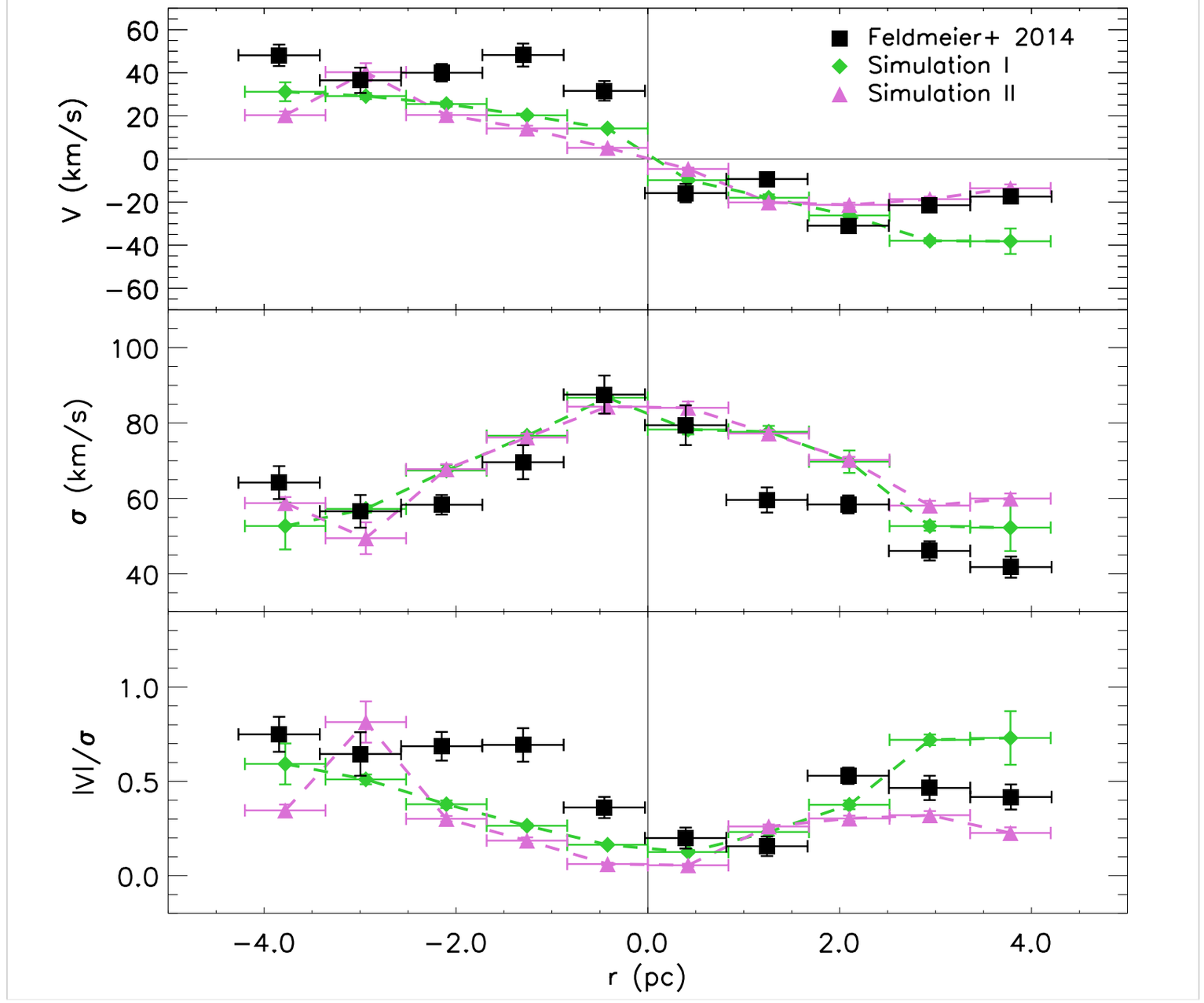


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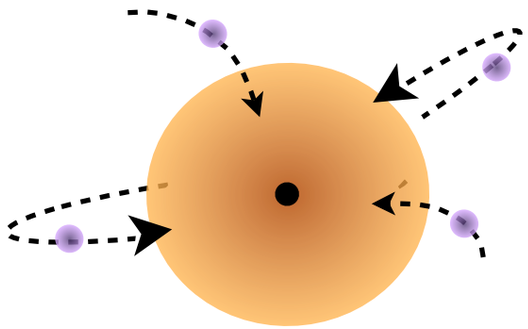

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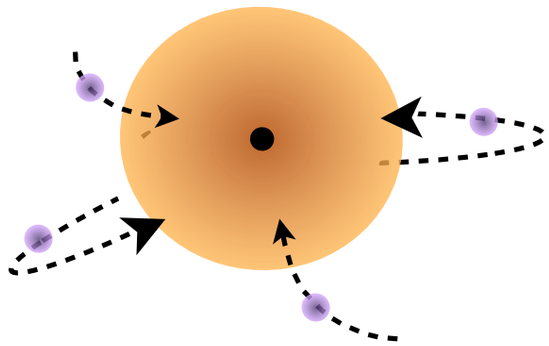

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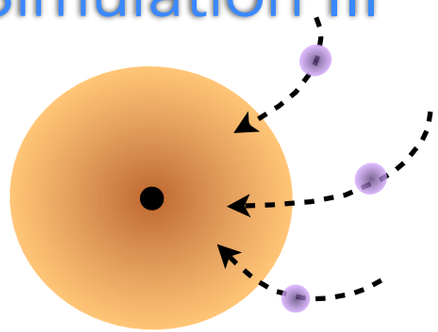

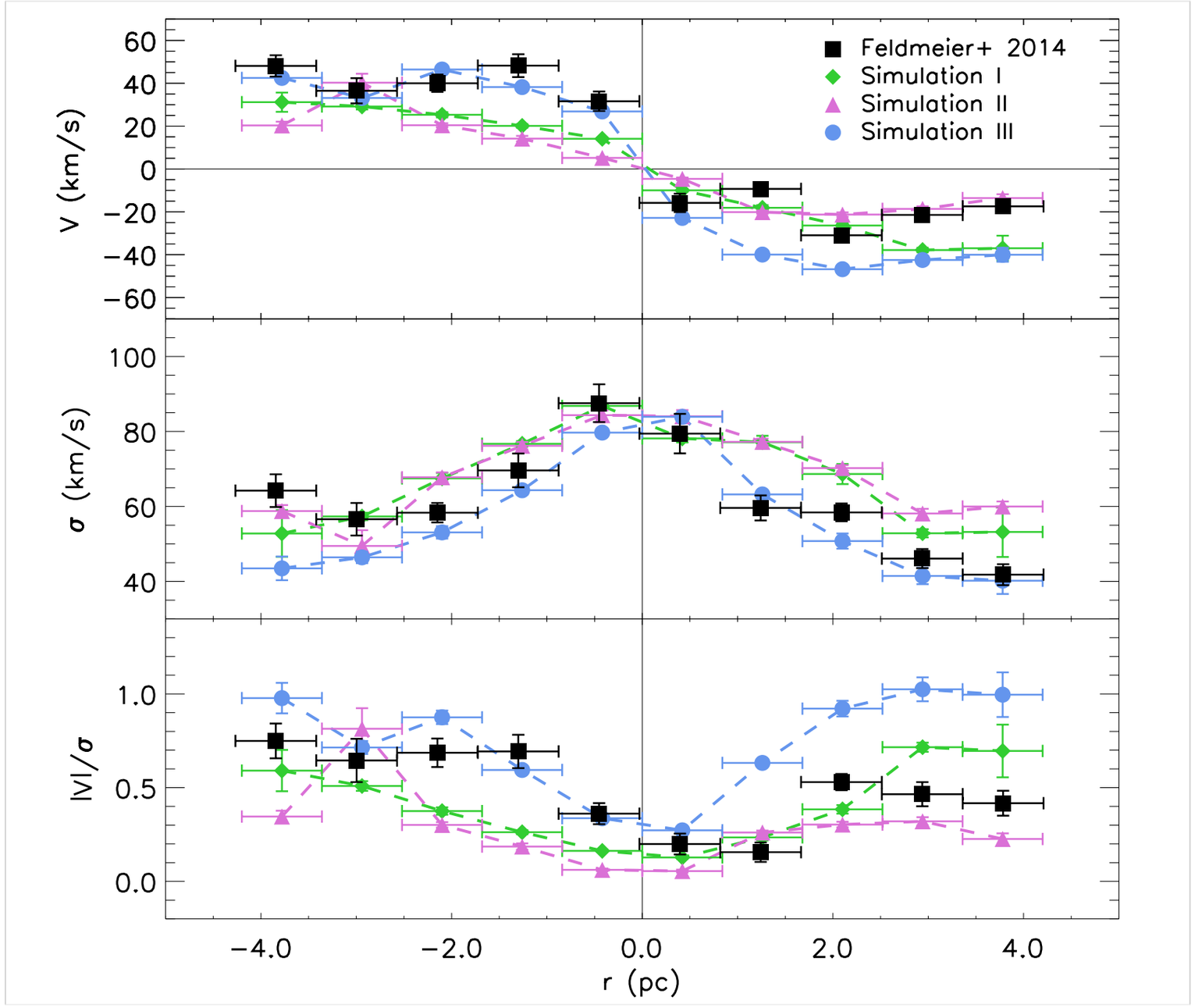


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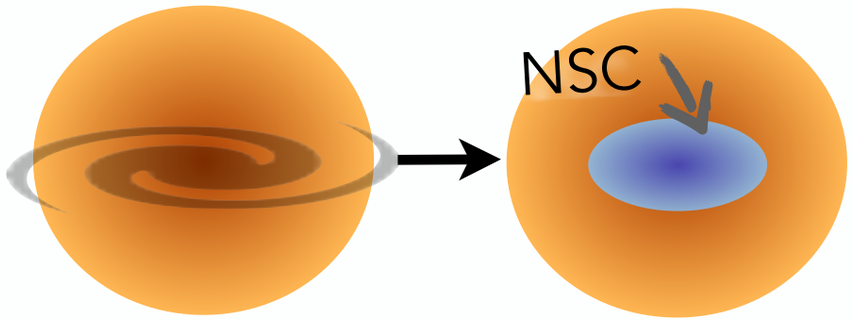
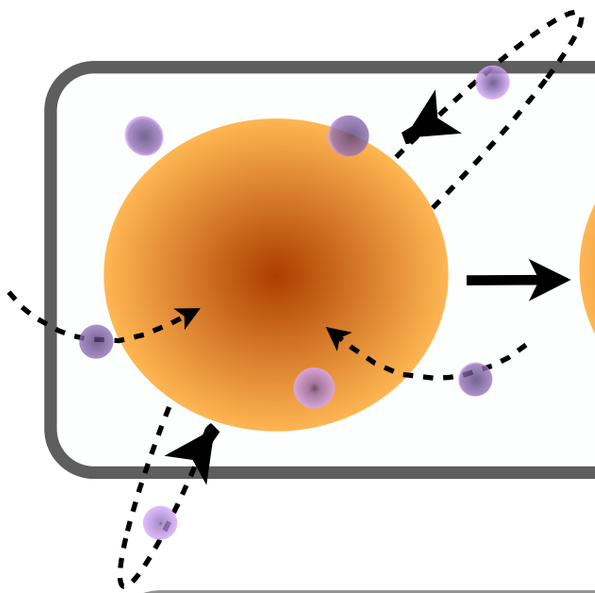
# NSCs form through cluster infall and/or in-situ star formation




**Gas accretion and in situ star formation**

(Loose+ 1982, Milosavljevic+ 2004, Pflamm-Altenburg+ 2009,...)




**Accretion & merger of star clusters**

(Tremaine+1975, Capuzzo-Dolcetta 1993, Antonini+2012, Arca-Sedda & Capuzzo-Dolcetta 2014, Gnedin+2014, Antonini 2015,...)

**Stellar populations:**
Range of metallicities

**Dynamics:**
NSCs rotate
NSCs are flattened

Both mechanisms could work together

e.g. Hartmann et al. 2011, Neumayer et al. 2011, Turner et al. 2012, de Lorenzi 2013, Feldmeier et al. 2014, den Brok et al. 2014, Feldmeier-Krause et al. 2015 & 2017, Guillard et al. 2016

Which is the **dominant** one?

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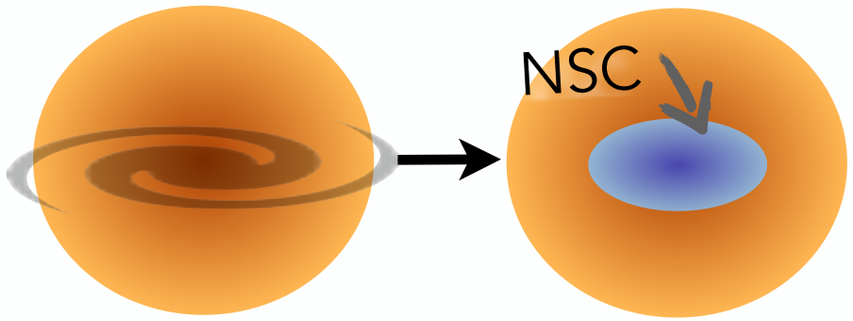


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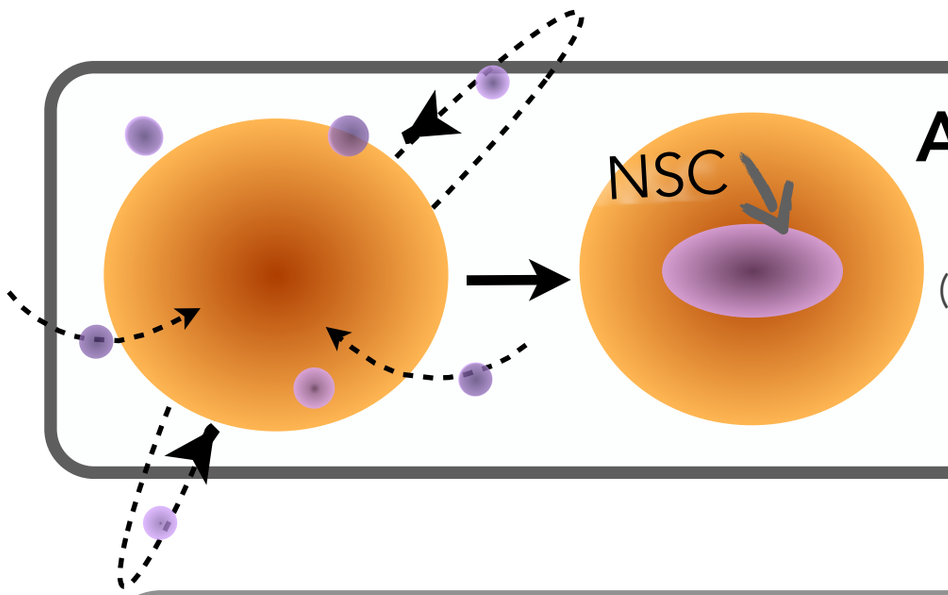


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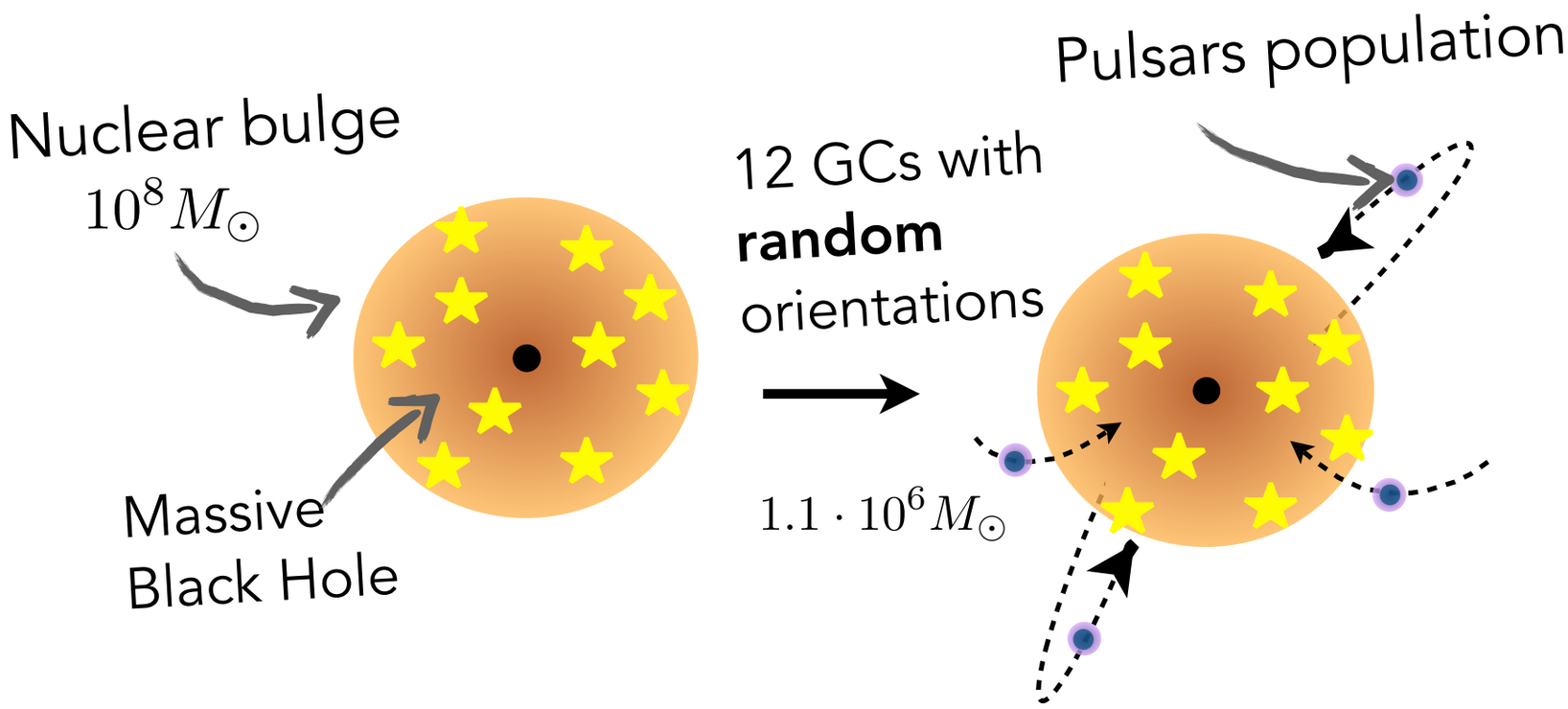
# We can use stellar tracers to constrain the origin of the NSC: millisecond pulsars

**Abbate, MB, Colpi, Possenti, Sippel & Dotti (2017)**



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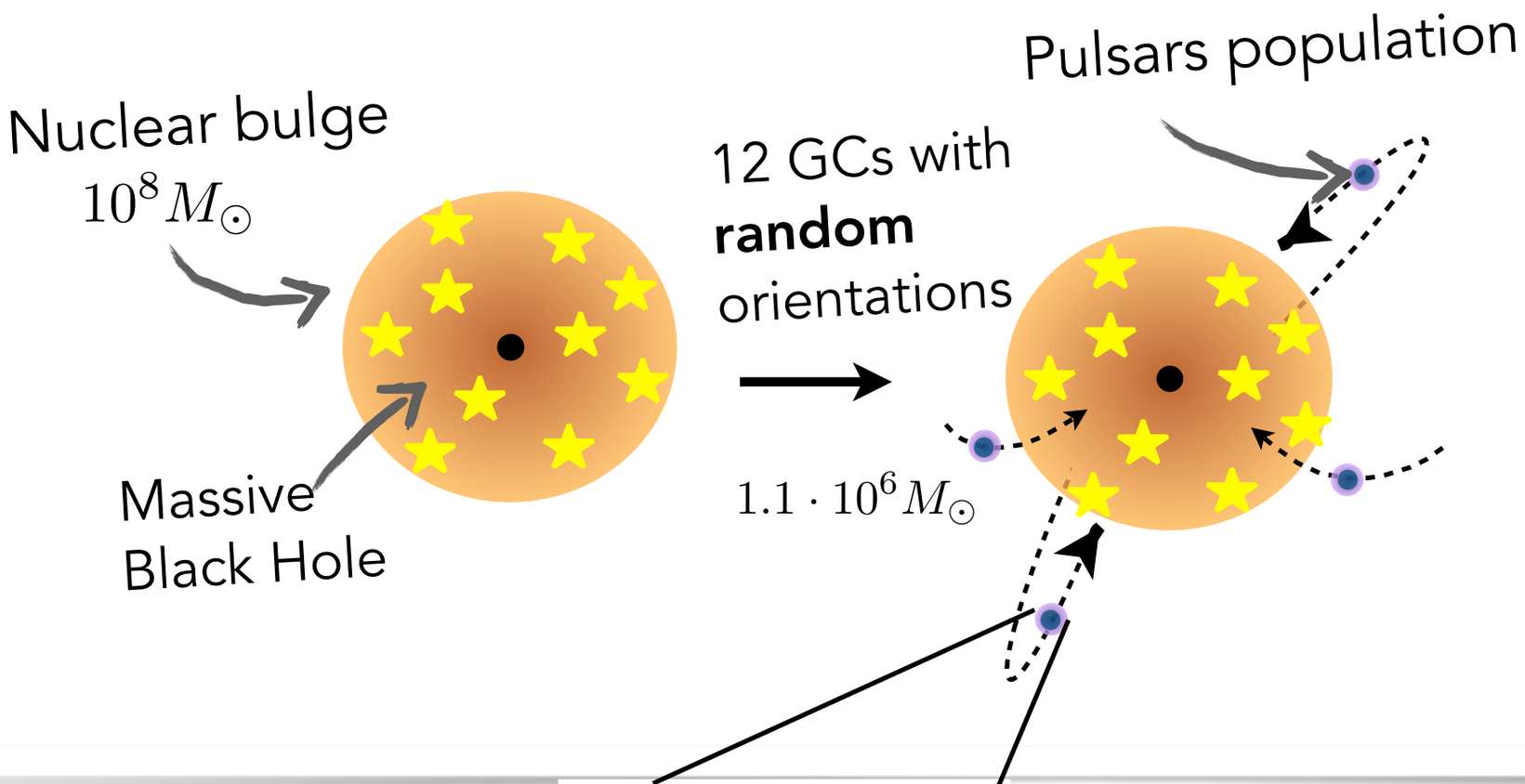


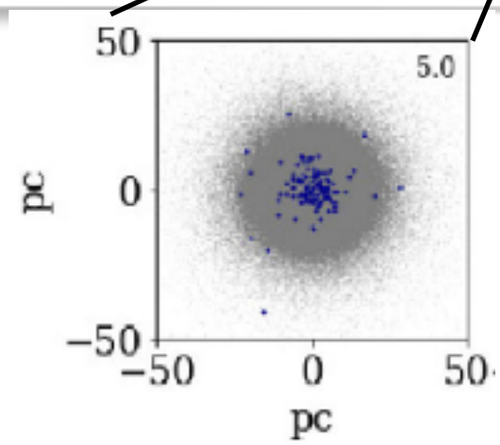


**Sippel & Hurley (2013)**

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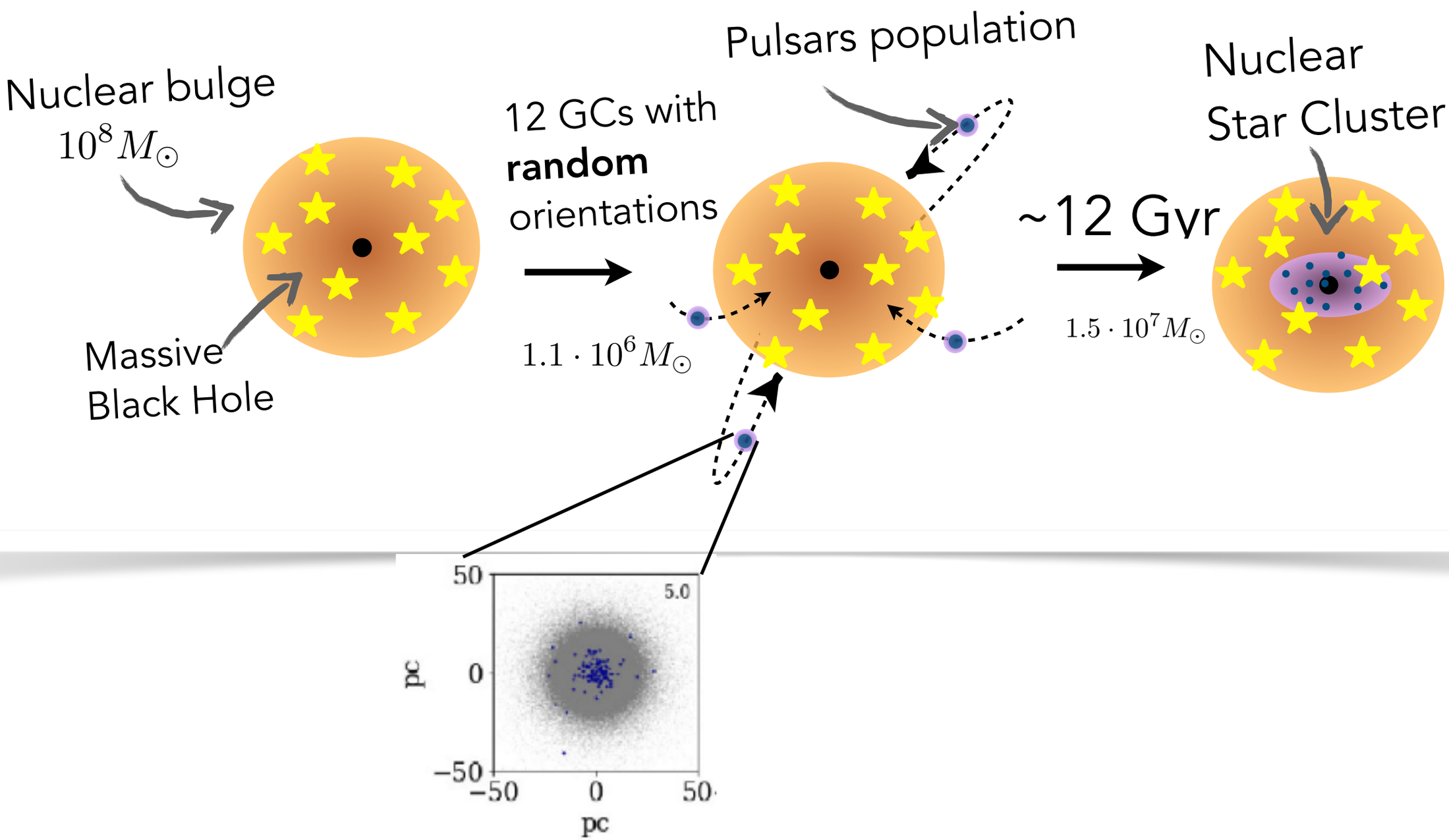





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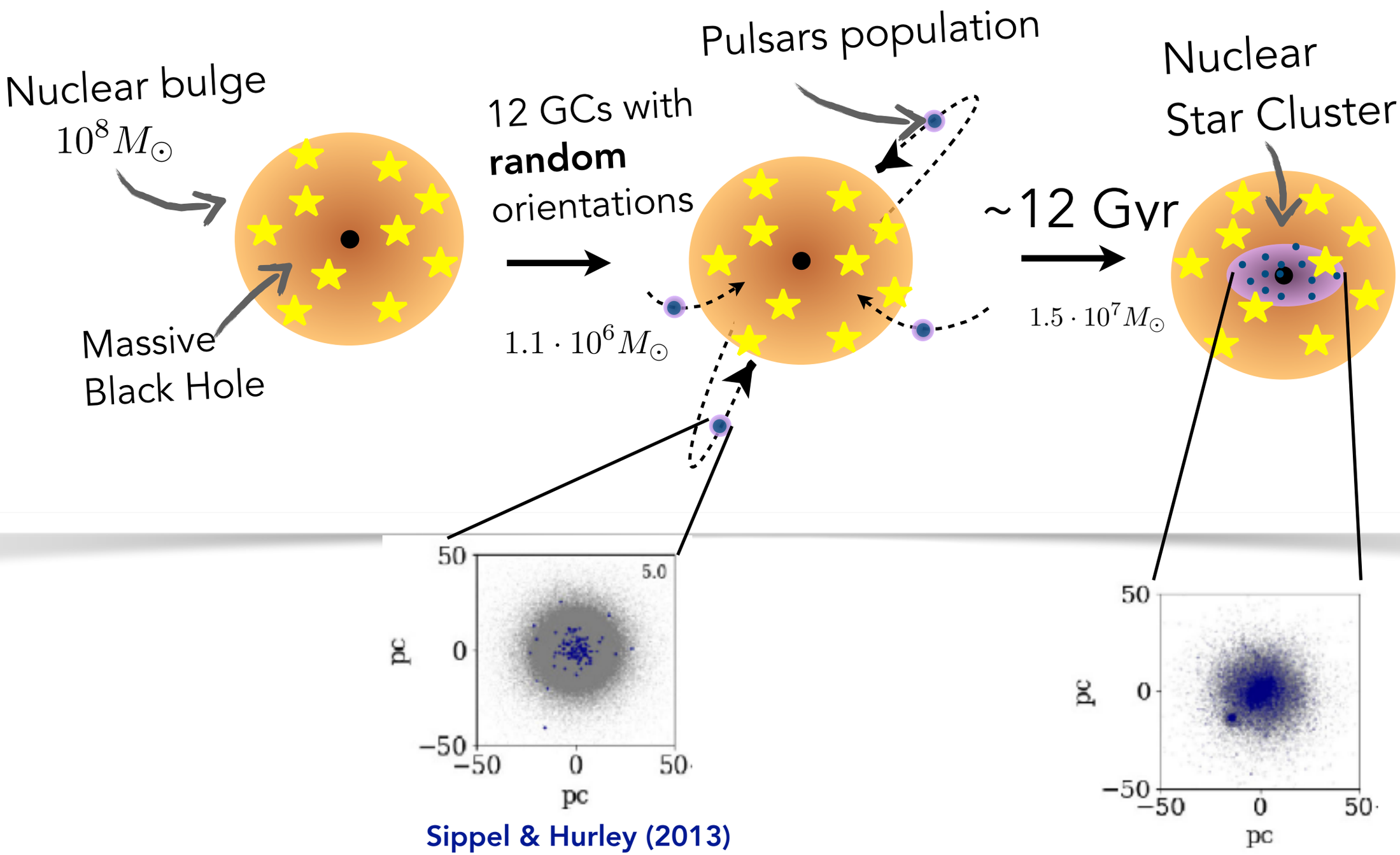


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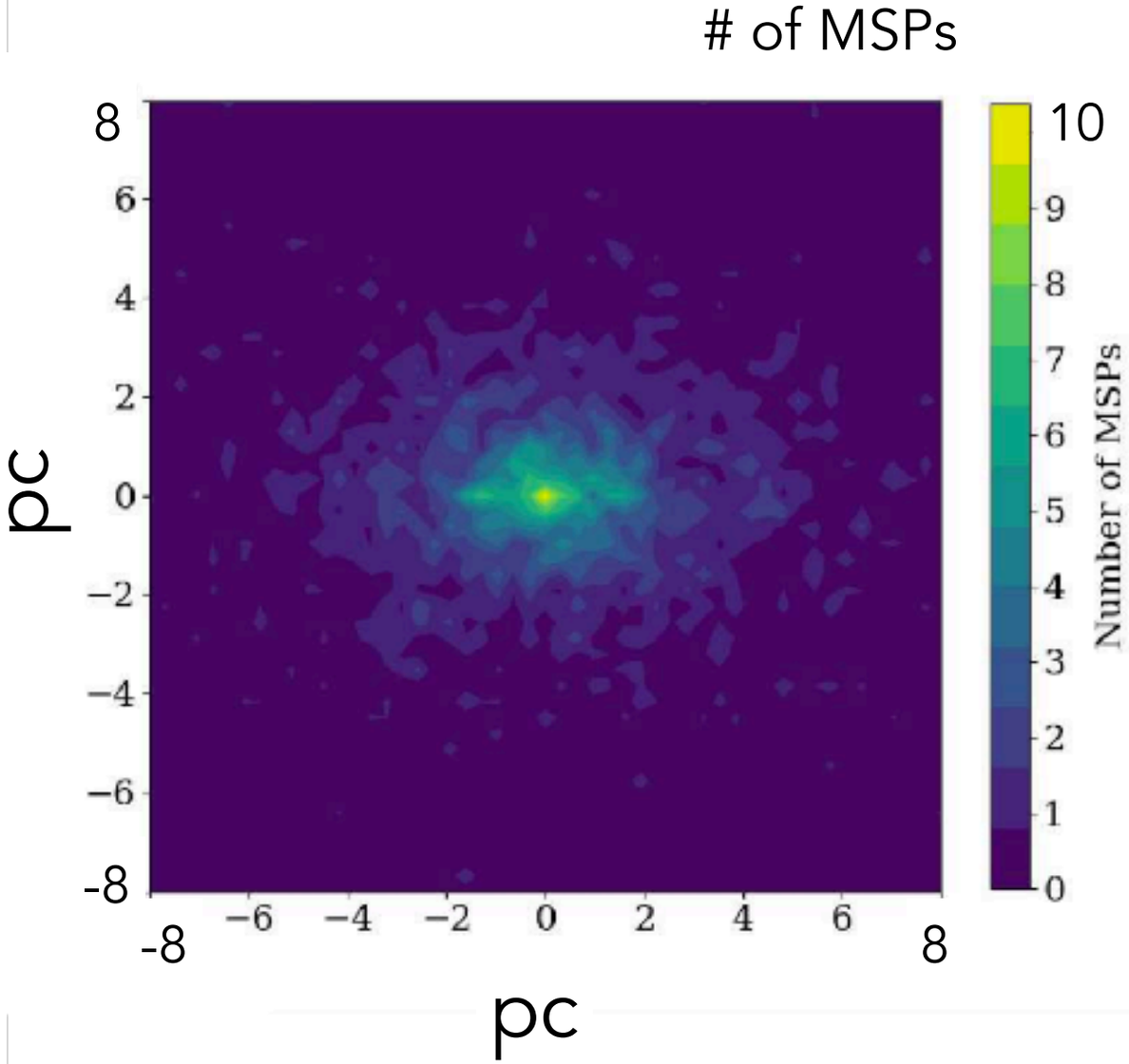


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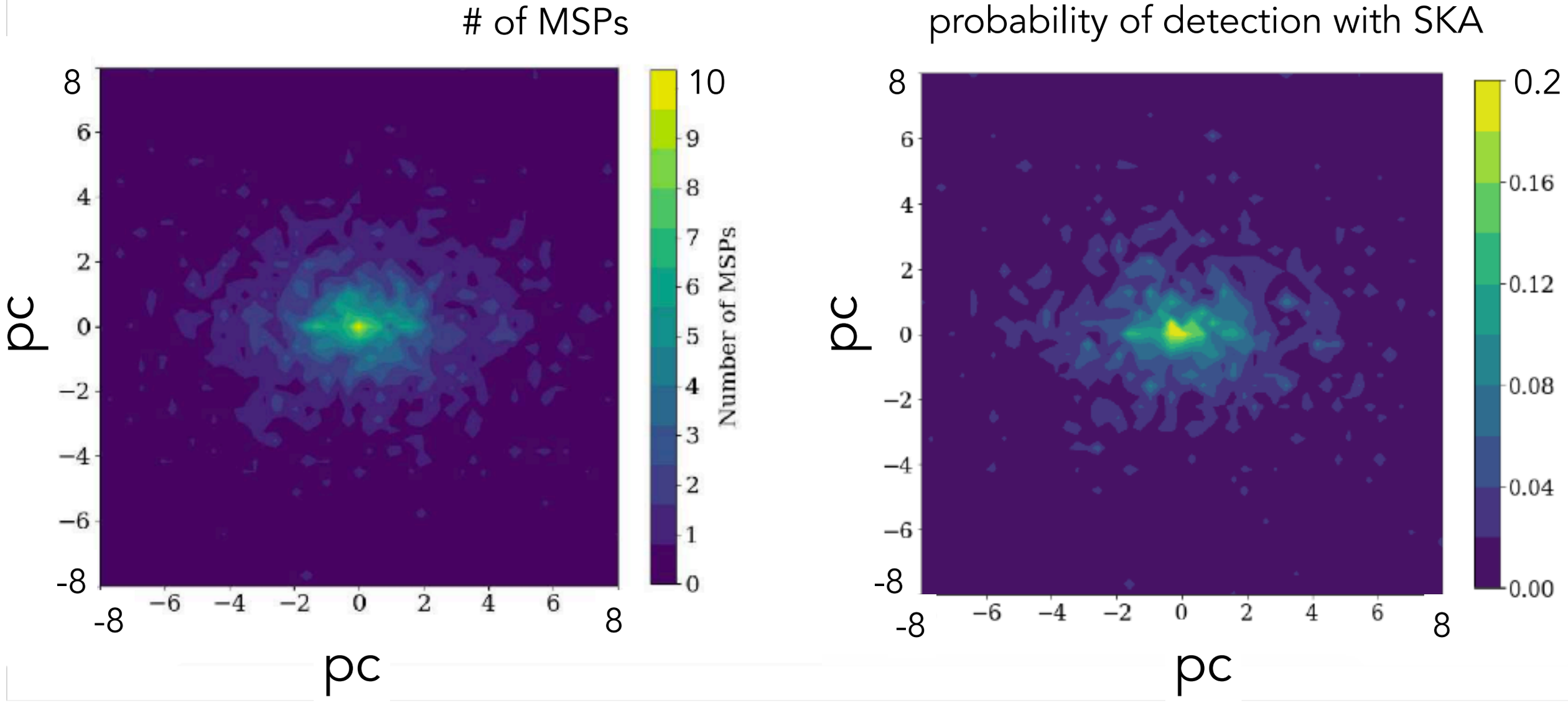


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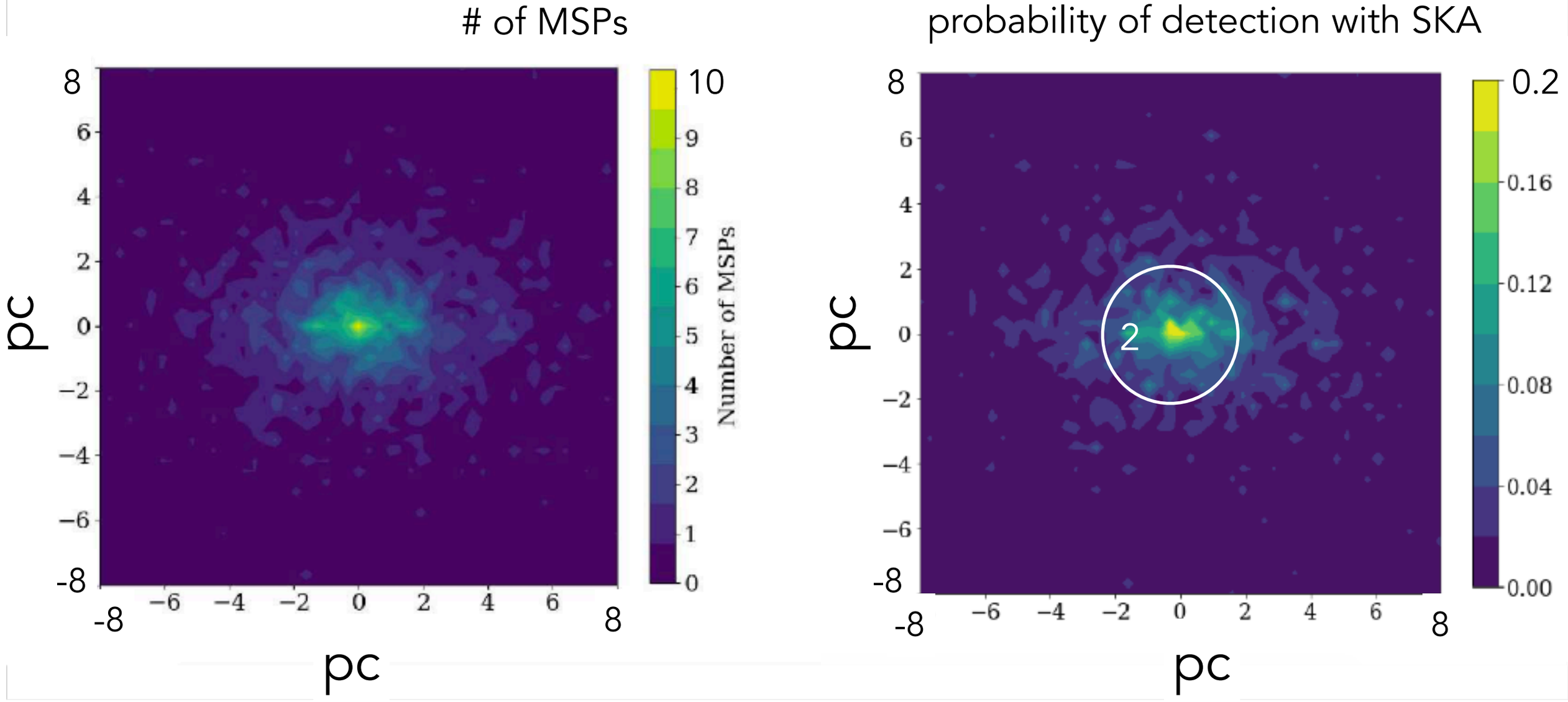


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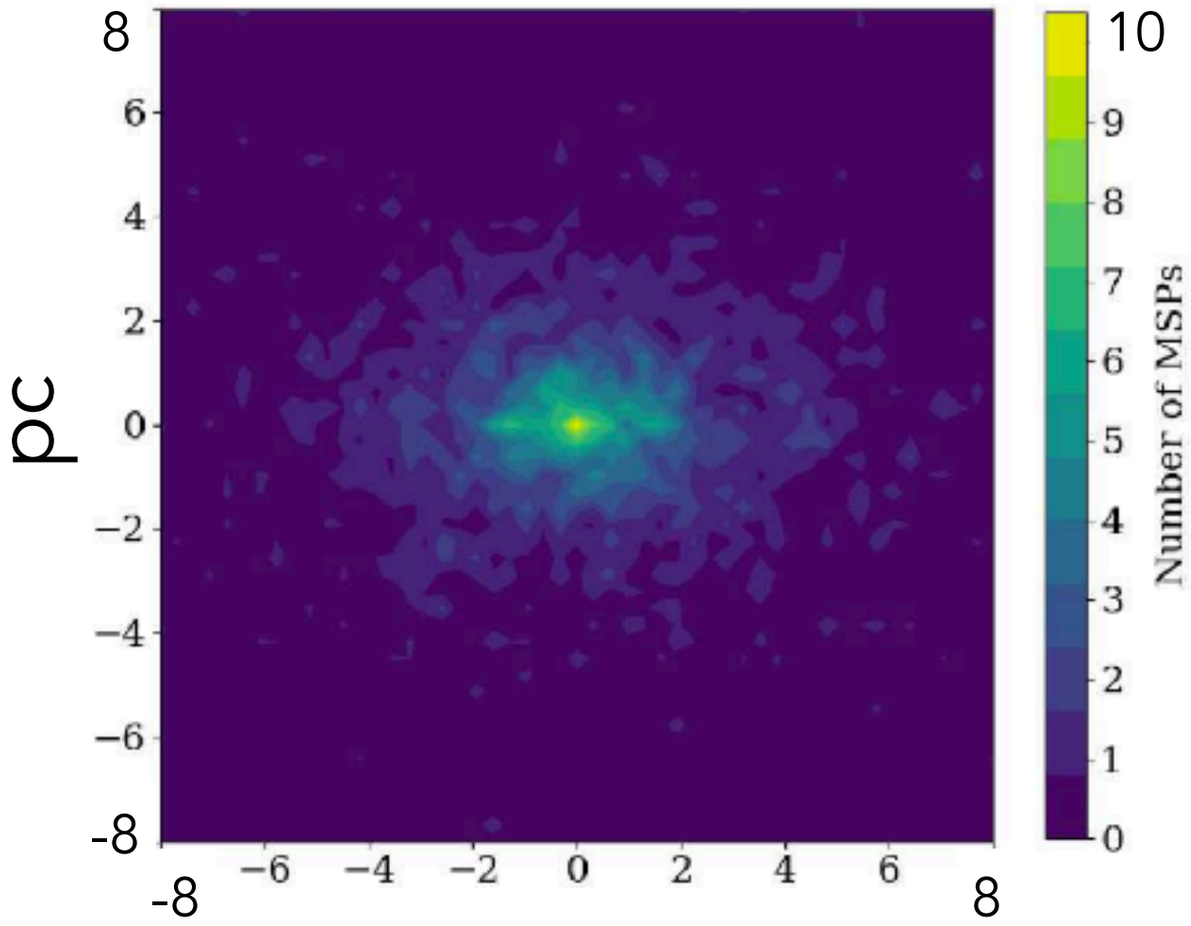
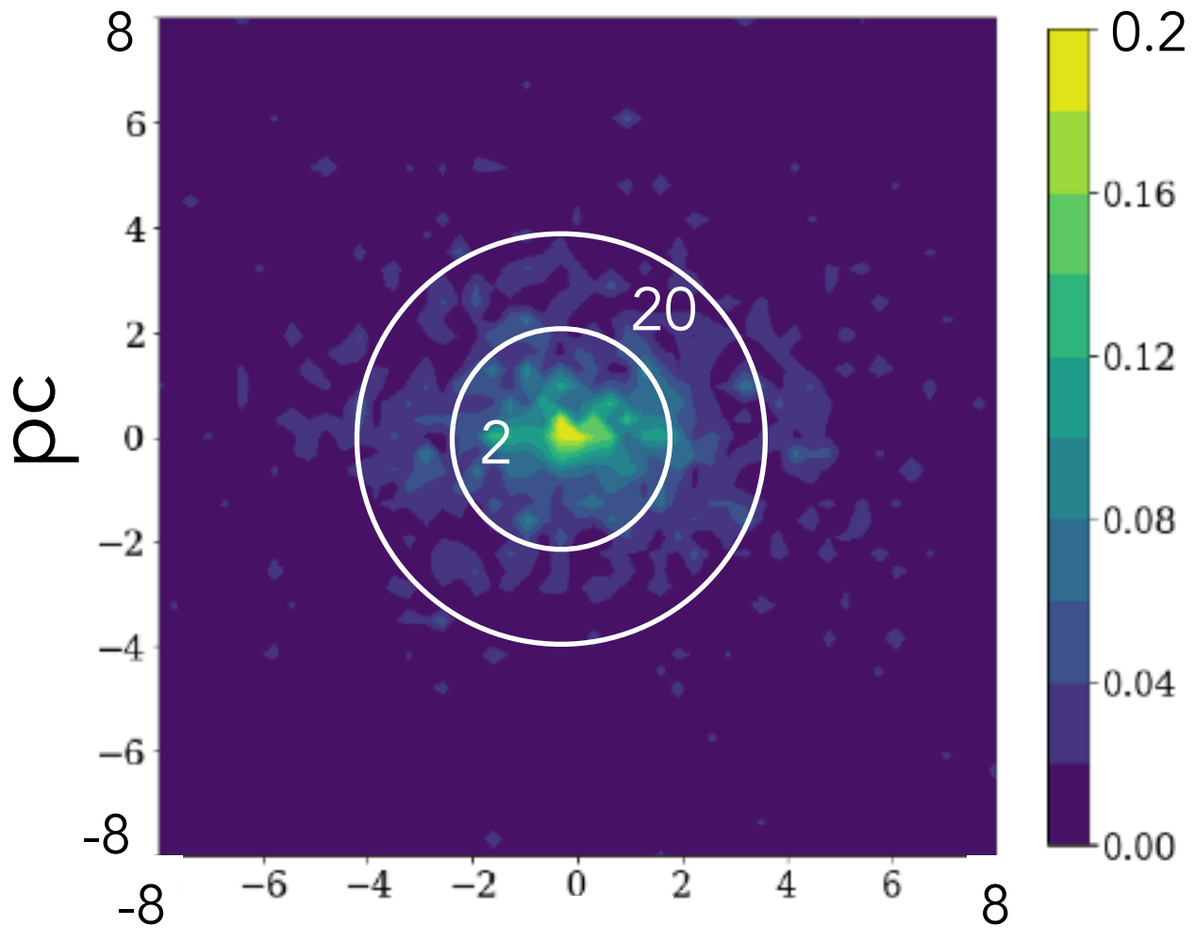
# of MSPs




probability of detection with SKA

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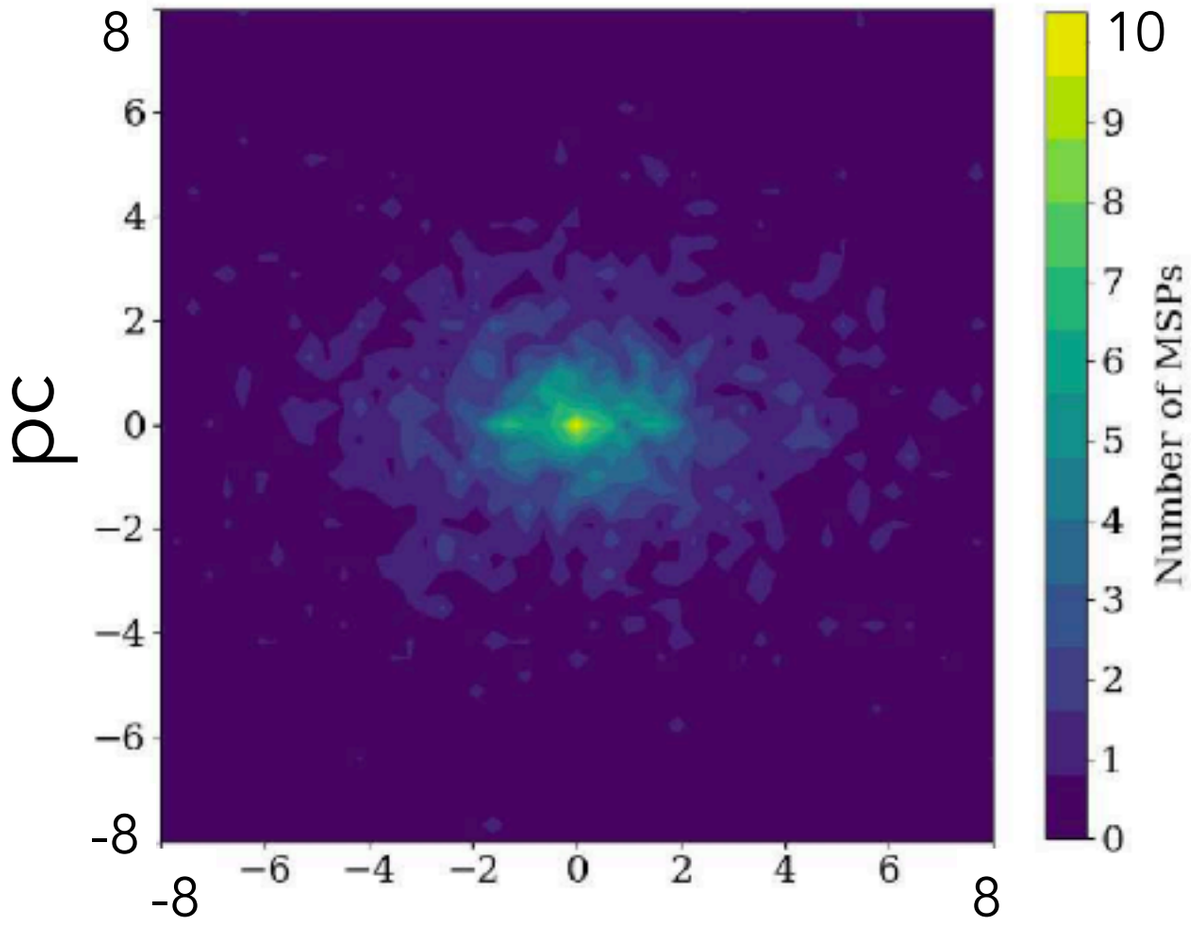
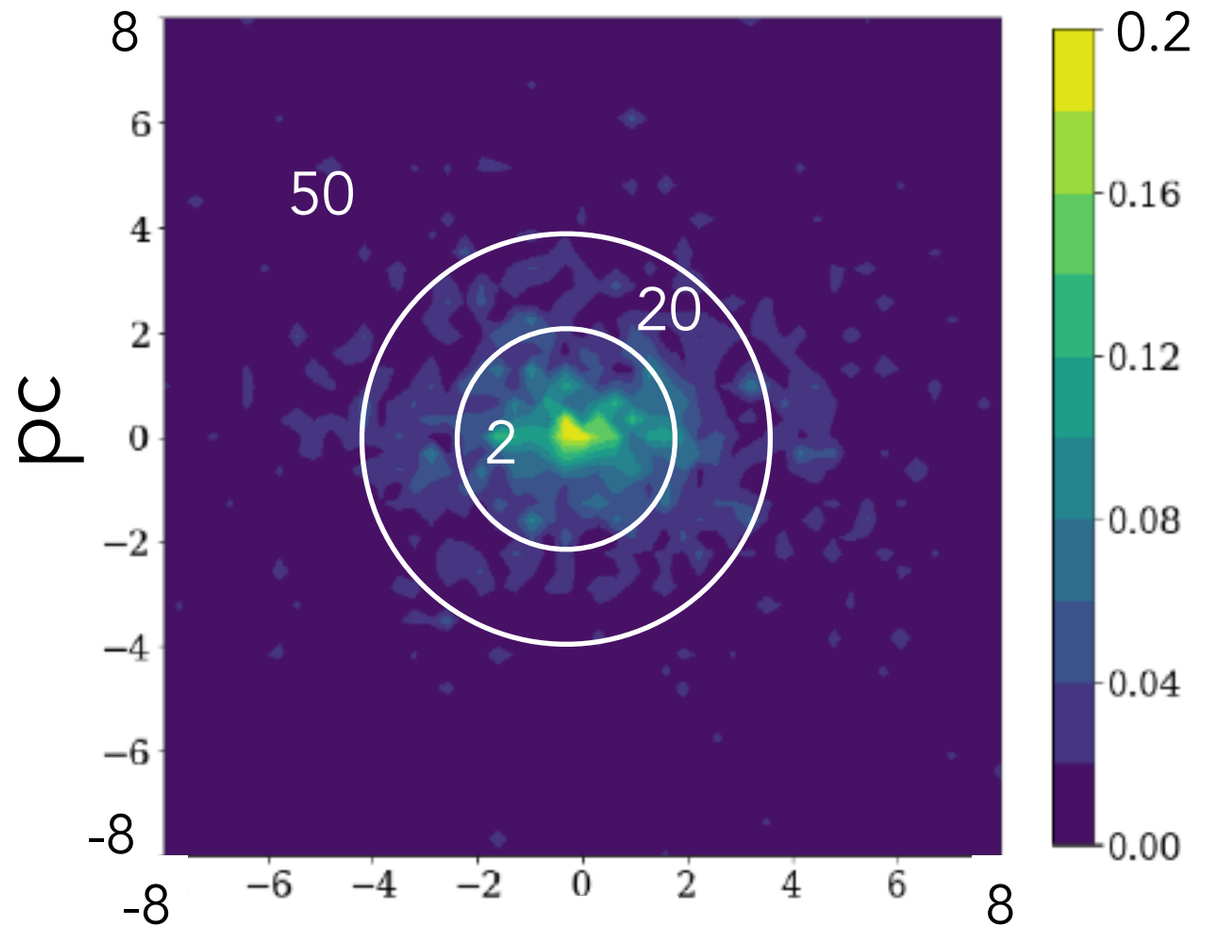
# We can use stellar tracers to constrain the origin of the NSC: millisecond pulsars

# of MSPs



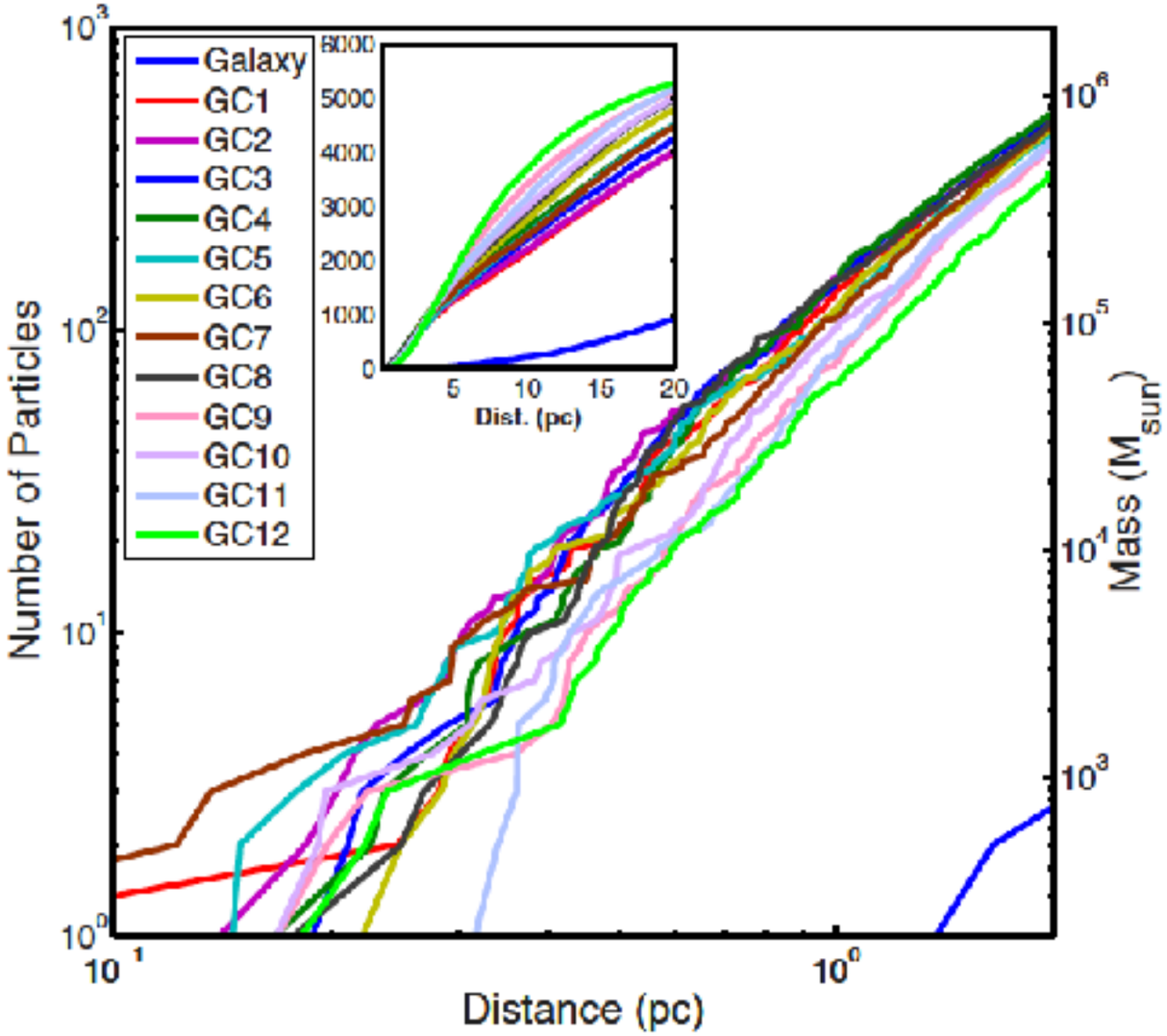

probability of detection with SKA




**Abbate, MB, Colpi, Possenti, Sippel & Dotti, 2017, MNRAS**

**(see also Arca-Sedda et al. 2018 and Fragione et al. 2018)**

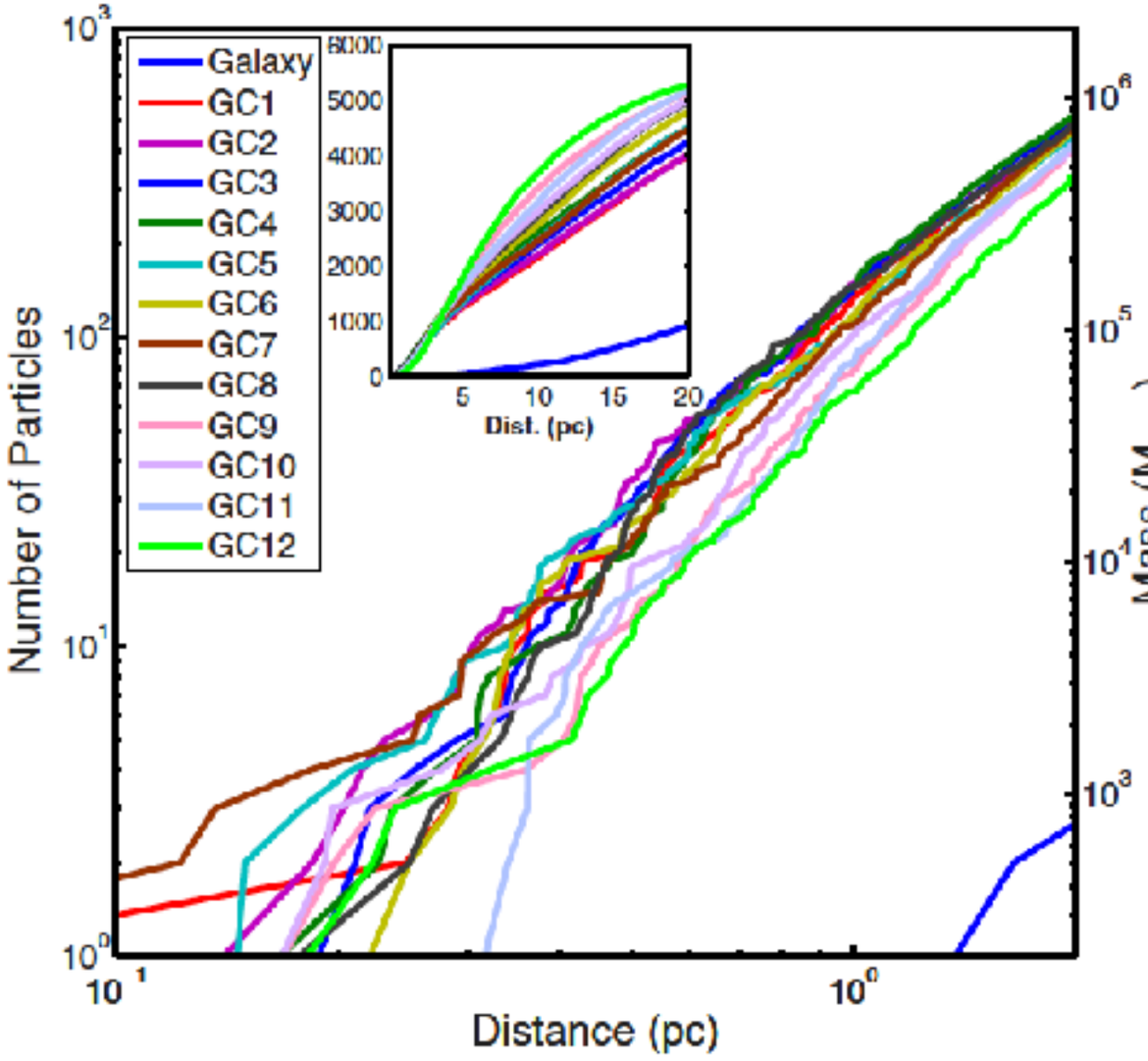
# The next step: combining dynamical and chemical information to unveil the origin of the Galactic NSC

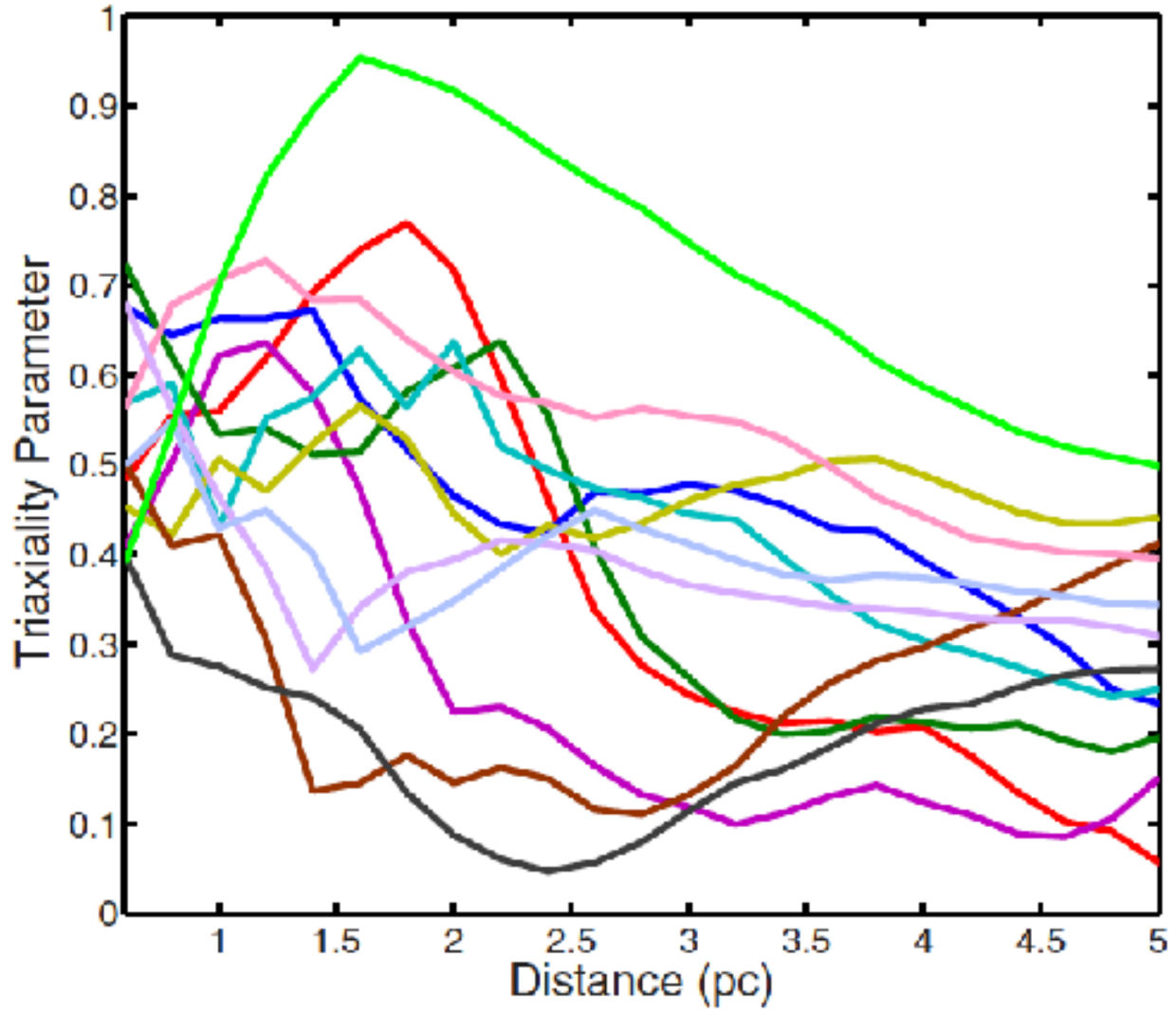



Different populations have different spatial distributions, shapes and kinematics. Chemical tagging of the simulations and comparison with observations are necessary to finally unveil the link between NSCs and GCs.

# The next step: combining dynamical and chemical information to unveil the origin of the Galactic NSC

Perets & Mastrobuono-Battisti (2014)

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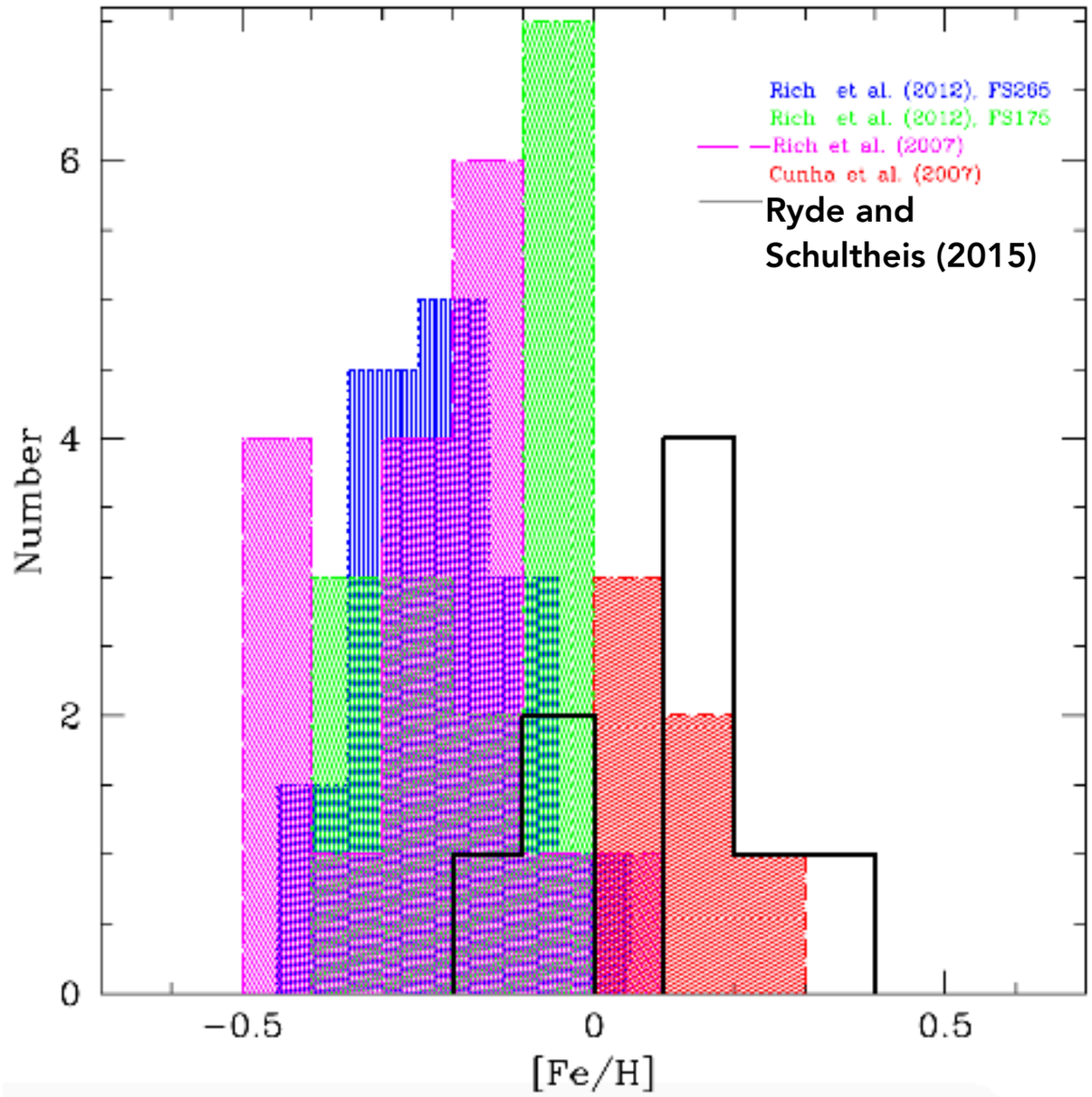
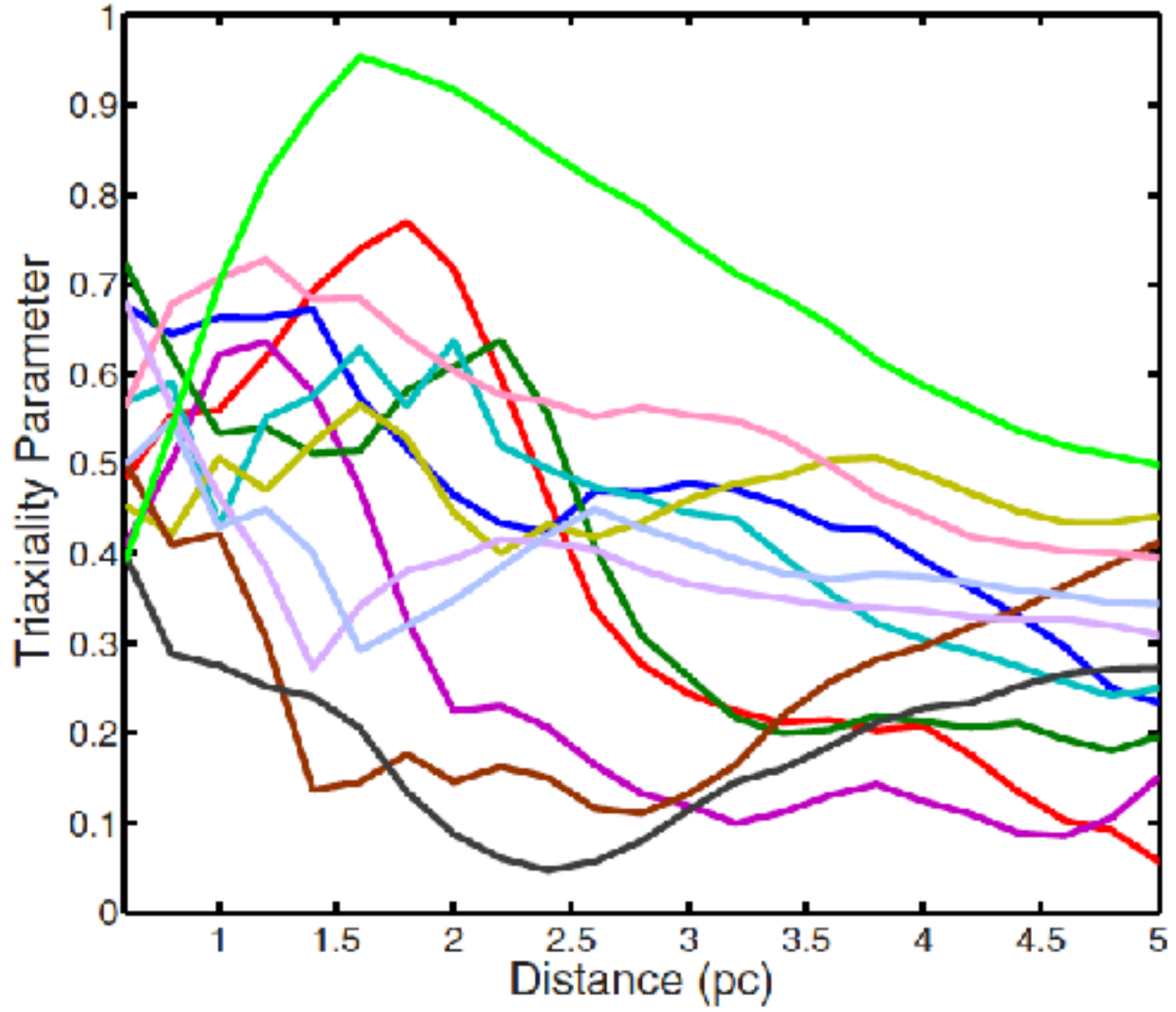



Perets & Mastrobuono-Battisti (2014)

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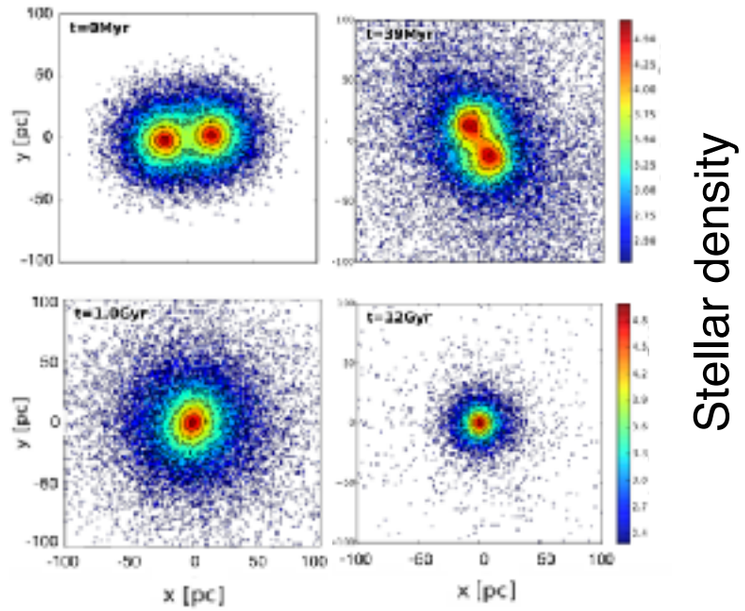
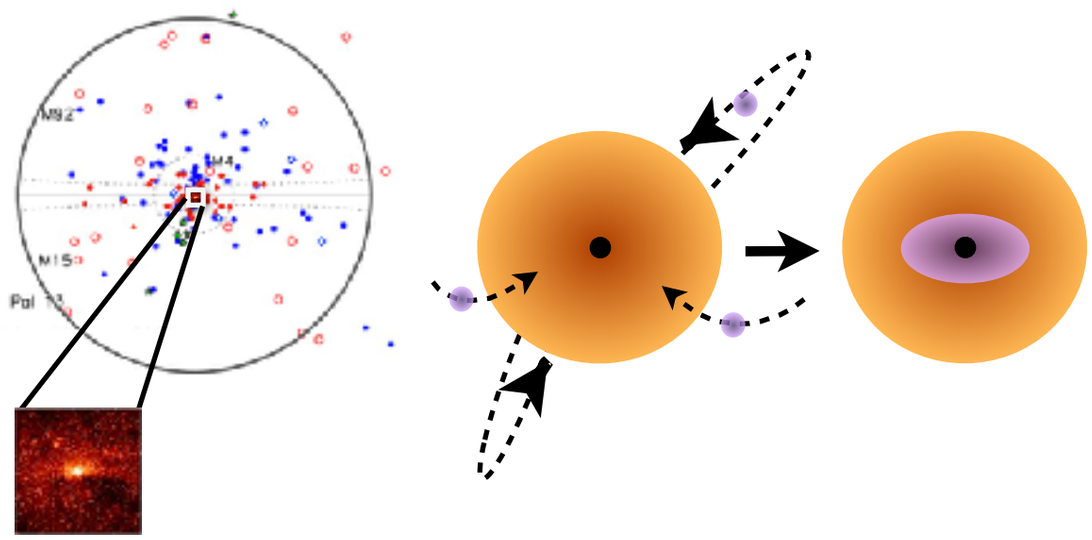
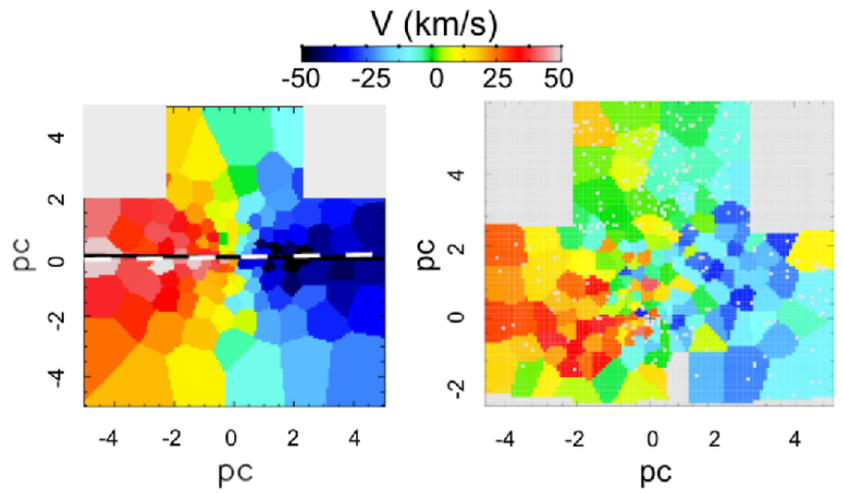
# Take-home messages

- **GCs do not evolve in isolation.** GCs primordial dynamical evolution can affect their internal metallicity distribution function through mergers and mass-exchanges.

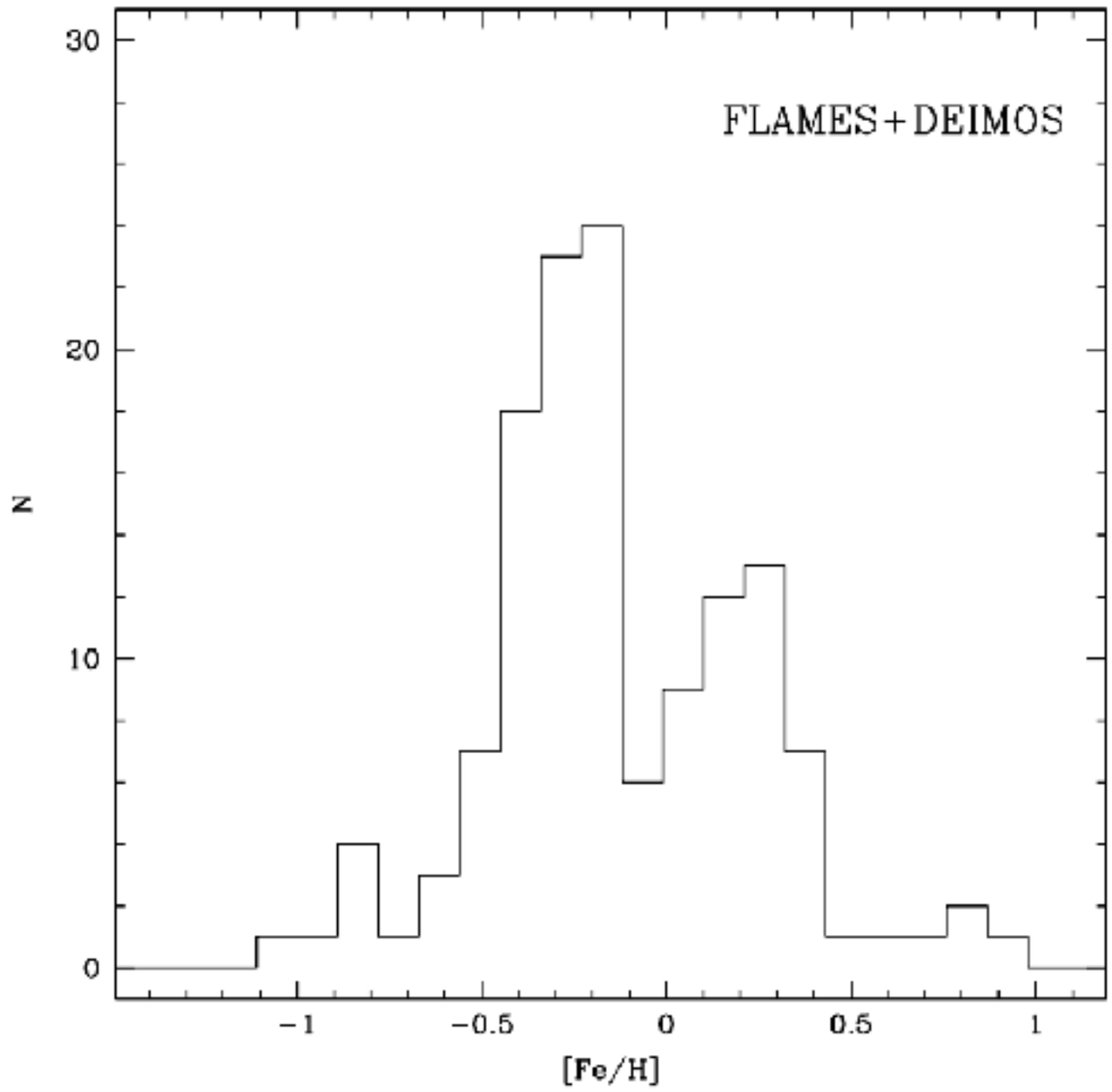
- **NSCs can form through the infall and merger of** massive and dense **globular clusters**, however we need to combine dynamics and chemistry of stars to disentangle the Galactic NSC history.



# Terzan 5's MDF has three peaks: -0.8 (6%), -0.3 (62%) and 0.25 (29%)




Massari et al. (2014)