Testing the formation of extended star clusters

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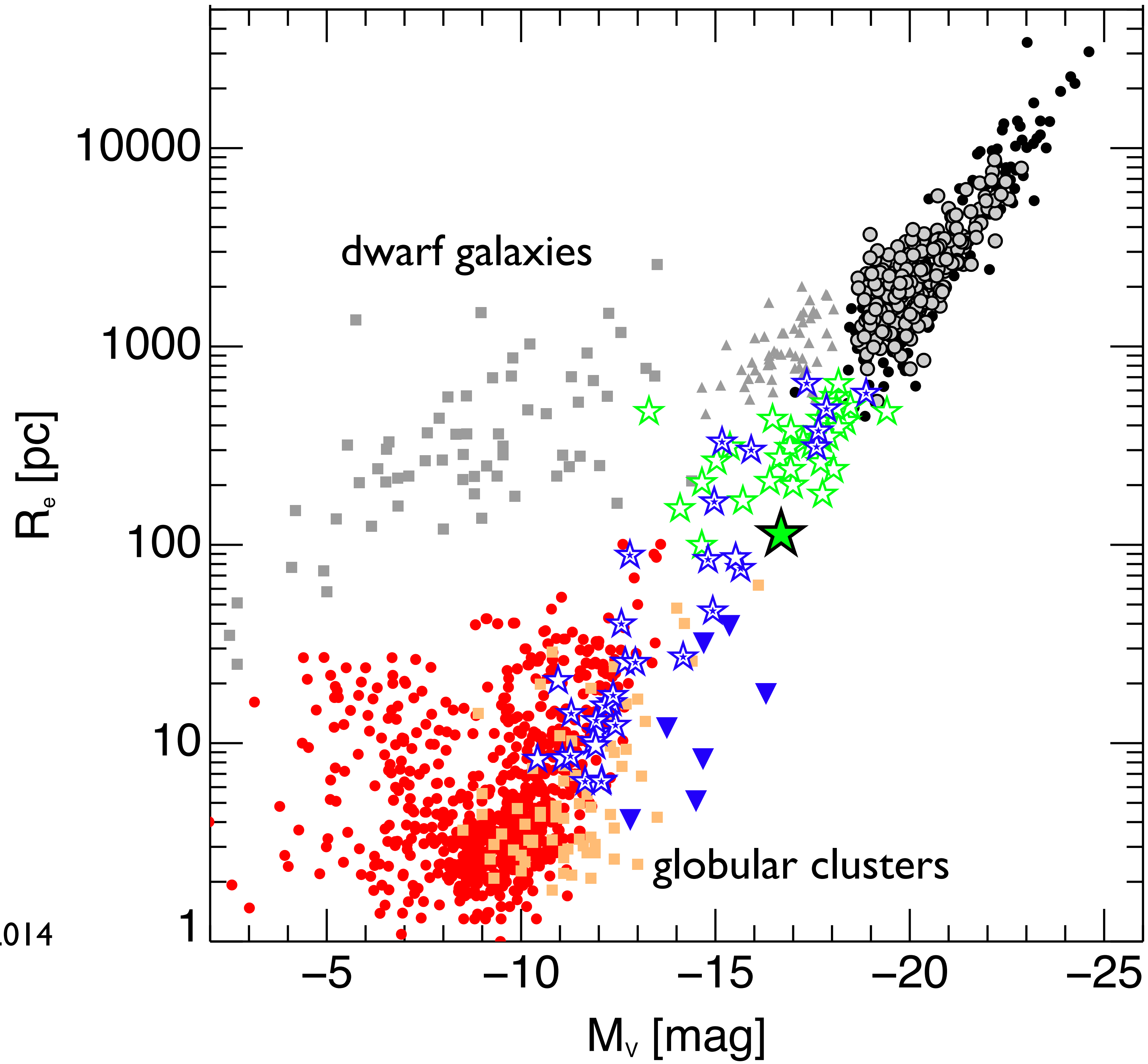
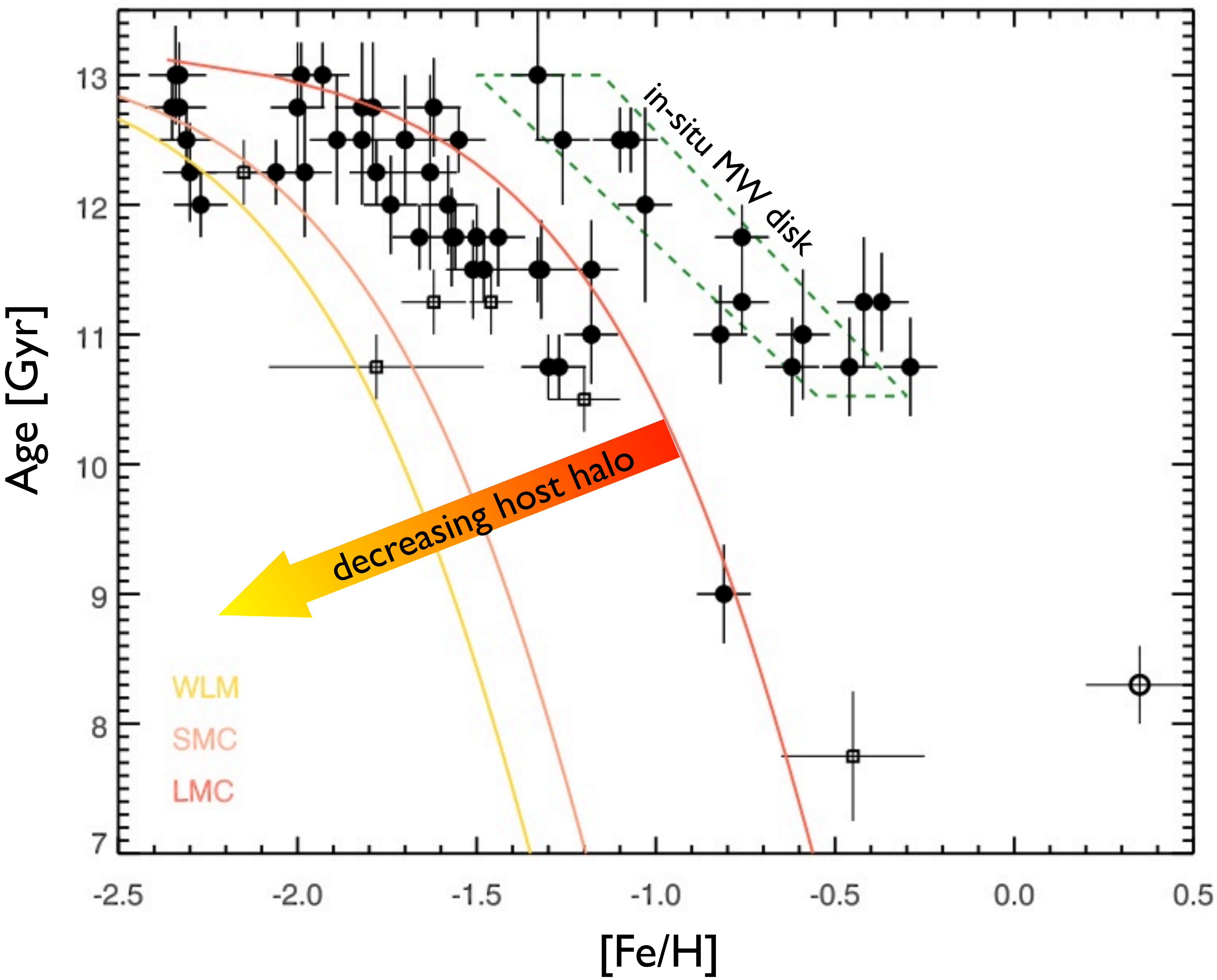
The zoo of small stellar systems



Norris et al. 2014

Origin of galactic GCs?

Leaman, VandenBerg & Mendel (2013)



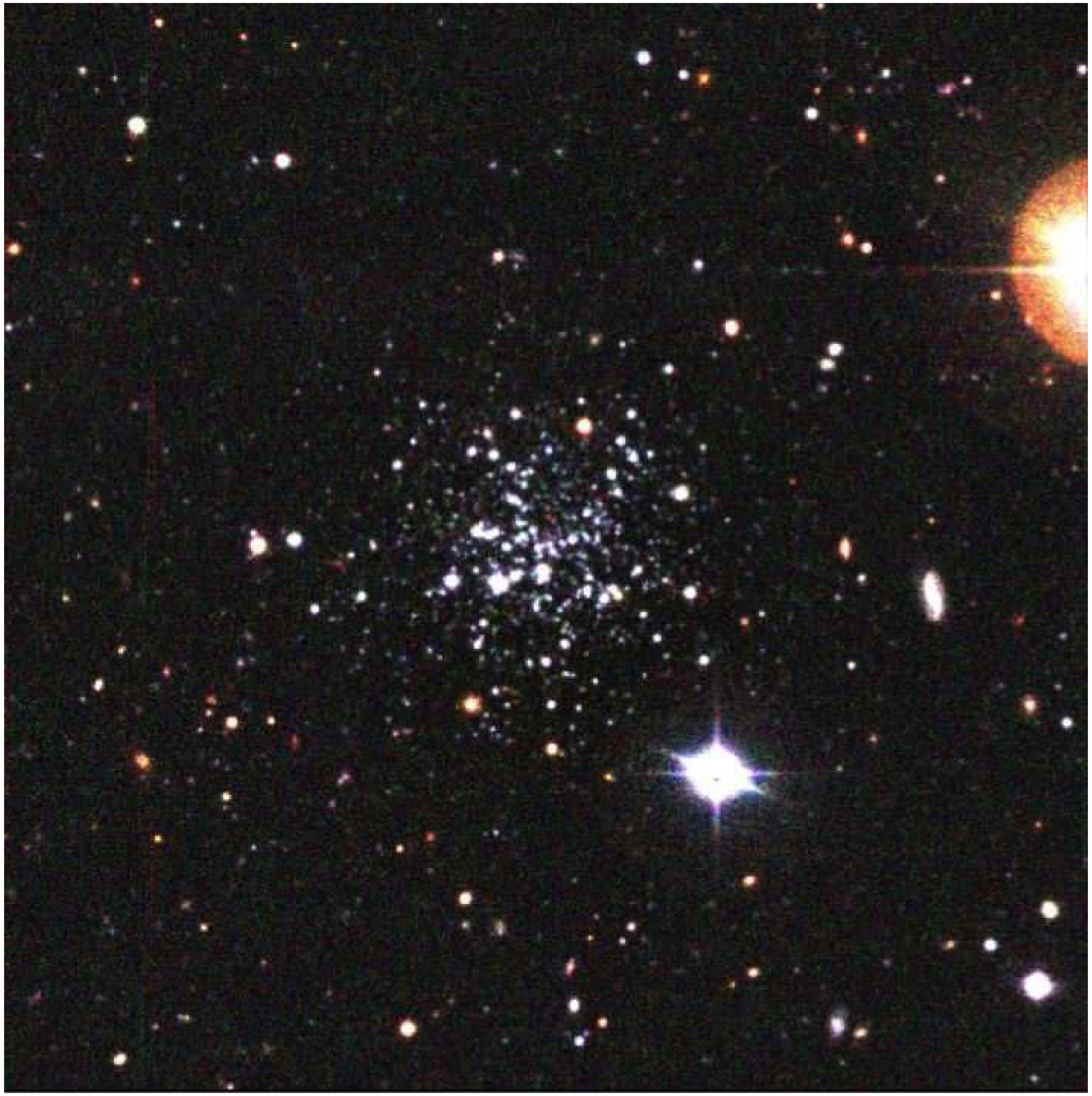
In-situ GCs

- GCs in disk-like orbits, consistent with age-metallicity of MW disk

Accreted GCs

- 2/3 of GCs in halo-like orbits
- accreted as part of 10^7-10^8 $M_\odot$ disrupted dwarf host galaxies

GC or dwarf galaxy?



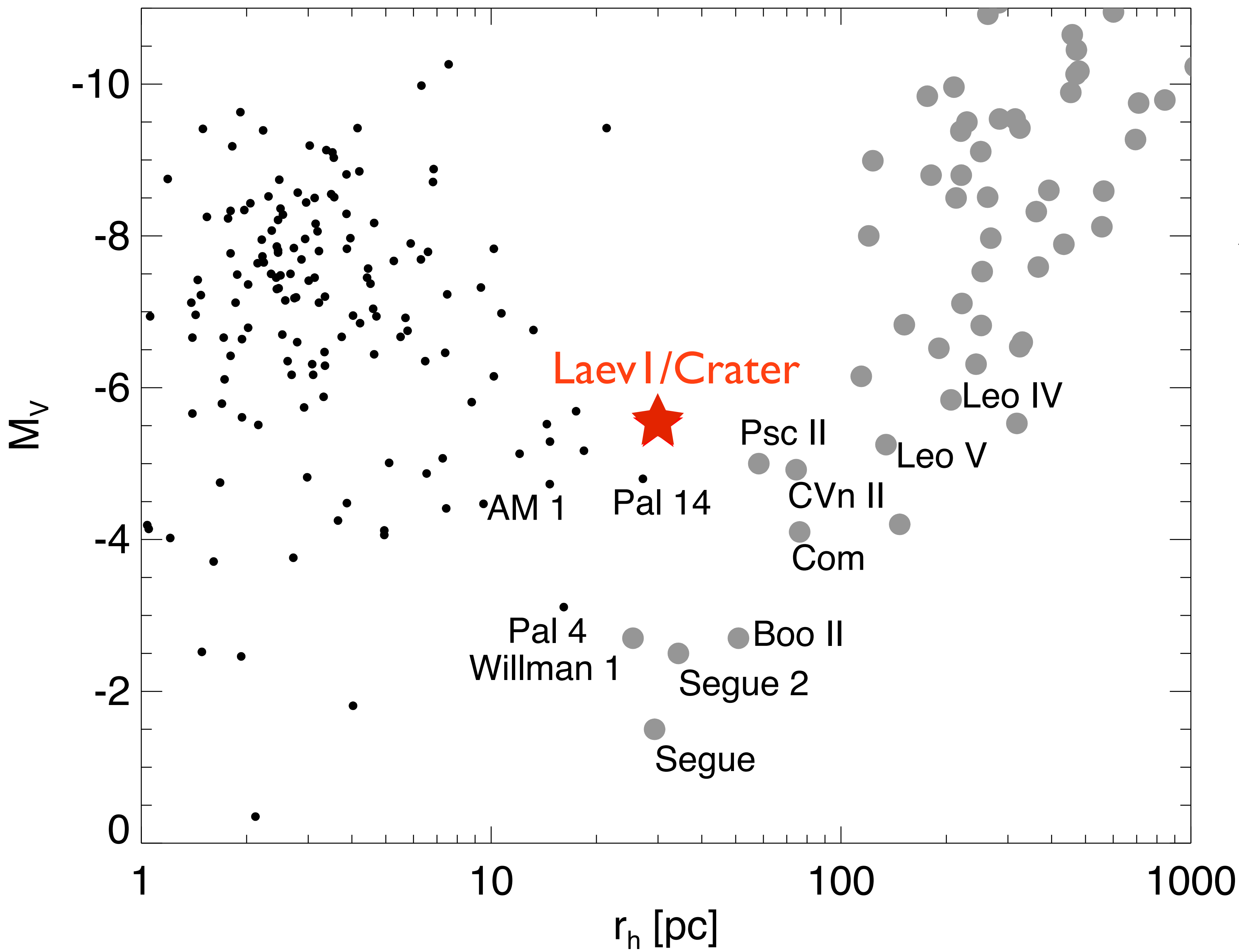
Laevens et al. 2014

Laevens 1 / Crater

Laevens et al. 2014:
- "most distant MW cluster"

Belokurov et al. 2014:
- "dwarf galaxy with unusual properties"

The zone of confusion



from Belokurov et al. 2014

EXTENDED CLUSTERS

Pal 14, Pal 4, AM 1, Laev 1, Arp 2, Terzan 8

- more extended than "normal" GCs

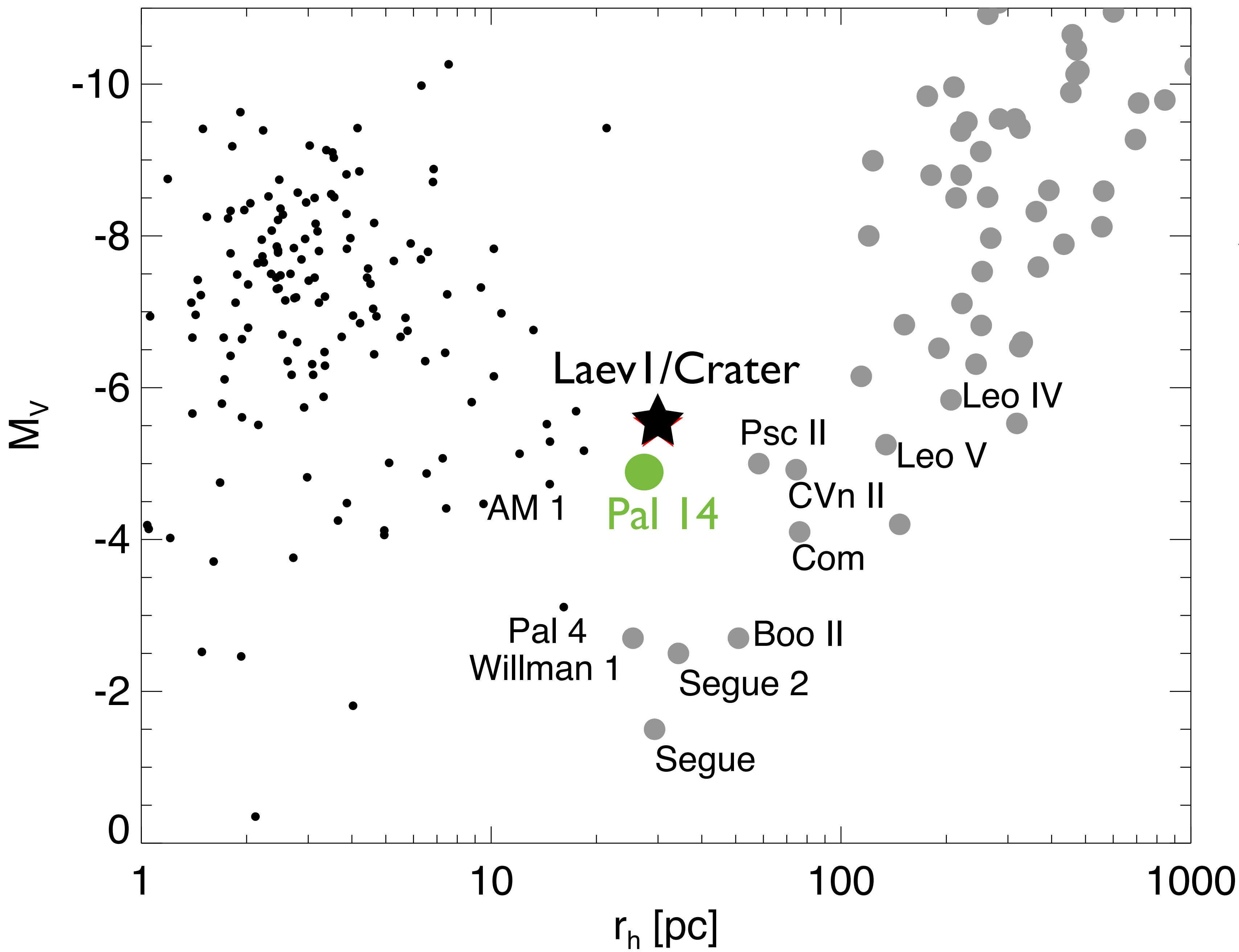
Rh≈20pc vs. Rh≈3pc

- preferentially in the outer MW halo
- several other extragalactic extended clusters

(e.g. Brodie & Larsen 2002, Huxor+)

HOW DID THEY FORM?

The zone of confusion



Belokurov et al. 2014

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HOW DID THEY FORM?

Formation of extended clusters

1) genuinly formed extended (Elmgreen 2008)

2) merging of 2 or more clusters (Fellahuer & Kroupa 2002)

3) formed compact and expanded because of peculiar evolution

e.g., Spitzer 1958; Mackey & Gilmore 2004

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accreted stellar systems (originally born in dwarf galaxies)

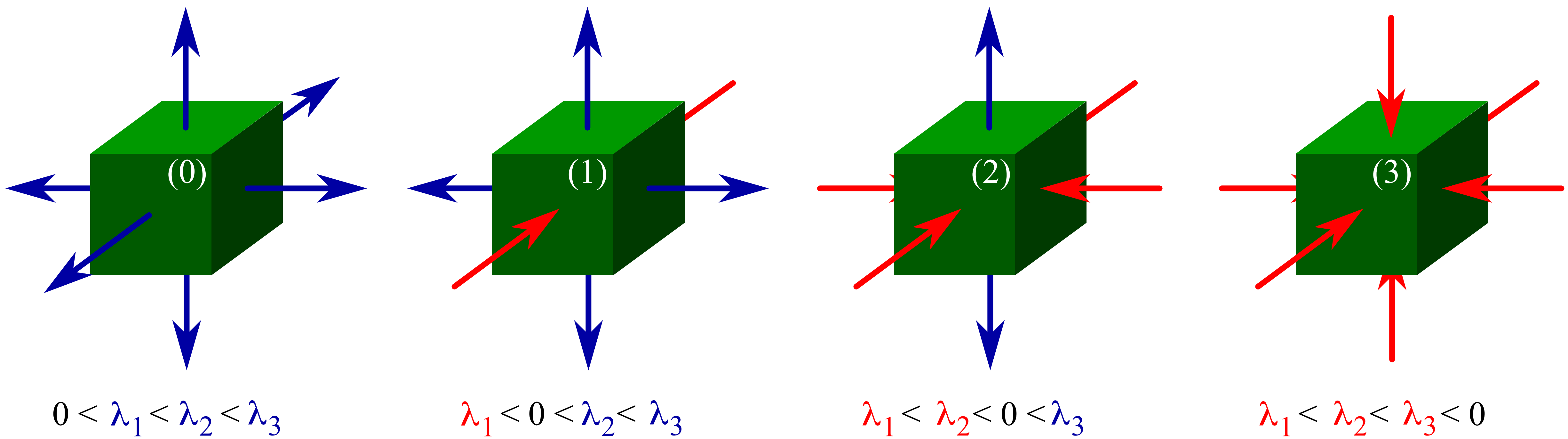
We test the following idea:

- cluster is born "normal" in the core of dwarf galaxy
- it experiences COMPRESSIVE TIDES
- it is later accreted into the Milky Way and it expands

Compressive tides

$$T^{ji} = -\partial^j \partial^i \phi_{ext}$$

$$T^{ji} = \begin{vmatrix} \lambda_1 & & \\ & \lambda_2 & \\ & & \lambda_3 \end{vmatrix}$$

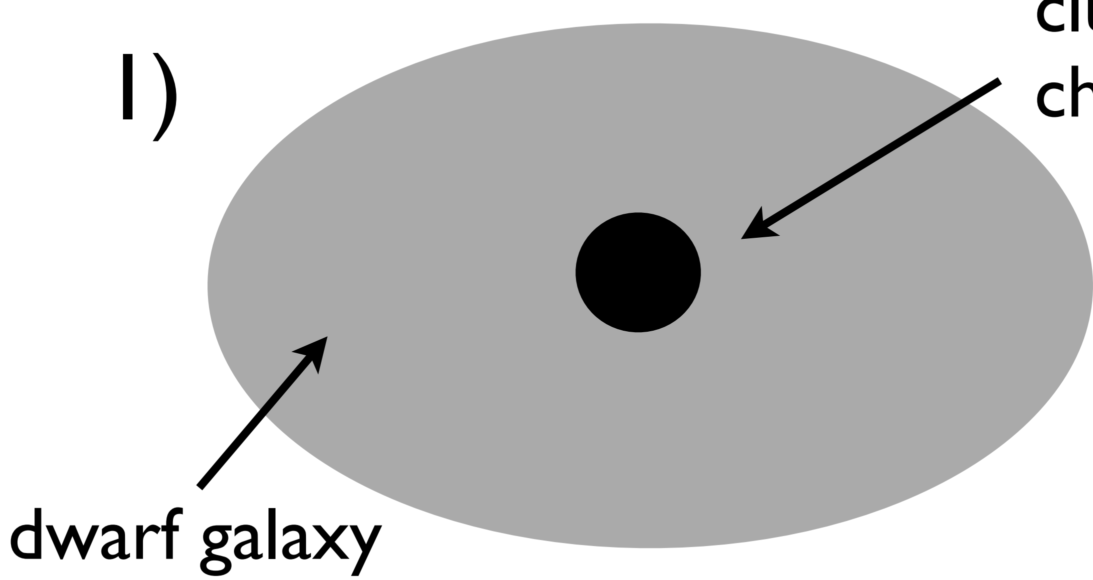


FULLY COMPRESSIVE TIDES

Renaud 2010

(simple) analytical description

1)

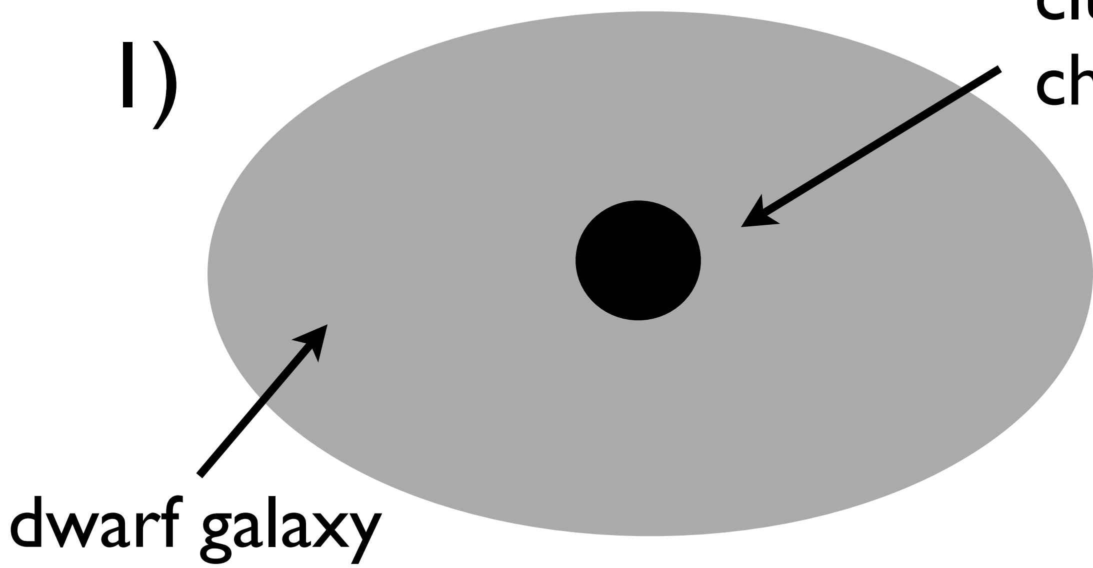


$$E_0 = \frac{1}{2}M\sigma^2 - \frac{GM^2}{2r_v} - \frac{1}{2}\lambda\alpha M R_t^2$$

(simple) analytical description

1)

cluster: mass M, dispersion σ, characteristic radii R_t and r_v



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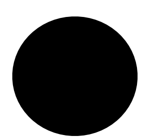
2)

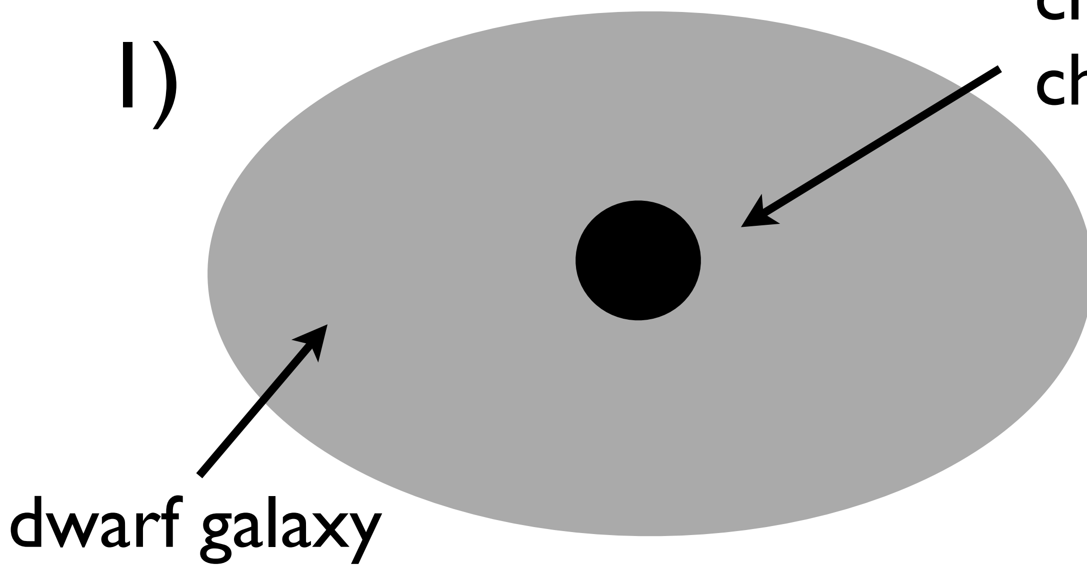


compressive tides are turned off

$$E_1 = \frac{1}{2}M\sigma^2 - \frac{GM^2}{2r_v}$$

(simple) analytical description

1)



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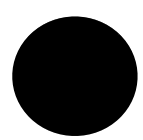

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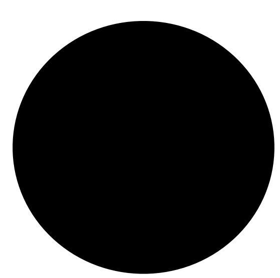
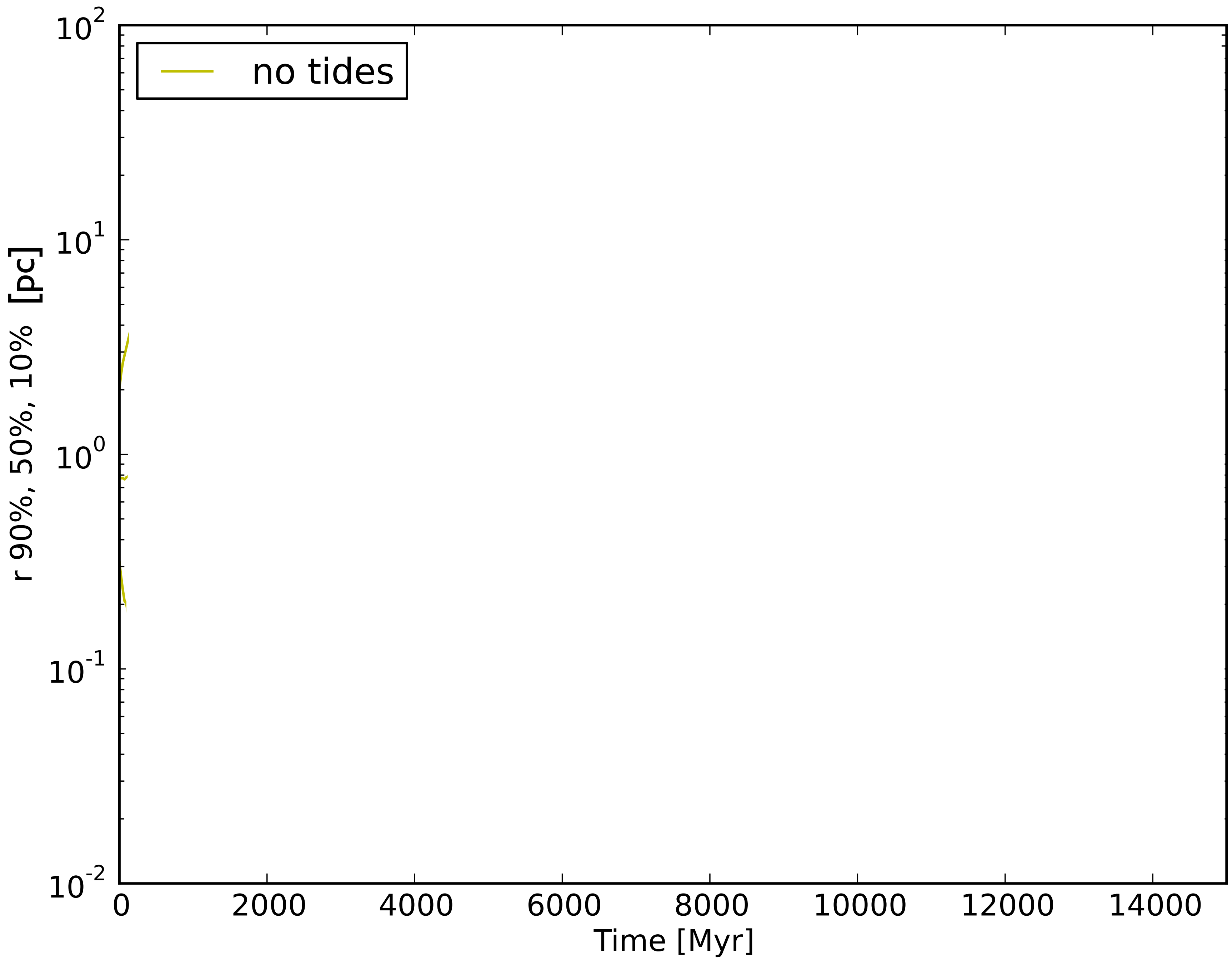


system reaches new virial equilibrium

$$r_v' = r_v \left(\frac{1}{1 + \frac{2\lambda\alpha R_t^2 r_v}{GM}} \right)$$

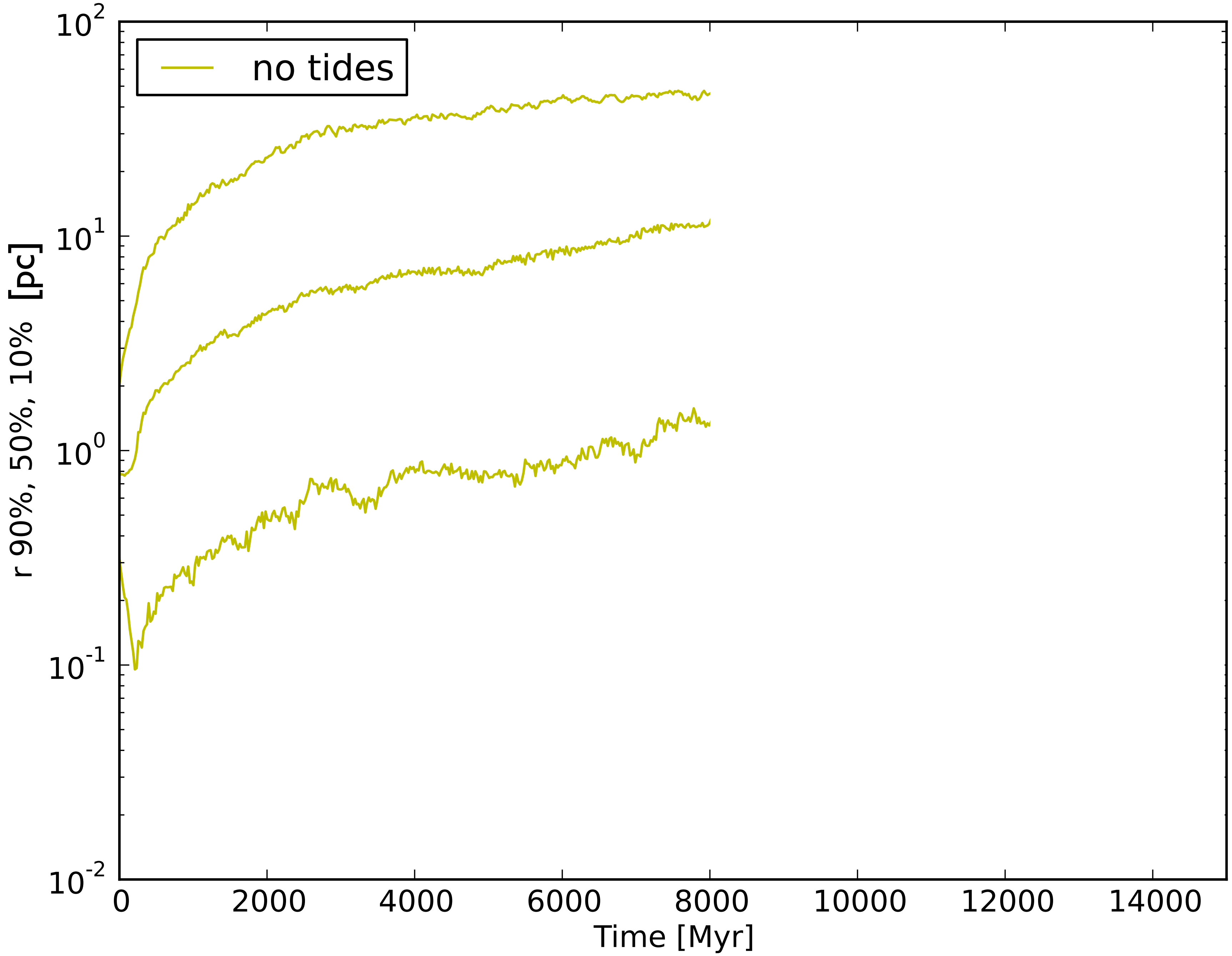
The cluster experiences a drastic change in tidal field and expands

N-body simulations



- nbody6tt (Renaud, Gieles & Boily 2011)
- initial conditions:
4k/8k particles from Plummer sphere
(no initial mass function)
- compressive tides given by the core of a Plummer potential
- switch-off the compressive tides, cluster back to isolation

N-body simulations



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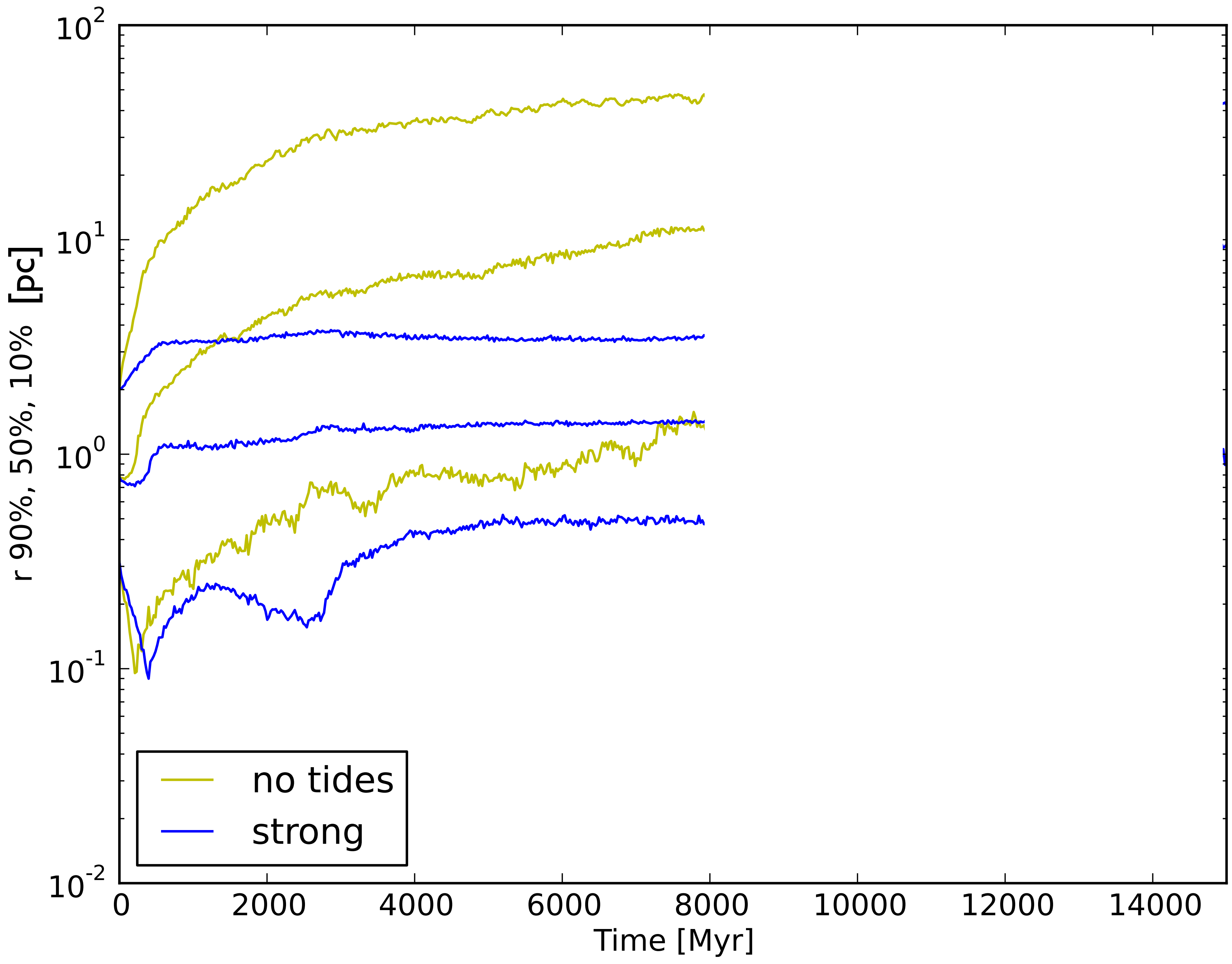


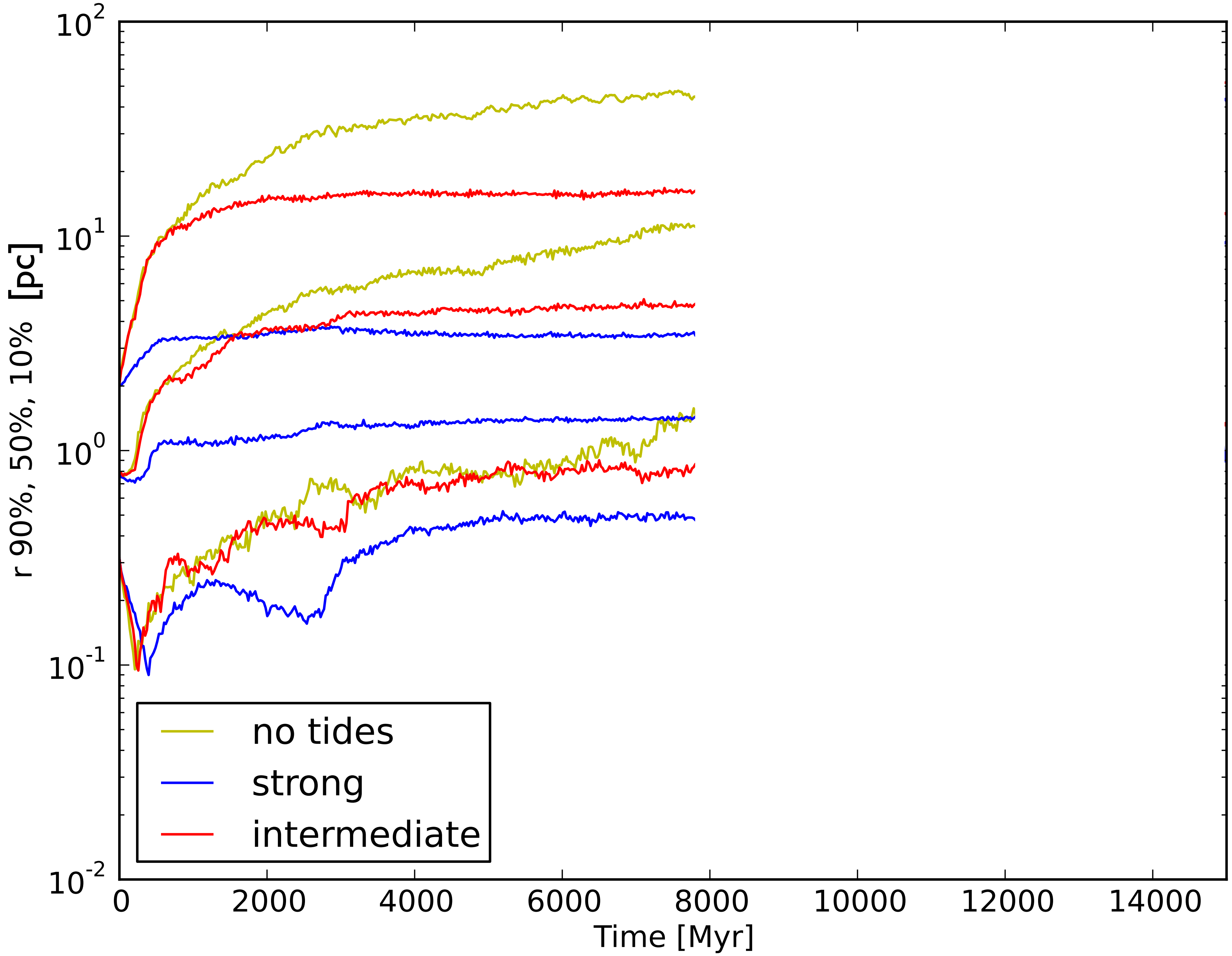
GC in the center of a Plummer potential with:

strong
- R=100 pc, M=10^8 M$_\odot$

intermediate
- R=500 pc, M=10^8 M$_\odot$

weak
- R=1000 pc, M=10^8 M$_\odot$

N-body simulations



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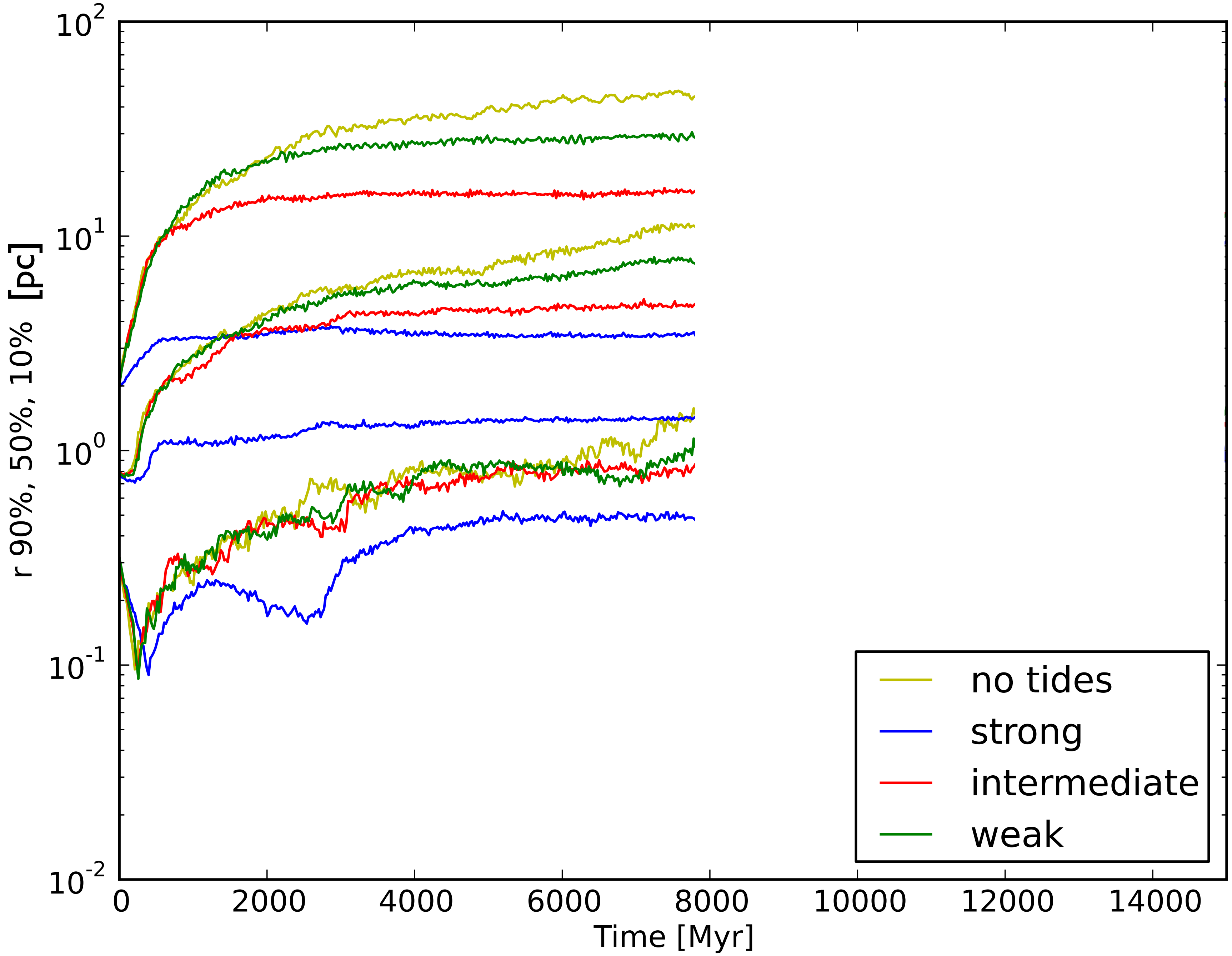

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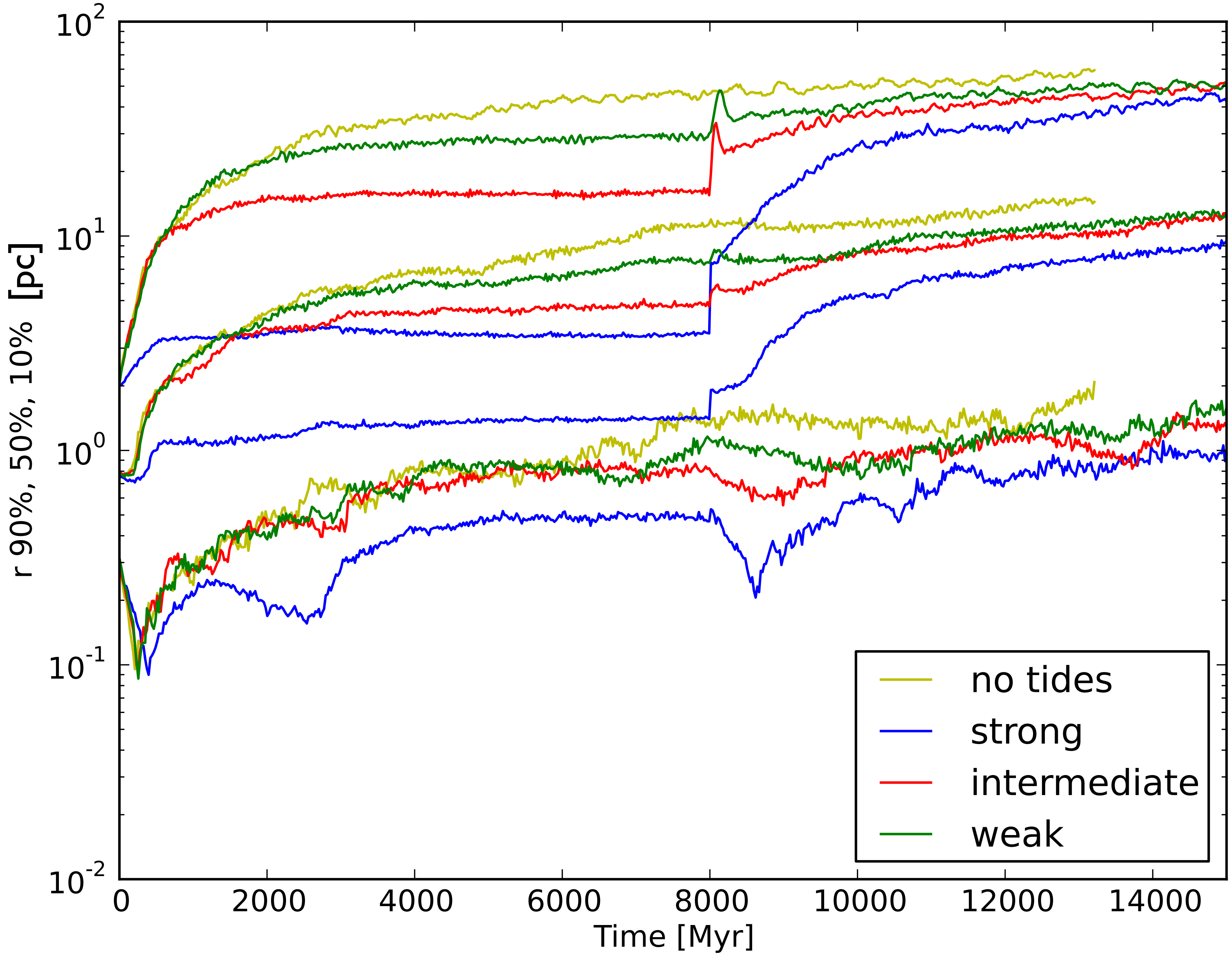

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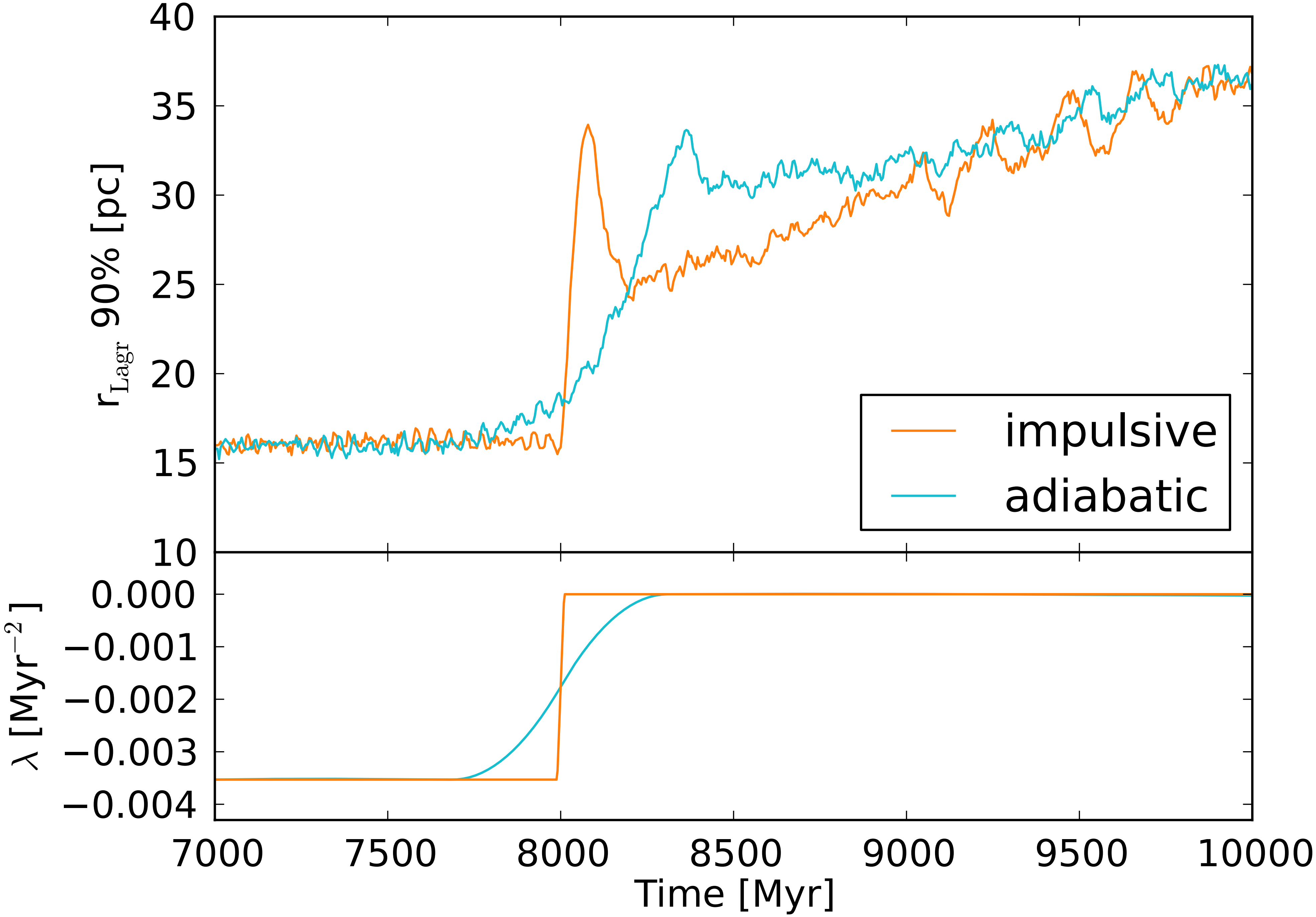
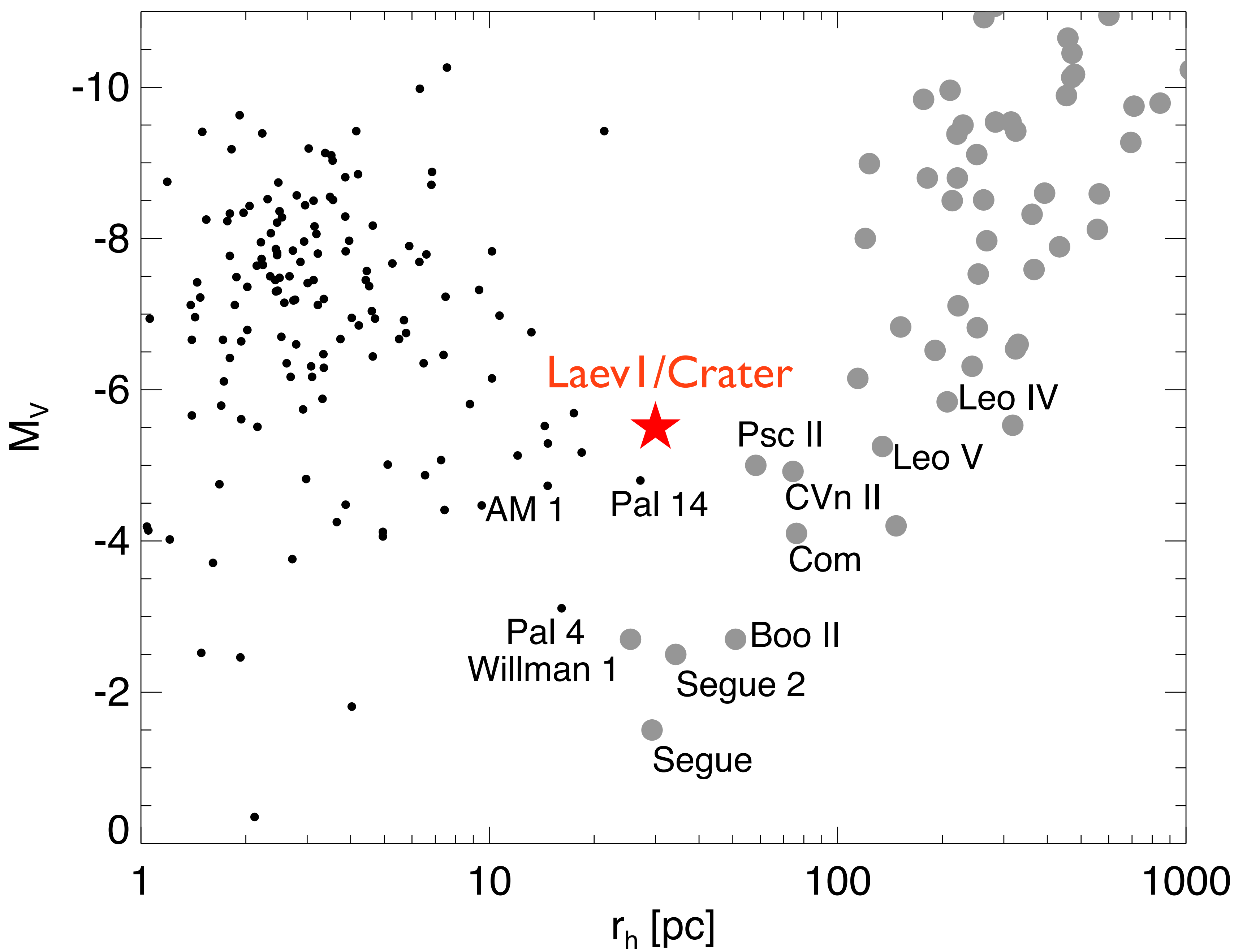
Impulsive vs. adiabatic

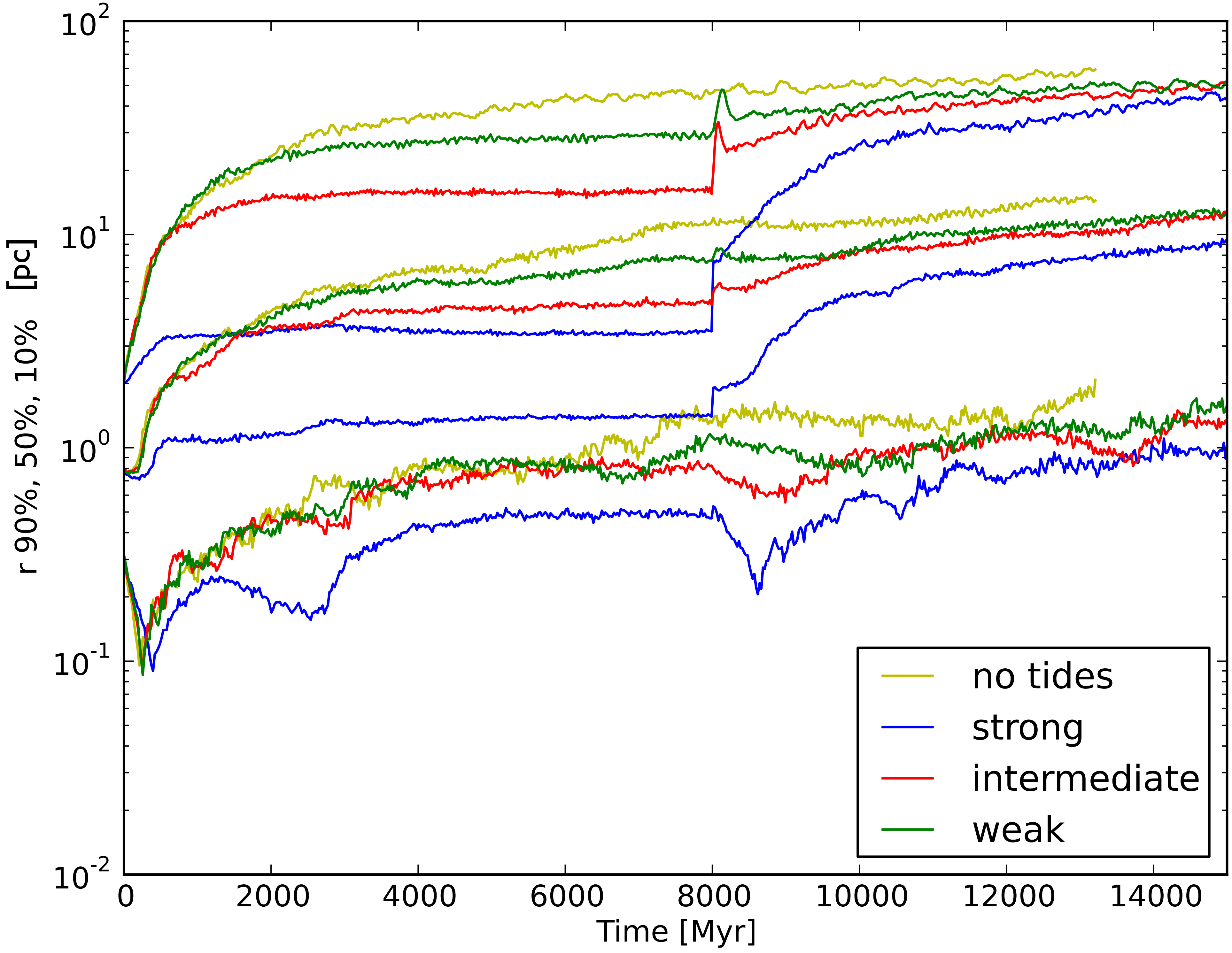


Is the expansion enough?



Belokurov et al. 2014

Is the expansion enough?



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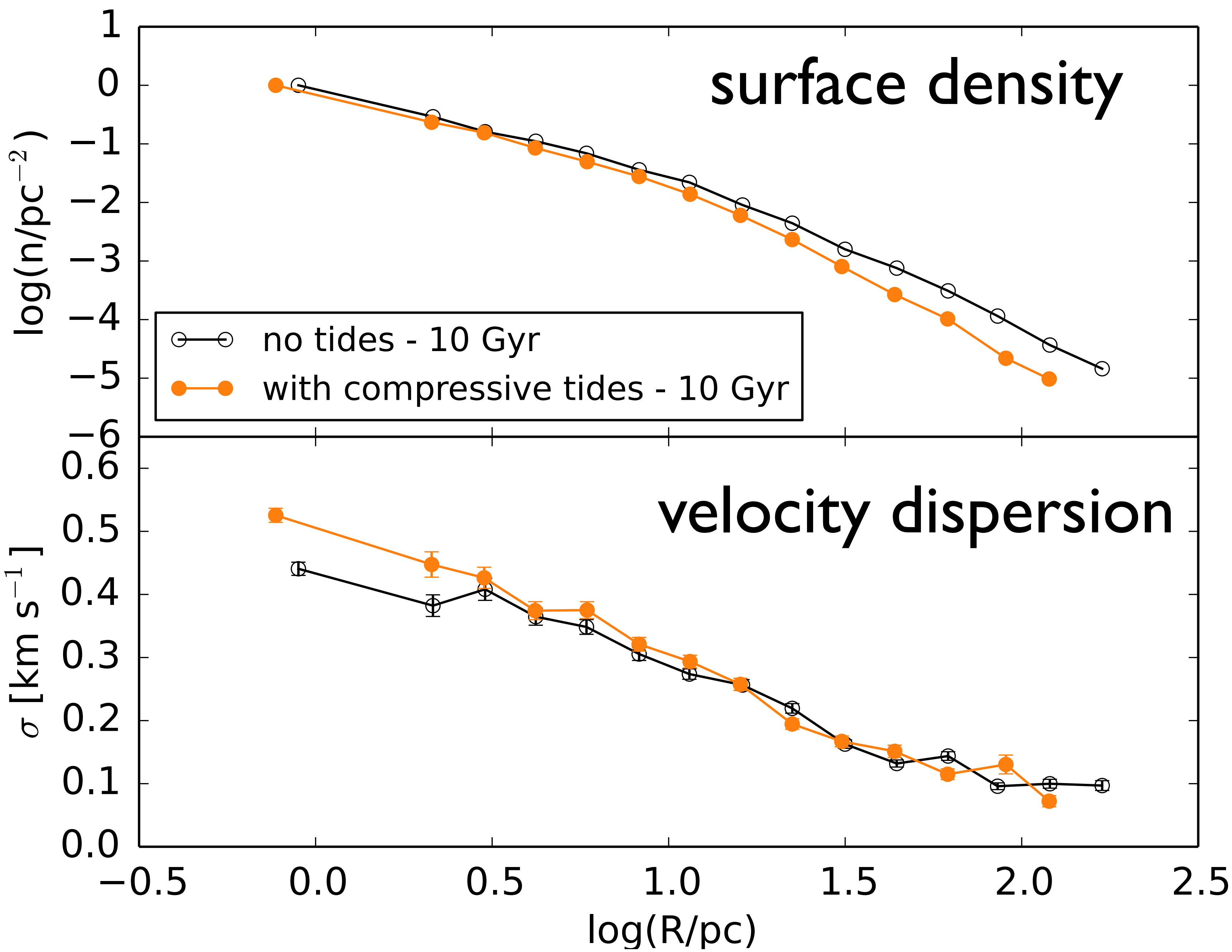


We DO NOT obtain clusters with density profiles more extended than the corresponding isolated case

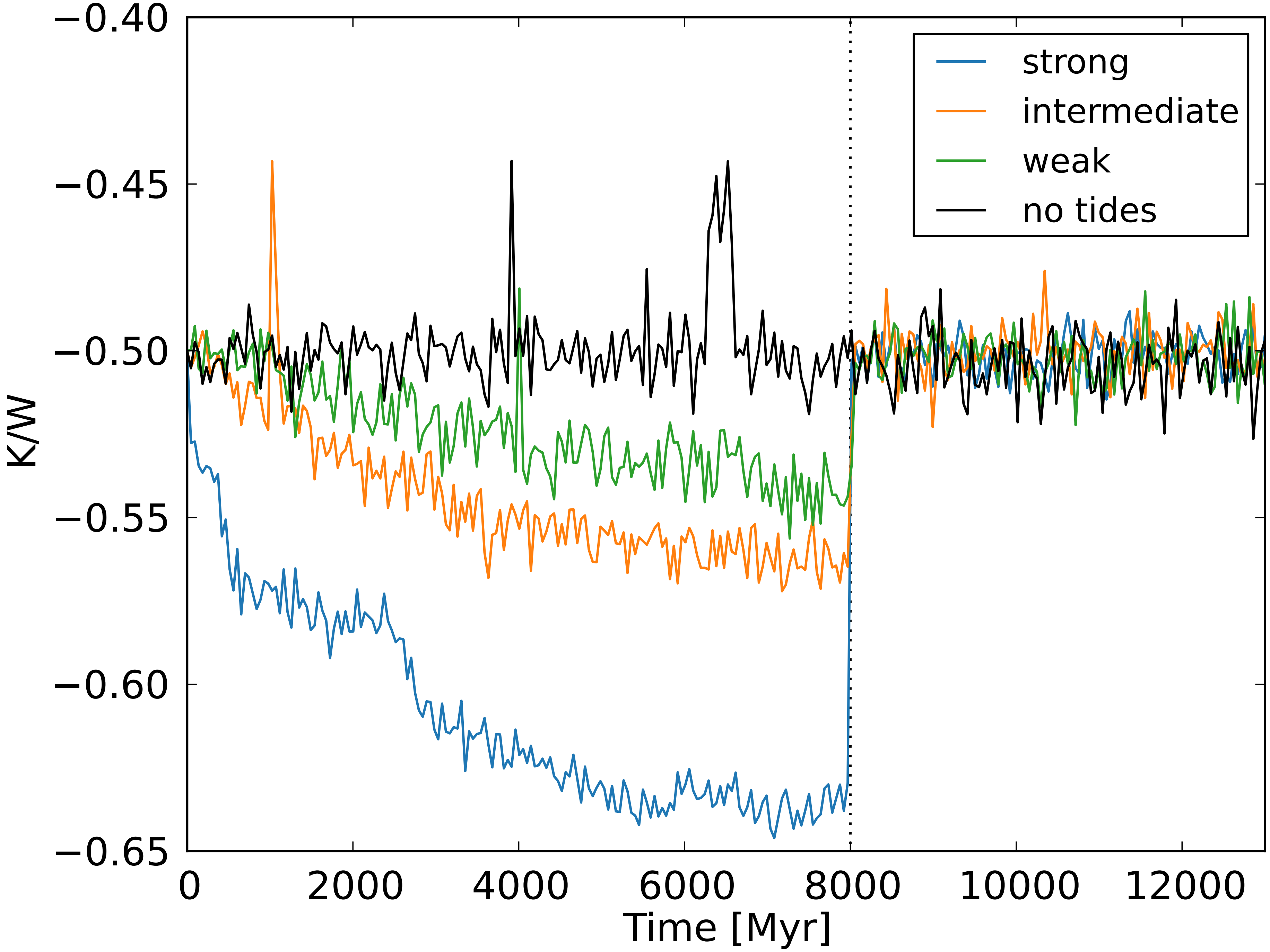
Conclusion

- we explored different initial conditions and configurations
- accreation process cannot explain extended clusters structure
- we tested an extreme case (compressive tides)
- our result is complemetary and consistent with the finding of Miholics et al. (2014)

OPEN QUESTION: how did extended clusters form?

- extended clusters seem to be connected to dwarf galaxies (e.g. extended cluster found in a dwarf, Da Costa et al 2009)

supervirial state



Compressive tides

where do we find these tides? example:

$$\phi(r) = -\frac{GM}{\sqrt{r_0^2 + r^2}}$$

Plummer (1911) potential

$$T^{ij} = -GM\frac{\delta^{ij}\left(r_0^2 + r^2\right) - 3x_i x_j}{\left(r_0^2 + r^2\right)^{5/2}}$$

associated tidal tensor

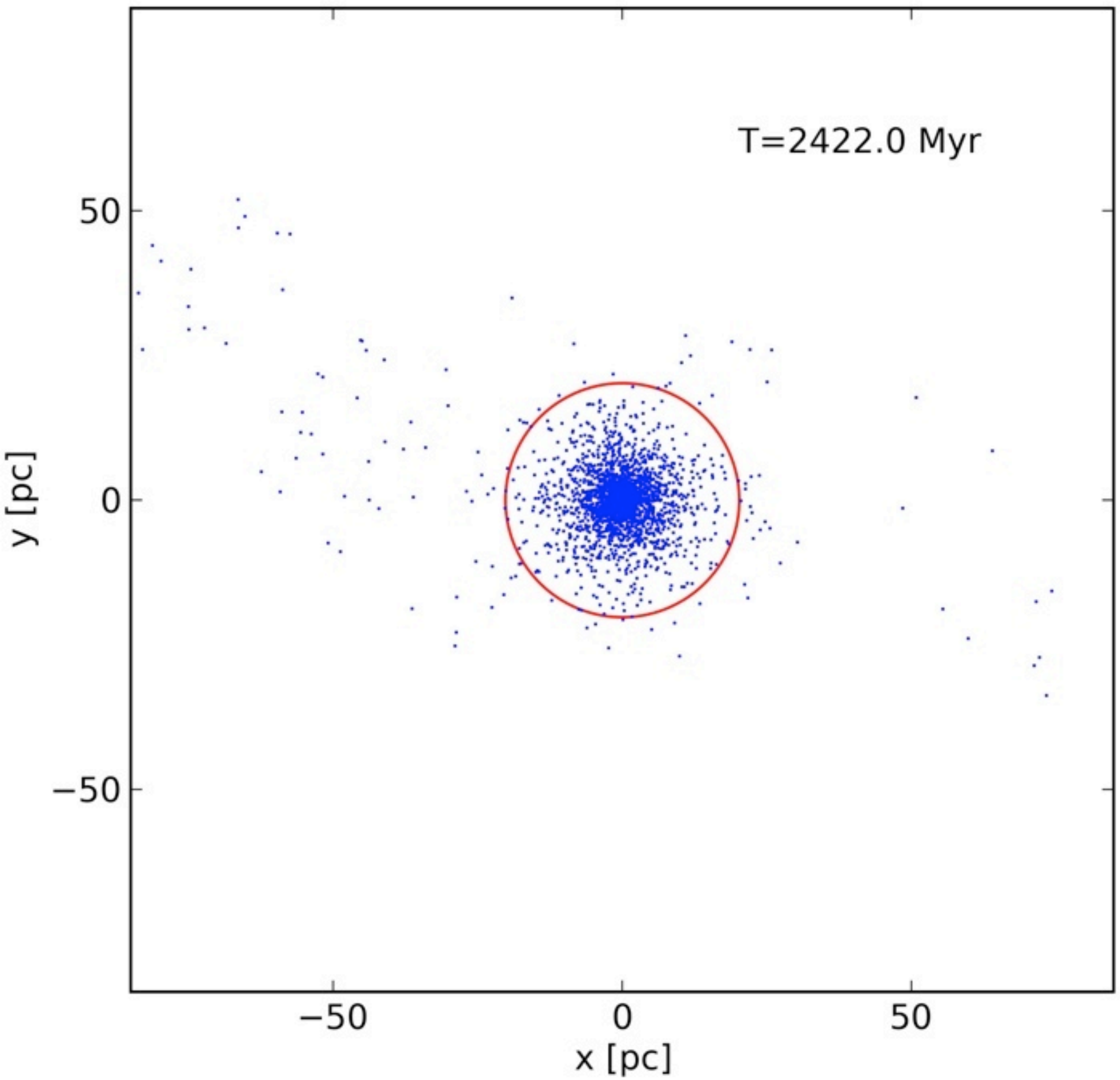
Compressive

$$\lambda_1, \lambda_2, \lambda_3 < 0$$

if

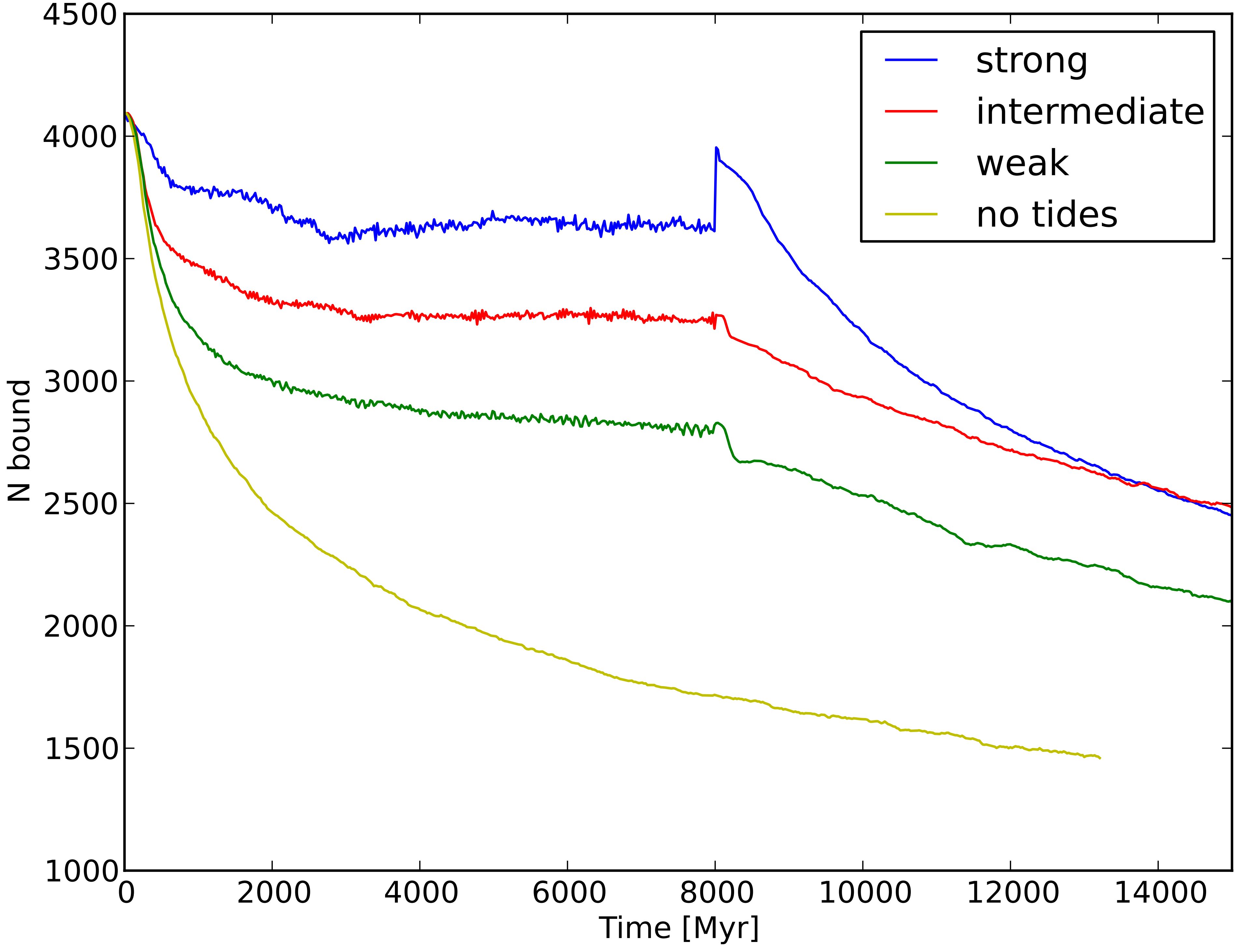
core region

$$r < \frac{r_0}{\sqrt{2}}$$

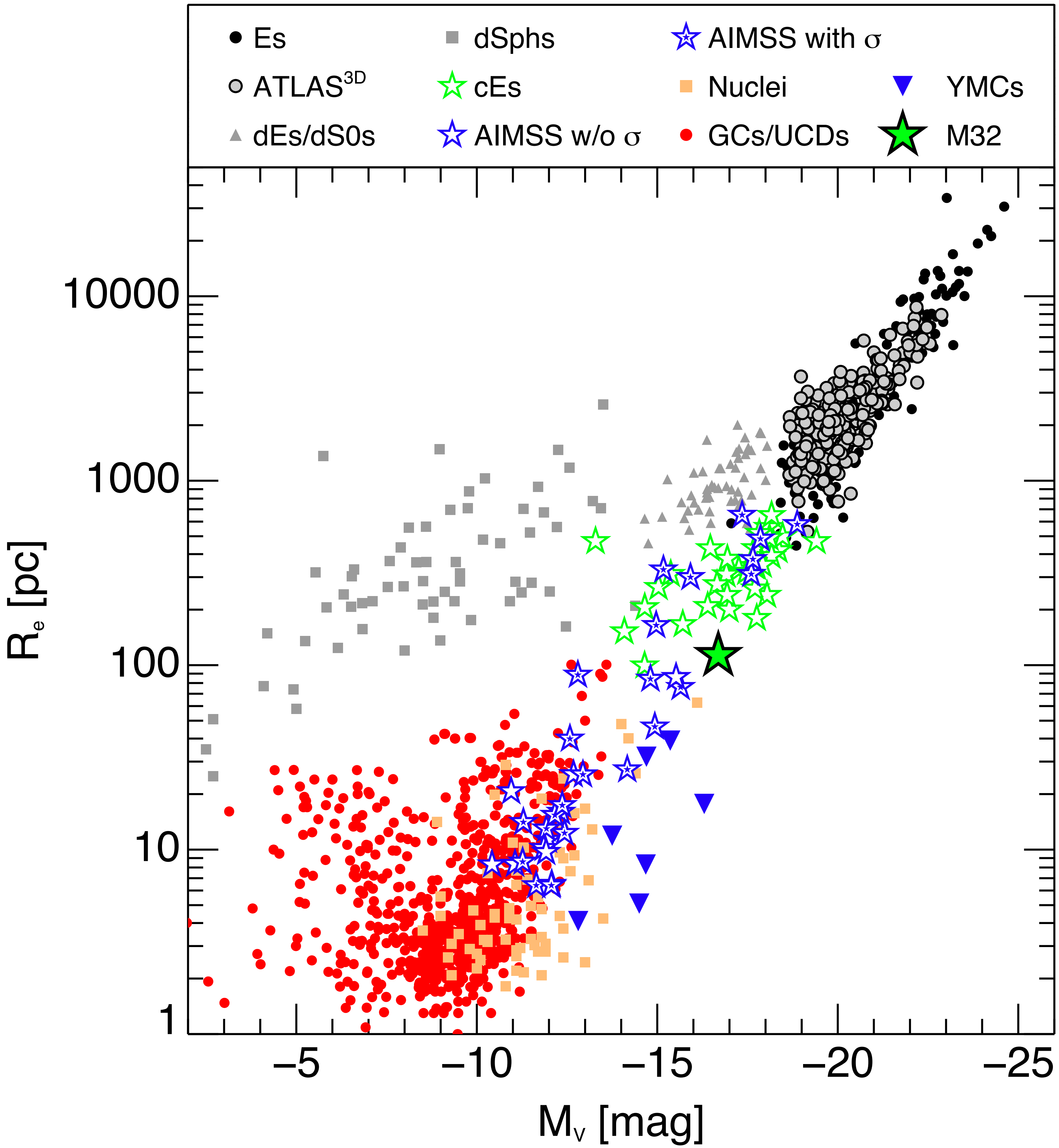


T=2422.0 Myr
50
0
−50
y [pc]
−50
0
50
x [pc]

mass loss



4500
4000
3500
3000
2500
2000
1500
1000
N bound
0
2000
4000
6000
8000
10000
12000
14000
Time [Myr]
strong
intermediate
weak
no tides


Es
dSphs
AIMSS with σ
ATLAS3D
cEs
Nuclei
YMCs
dEs/dS0s
AIMSS w/o σ
GCs/UCDs
M32
10000
1000
100
10
1
Re [pc]
−5
−10
−15
−20
−25
MV [mag]