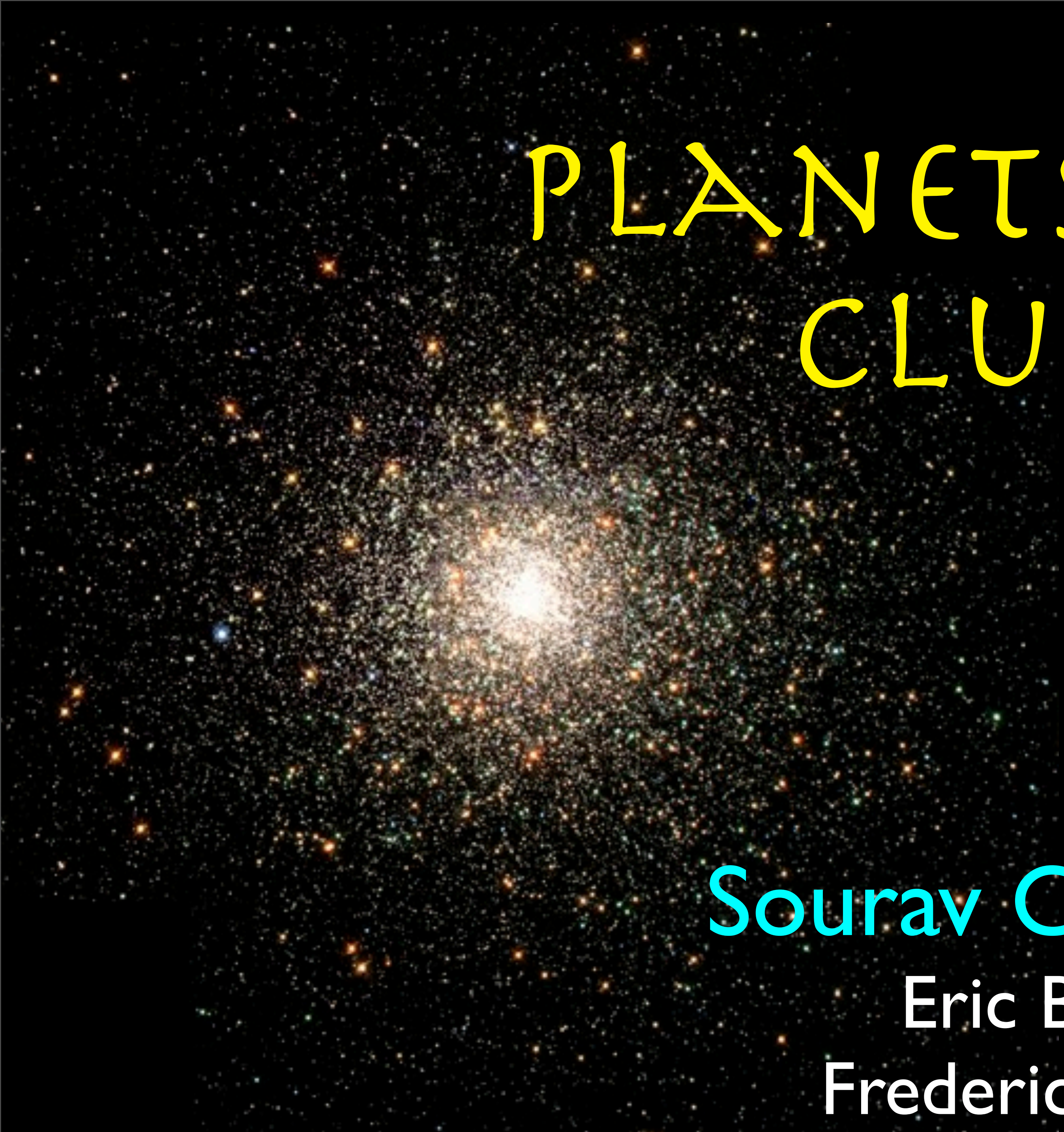
Planets in Star Clusters



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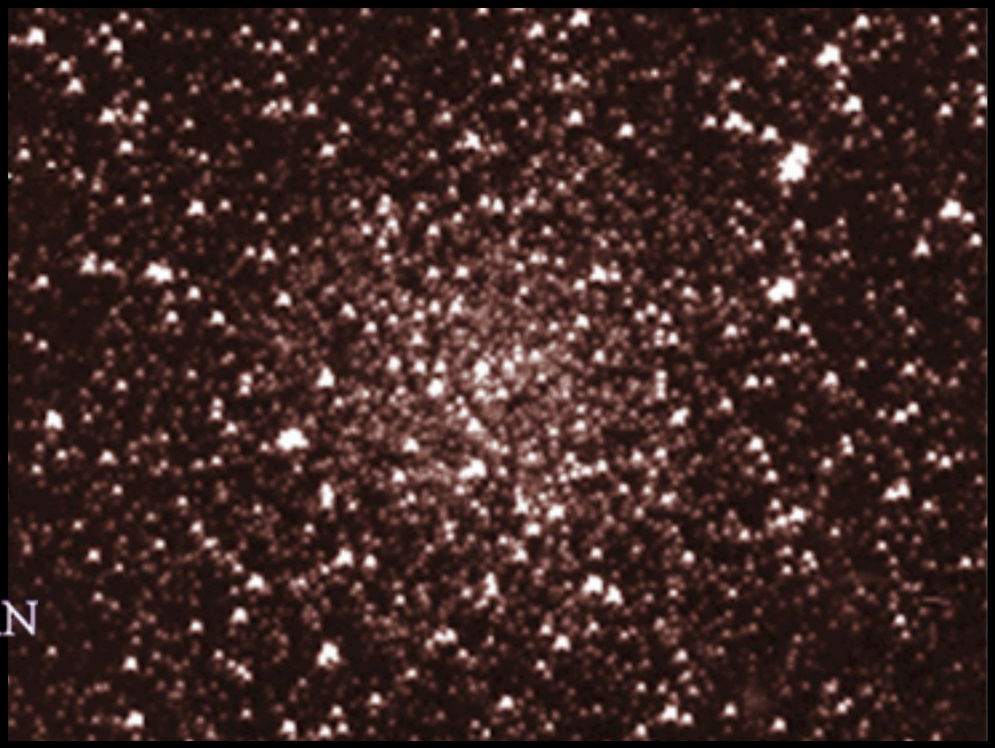

What do we know about planets in star clusters?

- Few observed planets in star clusters
  - Planet around giant ε Tauri in Hyades (Bunéi et al. 2007)
  - Null results in 47tuc (Gilliland et al. 2000, Weldrake et al. 2005)
  - Pulsar planets in M4 (e.g., Backer 1993; Thorsett et al. 1999)
- Possible explanations
  - Metallicity vs planet-occurrence correlation
  - Stellar dynamics

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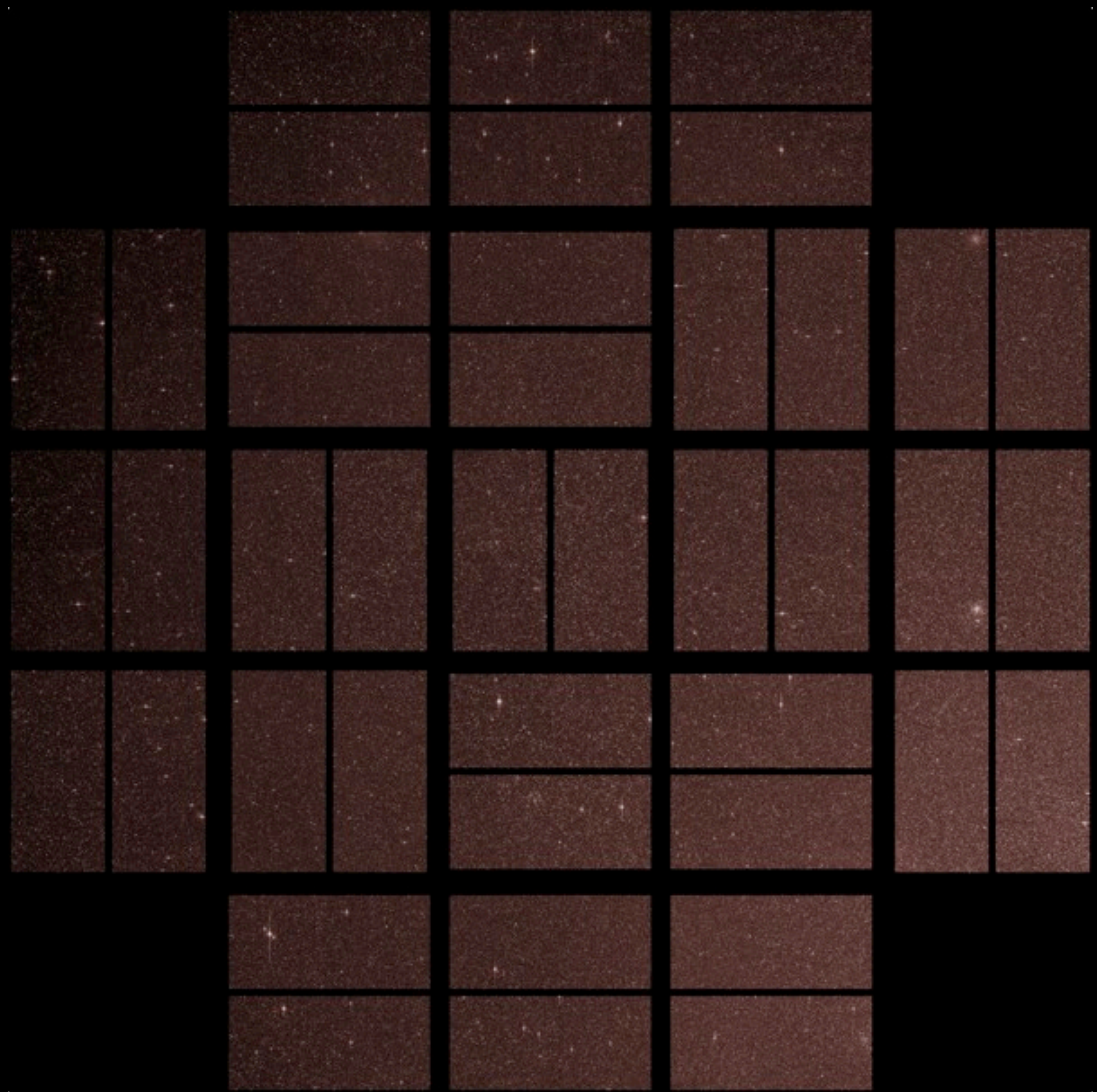
Do planets form around cluster stars at the same rate as they do around field stars?

Open Star Clusters in Kepler Field



Courtesy: kepler.nasa.gov

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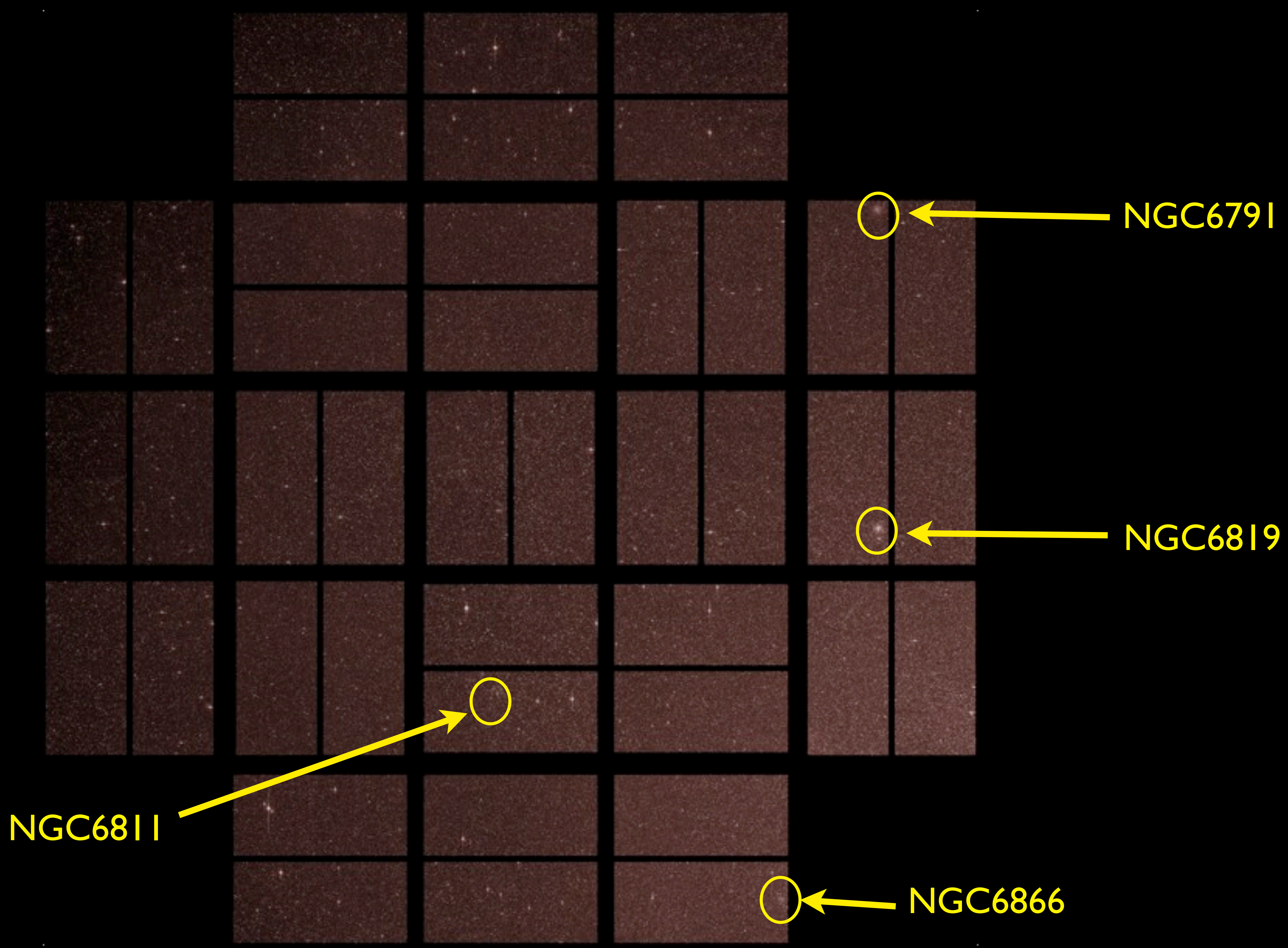

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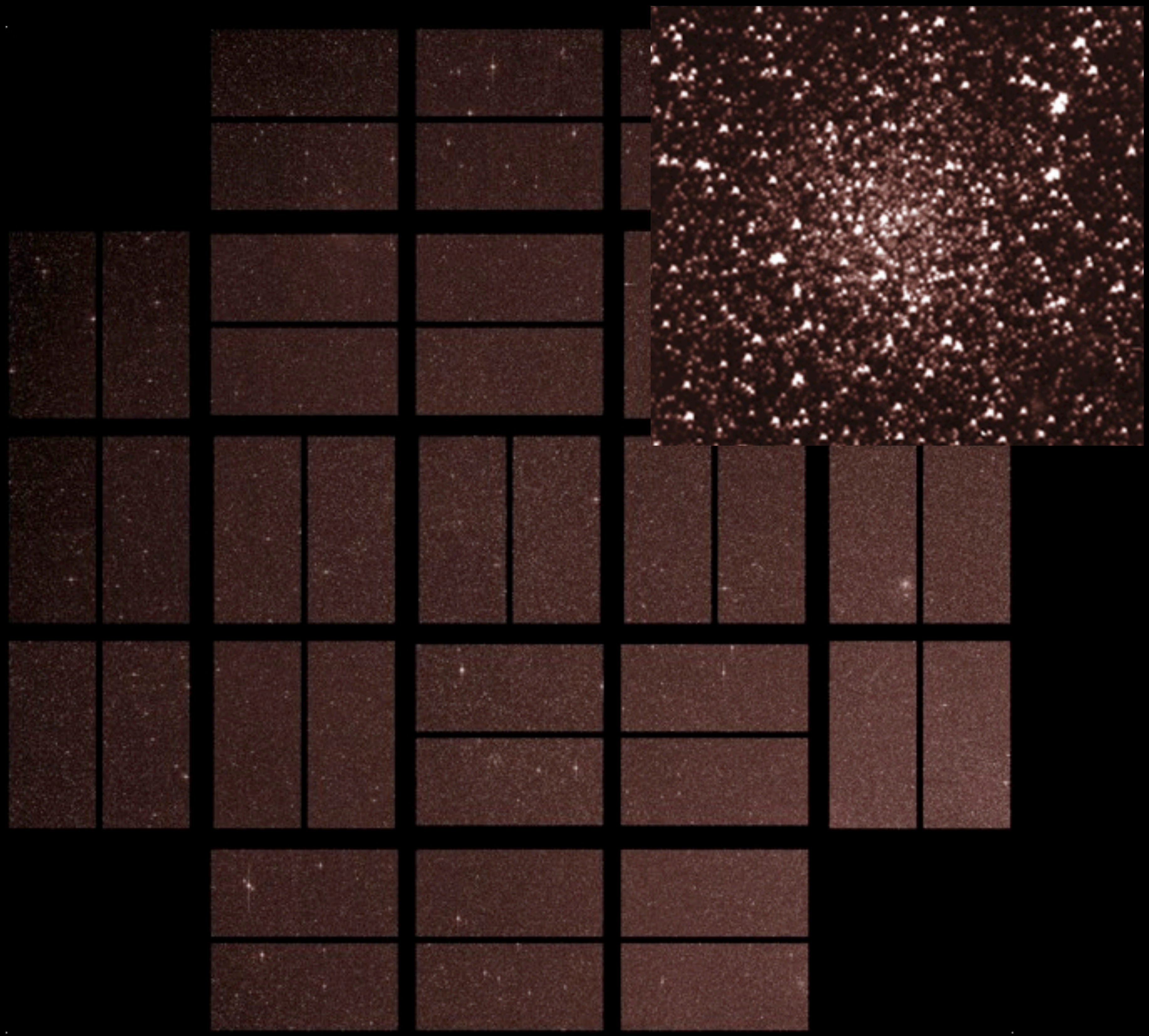
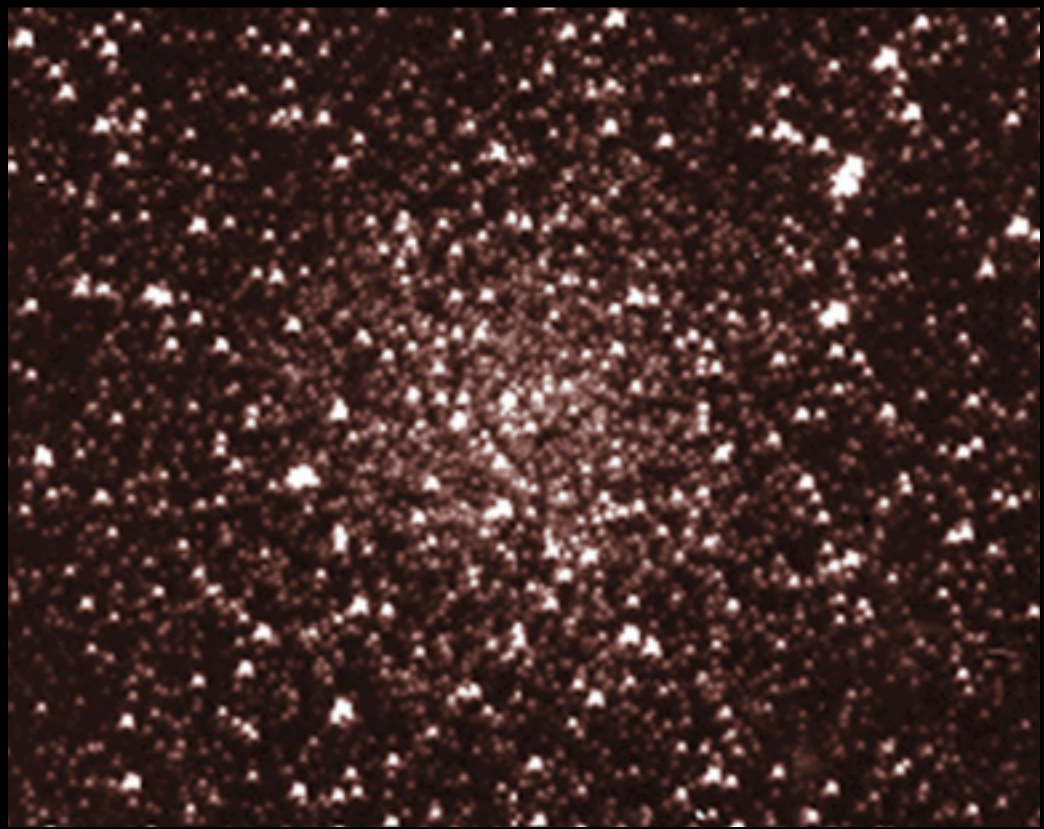


Courtesy: kepler.nasa.gov

Open Cluster NGC6791 in Kepler Field of View



- Super-Solar metallicity: Fe/H = 0.3
- High stellar number
- Low-density compared to typical GGCs
- In the field of view of Kepler

Property	Typical GC	NGC6791
Mass ($M_\odot$)	1×10^5	5×10^3
Central Density ($M_\odot pc^{-3}$)	1×10^4	30

METHOD

Hénon-type Monte Carlo Cluster Evolution Code

- Modeling star clusters using a Hénon-type Monte Carlo code "CMC"
  - Two-body relaxation (Joshi, Rasio, & Portegies Zwart 2000)
  - Single and binary stellar evolution (Chatterjee et al. 2010)
  - Strong interactions including physical collisions and binary mediated interactions (Fregeau & Rasio 2007)
  - Galactic tidal stripping (Joshi, Nave, & Rasio 2001; recently updated in Chatterjee et al. 2010)
- Large ranges of initial mass, compactness (w_0), initial binary fraction (f_b) are explored
  - A typical Galactic GC
  - NGC6791: Open cluster in the Kepler field of view

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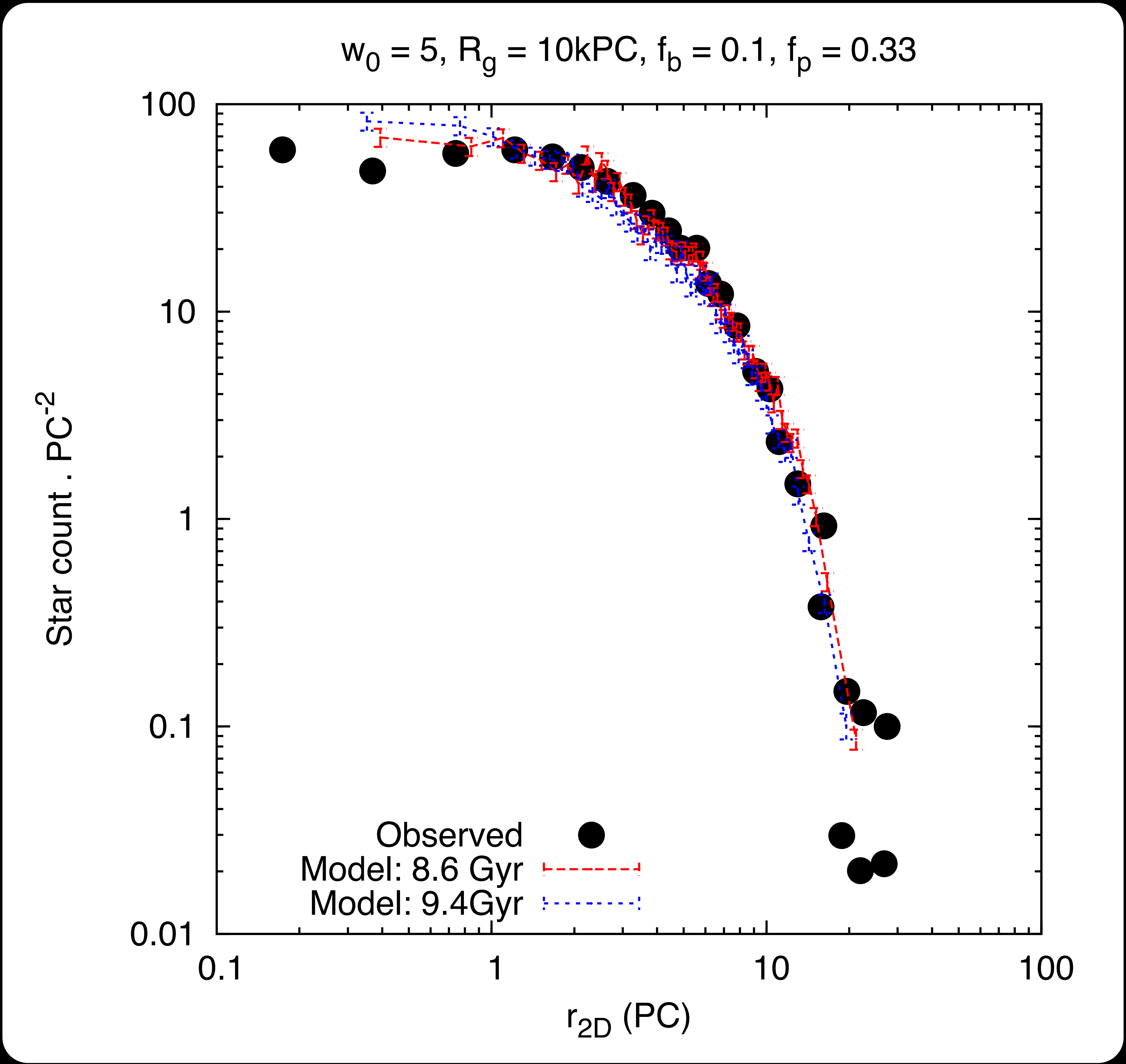
THE BEST-FIT MODEL OF NGC6791



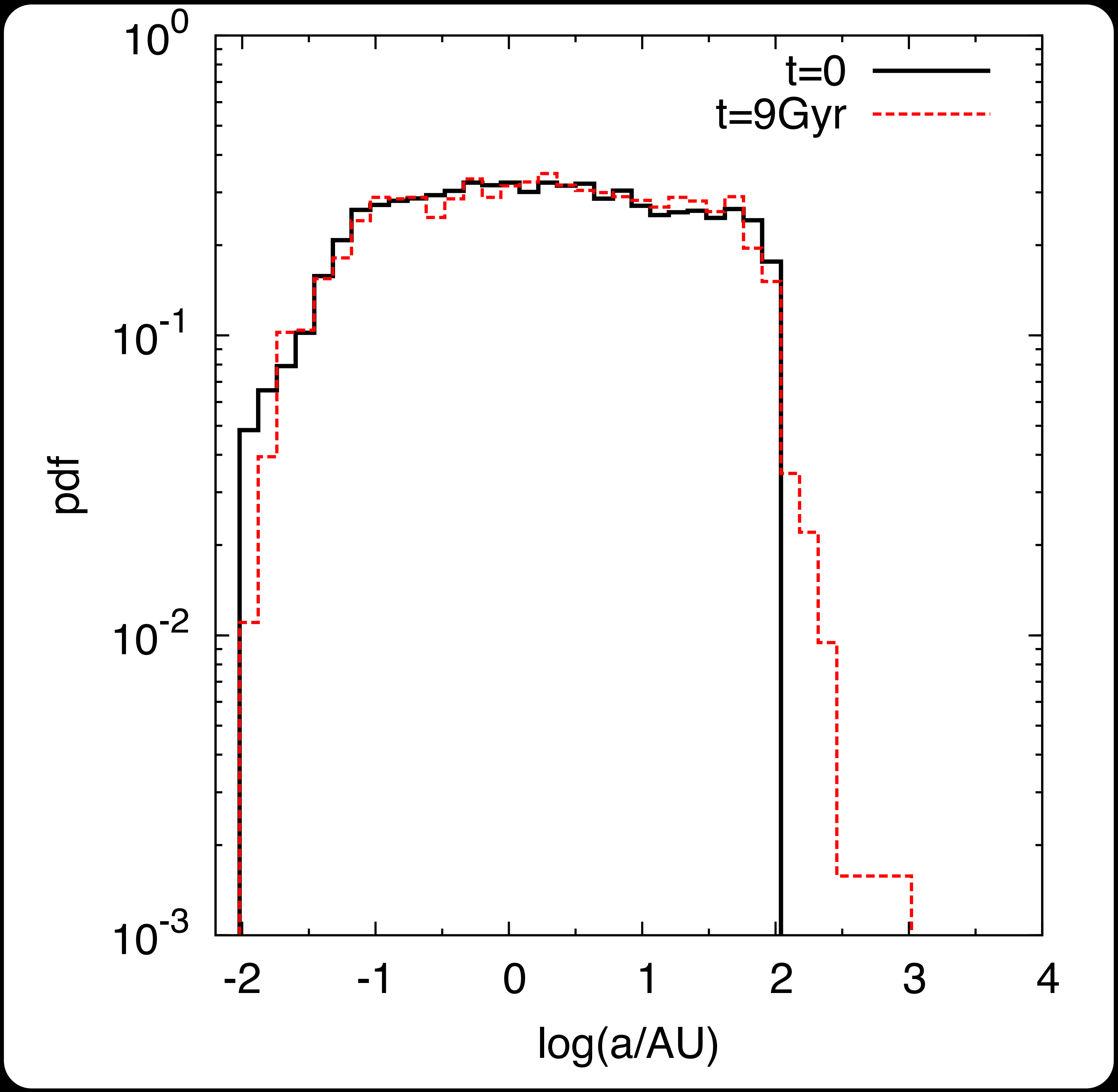
Best fit parameters out of ~200 models:

- $N_i = 5 \times 10^4$
- $w_0 = 5$
- $r_v = 8$ pc
- $R_g = 10$ Kpc
- $f_b = 0.1$
- $f_p = 0.33$

(Platais et al. 2011)

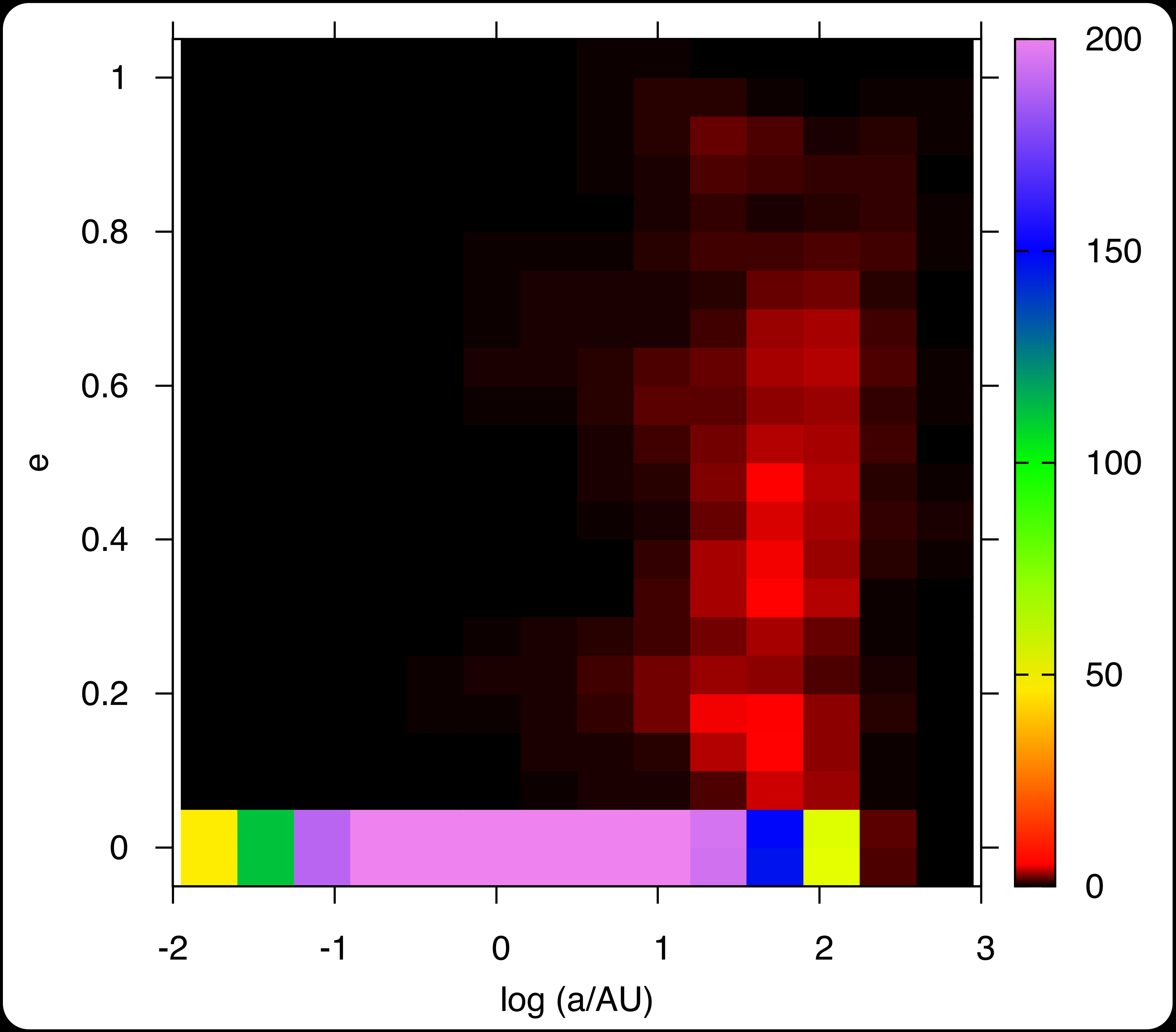
Effects of Stellar Dynamics on Planetary Orbits

a - distribution



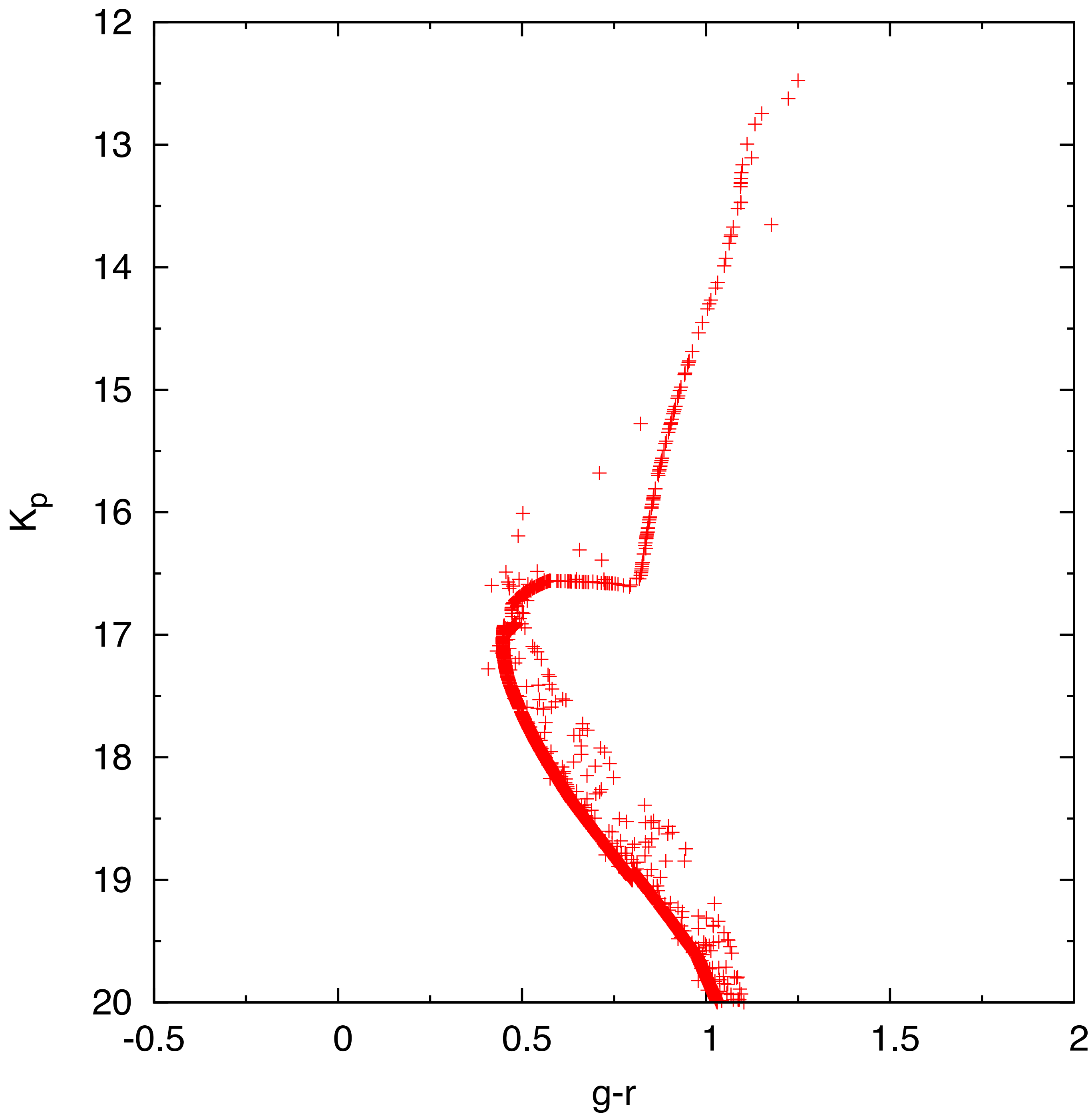
Semimajor axis distribution is mostly unchanged even for a ~ 100 AU

Effects of Stellar Dynamics on Planetary Orbits
a & *e*



- ~7% of large-a orbits acquire non-zero e
- Disturbed systems may create exotic planets
- Outer planet mediated indirect instability of close-in planets is rare

SYNTHETIC CMD FOR NGC6791



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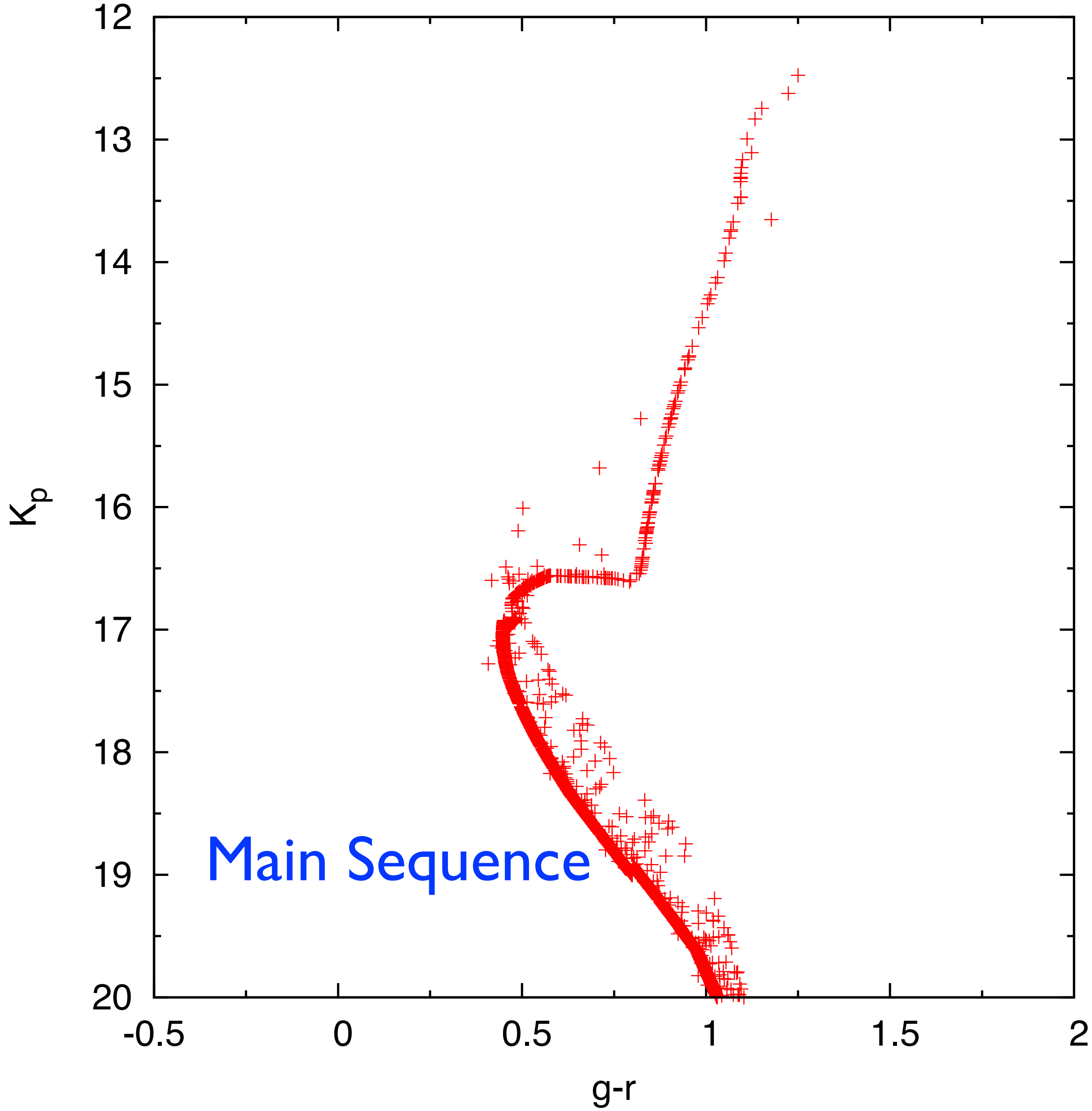
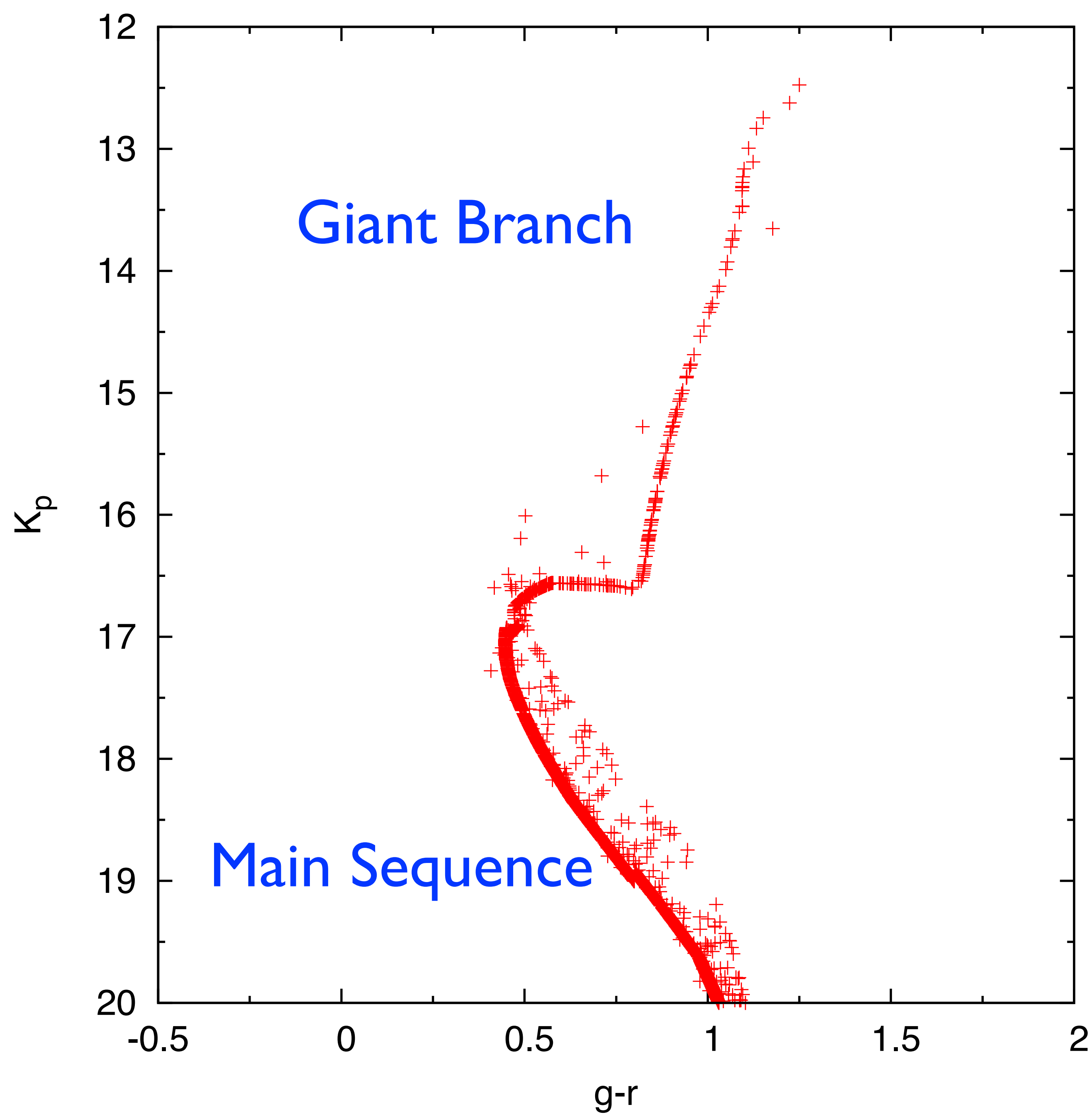


Synthetic CMD for NGC6791



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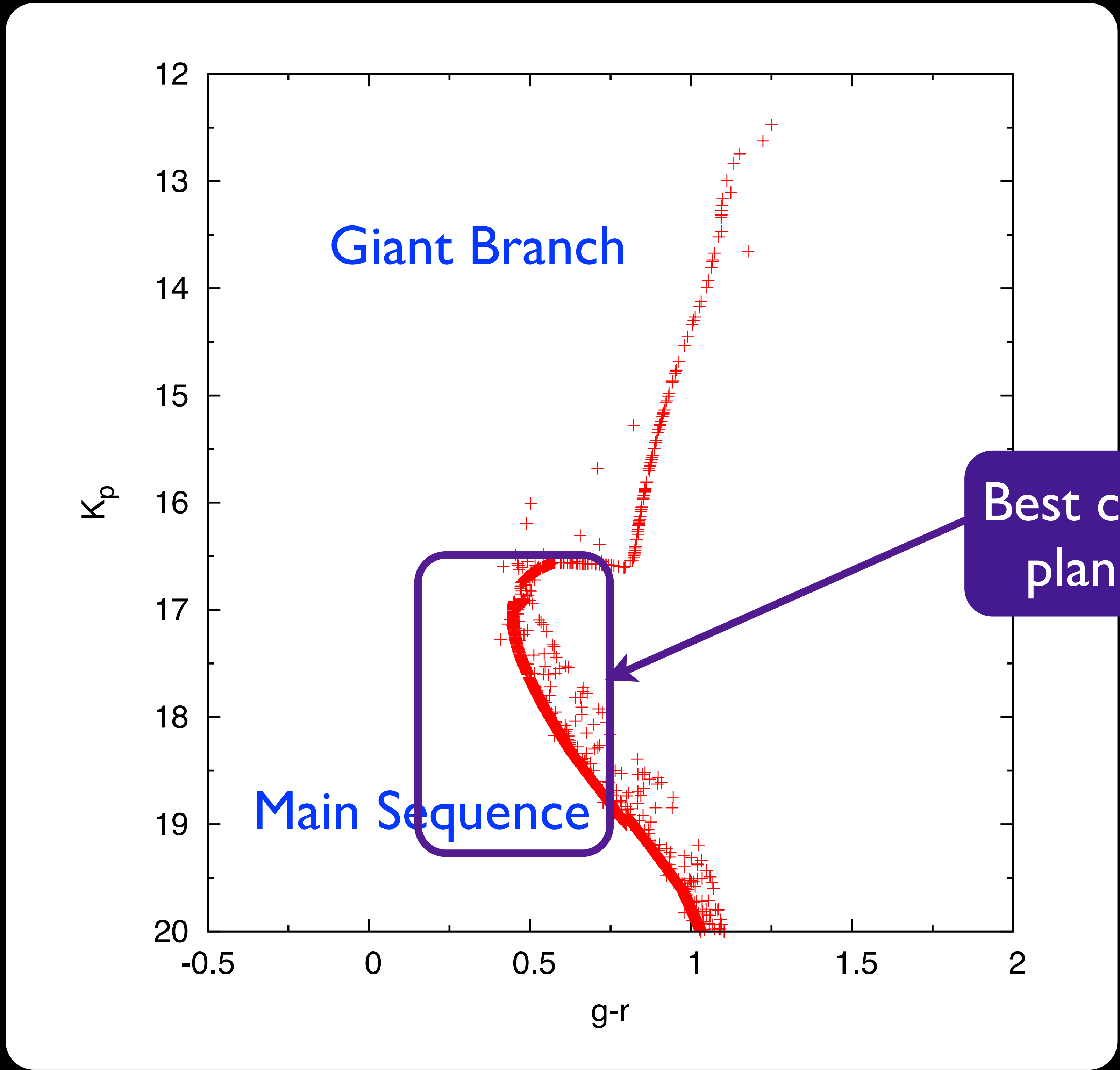
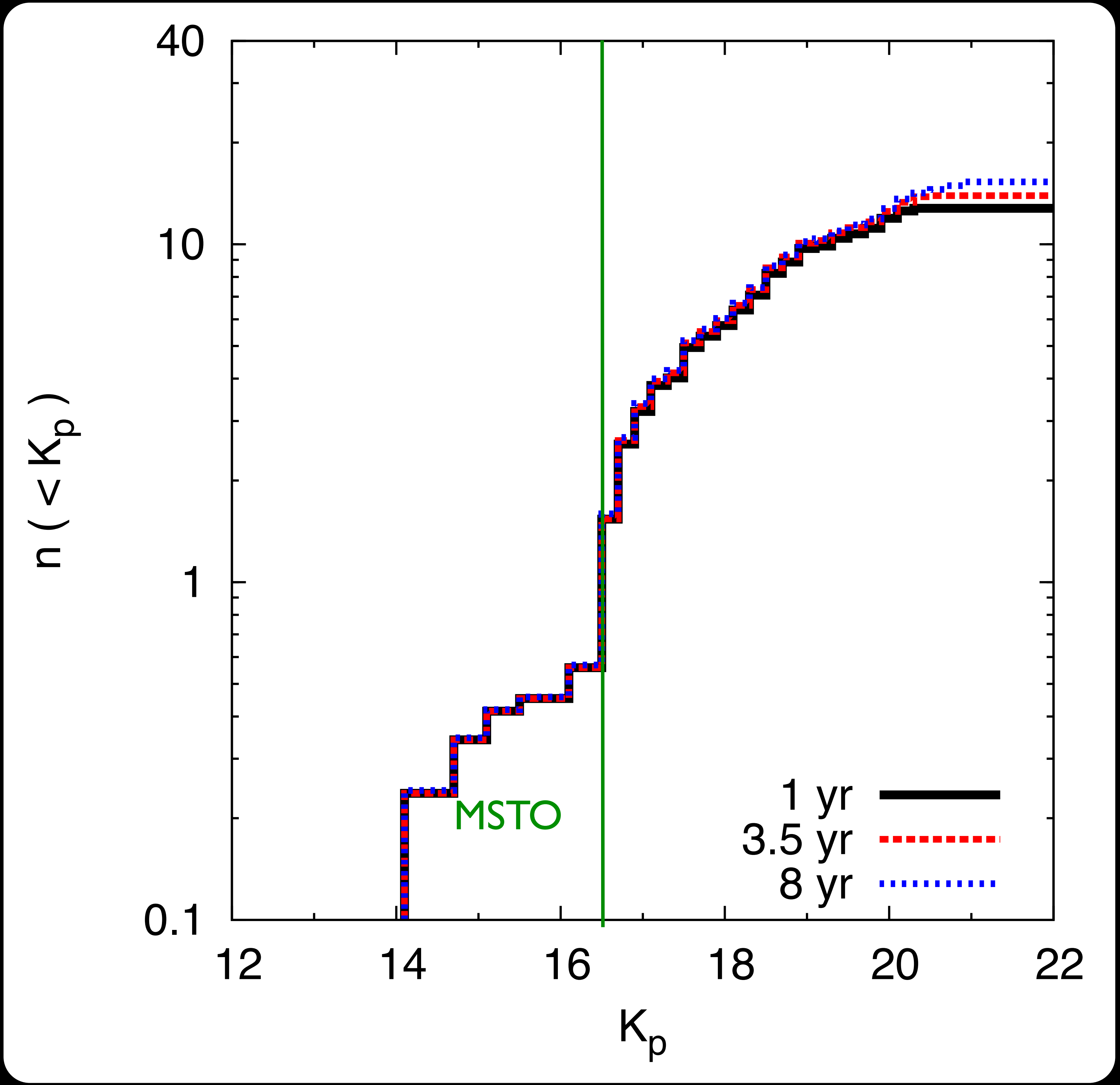


Best chance to discover planets using Kepler

Detectable Planets (SNR>7)

n_p vs K_p



Detectable Planets (SNR>7)

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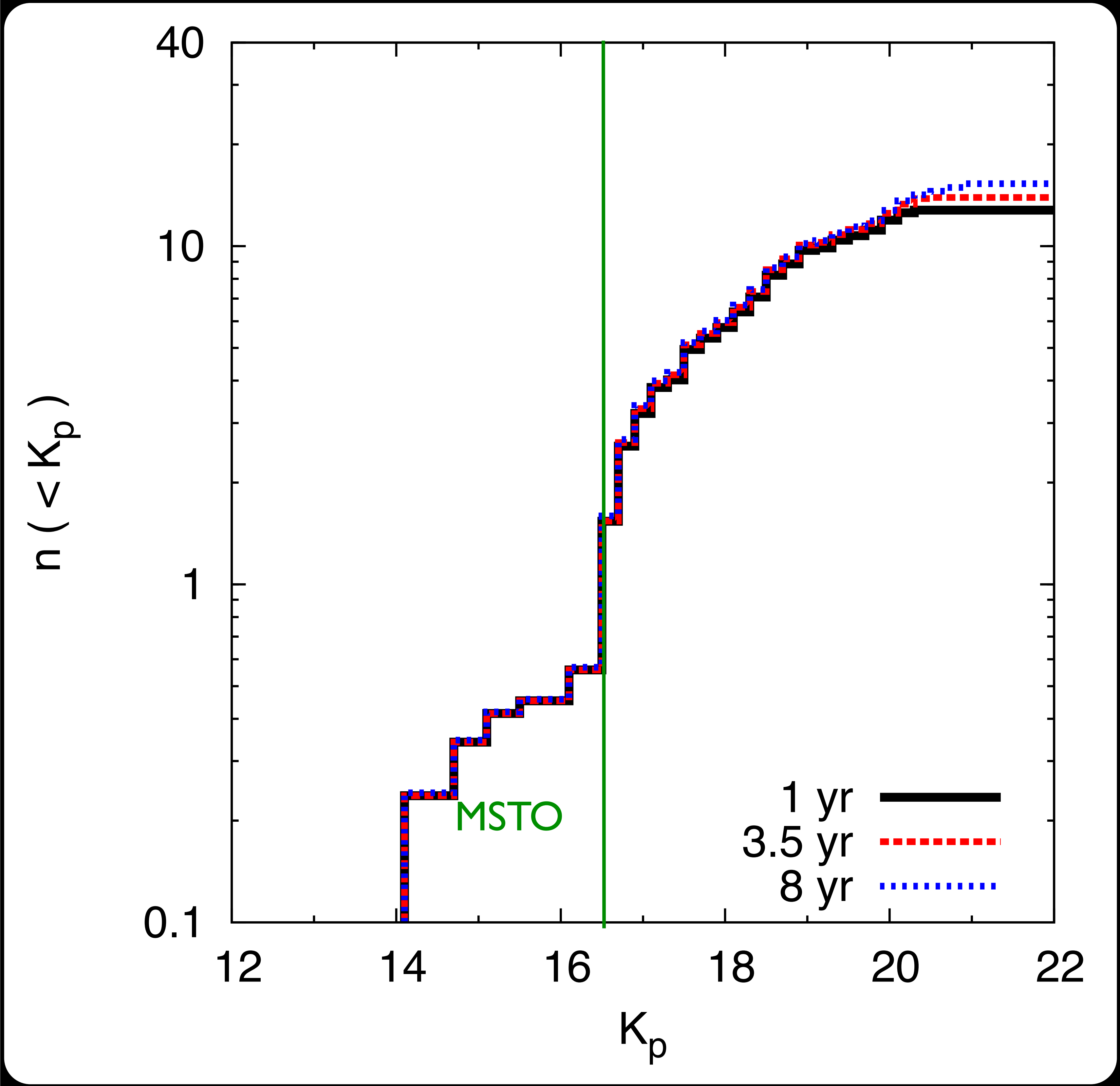
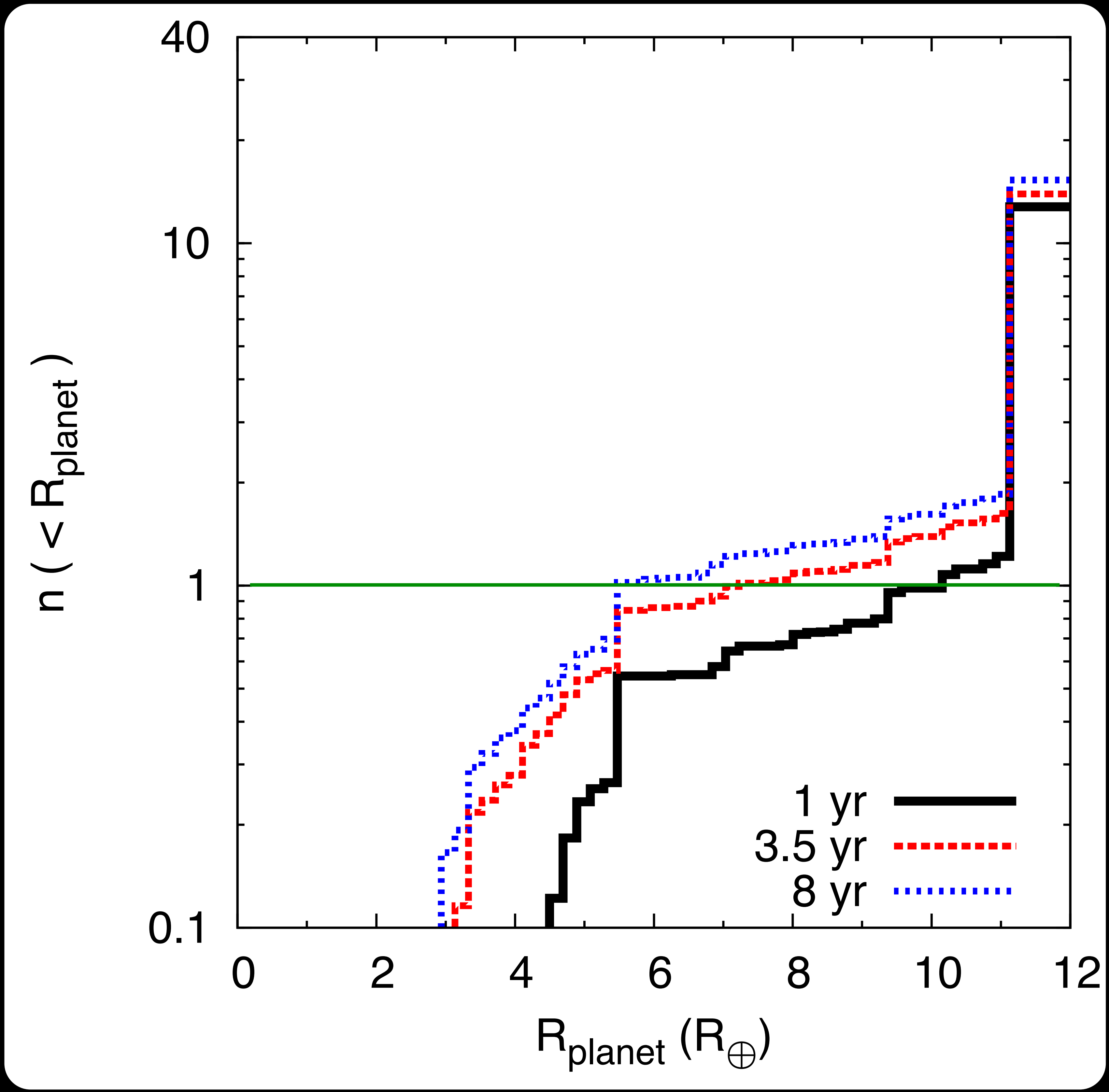


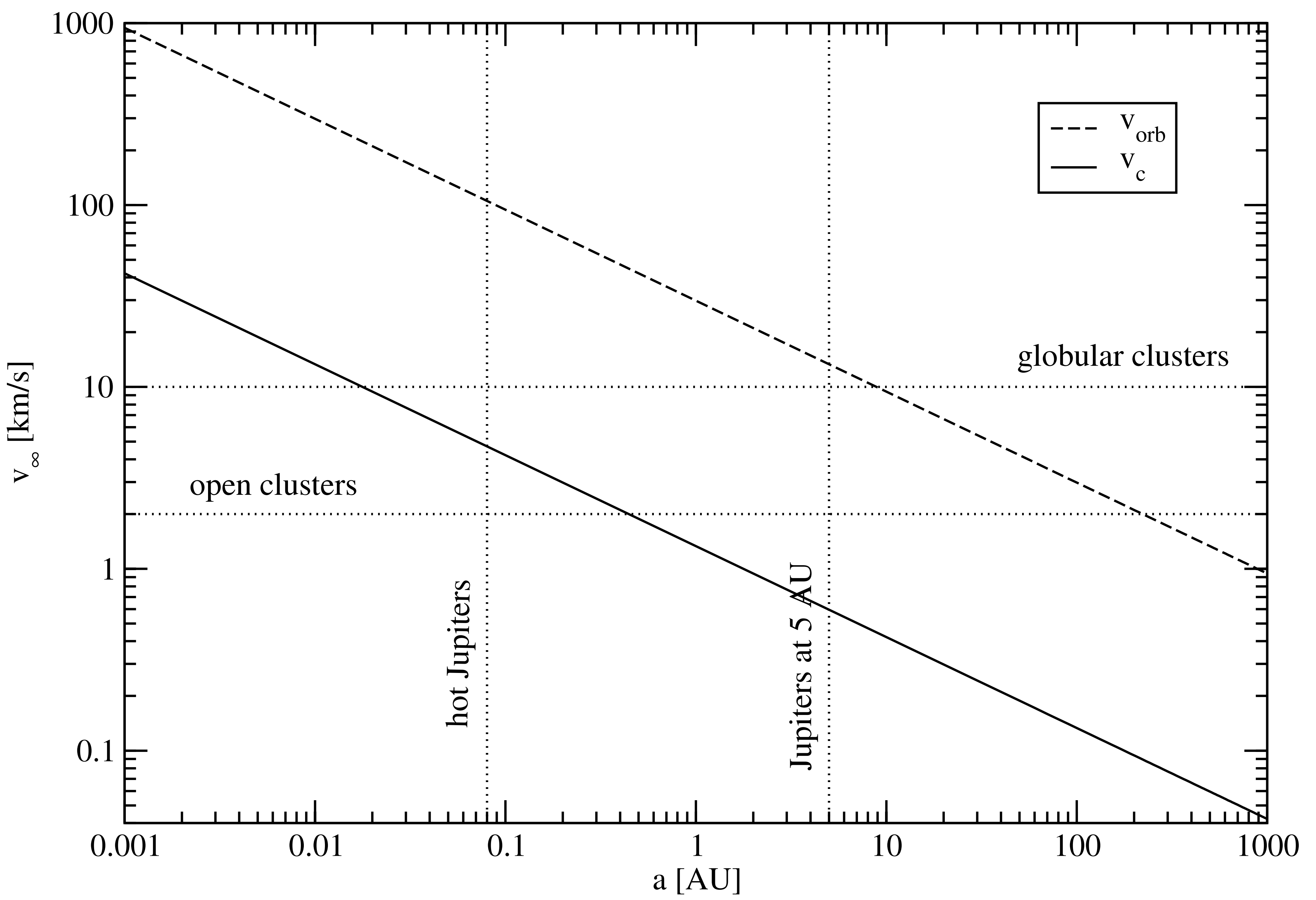
- ~10 detections within a year of data collection
- Faint stars should not be neglected (16.5 < K_p < 20)
- Kepler could be the first to discover *planets around normal MS cluster stars*

Detectable Planets (SNR>7)

n_p vs R_p



Can planets be exchanged into circumbinary orbits?



(Fregeau, Chatterjee, & Rasio 2006)

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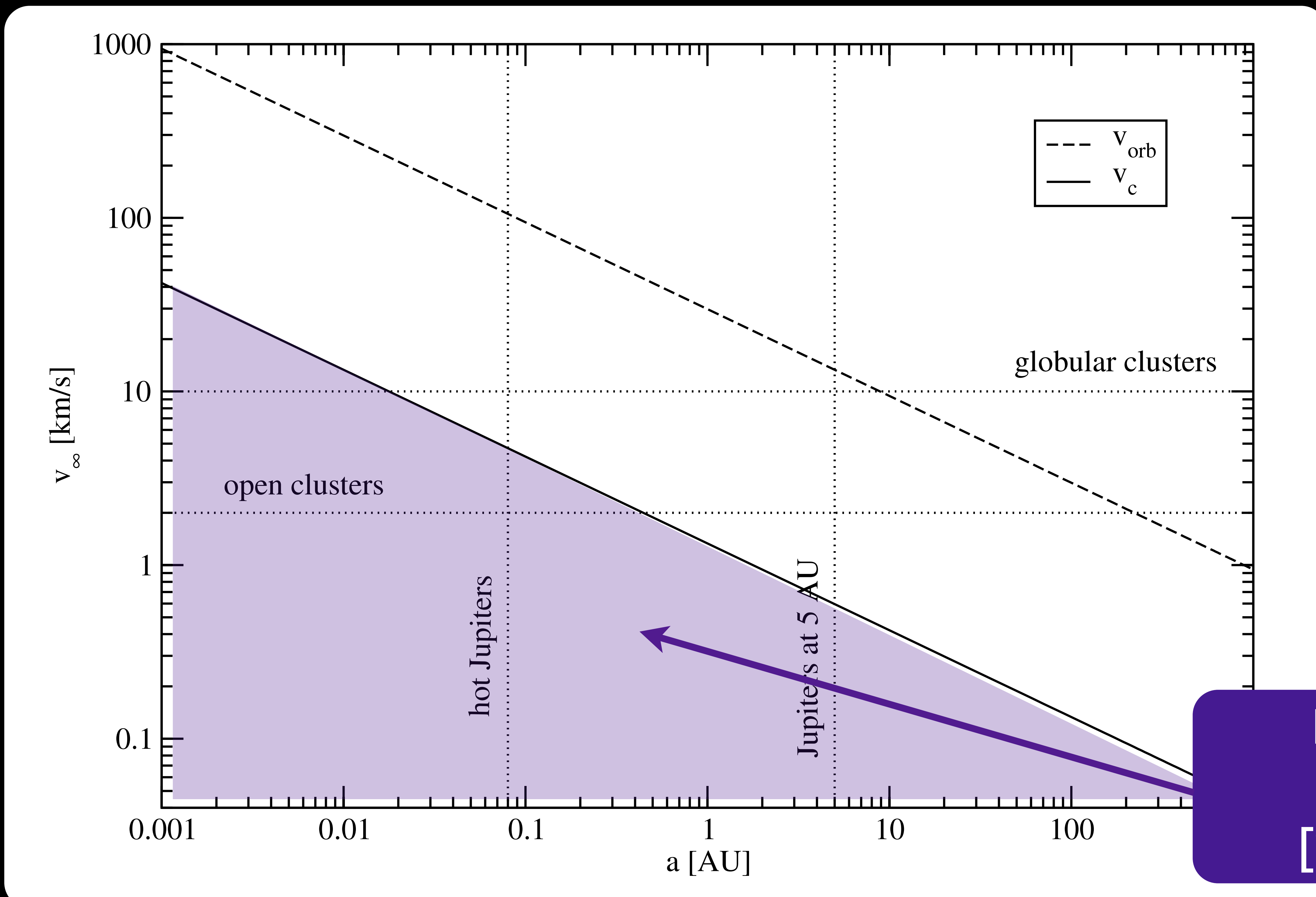

Resonant-type:
Planet Ejected
[S, P]B → [B, S]P

(Fregeau, Chatterjee, & Rasio 2006)

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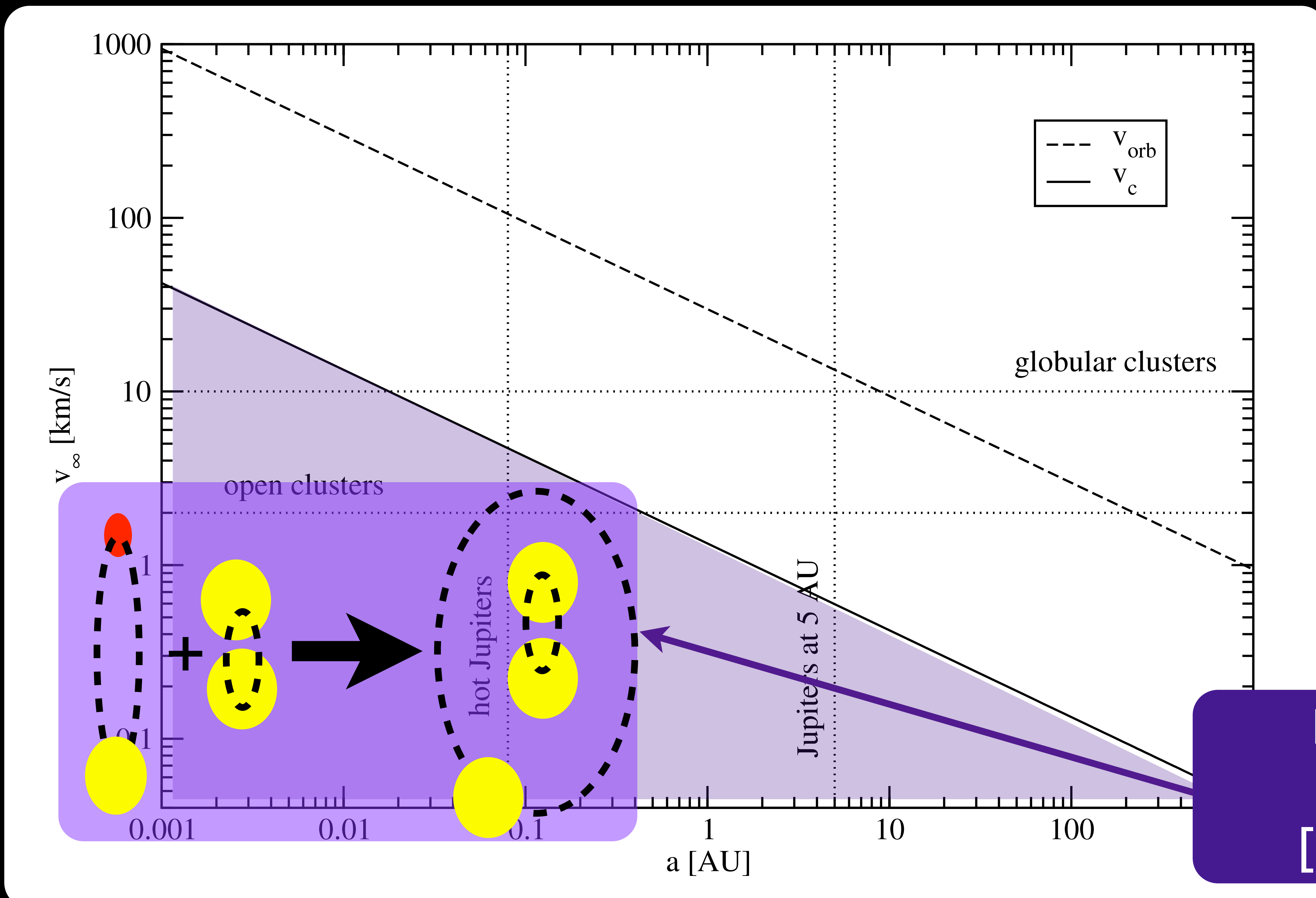

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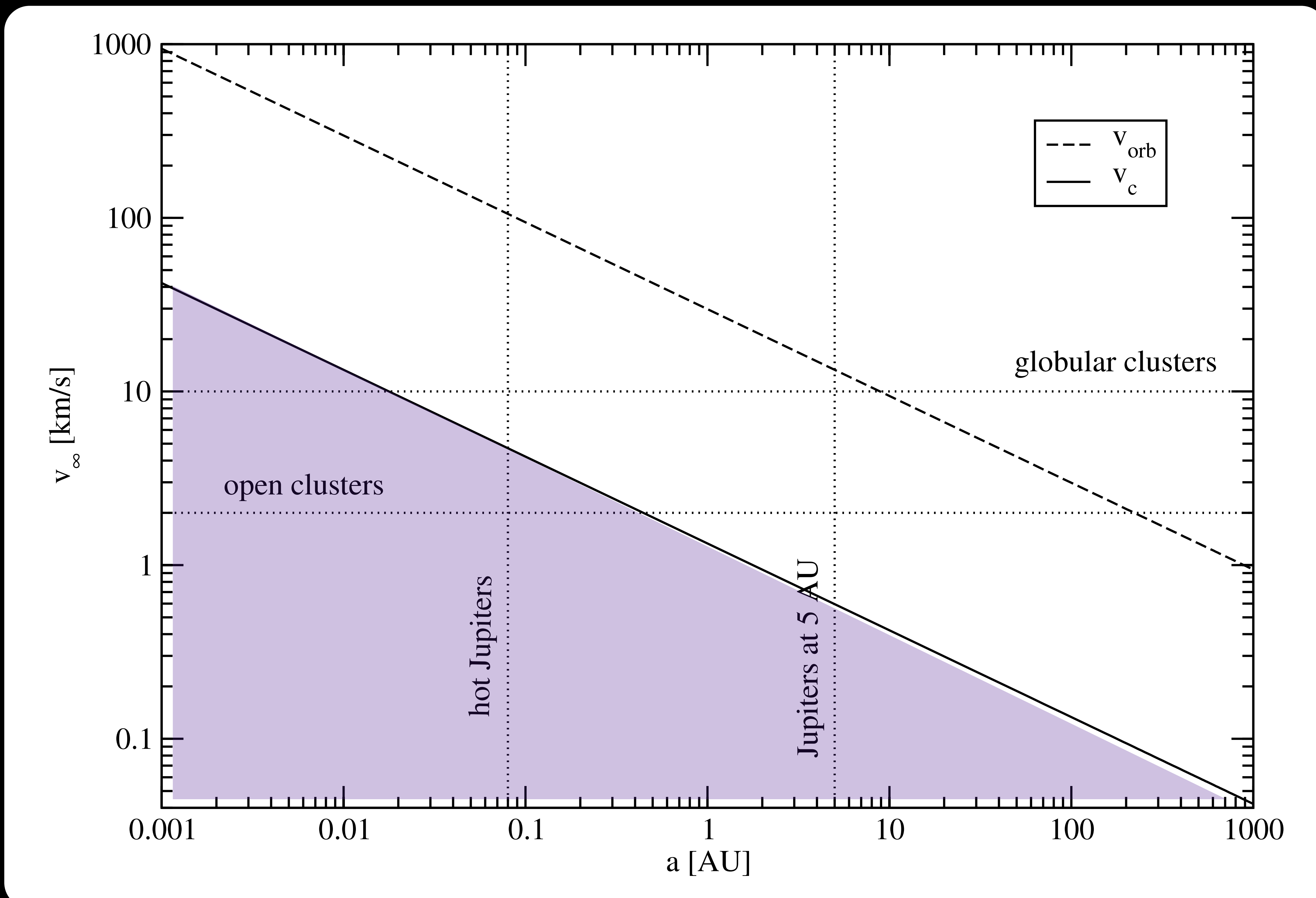

(Fregeau, Chatterjee, & Rasio 2006)

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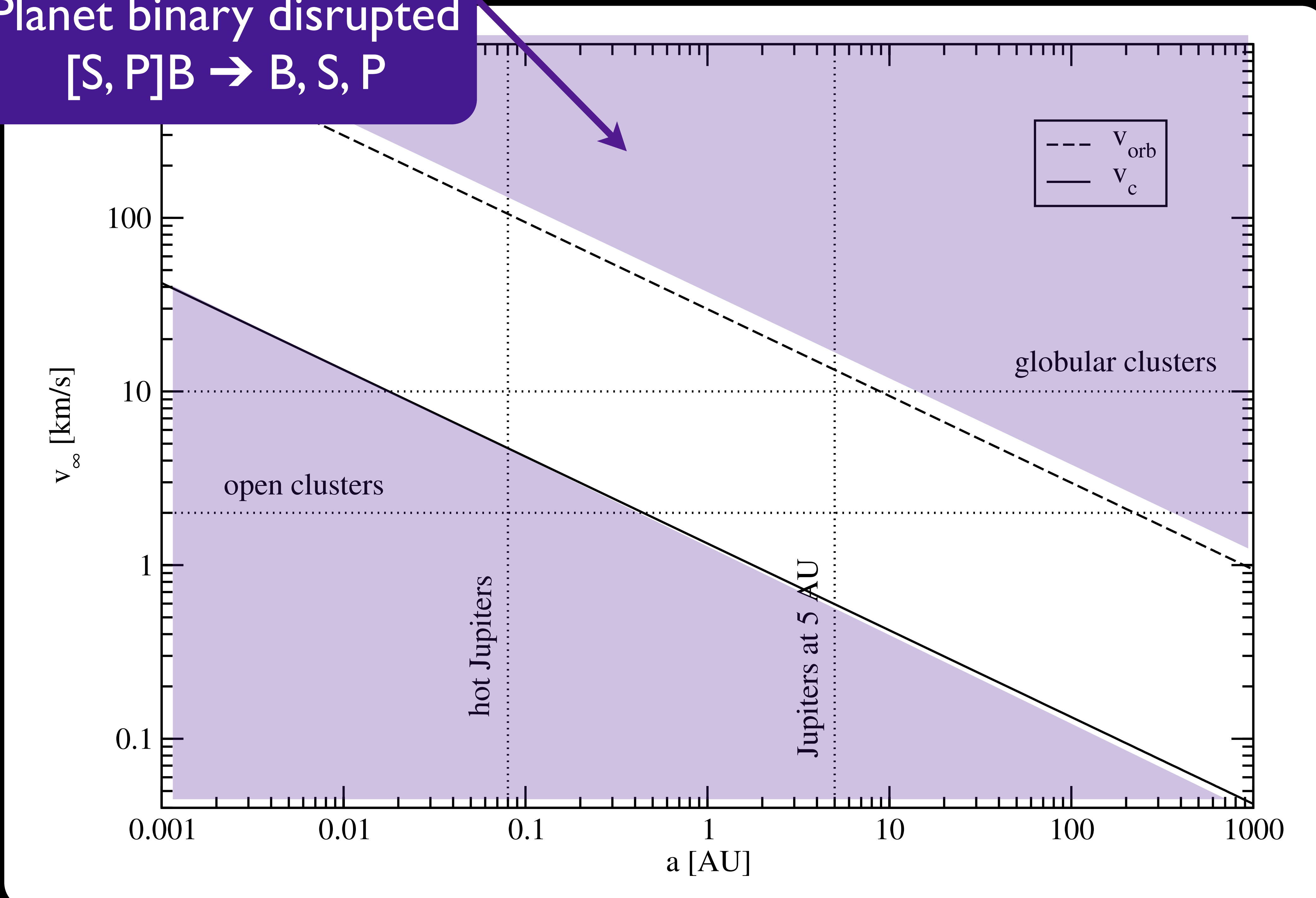
Ionization:
Planet binary disrupted
[S, P]B → B, S, P



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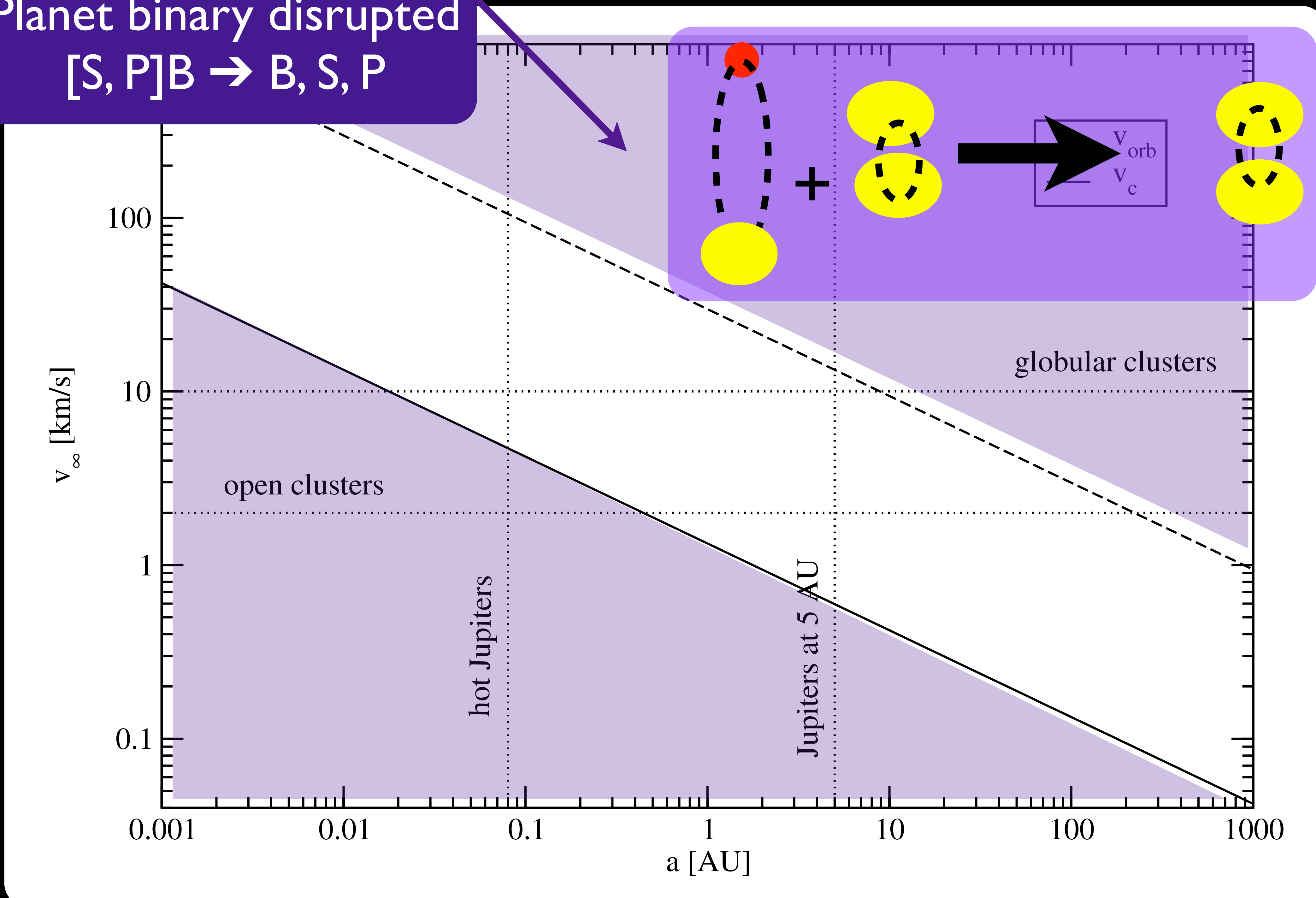

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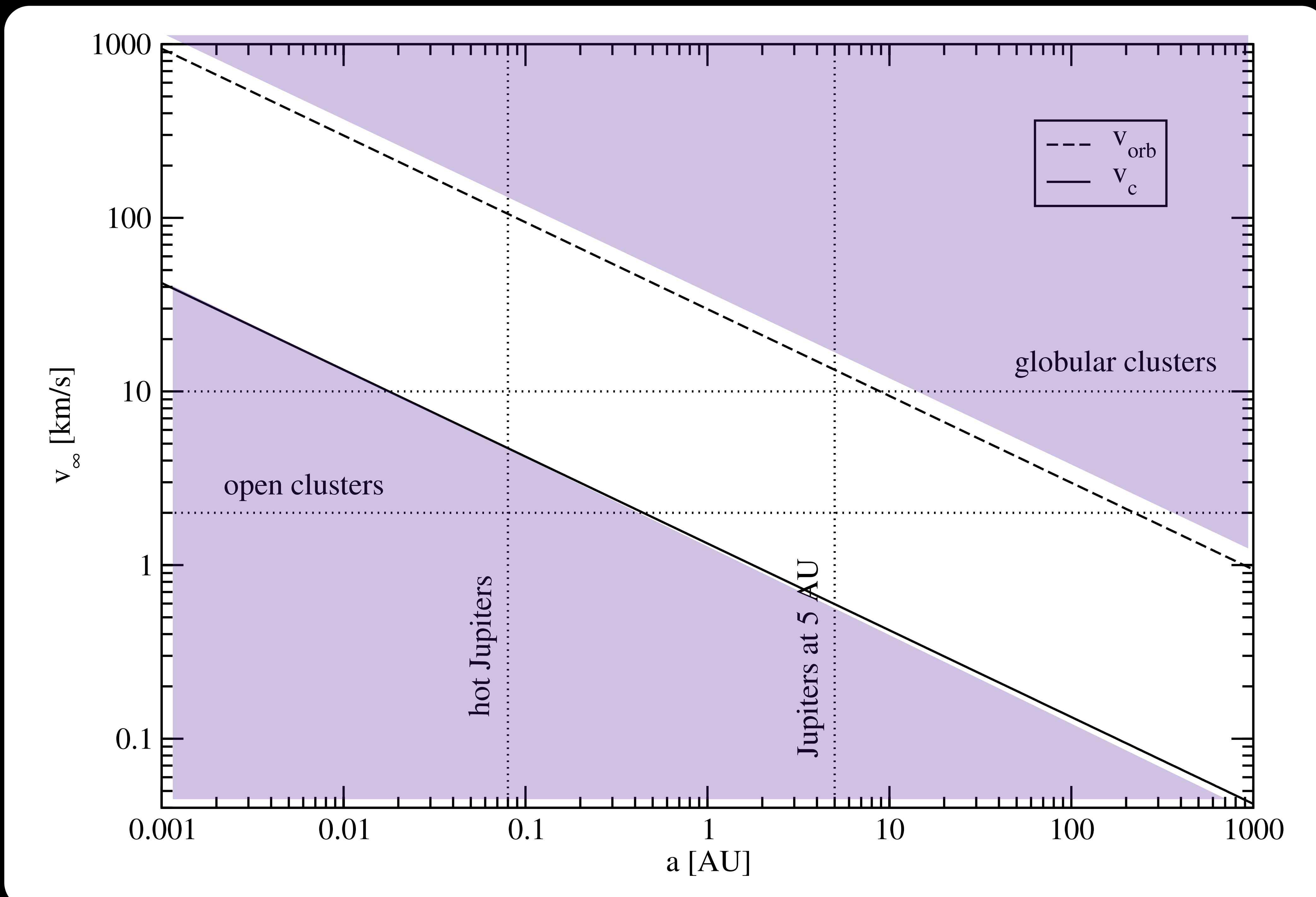

(Fregeau, Chatterjee, & Rasio 2006)

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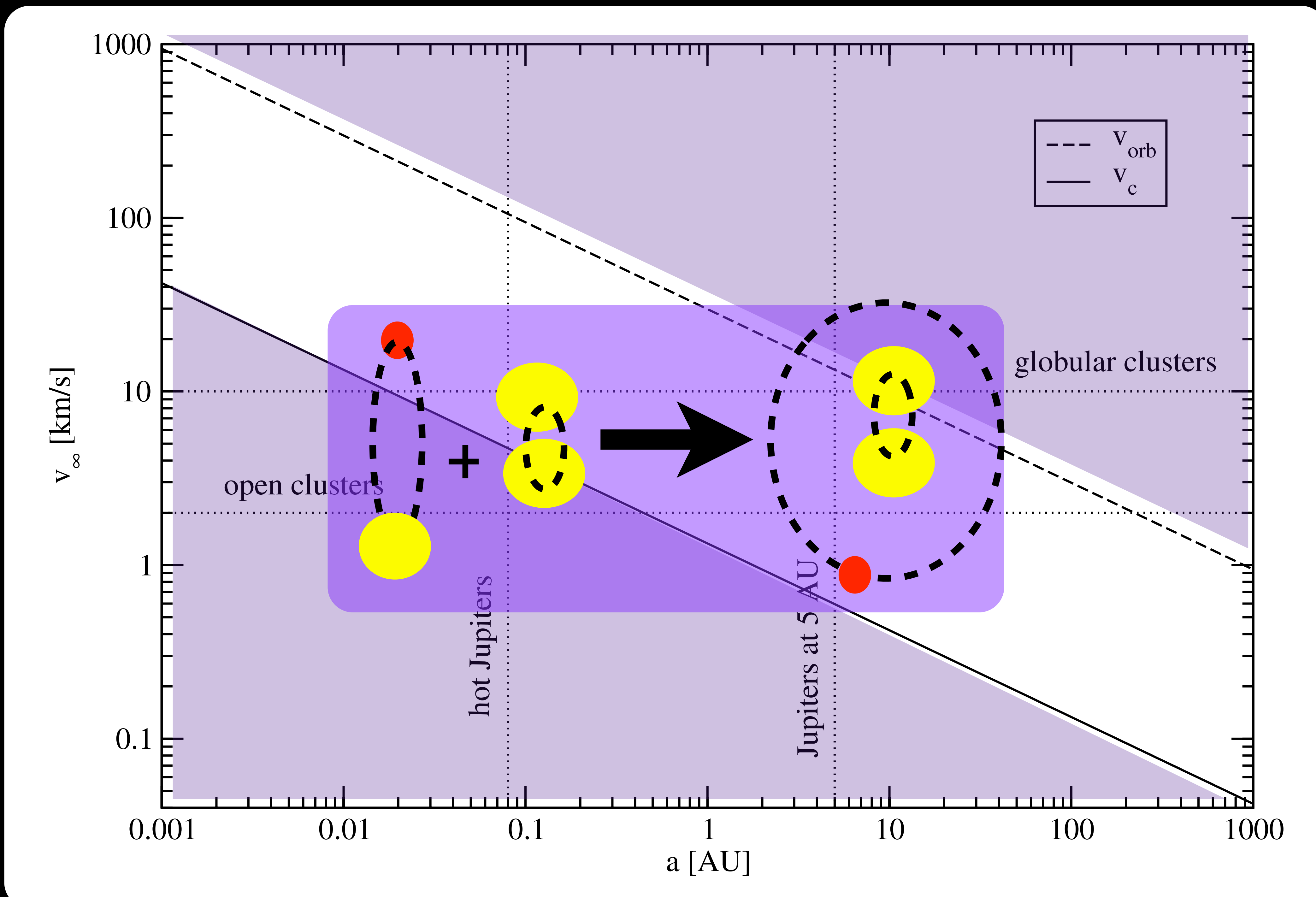


(Fregeau, Chatterjee, & Rasio 2006)

CONCLUSIONS

- Stellar dynamics has little effect on close-in planetary orbits
- Kepler should be able to discover planets in NGC6791
  - Fainter stars (16.5 < K_p < 20) should not be neglected
  - One year of observation may find ~10 giant planets (Rp > 10 $R_\oplus$; exact number depends on initial assumptions)
- Kepler may well answer *whether planets form around cluster stars in a similar way as they do around field stars*
- Occassionally circumbinary planets may be created in cluster environments
  - Planet forms around a single star
  - Interaction with a stellar binary
  - Forms circumbinary planet

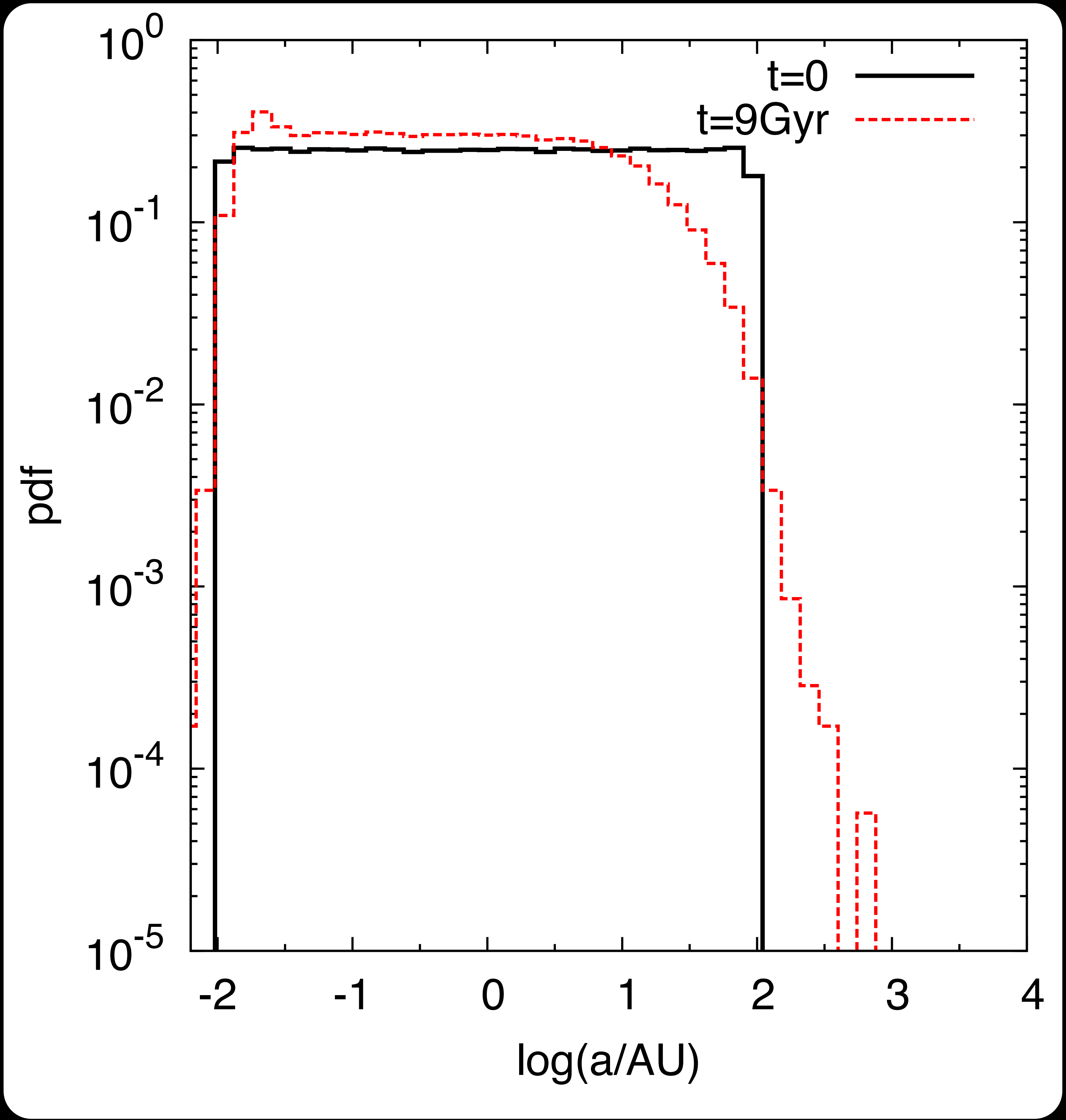
Planetary Orbit Initial Conditions

- a-distribution: Flat in logarithmic intervals between 10^{-2} - 10^{2} AU
- e-distribution: Circular
- M-distribution: Power-law, df/dlogM ~ $M^{-0.48}$ (Howard et al. 2011)
  - M_P is between 1 $M_\oplus$ - 5 M_J
- Planet's radius R_P = min ($M_P^{2.06}$, M_J)
- 1/3 of all stars have a planet

A Typical Galactic Globular Cluster

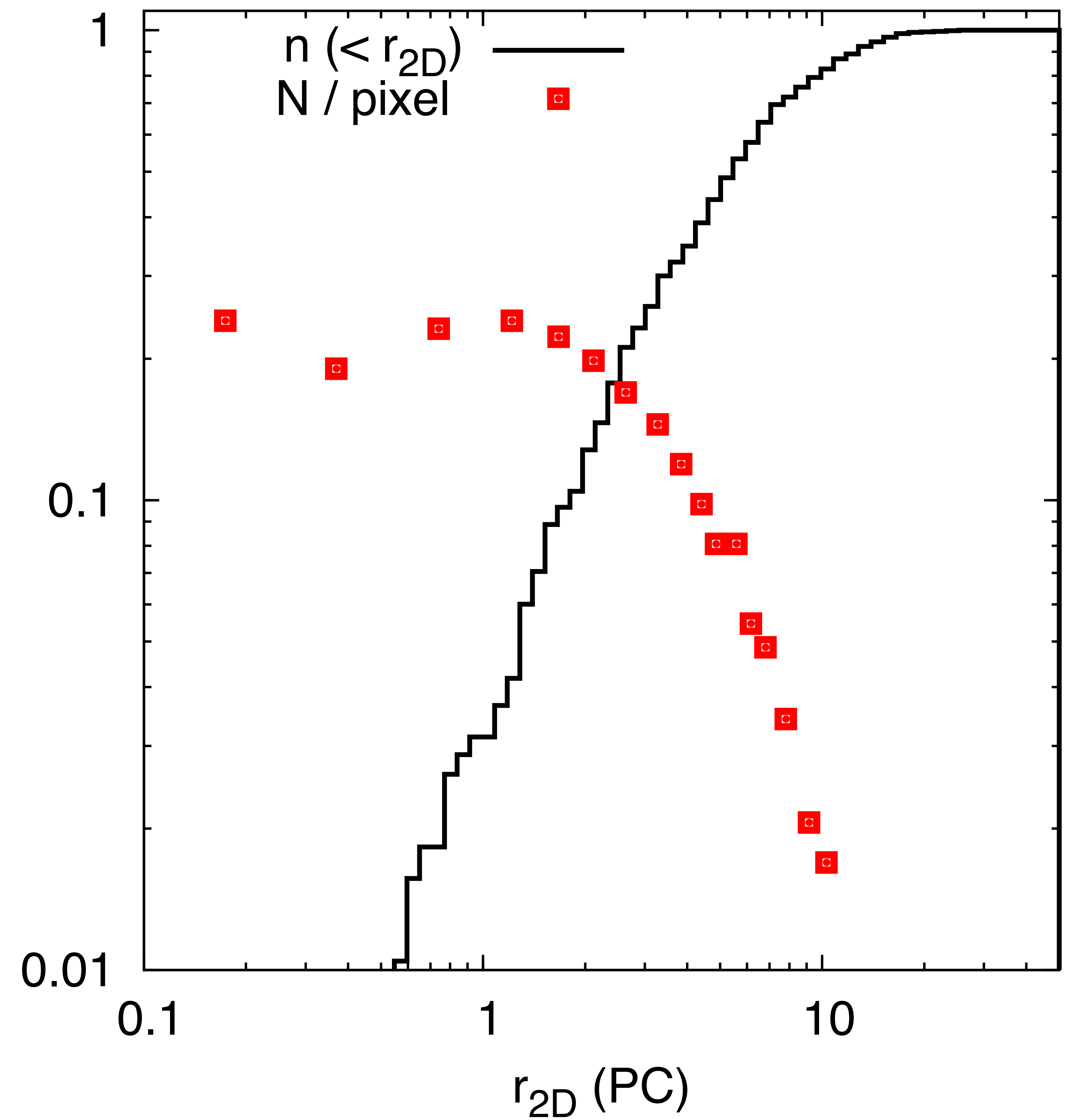
Property	Typical GC	Model
Mass ($M_\odot$)	1×10^5	2×10^5
Central Density ($M_\odot pc^{-3}$)	1×10^4	4×10^4

Effects of stellar dynamics on planetary orbits
a - distribution



Planets interrior to 10 AU are undisterbed even for globular clusters

Radial Distribution of Detectable Planets



(Platais et al. 2011)

Calculation of SNR for Kepler Detectability

- Stellar L and R are obtained from CMC.
  - L is converted first to B and V magnitudes using Lejunne spectra. K_P is then calculated using B and V assuming 4 Kpc distance.
- Planet's M and a are obtained from CMC.
  - Planet's R is calculated using R_P = min $(M_P^{2.06}, M_J)$.
- For a given K_P CDPP is calculated using a polynomial fit of Kepler's magnitude-dependent CDPP values (Gilliland et al. 2011).

$$SNR = \frac{\left(\frac{R_p}{R_\star}\right)^2}{CDPP}\sqrt{\frac{n_{tr}.t_{dur}}{6.5hr}}$$

(e.g., Howard et al. 2011)

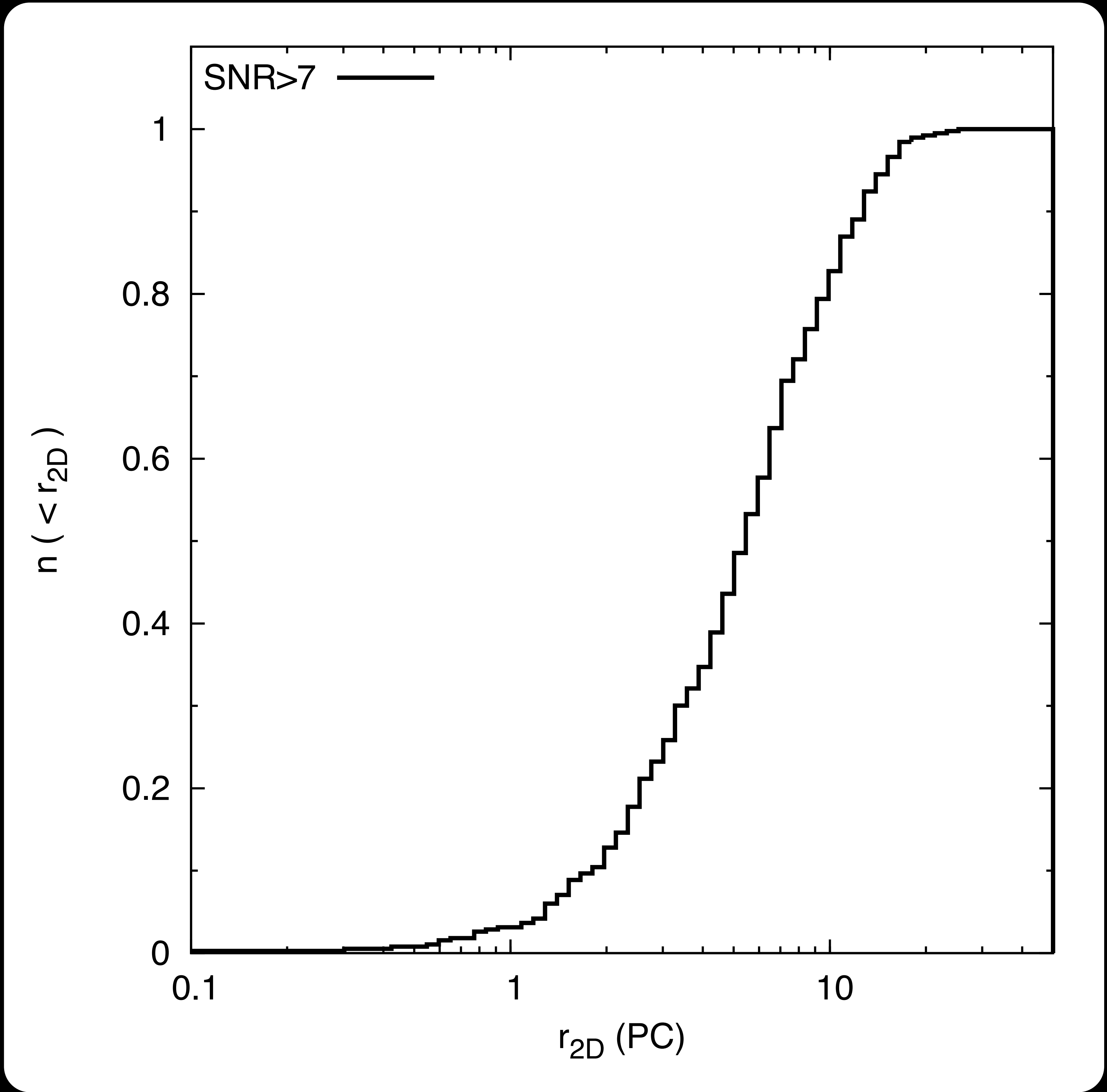
Modeling NGC6791

Explored Initial Conditions

Number of stars	10^4 - 10^5
Concentration w_0	3 - 6
Virial Radius (pc)	3 - 8
Galacto-centric distance (Kpc)	5 - 10
Stellar binary fraction (f_b)	0.1 - 0.5
Fraction of planet hosts (f_p)	0.33

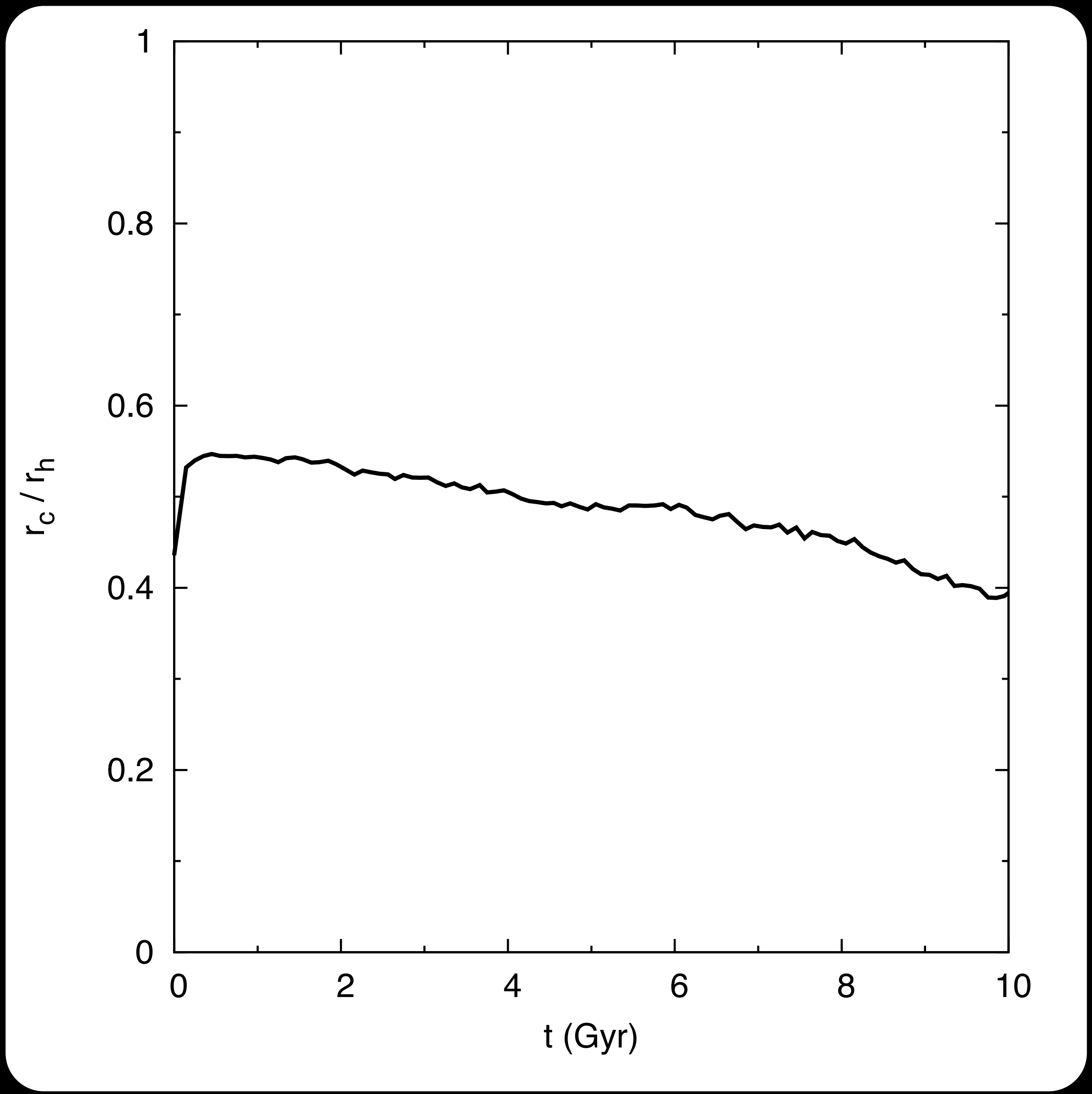
Initial Conditions for GC Model

Number of stars	6×10^5
Concentration w_0	6
Virial Radius (pc)	4
Galacto-centric distance (Kpc)	8.5
Stellar binary fraction (f_b)	0.1
Fraction of planet hosts (f_p)	0.33

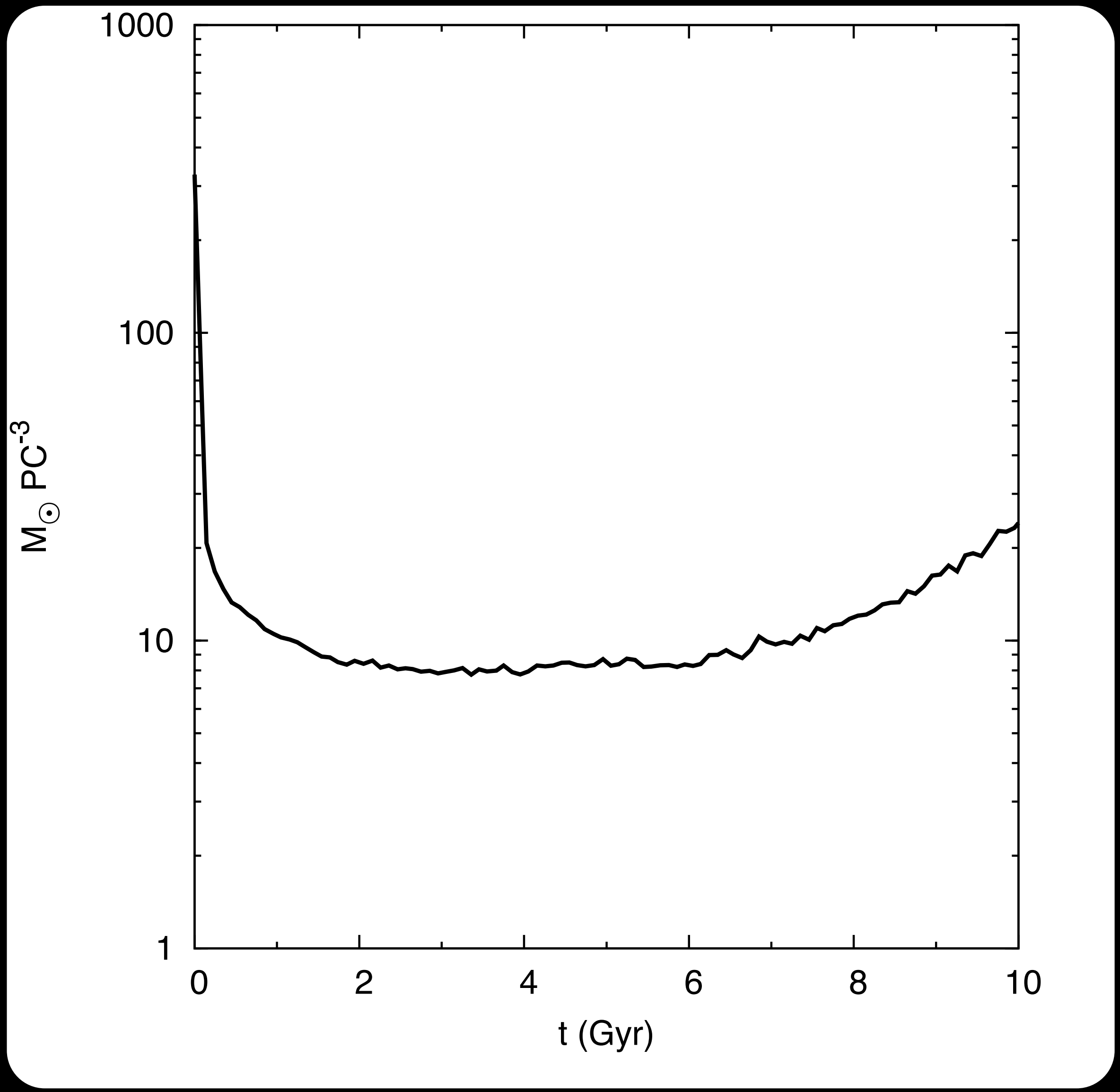

SNR>7
1
0.8
0.6
0.4
0.2
0
n (< r2D)
0.1
1
10
r2D (PC)

EVOLUTION OF R_C/R_H AND ρ_C

Core Radius

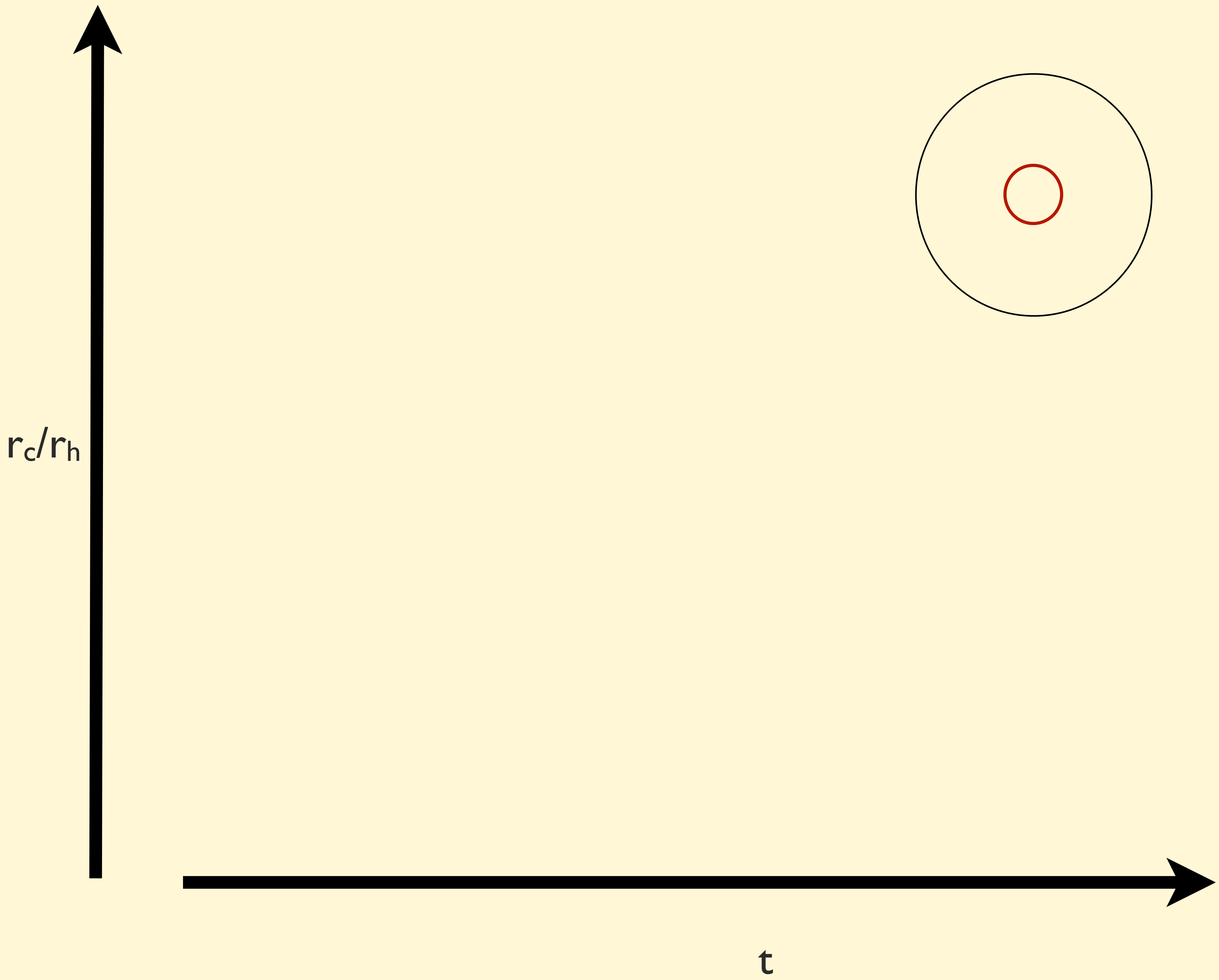


Central Density



- A regular non-core-collapsed cluster
- Low central density

Evolutionary stages of dense star clusters



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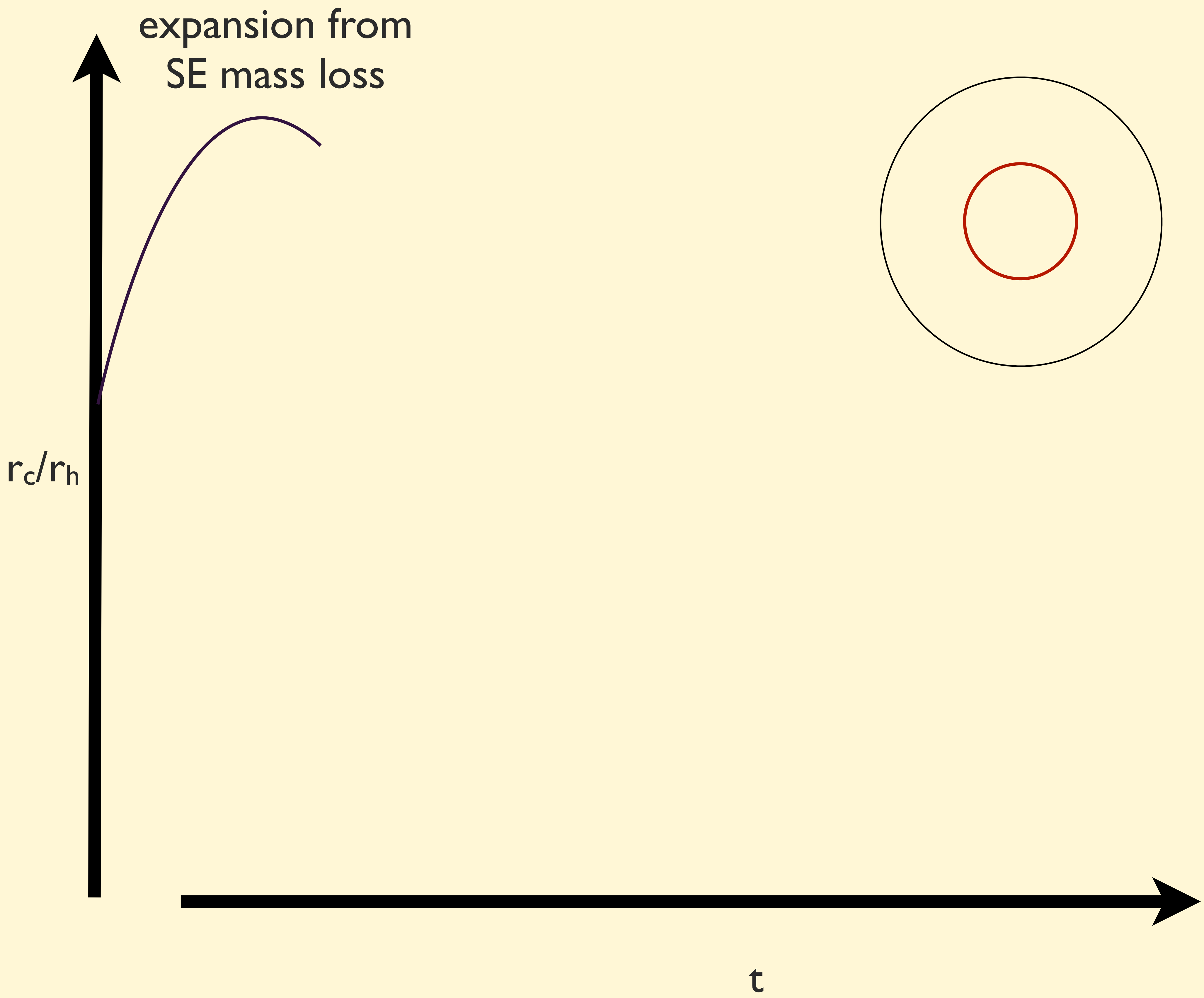

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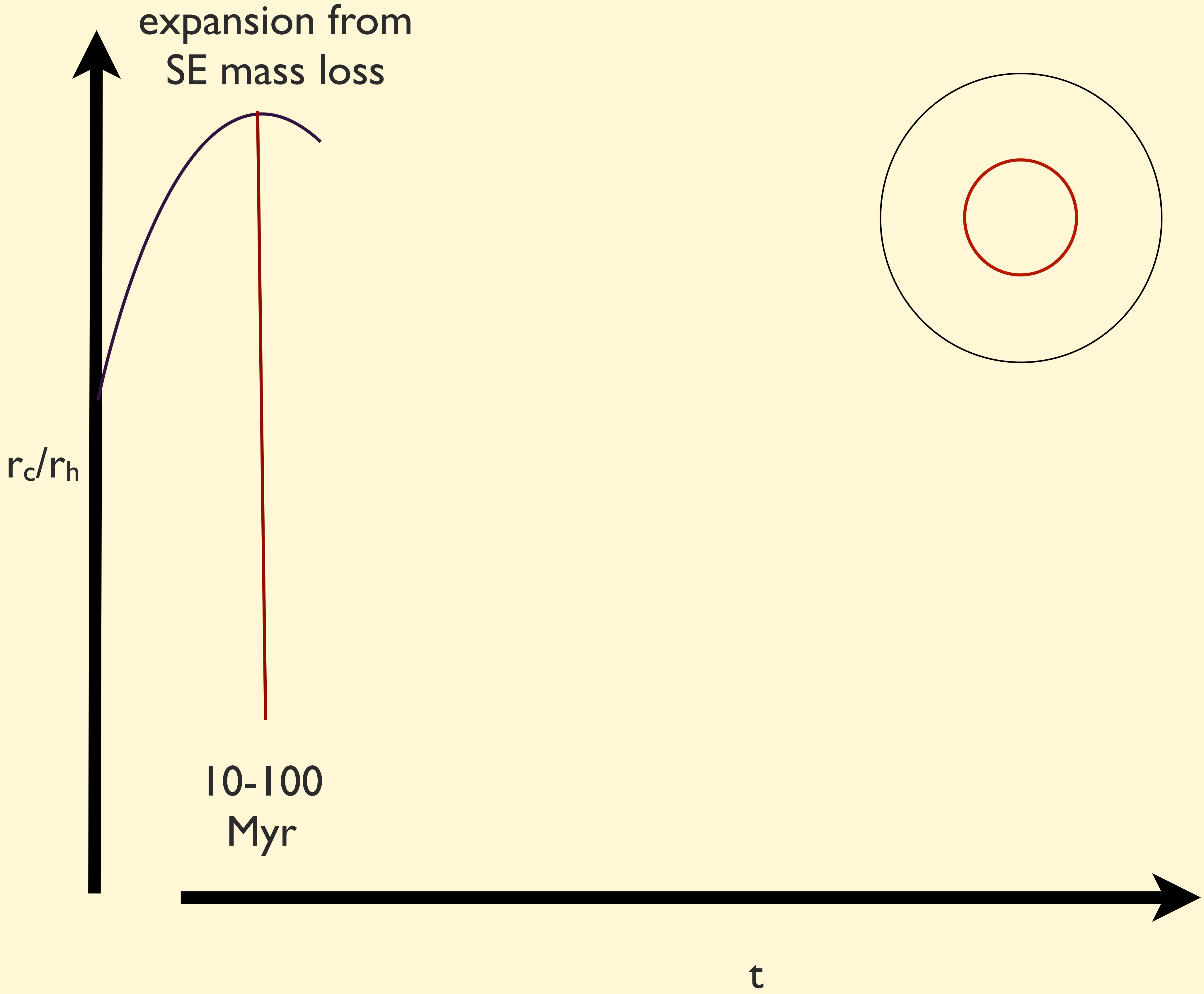

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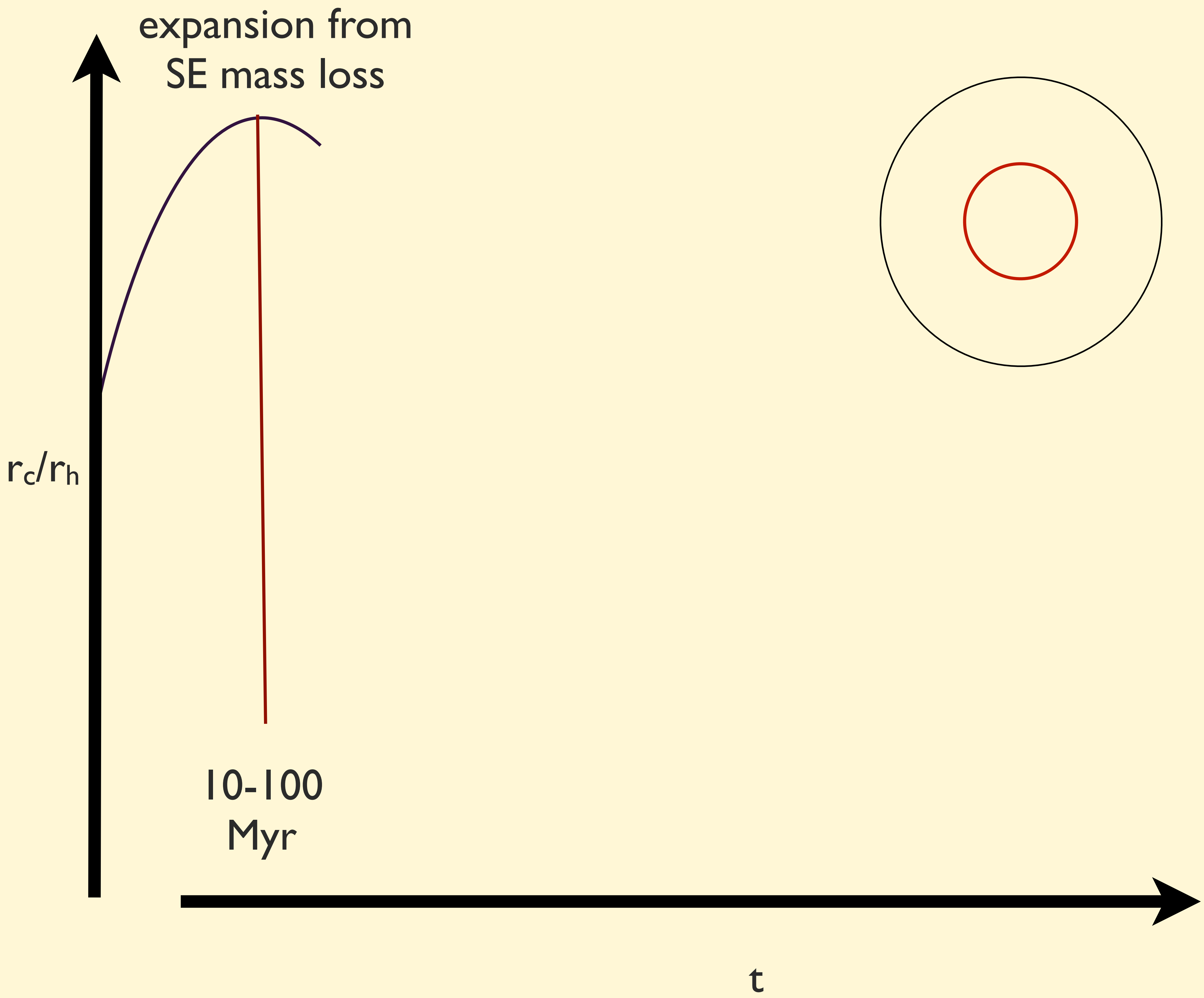

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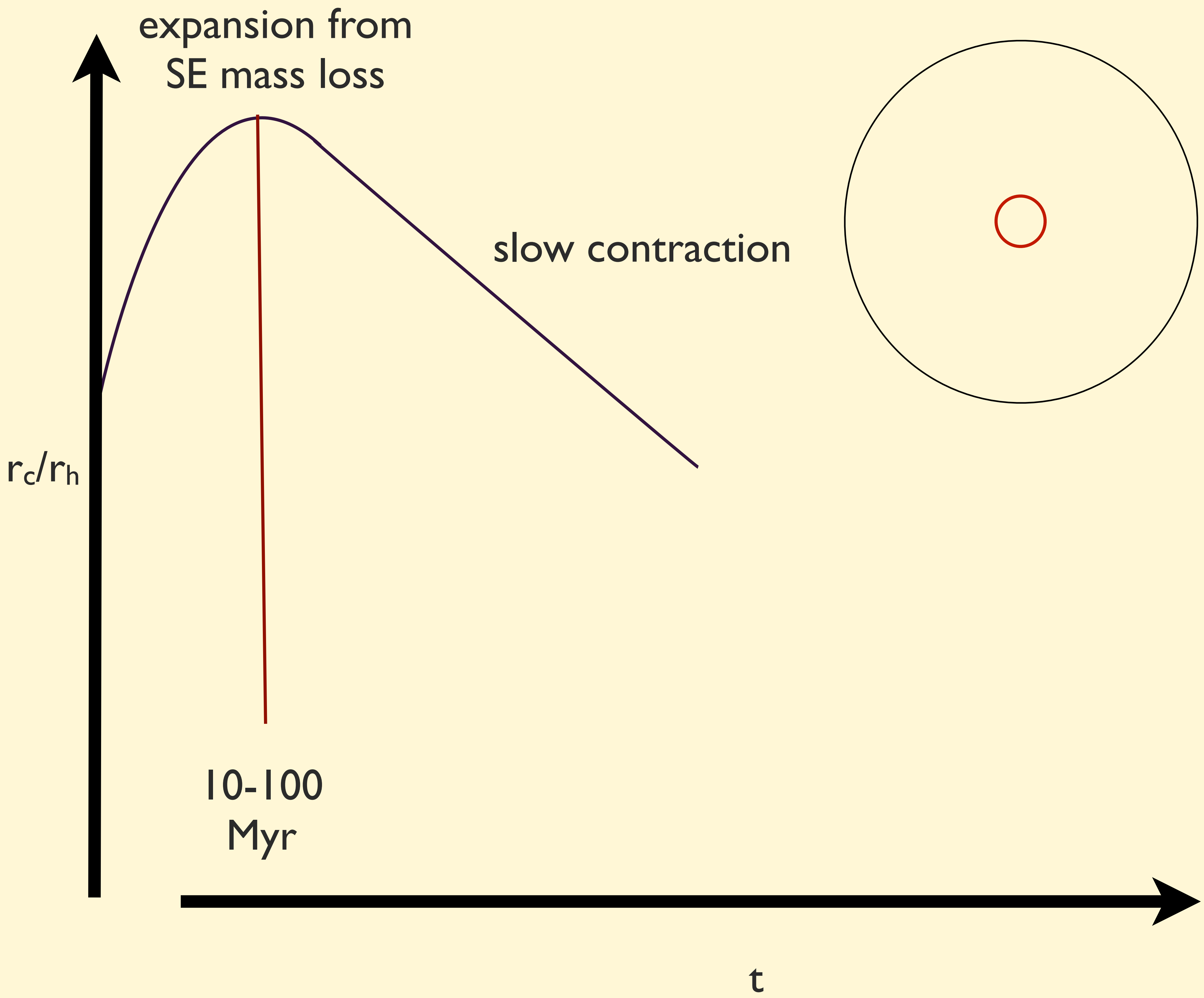

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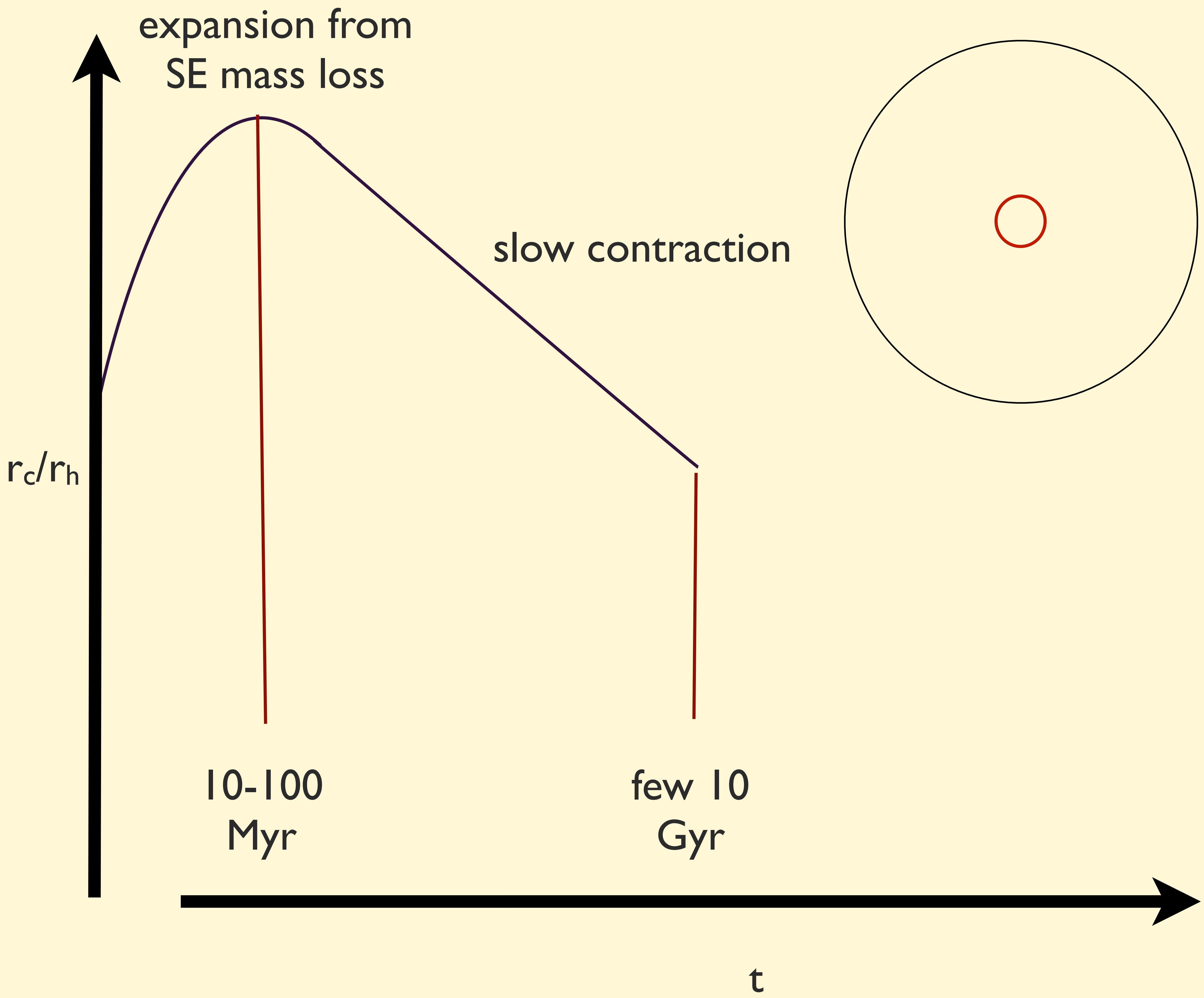

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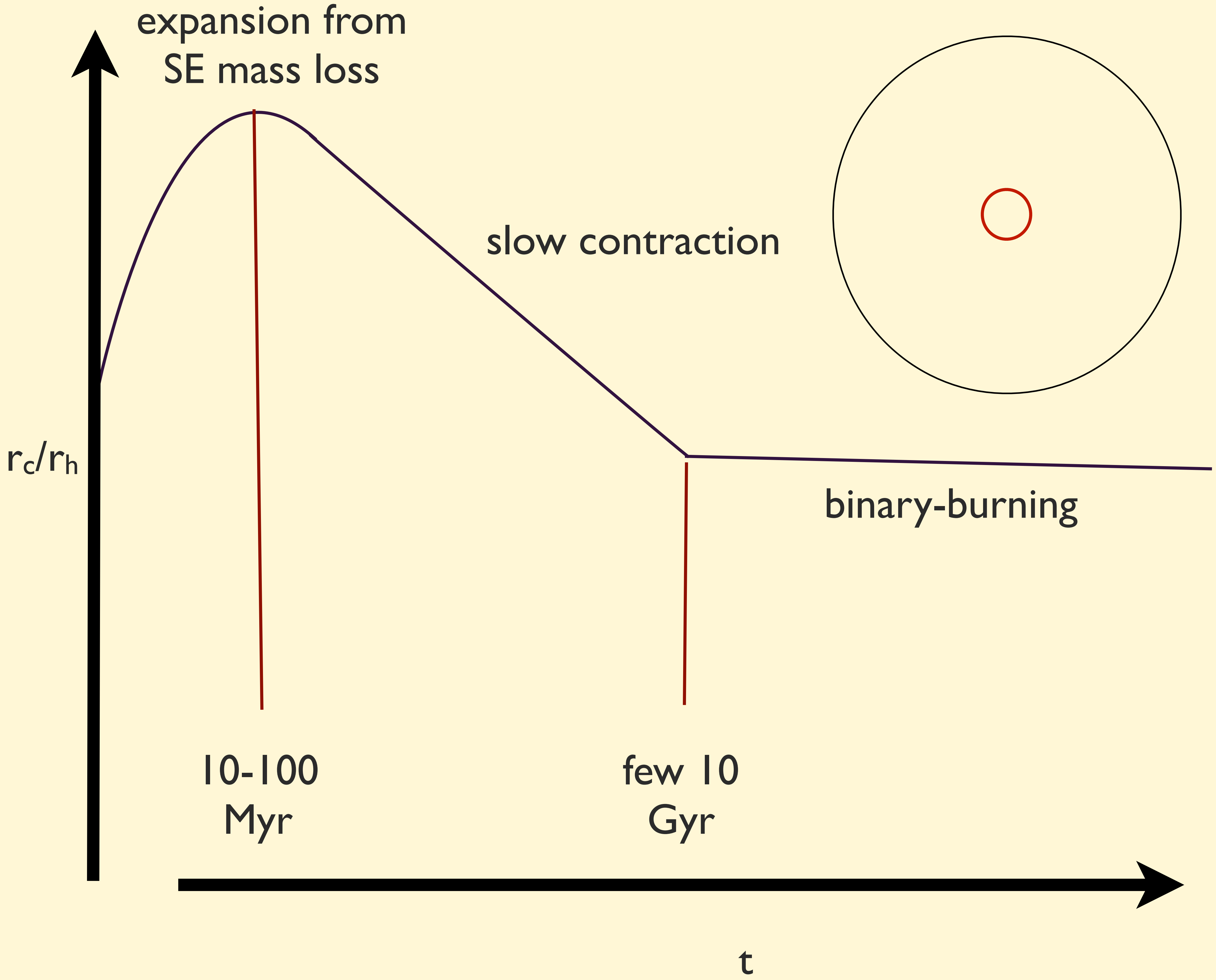

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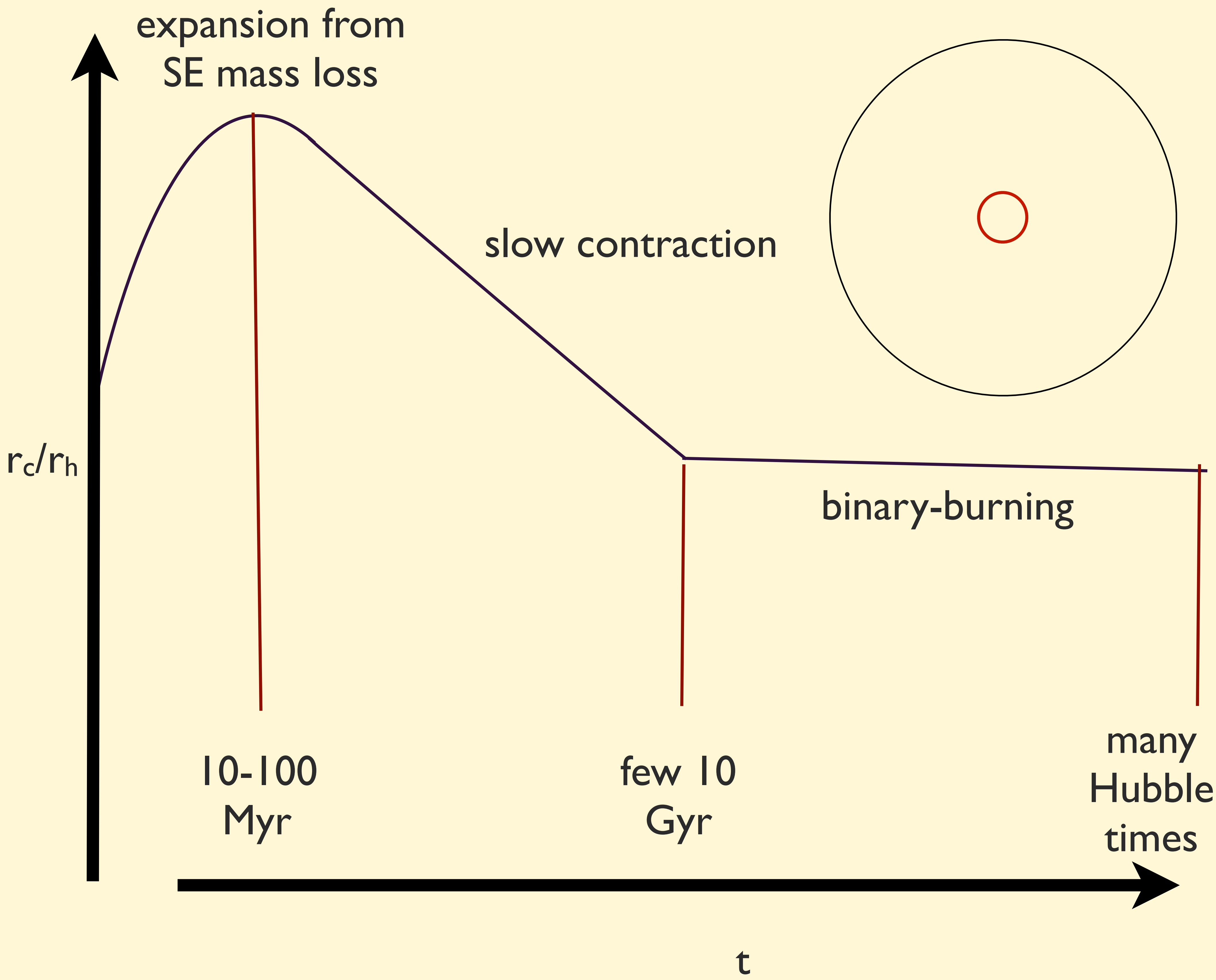

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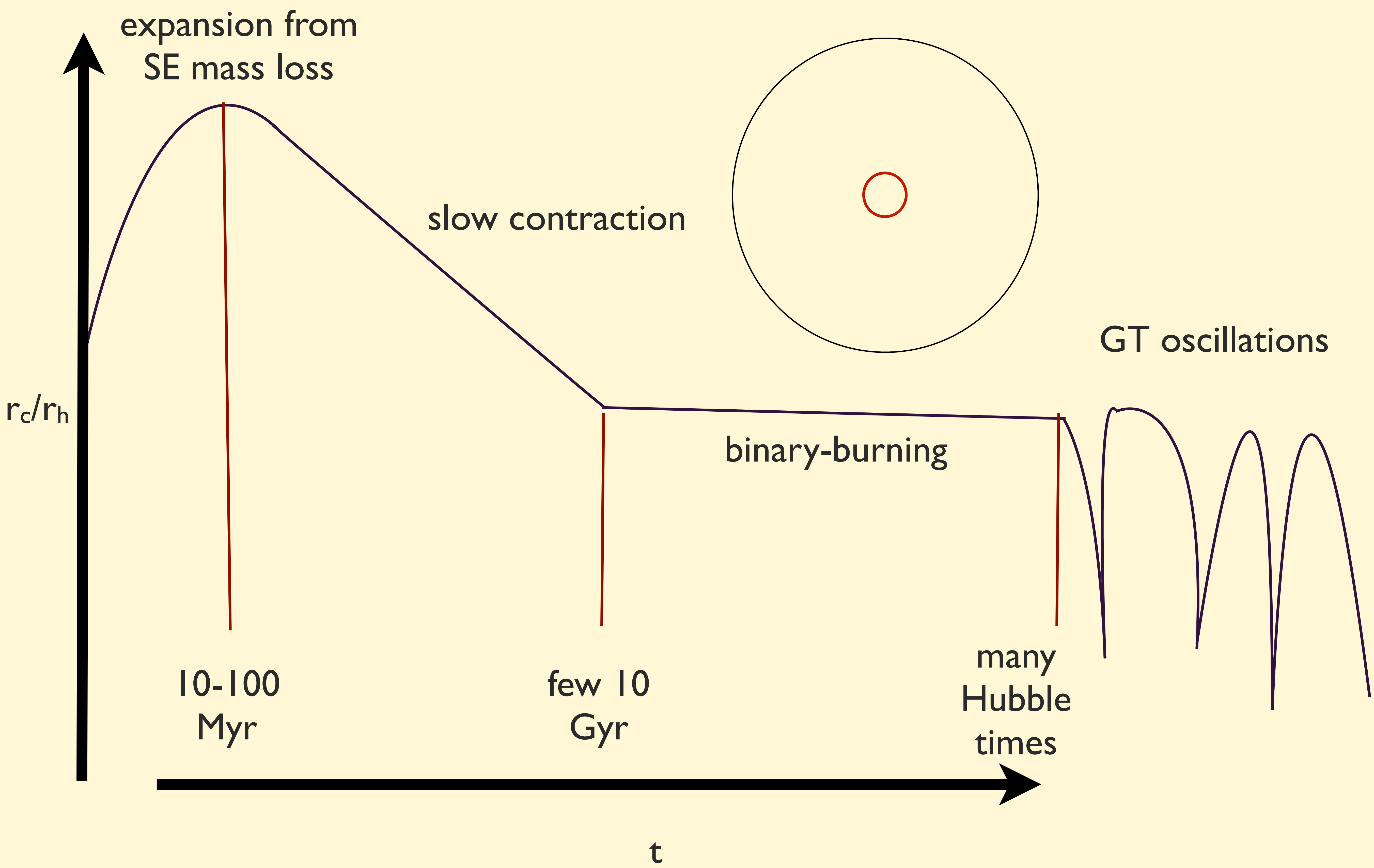

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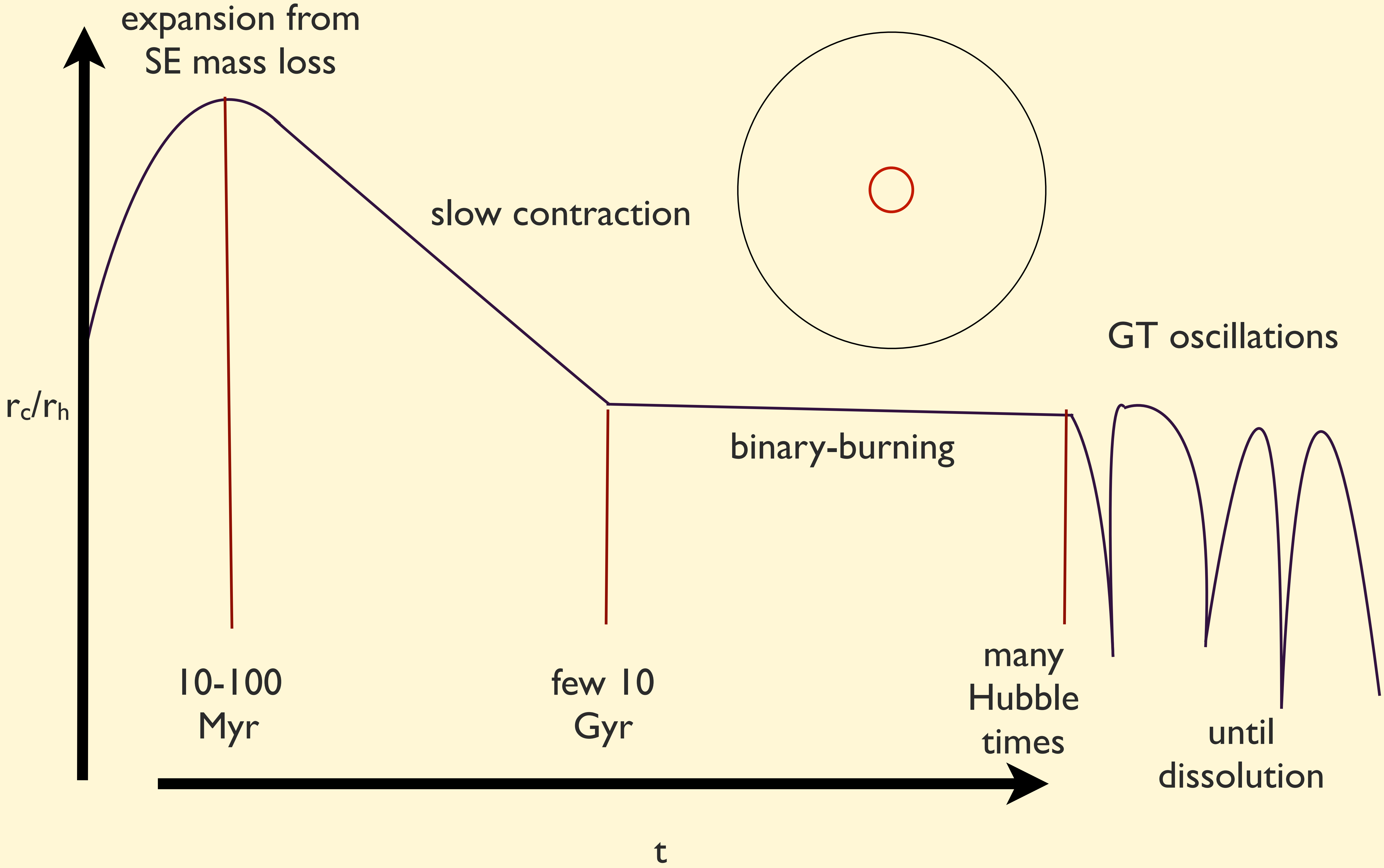
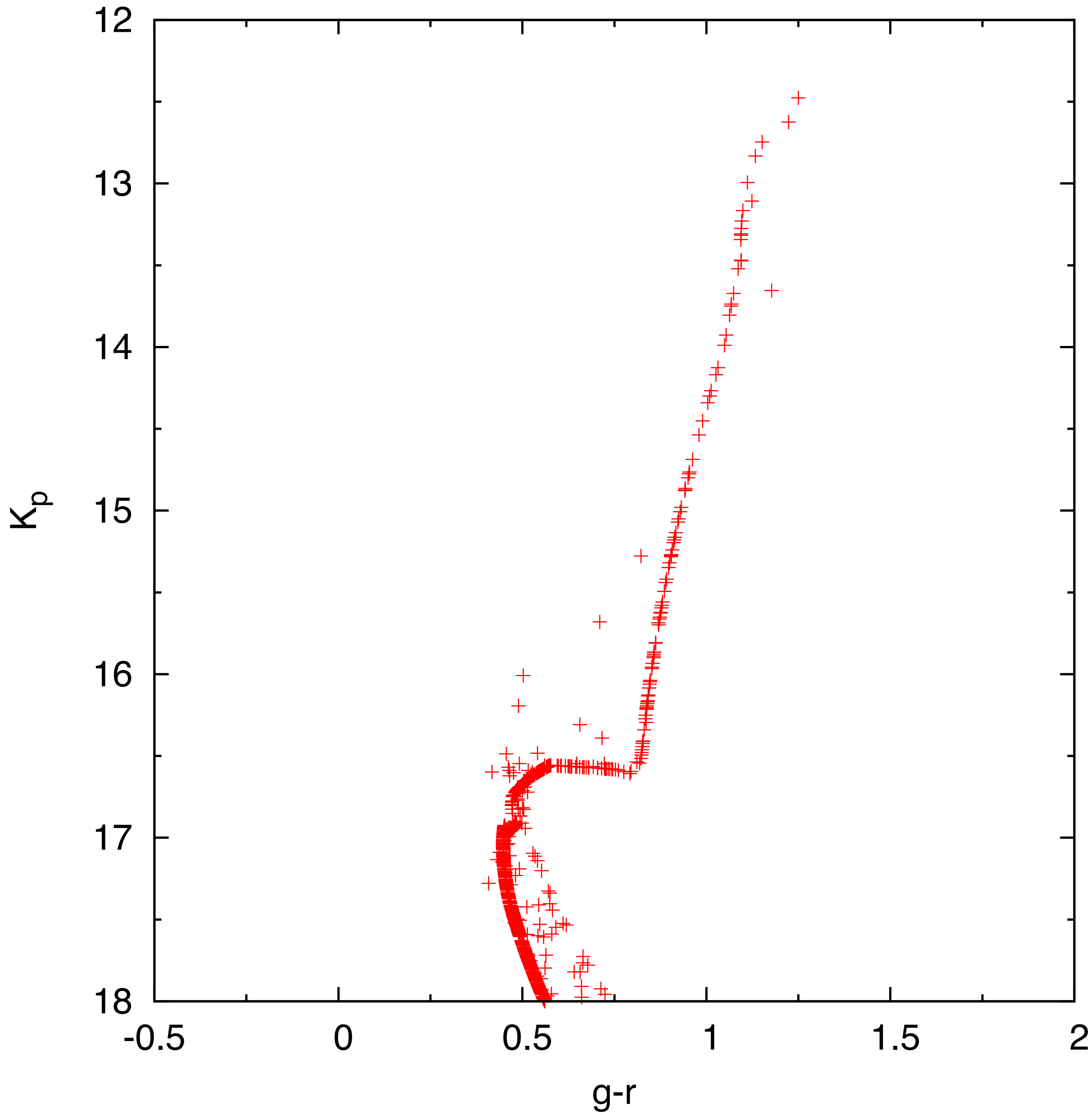
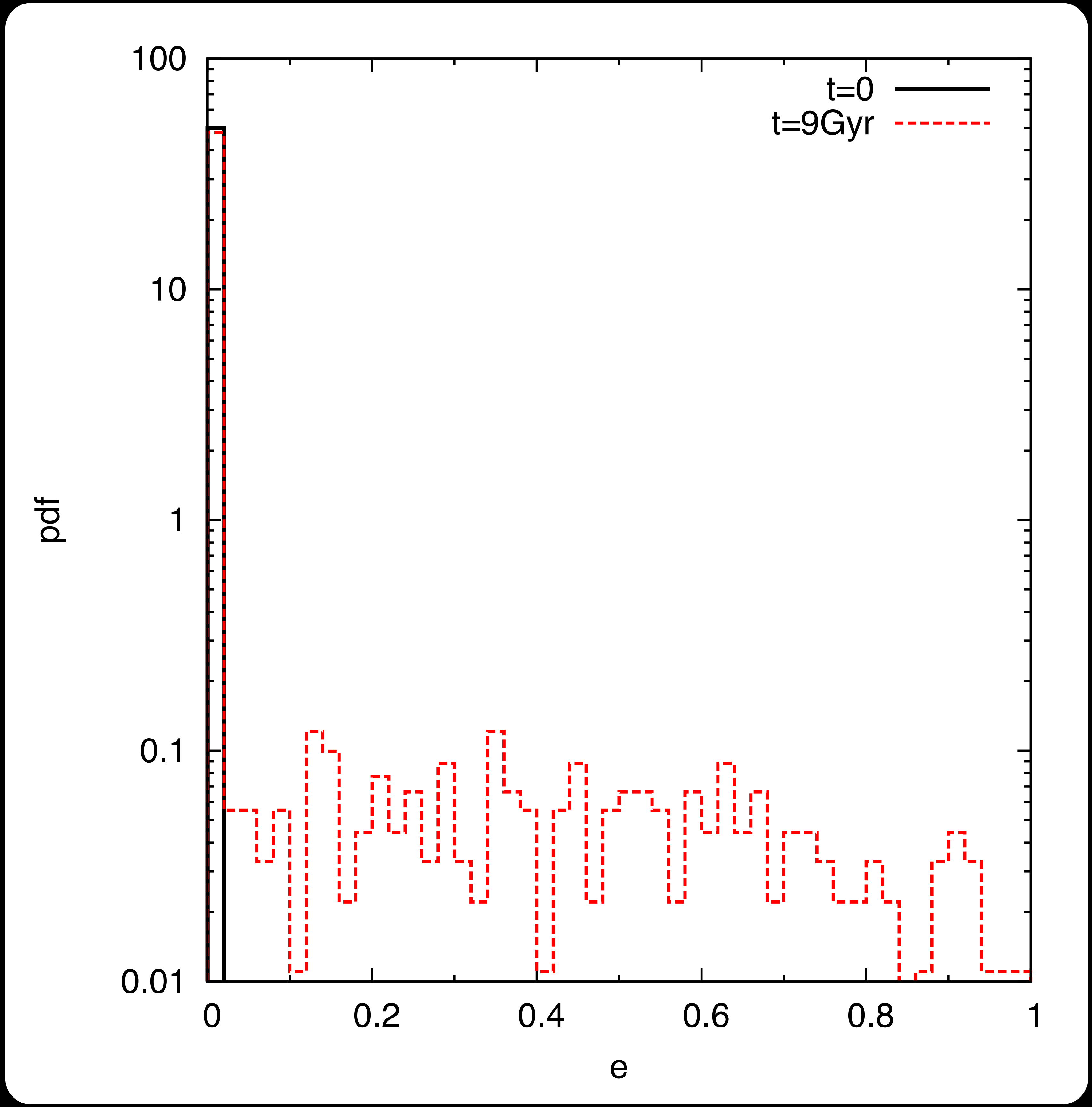
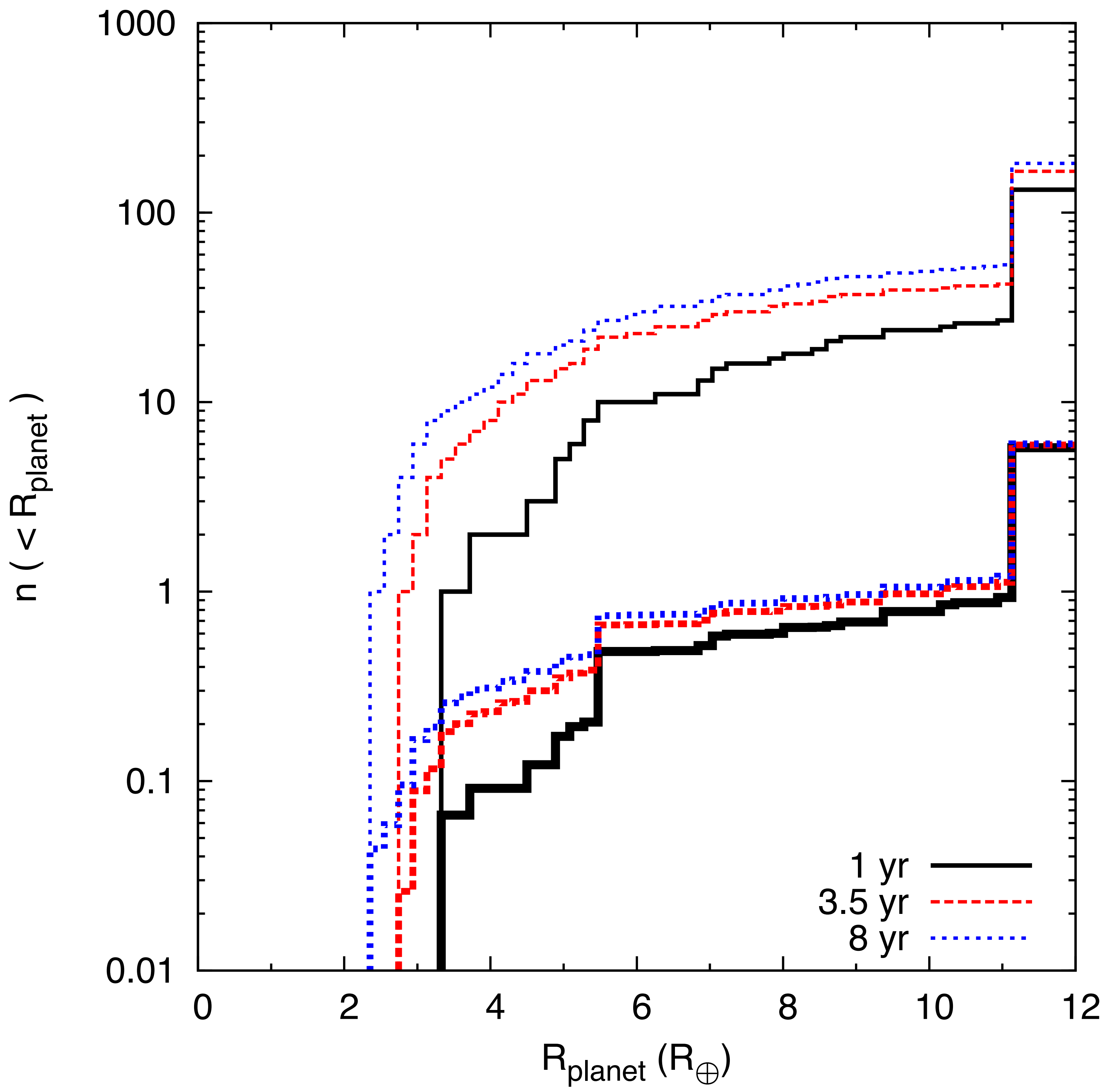




12
13
14
15
16
17
18
K_p
-0.5
0
0.5
1
1.5
2
g-r



100
10
1
0.1
0.01
pdf
0
0.2
0.4
0.6
0.8
1
e
t=0
t=9Gyr


1000
100
10
1
0.1
0.01
n (< R_{planet})
0
2
4
6
8
10
12
R_{planet} ($R_\oplus$)
1 yr
3.5 yr
8 yr

$K_p < 18$

Planets escaped from cluster