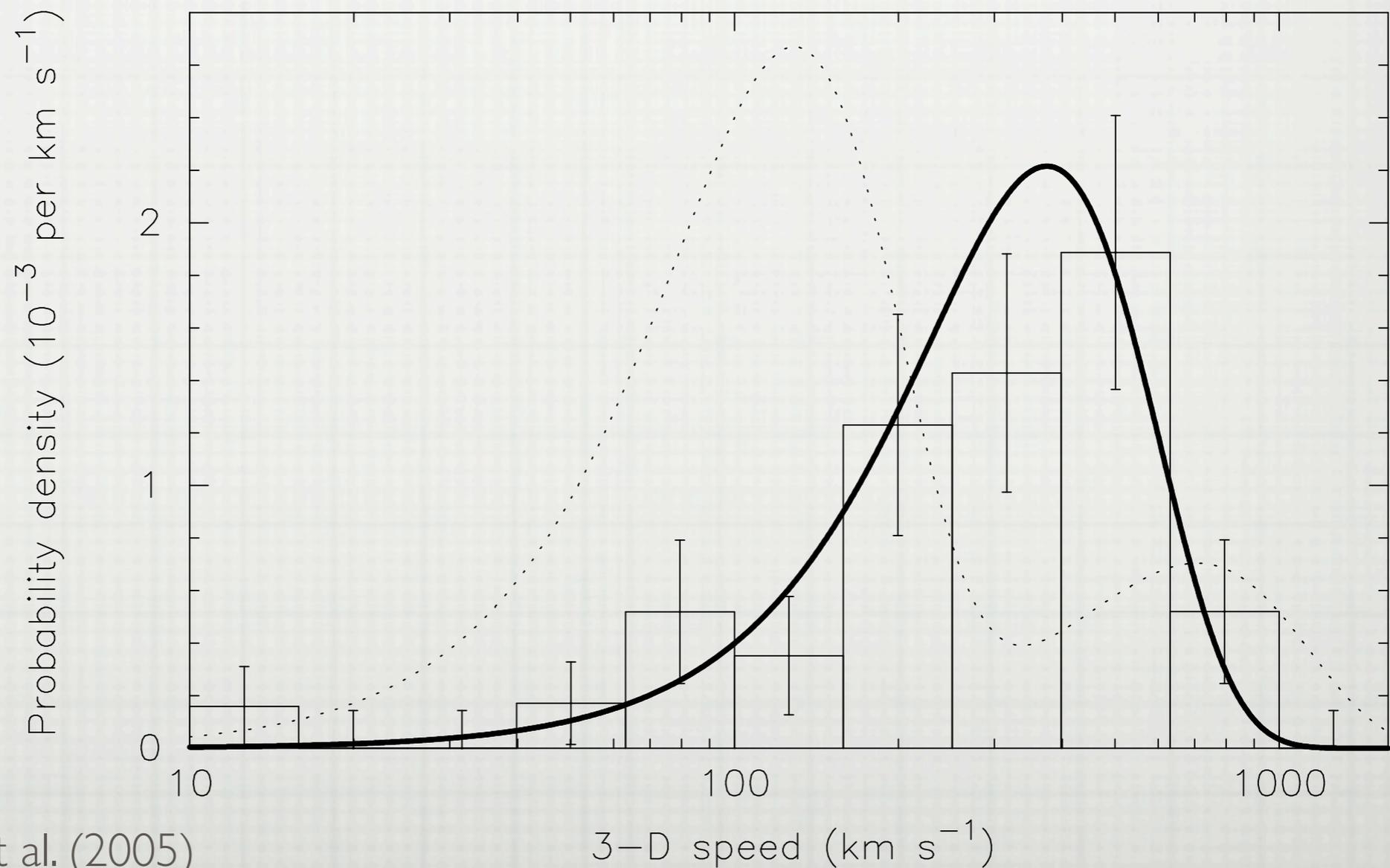


White Dwarf Kicks in Star Clusters

John Fregeau, Harvey Richer, Fred Rasio, Jarrod Hurley
KITP-UCSB, UBC, NU, Swinburne

Neutron Star Birth Kicks

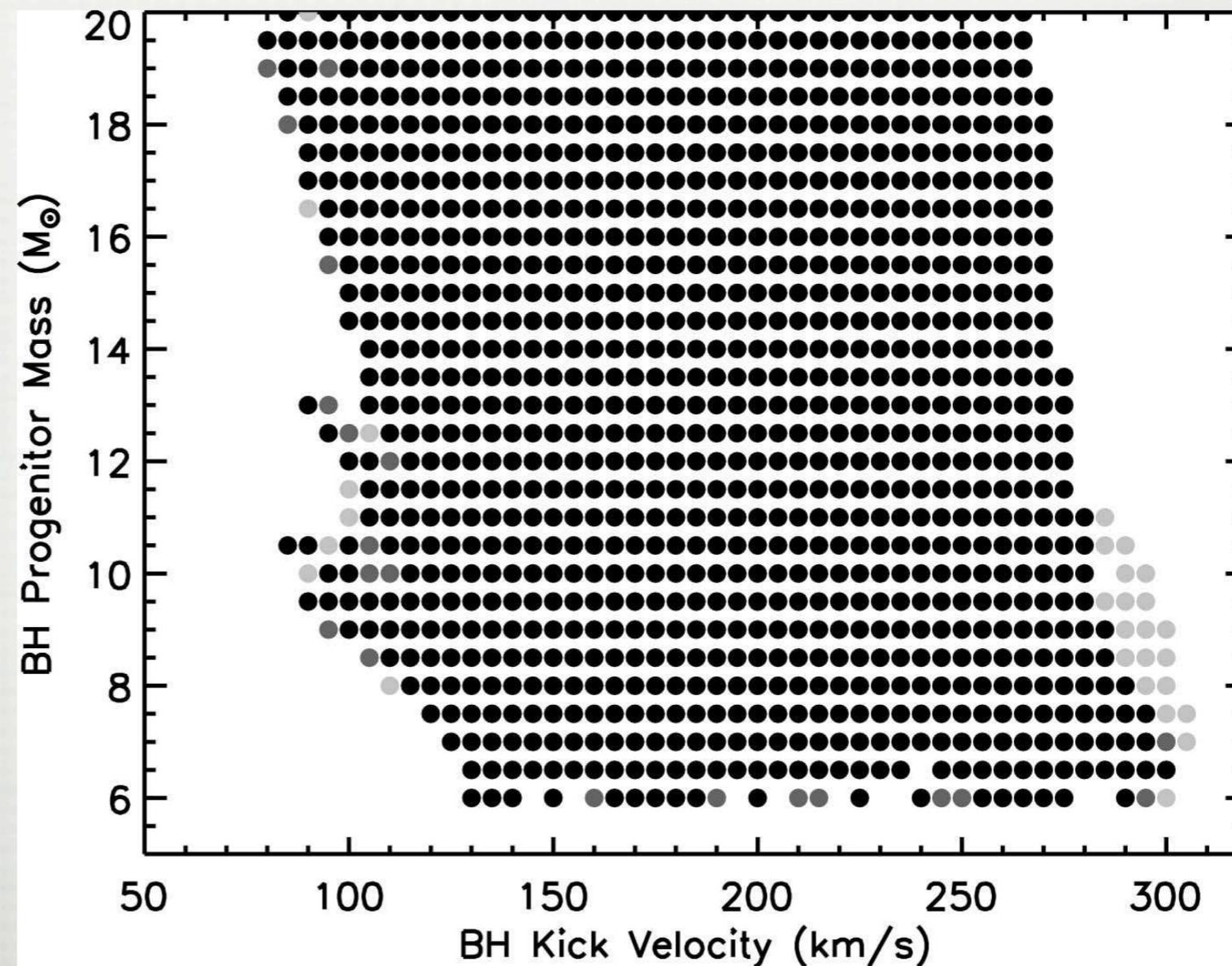
Radio pulsar proper motions imply a large kick speed.



Hobbs, et al. (2005)

Black Hole Birth Kicks

Can evolve BH XRB backward in time to constrain BH kick speed. Kick clearly required for XTE J1118+480.

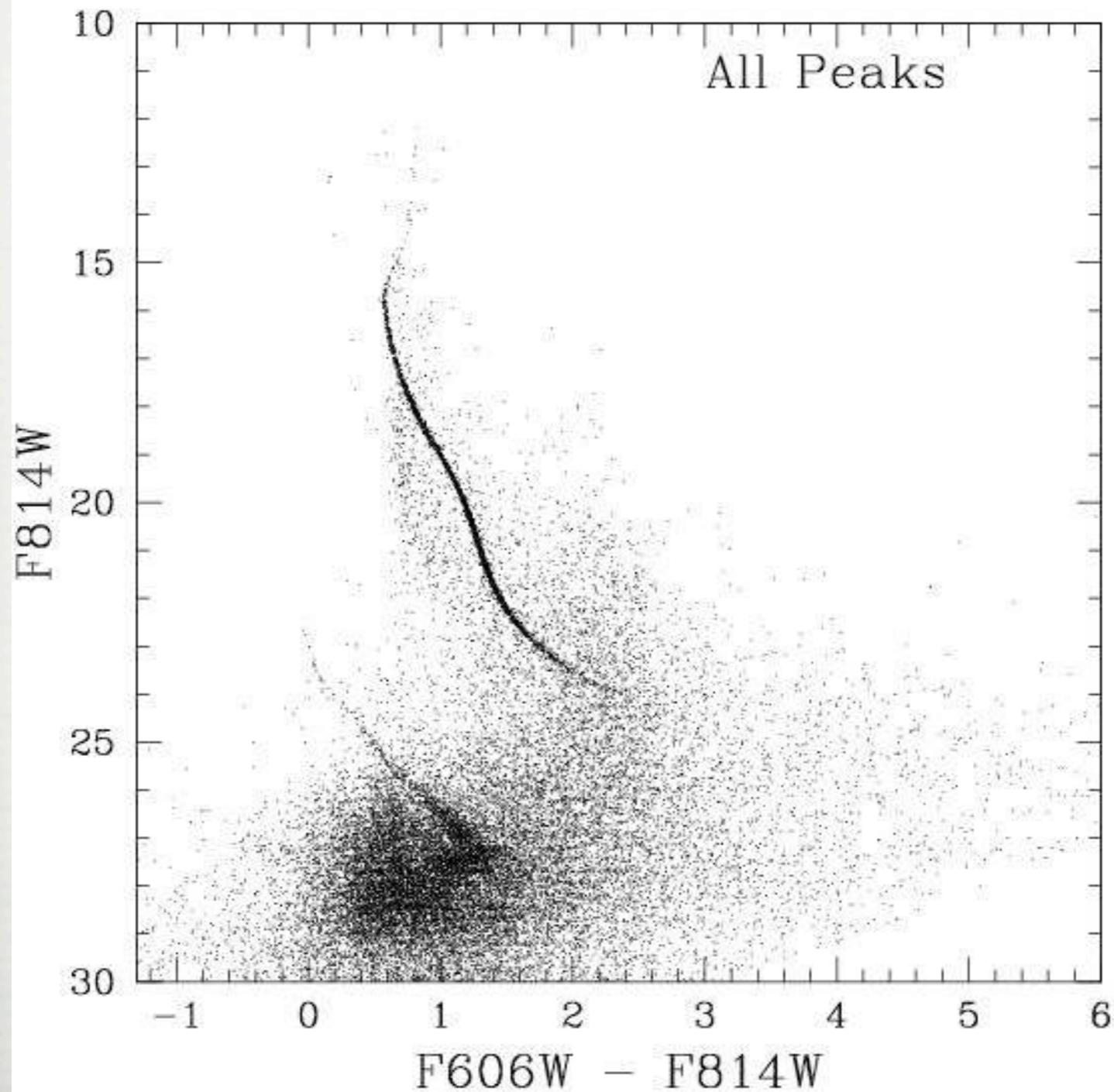


Fragos, et al. (2008)

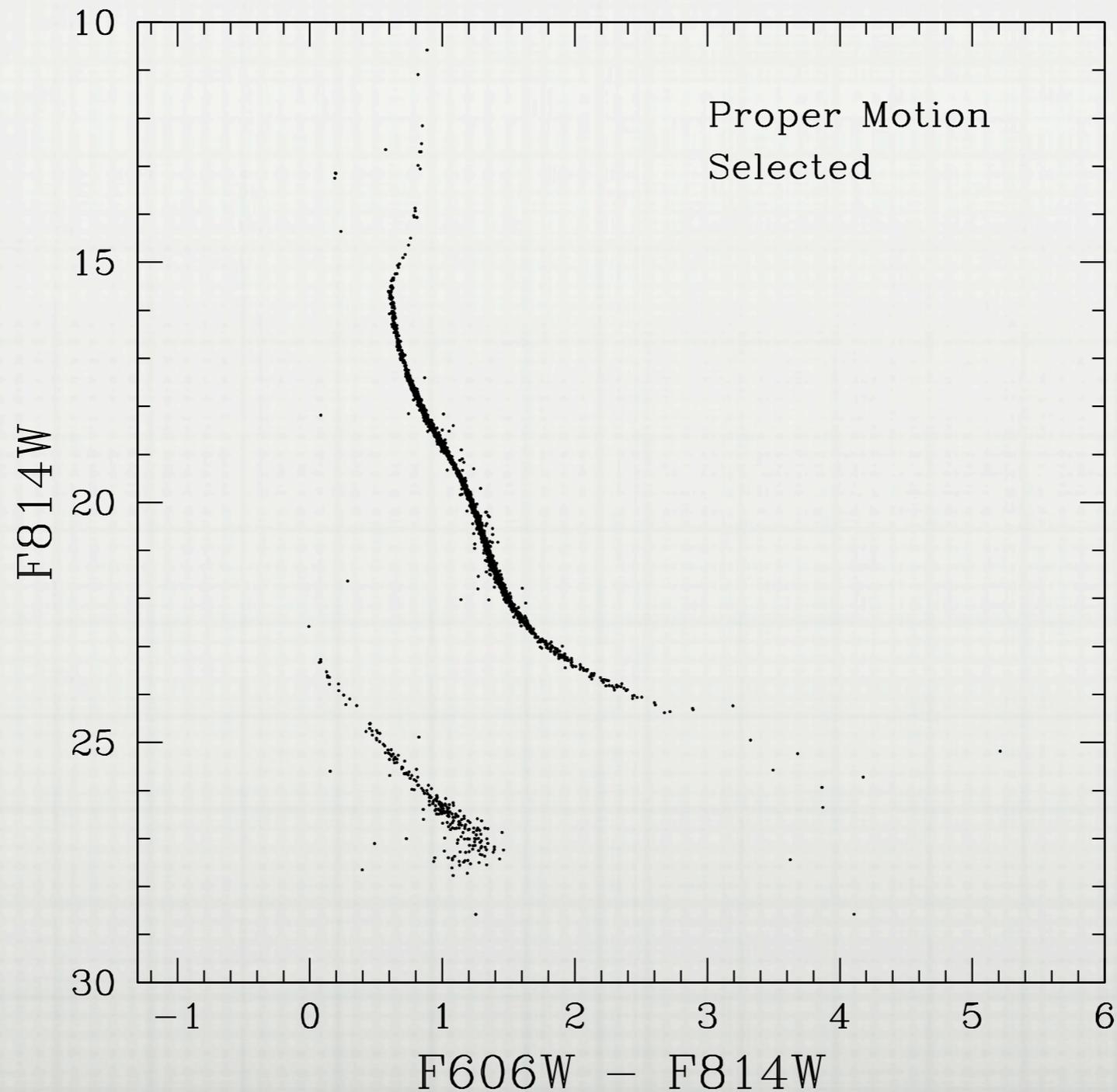
White Dwarf Birth Kicks?

- NSs and BHs likely acquire kicks due to asymmetries during core collapse, but WDs don't undergo core collapse.
- WD progenitors may lose significant amounts of mass during the AGB phase, though. An asymmetry in the mass loss could increase the systemic velocity of the resulting WD.
- Unfortunately, the magnitude of the WD kick is likely too small for it to make an appreciable impact on WD proper motions or the WD scale height in the Galactic disk.
- But WD kicks *would* be evident in globular clusters, where $v_{\sigma} \sim$ few km/s.

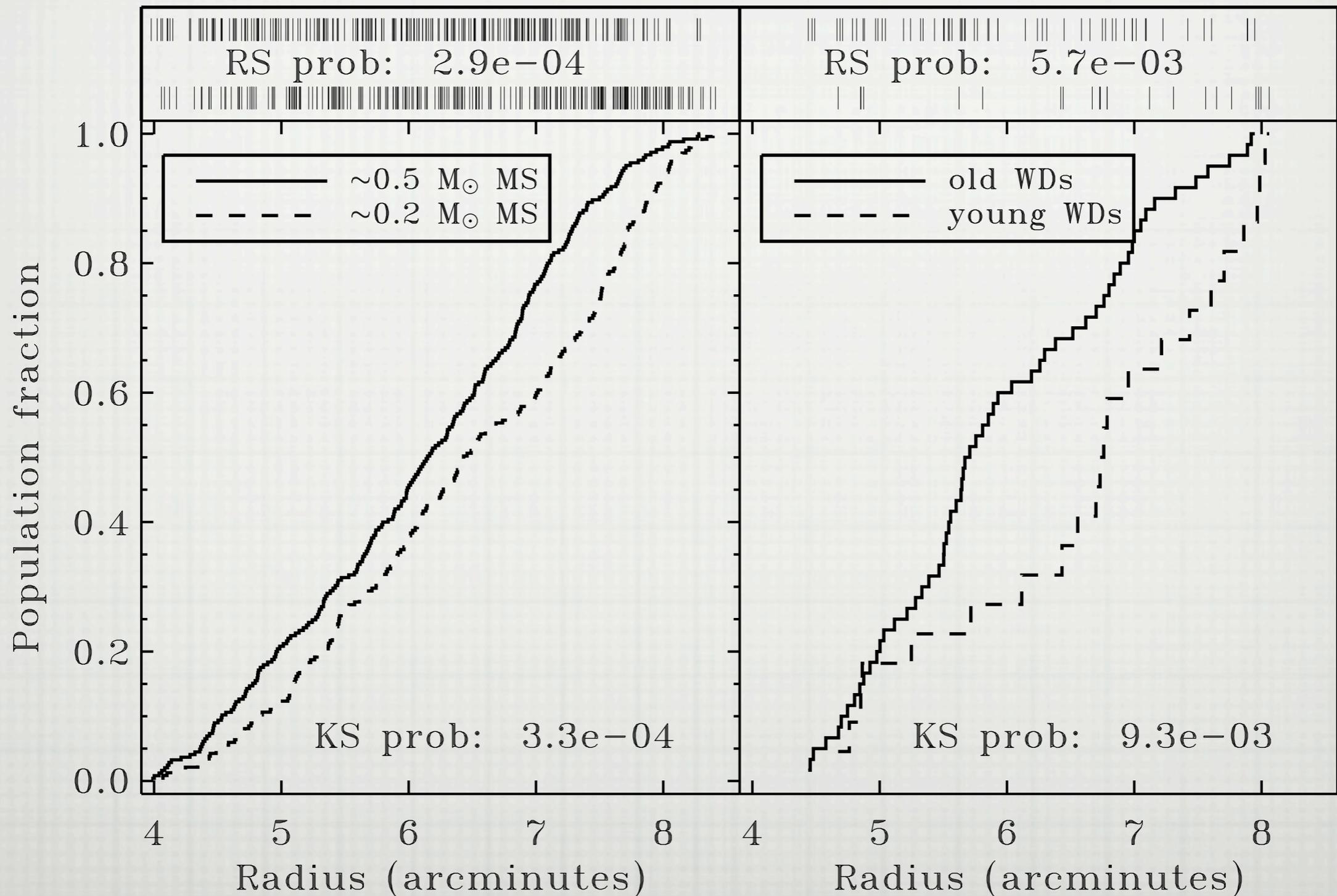
Deep Observations of NGC 6397 (Richer, et al. 2007)



Deep, Clean Observations of NGC 6397 (Richer, et al. 2007)



MS, WD Distributions in NGC 6397 (Davis, et al. 2008)



What Does It All Mean?

- Radial distributions of most stellar populations (MS, RGB, etc.) appear to agree with our understanding of mass segregation of relaxed populations.
- Younger WDs more radially extended in distribution than older WDs.
- Progenitors of WDs are $\sim 0.8 M_{\text{sun}}$ stars, while WDs are $\sim 0.5 M_{\text{sun}}$. From mass segregation, expect younger WDs to be more radially *concentrated* than older WDs, which have had time to mass segregate.
- Perhaps WDs receive a systemic “kick” late in their evolution as stars?
- From kinematics of NGC 6397, inferred kick speed is $\sim 3\text{-}5$ km/s.

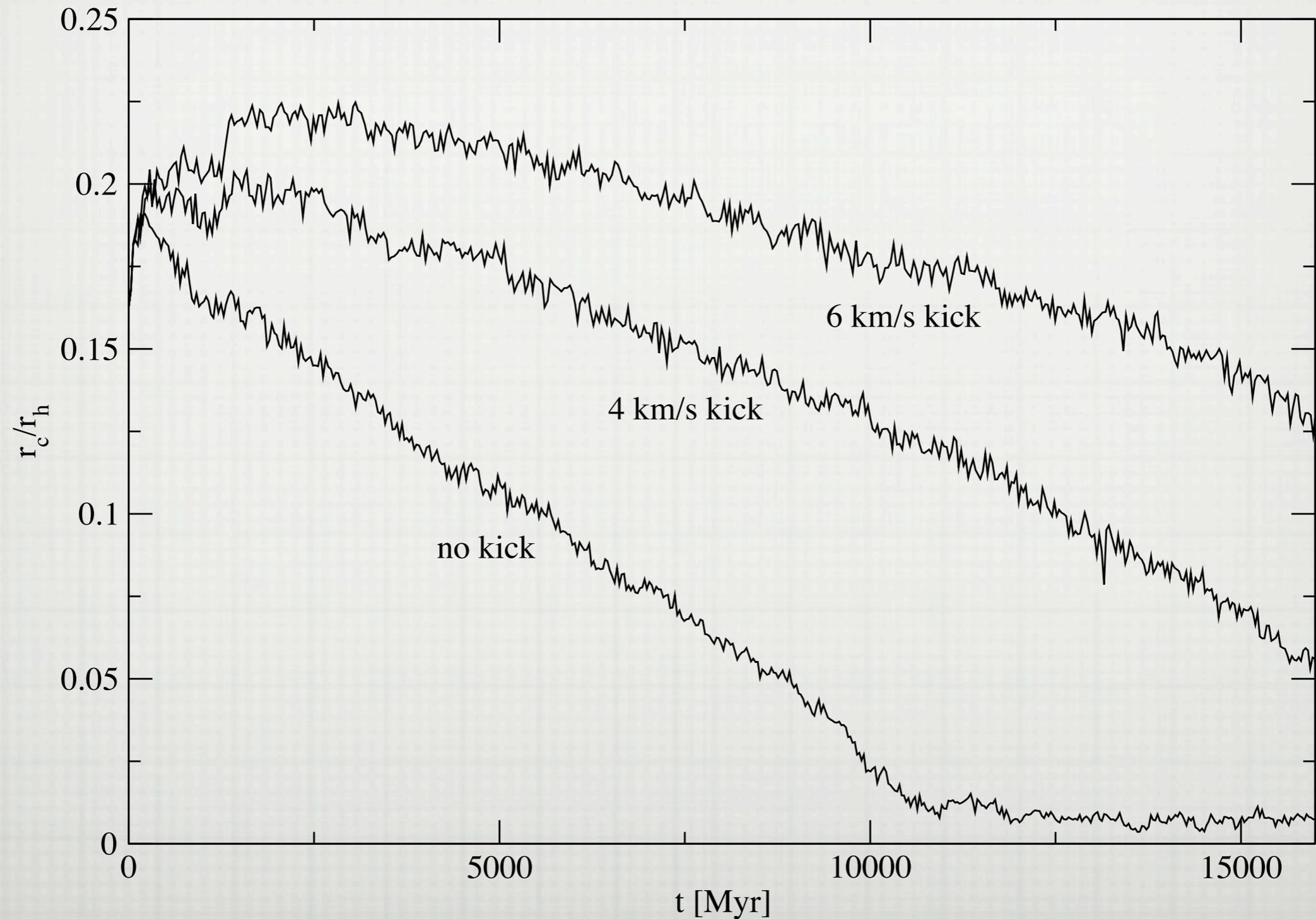
Where Does the Kick Come From?

- Asymmetric mass loss during the AGB phase?
- Asymmetry during the He flash?
- Observed WD rotation rates are consistent with non-axisymmetric mass loss at some point during evolution (Spruit 1998).
- Open clusters appear to be lacking WDs (e.g. Fellhauer, et al. 2003), although counting of binaries containing WDs may be an issue.

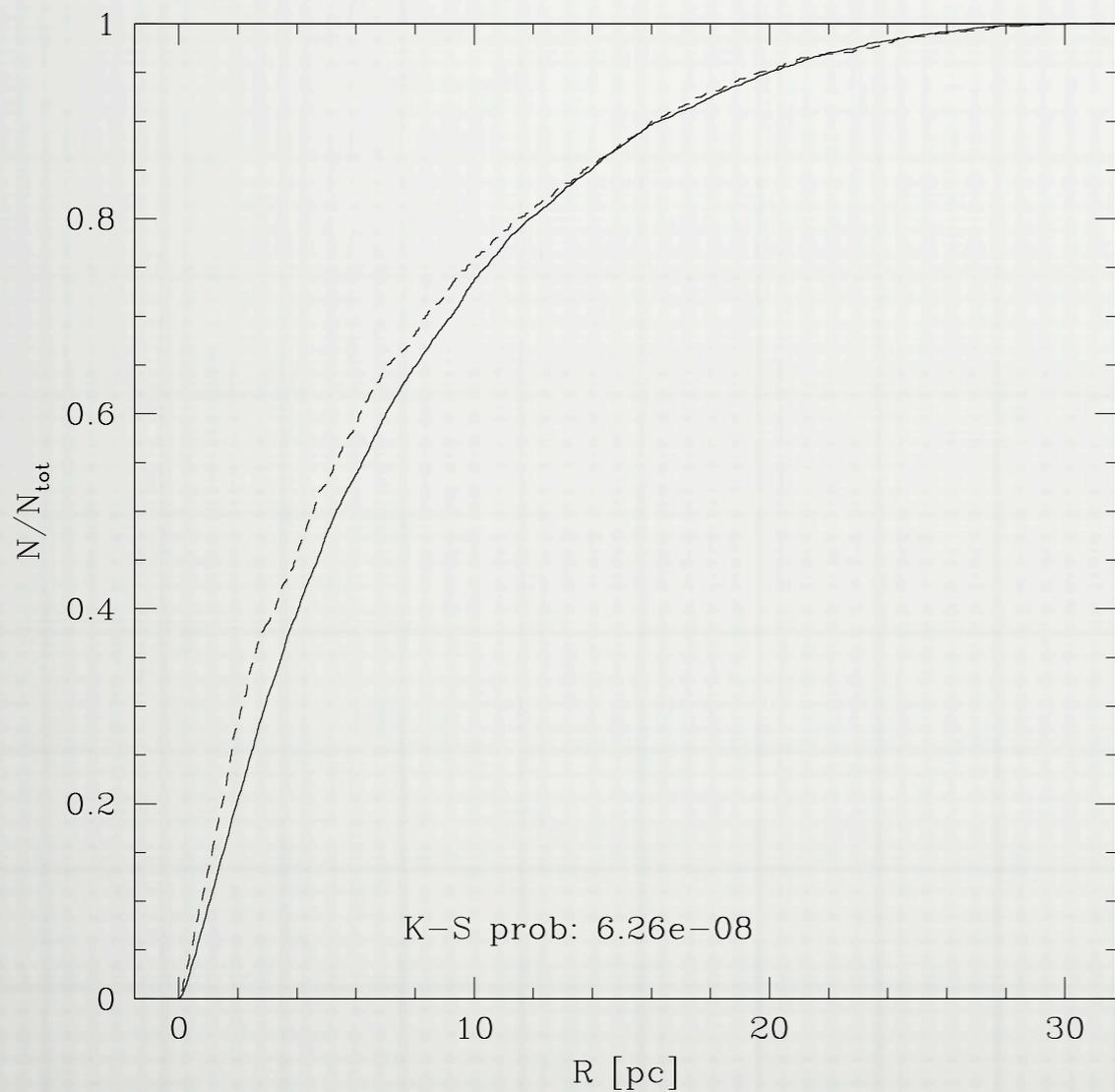
Let's Test the Effect of Kicks with our Monte Carlo Code

- Our Monte Carlo code treats nearly all relevant cluster physics: relaxation, binary scattering, collisions, single and binary star evolution. It has been tested carefully and shows very good agreement with direct N-body, but because it is orbit-averaged is *much* faster.
- WD kicks are easy to include, since they're analogous to the NS kicks we've been dealing with for years. We simply give a star a randomly-oriented kick of a fixed speed (2, 3, ..., 9 km/s) when it becomes a WD.
- We expect that WDs substantially younger than the local $t_{\text{mass-seg}}$ will be more radially extended than the older WDs.
- Since the kicks are an energy source, we expect larger cluster core radii.
- Expect the effect to be most pronounced for clusters with $v_{\sigma} \sim v_{\text{kick}}$.

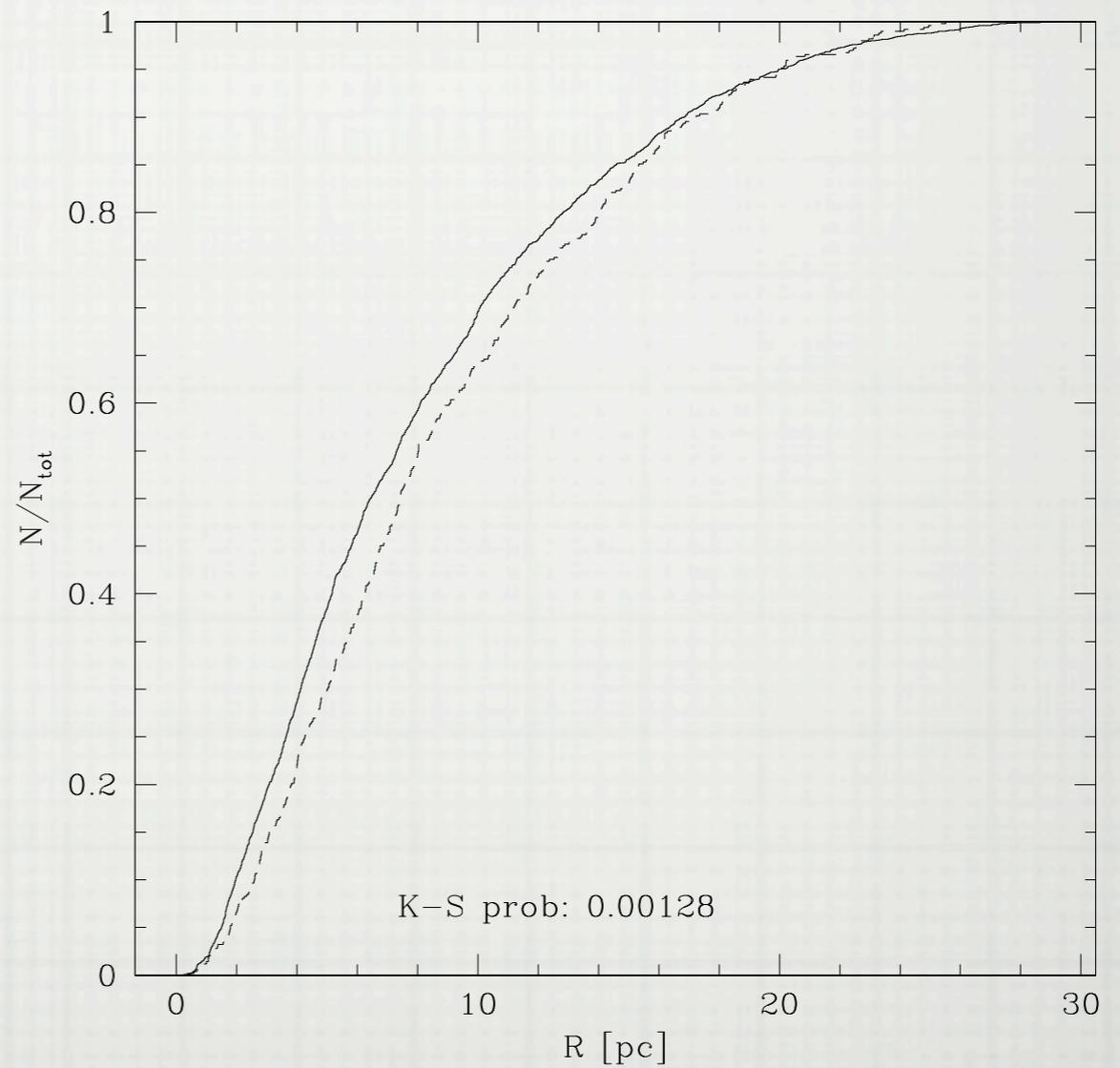
Long Term Evolution of Clusters with WD Kicks



Radial Distributions of WDs, Generally Speaking

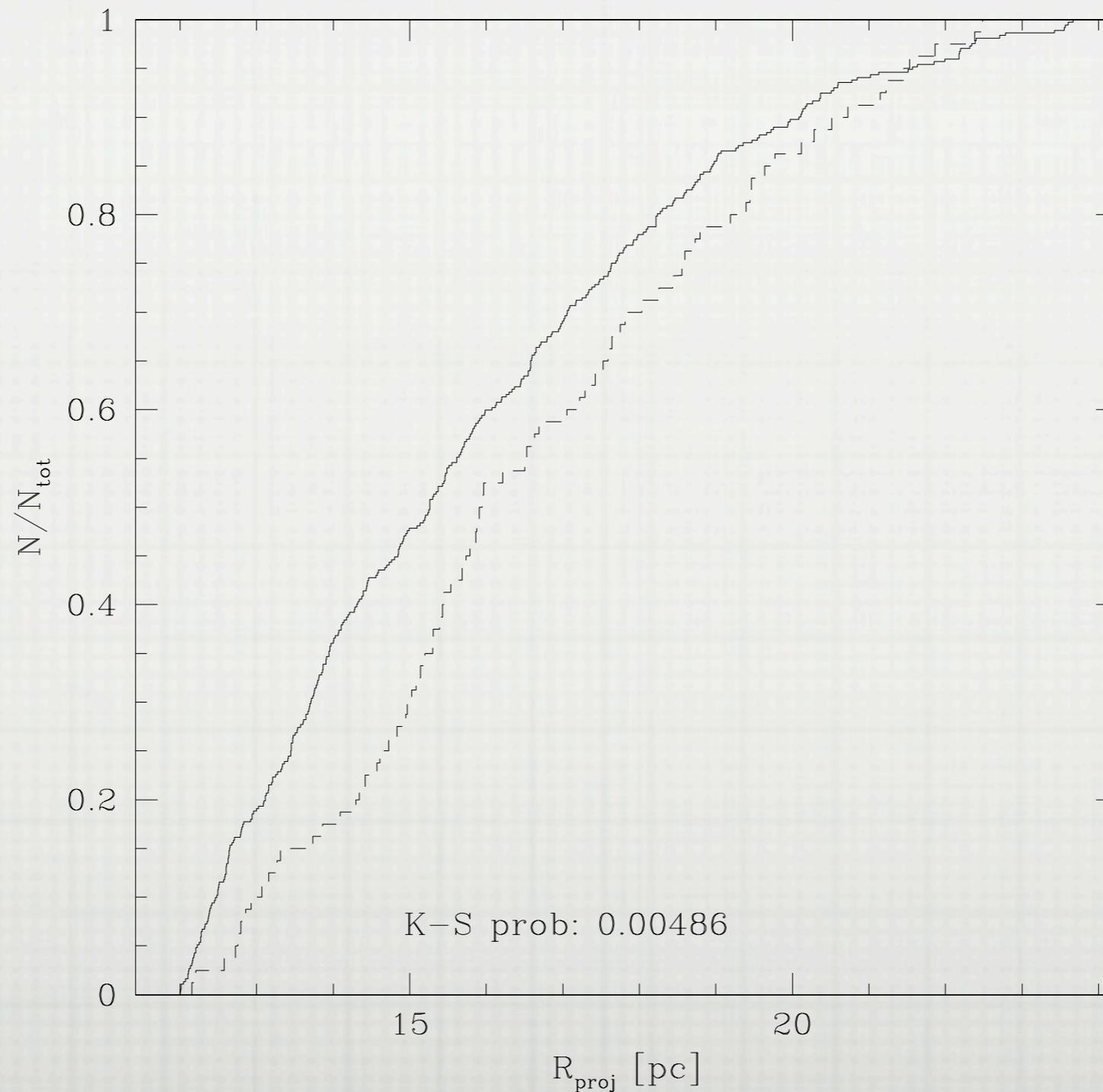


no kick



6 km/s kick

Projected Radial Distribution of WDs in NGC 6397 Field (4km/s Model)



Salient Points

- Radial distributions of old vs. young WDs in models with kicks agree well with observations. (And don't agree for models with no kicks.)
- WD kicks comparable to the cluster velocity dispersion yield cluster core sizes $\sim 10\times$ larger than models without kicks at late times.
- In typical non-“core-collapsed” clusters WD kicks thus represent a possible resolution of the factor of ~ 10 discrepancy between observations and theory in r_c/r_h .
- However, quantitative statements about statistical significance require more detailed modeling of NGC 6397 and Monte Carlo sampling.

Predictions, Objections, Complications

- If WD kick speed is not correlated with cluster properties, expect:
 - $v_{\text{kick}} < v_{\sigma}$ (e.g., 47 Tuc): little to no effect observed
 - $v_{\text{kick}} \sim v_{\sigma}$: older WDs more centrally concentrated than younger WDs, core larger than no-kick case
 - $v_{\text{kick}} > v_{\sigma}$ (e.g., NGC 288): large cluster core, missing WDs
- AGB wind speeds can be ~ 10 km/s (Marshall, et al. 2004). If the wind is retained by the cluster the effect of kicks may be weaker.
- AGB timescale can be $> 10^7$ yr, but typical orbit timescale is $\sim 10^5$ yr. If kick occurs during AGB phase, the dynamical result would not be that of a kick, but a weaker, adiabatic modification of the orbit.
- Upcoming WD proper motion observations should help clarify the issue.

Initial and Final Models

- Initial model

- King $W_0=7.5$

- $r_{\text{vir}} = 5 \text{ pc}$

- $N=3 \times 10^5$

- 1% binaries.

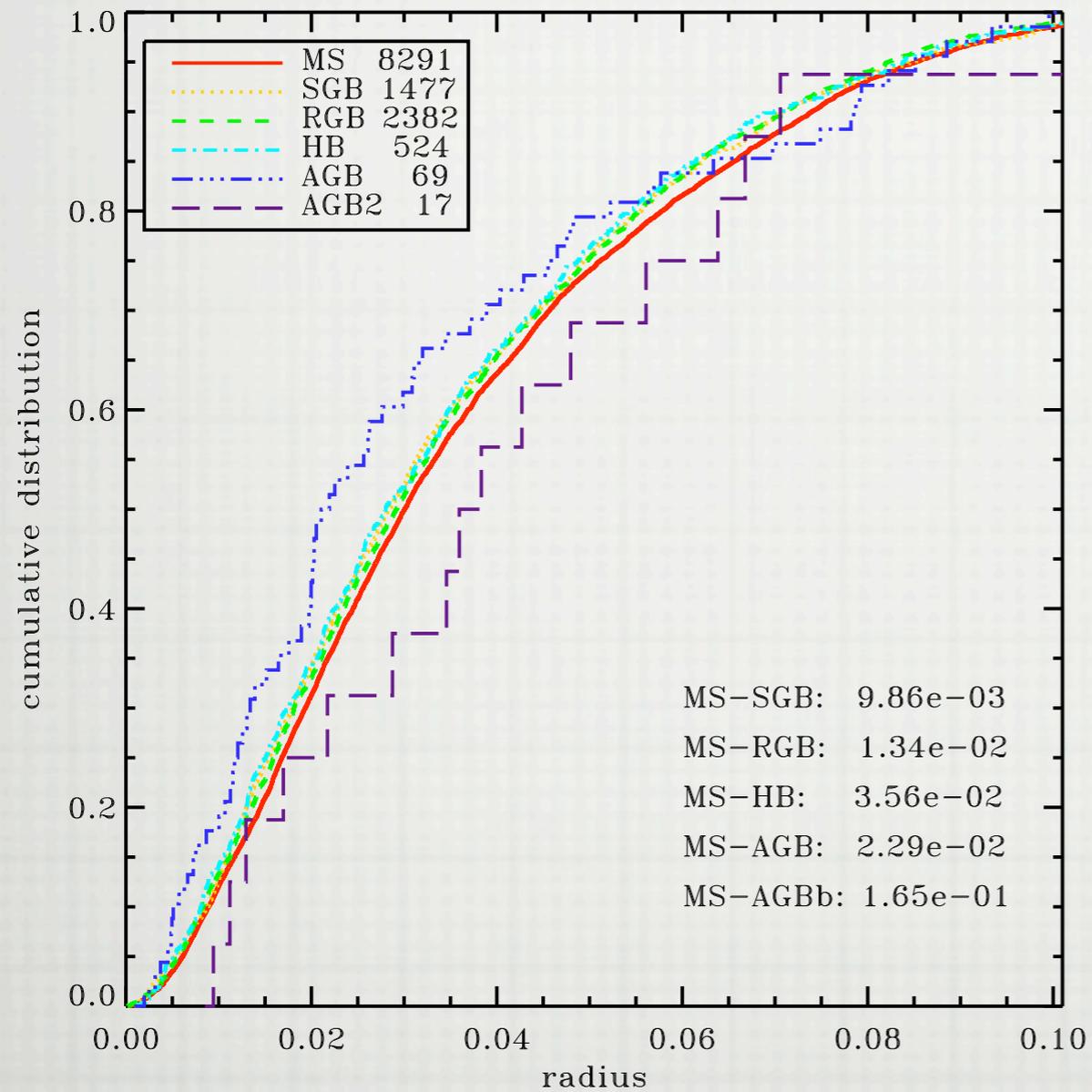
- Final model

- $v_\sigma, r_c/n_h$ (sort of), $f_b, f_{b,c}$ consistent with NGC 6397 observations

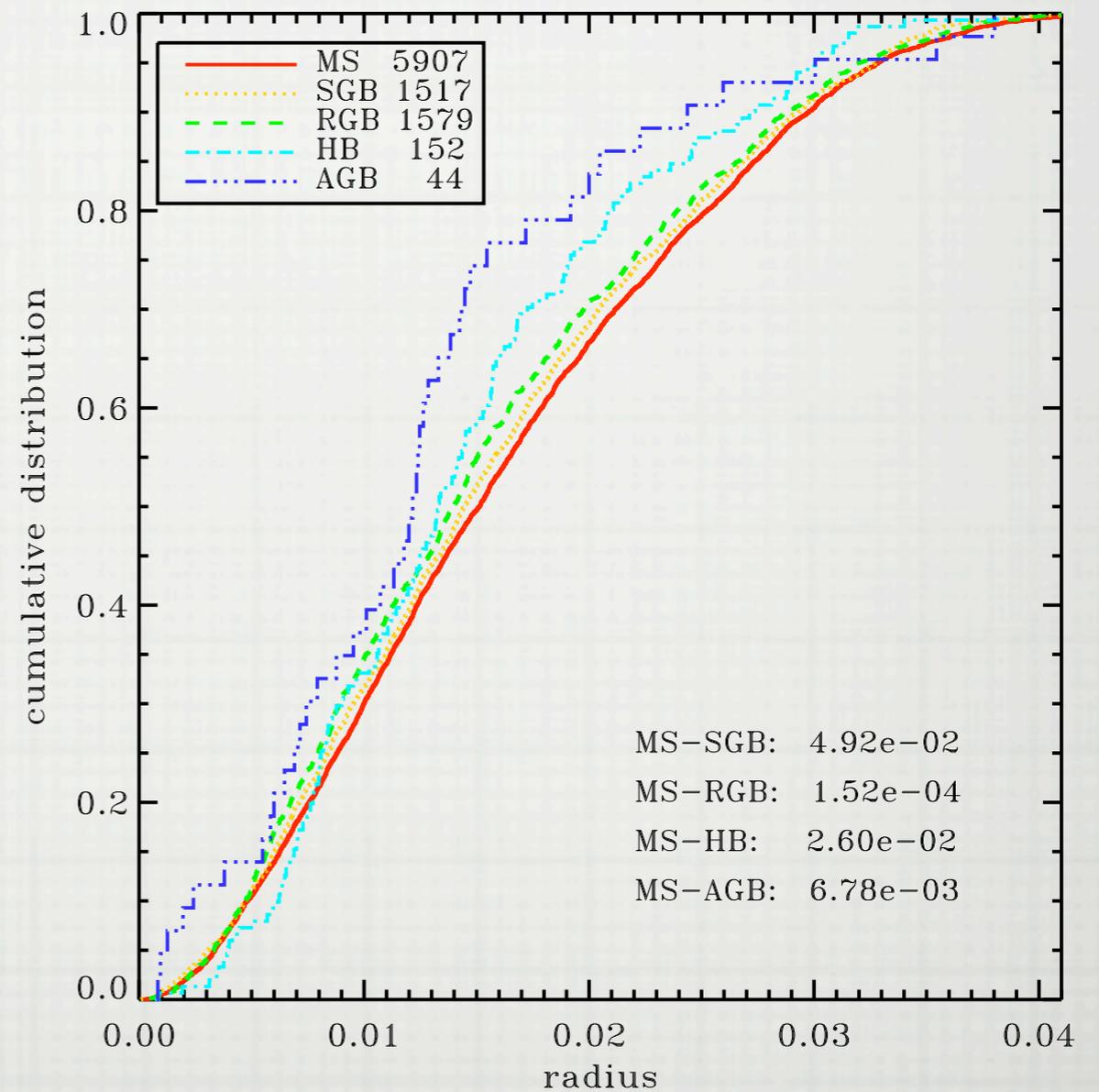
- $n_h \sim 4x$ too large.

Mass Segregation in Other Clusters

(Richer, et al.)

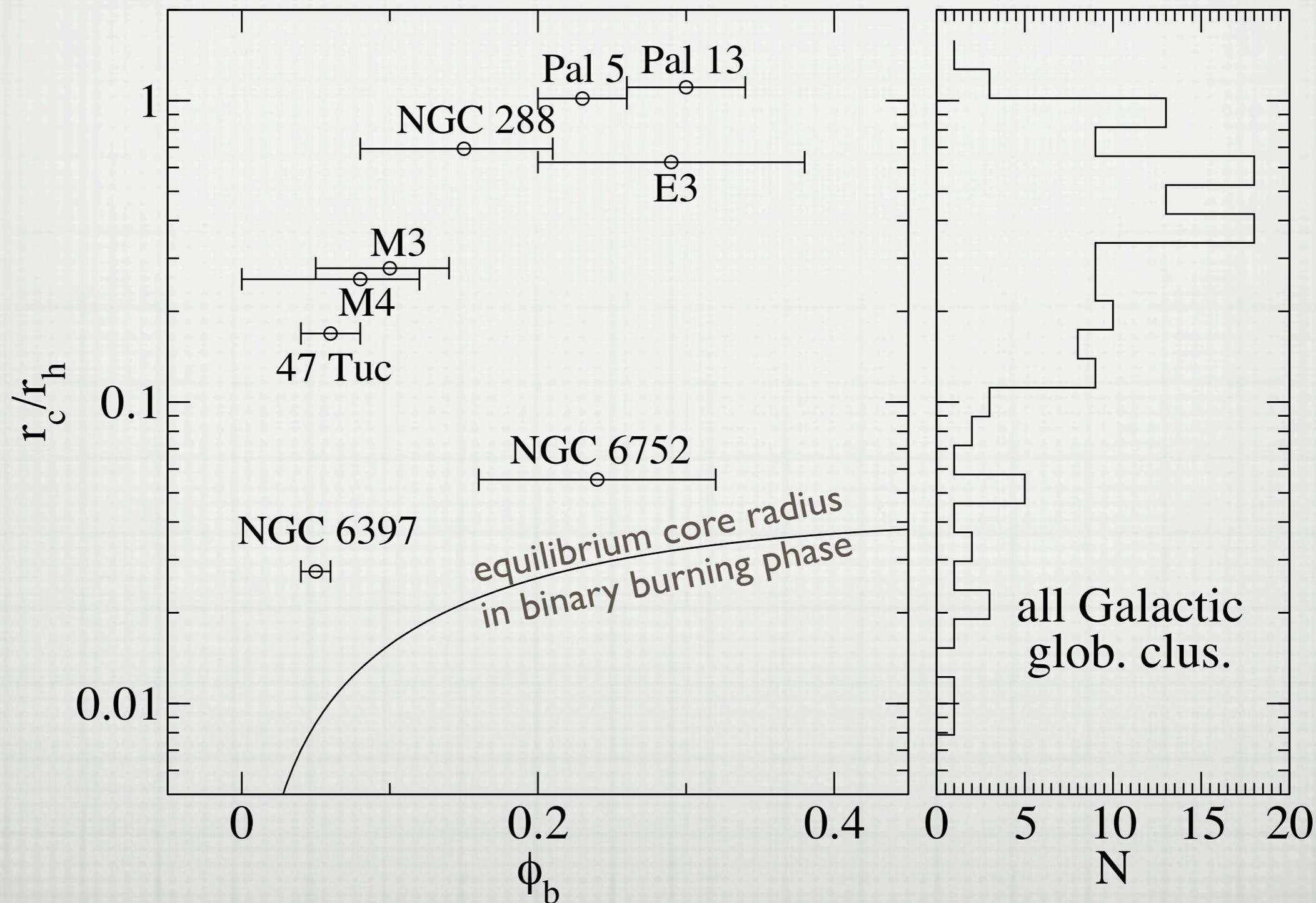


47 Tuc



M3

Disagreement Between Theory and Observations in Binary Burning Phase



Possible Resolutions of r_c/r_h Discrepancy

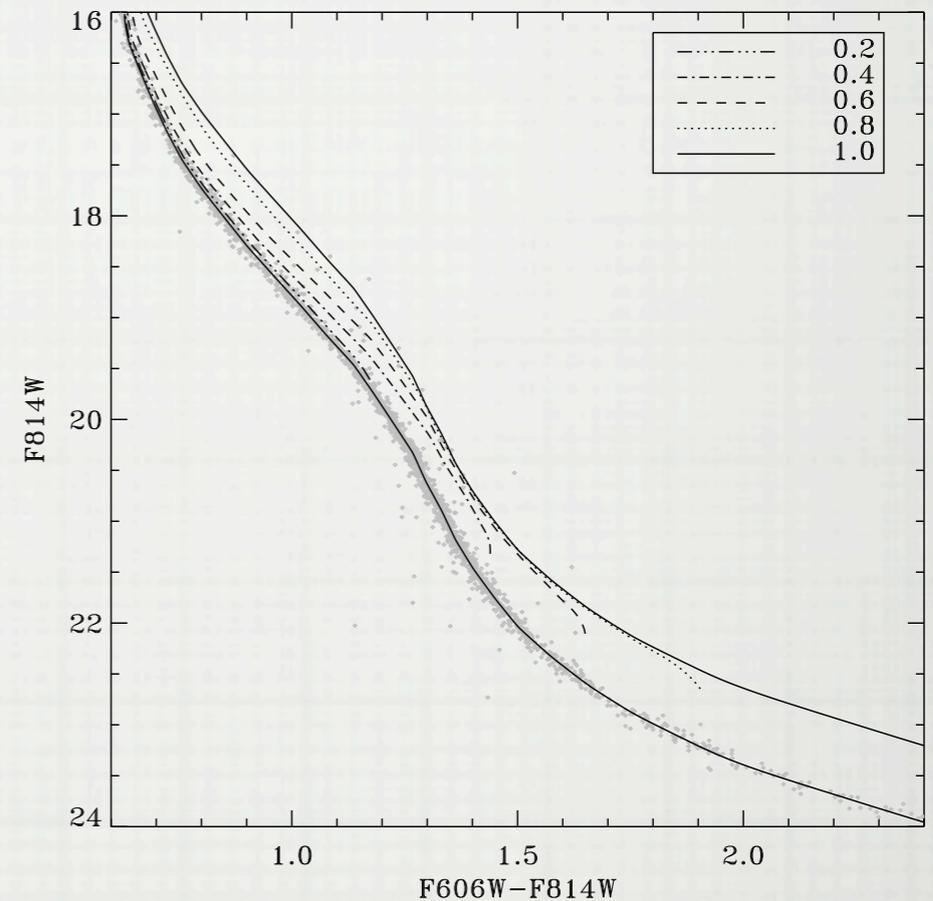
- Differing definitions of r_c/r_h can yield a factor of up to ~ 4 difference in the appropriate direction (Hurley 2007).
- Neglected physics in simulations important? Stellar evolutionary mass loss on long timescales (Hurley 2007), collisions of stars leading to expedited stellar evolution mass loss (Chatterjee, et al. 2007)?
- Additional energy sources: central IMBHs (Trenti 2006), prolonged mass segregation (Merritt, et al. 2004), evaporation of stellar-mass BH population (Mackey, et al. 2007)?
- Perhaps most clusters are simply not yet in the binary-burning phase (Fregeau 2008)?
- White dwarf birth kicks of ~ 5 km/s (Davis, et al. 2008; Fregeau, et al. 2009)?

Recent Wrinkles

□ Current cluster core binary fractions are difficult to determine, but can be measured via, e.g., main-sequence fitting. The binary fraction ranges from a few % to ~30%.

□ On the other hand, the observed binary fraction in low density environments, like the field or open clusters, is rather large ($> \sim 50\%$).

□ Recent simulations show that the core *hard* binary fraction generically increases dramatically with time (Fregeau, Ivanova, & Rasio 2009).

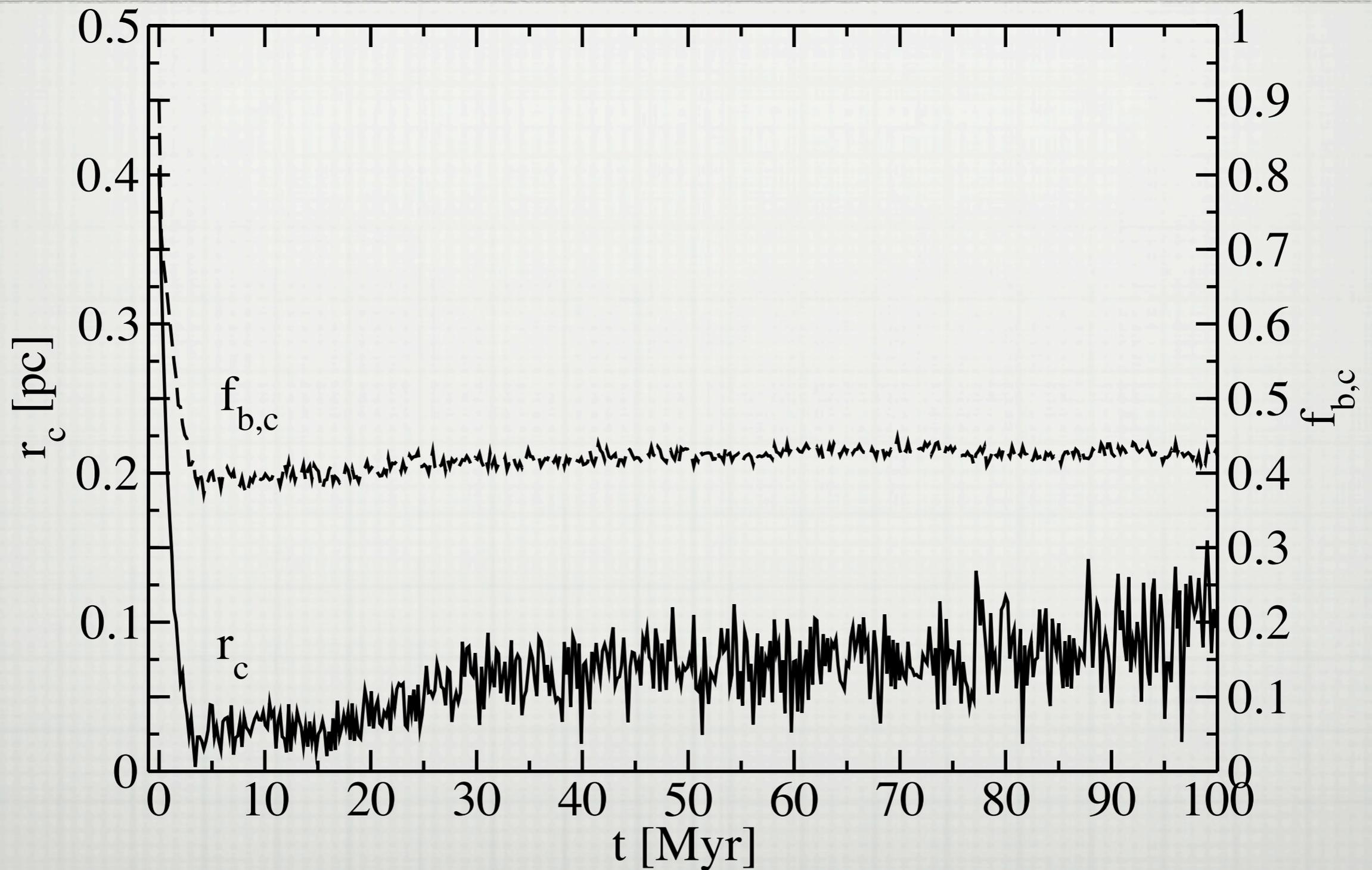


MS method in NGC 6397 (Davis, et al. 2008)

The Importance of Soft Binaries

- Hard binaries: binaries with binding energy *greater* than the local kinetic energy; tend to become more bound (harden) in scattering interactions.
- Soft binaries: binaries with binding energy *less* than the local kinetic energy; tend to become less bound (soften) in scattering interactions.
- Observed field binaries have orbital periods up to $\sim 10^7$ days.
- Binaries with orbits longer than $\sim 10^3$ days are soft in globular cluster cores. An initial $f_b=0.5$ with a field distribution of orbital properties quickly becomes $f_b=0.15$, so computational theorists tend to ignore soft binaries, since they're "dynamically irrelevant."
- However, soft binary disruption is an energy *sink*, and will cause a cluster core to contract significantly. A simple analytical argument shows that for typical initial conditions, a cluster with core radius of ~ 2 pc can shrink to ~ 0.2 pc in just a few Myr.

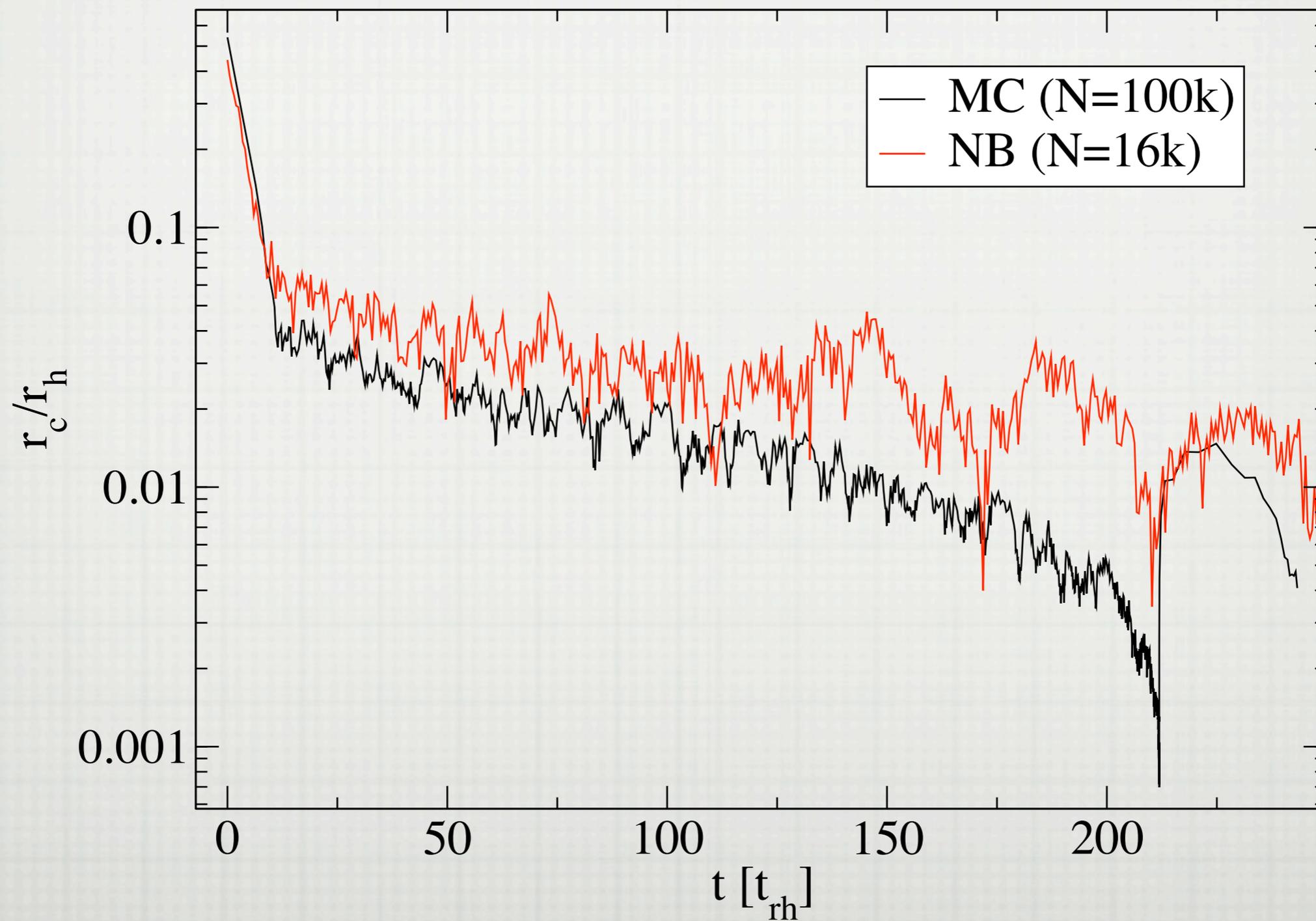
The Importance of Soft Binaries



Recap

- Observations of the WDs in NGC 6397 show that the youngest are more radially extended than the other (older) WDs.
- Cluster evolution simulations show that WD birth kicks yield WD young/old radial distributions that are consistent with the observations.
- Cluster simulations show that WD kicks lengthen the initial cluster “core contraction” phase, possibly delaying binary burning beyond a Hubble time, and yielding core sizes that are $\sim 10\times$ larger than without kicks.
- Recent simulations show that the core hard binary fraction generically increases with time, implying that clusters were born with very small hard binary fractions.
- If most primordial binaries in a cluster are soft, the cluster’s evolution is drastically different from the “standard,” with the onset of binary burning occurring within a few Myr.

Agreement Between N-Body and Monte Carlo



MC Code: Now With Stellar Evolution!

