White Dwarf Kicks in Star Clusters

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Harry the Unhappy Hammer Finally Finds a Nail

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Dutch Translation by Fred Rasio

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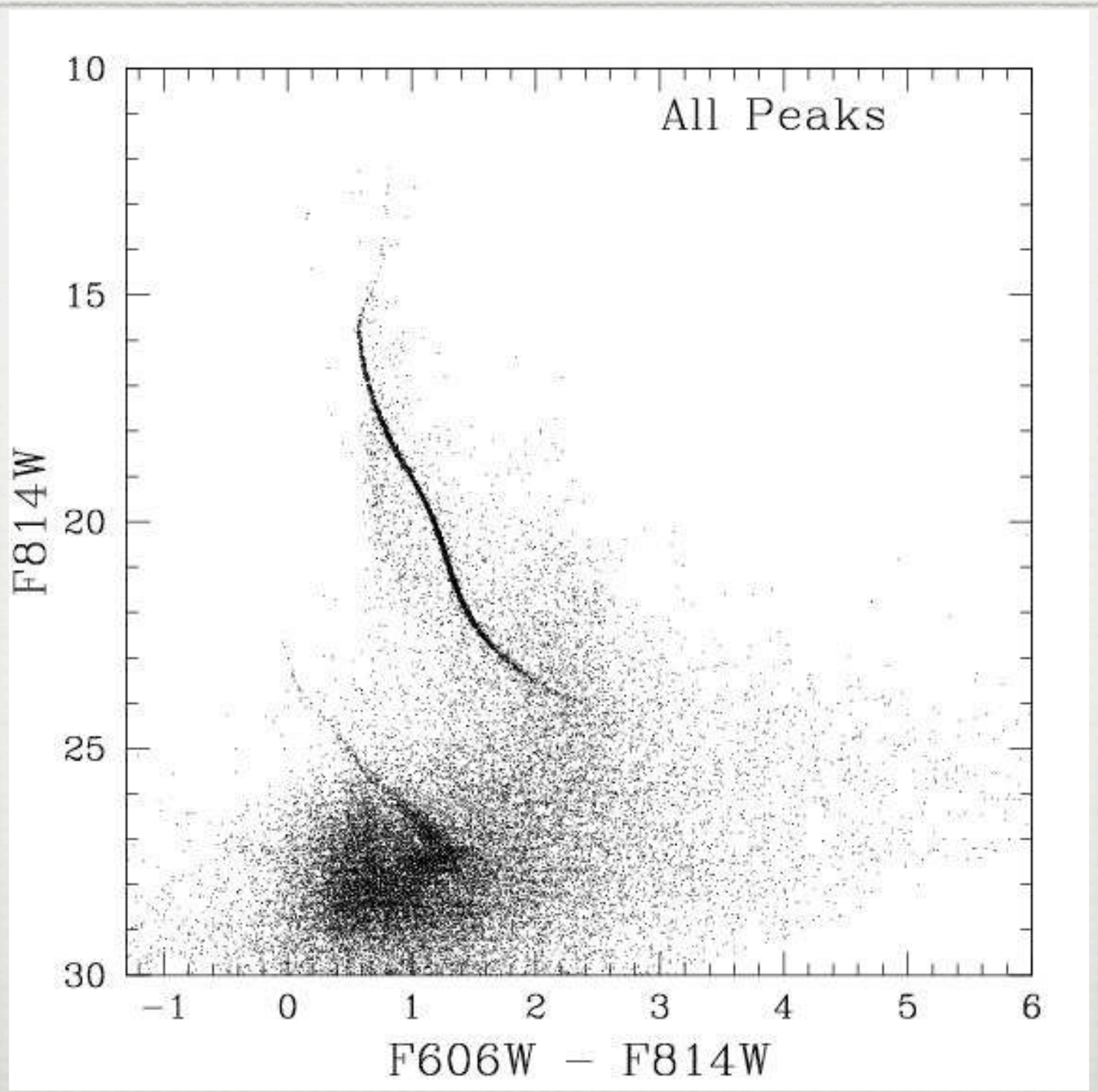
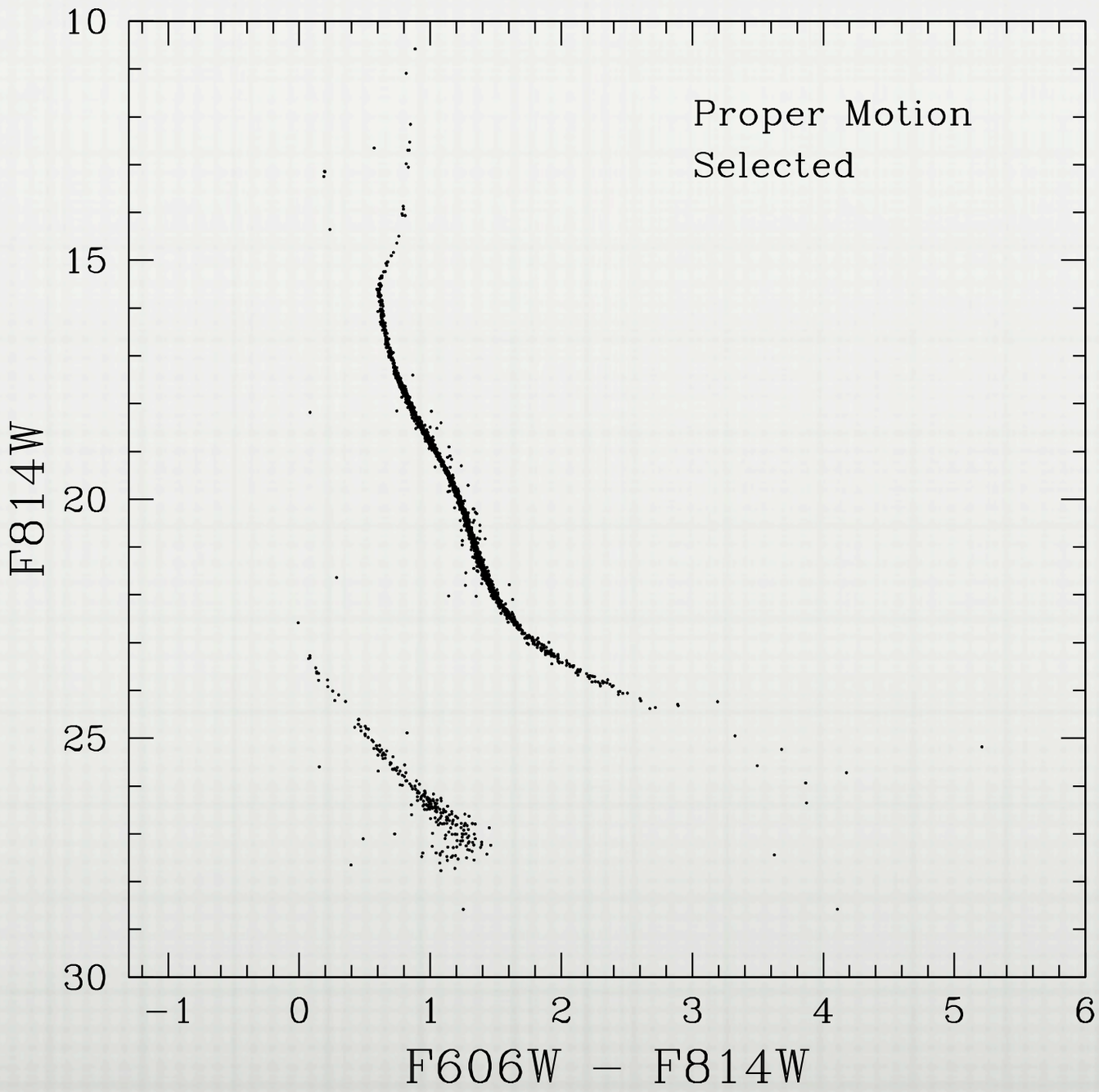
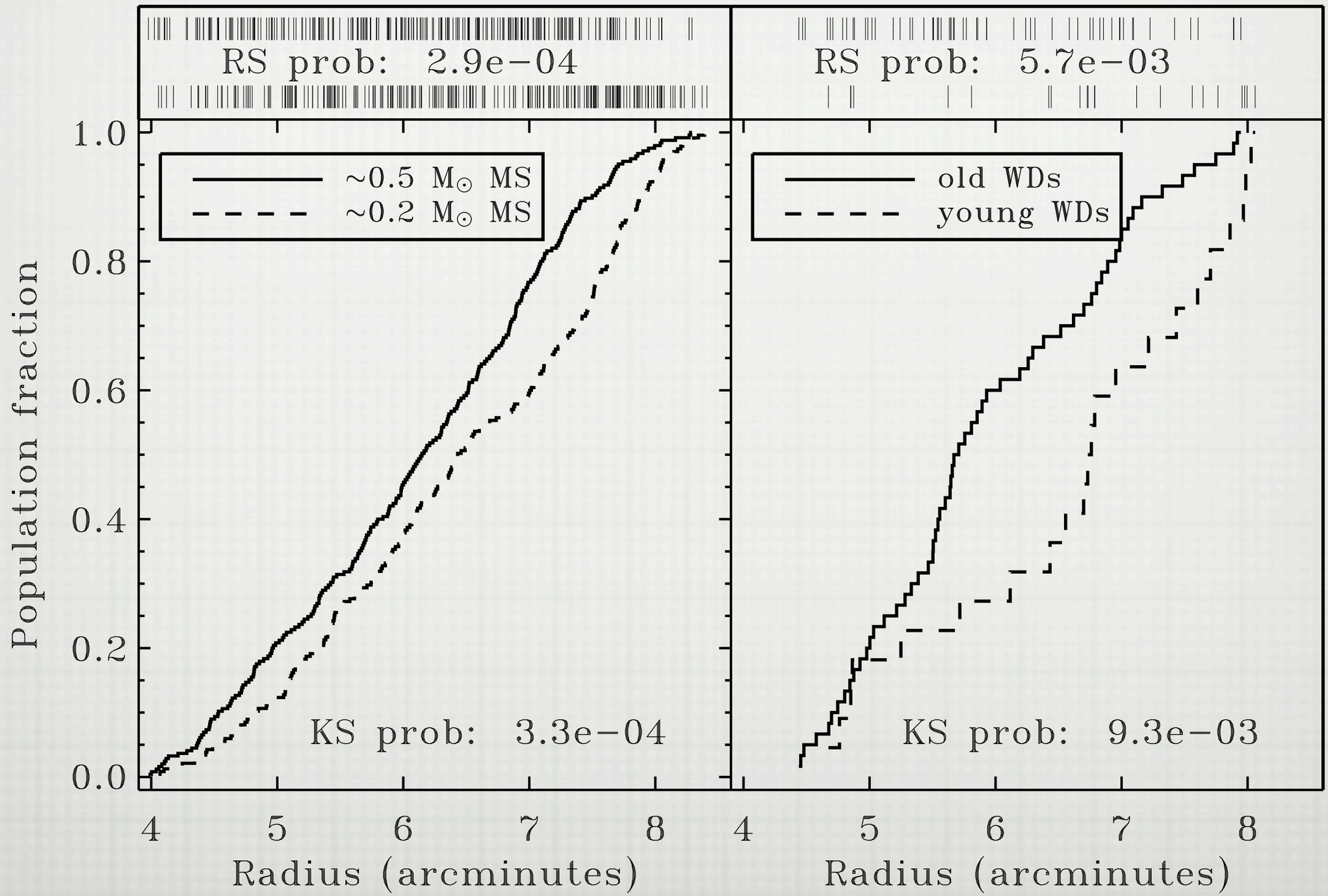
Deep Observations of NGC 6397 (Richer, et al. 2007)



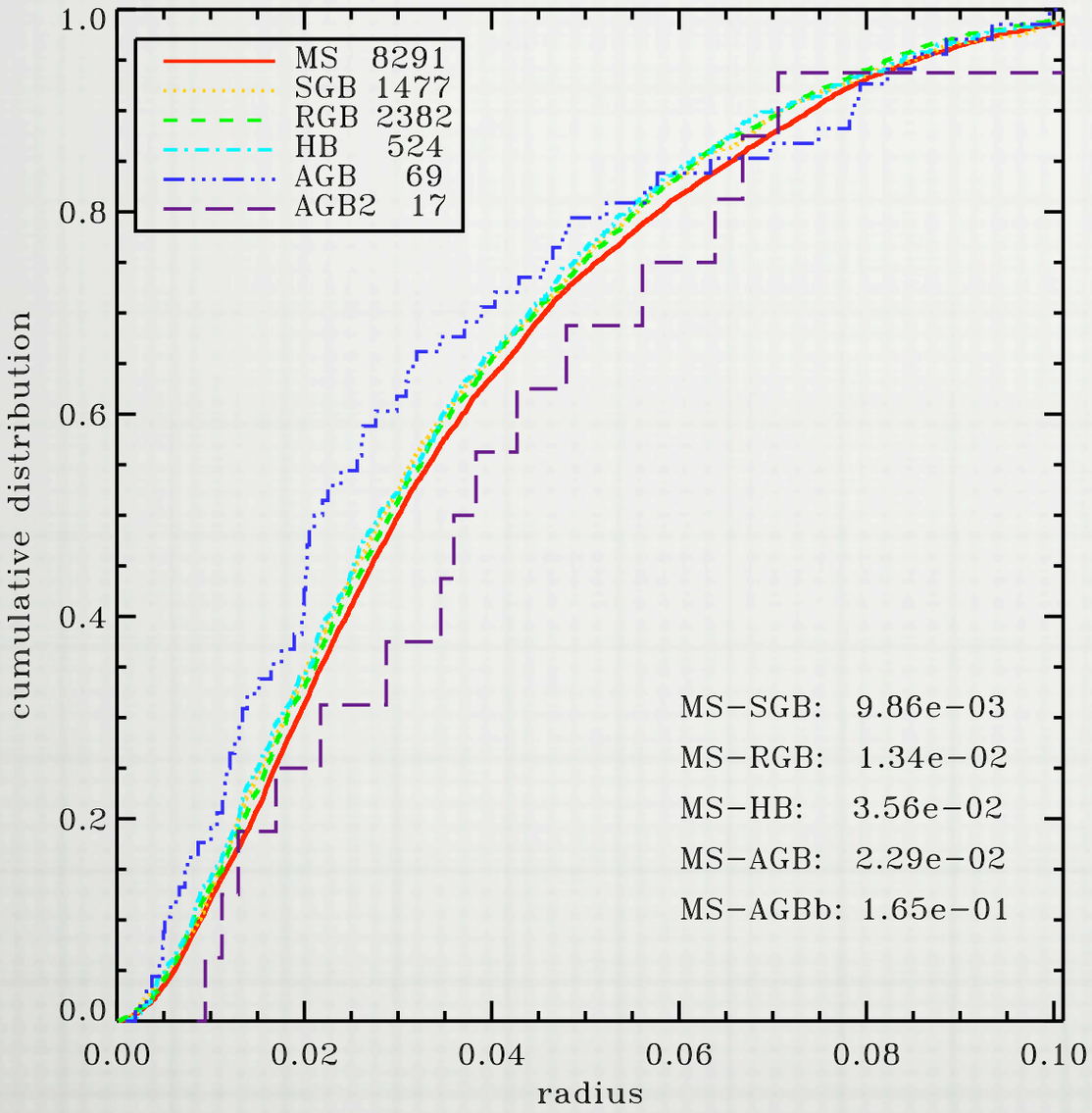
Deep, Clean Observations of NGC 6397 (Richer, et al. 2007)



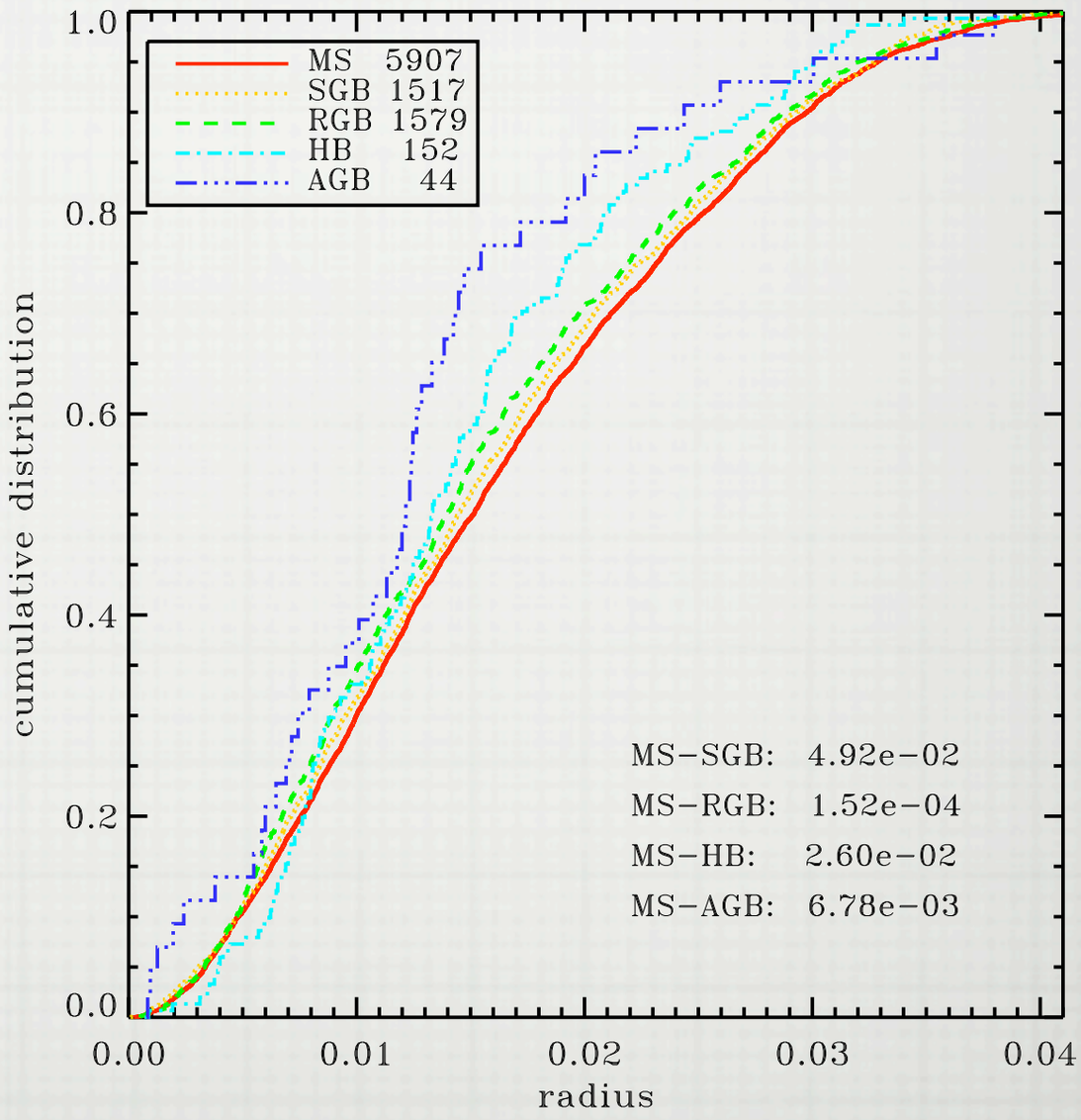
MS, WD Distributions in NGC 6397 (Davis, et al. 2008)



Mass Segregation in Other Clusters (Richer, et al.)



47 Tuc



M3

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 ~0.8 M_sun stars, while WDs are ~0.5 M_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 ~3-5 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., Kalirai, et al. 2001)

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.

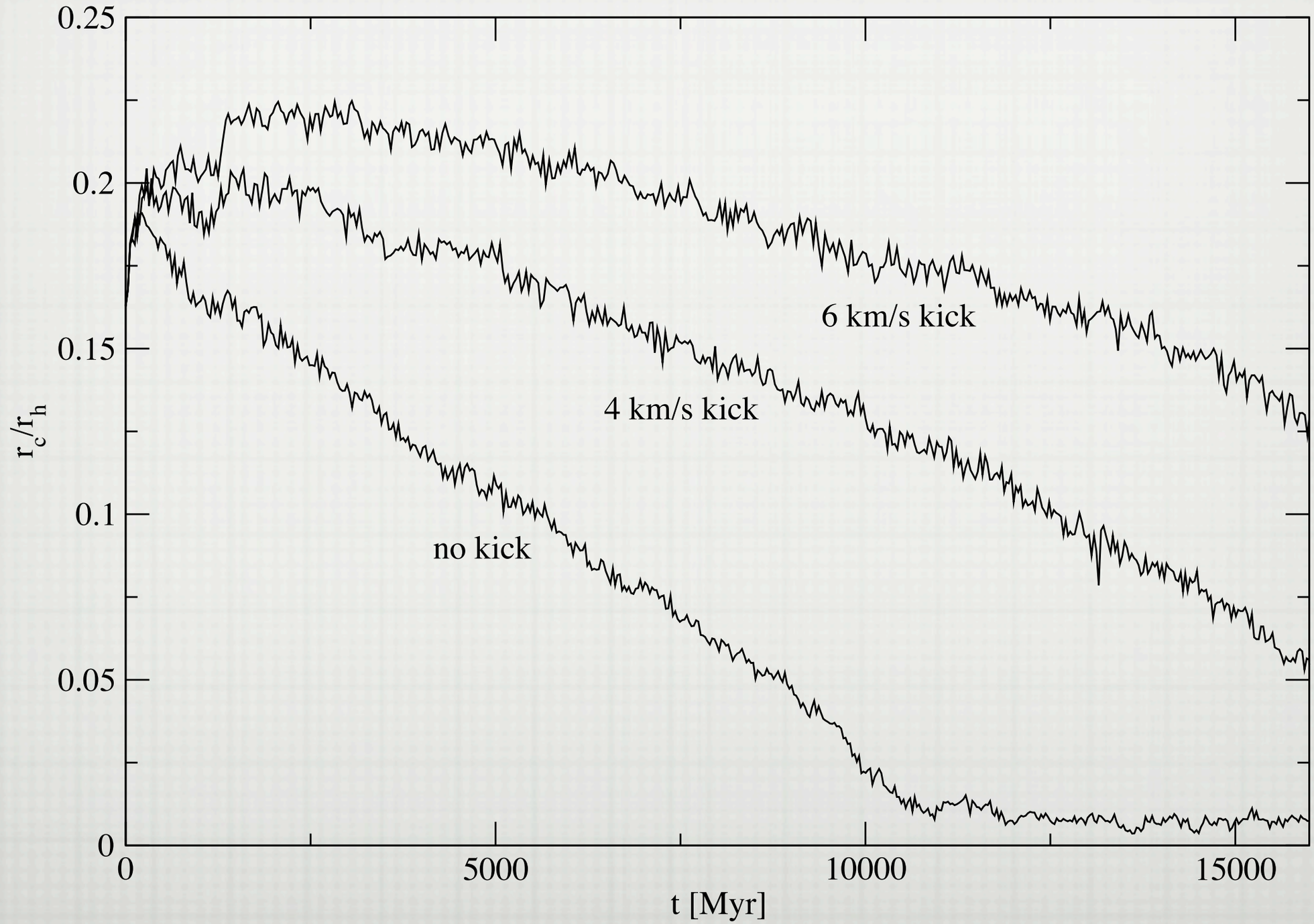
- Since the kicks are an energy source, we expect larger cluster core radii.

- Expect the effect to be most pronounced for clusters with $v_{\sigma} \sim v_{\text{kick}}$.

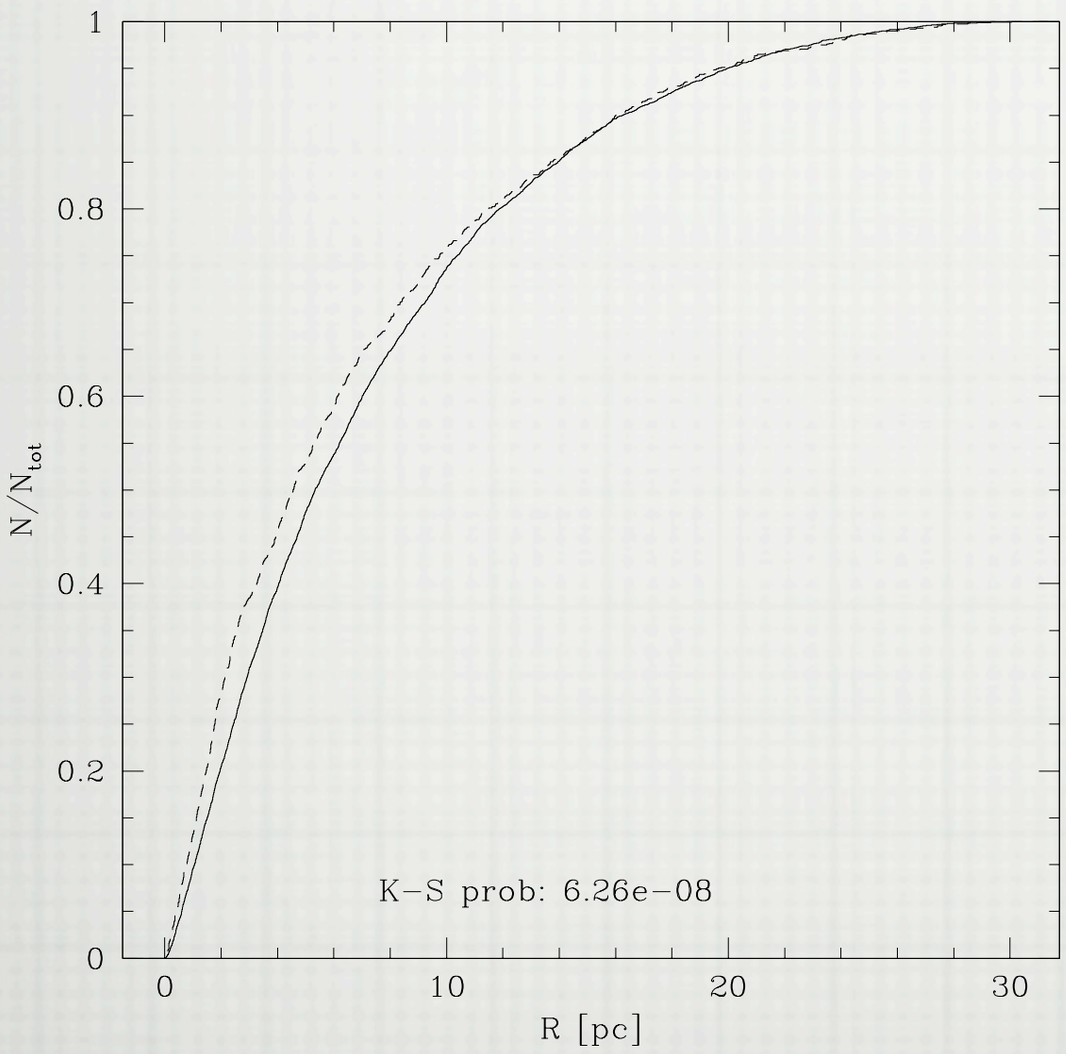
Initial and Final Models

- Initial model
  - King W_0=7.5
  - r_{vir} = 5 pc
  - N=3x10^5
  - 1% binaries.
- Final model
  - v_σ, r_c/r_h (sort of), f_b, $f_{b,c}$ consistent with NGC 6397 observations
  - r_h ~ 4x too large.

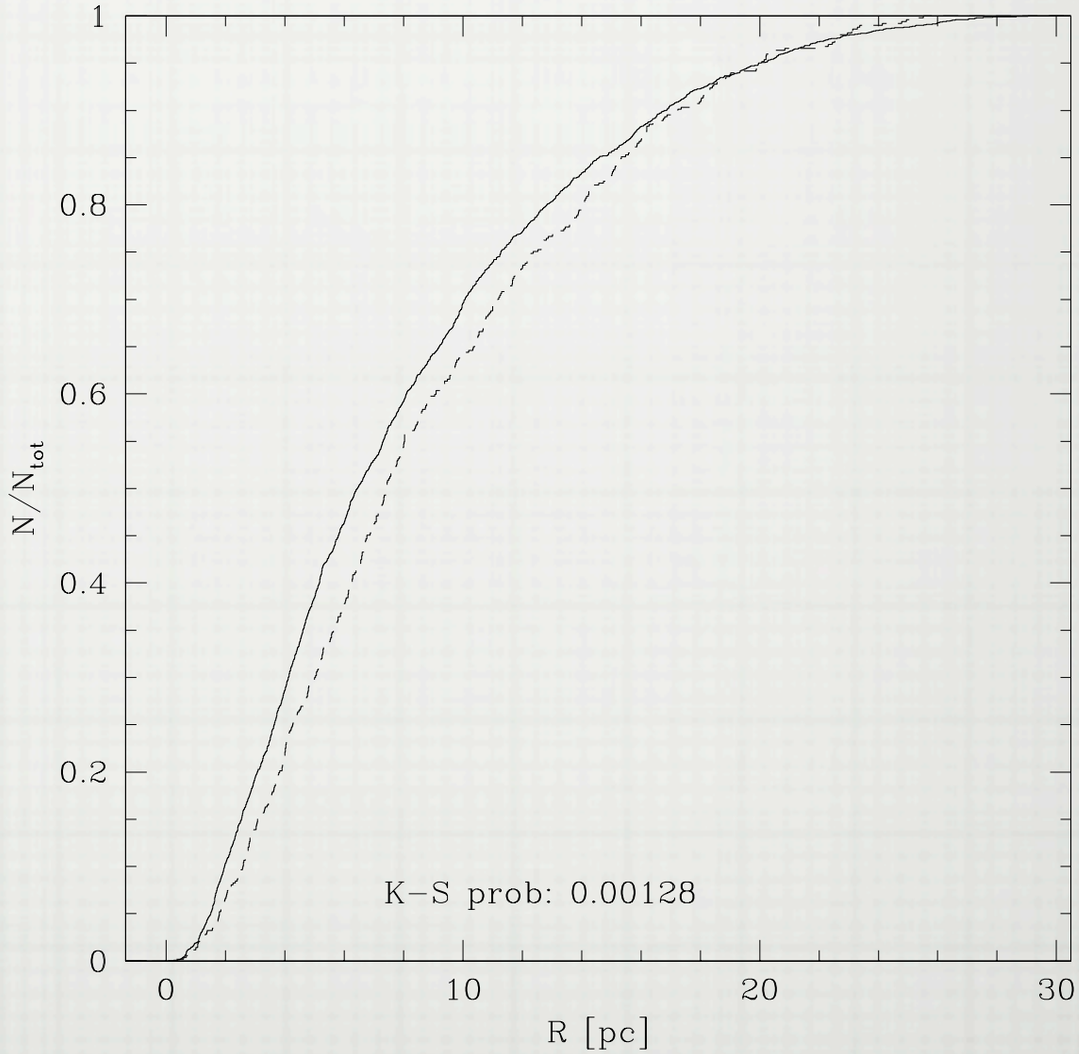
Long Term Evolution of Clusters with WD Kicks



Radial Distributions of WDs, Generally Speaking

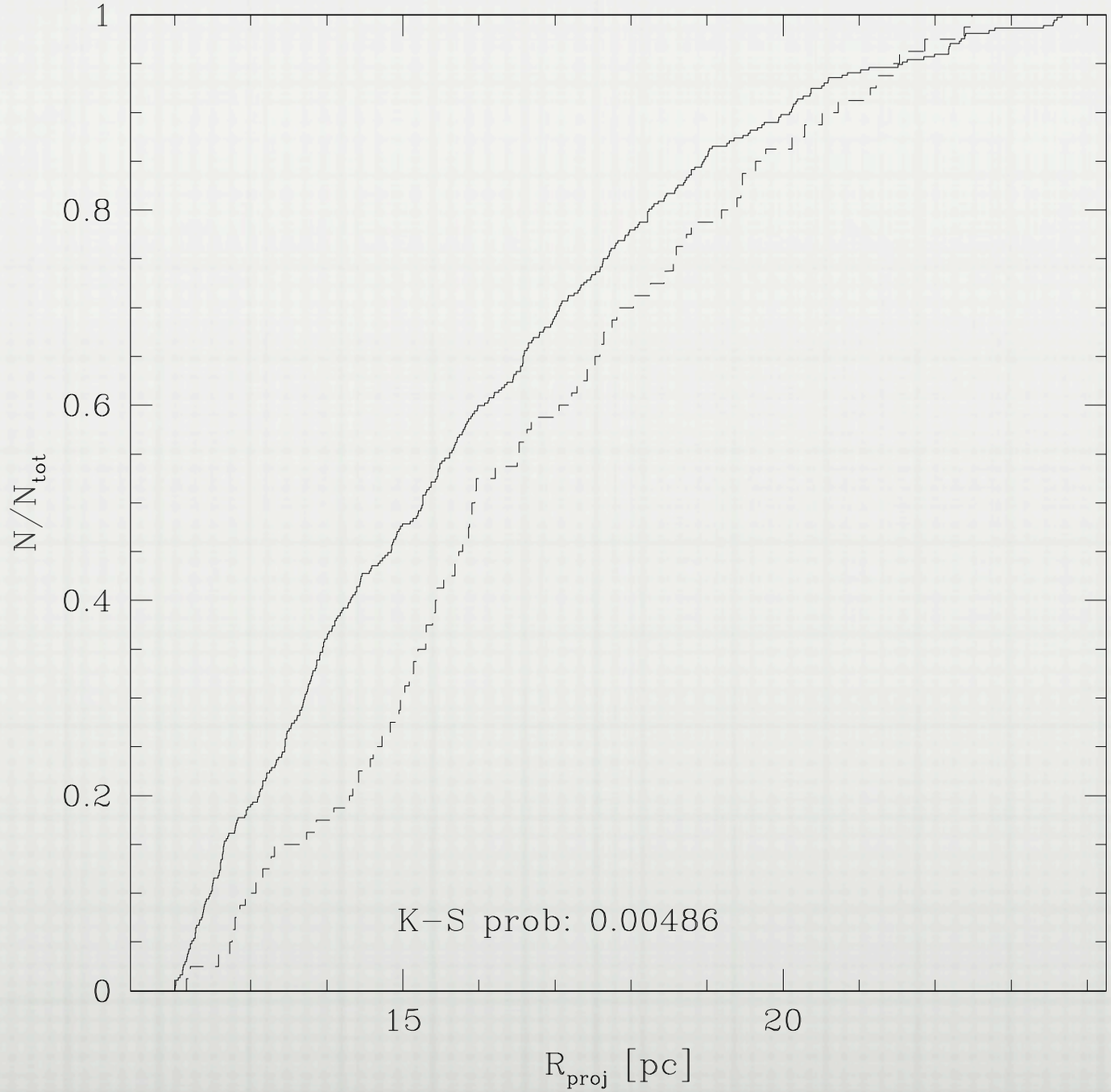


no kick



6 km/s kick

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



Salient Points

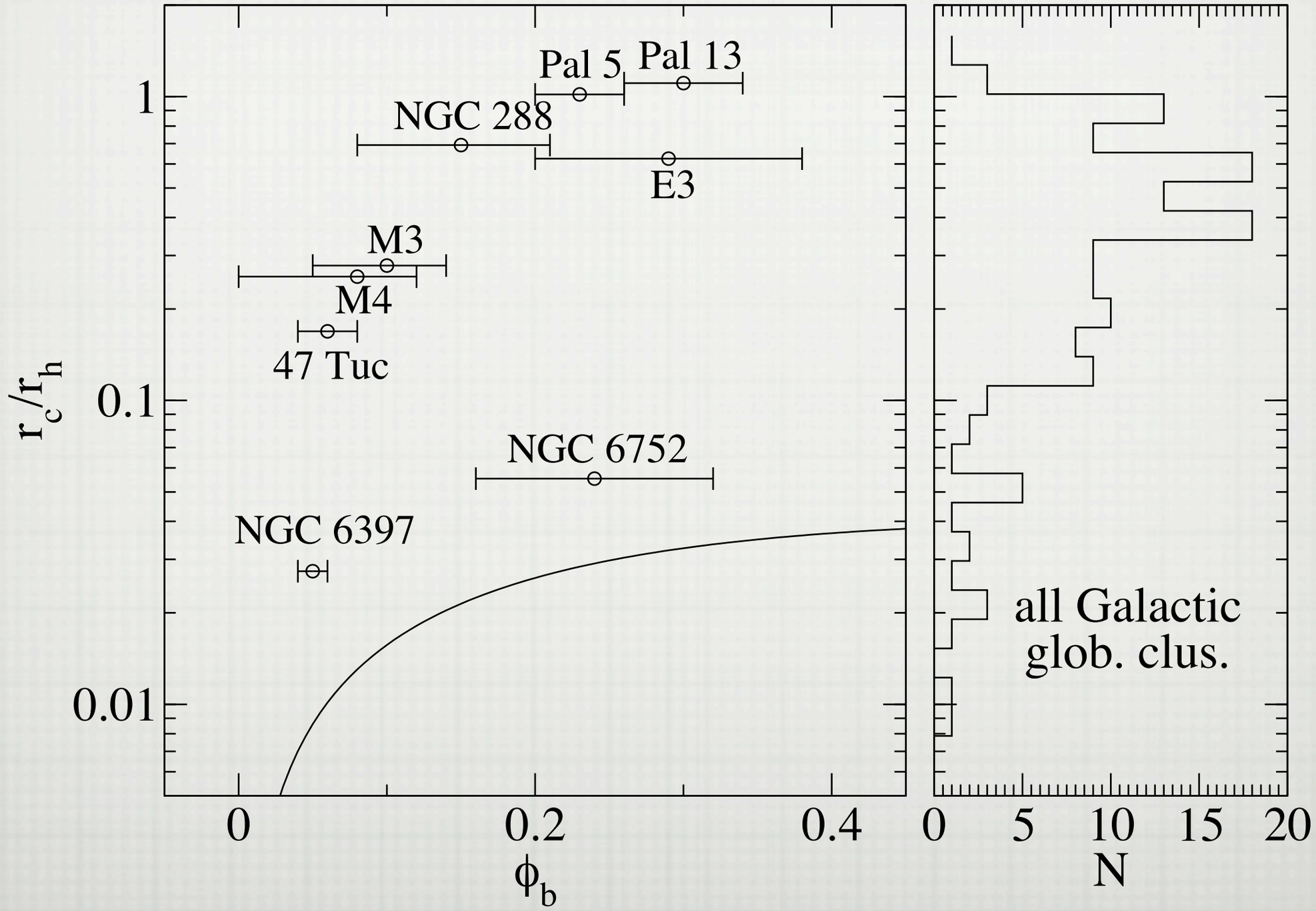
- Radial distributions of old vs. young WDs in models with kicks agree well with observations. (And don't agree for models with no kicks.)

- WD kicks comparable to the cluster velocity dispersion yield cluster core sizes ~10x 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.

Disagreement Between Theory and Observations in Binary Burning Phase



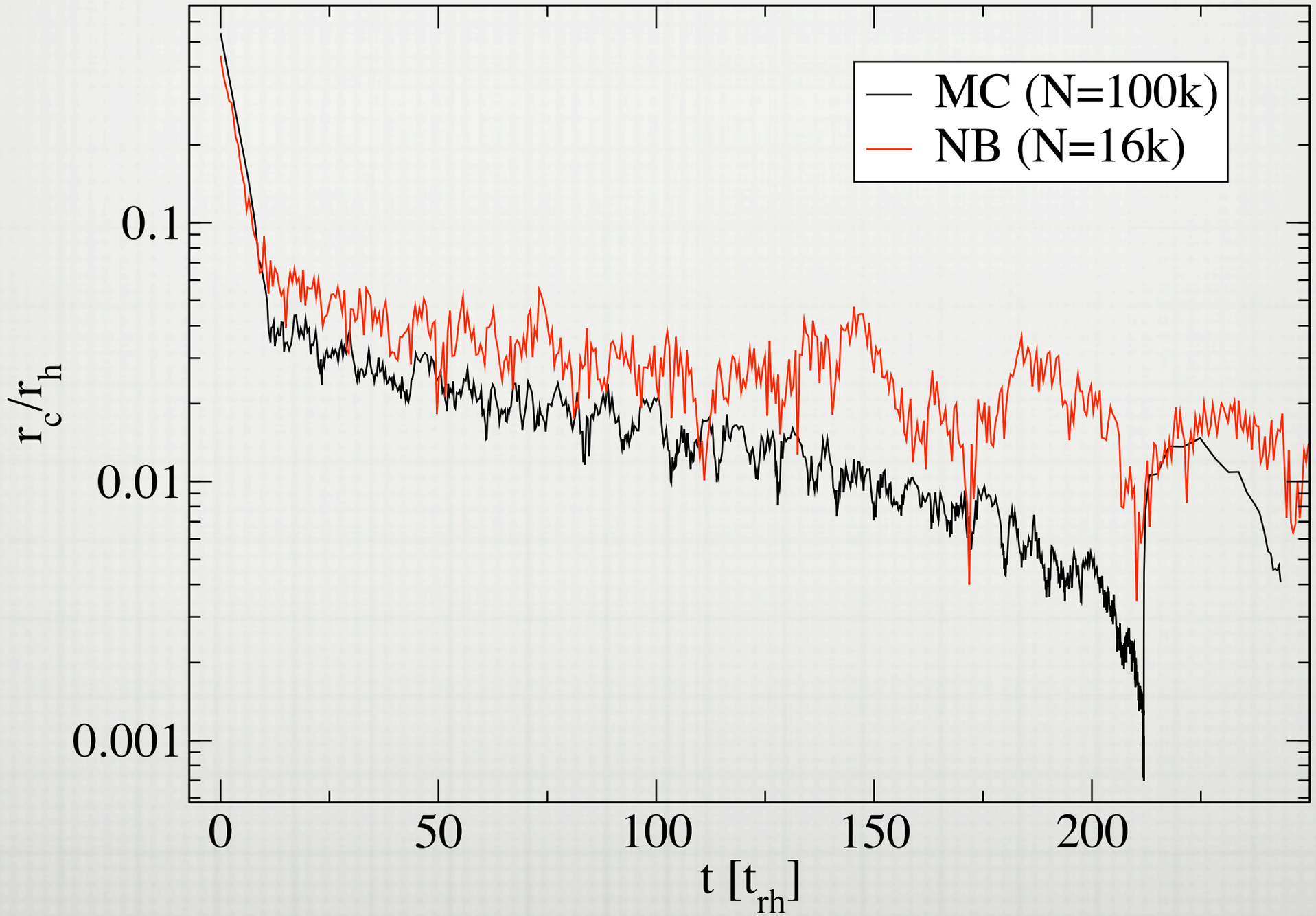
Possible Resolutions of r_c/r_h Discrepancy

- 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)?

Predictions, Objections, Complications

- If WD kick speed is not correlated with cluster properties, expect:
  - $v_{kick} < v_{\sigma}$ (e.g., 47 Tuc): little to no effect observed
  - $v_{kick} \sim v_{\sigma}$: older WDs more centrally concentrated than younger WDs, core larger than no-kick case
  - $v_{kick} > v_{\sigma}$ (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.

Agreement Between N-Body and Monte Carlo



MC Code: Now With Stellar Evolution!