NEA populations and impact frequency

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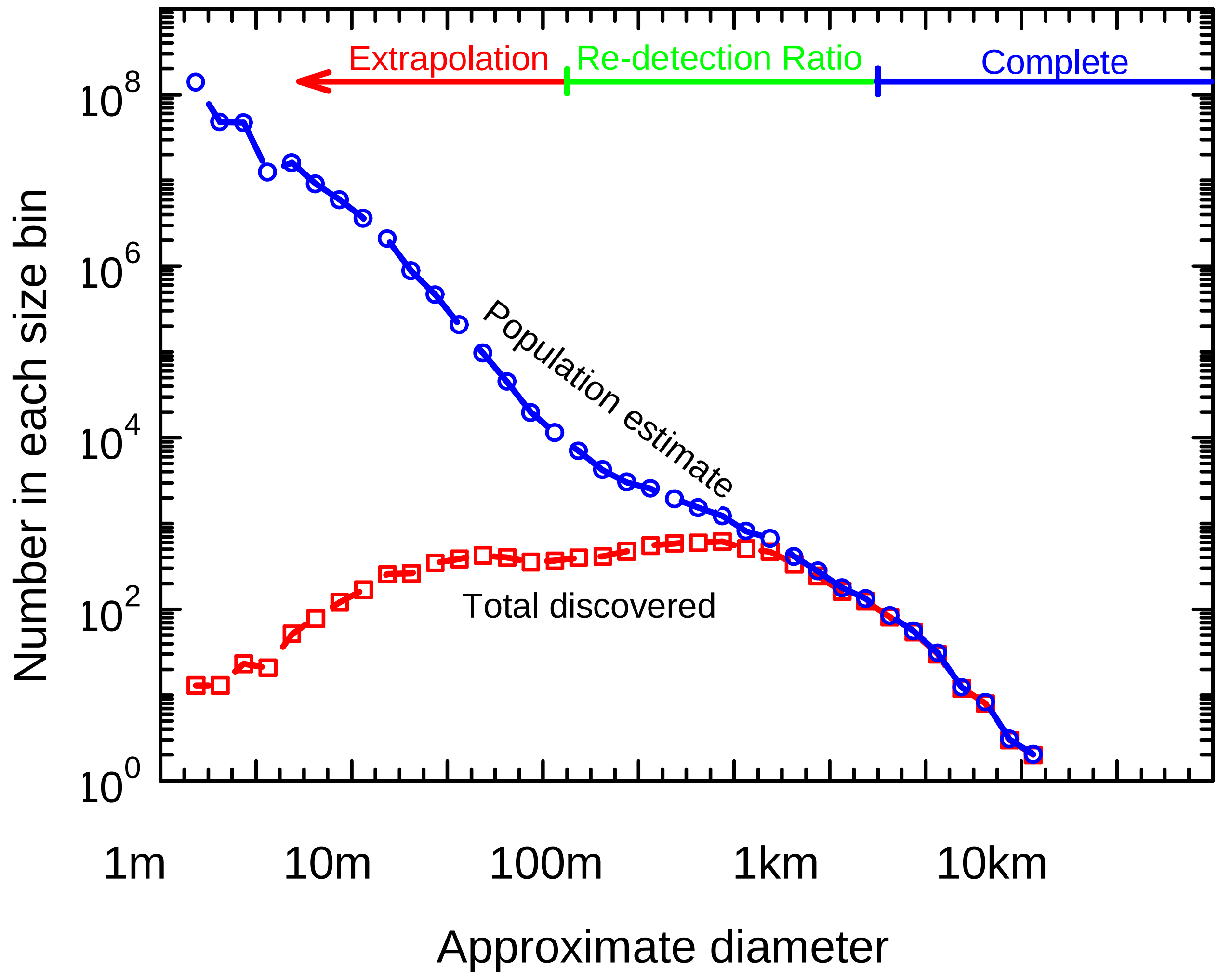
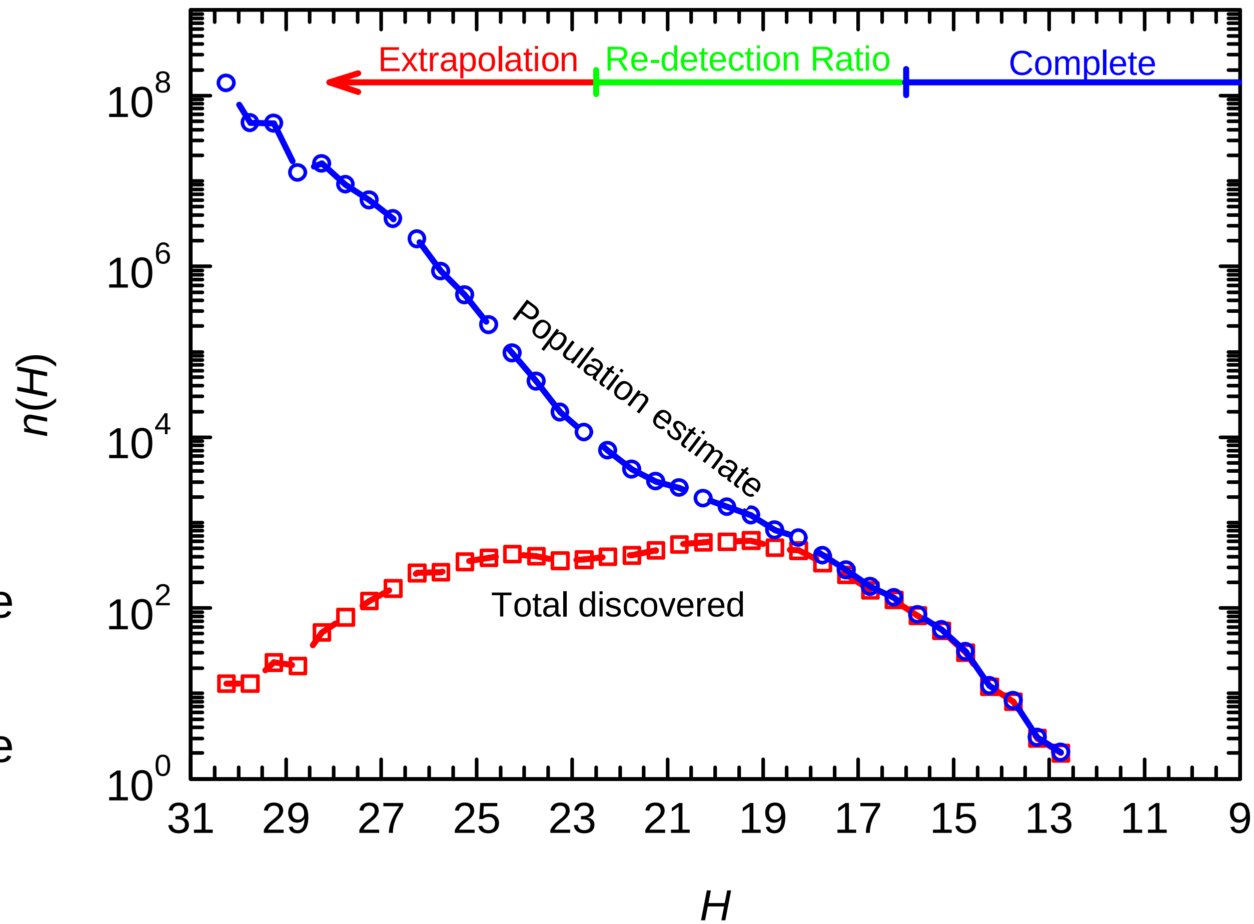
NEA Population: How do we know?

When a survey keeps re-detecting the same objects without finding any new ones, one can infer that the survey has essentially found them all. Going to smaller sizes, one can estimate the fraction discovered from the ratio of re-detections to total detections. Still smaller, where there are insufficient re-detections, one can estimate the relative detection efficiency versus size, and extrapolate the population estimate to still smaller objects.



Fundamental Scales

The working scale for number of objects is differential: the number in a range of absolute magnitude. This plot had bin widths of 0.5 magnitude, thus *n*(17.75) is the number of objects (discovered or estimated total) in the range 17.5 < *H* ≤ 18.0.



The absolute magnitude *H* is the sky magnitude an object would have if viewed at zero solar phase angle (like “full moon”), one astronomical unit (AU) from the sun and one AU from the observer (i.e., standing on the sun and looking out to the Earth – ouch!). *H* is estimated from the observed sky brightness “reduced” by inverse-square corrections for distances and a correction for solar phase angle.

Completion and Re-detection Ratio

If all asteroids of a given size were equally easy to detect, then the completion in a given size range would simply be the ratio of re-detected asteroids to the total number detected (new plus old) in a trial time interval.

The total population in that size range would be simply the number known divided by the completion (re-detection ratio). For example, if 200 asteroids in a given size range were already known, and in the next couple years 50 of those were re-detected by a survey and 50 new ones were discovered, we would infer the completion was 50%, and the total population would be 400.

But asteroids are not all equally easy to discover, due to the range of orbital parameters resulting in, among other factors, variable intervals of observability over time.

In order to obtain an accurate estimate of true completion, and thus population, one must bias-correct the observed re-detection ratio to estimate the true completion as a function of size of asteroid. We do this with a computer model simulating actual surveys.

Limitations on Re-detection Ratio

- As completion nears 100%, there are insufficient new discoveries to accurately estimate the number remaining to be discovered ($H < 18$, $D > 1$ km).
- At very low levels of completion (very small asteroids), there are too few re detections to accurately estimate completion fraction ($H > 23$, $D < 100$ m).

Computer Survey Simulations (1)

We generate a large number of synthetic NEA orbits matching as best we can the distribution of orbits of large discovered NEAs, where completion is high so that biases in the orbit distribution should be minimal. Rather than assign sizes to the synthetic asteroids, we define a parameter dm as follows:

$$dm = V_{\mathrm{lim}} - H$$

where V_{lim} is the limiting magnitude of the survey and H is the absolute magnitude of interest.

In the first step of a simulation, we compute the sky positions and other parameters that affect visibility (rate of motion, solar elongation, phase angle, galactic latitude, etc.) for each orbit (100,000) every few days for ten years. We tabulate these parameters, along with what would be the sky magnitude V, less absolute magnitude:

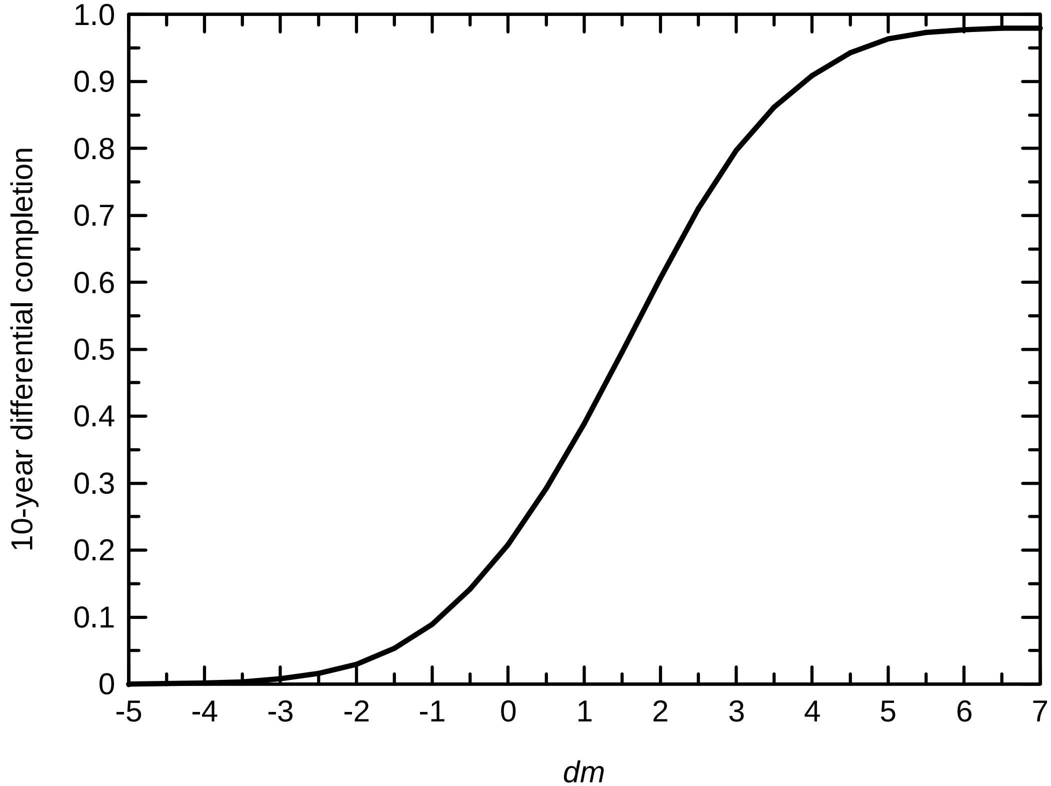
$$dm' = V - H = 5\log(r\Delta) + \Phi(\alpha)$$

where r and Δ are Earth and Sun distances and $\Phi(\alpha)$ is the phase relation for solar phase angle α.

Computer Simulation (2)

The massive “observation file” need be generated only once. For a specific simulation, we can specify a particular observing site, the area of sky to be covered, observing cadence, specific limits on declination, solar elongation, etc., and even impose modifications on dm' to account for expected magnitude loss due to zenith distance, trailing loss, sky brightness, seeing, etc. We can also specify how many detections over how much time constitutes a successful “discovery”.

For each “observation” where it is determined the object is in the field observed, a detection is scored if $dm' < dm$. The same observation file can be “scanned” repeatedly using different values of dm to build up a completion curve as a function of dm.



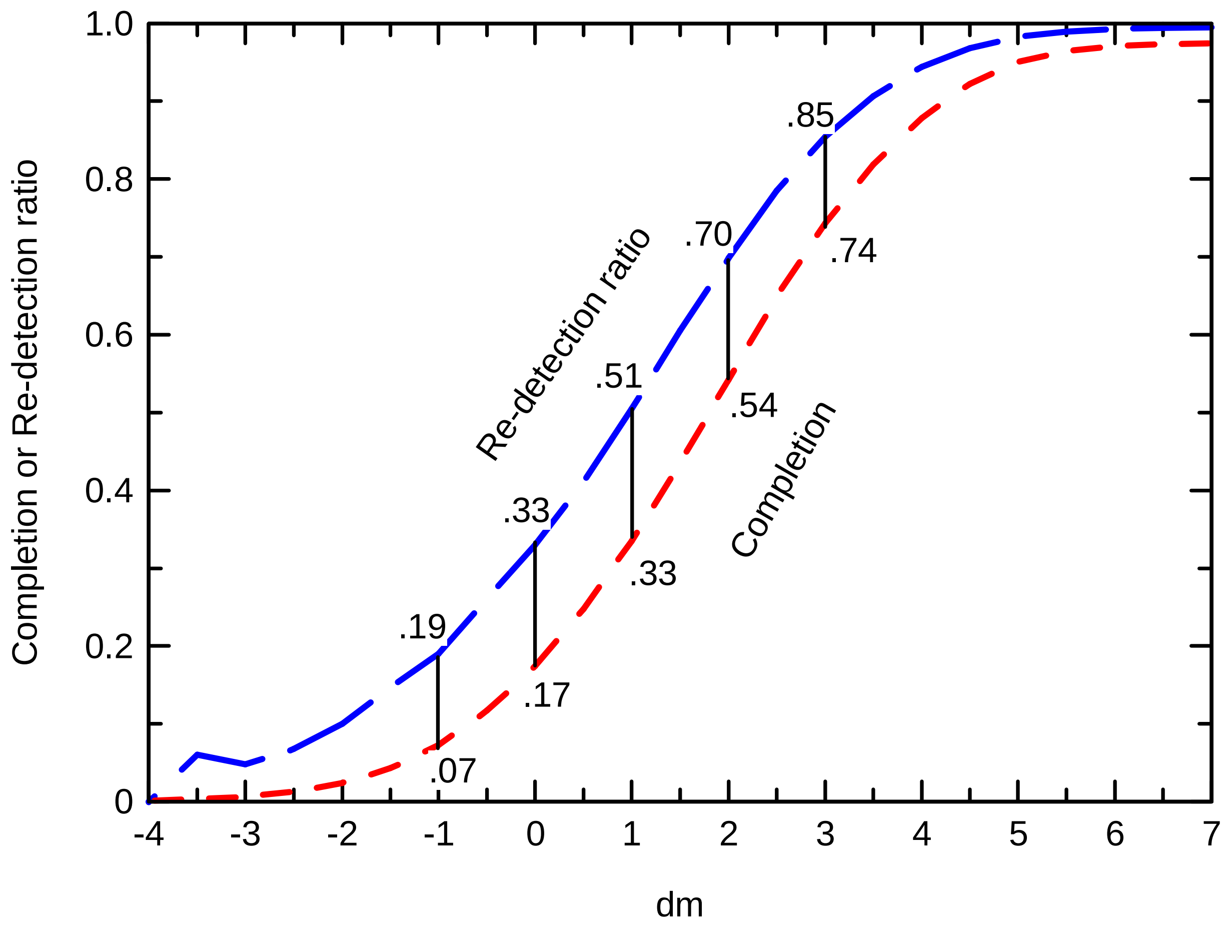
Notes on computer modeling

In doing the computer modeling in terms of *dm* instead of V_{lim} and H separately, we are making an implicit assumption that the distribution of NEA orbits is the same over all sizes. So far we have no direct observational evidence that this is not a valid assumption, but because of the different time scales versus size of the various orbital evolution processes (resonances, collisions, radiation pressure effects), there may be some variation of the distribution of orbits over the extreme range of size, particularly among the smallest objects.

On the other hand, a power of this method is that we can explore survey efficiency of various sub-populations by constructing our model population to contain only the sub-population of orbits we wish to examine, e.g., only PHAs, only very low encounter velocity objects (prospective ARM targets), or only impact trajectory objects.

Model Completion vs. Re-detection Ratio

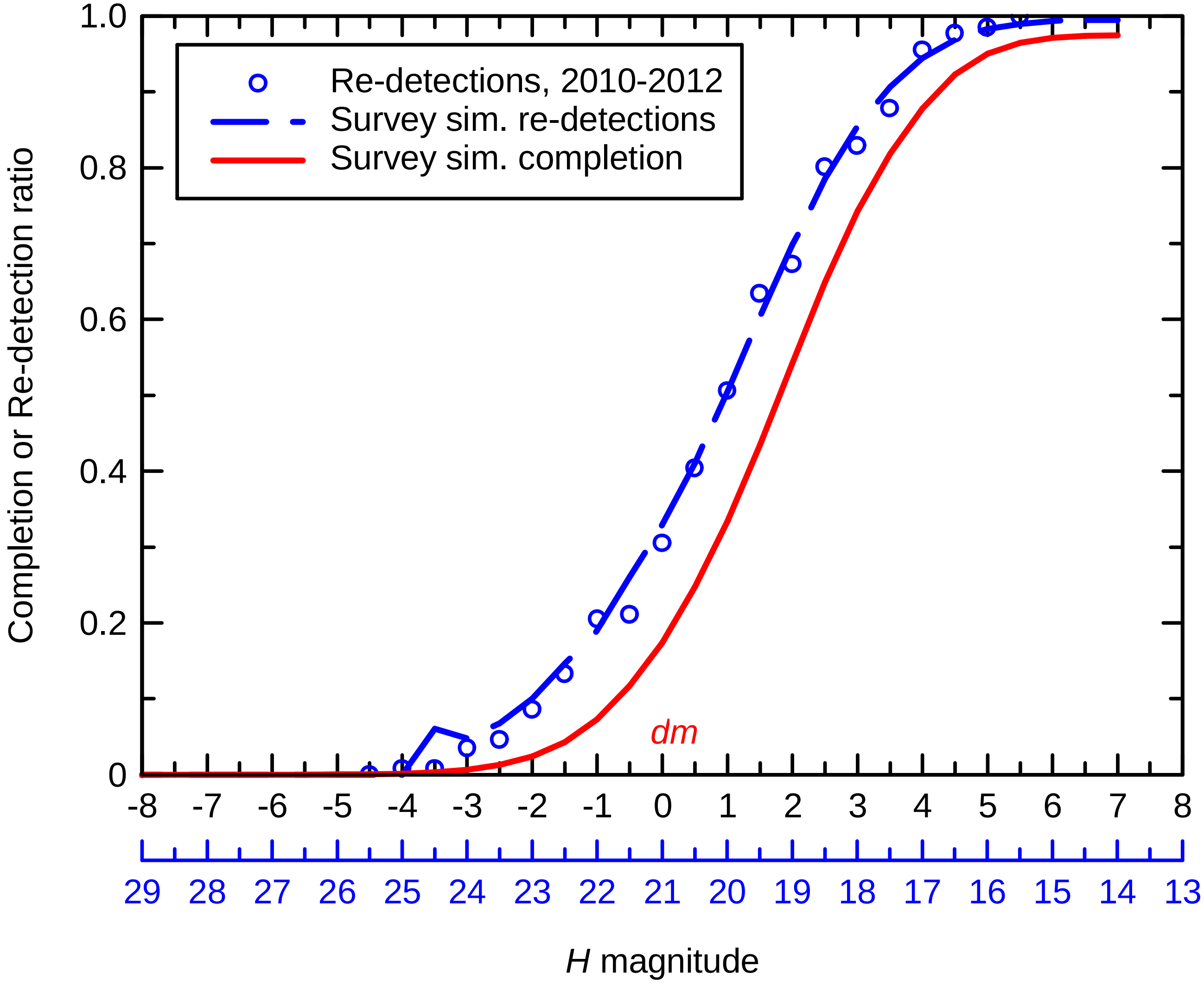
Unlike a real survey, in the computer simulation, we know the total population, so we can run a simulation, say for ten years, and also track the re-detection ratio for a trial interval, say the last two years of the simulation. Thus we can plot and compare the actual (model) completion along with the re-detection ratio.



After ten years or so of simulated survey, the shape of the completion curve is remarkably similar over a wide range of survey parameters; it simply moves to the left as time progresses.

Furthermore, the Re-detection ratio is similarly stable, tracking about 1.0 magnitude lower value of dm.

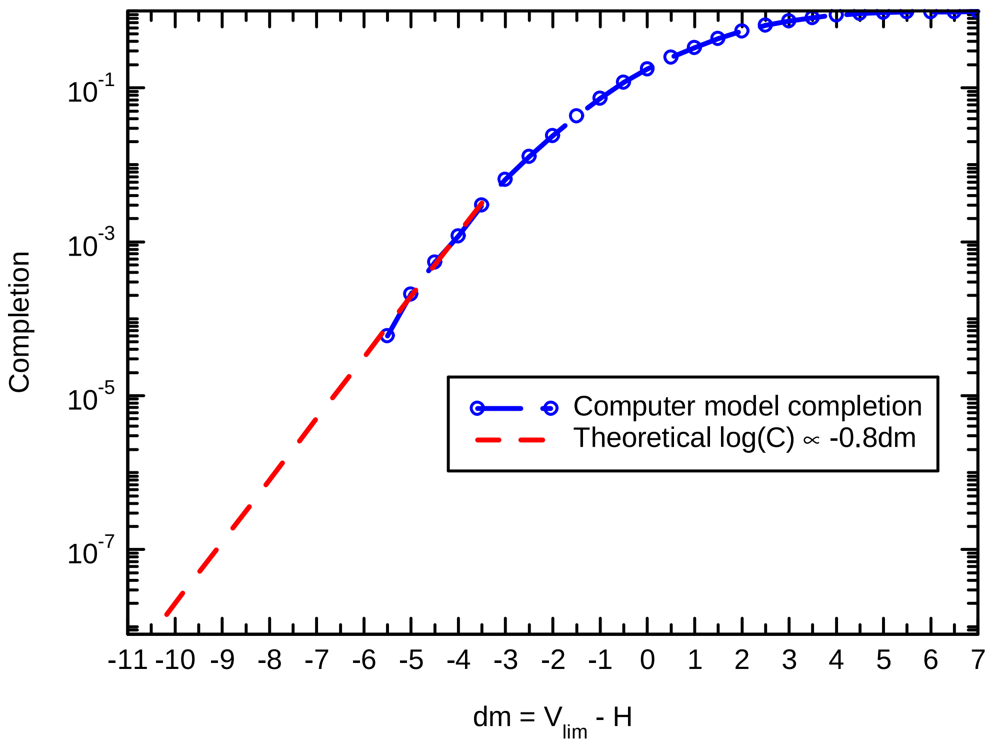
Model vs. actual survey re-detection ratio



The actual re-detection ratios for the combination of LINEAR, Catalina, and Siding Spring match the model curve within the uncertainties in the survey data. We thus adopt the model completion curve as representing current survey completion.

Extrapolation to smaller size

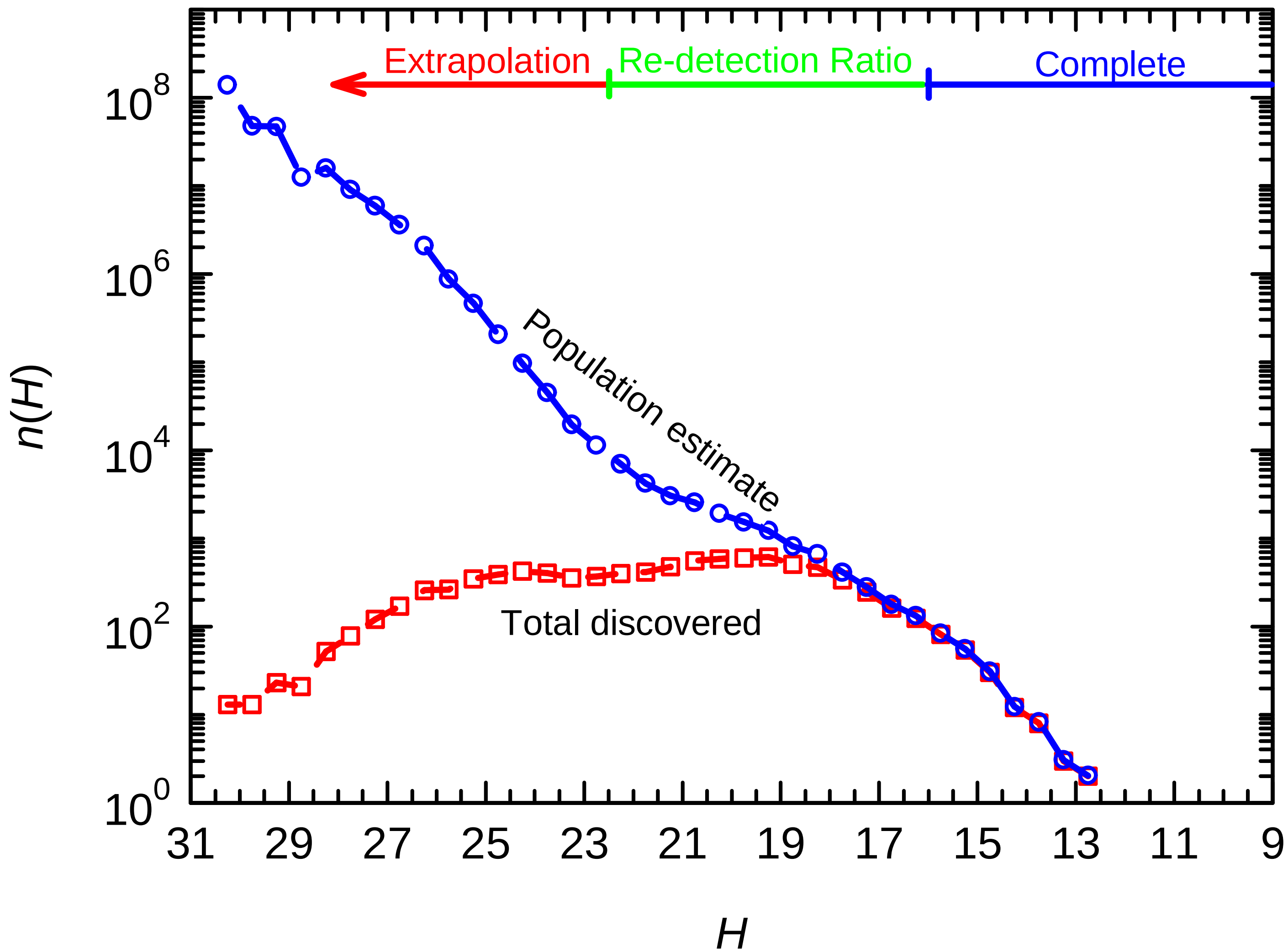
The observed re-detection ratio becomes uncertain below about 0.1 (that is, H greater than about 22) due to the low number of re-detections. However, having “calibrated” the completion curve in the range of good re-detection statistics, we can extend to still smaller sizes by assuming that the computer completion curve accurately models actual completion. This works until the number of “detections” in the computer model falls below a statistically useful number, say about 100 “detections” out of the 100,000 model asteroids, or a completion of about 10^{-3}. This corresponds to about dm = -4.0, or on the scaled curve to about H = 24.5.



Fortunately, below dm of ~3.0, detections are close to the Earth and can be modeled with rectilinear motion rather than accounting for orbital motion. An analytical completion function can be matched to the computer completion curve and extrapolated to arbitrarily small size.

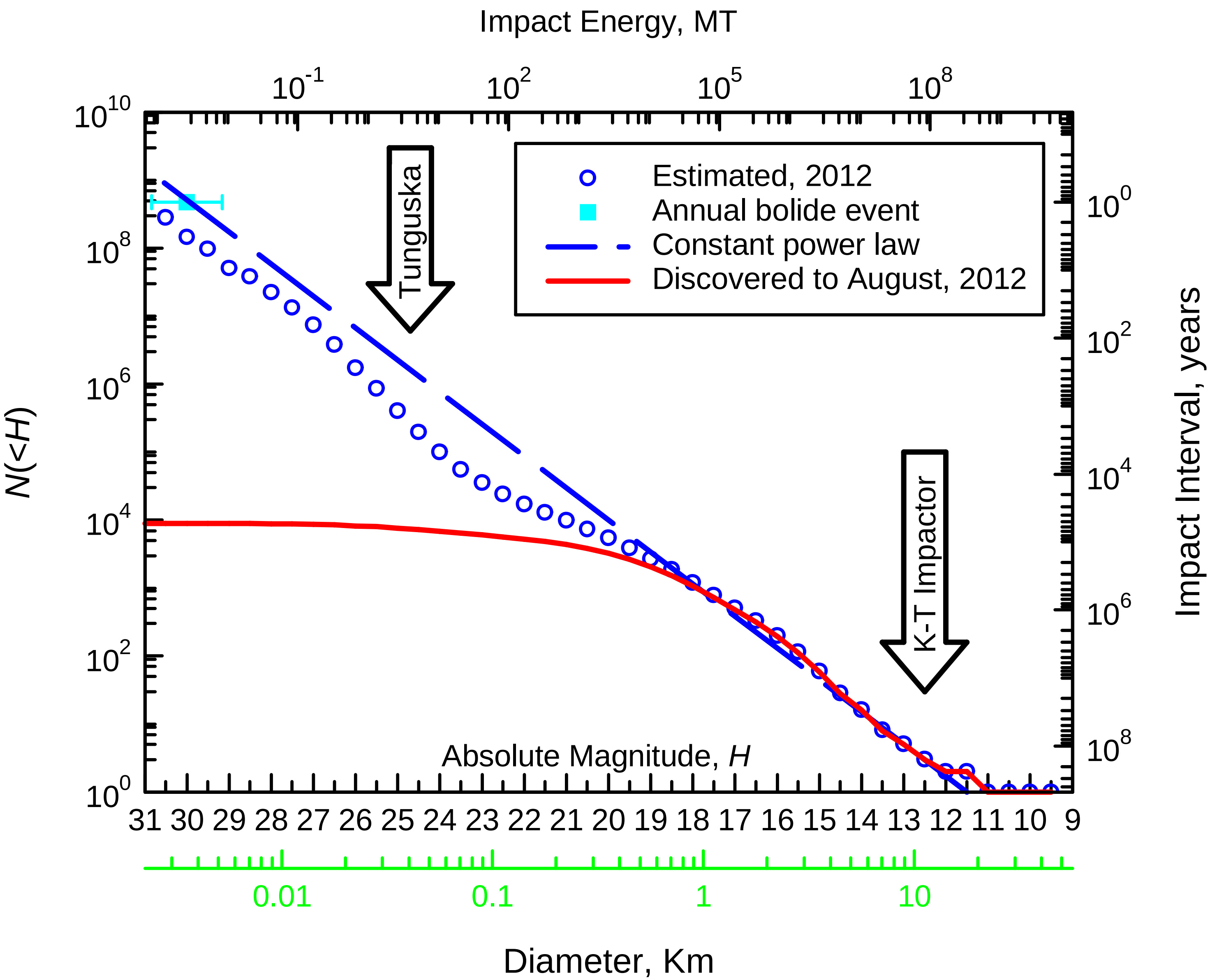
With these extensions, we now have an estimate of completion over the entire size range of observed objects.

Differential Population



Plotted here are the numbers in each half-magnitude interval, in red the total number discovered as of August 2012, and in blue the estimated total population in that size range, based on the completion curves of the previous graphs.

Cumulative Population



The cumulative population is the running sum of the differential population, from the previous plot. The number N is the total number of NEAs larger than the specified size (H or Diameter).

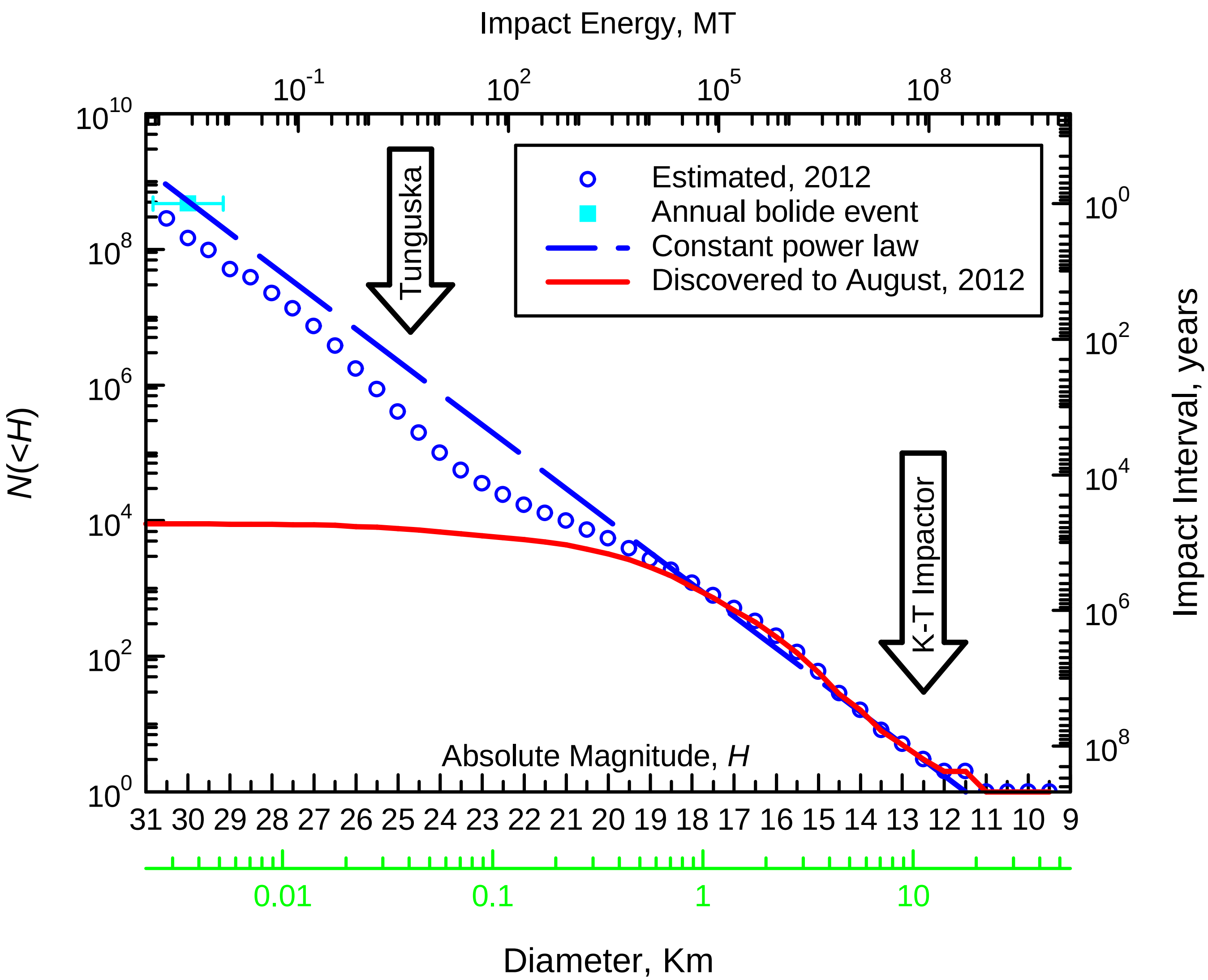
Ancillary Scales: Impact Frequency

The fundamental scales on a population plot determined from telescopic surveys are absolute magnitude, H, and cumulative number of objects, $N(<H)$. But we may want to know other scales, diameter in km, impact energy, or impact frequency,

The relation between number and impact frequency is determined in the process of modeling the orbital distribution for the computer simulations. Once the distribution of orbits is known, for example by using the nearly-complete sample of the thousand or so largest known NEAs, one can compute the mean impact frequency. This turns out to be an impact interval of about 475 million years for a single “average” object. Thus:

$$t = \frac{4.75 \times 10^{8}\ years}{N(< H)}$$

Ancillary Scales: Impact Frequency



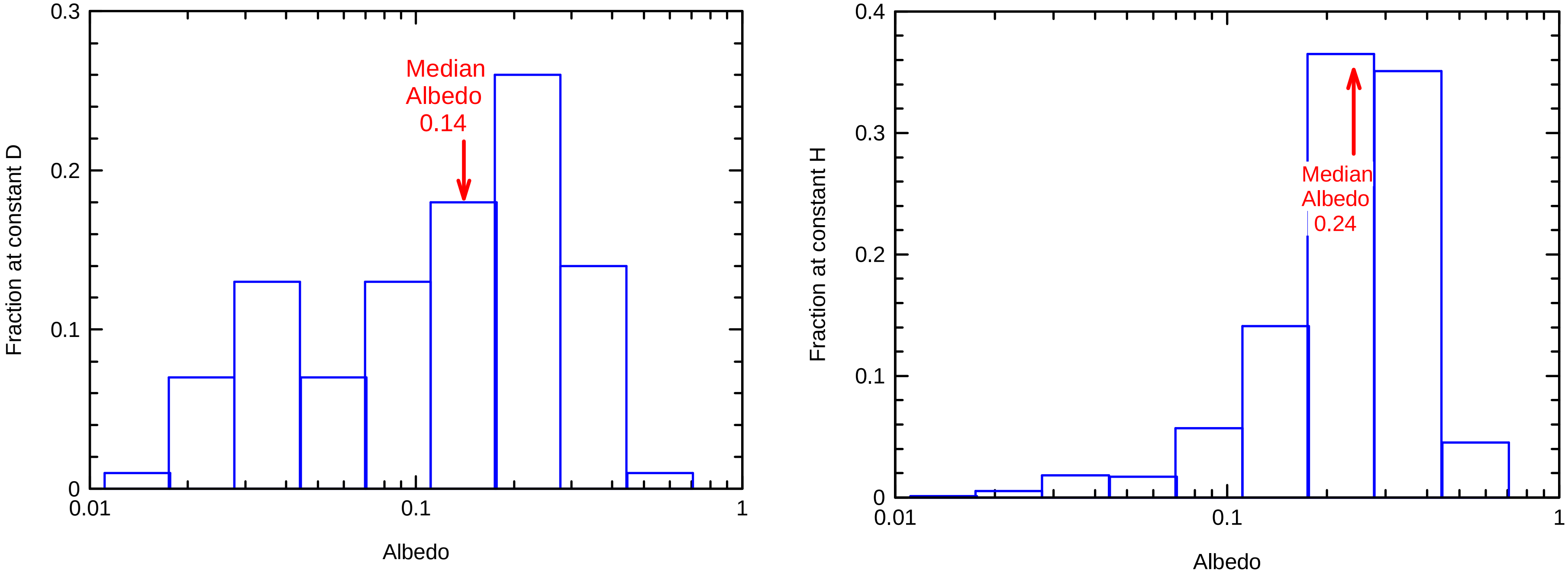
The "impact interval" scale on the right of the plot is just 475 million years divided by the number of objects, the scale on the left.

Ancillary Scales: Diameter

The relation between diameter and absolute magnitude, *H*, depends on albedo. Based on such albedo data as were available in the past decade, we inferred an average albedo of about 14%, We knew already that the distribution is not “bell-shaped”, but is rather bimodal, with peaks at around 6% and 25%, but the average seemed to be about 14%. For that albedo, the H magnitude corresponding to a diameter of 1 km is 17.75. Thus, the relation between diameter and albedo is

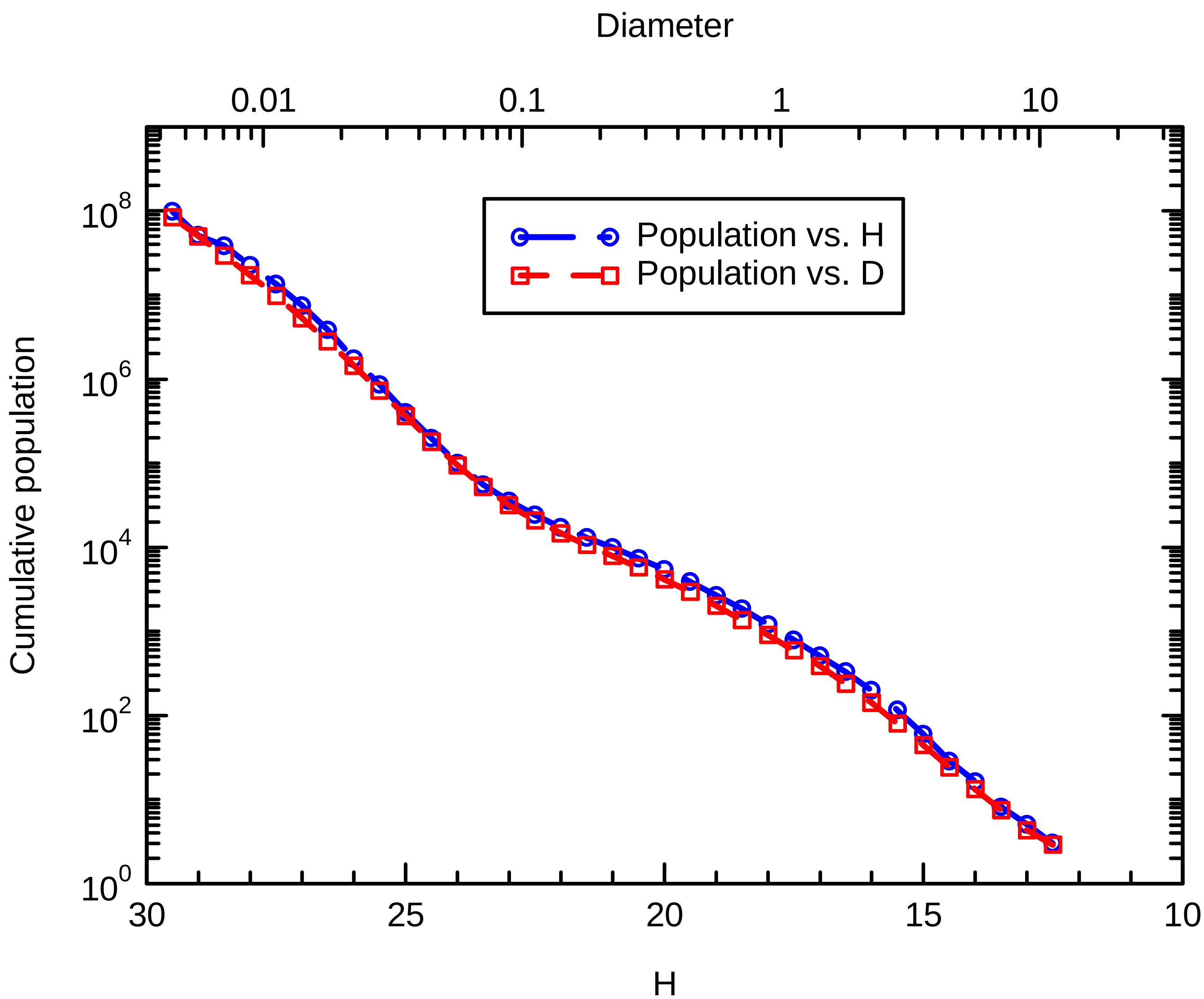
$$D = (1\,\mathrm{km}) \times 10^{(17.75 - H)/5}$$

$N(<H)$ vs. $N(>D)$: Mean albedo



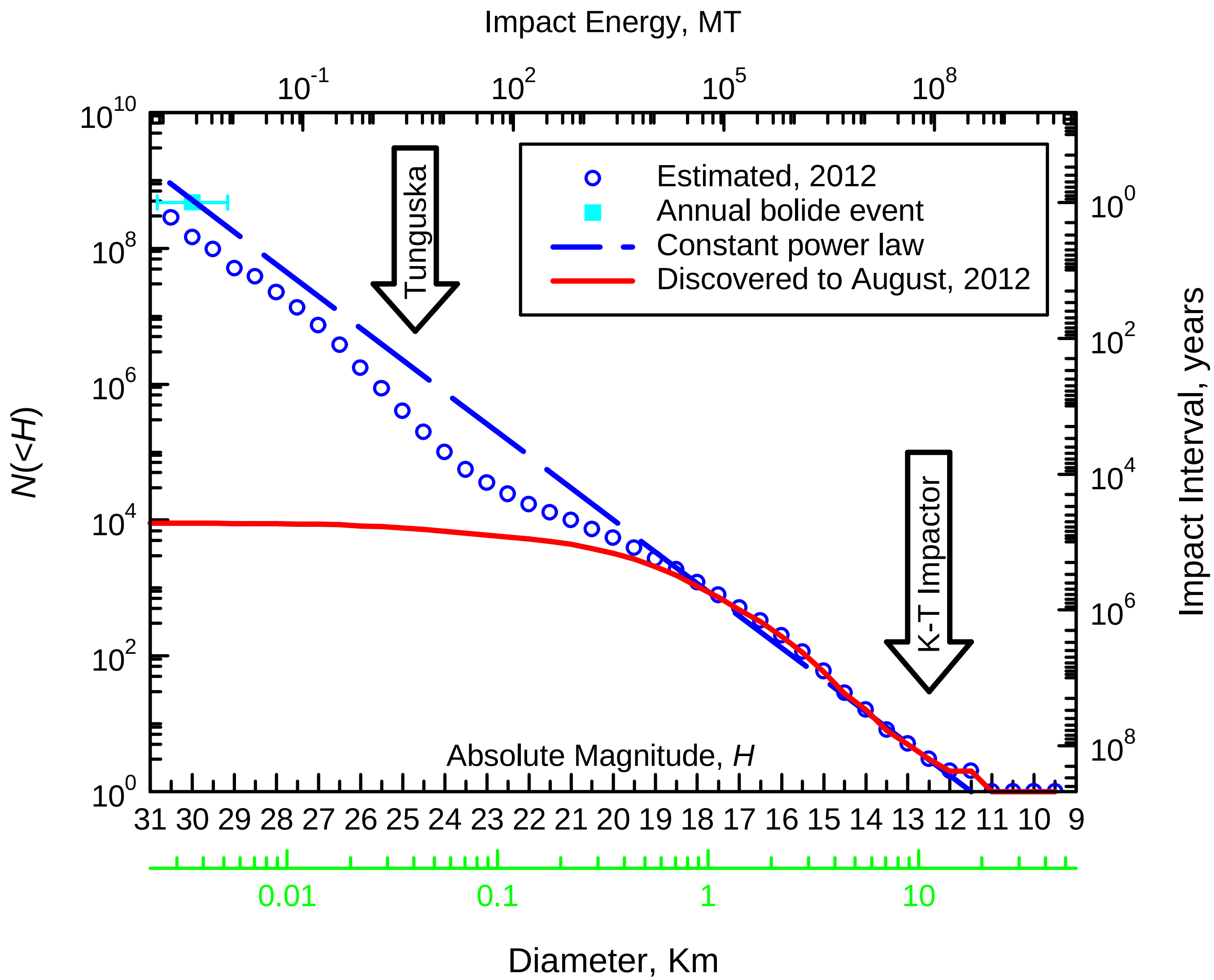
The figure on the left shows the NEA albedo distribution as determined by WISE. Since thermal IR detection does not depend much on albedo, this distribution closely represents the distribution of albedo at a given diameter. Because of the steeply sloping size-frequency distribution (in either *D* or *H*), there are far more high albedo (hence smaller) asteroids in a distribution at a given *H* magnitude, as shown on the right. This distribution more closely matches the distribution of albedos of NEAs discovered by optical surveys.

Comparison of *N*(<*H*) vs. *N*(>*D*)



When the size-frequency distribution is transformed from *N*(<*H*) to *N*(>*D*) using the albedo distribution from the right panel of the previous slide, the difference from the *N*(<*H*) distribution is less than the uncertainty of the estimated population.

So it seems the equivalence between H and D is about right



D = 1 km corresponds to *H* = 17.75

D = 100 m corresponds to *H* = 22.75

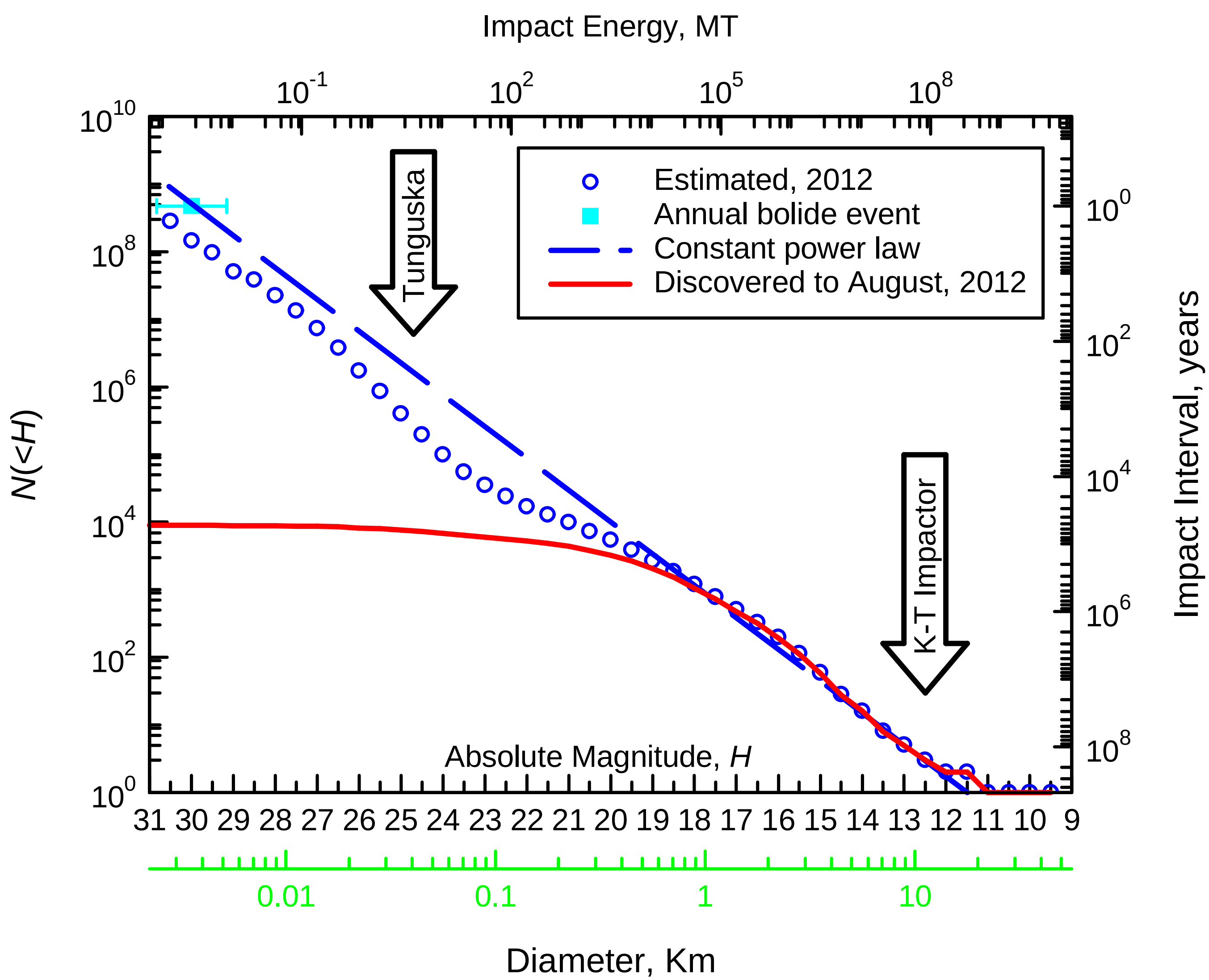
D = 10 m corresponds to *H* = 27.75

Ancillary Scales: Impact Energy

The mean impact energy of a given size impactor is just the kinetic energy at impact, ½ mv^2. The average impact velocity can be found from the same distribution of orbits used in the survey simulations, with a couple corrections for the gravitational focusing and acceleration as objects fall into the Earth's gravity well. The mean impact velocity turns out to be just about 20 km/sec. We need to assume an average bulk density in order to estimate *m* from *D*. Taking that as around 2.5 gm/cm^3, and then converting the energy to megatons equivalent TNT, the relation between diameter and impact energy becomes:

$$E = (60{,}000\,\mathrm{MT}) \times (D\,\mathrm{in\ km})^3$$

Ancillary Scales: Impact Energy

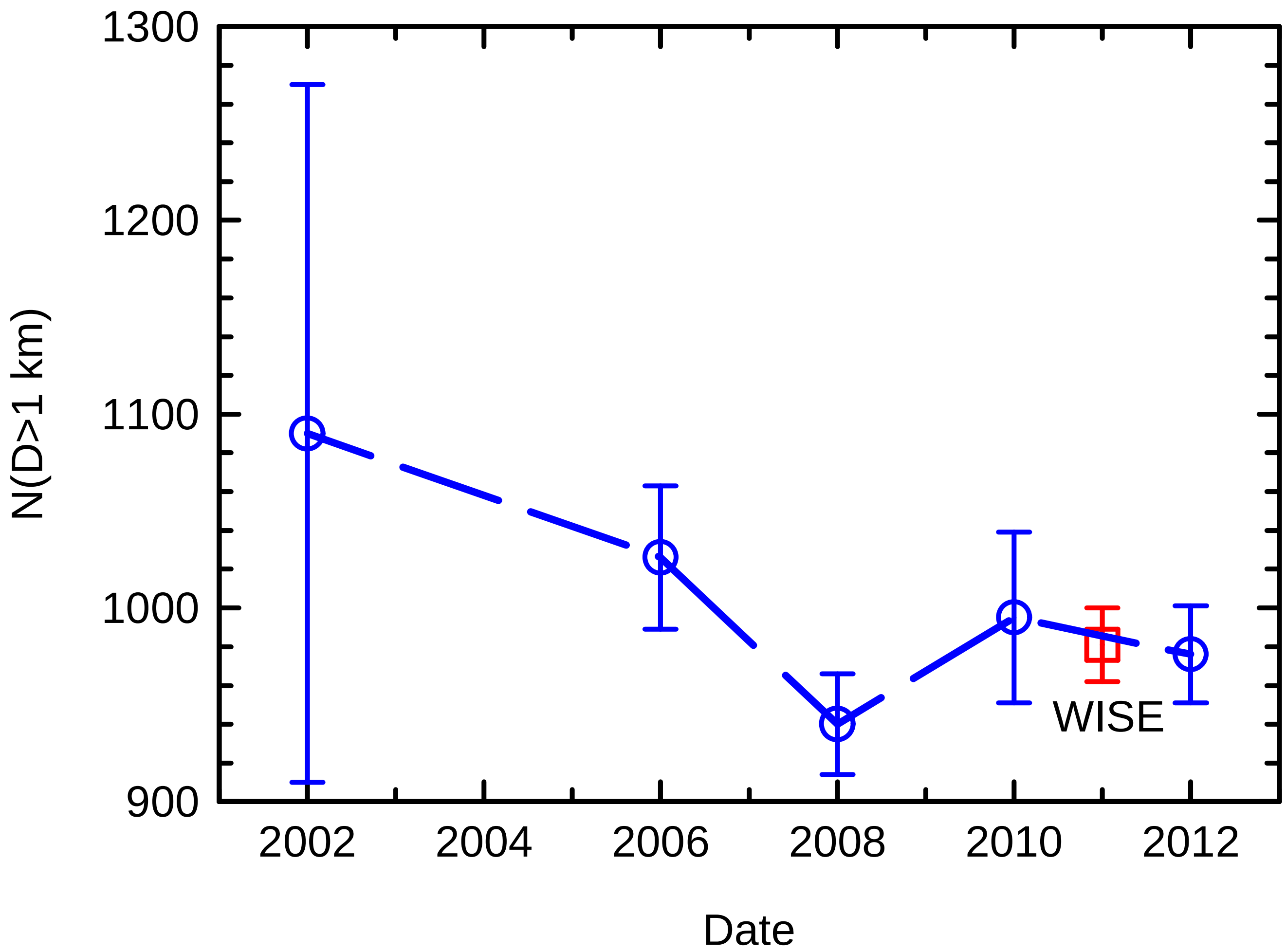


D = 1 km corresponds to E = 60 GT

D = 100 m corresponds to E = 60 MT

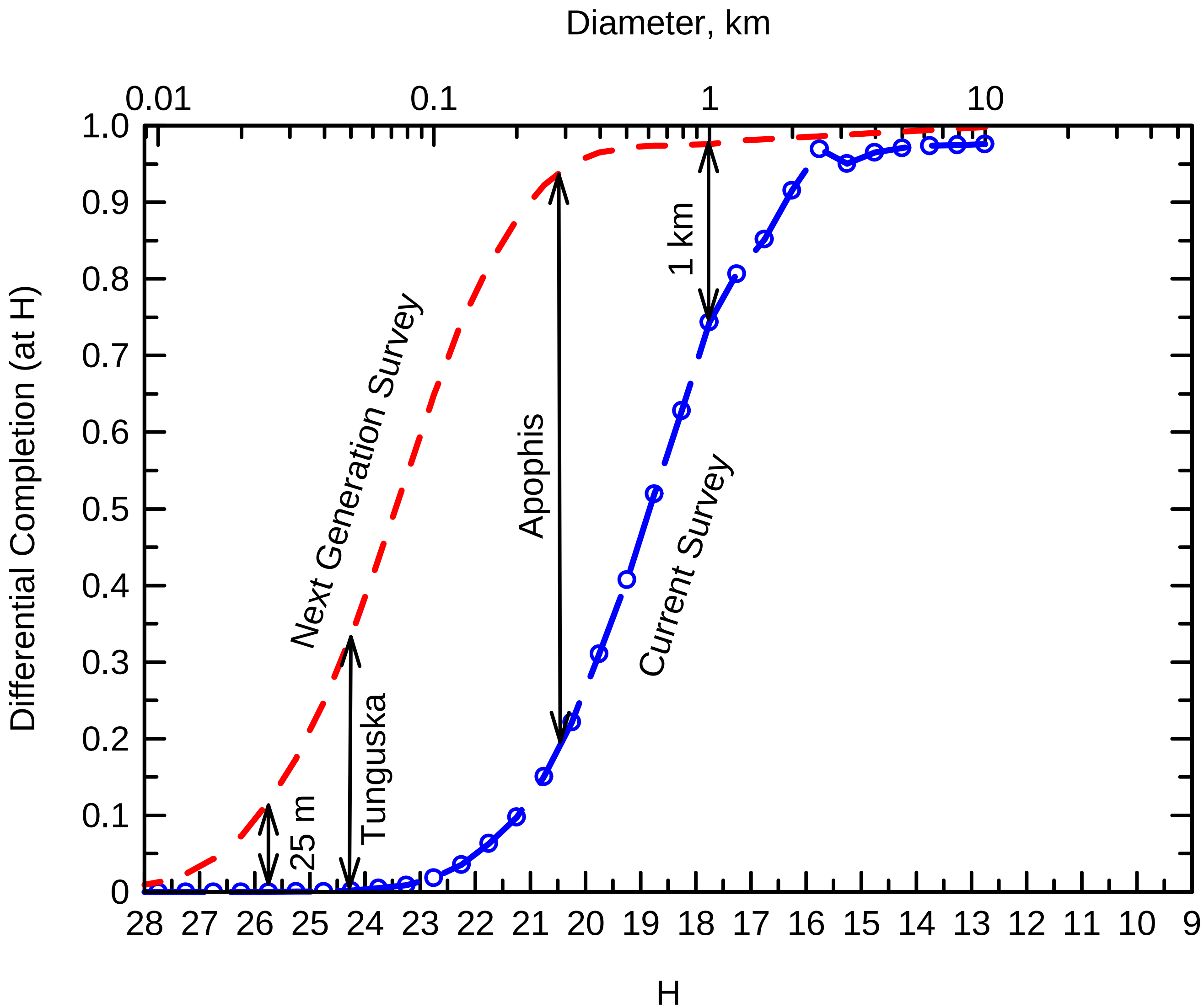
D = 10 m corresponds to E = 60 KT

Population estimates over time



For the last decade, I have been updating my estimate of the population of NEAs, N(D>1km), every couple years, as the survey progresses. The last few estimates have been quite stable, and in close agreement with the recent estimate by WISE.

Current and Future Survey Completion



This plot shows the completion vs. size at current survey level, and as expected for a survey that achieves 90% integral completion to a size of D > 140 m.

Summary of Population and Survey completion

- Latest (2012) estimated population of NEAs is little changed from 2006, 2008, and 2010 estimates:
  - $N(H<17.75) = N(D>1km) = 976 \pm 30$
  - $N_{disc}(H<17.75) = 866$ as of March 15, 2014; Completion = 89%
  - Size-frequency distribution still has dip in 50-500 m range, estimated population over the entire range is little changed.
- Next-Generation surveys to reach C(D>140m) of 90% will in the process:
  - Complete the survey to sensibly 100% of objects D > 1 km
  - Catalog and track >90% of “Apophis” sized objects
  - Discover ~1/3 of “Tunguska” sized objects and ~10% of anything large enough to make it to the ground (D > 25m)
- Current surveys have almost a 50% chance of detecting a “death plunge” small object with enough time for civil defense measures; future surveys have the potential to do even better with appropriate observing protocol.

Comparison of population estimates from surveys vs. WISE and bolide data

- At D ~1 km, Survey estimate and WISE agree almost exactly, agree on mean albedo.
- WISE extrapolation to small size has flat slope, yields ~5x lower population at “Tunguska” size.
- At D ~3 m, bolide population estimate is only a factor of 2-3 above survey population estimate.
- Bolide population estimate extrapolated to “Tunguska” size is ~10x higher than survey estimate.

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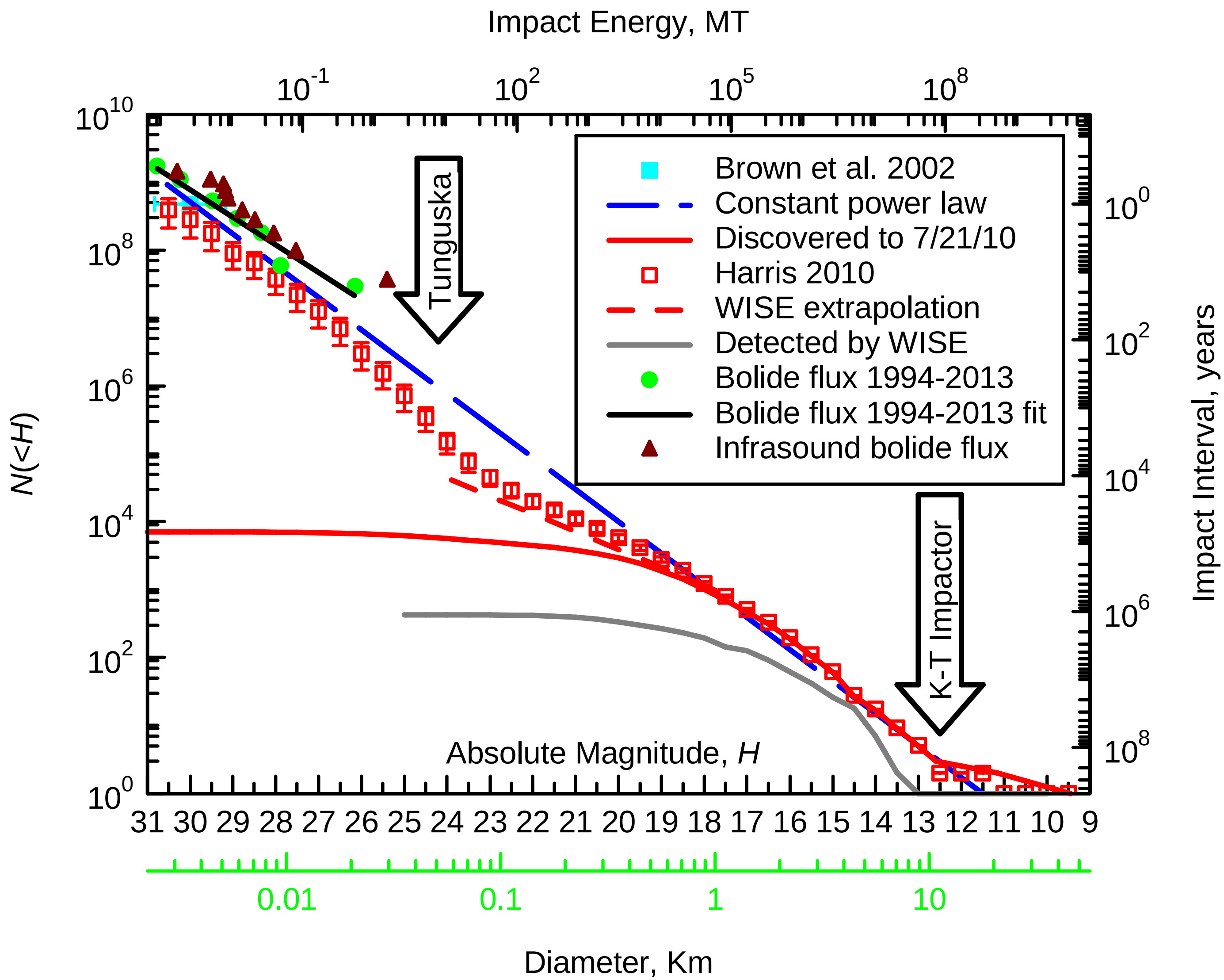

Conclusion:

Survey population is probably accurate down to D ~100 m, bolide estimate is probably better up to D ~10 m. Best estimate is probably to blend survey curve upward from ~100 m to match bolide estimate at ~10 m.

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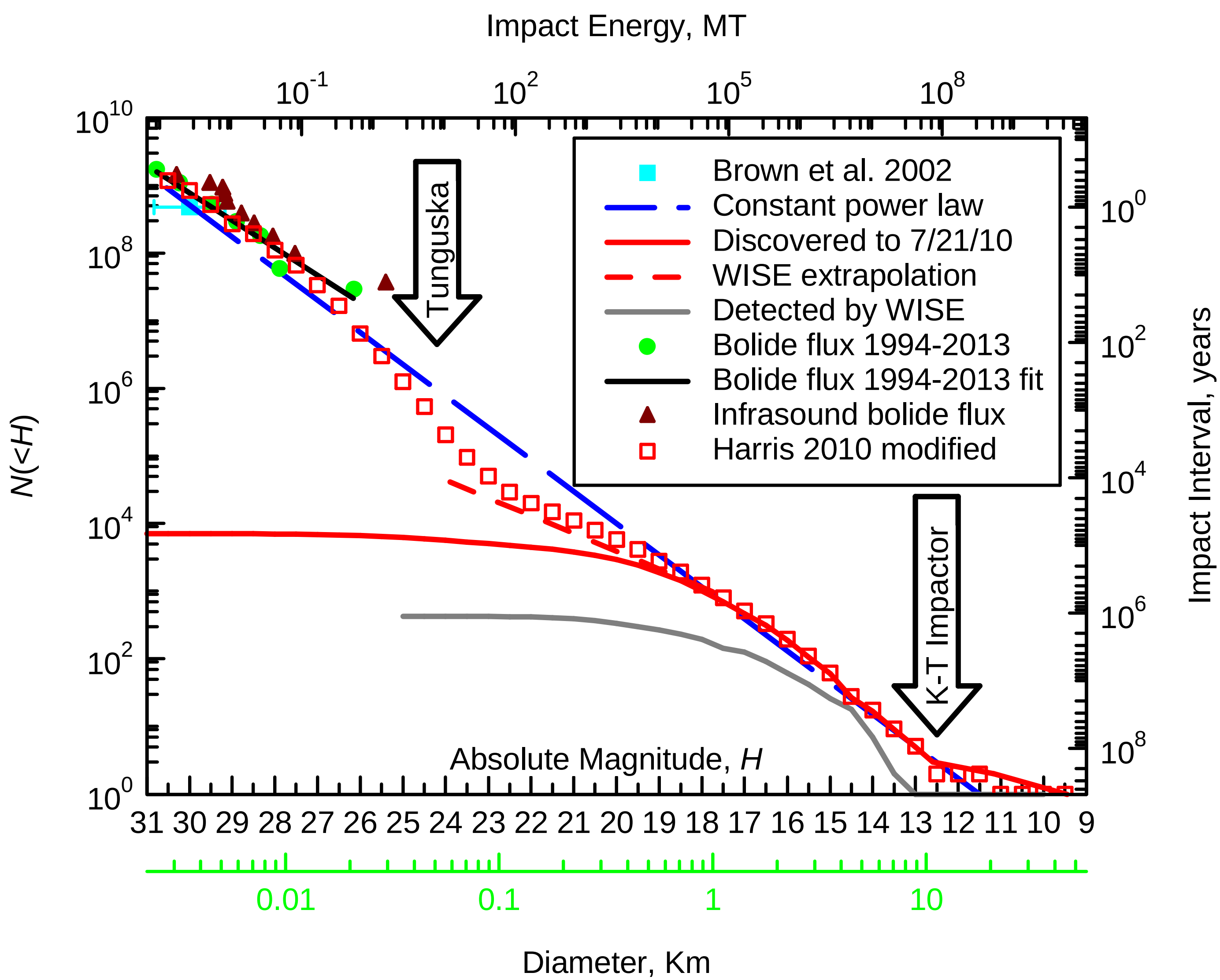
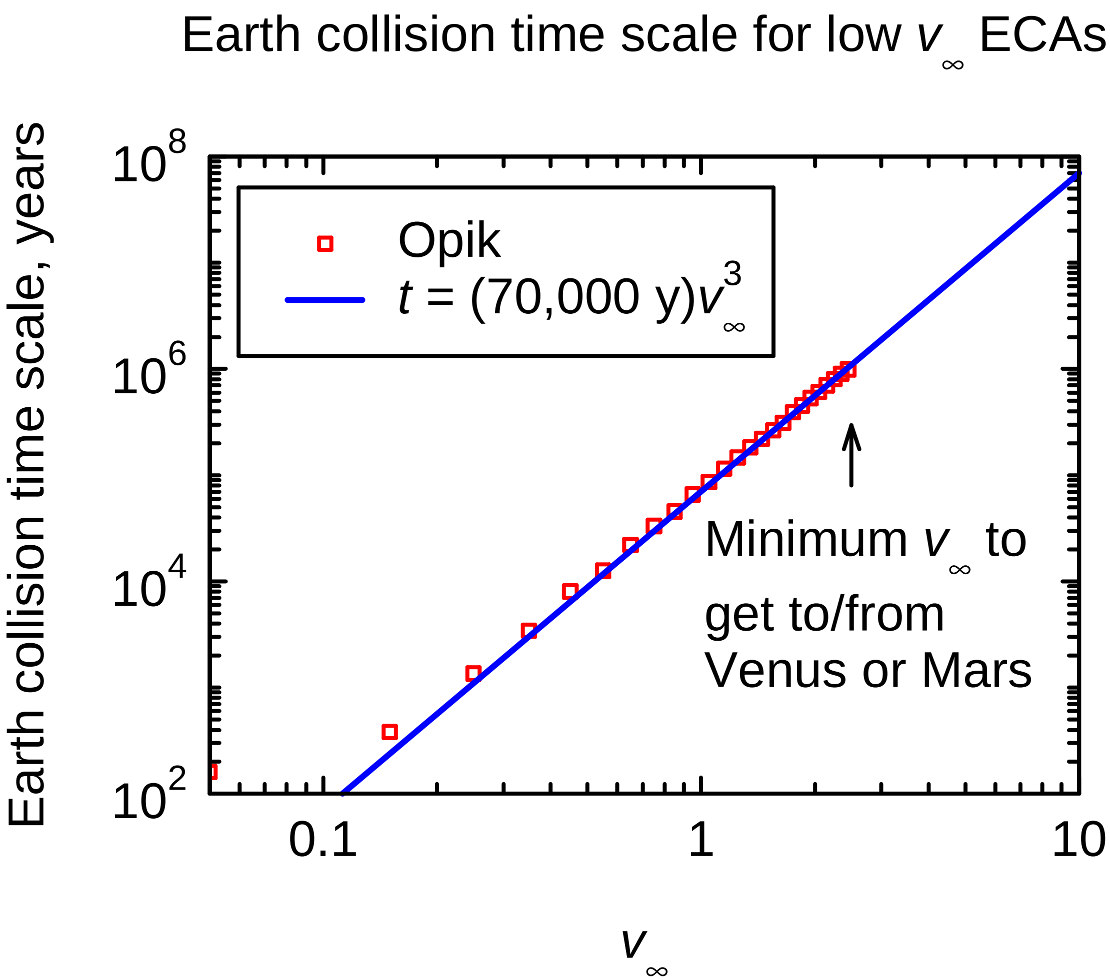


Conclusion:

Survey population is probably accurate down to D ~100 m, bolide estimate is probably better up to D ~10 m. Best estimate is probably to blend survey curve upward from ~100 m to match bolide estimate at ~10 m.

Plot so modified.

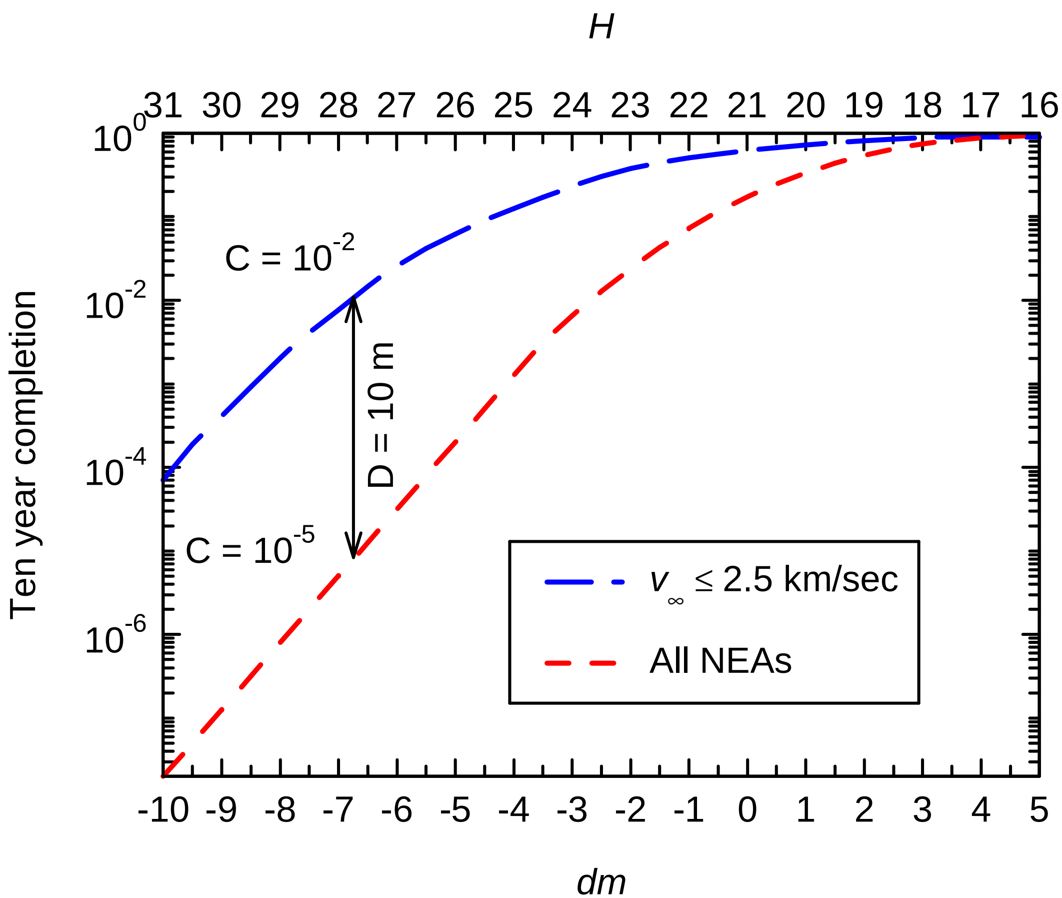
Survey efficiency in detecting "ARM target" asteroids



My previous survey simulations included no orbits with relative encounter velocity with the Earth less than ~2.5 km/sec. This is mostly just a consequence of the expected number of such bodies being so small due to the orbital dynamics of getting into such an orbit, but also the fact that the collisional lifetime of anything crossing the Earth's orbit at such a slow velocity is very short.

The above plot compares the mean collision time with the Earth versus encounter velocity from Opik's formulae versus an empirically fit simple power law.

Survey efficiency in detecting "ARM target" asteroids



Be that as it may, it is perfectly possible to do a simulation for *only* low-v_∞ objects. I generated a synthetic set of 100,000 orbits with v_∞ distributed isotropically and 3-D uniform with respect to the Earth. The result is surprising: at around ~10 m diameter, current ground-based surveys are about 1,000 times more efficient finding the low-v_∞ objects than the average v_∞ objects.

The current survey completion of ~10 m objects is only ~10^{-5}, but among objects with v_∞ < 2.5 km/sec, completion is estimated at about 10^{-2}. This is consistent with the fact that at least a couple such discovered objects are old rocket bodies, of which there are only about 100 out there. Still others may be lunar ejecta.

Wrap-up Summary

- Current surveys are ~90% complete for D > 1 km NEAs; there are just about 1,000 of them.
- Mean albedo of ~0.14 for relating diameter to absolute magnitude is about right (WISE).
- The size-frequency distribution is least well determined in the 10-100 m size range, but even there is likely known to within a factor of 3.
- “ARM targets” are relatively easy to detect, but there aren’t many out there (<1,000). A significant fraction may be old rocket hardware or lunar ejecta.