Updated Population and Risk Assessment for Airbursts from Near-Earth Objects (NEOs)

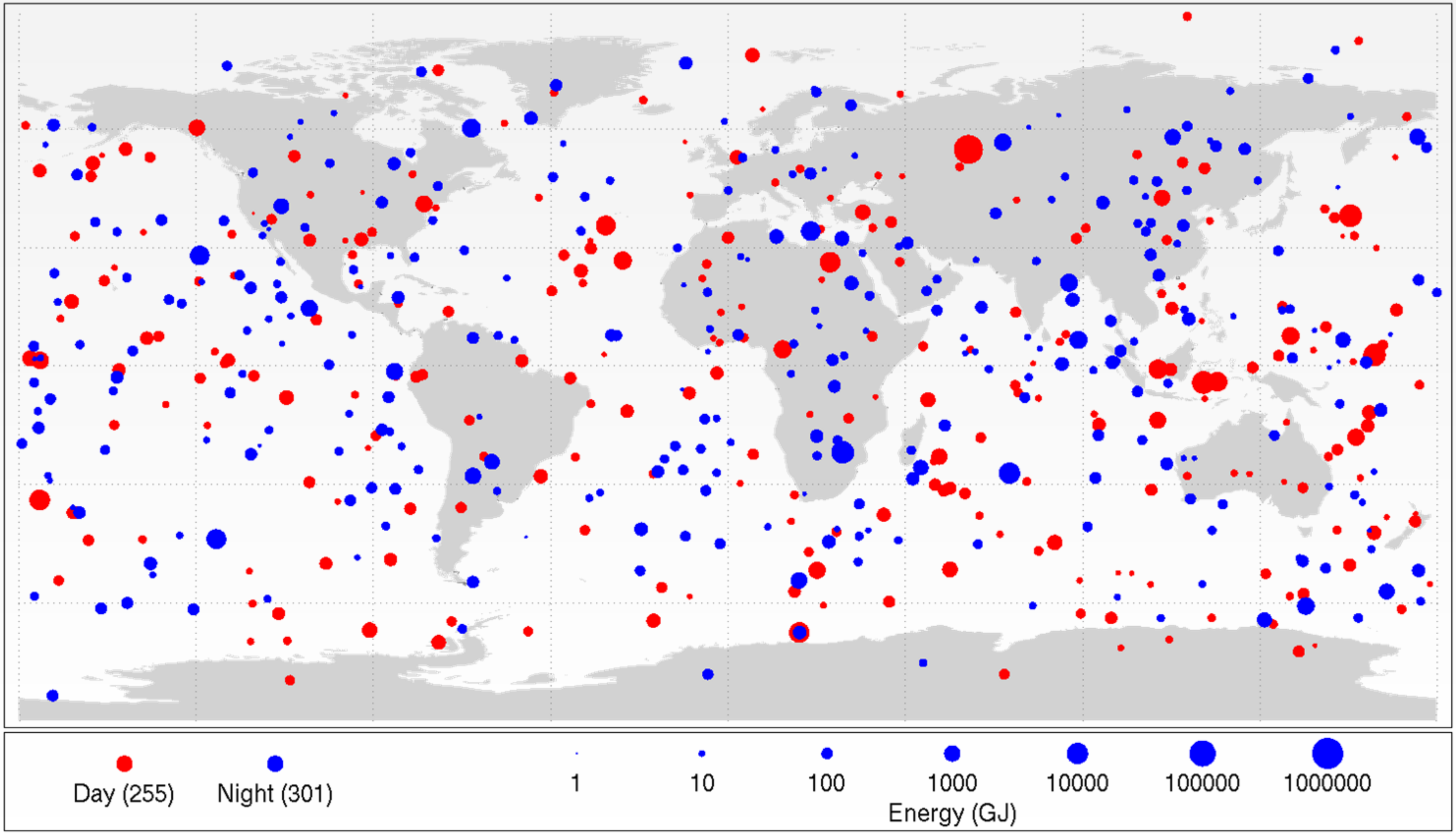
SAND2015-1735C

IEEE Aerospace Conference
Big Sky, Montana
March 7-14, 2015

Mark Boslough
Sandia National Laboratories
Peter Brown
University of Western Ontario
Alan Harris
MoreData! Inc.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Recorded Bolide Events 1994 - 2013



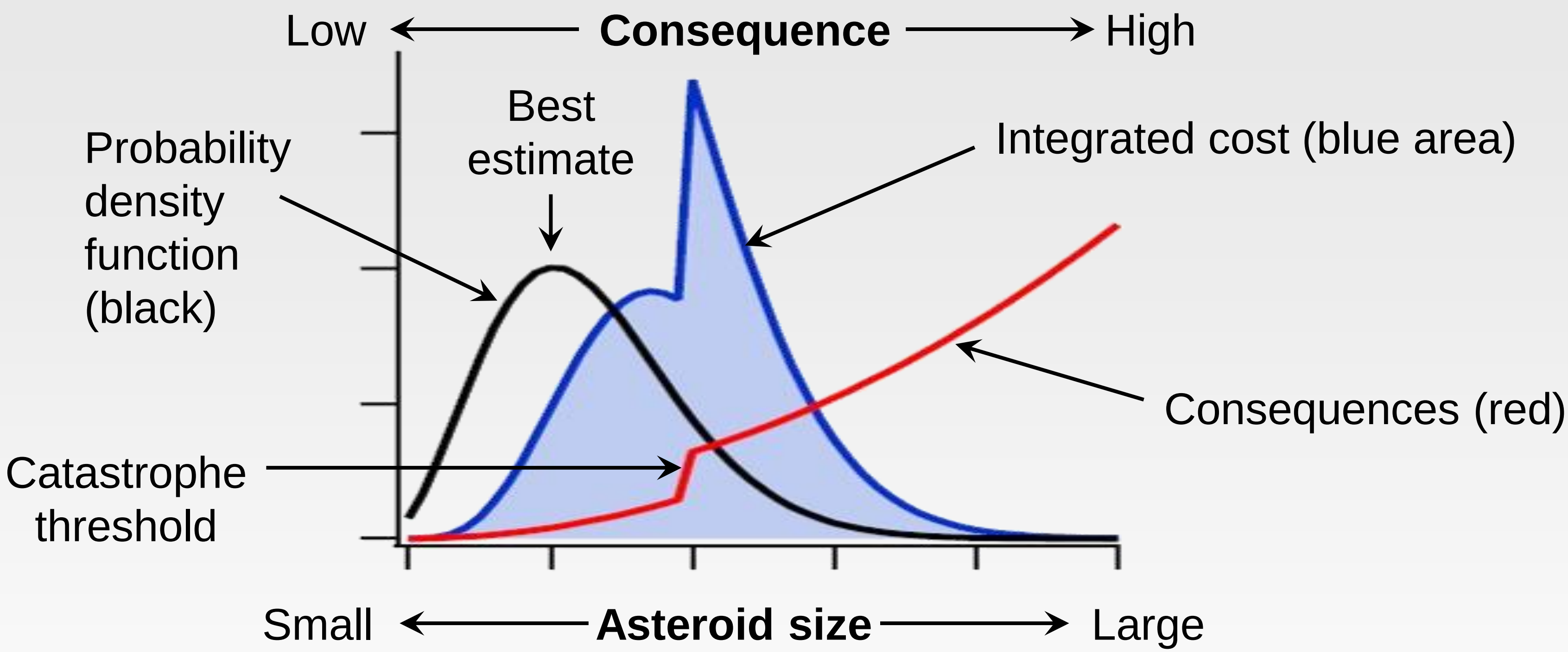
Outline

1) Risk Assessment: Review
2) Airburst Physics
3) The Chelyabinsk Airburst
4) Airburst Observation Statistics
5) Asteroid Observation Statistics
6) Risk Assessment: Updated
7) Uncertainty Reduction Strategies

1. Risk Assessment: Review

Probabilistic Risk Assessment

IPCC Workshop Report on Uncertainty and Risk (Manning, et al., 2004)



- Probability Density Function (black) for largest impact in time interval
- Consequences (red) are an increasing function of asteroid size.
- Estimated cost is the area under the product curve (blue).
- Best estimate of largest impact is not the most important value.
- High-consequence “fat tail” dominates risk when there is a threshold.
- Biggest asteroids should be dealt with first.

Nature VOL 367 6 January 1994

REVIEW ARTICLE

Impacts on the Earth by asteroids and comets: assessing the hazard

Clark R. Chapman & David Morrison

There is a 1-in-10,000 chance that a large (~2-km diameter) asteroid or comet will collide with the Earth during the next century, disrupting the ecosphere and killing a large fraction of the world's population. Although impacts of this magnitude are so infrequent as to be beyond our personal experience, the long-term statistical hazard is comparable to that of many other, more familiar natural disasters, raising the question of whether mitigation measures should be considered.

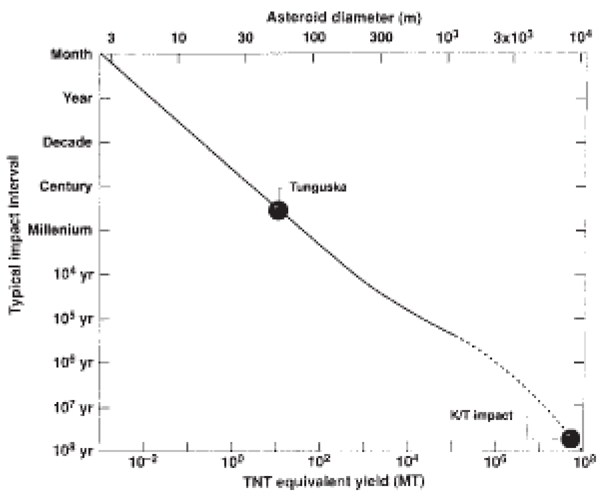


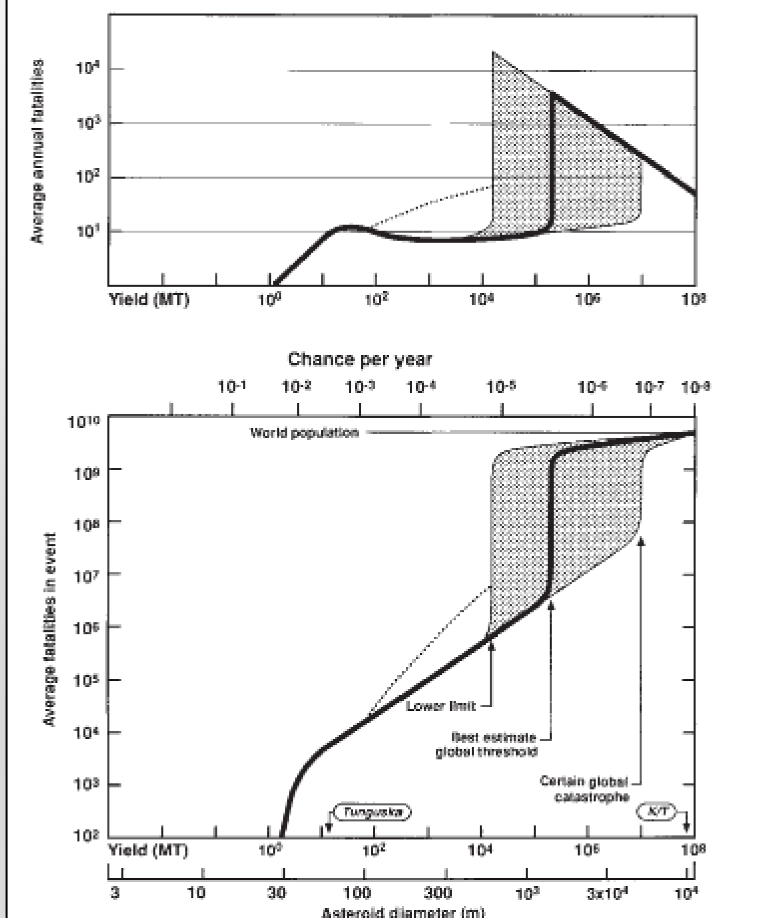
FIG. 1 Typical intervals between impacts equal to or larger than the specified yields. The solid line is Shoemaker's[21] "best estimate," extended (dashed line) to a minimum estimate of the K/T impact energy[6]. Impact frequencies could be uncertain by a factor of 10 near 0.01 MT and by a factor of 3 for >100 MT[18]. The current impact rate is dominated by small-number statistics in the region of the dashed line. Equivalent asteroid diameters are shown, assuming 20 km s^{-1} impact velocity and 3 g cm^{-3} density.

catastrophe.

The uncertainty in the threshold energy probably exceeds an order of magnitude above or below this value. As Turco *et al.*[45] wrote, in a nuclear winter context, "the total impact . . . on biological communities is more uncertain [than are climatic effects] because little is known about the effects of physical stresses on ecosystems . . . Thus, the important issue of synergisms between various ecological stresses . . . will not be resolved, [so] the global biological impacts—and hence the human impacts—of nuclear war will remain as the principal uncertainties." To reflect such uncertainties, as well as uncertainties in climate modelling and in other physical and chemical effects of an impact, we adopt (Table 1) a possible range of thresholds from 1.5×10^4 to 10^7 MT (0.6–5 km diameter). It would take a very unfavourable combination of parameters coupled with an assumption that human society is very fragile, to imagine that an object with a diameter of $\lesssim$0.5 km could produce a global catastrophe; on the other hand, a >5 km object would[42] create a global firestorm and so much darkness from stratospheric opacity that vision would cease—an environmental holocaust certainly exceeding any definition for the onset of global catastrophe.

Hazard analysis

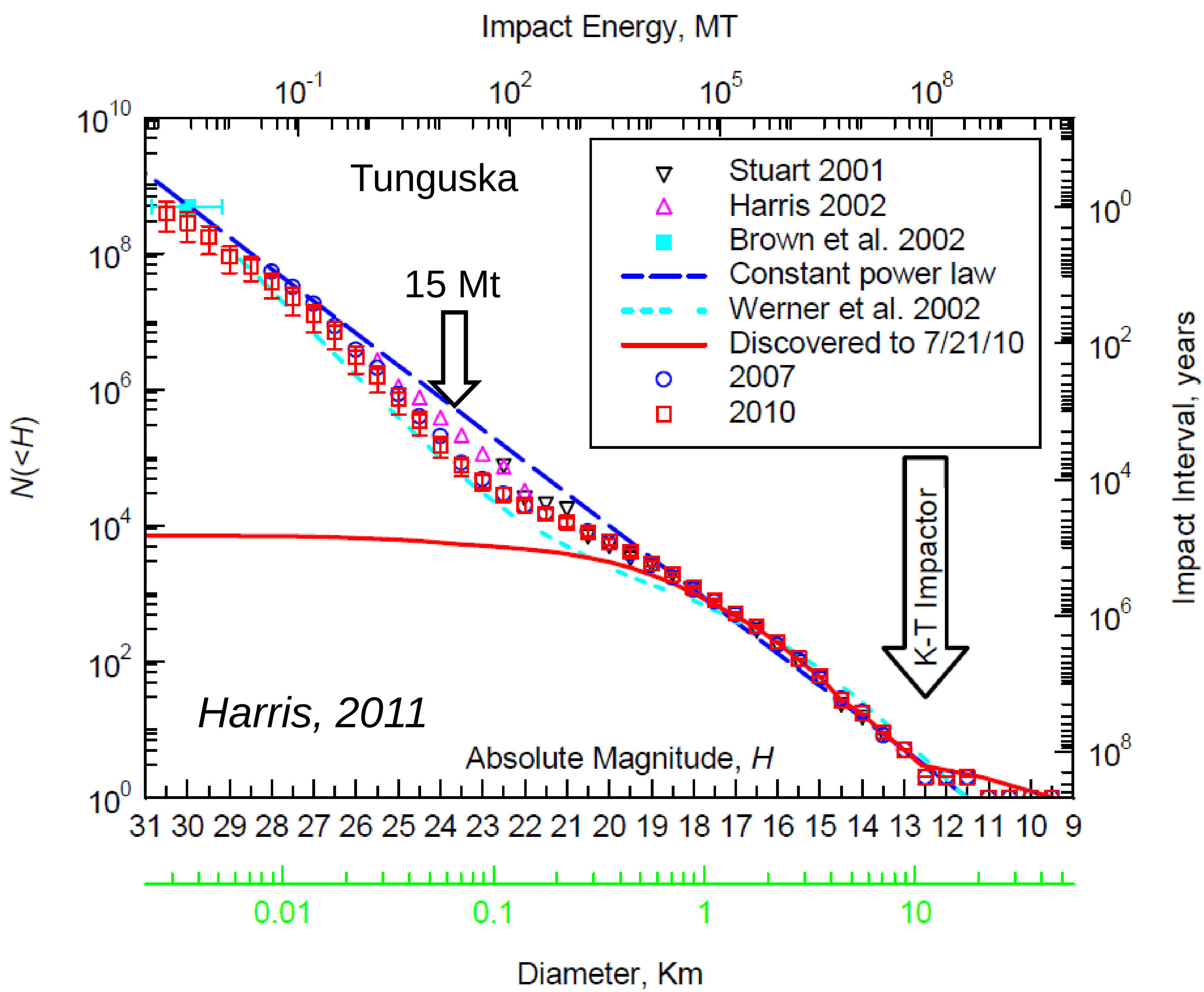
The area of mortality associated with airbursts or groundbursts from objects larger than our 50-m (10 MT) threshold for penetration into the lower atmosphere depends on terrain, nature of habitation, altitude of blast, and so on. (Here we ignore iron meteoroids, which account for <3% of falls and whose potential for cratering the Earth's surface has been well studied by Shoe-



Type of event	Diameter of impactor	Energy (MT)	Typical interval (yr)	Deaths	World deaths per year
High atmospheric break-up	<50 m	<9	N.A.	~0	~0
Tunguska-like events	50–300 m	9–2,000	250	5×10^3	20
Large sub-global events	300–600 m	2,000–1.5×10^4	35×10^3	3×10^5	8
	300–1.5 km	2,000–2.5×10^5	25×10^3	5×10^5	20
	300–5 km	2,000–10^7	25×10^3	1.2×10^6	45
Low global threshold	>600 m	1.5×10^4	7×10^4	1.5×10^9	2×10^4
Nominal global threshold	>1.5 km	2×10^5	5×10^5	1.5×10^9	3×10^3
High global threshold	>5 km	10^7	6×10^6	1.5×10^9	250
Rare K/T scale events	>10 km	10^8	10^8	5×10^9	50

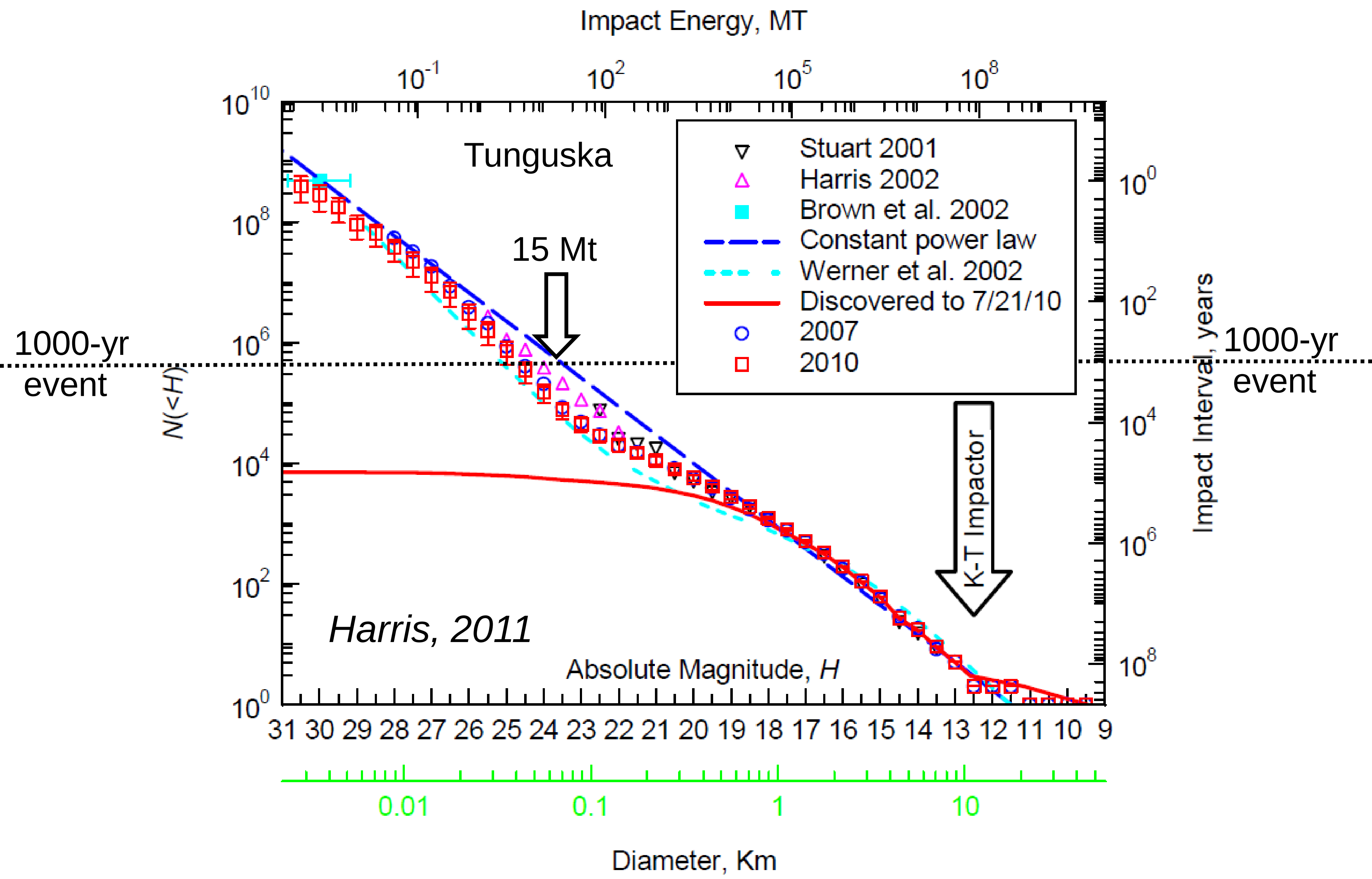
TABLE 2 Fatality rates and scale of impact for three different estimates of global threshold

What is frequency of Tunguska-scale events?



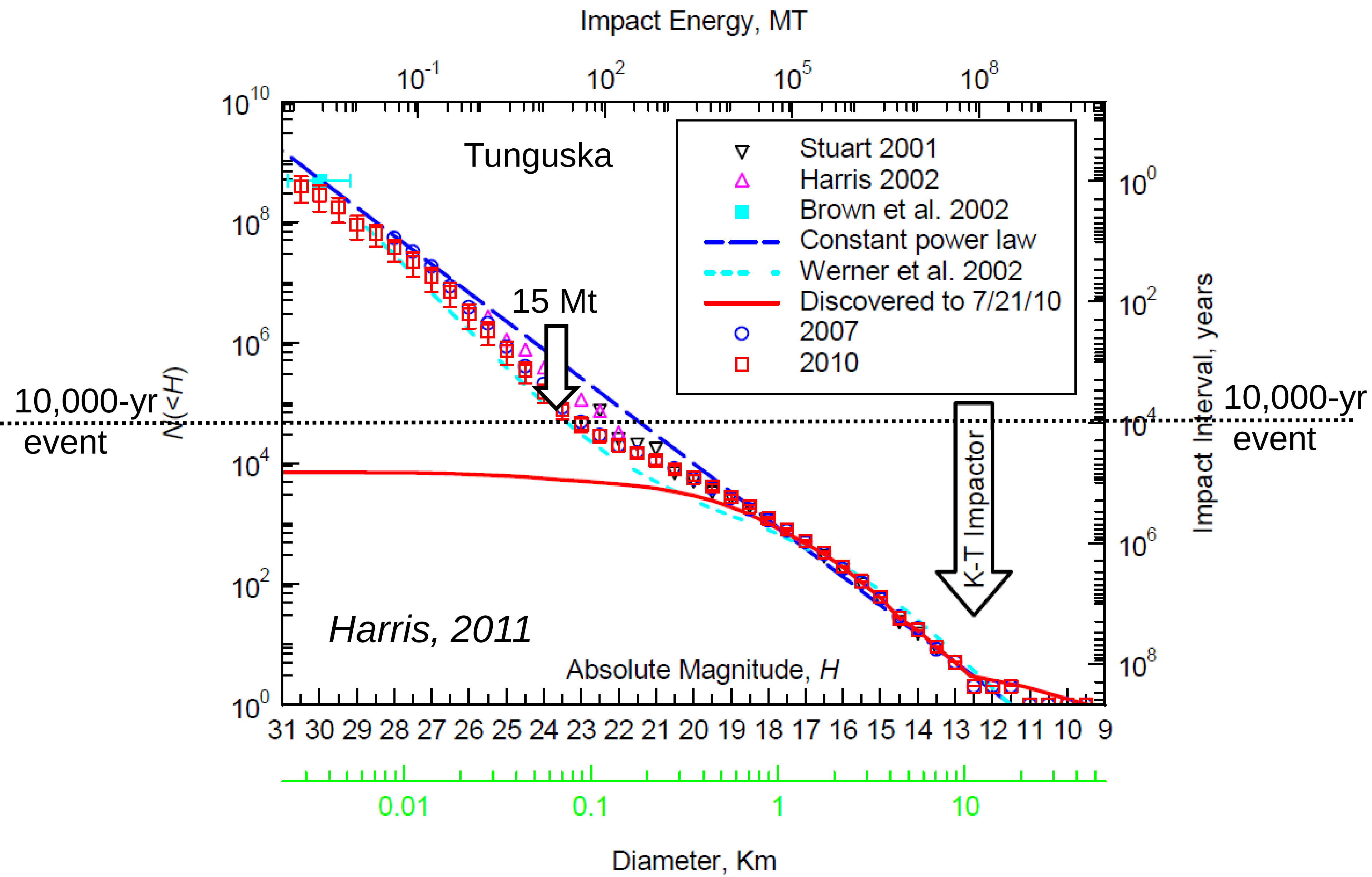
What is frequency of Tunguska-scale events?

Nuclear-weapon-scaled yield (15 Mt) with power-law size distribution: ~1000 years



What is frequency of Tunguska-scale events?

Nuclear-weapon-scaled yield (15 Mt) with 2011 survey distribution: ~10,000 years



1. Airburst Physics

LAAs are not point explosions

Unlike bombs, low-altitude airbursts…

…generate upward ballistic plumes

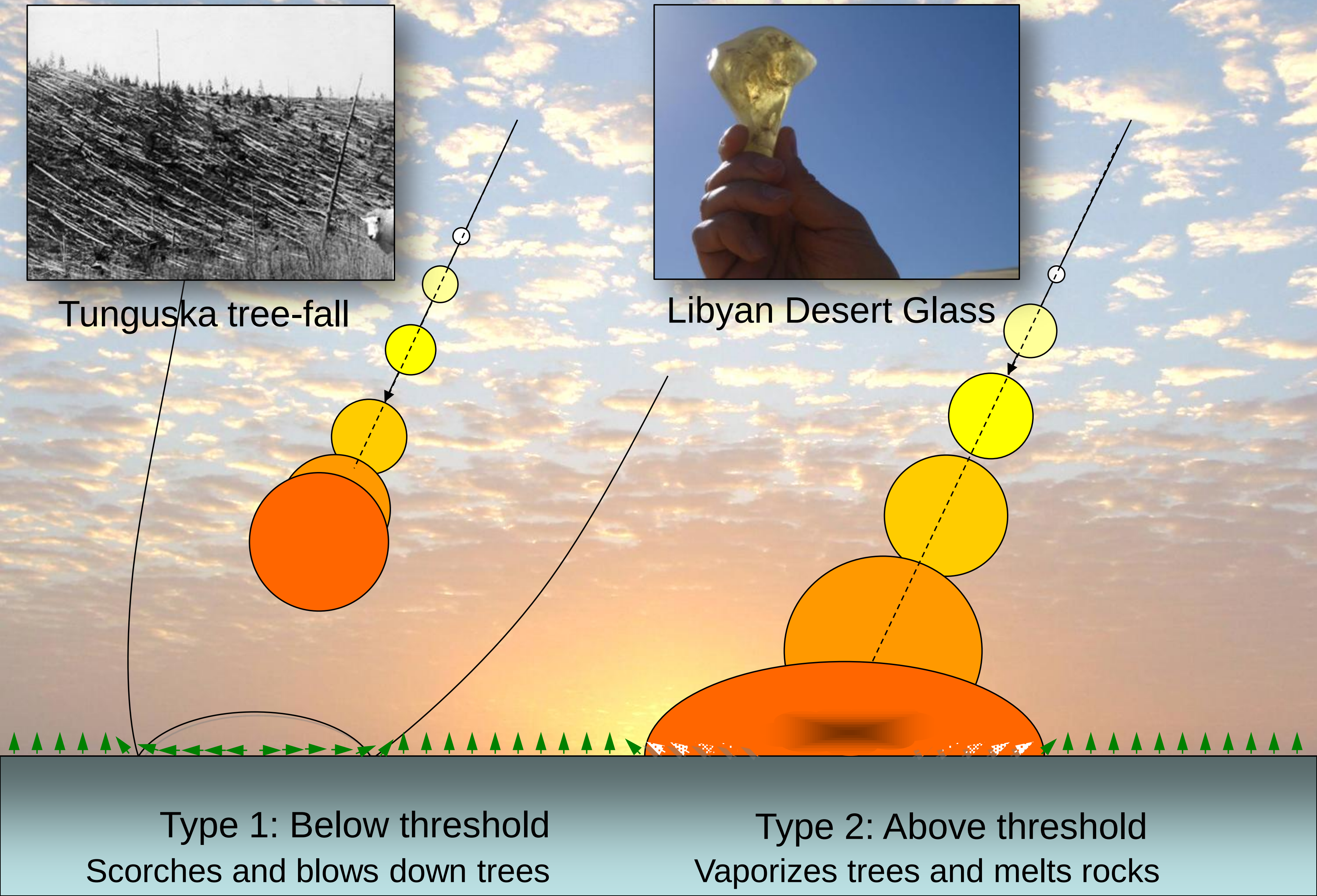
…generate downward vortex rings

…enhance heat transport to surface

…carry mechanical energy downward

…have anisotropic radiation patterns

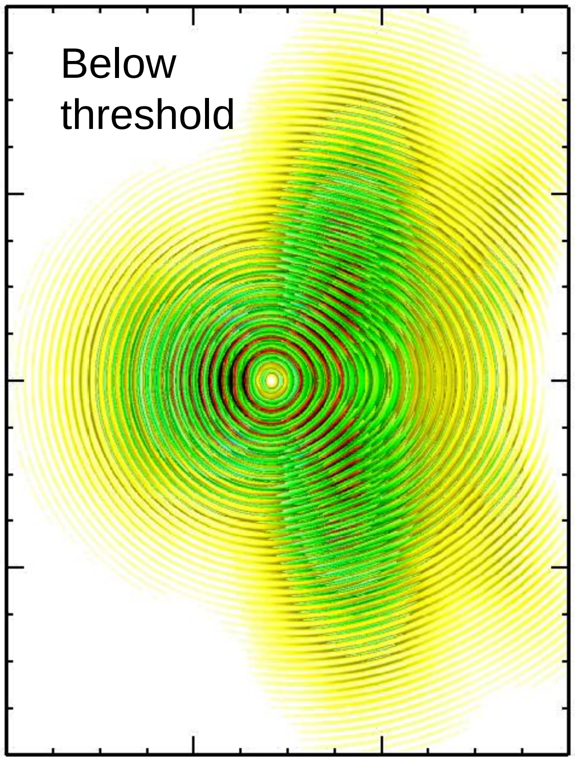
Two types of Low-Altitude Airburst



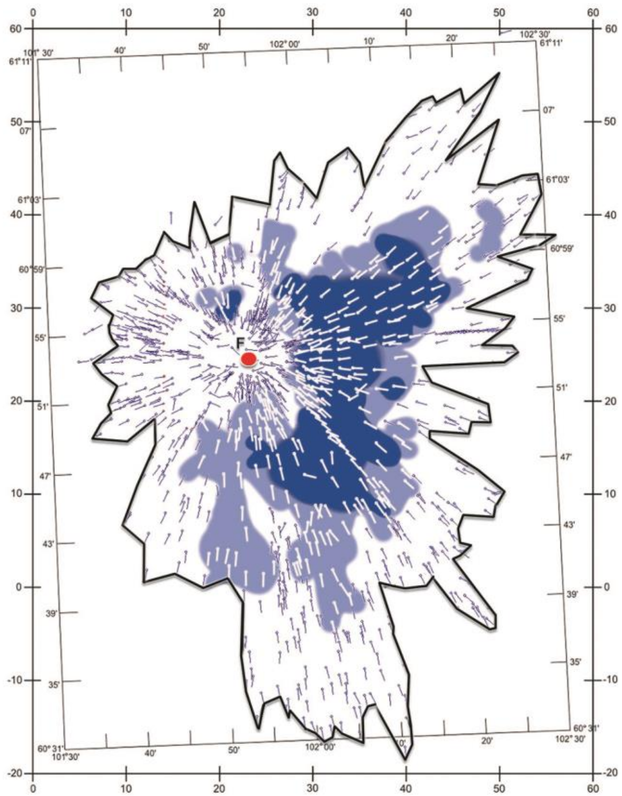
1908 Tunguska Airburst

"Experimental" data demonstrate that event was below threshold

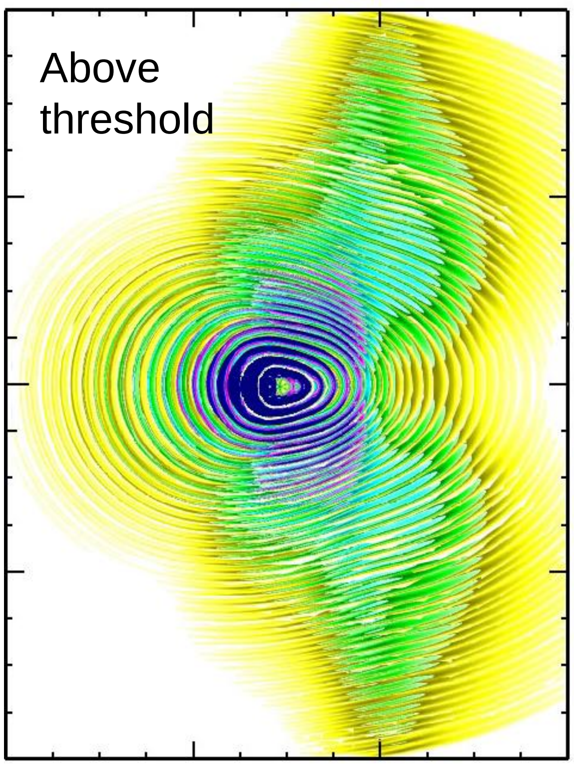
5 Megaton Airburst (3D)



Observed pattern



15 Megaton Airburst (3D)



90% on flat land (healthy forest)

90% on flat land (unhealthy forest)

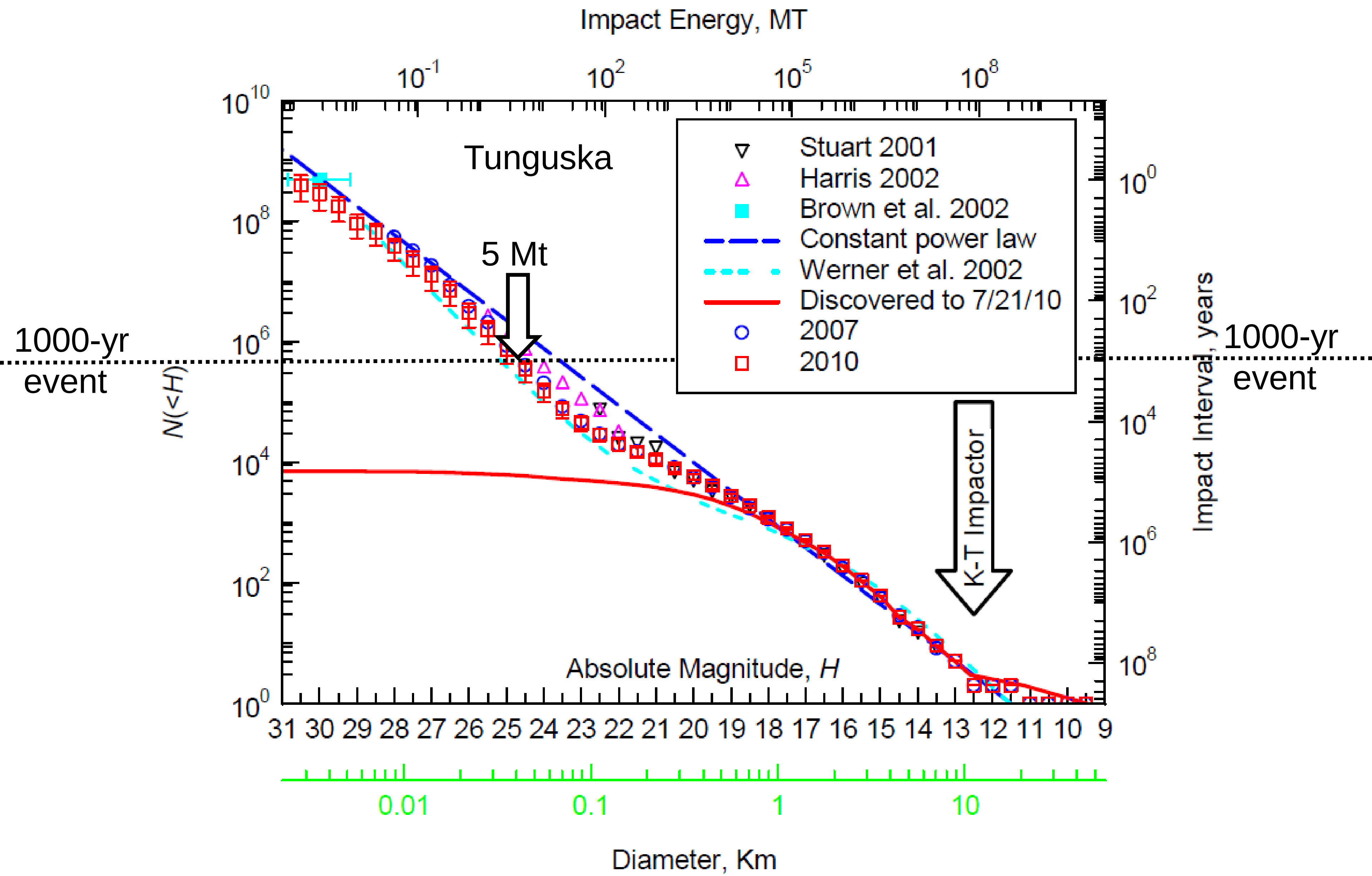
90% on ridge tops (unhealthy forest)

Wind speed (m/s)

60 50 40 30 20 10

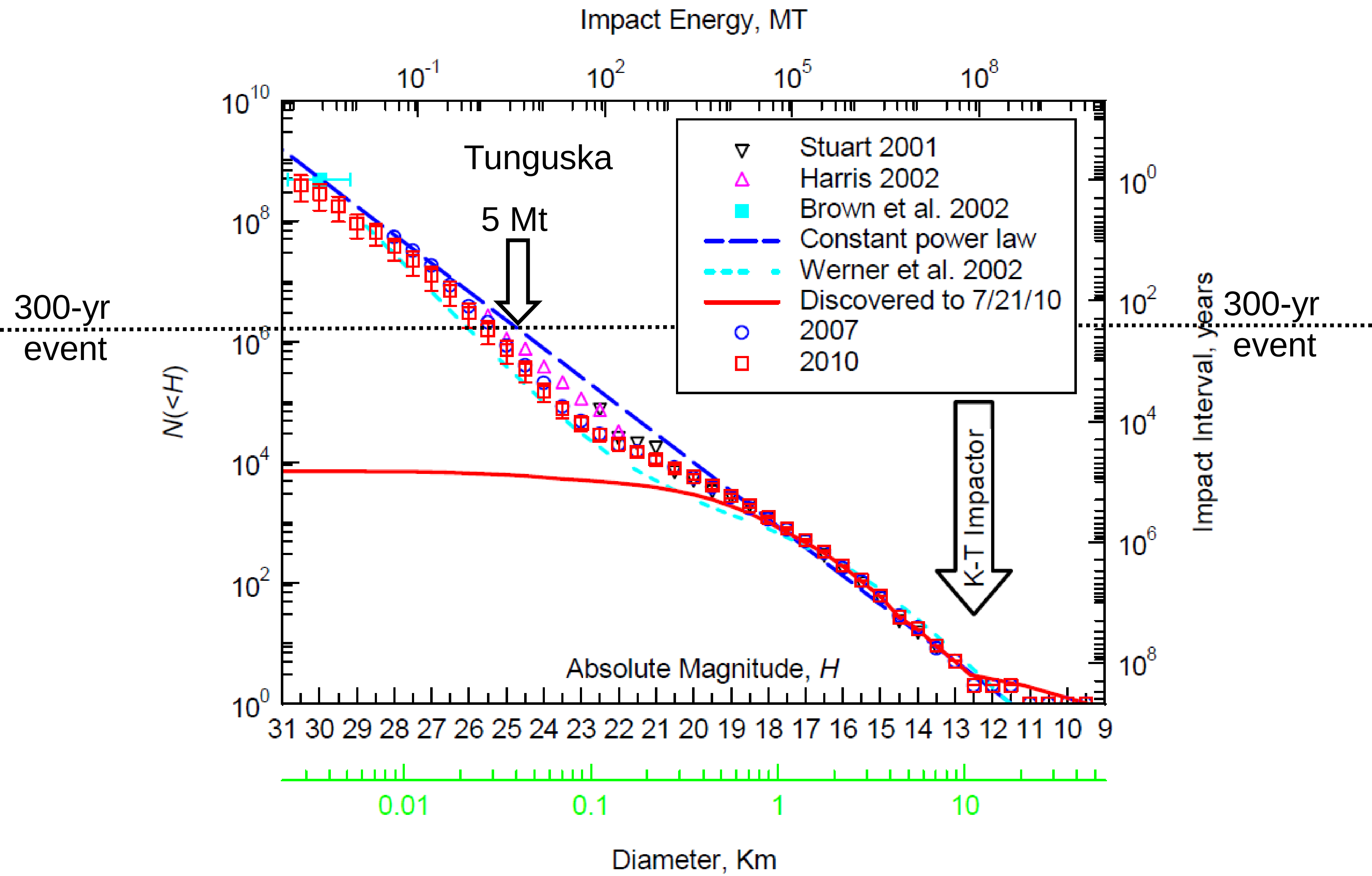
What is frequency of Tunguska-scale events?

Directed airburst yield (~5 Mt) with 2011 survey distribution: ~1000 years



What is frequency of Tunguska-scale events?

Directed airburst yield (~5 Mt) with 2011 survey distribution: ~300 years



3. The Chelyabinsk Airburst

US Government sensors

IIIIIIIIIIIIIIII START OF REPORT IIIIIIIIIIIIIIII

FOR PUBLIC RELEASE Distribution A
Bolide: On 15 February 2013
Sensors detected the following indications of a meteoroid entry into Earth's atmosphere:
a. Dateltime at peak brightness: 15 February 2013/03:20:33 GMT
b. Location at peak brightness: Latitude 54.8o N, Longitude 61.1o E
c. Altitude at peak brightness: 23.3 km
d. Velocity at peak brightness: 18.6 km/sec
e. Approximate total radiated energy: Under Assessment
f. Pre-entry velocity vector (ECF): X= +12.8 km/sec; Y = -13.3 km/sec;
Z=-2.4 km/sec

IIIIIIIIIIIIIIII END OF REPORT IIIIIIIIIIIIIIII

90 kT TNT

http://jpl.nasa.gov/fireball


OUTLOOK
The spine
nature
THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE
SKYFALL
The trajectory, origin and airburst behaviour of the Chelyabinsk fireball
PAGES 202, 235 & 238
TROPICAL DISEASE
CAN WE BEAT THE PARASITES?
Cryptosporidiosis and malaria are prime targets
PAGES 186 & 189
DRUGS
CHANGING MINDS
Cultural and medical histories of psychotropics
PAGE 194
OCEANOGRAPHY
TIME CAPSULE
Ancient sea water preserved in Chesapeake Bay crater
PAGE 252
NATURE.COM/NATURE
14 November 2013
$10.00US $12.99CAN

A 500-kiloton airburst over Chelyabinsk and an enhanced hazard from small impactors

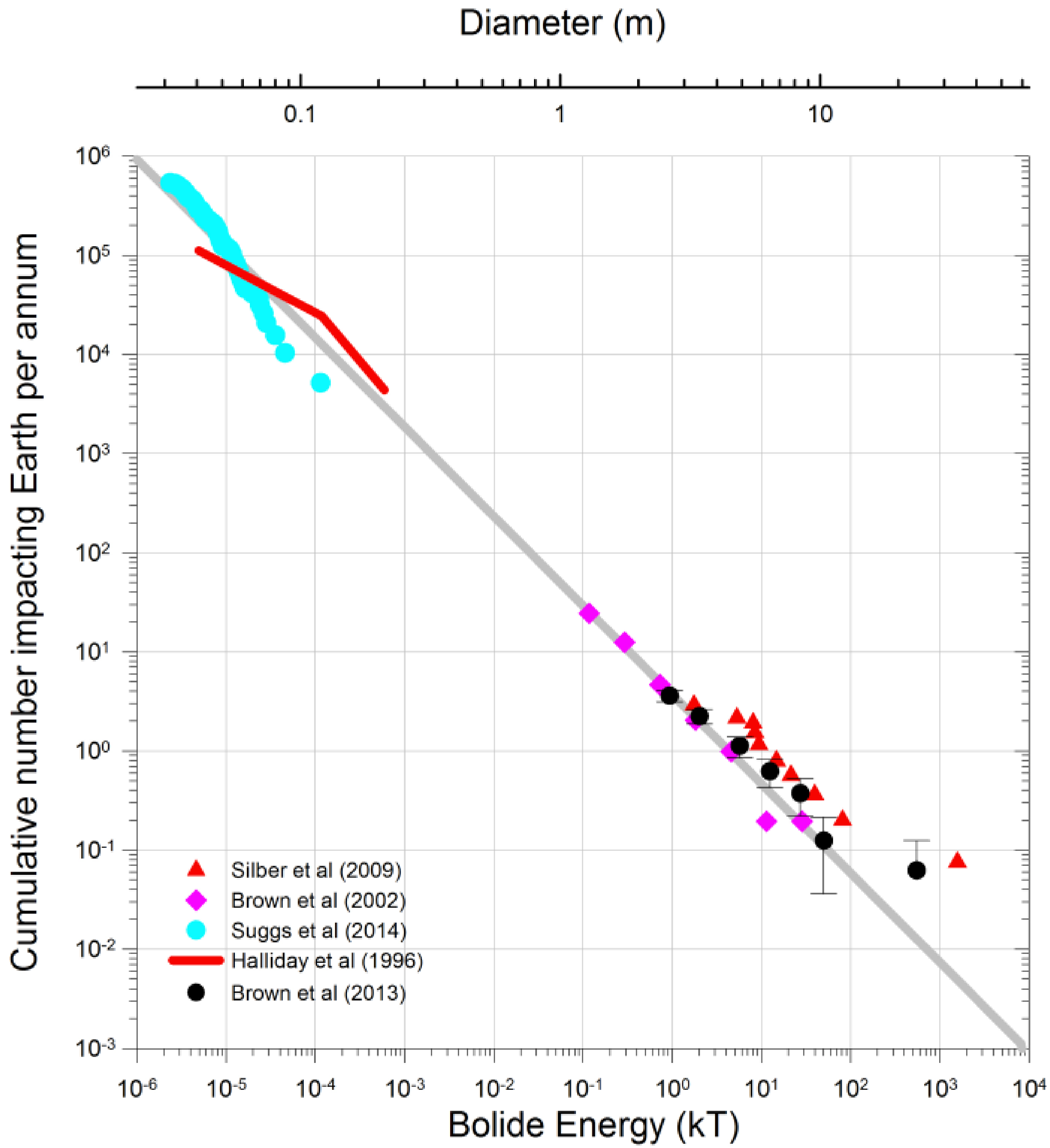
P. G. Brown[1,2], J. D. Assink[3], L. Astiz[4], R. Blaauw[5], M. B. Boslough[6], J. Borovička[7], N. Brachet[3], D. Brown[8], M. Campbell-Brown[1], L. Ceranna[9], W. Cooke[10], C. de Groot-Hedlin[4], D. P. Drob[11], W. Edwards[12], L. G. Evers[13,14], M. Garces[15], J. Gill[1], M. Hedlin[4], A. Kingery[16], G. Laske[4], A. Le Pichon[3], P. Mialle[8], D. E. Moser[5], A. Saffer[10], E. Silber[1], P. Smets[13,14], R. E. Spalding[6], P. Spurný[7], E. Tagliaferri[17], D. Uren[1], R. J. Weryk[1], R. Whitaker[18] & Z. Krzeminski[1]

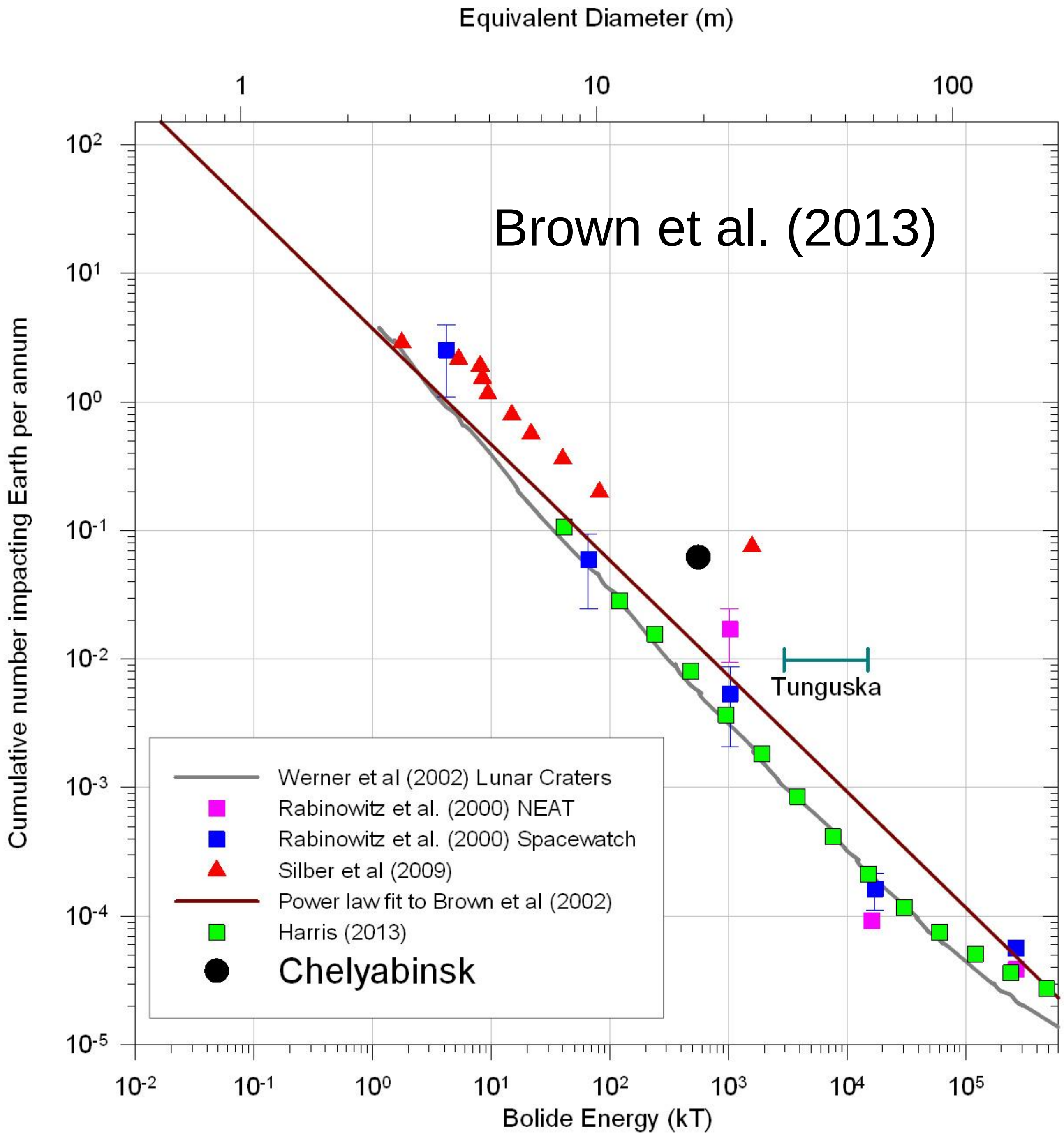
Most large (over a kilometre in diameter) near-Earth asteroids are now known, but recognition that airbursts (or fireballs resulting from nuclear-weapon-sized detonations of meteoroids in the atmosphere) have the potential to do greater damage[1] than previously thought has shifted an increasing portion of the residual impact risk (the risk of impact from an unknown object) to smaller objects[2]. Above the threshold size of impactor at which the atmosphere absorbs sufficient energy to prevent a ground impact, most of the damage is thought to be caused by the airburst shock wave[3], but owing to lack of observations this is uncertain[4,5]. Here we report an analysis of the damage from the airburst of an asteroid about 19 metres (17 to 20 metres) in diameter southeast of Chelyabinsk, Russia, on 15 February 2013, estimated to have an energy equivalent of approximately 500 (±100) kilotons of trinitrotoluene (TNT, where 1 kiloton of TNT = 4.185×10^{12} joules). We show that a widely referenced technique[4–6] of estimating airburst damage does not reproduce the observations, and that the mathematical relations[7] based on the effects of nuclear weapons—almost always used with this technique—overestimate blast damage. This suggests that earlier damage estimates[5,6] near the threshold impactor size are too high. We performed a global survey of airbursts of a kiloton or more (including Chelyabinsk), and find that the number of impactors with diameters of tens of metres may be an order of magnitude higher than estimates based on other techniques[8,9]. This suggests a non-equilibrium (if the population were in a long-term collisional steady state the size-frequency distribution would either follow a single power law or there must be a size-dependent bias in other surveys) in the near-Earth asteroid population for objects 10 to 50 metres in diameter, and shifts more of the residual impact risk to these sizes.

ACCORDING TO BROWN ET AL. (2013)

- Damage per airburst event is greater than previously thought
- Number of NEOs in 10-meter range may be order of magnitude greater!
- Integrated NEO risk is shifted to small (10-50 meter) asteroids

4. Airburst Observation Statistics

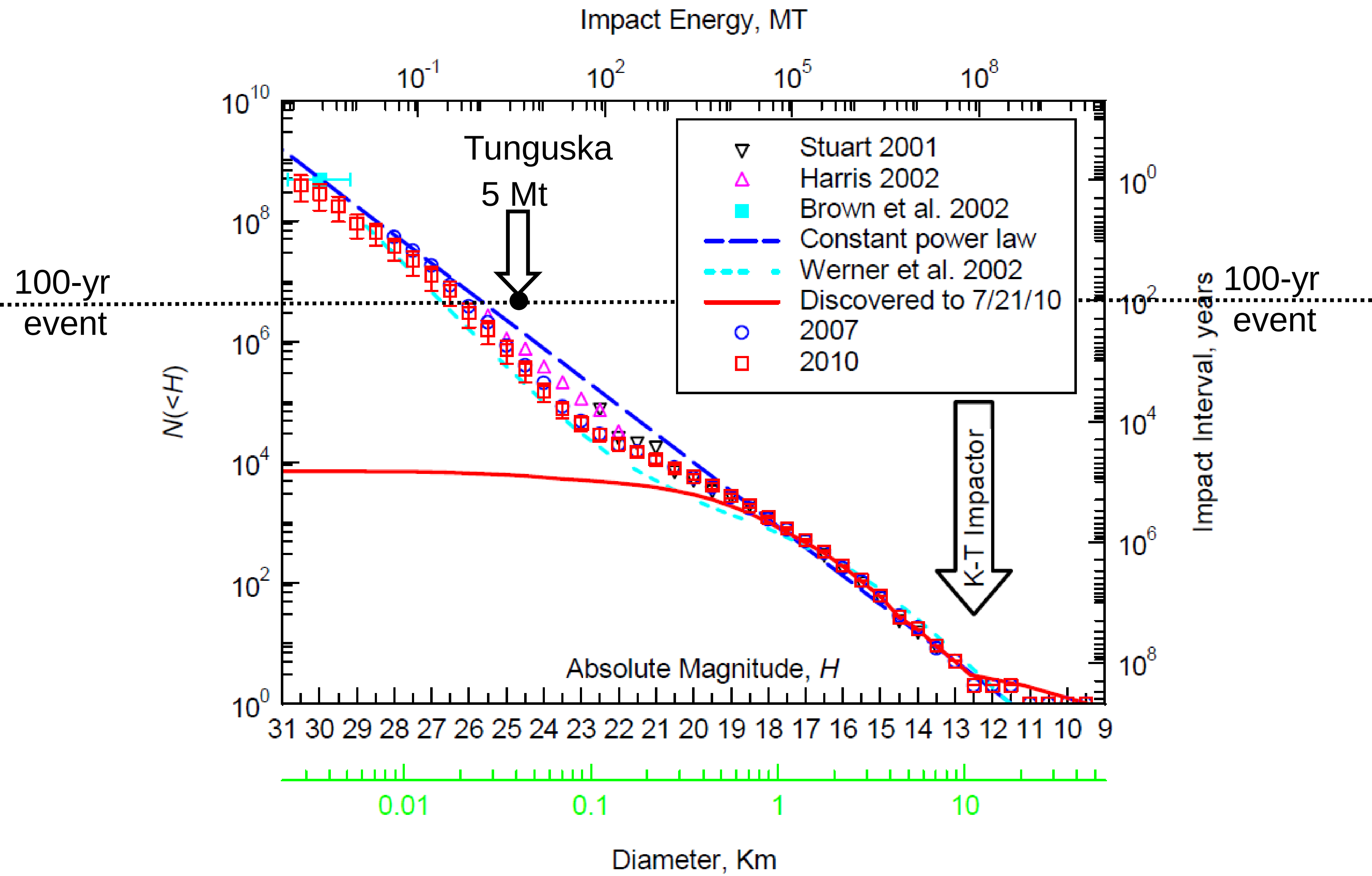

Diameter (m)
0.1
1
10
Cumulative number impacting Earth per annum
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
10^4
Bolide Energy (kT)
Silber et al (2009)
Brown et al (2002)
Suggs et al (2014)
Halliday et al (1996)
Brown et al (2013)



Equivalent Diameter (m)
1
10
100
Brown et al. (2013)
Cumulative number impacting Earth per annum
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
Tunguska
Werner et al (2002) Lunar Craters
Rabinowitz et al. (2000) NEAT
Rabinowitz et al. (2000) Spacewatch
Silber et al (2009)
Power law fit to Brown et al (2002)
Harris (2013)
Chelyabinsk
10^-2
10^-1
10^0
10^1
10^2
10^3
10^4
10^5
Bolide Energy (kT)

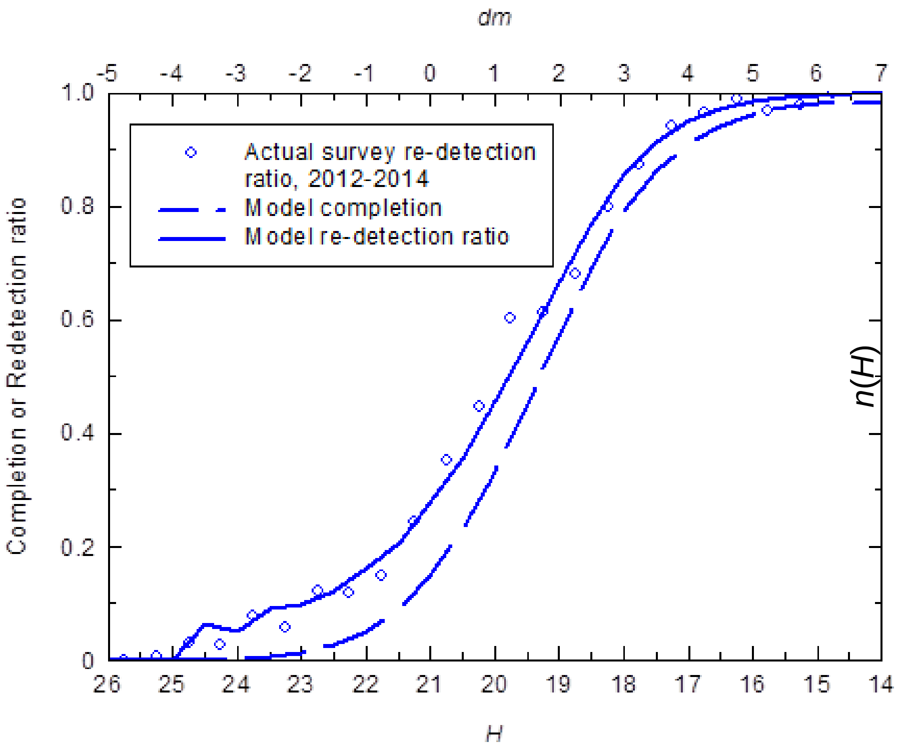
What is frequency of Tunguska-scale events?

Directed airburst yield (~5 Mt) with Brown et al. (2013) airburst statistics: ~100 years

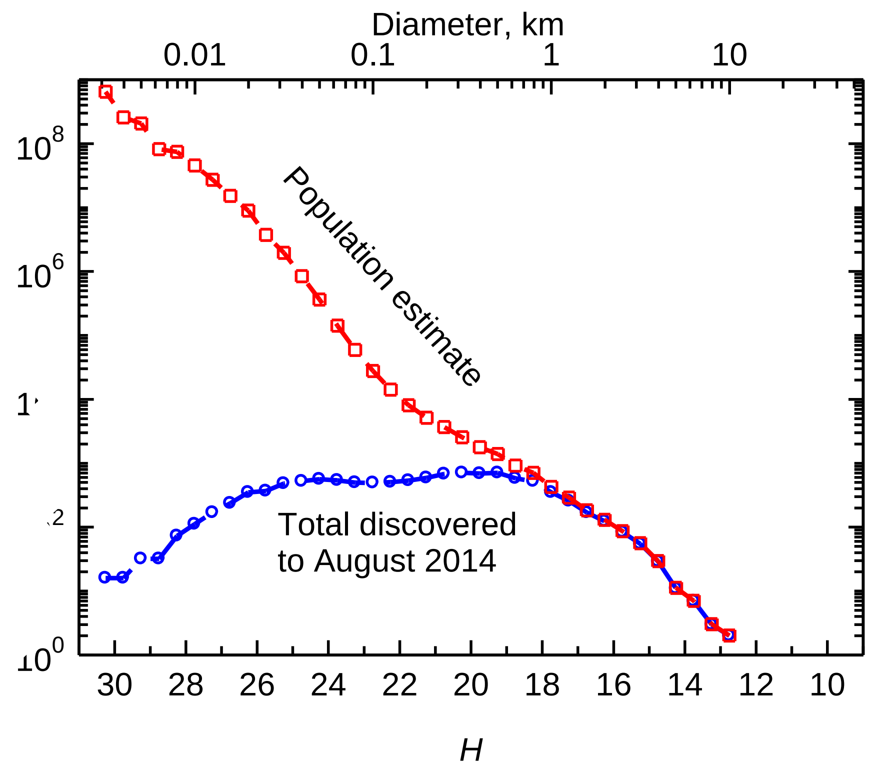


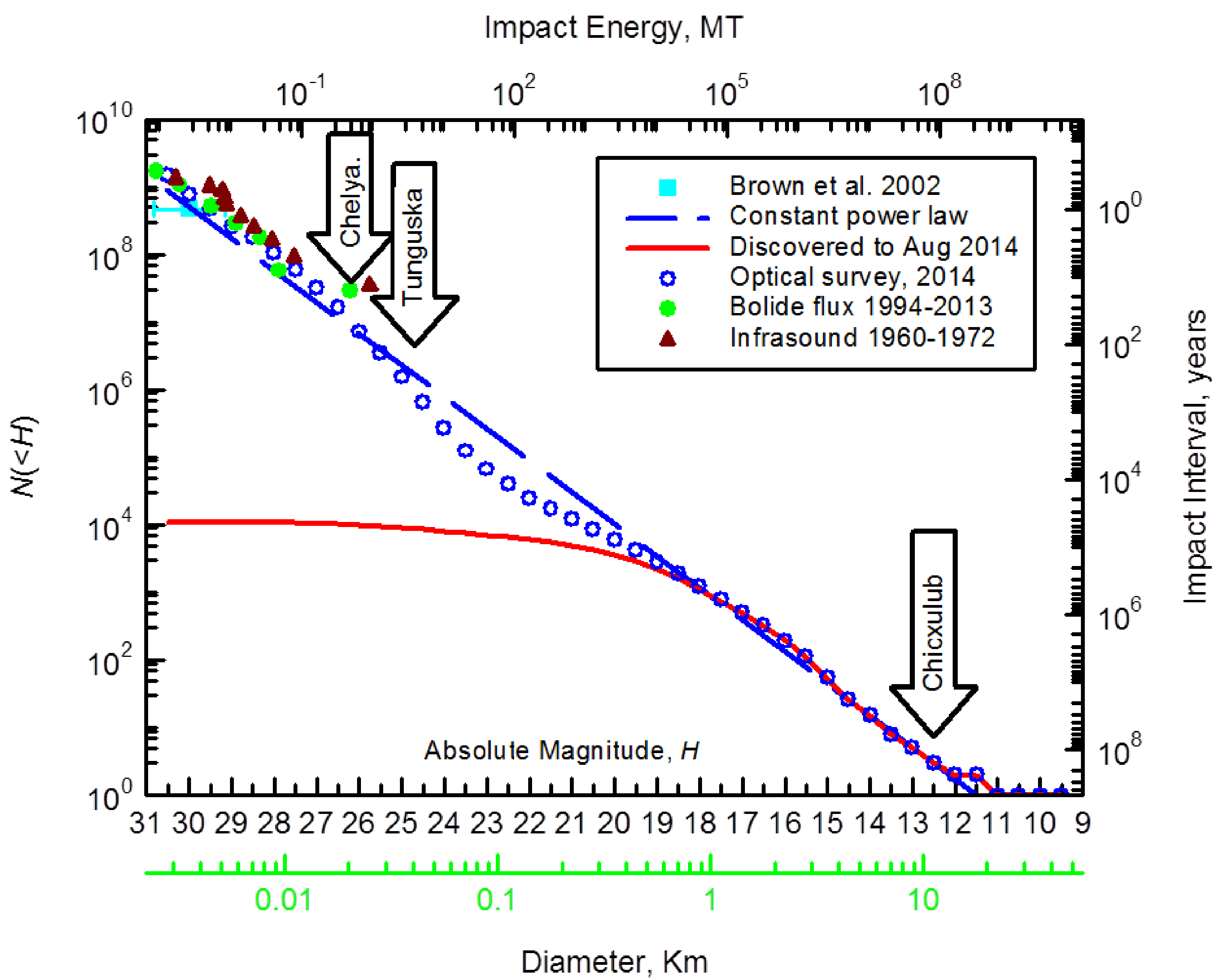
5. Asteroid Observation Statistics

Simulated completion and re-detection ratio

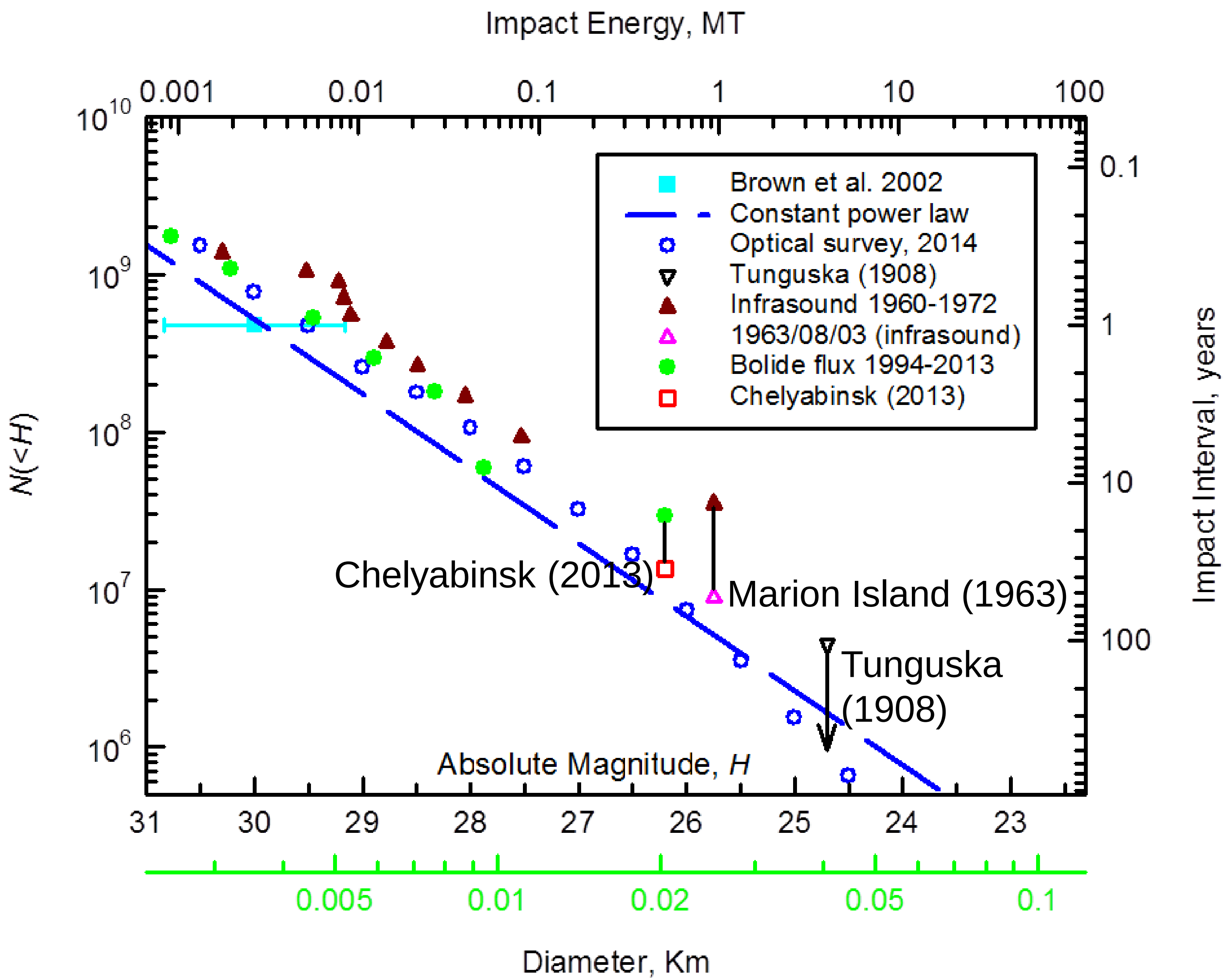


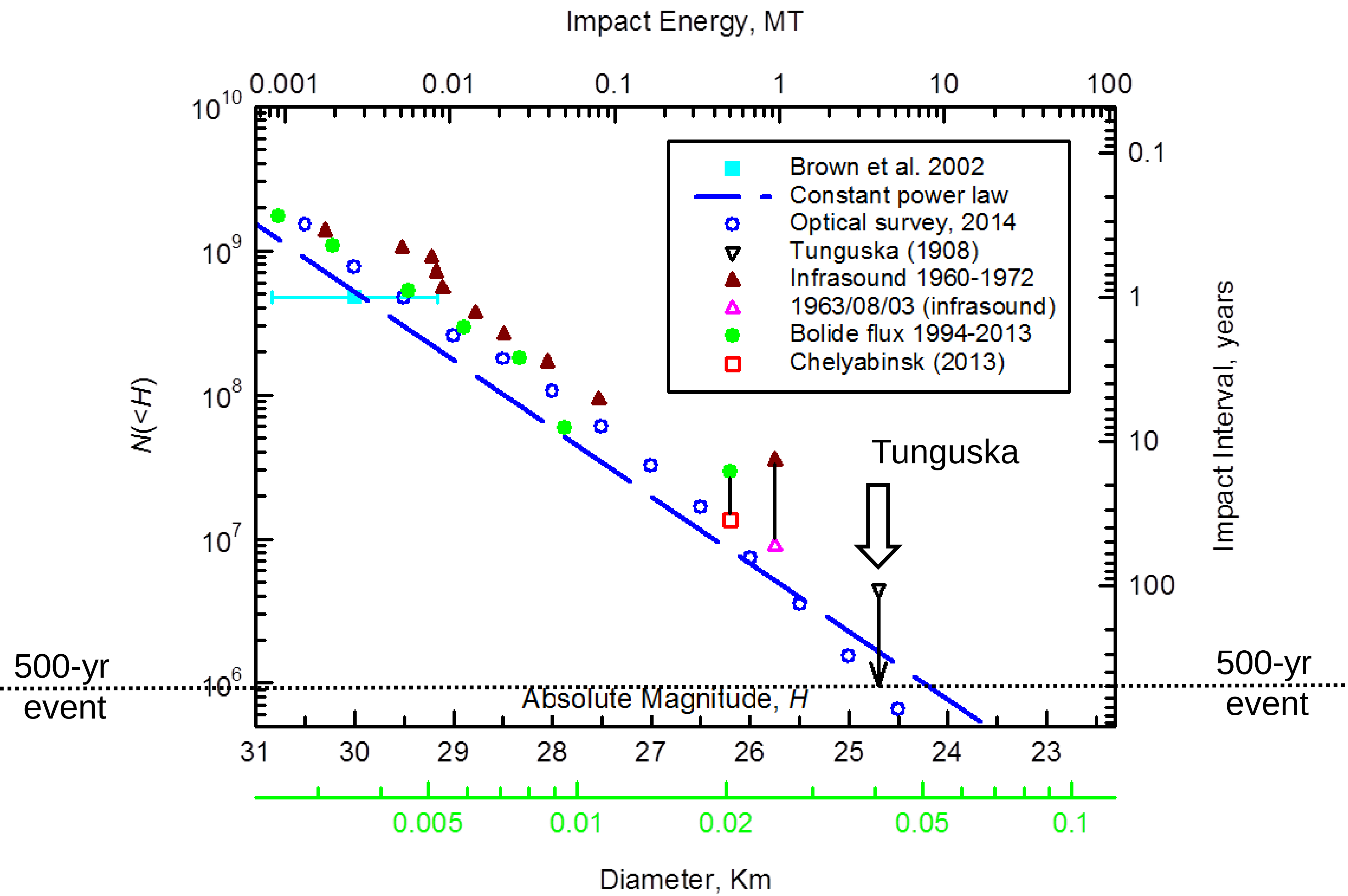
Differential population estimate (August, 2014)





Impact Energy, MT
10^-1
10^2
10^5
10^8
10^10
10^8
10^6
10^4
10^2
10^0
N(<H)
10^0
10^2
10^4
10^6
10^8
Impact Interval, years
Chelya.
Tunguska
Chicxulub
Brown et al. 2002
Constant power law
Discovered to Aug 2014
Optical survey, 2014
Bolide flux 1994-2013
Infrasound 1960-1972
Absolute Magnitude, H
31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9
0.01
0.1
1
10
Diameter, Km

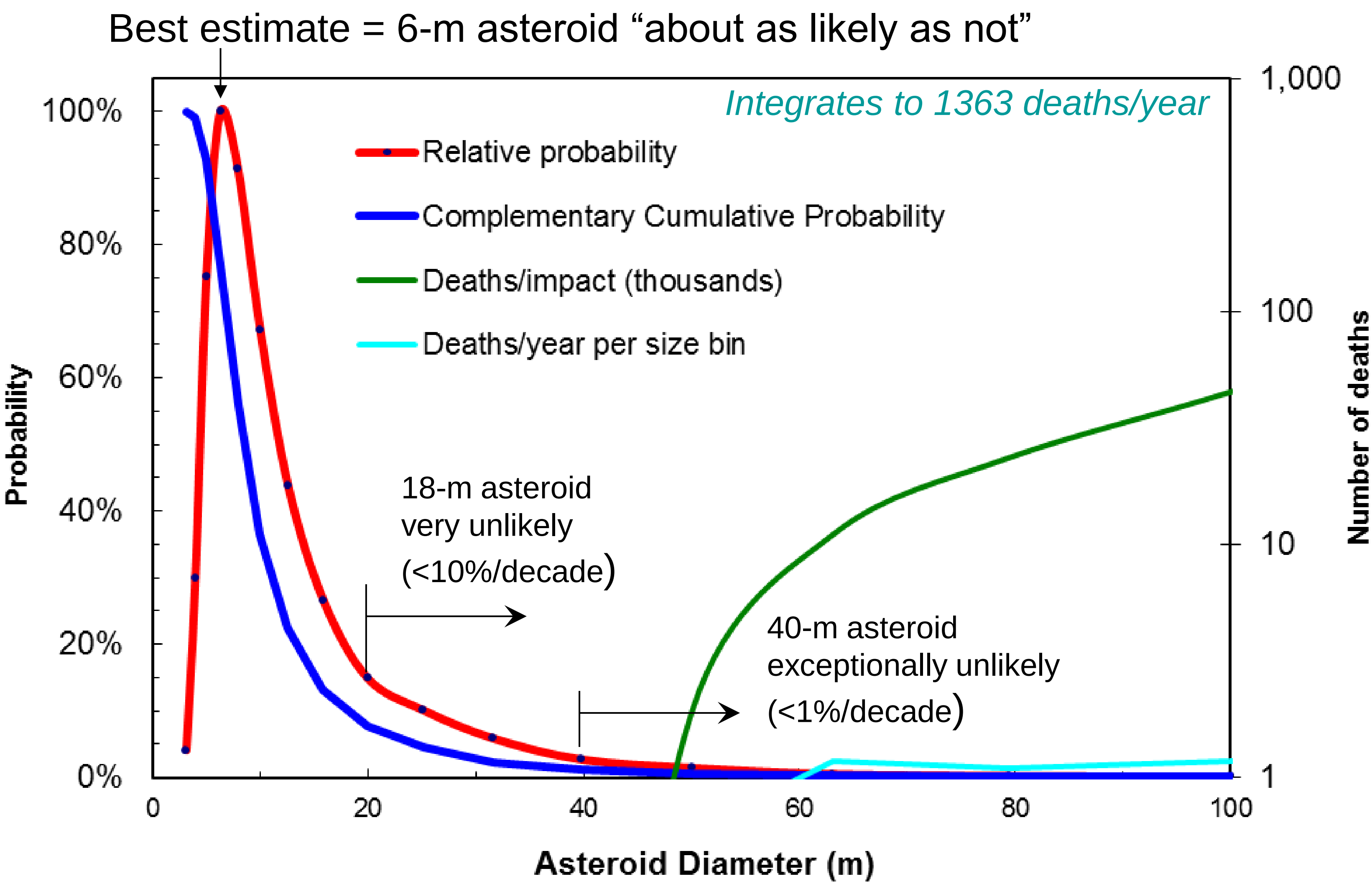

Impact Energy, MT
0.001
0.01
0.1
1
10
100
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
N(<H)
0.1
1
10
100
Impact Interval, years
Brown et al. 2002
Constant power law
Optical survey, 2014
Tunguska (1908)
Infrasound 1960-1972
1963/08/03 (infrasound)
Bolide flux 1994-2013
Chelyabinsk (2013)
Chelyabinsk (2013)
Marion Island (1963)
Tunguska
(1908)
Absolute Magnitude, H
31
30
29
28
27
26
25
24
23
0.005
0.01
0.02
0.05
0.1
Diameter, Km



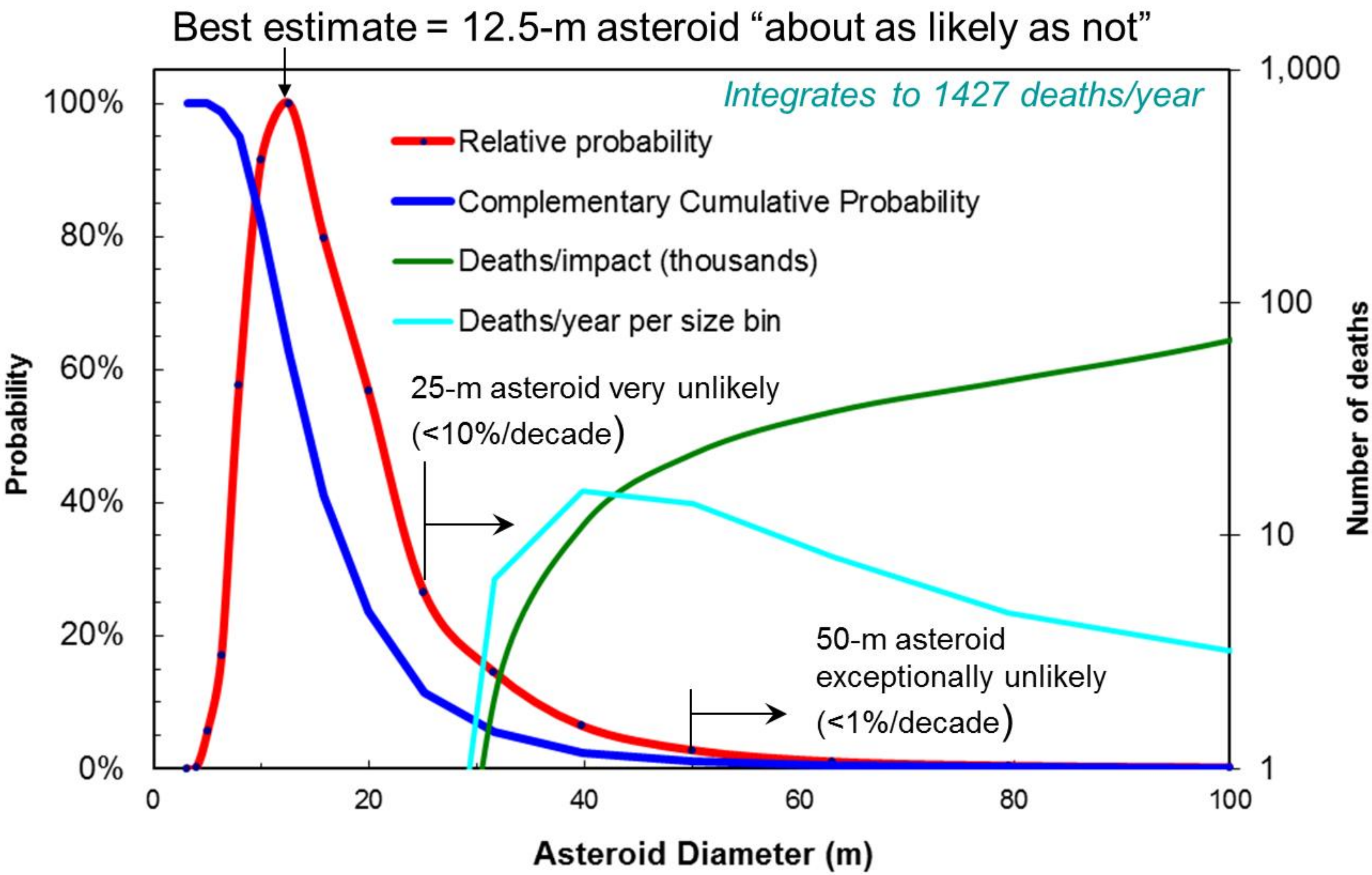
Impact Energy, MT
0.001
0.01
0.1
1
10
100
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
N(<H)
0.1
1
10
100
Impact Interval, years
Brown et al. 2002
Constant power law
Optical survey, 2014
Tunguska (1908)
Infrasound 1960-1972
1963/08/03 (infrasound)
Bolide flux 1994-2013
Chelyabinsk (2013)
Tunguska
500-yr event
500-yr event
Absolute Magnitude, H
31
30
29
28
27
26
25
24
23
0.005
0.01
0.02
0.05
0.1
Diameter, Km

6. Risk Assessment: Updated

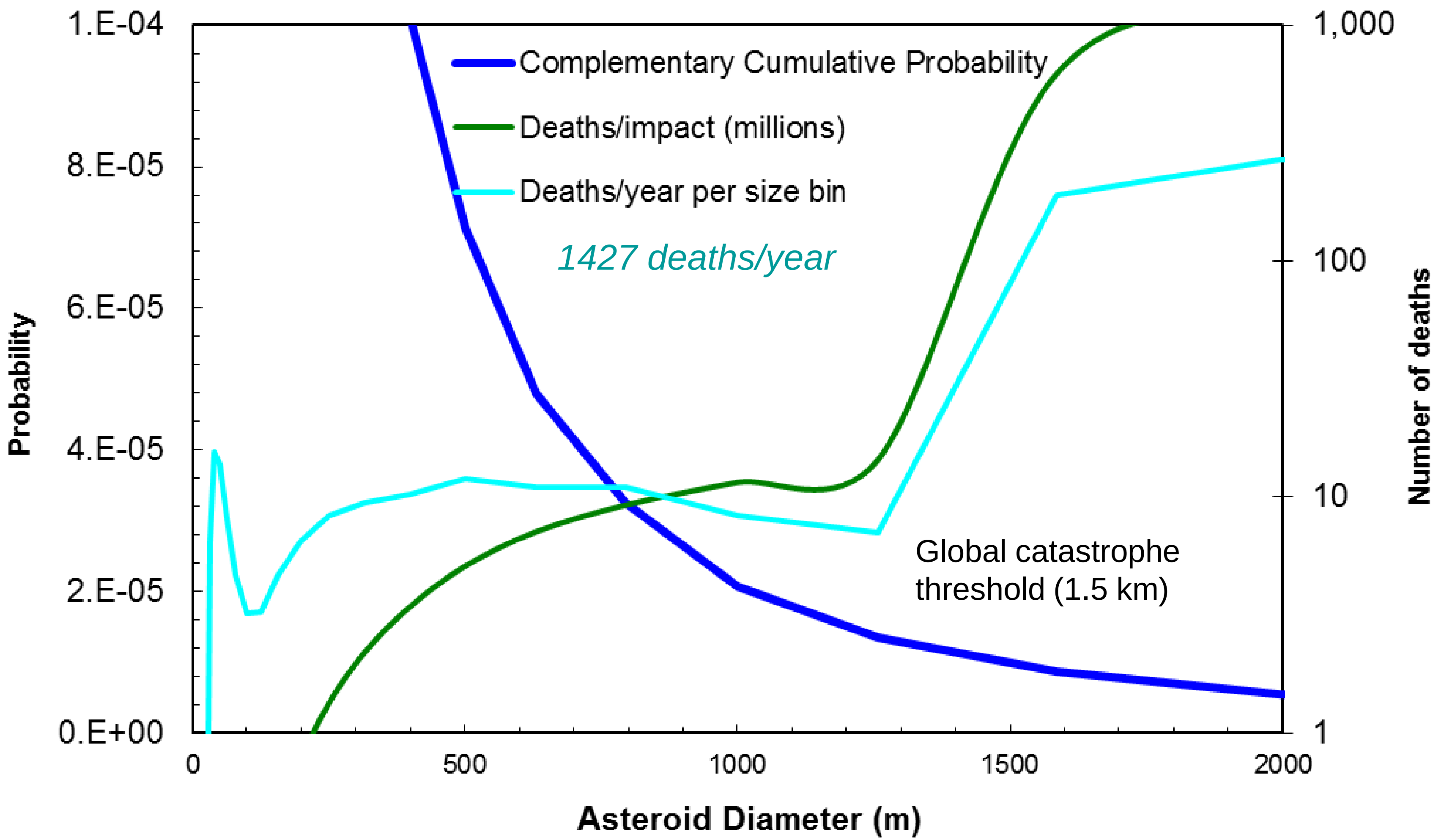
Point-source airbursts (green curve)
2010 population (red & blue curves)
Total probabilistic risk = 1363/year (risk based on no discovery)



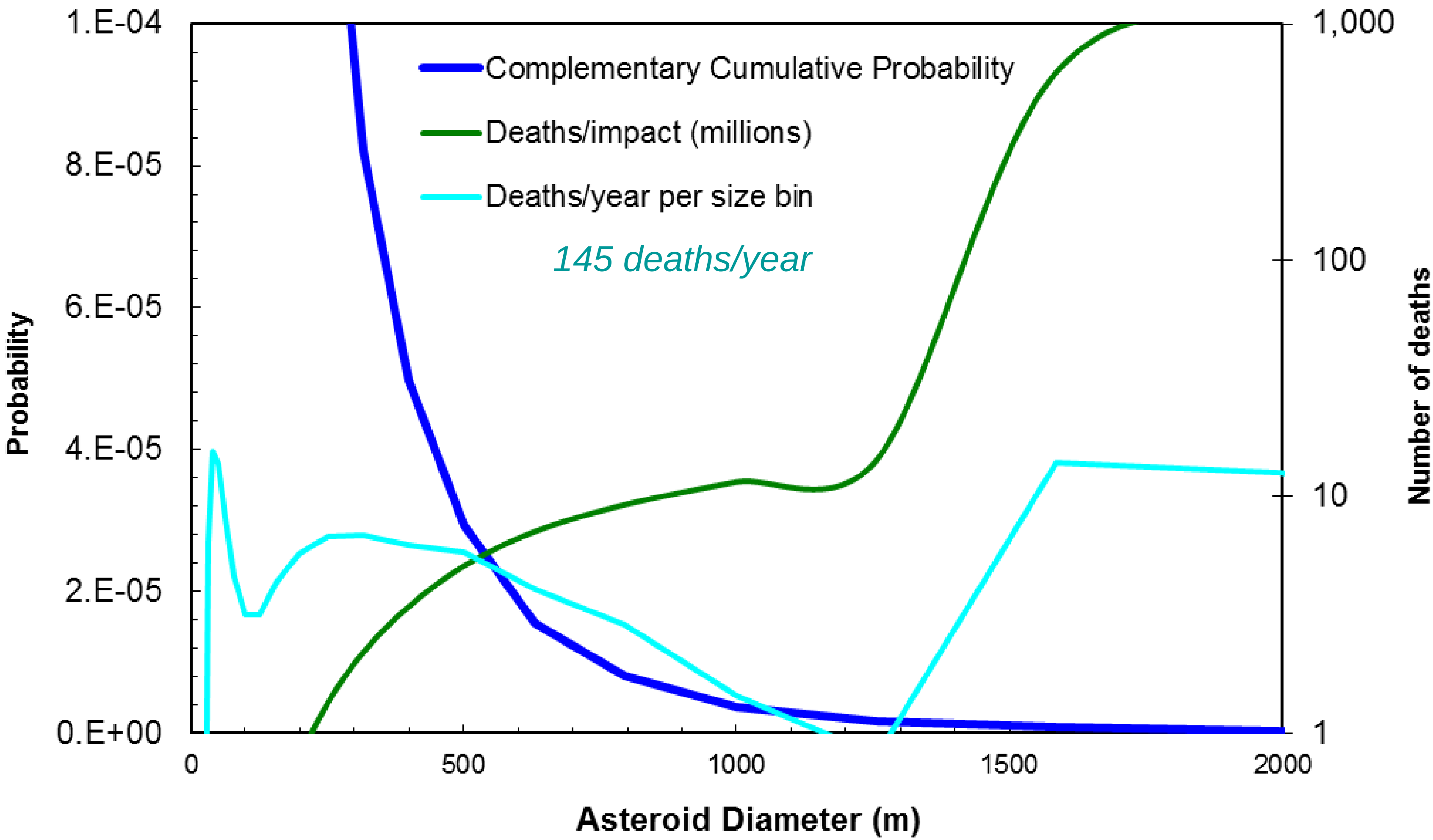
Directed airbursts (green curve)
2014 population (red & blue curves)
Total probabilistic risk = 1427/year (risk based on no discovery)



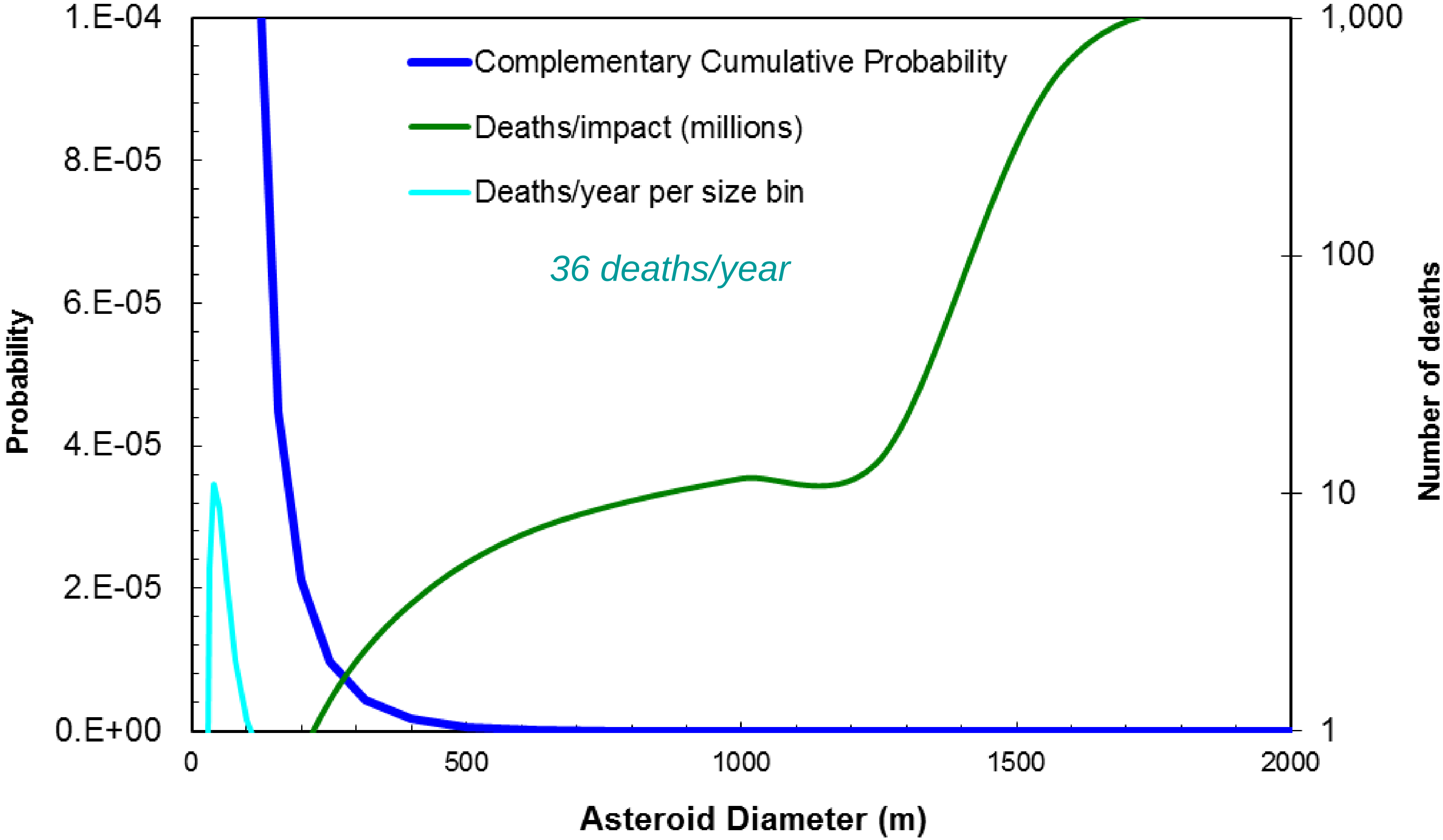
Directed airbursts (green curve)
2014 population (blue curve)
Total probabilistic risk = 1427/year (risk based on no discovery)
Previous graph was plotted on wider scale



Directed airbursts (green curve)
2014 population (blue curve)
Total probabilistic risk = 145/year (based on current survey)



Directed airbursts (green curve)
2014 population (blue curve)
Total probabilistic risk = 36/year (based on new survey)



7. Uncertainty Reduction Strategies

Transition surveys to short-warning after completion of George E. Brown survey

- Risk will be dominated by airbursts after completion of the next survey.
- Chelyabinsk (~20 m) asteroids pass within geosynchronous orbit every two years and within lunar orbit nearly once a week.
- A Tunguska-sized asteroid (~40 m) passes within a lunar distance several times a year.
- **A survey optimized to discover and count these objects would rapidly reduce the uncertainty in their populations.**
- Such a survey would also be the most likely way to save lives.
- A short-warning survey would also provide opportunities for airburst model validation, data collection on high-pressure properties of asteroids, meteorite collection, and adventure/astronomy tourism!

Questions?