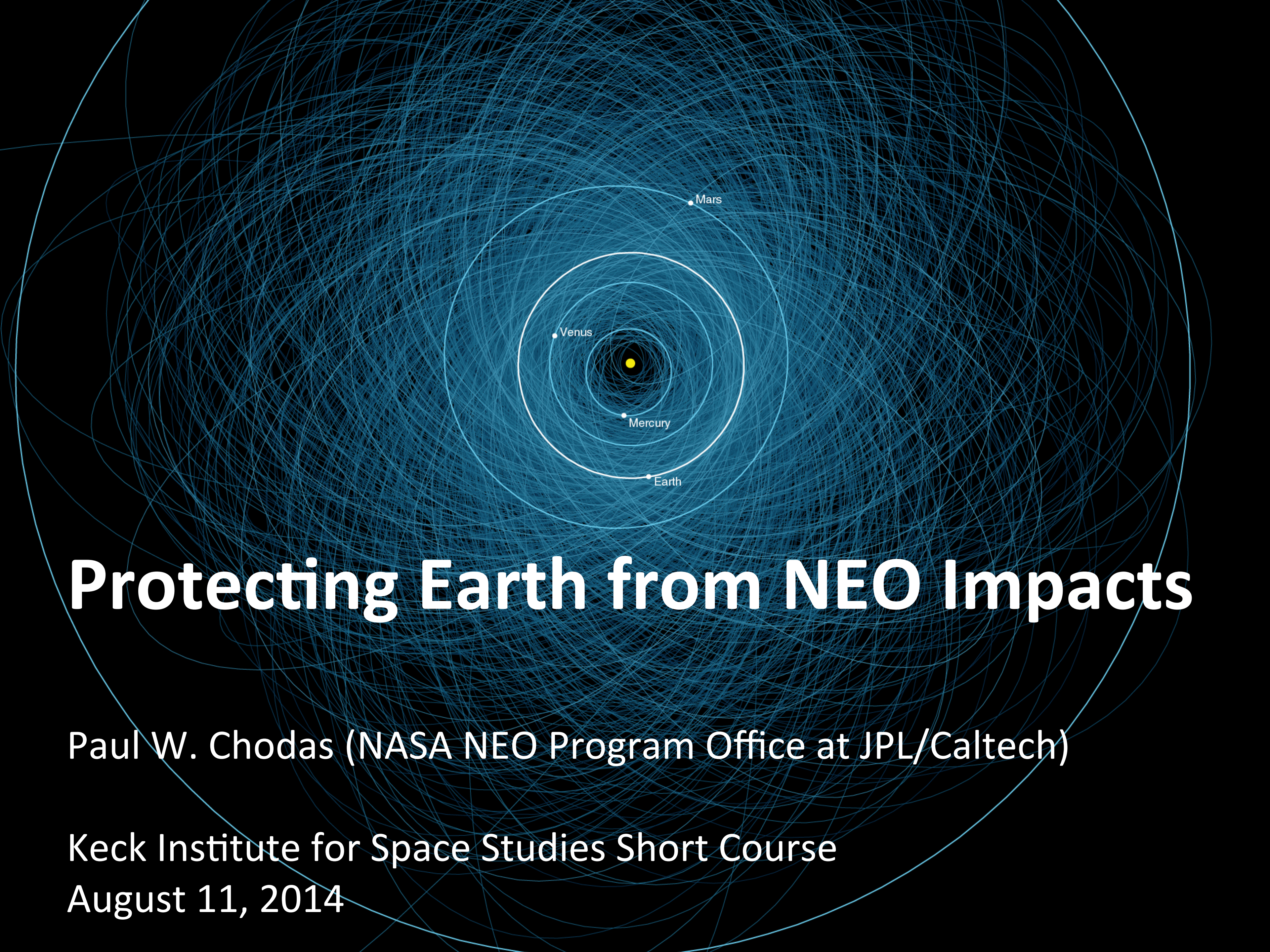
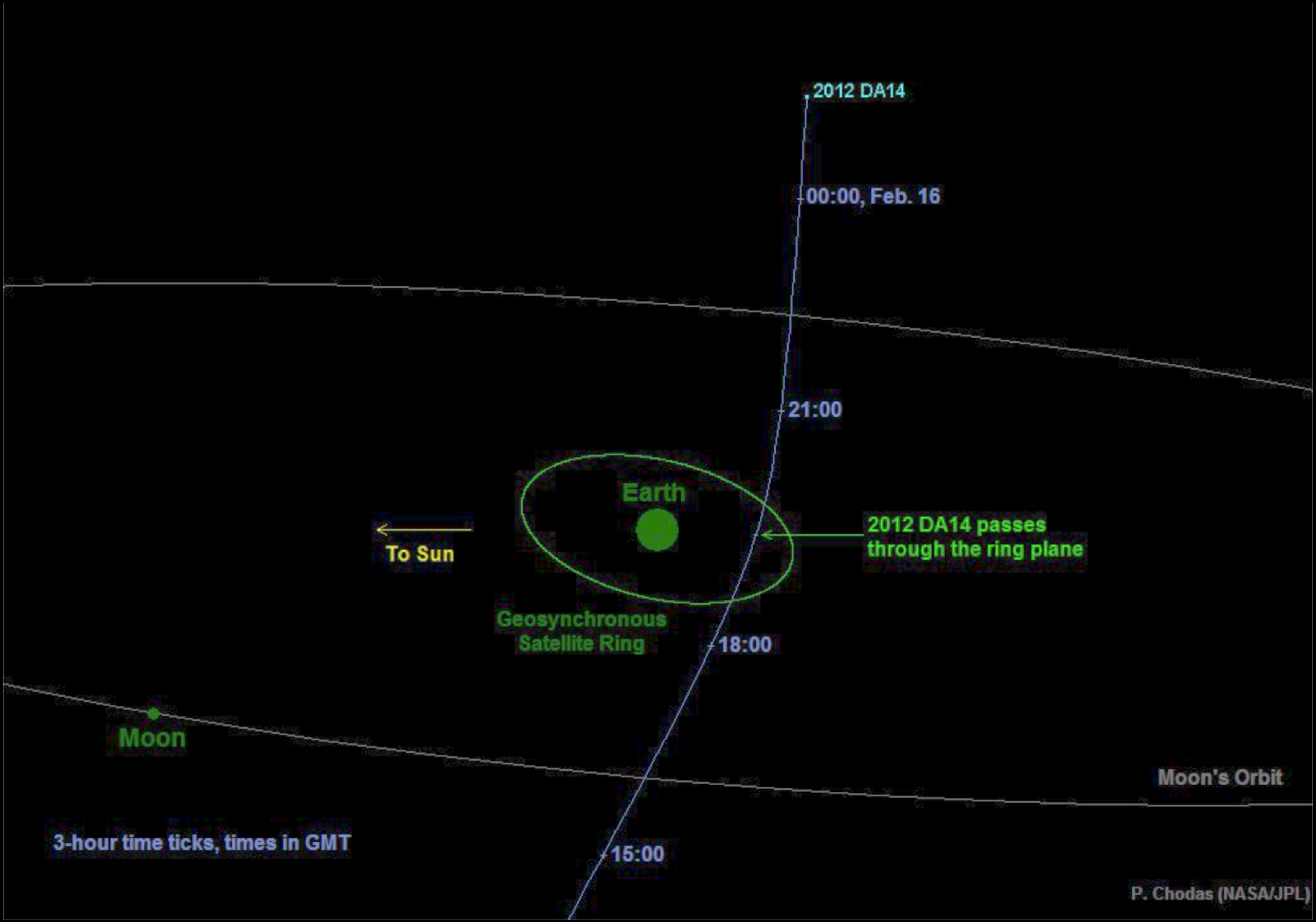


Protecting Earth from NEO Impacts

Paul W. Chodas (NASA NEO Program Office at JPL/Caltech)

Keck Institute for Space Studies Short Course
August 11, 2014

Close Approach of Asteroid 2012 DA14, Feb. 15, 2013



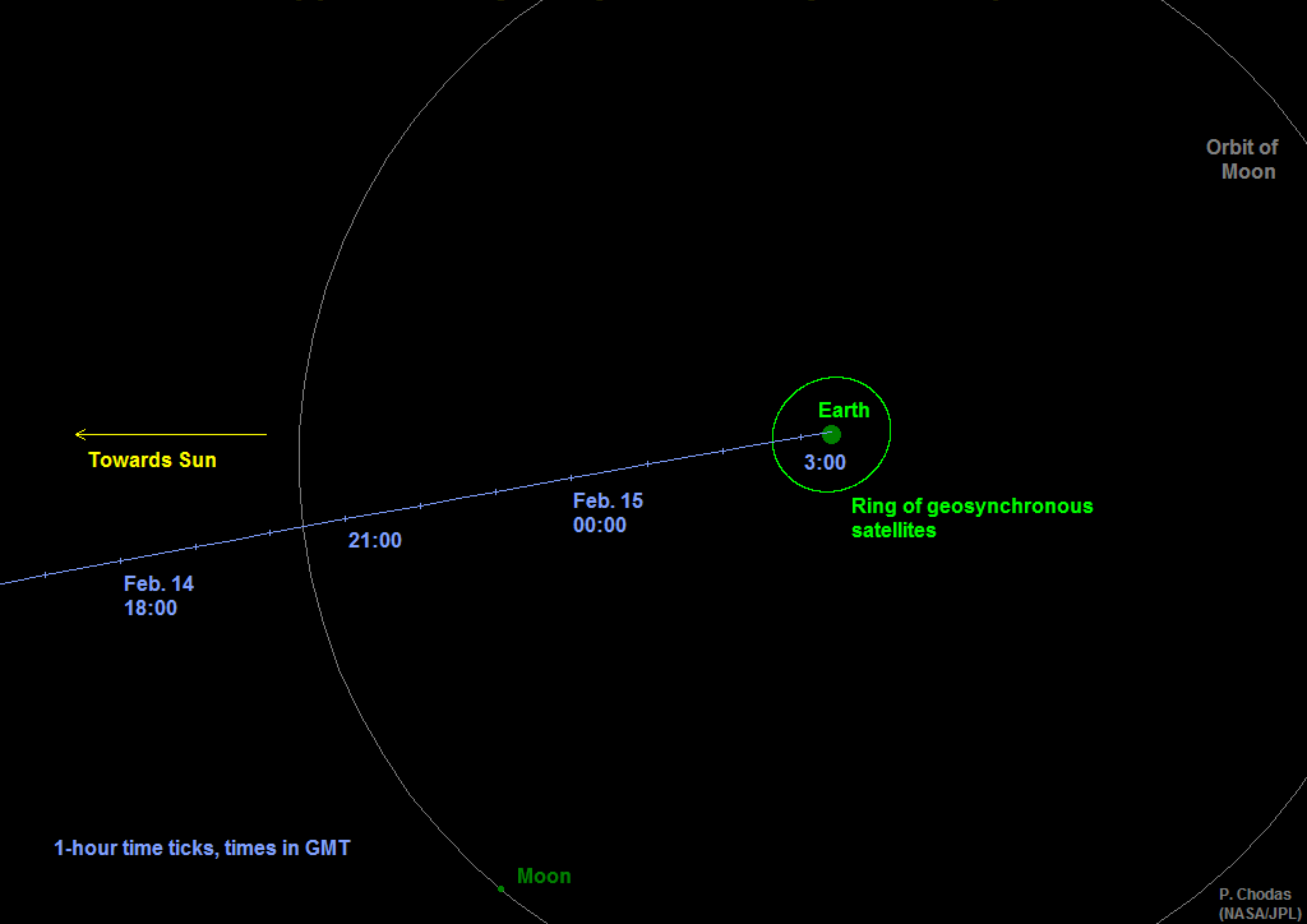
Chelyabinsk Airburst, Sunrise on Feb. 15, 2013

~20-meter asteroid, 500 kt of energy released at ~30 km altitude

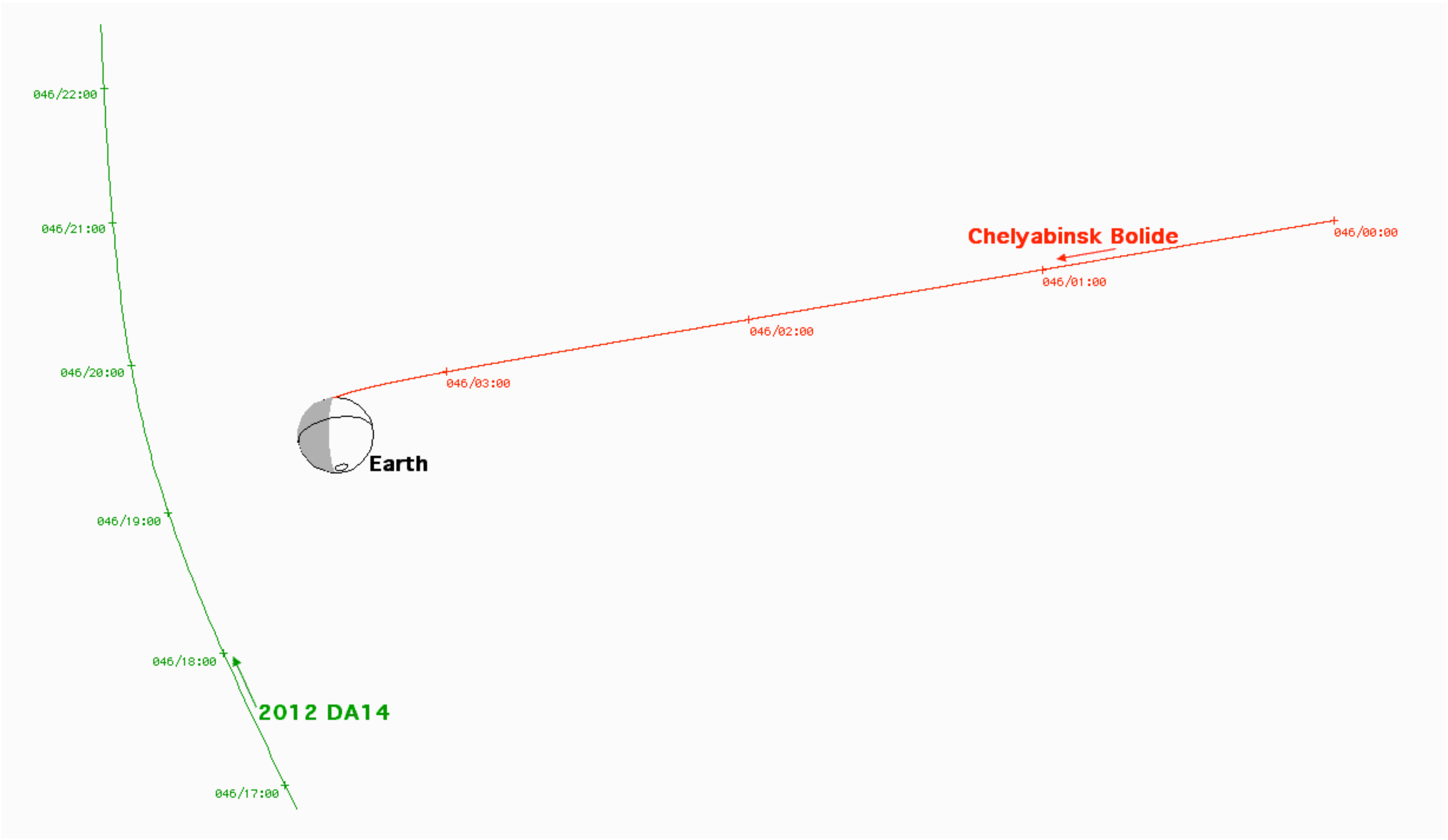
Main Mass Landed in Lake Chebarkul

- Final fragment ended ablation at ~15km altitude - estimated to be ~500 kg based on model comparisons to observed deceleration and brightness.
- Fragment traveled ~30 km horizontally and impacted in the Southern part of Lake Chebarkul, leaving a 8m hole in ice.
- Impact speed = ~200 m/s.
- Meteorite type : Ordinary Chondrite (LL5)

Final Approach Trajectory of the Chelyabinsk Impactor

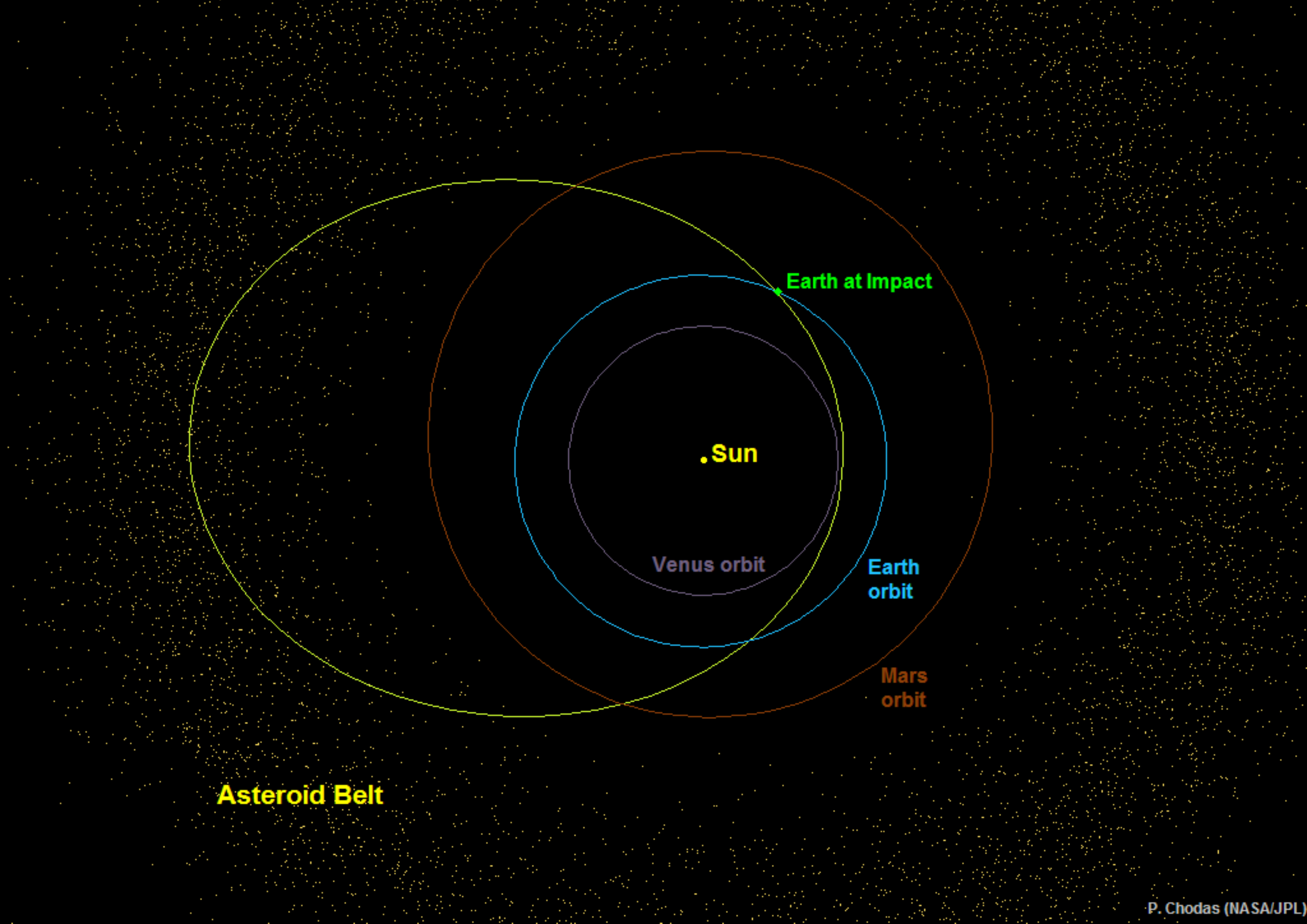


Two Extremely Close Approaches on Feb. 14



Courtesy of Dan Adamo

Pre-Impact Orbit About the Sun of the Chelyabinsk Impactor



Tunguska, Siberia (1908)

- 40m object; impacts of this size every few hundred years

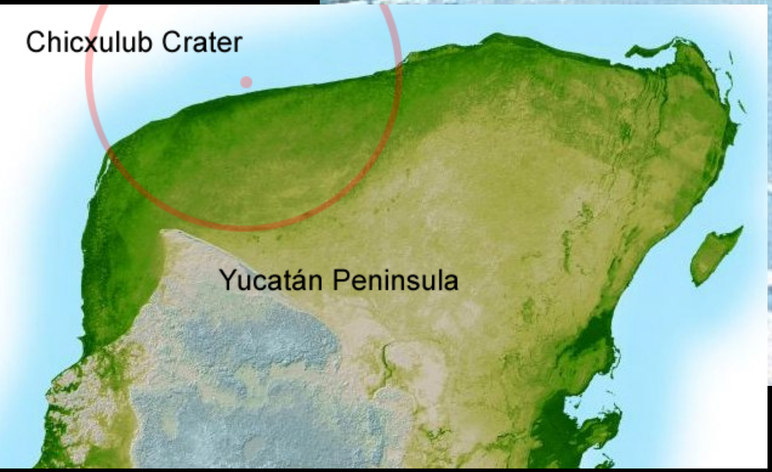
Meteor Crater, Arizona (50,000 years ago)

- A 40-50m asteroid, 1-km crater, ~50? mt
- Impacts like this occur every few thousand years

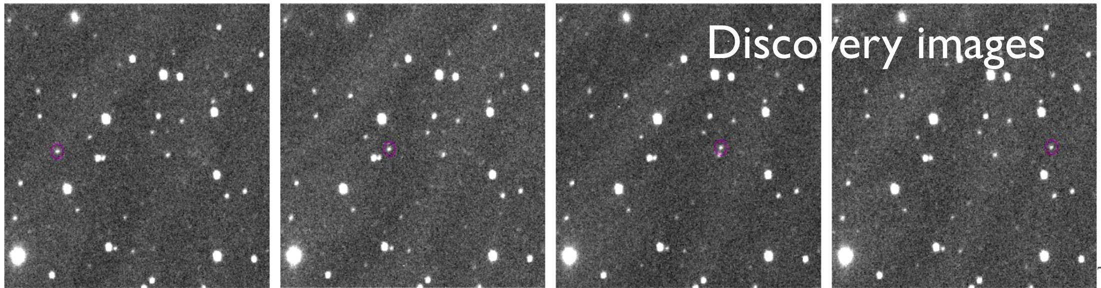
The Chicxulub Crater and the Demise of the Dinosaurs

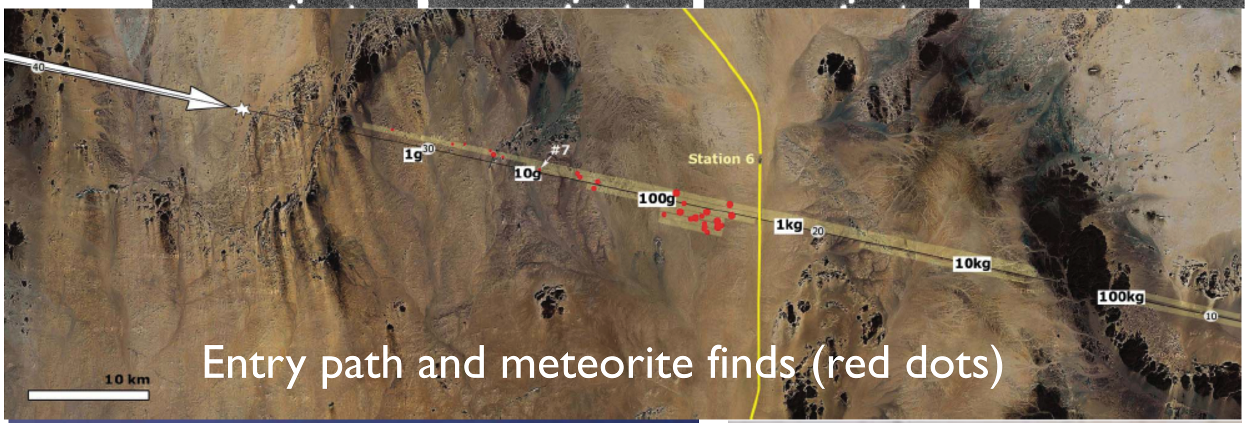
(65 million years ago)

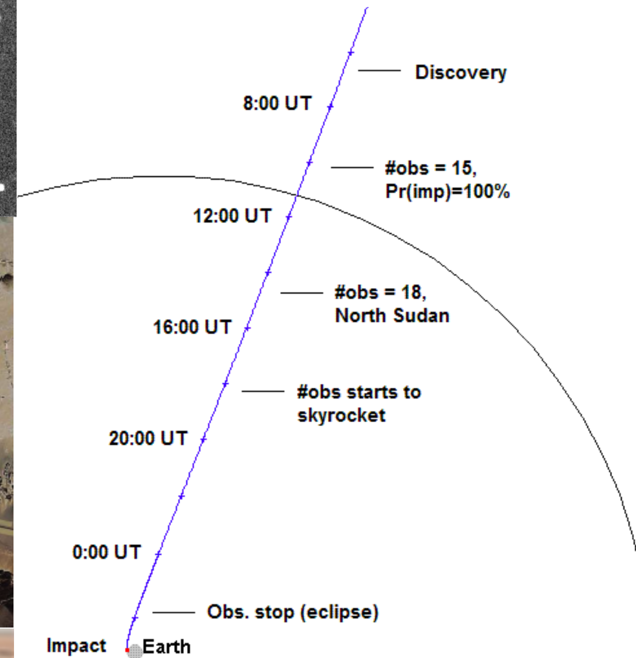
- Impacts of this size occur every 100 million years (or so)

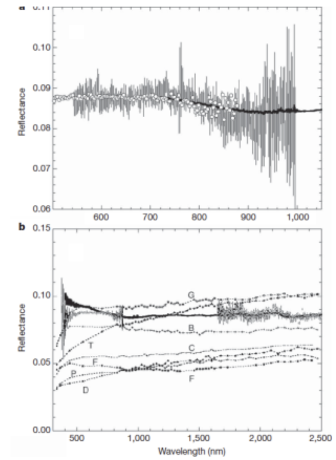


The amazing case of 2008 TC3



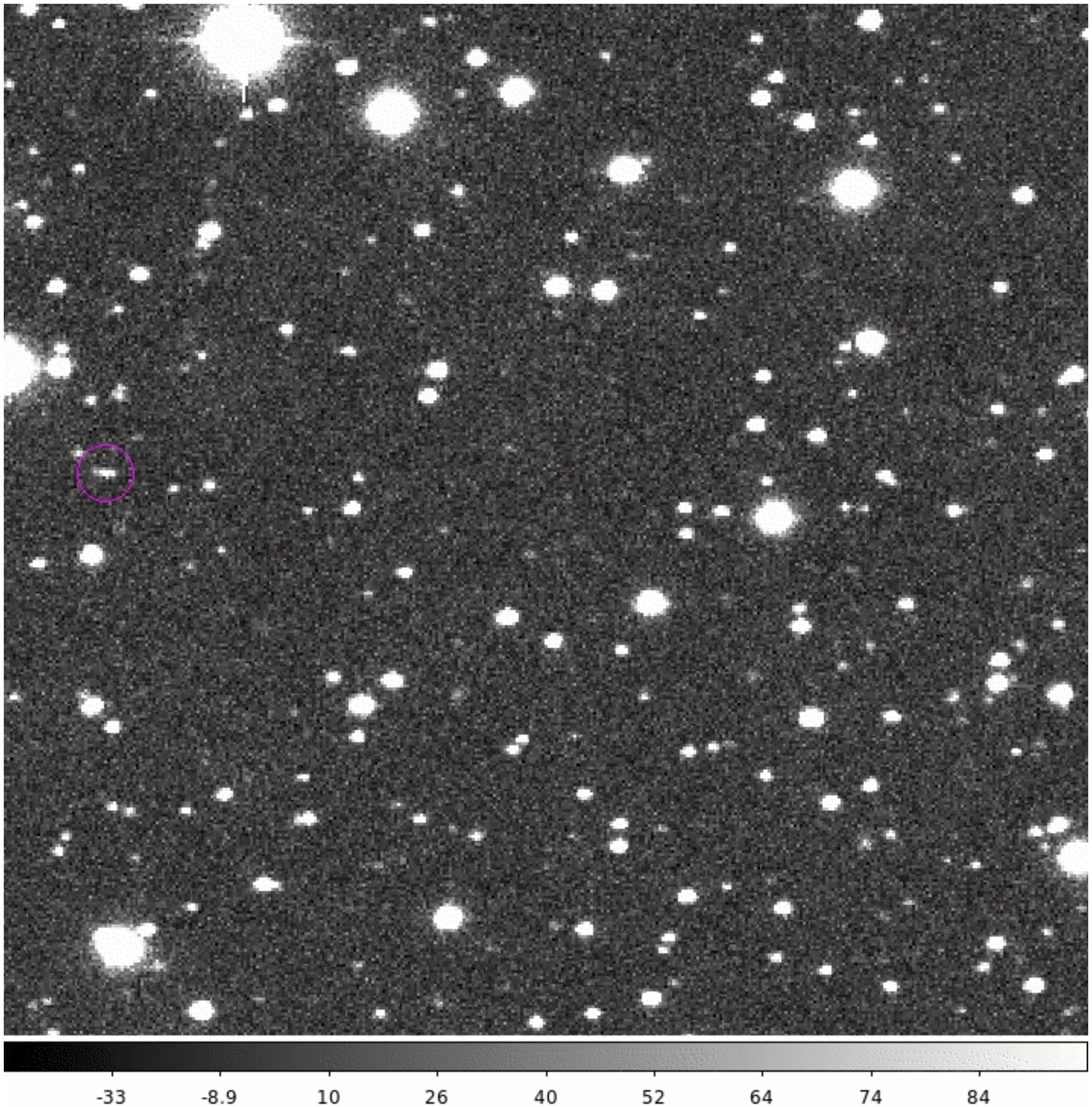






Spectrum
in space,
in lab

First Asteroid of 2014 Impacts the Earth

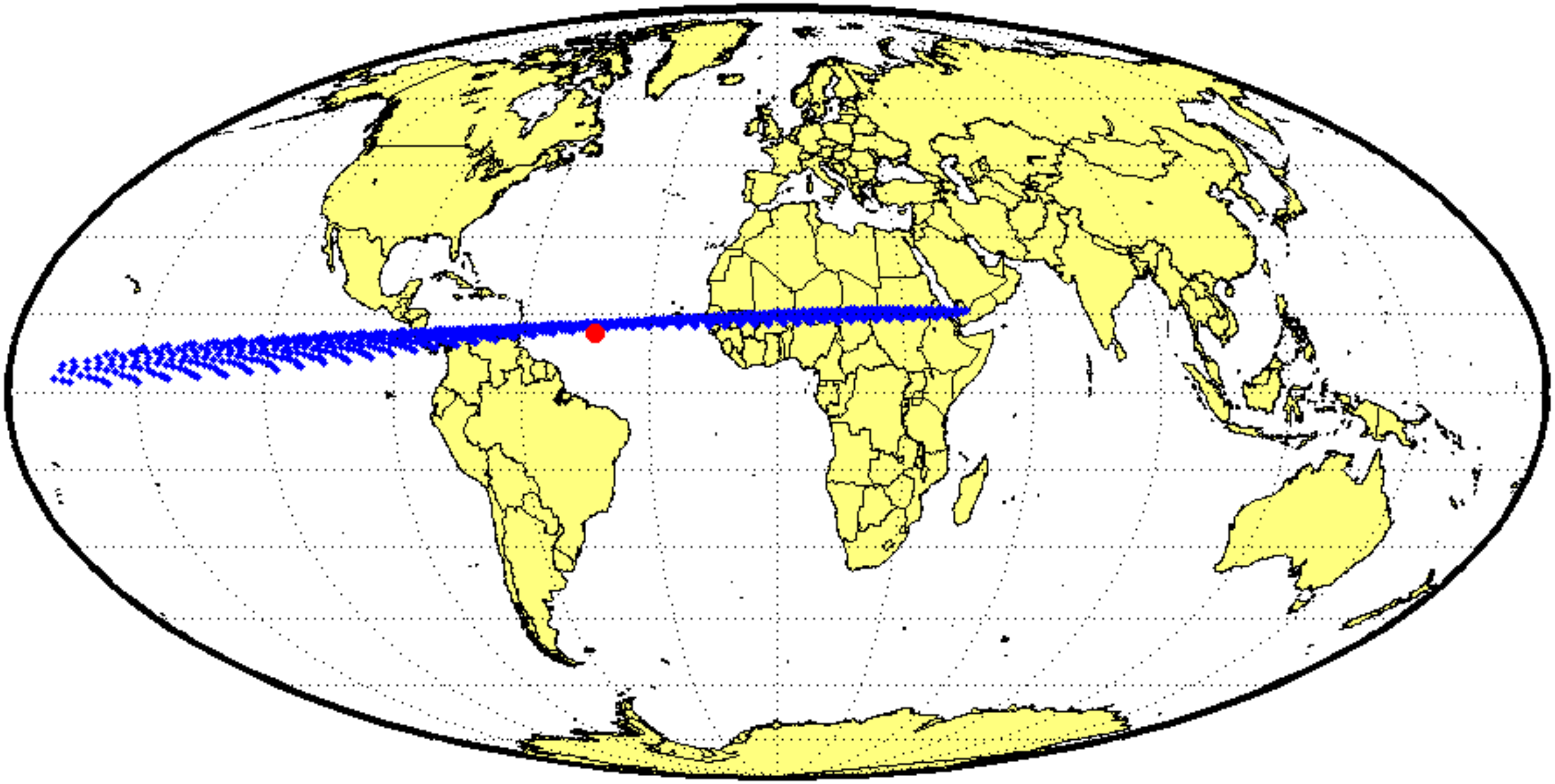


Discovered by the Catalina Sky Survey, Jan. 1, 2014

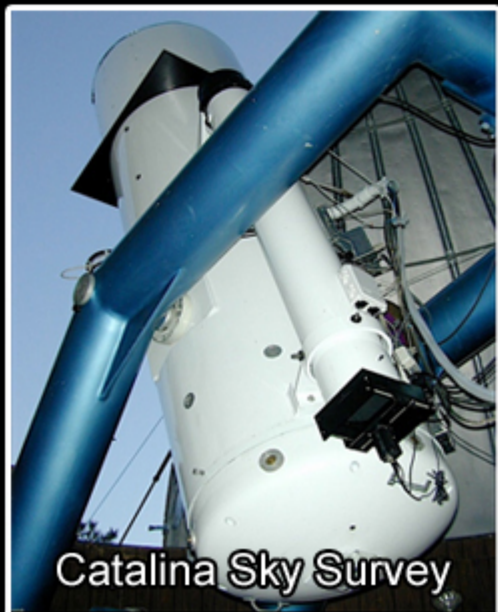
Not followed up Immediately

These are the only 4 observations!

2014 AA Impact Prediction

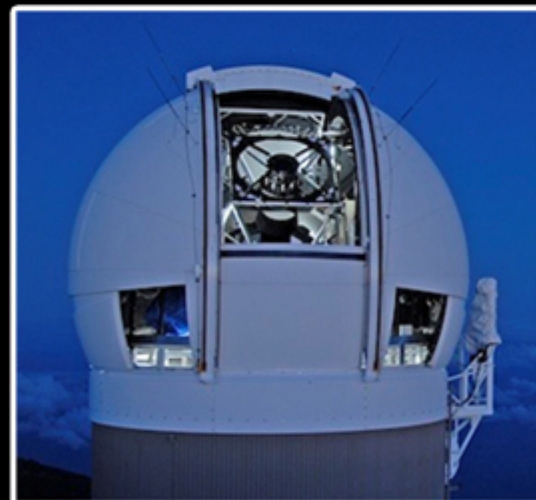


NASA's Current Asteroid Search Programs

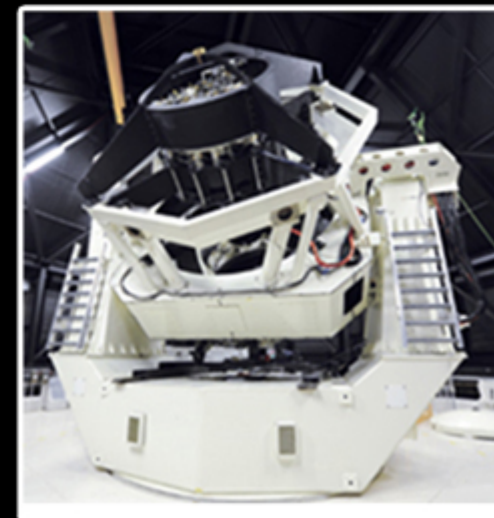


Catalina Sky Survey

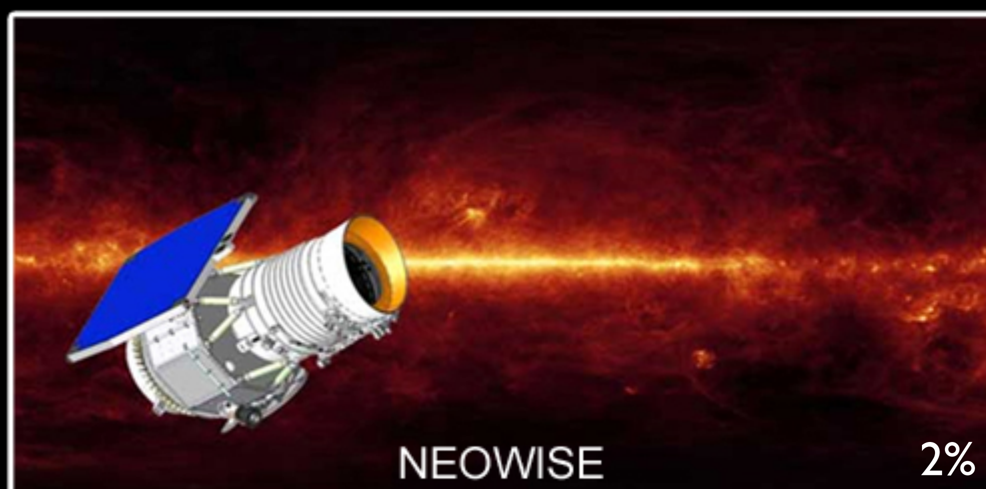
50%



Pan-STARRS-1 40%



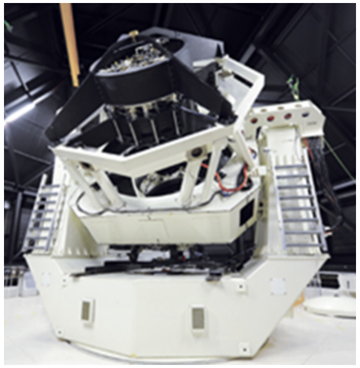
DARPA Space Surveillance Telescope

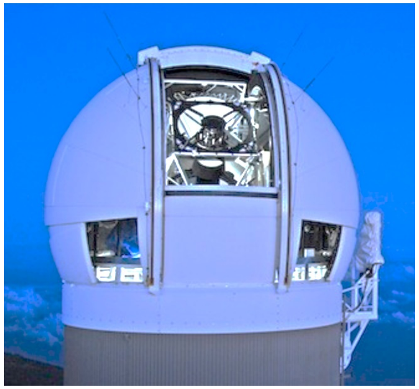


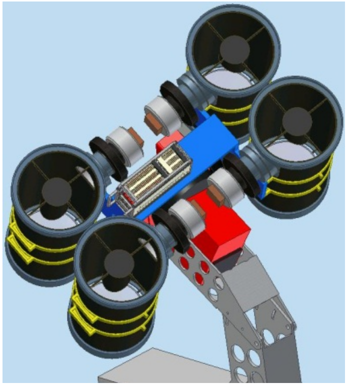
NEOWISE 2%

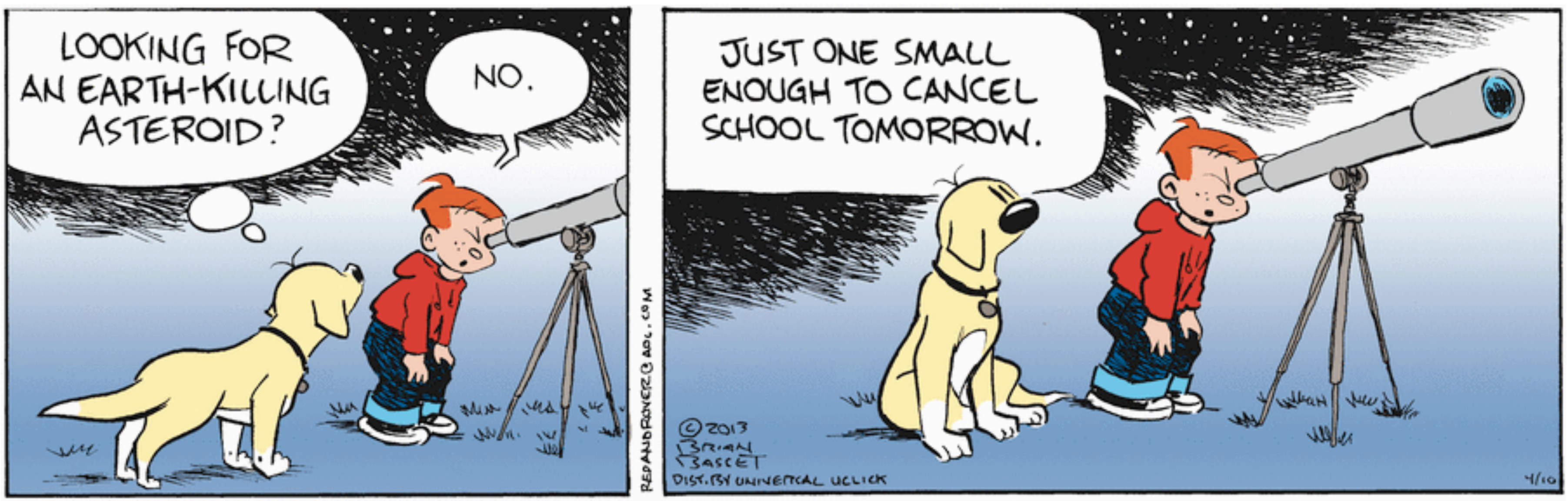
Primary Enhancements to Asteroid Surveys

- **NEO Time on DARPA Space Surveillance Telescope**
  - Large 3.6m telescope, first light: Feb 2011, now in testing
  - Developed for DoD Space Situational Awareness
  - Routine NEO observing started in **Summer 2014**
  - 130,000 obs have already been delivered to MPC
- **Enhancing Pan-STARRS 1, Completing Pan-STARRS 2**
  - Increase NEO search time to 100% on PS1: **March 2014**
  - Complete PS2 (improved copy of PS1): **Early 2015**
- **Accelerated Completion of ATLAS**
  - Set of small telescopes with extremely wide fields of view covering the entire night sky every night, but not as deeply
  - Final design completed. 1st system completion: **Late 2015**
  - Prototype being set up at Mauna Loa NOAA site
- **New telescopes with increased aperture and sensitivity, on the ground and in space, are needed to find the majority of the smaller (~100-300 m) asteroids**

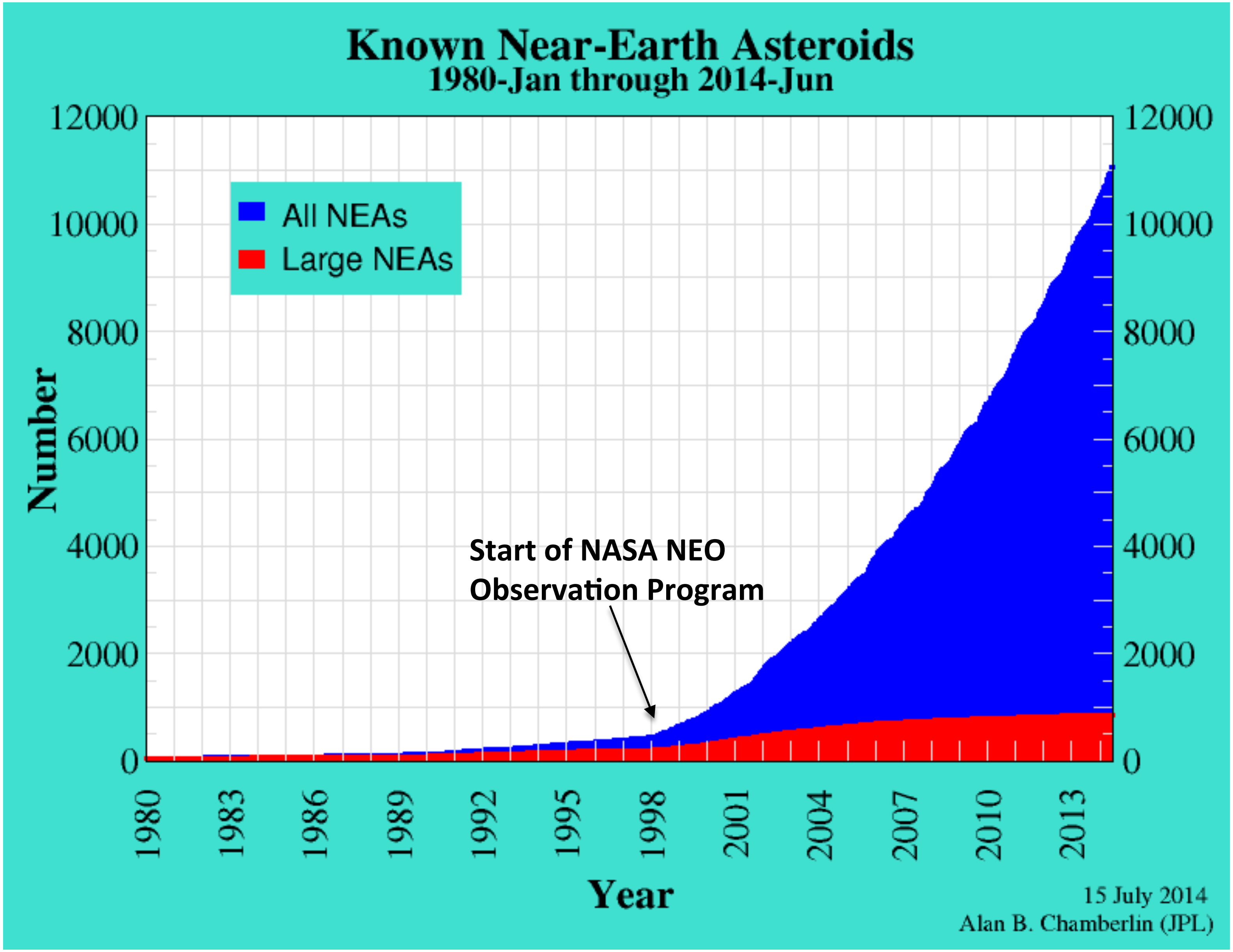







LOOKING FOR AN EARTH-KILLING ASTEROID?
NO.
JUST ONE SMALL ENOUGH TO CANCEL SCHOOL TOMORROW.
REDANDROVER.COM
© 2013 BRIAN BASSET
DIST. BY UNIVERSAL UCLICK
4/10

Near-Earth Asteroids (NEAs)

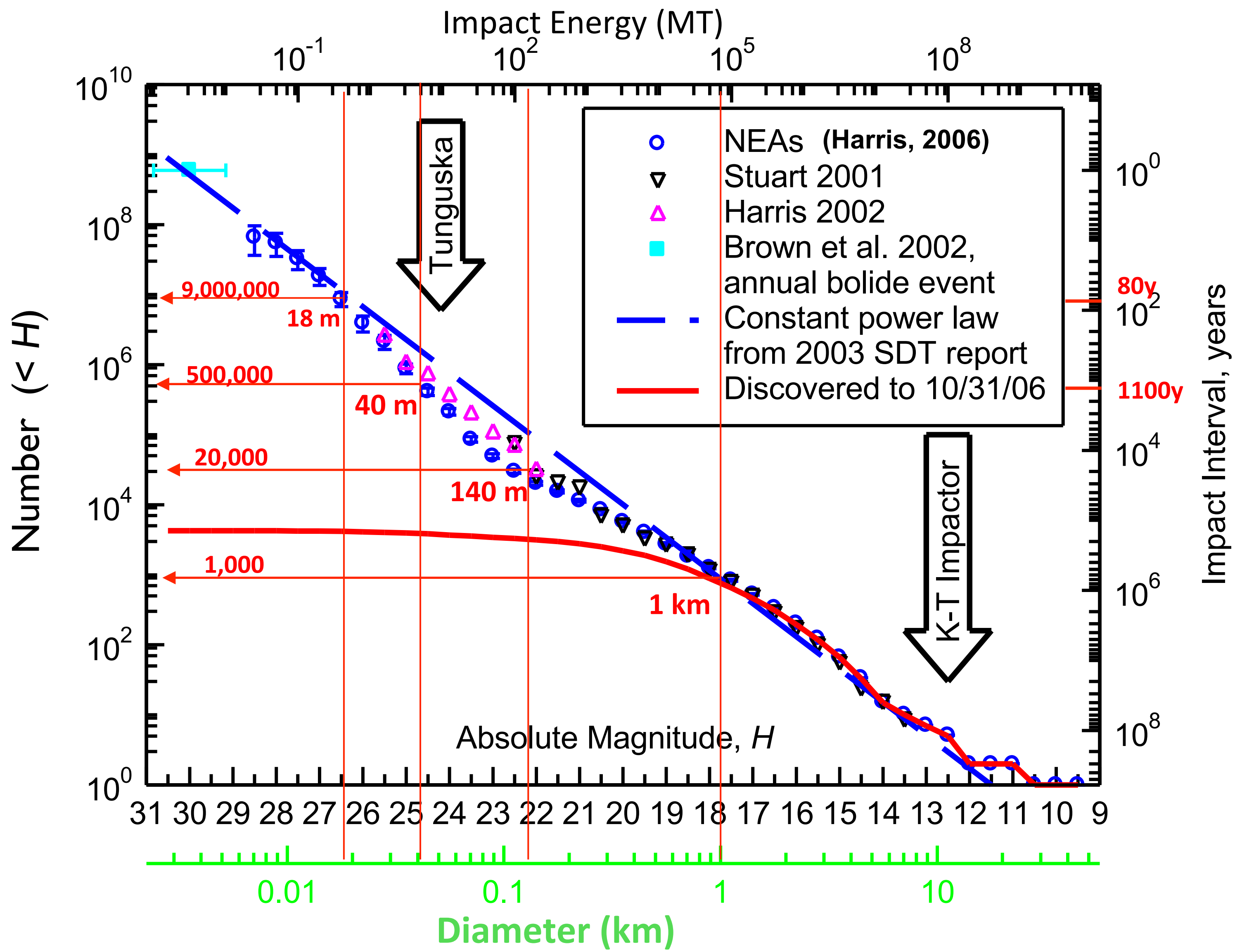


11,216 NEAs Currently Known (1200/year)

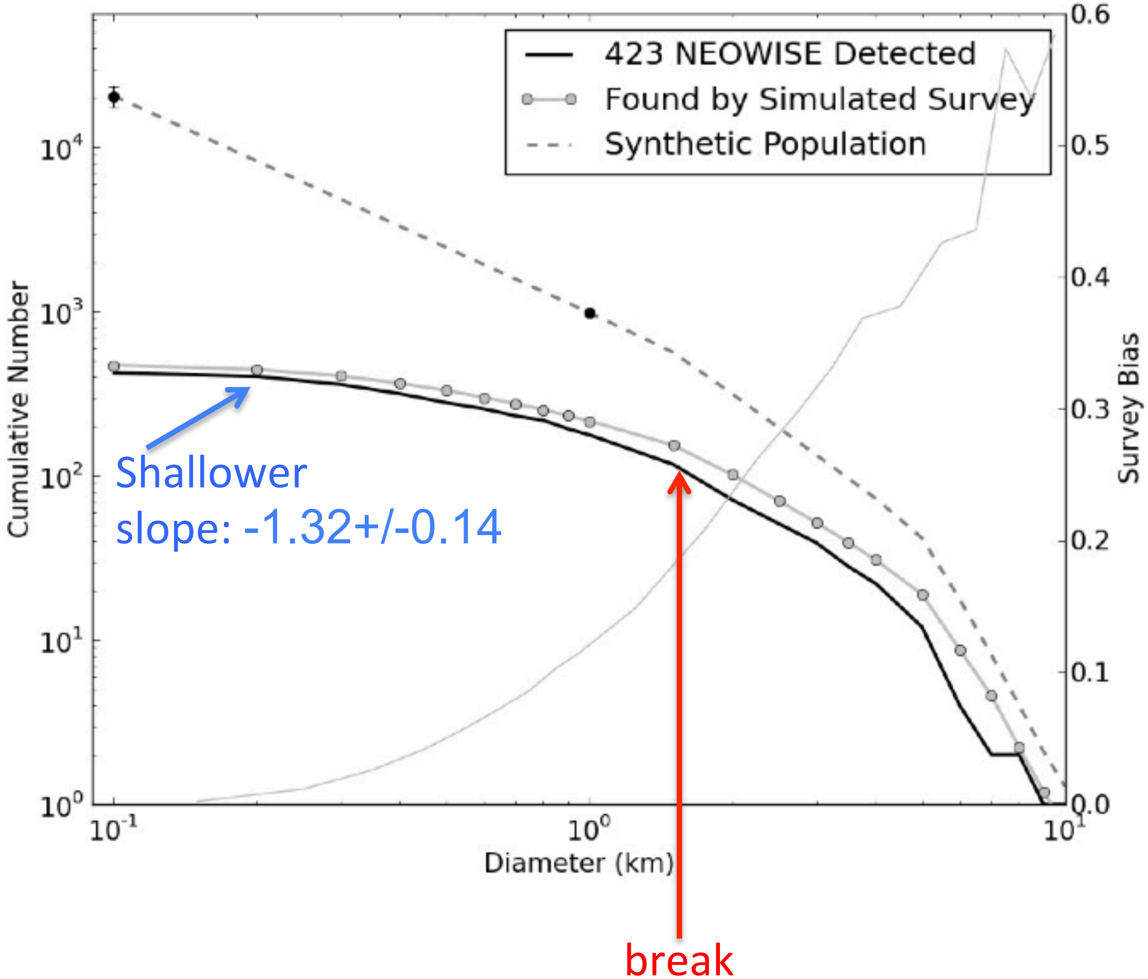
865 are "Large" (> 1 km in diameter)

Large NEAs are those that would produce a global catastrophe if they hit the Earth

Population & Impact Frequency vs. Abs. Magnitude & Size

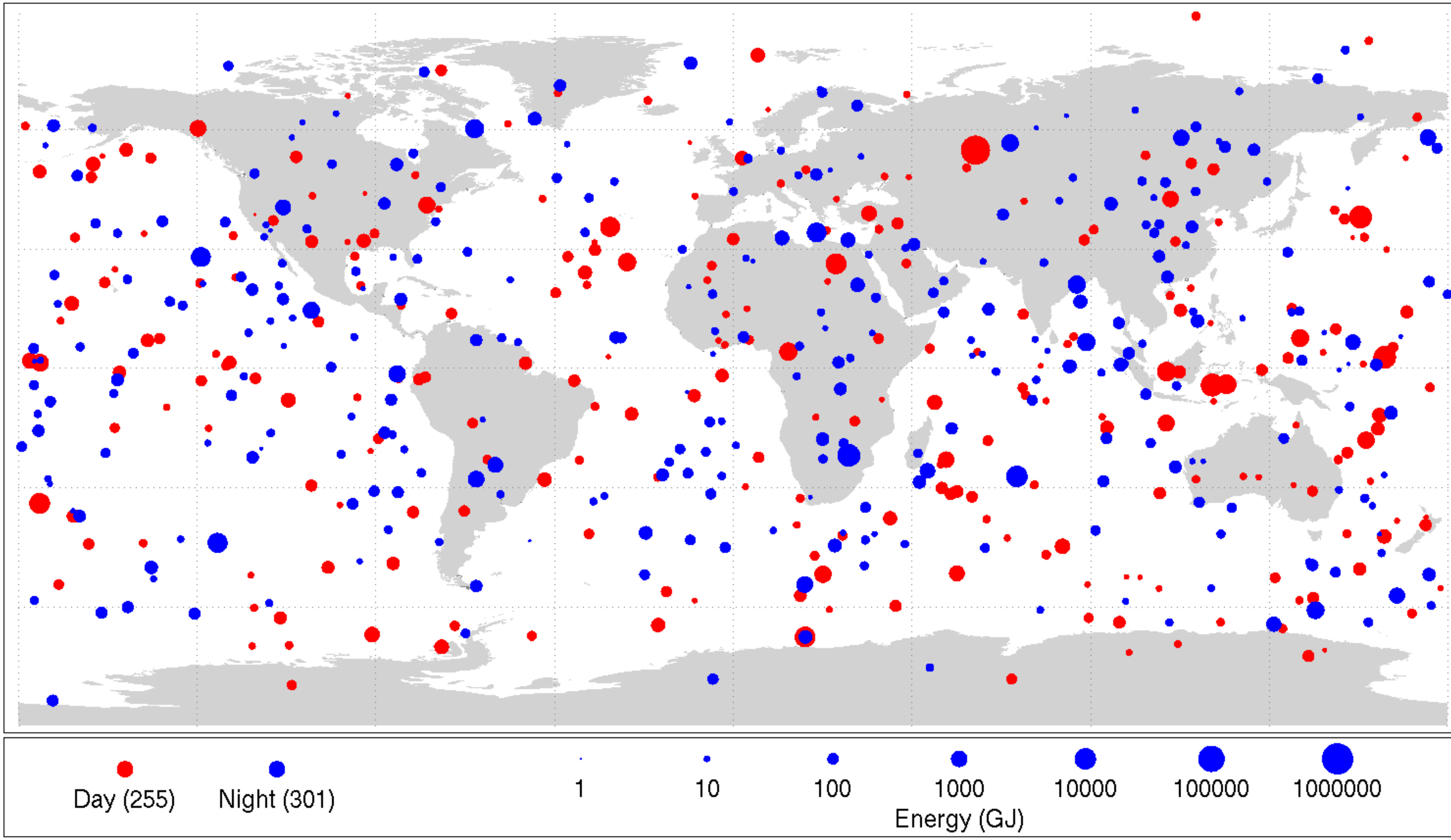


Near-Earth Asteroid Numbers & Sizes

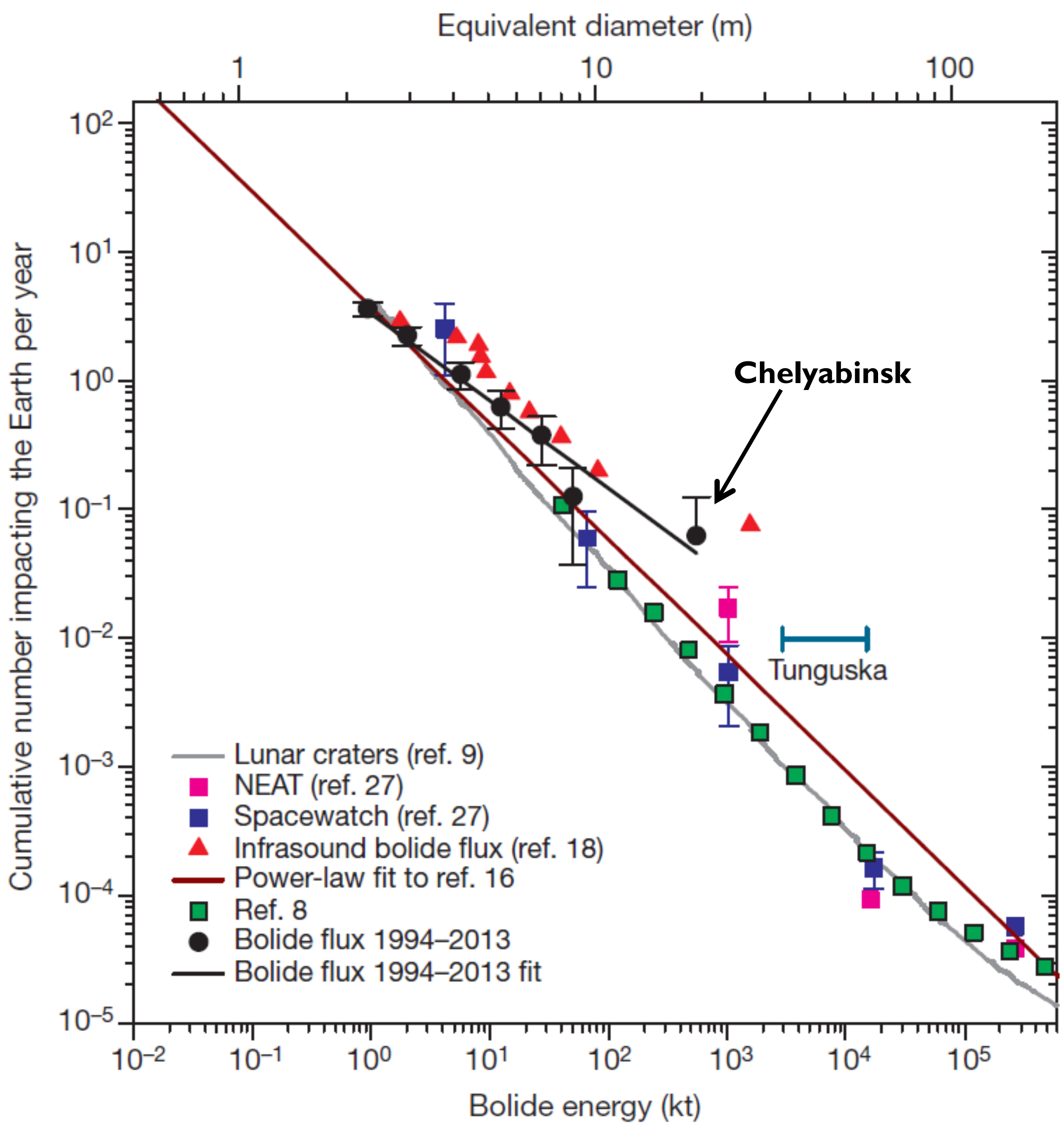


- Use well-known sensitivity & uniformity of four band survey to compute total numbers from observed sample
- 20,500+/-3000 @ 100m vs. prior estimates of 36,000 – 100,000
- Mainzer et al. 2011 ApJ 743, 156

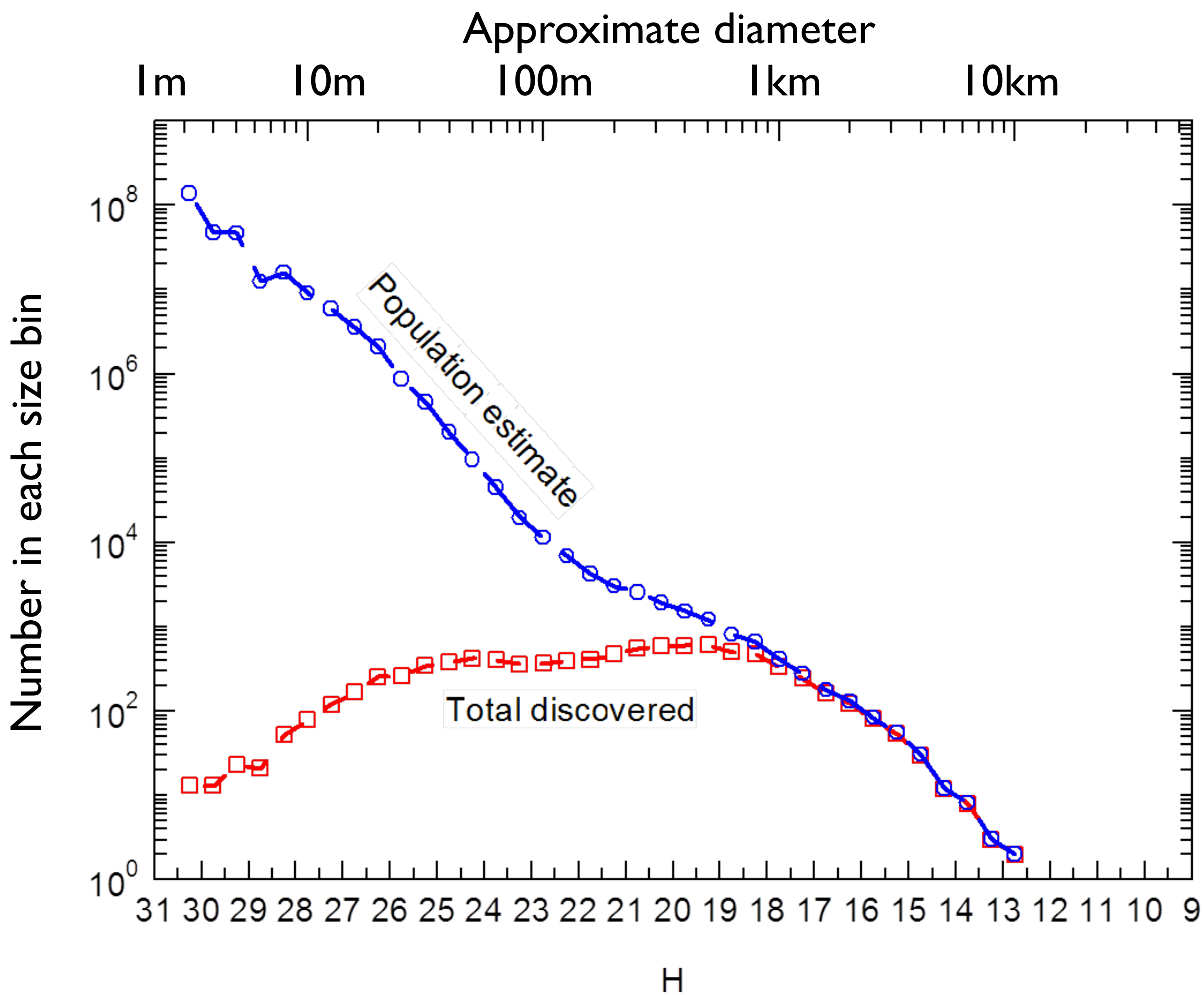
Bolide Events 1994 - 2013



Estimated Cumulative Flux of Small Impactors (Brown et al. 2013)



Estimated NEA Population vs. Size



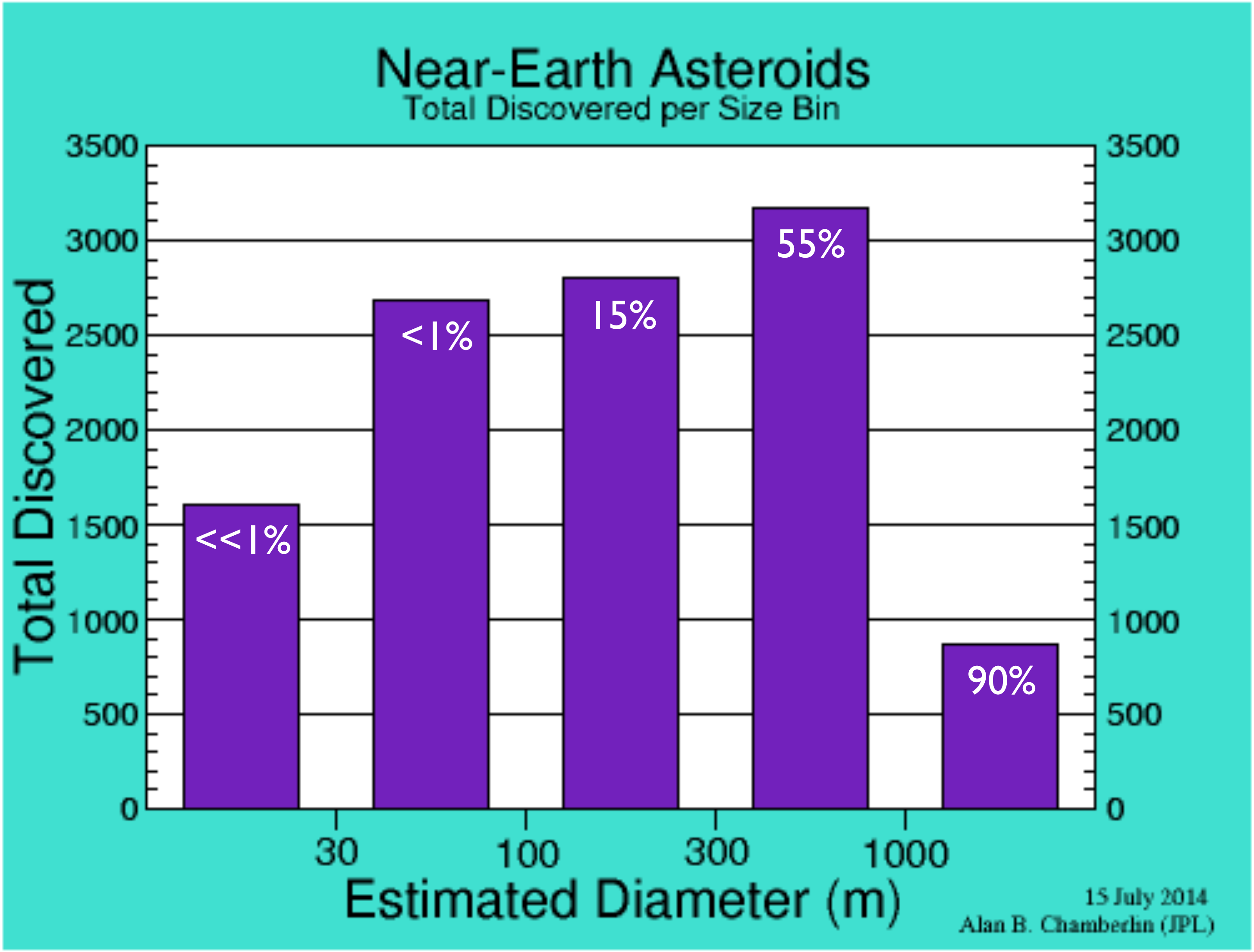
Courtesy of
Al Harris (MoreData!)

Asteroid Impact Effects vs. Object Size

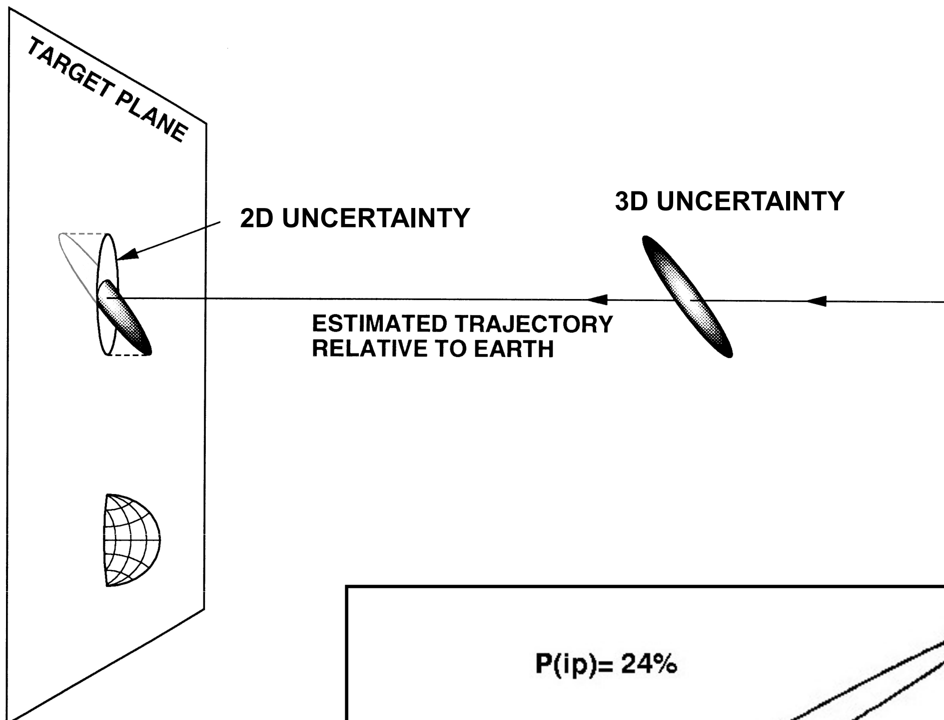
Diameter of Impacting Asteroid	Type of Event	Approximate Impact Energy (MT)	Average Time Between Impacts (Years)
5 m	Bolide	0.01	3
25 m	Airburst	1	200
50 m	Local Scale Devastation	10	2000
140 m	Regional Scale Devastation	300	30,000
300 m	Continent Scale Devastation	2,000	100,000
600 m	Below Global Catastrophe Threshold	20,000	200,000
1 km	Possible Global Catastrophe	100,000	700,000
5 km	Above Global Catastrophe Threshold	10,000,000	30 million
10 km	Mass Extinction	100,000,000	100 million

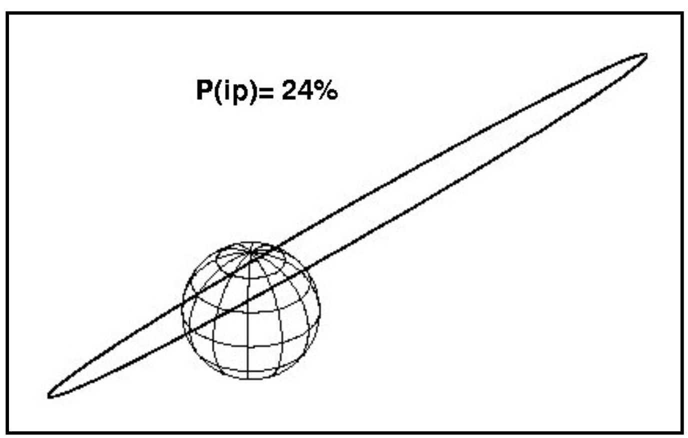
Adapted from table by Bill Ailor (Aerospace)

NEA Discovery Completeness vs. Size



Impact Probability





- Predict 3D position uncertainty at time of close approach.
- Set up Target plane ("*b-plane*") perpendicular to velocity relative to Earth.
- "Squash" the 3D uncertainty into a 2D uncertainty in the plane.
- Impact probability is roughly the fraction of the 2D uncertainty that overlaps the Earth disc.

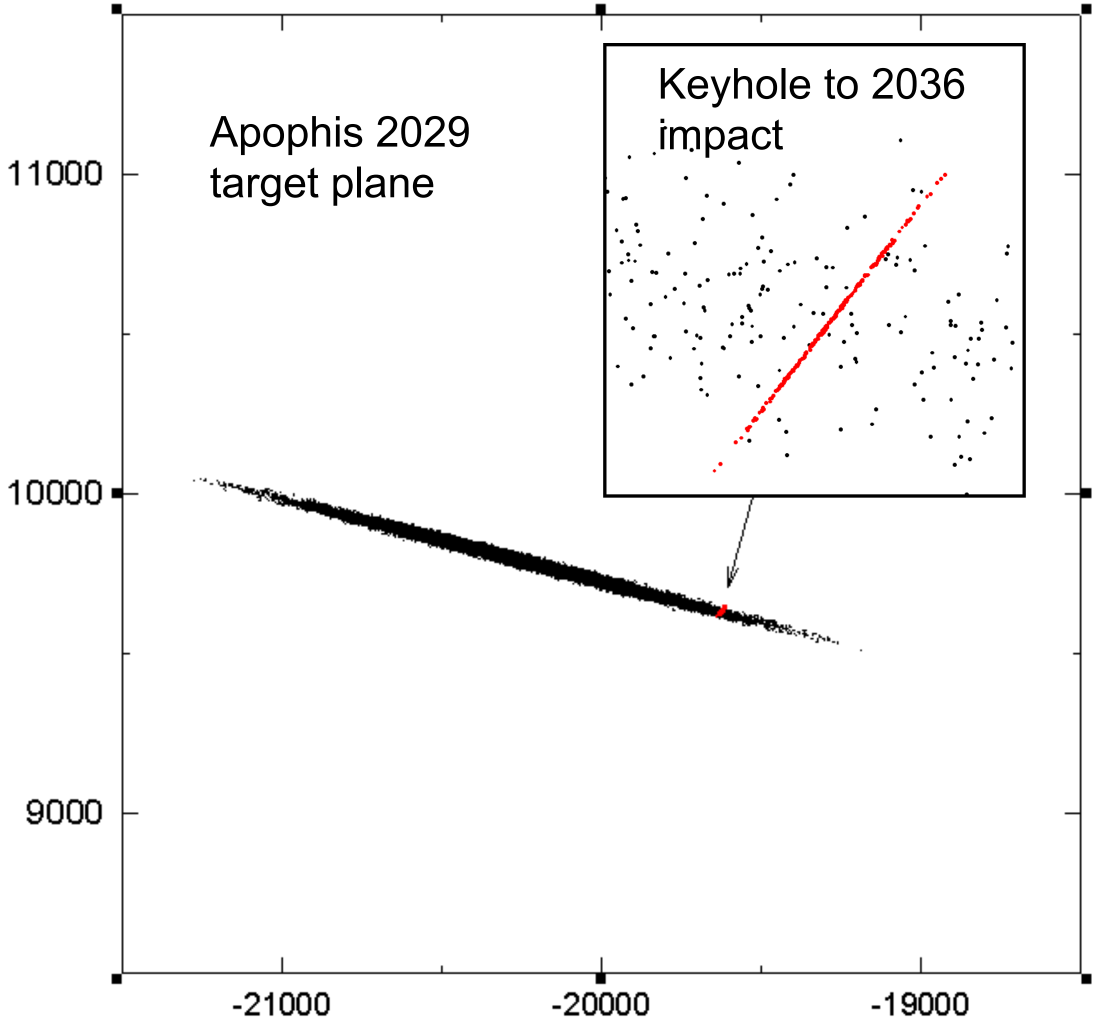
Sentry Risk Table: http://neo.jpl.nasa.gov/risk

511 NEAs: Last Updated Aug 10, 2014
Sort by Palermo Scale (cum.) or by Object Designation

Recently Observed Objects
(within past 60 days)

Object Designation	Year Range	Potential Impacts	Impact Prob. (cum.)	$V_{infinity}$ (km/s)	H (mag)	Est. Diam. (km)	Palermo Scale (cum.)	Palermo Scale (max.)	Torino Scale (max.)
2014 OO6	2045-2110	23	2.5e-05	17.85	23.2	0.076	-3.53	-3.76	0
2014 OM339	2070-2087	2	2.4e-06	9.51	21.2	0.200	-3.91	-3.91	0
2014 NZ64	2017-2113	394	2.1e-06	6.63	22.5	0.108	-4.28	-5.03	0
2013 XK22	2101-2114	2	4.2e-05	6.90	24.0	0.053	-4.30	-4.31	0
2014 PB58	2028-2113	11	1.2e-07	28.78	20.6	0.260	-4.35	-4.63	0
2014 NG65	2025-2114	112	5.7e-07	7.83	21.6	0.162	-4.52	-5.28	0
2014 ML67	2019-2113	27	6.9e-07	21.16	24.2	0.050	-5.02	-5.25	0
2014 MO68	2017-2113	251	1.5e-06	8.41	23.5	0.067	-5.09	-6.11	0

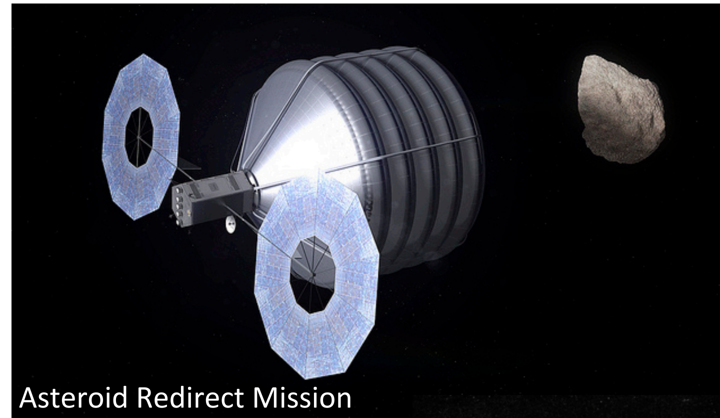
Keyholes

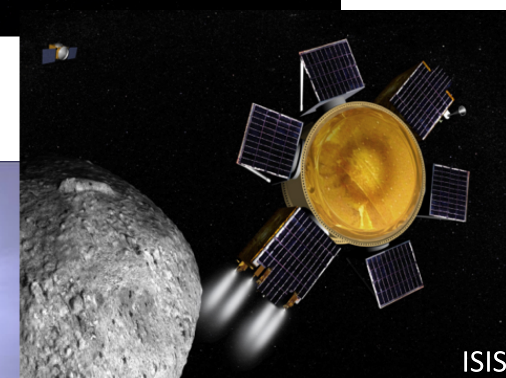


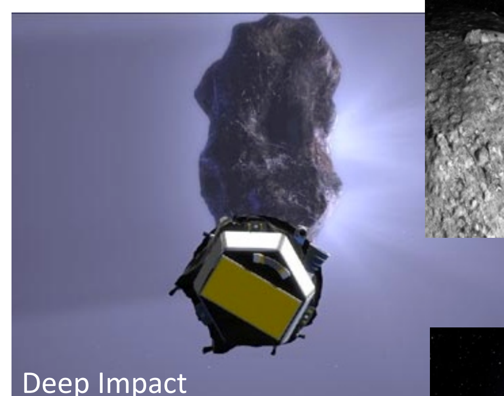
- **Keyhole**: narrow slice through the uncertainty region leading to impact in a later year.
- There may be many keyholes for impacts in many different years.
- Typically 10–100 km wide, but the Apophis 2036 keyhole was only 600m wide.
- Positions and widths of keyholes are essentially fixed by the encounter geometry.

Preventing an Impact

- An asteroid impact can be predicted and prevented by slightly altering the asteroid's orbit
- Possible deflection methods:
  - Kinetic Impactor (KI)
  - Standoff nuclear detonation
  - Gravity tractor
  - Ion Beam Deflection (IBD)
  - Laser ablation
- Solar electric propulsion (SEP) would be an enabling technology
- Key questions:
  - Size, density and mass
  - Strength, internal structure
  - Chemical composition
- Deflection demonstration missions are needed ahead of time


Asteroid Redirect Mission


ISIS

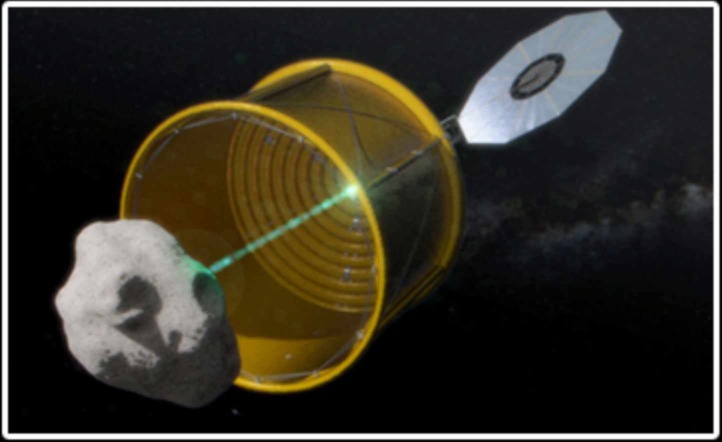

Deep Impact


Gravity Tractor

Summary of Current and Future ARM Candidates

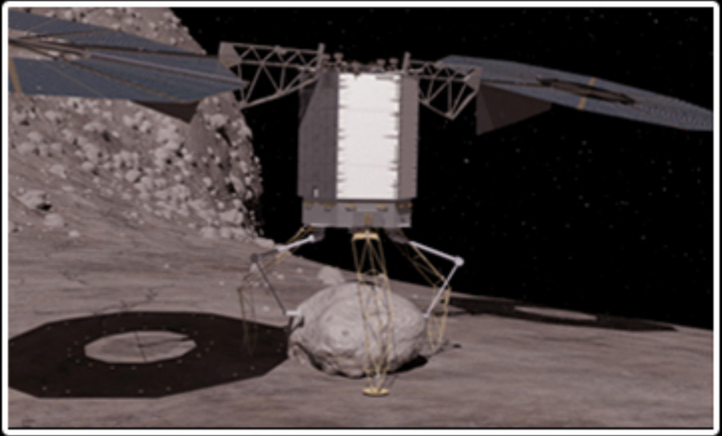
For Option A:

- 9 potential candidates;
  3 found last year
- 3 valid candidates so far:
  - 2009 BD, 2013 EC20 and now 2011 MD
- Additional valid candidates expected at 1 to 2 per year

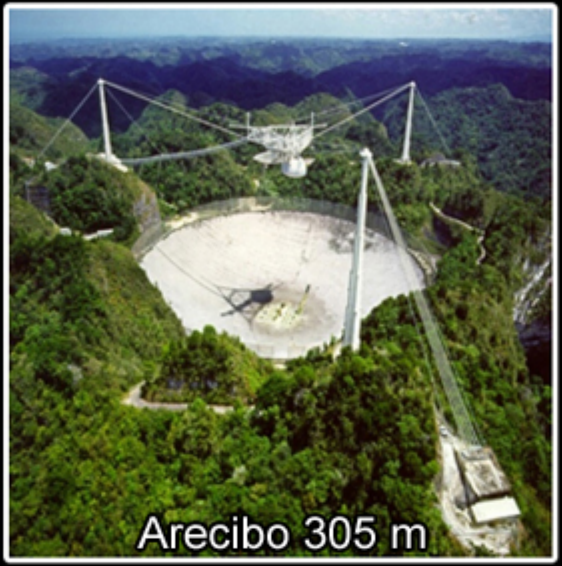


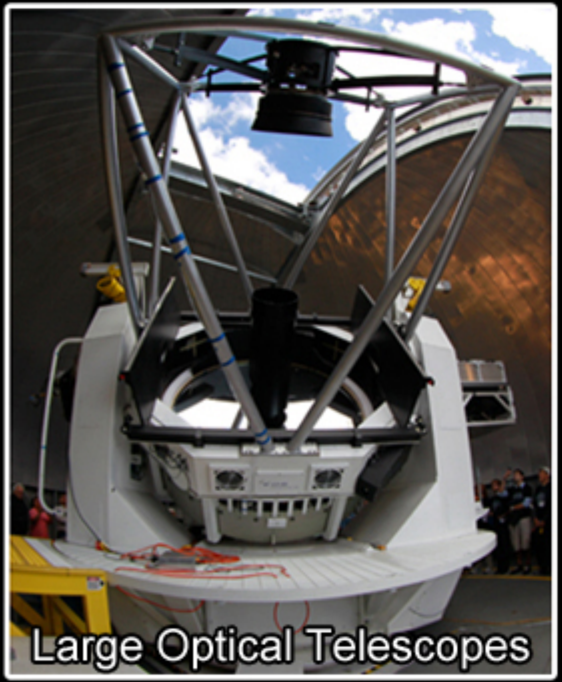
For Option B:

- Lots of potential candidates
- 3 valid candidates so far:
  - Itokawa, 2008 EV5 and Bennu
- Additional candidates validated by radar about 1 per year

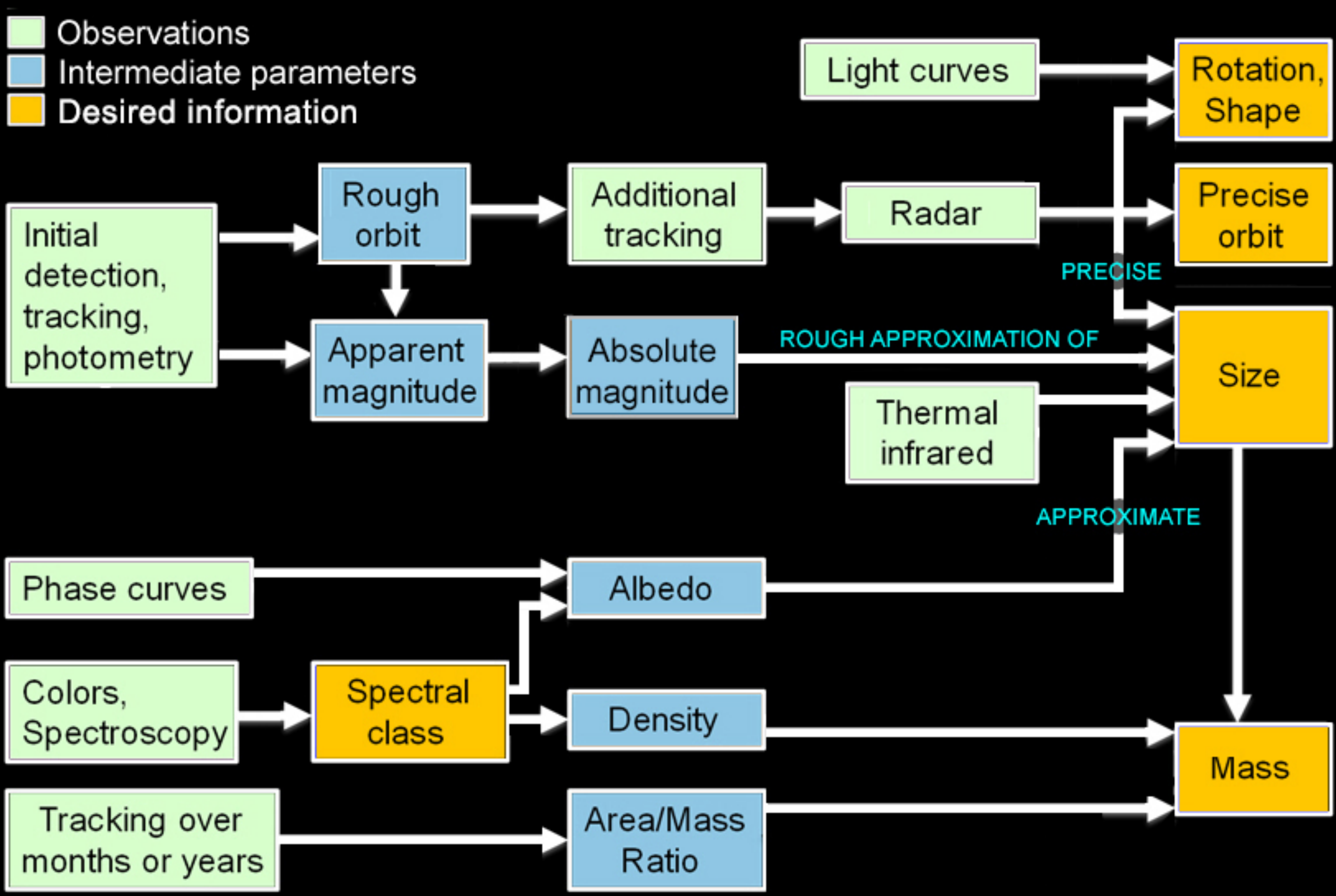


Characterizing Asteroids





Asteroid Characterization Process



The Case of 2011 AG5 (Late 2011)

- Asteroid 2011 AG5 was discovered in early 2011, and by mid-2011 had a 1-in-500 chance of impacting Earth in 2040
- Then the asteroid became unobservable for a long period
- Impact required passage through a 365 km keyhole in 2023
- Post-keyhole deflection would be ~50x harder than pre-keyhole deflection
- In 2012, JPL performed a study to decide whether NASA could wait until the asteroid became observable again (to see whether it truly was on an impact trajectory), or whether it should begin work on designing a deflection mission

Sample Sentry Risk Page (NB: Automatically Updated)

http://neo.jpl.nasa.gov/risk/

2011 AG5
Earth Impact Risk Summary

Torino Scale (maximum)	1
Palermo Scale (maximum)	-1.01
Palermo Scale (cumulative)	-1.00
Impact Probability (cumulative)	2.0e-03
Number of Potential Impacts	4

Analysis based on
210 observations spanning 316.77 days
(2010-Nov-08.629742 to 2011-Sep-21.398727)

V_{impact}	14.67 km/s
$V_{infinity}$	9.55 km/s
H	21.8
Diameter	0.140 km
Mass	4.1e+09 kg
Energy	1.1e+02 MT

all above are mean values weighted by impact probability

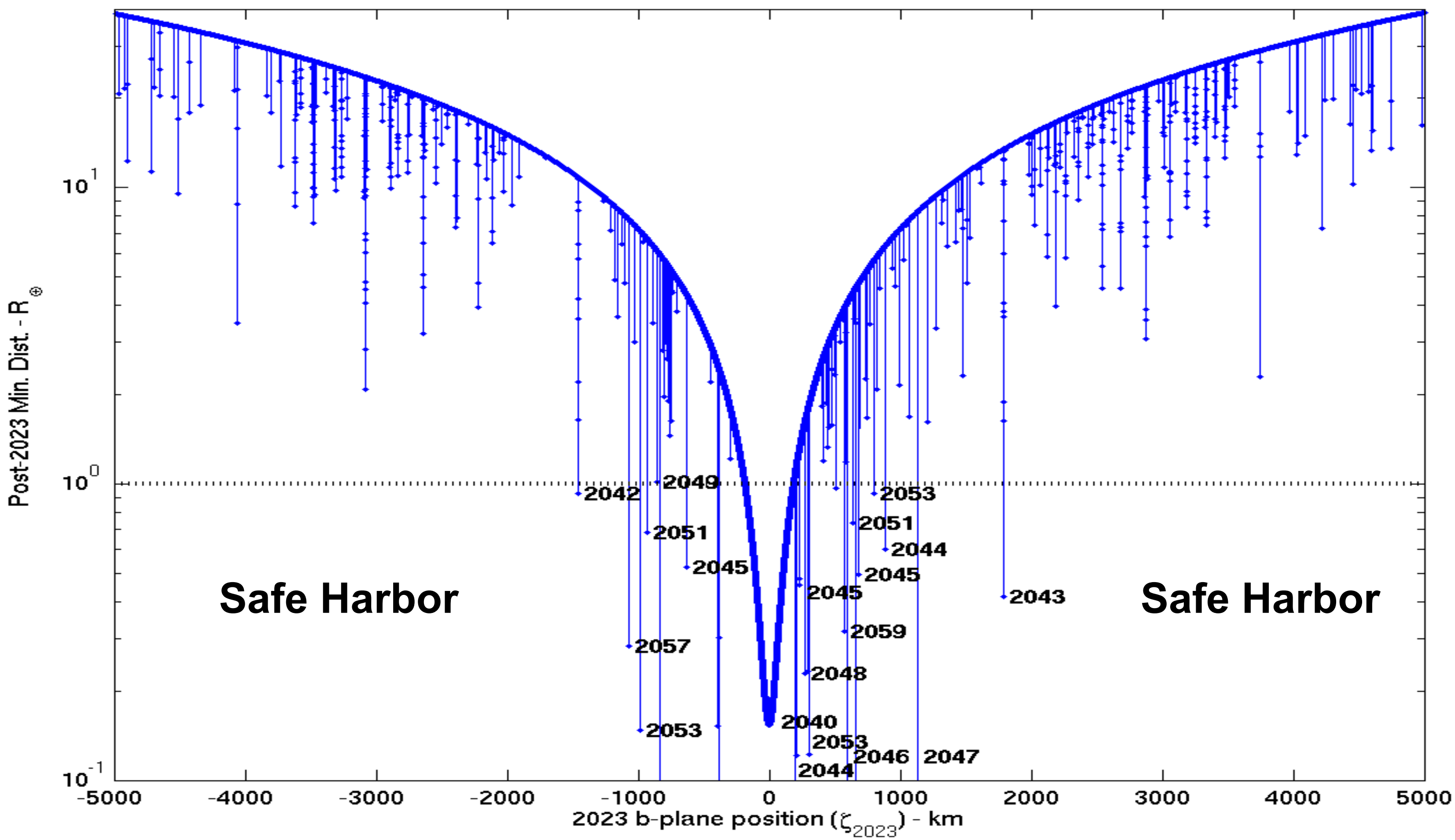
Orbit diagram and elements available here.

These results were computed on Mar 31, 2012

2011 AG5
Earth Impact Table

Date	Distance	Width	Sigma Impact	Sigma LOV	Stretch LOV	Impact Probability	Impact Energy	Palermo Scale	Torino Scale
YYYY-MM-DD.DD	(r_{Earth})	(r_{Earth})			(r_{Earth})		(MT)		
2040-02-05.16	0.31	1.04e-03	0.000	0.26494	3.70e+02	2.0e-03	1.05e+02	-1.01	1
2043-02-04.90	0.56	< 1.e-04	0.000	0.24025	1.39e+06	4.6e-07	1.05e+02	-4.68	0
2045-02-04.43	0.52	1.01e-03	0.000	0.09607	5.53e+04	1.2e-05	1.05e+02	-3.29	0
2047-02-04.92	0.57	9.82e-04	0.000	0.37496	1.69e+05	3.6e-06	1.05e+02	-3.84	0

Keyhole Map for 2011 AG5 in the 2023 B-Plane

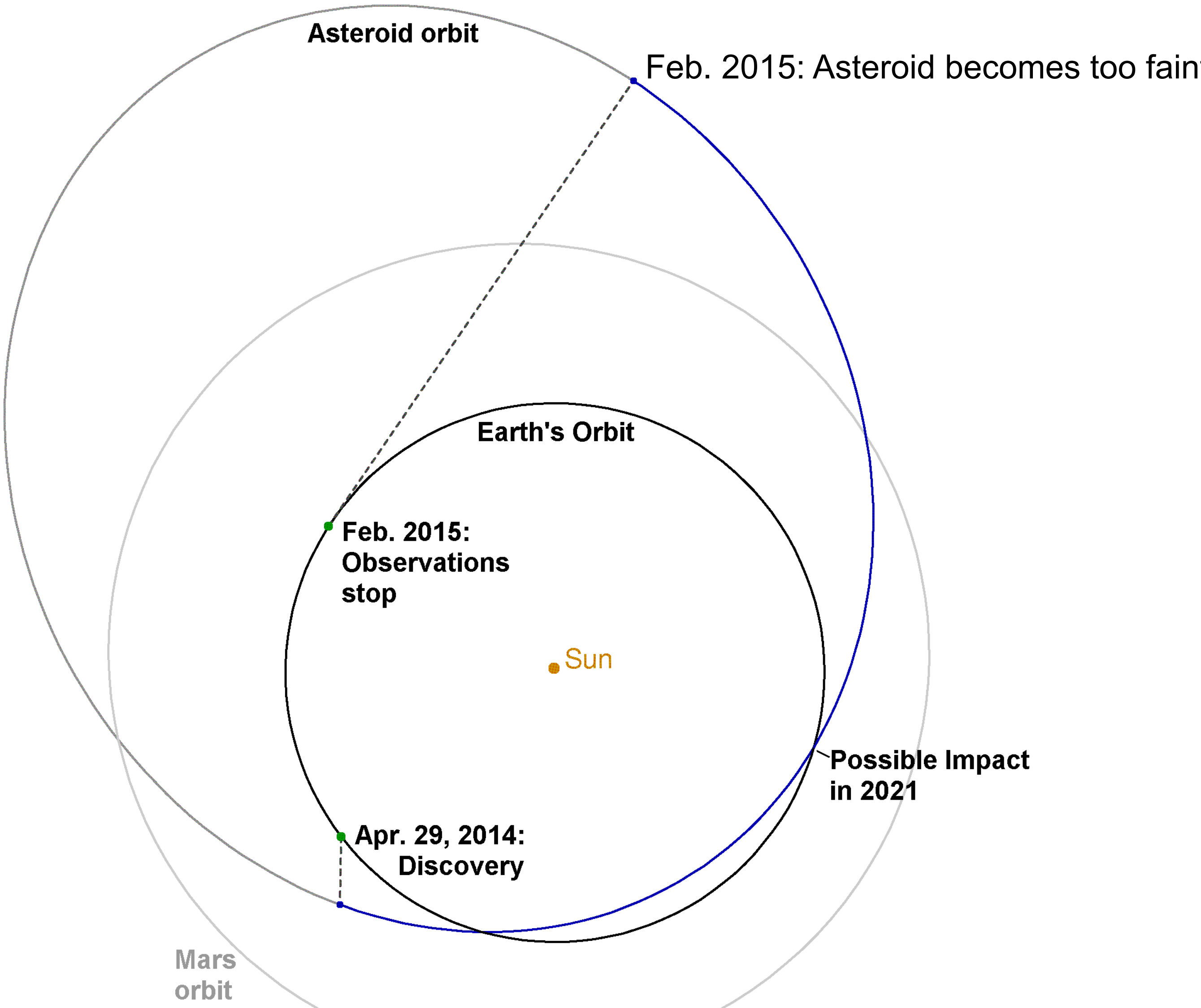


- Secondary keyholes exist but are < 100 m down to a few meters wide.
- Safe harbor zones: -8,000 km to -1,500 km on left & +2,00 km to +12,00 on right
- Left safe harbor is preferred because it corresponds to front side impact by S/C

2014 DARPA/FEMA Asteroid Impact Exercise

- Hypothetical asteroid 2014 TTX discovered in Apr. 2014
- Typical NEA orbit, size between 120 and 300 meters
- Initially, just one of 1500 Potentially Hazardous Asteroids (PHAs)
- As the asteroid is tracked, however, the Sentry system detects the possibility of impact in 2021, only 7 years away.
- Impact probability rises gradually over the next few months until it reaches ~10% in August 2014.
- Can the impact of a 100-300 meter asteroid be averted in only 7 years?
- Kinetic Impactor (KI) deflection method was chosen

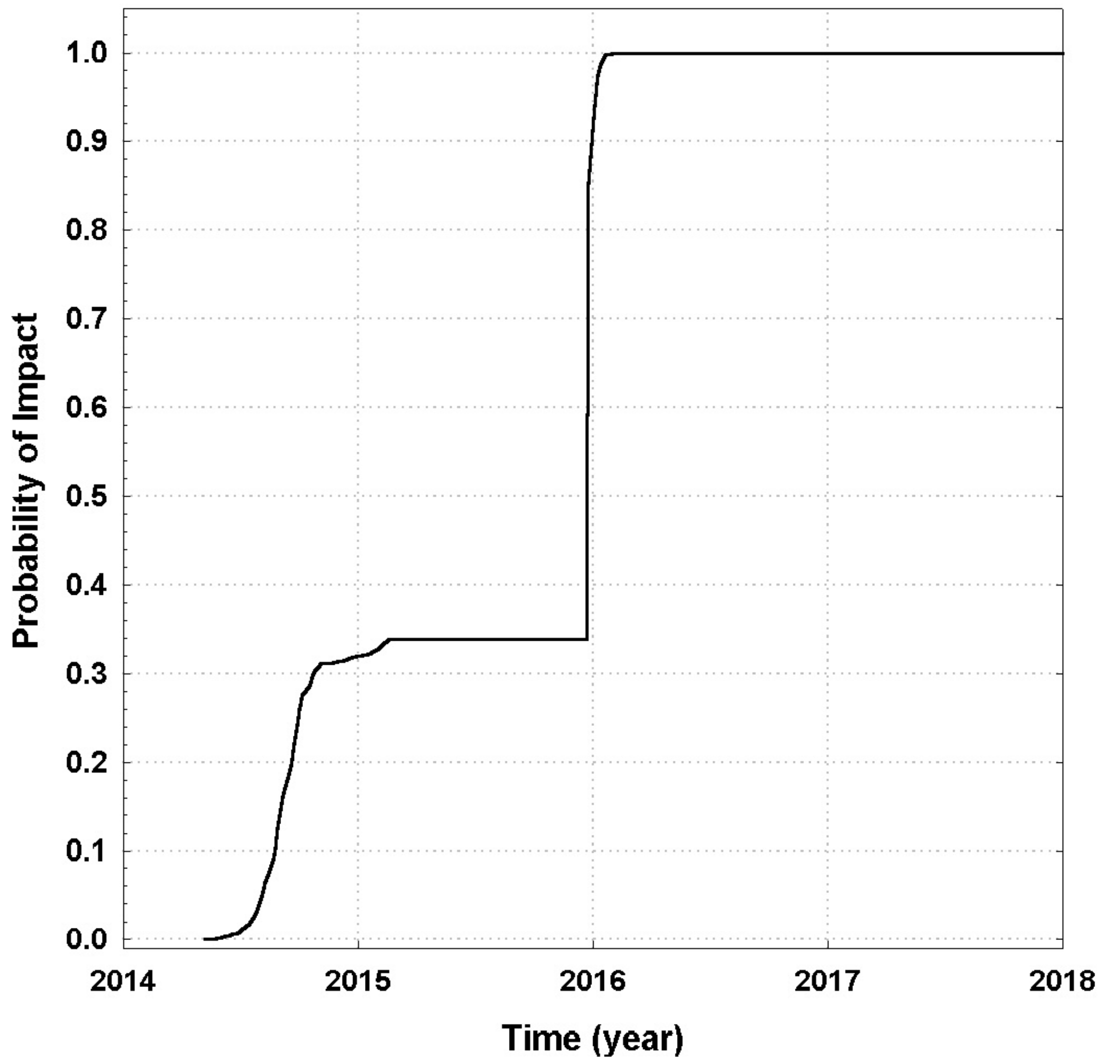
Orbit of Asteroid 2014 TTX



2014 DARPA/FEMA Tabletop Scenario (Cont'd)

- In Feb. 2015, the asteroid becomes unobservable for 10 months, while the impact probability is 35%
- At the end of the 10 months, the probability will either fall quickly to zero or rise quickly to 100%
- Work on a deflection mission must begin, because the last chance to launch it is Aug. 2018

2014 TTX: Impact Probability vs. Time

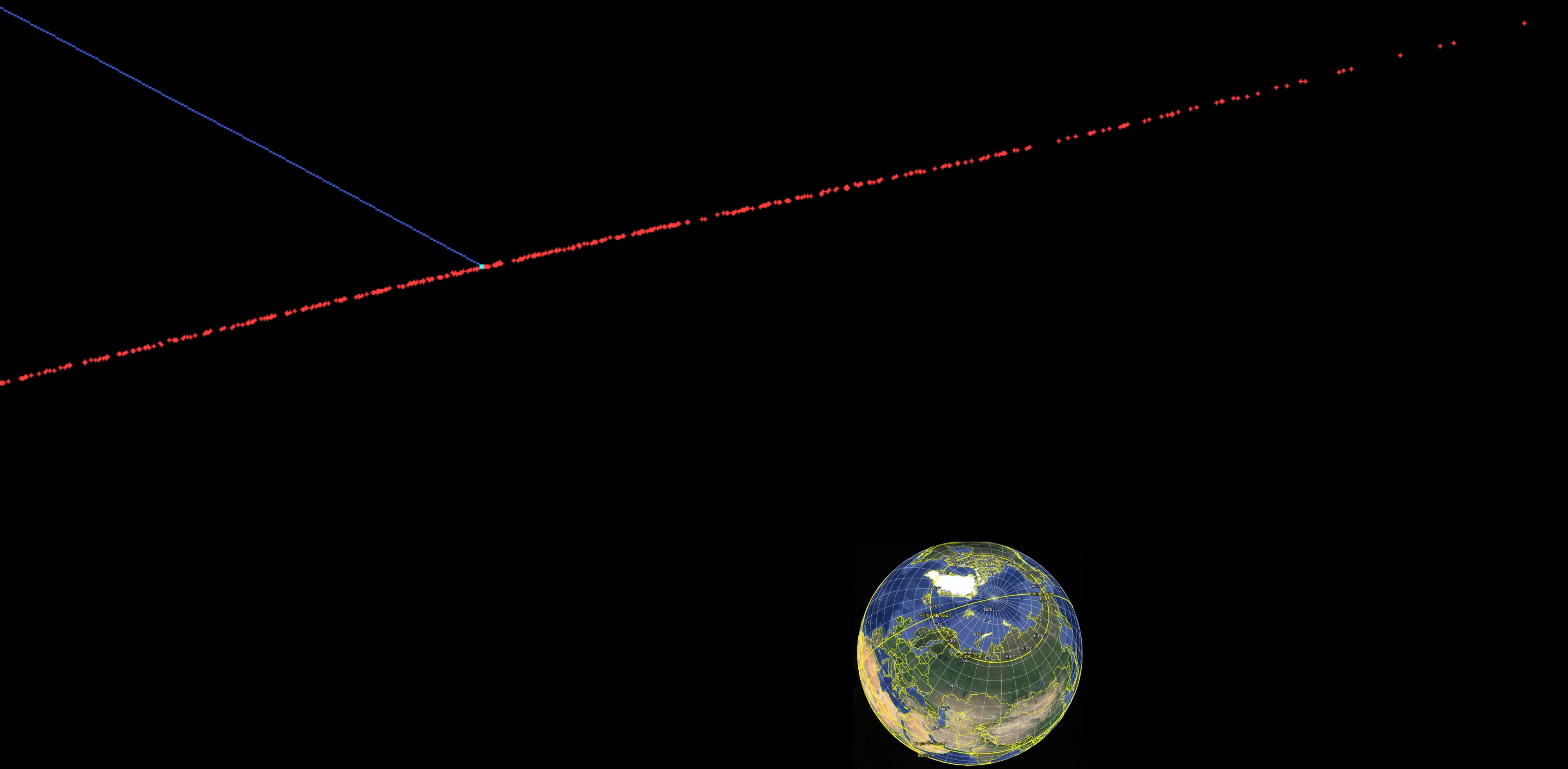


2014 TTX: Risk Corridor

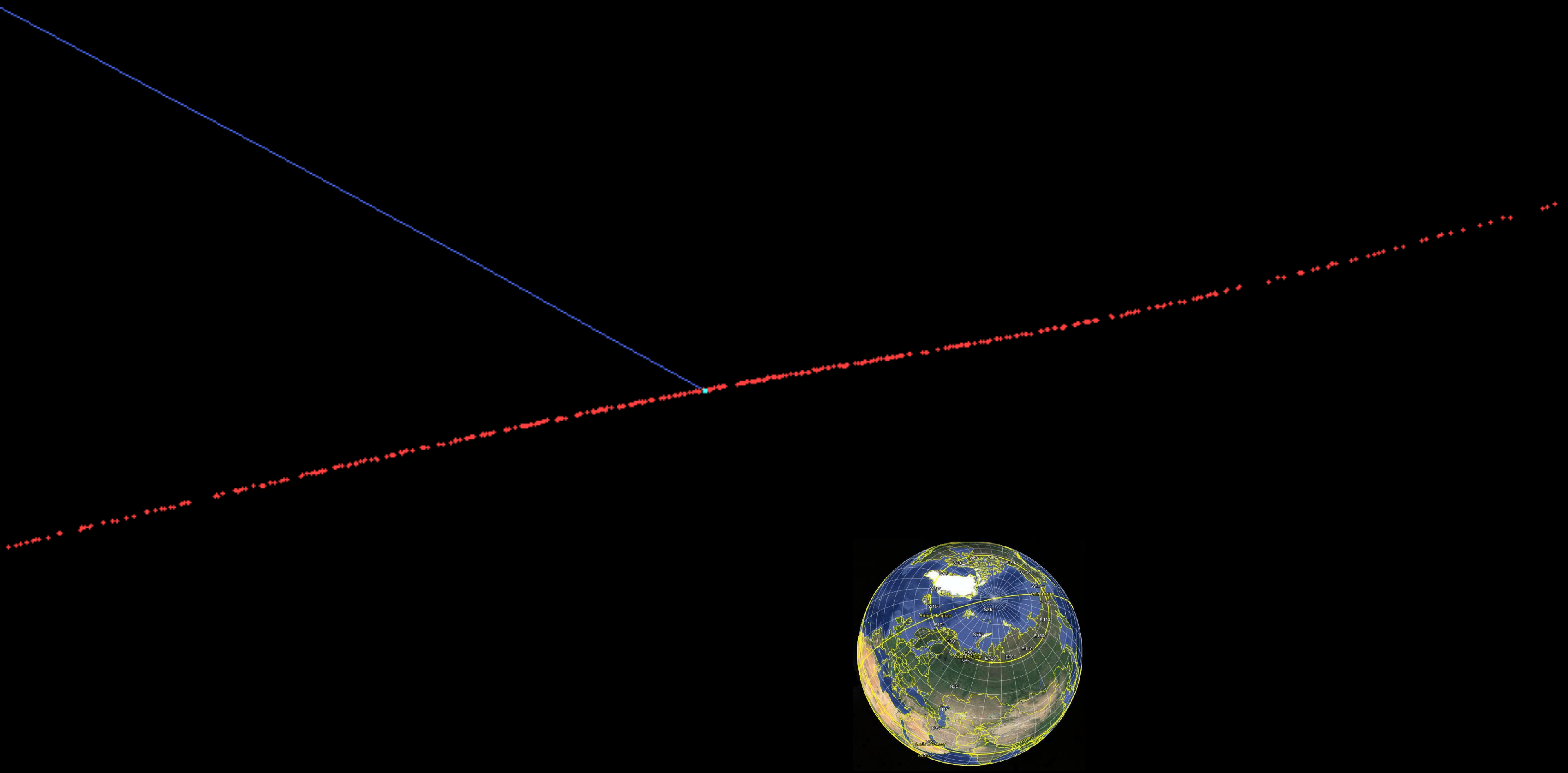
- Asteroid's orbit is uncertain because the observations on which it is based are uncertain and made at large distances.
- Predicted position of the asteroid at potential impact on Sept. 5, 2021 is uncertain, mostly along the orbit path.
- Trace the region with red points, but really it is continuous
- In 2015, the uncertainty region is larger than the Earth, since the impact probability is < 100%.
- The Earth will slice right through the region, producing a "risk corridor" of points on the globe.
- If the impact happens, it will happen somewhere along the corridor.

Asteroid Uncertainty Region in Space Creates a Risk Corridor on the Earth

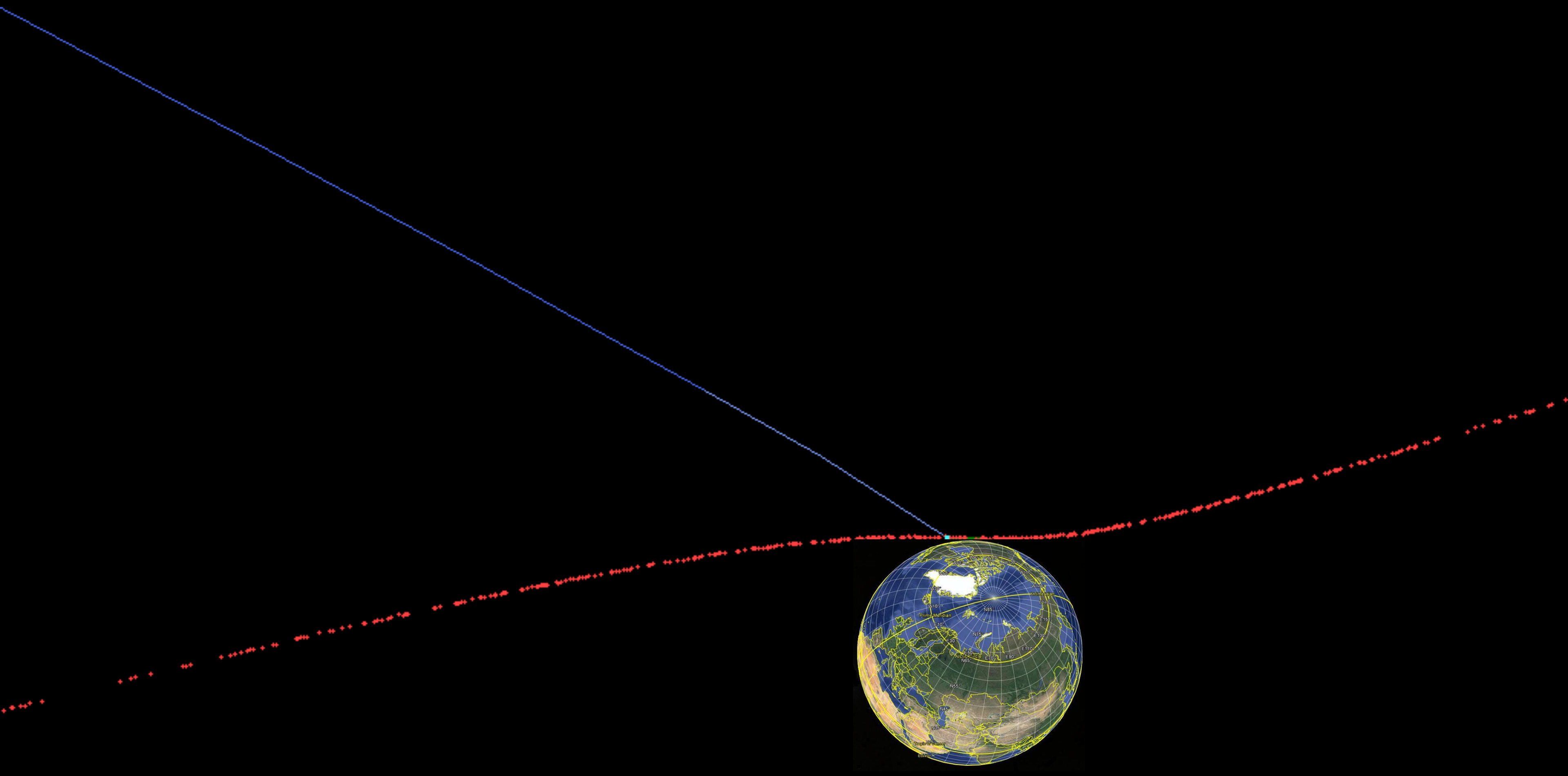
Asteroid Uncertainty Region in Space Creates a Risk Corridor on the Earth



Asteroid Uncertainty Region in Space Creates a Risk Corridor on the Earth



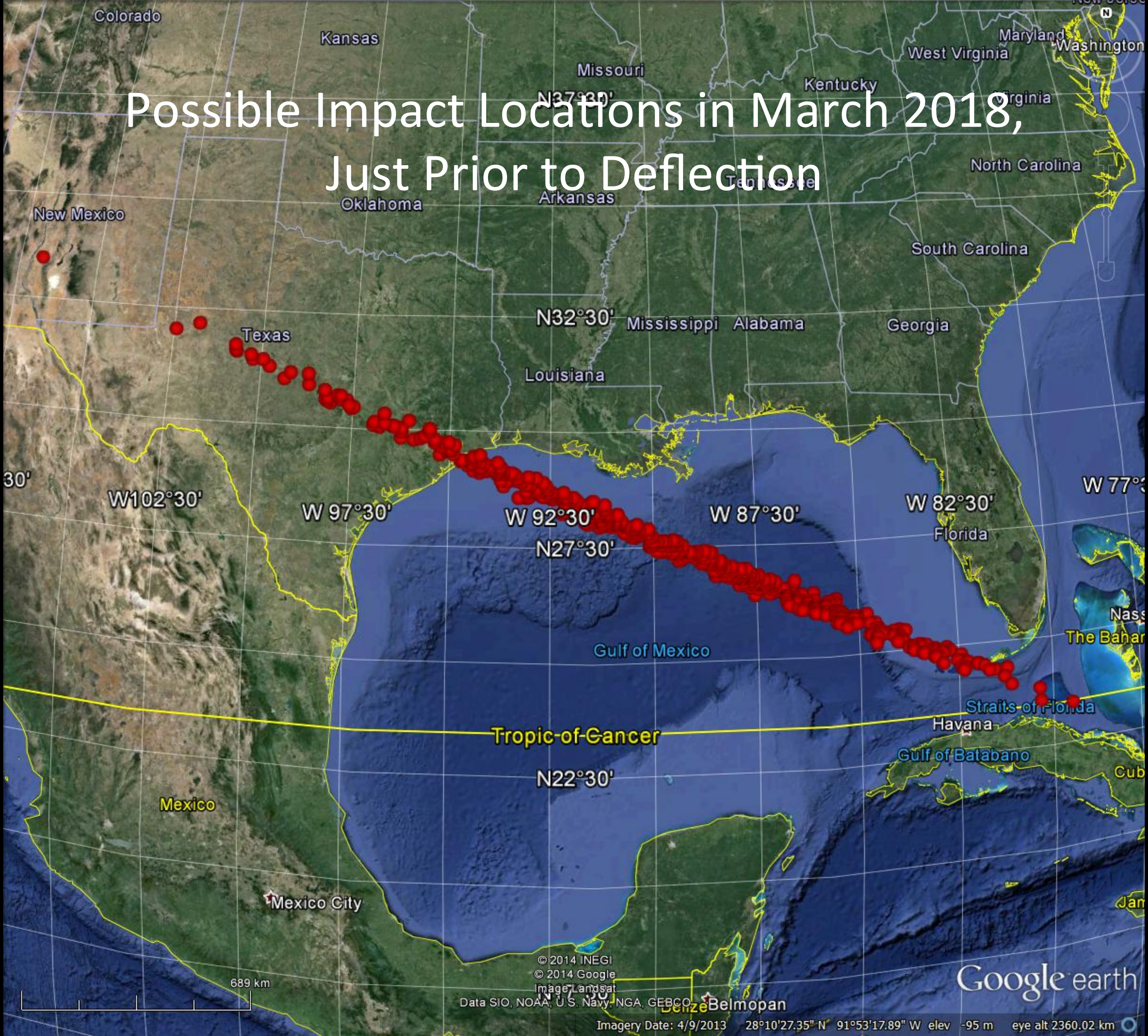
Asteroid Uncertainty Region in Space Creates a Risk Corridor on the Earth



Risk Corridor, Western Portion

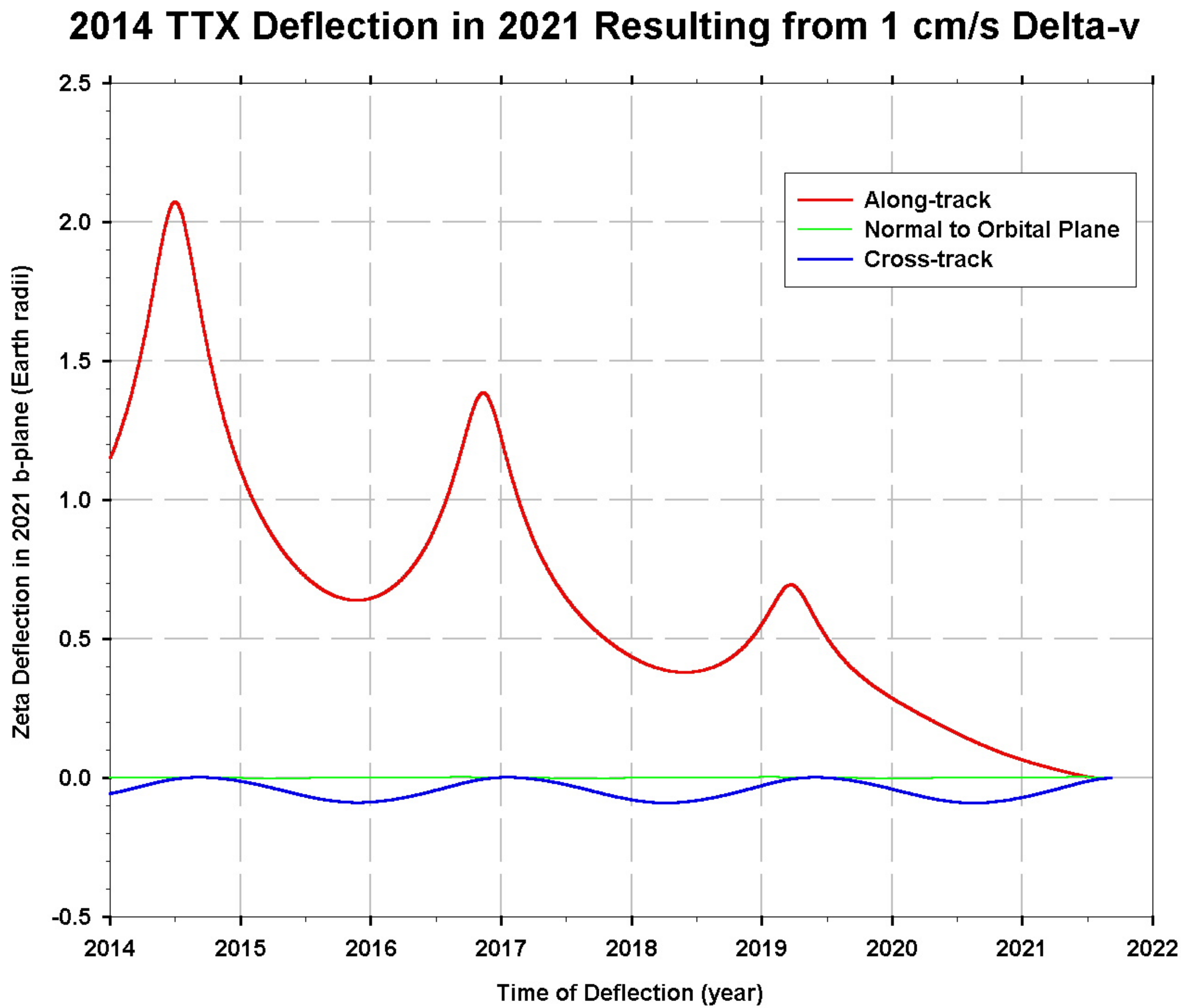
Risk Corridor, Eastern Portion

Possible Impact Locations in March 2018, Just Prior to Deflection



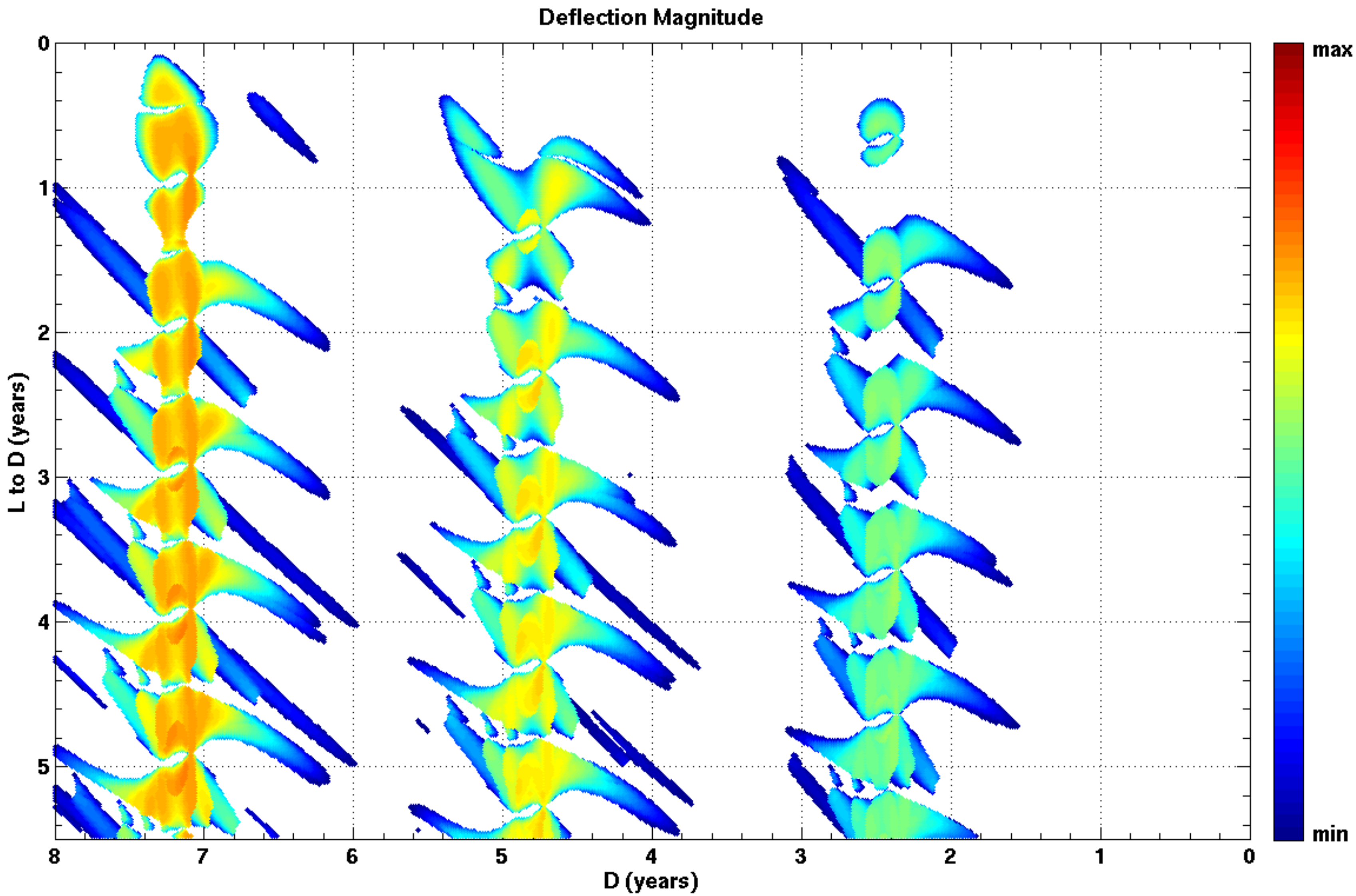
2014 TTX – Deflection Issues

- The shortest direction to deflect the asteroid off the Earth is westwards, which corresponds to moving the asteroid ahead on its orbit
- Because of orbital dynamics, moving the asteroid ahead requires a decrease in its orbital period, which means the asteroid must be slowed down (!)
- Warning time was so short that there was no time for a characterization mission, or an observer mission
- Deflection occurred in early March, 2019, just over one asteroid orbit (18 months) before the potential impact
- Because the mass of the asteroid was very uncertain, several deflection missions were launched



2014 TTX Deflection in 2021 Resulting from 1 cm/s Delta-v
Along-track
Normal to Orbital Plane
Cross-track
Zeta Deflection in 2021 b-plane (Earth radii)
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
2014
2015
2016
2017
2018
2019
2020
2021
2022
Time of Deflection (year)

2014 TTX: KI Deflection Magnitude Map



ASTEROIDS

...are nature's way of asking:

"How's that space program coming along?"