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Studying Trans-Neptunian objects via stellar occultations: ground-based and air-based with SOFIA

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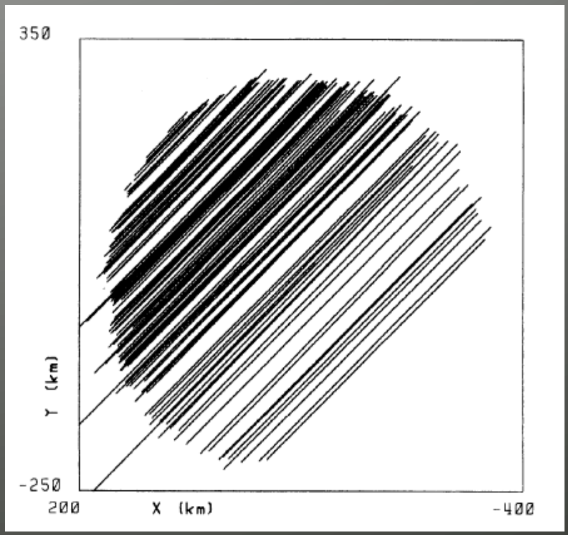
+ observations from collaborators (Williams College and other)
+ supporting slides and information from SOFIA team

Outline

- What can we learn about TNOs from occultations?
- Predictions with the MIT Ephemeris Correction Model
- Ground-based observations
- Air-based observations with SOFIA
- Near-term expectations

Returns from occultation observations

- Accurate size measurement
  - spatial resolution of a few km at 30 AU
- Sensitive atmospheric probe
  - temperature, number density, and pressure to microbar levels
  - detect extinction
- Spatial and temporal variability
  - object shape
  - local atmospheric density variations
  - changes in observed parameters over time
- Targeted (or serendipitous) discoveries
  - rings (e.g. Uranus, Elliot *et al.* 1977)
  - atmospheres (e.g. Pluto, Elliot *et al.* 1988)
  - companions (e.g. Larissa, Reitsema *et al.* 1982)



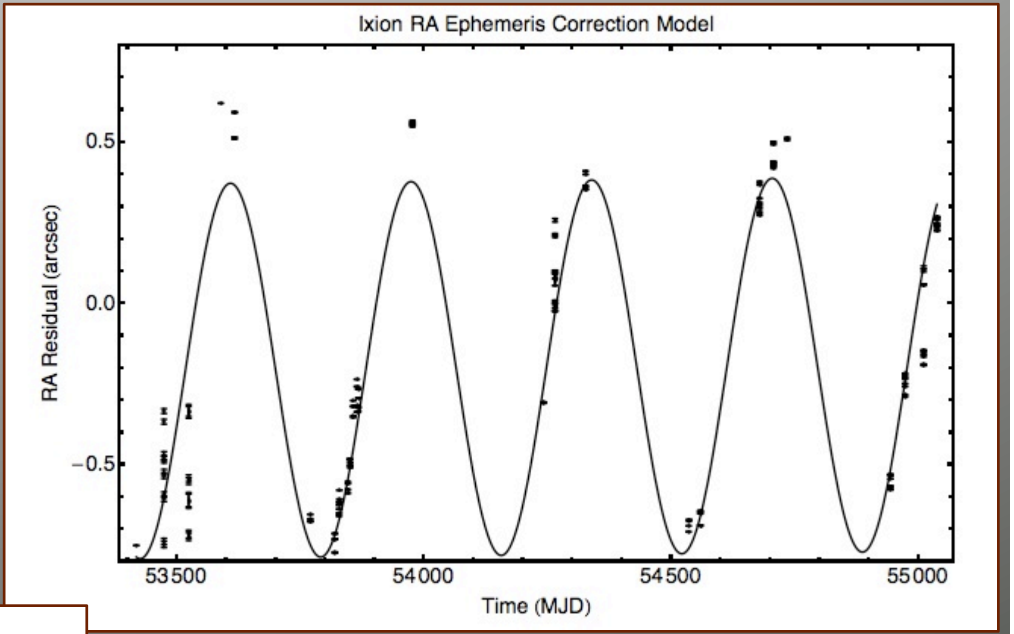
Observation of a stellar occultation by asteroid Pallas with 130 chords (Dunham et al., AJ, 1990).

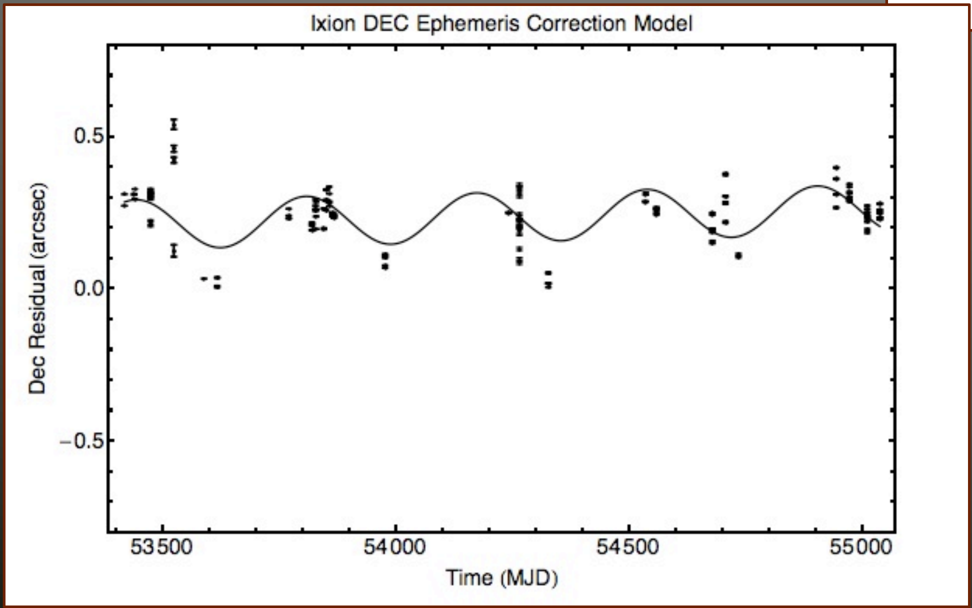
Predicting stellar occultations by TNOs

- Astrometric measurements for 35 largest objects (in angular diameter)
- Telescopes used:
  - Lowell 42 inch (bi-monthly since Dec. 2004)
  - SMARTS 0.9 m at CTIO (monthly to bi-monthly since May 2005)
  - USNO 61 inch (for pre-event refinement)
- Generate offsets to JPL coordinates by fitting an annual-period Fourier series and linear slope

MIT ECM* fit: Ixion

** Ephemeris Correction Model.*





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  - USNO 61 inch (for pre-event refinement)
- Generate offsets to JPL coordinates by fitting an annual-period Fourier series and linear slope
- Current focus/refinement is on a list of 9 TNOs + Pluto
  - large in angular diameter
  - currently in high-density star fields
  - range of RAs so observations can be taken all year

MIT ECM targets and positional errors

Body	Class	V[1]	D[1] (AU)	Radius[2] (km)	Radius[2] (")	JPL Pos. Error[1] (")	MIT ECM Pos. Error[3] Min-max
Pluto	3:2*e*	14.0	31.0	1152	0.050	0.01	0.009-0.030
Makemake	S	16.8	52.0	750	0.019	0.12	0.003-0.007
Eris	S	18.8	96.0	1300	0.019	0.15	0.021-0.039
Haumea	S	17.4	51.0	575	0.015	0.11	0.029-0.055
Varuna	C	20.0	44.5	482	0.015	0.17	0.013-0.042
Orcus	3:2*e*	19.2	48.2	474	0.014	0.13	0.009-0.032
Quaoar	C	19.1	42.3	422	0.013	0.16	0.029-0.053
Ixion	3:2*e*	19.5	40.5	325	0.011	0.26	0.026-0.059
55638	3:2*e*	20.0	28.2	162	0.008	0.28	0.038-0.078
55636	S	19.6	41.2	<200	<0.007	0.18	0.006-0.055

[1] From JPL. [2] From Lowell Obs. database. [3] From MIT ECM models over 1-yr period.

Ground-based obs.: two appulses and two occultations

- Appulses by Ixion and 55638 observed in 2008 from IRTF (Mauna Kea)

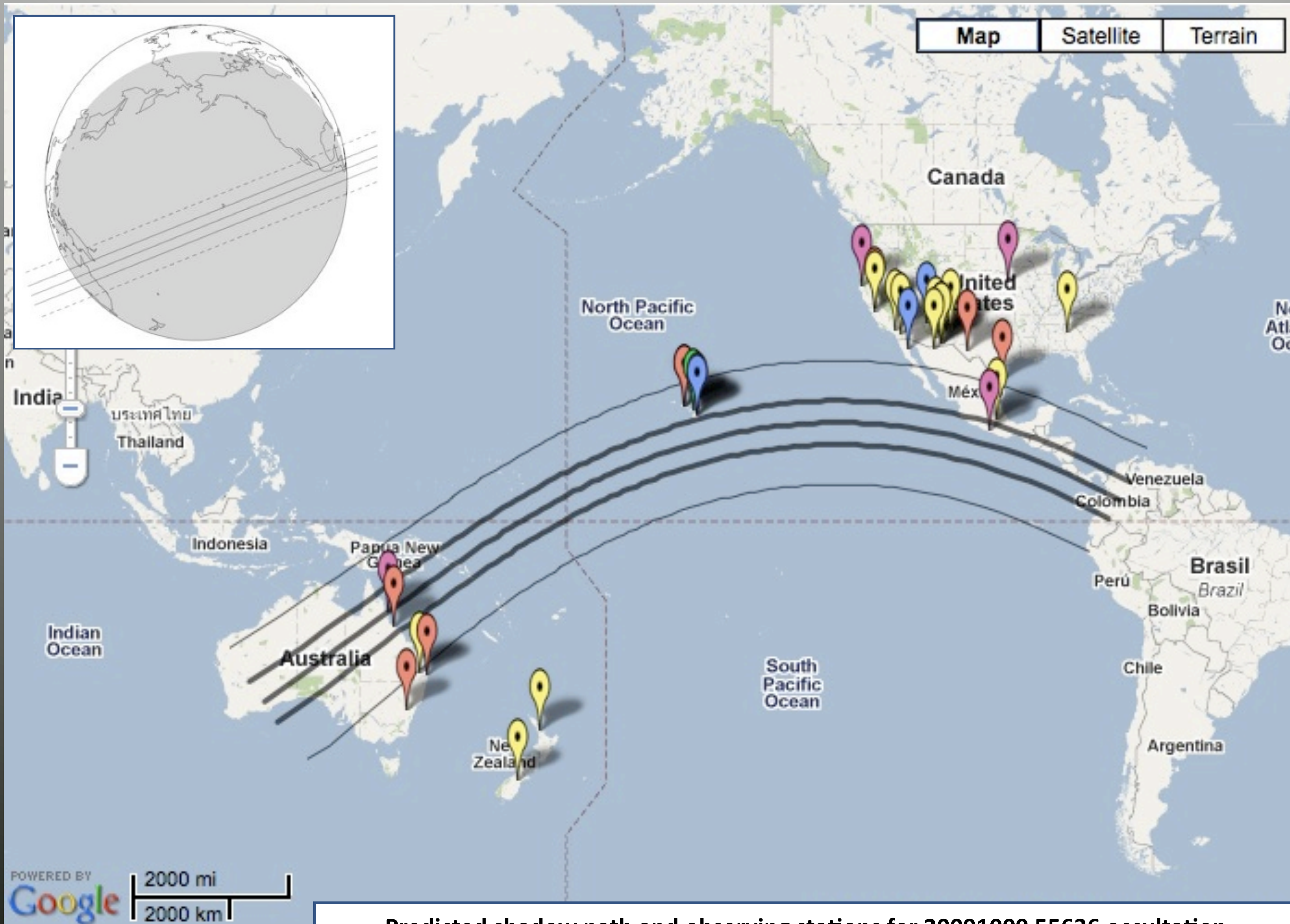
- MORIS (MIT Optical Rapid Imaging System) on the IRTF
  - similar to our portable POETS systems; high QE, low read noise, readout of a few Hz to a few hundred Hz with minimal deadtime, GPS trigger, various filters
  - mounted on side-facing exit window of SpeX

Results:

	Closest approach (arcsec)			Midtime (hh:mm:ss.ss)		
Target.Date	Predicted	Observed	Difference	Predicted	Observed	Difference
Ixion.20080507	0.170±0.00 9	0.218±0.01 6	0.048±0.01 8	12:06:27±00:00: 2 7	12:07:33±00:00: 0 6	00:01:06±00:00: 2 7
55638.2008081 0	0.393±0.02 3	0.389±0.02 6	0.005±0.03 5	13:53:15±00:00: 4 1	13:55:00±00:00: 0 6	00:01:45±00:00: 4 1

Ground-based obs.: two appulses and two occultations

- Occultation by 55636 in 2009 (Elliot *et al.,* Nature, 17 June 2010)
  - shift in observing strategy from a handful of sites to dozens



Predicted shadow path and observing stations for 20091009 55636 occultation.

Ground-based obs.: two appulses and two occultations

- Occultation by 55636 in 2009 (Elliot *et al.*, 2010, Nature, 465,897-900)
  - shift in observing strategy from a handful of sites to dozens
  - successful observation

Results:

	Closest approach (arcsec)			Midtime (hh:mm:ss.ss)		
Target.Date	**Predicted**	**Observed**	**Difference**	**Predicted**	**Observed**	**Difference**
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55636.2009100 9	0.059±0.01 5	0.0416±0.0002	0.017±0.00 2	10:30:07±00:00: 2 0	10:29:42±00:00: 0 4	00:00:20±00:00: 2 0

Digression: results from occultation by 55636

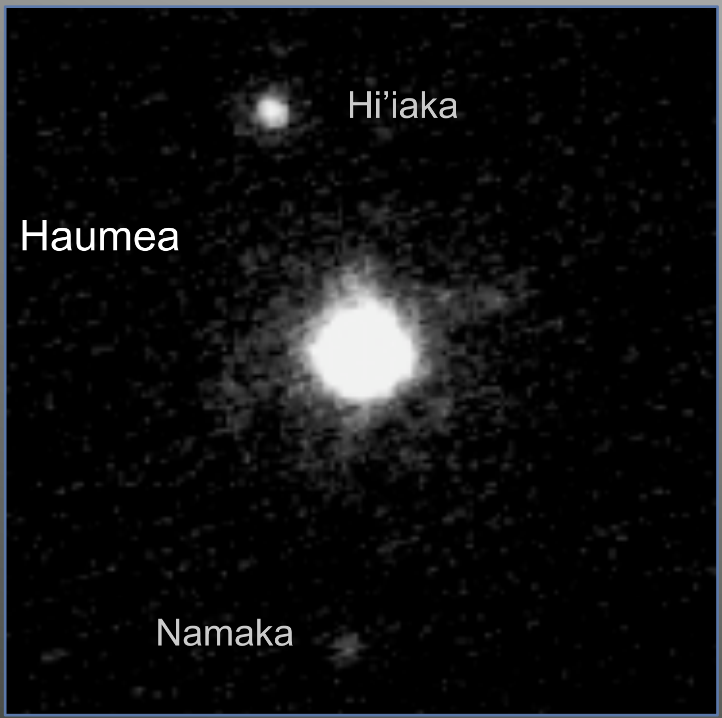
- 55636 (2002 TX_{300})
  - orbital parameters: a = 43 AU, e = 0.124, i = 25.9º
  - absolute magnitude: H_V = 3.5
  - rotational variability: 0.09 mag over 7.9 h (could be surface feature, shape, or combination)
  - Size (radius): upper limits only – < 400 km (Spitzer), < 354.5 km (ground-based IR)

    corresponding albedo > 0.1 and > 0.19

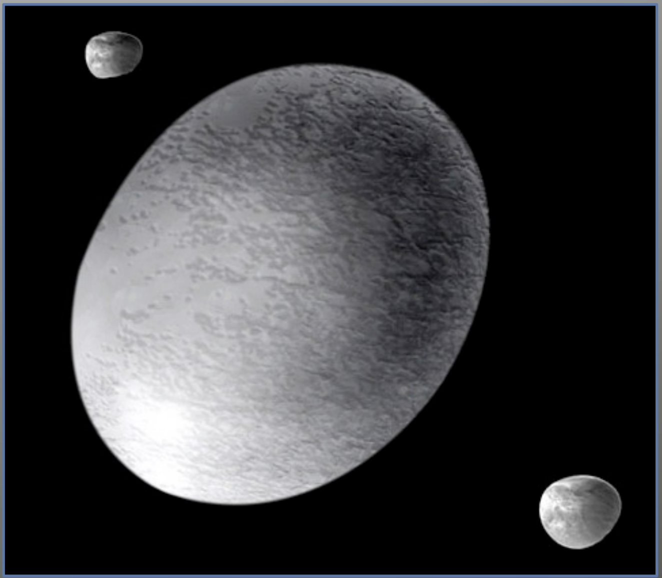
    implies angular diameter of < 0.03”
  - spectrum: similar to Charon, deep water ice absorption

Orbit + brightness + spectrum imply Haumea-family object, collisionally fragmented

Digression: results from occultation by 55636

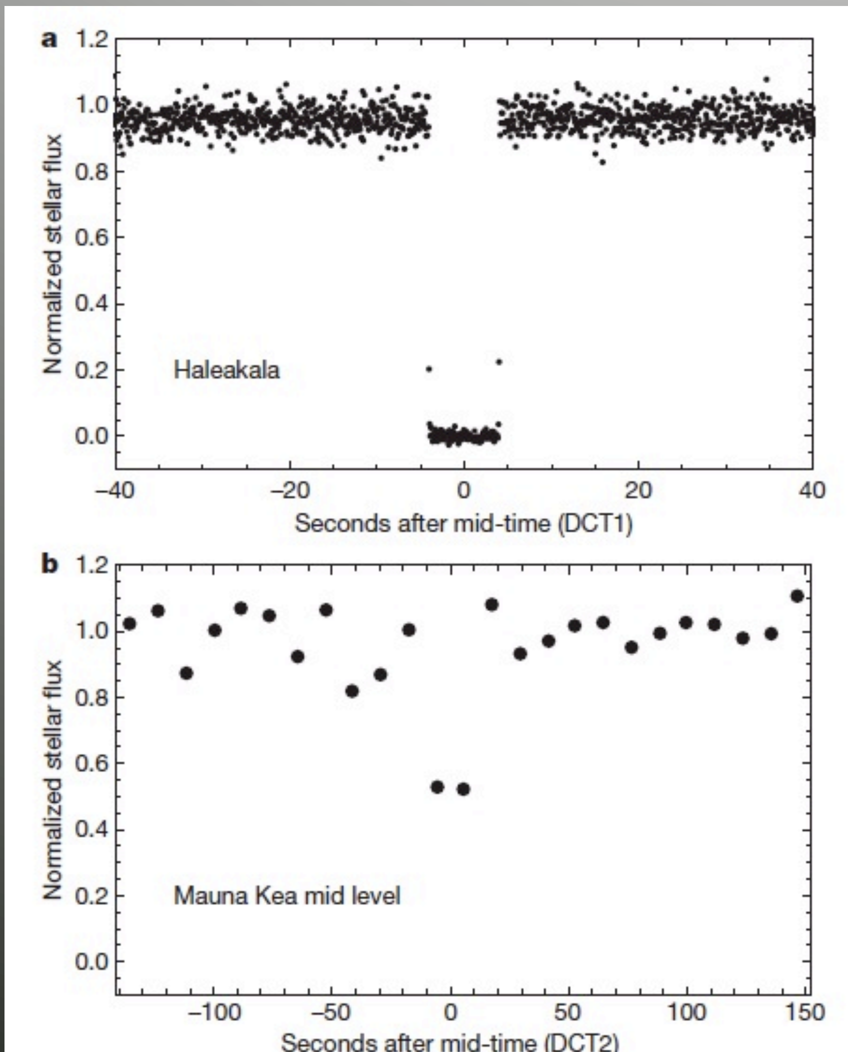


Keck image of Haumea system.
Credit: Brown et al. ApJ 639:L43, 2006.

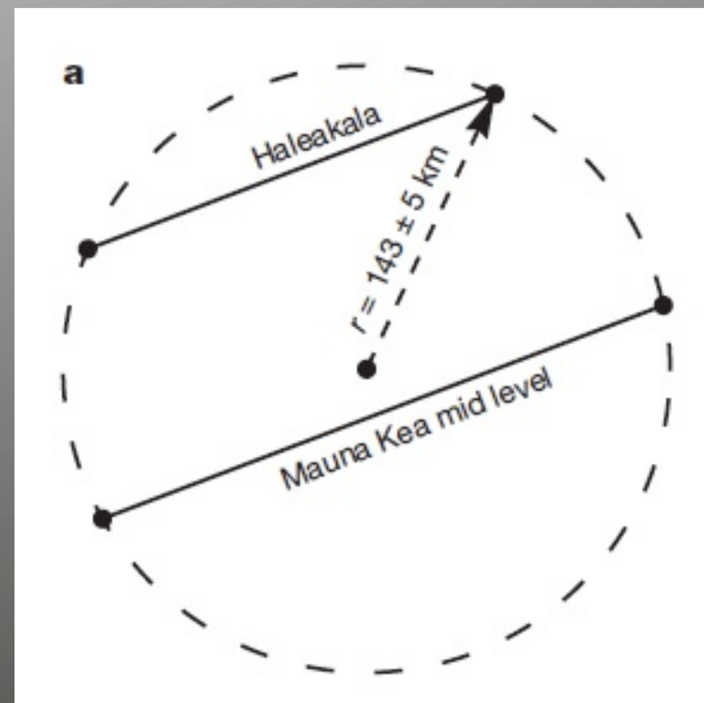


Artist's concept of Haumea and its moons.

Digression: results from occultation by 55636



Successful 55636 occultation lightcurves (Elliot et al., Nature, 2010).



Occultation chords and derived circular figure for 556365.

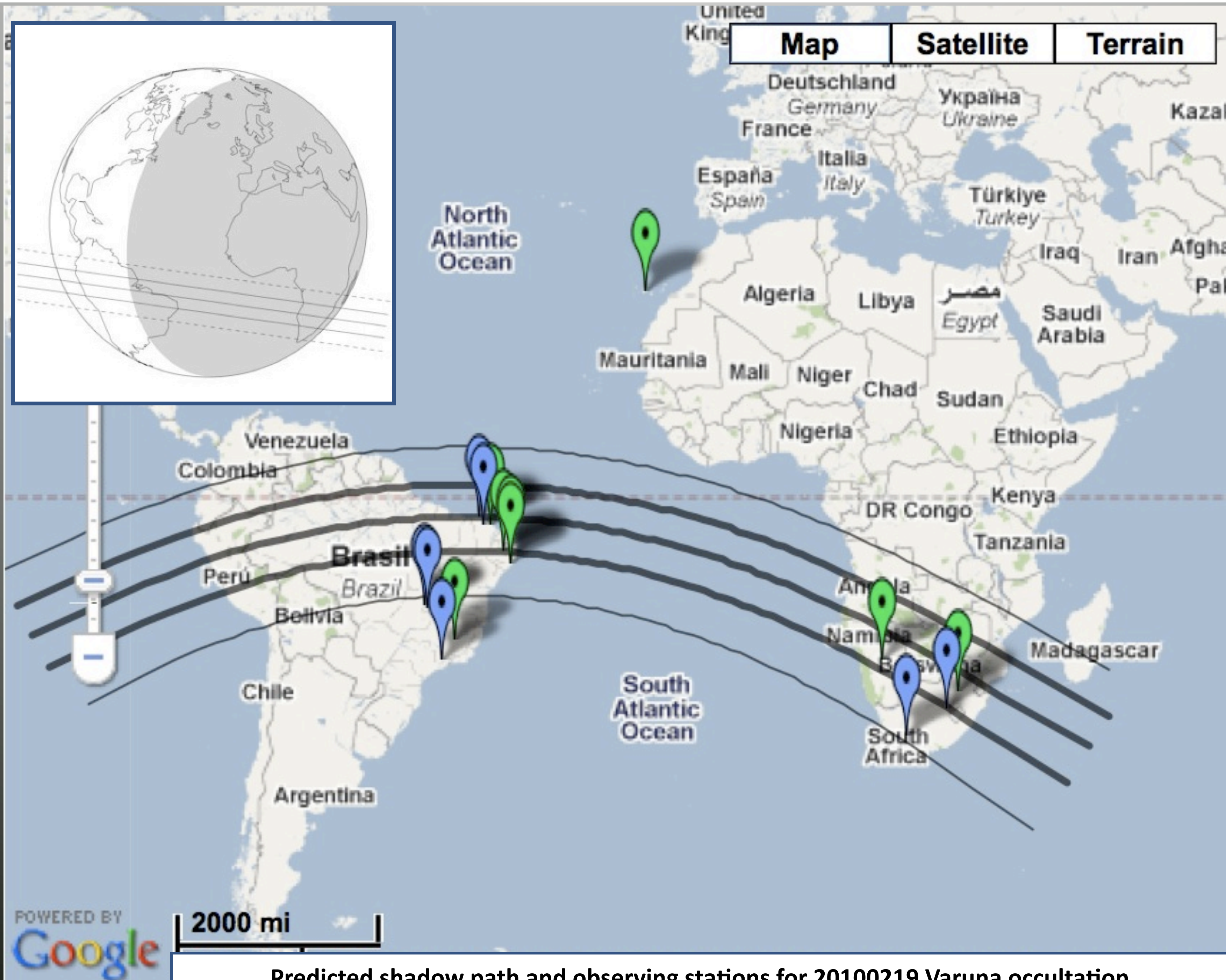
Digression: results from occultation by 55636

- From two successful chords (12 non-detections; 7 weathered out)
  - size: 143 ± 5 km (circular solution)
  - geometric albedo (V): $0.88^{+0.15}_{-0.06}$
  - atmosphere: non-existent (3σ upper limit of 2×10^{15} cm^{-3})
  - satellites: none detected

Intriguing dilemma: a surface this old (likely 1 Gyr from collisional formation) should not be so bright!

Ground-based obs.: two appulses and two occultations

- Occultation by Varuna in 2010
    - observed from handful of sites; coordinated with others



Predicted shadow path and observing stations for 20100219 Varuna occultation.

SOFIA: the Stratospheric Observatory for Infrared Astronomy

Credit: NASA/Carla Thomas on 18 Dec. 2009.

Modified Boeing 747SP with a 100-inch telescope

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SOFIA: Instruments

First generation instruments for occultation observations:

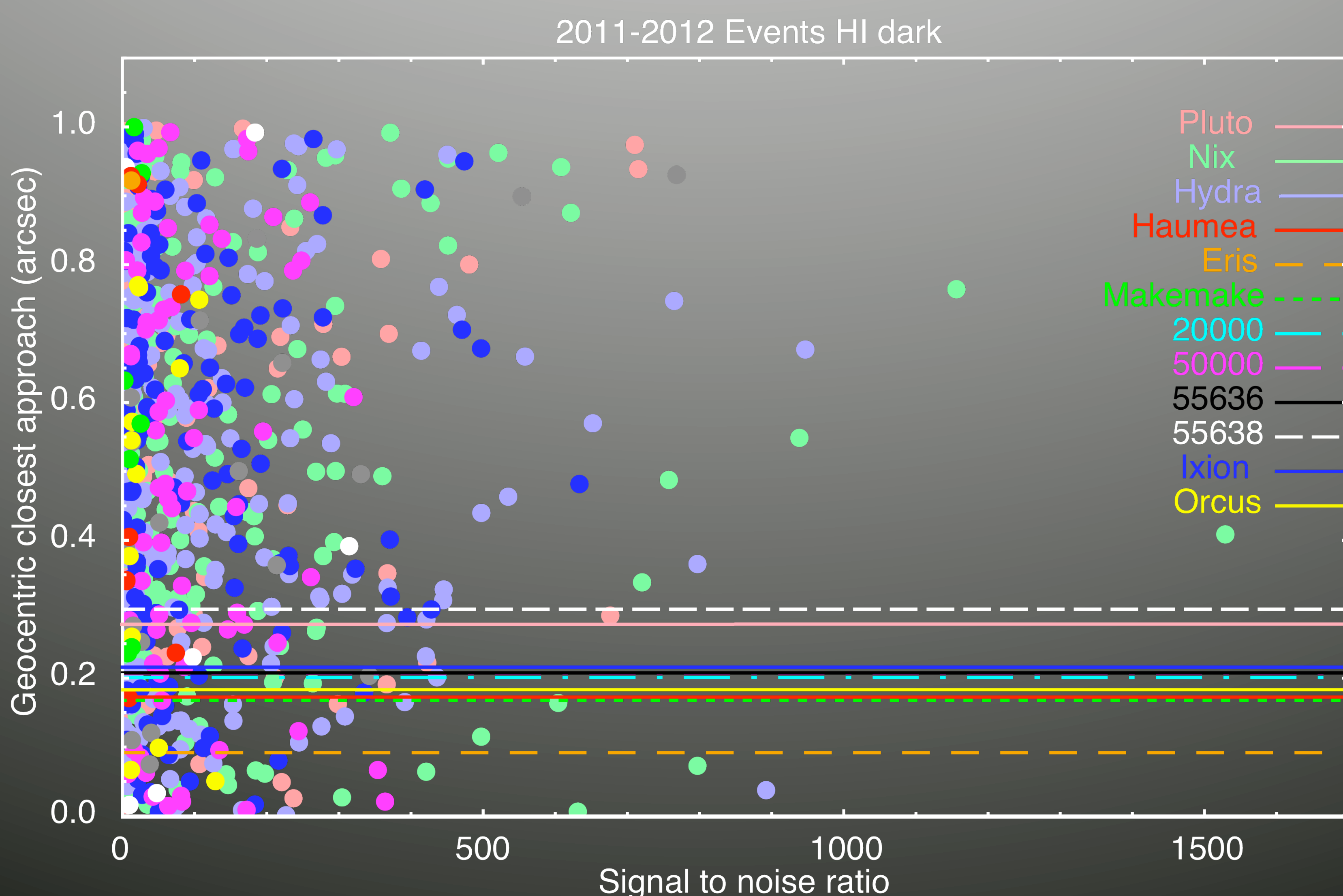
- HIPO (High-speed Imaging Photometer for Occultations)
  - 0.3–11 microns; can split to obtain two wavelengths simultaneously
  - Johnson U, B, V, R, I, & narrow band
  - 5.6’ x 5.6’ field of view; 0.33”/pixel
  - full frame readout 2 Hz; up to hundreds of Hz with subframes
  - readoise 6e~/pixel
  - timed using hardware triggers to precision of a few microseconds
- FLITECAM (First Light Infrared Test Experiment CAmera)
  - 1.0 –5.5 micron imager and grism spectrometer
  - J, H, K, L’, M, KL, and narrow-band
  - full 8’ x 8’ field of view; 0.48”/pixel
  - full frame readout 12 Hz; up to 30kHz with subframes

HIPO and FILTCAM can observe simultaneously using a dichroic beam splitter

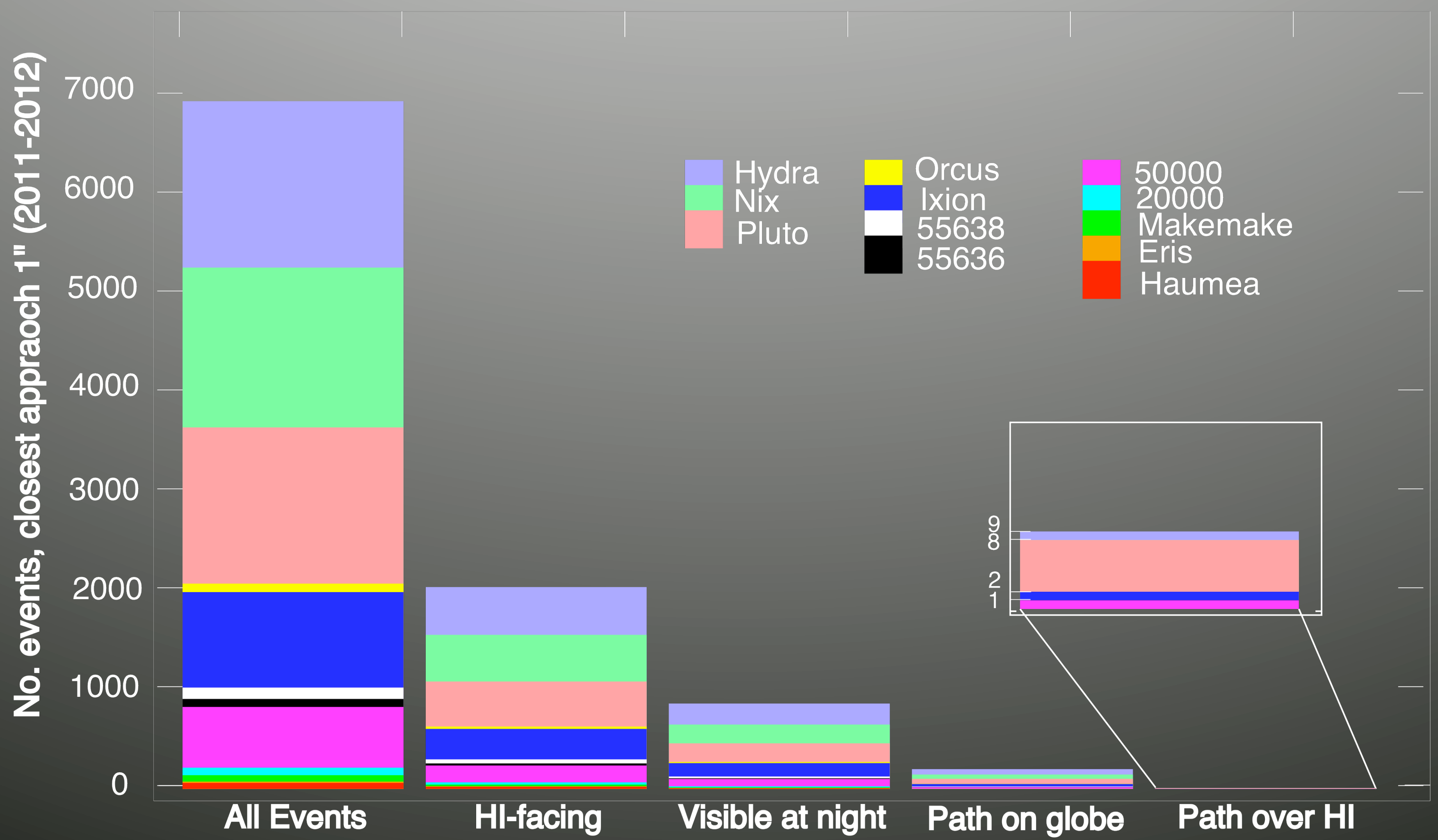
Near-term expectations

- Continue astrometic measurement and ECM refinement
  - increase the target list to add interesting objects
- Ground-based observations
  - How many events? Statistics suggest a few per year

Hawaii predictions: SNRs



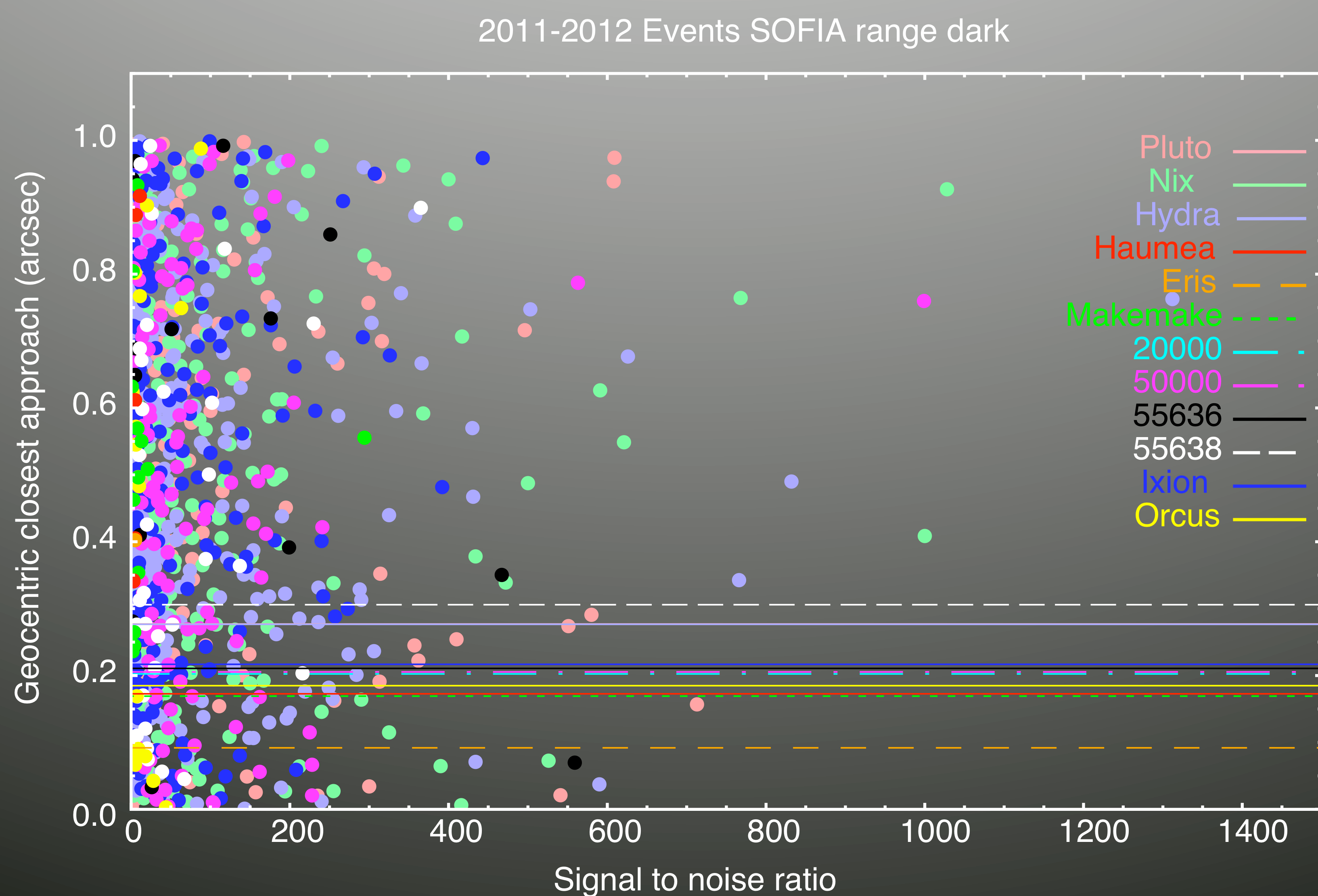
Hawaii predictions: event statistics



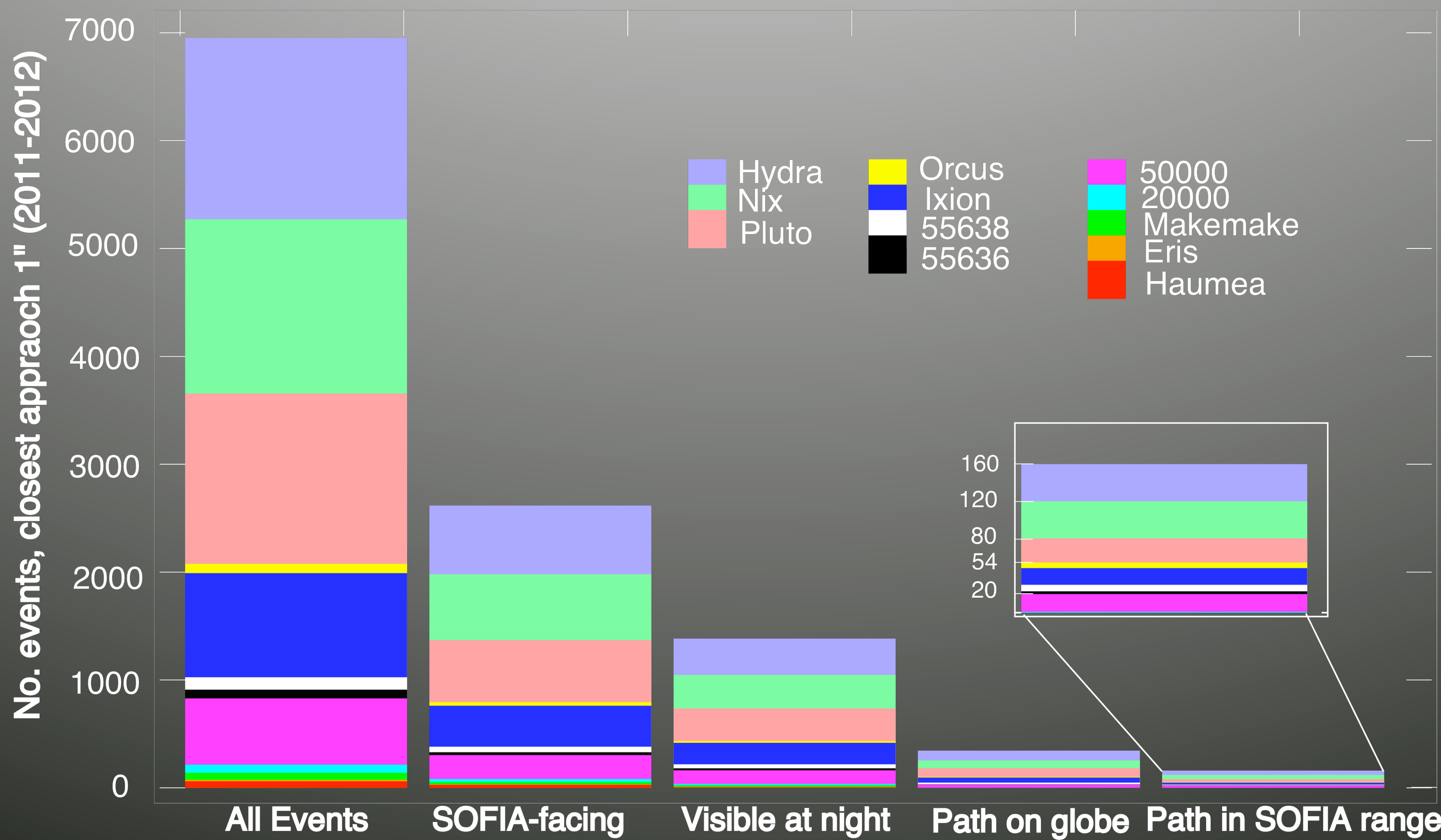
Near-term expectations

- Continue astrometic measurement and ECM refinement
  - increase the target list to add interesting objects
- Ground-based observations
  - How many events? Statistics suggest a few per year
- SOFIA observations
  - A small number of events during commissioning
  - More during full science operations – statistics are much higher than for a ground-based site

SOFIA predictions: SNRs



SOFIA predictions: event statistics



Conclusions

- Stellar occultations provide detailed information about specifically targeted TNOs

- Prediction and observation techniques have become accurate enough for successful observations of increasingly small (and/or distant) objects

- Instrumentation coming online (e.g. MORIS, SOFIA) increases our chances for obtaining excellent data

- In the near future (next few years), we hope to characterize a handful of objects

unknown: accurate positions for most TNOs