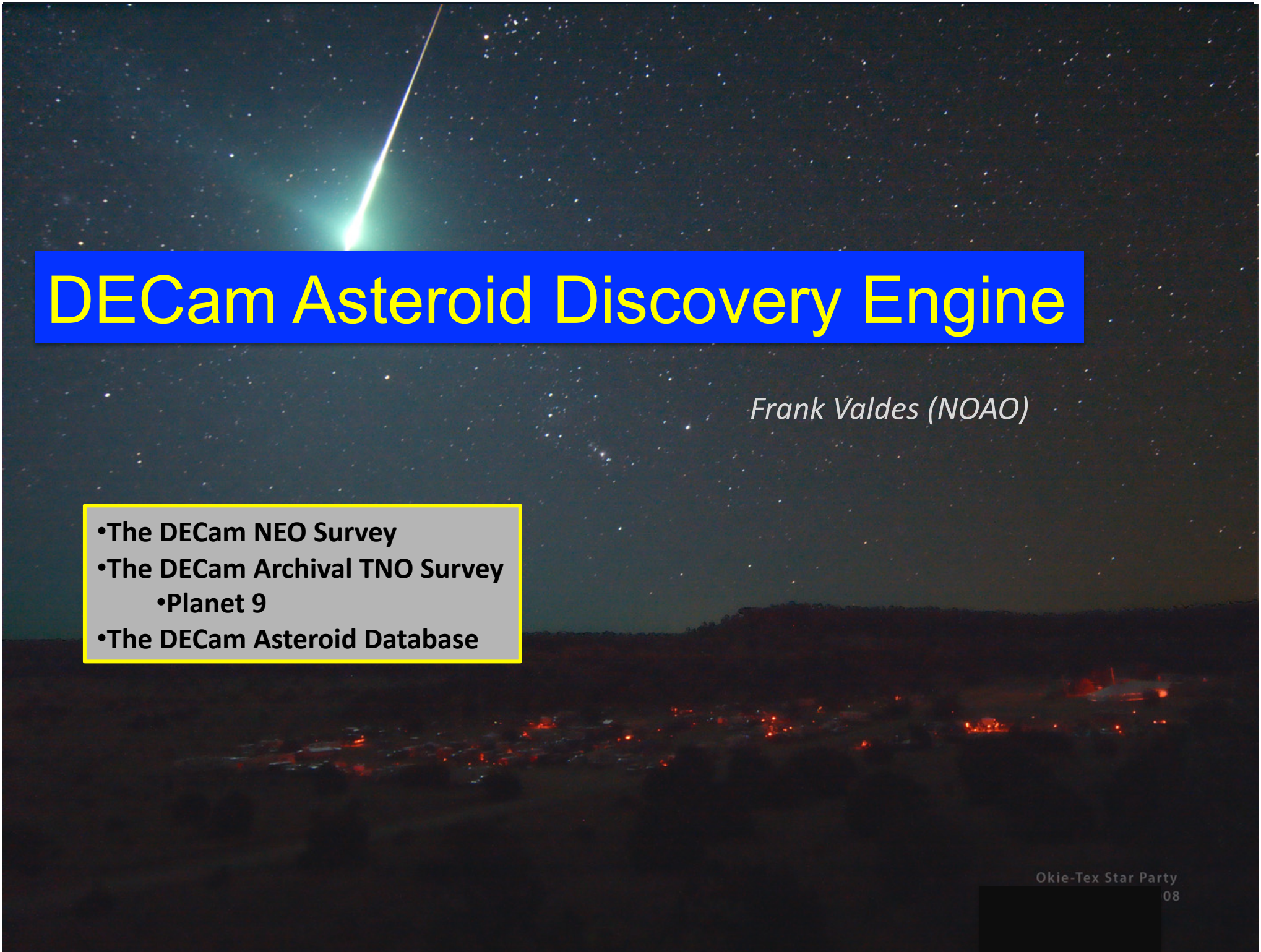
DECam: An Asteroid Discovery Machine

Frank Valdes (NOAO)

The DECam Community

DECam explores the Solar system

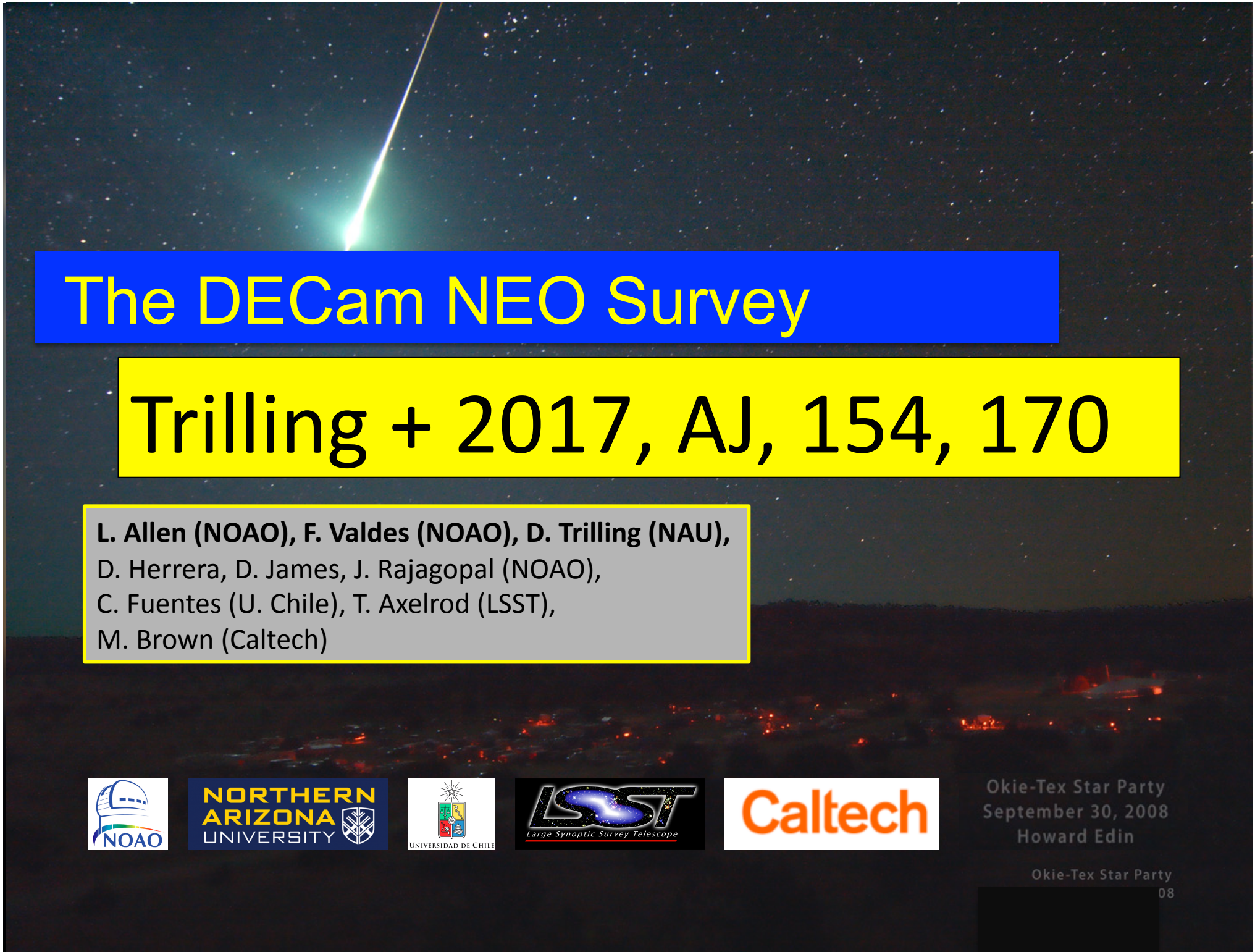
2016ApJ...827L..24C	Chen, Y.T., et al, 2016, 827, 24, "Discovery of a New Retrograde Trans-Neptunian Object: Hint of a Common Orbital Plane for Low Semimajor Axis, High-inclination TNOs and Centaurs"
2017MNRAS.467L..66D	de León, J., de la Fuente Marcos, C., de la Fuente Marcos, R. 2017, MNRAS, 467, L66, "Visible spectra of (474640) 2004 VN₁₁₂-2013 RF₉₈ with OSIRIS at the 10.4 m GTC: evidence for binary dissociation near aphelion among the extreme trans-Neptunian objects"
2017ApJ...839L..15G	Gerdes, D. W., … Walker, A. R., … Abbott, T. M. C., … James, D. J., … Smith, R. C., et al. 2017, ApJ, 839, L15, "Discovery and Physical Characterization of a Large Scattered Disk Object at 92 au"
2016AJ....152..147L	Lin, H. W., et al. 2016, AJ, 152, 147, "The Pan-STARRS 1 Discoveries of Five New Neptune Trojans"
2017AJ....153...38M	Meisner, A. M., Lang, D., Schlegel, D. J. 2017, AJ, 153, 38, "Full-depth Coadds of the WISE and First-year NEOWISE-reactivation Images"
2016AJ....152...63N	Nugent, C.R., et al. 2016, AJ, 152, 63, "NEOWISE Reactivation Mission Year Two: Asteroid Diameters and Albedos"
2016AJ....152..221S	Sheppard, S. S., Trujillo, C. 2016, AJ, 152, 221, "New Extreme Trans-Neptunian Objects: Toward a Super-Earth in the Outer Solar System"
2015AJ....149...44S	Sheppard, S., Trujillo, C. 2015, AJ, 149, 44, "Discovery and Characteristics of the Rapidly Rotating Active Asteroid (62412) 2000 SY178 in the Main Belt"
2016ApJ...825L..13S	Sheppard, S.S., Trujillo, C., Tholen, D.J. 2016, ApJL, 825, 13, "Beyond the Kuiper Belt Edge: New High Perihelion Trans-Neptunian Objects with Moderate Semimajor Axes and Eccentricities"
2014Natur.507..471T	Trujillo, C.A., Sheppard, S.S. 2014, Natur, 507, 471, "A Sedna-Like Body with a Perihelion of 80 Astronomical Units"
2017PASP..129c4402W	Waszczak, A., et al. 2017, PASP, 129, 034402, "Small Near-Earth Asteroids in the Palomar Transient Factory Survey: A Real-Time Streak-detection System"



DECam Asteroid Discovery Engine

Frank Valdes (NOAO)

- **The DECam NEO Survey**
- **The DECam Archival TNO Survey**
  - **Planet 9**
- **The DECam Asteroid Database**



The DECam NEO Survey

Trilling + 2017, AJ, 154, 170

L. Allen (NOAO), F. Valdes (NOAO), D. Trilling (NAU),
D. Herrera, D. James, J. Rajagopal (NOAO),
C. Fuentes (U. Chile), T. Axelrod (LSST),
M. Brown (Caltech)

Okie-Tex Star Party
September 30, 2008
Howard Edin

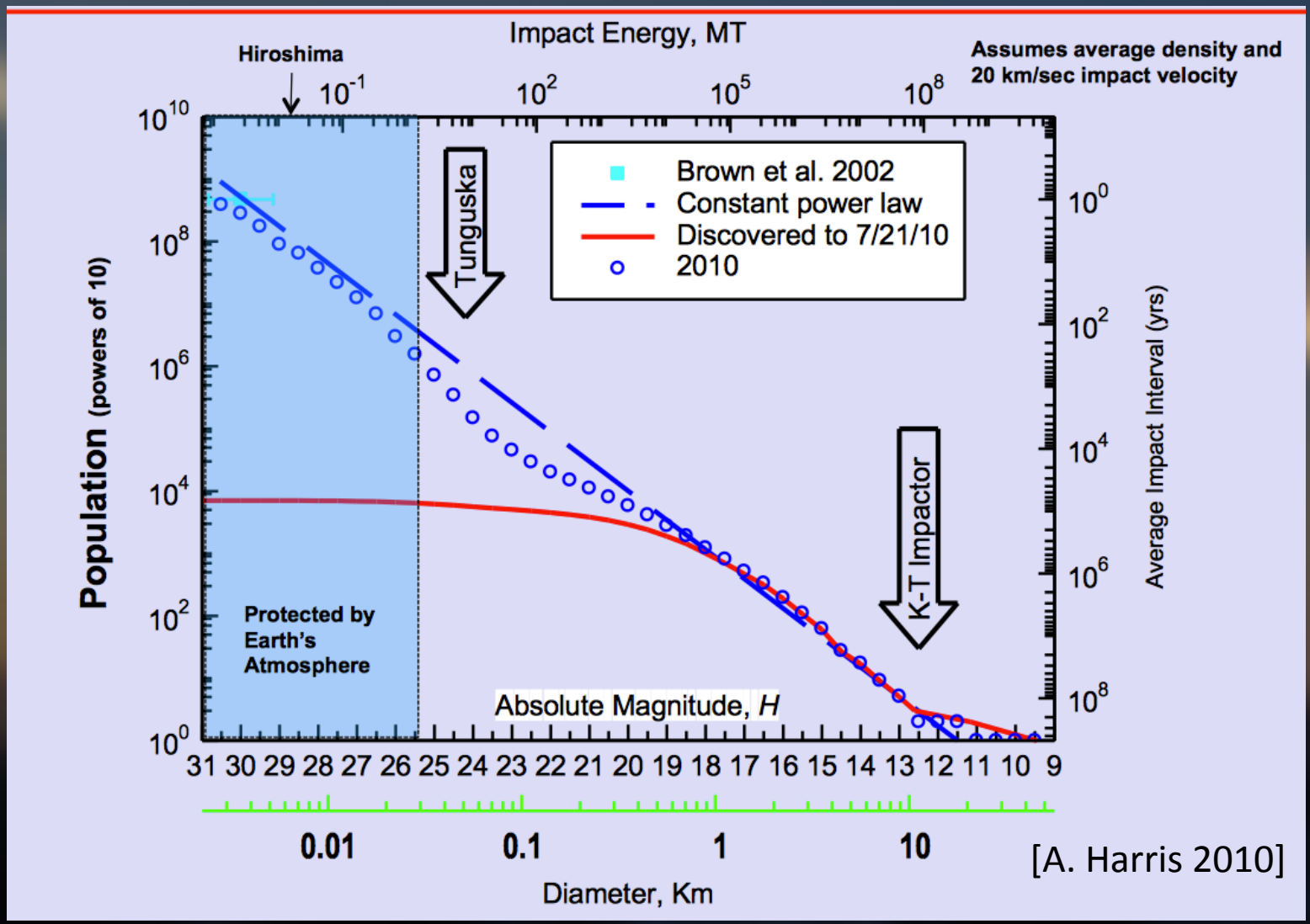

Exploding Death Rocks from
Outer Space:
Finding Near-Earth Objects
before they find us!

Chelyabinsk (15 Feb 2013)

- Diameter ~20 m
- Exploded 25km up
- ~ 1500 injuries
- Pop. unknown

Okie-Tex Star Party
September 30, 2008
Howard Edin

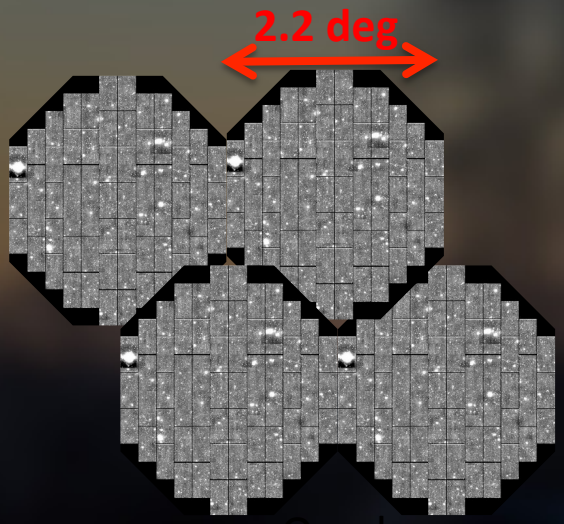
NEOs by Size, Brightness, Impact Energy



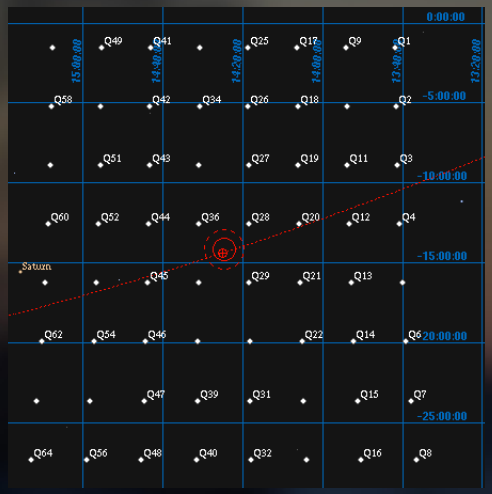
[A. Harris 2010]

NEO Survey Observations

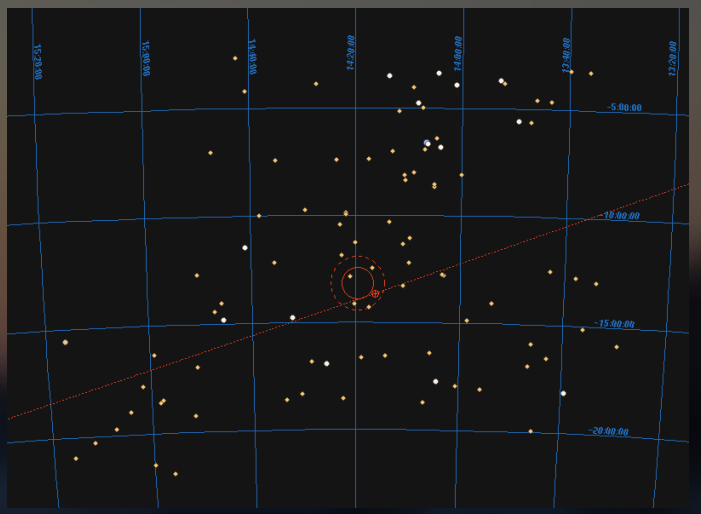
- DECam Survey: 30 nights over 3 semesters
- Cover >340 sq. deg. in ~600 exposures per full night
- 40 sec. exposures in VR filter (5σ = 23.5 mag)
- 5 exposures per field with 5 minute cadence = 1 “quad”
- repeat fields on 2nd and 3rd (and 4th…) night



Quad

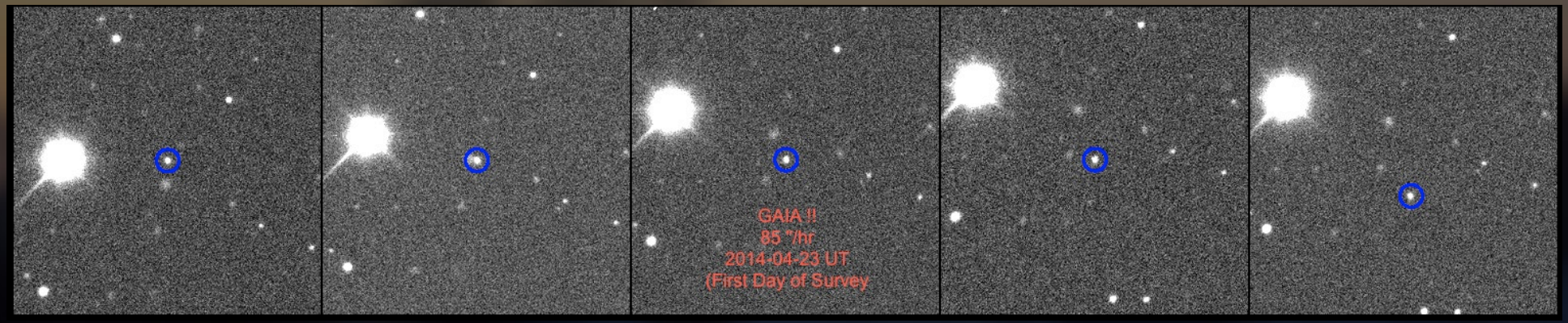


Map grid


Detected moving objects

Data Handling

- 1.2 Gb/exposure, ~600 exp/night, ~0.72 Tb/night
- Transported to Tucson immediately
- Calibrated using NOAO Community Pipeline (CP)
  - "quad by quad" processing
- Tracklets found with the CP Moving Object Detection System
  - Valdes (2014)
- Results reviewed and reported to Minor Planet Center (MPC)



Moving Object Detections

- Median stack + difference images for each pointing
  - Catalog sources in difference images (exposure - median)
  - Pre-filter for common sources of contamination
  - Form pairs within the range of desired motions; require similarity (mag, shape, …)
  - Extend motion calculated from pairs to position at a common epoch
  - Cluster positions to identify tracklet
  - Filter based on moving object signature to eliminate non-physical groupings

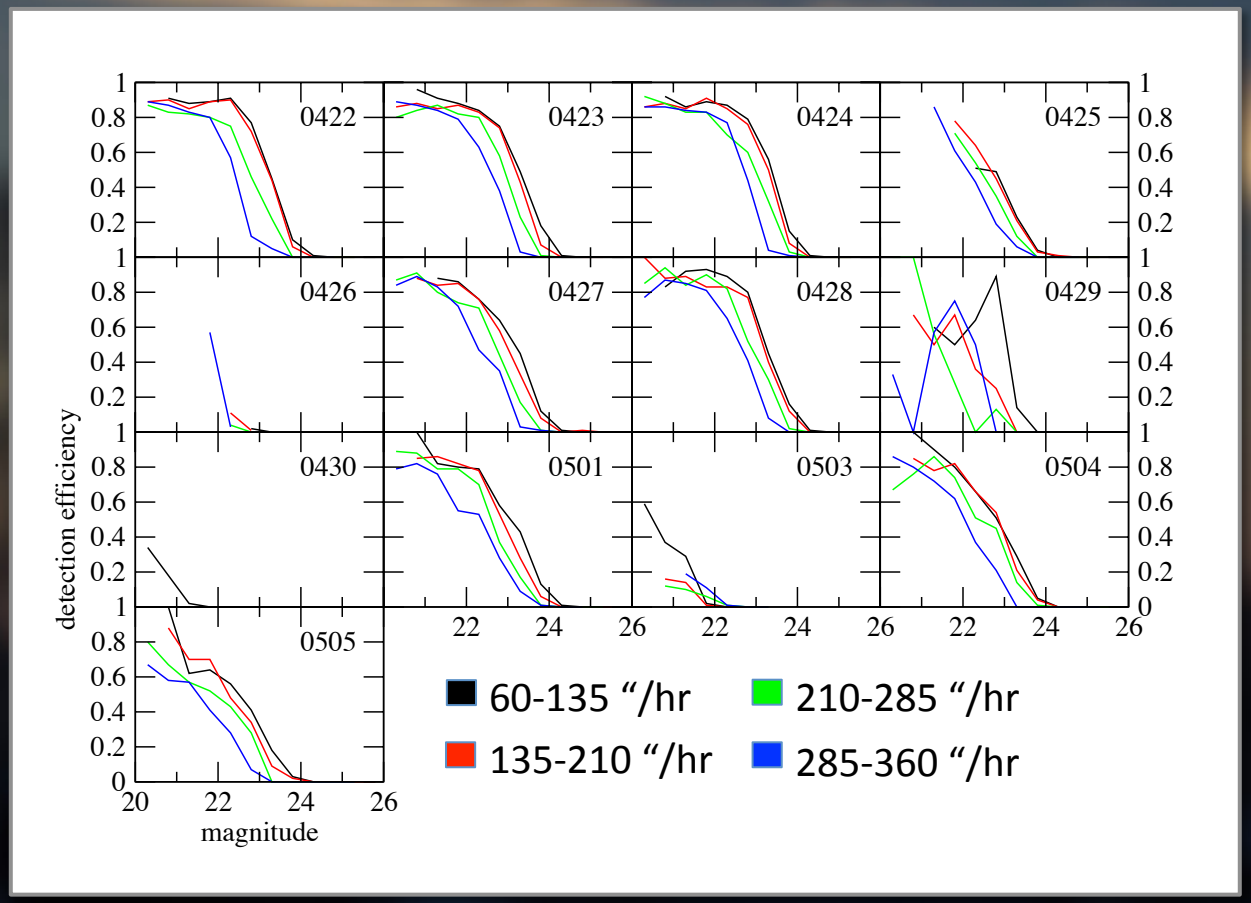
Identifying NEOs

- Create cutouts
- Use MPC **`digest2`** program (>40%) ➔ detections of interest (NEO's, Trojans, Centaurs and unusual motions)
- Visually review NEOs to eliminate remaining contamination
  - Virtually all 4 & 5 exposure detections are real
  - A small fraction (<10%) of 3-exposure detections are real (work continues to eliminate contamination automatically)
- Report to MPC
- MPC provides linkages and enables follow-up by community

Detection efficiency

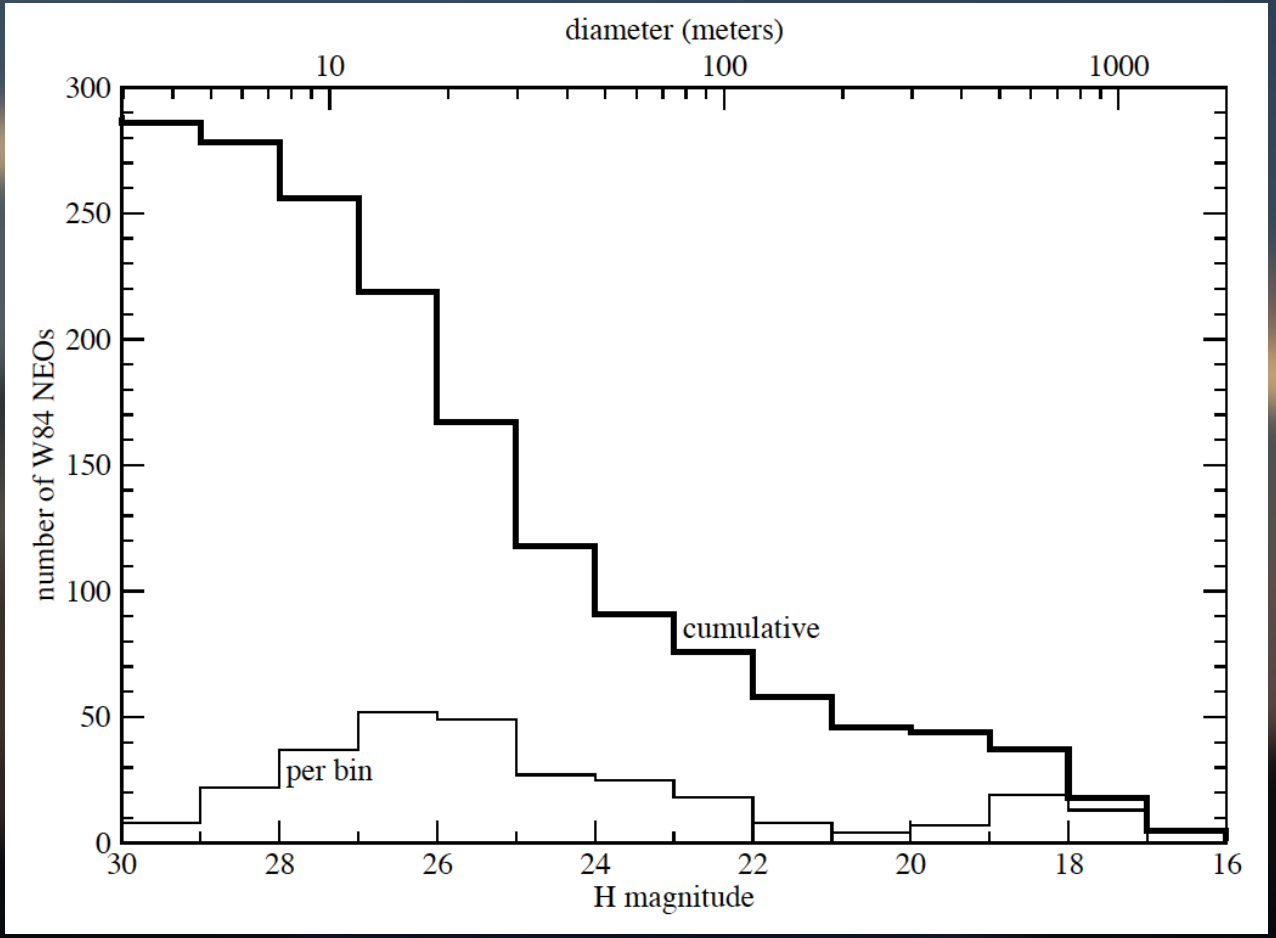
- Add simulated asteroids to data (~70/exposure)
  - Use each exposure's image quality
  - Distributions provide sampling at all magnitudes and NEO rates

Efficiency functions for all nights of 2014 April-May observing run, based on the injection and recovery of many thousands of synthetic objects.

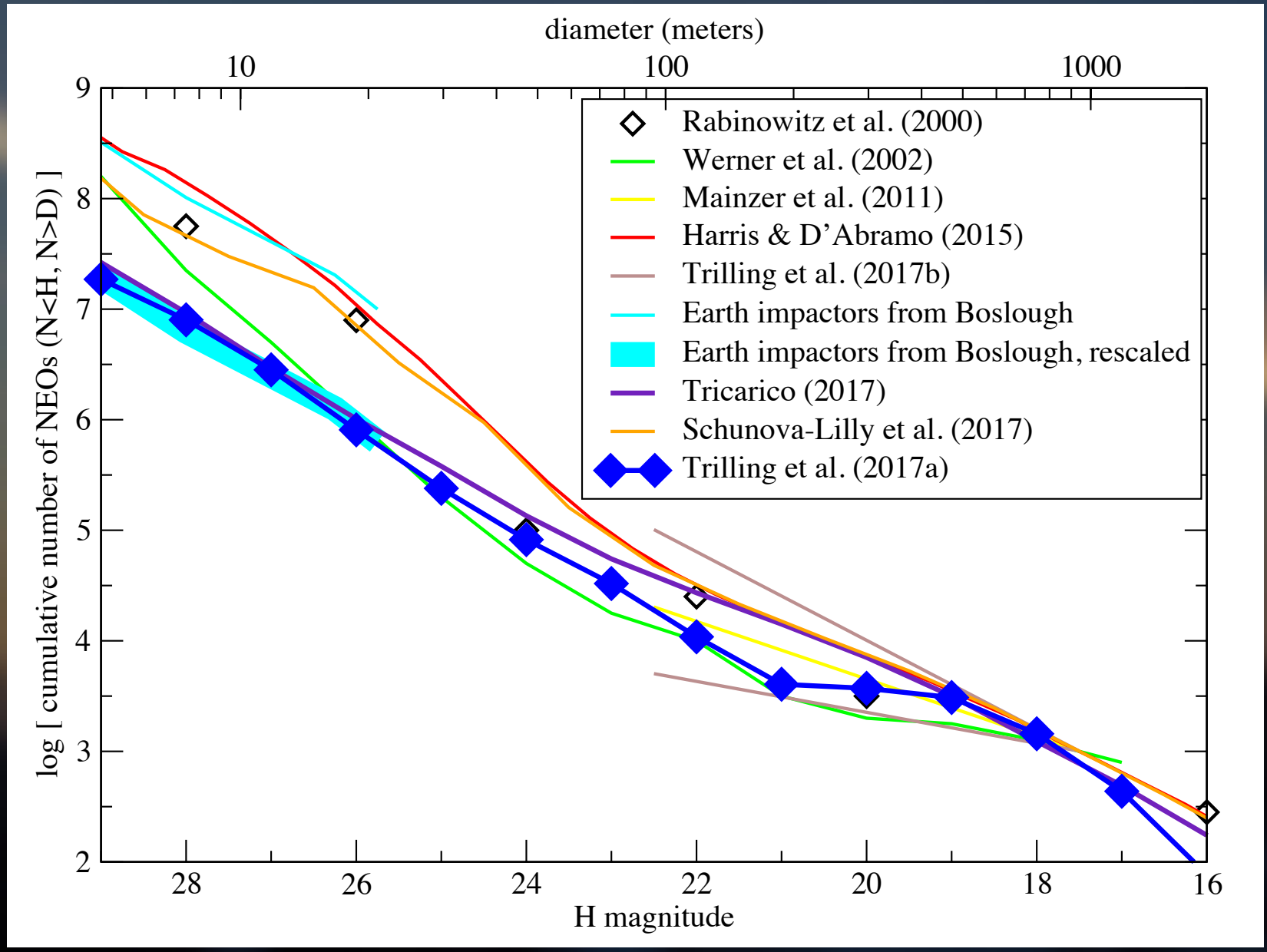


Size distribution

H magnitude distribution of all detected NEOs. Top axis shows diameter (m), assuming albedo=0.2. Thin line = number of objects per (0.5mag) bin; thick line = cumulative number brighter than a given H.

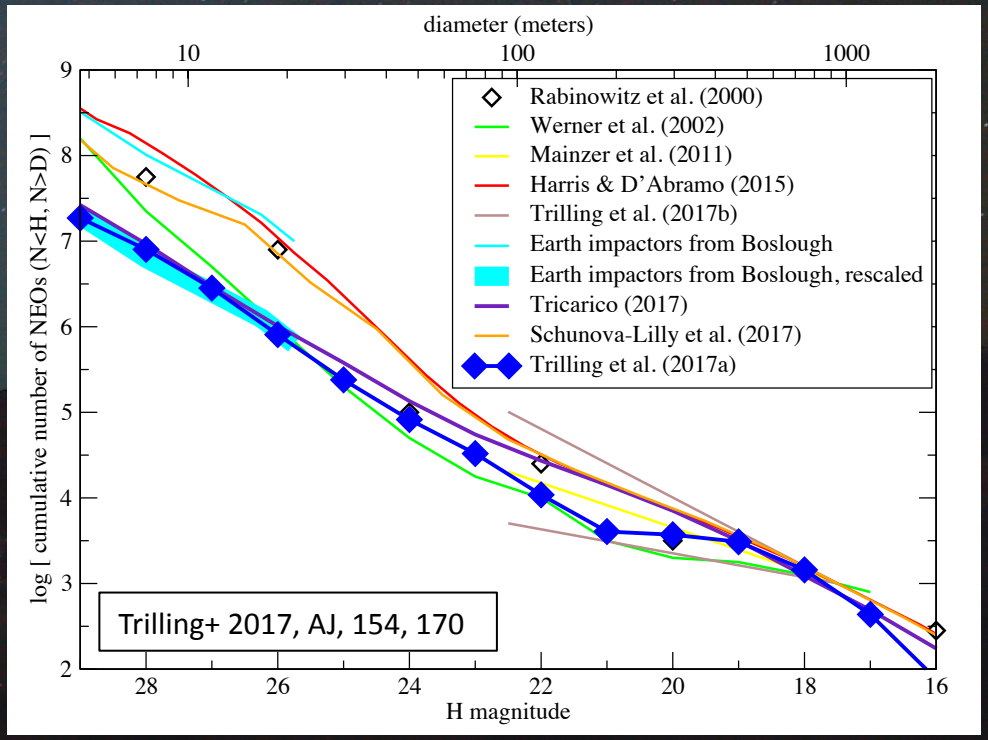


Size distribution of NEOs

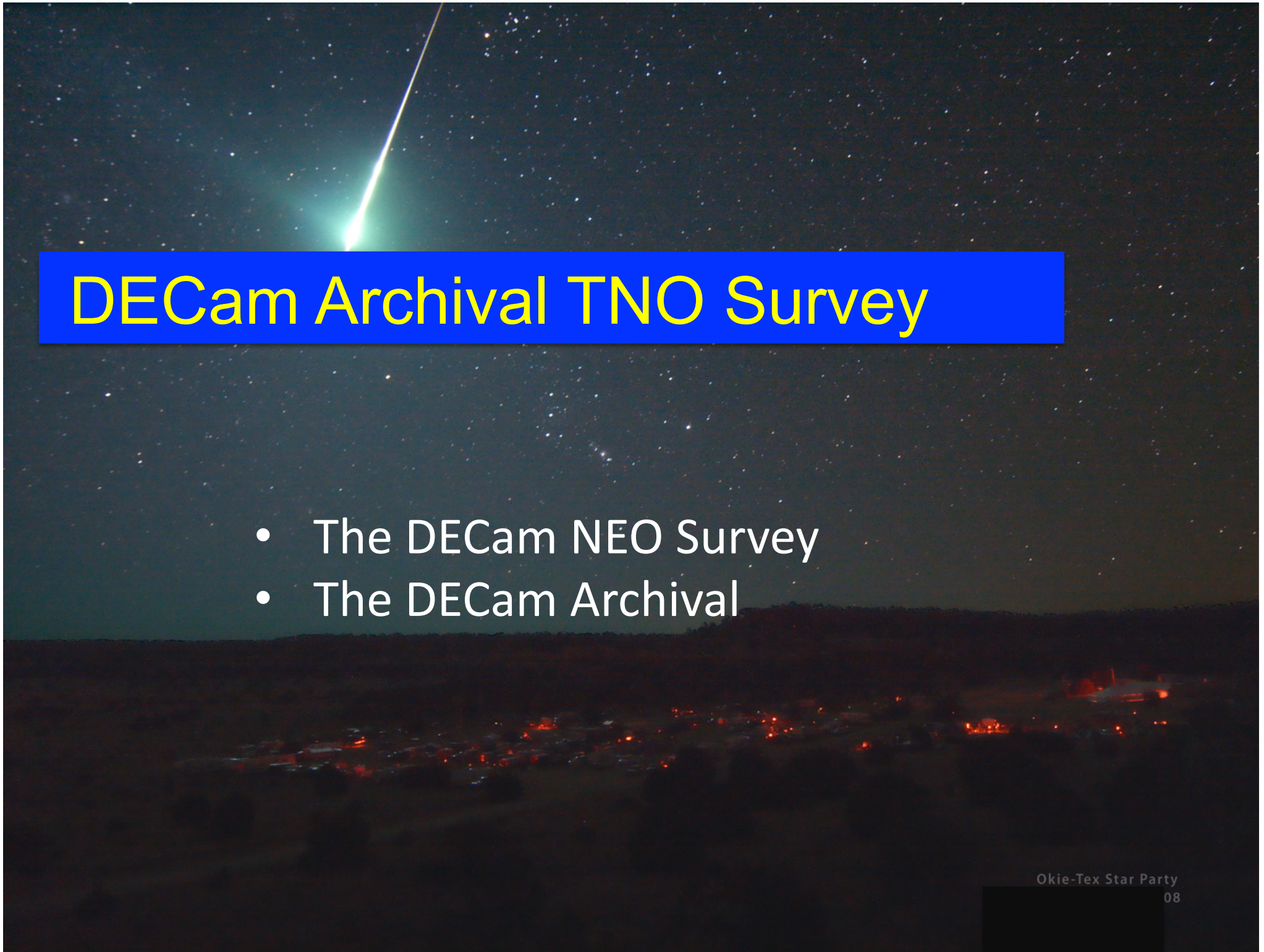


Summary

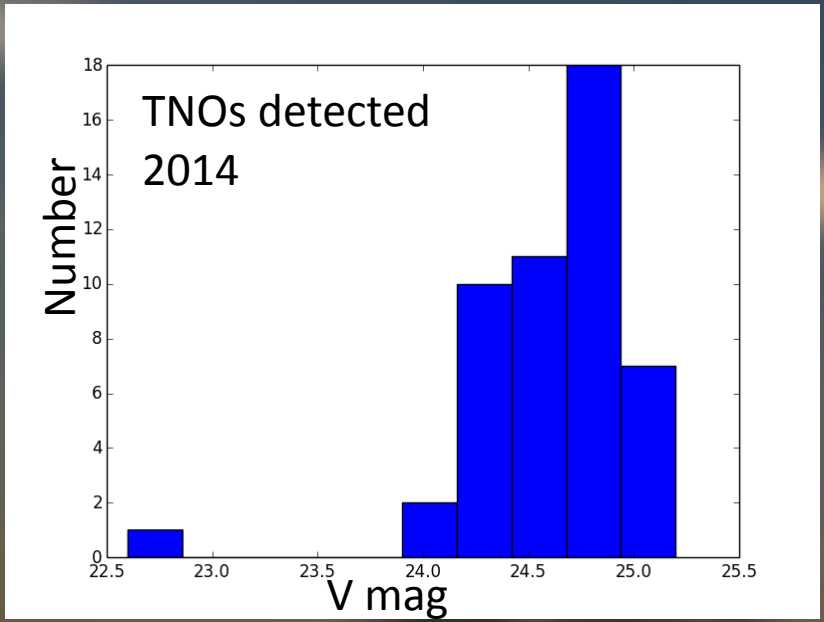
- $10^{6.6}$ +/- 10% NEOs larger than 10 +/- 4 meters
- Implied impact risk for Chelyabinsk-sized object 10x less than previous estimates (e.g. Boslough et al. 2015)
- 20 more nights of data to be added
- More data mining to do (undesignated NEO, MBA, TNO, other transients)

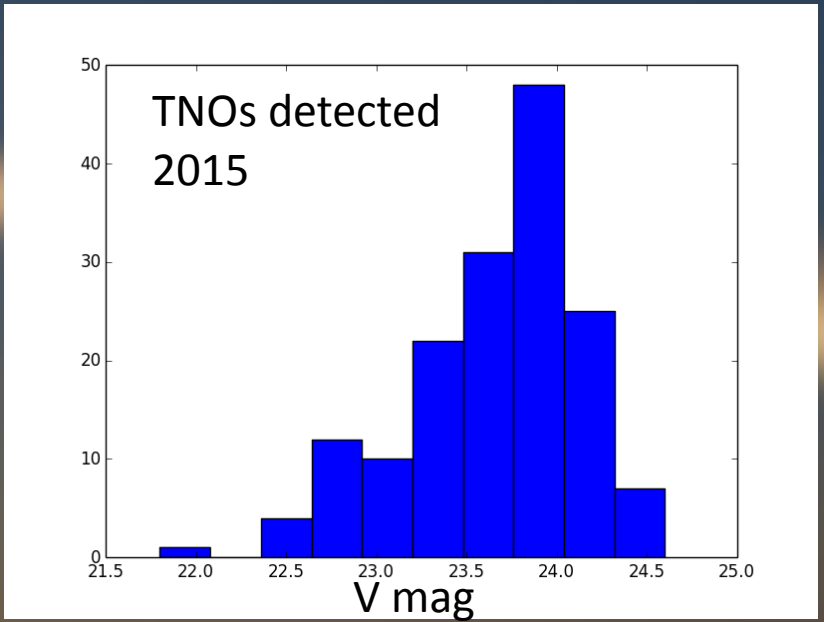


Okie-Tex Star Party
September 30, 2008
Howard Edin


DECam Archival TNO Survey
• The DECam NEO Survey
• The DECam Archival
Okie-Tex Star Party
08

TNOs from the NEO Survey





- TNOs (known/discovered?) submitted to MPC
  - 2014: 6/49
  - 2015: 31/160
  - 2016: 9/57

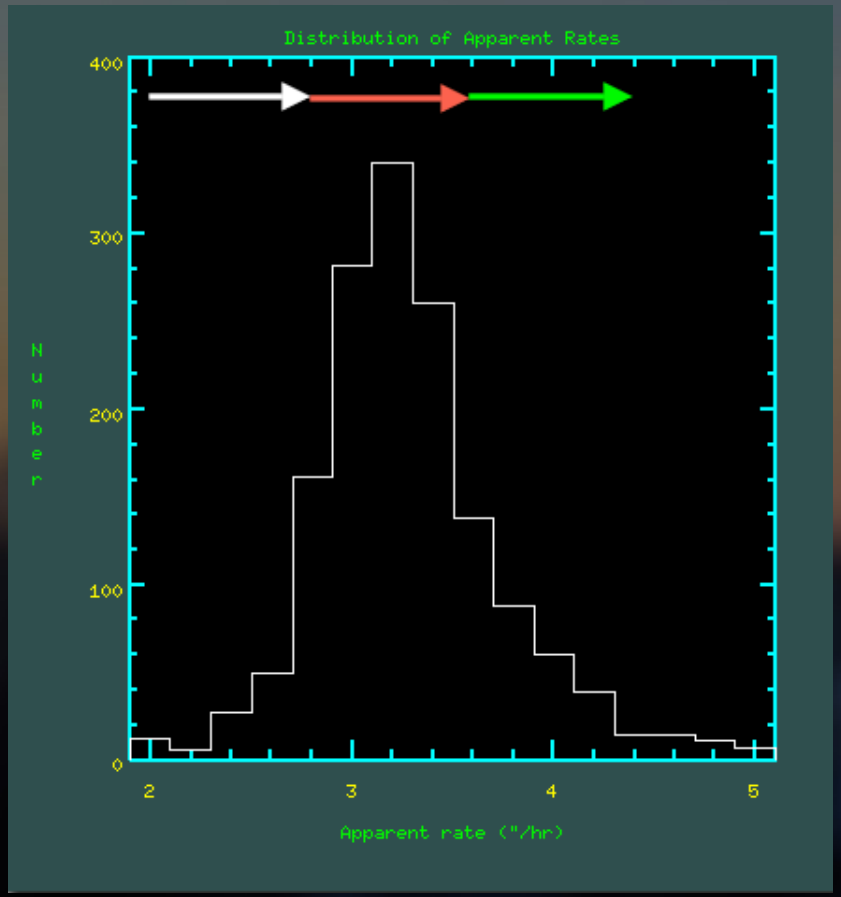
TNOs from the DECam Archive

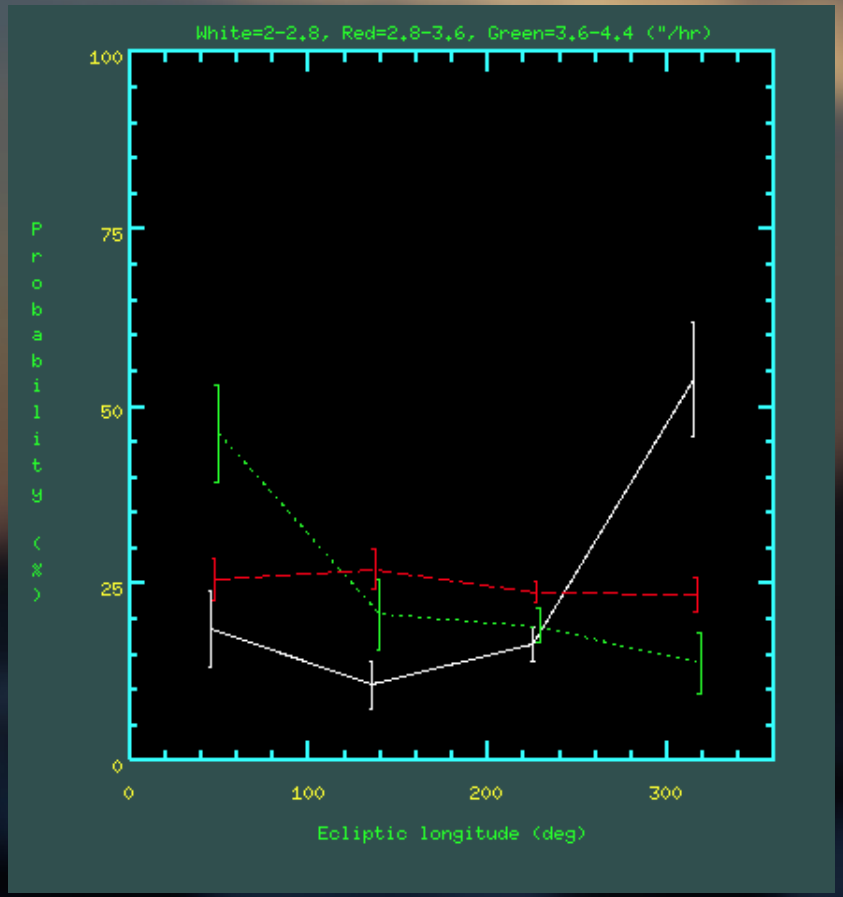
- Create a query to select datasets suitable for MODS over all the DECam exposures
  - several different experiments with different ways to select datasets
- Run through the CP with MODS turned on
  - several different experiments with different tuning
  - most recent with artificial sources added
- Detect TNOs and add to DAD

There are many caveats!

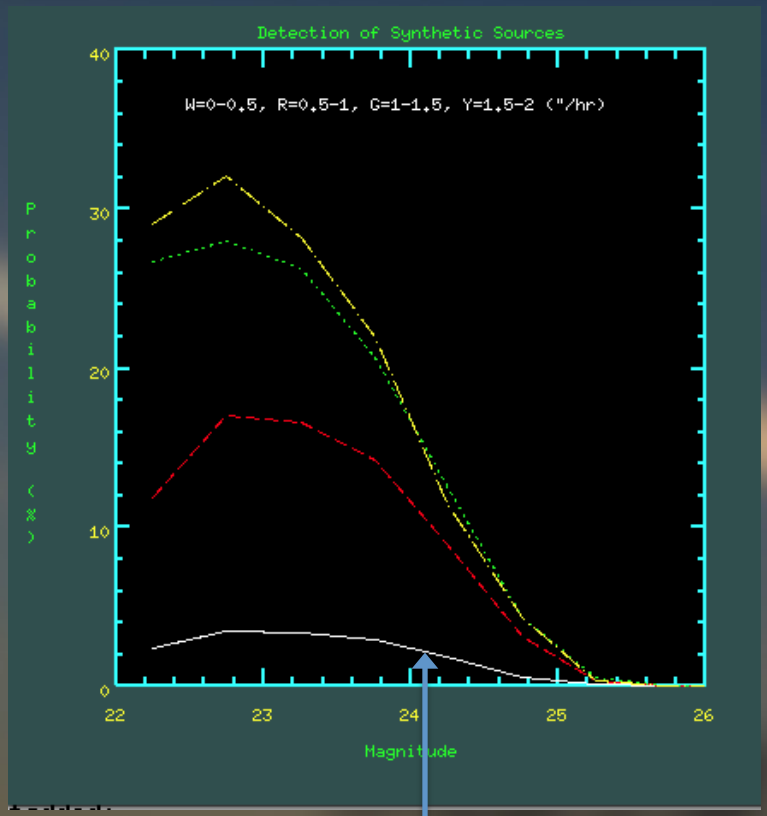
- Very inhomogeneous except for certain surveys and even then variable conditions strongly affect detection statistics.
- Detections come from a particular algorithm (MODS):
  - differences (exposure – median) with no PSF matching
  - limits on maximum position difference
  - detections are VERY dependent on conditions and variations between exposures
- There is no linkages of tracklets so, depending on the program, tracklets over-count asteroids
- The challenge for the SS is identifying suitable fields and groupings in an automatic way. There are many ways to segment the available archival data for MODS.
- DECam goes fainter than most dedicated programs (Pan-STARRS, Catalina) so follow up and orbit determination is hard; hence try and use large statistical numbers to make up for actual orbital parameters.

Distribution of apparent rates for slow moving tracklets. There is an assumption that a large majority are in the Kuiper Belt. There is an indication that the slowest and fastest objects have a spatial clustering along the ecliptic. The relative probability (%) is the likelihood of finding a tracklet in the rate bin *per DECam exposure* compared to other ecliptic areas in the same rate bin. Inserted synthetic sources are used as calibration for selection and detection effects. Error bars are root N.





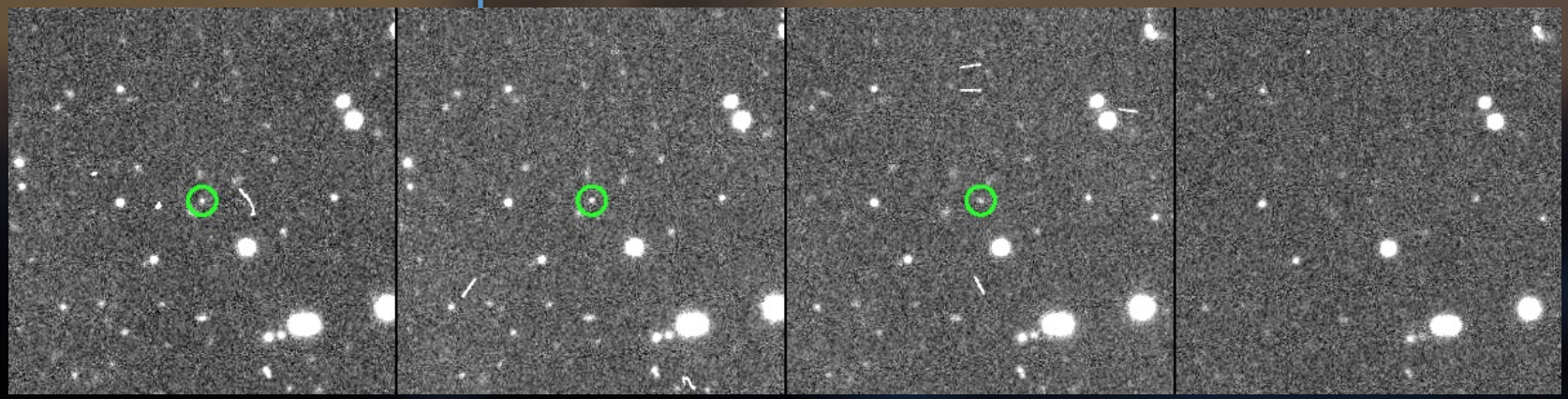
Planet 9



The serendipitous search for a very distant Planet 9 looks for a very slow apparent rate. Synthetic sources are used to estimate the sensitivity of the algorithm and the data used. The figure shows the recovery probability of sources slower than 2"/hr.

Conclusion: It is possible to find very slow sources but nothing distant was found in ~ 700 pointings (with the hours to consecutive night cadences).

0.22 "/hr over 2 nights with 75 min between pairs.
This is relatively good conditions.



DECam Asteroid Database

and education

- Asteroid database for data publication and many potential uses
  - Statistical studies
  - Education

Statistics: Total Tracklets = 663957

PI	Fields	Tracklets
Allen	3013	608829
Sheppard	611	48636
Forster	192	3353
Fuentes	191	1267
Dell'Antonio	19	433
Munoz	43	270
French	53	185
Carlin	16	140
Vivas	19	120
Rich	12	108
Sullivan	32	73
Saha	30	62
Trilling	22	59

PI	Fields	Tracklets
Yip	12	46
Geha	8	39
Frieman	24	39
Dai	23	35
Rest	20	35
Bonaca	4	32
Mamajek	13	30
Heinze	3	27
Crnojevic	14	22
Konstantopoulos	4	21
Hargis	3	18
Mackey	10	16
Taylor	13	16

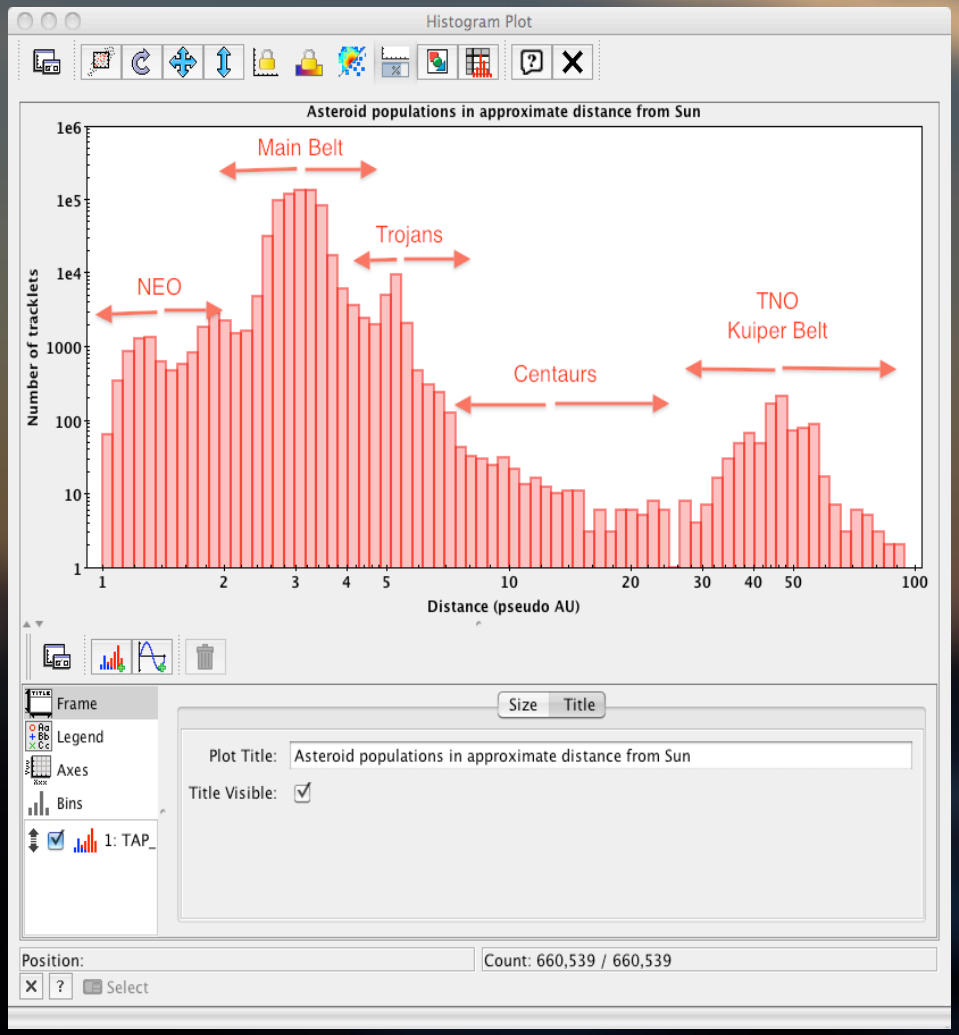
PI	Fields	Tracklets
McMonigal	4	10
Calamida	4	7
Walker	4	7
Sheen	1	6
Briceno	2	3
Rusu	1	2
McCleary	2	2
Penny	1	2
Curtin	2	2
NOAO	1	2
Schlegel	1	1
Yan	1	1
Geisler	1	1

Filter	Tracklets
VR	636107
r	23708
g	3701
i	253
z	124
u	52
Y	12

The Allen program is mostly main belt and NEOs with its short 40s x 5 min cadence.
The Sheppard programs are TNO with long cadences.

Education

- High School Teen Astronomy Café
  - http://dec01.tuc.noao.edu/NHPPS_DATA/Allen/doc/TAC1802/Part1.html
  - http://dec01.tuc.noao.edu/NHPPS_DATA/Allen/doc/TAC1802/Part2.html



Example TOPCAT plot from DAD through the NOAO Data Lab.

Pseudo distance is a function of the inverse apparent rate for illustration (see the link to Part2 for details.

Things to Do

- It is a challenge to connect this to the MPC database. I am looking forward to getting access to the version being developed at LPL.
- For the most recent (best) TNO pass through the archive a large number of artificial sources were embedded and detected. This dataset ~~will be added to DAD soon~~ has been added and used for statistical calibration. The NEO Survey has a synthetic source component that is not yet added.
- There are table fields that need to be populated (including entering datasets that produced no detections for statistical studies), a connection made to the cutouts through the Data Lab, many entries with main belt rates have not been visually checked so there is some level of false contamination.
- As always, documentation.