Solar System observations with the Zwicky Transient Facility

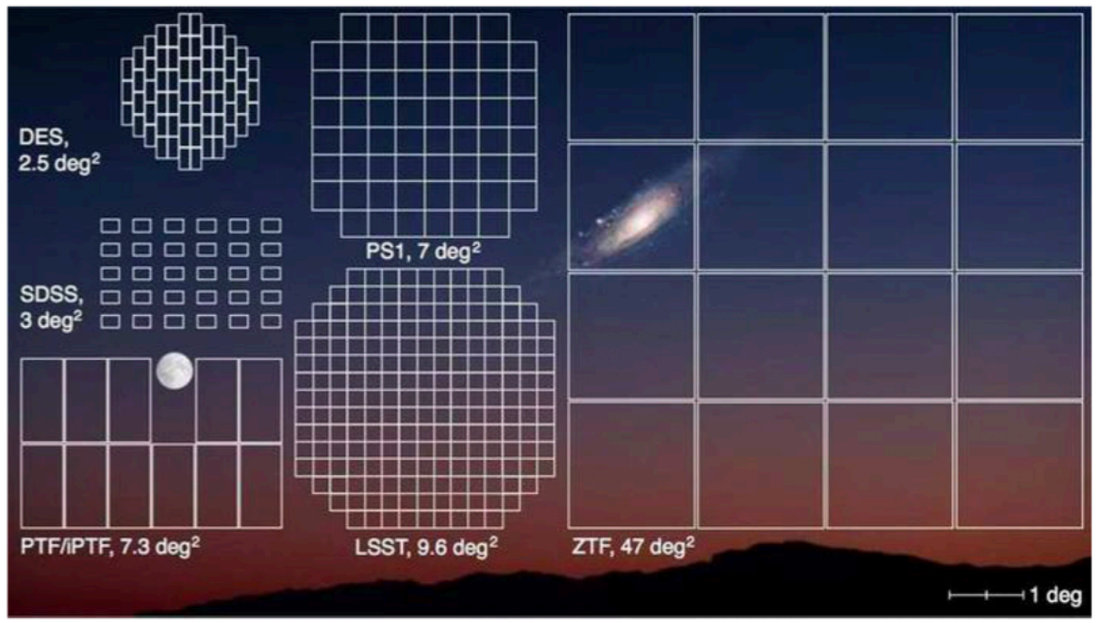
Bryce T. Bolin (CIT/IPAC), George Helou (IPAC), Tom Prince (CIT), Emily Kramer (JPL), Frank Masci (IPAC)

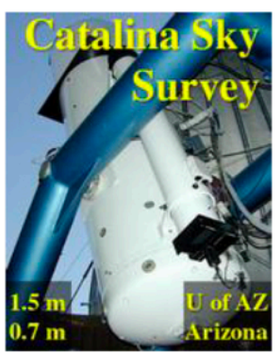
In collaboration with:

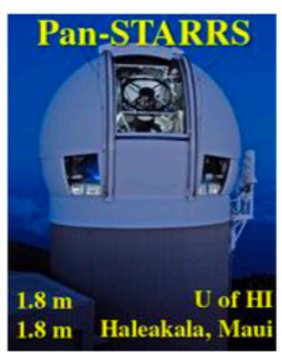
Robert Armstrong (LLNL), James Bauer (UMD), Dennis Bodewits (AU), Tony Farnham (UMD), Nate Golovich (LLNL) Wing-Huen Ip (NCU), Michael S. Kelley (UMD), Zhong-Yi Lin (NCU), Chow-Choong Ngeow (NCU), Quanzhi Ye (UMD), Travis Yeager (LLNL)

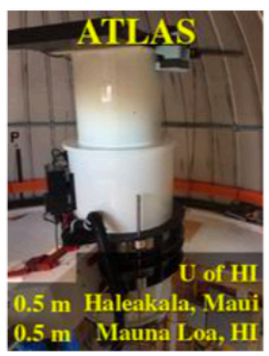
ZTF Team Meeting Oct 19 - 21, 2020

ZTF has an enormous field of view + moderate depth!







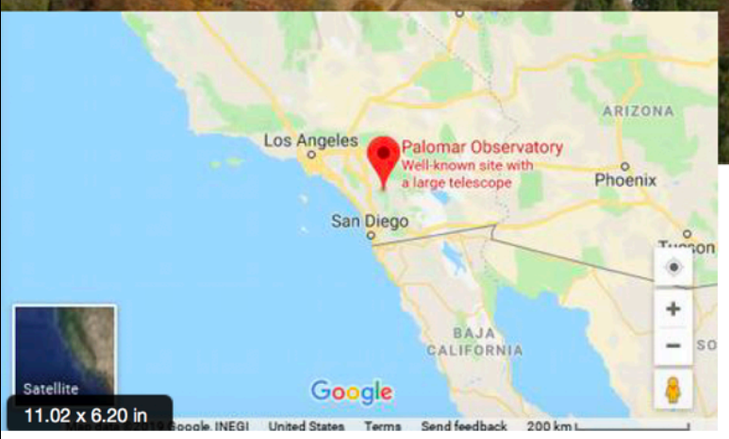


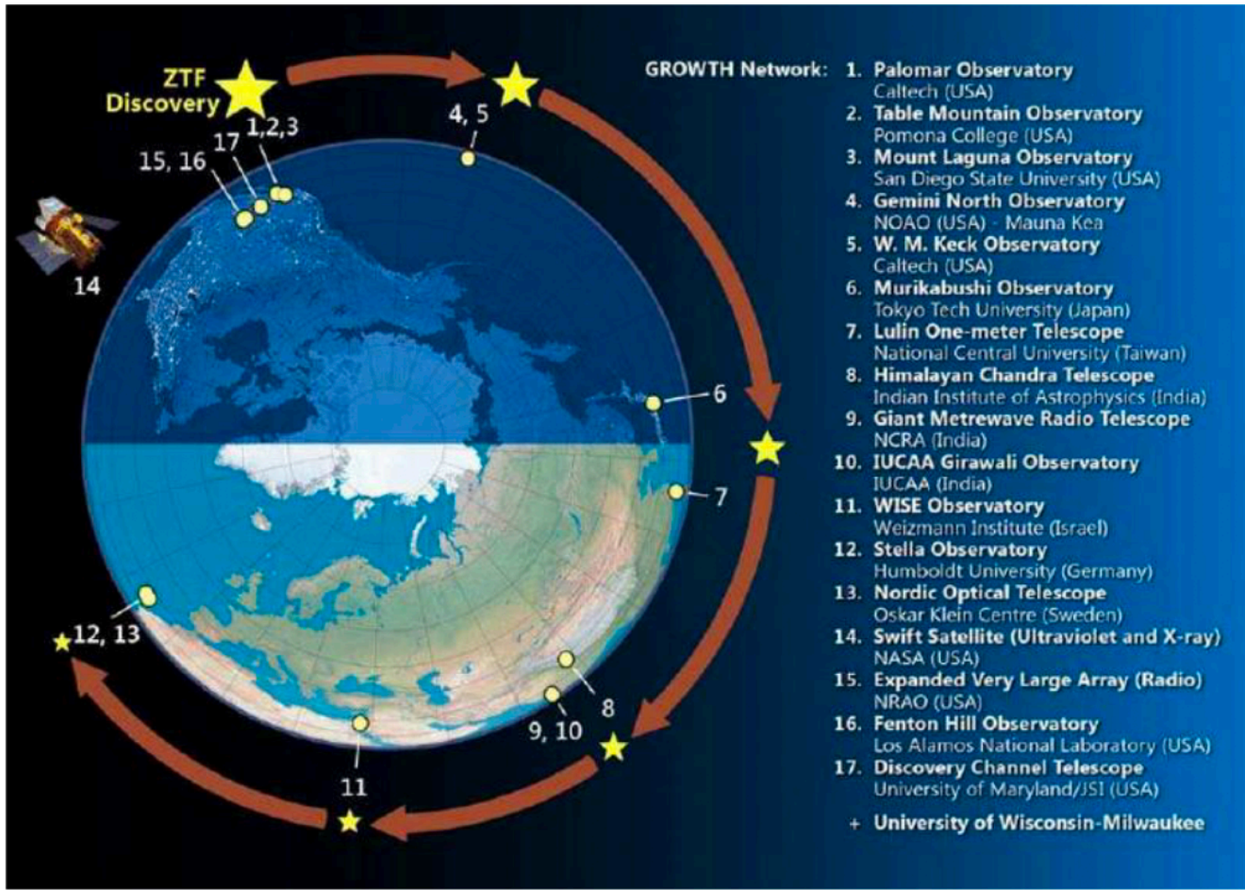
CSS 0.7-m

ATLAS 0.5-m (single system)

Surveys 3800 sq. deg/ h to r~20.5

ZTF is not alone!





Global Relay of Observatories Watching Transients Happen (GROWTH)

We can follow up NEO candidates with Palomar/GROWTH Assets

ZTF/GROWTH Solar System Science

- **Piggybacked** on other ZTF programs
- **Discover**, **characterize**, and **monitor** small bodies in the solar system
- Enable **rapid response** on transient events (NEO flybys, comet outbursts, active asteroids)
- **Twilight survey** specifically targeting small solar elongations during evening and morning twilight

NEO Discovery (Bolin, Helou, Kramer, Masci, Prince)

>180 NEOs discovered to date

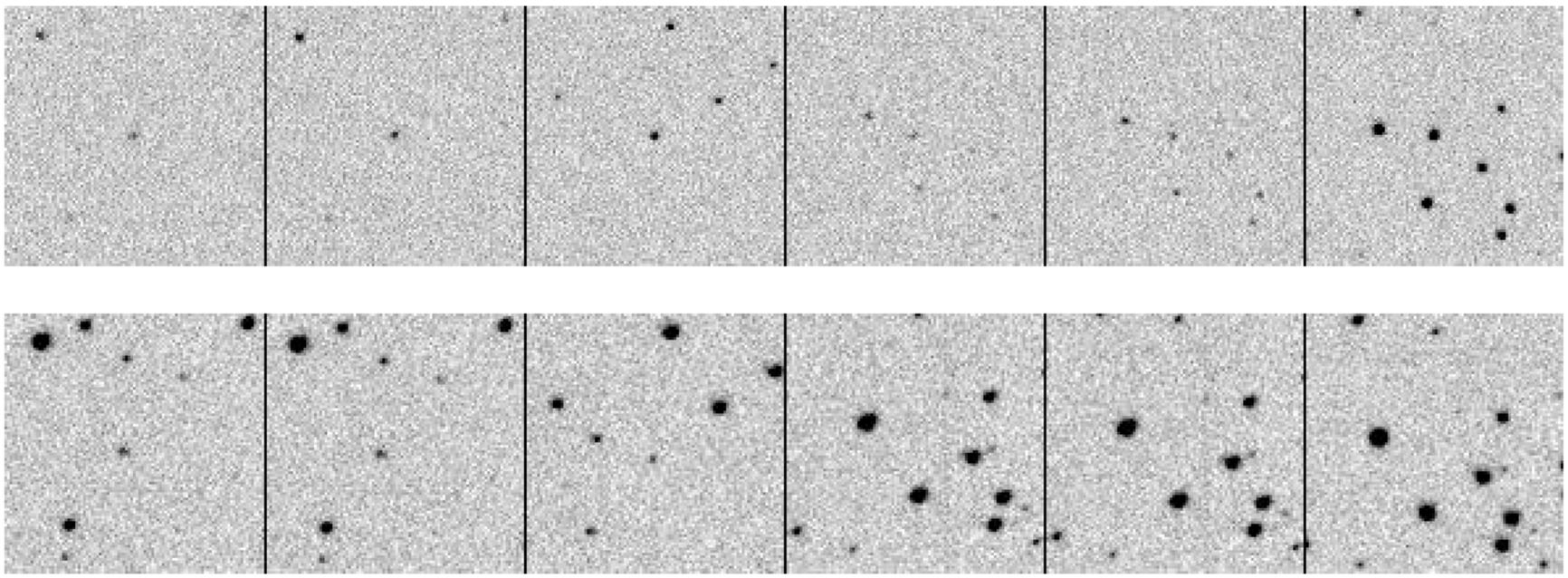
- ZMODE: detection of point-like moving object
  - Main-belt asteroids; distant NEAs; comets

Masci et al. 2019

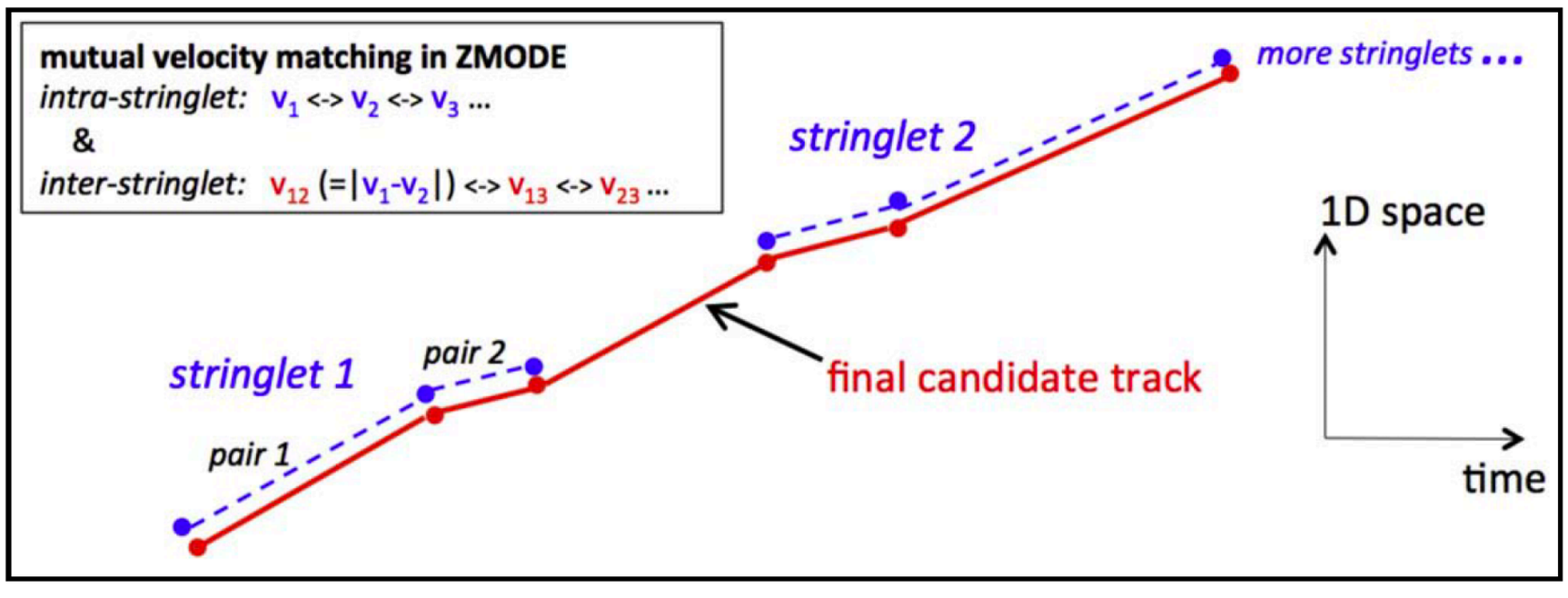
- ZSTREAK: detection of fast-moving objects (streaks)
  - Asteroids less than 0.01 au (~5 lunar distances) from the Earth
  - Also detect a lot of artificial satellites (a few dozens a night)
  - The new DeepStreaks algorithm reduced the false positive rate by 100x (thank you **Dima Duev** and **Ashish Mahabal**!)

ZMODE: Moving object detection

ZTF0002

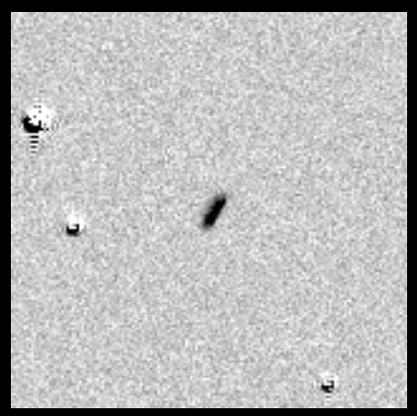


Digest2 score < 65, probable non-NEO



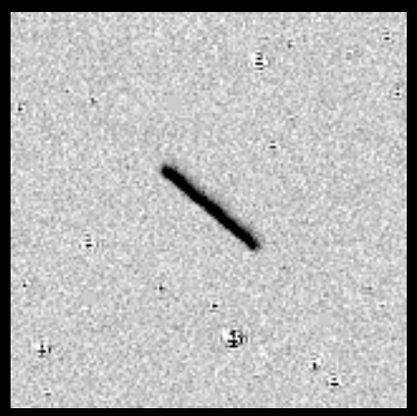
Masci et al. 2019

What do ZSTREAK detections look like?

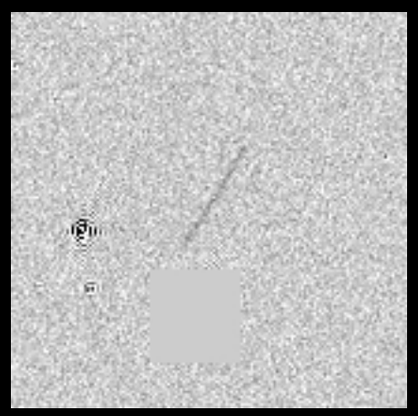


Asteroid 2018 KM1

Unkown object



Space debris

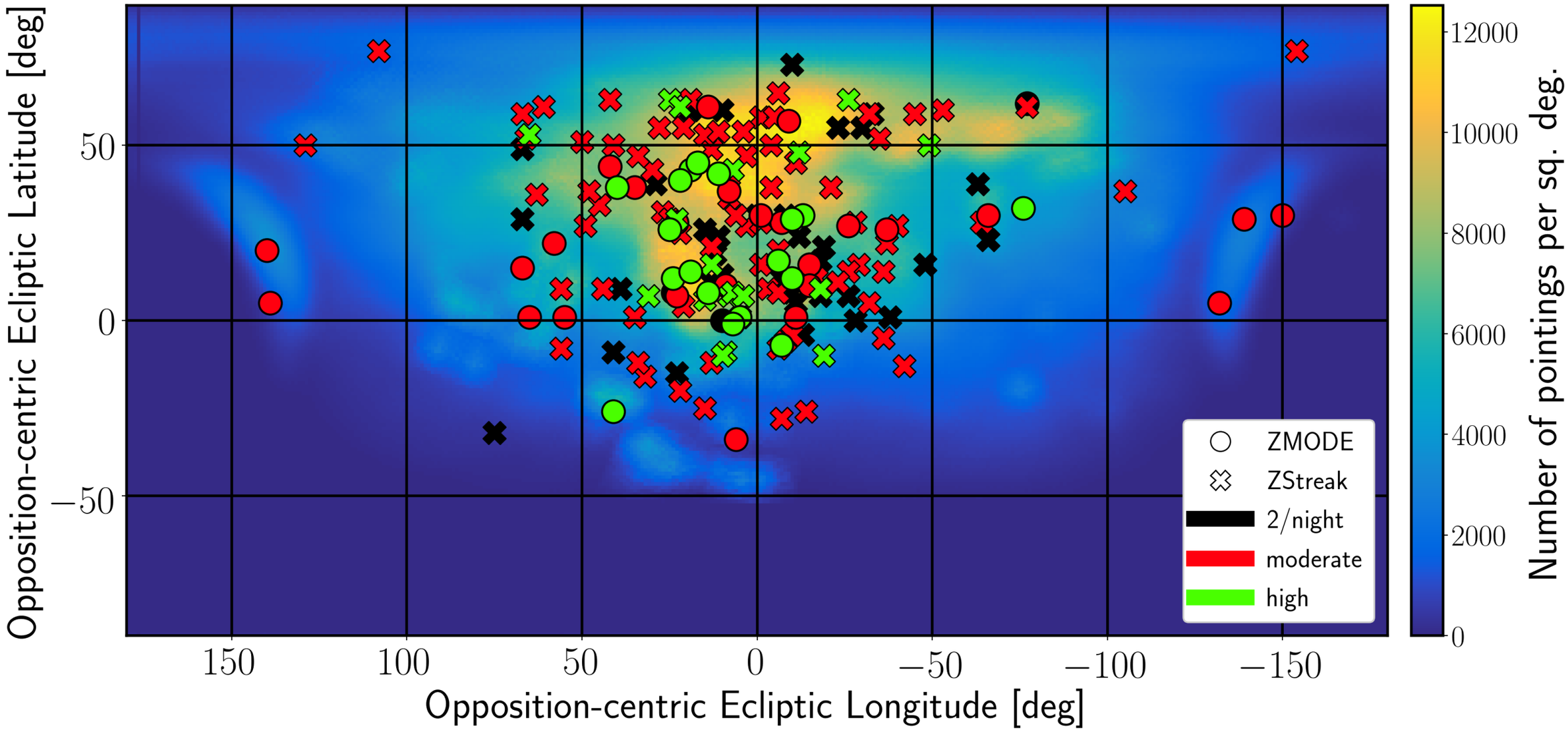


Unkown object

A real streak will look like a star smeared across the image. The edge should be soft due to atmospheric and optic effect on the light, and the width and brightness should be somewhat uniform. As ZTF has relatively short exposure time (30 seconds), a real asteroidal FMO usually does not extend beyond the size of the stamp (which is about 150 by 150 arcsec). Anything longer than that is most likely an artificial object.

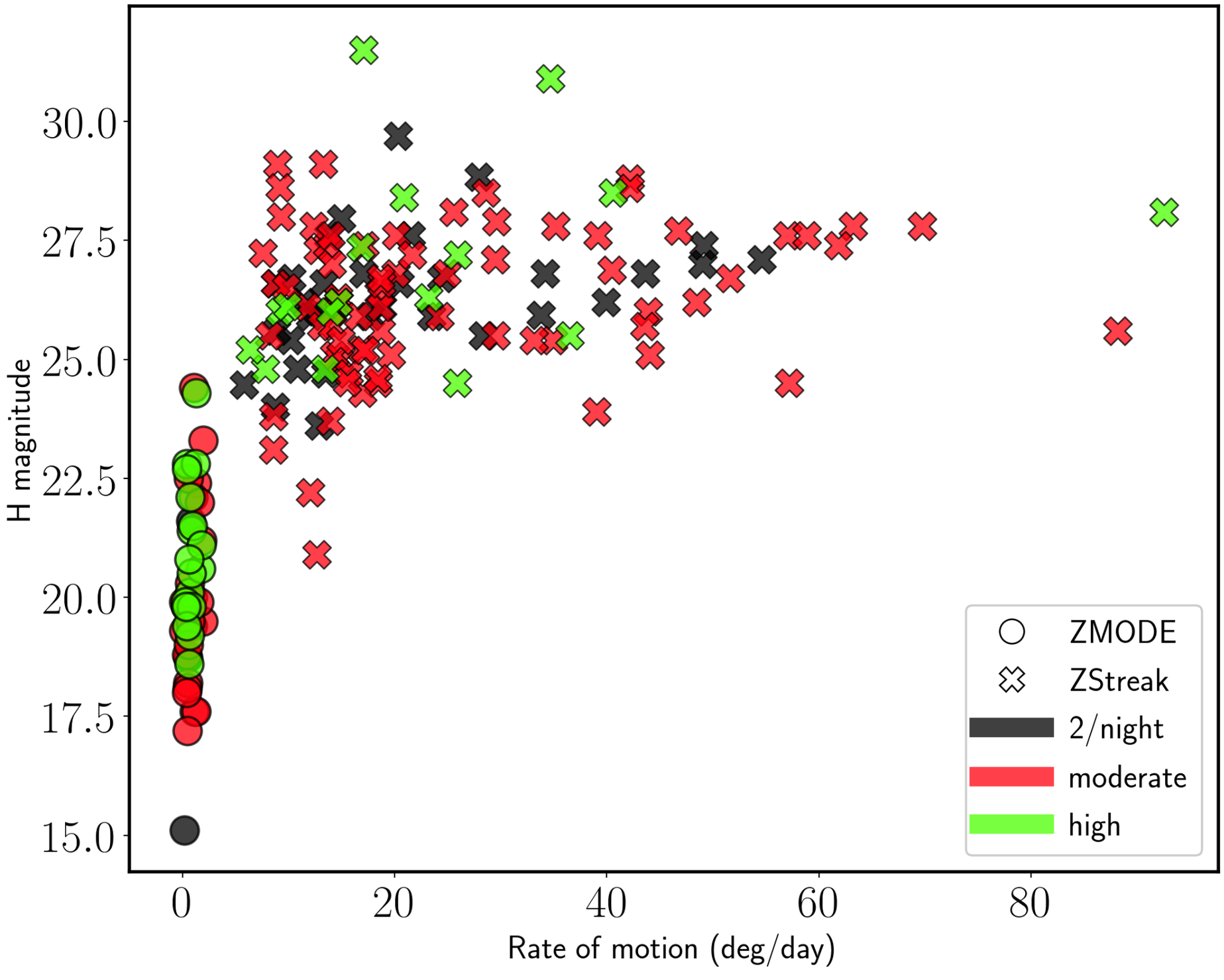
Waszczak et al. 2013, Ye et al. 2019, Duev et al. 2019

Skyplane Distribution



Bolin et al. in prep

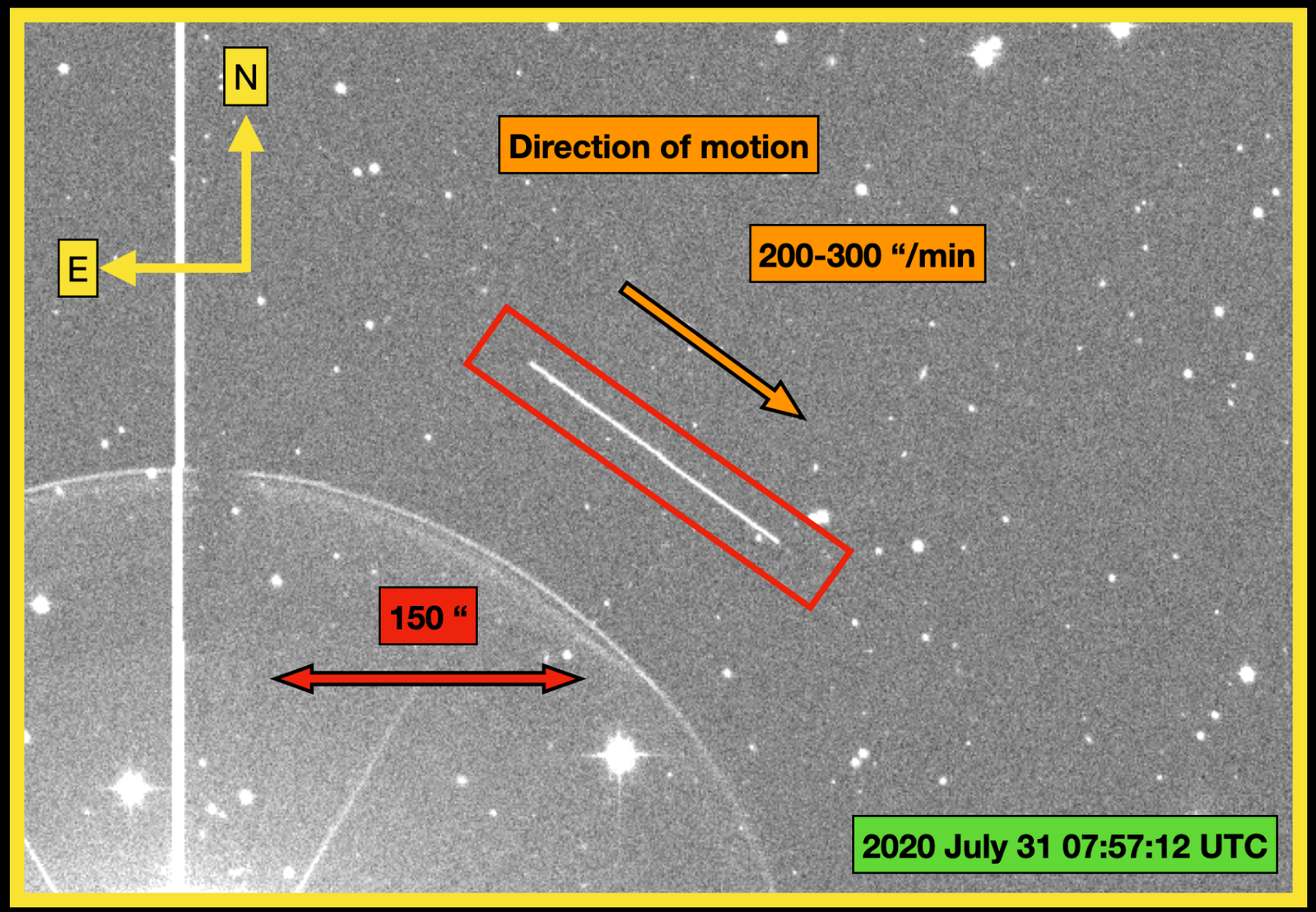
ZSTREAK Objects



Bolin et al. in prep

ZTF ZSTREAKS

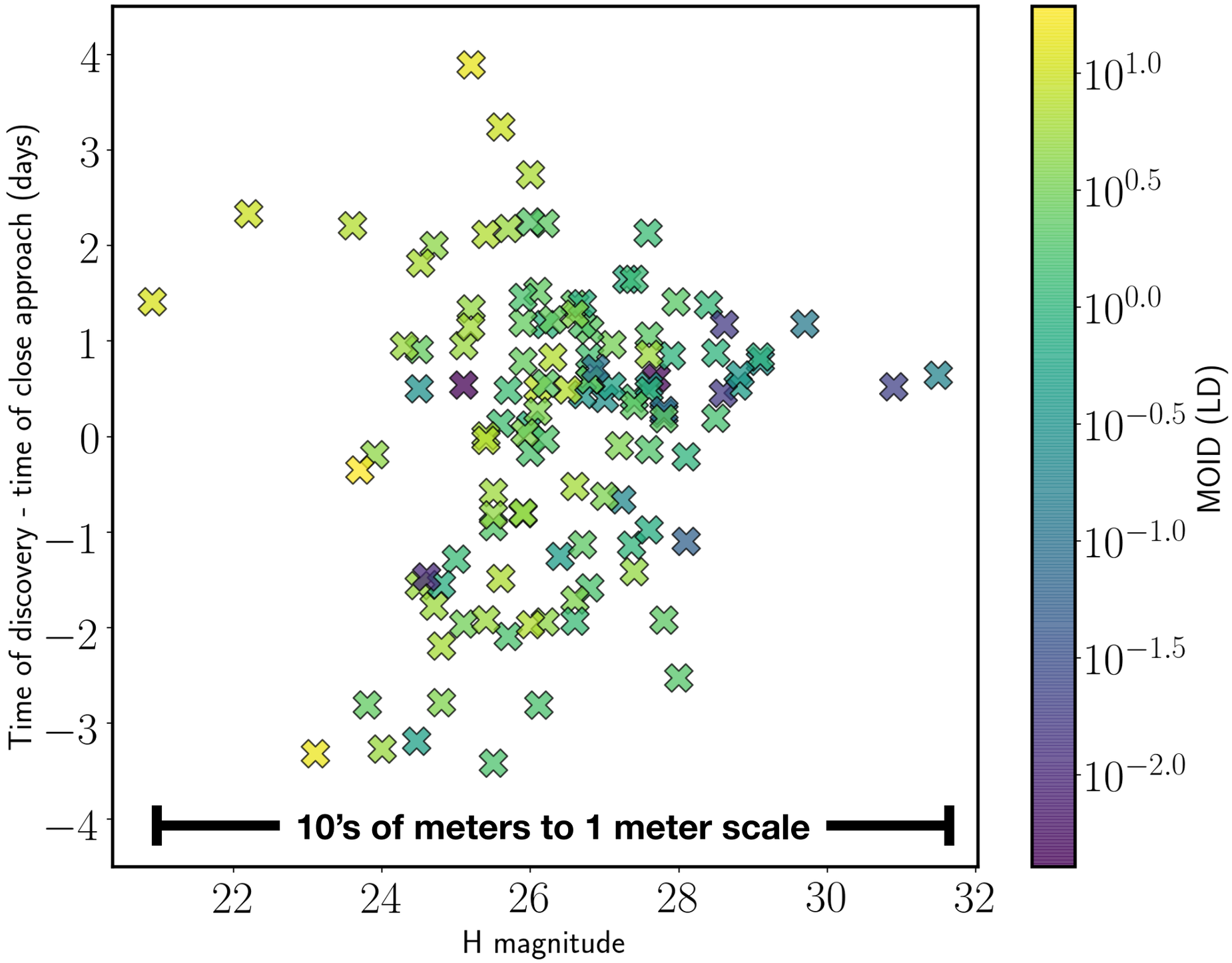
Bolin et al. 2020a, MPEC 2020-P04



2020 OQ6 motion > 130 deg/day!

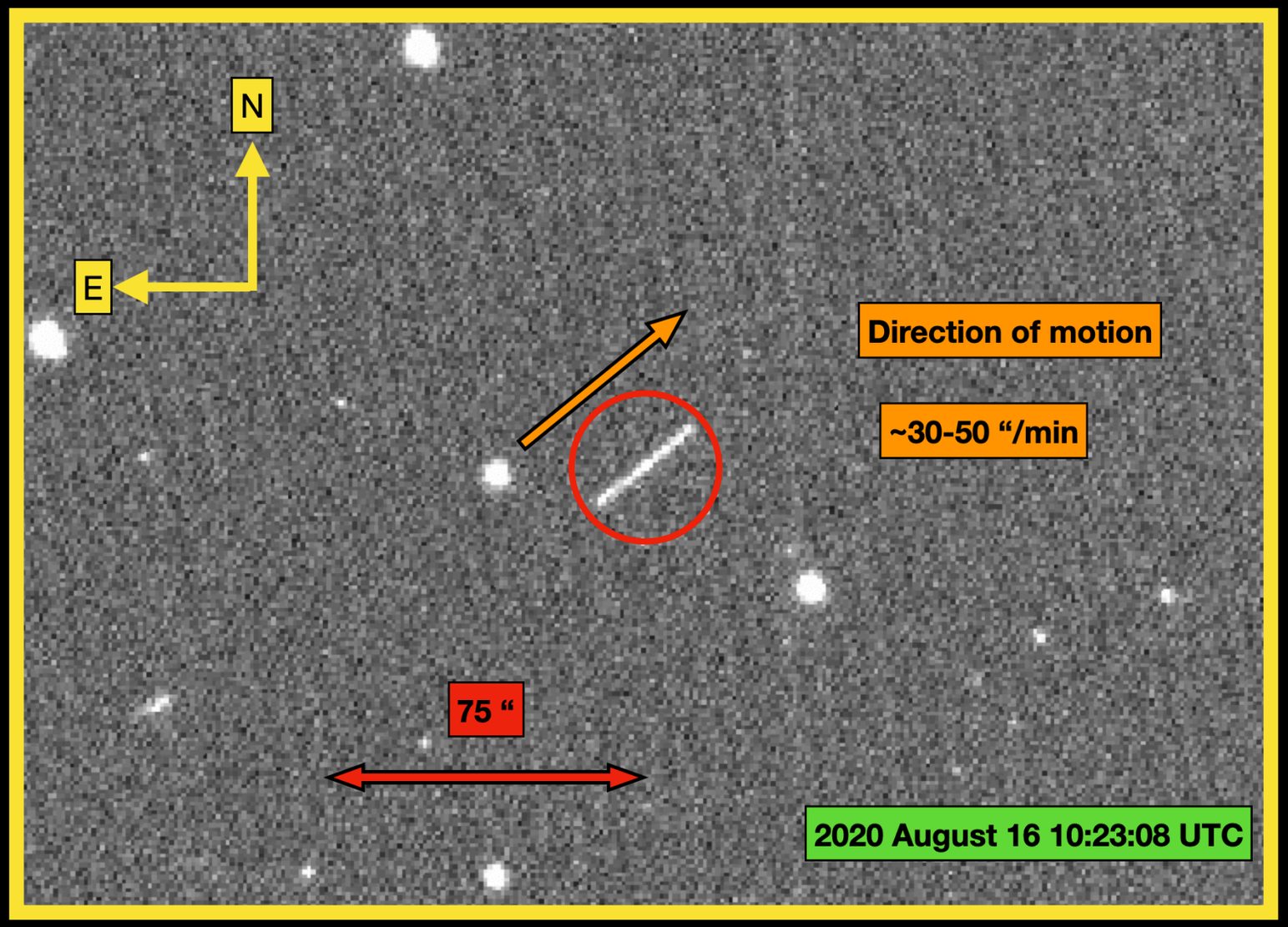
Streaks are caused by asteroids and other objects moving fast enough to be streaked during the camera exposure. Notice how the moving streak object is elongated compared to the stationary background stars.

ZSTREAK Objects



Bolin et al. in prep

2020 QG



Kunal Deshmukh (IITB)

Kritti Sharma (IITB)

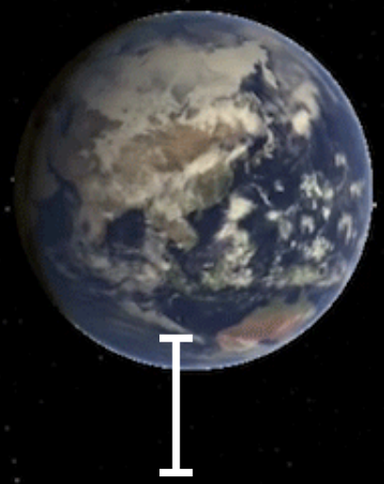
Chen-Yen Hsu (NCU)

Closest asteroid to fly-by the earth passing only 3,000 km above its surface

Discovered by student volunteers Kunal Deshmukh (IITB), Kritti Sharma (IITB), Chen-Yen Hsu (NCU)

Bolin et al. 2020a, MPEC 2020-Q51

2020 QG

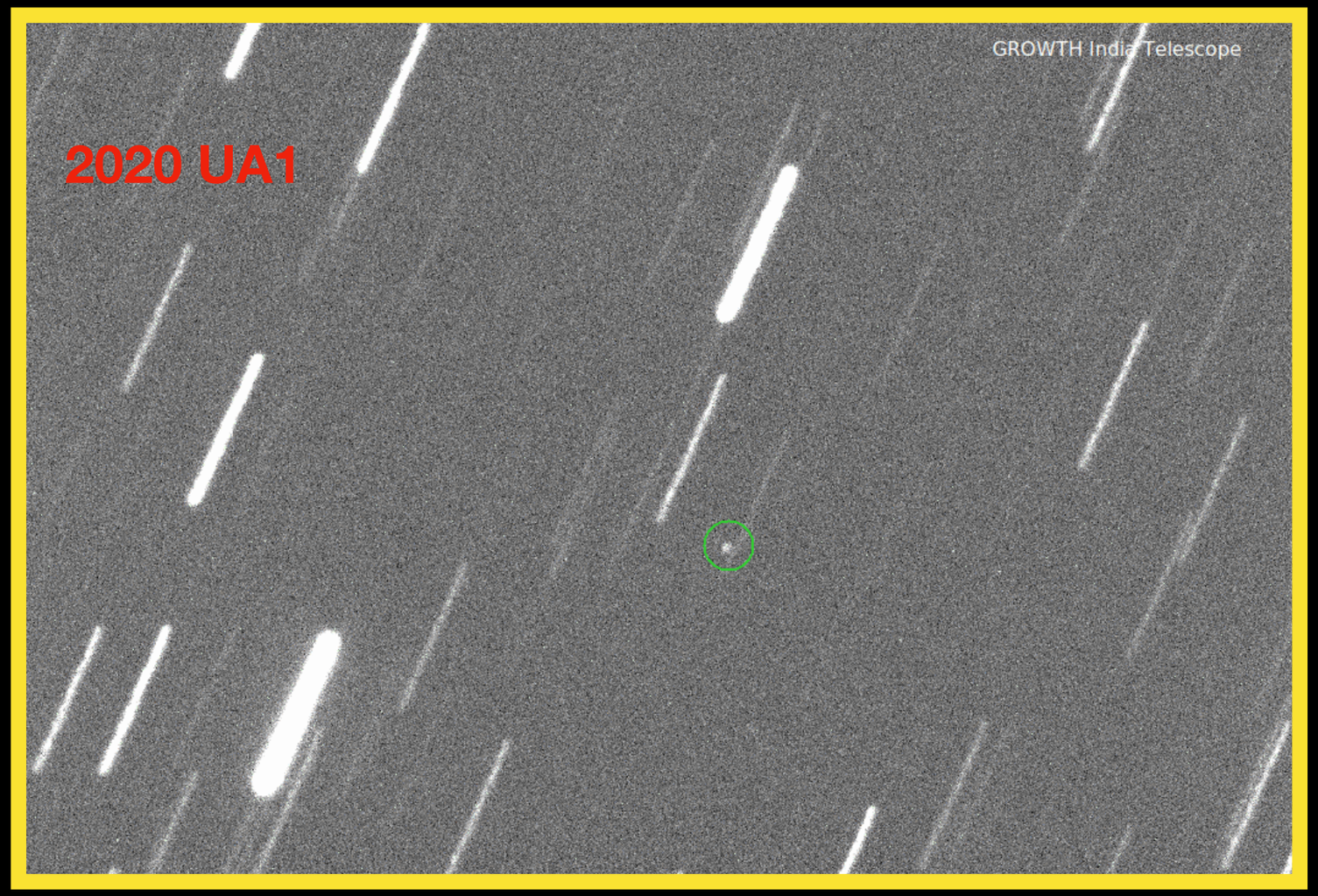


3,000 km

JPL/Farnocchia

Closest asteroid to fly-by the earth passing only 3,000 km above its surface

Follow up team



Kunal Deshmukh (IITB)

Kritti Sharma (IITB)

Chen-Yen Hsu (NCU)

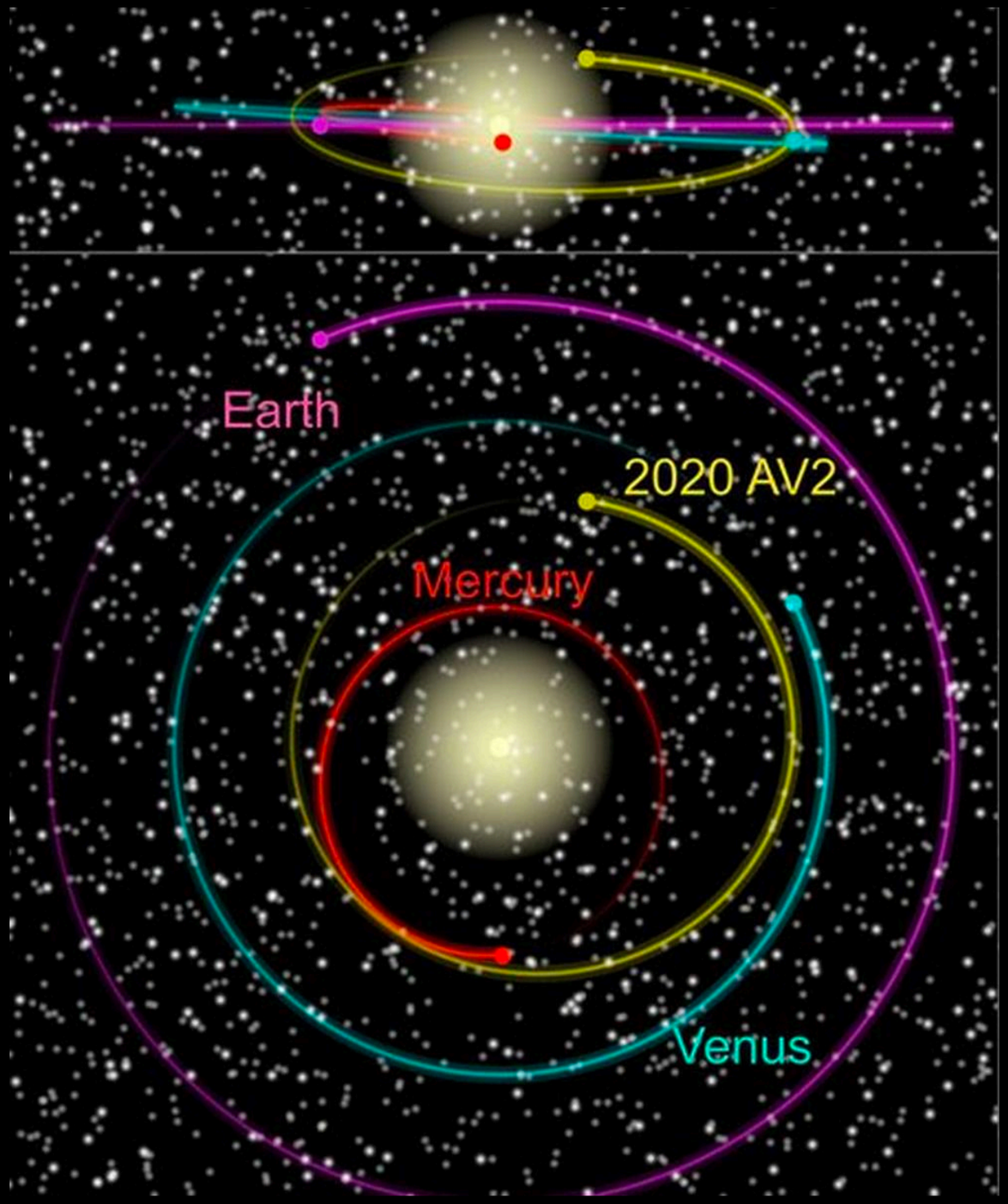
Josiah Purdum (SDSU)

Team consists of Liverpool Telescope, Table Mountain, Lulin Observatory, Mount Laguna, GROWTH India and others

Recent follow-up of fast moving object 2020 UA1 by GIT

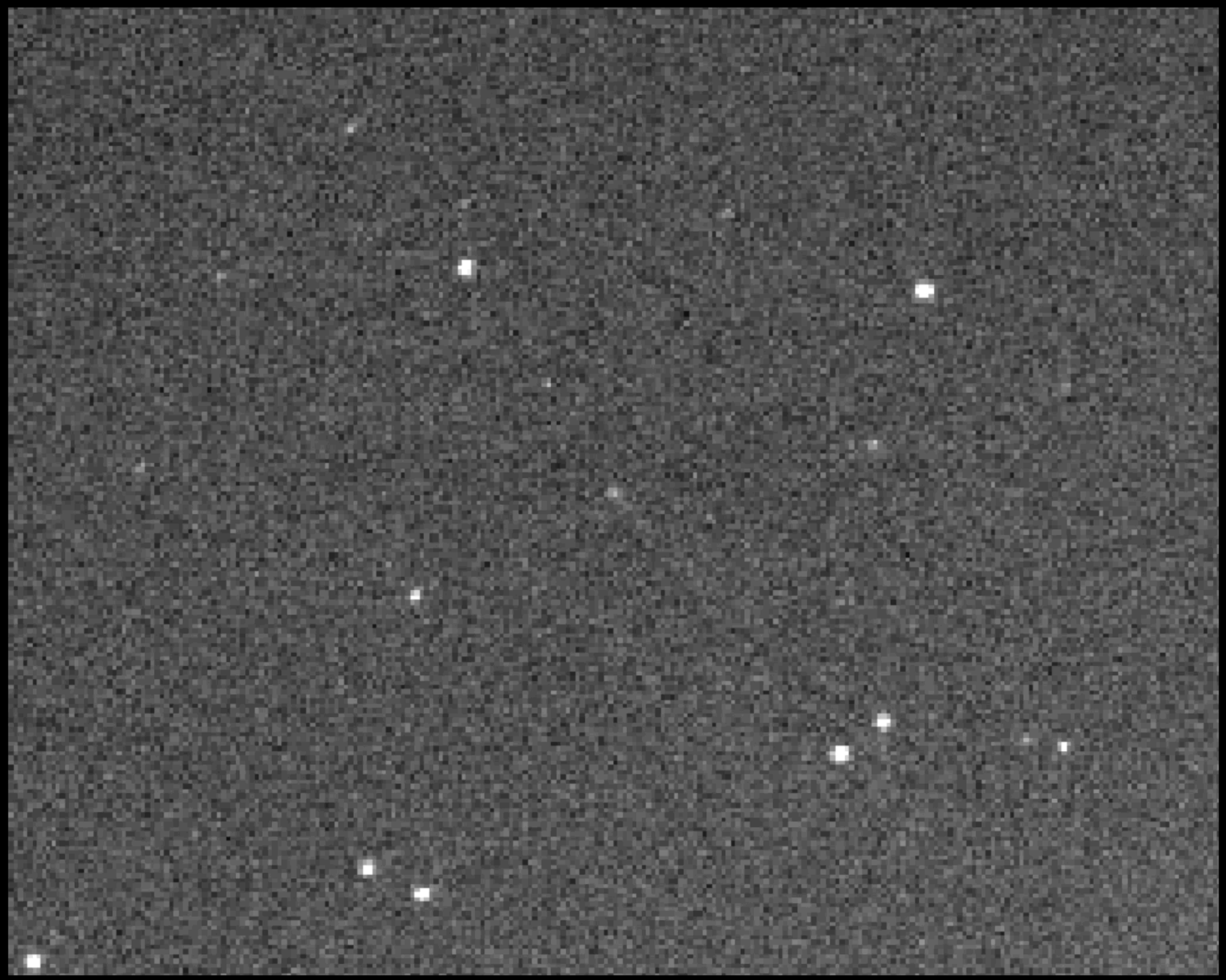
Bolin et al. 2020b, MPEC 2020-U92

Twilight Survey: discovery and characterization of the first inner-Venus Asteroid 2020 AV2



Bryce Bolin, Wing-Huen Ip, Frank Masci, and George Helou
Caltech/IPAC/NCU

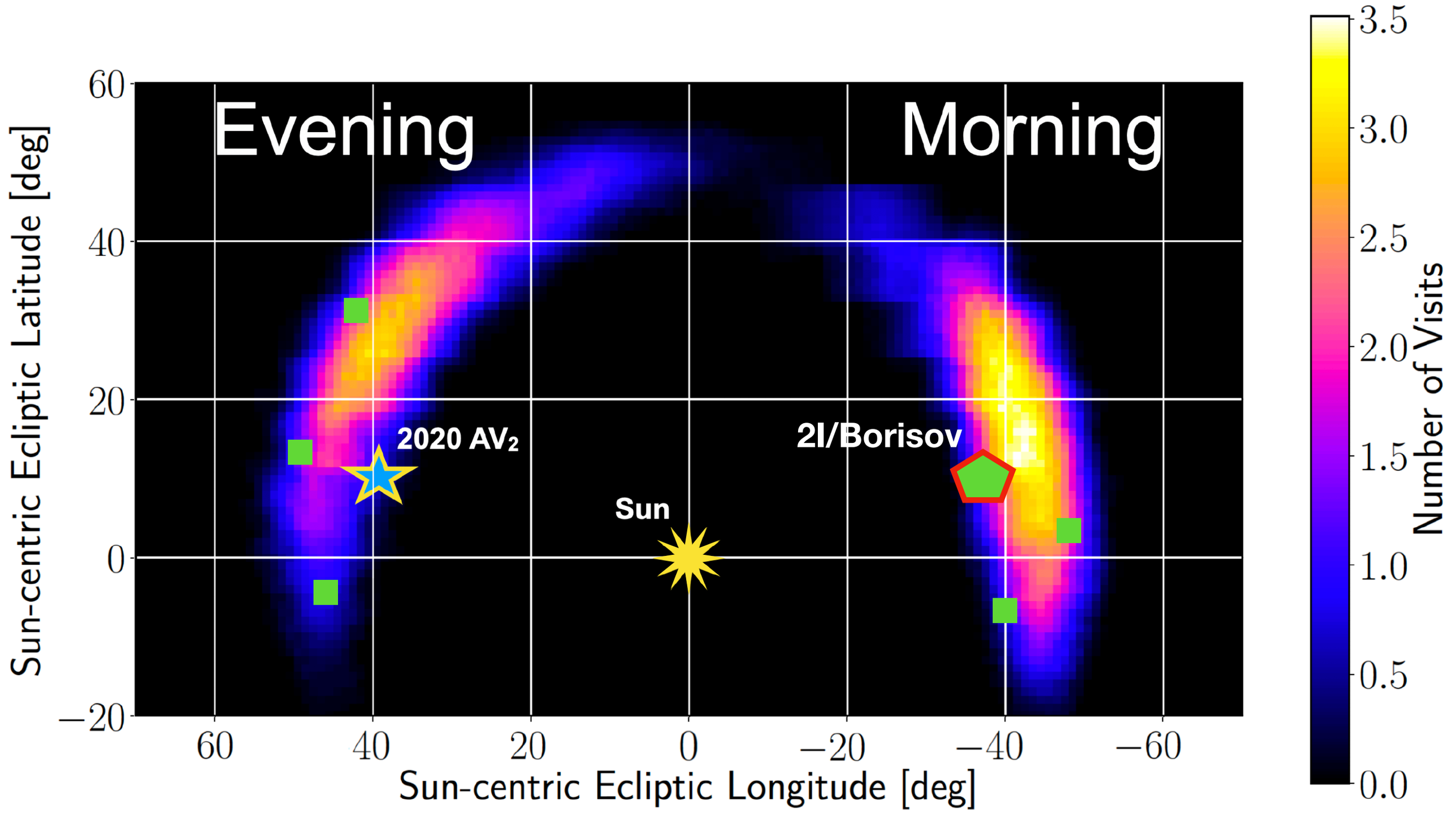
Discovery images



Discovered 2020 January 4, by ZTF, astrometric follow up by SEDM/KPED

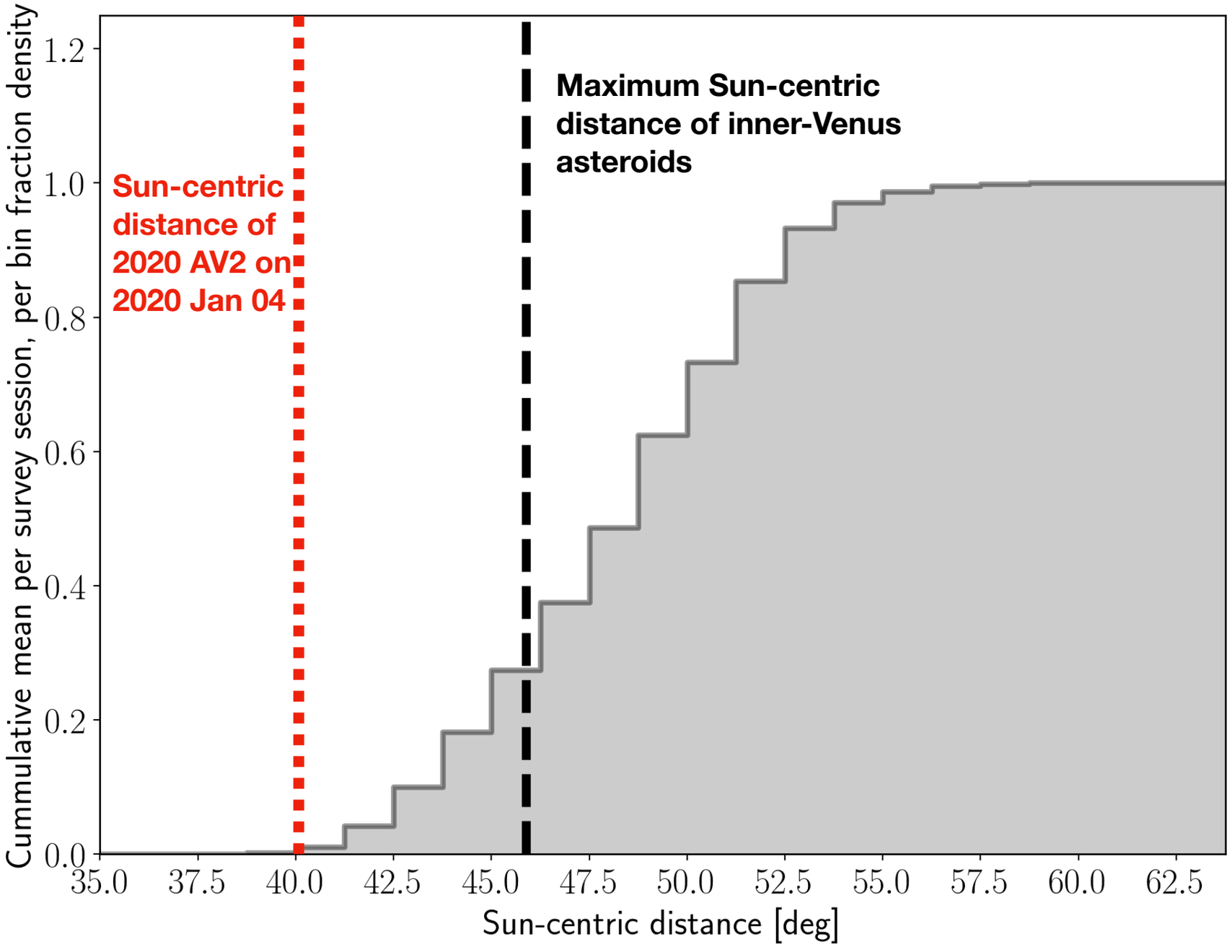
Bolin et al. 2020c, MPEC 2020-O66; Ip, Bolin et al., under review

Twilight survey



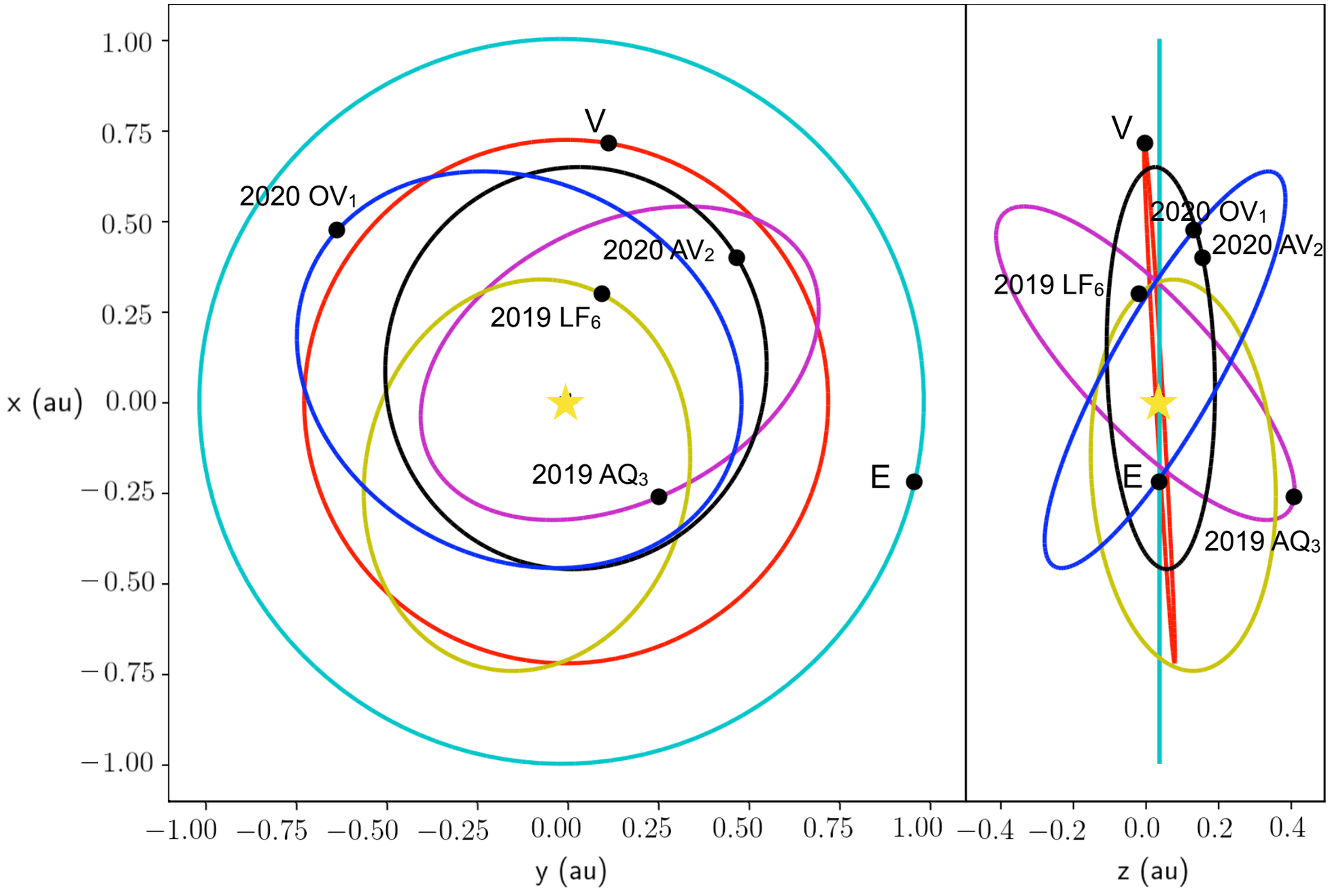
surveys sky ~18 deg. Twilight

TS Sun-centric distance



Allows survey of Sun-centric distances < 46 degrees where IVOs are located

Inner-Earth/Inner-Venus objects



3 Atira/inner-Earth objets, 1 inner-Venus object

In 2020: inner-Venus object 2020 AV2 (Bolin et al. 2020c, MPEC 2020-A99) , Atira 2020 OV1 (Bolin et al. 2020d, MPEC 2020-O66)

2020 AV2 presently the shortest orbital asteroid: 151.192 days

Interstellar Objects

Only two known ISOs: 1I/'Oumuamua and 2I/Borisov

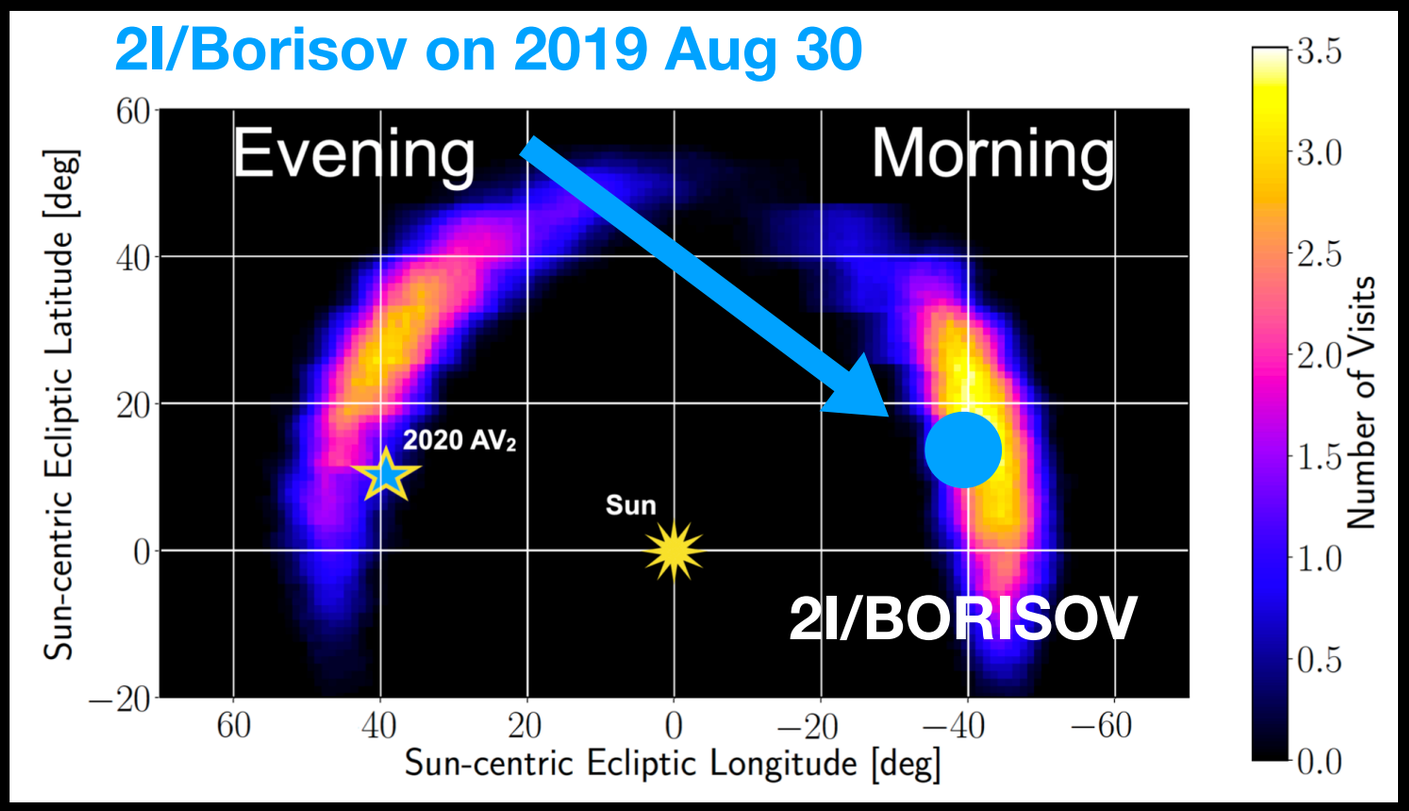
Eccentricity >1 !!!

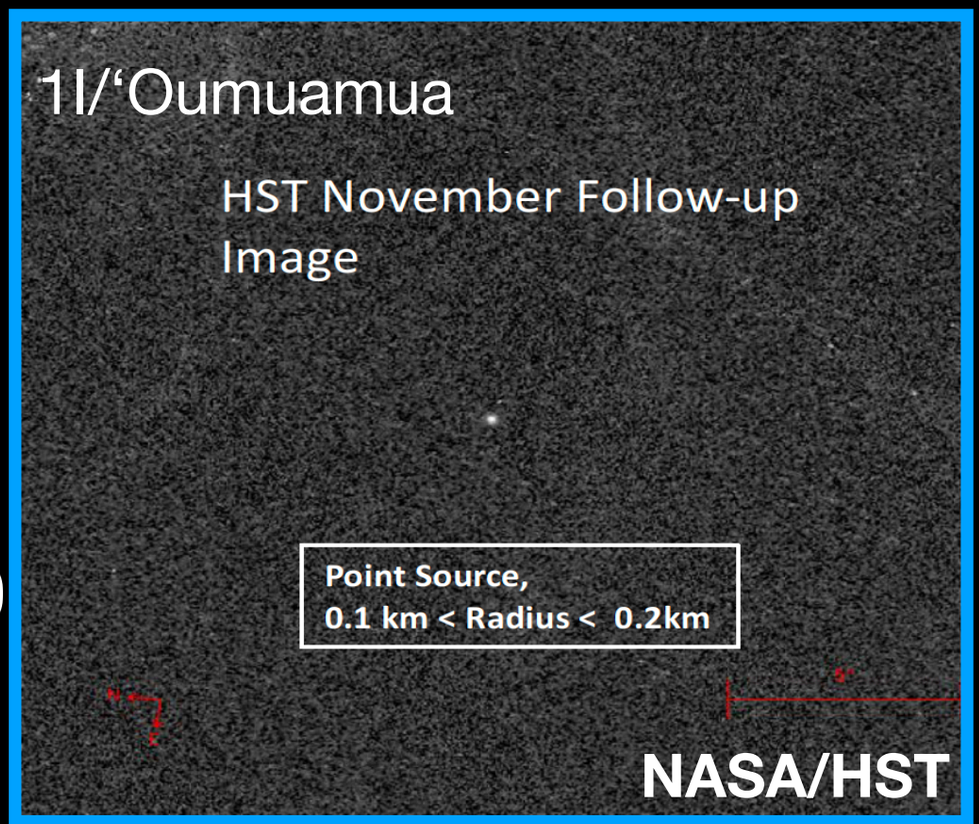
$e_{1I} = 1.20$, q = 0.25 au, $v_\infty = 26.3$ km/s

$e_{2I} = 3.35$, q = 2.0 au, $v_\infty = 32.5$ km/s

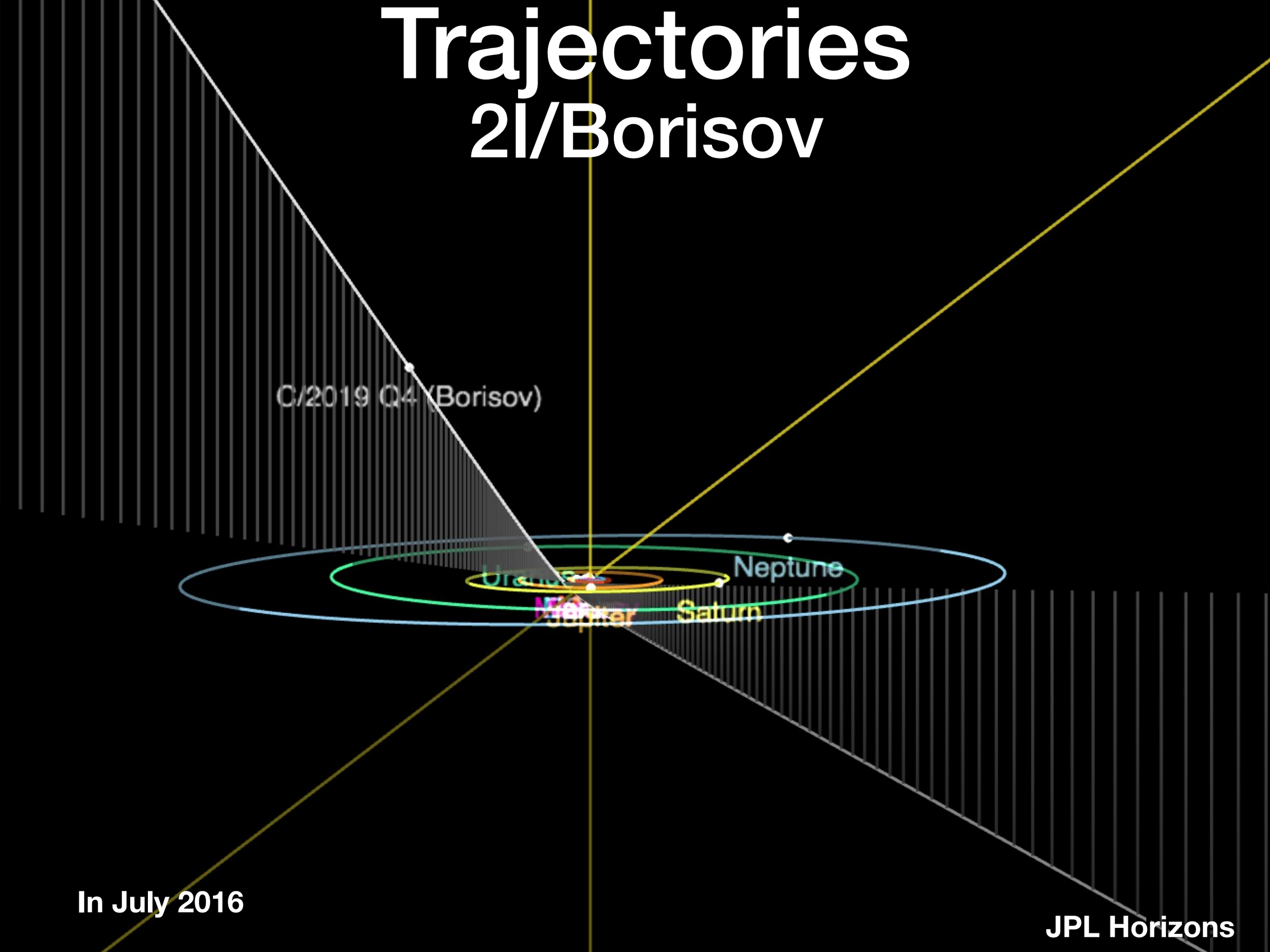
2I Discovered by G. Borisov on 2019 Aug 30

Found at V~18 in morning twilight





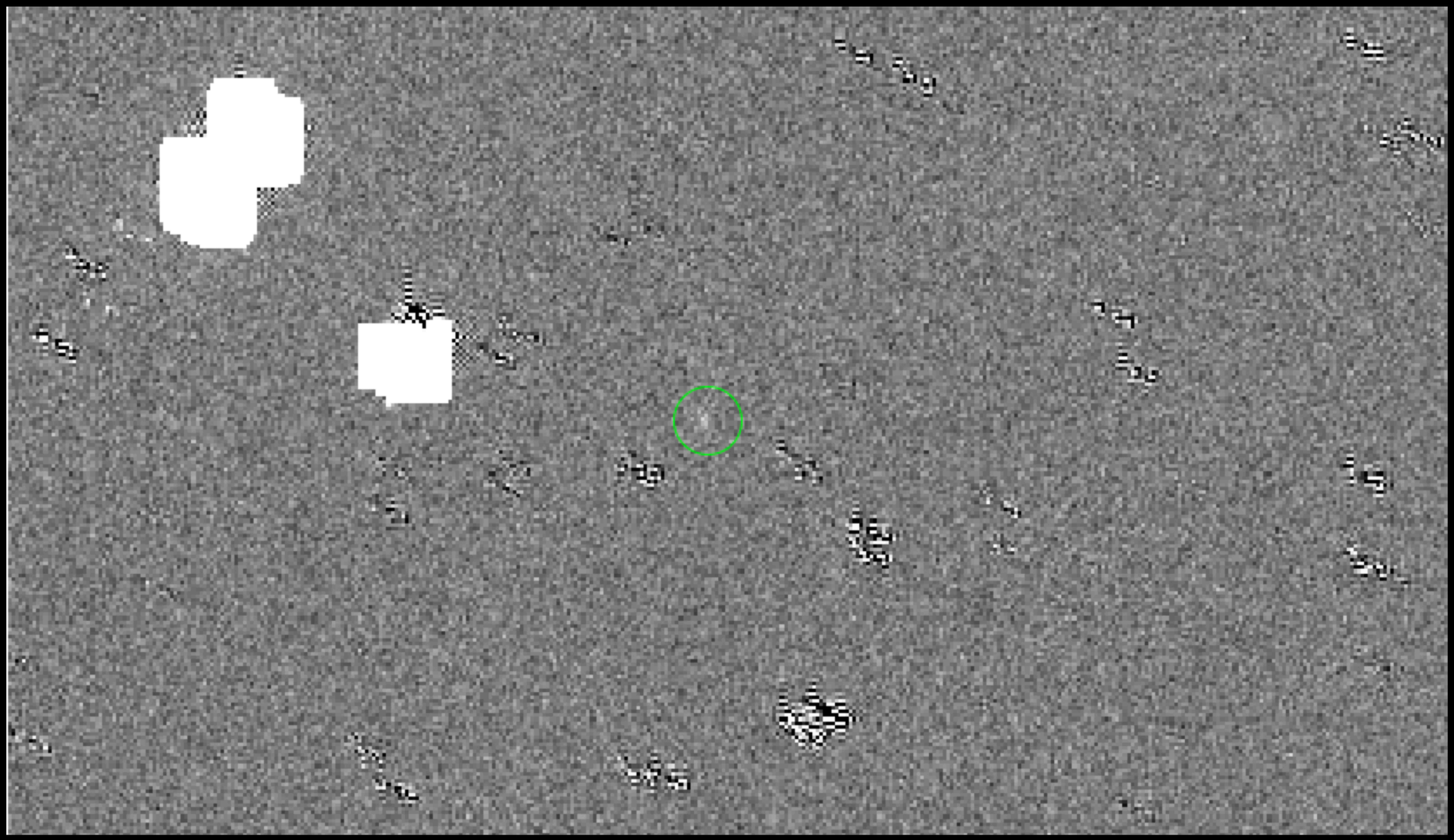
Trajectories
2I/Borisov



In July 2016

JPL Horizons

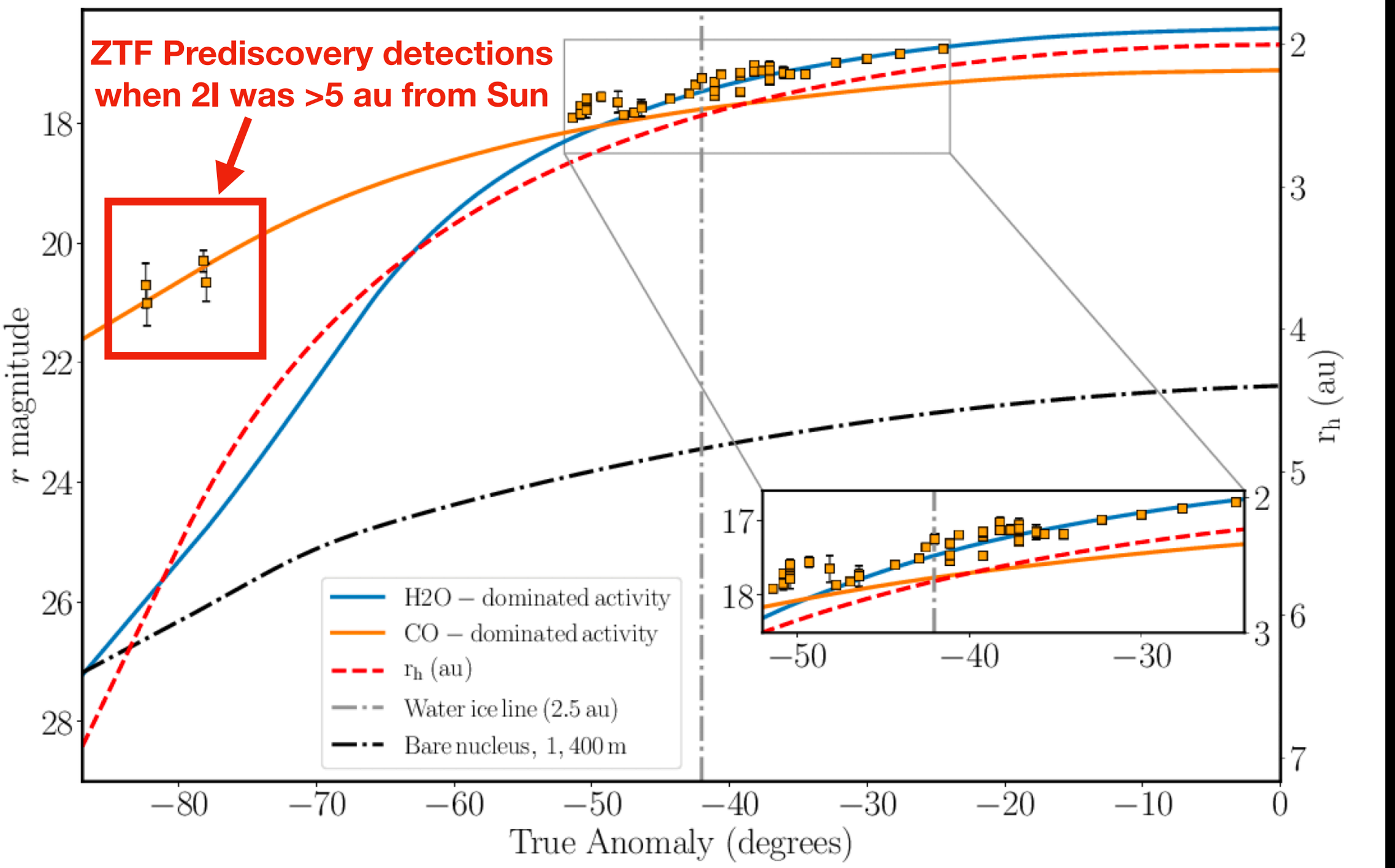
ZTF Pre-disovery data



2019-05-02 180 s r band stack,
more detections as far back as Dec 2018

Bolin et al. 2020, Ye et al. 2020

Long-term Lightcurve



Brightness in pre-discovery images implies activity at >6 au, supervolatile (CO) activity

Recent turn on of H_2O

Bolin et al. 2020, Ye et al. 2020

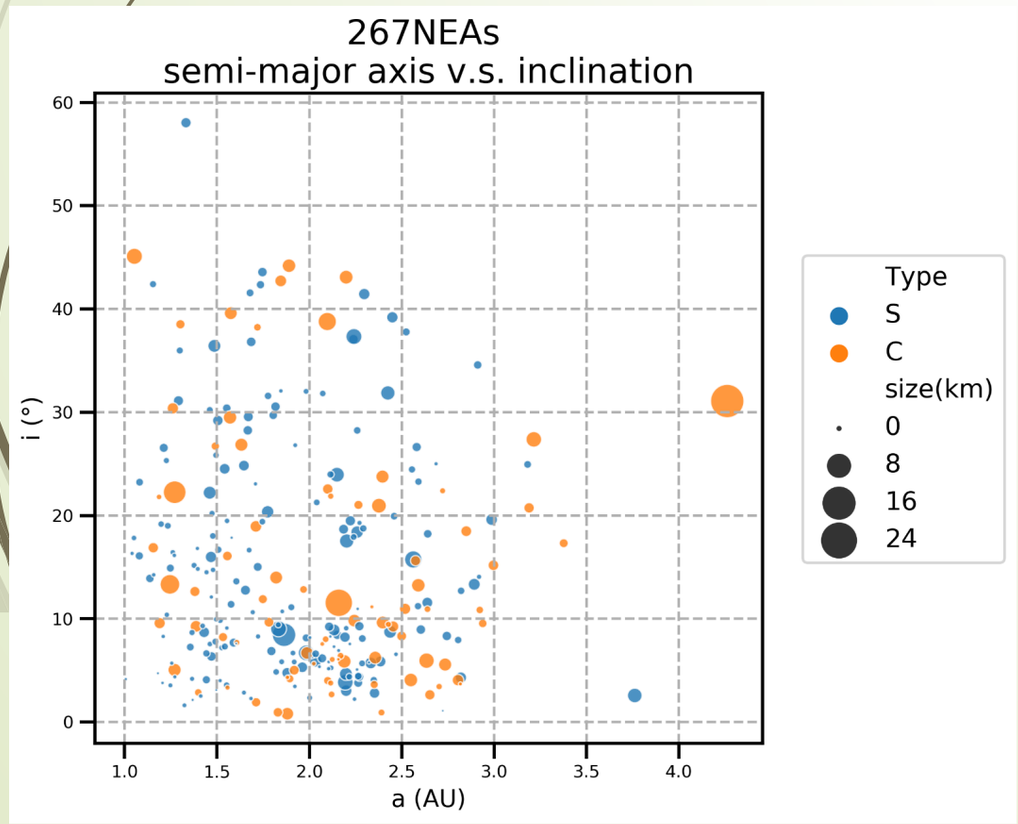
Asteroid taxonomic signatures from photometric phase curves

Student : Cheng, Chung- Chien /NTNU

Supervisor : Z.-Y. Lin (NCU),W.-L. Tseng(NTNU), Rex Chang (ASIAA), W.-H. Ip (NCU)

	Raw data	Auto	Manual (known + unknown)
NEAs	1039	302	267 (76+191)
MBAs	3812(Oct. 2020)	2969	2911 (1119+1792)

Taxonomic classifcation of NEAs by phasecurve parameters.
(G-value :C-complex ~ 0.111, S-complex~0.273)



S (185) : ~69%
C (82) : ~31%
S-/C-cluster : ~2.2

2911 MBAs

S-group	1857 (65%)
C-group	1054 (35%)
S-/C- cluster	1.76

H-G function

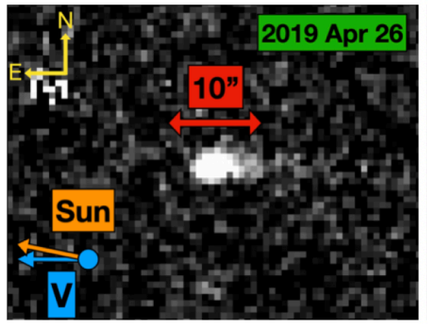
$$H = H(a) + 2.5\log[(1-G)\varphi 1(a) + G\,\varphi 2(a)]$$

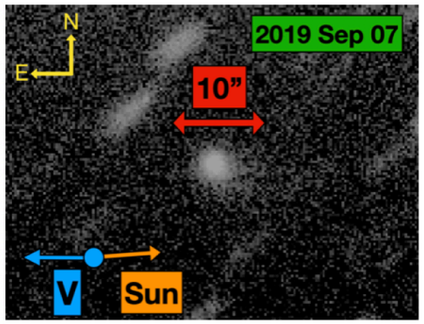
a is the phase angle, G is the slope parameter

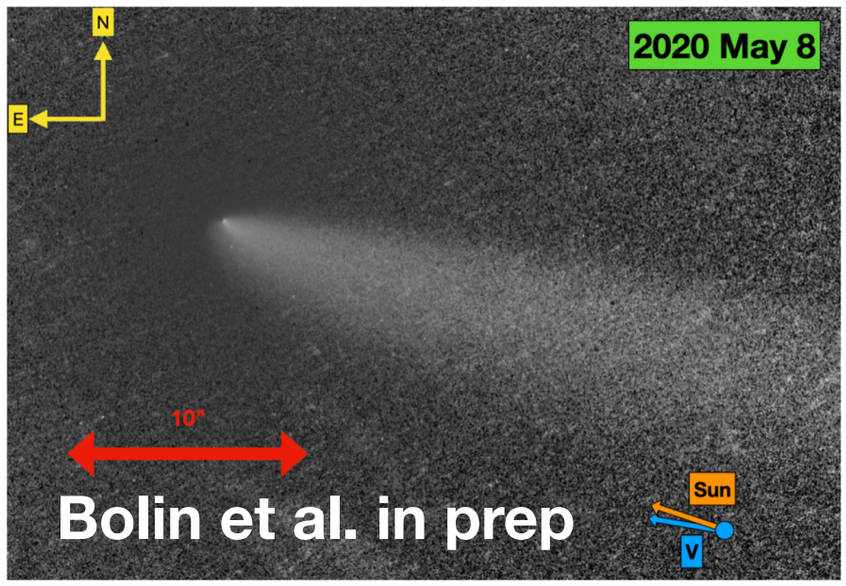
Active Centaurs/Outbursting comets

Active Centaurs/Outbursting comets

- P/2019 LD2 (ATLAS): Jovian co-orbital centaur in transition to becoming a Jupiter family comet
- Observations by ZTF as early as April 2019 show activity
- Follow up by *Spitzer* and *HST* tracking activity of object
- Likely cause of activity sublimation of volatiles such as H_2O and CO/CO_2

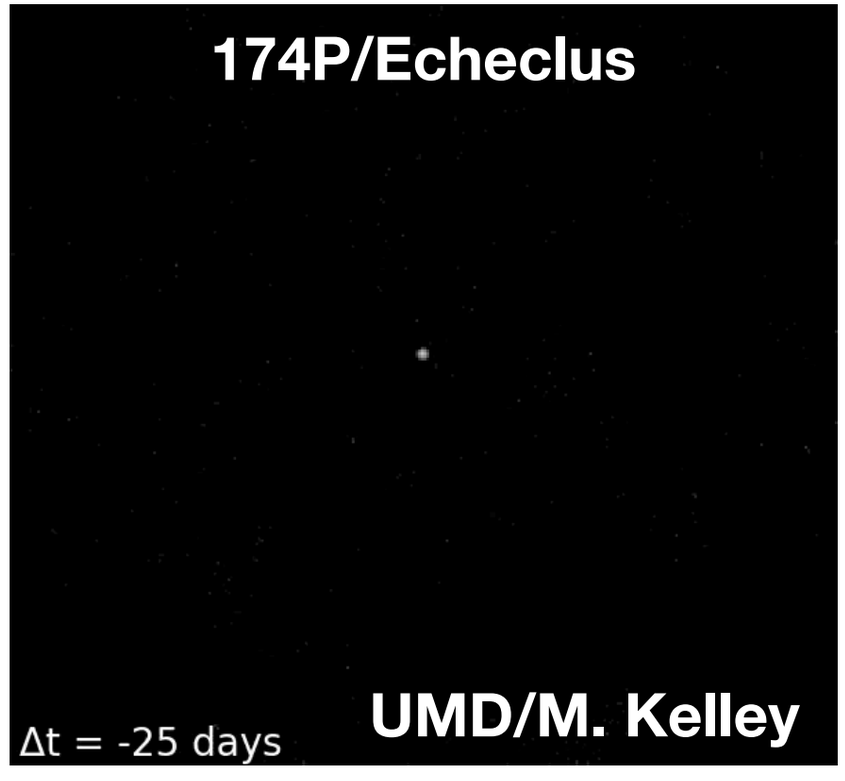






Cometary Outbursts

- Rapid rise in brightness and mass-loss rate (<1 hr).
- A variety of causes, some hypothesized:
  - Rotational break up.
  - Catastrophic fragmentation.
  - Exothermic transition of water ice from amorphous to crystalline states.
  - Gas pressure build up and catastrophic release.



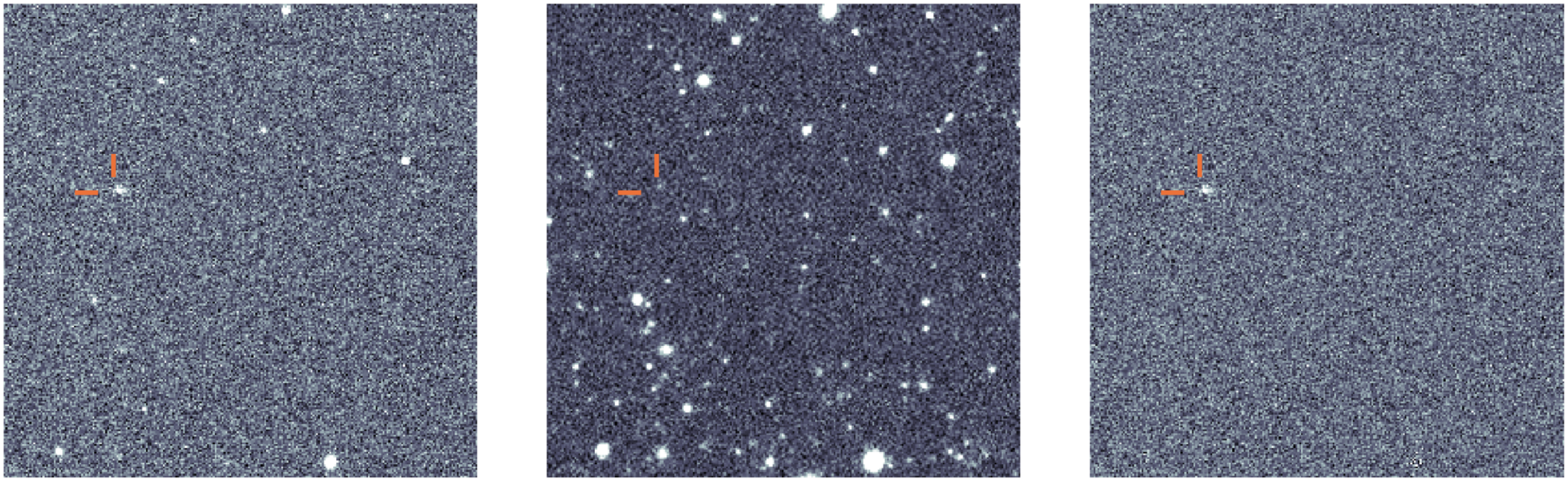
Cometary discovery

- Thanks to Tails by Duev et al.
- AI-discovery of comets, currently running on Twilight Survey
- Will run on the rest of ZTF survey data
- First candidate found, ZTFDD01 on 2020 October 7 UTC
- See ML talk by Mahabal

Active Centaurs/Outbursting comets

ztf_20201007514745_000622_zr_c14_o_q4_0

index	id	ni	jd	datestr	p	x	y	ra	dec	radecstr	tails_v	inspected	label
0	ztf_20201007514745_000622_zr_c14_o_q4	0	2.459130e+06	2020 10 7.51474537037037	0.961563	1474.802422	2041.471573	167.651024	28.432082	11h10m36.2458s +28d25m55.4959s	../nb/checkpoints-loc-l1-loss-5/tails	True	comet



MPChecker query results:
No Solar system object found with MPChecker
Skybot query results:
No Solar system object found with Skybot

Tails Candidate ZTFDD01 by Dima Duev

Cometary discovery

- Thanks to Tails by Duev et al.
- AI-discovery of comets, currently running on Twilight Survey
- Will run on the rest of ZTF survey data
- First candidate found, ZTFDD01 on 2020 October 7 UTC
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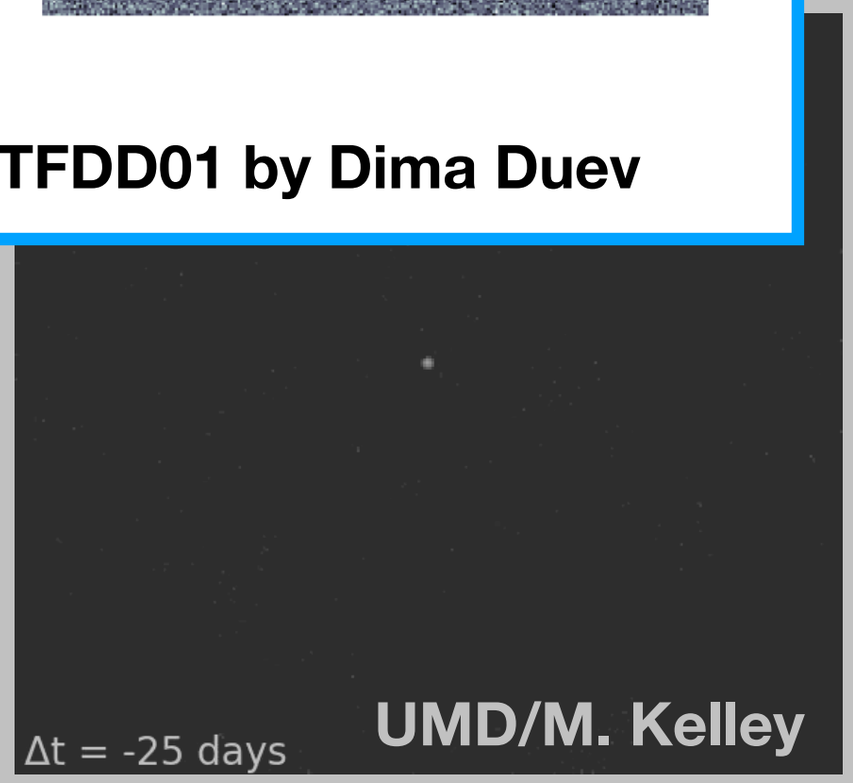
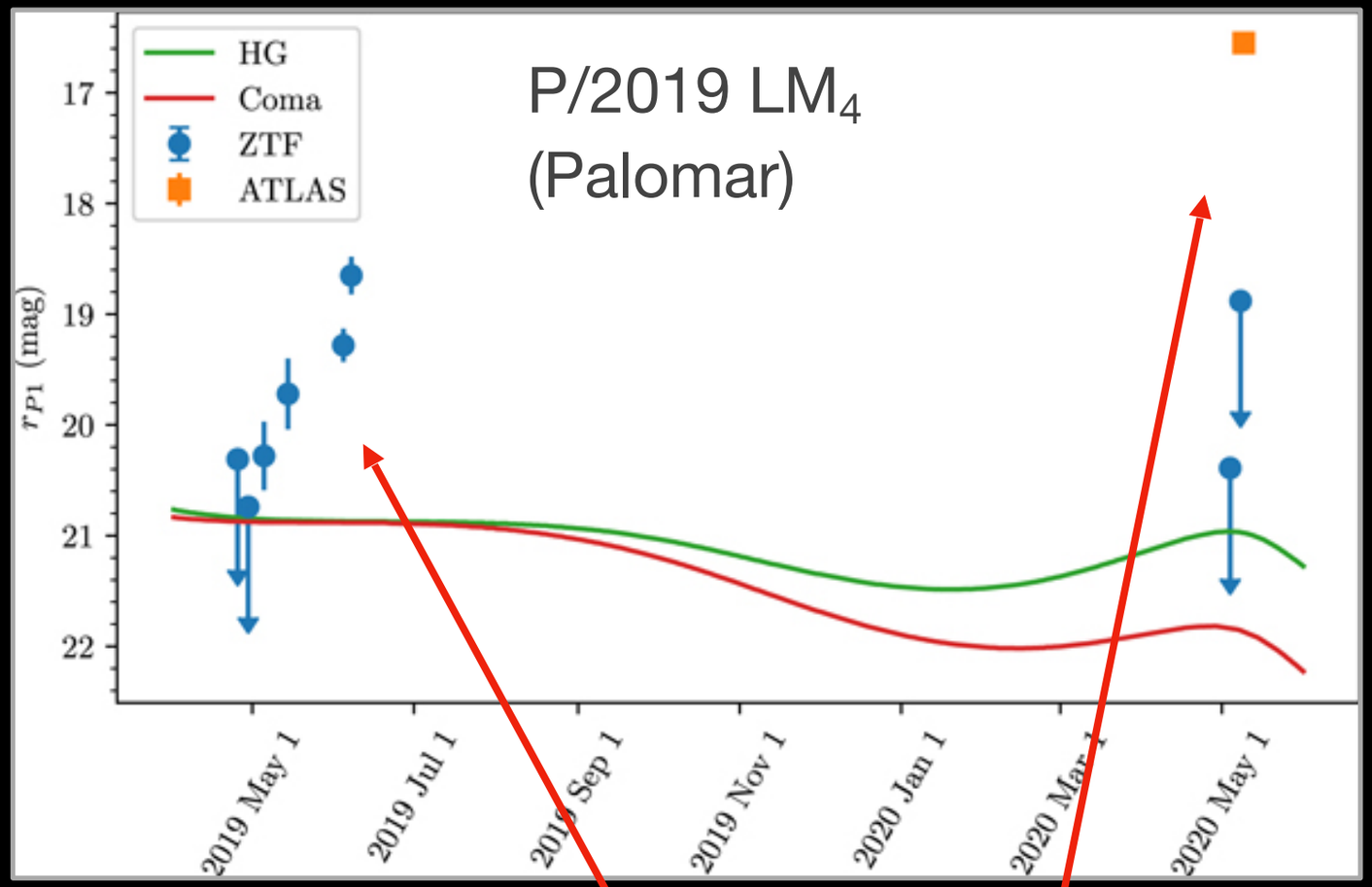


Cometary Outburst Update

Newly identified events:

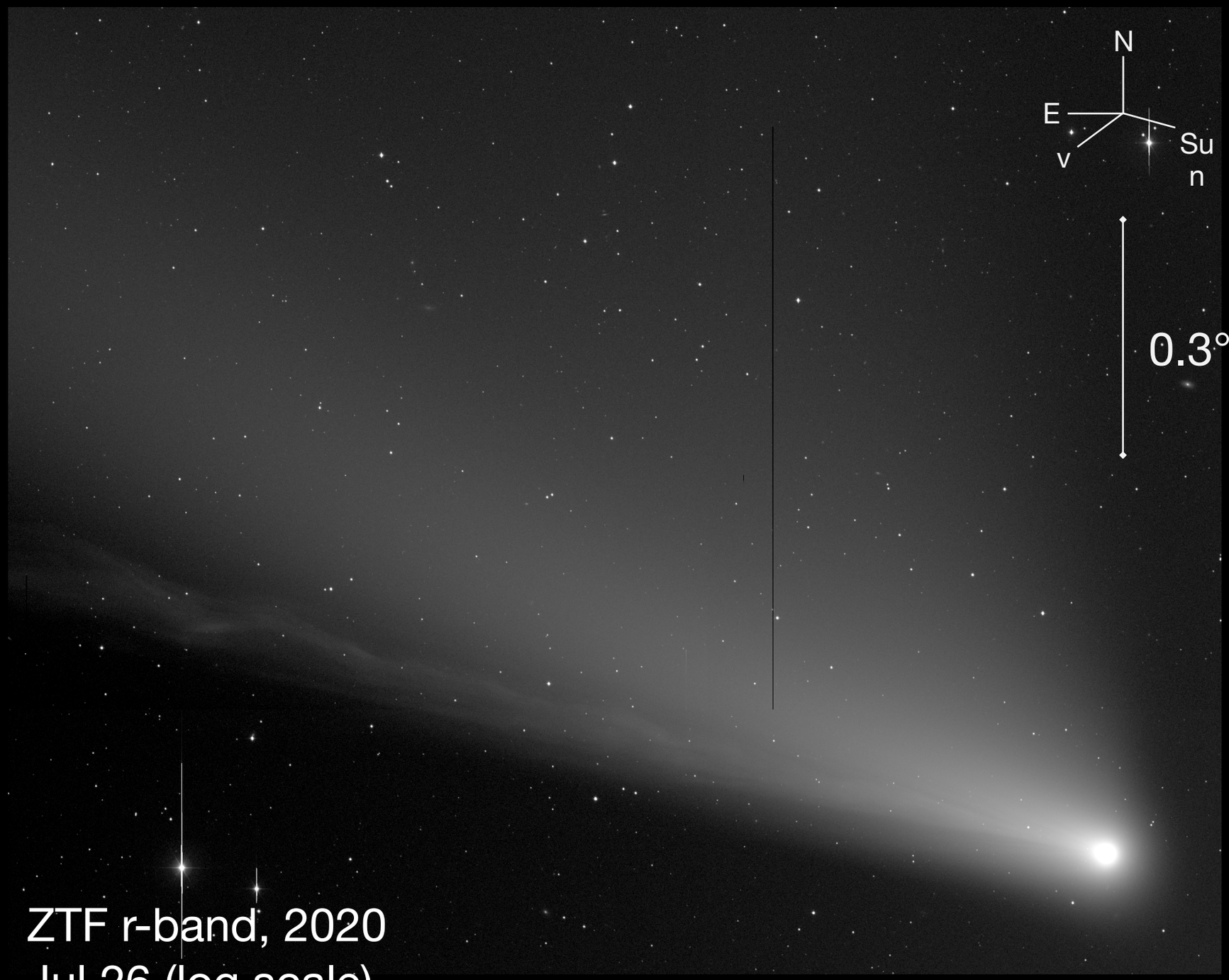
- Two small outbursts (> -0.5 mag):
  - 115P/Maury (ATel 13836)
  - P/2020 P2 (submitted to CBAT)
- P/2019 LM_4 (Palomar):
  - Fourth ZTF-discovered comet
  - Two outbursts: -2 and -4 mag
  - Ye et al. 2020, RNAAS
- C/2020 Q1 (Borisov)
  - ~ -3 mag (in preparation)



Unusual brightening at discovery.

Ye et al. 2020

Recovered 1 year later during strong outburst.



ZTF r-band, 2020 Jul 26 (log scale)

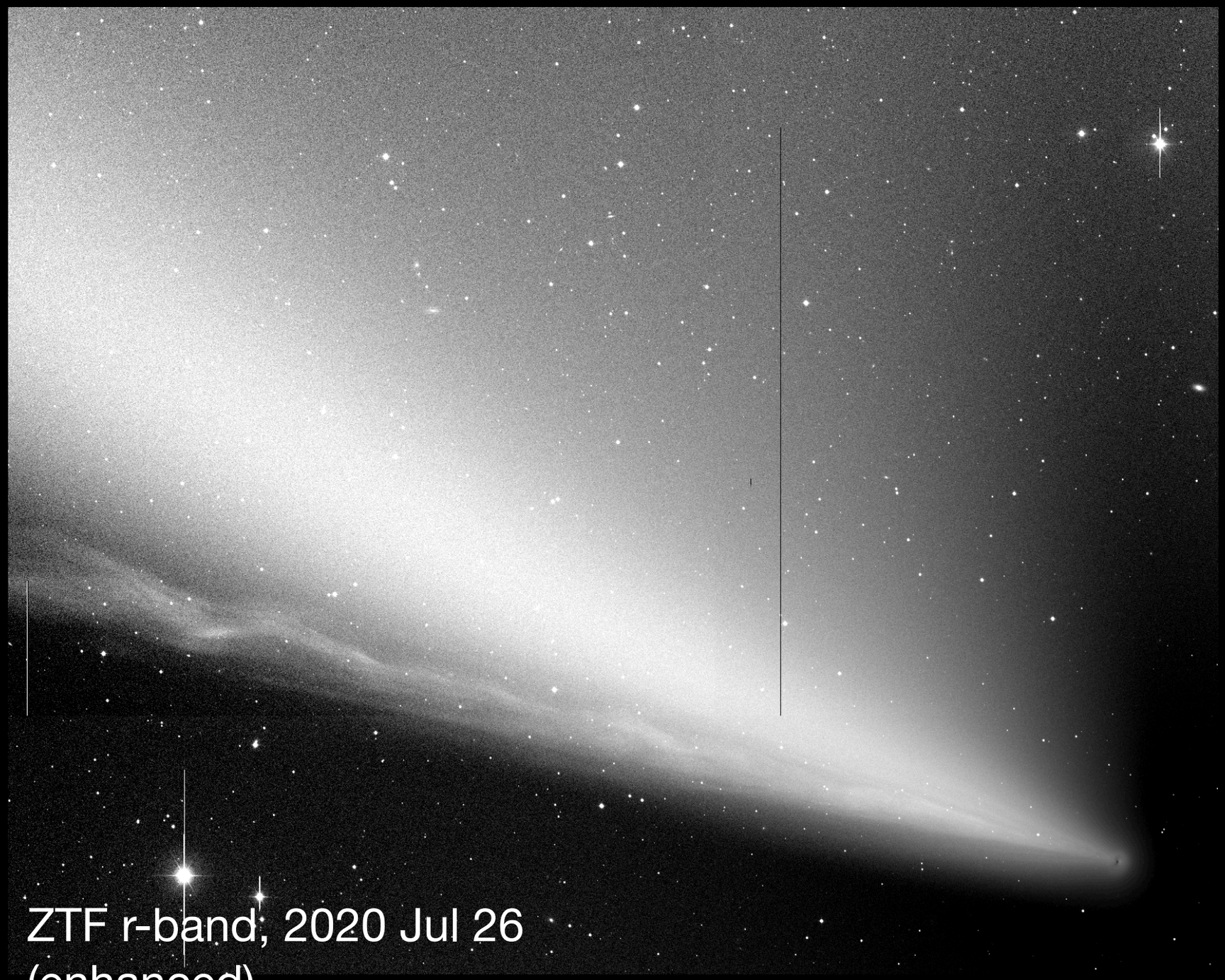
C/2020 F3 (NEOWISE)

One of the brightest comets in the last decade.

Several nights of ZTF imaging.

Goal: assemble giga-pixel mosaics of the comet's tail.

Challenge: bright twilight illuminated the chip, interfering with the large, faint tail



ZTF r-band, 2020 Jul 26
(enhanced)

C/2020 F3 (NEOWISE)

This enhanced *r*-band image shows a smooth dust tail, and a filamentary ion tail.

Enhancement is a normalization of the image by the distance to the nucleus.

Summary

- **ZTF: Large étendue optical survey**
- **Two distinct modes of NEO detection: ZMODE and ZSTREAK**
- **Unique capability to identify fast-moving and close in objects (2020 OQ6, 2020 QG!)**
- **Capability of finding inner-Venus and inner-Earth objects (2020 AV2, 2020 OV1)**
- **Now can discovery comets!**
- **Physical properties of many asteroids**
- **Monitoring of cometary activity**
- **Supports Solar System Science (Comets, fast rotators, Interstellar Objects)**