Asia-Pacific Regional IAU Meeting @ Taipei July 3-7, 2017

Ultra Faint Meteor Observation using High Power Large Aperture Radar and Wide-field CMOS Camera

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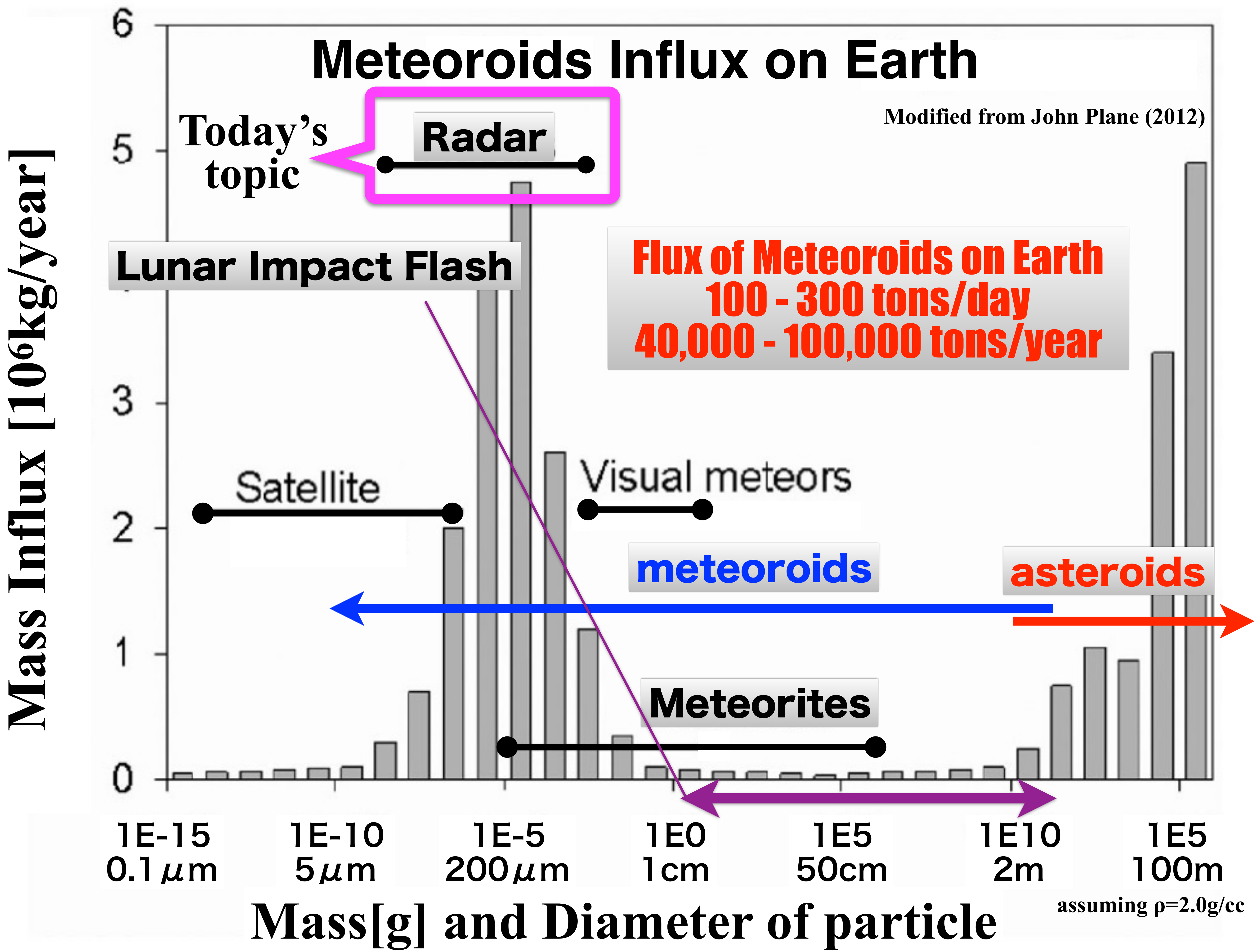
(5)National Astronomical Observatory of Japan, Mitaka, Tokyo, Japan

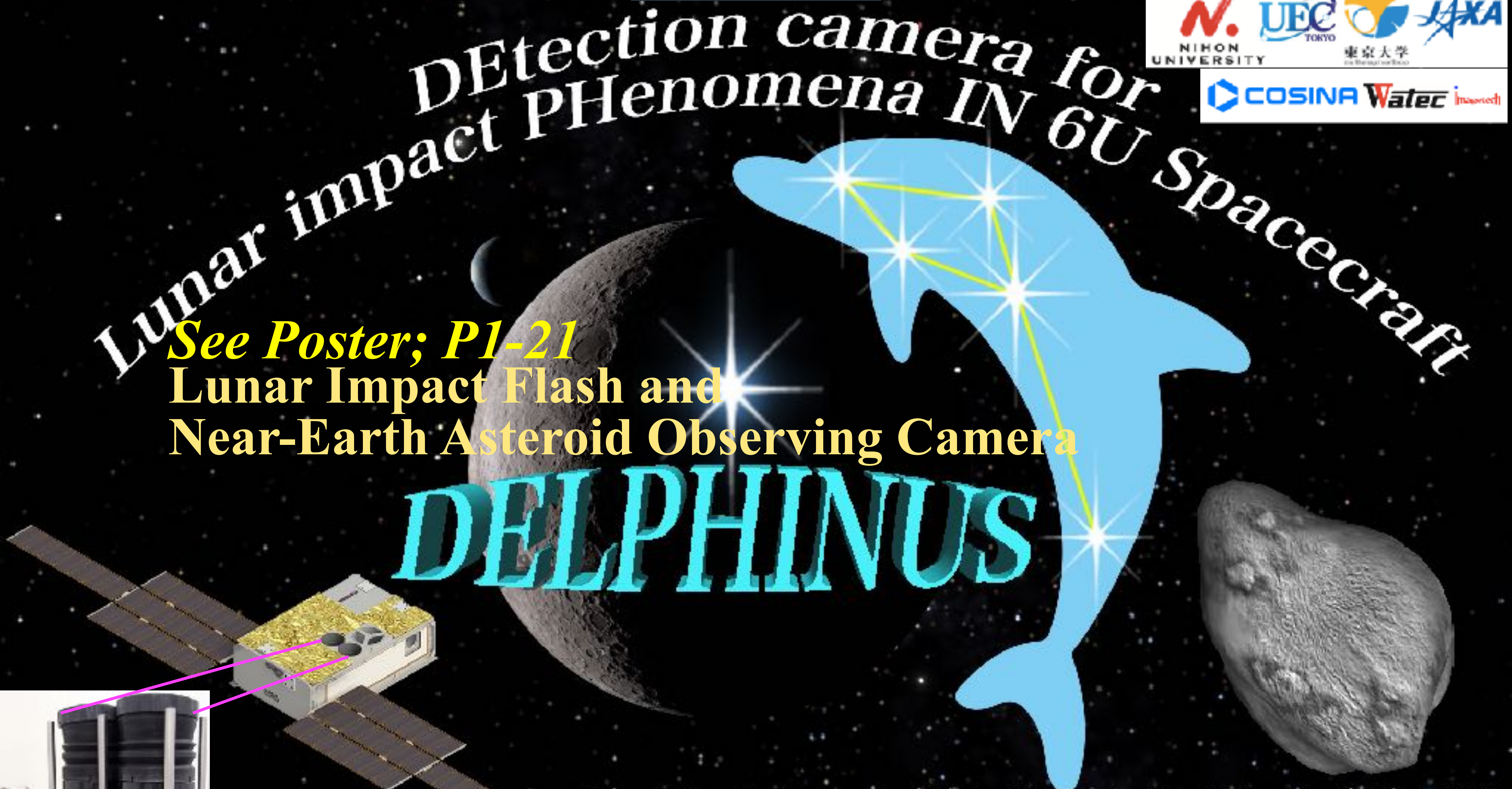
Leonid Meteor Shower by Abe, Yano, NHK, NASA Leonid MAC



Meteoroids Influx on Earth
Modified from John Plane (2012)
Today's topic
Radar
Lunar Impact Flash
Flux of Meteoroids on Earth
100 - 300 tons/day
40,000 - 100,000 tons/year
Satellite
Visual meteors
meteoroids
asteroids
Meteorites
Mass Influx [10^6kg/year]
0
1
2
3
5
6
1E-15
0.1μm
1E-10
5μm
1E-5
200μm
1E0
1cm
1E5
50cm
1E10
2m
1E5
100m
Mass[g] and Diameter of particle
assuming ρ=2.0g/cc

EQUULEUS From Japan to EML2

EQUULEUS (<u>EQU</u>ilibri<u>U</u>m <u>L</u>unar-<u>E</u>arth point 6<u>U</u> <u>S</u>pacecraft) is a deep-space 6U spacecraft that will demonstrate low-energy trajectory control technologies by cruising to the Earth-Moon libration point 2.

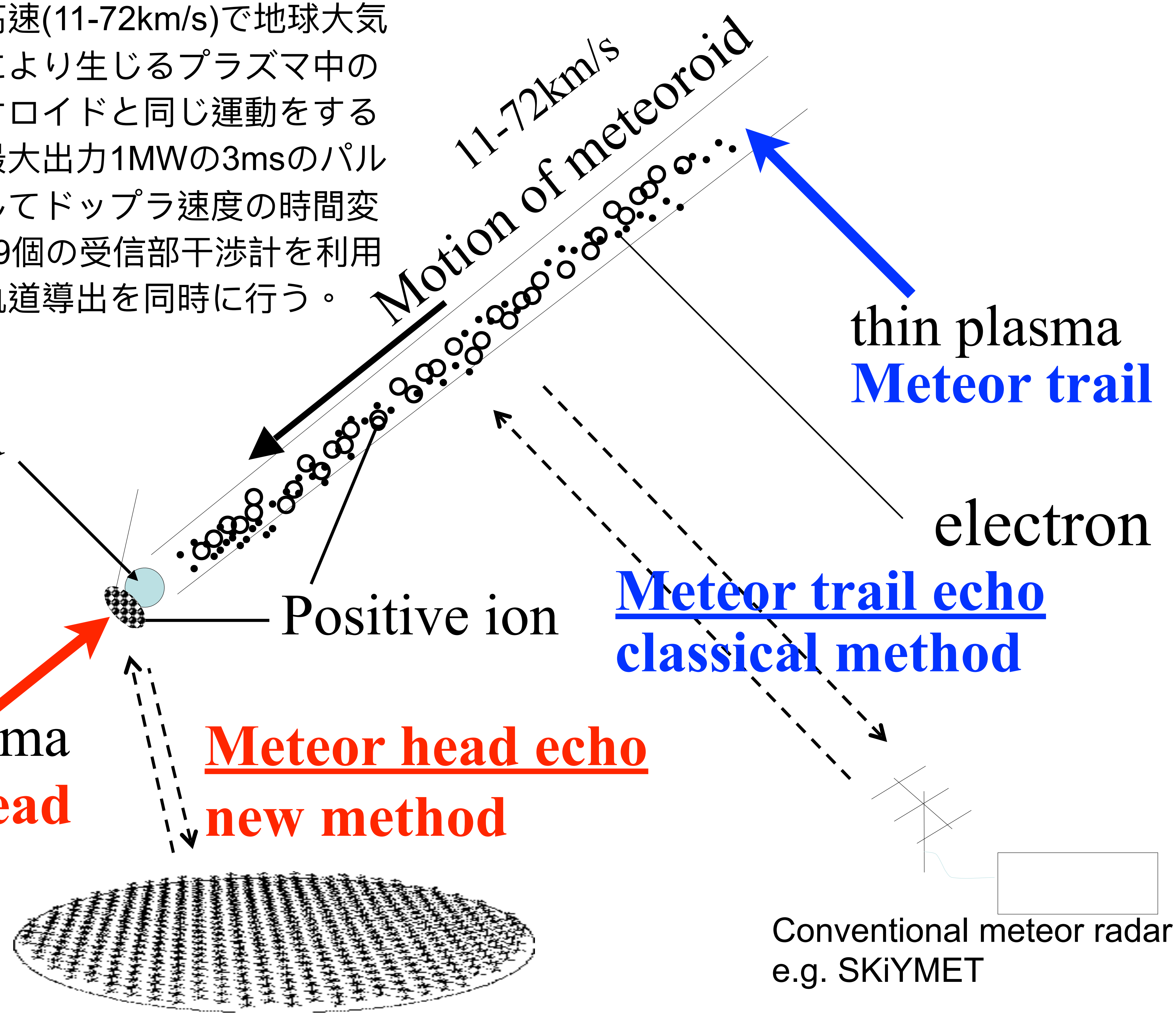


Nihon University, University of Electro-Communications, University of Tokyo, JAXA
COSINA Co., Ltd., WATEC CO., LTD., Imagetech Co., Ltd.

http://issl.space.t.u-tokyo.ac.jp/equuleus/en/

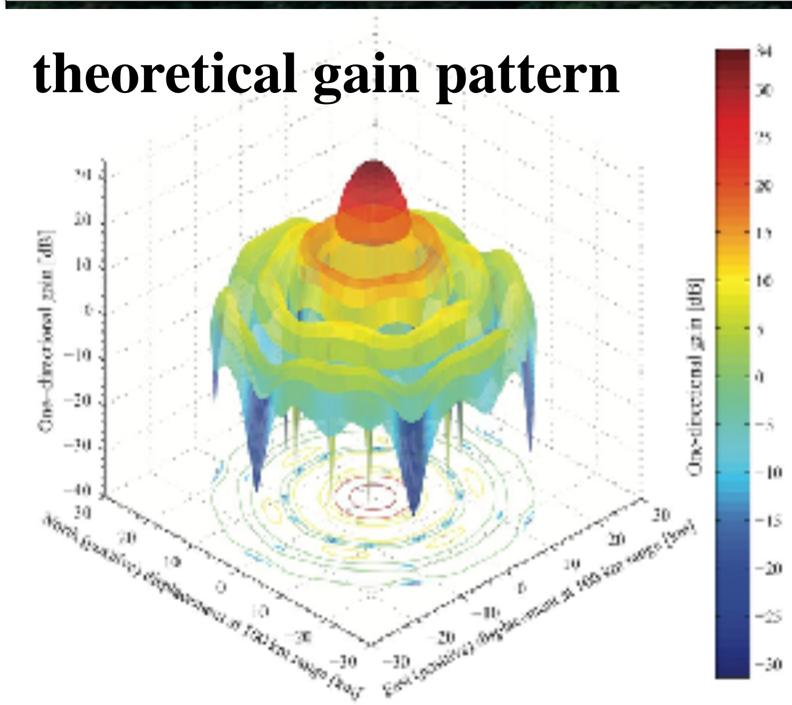
Meteor Head Echo and Meteor Trail Echoes

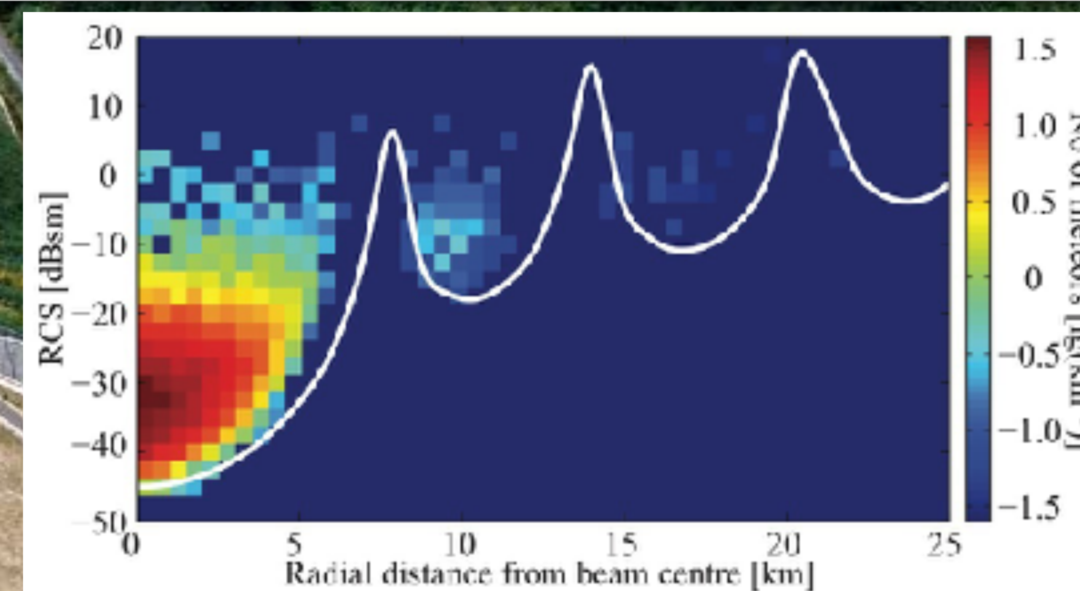
メテオロイドが超高速(11-72km/s)で地球大気圏に突入することにより生じるプラズマ中の電子のうち，メテオロイドと同じ運動をするヘッドプラズマに最大出力1MWの3msのパルスレーダーを照射してドップラ速度の時間変化を計測。また，19個の受信部干渉計を利用した位置計測から軌道導出を同時に行う。



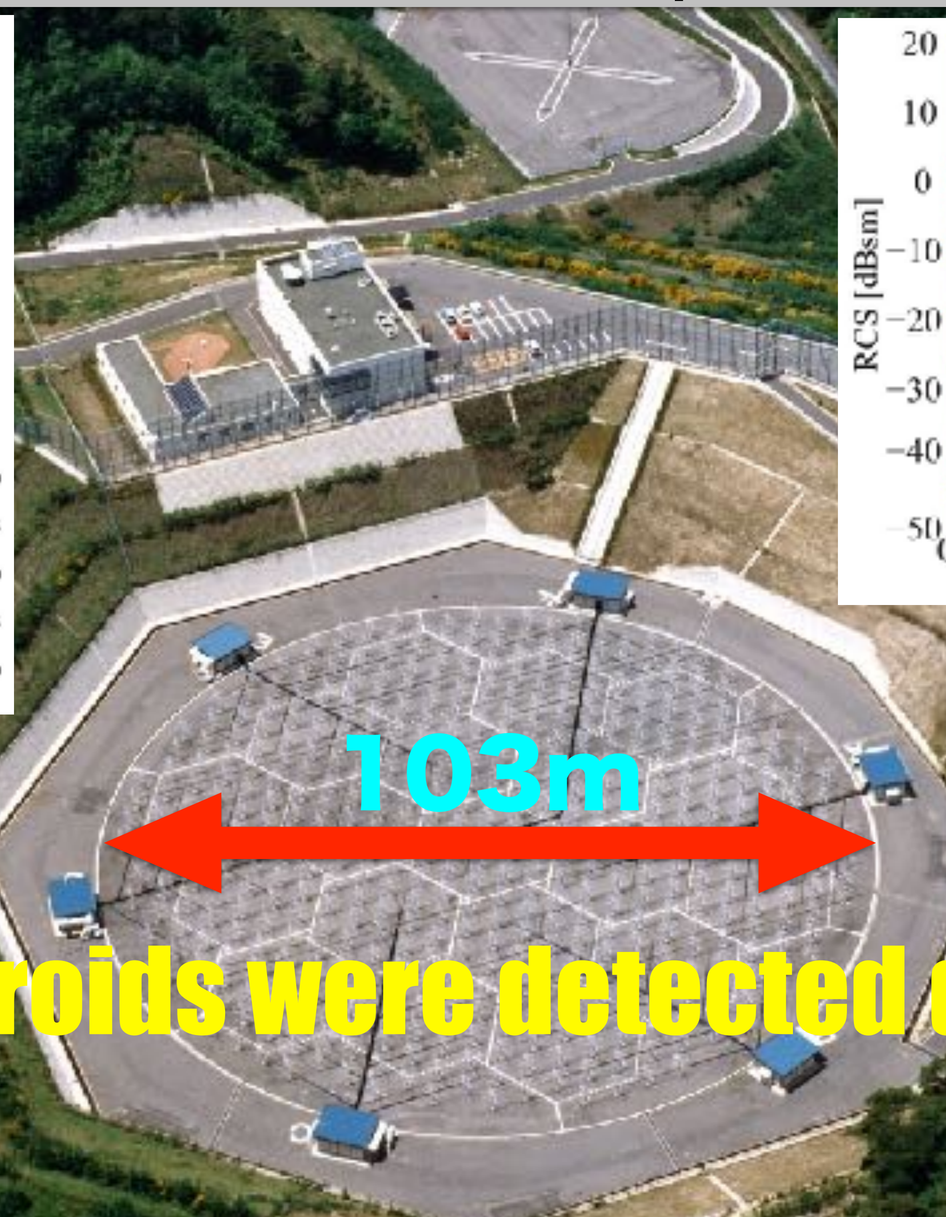
Kyoto University RISH MU Radar
Middle and **U**pper Atmosphere **Radar**

Monostatic coherent pulse Doppler radar
VHF (46.5 MHz), 1MW peak power, 475 crossed Yagi antennas
Pulse length: 1-500μs, Antenna aperture: 8330m² (D=103m)





Observed number of meteors, normalized by beam area, versus RCS (Radar Cross Section) and radial distance from beam centre.



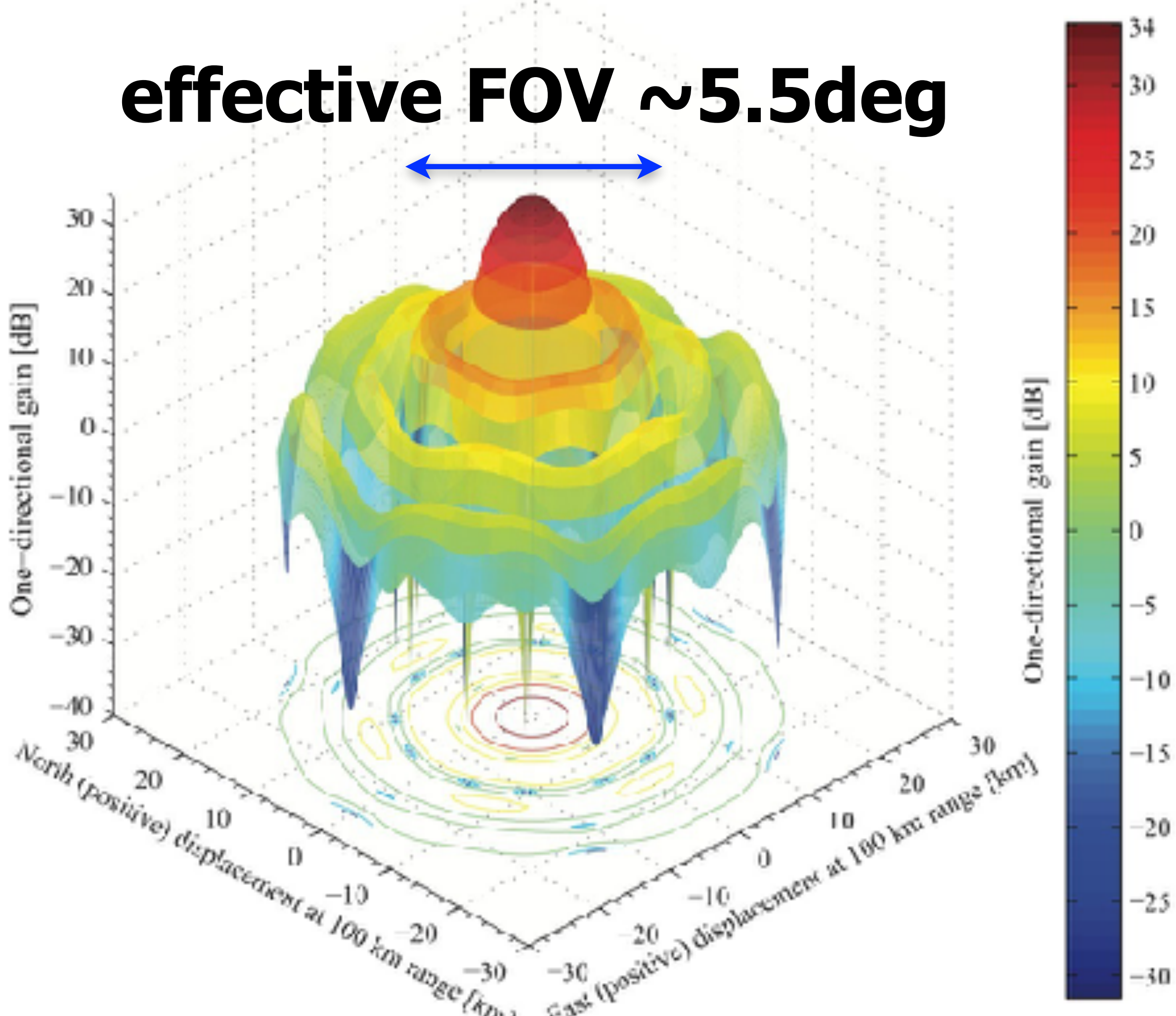
>180k meteoroids were detected during 2009-2016

average velocity error = 0.25 km/s
average perihelion distance = 0.003 AU
3,000 - 4,000 meteor head echoes / day

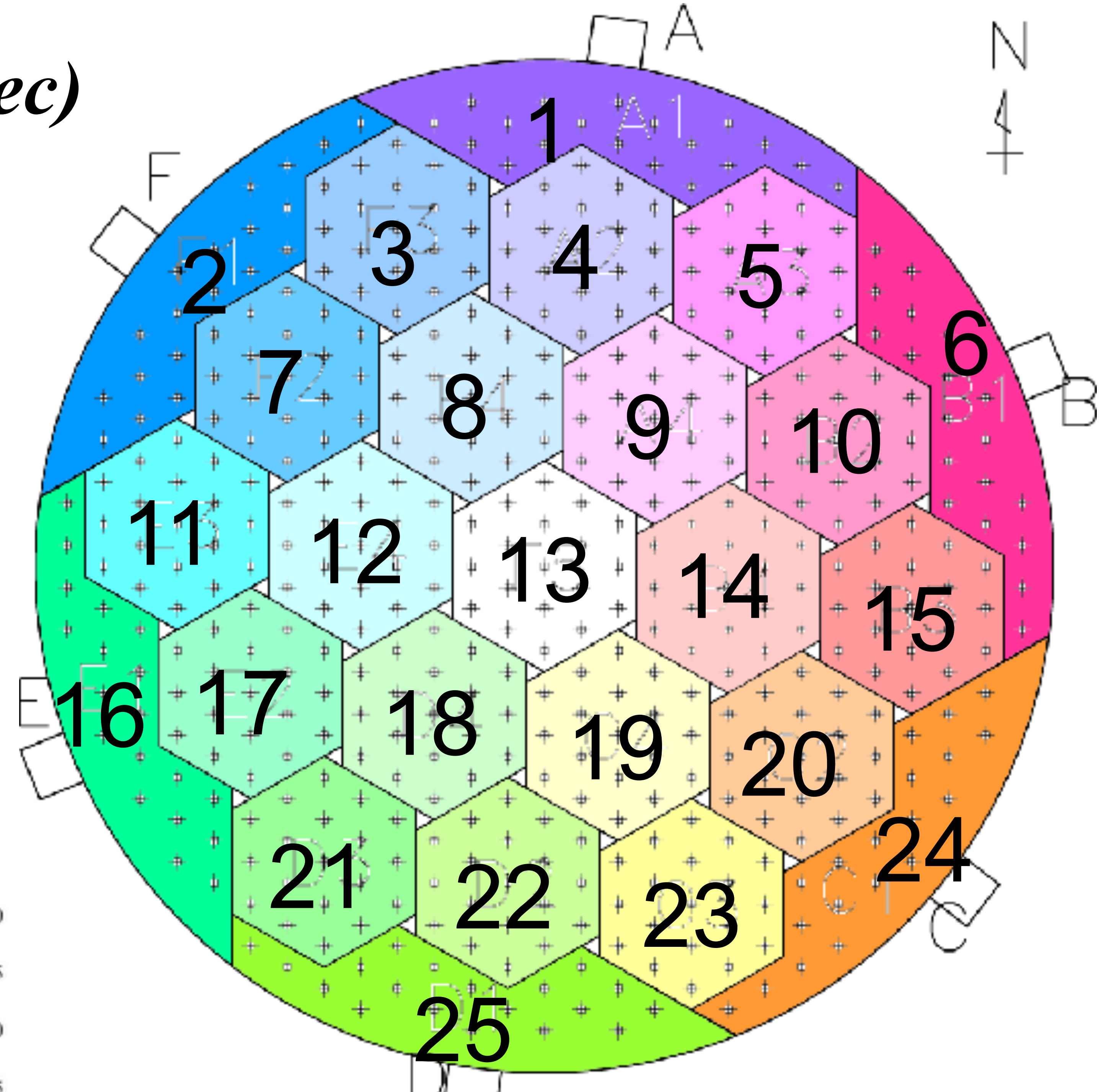
Kyoto University RISH MU Radar
Middle and **U**pper Atmosphere **Radar**

- ***Digital 25 channels***
- ***332 times per second (3 msec)***
- ***85 ranges every 3 msec***
- ***Data rate ~20 GB/hour***

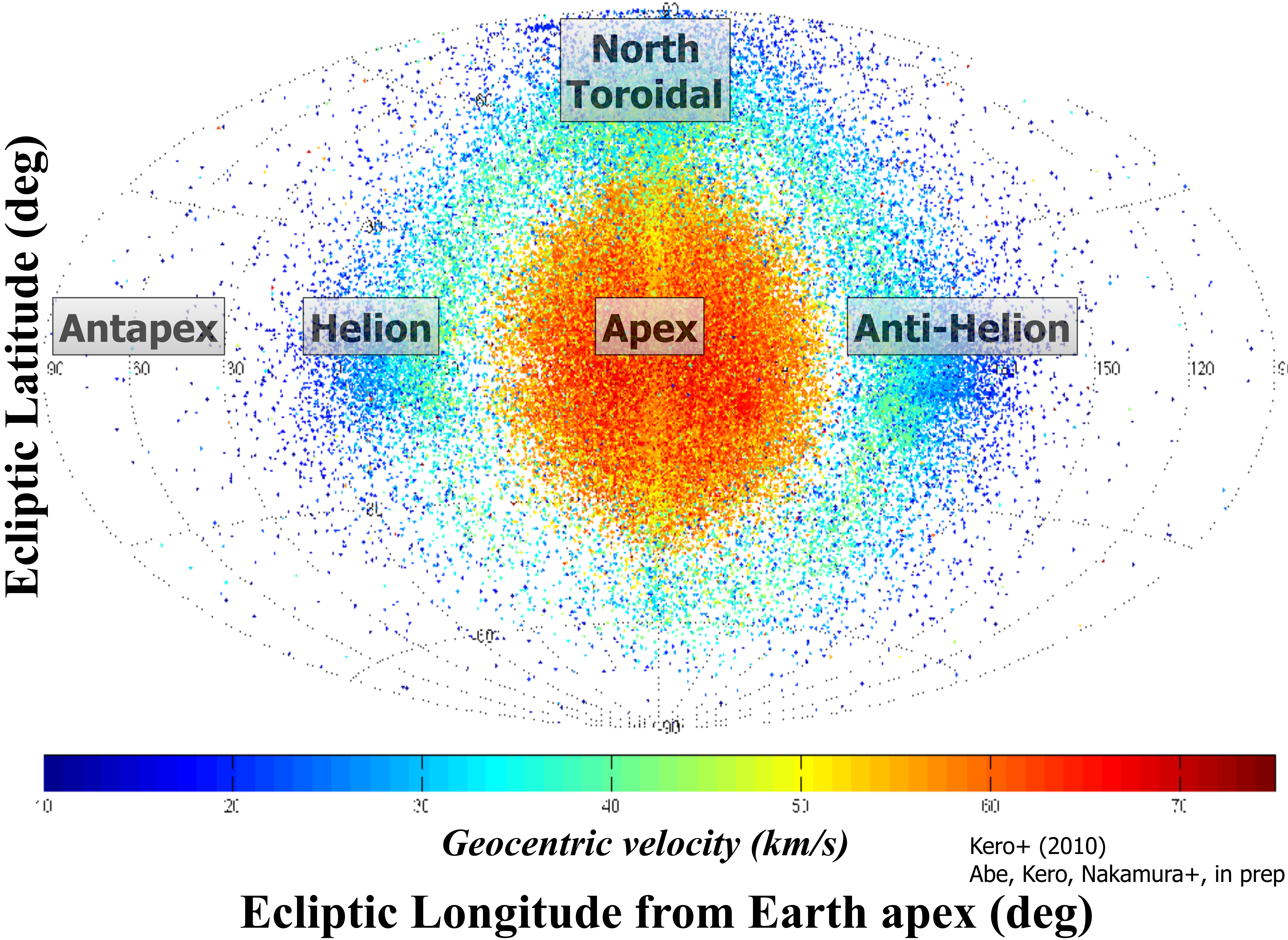
effective FOV ~5.5deg

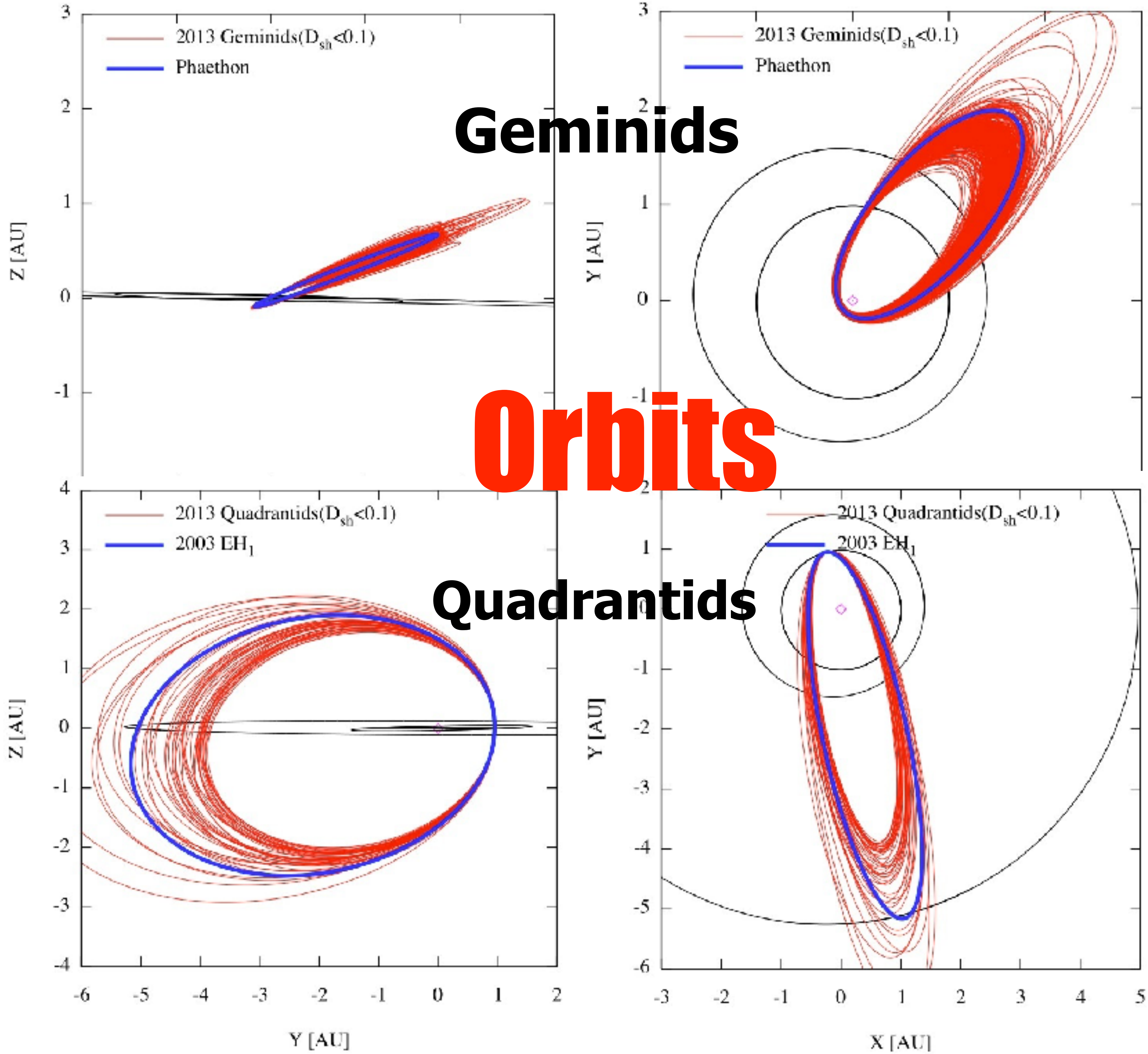


theoretical gain pattern



Doppler velocity
19 Interferometers


North Toroidal
Antapex
Helion
Apex
Anti-Helion
Ecliptic Latitude (deg)
10
20
30
40
50
60
70
Geocentric velocity (km/s)
Kero+ (2010)
Abe, Kero, Nakamura+, in prep
Ecliptic Longitude from Earth apex (deg)

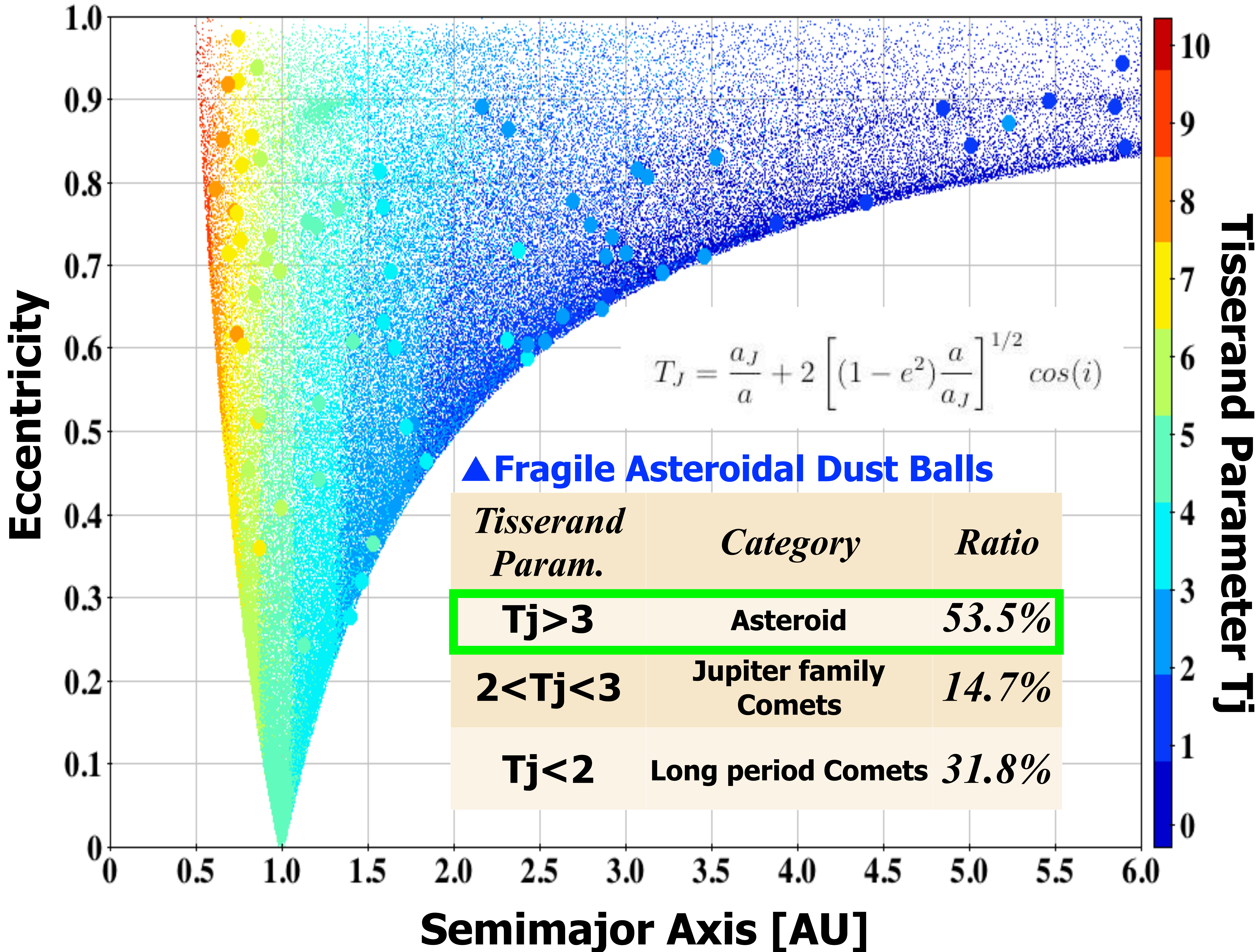

Geminids
Orbits
Quadrantids
2013 Geminids(D_sh<0.1)
Phaethon
2013 Quadrantids(D_sh<0.1)
2003 EH_1
Z [AU]
Y [AU]
X [AU]

Comparison of Orbits between MU Radar and Optical Observations

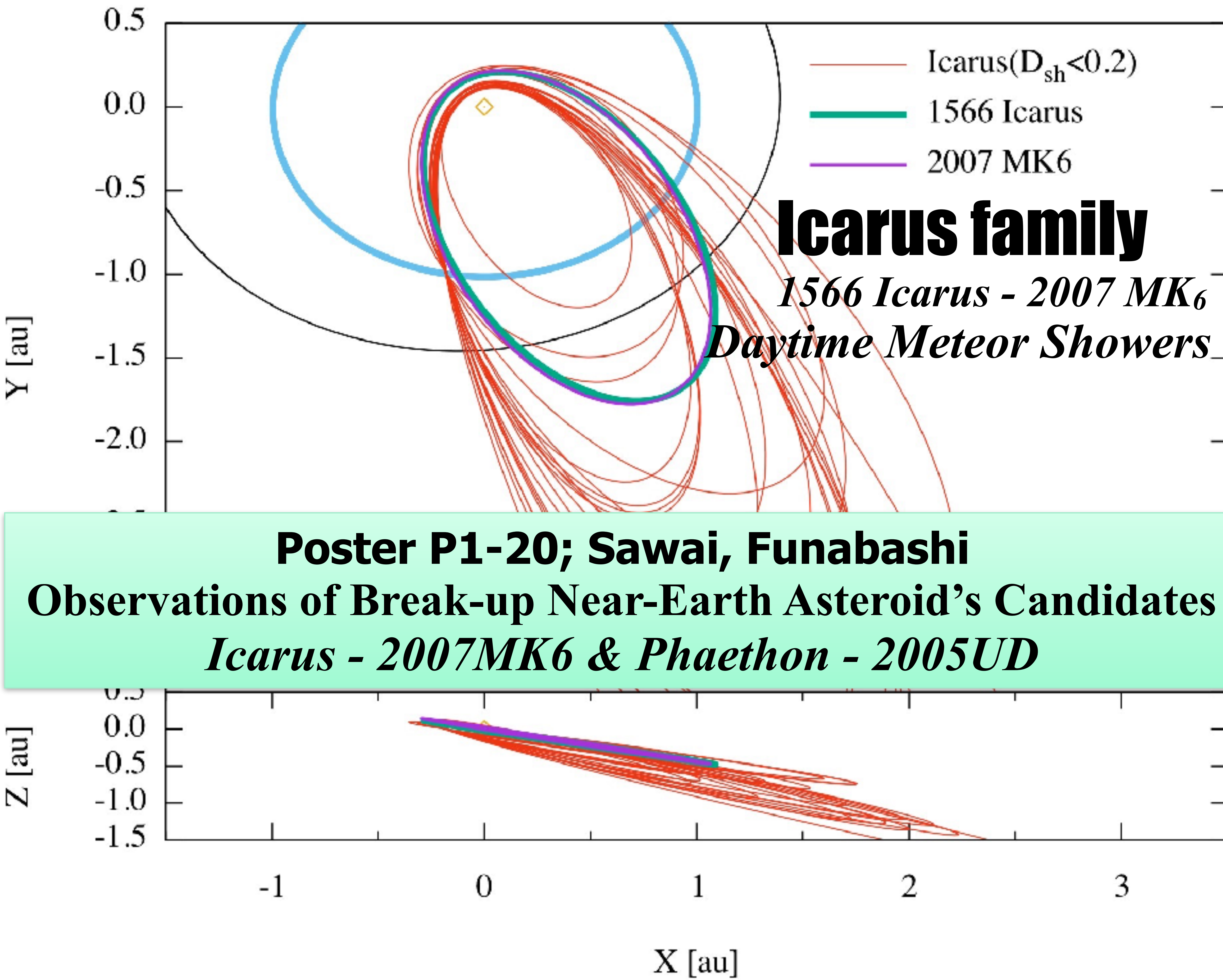
Object	*Date*	a	*e*	*i*	*ω*	*Ω*	D_{sh}
	UT	au	–	°	°	°	–
Phaethon	-	1.27	0.89	22.2	322.1	265.2	-
1-radar	Dec/14	1.27	0.89	23.6	325.1	262.6	0.013
1-opt	15:29	1.22	0.88	23.5	325.1	262.6	
2-radar	Dec/13	1.20	0.89	24.1	325.8	261.7	0.030
2-opt	18:49	1.39	0.91	23.2	325.8	261.7	
3-radar	Dec/13	1.21	0.89	22.5	324.5	261.6	0.037
3-opt	16:14	1.26	0.88	22.7	324.5	261.6	
Geminids	2010	1.30	0.899	25.0	326.1	262.3	-

Orbital determination by Meteor Head-echo and optical observation is comparable.

Abe et al. Proc. ISTS (2015)



Tisserand Param.	*Category*	*Ratio*
Tj>3	Asteroid	*53.5%*
2<Tj<3	Jupiter family Comets	*14.7%*
Tj<2	Long period Comets	*31.8%*

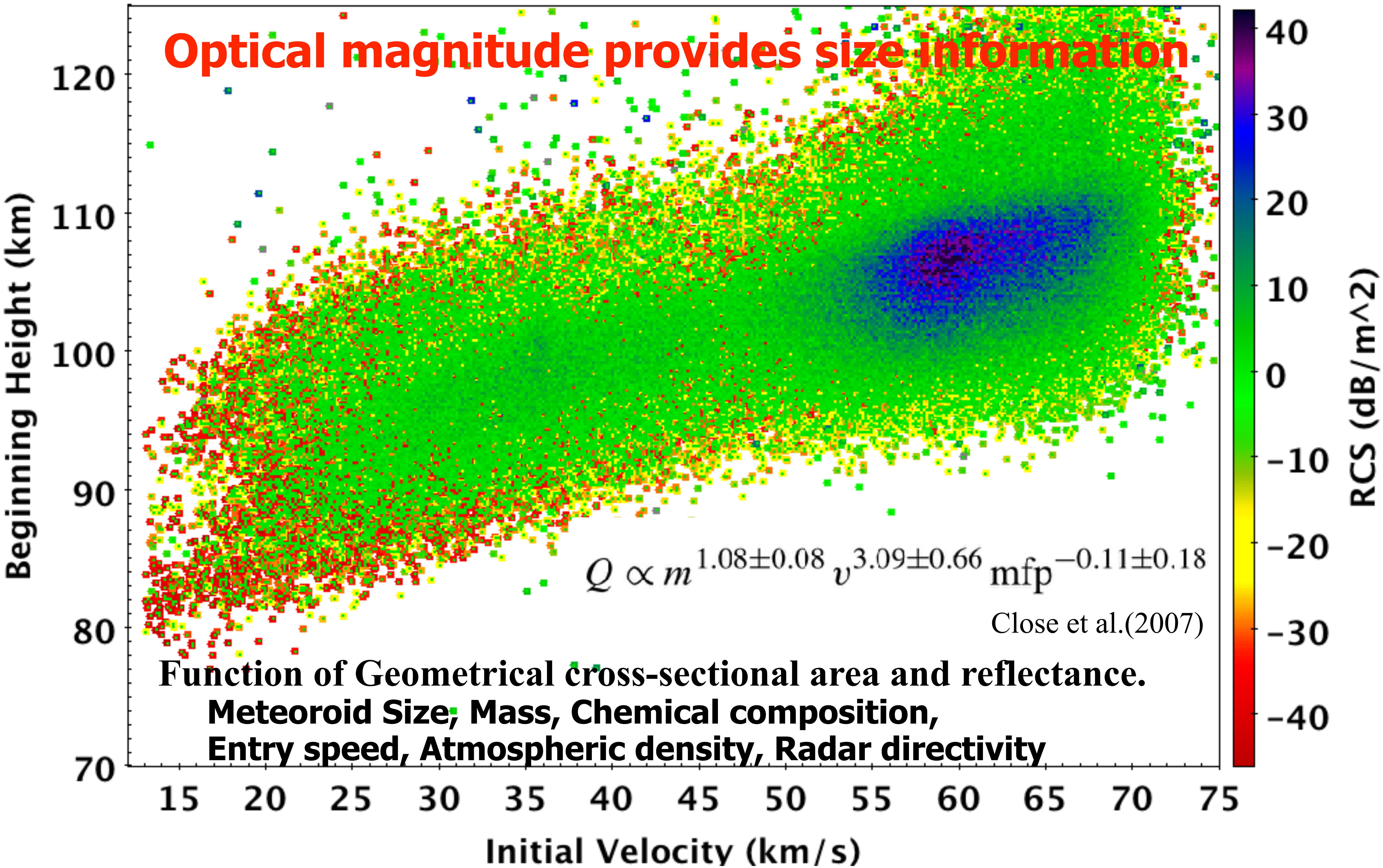


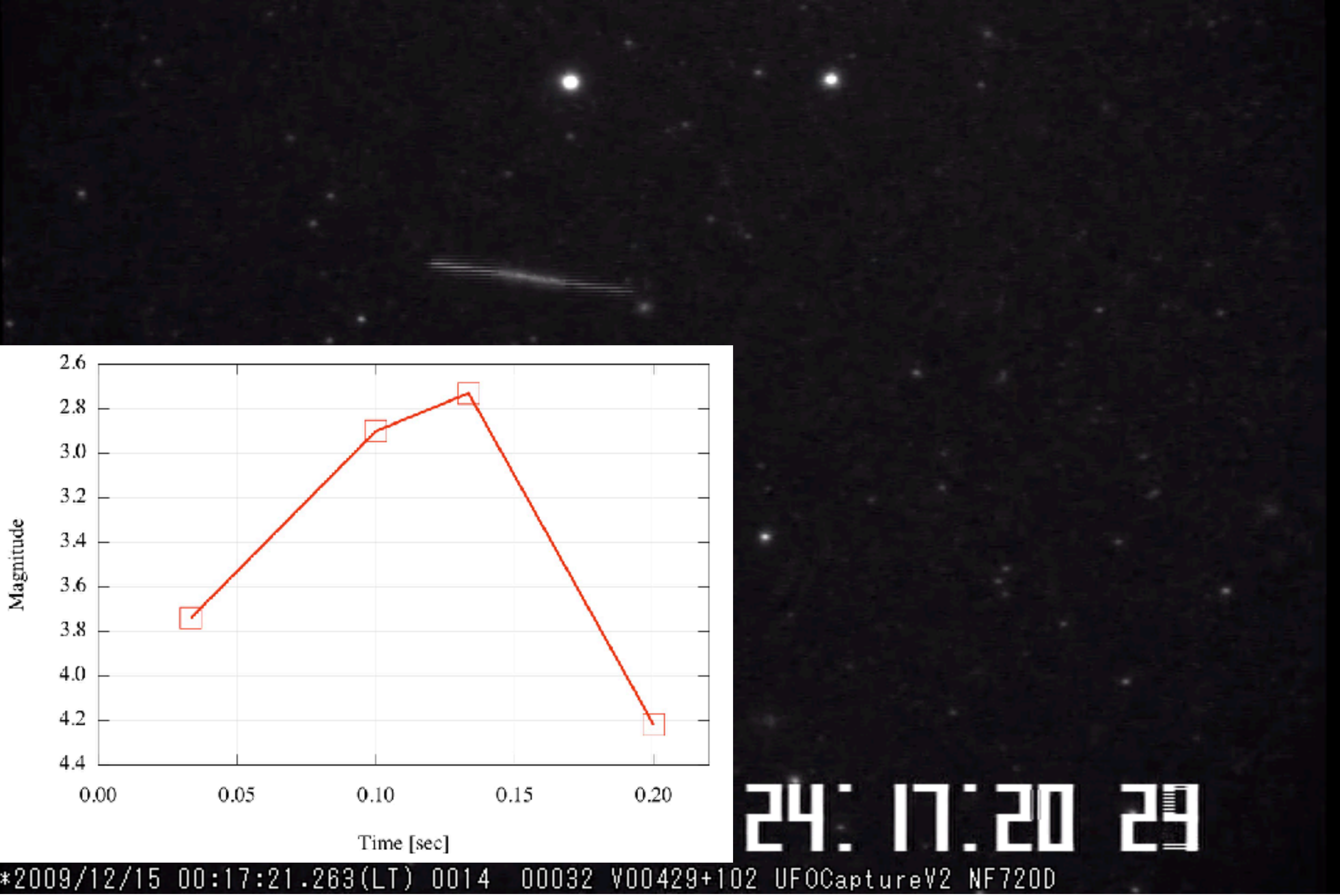
Poster P1-20; Sawai, Funabashi

Observations of Break-up Near-Earth Asteroid's Candidates

Icarus - 2007MK6 & Phaethon - 2005UD

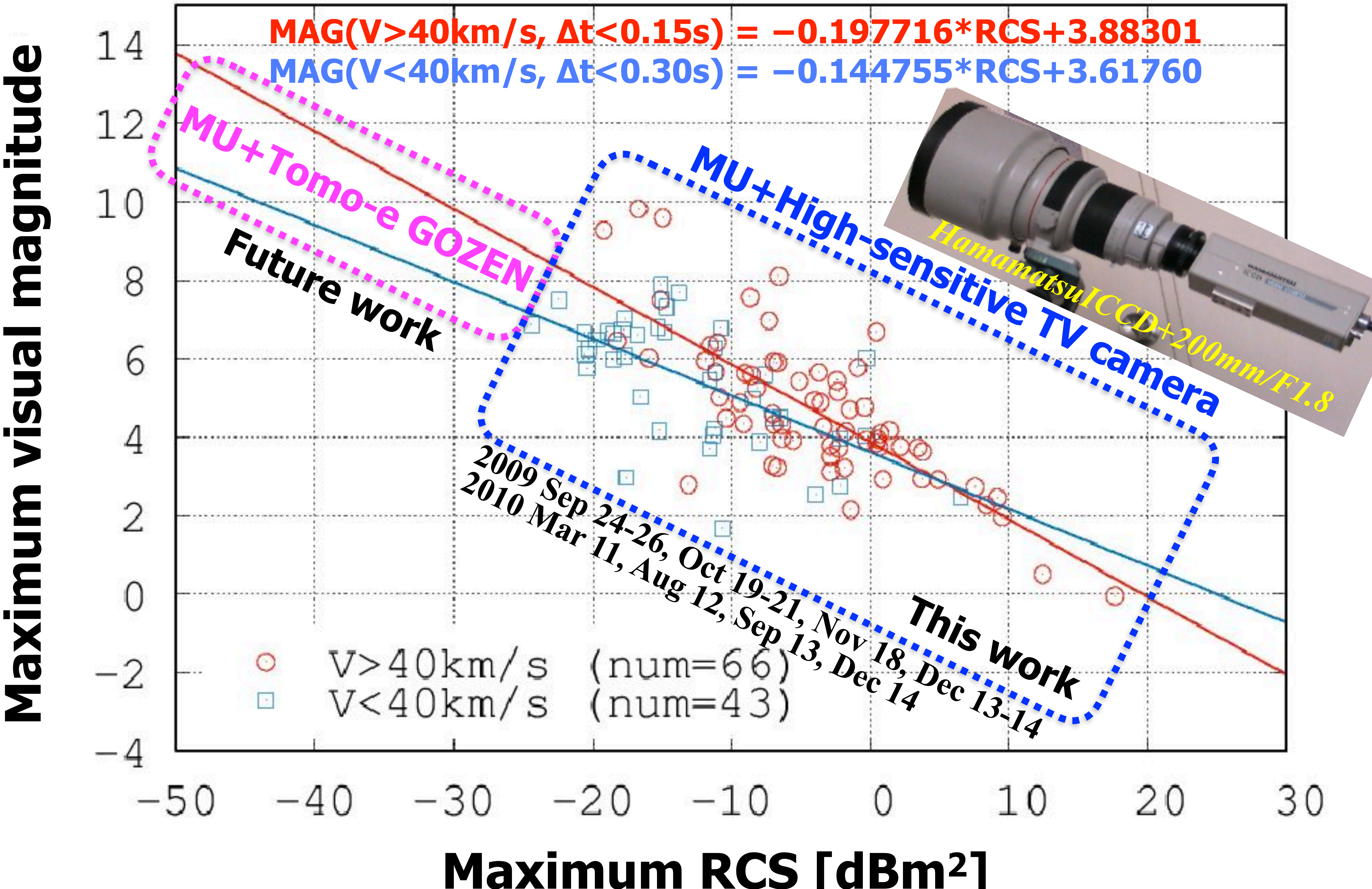
RCS (Radar Cross Section) controversy

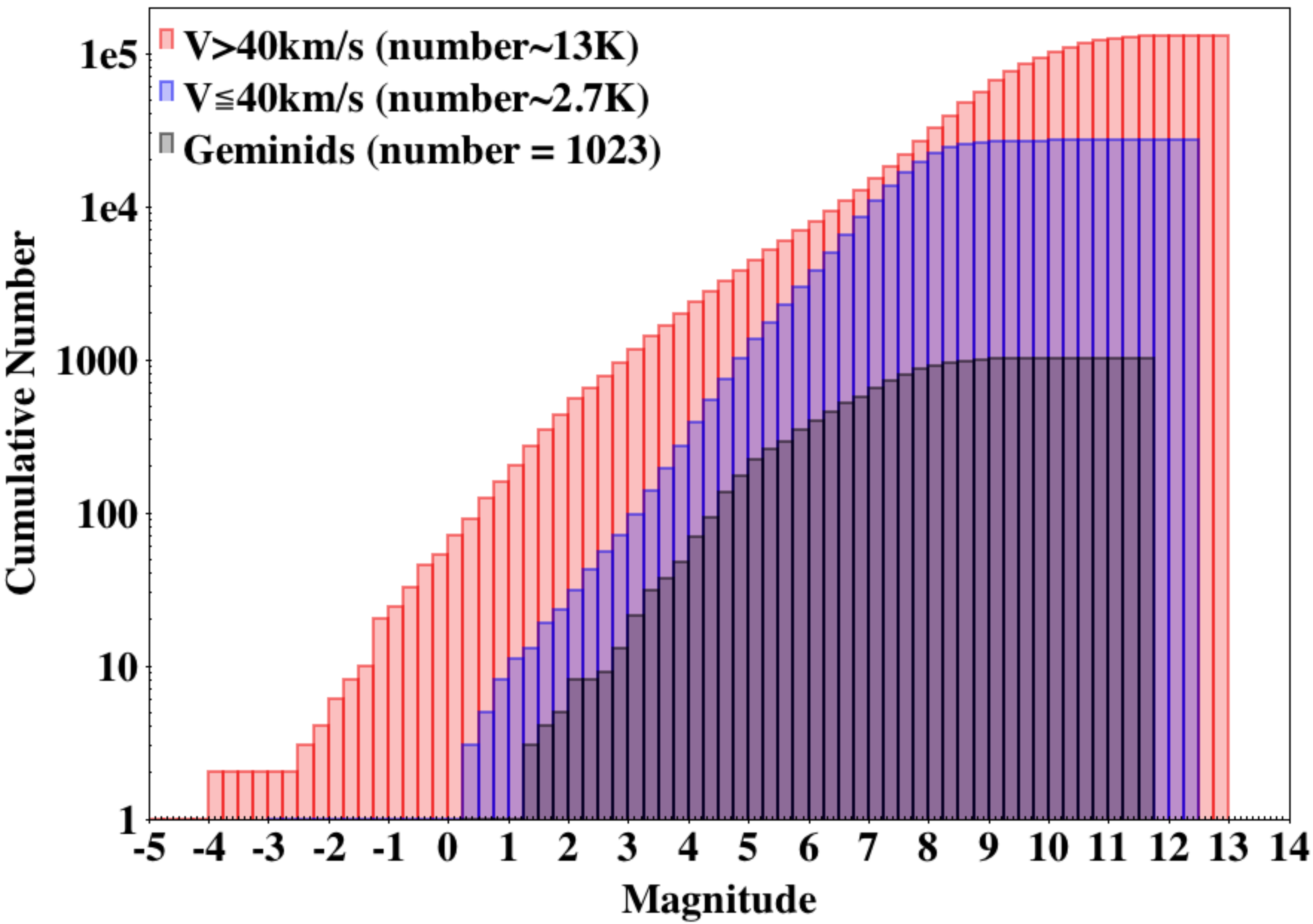


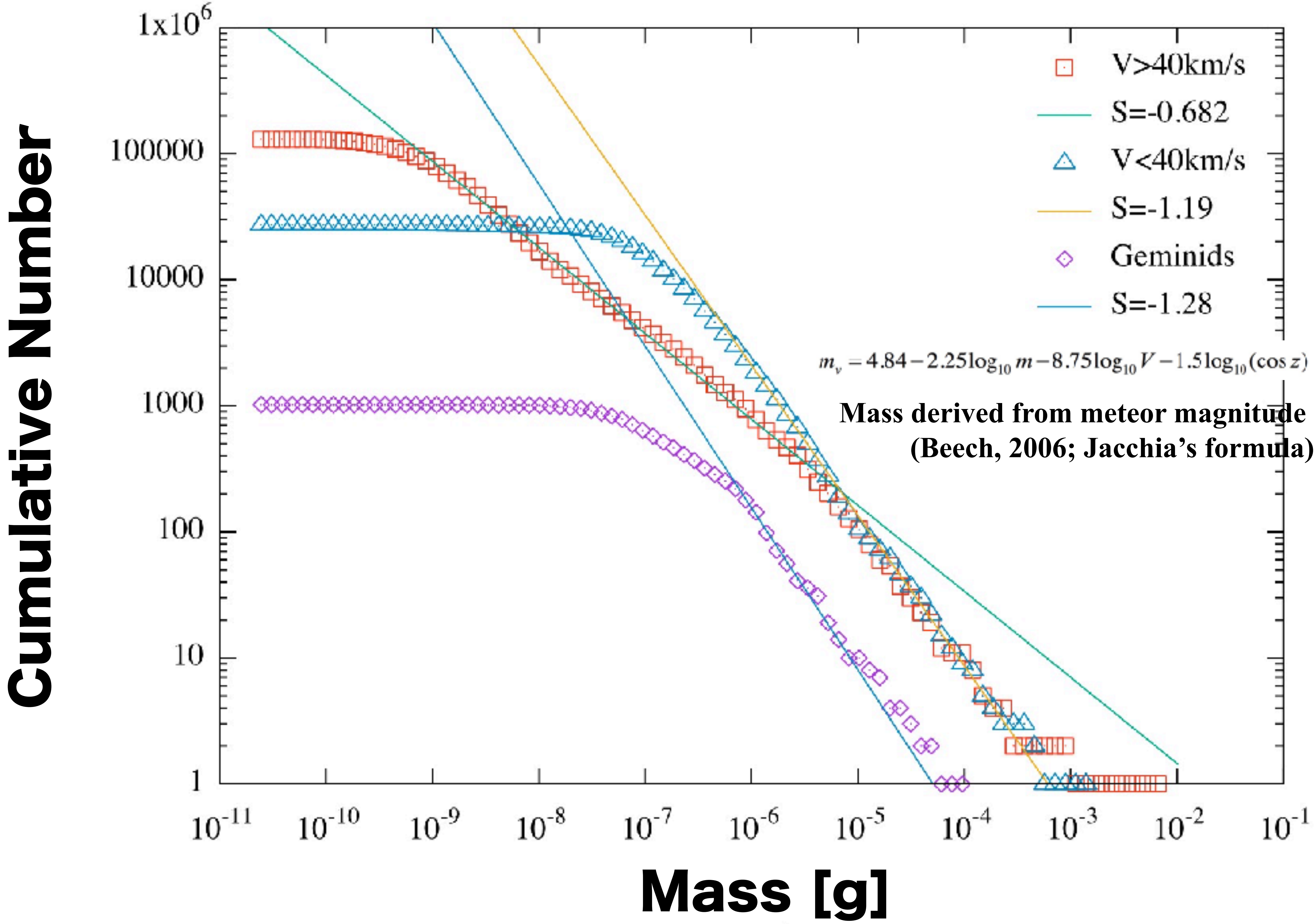


Simultaneous observation with MU Head-echo and TV

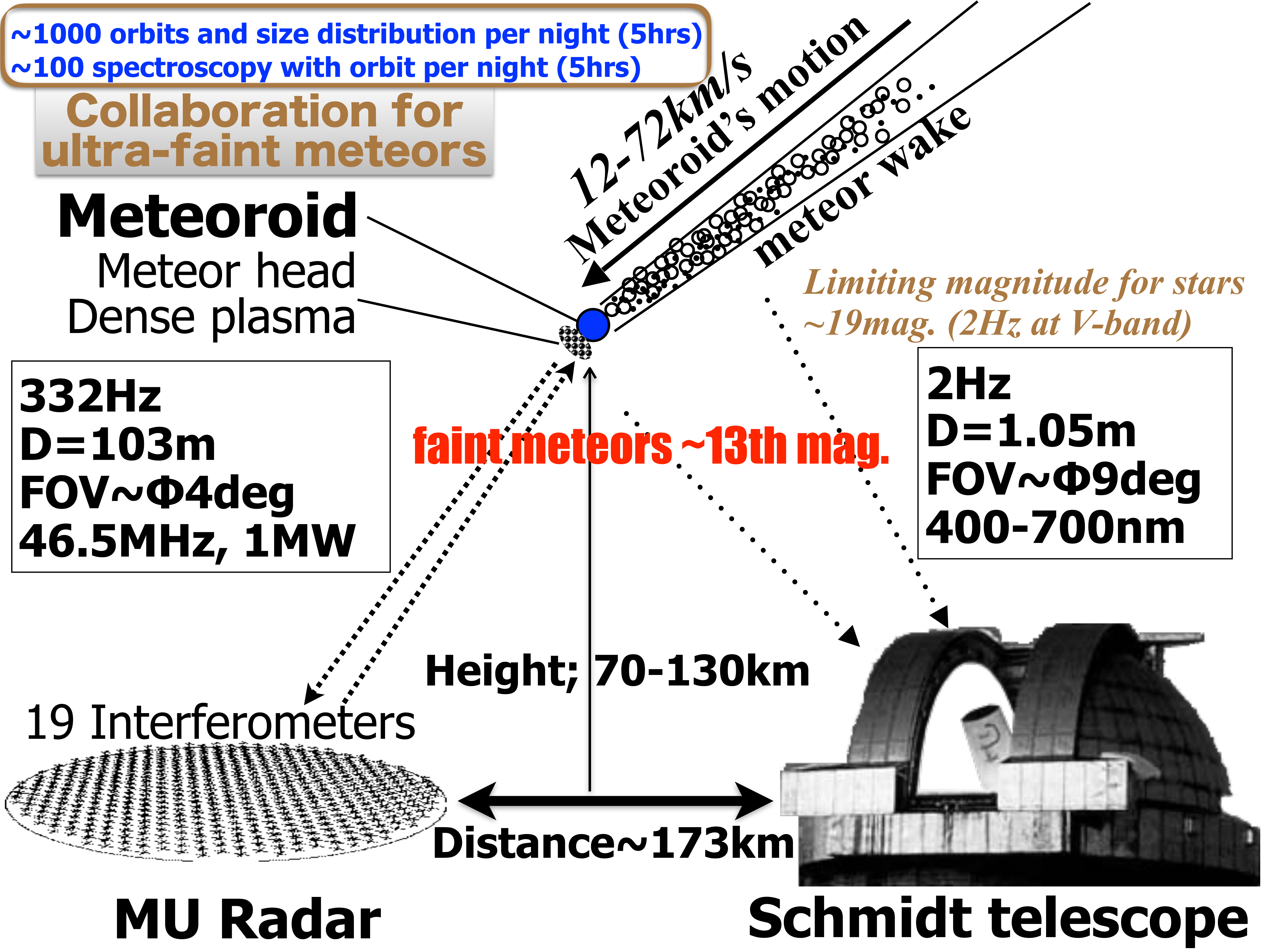
Visual magnitude as functions of RCS




V>40km/s (number~13K)
V≦40km/s (number~2.7K)
Geminids (number = 1023)
Cumulative Number
1e5
1e4
1000
100
10
1
-5
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Magnitude



Cumulative Number
1x10^6
100000
10000
1000
100
10
1
10^-11
10^-10
10^-9
10^-8
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
Mass [g]
V>40km/s
S=-0.682
V<40km/s
S=-1.19
Geminids
S=-1.28
$m_v = 4.84 - 2.25\log_{10} m - 8.75\log_{10} V - 1.5\log_{10}(\cos z)$
Mass derived from meteor magnitude
(Beech, 2006; Jacchia's formula)

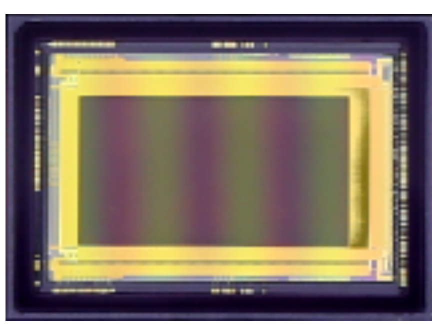

~1000 orbits and size distribution per night (5hrs)
~100 spectroscopy with orbit per night (5hrs)
Collaboration for ultra-faint meteors
Meteoroid
Meteor head
Dense plasma
12-72km/s
Meteoroid's motion
meteor wake
Limiting magnitude for stars ~19mag. (2Hz at V-band)
332Hz
D=103m
FOV~Φ4deg
46.5MHz, 1MW
faint meteors ~13th mag.
2Hz
D=1.05m
FOV~Φ9deg
400-700nm
Height; 70-130km
19 Interferometers
Distance~173km
MU Radar
Schmidt telescope

the first astronomical wide-field CMOS camera

the Tomo-e Gozen

東京大学
THE UNIVERSITY OF TOKYO

- **Telescope   Kiso 105-cm wide-field Schmidt**
- **Field of view   20 deg2 in ϕ9 deg**
- **Data acquisition rate 2 fps (max)**
- **Data production rate 30 TB/night (max)**
- **Commissioning Aug. 2018**
- **Operation   10 years**

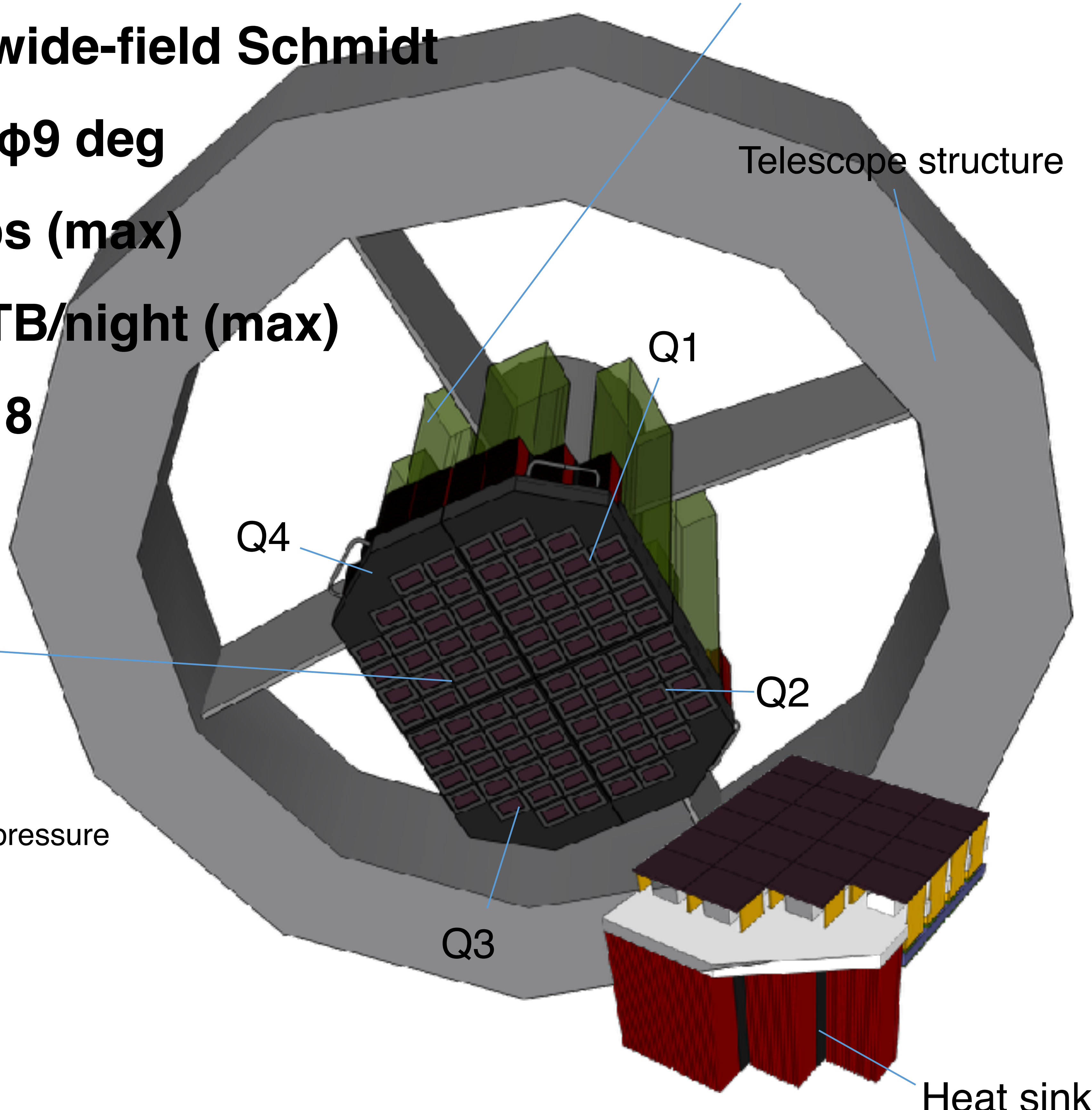


front-side CMOS
w micro-lenses

Canon

CMOS sensor x84
Room temperature and ordinal atmospheric pressure
Low noise

Final model of Tomo-e Gozen

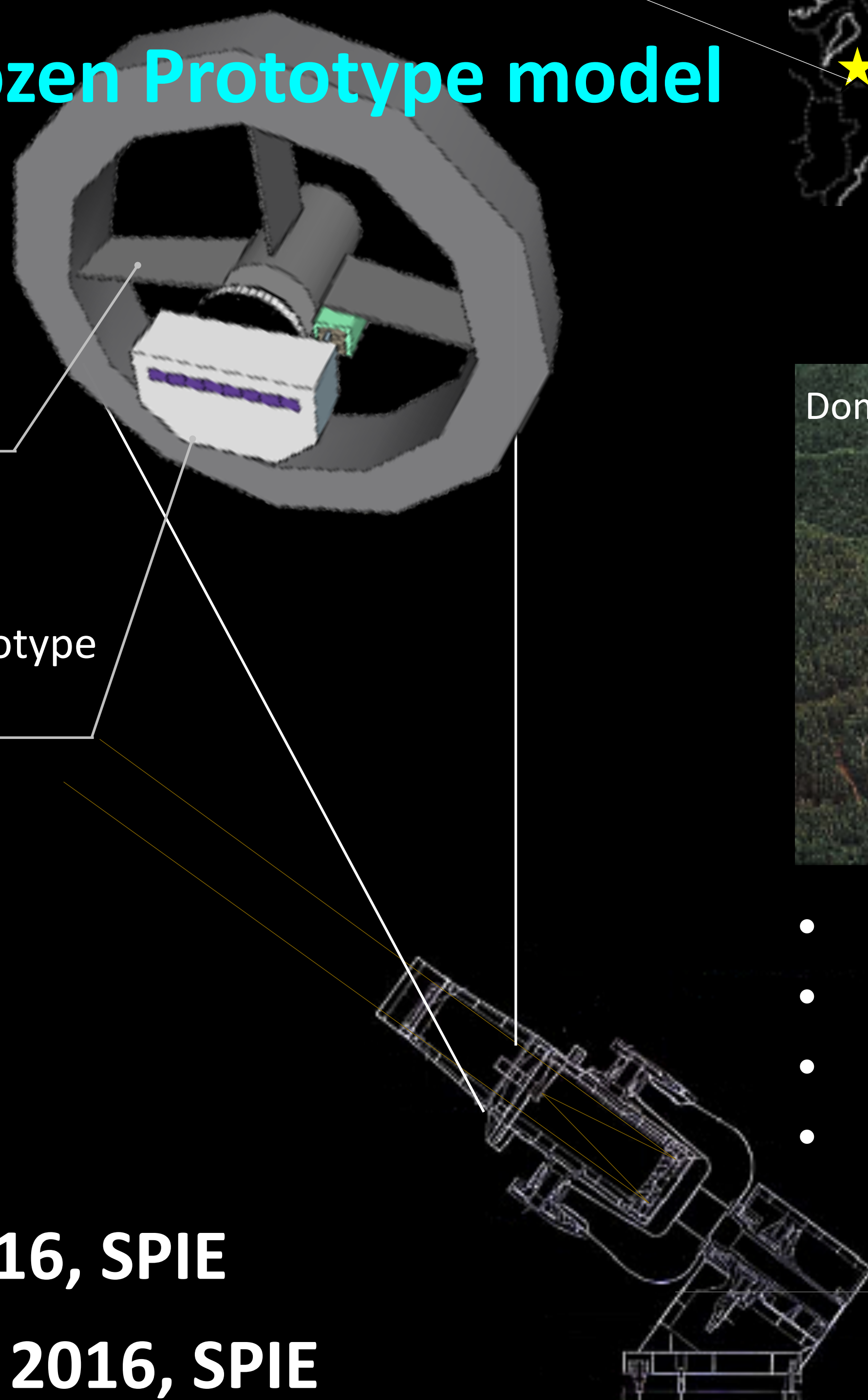


Sako et al. 2016, SPIE
Ohsawa et al. 2016, SPIE

Kiso observatory, Institute of Astronomy, the University of Tokyo

東京大学
THE UNIVERSITY OF TOKYO

Tomo-e Gozen Prototype model



8 chips of CMOS sensor

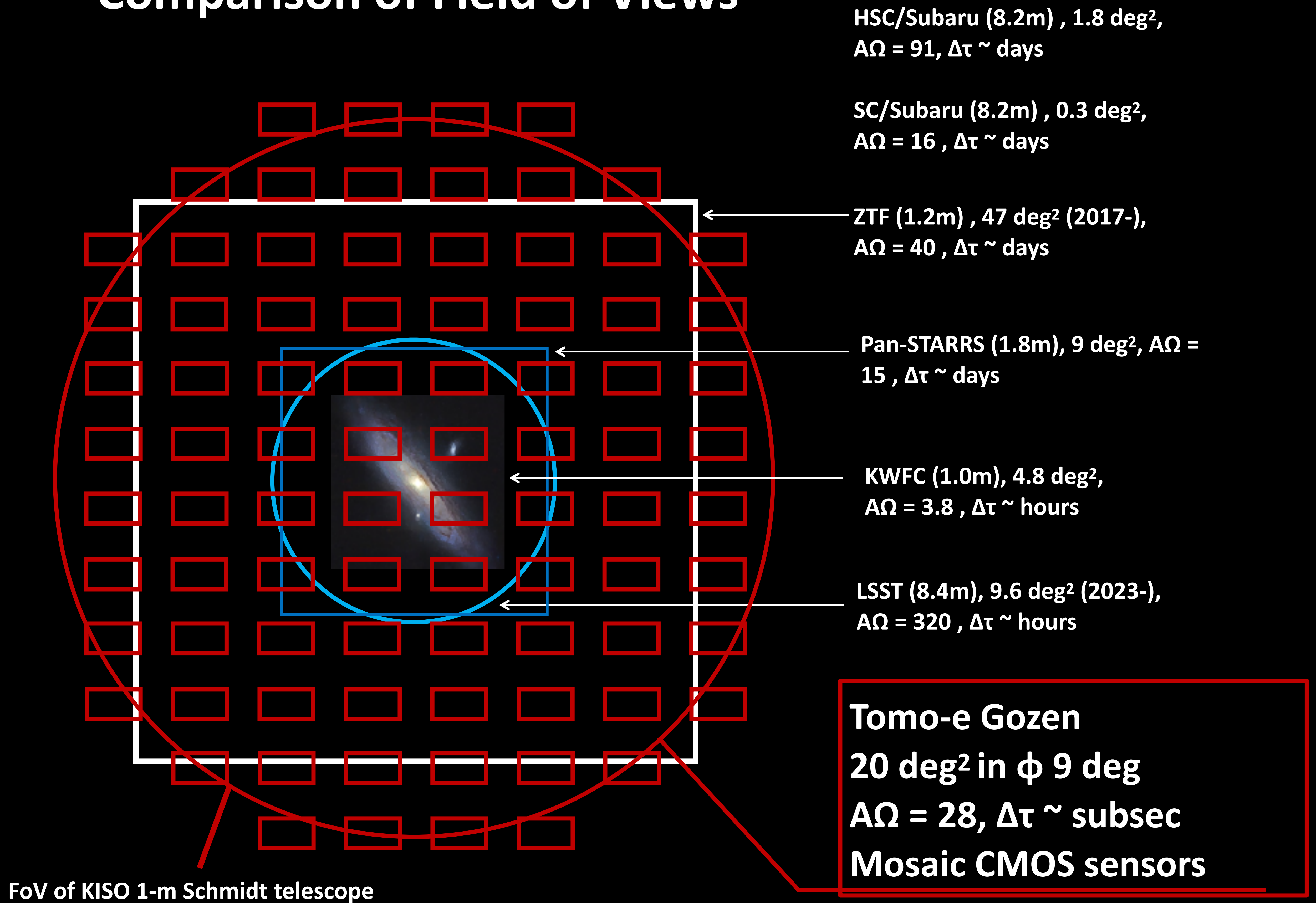
- Established in 1974
- Open use operation
- Dark sky, 1120-m altitude
- Accommodation, Cafeteria

Kiso 105cm Schmidt telescope

Sako et al. 2016, SPIE

Ohsawa et al. 2016, SPIE

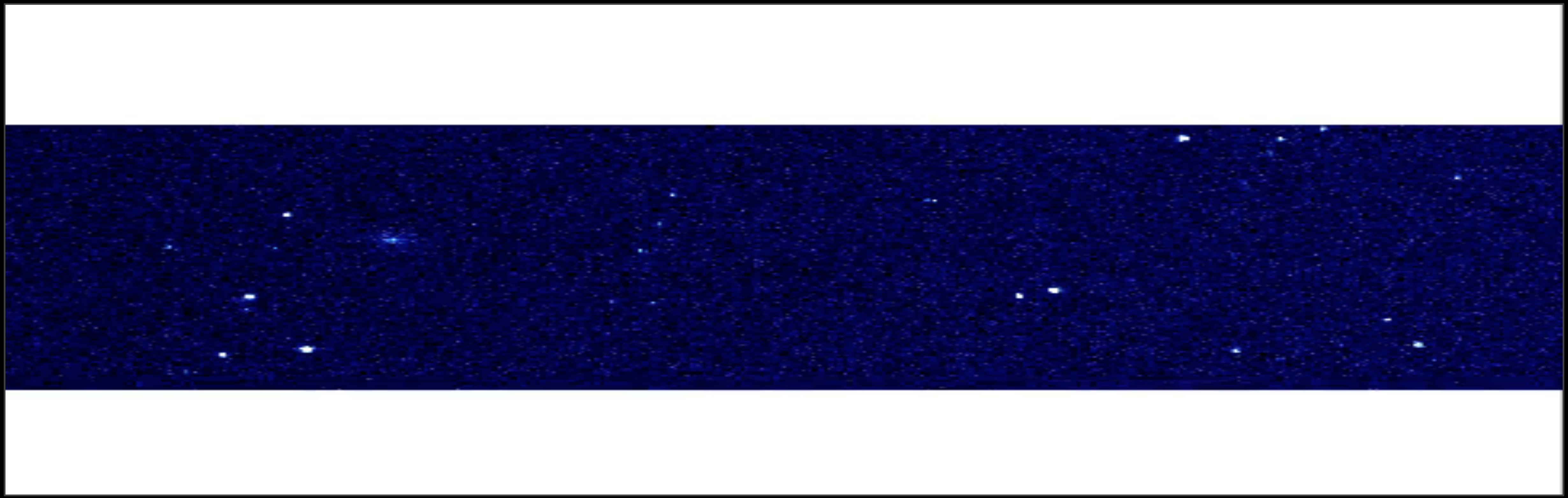
Comparison of Field of Views



Data sample obtained by Tomo-e PM

First light image, h-x Per open star cluster
(1 chip, 5 sec exposure, FoV of 39.7’ x 22.4’)

High dynamic image of M42 Orion nebula
(1 chip, 0.5 sec/exposure x 5,018 frames)



Movie data (10 fps, partial readout, 1 chip)

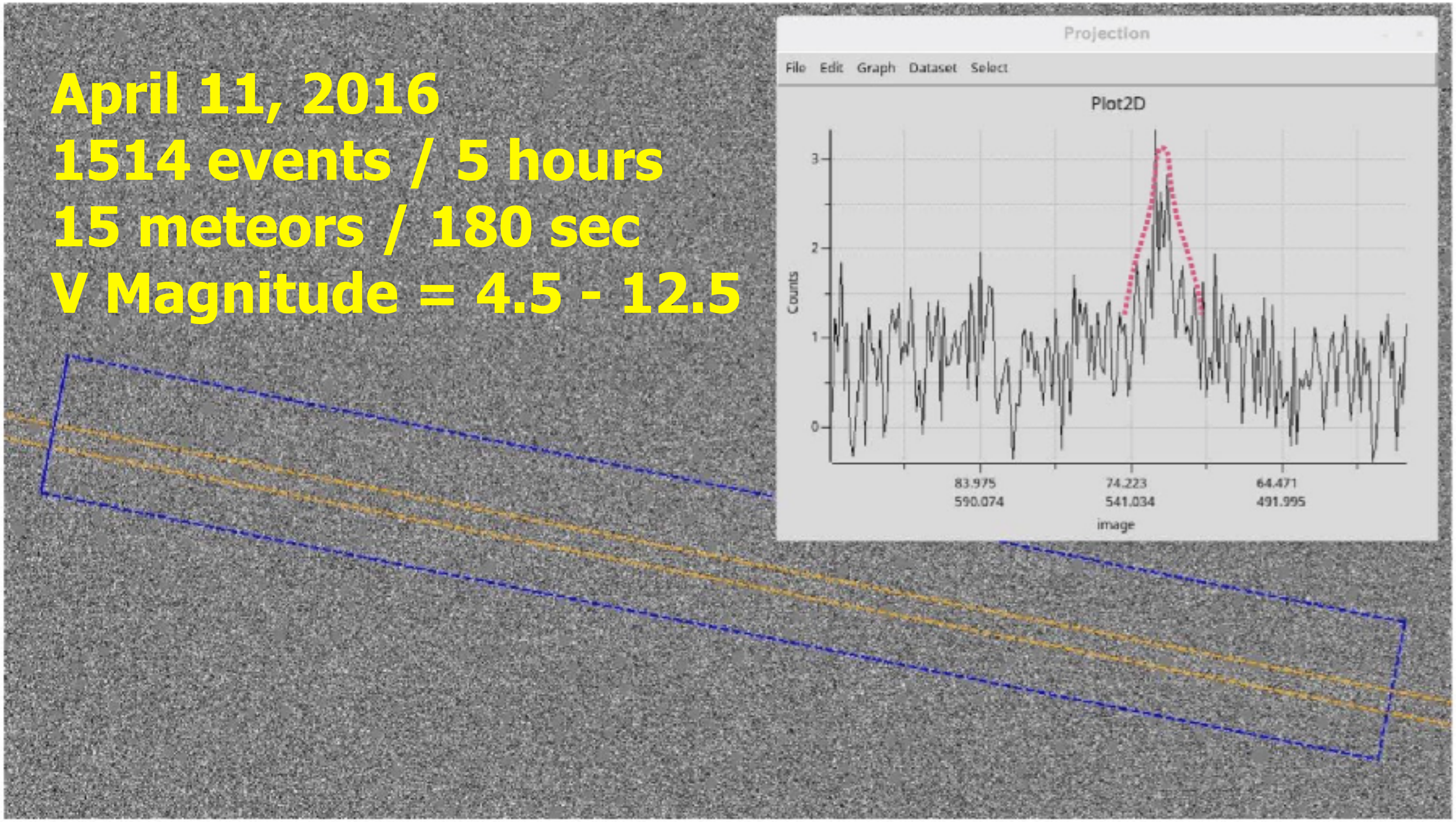
Example of Faint meteors by Tomo-e GOZEN

Trail of faint meteor

- Faint meteors up to 13 - 14 mag detected. (World record).
- About 1,000 events of sporadic meteors detected in a night (World record).

Faint Meteors Imaging ~13th magnitude

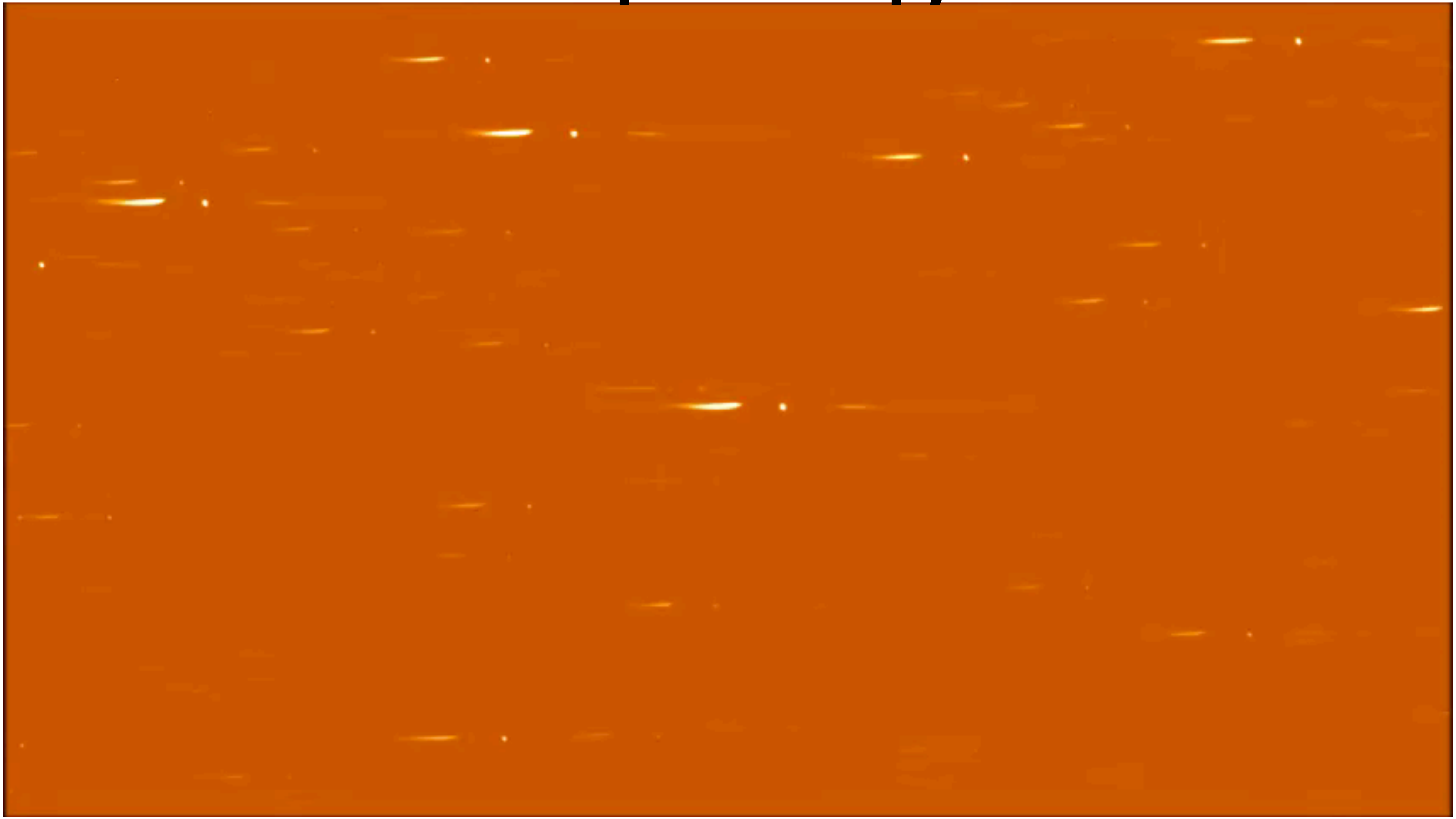
An Image containing a faint meteor (stellar sources are masked)



Detected Faint Meteors by Hough transform algorithm

Osawa, Sako, et al. (Univ. Tokyo)

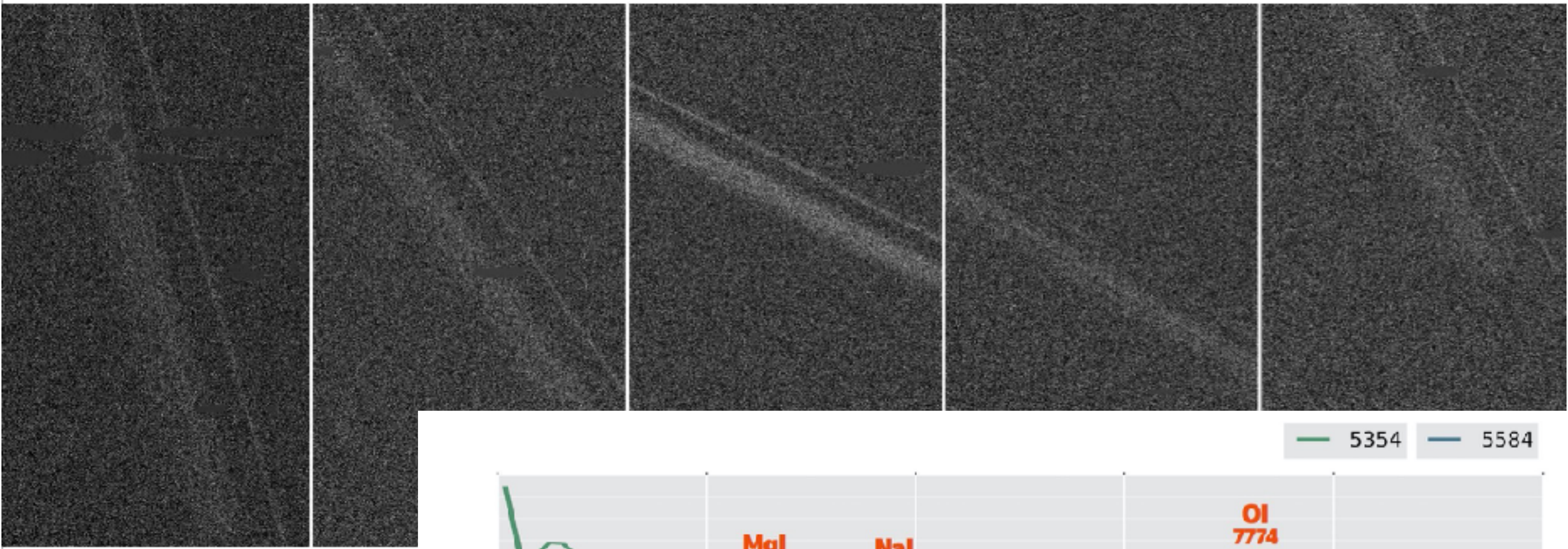
Movie data of Grism spectroscopy for faint meteors

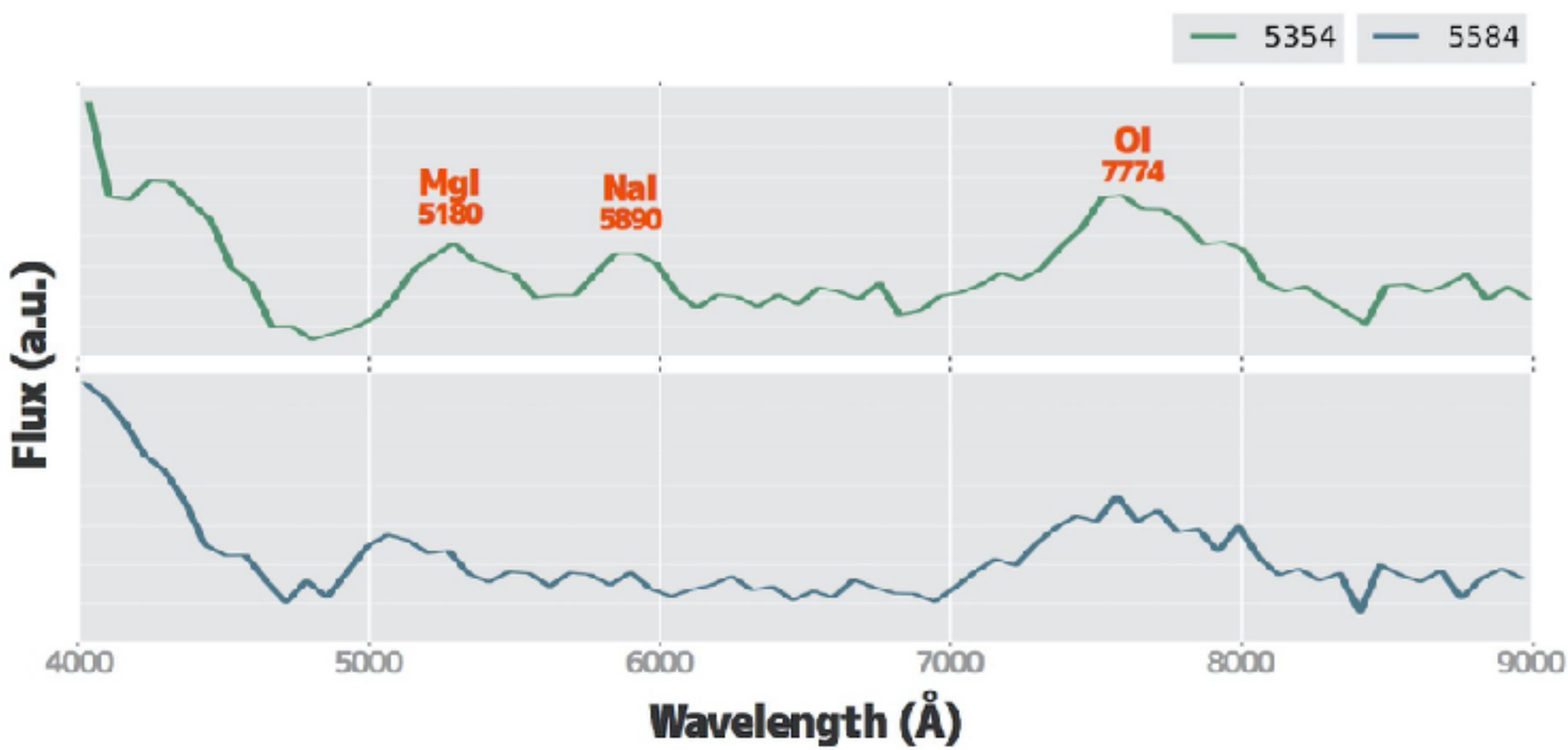


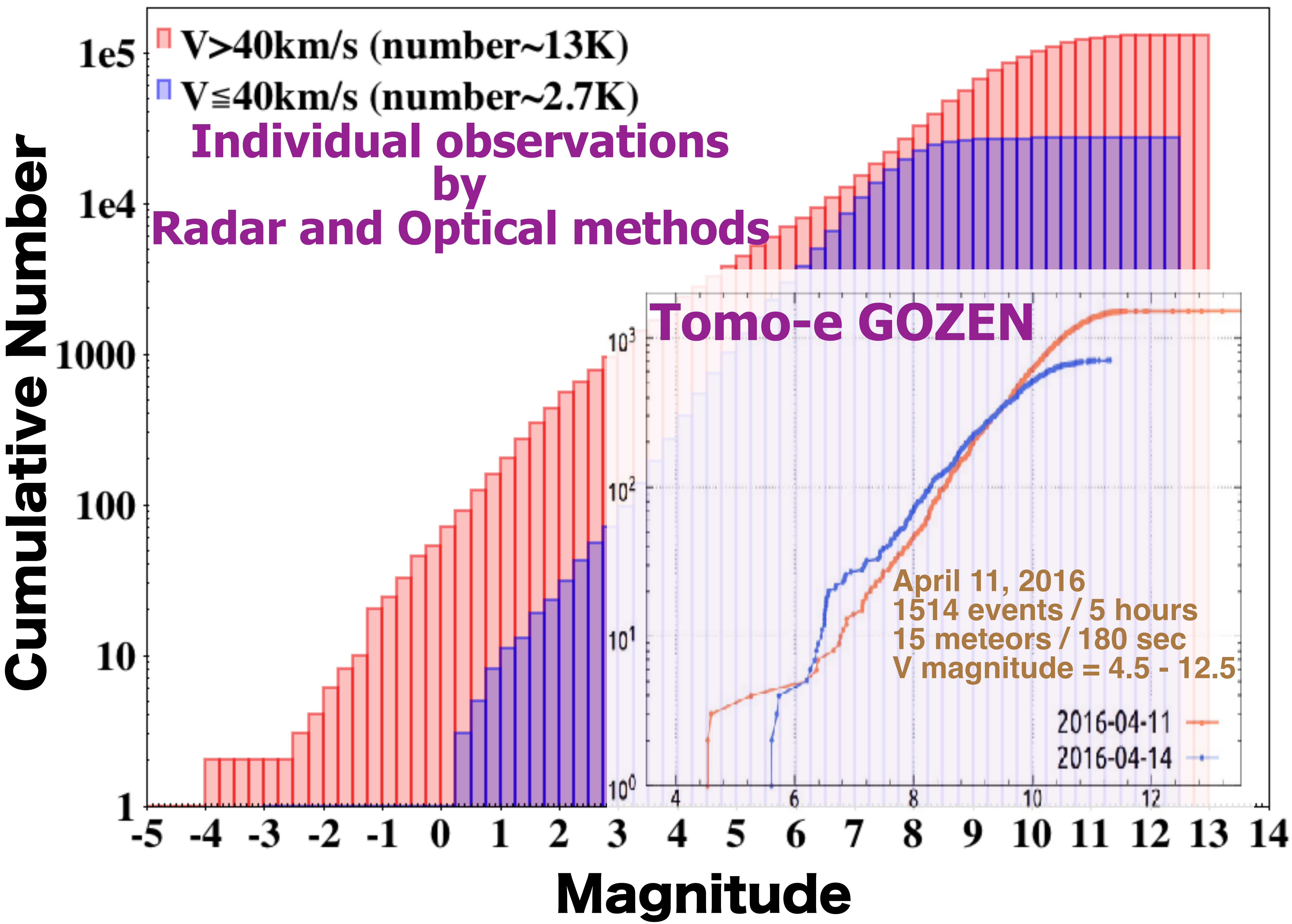
~8-9th magnitude with R=10

Spectroscopy for Ultra-faint Meteors

~8-9th magnitude with R=10

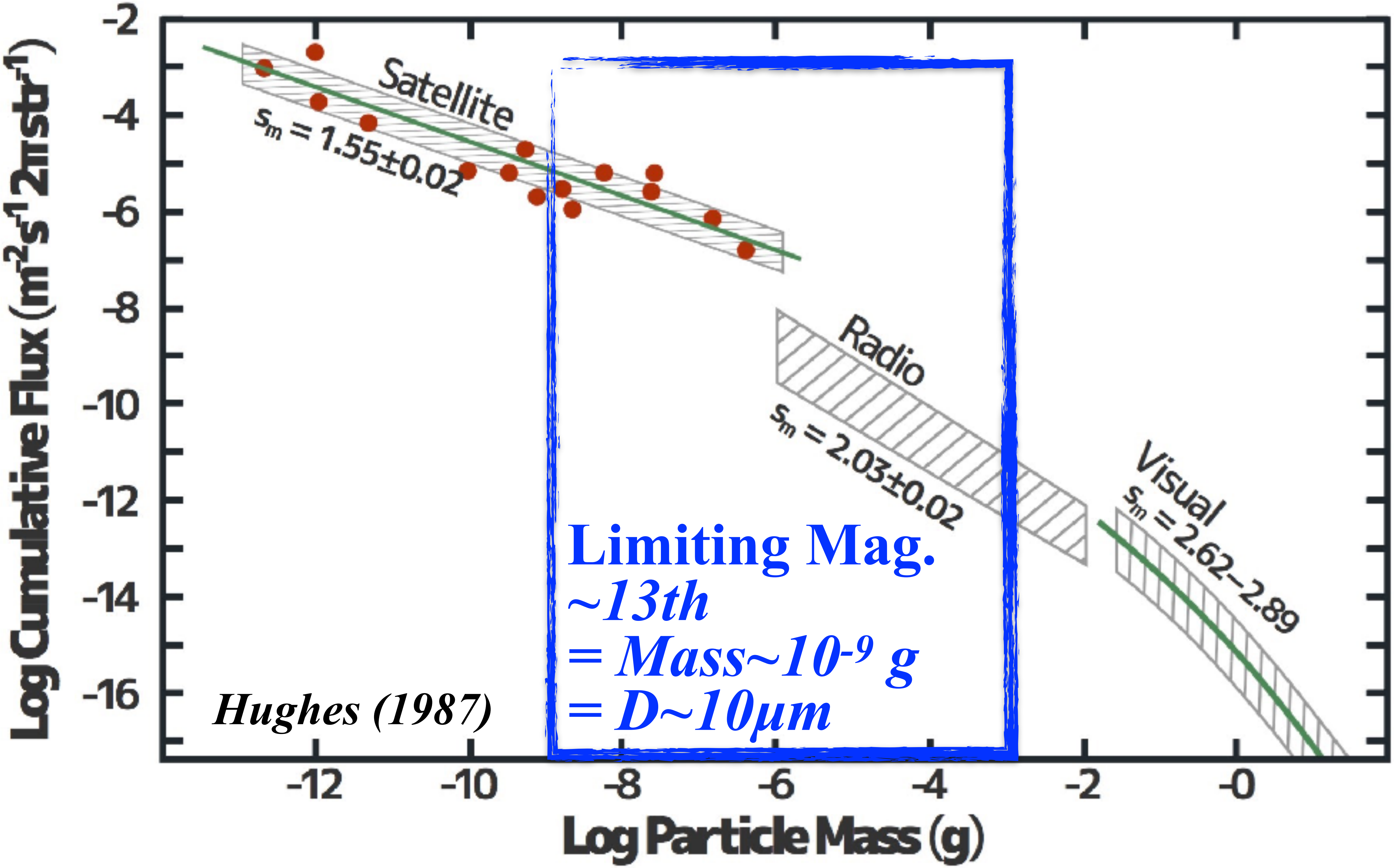






V>40km/s (number~13K)
V≦40km/s (number~2.7K)
Individual observations by Radar and Optical methods
Tomo-e GOZEN
April 11, 2016
1514 events / 5 hours
15 meteors / 180 sec
V magnitude = 4.5 - 12.5
2016-04-11
2016-04-14
Cumulative Number
Magnitude

Sensitivity of MU Radar Meter Head-echo & Tomo-e Observations



Summary

invisible Earth impactors are essential

New population "Fragile Dust Balls" was discovered.

D~100μm, V<20km, ~0.7%(biased) → ~10% or more

Relationship btw RCS(Radar Cross Section) and Optical magnitude for faint meteors (~8th) was obtained.

Limiting Mag~13th = Mass~10^{-9} g = D~10μm

Simultaneous observation for ultra-faint meteors (~13th) using Radar and Optical Schmidt telescope is ready —> next winter

~1000 orbits and size distribution per night (in 5hrs)

~100 spectroscopy with orbit per night (in 5hrs)

STAR-ALE PROJECT

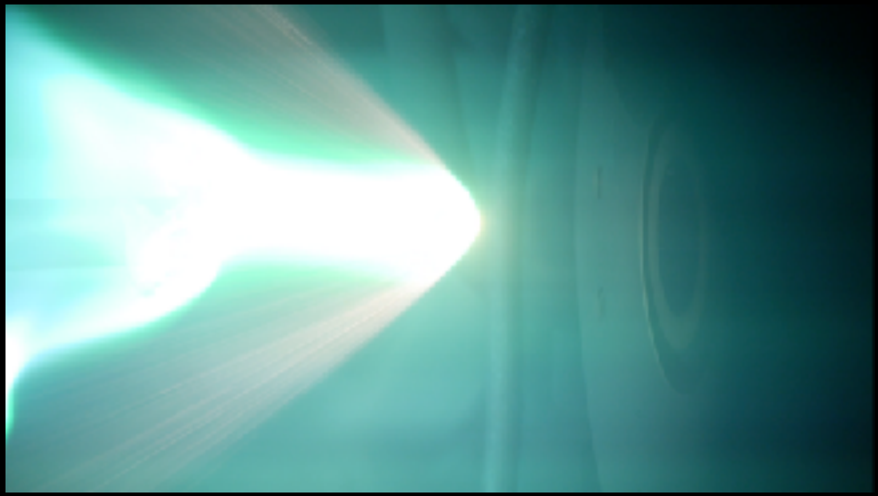
Artificial meteors for calibrating

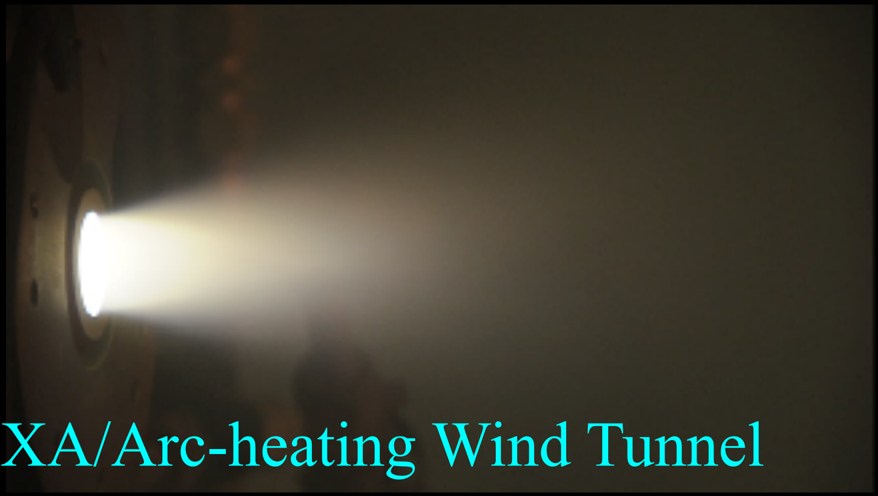
Meteor observations by Radar and Optical

Thank You 謝謝

Artificial Meteors for Business & Science

Star-ALE Co. Ltd.; http://www.star-ale.com

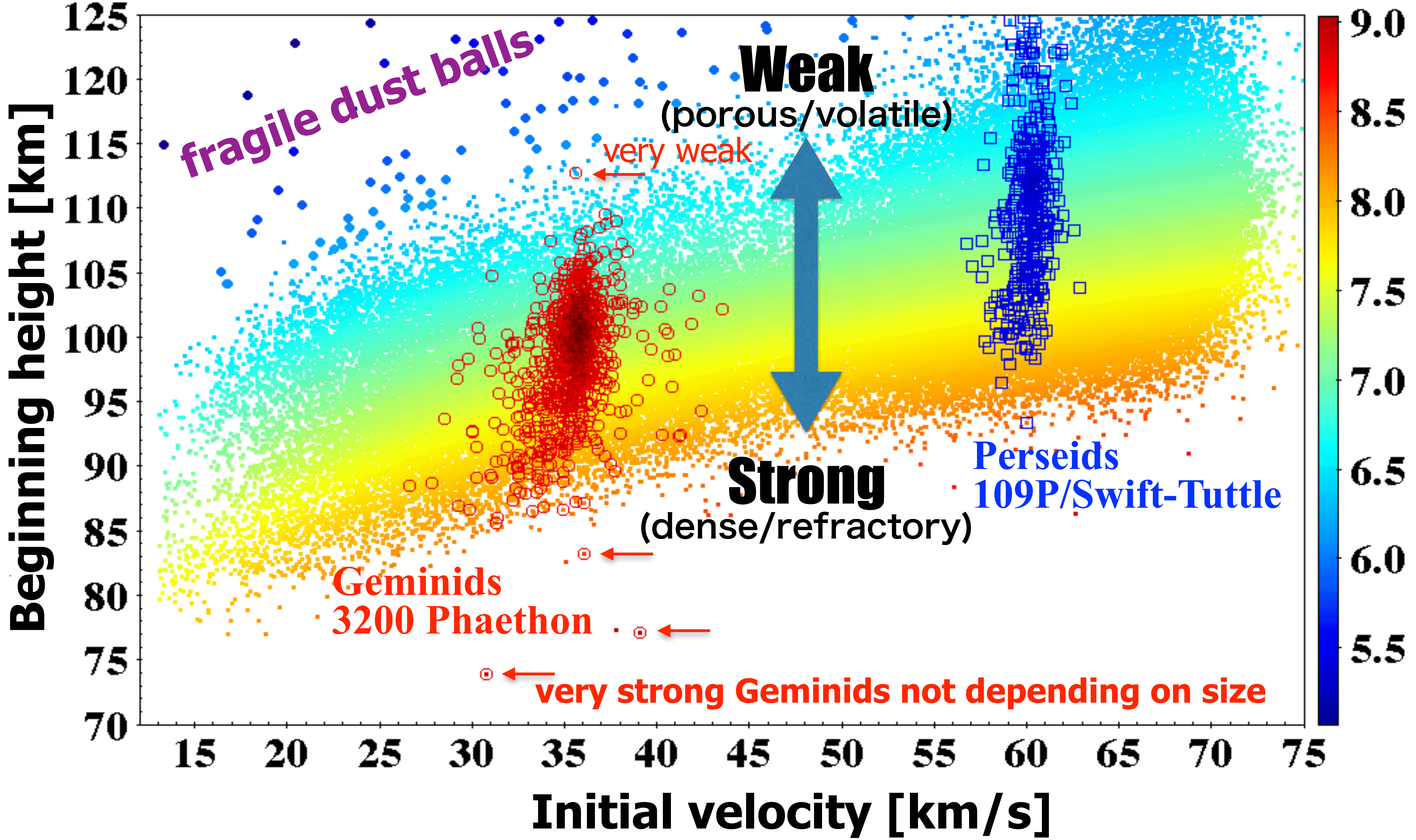




Meteor ablation tests using JAXA/Arc-heating Wind Tunnel

Strength of Meteoroids

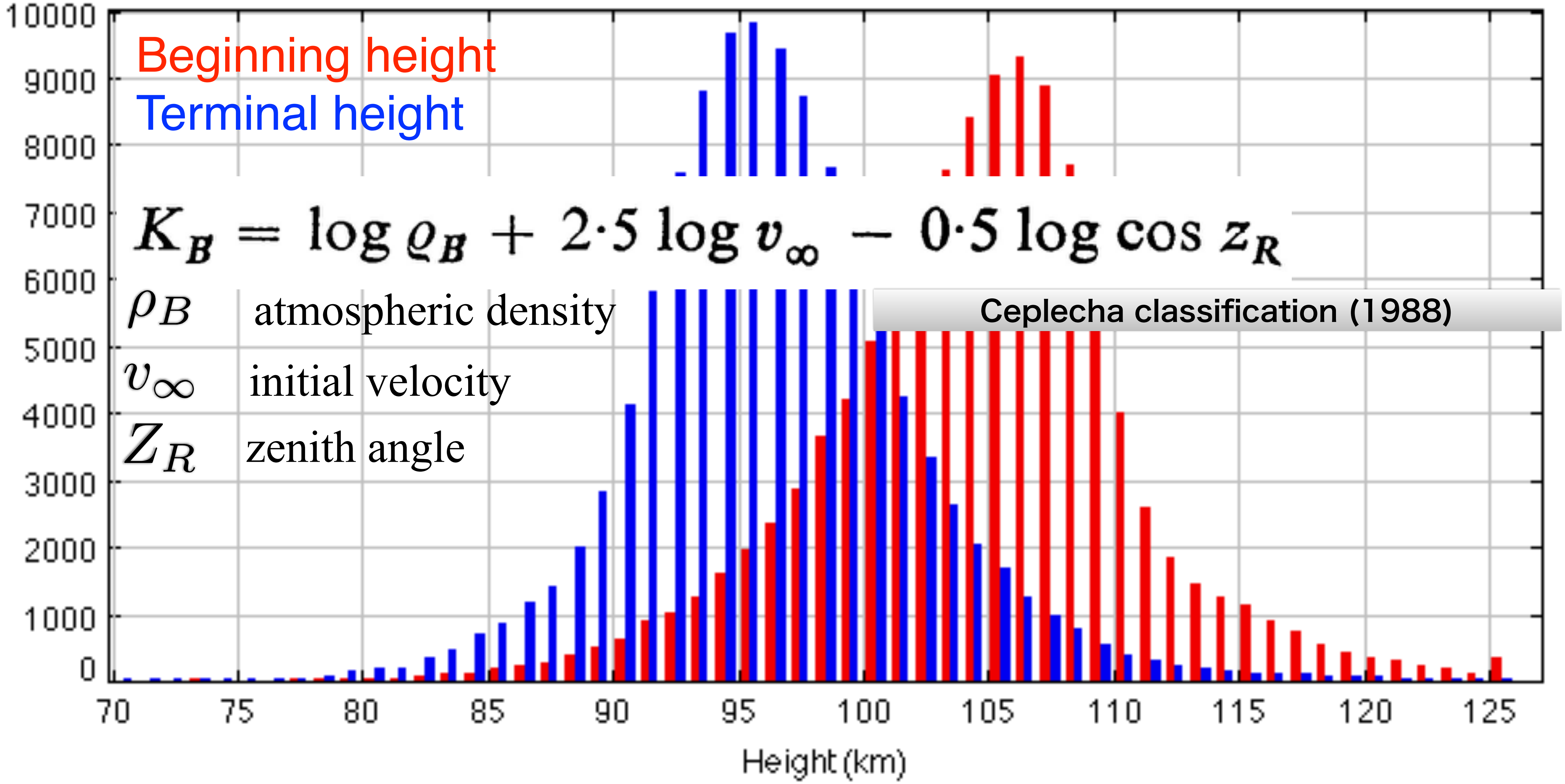
classified by Kb parameter



Abe, Kero, Nakamura+, in prep

Height distributions of meteoroids by MU radar.

Entry angle, atmospheric density and beginning height reflect ablation process.



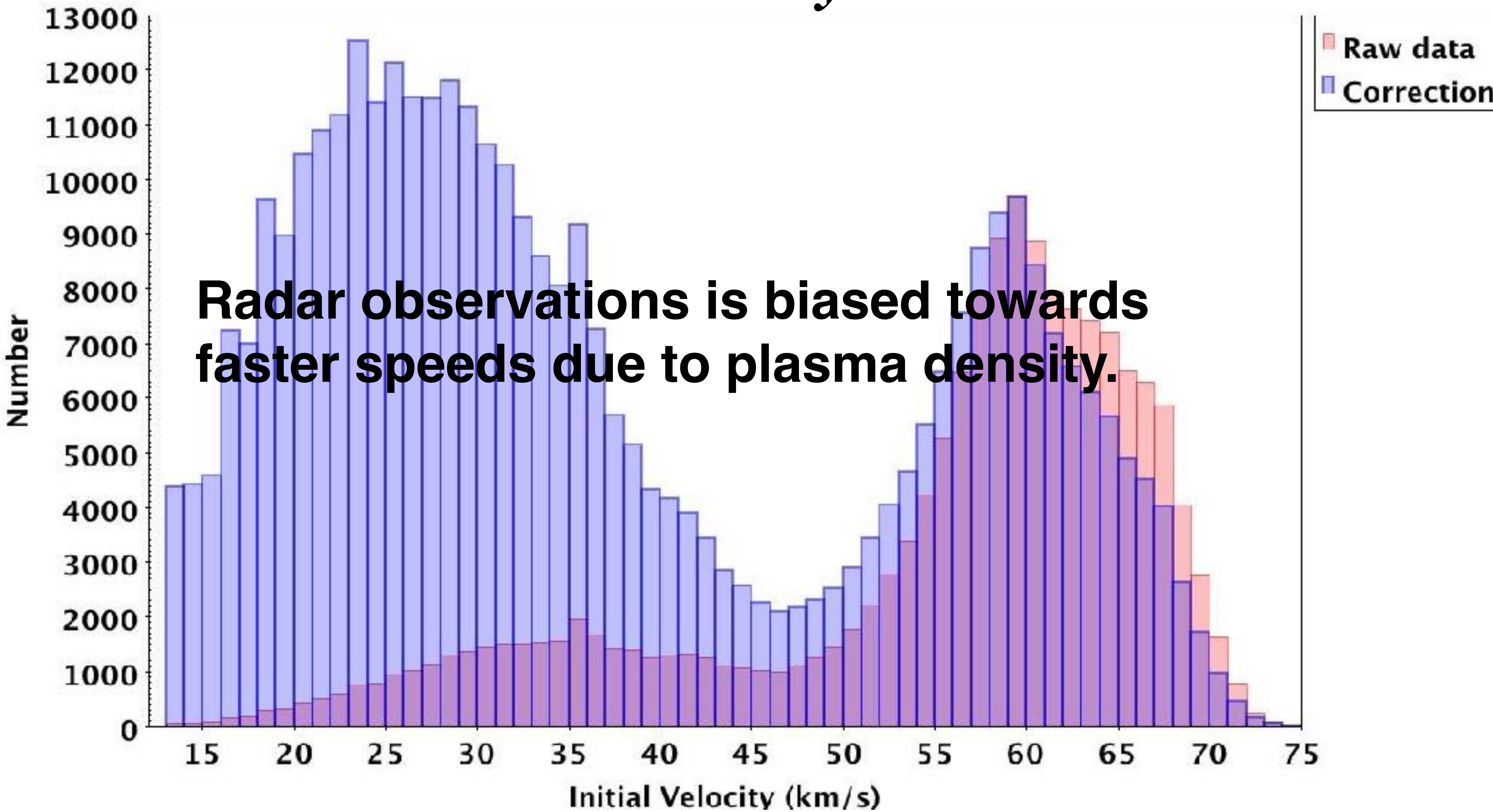
$$K_B = \log \varrho_B + 2{\cdot}5 \log v_\infty - 0{\cdot}5 \log \cos z_R$$

ρ_B	atmospheric density
v_∞	initial velocity
Z_R	zenith angle

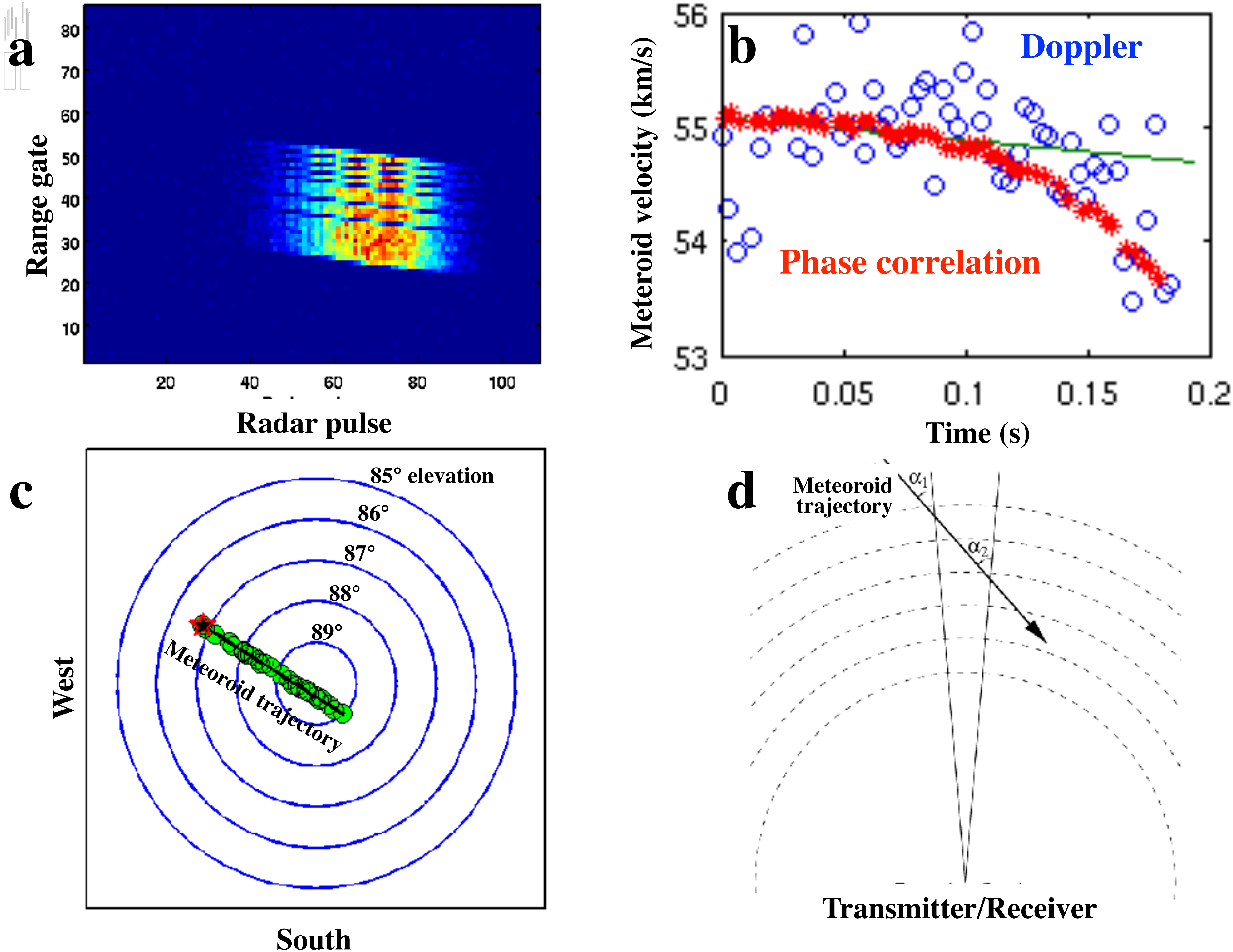
Height [km]

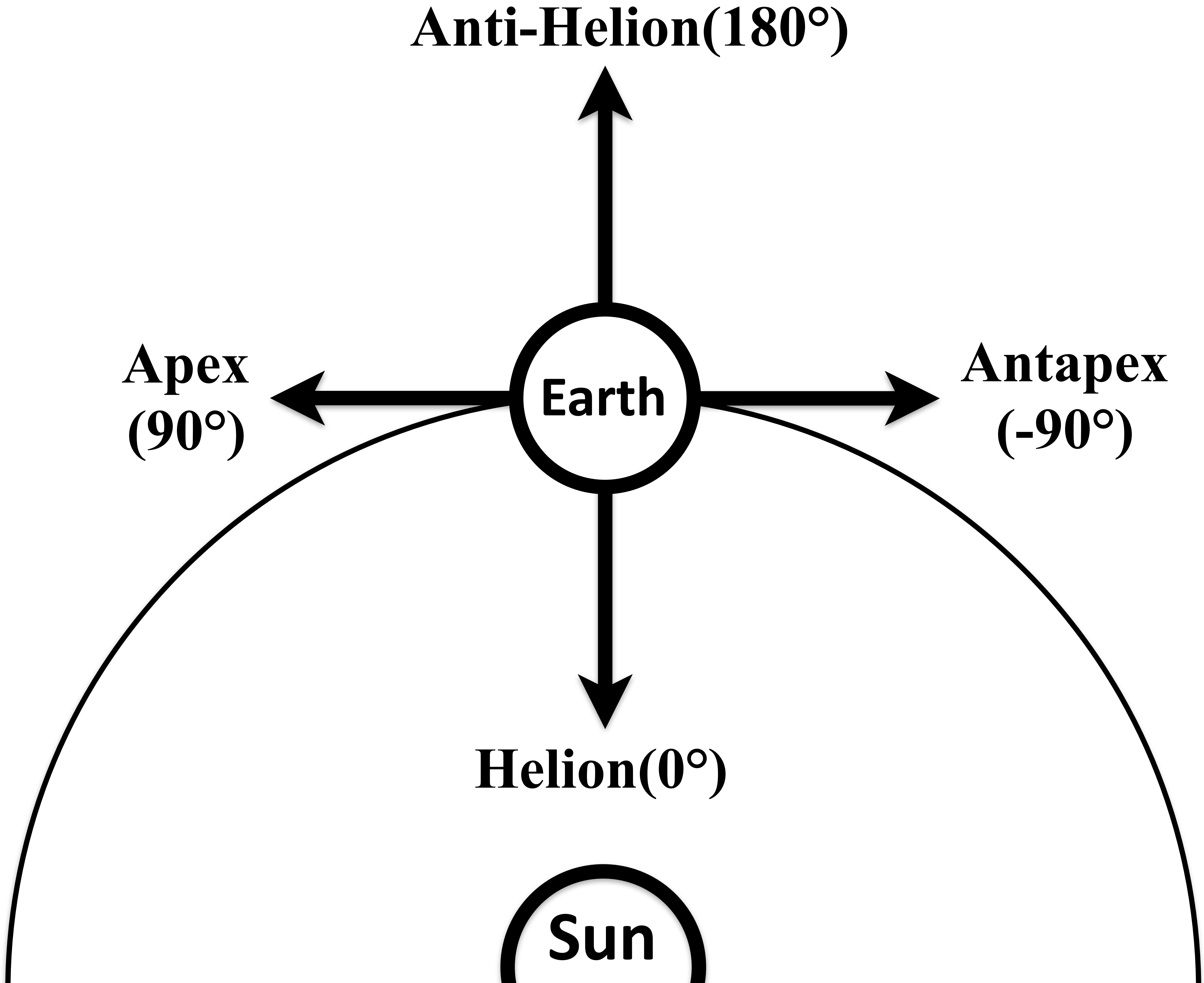
Velocity distribution

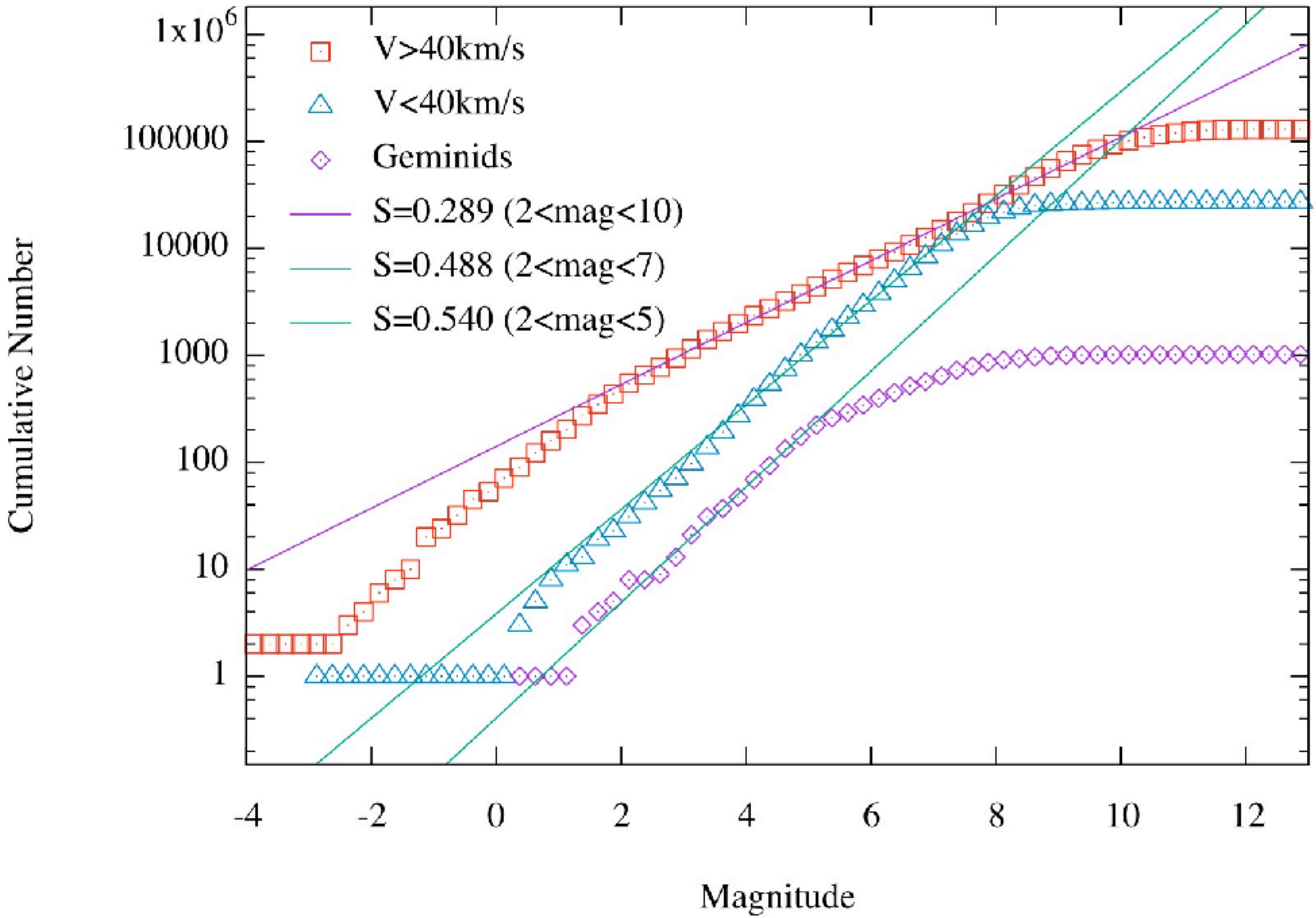
biased by v^3



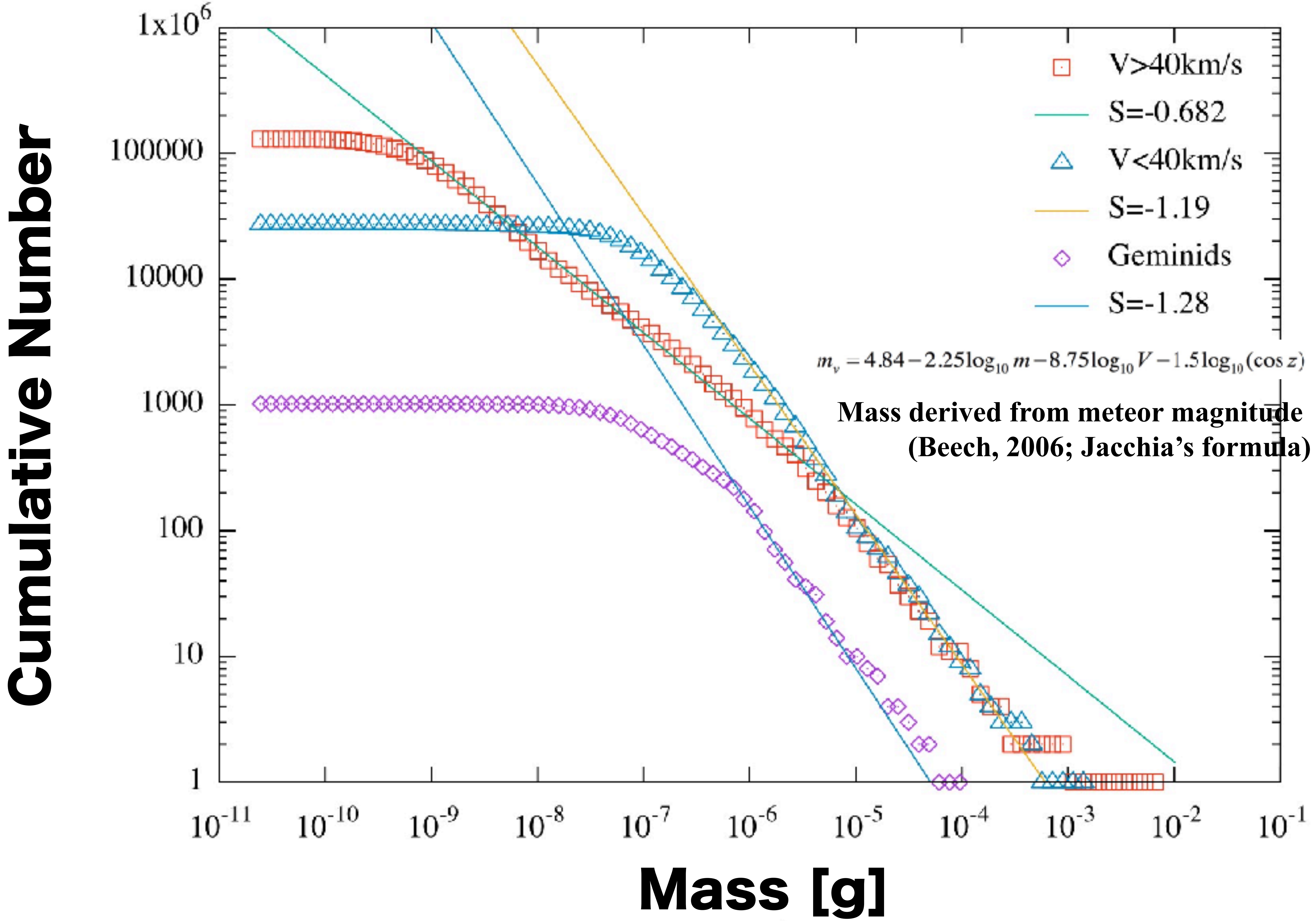
v~25km/s is dominant after de-biased.


a
Range gate
80
70
60
50
40
30
20
10
20
40
60
80
100
Radar pulse
b
Meteroid velocity (km/s)
56
55
54
53
0
0.05
0.1
0.15
0.2
Time (s)
Doppler
Phase correlation
c
85° elevation
86°
87°
88°
89°
Meteoroid trajectory
West
South
d
Meteroid trajectory
α_1
α_2
Transmitter/Receiver


Anti-Helion(180°)
Apex
(90°)
Earth
Antapex
(-90°)
Helion(0°)
Sun

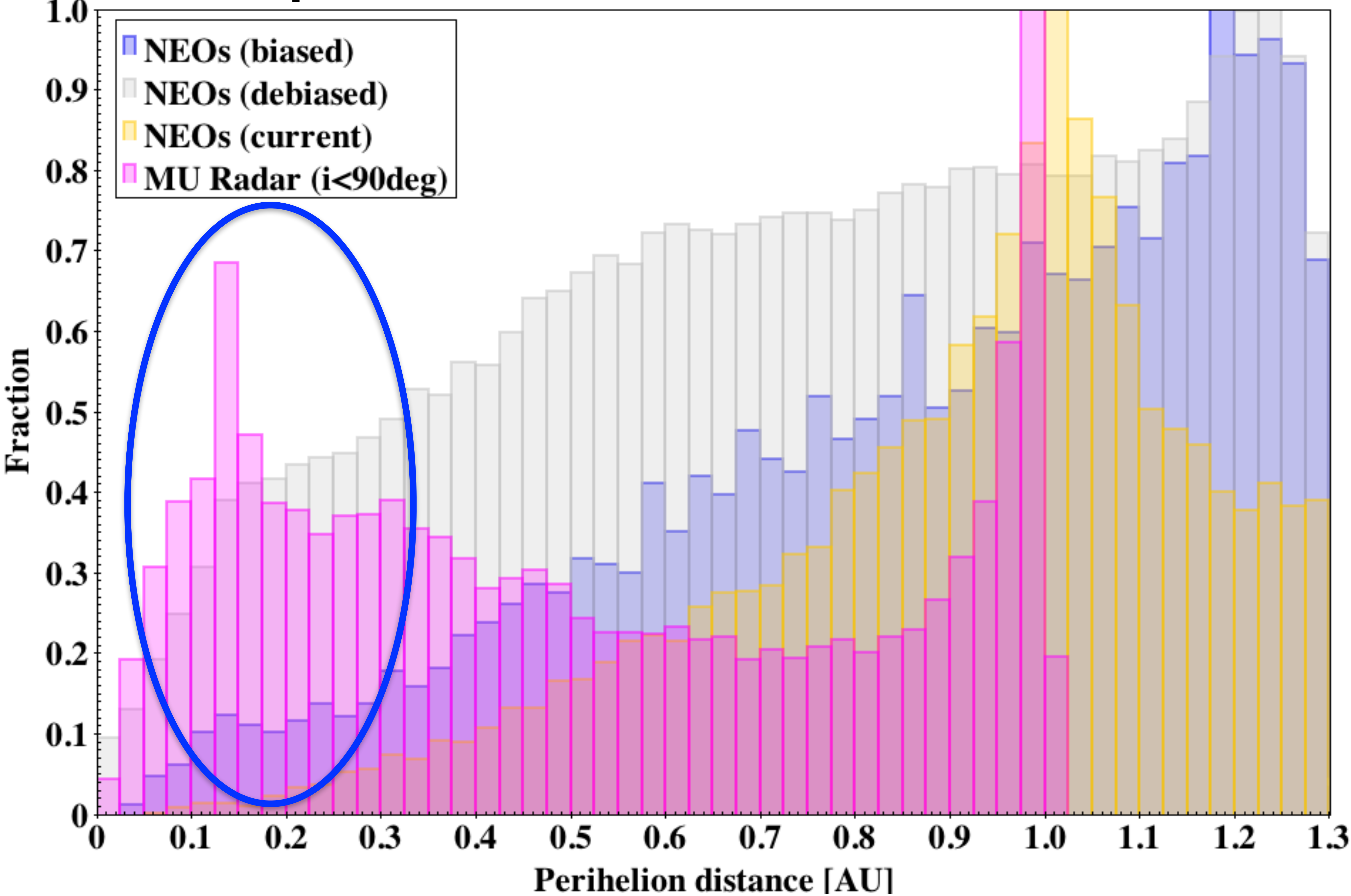


1x10^6
100000
10000
1000
100
10
1
V>40km/s
V<40km/s
Geminids
S=0.289 (2<mag<10)
S=0.488 (2<mag<7)
S=0.540 (2<mag<5)
Cumulative Number
-4
-2
0
2
4
6
8
10
12
Magnitude



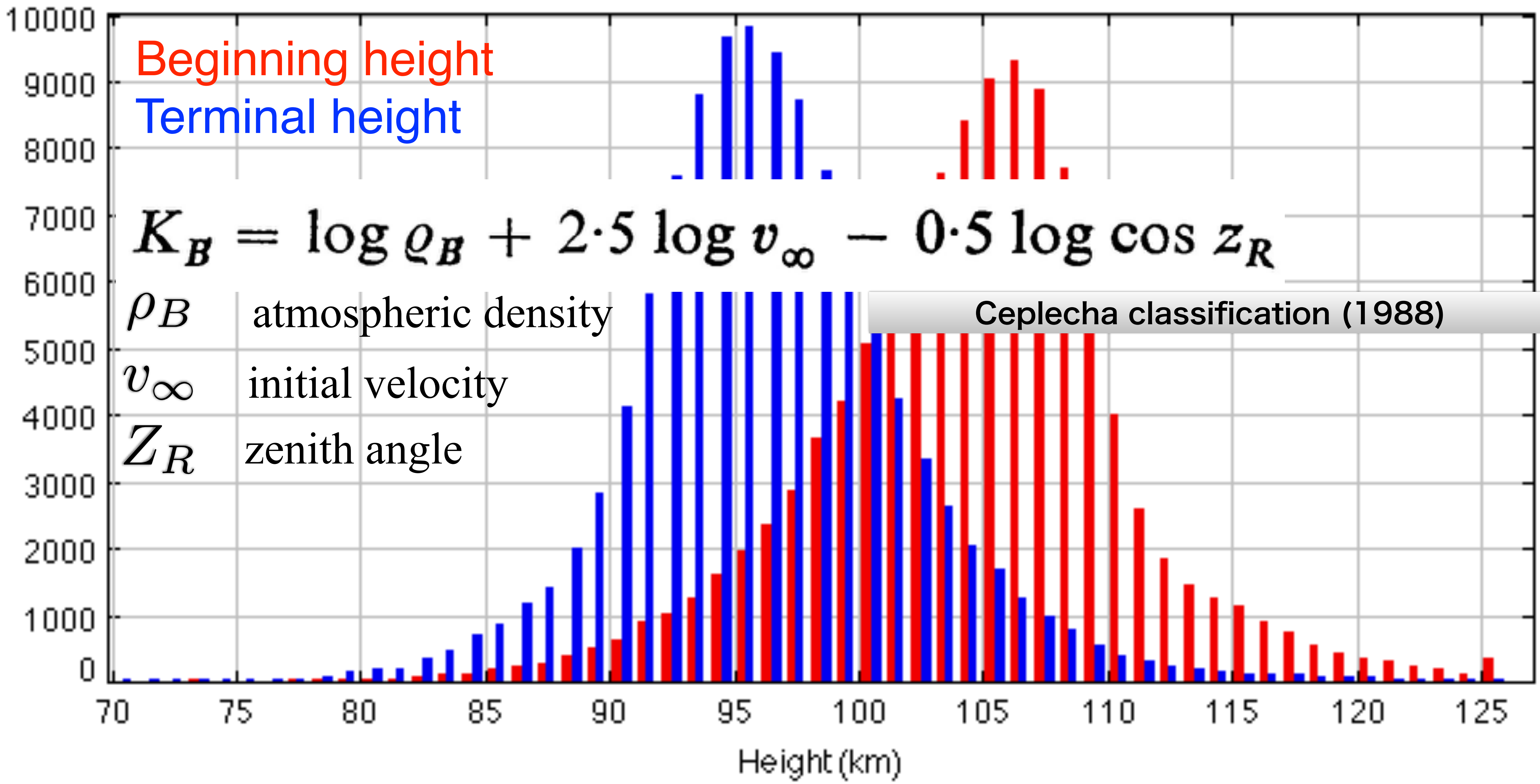
Cumulative Number
1x10^6
100000
10000
1000
100
10
1
10^-11
10^-10
10^-9
10^-8
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
Mass [g]
V>40km/s
S=-0.682
V<40km/s
S=-1.19
Geminids
S=-1.28
$m_v = 4.84 - 2.25\log_{10} m - 8.75\log_{10} V - 1.5\log_{10}(\cos z)$
Mass derived from meteor magnitude
(Beech, 2006; Jacchia's formula)

Population of NEOs and Meteoroids



Height distributions of meteoroids by MU radar.

Entry angle, atmospheric density and beginning height reflect ablation process.



$$K_B = \log \varrho_B + 2{\cdot}5 \log v_\infty - 0{\cdot}5 \log \cos z_R$$

ρ_B	atmospheric density
v_∞	initial velocity
Z_R	zenith angle

Height [km]

Ceplecha classification

Ceplecha classification (1988)

$$K_B = \log \varrho_B + 2{\cdot}5 \log v_\infty - 0{\cdot}5 \log \cos z_R$$

"asteroidal meteors":

("ast"): $8{\cdot}00 \leqq K_B$

group A: $7{\cdot}30 \leqq K_B < 8{\cdot}00$

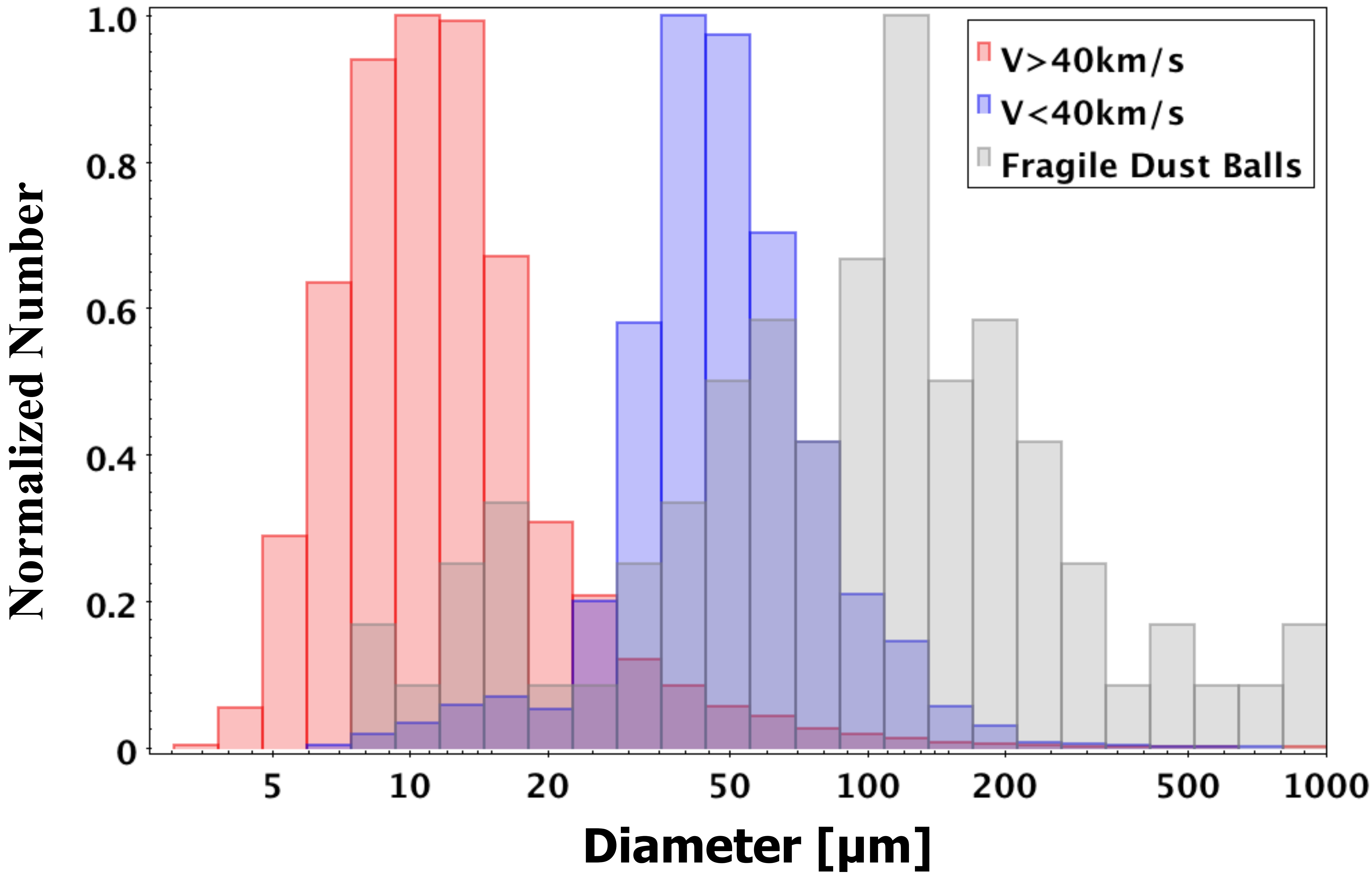
group B: $7{\cdot}10 \leqq K_B < 7{\cdot}30$; $q \leqq 0{\cdot}30$ A.U.

group C1: $6{\cdot}60 \leqq K_B < 7{\cdot}10$; $a < 5$ A. U. ; $i \leqq 35°$

group C2: $6{\cdot}60 \leqq K_B < 7{\cdot}10$; $a \geqq 5$ A. U.

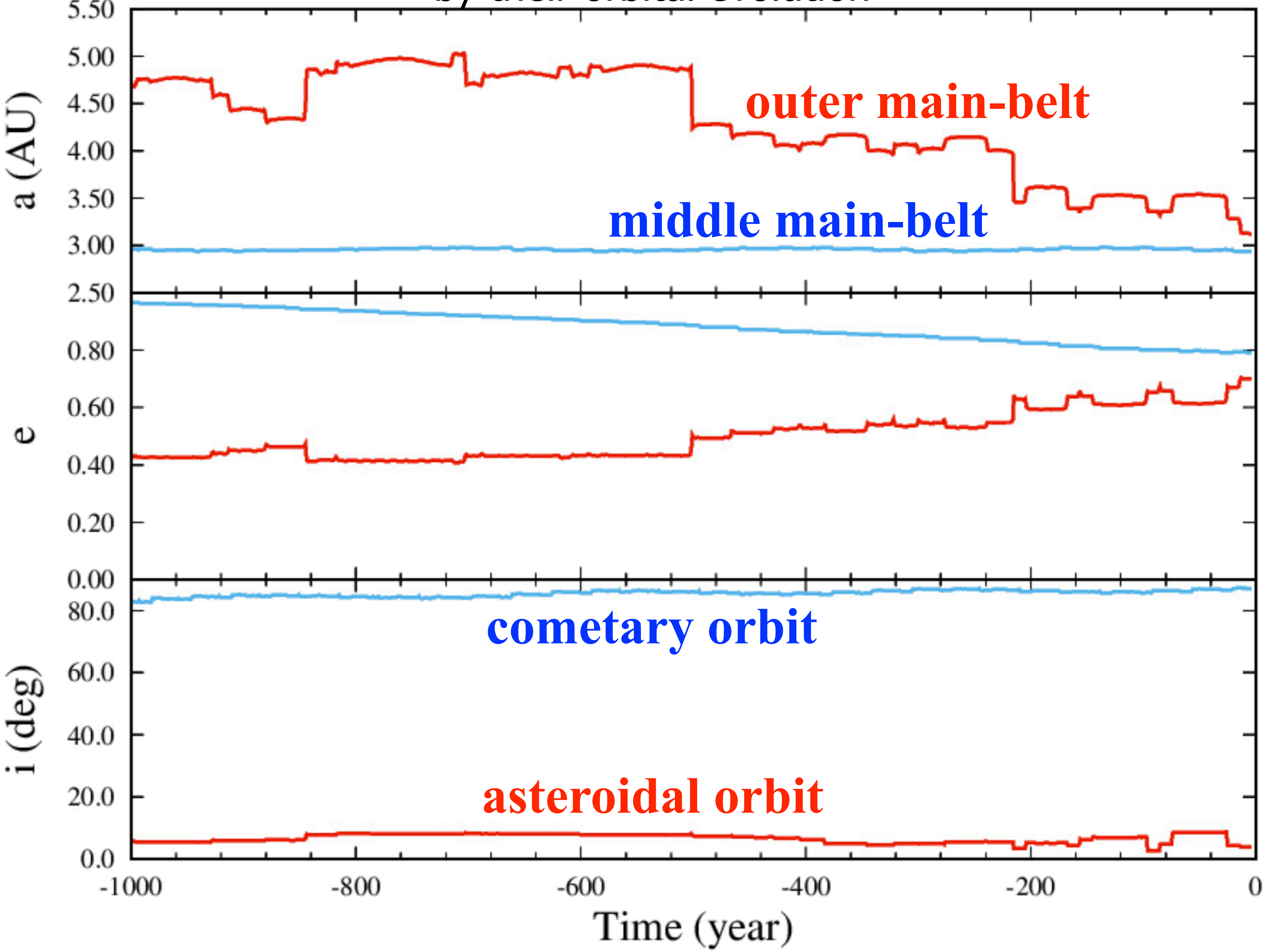
group C3: $6{\cdot}60 \leqq K_B < 7{\cdot}10$; $a < 5$ A. U.; $i > 35°$

group D: $K_B < 6{\cdot}60$

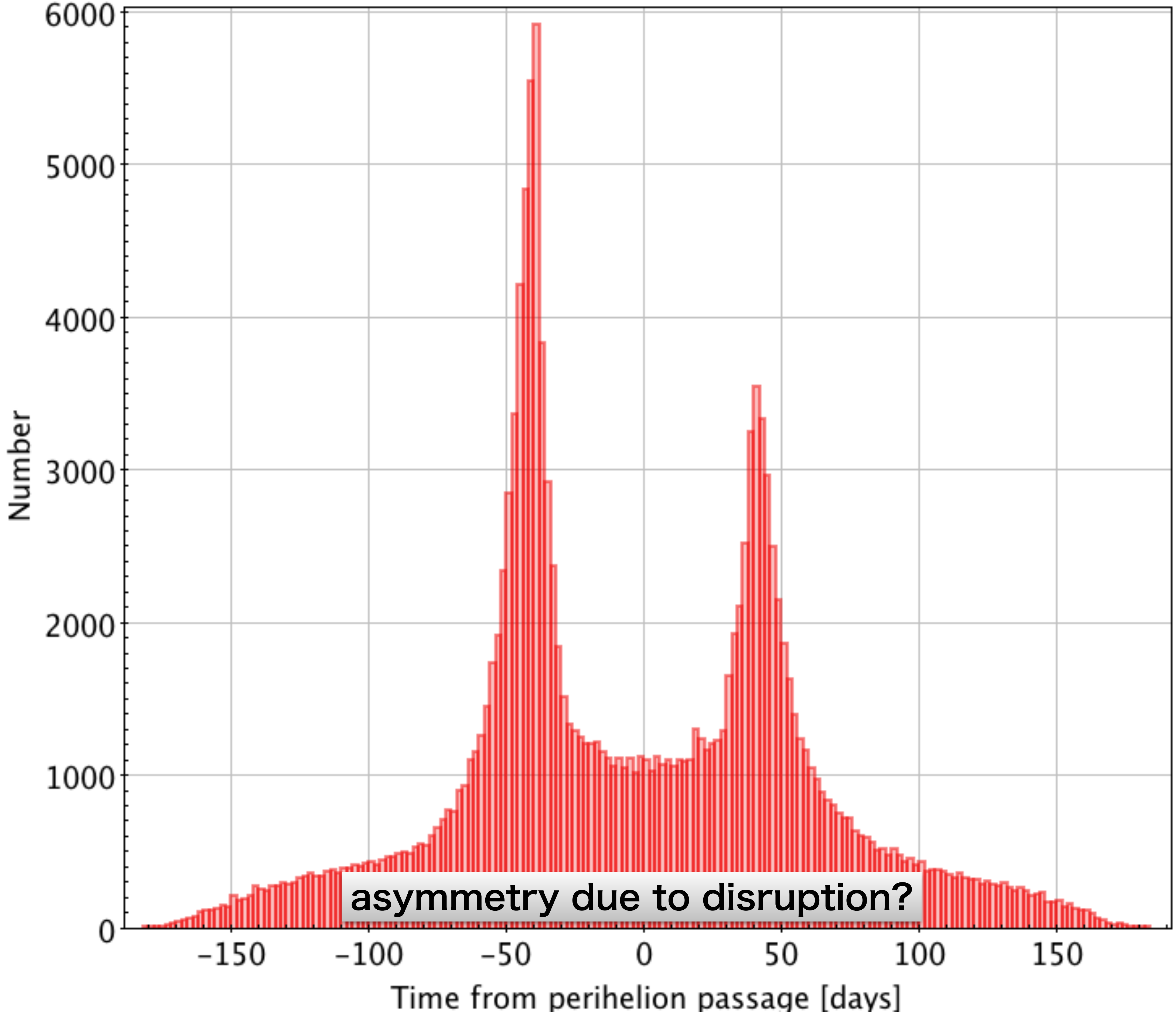

V>40km/s
V<40km/s
Fragile Dust Balls
Normalized Number
Diameter [μm]
0
0.2
0.4
0.6
0.8
1.0
5
10
20
50
100
200
500
1000

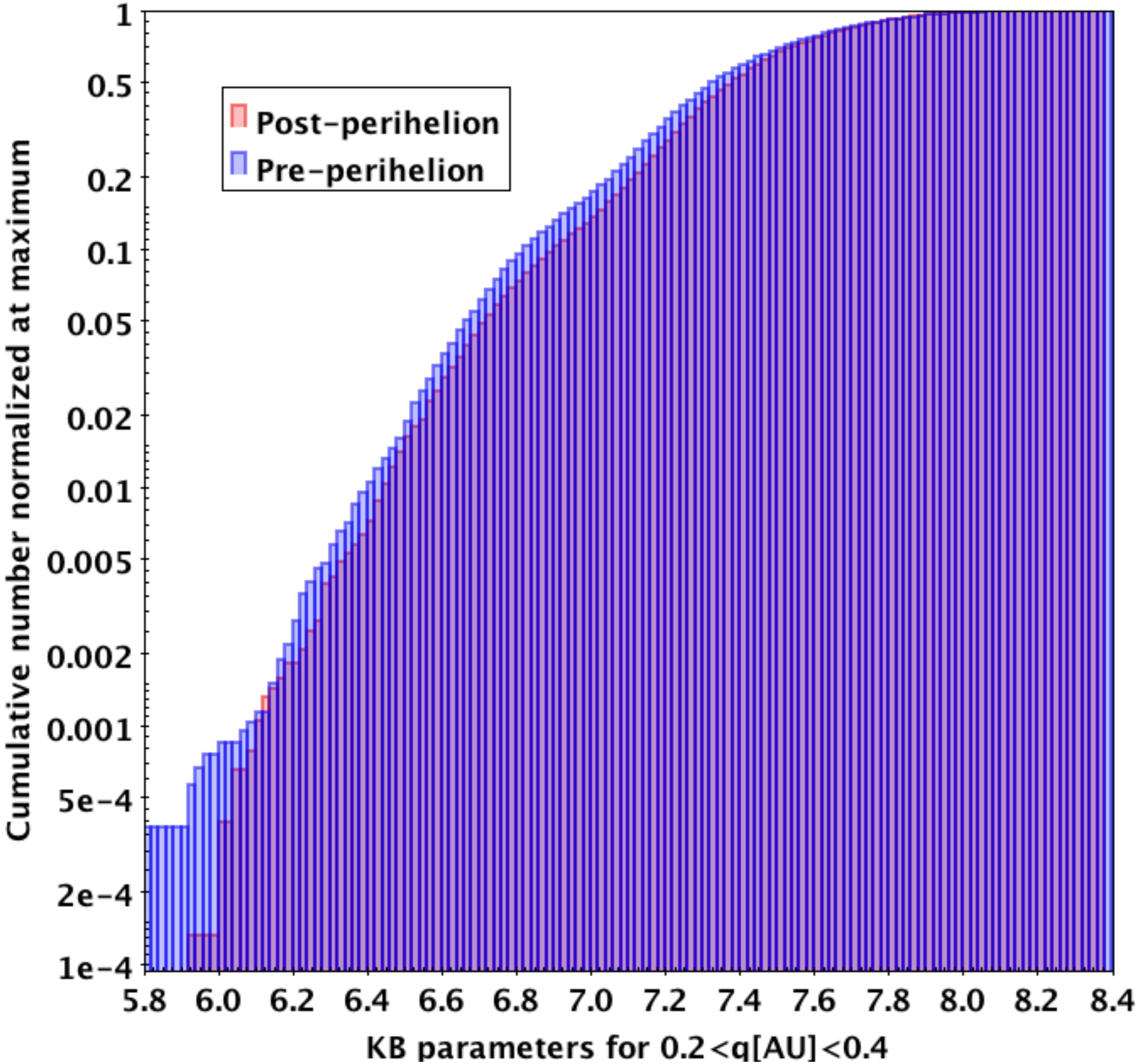
Possible Origin of Fragile Dust Balls

by their orbital evolution

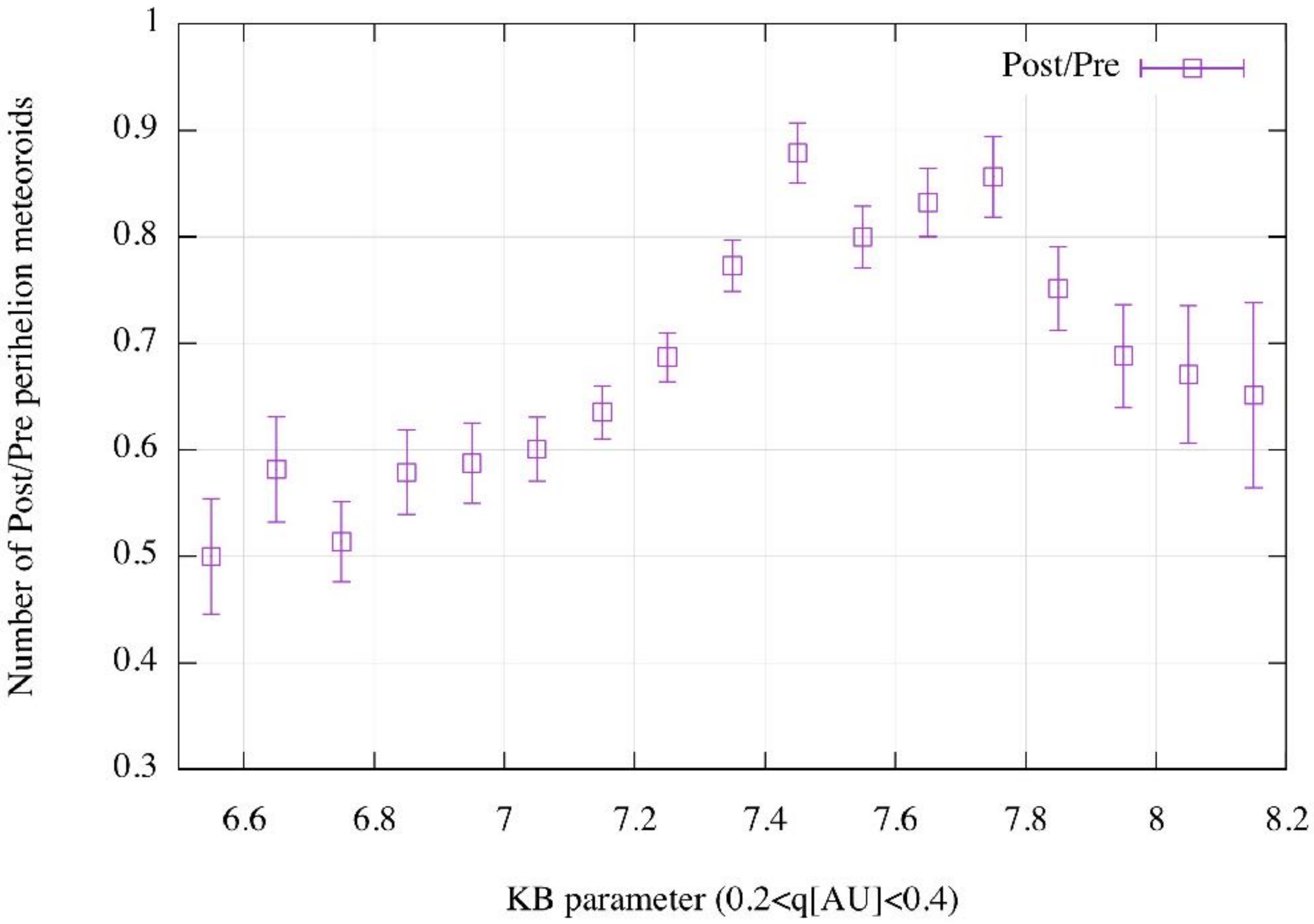


Pre & Post Perihelion of Meteoroid Dusts by MU Radar





Post-perihelion
Pre-perihelion
Cumulative number normalized at maximum
1
0.5
0.2
0.1
0.05
0.02
0.01
0.005
0.002
0.001
5e-4
2e-4
1e-4
5.8
6.0
6.2
6.4
6.6
6.8
7.0
7.2
7.4
7.6
7.8
8.0
8.2
8.4
KB parameters for 0.2<q[AU]<0.4

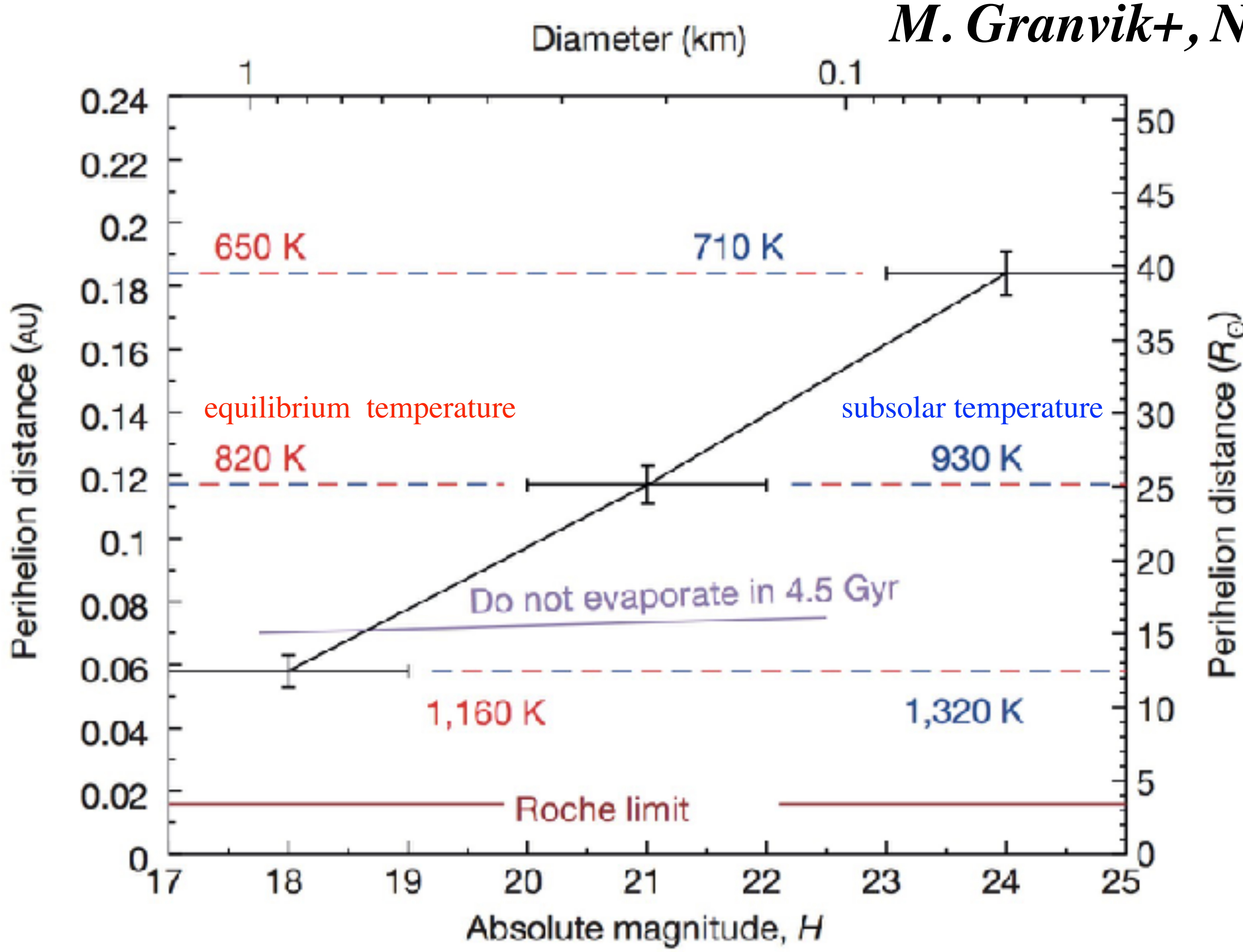


Post/Pre
Number of Post/Pre perihelion meteoroids
KB parameter (0.2<q[AU]<0.4)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
6.6
6.8
7
7.2
7.4
7.6
7.8
8
8.2

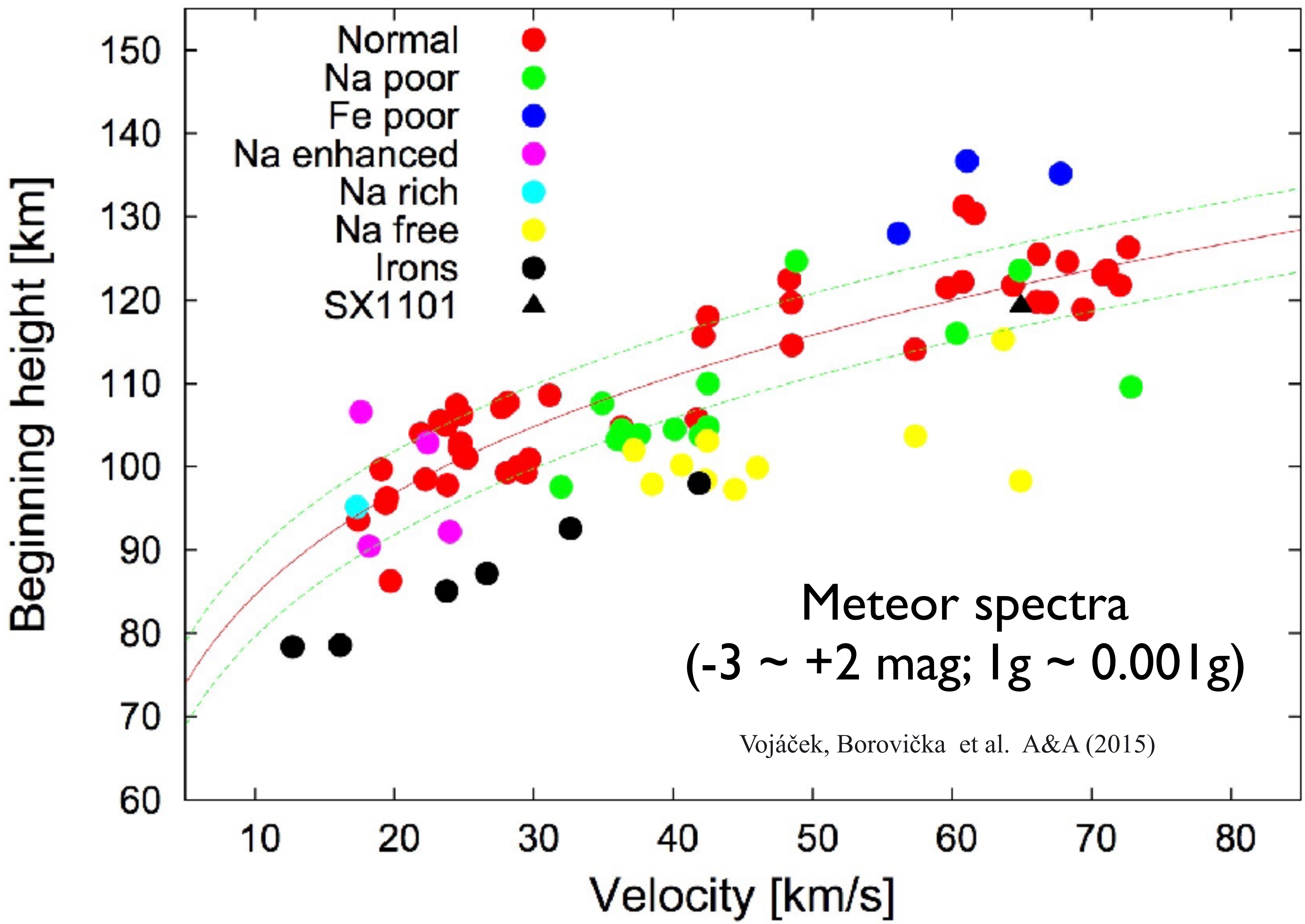
NEOs' Super-catasrophic breakup

Average disruption distance as a function of absolute magnitude and an asteroid's physical size

M. Granvik+, Nature (2016)



Majority of NEOs are S/Q-type
90% of Meteorites are Q-type.
More than 300 NEOs (D<100m); 80%; C/D/X-type, 20%; S/Q-type
Moskovitz et al. MANOS(Mission Accessible Near-Earth Object Survey)



MANOS(Mission Accessible Near-Earth Object Survey)による約250個のNEOタイプを見ると，直径が100m以下のNEOでは，C/D/Xタイプ小惑星が約80%，S/Qタイプ小惑星が約20%

Icarus - $2007MK_6$ orbital & spectrum similarity