東大Tomo-e Gozenと京大MUレーダーによる微光流星の同時観測

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Tomo-e Gozen project, and MU Radar project

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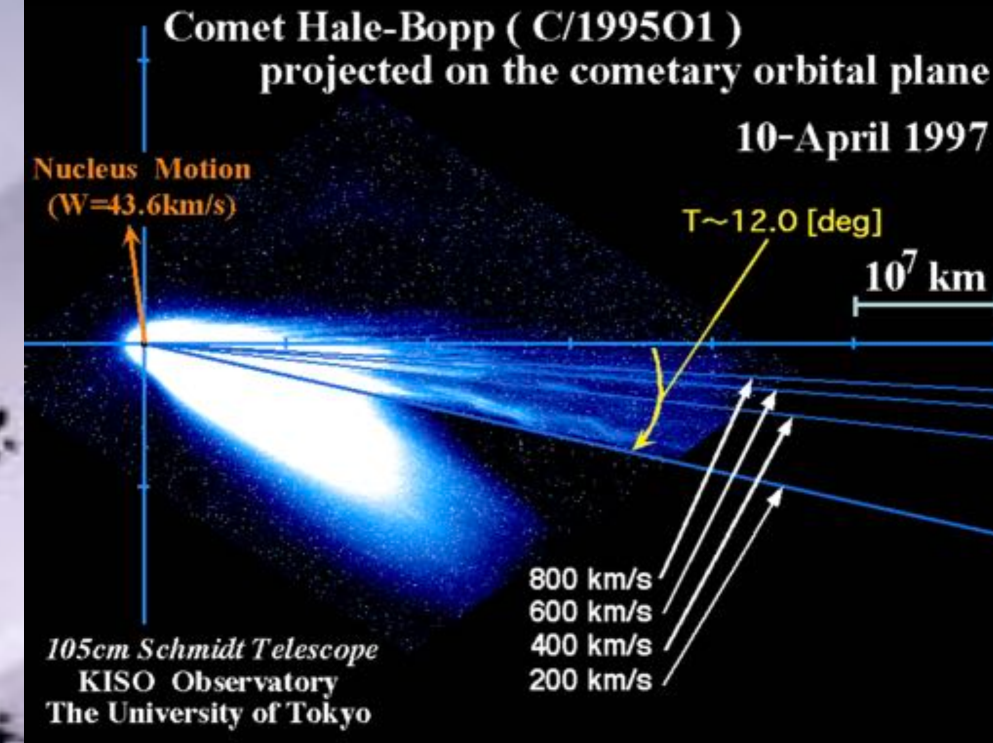
記念すべき乾板 No. 7000

大学院修士時代
（名古屋大STE研）



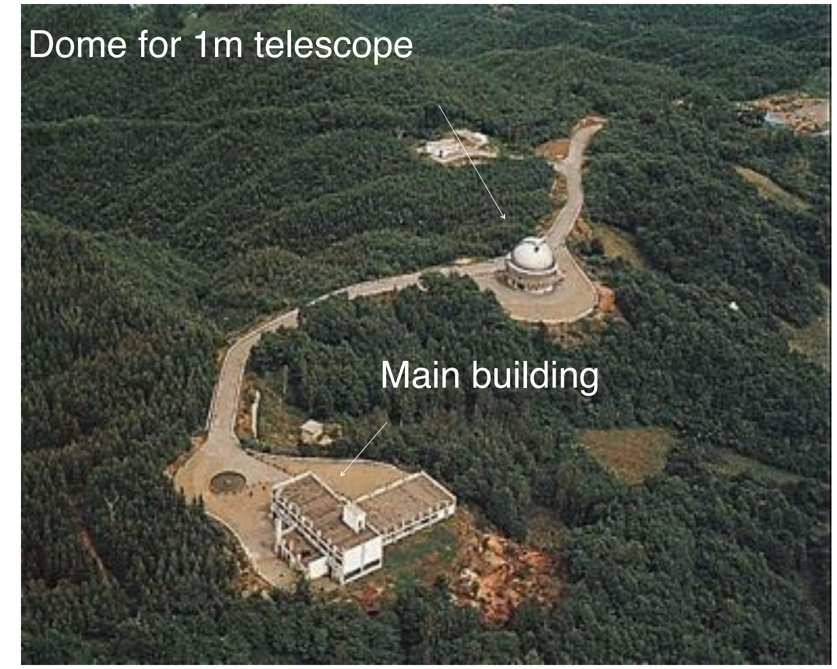
マイクロデンシトメーター
を用いたデジタル化(1枚24時間)

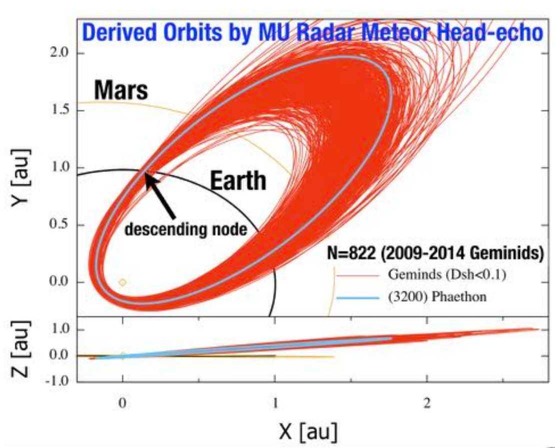
Photometric Data Systems社

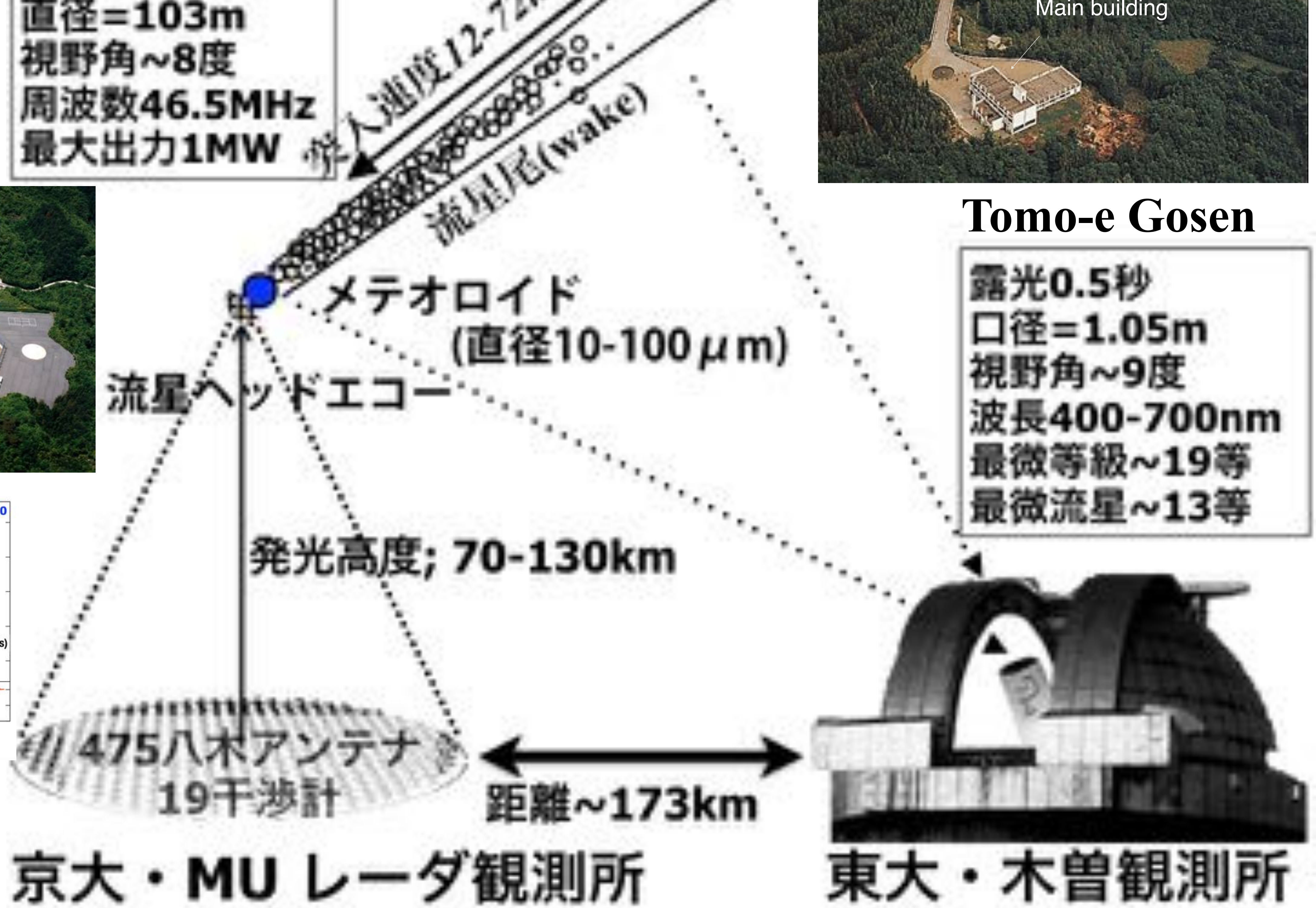
*1997*年春，東大木曽観測所が所有する*B*バンド写真乾板を*Hale-Bopp*彗星観測で全て使い果たした。

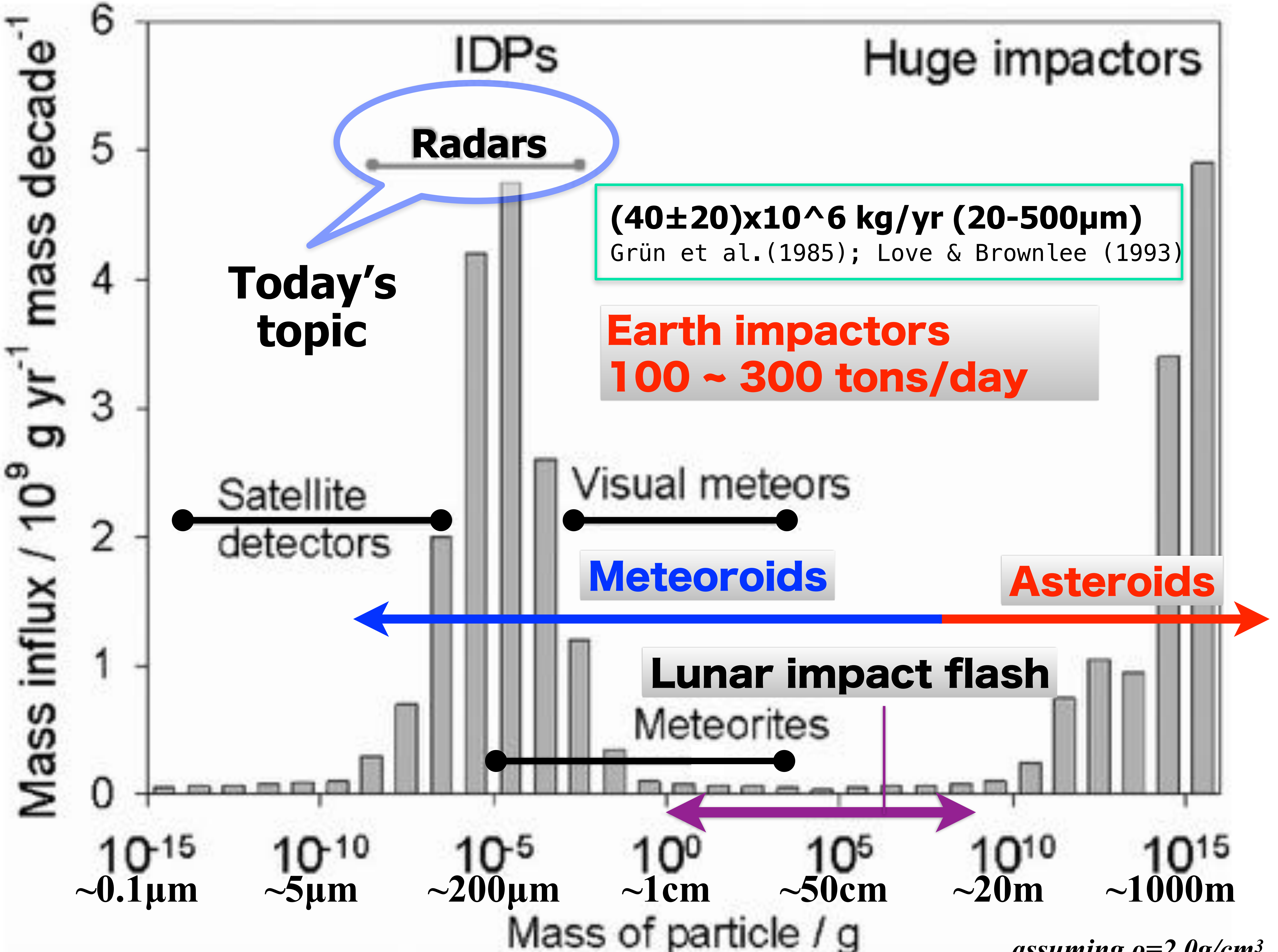
京大MUレーダー流星ヘッドエコーとTomo-e Gozenによる

微光流星同時観測





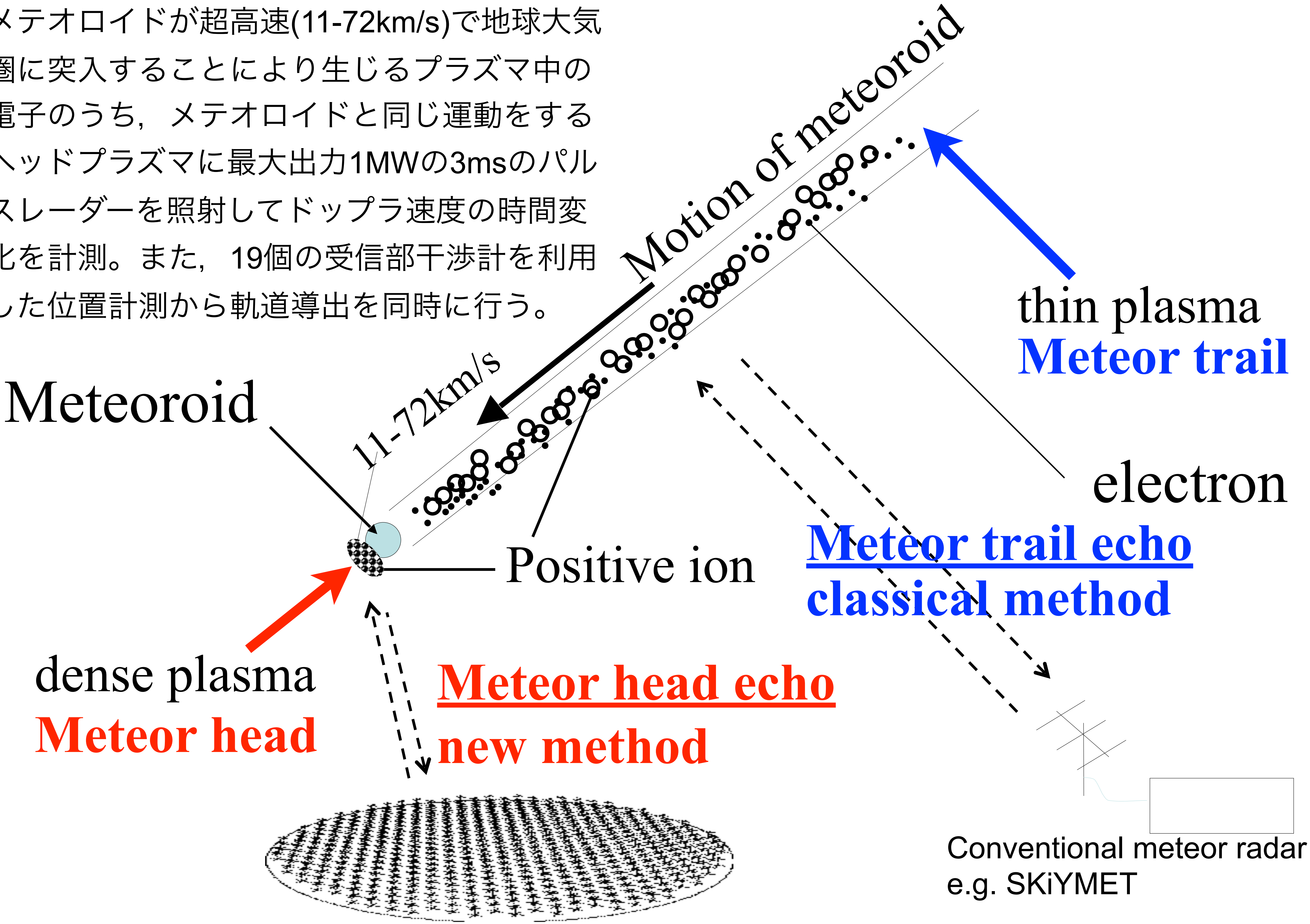




Modified from John Plane (2012)

Meteor Head Echo and Meteor Trail Echoes
流星ヘッド・エコー & 流星トレイル・エコー

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。

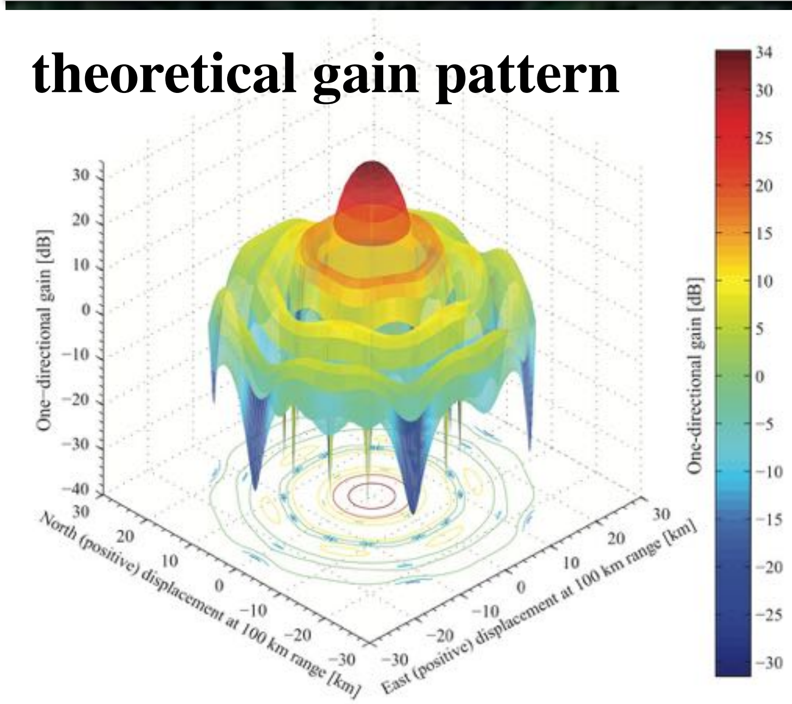


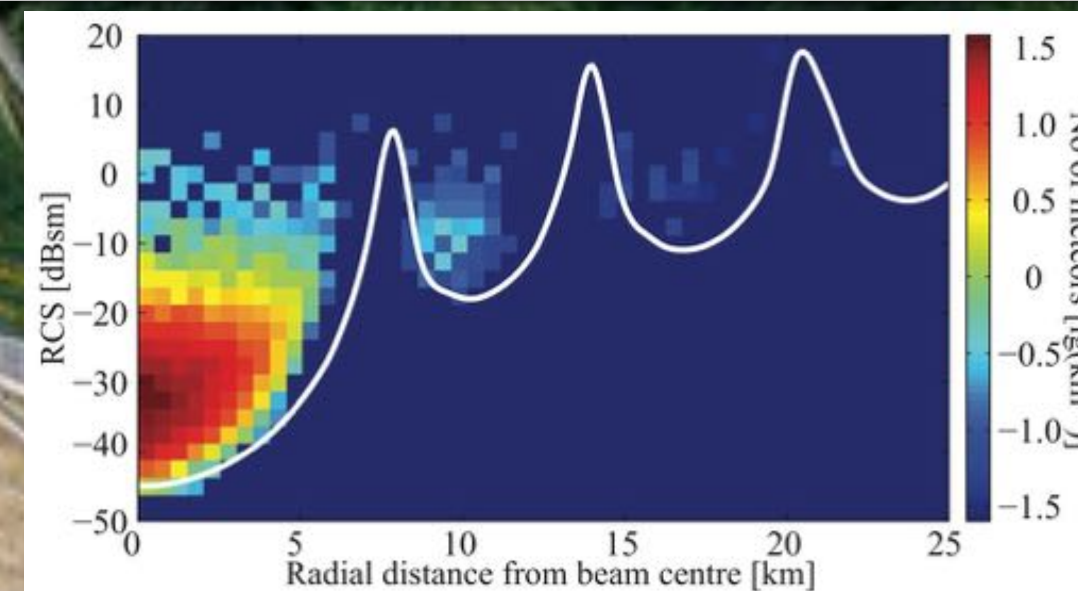
Kyoto University RISH MU Radar
Middle and **U**pper Atmosphere **Radar**

Monostatic coherent pulse Doppler radar

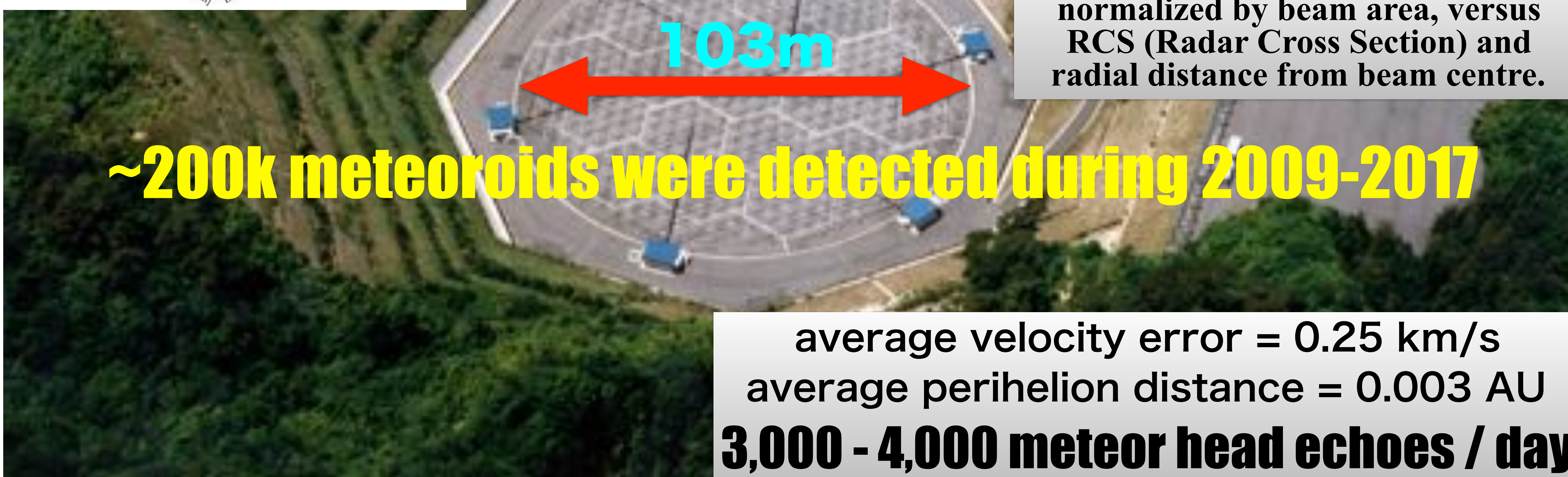
VHF (46.5 MHz), 1MW peak power, 475 crossed Yagi antennas

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.



~200k meteoroids were detected during 2009-2017

average velocity error = 0.25 km/s

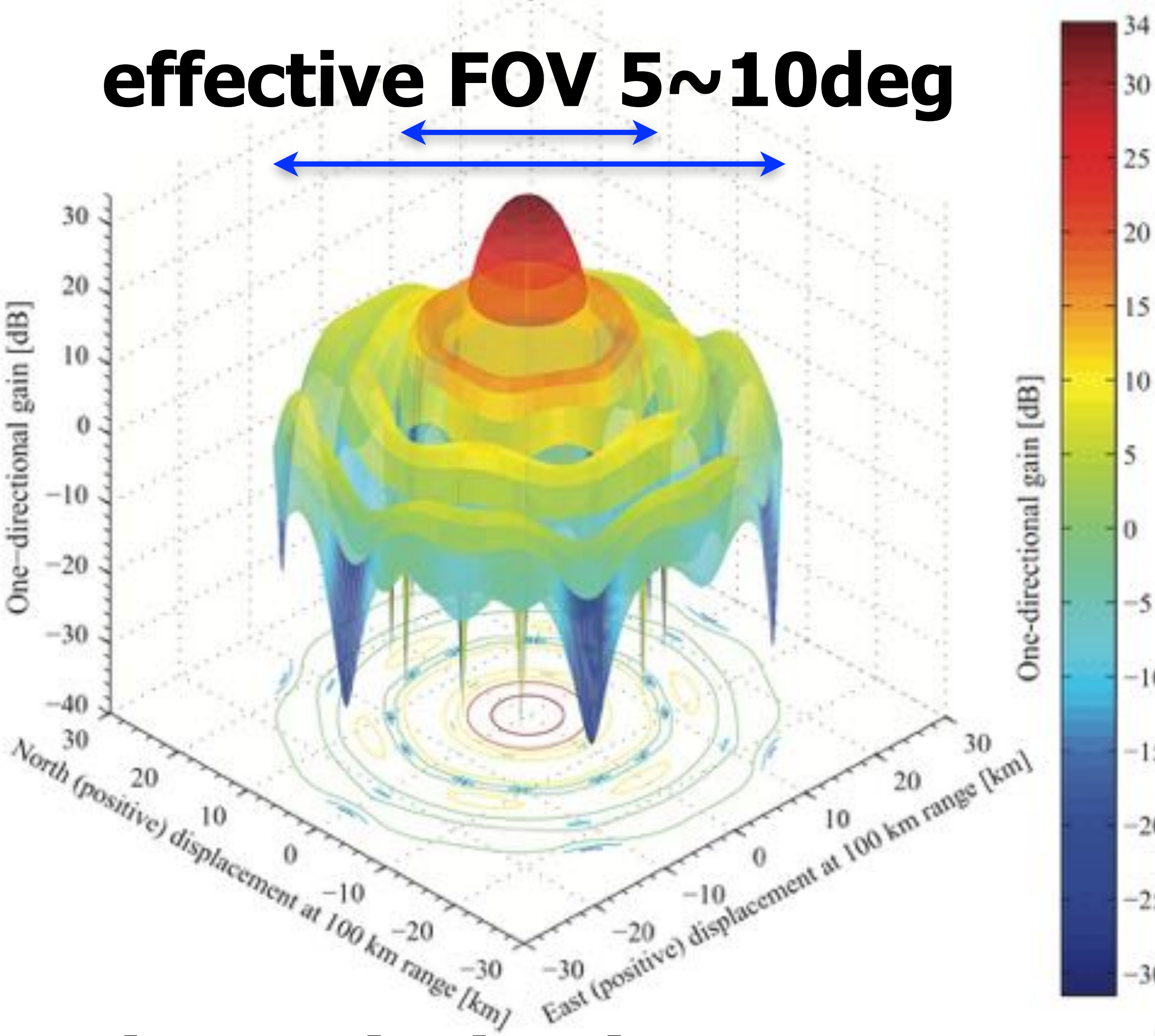
average perihelion distance = 0.003 AU

3,000 - 4,000 meteor head echoes / day

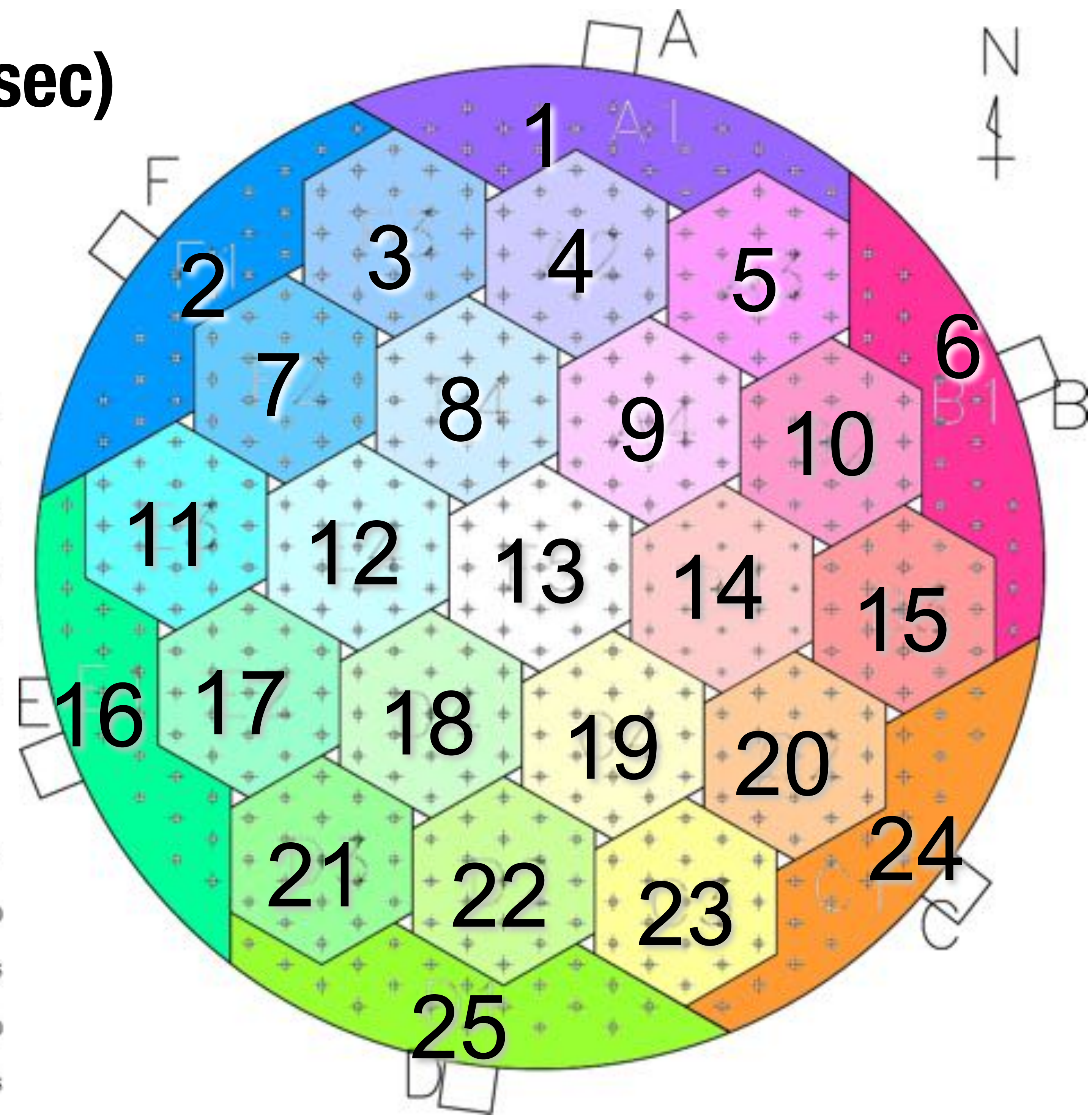
Kyoto University RISH MU Radar
Middle and **U**pper Atmosphere **Radar**

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

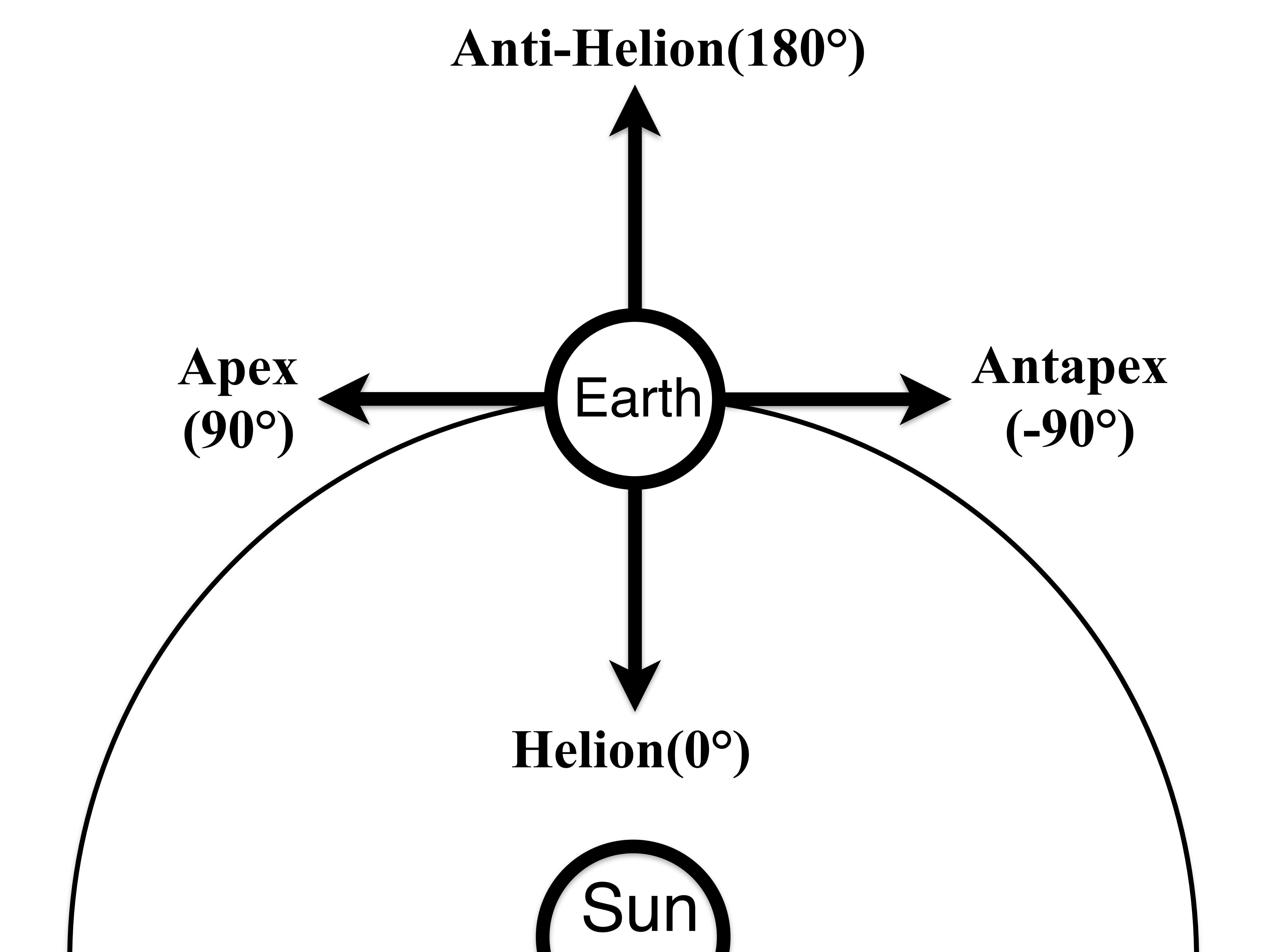
effective FOV 5~10deg

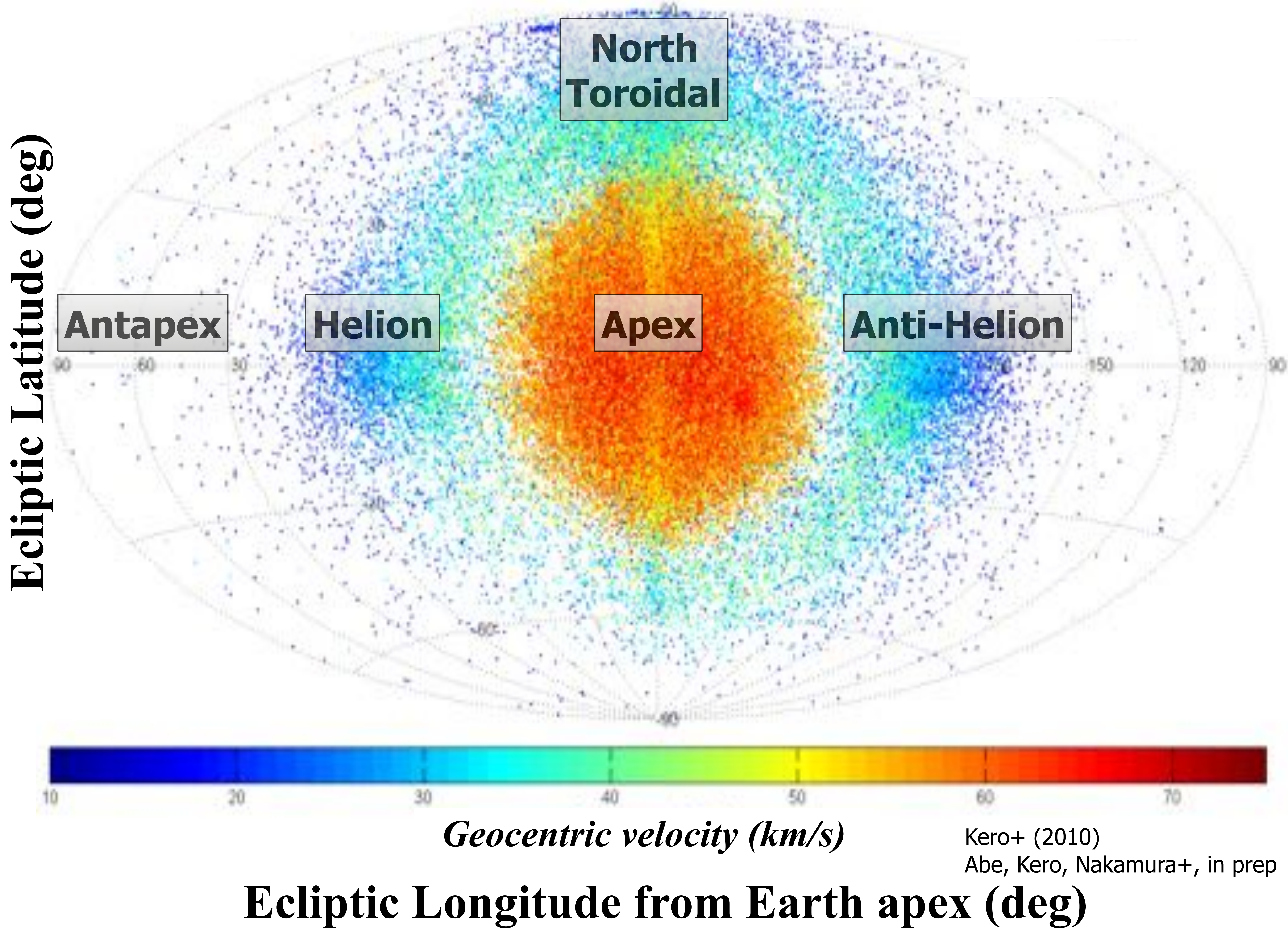


theoretical gain pattern

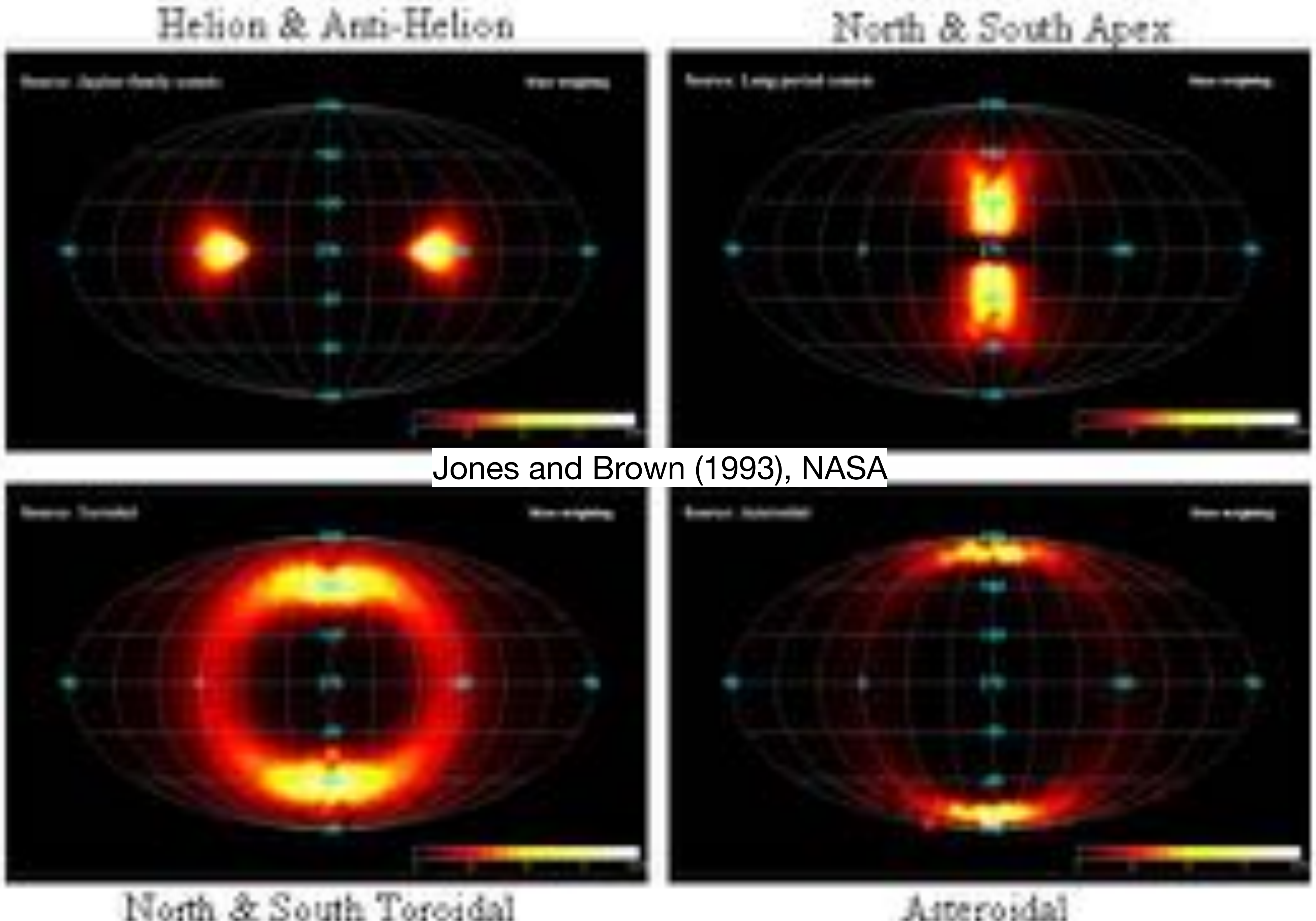


Doppler velocity by 19 Interferometers


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



Kero+ (2010)
Abe, Kero, Nakamura+, in prep



4 major sources of Sporadic Meteoroids

Equatorial coordinate(λ,β)

Sporadic meteoroid sources 散在流星の放射点； 6 radiants

Cometary sources ?

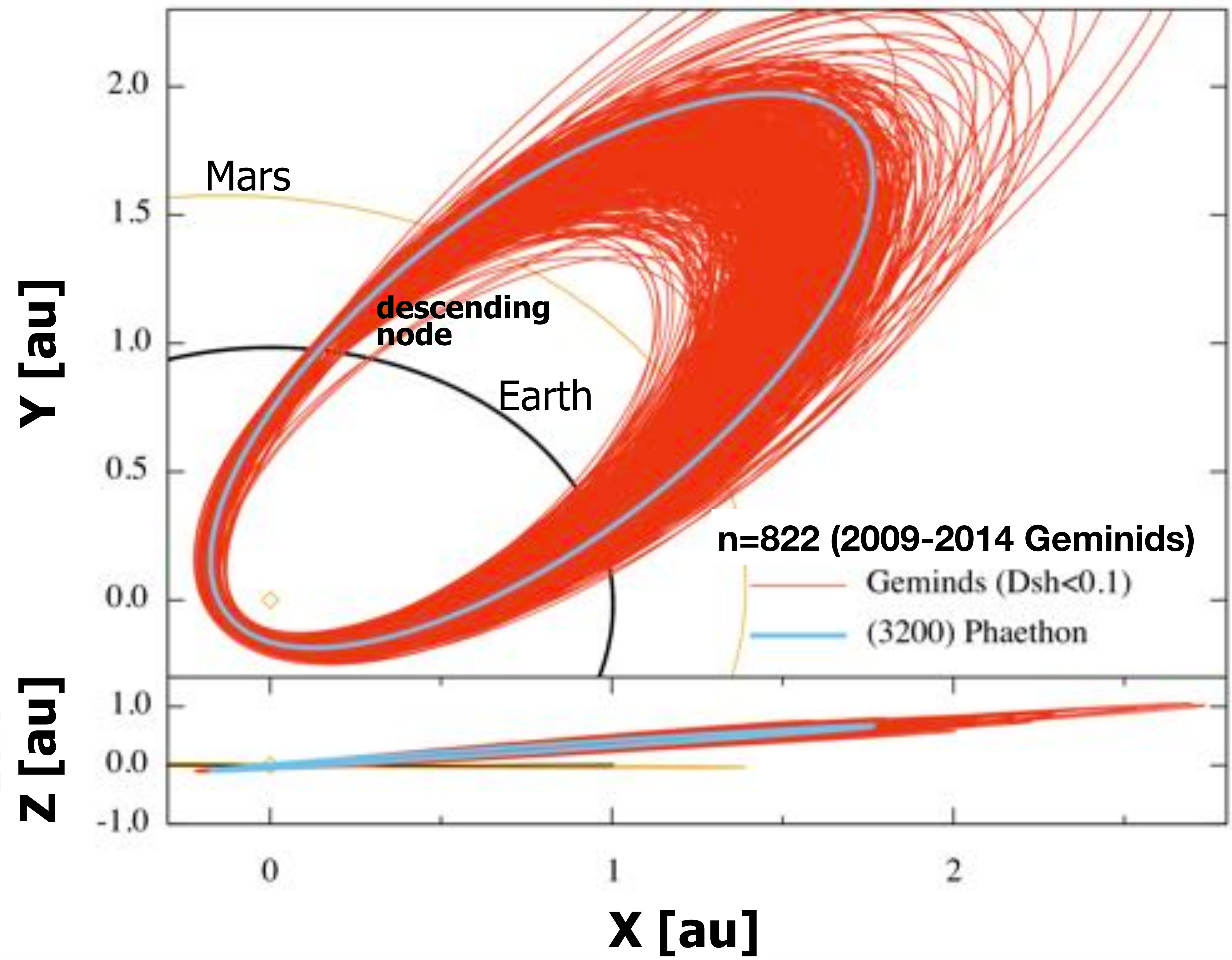
Helion(λ~342º)/Anti-Helion(λ~198º); 太陽方向・半太陽方向

North(λ~271º)/South(λ~273º) Apex; 地球向点方向で黄道を跨ぐ

North/South Toroidal; トーラス状

Asteroidal sources ?

Ecliptic pole(β~ ±90º); 黄道の極方向 …


Mars
descending node
Earth
n=822 (2009-2014 Geminids)
Geminds (Dsh<0.1)
(3200) Phaethon
Y [au]
Z [au]
X [au]
2.0
1.5
1.0
0.5
0.0
1.0
0.0
-1.0
0
1
2

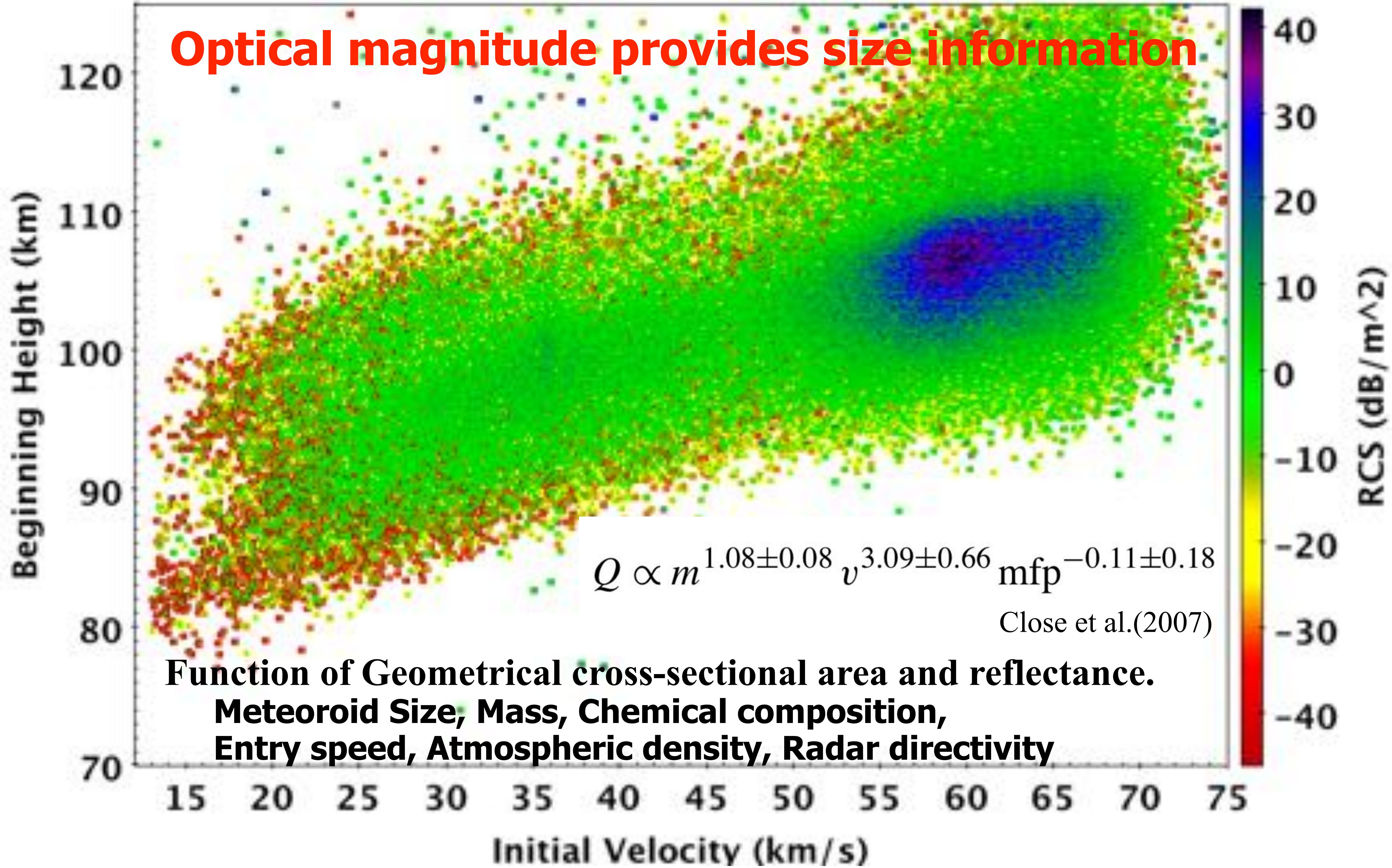
Comparison of Orbits between MU Radar and Optical Observations

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	
1-opt	15:29	1.22	0.88	23.5	325.1	262.6	0.013
2-radar	Dec/13	1.20	0.89	24.1	325.8	261.7	
2-opt	18:49	1.39	0.91	23.2	325.8	261.7	0.030
3-radar	Dec/13	1.21	0.89	22.5	324.5	261.6	
3-opt	16:14	1.26	0.88	22.7	324.5	261.6	0.037
Geminids	2010	1.30	0.899	25.0	326.1	262.3	-

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

Abe et al. Proc. ISTS (2015)

RCS (Radar Cross Section) controversy



RCS強度は，大気突入天体のサイズに単純に比例しない!

MUレーダーとTomo-e Gozenによる微光流星同時観測

Brief Summary of Observations

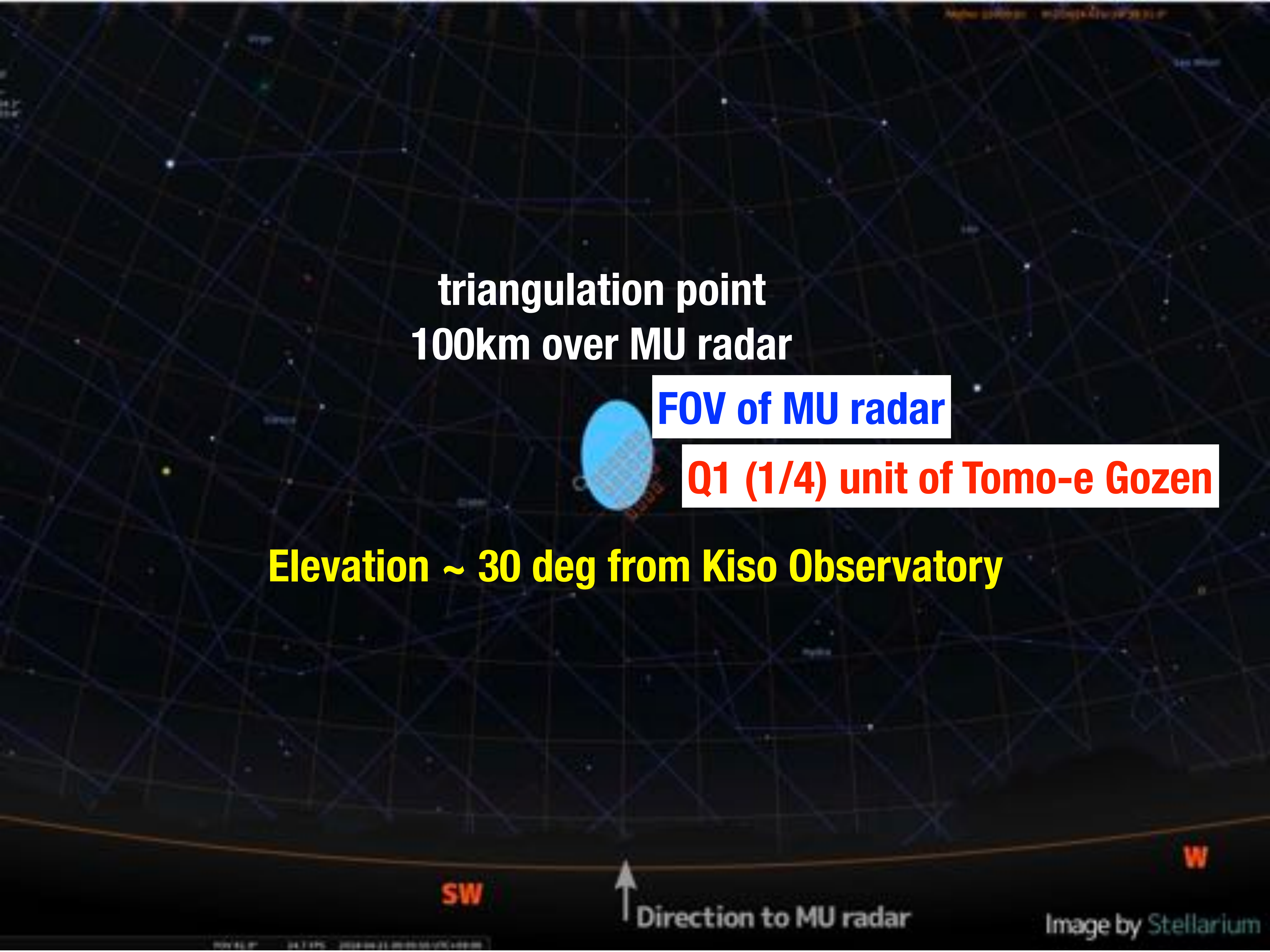
	Time (JST)	comment
Day 1	2018-04-18 20:00 — 2018-04-19 05:00	partly cloudy
Day 2	2018-04-19 20:00 — 2018-04-20 05:00	clear sky
Day 3	2018-04-20 20:00 — 2018-04-21 05:00	clear sky
Day 4	2018-04-21 20:00 — 2018-04-22 05:00	clear sky

Univ. Tokyo
Kiso Schmidt telescope

the telescope pointed toward 100 km above MU radar.
tracking the sky, repointed every 3 minitues;
continuously monitoring at 2 Hz with 20 sensors.

Kyoto Univ. MU Radar

optimized for meteor observations;
the beam pointed toward the zenith;

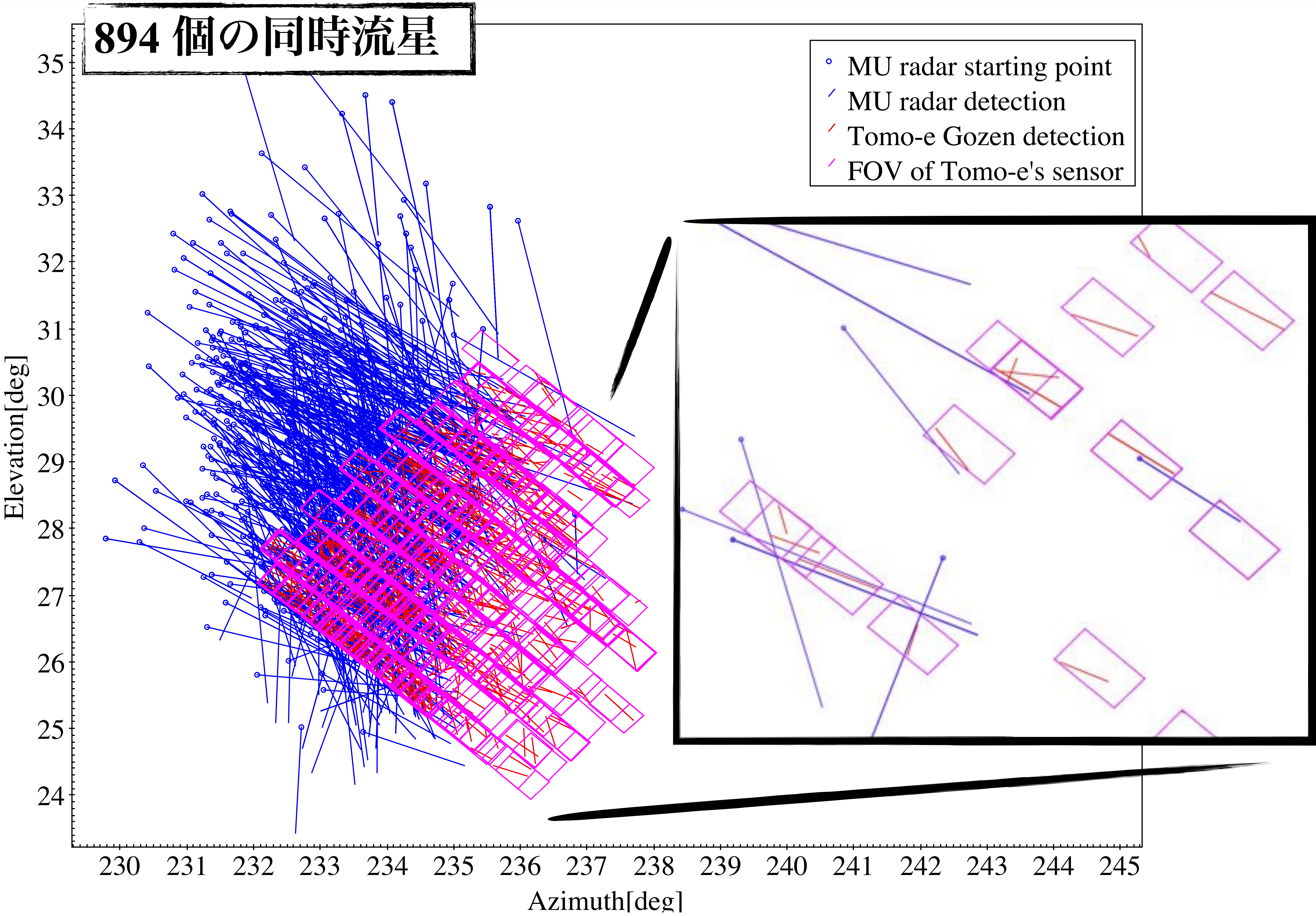

triangulation point
100km over MU radar
FOV of MU radar
Q1 (1/4) unit of Tomo-e Gozen
Elevation ~ 30 deg from Kiso Observatory
SW
W
Direction to MU radar
Image by Stellarium

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).

Results


894 個の同時流星
MU radar starting point
MU radar detection
Tomo-e Gozen detection
FOV of Tomo-e's sensor
Elevation[deg]
Azimuth[deg]
35
34
33
32
31
30
29
28
27
26
25
24
230
231
232
233
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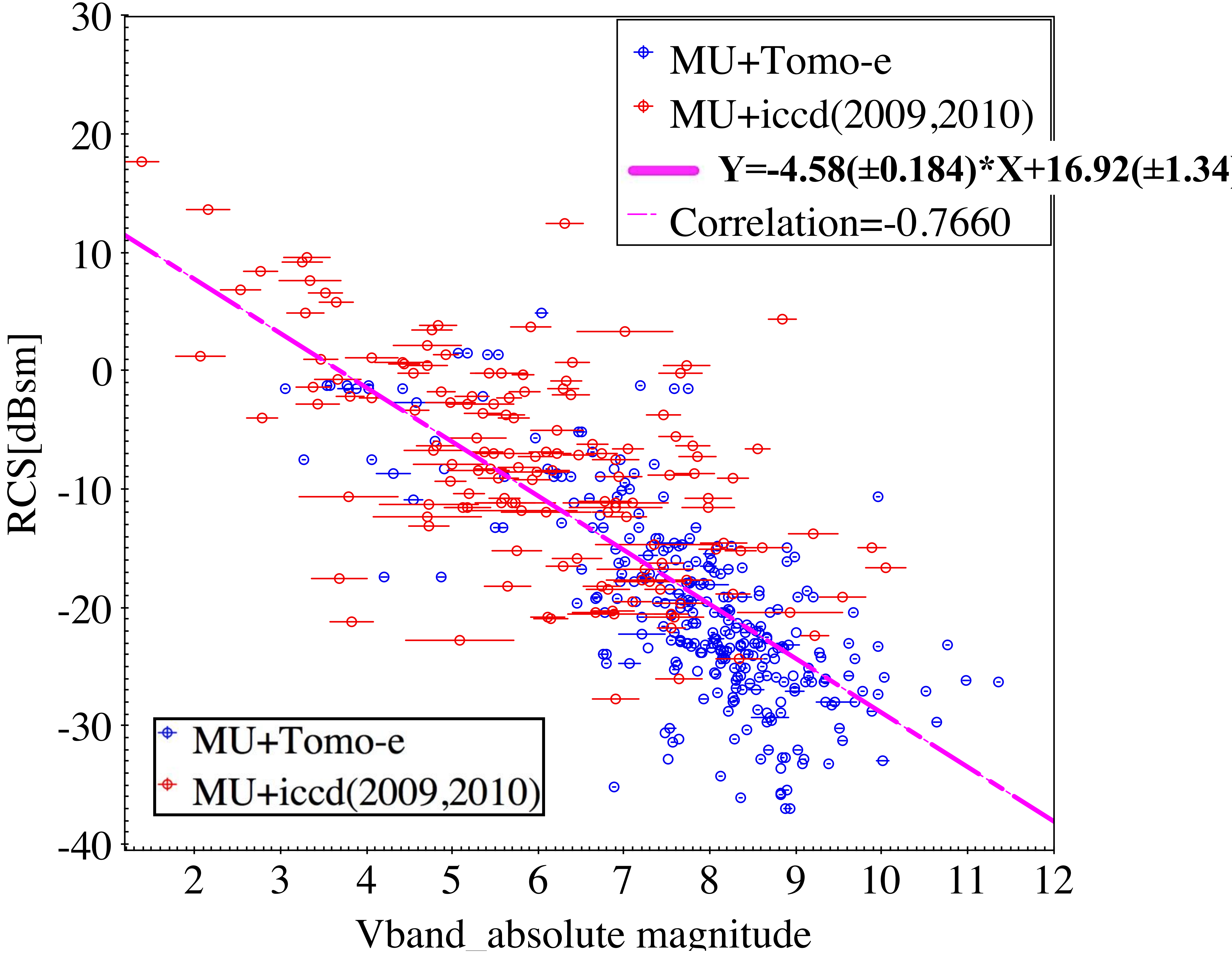
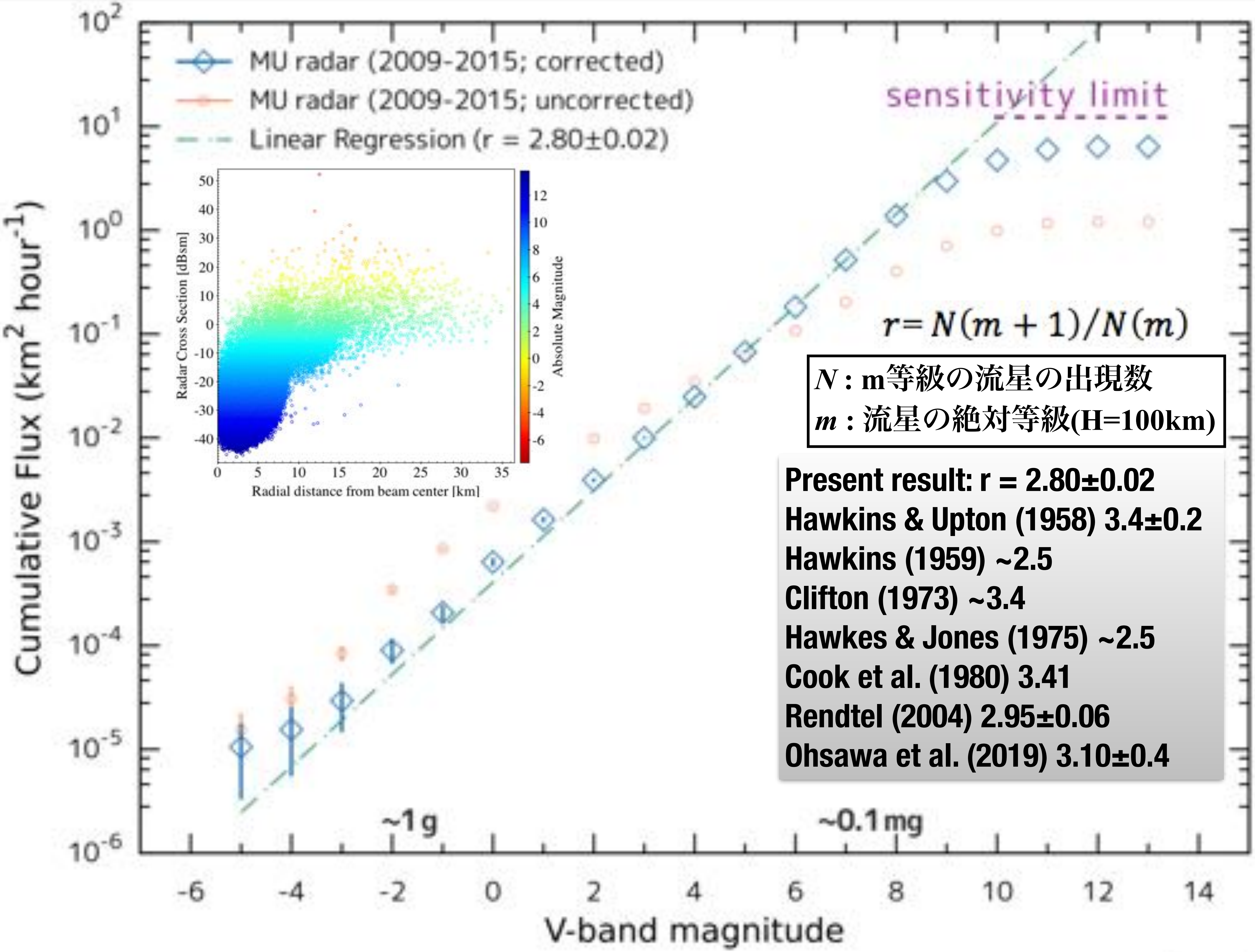
245

流星ヘッドエコー・RCSと等級の関係



Conversion from GAIA-DR2 G-band (320-1000nm) to Johnson V band

Luminosity Function of Meteor Absolute Magnitude

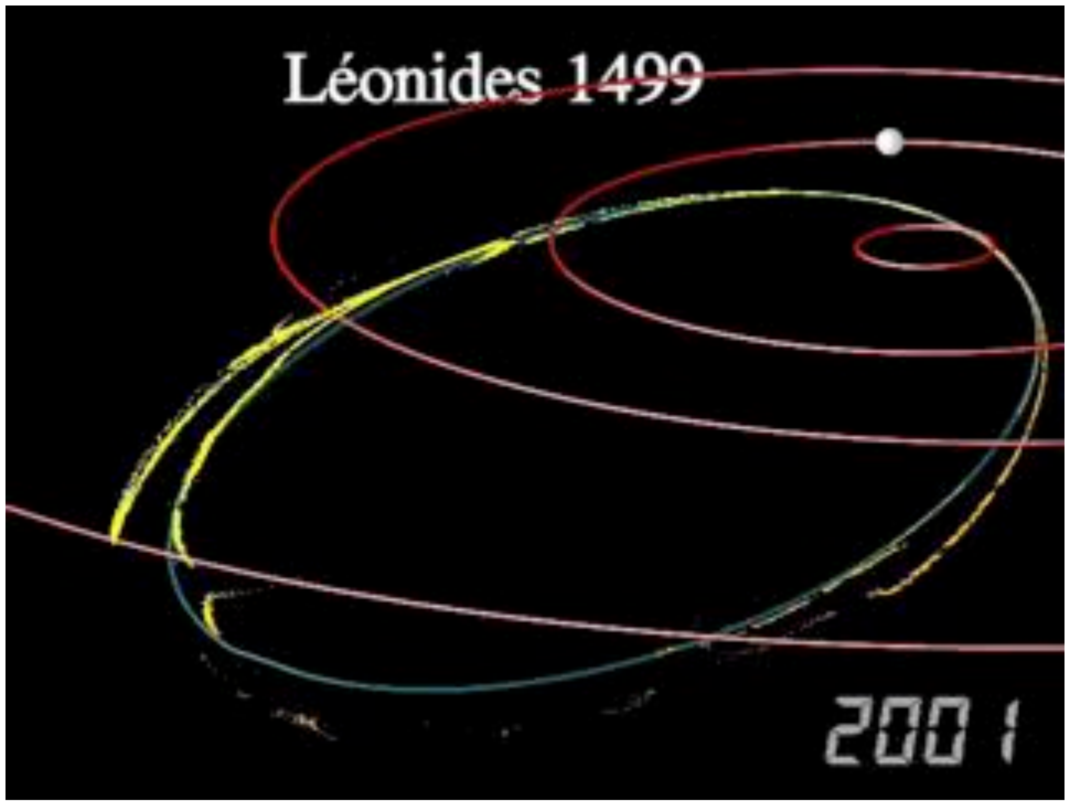


$r = N(m+1)/N(m)$

N : m等級の流星の出現数
m : 流星の絶対等級(H=100km)

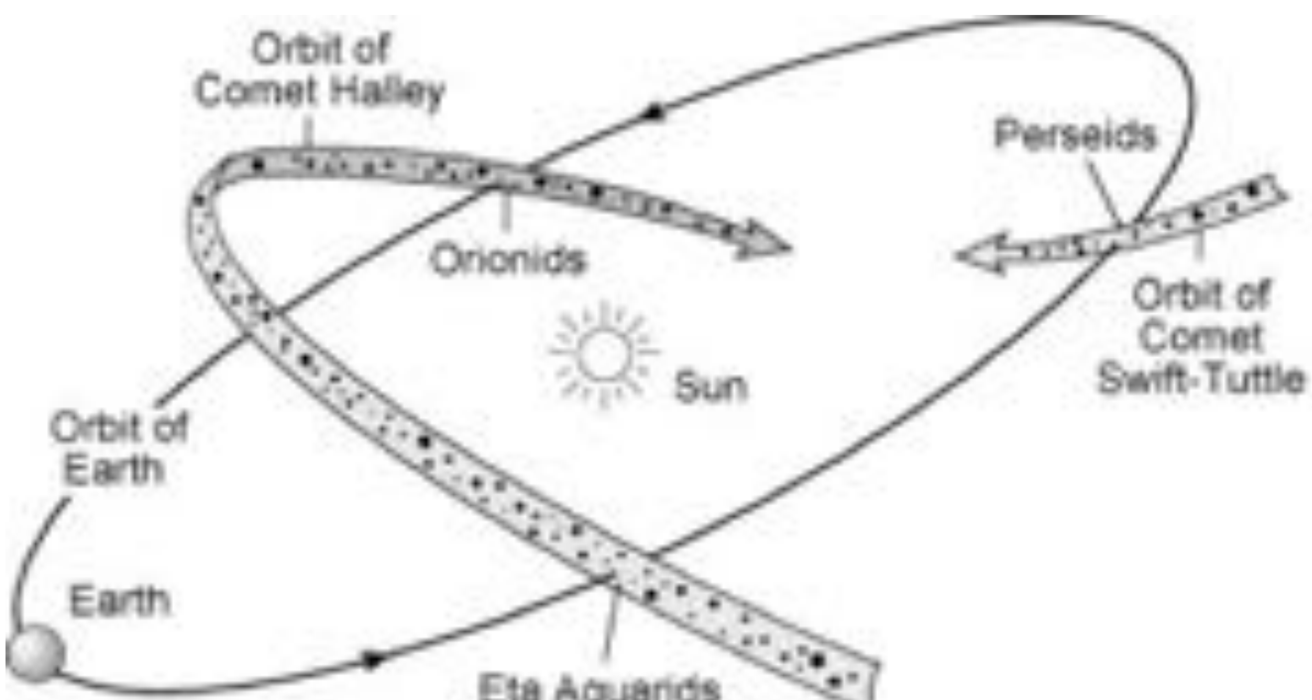
Present result: r = 2.80±0.02
Hawkins & Upton (1958) 3.4±0.2
Hawkins (1959) ~2.5
Clifton (1973) ~3.4
Hawkes & Jones (1975) ~2.5
Cook et al. (1980) 3.41
Rendtel (2004) 2.95±0.06
Ohsawa et al. (2019) 3.10±0.4

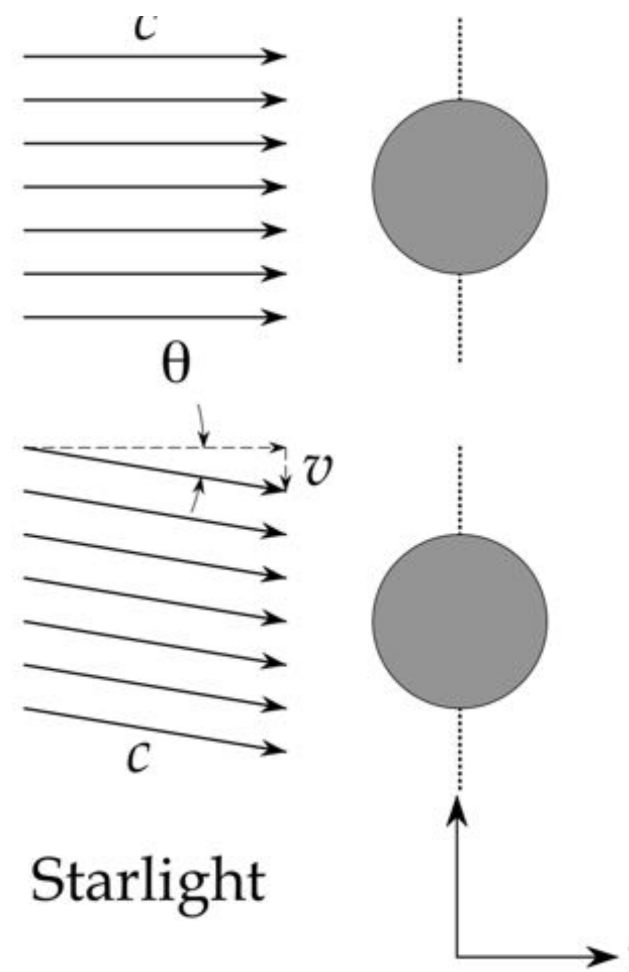
太陽輻射圧を考慮した軌道進化計算→微光流星や太陽接近軌道で効く
Considering Poynting-Robertson effect



$$F_{\rm PR} = \frac{v}{c^2}W = \frac{r^2 L_{\rm s}}{4c^2}\sqrt{\frac{GM_{\rm s}}{R^5}}$$

$$\beta = \frac{F_{\rm r}}{F_{\rm g}} = \frac{3LQ_{\rm PR}}{16\pi GMc\rho s}$$





Summary

invisible Earth impactors are essential

- **46.5MHz レーダーRCS(Radar Cross Section)と可視等級(~11th)のリニアな関係が得られた。**

  Limiting Mag~11th = Mass~10^{-7} g = D~50μm

- **電波と光学の２波長による微光流星の同時観測により「軌道・等級(サイズ)・組成」のビックデータ取得が期待され，太陽系小天体の起源・進化や超高層大気科学の解明に新たな展開をもたらす可能性がある。**
- **TCO(Mini-moon), ISO(Interstellar Object)も期待。**

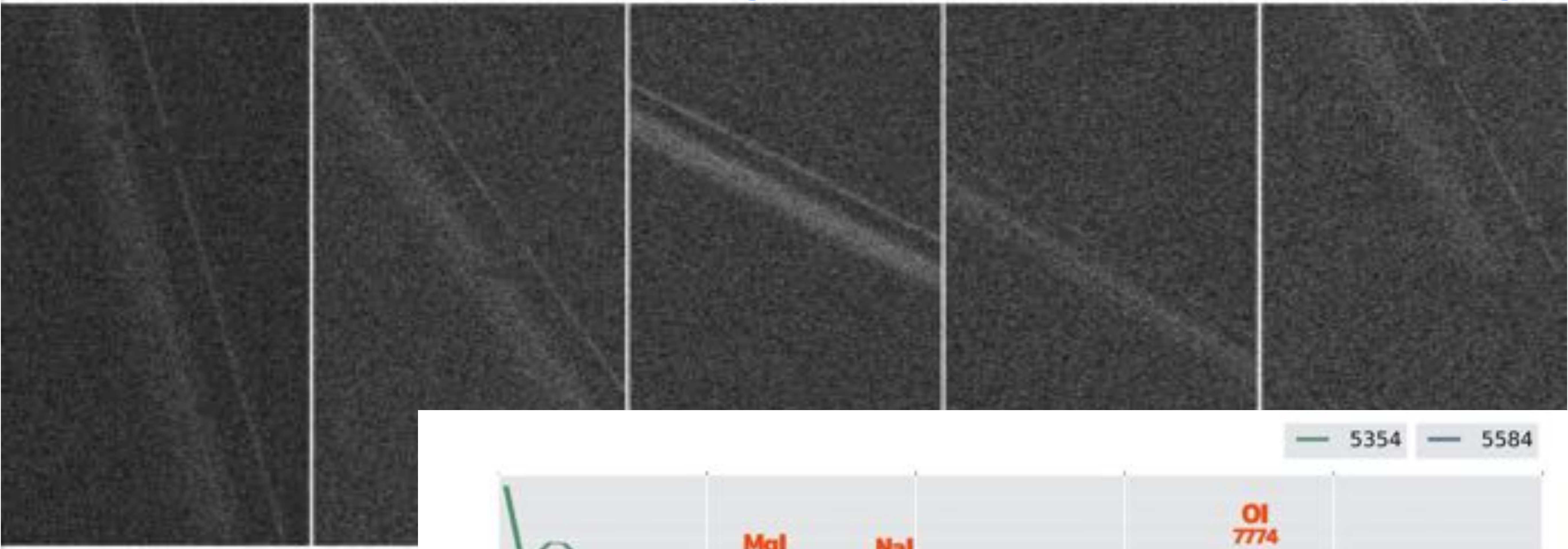
今後の計画 Future plan

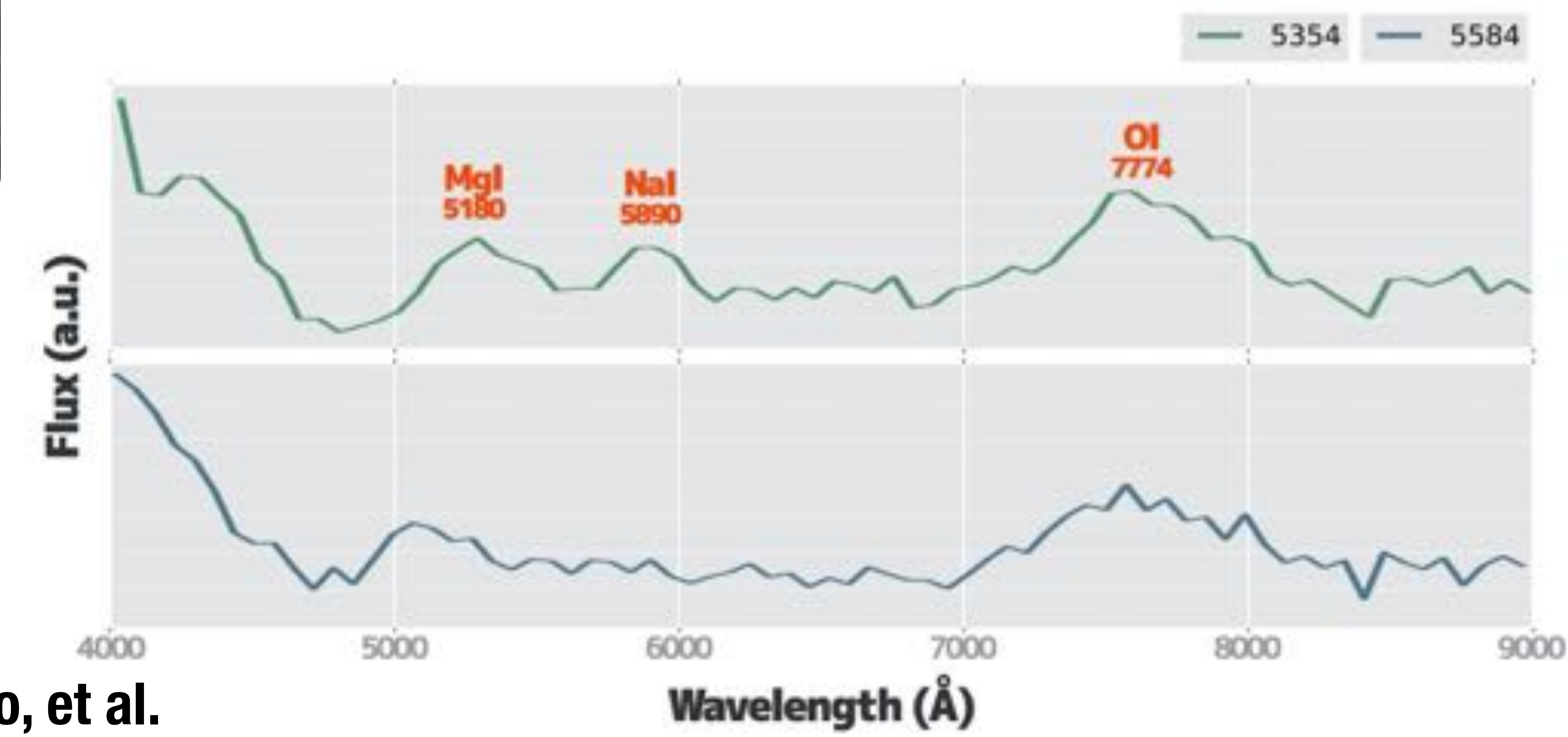
- **2019/10/21-23 (2 clear nights); オリオン座流星群**
- **2019/11/4-7 (2 clear nights); おうし座流星群**
- **2020; 人工流星観測，分光観測**
- **2020; ふたご座流星群; 小惑星フライバイミッションDESTINY+**

『君の名は。』(新海誠監督)

Faint Meteors Spectroscopy by Tomo-e

~8-9th magnitude with R=10 Grating





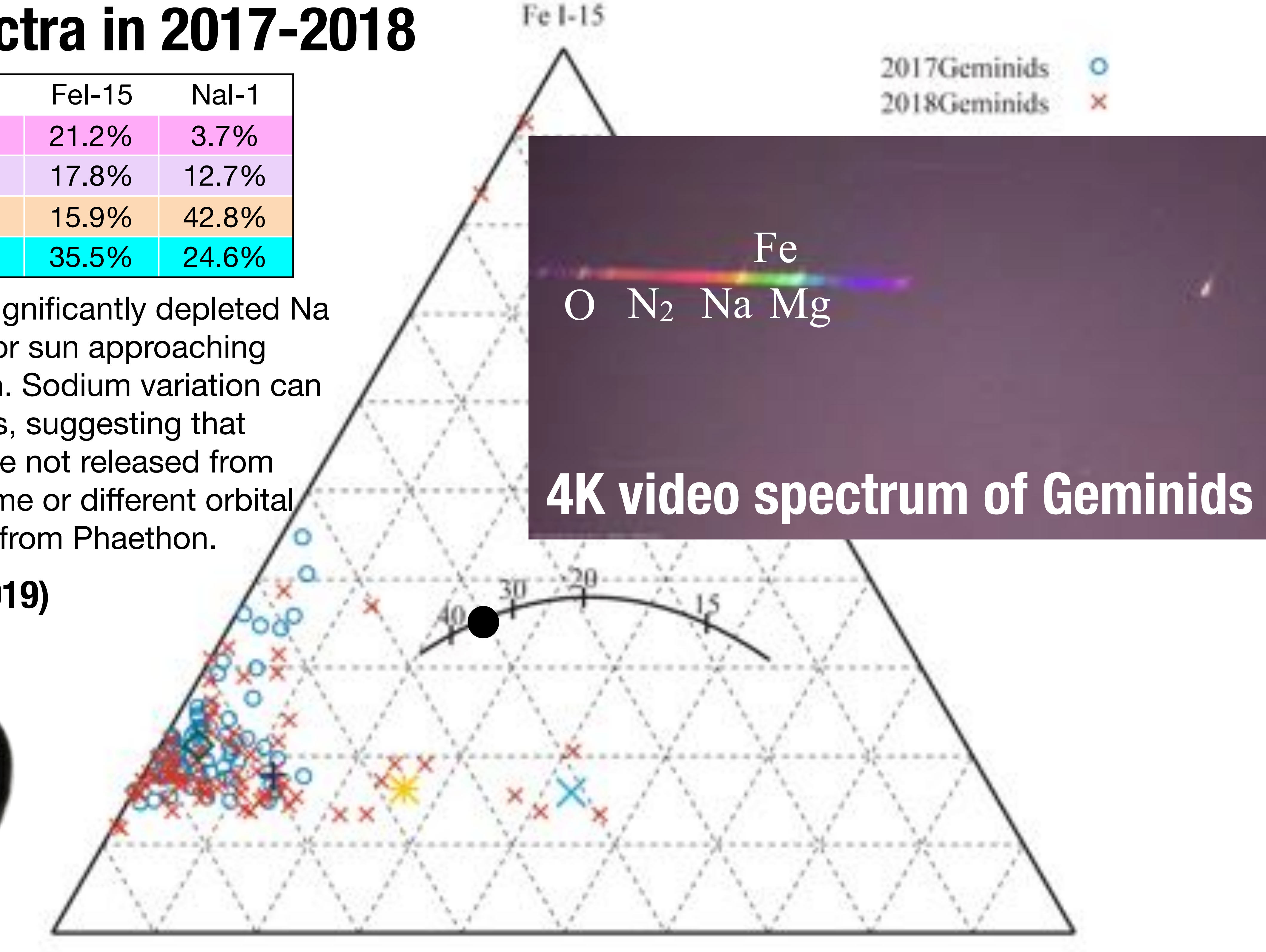
Osawa, Sako, et al.

Geminids' Spectra in 2017-2018

	MgI-2	FeI-15	NaI-1
Na free	75.1%	21.2%	3.7%
Na poor	69.5%	17.8%	12.7%
Na enhanced	41.3%	15.9%	42.8%
Solar abundance	39.9%	35.5%	24.6%

Loss of Na (Na free) or significantly depleted Na (Na poor) are the trend for sun approaching object such as Phaethon. Sodium variation can be seen in different years, suggesting that Geminid meteoroids were not released from Phaethon at the same time or different orbital evolution after releasing from Phaethon.

Ogawa, Abe, Maeda(2019)



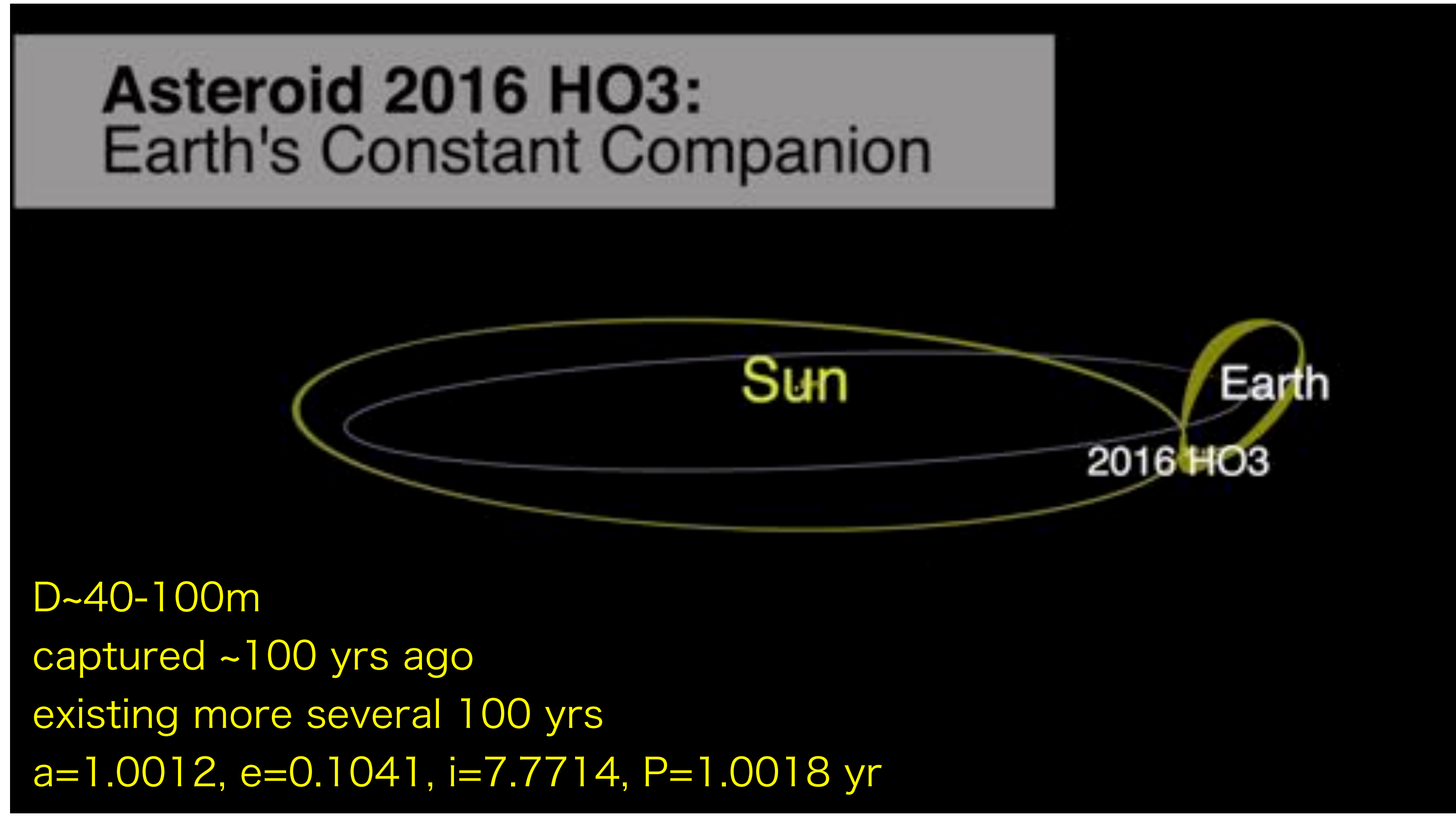
SONY α7S
600/mm grating

Abe, Ogawa, Maeda (2019)

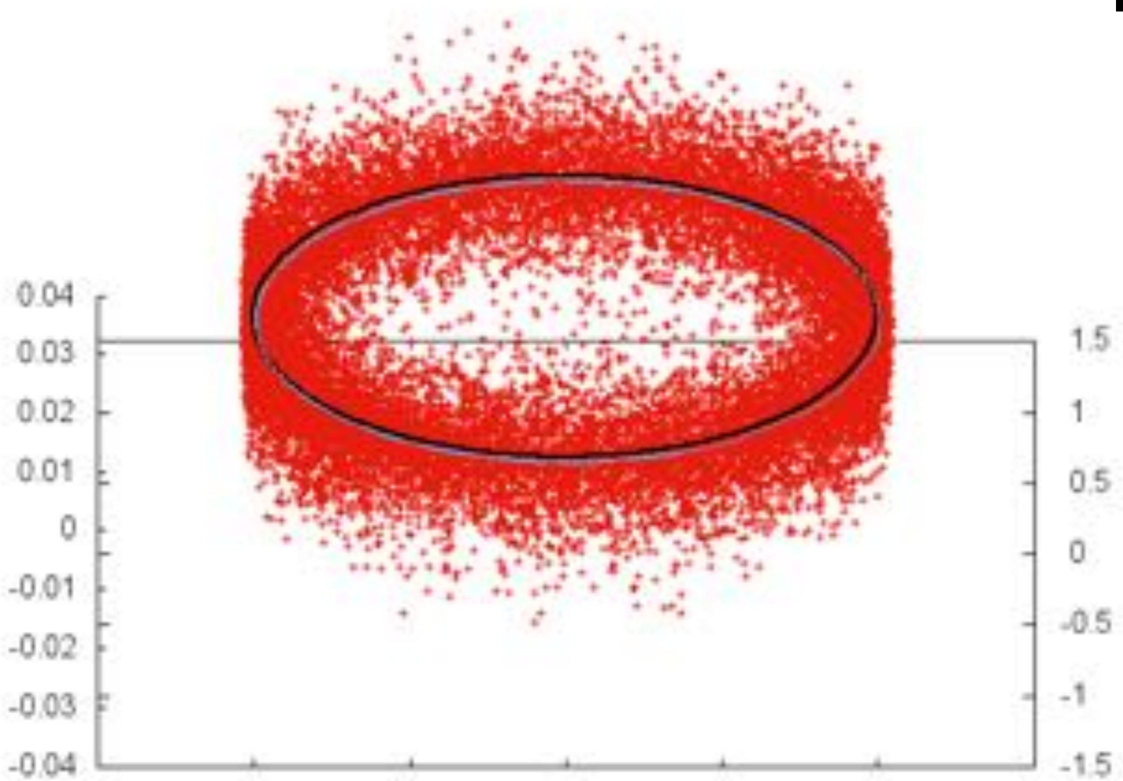
150 spectra of Geminid meteor shower in 2017 and 2018 were carried out using 4K high-sensitive camera. The solid curve shows the relative intensities of the Mg I (2), Na I (1), and Fe I (15) multiplets in meteor spectra assuming chondritic composition as a function of meteor speed. The speeds (in km/s) are marked with numbers. For speeds larger than 40 km/s, the line ratios should not change substantially. A chondritic Geminids with a initial velocity of 35 km/s is indicated as a black circle.

TCOs=Temporarily Captured Orbiters (Mini Moons)

D=1.0m ; 2
D=0.5m ; dozen
D=0.1m ; 1000
~0.1% of meteors
M. Granvik et al. (2012)



Earth orbit
Lunar orbit



TCO model
M. Granvik+(2017)

TCOs can be captured at Sun-Earth L1/L2

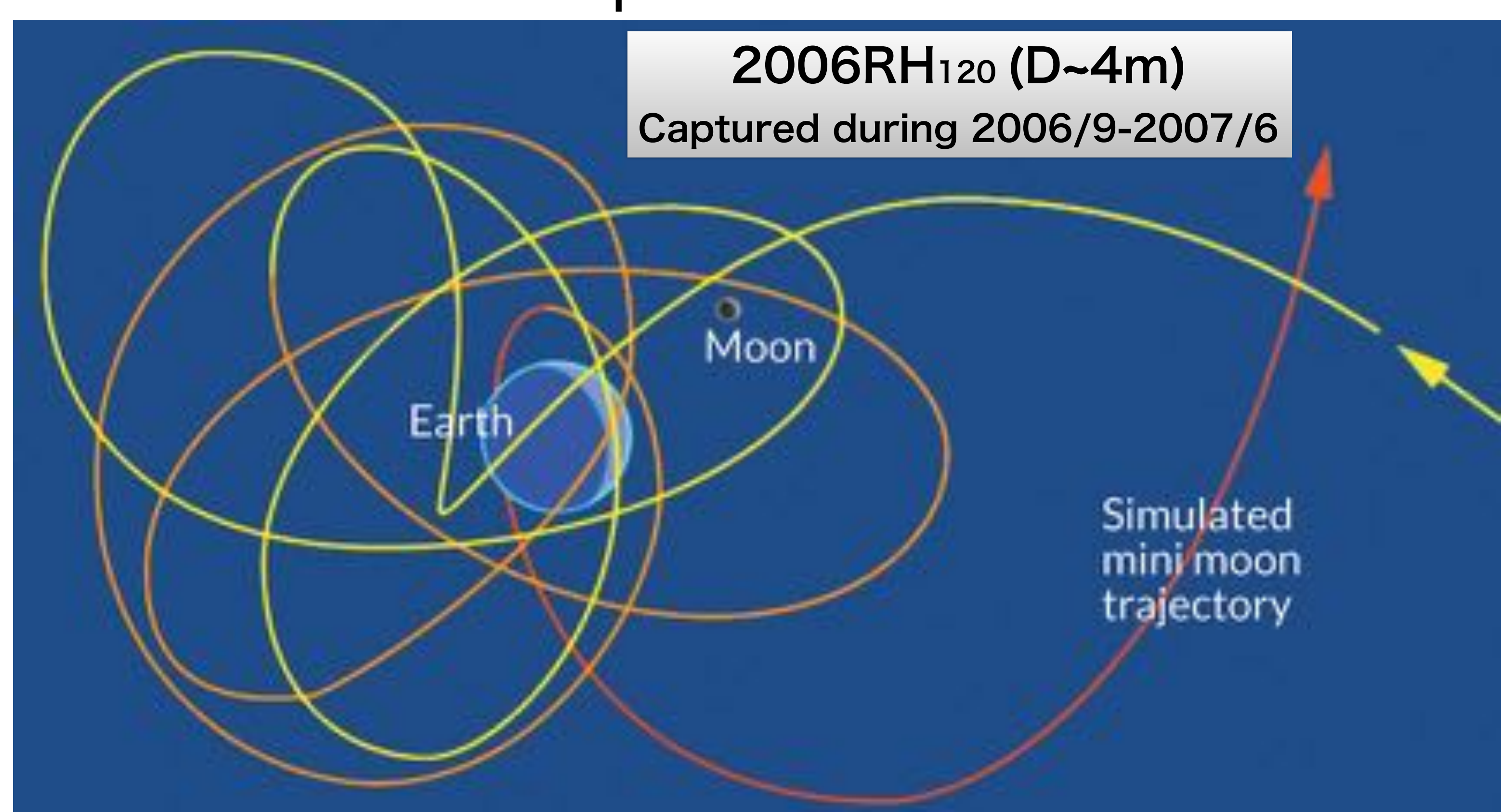


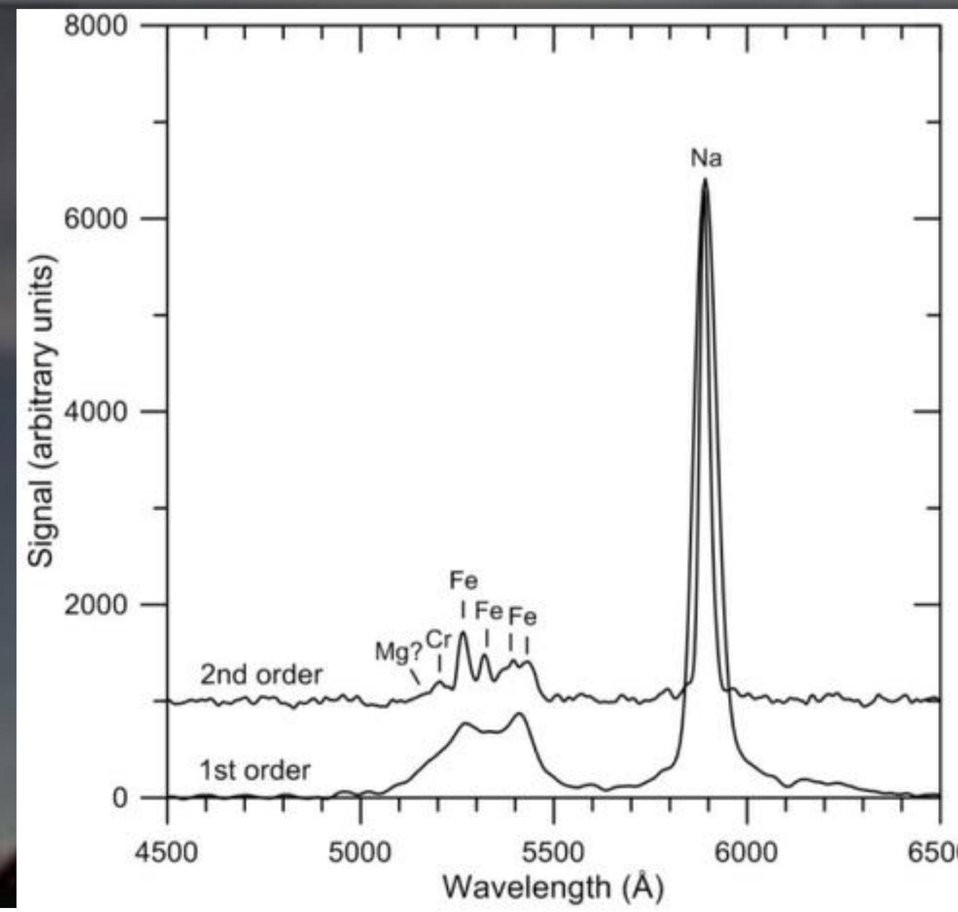
Table 1
In-atmosphere Trajectory, Mass, and Fireball Type Determined for EN130114

	Beginning	Terminal
Time (UT)	3:01:37.62 UT	3:01:45.70
Height (km)	74.589 ± 0.015	32.494 ± 0.009
Longitude (deg E)	13.42570 ± 0.00014	13.67707 ± 0.00013
Latitude (deg N)	49.07656 ± 0.00006	48.52321 ± 0.00005
Mass (kg)	5	0.2
Slope (deg)	33.302 ± 0.014	32.724 ± 0.014
Maximum absolute magnitude	−7.6	
Total length (km)/Duration (s)	77.26/8.08	
PE/Type	−4.60/*I*	
EN stations	02 Kunžak (DAFO), 20 Ondřejov (DF)	

Note. PE/Type: Empirical end height criteria and resulting fragmentation class/type; see Ceplecha & McCrosky (1976). DAFO: Digital Autonomous Fireball Observatory, DF: Digital Camera—imaging parameters are the same.

Radiant and Velocity		
R.A. (°)	Decl. (°)	v (km s^{-1})
35.98 ± 0.07	69.88 ± 0.20	10.917 ± 0.035

TCO (Mini-moon) fireball



D. L. Clark, P. Spurný, et al, Astronomical Journal, 151, 6, 2016

Thank You

Astro Live Experiences

Artificial meteors for calibrations on the sky observed by Radar and Optical observations

Meteor ablation tests using JAXA/Arc-heating Wind Tunnel