

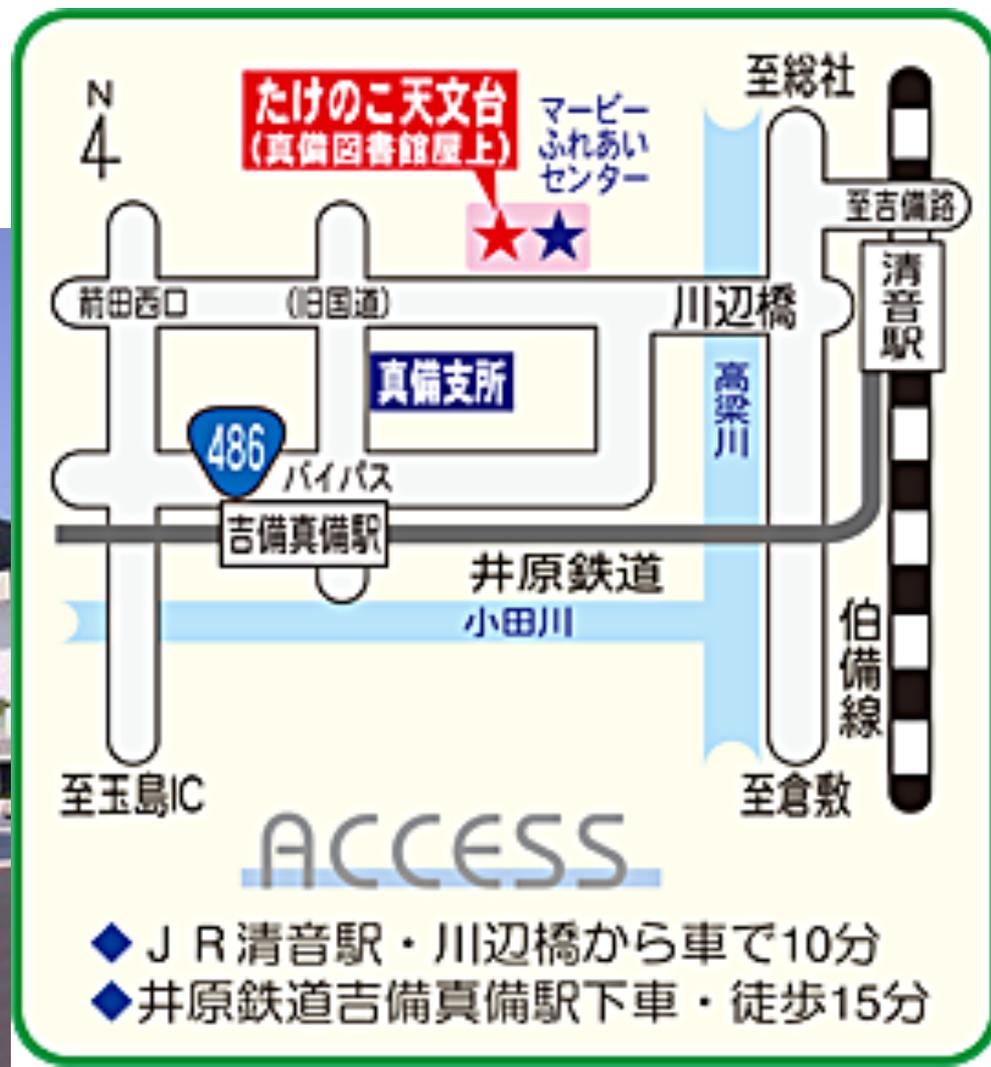
# 地球接近天体2012 TC<sub>4</sub>の観測

木曾広視野カメラTomo-e Gozenを用いた高時間分解ライトカーブ

浦川 聖太郎<sup>1</sup>, 大澤 亮<sup>2</sup>, 酒向 重行<sup>2</sup>, 奥村 真一郎<sup>1</sup>, 櫻井 友里<sup>3</sup>, 高橋 隼<sup>4</sup>,  
今村 和義<sup>5</sup>, 内藤 博之<sup>6</sup>, 岡崎 良<sup>7</sup>, 関口 朋彦<sup>7</sup>, 石黒 正晃<sup>8</sup>, 吉川 真<sup>9</sup>,  
Tomo-e Gozenメンバー

<sup>1</sup>日本スペースガード協会, <sup>2</sup>東京大学, <sup>3</sup>岡山大学, <sup>4</sup>兵庫県立大学, <sup>5</sup>阿南市立科学センター, <sup>6</sup>なよろ市立天文台, <sup>7</sup>北海道教育大学, <sup>8</sup>ソウル大学, <sup>9</sup>JAXA

# 真備町たけのこ天文台



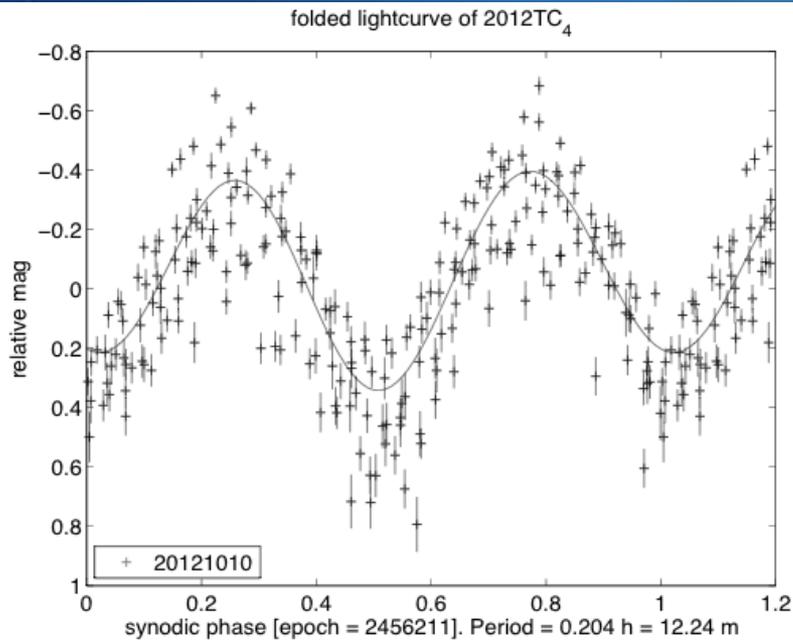
# まとめ

- 地球接近天体2012 TC<sub>4</sub>を様々な望遠鏡で観測
- タンブリング小惑星
- 自転周期：8.47分 歳差周期：12.25 分
- 反射スペクトルタイプ：X-type
- 直径：6 - 20 m
- 形状&運動モデルを作成
- Flatten and elongated shape：3.3 m : 8.0 m : 14.3 m

# 地球接近天体 2012 TC<sub>4</sub>

- ◆ 2012年にPan-STARRsで発見
- ◆ 2012年における最接近距離:95,000 km
- ◆ 2012年における推定直径: 7 - 34 m (Polishook 2013)
- ◆ 2012年における自転周期: 12.24 分(Polishook 2013)

# 2012年におけるライトカーブ



いくつかのデータはフィッティングカーブに上手くフィットしていない。

Figure 1. The lightcurve for 2012 TC4 phased to a period 12.24 min.

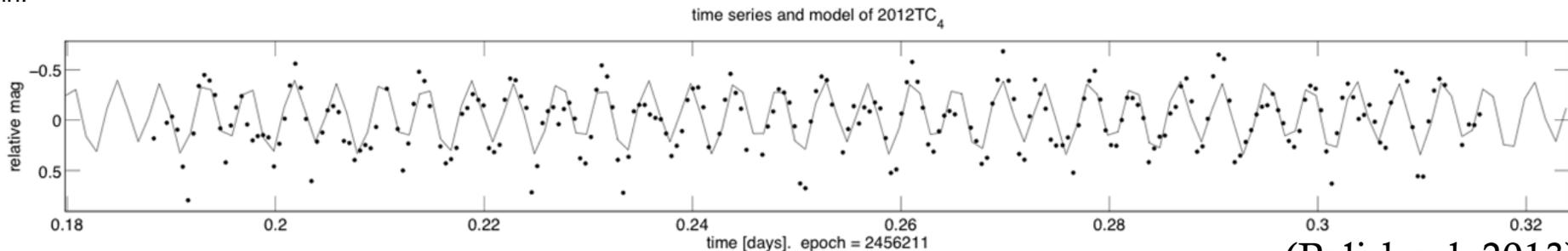
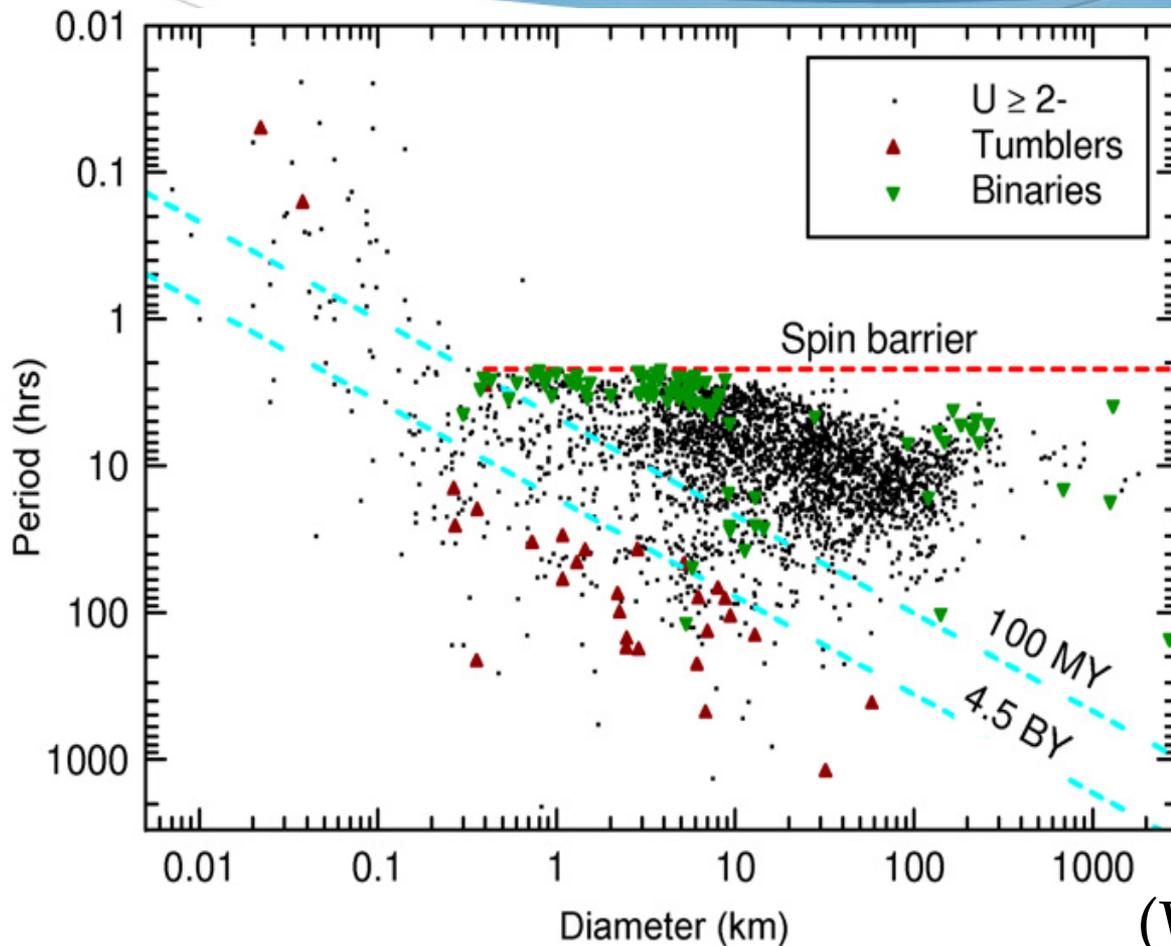


Figure 2. Raw time series plot of 2012 TC4 data.

(Polishook 2013)

# 高速自転小惑星



2.2時間以下  
=>一枚岩小惑星

2.2時間以上  
=>ラブルパイル  
(重力による維持可能)

(Warner et al. 2009)



©JAXA、東大など

# 地球接近天体 2012 TC<sub>4</sub>

- ◆ 2012年にPan-STARRsで発見
- ◆ 2012年における最接近距離:95,000 km
- ◆ 2012年における推定直径: 7 - 34 m (Polishook 2013)
- ◆ 2012年における自転周期: 12.24 分(Polishook 2013)
- ◆ 一枚岩小惑星(Monolithic asteroid)、表面はレゴリス層に覆われていない。
- ◆ 2017年に再び接近。最接近距離50,000 km(10月12日)

# Purposes

- ◆ Spaceguard exercise

If an impact hazard asteroid comes to the Earth, we must clarify the physical properties of the asteroid.

- ◆ Science of small monolithic asteroids

Taxonomic class, Shape => How to produce small monolithic asteroid?

# Observations





- Lightcurve (Visible photometry) (写真：東京大学、阿南市立科学館、なよろ市立天文台、兵庫県立大学)

Kiso 1.05 m + The Tomo-e Gozen Camera/  
 Bisei Spaceguard Center (BSGC) 1.0 m/Anan 1.13 m /  
 Nayoro 0.4 m

- Visible multiband photometry ( $g'$ ,  $r'$ ,  $i'$ ,  $z'$  band)

BSGC 1.0 m

- Near-infrared multi-band photometry ( $J$ ,  $H$ ,  $K_s$  band)

Nishi-harima 2.0 m + NIC (three-band simultaneous camera)

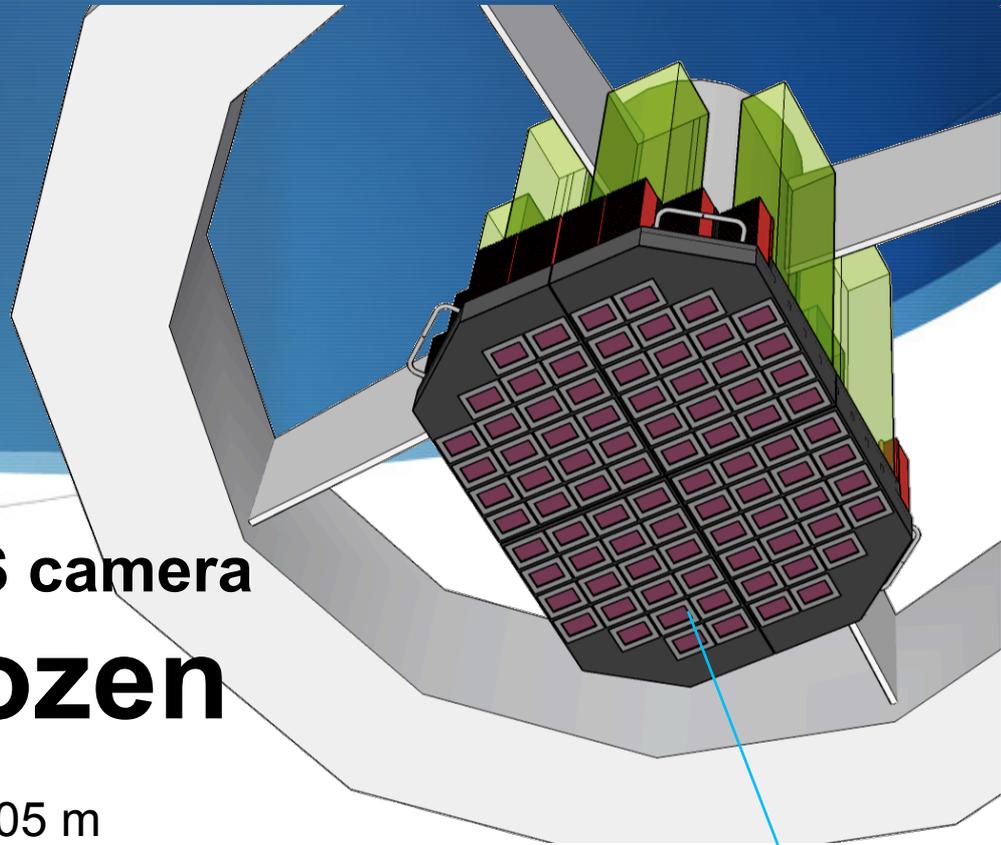
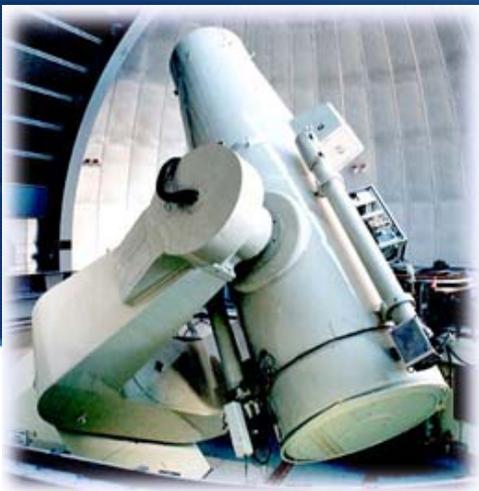
---



---

Year/Mon/Day (UT)	Geocentric distance (AU)	Phase angle ( $^{\circ}$ )	Sky motion "/min
2017/10/9.4578 – 9.4998	0.011 – 0.010	31.4 – 31.5	4.16 – 4.54
2017/10/10.4029 – 10.5808	0.007 – 0.0064	33.3 – 34.1	6.77 – 9.36
2017/10/11.4283 – 11.6130	0.0032 – 0.0025	38.0 – 40.7	28.17 – 43.24

---

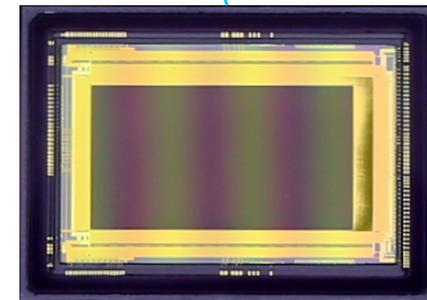


## Extremely wide-field CMOS camera **The Tomo-e Gozen**

- Telescope      Kiso Observatory 1.05 m
- FoV            9 deg in diameter
- Sensor        Canon CMOS x 84
- Estimated completion date    2019
- Frame rate(max)    2 frames/sec = 0.5 sec exposure

The high frame rate of the Tomo-e Gozen is suitable for observations of fast moving objects.

Duration of test observation by using 4 chips: October 2017



35 mm full HD, 1k × 2k pix<sup>2</sup>,  
84 chips

**Canon**

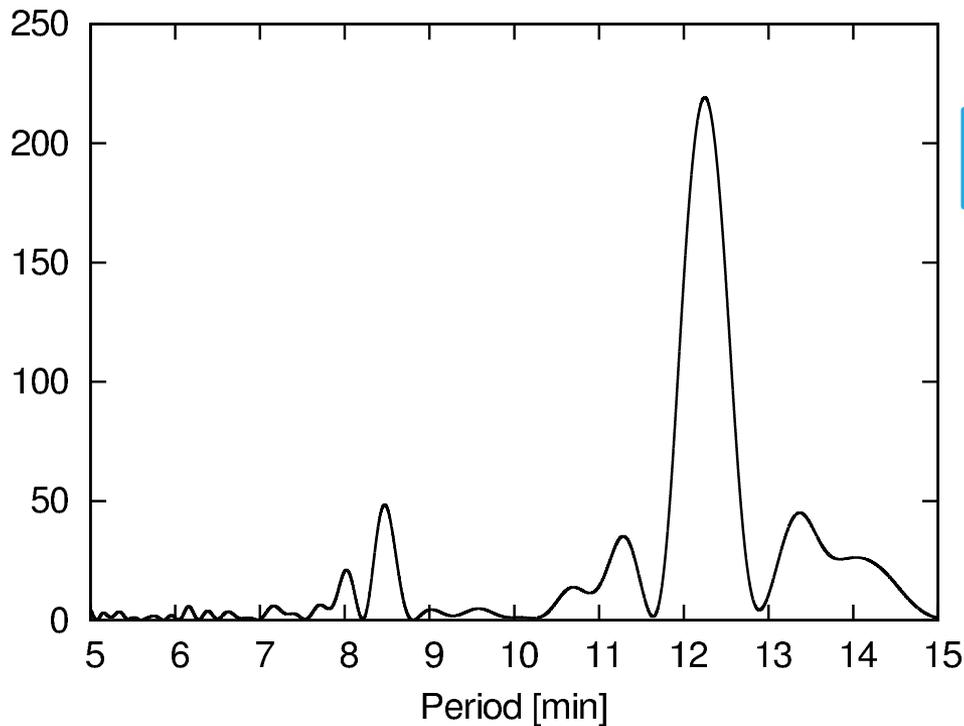
# Video of TC4 by the Tomo-e Gozen



# Lightcurve



# 周期解析



Lomb-Scargle periodogram  
(Lomb 1972, Scargle 1982)

$$P_{\psi} = 8.47 \text{ 分}, P_{\phi} = 12.24 \text{ 分}$$

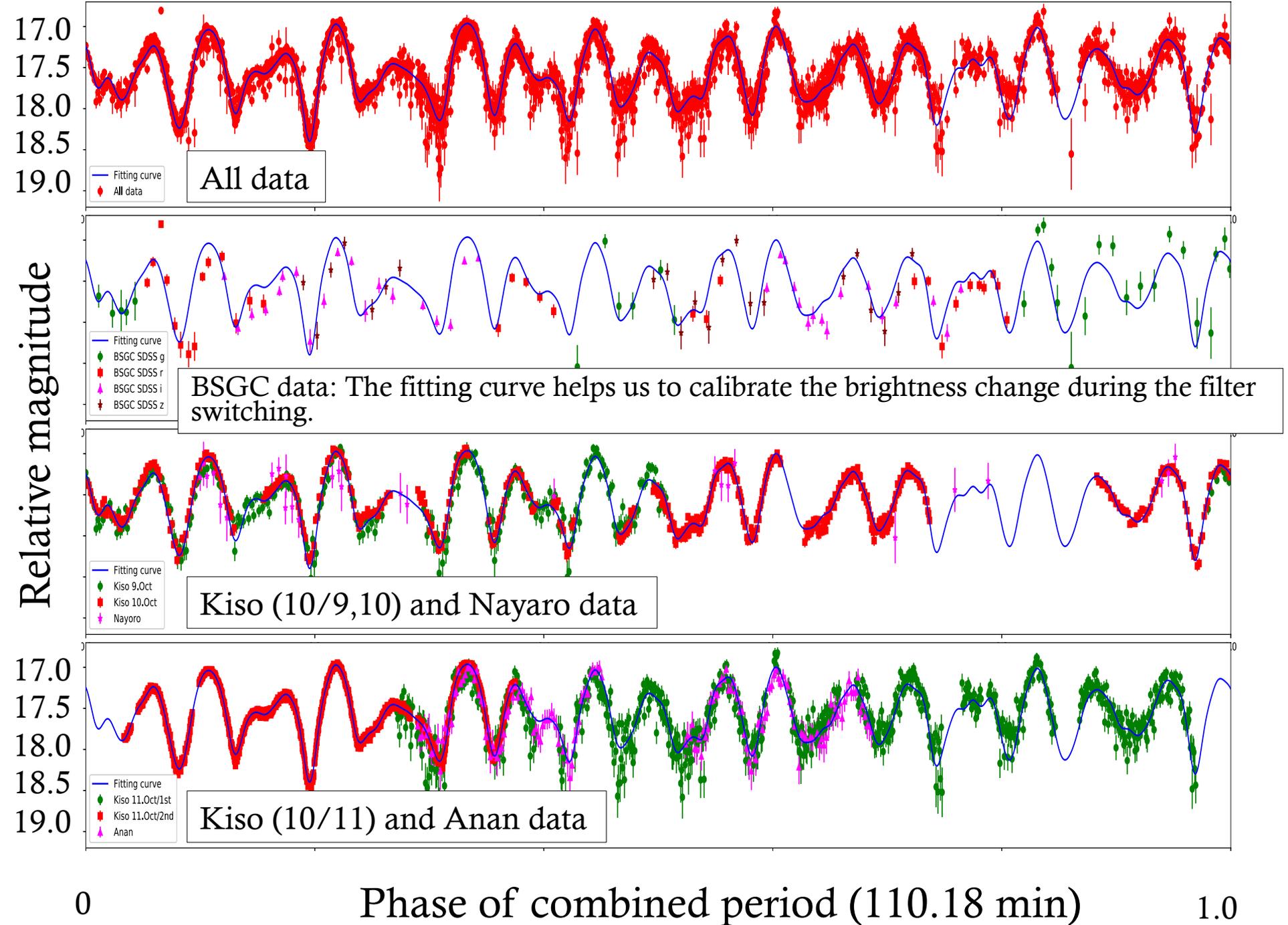
TC4はタンブリング小惑星！

$$P_{\psi} : P_{\phi} \sim 9 : 13$$

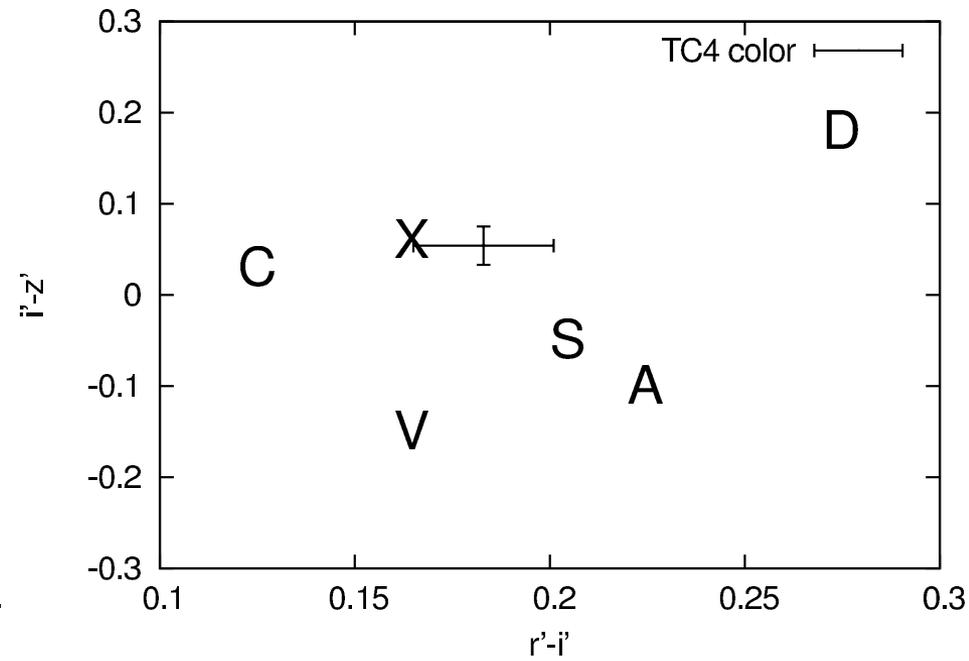
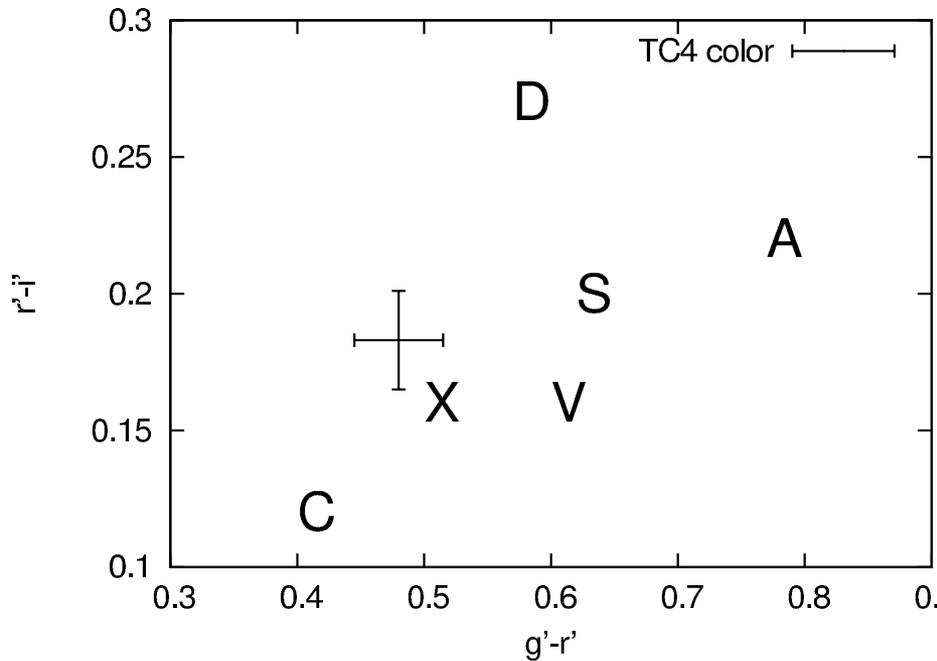
複合周期  $P_c$ :

$$P_c = \frac{9P_{\psi} + 13P_{\phi}}{2} = 110.18 \text{ 分}$$

複合周期ごとにTC4の同じ  
面が観測者に向く



# 反射スペクトルタイプと直径



$$J - H = 0.226 \pm 0.041, H - K_s = 0.034 \pm 0.045$$

(X-type:  $J - H = 0.31 \pm 0.12, H - K_s = 0.14 \pm 0.07$ ) (Popescu 2016)

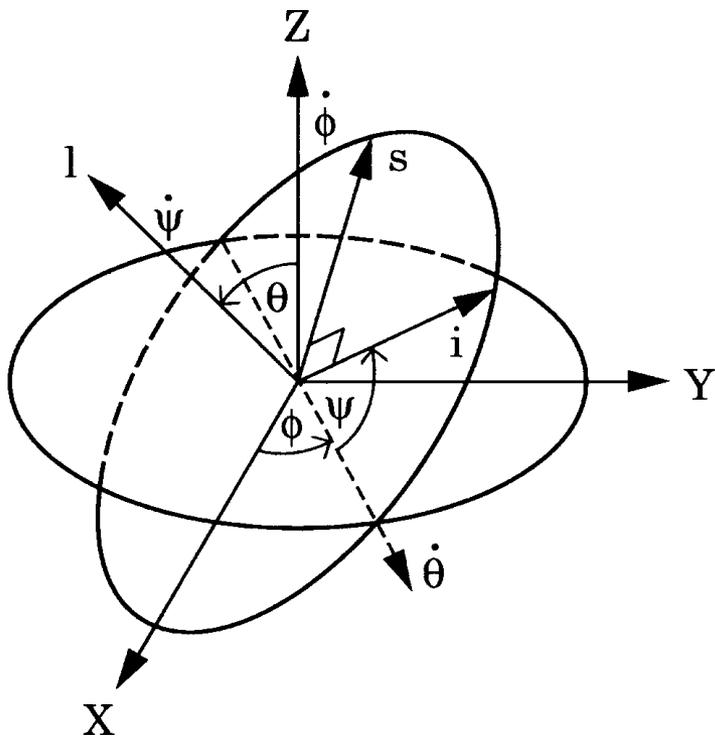
反射スペクトルタイプ: **X-type** (鉄隕石、分化石質隕石の母天体小惑星)

直径: **6 – 20 m** (X-type albedo: 0.098, Usui+ 2013)

# 形状と運動モデル



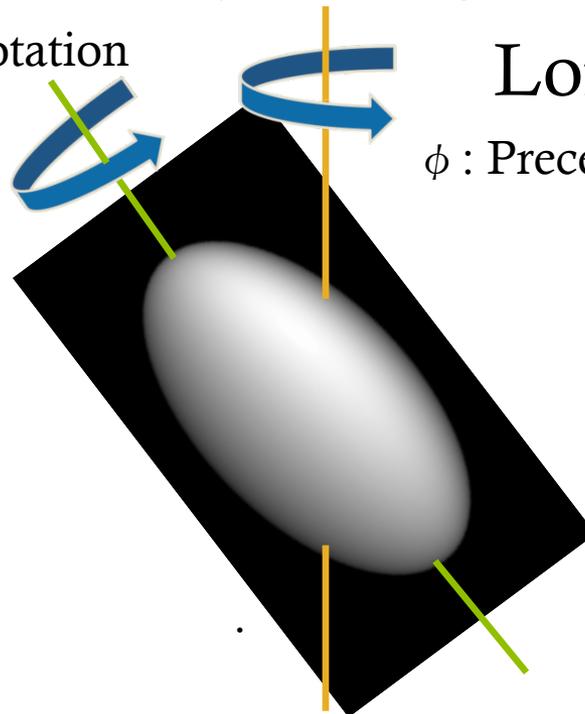
# 三軸不等剛体の運動の解析



The Euler angles  $\theta$ ,  $\phi$ , and  $\psi$  describe the motion of body with respect to the external observer.

The lightcurve inversion program (Kaasalainen 2001) is not released for tumbling asteroids. Asteroids motion can be described with the dynamics of a force-free asymmetric rigid body motion.

$\psi$  : Rotation

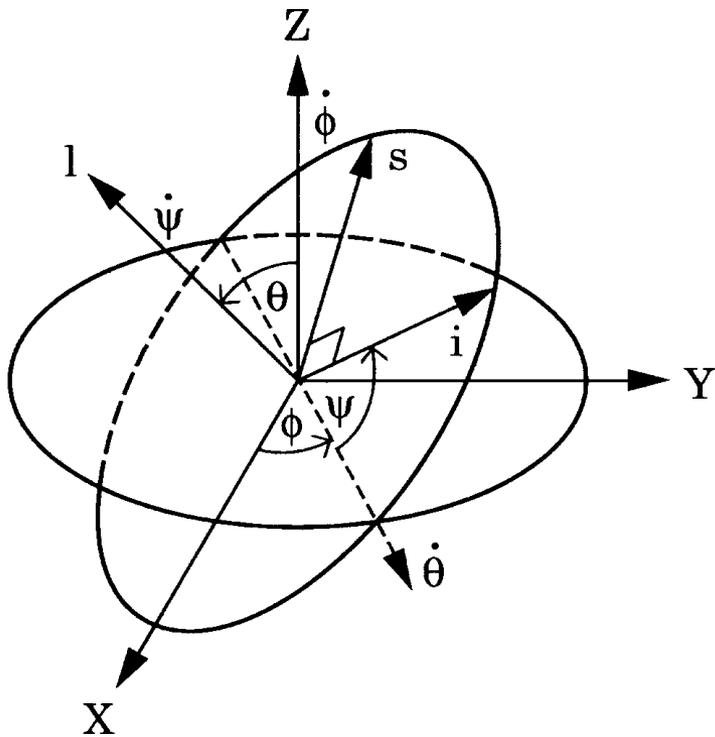


## Long axis mode

$\phi$  : Precession

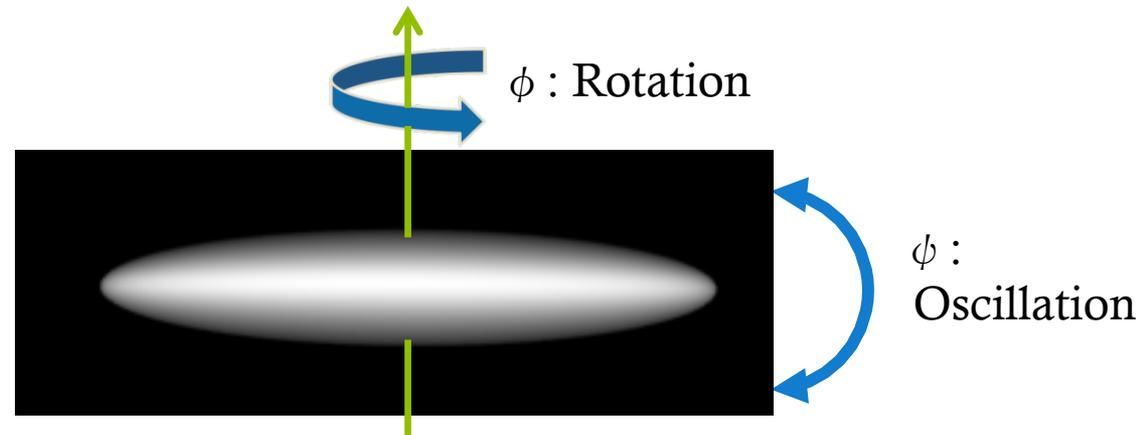
The analytical solution can give the limit for the axis ratios of TC4. The axis ratios deduce the  $\theta(t)$ ,  $\phi(t)$ ,  $\psi(t)$ , and  $\dot{\phi}(t)$ .

# 三軸不等剛体の運動の解析



The Euler angles  $\theta$ ,  $\phi$ , and  $\psi$  describe the motion of body with respect to the external observer.

## Short axis mode



The analytical solution can give the limit for the axis ratios of TC4. The axis ratios deduce the  $\theta(t)$ ,  $\phi(t)$ ,  $\psi(t)$ , and  $\dot{\phi}(t)$ .

# Shape and motion

Input:

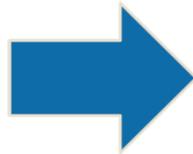
Observational results

Out put:

Rotation period

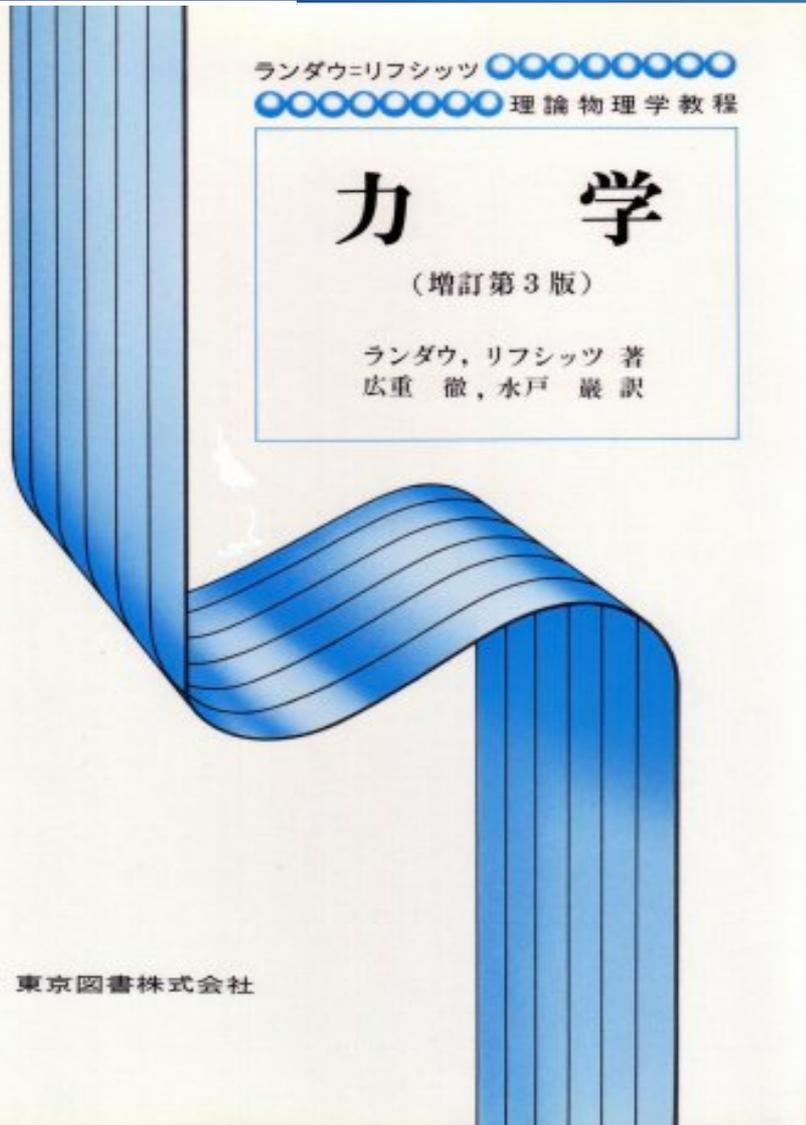
Lightcurve  
amplitude

Diameter



An analysis of  
force-free  
asymmetric  
rigid body  
(We assume a long  
axis mode)

# Equations



$$\psi = \text{atan2} \left( \sqrt{\frac{I_i \left( I_s - \frac{M^2}{2E} \right)}{I_s - I_i}} \text{sn}\tau, \sqrt{\frac{I_s \left( \frac{M^2}{2E} - I_l \right)}{I_s - I_l}} \text{dn}\tau \right)$$

$$\frac{P_\psi}{P_\phi} \geq \sqrt{\frac{(L_l^2 + L_s^2)(L_i^2 + L_s^2)}{(L_l^2 - L_s^2)(L_i^2 - L_s^2)'}}$$

$$\frac{P_\psi}{P_\phi} > 1$$

(Landau and Lifshitz 1976,  
Samarasinha and A'Hearn  
1991, Kaasalainen 2001 )

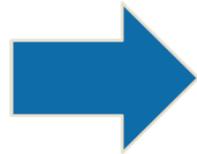
# Shape and motion

Input:  
Observational results

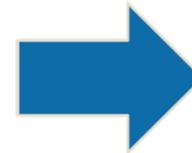
Rotation period

Lightcurve  
amplitude

Diameter



An analysis of  
force-free  
asymmetric  
rigid body  
(We assume long  
axis mode)



$$L_i = 2.40 L_s$$

$$L_1 \geq 3.69 L_s$$

$$\theta(t), \phi(t), \\ \dot{\phi}(t), \dot{\phi}(t)$$

Out put:

Axial lengths ( $L_1, L_i, L_s$ )  
 $\theta(t), \phi(t), \dot{\phi}(t), \dot{\phi}(t)$

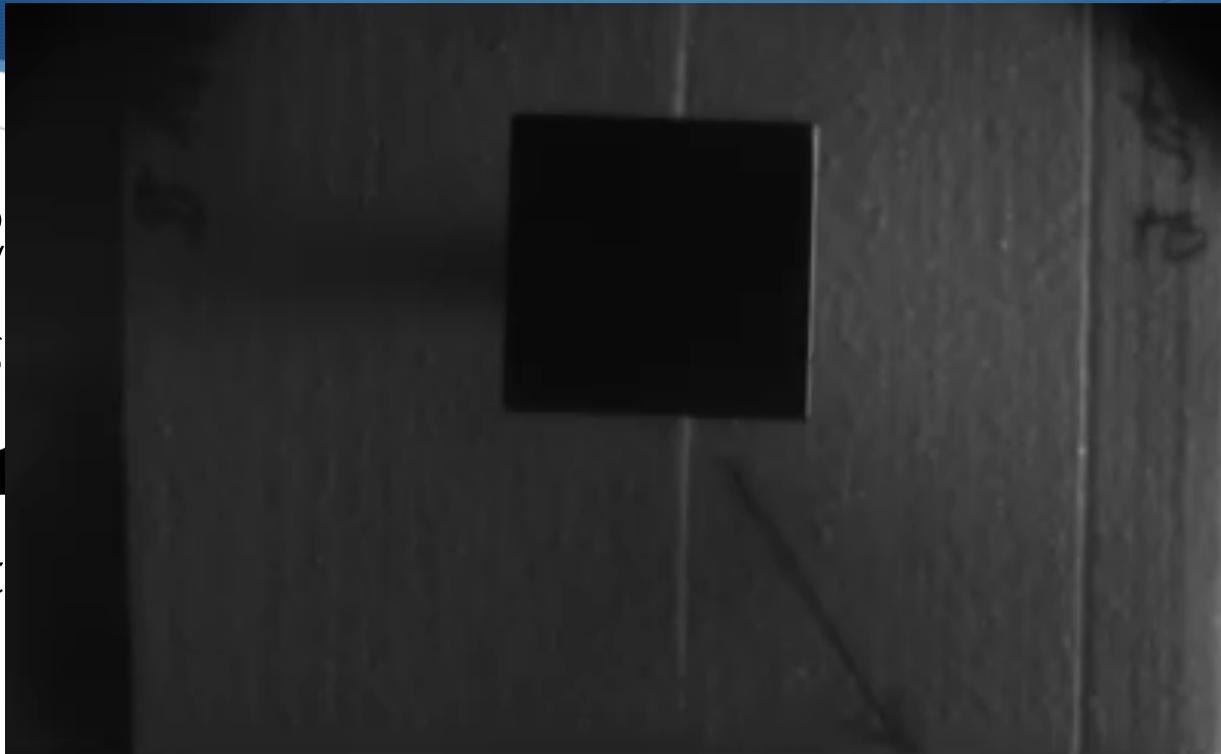
A representative axial length combination:  $L_s = 3.3$  m,  $L_i = 8.0$  m,  $L_1 = 14.3$  m

# 代表的なモデル



# まとめと議論

- 2012
- 自転
- X-type
- Flatt



Axis ratios of boulders on surface of asteroids is  $\sim 2 : \sqrt{2} : 1$

Axis ratio ( $L_s/L_1$ ) of spall fragments is  $\sim 0.4$  (Michikami+ 2016)

TC4は衝突現象で発生した破片だろう。