ライトカーブ遅延法による
高速自転小惑星の熱慣性推定

Thermal Inertia Estimation of Fast Rotating Asteroids by Light Curve Phase Lag Method

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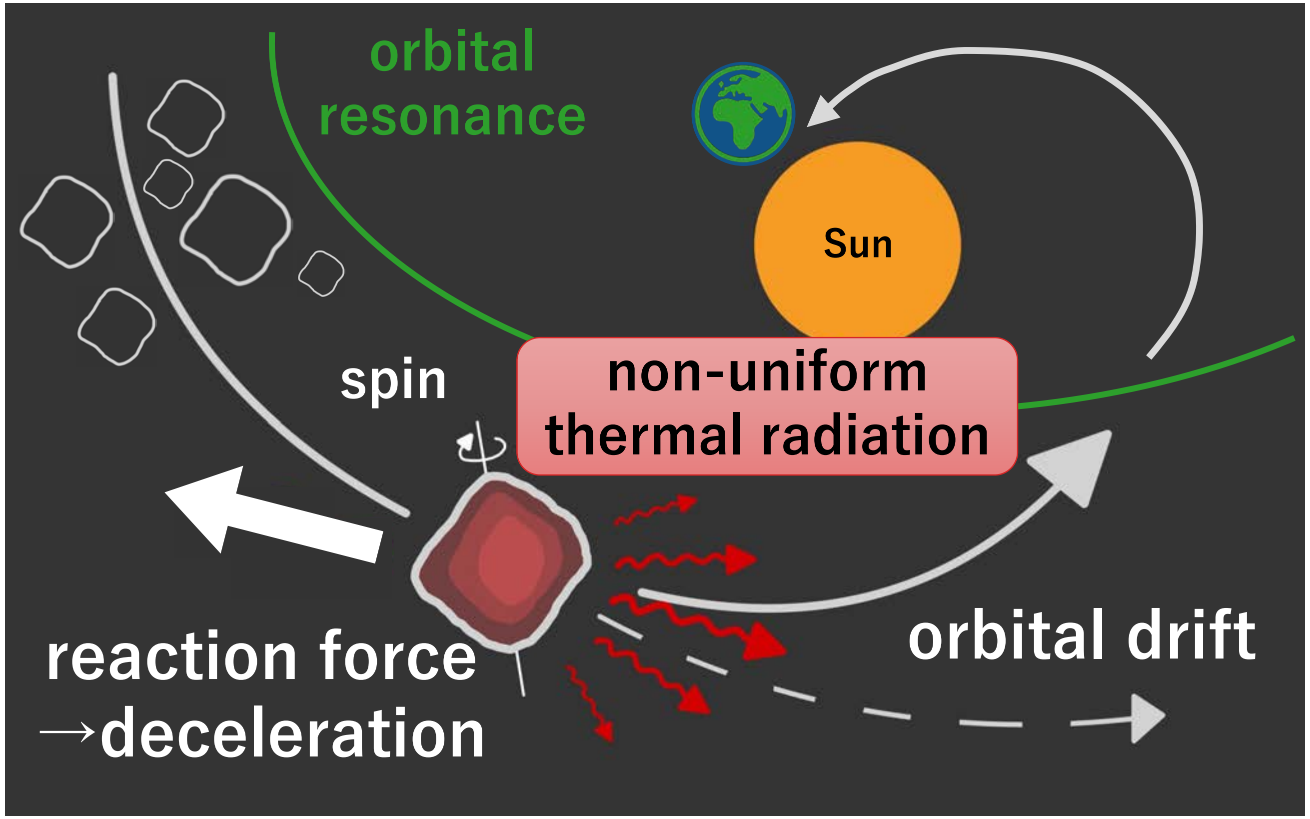
Orbital evolution of asteroids

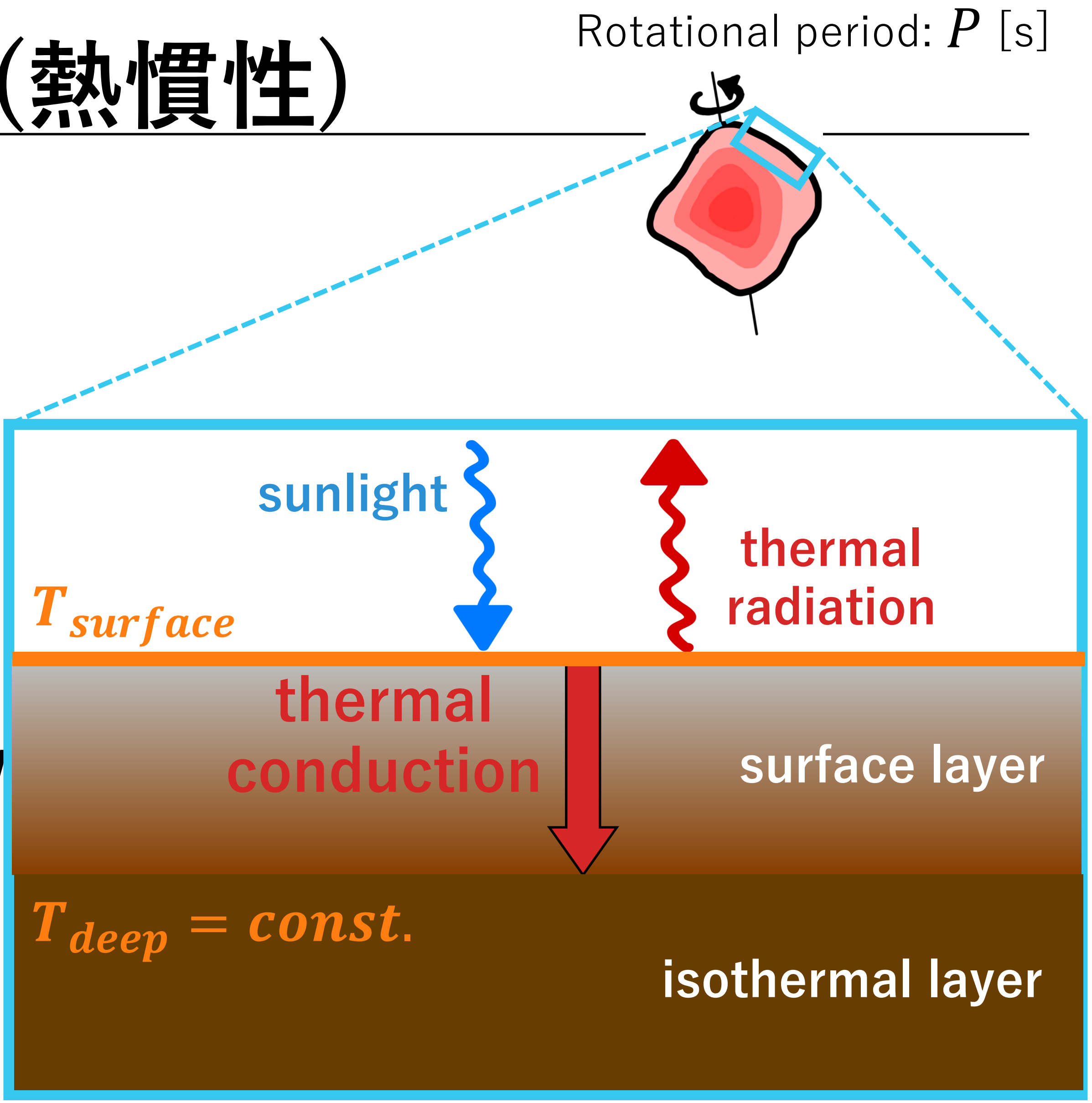
- Asteroids that formed in the main belt and were rich in hydrous minerals delivered water to early Earth. (Peslier+2017)
- The orbital evolution is driven by **Yarkovsky effect.** (Vokrouhlicky 1998)
  - Force caused by non-uniform thermal radiation
- The surface temperature strongly depends on **thermal inertia (熱慣性)**

Main Belt



Thermal Inertia (TI) Γ （熱慣性）

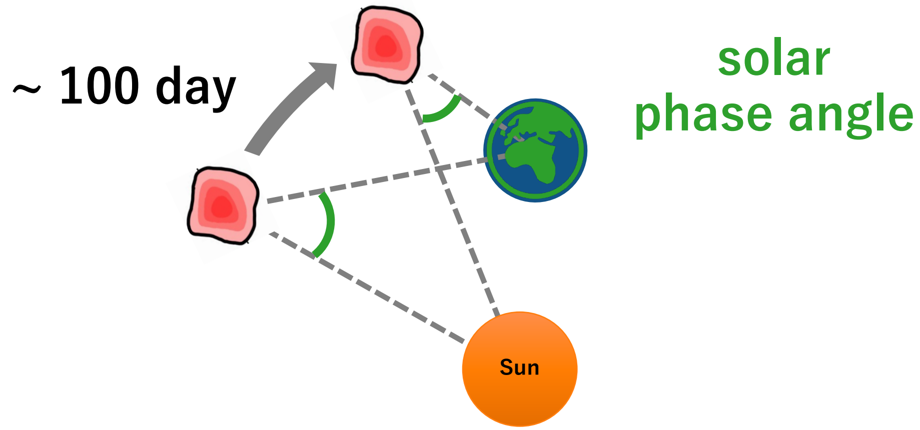
- Definition: $\Gamma = \sqrt{k\rho C_p}$ [tiu]
  - k: thermal conductivity [W/m/K]
  - ρ: bulk density [$\mathrm{kg/m^3}$]
  - C_p: specific heat capacity [J/kg/K]
- Significance
  - **Determine the temperature distribution in the depth direction.**
  - **Large TI causes slow cooling and slow warming.**



Two-layer (simple) model

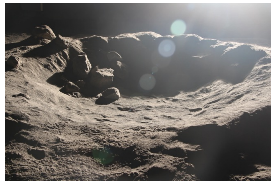
Estimation of TI

- Standard method
  - Based on mid-infrared observations at **multiple solar phase angles.**
    (e.g. MacLennan&Emery2021)

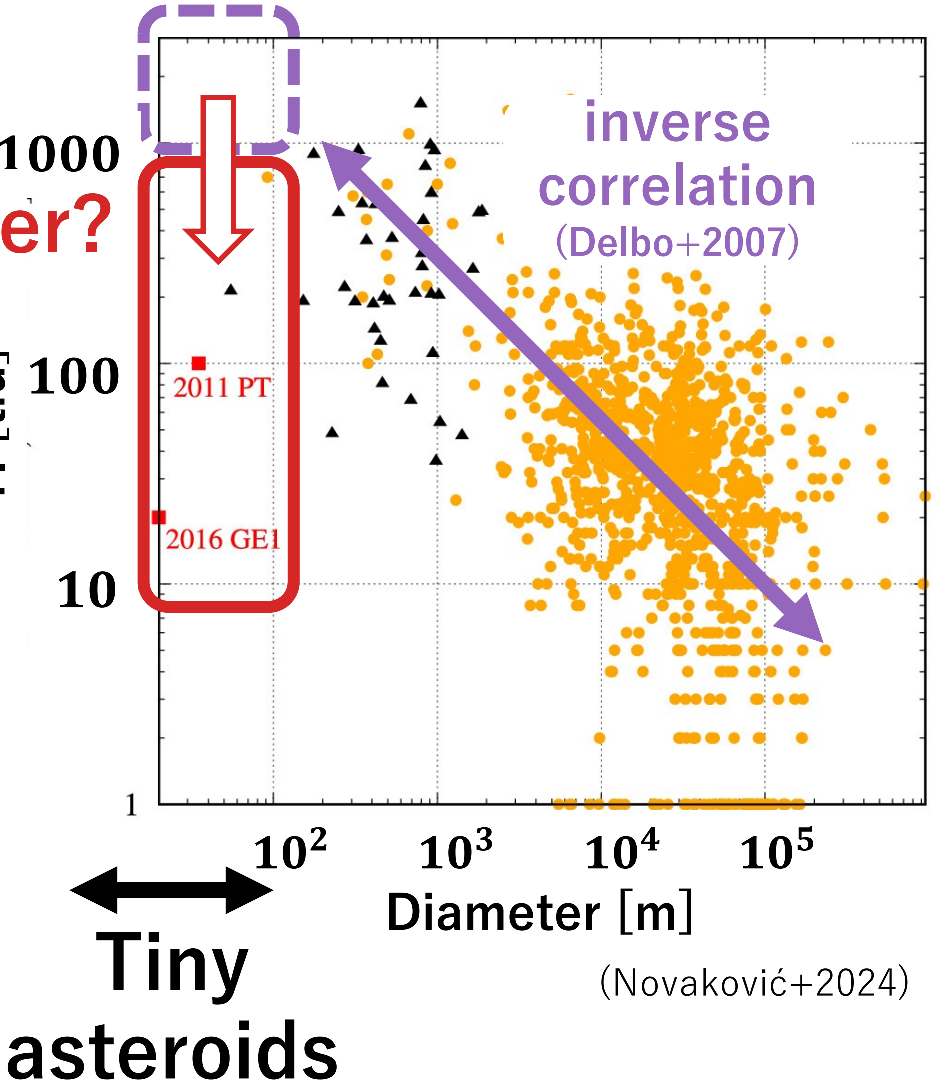


- TI of tiny asteroids (< 100 m)
  - **Estimated for only 4 objects**
  - **Smaller than expected**
    (Novaković+2024)

meteorite
(TI ~ 1000tiu)
©Jim Strope



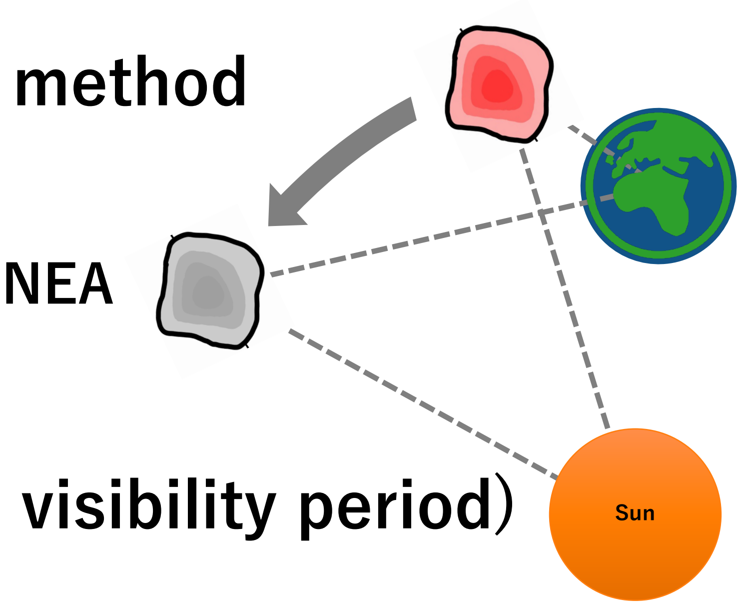
lunar surface
(TI ~ 10tiu)
©NASA



Proposal of a new method to estimate TI

- To estimate TI of tiny asteroids, I focus on Near-Earth Asteroids (NEAs), which are much brighter than Main Belt Asteroids.
- The standard method for TI is difficult to apply to NEAs due to their limited visibility period of only a few days.
- In this study, we developed a new method by **utilizing the dependence of light curves on rotational phase**.

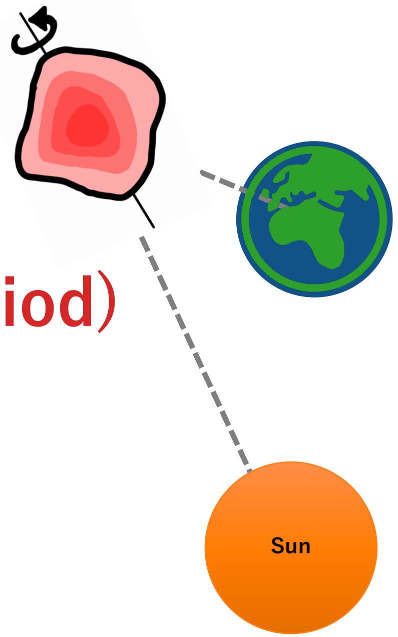
Standard method



~ 100 day
(> limited visibility period)

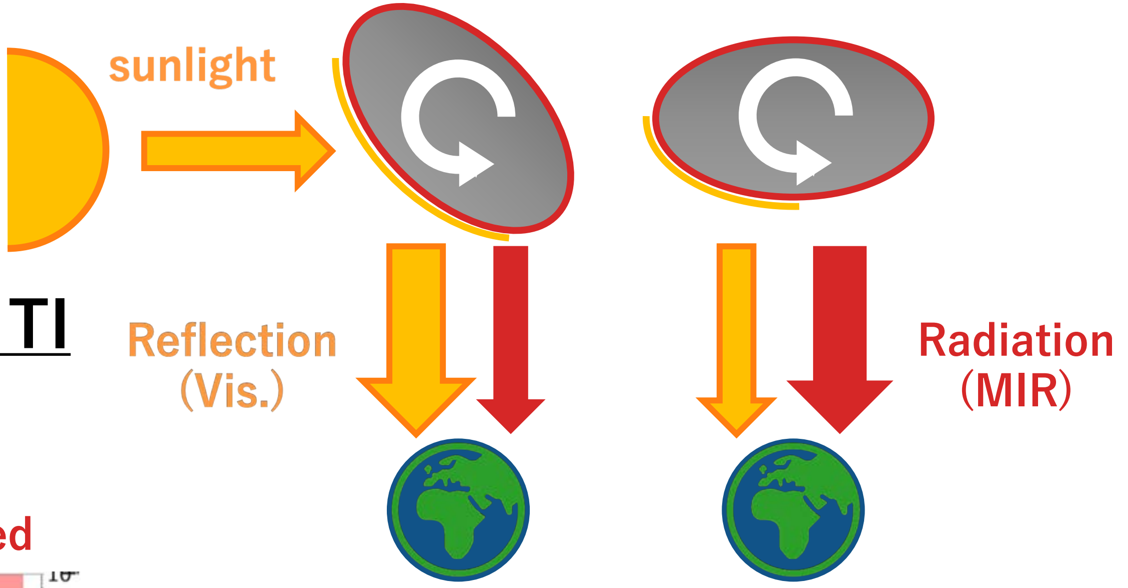
New method

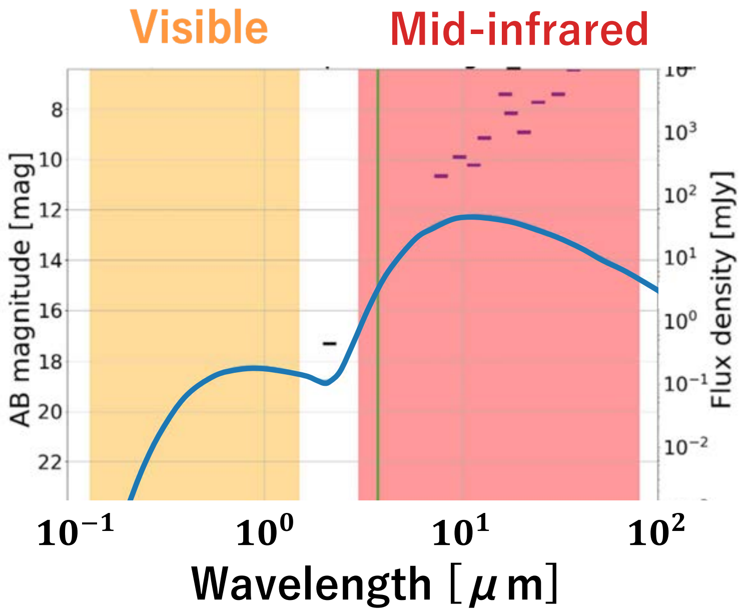
~ 1 day
(< limited visibility period)



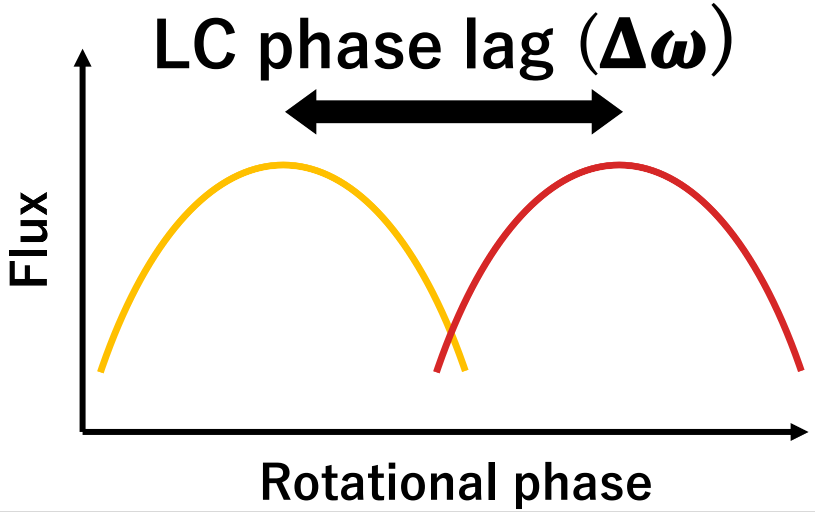
Light curve phase lag method

- Phase lags exist between mid-infrared and visible light curves. (Morrison1976, Harris+2005)
- **Phase lags strongly depend on TI.**
- **<u>We developed a new method to estimate TI by observing phase lags.</u>**





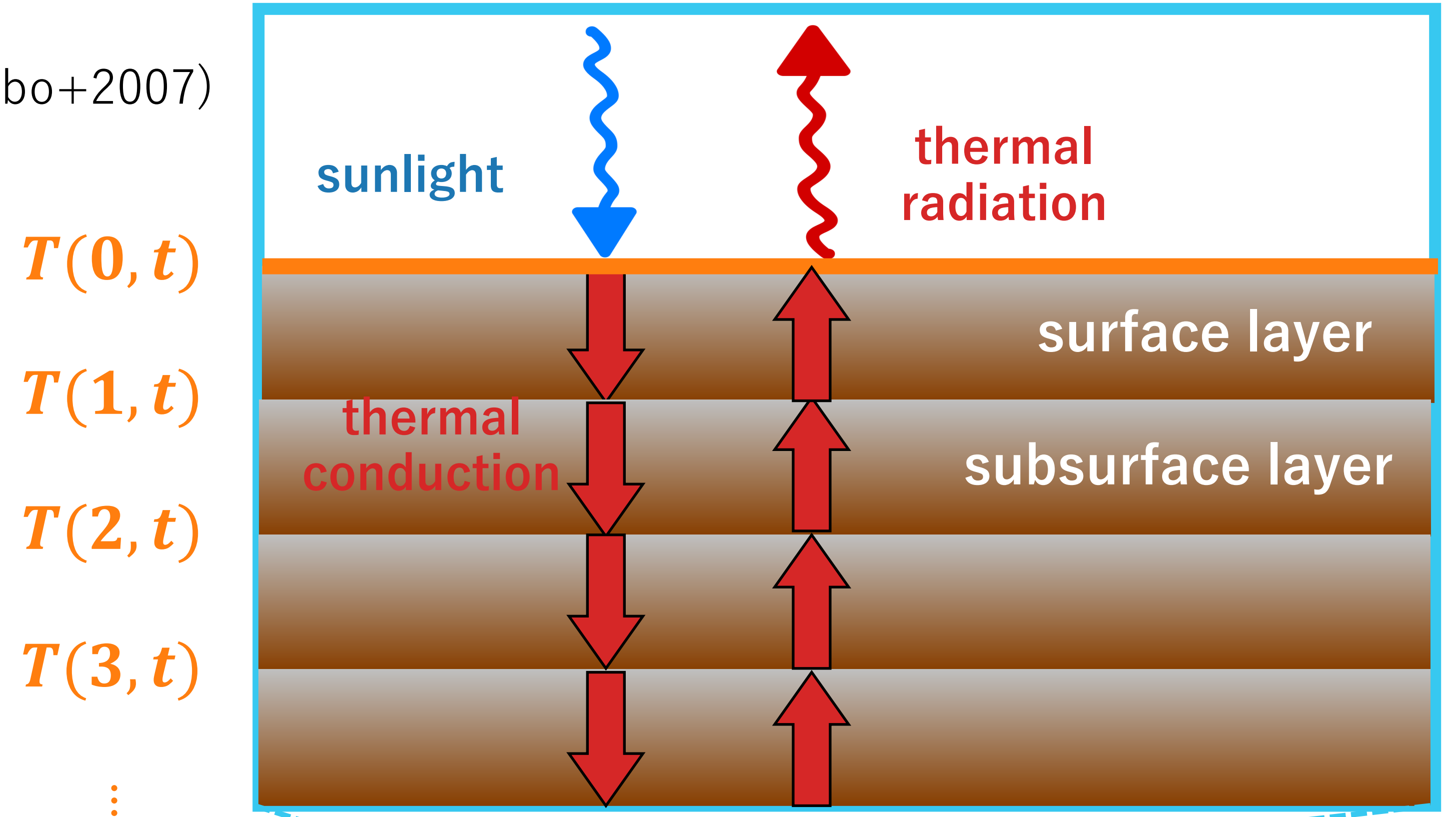
Typical SED of asteroid

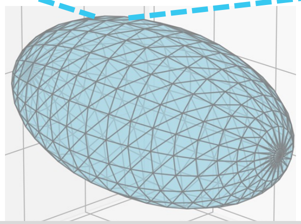


Thermal radiation intensity calculations

- Thermo-Physical Model(TPM) (Delbo+2007)
  - Multiple layer model
  - 1-D calculation (vertical)

Representative parameters
Object model
Rotational period P
Rotational axis
Number of slabs (層数)
TI Γ
Emissivity



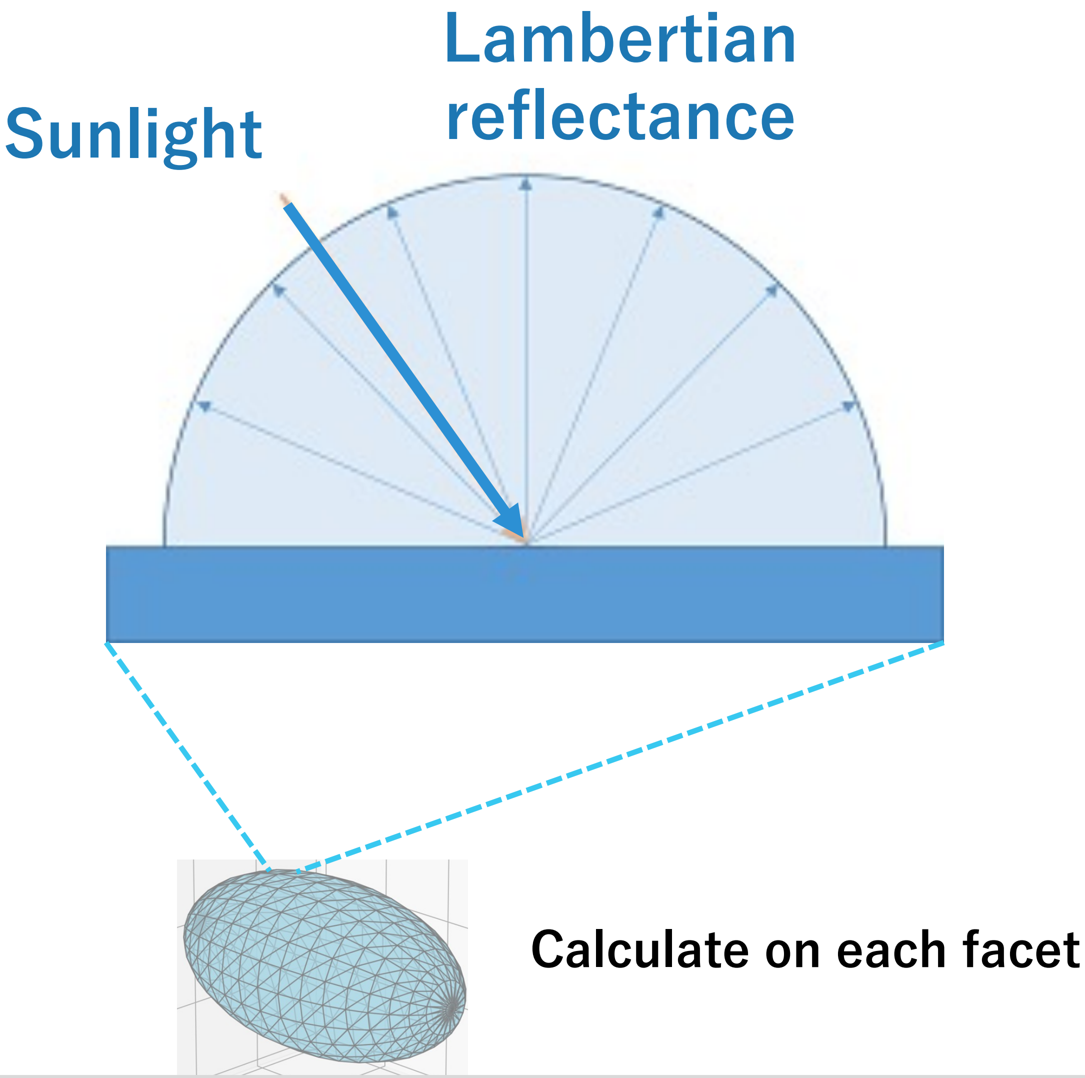


Calculate on each facet

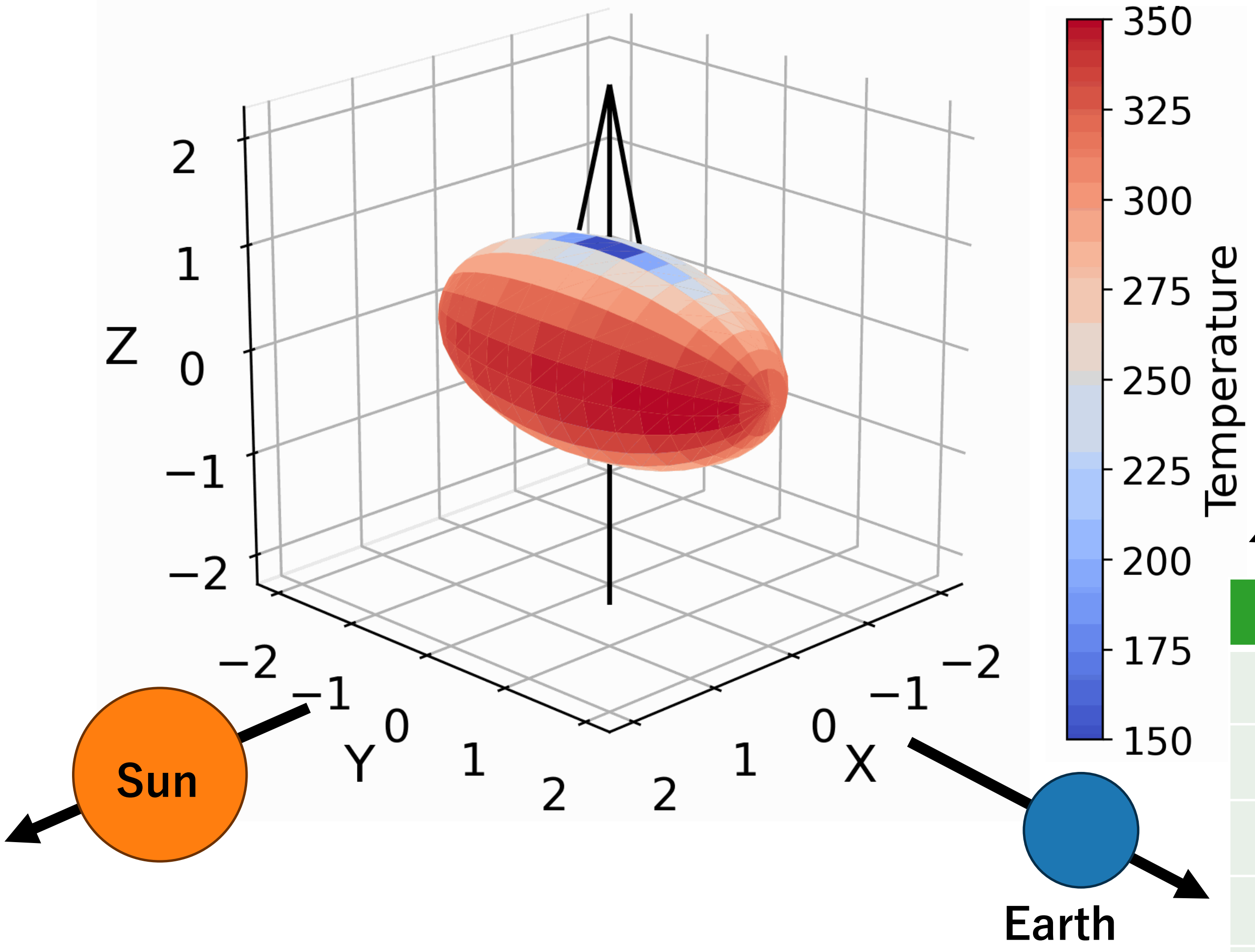
Reflected light intensity calculations

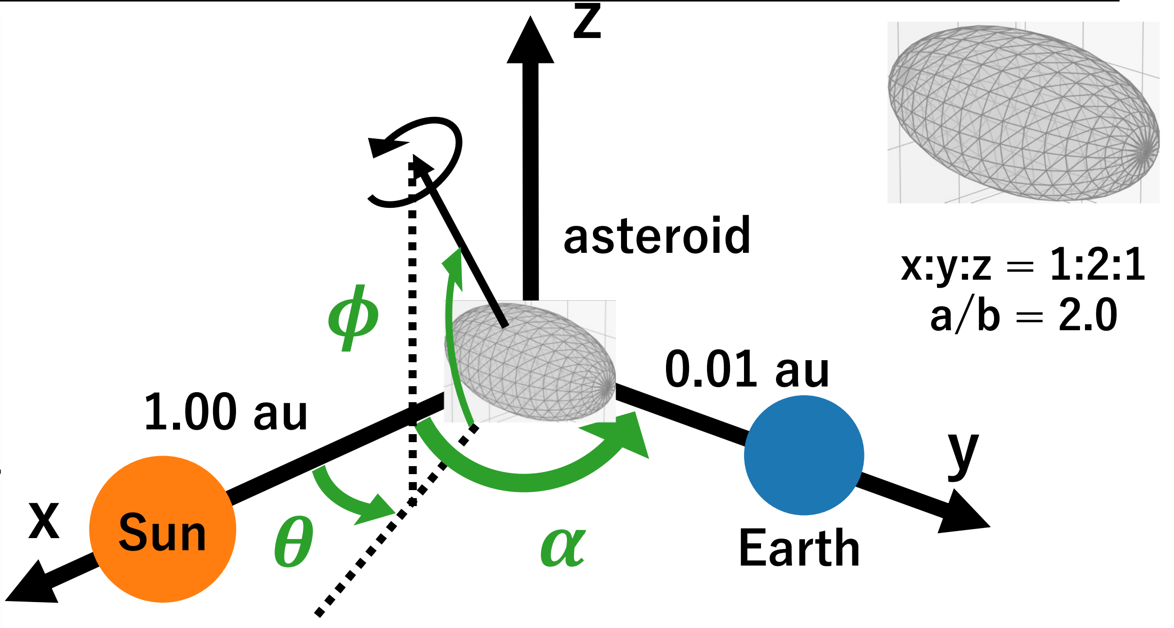
- We developed a simple reflection model.
  - Assuming the Lambertian reflectance

Representative parameters
Object model
Rotational period P
Emissivity
Solar phase angle α



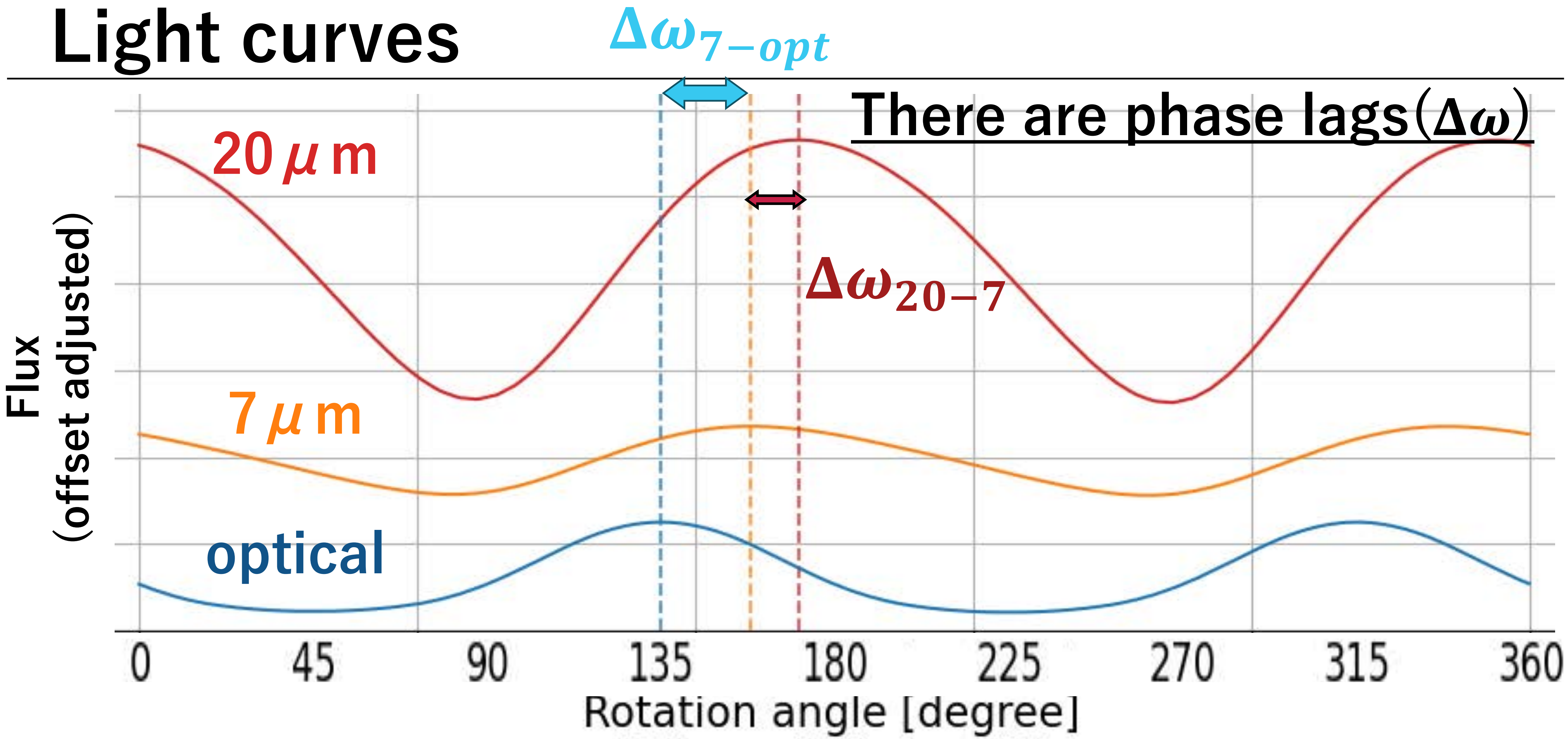
Surface temperature distributions





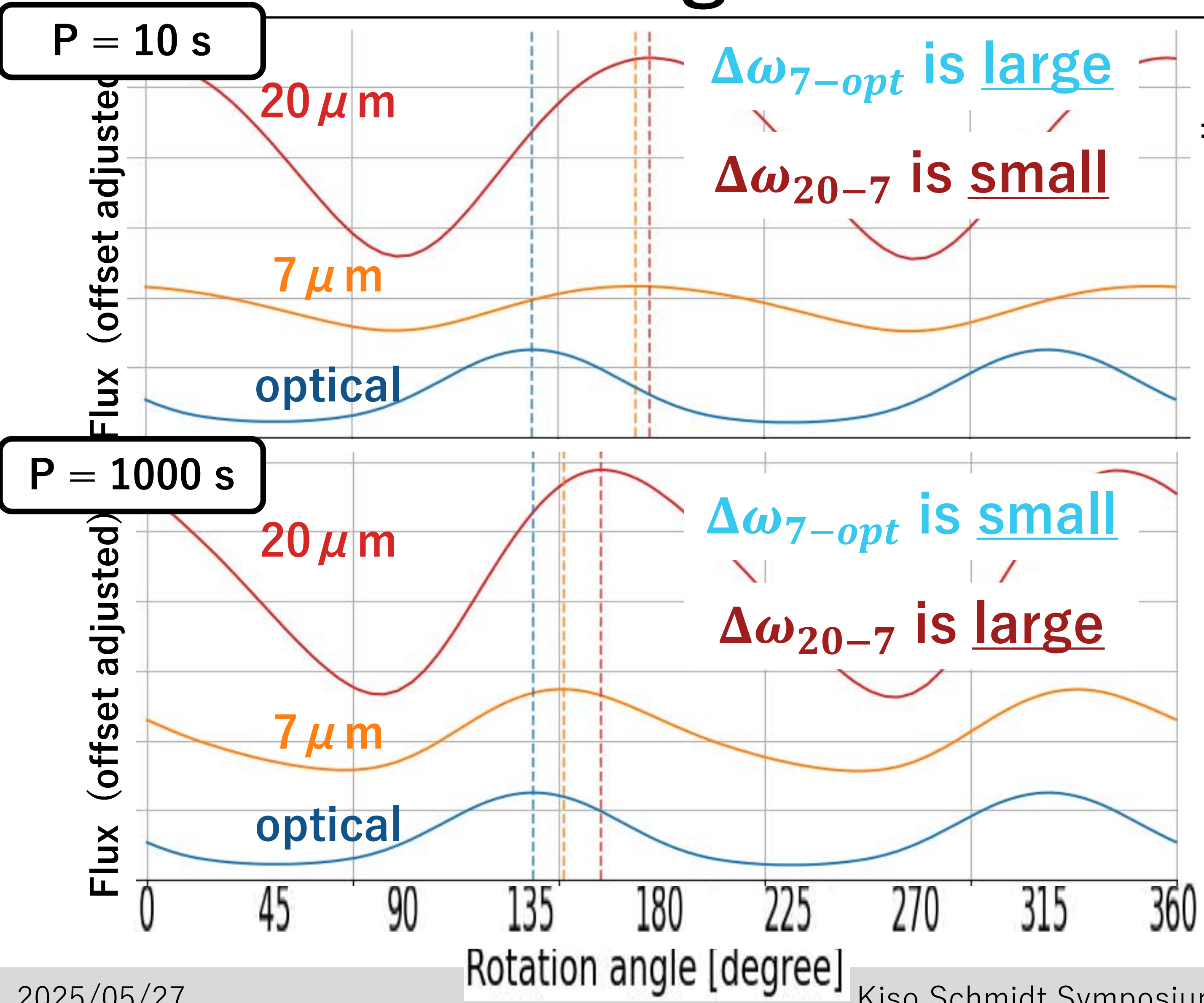
Parameters	Values
Rotational period P	100 s
Rotational axis (θ, ϕ)	$(0°, 90°)$
Thermal Inertia, TI Γ	100 tiu
Axis ratio a/b	2.0
Solar phase angle α	90°

Light curves



$P, \theta, \phi, \Gamma, a/b, \alpha = 100\ \mathrm{s}, 90°, 90°, 100\ \mathrm{tiu}, 2.0, 90°$

Variations in light curves



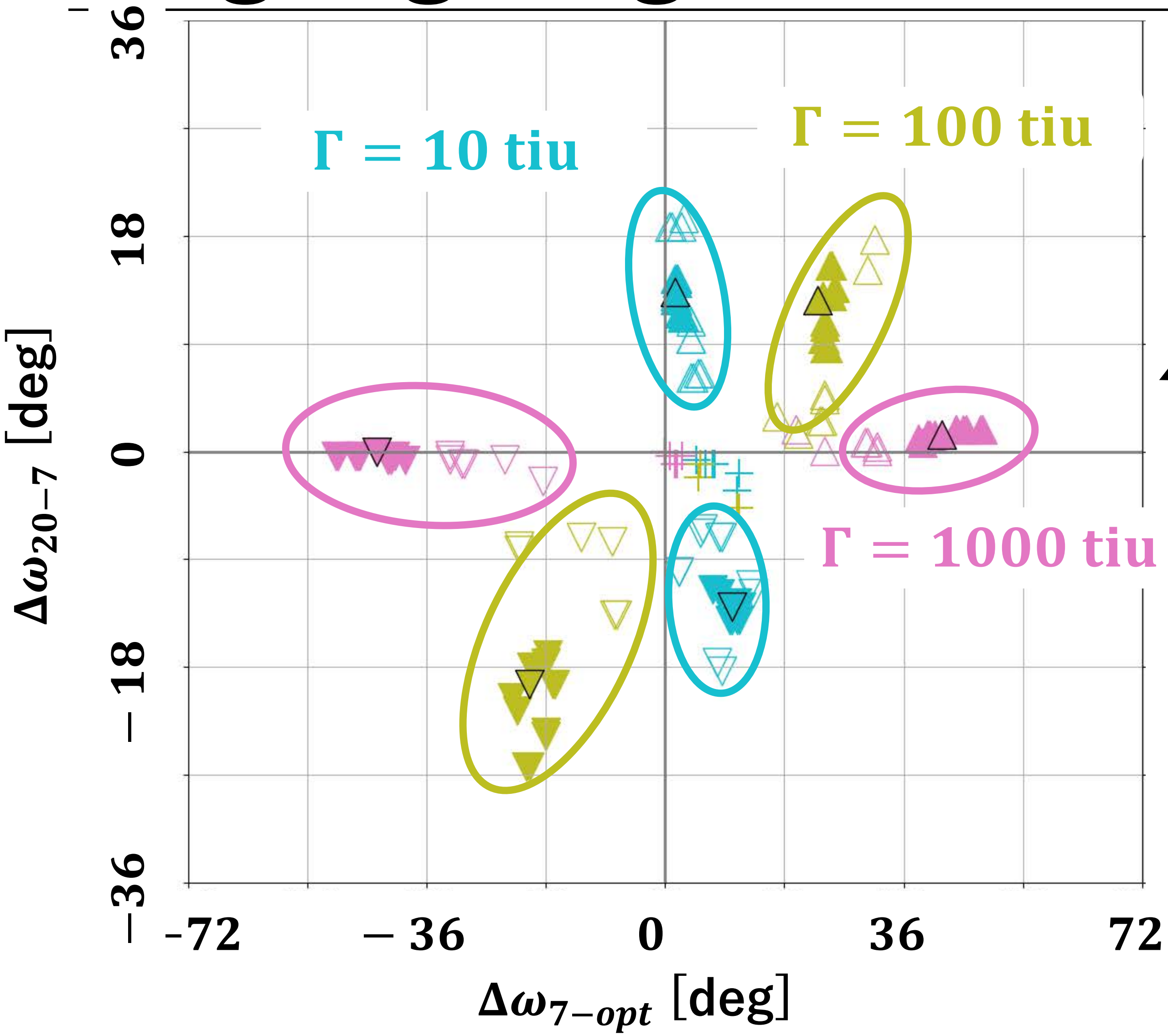
$P, \theta, \phi, \Gamma, a/b, \alpha = 10\ \mathrm{s}, 90°, 90°, 100\ \mathrm{tiu}, 2.0, 90°$

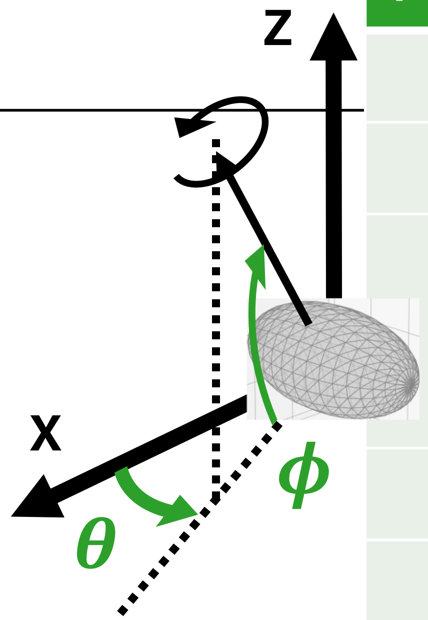
Calculated for all combinations.

Parameters	Values
P	$[10, 100, 1000]$ s
θ	$[-150°, -120°, \ldots, 180°]$
ϕ	$[-90°, -60°, \ldots, 90°]$
Γ	$[10, 100, 1000]$ tiu
a/b	$[1.5, 2.0, 3.0]$
α	$[0°, 30°, 60°, 90°, 120°]$

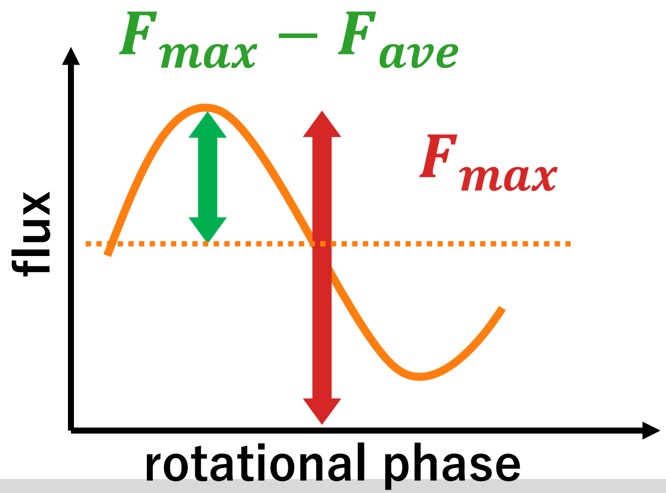
$P, \theta, \phi, \Gamma, a/b, \alpha = 1000\ \mathrm{s}, 90°, 90°, 100\ \mathrm{tiu}, 2.0, 90°$

Lag-lag diagram



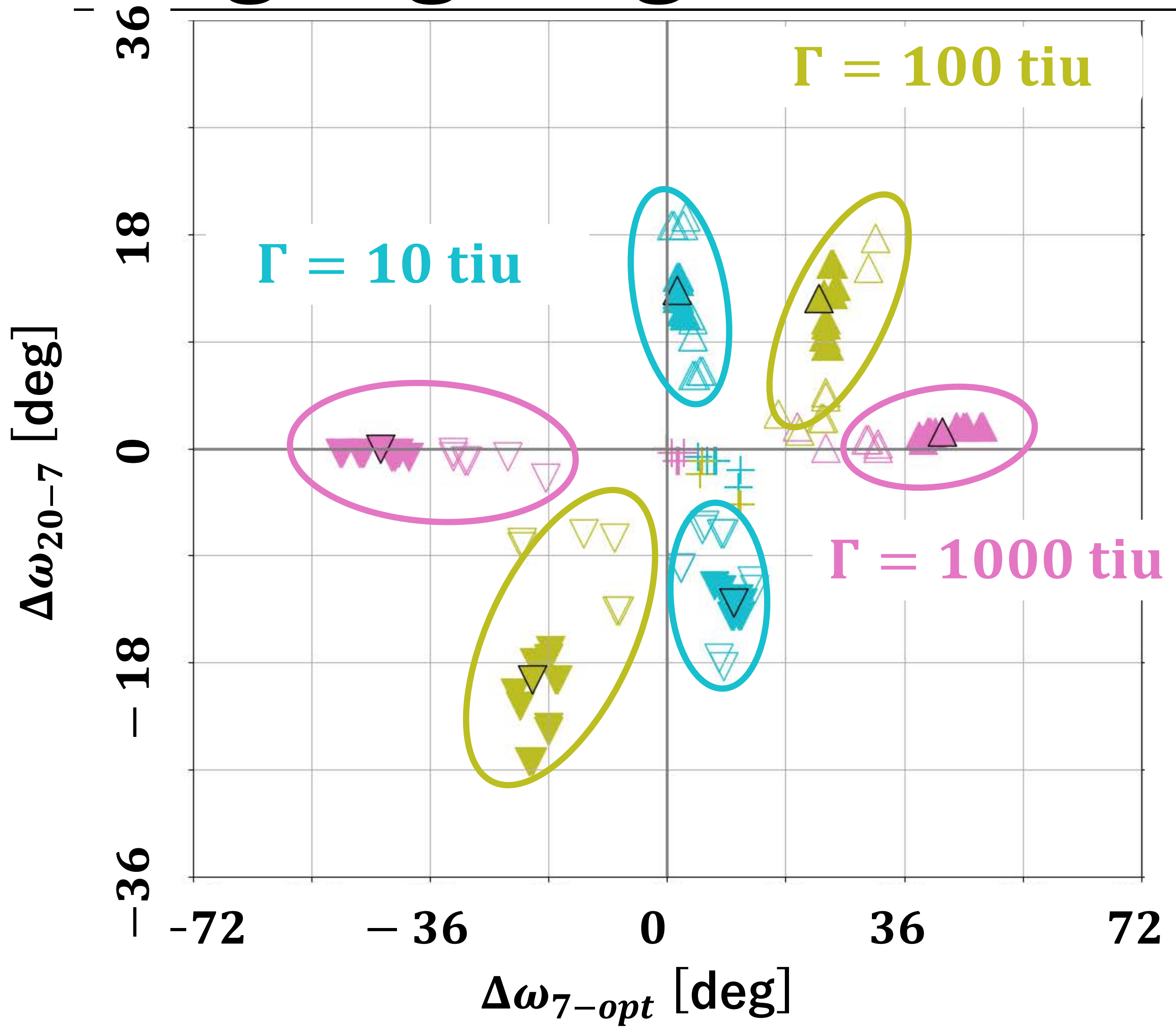


Parameters	Values
P	100 s
θ	$[-150°, -120°, \ldots, 180°]$
ϕ	$[0°, \pm30°, \pm60°, \pm90°]$
Γ	$[10, 100, 1000]$ tiu
a/b	2.0
α	90°

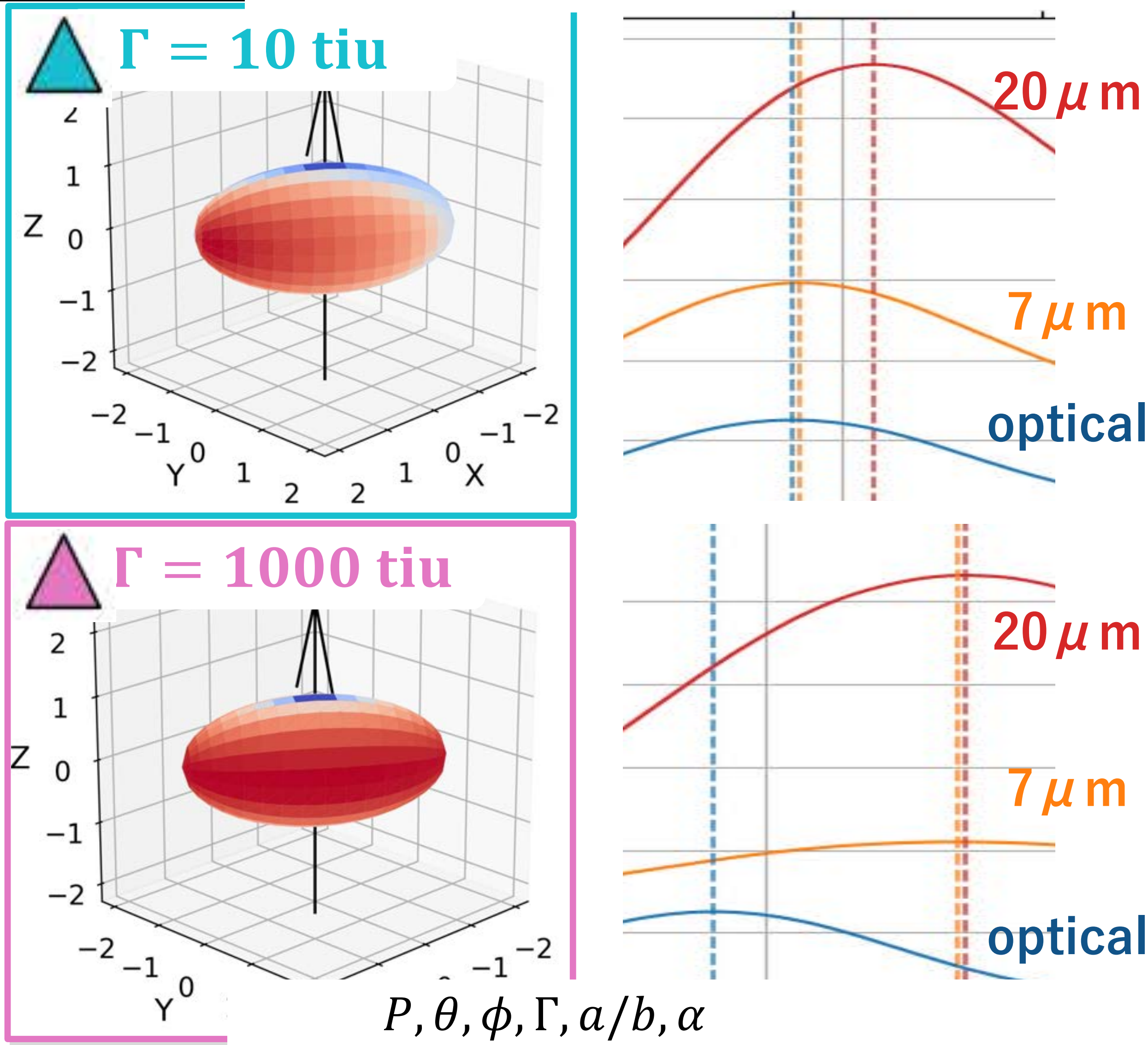


$$\textit{Amplitude} = \frac{F_{max} - F_{ave}}{F_{max}} \geq 0.1$$

Lag-lag diagram

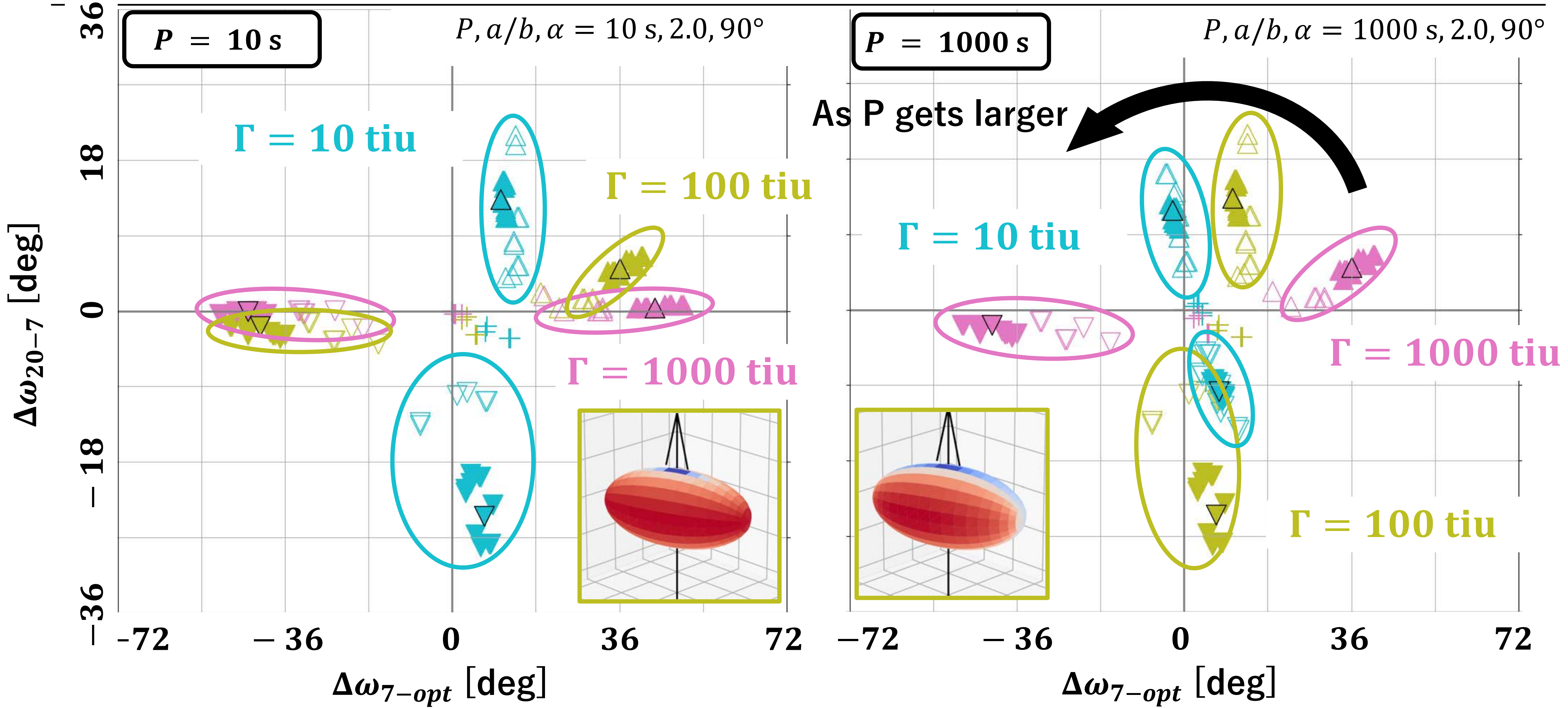


$P, \theta, \phi, \Gamma, a/b, \alpha$
$= 100\ \mathrm{s}, 90°, 90°, 10\ \mathrm{tiu}, 2.0, 90°$

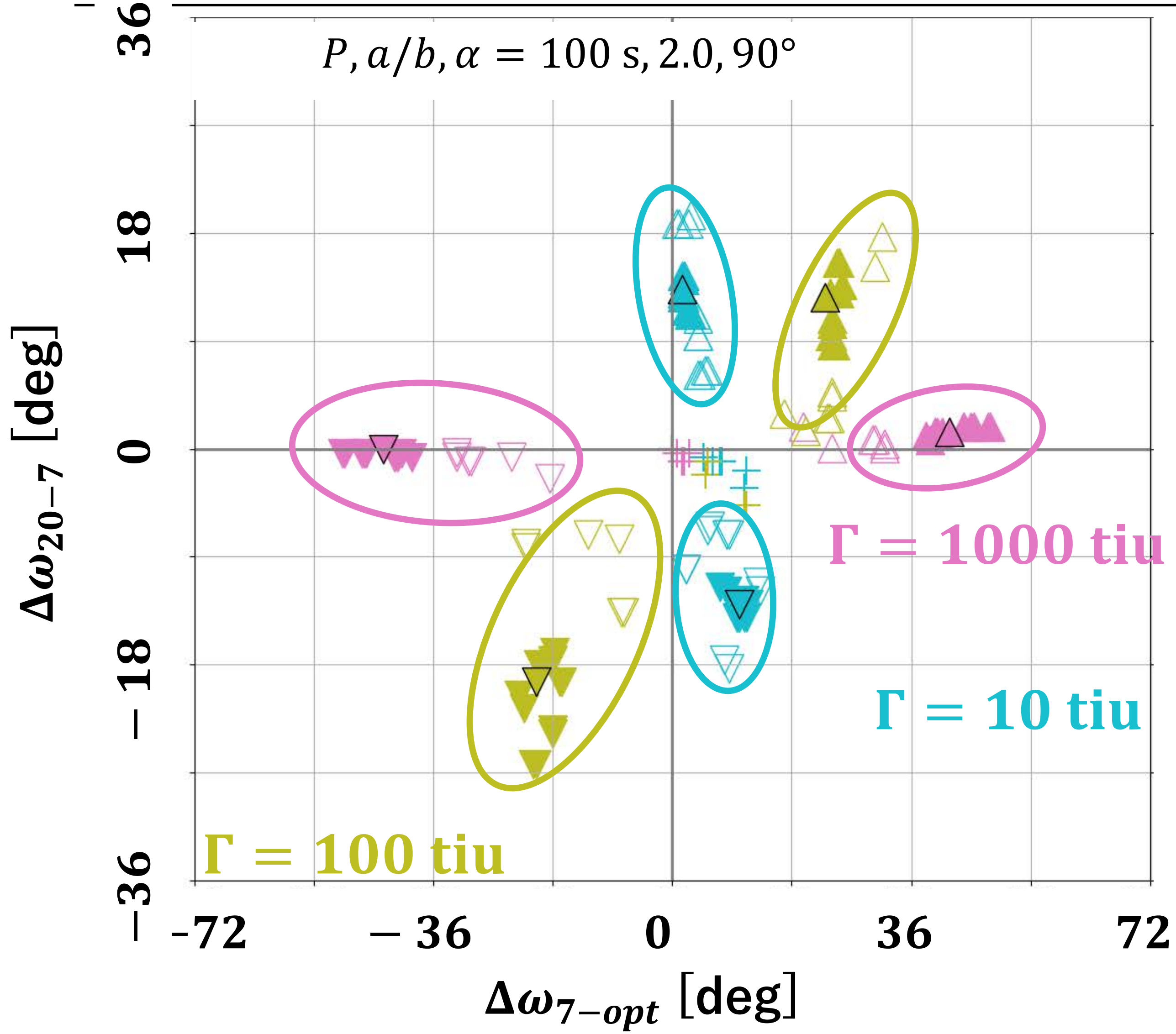


$P, \theta, \phi, \Gamma, a/b, \alpha$
$= 100\ \mathrm{s}, 90°, 90°, 1000\ \mathrm{tiu}, 2.0, 90°$

Variations in lag-lag diagrams (rotational period P)



Estimation of TI with lag-lag diagram



- The distribution strongly depends on TI.
- The distribution is clearly distinguishable TI.
- Additionally, we can distinguish the rotational direction.

We can estimate TI on this diagram.

Observation strategy

1. Detection and orbit determination (α)
   - CSS, Pan-STARRS, ZTF, Tomo-e Gozen, etc.
2. Derivation of $\mathrm{P}, a/b$
   - Follow-up observation by Tomo-e Gozen
3. Derivation of $\Delta\omega$
   - Observe light curves
     - Optical by Tomo-e Gozen
     - MIR with TAO 6.5m
4. Estimation of Γ
   - Compare derived and simulated $\Delta\omega$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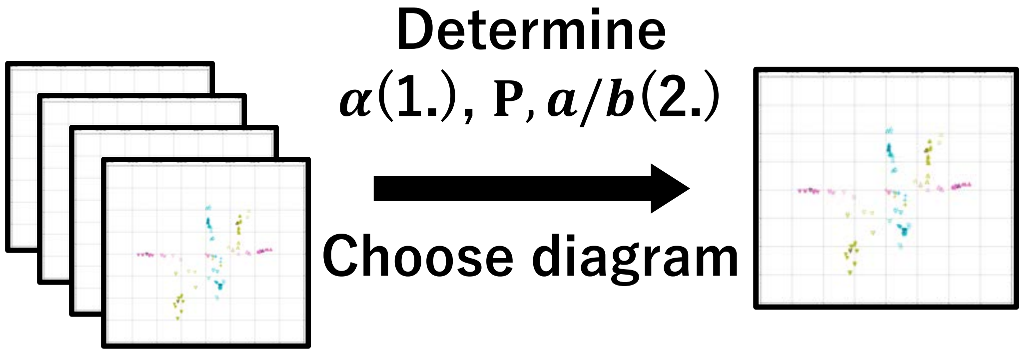
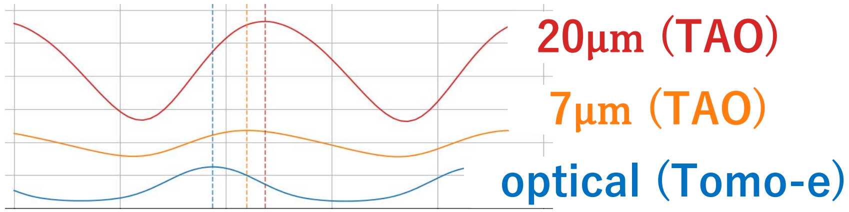
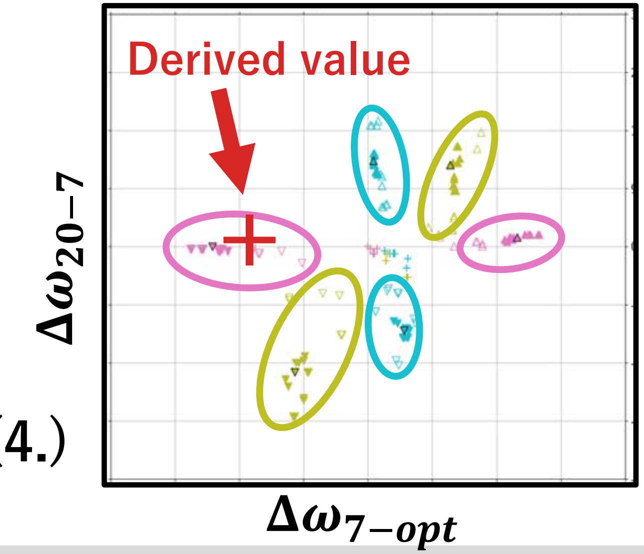


Derivate $\Delta\omega_{7-opt}$ and $\Delta\omega_{20-7}$ (3.)



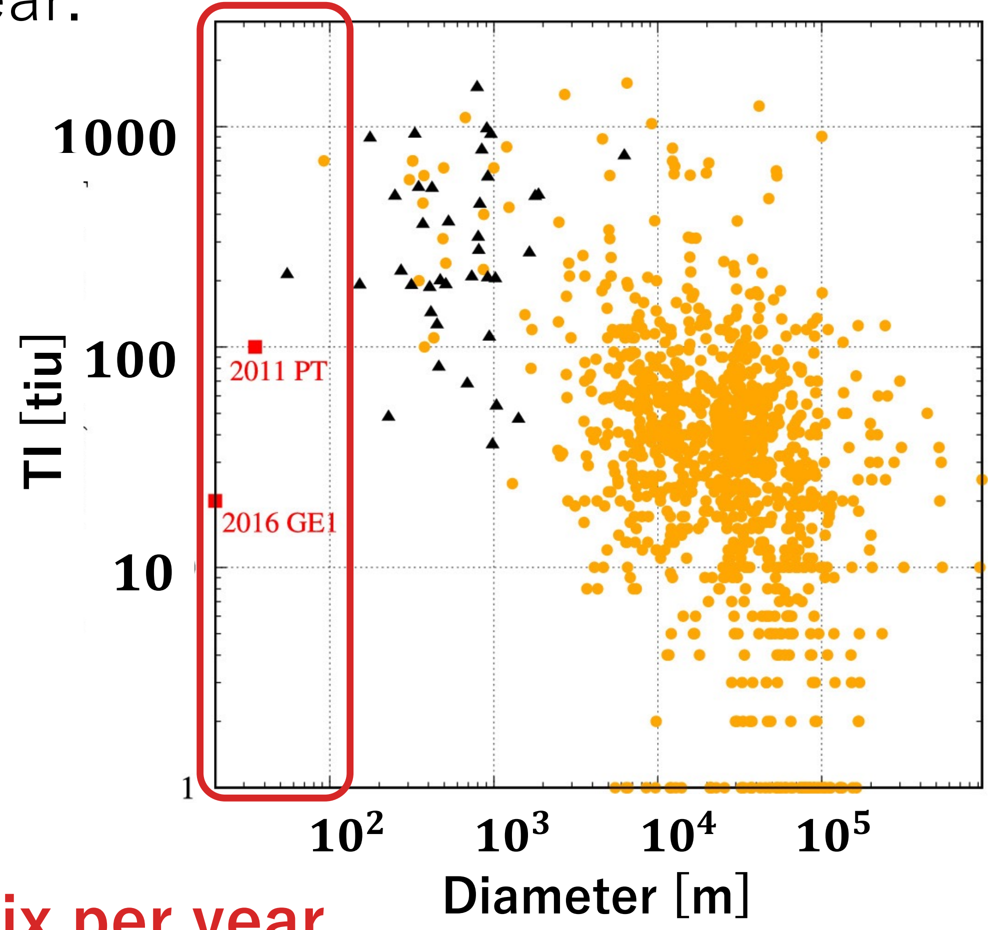
Estimate TI (4.)



Expected outcomes

We can estimate **more than six** TI values per year.

- ~ 30: Limitation by equipment
  - Has an observable rotational period
    (Counted from LCDB Updated Oct. 2023 (Warner et al. (2009)))
    - $P \geq 10$ s: The rotational phase is derivable
    - $P \leq 1000$ s: The observation finishes in 30 minutes
- x 1/3: Limitation by observational conditions
  - Enables observation from both Kiso and TAO sites
- x 3/5 (at least): Limitation by rotational axis
  - Has enough amplitude of light curves



More than six per year

(Novaković+2024)

Summary

- It is difficult to estimate thermal inertia of tiny asteroids, which are responsible for the origin of water to the Earth, by the standard methods.
- **We have developed a new method to enable estimation of thermal inertia of tiny Near-Earth Asteroids**.
- Thermal inertia can be estimated utilizing a lag-lag diagram.
- We can realize the method by Tomo-e Gozen and with TAO.