NeD 2019

Rotational Properties of Asteroids

Daniela Lazzaro, Takeshi Kodama
Hissa Medeiros, Elvis Soares, Carlos Aguiar, Tomoi Koide

Observatório Nacional
INCT-FNA
INSTITUTO NACIONAL DE CIÊNCIA E TECNOLOGIA FÍSICA NUCLEAR E APLICAÇÕES
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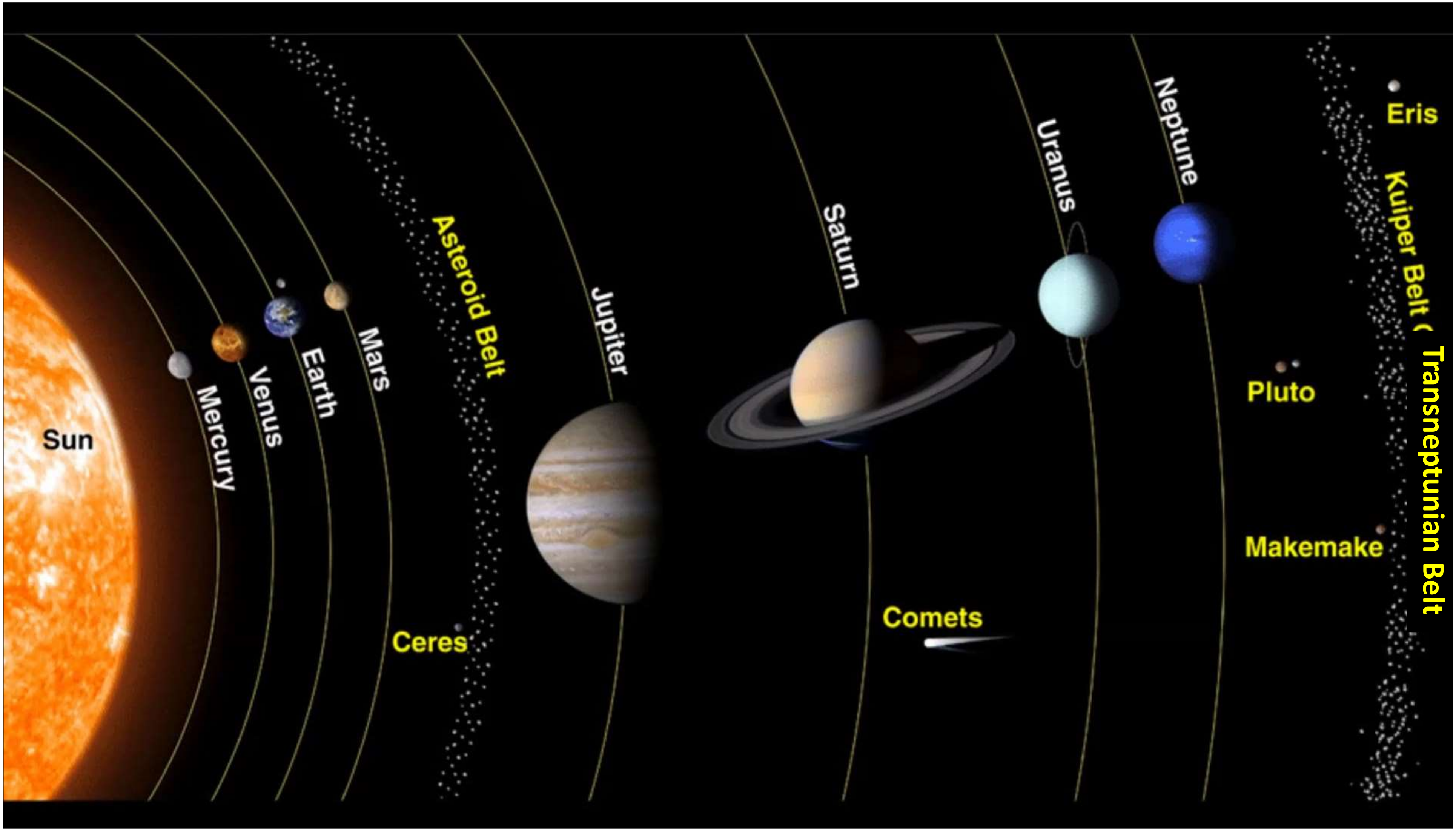
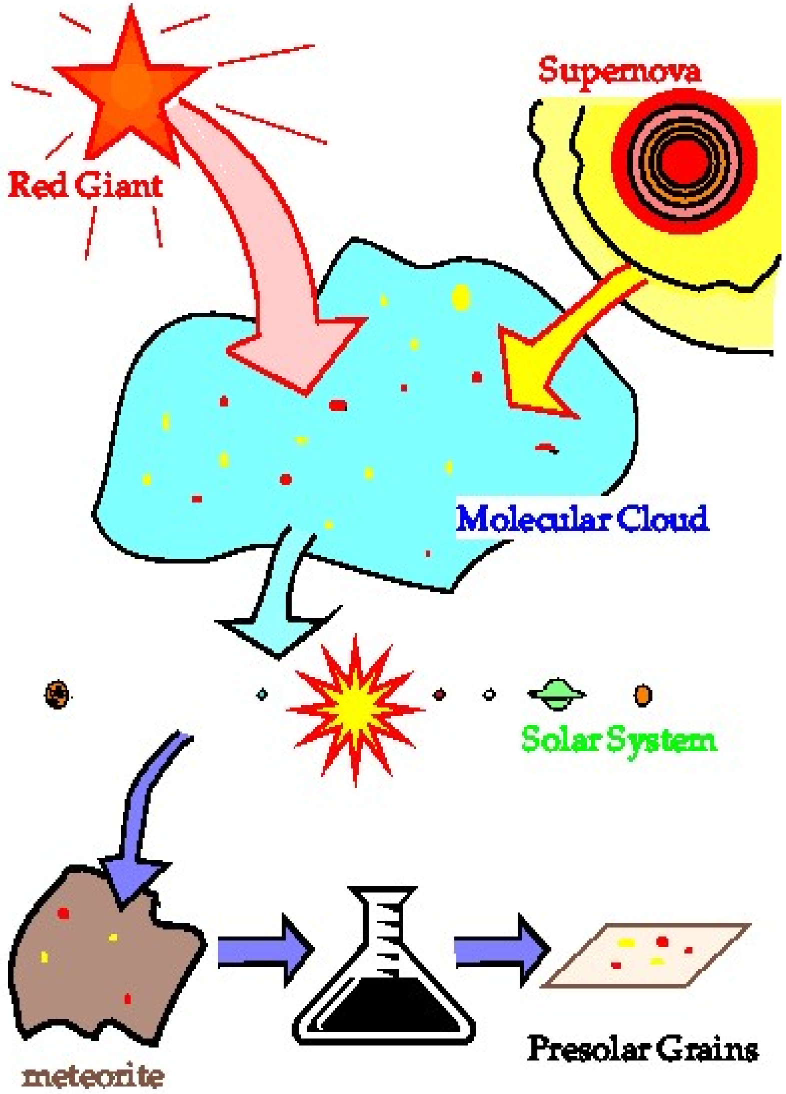
UFRJ

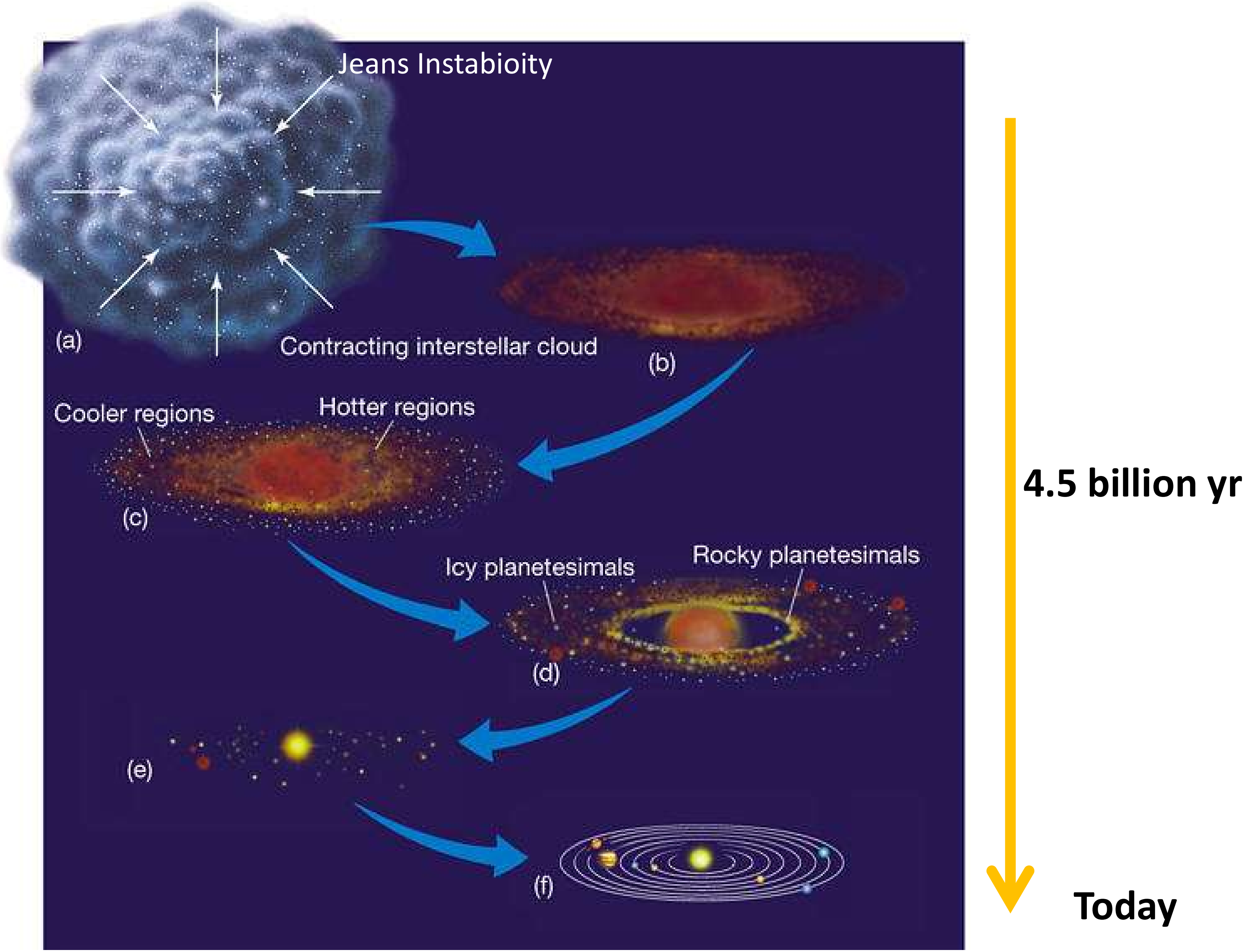
The Solar System



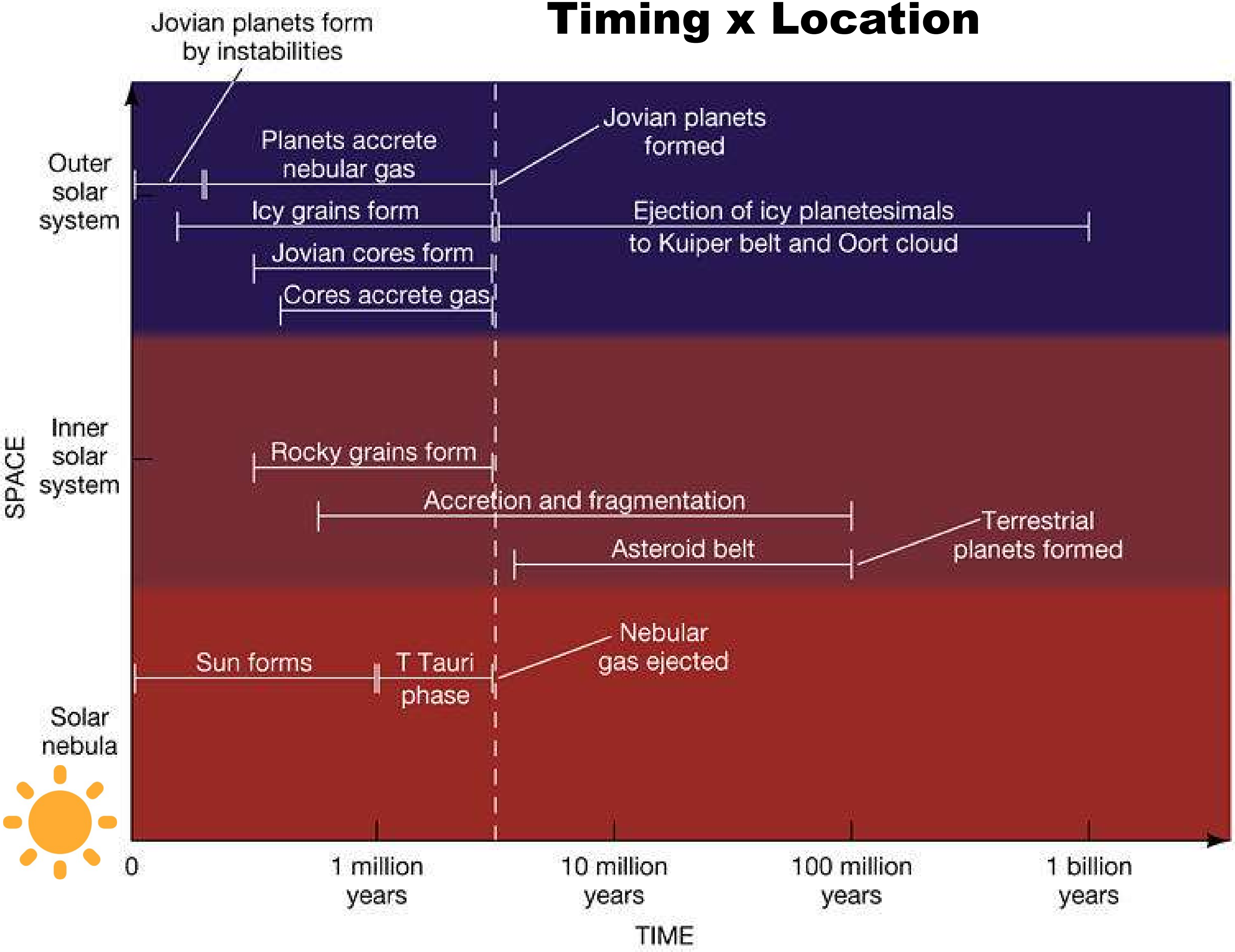
Origin of the Solar System

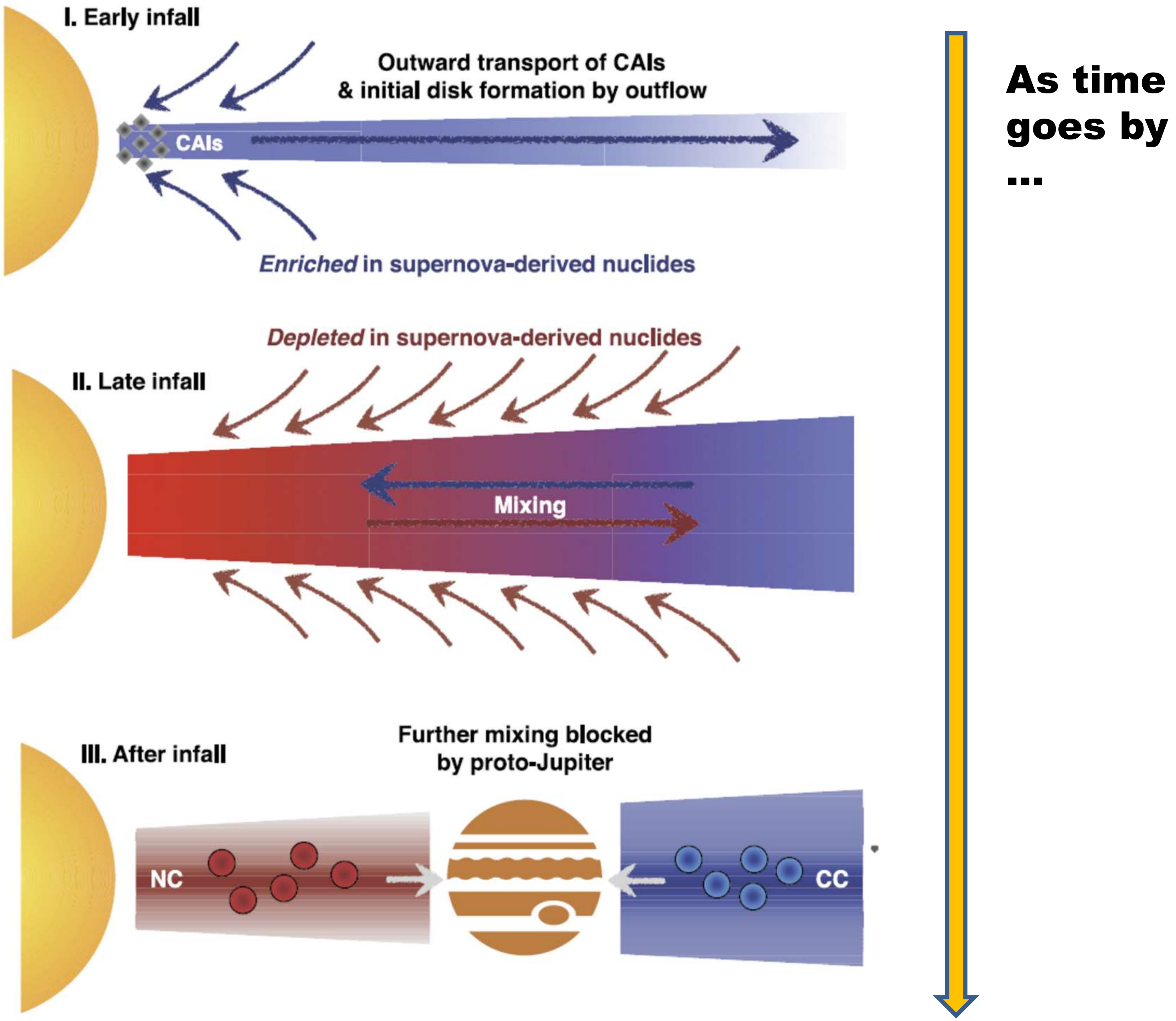
- Elements are synthesized in the interiors of stars
- Upon ejection into interstellar space from dying stars, some elements condense into dust grains (presolar grains) and amorphous dust, either in stellar atmospheres or in interstellar space
- Gas and dust collect into giant, cold molecular clouds
- Dense cores collapse into stars, such as the Sun
- Planets, asteroids and comets are formed
- Fragments of asteroids fall on Earth as meteorites (which carry information of the solar system formation)




Jeans Instabioity
(a)
Contracting interstellar cloud
(b)
Cooler regions
Hotter regions
(c)
Icy planetesimals
Rocky planetesimals
(d)
(e)
(f)
4.5 billion yr
Today

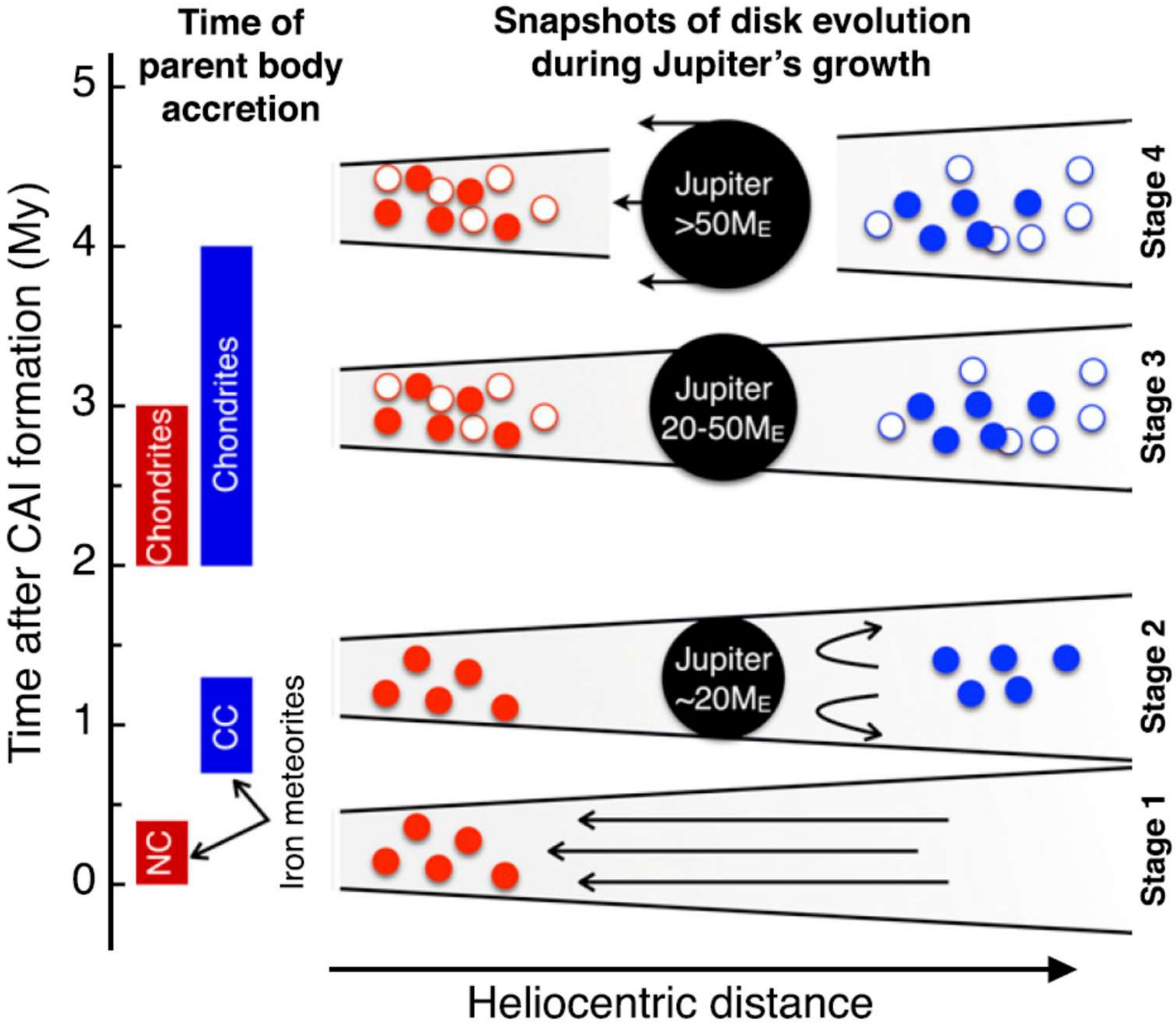
Timing x Location





Nanne et al. 2017

CAI = Calcium+Alminium Inclusion, NC=NonCondrites, CC=Condrite Carbonacios



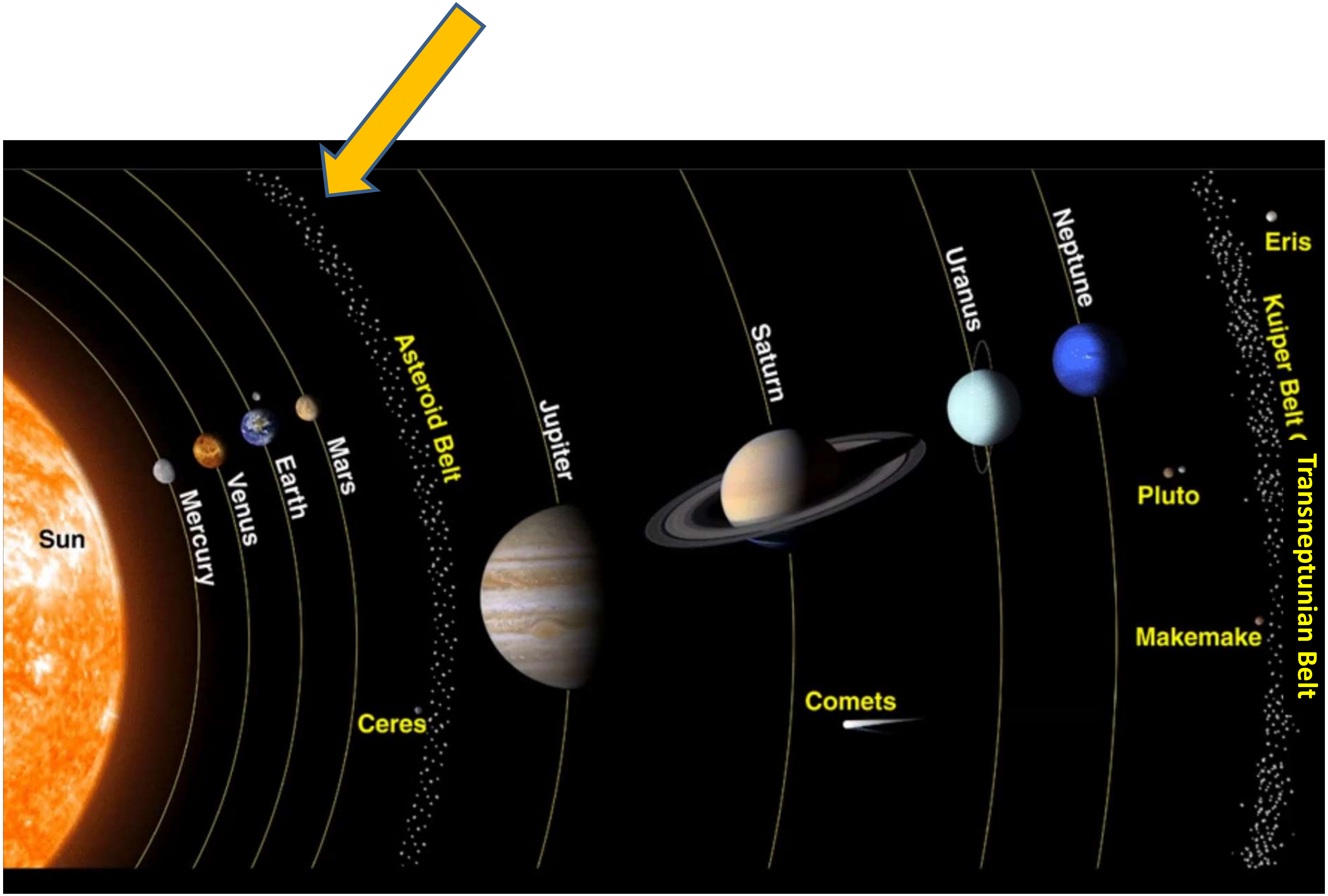
Kruijer et al. 2017

Time Evolution of the Solar System?

<u>One Event</u> !

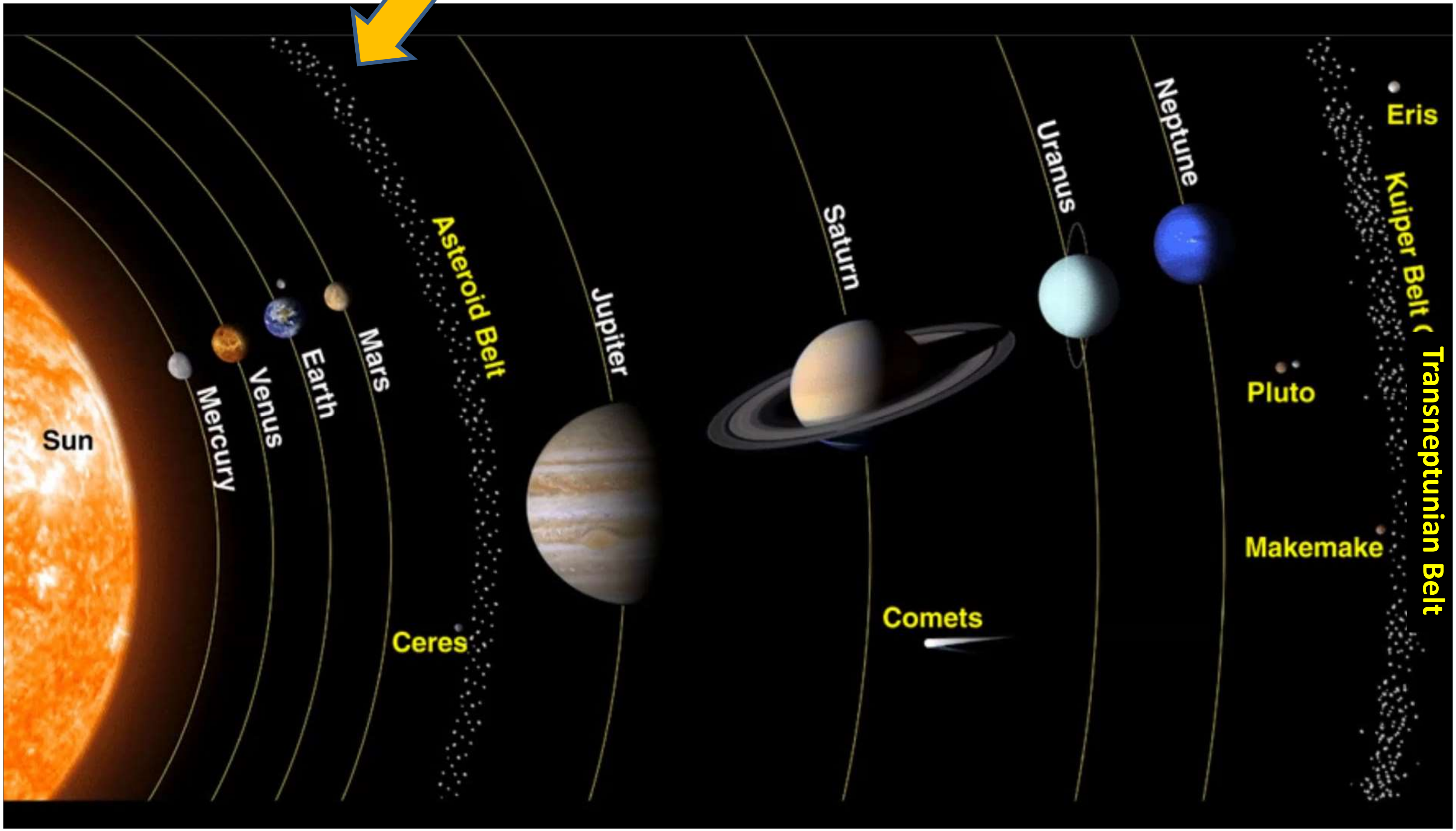
But....

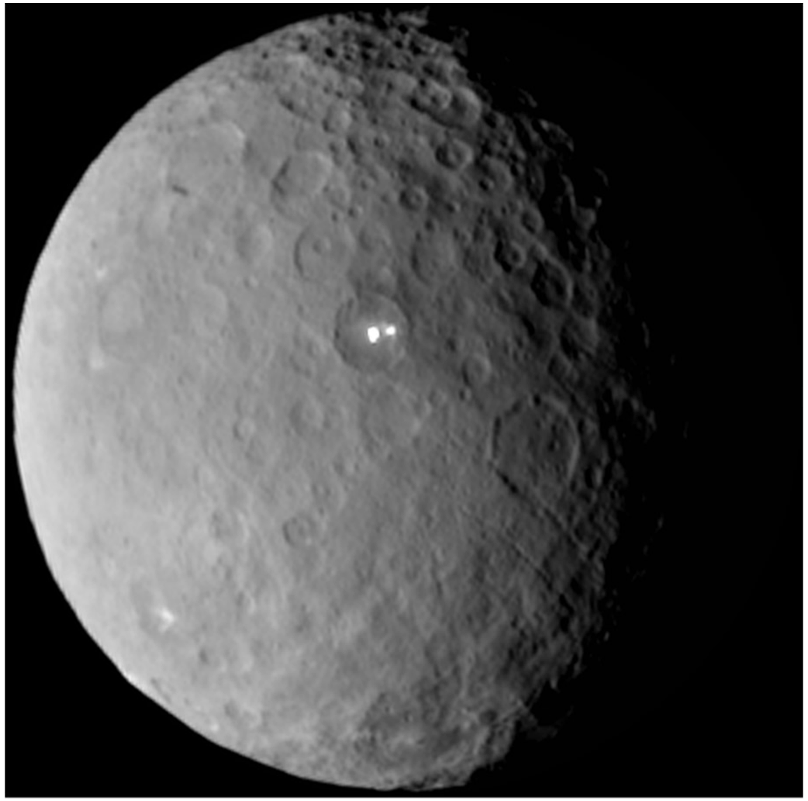
Lots of Asteroids



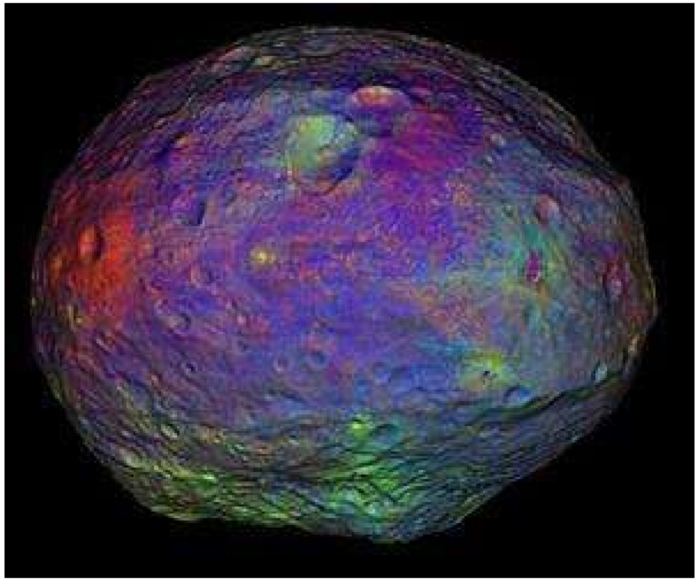
Lots of Asteroids

left-over Solar System formation

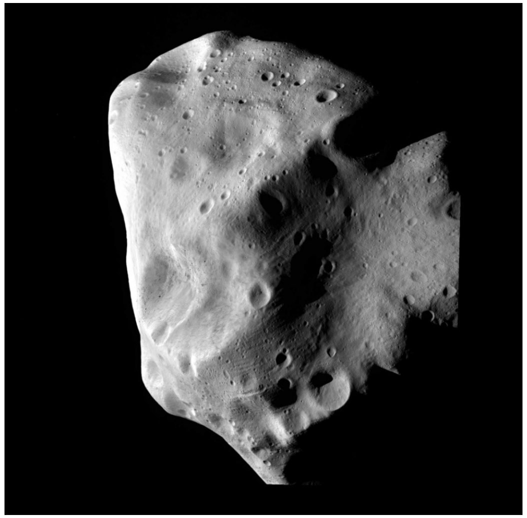




1 Ceres
~950km



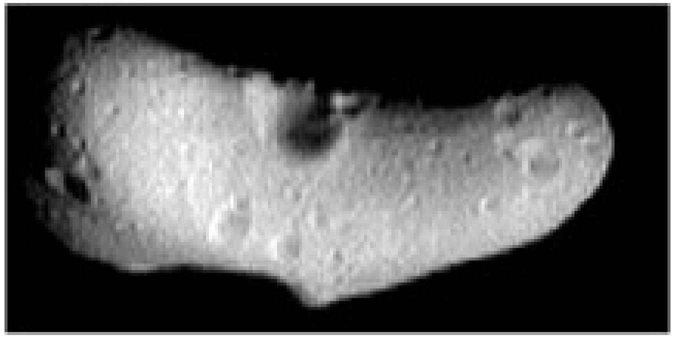
4 Vesta
~520km



21 Lutetia
121 x 101 x 75 km

253 Mathilde
59 x 47 km

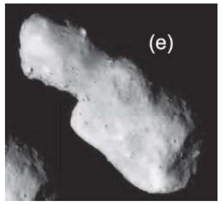
243 Ida
56 x 24 x 21 km



221 Eros - 33 x 13 x 13 km

951 Gaspra – 19 x 12 x 11 km

2867 Steins
6.8 x 5.7 x 4.4 km



4179 Toutatis
4.75 x 1.95 km

25143 Itokawa
0.6 x 0.3 x 0.2 km

Itokawa 0.6 x 0.3 x 0.2 km

By Hayabusa 1

Some Important Questions

- Formation & Evolution
  - Are the present asteroids primordial bodies?
    - how to explain the excitation of their orbits?
  - Are they the result of intense collisional evolution?
    - what the fraction of primordial bodies?
  - How can we distinguish primordial & fragment?
- Composition & Evolution
  - Why differentiated and non-heated (primordial) bodies?
    - just a question of accretion age?
    - implantation?
  - Energetic collisions modified compositions?

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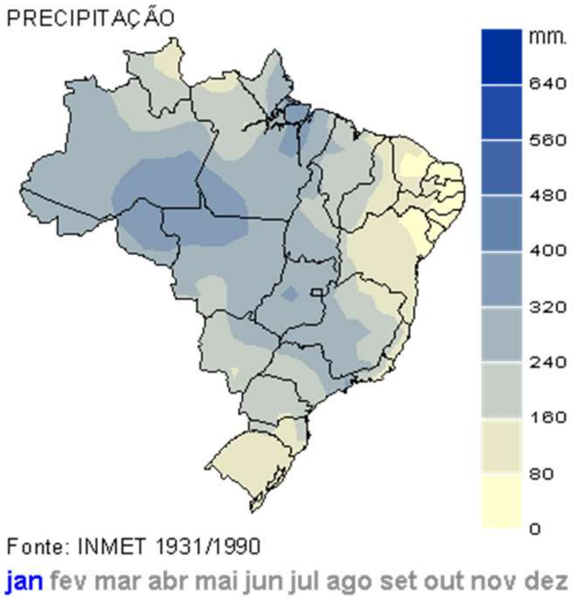
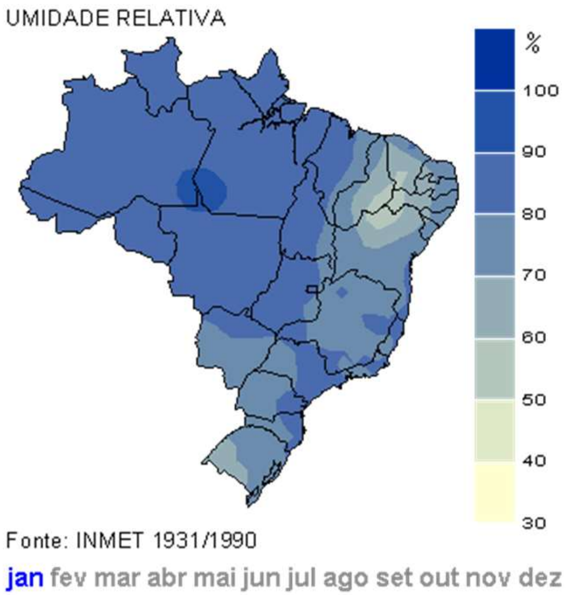
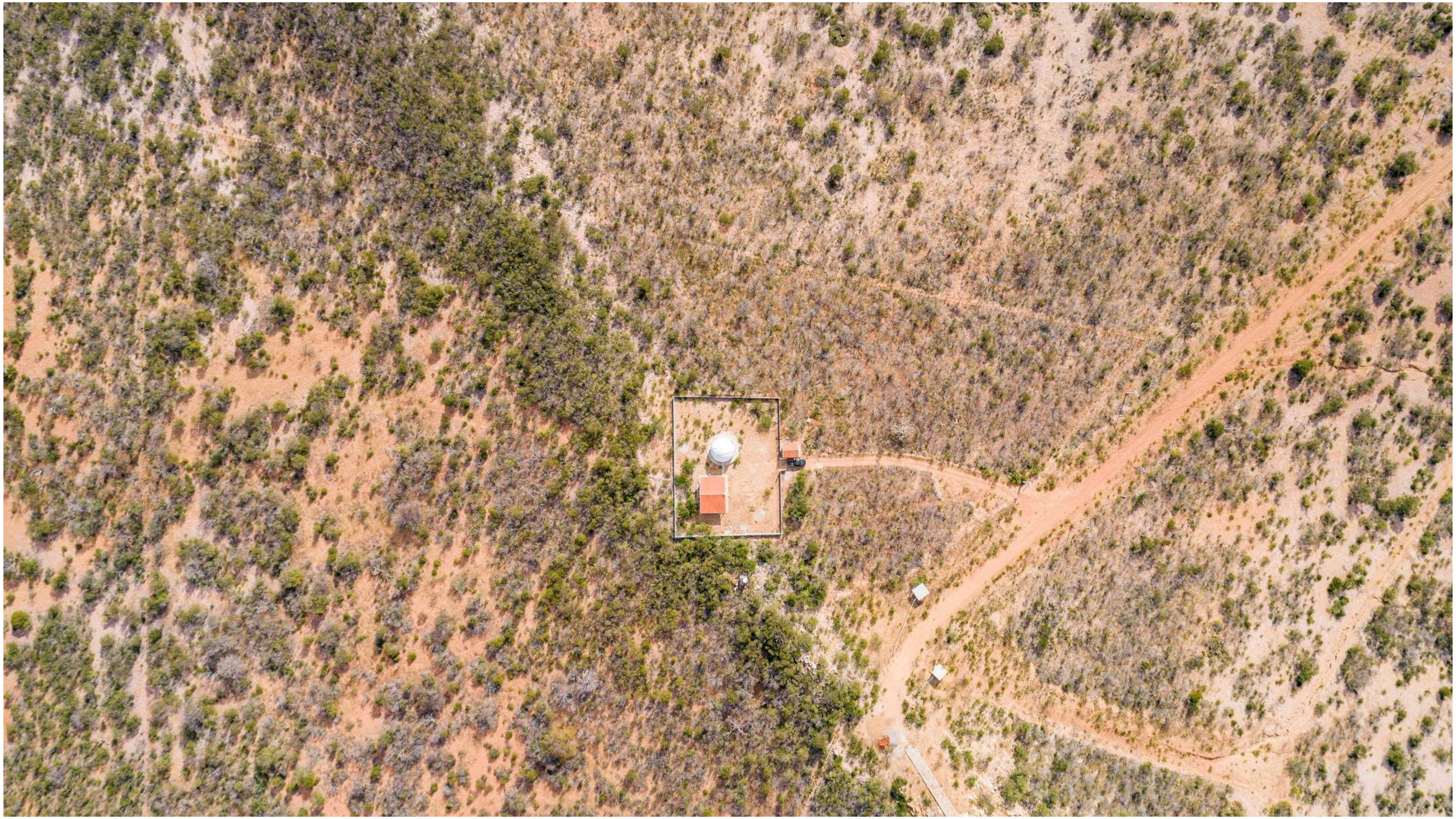
Data: Orbits, rotations, forms, axis…

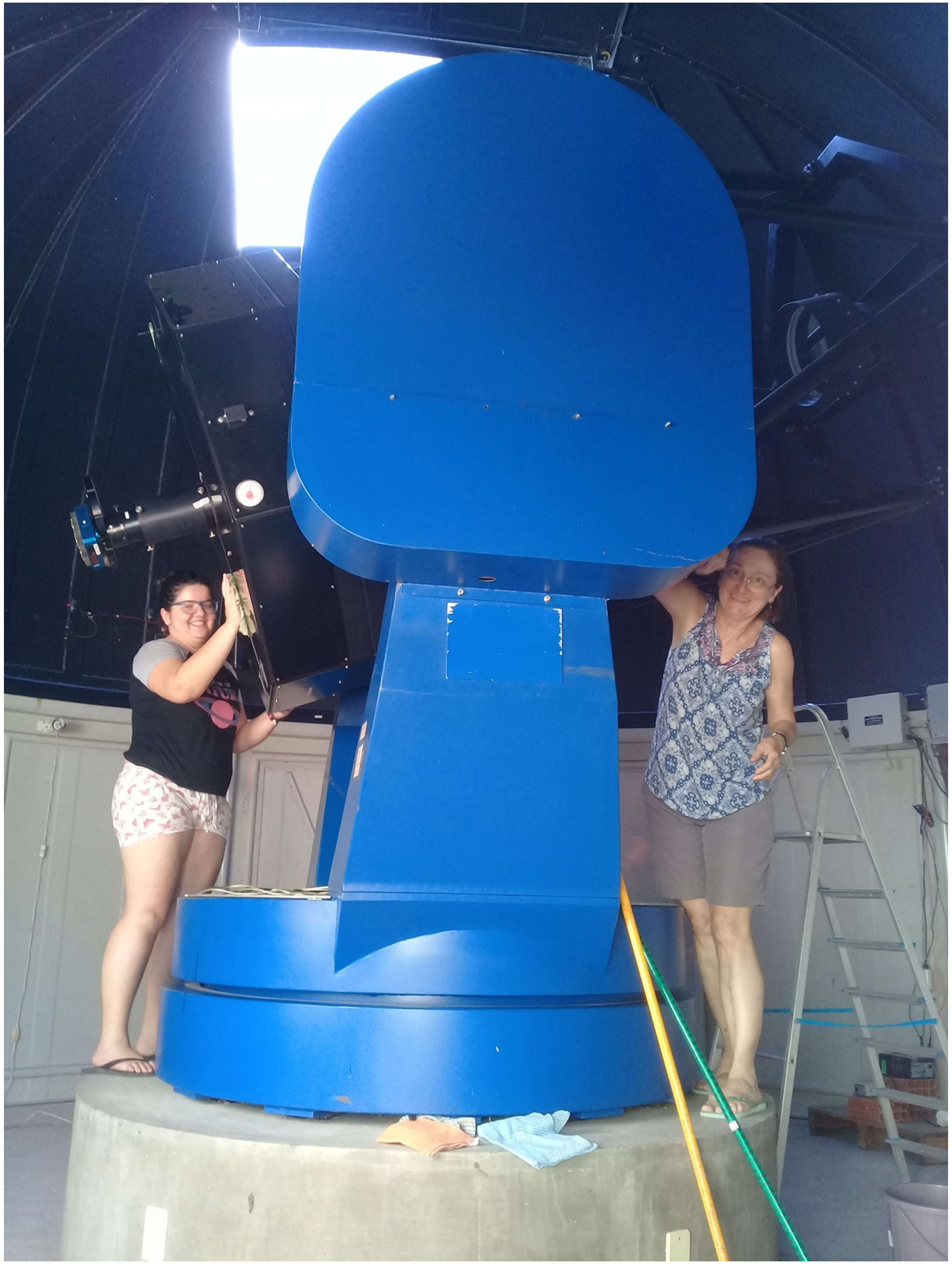




480 km from Recife
260 km from Petrolina
~4000 inhabitants
280-300 days with no rain



Remote Observation



Rotational Properties

Some historical background

The initial works : angular momentum distribution in comparison with that of the planets (Hartmann and Larson, 1967, Burns 1975), considering (L=angular momentum, P = period)

$$L/M \propto R^2\omega \propto M^{2/3}/P$$

and, for P = constant,

$$L/M \propto M^{2/3}.$$

The relatively good agreement for the planets and of 67 asteroids (Burns 1975)

Later, for the larger dataset of asteroid (Harris and Burns -1979) using a sample of 182, concluded "*in excellent agreement with a 3D-dimensional Maxwellian distribution*".

↓

3D Collisional Processes in Statistical Equilibrium

Subsequent studies:

1) the large asteroids ($R \geq 50\,km$) follow a 3D Maxwellian distribution,
2) significant deviations for smaller asteroides (Pravec & Harris, 2000),
3) Small asteroids affected the so called “YORP(Yarkovsky–O'Keefe–Radzievskii–Paddack ” effect (Pravec et al. 2008).

See e.g., Durech et al. (2015)

Let us see...

Asteroid Lightcurve Database available

13546 spin rates of Main Belt asteroids and 1082 of NEA, with quality code Q=2 and 3

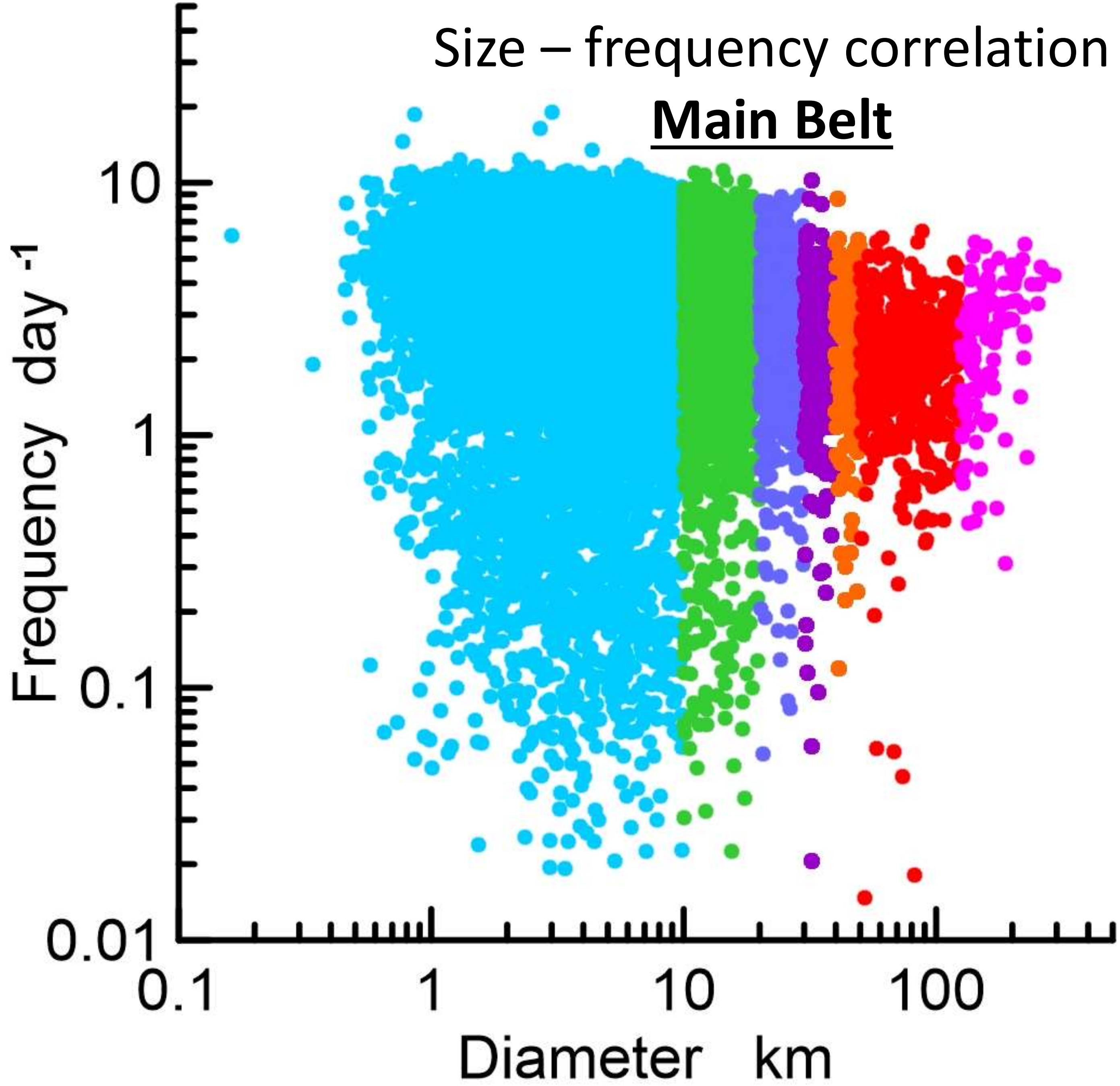
NEA = Near Earth Asteroids

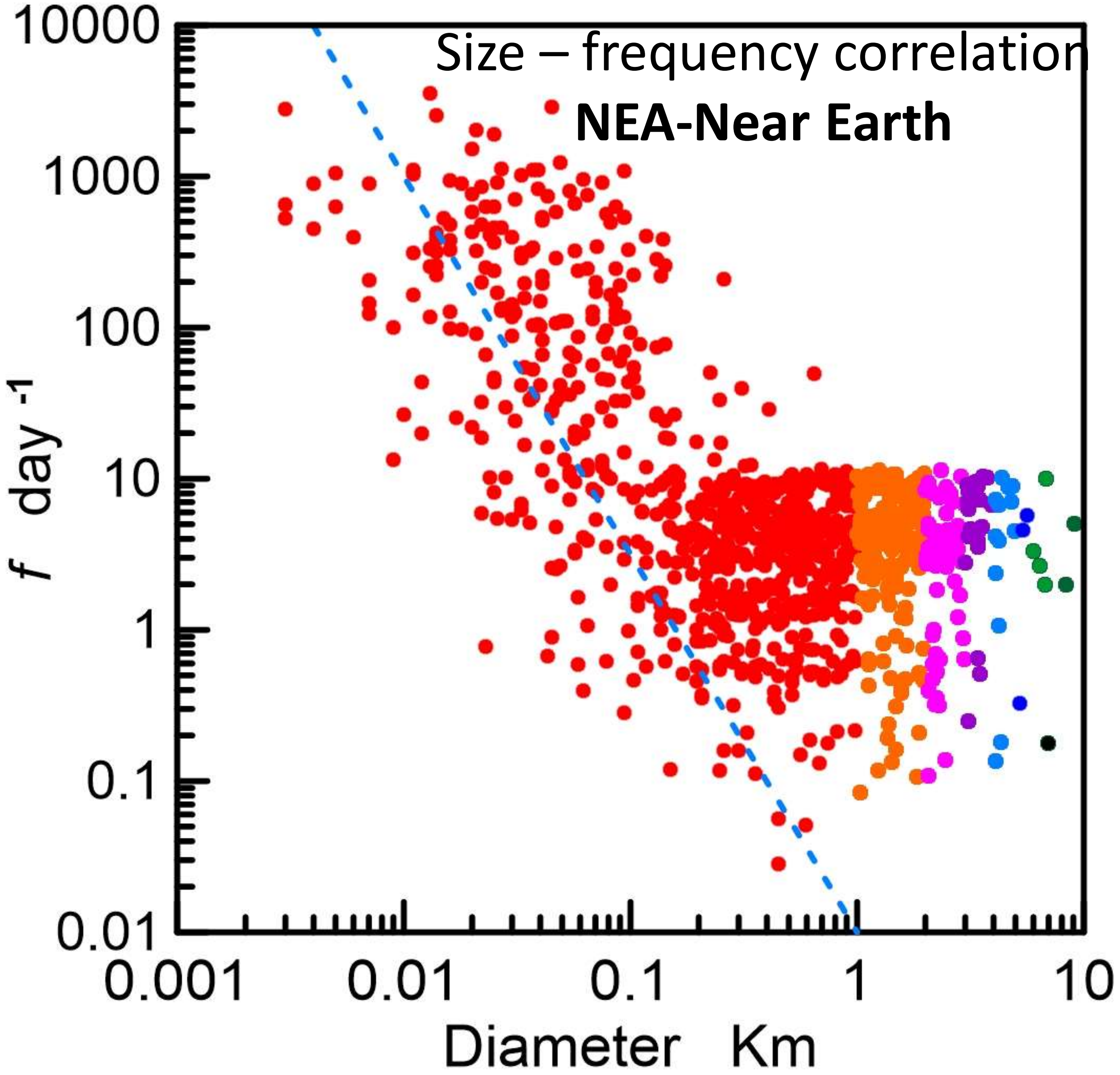
Let us see...

Asteroid Lightcurve Database available

13546 spin rates of Main Belt asteroids and 1082 of NEA, with quality code Q=2 and 3

NEA = Near Earth Asteroids, some dangerous.. 


Size – frequency correlation
Main Belt
Frequency day -1
10
1
0.1
0.01
0.1
1
10
100
Diameter km


Size – frequency correlation
NEA-Near Earth
10000
1000
100
10
1
0.1
0.01
f day -1
0.001
0.01
0.1
1
10
Diameter Km

Commonly accepted vision:

1) the large asteroids ($R \geq 50\,km$) follow a 3D Maxwellian distribution,
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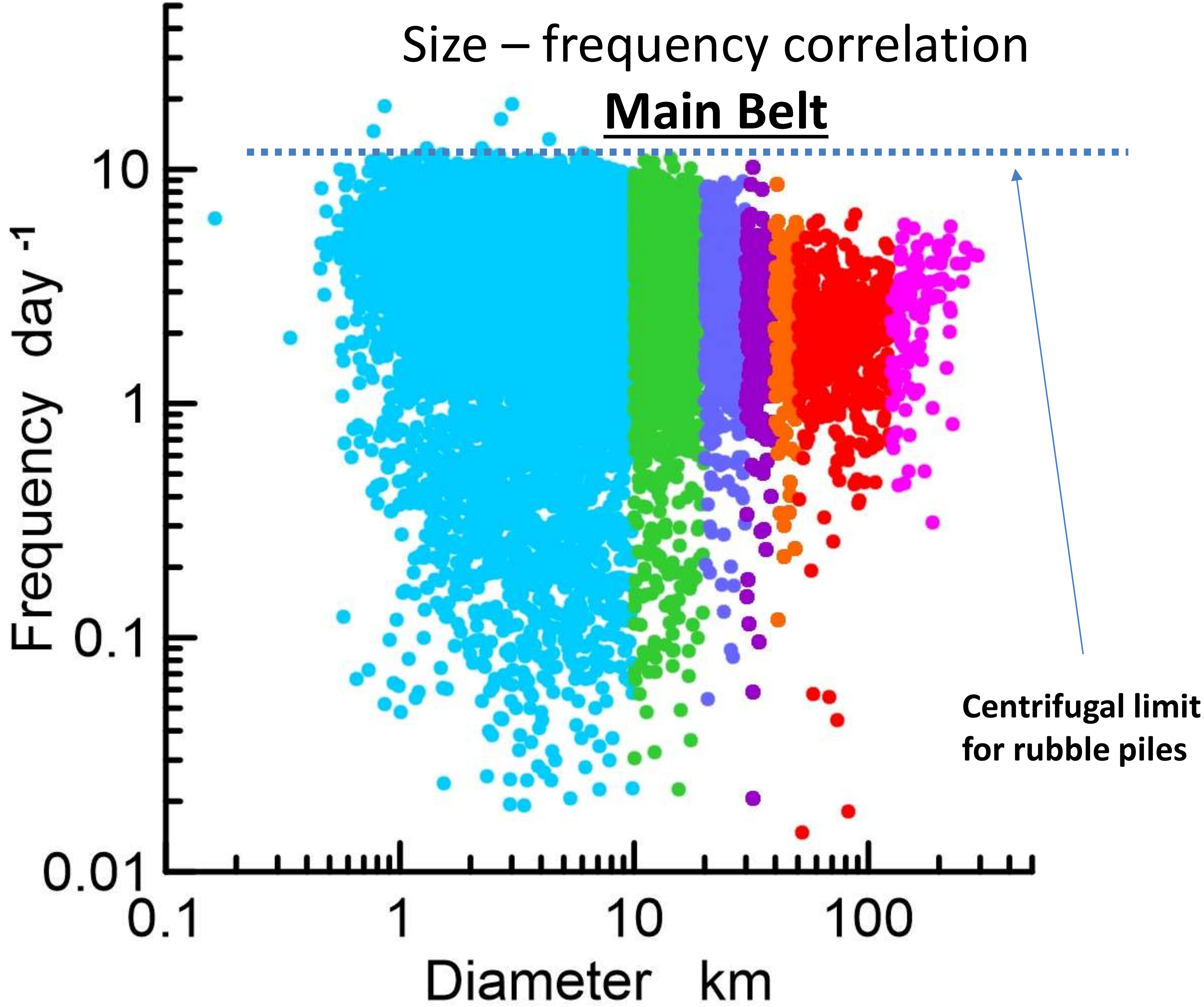

Size – frequency correlation
Main Belt
Frequency day -1
Diameter km
0.01
0.1
1
10
0.1
1
10
100
Centrifugal limit
for rubble piles

Commonly accepted vision:

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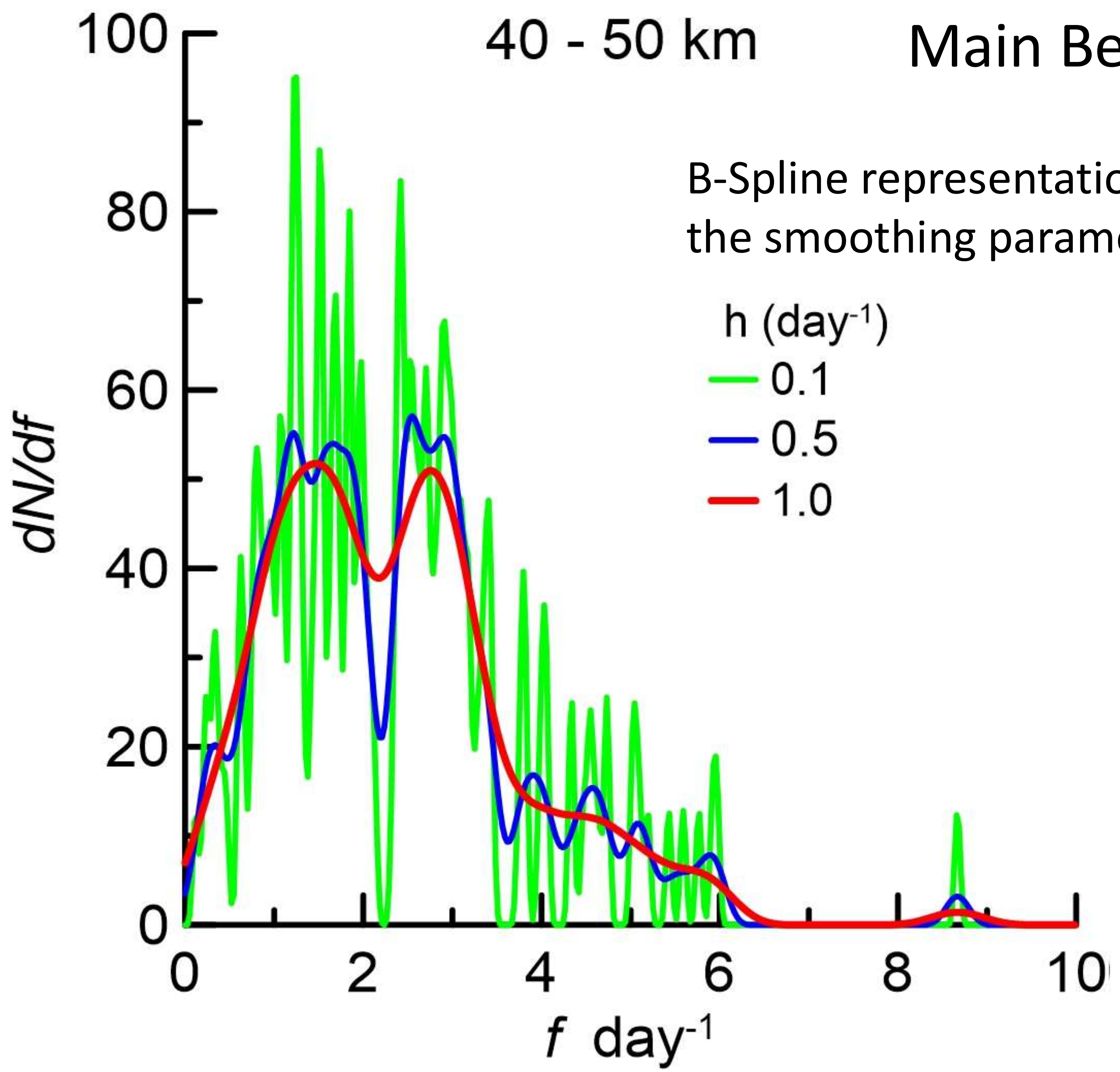
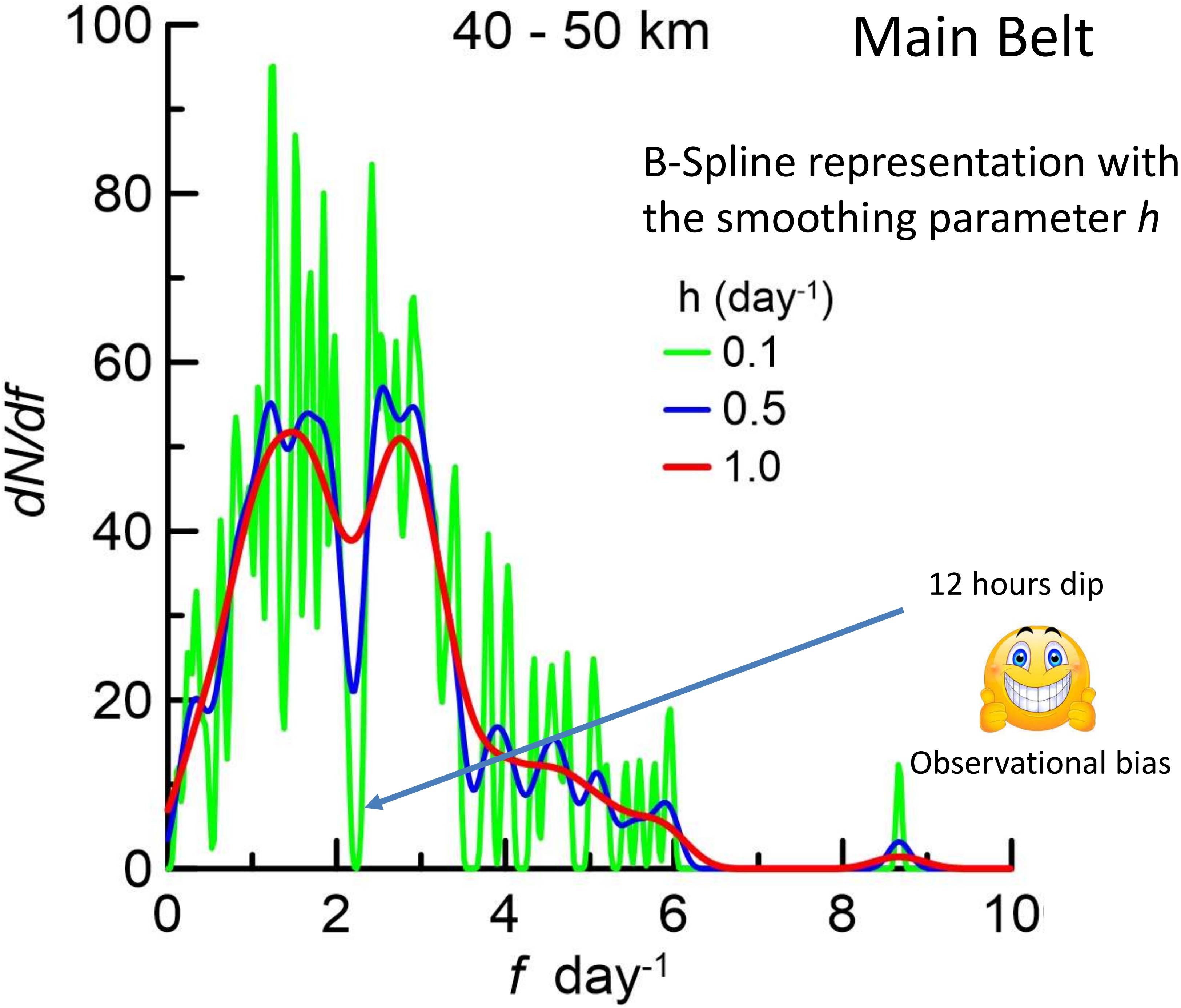
Main Belt

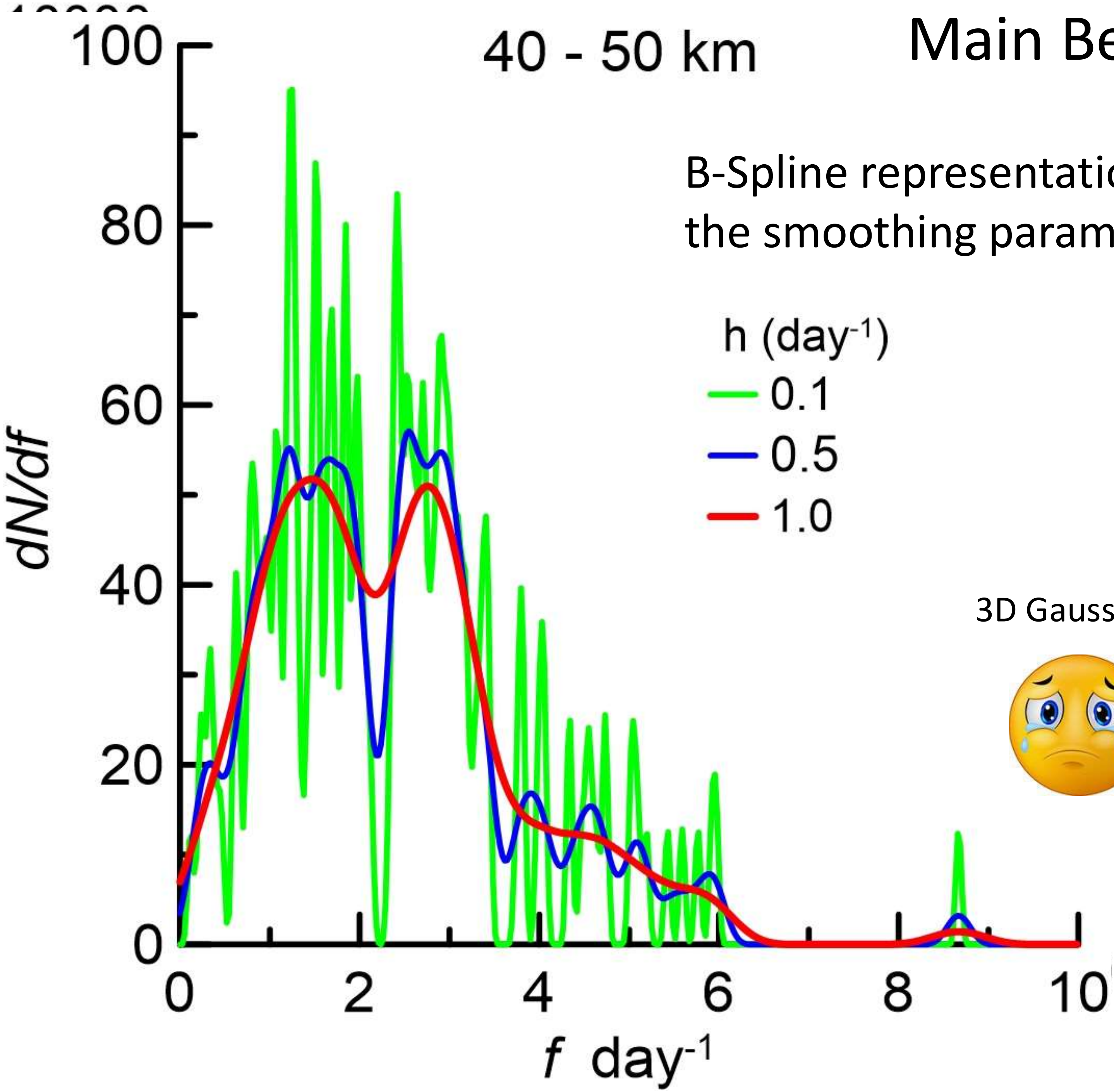
B-Spline representation with the smoothing parameter *h*



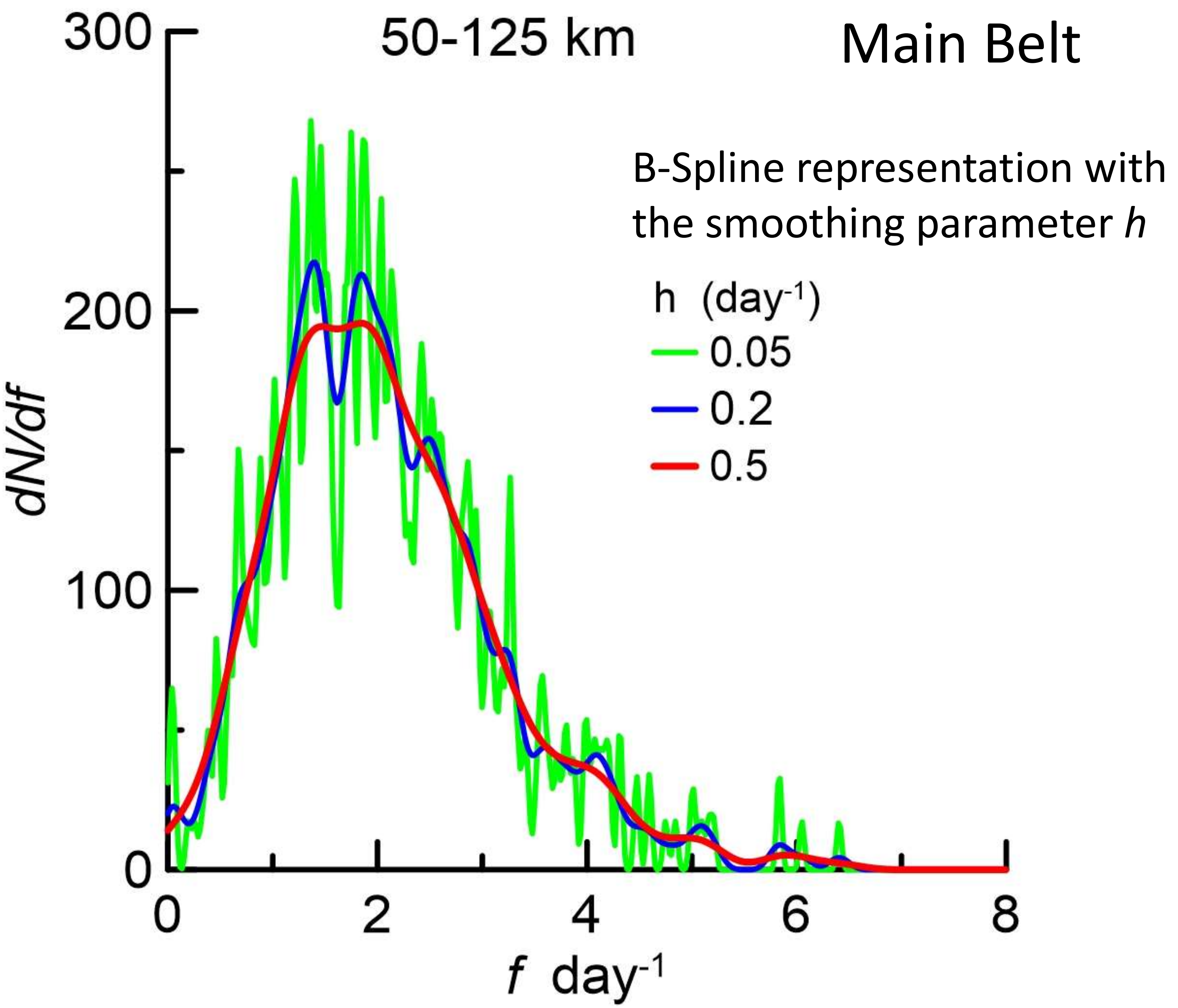

40 - 50 km
Main Belt
B-Spline representation with the smoothing parameter *h*
h (day^{-1})
0.1
0.5
1.0
12 hours dip
Observational bias
dN/df
0
20
40
60
80
100
0
2
4
6
8
10
f day^{-1}

Main Belt

B-Spline representation with the smoothing parameter *h*



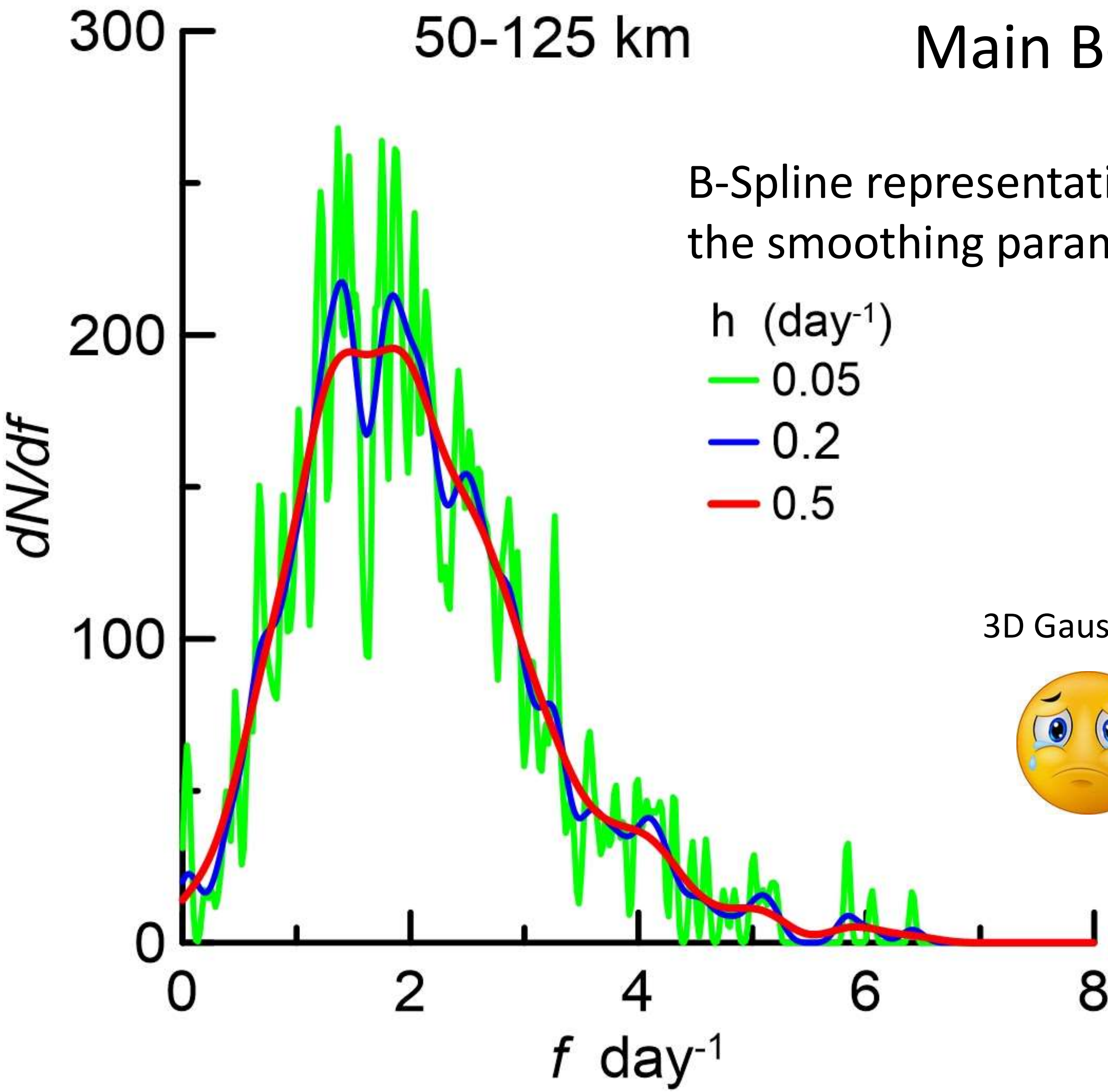
3D Gaussian ??



50-125 km
Main Belt
B-Spline representation with the smoothing parameter *h*
h (day-1)
0.05
0.2
0.5
dN/df
f day-1
300
200
100
0
0
2
4
6
8

Main Belt

B-Spline representation with the smoothing parameter *h*

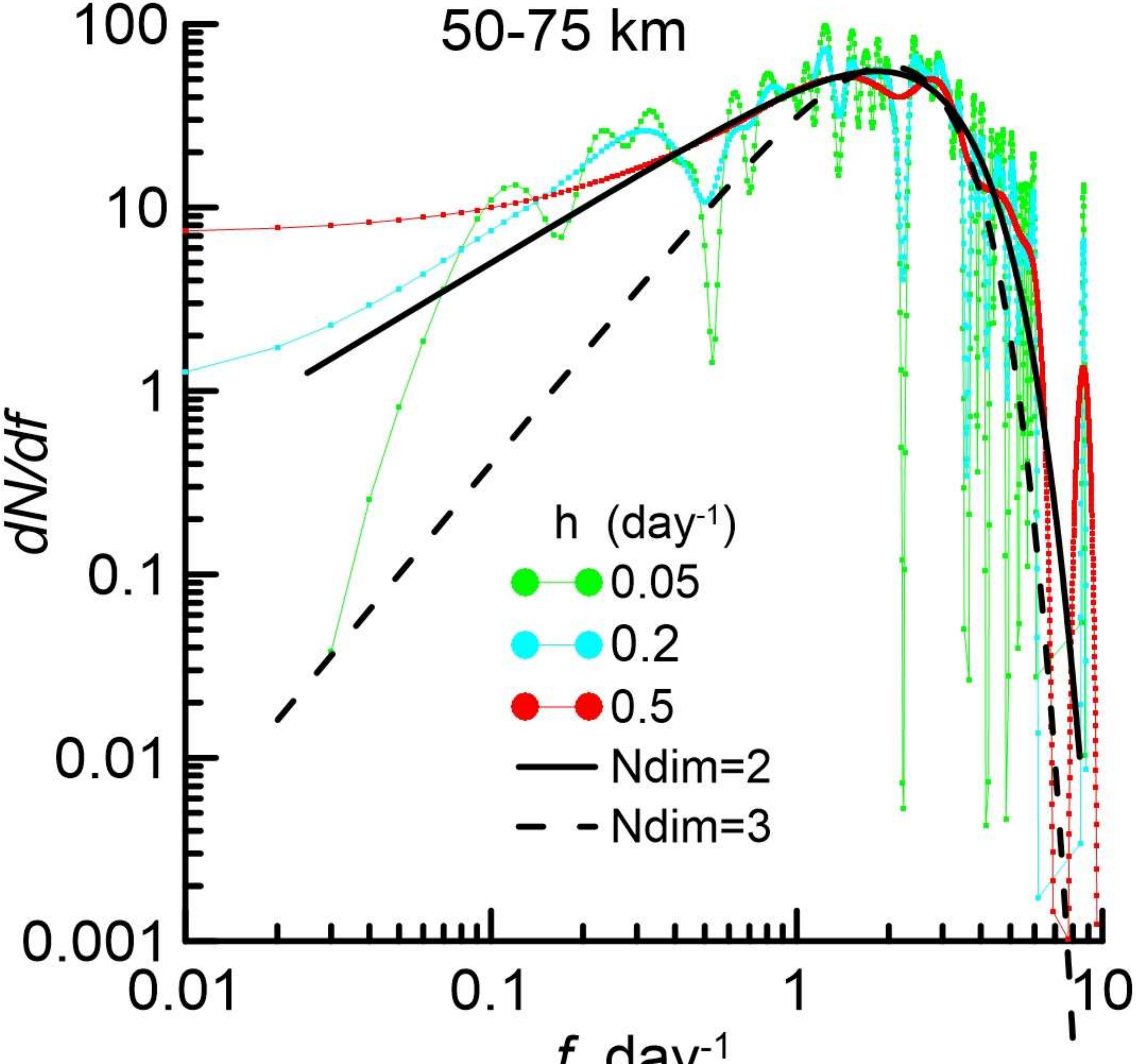


3D Gaussian ??

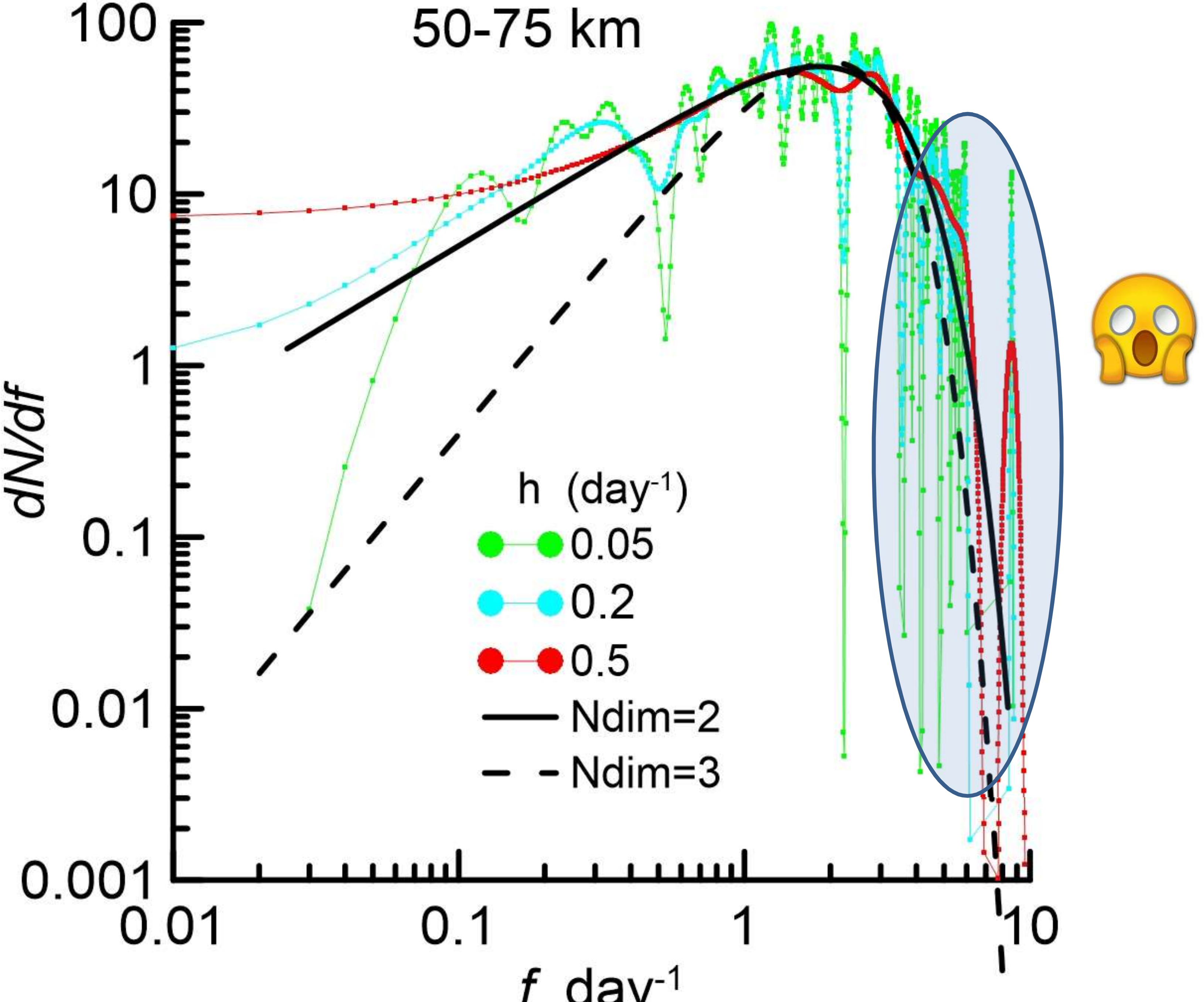
Are they really consistent to the 3-D Gaussian?

Simple χ square fit doesn´t work.....

Better way to see?



50-75 km
100
10
1
0.1
0.01
0.001
dN/df
0.01
0.1
1
10
f day-1
h (day-1)
0.05
0.2
0.5
Ndim=2
Ndim=3



50-75 km
100
10
1
0.1
0.01
0.001
dN/df
h (day-1)
0.05
0.2
0.5
Ndim=2
Ndim=3
0.01
0.1
1
10
f day-1

Cummulative distribution

$$N(f) = \int_0^f df' \frac{dN}{df}(f')$$

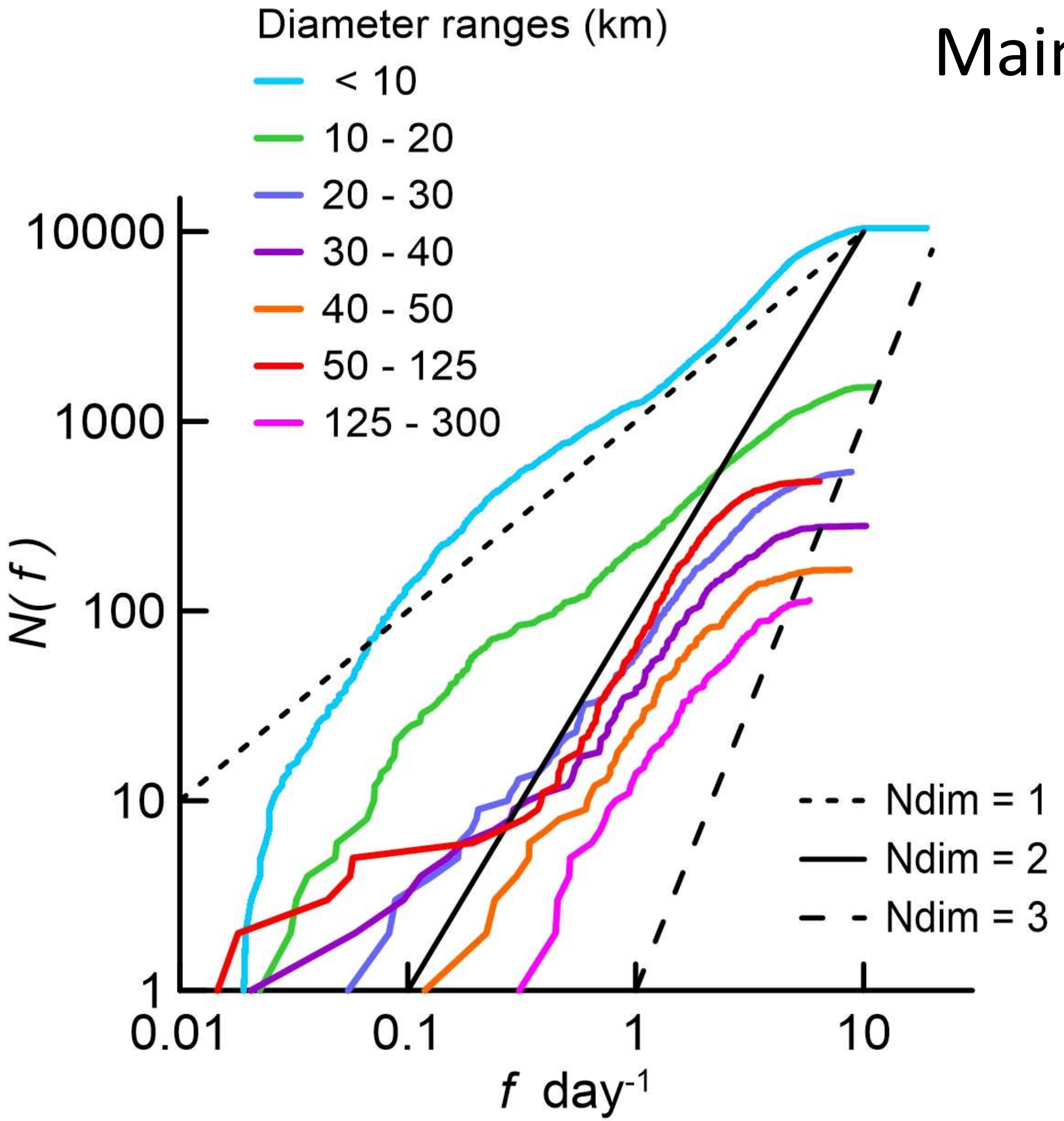
Dimensionality of the rotational phase space (Gaussian)

$$\frac{dN^{(1)}}{df}(f) \propto \exp(-\alpha_1 f^2)$$

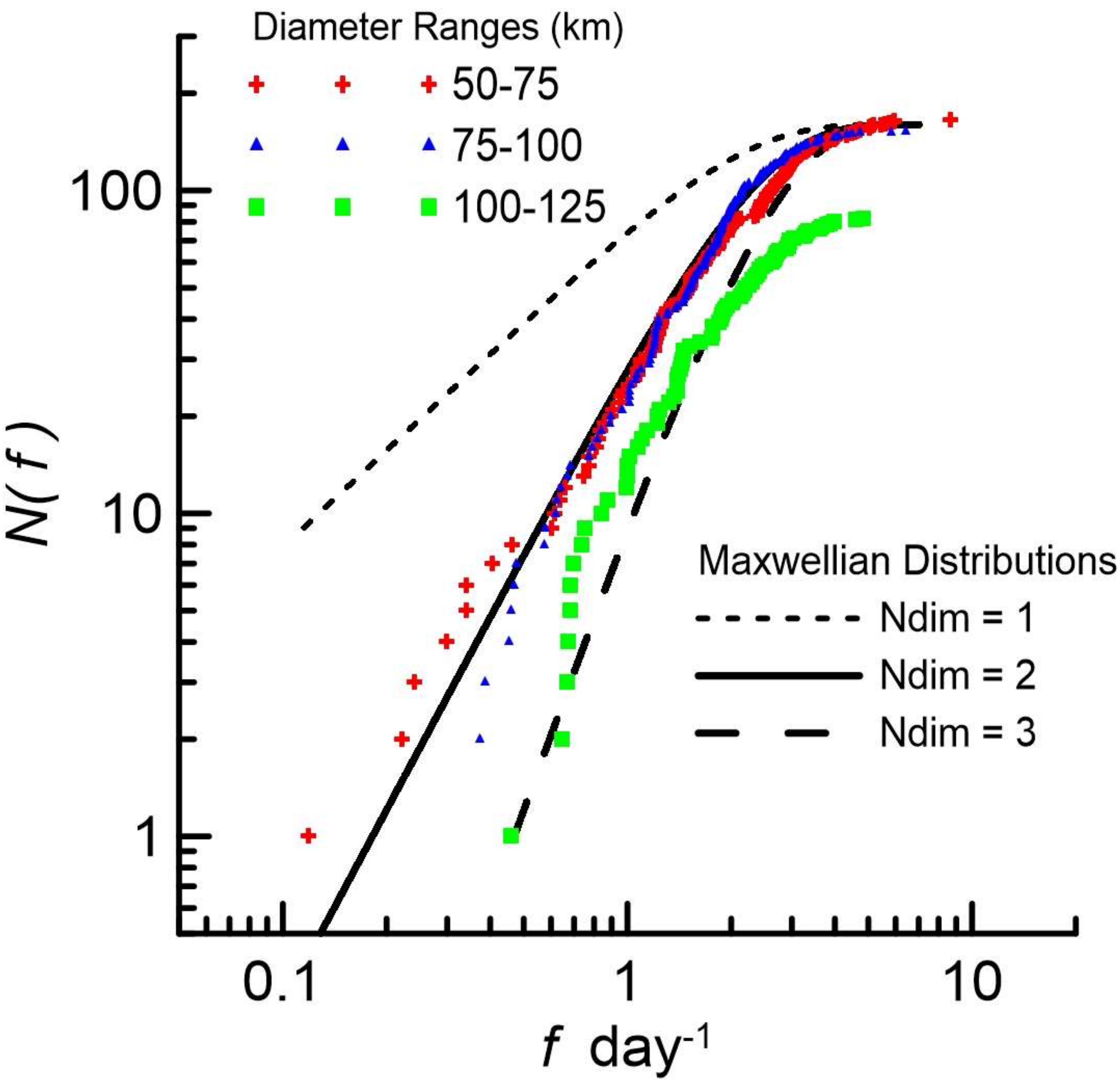
$$\frac{dN^{(2)}}{df}(f) \propto f \exp(-\alpha_2 f^2)$$

$$\frac{dN^{(3)}}{df}(f) \propto f^2 \exp(-\alpha_3 f^2)$$

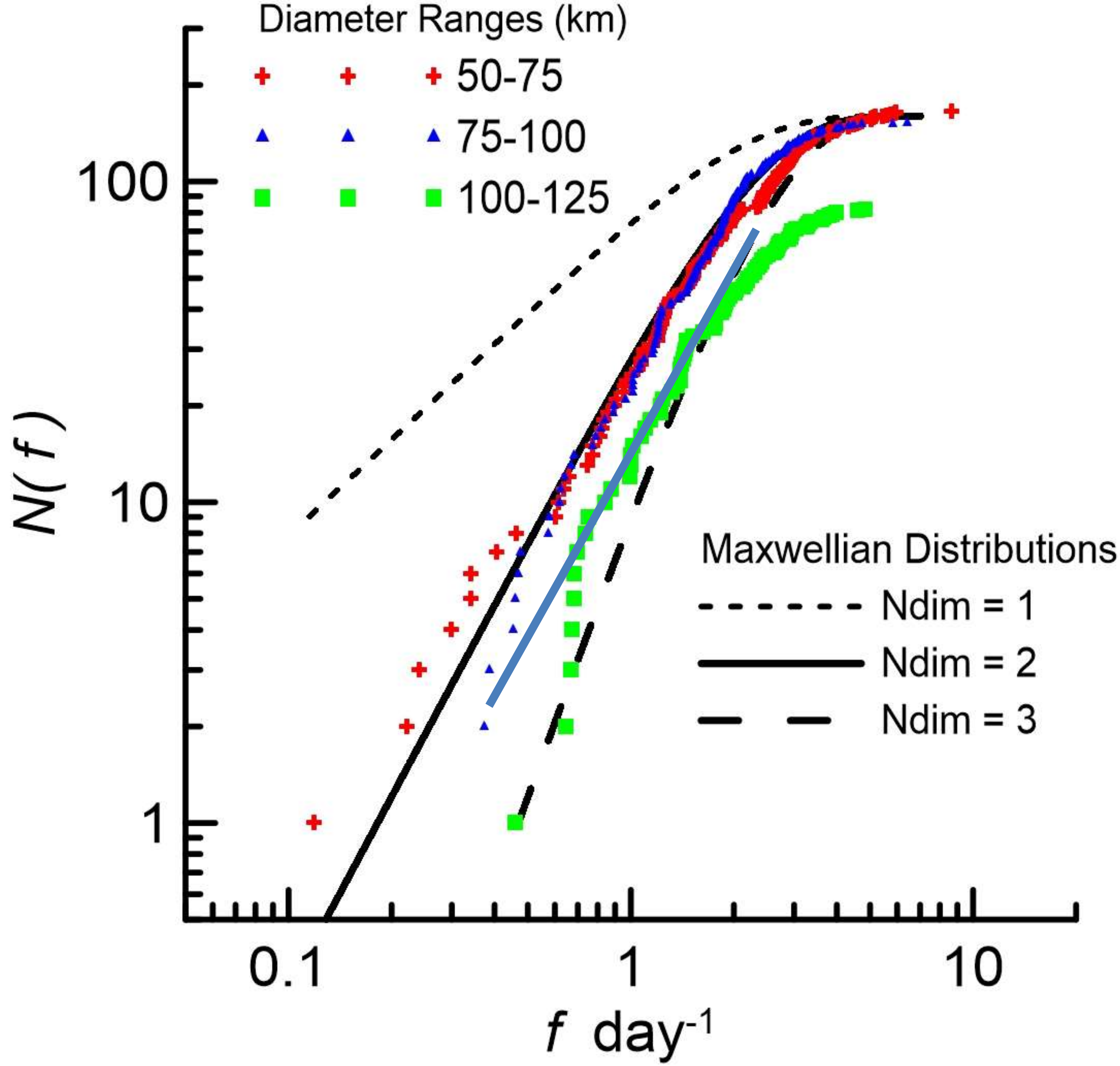
Main Belt



Diameter ranges (km)
< 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 125
125 - 300
10000
1000
100
10
1
N(f)
0.01
0.1
1
10
f day⁻¹
Ndim = 1
Ndim = 2
Ndim = 3



Diameter Ranges (km)
50-75
75-100
100-125
Maxwellian Distributions
Ndim = 1
Ndim = 2
Ndim = 3
N(f)
100
10
1
0.1
1
10
f day-1



Diameter Ranges (km)
50-75
75-100
100-125
Maxwellian Distributions
Ndim = 1
Ndim = 2
Ndim = 3
N(f)
100
10
1
0.1
1
10
f day-1

- The cumulative distribution $N(f) = \int_0^f df \frac{dN}{df}$ of rotational frequency of heavy asteroids (> 100 km) obeys a power law,

$$N(f) \propto f^2$$

for $f < 2$ day^{-1} .

- If the frequency distribution comes from a statistical equilibrium through the collisional process in an isotropic medium, the power above should be 3.
- Why 2 Dim ?

Possible causes:

A. Simply due to the observational biases or errors.

B. Due to the triaxial nature of non spherical asteroids the observed frequencies do not behave linearly to the angular momentum.

C. The slowly rotating heavy asteroids aquire their angular momenta through the collisional process where the colliding objects are in kinematical equilibrium in a plane (e.g., protoplanetary disk)

Gaussian Ellipsoid

$$\rho^{(C)}\left(\vec{r}\right) = \rho_0 e^{-\frac{1}{2M}\vec{r}\ \hat{I}_0^{-1}\ \ A\vec{r}} = \rho_0 e^{-\frac{1}{2}\vec{r}\ \hat{E}_0\ \ A\vec{r}},$$

$$\hat{I}_0 = M\begin{pmatrix} R_{x_0}^2 & 0 & 0 \\ 0 & R_{y_0}^2 & 0 \\ 0 & 0 & R_{z_3}^2 \end{pmatrix}.\ \hat{E}_0 \ \equiv\ M\ \hat{I}_0^{-1} = \begin{pmatrix} R_1^{-2} & 0 & 0 \\ 0 & R_2^{-2} & 0 \\ 0 & 0 & R_2^{-2} \end{pmatrix}$$

$$\rho_0 = \left(\frac{1}{2\pi\det\left[\hat{I}_0^{-1}\right]}\right)^{3/2} = \left(\frac{1}{2\pi}\right)^{3/2}\frac{M}{R_1 R_2 R_3}.$$

Time-dependente Rotation

$$\vec{r}(t) = \hat{A}(t)\ \vec{r}^{(C)}$$

$$\rho(\vec{r}, t) = \rho_0 e^{-\frac{1}{2}\vec{r}^T \hat{E}(t)\vec{r}}.$$

$$\hat{I}(t) = A^T(\alpha, \beta, \gamma)\, \hat{I}_0 A(\alpha, \beta, \gamma).$$

$$\hat{I}_0 = \begin{pmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{pmatrix}$$

Rotational Kinetic Energy (Euler Angles)

$$\vec{\omega}^{(C)} = \begin{pmatrix} \sin\beta\cos\gamma & \sin\gamma & 0 \\ \sin\beta\sin\gamma & -\cos\gamma & 0 \\ \cos\beta & 0 & 1 \end{pmatrix} \begin{pmatrix} \dot{\alpha} \\ \dot{\beta} \\ \dot{\gamma} \end{pmatrix}$$

$$\vec{\omega} = \hat{A}\vec{\omega}^{(C)},$$

$$K_R = \frac{1}{2}\vec{\omega}^T \hat{I} \vec{\omega},$$

Quartanions (Gauss, Hamilton)

$$\tilde{q} \sim \sqrt{A(\alpha, \beta, \gamma)}$$

$$\begin{aligned} \tilde{q} &= (q_4, \vec{q}) = \tilde{a}\tilde{b} \\ &= \left(a_4 b_4 - \vec{a} \cdot \vec{b},\ a_4 \vec{b} + b_4 \vec{a} + \left(\vec{a} \times \vec{b}\right)\right) \end{aligned}$$

$$\vec{r}' = \vec{r}\cos\theta + (1 - \cos\theta)\,\vec{n}\,(\vec{n} \cdot \vec{r}) + \sin\theta\,\vec{n} \times \vec{r}.$$

$$\tilde{r}' = \tilde{q}\tilde{r}\tilde{q}^*$$ for $$\tilde{r} = (0, \vec{r})\,.$$

$$q_4 = \cos\frac{\theta}{2}, \quad \vec{q} = \sin\frac{\theta}{2}\vec{n},$$

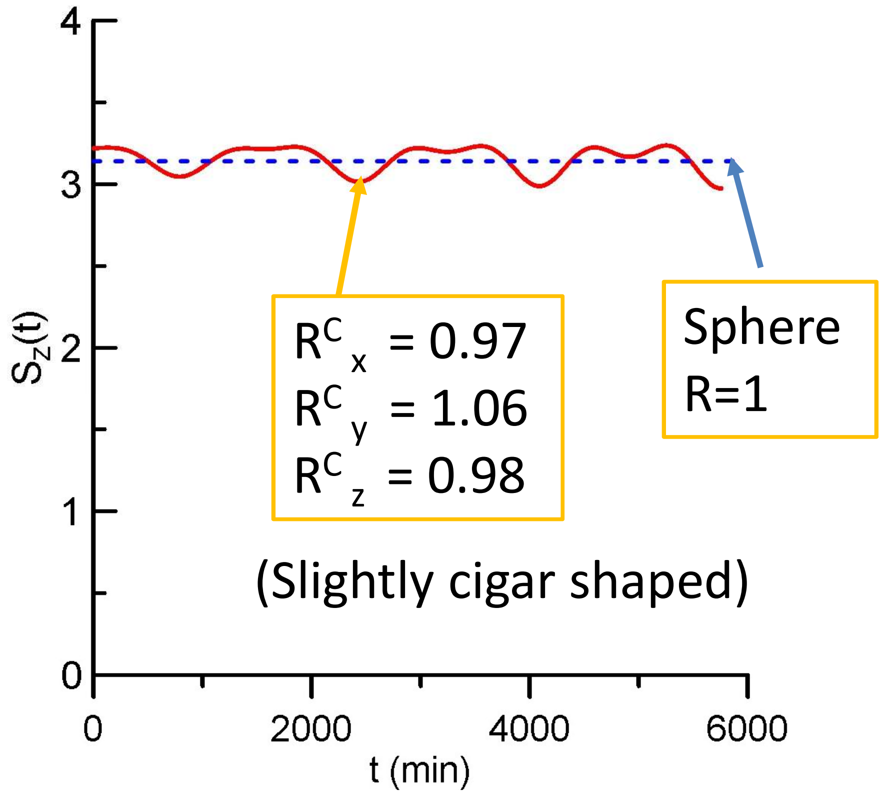
Quartanion representation of Dynamics

$$\begin{pmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{pmatrix} \rightarrow |q\rangle$$

$$\tilde{L} = \frac{1}{2} \langle q| T(q) |q\rangle - \frac{1}{2} f(t) \left(\langle q|q\rangle - 1 \right)$$

$$\langle q|\dot{q}\rangle = 0$$

Examples of Possible Origin of Observational Bias
a) rather irregular

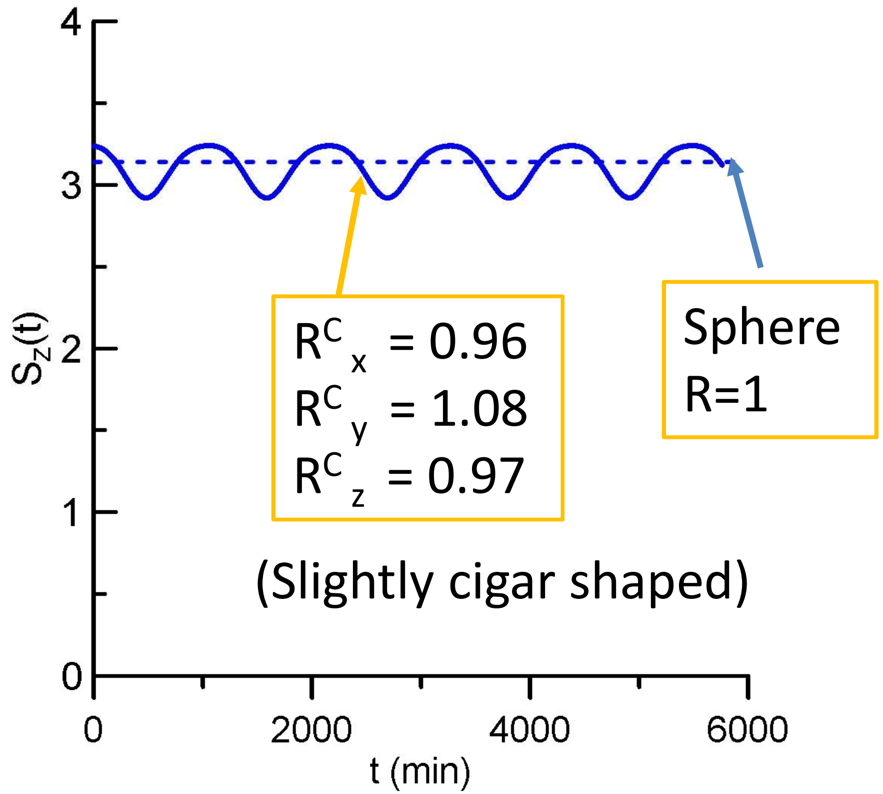


t : time

Sz : Area of projection to the line of sight

$R^c_{x,y,z}$: Length of intrisic axis in the unit of the mass density is unity.

Examples of Possible Origin of Observational Bias
b) Regular but not harmonic



t : time

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$R^c_{x,y,z}$: Length of intrisic axis in the unit of the mass density is unity.

Possible causes:

A. ~~Simply due to the observational biases or errors.~~
   To much regular.....

B. Due to the triaxial nature of non spherical asteroids the observed frequencies do not behave linearly to the angular momentum.

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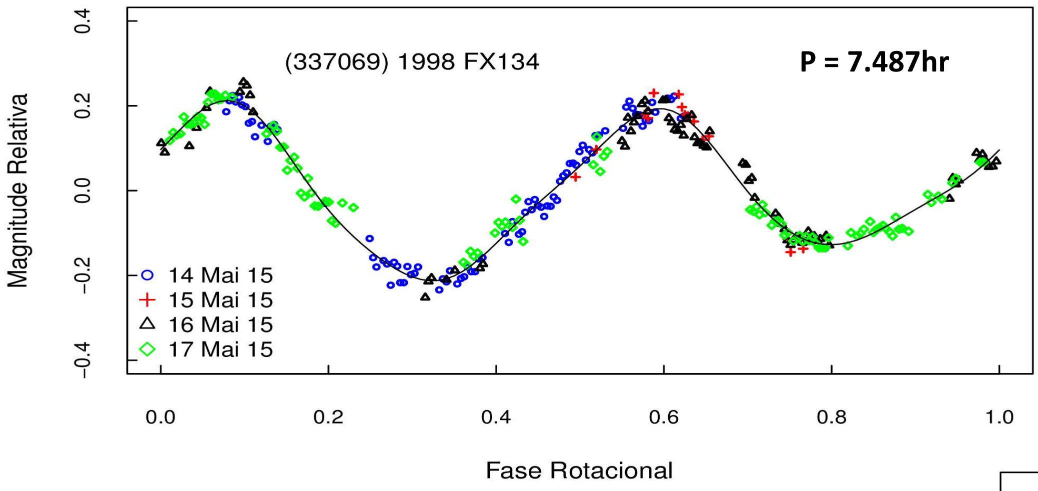
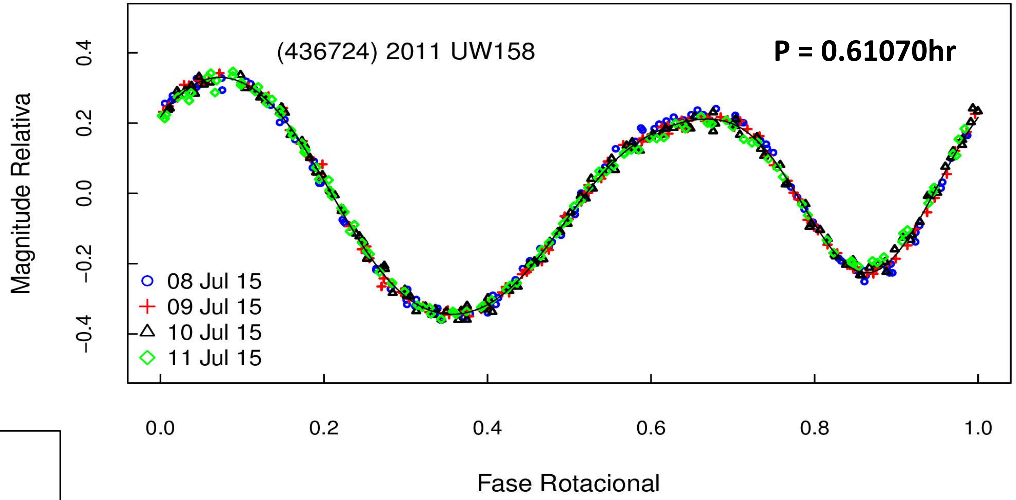
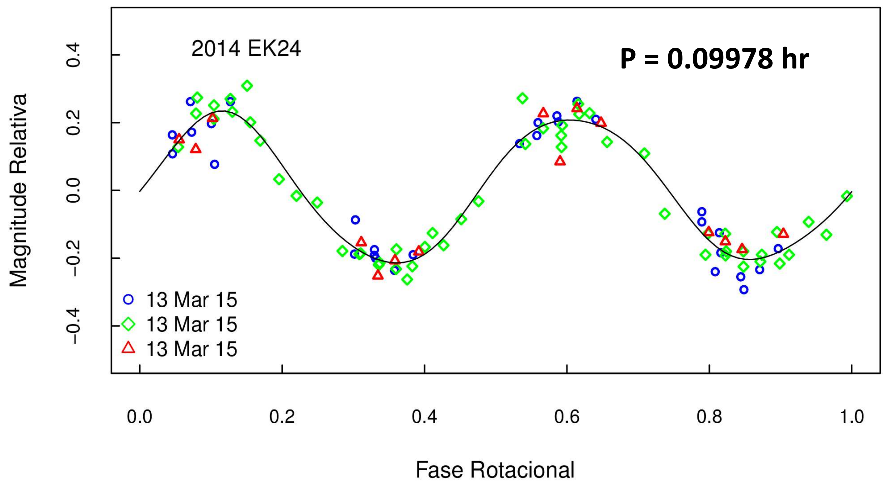
IMPACTON

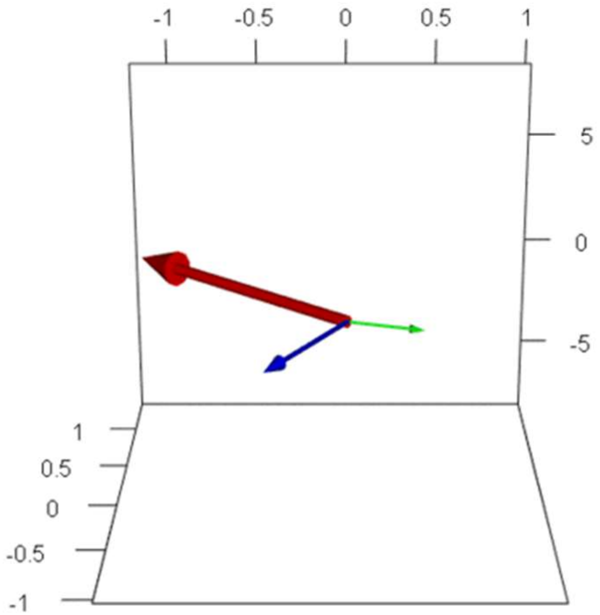


36,64min

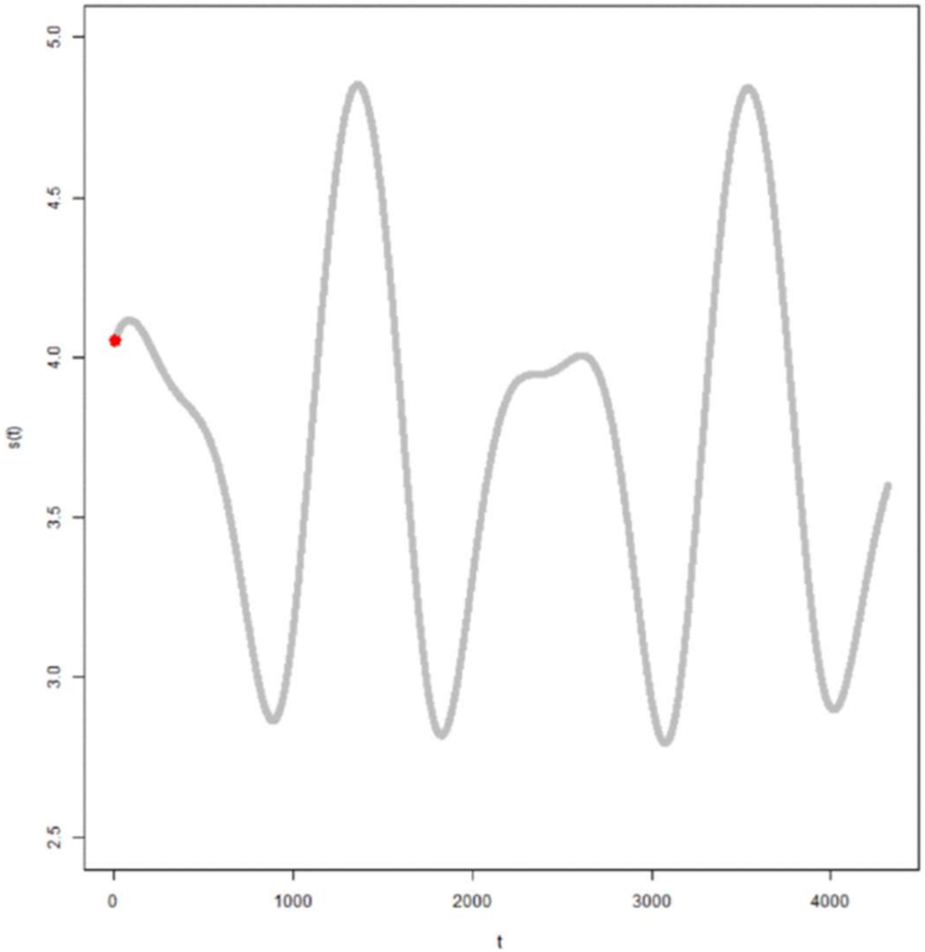




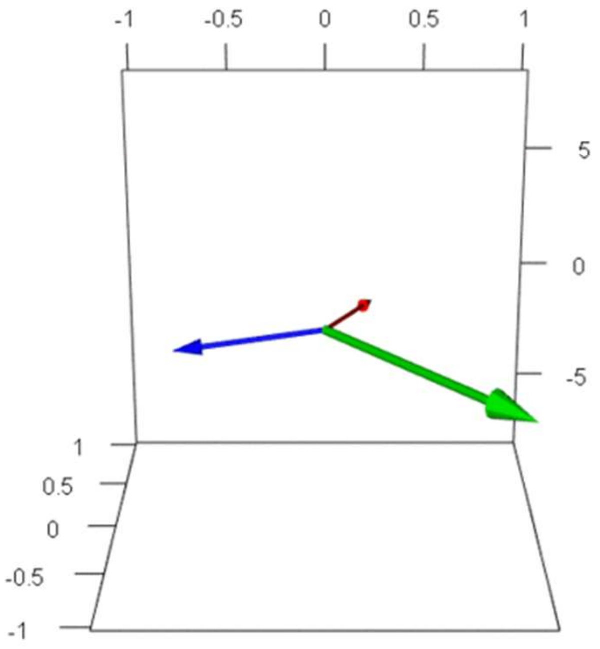
5,94 min



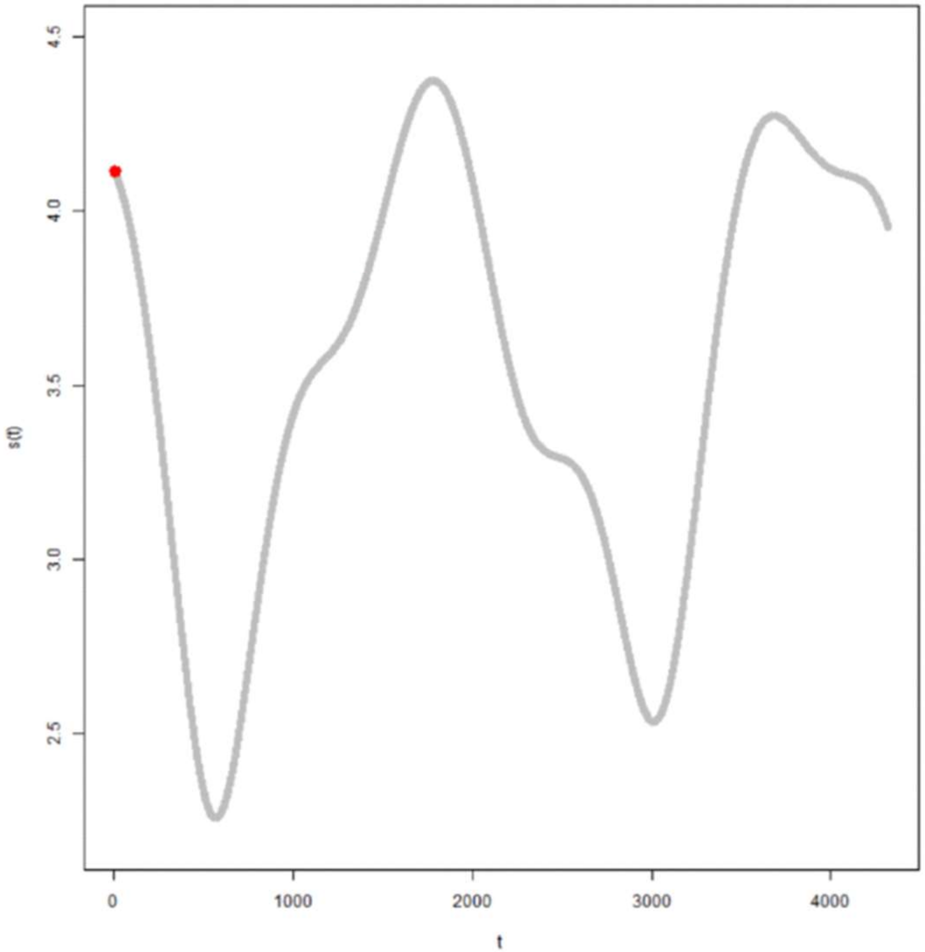
-1
-0.5
0
0.5
1
5
0
-5
1
0.5
0
-0.5
-1



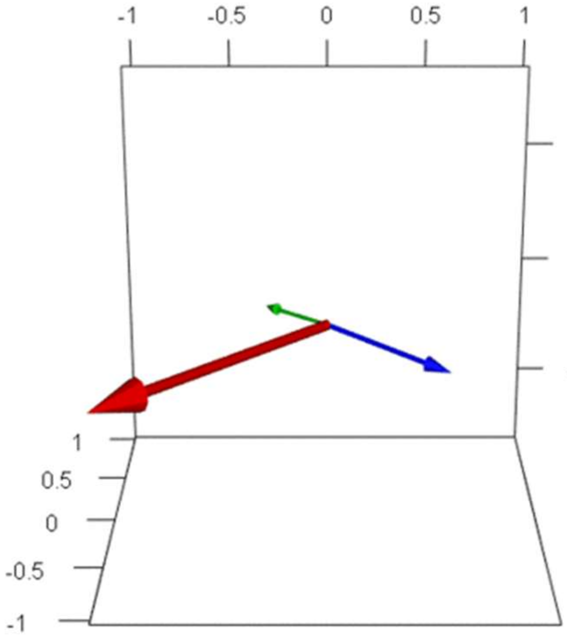
5.0
4.5
4.0
3.5
3.0
2.5
s(t)
0
1000
2000
3000
4000
t

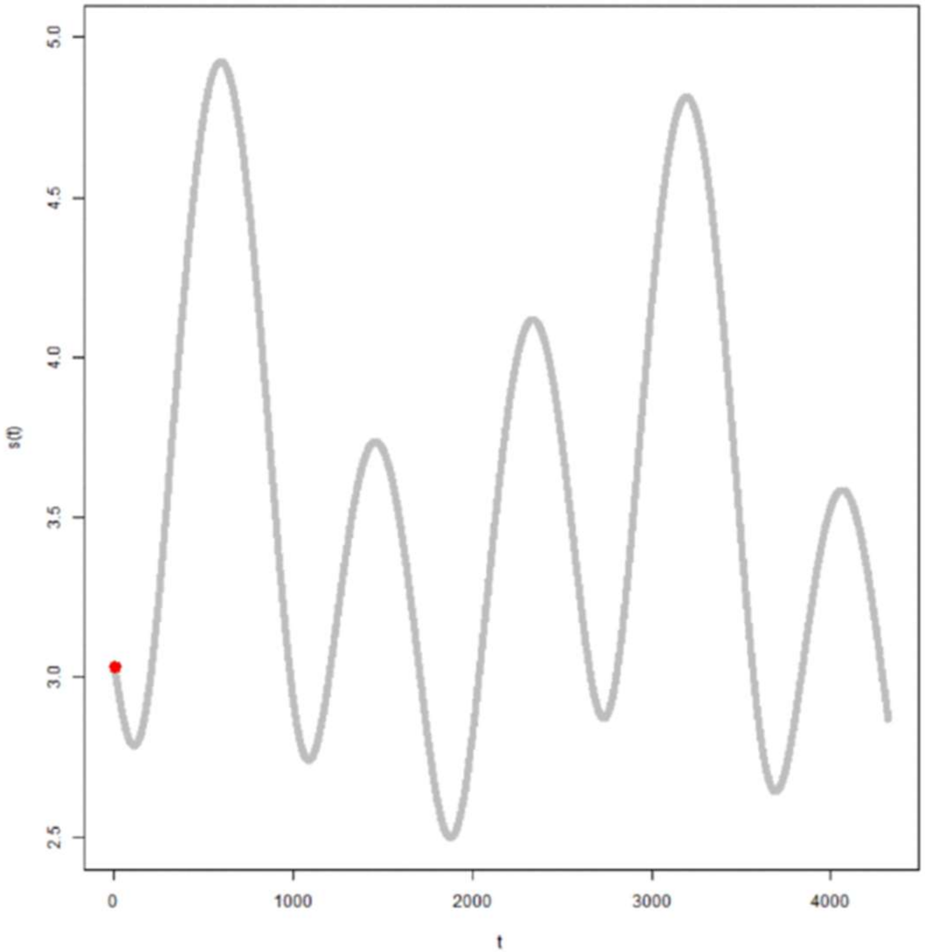


-1
-0.5
0
0.5
1
5
0
-5
1
0.5
0
-0.5
-1



s(t)
4.5
4.0
3.5
3.0
2.5
0
1000
2000
3000
4000
t


-1
-0.5
0
0.5
1
5
0
-5
1
0.5
0
-0.5
-1


5.0
4.5
4.0
3.5
3.0
2.5
s(t)
0
1000
2000
3000
4000
t

Summary

Possible causes:

Can not explain why exactly the power 2 if not any accidental coincidences

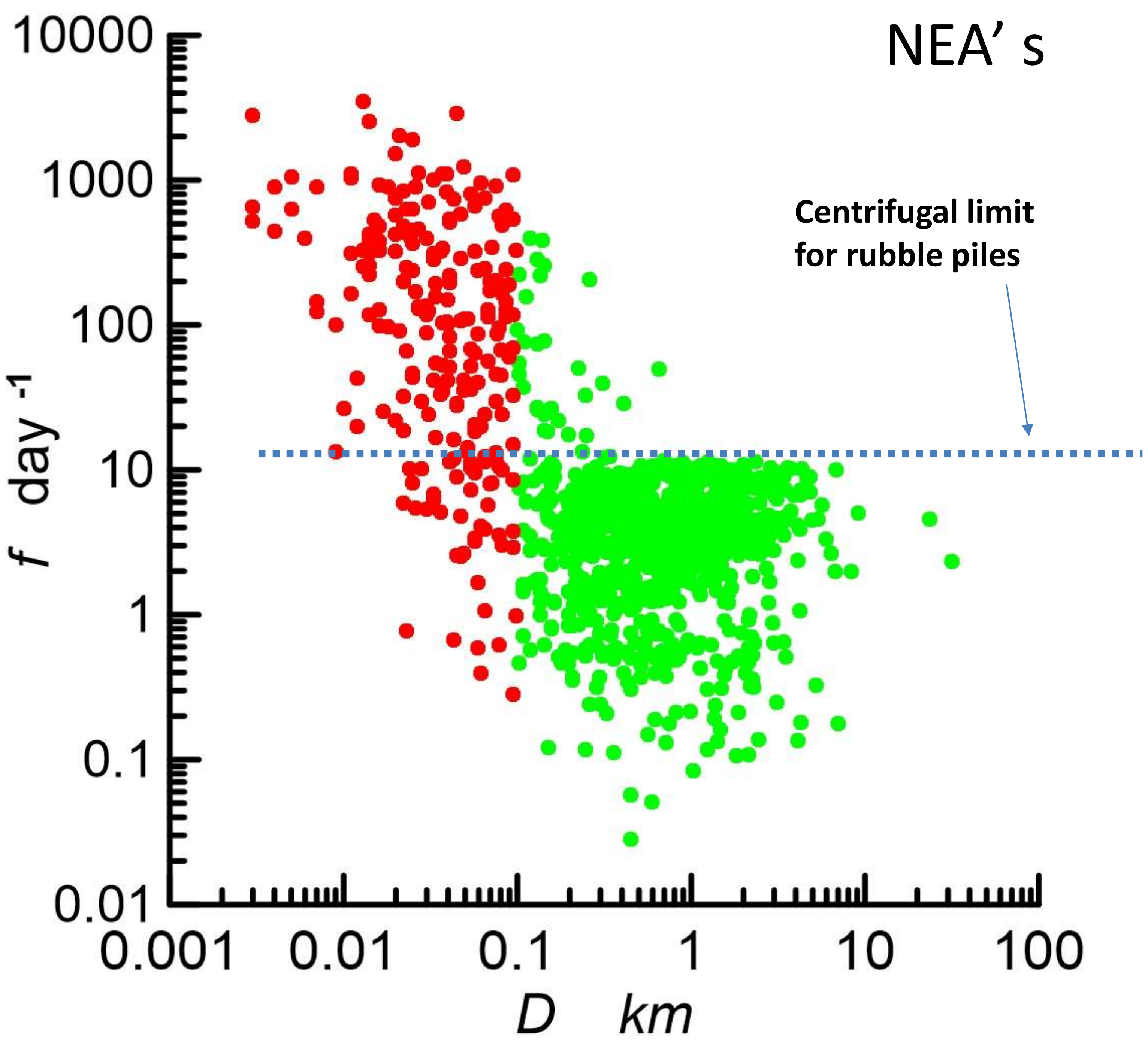
A. ~~Simply due to the observational biases or errors.~~

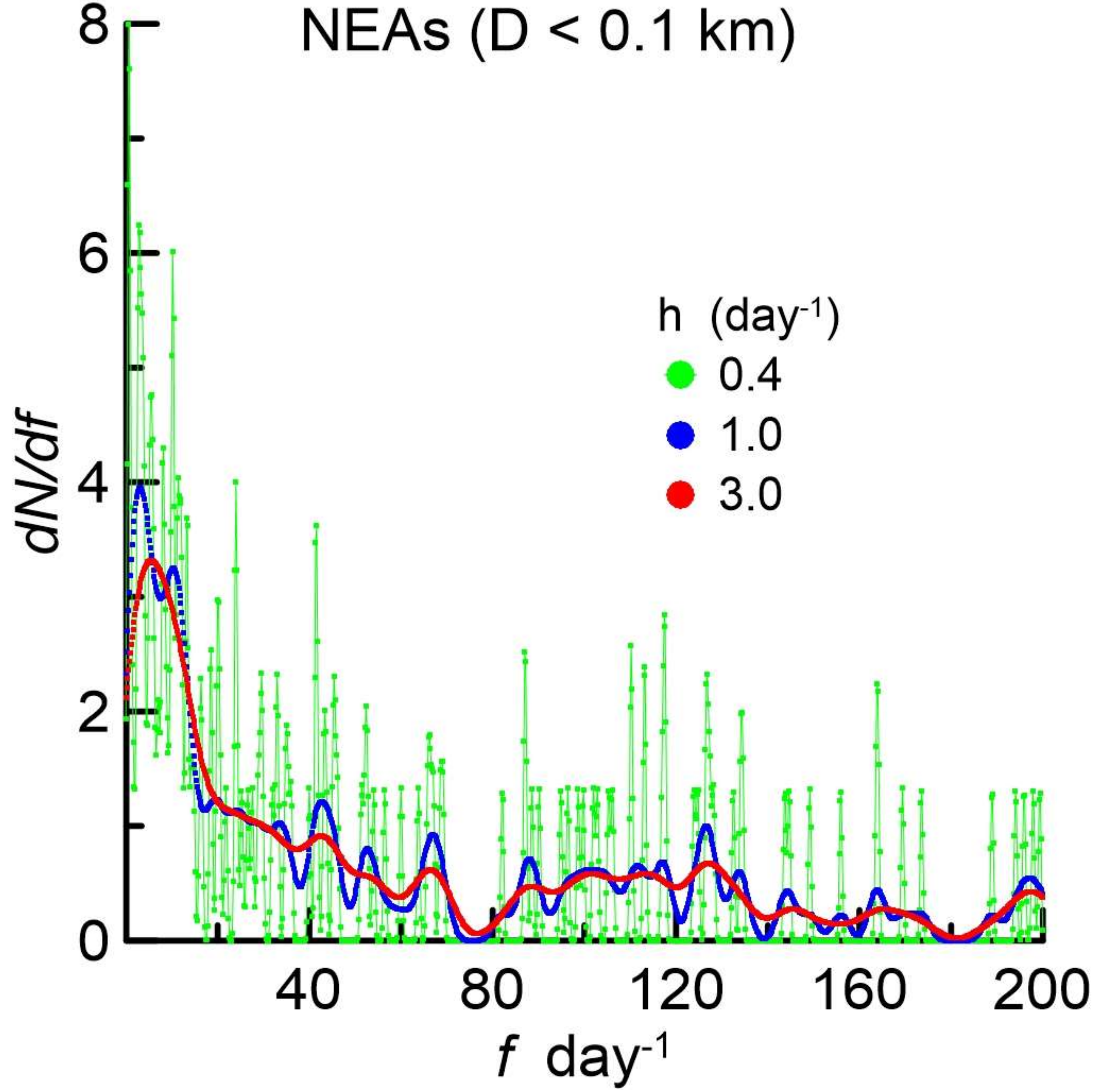
B. ~~Due to the triaxial nature of non spherical asteroids the observed frequencies do not behave linearly to the angular momentum.~~

C. The slowly rotating heavy asteroids aquire their angular momenta through the collisional process where the colliding objects are in kinematical equilibrium in a plane (e.g., protoplanetary disk).

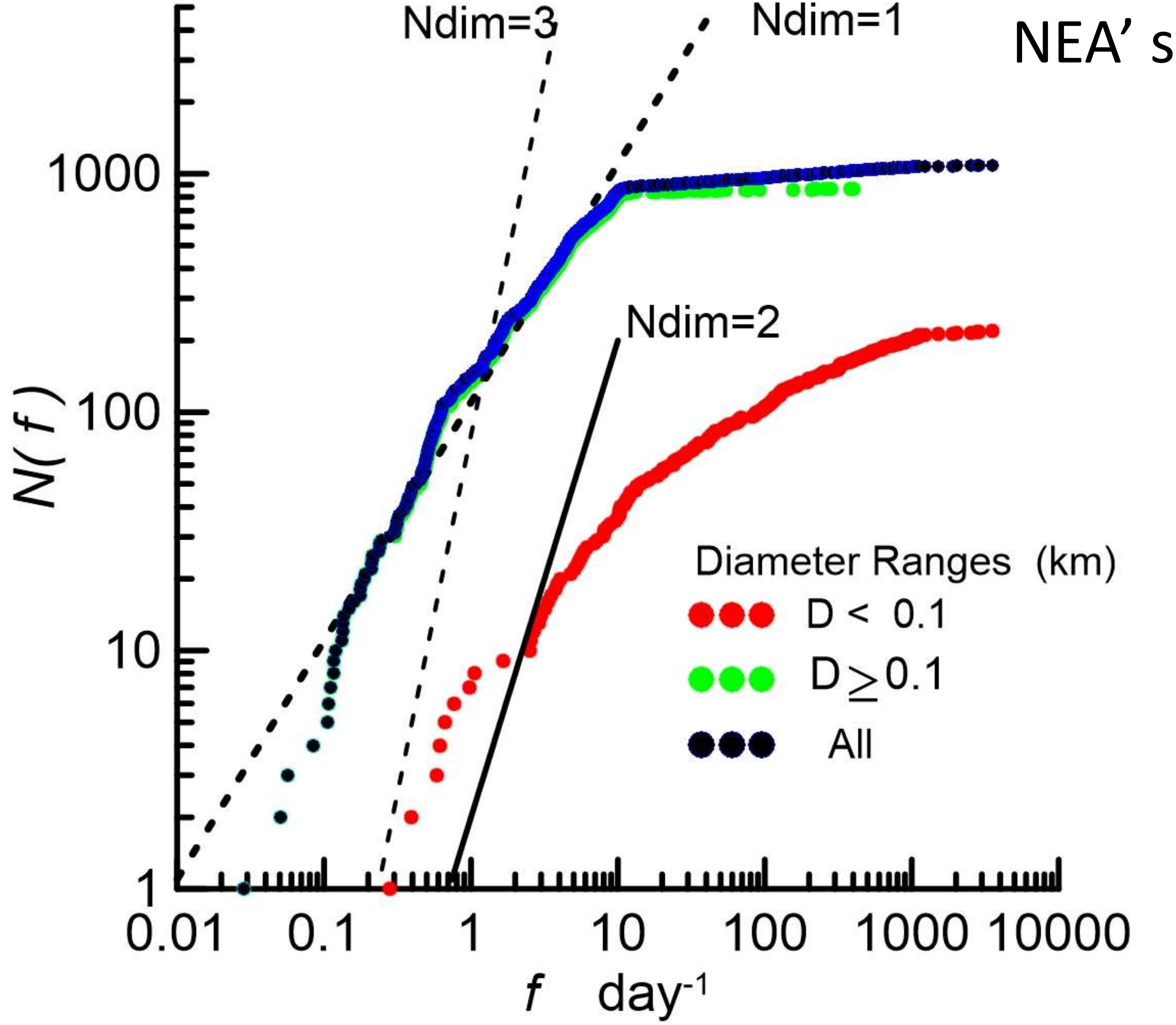
Conclusion

- Rotational frequency distribution of main-belt large asteroids may carry some important information on the kinematical structure of the protoplanetary disk, such as energy distribution, density and temperature. etc.
- Systematic numerical sumulatons are being in progress.

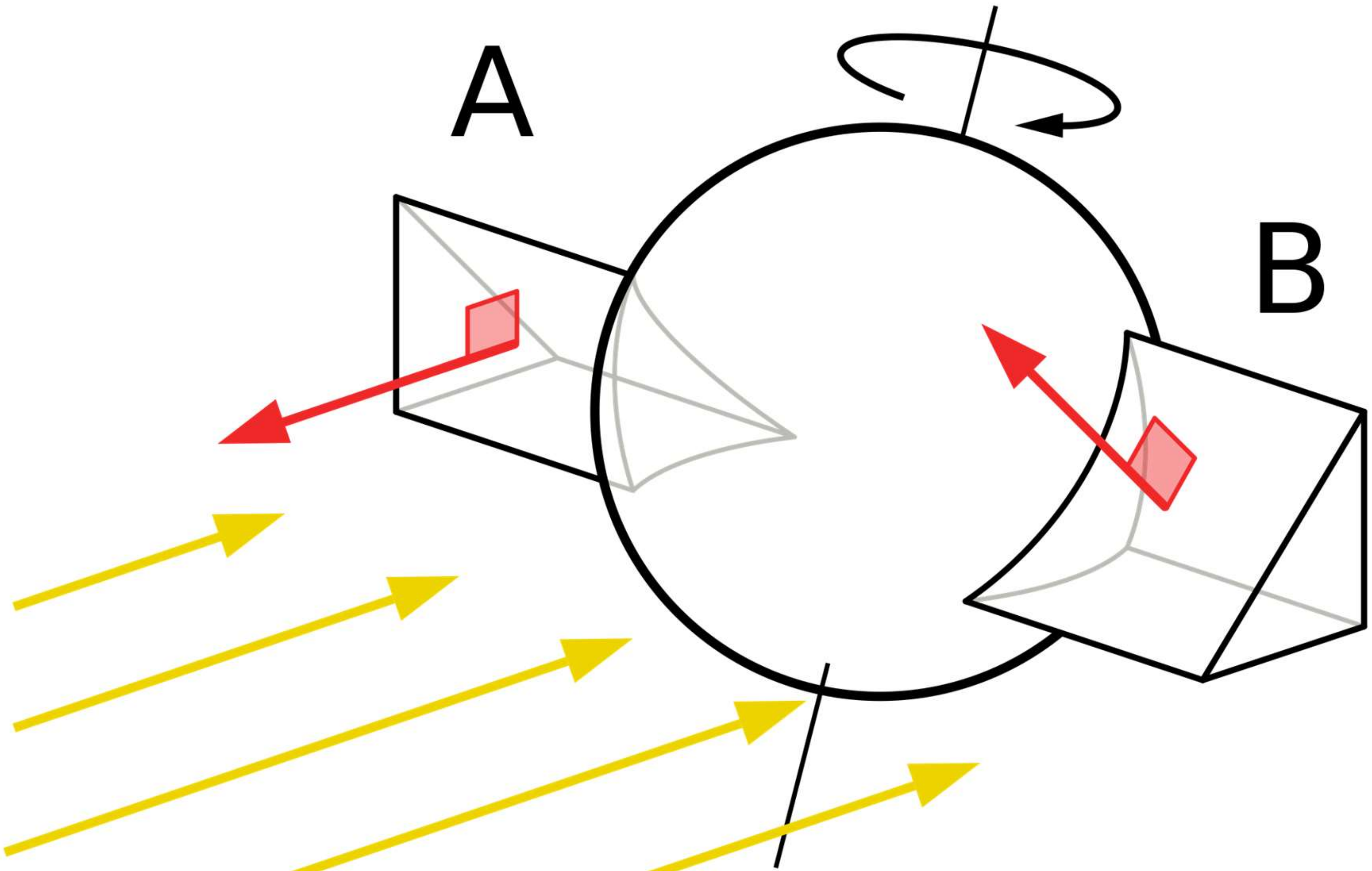

NEA' s
Centrifugal limit
for rubble piles
10000
1000
100
10
1
0.1
0.01
f day -1
0.001
0.01
0.1
1
10
100
D km



NEAs (D < 0.1 km)
8
6
4
2
0
40
80
120
160
200
dN/df
f day-1
h (day-1)
0.4
1.0
3.0



NEA' s
Ndim=3
Ndim=1
Ndim=2
N(f)
1000
100
10
1
0.01
0.1
1
10
100
1000
10000
f day-1
Diameter Ranges (km)
D < 0.1
D ≥ 0.1
All



YORP Effect
(Yarkovsky–O'Keefe–Radzievskii–Paddack)

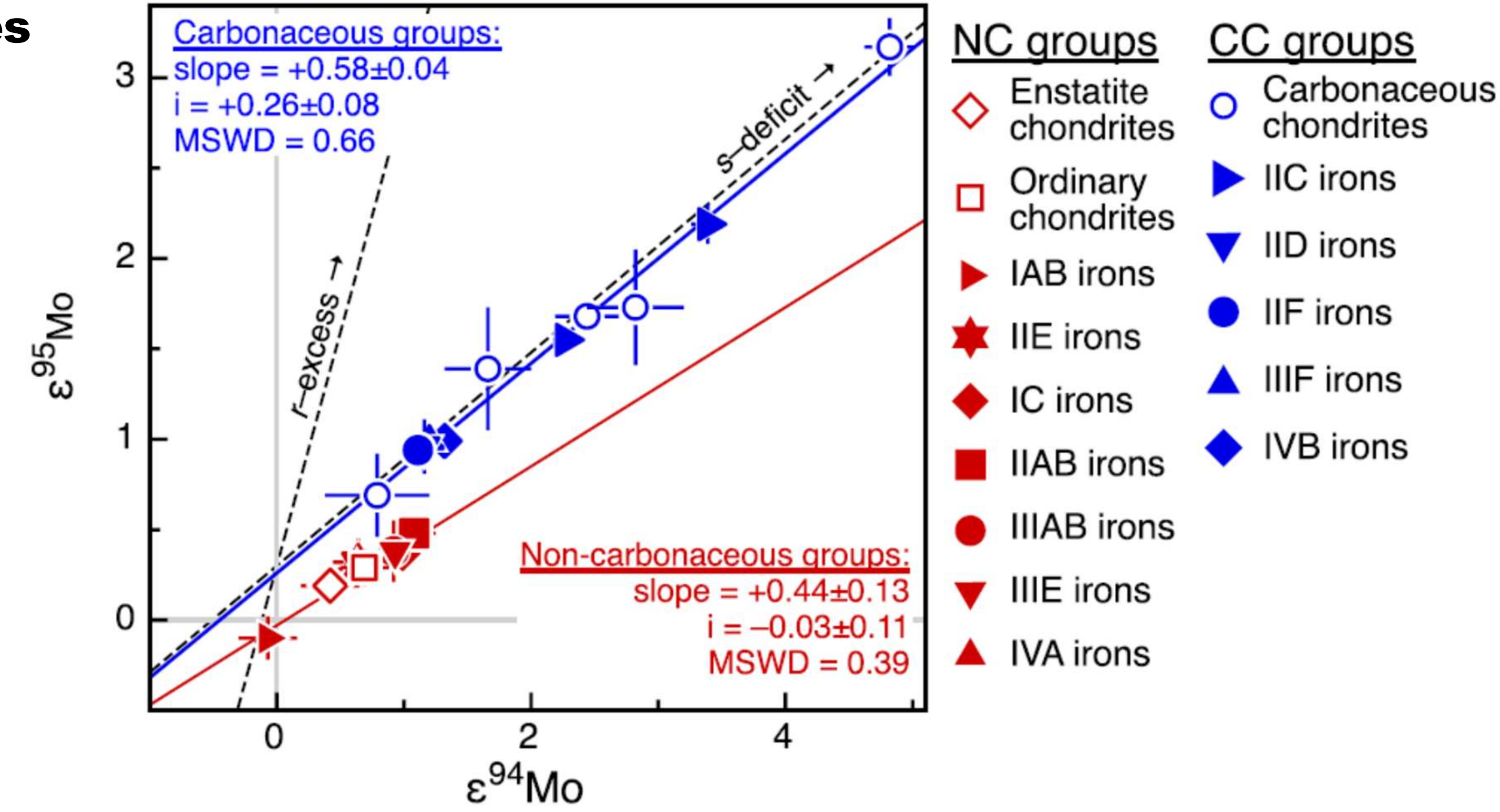
Conclusion

- Slowly rotating Heavy Main Belt asteroids should carry the promodial proto-planetary disk (2 dimensional),
- Near Earth Asteroids with D>0.1km are consistent to 1D rotational phase space (possibly YORP effects).
- Further smaller ones might be collisional fragments....

Thank you and see you again,

Buon Viaggio !!

Ages



Kruijer et al. 2017

Meteorites

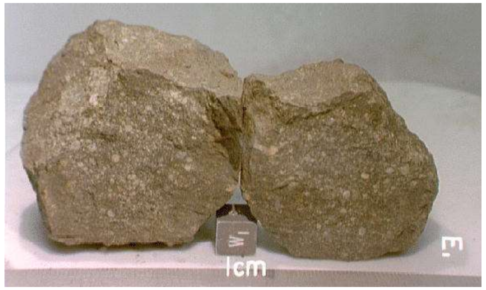
Achondrites (non-chondrite)

Iron

HED (basaltic)

Chondrites

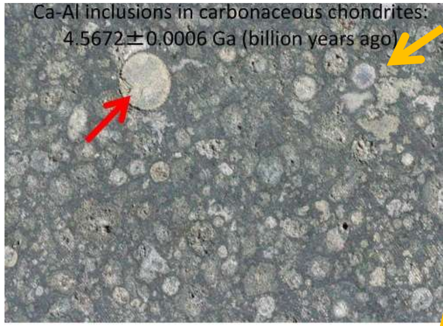
Carbonaceous



Ordinary

Chondrules

Ca-Al-rich inclusions (CAI)



Highly Heated

Never or slightly heated

85-87% all meteorites