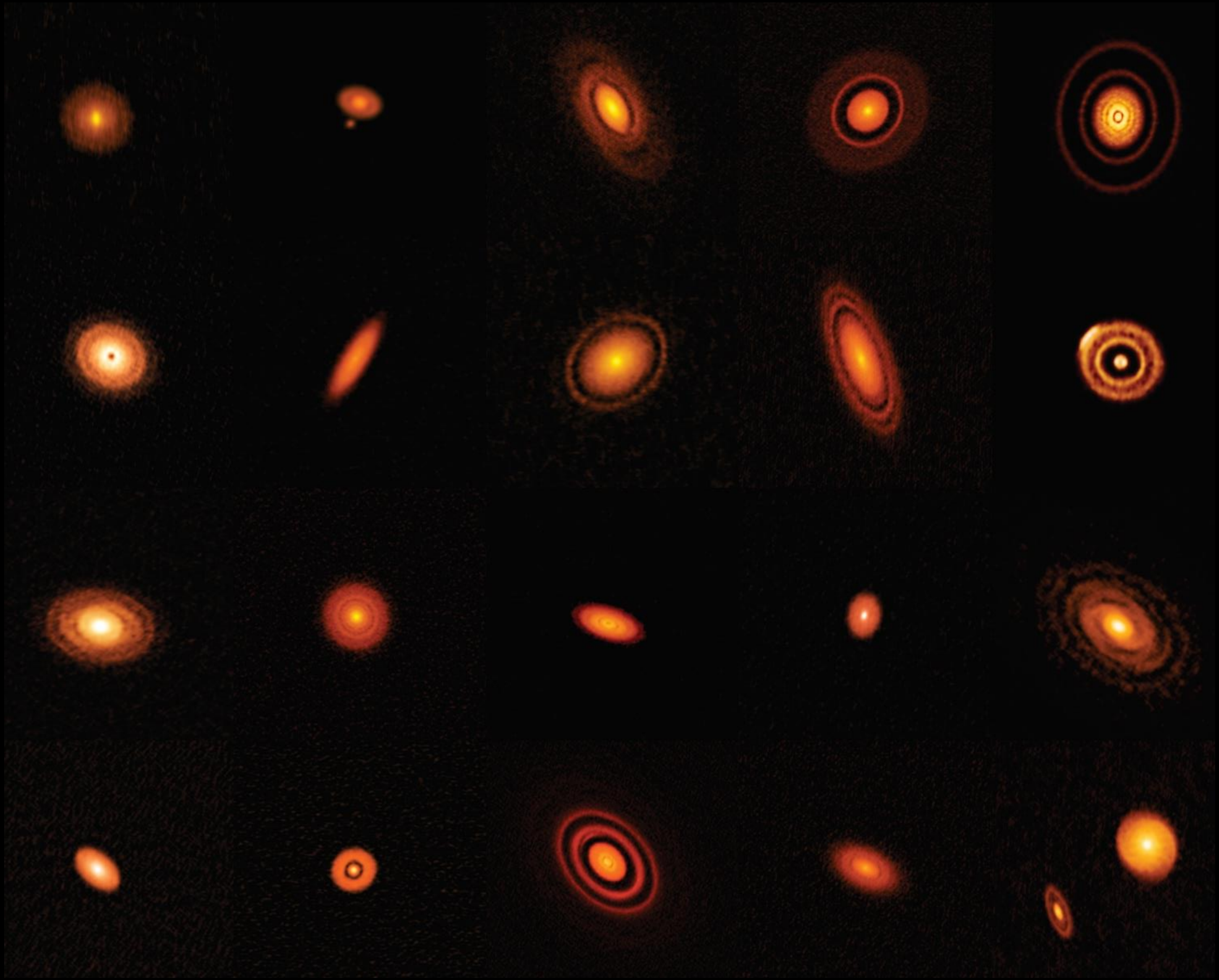
The Massalia asteroid family as the main source of meteorites

Marsset, Vernazza, Brož et al. (2024) - Nature

Michaël Marsset

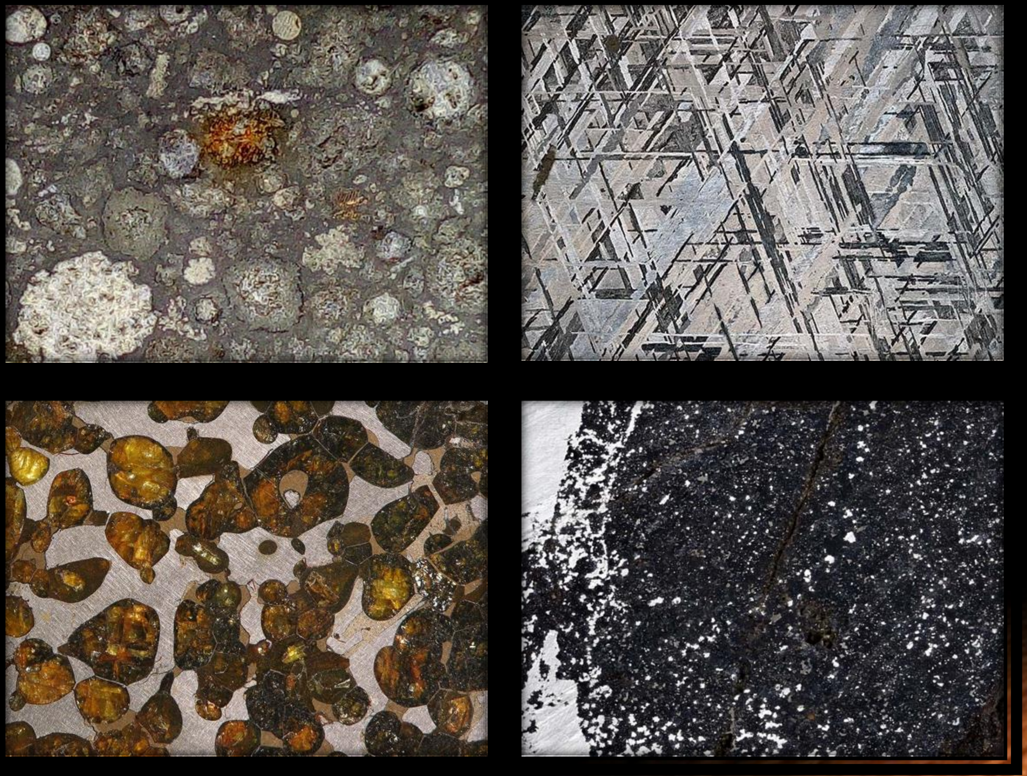
ESO-Paranal Research Fellow

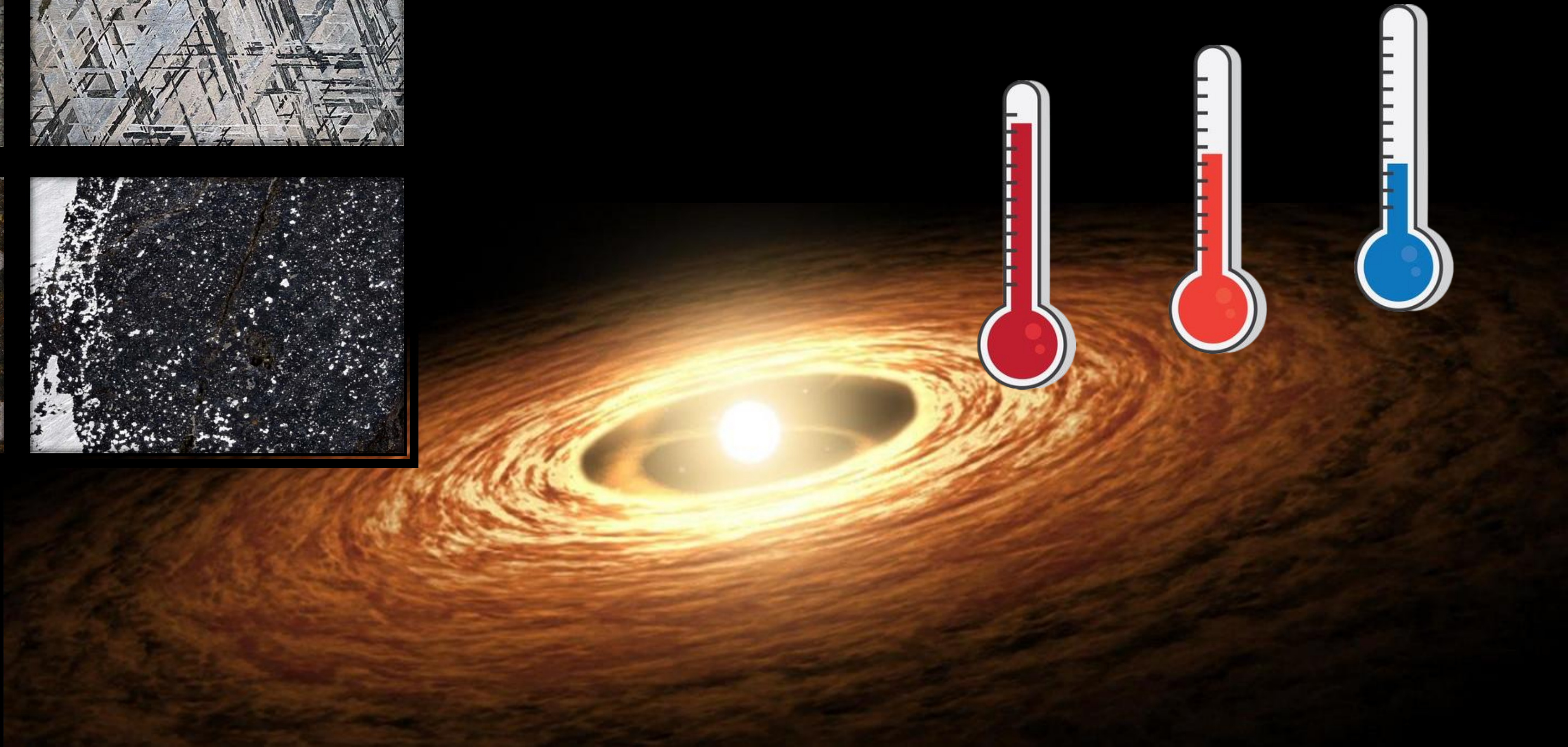
03/09/2024 – OCA, Nice



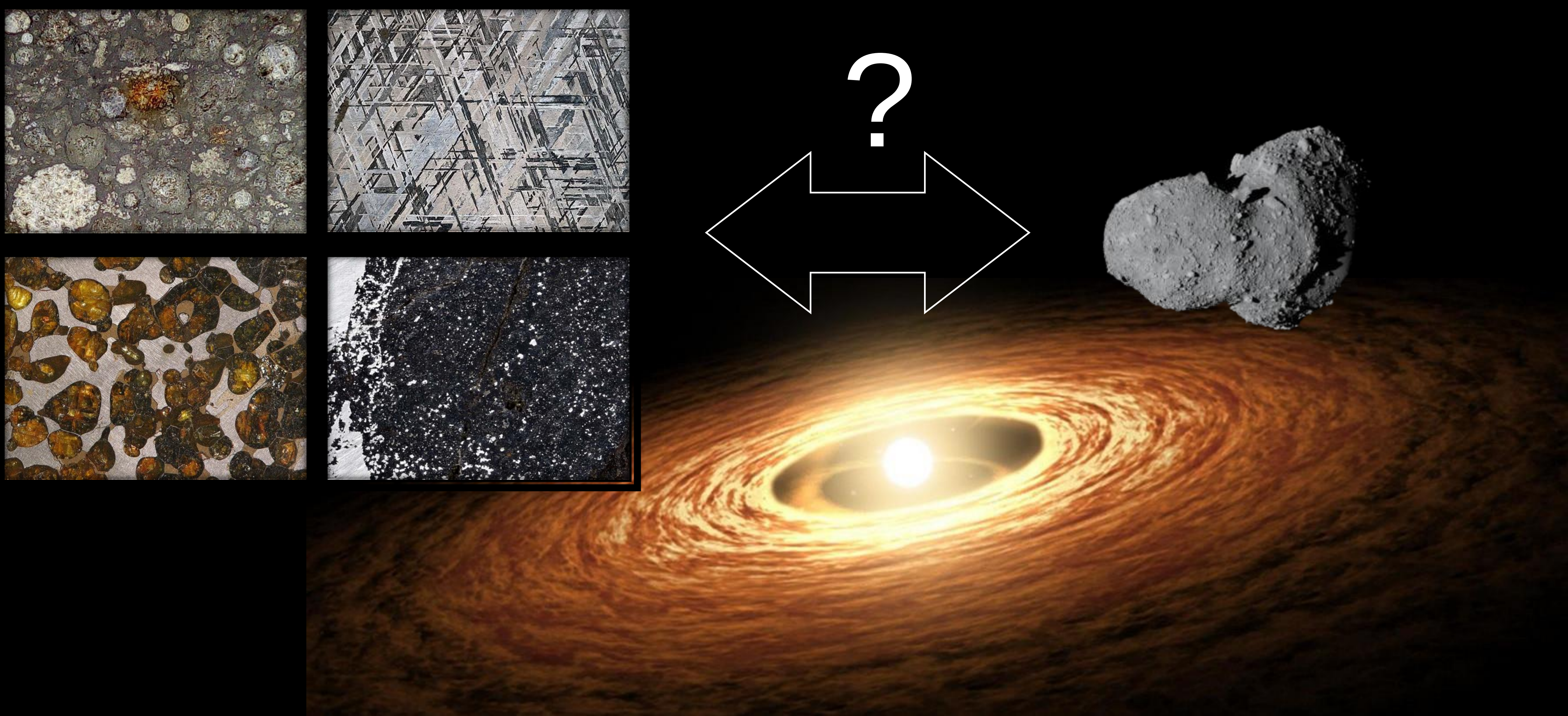



Where from?



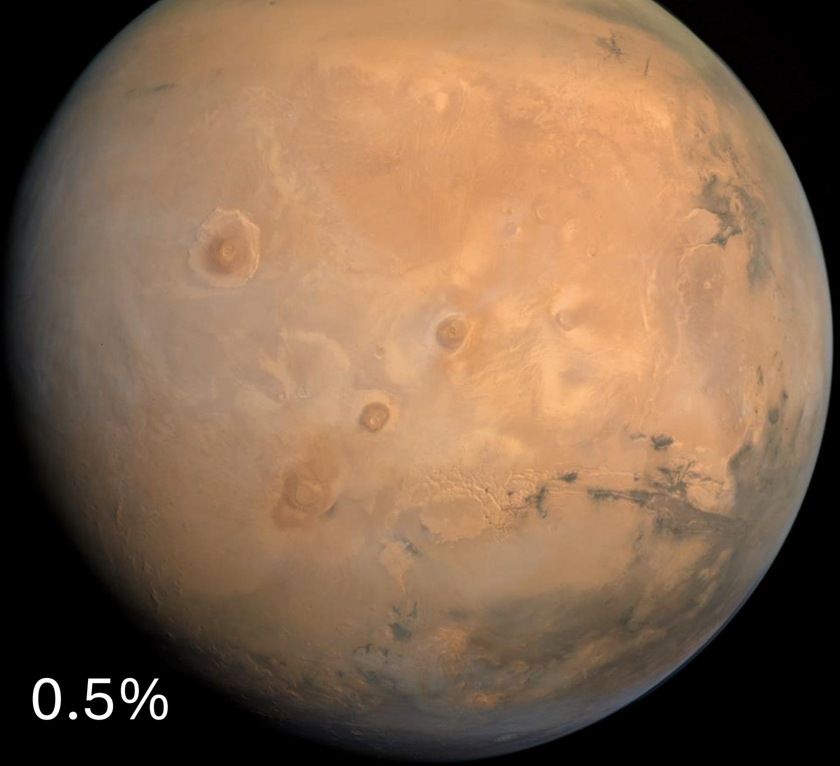


What asteroids from?



We know the origins of 7% of meteorites

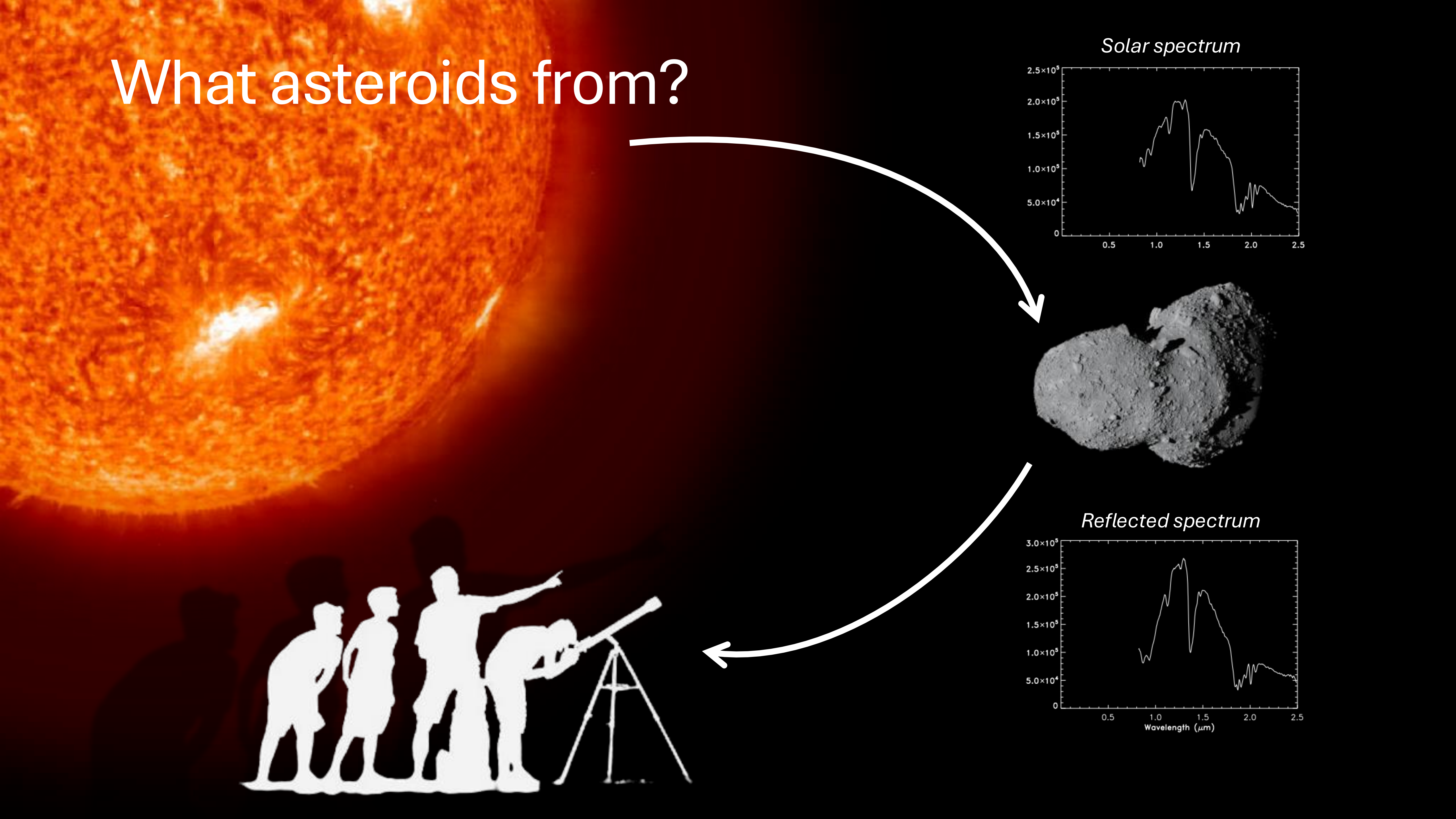
0.7%



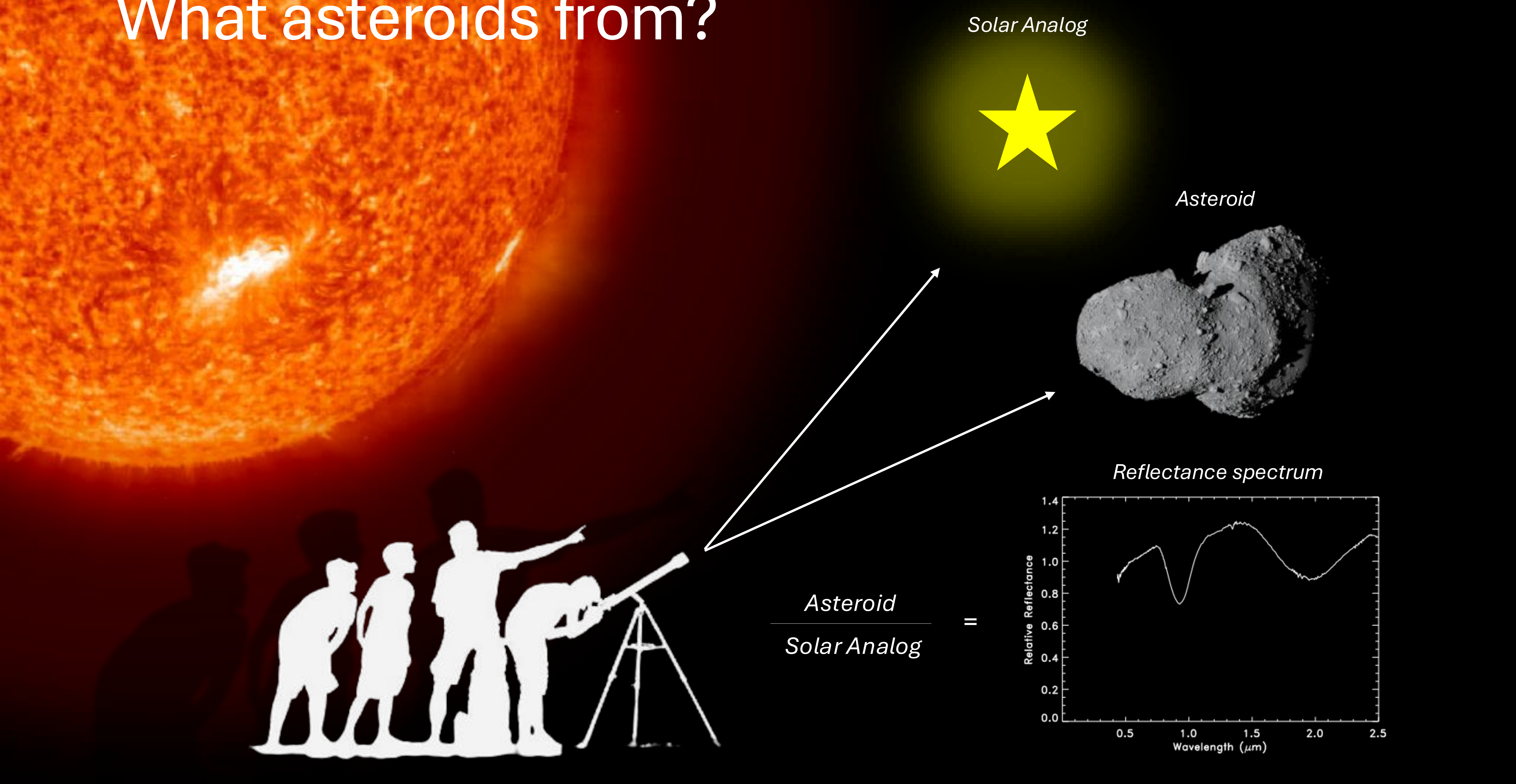
0.5%

6.0%

What asteroids from?



What asteroids from?



What asteroids from?

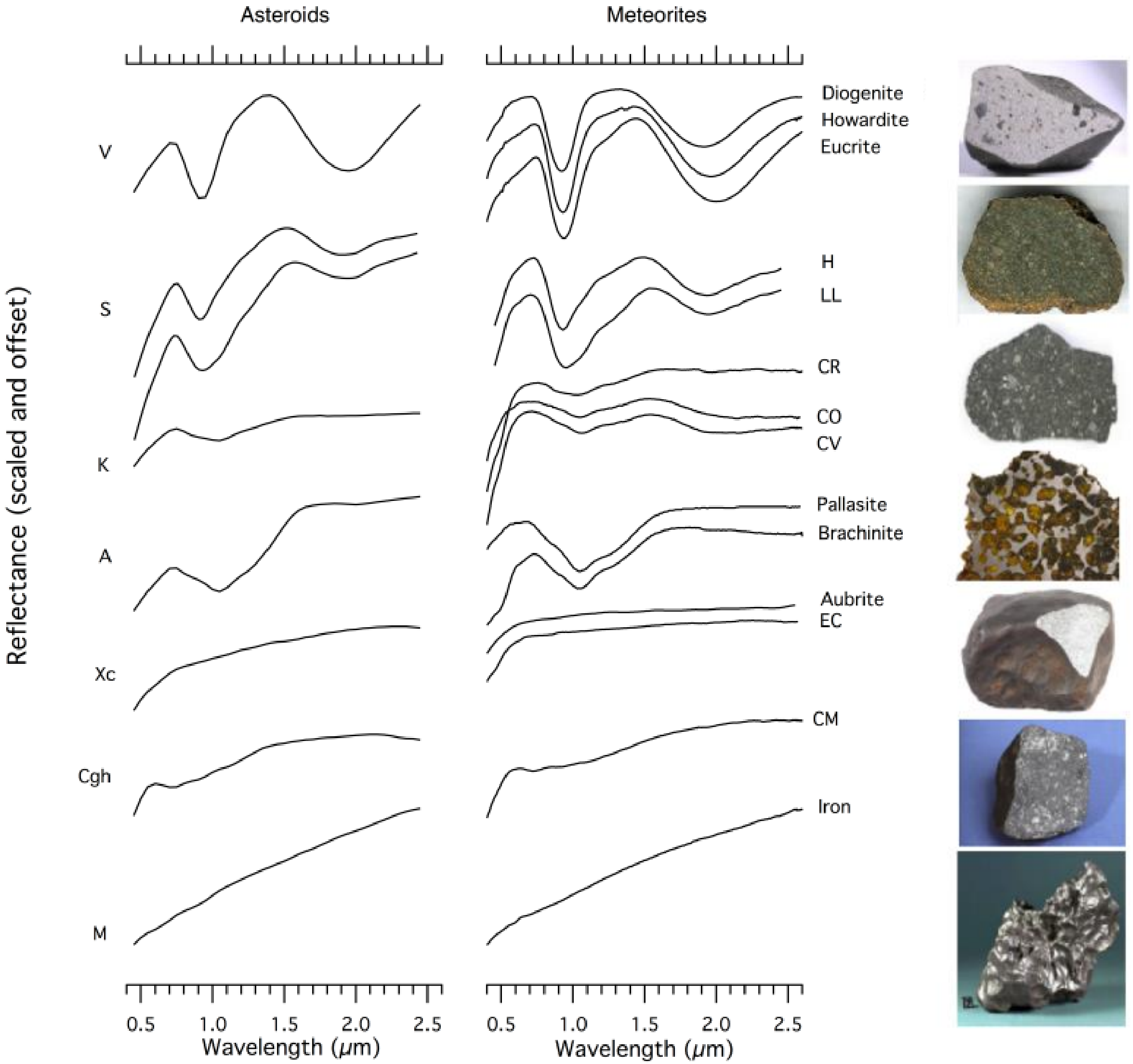
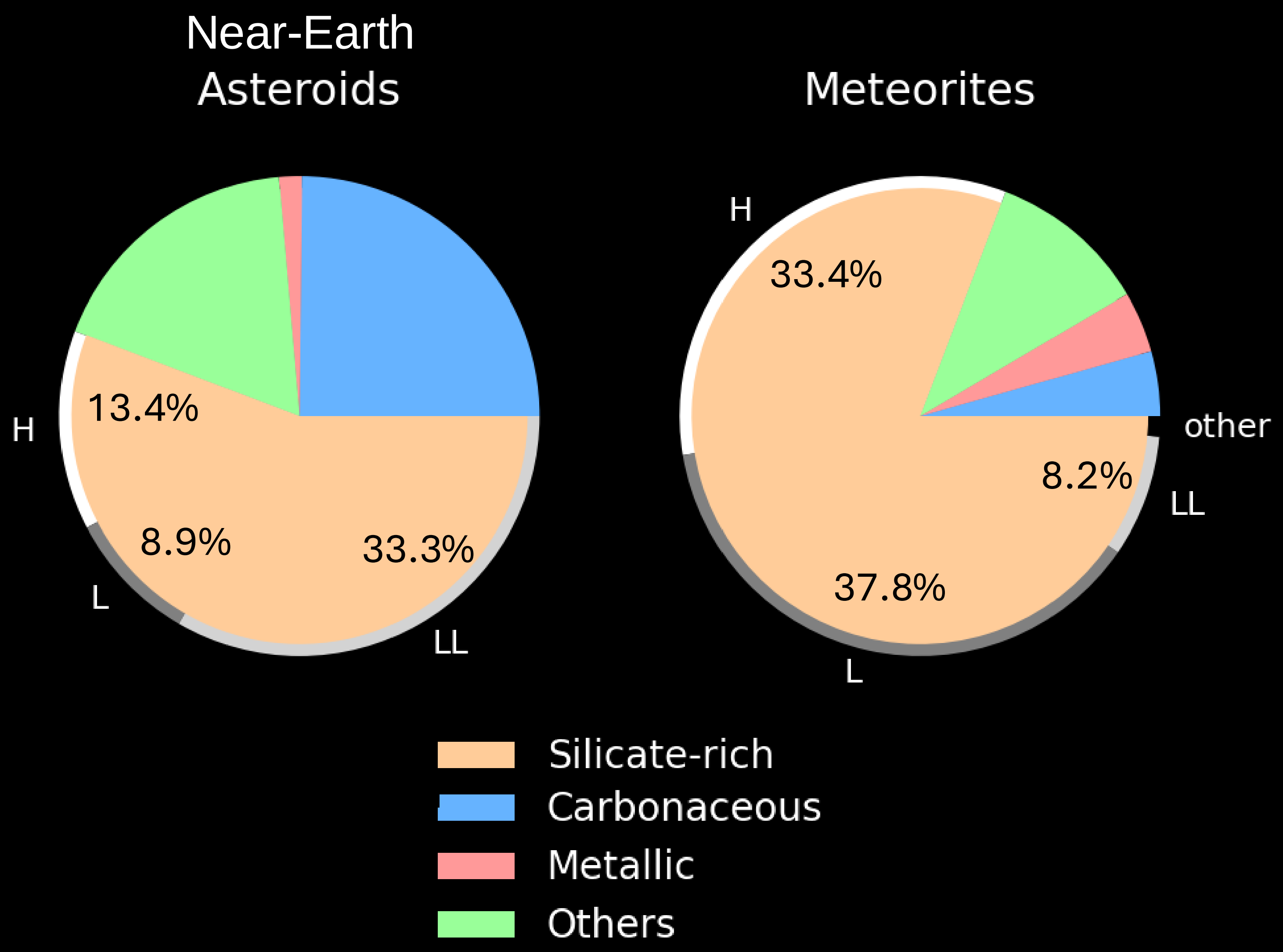


Figure adapted from
Vernazza & Beck (2016)

The asteroid-meteorite conundrum



Letter | Published: 14 August 2008

Compositional differences between meteorites and near-Earth asteroids

P. Vernazza, R. P. Binzel, C. A. Thomas, F. E. DeMeo, S. J. Bus, A. S. Rivkin & A. T. Tokunaga

Nature **454**, 858–860 (2008) | Cite this article

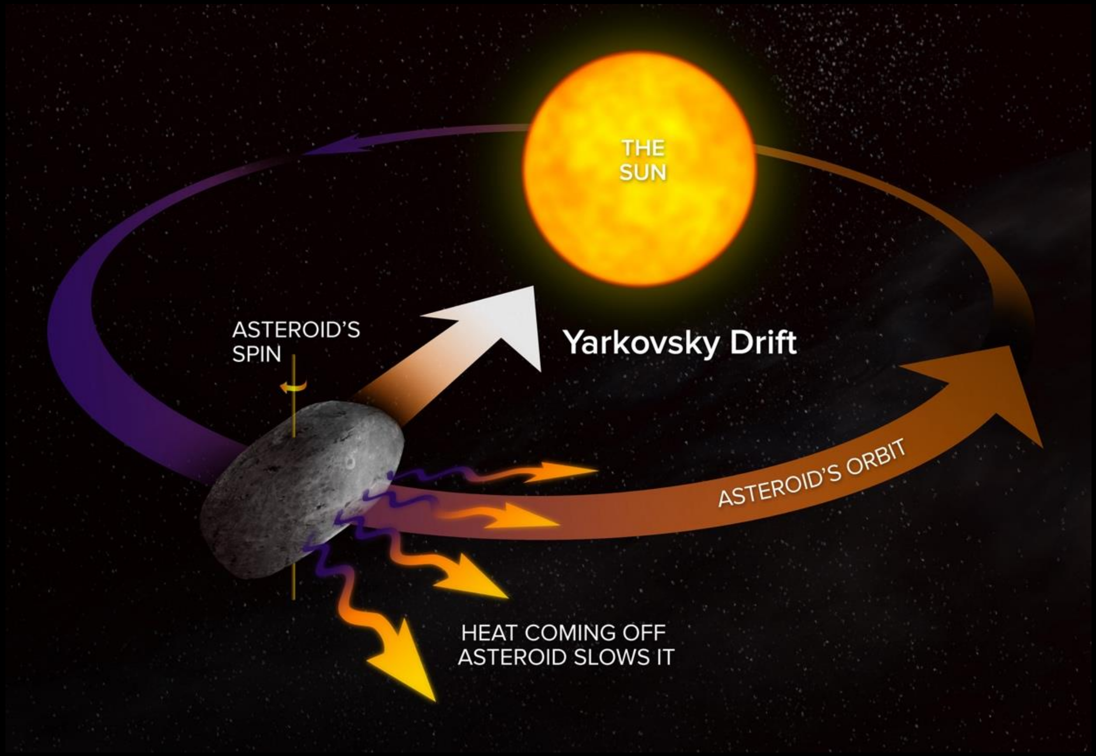
How do asteroids move around in the Solar System?

Stochastic processes

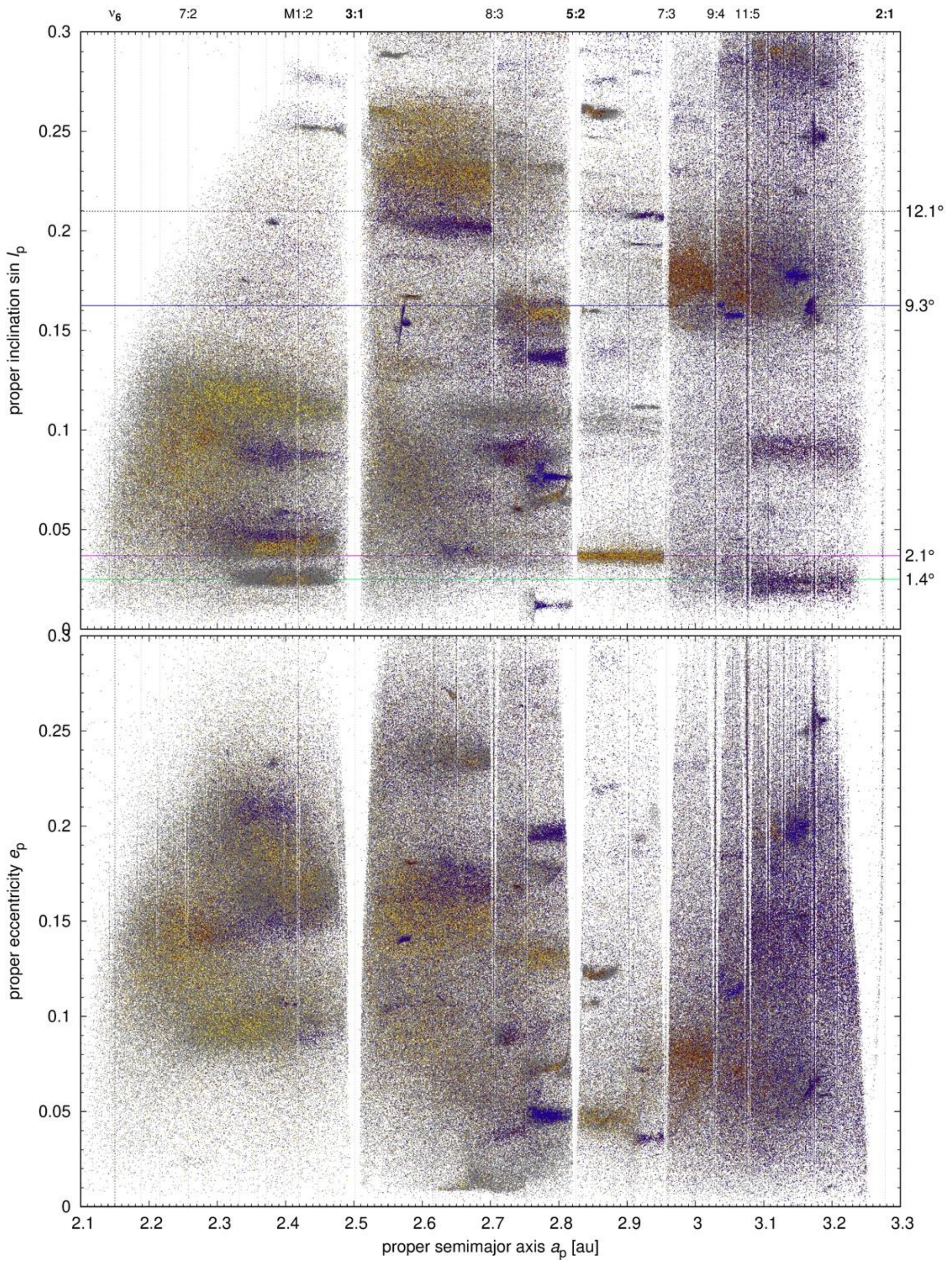
- Chaotic diffusion
- Planetary encounters
- Collisions

Deterministic processes

- Yarkosky drift
- Mean-motion resonances
- Secular resonances
- Kozai resonances
- Poynting Robertson (dust)



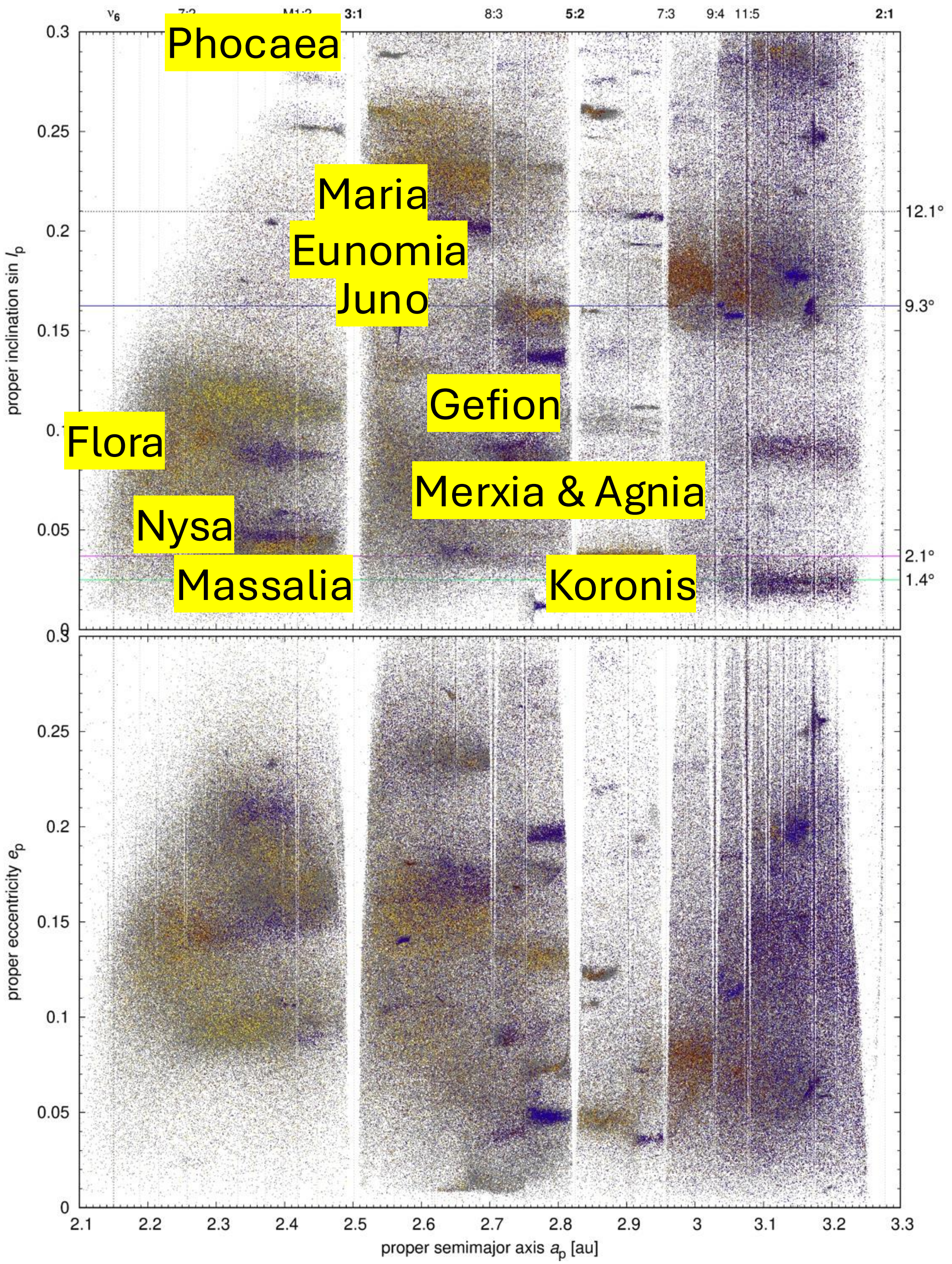
Orbital distribution of the main belt



Color means albedo
From bright to faint

Figure from
Brož, Vernazza, Marsset
et al. 2024, *Nature*

Spectroscopic survey of asteroid families



Silicate-rich families

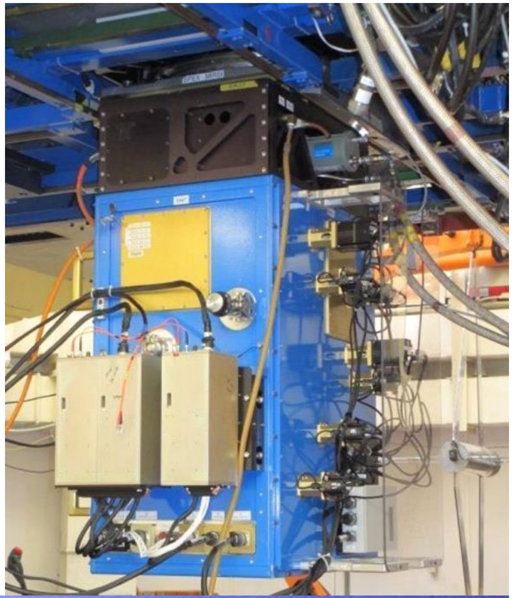
Color means albedo
From bright to faint

Figure from
Brož, Vernazza, Marsset et al. 2024, *Nature*

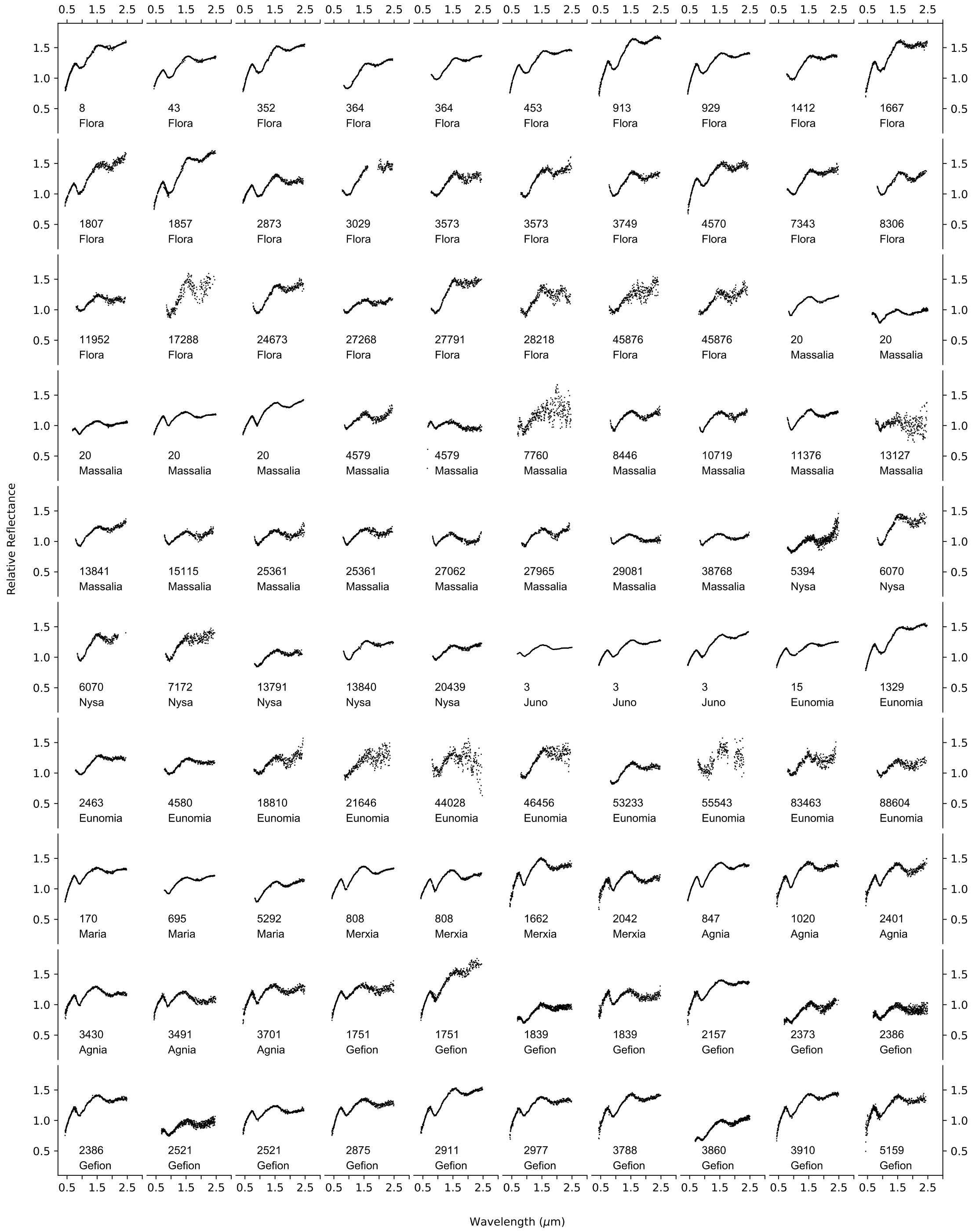
Spectroscopic survey of asteroid families

SpeX

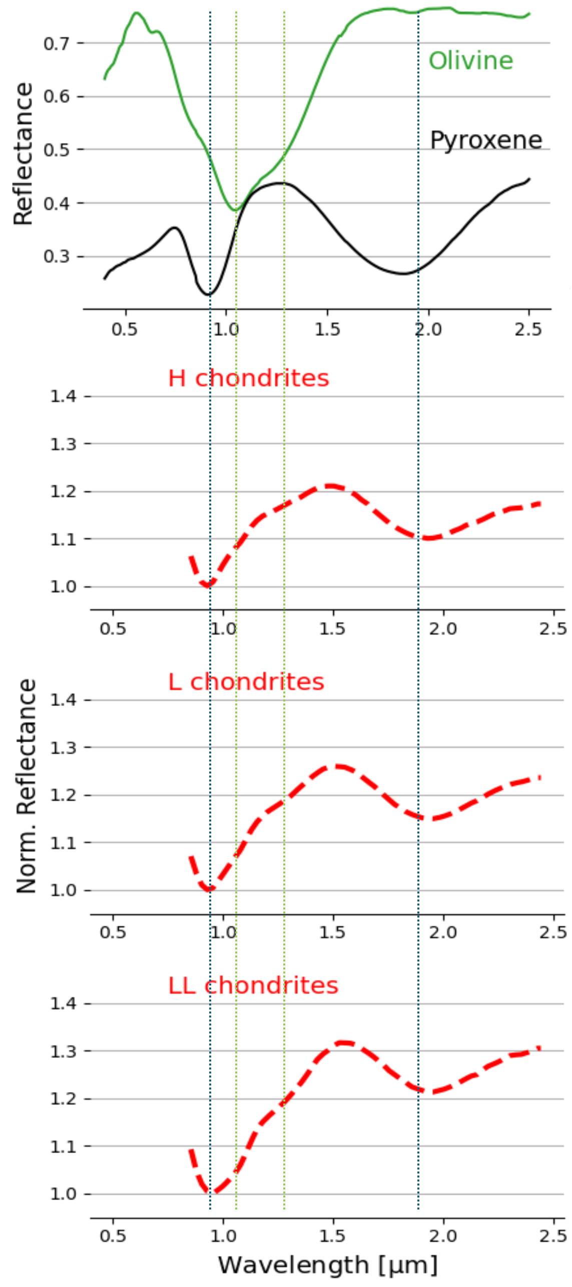
- Medium-resolution 0.8-5.4 µm spectrograph
- Mounted on the Cassegrain focus of the 3m IRTF telescope at Mauna Kea
- Used in the low-resolution 0.8-2.5 µm prism mode



Spectroscopic survey of asteroid families



H, L, LL chondrites: how to identify them?



Silicate data from Kohout (2021)
Meteorite data from RELAB
https://sites.brown.edu/relab/relab-spectral-database/

Spectral modelling

Inputs

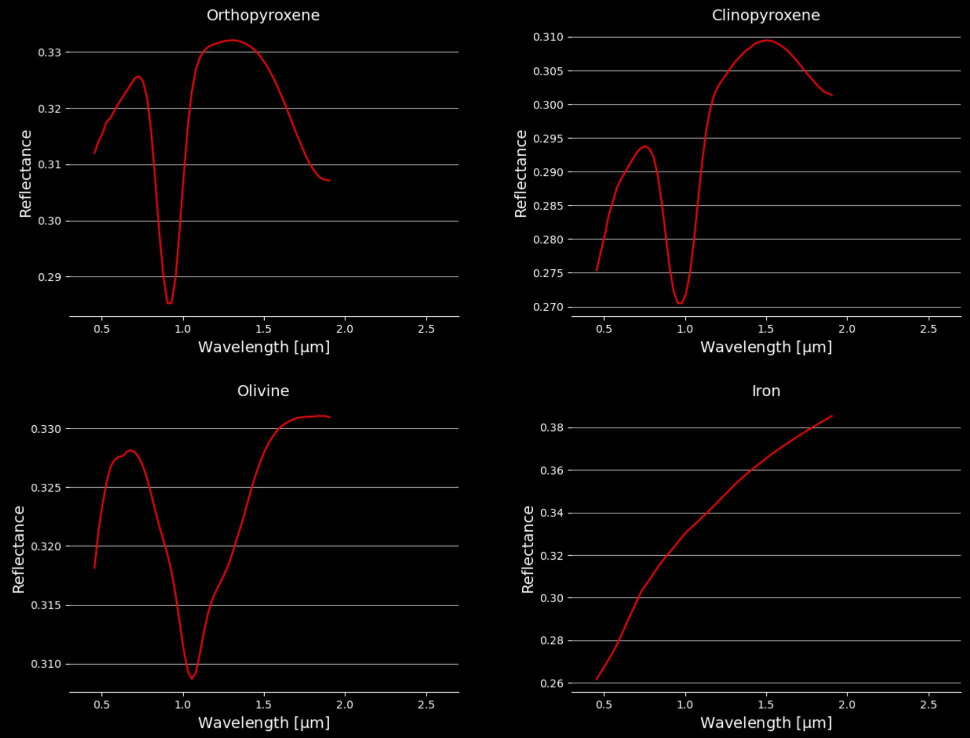
- Optical constants (n+ik)
- Observing geometry (incidence & reflect. angles)
- Grain sizes
- Reddening function
- Others…

Spectral model

e.g., Hapke, Shkuratov

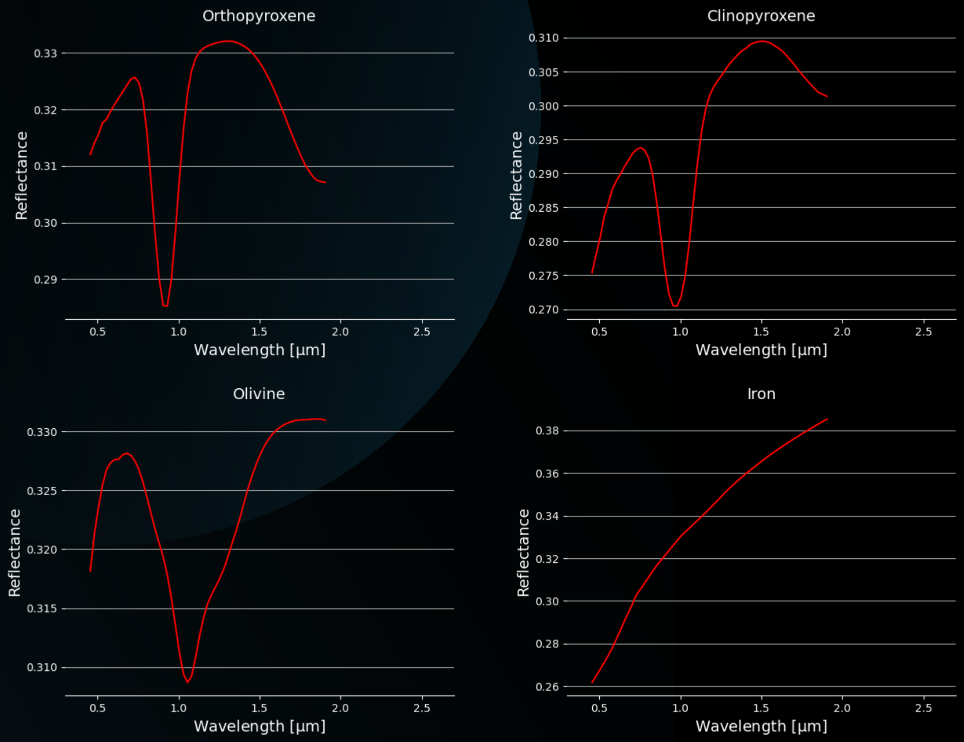
Output

Synthetic mineral spectra

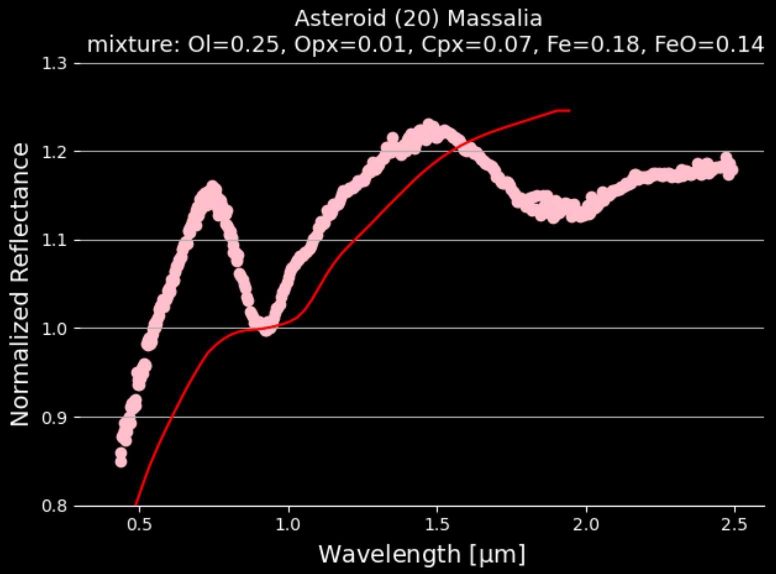


Optimization

Synthetic mineral spectra

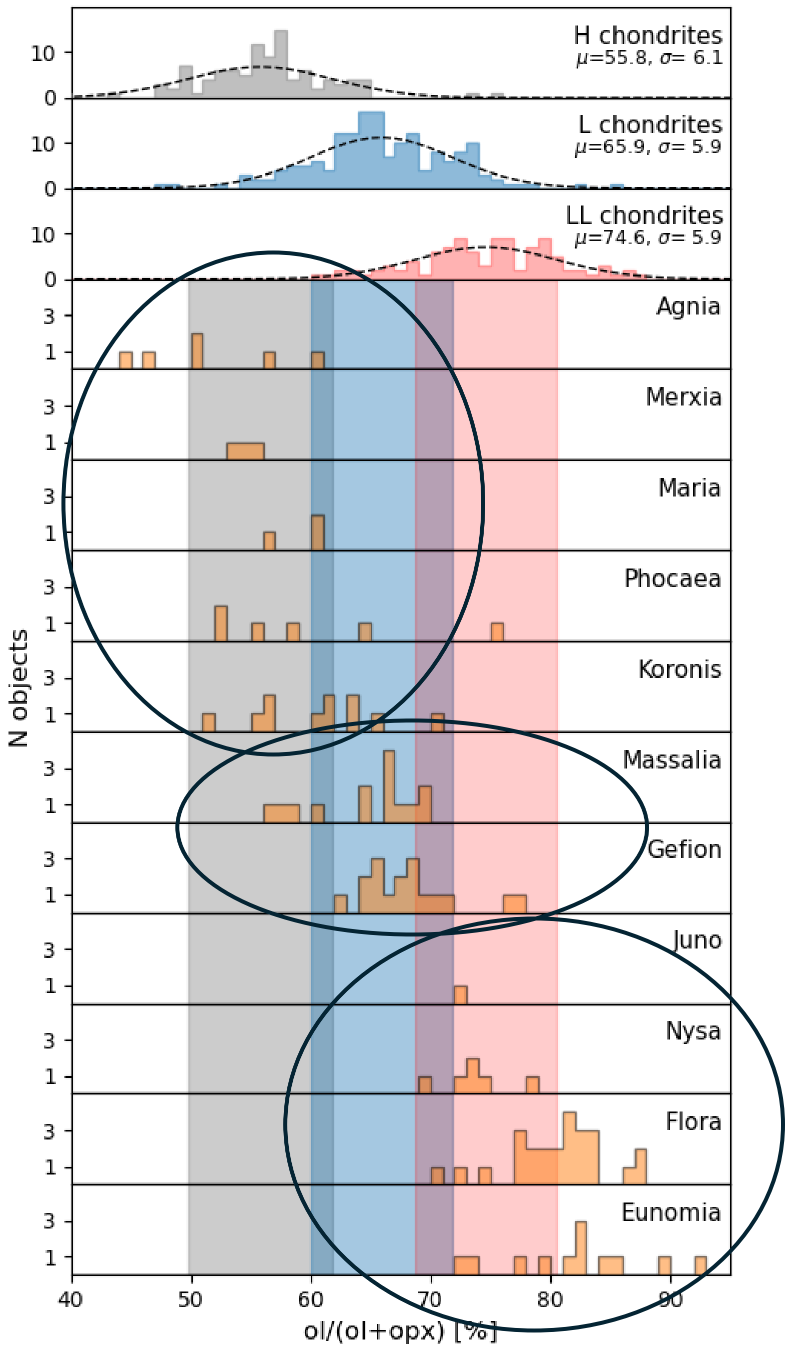


Optimization



Best-fit
mineral abundances
Ol / (Ol+Opx)

Spectroscopic survey of asteroid families



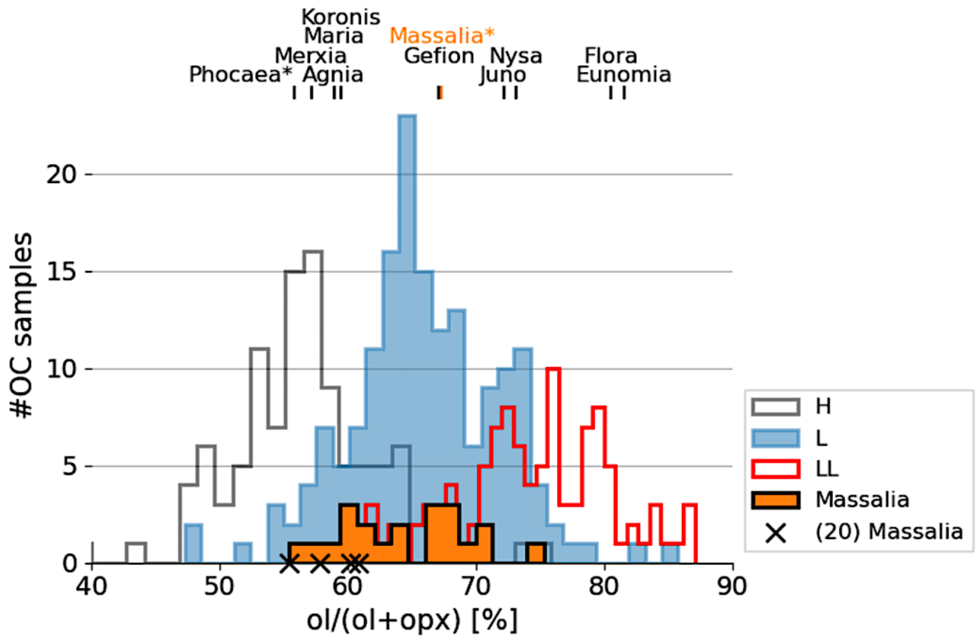
H chondrites

L chondrites

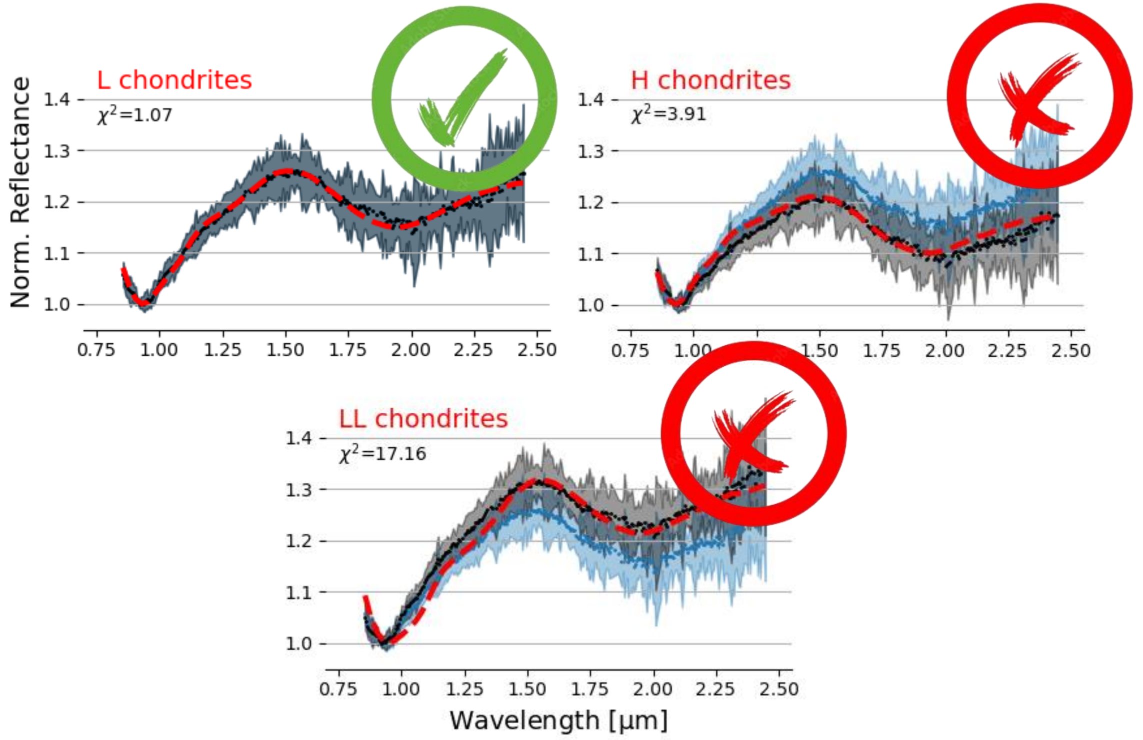
LL chondrites

L-ordinary-like composition for the Massalia family

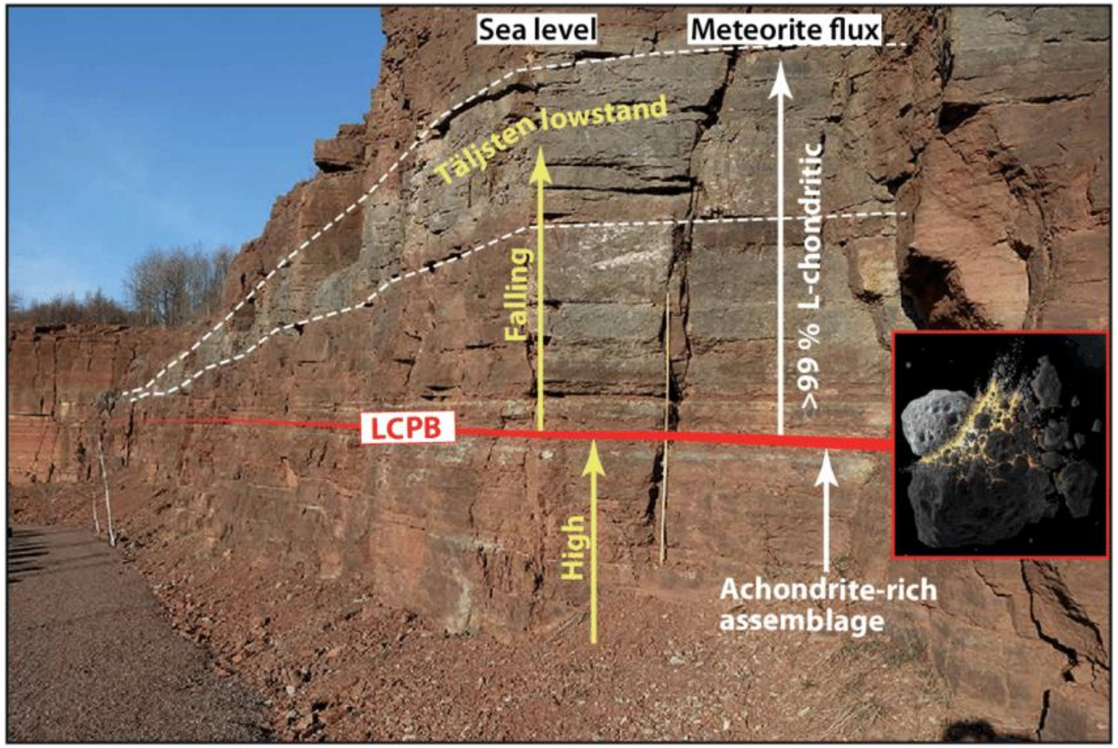
Mineralogy distribution



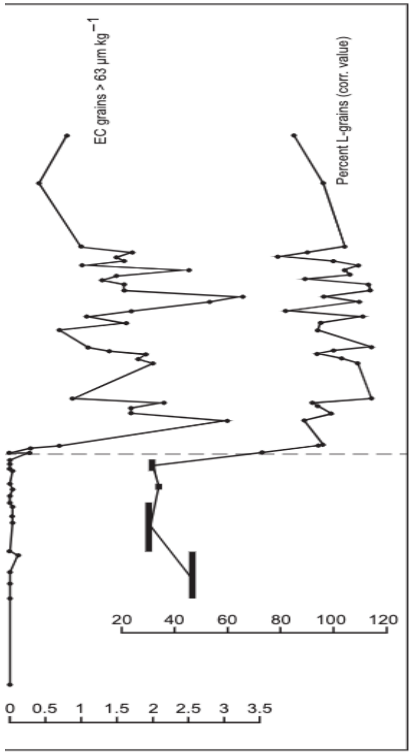
Spectral fits



A rain of L chondrites during the mid-Ordovician period!

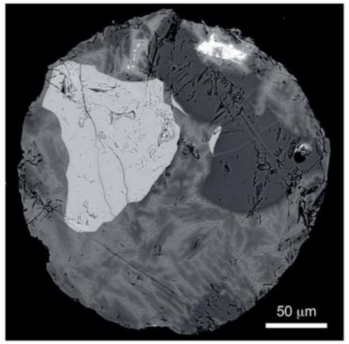


The mid-Ordovician Hällekis section in southern Sweden



Micrometeorites abundance

Back-scattered electron image of chromite grain (light gray) in an Antarctic micrometeorite.



PLANETARY SCIENCE

An extraterrestrial trigger for the mid-Ordovician ice age: Dust from the breakup of the L-chondrite parent body

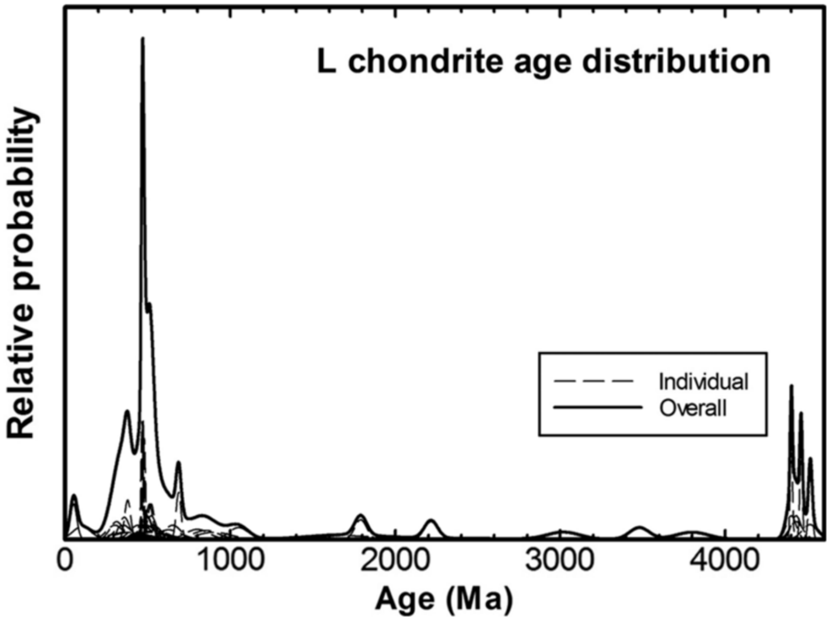
Birger Schmitz[1*], Kenneth A. Farley[2], Steven Goderis[3], Philipp R.
Samuele Boschi[1], Philippe Claeys[7], Vinciane Debaille[8], Andrei Dr
Matthias van Ginneken[11], David A.T. Harper[12], Faisal Iqbal[1], Joha
Ellinor Martin[1], Matthias M. M. Meier[15,16], Bernhard Peucker-Ehre
Rainer Wieler[15], Fredrik Terfelt[1]

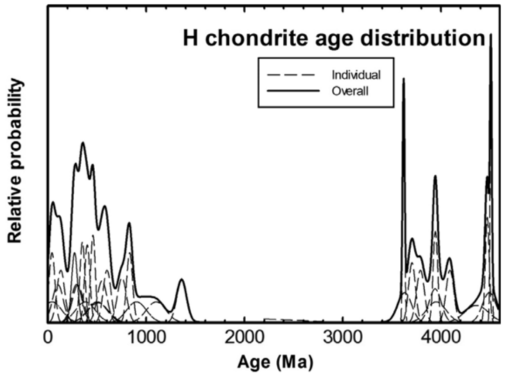
The breakup of the L-chondrite parent body in the asteroid belt 466 millio
third of all meteorites falling on Earth. Our new extraterrestrial chromite a
show that the breakup took place just at the onset of a major, eustatic se
Ordovician ice age. Shortly after the breakup, the flux to Earth of the most
increased by three to four orders of magnitude. In the present stratosphere
all the dust and has no climatic significance. Extraordinary amounts of dust
>2 Ma following the L-chondrite breakup cooled Earth and triggered Ordov
and major faunal turnovers related to the Great Ordovician Biodiversificati

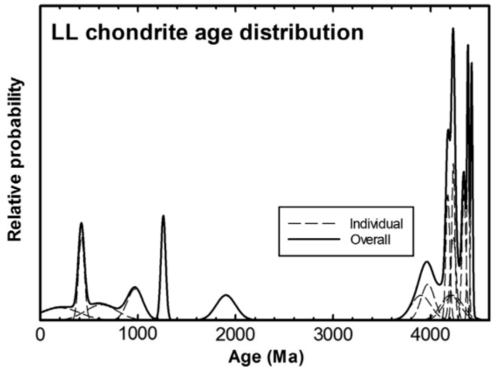
Most (all?) present-day L chondrites trace back to the mid-Ordovician event

Argon isotope age of ordinary chondrites

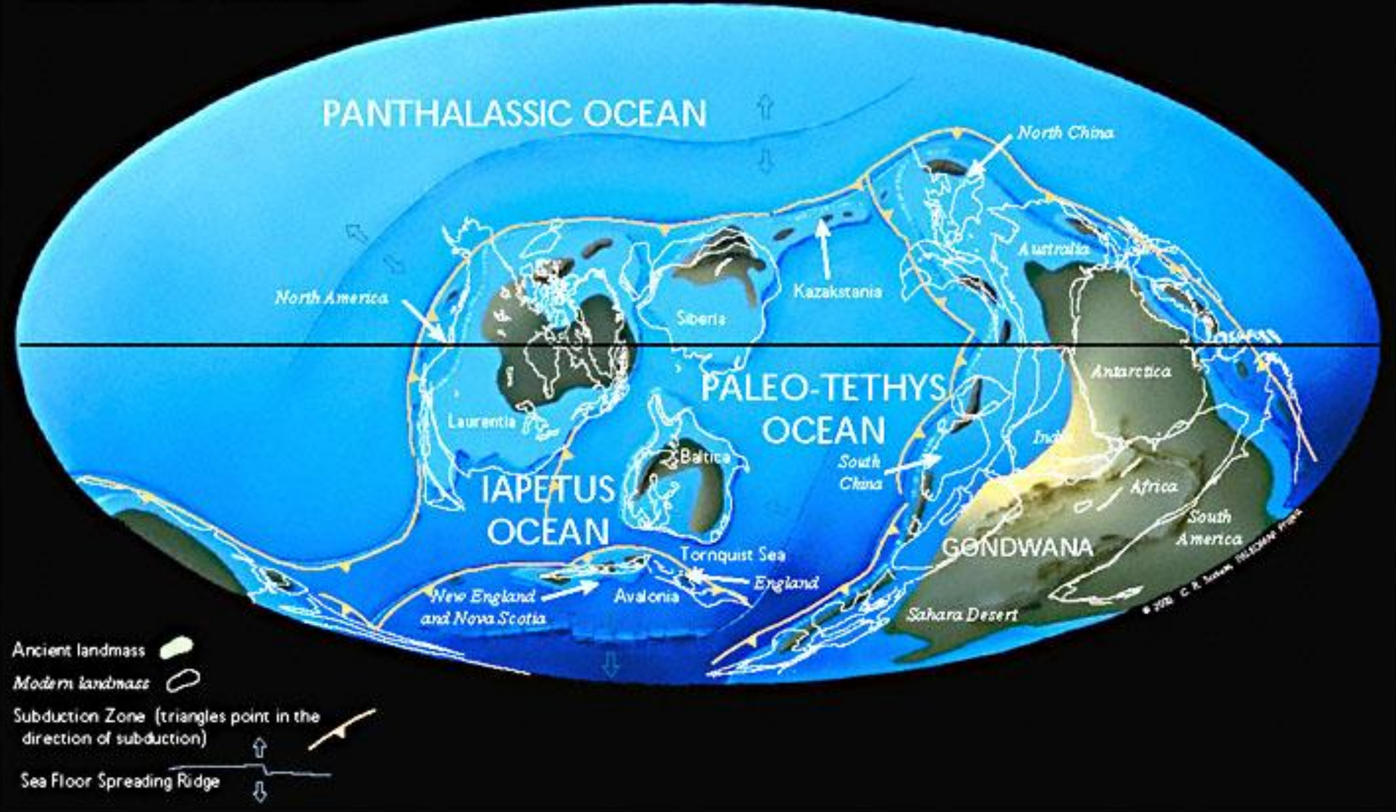
Swindle et al. (2014)

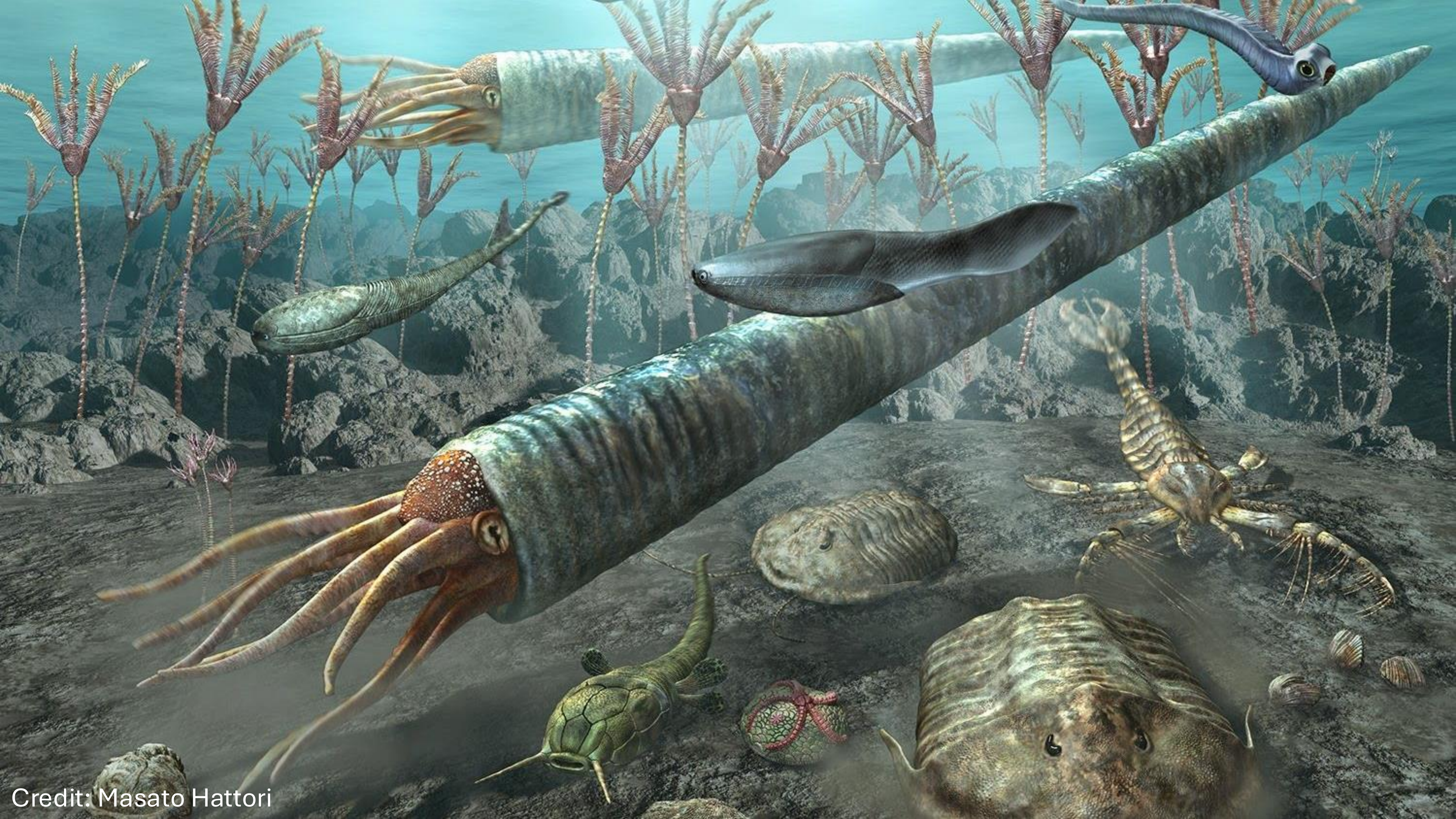






Middle Ordovician 458 Ma

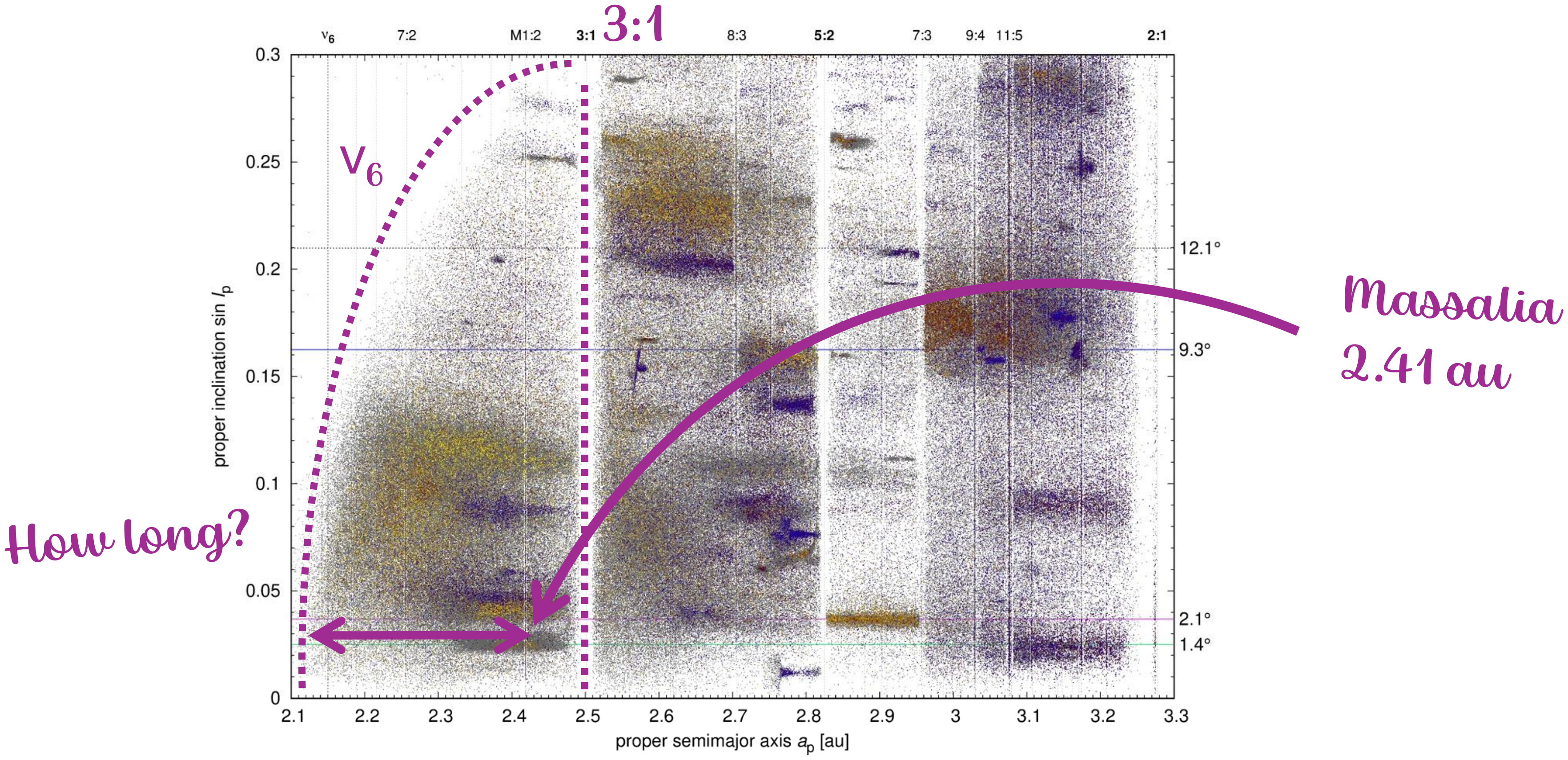




Credit: Masato Hattori

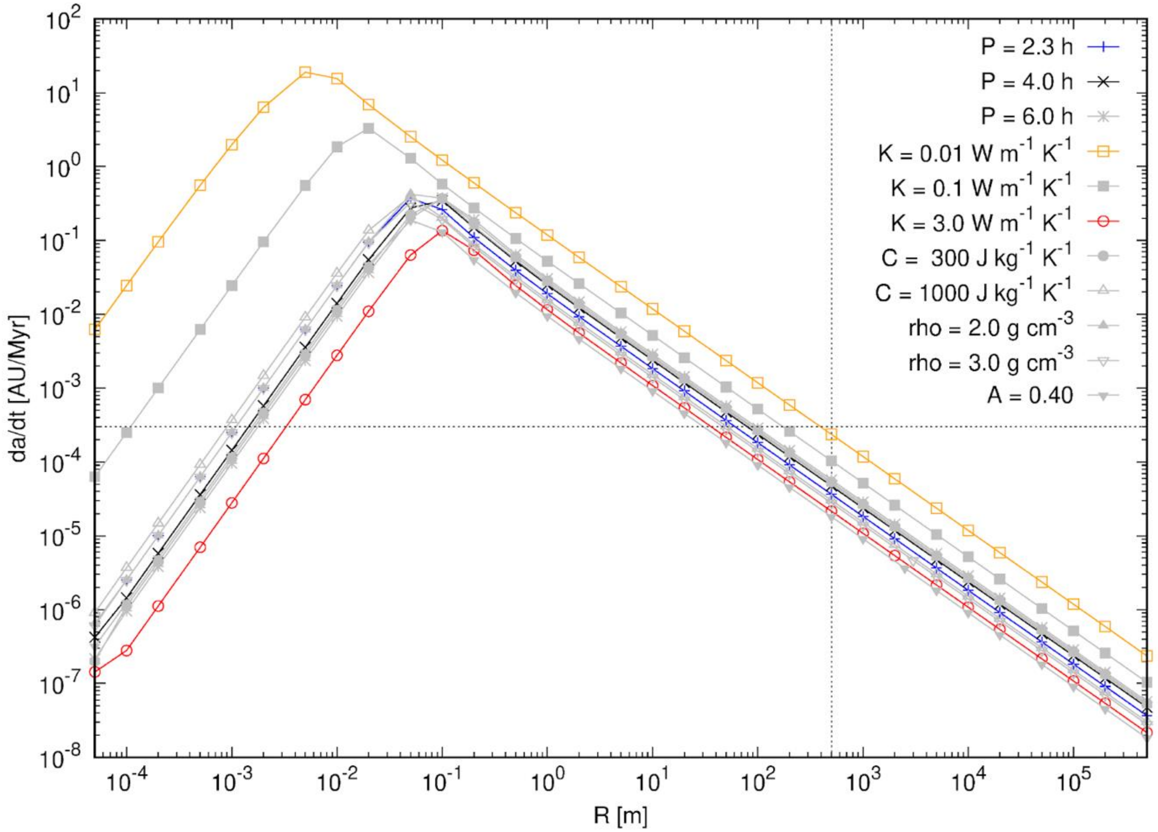
1. Near-Earth Objects

Orbital pathways to the Earth



What objects can reach the resonances?

Yarkovski drift rate



Distance = 0.26 au

Diameter = 1 m → t = 7 – 130 Myr

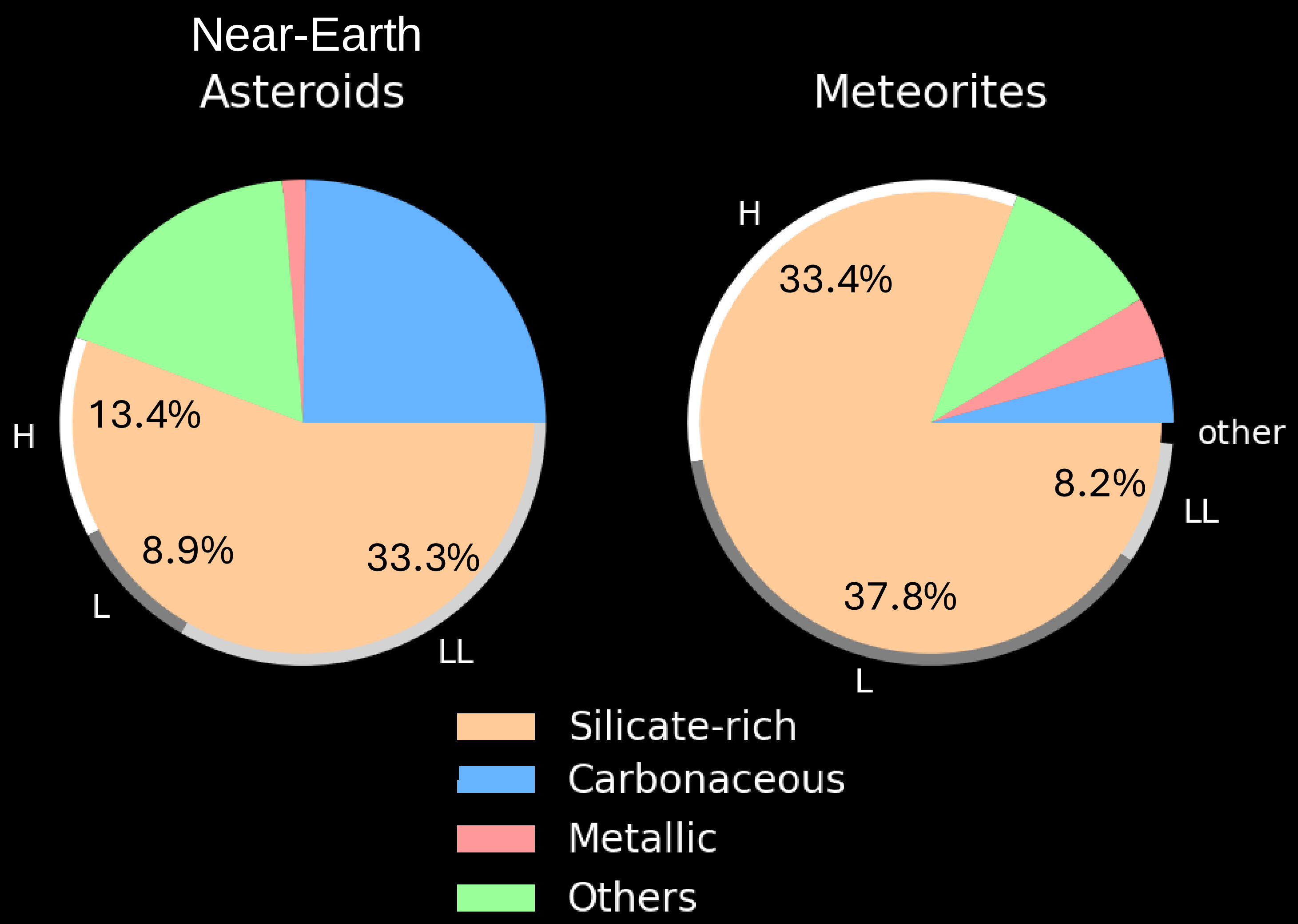
Diameter = 300 m → t = 870 Myr – 13 Byr

Reminder: The Ordovician event happened 470 Myr ago

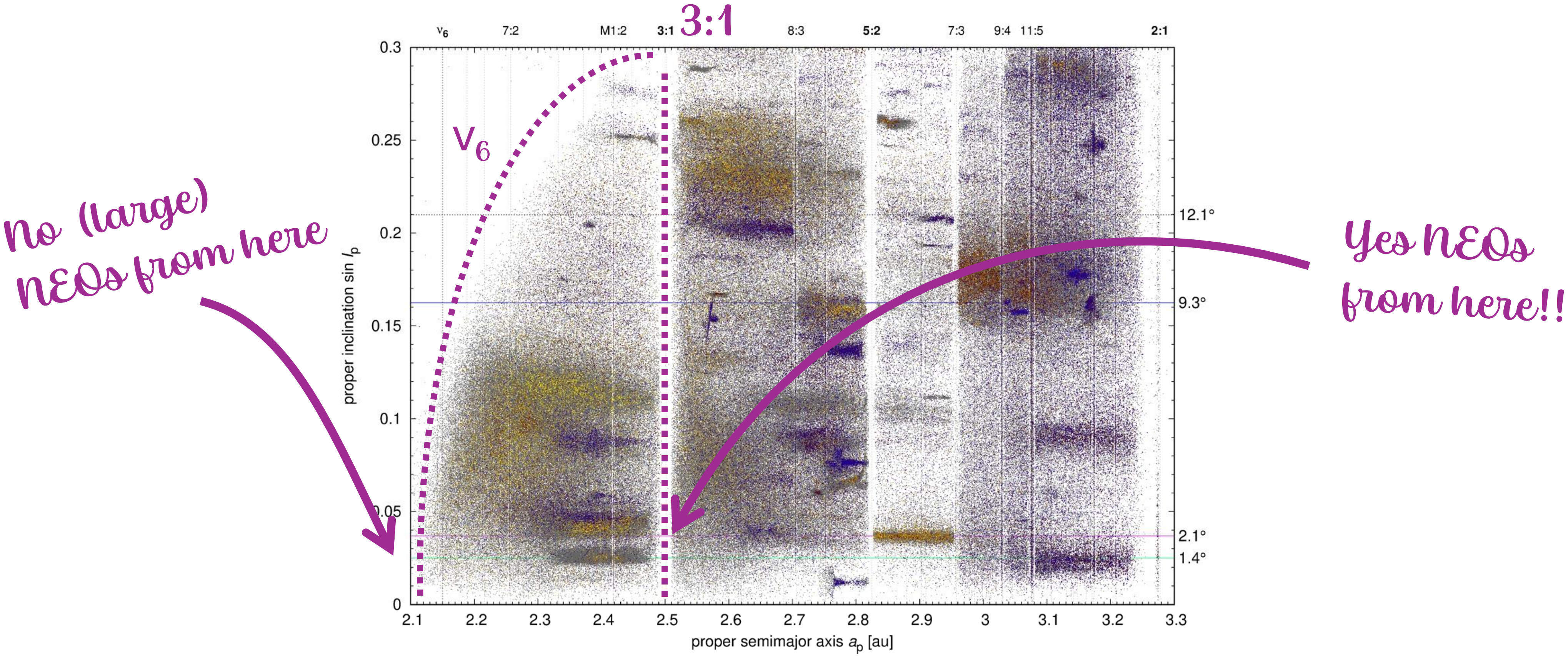
→ Meteorites from Massalia reached the ν_6

→ Large NEOs did not!

The asteroid-meteorite conundrum (partially) solved!



A prediction to be tested!



Where do km-size NEOs come from?

Planetary Spectroscopy at MIT

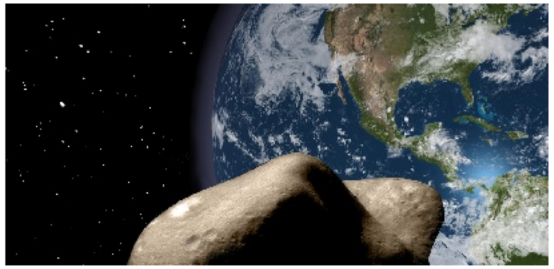
Joint Campaign Observations

Published Datasets

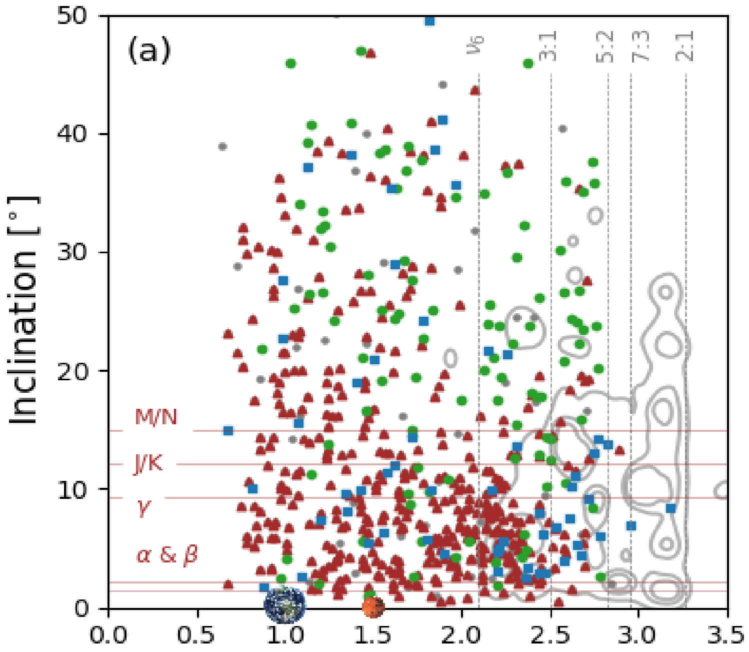
Data format, rejection, and normalization

MITHNEOS MIT-Hawaii Near-Earth Object Spectroscopic Survey

Cristina A. Thomas (NAU)
Francesca E. DeMeo (MIT)
Michael Marsset (MIT)
Richard P. Binzel (MIT)
David Polishook (Weizmann Institute)
Brian Burt (Lowell Observatory)
Andrew S. Rivkin (APL)
Schelte J. (Bobby) Bus (University of Hawaii)
Alan Tokunaga (University of Hawaii)



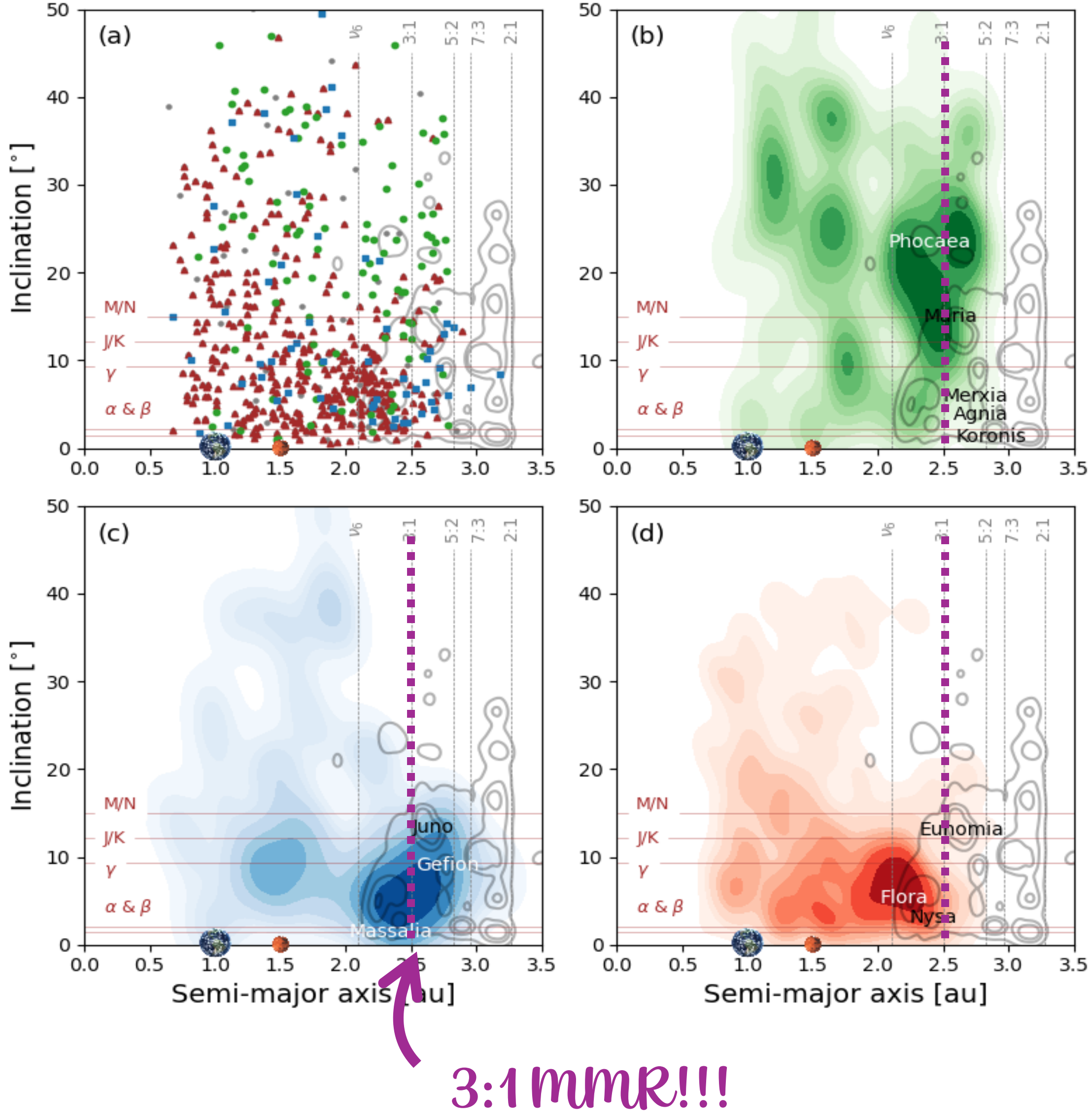
The resources and asteroid observing expertise of MIT, the University of Hawaii, and the NASA IRTF are being combined in a joint campaign to perform routine spectroscopic reconnaissance of near-Earth objects (NEOs). All spectroscopic observations obtained in this joint campaign are being made publicly available in near-real time via this website.



621 S-type asteroids
A bit messy, hey?

LL chondrite
L chondrite
H chondrite
ambiguous

Where do km-size NEOs come from?



621 S-type asteroids

LL chondrite

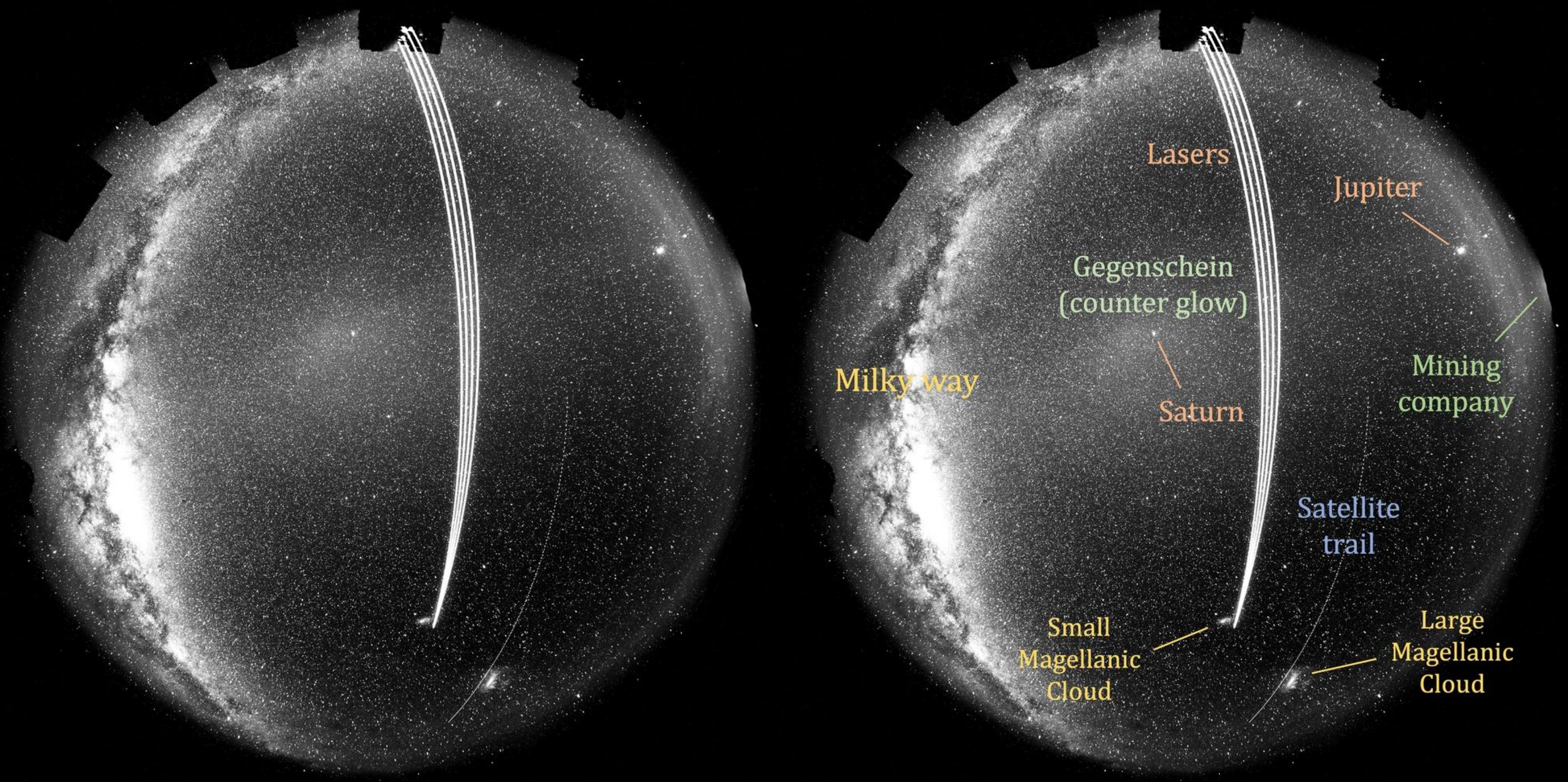
L chondrite

H chondrite

ambiguous

2. The Zodiacal dust

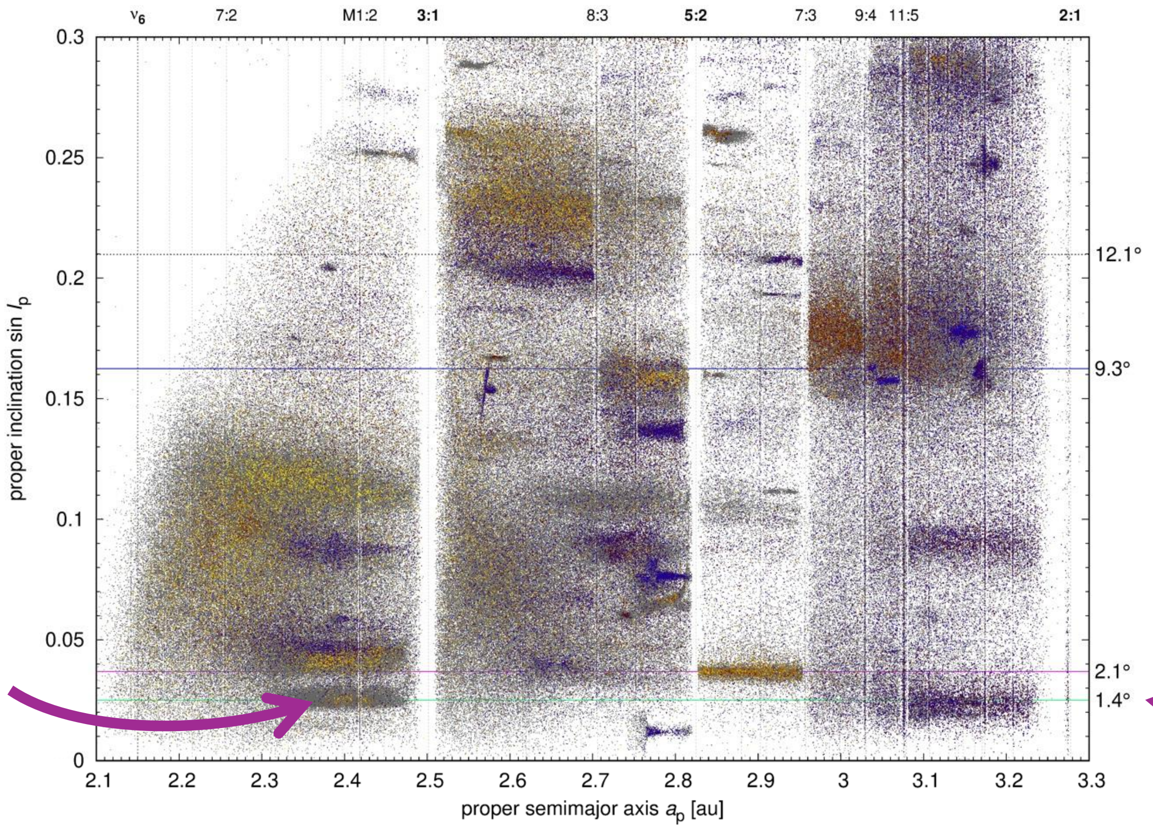
Credit: ESO/Y. Beletsky



Credit: ESO/Paranal ALPACA

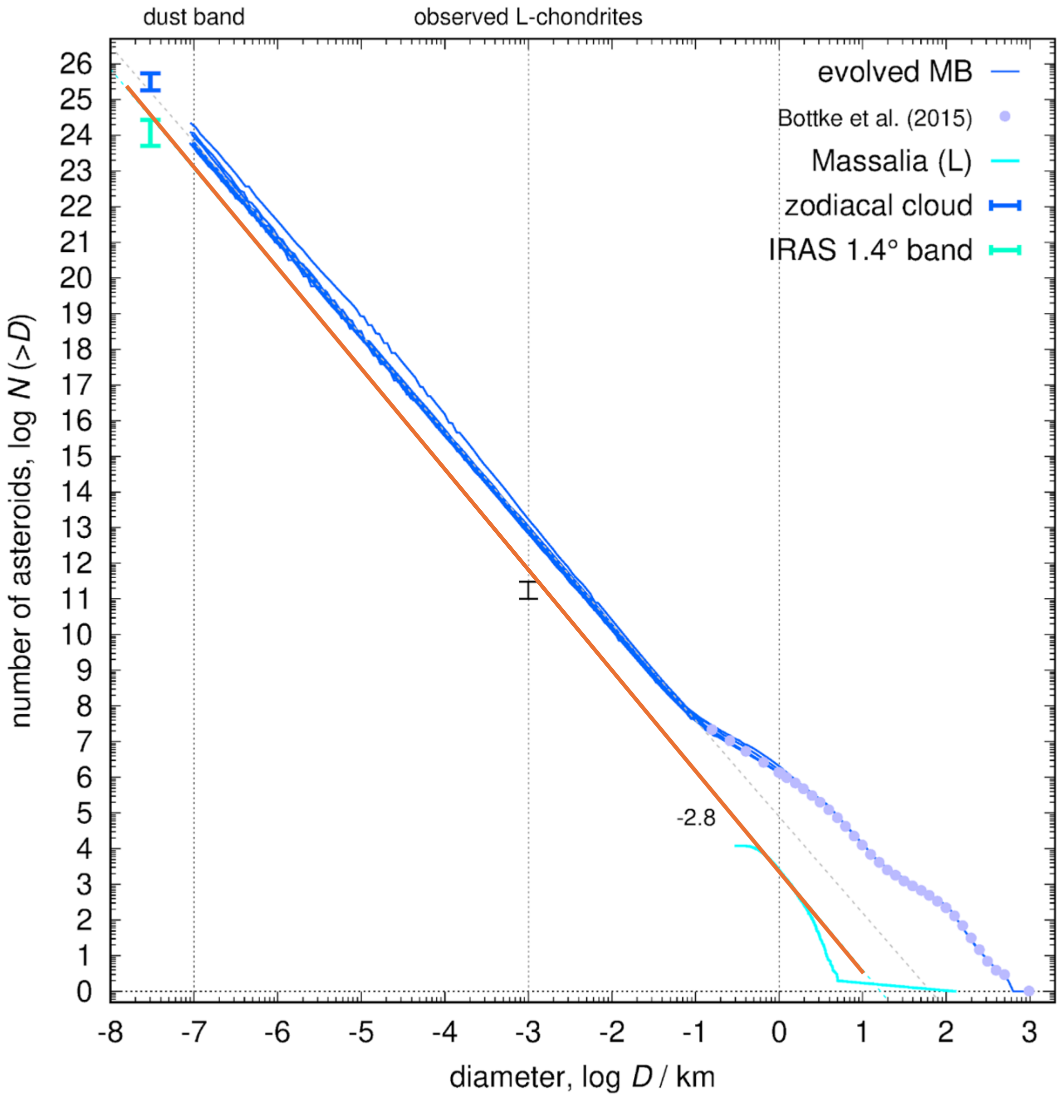
A zodiacal dust band intersecting the Massalia family

Massalia
mean(i) = 1.42°



DUST!

The family SFD can explain the dust abundance

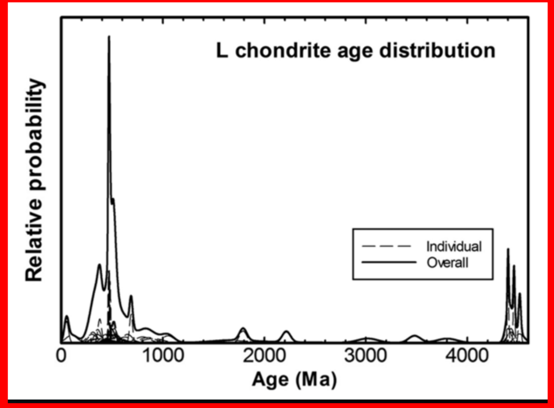


The family SFD can explain the dust abundance*

*2-impact scenario:

470 My ago (argon ages)

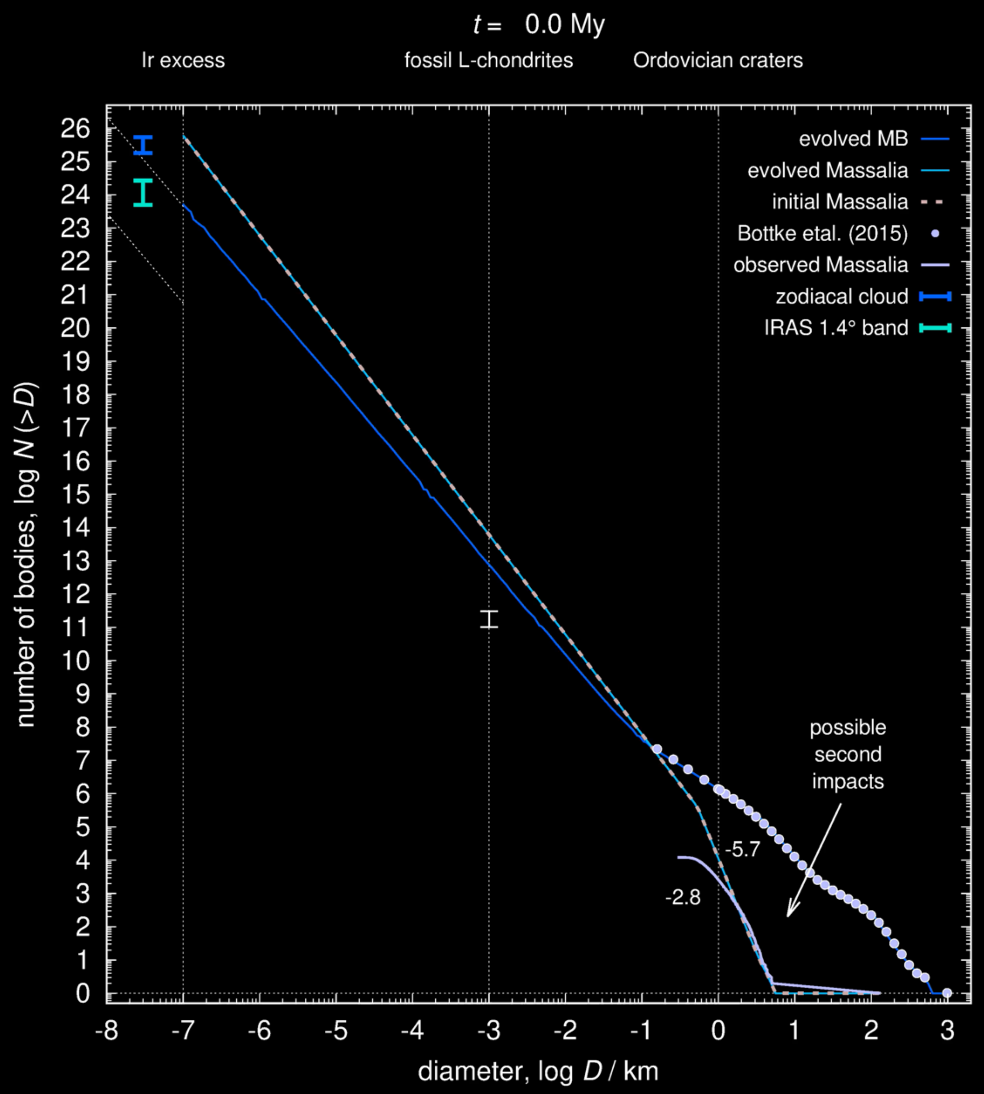
40 My ago (CRE ages)



Swindle et al. (2014)

Simulations by Mira Brož

Boulder code - Morbidelli et al. 2009



The family SFD can explain the dust abundance*

*2-impact scenario:

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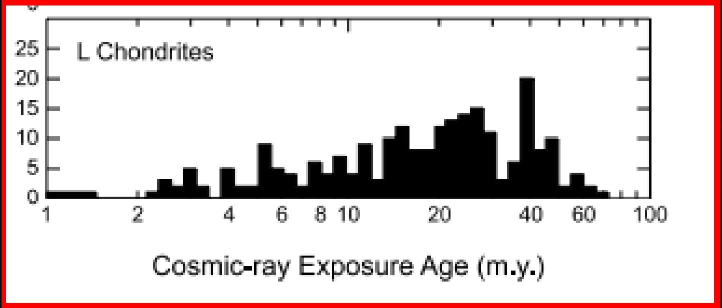
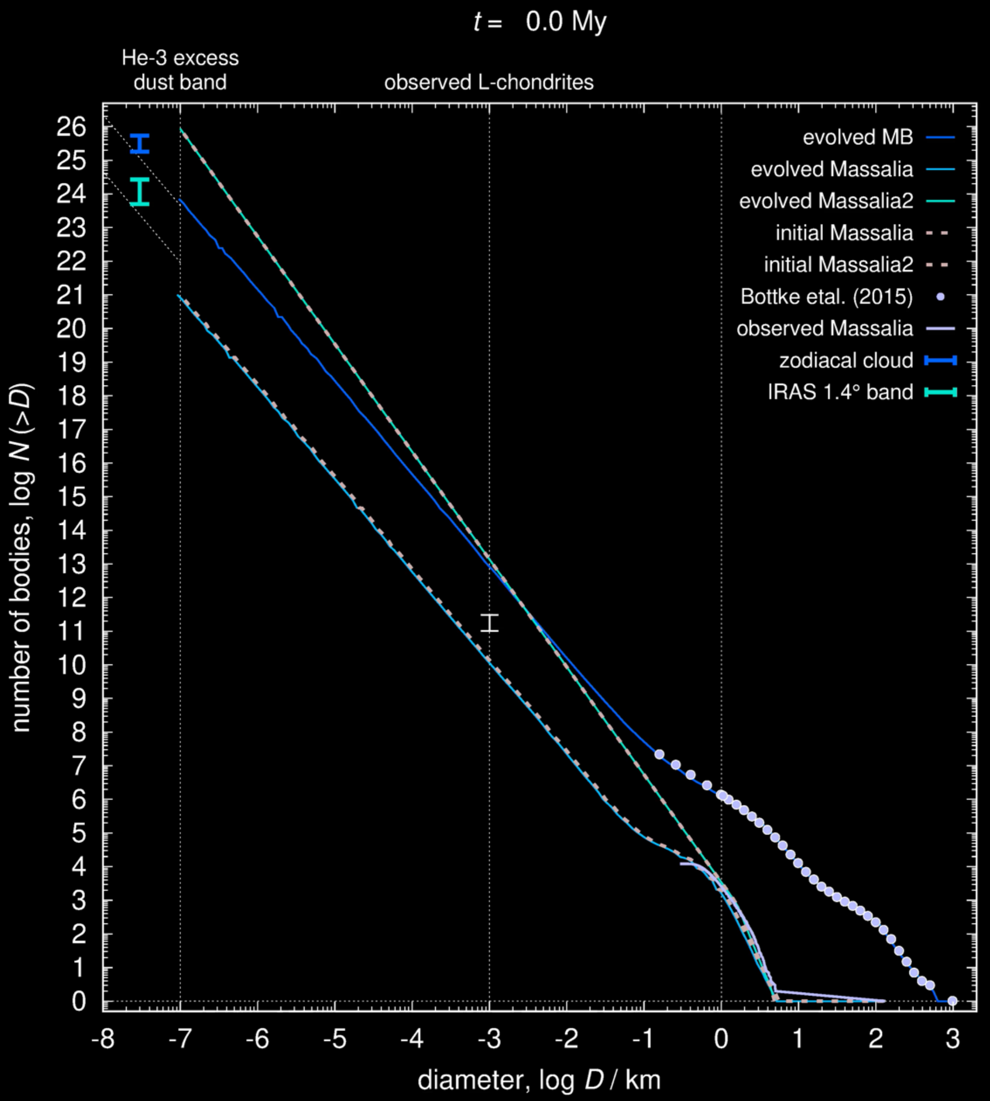


Adapted from Eugster et al. (2014)

Simulations by Mira Brož

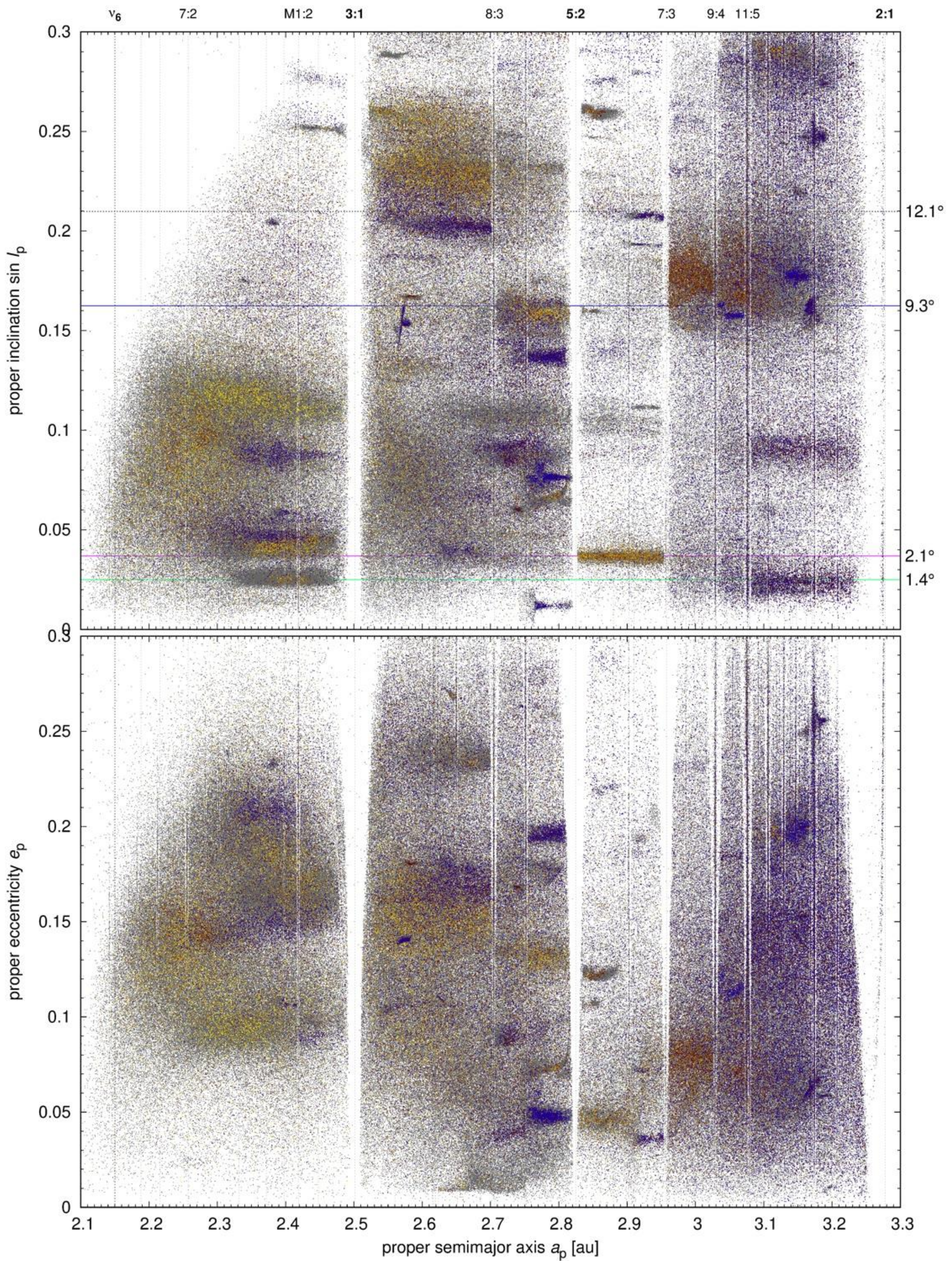
Boulder code - Morbidelli et al. 2009



3. The “faint” main belt

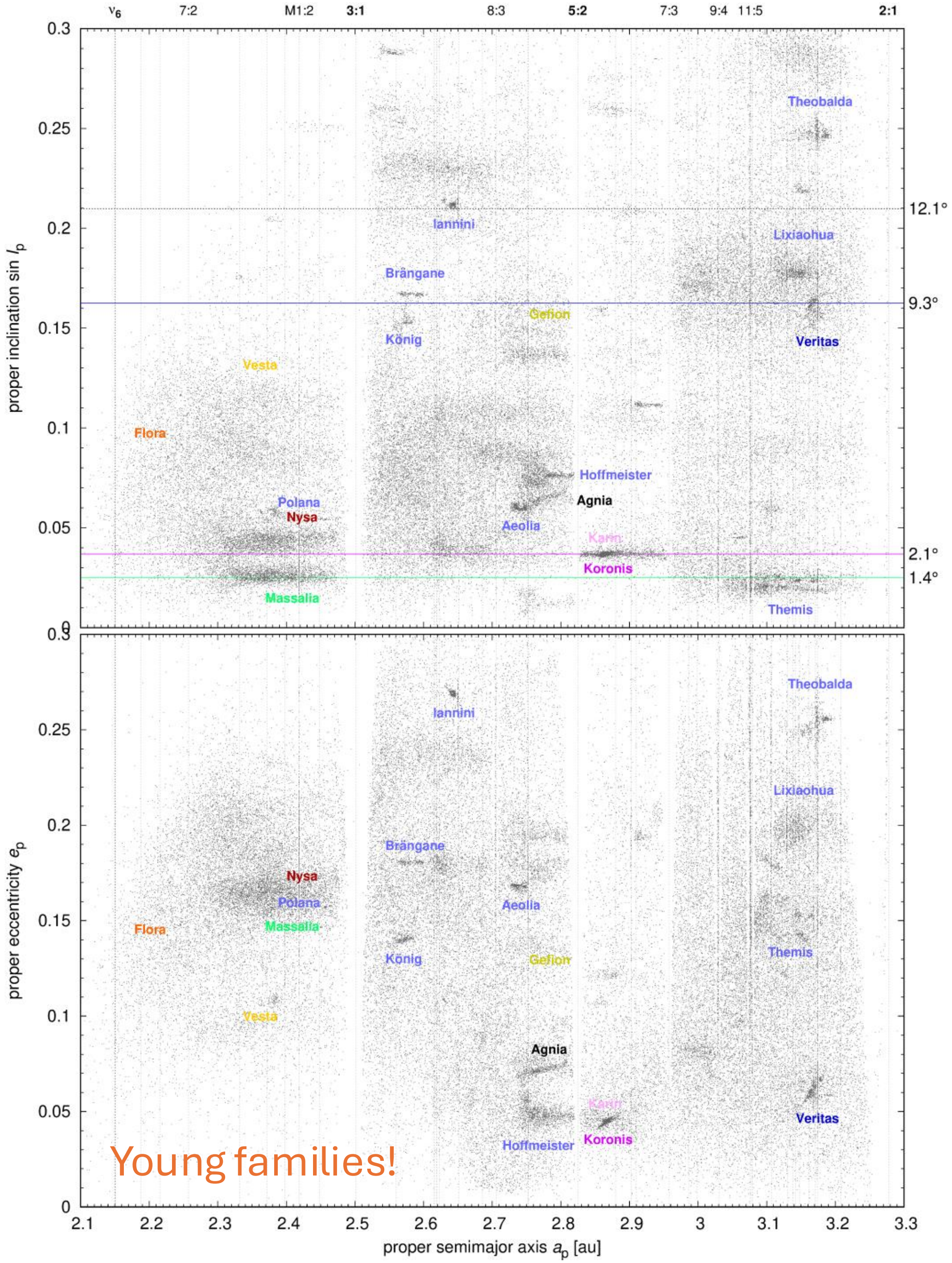
The “bright” main belt

(Yes… that figure again)



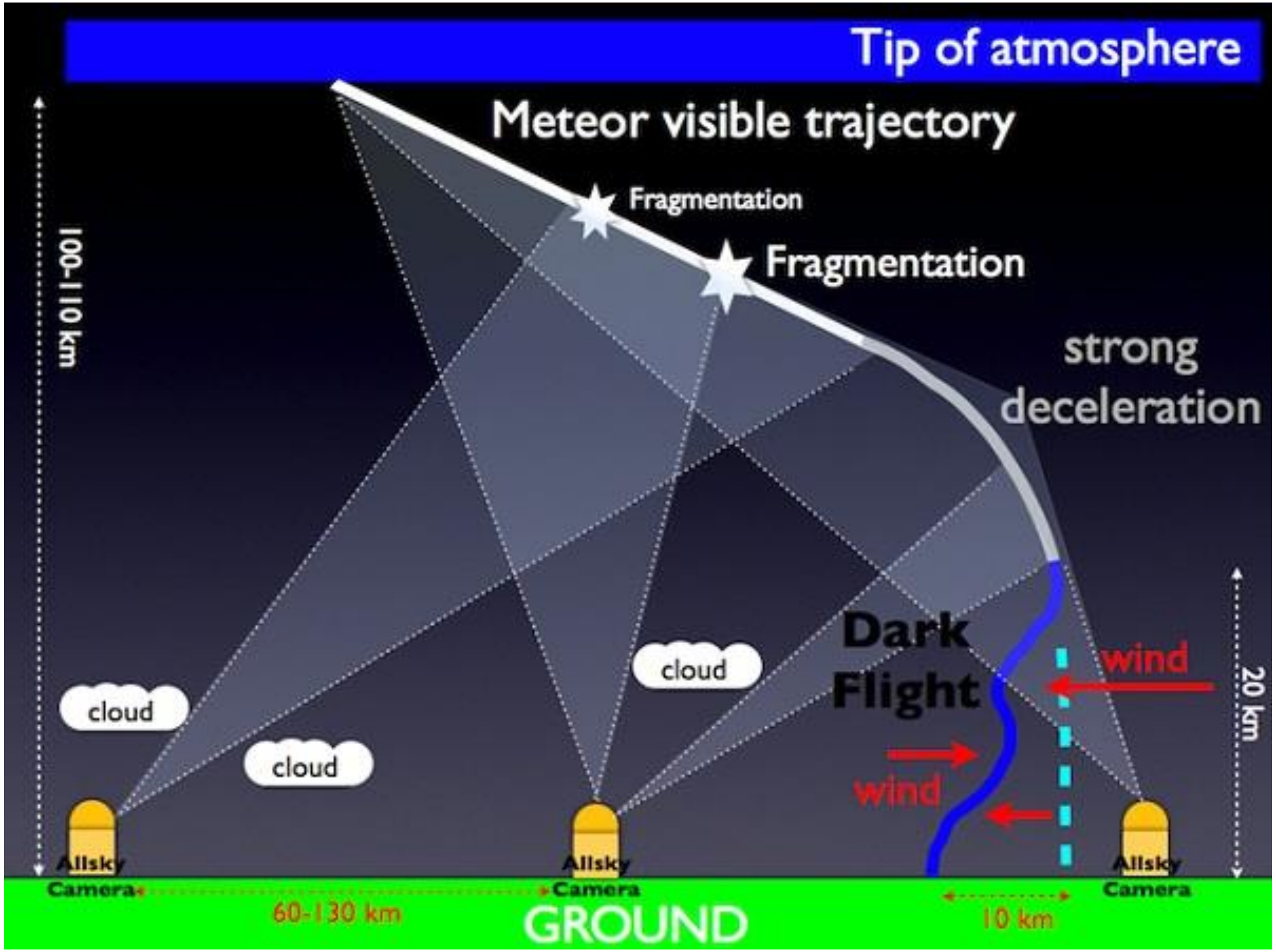
The “faint” main belt

Now, only small objects!



4. Meteors

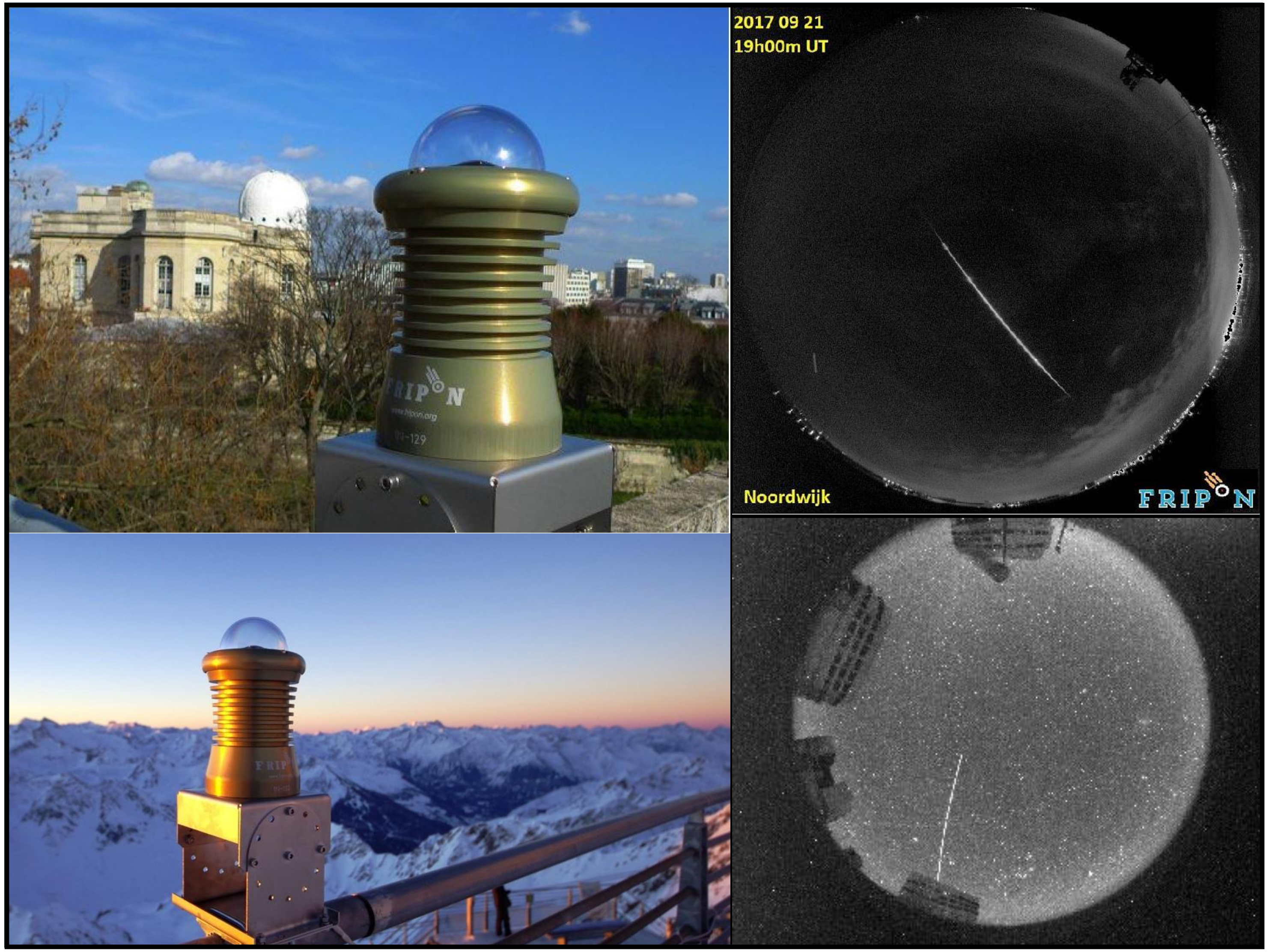
Camera networks



Camera networks

Colas et al. 2020

FRIPON cameras



Camera networks

Colas et al. 2020

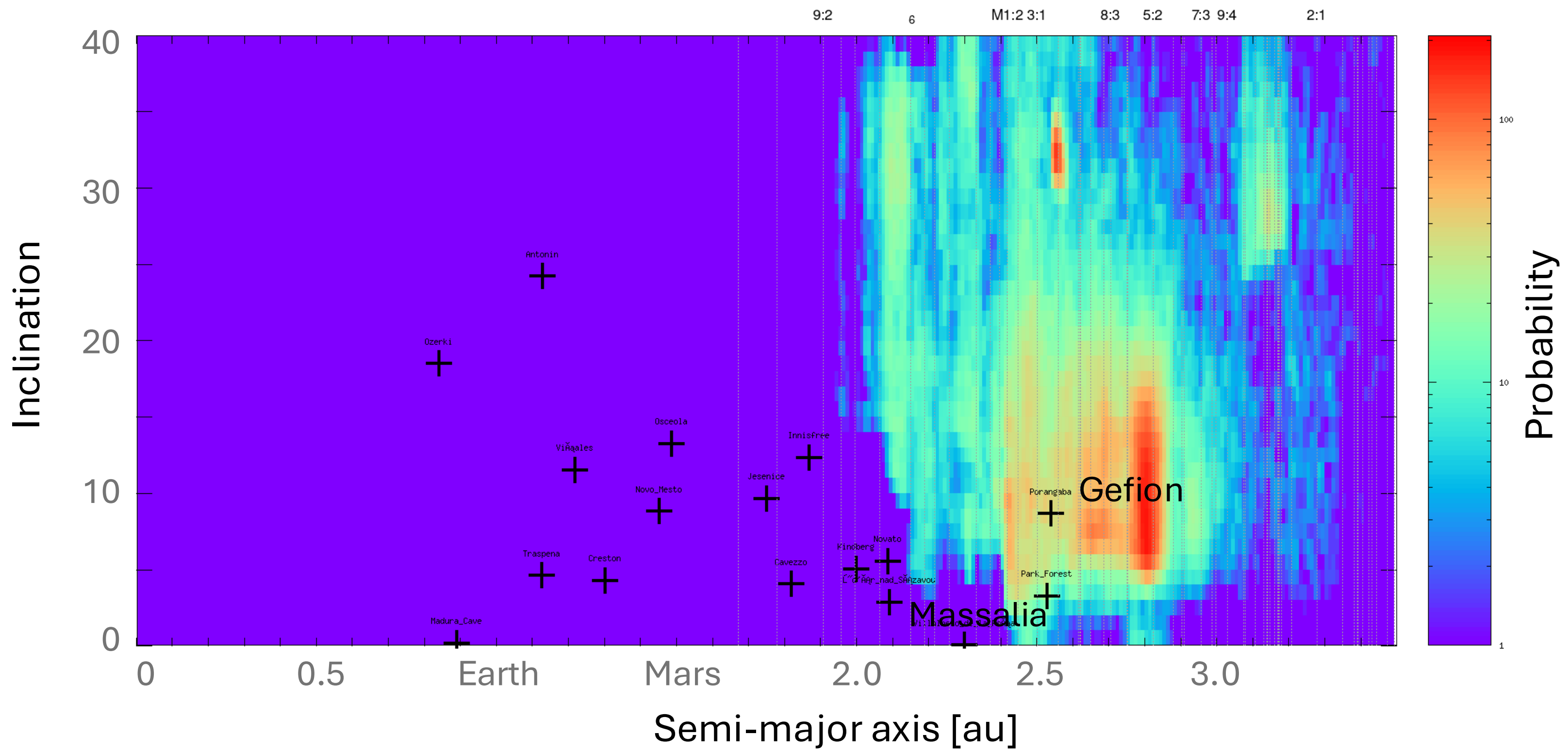
FRIPON cameras

Pre-atmospheric orbits vs. forward particle integrations

Transport model

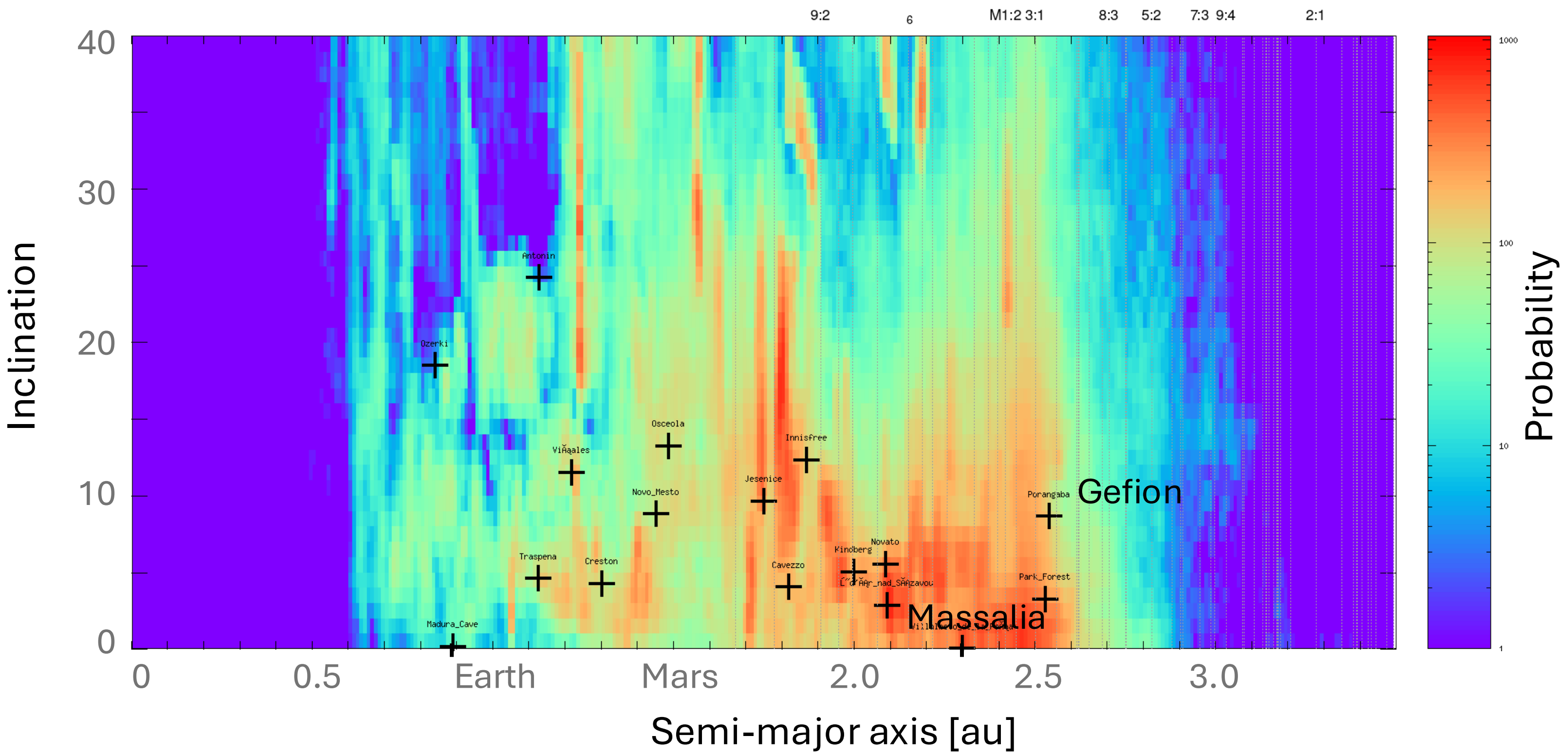
- N-body simulations for the orbital evolution of a set of particles starting from a given location in the asteroid belt
- Physics include:
    - Gravity,
    - Yarkovski,
    - YORP,
    - collisional reorientations.
- When an object enters the near-Earth space ($q<1.3$ au), we record its orbit at each step of the simulation until it “dies”.
- We then produce probability maps showing where the objects spent most of their life.

Pre-atmospheric orbits vs. forward particle integrations



Particles starting from Gefion

Pre-atmospheric orbits vs. forward particle integrations



Particles starting from Massalia

A few words about the companion papers…

“Young asteroid families as the primary source of meteorites”

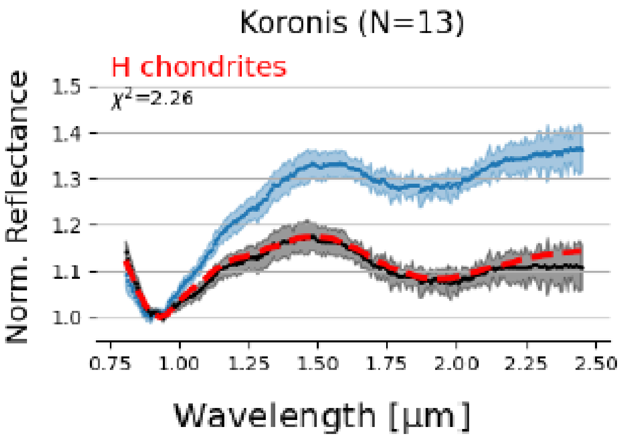
Brož, Vernazza, Marsset et al. (2024), *Nature*

“Source regions of carbonaceous meteorites and near-Earth objects”

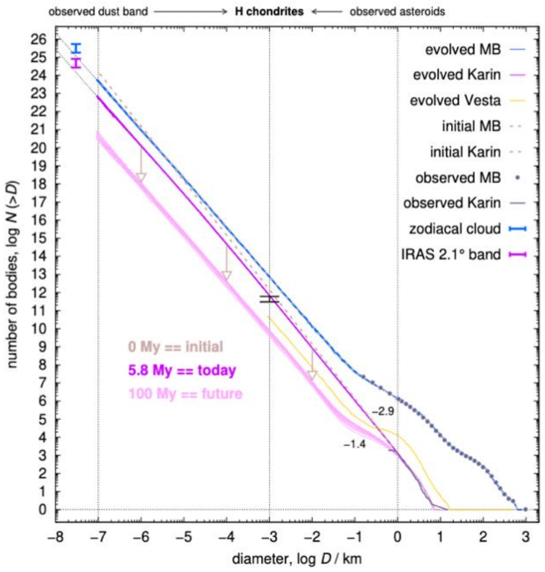
Brož, Vernazza, Marsset et al. (2024), *A&A*

The Koronis family as the source of H chondrites

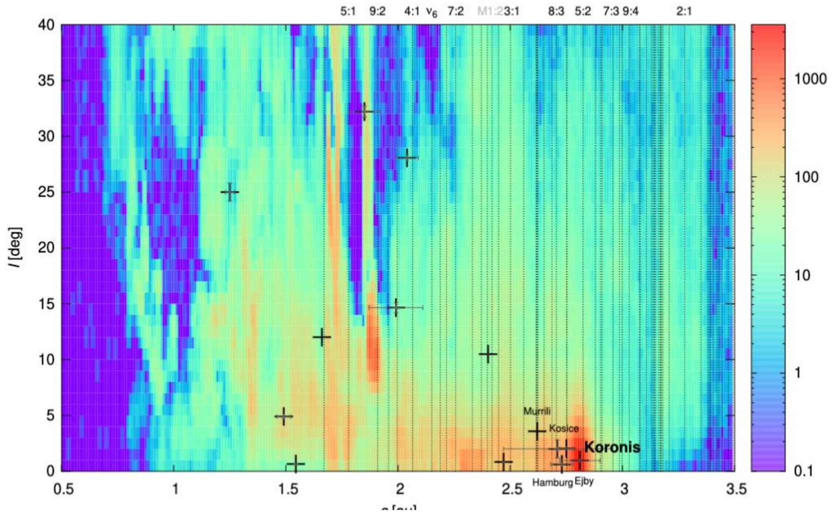
Spectral fit ✓



Dust band ✓



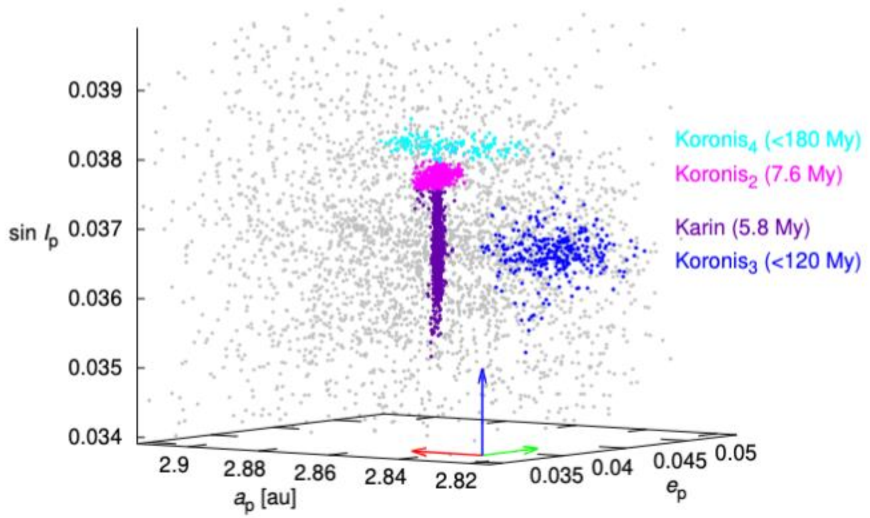
Pre-atmospheric orbits ✓



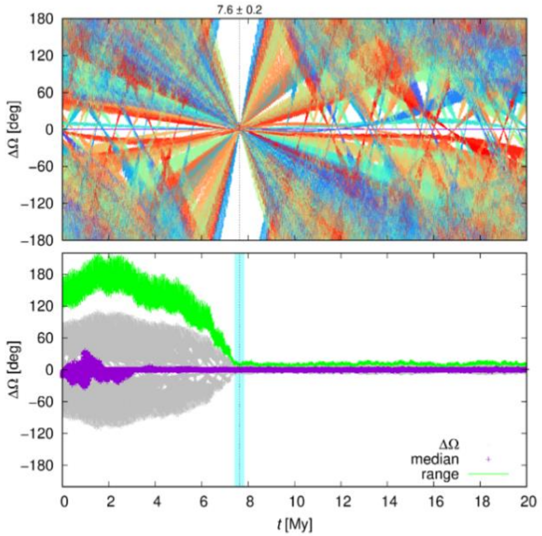
Brož, Vernazza, Marsset et al. 2024, *Nature*

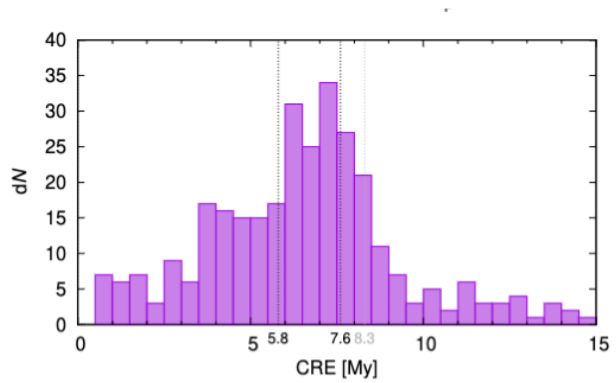
The Koronis family as the source of H chondrites

Ongoing collisional cascade! ✓



Family age = cosmic-ray exposure age (backward integrations) ✓





Brož, Vernazza, Marsset et al. 2024, *Nature*

Summary

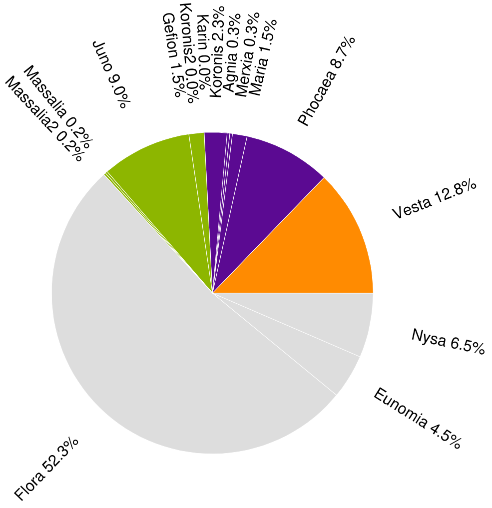
- The present-day meteorite flux is dominated by two meteorite classes: **the ordinary L and H chondrites,** accounting for 37% and 33% of falls,
- Their **pre-atmospheric orbits** perfectly align with two asteroid families that happen to have the exact **same composition**,
- The location of the families in the main belt also coincides with **overabundances of small main-belt asteroids and near-Earth Objects,**
- These two families happen to exhibit the **steepest size frequency distributions (SFD)** observed in the main belt,
- Each of these families is aligned with a **zodiacal dust band**. When extrapolating their SFDs, they can account for the **observed abundances** of zodiacal dust and meteorites,
- The **age of the families** agrees well with the argon isotope and cosmic-ray exposure ages of their associated meteorites.
- **Lesson learned: young (<40 Myr-old) families dominate the flux of meteorites!**

The meteorite flux finally explained!

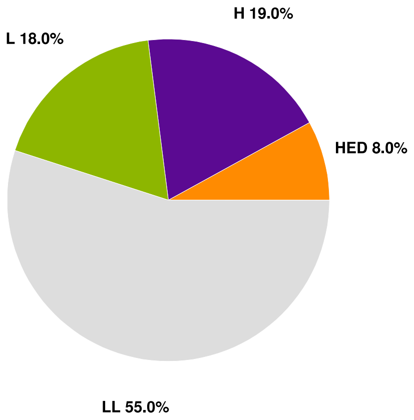
Brož, Vernazza, Marsset et al. 2024, Nature

Near-Earth Objects

Synthetic

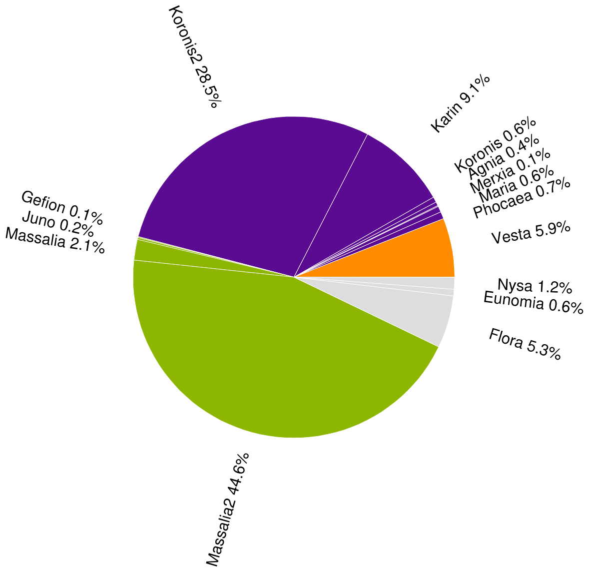


Observed

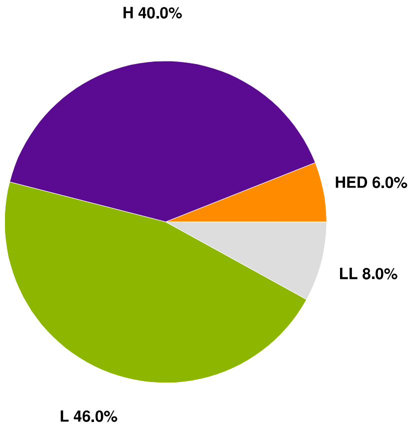


Meteoroids

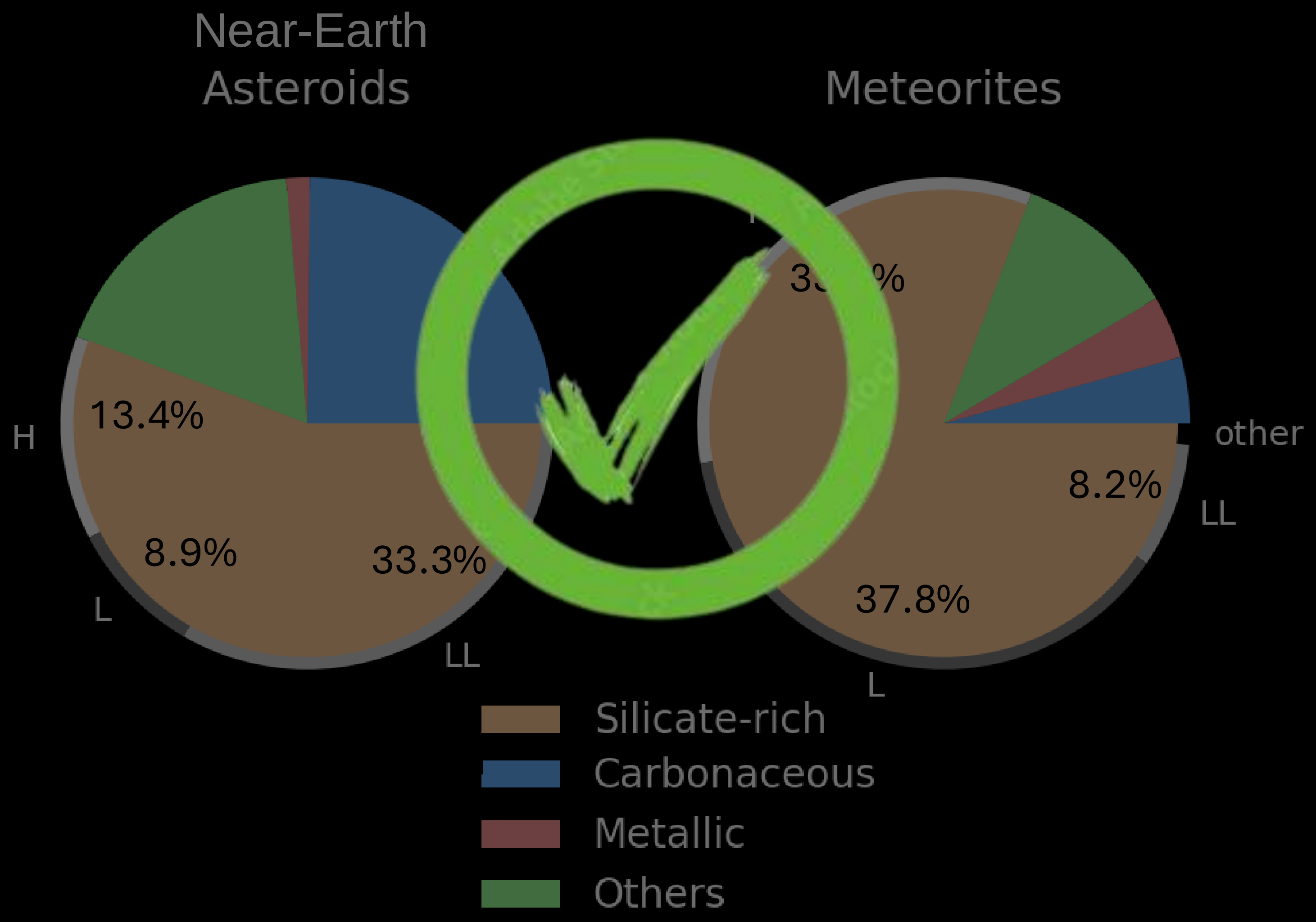
Synthetic



Observed



The asteroid-meteorite conundrum ~~(partially)~~ solved!

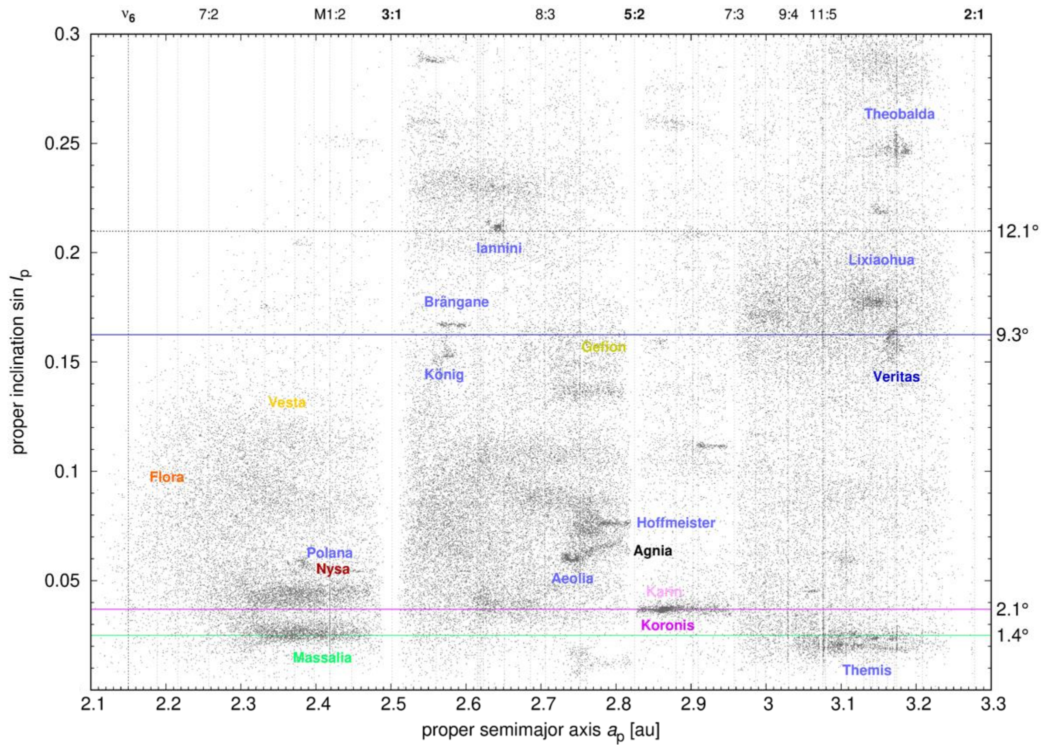


Some predictions about Massalia…

- Size-frequency distribution — LSST will find that it remains steep down to the completeness limit of the survey
- NEO composition — Spectroscopic surveys will find that the relative fraction of L-chondrite-like

- Pre-atmospheric orbits — es have short semi-major axis
- Spin orientation — th different spin orientation from that of the rest of the family
- Shape of (20) Massalia — We will image a large crater or a rejunevated surface on Massalia

What's next?



We explained 70% of meteorites, let's get the rest of them!

→ VLT/X-SHOOTER large spectroscopic survey of 18 asteroid families

None of this would have been possible without…

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None of this would have been possible without...

Francesca DeMeo
MIT

Richard Binzel
MIT

Cristina Thomas
Northern Arizona University

And all co-authors...


Gracias!
Credit: Masato Hattori

ESO 2025 opportunities

Studentship Programme
for Ph.D. students
duration: 6months – 2 years
deadline October 30th

Fellowship Programme
for PostDocs
duration: 3+1 years
deadline October 15th

La Silla Summer School
for Ph.D. students
February 10 - 21, 2025
deadline September 30th

Internships
for Master and Ph.D. students