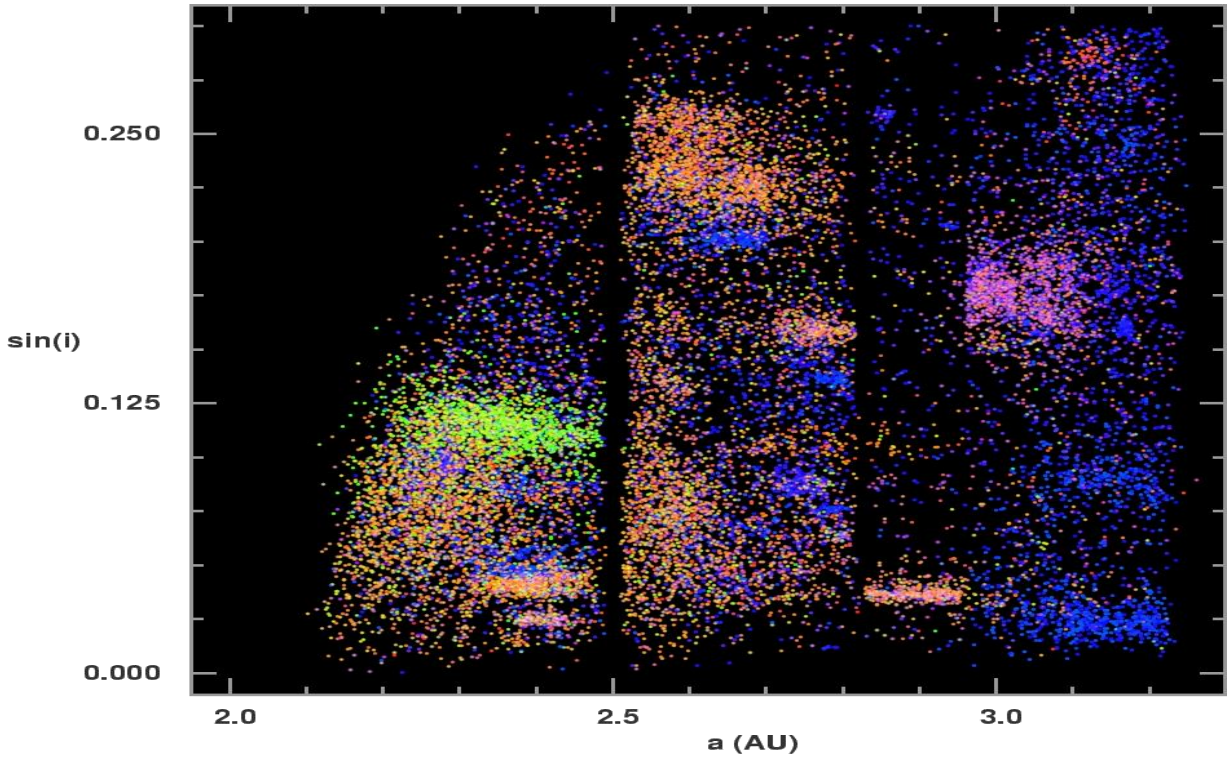
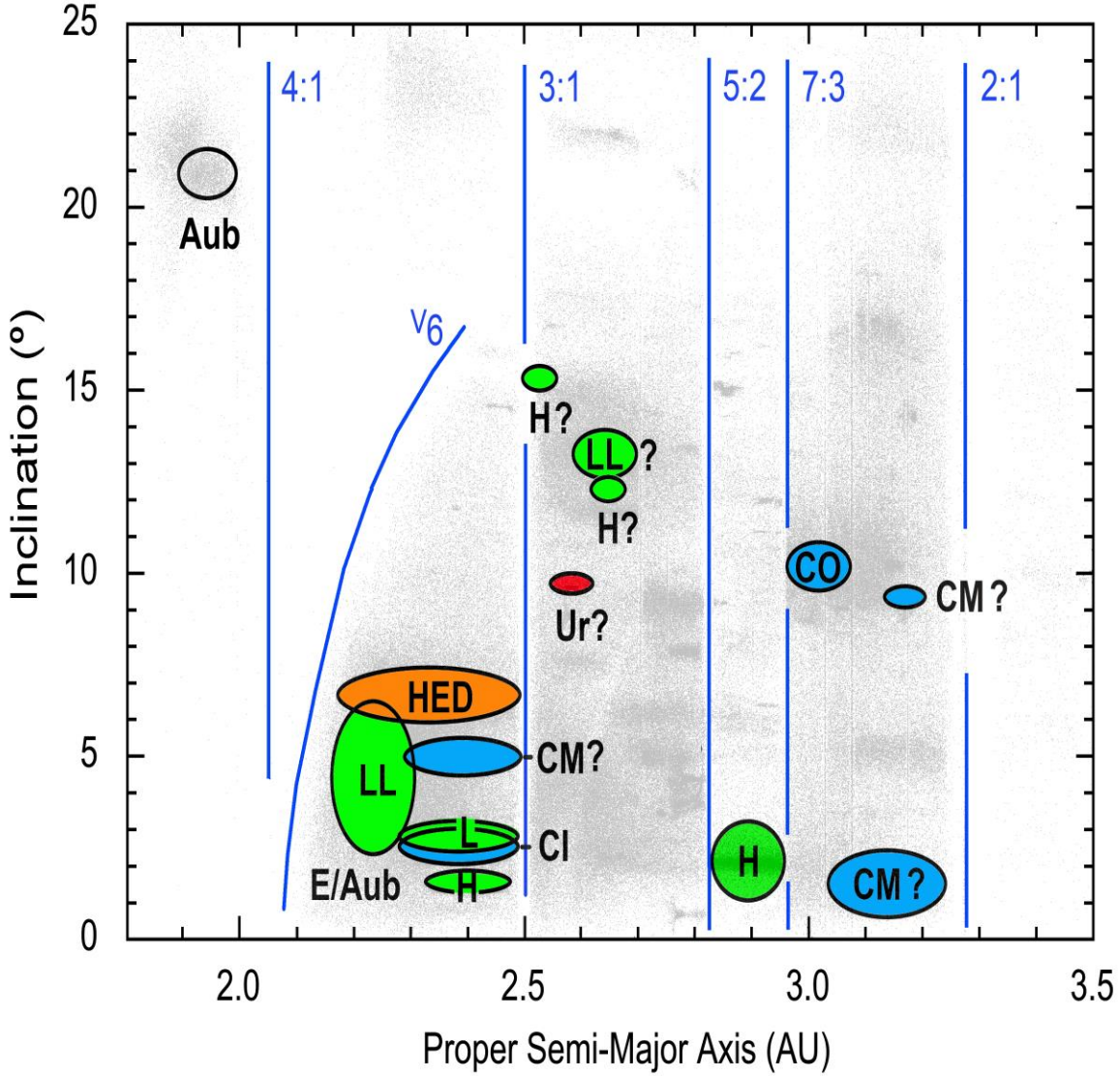
# Review of instrumentally recorded falls of meteorites that are geological hand specimens of asteroid families

Peter Jenniskens
SETI Institute

IAA-PDC-25-05-243 (May 7, 2025)

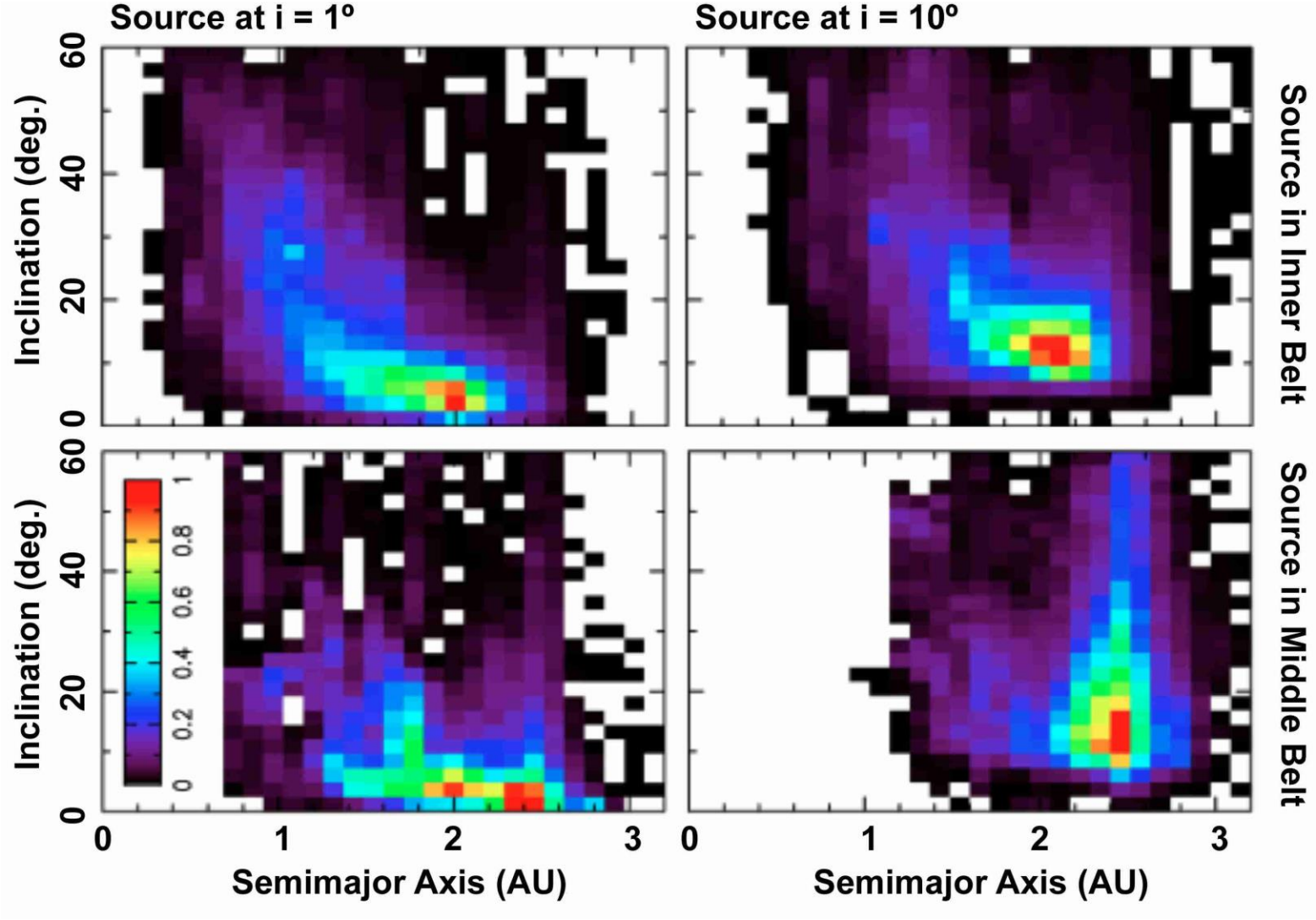



SDSS colors 33,000 asteroids: Ivezić et al. (2002)




Jenniskens & Devillepoix (2025) MAPS 60, 928-973

# At Earth: impact orbit of 20 cm meteoroids 50 Ma after collision

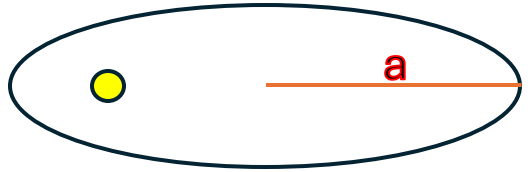



Nesvorny (2018)

Hard to change:

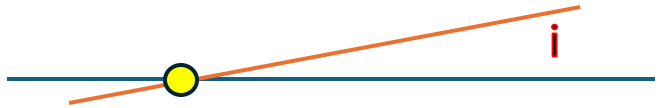
**Semi-major axis (a, where $P = a^{1.5}$)**

(= orbital period, energy orbit)




**Inclination (i)**

(change mostly by close encounters with Mars, Earth, ...)




Impact Earth on orbits:

a = that of delivery resonance

*Inner Main Belt: nu6*

*Central Main Belt: 3:1*

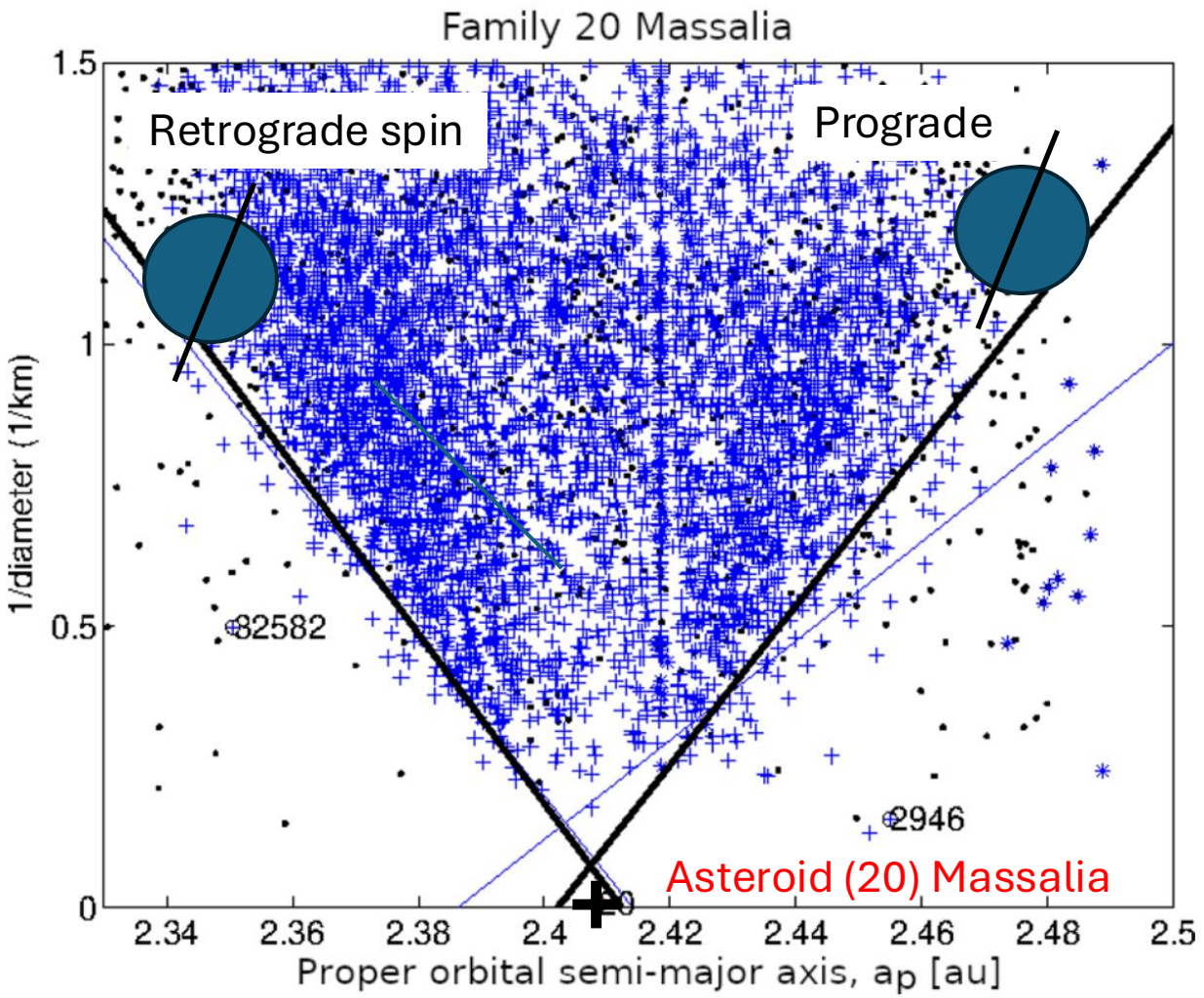
i = that of source region, but changed by

*close encounters Earth*

*pumping up by 3:1*

# Dynamical age of an asteroid family






From big to small >

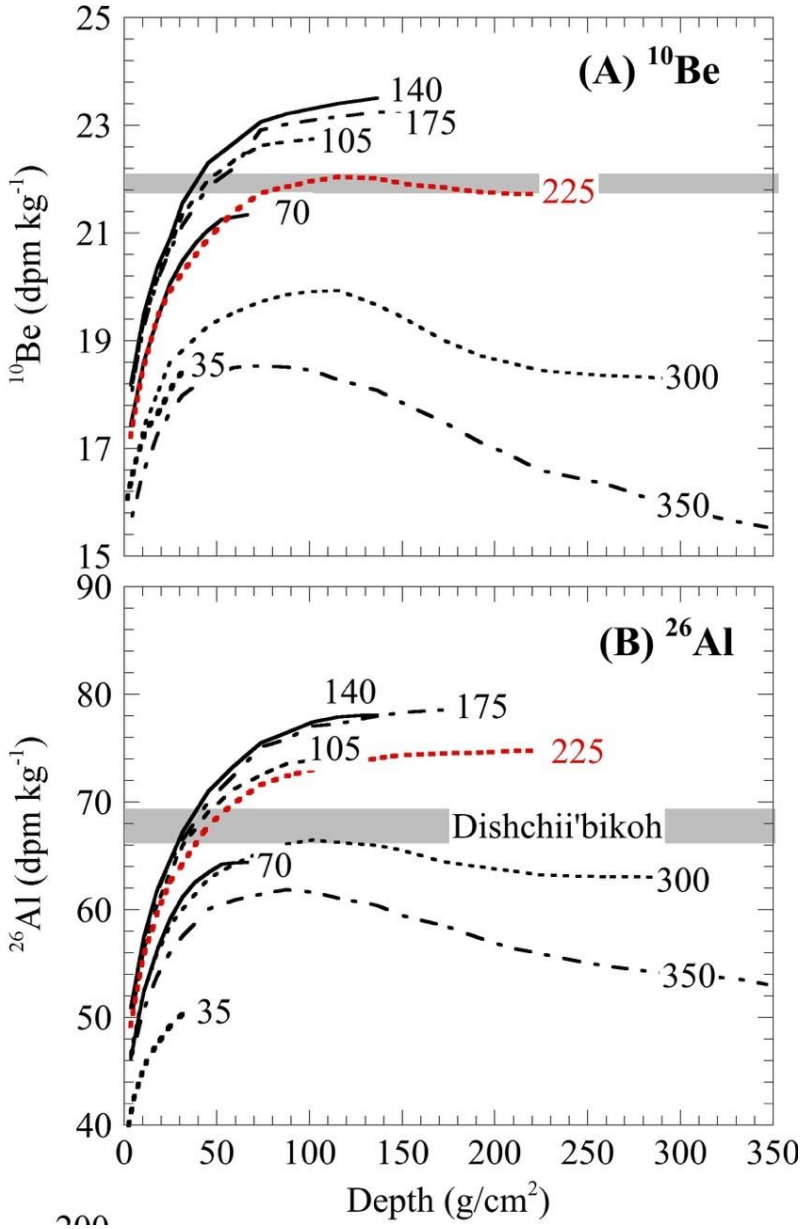
< Small asteroids increase/decrease semi-major axis quickly by Yarkovsky effect

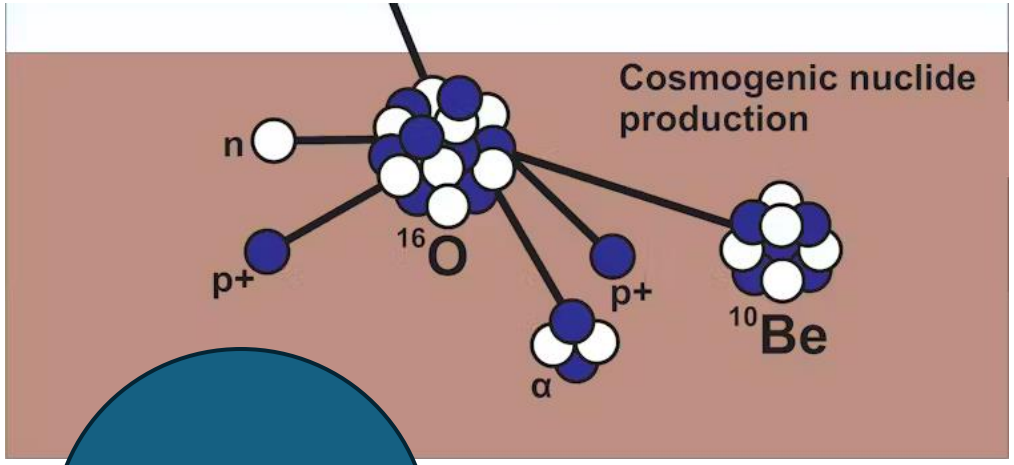
< Large asteroids are hard to accelerate

From short to long orbital period >

# Cosmic Ray Exposure (CRE) Age of a meteorite

Dishchii’bicoh: Caffee & Welten



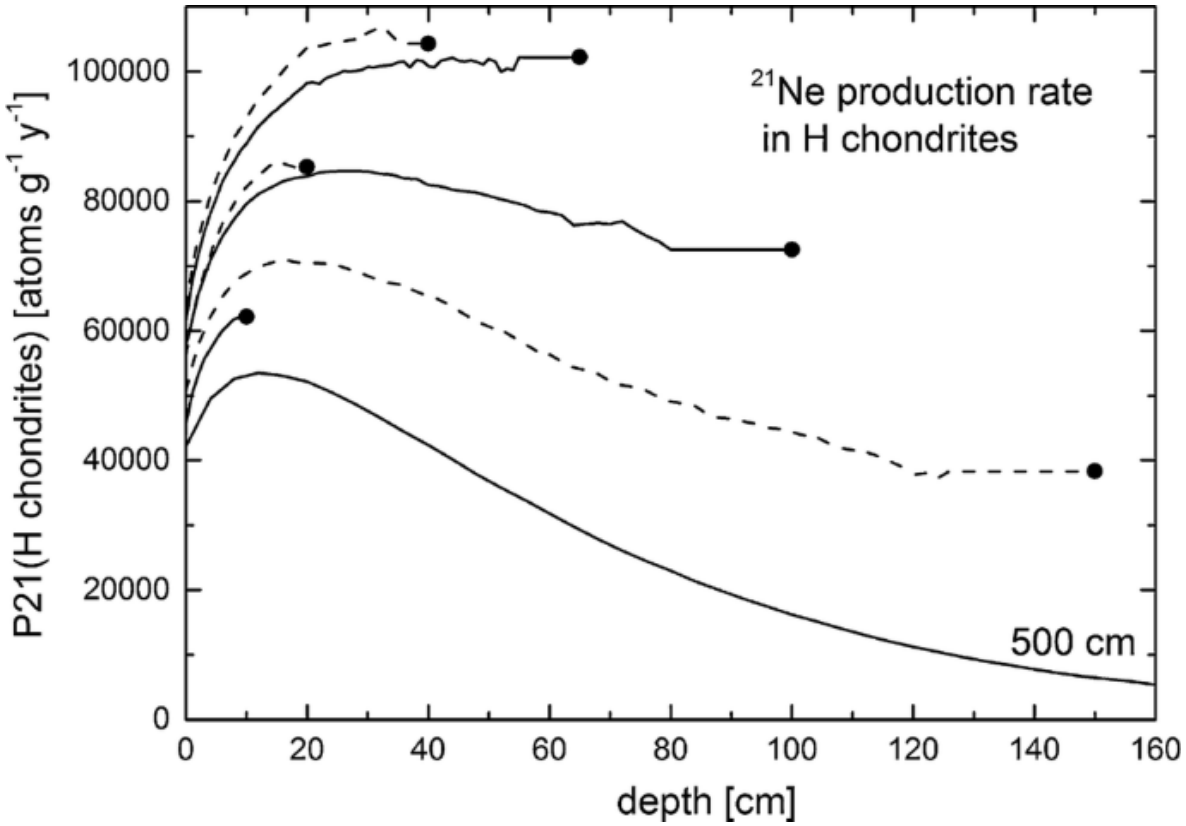




Size < 2m



Henner Busemann
ETH Zürich
Kees Welten
UC Berkeley
Marc Caffee
Purdue University


Wieler, 2018



# Fireball Camera Networks

# meteorite falls with orbits: 75 as of 4/1/2024

- European Fireball Network (N = 18)
- Global Fireball Observatory / DFN (N = 17)
- USG satellites (N = 17)
- Allsky7 (N = 10)
- FRIPON/PRISMA (N = 6)
- GMN (N = 5)
- CAMS (N = 4)
- A^3N (N = 2)
- NASA FN (N = 2)
- FNN (N = 2)
- SACN (N = 2)
- SonotaCo (N = 1)
- ….

- Video and dashcam footage (N = 36)


Pavel Spurny


Hadrien Devillepoix


Francois Colas


Mike Hankey


Toru Kanamori


Peter Brown

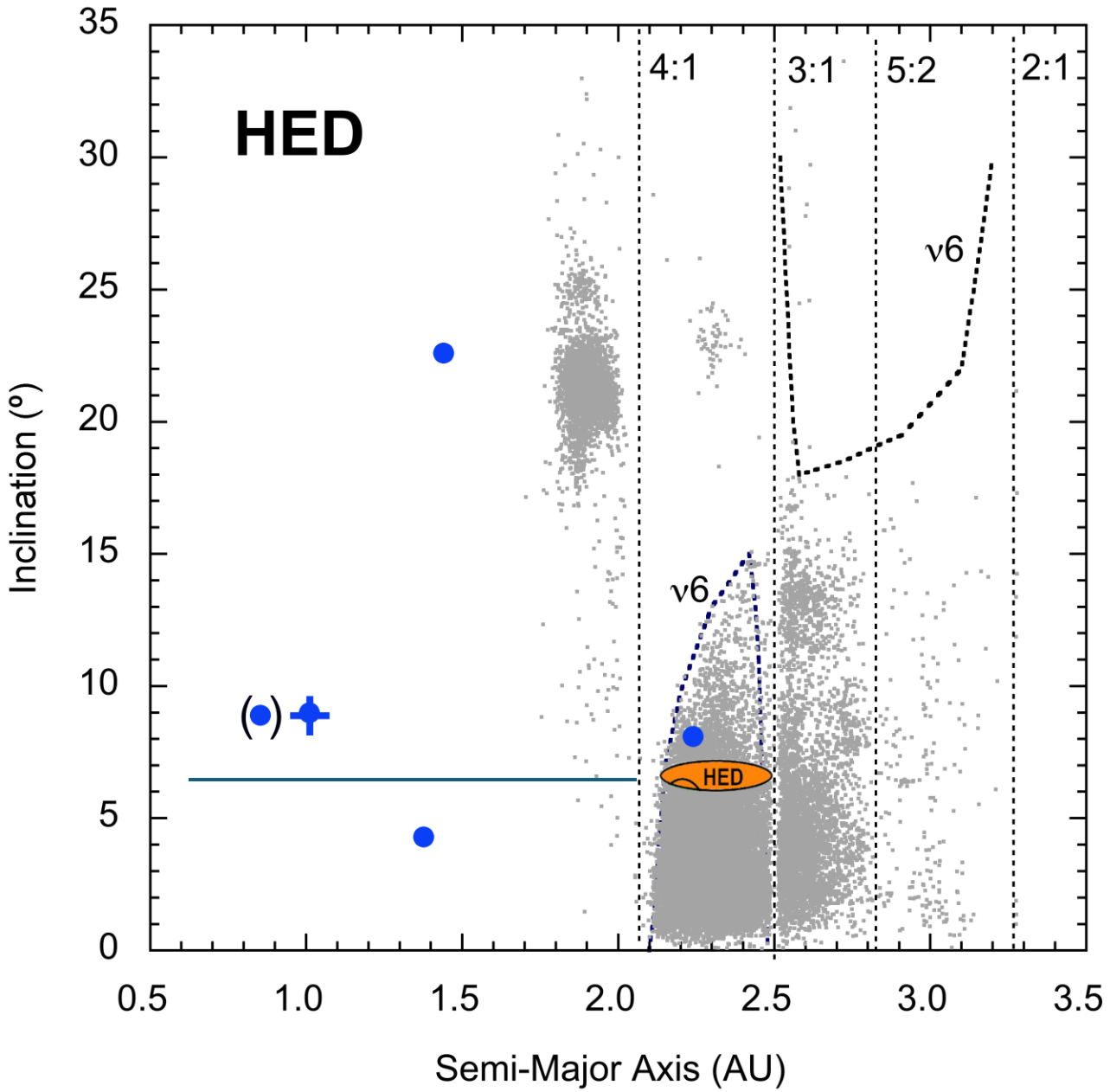

Pete Gural


Denis Vida

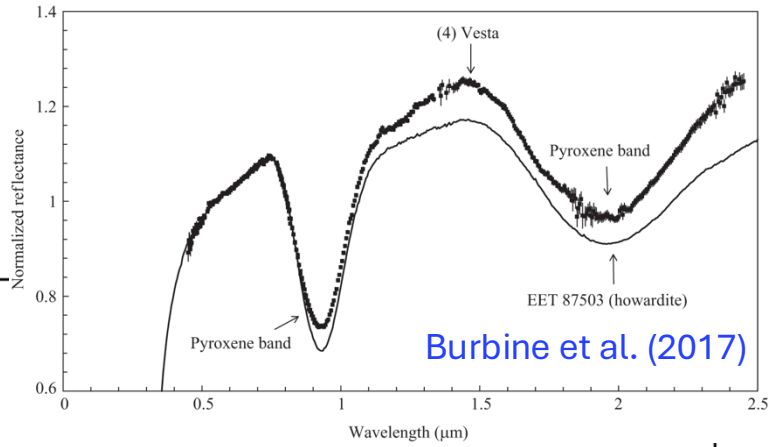
Meteorite types:

| | 2018: | 2024: |
|---|---|---|
| • H | 14 | 28 |
| • L | 8 | 20 |
| • LL | 5 | 6 |
| • L/LL | 2 | 5 |
| • Mix | 0 | 1 |
| • How | 1 | 3 |
| • Eu, ann | 1 | 1 |
| • Dio | 0 | 0 |
| • Aubrite | 0 | 1 |
| • EL | 1 | 1 |
| • EH | 0 | 1 |
| • Ur | 1 | 1 |
| • Iron | 0 | 1 |
| • CM | 2 | 4 |
| • C1 ung | 0 | 1 |
| • C2 ung | 1 | 1 |

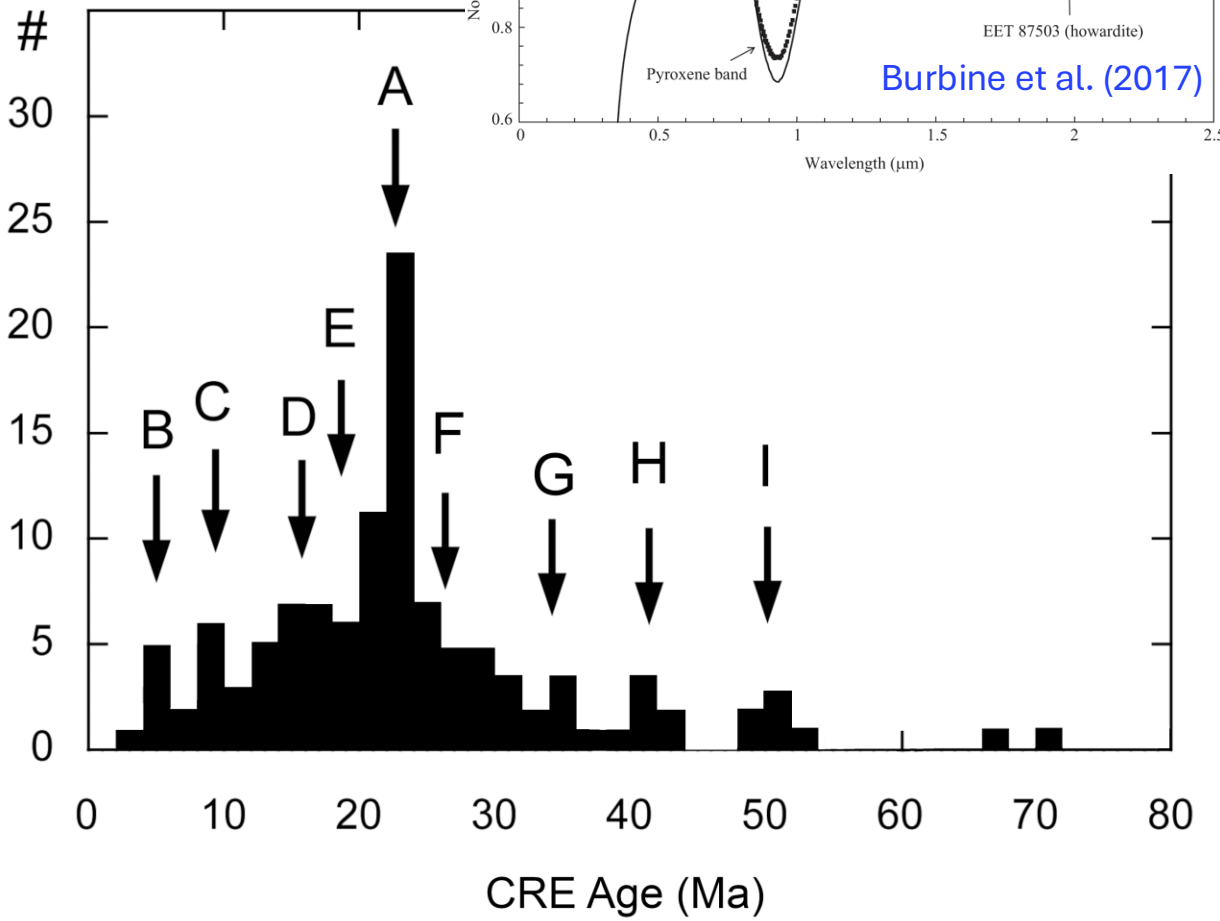
# HED achondrites: Vesta or Vesta family



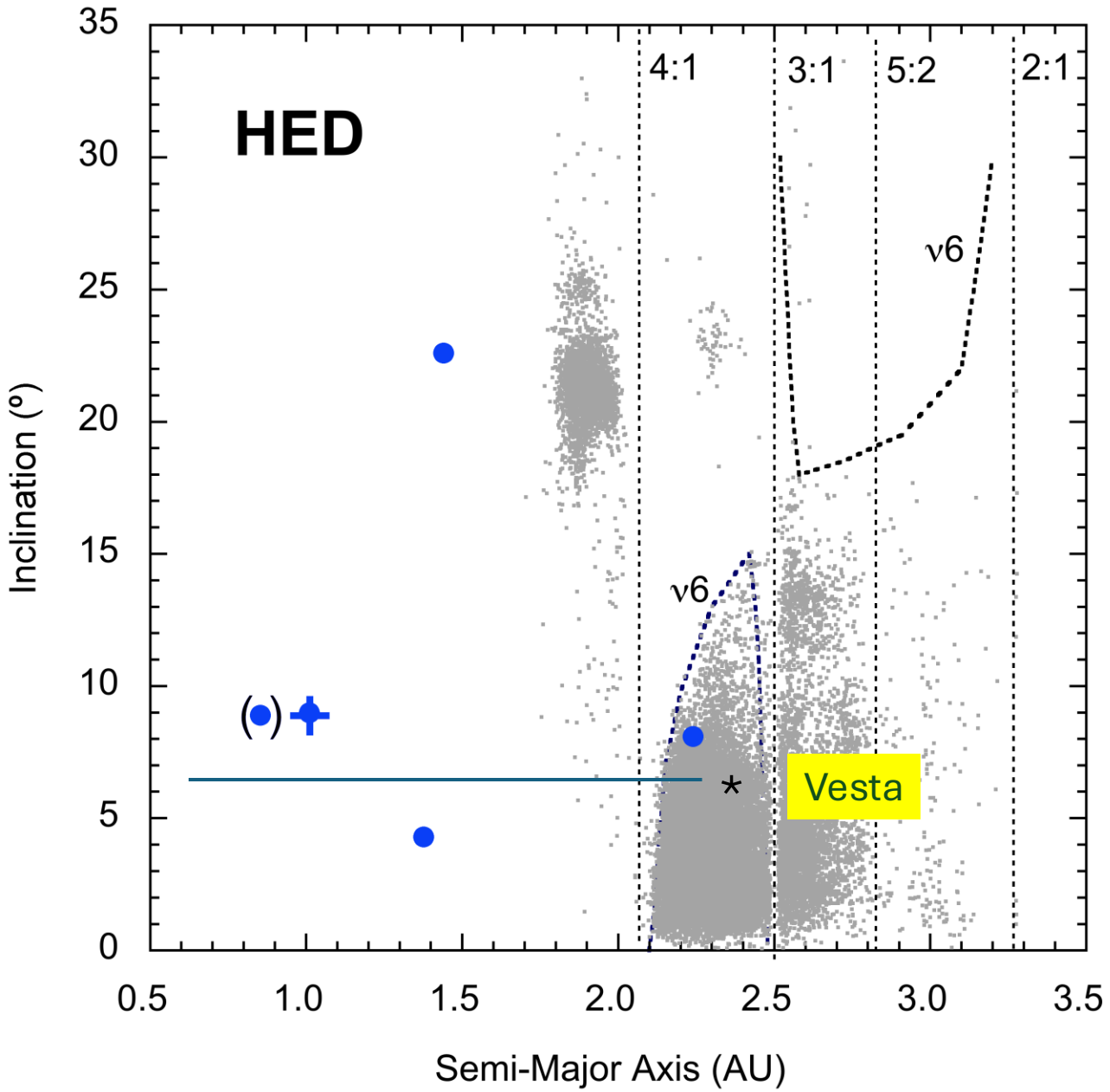

HED Spectra similar to Vesta: McCord et al., 1970




Burbine et al. (2017)



# HED achondrites: Vesta or Vesta family

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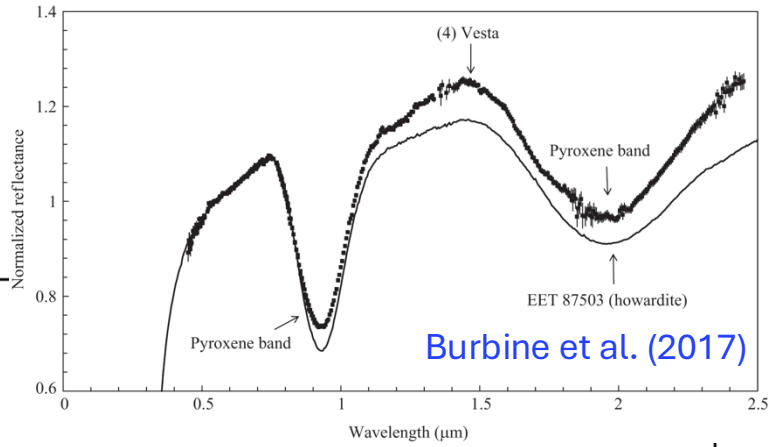


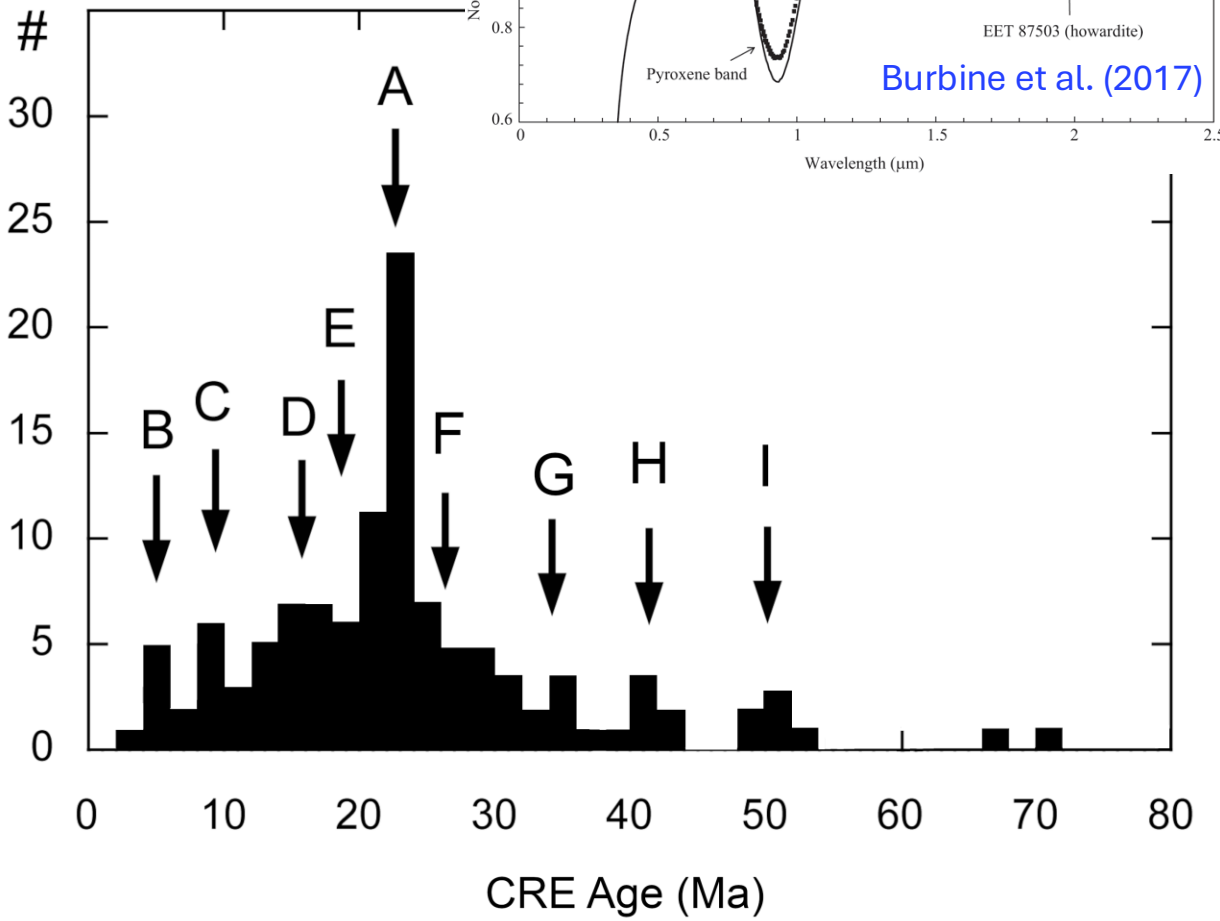

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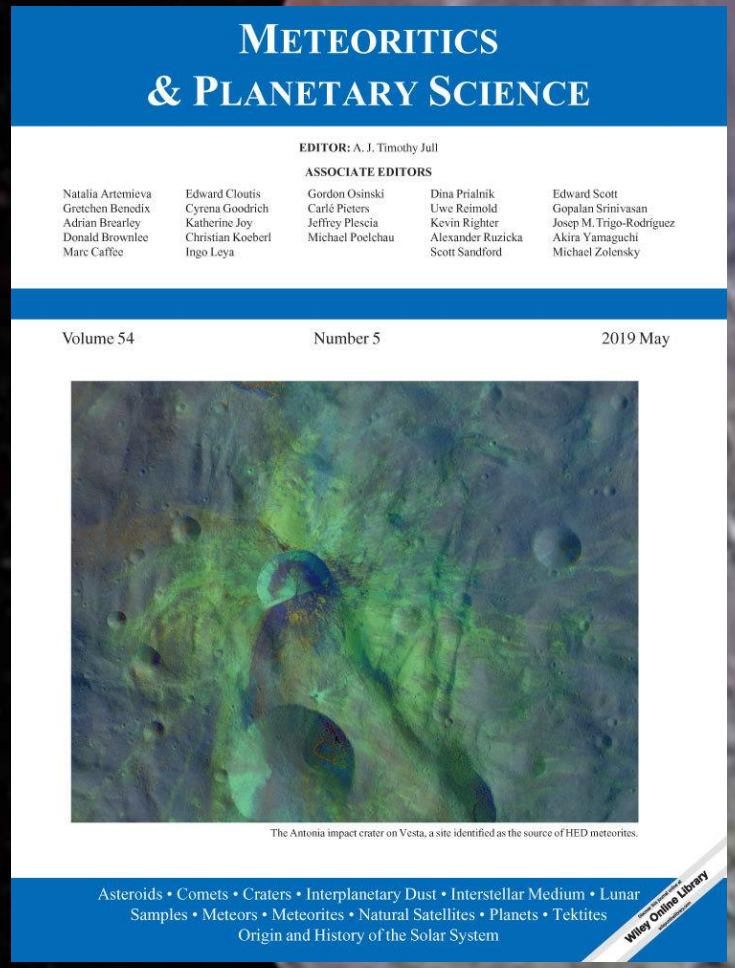


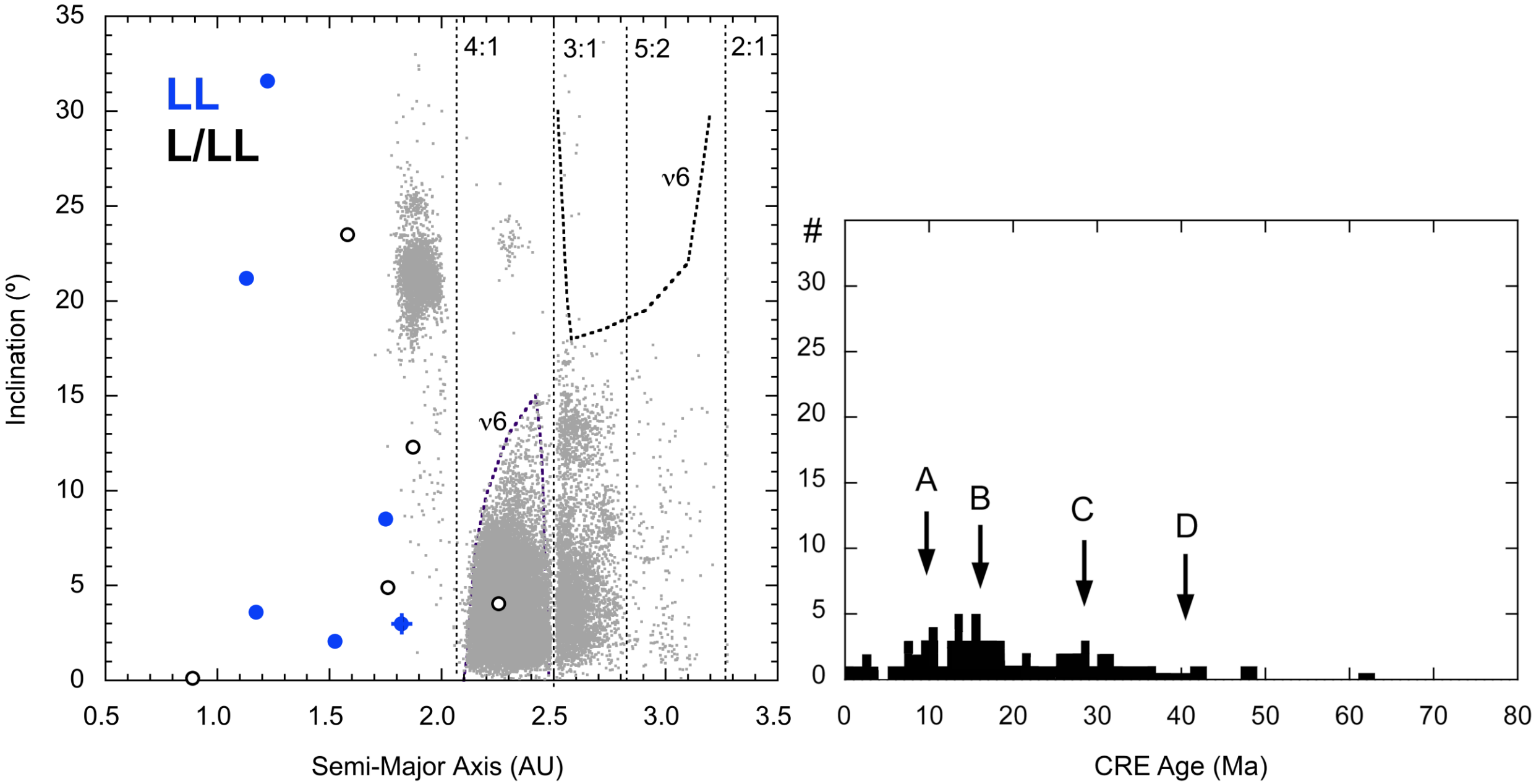

Unsalan et al. (2019) MAPS

Meteorites are from Vesta:
Larger surface area than large Vestoids

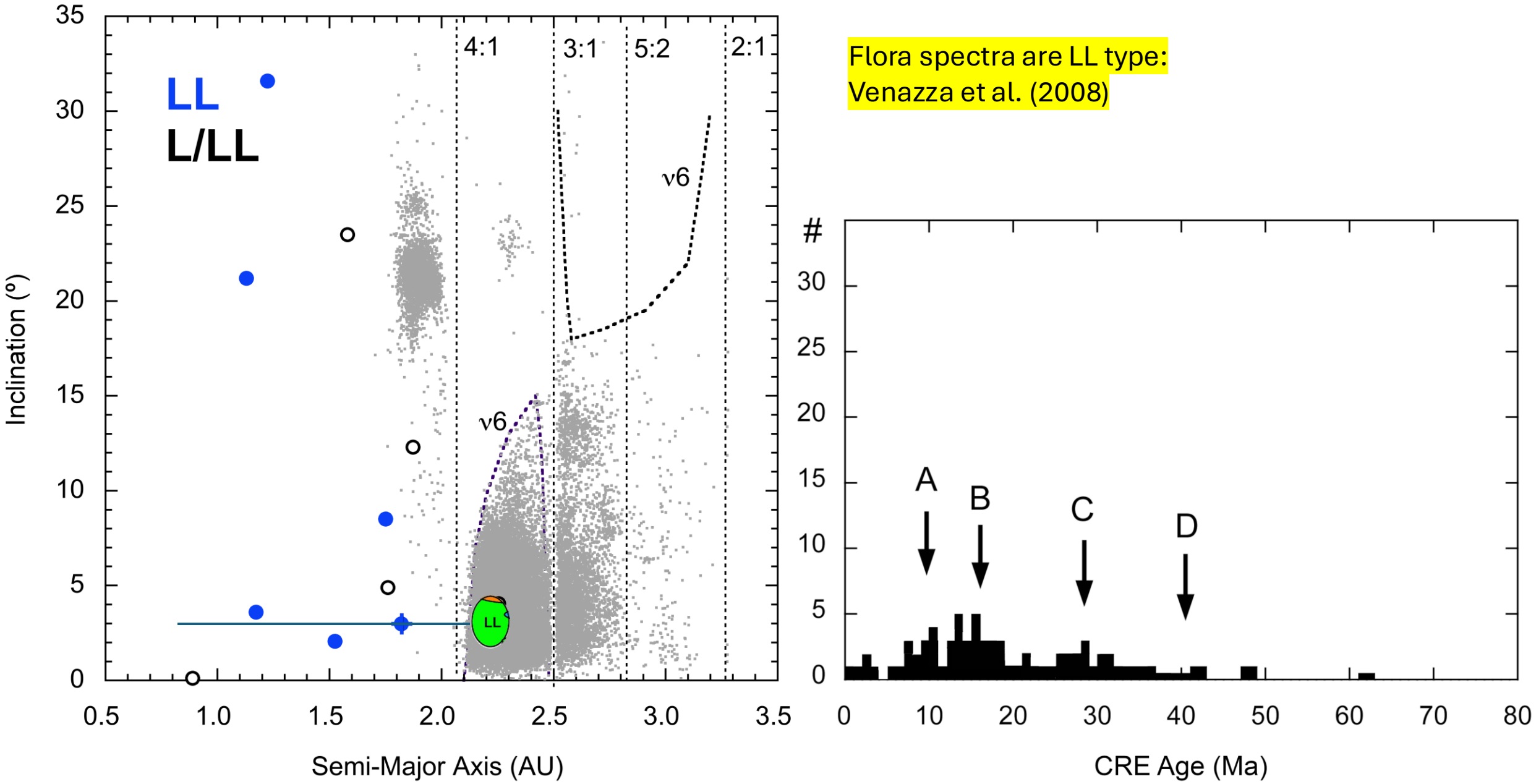
V-class NEA are from Vesta family

Antonia

# LL chondrites



# LL chondrites

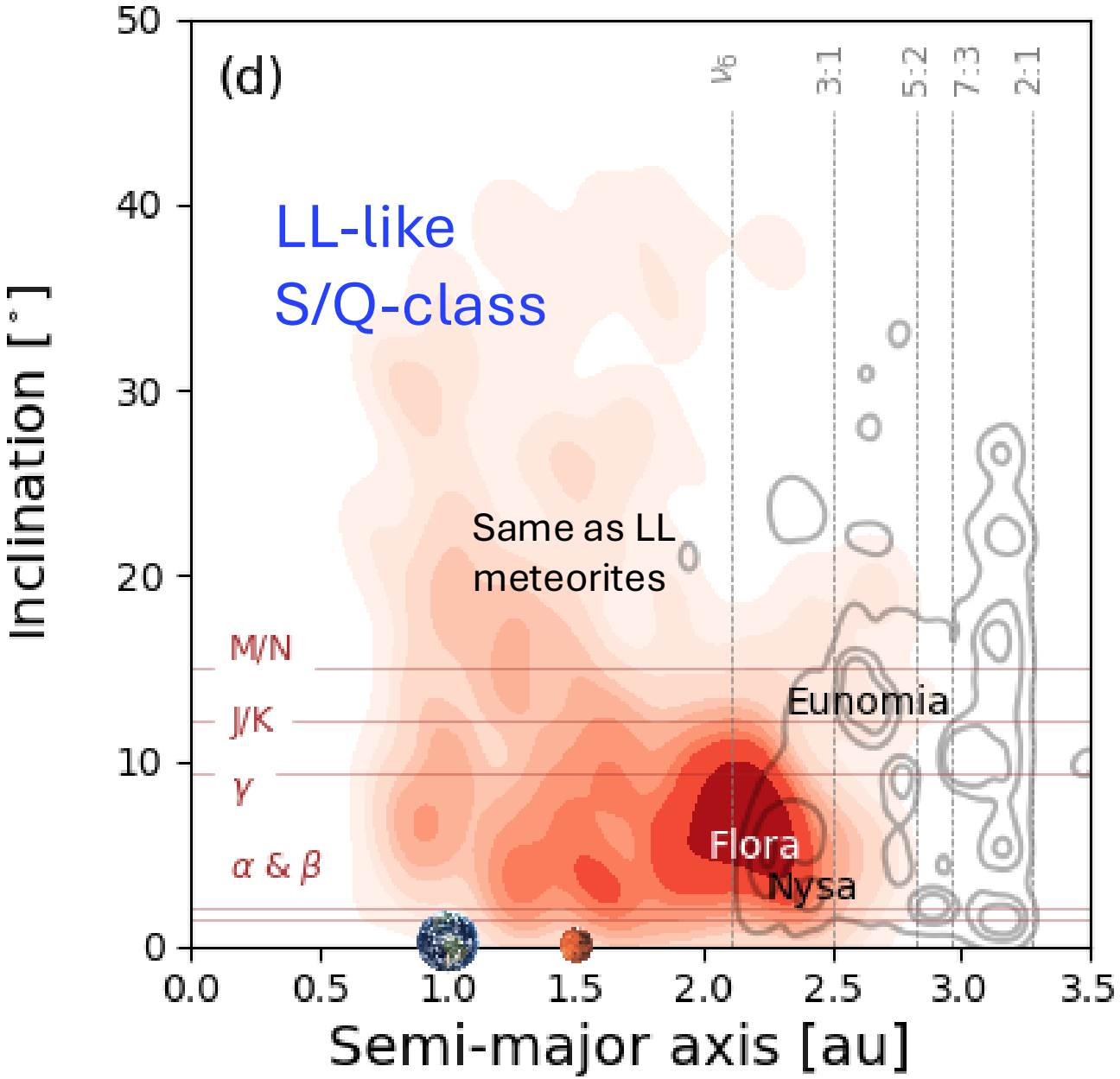


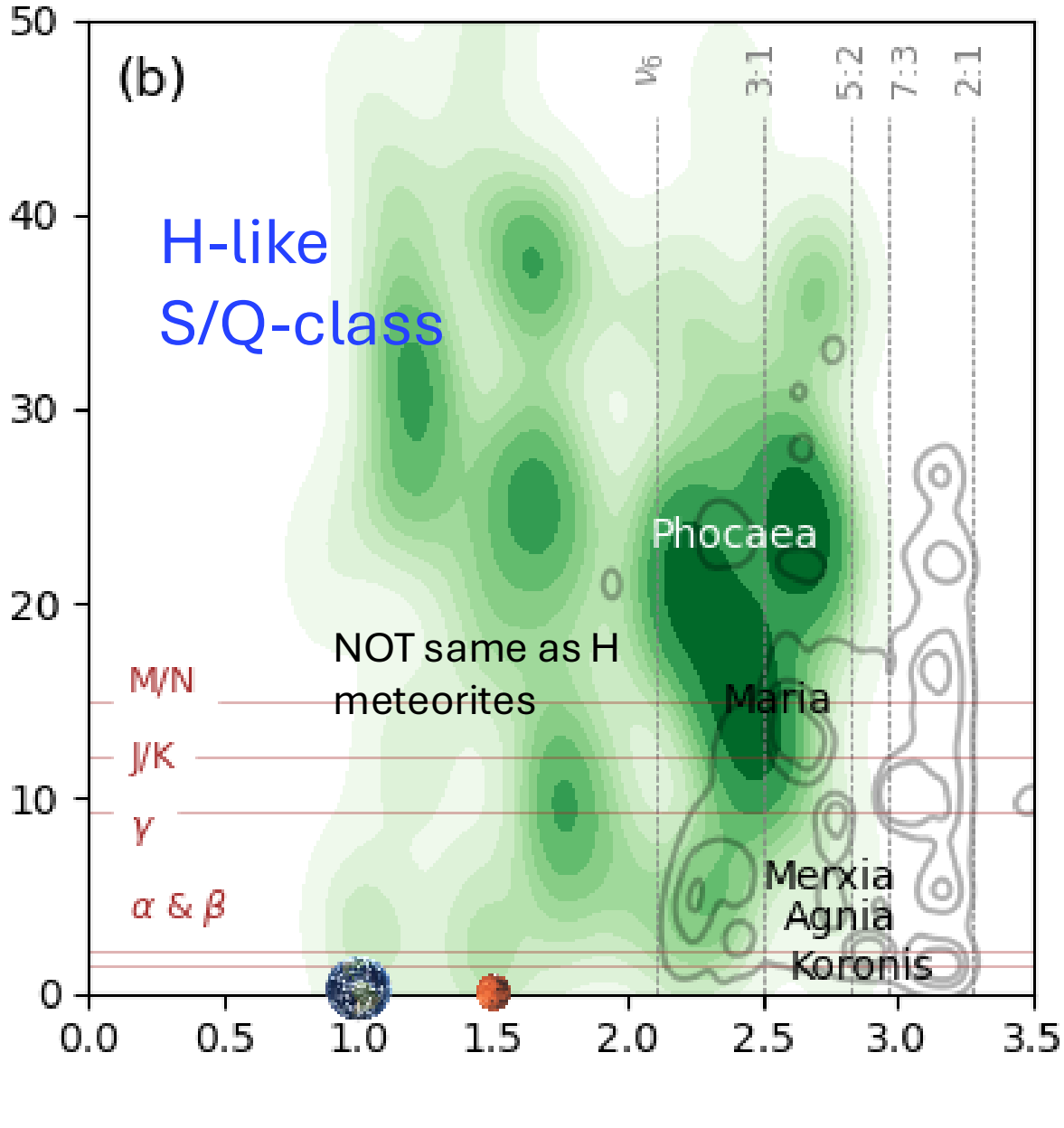

Flora spectra are LL type:
Venazza et al. (2008)

## LL-like NEA (~ 1 km)

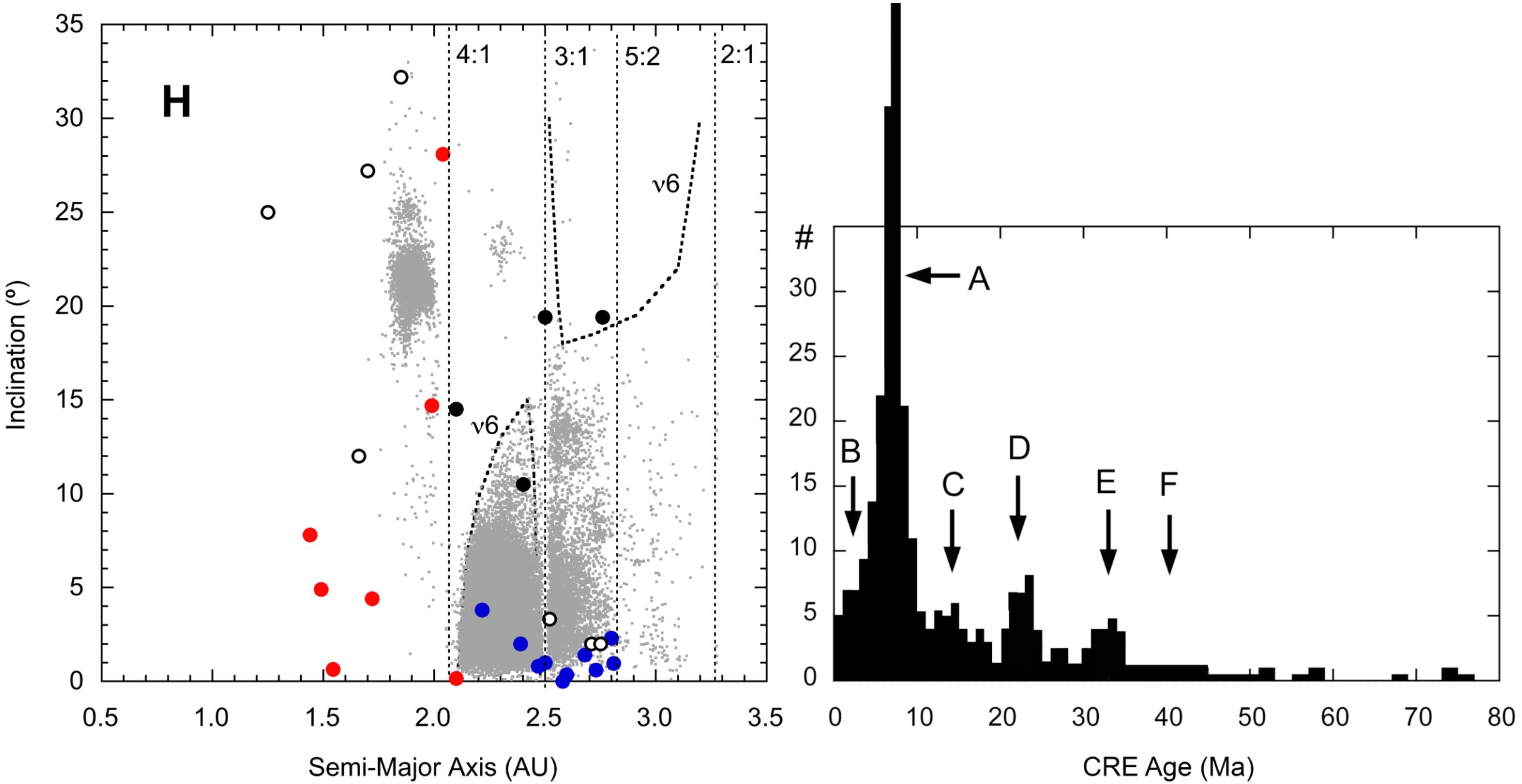
## H-like NEA

Marsset et al. (2024)



# H chondrites



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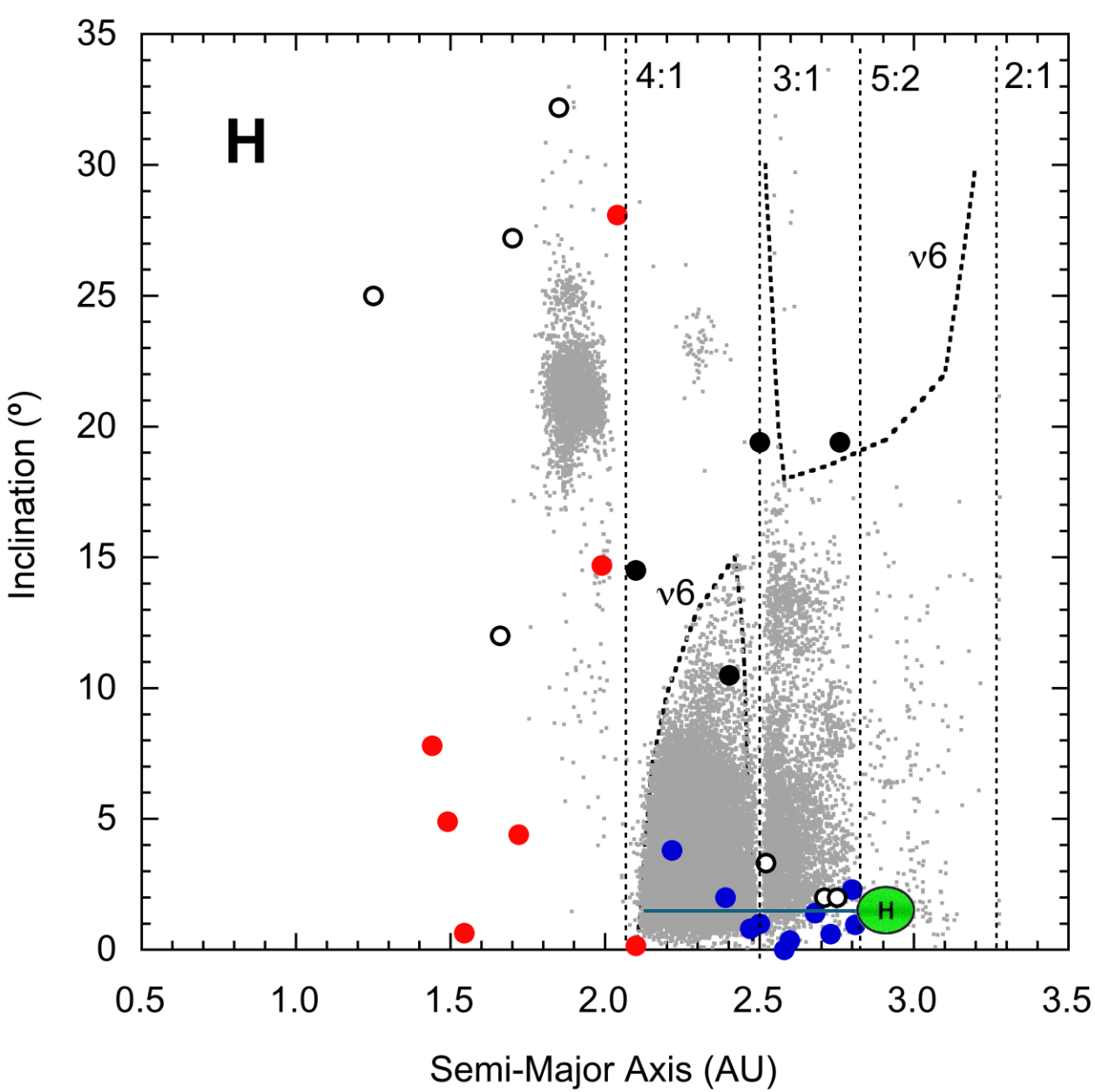
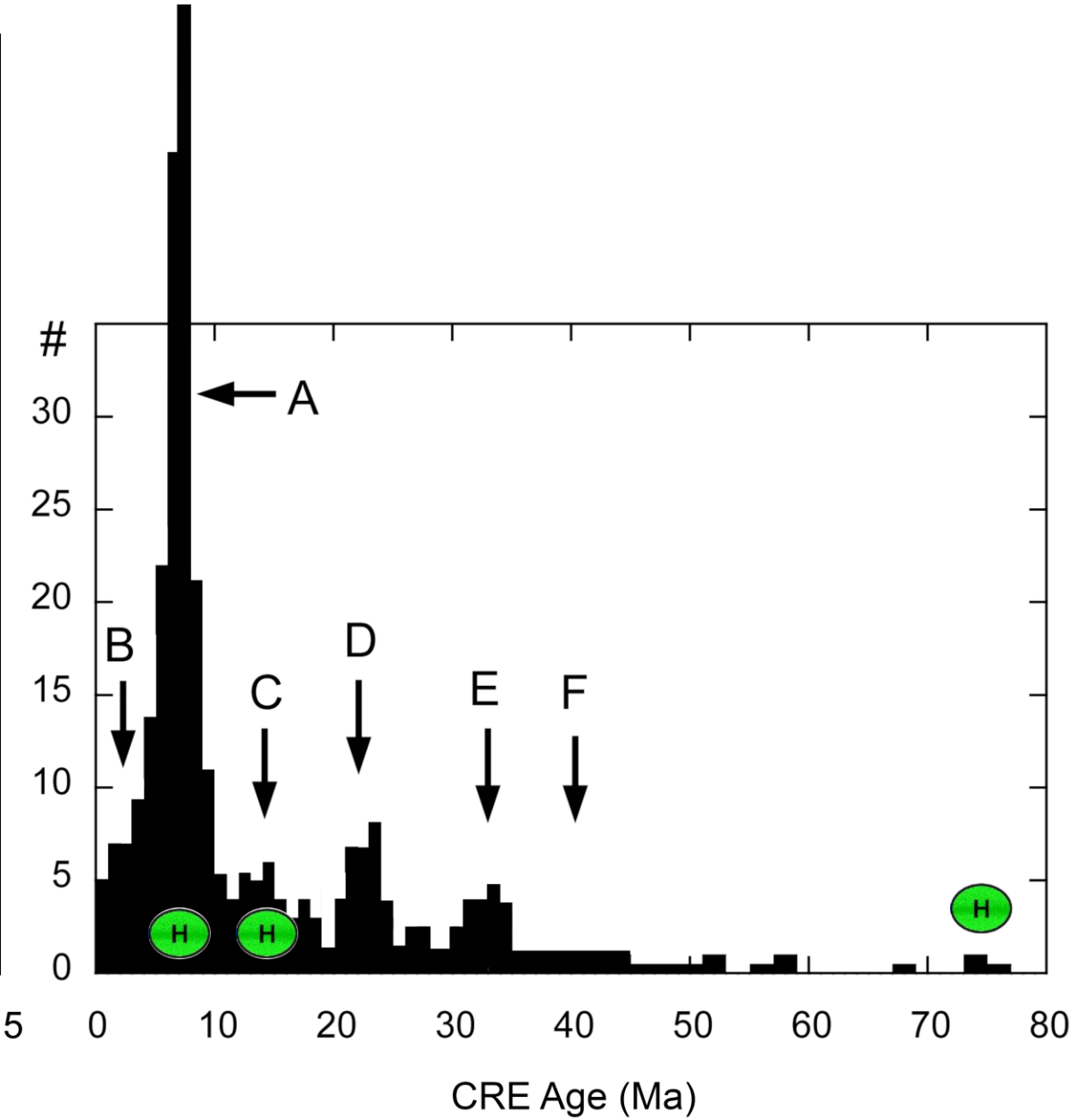
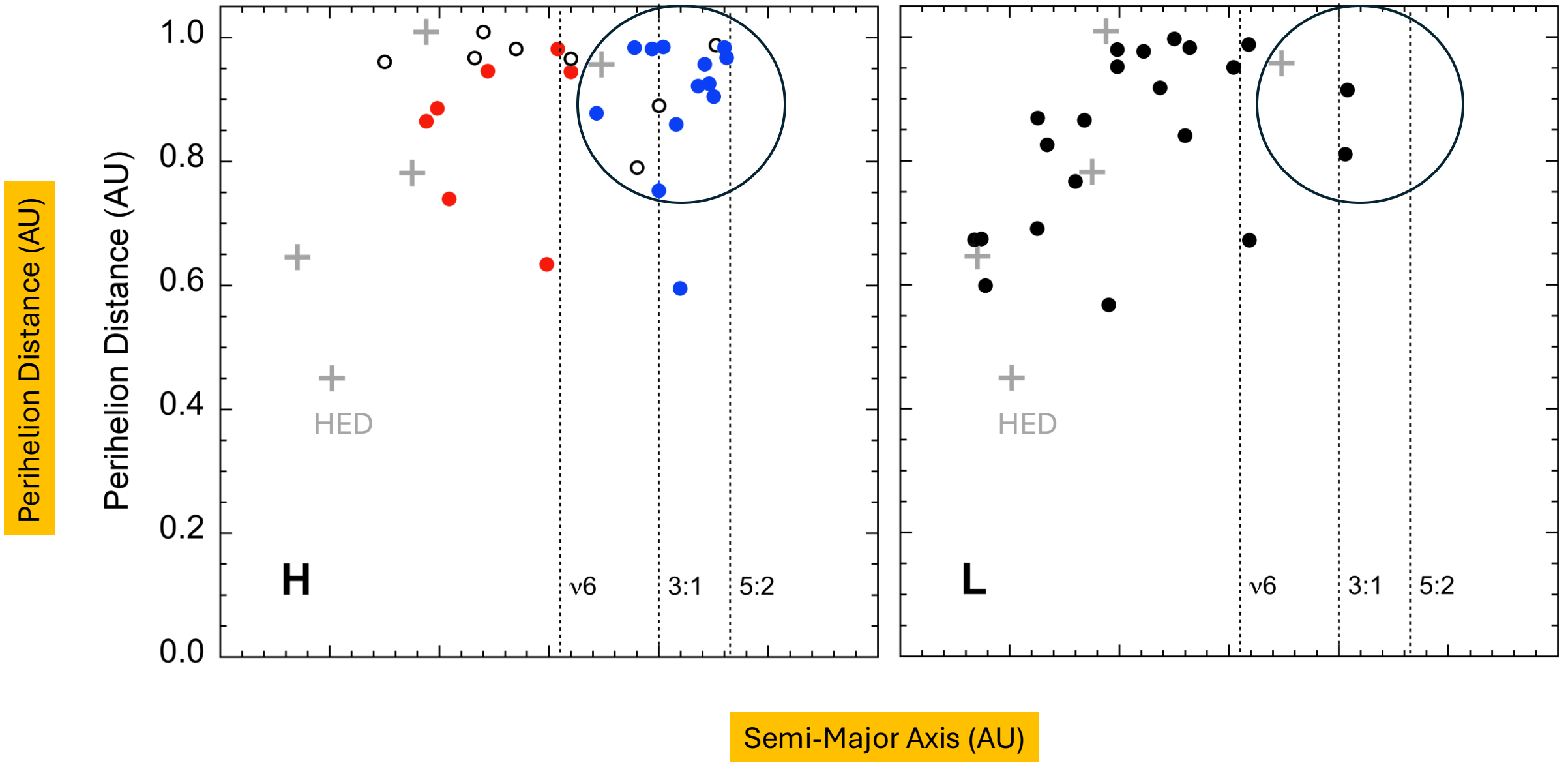


# H chondrites: Source just outside 5:2

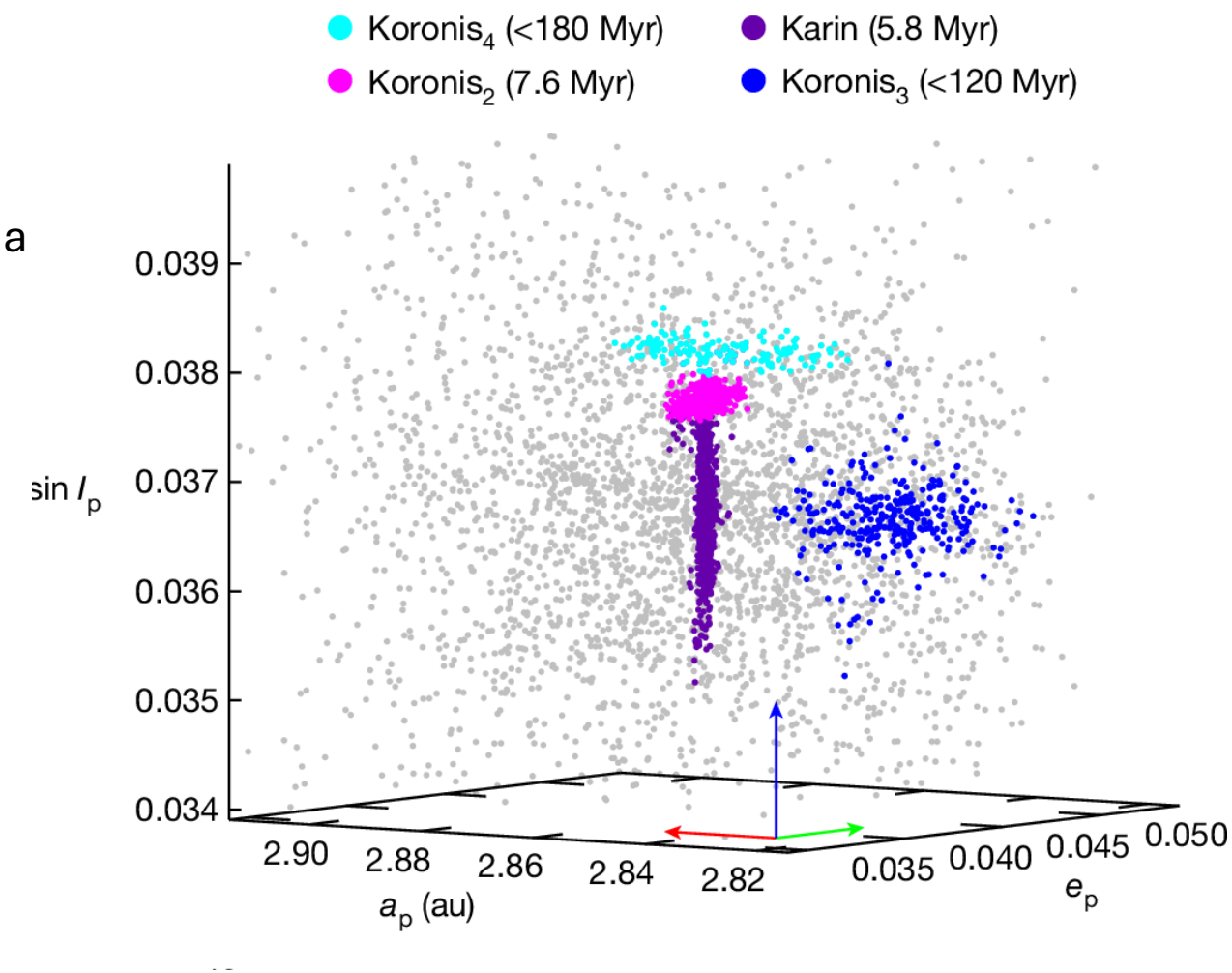


# Source of H chondrites (high a, low-i cluster)

| | | CRE Age: |
|---|---|---|
| **Karin cluster (5.8 Ma):** | | |
| • Košice, Slovakia | H5 | 6.0 ± 1.0 Ma |
| • Murrili, Australia | H5 | 6.6 ± 1.0 Ma |
| • Arpu Kuilpu, Australia | H5 | 7.0 ± 1.0 Ma |
| **Koronis_2 cluster (10-15 Ma):** | | |
| • Hamburg, USA | H4 | 11.8 ± 0.7 Ma |
| • Mason Gully, Australia | H5 | ~14 Ma |
| • Ejby, Denmark | | |
| • **Koronis_3 cluster (< 100Ma):** | H5/6 | 83 ± 11 Ma |
| • Tanxi, China | H6 | -.- |
| • Kybo-Lintos, Australia | H4/5 | -.- |
| • Benghazi Dam, Australia | H5 | -.- |
| • Great Salt Lake, USA | H5 | -.- |
| • Neuvy-sur-Barangon, France | H5 | -.- |
| • Crawford Bay, Canada | H6 | -.- |

Proposed source: Venezza et al., 2014

## Koronis family




Broz et al. (2024, Nature)

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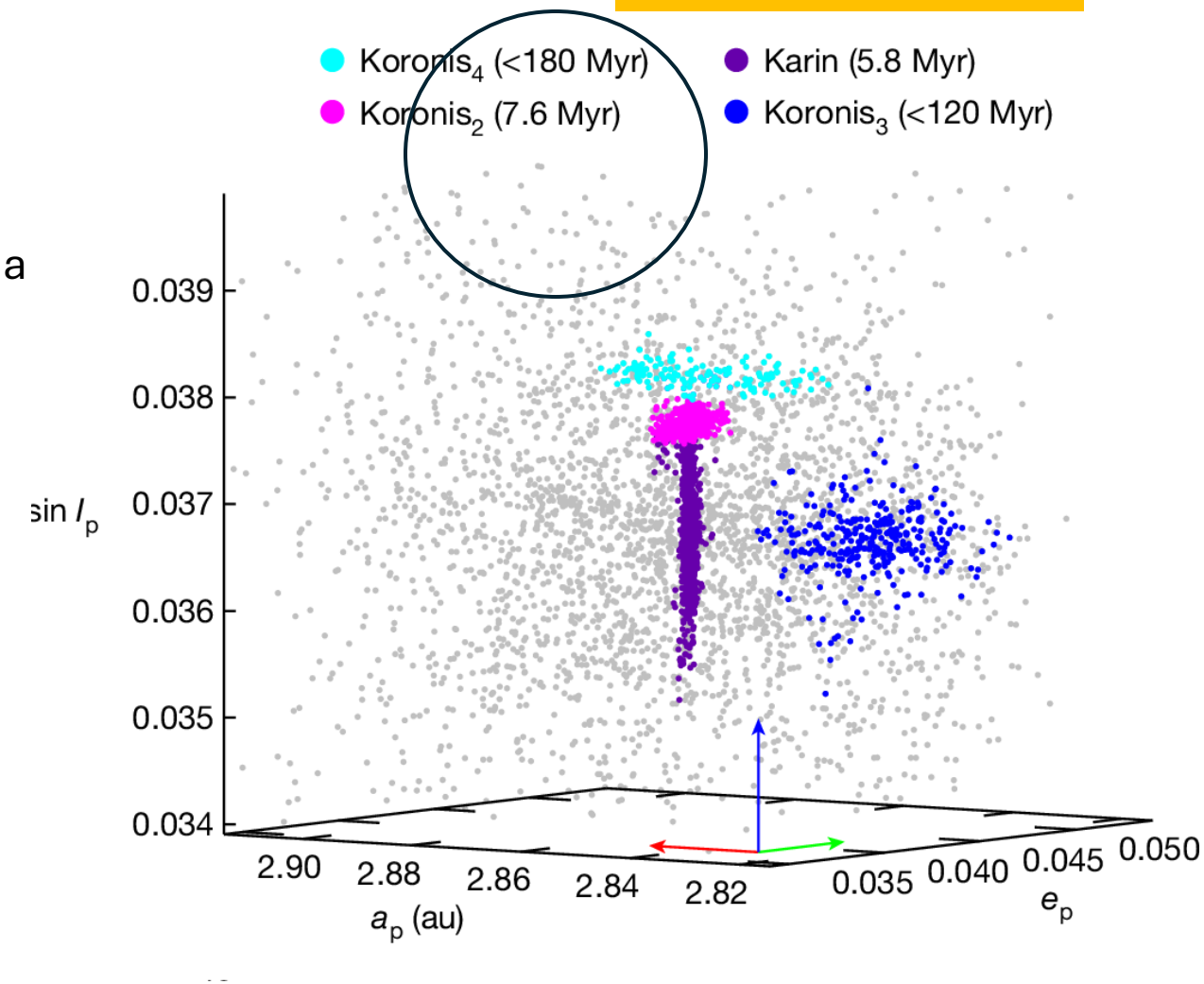
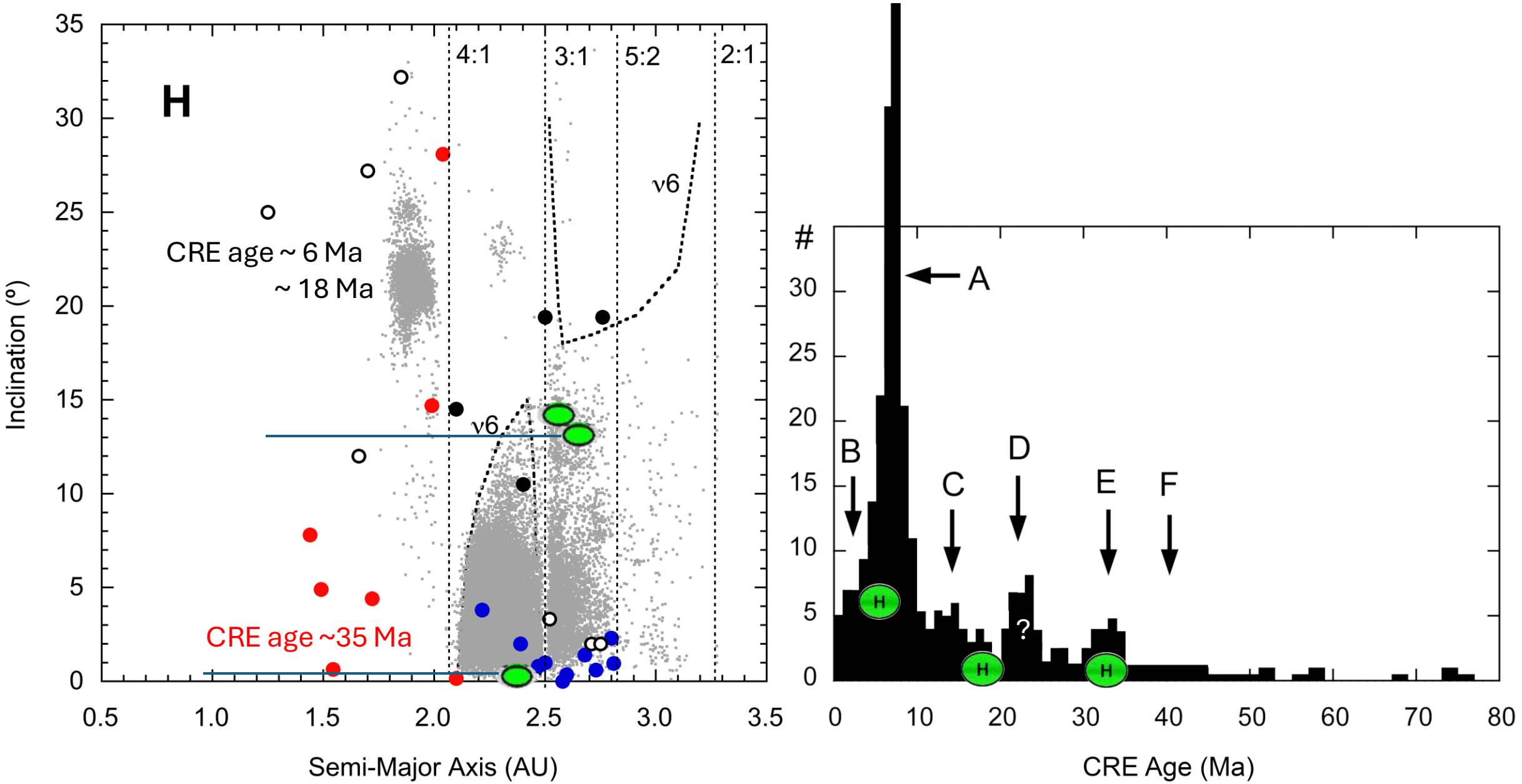
Proposed source: Venezza et al., 2014

Koronis family




Broz et al. (2024, Nature)

# H chondrites NOT from the Koronis family



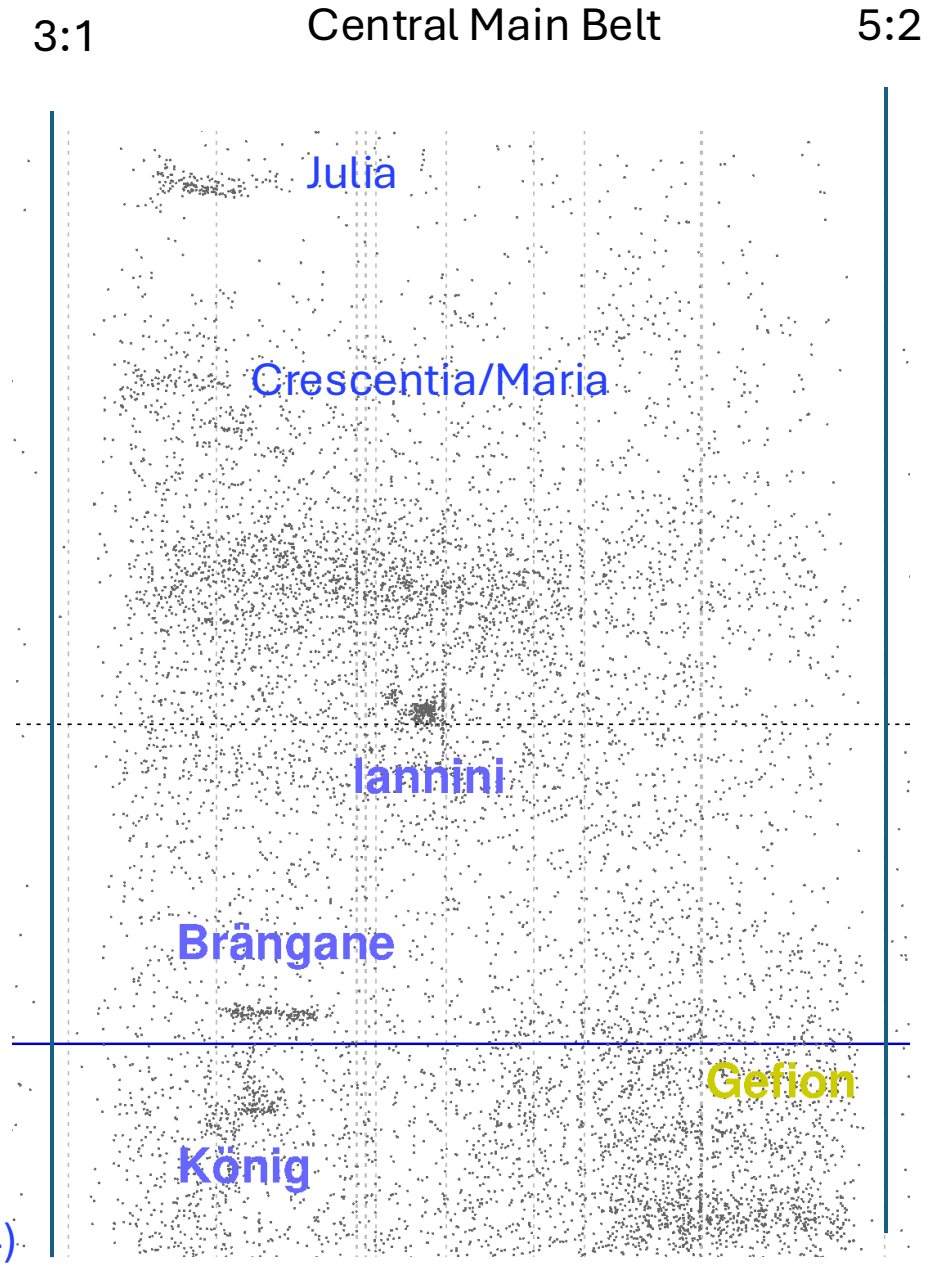
# H chondrites (Central Main Belt)

Nele = Ianini (6 Ma):

| | | CRE Age: |
|---|---|---|
| • Morávka, Czech Republic | H5 | 6.7 ± 1.0 Ma |
| • Lost City, USA | H5 | 7.0 ± 0.4 Ma |
| • Buzzard Coulee | H5 | ~6 Ma |
| • Pusté Úlany | H5 | 4 ± 1 Ma |

Crescentia cluster in Maria family?

| | | |
|---|---|---|
| • Pribram, Czechia | H5 | 17 ± 2 Ma |
| • Elmshorn, Germany | H3-6 | 18.5 ± 1.5 Ma |

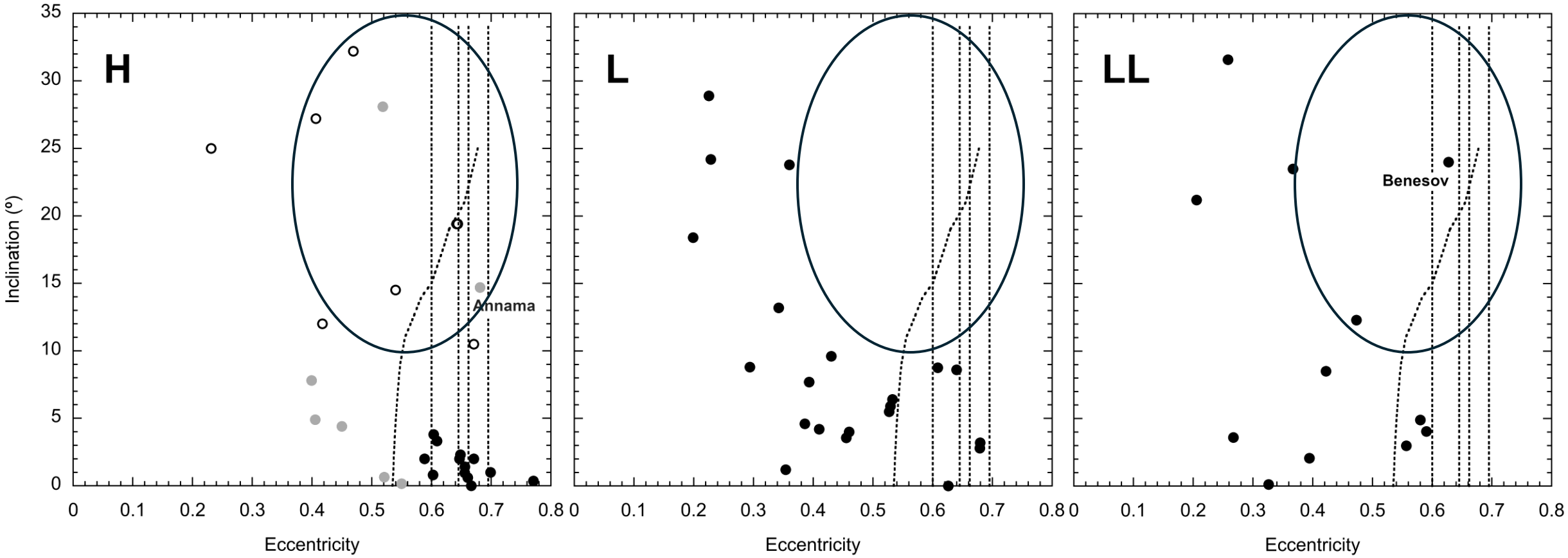



Broz et al. (2024)

# H chondrites (Central Main Belt)

Nele:

Eunomia:




Inclination (°)

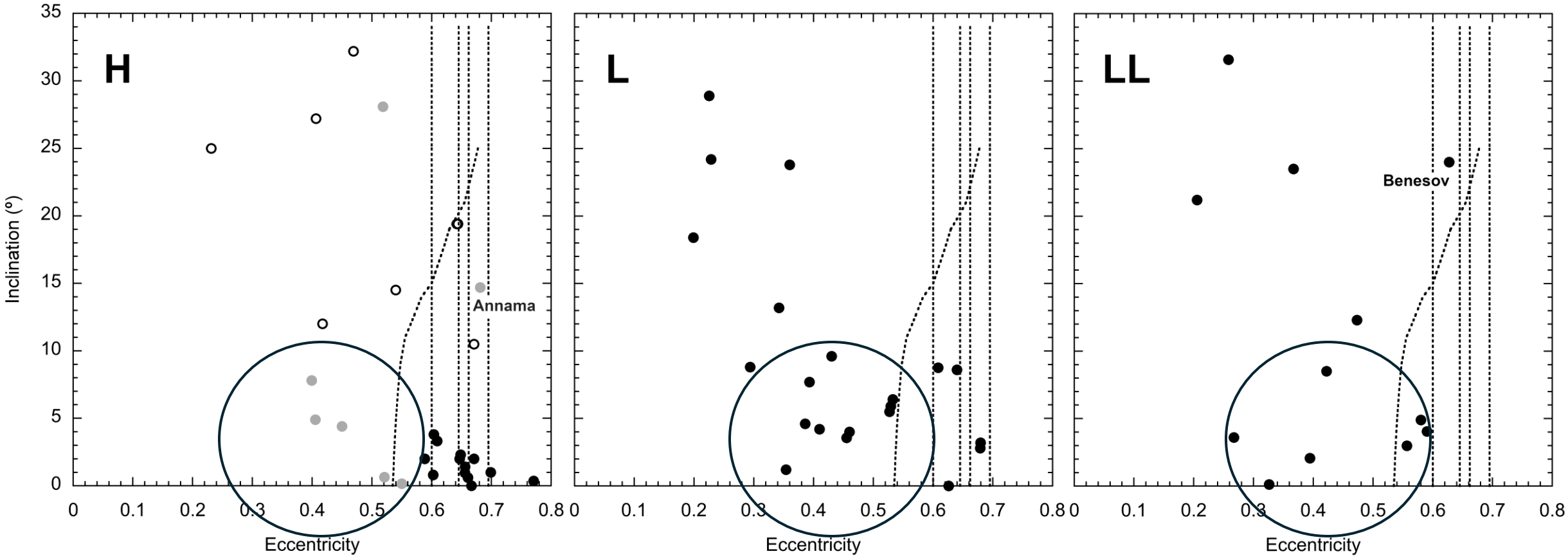
Eccentricity

# H chondrites (Inner Main Belt)

Massalia_2:

Hertha:

Flora:




Inclination (°)

Inner Main Belt
Source of H

Eccentricity

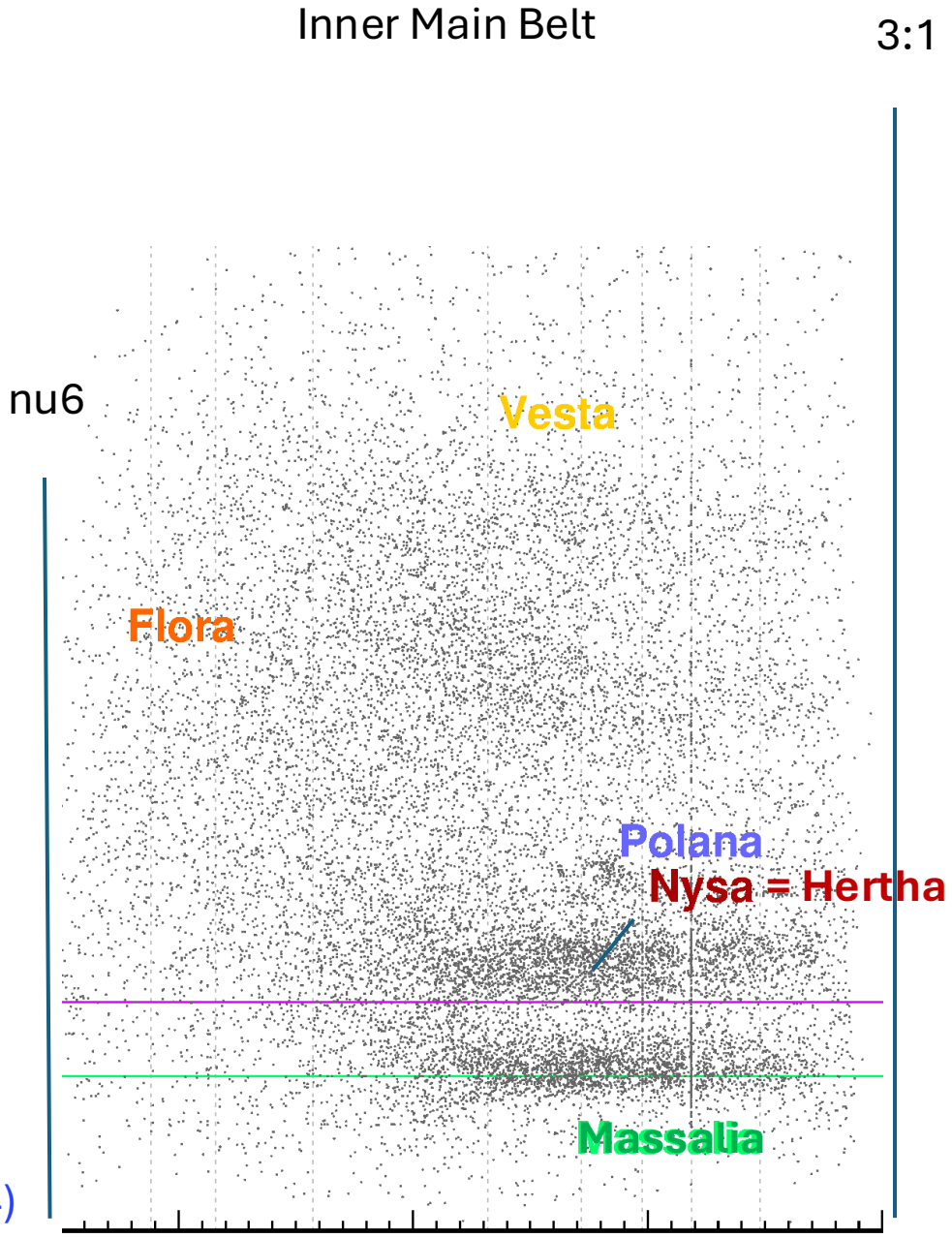
# H chondrites (Inner Main Belt)

Massalia_2 (~40 Ma):

| | | CRE Age: |
|---|---|---|
| Narashino, Japan | H5 | 40 Ma |
| Grimsby, Canada | H5 | ~35 Ma |
| Peekskill, USA | H6 | 32 Ma |
| Annama | H5 | 30 Ma |
| Santa Filomena | H5-6 | |
| Krizevci | H6 | |
| Al-Khadhaf | H5-6 | |

Massalia family: cratering (20) Massalia ~150 Ma ago:
Vokrouhlicky et al. (2006)
Gaffey & Fieber-Beyer (2019)

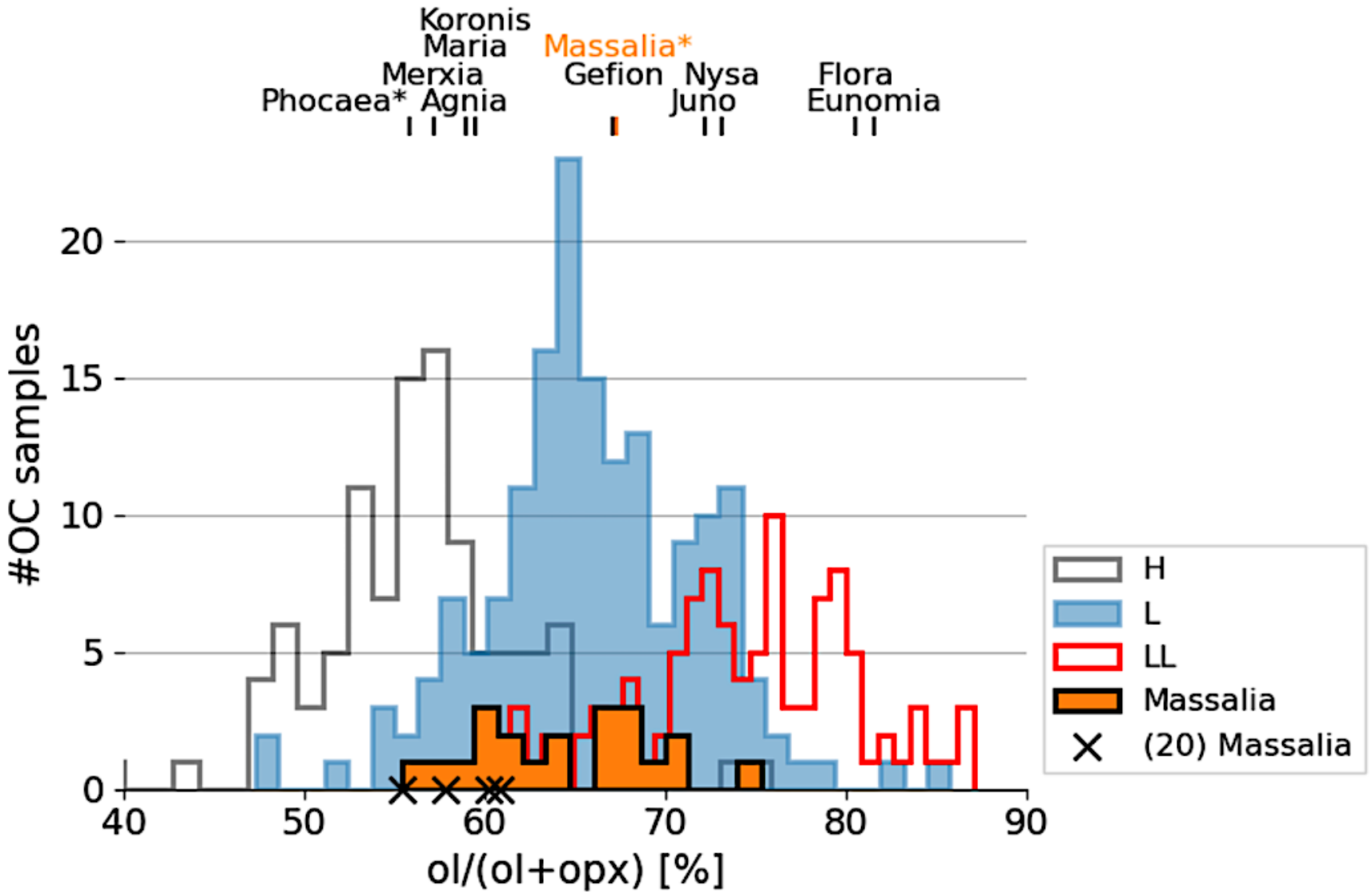
40 Ma cluster in Massalia identified by Marsset et al. (2024)

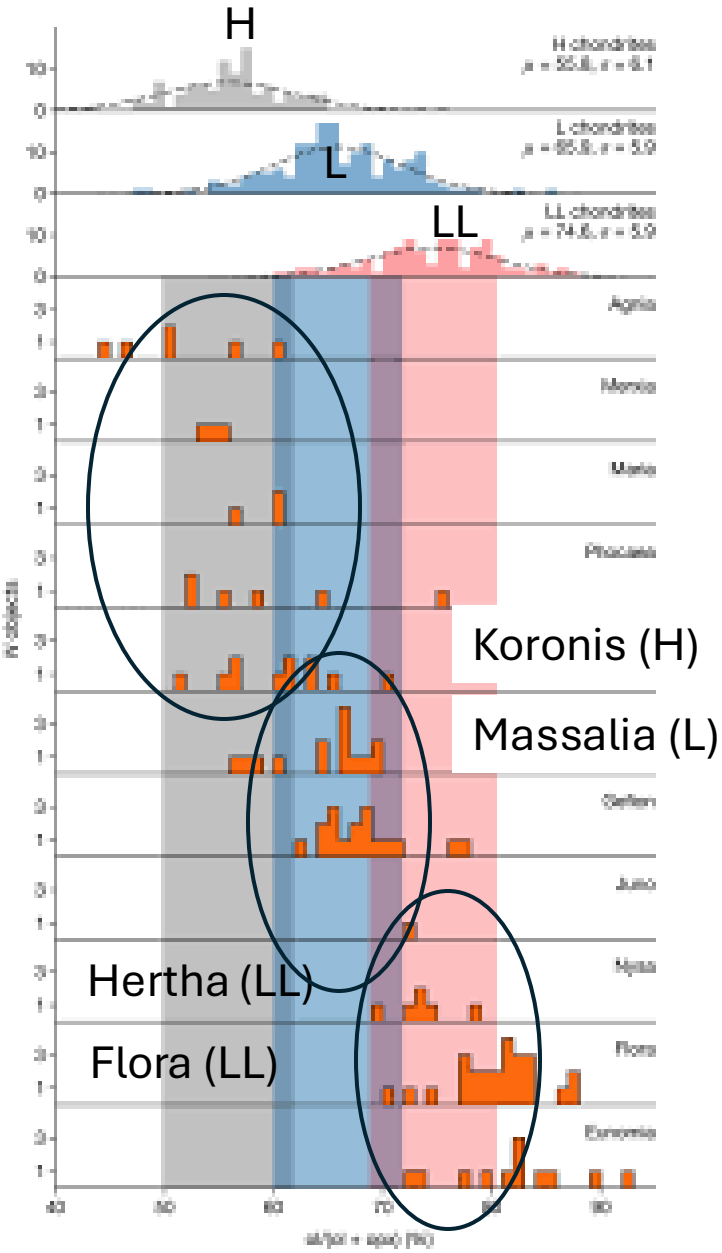



Broz et al. (2024)

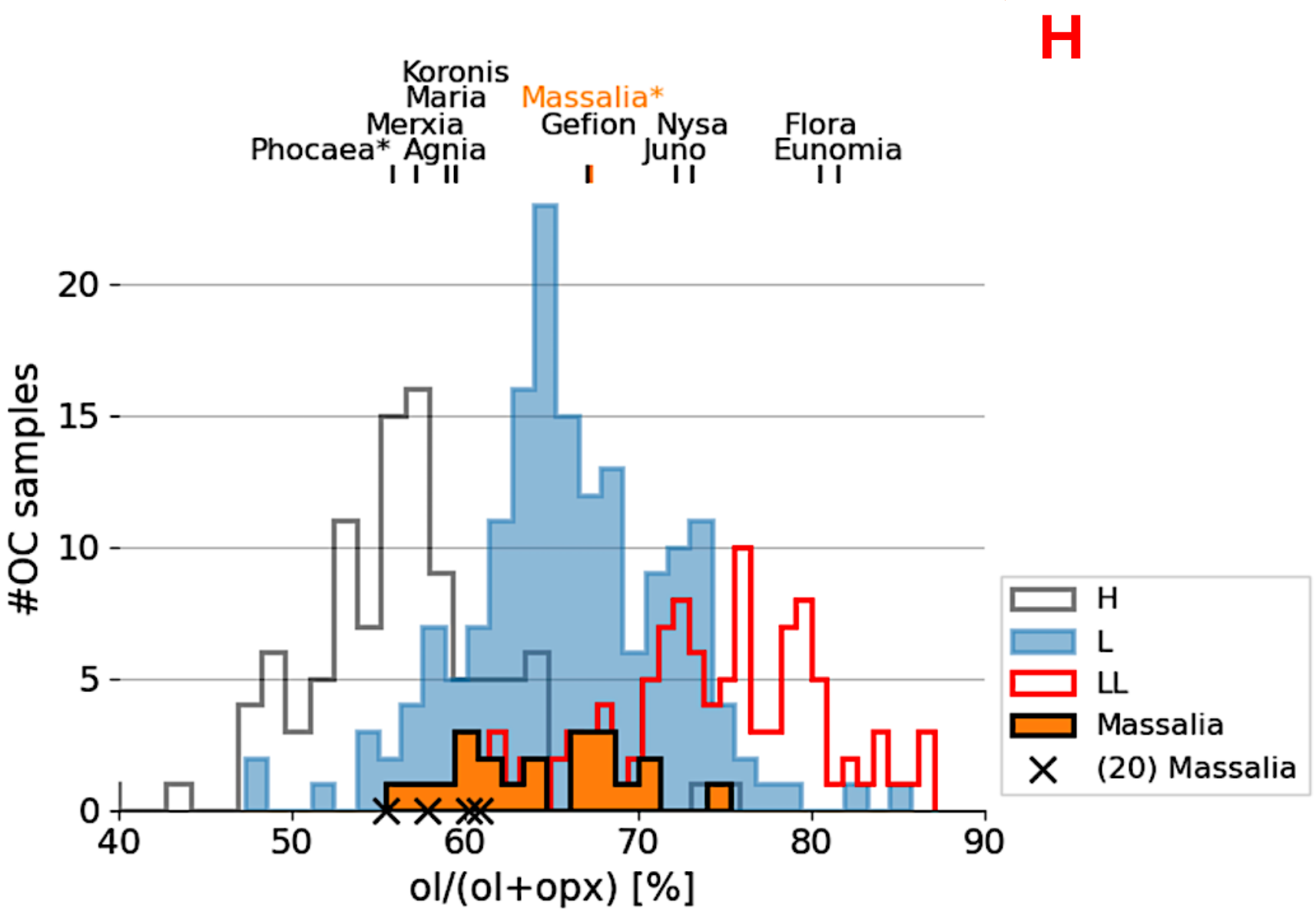
# Massalia as source of L chondrites

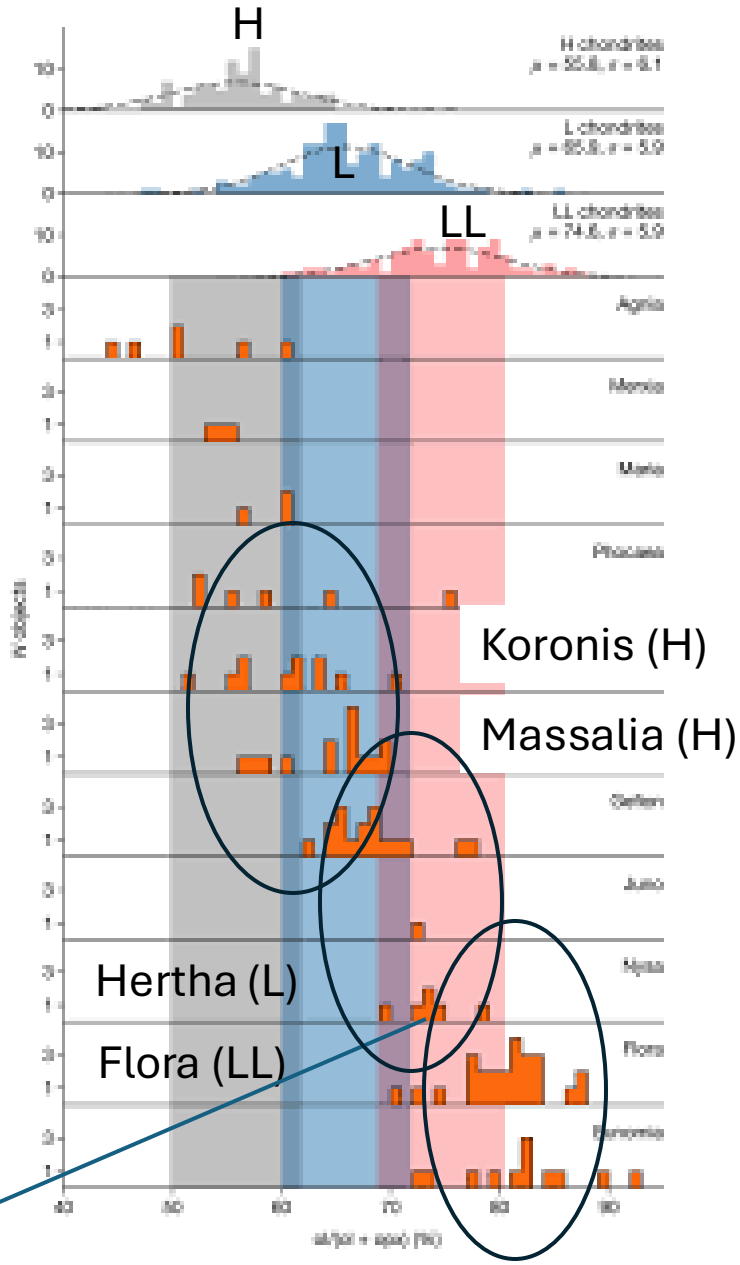
Marsset et al. (2024) Nature



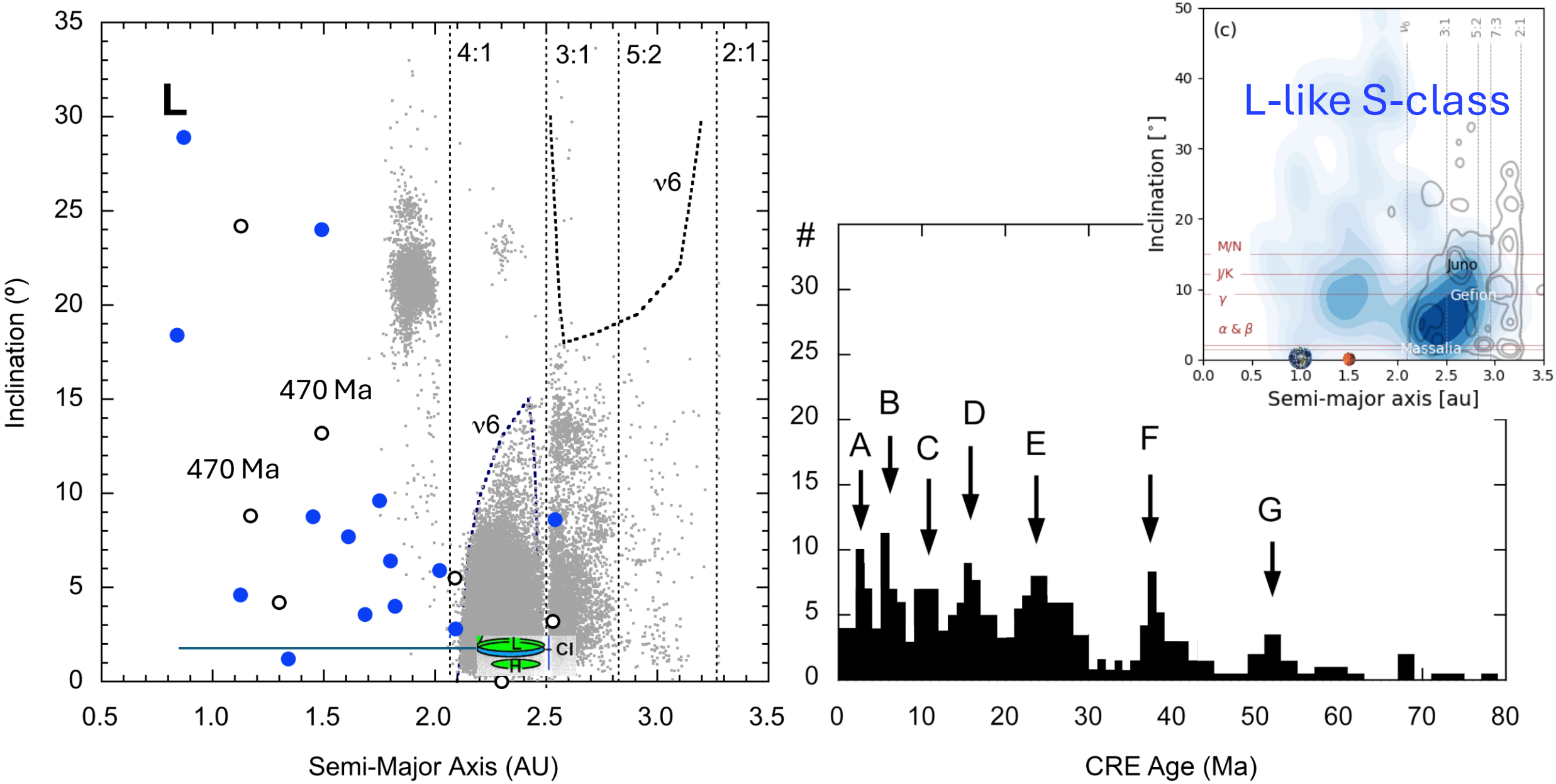
# Massalia as source of L chondrites



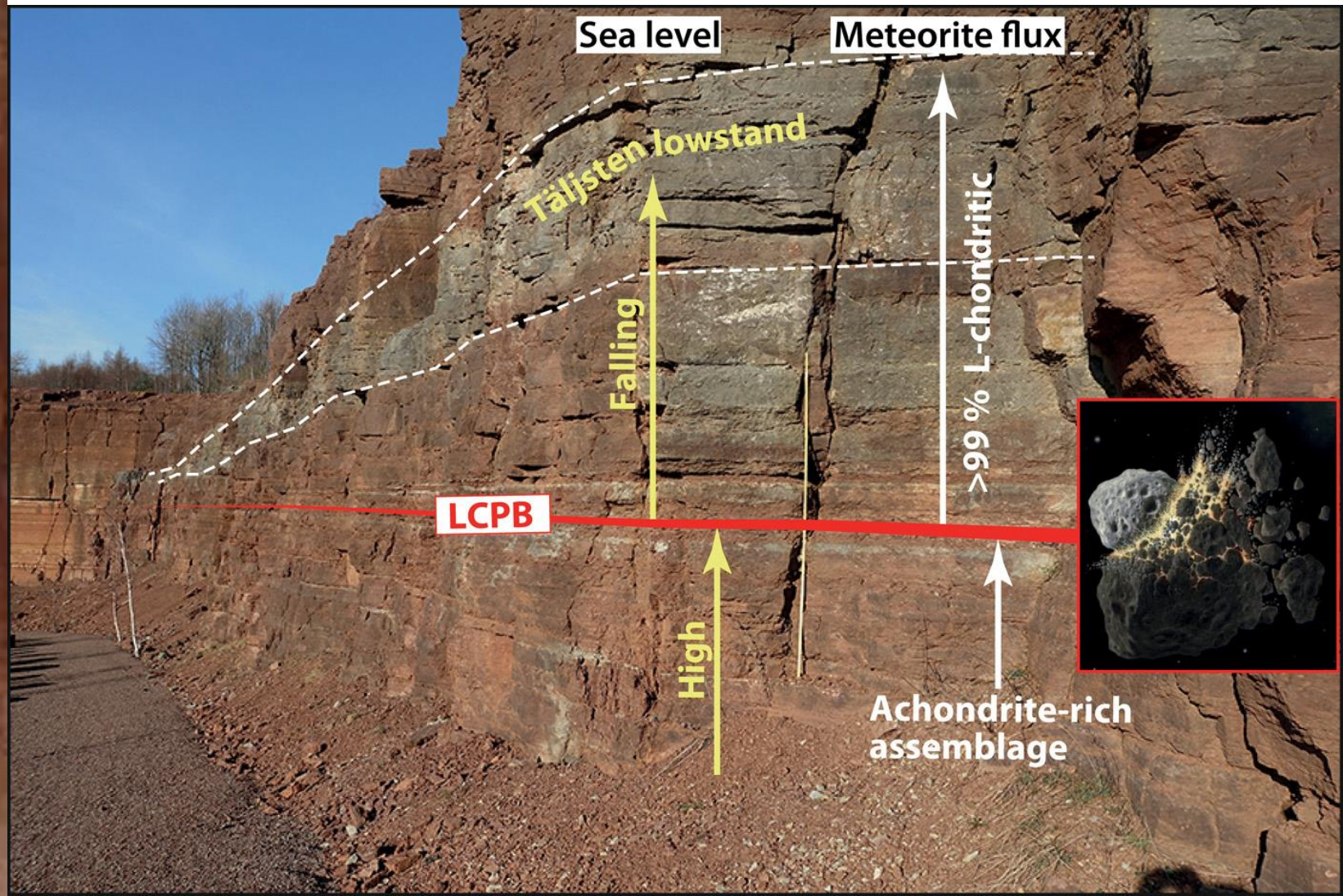

Hertha plots in between Massalia (H) and Flora (LL)

# L chondrites: One source in Inner Main Belt



# 468 Ma L-chondrite influx event

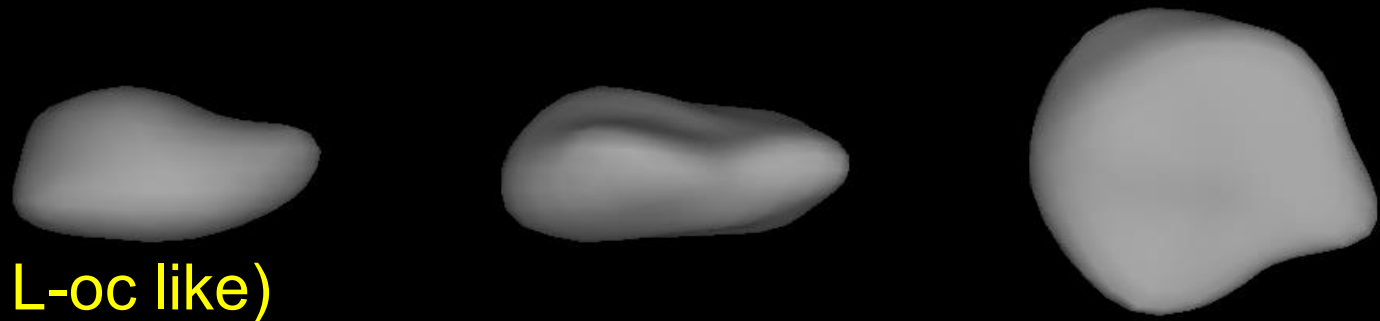
Fossil meteorite 468 Ma, Sweden, **Middle Ordovician**
(Schmitz et al.)



# (135) Hertha and (20) Massalia

(135) Hertha

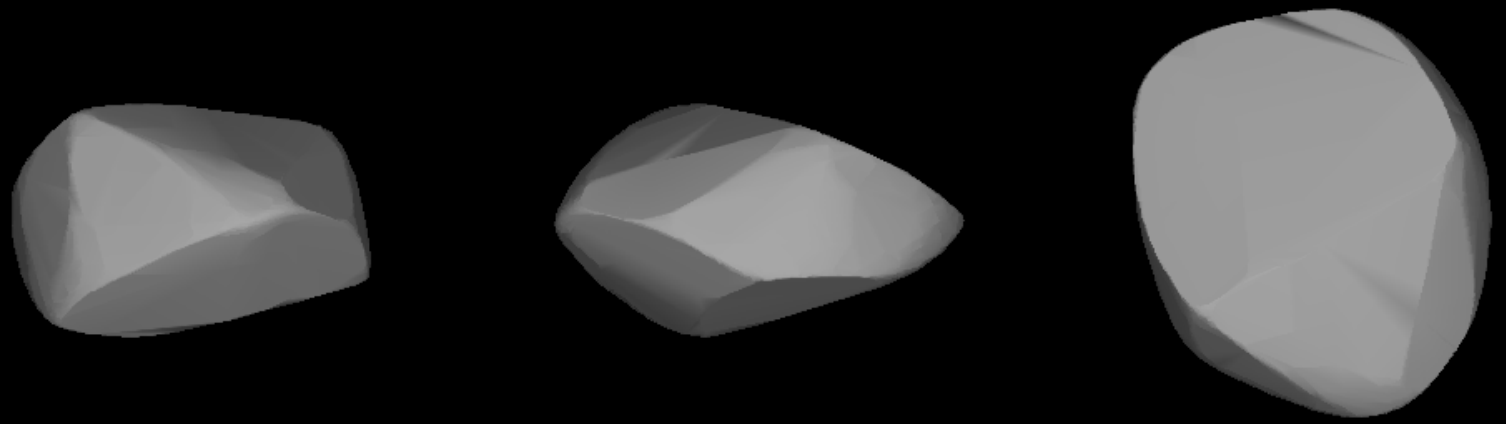
M / X (shock-blackened L-oc like)
- S (L-oc) fragments
- Less mass survives?
- Age ~300 (468) Ma



79 km

(20) Massalia

S (H-oc like)
- S (H-oc) fragments
- Lower ejection speeds
- Age ~150 (234) Ma

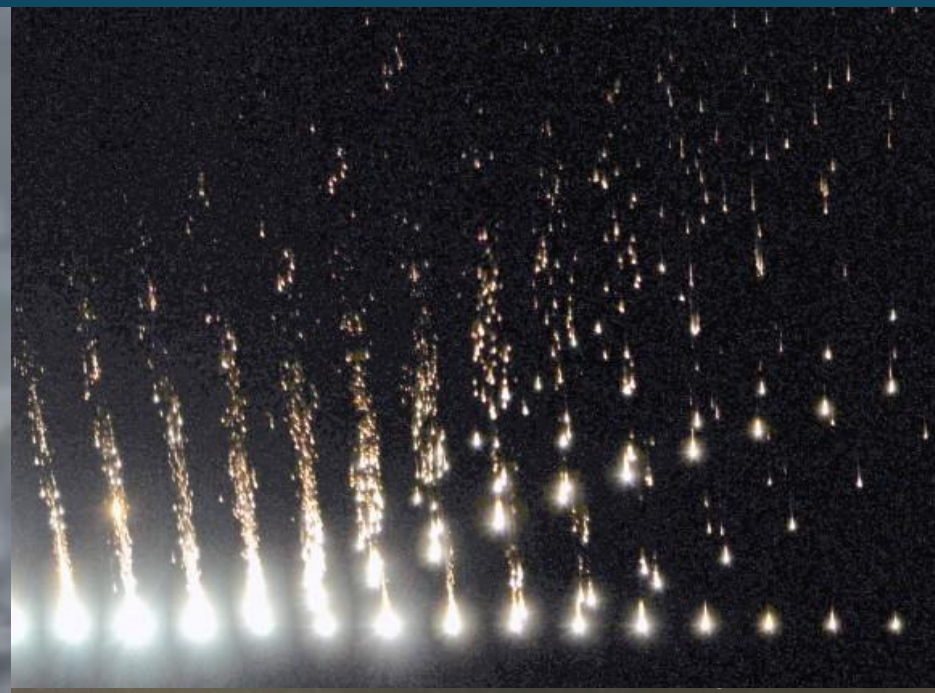


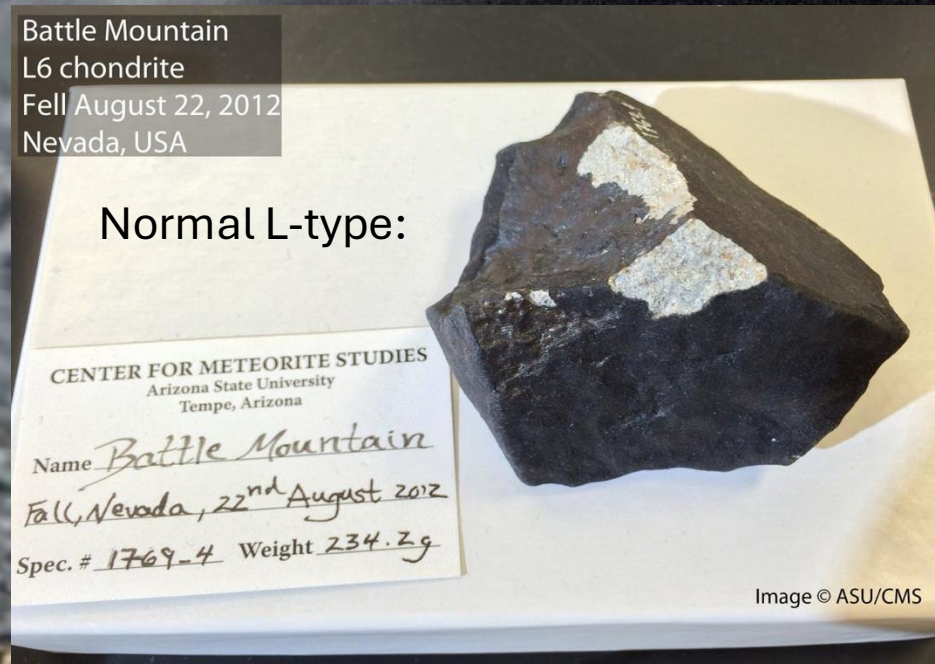
145 km

Hanuš *et al.* (2017)

# 470 Ma L-chondrite Ar-Ar age

Novato (470 Ma K-Ar resetting age):
Shock blackened

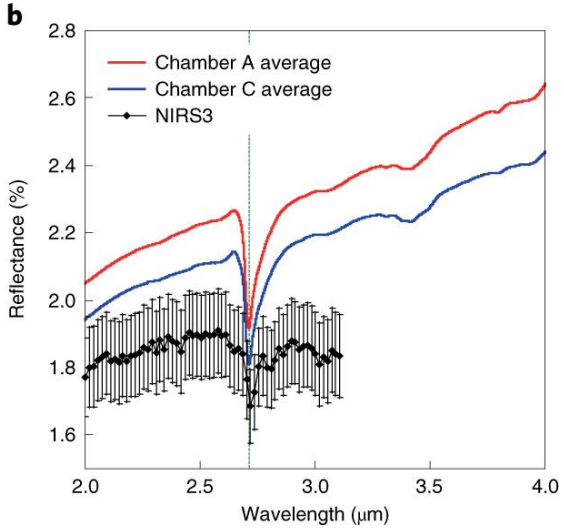




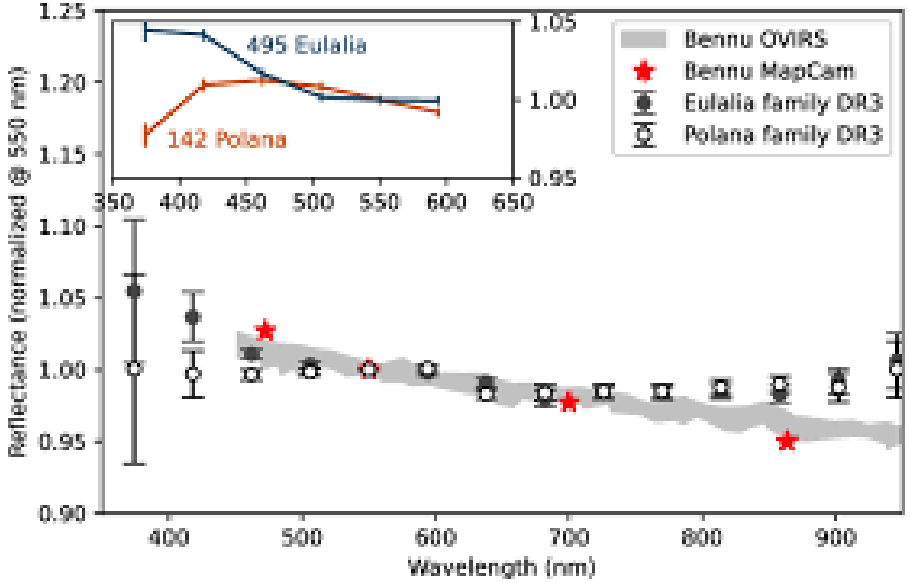
# CI chondrites: Polana/Eulalia

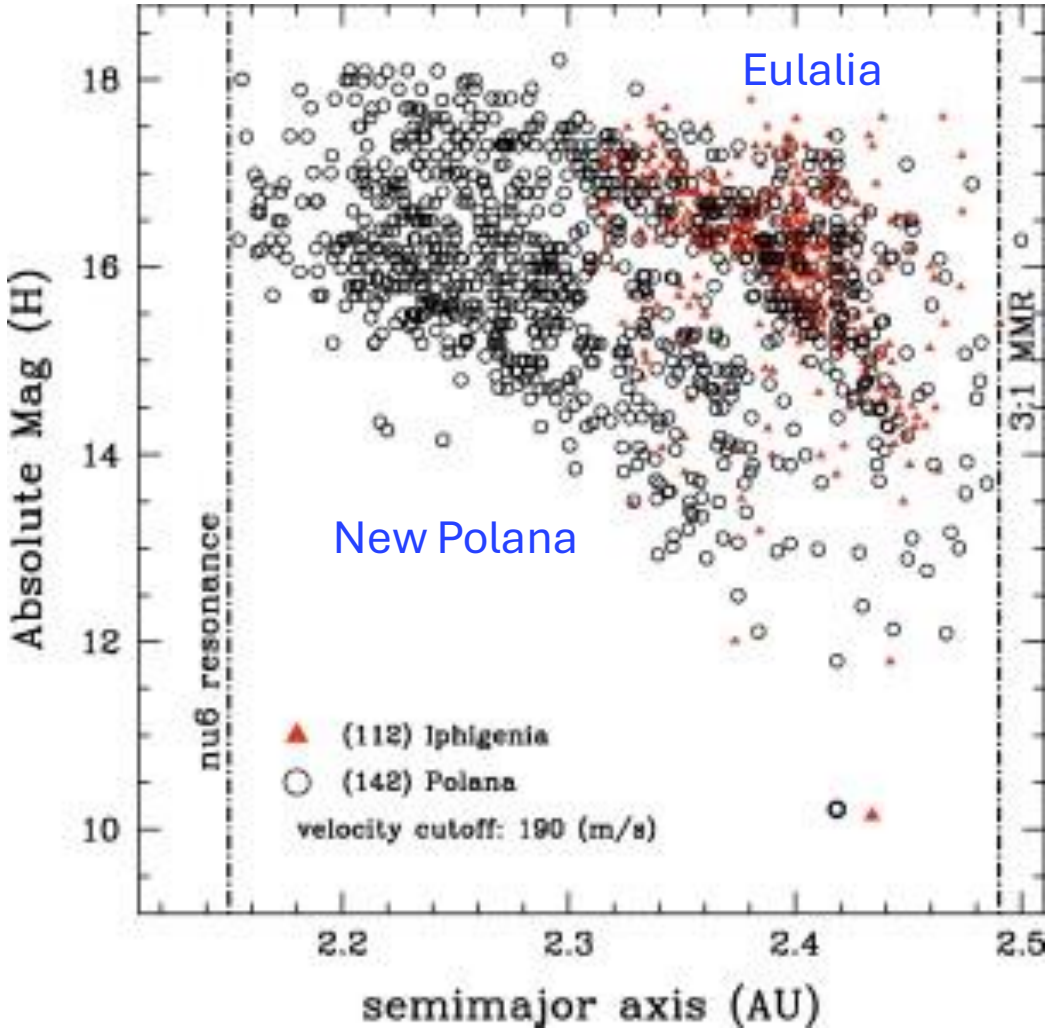
Ryugu: New Polana


Delbo et al. (203)

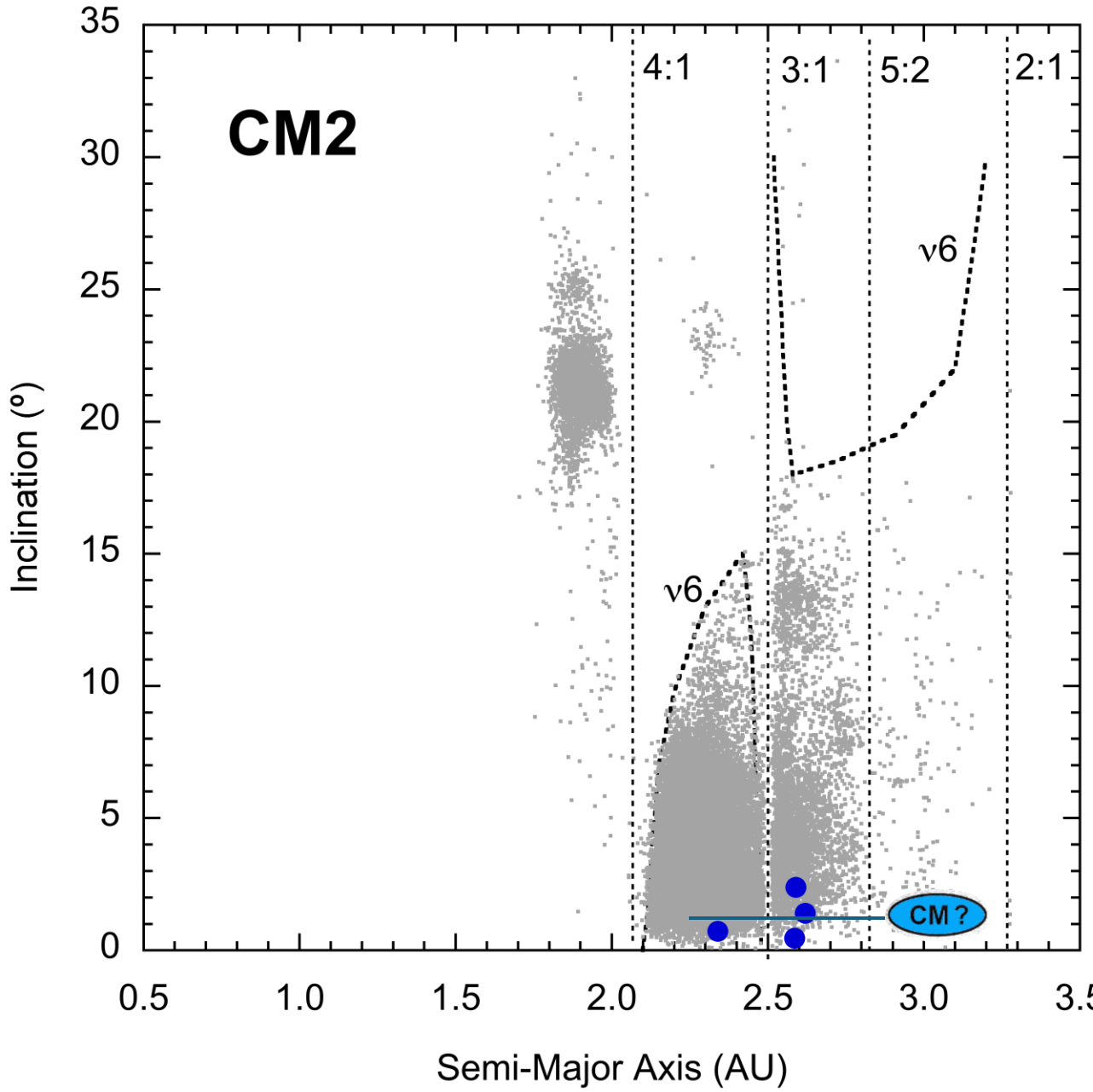



Bennu: Eulalia

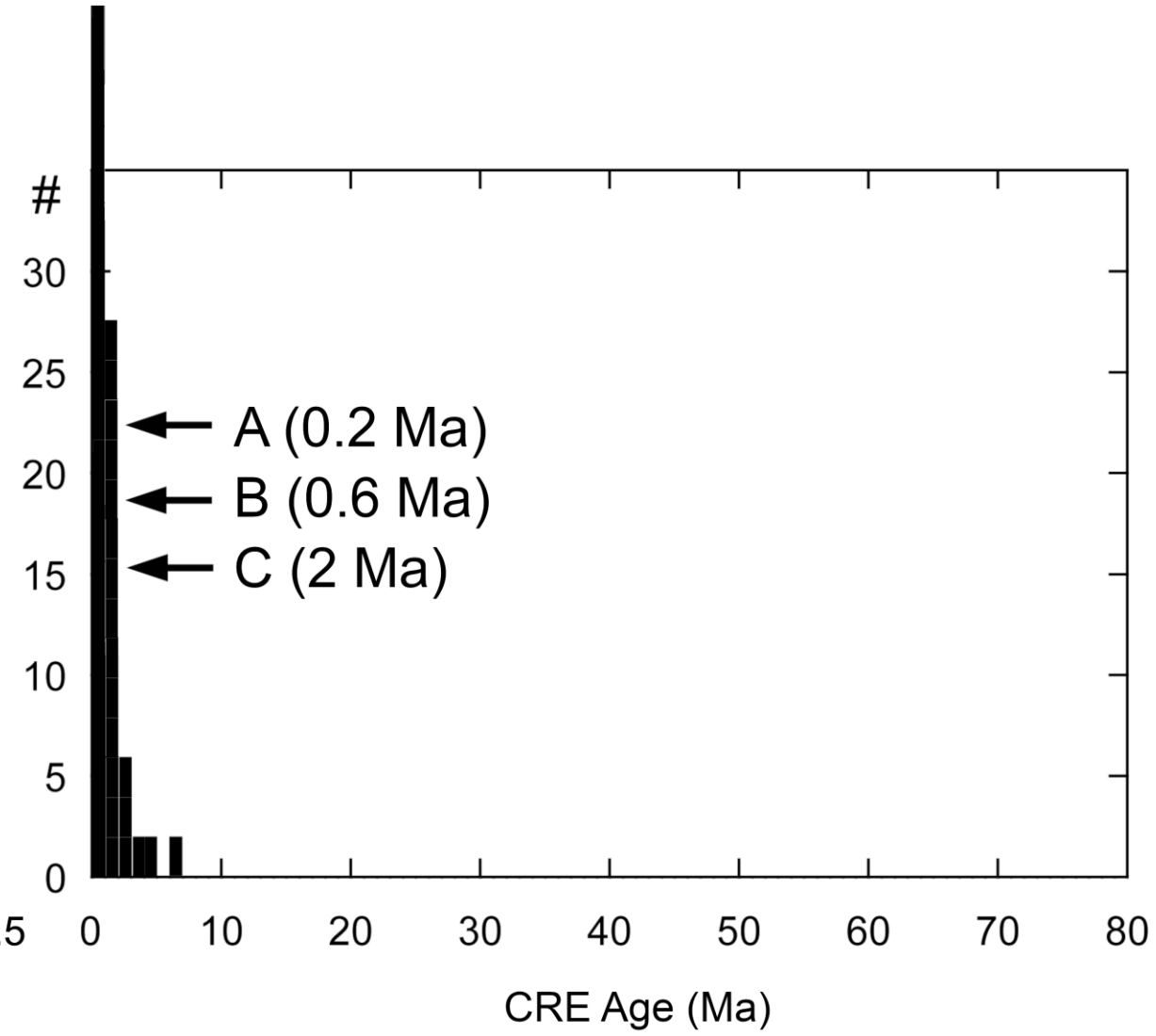


# CM chondrites: Themis/Beagle?




Difficult: Meteoroids are from asteroids that have already evolved to inner solar system



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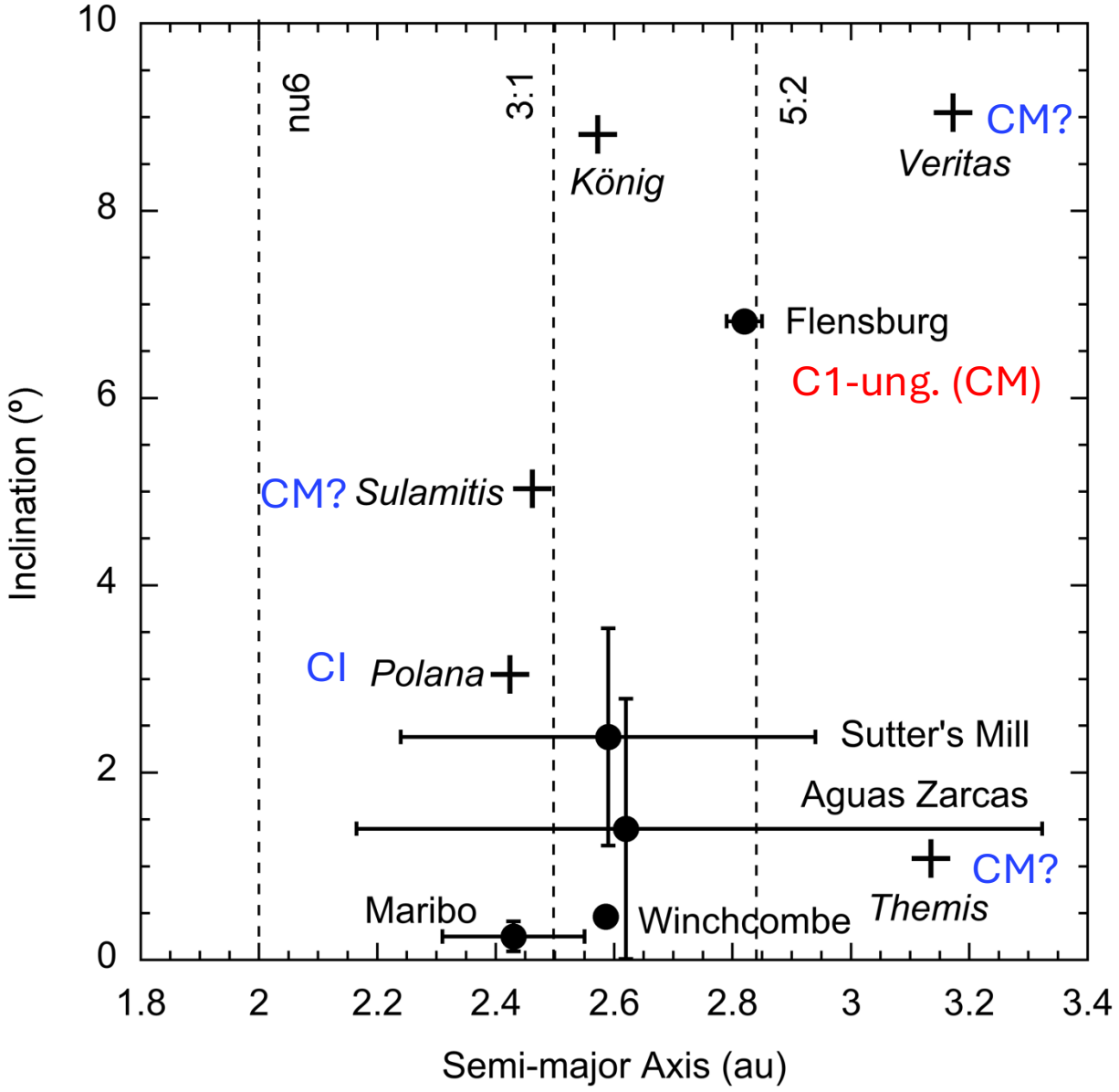
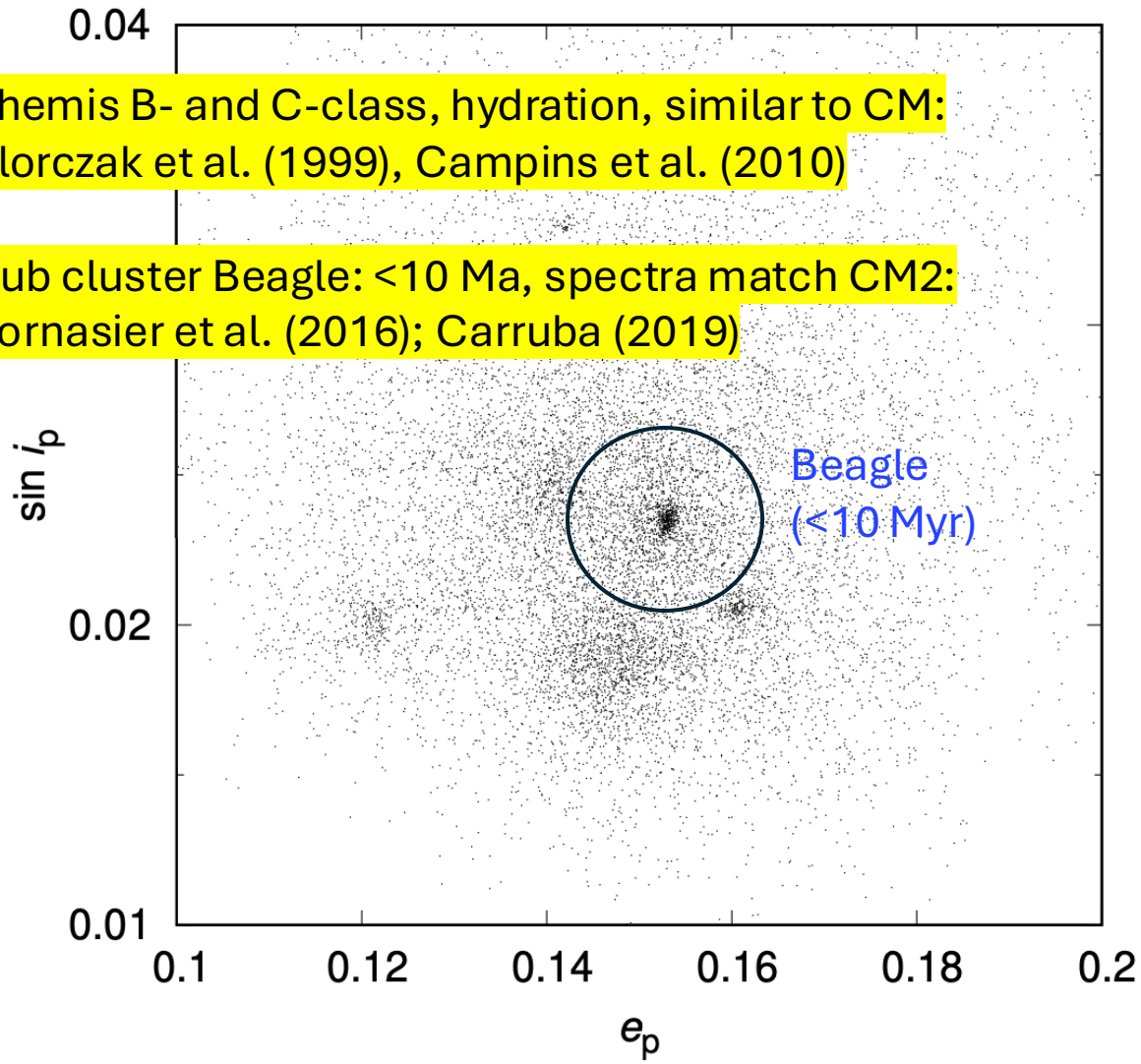



Jenniskens et al., 2024 (MAPS, submitted)

## Themis family

Themis B- and C-class, hydration, similar to CM:
Florczak et al. (1999), Campins et al. (2010)

Sub cluster Beagle: <10 Ma, spectra match CM2:
Fornasier et al. (2016); Carruba (2019)




Broz et al. (2024 A&A)

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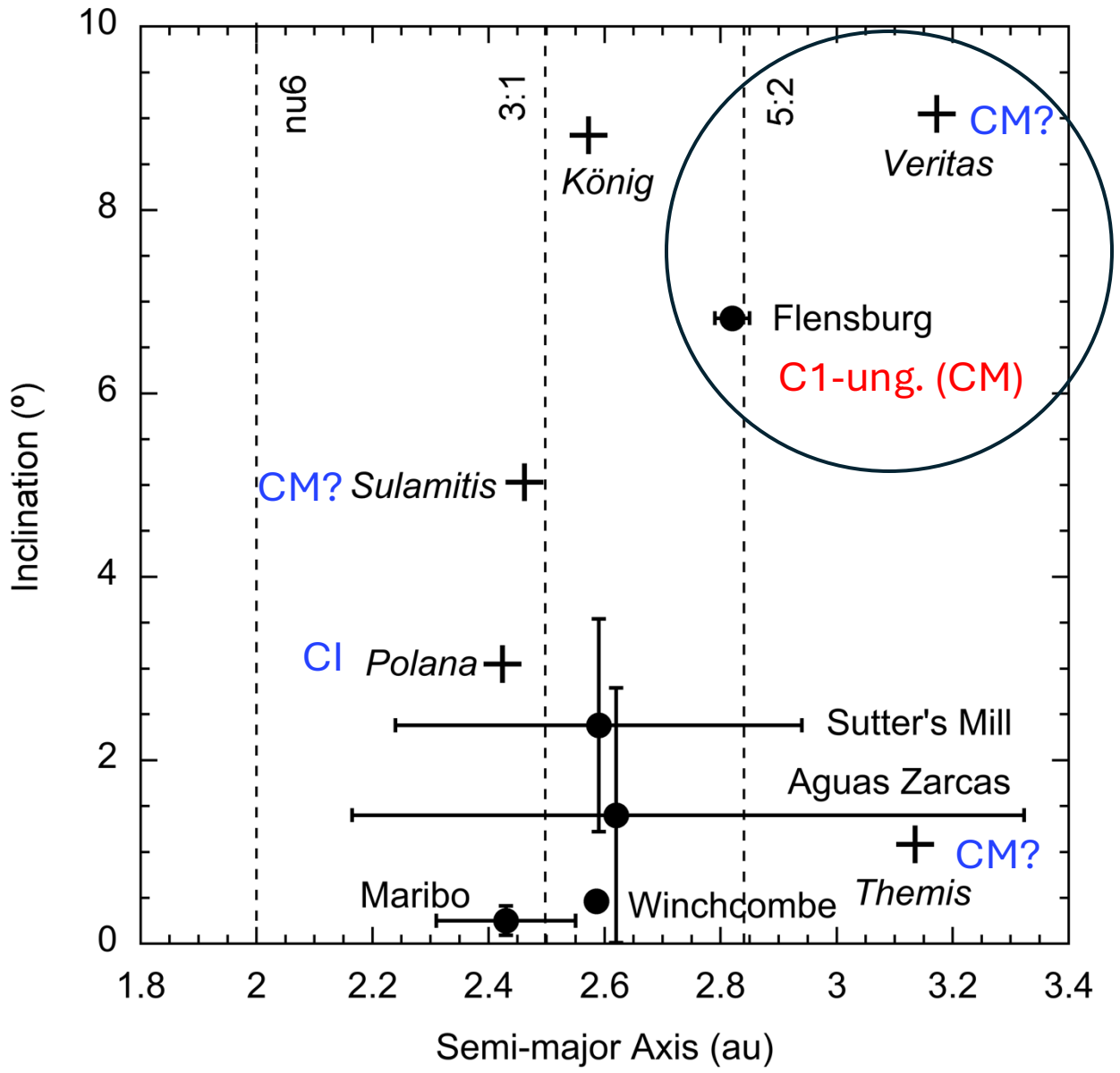


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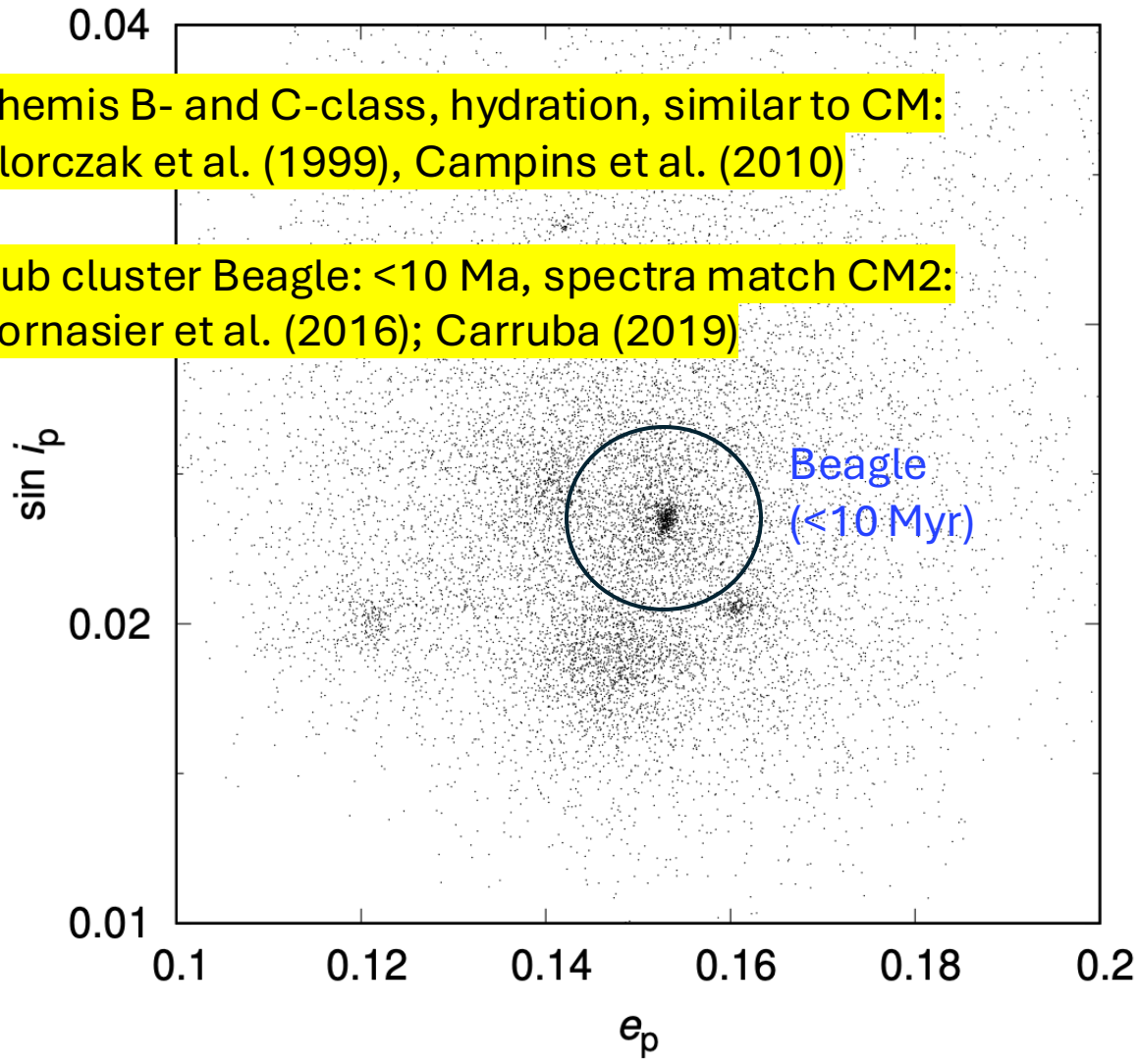
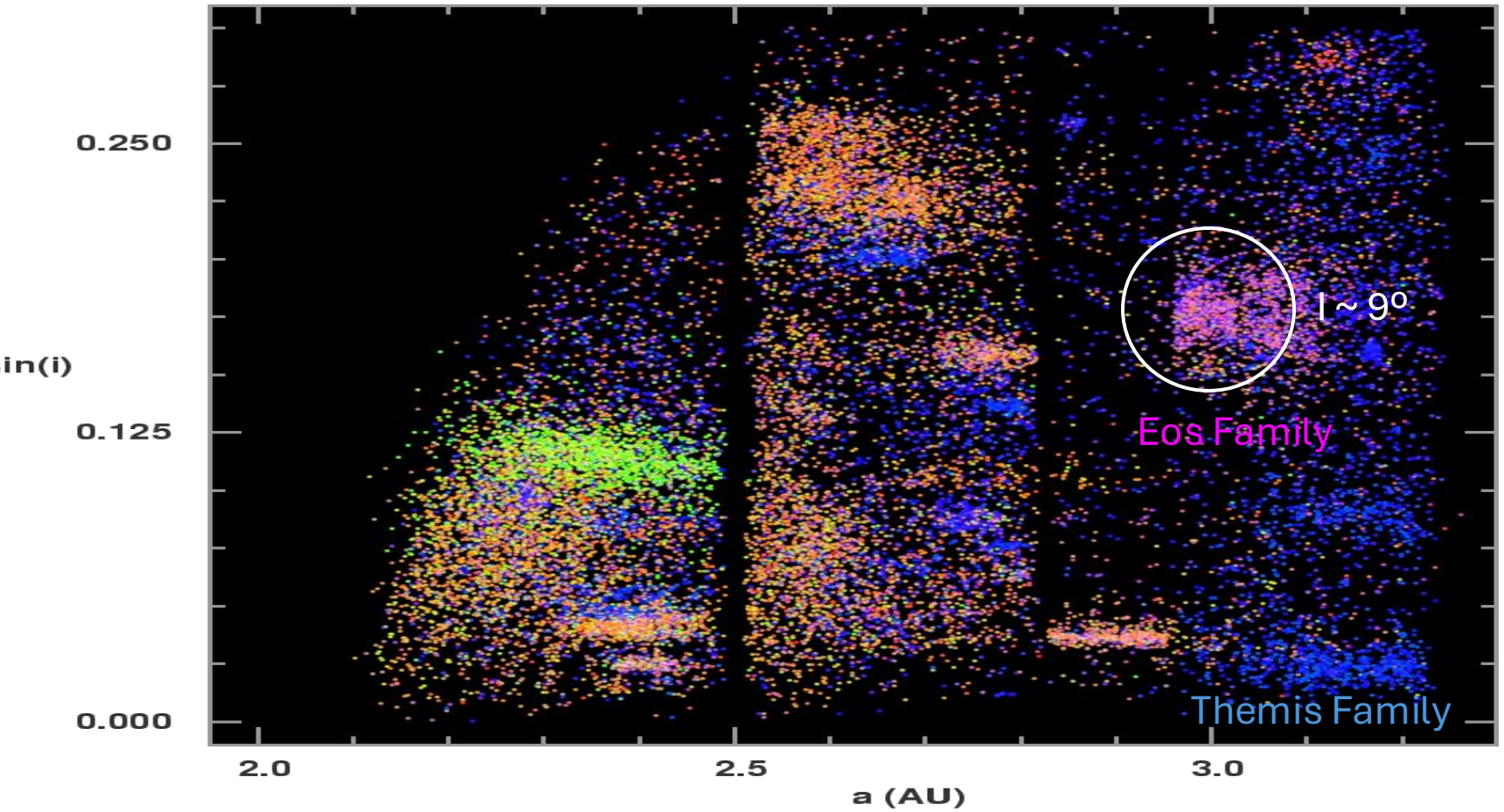


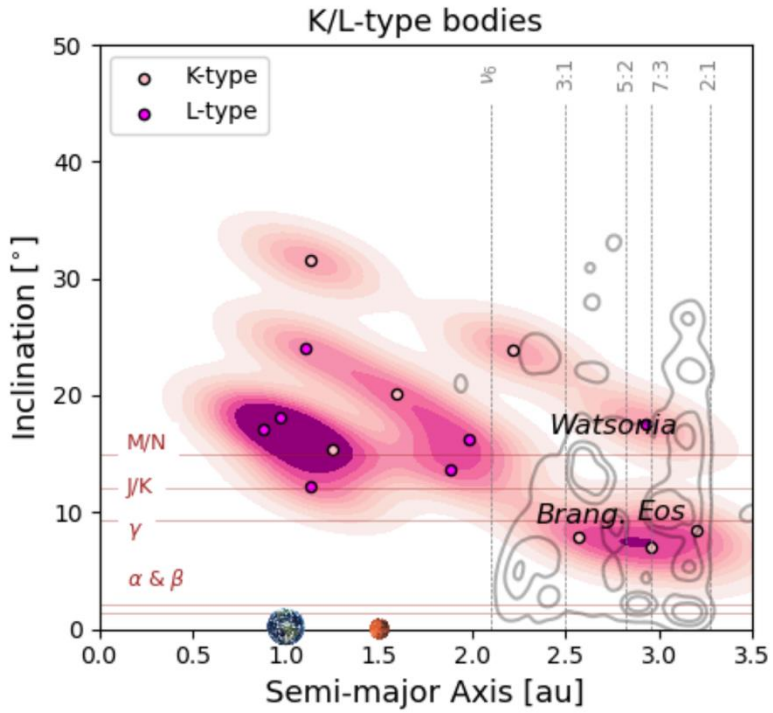

Broz et al. (2024 A&A)

# CO/CV/CK: Eos family?



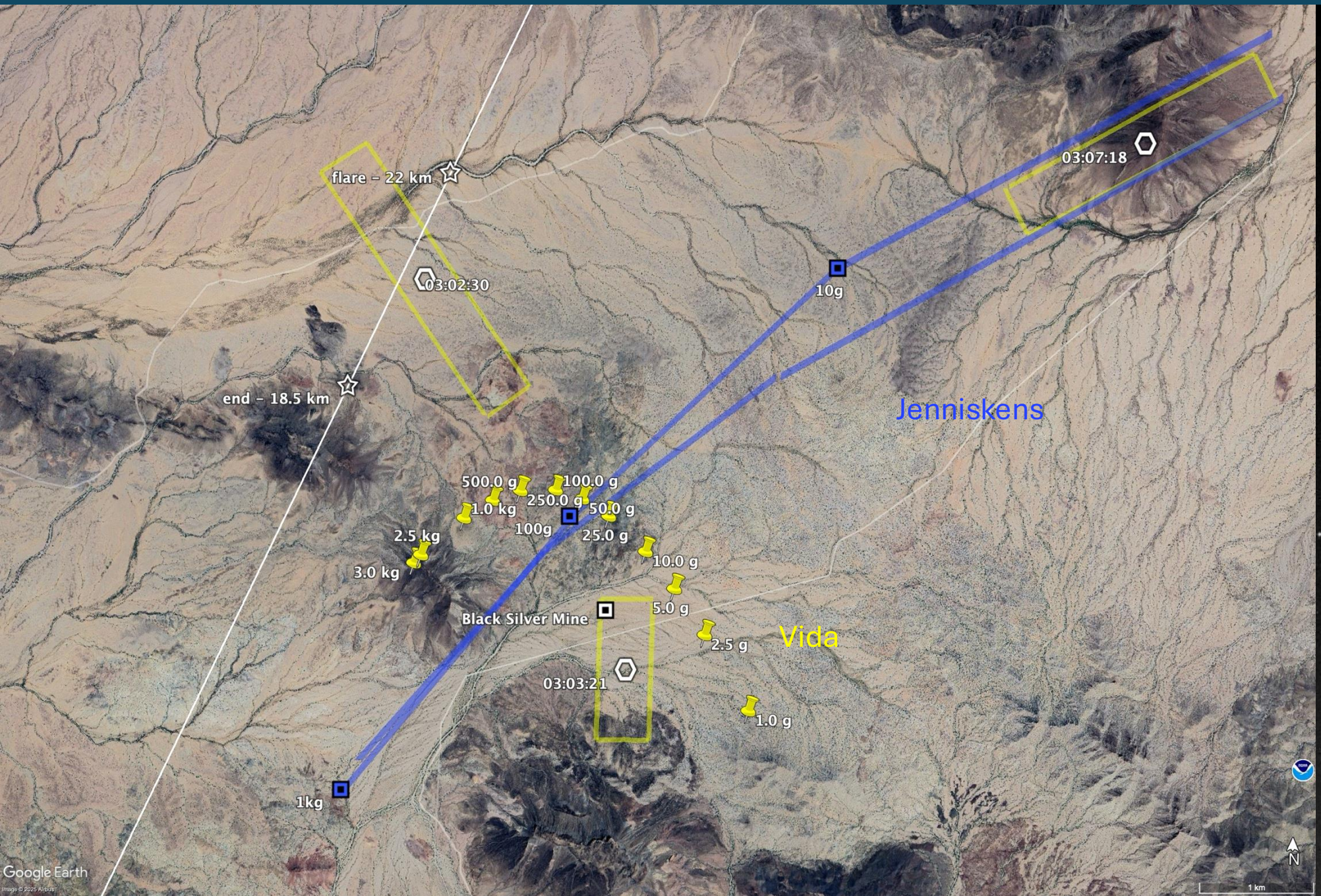

Broz et al. (2024 A&A)

## L-class NEA




Sadly, no recovered meteorites of CO/CV/CK type before April, 2024

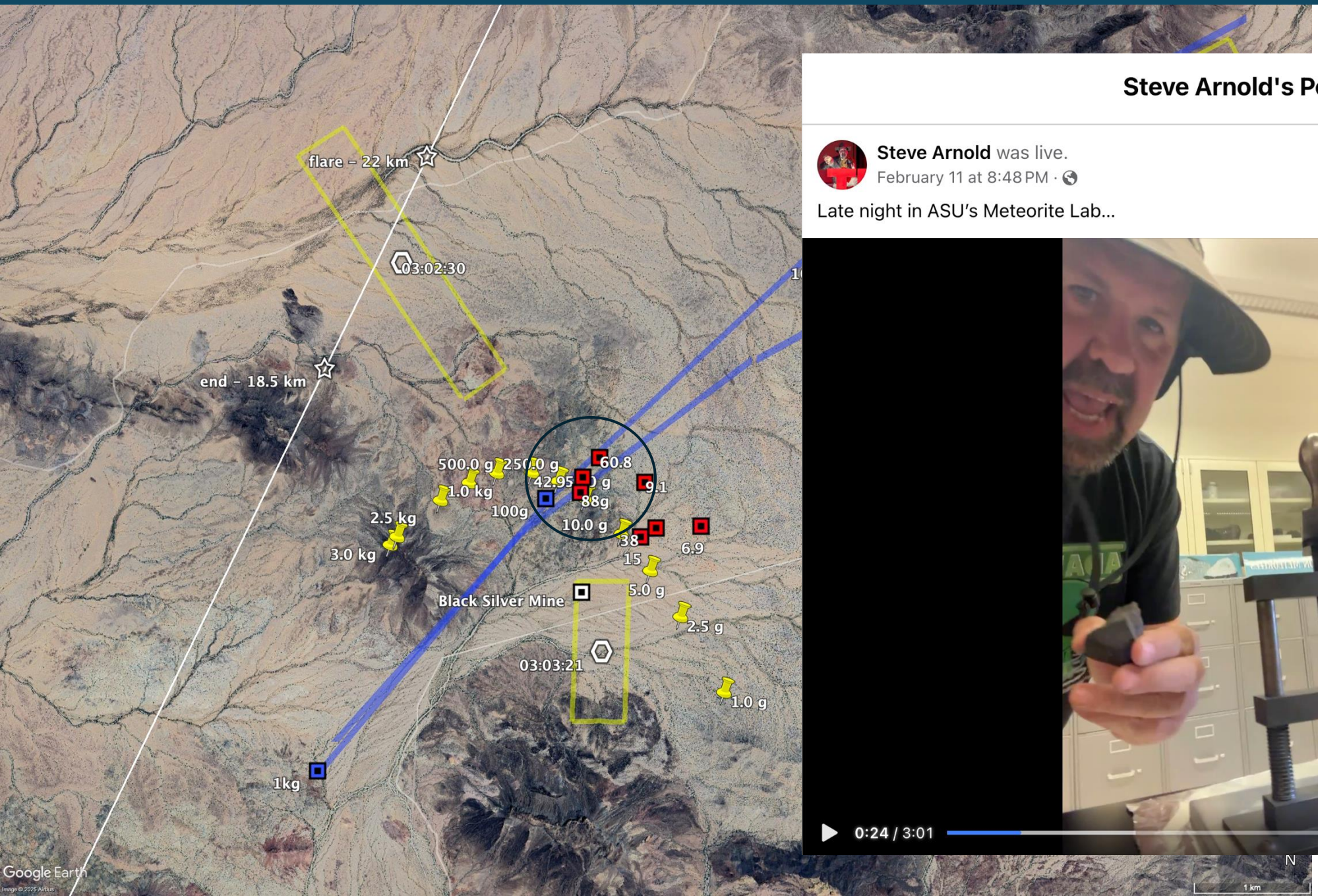
# 2024-04-17: Arizona fall (west of Phoenix)




Orbit is that expected for Eos family: a CV/CO or CK type.

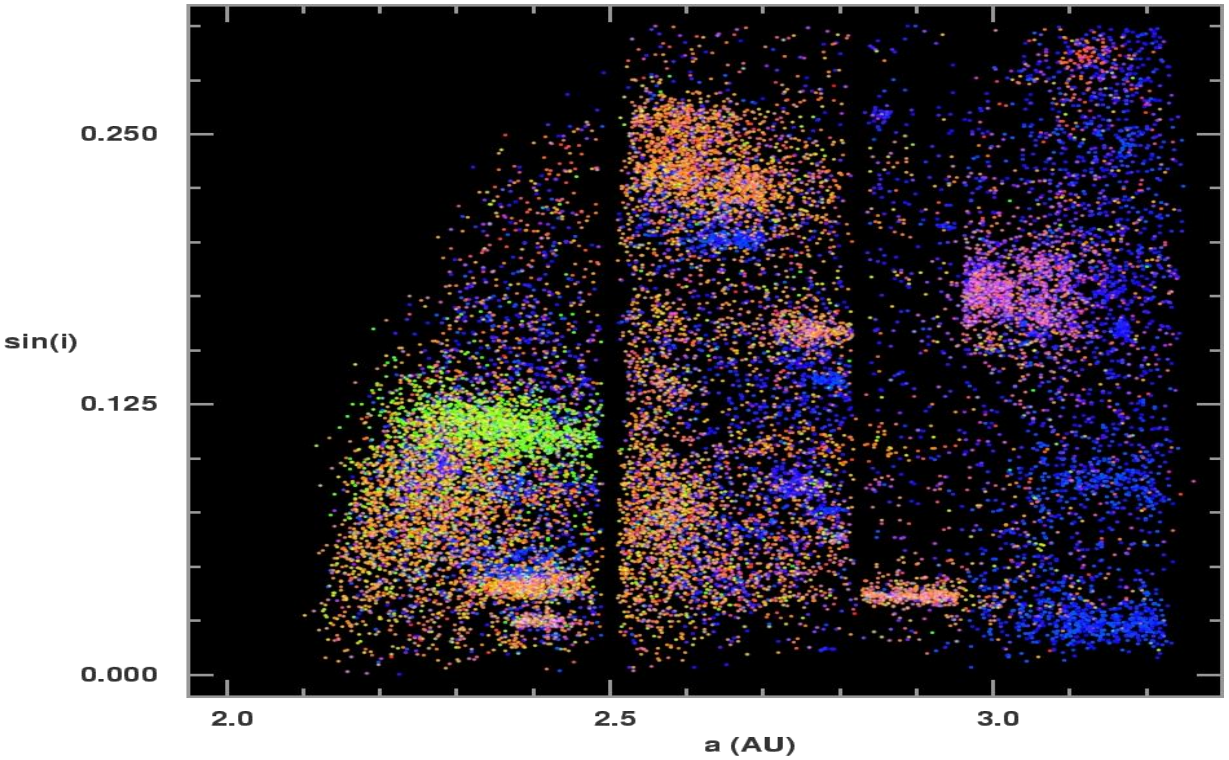
Orbit:
a = 2.74 AU
i = 14.3°

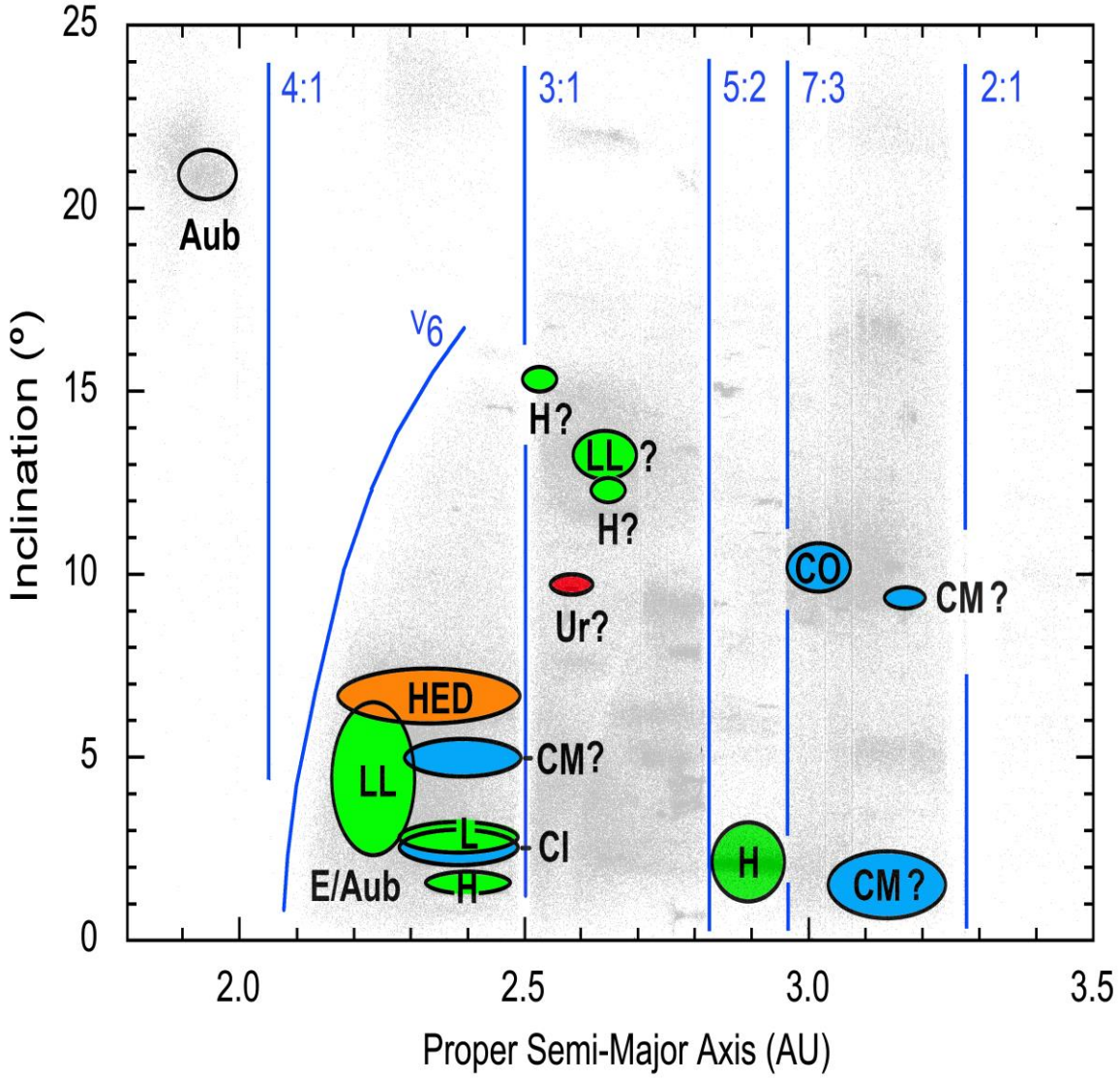
# 2025-02-11: Found – CK: “Black Silver Mine (prov.)”



# Conclusion

Applied to Planetary Defense:
**Impact orbit is a clue to the asteroid/meteoroid type**




Acknowledgements:
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Jenniskens & Devillepoix (2025) MAPS 60, 928-973