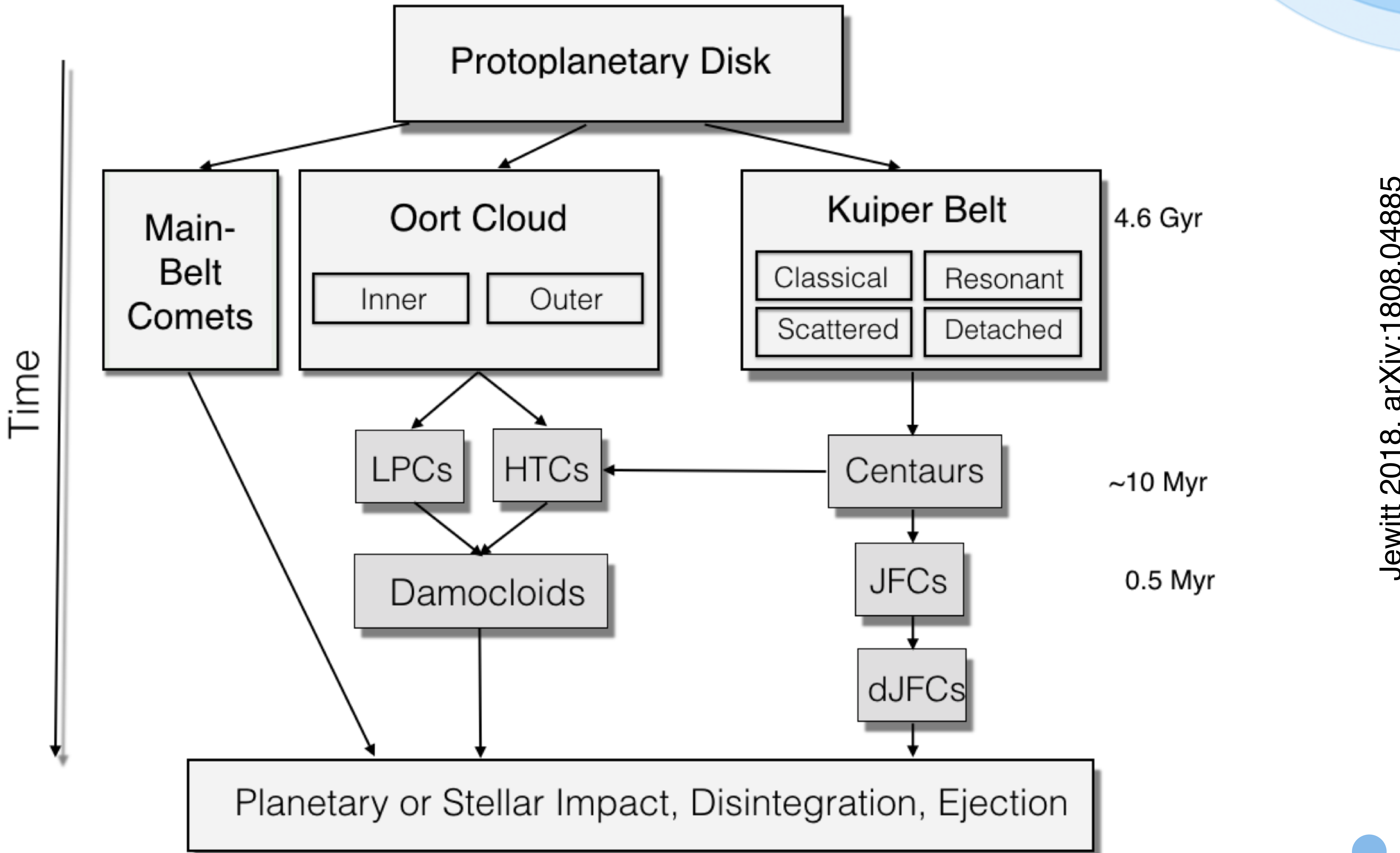
Exploring the next frontier: the Main Belt Comets

Colin Snodgrass

Life-changing Learning

Evolution of different comet types

Pathways for icy bodies from planet forming disc



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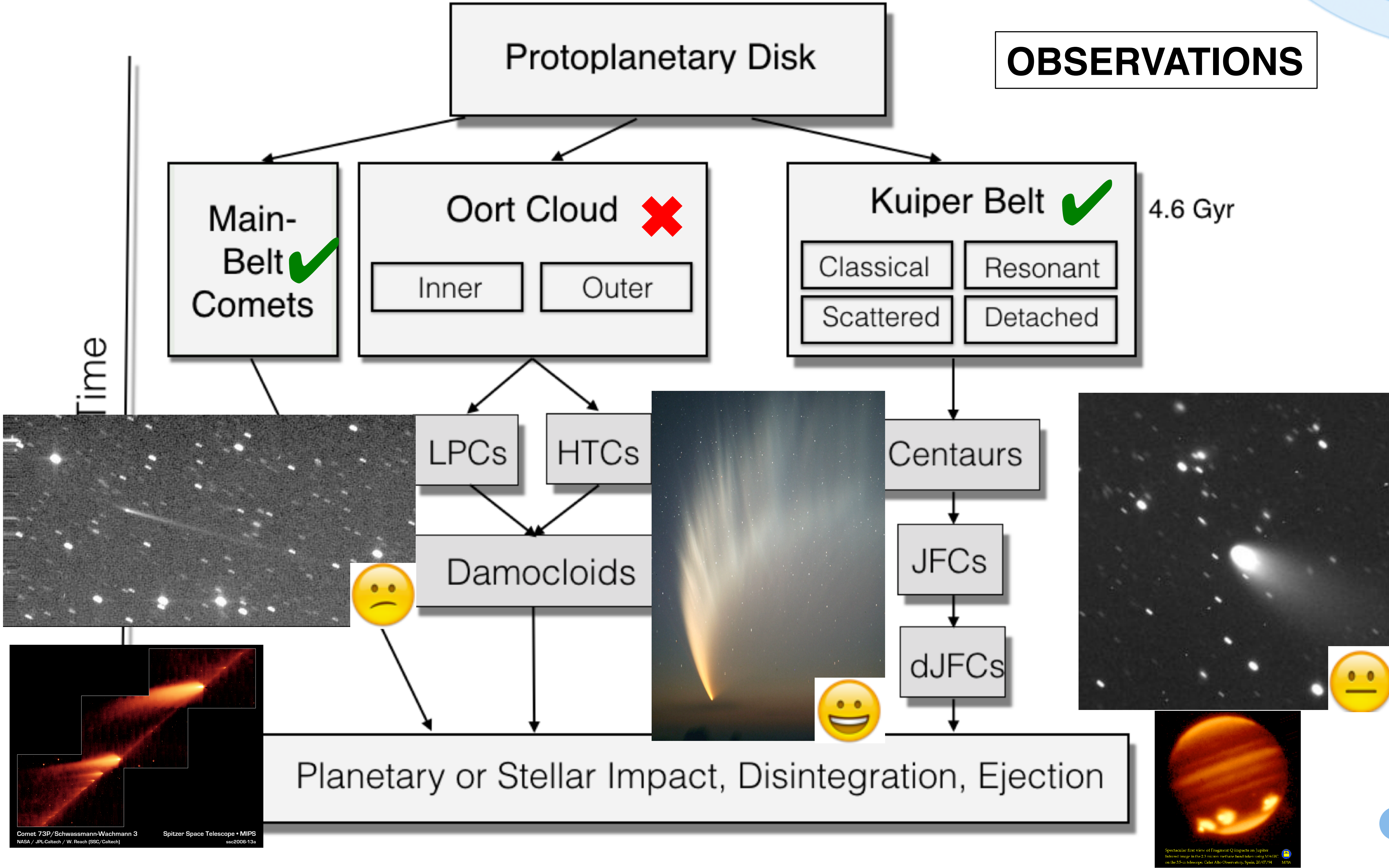
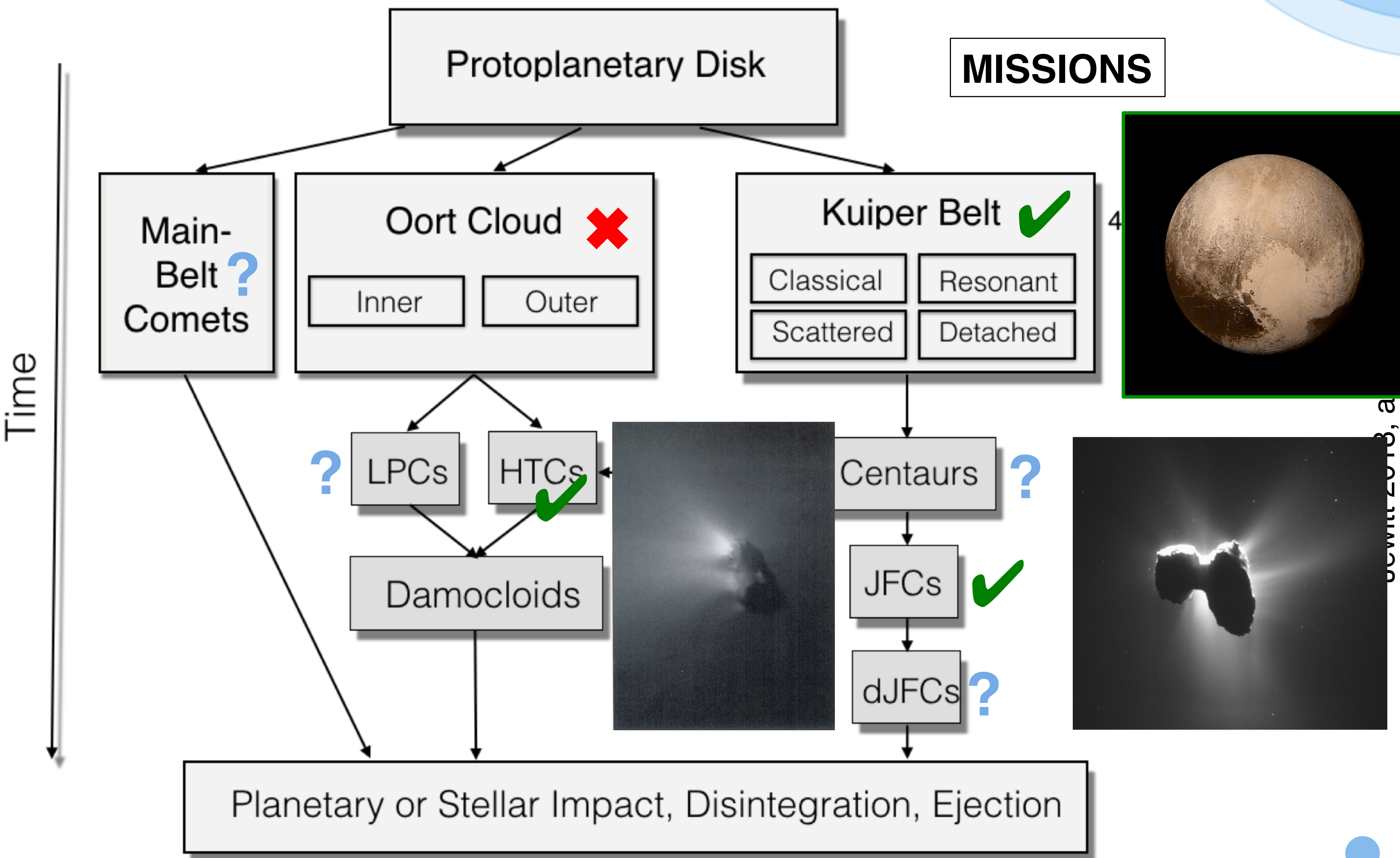


Jewitt 2018, arXiv:1808.04885

Evolution of different comet types

Pathways for icy bodies from planet forming disc



Where next?

Options for future missions

- Evolution of single body in active phase
  - Return to previously visited comet(s) again
- More detailed information
  - Sample return

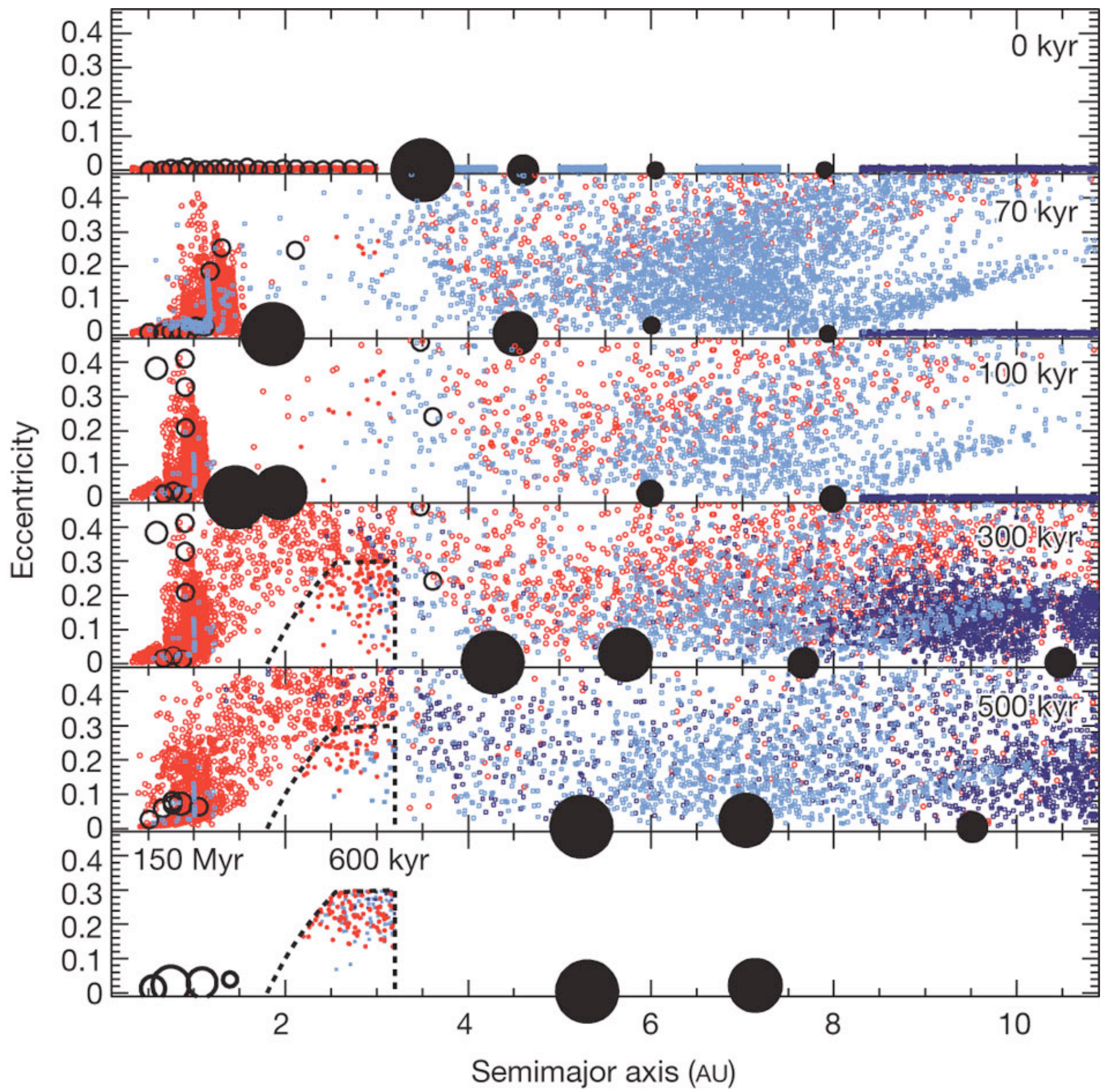
See next talk

- Visit objects at other evolutionary stages
  - Centaur (active/inactive) → More difficult to reach. 29P? Chariklo?
  - Asteroid in cometary orbit / old and very low activity comet
- Visit other classes of comet
  - Dynamically new LPC
  - Main Belt Comet

Some NEOs, but mostly high Δv?
Need to be sure of identification

- Visit many comets
  - CONTOUR-like mission, explore diversity within JFCs (+ others?)

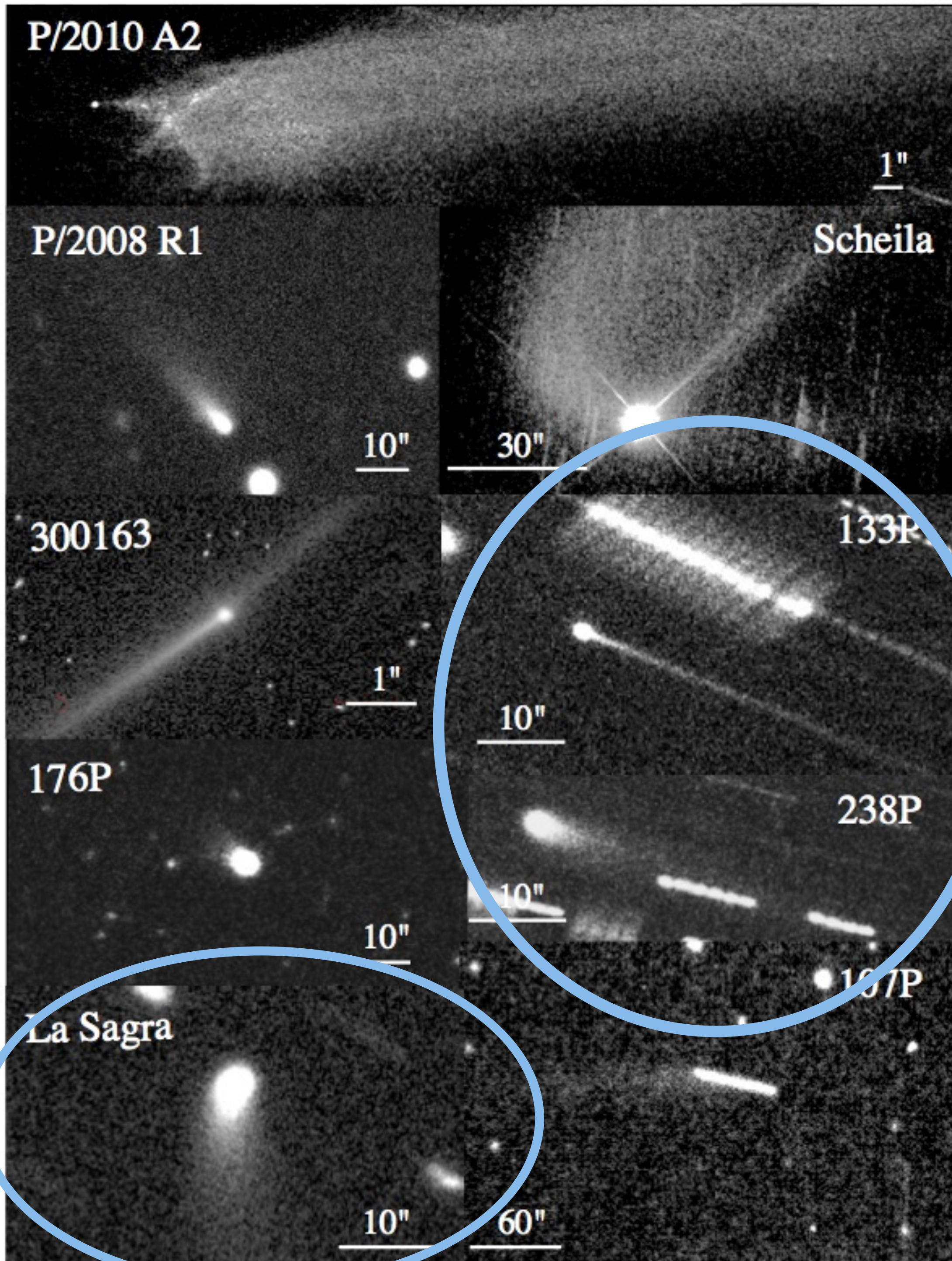
Water in the asteroids?

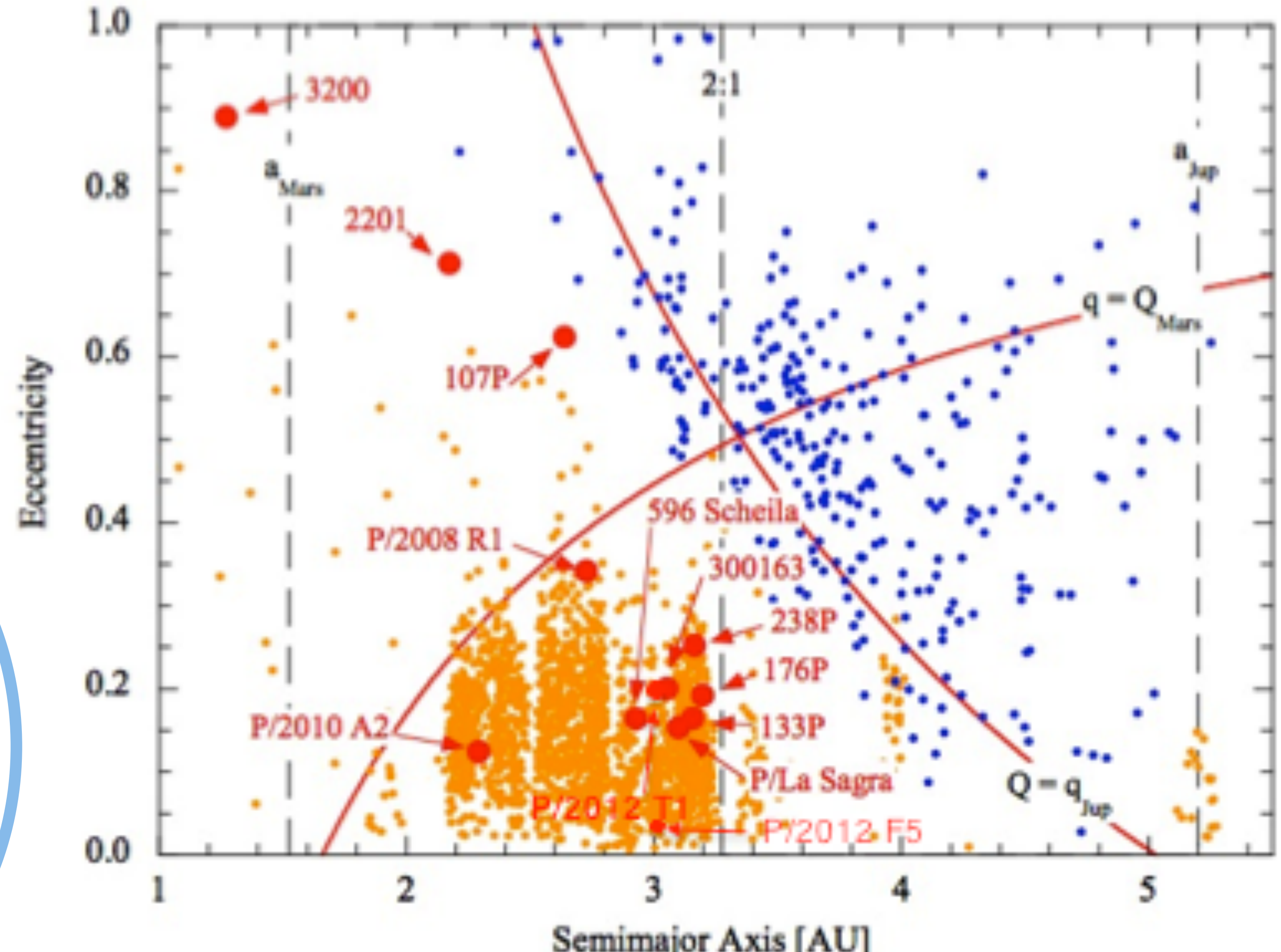


Walsh et al. ‘Grand Tack’ model

- Asteroid belt has various types
- More ‘primitive’ bodies in outer part
  - These should have formed with water
- Migration of planets causes mixing in early solar system
  - Brings water inside snow line
- How much water is still there today?

Active asteroids / MBCs





Jewitt 2012

- Mass losing bodies in asteroid belt
- Cometary activity -> ice?

The Main Belt Comets

Population of active icy bodies in the asteroid belt

- MBCs a subset of active asteroids driven by ice sublimation
  - Identified by repeated activity at perihelion
  - No direct detection of gas coma yet, too faint / weakly active
- Ice not stable at surface equilibrium temperature
  - Buried water ice can survive under 1-10m of insulating mantle
- Unique among comets in that they are active in their parent reservoir
  - Orbits stable over age of the Solar System
  - Activity triggered by uncovering of buried ice instead of orbital change*
- Associated with collisional families
  - Fragments of original larger bodies, but still contain ice

* Probably. Kim et al 2018 suggest that known MBCs have eccentricity temporarily increased by Jupiter interactions

MBC questions

Need for space missions

- Can we confirm that their activity is driven by water ice?
- How much water is there?
- What other species are present? Organics? Ices? Silicates?
- What are the isotopic ratios (D/H and other species)?
  - Does Earth's water come from the main belt?
- Are the bulk properties more comet-like or asteroid-like?

→ Constraints on planet formation / evolution models

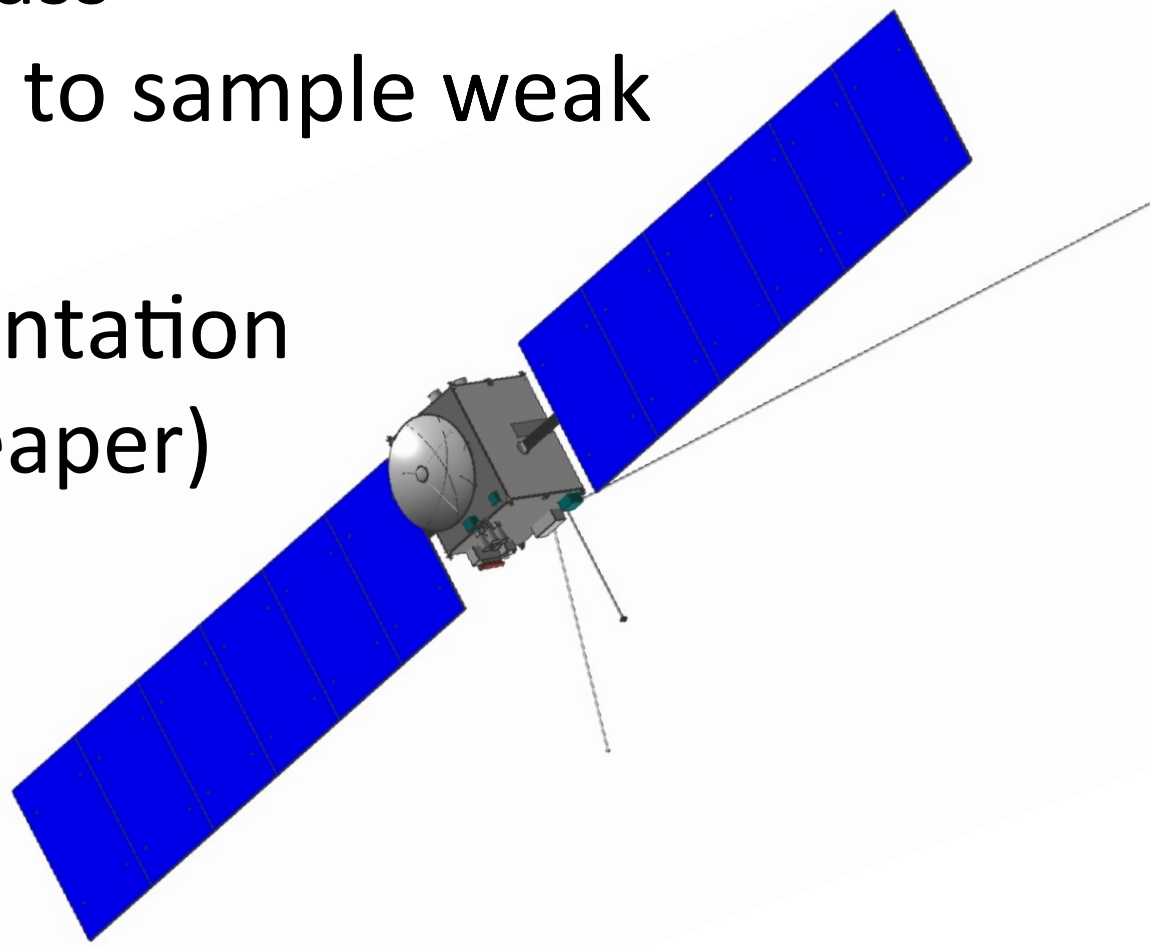
Active asteroids / MBCs

Object	a	e	i	Tj	Nature	Comments
133P/Elst-Pizarro	3.161	0.162	1.387	3.19	MBC	Castalia primary target. Long lasting activity; Themis family member. Active during 4 consecutive perihelion passes.
176P/Linear	3.196	0.193	0.235	3.17	MBC candidate	Long lasting activity. Not active at 2nd perihelion
238P/Read	3.164	0.253	1.265	3.15	MBC	Castalia secondary target. Long lasting activity. Active during 3 consecutive perihelia.
259P/Garradd	2.728	0.341	15.899	3.22	?	Orbit not stable; probably recently arrived
288P/2006VW139	3.051	0.199	3.239	3.20	MBC	Long lasting activity; Themis family member; binary!
P/2010 A2 (LINEAR)	2.290	0.125	5.257	3.59	Active asteroid	Short, impulsive activity. Probably an impact, possibly rotational disruption
P/2012 F5 (Gibbs)	3.005	0.041	9.738	3.27	Active asteroid	Short, impulsive activity Impact
P/2012 T1 (PANSTARRS)	3.150	0.237	11.057	3.18	MBC candidate	Long lasting activity; member of Lixiaohua family; no water detected (Herschel+XShooter)
596 Scheila	2.926	0.165	14.662	3.21	Active asteroid	Short, impulsive activity; probably an impact
324P/La Sagra	3.095	0.154	21.419	3.20	MBC	Long lasting activity. Active at 2nd perihelion.
311P/PanSTARRS	2.189	0.115	4.969	3.66	Active asteroid	Activity over a long period, but as very short bursts: Probably rotational shedding.
P/2013 R3 (Catalina-PANSTARRS)	3.036	0.273	0.899	3.18	Active asteroid	Fragmentation in at least 4 pieces. Rotational disruption?
233P/La Sagra	3.032	0.411	11.279	3.08	?	Poorly studied.
313P/Gibbs	3.155	0.242	10.967	3.13	MBC	Discovered active; Seen active at 2003 perihelion (pre-discovery), not observed 2009. Member of Lixiaohua family
62412 (2000 SY178)	3.146	0.090	4.765	3.20	?	Fast rotator, long-lived activity. Hygiea family.
P/2015 X6 (PANSTARRS)	2.755	0.170	4.558	3.32	MBC candidate	Long lasting activity
P/2016 G1 (PANSTARRS)	2.583	0.210	10.968	3.37	Active asteroid	Short disruptive event

Castalia mission

Rendezvous with a MBC

- ESA Class-M Mission to a Main Belt Comet
  - A new class of objects!
- Baseline target: 133P/Elst-Pizarro
- Spacecraft feasible within ESA M-class
- Rendezvous, orbit, close approach to sample weak outgassing
- Remote sensing & in situ instrumentation
- Rosetta-like, but much simpler (cheaper)

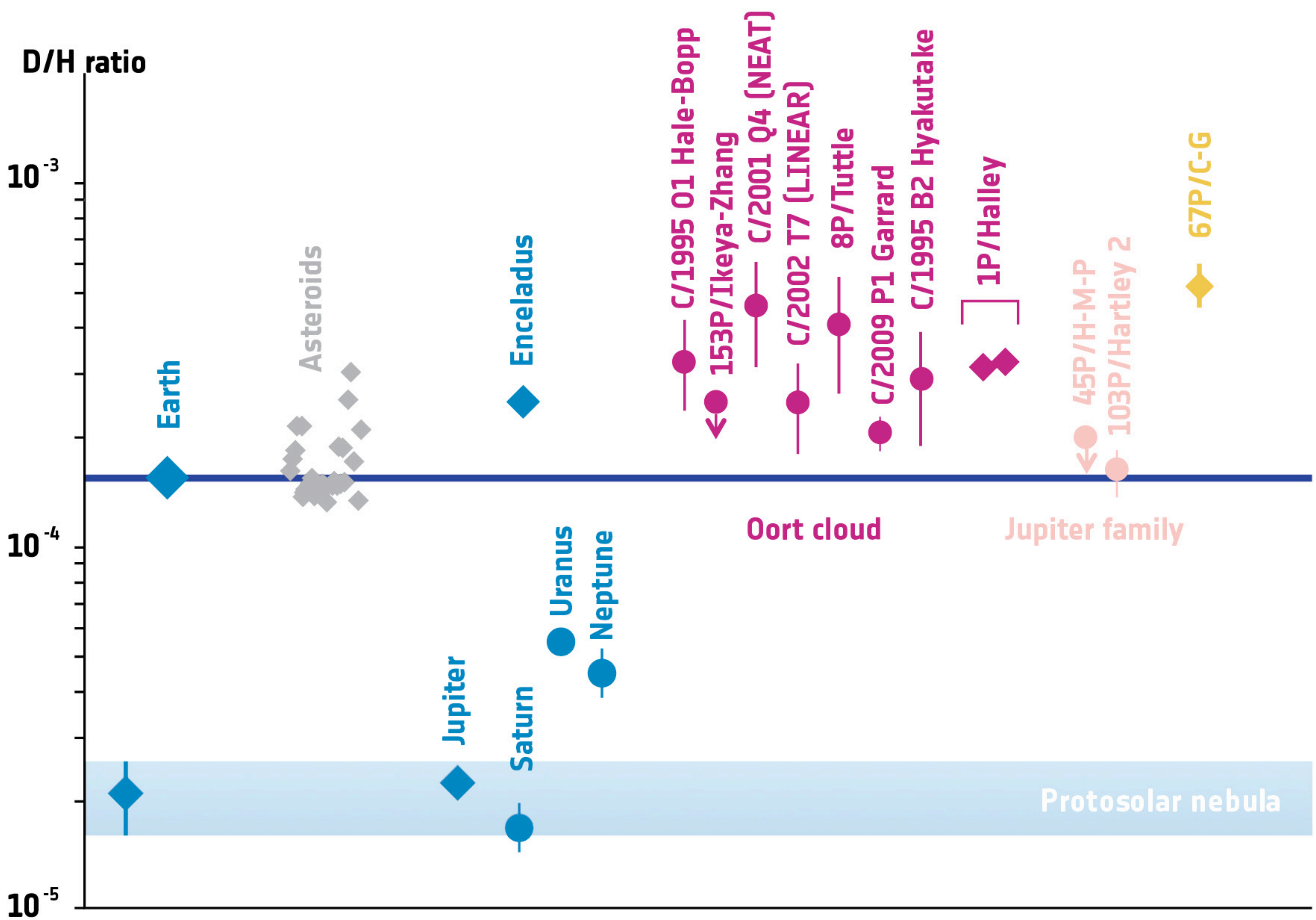


Science goals

- **Characterise a new Solar System family —** the MBCs— by in-situ investigation.
- Understand the **physics of activity in MBCs**.
- Directly **detect water in the asteroid belt**.
- Test if MBCs are viable **source for Earth's water.**
- Use MBCs as tracers of **planetary system formation and evolution.**

The source of Earth's water?

D/H ratio key for Earth's water and planet formation models



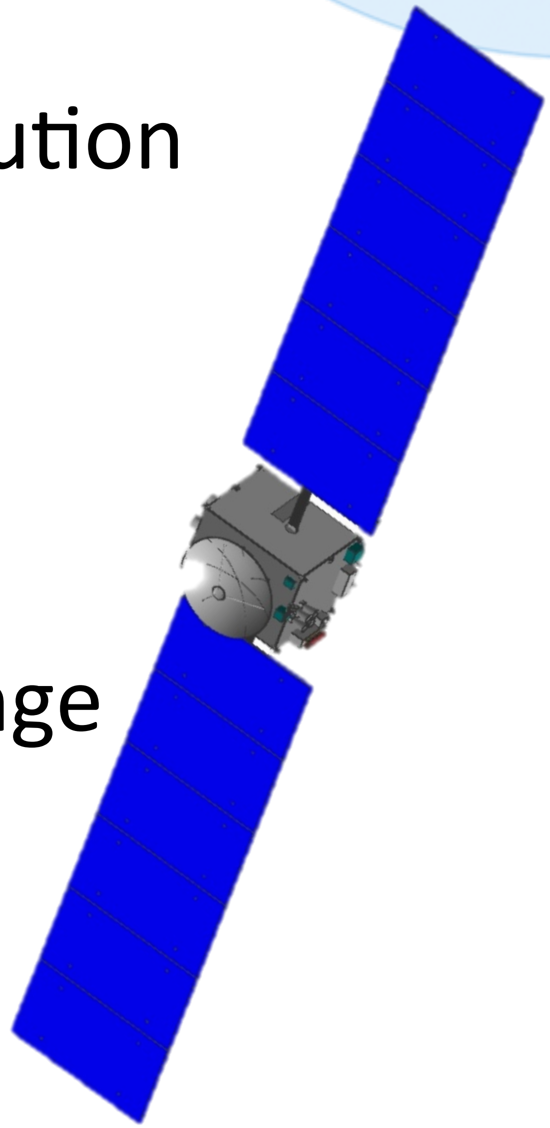
In situ measurement the only way to measure this for weakly active body!

Castalia payload

Four packages, simple operations. One science team!

Package	Instrument (Name, Purpose)	Mass (kg)	Power (W)	TRL	Pointing	Heritage
Surface remote sensing	MBCCAM Vis/NIR Imager	20	17-30	>5 >5	Nadir, limb, dust	DAWN FC, Rosetta OSIRIS WAC
	TMC Thermal IR Imager	6	8	8	Nadir, limb	UKTechDemoSat,
Interior	SOURCE Deep Radar	20.2	150	≥6	Nadir	MRO Sharad, MEx MARSIS, Rosetta CONSERT
	SSR Shallow Radar	1.7	16	>5.6	Nadir	ExoMars WISDOM, Rosetta CONSERT, AIM
	Radio Science	n/a	n/a	9	n/a	Rosetta RSI
Material and composition	CAMS (+COUCH) Mass Spectrometer	6.44 (1.5)	14.03 (20)	CAMS: 7, CADS: 9, (COUCH: 6-9)	Nadir	Rosetta ROSINA, (Philae Ptolemy)
	GIADA Dust detector	7.8	22	9	Nadir	Rosetta GIADA
	COSIMA Dust composition	20	28	9	Nadir	Rosetta COSIMA
	DIDIMA Combined dust inst.	23	27	5 - 6	Nadir	Rosetta GIADA and COSIMA
Plasma environment	MAG Magnetometer	0.25	1	Sensor: 9 Electronics: 5	None	CINEMA
	ChAPS Plasma Package	0.65	1	5-6	Various	TechDemoSat, Solar Orbiter

Castalia Spacecraft Bus



- Ion Engines: no suitable chemical propulsion solution
- Solar panels
  - no RTG available
  - Ion Engines + large heliocentric distance

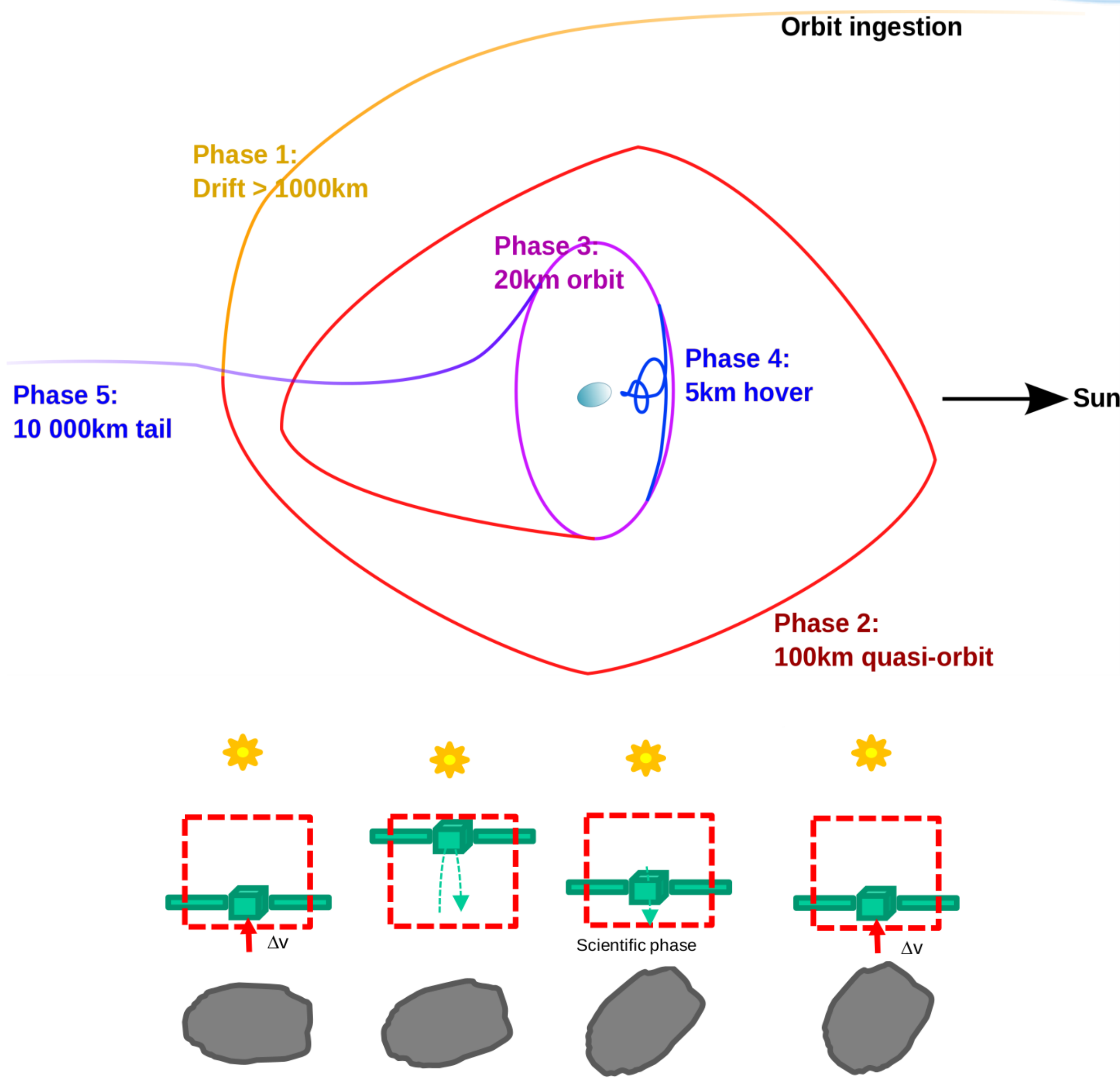
    ➔ large panels
- Navigation: Star trackers, cameras, LIDAR for range ≤100km
- Control: Hydrazine and reaction wheels
- Antenna and radio / data rate:

  Observations 50% of the time + transmission 50%
- Mass compatible with Soyuz Fregat (Ariane 62) launch

Castalia Mission

Mission phases – 6-12 months at MBC

- 100km quasi-orbit:
  Long drifts near the comet, with orbit corrections to change direction
- 20km orbit
  - Survey & “parking” orbit
  - Terminator orbit is stable
- 5km hover
  - 3.5h control cycle, incl. 1.5h science mode with no contamination
  - Fully autonomous, with redundant failure detection and collision avoidance maneuver



Castalia v Rosetta

Rosetta like science, but much simpler mission

- Much easier target
  - Circular orbit in outer belt, orders of magnitude lower activity, probably not duck shaped. More asteroid-like than comet-like from ops POV.
- Simpler spacecraft
  - Smaller, no lander, fixed HGA
- Fewer instruments
  - Organised into 4 packages for simple ESA-team interactions
  - Single science team across all instruments
- Simplified operations
  - One thing at a time – separate comms mode, competing science (e.g. pointed remote sensing vs in situ sampling) takes place in different phases (orbit vs hovering)
  - On board autonomous GNC
  - Shorter mission (6-12 months at MBC)

M5 outcome

We didn't win

- Castalia passed tech & programmatic assessment
- One of 13 assessed by science panel (6 planetary)
- Selected missions for phase A: EnVision (Venus orbiter), SPICA (IR telescope), THESEUS (Swift-like, gamma-ray observatory)
- Castalia feedback very supportive, main criticism is that it would only do one target…

> After the Rosetta mission around a comet, and the samples of carbonaceous asteroids returned from Hayabusa2 (2020) and OSIRIS-Rex (2023), a better understanding of the two end-members (asteroids and comets) should be provided. The study of an MBC, as proposed by Castalia, is then a logical step in the exploration of small bodies.

> There is a risk that the studied MBC may not be representative of the population as a whole. For example, it is not clear how the measurement of the D/H ratio in a single MBC can lead to solid conclusions about whether MBCs are the source of water on Earth.

Future options

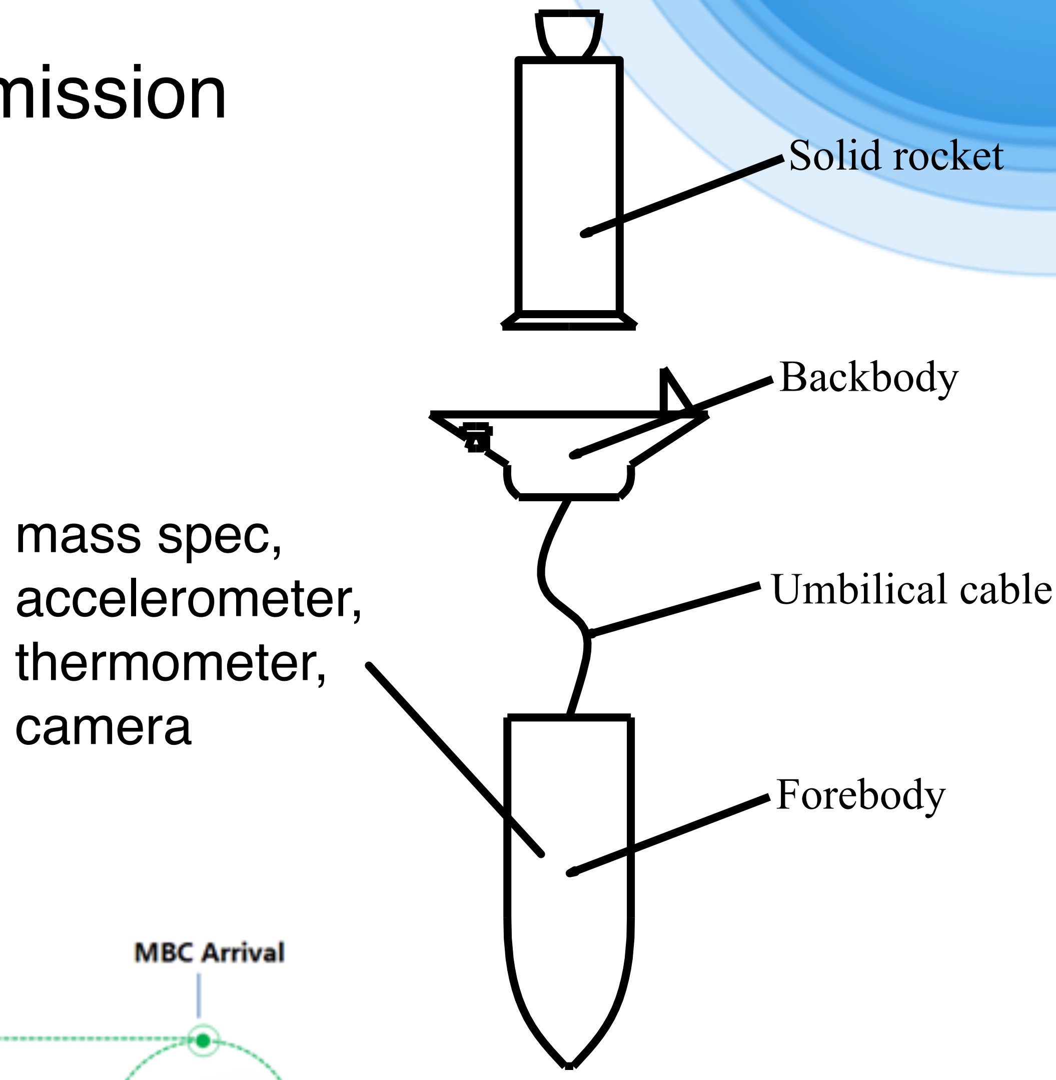
What can we do next?

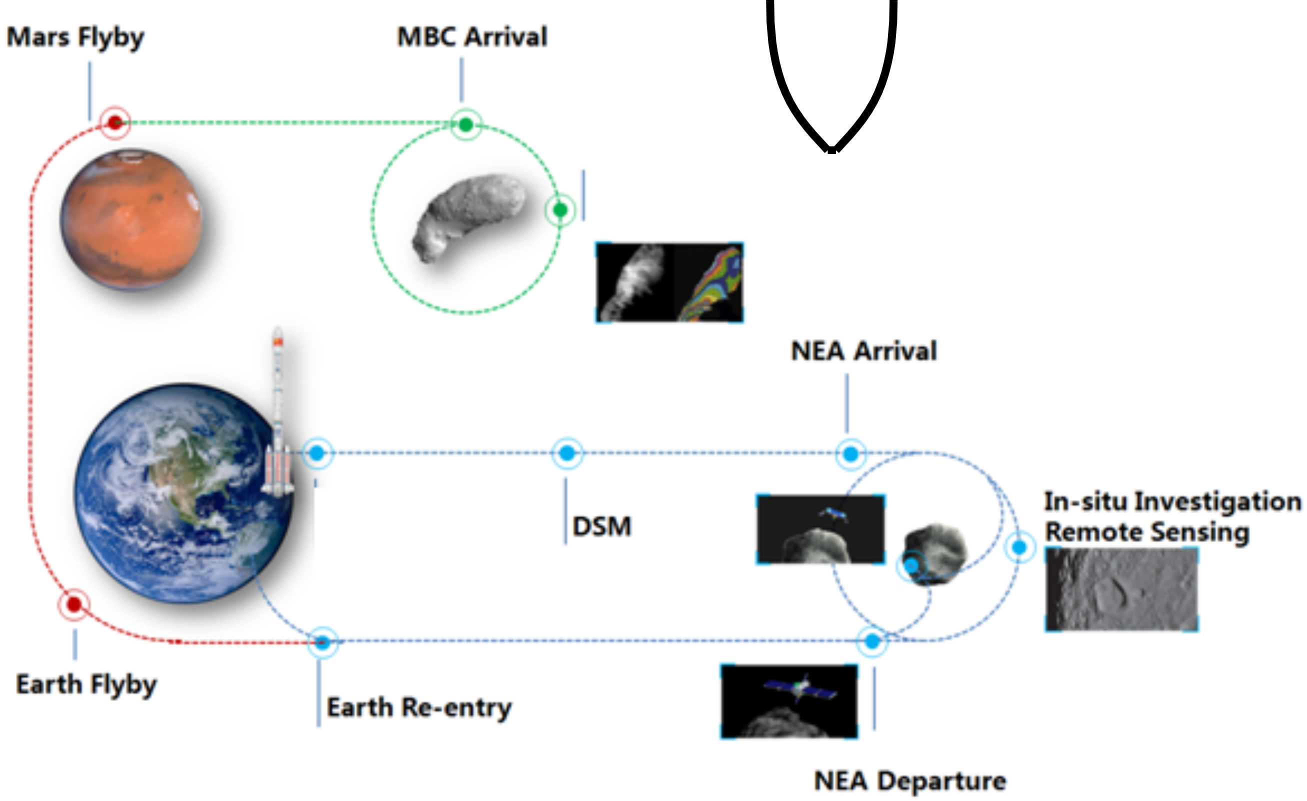
- Next M-class call expected to be some time away (M6 is cancelled)
  - Resubmission of Castalia seems sensible at the moment, TBC when the call comes out. Mission in 2040s?
- Contributions to other missions (NASA, China,…)
  - Instruments? Small s/c hitching a ride?
- Telescope observations
  - Water search would be worthwhile.
  - Possible with small UV telescope.
- ESA F-class call open
  - What can we do with small satellites?

Chinese MBC mission

Potential European contributions to Zhenghe mission

- CAST proposal for NEO sample return + MBC rendezvous
- Decision pending (soon?), launch ~2024, 133P arrival 2032
- Potential for international payload contributions
- UK proposing penetrator, to get mass spec to subsurface ice
  - Important if mission only operates at MBC in inactive state
  - Based on work on penetrator concepts for moon / Europa
  - MBC much easier (low speed)

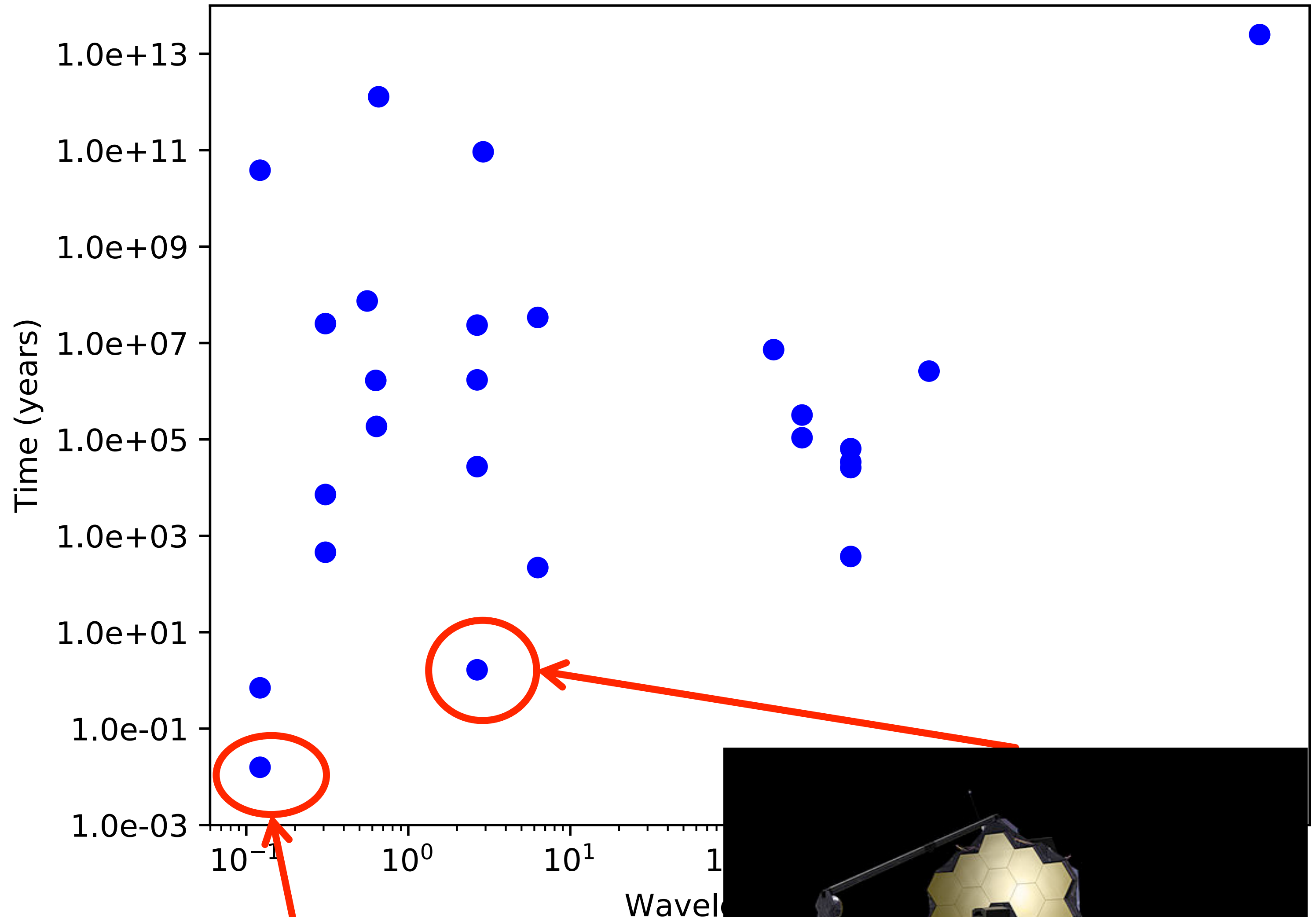


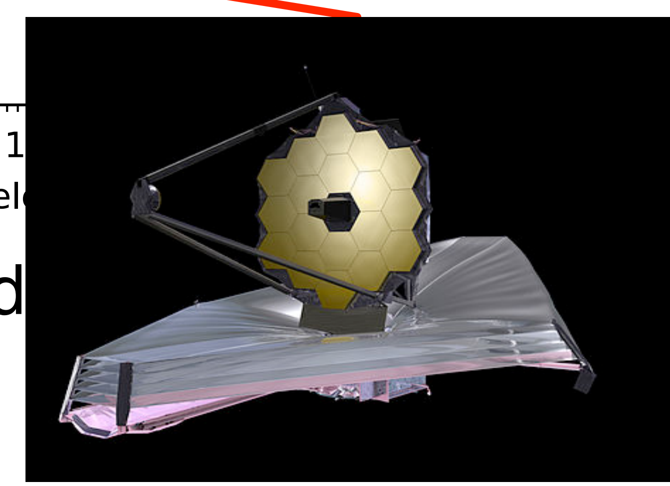


MBC gas detection

Remote water observation?

- Can’t use CN as per normal comets
- Review of attempts and possible methods for water detection
  - Snodgrass et al., A&ARv 2017
- Attempted (didn’t work):
  - OH 308nm (X-shooter)
  - water 557 GHz (Herschel)
  - O[I] 630nm (UVES)
- Good options:
  - FUV: Ly-alpha
  - NIR: 2.66 micron





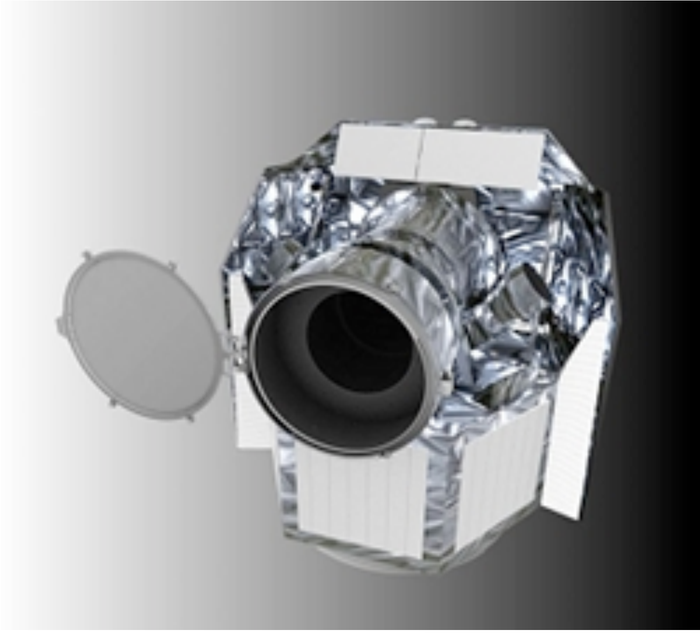
Q=10^24, r=3au and telescope

~10^5 seconds

~10^5 seconds

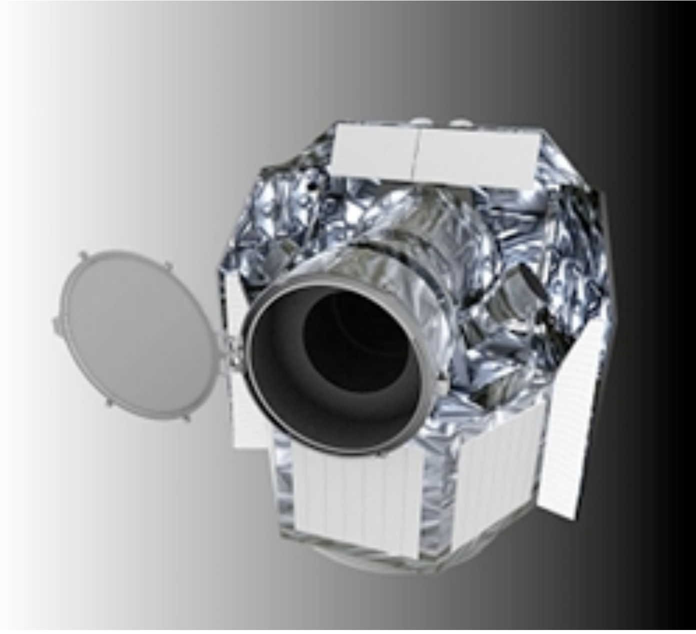
A survey mission

Water detection



- Small space telescope (30-50cm)
  - Various similar missions have been done for astronomy, e.g. CHEOPS (ESA S-class), MOST (Canada), Twinkle (UK concept)
  - Possible for ambitious single country, or few countries – doesn't have to be major agency mission
  - CubeSat possibilities?
- Dedicated instrumentation, optimised for water observations.
  - Ly-alpha? 308nm? 2.66 micron?

A survey mission



Water detection

- 1-3 year survey
  - Can stare at each target for many hours to build up S/N
  - Target known MBCs, other asteroids in same region, Ceres (to understand seasonal variation in outgassing)
  - Also useful for icy moons, ‘normal’ comets, ISRU surveying?
- $Q=10^{24}$ molec/s challenging, but sensitivity to $Q=10^{25}$ useful

- If looking at Ly-alpha, geocorona dominates in LEO
- Lunar orbit? Earth-Moon L1? Earth-Sun L2 (free ride for F-class)
  - Lots of interest in the Moon at the moment, Deep Space Gateway, many lunar cubesat launch opportunities
  - Also opportunity to add Earth observation (of geocorona, space weather reactions, Earth-as-an-exoplanet studies)
  - Some astrophysical hydrogen interest? Exoplanets!

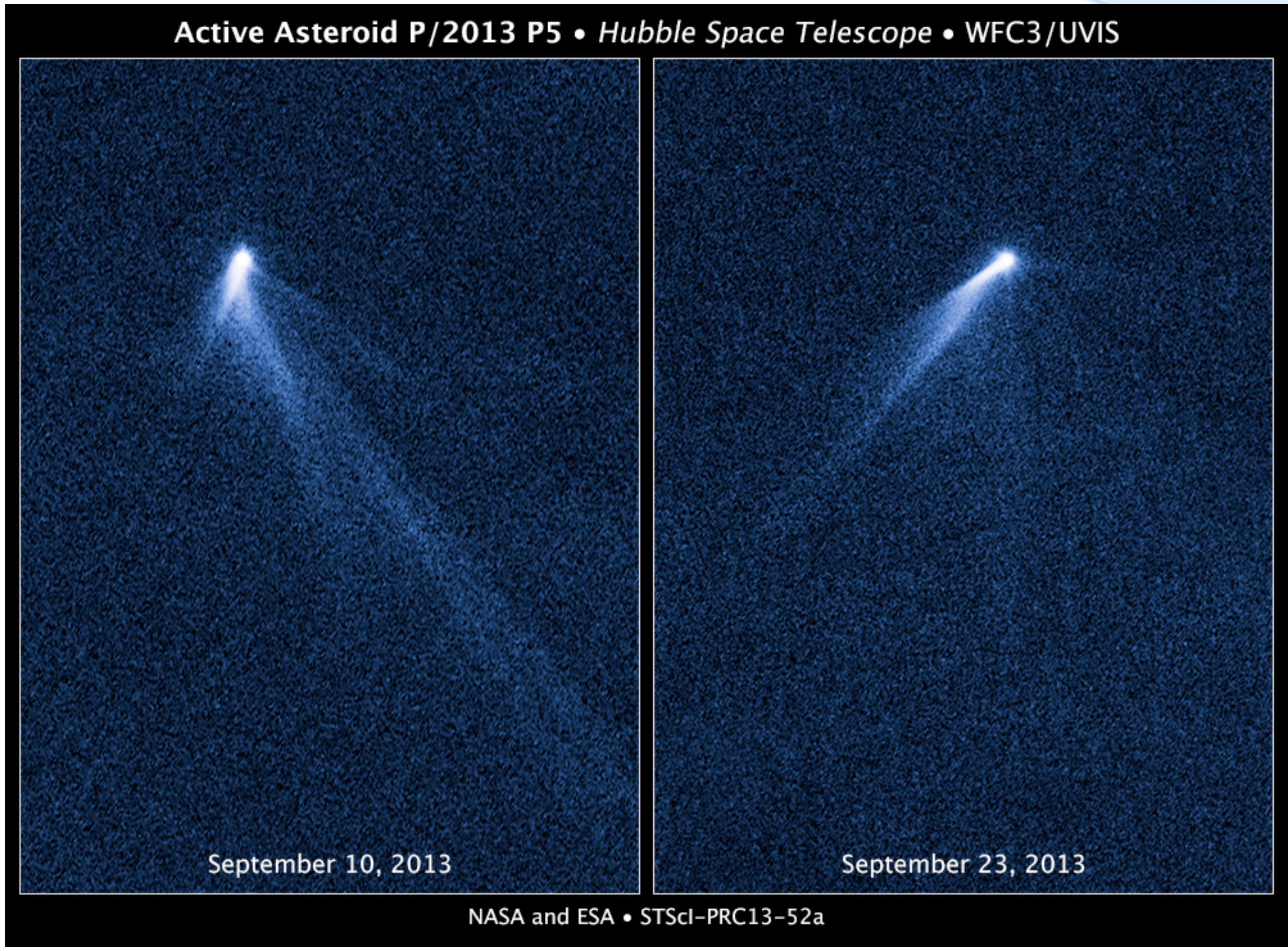
F-class

Next ESA opportunity

- F-class ("fast") call open. Deadline (phase 1) Oct 25.
- 150M€ cost to ESA, not including launch
  - Shared launch with another mission, e.g. Ariel to L2 in 2028
  - Wet mass limit ~1000kg.
- Interest in multi-point missions
  - i.e. combination of small spacecraft instead of one big one
  - Possibly lower TRL instruments (mini versions) – needs TRL ~5.
  - Probably not true CubeSats – real spacecraft, but smaller
- Interest in international collaboration
  - JAXA particularly interested in participation in this call
- Open call (not aimed at specific science area)
  - But MBCs + NEOs explicitly mentioned in call

ESA CDF study - MBC

Future planetary missions study, volatile case



- Target: 311P/PANSTARRS
- Four small spacecraft + mothership (comms)
- Instruments all in smaller spacecraft
- Goals:
  - Multi-point simultaneous sampling of cometary coma
- CDF study document published
  - http://sci.esa.int/future-missions-department/60411-cdf-study-report-small-planetary-platforms-spp/
  - Study finds mission is possible and implies compatible with F-class (but not really)

ESA CDF study - MBC

Future planetary missions study, volatile case

- SC1
  - mass spectrometer (EVITA)
  - pressure sensor (full COPS/ Rosetta)
  - radio science
- SC2
  - mass spectrometer (EVITA)
  - magnetometer (MAGIC/M-ARGO)
  - ion/electron (CHAPS/M-ARGO)
  - radio science
- SC3
  - camera (orbiter CUC/ ExoMars/MarcoPoloR)
  - magnetometer (MAGIC/M-ARGO)
  - ion/electron (CHAPS/M-ARGO)
  - radio science
- SC4
  - IR spec (BIRCHES/ LunarIceCube, NASA)

ESA CDF study - MBC

Future planetary missions study, volatile case

- Is this really compatible with F-class? (No)
- Who does ops (ESA too expensive)?
- Can we reach a real MBC? (No)
  - 311P fragmenting asteroid, not sublimation driven
  - Not really a “volatile case” – chosen as it is inner belt
  - Targets with diameter > 1 km more challenging
- Strawman payload just an example – what could we include (compatible with small sats)?
- Is this really a better approach than Castalia?
  - A very different mission – but would it hurt a future M7 bid?

MBC Conclusions

- Main Belt Comets are an important and unexplored reservoir of Solar System ice
- M5 Castalia bid well received, but not selected for phase A this time
- There isn’t another option for major ESA planetary mission for a while
- Can we do something cheaper?
  - Telescope searches for water would be useful.
  - Could put a good FUV telescope (Ly-α) at L2 with F-class
- ESA ‘small platforms’ study looked at 311P with multi-point mission
  - Not really compatible with F-class, not really a MBC…

F-class mission to a LPC

Fly-by of dynamically new comet, multi-point measurements

- Mission ‘parked’ at L2 after launch, waits for new target discovery (within 2-3 years) by LSST etc
- Short cruise and fast flyby near 1 AU
- See new type of comet, first approach to Sun
  - Some possibility of finding a suitable interstellar object
- Mothership with remote sensing payload, distant ‘safe’ flyby (few 1000km)
- Released cubesat-size probes take instruments on different trajectories through coma, including much closer to nucleus
  - In situ sampling (mass spec) in multiple places, magnetometers simultaneously sampling many scales, simple cameras for close nucleus images / dust, dust impact detector options?
- Proposal coordinated by Geraint Jones (MSSL)