Spacecraft Missions to Interstellar Comets and Oort Cloud Comets

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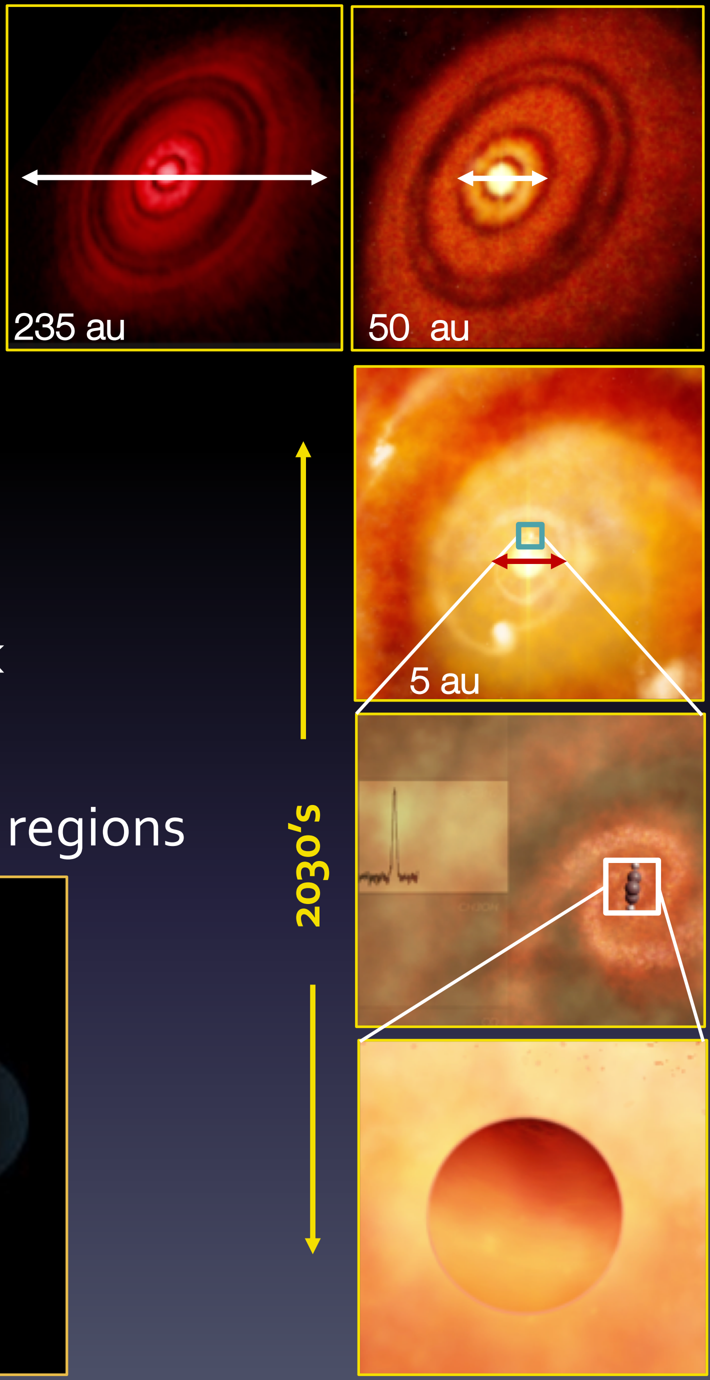
SBAG
November 2, 2020

C/2006 P1 McNaught, S. Deiries

Transformative science in the 2030's



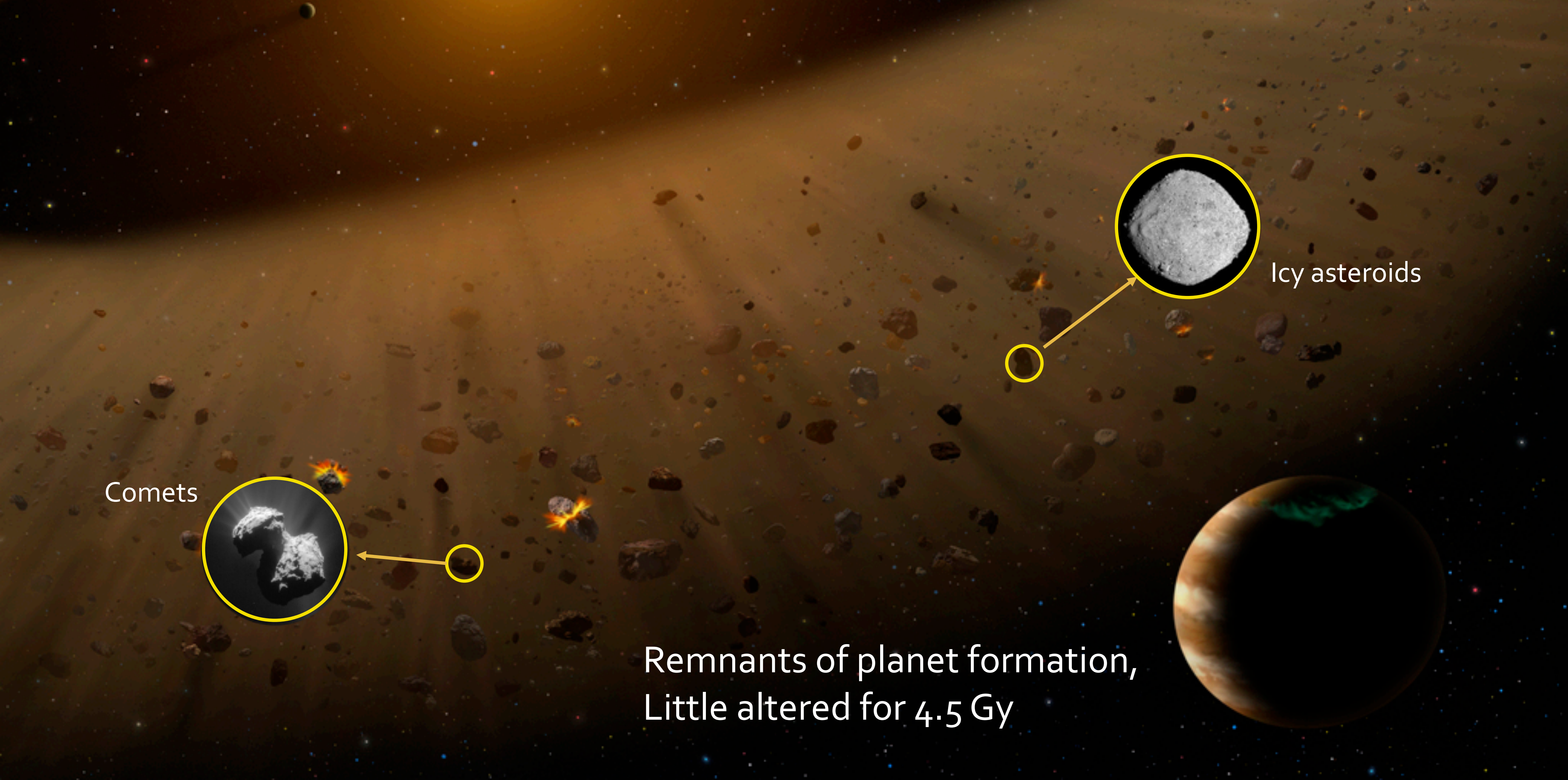
Astrobiology objectives

- Trace physics & chemistry of terrestrial planet formation in the pp disk
- ALMA's sensitivity and resolution can reach giant planets > 20-30 au
- The next generation telescopes will probe terrestrial planet formation regions

TRAPPIST1 System. Credit: NASA/JPL-Caltech

Credits: ALMA, ngVLA

How do we explore Habitable Planet formation in our Solar System?



Remnants of planet formation,
Little altered for 4.5 Gy

Primitive Tracers

A. Meteorites (well-studied)
- Contain water, have been altered

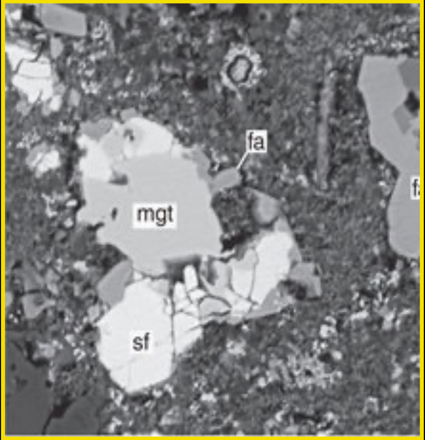
B. Icy asteroids (unexplored)
- Formed locally, or migrated from farther out
- Contain unaltered material

C. Comets (many missions, ground, but no OCCs)
- Formed cold, remained cold, untraceable dynamics

D. Icy satellites (Cassini)
- Formed cold, have been heated – evolved

E. Interstellar objects (unexplored….)

A



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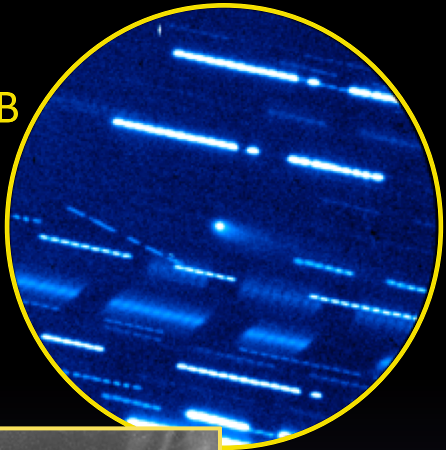

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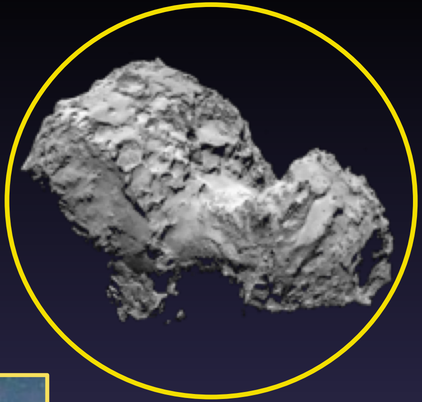

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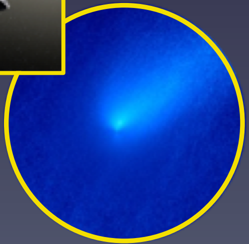
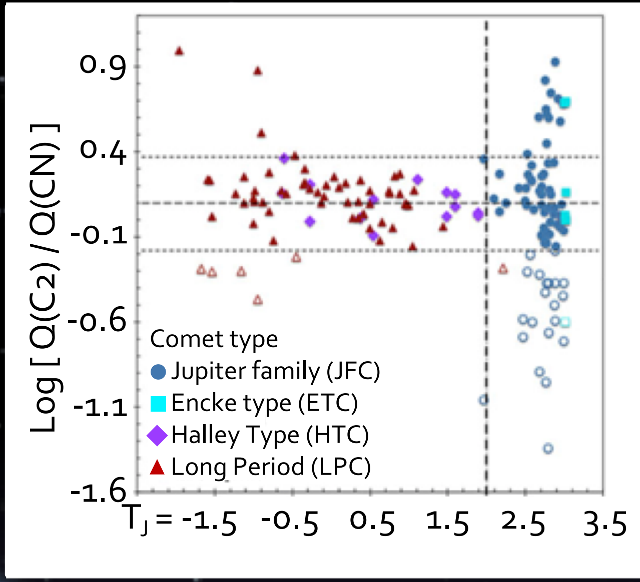
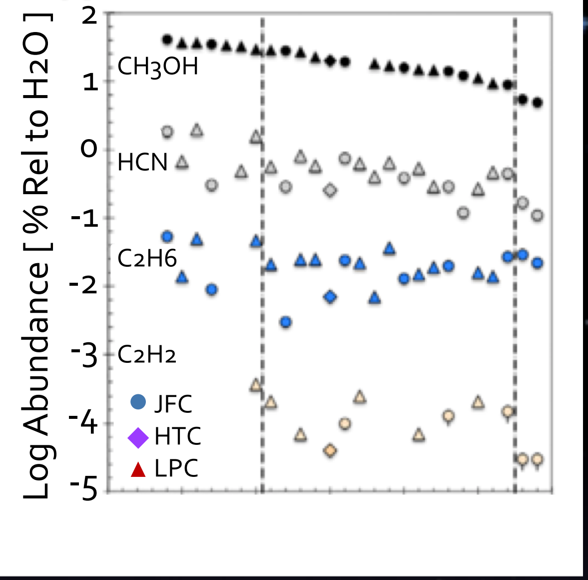


Small Body Tracers

- Comets – Ground Based
  - Parent organics & daughter fragments – chemistry uncorrelated with dynamical type
  - Isotopes D/H, $^{15}N/^{14}N$, $^{13}C/^{12}C$ (~20)

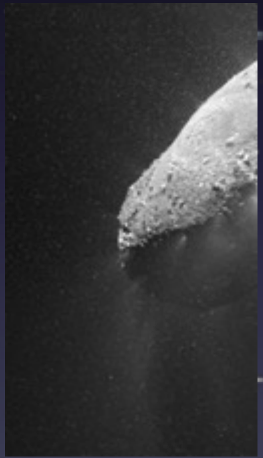


After A'Hearn et al 1995

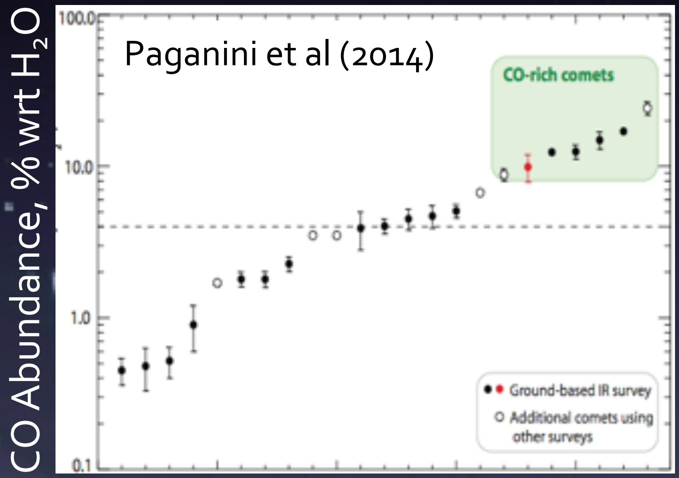


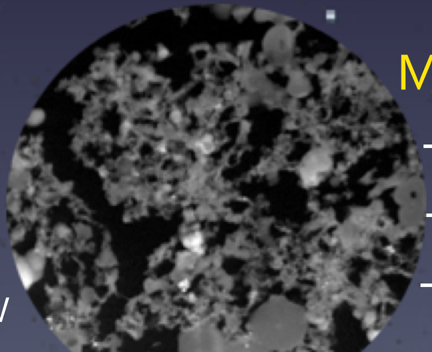
After Mumma & Charnley, 2011

- Space Missions (Pre-Rosetta)
  - CO_2 a major driver of activity (uncorrelated with dynamics)
  - Comets are very low density, very low thermal inertia
  - Very dark organic rich surfaces
  - Silicates – nebular processing
  - Stardust – significant nebular mixing



EPOXI: 103P/Hartley 2

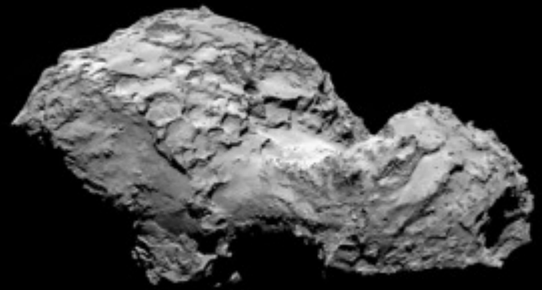




C. Alexander, CIW

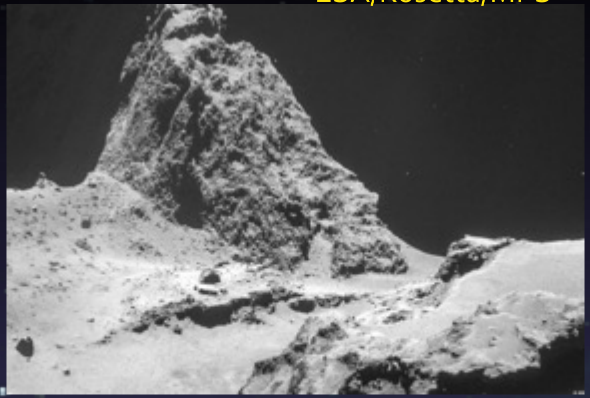
Meteorites
- Aqueous alteration (everywhere)
- Chondrite classes – different zones
- No Earth feeding zone material

Small Body Volatile Tracers: Rosetta



ESA/Rosetta/MPS

ESA/Rosetta/MPS



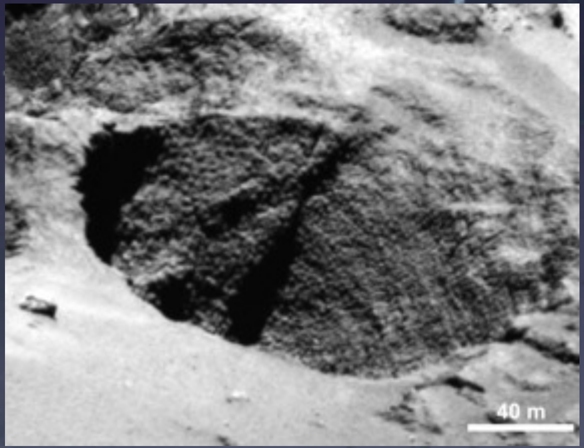
Formed very cold

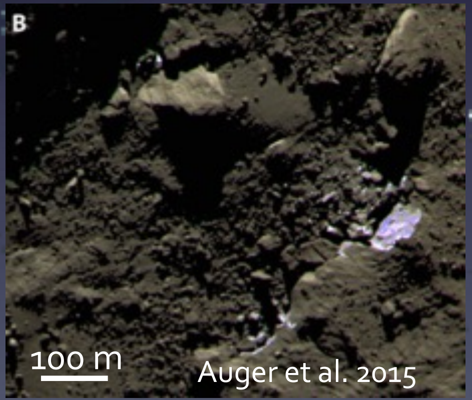
- Abundant supervolatiles: CO (13%), CO_2(8%), O_2 (4%), N_2 (0.07%), noble gases
- Rich array of pre-biotic chemical species
- Inheritance from pre-solar cloud . . .

Comets are low density, low strength – preserve early SS history

Questions

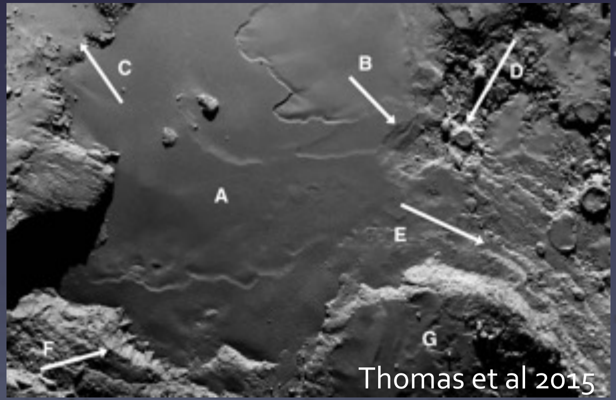
- What is primordial and what is the effect of insolation? (How do comets work)
- How and where do comets form?
- What role do comets play in bringing volatiles to the inner solar system, to Earth?



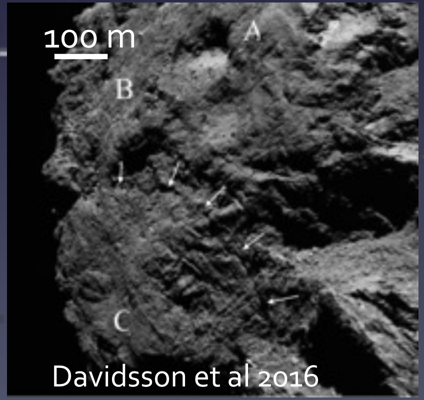


Auger et al. 2015

Fornasier et al. 2016



Thomas et al 2015

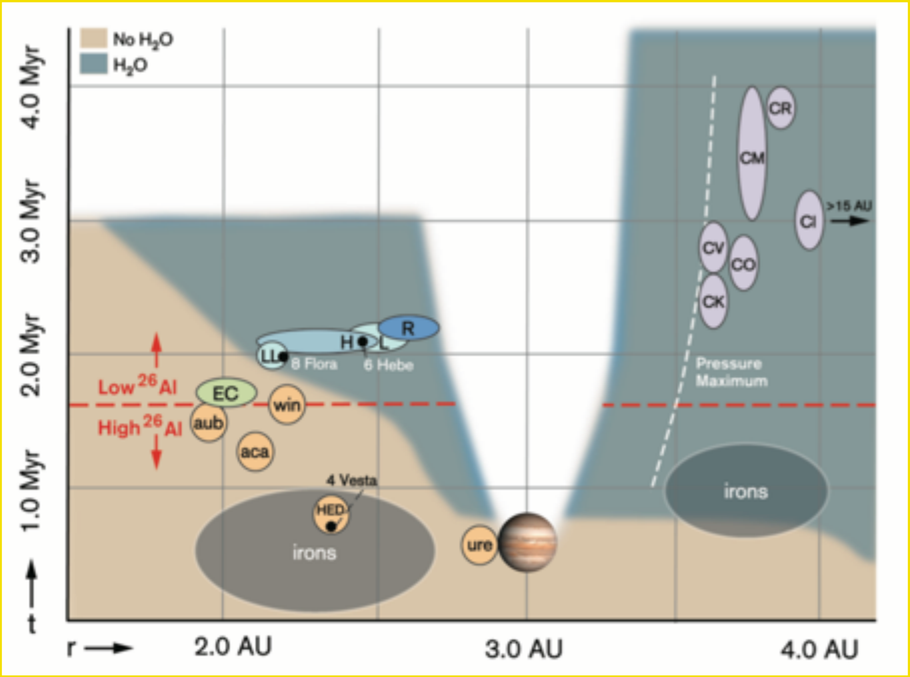


Davidsson et al 2016

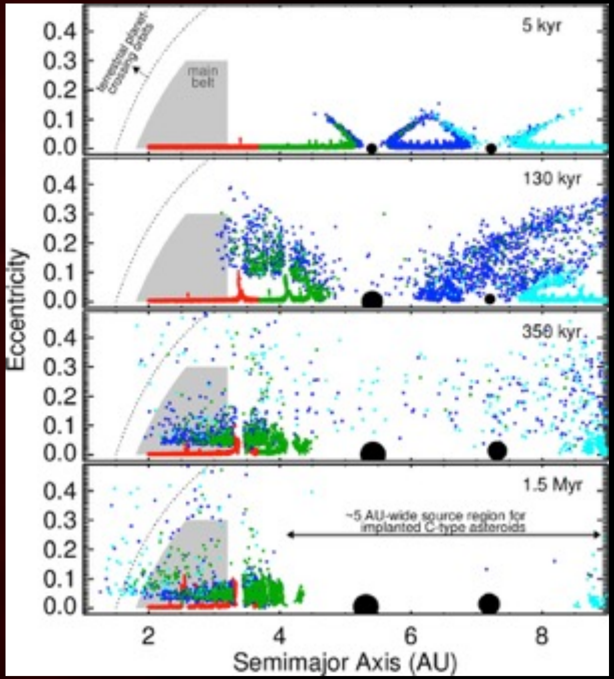
Cosmochemical clues

Jupiter forms early, opens gap (Kruijer et al 2017)

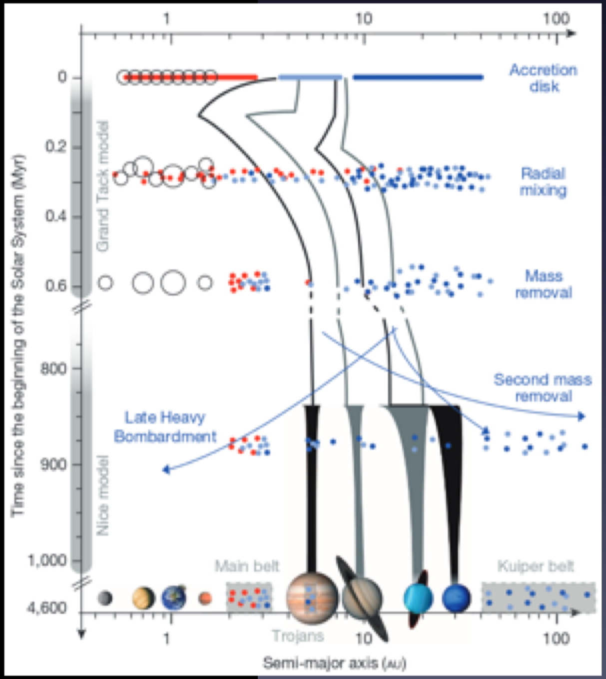
- Impedes inward flow of icy material
- Terrestrial planets form in warm inner disk
- Giant planet growth → scatters planetesimals
- From where depends on where Jupiter formed, and if it migrated



Desch et al 2018



Raymond & Izidoro (2017), Icarus

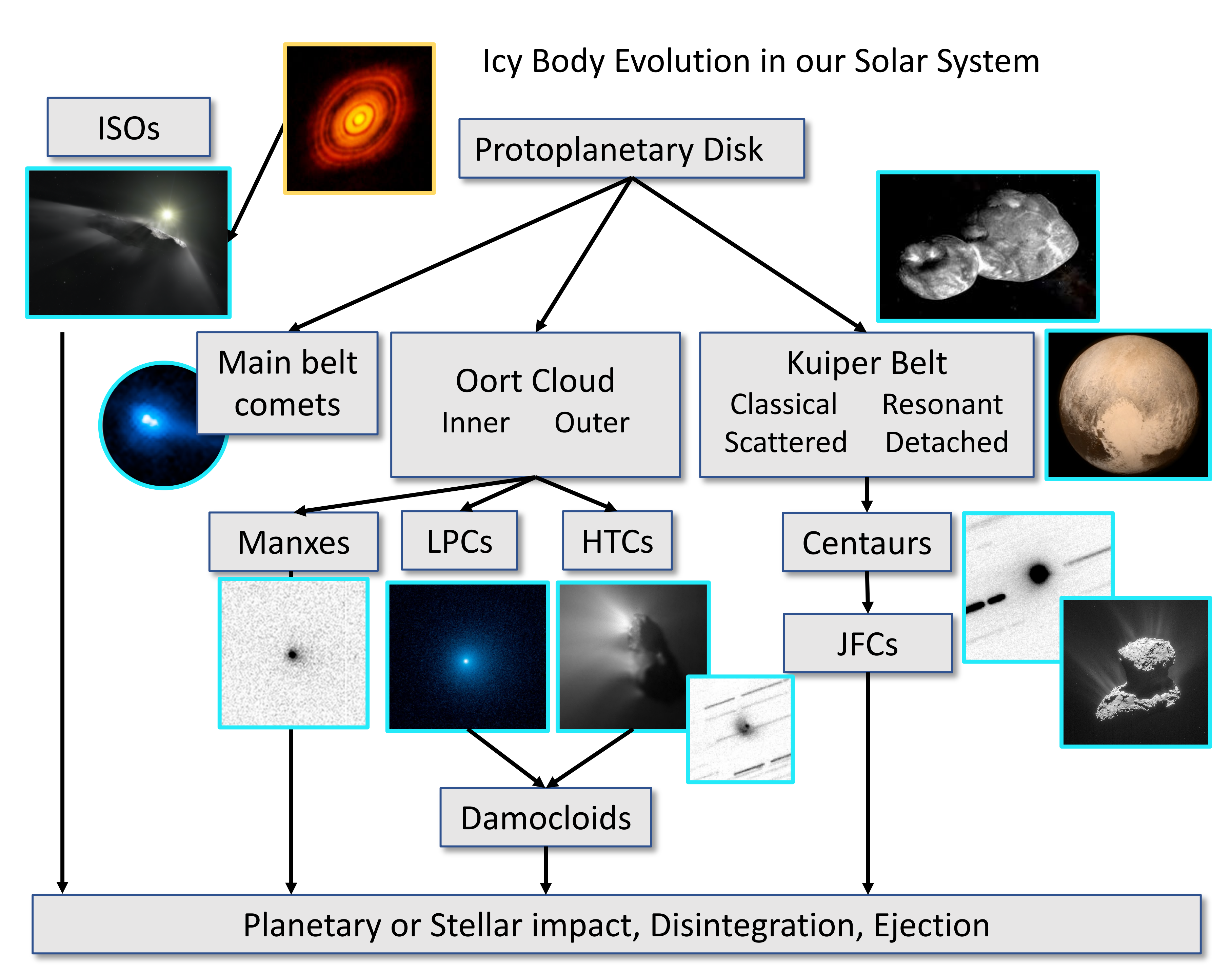


DeMeo & Carry (2014), Nature

Earth volatile scenarios

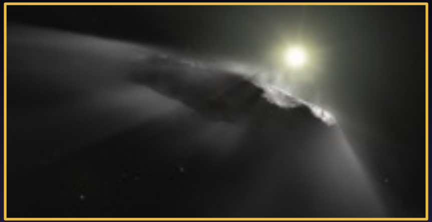
1. Earth captured volatiles & organics from inner disk
2. Delivery from scattered planetesimals

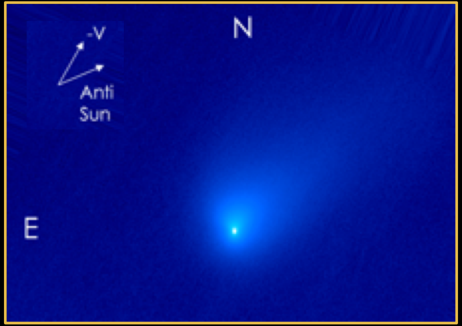
Credit: S. Andrews, B. Saxton, ALMA



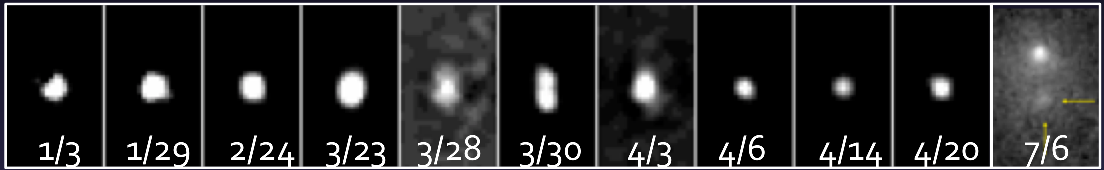
Icy Body Evolution in our Solar System
ISOs
Protoplanetary Disk
Main belt comets
Oort Cloud
Inner
Outer
Kuiper Belt
Classical
Resonant
Scattered
Detached
Manxes
LPCs
HTCs
Centaurs
JFCs
Damocloids
Planetary or Stellar impact, Disintegration, Ejection

ISO "Legacy"

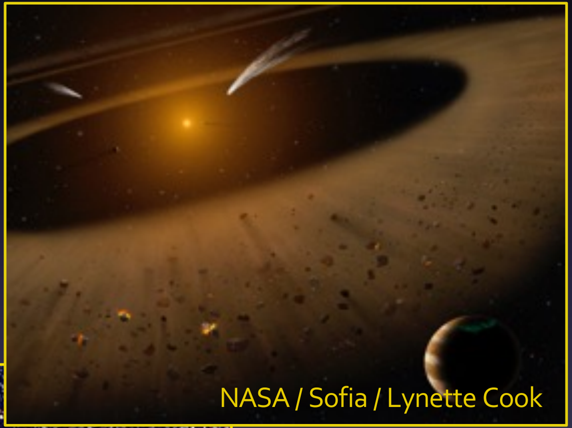


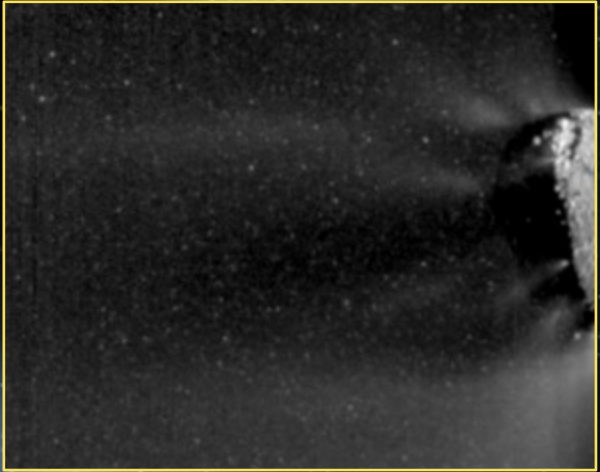


- Characteristics
  - 1I: Very small 102 m for 4% albedo, excited rotation, surface reflectivity like outer SS material, excited rotation, no dust, no gas directly detected, but non-gravitational acceleration
  - 2I: Looks like a typical comet, but very CO-rich, C-Chain depleted, changing comp w/distance

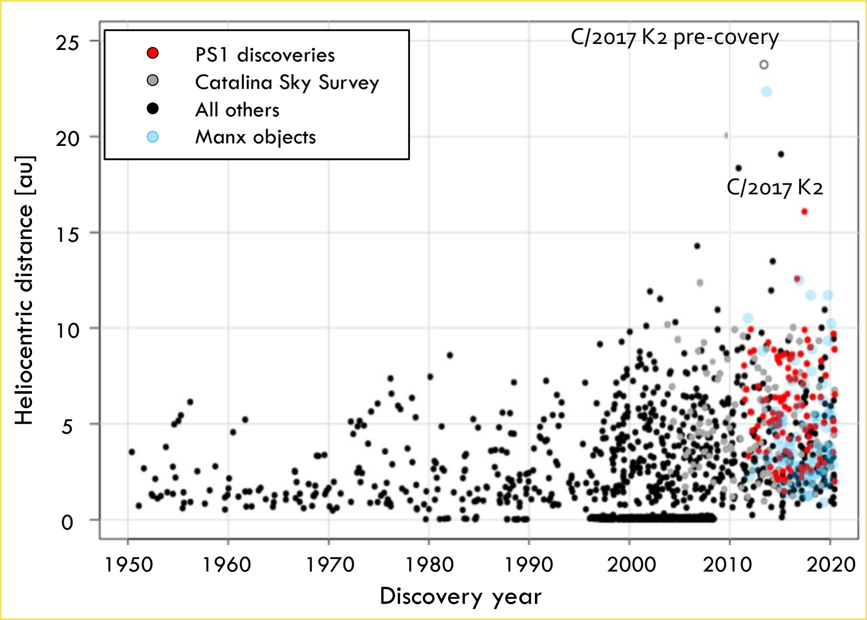


- Interpretation
  - Planetesimal ejected during extrasolar system formation
  - Tidal disruption (giant planets, white dwarf)
  - Fluidization of material during red giant phase
  - Molecular hydrogen iceberg
  - Alien visitors

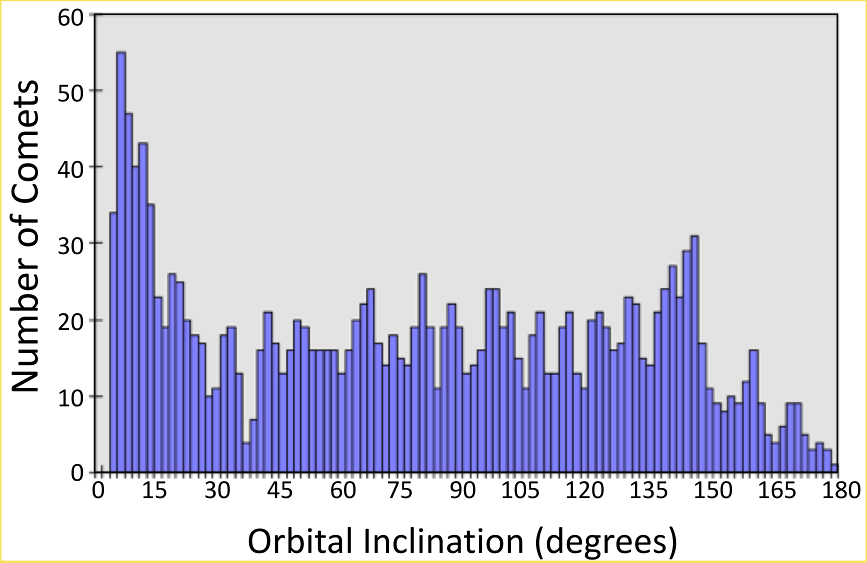

NASA / Sofia / Lynette Cook



LP Objects – Once in a Lifetime Targets



Meech, Yang, Kleyna (2016)



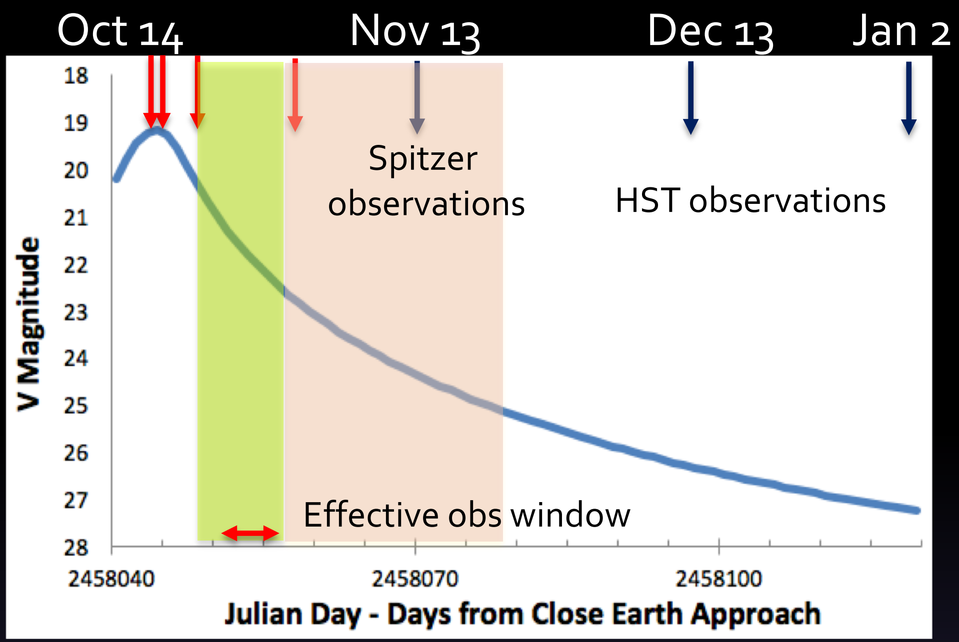
- Transformative science
  - Unheated objects best preserve the early solar system environment
  - Critical constraints for planet building in our and other solar systems
  - Want to know detailed chemical & physical properties
- Mission challenges
  - LSST (first light 2022) may detect LPOs ~ 10 yr pre-perihelion
  - All inclinations – more challenging for rendezvous
  - LPCs are driven by CO, CO_2 → large debris
  - Small objects: characterization requires very large aperture from Earth, much science demands in-situ

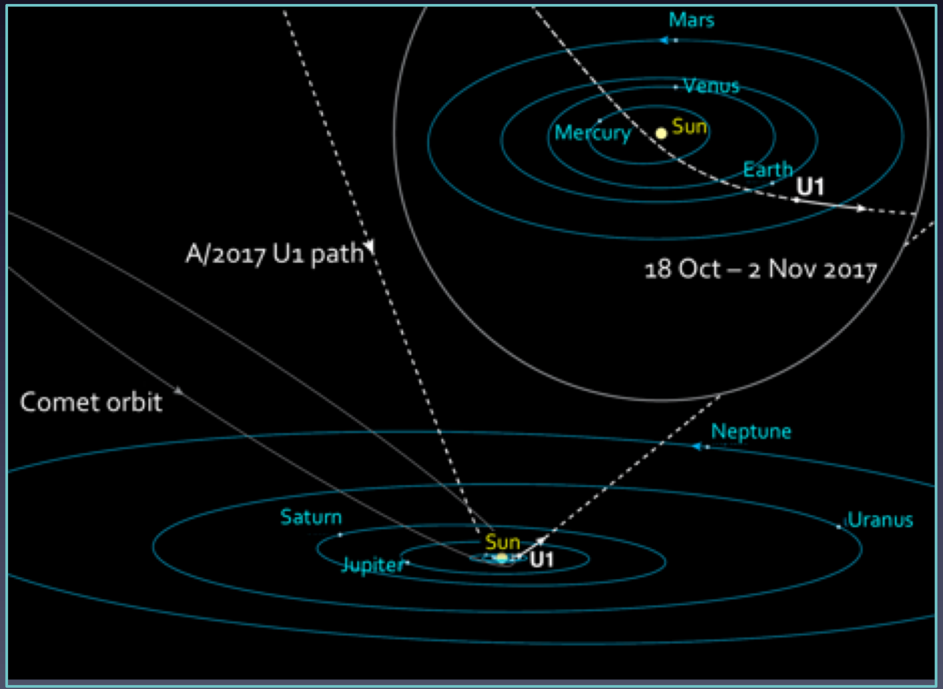
Challenging Timelines

1I/`Oumuamua's Circumstances (worst case)

- Observations – best over a few weeks
- ~65 hrs on 4-10 m telescopes over 1 wk
- 30 hrs on Spitzer, 9 HST orbits
- >130 papers

Sun	Mon	Tue	Wed	Thu	Fri	Sat
← Sep 9 Perihelion						14- Close Earth, CSS Pre-covery
15	16	17	18-PS1 Pre-covery	19-PS1 Discovery	20-Astrometry	21-Astrometry
22- Hyperbolic orbit confirmed	23-DD prop VLT, GS; VLT Approve	24- GS prop Approved; MPEC orbit announce	25-VLT Obs, HST prop submit, UKIRT DD award; ★	26- VLT, GS obs; HST Approve; PR ★	27- GS,CFHT, UKIRT, Keck obs	28- UKIRT obs ★
29 – Hawaiian name	30- ★	31- Nature paper submit	1	2	3	4
5	6-Ref. Rpt. IAU Name OK	7	8-Resubmit paper	9	10-Paper in production	11





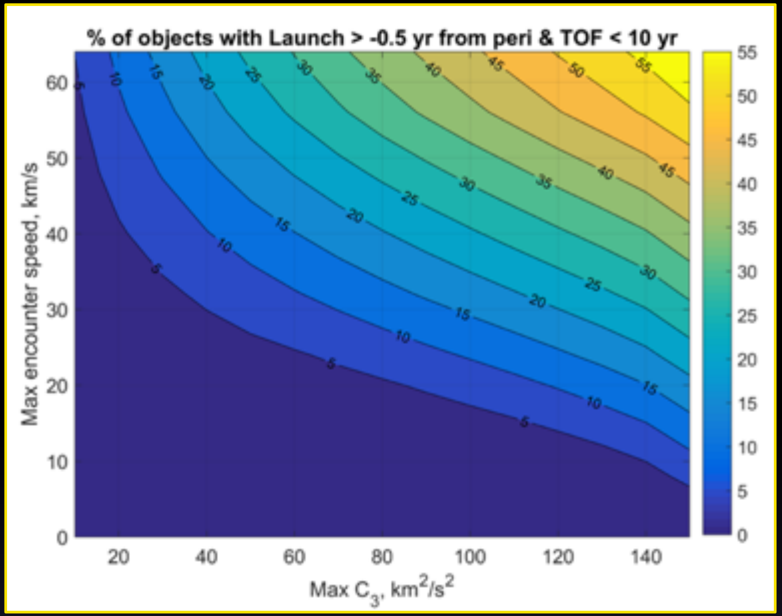
2I/Borisov (a good case)

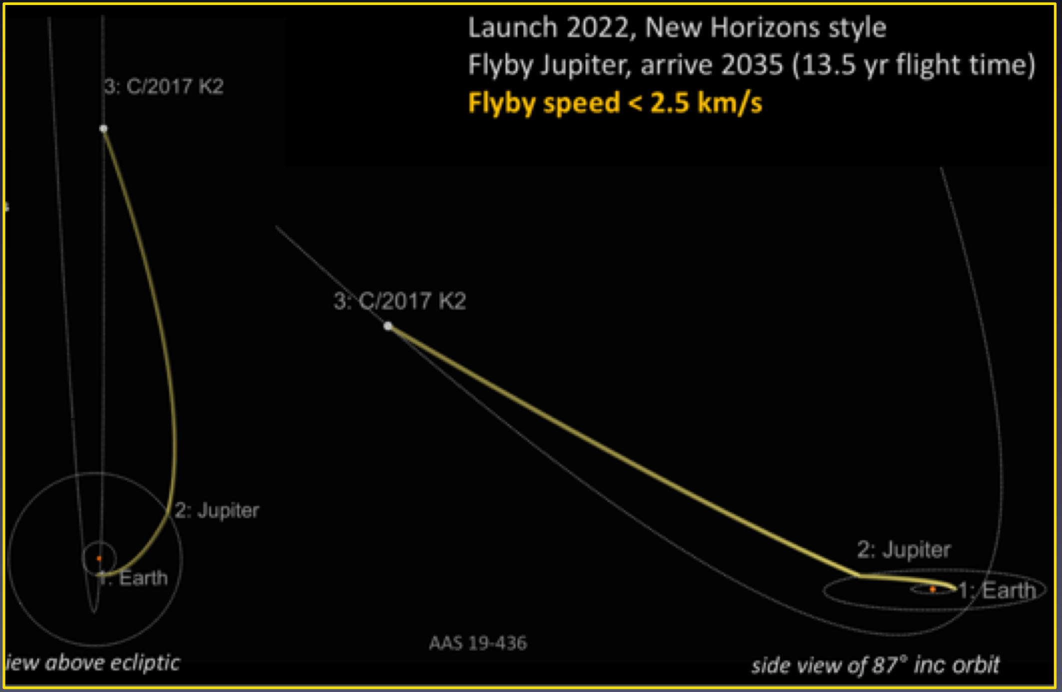
- Discovered Aug 30, 2019, perihelion in December 2019
- Major observing campaign → went into solar conjunction in Oct 2020
- Visible again in Mid Jan 2021 – and likely still bright enough for observations

LPO Mission Challenges

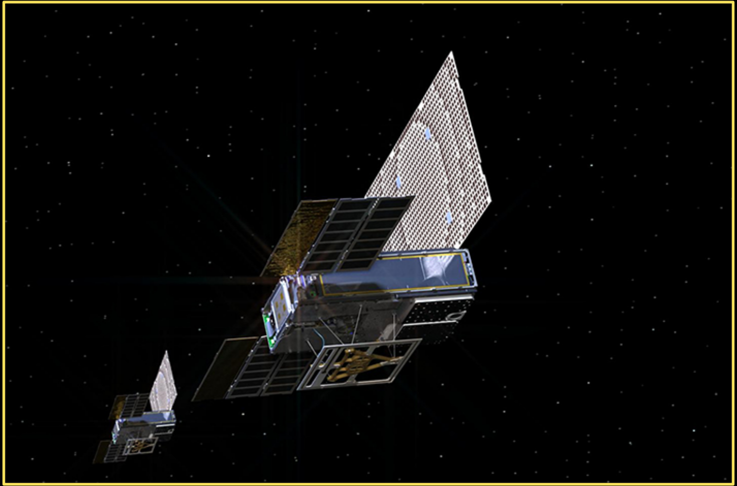
- High relative velocities (50-90 km/s)
  - Giotto was destabilized by 1 gm grain impact at 68 km/s
- Unique challenge for missions
  - Changes paradigm of how missions are done now: proposal to launch ~ 6 yrs
  - Spacecraft needs to be implemented fast or ready to go
- How many targets are likely?
  - Want rendezvous, can only get flybys

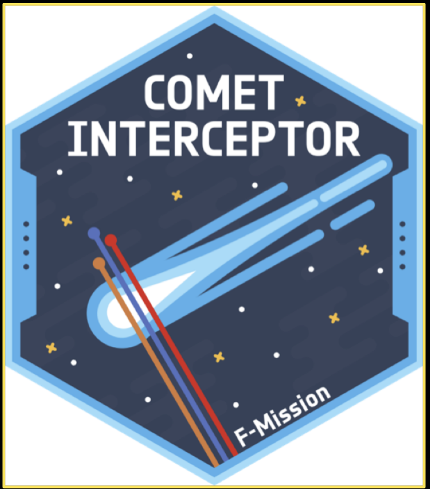
Launch E	Enc Velocity	% reachable	Comment
High	High (< 64 km/s)	90	
Low	High	20	
High	Low (< 4 km/s)	2-5	Long travel time





What and How?





- Compelling Science – solar system formation
  - Detailed information on: refractory & volatile isotopic composition, nucleus structure and density
  - Instruments: vis camera, UV spectrometer, sub-mm spectrometer, dust, mass spectrometer
- New Mission Paradigm
  - New type of reactive NASA mission
    - Launch within < 2 years of discovery
    - Spacecraft on parking orbit waiting for target (e.g. Comet Interceptor)
  - Multi-spacecraft architectures increase the observation window with stage deployment of small daughtercraft
  - Long-term spacecraft storage (on earth, in orbit)
  - Synergy with needs for planetary defense missions
- Multi-spacecraft Architectures
  - Provides redundancy / hazard mitigation
  - Multiple vantage points
  - Multiple experiments enabled
- Cubesat development is enabling
  - Low-cost multiple space craft
  - Requires coordinated autonomy
  - Accomplish rendezvous goals with a flyby

Feasibility requires further study

Programmatic Recommendations

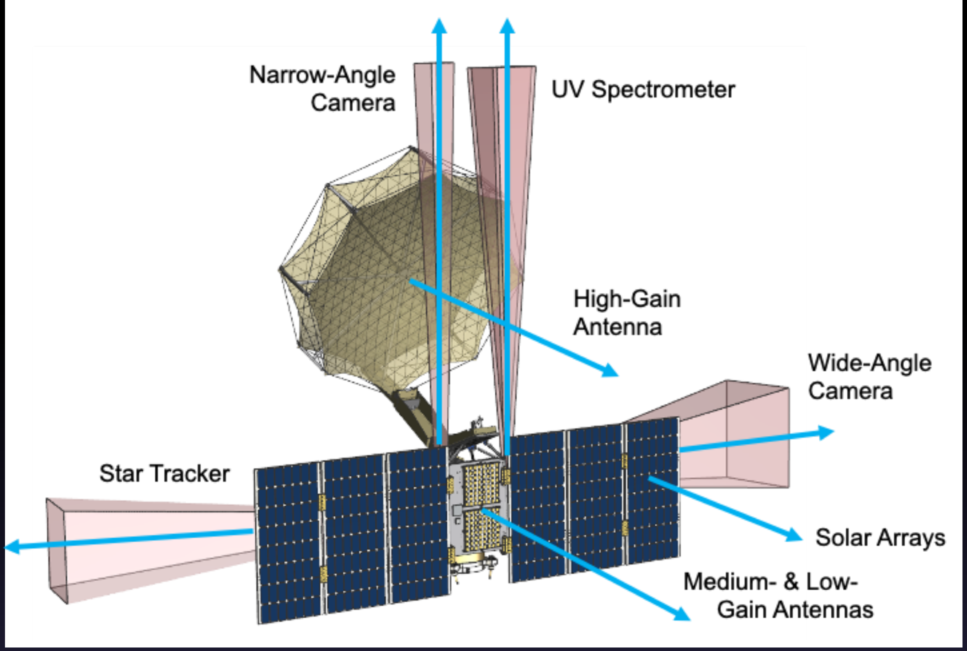
- SIMPLEx modifications required to enable smallsat ISO or OCC exploration
  - Larger cost cap
  - Allowance for dedicated launch vehicle
  - Allowance for flexible targets
- Discovery/New Frontiers modifications required to enable OCC exploration
  - Flexible targets
- Alternatively, rapid response mission category could enable exploration of targets of this class
  - Could provide annual resources for storage

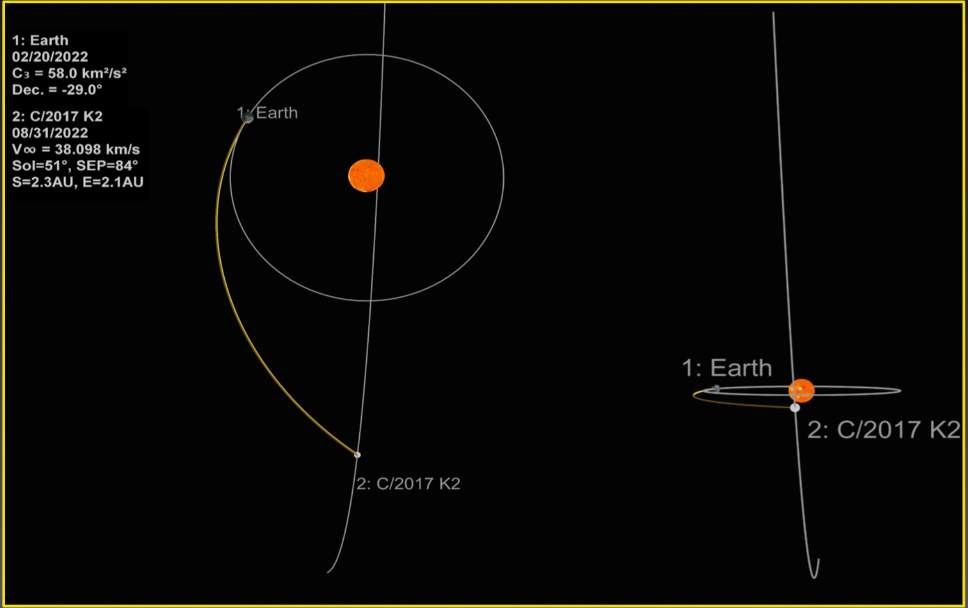
Architecture	Sched. Risk	Cost Risk	Technical Risk	Operations Risk
A1 – Ground Storage	Low	Med	Med	Low
A2 – Space Storage	Low	Med	Low	High
A3 – Build After Detection	High	Low	Med	Low

Extra Slides

Xenia

- Focused study in FY19 to develop twin-smallsat flight systems to encounter C/2017 K2
  - 2 x 75-kg smallsat with high resolution imager, UV spectrometer
  - Predominantly COTS parts, where possible
- Significant conclusions:
  - Smallsat exploration of Oort cloud comets or ISOs is technically feasible given that there is > 2 years notice between discovery and launch
  - Developments in autonomy, smallsat telecom, smallsat propulsion, and miniaturized instrumentation would enhance mission and reduce risk
  - Programmatically, there is no path for a rapid response mission concept

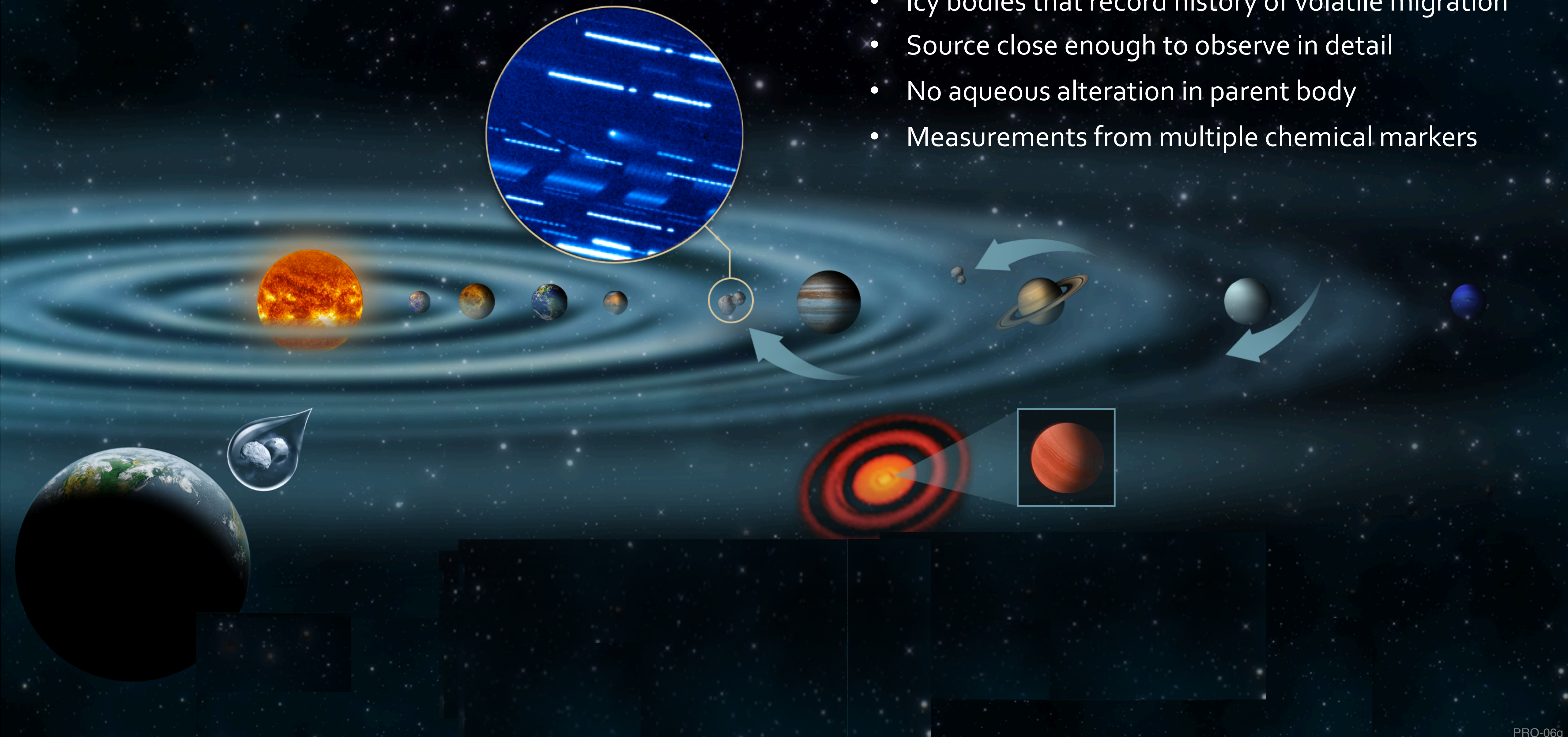




Tracing the volatiles

Required Source

- Icy bodies that record history of volatile migration
- Source close enough to observe in detail
- No aqueous alteration in parent body
- Measurements from multiple chemical markers

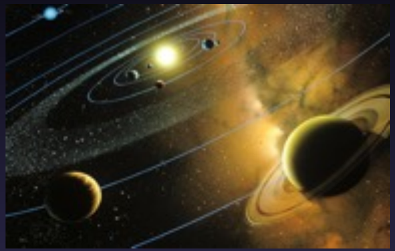


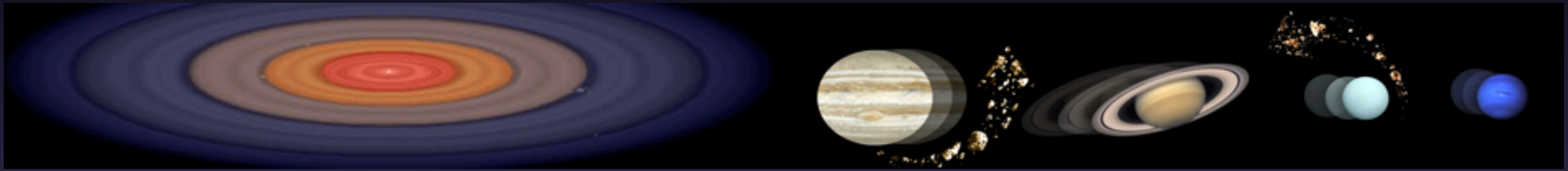
SMD Vision & Voyages (2013-2022) & the Astrobiology Roadmap

How do Habitable Worlds Form?

With thousands of exoplanetary systems known, ours, so far is unique in its architecture with a habitable planet in the habitable zone. Water is the most abundant condensable molecule so solar composition gas should condense water-rich planets, yet the inner solar system is dry.

- Planetesimals gain chemical fingerprints from the disk
- Planetesimals were then scattered by the giant planets





- Did planetesimals drive inward from beyond the snow line to form terrestrial planets?
- Meteorites (cosmochemistry) gives us clues to what happened
- Volatiles in small primitive bodies are the best connection to protoplanetary disks and how habitable worlds are built.