## Chemical Fingerprints of the Early Solar System and its Dynamical Evolution

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Habitability for terrestrial planets – bringing water to the inner solar system
Chemistry and isotopic signatures vary with temperature in the disk

- Planetesimals formation and scattering by giant planets
- Unwinding the clock perils of using one isotope to trace the history
- Where to look: Clues from meteorites the NC/CC dichotomy
- Testing dynamics with Manx comets
- Value of sample return to assess volatiles in the asteroid belt

Image: NASA/JPL-Calte



### Life, water and Astrobiology....

Credits: NASA

- Astrobiology seeks to understand how habitable worlds are made
- Habitability = water + organics + energy + the right temperature



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As of Sep 8, 2024: ~30-70 potentially habitable planets 5,756 confirmed, 7217 candidates, 4,297 planet systems



Credits: ALMA, ngVLA

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5 αι

2030's

# Is our Solar System Unusual?



Habitable zone

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hot

Too cold

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



Comets

Remnants of planet formation, Little altered for 4.5 Gy

Credit: NASA/SOFIA/Lynette Cooke

## It is a complex process . . .



## Chemistry is set by temperature (location)

## Giant planets move things as they grow

**Externa** 

ft (Dust+lce)

## What does life need on a planet?

- Organic & other compounds
- A source of energy
- Solvent: Liquid water (just the right amount . . . .)

But our inner solar system is dry . . . .



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Dry

Lost its water Ocean 0.023%

Ocean 0.023% Dry – water at Total ~ 0.05-0.1% poles, subsurface

r at Almost Dry surface

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Balsiger 1995, JGR 100 Owen & Bar-Nun 1995, Icarus 116

Earth's Ocean



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### Giotto Mission D/H 1986

- Comet delivery of water

30X -

12X

3X

D/H



A few comets Meier, R. 1998, Science Bockelee-Morvan, 1998, Icarus



Meteorites

Initial solar system Geiss & Gloeckler 1998, SSR 84







Balsiger 1995, JGR 100 Owen & Bar-Nun 1995, Icarus 116

### Earth's Ocean







# Isotopic fingerprints



Meech & Raymond (2020)

## Meteorite clues



Cr Isotopes

#### Credit: S. Andrews, B. Saxton, ALMA

## Meteorite clues



### Earth's water origin scenarios

- 1. Earth captured water & organics from inner disk gas
- 2. Delivery from materials tossed in by Jupiter

### **Testing the Hypothesis**

- Material tossed in by Jupiter hit all the rocky planets
- Some got trapped in the asteroid belt . . . Where they remain today . . . .

## Tracing the formation

## What do we need

- Icy bodies that record history of where they formed
- Need to have the ices survive
- Multiple isotopes
- A source close enough to observe in detail

 $\rightarrow$  Requires an in-situ or sample return mission





## What about the dynamics?

Hsieh & Jewitt (2006) Science 312



Meech et al. 2016. Sci. Adv.

## Manxes: A New type of LPC



- Aug 2013 Pan-STARRS1 Survey discovers unusual LPC
  - Heliocentric light curve  $\rightarrow$  H2O sublimation
  - Does this solve Oort's missing comet problem (run out of volatiles)?
  - Spectrum consistent with inner solar system rocky asteroids







Meech et al. 2016. Sci. Adv.

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  - Spectrum consistent with inner solar system rocky asteroids
  - Formed near the SS snowline, ejected to Oort cloud early in SS history?

# Manx Implications: Early solar system dynamics



0.4

0.5

0.6

0.7

Wavelength [microns]

0.8

0.9

1.0

- Gas giants interact with planetesimals
  - Scattered Oort cloud material composition depends on scenario
- Manxes have a range of surface colors (& formation locations?)
  - Are these just bodies that form near the ice-line, do they include samples of evolved comets?

# Floodgates opening



### • LSST Timeline

Early 2025 1<sup>st</sup> light, Survey late 2025, early 2026

### LSST & Small bodies (10 yr survey)

- ~ 100 new MBCs
- ~10,000 comets, 50 data pts along orbit, multiple filters
- 30,000 TNOs
- 5 x 10<sup>6</sup> Main belt asts, 3 x 10<sup>5</sup> Jovian trojans, 1 x 10<sup>5</sup> NEOs



## Value of Sample return

- Rich detail on multiple isotope systems that can constrain solar system formation models
  - Example here with origin of Earth's water
  - Return of refractory material also key for habitability story
- Ideally want this for a range of small body classes
  - MBCs, Manxes, LPCs, Jupiter Trojans, small KBOs, ... And of course, ISOs!
- Helps address processes that lead to the formation of habitable worlds in planetary system habitable zones