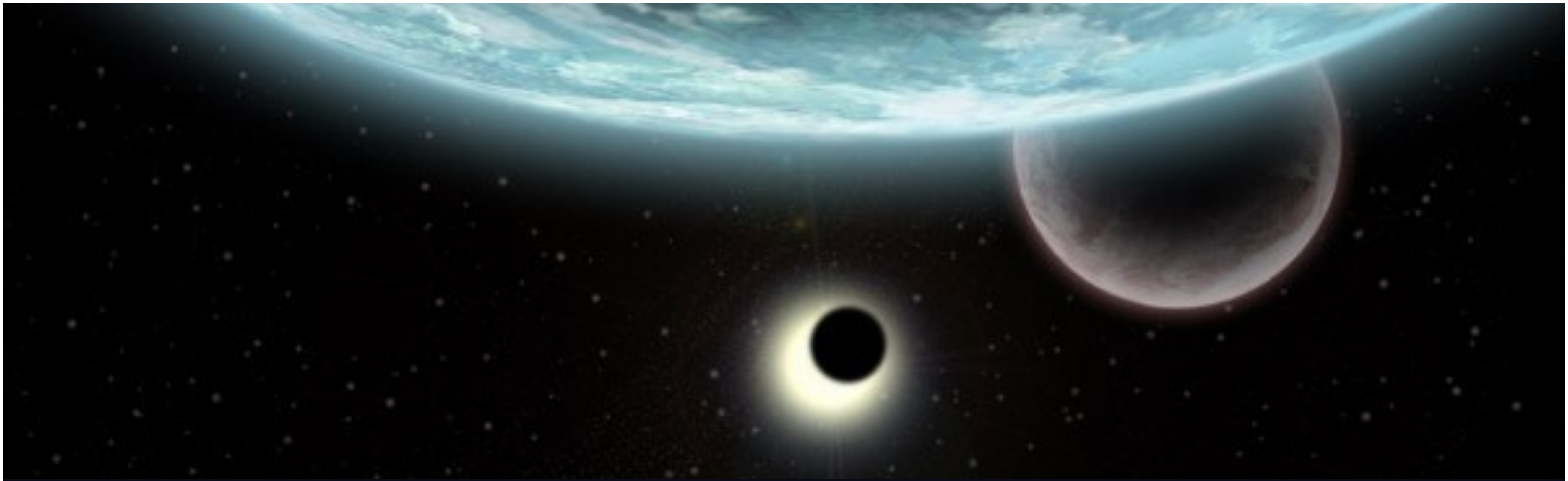
New Directions in Solar System Small Body Science with the TMT

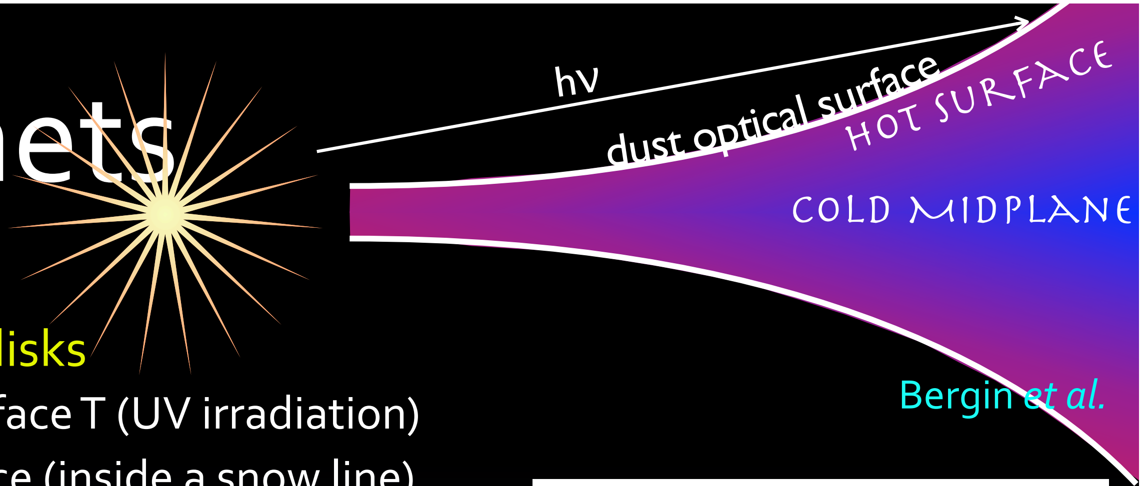
K. J. Meech
Institute for Astronomy, University of Hawai'i

TMT Science Forum, July 18, 2014

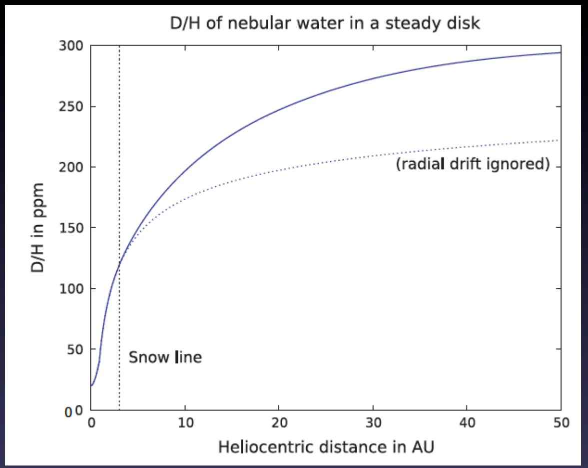


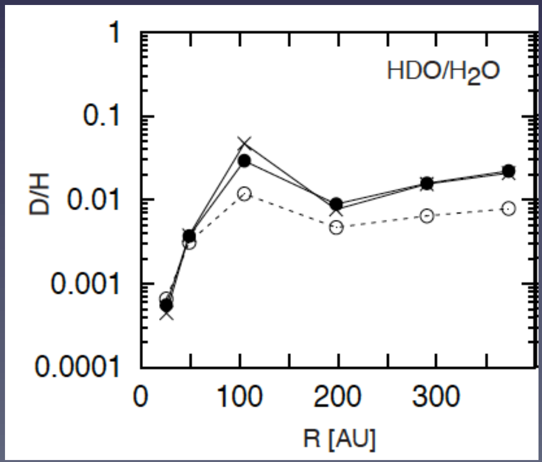
- Key Planetary Science Decadal Goals – small bodies
  - Understanding how habitable worlds are created
  - What were the initial stages, conditions and processes of solar system formation?
  - What governed the accretion, supply of H_2O & inner planet chemistry?
  - From where did Earth get its water?
- A rapidly changing landscape
  - Dynamical models are starting to reproduce structure, but not chemistry
  - Disk chemical models predict chemical gradients, but many models & don't fold in dynamics

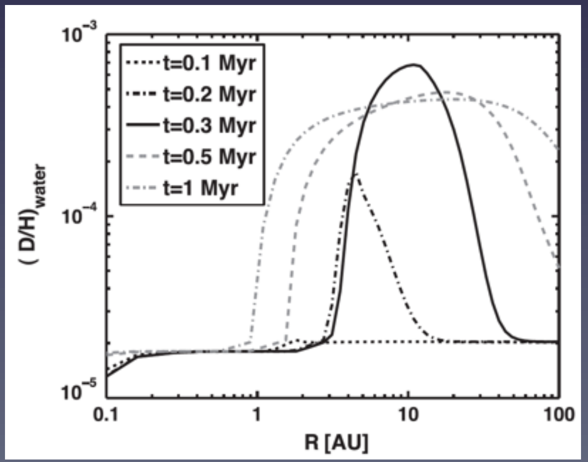
Disks to Planets



- Planets form in circumstellar disks
  - Disks are flared → higher surface T (UV irradiation)
  - Volatiles present as gas and ice (inside a snow line)
  - Key volatiles: H_2O, CO, CO_2
- New Chemical models & Tracers
  - Solar system starts enriched from D in ISM
  - Isotopic exchange as T increases
  - Viscous transport moves inner nebula gas outward
  - D/H of disk gas a mix of infalling and transported gas

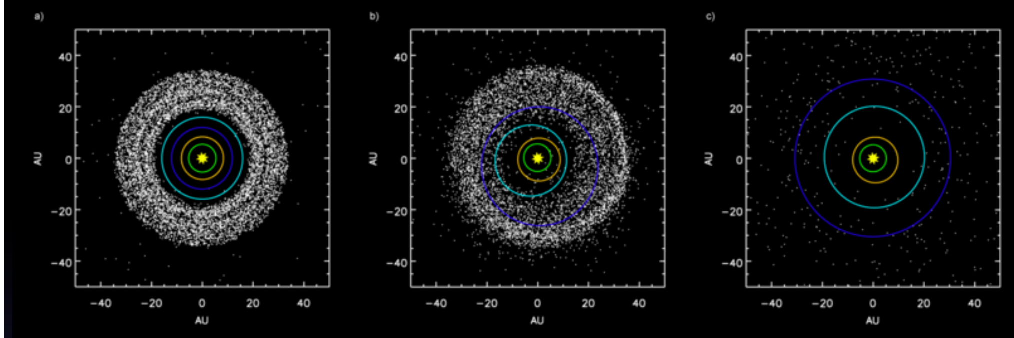




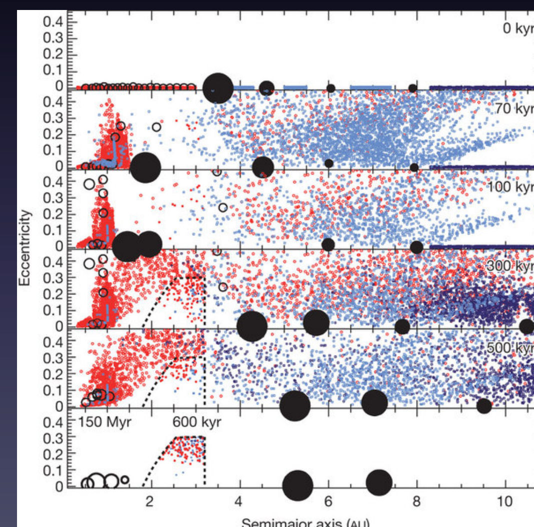


Left: Aikawa *et* al (2002);
Top Right: Jacquet & Robert (2013)
Right: Yang *et al* (2013)

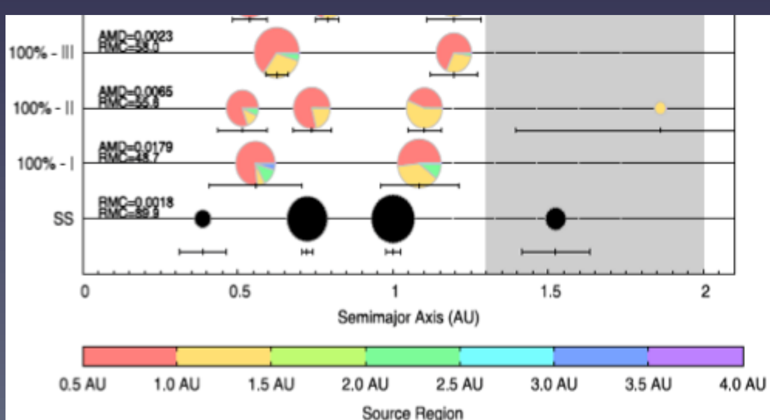
Evolving Dynamical Models



- Nice Models (Morbidelli *et al* '00-'10)
  - Post-Jupiter formation
  - Explains much of SS architecture
  - Levison '09, KBOs captured into outer main belt



- Grand Tack Models (Walsh *et al* '11)
  - Allows gas giants to migrate in a disk
  - Explains low mass of asteroid belt
  - Redistributes icy objects from outer regions into belt



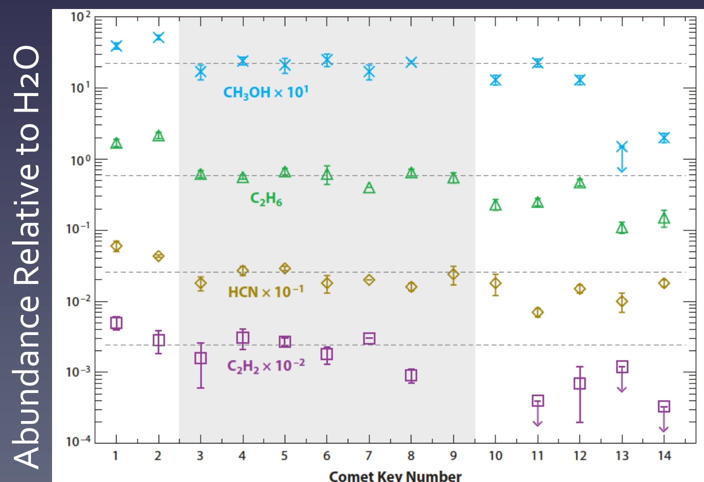
- Disk Depletion (Izidoro *et al* '14)
  - 50-75% depletion in mass between 1.3-2.0 AU (caused by differing viscosity)
  - Earth can form mostly from local disk

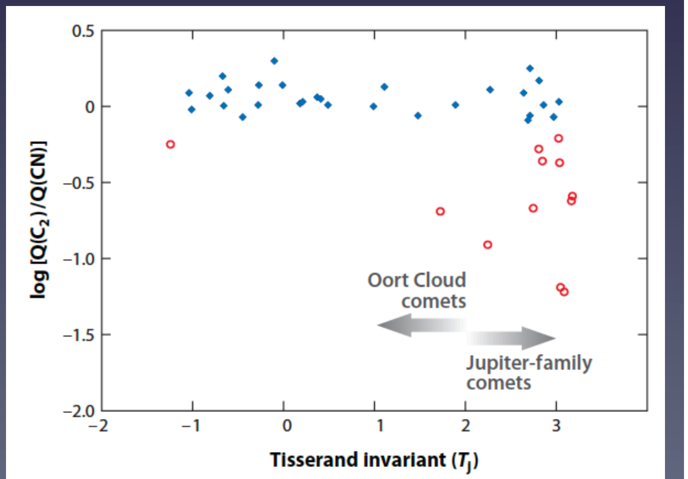
Quick Comet History – Taxonomies

Comet (Primitive) Mixing Ratios			
	Low	High	# comets
H2O	100	100	
CO	<0.01	26	27
CO2	0.0005	89	35
CH3OH	<0.1	6	>10
CH4	0.2	1.5	>10
C2H2	0.1	0.5	>10
C2H6	0.1	0.7	>10
H2CO	0.15	4	>10
NH3	<0.2	1.5	>10
HCN	0.08	0.5	>10
CH3CN	0.009	0.04	>10
H2S	0.13	1.5	>10
HCOOH	0.05	0.15	3
HOCH2CH2OH	0.03	0.03	1
HCOOCH3	0.08	0.08	1
CH3CHO	0.02	0.02	1
NH2CHO	0.015	0.015	1
HNCO	0.02	0.1	6
HNC	0.003	0.05	>10
HC3N	0.003	0.07	4
OCS	0.1	0.4	3
SO2	0.2	0.2	1
CS2	0.06	0.2	6
H2CS	0.05	0.05	1
NS	0.02	0.02	1
S2	0.001	0.15	5

- Tracing chemistry
  - Optical, UV – mostly dissociation fragments
  - Parent species – IR, sub-mm
  - Noble gases – far UV (λ < 1200 A)
- Primary volatiles
  - H2O – near IR (2.9 μm), Proxy CN, OH
  - CO – UV
  - CO2 – 4.26 μm (space)
- Isotopes
  - ISO, Herschel, Sub-mm, High resolution optical
  - C, N ~ 18, D/H ~ 8, O ~ 5 comets

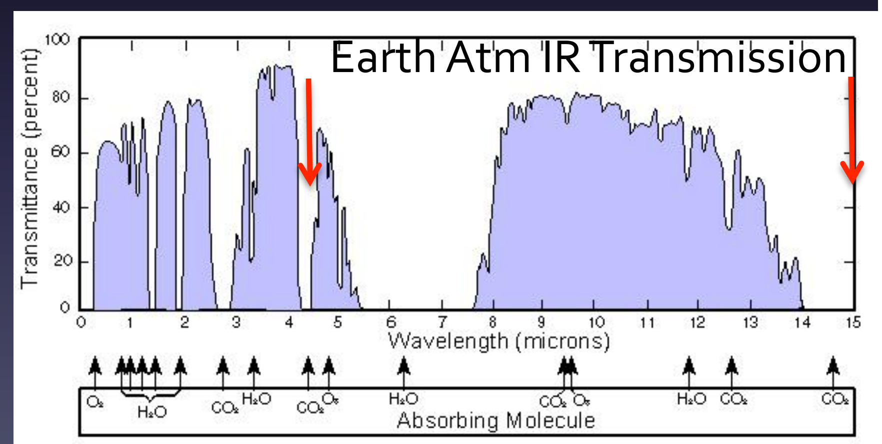
Mumma & Charnley 2011;
A'Hearn et al 1995





In-Situ Data

- Comets: pre- In situ Missions
  - Comets a mix of dust & volatiles
  - Comet taxonomies
  - Primary Volatile is H_2O (CO+ CO_2)
- In-Situ new results
  - Comets are very diverse
  - Excellent insulators
  - Comets have high & low T materials
  - CO_2 drives activity at q

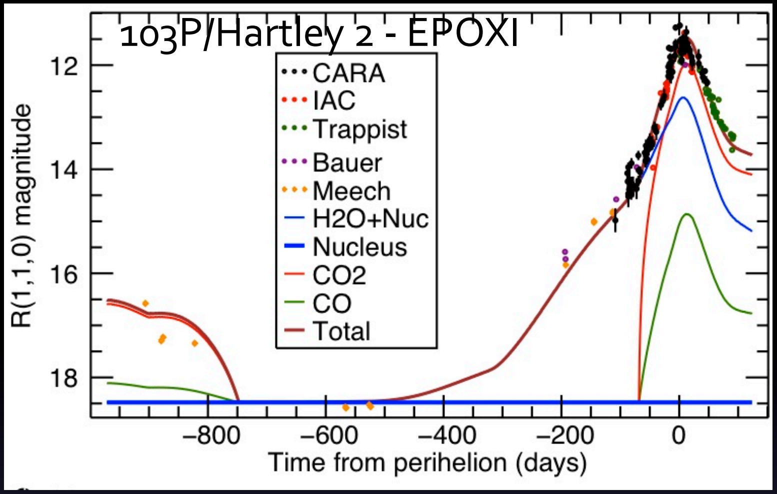


- ⊕ Atm opaque at 4.26 & 15 μm
  - Limited information on CO_2
    - Missions & space telescopes: Deep Impact, EPOXI, ISO, Akari, Spitzer, WISE
    - Forbidden CO emission during photo-dissociative excitation of CO

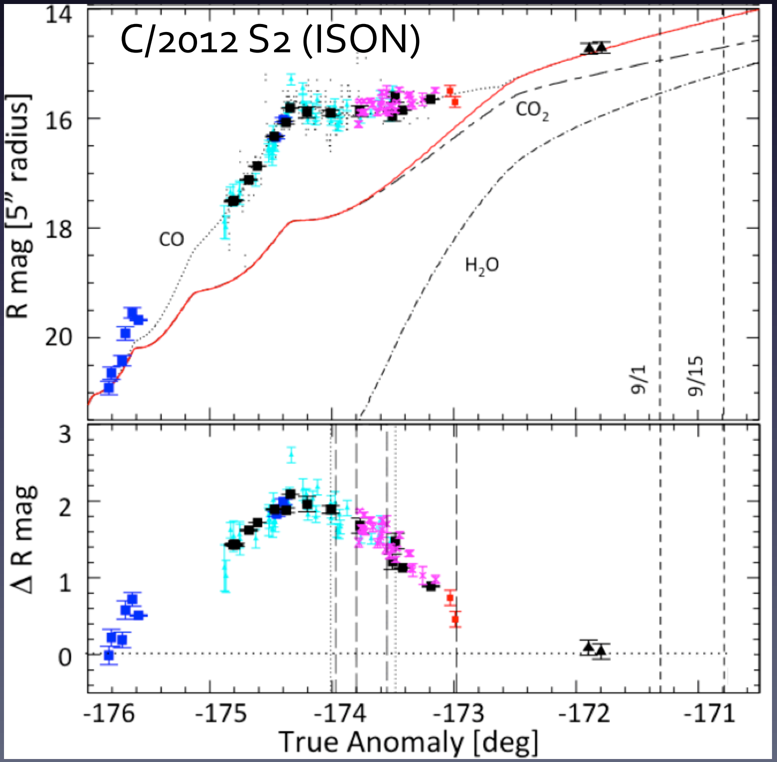
Heliocentric Light Curve & Models

Incident E		Thermal		Sublimation		Conduction

$$F_{\odot}(1-A) / r^2 = \beta\, [\varepsilon\, \sigma\, T^4 + L(T)\, dm_s/dt + \kappa(z,T)\, \partial T/\partial Z]$$

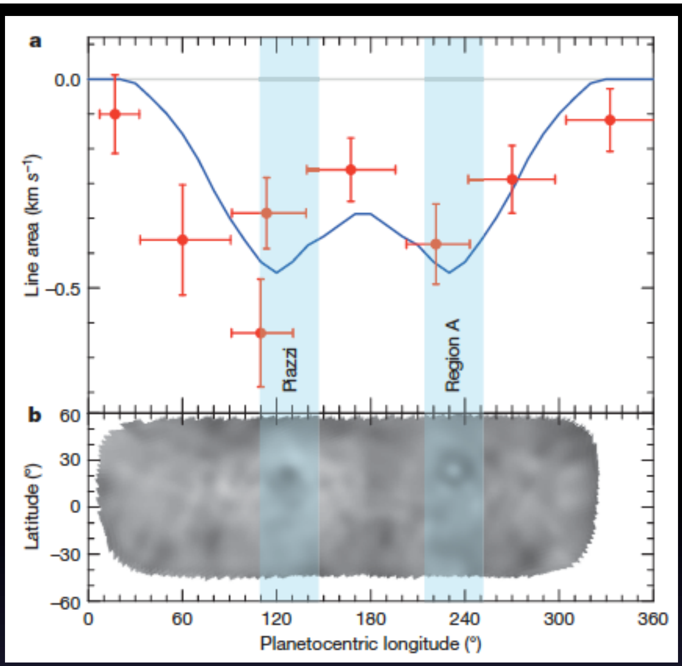


- Surface sublimation models
  - Energy balance at nucleus surface
  - Ices sublimate, drags dust → larger surface
  - Compare measured & computed brightness
- EPOXI & Hartley 2
  - Activity at q driven by CO2 outgassing
  - Light curve provides information about CO2
- C/2012 S1 ISON
  - Matches Spitzer CO+CO2, ground H2O
  - Activity at large r CO2 + CO outburst

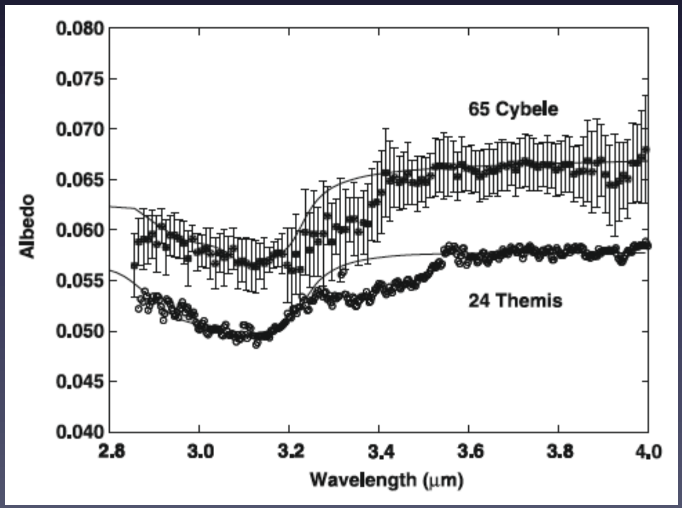


Top: Meech, et al (2011); Bottom: Meech et al (2013)

A Wet outer belt



Kuppers *et al.* (2014)

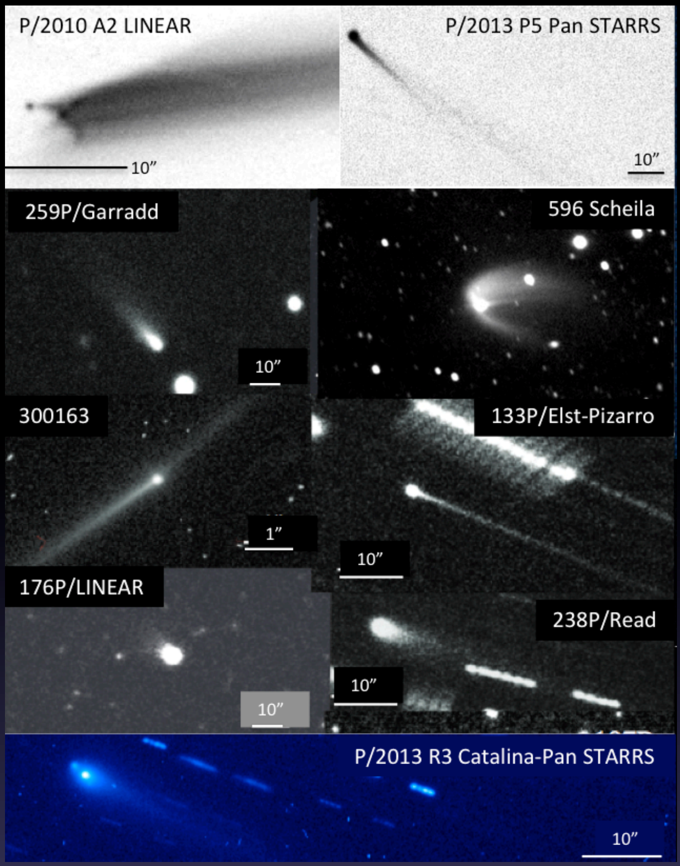


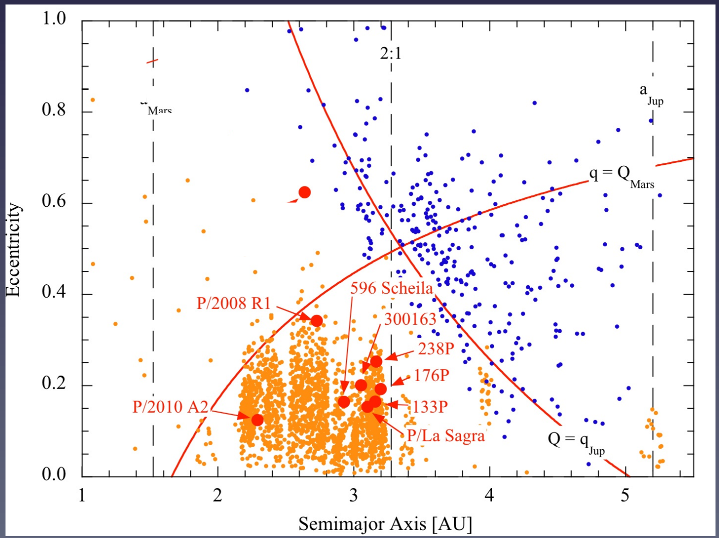
Rivkin & Emery (2008)
Campins *et al.* (2009)
Licandro *et al* (2011)

- Water outgassing observed on Ceres
  - Herschel search for H_2O from 11/11-3/13
  - Outgassing correlated with dark areas
  - Activity correlated with perihelion
- Surface ice & organics
  - Detected on 24 Themis, & 65 Cybele
- Discovery of a new class of 'wet' objects
  - Main belt comets

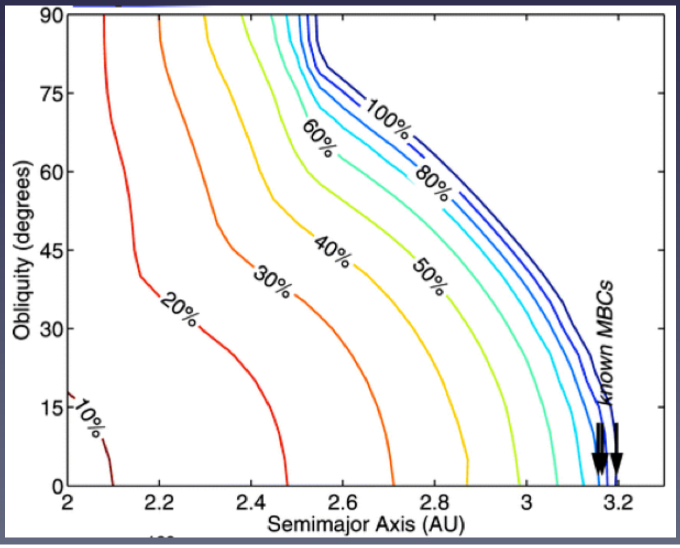
"Main Belt Comets"

- First Discovered in 1996 (Elst-Pizarro)
  - 12 now known
- Characteristics
  - Dynamicaly asteroidal, appear cometary
  - Amount of dust is small
- Several are collisional family members
  - Themis family ~ 2 Gyr
  - Beagle – sub-family of Themis (~10 Myr)





Jewitt, 2012

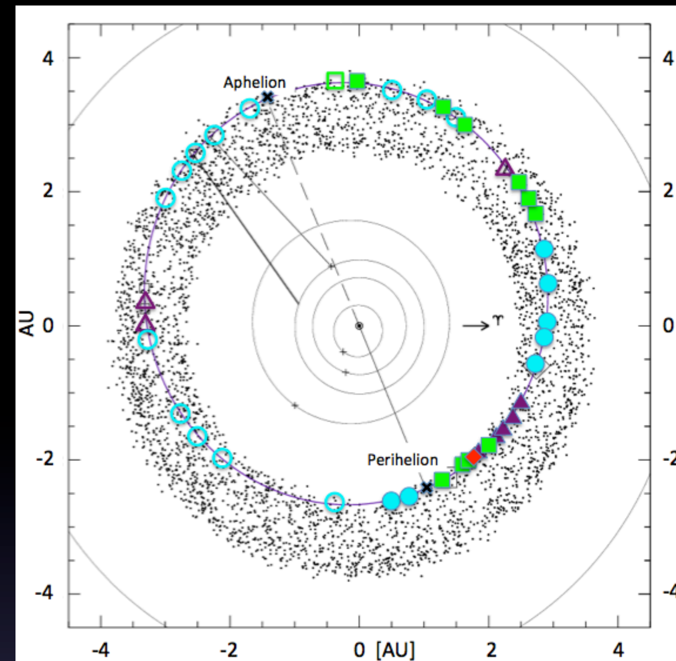


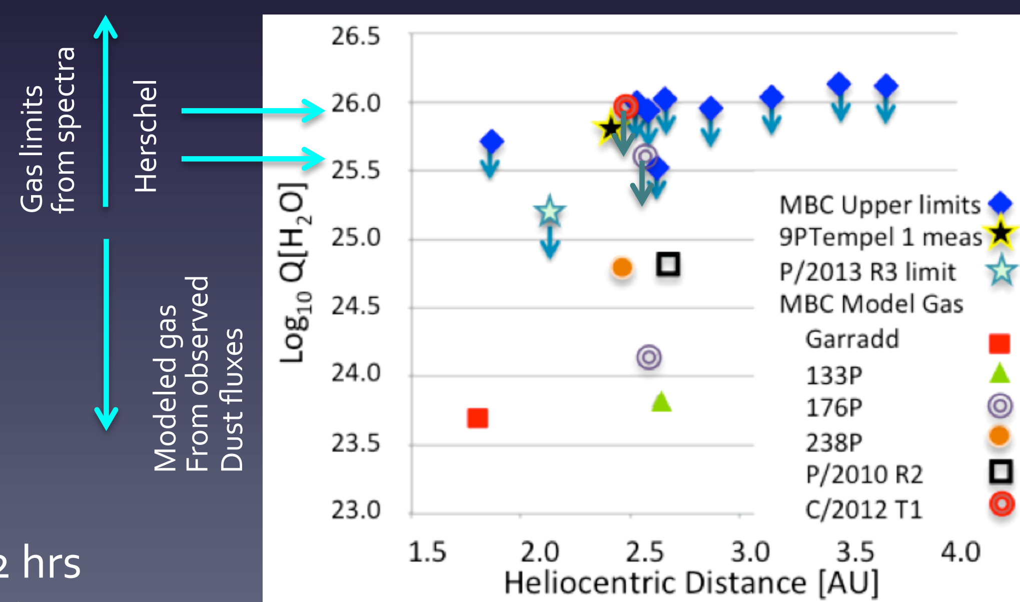
Schorghofer, 2008

"Main Belt Comets"

- Mechanisms
  - Collision (3 likely)
  - Spin up
  - Volatile outgassing – H2O not stable on surface
- Repeat activity
  - 2 have been seen active more than 1x
- No gas detected
  - Below limits of detection

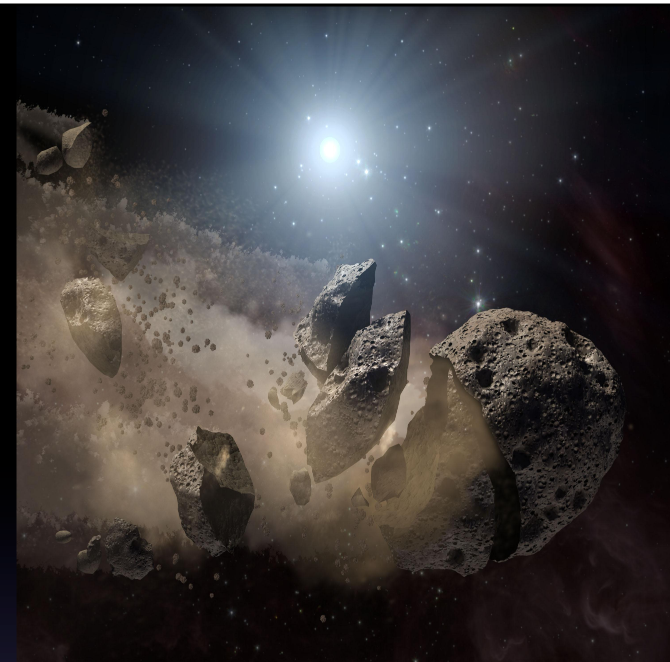
Filled	active
Purple	1996-2001
Blue	2001-2007
Green	2007-2009
Red	2013



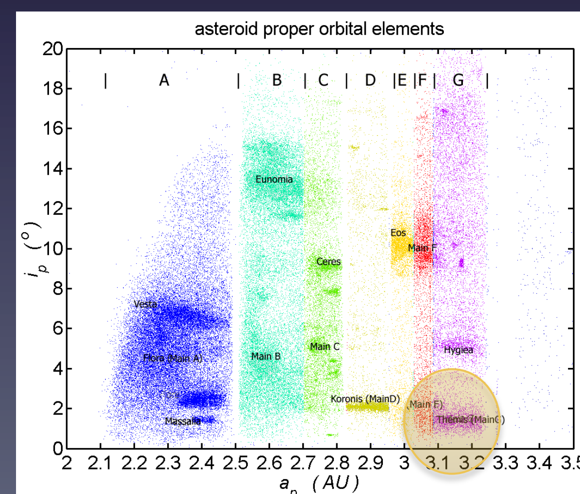


☆ Keck spectrum, 2 hrs
Meech et al (2011)

Themis Family

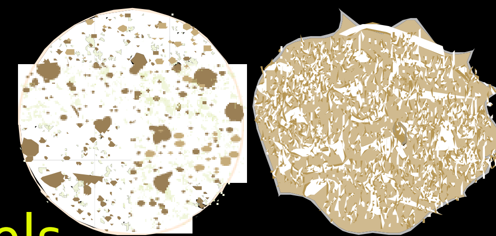


- Family Characteristics
  - > 580 members
  - Mainly C type, but also B & D-type (primitive)
  - Largest fragment, 24 Themis (198 km, $\rho=2.8\pm1.4$ g/cm^3)
  - Disruption 2 Gyr ago
- Parent Body
  - 380-450 km diameter
  - Water-rich protoplanet
  - Formation *t* dictates thermal evolution



Castillo-Rogez & Schmidt, (2010)

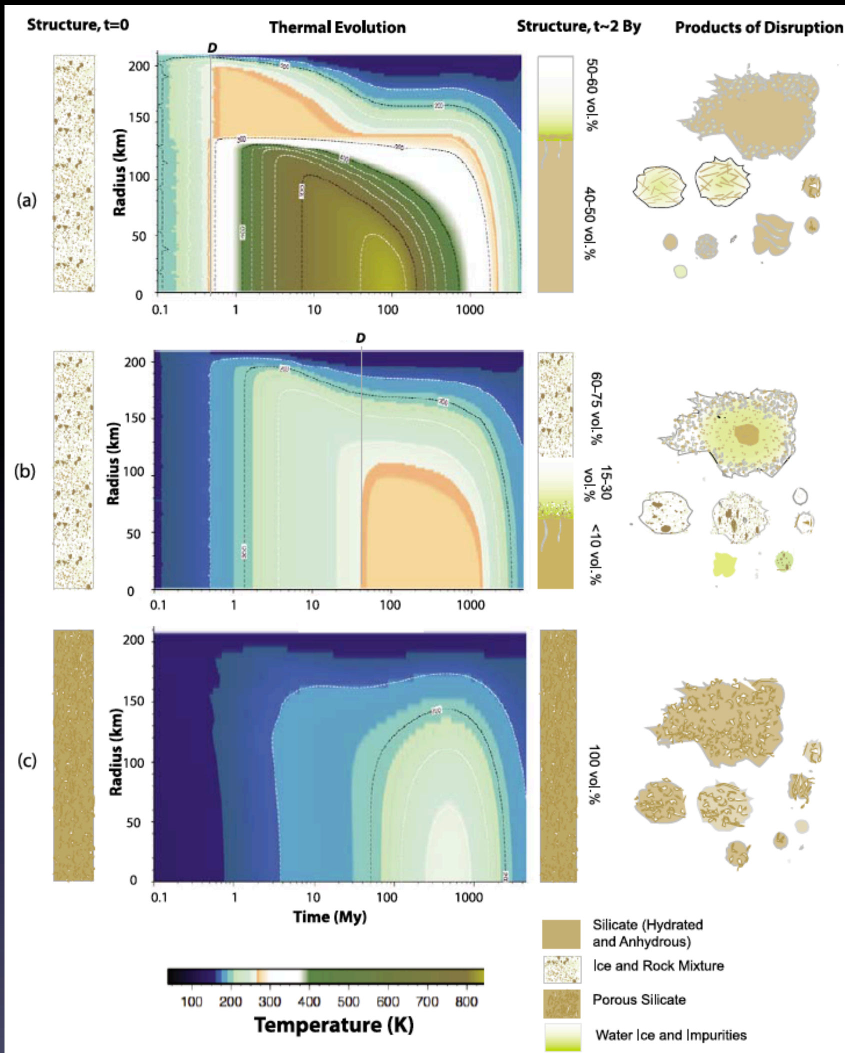
Primitive? Evolved?



- Thermal models
  - 2 cases – (1) mix of ice and silicates, or (2) hydrated silicates
  - internal heating (radioisotopes)
- Model results
  a) Melting & differentiation
     - Core: hydrated silicates
     - Shell ice has organics

  b) Partial differentiation (40% of vol.)

  c) Little geophysical evolution



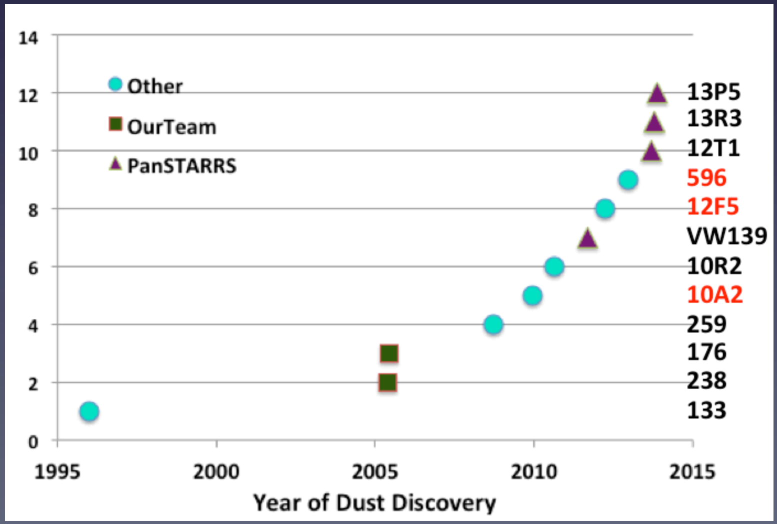
[a,b] Mix of ice and rock, ρ=2.0 g/cm^3;
[c] hydrated silicates ρ=2.7 g/cm^3.
Formation [a] 3 Myr [b,c] 5 Myr after CAIs).

Castillo-Rogez & Schmidt, (2010)

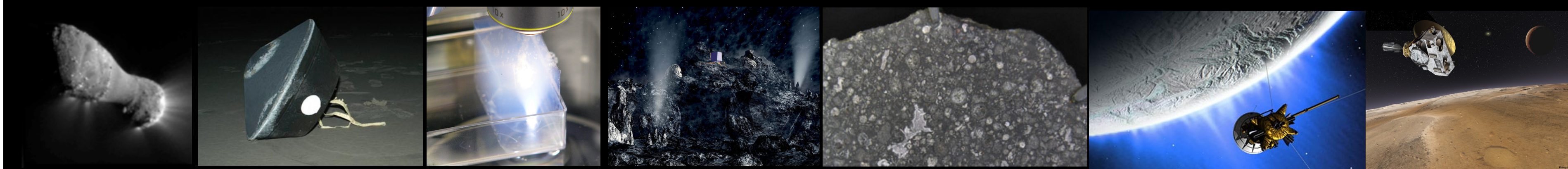
Themis likely accreted later, and family preserves primitive volatile material

MBC Accelerating Discoveries

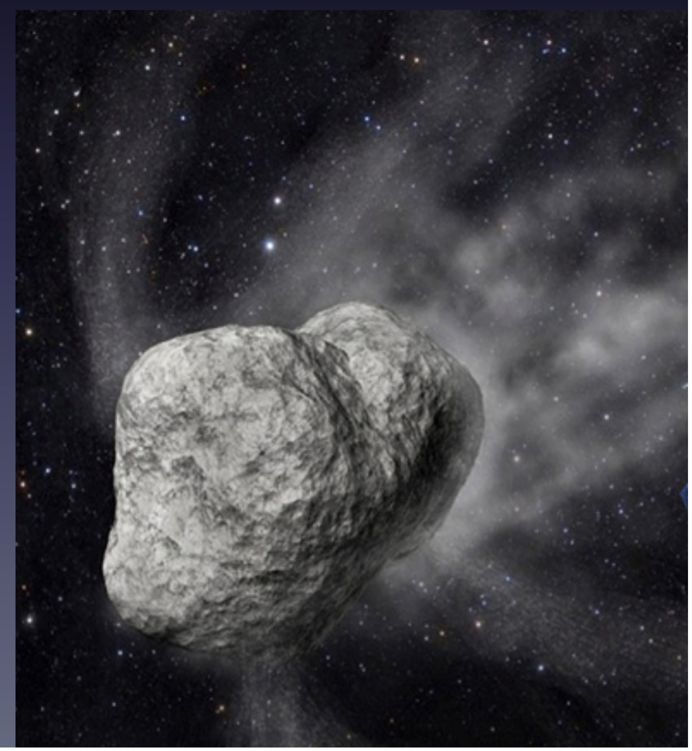
- Pan STARRS
  - Operations began in 2008
  - From mid 2010 PS1 dedicated 5% to solar system observations
  - 11/2012 this increases to 11%
  - 4/1/14 100% ecliptic NEO survey
  - PS2 online by end of year
  - March 2015 90% of PS1&PS2 for SS
- Survey Impacts
  - PS now is main discoverer of MBCs
  - New reprocessing of data



MBCs – An Unsampled Volatile Reservoir

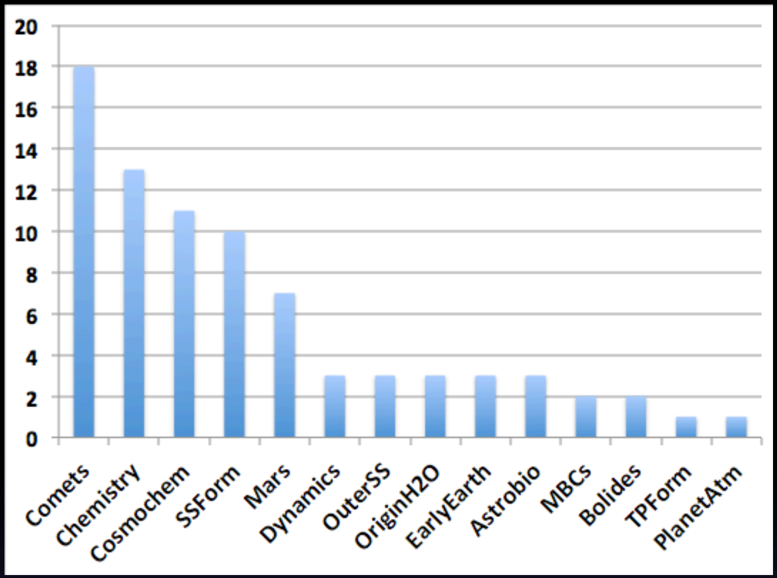


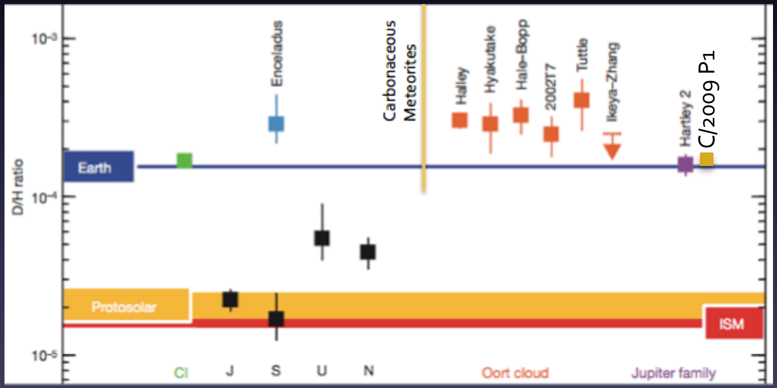
- We have detailed information from
  - JF comets (EPOXI, Stardust,… Rosetta)
  - Inner asteroid belt / NEOs (meteorites)
  - Icy outer moons (Cassini)
  - Kuiper belt (New Horizons)
- Sample a new H_2O reservoir: MBCs
  - Measurement of isotopic fingerprints
  - Testing dynamical models
  - Testing disk chemistry models



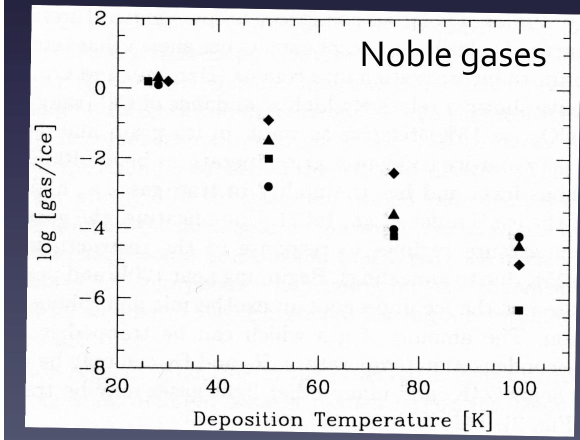
Isotope Fingerprints

- A single isotope changes everything. . . .
  - Herschel measures D/H in Jupiter Family comet 103P/Hartley 2
  - Hartogh (2011) *Nature* heavily cited by many communities
  - A rush to change models





Hartogh et al. (2011)

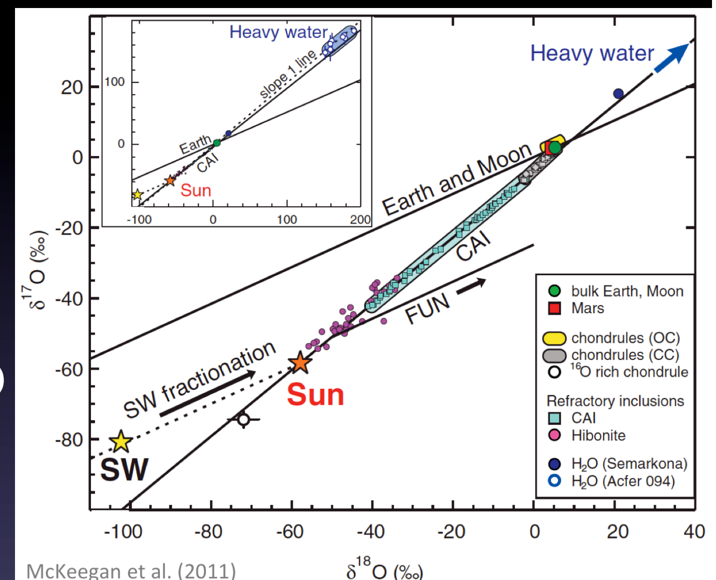


After Owen & Bar Nun

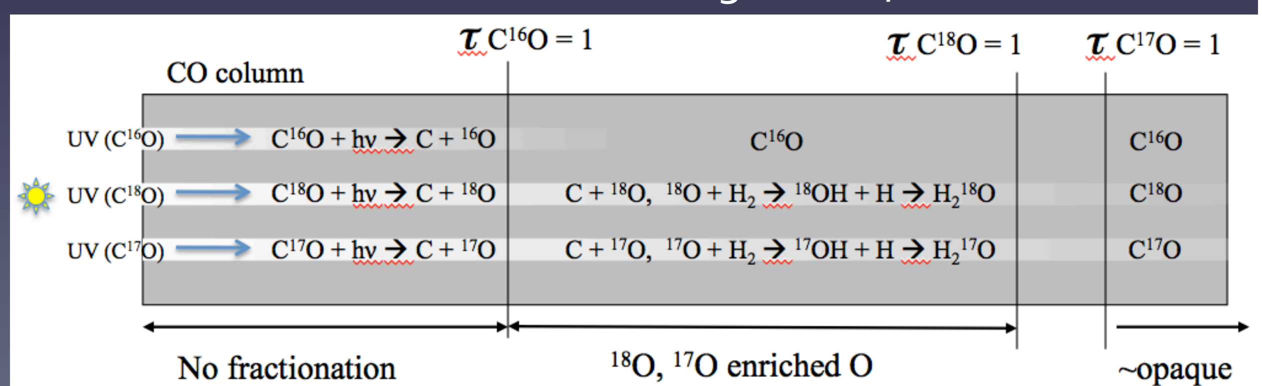
- Noble gases
  - An ice condensation thermometer

Isotopic Fingerprints

- CO self shielding Models (Lyons *et al* 2005)
  - Sun & CCs have slope 1 – mixing of ^{16}O-poor and ^{16}O-rich reservoirs
  - CO isotopologues dissociate at different UV λ
  - O then combines with nebular H2 to make H2O
  - When $C^{16}O$ becomes optically thick, nebula makes ^{17}O- and ^{18}O-rich H2O
- Nitrogen isotopes
  - Inherit from ISM
  - N2 self shielding



McKeegan et al, 2011



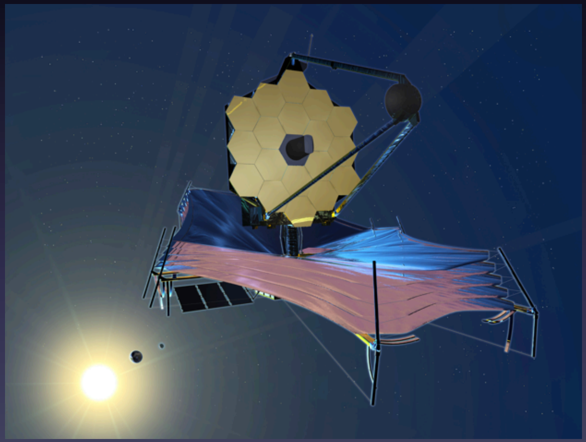
E. Young, J. Lyons

TMT, JCMT, ALMA as Game Changers

- Parent volatiles & isotopes
  - ~1-2 comets/yr bright enough
  - CO_2 needs space observations
  - Can't presently do MBCs w/o in-situ visit

A Comprehensive combined approach

- TMT
  - 1st light instruments
    - Q_{H_2O} many comets → modeling
    - First direct measure of H_2O in asteroid belt
  - Next generation
    - Isotopes (optical spectra R~ 60,000)
    - Near IR parent volatiles (CO), D/H (R~20,000)
- JWST
  - CO, CO_2 direct observations in comets
  - Snowlines
- ALMA – Mapping CO in disks

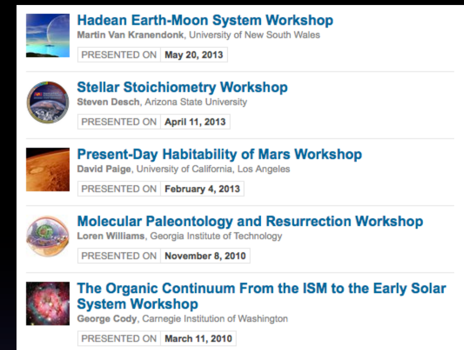


A paradigm shift is underway – there may be water everywhere in the outer belt, and this may profoundly change our understanding of the formation and location of habitable worlds. . . .

The key is mapping distribution of volatiles & isotopes in small bodies & disks

Understanding how habitable worlds form in our SS has implication for habitability in extra solar planetary systems

Workshops Without Walls

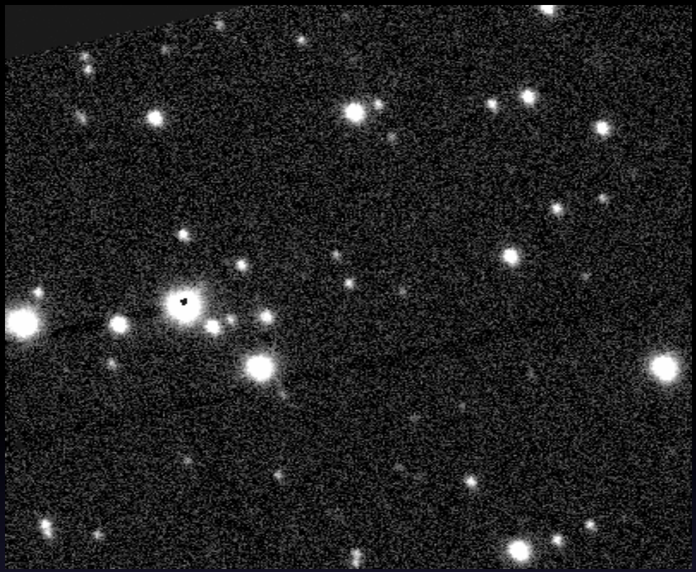


WWW #2 – 11/8/2010: 560 participants, 31 states, 30 countries

- A means to foster development of
  - Key Programs & Partner collaborations
- What are WWWs – Science meetings without cost
  - NASA Astrobiology Institute development
  - Videoconferencing + online meeting software (talks are archived)
  - Allows for screen sharing / user control of talk
  - Multiple Chat rooms (breakouts / coffee break)

https://astrobiology.nasa.gov/seminars/featured-seminar-channels/workshops-without-walls/

A Key Reminder . . .



- Solar system objects *move!!!*

Courtesy L. Dennau

- Build planetary capabilities in from the start
  - Non-sidereal guiding
  - AO that can handle moving objects
  - Smooth interfaces to national databases of orbital elements for ephemeris computation