From Kuiper Belt to Comet

David Jewitt, UCLA

KISS Comet Workshop - 2017 June 5

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Instructions:

1) "…the short course is designed to provide a foundation for everyone to understand your field. Please limit your material to your discipline's "101" level…"

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Instructions:

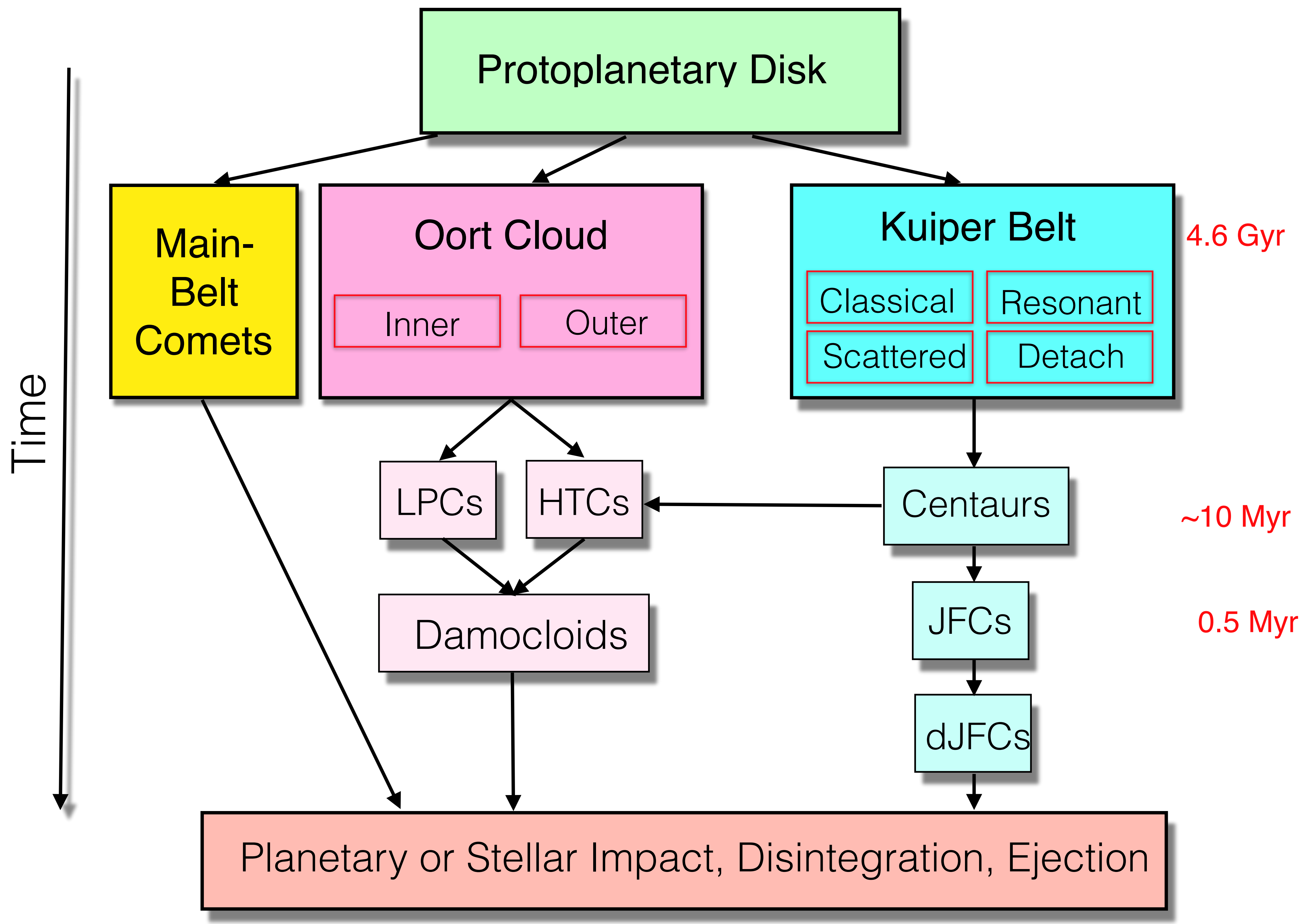
1) "…the short course is designed to provide a foundation for everyone to understand your field. Please limit your material to your discipline's "101" level…"

2) "…please wear solid colors (navy blues, grays, purples, dark creams and browns look good on camera)".

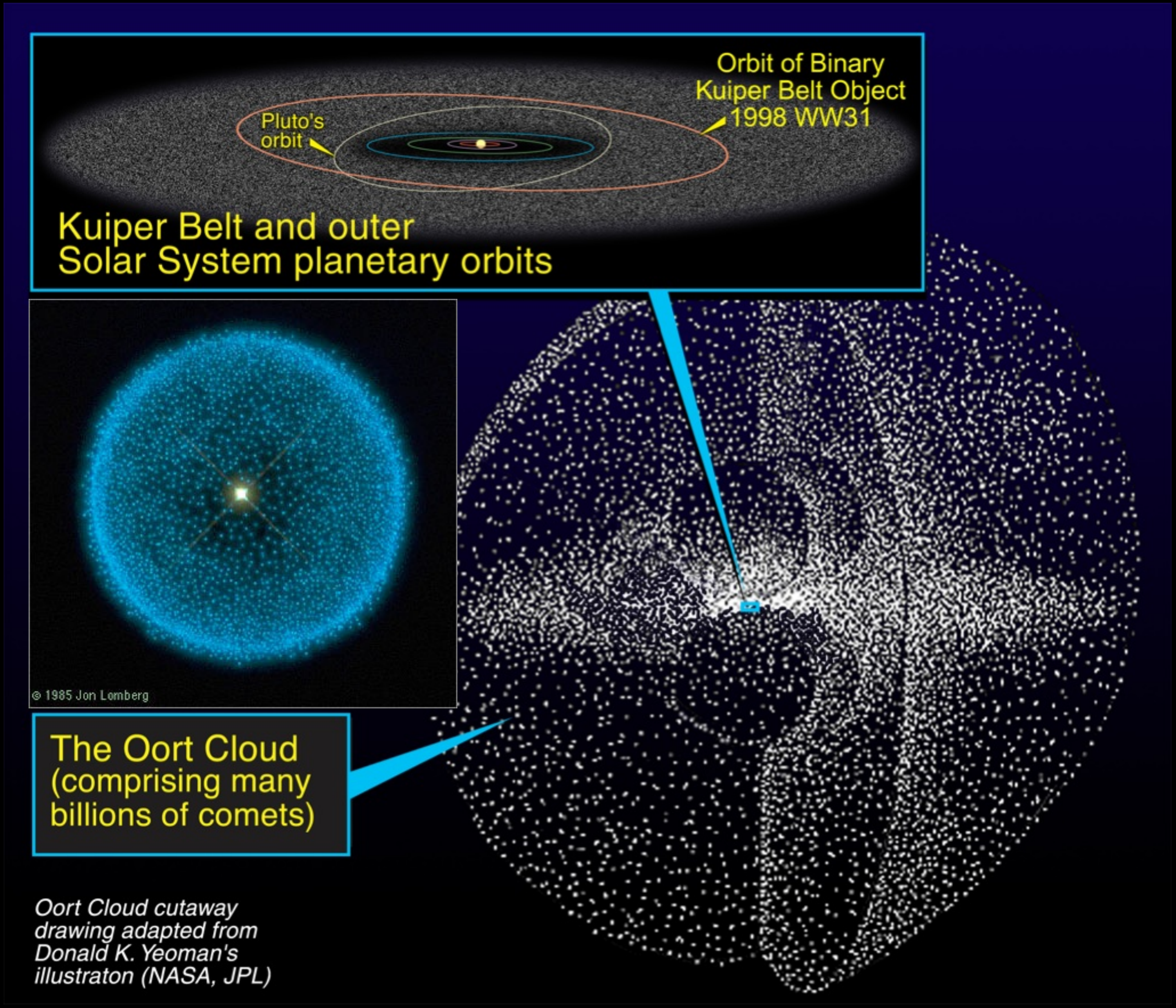
Background

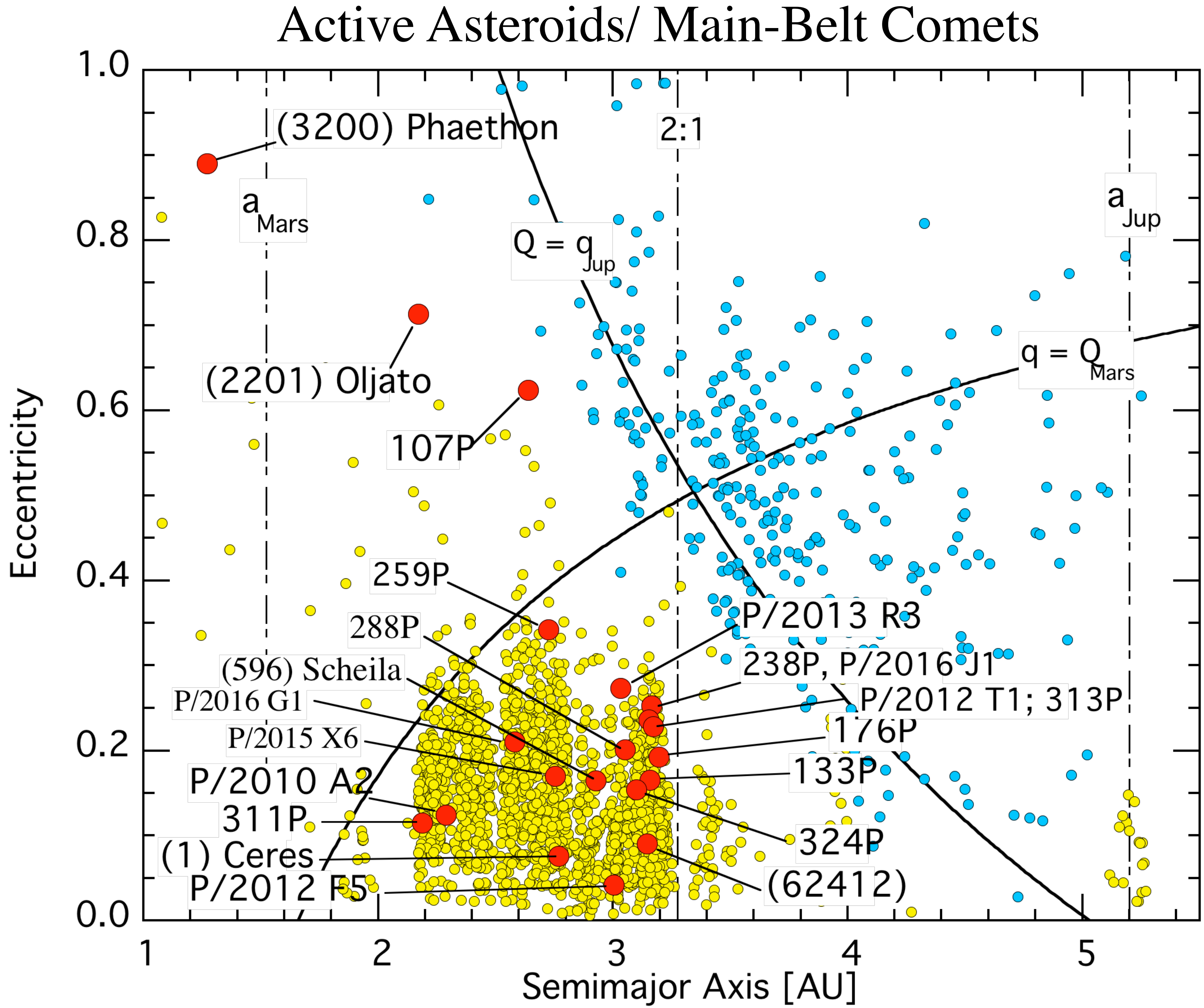
Three sources of comets:

- Kuiper Belt
- Oort Cloud
- Main Belt



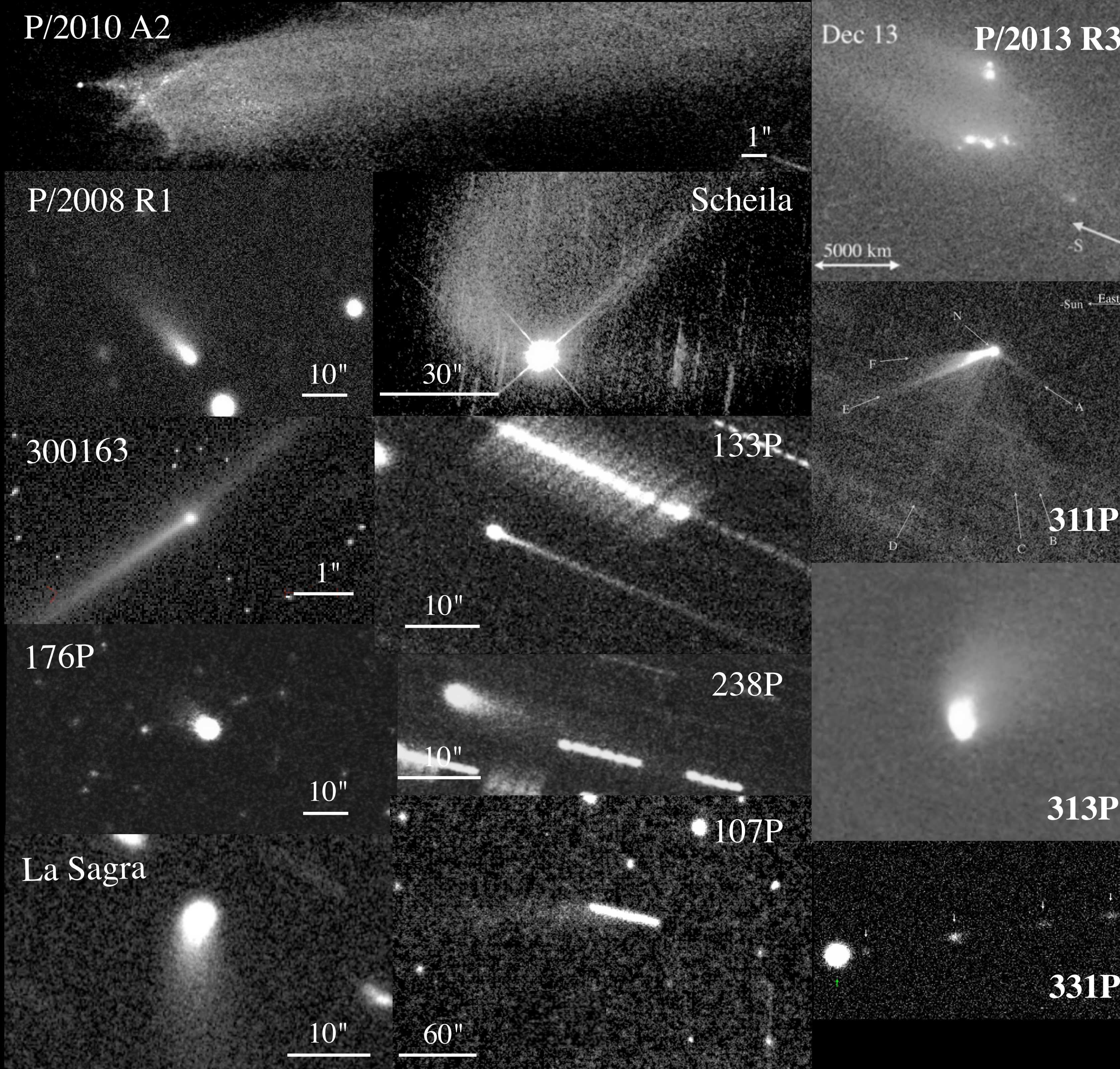
Protoplanetary Disk
Main-Belt Comets
Oort Cloud
Inner
Outer
Kuiper Belt
Classical
Resonant
Scattered
Detach
4.6 Gyr
Time
LPCs
HTCs
Centaurs
~10 Myr
Damocloids
JFCs
0.5 Myr
dJFCs
Planetary or Stellar Impact, Disintegration, Ejection


Orbit of Binary
Kuiper Belt Object
1998 WW31
Pluto's
orbit
Kuiper Belt and outer
Solar System planetary orbits
© 1985 Jon Lomberg
The Oort Cloud
(comprising many
billions of comets)
Oort Cloud cutaway
drawing adapted from
Donald K. Yeoman's
illustraton (NASA, JPL)

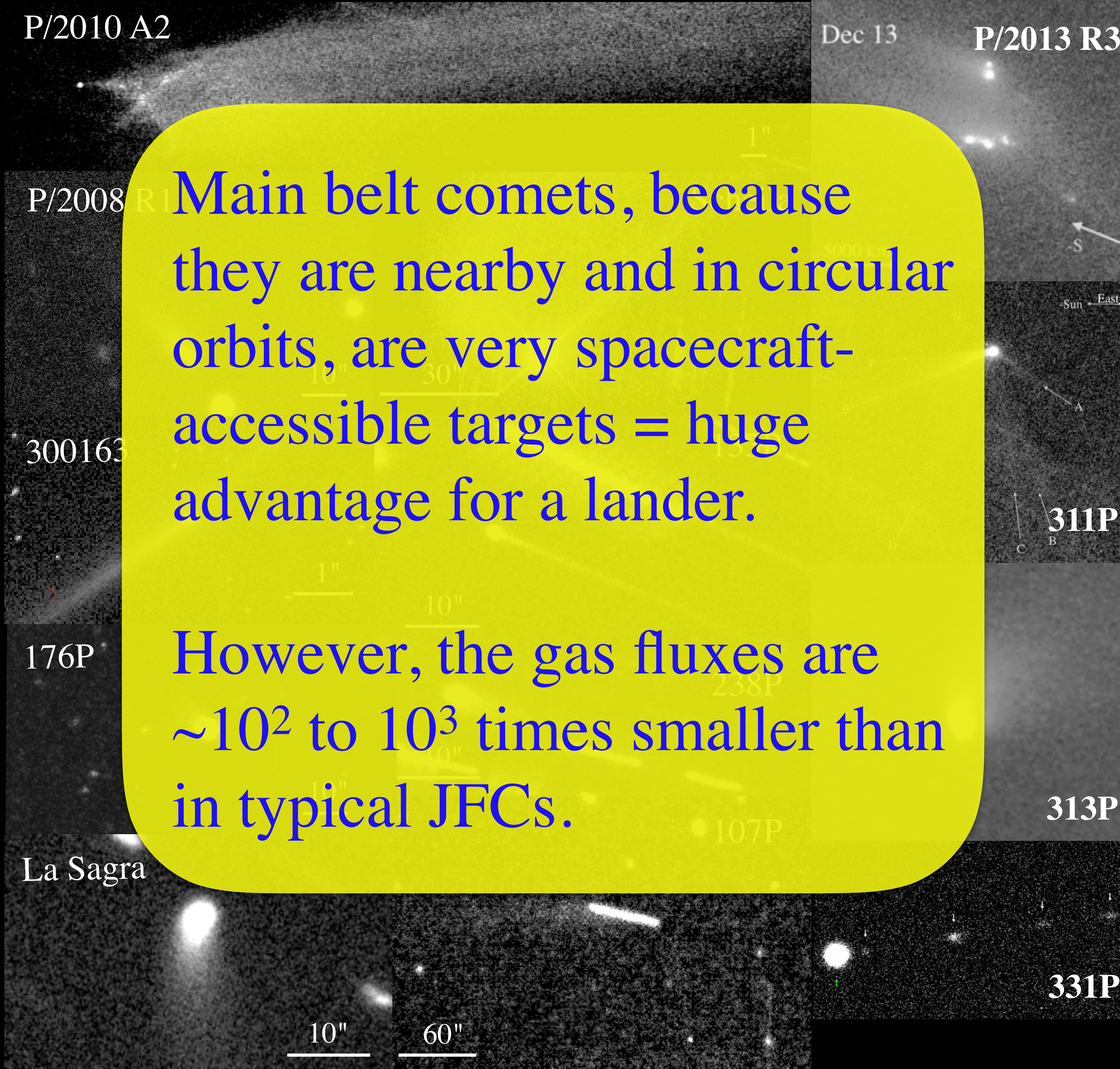


Active Asteroids/ Main-Belt Comets
Eccentricity
Semimajor Axis [AU]
1.0
0.8
0.6
0.4
0.2
0.0
1
2
3
4
5
(3200) Phaethon
a Mars
Q = q Jup
2:1
a Jup
(2201) Oljato
107P
q = Q Mars
259P
288P
(596) Scheila
P/2016 G1
P/2015 X6
P/2010 A2
311P
(1) Ceres
P/2012 F5
P/2013 R3
238P, P/2016 J1
P/2012 T1; 313P
176P
133P
324P
(62412)

Resolved Objects Only

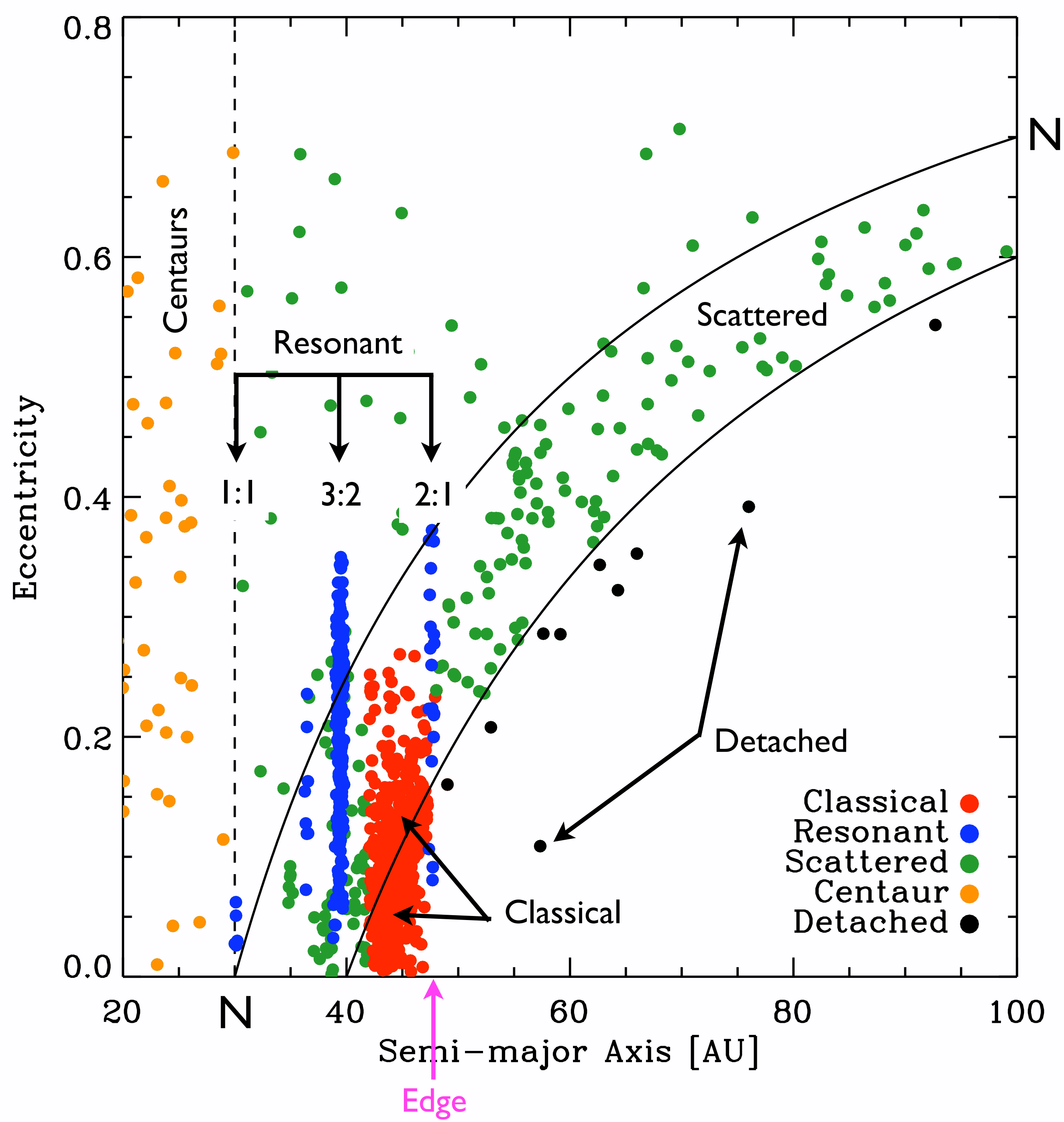


Resolved Objects Only



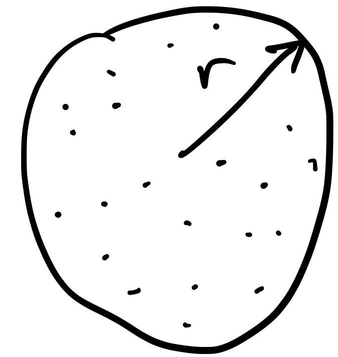
Main belt comets, because they are nearby and in circular orbits, are very spacecraft-accessible targets = huge advantage for a lander.

However, the gas fluxes are ~10^2 to 10^3 times smaller than in typical JFCs.



0.8
0.6
0.4
0.2
0.0
Eccentricity
20
N
40
60
80
100
Semi-major Axis [AU]
Edge
Centaurs
Resonant
1:1
3:2
2:1
Scattered
N
Detached
Classical
Classical
Resonant
Scattered
Centaur
Detached

Thermal Diffusivity



Heat Content $\quad H = m c_p T = \frac{4\pi}{3} \rho r^3 c_p T \qquad J$

Loss Rate $\quad \frac{dH}{dt} = 4\pi r^2 k \frac{dT}{dr} \simeq 4\pi r^2 k \left(\frac{T}{r}\right)$

Conduction Time $\quad \tau_c \sim \frac{H}{\dot{H}} \sim \frac{\rho r^3 c_p T}{r^2 k (T/r)} \sim \left(\frac{\rho c_p}{k}\right) r^2$

or $\quad \boxed{\tau_c = \frac{r^2}{\kappa}}$

where $\quad \kappa \equiv \frac{k}{\rho c_p} \quad$ = Thermal Diffusivity

$$[\kappa] = m^2 s^{-1}$$

eg: dielectric solids

$$K \sim \frac{1\ W m^{-1} K^{-1}}{10^{3}\ kg m^{-3} \cdot 10^{3}\ J kg^{-1} K^{-1}} \sim 10^{-6}\ m^{2} s^{-1}$$

eg: dielectric powders $K \sim 10^{-8}\ m^{2} s^{-1}$

eg: largest body that can cool in age of solar system is

$$r \sim \sqrt{K t_{ss}} \sim \left(10^{-8} \cdot 4.5 \times 10^{9} \times 3 \times 10^{7}\right)^{1/2} \sim 30\,km$$

→ Most comets have lost primordial heat

eg: Conduction time for 1 km comet

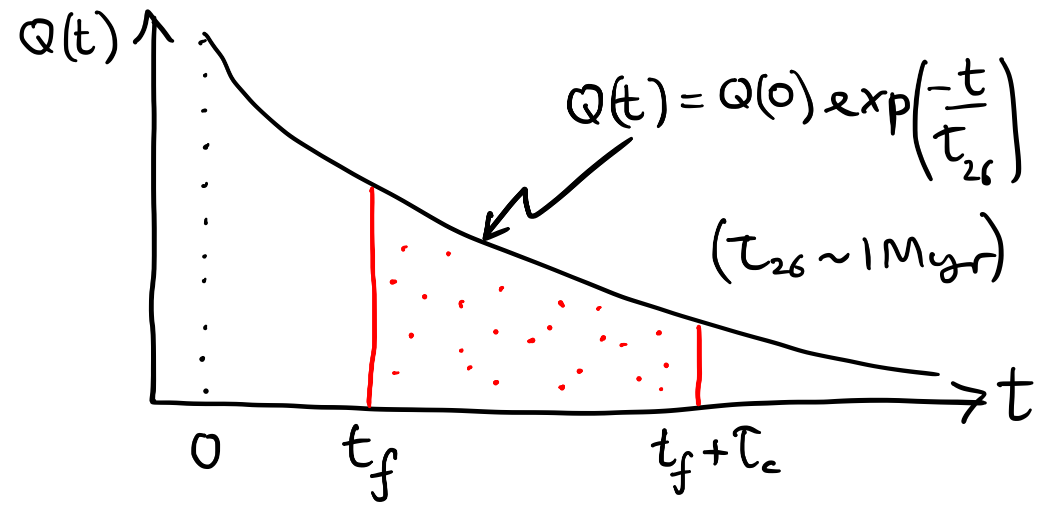
$$\tau_c \sim \frac{10^{6}}{10^{-8}} \sim 10^{14}\,s \sim 10\,Myr$$

Al^{26} Heating

Heat trapped between

t_f (time of formation)

& $t_f + \tau_c$



$$H = \int_{t_f}^{t_f+\tau_c} Q(t)\,dt = \int_{t_f}^{t_f+\tau_c} Q(0)\exp\left(-\frac{t}{\tau_{26}}\right)dt$$

$$= Q(0)\,\tau_{26}\left[\exp\left(\frac{-t_f}{\tau_{26}}\right) - \exp\left[-\left(\frac{t_f+\tau_c}{\tau_{26}}\right)\right]\right]$$

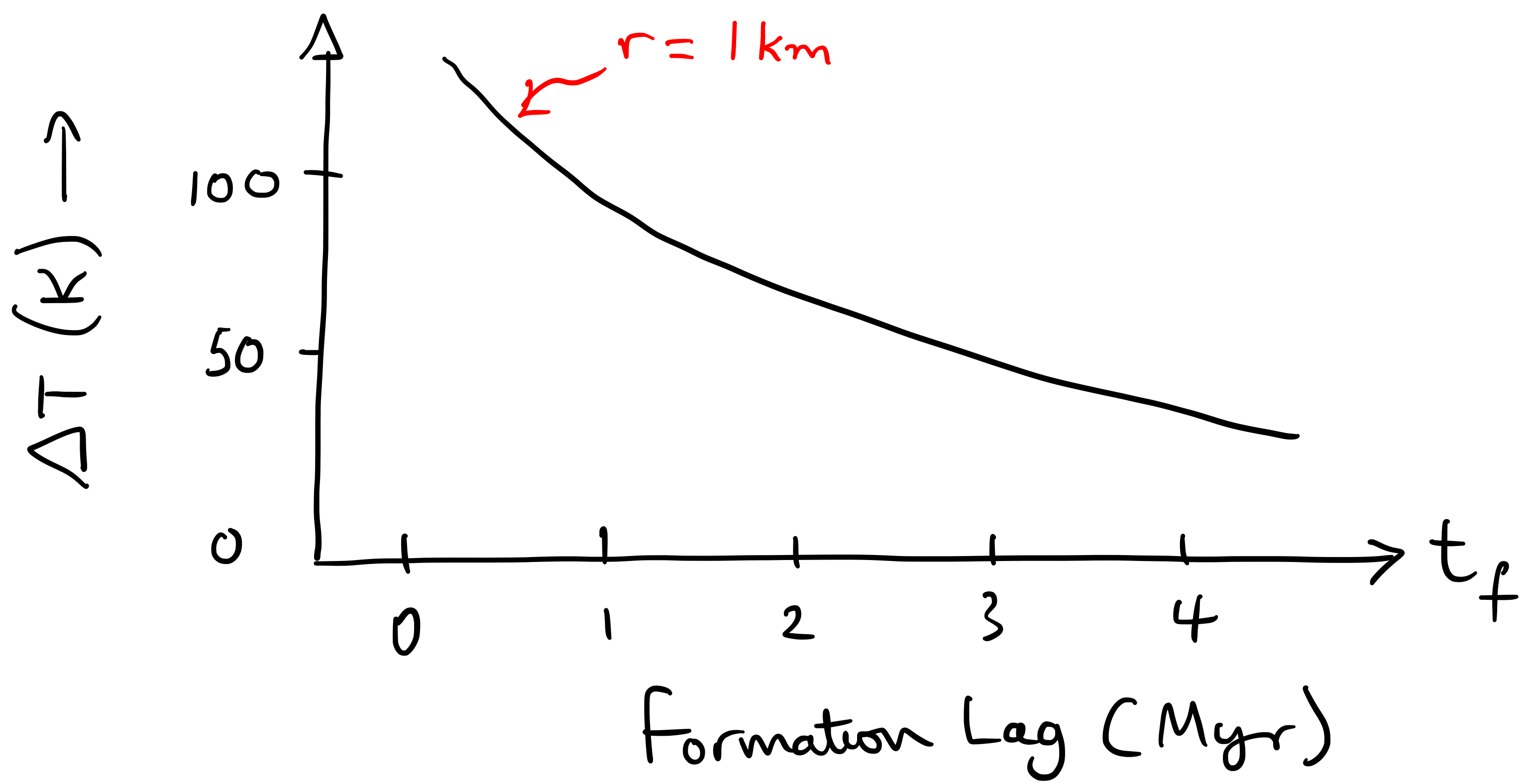
also $\quad H = m\,c_p\,\Delta T$

so $$\Delta T = \frac{3\,Q(0)\,\tau_{26}}{4\pi\rho\,r^3\,c_p}\left[\exp\left(\frac{-t_f}{\tau_{26}}\right) - \exp\left[-\frac{(t_f + r^2/\kappa)}{\tau_{26}}\right]\right]$$

Measurements suggest $\Delta T \lesssim 30$ or $40\,K$ for $r \sim 1\,km$)

so $\Delta T = \Delta T(r, t_f)$ constrains t_f

Absence of strong heating suggests delayed formation



Models in which KBOs form quickly and/or large (eg: "Asteroids are Born Big" by Morbidelli (2009)) must struggle to avoid large ΔT due to Al^{26}.

Rapid formation models (eg: streaming or other instabilities) ignore the volatile nature of comets

Slow accumulation is much more likely, where "slow" means $t_f \gg \tau_{26}$

Dynamical Transport Time from KB $\rightarrow$ JFC

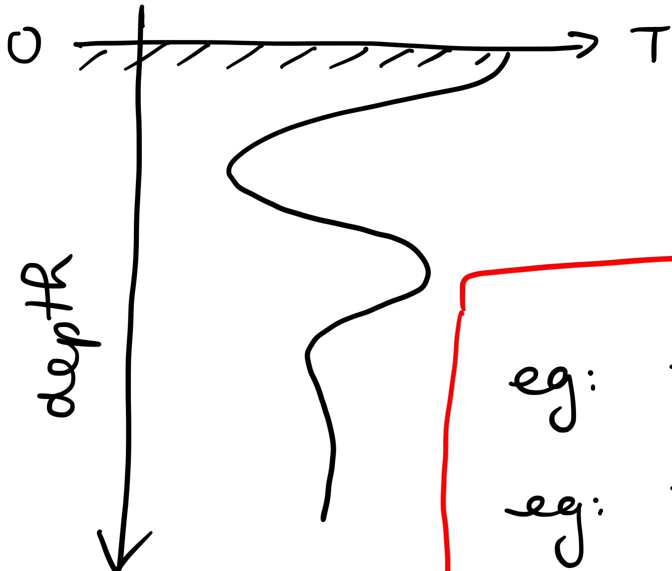
$\tau_d \sim 10\,\text{Myr}$

$\tau_c(1\,\text{km}) \sim \tau_d$ $\rightarrow$ Nucleus is always out of thermal equilibrium

Dynamical Lifetime of JFCs $\tau_{JFC} \sim 0.5\,\text{Myr}$

$\tau_c(1\,\text{km}) \gg \tau_{JFC}$ $\rightarrow$ JFCs strongly out of thermal equilibrium

Actual solution to conduction equation with a cyclic (day/night) illumination is a damped sine wave



} Wavelength $l \sim \sqrt{\kappa t}$, period

eg: $t = 10^{hr}$ (rotation) $l \sim 2$ cm (diurnal)

eg: $t = 10^{yr}$ (orbit) $l \sim 1.7$ m (annual)

eg: $t = 0.5$ Myr (JFC life) $l \sim 400$ m (life)

Depending on the specific (unknowable, because of chaos) orbital history, it is entirely possible to find Kuiper belt temperatures (40K) in hot JFC nuclei $\gtrsim 1$ km

Sublimation Energy Balance

$$\frac{F_\odot}{r_H^2}(1-A)\cos\theta = \chi\left[\varepsilon\sigma T^4 + \dot{m}L(T)\right]$$

- $F_\odot$: solar constant
- r_H: distance from $\odot$
- A: albedo
- θ: slope
- χ: geometric term $(1 \le \chi \le 4)$
- $\varepsilon\sigma T^4$: radiation term
- $\dot{m}L(T)$: sublimation term
- $L(T)$: latent heat ($J\,kg^{-1}$) sublimation

For $r_H \lesssim 1$ AU; sublimation dominates, then

$$\dot{m} \sim \frac{F_\odot(1-A)\cos\theta}{\chi L(T)\, r_H^2}$$

@ $r_H = 1$ AU

$$\sim \frac{1360\,(1-0)\,1}{1 \times 2\times10^6 \times 1^2} \sim 5\times10^{-4}\ kg\,m^{-2}s^{-1}$$

Surface Recession Rate

$$\frac{dr}{dt} \sim \frac{\dot{m}}{\rho}\ \frac{(kg\,m^{-2}s^{-1})}{(kg\,m^{-3})} \sim \frac{5\times10^{-4}}{5\times10^{2}} \sim 10^{-6}\ m\,s^{-1}$$

[c.f. my daughter $dl/dt \sim 10^{-8}\,m\,s^{-1}$

a tree $dl/dt \sim 10^{-8}\,m\,s^{-1}$]

Timescale to free-sublimate nucleus

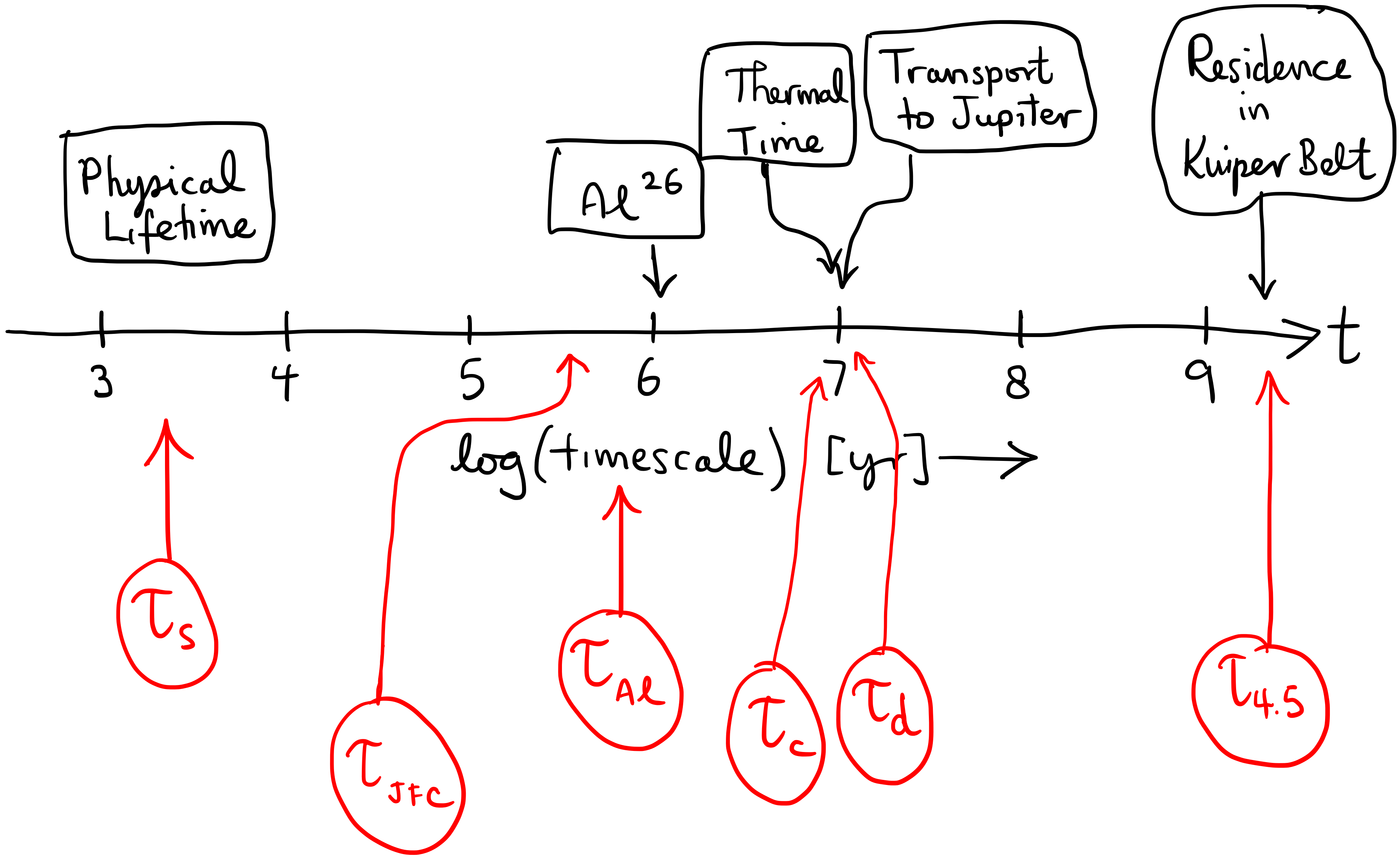
$$\tau_s \sim \frac{r}{dr/dt} \sim \frac{10^3\,m}{10^{-6}\,m\,s^{-1}} \sim 10^9\,s \quad (30\,yr)$$

Actual time is longer because a) $r_H > 1\,AU$ $(e > 0)$

b) mantle forms

Still, physical lifetime is smaller than dynamical lifetime:

$$\boxed{\tau_s \ll \tau_{JFC}}$$


Physical Lifetime
Al 26
Thermal Time
Transport to Jupiter
Residence in Kuiper Belt
t
3
4
5
6
7
8
9
log(timescale) [yr]
τs
τJFC
τAl
τc
τd
τ4.5

Questions

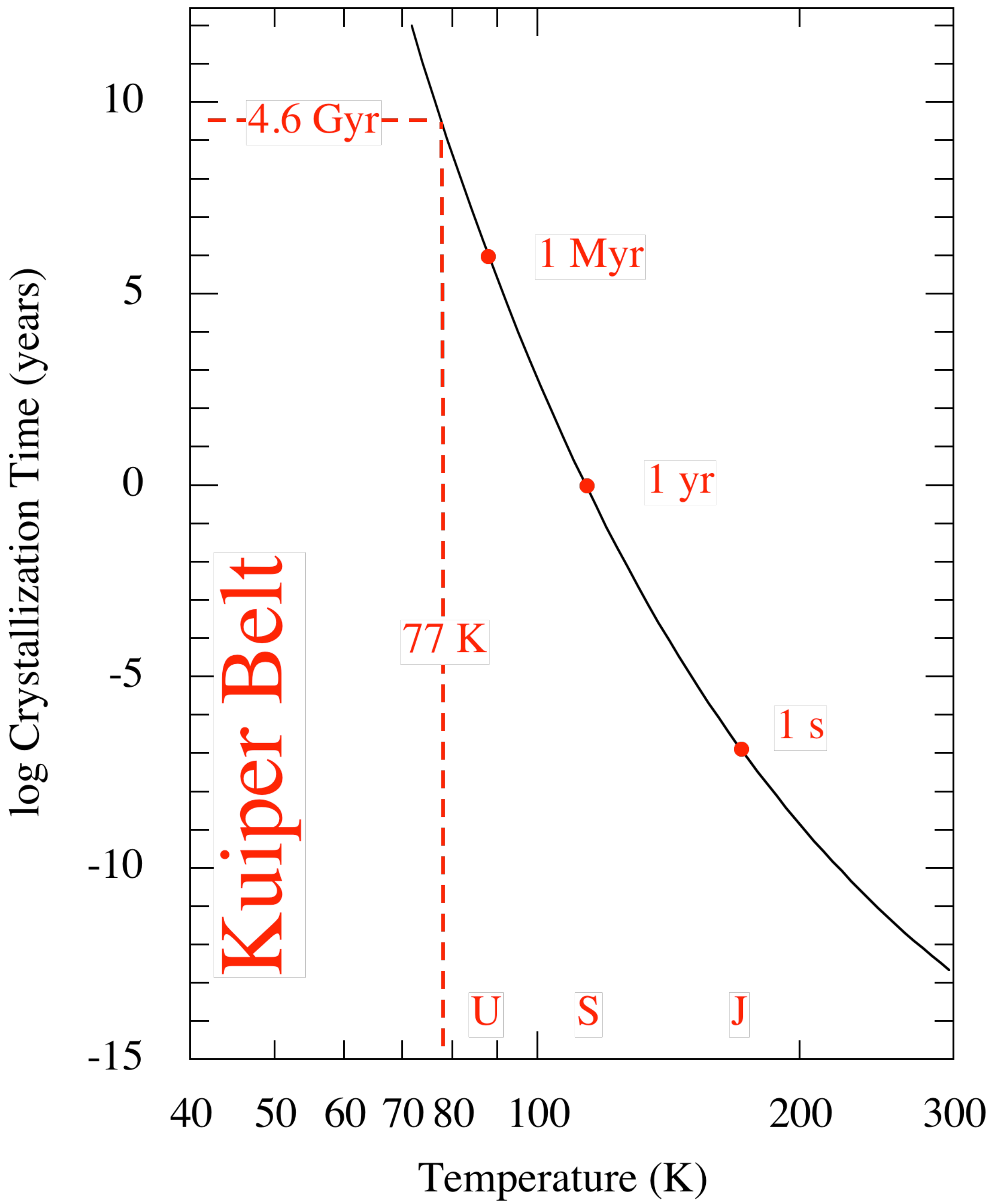
• JFCs are from the Kuiper belt but, **from where** in the Kuiper belt (resonances vs. scattered KBOs vs. other)?

• Where and when were the JFCs formed?

• What is relation between volatiles in main-belt comets and Jupiter-family comets?

• What limits the physical lifetimes of comets? Loss of volatiles? Physical decay (breakup)?

Amorphous Ice



$$\tau_{CR} = 3.0 \times 10^{-21} \exp(E_A/(kT))$$

$$E_A/k = 5370 \text{ K (Schmitt et al. 1989)}$$

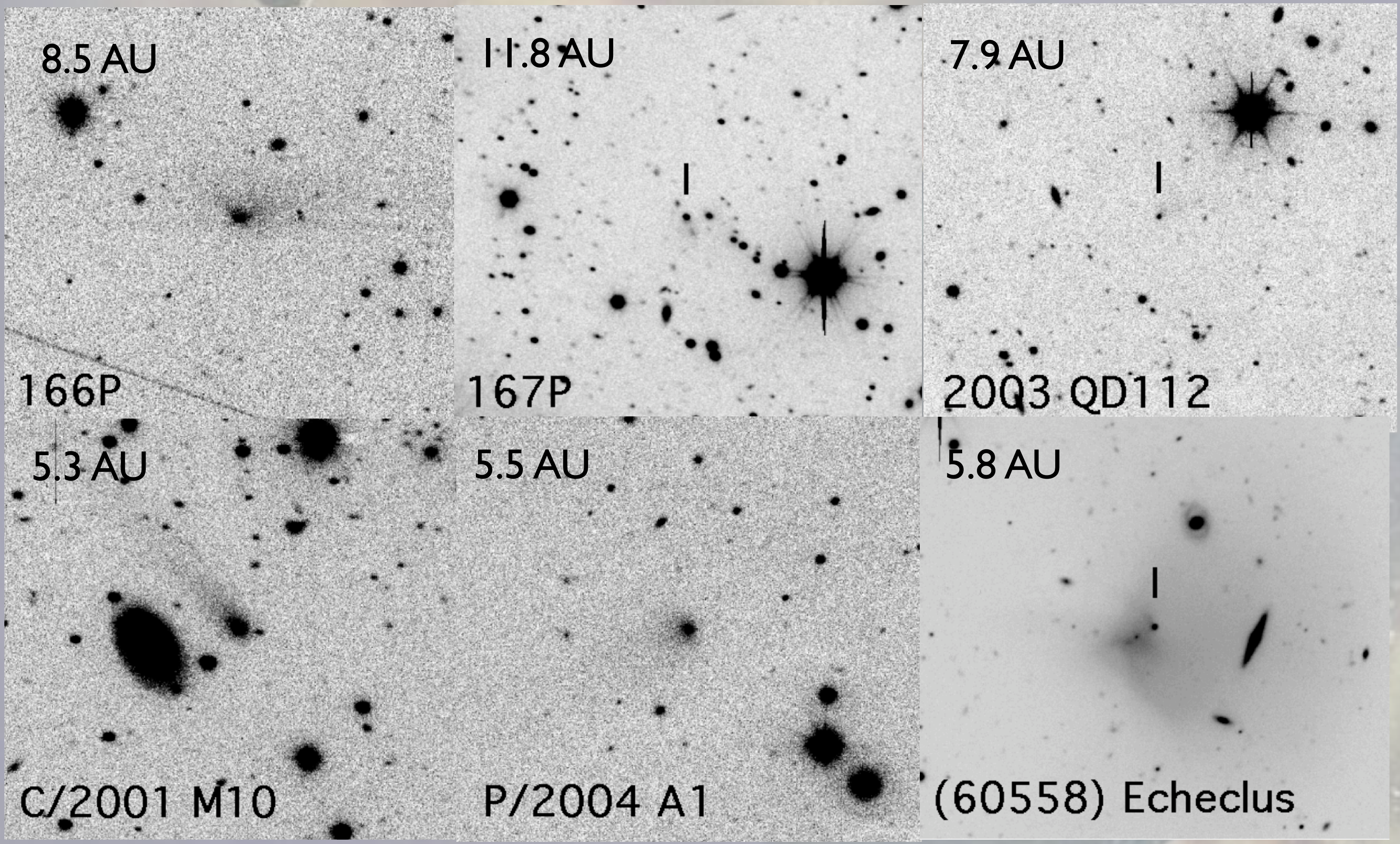
Entire Kuiper Belt has T < 77 K and so could retain amorphous ice indefinitely

Large objects likely crystallized from heat of formation

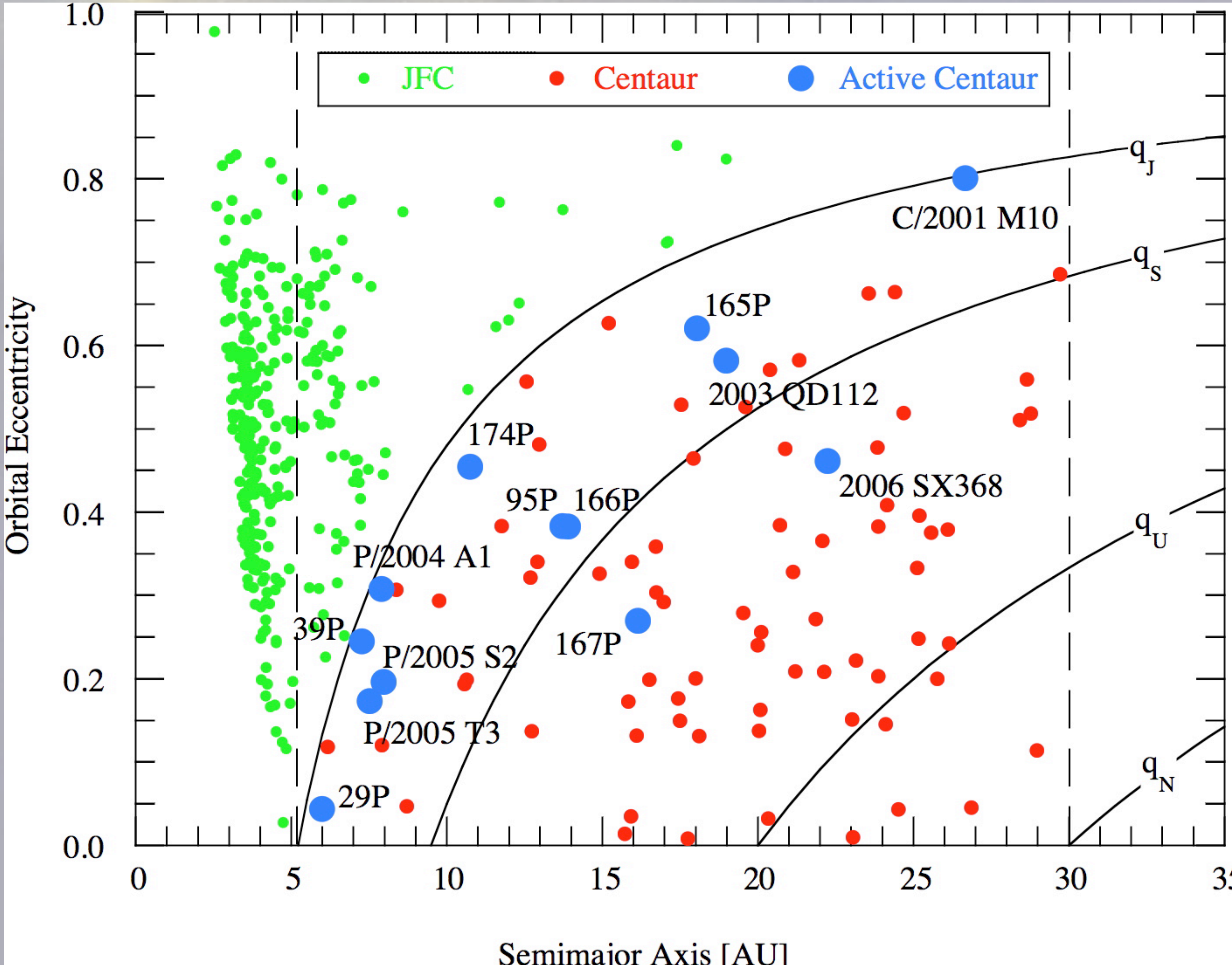
Spectra show *crystalline* ice on KBOs

$\Delta E \sim 10^5 \text{ J kg}^{-1}$

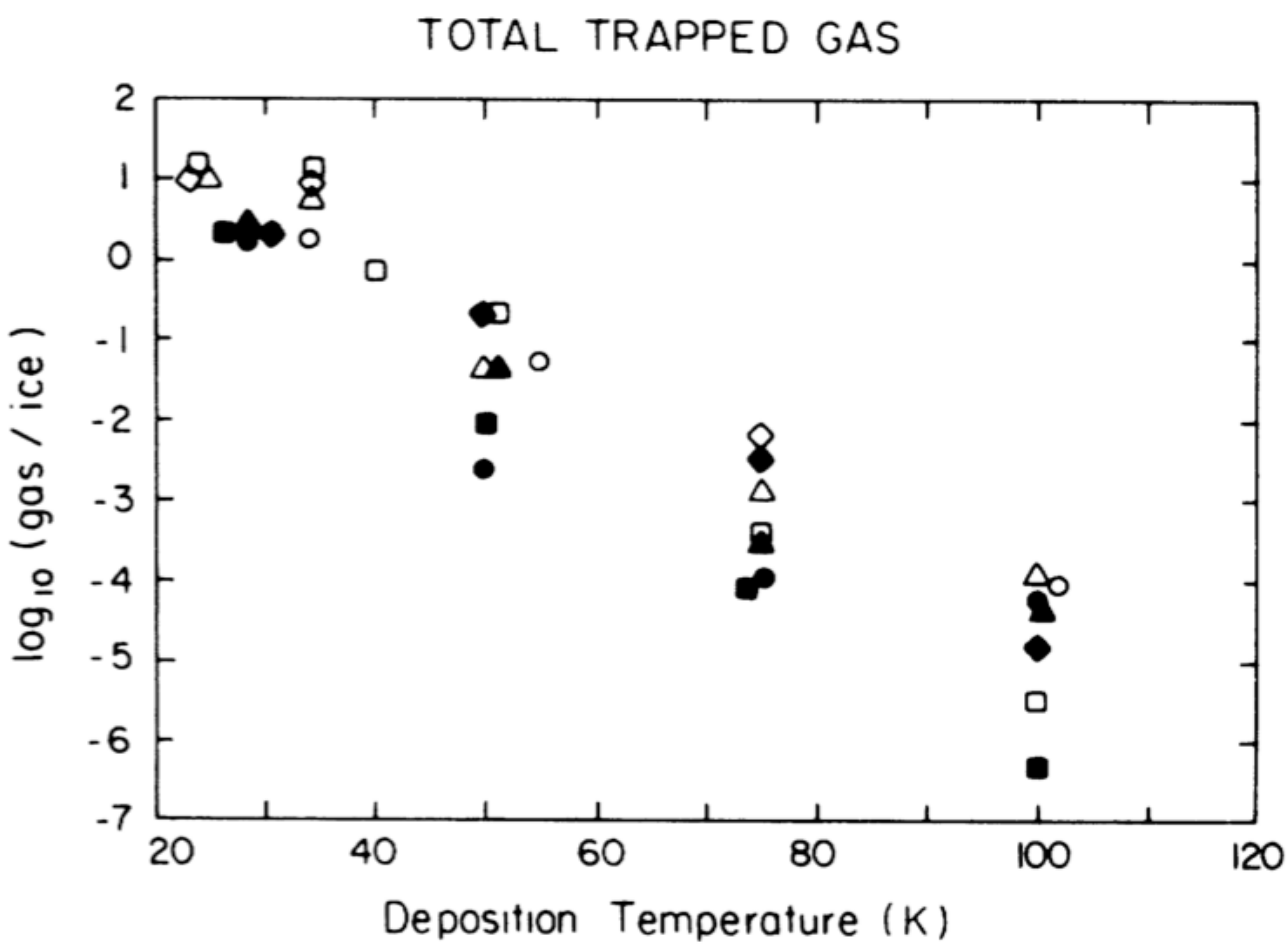
The Centaurs



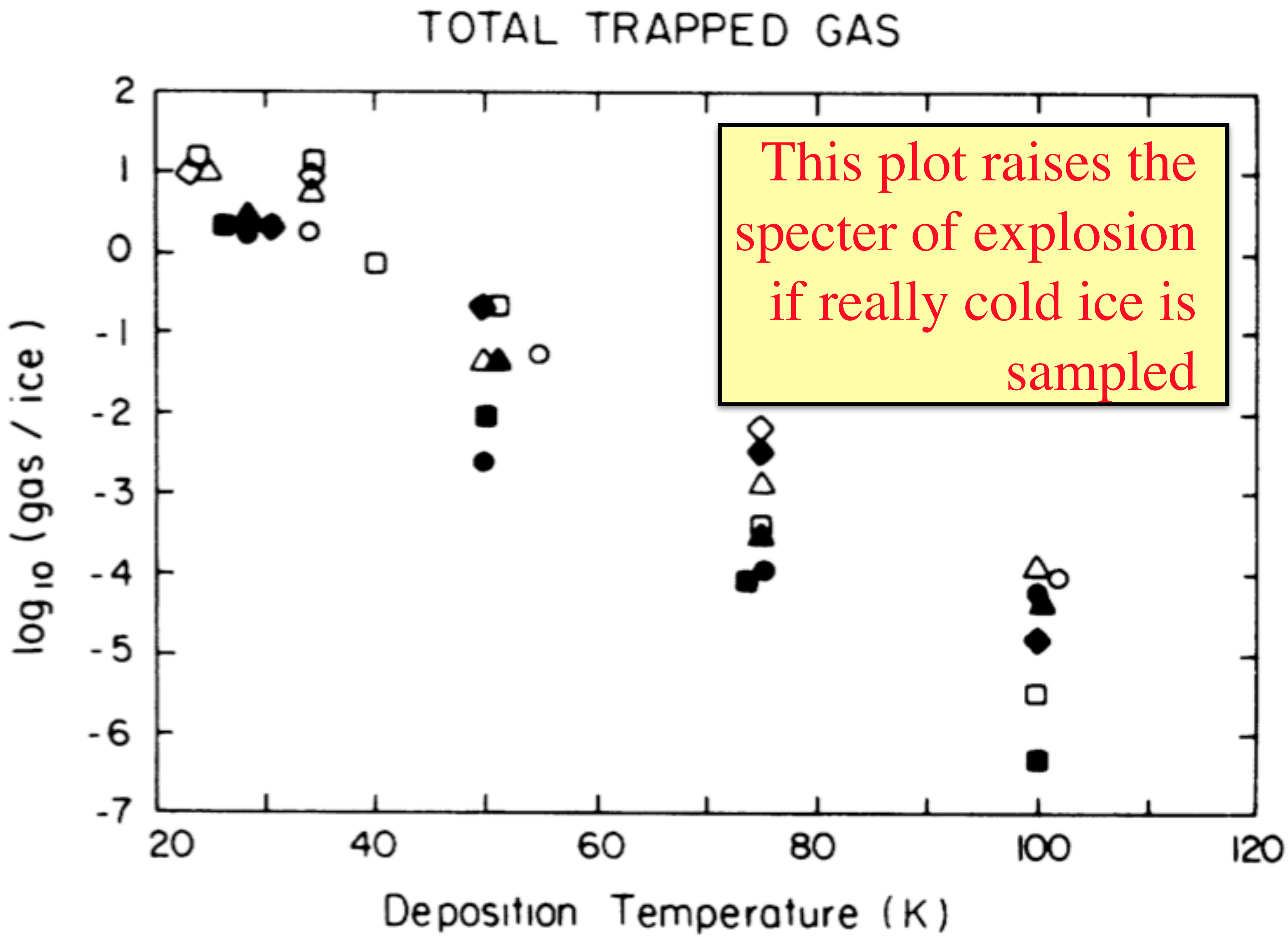
Sample Active Centaurs - Keck and UH 88



JFC
Centaur
Active Centaur
Orbital Eccentricity
Semimajor Axis [AU]
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
25
30
35
q_J
q_S
q_U
q_N
C/2001 M10
165P
2003 QD112
174P
2006 SX368
95P
166P
P/2004 A1
39P
167P
P/2005 S2
P/2005 T3
29P



Bar-Nun et al. 1988



Bar-Nun et al. 1988

Questions

- Is amorphous abundant in comets?
- If so, how deep?
- Does amorphous ice drive cometary activity?
- If comets are amorphous then so must be the Centaurs
- If Centaurs are amorphous, then so must be the Kuiper Belt Objects
- If so, why do their spectra show crystalline ice?

Questions?