# Open Problems in Outer Planetary Systems

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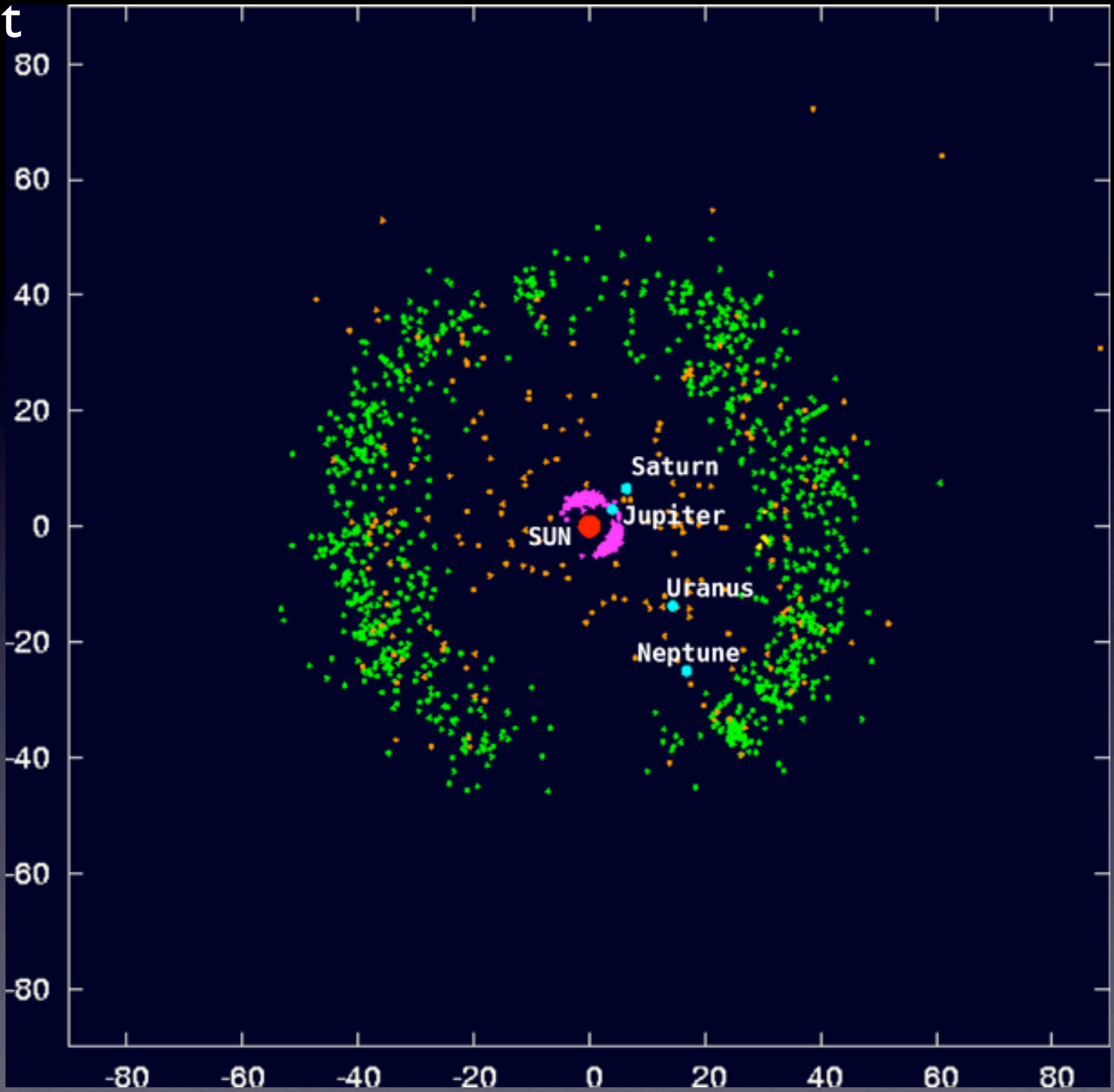
## Outer Planetary Systems:

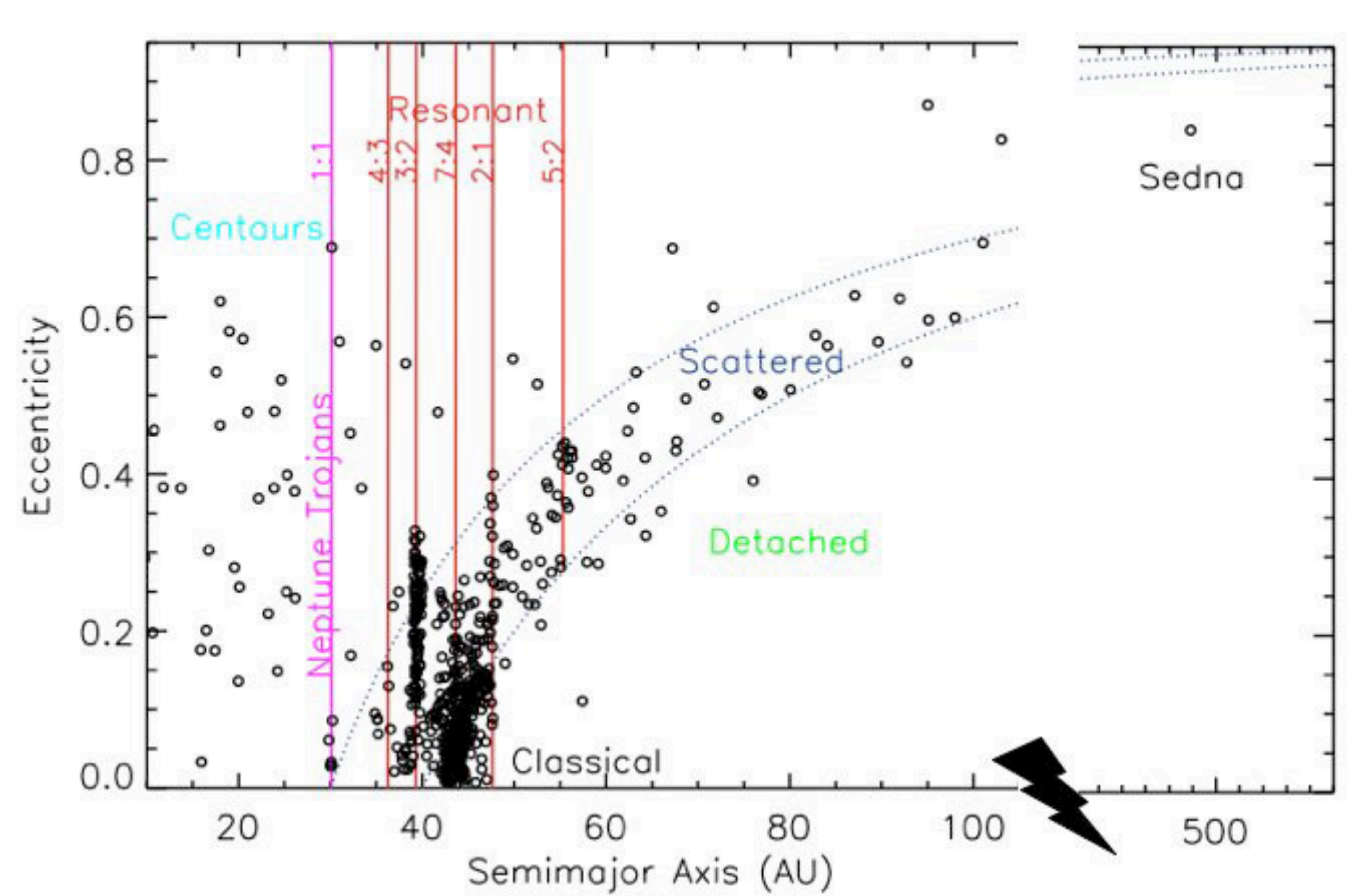
1) formation did not proceed to giant planets

2) planetesimals(km - 1000km) produced & stirred

3) ground down to dust grains

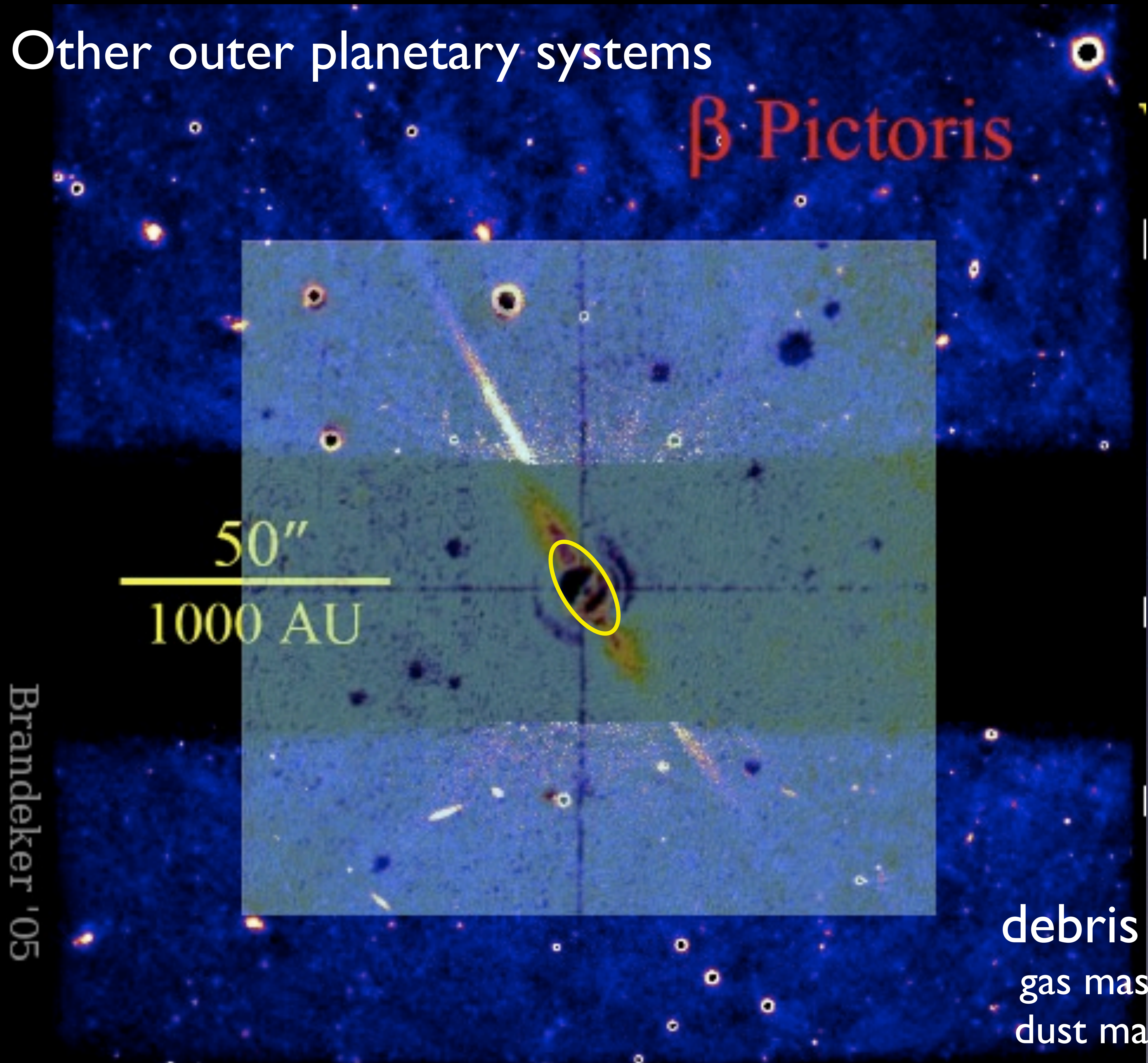
# The Kuiper Belt






~0.1 M_E (half scattered belt, half cold classical)
scattered belt: significantly disturbed by an 'event'
cold classical belt: appear un-eventful

# Other outer planetary systems




debris disk (ring)

gas mass ~0.02 M_E

dust mass ~ 0.1 M_E

Hillenbrand et al, 2008

sun-like stars

$T_{dust}$ ~ 50 K
r ~ 30 AU

erosion inside-out

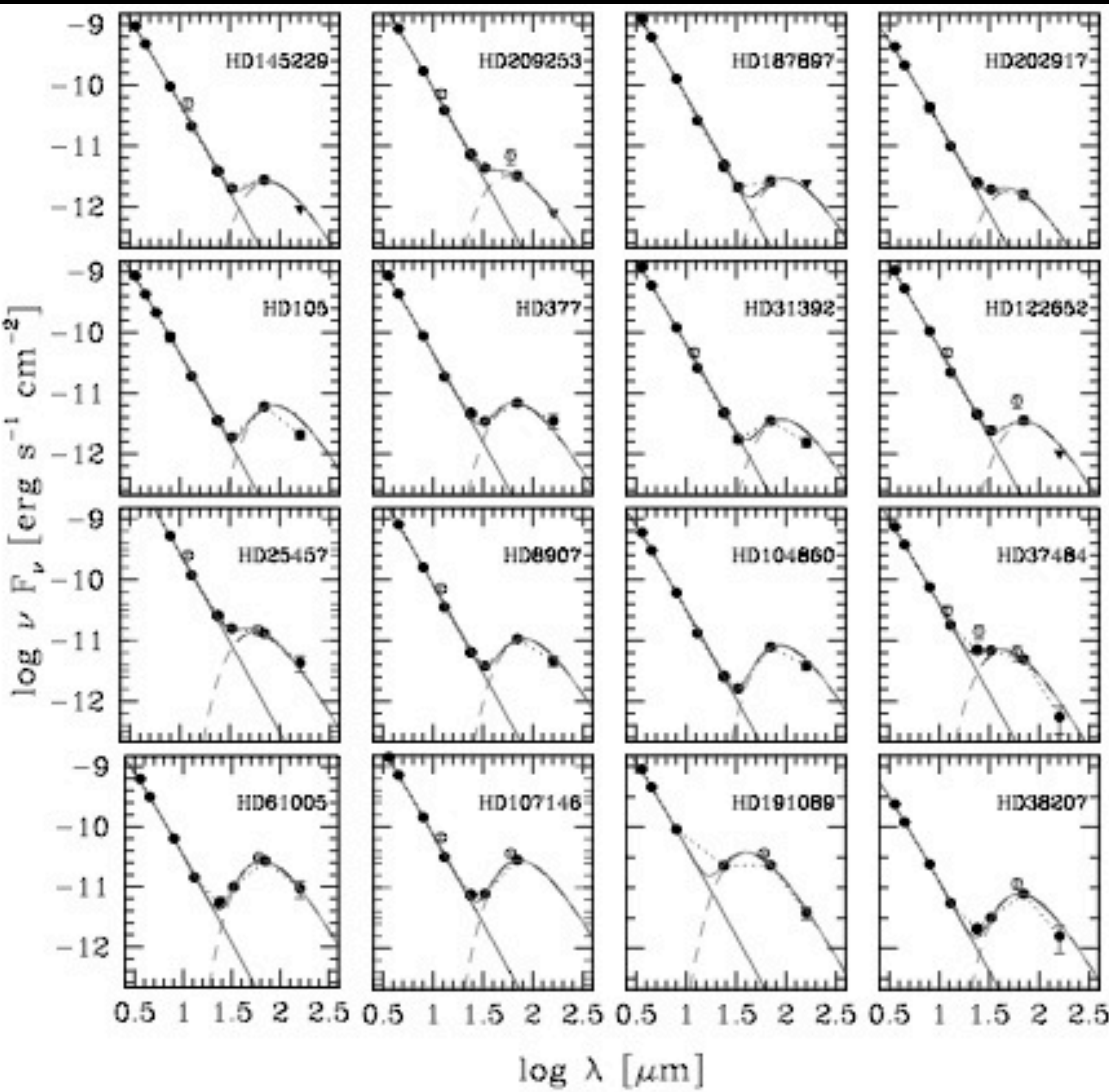
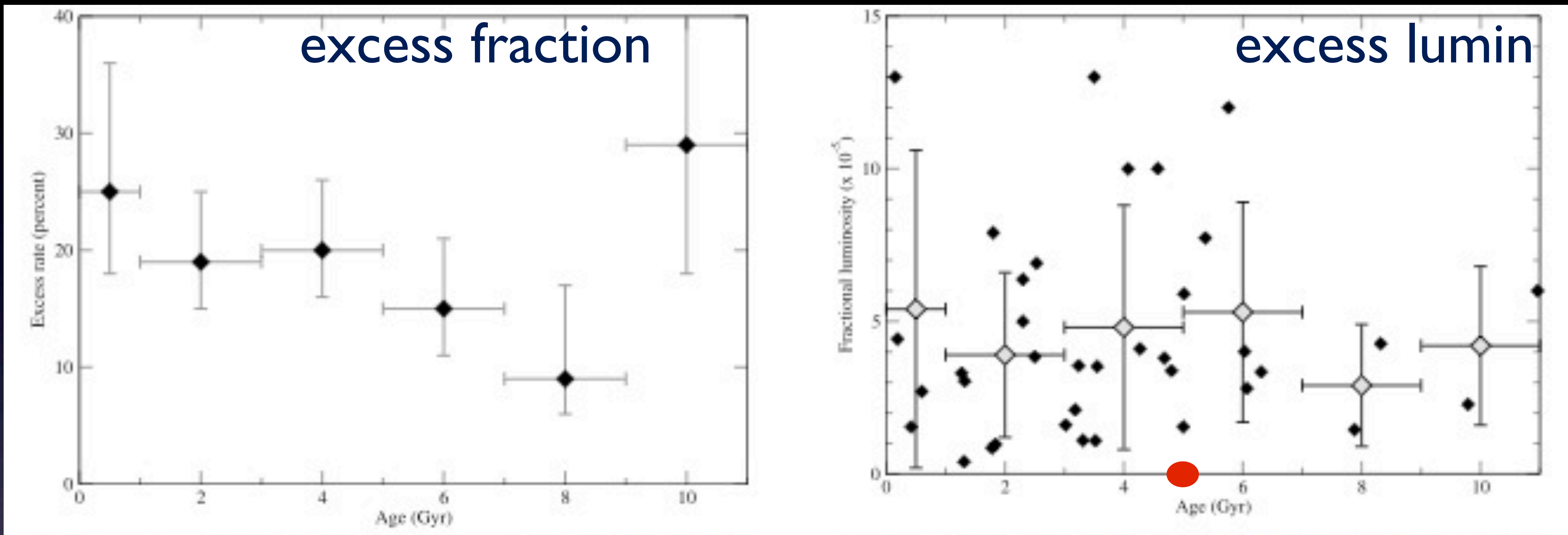



FIG. 7.—SEDs for the 70 μm excess sources in the FEPS debris disk sample, having >3 σ significance in 25 cases and >2 but <3 σ significance in six cases. Objects are ordered most significant excess at bottom left to least significant excess at top right (see Table 3). Symbols and lines are as in Fig. 6. Single-temperature blackbody fits are generally to the 33–70 μm color excess and slightly underpredict the 24 μm excess while overpredicting the 160 μm excess (when detected). The fits are

# infrared excess around sun-like stars (Spitzer)

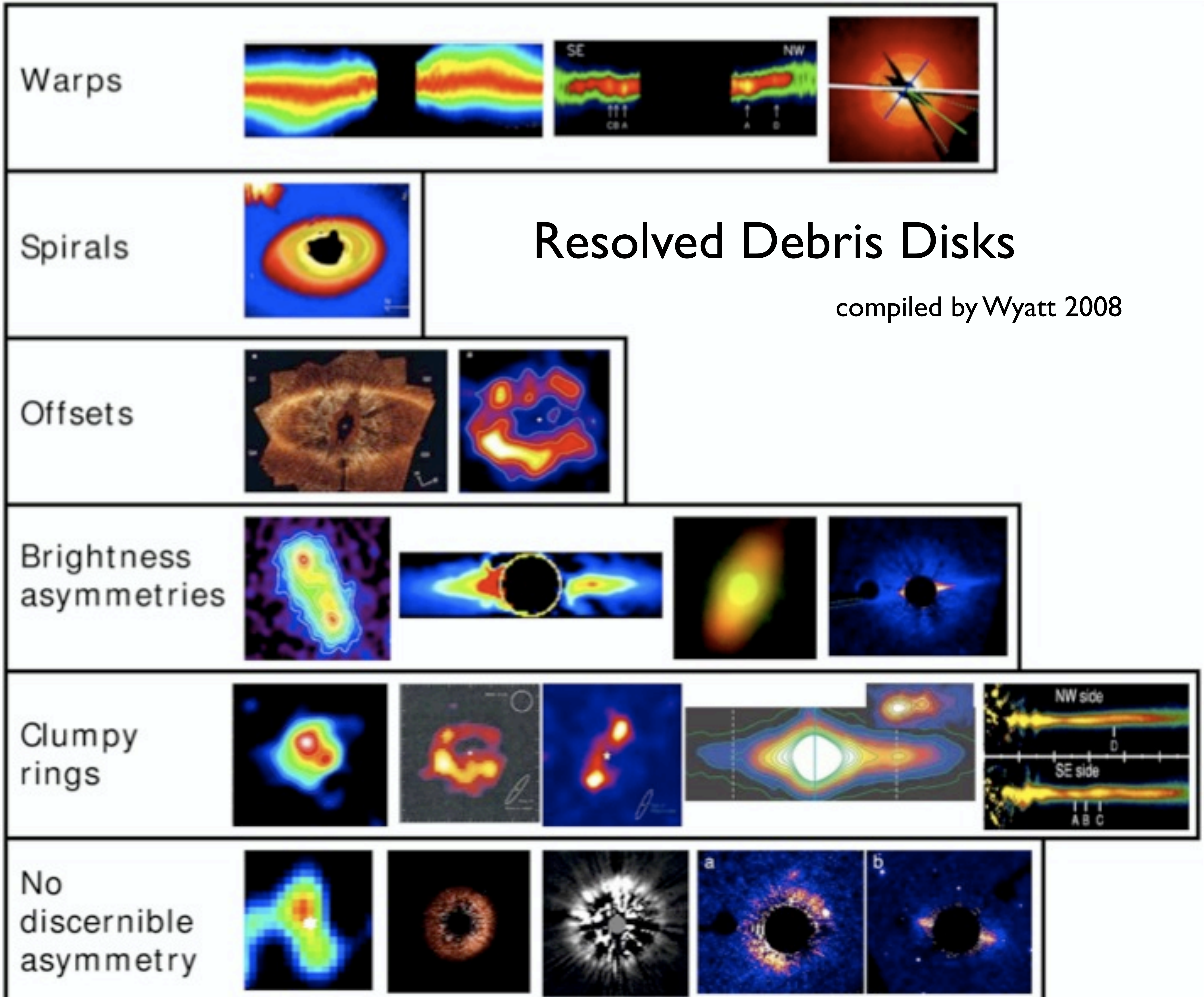
Trilling et al, ApJ 2008




- ~20% of all stars have detectable dusty disks
  fraction indept. of age
- cold dust (~50AU)
- lumin. ~ $10^{-4}$ $L_*$ (~100 zodiacal/Kuiper dust)
  lumin decays mildly with age

# Resolved Debris Disks

compiled by Wyatt 2008



# The closest debris disk

asteroid belt debris disk:

medium 40 micron grains
strong forward scattering

inward spiral by Poynting-Robertson, then sublimate

mass loss rate ~ $10^6$ g/s;
or 1 Ceres/life

vertical optical depth $10^{-7}$
(0.3AU ~ Earth)

only upper limits for Kuiper belt debris disk (L ~ 10-6 L_sun)

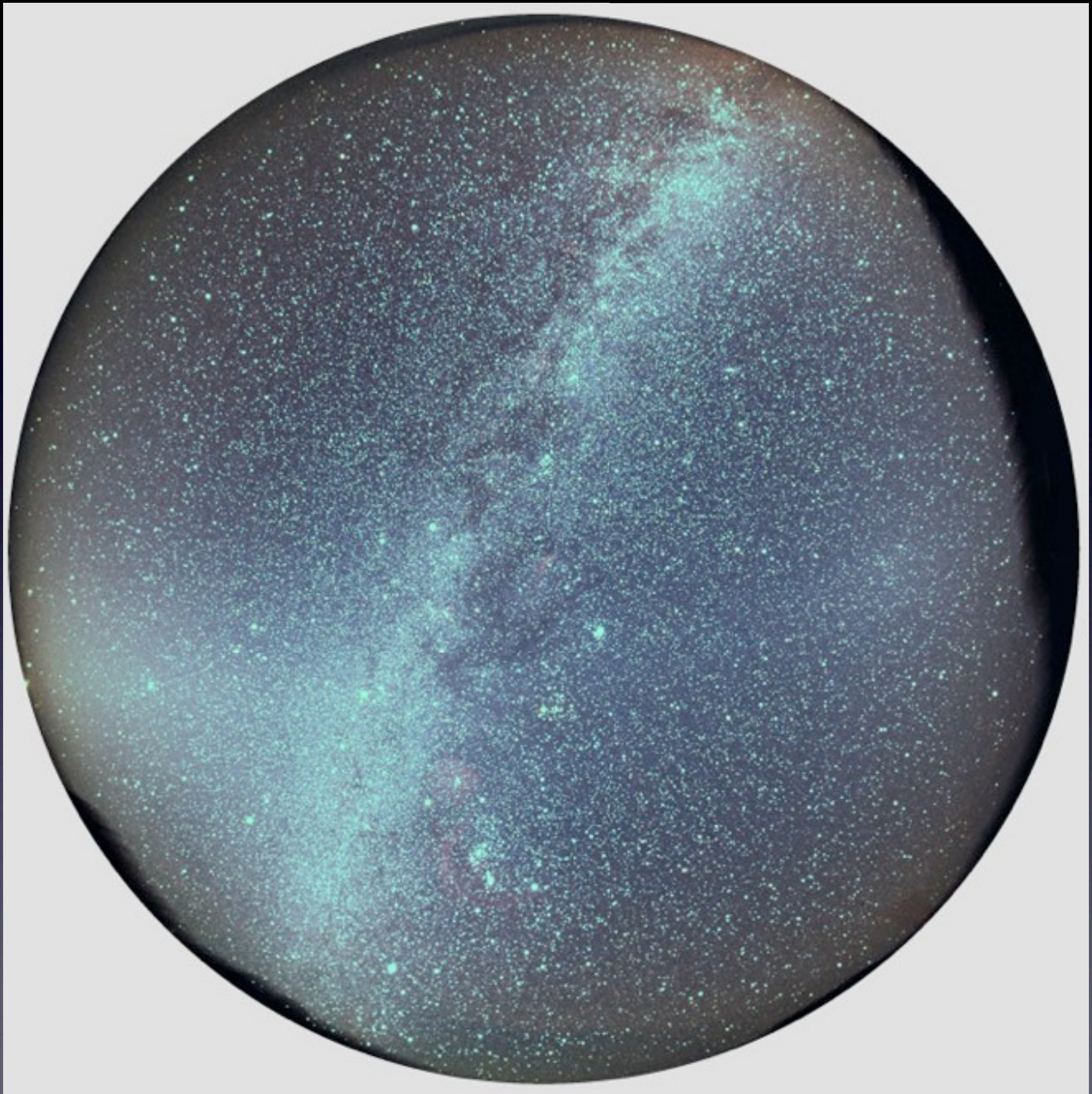


image by D. Zubenel

# Open Issues in Outer Planetary Systems

## the outer solar system

1)where have the primordial solid gone? ('mass')

2)what stirred up the Kuiper Belt Objects? ('excitation')

3)why is there an outer edge? ('Kuiper Cliff')

4)formation

5)dynamics: Sedna, Oort cloud, scattered belt, resonant objects...

6)binaries: formation, inclination, colour,

7)record of collisional history: size-break,satellites...

## debris disks

1) why such bright debris disks, even at Gyrs

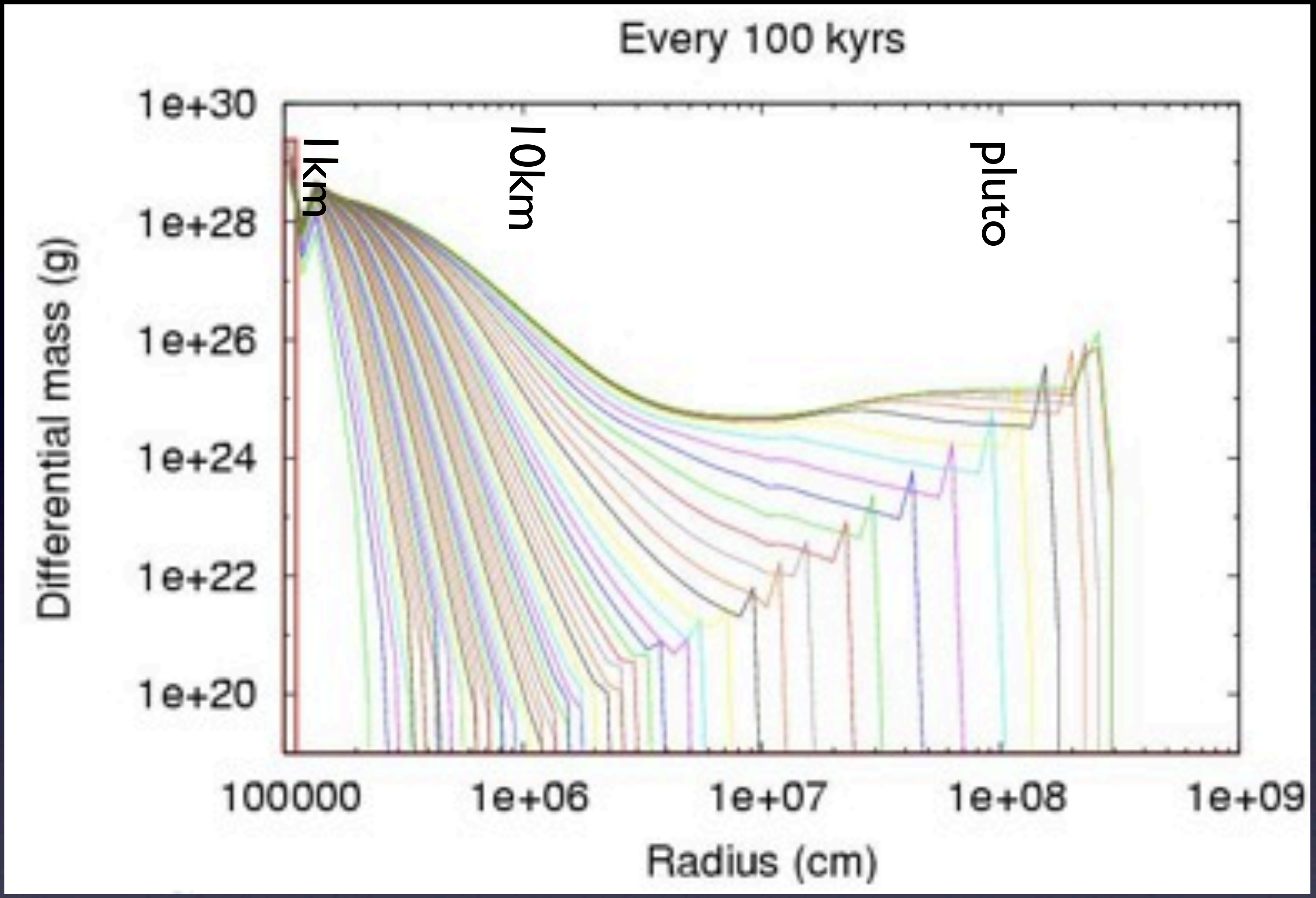
2) planetary perturbations significant?

3) why 'debris rings'?

4) ... (unknown unknowns)

how unique is the solar system?

# Particle-in-a-box simulations of boulder growth




initial: ~10 M_E of 1km

final: ~ 0.1 M_E in > 10km

inefficiency results from self-excitation

$$\frac{dN}{ds} \propto s^{-q}$$

q~4

# growth continues until collisions are destructive

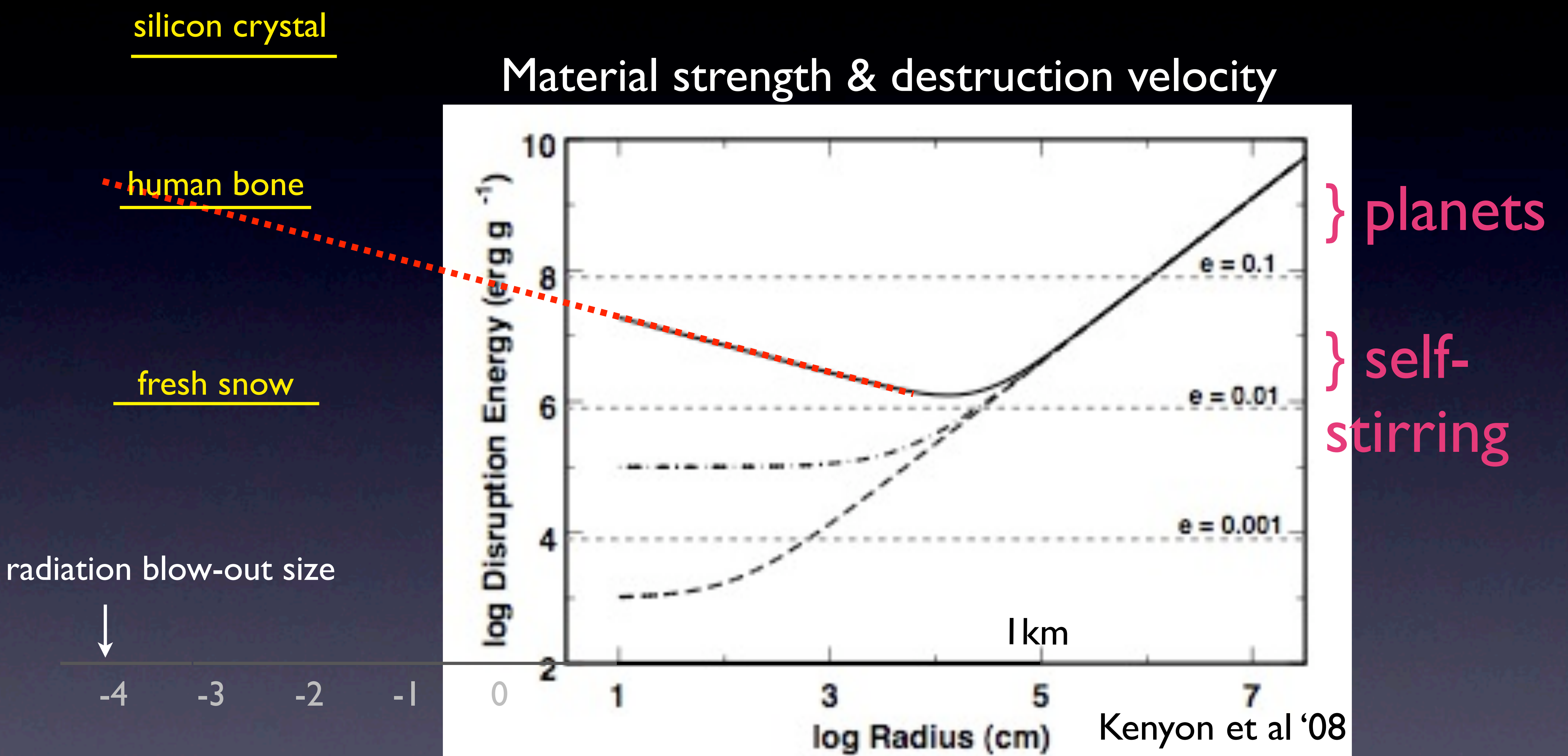
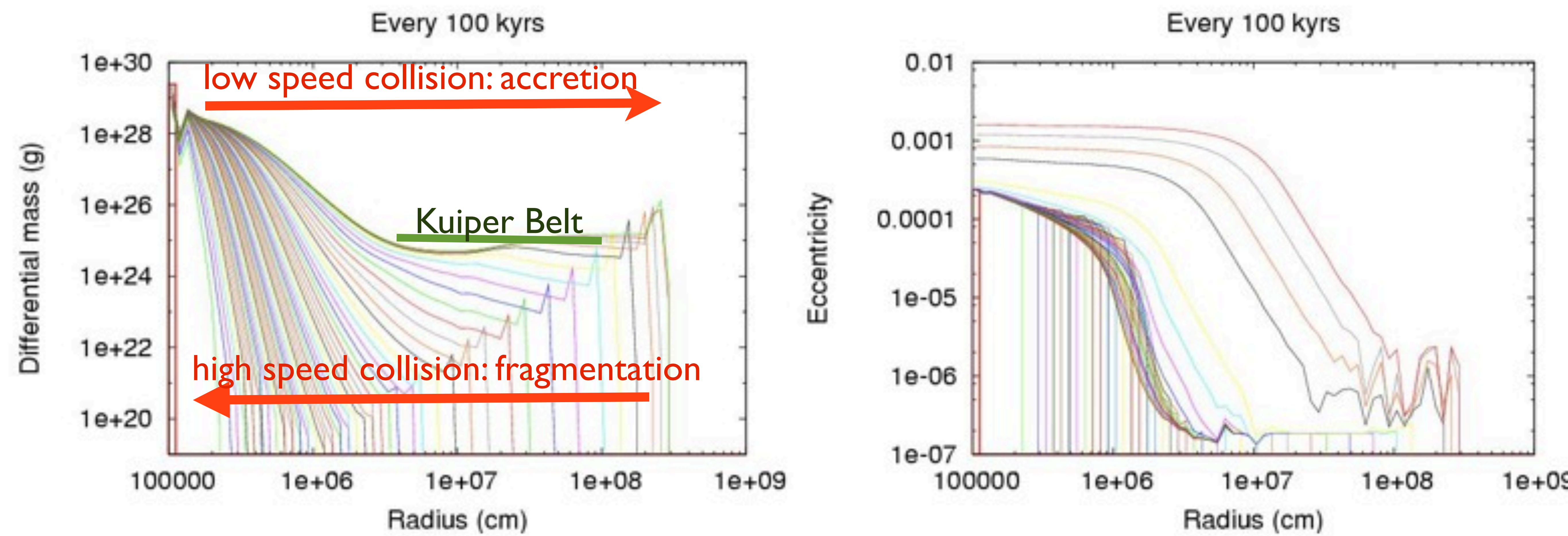



Fig. 1.— Disruption energy, $Q_D^*$, for icy objects. The solid curve plots a typical result derived from numerical simulations of collisions that include a detailed equation of state for crystalline ice ($Q_b = 1.6 \times 10^7$ erg g$^{-1}$, $\beta_b = -0.42$, $\rho = 1.5$ g cm$^{-3}$, $Q_g = 1.5$ erg cm$^{-3}$, and $\beta_g = 1.25$; Benz and Asphaug 1999). The other curves plot results using $Q_b$ consistent with model fits to comet

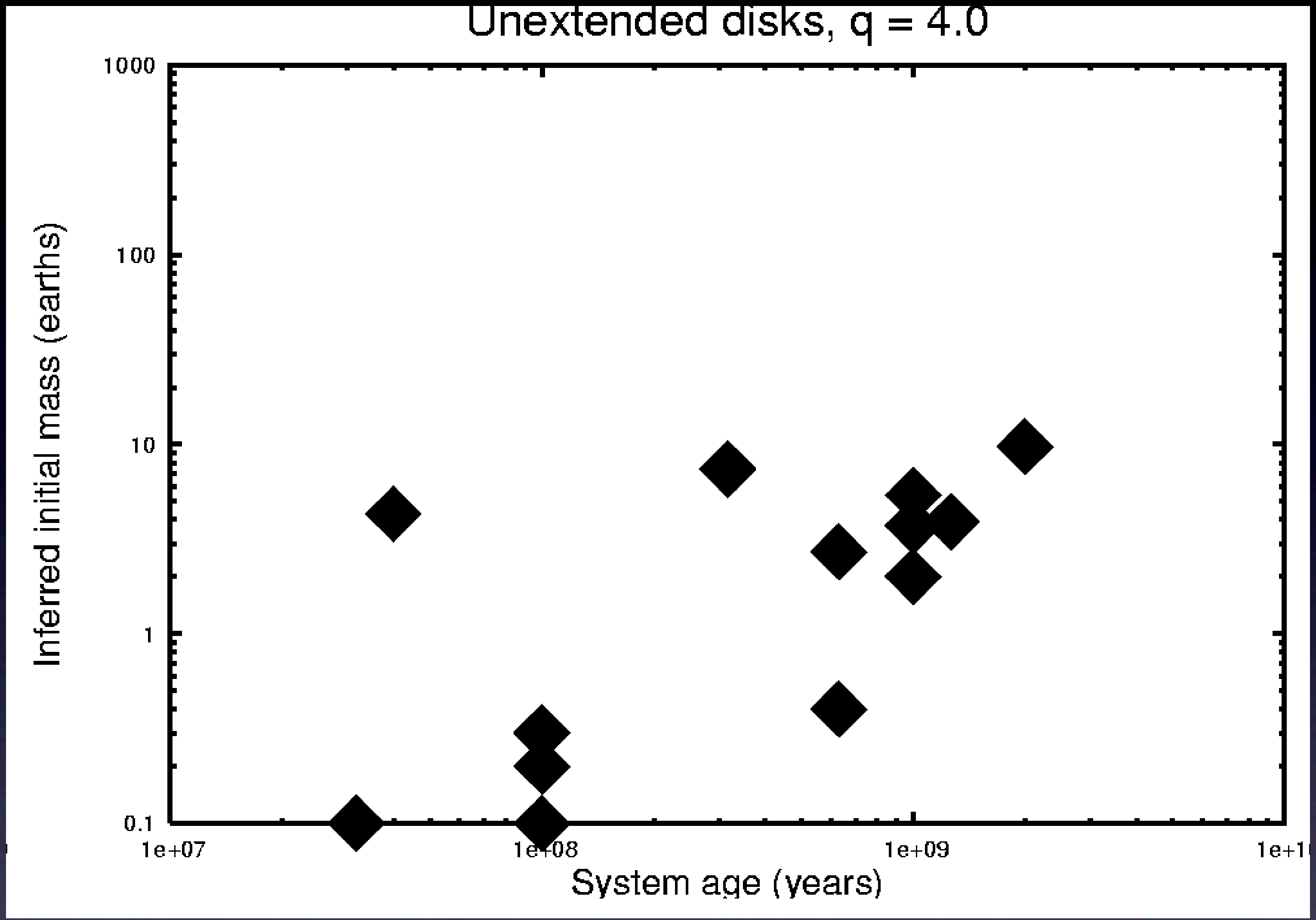



Kuiper belt:  e ~ 0.1, ~ 0.1 M_E
99.9% mass (@km) lost through grinding
currently very dim
but:  superluminous at youth,
radiative bottle neck
all boulders have to survive

(Wu, Lithwick & Shannon, in prep)

# Boulder mass is 100x higher in extra-solar debris disks

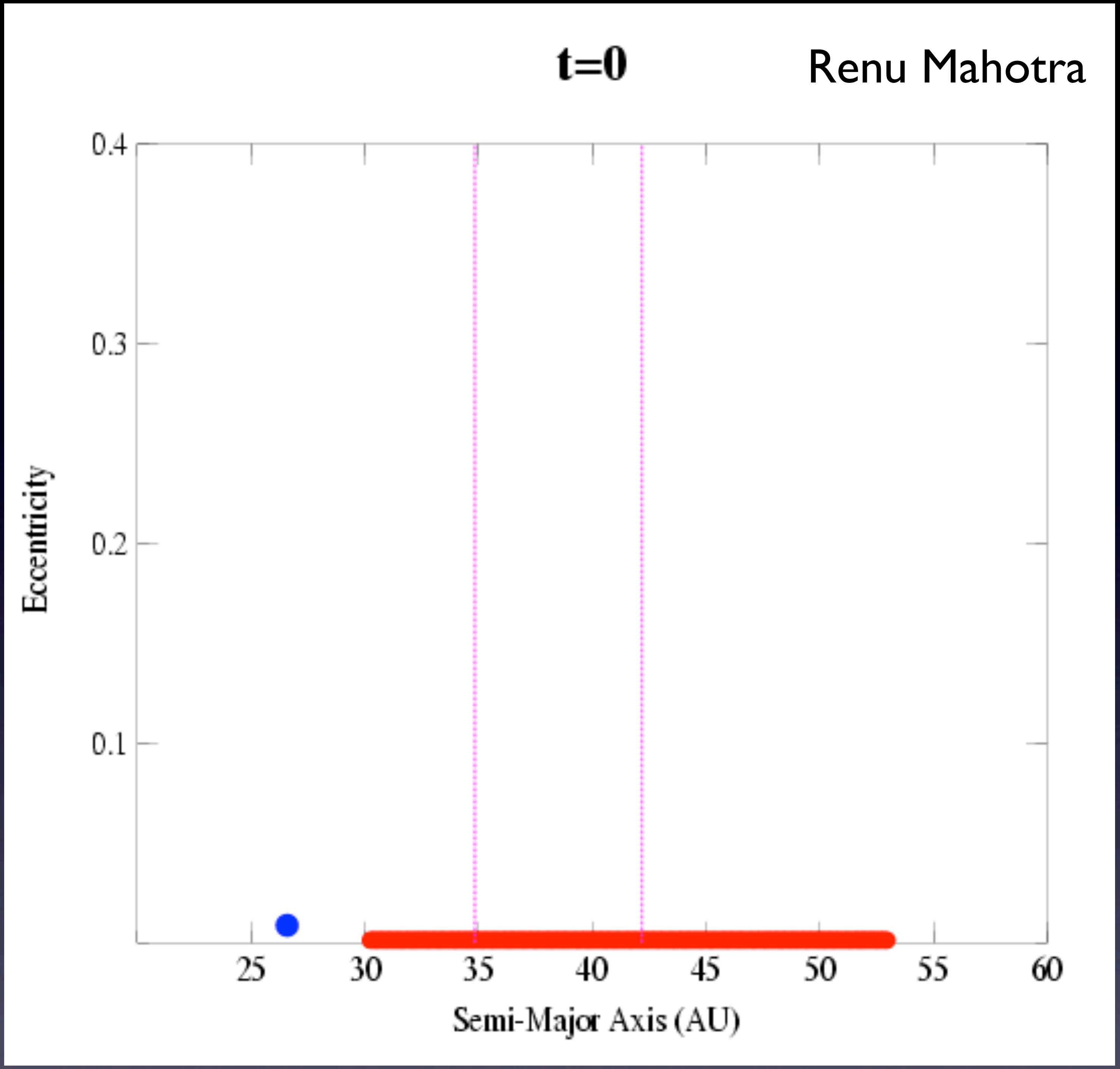
We can infer initial mass and size distribution of debris disks by assuming that disks across all ages are a uniform sample.




using only un-extended Spitzer FEPs detections
Shannon & Wu (submitted)

- q ~ 4.0 between 1 and 100 km
- maximum mass ~ 10 $M_E$
- many disks anemic

# how many Plutos were made?




- Close-encounters w/ Neptune increases/decreases orbital energy ~ symmetrically

- smaller orbits may encounter Jupiter and be chucked out
- larger orbits keep returning to Neptune

- the asymmetry propels Neptune into the Kuiper Belt, depleting the belt by 99%

Neptune: 23 --> 30 AU (after ~10^9 yrs)
KBOs: 30 --> 40AU

- a few $M_E$ of the ejected KBOs form Oort cloud   Malhotra '93, Levinson & Morbidelli '03,....

the scattering event: a factor of 100 depletion

We are forced to conclude:

1) scattered belt, currently ~ 10 Plutos, had 100x more Plutos before the 'event'
boulder mass ~ 10 M_E ~ mass of MMSN solid

2) cold classical belt did not suffer the event, boulder mass ~ 0.1 M_E, made out of 0.1 M_E (a 'cliff' in the solar nebula)

3) both need ~100% efficiency

the new model for planetesimal conglomeration

Goldreich, Lithwick & Sari

why is the Kuiper belt so dim?

because it has little mass