Orbital Evolution of Dust Grains and Rocks During FU Orionis Outbursts

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Transformational Science with ALMA: From Dust to Rocks to Planets
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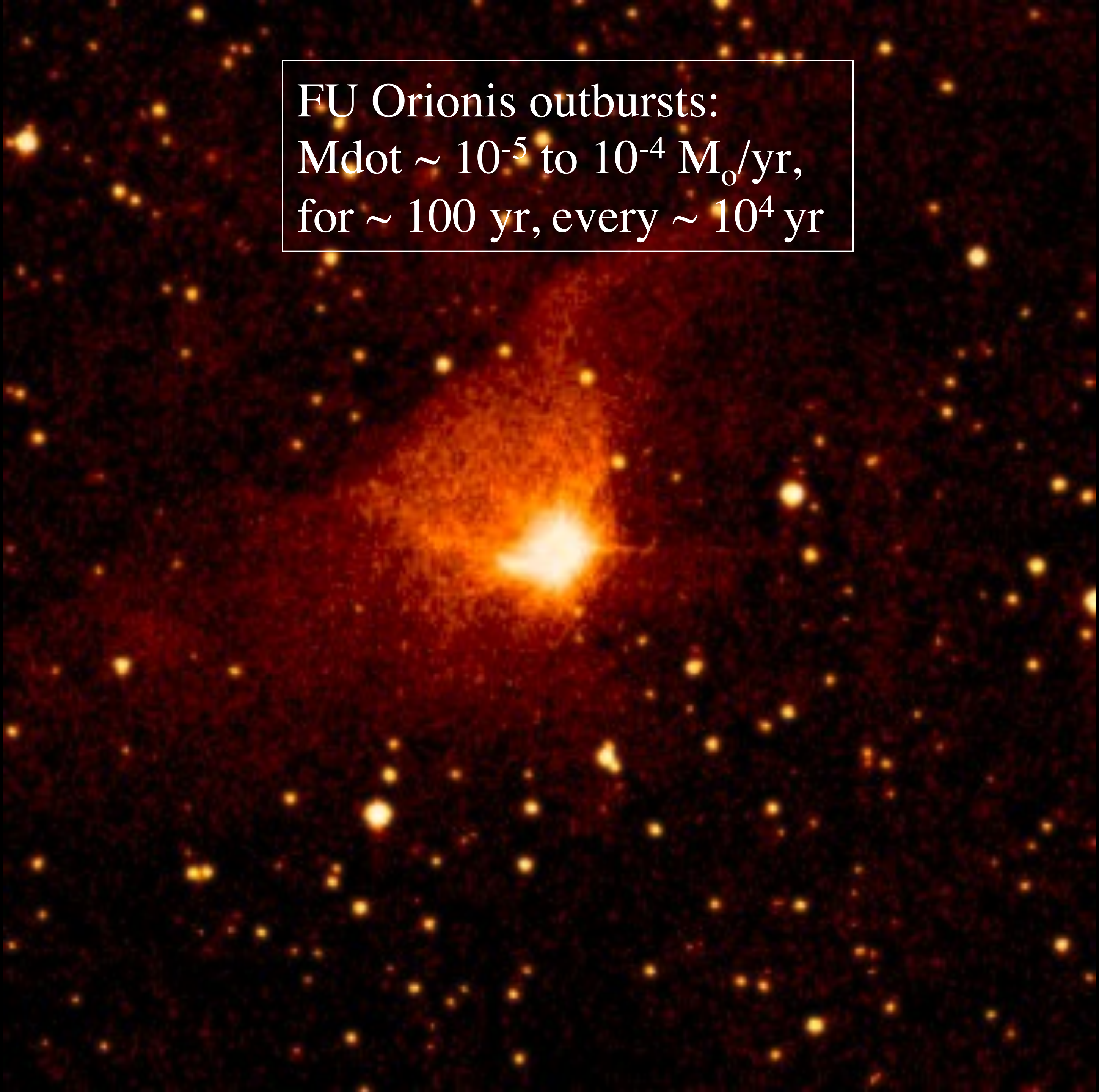
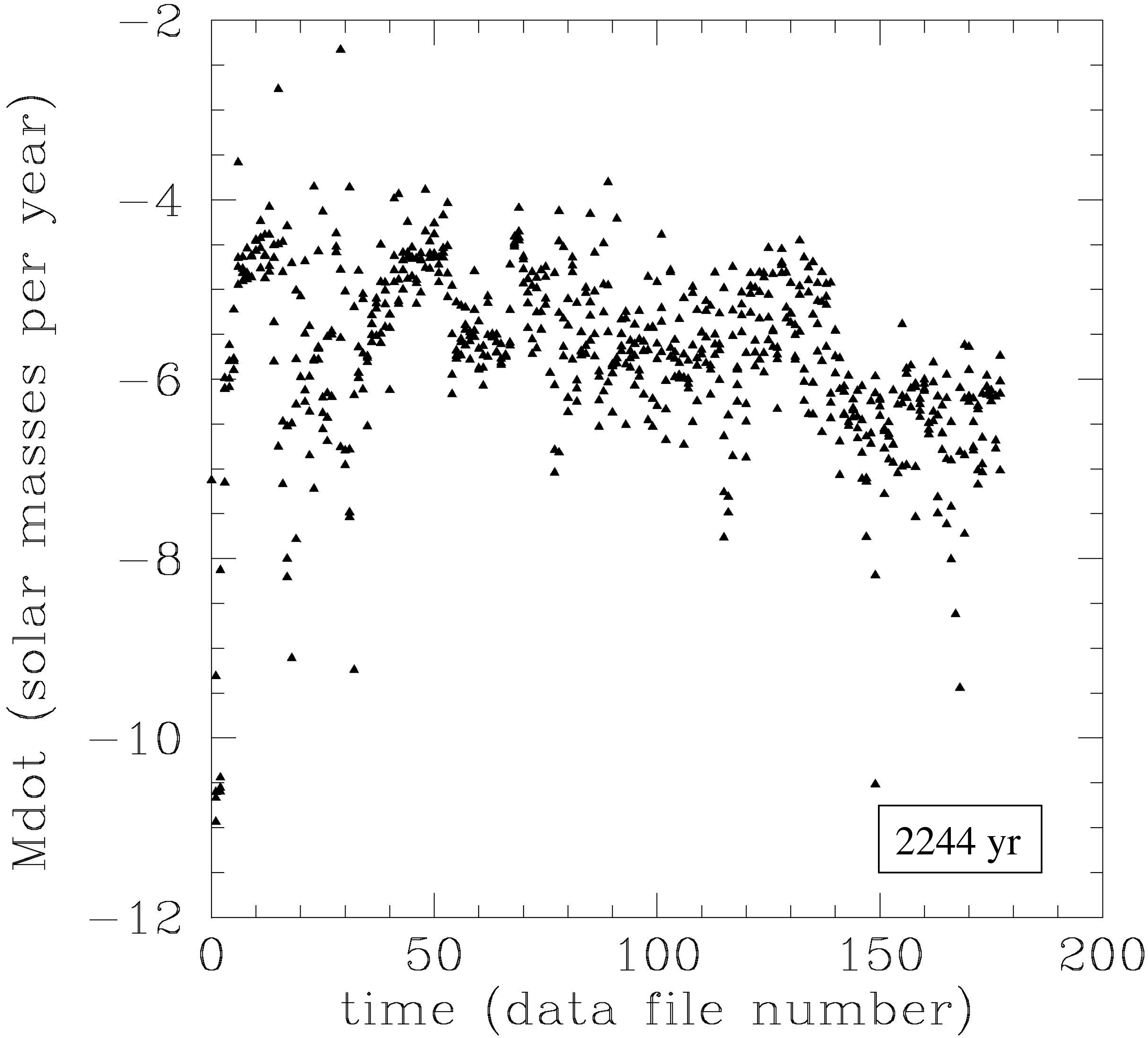
FU Orionis outbursts:

Mdot ~ 10^{-5} to 10^{-4} M_o/yr,

for ~ 100 yr, every ~ 10^4 yr



Boss (2011): MGU disk model with mass accretion onto central protostar

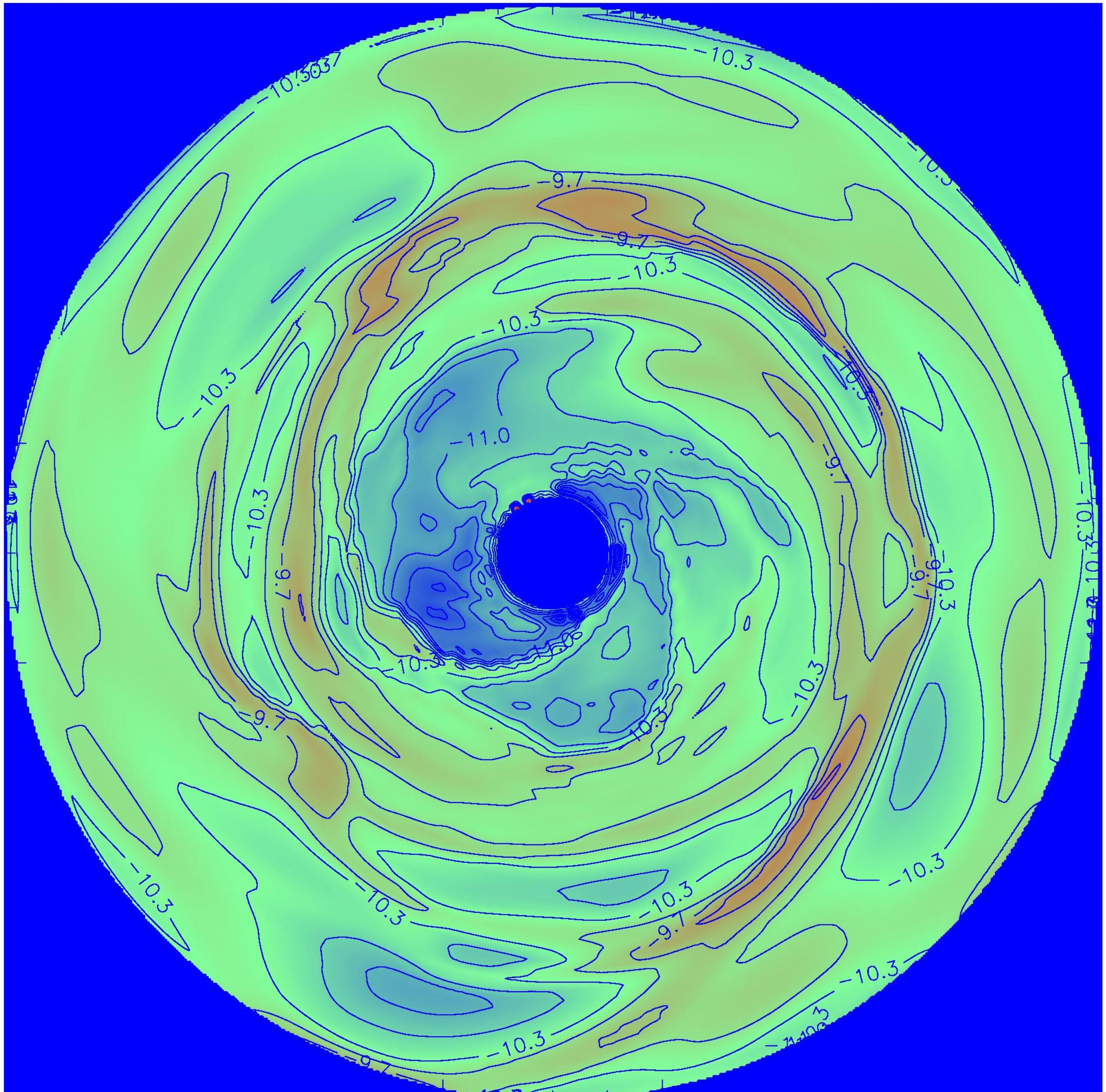


Initial midplane density of marginally gravitationally unstable (MGU) disk evolution

M_{disk} = 0.05 M_{sun}

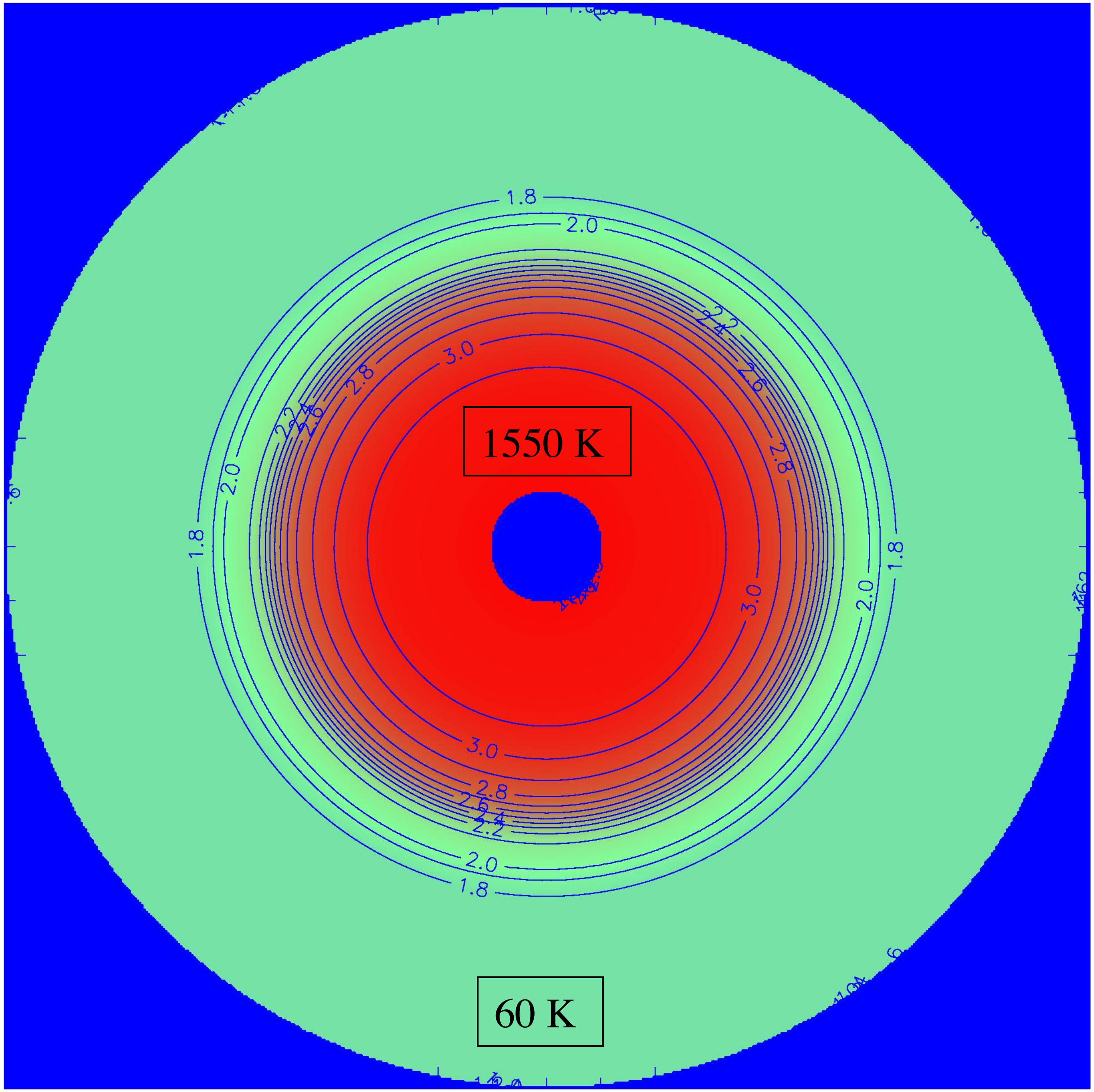
10 AU radius disk

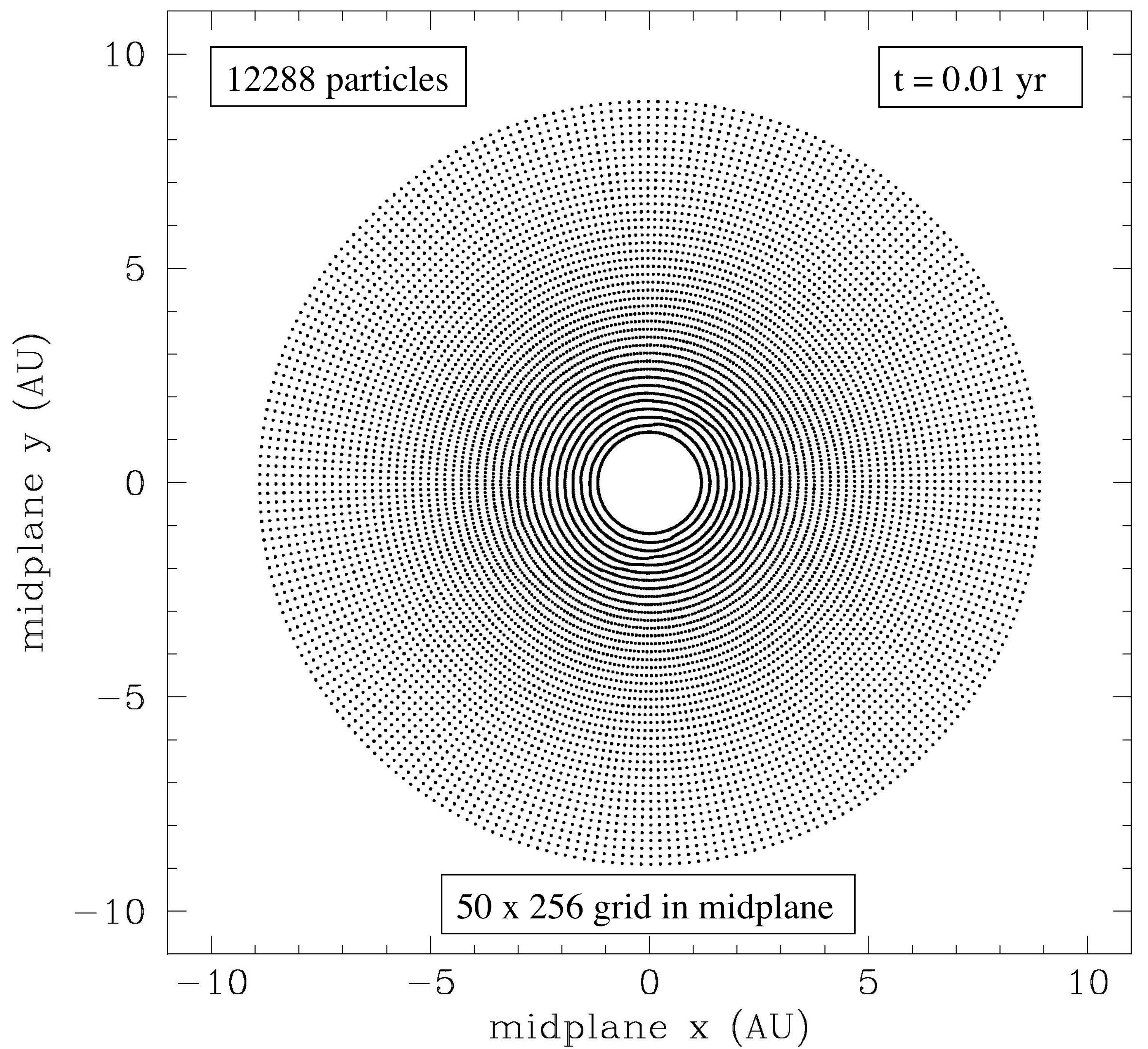
M_{star} = 1.0 M_{sun}

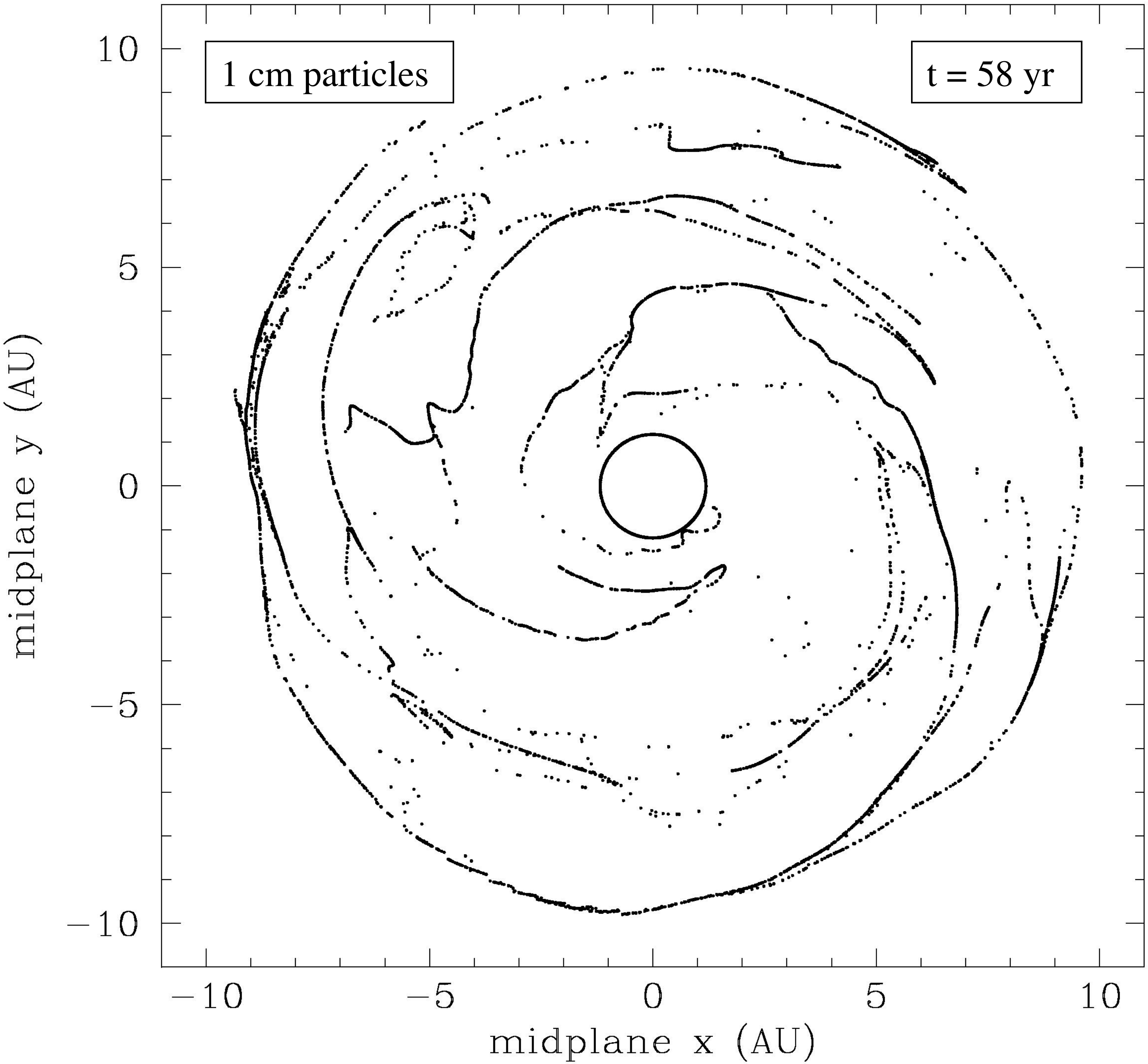


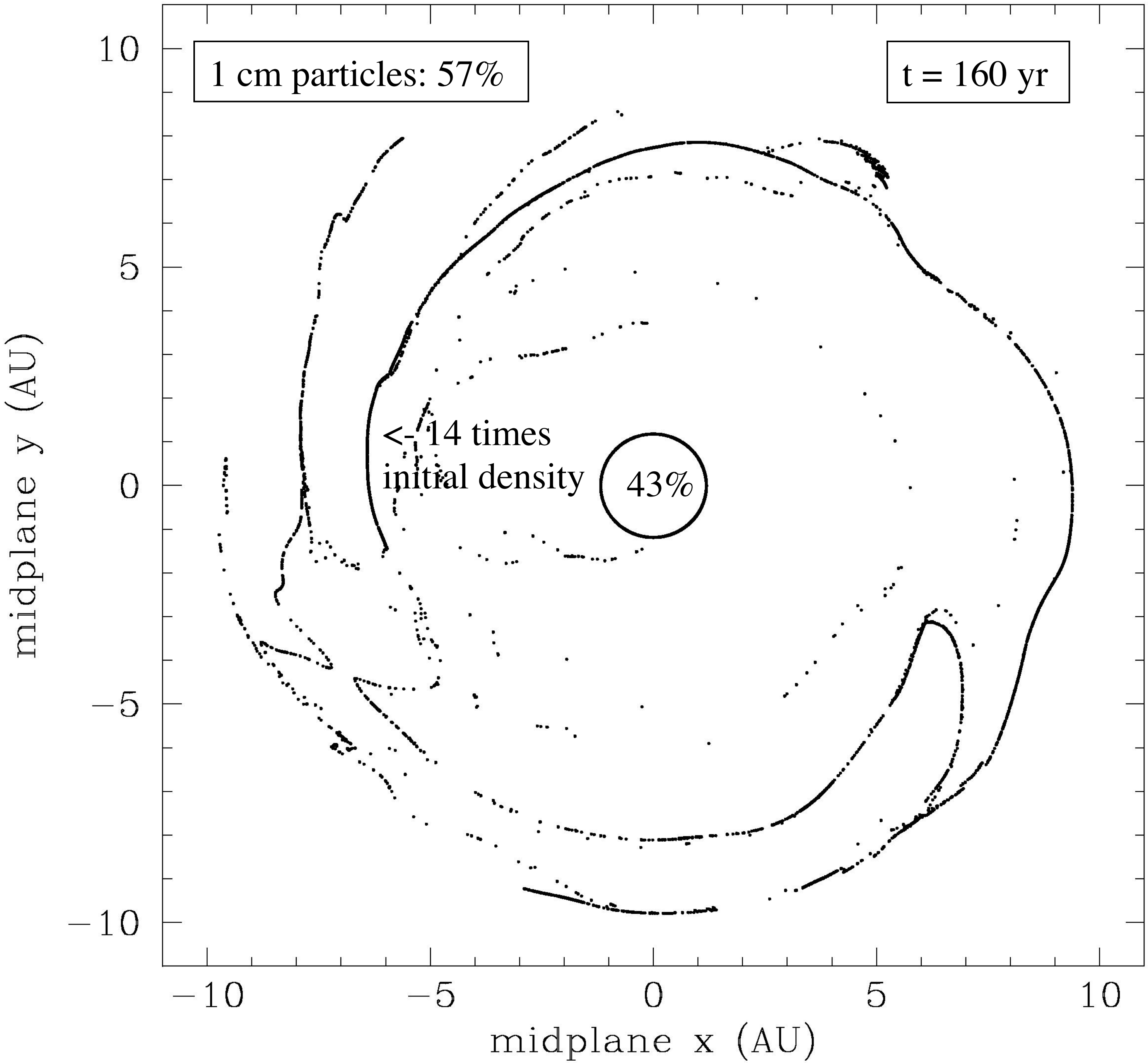
Midplane temperatures of marginally gravitationally unstable (MGU) disk evolution

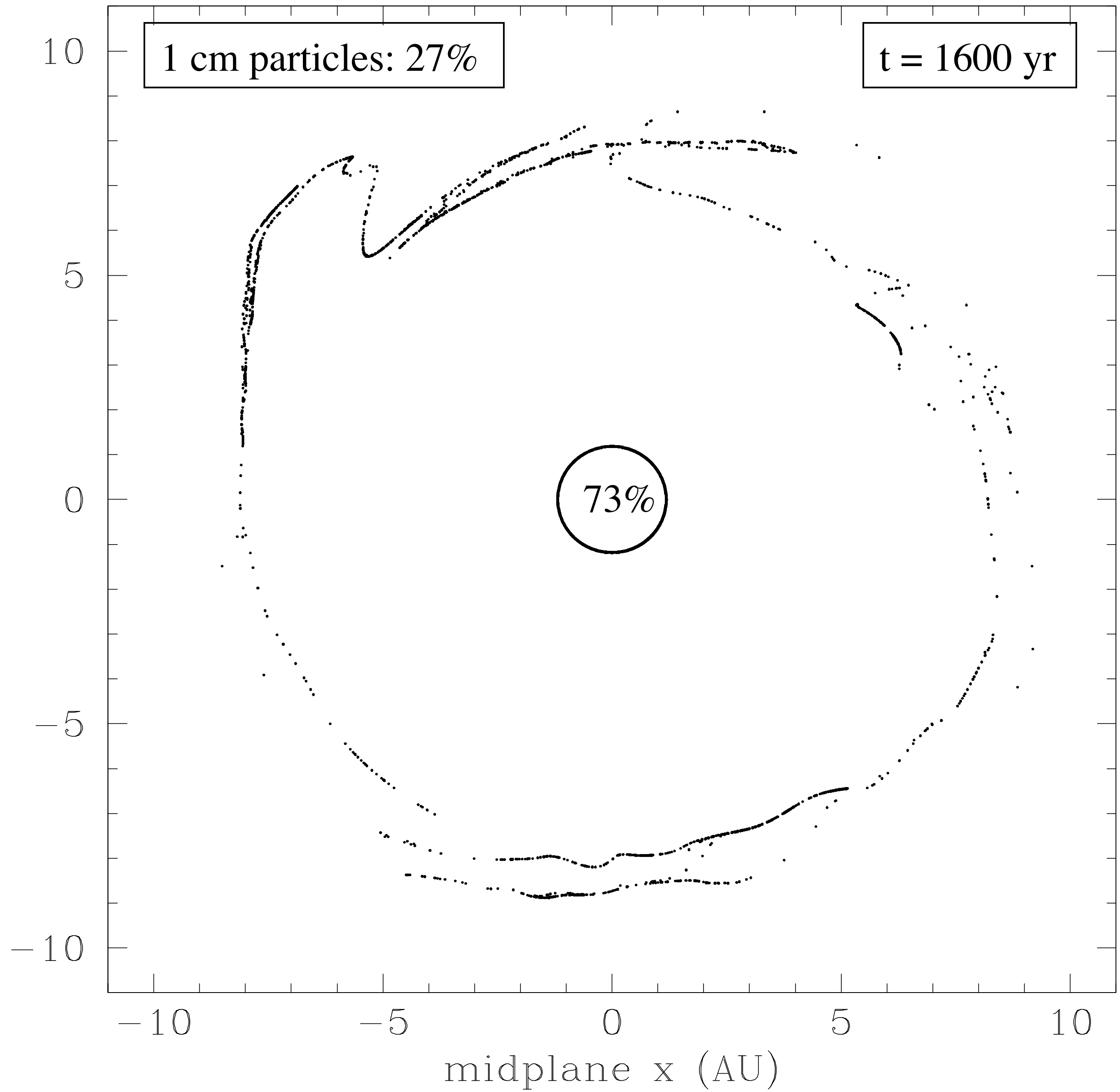
10 AU radius disk



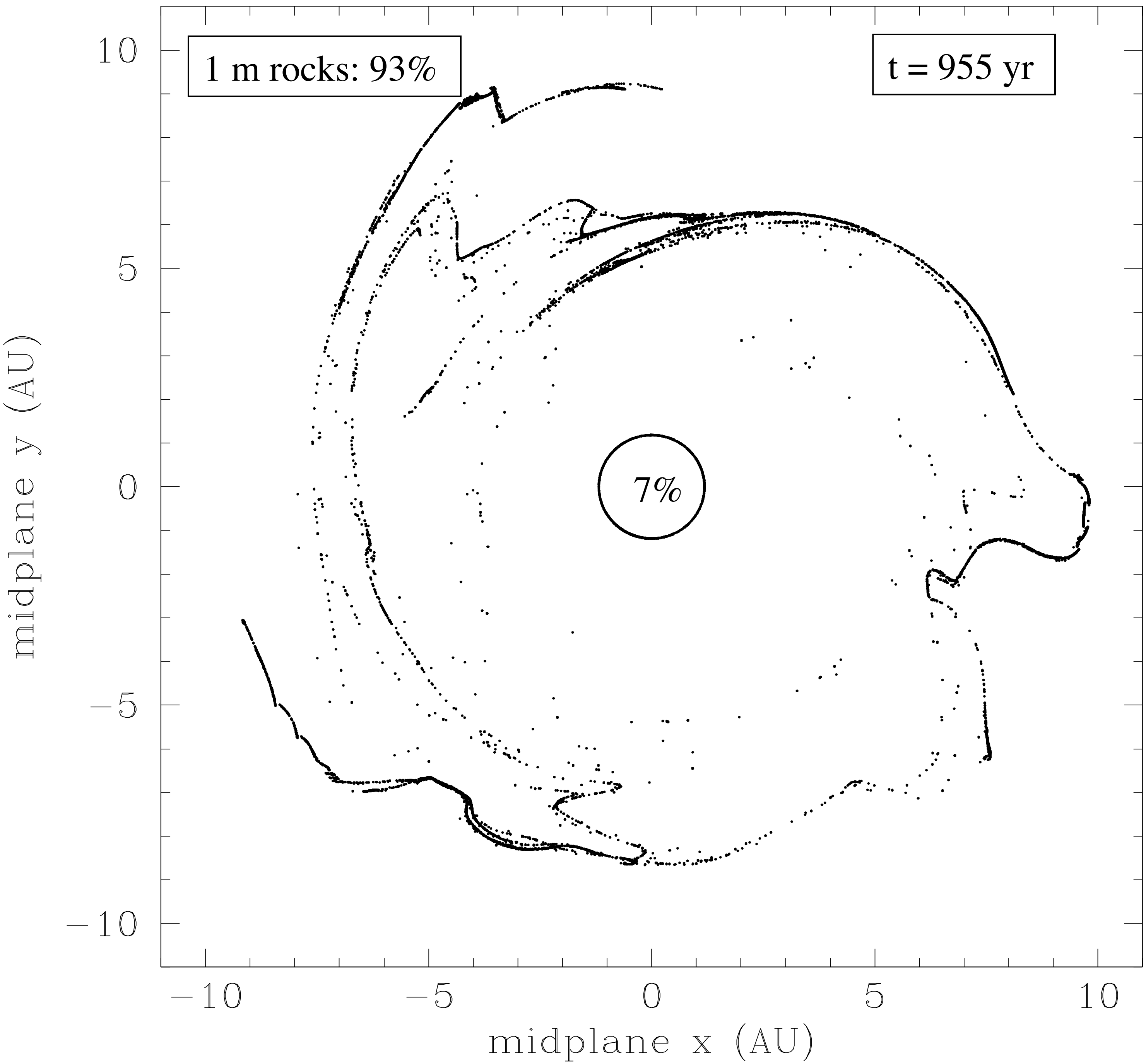

12288 particles
t = 0.01 yr
50 x 256 grid in midplane
midplane x (AU)
midplane y (AU)
−10
−5
0
5
10


1 cm particles
t = 58 yr
10
5
0
−5
−10
midplane y (AU)
−10
−5
0
5
10
midplane x (AU)

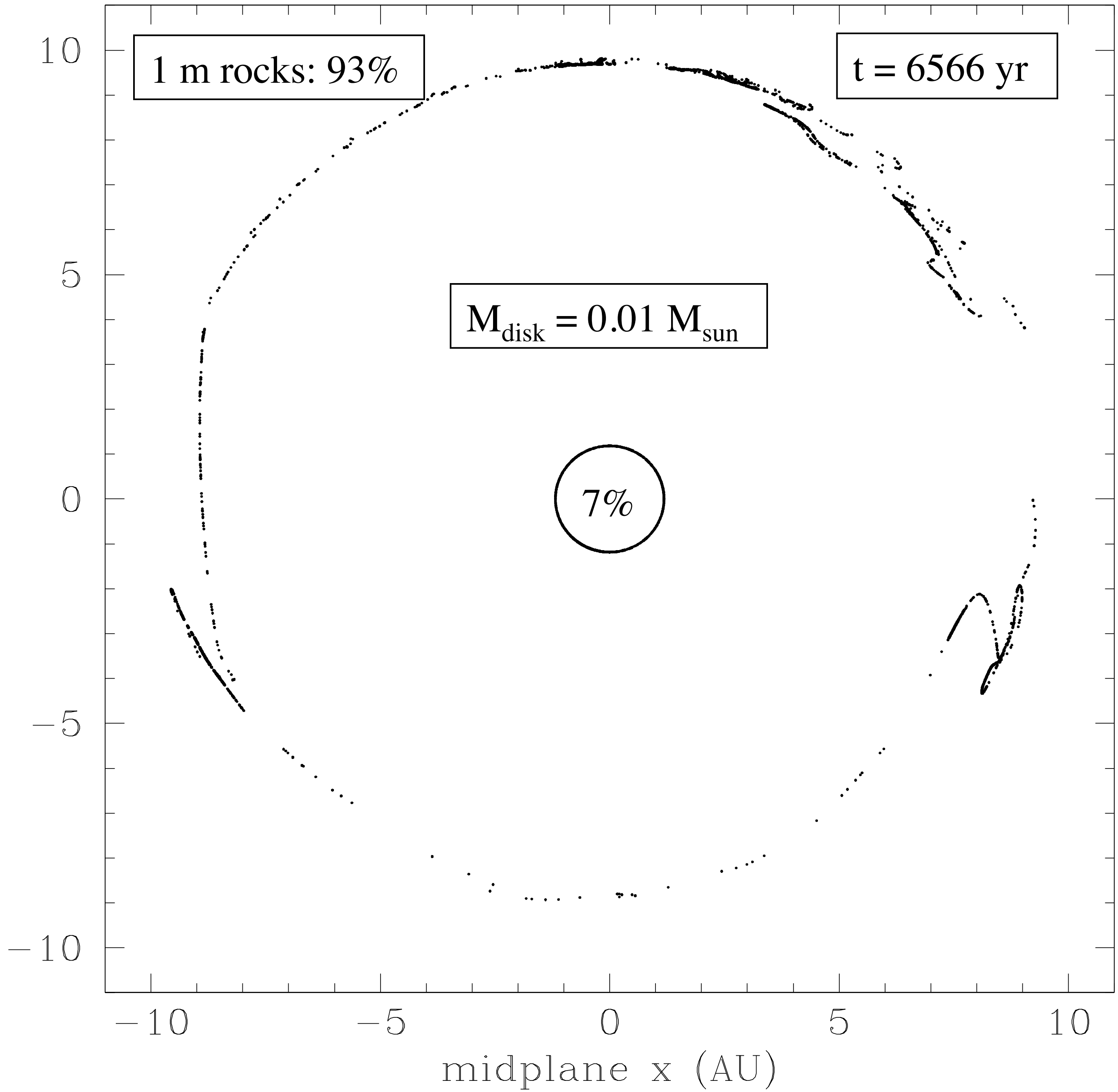

1 cm particles: 57%
t = 160 yr
<- 14 times
initial density
43%
midplane y (AU)
midplane x (AU)
10
5
0
−5
−10
−10
−5
0
5
10



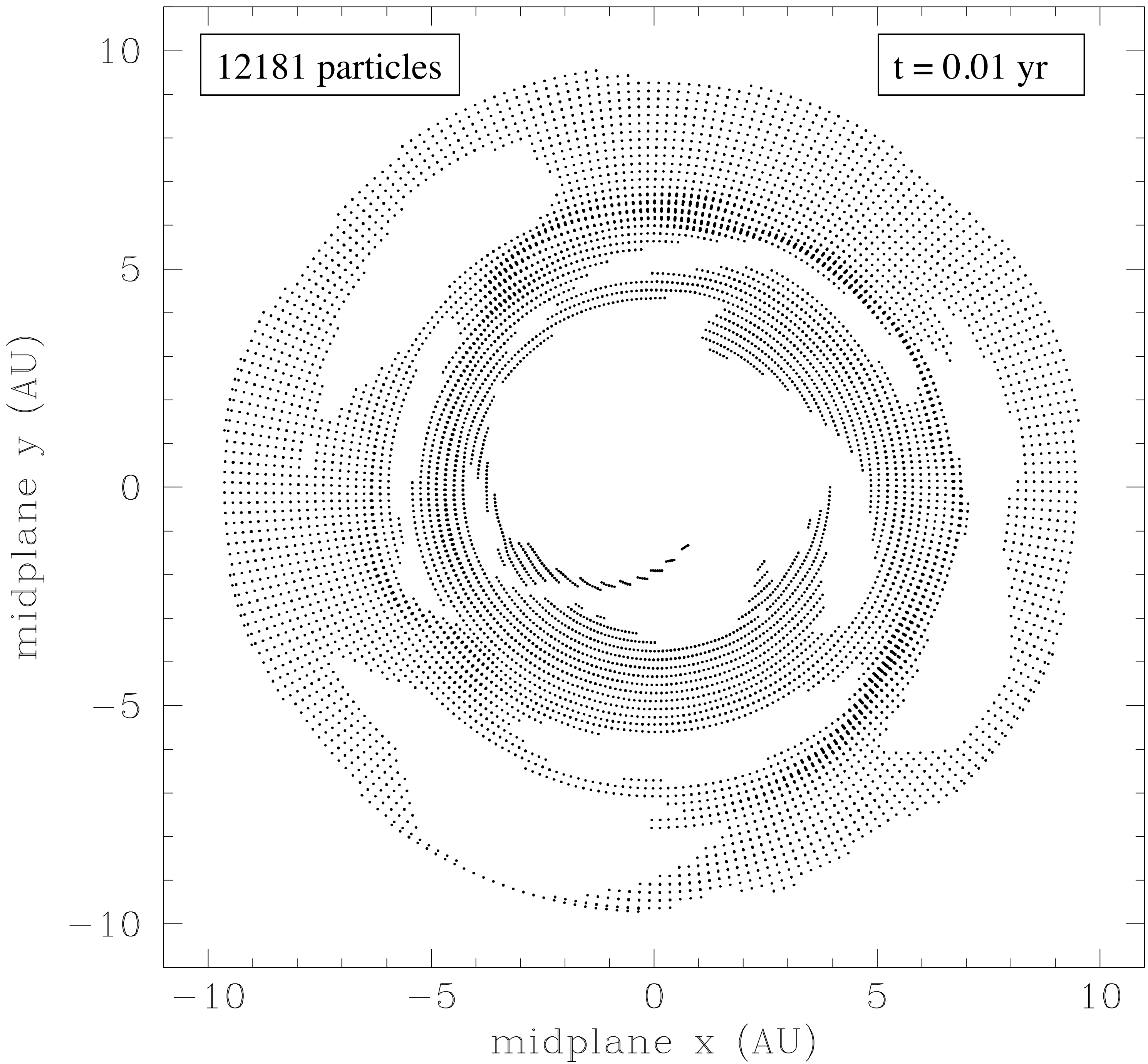
1 cm particles: 27%
t = 1600 yr
73%
midplane y (AU)
midplane x (AU)
10
5
0
−5
−10
−10
−5
0
5
10

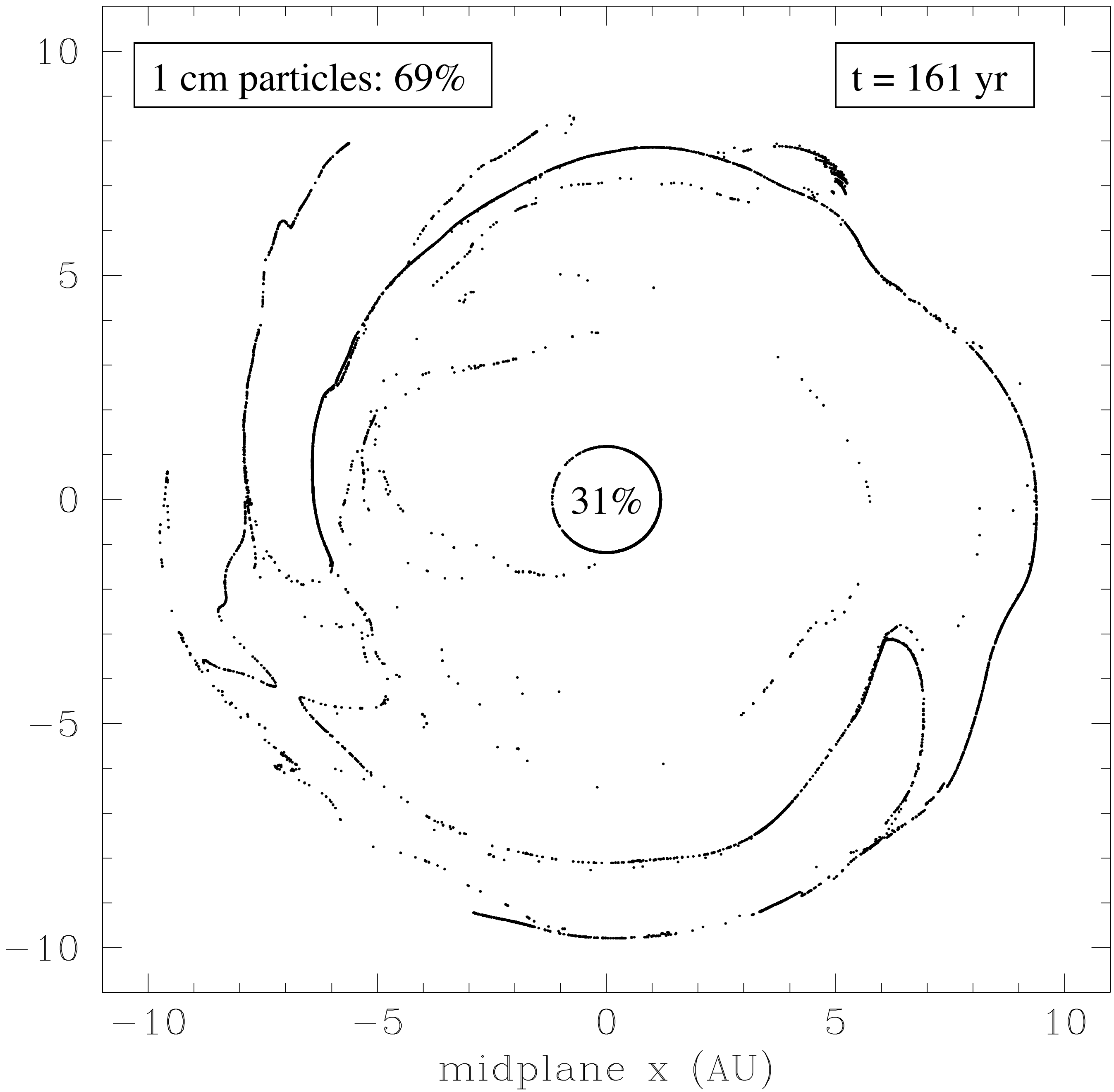


1 m rocks: 93%
t = 955 yr
7%
10
5
0
−5
−10
−10
−5
0
5
10
midplane y (AU)
midplane x (AU)

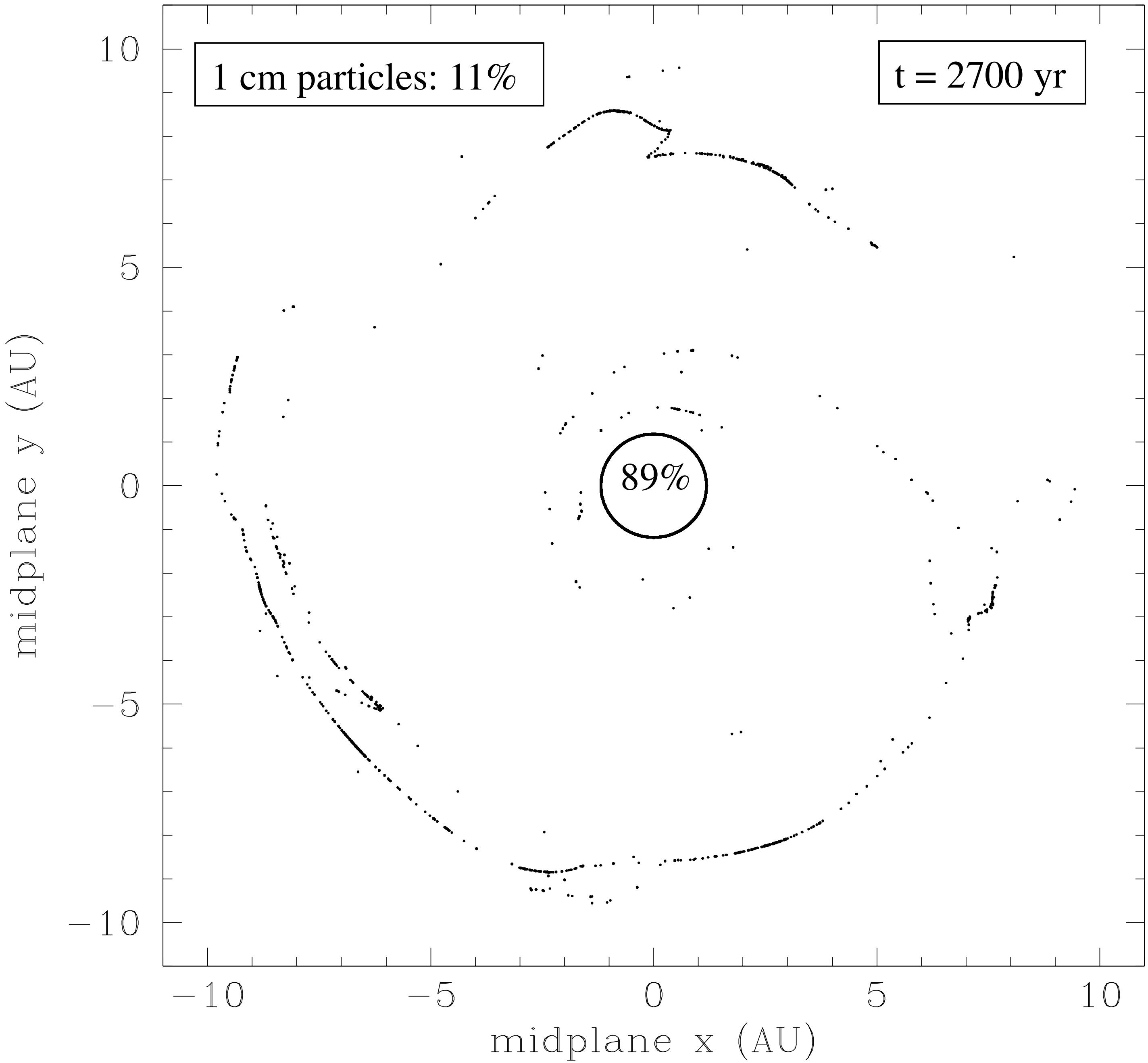


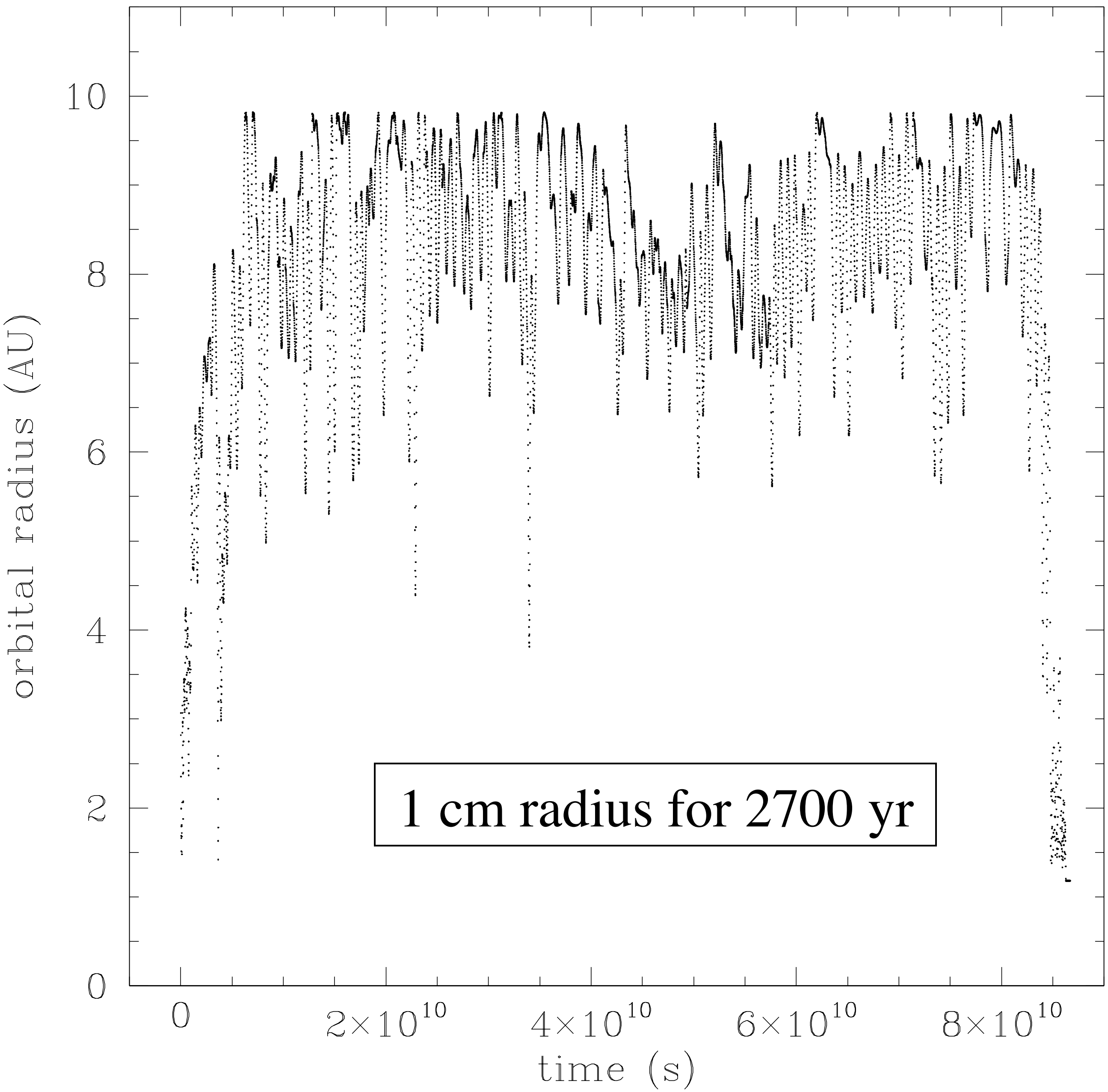
1 m rocks: 93%
t = 6566 yr
M_disk = 0.01 M_sun
7%
10
5
0
−5
−10
−10
−5
0
5
10
midplane y (AU)
midplane x (AU)


12181 particles
t = 0.01 yr
midplane y (AU)
midplane x (AU)
10
5
0
−5
−10
−10
−5
0
5
10

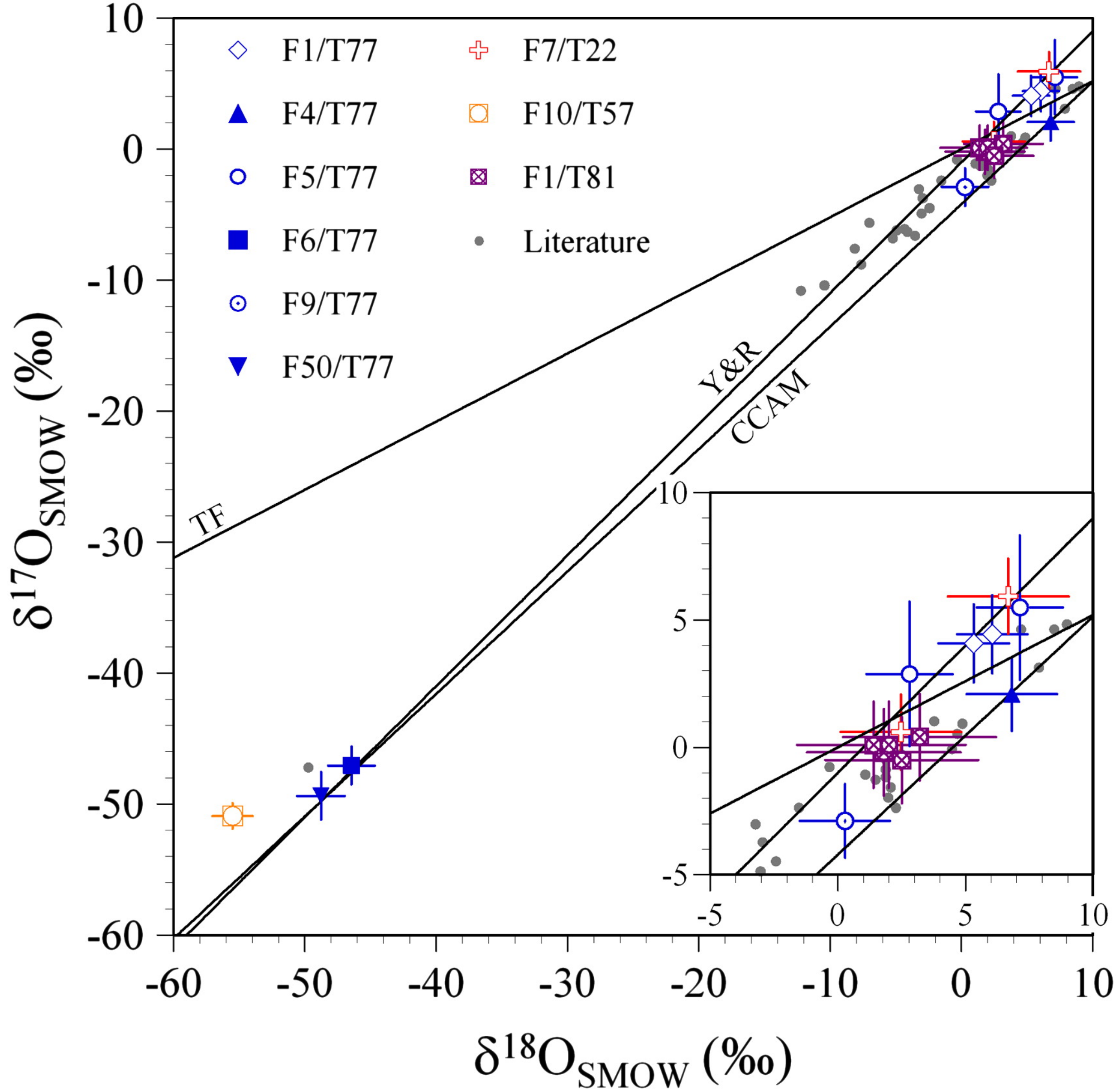


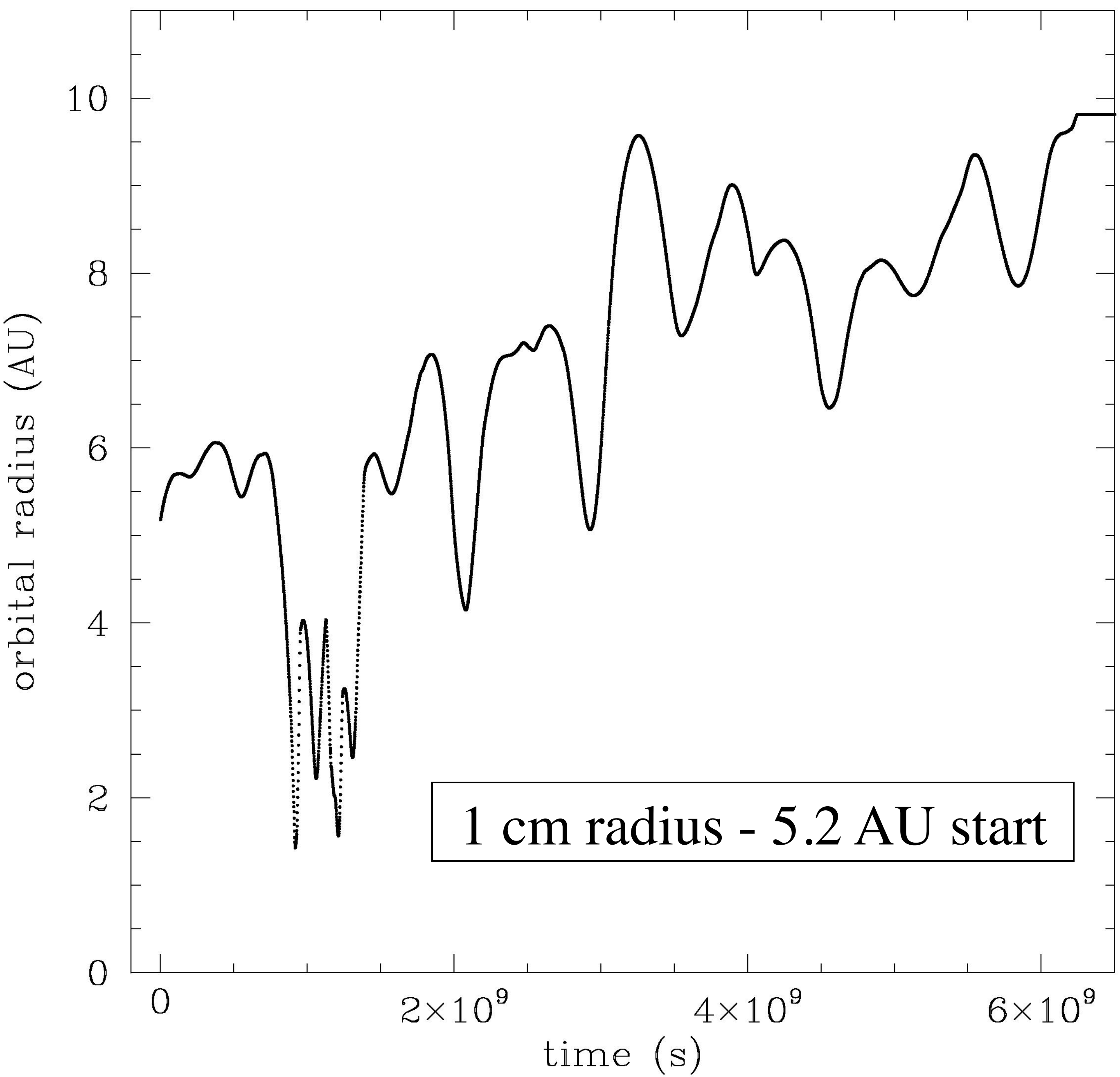
1 cm particles: 69%
t = 161 yr
31%
midplane y (AU)
midplane x (AU)
10
5
0
−5
−10
−10
−5
0
5
10


1 cm particles: 11%
t = 2700 yr
89%
midplane y (AU)
midplane x (AU)
10
5
0
−5
−10
−10
−5
0
5
10

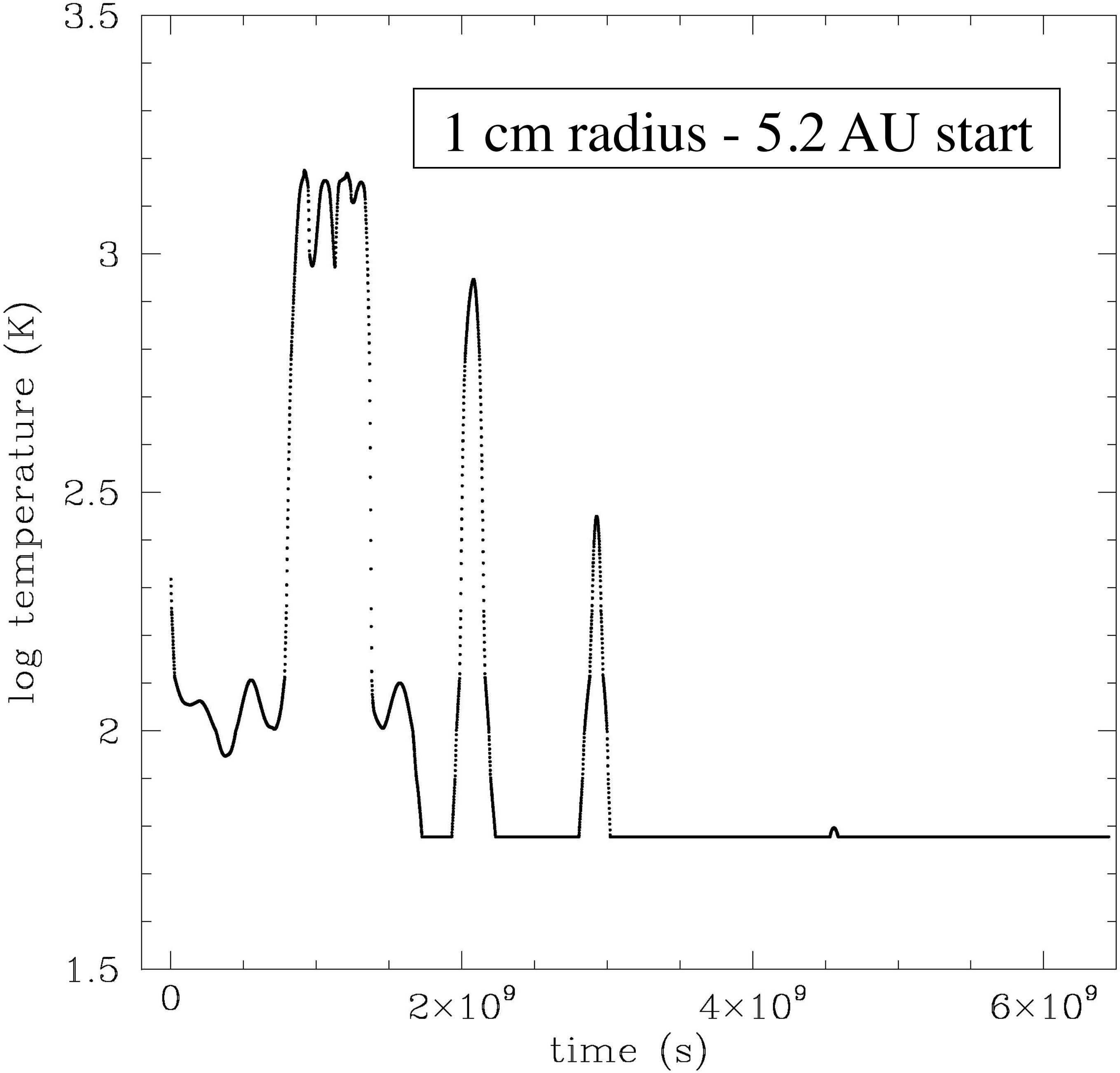

1 cm radius for 2700 yr
orbital radius (AU)
time (s)
0
2
4
6
8
10
0
2×10^10
4×10^10
6×10^10
8×10^10

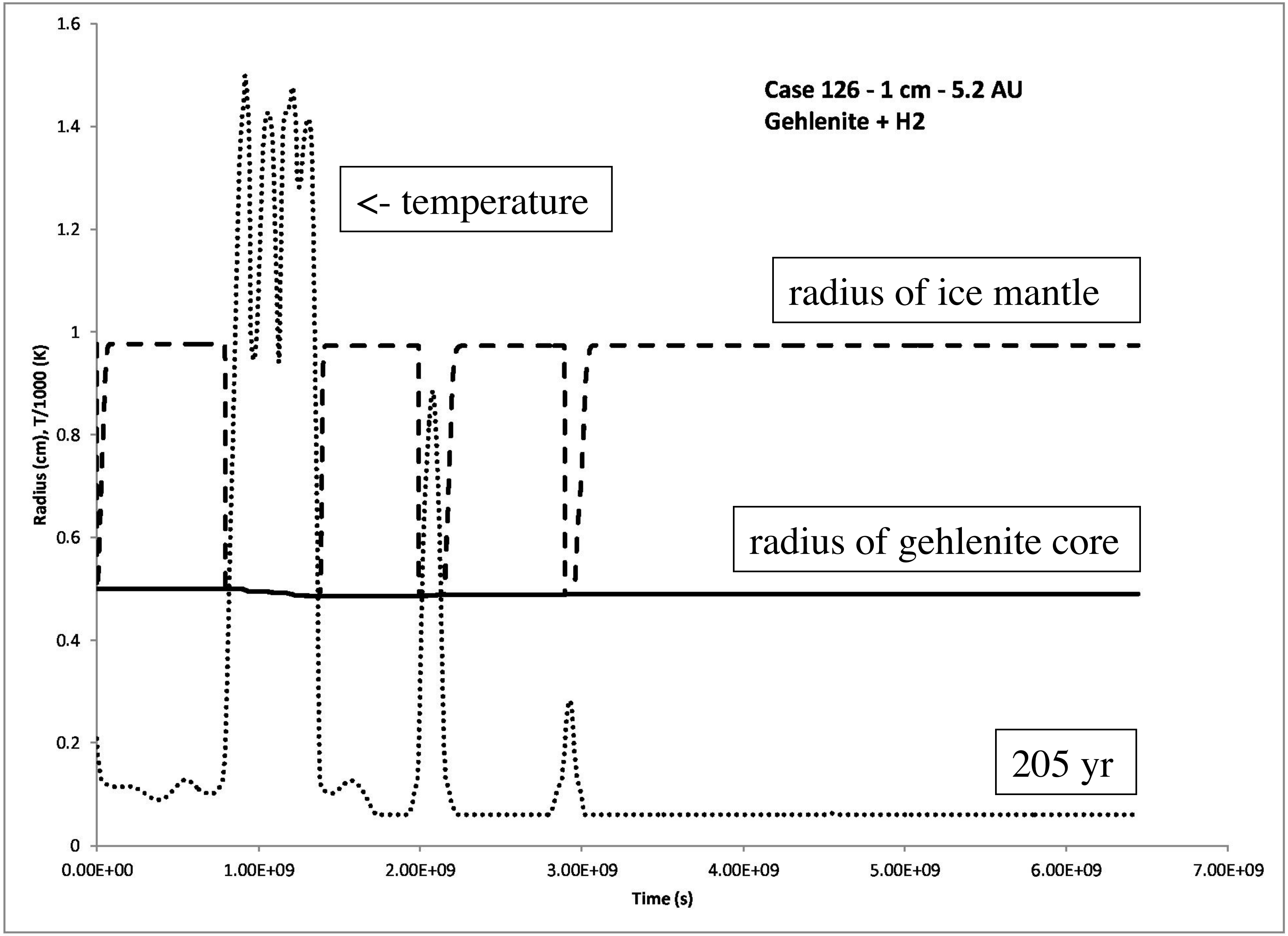
Nakashima et al. (2013): Comet Wild 2 particles



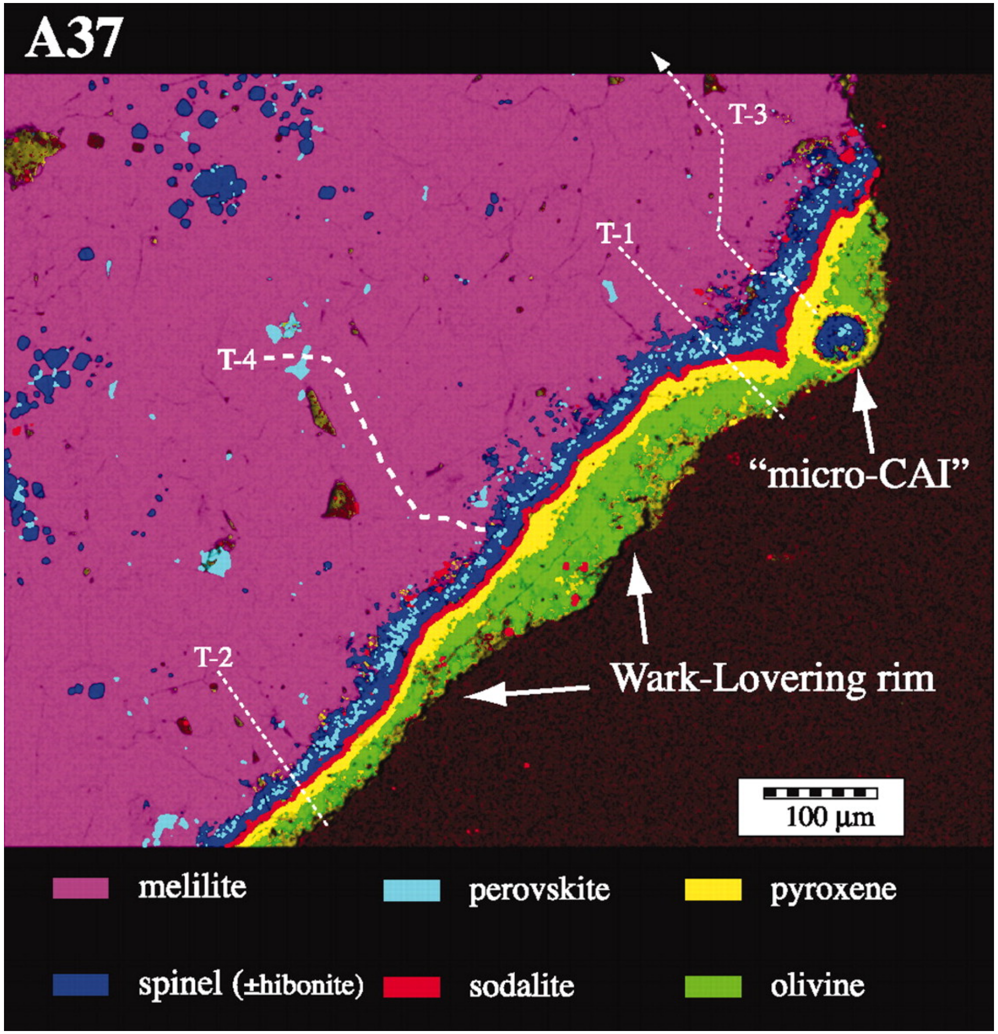


orbital radius (AU)
10
8
6
4
2
0
0
2×10^9
4×10^9
6×10^9
time (s)
1 cm radius - 5.2 AU start


1 cm radius - 5.2 AU start
log temperature (K)
time (s)
3.5
3
2.5
2
1.5
0
2×10⁹
4×10⁹
6×10⁹

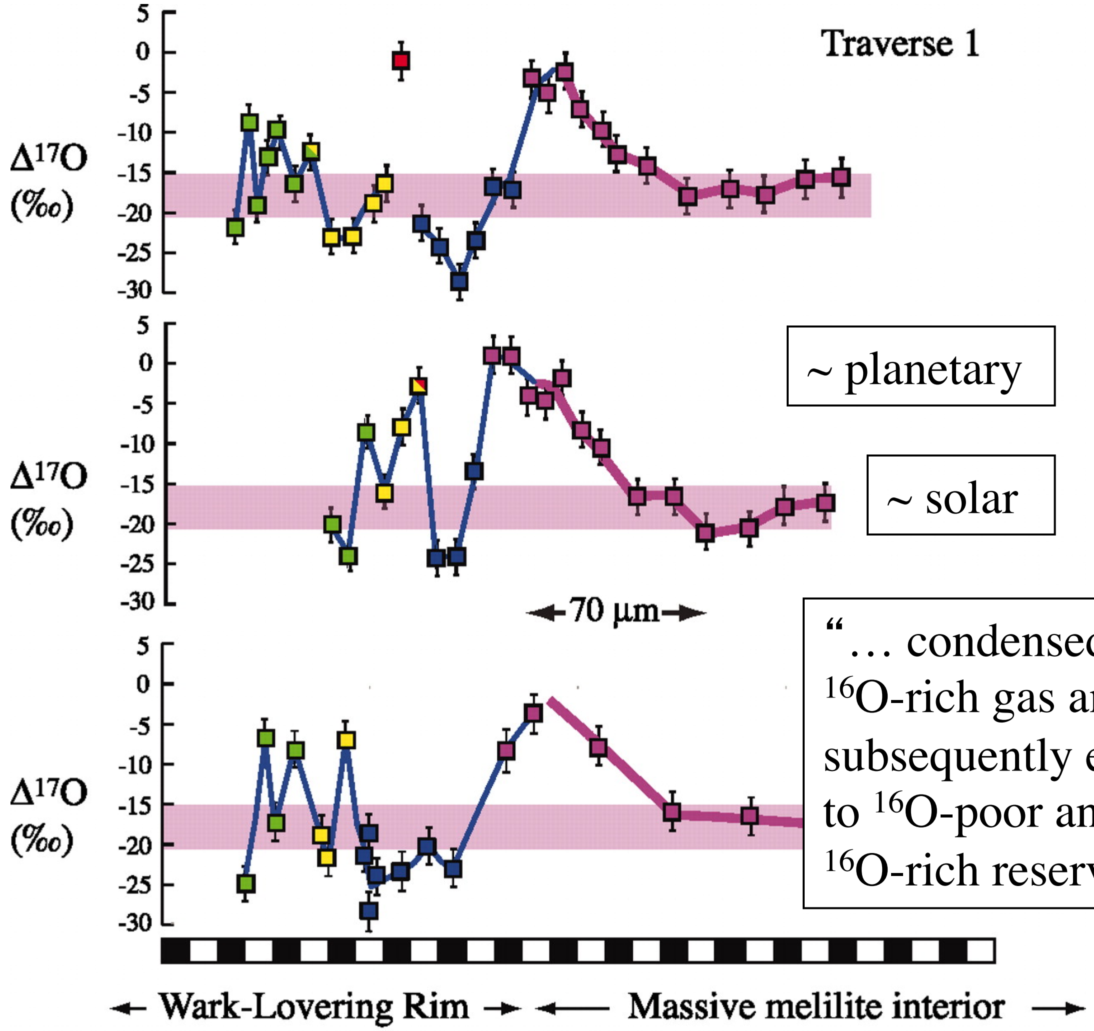

Case 126 - 1 cm - 5.2 AU
Gehlenite + H2
<- temperature
radius of ice mantle
radius of gehlenite core
205 yr
Radius (cm), T/1000 (K)
Time (s)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
0.00E+00
1.00E+09
2.00E+09
3.00E+09
4.00E+09
5.00E+09
6.00E+09
7.00E+09

Compositional X-ray image of the rim and margin of A37, a typical Type A CAI within the Allende meteorite (Simon et al. 2011)



J I Simon et al. Science 2011;331:1175-1178

Oxygen isotope zoning across the WL rim and outer margin typical of Allende Type A CAI A37, defined by ion microprobe traverses (Simon et al. 2011)



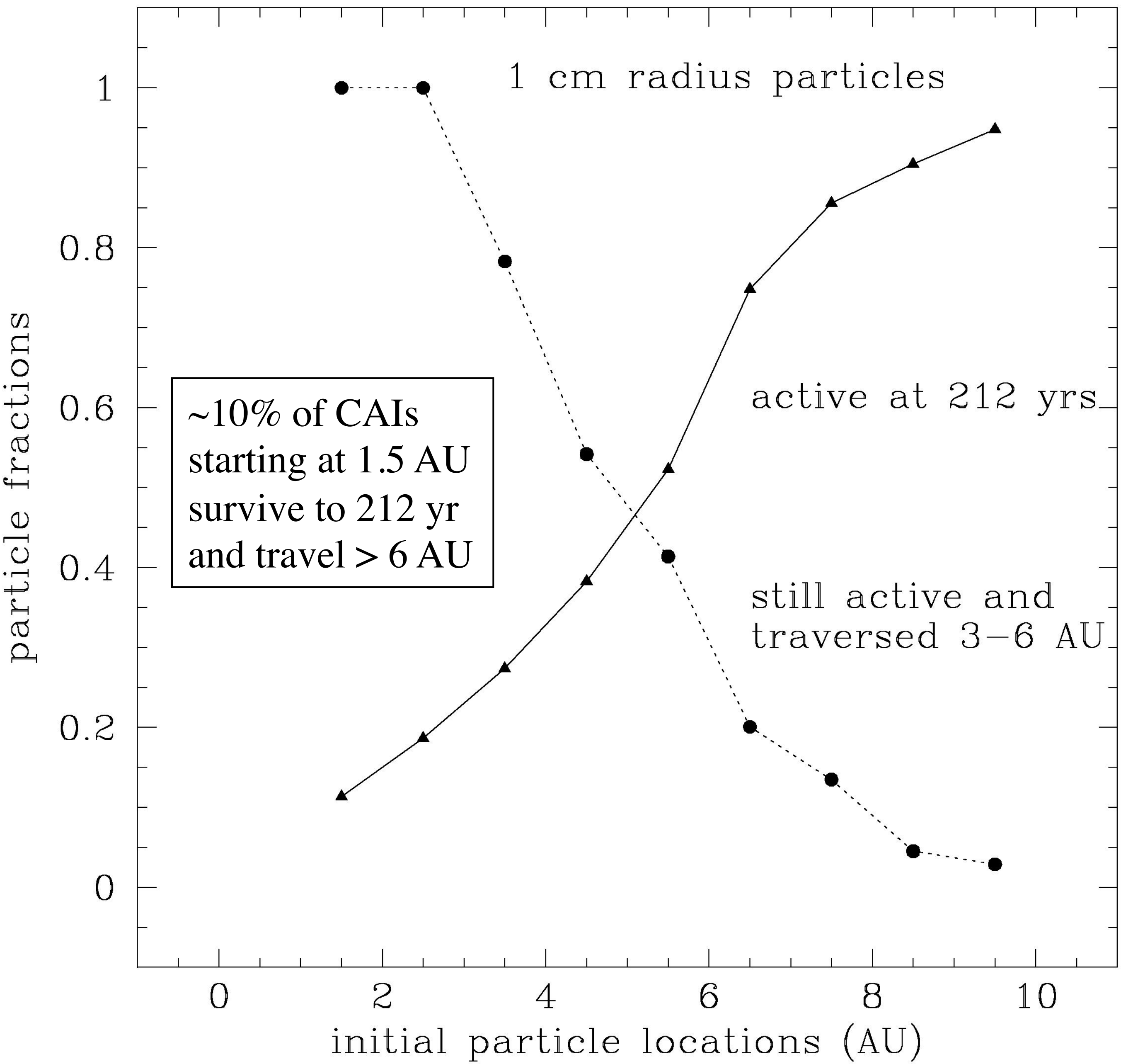
~ planetary

~ 5%

~ solar

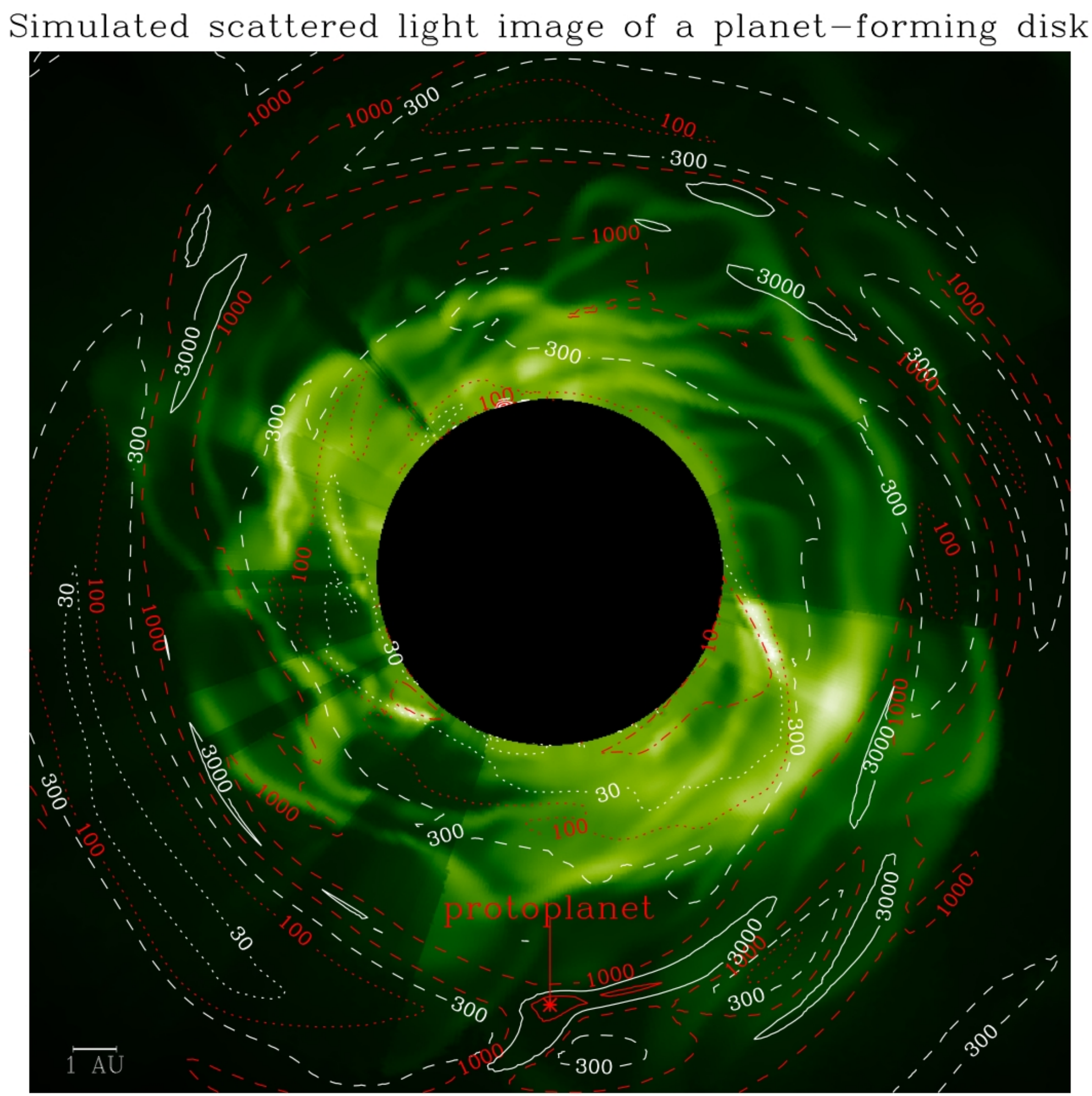
"… condensed from an ^{16}O-rich gas and was subsequently exposed to ^{16}O-poor and then ^{16}O-rich reservoirs."

J I Simon et al. Science 2011;331:1175-1178



1 cm radius particles
~10% of CAIs starting at 1.5 AU survive to 212 yr and travel > 6 AU
active at 212 yrs
still active and traversed 3−6 AU
particle fractions
initial particle locations (AU)
0
0.2
0.4
0.6
0.8
1
0
2
4
6
8
10

Jang-Condell & Boss (2007) – see Friday talk



Conclusions

- Phases of marginal gravitational instability offer a natural means to explain FU Orionis outbursts and to achieve large scale transport and mixing of gas and small particles
- Local cm-sized particle densities can be enhanced by factors of 14 or more in spiral arms over an initial uniform density, which should accelerate their collisional growth
- cm-sized grains are largely (< 90%) lost to the protostar
- m-sized rocks migrate outward and largely (> 90%) survive
- cm-sized particles can traverse the inner and outer disk several times or more, experiencing large temperature variations (1550 K to 60 K) and transporting water ice
- Type A Allende CAI A37 (Simon et al. 2011) may have experienced a phase of evolution similar to that of a cm-sized particle in an MGU disk, resulting in a WL rim sequence and oxygen isotope variations, with a “planetary” outer core
- ALMA should search for spiral arms in protoplanetary disks!