The Shifting Snowline Delivered the  's Water

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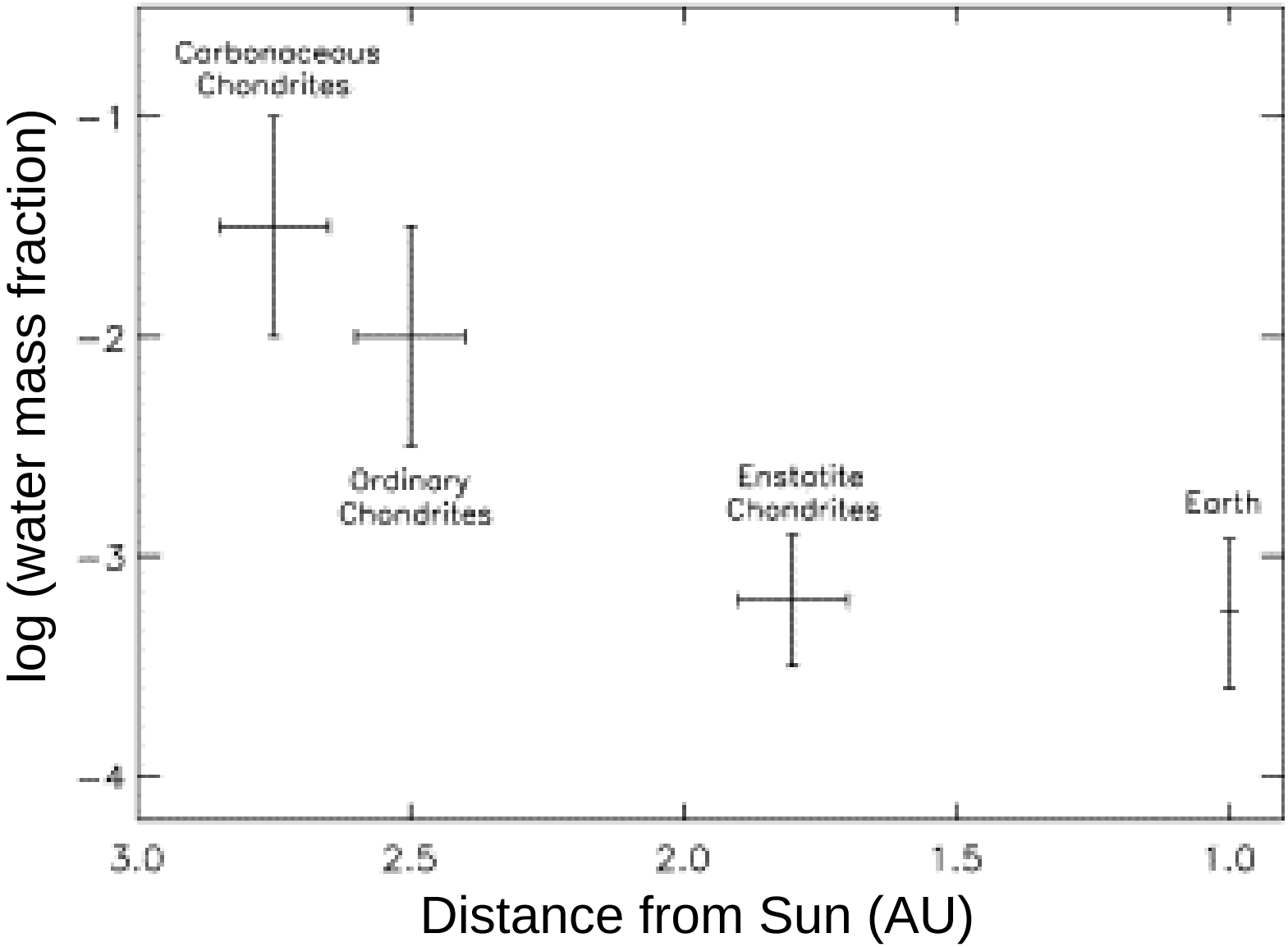
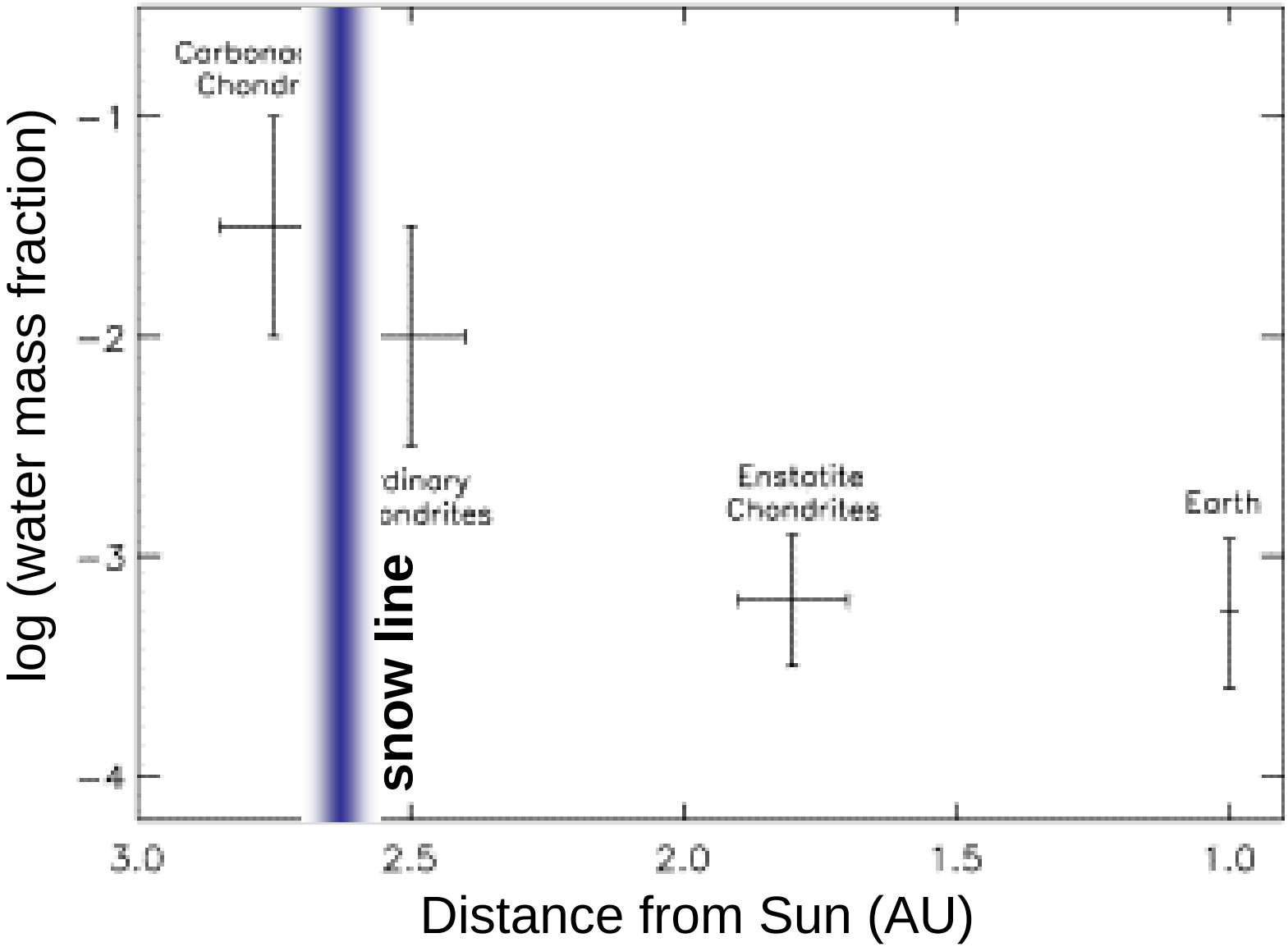
Abe 2000, Raymond et al. 2004



Abe 2000, Raymond et al. 2004



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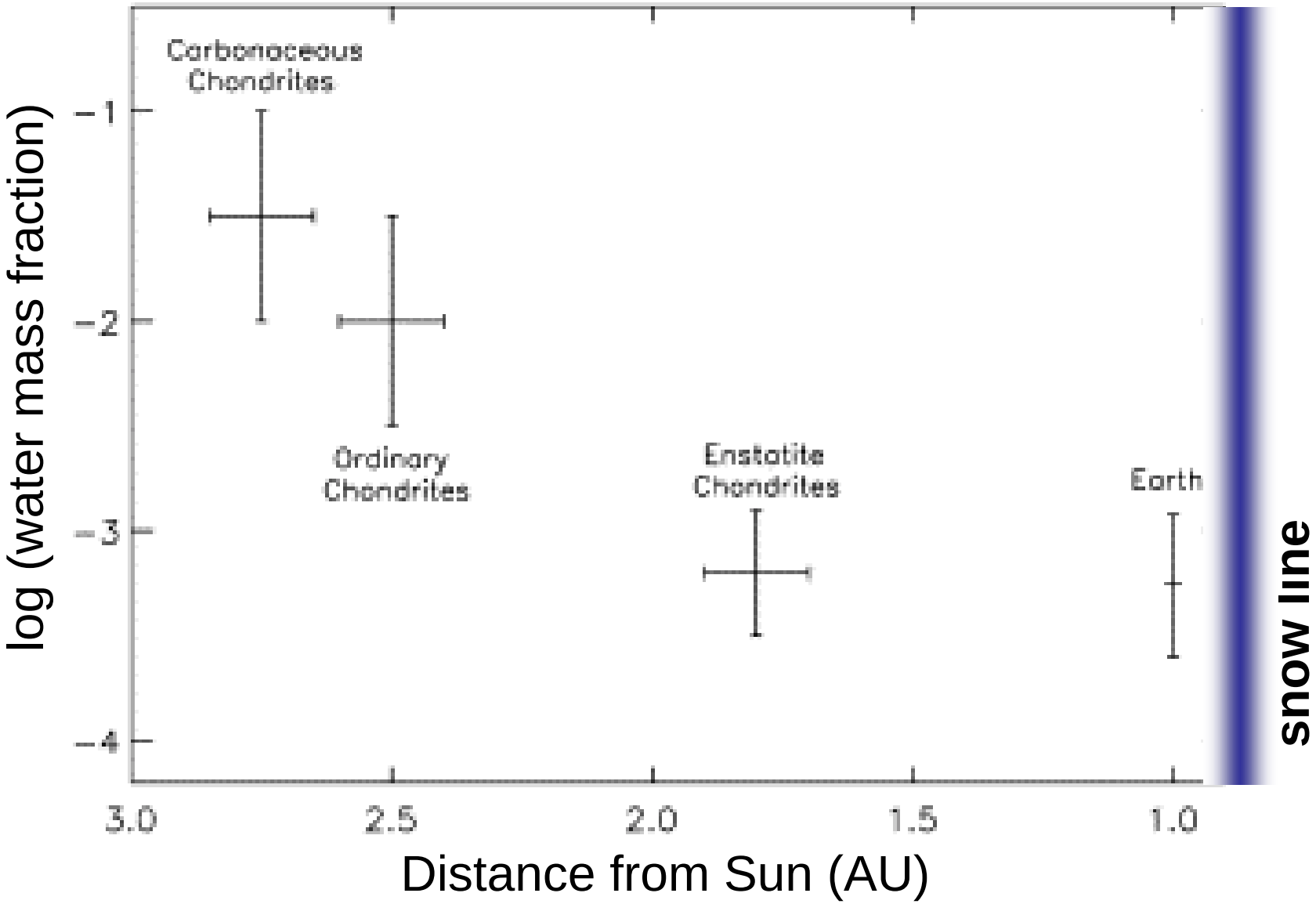
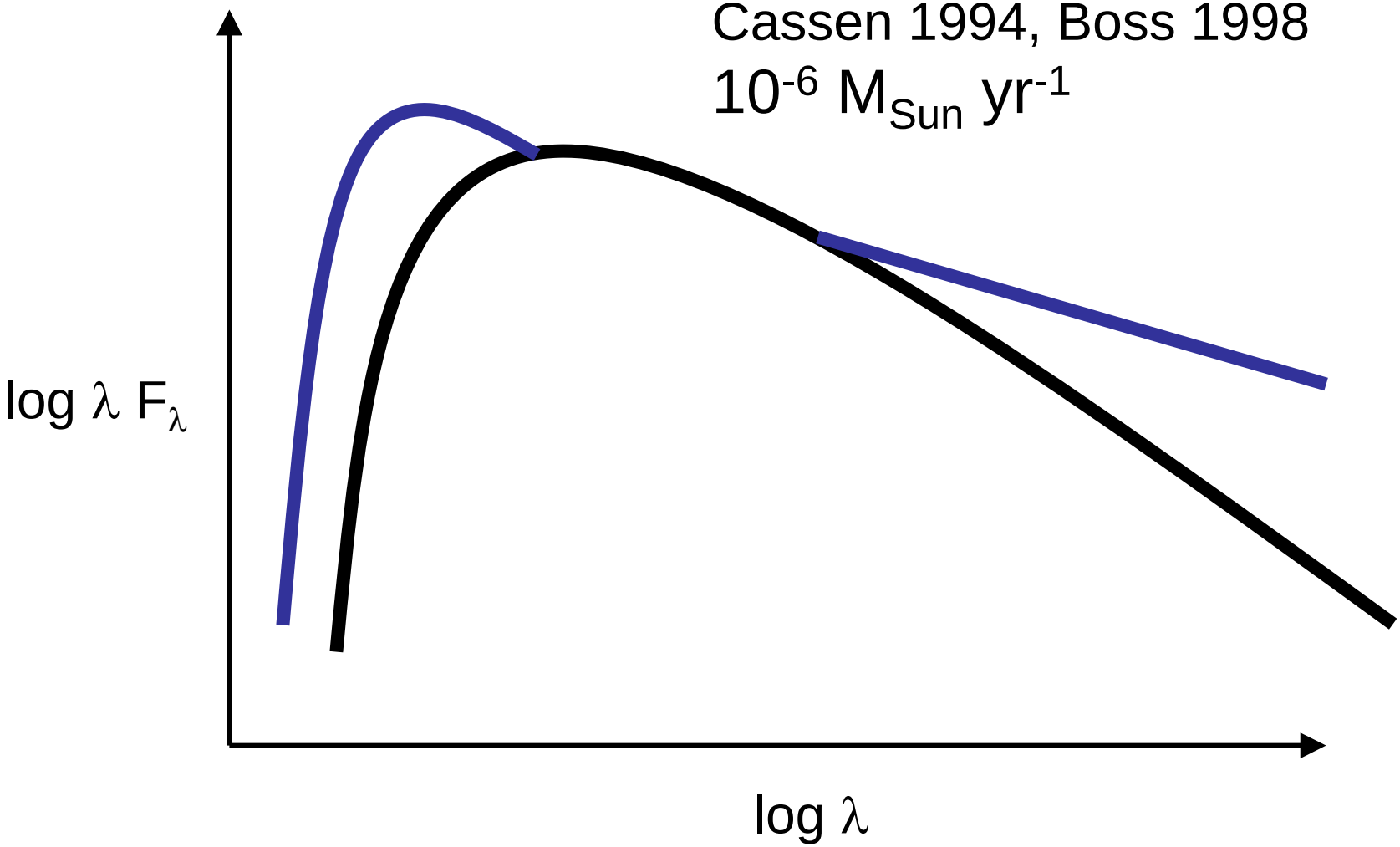
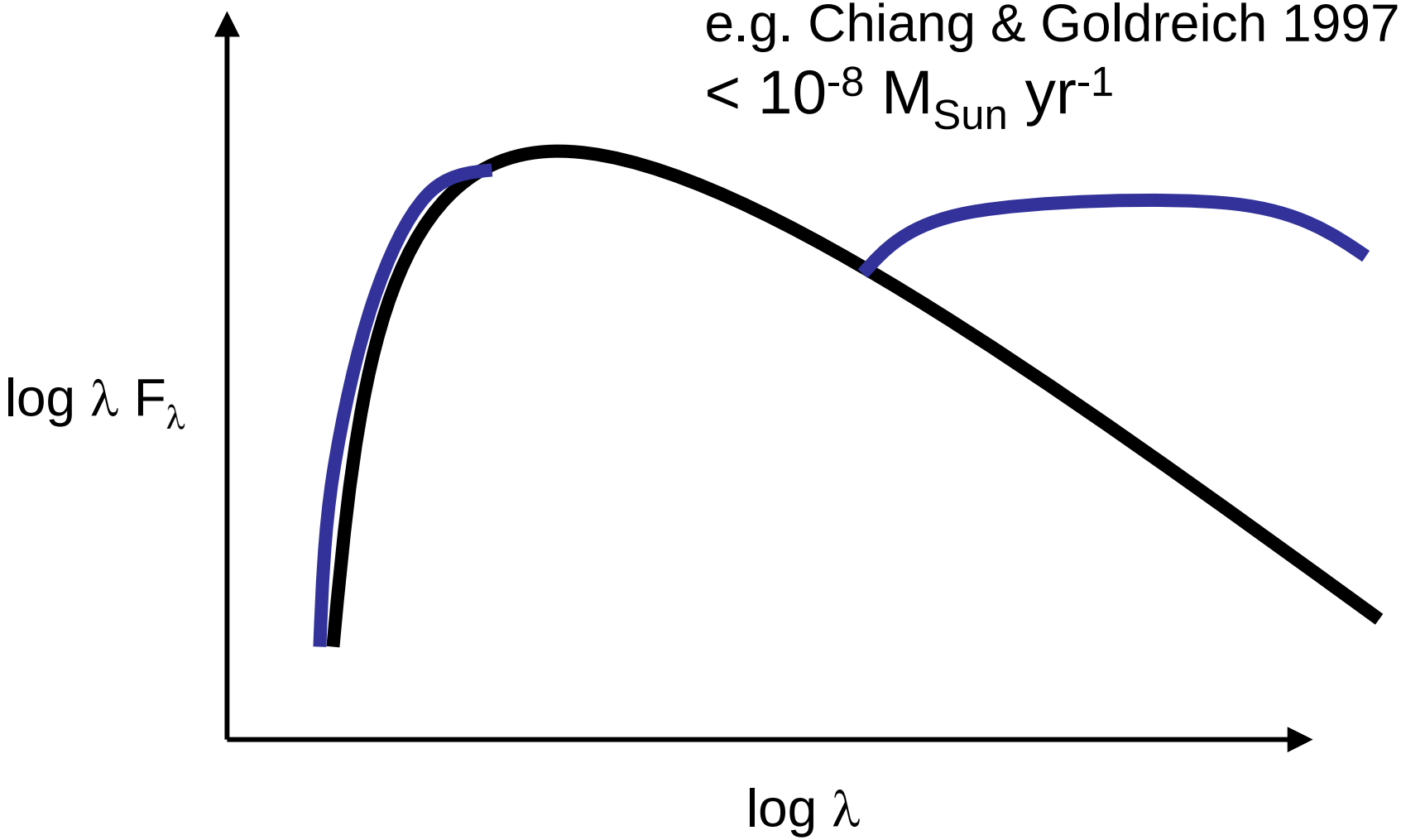
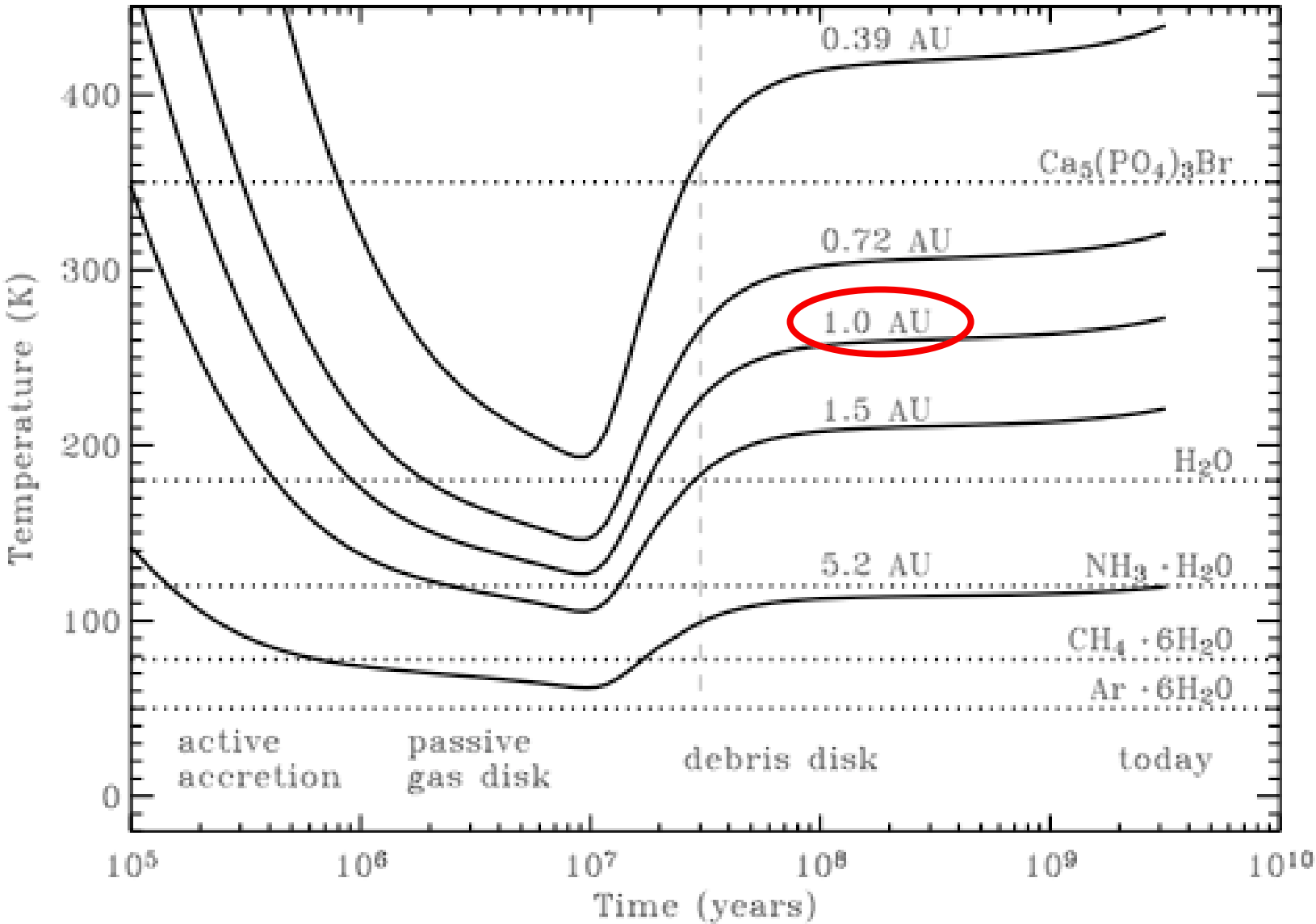
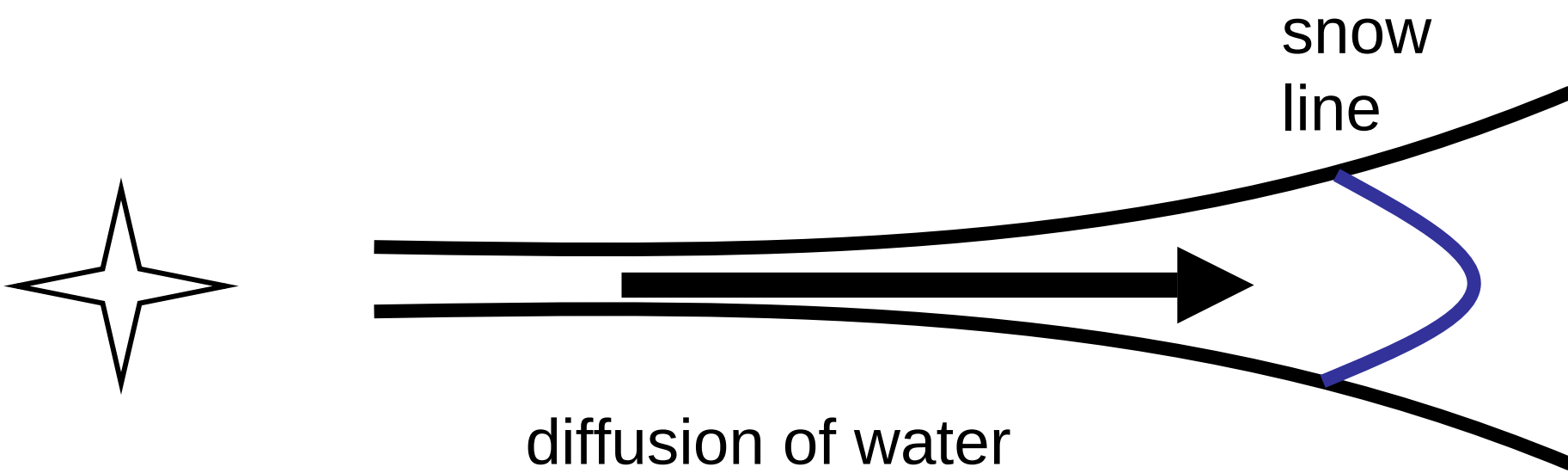
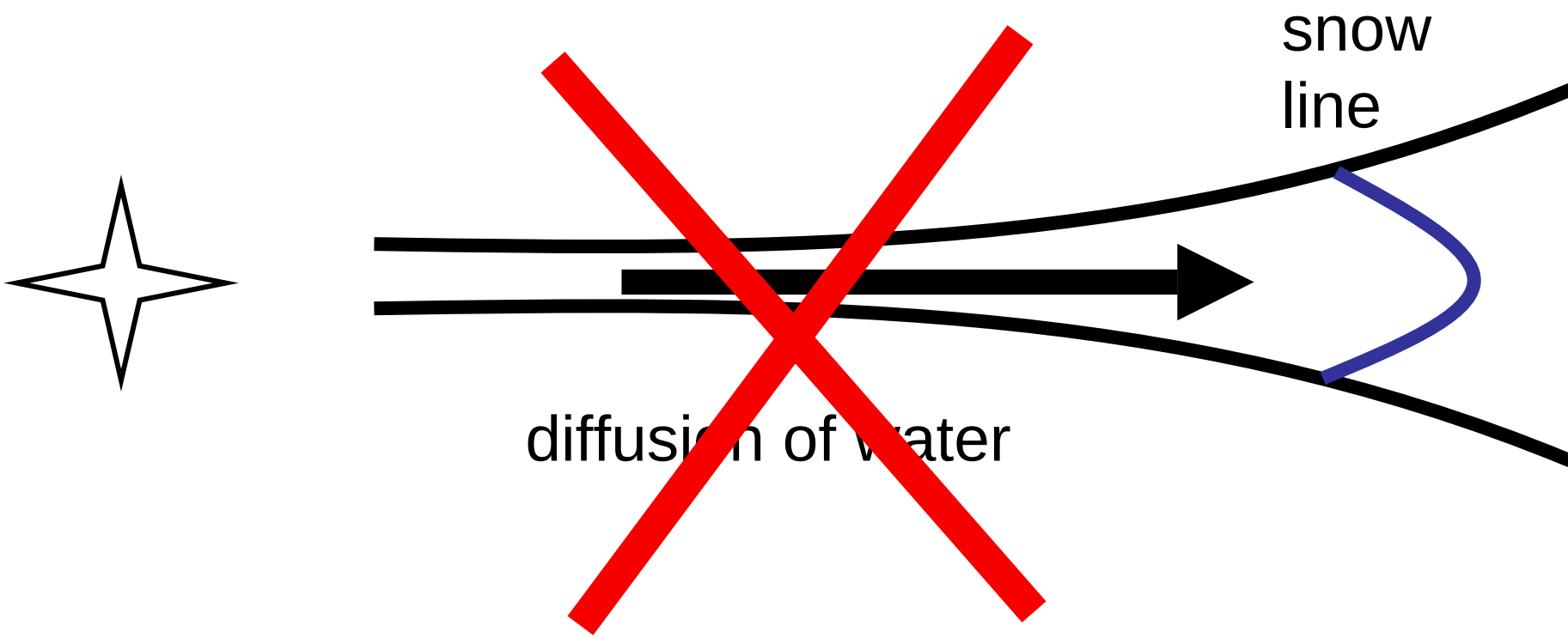



accretion-powered disk
Cassen 1994, Boss 1998
10^{-6} M_{Sun} yr^{-1}
log λ F_λ
log λ


passive disk
e.g. Chiang & Goldreich 1997
< 10-8 MSun yr-1
log λ Fλ
log λ


0.39 AU
$Ca_5(PO_4)_3Br$
0.72 AU
1.0 AU
1.5 AU
H_2O
5.2 AU
$NH_3 \cdot H_2O$
$CH_4 \cdot 6H_2O$
$Ar \cdot 6H_2O$
active accretion
passive gas disk
debris disk
today
Temperature (K)
0
100
200
300
400
10^5
10^6
10^7
10^8
10^9
10^{10}
Time (years)


snow
line
diffusion of water


snow
line
diffusion of water

where does the snow go?

Neglect effect of body on gas:

Two capture regimes for bodies on circular orbits:

$f \sim f_z \, (1/\tau_s)(r_{eff}/a)$ for $r_{eff}/a << \eta$

$f \sim f_z \, (1/\eta)(r_{eff}/a)^2$ for $r_{eff}/a >> \eta$

where $1 - \eta = V_{gas}/V_{kepler}$

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Two capture regimes for bodies on circular orbits:

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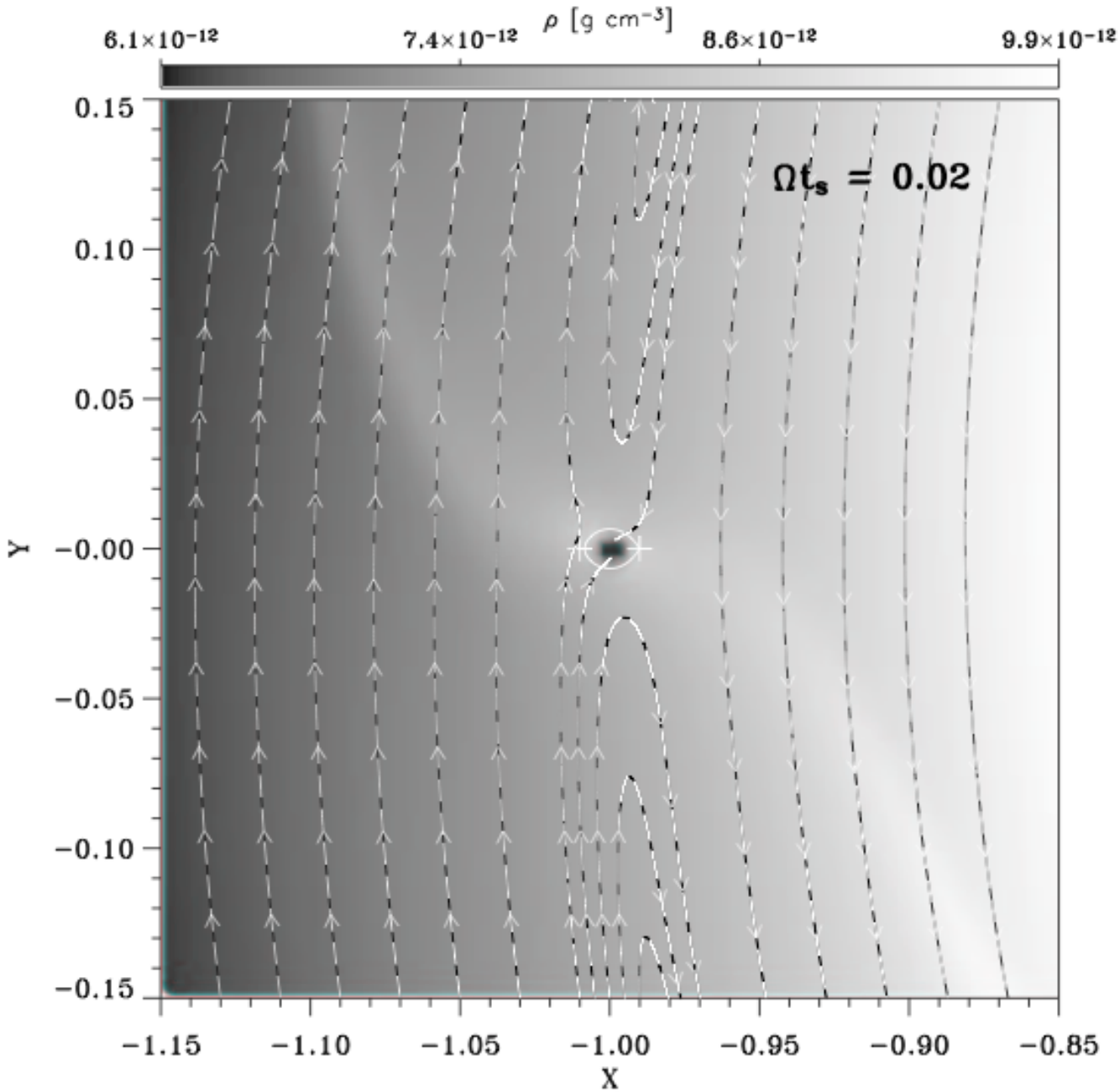
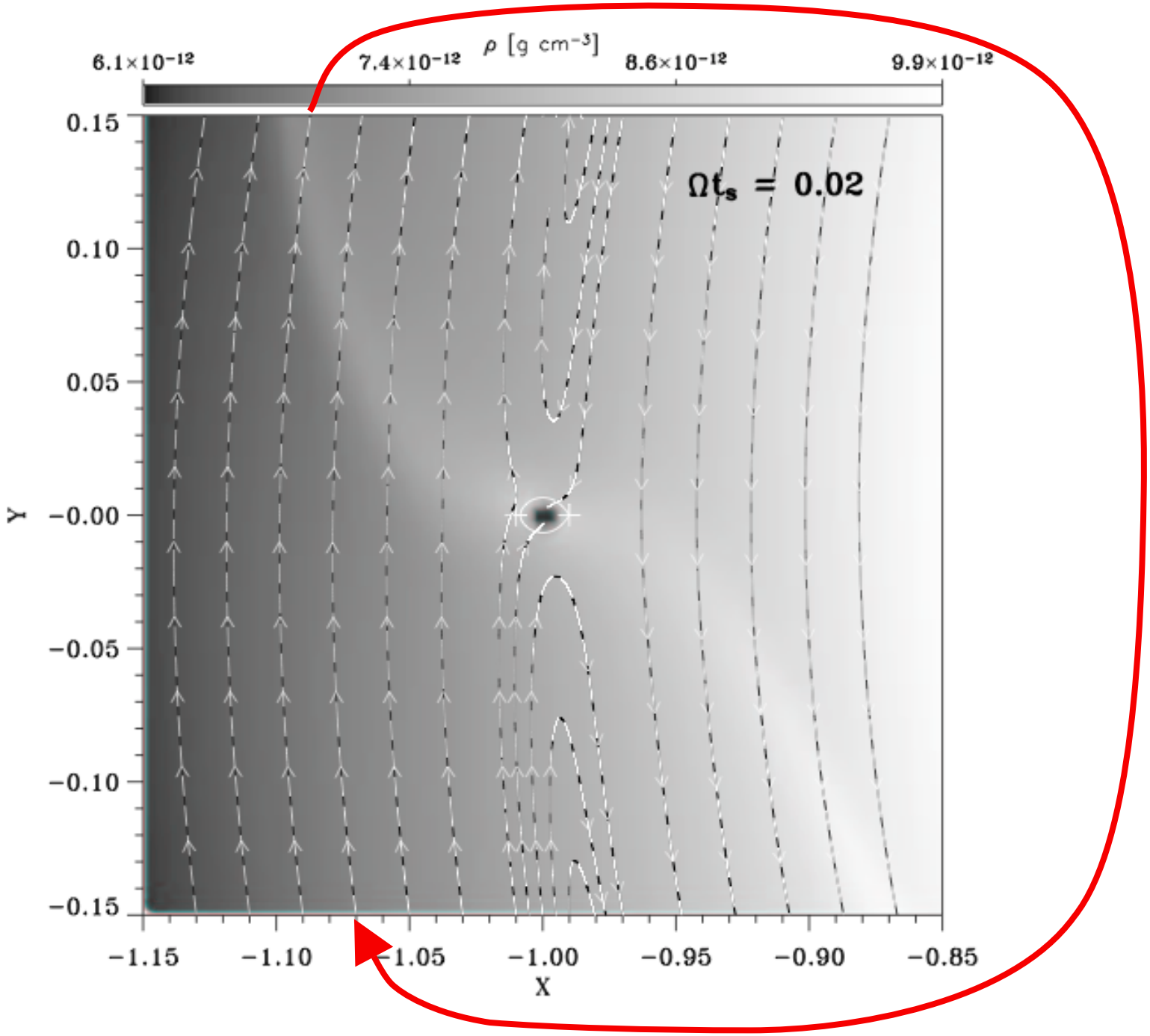
$f \sim f_z \, (1/\eta)(r_{eff}/a)^2$ for $r_{eff}/a >> \eta$

where $1 - \eta = V_{gas}/V_{kepler}$

Eccentric/inclined orbits:

increase f by a factor of $(e^2 + i^2)^{1/2}/\eta$


ρ [g cm⁻³]
6.1×10⁻¹²
7.4×10⁻¹²
8.6×10⁻¹²
9.9×10⁻¹²
Ωt_s = 0.02
0.15
0.10
0.05
−0.00
−0.05
−0.10
−0.15
Y
−1.15
−1.10
−1.05
−1.00
−0.95
−0.90
−0.85
X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Ωt_s = 0.02
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−0.10
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Y
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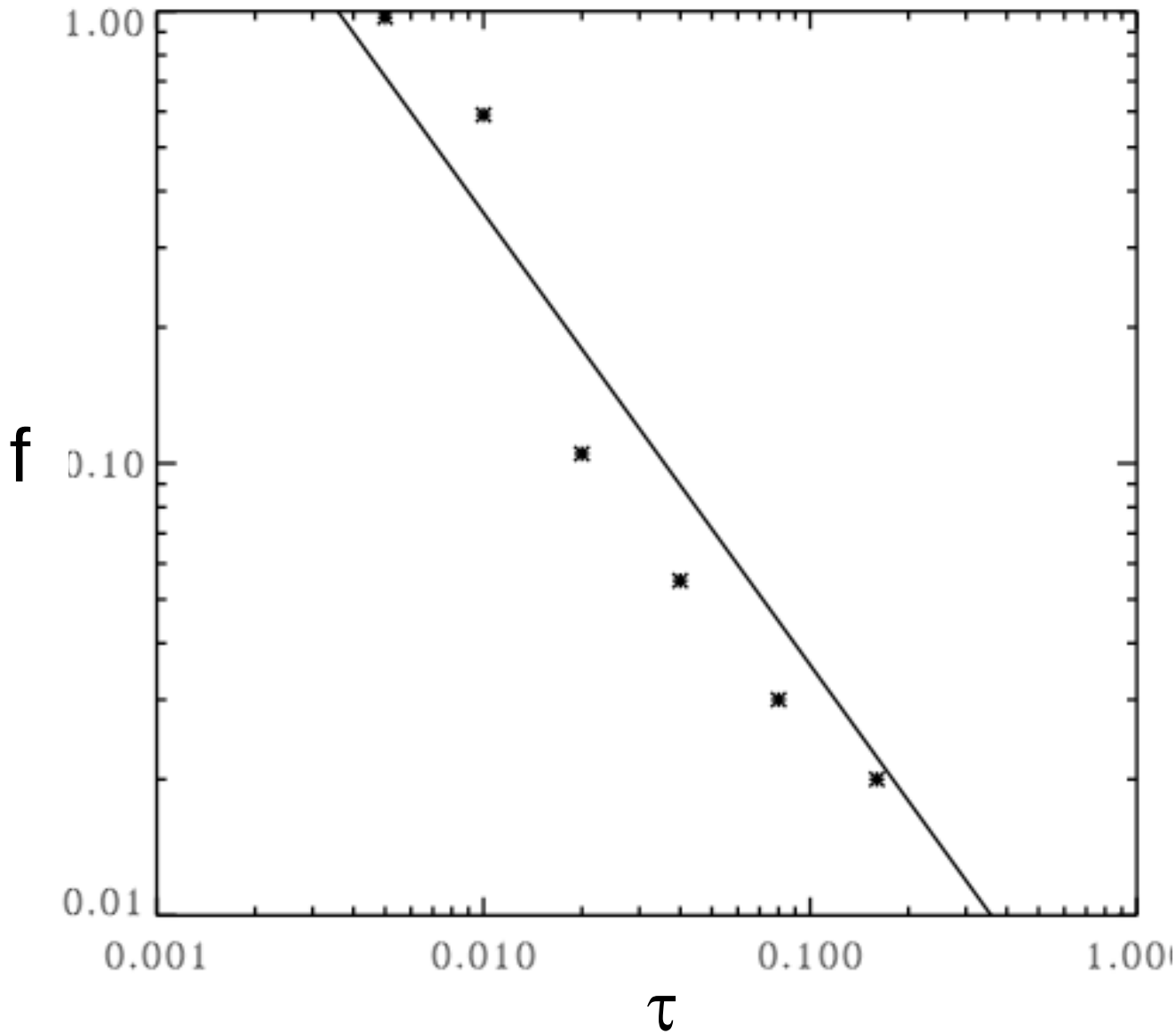
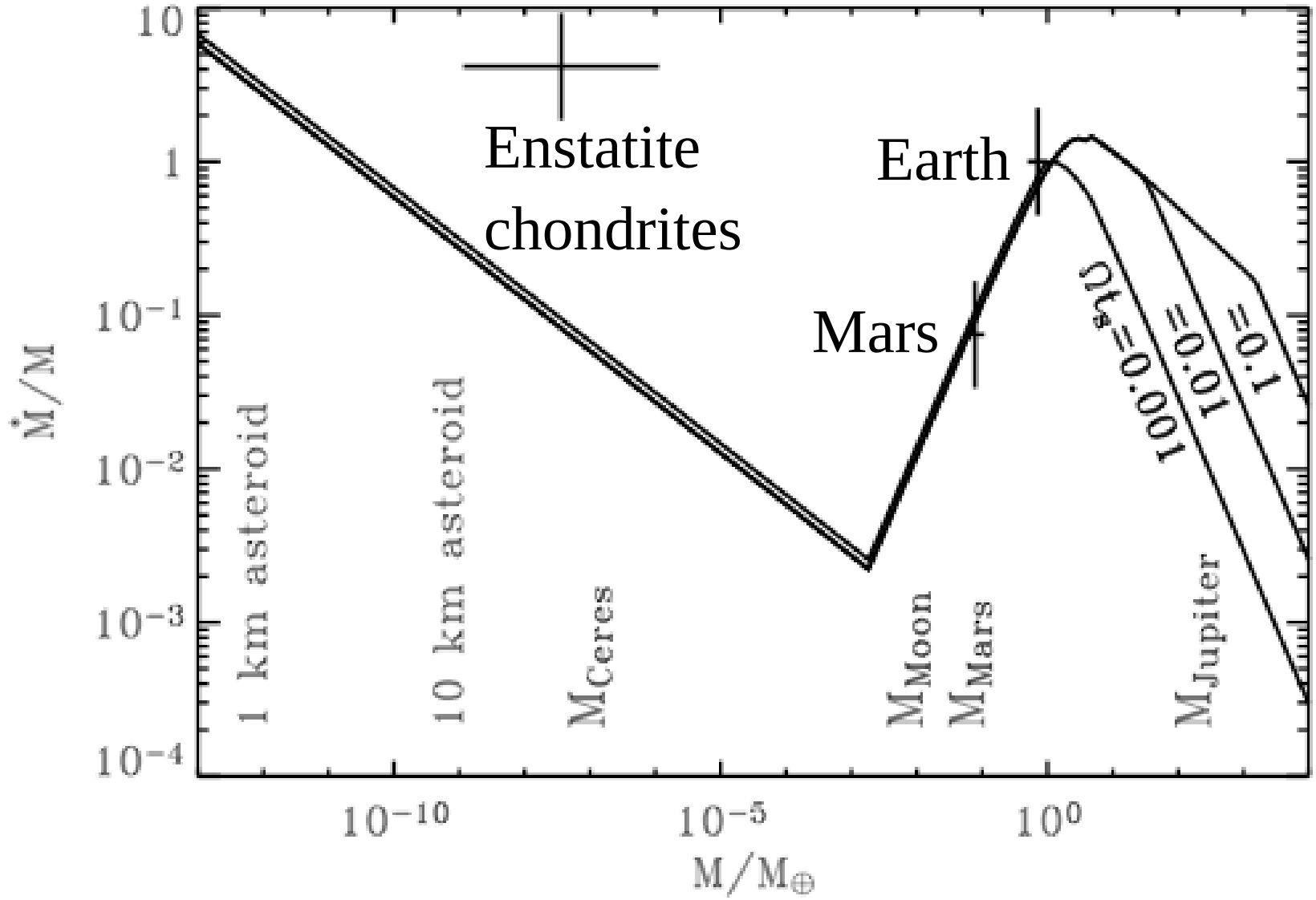
−1.00
−0.95
−0.90
−0.85
X


1.00
0.10
0.01
f
0.001
0.010
0.100
1.00
τ


Enstatite
chondrites
Earth
Mars
1 km asteroid
10 km asteroid
M_{Ceres}
M_{Moon}
M_{Mars}
$M_{Jupiter}$
Ωt_s=0.001
=0.01
=0.1
$\dot{M}/M$
$M/M_\oplus$
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-10}
10^{-5}
10^{0}

Water Delivery by Icy Planetesimals

- Fine tuning: no giant asteroids seen today

- Giant asteroid must match composition of PUM, unlike any known asteroids (Drake & Righter 2000)

- Lunar-mass objects are likely water-poor