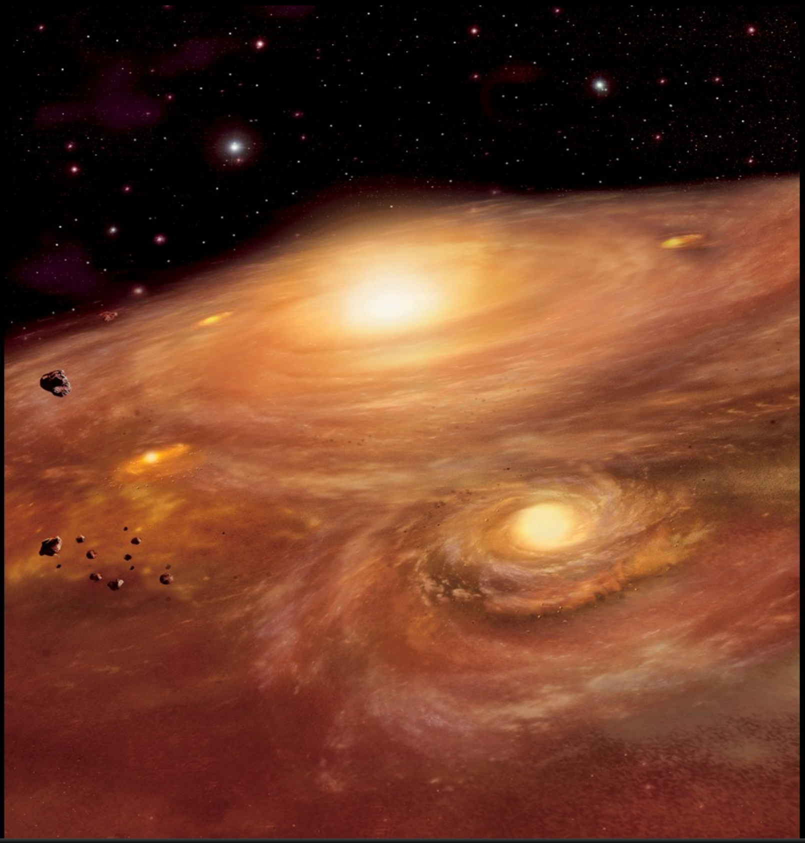
Planetesimal Formation by Turbulent Concentration



Artwork depicting one theory of how gas-giant planets form
Artwork courtesy Moonrunner Design

NATIONAL GEOGRAPHIC

Ron Ballouz
Terps 2012

Planet Formation

1. micrometer dust particles

    -collisions + gravitational collapse

2.Kilometer sized planetesimals

    -collisions

3.1000 km + planetary embryos

    -giant collisions

Proto-planet

...

Problem: Turbulence

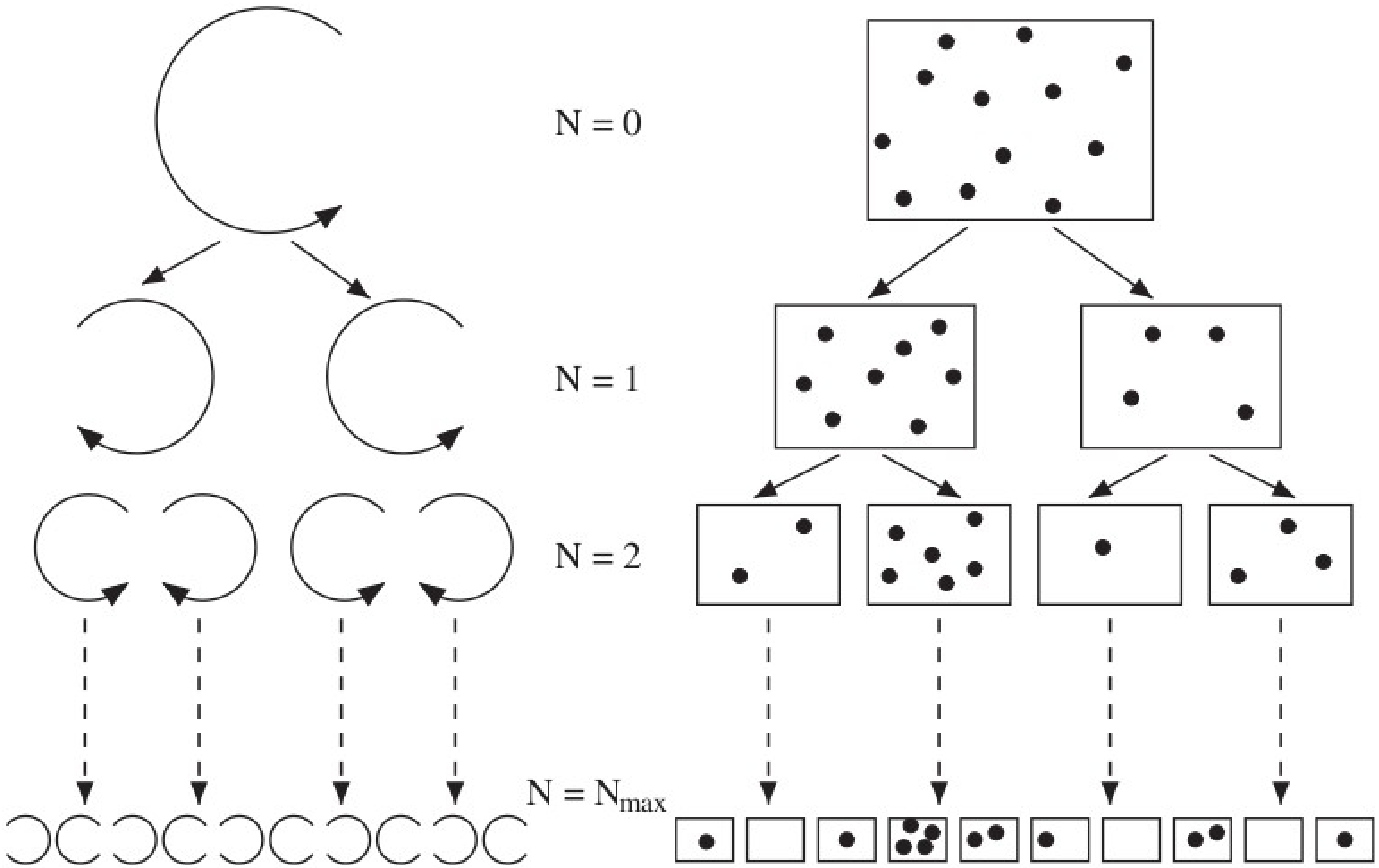
- Gas travels at sub-Keplerian velocities creating a shear.
- Generates turbulence which frustrates particle growth
- Gravitational Instability: even low levels of turbulence prevents particles from settling in to mid-plane
- Pair-wise Sticking:
  - turbulence leads to large collision speeds.
  - Once meter-sizes are reached particles drift inwards in short timescale... need another mechanism

Solution: Turbulence

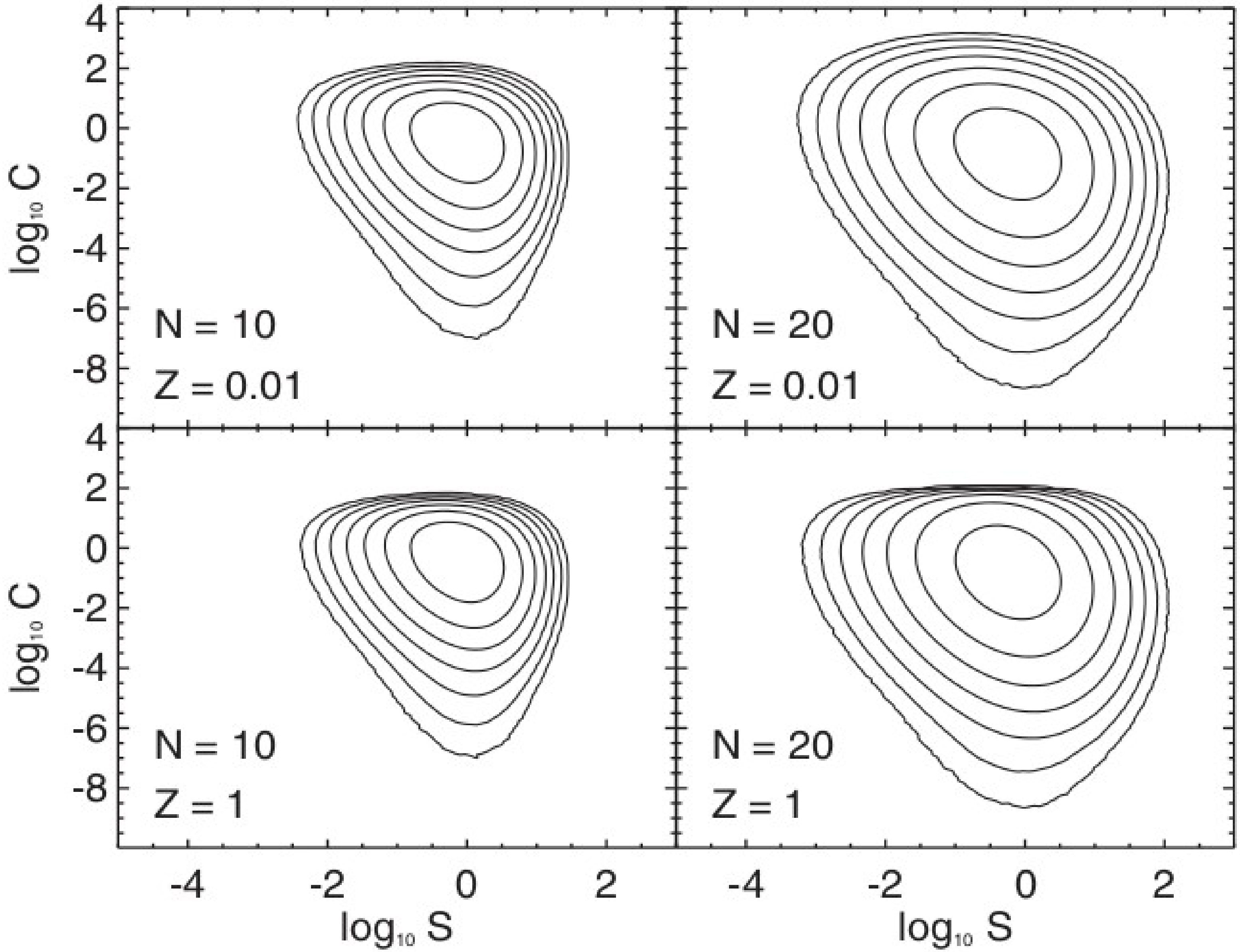
- Particles concentrate in low vorticity regions

- Concentrations become high enough for gravitational instability

Cascade Model



$$C = \frac{\rho_{particle}}{\bar{\rho}_{particle}} \qquad S = \frac{\omega^2}{\bar{\omega}^2}$$



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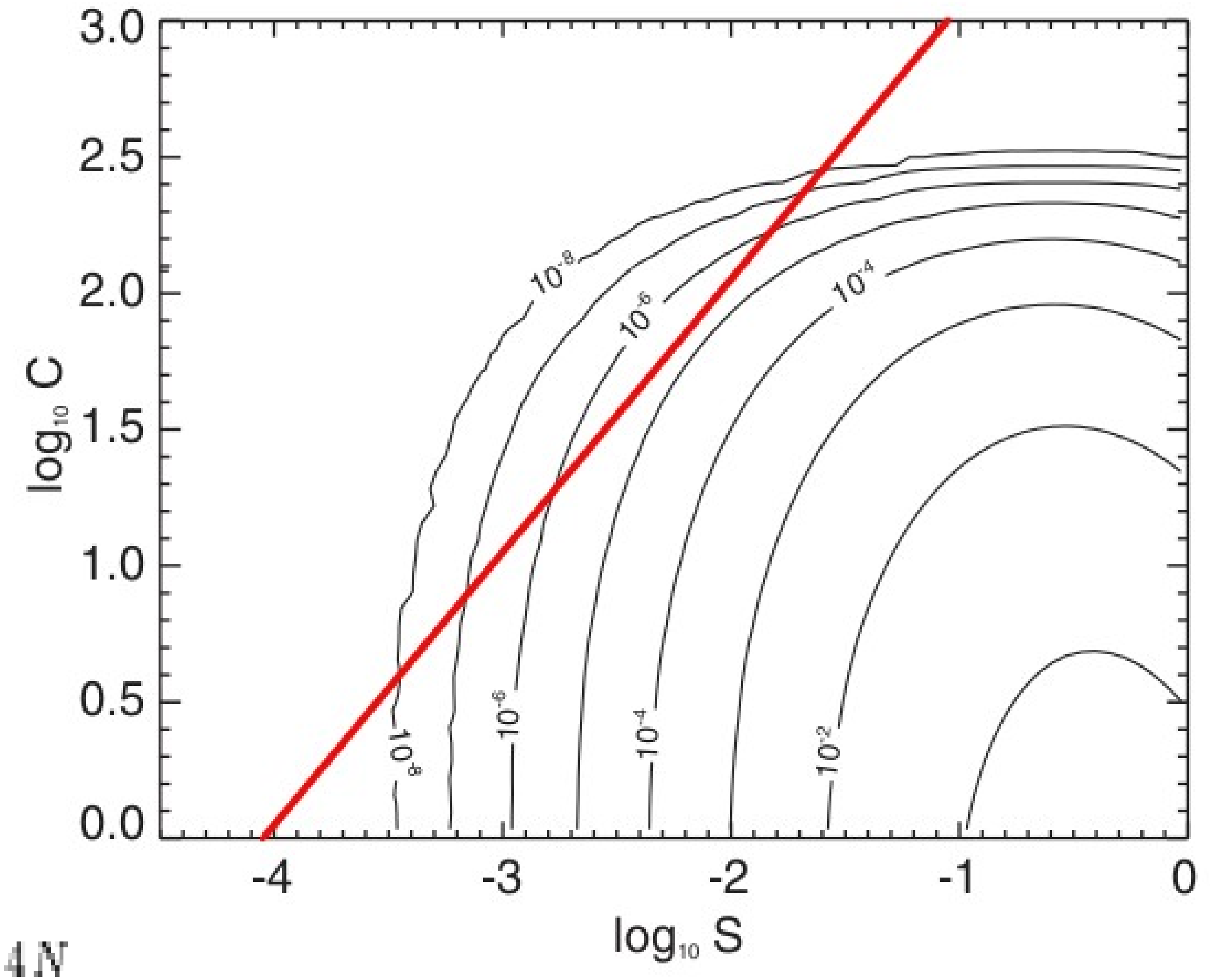
Constraint: Rotational Breakup

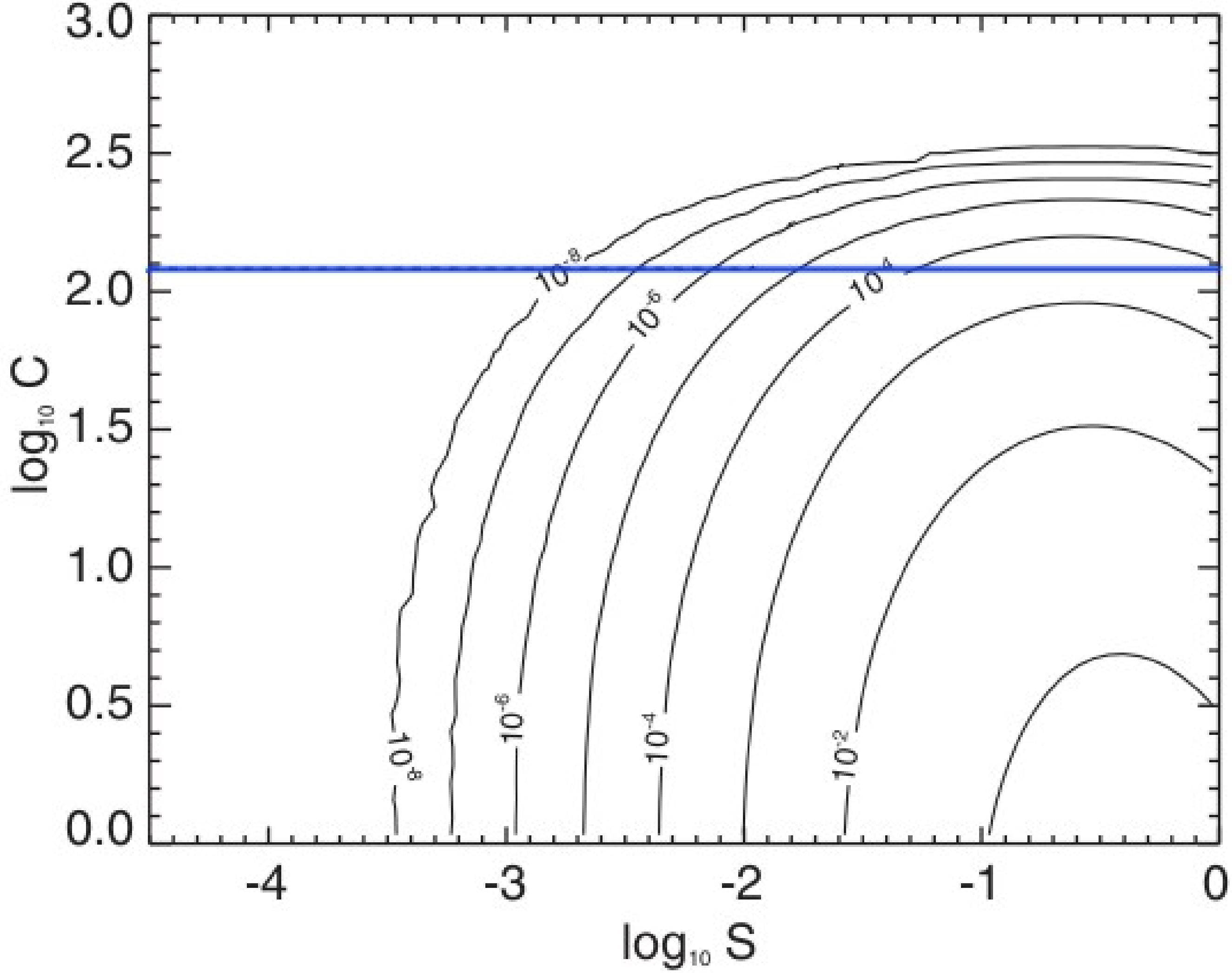


$$\omega^2 R \leq \frac{GM}{R^2}$$

$$\frac{C}{S} \geq \frac{B_1}{Z} \times 2^{\frac{4N}{9}}$$

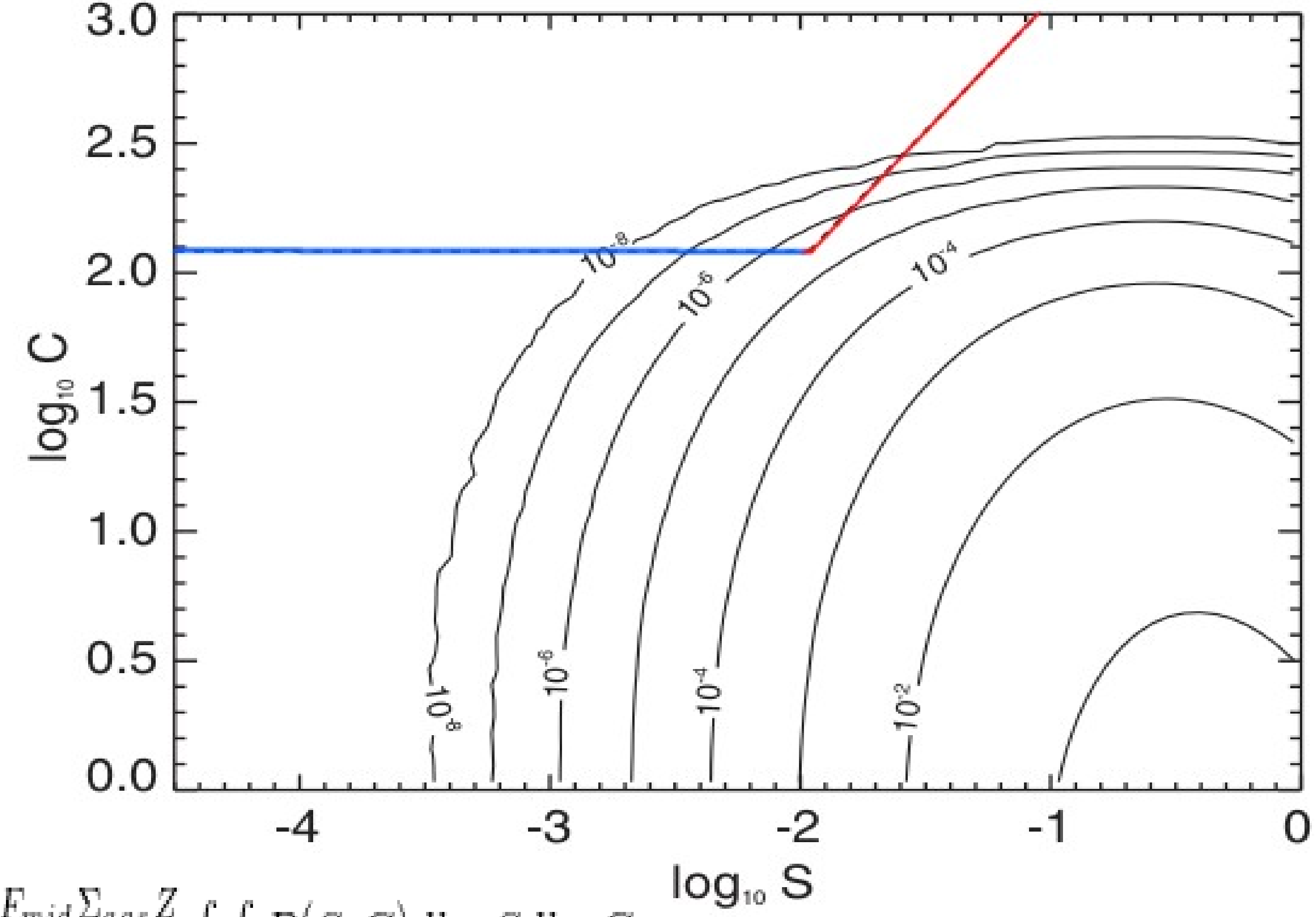
$$B_1(a) = \frac{3}{2\pi}\left(\frac{M_*}{\Sigma_{gas} a^2}\right)\left(\frac{Hgas}{a}\right)$$

Constraint: Ram Pressure



$$\frac{3C_D \rho_{gas} v_{rel}^2}{8\pi G R^2 \rho_{rel}^2} \leq 10 \qquad C \geq \frac{B_2}{Z(1+Z)} \times 2^{\frac{4N}{9}}$$

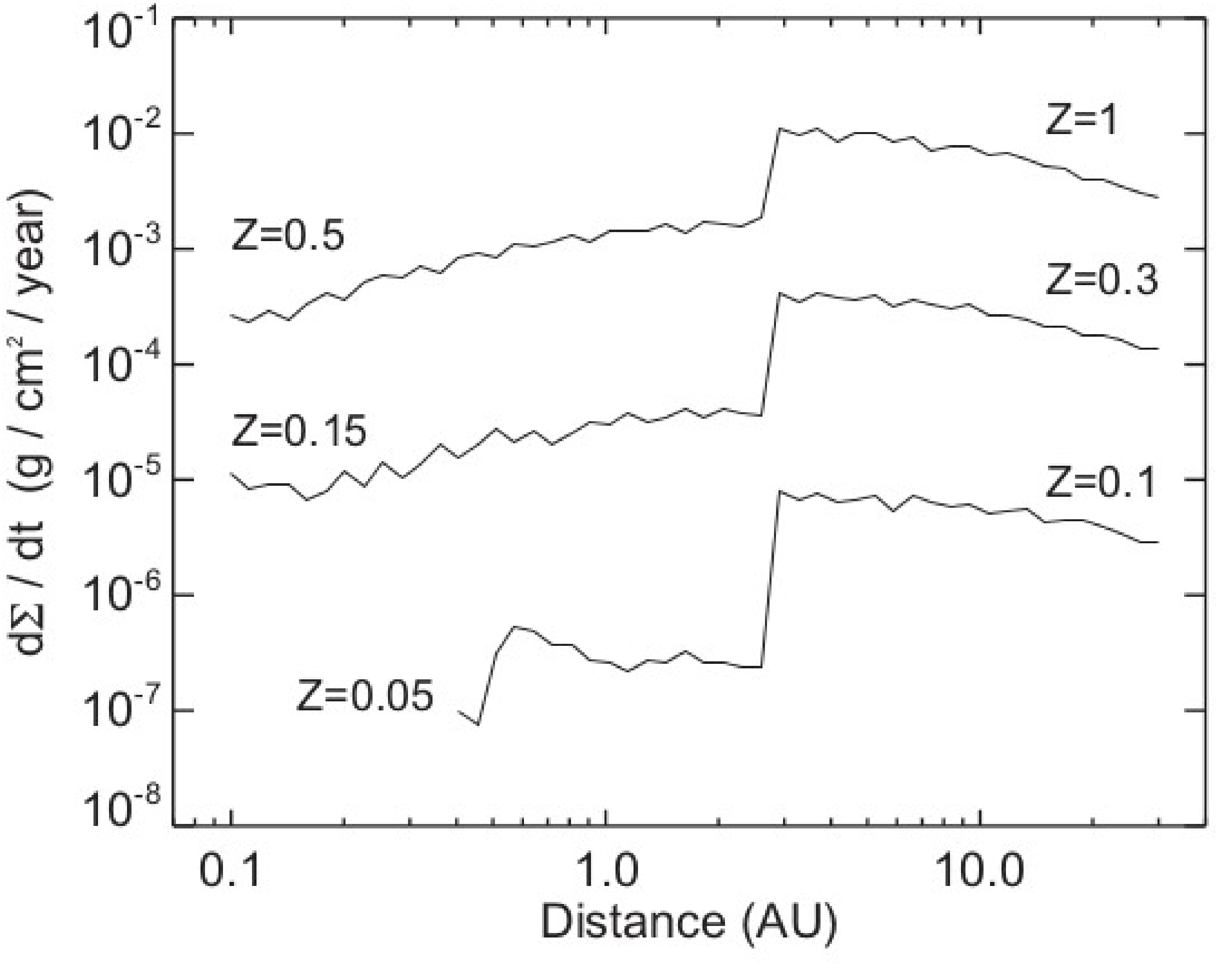
Constrain Probability Distribution



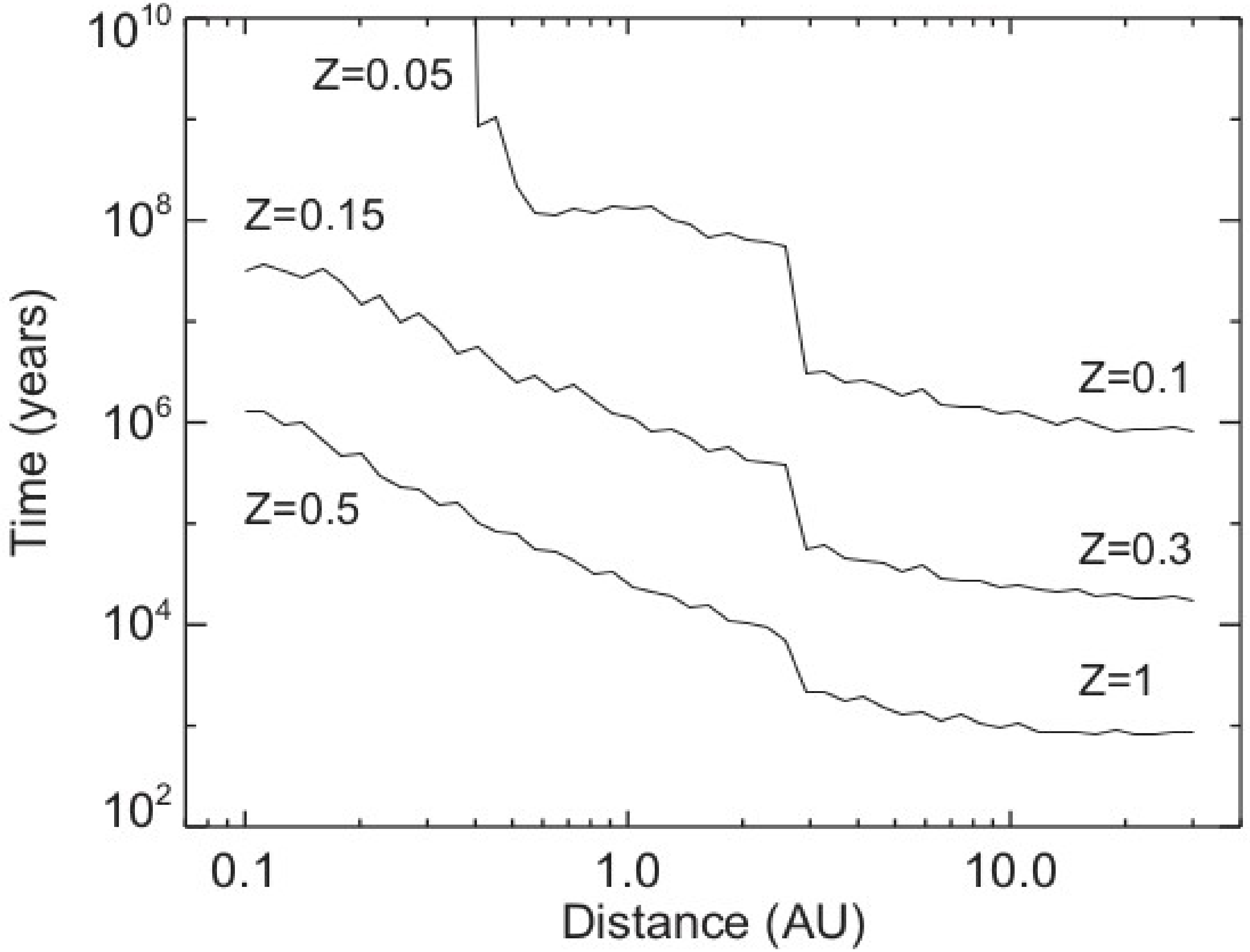
$$\frac{d\Sigma_{plan}}{dt} = \frac{F_{mid}\Sigma_{gas}Z}{\tau_{eddy}} \int\int P(S,C)dlogSdlogC$$

$$t_{plan} = \Sigma_{solid}\left(\frac{d\Sigma_{plan}}{dt}\right)^{-1}$$

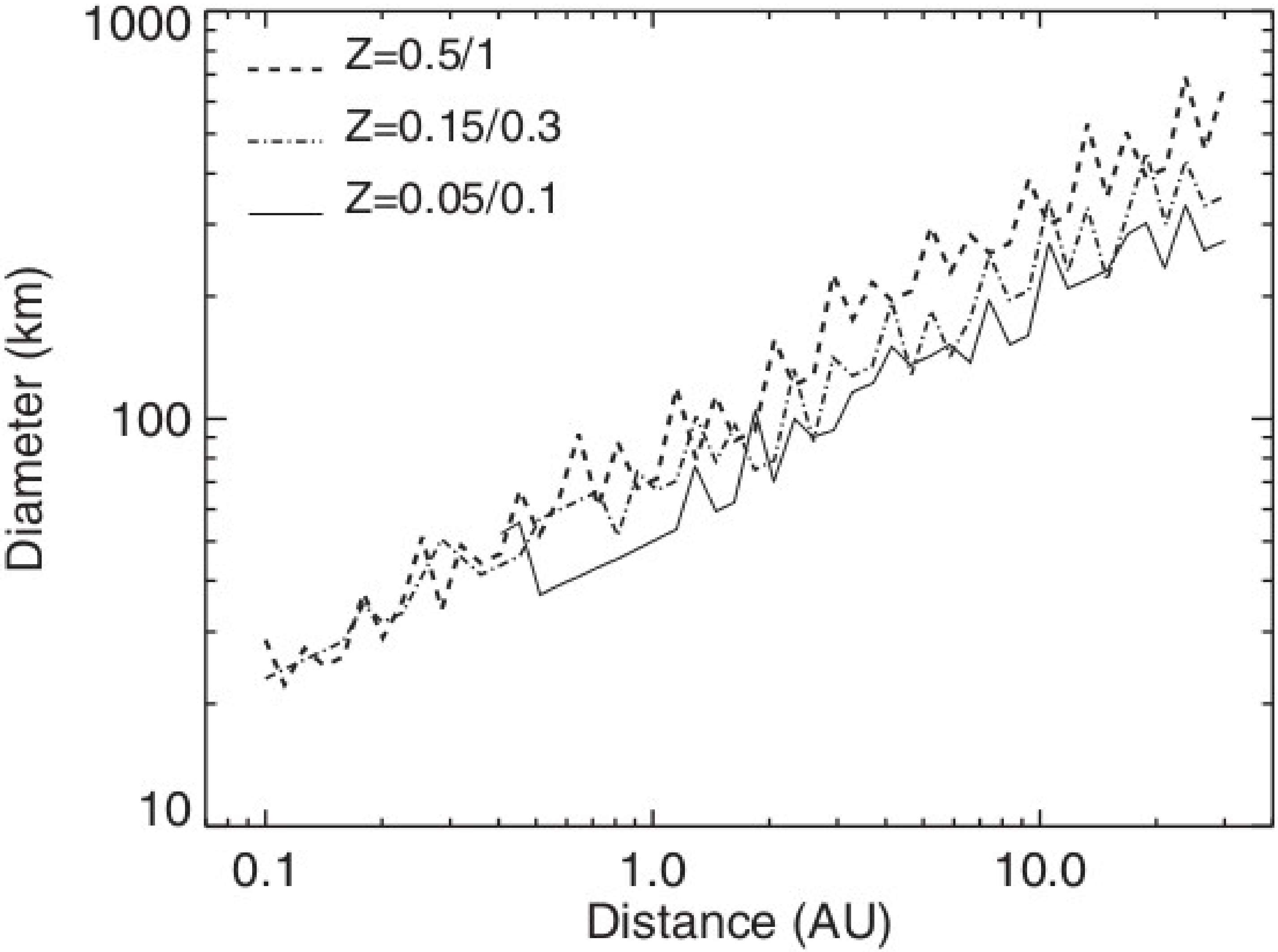
Planetesimal Formation Rate



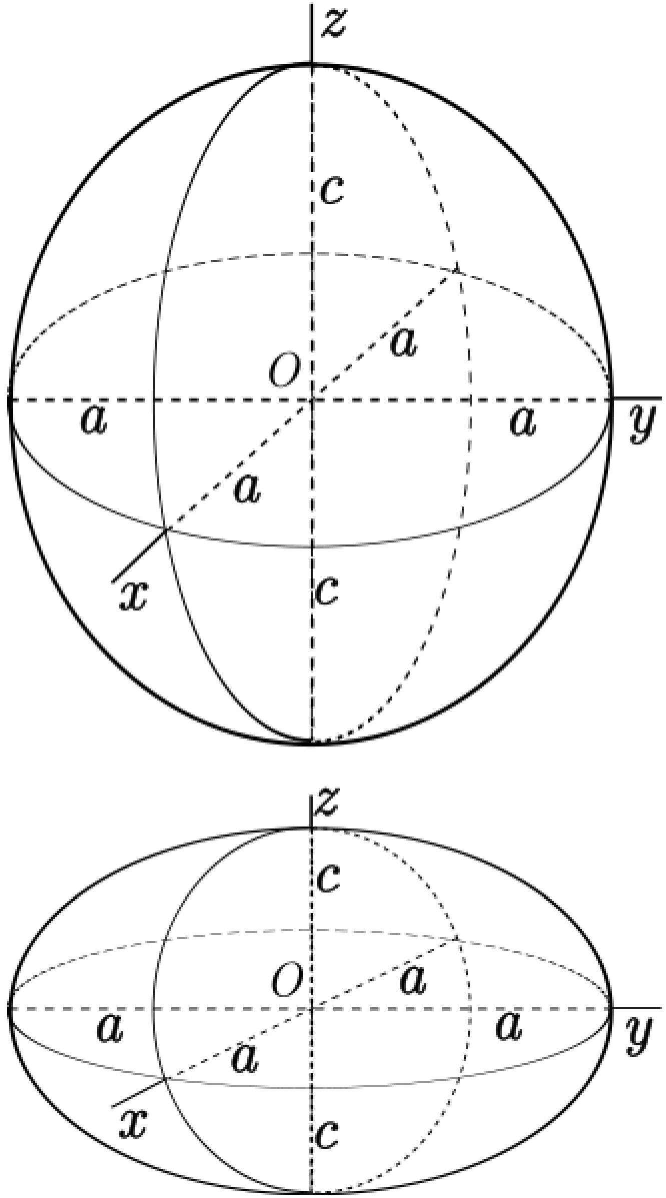
Formation Timescale

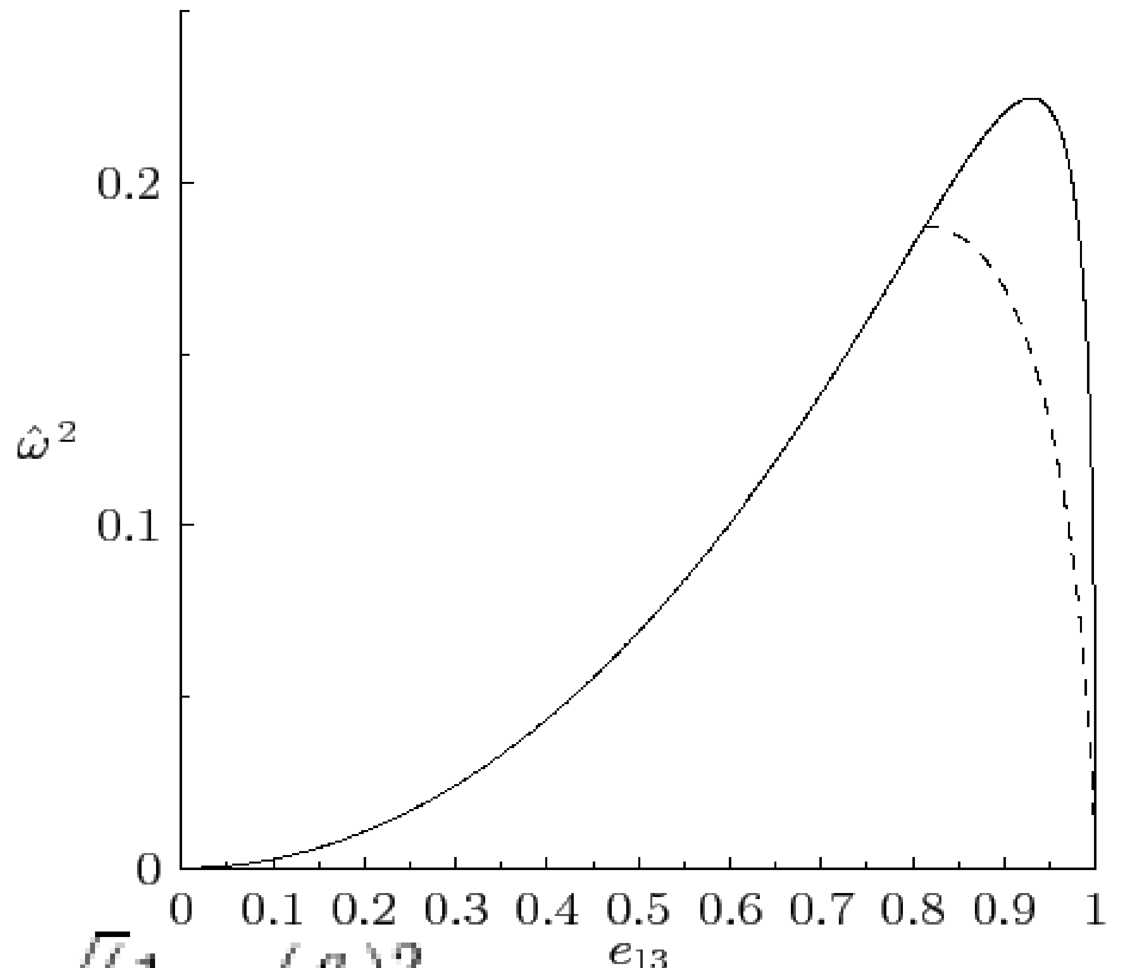


Planetesimal Sizes



Adding a new Constraint: MacLaurin Spheroids

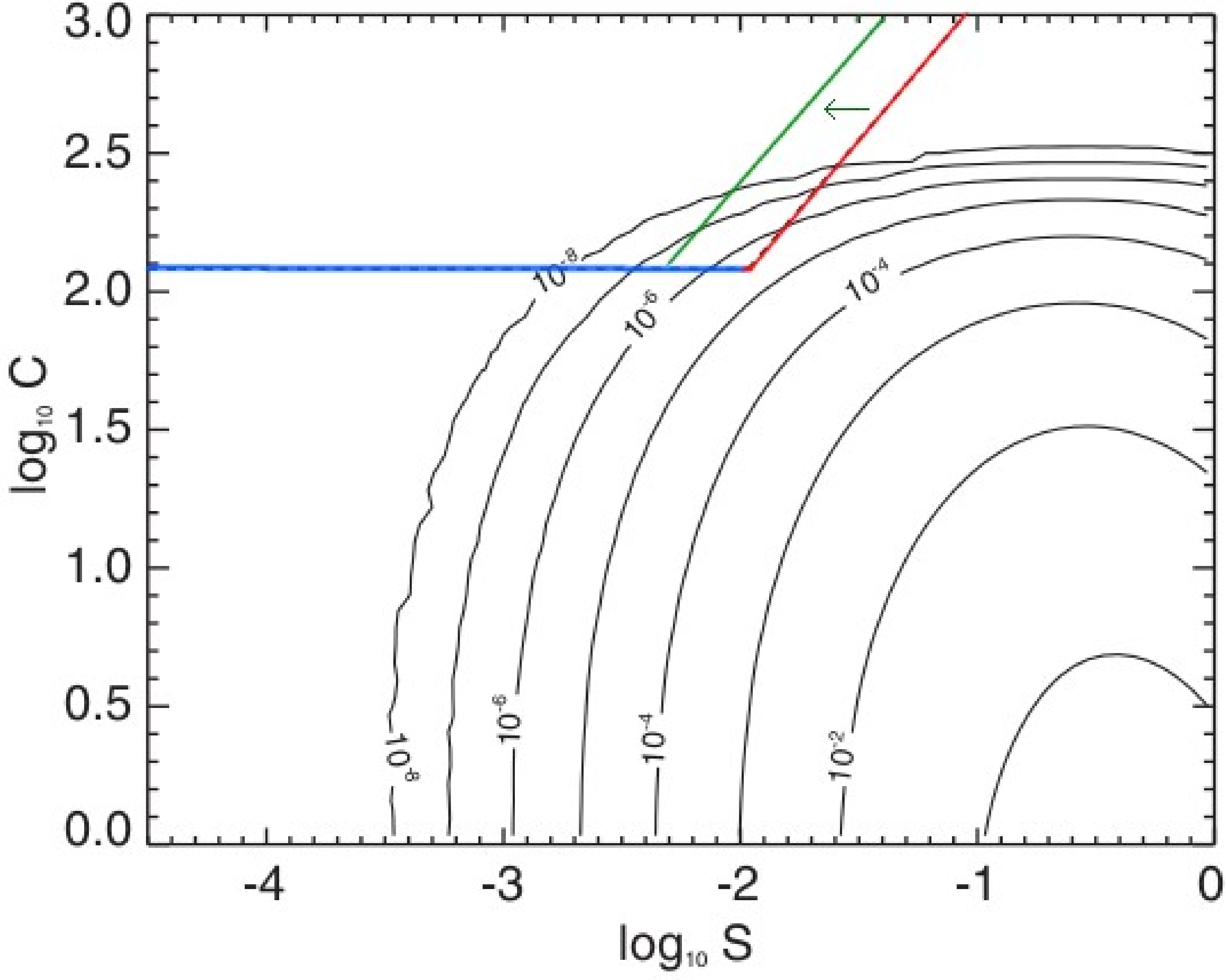




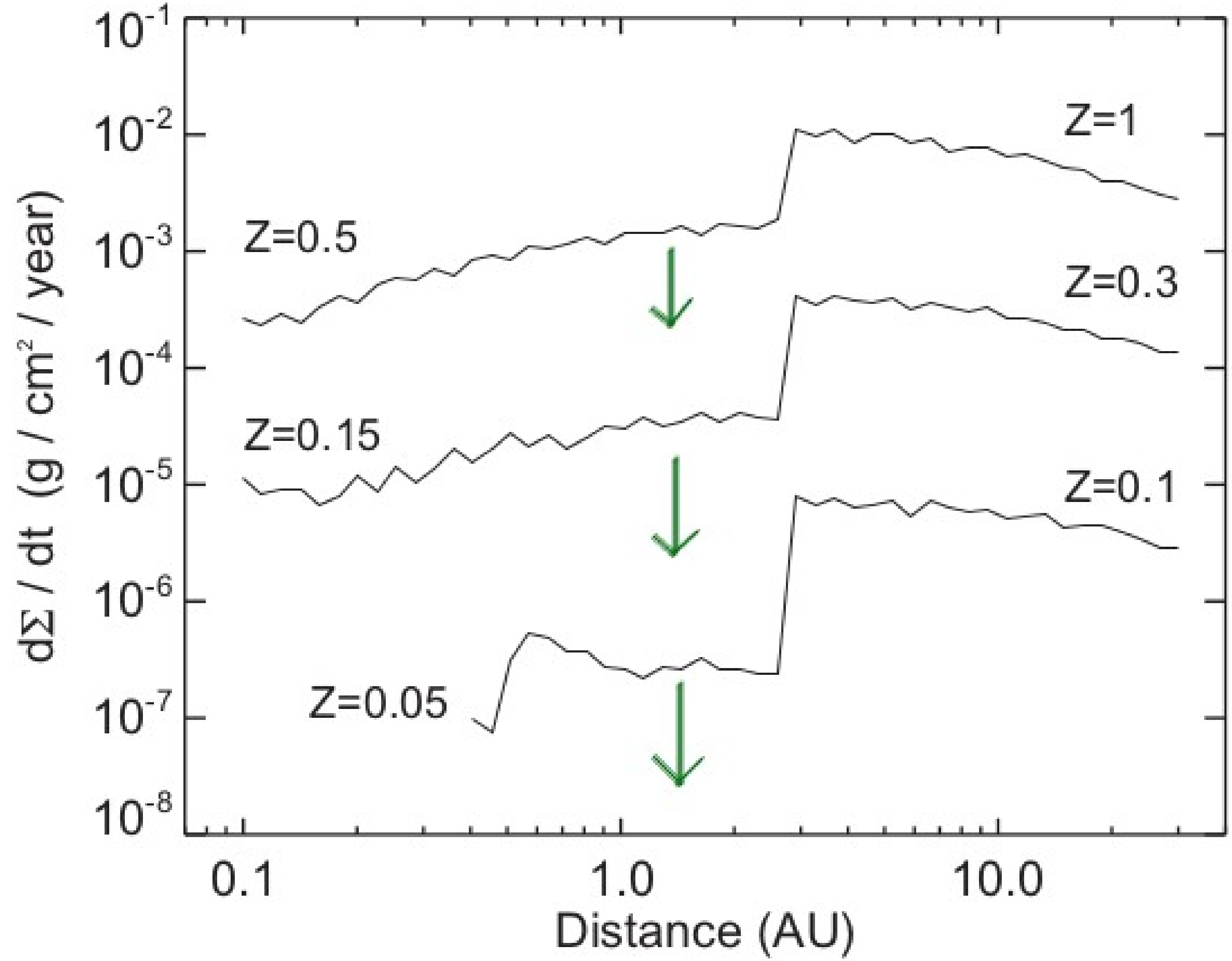
$$e = \sqrt{(1 - (\frac{a}{c})^2}$$

$$\frac{\omega^2}{2\pi G\rho} \leq \frac{\sqrt{1-e^2}}{e^3}[(3-2e^2)arcsin(e) - 3e\sqrt{1-e^2}]$$

Limitation: Oblate Spheroid



$$\frac{C}{S} \geq \frac{1}{0.22\pi Z} \frac{H_{gas}}{\Sigma_{gas}} \frac{M_*}{a^3} \times 2^{\frac{4N}{9}}$$



Z=1
Z=0.5
Z=0.3
Z=0.15
Z=0.1
Z=0.05
dΣ / dt (g / cm² / year)
Distance (AU)
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
0.1
1.0
10.0