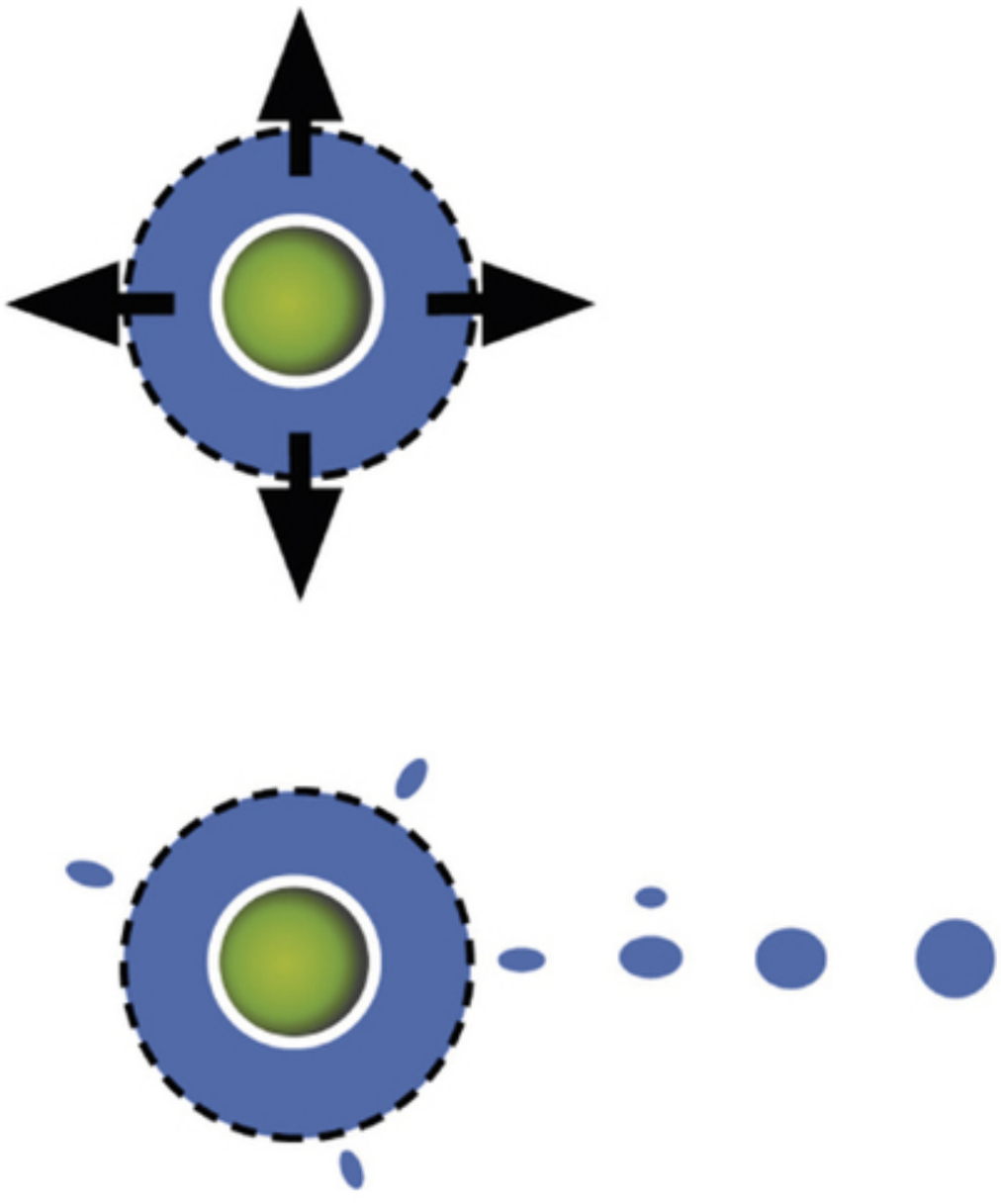
Exoplanet recycling

in massive white-dwarf debris discs

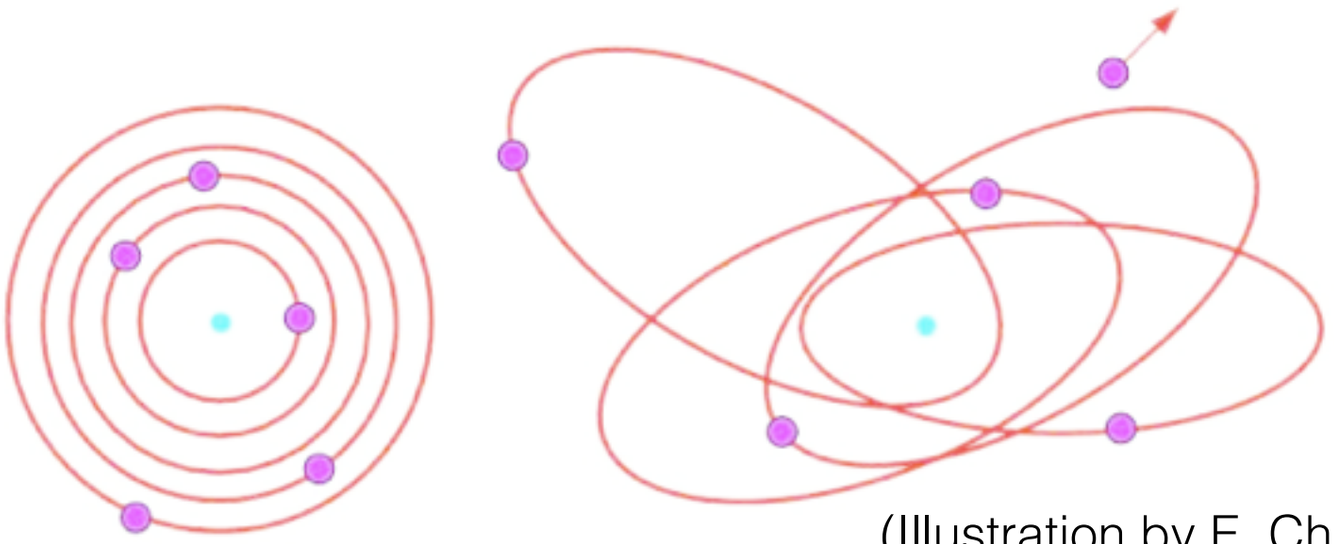


Rik van Lieshout
lieshout@ast.cam.ac.uk

With:
Quentin Kral
Sébastien Charnoz
Mark Wyatt
Andrew Shannon

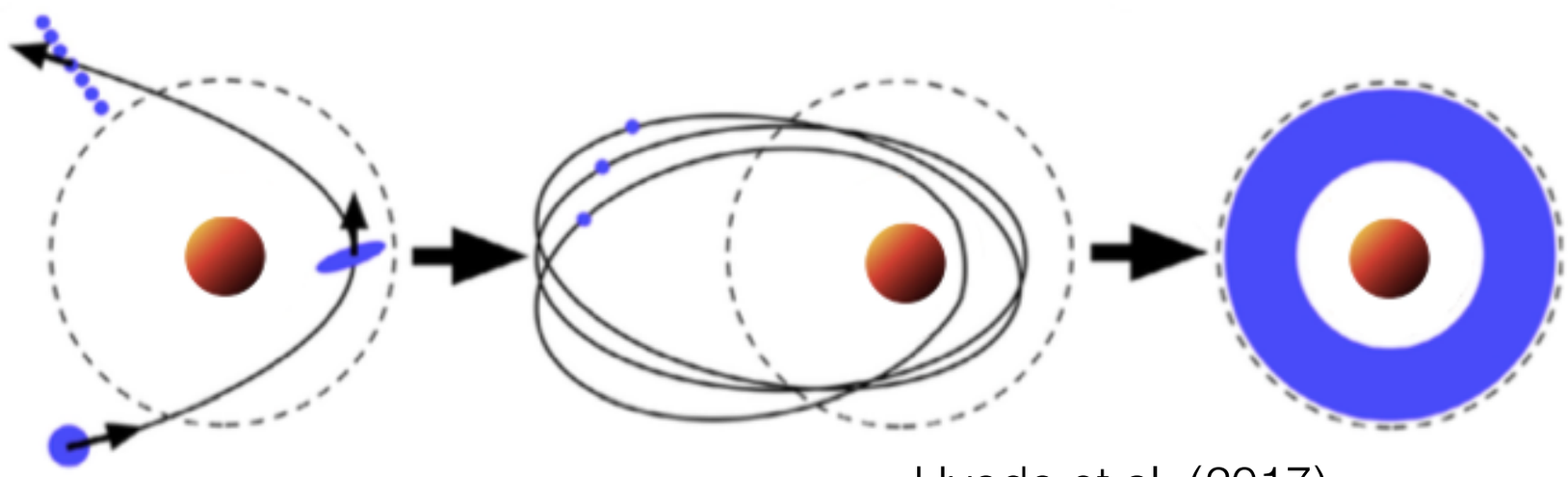
(Illustration by Mark Garlick)

How to pollute a white dwarf?



(Illustration by E. Chiang)

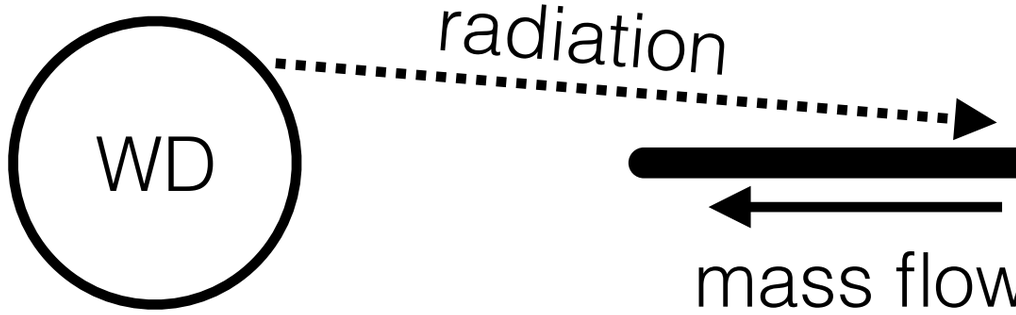
After AGB mass loss, objects can be scattered onto star-grazing orbits



Hyodo et al. (2017)

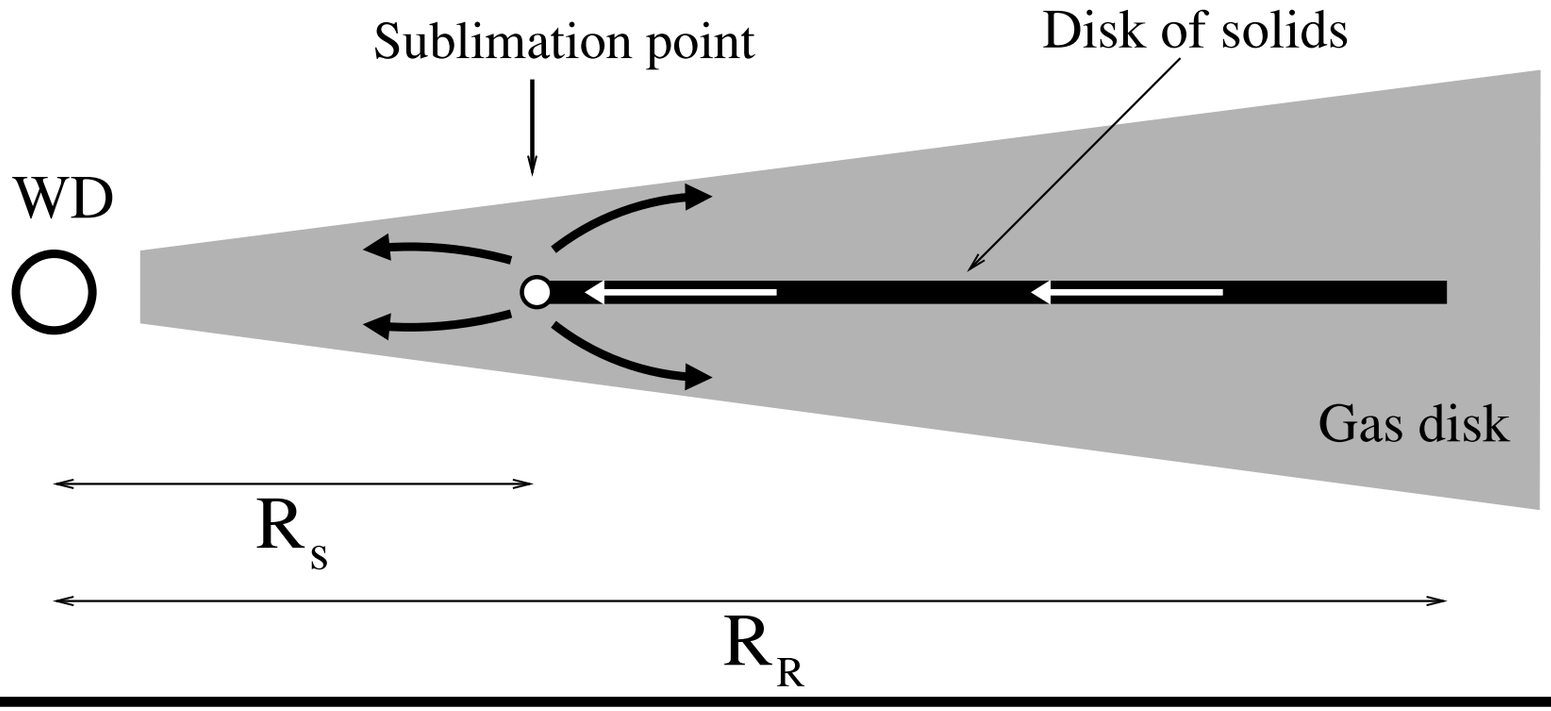
Tidal disruption, circularisation of debris

Accretion from debris disc onto white dwarf



PR drag

Rafikov (2011a)



Gas drag

(runaway accretion)

Rafikov (2011b)

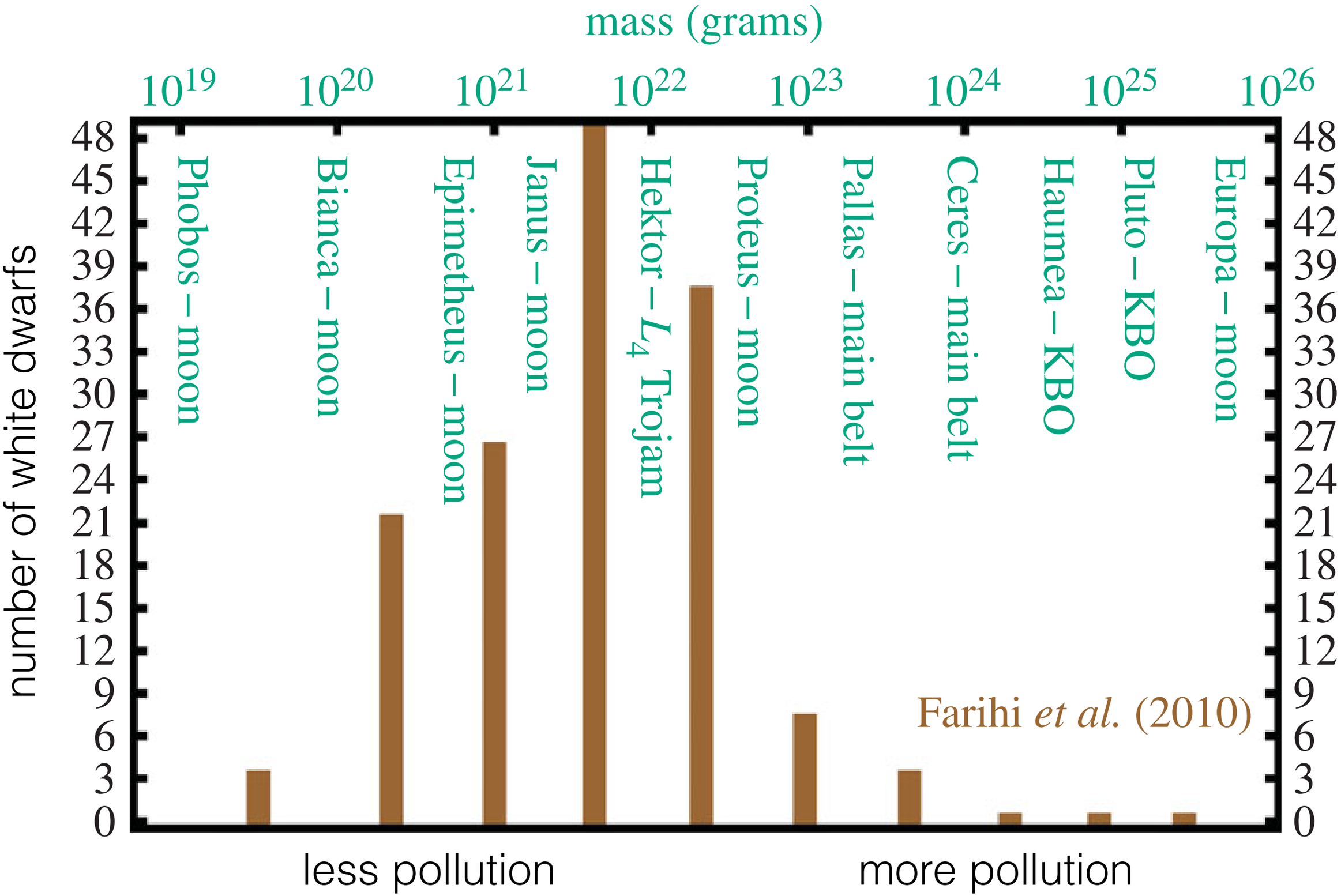
1000 km
100 m
1 cm
1 μm
1 Å
particle size
WD radius
Roche limit
AGB radius
planets & asteroids
debris disc
solid
gas
pollution
gas disc
1 $R_\oplus$
1 $R_\odot$
1 AU
radial distance

1000 km
100 m
1 cm
1 μm
1 Å
particle size
WD radius
tidal disruption
Roche limit
sublimation
AGB radius
planets & asteroids
debris disc
solid
gas
pollution
gas disc
1 $R_\oplus$
1 $R_\odot$
1 AU
radial distance

1000 km
100 m
1 cm
1 μm
1 Å
particle size
WD radius
tidal disruption
Roche limit
sublimation
PR drag
scattering
circularisation
AGB radius
planets & asteroids
debris disc
solid
gas
viscous accretion
pollution
gas disc
1 $R_\oplus$
1 $R_\odot$
1 AU
radial distance

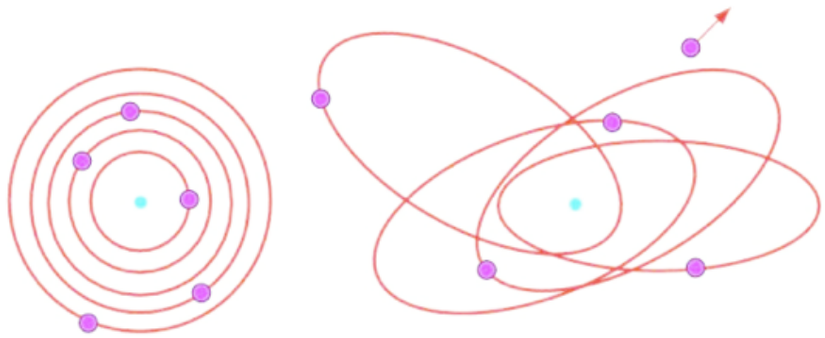
1000 km
100 m
1 cm
1 μm
1 Å
particle size
WD radius
tidal disruption
Roche limit
sublimation
recycled planets
planets & asteroids
AGB radius
PR drag
scattering
circularisation
debris disc
solid
gas
viscous accretion
pollution
gas disc
1 $R_\oplus$
1 $R_\odot$
1 AU
radial distance

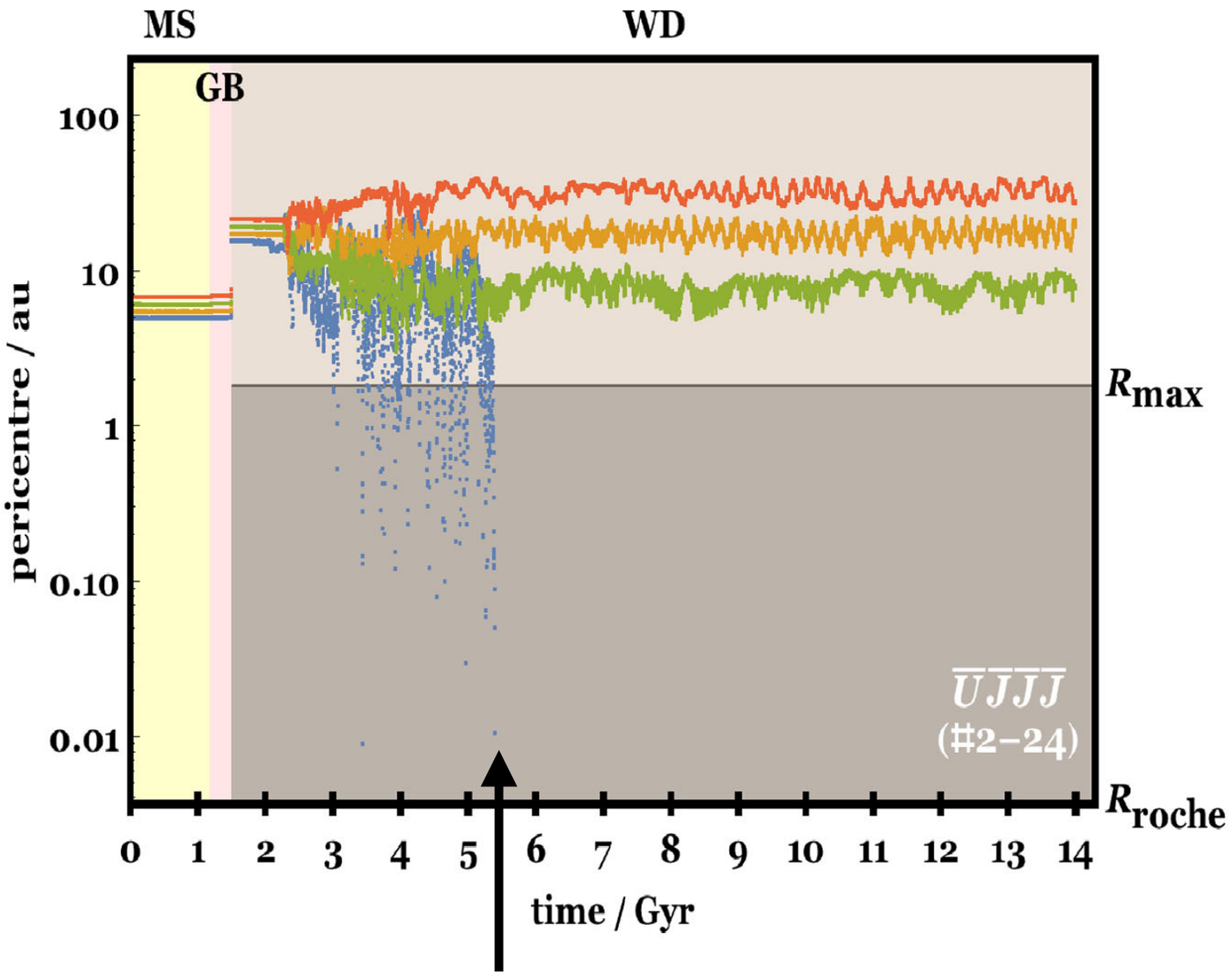
What type of objects are accreted?



Veras (2016)

Dynamical instability in remnant planetary system

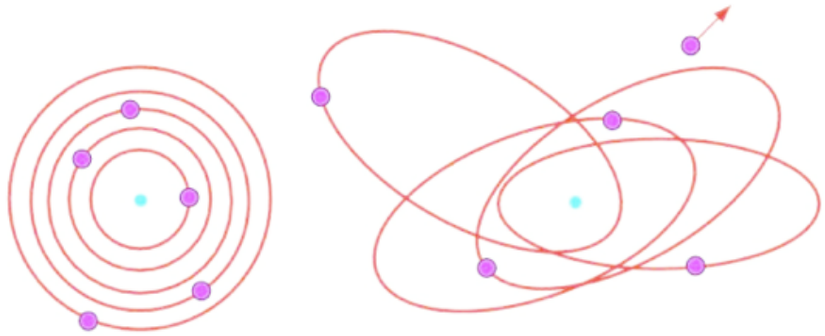


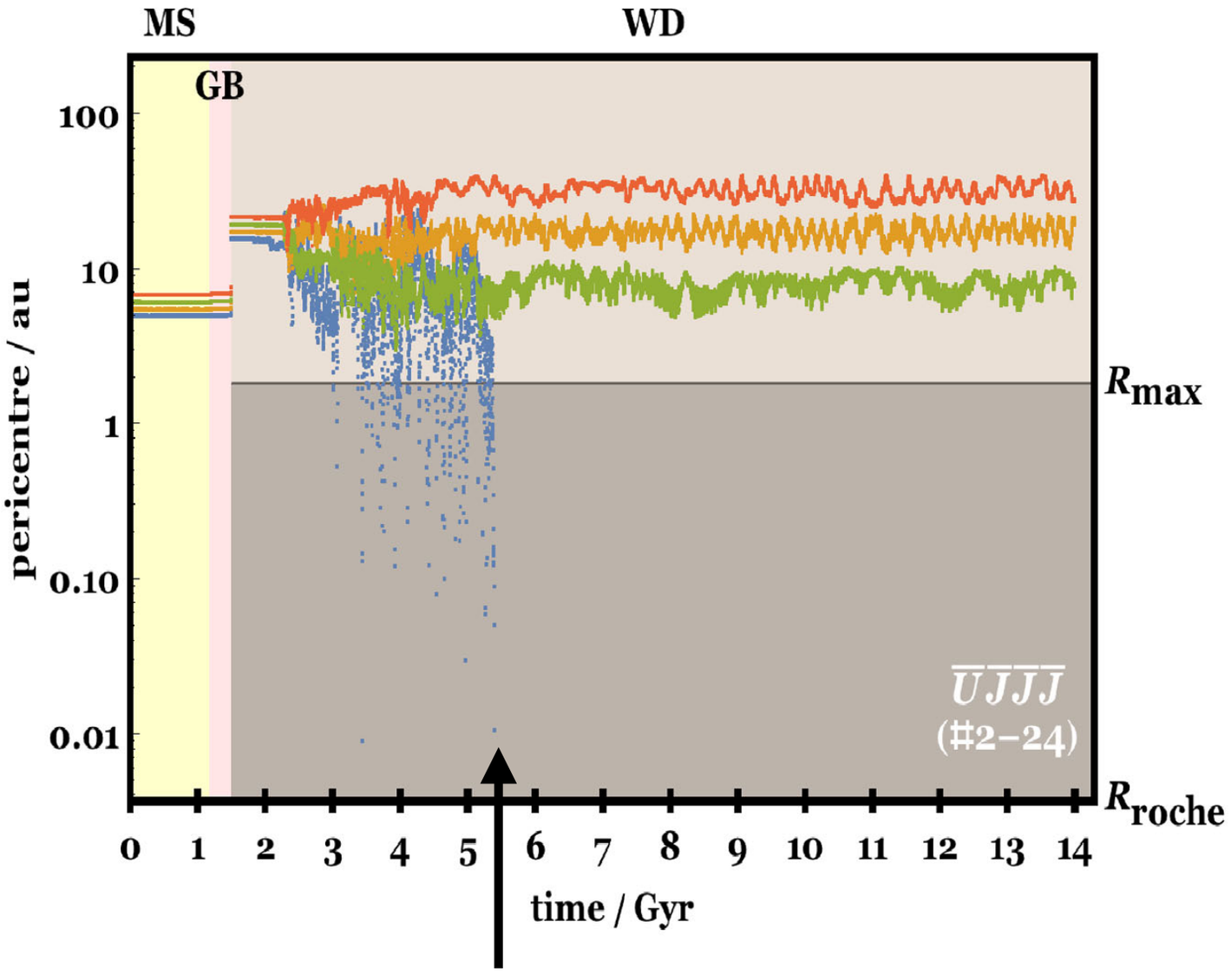


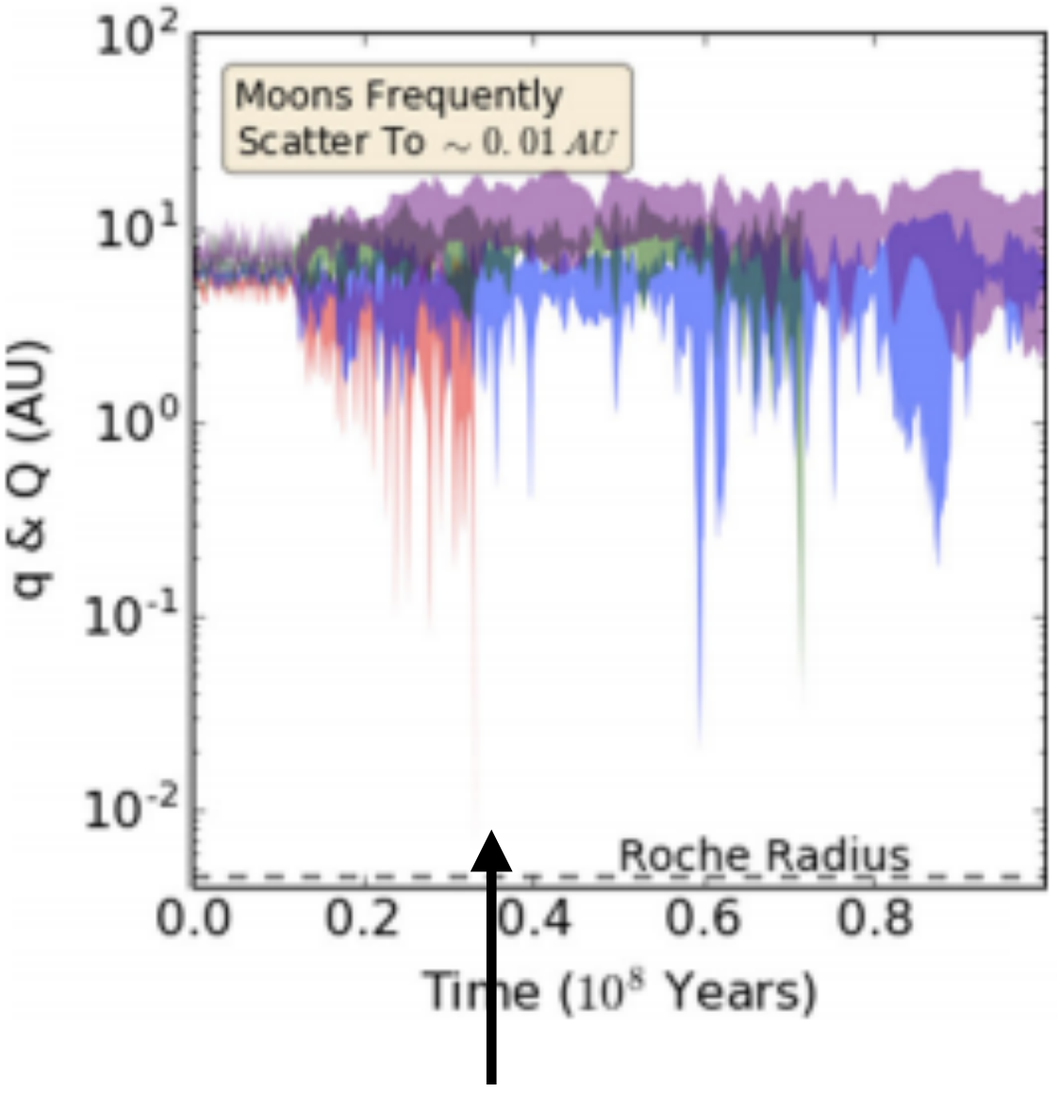
planet goes inside Roche limit

Veras et al. (2016)

Dynamical instability in remnant planetary system







planet goes inside Roche limit

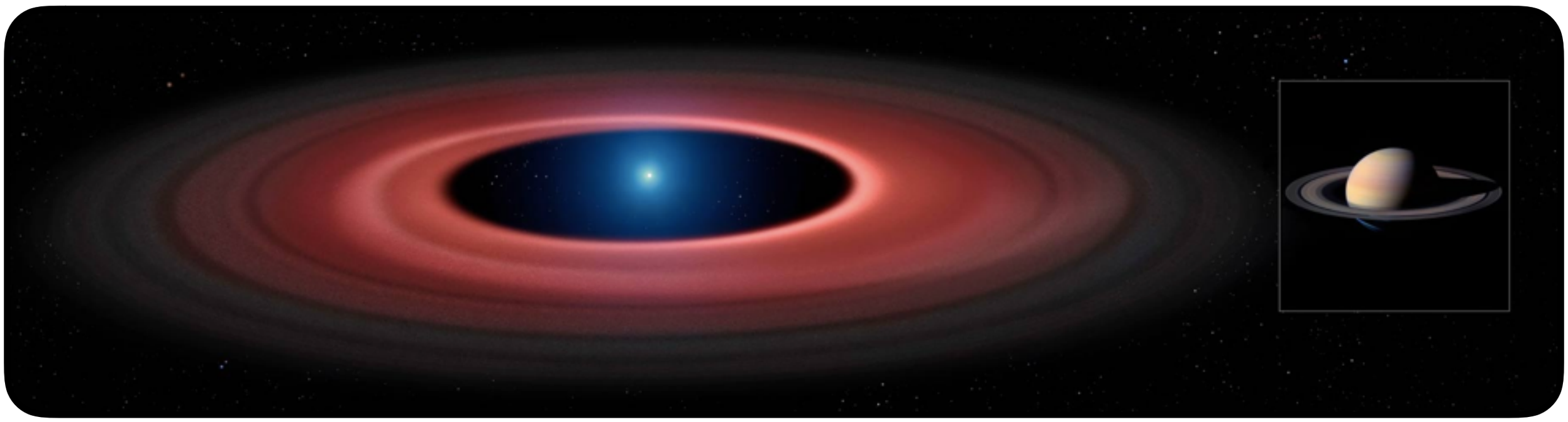
liberated moon within 0.01 AU

Veras et al. (2016)

Payne et al. (2017)

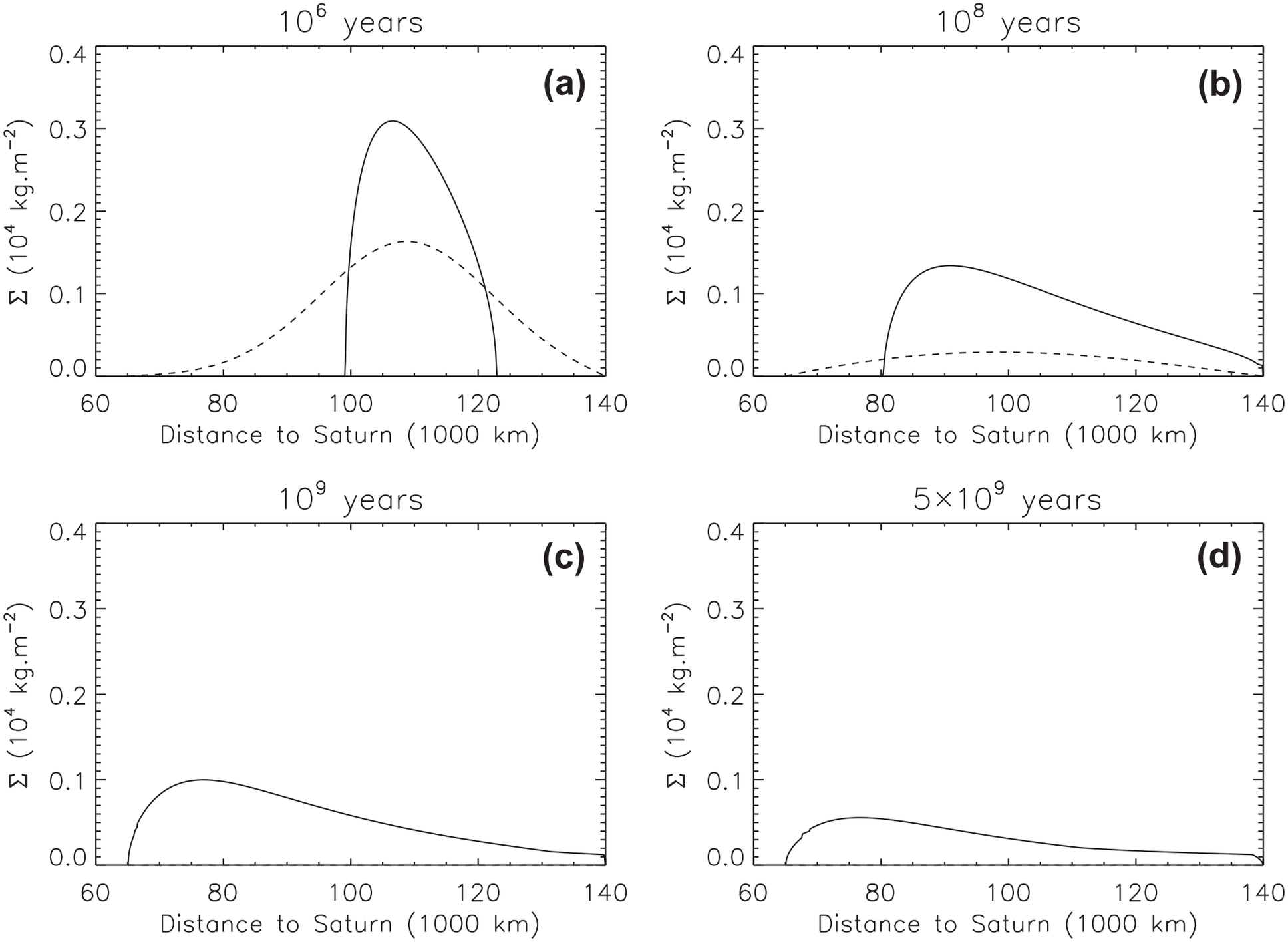
What determines the evolution of very massive WD debris discs?

$$(M_{\rm disc} \gtrsim {\rm M}_{\rm Ceres} \sim 10^{24}\,{\rm g})$$



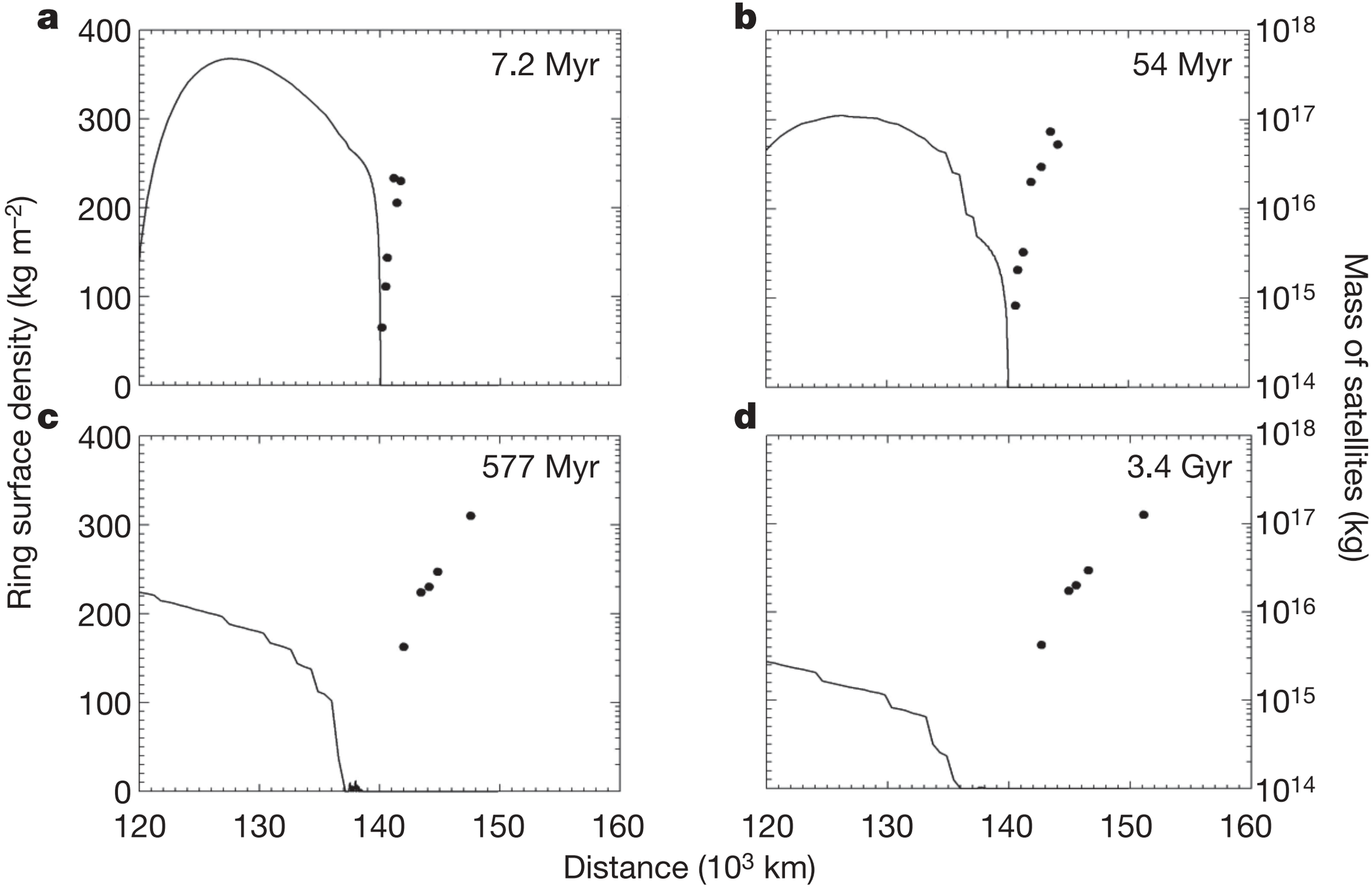
(Illustration by Mark Garlick)

Viscous spreading of Saturn's rings



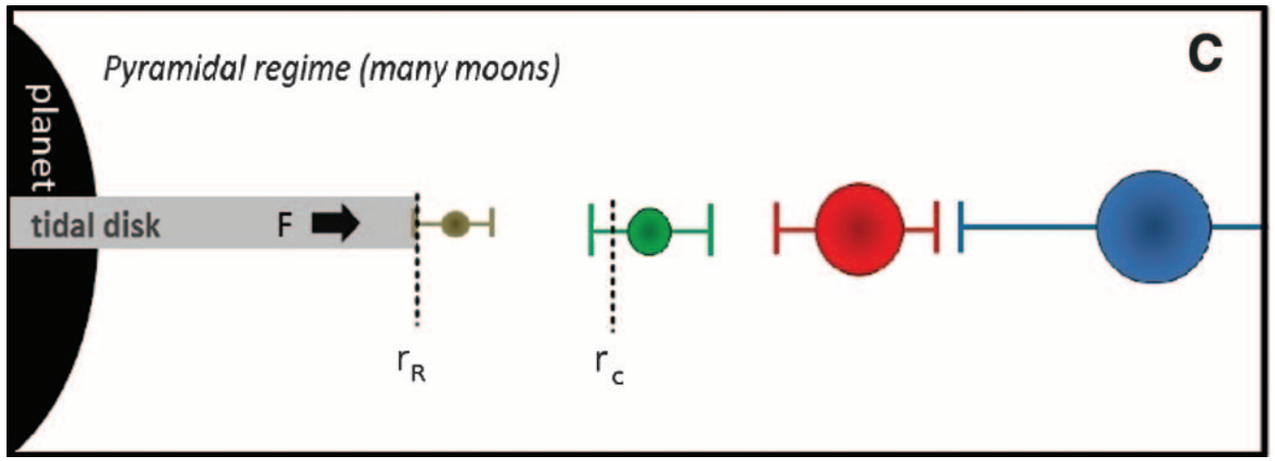
Salmon et al. (2010)

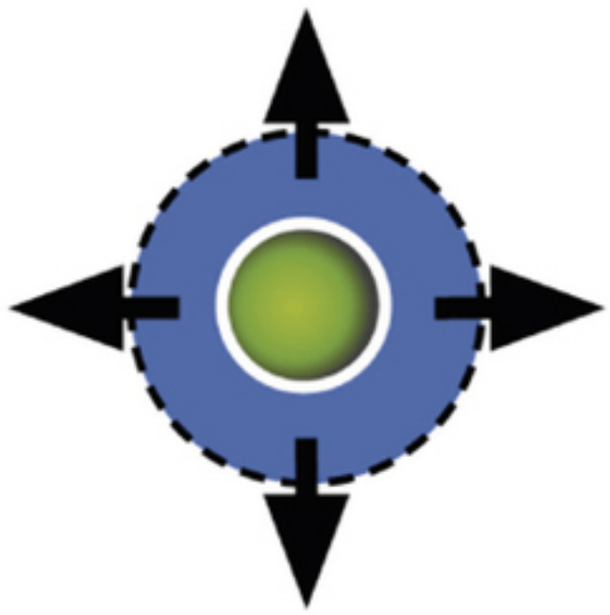
Moonlets form at the Roche limit

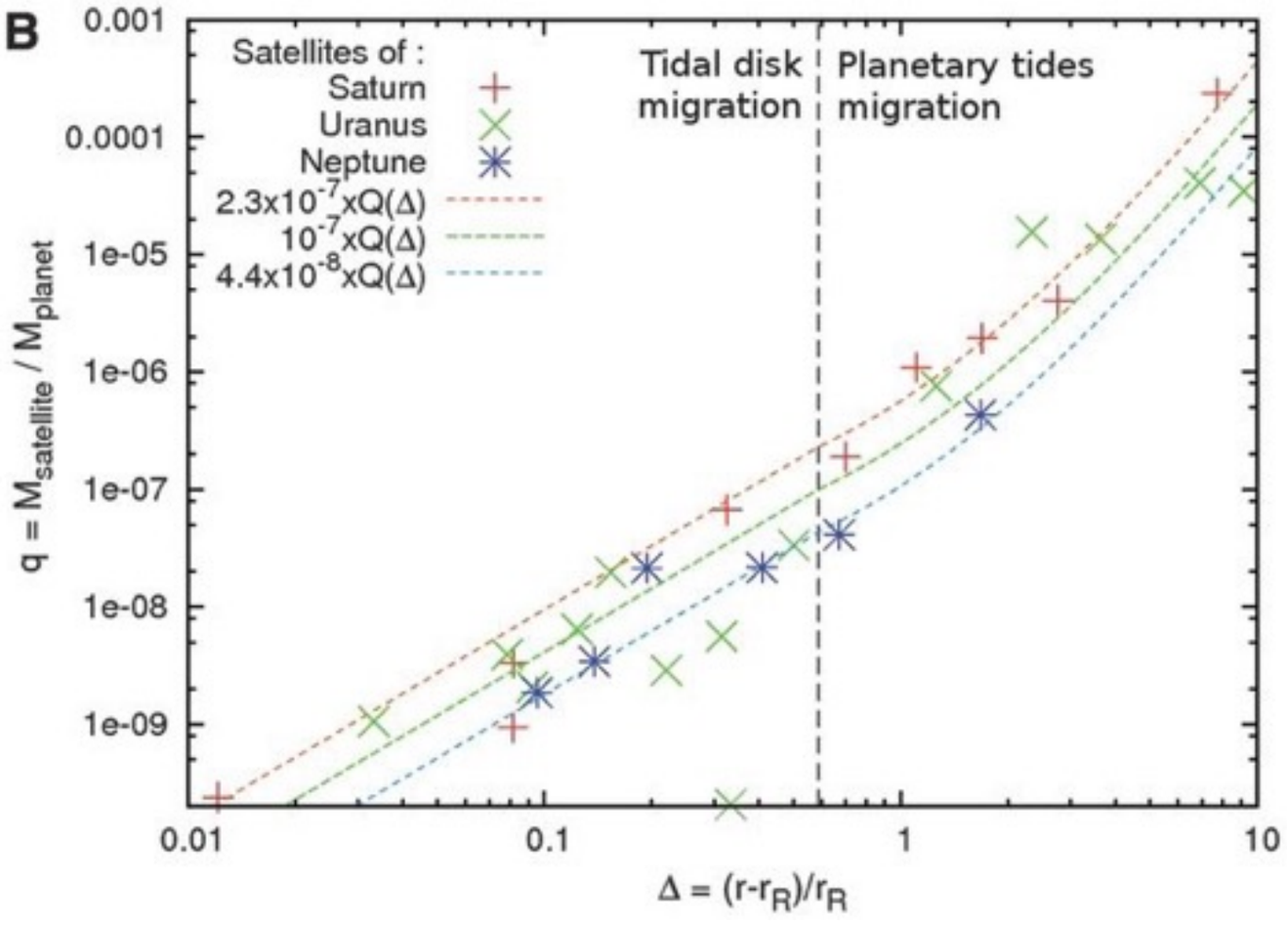


Charnoz et al. (2010)

Moonlets form at the Roche limit





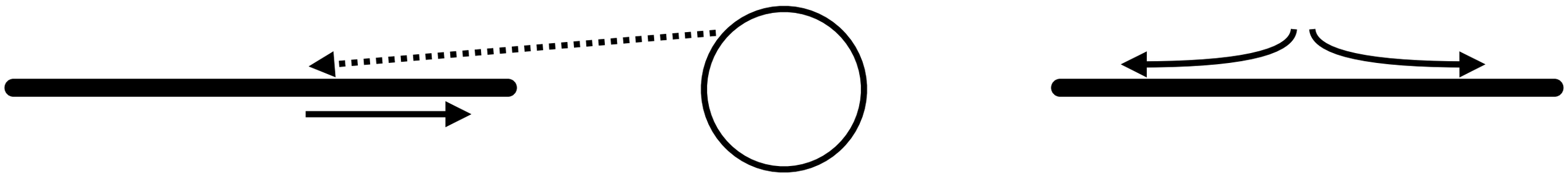


Crida & Charnoz (2012)

Hyodo & Ohtsuki (2015)

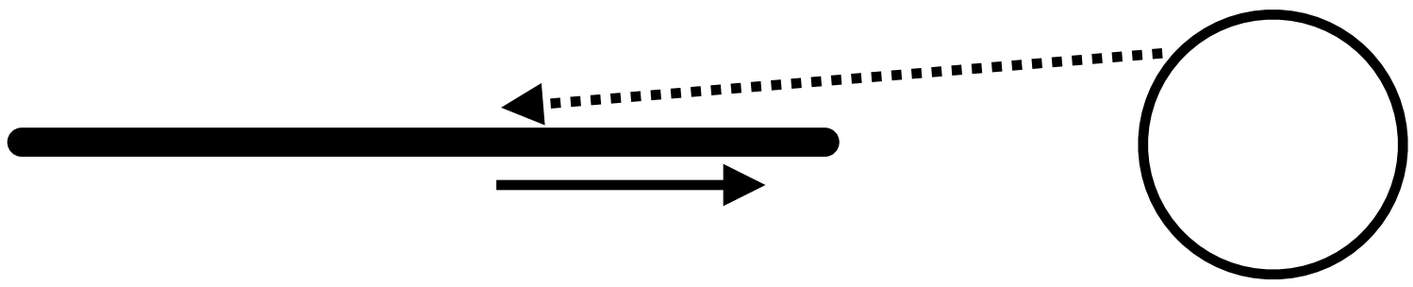
PR drag

Viscous spreading



PR drag

Viscous spreading

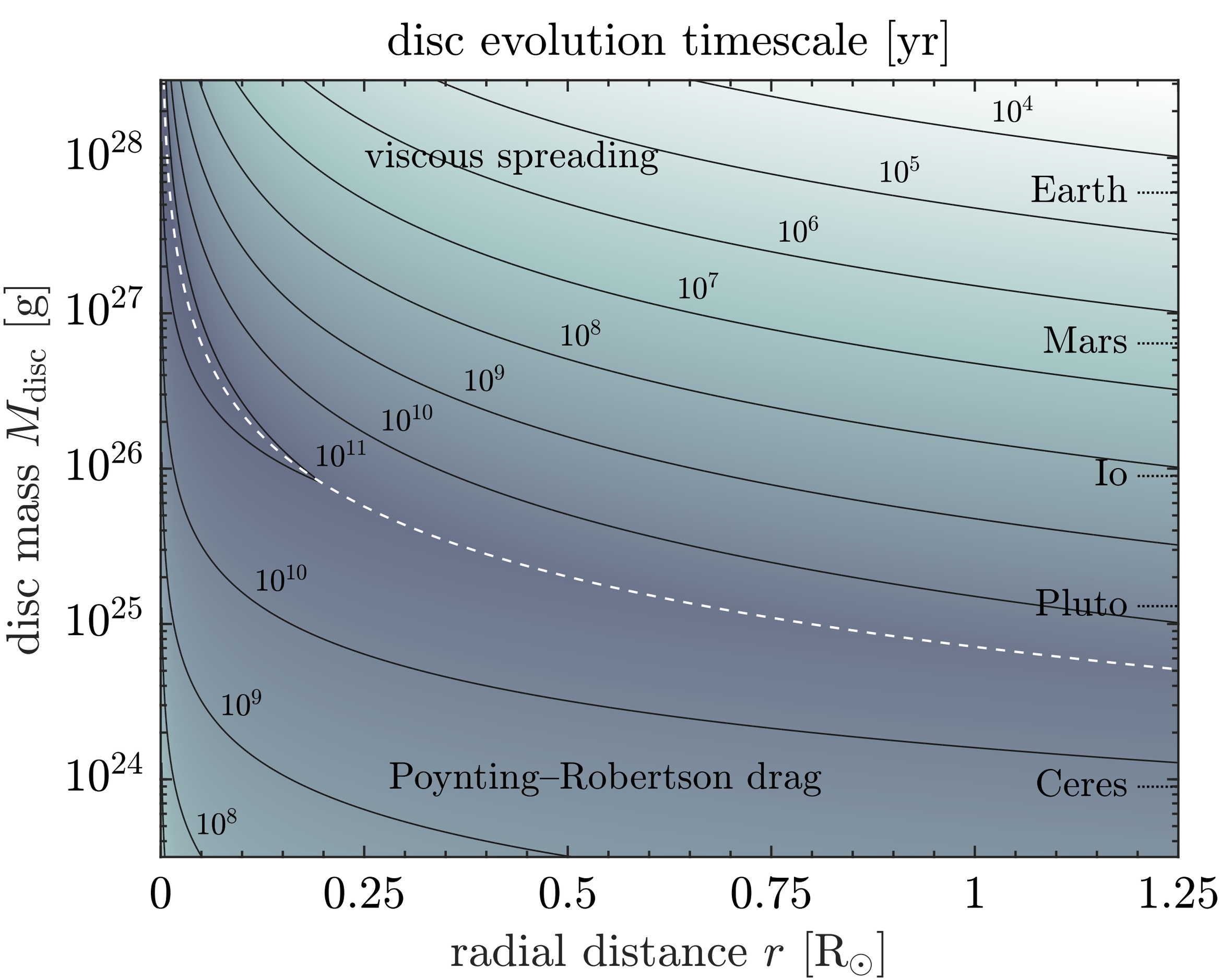


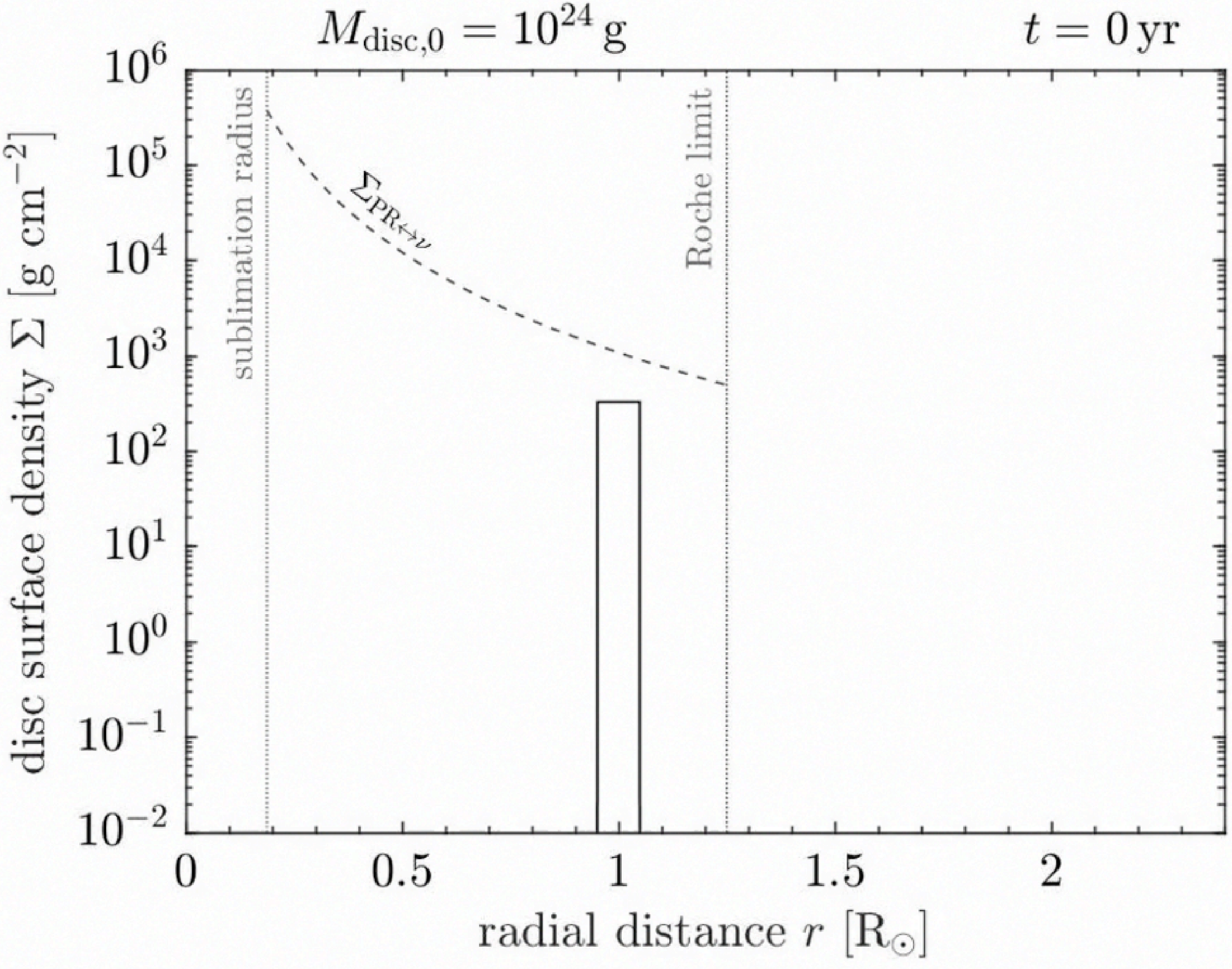
$$t_{\rm PR}^{\rm thick} \propto \Sigma r^3$$

$$t_{\nu}^{\rm sg} \propto \frac{1}{\Sigma^2 r^{15/2}}$$

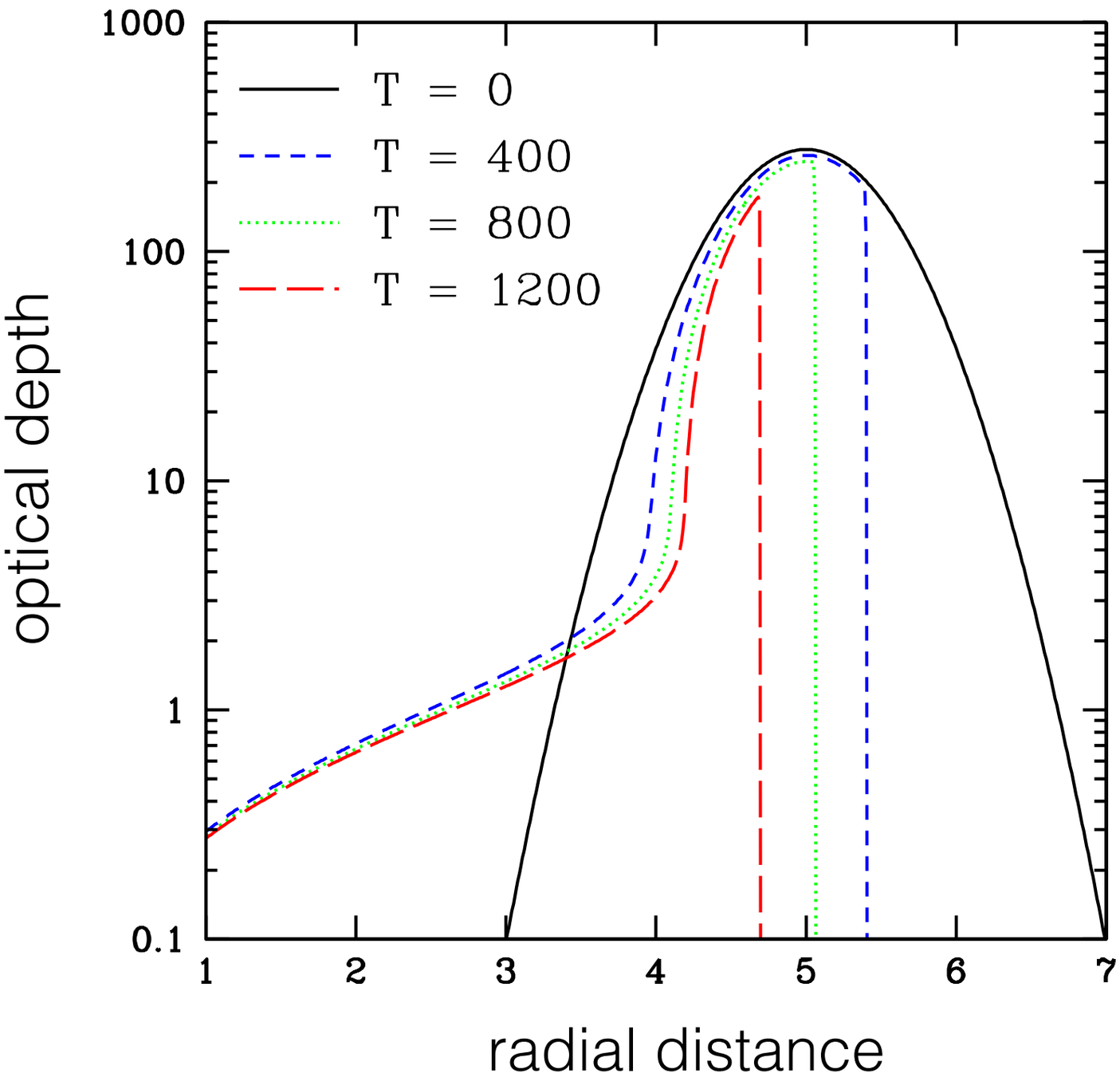
Bochkarev & Rafikov (2011)

Daisaka et al. (2001)

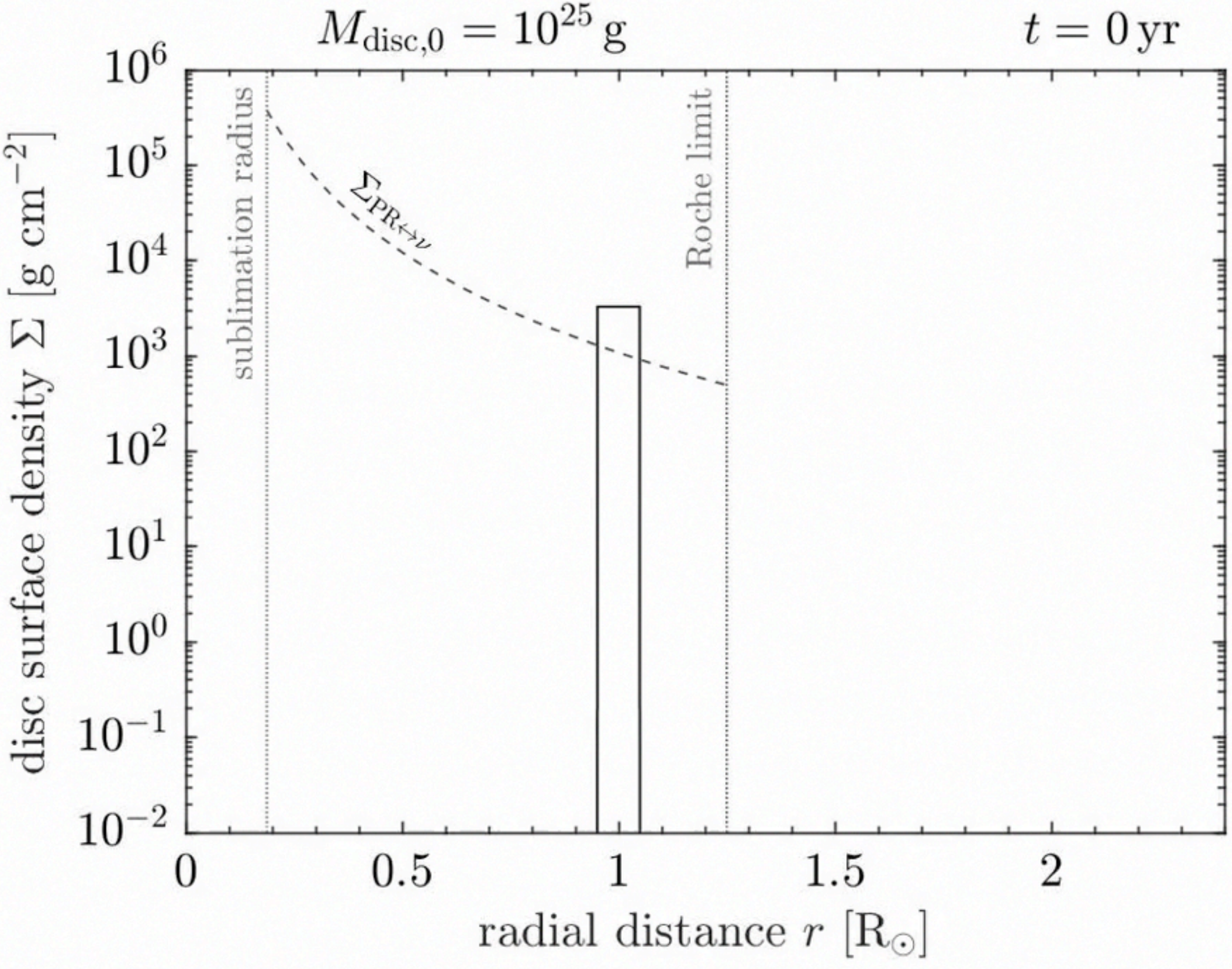

disc evolution timescale [yr]
10^{28}
10^{27}
10^{26}
10^{25}
10^{24}
disc mass $M_{\rm disc}$ [g]
viscous spreading
Poynting–Robertson drag
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
10^{10}
10^{9}
10^{8}
Earth
Mars
Io
Pluto
Ceres
0
0.25
0.5
0.75
1
1.25
radial distance r [$\mathrm{R}_\odot$]

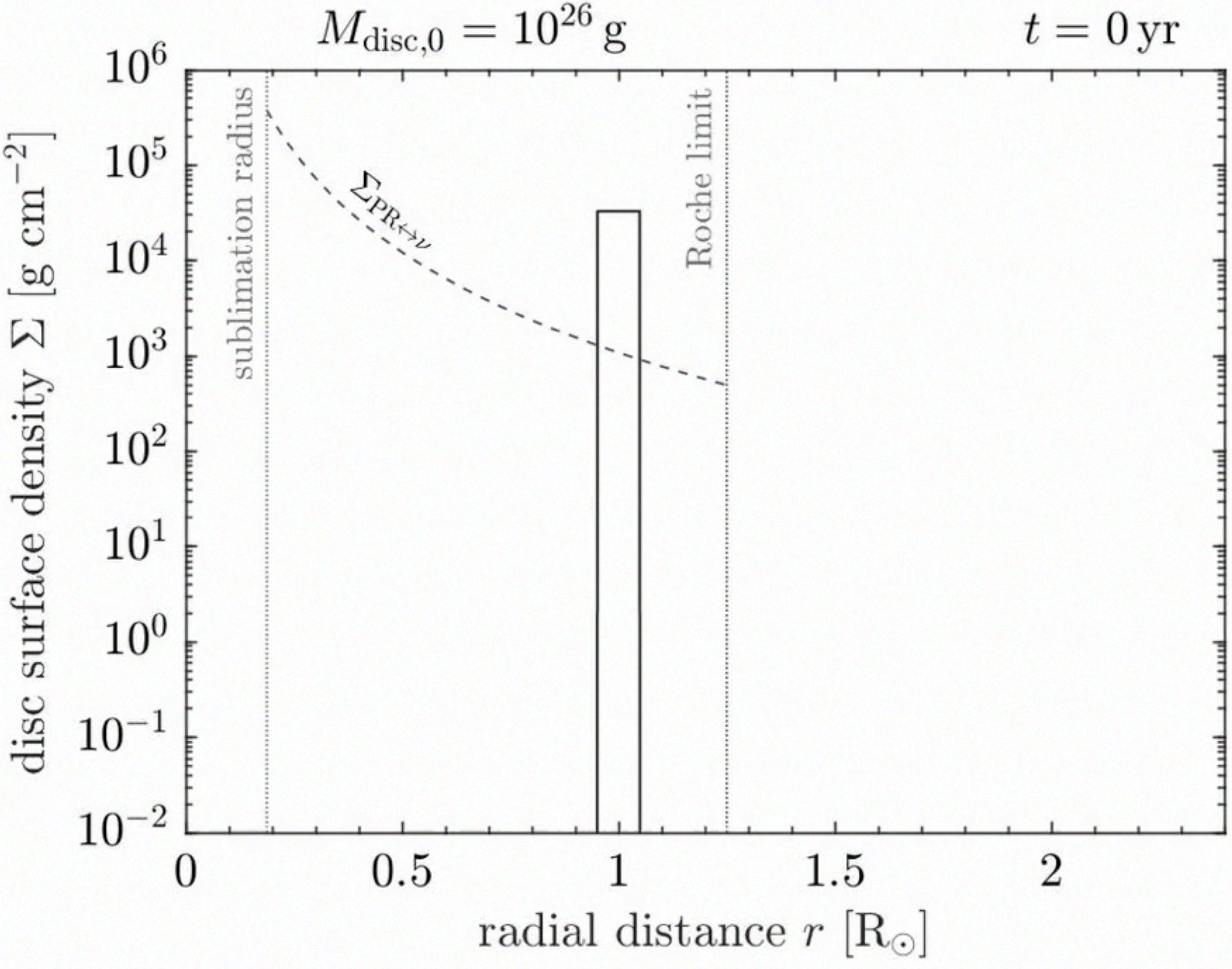

$M_{\rm disc,0} = 10^{24}\,{\rm g}$
$t = 0\,{\rm yr}$
sublimation radius
Roche limit
$\Sigma_{\rm PR+\nu}$
disc surface density Σ [g cm^{-2}]
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
0
0.5
1
1.5
2
radial distance r [R$_\odot$]

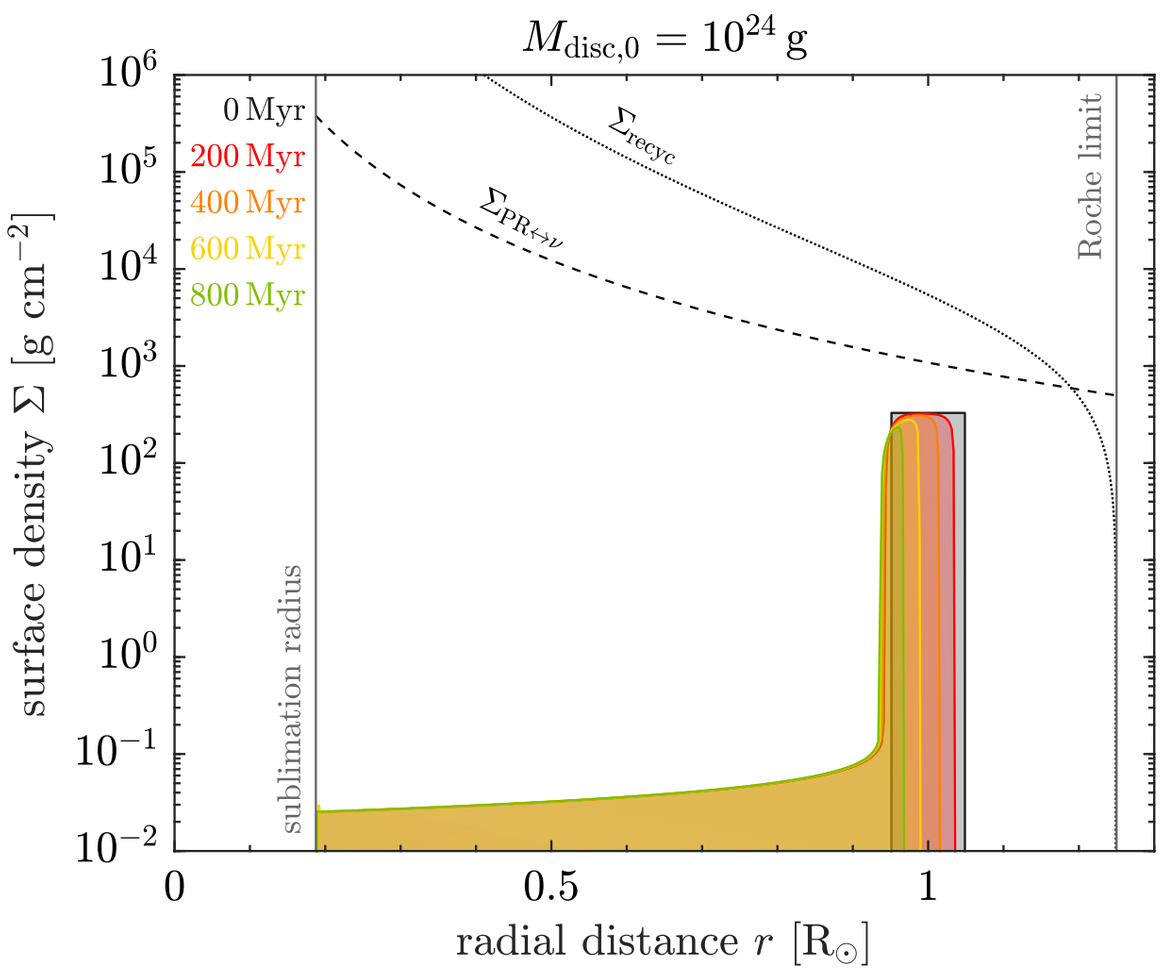
Disc evolution due to Poynting-Robertson drag

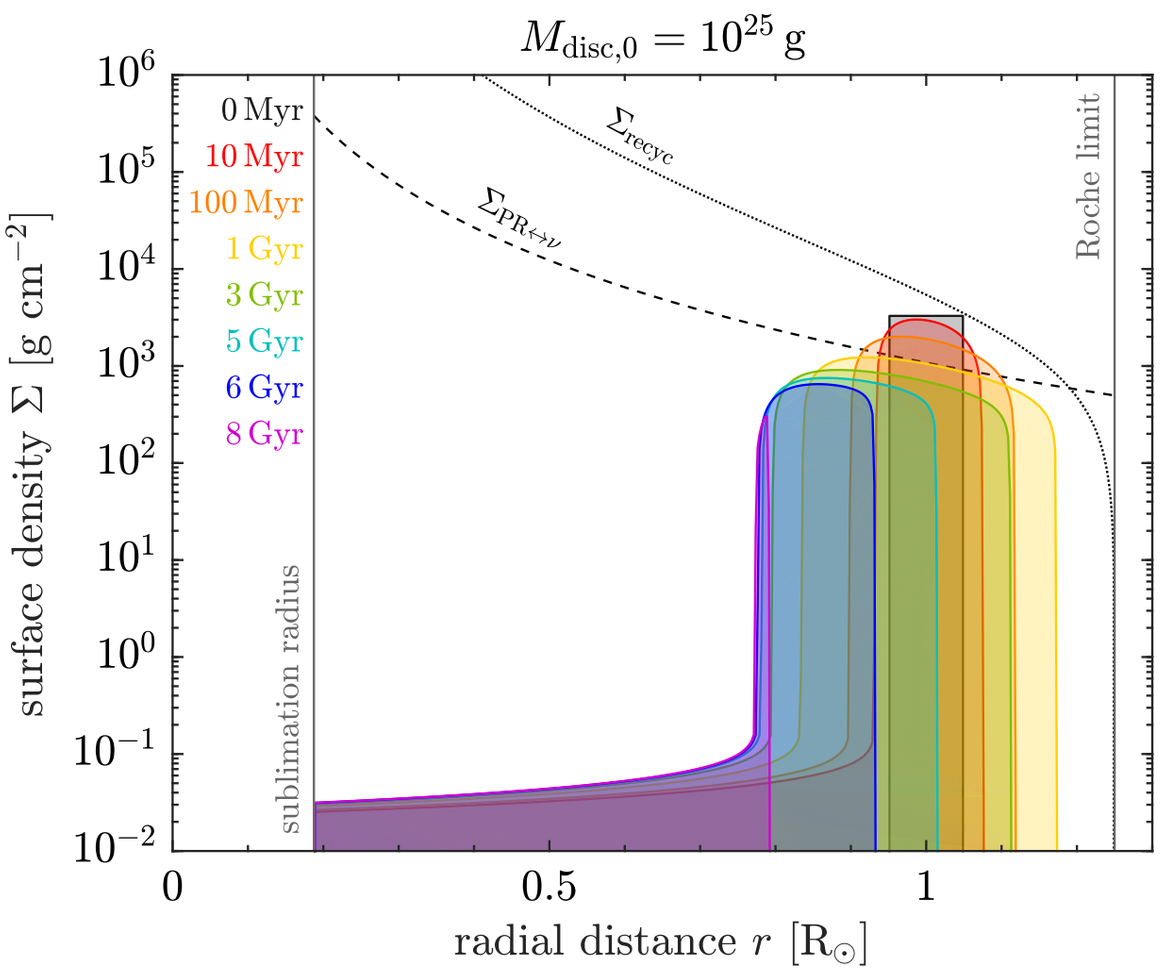


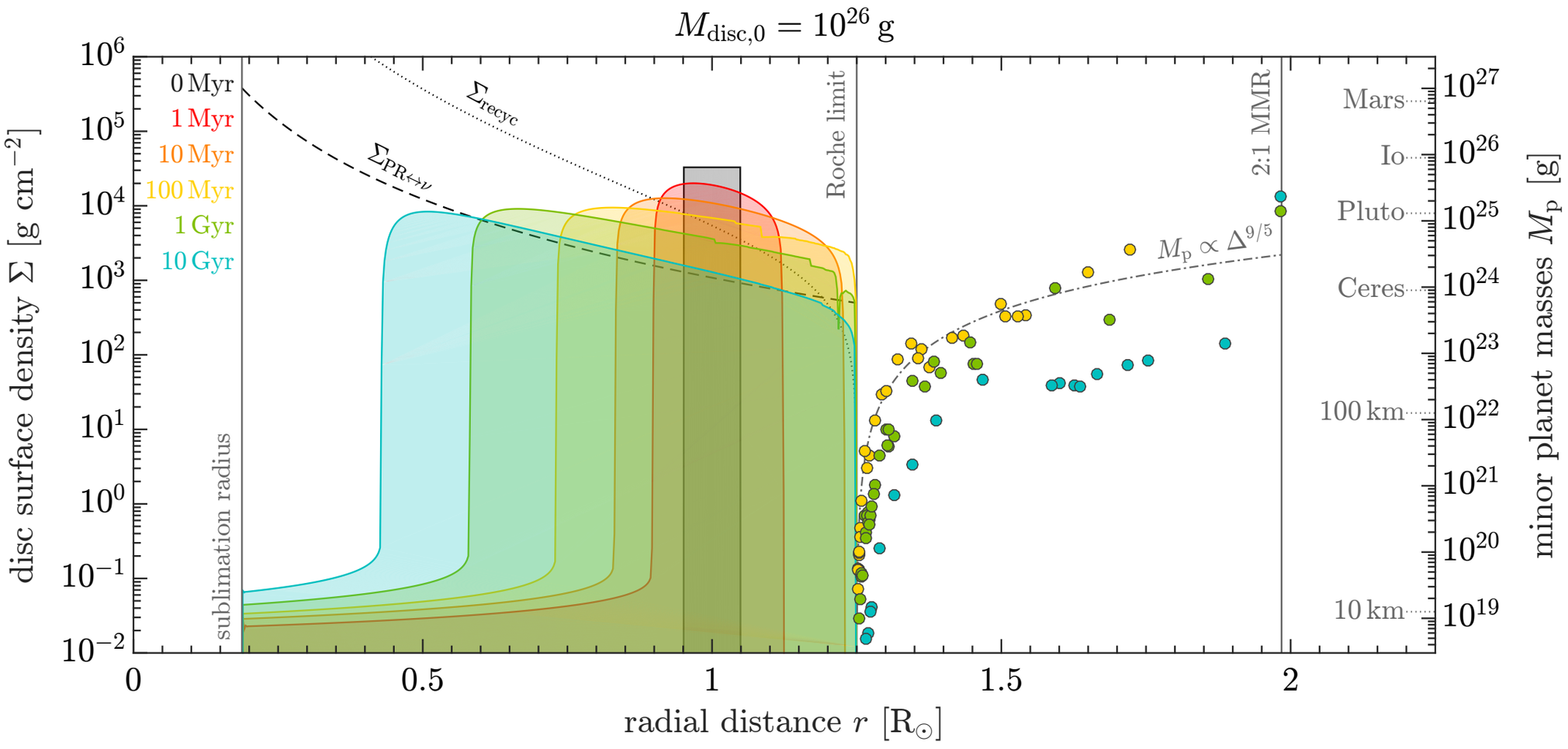
Bochkarev & Rafikov (2011)


$M_{\rm disc,0} = 10^{25}\,{\rm g}$
$t = 0\,{\rm yr}$
sublimation radius
$\Sigma_{\rm PR\leftrightarrow\nu}$
Roche limit
disc surface density Σ [g cm^{-2}]
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
0
0.5
1
1.5
2
radial distance r [R$_\odot$]


$M_{\rm disc,0} = 10^{26}\,{\rm g}$
$t = 0\,{\rm yr}$
sublimation radius
Roche limit
$\Sigma_{\rm PR\leftrightarrow\nu}$
disc surface density Σ [g cm^{-2}]
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
0
0.5
1
1.5
2
radial distance r [R$_\odot$]


$M_{\rm disc,0} = 10^{24}$ g
0 Myr
200 Myr
400 Myr
600 Myr
800 Myr
$\Sigma_{\rm recyc}$
$\Sigma_{\rm PR\leftrightarrow\nu}$
sublimation radius
Roche limit
surface density Σ [g cm^{-2}]
radial distance r [R$_\odot$]


$M_{\rm disc,0} = 10^{25}$ g
0 Myr
10 Myr
100 Myr
1 Gyr
3 Gyr
5 Gyr
6 Gyr
8 Gyr
$\Sigma_{\rm recyc}$
$\Sigma_{\rm PR\leftrightarrow\nu}$
sublimation radius
Roche limit
surface density Σ [g cm^{-2}]
radial distance r [R$_\odot$]


$M_{\rm disc,0} = 10^{26}$ g
0 Myr
1 Myr
10 Myr
100 Myr
1 Gyr
10 Gyr
$\Sigma_{\rm recyc}$
$\Sigma_{\rm PR\leftrightarrow\nu}$
sublimation radius
Roche limit
2:1 MMR
$M_{\rm p} \propto \Delta^{9/5}$
Mars
Io
Pluto
Ceres
100 km
10 km
disc surface density Σ [g cm^{-2}]
minor planet masses $M_{\rm p}$ [g]
radial distance r [R$_\odot$]

radial distance r [$\mathrm{R}_\odot$]

0

0.5

1

planet-forming disc mass M_{recyc} [g]

10^{28}

10^{27}

10^{26}

10^{25}

10^{24}

$M_\star = 0.6\ \mathrm{M}_\odot$

$R_\star = 0.0125\ \mathrm{R}_\odot$

$C_\mathrm{R} = 1.9$

$\rho_\mathrm{d} = 3\ \mathrm{g\ cm^{-3}}$

$T_\star = 20{,}000$ K

$T_\star = 10{,}000$ K

$T_\star = 5{,}000$ K

$C_\mathrm{R} = 1.5$

$C_\mathrm{R} = 2.5$

$\rho_\mathrm{d} = 1\ \mathrm{g\ cm^{-3}}$

$\rho_\mathrm{d} = 6\ \mathrm{g\ cm^{-3}}$

$M_\star = 0.3\ \mathrm{M}_\odot$, $R_\star = 0.0178\ \mathrm{R}_\odot$

$M_\star = 1.2\ \mathrm{M}_\odot$, $R_\star = 0.0057\ \mathrm{R}_\odot$

Earth

Mars

Io

Pluto

Ceres

0

0.25

0.5

0.75

1

scaled radial distance r/r_R

mass recycling efficiency [%]

initial disc mass $M_{\mathrm{disc},0}$ [g]	0	0.25	0.5	0.75	1
10^{28} (Earth)	6.1	18	27	36	44	51	57	64
	4.2	16	25	34	42	49	55	62
10^{27} (Mars)	0.023	10	19	28	36	43	50	56
			4.9	14	22	31	38	46
10^{26} (Io)					5.2	15	24	34
							8.5	20
10^{25} (Pluto)								8.9
10^{24} (Ceres)								

initial radial distance r_0 [$\mathrm{R}_\odot$]

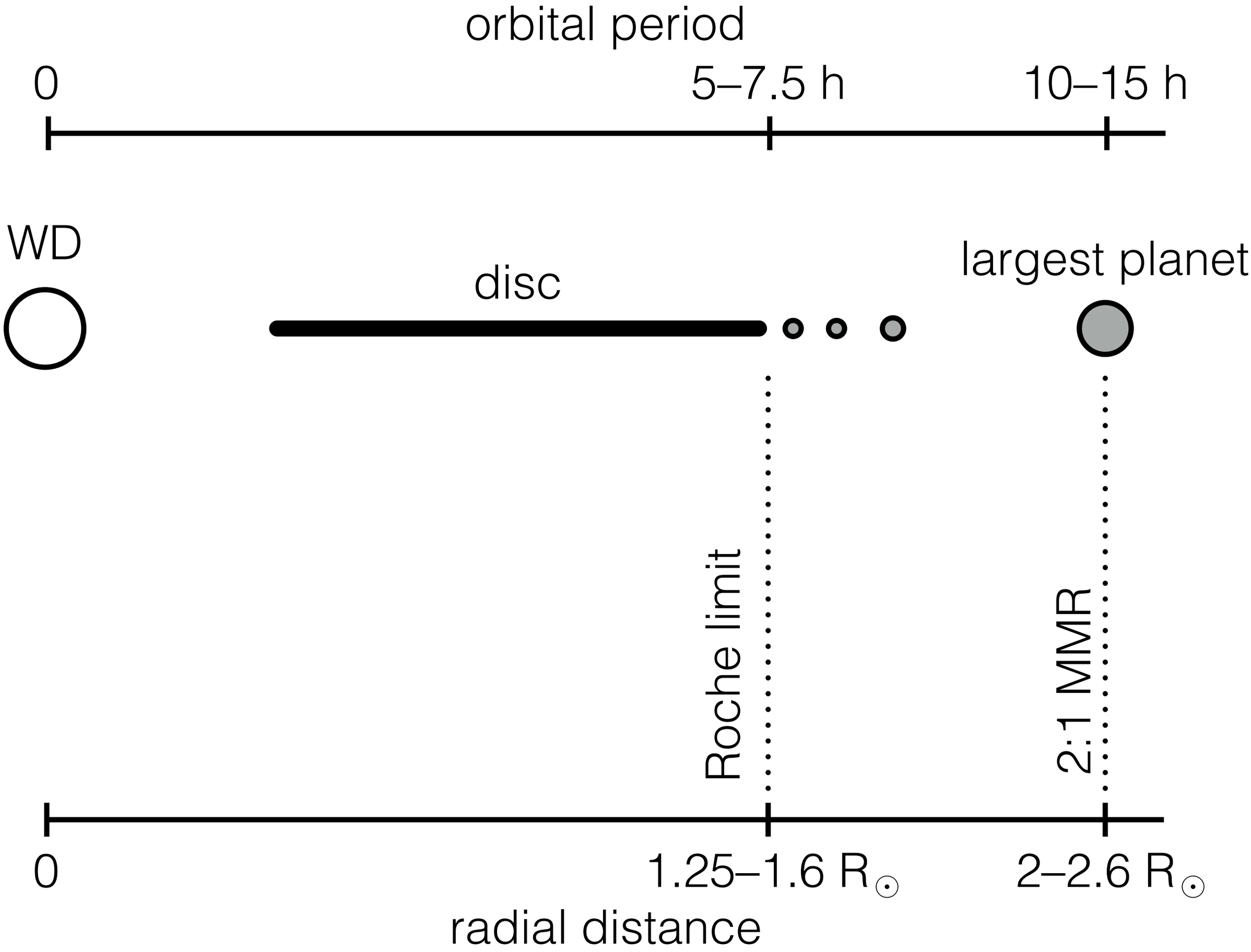
largest planet mass [$M_\oplus$]

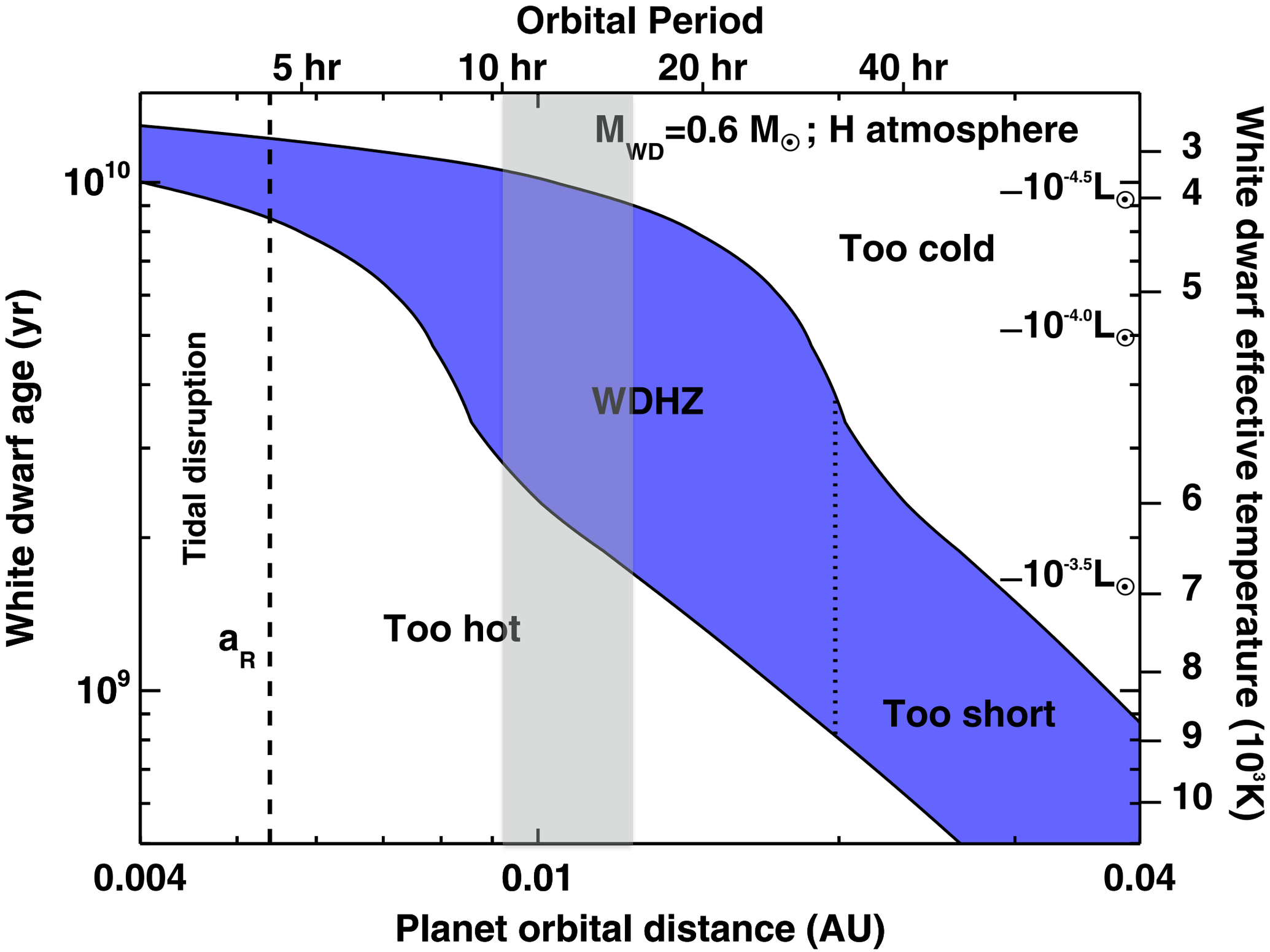
initial disc mass $M_{\mathrm{disc},0}$ [g]	0.10	0.32	0.46	0.63	0.73	0.87	0.96	1.09
10^{28}	0.02	0.09	0.13	0.19	0.22	0.27	0.29	0.33
10^{27}	10^{-5}	0.02	0.03	0.05	0.06	0.07	0.08	0.10
10^{26}			10^{-3}	10^{-2}	10^{-2}	0.02	0.02	0.02
10^{25}					10^{-3}	10^{-3}	10^{-2}	10^{-2}
10^{24}						10^{-3}	10^{-3}	10^{-4}

Earth
Mars
Io
Pluto
Ceres

0 0.25 0.5 0.75 1

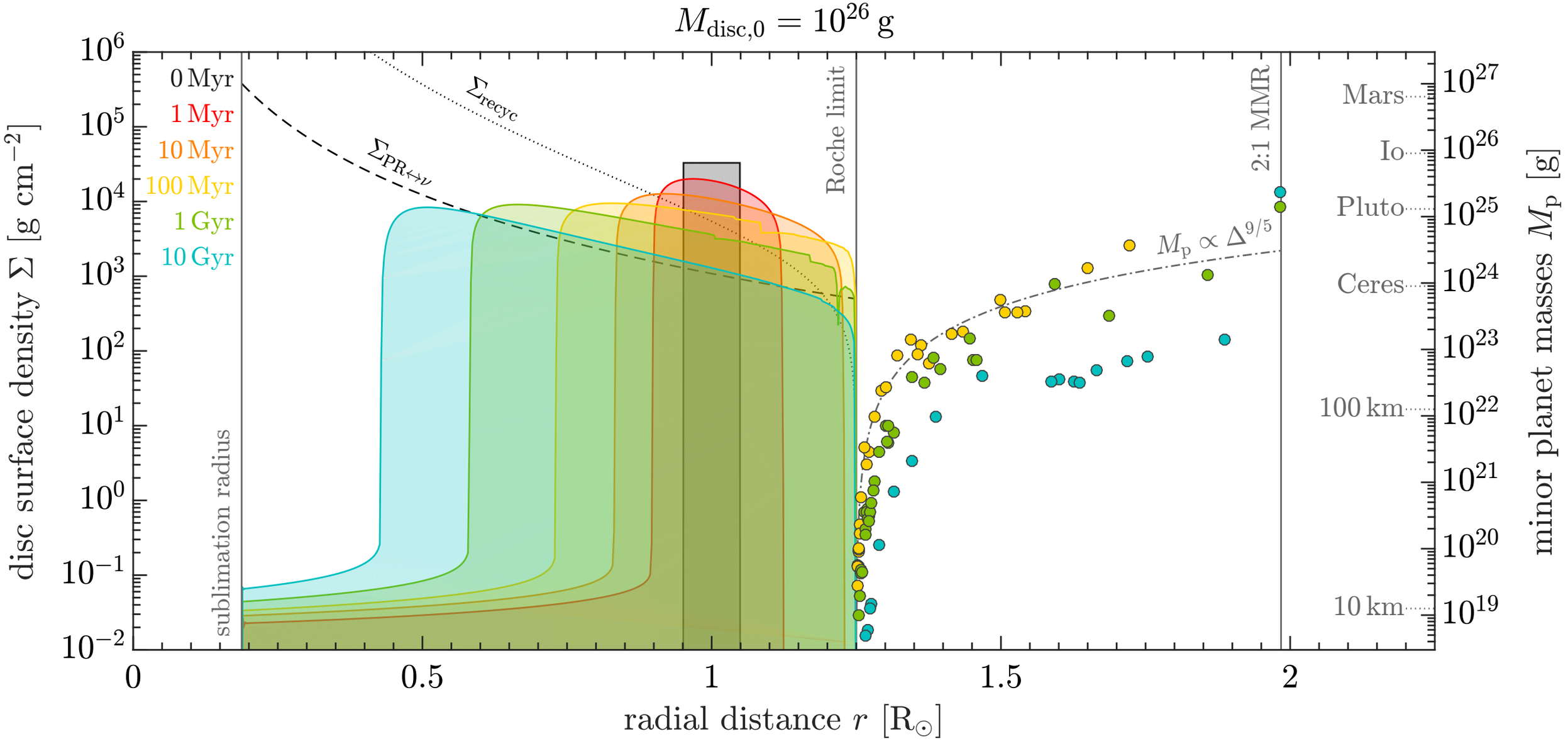
initial radial distance r_0 [$R_\odot$]


orbital period
0
5–7.5 h
10–15 h
WD
disc
largest planet
Roche limit
2:1 MMR
0
1.25–1.6 R⊙
2–2.6 R⊙
radial distance


Orbital Period
5 hr
10 hr
20 hr
40 hr
M_{WD}=0.6 $M_\odot$; H atmosphere
10^{10}
10^9
White dwarf age (yr)
Tidal disruption
a_R
$-10^{-4.5}L_\odot$
$-10^{-4.0}L_\odot$
$-10^{-3.5}L_\odot$
Too cold
WDHZ
Too hot
Too short
3
4
5
6
7
8
9
10
White dwarf effective temperature (10^3K)
0.004
0.01
0.04
Planet orbital distance (AU)

Agol (2011)

Take-home message

Massive ($\gtrsim 10^{26}$ g) debris discs around WDs spread viscously.

Such discs produce new planets just beyond the Roche limit.