Signposts of planetary systems around metal-rich white dwarfs

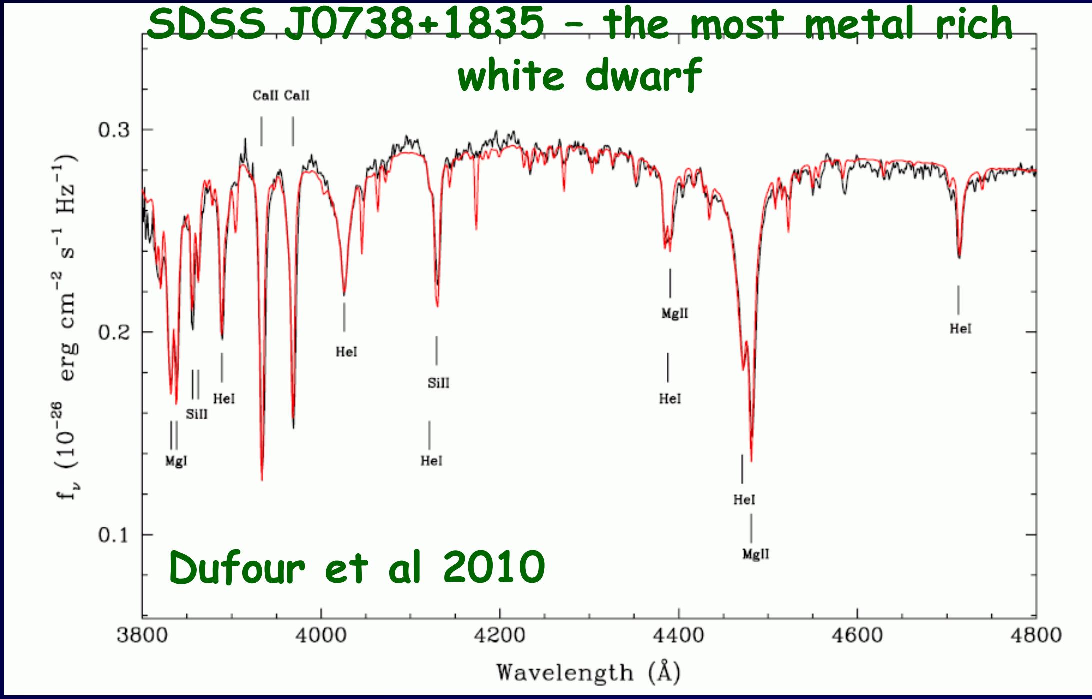
Roman Rafikov
(Princeton)

in collaboration with Brian Metzger, Konstantin Bochkarev, Jose Garmilla

Metal-rich WDs

Metal rich white dwarfs

- WDs exhibiting photospheric absorption metal lines



- Metal-rich WDs are denoted with "Z", e.g.

  DAZ – metal-rich hydrogen WD

  DBZ – metal-rich helium WD

- Tens of % of WDs are known to be metal-rich

  N(DAZ)/N(DA) ~ 25% (T < 10,000 K)

  N(DAZ)/N(DA) ~ 5% (T > 10,000 K)

Things to note:

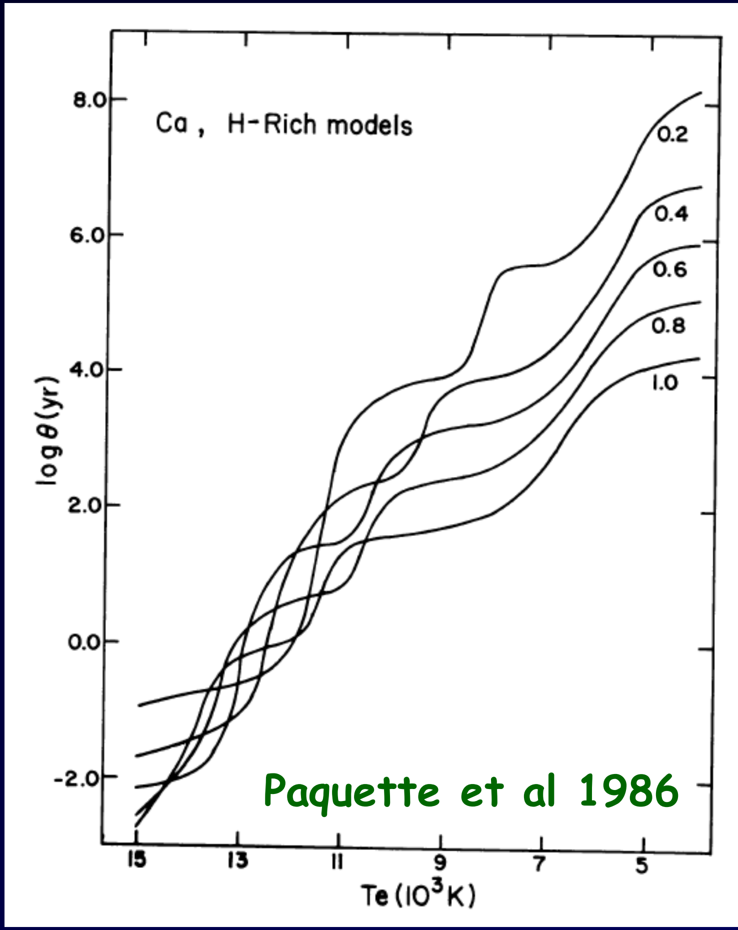
- Massive CO WD with thin convective He envelope
- Long age ~0.6 Gyr
- Very low Hydrogen abundance – below O, Mg, Fe, etc. !
- Undetectable Carbon

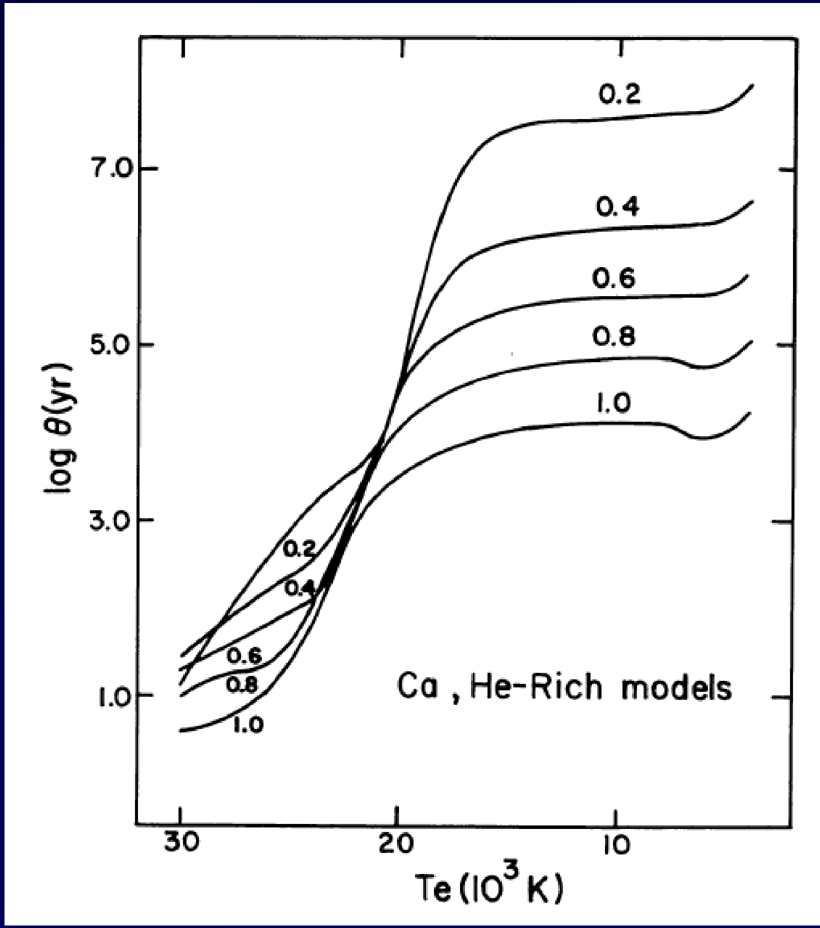
Stellar Parameters for SDSS J0738+1835

Dufour et al 2010

Parameter	Value
$T_{\rm eff}$(K)	13600 ± 300
$\log g$	8.5 ± 0.2
$M_{\rm WD}/M_\odot$	0.907 ± 0.128
$M_{\rm init}/M_\odot$	4.4 ± 1.0[a]
$R/R_\odot$	0.00886 ± 0.0015
$\log L/L_\odot$	-2.62 ± 0.14
D	136 pc $\pm$ 22
Cooling age	595 Myr $\pm$ 219
log H/He	-5.7 ± 0.3
log O/He	-4.0 ± 0.2
log Mg/He	-4.7 ± 0.2
log Si/He	-4.9 ± 0.2
log Ca/He	-6.8 ± 0.3
log Fe/He	-5.1 ± 0.3
$\log(M_{\rm He}/M_\star)$	$-6.5 + 0.8/-0.25$

BUT! Heavy elements settle down on timescales which are much shorter than WD ages (Gyrs)





Why are there any metals left in WD atmospheres?

ISM accretion hypothesis

- Metals must be replenished by external accretion
- They can accrete directly from the ISM
- Accretion would occur at the Bondi rate

$$\dot{M}_{Bondi} \sim n_Z \times v \times \pi \left(\frac{G M_{WD}}{v^2} \right)^2 ,$$

$$\dot{M}_{Bondi} \sim 10^6 \mathrm{g\ s^{-1}} \frac{n_H}{1\ \mathrm{cm^{-3}}} \frac{[Z/H]}{0.01} \left(\frac{M_{WD}}{0.5 M_\odot} \right)^2 \left(\frac{v}{50\ \mathrm{km\ s^{-1}}} \right)^3$$

- Relative elemental abundances should then be compatible with ISM values

Problems with ISM accretion

- ISM accretion should be mainly H and it must stay in the atmosphere (!), however metal enriched He WDs do not show this – metals dominate over H

- This is the strongest argument against ISM accretion

- Enrichment of majority of WDs requires accretion rates much higher that 10^6 g/s

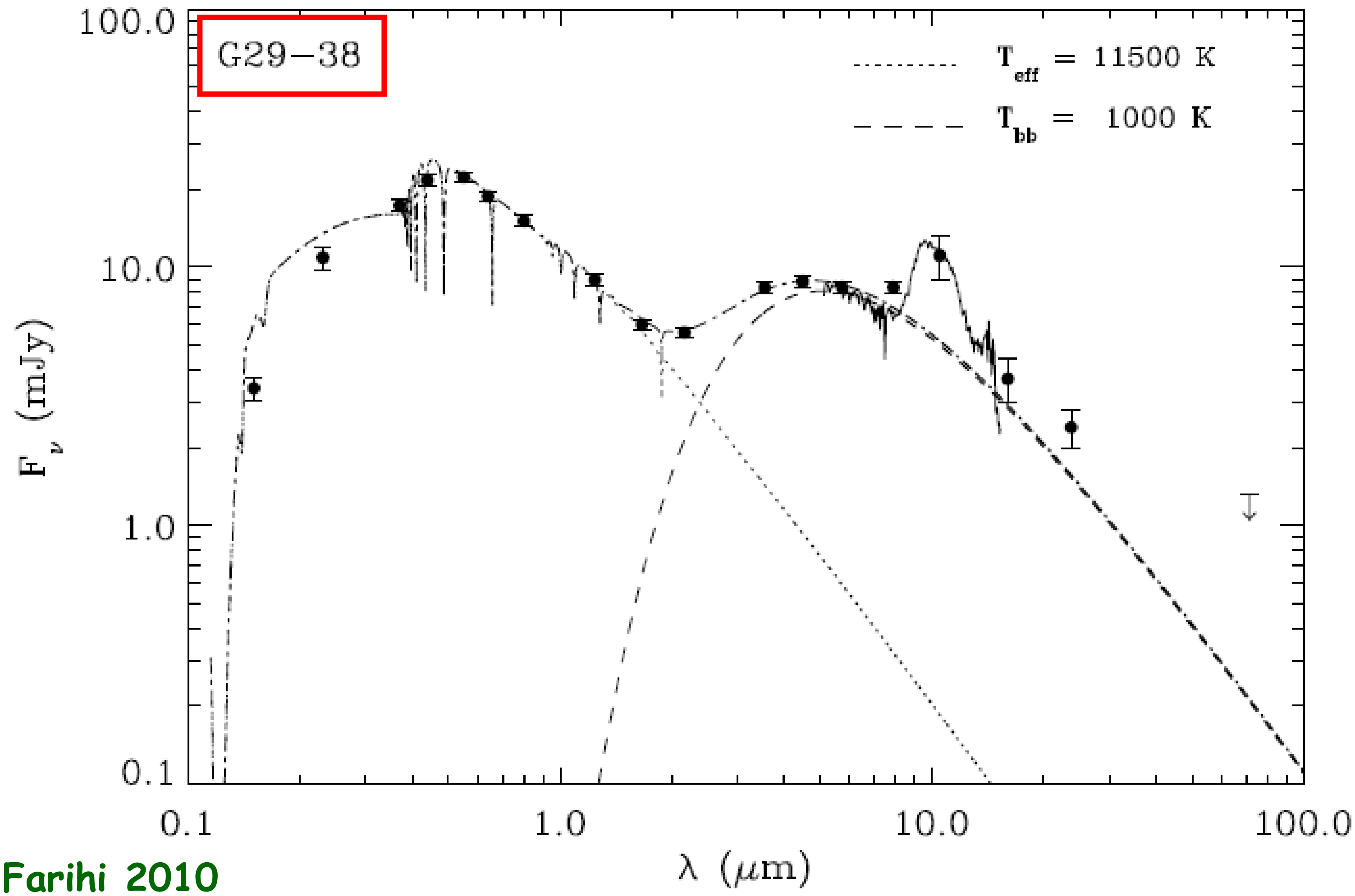
Alternative suggestion:

Accreted material has not interstellar but **circum**stellar origin

Debris disks around WDs

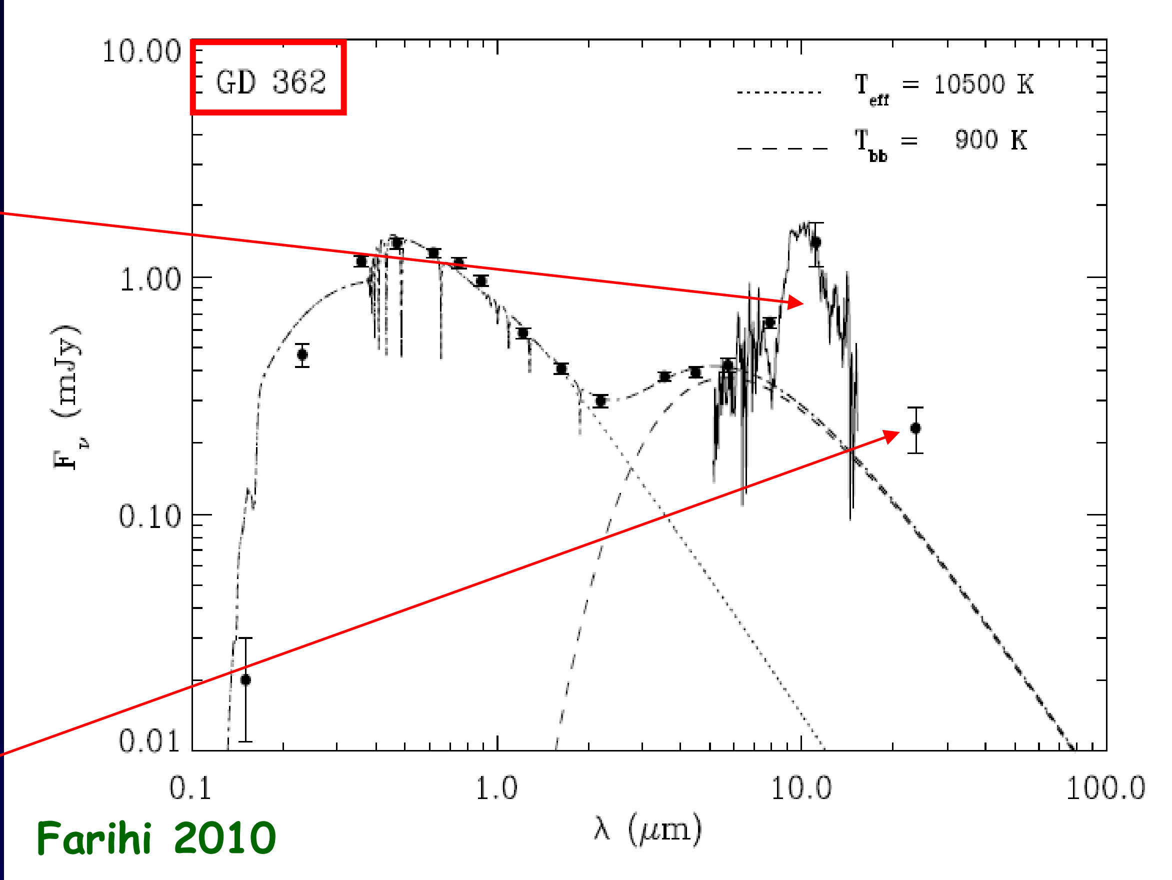
Hot dust around WDs

>20 metal-rich WDs are known to have near-IR excesses

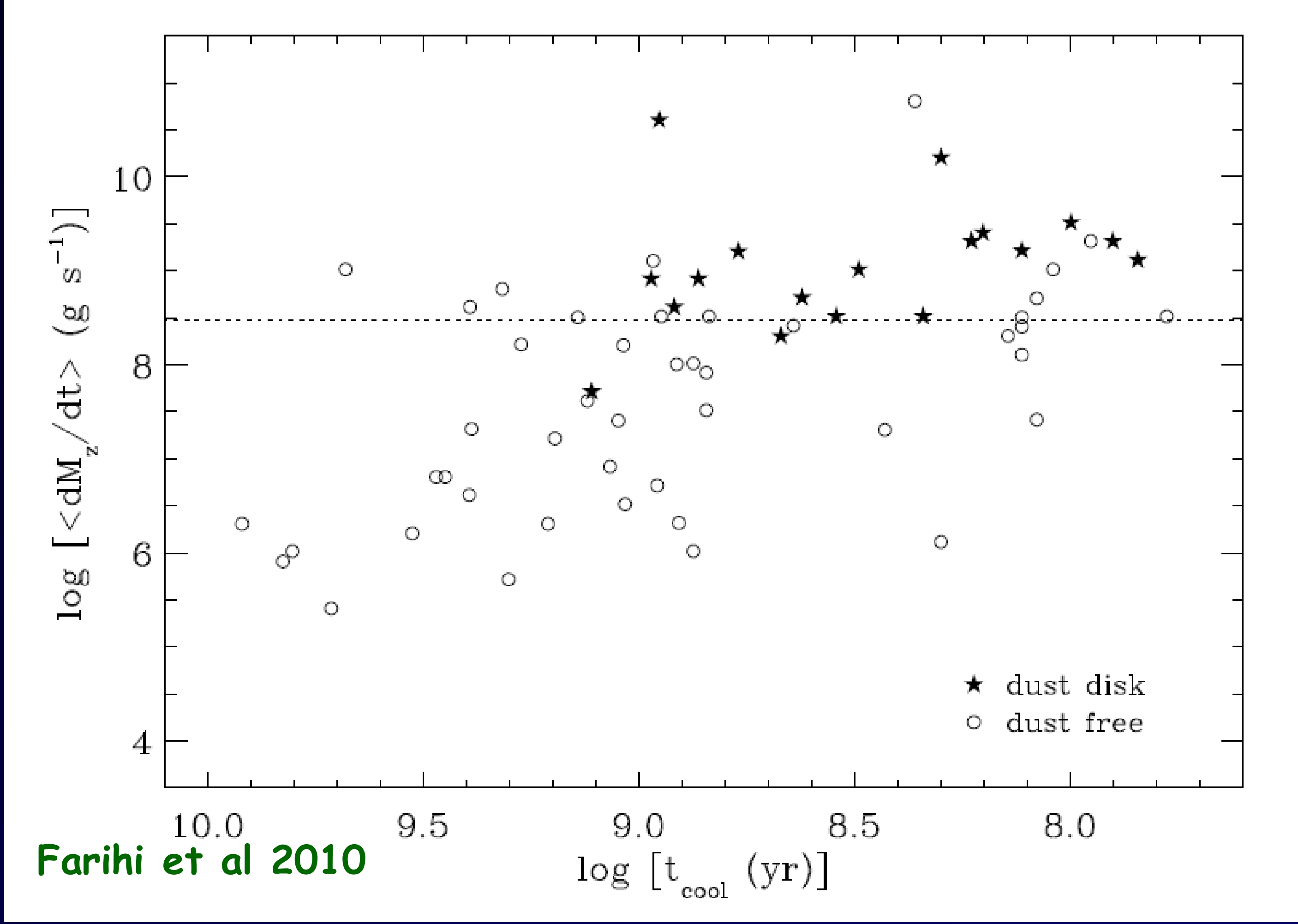


Farihi 2010

- Strong silicate emission feature at 10 microns – evidence for micron-size particles in disks
- Single-T BB does not fit well – need broad ring with a range of T to get agreement at long wavelengths



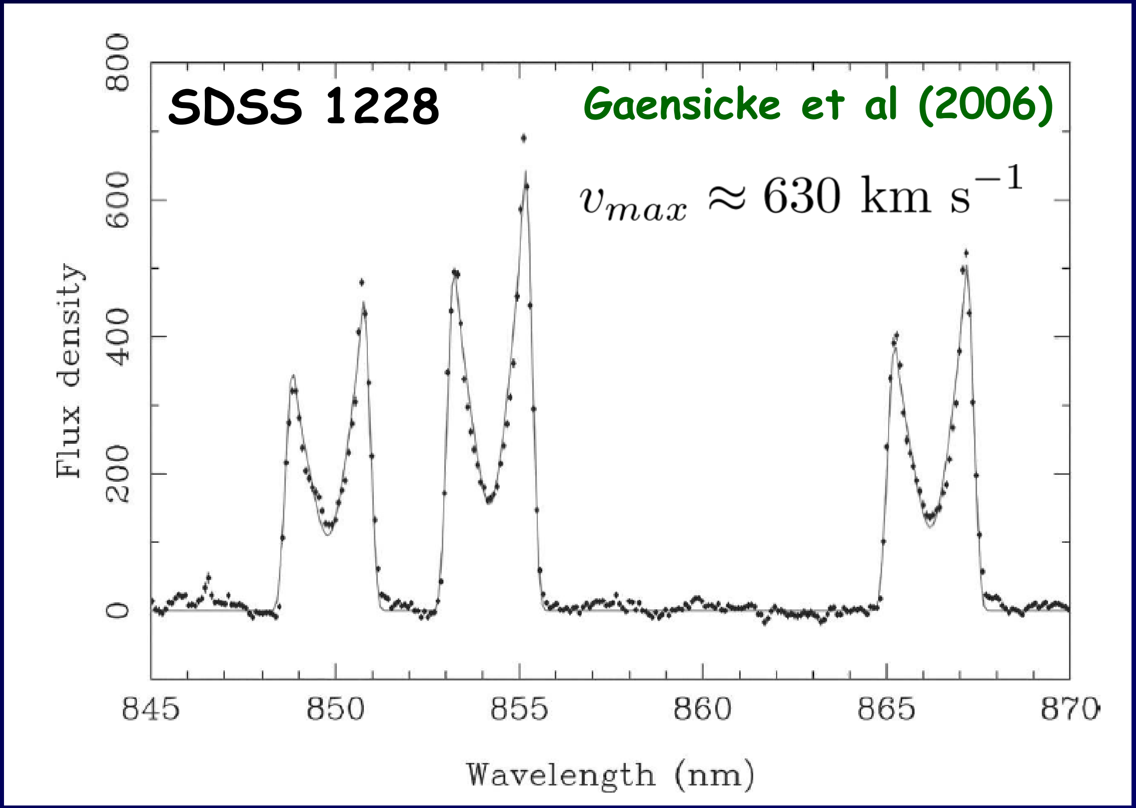
- Weak emission at long wavelengths – lack of material far from WD – disks are compact, within R_Sun
- Spectrum is very similar to an optically thick, geometrically thin protoplanetary disk spectrum



- Most metal-rich WDs have higher chance of hosting detected debris disks
- Others may still have weaker disk (below current detection limit), or have had it in recent past

Gaseous disks around WDs

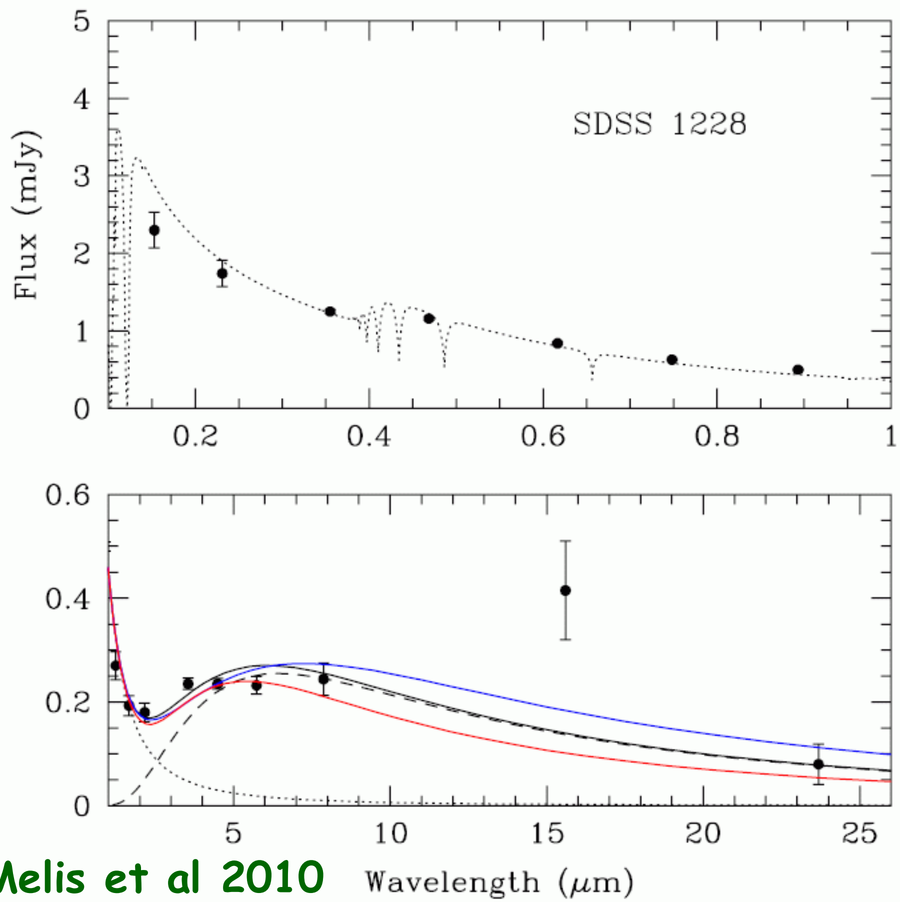
- Optical emission lines of metals (Ca II) have been measured in some WDs
- Have double peaked shape characteristic of origin in a Keplerian disk
- Very close to WD – within 10-50 WD radii (from rotation speed)
- Line peaks are often asymmetric – indication of eccentric disk (?)



Coexisting gaseous and debris disks

Disk Dimensions

Name	Gas Disks			Dust Disks		
	v_{max} (km s^{-1})	$R_{inner,gas}$ (R_{WD})	$R_{outer,gas}$ (R_{WD})	$R_{inner,dust}$ (R_{WD})	$R_{outer,dust}$ (R_{WD})	T_{outer} (K)
SDSS1228	575 ± 17	40 ± 3	108	26 ± 2	93 ± 17	500
Ton 345	709 ± 20	27 ± 2	~100	17 ± 2	100 ± 18	400
SDSS1043	923 ± 52	12 ± 2	81	23 ± 2	80 ± 15	470



Melis et al 2010

- In all 7 cases with gas disks IR have been detected
- Have been successfully modeled as optically thick, geometrically thin disks of dust
- Gas and dust disks spatially overlap

Origin of the refractory circumstellar material close to the WD

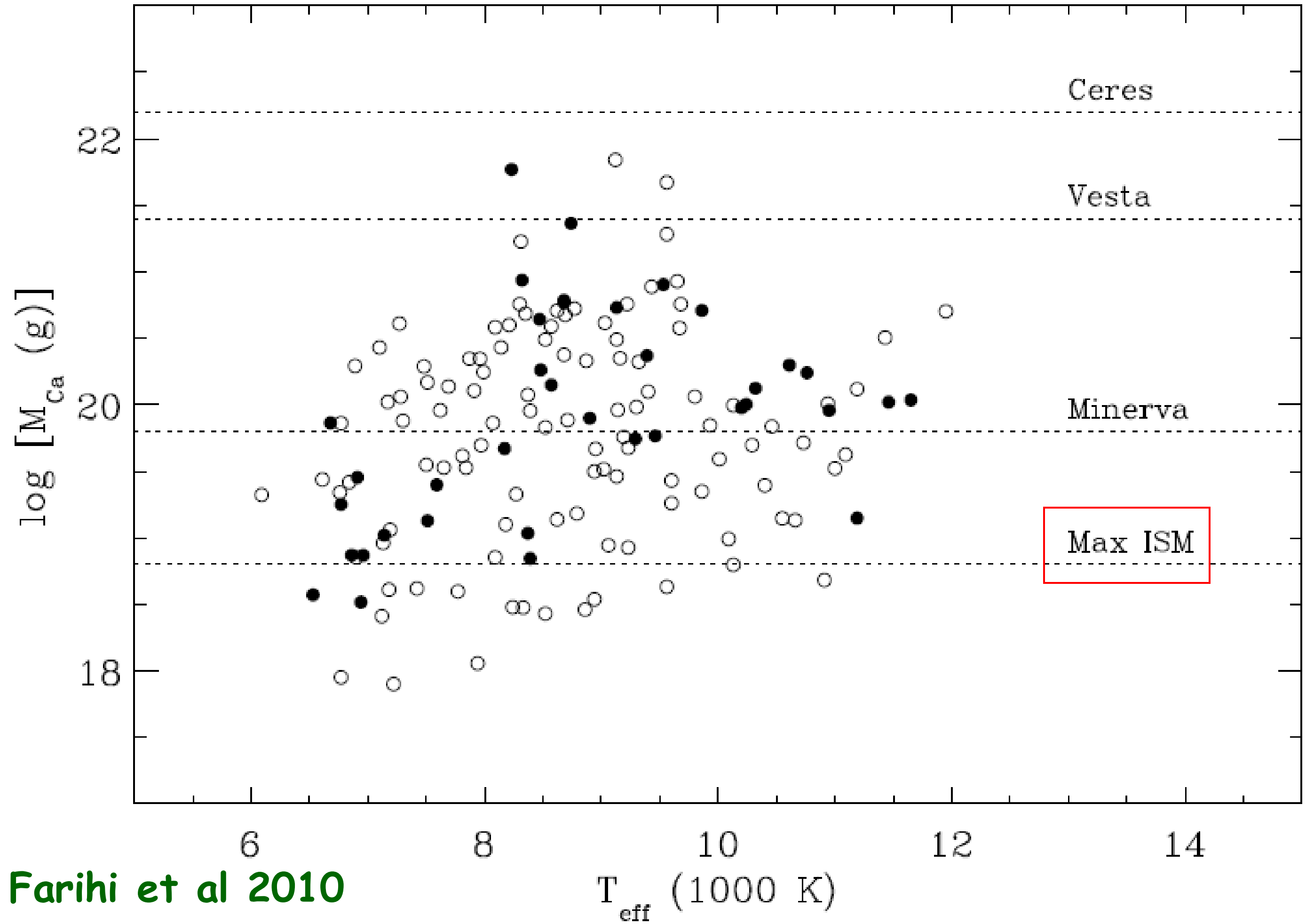
Asteroid disruption

- Dust disks have well defined outer radii ~R_Sun – there is no dust beyond this radius
- But 1 R_Sun is also a Roche radius for bodies with normal density

$$R_R \sim (M_{WD}/\rho)^{1/3} \sim 1\ R_\odot \left(\frac{M_{WD}}{M_\odot} \frac{1\text{g cm}^{-3}}{\rho} \right)^{1/3}$$

- This coincidence suggests that disks are remnants of tidally disrupted asteroid-like bodies (Jura 2003)
- They get ground down to small sizes by collisions and settle into a Saturn ring-like configuration: optically thick and geometrically thin

Mass in high-Z elements

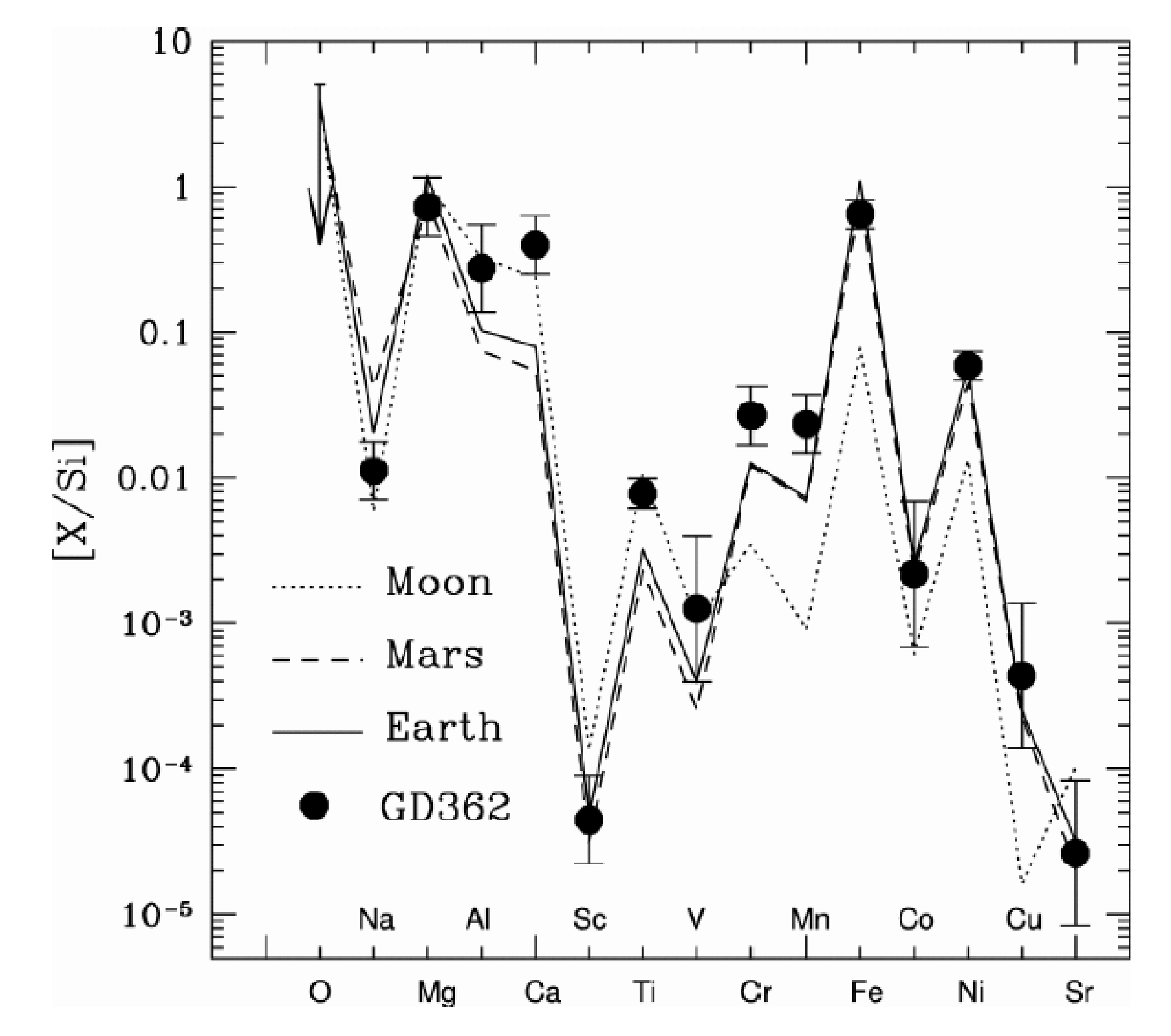


Farihi et al 2010

Compatible with several 100-km asteroid disruption

Composition

Photospheric metal lines **preserve information** about the abundance ratios of different elements that made it into WD



Refractory composition in convective zones of WDs is **very similar** to that of objects formed in **terrestrial zone in the SS (e.g. note low Carbon abundance)**

How do asteroids get there?

Debes & Sigurdsson 2002

- Post-main sequence stars lose a lot of mass to become WDs
- If there are planets around them their orbits expand
- Decrease of stellar mass destabilizes planetary system, chaos follows
- Unstable massive planets excite minor bodies, scatter some of them in, close to WD, where they get tidally destroyed
- Will happen for Solar System !

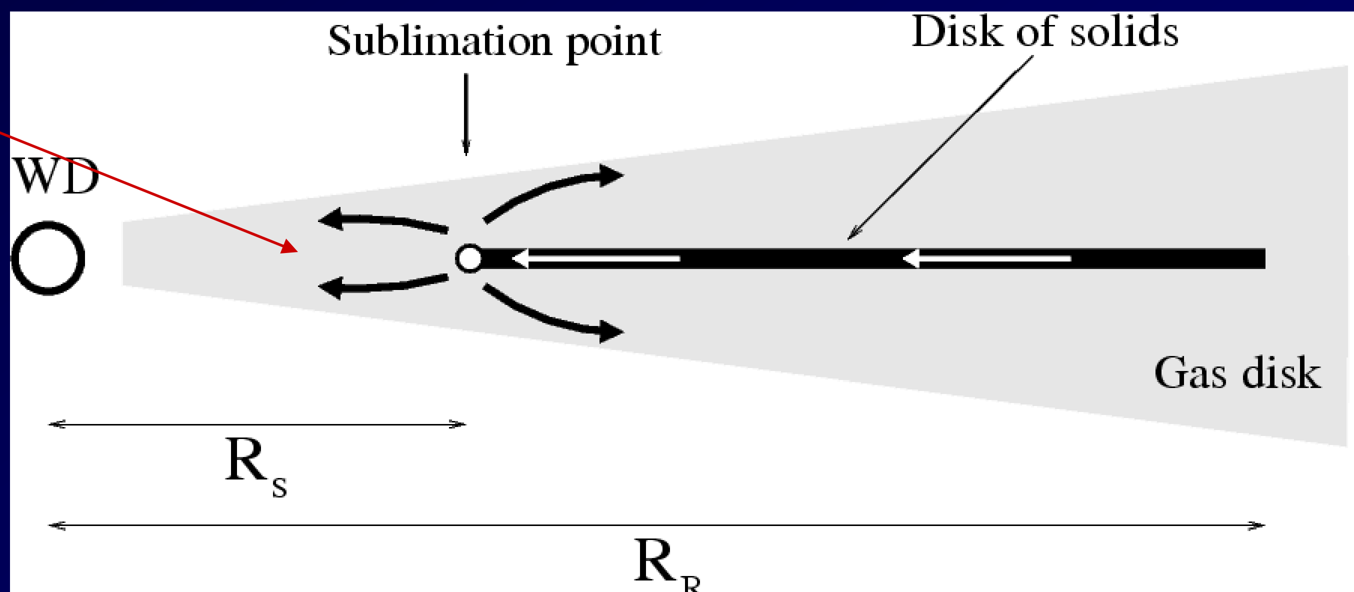
Accretion of metals from debris disk onto the WD

Accretion from a particulate disk

- IR excesses imply existence of sufficient mass reservoir for accretion. High Mdot ~ 10^8-10^11 g/s.
- Dust sublimates at the inner radius

$$R_s = \frac{R_\star}{2}\left(\frac{T_\star}{T_s}\right)^2 \approx 22\, R_\star\, T_{\star,4}^2 \left(\frac{1500\,\mathrm{K}}{T_s}\right)^2$$

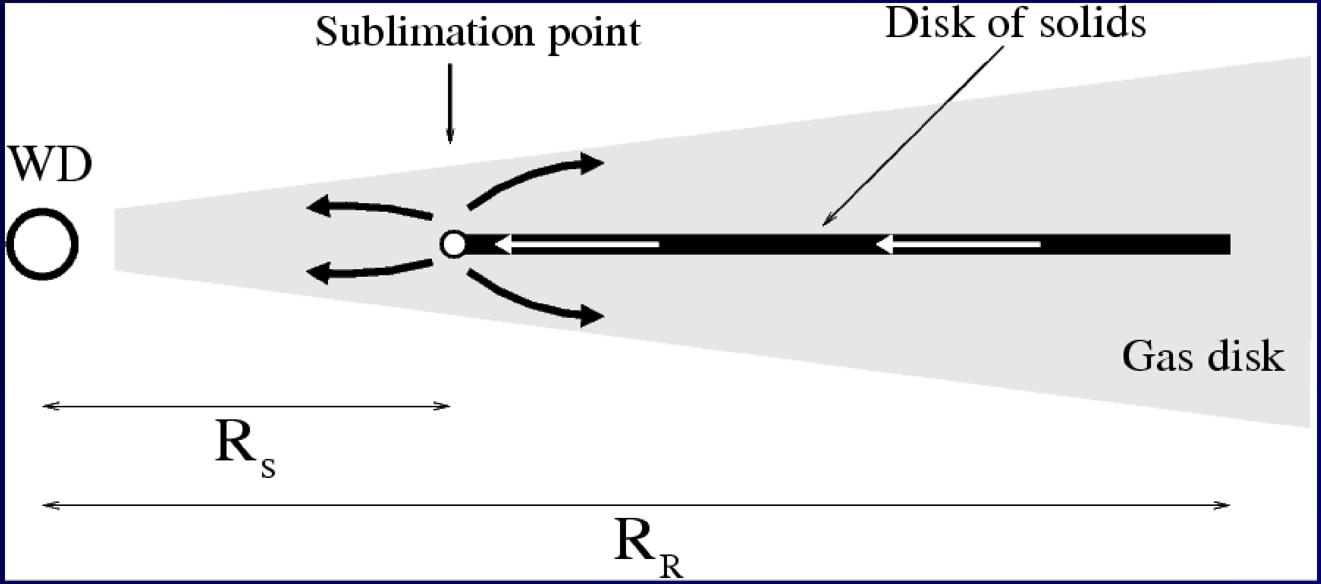
- Broad inner cavity in dust disk!



- Metals get ultimately accreted by the WD as gas
- Timescale for viscous accretion is very short

$$t_\nu \sim \frac{R_s^2}{\nu} \sim 200\ \mathrm{yr}\frac{10^{-2}}{\alpha}\left(\frac{R_s}{0.2R_\odot}\right)^{1/2}\left(\frac{5000\ K}{T_{gas}}\right)$$

Accretion rate must be regulated by inward migration of particles in the disk of solids!

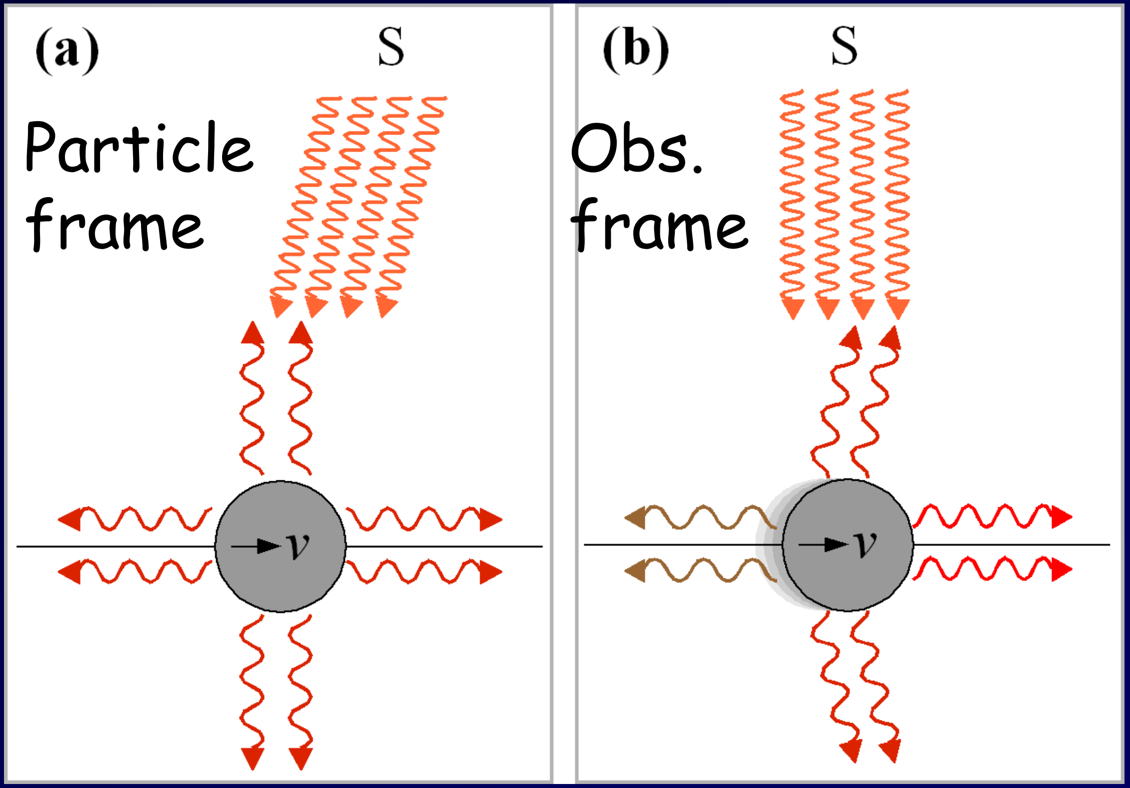


Poynting-Robertson drag

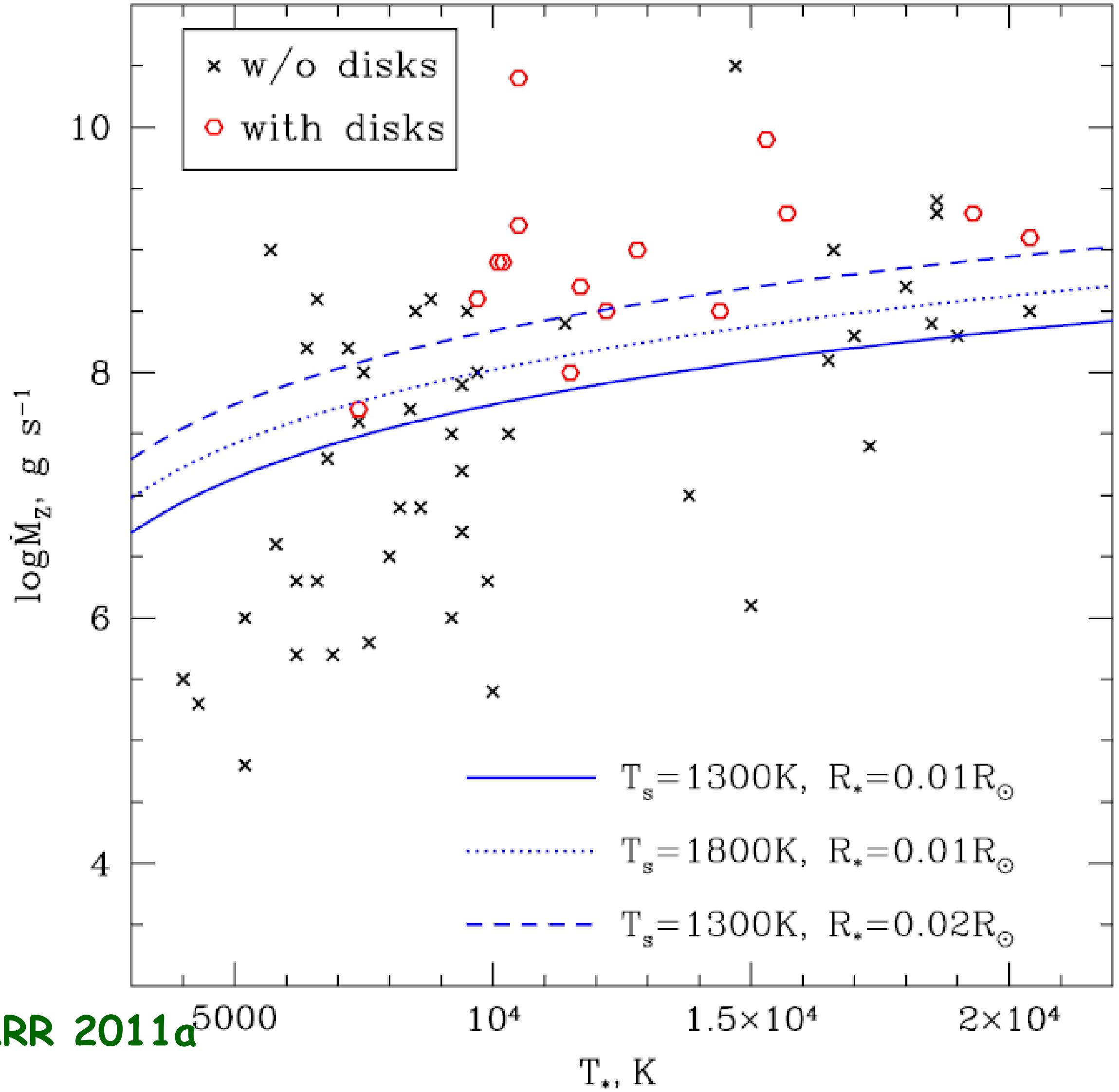
- PR drag is a special relativistic effect
- Aberration of light – stellar radiation arrives at an angle

$$\delta = v/c$$

- Azimuthal force
- Inward drift of small bodies orbiting luminous objects
- Well known in planetary sciences



$$\dot{M}_{PR} = 2\pi r \Sigma v_r = \alpha \frac{L_\star}{c^2} \approx \frac{R_\star}{r} \frac{L_\star}{c^2}$$



RRR 2011a

$$\dot{M}_{PR} \approx 10^8 \text{ g s}^{-1} \left(\frac{R_\star}{0.01 R_\odot} \frac{T_\star}{10^4 K} \frac{T_s}{1500K} \right)^2$$

- All systems with detected disks have

$$\dot{M}_Z > \dot{M}_{PR}$$

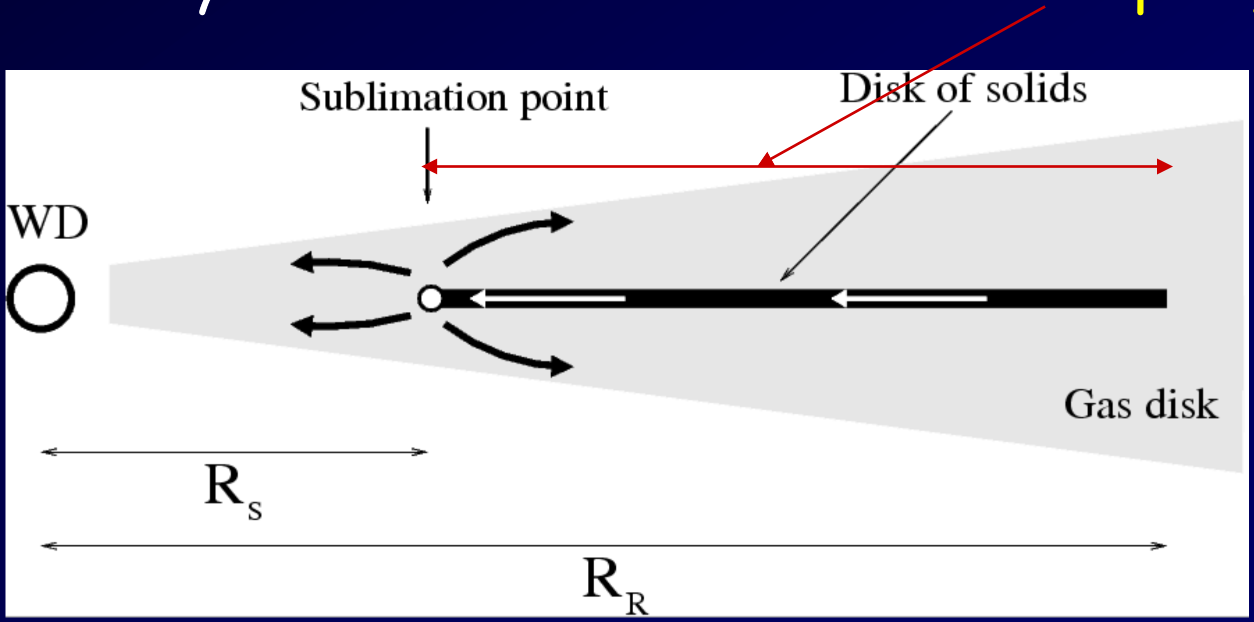
- PR drag works!

Note:

- A number of systems have significantly higher accretion rates
- Many have lower rates

How to explain highest measured accretion rates?

- At sublimation point dust disk evaporates and feeds gas disk, which spreads in **and out**
- Need to study their interaction in the overlap region

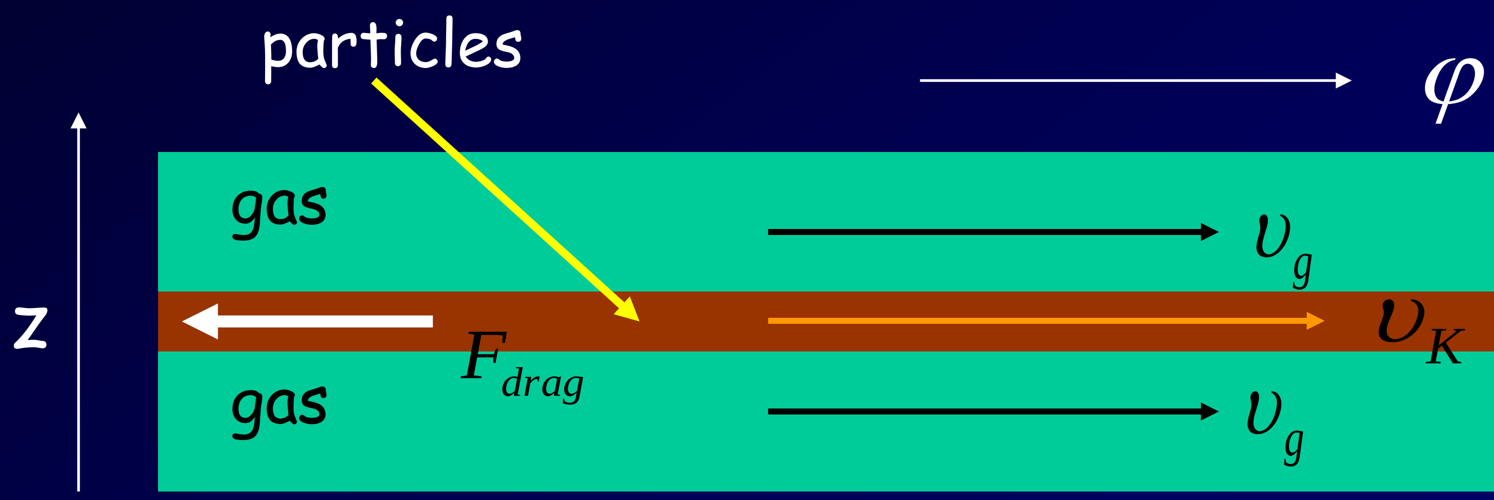


Coupling of gas and particle disks

RRR 2011b

- Radial pressure gradient in gas makes it rotate slower than particles

$$v_K - v_g \approx -\frac{r}{2 v_K \rho_g}\frac{\partial P_g}{\partial r} \sim c_s \frac{c_s}{v_K} \sim 1 \text{ m s}^{-1}$$



- Aerodynamic drag slows particles, leads to radial drift
- Similar to "1-m problem" in planet formation (Weidenschilling 1977)

Evolution of coupled gas+particle disks

Solids evaporate at sublimation radius creating gas

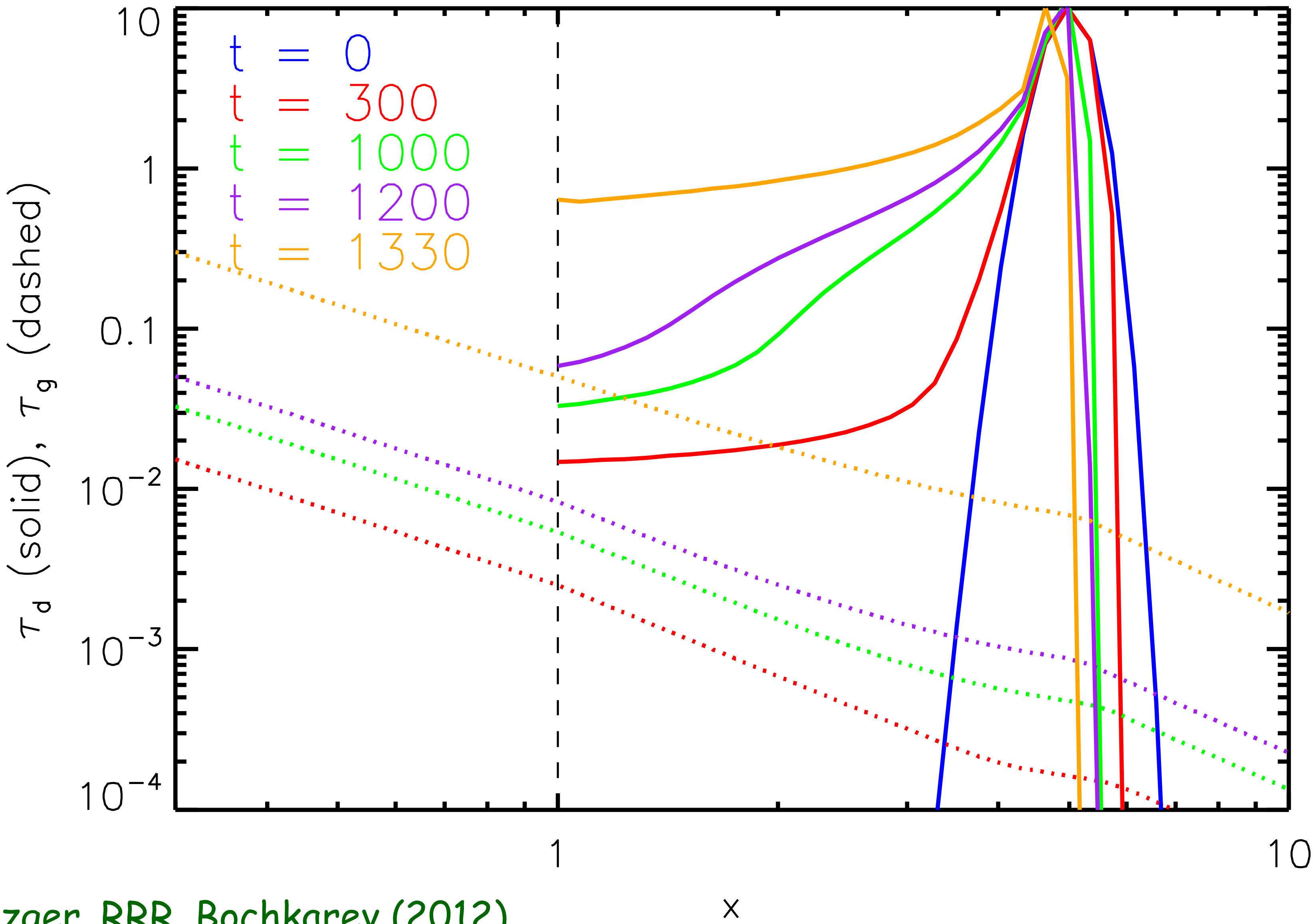
Gas viscously spreads, both in and out

Gas rotates slower than solids, decelerates them

Solids migrate towards the sublimation region

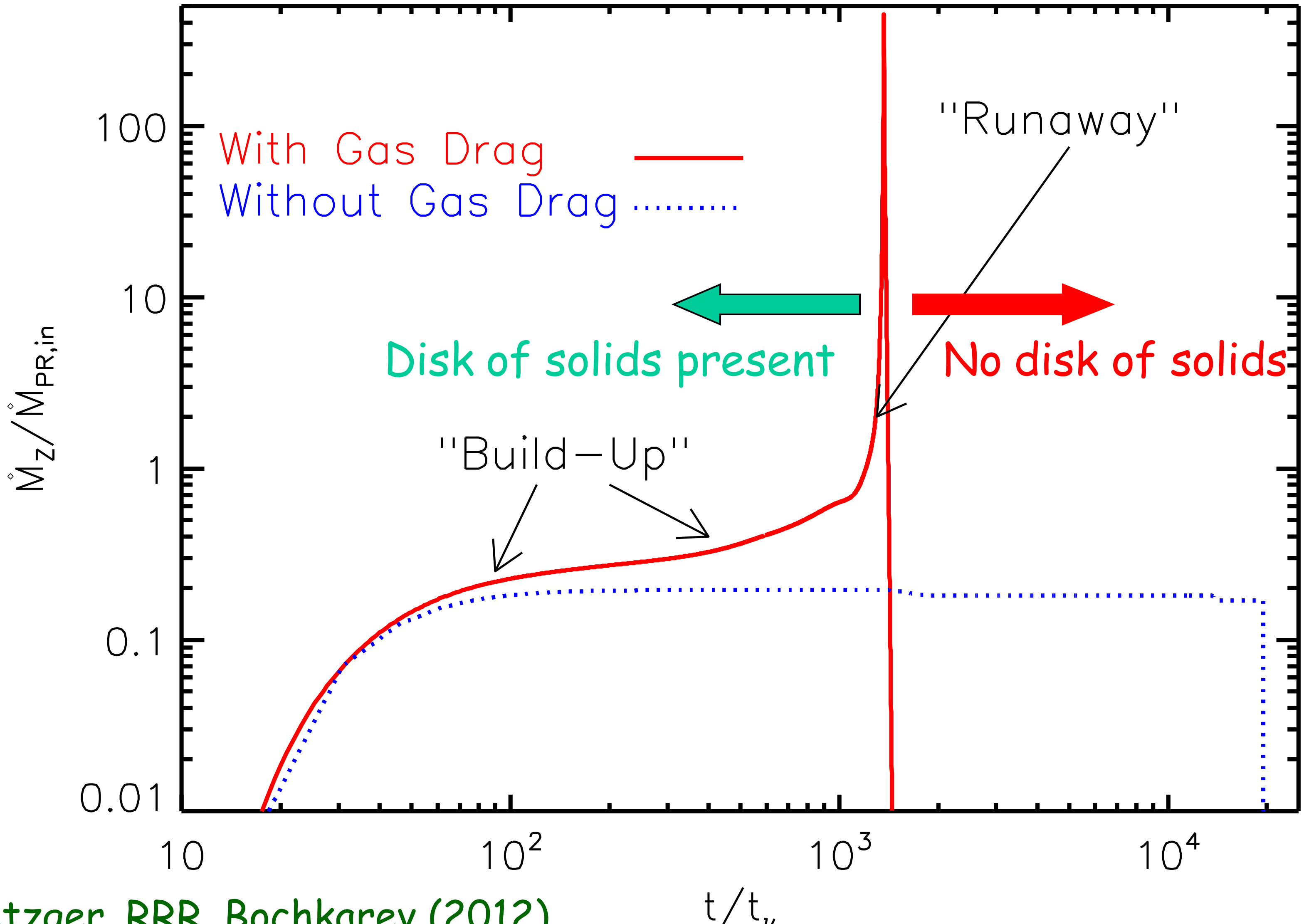
Positive feedback !

Evolution of coupled gas+particle disks



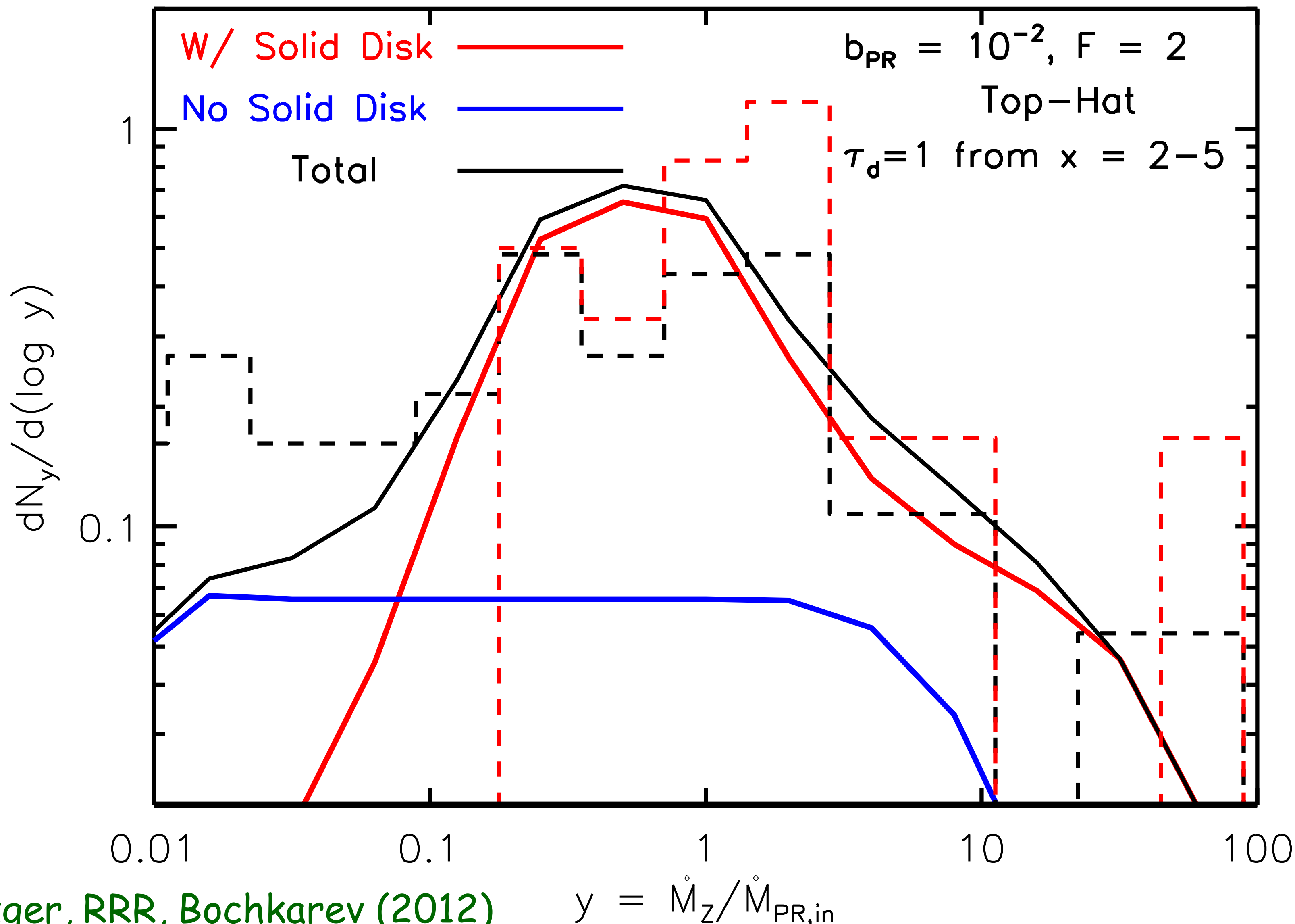
Metzger, RRR, Bochkarev (2012)

Very different mass accretion histories!



Metzger, RRR, Bochkarev (2012)

Accretion rate distribution for runaway



Metzger, RRR, Bochkarev (2012)

Summary

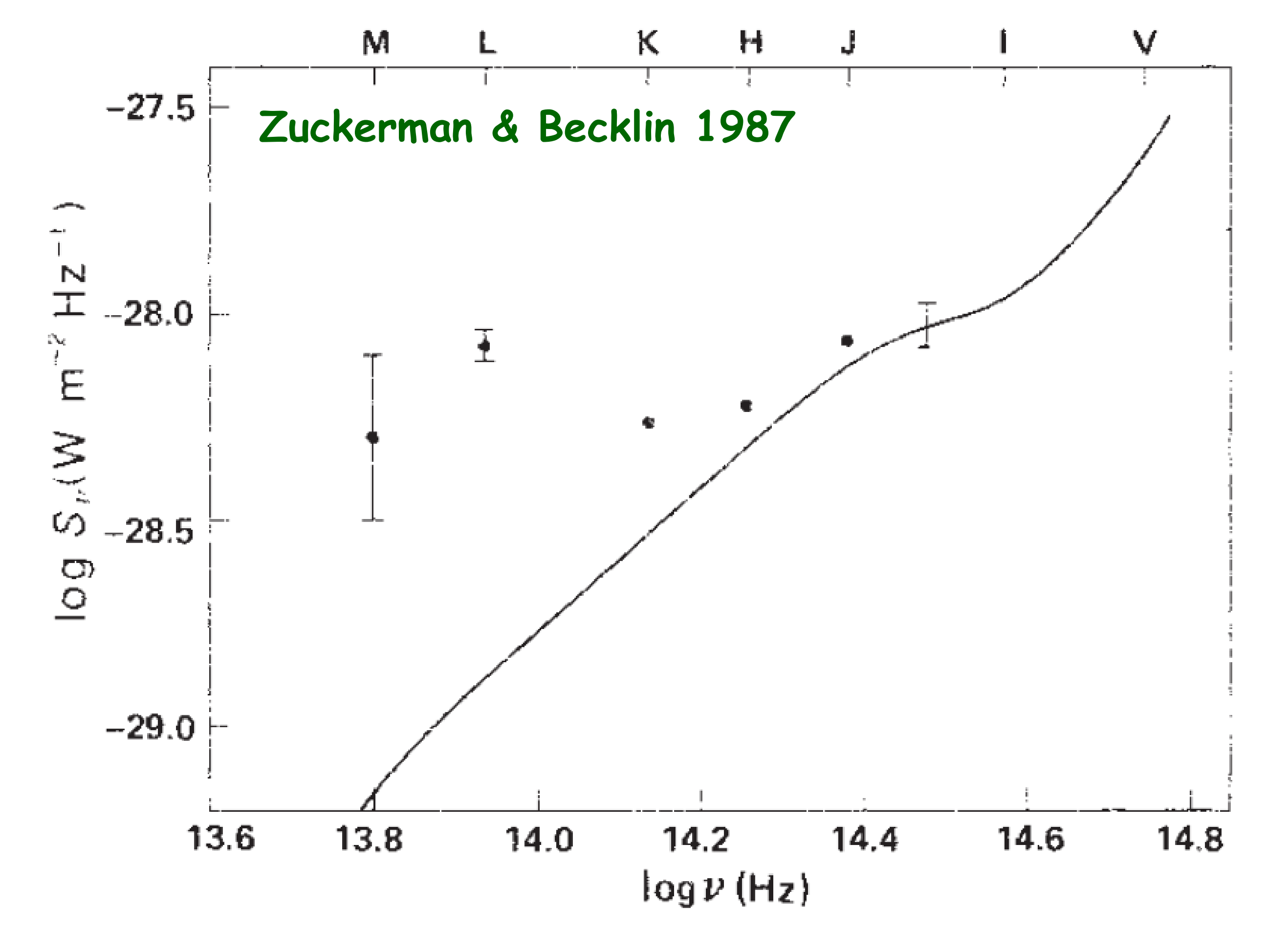
- Metal-rich WDs can't be explained by ISM accretion
- Compact dust disks have been discovered via IR excesses around many metal-rich WDs. Accretion from them can explain WD metal pollution.
- Sometimes they are accompanied by gaseous disks
- Disks are likely the remnants of tidally disrupted minor planets. This implies possibility of planet formation around stars more massive than the Sun
- Evolution of compact debris disks is driven by the Poynting-Robertson drag and non-trivial coupling with the gaseous disks (fed by sublimation).

First evidence for circum-WD material

- Detection of IR excess around WD Giclas 29-38 with IRTF (Zuckerman & Becklin 1987)

- Indicative of dusty material around WD, reprocessing WD emission in IR

- High temperature implies material close to the WD



Current statistics

- Tens of % of WDs are metal enriched
- Over 50% of single metal-rich WDs with high

$$\dot{M}_Z > 3 \times 10^8 \ \mathrm{g\ s^{-1}}$$

are showing IR excess due to hot dust in their vicinity

- It is estimated that 1-3% of single WDs younger than 0.5 Gyr possess circumstellar dust
- All 7 WDs with compact gaseous disks around them also host compact dust disks, spatially coincident with gas

How do asteroids get there?

Debes & Sigurdsson 2002

- Post-main sequence stars lose a lot of mass to become WDs
- If there are planets around them their orbits expand
- Stability of planetary system is determined by

$$\frac{R_H}{\Delta a} = \frac{1}{a_2 - a_1} \frac{a_1 + a_2}{2} \left(\frac{M_1 + M_2}{M_\star} \right)^{1/3} = \left(\frac{R_H}{\Delta a} \right)_0 \left(\frac{M_\star(0)}{M_\star} \right)^{1/3}$$

- The bigger is the ratio the more unstable is the system
- Mass loss increases the ratio, destabilizes system
- Unstable massive planets excite minor bodies, scatter some of them in, close to WD; also create "Kuiper Belts"

System setup - theorist's view
(a.k.a. "spherical horse in vacuum")

- Optically thick, geometrically thin disks of solid debris – similar to rings of Saturn
- Range of radii are broadly consistent with
  T < (sublimation temperature of silicates)
- Contain some mass in small (micron size) Si dust
- Sometimes accompanied by gaseous disks
- Gas line asymmetries indicate noncircular motions
- Broad range of metal accretion rates onto WD
- Live for 10^5-10^6 yr

RRR 2011a

PR drag per unit area of the disk

$$f_{PR} = \alpha \times \frac{L_\star}{4\pi r^2 c} \times \frac{v_K}{c}$$

Conservation of angular momentum

$$\Sigma \frac{d}{dt}\sqrt{GM_\star r} = r \times f_{PR}, \qquad \rightarrow \qquad \frac{dr}{dt} \equiv v_r = \frac{2 f_{PR} r}{v_K \Sigma}$$

Mass accretion rate

$$\dot{M}_{PR} = 2\pi r \Sigma v_r = \alpha \frac{L_\star}{c^2} \approx \frac{R_\star}{r}\frac{L_\star}{c^2}$$

Independent of surface density, particle size, physical properties !

RRR 2011a

At sublimation radius

$$R_s = \frac{R_\star}{2}\left(\frac{T_\star}{T_s}\right)^2 \approx 22\, R_\star\, T_{\star,4}^2 \left(\frac{1500\,\mathrm{K}}{T_s}\right)^2$$

mass accretion rate

$$\dot{M}_{\mathrm{PR}}(r) = \frac{4\phi_r}{3\pi}\frac{R_\star}{r}\frac{L_\star}{c^2} \approx 10^8\ \mathrm{g\ s^{-1}}\,\phi_r \frac{L_\star}{10^{-3}L_\odot}\frac{20}{r/R_\star}$$

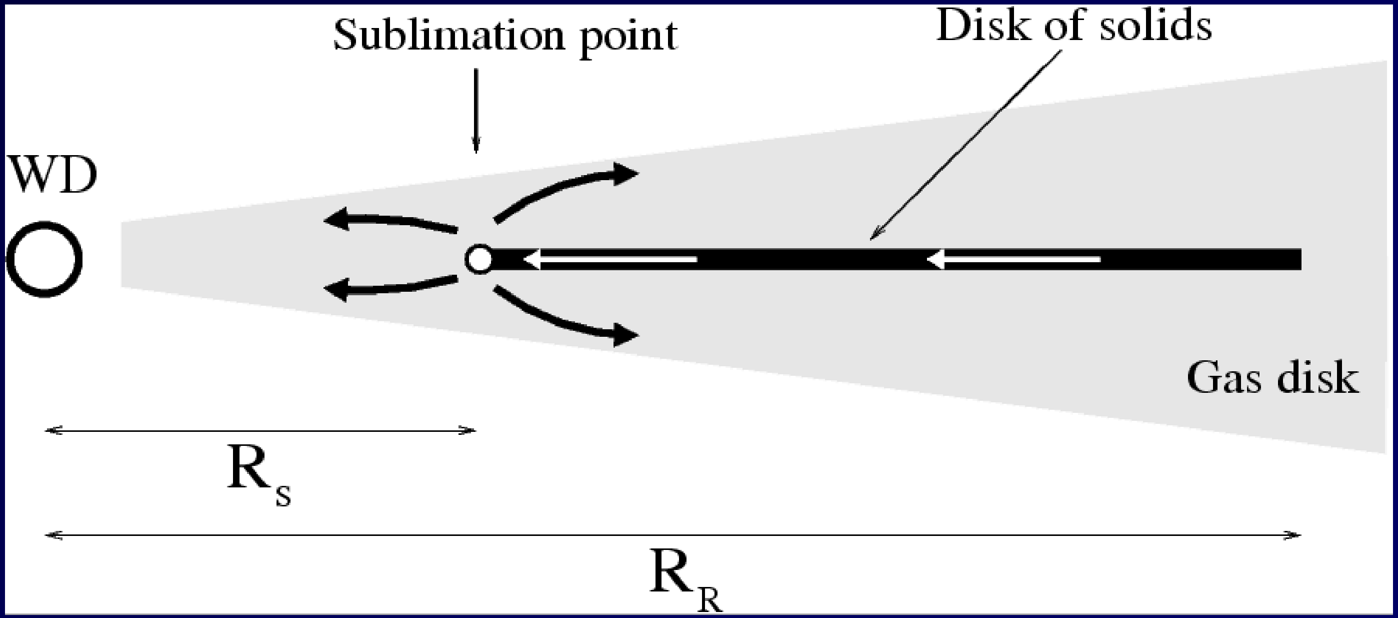
becomes

prediction

$$\dot{M}_{PR} \approx 10^8\ \mathrm{g\ s^{-1}} \left(\frac{R_\star}{0.01R_\odot}\frac{T_\star}{10^4 K}\frac{T_s}{1500K}\right)^2$$

Accretion from a particulate disk

- BUT! Actually transporting this mass from dusty disk to WD is not easy!
- Need to explain very high accretion rates in dusty disk (10^8 - 10^{11} g/s)
- Collisional viscosity in the ring-like environment is inefficient (Metzger, RRR, Bochkarev 2012)



Radiative effects

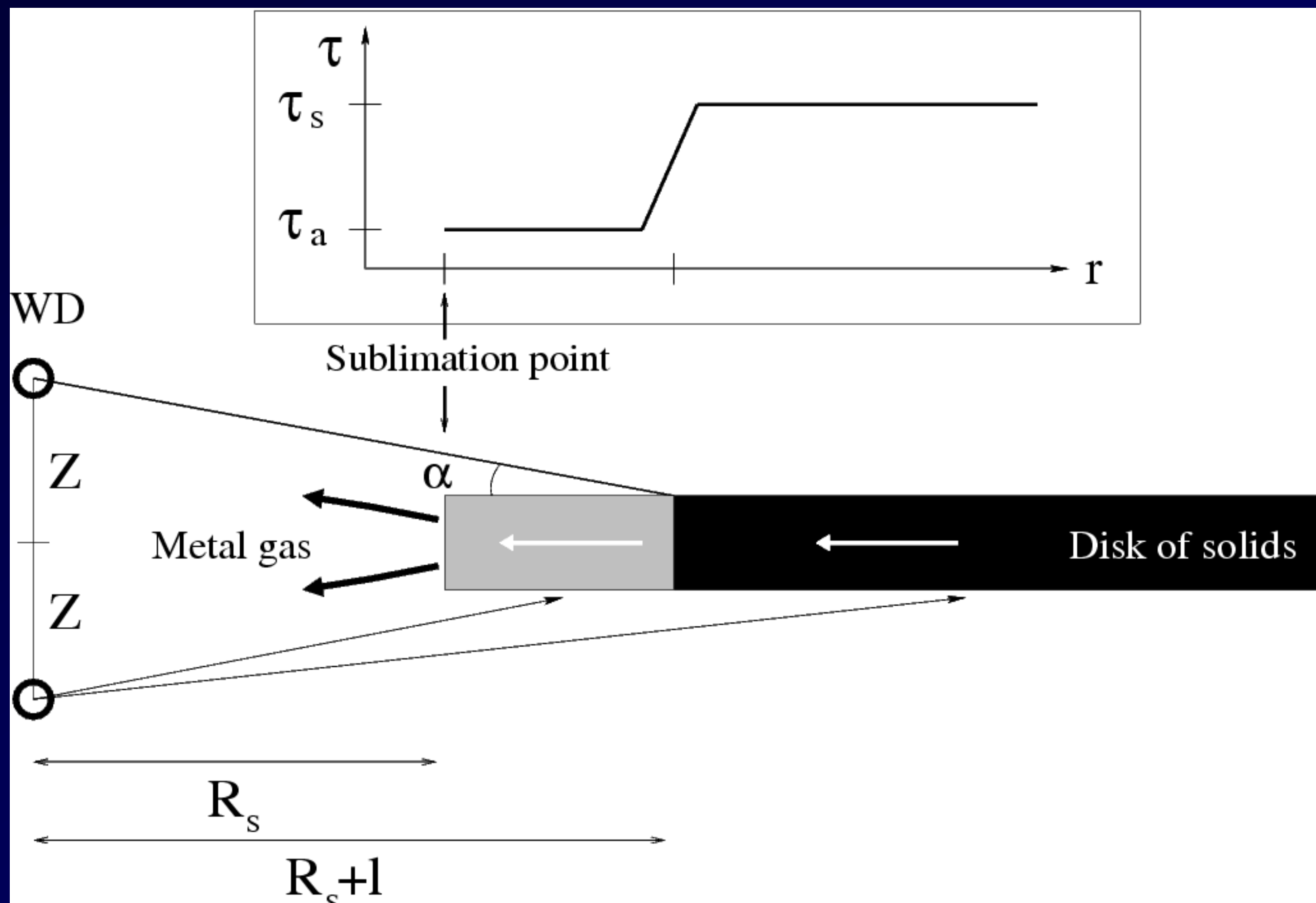
WD radiation can alter disk dynamics

Low luminosity $L_\star \sim 10^{-3} L_\odot$ but the disk is close, $\sim R_\odot$

- Disk is flat
- WD has finite size
- Grazing incidence

$$\alpha \sim R_\star / r$$

- Efficiently absorbed



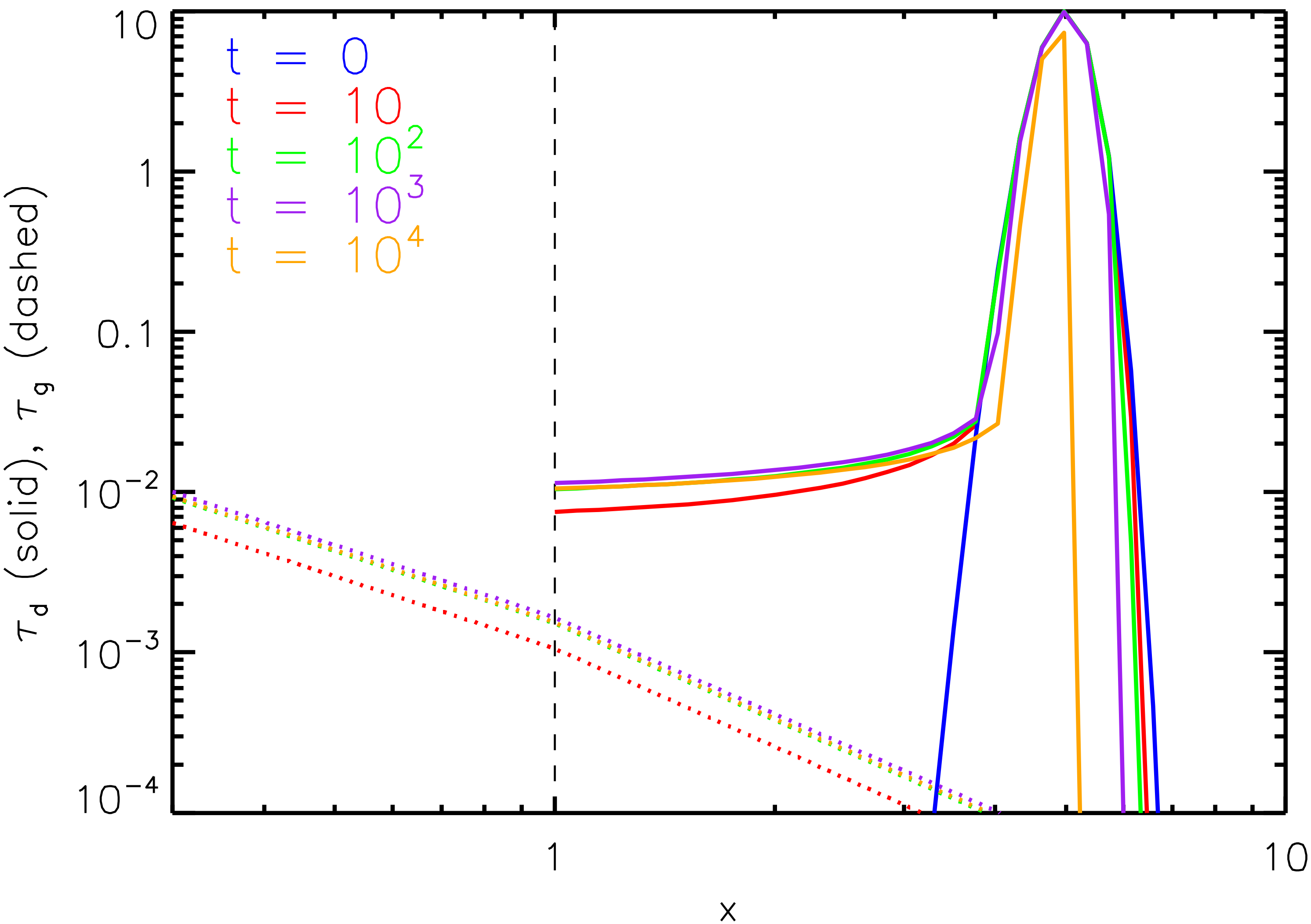
Runaway evolution: what governs it?

- When viscous time is longer than the time to replenish gas by sublimation $t_{repl} = \Sigma / \dot{\Sigma}$ density of gas grows with time
- This further enhances coupling and accretion through the disk of solids → **system runs away**
- Very high accretion rates of metals can be achieved
- Feedback parameter

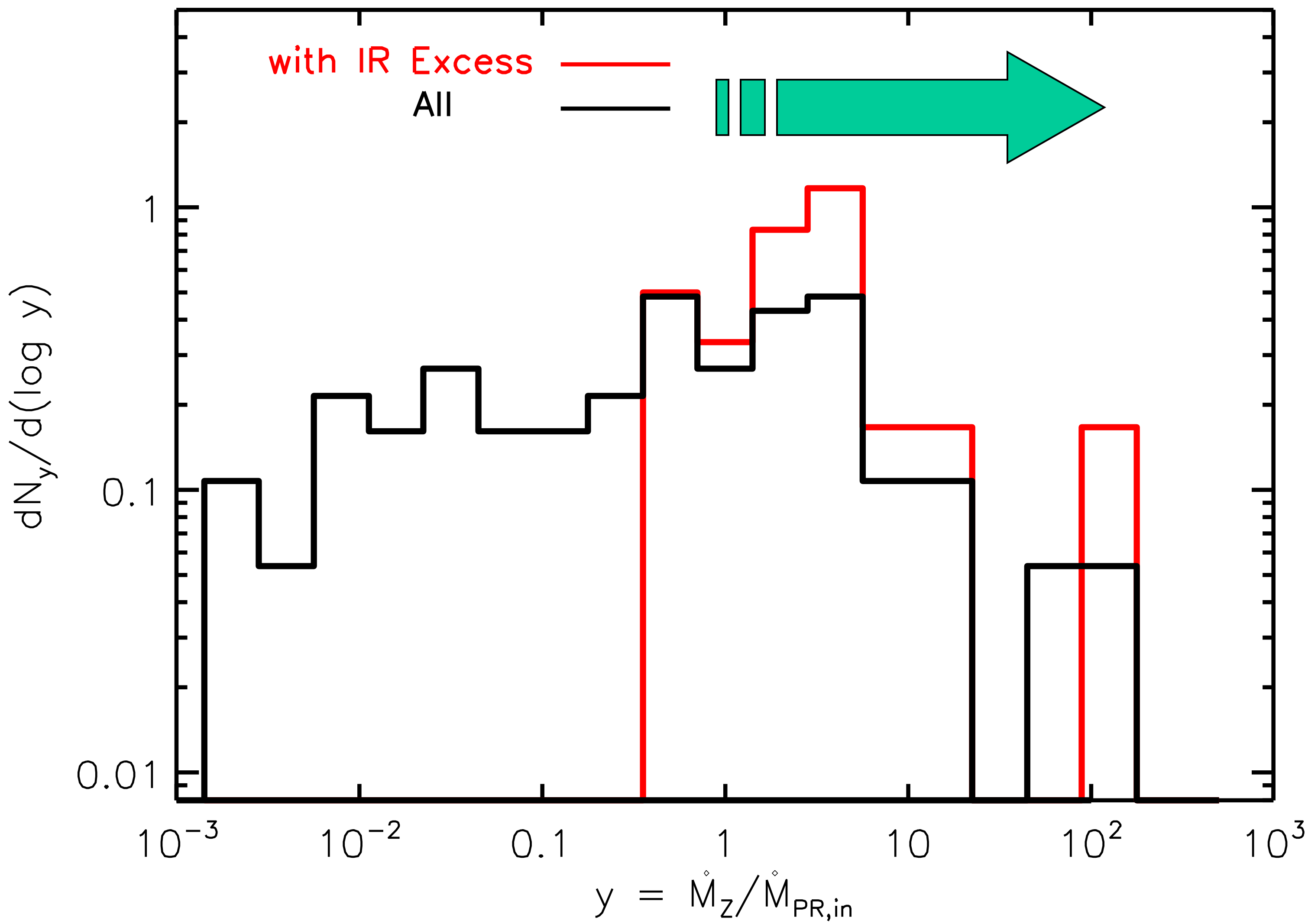
$$F \equiv \frac{t_\nu}{t_{\rm repl}}$$

- $F > 1$ results in runaway (Rafikov 2011b)

Evolution with aerodynamic drag removed



Metzger, RRR, Bochkarev (2012)



Metzger, RRR, Bochkarev (2012)