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# MHD Simulations of Protoplanetary Disks with Non-equilibrium Ionization Chemistry


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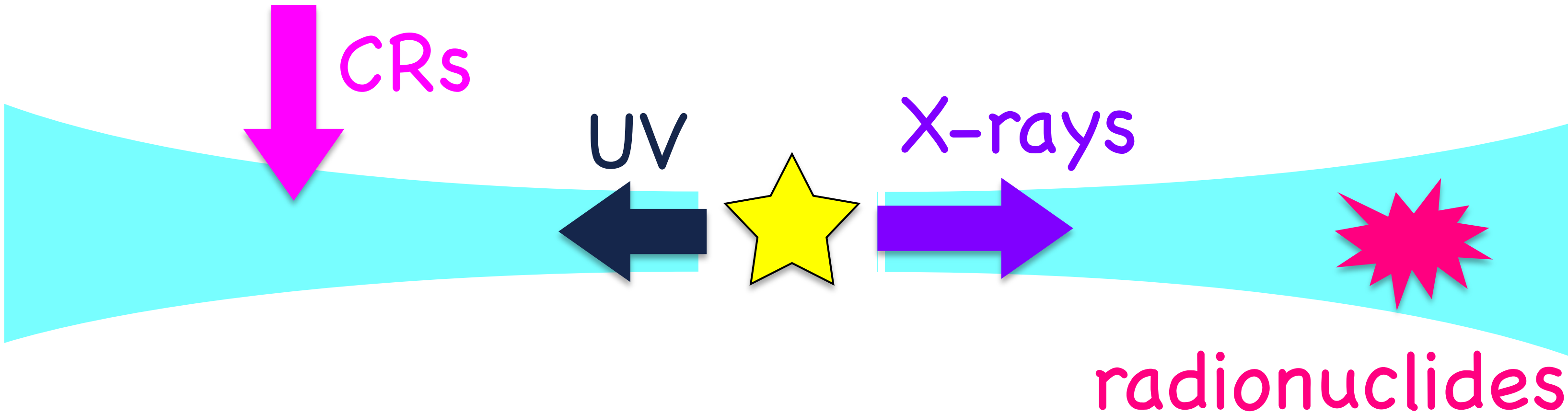
# Weak Ionization of PPDs

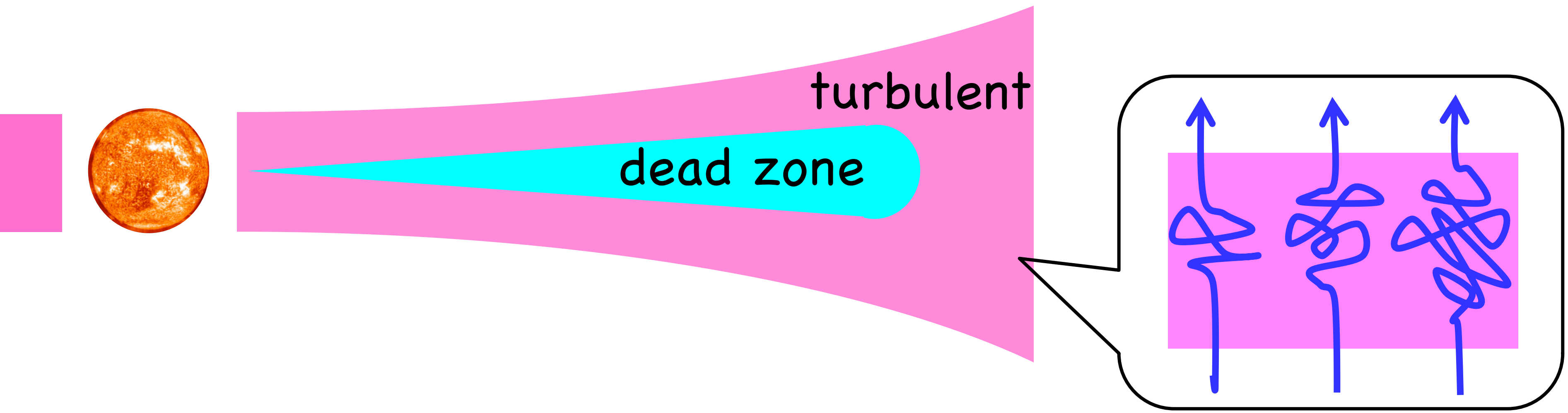
protoplanetary disks




PPDs are cool and dense
⇒ not coupled to magnetic fields everywhere
⇒ need to consider non-ideal MHD effects

# Are PPDs Turbulent?

Strength of turbulence is important for planet formation



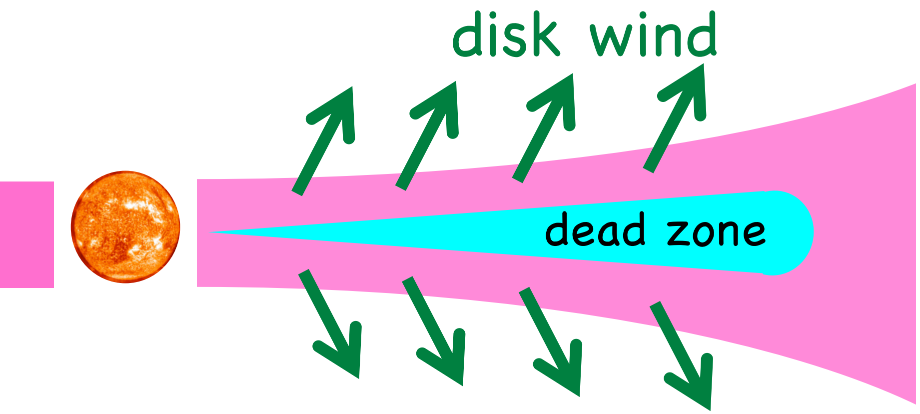

Disk dynamics depends on MRI*

- active layer: high accretion rate
- dead zone: low accretion rate

disk gas must be sufficiently ionized

*MRI: magnetorotational instability (Balbus & Hawley (1991)

# Disk Dynamics due to MRI




disk wind: mass loss from disk surface

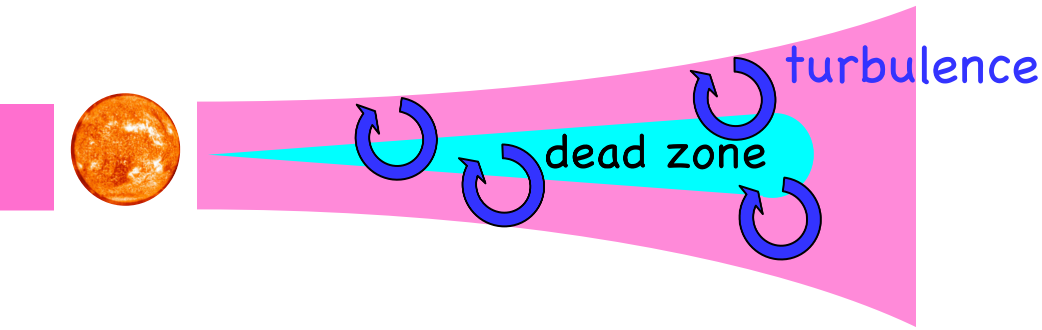
Suzuki & Inutsuka (2009), Suzuki et al. (2010), Bai & Stone (2013)

turbulence affects dead-zone boundary

Turbulent mixing may change dead-zone size (dust-free case).

Inutsuka & Sano (2005), Turner et al. (2007), Ilgner & Nelson (2008)

# Disk Dynamics due to MRI

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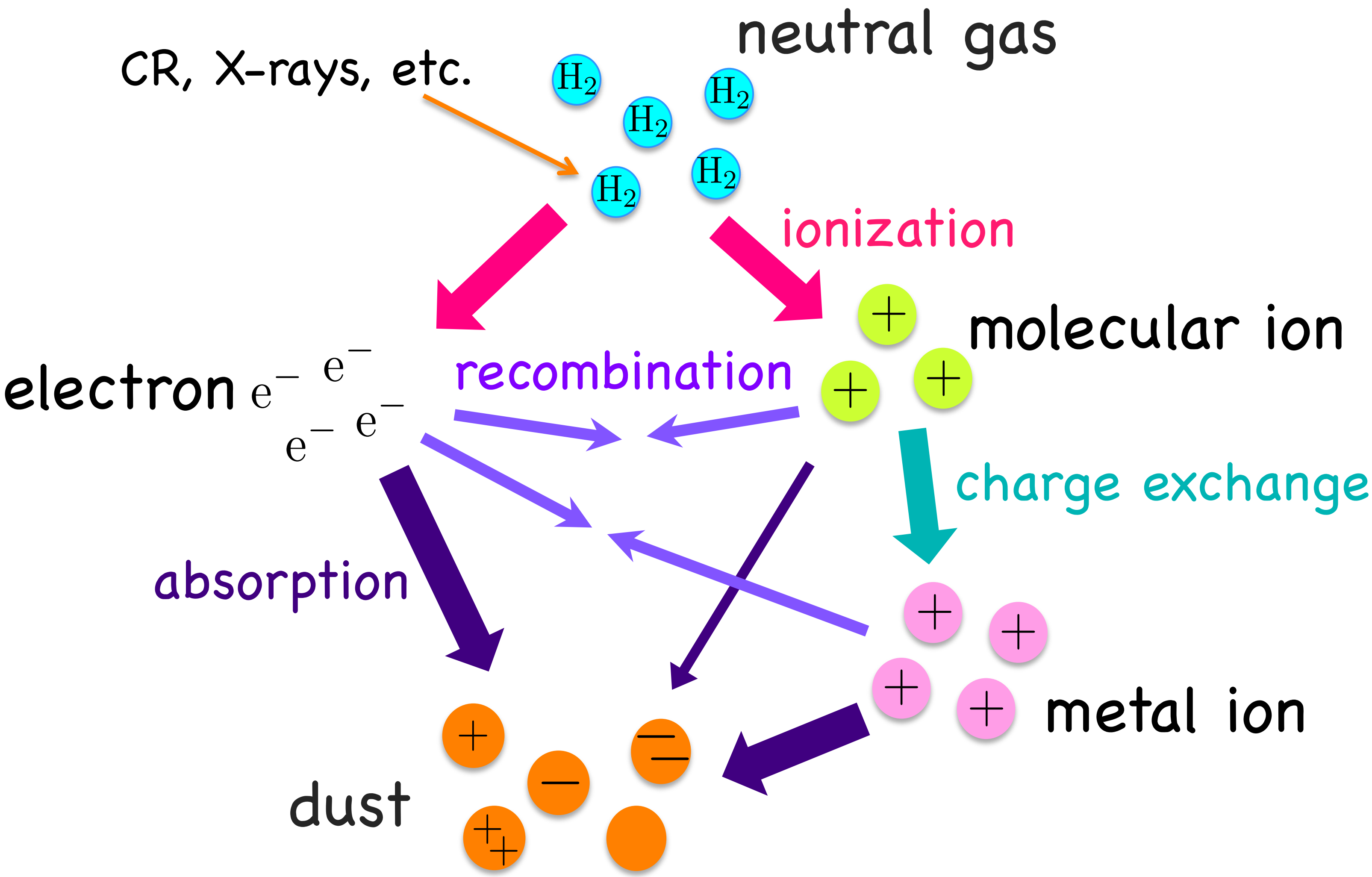
What about with dust grains?

# Simplified Chemical Network



# Reaction Equations

$m^+$ : mol. ion
$M^+$ : metal ion
e : electron
d : dust grains
Z : dust charge

molecular ion's number density

$$\frac{dn_{m^+}}{dt} = \zeta n_n - \alpha_{m^+} n_{m^+} n_e - \beta n_{m^+} n_M - \sum_Z k_{m^+d}(Z) n_d(Z) n_{m^+}$$

ionization   recombination   charge exchange   absorption by grains

metal ion's number density

$$\frac{dn_{M^+}}{dt} = -\alpha_{M^+} n_{M^+} n_e + \beta n_{m^+} n_M - \sum_Z k_{M^+d}(Z) n_d(Z) n_{M^+}$$

recombination   charge exchange   absorption by grains

electron's number density

$$\frac{dn_e}{dt} = \zeta n_n - \alpha_{m^+} n_{m^+} n_e - \alpha_{M^+} n_{M^+} n_e - \sum_Z k_{ed}(Z) n_d(Z) n_e$$

ionization   recombination   absorption by grains

number density of grains with charge "Z"

$$\frac{dn_d(Z)}{dt} = -k_{m^+d}(Z) n_d(Z) n_{m^+} - k_{M^+d}(Z) n_d(Z) n_{M^+}$$
$$- k_{ed}(Z) n_d(Z) n_e + k_{m^+d}(Z-1) n_d(Z-1) n_{m^+}$$
$$+ k_{M^+d}(Z-1) n_d(Z-1) n_{M^+} + k_{ed}(Z+1) n_d(Z+1) n_e$$

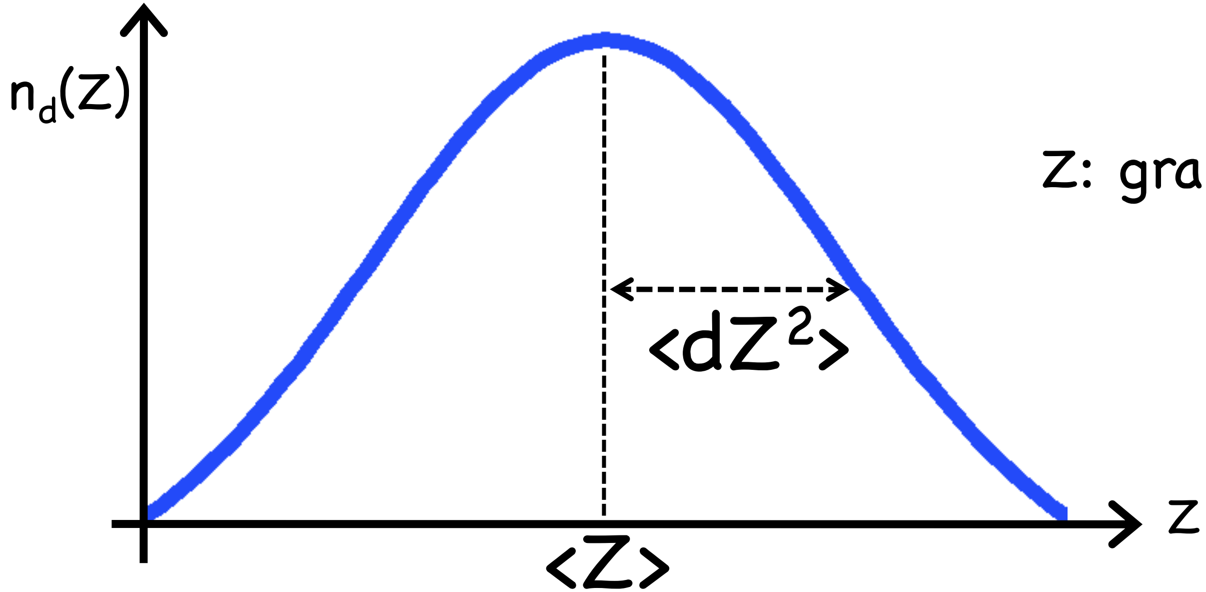
e.g. Oppenheimer & Dalgarno (1974)
Sano et al. (2000)
Ilgner & Nelson (2009)
Okuzumi (2009)
Fujii et al. (2011)

# Dust Charge Distribution

- approximated by Gaussian distribution

(Okuzumi, 2009)

- solve $\langle Z \rangle$ and $\langle dZ^2 \rangle$ instead of $n_d(Z)$

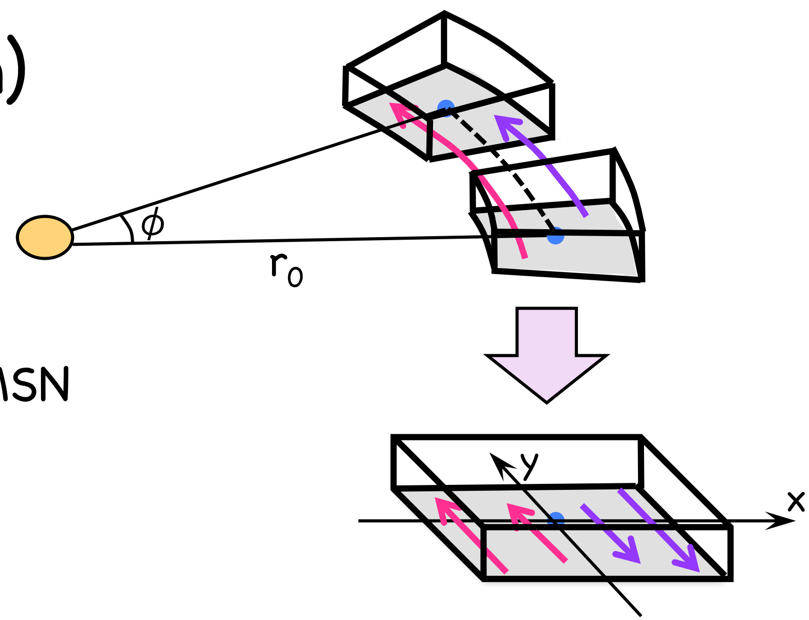



Z: grain charge

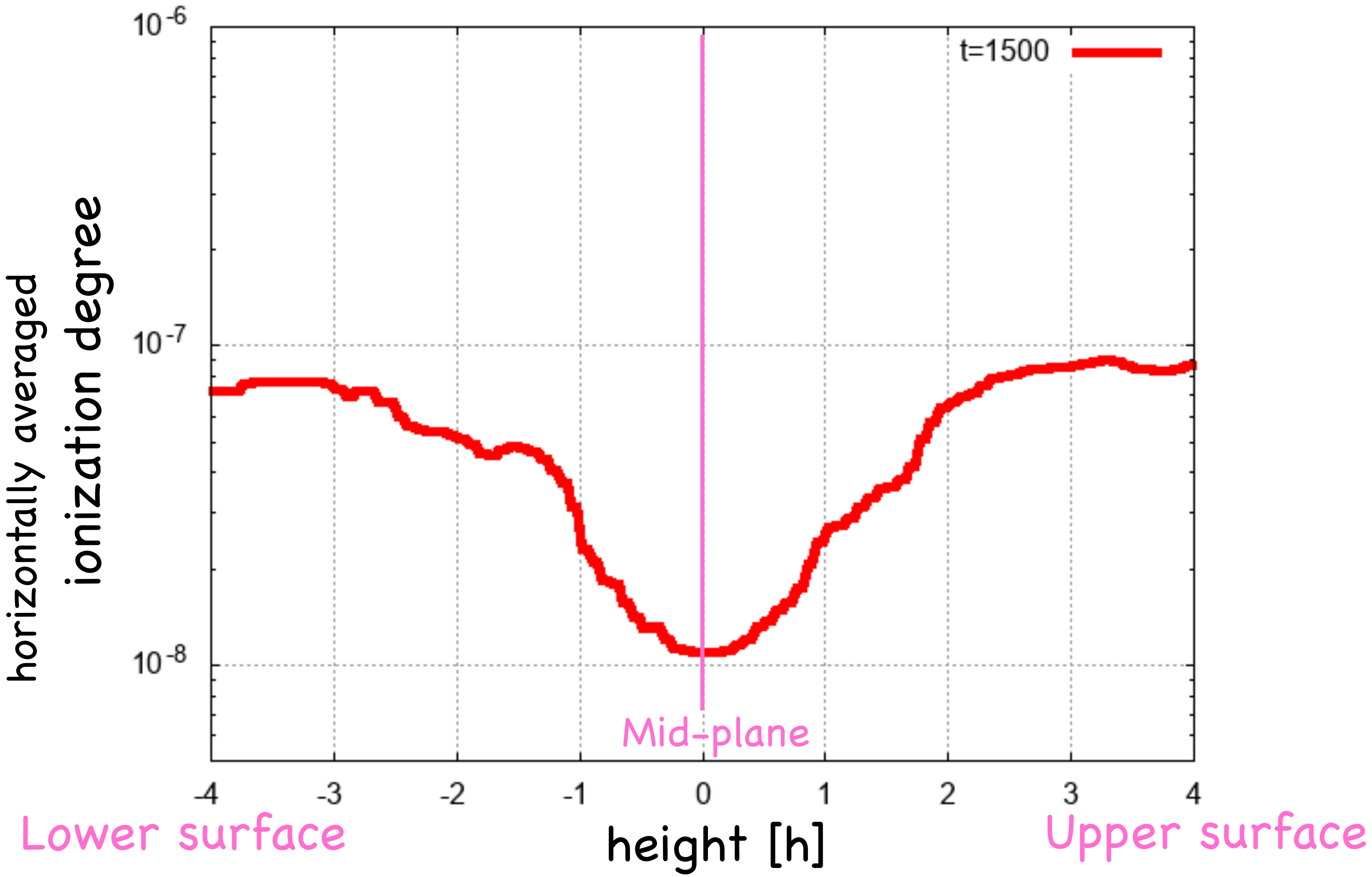
⇒ number of equations can be reduced

# 3D Non-ideal MHD Simulations

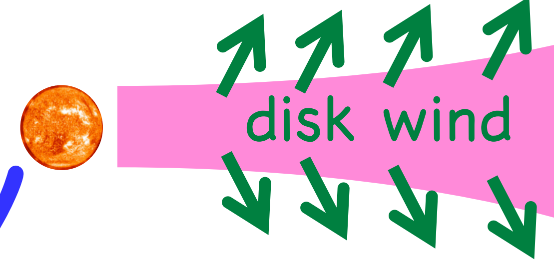
- Setup (local box @2AU)
  - Athena MHD code with time-dependent ionization
    (Stone et al., 2008) (Fujii et al. 2011 +$\alpha$)
  - box size
    $(x, y, z) = (\pm 0.5h, \pm 2h, \pm 4h)$
    $h=\sqrt{2}c_s/\Omega$
  - 16x32x192 grids
  - surface density: $\Sigma = 0.01\Sigma_{MMSN}$
  - dust-to-gas ratio: $f_{dg}=10^{-4}$
  - dust radius: $a=1\mu m$



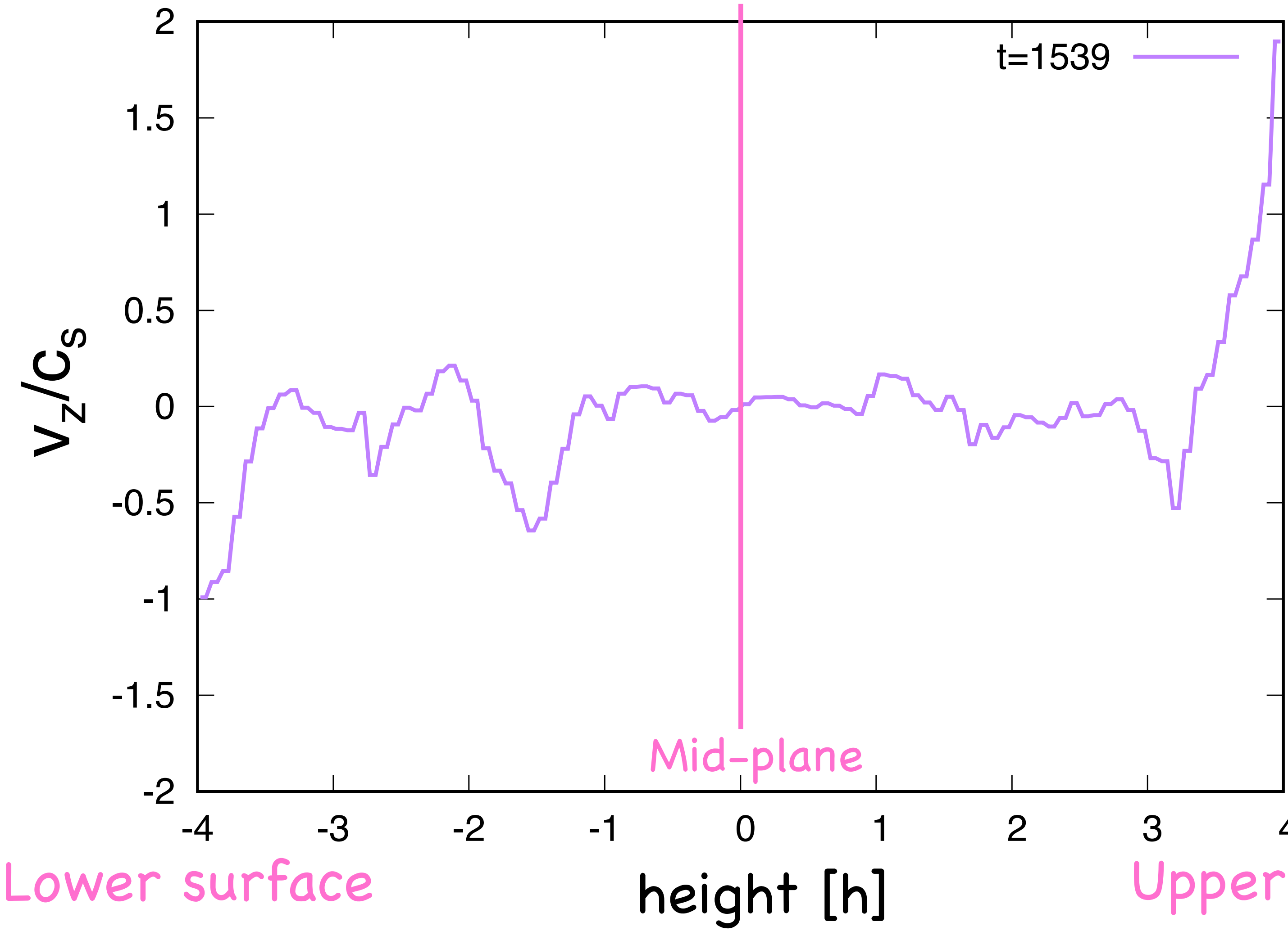
# Propagation of Ionization Degree



# Wind Velocity



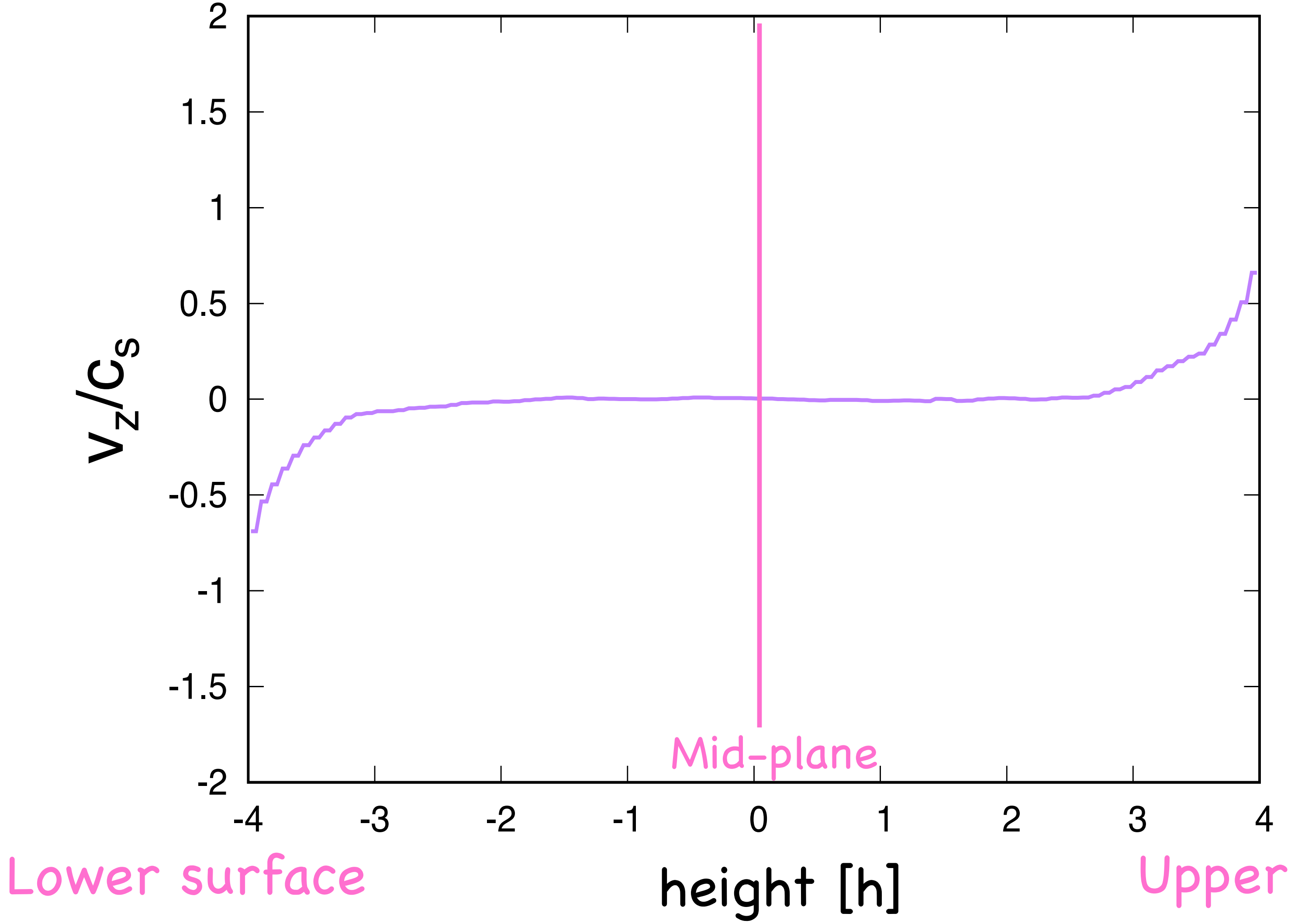

Lunched every 5-10 orbital periods




$$\langle v_{\rm z} \rangle = \frac{\langle \rho v_{\rm z} \rangle}{\langle \rho \rangle}$$

horizontally averaged

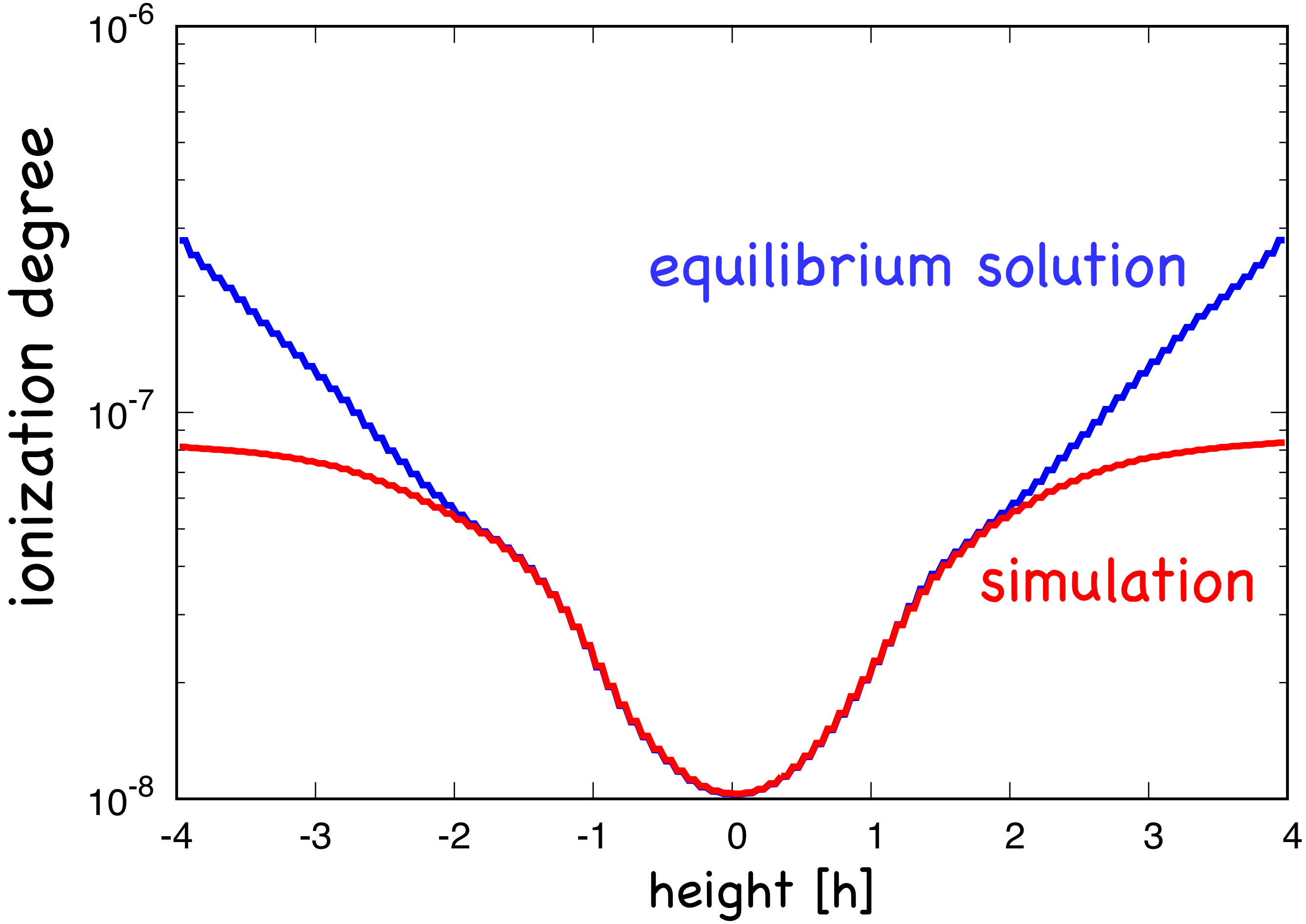
# Time-averaged Wind Velocity




$$\langle v_{\rm z} \rangle = \frac{\langle \rho v_{\rm z} \rangle}{\langle \rho \rangle}$$

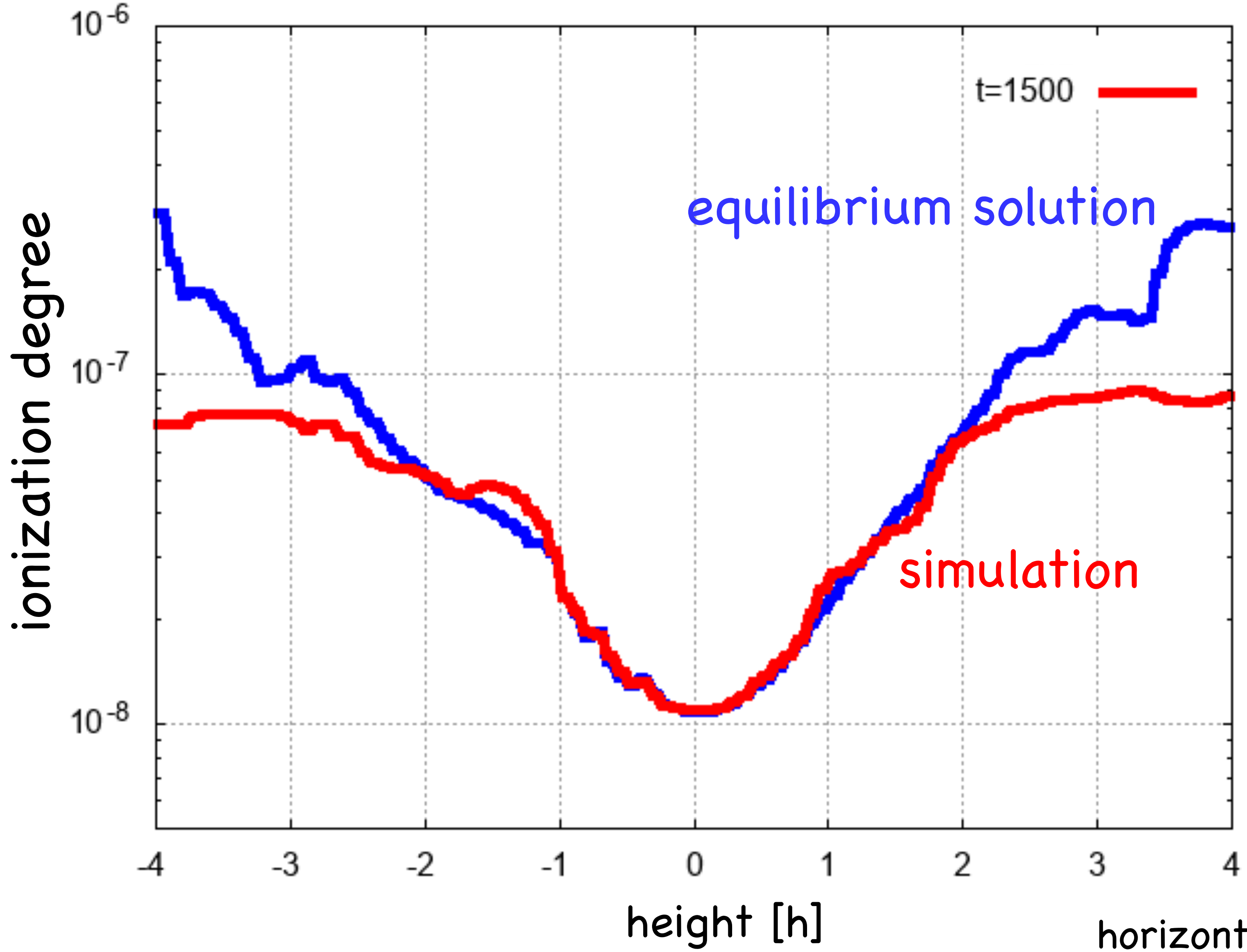
# Time-Averaged Ionization Degree

over 200 orbits



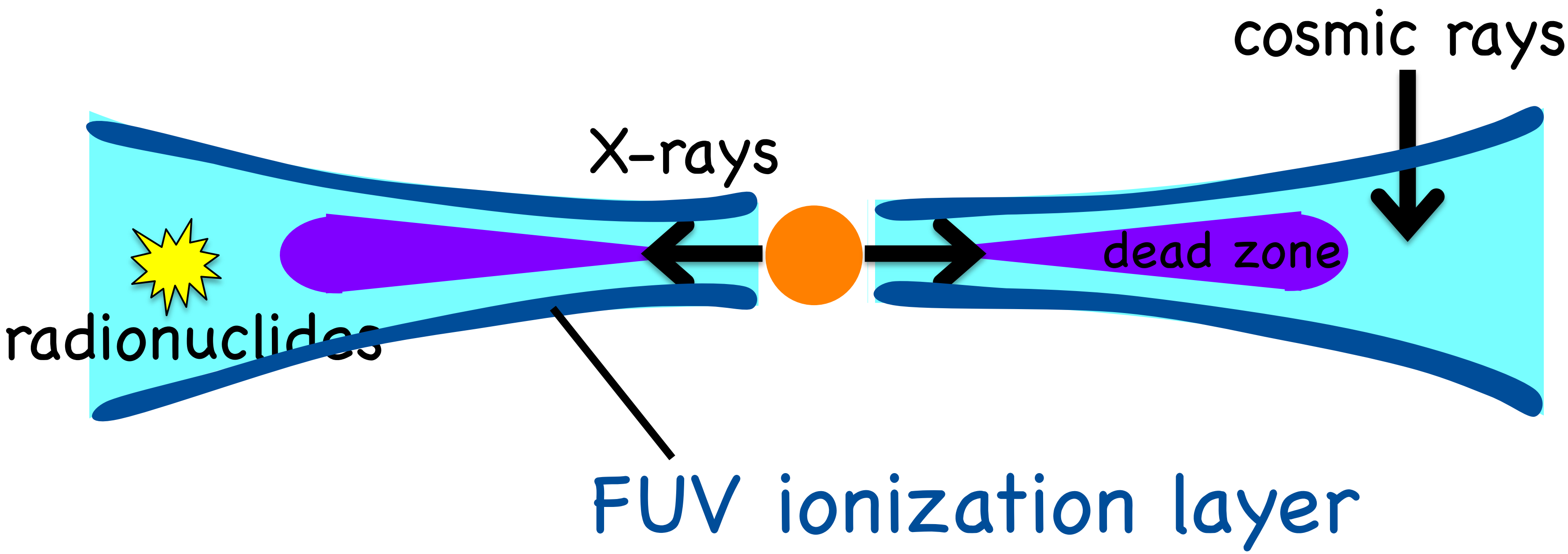

Lower than equilibrium ionization at high altitude

# Comparison with Equilibrium $x_e$




horizontally averaged

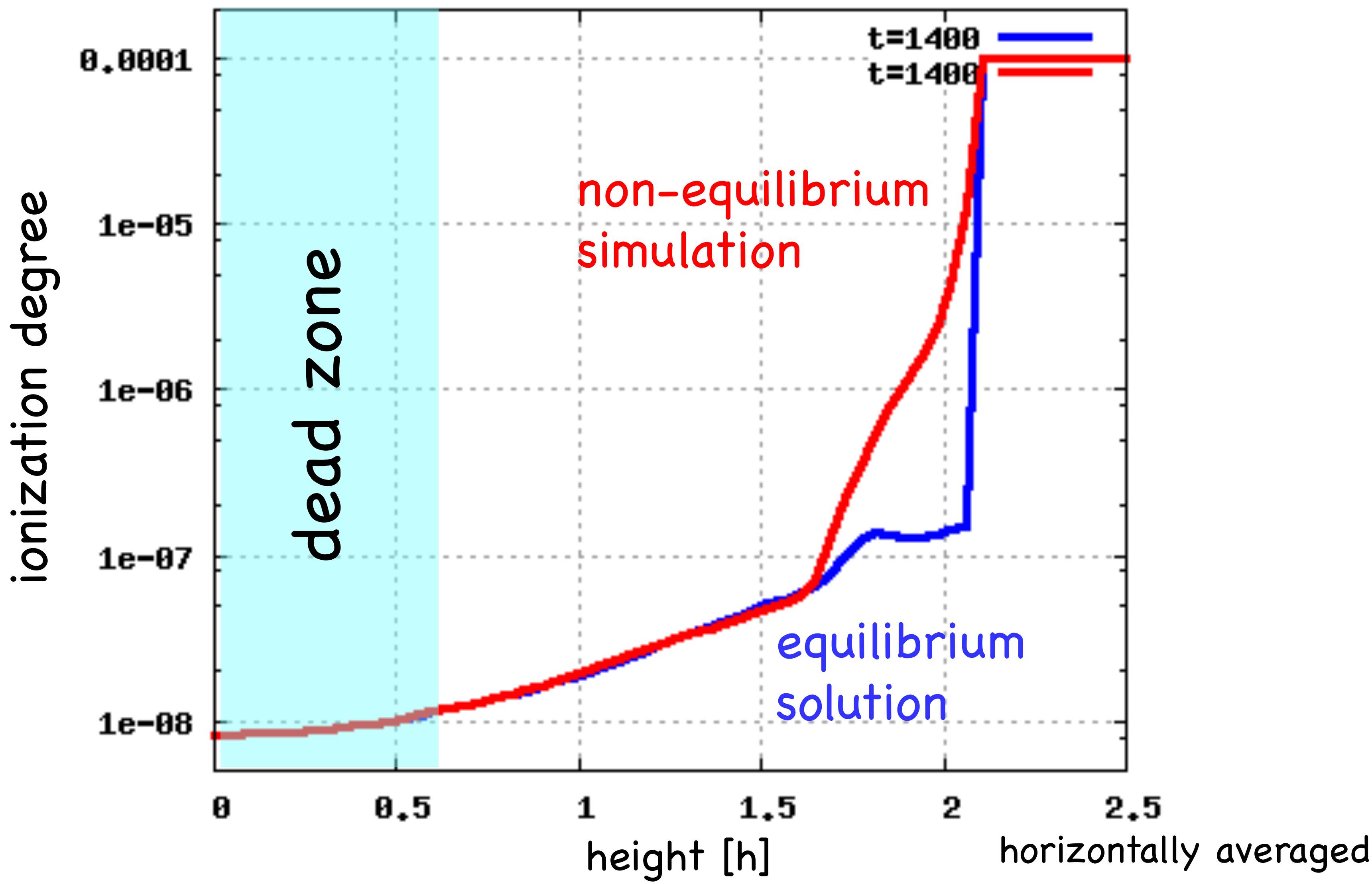
# Photoionization



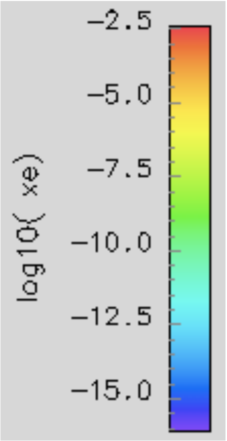

$$\Sigma<0.01 \text{ g/cm}^2 \Rightarrow x_e=10^{-4}$$

Ambipolar diffusion is also considered
Molecular ions are omitted

# Comparison with Equilibrium $x_e$



# Global MHD simulations




with advection of chemical species

without advection

preliminary

The difference becomes larger in later evolution stage of disk

# Summary

- Presence of dust grains makes turbulent mixing less/not effective
- Ionization degree has time variation
  ⇒ indirect evidence of disk wind?

Without FUV layer:

- Poorly ionized gas is brought upward by disk wind

Wit FUV layer:

- Boundary of FUV layer is smoothed

- Affected layers are MRI-active region
  - Dead zone size is not likely to be modified
  - Chemical evolution may be affected