Magnetic drift in molecular clouds and protoplanetary disks

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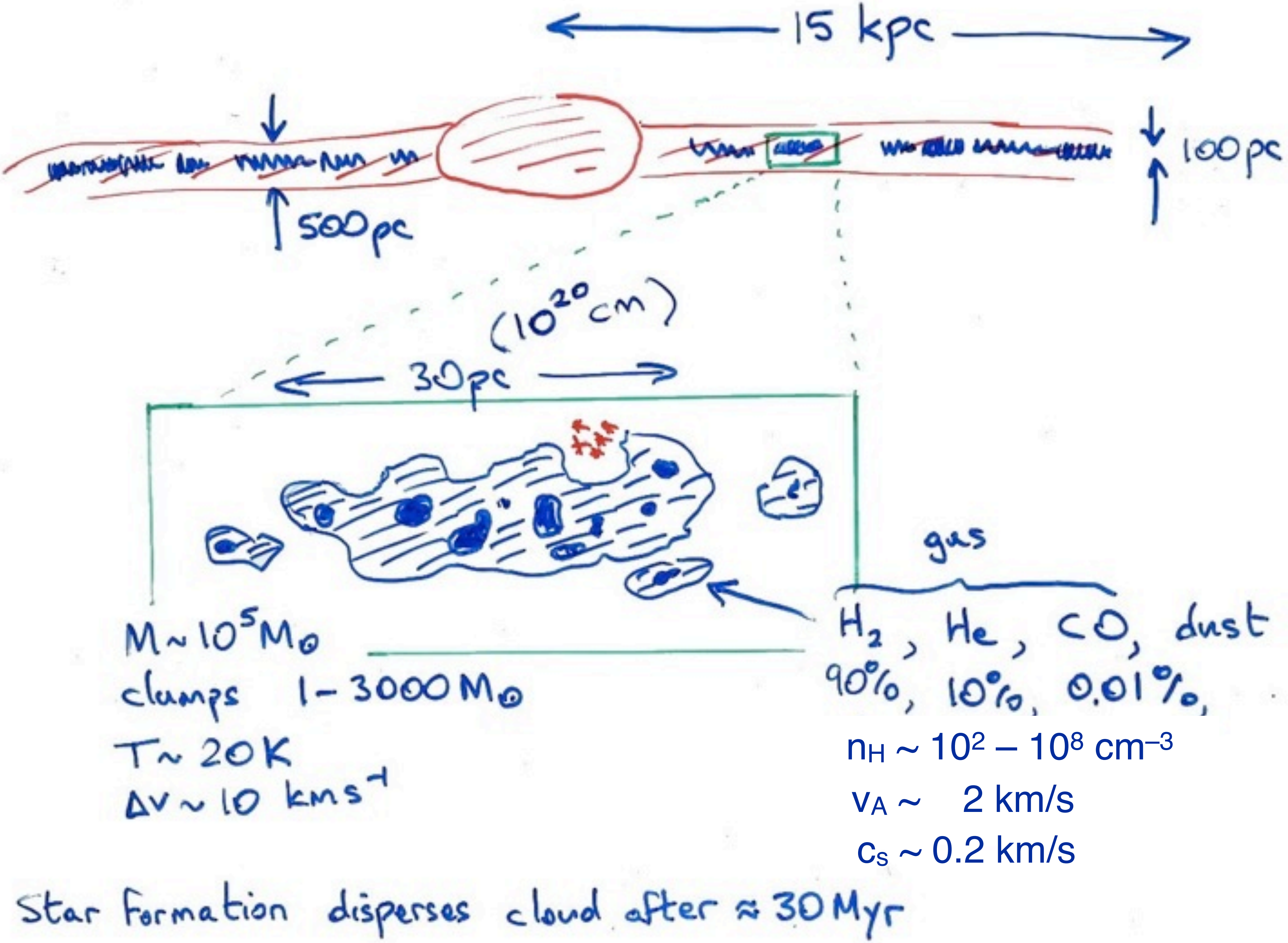
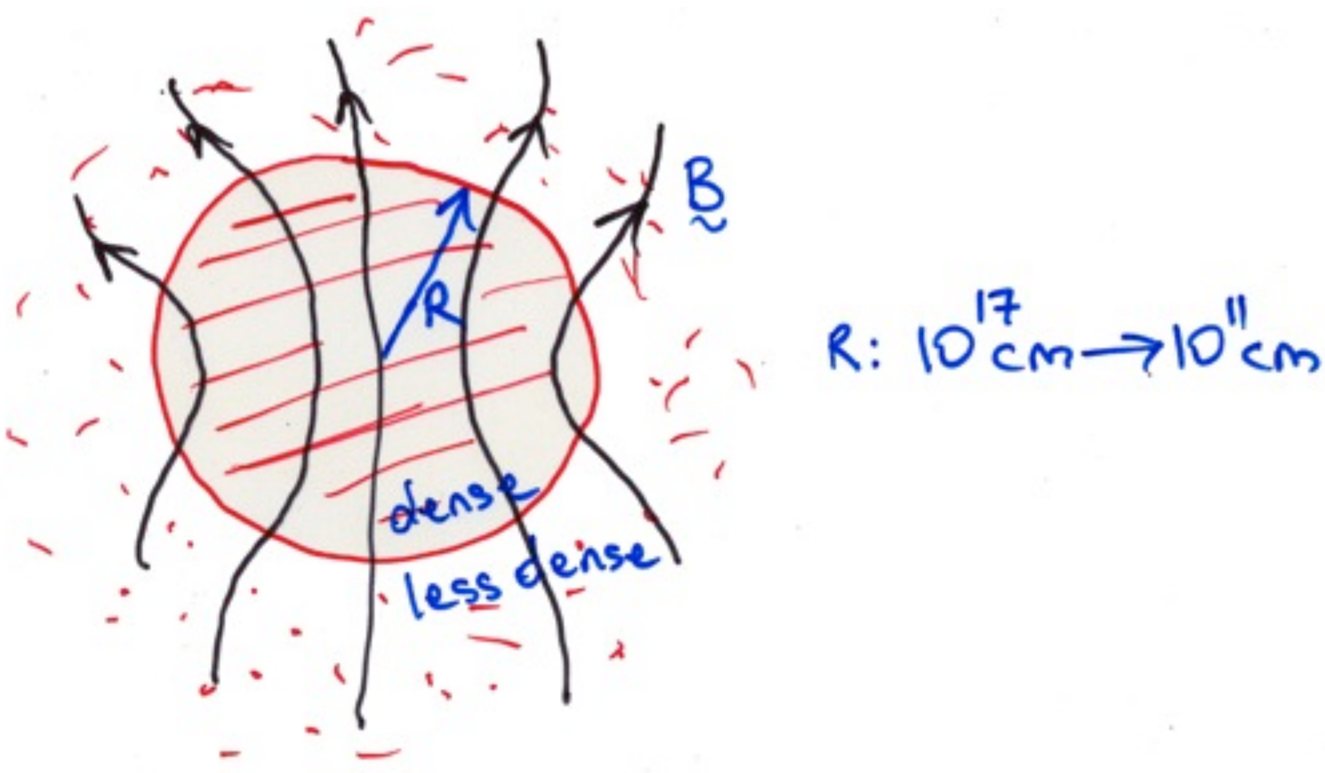
Physical conditions
Magnetic diffusion
Shock waves
Gravitational collapse
Magnetorotational instability
Jet launching

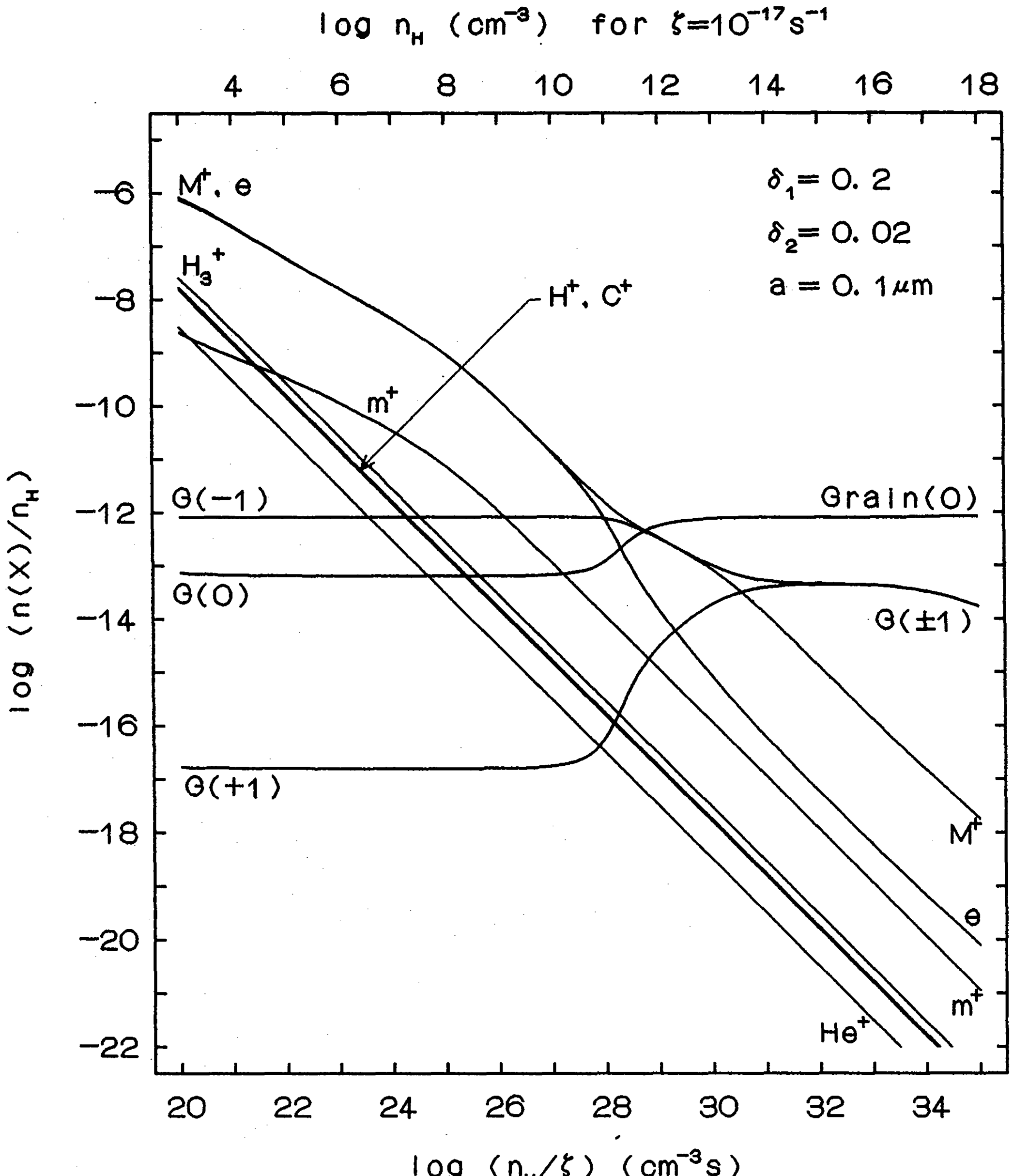

15 kpc
500pc
100pc
(10^{20} cm)
30pc
gas
H_2, He, CO, dust
90%, 10%, 0.01%,
$M \sim 10^5 M_\odot$
clumps 1–3000 $M_\odot$
T ~ 20K
$\Delta v \sim 10$ kms^{-1}
$n_H \sim 10^2 - 10^8$ cm^{-3}
$v_A \sim$ 2 km/s
$c_s \sim 0.2$ km/s
Star formation disperses cloud after ≈ 30 Myr

- Magnetic fields play a critical role
  - P_{mag} is 30–100 times P_{gas} in molecular clouds

    $v_A \sim 2$ km/s , $c_s \sim 0.2$ km/s
  - energy density of magnetic field, fluid motions and self-gravity are similar
  - field removes angular momentum from cloud cores and protostellar/ protoplanetary disks



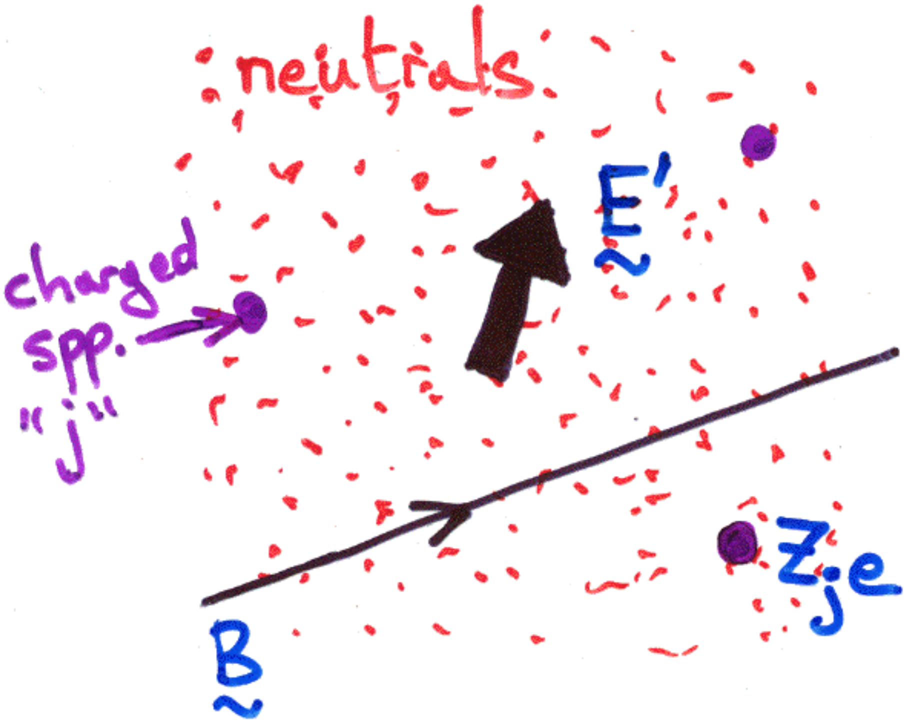
Low fractional ionisation



0.1μm grains

Umebayashi & Nakano 1990

Microphysics



$$Z_j e \boldsymbol{E}' + Z_j e \frac{\boldsymbol{v}_j}{c} \times \boldsymbol{B} - \gamma_j m_j \rho \boldsymbol{v}_j = 0$$

$$\gamma_j = \frac{< \sigma v >_j}{m_j + m}$$

$$\beta_j = \frac{Z_j e B}{m_j c} \frac{1}{\gamma_j \rho} = \frac{\text{gyrofrequency}}{\text{collision frequency}}$$

$|\beta_j| \gg 1 : \quad Z_j e \boldsymbol{E}' \approx -Z_j e \frac{\boldsymbol{v}_j}{c} \times \boldsymbol{B}$ particles tied to field

$|\beta_j| \ll 1 : \quad Z_j e \boldsymbol{E}' \approx \gamma_j m_j \rho \boldsymbol{v}_j$ particles tied to neutral fluid

Cowling 1957

	fully ionized	**weakly ionized**
Ideal MHD	ions and electrons tied to field	ions, electrons and neutrals tied to field
Ambipolar diffusion	–	neutrals decoupled
Hall drift	ions decoupled $\omega > \frac{eB}{m_i c}$	ions and neutrals decoupled $\omega > \frac{eB}{m_i^* c}$ $m_i^* = m_i \frac{\rho}{\rho_i}$
Ohmic diffusion	ions and electrons decoupled	ions, electrons and neutrals decoupled

Pandey & Wardle 2008

Magnetic drift

regime	magnetised component	unmagnetised component	B drift through neutrals
Ideal MHD	neutrals, ions, electrons	–	0
Ambipolar	ions, electrons	neutrals	$\mathbf{v_i} - \mathbf{v_n} = \dfrac{\mathbf{J} \times \mathbf{B}}{c\gamma\rho_i\rho}$
Hall	electrons	neutrals, ions	$\mathbf{v_e} - \mathbf{v_i} = -\dfrac{\mathbf{J}}{en_e}$
Ohmic	–	neutrals, ions, electrons	$c\dfrac{\mathbf{E}' \times \mathbf{B}}{B^2} = \dfrac{4\pi\eta}{c}\dfrac{\mathbf{J} \times \mathbf{B}}{B^2}$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla\times(\boldsymbol{v}\times\boldsymbol{B}) - \nabla\times\left[\eta\ \nabla\times\boldsymbol{B} + \eta_{\rm H}(\nabla\times\boldsymbol{B})\times\hat{\boldsymbol{B}} + \eta_A(\nabla\times\boldsymbol{B})_\perp\right]$$

- If the only charged species are ions and electrons,

$$n_i Z_i = n_e \qquad \eta_{\rm H} = |\beta_e|\,\eta$$

$$|\beta_e| \gg \beta_i \qquad \eta_{\rm A} = \beta_i|\beta_e|\,\eta$$

$$\beta_j = \frac{Z_j e B}{m_j c}\frac{1}{\gamma_j \rho} = \frac{\text{gyrofrequency}}{\text{collision frequency}}$$

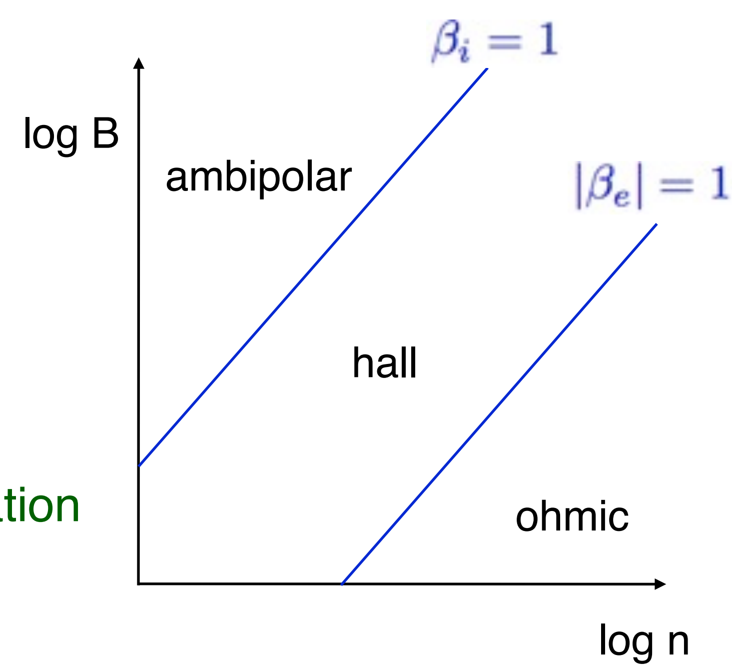
- Three distinct diffusion regimes:

$\beta_i \ll |\beta_e| \ll 1$ – Ohmic (resistive)

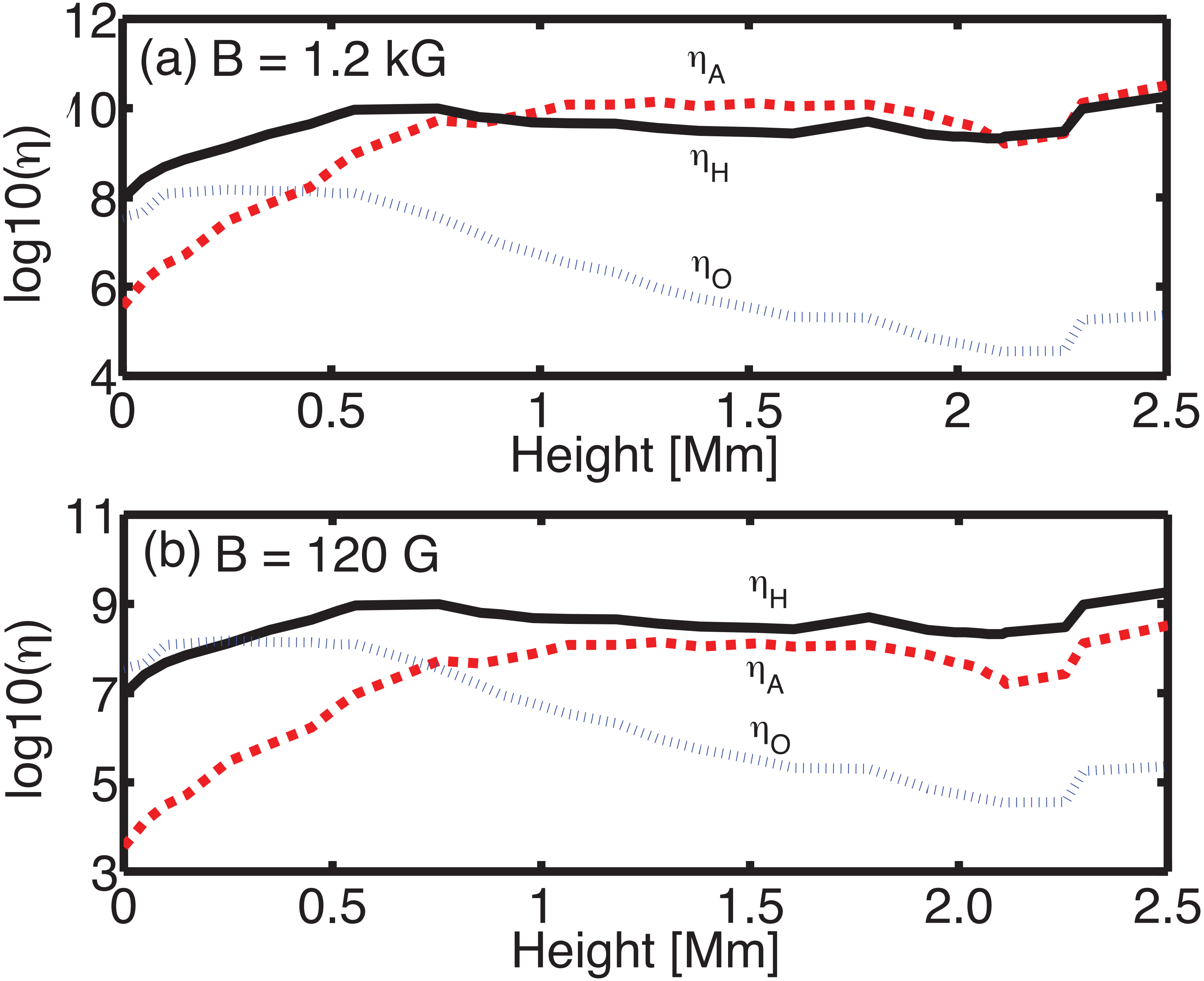
$\beta_i \ll 1 \ll |\beta_e|$ – Hall

$1 \ll \beta_i \ll |\beta_e|$ – Ambipolar

– see Pandey & Wardle (2008) for generalisation to all levels of ionisation



The solar chromosphere



Pandey & Wardle 2013

$$\beta_j = \frac{Z_j e B}{m_j c}\frac{1}{\gamma_j \rho} = \frac{\text{gyrofrequency}}{\text{collision frequency}}$$

- For ions,

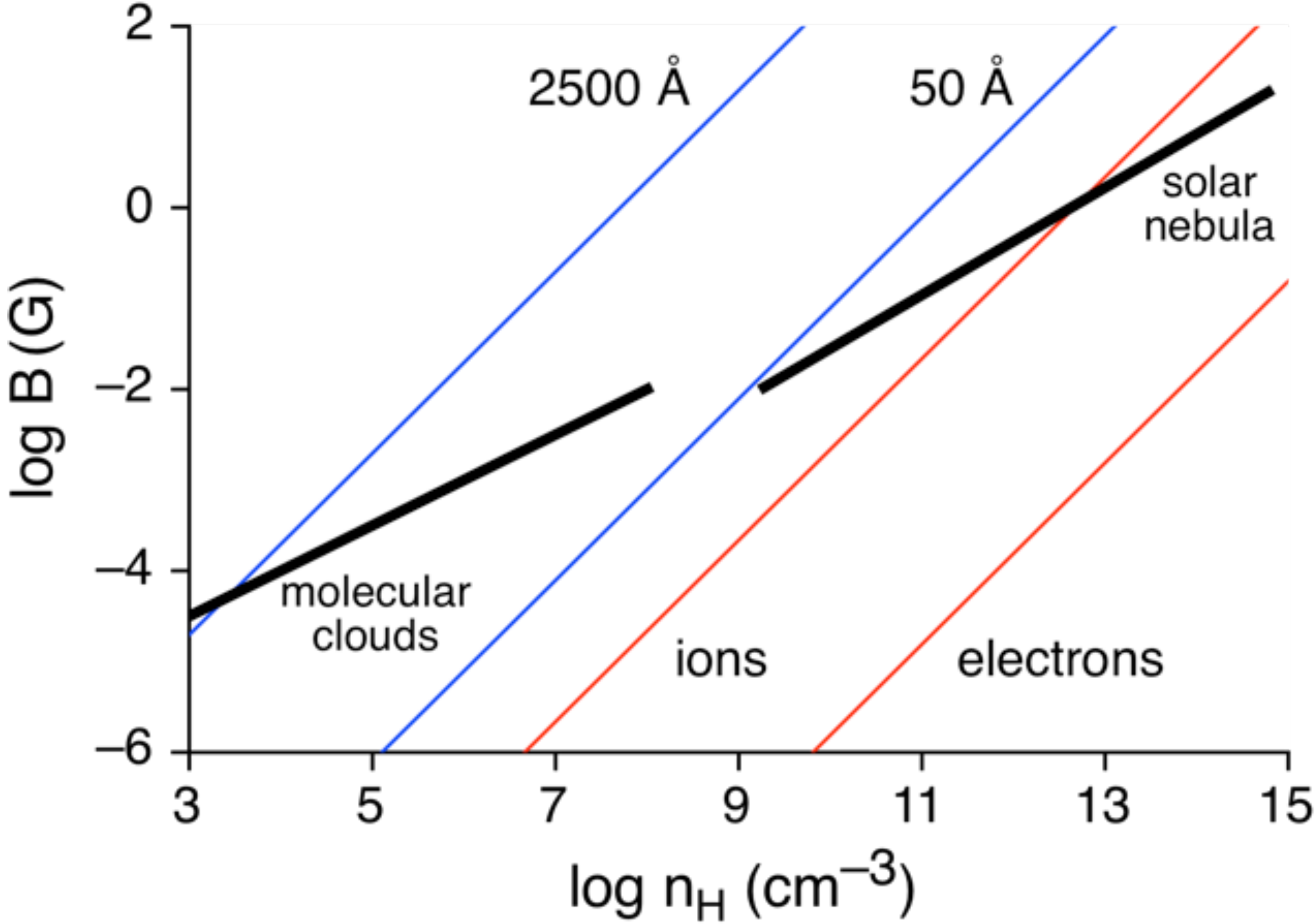
$$m_i \approx 30 m_{\rm H} \qquad <\sigma v>_i \approx 1.6\times 10^{-9}\,{\rm cm^3\,s^{-1}}$$

$$\beta_i \approx 4.6\times 10^{-3}\left(\frac{B}{1\,{\rm G}}\right)\left(\frac{n_{\rm H}}{10^{15}\,{\rm cm^{-3}}}\right)^{-1}$$

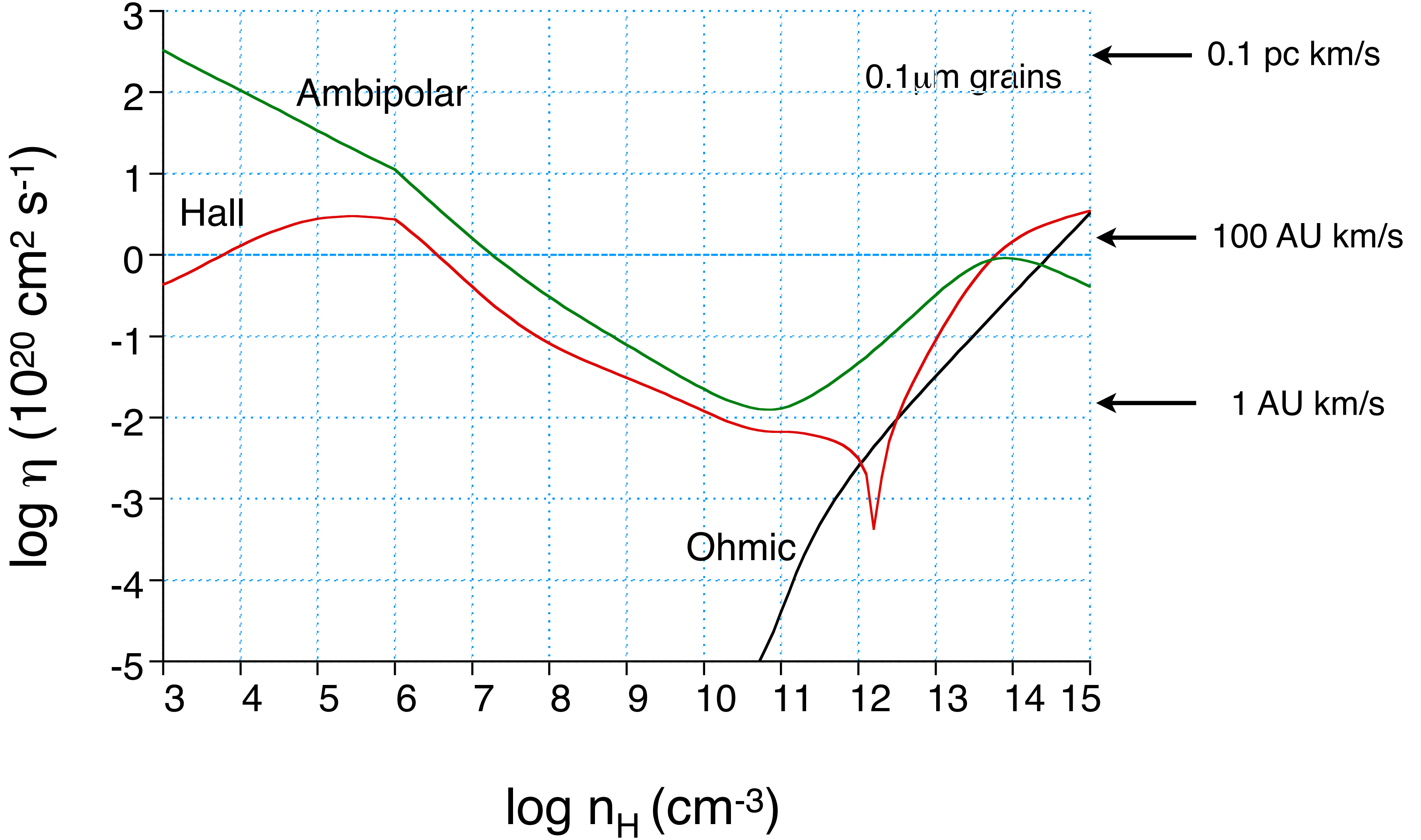
- For electrons,

$$<\sigma v>_e \approx 1\times 10^{-15}\,{\rm cm^2}\left(\frac{128kT}{9\pi m_e}\right)^{1/2}$$

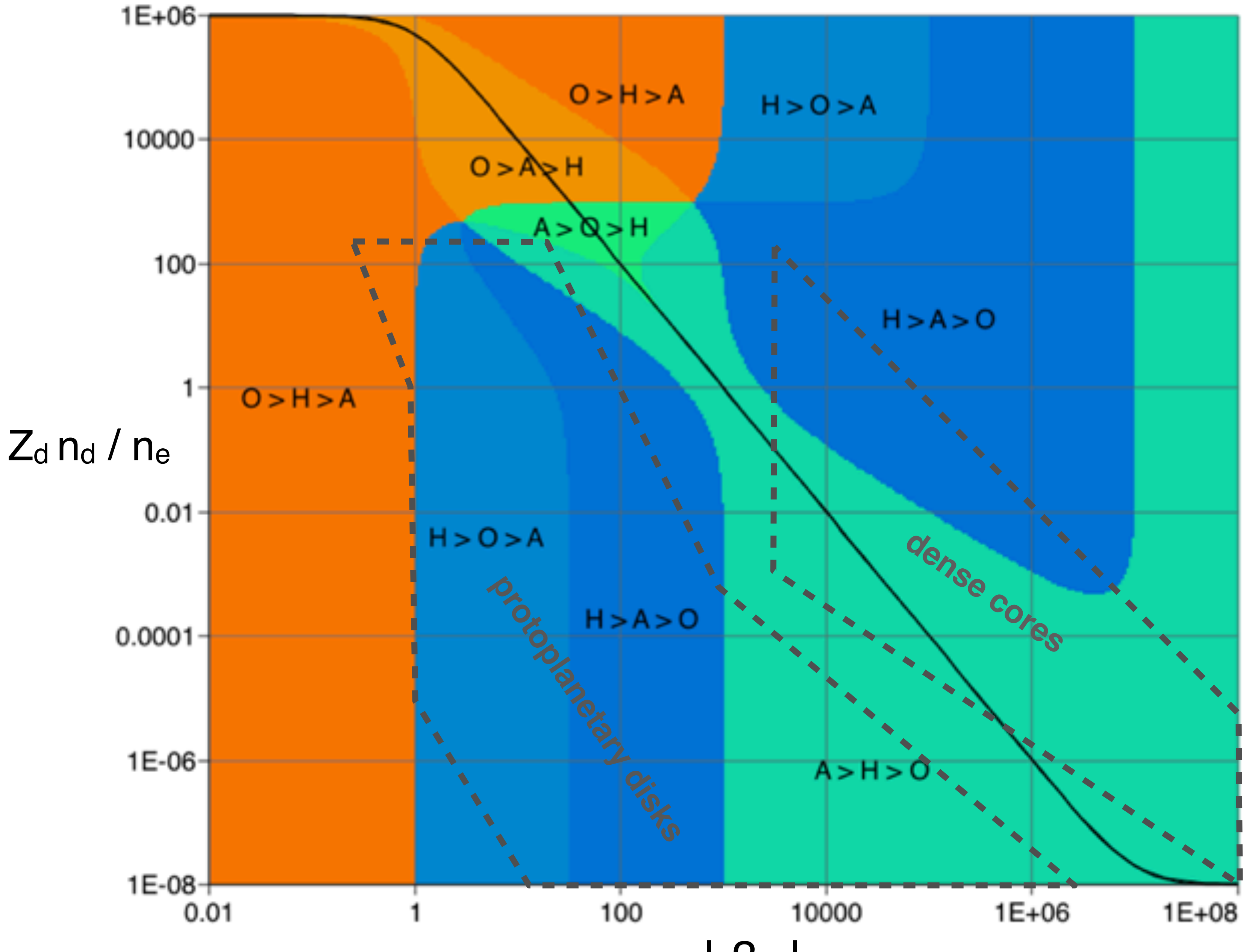
$$\beta_e \approx -3.5\left(\frac{B}{1\,{\rm G}}\right)\left(\frac{n_{\rm H}}{10^{15}\,{\rm cm^{-3}}}\right)^{-1}\left(\frac{T}{100\,{\rm K}}\right)^{-1/2}$$


2
0
−2
−4
−6
log B (G)
3
5
7
9
11
13
15
log n_H (cm^{-3})
2500 Å
50 Å
solar nebula
molecular clouds
ions
electrons

Wardle 2007



0.1 pc km/s
0.1μm grains
Ambipolar
Hall
100 AU km/s
1 AU km/s
Ohmic
log η (10^20 cm^2 s^-1)
log n_H (cm^-3)
3
2
1
0
-1
-2
-3
-4
-5
3 4 5 6 7 8 9 10 11 12 13 14 15



Wardle & Pandey in prep

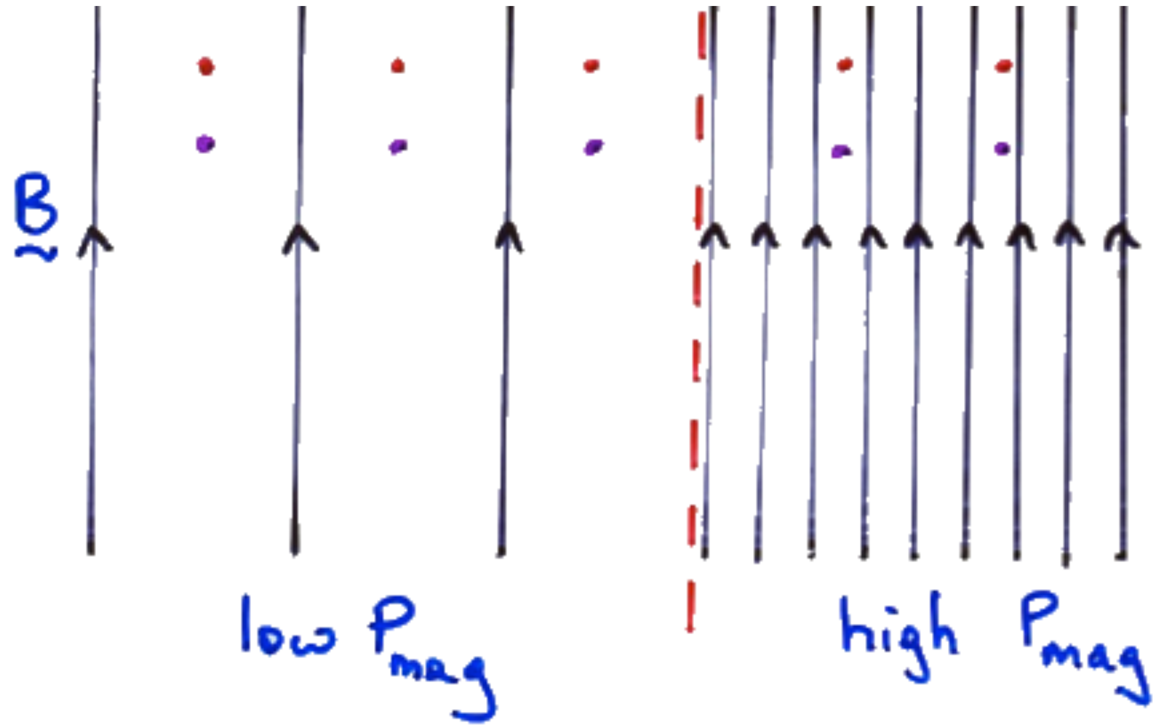
$$\eta_A = \frac{1 + \beta_g^2 + (1 + \beta_i \beta_g) P}{(1 + P/P_0)^2 + (\beta_g + \beta_i P)^2} \frac{B^2}{4\pi \gamma \rho_i \rho}$$

$$\eta_H = \frac{1 + \beta_g^2 - \beta_i^2 P}{(1 + P/P_0)^2 + (\beta_g + \beta_i P)^2} \frac{cB}{4\pi e n_e}$$

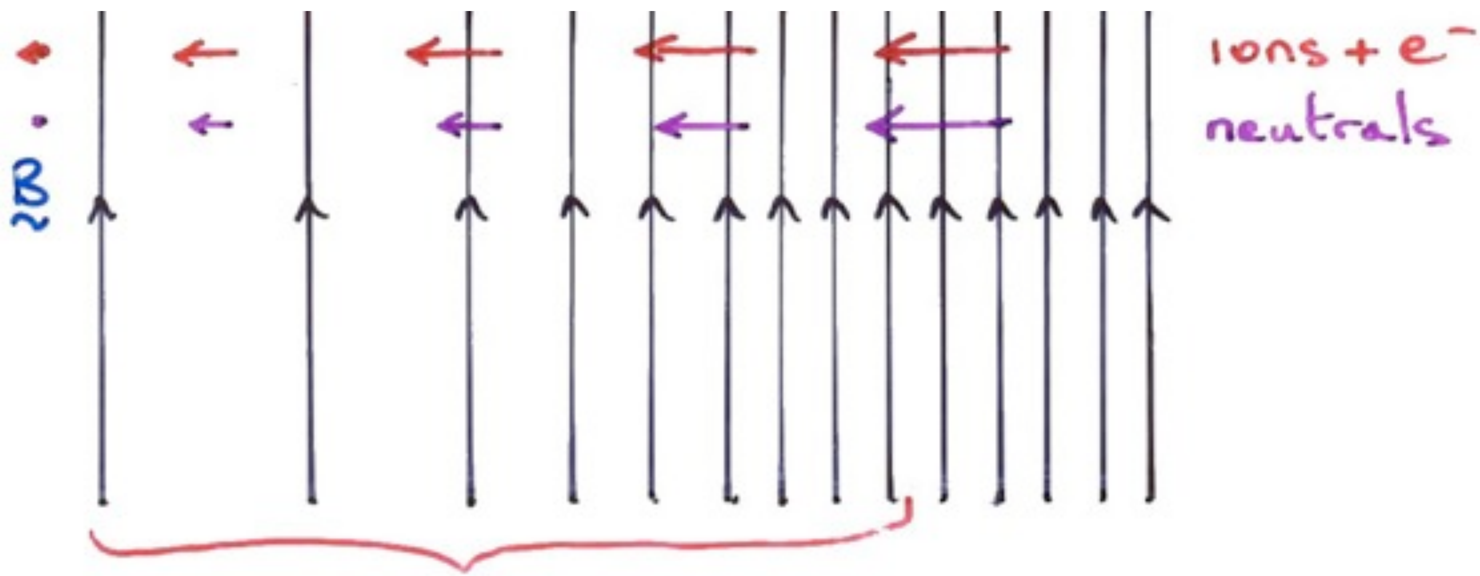
$$\eta = \frac{1}{1 + P/P_0} \frac{c^2}{4\pi \sigma_e}$$

C-type shock

t = 0

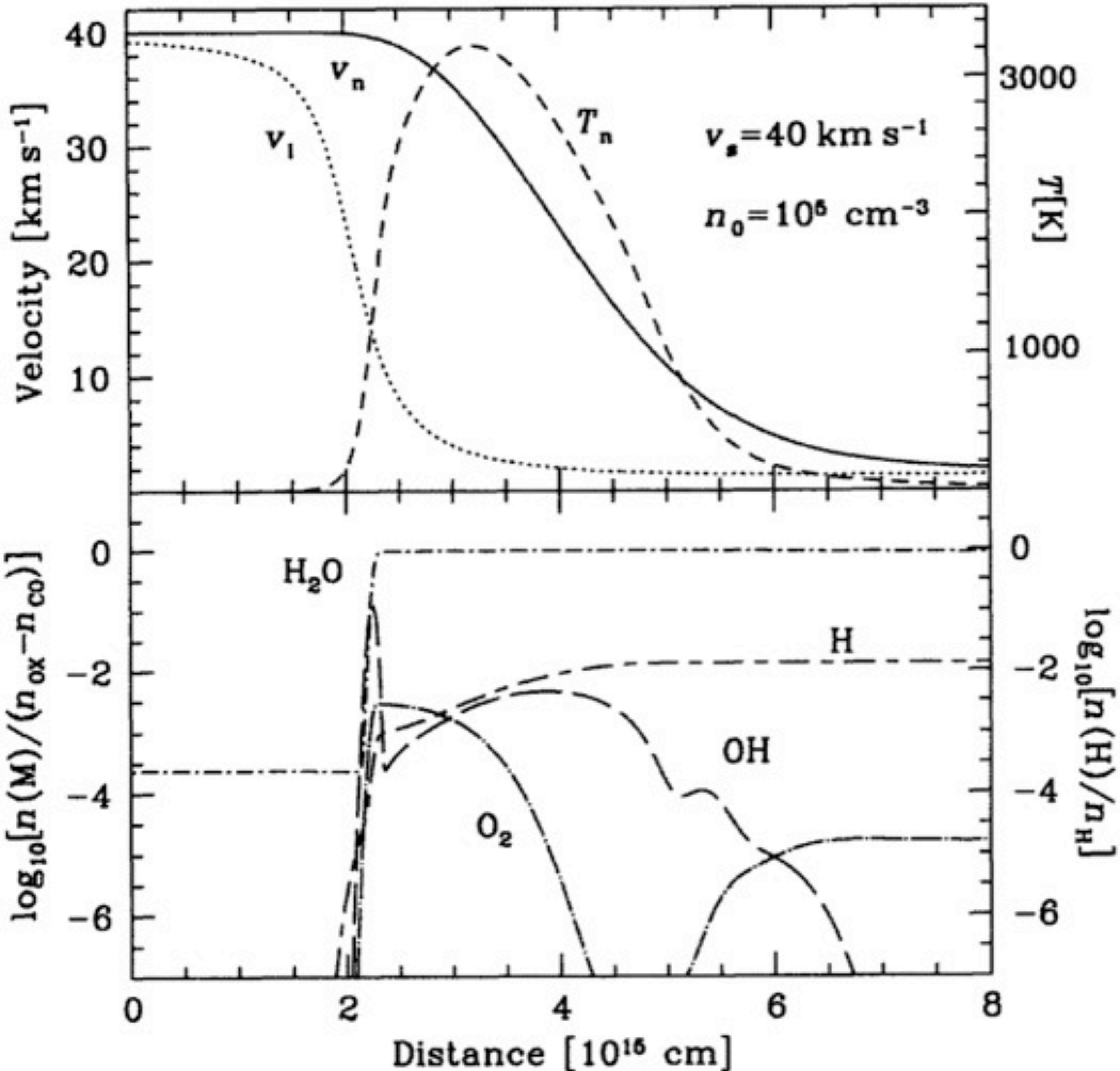


t > 0

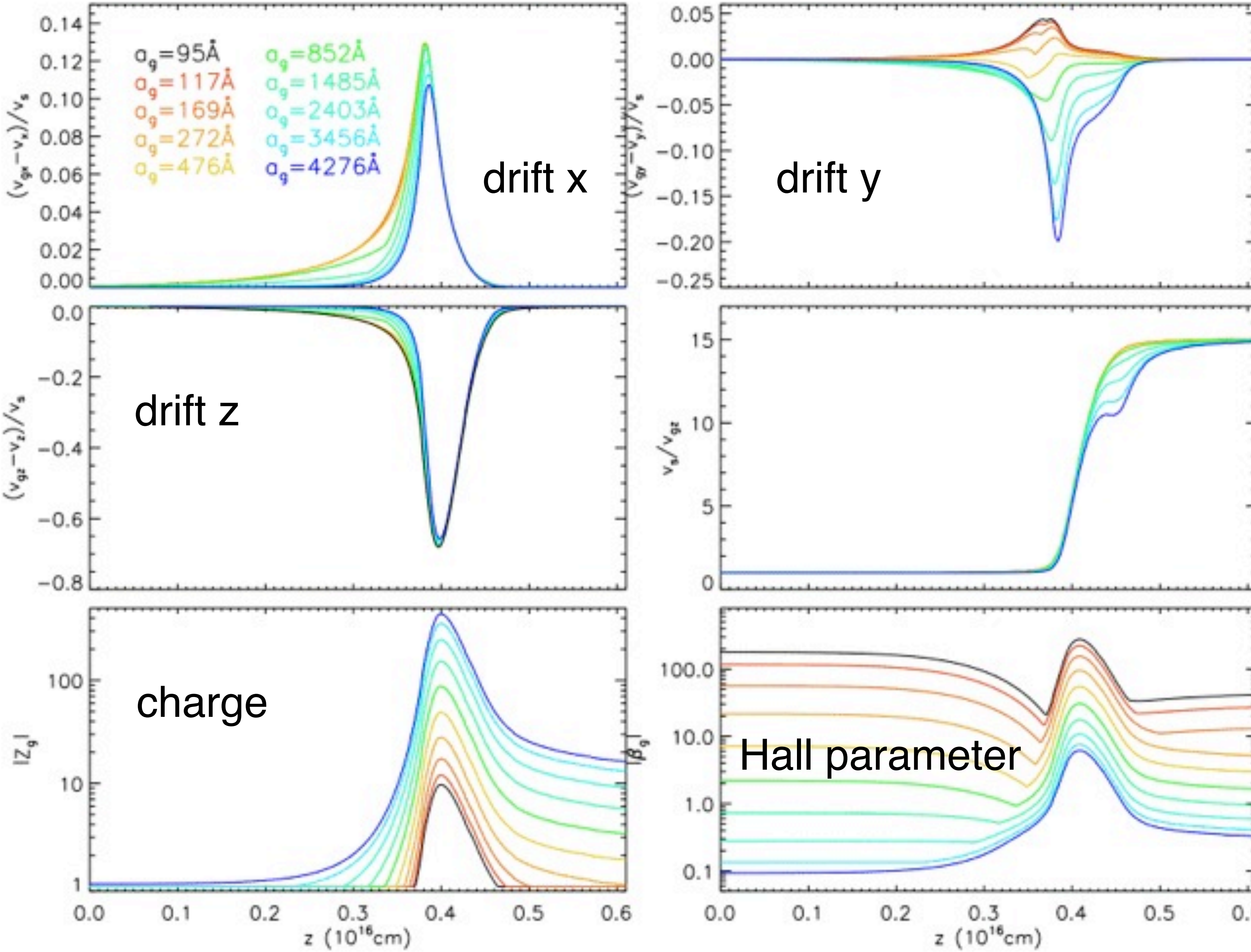


shock

Mullan 1971; Draine 1980

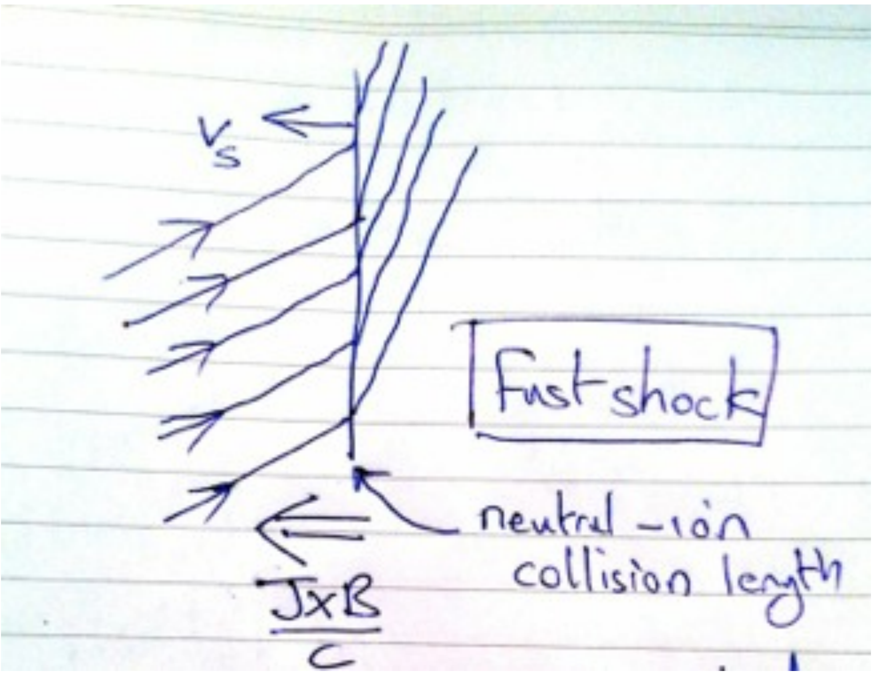


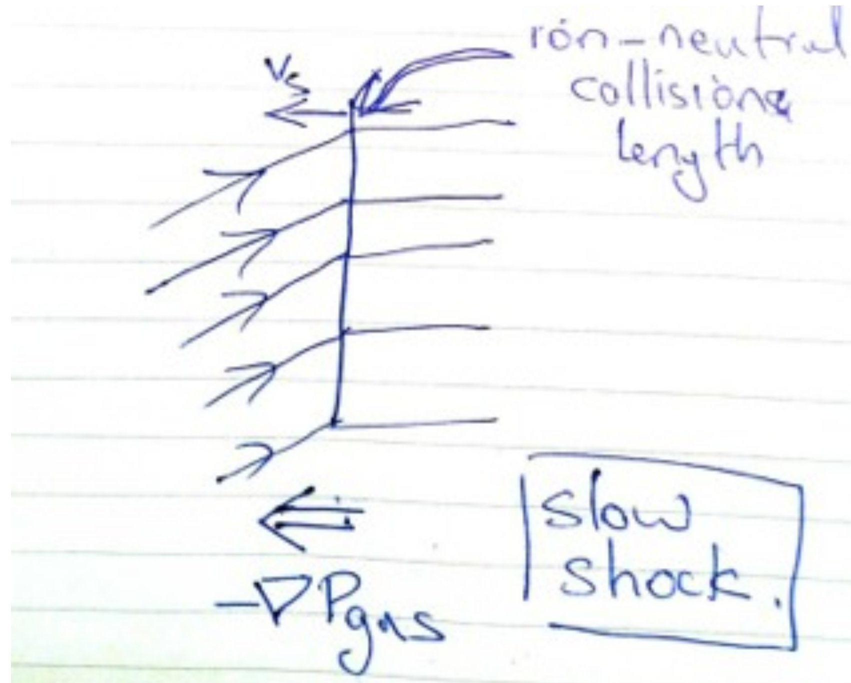
Kaufmann & Neufeld 1996

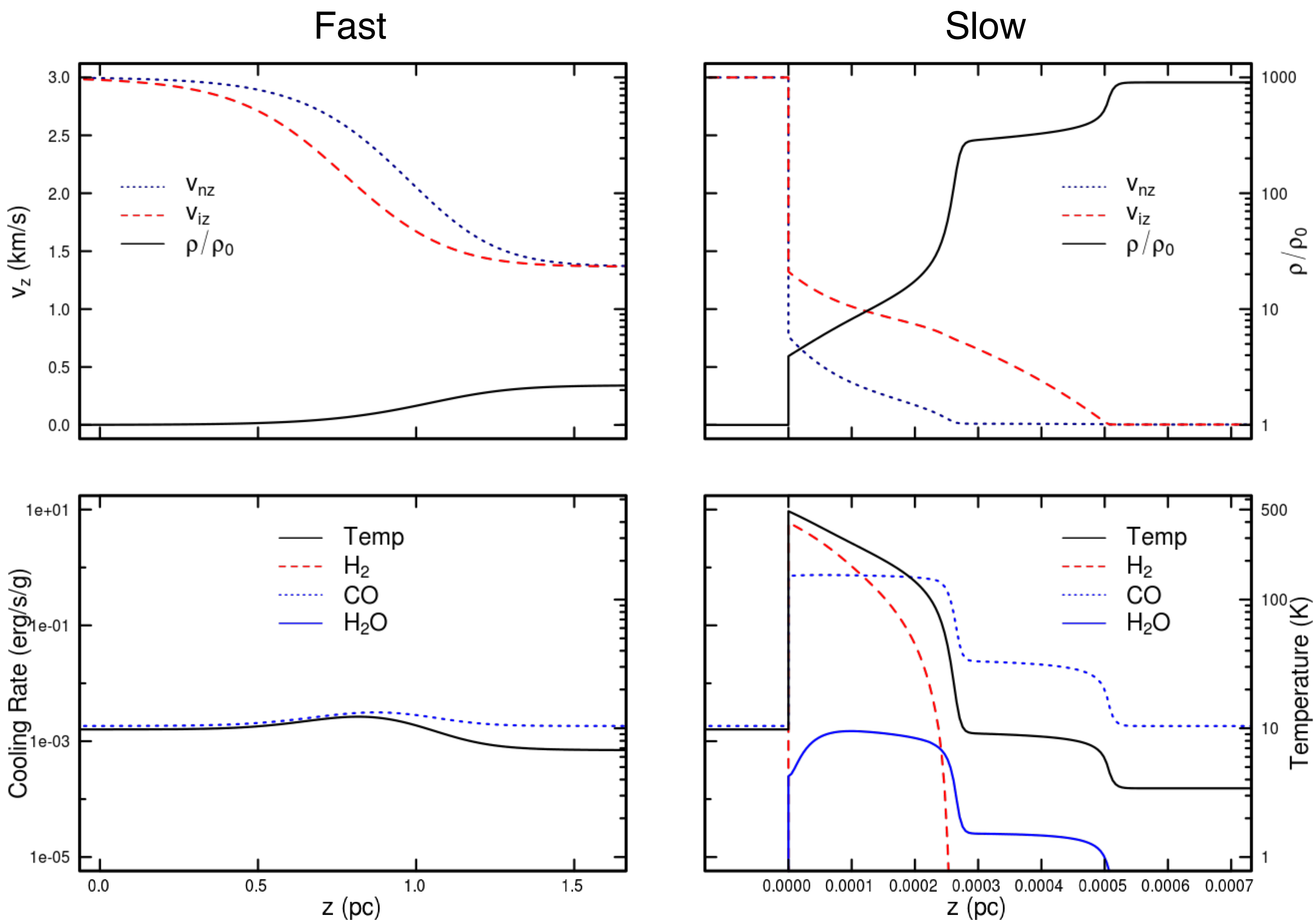


Chapman & Wardle 2006

Fast vs slow MHD shocks

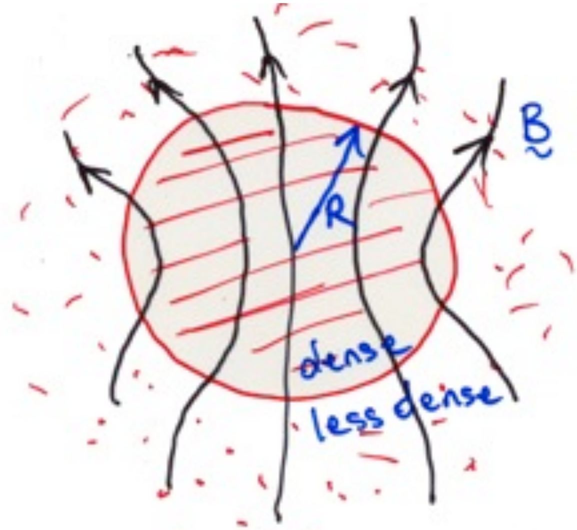




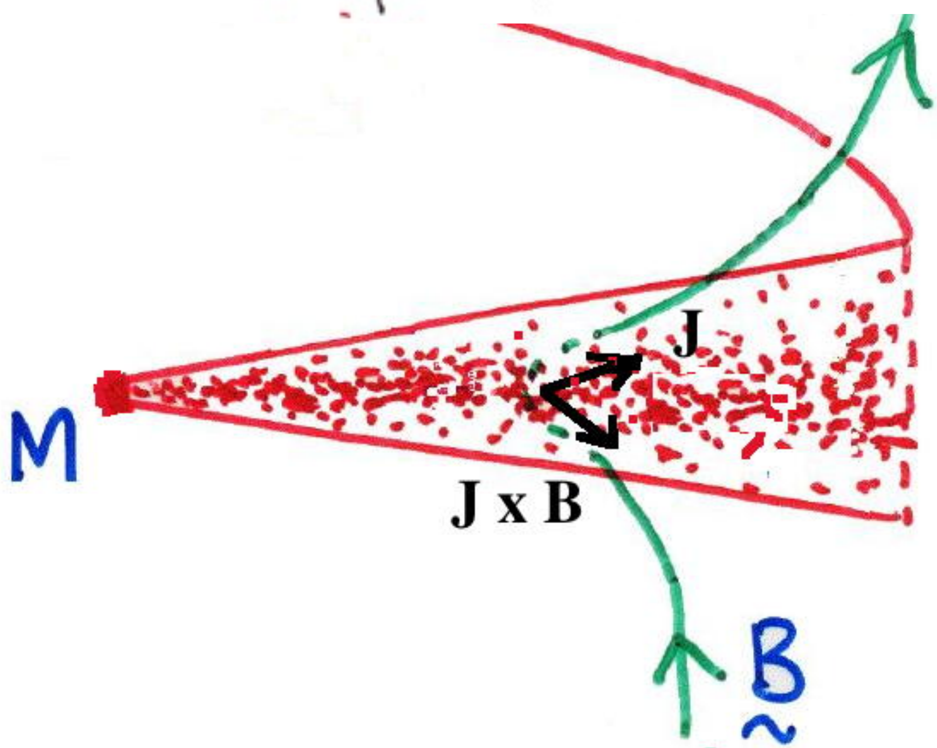


Lehmann & Wardle in prep

Field line drift: collapsing cores / protoplanetary disks



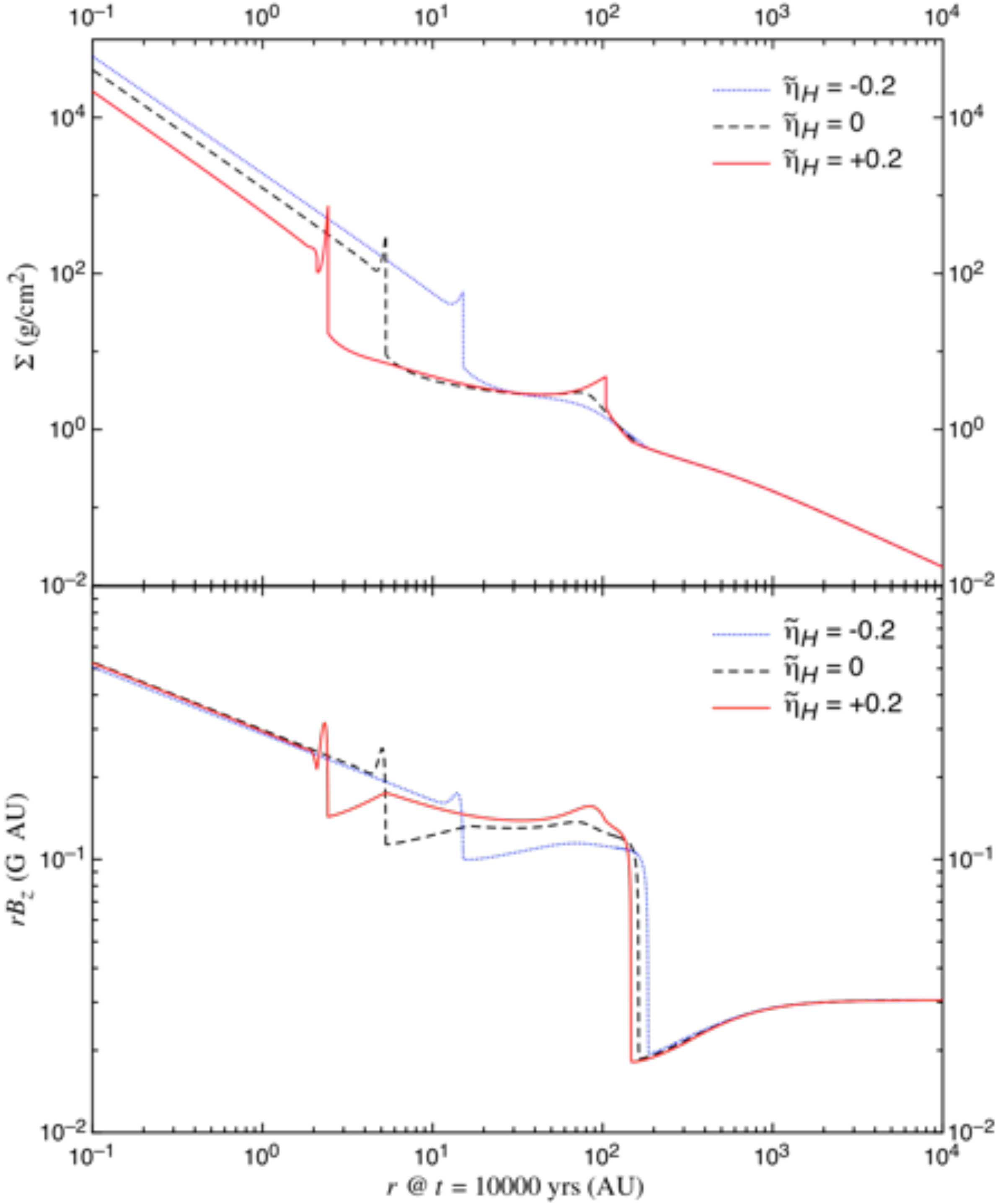
– Hall drift is "sideways"
  tends to induce or reduce twisting in B
– Sense depends on sign of B



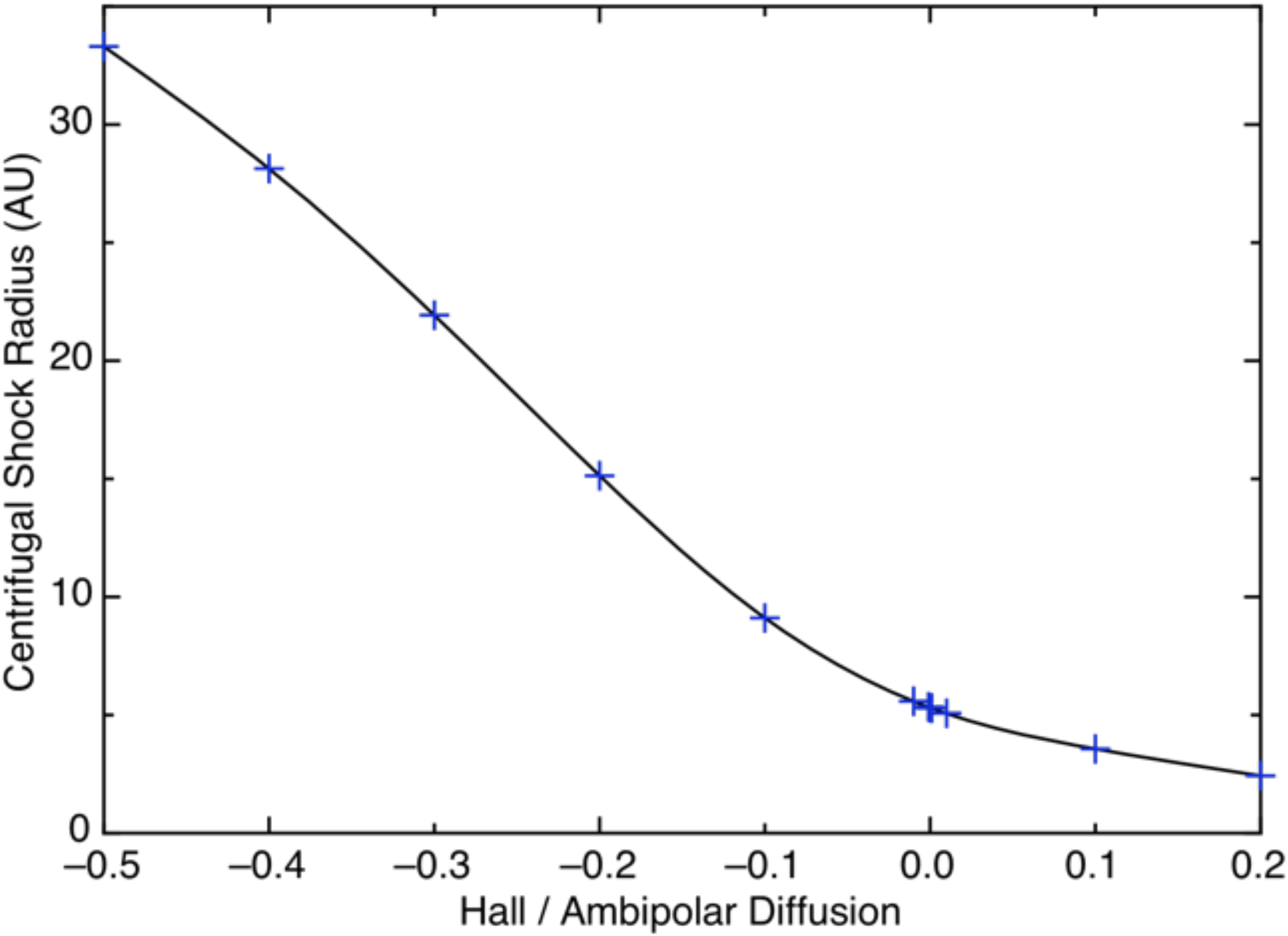
Ambipolar: $\dfrac{\mathbf{J}\times\mathbf{B}}{c\gamma\rho_i\rho}$

Ohmic: $\dfrac{4\pi\eta}{c}\dfrac{\mathbf{J}\times\mathbf{B}}{B^2}$

Hall: $-\dfrac{\mathbf{J}}{e\,n_e}$



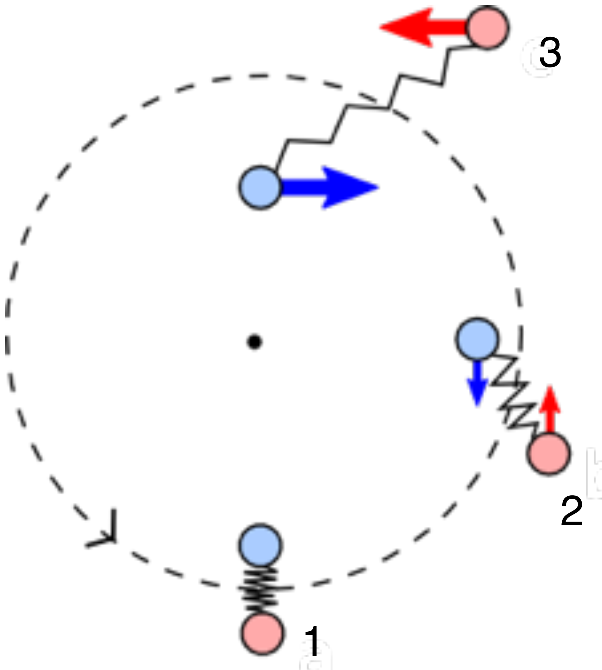
Braiding & Wardle 2012

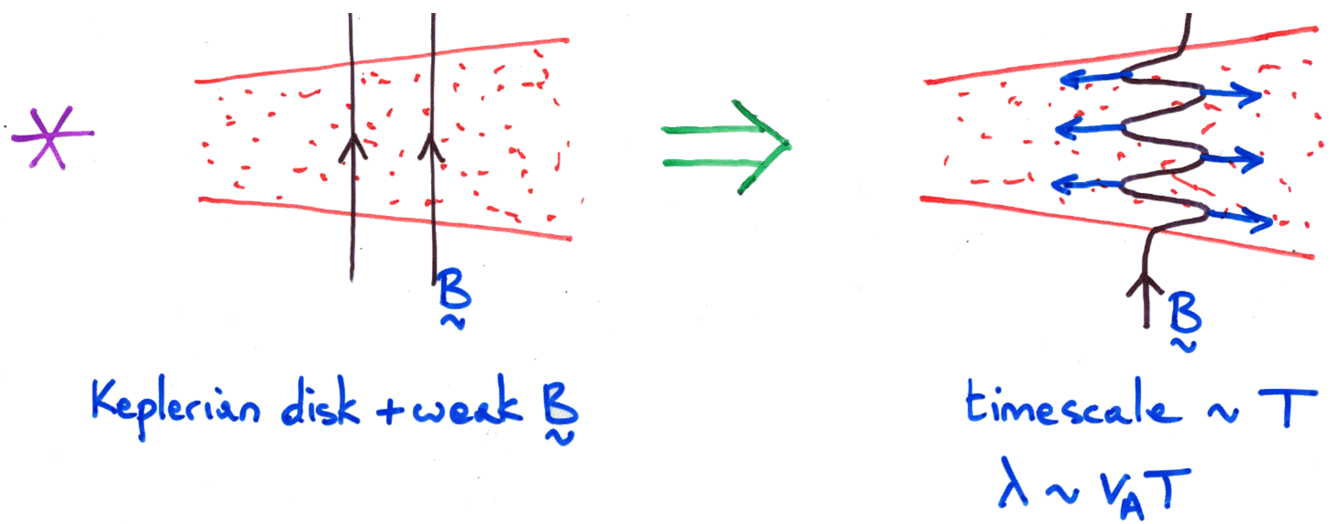


Braiding & Wardle 2012

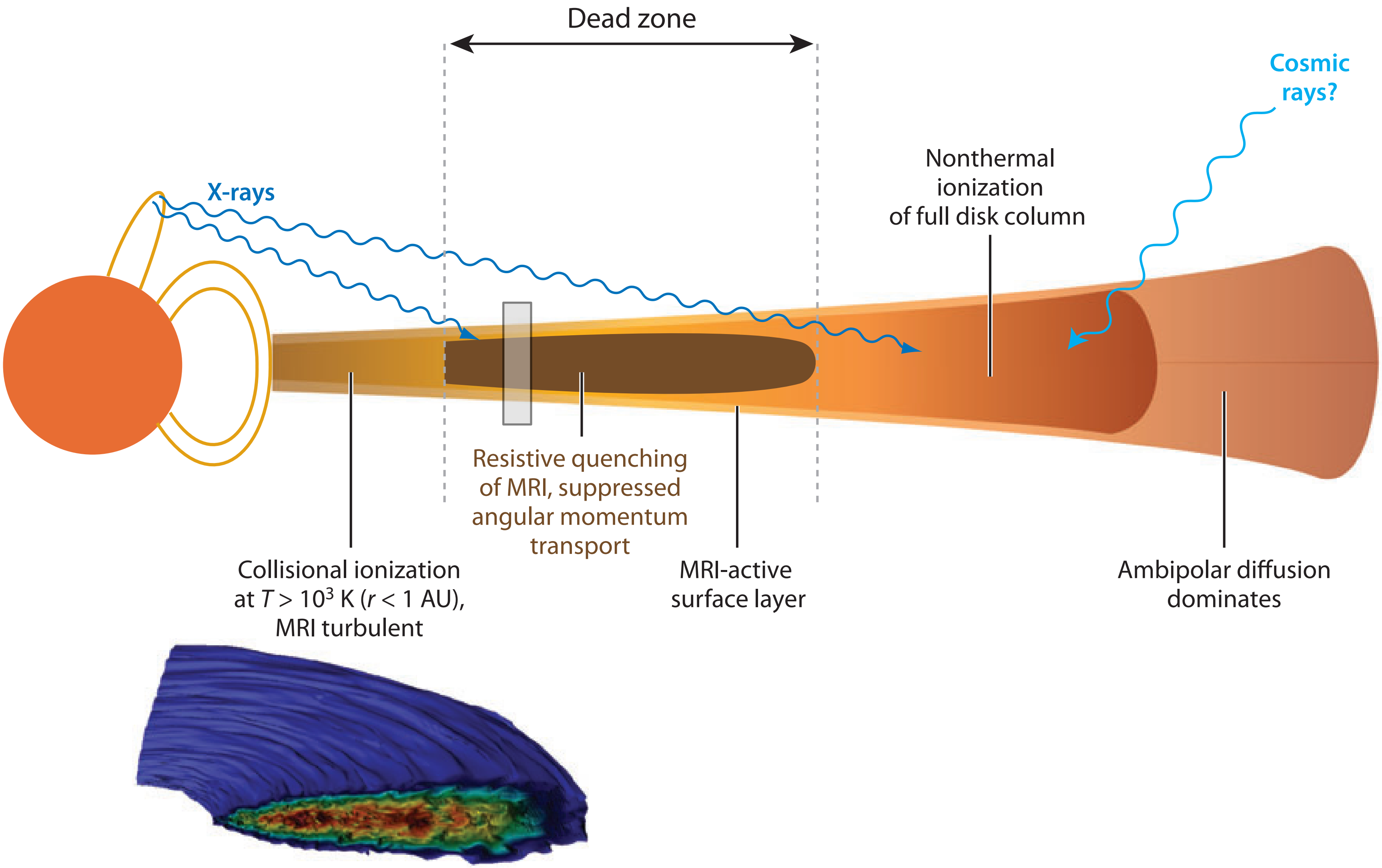
Magnetorotational instability (MRI)

- Satellites joined by a spring
  - angular momentum transferred from inner --> outer
  - spiral inwards and outwards, respectively
  - stretch spring, increases torque
  - runaway process
- Buckled magnetic field
  - couples fluid elements at different radii
  - tension plays role of spring
  - buckling increases
  - generates MHD turbulence





Dead Zones



Armitage 2011

MRI – with dead zone

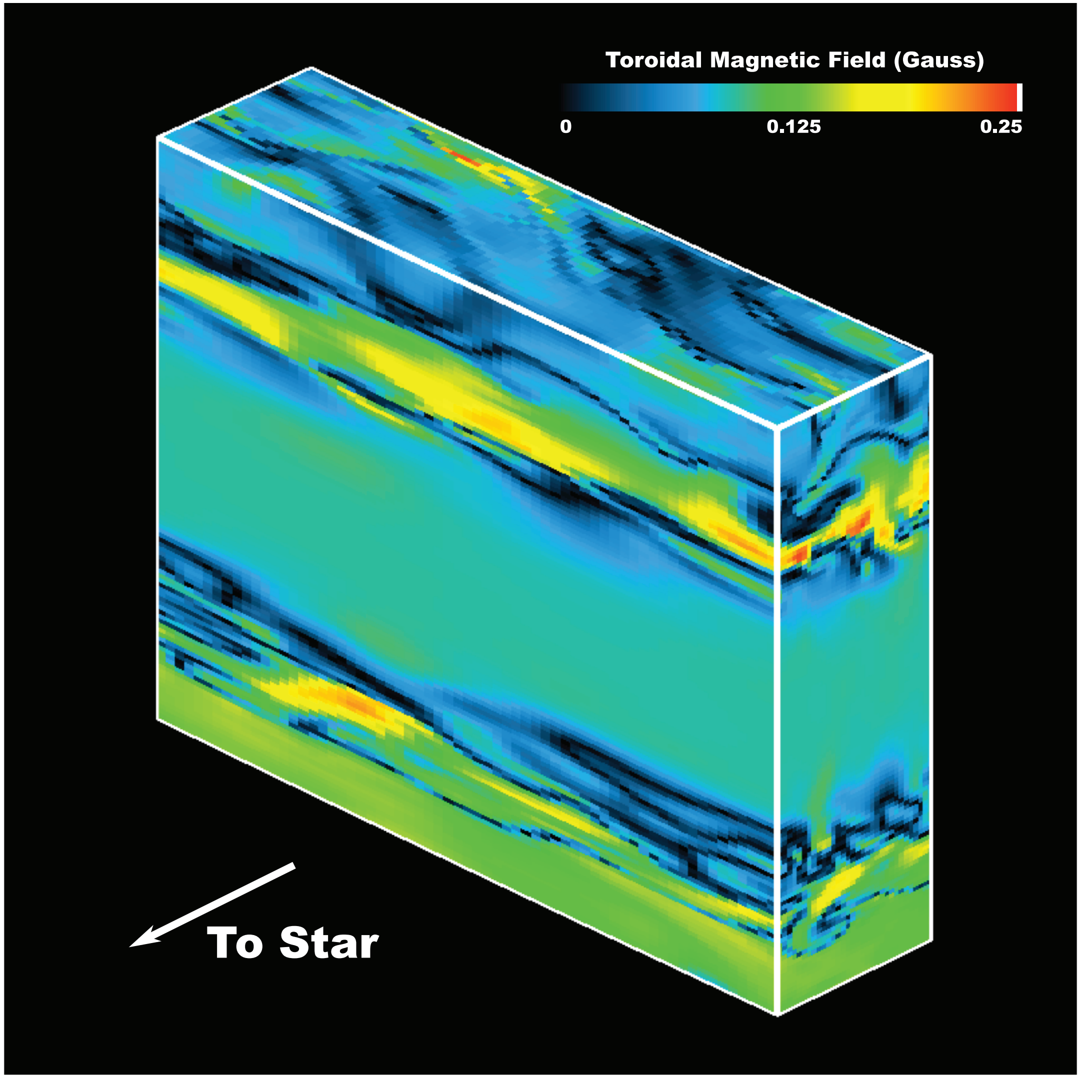
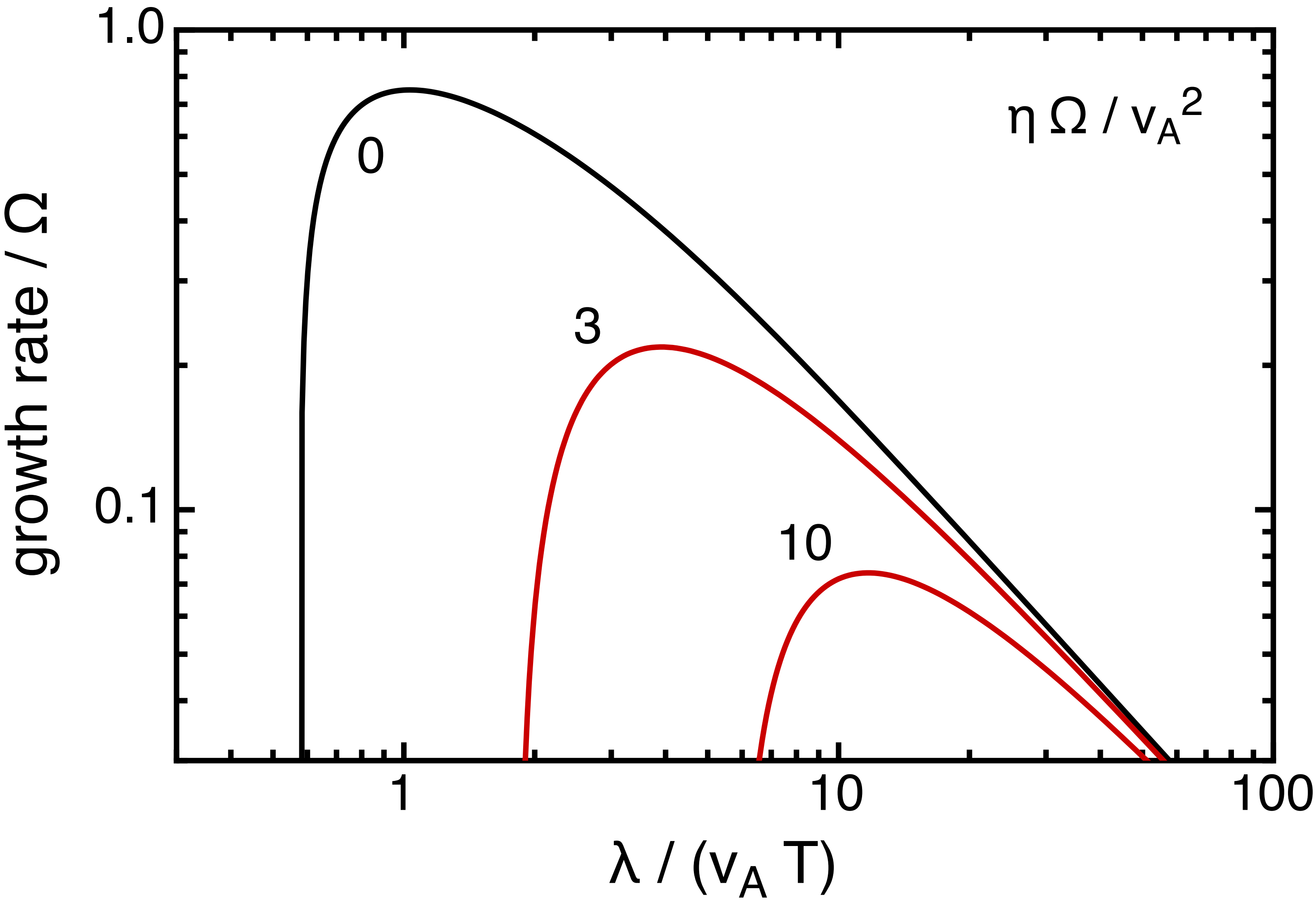
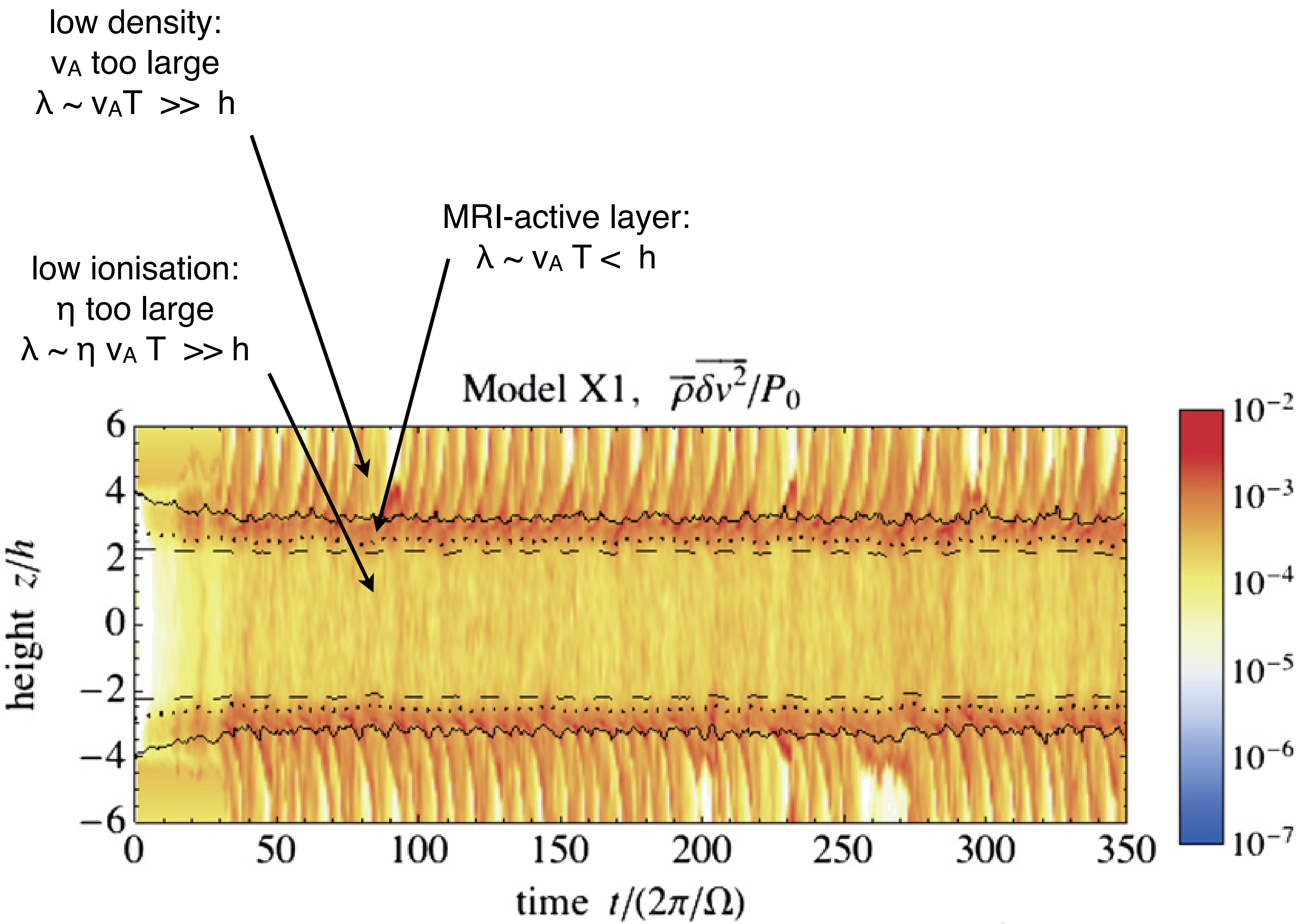


FIG. 2.—Snapshot of the toroidal magnetic field strength at 55 orbits in a resistive MHD calculation of a patch of the protosolar disk at 5 AU including well mixed 1 μm grains. The undead zone at center is filled with a uniform, 0.1 G shear-generated toroidal magnetic field while patchy fields are found in the turbulent layers above and below. The star lies off-page to the lower left and the disk midplane is horizontal through the image center.

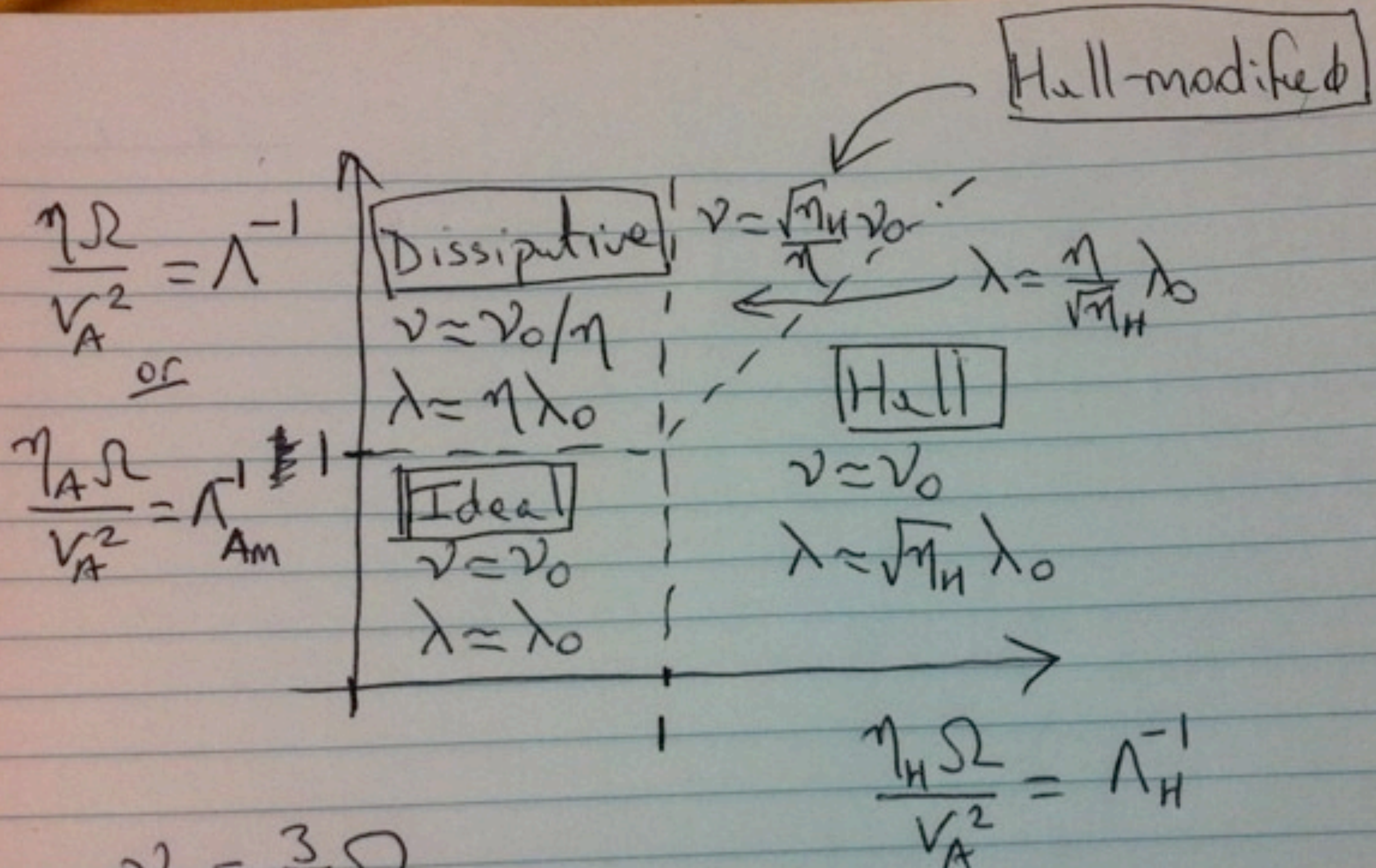
Turner & Sano 2008

MRI growth rate - ohmic and/or ambipolar diffusion





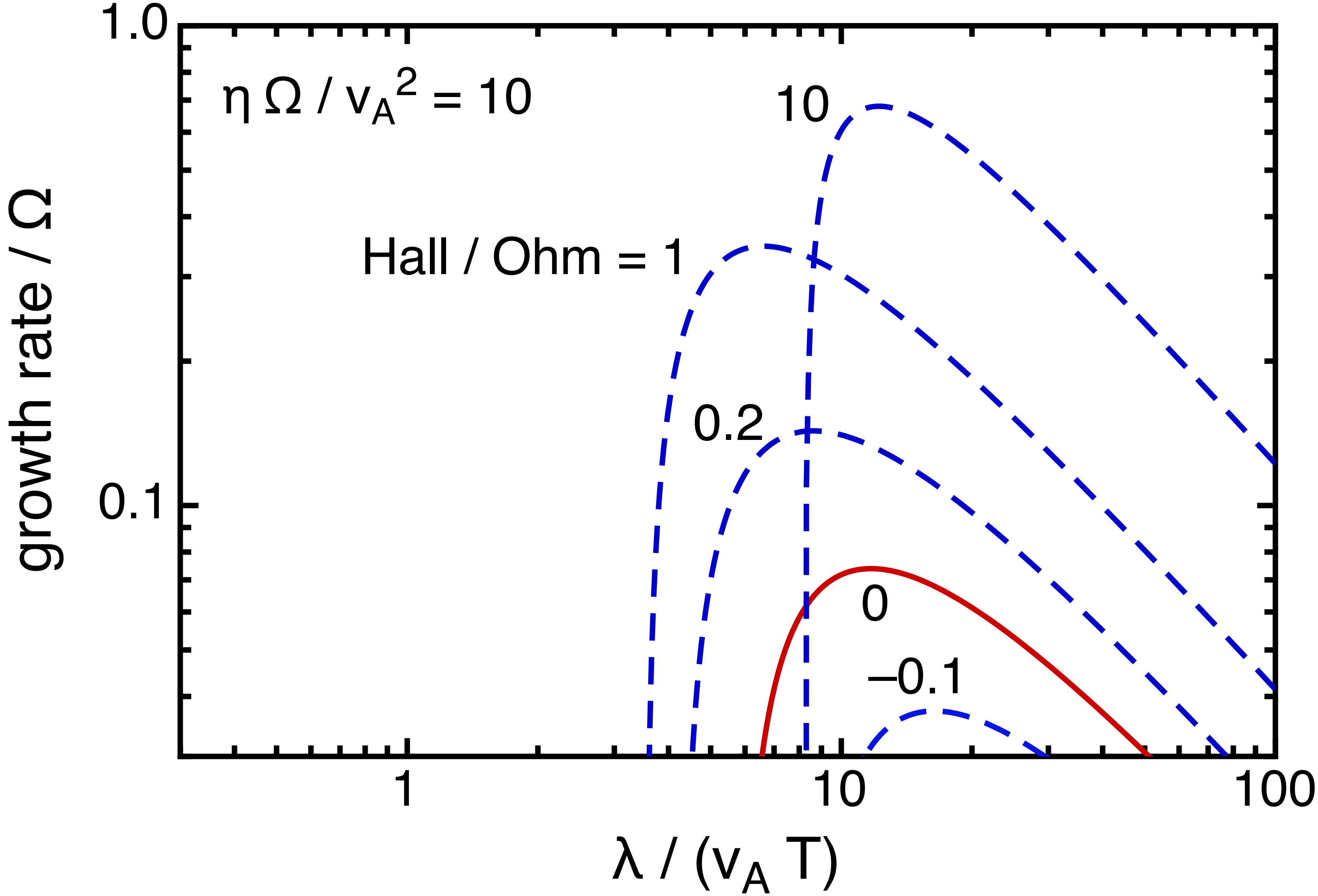
Okuzumi & Hirose 2011



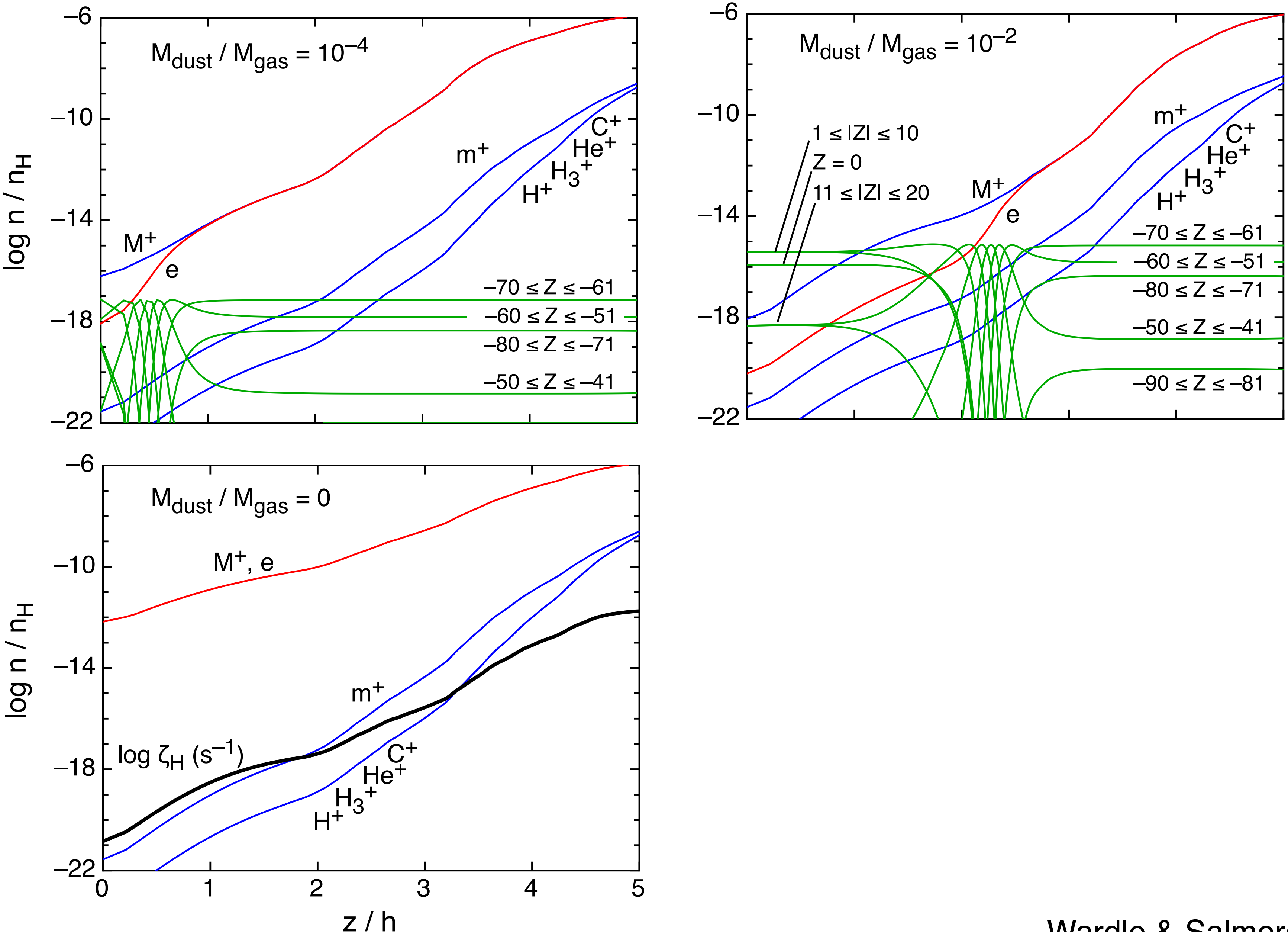
$$\nu_0 = \frac{3}{4}\Omega$$

$$\lambda_0 = v_A T$$

MRI growth rate - ohmic (and/or AD) vs Hall

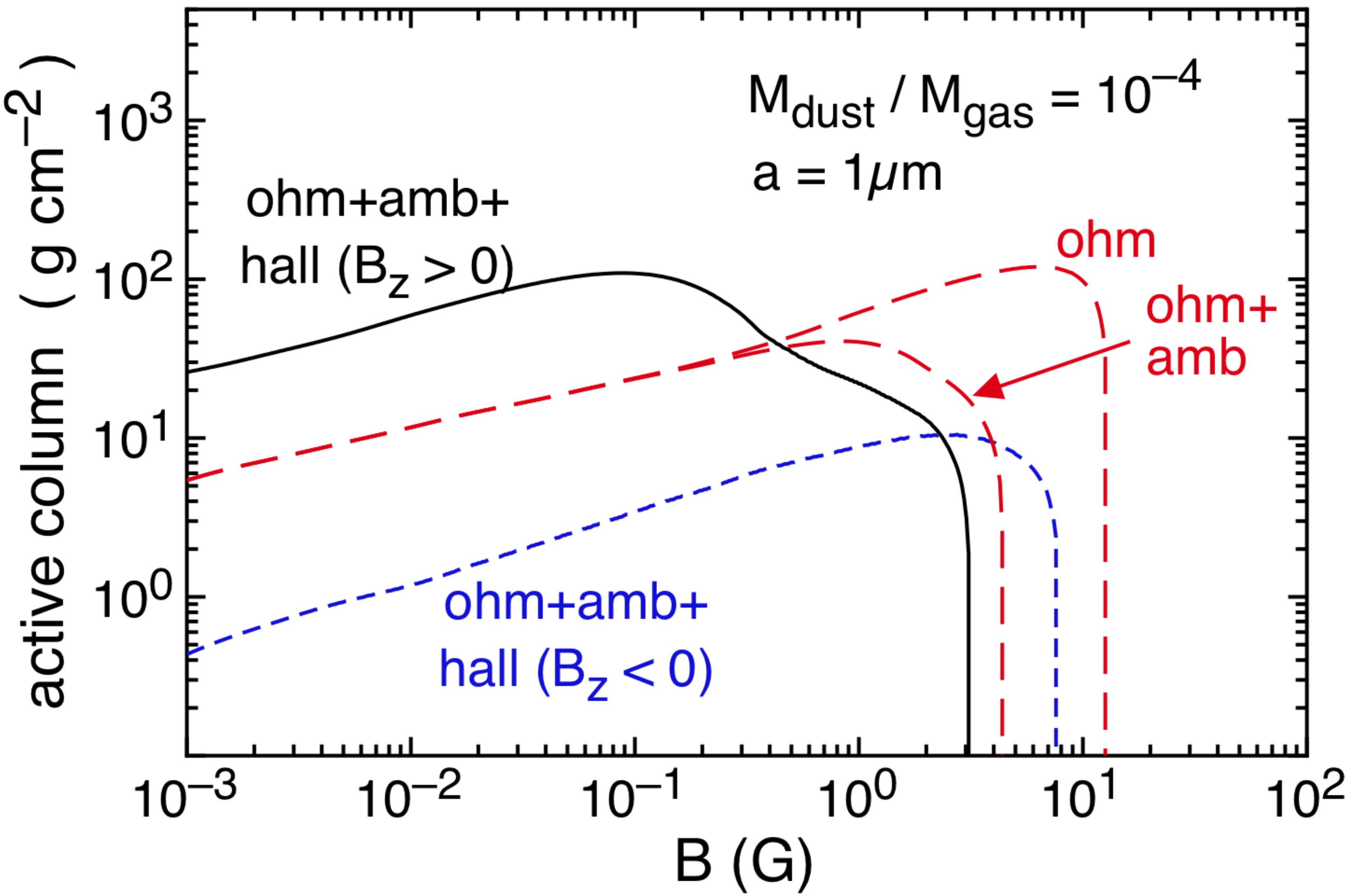


Charged particle abundances



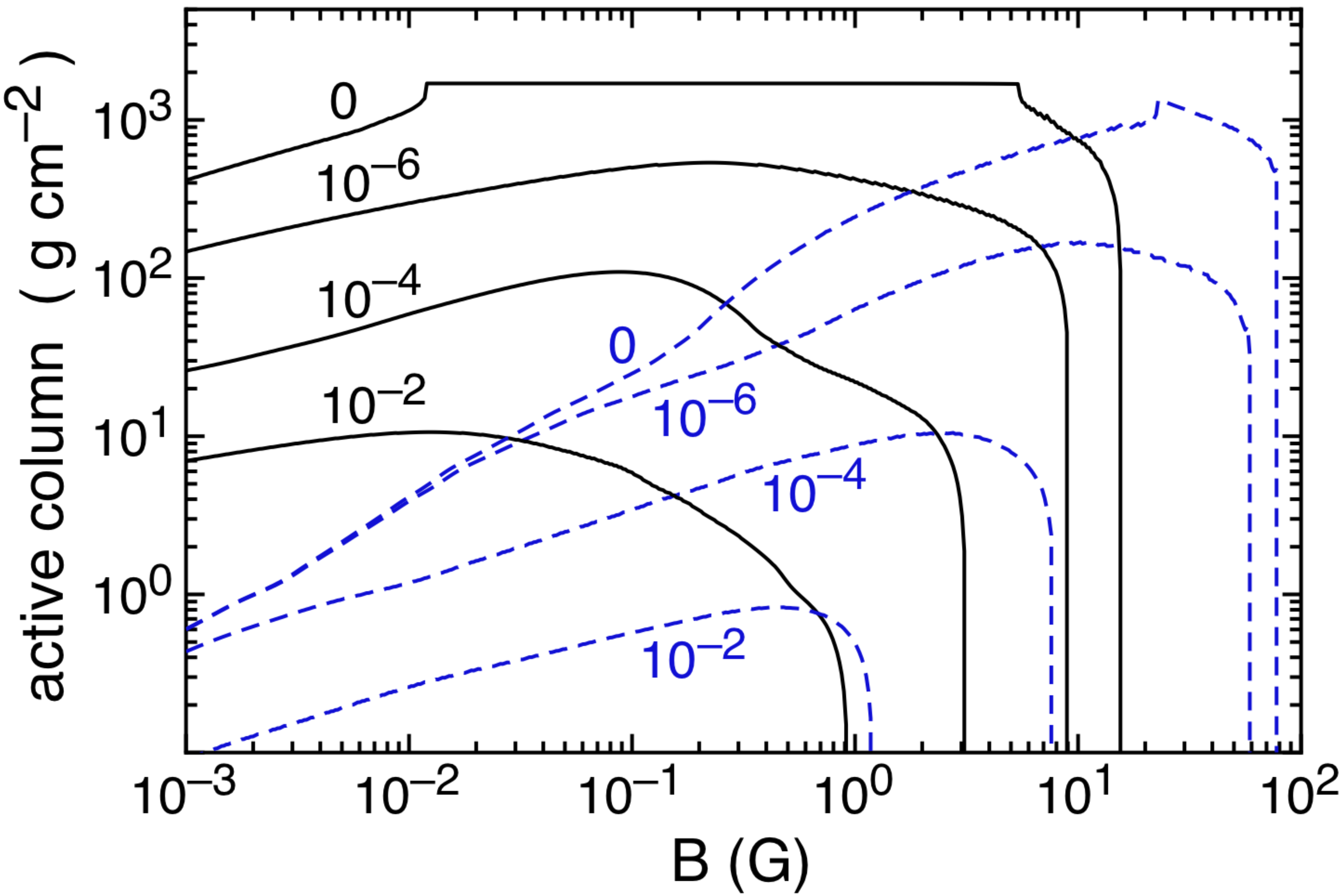
Wardle & Salmeron 2012

Column density of active layer

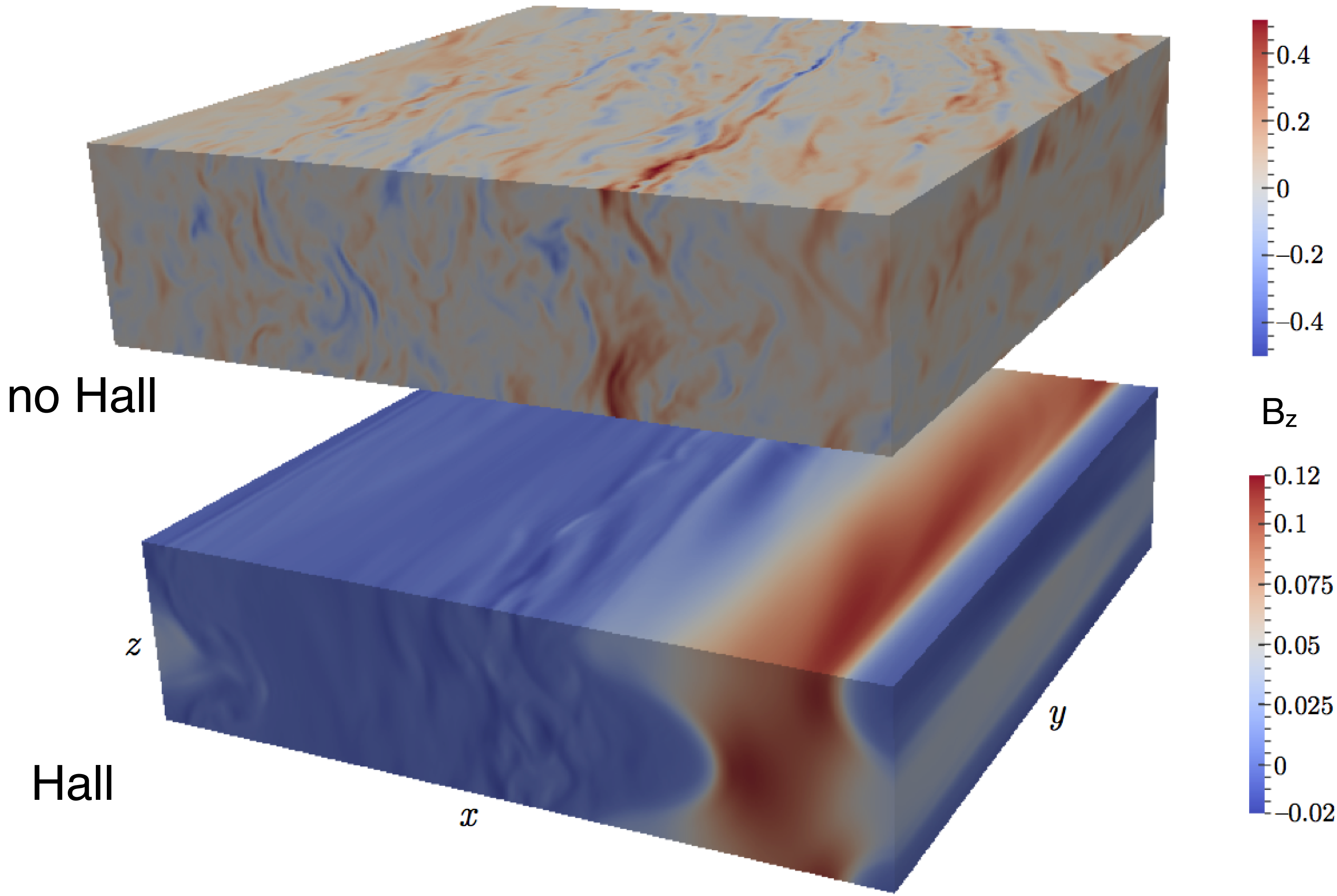


Wardle & Salmeron 2012

Column density of active layer

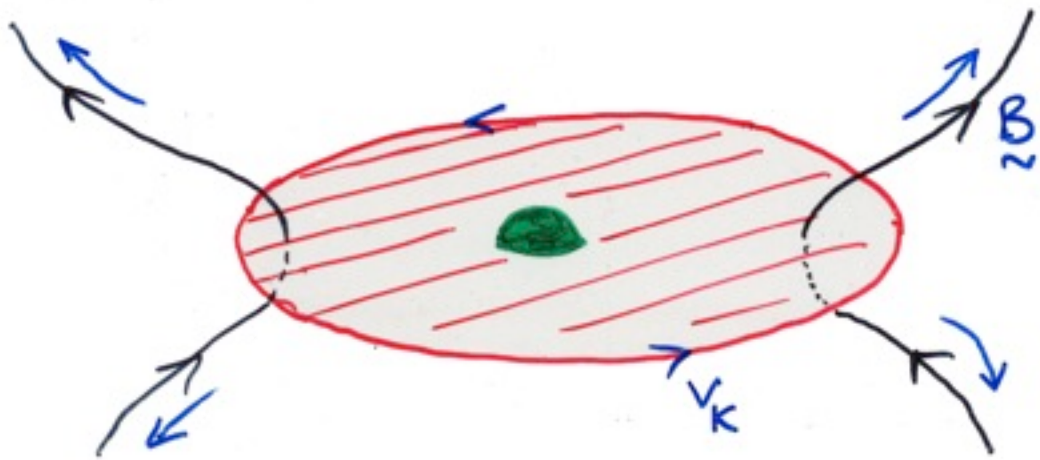


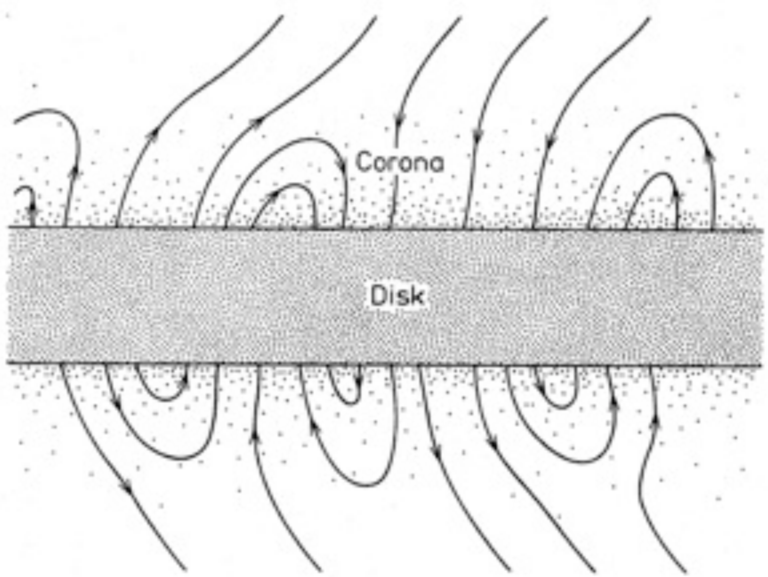
Wardle & Salmeron 2012



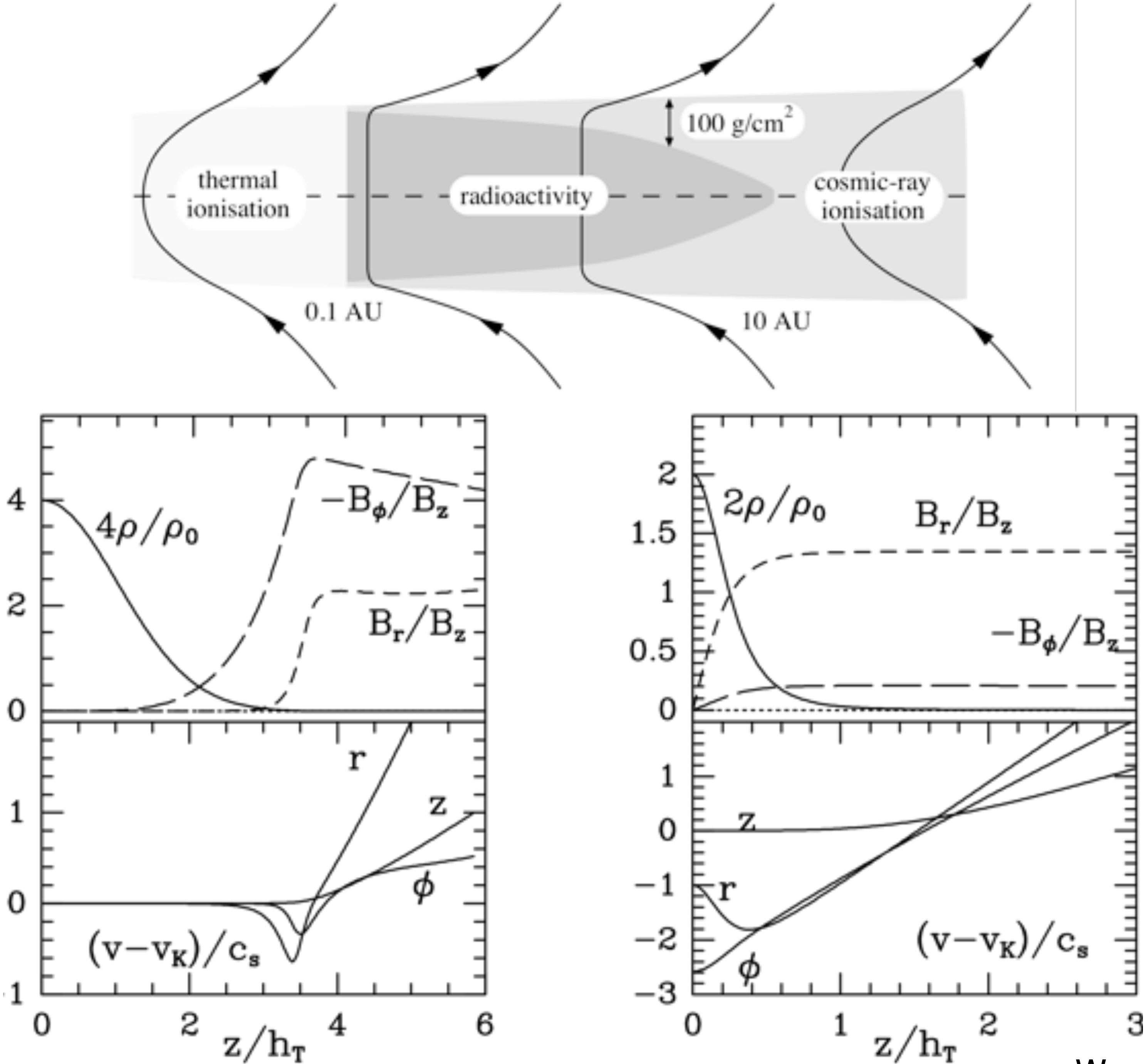
Kunz & Lesur 2013

Magnetically-driven jets



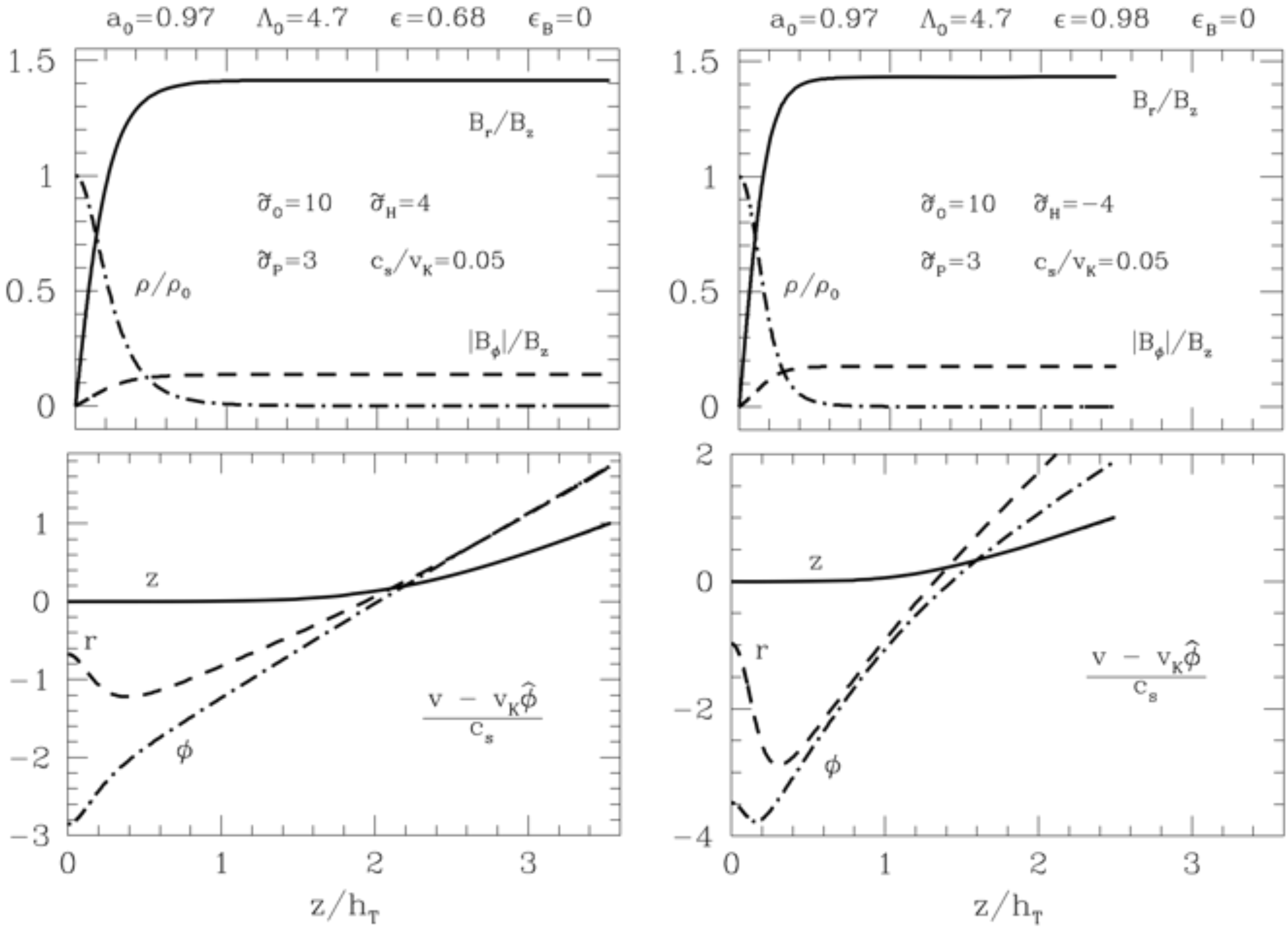


Blandford & Payne 1982

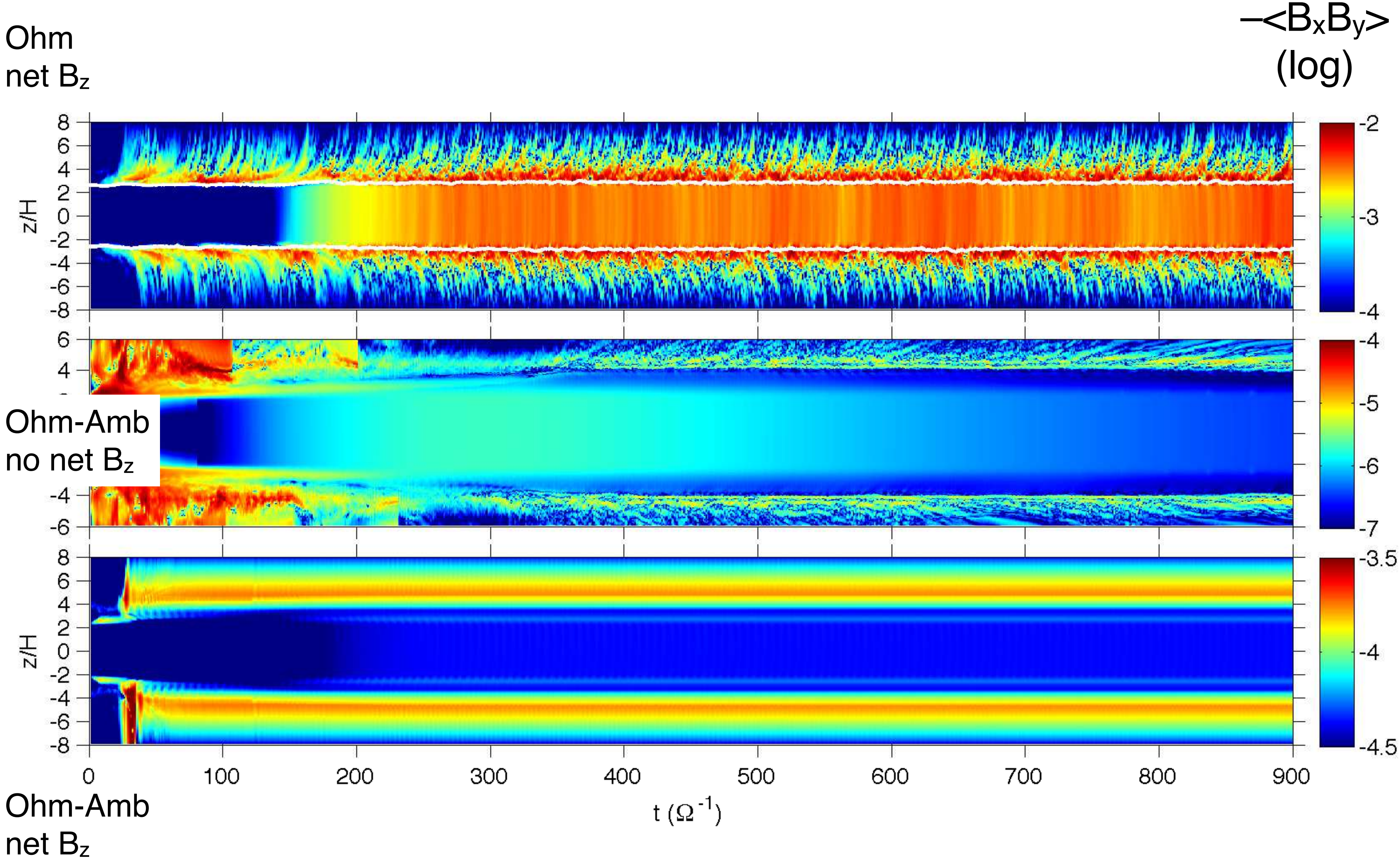


100 g/cm²
thermal ionisation
radioactivity
cosmic-ray ionisation
0.1 AU
10 AU
4ρ/ρ₀
−B_φ/B_z
B_r/B_z
r
z
φ
(v−v_K)/c_s
z/h_T
2ρ/ρ₀
B_r/B_z
−B_φ/B_z
z
r
φ
(v−v_K)/c_s
z/h_T

Wardle 1997

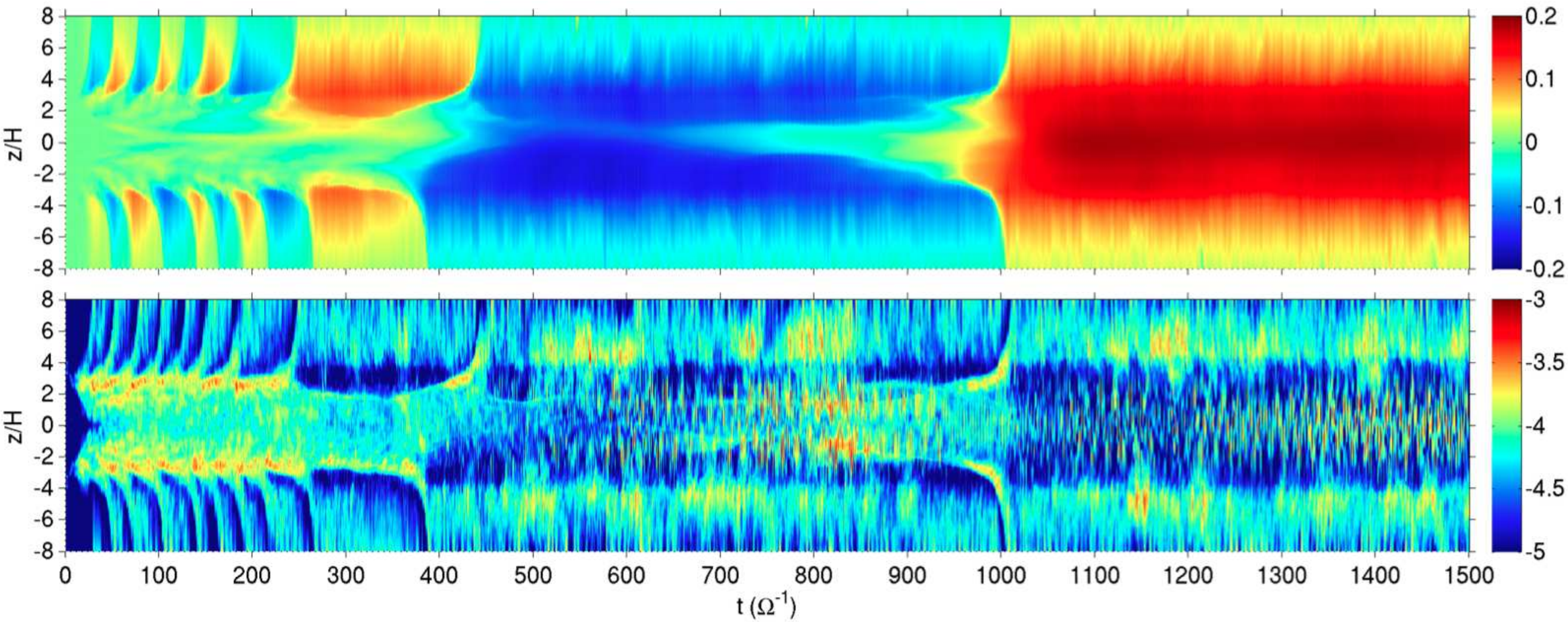


Salmeron, Konigl & Wardle 2011



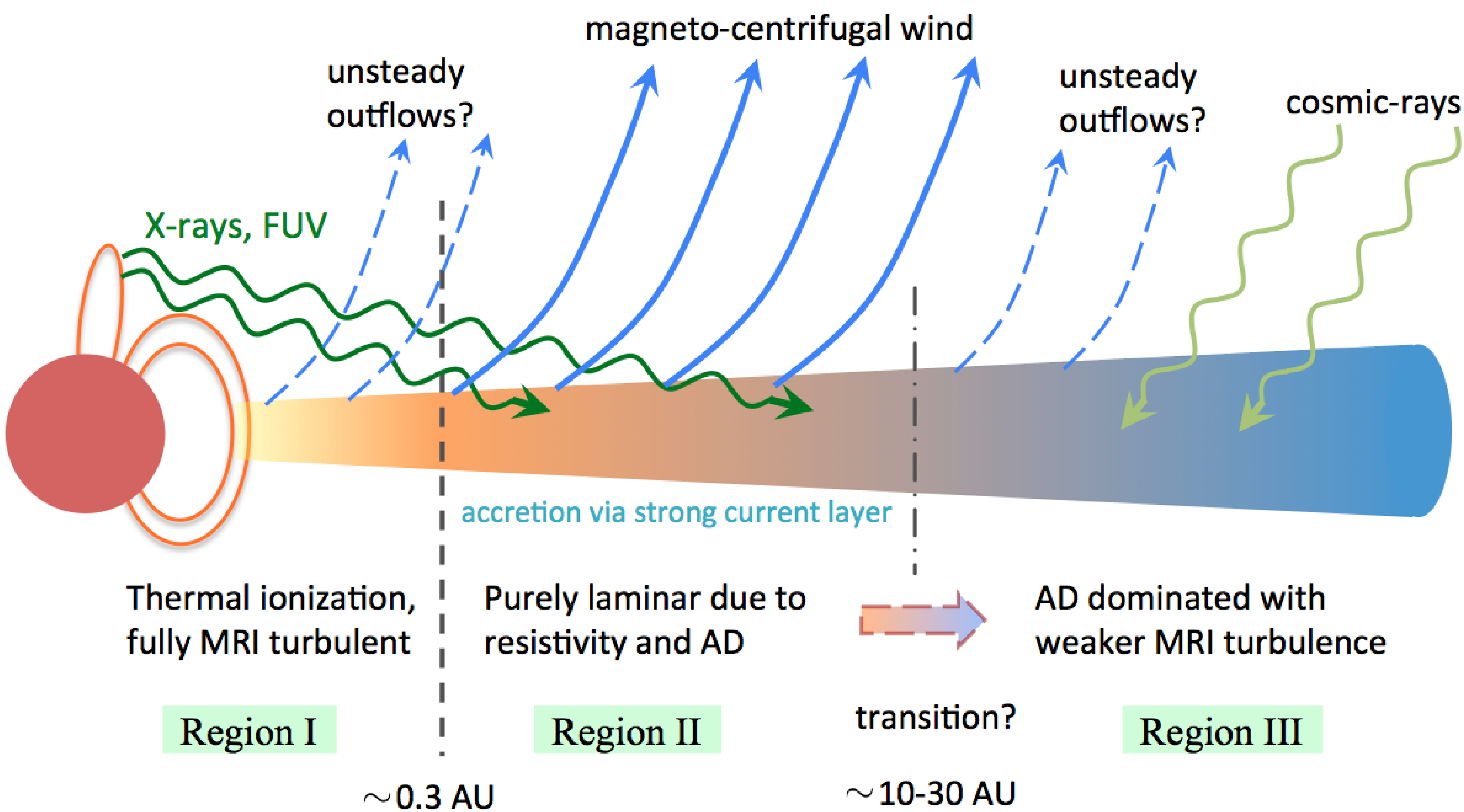
Bai & Stone 2013

$\langle B_y \rangle$
(log)



$\langle \rho v_z^2/2 \rangle$
(log)

Bai 2013


magneto-centrifugal wind
unsteady outflows?
unsteady outflows?
cosmic-rays
X-rays, FUV
accretion via strong current layer
Thermal ionization, fully MRI turbulent
Purely laminar due to resistivity and AD
AD dominated with weaker MRI turbulence
Region I
Region II
transition?
Region III
∼0.3 AU
∼10-30 AU

Bai 2013

Summary

- Ideal MHD breaks down on scale of molecular cloud cores and protoplanetary disks (not just in localised current sheets!)
  - – dissipation of fluid motions, structure of shock waves
  - – core collapse: angular momentum, magnetic flux
  - – protoplanetary disks: distribution and nature of MHD turbulence
  - – disk-driven jets: launching, coupling between jet and disk

- Determined by well-defined microscopic processes
  - – "low" densities (clouds, cores): ambipolar diffusion (Mestel & Spitzer 1956)
  - – high densities (protoplanetary disks): ohmic resistivity (e.g. Hayashi 1981)
  - – Hall effect overlooked (shocks, collapsing cores and disks) (Wardle 1998, 1999, Wardle & Ng 1999)
  - – uncertainties: grain population, ionizing sources, "turbulent" transport

    Amb: $v_B \sim JxB \sim B^2$

    Hall: $v_B \sim \pm J \sim B$; depends on sign of B ; no dissipation

    Ohm: $v_B \sim JxB / B^2 \sim B^0$; important only for high density, weak fields

- cf solar chromosphere
  - – Hall ~ Ambipolar >> Ohm