Dead zones in protoplanetary discs

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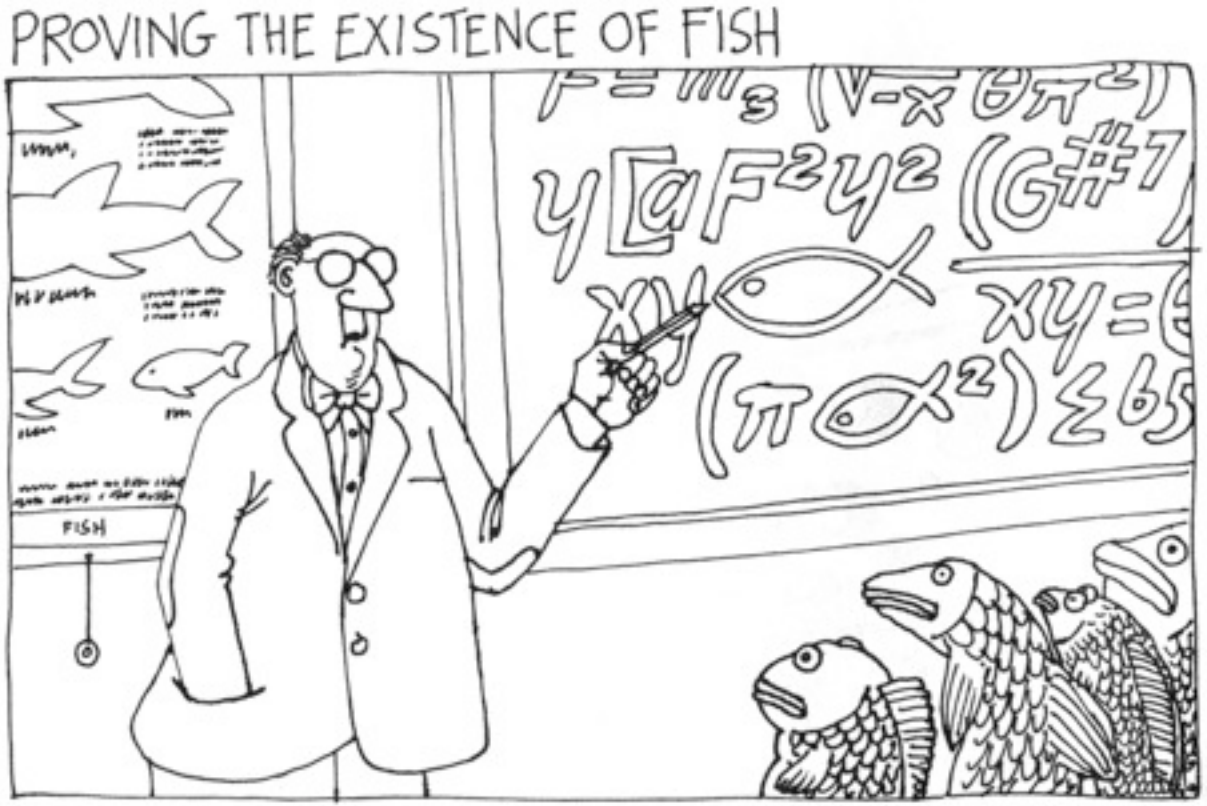


Protoplanetary discs

Magnetic fields

Dead zones

MRI and diffusion

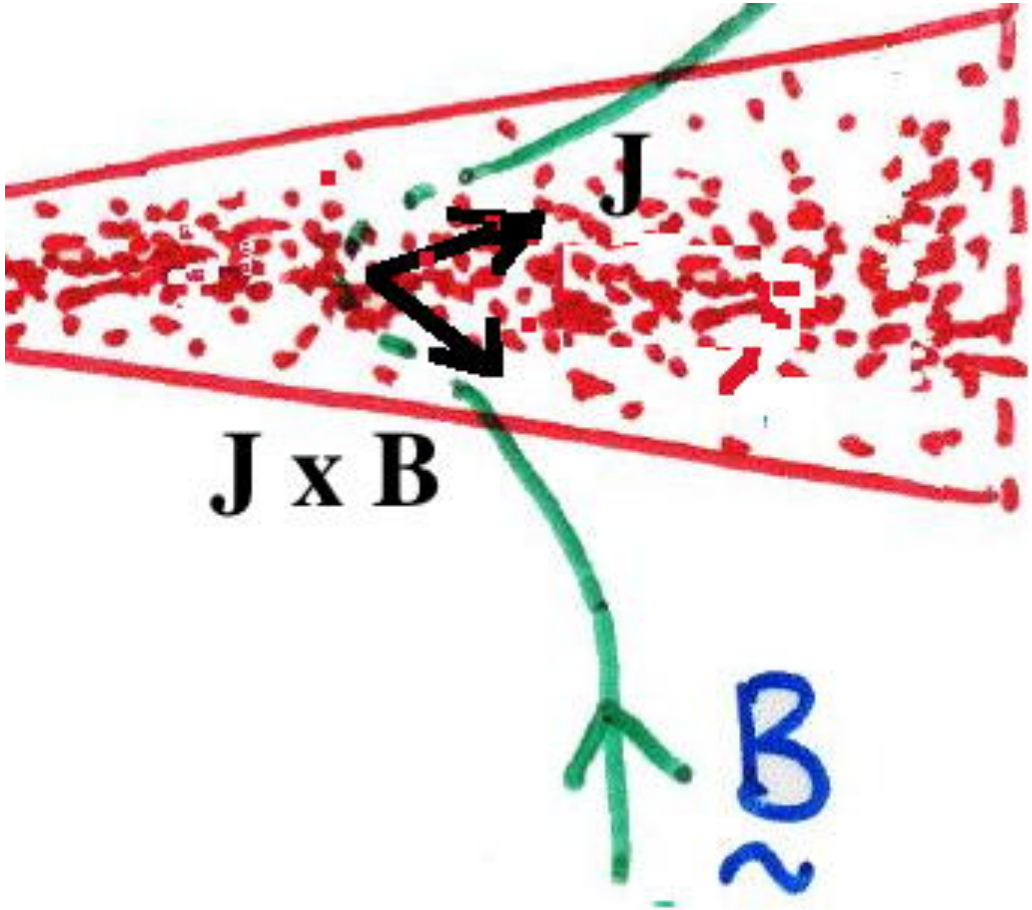
Modification to dead zones

Magnetic fields

- Magnetic fields are present in PPDs
  - measured B in molecular clouds ==> B>10 mG in PPDs
    Zeeman, submm polarization

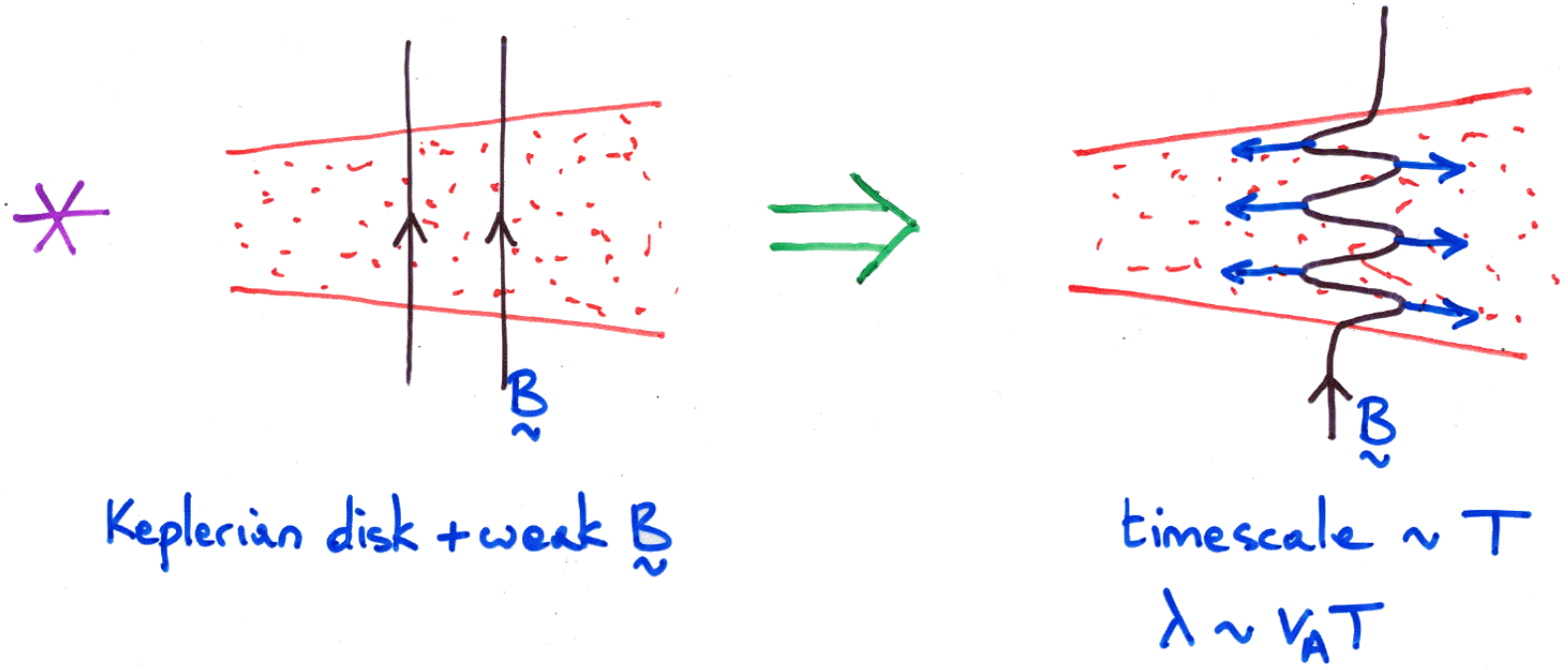
- Weak magnetic fields create turbulence
  - subequipartition B and rotational shear ==> MHD turbulent torque
    magnetorotational instability (MRI)
  - accretion, heating, stirring (chemistry, dust grains)
    disc evolution
    observational signatures
    planet formation
    planet migration (!)

- Accretion rates require B ~ 0.1 – 1G at 1AU


J
J x B
B

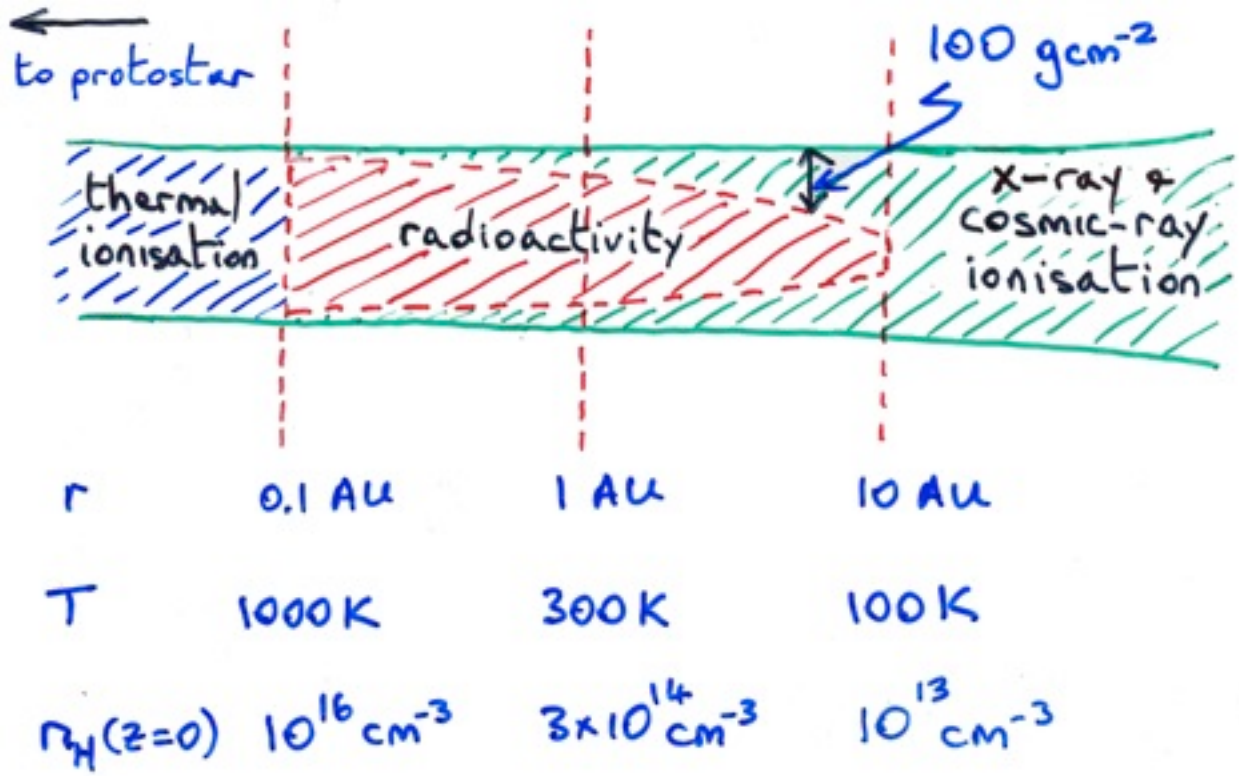
Magnetorotational instability (MRI)

- magnetic field couples different radii in disc
- tension transfers angular momentum outwards
- $kh > 1$ required to fit in disc, i.e. $v_A/c_s < 1$
- resulting turbulence transports angular momentum outwards



Flux freezing breaks down in PPDs

- high density and low ionisation
  - drag on charged particles
- deeper layers shielded from ionising radiation for r < 5 AU
  - x-ray attenuation column ~10 g/cm^2
  - cosmic ray attenuation column ~100 g/cm^2
  - “dead zone” near midplane (Gammie 1996)



MRI with dead zone

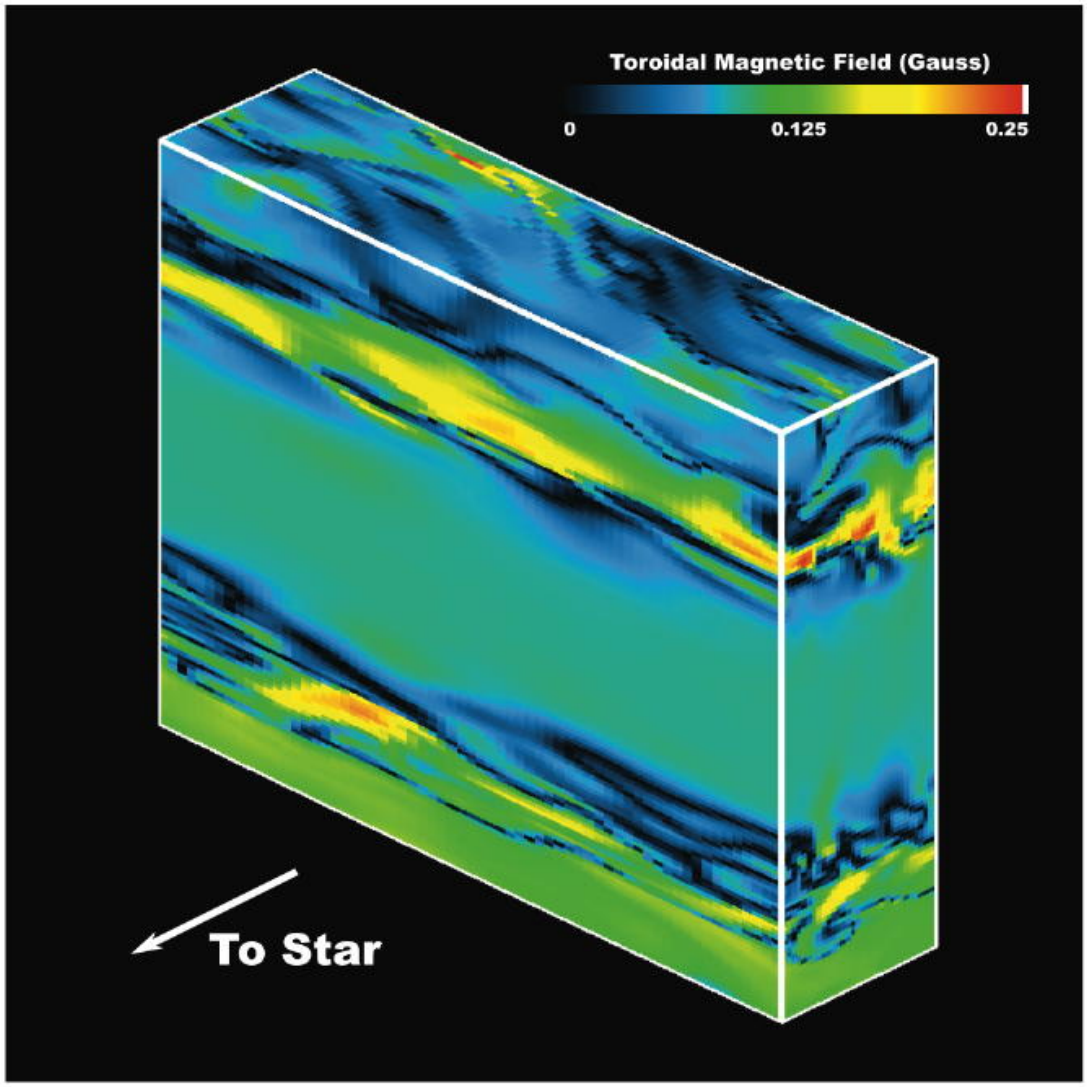
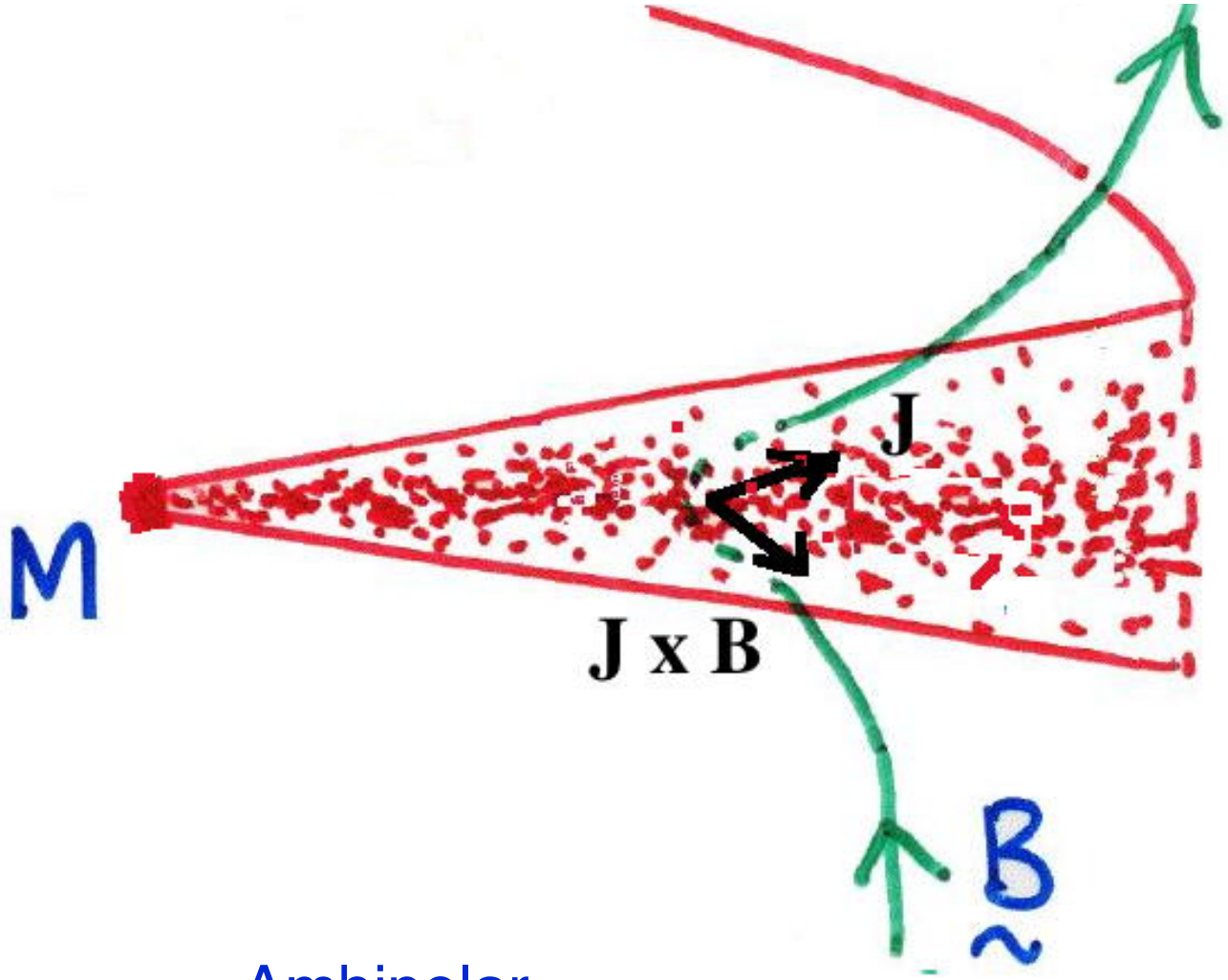


FIG. 2.—Snapshot of the toroidal magnetic field strength at 55 orbits in a resistive MHD calculation of a patch of the protosolar disk at 5 AU including well mixed 1 μm grains. The undead zone at center is filled with a uniform, 0.1 G shear-generated toroidal magnetic field while patchy fields are found 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

Magnetic diffusion

Ideal MHD	electrons, ions and neutrals tied to magnetic field
Ambipolar diffusion	neutrals decoupled
Hall diffusion	ions and neutrals decoupled
Ohmic diffusion	electrons, ions and neutrals decoupled

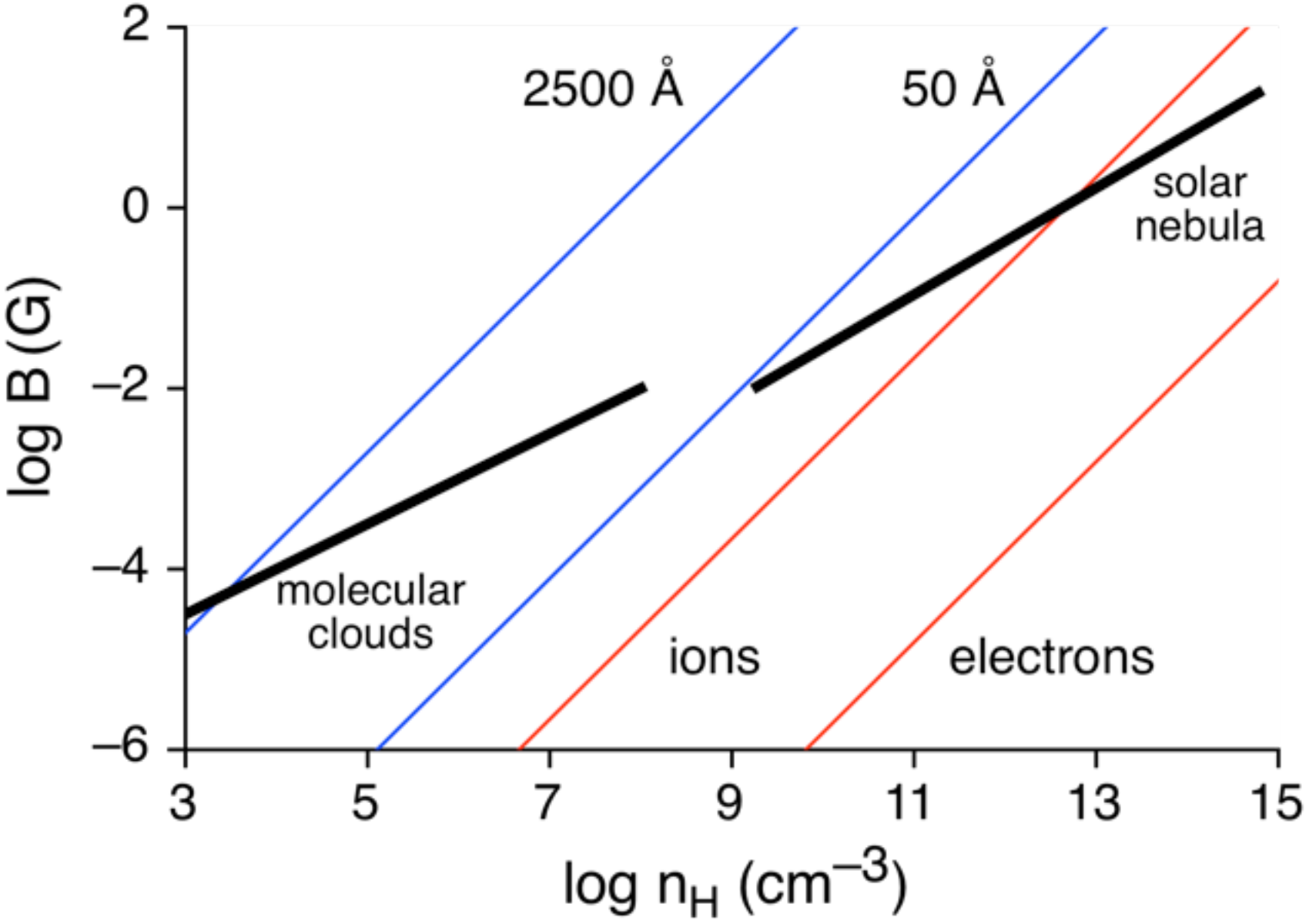


Ambipolar

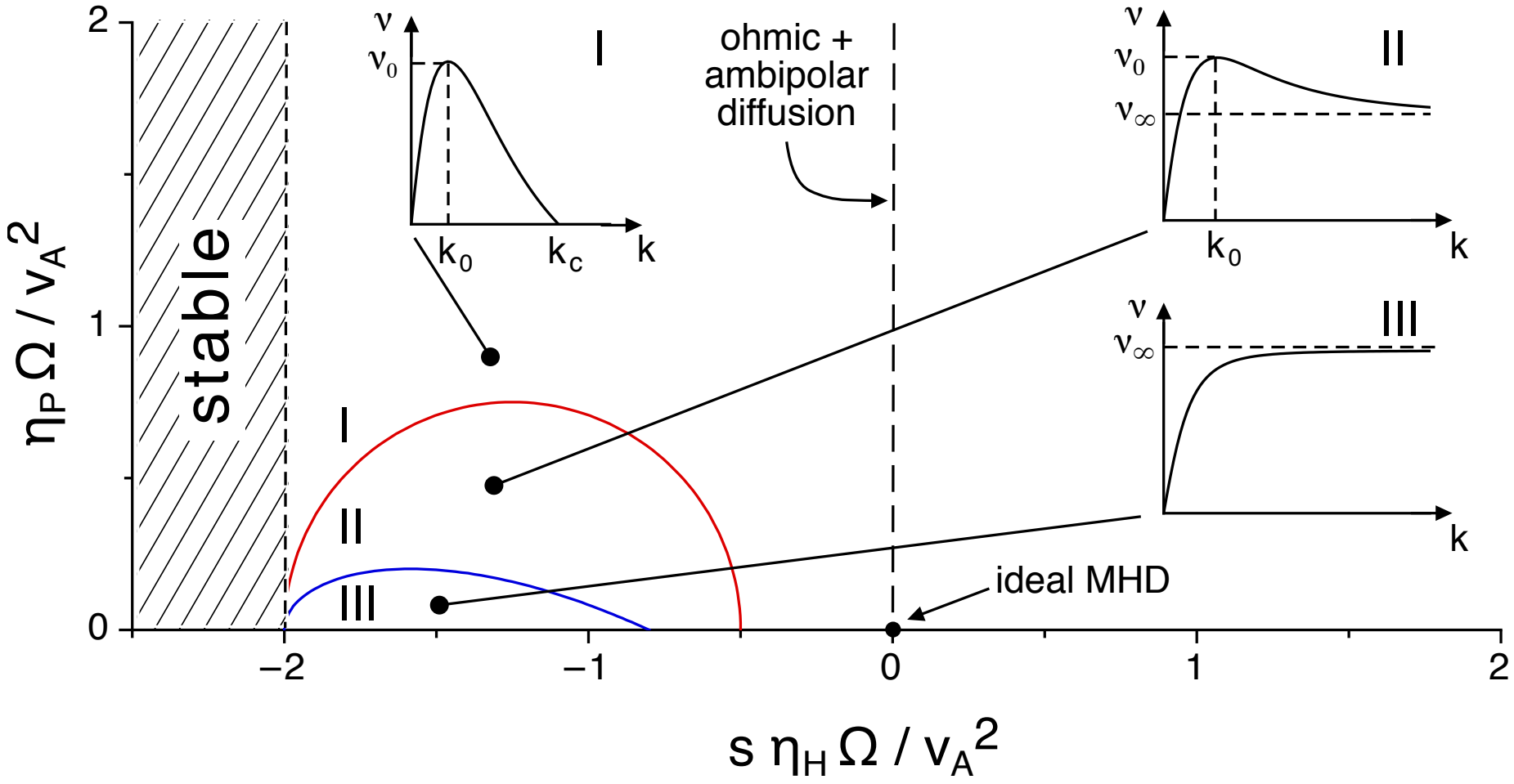
$$\boldsymbol{v}_{\rm B} = \boldsymbol{v}_i - \boldsymbol{v} = \frac{\boldsymbol{J}\times\boldsymbol{B}}{c\gamma_i\rho_i\rho}$$

Hall

$$\boldsymbol{v}_{\rm B} = \boldsymbol{v}_e - \boldsymbol{v}_i = -\frac{\boldsymbol{J}}{en_e}$$

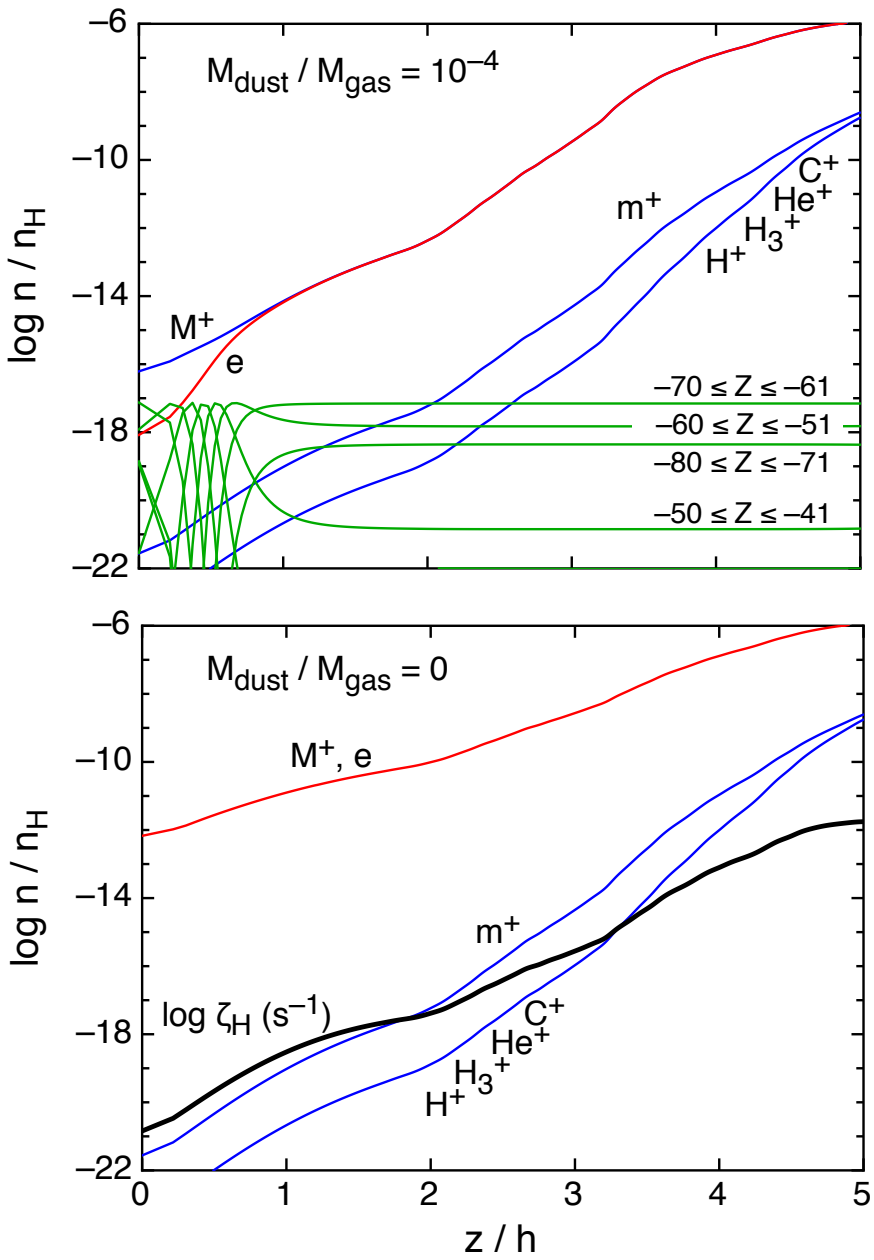

2
0
−2
−4
−6
log B (G)
2500 Å
50 Å
solar
nebula
molecular
clouds
ions
electrons
3
5
7
9
11
13
15
log n_H (cm^{-3})

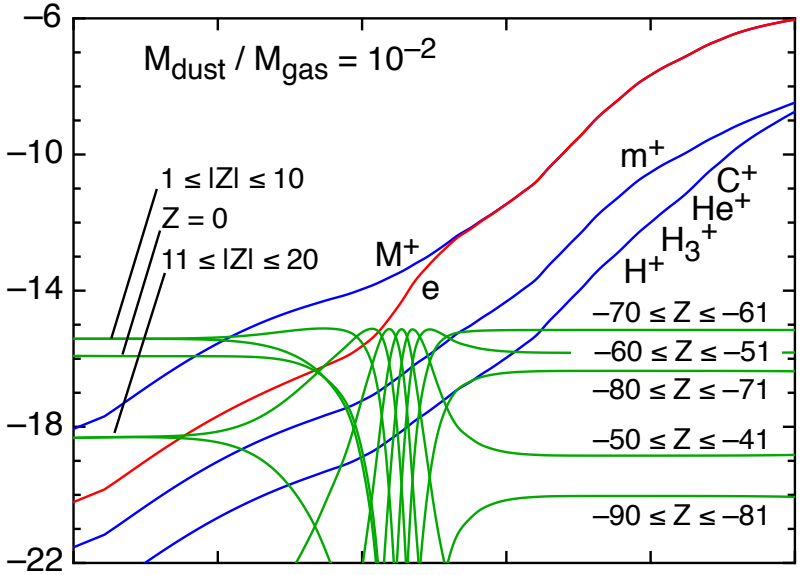
Wardle 2007



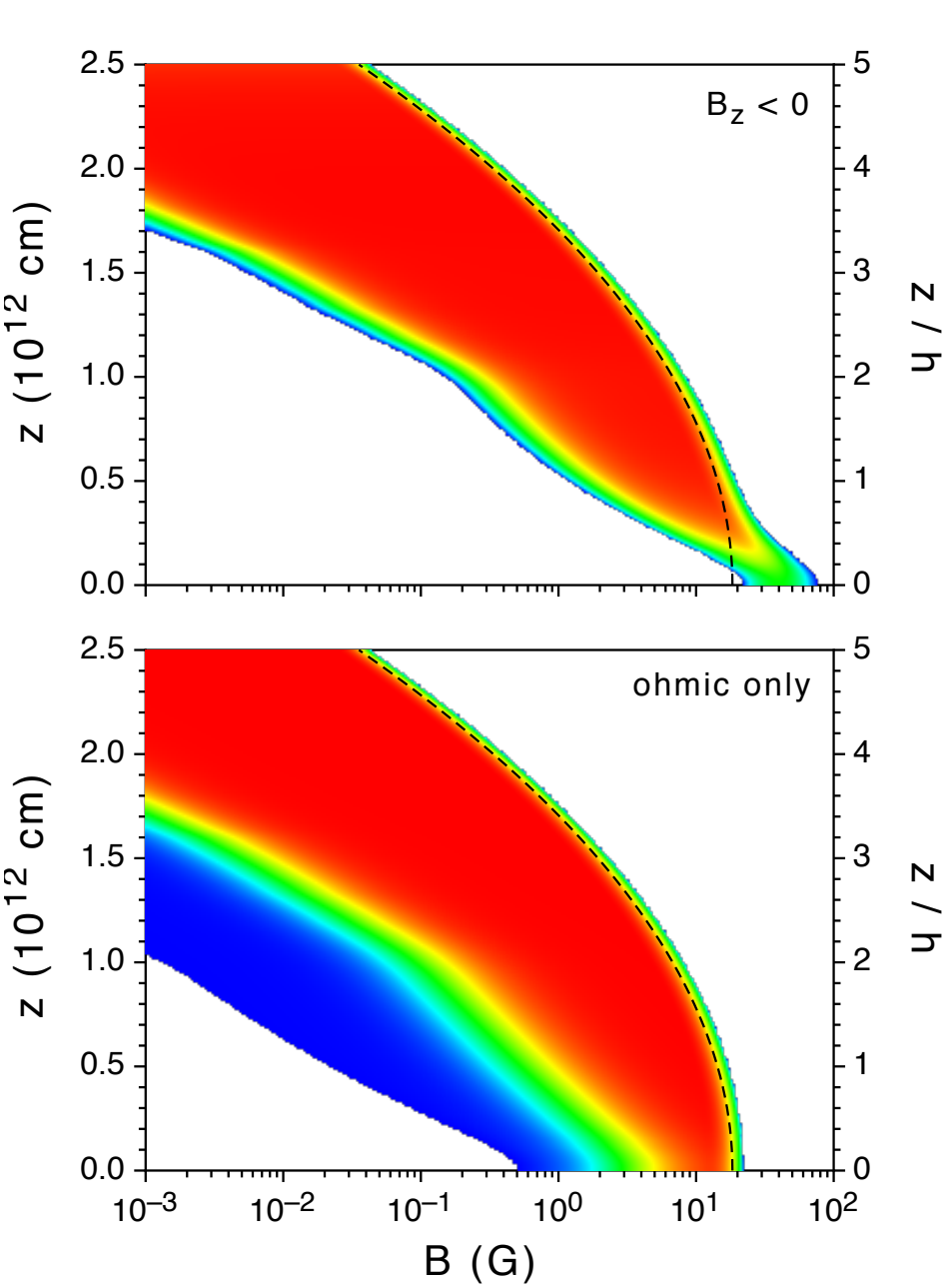
Wardle & Sameron 2012

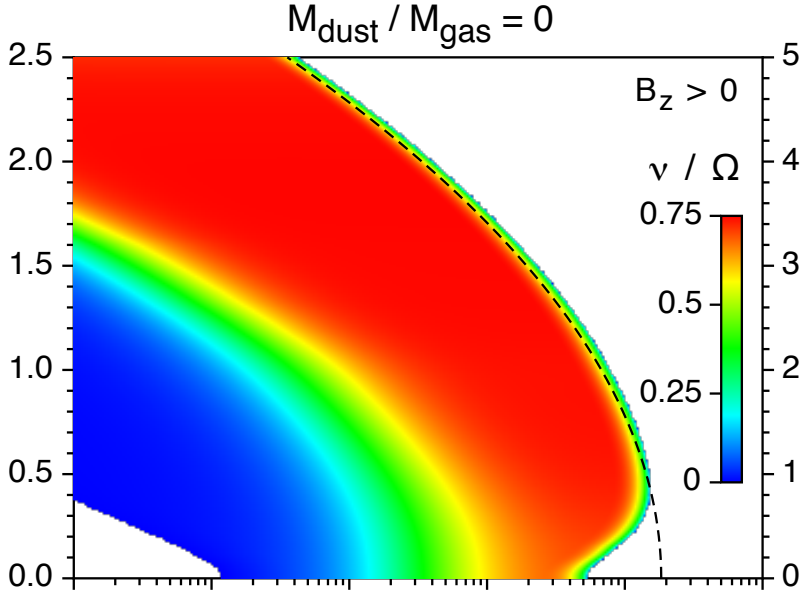
Charged particle abundances





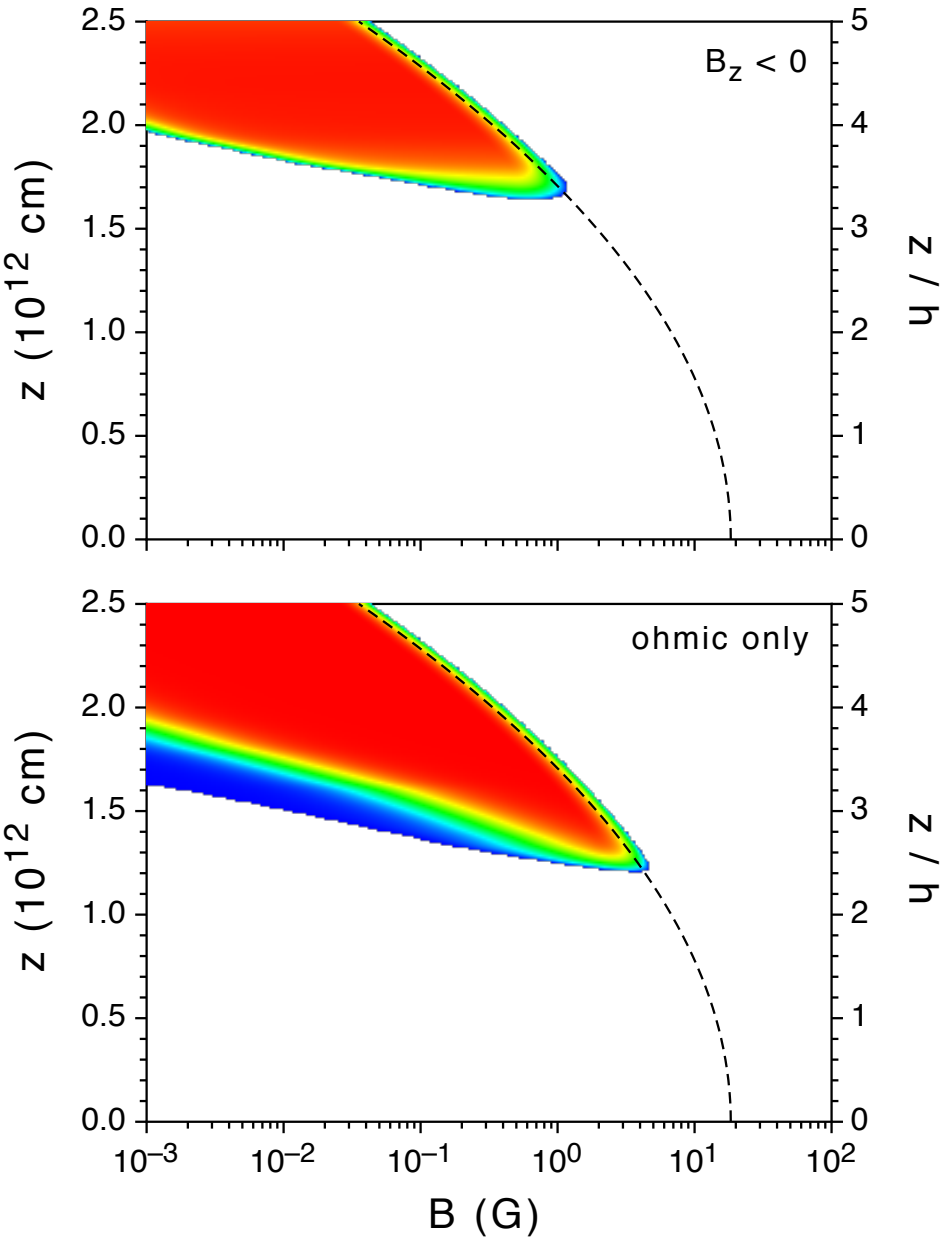
Max growth rate: no dust

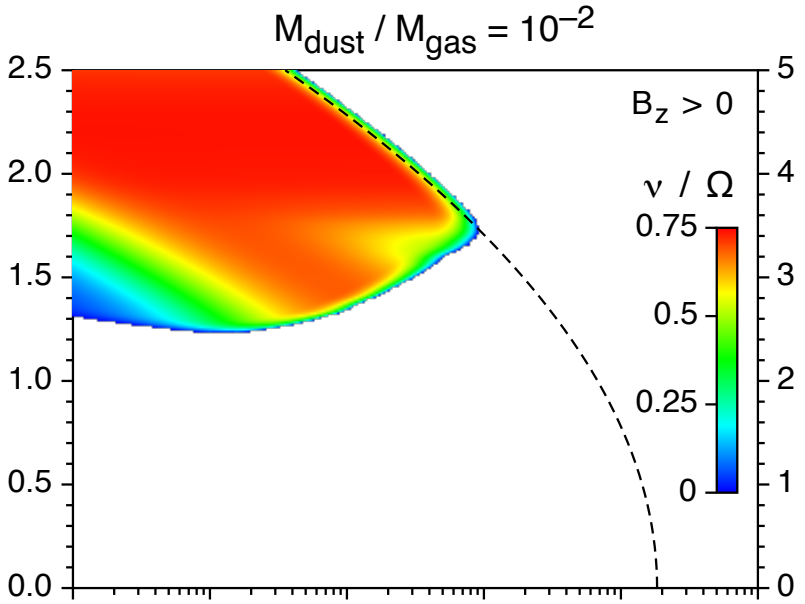




Wardle & Sameron 2012

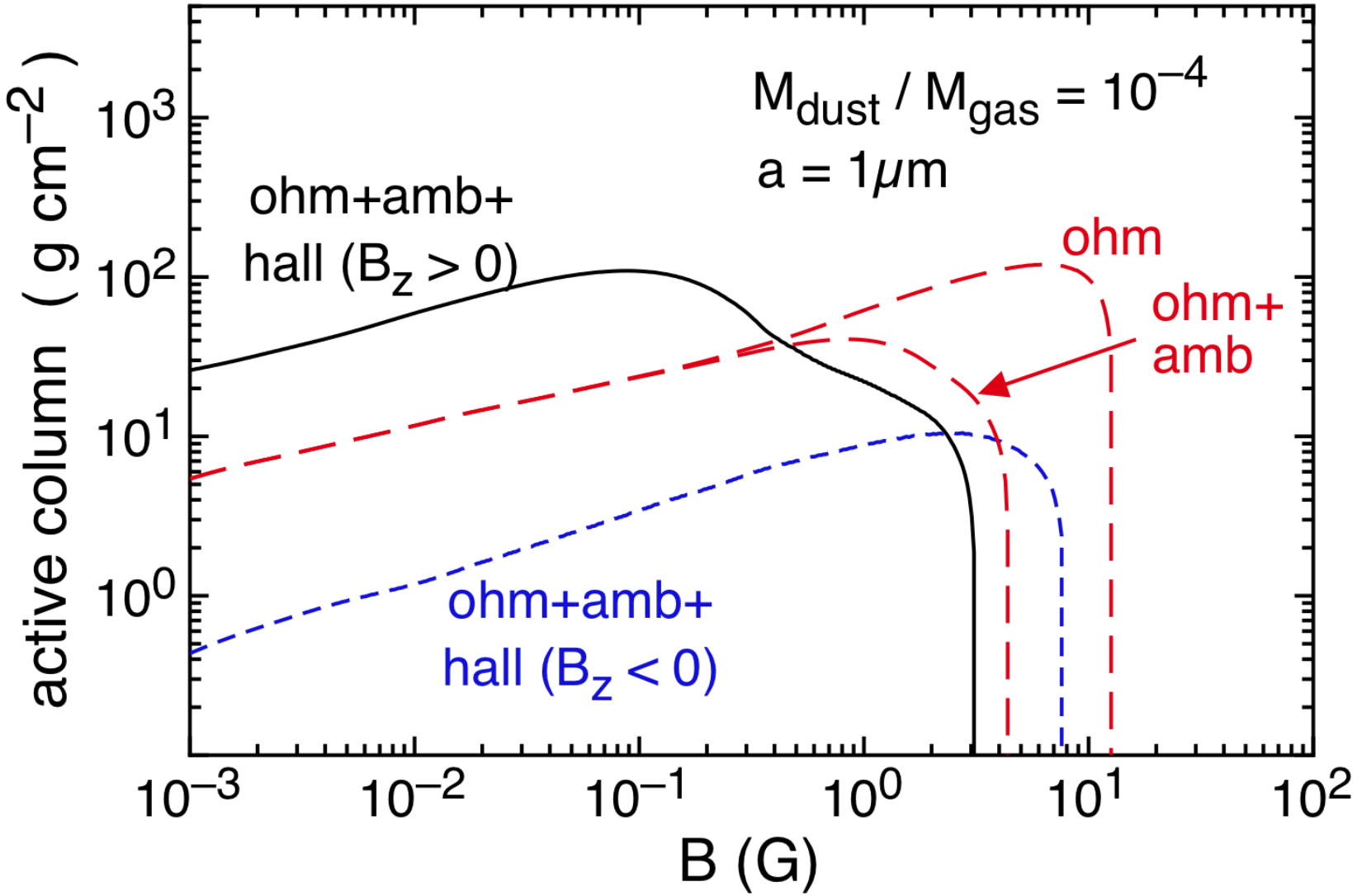
Max growth rate: $M_{dust} / M_{gas} = 10^{-2}$





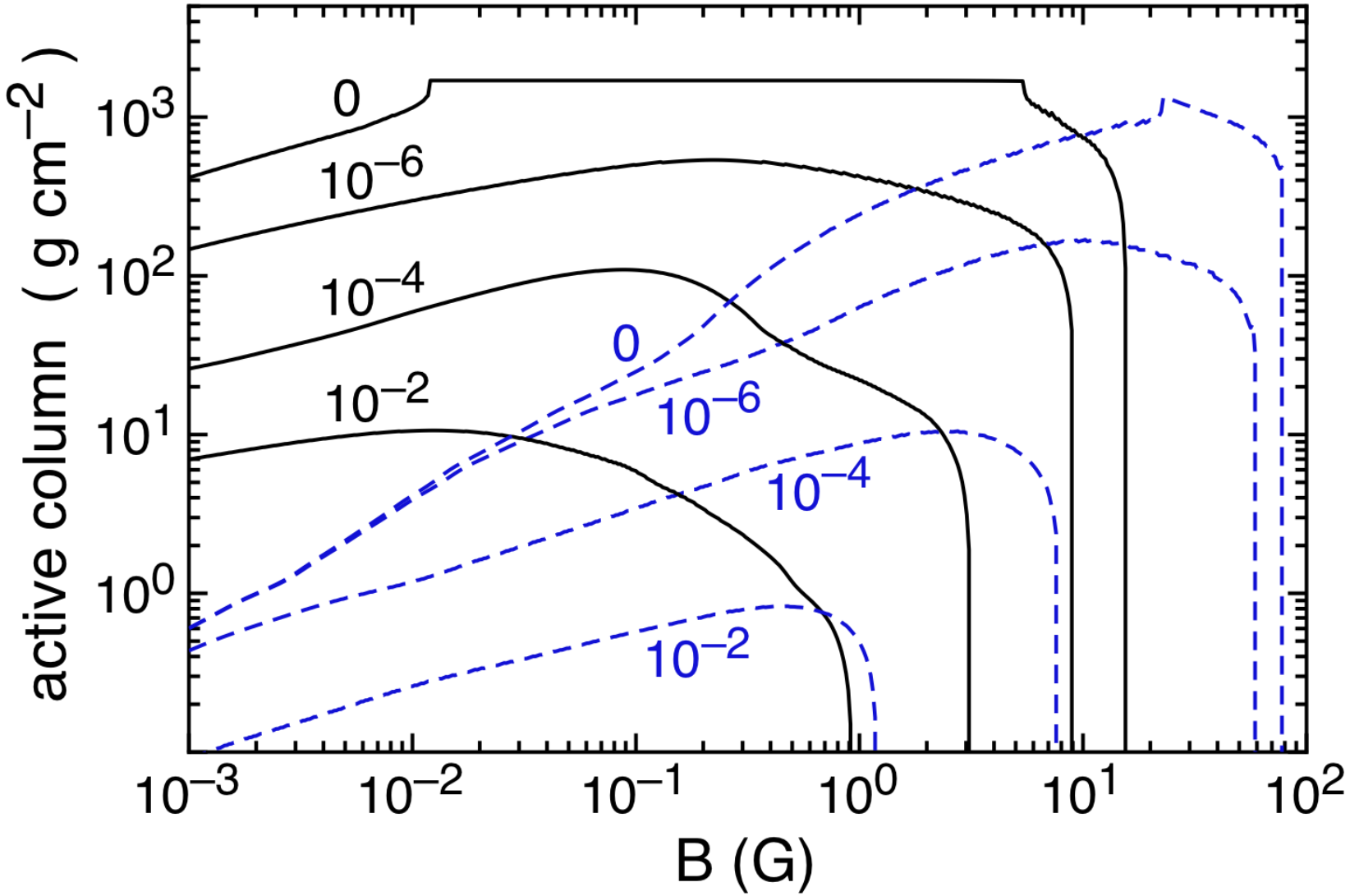
Wardle & Sameron 2012

Column density of active layer



Wardle & Sameron 2012

Column density of active layer



Wardle & Sameron 2012

Summary & Discussion

- Ionisation levels determine extent of magnetically turbulent regions in protoplanetary discs
  - dead zones: ~ 0.3 – 3 AU from central star
  - topped by magnetically active layers
- Hall diffusion modifies thickness of active layer by an order of magnitude
  - dead zones: $B_z < 0$ vs $B_z > 0$; depends on magnitude of B
  - can sustain accretion rates in these layers across radial extent of dead zone
  - may drive “undead” zones
  - more general geometries destabilise disk (Pandey & Wardle submitted)
- MHD simulations?
  - linear analysis such as used here appears to be a good predictor of dead zone extent
  - no MHD simulations with strong hall diffusion (yet)
  - PS: simulations with non net flux are unrealistic