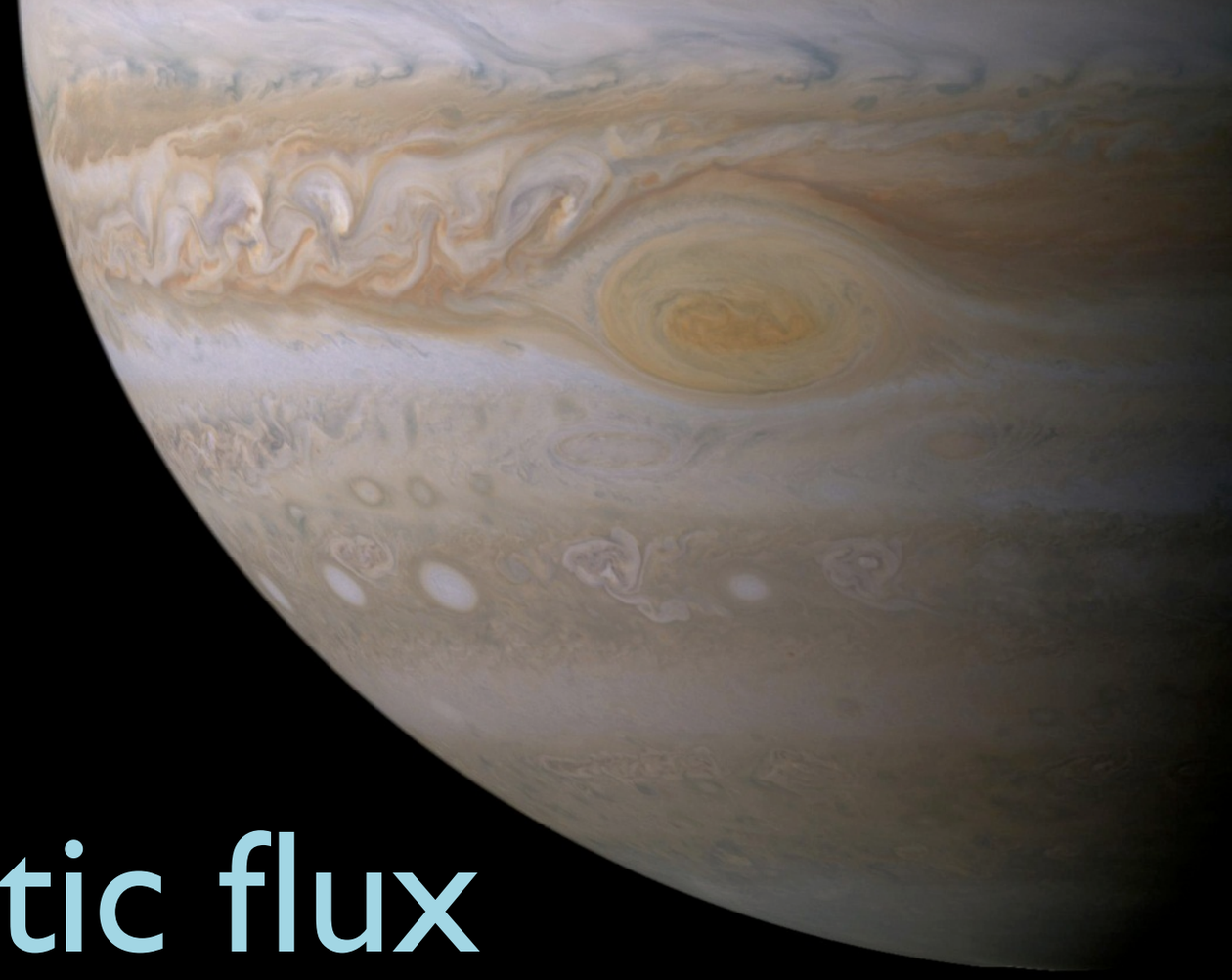


Non-ideal magnetic flux transport in protoplanetary accretion zones

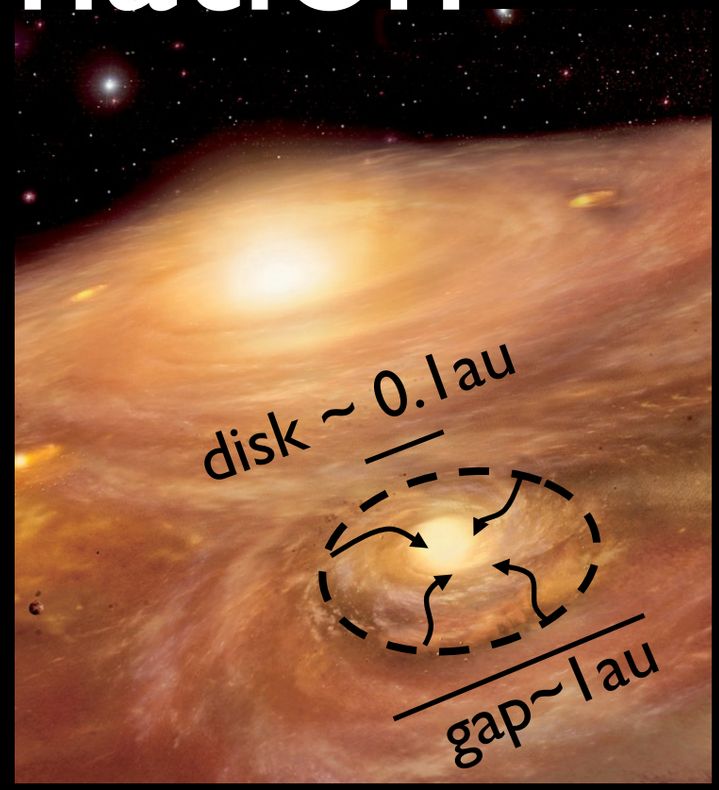
Sarah Keith

Macquarie University

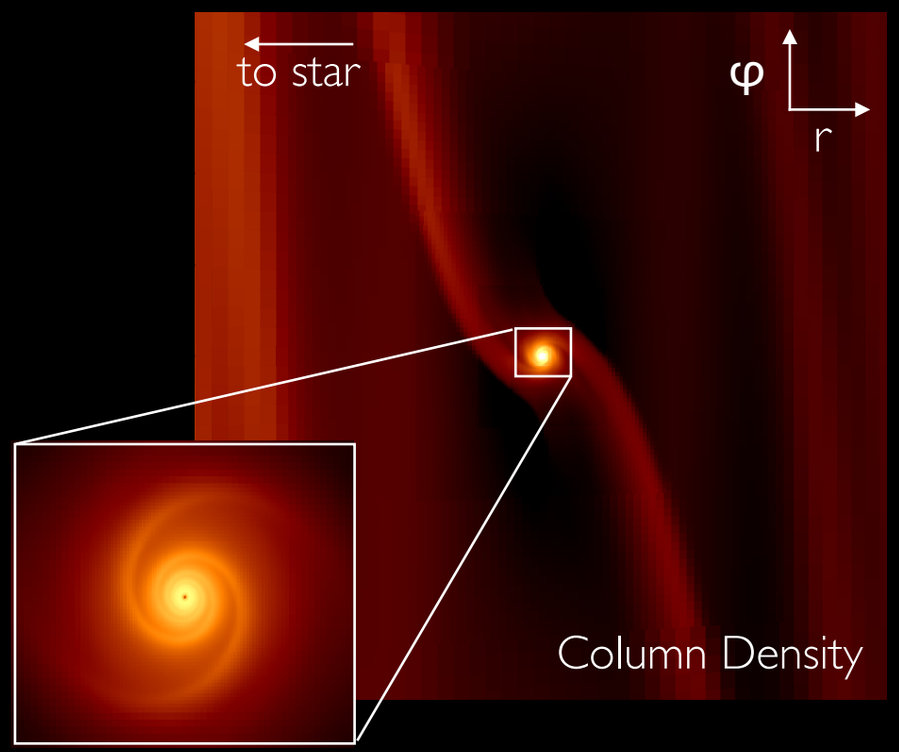
Email: sarah.l.keith@mq.edu.au

Giant planet formation

- Runaway growth of giant planet evacuates gas from the protoplanetary disk, opening a gap around the planet
- Accretion flow forms and passes through a circumplanetary disk ringing the protoplanet
- Protoplanet growth requires an accretion mechanism in the circumplanetary disk



source: National Geographic



Tanigawa+2012

Magnetic fields and accretion

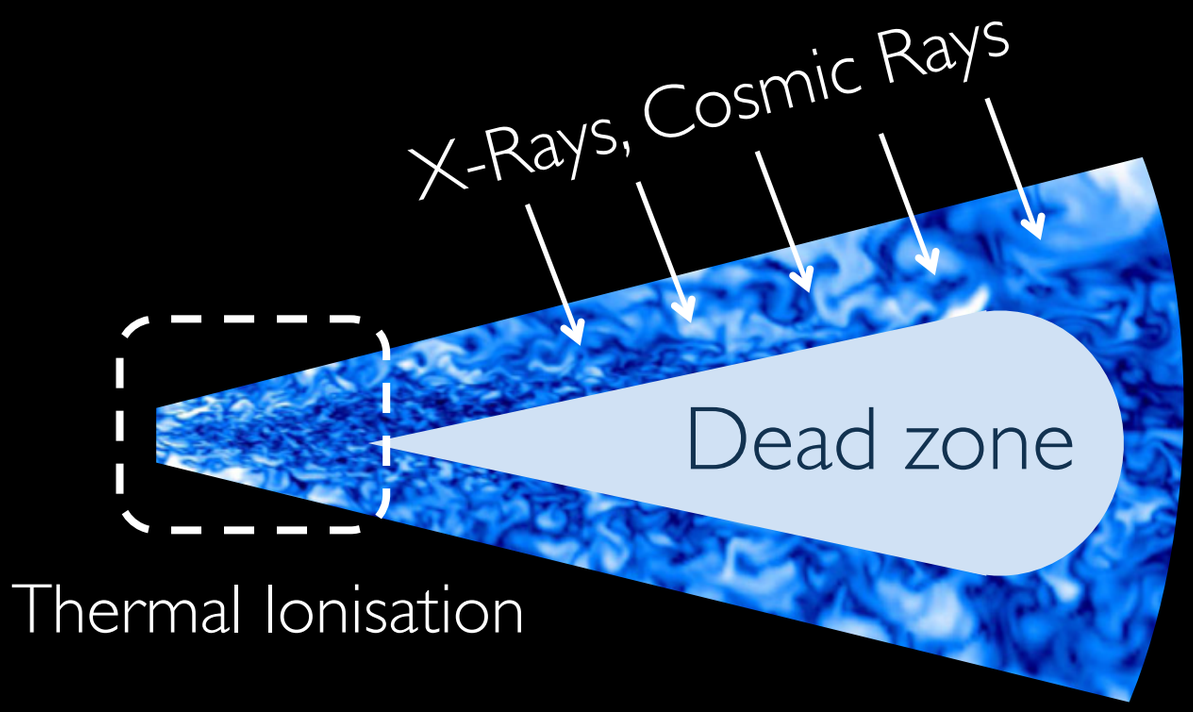
Magnetic forces are likely required to drive accretion

Magnetorotational Instability (MRI)
turbulent or toroidal accretion

Vertical field
drawn in from GMC

Toroidal field
wound up by keplerian rotation

Sufficient ionisation is required to transmits magnetic forces



+Radioactive Decay

Non-ideal MHD

Neutral collisions inhibit the necessary interaction between the magnetic field and gas.

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla(\mathbf{v} \times \mathbf{B}) - \nabla \times \{\eta_O(\nabla \times \mathbf{B}) + \eta_H(\nabla \times \mathbf{B}) \times \hat{\mathbf{B}} - \eta_A[(\nabla \times \mathbf{B}) \times \hat{\mathbf{B}}] \times \hat{\mathbf{B}}\}$$

Ohmic Hall Ambipolar

Diffusivity	Density	Coupled to field? Electrons	Ions
Ohmic, η_O	High	✗	✗
Hall, η_H	Intermediate	✓	✗
Ambipolar, η_A	Low	✓	✓

Low diffusivity - field interacts with gas

High diffusivity - field poorly/not coupled to flow

Gap-crossing model so far

The Astrophysical Journal, 747:47 (16pp), 2012 March 1 doi:10.1088/0004-637X/747/1/47

DISTRIBUTION OF ACCRETING GAS AND ANGULAR MOMENTUM ONTO CIRCUMPLANETARY DISKS

Takayuki Tanigawa[1,2], Keiji Ohtsuki[1,3,4], and Masahiro N. Machida[5]
[1] Center for Planetary Science, Kobe University, Kobe, Japan; tanigawa@cps-jp.org
[2] Institute of Low Temperature Science, Hokkaido University, Sapporo, Japan
[3] Department of Earth and Planetary Sciences, Kobe University, Kobe, Japan
[4] Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO, USA
[5] Department of Earth and Planetary Sciences, Graduate School of Sciences, Kyushu University, Fukuoka, Japan
Received 2011 July 21; accepted 2011 December 15; published 2012 February 13

Pure Hydro

Mon. Not. R. Astron. Soc. **339,** 993–1005 (2003)

The interaction of a giant planet with a disc with MHD turbulence – II. The interaction of the planet with the disc

Richard P. Nelson★ and John C. B. Papaloizou
Astronomy Unit, Queen Mary, University of London, Mile End Road, London E1 4NS

Ideal MHD

The Astrophysical Journal, 779:59 (22pp), 2013 December 10 doi:10.1088/0004-637X/779/1/59

GLOBAL HYDROMAGNETIC SIMULATIONS OF A PLANET EMBEDDED IN A DEAD ZONE: GAP OPENING, GAS ACCRETION, AND FORMATION OF A PROTOPLANETARY JET

O. Gressel[1,2], R. P. Nelson[2], N. J. Turner[3], and U. Ziegler[4]
[1] NORDITA, KTH Royal Institute of Technology and Stockholm University, Roslagstullsbacken 23, SE-106 91 Stockholm, Sweden; oliver.gressel@nordita.org
[2] Astronomy Unit, Queen Mary University of London, Mile End Road, London E1 4NS, UK; r.p.nelson@qmul.ac.uk
[3] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA; neal.j.turner@jpl.nasa.gov
[4] Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, D-14482, Potsdam, Germany; uziegler@aip.de
Received 2013 July 3; accepted 2013 October 17; published 2013 November 25

Resistive MHD

Gap-crossing model so far

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TAKAYUKI TANIGAWA[1,2], KEIJI OHTSUKI[1,3,4], AND MASAHIRO N. MACHIDA[5]
[1] Center for Planetary Science, Kobe University, Kobe, Japan; tanigawa@cps-jp.org
[2] Institute of Low Temperature Science, Hokkaido University, Sapporo, Japan
[3] Department of Earth and Planetary Sciences, Kobe University, Kobe, Japan
[4] Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO, USA
[5] Department of Earth and Planetary Sciences, Graduate School of Sciences, Kyushu University, Fukuoka, Japan
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Pure H

All three non-ideal effects are important and needed

Ideal MHD

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[1] NORDITA, KTH Royal Institute of Technology and Stockholm University, Roslagstullsbacken 23, SE-106 91 Stockholm, Sweden; oliver.gressel@nordita.org
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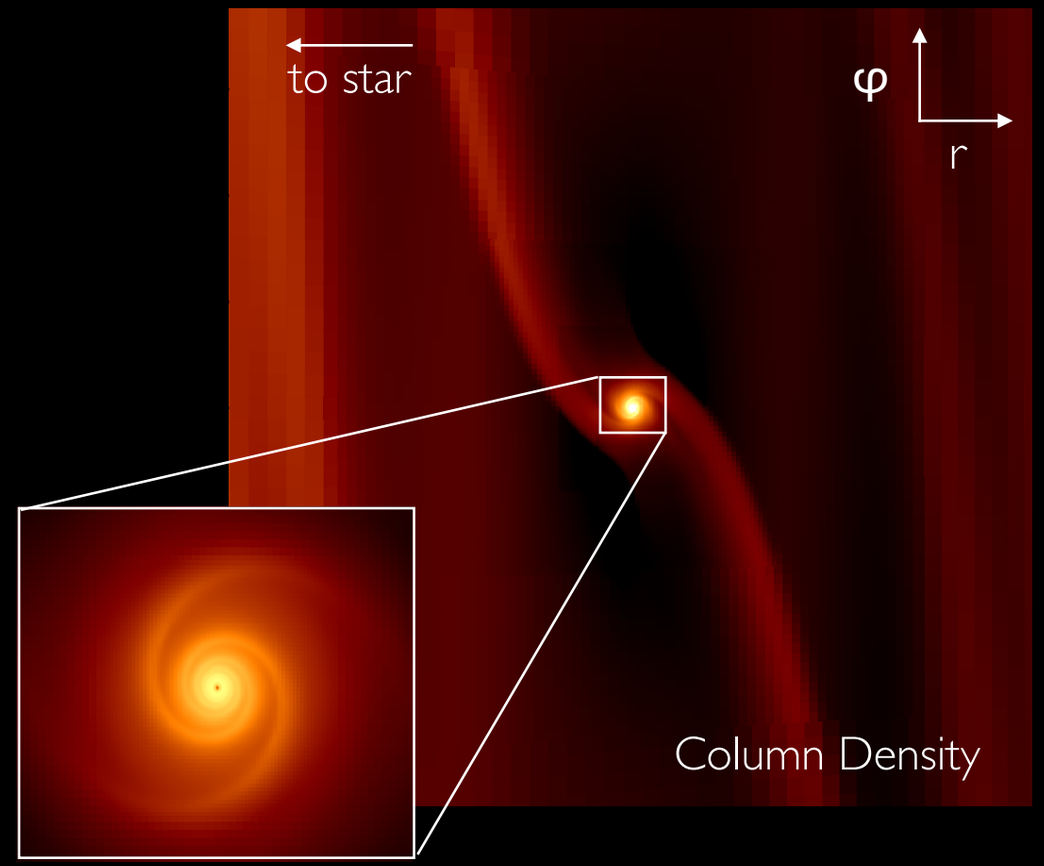
Resistive MHD

Magnetic fields in gap crossing

<u>Aim:</u> identify magnetic structure and accretion mechanisms in gap and cirumplanetary disk

We use a snapshot of flow in a hydrodynamic gap simulation.

We post-calculate detailed maps of the ionisation, field strength & geometry, magnetic forces, & strength of non-ideal effects … *cheaply*

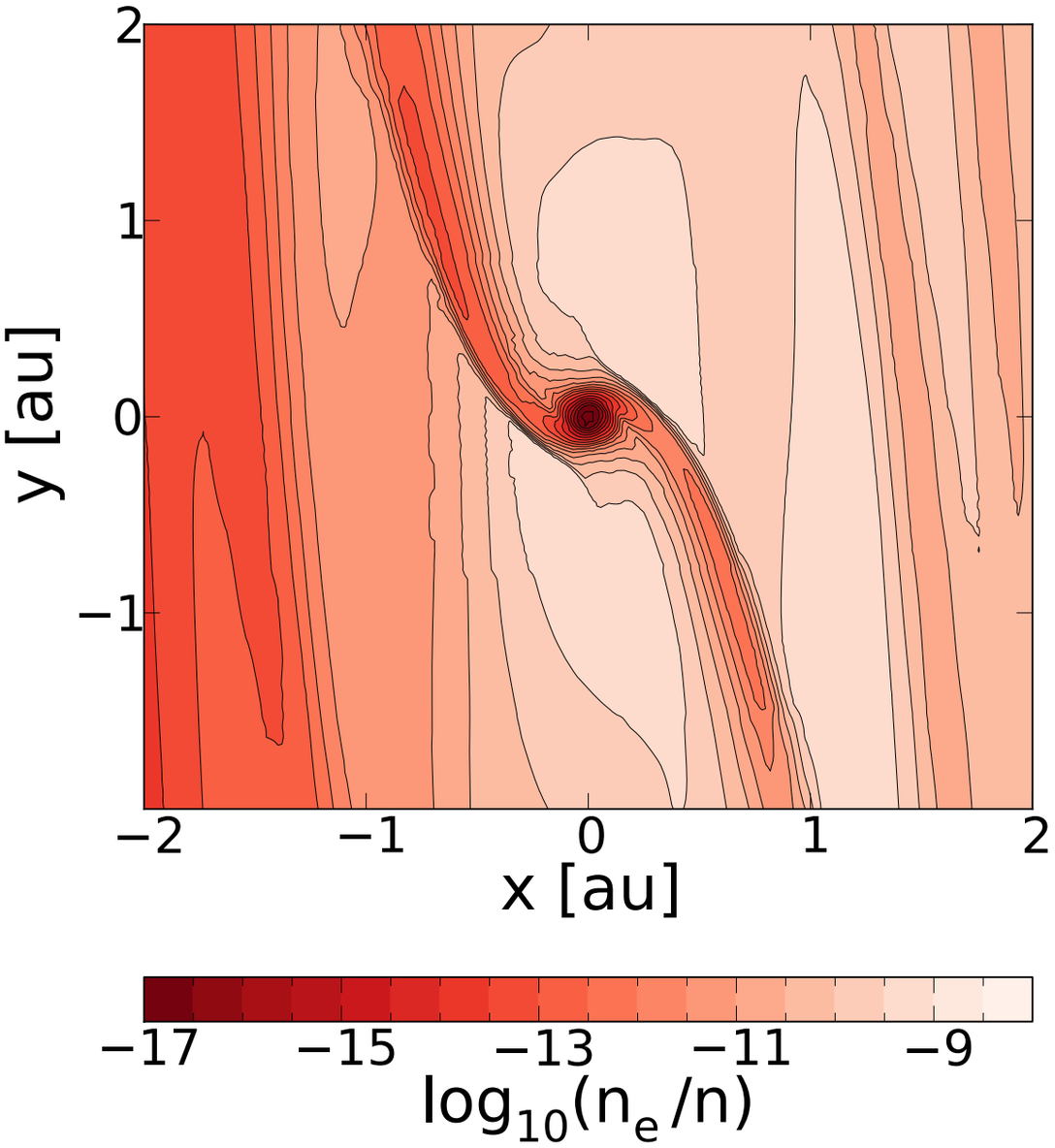


Tanigawa+2012

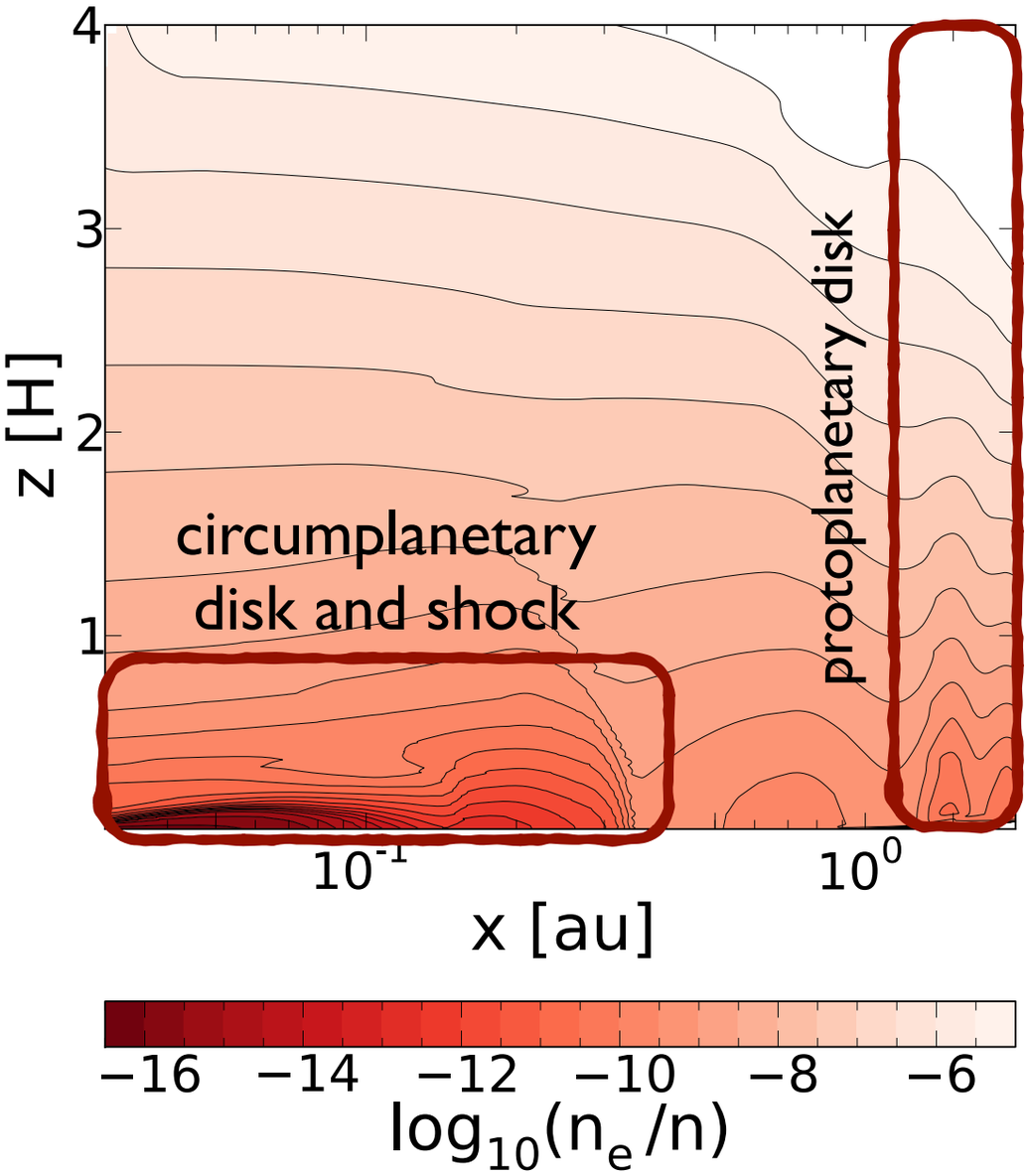
Disks and gap model

- Disk model: Tanigawa et al (2012) 3D hydrodynamic simulation rescaled to the MMSN for a Jovian-like protoplanet.
- Ionisation sources/sinks: X-rays, cosmic rays, radioactive decay, charge capture by grains ($f_{dg}=10^{-4}$).
- Magnetic field: Flux conserved vertical field, with additional toroidal and MRI fields according to coupling.

Ionisation fraction

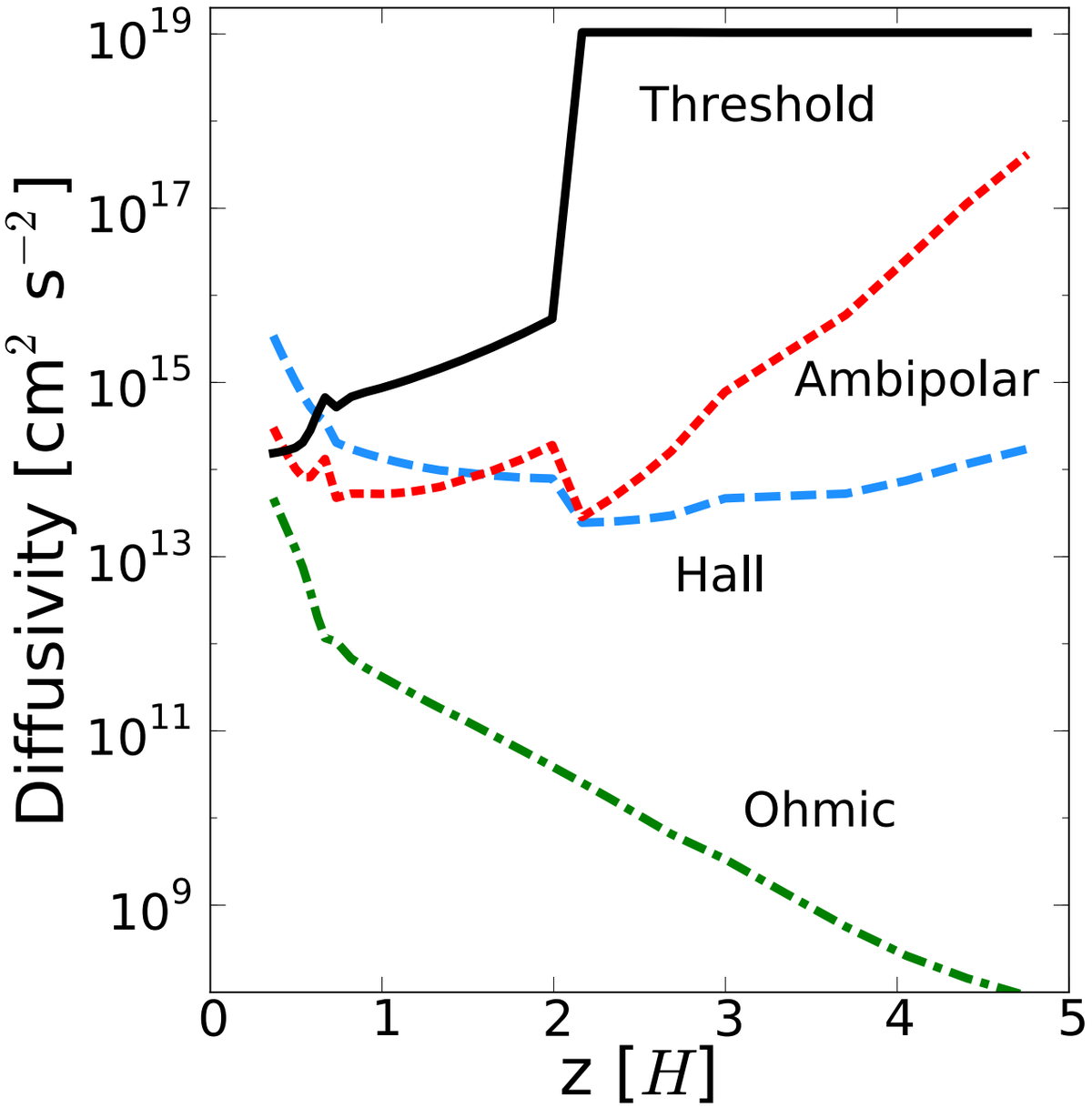


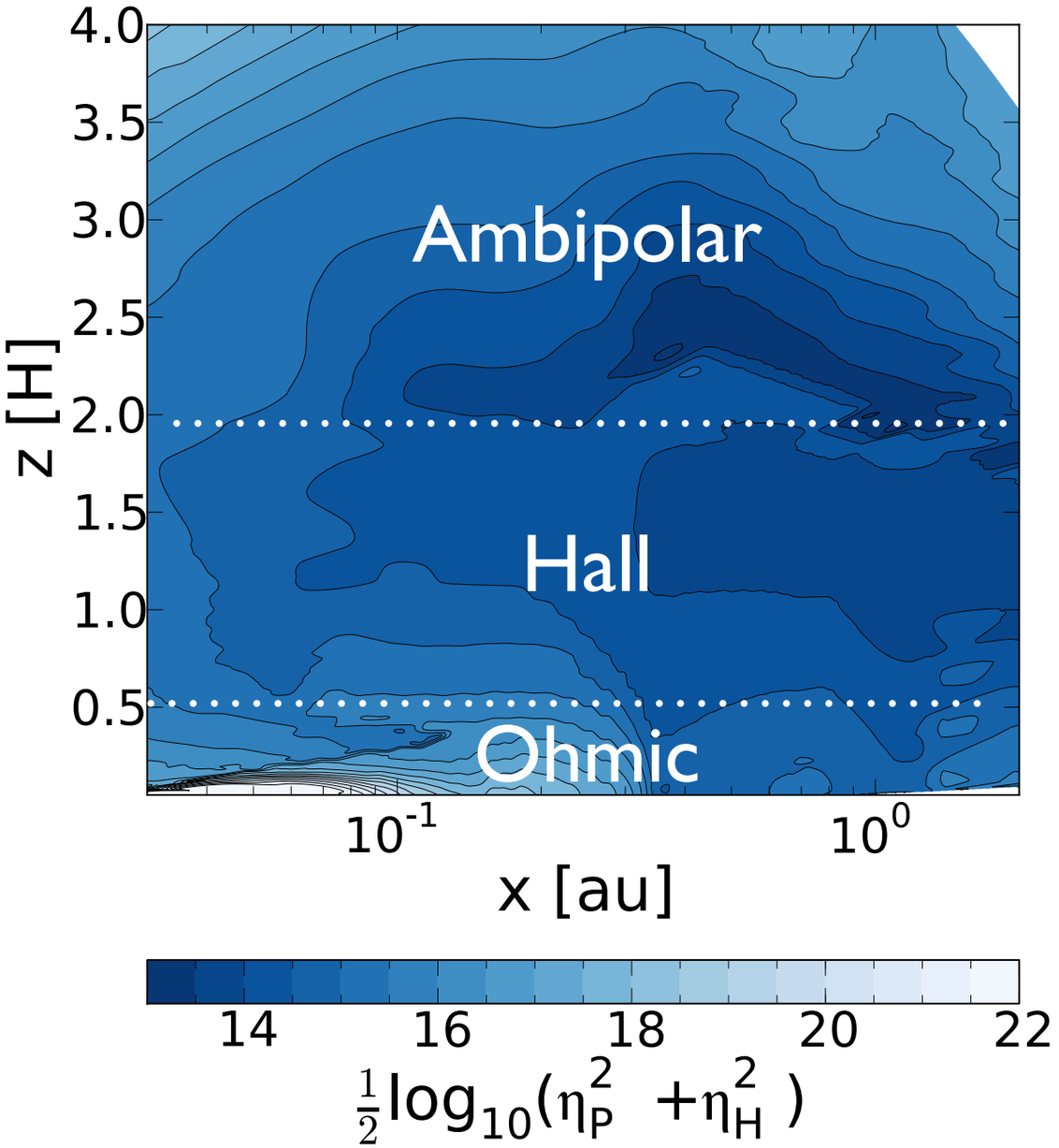
top-down



edge-on

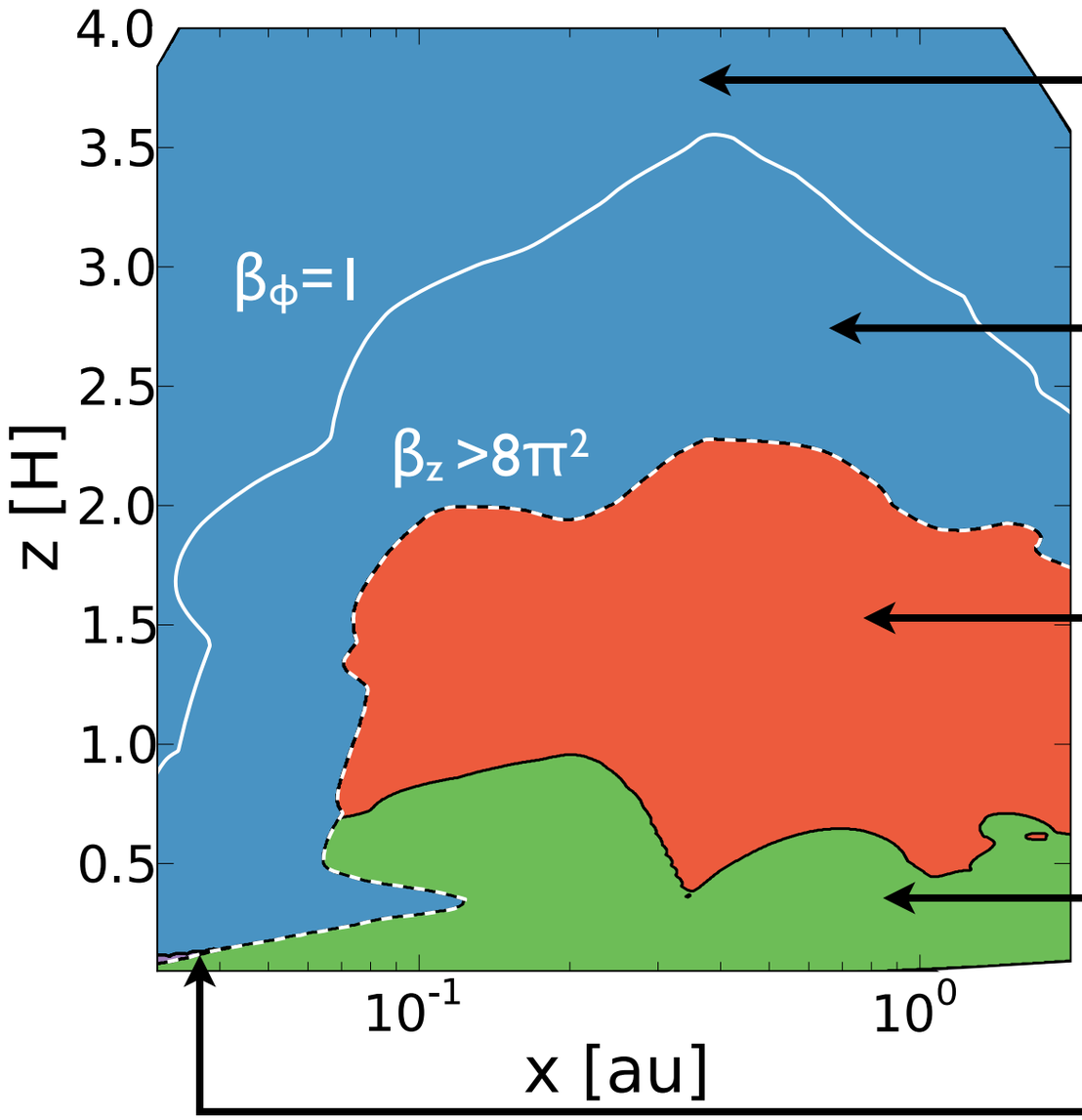
Non-ideal effects





Good coupling ☛ Magnetic field drawn along

Field Geometry



Toroidal/Vertical

Toroidal Field

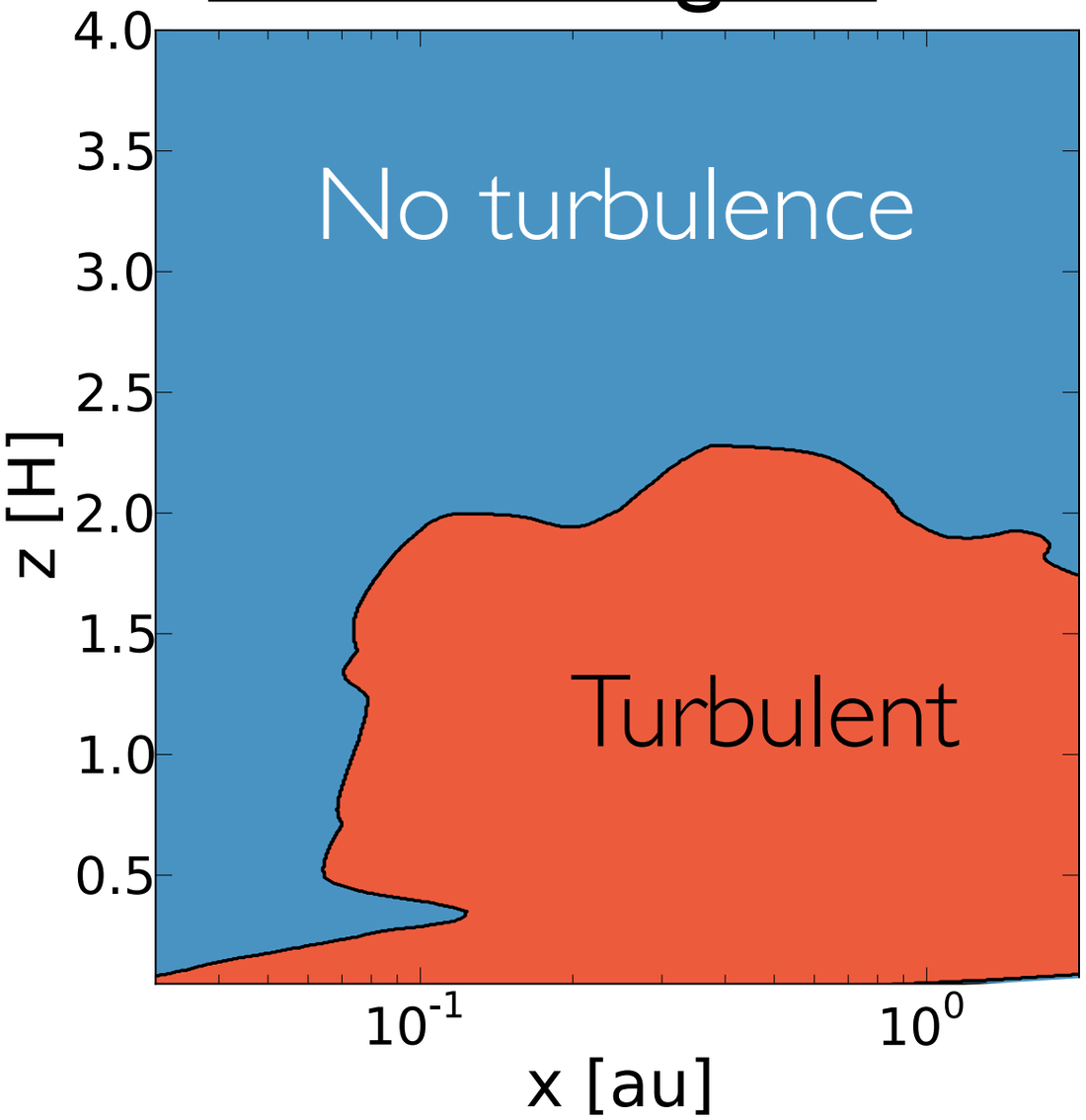
Ideal MRI

Hall MRI

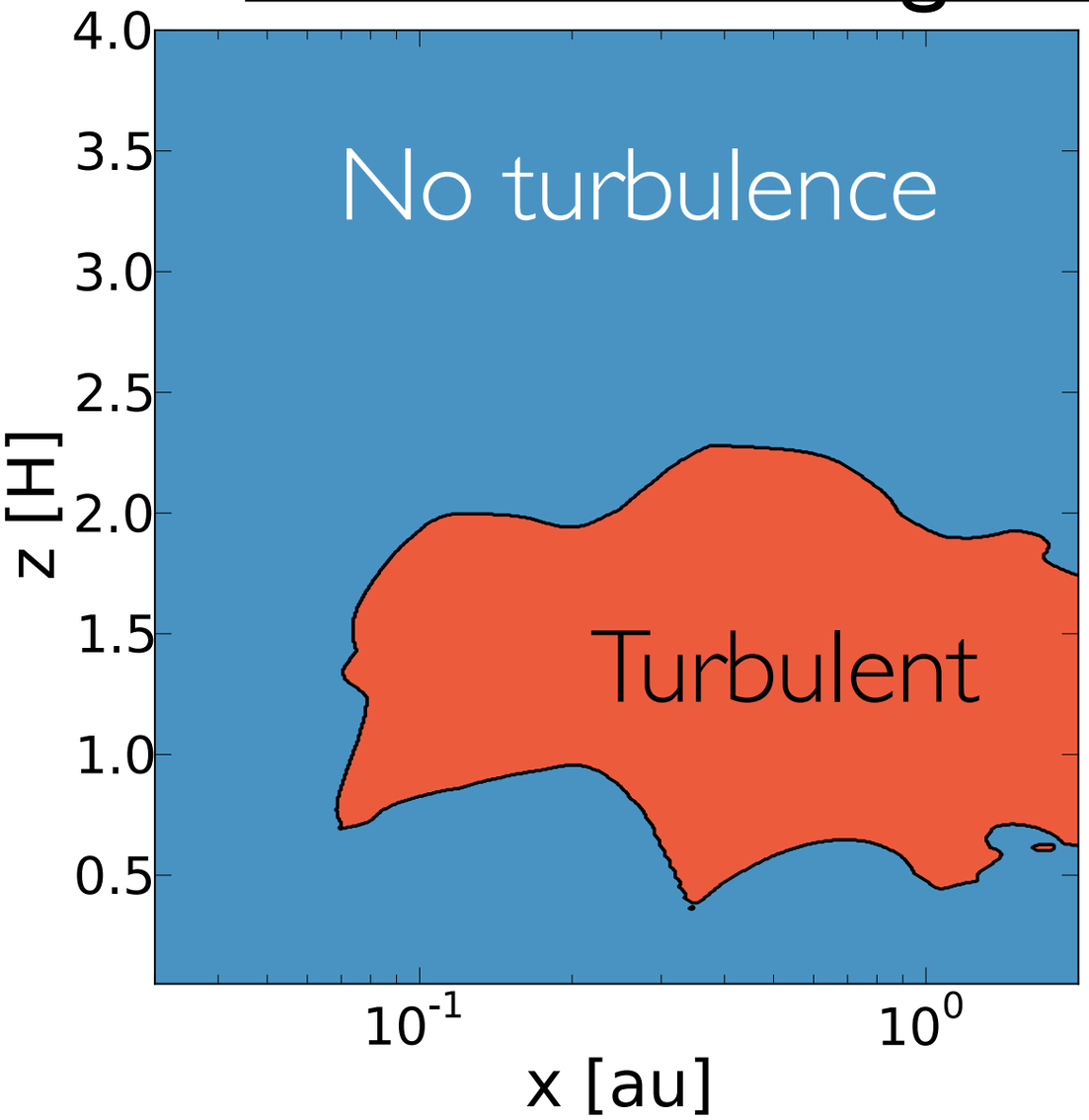
Vertical Field

MRI susceptibility

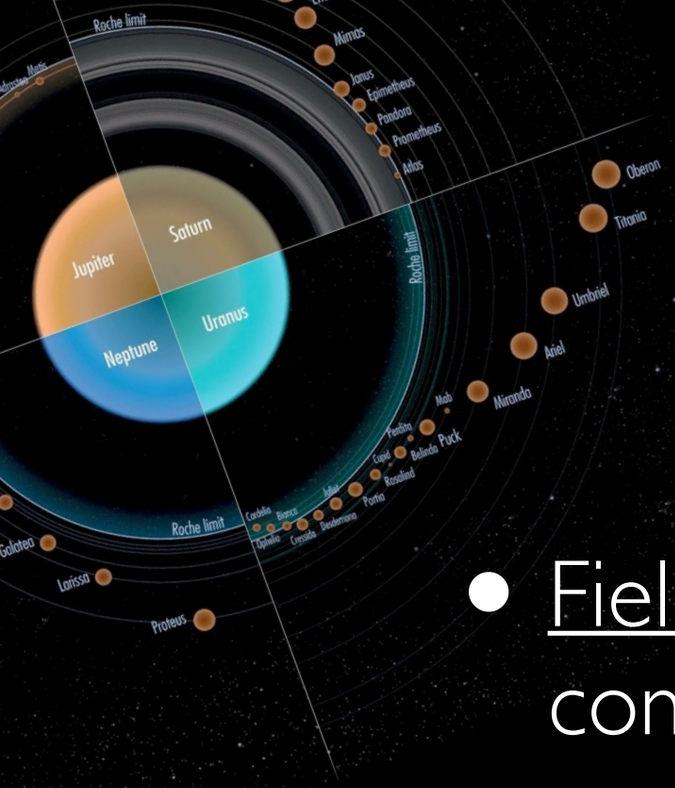
Ω and B aligned



Ω and B anti-aligned



Cirumplanetary disk ☛ could be active OR dead



Implications

- Field is dragged in with gas and geometry is complex
- Magnetic fields (large-scale or turbulent) may drive accretion in circumplanatary disk **depending on global field orientation** - bimodal outcome?
- Non-ideal effects are considerable and each must be included. Improved Hall simulations are needed.