Australian National University

Protostellar accretion disks and their outflows

- Physically-viable wind-driving solutions in diffusive disks
- 1+1D wind-driving disk models
- Thermal structure & emitted spectrum
- Observational properties & link to launching conditions (DG Tau)
- Summary & Conclusions

Raquel Salmeron

The Australian National University

Collaborators

Mark Wardle, Arieh Königl, G. Bicknell, P. McGregor, Jan Budaj, Ralph Sutherland, Tracy Beck

Students: Marc White, Chris Nolan

Magnetic Diffusion

$$\frac{\partial \mathbf{B}}{\partial t} = \underbrace{\nabla \times (\mathbf{v} \times \mathbf{B})}_{\text{Inductive [ideal MHD]}} - \nabla \times [\underbrace{\eta_{\rm O} \nabla \times \mathbf{B}}_{\text{Ohm}} + \underbrace{\eta_{\rm H} (\nabla \times \mathbf{B}) \times \hat{\mathbf{B}}}_{\text{Hall}} + \underbrace{\eta_{\rm A} (\nabla \times \mathbf{B})_{\perp}}_{\text{Ambipolar}}]$$

Inductive [ideal MHD] — **O**hm — **H**all — **A**mbipolar

$$\mathbf{J} \cdot \mathbf{E}' = \frac{4\pi}{c^2} \left[\eta_{\rm O} \mathbf{J}_{\parallel}^2 + (\eta_{\rm O} + \eta_{\rm A}) \mathbf{J}_{\perp}^2 \right]$$

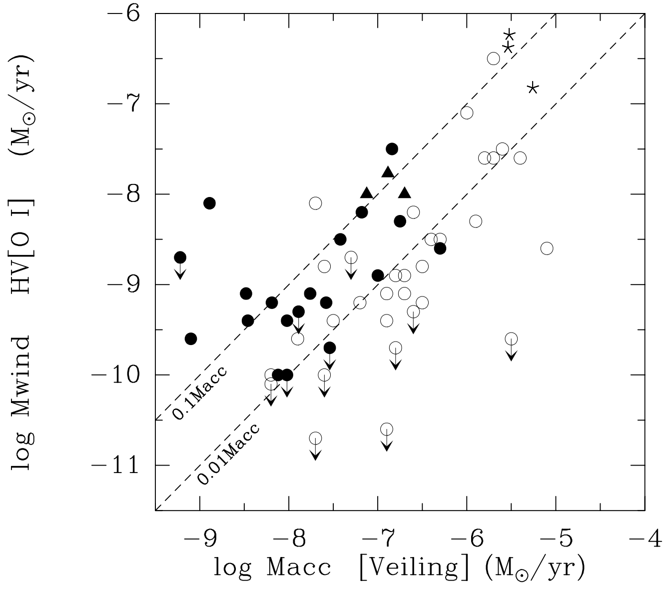
$$\eta_{\rm O} + \eta_{\rm A} = \eta_{\rm P}$$

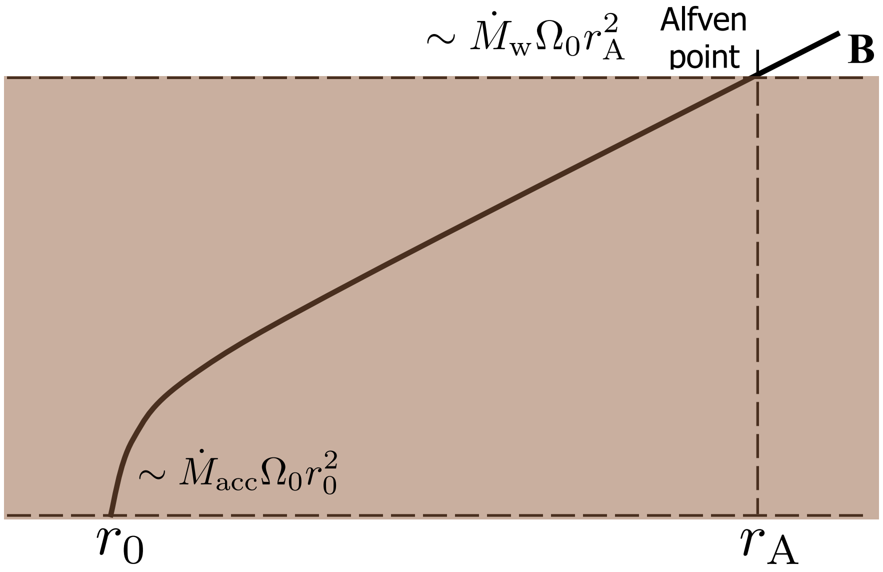
- **Three diffusion mechanisms**
  - Which one dominates?
  - Can the magnetic field couple to matter?
  - Impact on the thermal and dynamical structure, evolution and observational signatures of disks

e.g. Wardle (2007)

Accretion-outflow correlation

Cabrit 2007



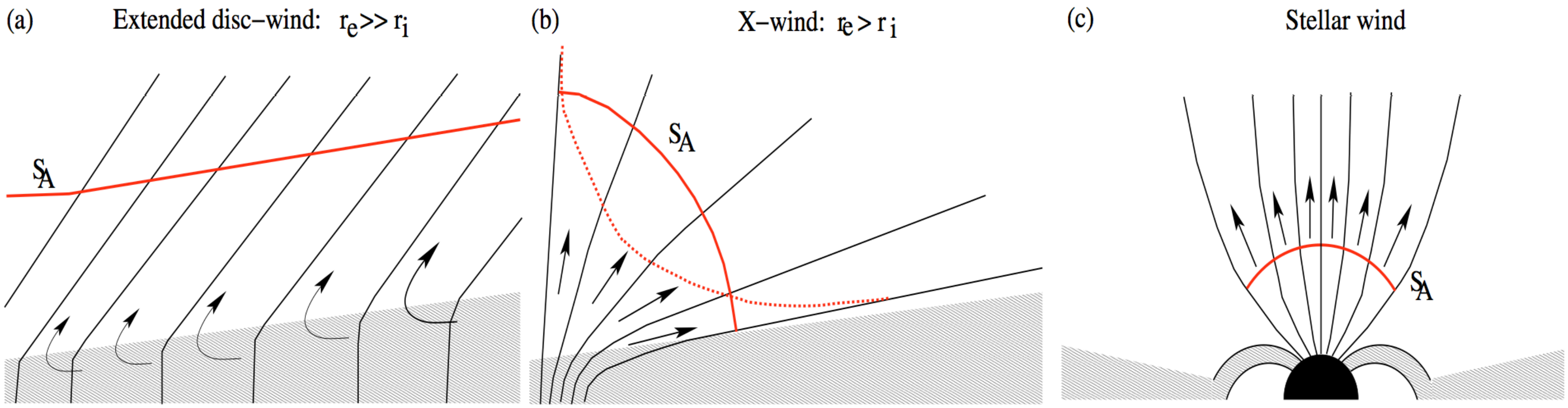


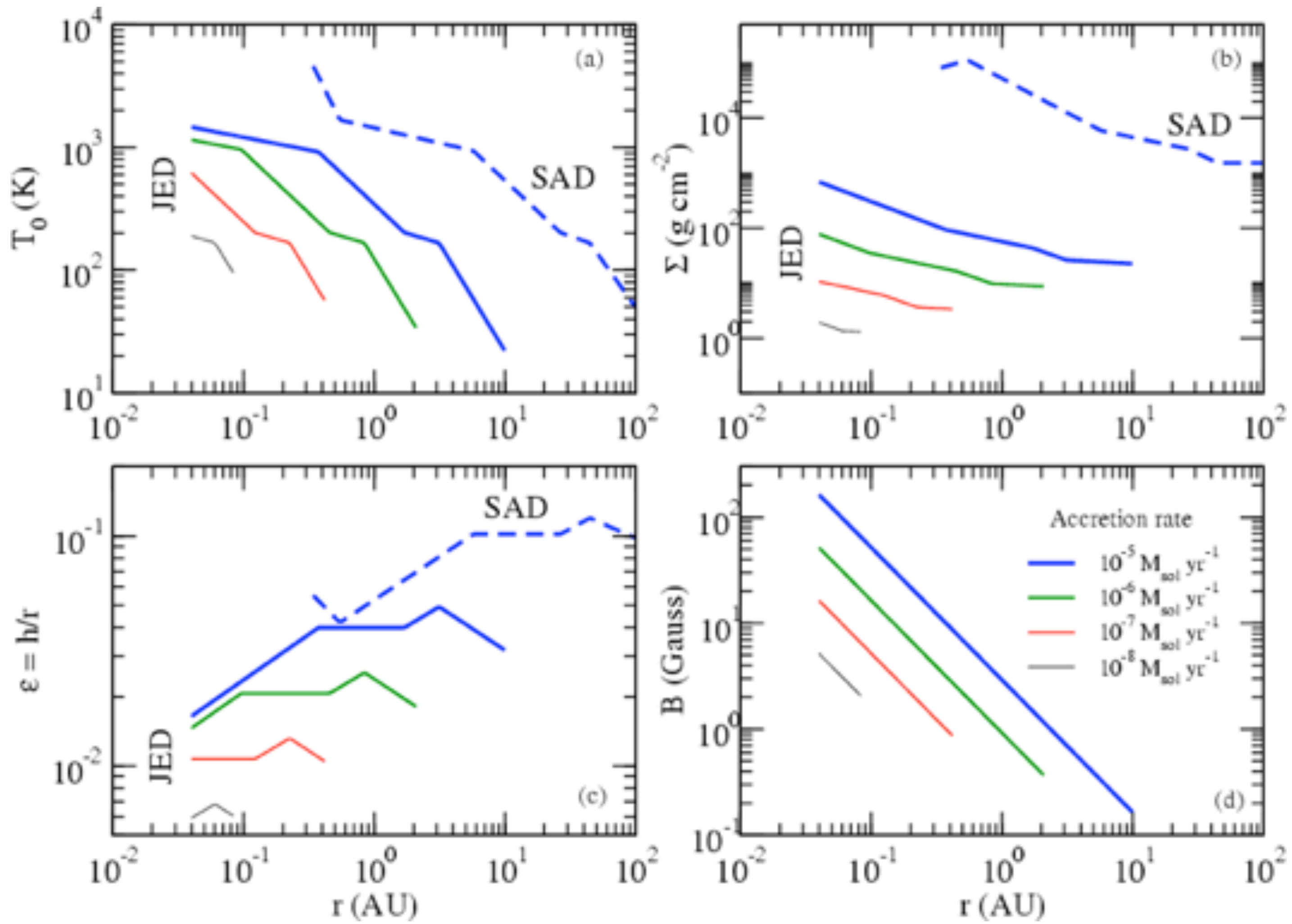
$$\dot{M}_{\rm acc}\Omega_0 r_0^2 = \dot{M}_{\rm w}\Omega_0 r_{\rm A}^2$$

$$\dot{M}_{\rm acc} \sim (r_{\rm A}/r_0)^2 \dot{M}_{\rm w}$$

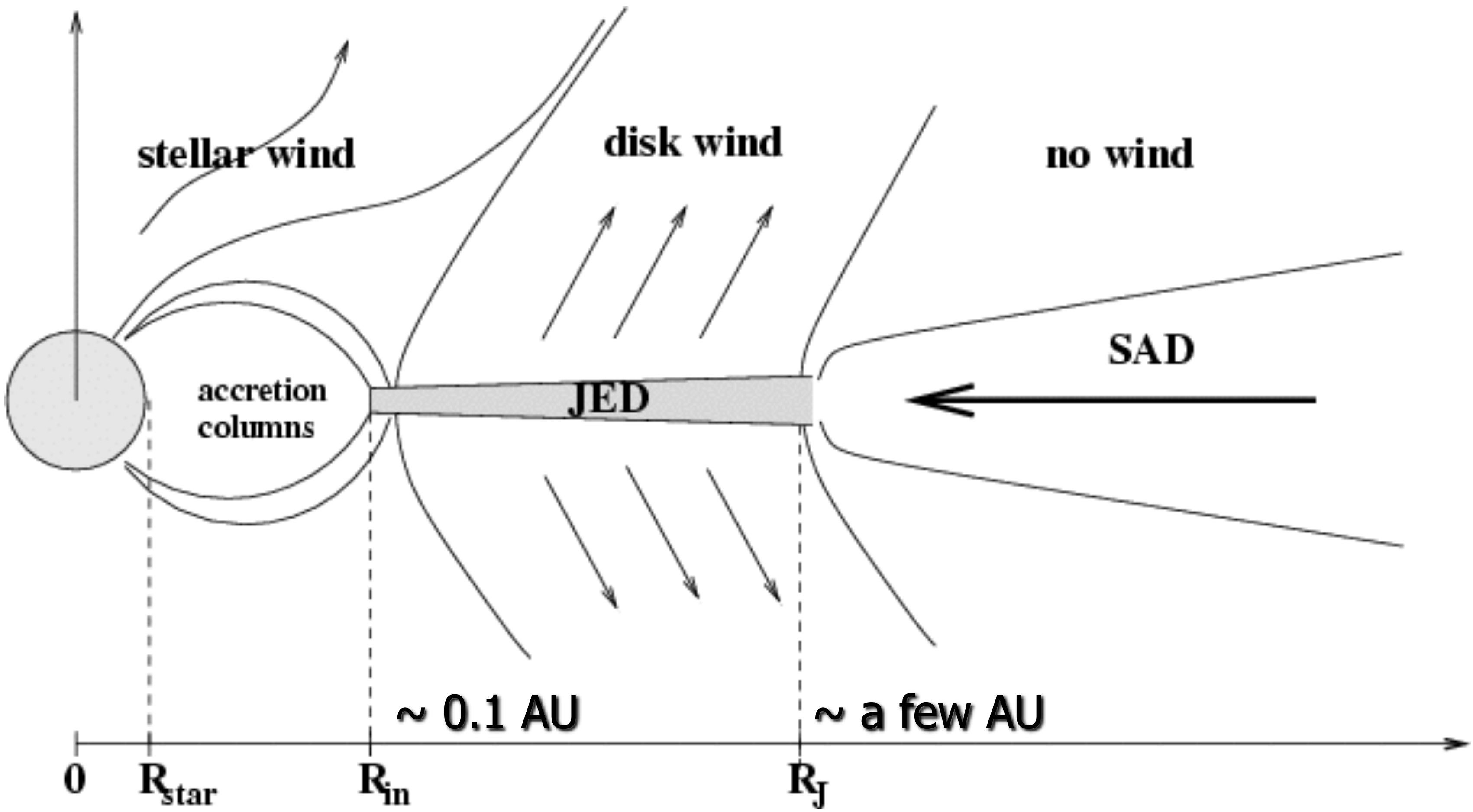
$$\dot{M}_{\rm w} \sim 0.1\ \dot{M}_{\rm acc} \quad \text{for } r_{\rm A}/r_0 \sim 3$$

Jet launch mechanisms



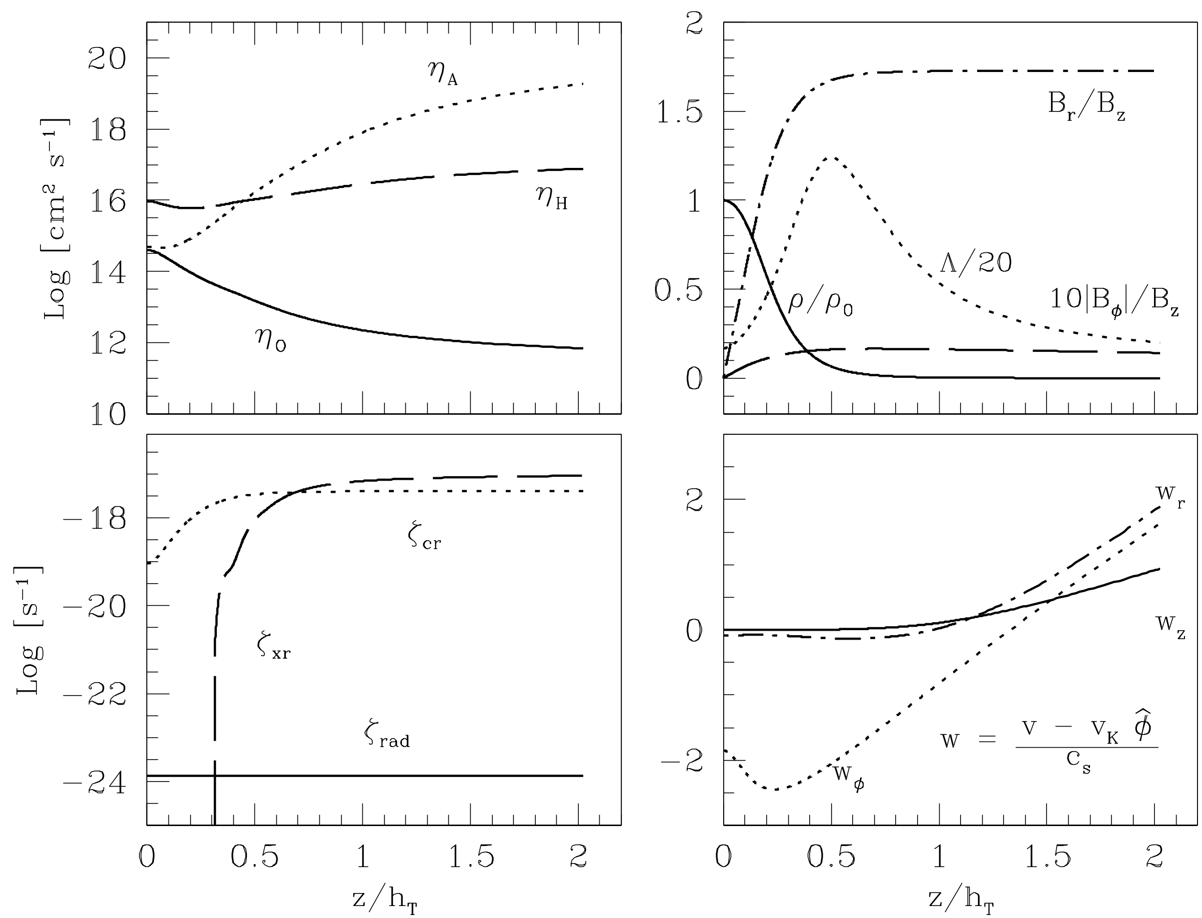


JED: Jet-Emitting Disk
SAD: Standard Accretion Disk



JED: Jet-Emitting Disk
SAD: Standard Accretion Disk (MRI)

Radially-localised wind-driving disk solutions



$R = 1\ \mathrm{AU}\,,\ \Sigma = 600\ \mathrm{g\ cm^{-2}}\,,\ a_0 = 0.8$

Wardle & Königl (1993), Königl, Salmeron & Wardle (2010), Königl & Salmeron (2011)

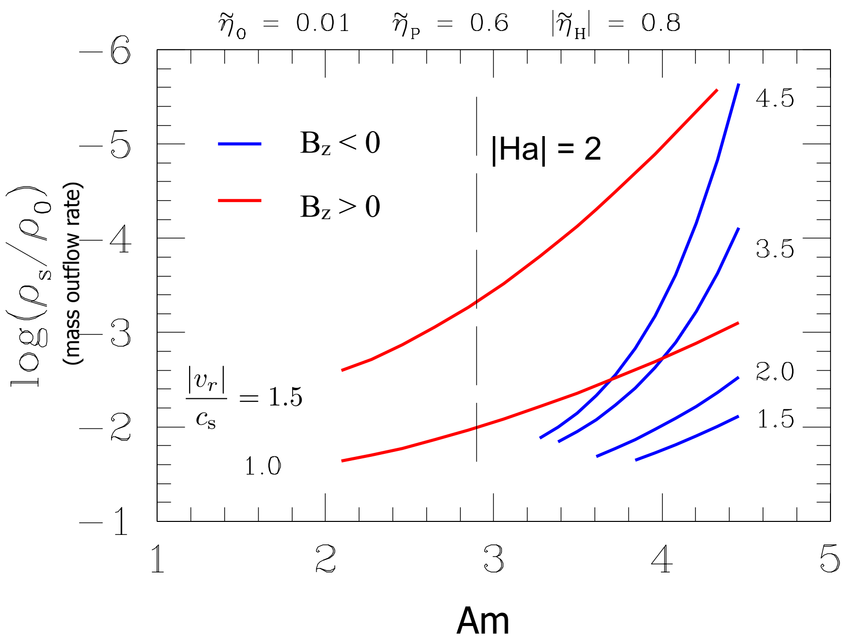
Outflow criteria - Hall diffusion

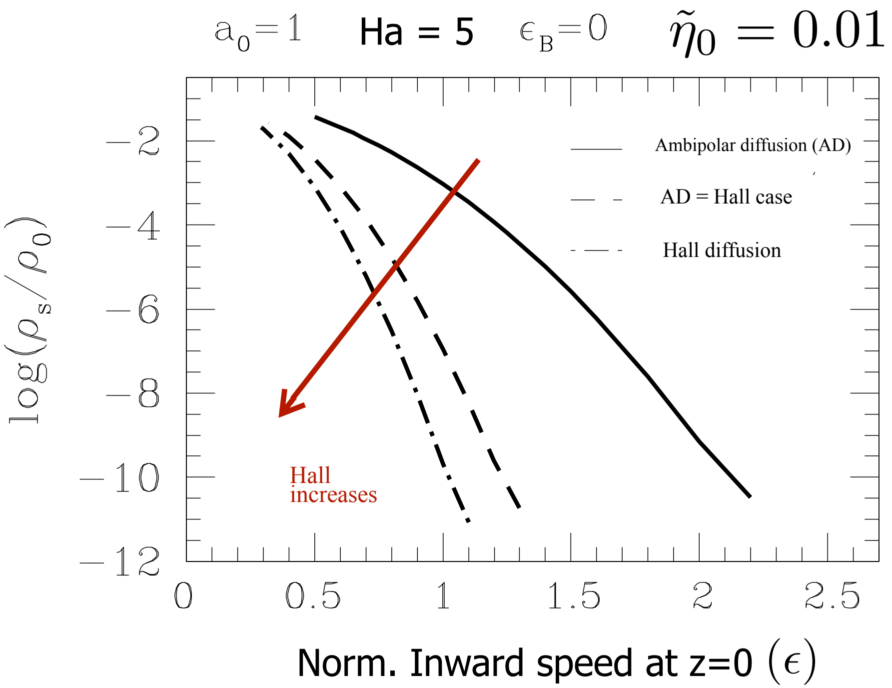
	η_A/η_O	Ha	Parameter constraints								
(i)	>1	$>1/2$	$(2\mathrm{Am})^{-1/2}$	$\lesssim$	a_0	$\lesssim$	2	$\lesssim$	$\epsilon \mathrm{Am}$	$\lesssim$	$v_K/2c_s$
(ii)	>1	$<1/2$	$(\eta_A/\eta_H)^{1/2}$	$\lesssim$	a_0	$\lesssim$	$2\mathrm{Ha}^{1/2}$	$\lesssim$	$(\epsilon/2)(\eta_H/\eta_A)$	$\lesssim$	$\mathrm{Ha}\, v_K/c_s$
(iii)	<1	$>1/2$	$(2\mathrm{Am})^{-1/2}$	$\lesssim$	a_0	$\lesssim$	2	$\lesssim$	$\epsilon a_0^2/\tilde{\eta}_O$	$\lesssim$	$v_K/2c_s$
(iv)	<1	$<1/2$	$(\eta_A/\eta_H)^{1/2}$	$\lesssim$	a_0	$\lesssim$	$2\mathrm{Ha}^{1/2}$	$\lesssim$	$(\epsilon/2)(\eta_H/\eta_O)$	$\lesssim$	$\mathrm{Ha}\, v_K/c_s$

$$a = \frac{v_A}{c_s} \qquad \epsilon = -\frac{v_{r0}}{c_s}$$

$$\mathrm{Ha} \equiv \frac{v_A^2}{\Omega \eta_H} \qquad \mathrm{Am} \equiv \frac{\gamma_i \rho_i}{\Omega} = \frac{v_A^2}{\Omega \eta_A}$$

Hall diffusion and wind properties

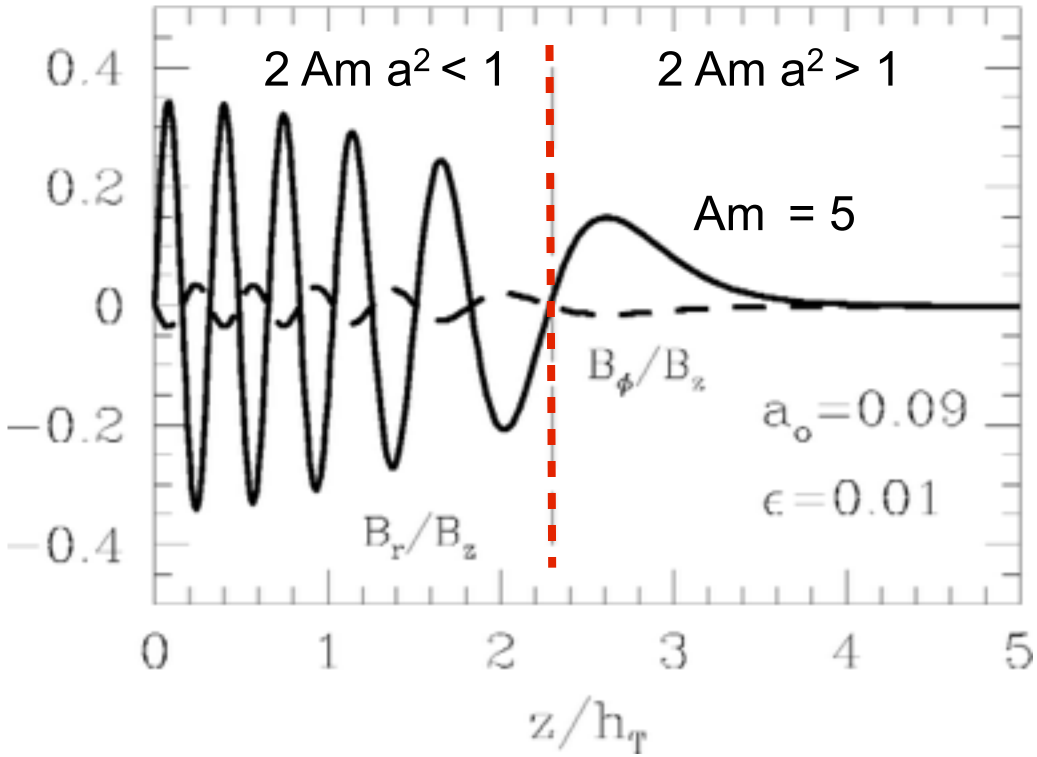




$$\mathrm{Ha} \equiv \frac{v_A^2}{\Omega \eta_H} \qquad \mathrm{Am} \equiv \frac{v_A^2}{\Omega \eta_A}$$

Weak-field solutions

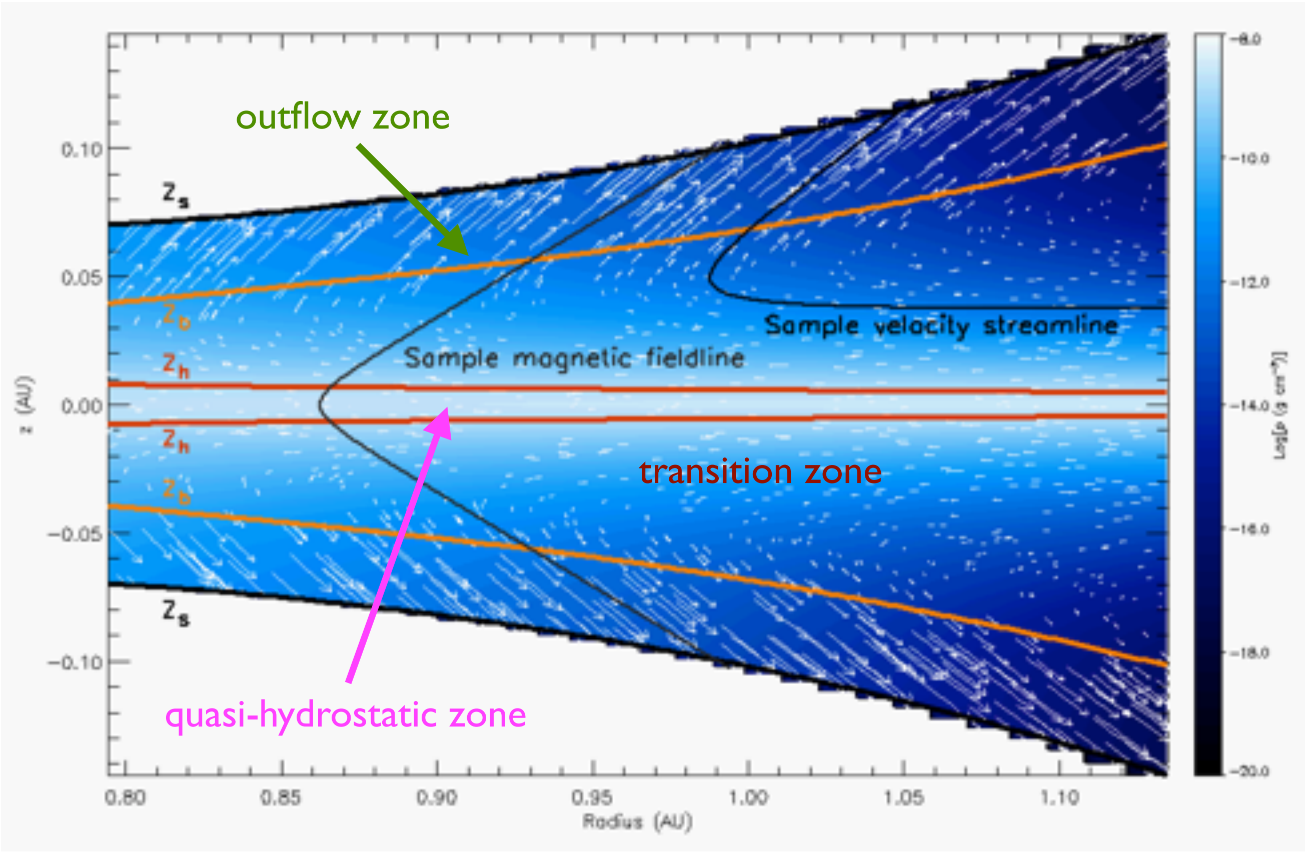
$$(2\mathrm{Am})^{-1/2} \lesssim a \lesssim 2 \lesssim \epsilon \mathrm{Am}$$



$$a = \frac{v_\mathrm{A}}{c_\mathrm{s}}$$

2 Am $a^2 < 1$ => Radial Transport

Global (1+1D) wind-driving disk models



$$a_0 \equiv \frac{v_{A0}}{c_s} = 1$$

$$\dot{M}_{acc} = 10^{-5}\ M_\odot/\mathrm{yr}$$

$$\Sigma(r) = 630\ \left(\frac{r}{\mathrm{AU}}\right)^{-1}\ \mathrm{g/cm^2}$$

$$\dot{M}_w(r) = \int_r^\infty 4\pi r \rho^+ v_z^+ dr$$

$$\dot{M}_a(r) = -2\pi r \Sigma v_r$$

$$\dot{M}_a(r) + \dot{M}_w(r) = \mathrm{const.}$$

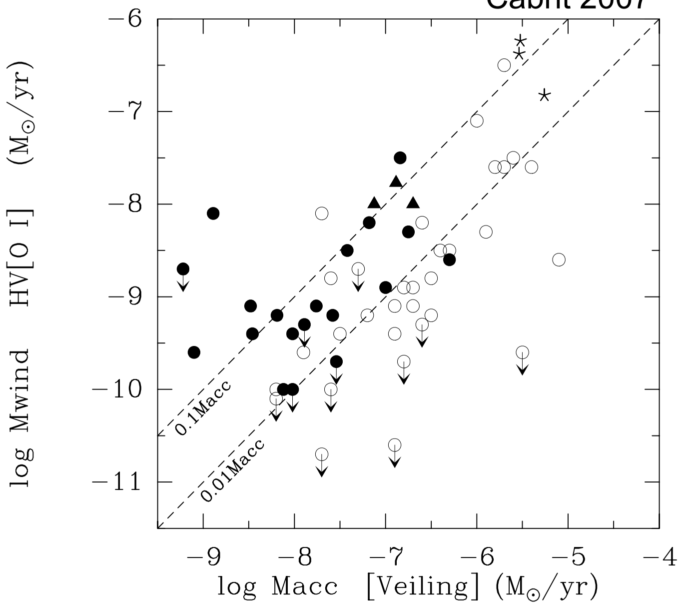
Ejection-accretion ratio

$\dot{M}_w/\dot{M}_a$	a_0 = 0.25	a_0 = 0.5	a_0 = 1.0
$\dot{M}_a = 10^{-4}\,M_\odot$/yr	0.182	0.018	0.023
$\dot{M}_a = 10^{-6}\,M_\odot$/yr	0.199	0.171	0.305
$\dot{M}_a = 10^{-8}\,M_\odot$/yr		0.709	0.520

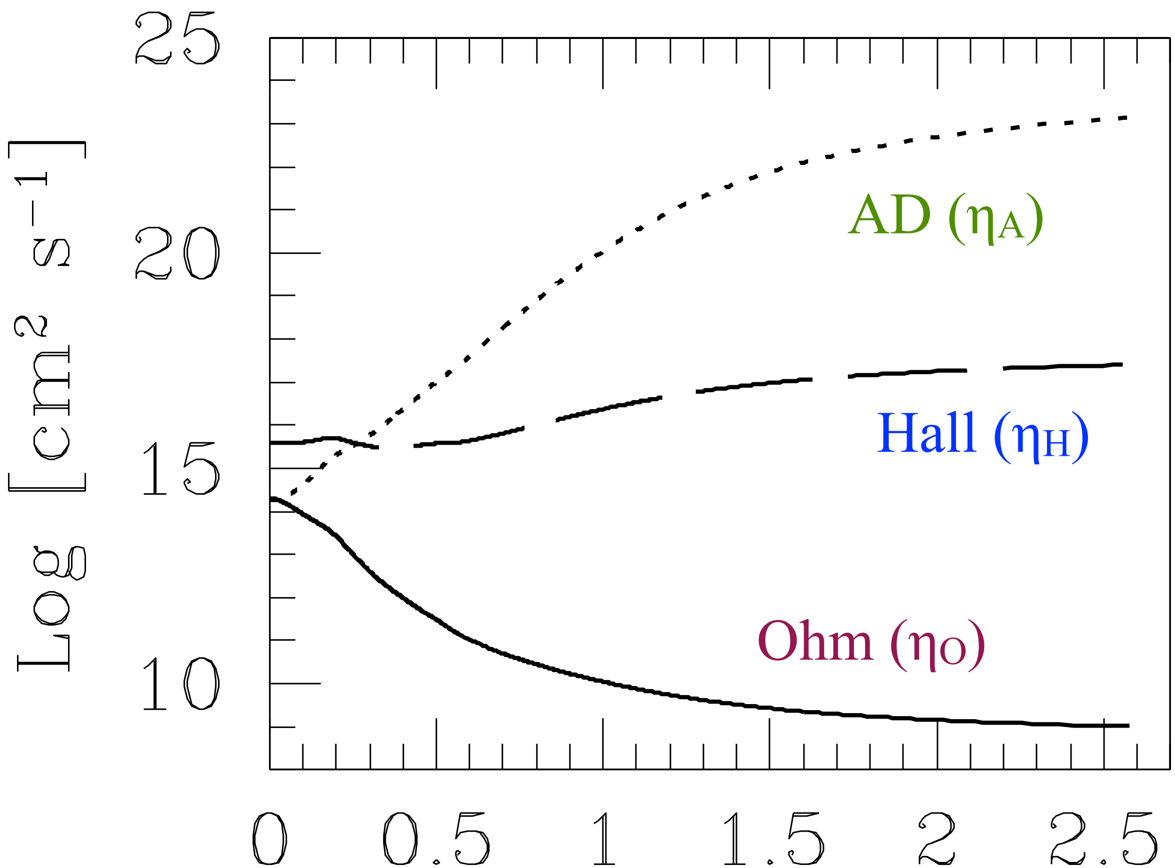
$$\Sigma(r) = \Sigma_0 \left(\frac{r}{\mathrm{AU}}\right)^{-1} \mathrm{g/cm^2}$$

$$a = \frac{v_\mathrm{A}}{c_\mathrm{s}}$$

Cabrit 2007



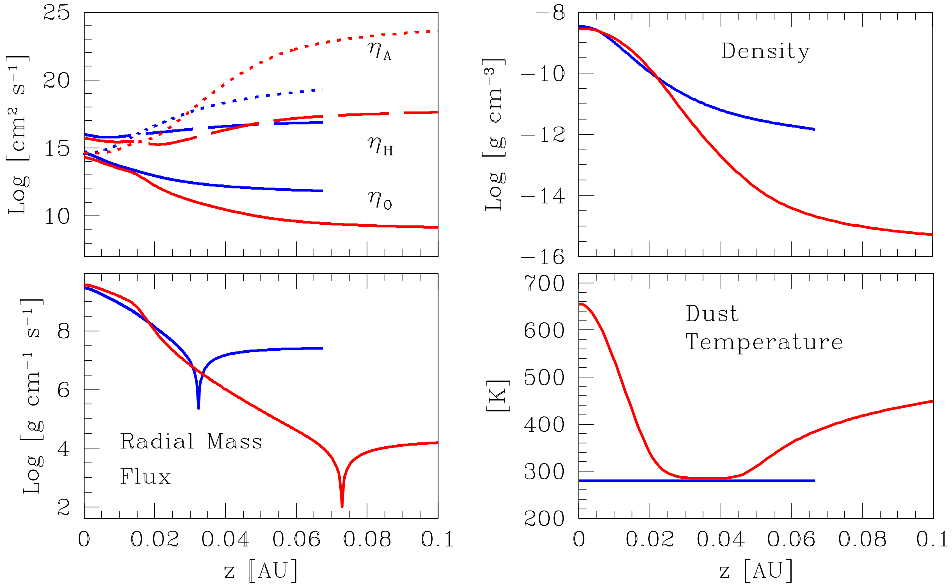
Magnetic diffusivity and heating



$$\mathbf{J}\cdot\mathbf{E}' = \frac{4\pi}{c^2}\left[\eta_O \mathbf{J}_\parallel^2 + (\eta_O+\eta_A)\mathbf{J}_\perp^2\right]$$

Vertical temperature profile
Wind solutions

$$R = 1 \text{ AU}\,,\ \Sigma = 900 \text{ g cm}^{-2}\,,\ a_0 = 0.8\,,\ \epsilon = 0.09$$



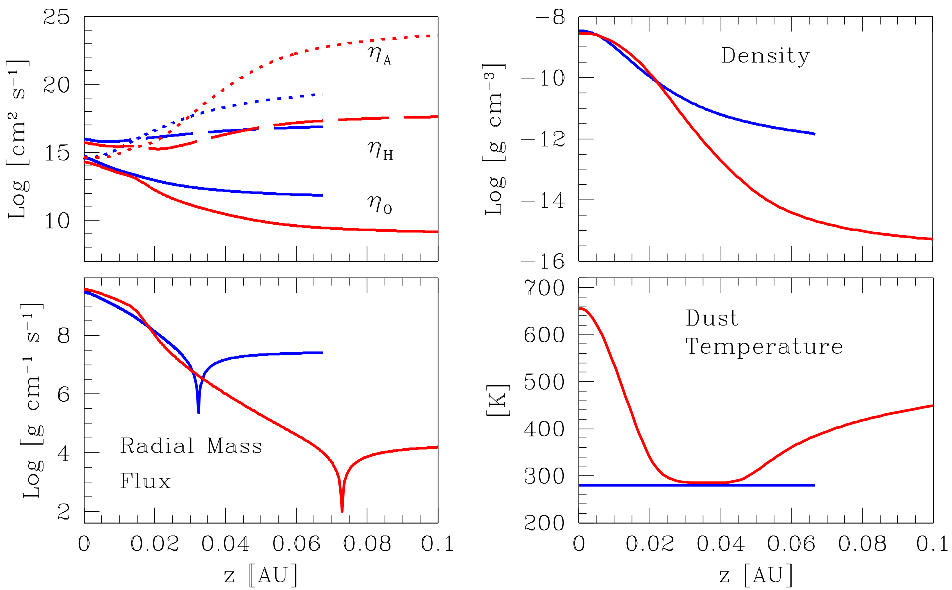
Disc/outflow properties	Isothermal solution	Non-isothermal solution
T_0 [K]	280	655
h_{T0} [cm]	5.0×10^{11}	7.6×10^{11}
h [cm]	9.6×10^{10}	1.2×10^{11}
z_b[cm]	4.8×10^{11}	1.1×10^{12}
z_s [cm]	1.0×10^{12}	2.8×10^{12}
ρ_0 [g cm^{-3}]	3.4×10^{-9}	2.9×10^{-9}
ρ_s/ρ_0	4.3×10^{-4}	7.3×10^{-8}
$\dot{\mathcal{M}}_{\rm in}$ [$M_\odot$/yr]	1.0×10^{-5}	1.5×10^{-5}
$\dot{\mathcal{M}}_{\rm out}$ [$M_\odot$/yr]	3.3×10^{-6}	7.2×10^{-12}

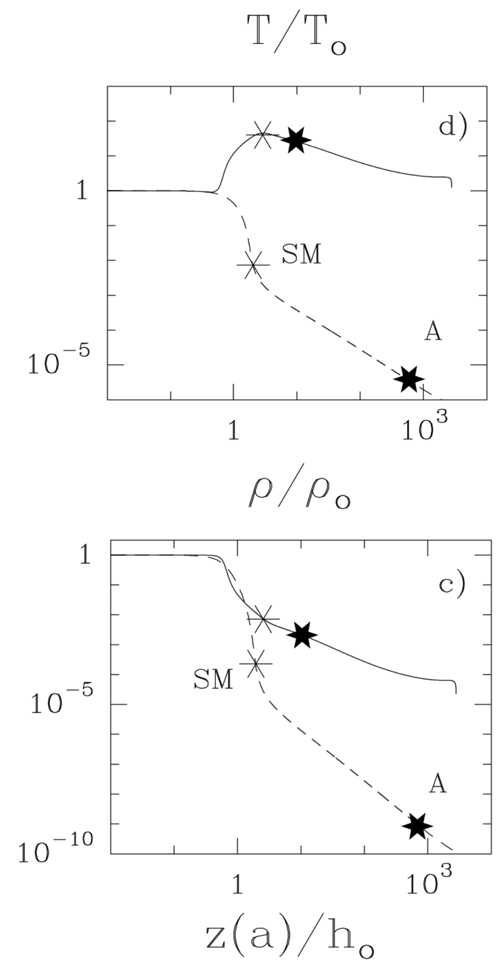
Heating sources: Stellar irradiation & Joule dissipation.
C. Dullemond's Radiative transfer code (e.g. Dullemond et al. 2002)

$$\frac{m_{\rm dust}}{m_{\rm gas}} = 2 \times 10^{-4}$$

Vertical temperature profile

Wind solutions

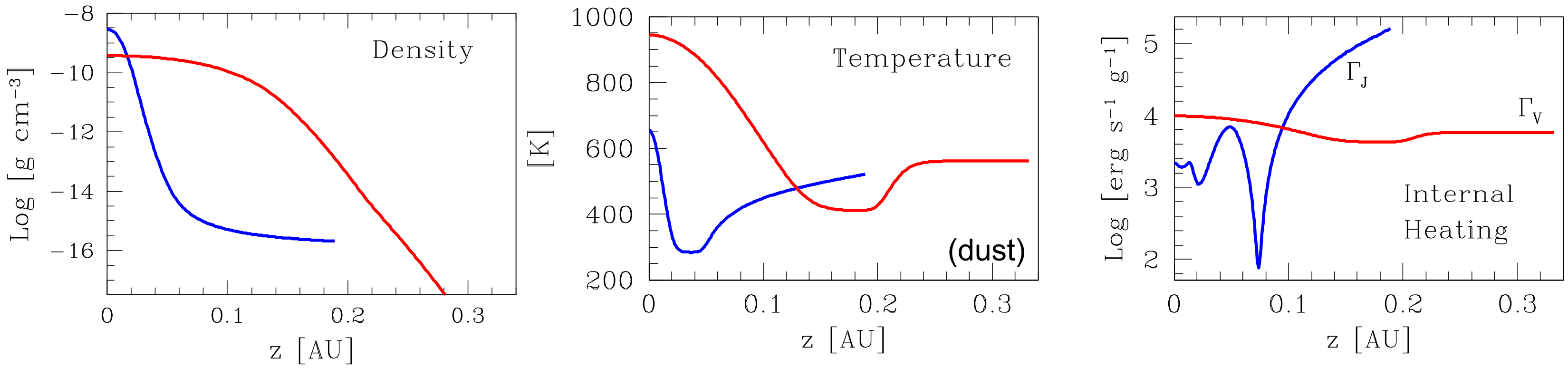




Casse & Ferreira 2000

Wind-driving disks versus viscous disks

$R = 1\ \mathrm{AU}\,,\ \Sigma = 900\ \mathrm{g\ cm^{-2}}$

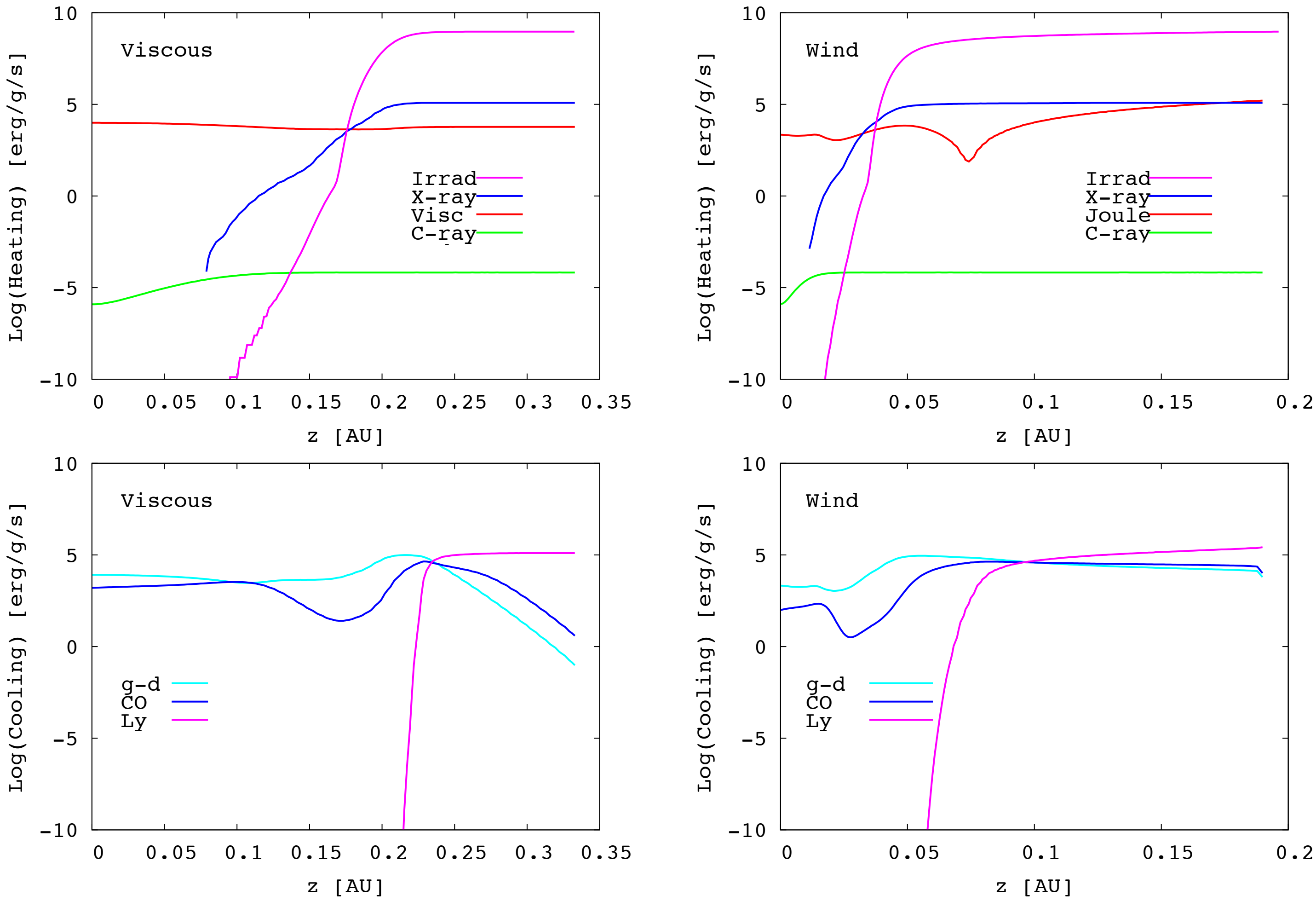


wind model $$\mathbf{J}\cdot\mathbf{E}' = \frac{4\pi}{c^2}\left[\eta_{\rm O}\mathbf{J}_\parallel^2 + (\eta_{\rm O}+\eta_{\rm A})\mathbf{J}_\perp^2\right]$$

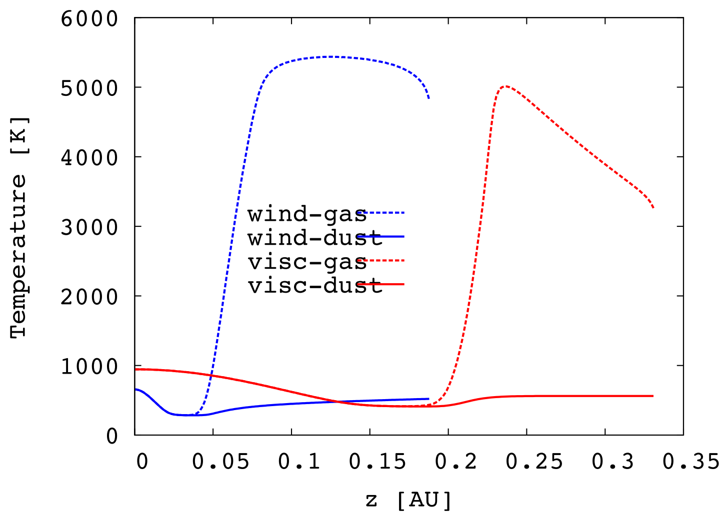
$$a_0 = 0.8\,,\ \epsilon = 0.09$$

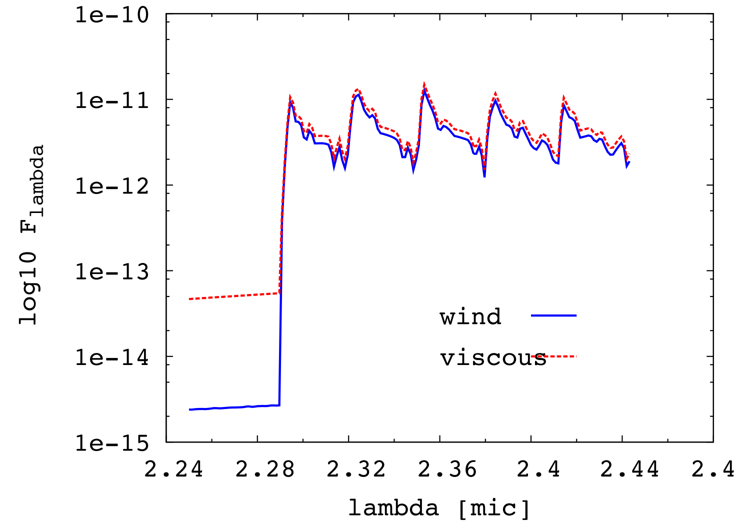
viscous model $$\Gamma = \frac{9}{4}\rho\alpha\Omega_{\rm K}c_{\rm s}^2$$

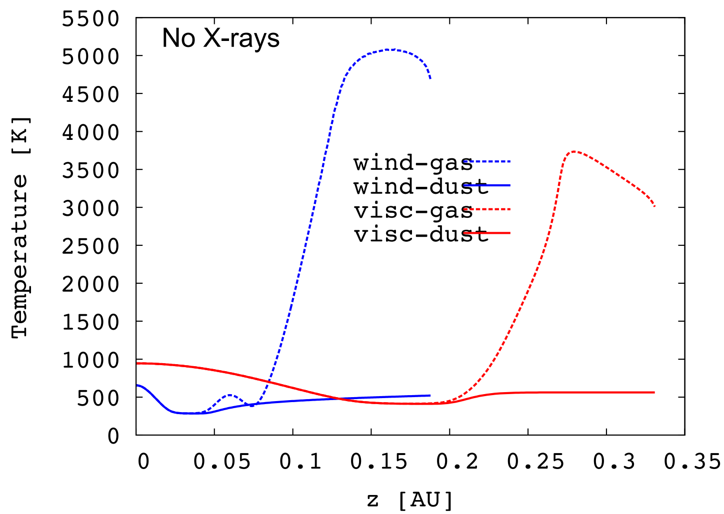
Wind-driving versus viscous disks

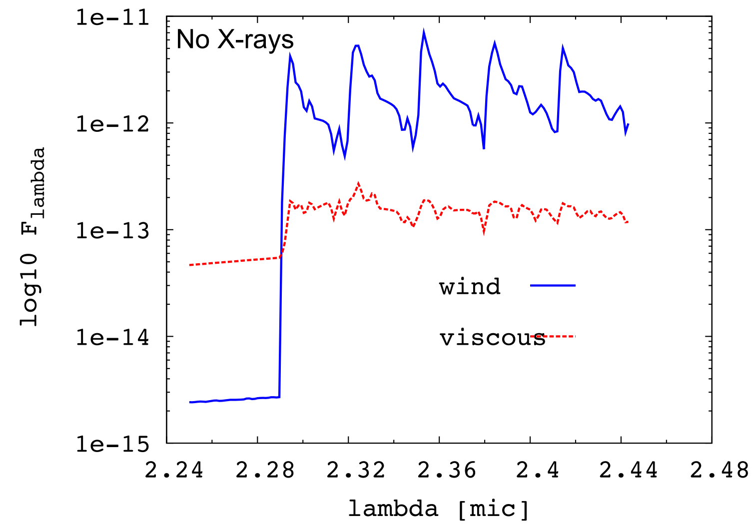


Wind-driving versus viscous disks

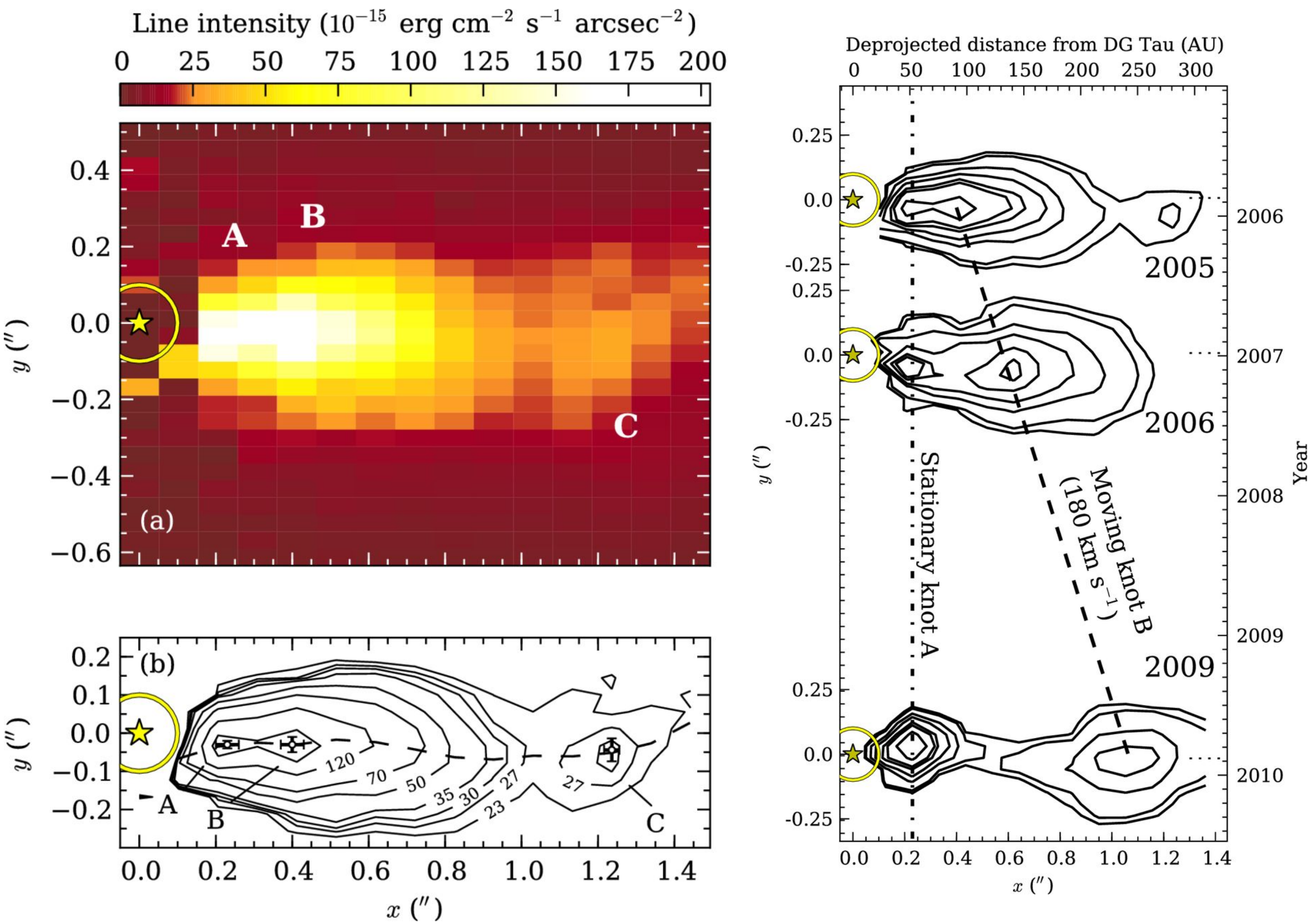






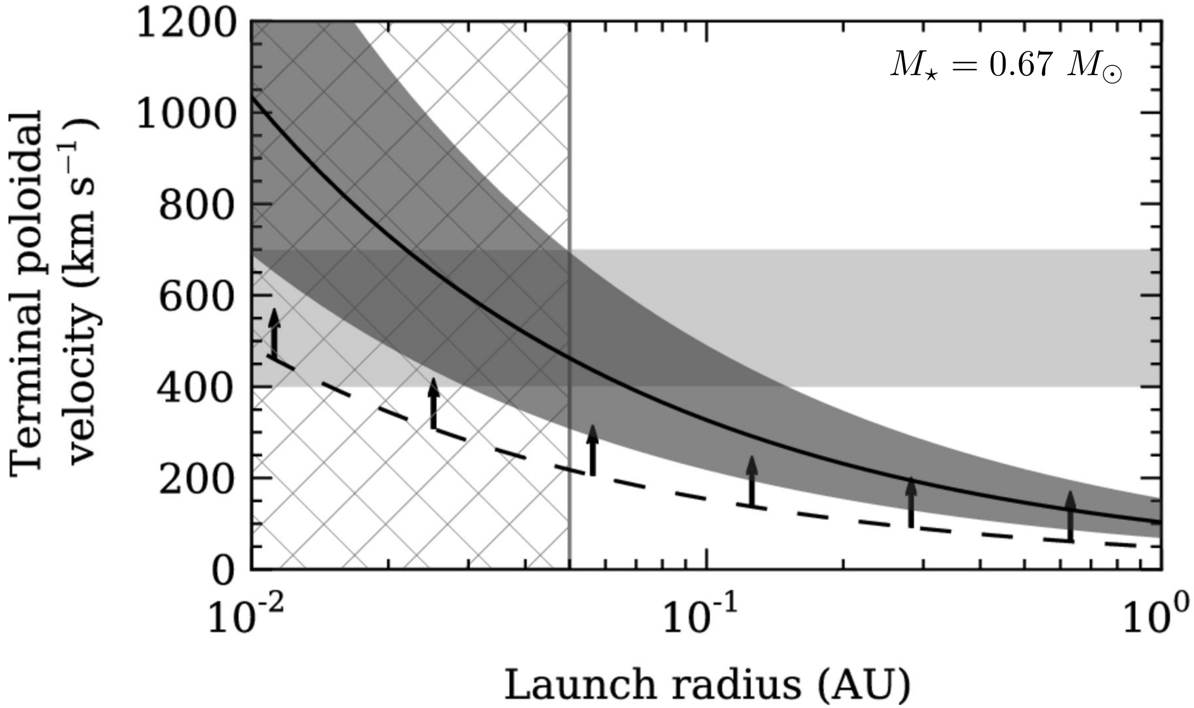


DG Tau - Approaching outflow



[Fe II] 1.644 μm

Asymptotic poloidal jet velocity vs launch radius



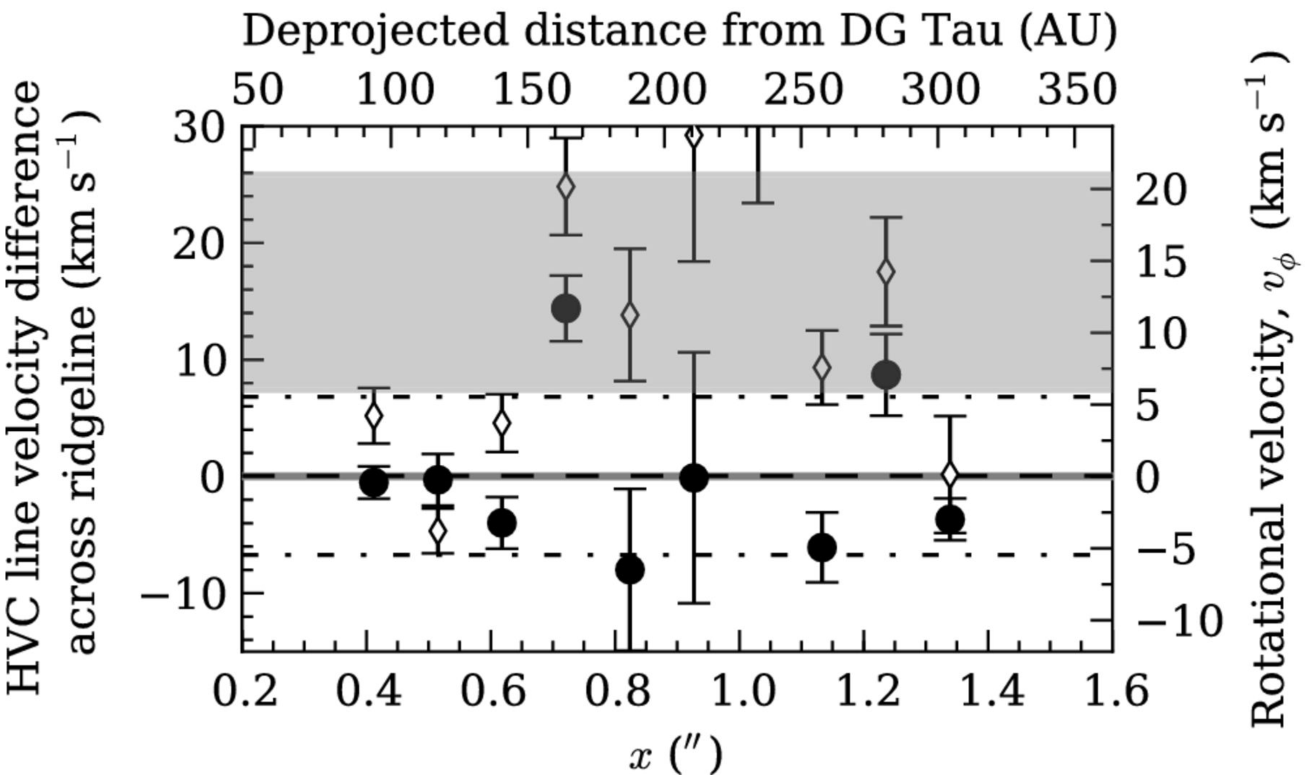
$$v_{\mathrm{p},\infty} = 400 - 700\ \mathrm{km\ s^{-1}}$$

$$4 \lesssim (r_\mathrm{A}/r_0)^2 \lesssim 20$$

$$r_0 = 0.02 - 0.15\ \mathrm{AU}$$

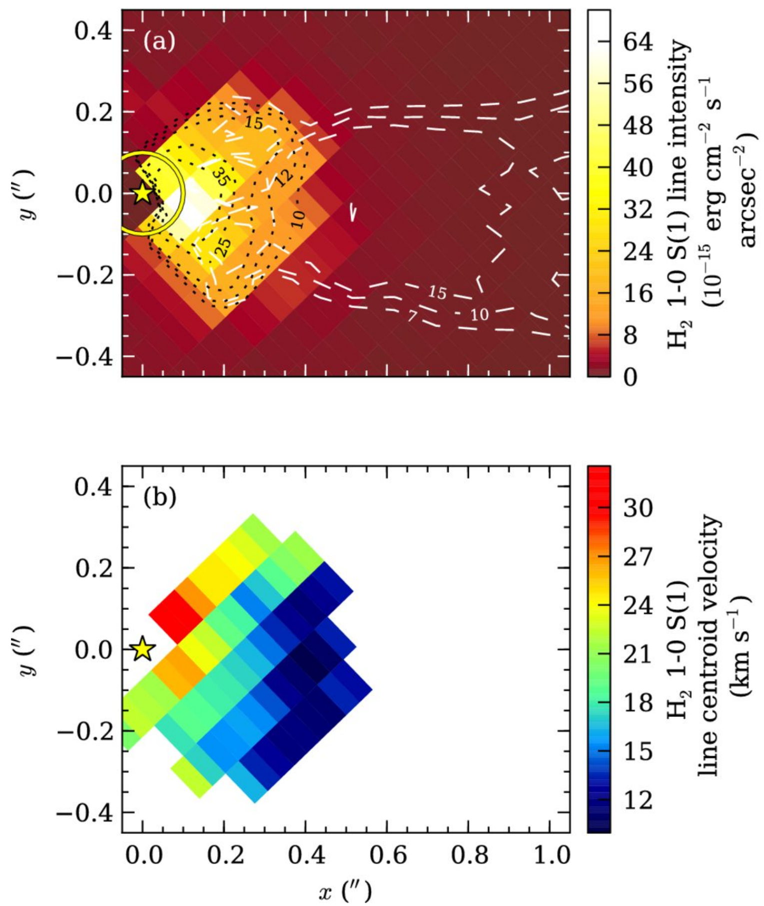
$$v_{\mathrm{p},\infty} = \sqrt{2} v_\mathrm{K} \frac{r_\mathrm{A}}{r_0} \approx 109\ \mathrm{km\ s^{-1}} \left(\frac{r_0}{0.1\ \mathrm{AU}}\right)^{-1/2} \left(\frac{r_\mathrm{A}}{r_0}\right)$$

Velocity differences across the jet ridgeline



Average velocity difference across the jet ridge line is 0.0 ± 6.8 km s^{-1}, corresponding to v_Φ = 0.0 ± 6.8 km s^{-1}, after correction for the jet inclination.

A more extended molecular wind?



H_2 1–0 S(1) 2.1218 μm line emission from the near side of the DG Tau circumstellar disc

Summary & Conclusions

- Wind-driving protostellar disc models with stratified vertical ionisation and diffusivity structure
- Parameter constraints for physically-viable wind solutions to exist.
- In Hall diffusivity dominated discs the viability and the properties of the solutions are dependent on the magnetic field polarity
- Extent of wind launch region as a function of the surface density profile, field strength and accretion rate onto the source
- Viscous versus wind-driving disks
- Impact of internal heating on the thermal structure and predicted spectrum of disks
- Observations of the DG Tau jet with NIFS and links to properties at the launch point