2nd European Conference on MR in Plasmas, 2025

Magnetic reconnection in partially ionized plasmas

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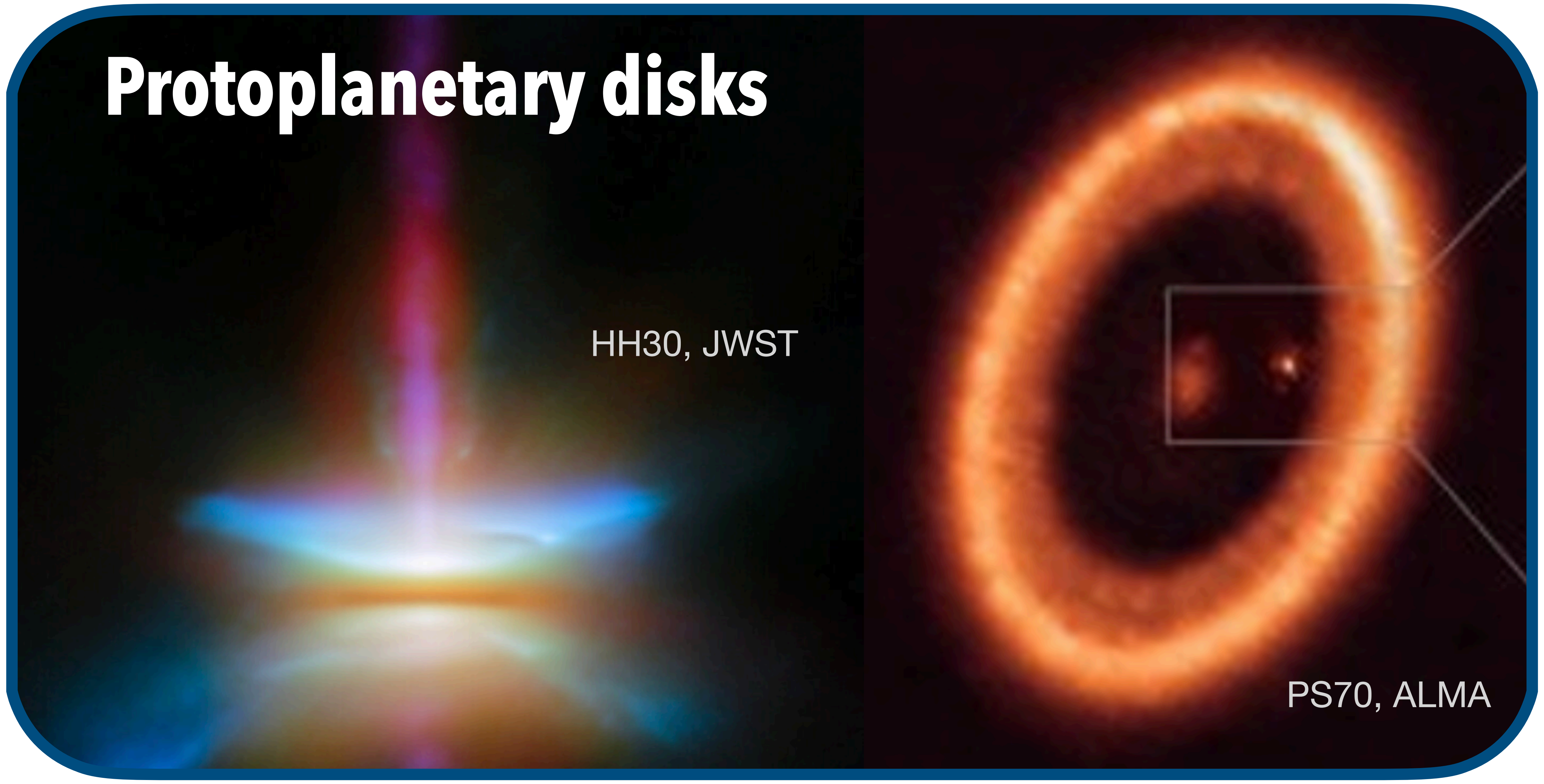
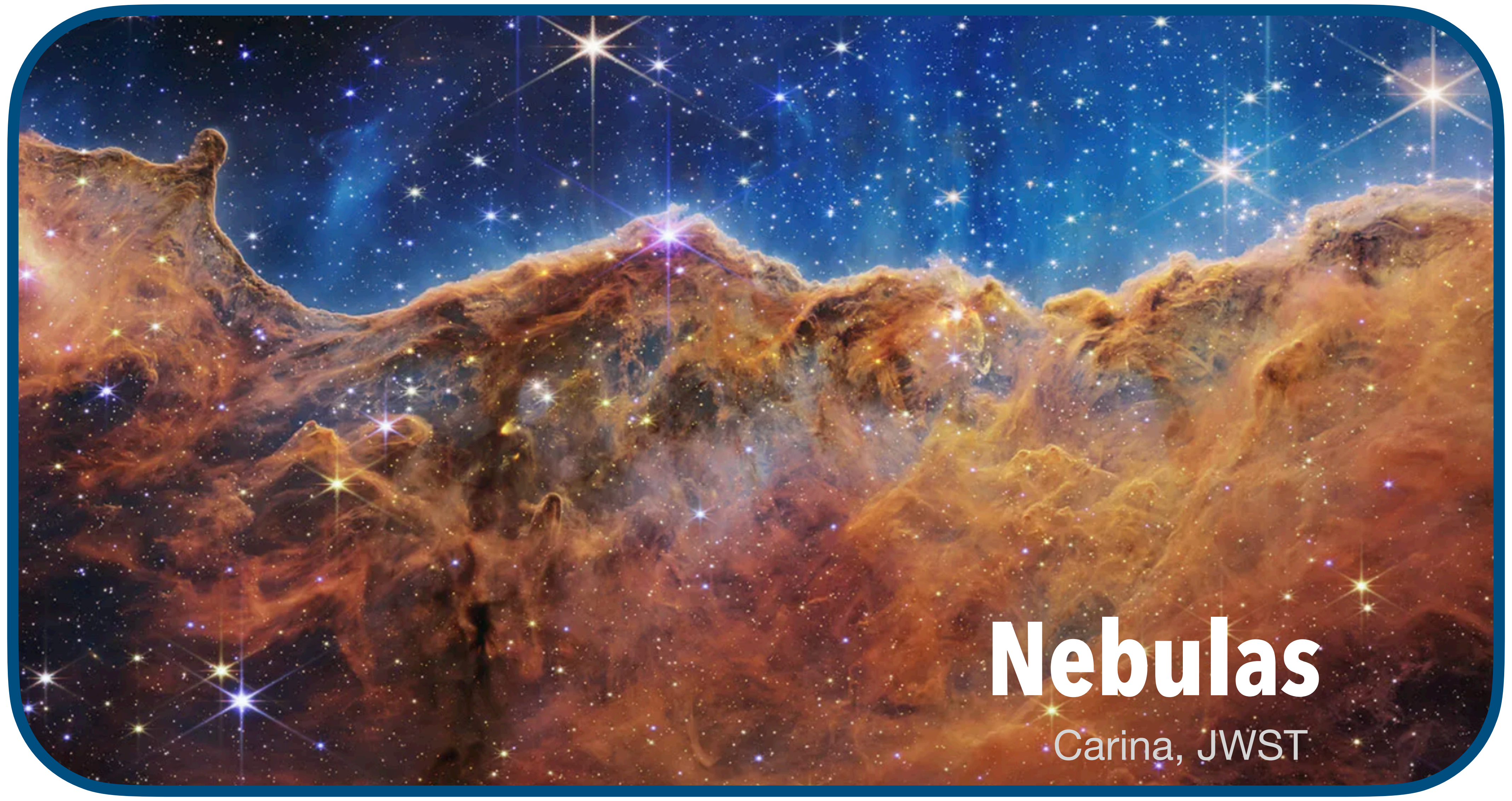
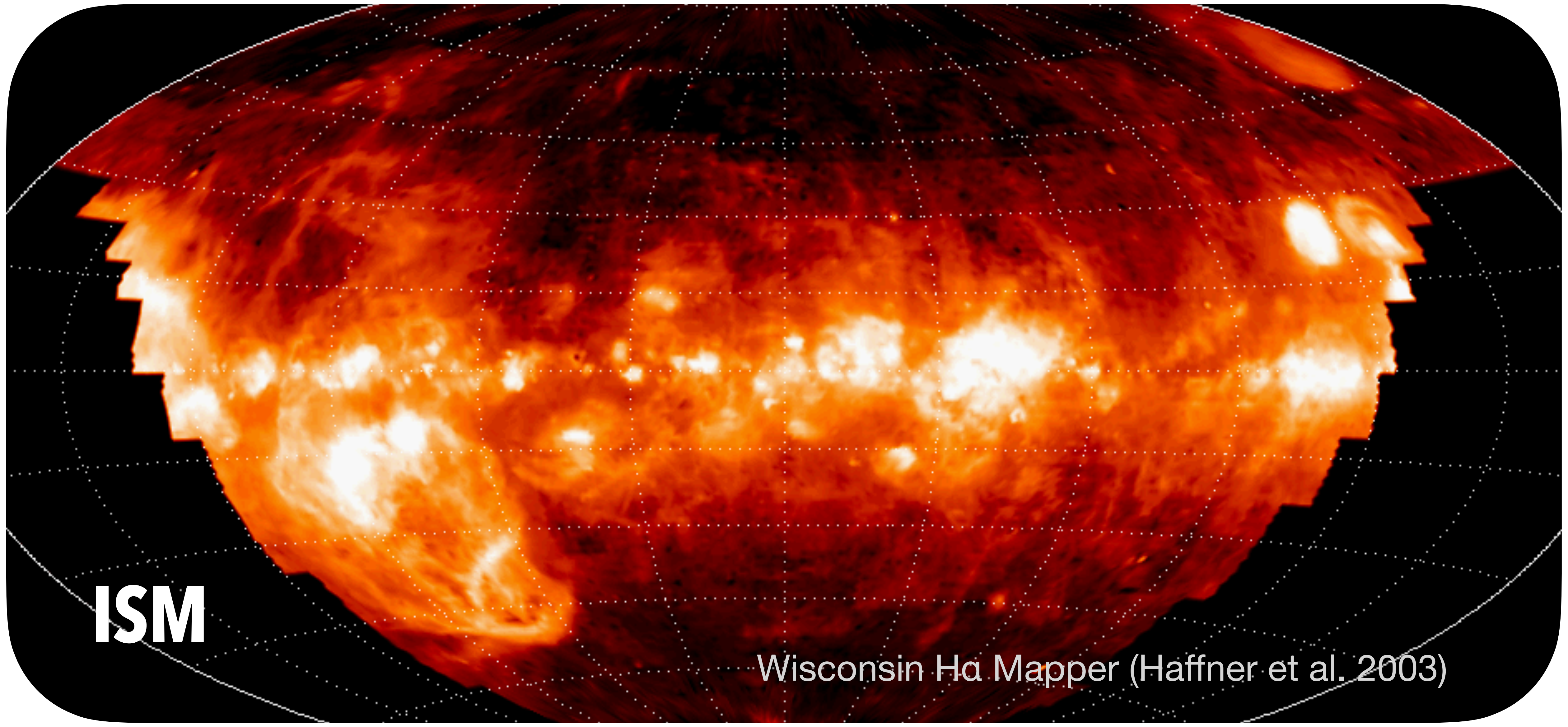
Outline

- Examples of partially ionized astrophysical and laboratory plasmas (PIP)
- Fluid models to describe the physics of PIP, non ideal effects
- Tearing instability in PIP: reconnection regimes and onset of fast reconnection
- Application of the model to the solar atmosphere: photosphere and chromosphere
- The case of Protoplanetary disks: reconnection as a potential source of heating and ionization.
- Conclusions, literature and some of the interesting things that unfortunately have not been covered here…


Sun and sun-like stars
Image credit: ESA/NASA/Soho

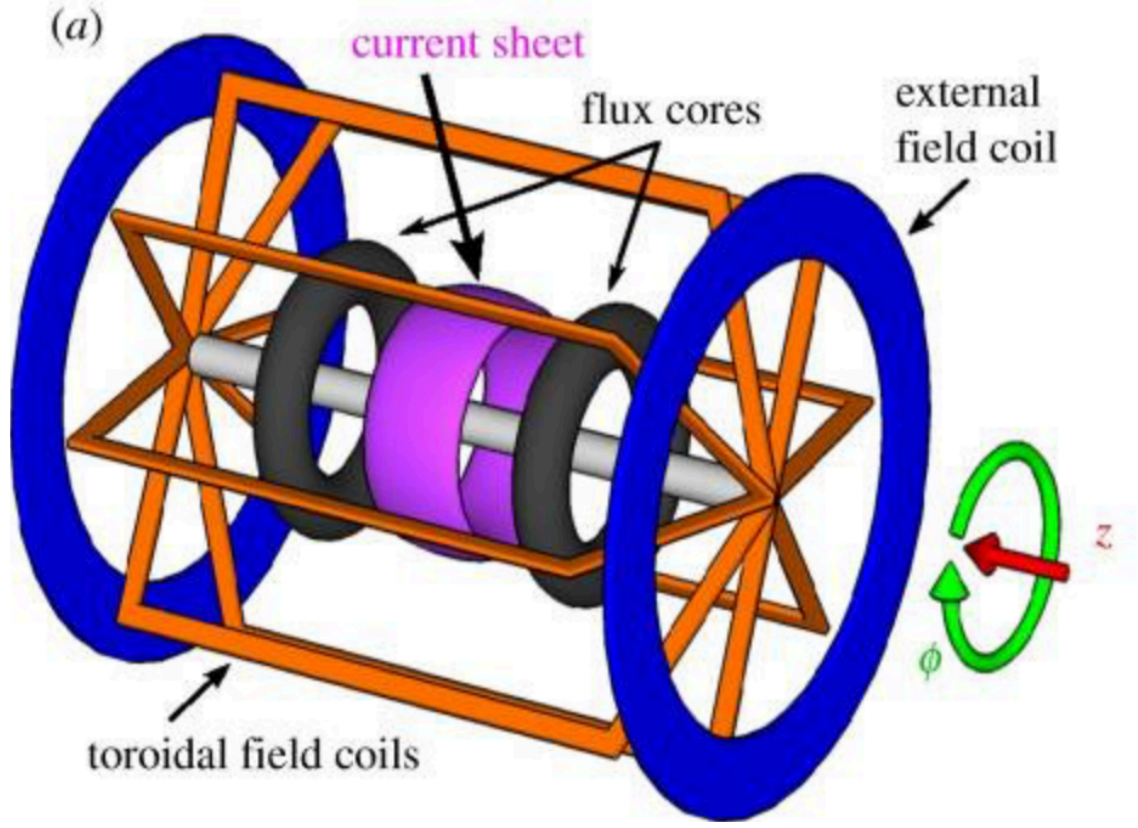

Protoplanetary disks
HH30, JWST
PS70, ALMA

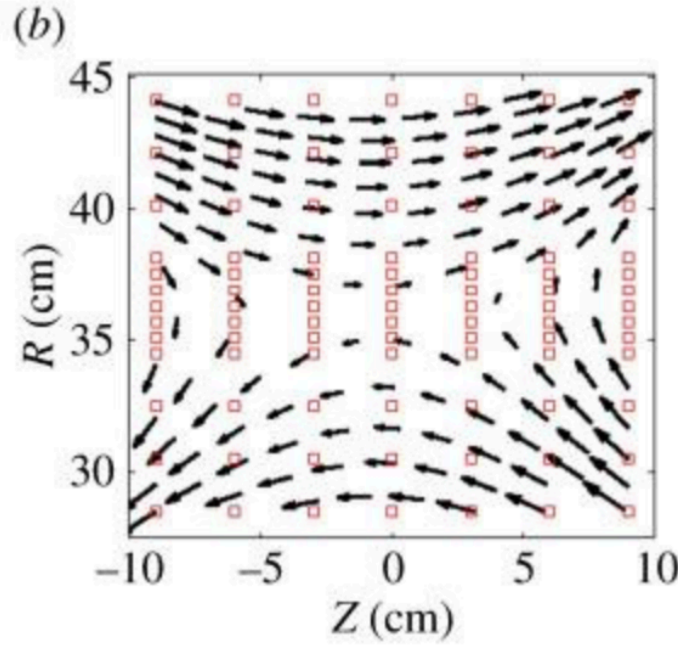

Nebulas
Carina, JWST


ISM
Wisconsin Hα Mapper (Haffner et al. 2003)

Laboratory

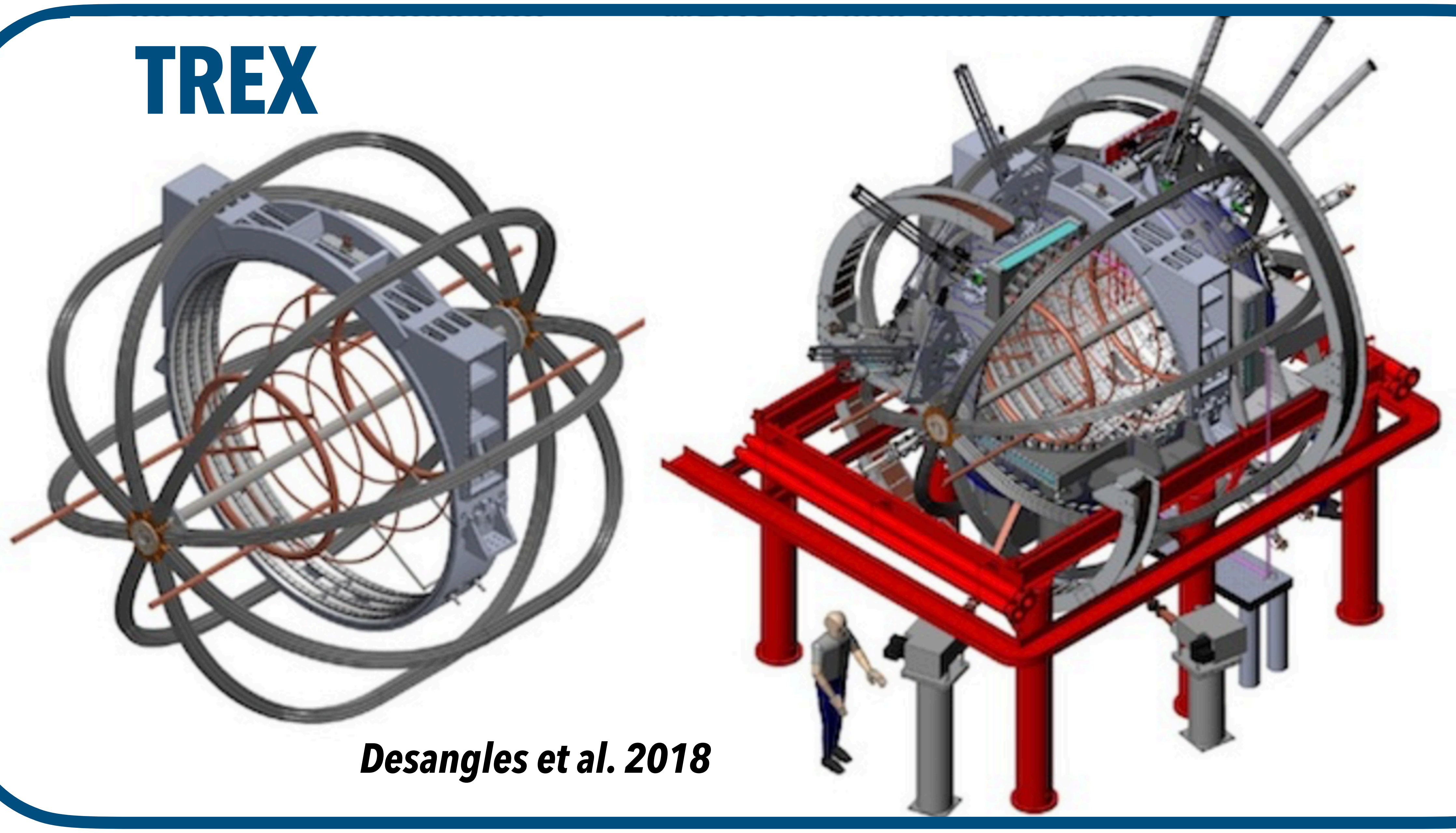
MRX



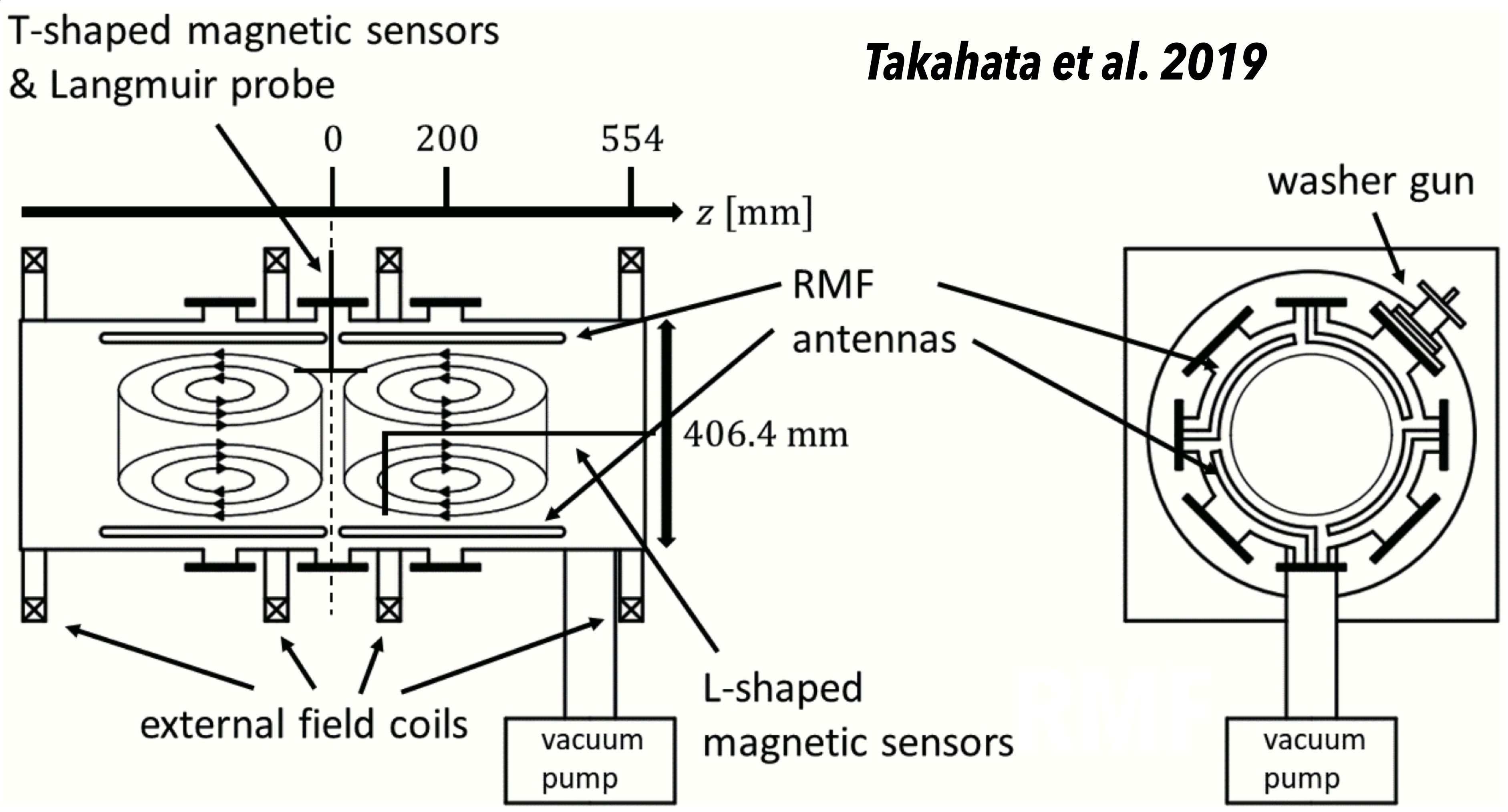


Lawrence et al. 2013

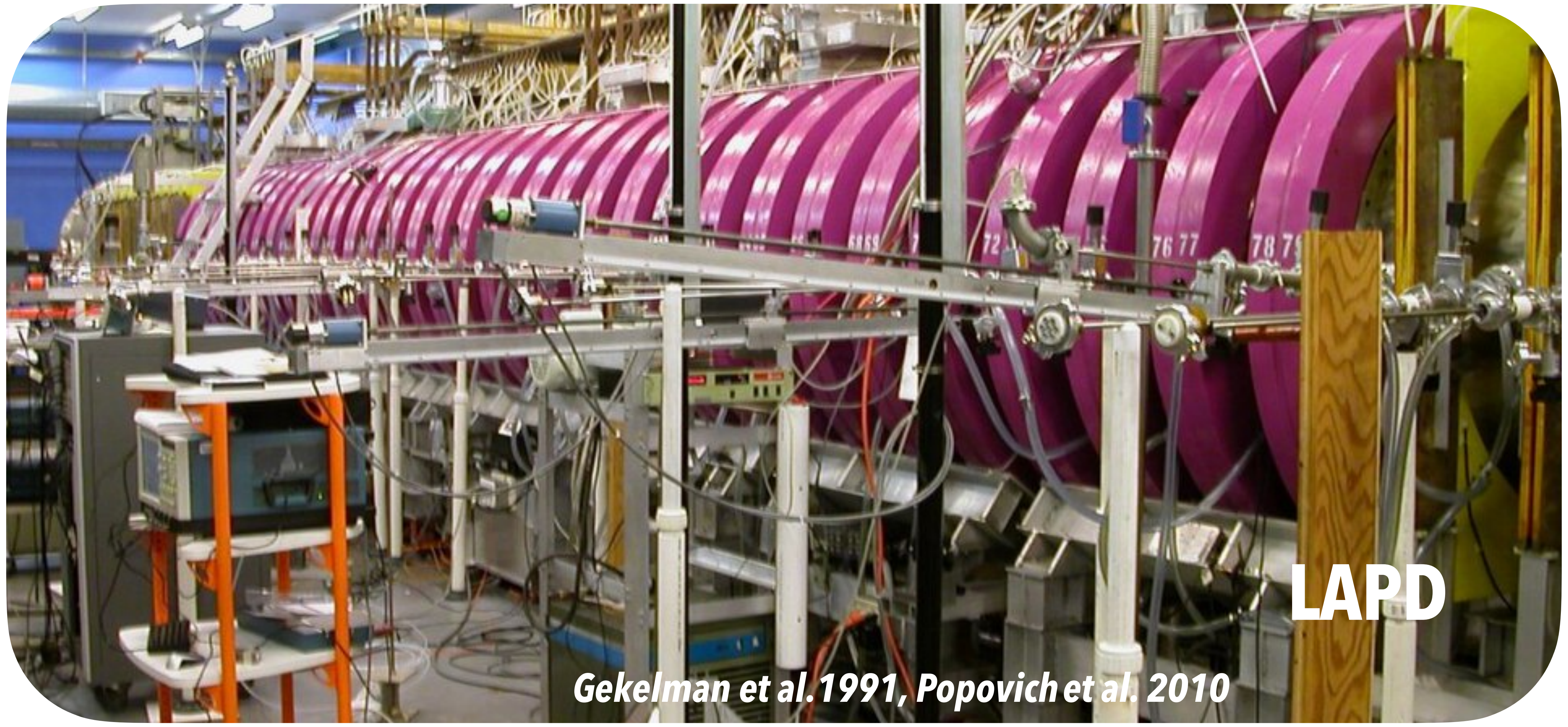
TREX



Desangles et al. 2018



Takahata et al. 2019



LAPD

Gekelman et al. 1991, Popovich et al. 2010

Multi-fluid description and all we'll be sweeping under the carpet…

Following Braginskii 1965 and Meier and Shumlak 2012 (MS12)

- Compose the three-fluid electron-ion-neutral model, which is a generalization of the two-fluid plasma model to include reacting neutrals: start with taking moments of the Boltzmann equation

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \mathbf{v}_i) = \Gamma_i^{ion} - \Gamma_n^{rec}$$

$$\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \mathbf{v}_e) = \Gamma_i^{ion} - \Gamma_n^{rec}$$

$$\frac{\partial n_n}{\partial t} + \nabla \cdot (n_n \mathbf{v}_n) = \Gamma_n^{rec} - \Gamma_i^{ion}$$

E.g. 0-th order Moments

$$\Gamma_n^{ion} = -\Gamma_i^{ion} = -n\, n_e \langle \sigma_{ion} v_e \rangle$$

$$\Gamma_i^{rec} = \Gamma_e^{rec} = -n_i n_e \langle \sigma_{rec} v_e \rangle$$

Being ϕ_{ion} the effective Ionization Potential

$e^- + n \rightarrow i^+ + 2e^- - \phi_{ion}$ **Electron Impact Ionization**

$e^- + i^+ \rightarrow n + h\nu$ **Radiative Recombination**

$i^+ + n \rightarrow n + i^+$ **Resonant charge exchange(elastic)**

Elastic Collisions

$$\frac{\partial}{\partial t}(m_i n_i \mathbf{v}_i) + \nabla \cdot (m_i n_i \mathbf{v}_i \mathbf{v}_i + \mathbb{P}_i) = q_i n_i (\mathbf{E} + \mathbf{v}_i \times \mathbf{B}) + \mathbf{R}_i^{ie} + \mathbf{R}_i^{in} + \Gamma_i^{ion} m_i \mathbf{v}_n - \Gamma_n^{rec} m_i \mathbf{v}_i + \Gamma^{cx} m_i (\mathbf{v}_n - \mathbf{v}_i) + \mathbf{R}_{in}^{cx} - \mathbf{R}_{ni}^{cx}$$

$$\frac{\partial}{\partial t}(m_e n_e \mathbf{v}_e) + \nabla \cdot (m_e n_e \mathbf{v}_e \mathbf{v}_e + \mathbb{P}_e) = -q_e n_e (\mathbf{E} + \mathbf{v}_e \times \mathbf{B}) - \mathbf{R}_i^{ie} + \mathbf{R}_e^{en} + \Gamma_i^{ion} m_e \mathbf{v}_n - \Gamma_n^{rec} m_e \mathbf{v}_e$$

$$\frac{\partial}{\partial t}(m_n n_n \mathbf{v}_n) + \nabla \cdot (m_n n_n \mathbf{v}_n \mathbf{v}_n + \mathbb{P}_n) = -\mathbf{R}_i^{in} - \mathbf{R}_e^{en} + \Gamma_n^{rec} (m_i \mathbf{v}_i + m_e \mathbf{v}_e) - \Gamma_i^{ion} m_n \mathbf{v}_n + \Gamma^{cx} m_i (\mathbf{v}_i - \mathbf{v}_n) - \mathbf{R}_{in}^{cx} + \mathbf{R}_{ni}^{cx}$$

Then you have an energy equation…

“Multicomponent Plasma” description

Following Braginskii 1965 and Meier and Shumlak 2012 (MS12)

With the usual MHD approximations, low frequency regime $m_e \to 0 \qquad n_e \sim n_i \qquad \mathbf{v}_e = \mathbf{v}_i - \frac{\mathbf{J}}{qn} \Rightarrow$

Electron momentum equation valid for both PIP as well as fully ionized

$$0 = -q_e n_e \left[\mathbf{E} + \left(\mathbf{v}_i - \frac{\mathbf{J}}{qn}\right) \times \mathbf{B}\right] - \mathbf{R}_i^{ie} + \mathbf{R}_e^{en}$$

Defining

$$\mathbf{v} = \frac{1}{\rho}\Sigma_\alpha m_\alpha n_\alpha \mathbf{v}_\alpha = \frac{1}{\rho}\left(m_i n_i \mathbf{v}_i + m_e n_e \mathbf{v}_e + m_n n_n \mathbf{v}_n\right) \Rightarrow \mathbf{v}_i = \frac{\rho \mathbf{v} - m_n n_n \mathbf{v}_n}{m_i n_i}$$

Ohm’s law becomes

$$\mathbf{E} = \left[\left(\frac{\rho \mathbf{v} - m_n n_n \mathbf{v}_n}{m_i n_i} - \frac{\mathbf{J}}{qn}\right) \times \mathbf{B}\right] - \mathbf{R}_i^{ie} + \mathbf{R}_e^{en}$$

Additional resistivity

Ambipolar diffusion

Non ideal effects in the induction equation

Wardle 2007

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) - \nabla \times [\eta_{\mathrm{O}} \nabla \times \boldsymbol{B} + \eta_{\mathrm{H}} (\nabla \times \boldsymbol{B}) \times \hat{\boldsymbol{B}} + \eta_{\mathrm{A}} (\nabla \times \boldsymbol{B})_{\perp}]$$

$\mathbf{v}$ also depends on the velocity of the neutral fluid

Proton-Electron Plasma

$$\eta_O = \frac{c^2}{\omega_{pe}^2}(\nu_{ei} + \nu_{en}) + \frac{c^2}{\omega_{pi}^2}\nu_{in}$$

$$\eta_{AD} = \frac{|\mathbf{B}|^2}{|\mu_0|}\left(\frac{\rho_n}{\rho}\right)^2 (\rho_i \nu_{in} + \rho_e \nu_{en})^{-1}$$

E.g. Ni et al. 2020

General Case

$$\eta_O = \frac{c^2}{4\pi\sigma_O} \qquad \sigma_O = \frac{ec}{B}\sum_j n_j |Z_j| \beta_j$$

$$\eta_{\mathrm{H}} = \frac{c^2}{4\pi}\frac{\sigma_H}{\sigma_{\mathrm{H}}^2 + \sigma_{\mathrm{P}}^2} \qquad \sigma_{\mathrm{H}} = \frac{ec}{B}\sum_j \frac{n_j Z_j}{1+\beta_j^2}$$

$$\eta_{\mathrm{A}} = \frac{c^2}{4\pi}\frac{\sigma_{\mathrm{P}}}{\sigma_{\mathrm{H}}^2 + \sigma_{\mathrm{P}}^2} - \eta_{\mathrm{O}} \qquad \sigma_{\mathrm{P}} = \frac{ec}{B}\sum_j \frac{n_j |Z_j| \beta_j}{1+\beta_j^2}$$

Ion spiecies

Magnetic Field-density diagrams for non-ideal coefficients

$$\beta_j = \frac{|Z_j|eB}{m_j c}\frac{1}{\gamma_j \rho}$$

Hall Parameter

IS DETERMINED BY

$$\gamma_j = \langle \sigma v \rangle_j / (m_j + m)$$

Neutral mean mass

rate coefficient for collisional transfer between ions and neutrals

See Draine 1989
Wardle and Ng 1999

$$< \sigma v >_{\mathrm{i}} = < \sigma v >_{\mathrm{g}} = 1.6 \times 10^{-9}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$$

$$< \sigma v >_{\mathrm{e}} = 1 \times 10^{-15}\ \mathrm{cm}^2 \left(\frac{128kT_e}{9\pi m_e}\right)^{1/2}$$

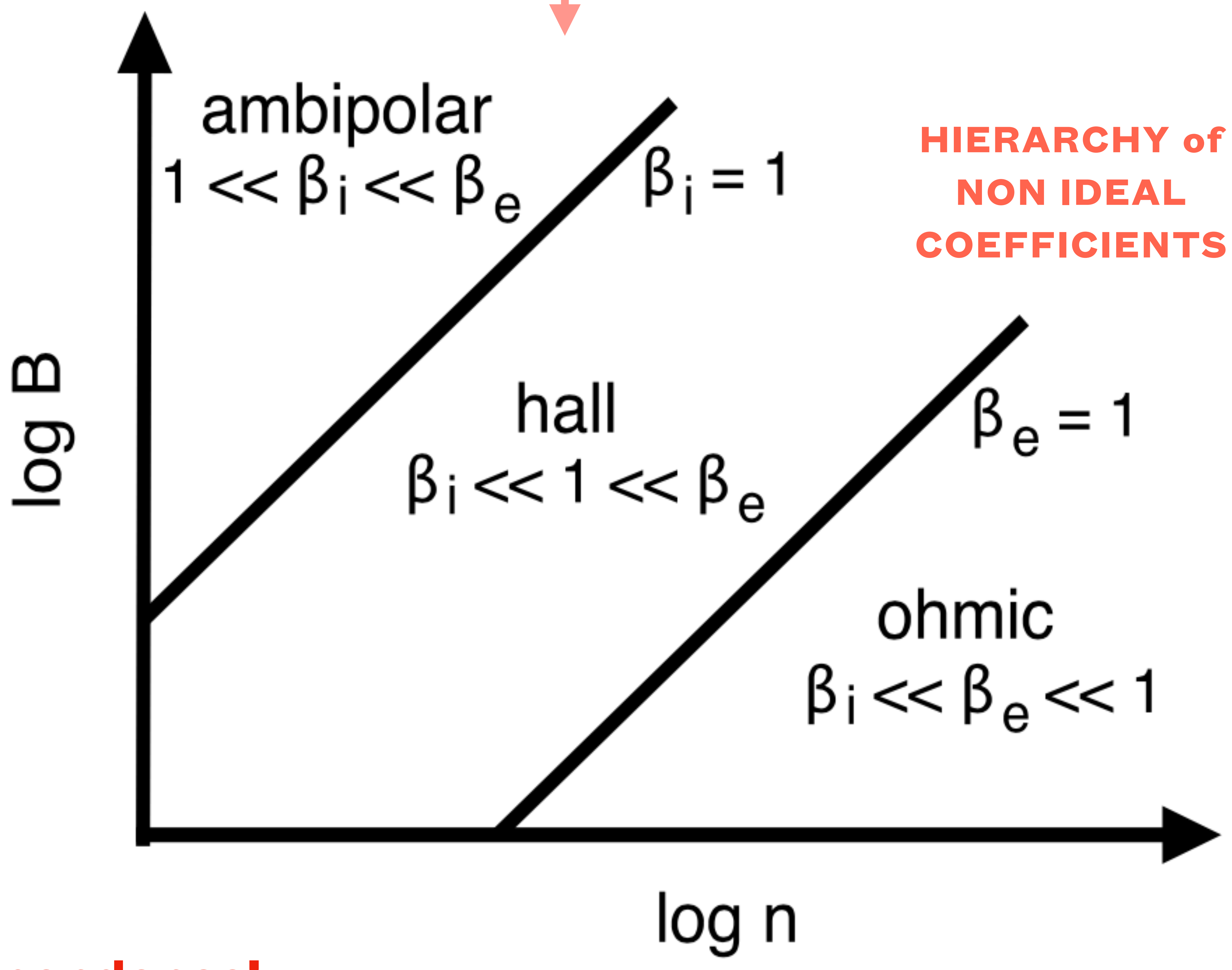
$$< \sigma v >_{\mathrm{G}} = \pi a^2 \left(\frac{128kT}{9\pi m}\right)^{1/2}$$

a is the grain size

Notice the temperature dependence!

DETERMINES

Wardle 2007



HIERARCHY of NON IDEAL COEFFICIENTS

Zweibel 1989, Pucci et al 2020

Tearing Mode in PIP

$$\frac{\partial}{\partial t}(m_i n_i \mathbf{v}_i) + \nabla \cdot (m_i n_i \mathbf{v}_i \mathbf{v}_i + \mathbb{P}_i) = q_i n_i (\mathbf{E} + \mathbf{v}_i \times \mathbf{B}) + \mathbf{R}_i^{ie} + \mathbf{R}_i^{in}$$

$$\nu_{ei} = \frac{n_i m_i}{n_e m_e} \nu_{ie} \Rightarrow \nu_{ie} \ll \nu_{ei}$$

Electrons are light so they don't move the ions when they bounce on them

$$\rho_i \left(\frac{\partial}{\partial t} + \boldsymbol{v}_i \cdot \boldsymbol{\nabla} \right) \boldsymbol{v}_i = \boldsymbol{F}_i - \rho_i \nu_{in} (\boldsymbol{v}_i - \boldsymbol{v}_n)$$

How to express this additional term?

Linearizing for small perturbations the neutral equation

$$\rho_n \left(\frac{\partial}{\partial t} + \boldsymbol{v}_n \cdot \boldsymbol{\nabla} \right) \boldsymbol{v}_n = \boldsymbol{F}_n - \rho_n \nu_{ni} (\boldsymbol{v}_n - \boldsymbol{v}_i)$$

then take the curl

$$\boldsymbol{\nabla} \times \boldsymbol{v}_n = \frac{\nu_{ni} (\boldsymbol{\nabla} \times \boldsymbol{v}_i)}{\gamma + \nu_{ni}}$$

$$\rho_i \nu_{in} \boldsymbol{\nabla} \times (\boldsymbol{v}_i - \boldsymbol{v}_n) = \frac{\gamma \rho_i \nu_{in}}{\gamma + \nu_{ni}} (\boldsymbol{\nabla} \times \boldsymbol{v}_i)$$

Zweibel 1989, Pucci et al 2020

PIP regimes for a thinning current sheet

$$\psi = \bar{k}F\phi + \frac{1}{\bar{S}\gamma\bar{\tau}_{Ai}}(\psi'' - \bar{k}^2\psi)$$ *INDUCTION*

All barred quantities normalized with a, CS thickness

$$\bar{\tau}_{Ai}\left(1+\frac{\nu_{in}}{\gamma+\nu_{ni}}\right)^{1/2} := \bar{\tau}_{Ai}f^{1/2} \to \bar{\tau}_A^*$$

$$\bar{S}_A^* := \bar{S}\frac{\bar{\tau}_{Ai}}{\bar{\tau}_A^*}$$

$$(\gamma\bar{\tau}_{Ai})^2\left(1+\frac{\nu_{in}}{\gamma+\nu_{ni}}\right)(\phi'' - \bar{k}^2\phi) = -F(\psi'' - \bar{k}^2\psi) + F''\psi$$ *MOMENTUM*

$$\gamma\bar{\tau}_A^* \sim (\bar{S}_A^*)^{-1/2} \qquad (1)$$

$$\nu_{\mathrm{ni}} = \frac{n_{\mathrm{i}}m_{\mathrm{i}}}{n_{\mathrm{n}}m_{\mathrm{n}}}\nu_{\mathrm{in}} \qquad \rho = \rho_i + \rho_n$$

For the COUPLED REGIME $\quad \gamma \ll \nu_{ni} \ll \nu_{in}$

$$f = \left(1+\frac{\nu_{in}}{\gamma+\nu_{ni}}\right) = \left(1+\frac{\nu_{in}}{\nu_{ni}}\right) = \left(1+\frac{\rho_n}{\rho_i}\right) = \left(\frac{\rho}{\rho_i}\right)$$

$$(2) \quad \gamma\bar{\tau}_{Ai} \sim \bar{S}^{-1/2}\left(\frac{\rho}{\rho_i}\right)^{-1/4} \ll \nu_{ni}\bar{\tau}_{Ai} \Rightarrow \left(\frac{av_{Ai}}{\eta_m}\right)^{-1/2}\left(\frac{\rho}{\rho_i}\right)^{-1/4} \ll \nu_{ni}\frac{a}{v_{Ai}} \Rightarrow a \ll \left(\frac{\eta_m v_{Ai}}{\nu_{in}^2}\right)^{1/3}$$

Fast reconnection in the three regimes and dependence on system scales

"Ideal" Tearing $a \rightarrow L$

	PIP regimes CS thickness	Transition length scales	Tearing CS thickness	Growth rate at transition	Reconnection time
Coupled	$a \gg a_{c1}$		$a_c \sim LS^{-1/3}(\rho_n/\rho_i)^{1/6}$		$\bar{\tau}_{Coupl} = \bar{\tau}_A$
		$a = a_{c1} = \left(\frac{\eta_O v_A}{\nu_{ni}^2}\right)^{1/3}$		$\gamma \sim \nu_{ni}$	
Intermediate	$a_{c1} \gg a \gg a_{c2}$		$a_c \sim LS^{-1/3}(\nu_{in}\tau_{Ai})^{1/3}$		$\bar{\tau}_{Inter} = \bar{\tau}_{Ai}(\nu_{in}\bar{\tau}_{Ai})$
		$a = a_{c2} = \left(\frac{\eta_O v_{Ai}}{\nu_{in}^2}\right)^{1/3}$		$\gamma \sim \nu_{in}$	
Decoupled	$a \ll a_{c2}$		$a_c \sim LS^{-1/3}(\nu_{in}/\tau_{Ai})^{-\zeta}$		$\bar{\tau}_{Uncpl} = \bar{\tau}_{Ai}$

Thinning current sheet

Increasing Ideal Tearing growth rate

Pucci et al 2020, Pucci et al 2024

Application to the solar Atmosphere

Pucci et al 2024

$$L <= (min)(H_p, L_{conv})$$

Current sheets scale

$$R_\mathrm{m} = \frac{H_p c_s}{\eta_O}$$

Takeuchi and Shibata 2001

	Avrett & Loeser (2008)					*Zhadnov 1962*										
	Height	T[K]	n_e	n_n	n_{HeI}	n_{HeII}	ν_{ei}	ν_{en}	ν_{in}	η_O	η_H	η_{AD}	v_A	H_p	S	R_m
Bottom of the Photosphere	0	6 583	$8.4 \cdot 10^{13}$	$1.19 \cdot 10^{17}$	$1.18 \cdot 10^{16}$	11.7	$6.4 \cdot 10^9$	$7.97 \cdot 10^9$	$2.63 \cdot 10^9$	$4.83 \cdot 10^7$	$7.1 \cdot 10^7$	$3.09 \cdot 10^5$	$6.67 \cdot 10^5$	$4 \cdot 10^7$	$1.1 \cdot 10^6$	$1.12 \cdot 10^6$
	800	5 090	$5.46 \cdot 10^{10}$	$1.5 \cdot 10^{14}$	$1.91 \cdot 10^{13}$	68.7	$7.11 \cdot 10^6$	$8.84 \cdot 10^6$	$1.45 \cdot 10^6$	$8.26 \cdot 10^7$	$1.48 \cdot 10^{10}$	$1.55 \cdot 10^{10}$	$1.8 \cdot 10^6$	$3.09 \cdot 10^7$	$4.44 \cdot 10^5$	$4.49 \cdot 10^5$
Top of the chromosphere	2 098	6 700	$3.29 \cdot 10^{10}$	$2.26 \cdot 10^{10}$	2 530	6.16	$2.9 \cdot 10^6$	1 520	252	$2.5 \cdot 10^7$	$2.28 \cdot 10^9$	$5.19 \cdot 10^{11}$	$4.51 \cdot 10^6$	$4.07 \cdot 10^7$	$2.23 \cdot 10^6$	$2.28 \cdot 10^6$

$$B = B_s \left(\frac{\rho}{\rho_s}\right)^\alpha$$

Leake et al. 2005

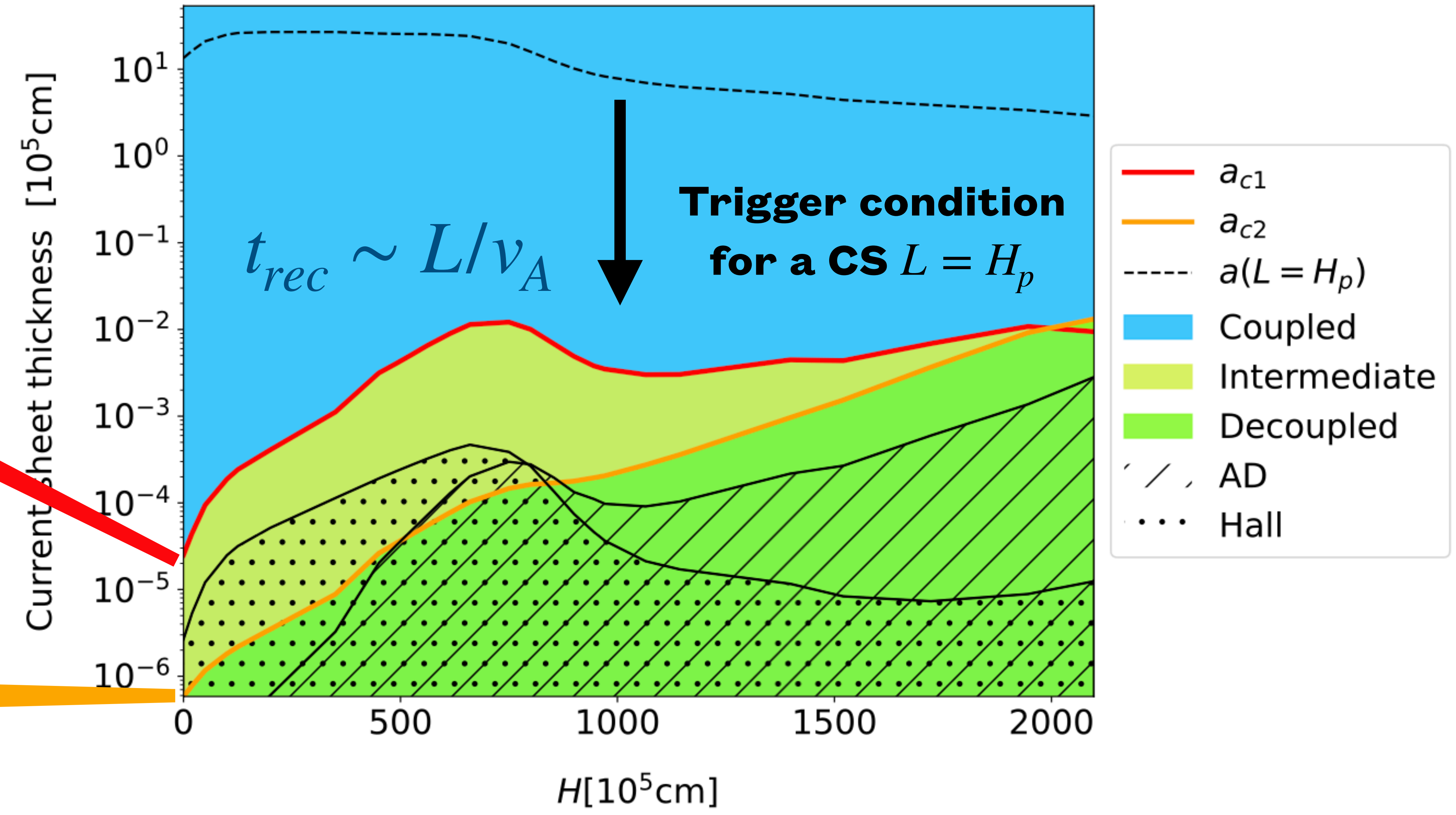
$$\alpha \in (0.3 - 0.6)$$

$$B_s \in (1200,2200)\mathrm{G}$$

Singh & Krishan 2010b

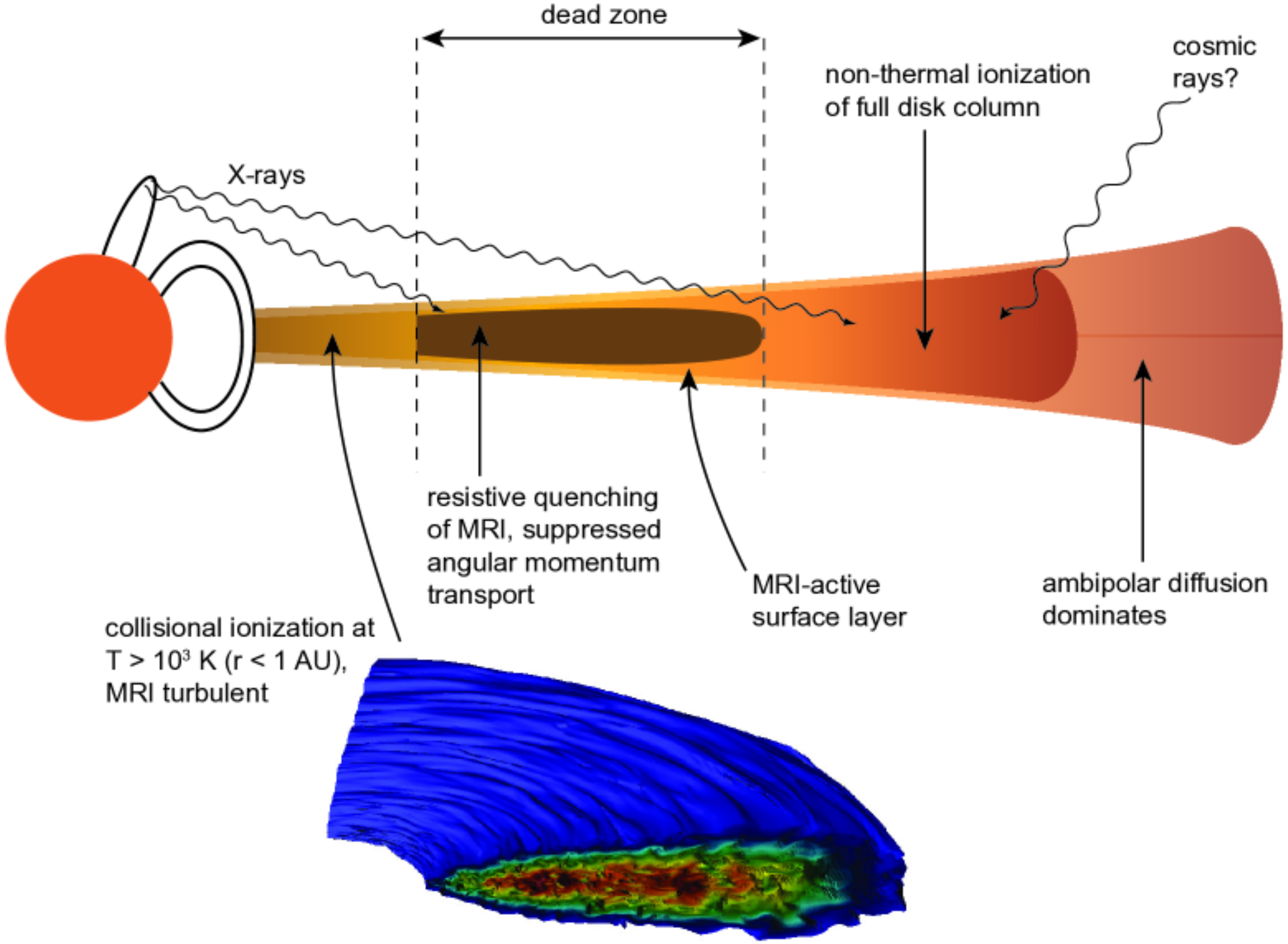
$$\boxed{a_{c1} = \left(\frac{\eta_m v_A}{\nu_{ni}^2}\right)^{1/3}}$$

$$\boxed{a_{c2} = \left(\frac{\eta_m v_{Ai}}{\nu_{in}^2}\right)^{1/3}}$$

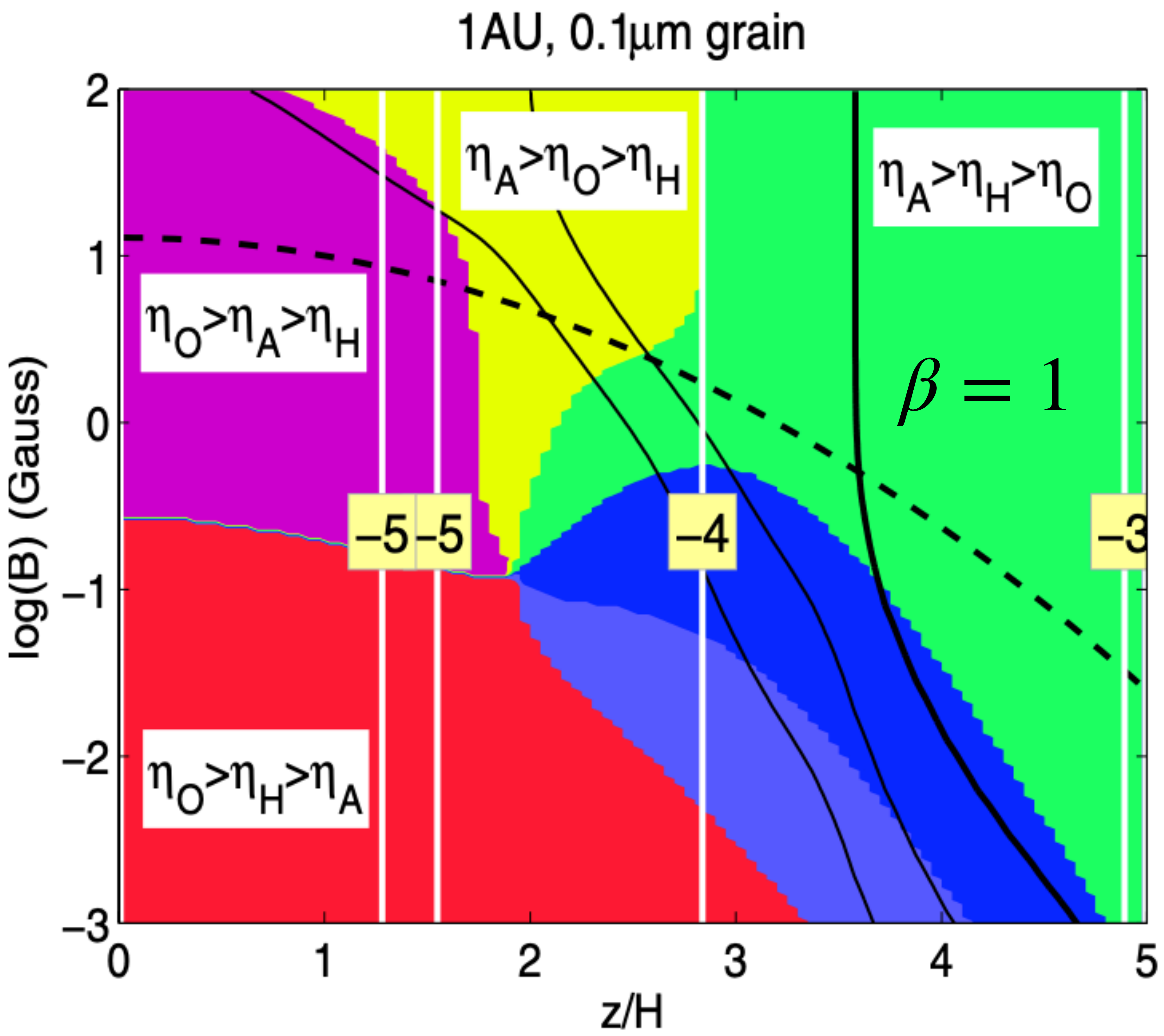


$a \sim 100\mathrm{km}$ could be resolved by DKIST or SOLAR-C (Watanabe 2014; Shimizu et al. 2020; Rimmele et al. 2020)!

Application to astrophysical plasmas PPDs

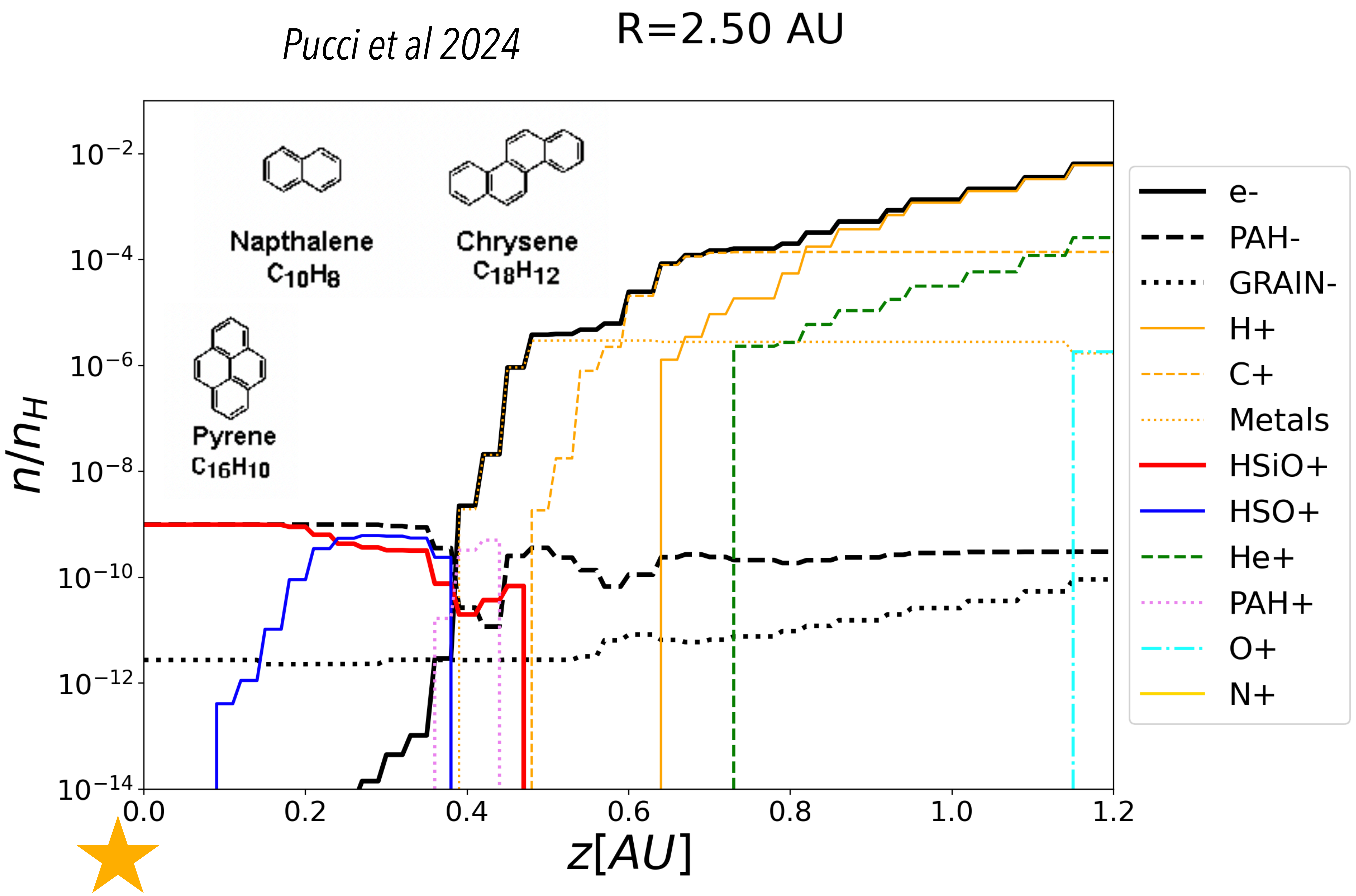


With simplified Thermochemistry Bai 2011

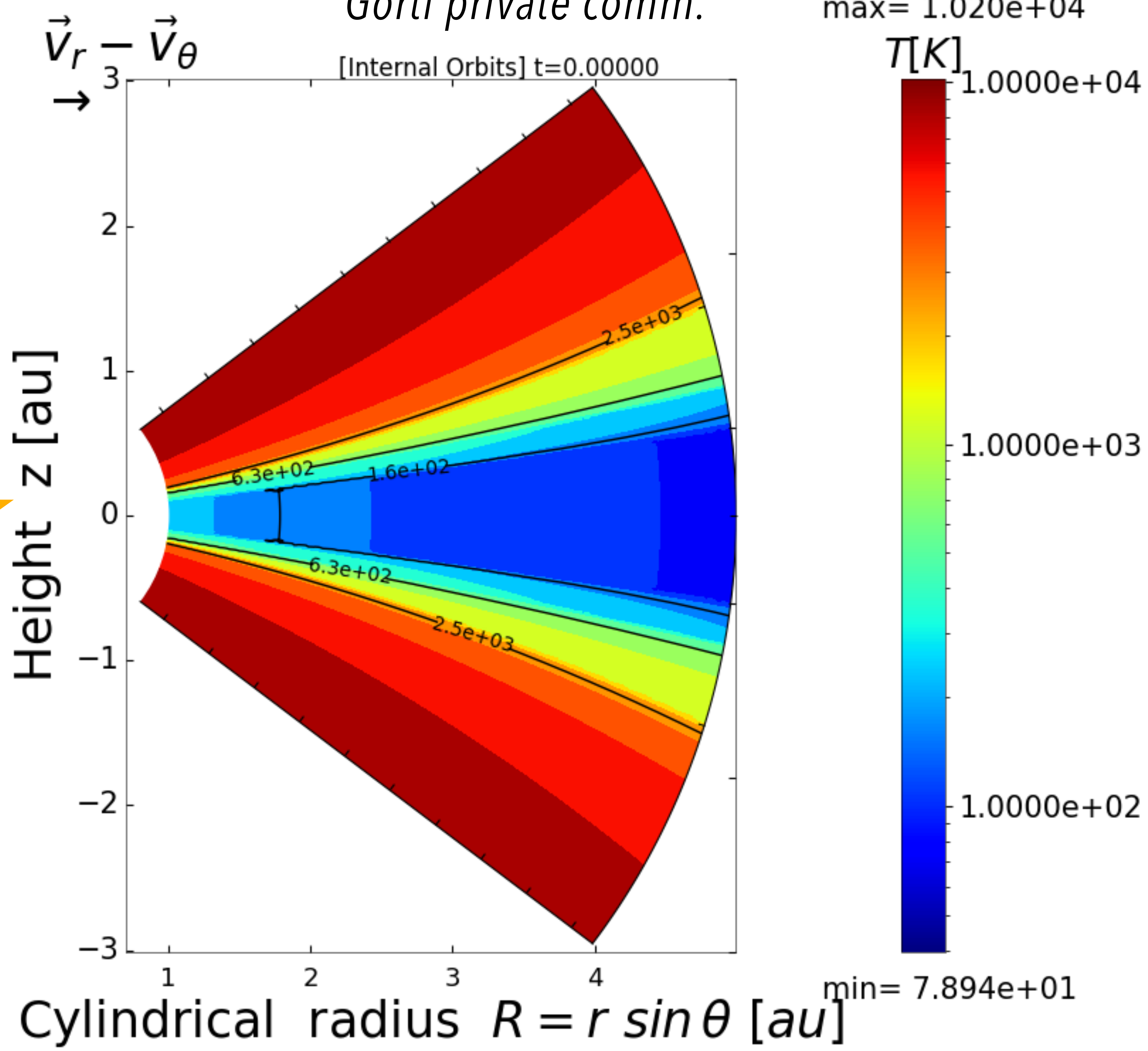


Ruaud and Gorti 2019, our complete thermochemistry network

Pucci et al 2024

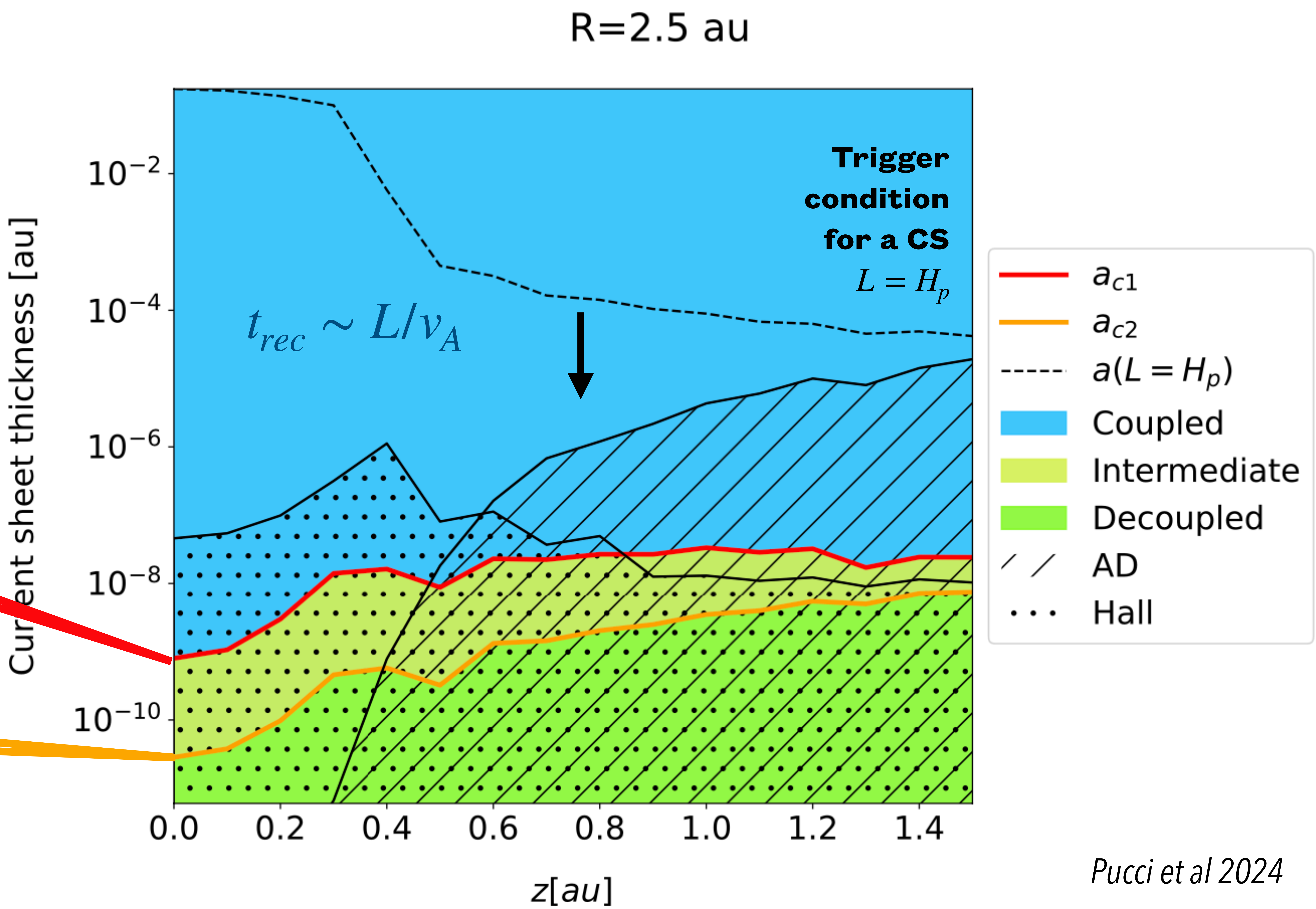


Gorti private comm.



PAHS- are the negative charge carriers at the disk mid plane (Arulanantham 2024 found in sub-solar mass star Tau 042021).

Onset of fast, "efficient" magnetic reconnection and energy conversion.



$$a_{c1} = \left(\frac{\eta_m v_A}{\nu_{ni}^2}\right)^{1/3}$$

$$a_{c2} = \left(\frac{\eta_m v_{Ai}}{\nu_{in}^2}\right)^{1/3}$$

Pucci et al 2024

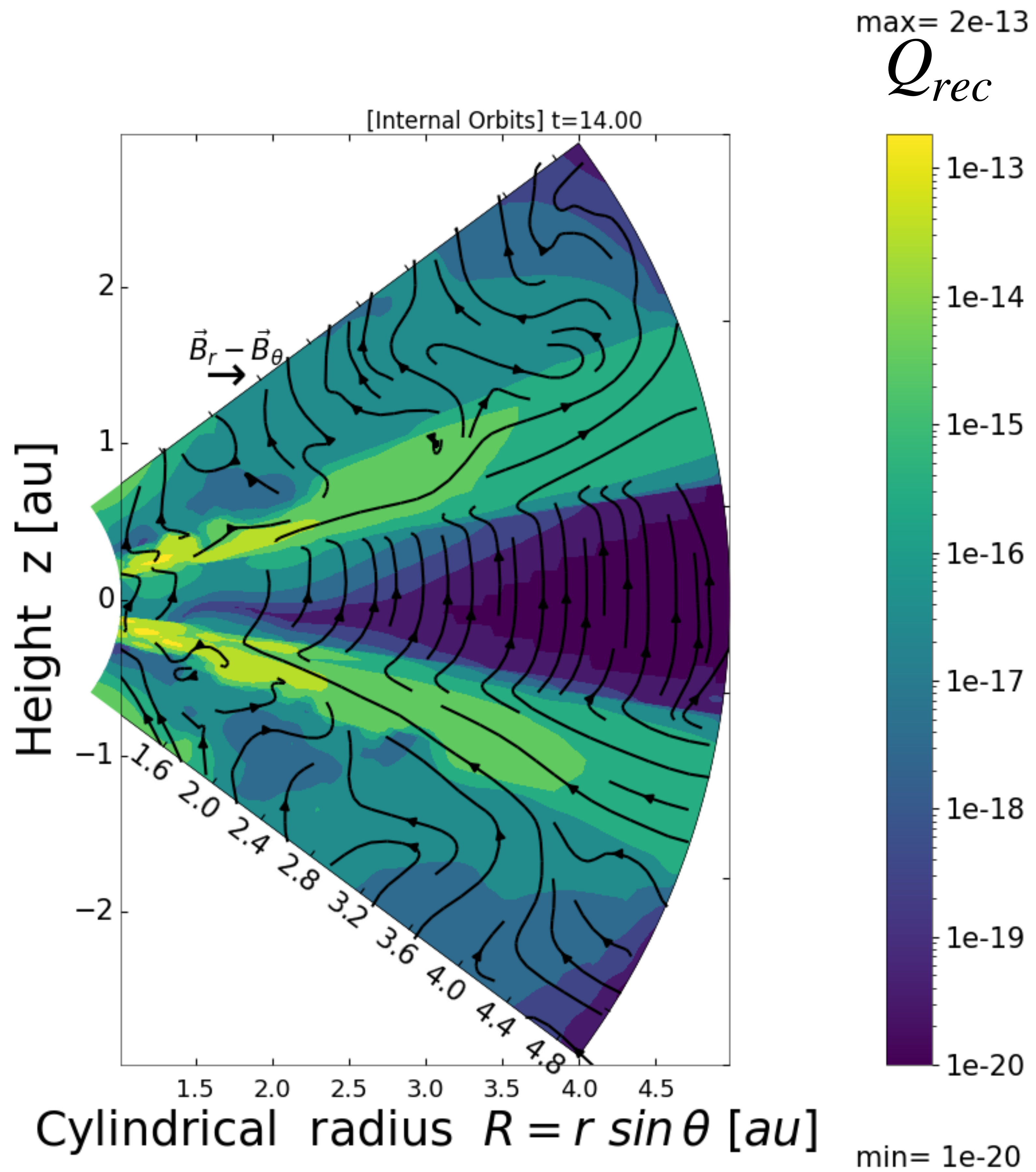
Reconnection feedback on disk heating

$$Q_{rec} = \frac{dE_M}{dt} = \frac{B^2}{8\pi}\frac{v_A}{L}$$

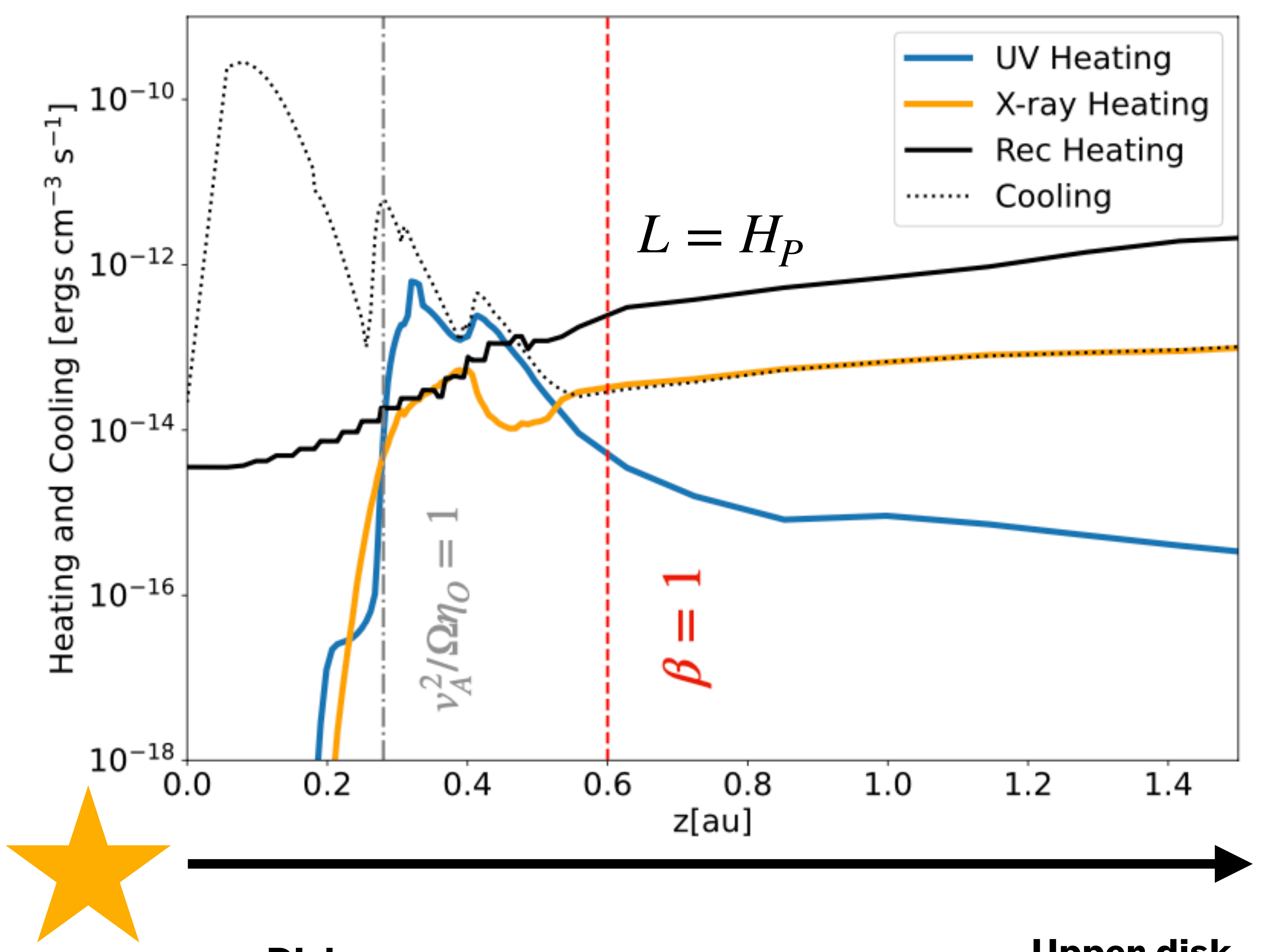
Pucci et al 2024

Pucci et al in prep.

$R = 2.5\text{au}$



Using limitation by accretion power from Pringle et al 1981…



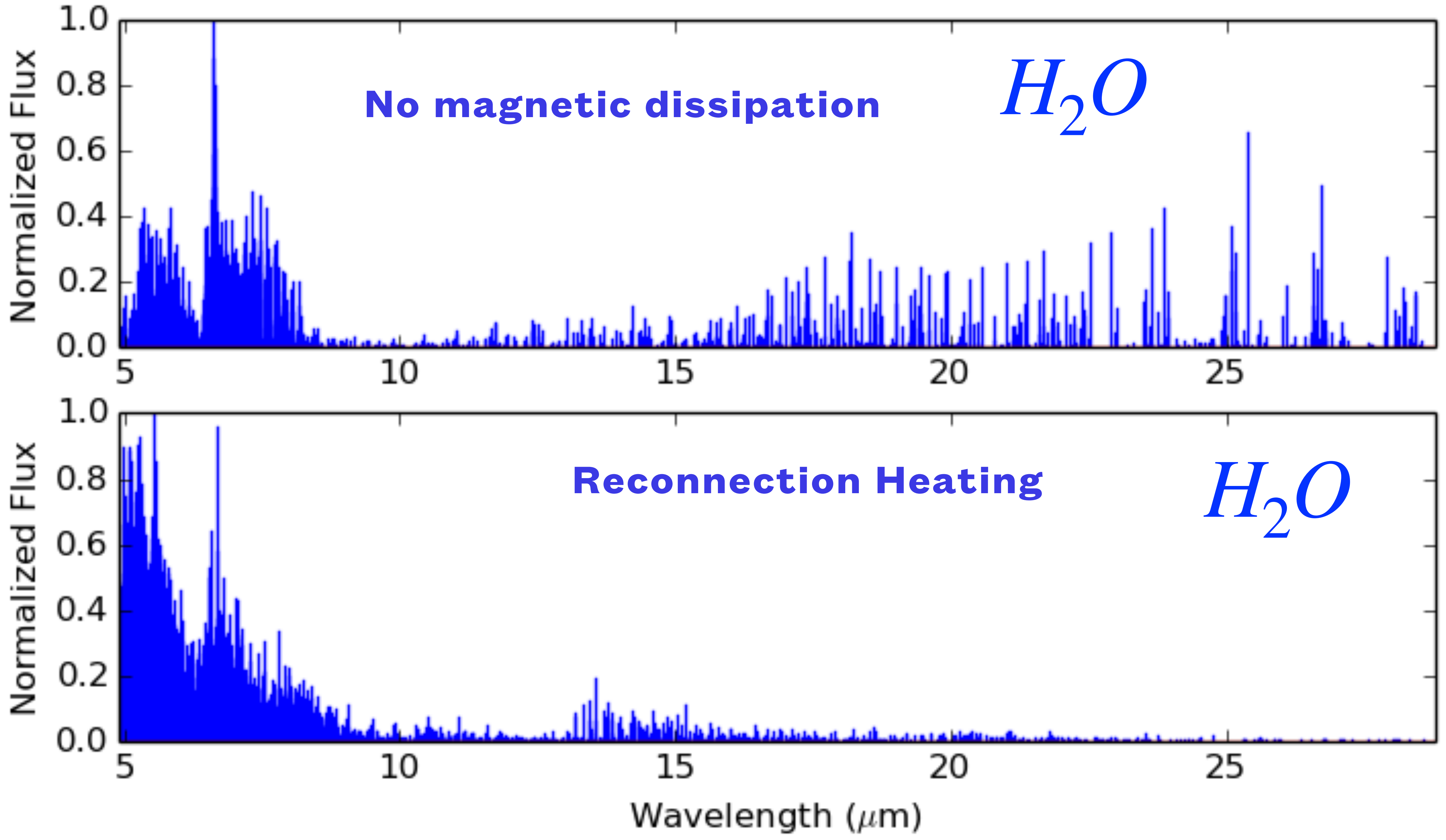
Disk Midplane

Upper disk atmosphere

Additional source of heating/ionization for the thermochemistry code: feedback from MHD

Gorti private comm.

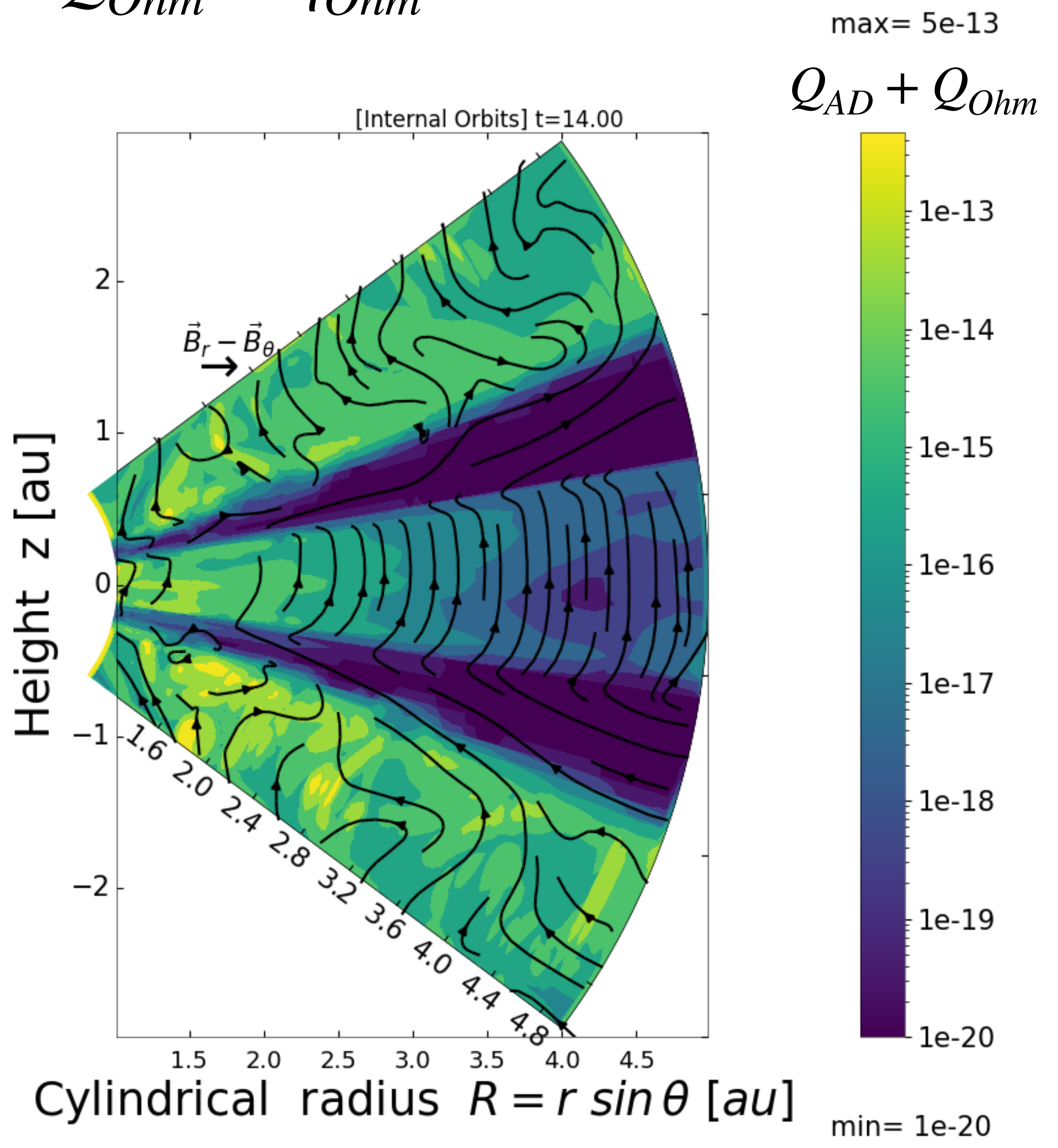
nLTE radiative transfer solved for the LAMBDA database



$$Q_{AD} = \eta_{AD} J_{\perp}^2$$

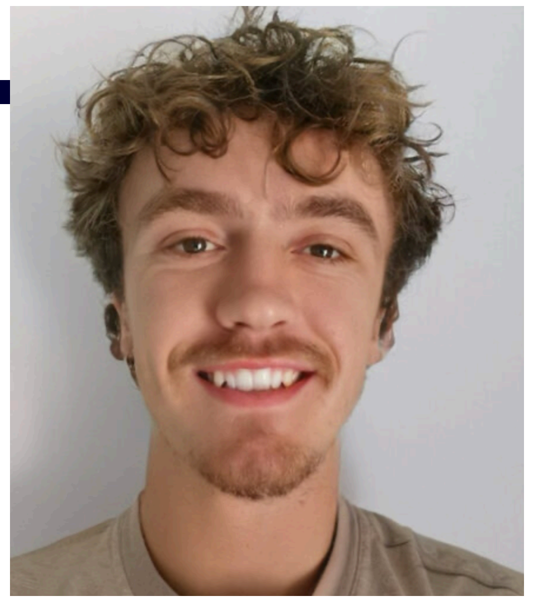
$$Q_{Ohm} = \eta_{Ohm} J^2$$

Pucci et al in prep.



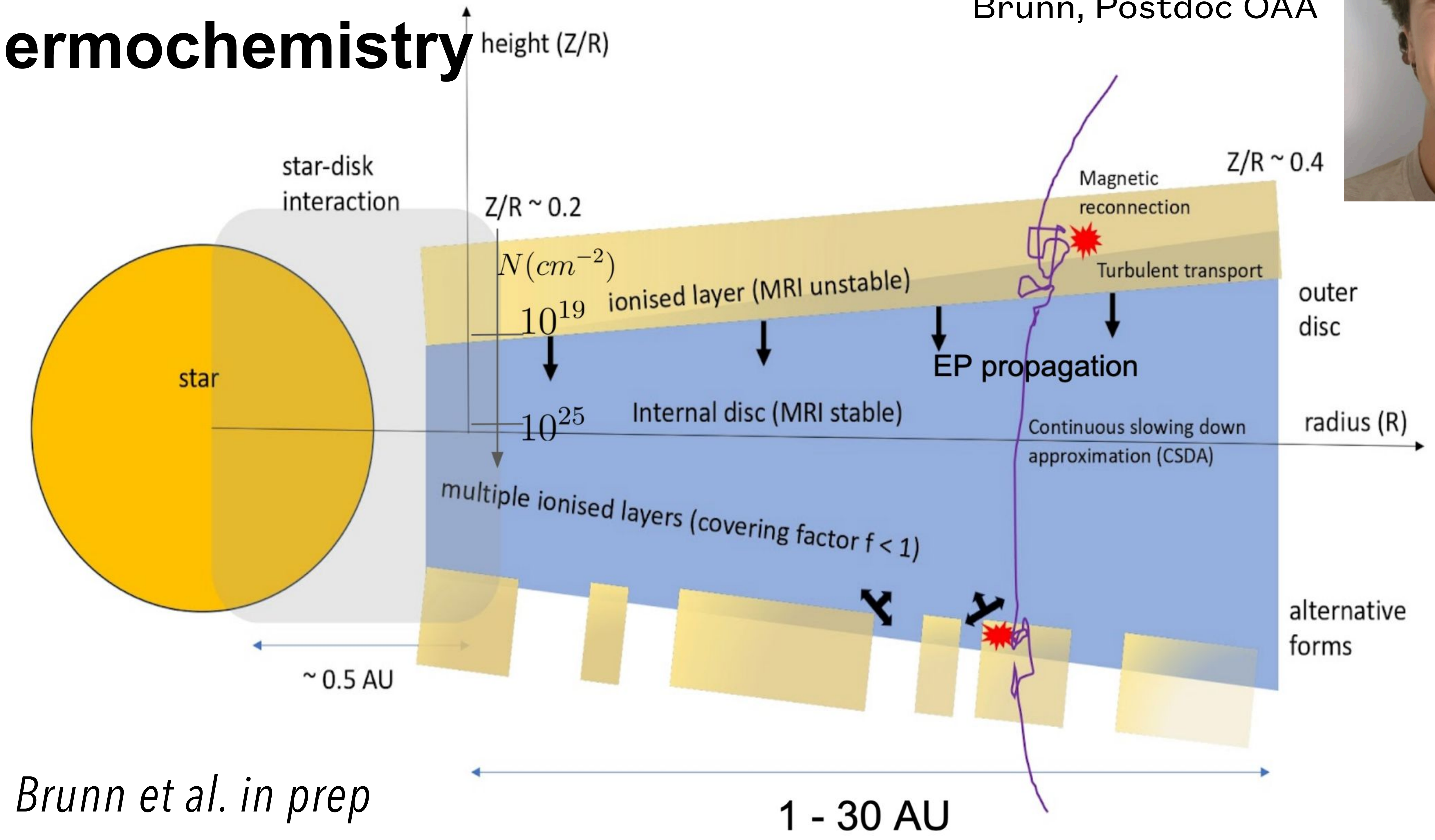
Additional source of ionisation for thermochemistry *(Work in progress)*

Valentin Brunn, Postdoc OAA



Energetic particles (EPs) acceleration by reconnection in turbulence

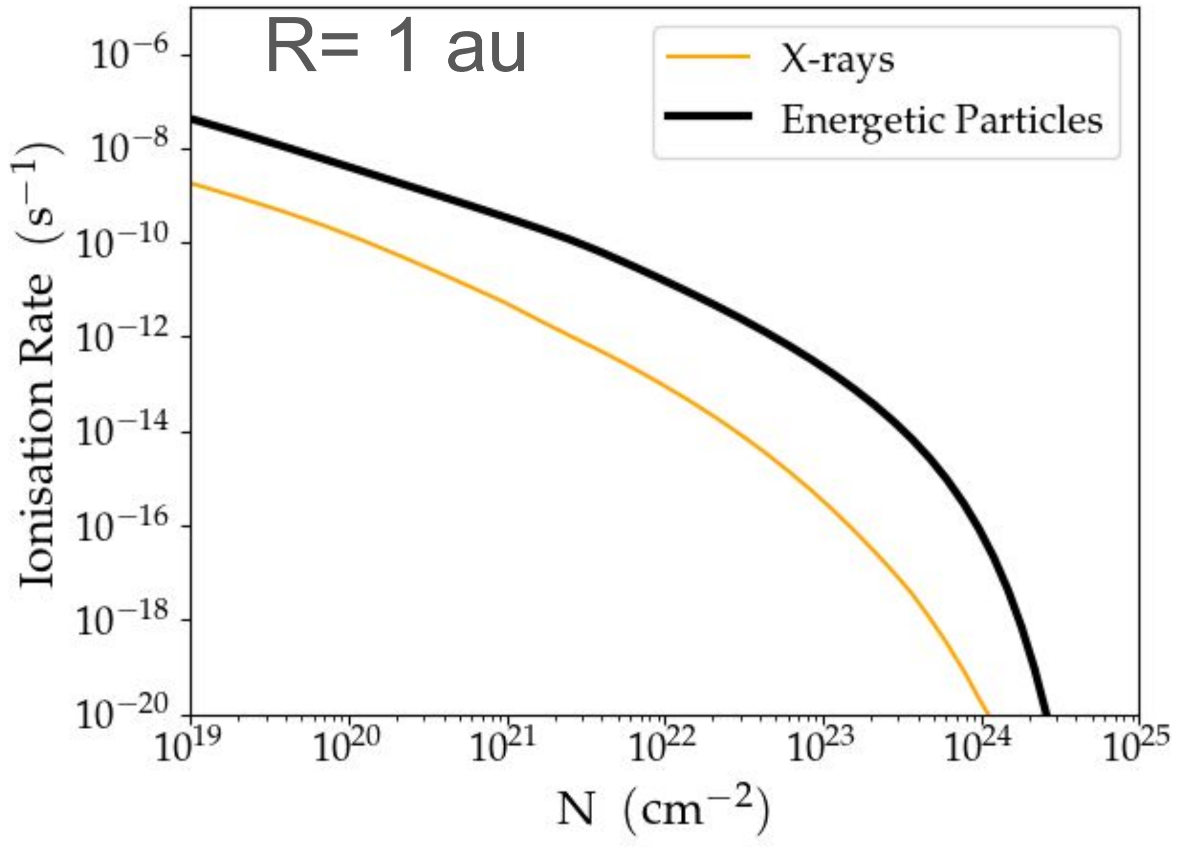
- A fraction of **magnetic energy** $(Q_{\rm rec})$ goes into low-energy particles with E<100 MeV.
- These **non-thermal particles** ionize the disc as they propagate
- Energy is deposited **deep in the disc**, reaching midplane regions



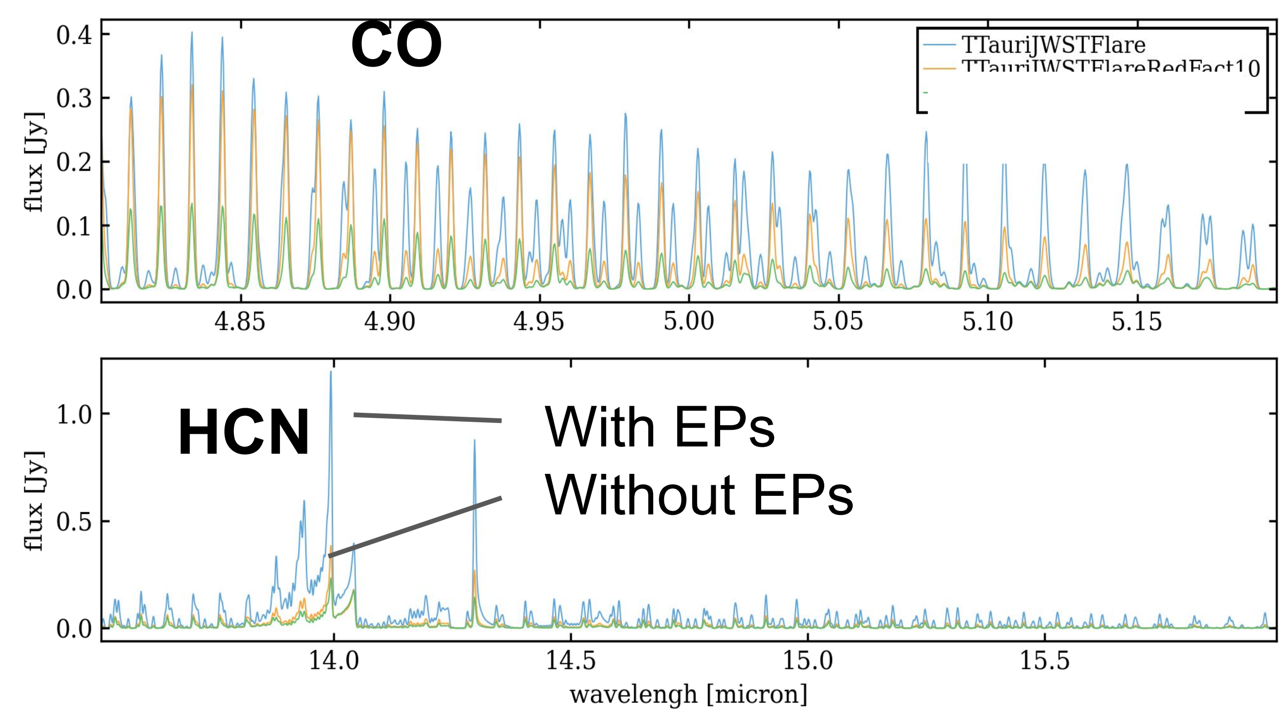
Brunn et al. in prep

Impact on the disc chemistry with ProDiMo

- **One order of magnitude** enhancement of ionization rate compared to the standard ionisation sources (X-rays/UV)
- Increase in abundance of **ionisation tracers** e.g HCO^+
- New ingredient for thermochemical models **boost synthesis of complex molecules** e.g HCN



Synthetic JWST/MIRI spectra



Conclusions

- Magnetic reconnection (MR) occurs in partially ionized astrophysical and space plasmas and laboratory devices have experimented or been in part dedicated to the study of this process.

- A simplified fluid approach is provided by the "multicomponent plasma" (Braginskii 1965) which allows us to understand, the role of elastic collisions between the species in MR, neglecting particles production and charge exchange reactions.

- In collapsing current sheets the analysis provided by Zweibel 1989 is reviewed (Pucci et al 2020) to discuss the PIP regimes (coupled, weakly coupled, decoupled), and the onset of fast magnetic reconnection.

- Application of the model to the solar photosphere and chromosphere provides a lower limit for the fast reconnecting CS of $a \sim 100\mathrm{km}$ (Pucci et al. 2024), which could be resolved by DKIST or SOLAR-C (Watanabe 2014; Shimizu et al. 2020; Rimmele et al. 2020).

- Application of the model to PPDs: heating and ionization by MR can change the chemistry and elements available for planet formation and local sound speed, changing the winds launching speed (Suzuki et al 2010, McNally 2013, Pucci et al 2024, Brunn et al 2024).

- A refined model including multi species analysis and local heating functions would significantly improve the estimate on MR impact in energy transfer processes (see e.g. Wargnier et al 2022 10.3847/1538-4357/ac6e62).

Additional literature (some)

Chiueh 1998 10.1086/305180**,** *Ambipolar Diffusion--driven Tearing Instability in a Steepening Background Magnetic Field*

Lazarian and Vishniac 1999 10.1086/306643, *Reconnection in the Interstellar Medium*

Ji, H. S. et al. 2001 *10.1086/319012,* *Exact Solutions for Two-dimensional Steady State Magnetic Reconnection in Partially Ionized Plasmas*

Tsap and Stepanov 2011 10.1017/S1743921311007174 *Ambipolar Diffusion and Magnetic Reconnection*

Howes 2018 *10.1063/1.5025421,* *Laboratory space physics: Investigating the physics of space plasmas in the laboratory*

Jara-Almonte et al 2019 10.1103/PhysRevLett.122.015101,
Kinetic Simulations of Magnetic Reconnection in Partially Ionized Plasmas

Jara-Almonte et al 2021 10.1063/5.0039860,
Multi-fluid and kinetic models of partially ionized magnetic reconnection

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