Dynamics and diagnosis of protostellar disks with consistent thermochemistry

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Apropos this morning's talks

It is a profoundly erroneous truism, repeated by all copy-books and by eminent people when they are making speeches, that we should cultivate the habit of thinking of what we are doing. The precise opposite is the case. ***Civilization advances by extending the number of important operations which we can perform without thinking about them.*** *Operations of thought are like cavalry charges in a battle—they are strictly limited in number, they require fresh horses. It must only be made at decisive moments.*

—Alfred North Whitehead
(with apologies to John Lattanzio)

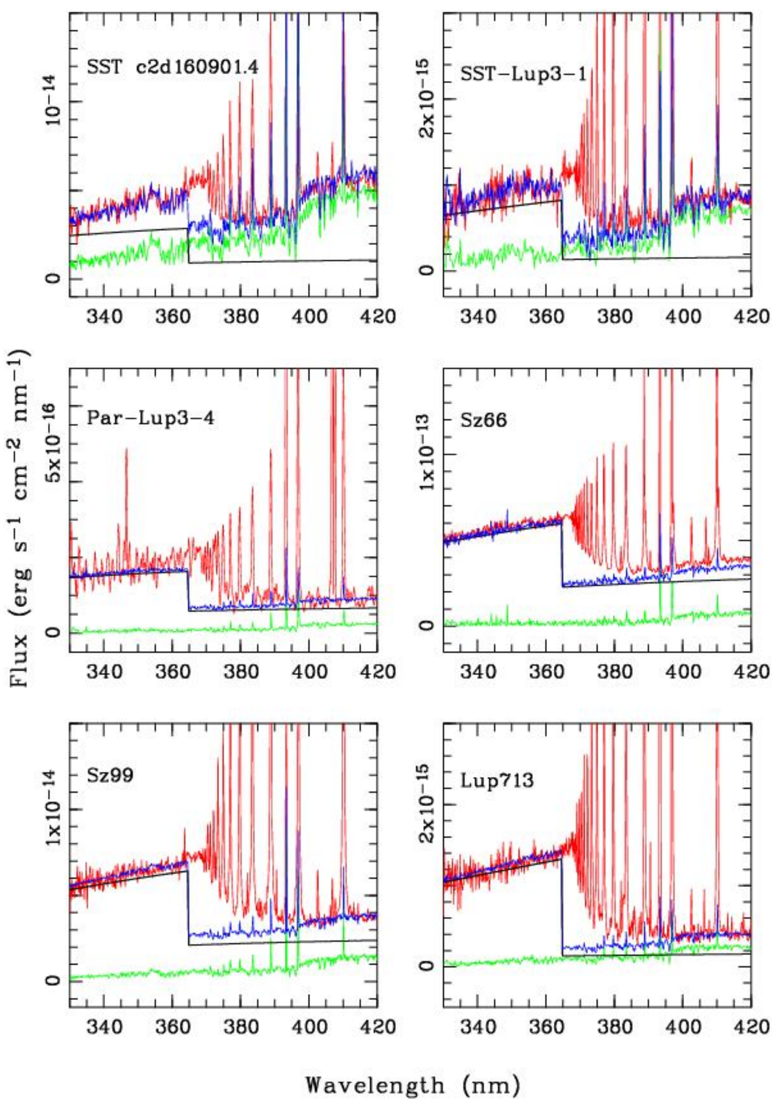
A sad spectacle. If they be inhabited, what a scope for misery and folly. If they be not inhabited, what a waste of space.

—Thomas Carlyle
(with apologies to Didier Queloz)

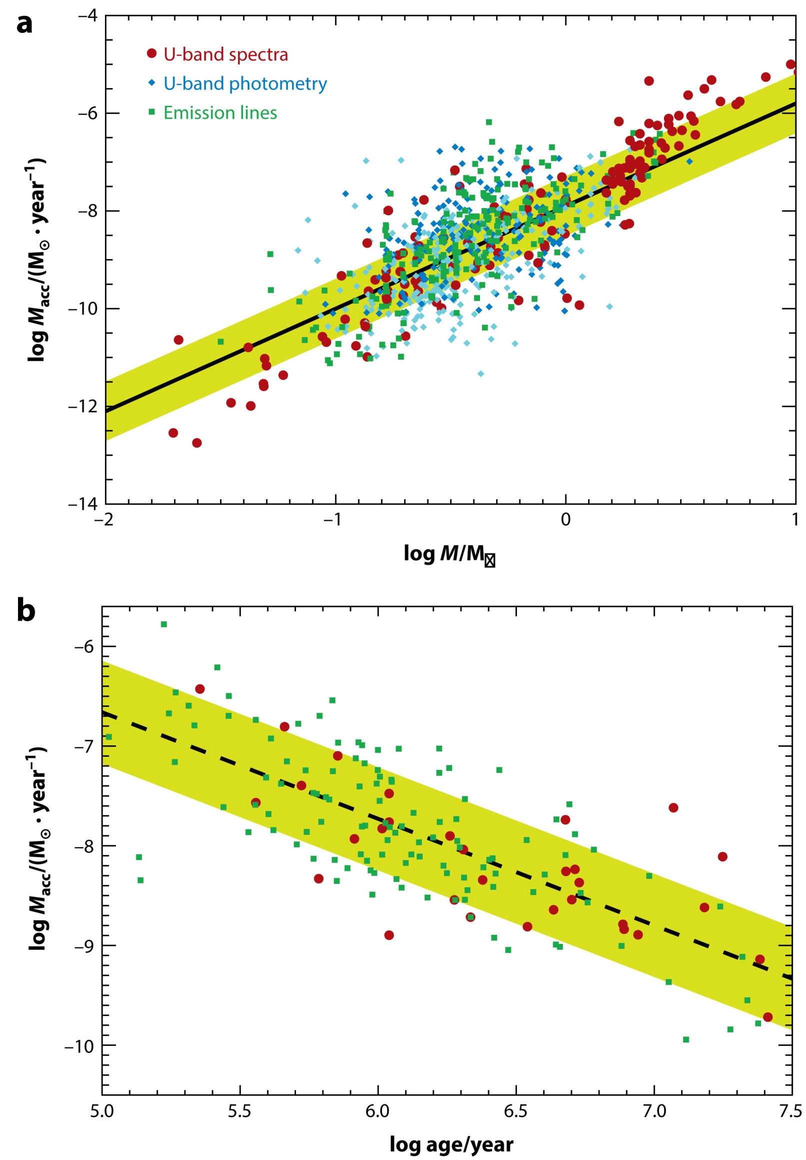
Outline

- Observational constraints on accretion, photoevaporation, and winds
- The need for realistic thermochemistry in dynamical models
- Hydrodynamic photo-evaporation
- Magnetohydrodynamic photoevaporation
- Appendix: Accretion in transitional disks

Accretion rates of PPDs are measured

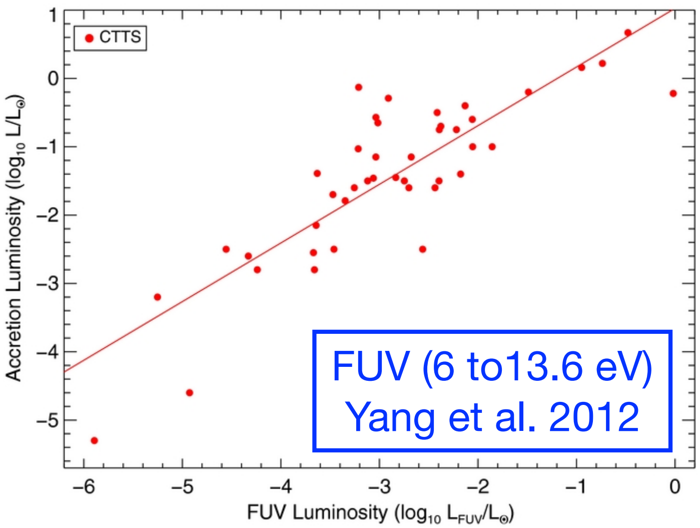


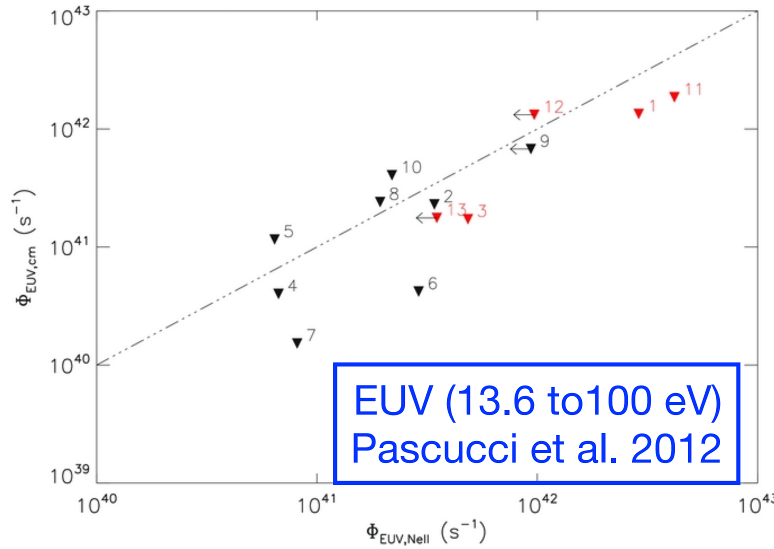
Alcalá et al. 2014



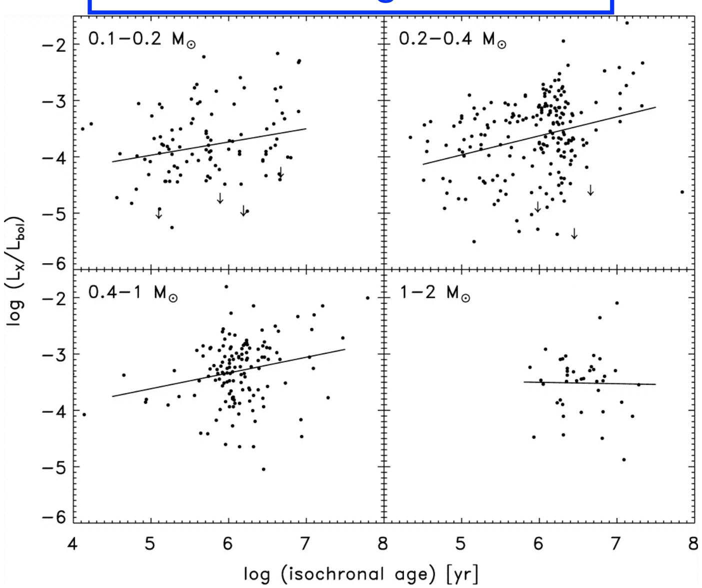
Hartmann L, et al. 2016.
Annu. Rev. Astron. Astrophys. 54:135–80

…As are their stars' hard-photon luminosities





Xrays (0.5 to 8 keV)
Preibisch & Feigelson 2005

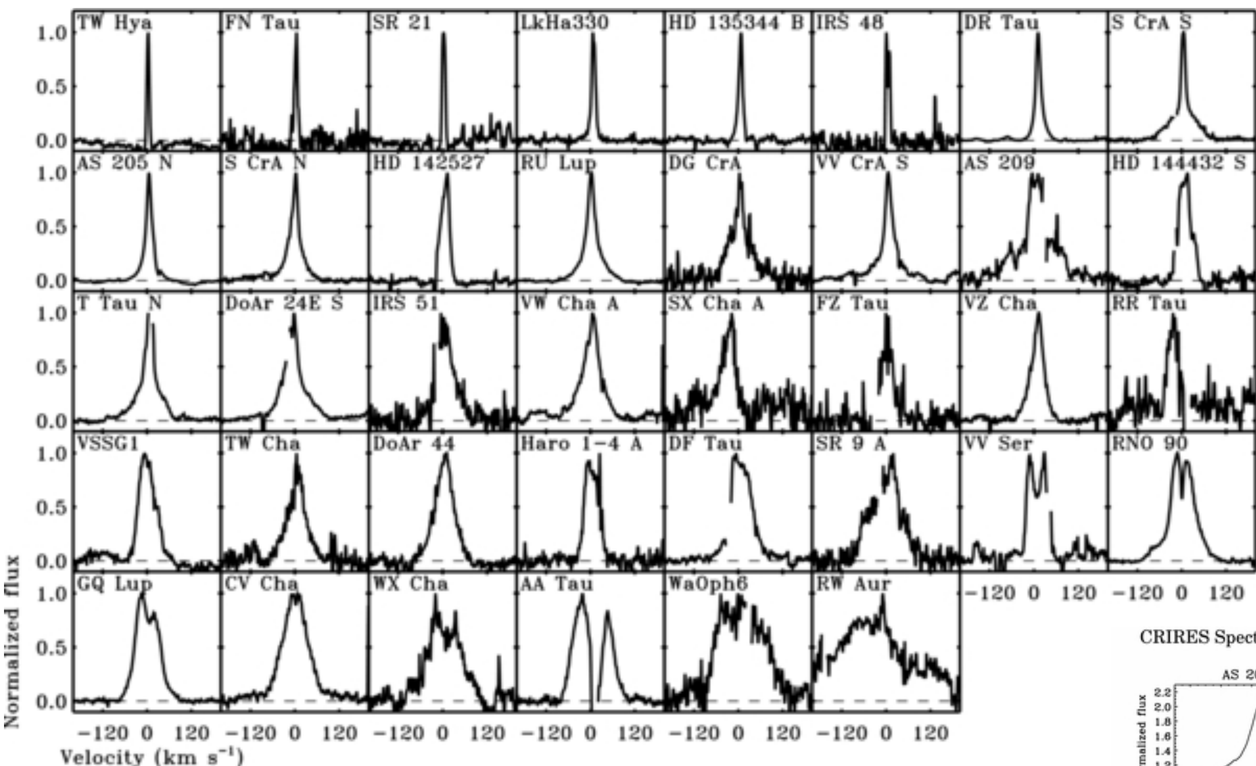


$$\log(L_{\rm hard} / L_{\rm bol}) \approx -3 \pm 0.5$$

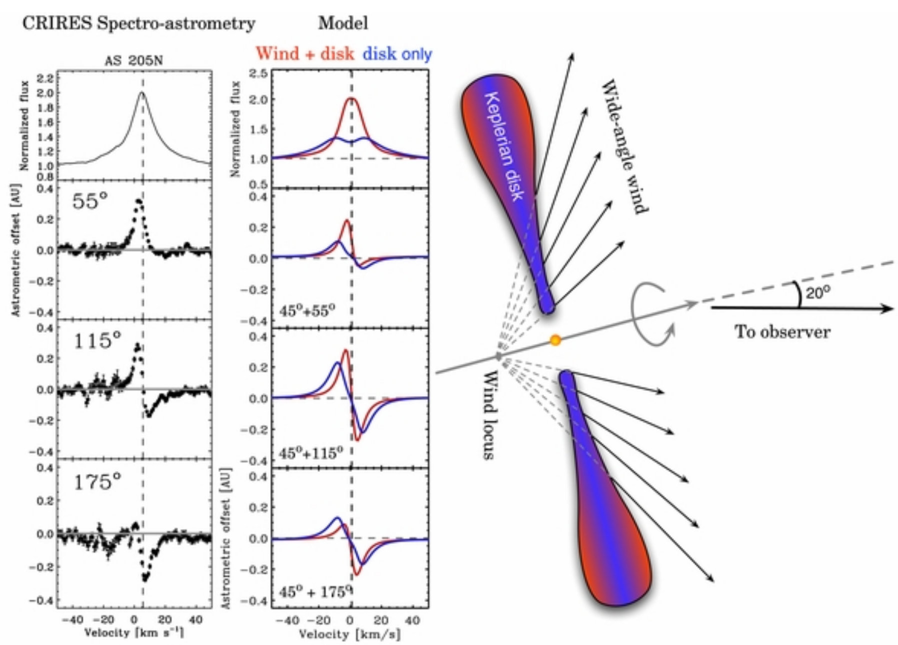
$$t_{\rm evap} \gtrsim \frac{GM_* M_{\rm d}}{2\eta L_{\rm hard} r_{\rm d}}$$

$$\sim 10^6 \eta_{0.1}^{-1} \left(\frac{M_{\rm d}}{0.015 M_\odot} \right) \left(\frac{r_{\rm d,h}}{10\,{\rm AU}} \right)^{-1} {\rm yr}$$

Single-peaked CO ro-vibrational lines suggest a slow, wide-angle wind



Brown et al. 2013



Pontoppidan et al 2011

Mechanisms for angular momentum transport and turbulence

- Hydrodynamic mechanisms:
  - High-Reynolds-number turbulence driven by radial shear
  - Thermally supported instabilities (leading to turbulence)
    - vertical convection
    - Baroclinic (radial entropy gradient) in-/over-stability
    - Vertical shearing/Goldreich-Schubert-Fricke instability
  - Planetary density-wave wakes
  - Self-gravity
- Magnetic mechanisms:
  - Magnetorotational instability
  - Magnetized winds

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Minimal magnetic fields for accretion

- MRI-driven accretion:

$$(-B_R B_\phi)^{1/2} \approx \left(\frac{\dot{M}_{\rm acc}\Omega}{H} \right)^{1/2} \approx 0.5\,\dot{M}_{-8}^{1/2} r_{\rm AU}^{-11/8}\ \text{Gauss}$$

- Wind-driven accretion:

$$(-B_z B_\phi)^{1/2} \approx \left(\frac{\dot{M}_{\rm acc}\Omega}{2R} \right)^{1/2} \approx 0.07\ \dot{M}_{\rm acc}^{1/2} r_{\rm AU}^{-5/4}\ \text{Gauss}$$

➡ **Winds allow fields to be weaker by ~ $(H/R)^{1/2}$**

Past work on photoevaporation of PPDs

- Hollenbach, Johnstone, Lizano, & Shu (1994)
  - EUV only; analytic
- Font, McCarthy, Johnstone, & Ballantyne (2004)
  - EUV + 2D hydro (ZEUS); $c_s \rightarrow 10$ km s^{-1}
  - Microphysics post-hoc, including forbidden-line predictions
- Alexander, Clarke, & Pringle (2006): similar to Font et al. '04
- Gorti & Hollenbach (2008, 2009)
  - FUV, EUV, & X-rays
  - Detailed microphysics, analytic hydro (spherical Parker wind)
- Owen, Ercolano, Clarke, & Alexander (2010)
  - EUV & X-rays; temperature via lookup table in ionization parameter
  - 2D hydro (ZEUS) w.

Why thermochemistry?

- To get the dynamics right.
  - The flow depends strongly on gas temperature, molecular weight, and (when magnetized) ionization level.
- To confront observations.
  - There is a wealth of atomic [OI, NeII, …] and molecular [CO, H_2O,…] line data that may constrain winds & turbulence.
  - Much of the chemistry for this purpose could be modeled in post-processing, but reactions are not always in local equilibrium.
    - E.g., flow and dissociation timescales for CO can be comparable at the wind base.

Methods: Chemistry

- Reduced set of chemical ``species", including grains:
  - Non-MHD runs: e^-, H^+, H, H_2, H_2^*, He, He^+, O, O^+, O^*, OH, H_2O, C, C^+, CO, S, S^+, Si, Si^+, Fe, Fe^+, *Gr*, *Gr^+*, *Gr^-* [24 species]
  - MHD runs: *as above, plus* OH^+, HCO^+, CH^+, SiO, SiO^+ ; *minus* O^*, Fe, Fe^+ [26 species]
- Reactions involving these species:
  - 2-body reactions from UMIST 2012
  - Photoionization/photodissociation reactions (various sources)
  - Dust reactions: molecule formation, charge exchange
- Reactions are computed on a GPU
  - ~ 100-fold speedup compared to CPUs

Methods: Radiation

- Ray tracing from r=0 for FUV, EUV, X-rays
  - Plus (with MHD) vertical diffusion of X-rays in disk, following Igea & Glassgold (1999)
  - Diffuse Lyα tested (via Monte Carlo) but found unimportant
- A floor is set on the dust temperature in the disk, to avoid having to calculate the diffuse IR field
- Prescriptions for ``pre-absorption" of low-latitude hard photons interior to inner boundary (r < 1 AU)

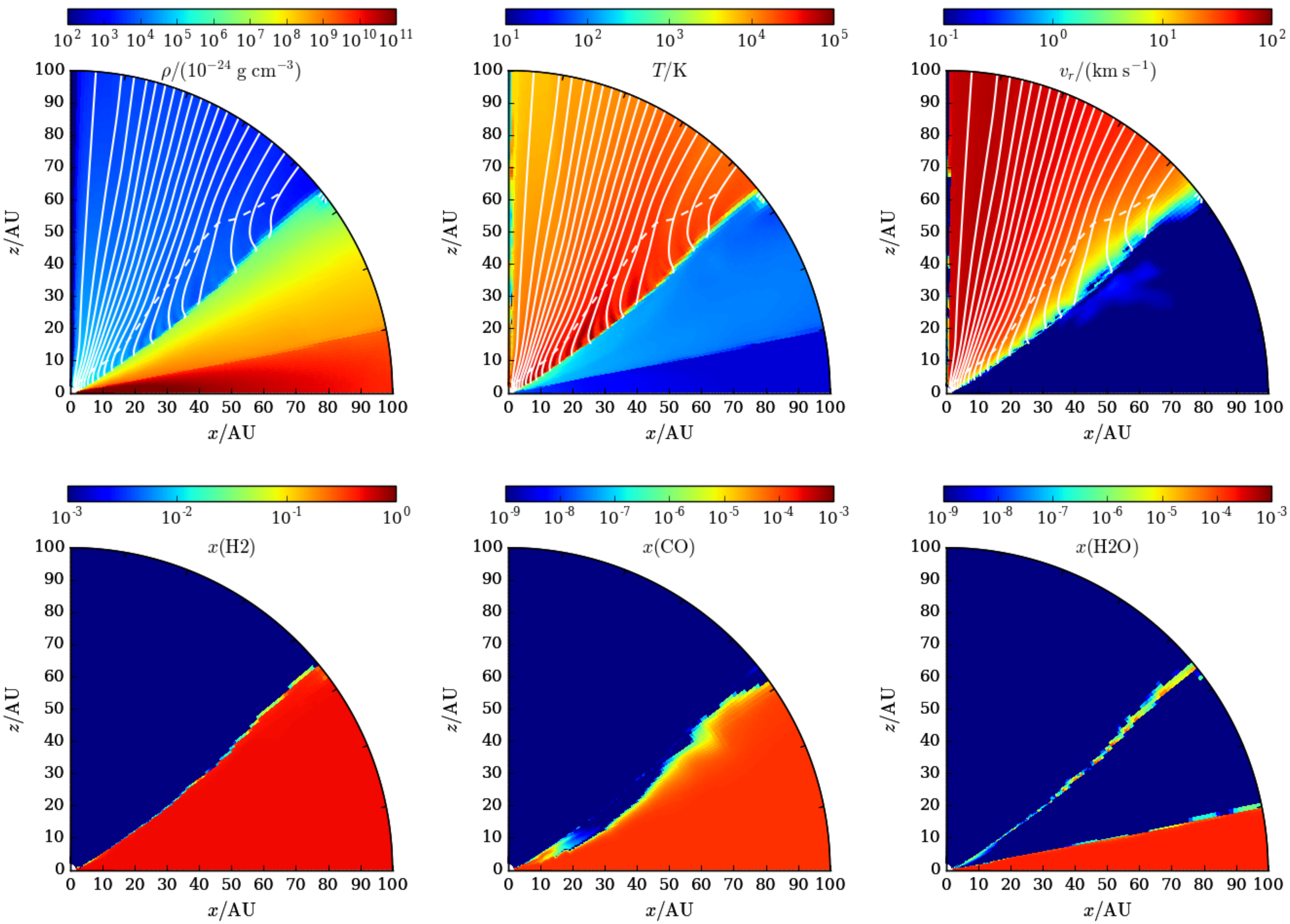
Methods: Temperature

- ✦ Heating:
  - ✳ ionization by EUV & X-rays
  - ✳ photodissociation with self- & cross-shielding of H_2 & CO
  - ✳ H_2 excitation by Lyman-Werner photons ($13.6 > h\nu > 11.3$ eV)
  - ✳ photoelectric emission by grains
  - ✳ thermal accommodation on dust
- ✦ Cooling:
  - ✳ Atomic recombination
  - ✳ Atomic forbidden lines
  - ✳ Ro-vibrational lines (CO, OH, H_2O) w. escape probability
  - ✳ Thermal accommodation on dust

Methods: Hydro and MHD

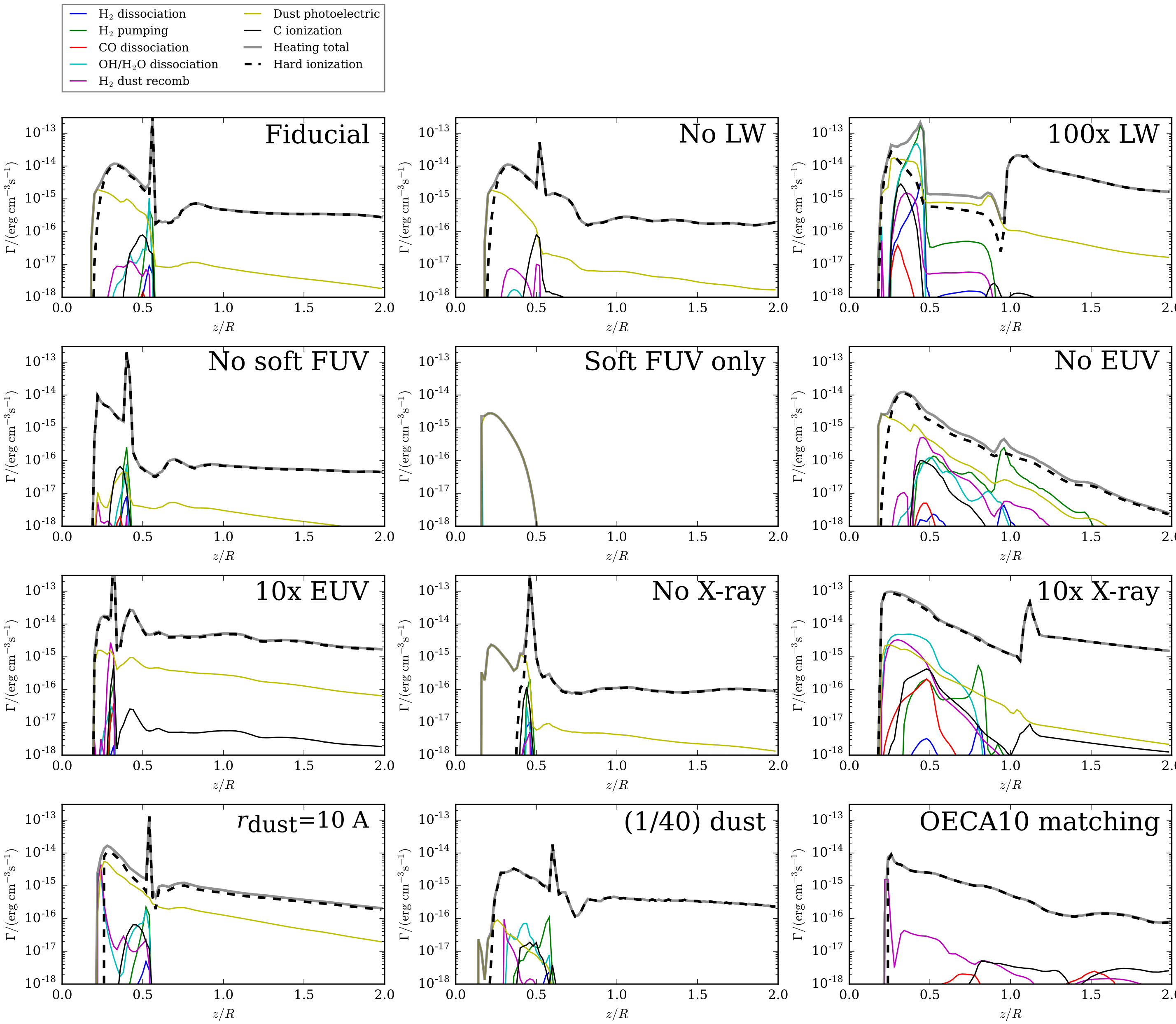
- Athena++
- Axisymmetric (2.5D), also symmetric about midplane
- Spherical polars
  - Logarithmic grid in $r \in (1,50)/(2,100)$ AU; 256/384 zones typically
  - Linear grid in $\theta \in (0, \boldsymbol{\pi}/2)$; 128 zones
- Non-ideal MHD via tensorial diffusivity
  - Ohmic and ambipolar terms, but not Hall
- Disk initial conditions after Nelson et al. (2013)

Flow structure in the fiducial hydro model



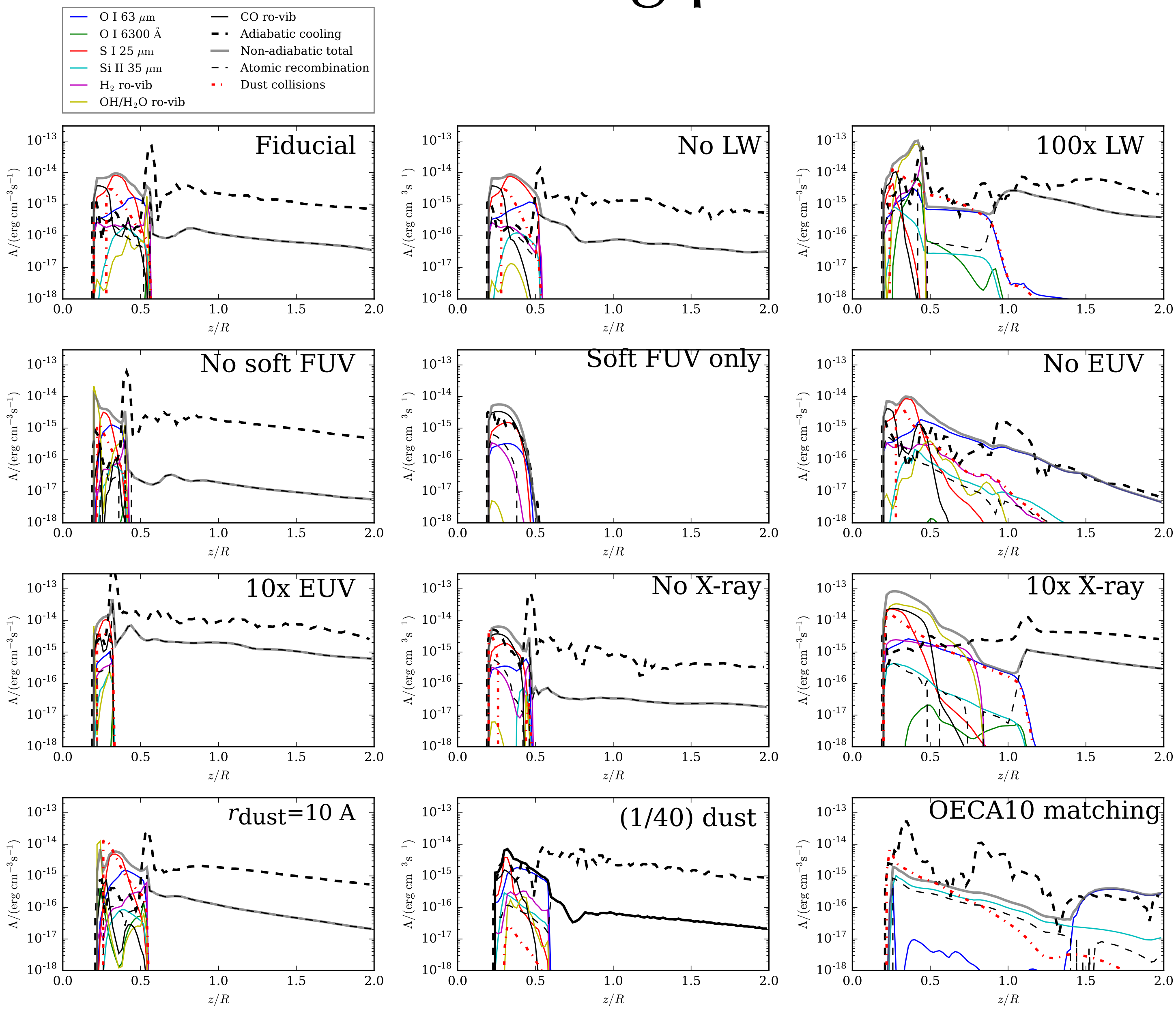
WG17b

Heating processes



WG17b

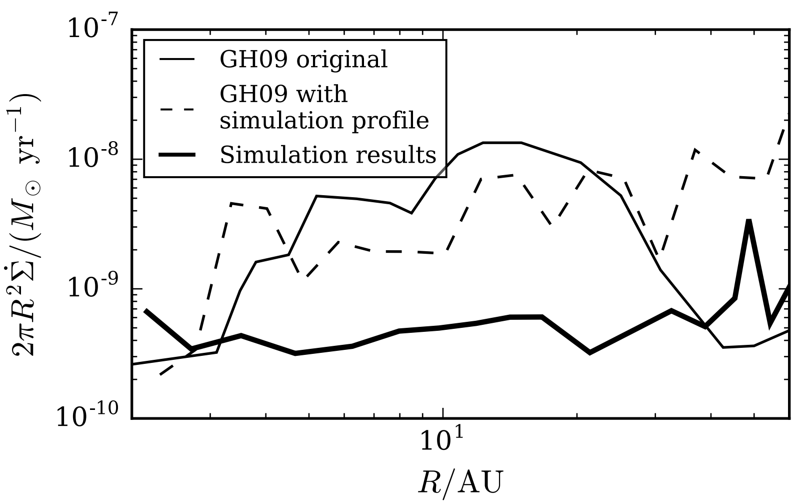
Cooling processes

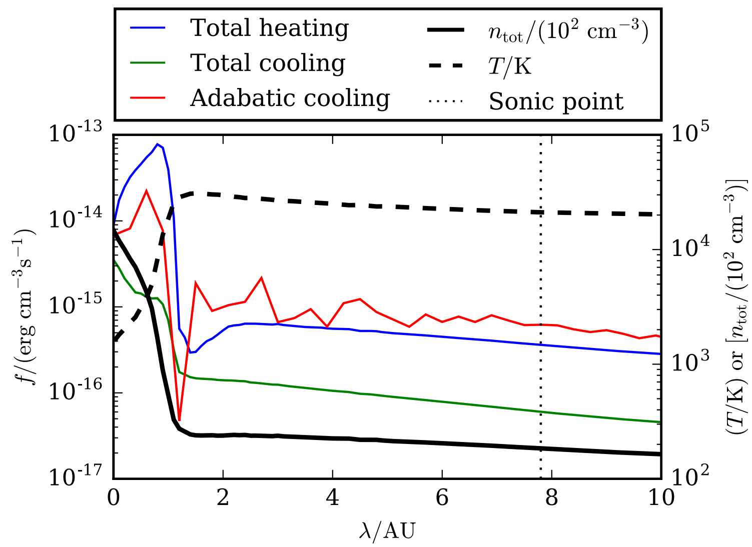


WG17b

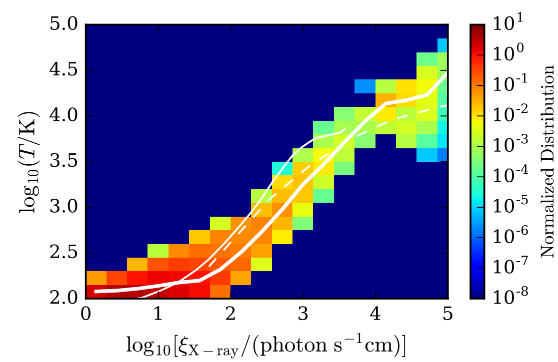
Mass loss rates of hydrodynamic models

- ✦ Our Mdot is 5-10x less than GH09 for similar parameters
  - ✳ ~10^{-9} vs. ~10^{-8} $M_\odot$ yr^{-1}

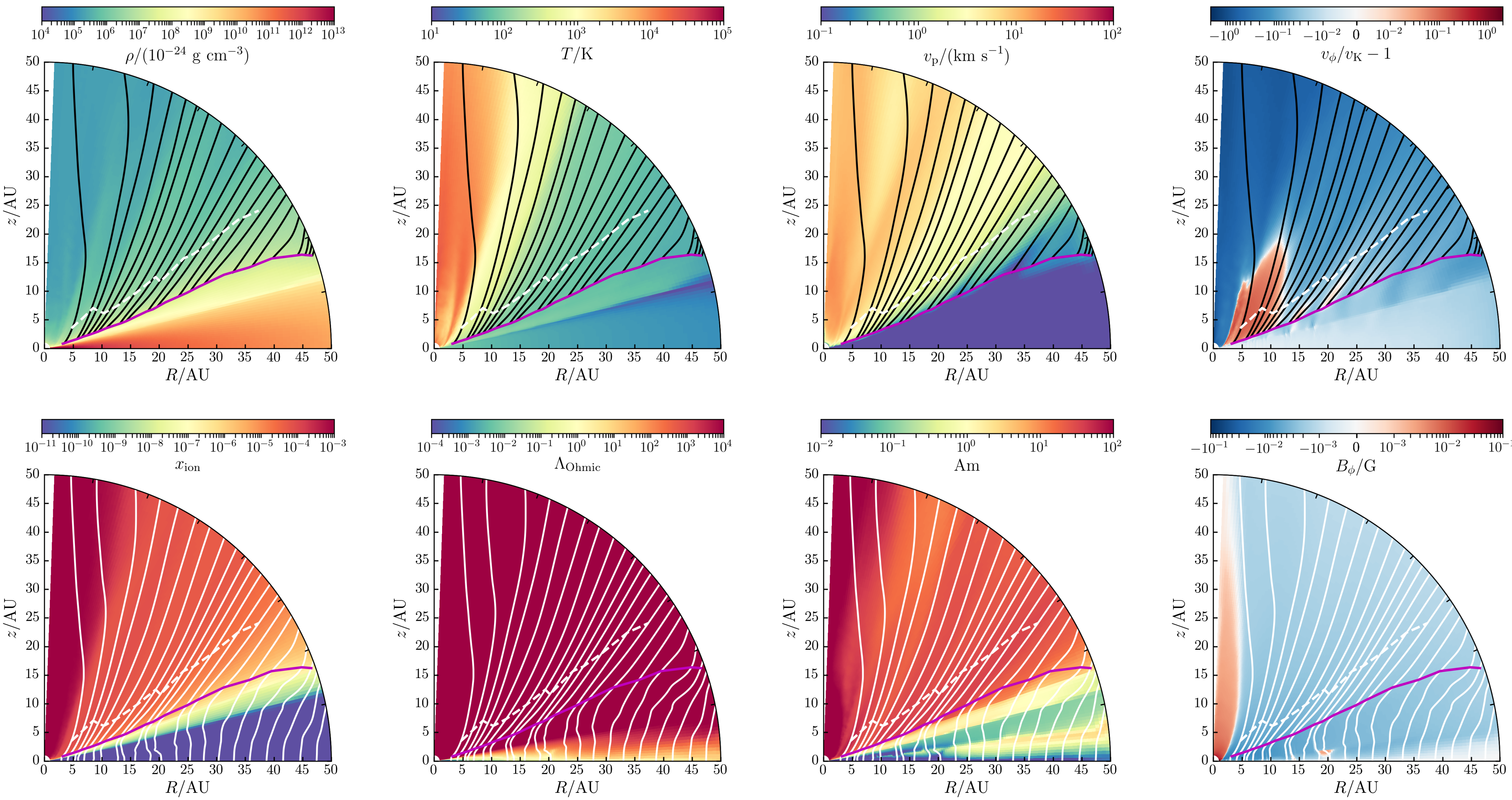




- ✦ X-rays alone (w/o EUV) yield very little mass loss, unless
  - ✳ we omit coolants that OEAC10 neglected,
  - ✳ or if $L_X \gg 10^{30.4}$ erg s^{-1}

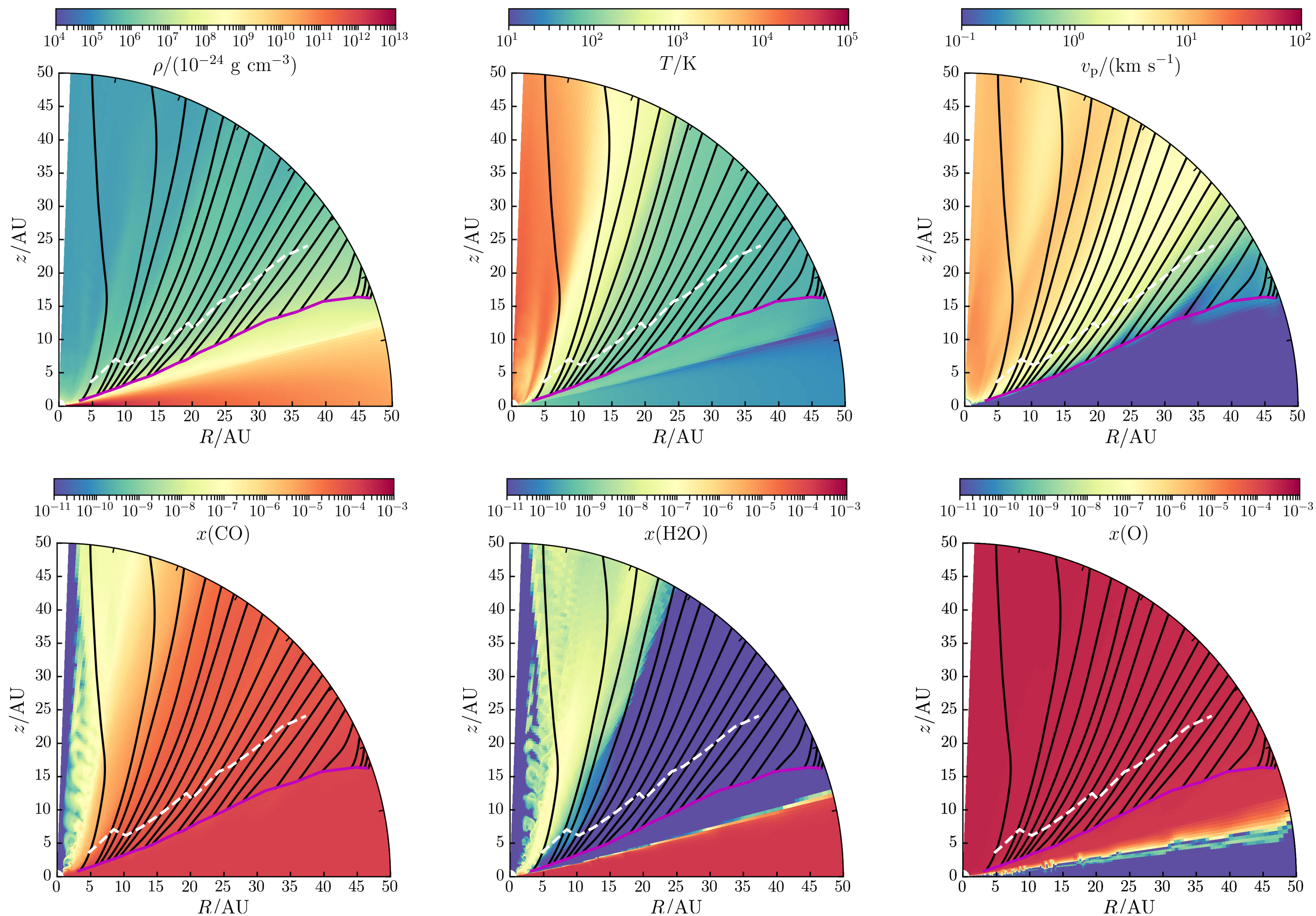


Fiducial (no EUV) MHD run: Flow structure

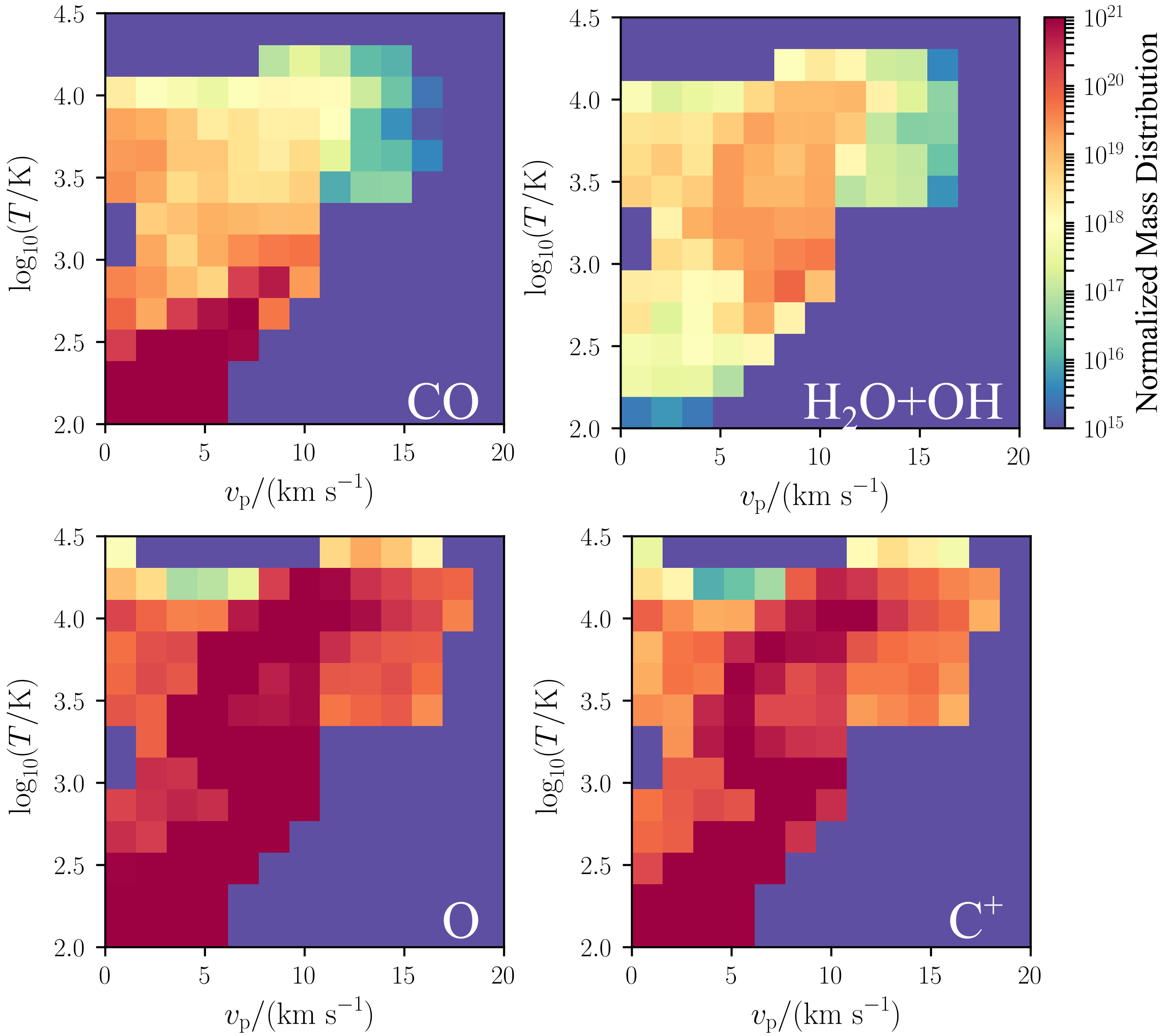


L(7 eV) [erg s-1]	*L*(12 eV)	*L*(25 eV)	*L*(3 keV)
dex(31.7)	dex(29.5)	0	dex(30.0)

Fiducial MHD run: Molecules



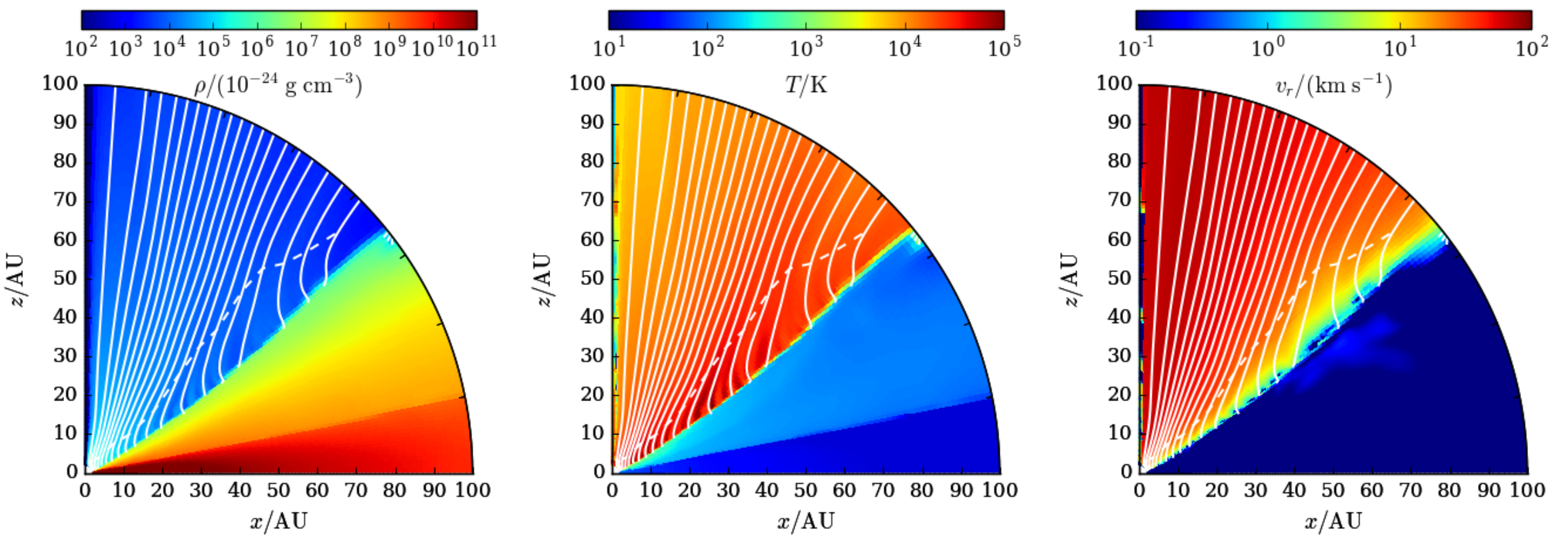
Fiducial MHD run: Molecules



Wind mass-loss rates: Hydro (w. EUV) vs. MHD (w/o EUV)

Hydro:

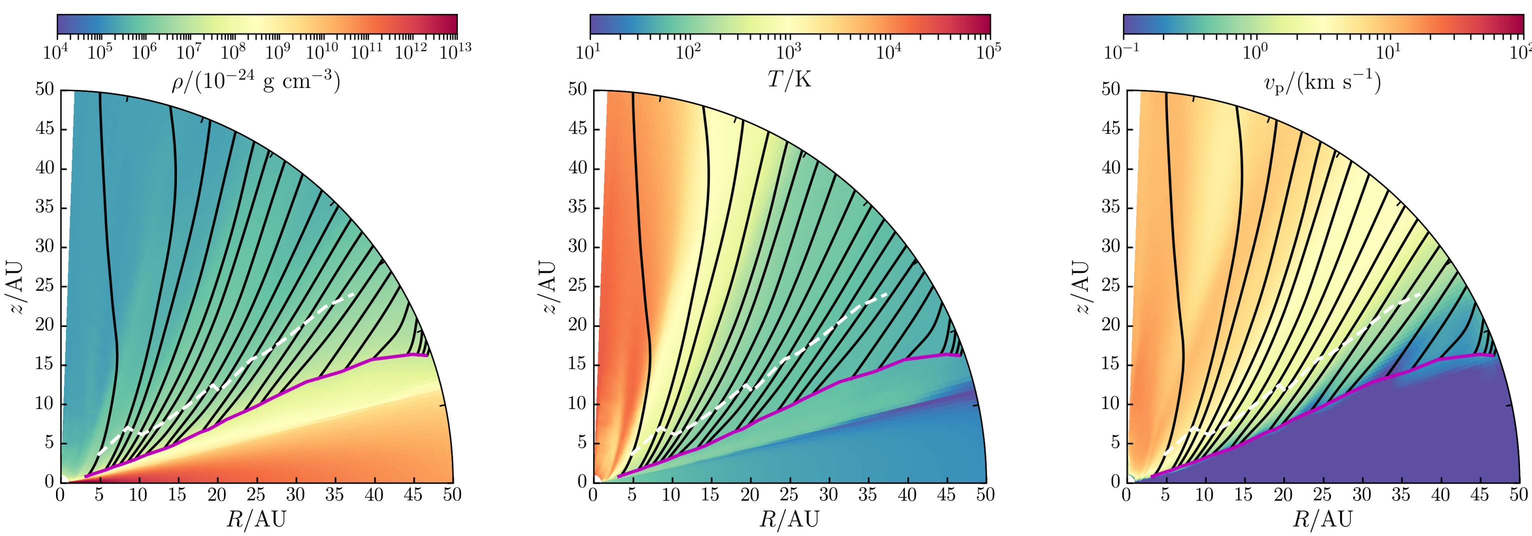
dex(-9) $\dot{M}_\odot$ yr^{-1}



MHD :

dex(-8) $\dot{M}_\odot$ yr^{-1}

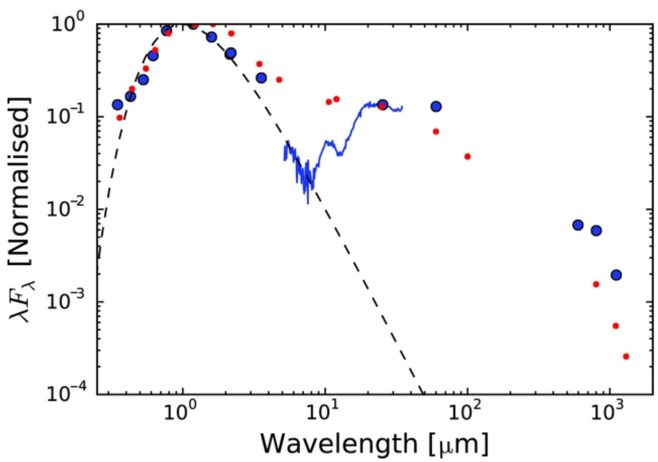
[$\beta_0 = $ dex(-5)]

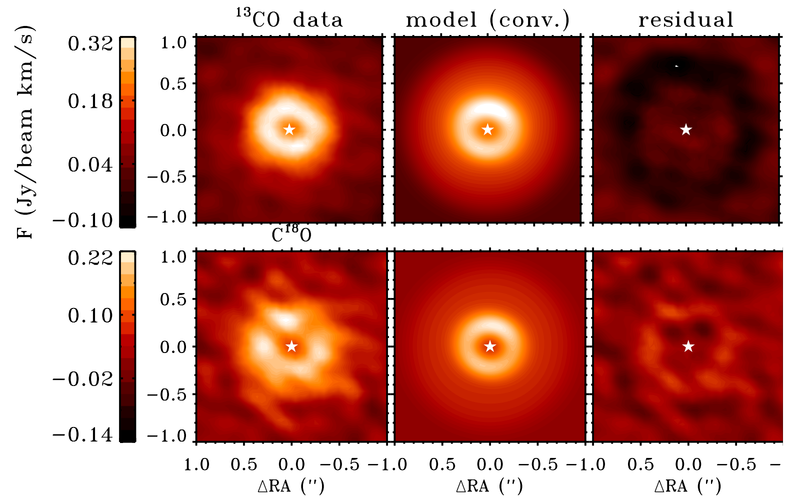


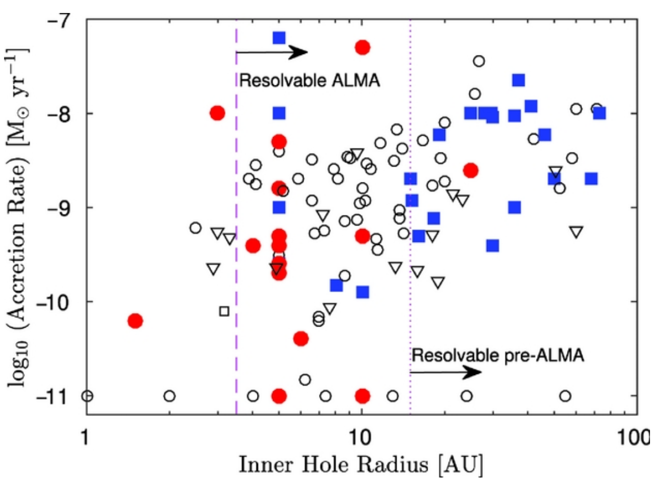
Mass loss & accretion: Main points

- ✦ Purely hydrodynamic models do not accrete.
- ✦ Our standard hydro models without EUV lose little mass.
  - ✳ unless X-rays are enhanced or cooling suppressed
- ✦ Mass loss ($\dot{M}_{wind}$) is comparable to accretion ($\dot{M}_{acc}$) for the minimally magnetized model [β_0=dex(-5), no EUV]
- ✦ Mass loss increases with magnetization (?)
  - ✳ E.g., $\dot{M}_{wind}$ increases ~×5 for β_0=dex(-4)
- ✦ Adding EUV to MHD *decreases* $\dot{M}_{wind}$ (by ~×1/2)
  - ✳ A faster (~ 40 km s^{-1}), more energetic, but lower-$\dot{M}$ wind

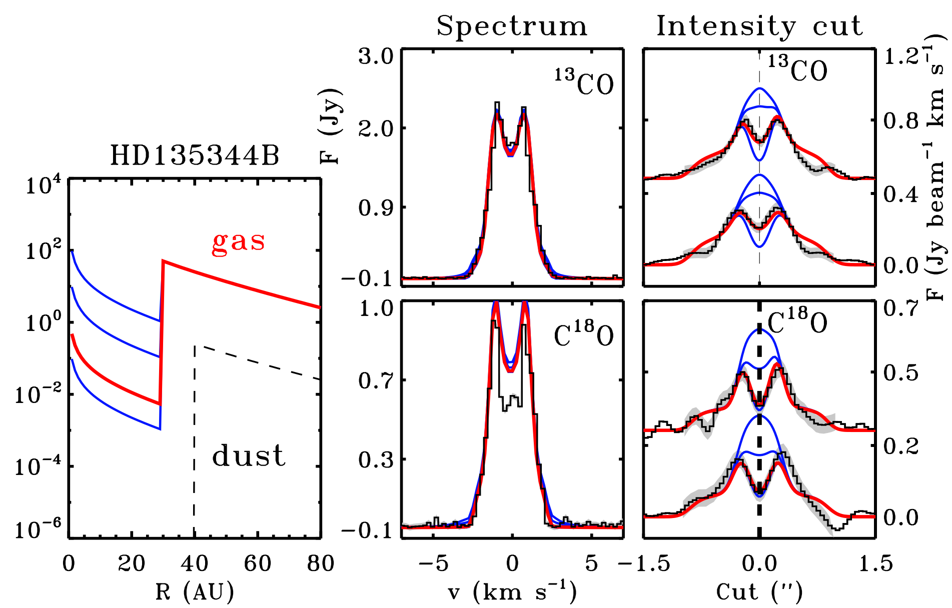
Transition disks







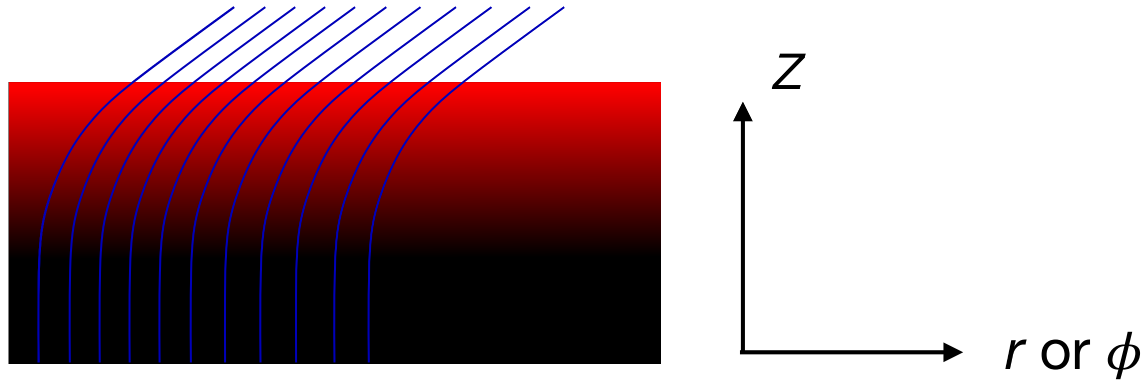
Owen 2016



van der Marel et al. 2016

Maximal accretion speeds

- ✦ For both MRI & winds, $\boldsymbol{\beta} \equiv P_{\mathrm{gas}}/P_{\mathrm{mag}} \geqq 1$within accreting layer.



- ✦ $P_{\mathrm{mag,wind}} \sim (H/R) \times P_{\mathrm{mag,MRI}}$ for the same accretion rate

➡ At the same sound speed (c_s), the accreting density can be lower by O(H/R) when driven by a wind rather than MRI, possibly explaining how transition disks with large gas cavities continue to accrete at "normal" rates. **(Wang & Goodman 2017a)**

$$v_{\mathrm{acc,MRI}} \lesssim c_s \frac{H}{R}; \qquad v_{\mathrm{acc,wind}} \lesssim c_s$$