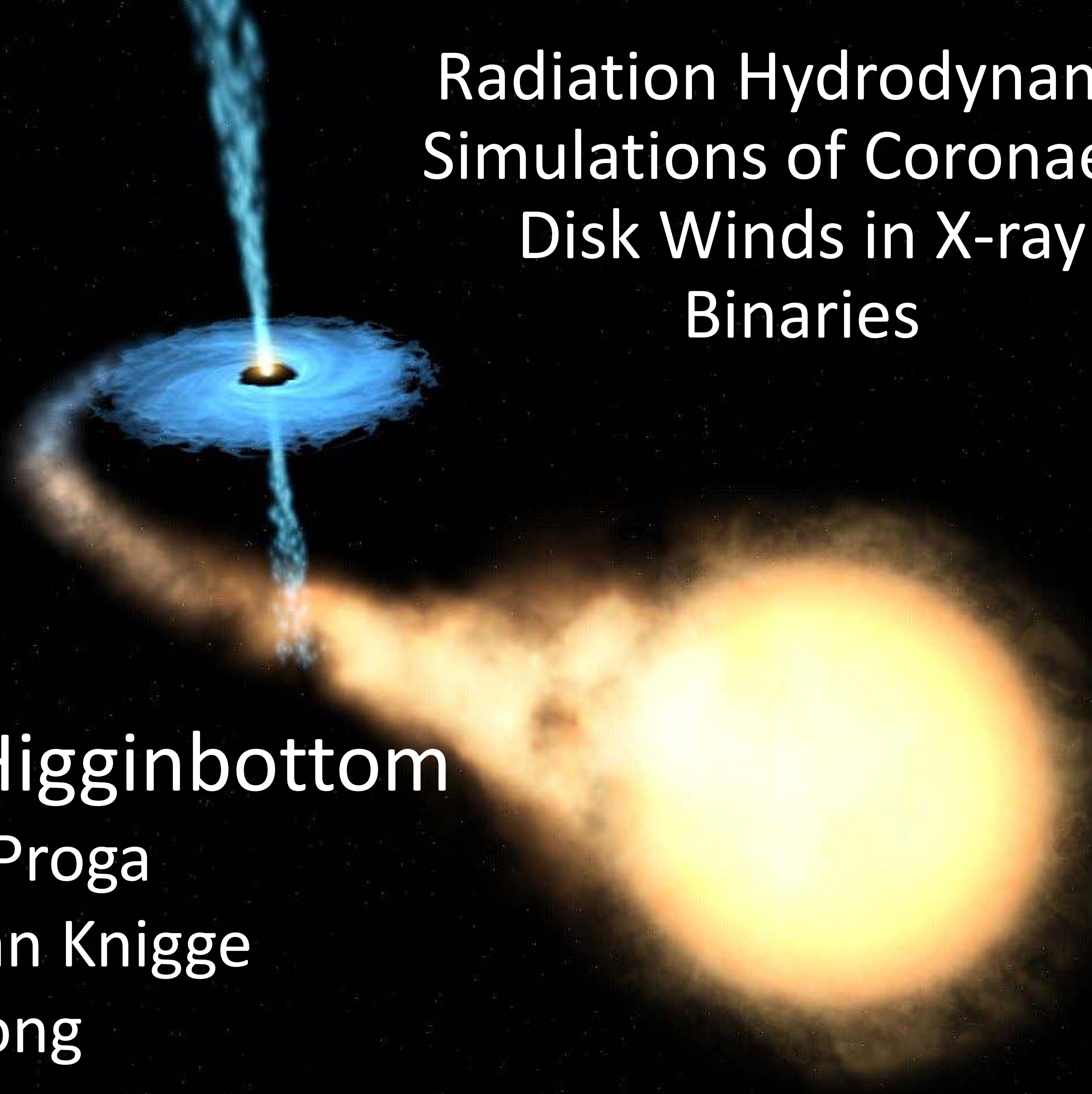
Radiation Hydrodynamic Simulations of Coronae & Disk Winds in X-ray Binaries



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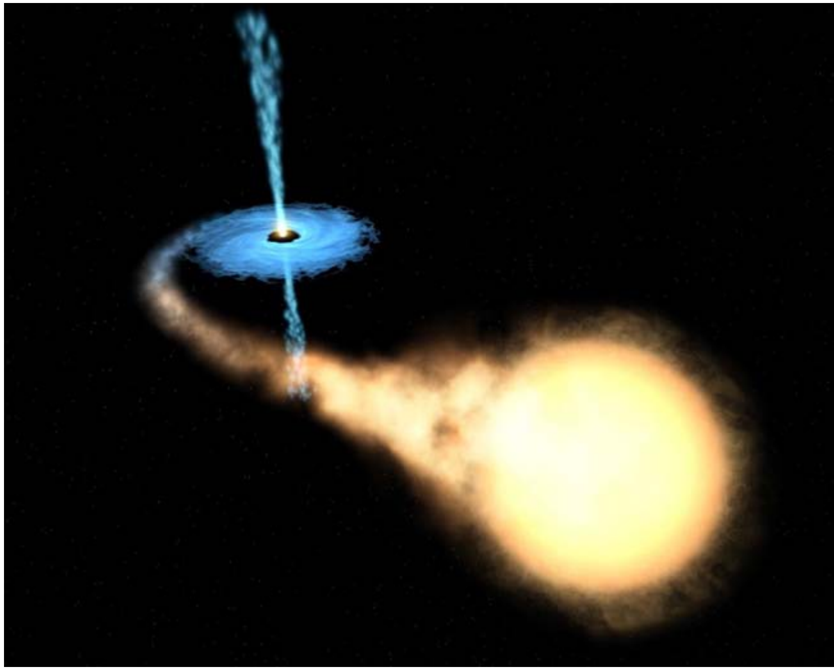
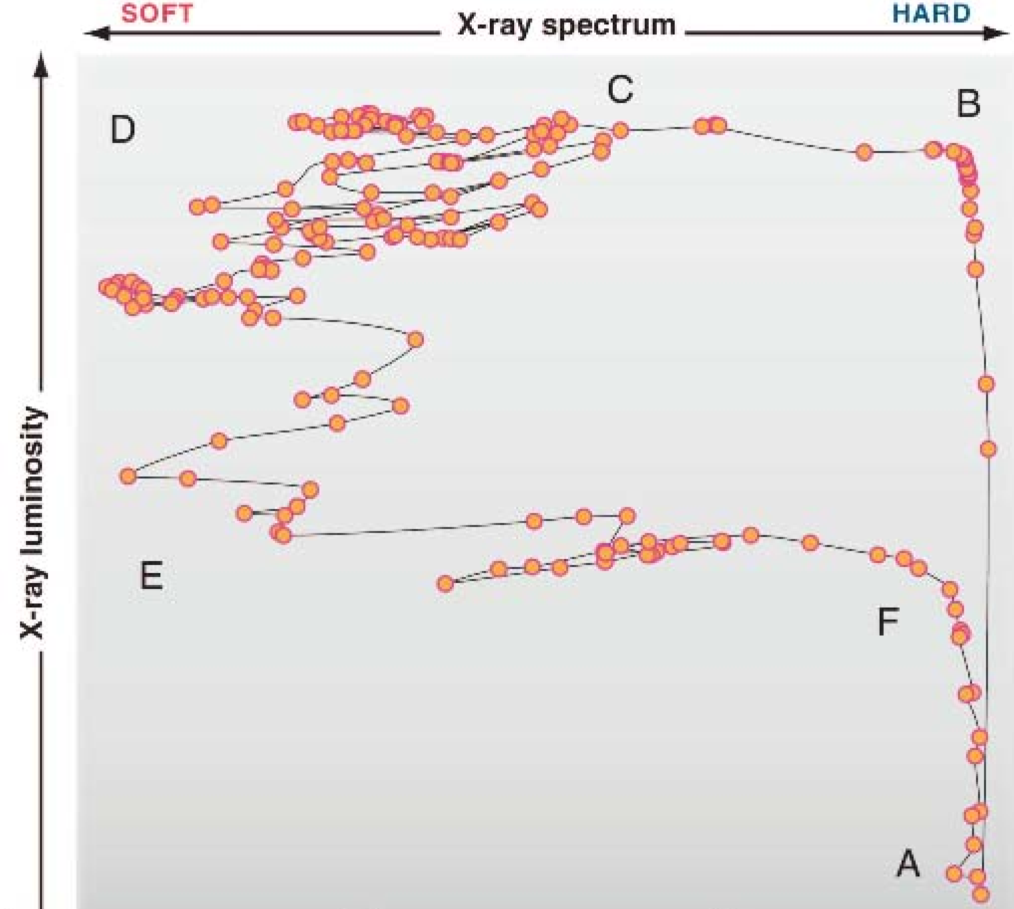
Overview

- Low Mass X-ray Binaries
  - LMXB Absorbers/Outflows
  - Possible outflow driving mechanisms
- Hydrodynamic simulations of thermally driven outflows
  - Significant mass loss rates
  - Velocities approaching those seen in observations

X-Ray binaries

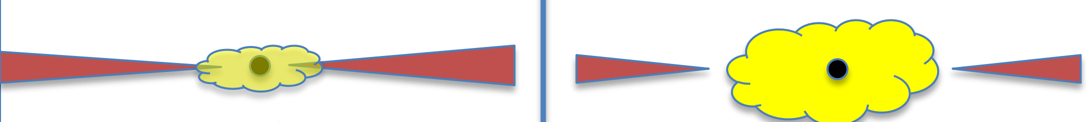
- A neutron star or black hole in orbit with a secondary
  - O/B star = High mass X-ray binary (HMXB)
  - Smaller star = Low mass X-ray binary (LMXB)
- We concentrate on LMXB
  - secondary has filled its Roche lobe, and is fuelling an accretion disk around the compact object





High/Soft state

Low/Hard state



Accretion disk extends to ISCO
Weaker X-ray corona

Truncated disk
Strong X-ray corona
Jets?

LMXB states

- Low/Hard state (A-B) truncated inner disk + hot `corona'.
- B-D – jet shuts off, spectrum softens
- D-E – high/soft state – spectrum dominated by accretion disk
- E-F– disk receeds? Jet can reappear.

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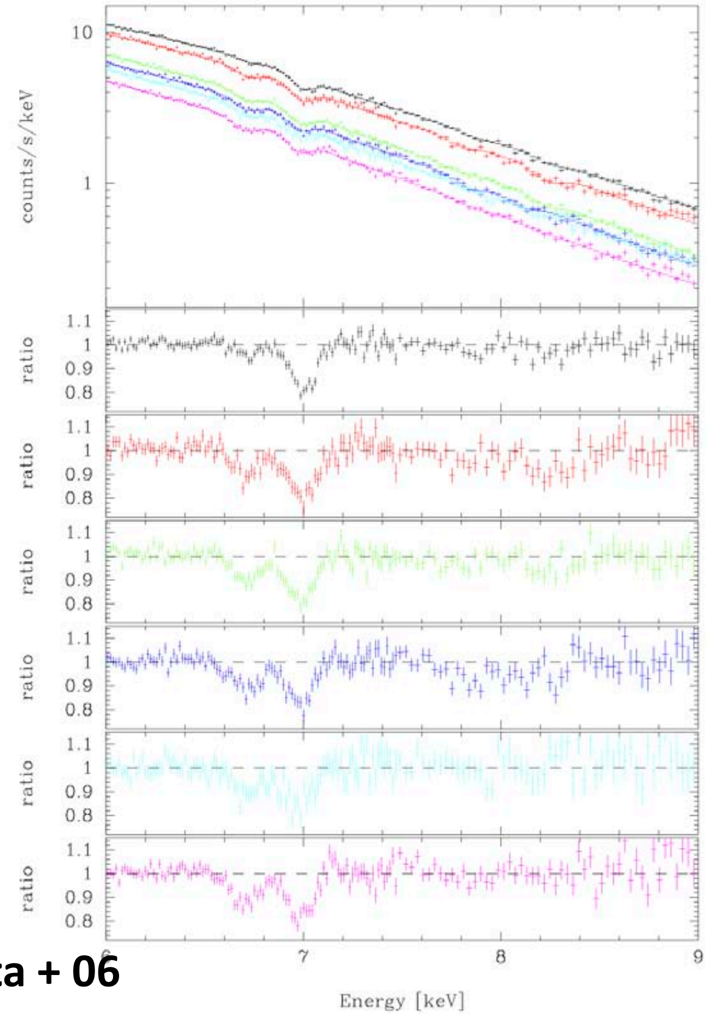
X-ray binary spectra – evidence of an absorber

- 4U 1630-472



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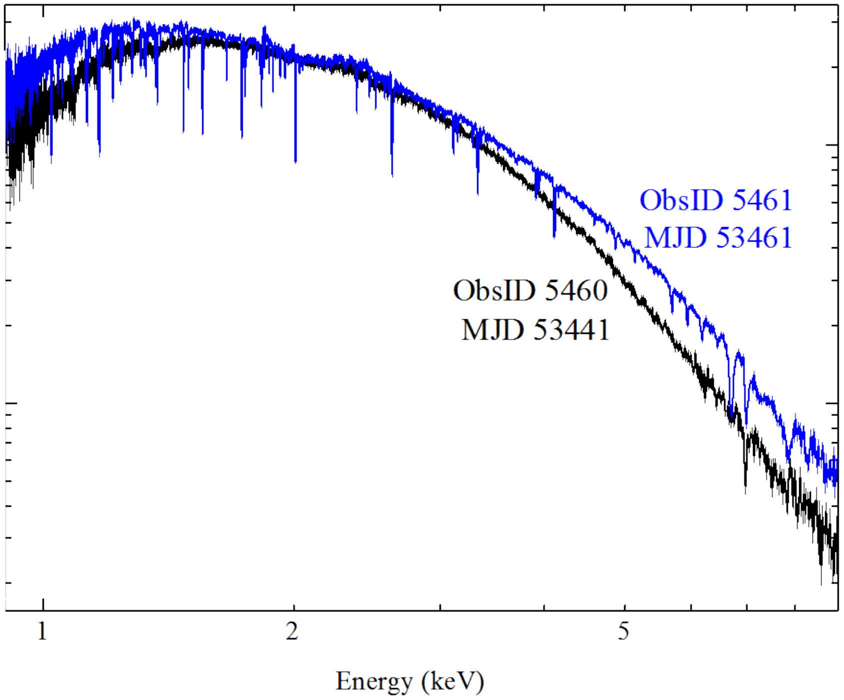


- GRO J1655-40
- Black = high state
- Blue = low state

Neilson & Homan 12

LMXB absorbers

- Mainly seen in X-ray lines of He and H like Iron
  - Highly ionized ($\xi > 10^3$)
  - $N_H \approx 10^{21}$ -10^{24} cm^{-2}

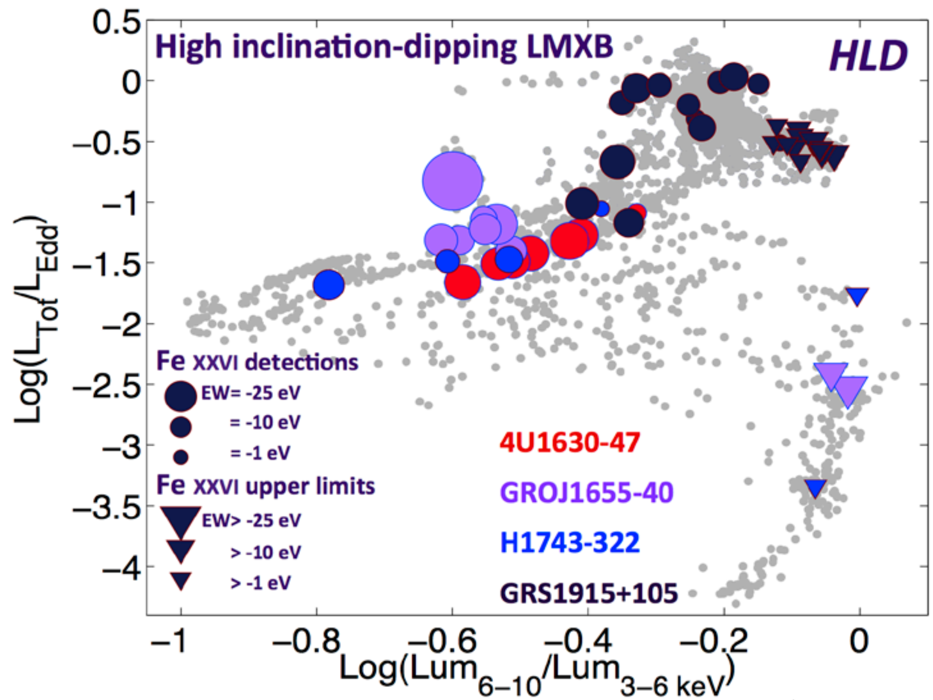
$$\xi = \frac{L_X}{n_H r^2}$$

- Ubiquitous in high inclination systems
- 8 systems show blue shifts of 400-3000 km/s
- Preferentially seen in systems with large P_{orb}
- Never seen at the same time as jets
- Seen exclusively in the high/soft state

Díaz Trigo & Boirin 16

Motivation to study XRB disk winds

- Mass transfer - $\dot{M}_{wind} > \dot{M}_{acc}$?
- Angular momentum transfer
  – If winds are connected to the disk via magnetic field lines
- State change
- Veiling
  – If winds exist, we view the system through them



Ponti+ 2012

Driving mechanisms for XRB disk winds

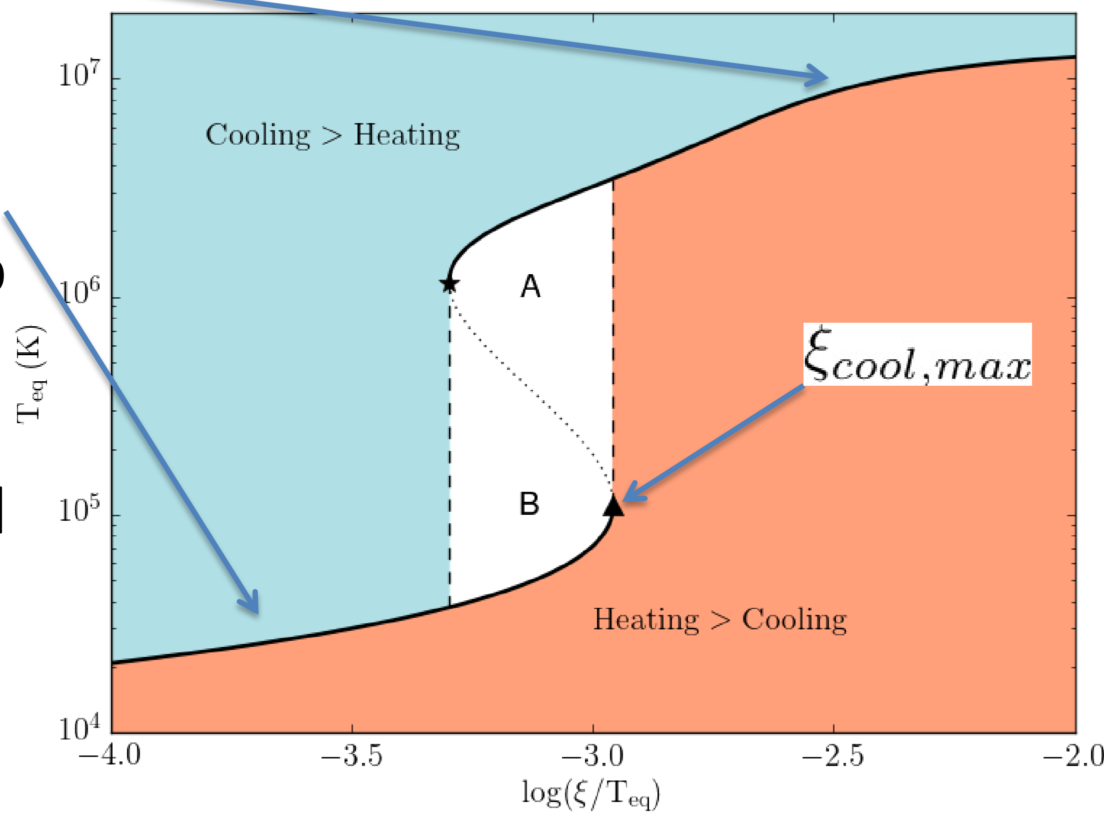
- Magnetic
  - B fields required for MRI, can also drive a wind
- Radiation
  - pressure on lines and electrons
  - Unlikely for XRBs due to high ionization state
- Thermal –
  - Thermal velocity at the surface of the disk exceeds local escape velocity
  - Radius at which gas at Compton temperature can escape given by

$$R_{IC} = \frac{GM_{BH}\mu m_H}{k_B T_{IC}}$$

  - This is rather large – 10^5 R_G

Thermal wind launching mechanism

- Upper branch, gas is at Compton temperature and can escape.
- Lower branch, PI heating balanced by Line+Recomb cooling
- At $\xi_{cool,max}$ gas heats rapidly – gains energy and accelerates
- Precise location of $\xi_{cool,max}$ and shape of curve defines energy increase and resulting flow
- Atomic physics!



$$\xi = \frac{L_X}{n_H r^2}$$

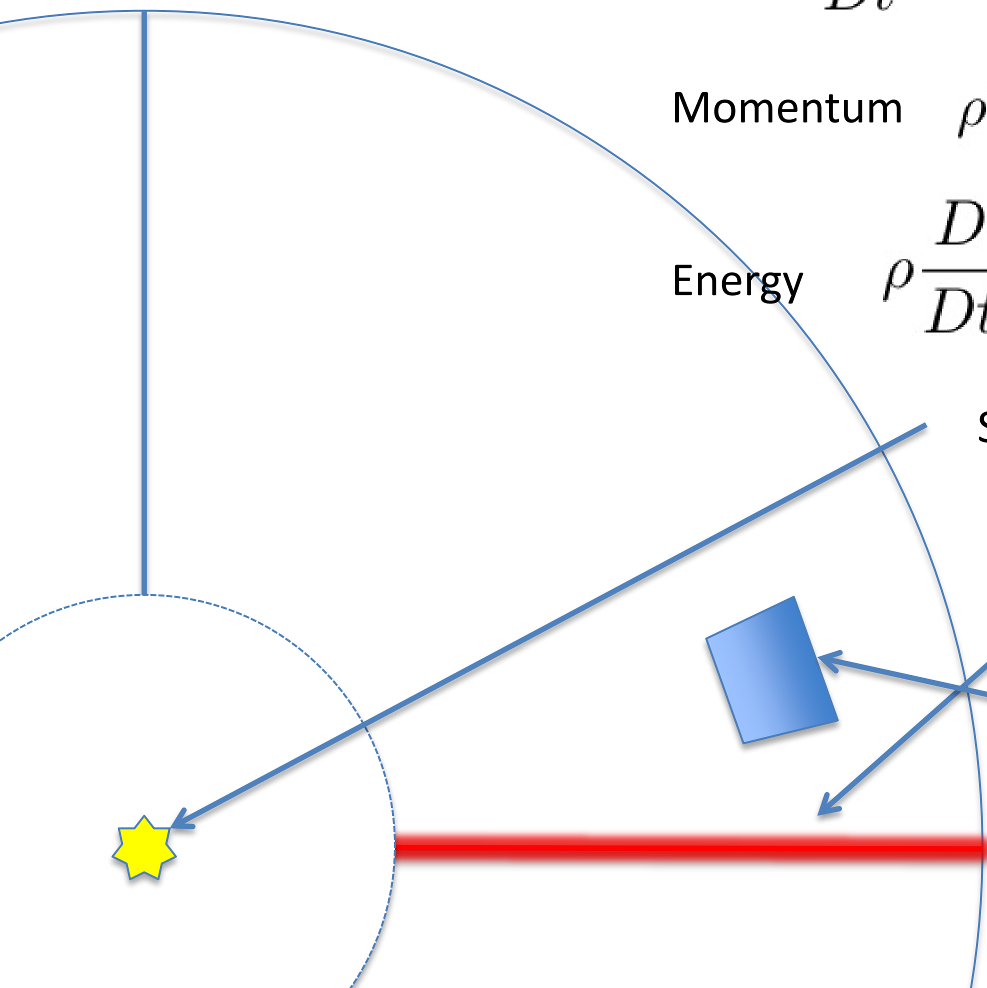
Simulating thermal disk winds

- We use ZEUS to solve the equations of hydrodynamics

Mass $$\frac{D\rho}{Dt} + \rho\nabla\cdot v = 0$$

Momentum $$\rho\frac{Dv}{Dt} = -\nabla P + \rho g$$

Energy $$\rho\frac{D}{Dt}\left(\frac{e}{\rho}\right) = -P\nabla\cdot v + \rho\mathcal{L}\left(\xi, T\right)$$



Source of ionizing radiation L_X=3.3x10^{37}erg s^{-1}

Fixed density boundary $\rho(r) = \rho_0\left(\frac{r}{R_{IC}}\right)^{-2}$

For a given cell, we calculate the radiative heating/cooling rate from ionization parameter and temperature

Analytic heating and cooling rates

Initial investigations used analytic expressions for heating and cooling rates from Blondin (1994)

$$\rho\mathcal{L} = n^2(G_{Compton} + G_X - L_l - L_b)$$

Compton heating /cooling

$$G_{Compton} = 8.9 \times 10^{-36}\xi(T_X - 4T)$$

X-ray (photoionization) heating

$$G_X = 1.5 \times 10^{-21}\xi^{1/4}T^{-1/2}(1 - T/T_X)$$

Bremstrahlung cooling

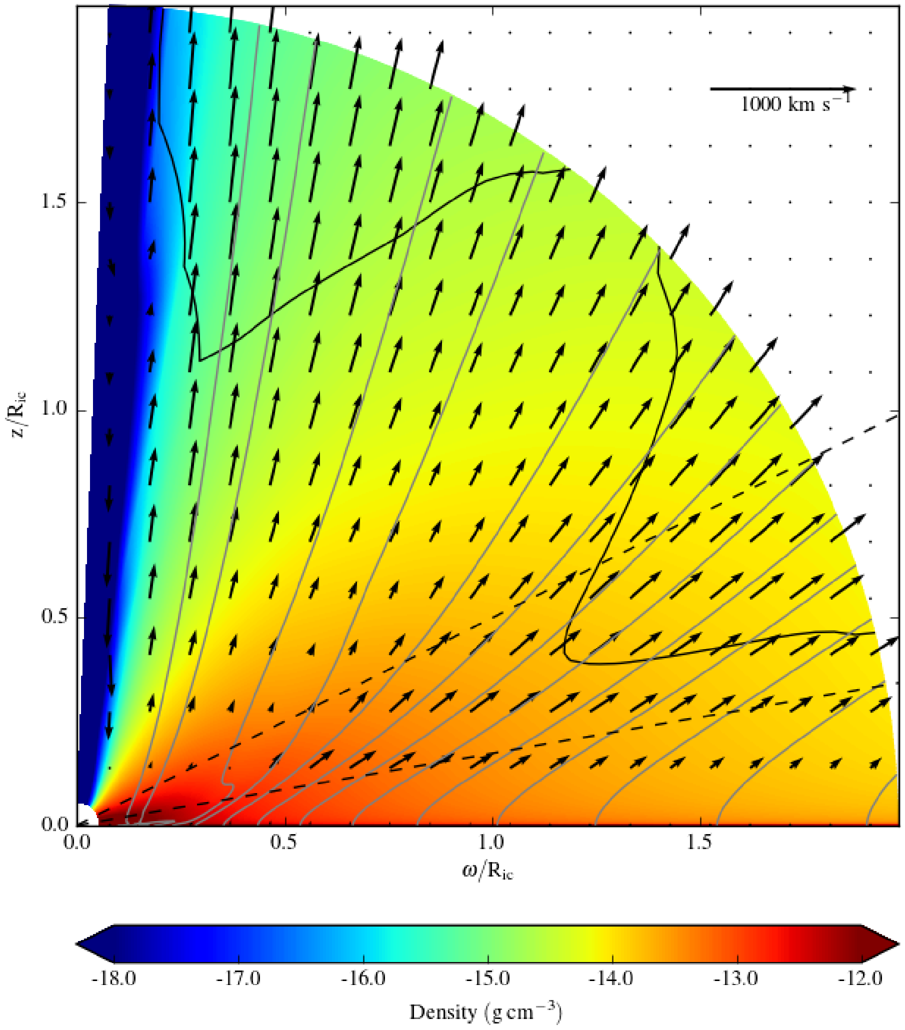
$$L_b = 3.3 \times 10^{-27}T^{1/2}$$

Line (bound-bound and free-bound) cooling

$$L_l = \left[1.7 \times 10^{-18}\exp\left(-T_L/T\right)\xi^{-1}T^{-1/2} + 10^{-24}\right]\delta$$

Thermal outflow 1

- High density ($n_H > 10^{12}$) gas is slow moving ($<100 kms^{-1}$)
- Failed in the stated aim to model GRO1655-50
- However - wind outflow rate approx. 7x accretion rate
- GRO1655-40 is perhaps an extreme source….



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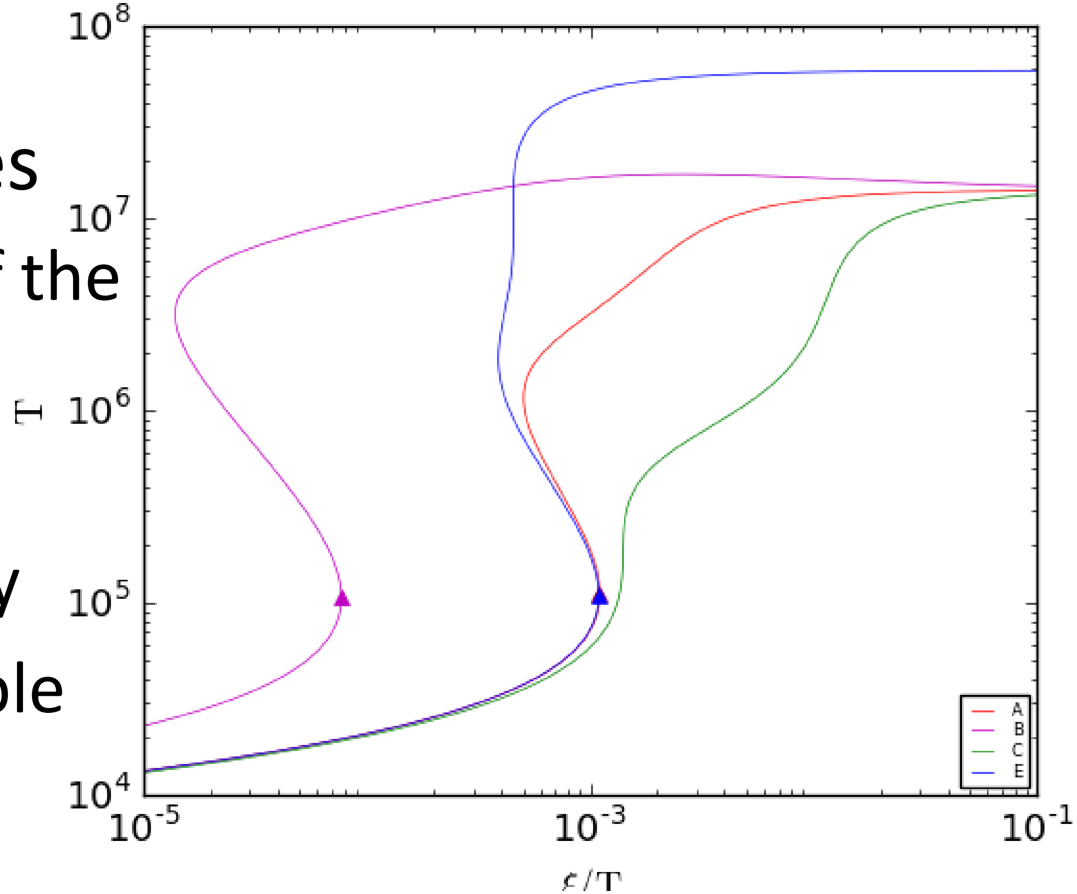
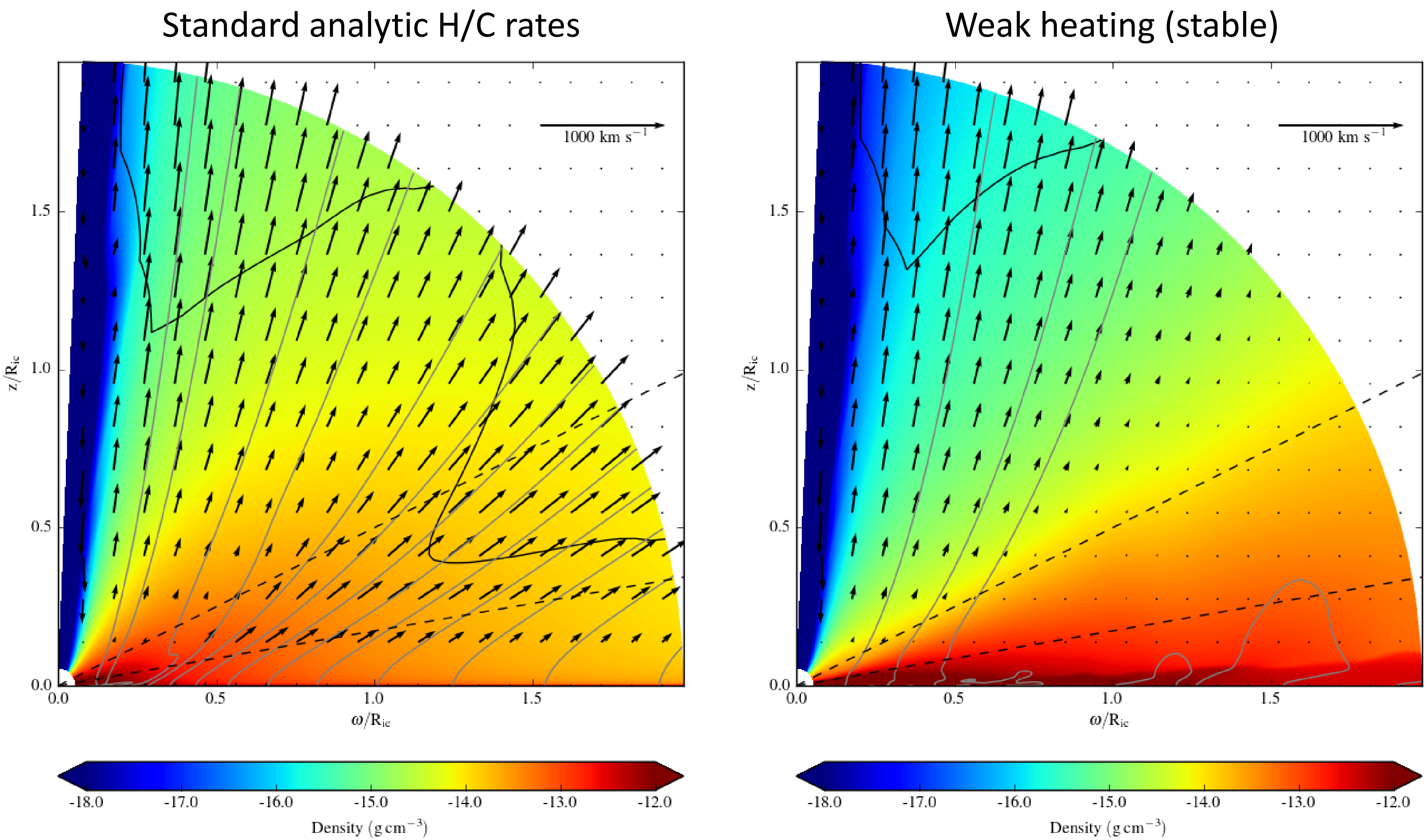
Investigating the effect of modifying the heating and cooling rates

- Physically motivated changes to heating/cooling rates
  - Changes the form of the stability curve
  - B: Change $\xi_{cool,max}$
  - C: Remove instability
  - E: Extend the unstable zone



Higginbottom and Proga 15

Results 1: No instability = no outflow



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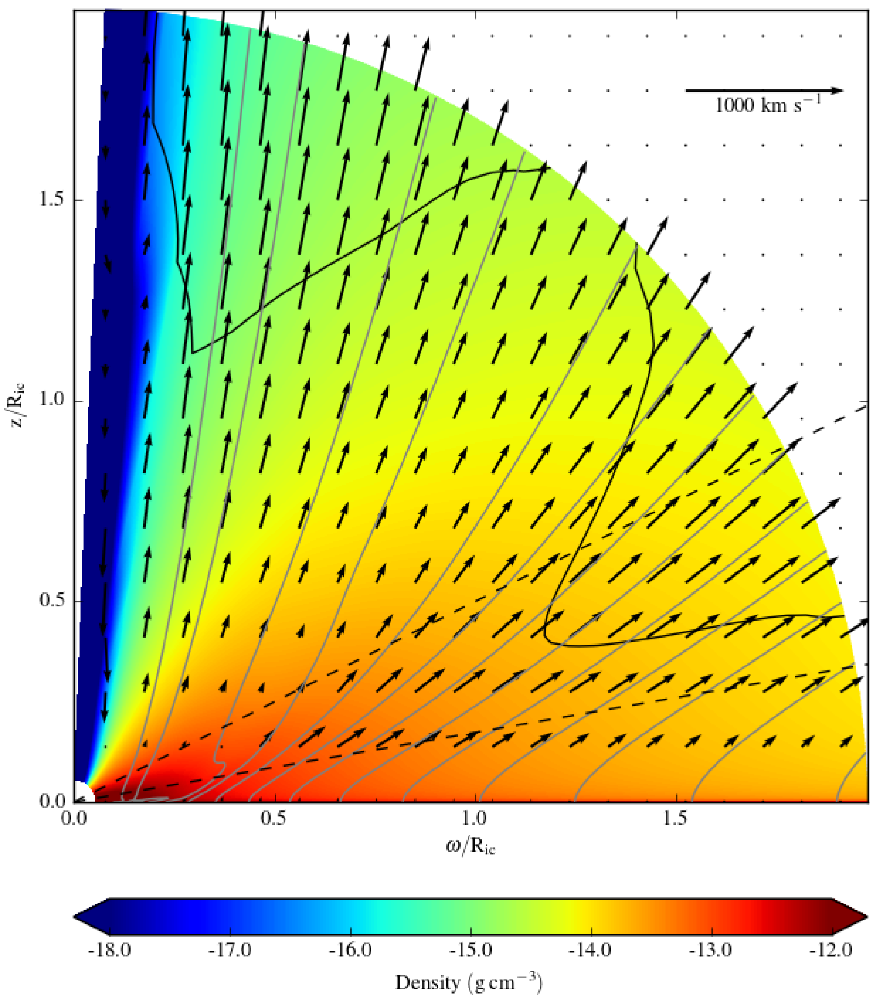
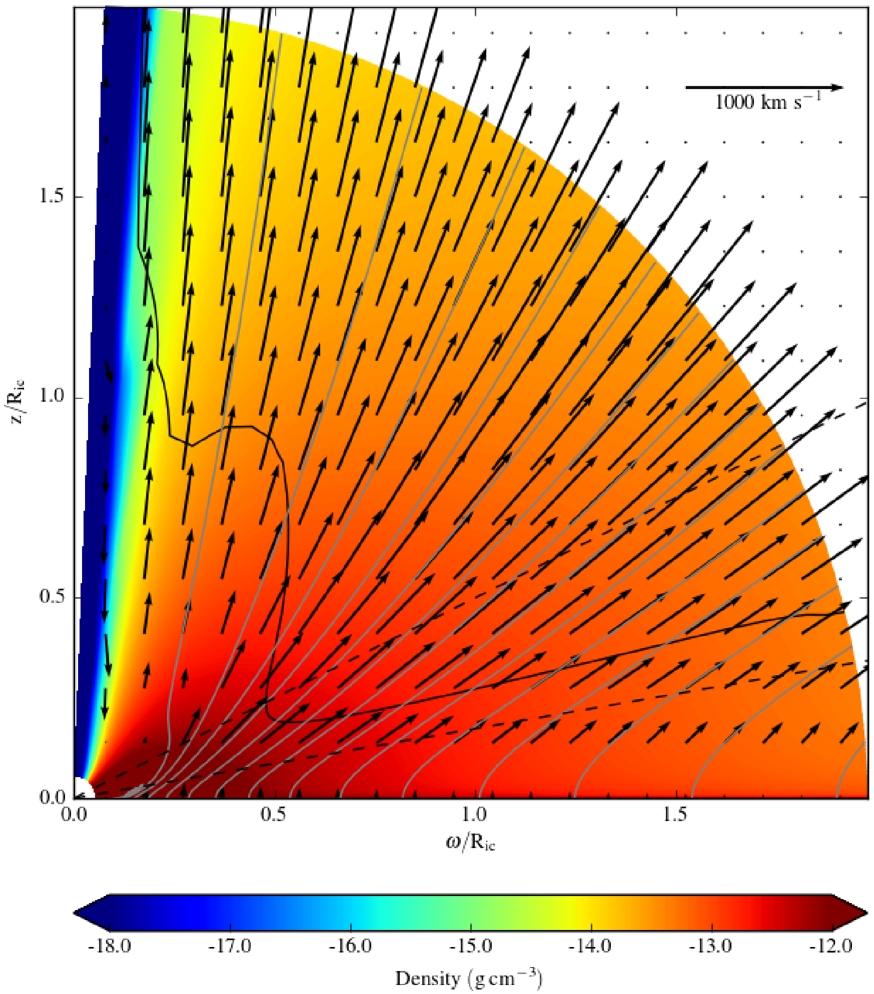
Results 2: Denser base = denser flow

Standard analytic H/C rates



Strong heating (unstable/catastrohphic)



Mass loss rate = 40 x accretion rate

Much denser, and somewhat faster

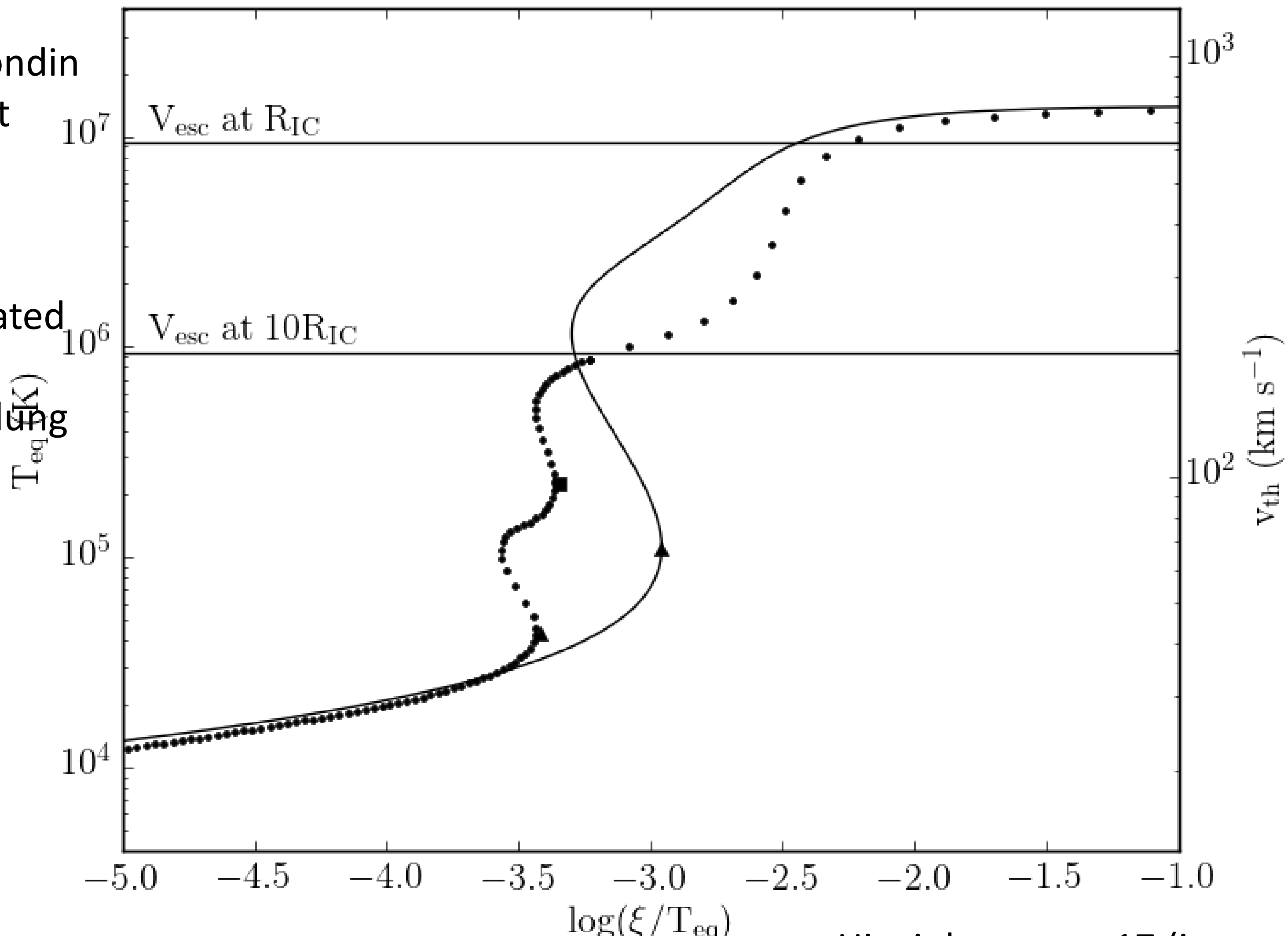
Next step

- We demonstrated that the heating and cooling rates have major effect on the outflow
- We want to test the plausibility of our modified heating and cooling rates
- Use photoionization code to compute them
  - net heating/ net cooling(ξ,T) lookup tables calculated in Cloudy (see Daniel's talk next)
  - Modify Zeus to use these tables
  - Initially still using optically thin assumption

Stability curve computed in cloudy

Solid line from Blondin (1994) – different atomic data, analytical fit

Dotted line calculated from Cloudy 50keV Bremstrahlung SED.



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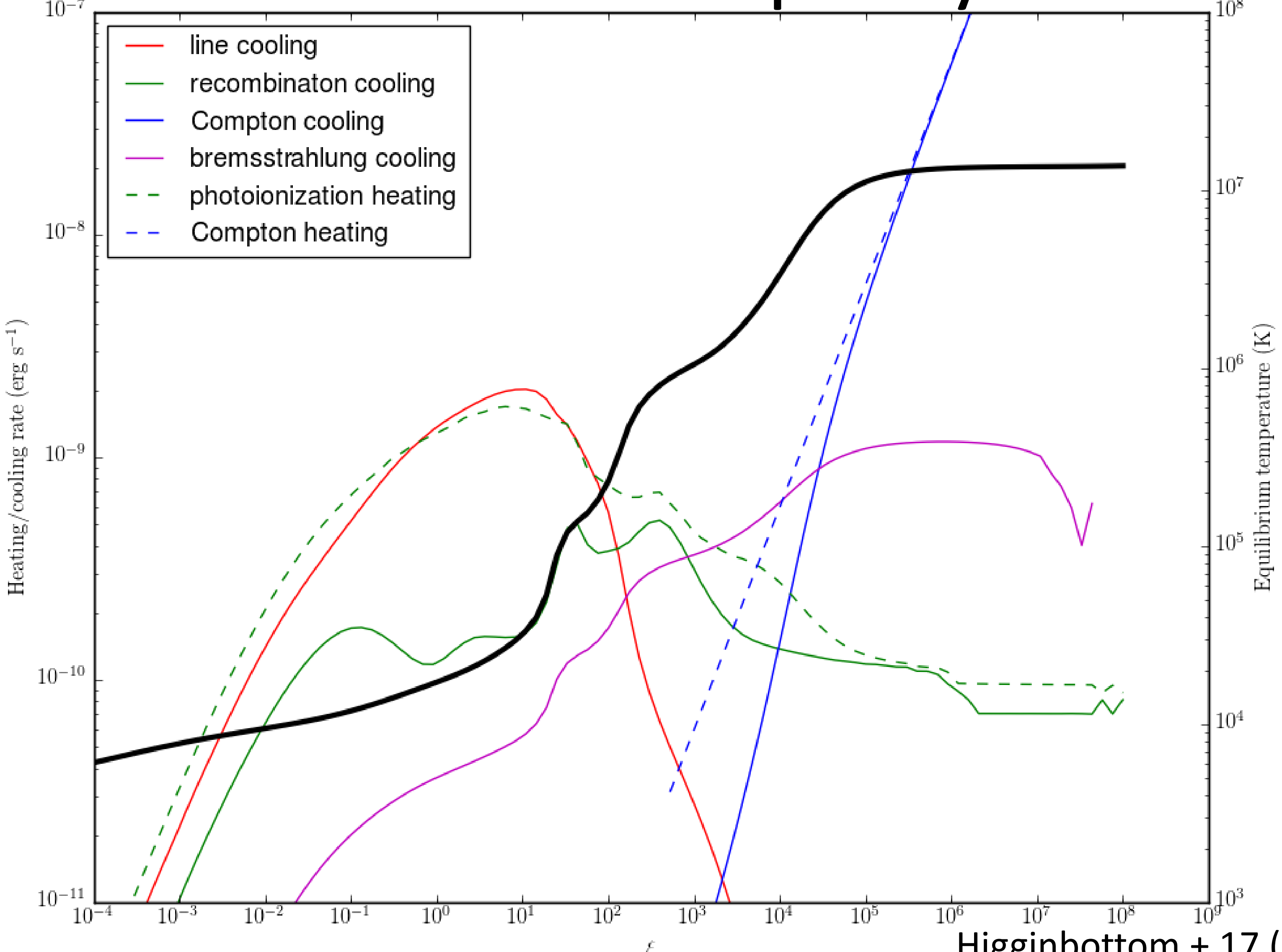
Heating and cooling mechanisms – the source of compexity



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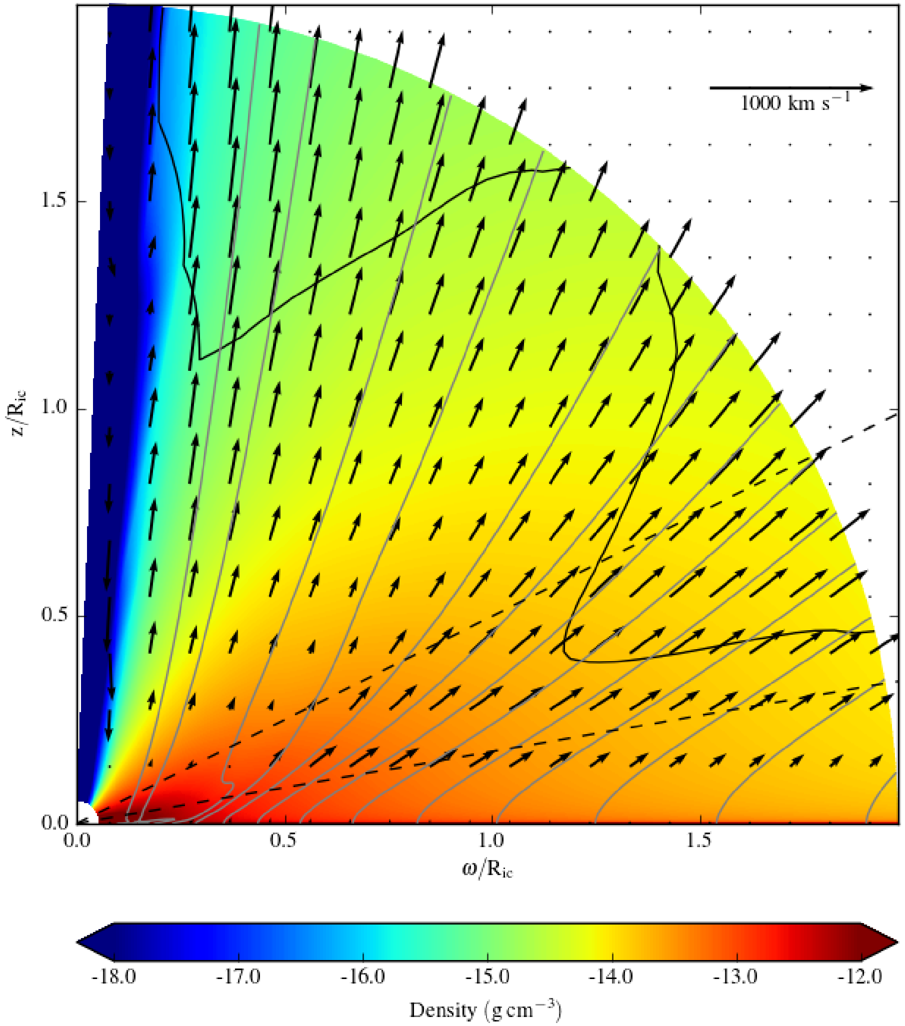
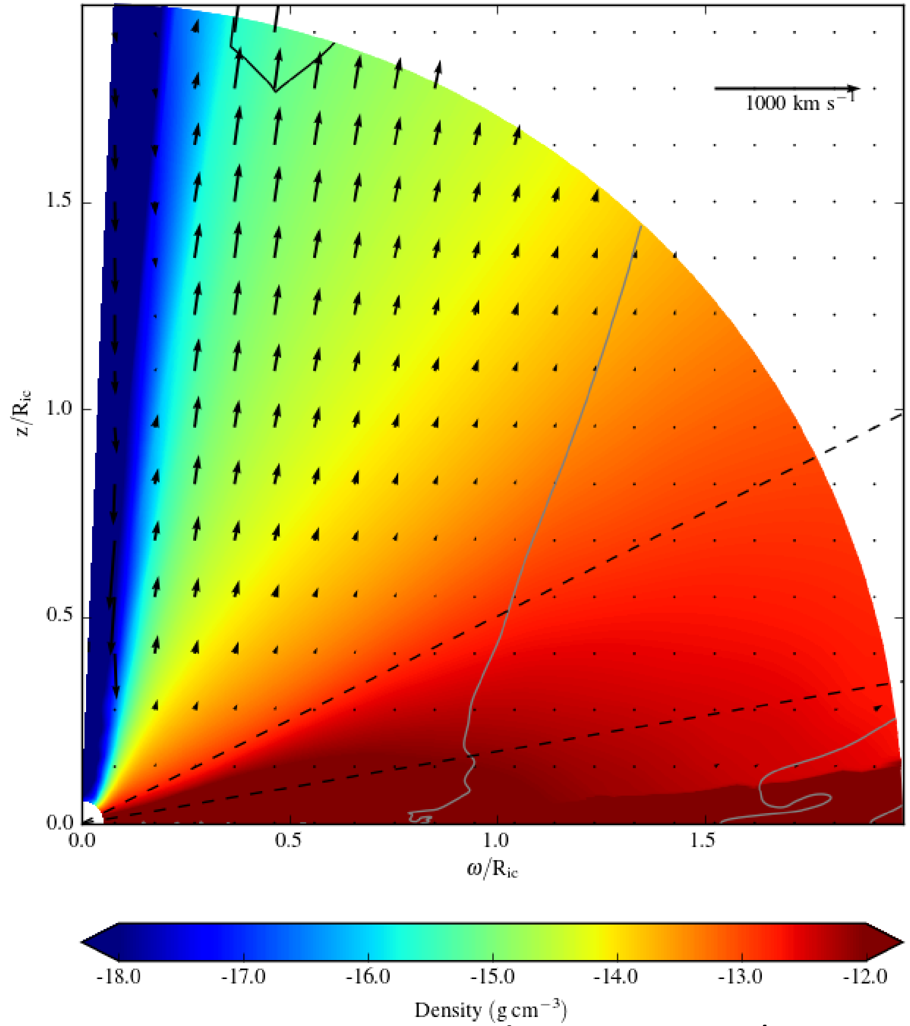
Outflow with accurate heating and cooling rates

Analytic fits to H/C rates



Detailed lookup H/C rates



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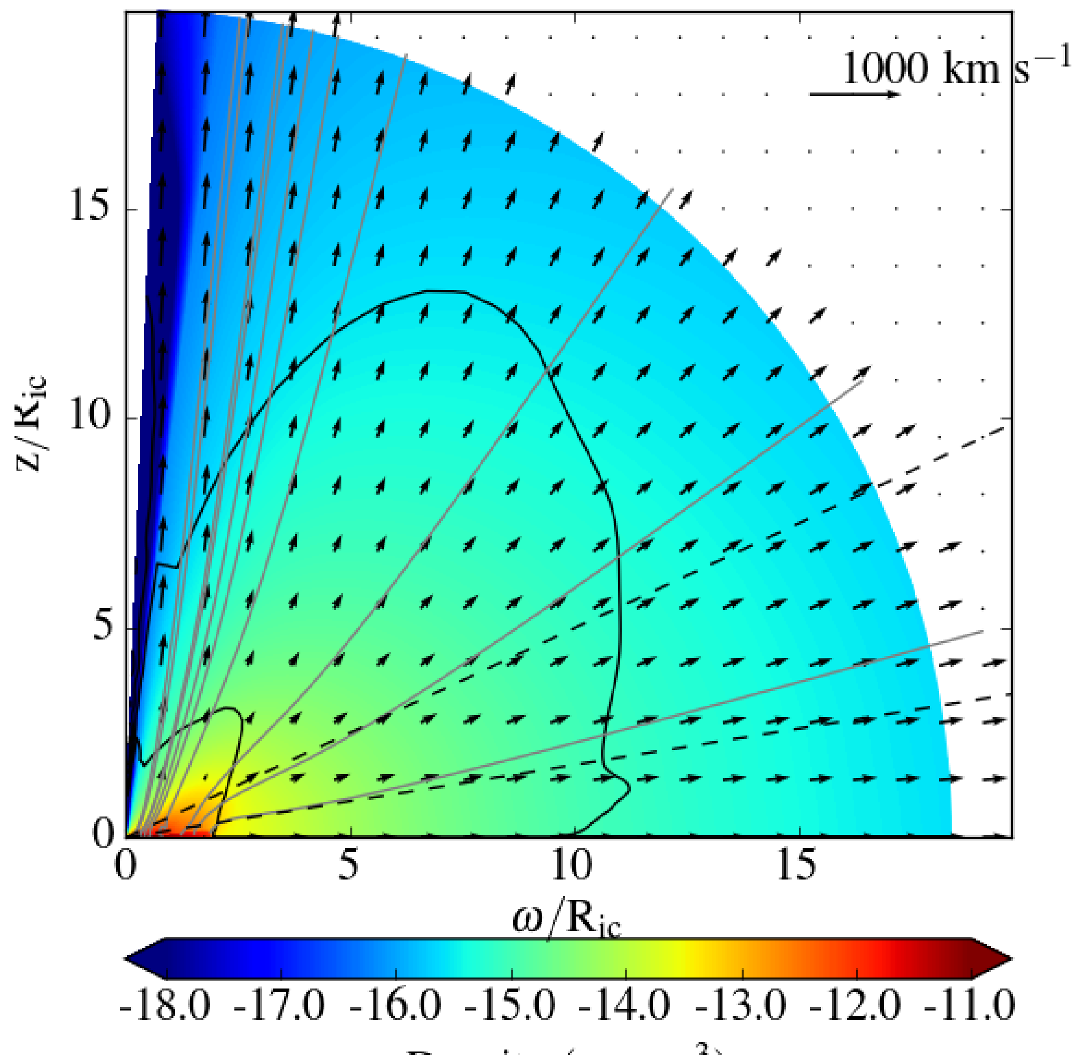
Chasing the Mach 1 surface

- Increased domain size – requires much more space to accelerate
- Outflow arises outside $1R_{IC}$ – long period sysems only?
- Mass loss rate is 15x accretion rate – could destabilise disk



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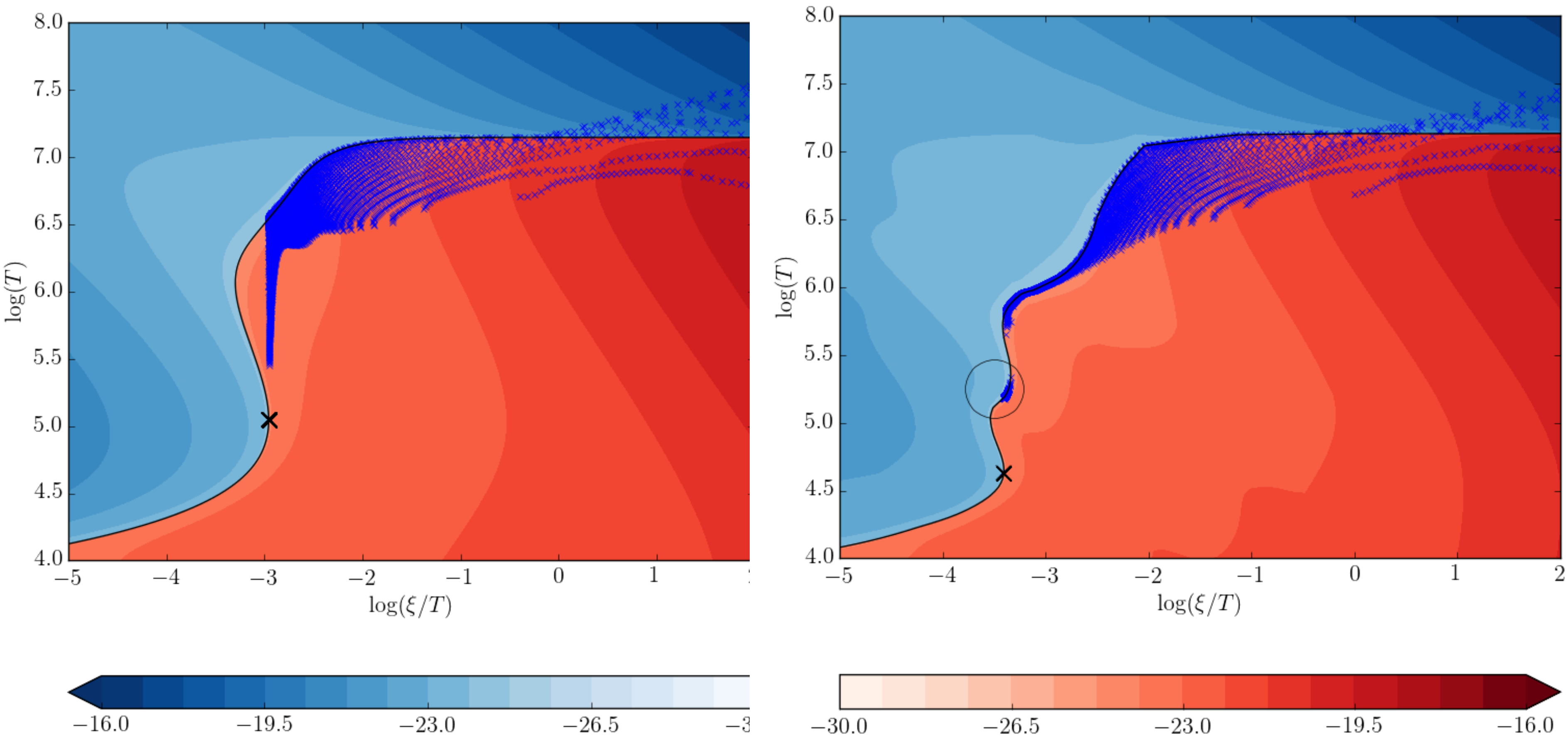
Phase diagrams explain why flow is so different.

Approximate analytic H/C rates

Exact numerical rates



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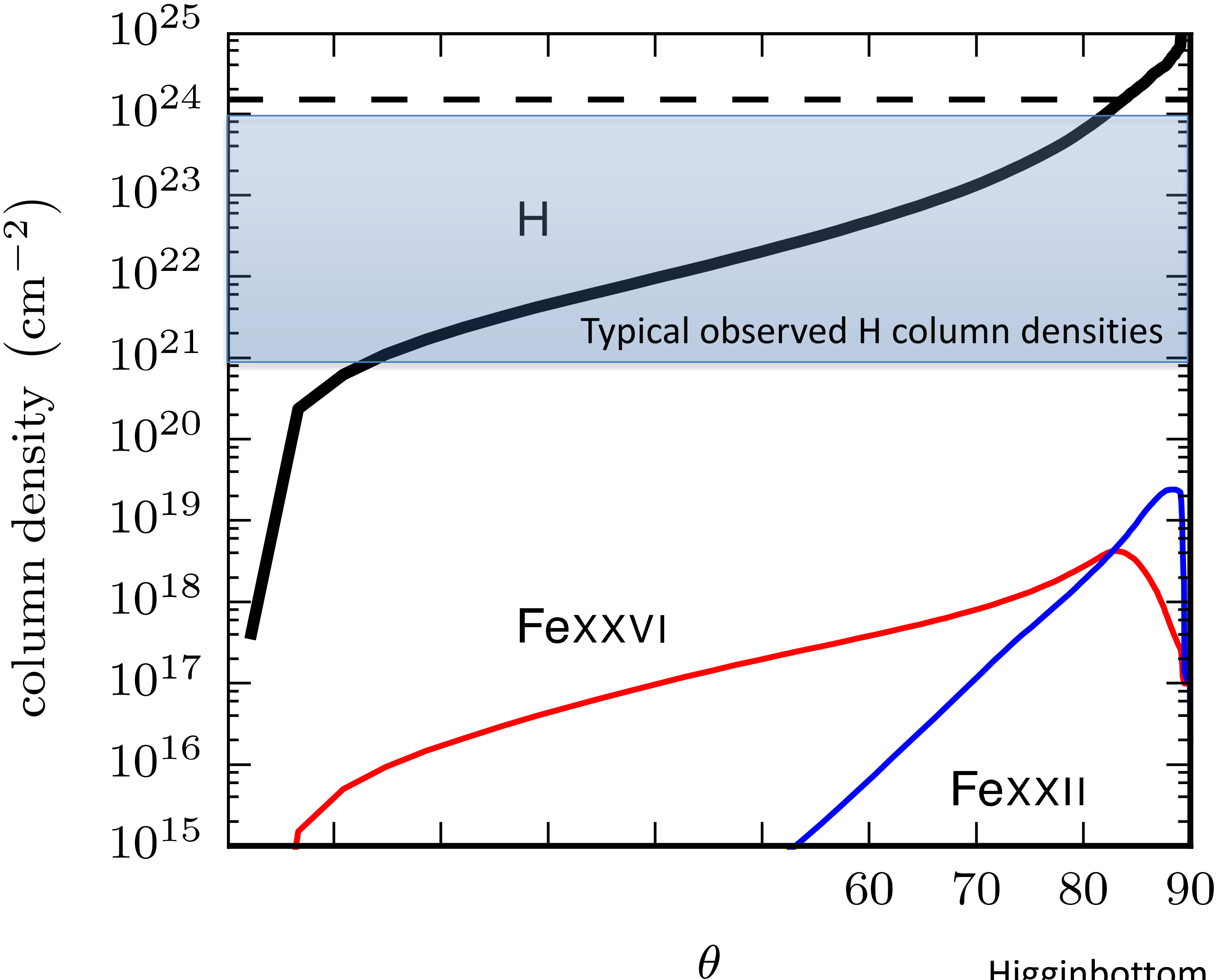
Observables 1: Column densities



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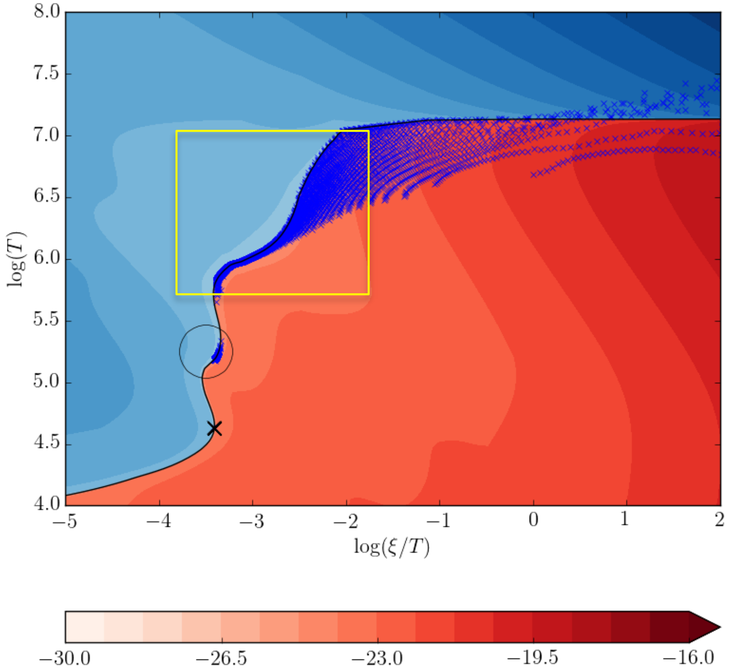
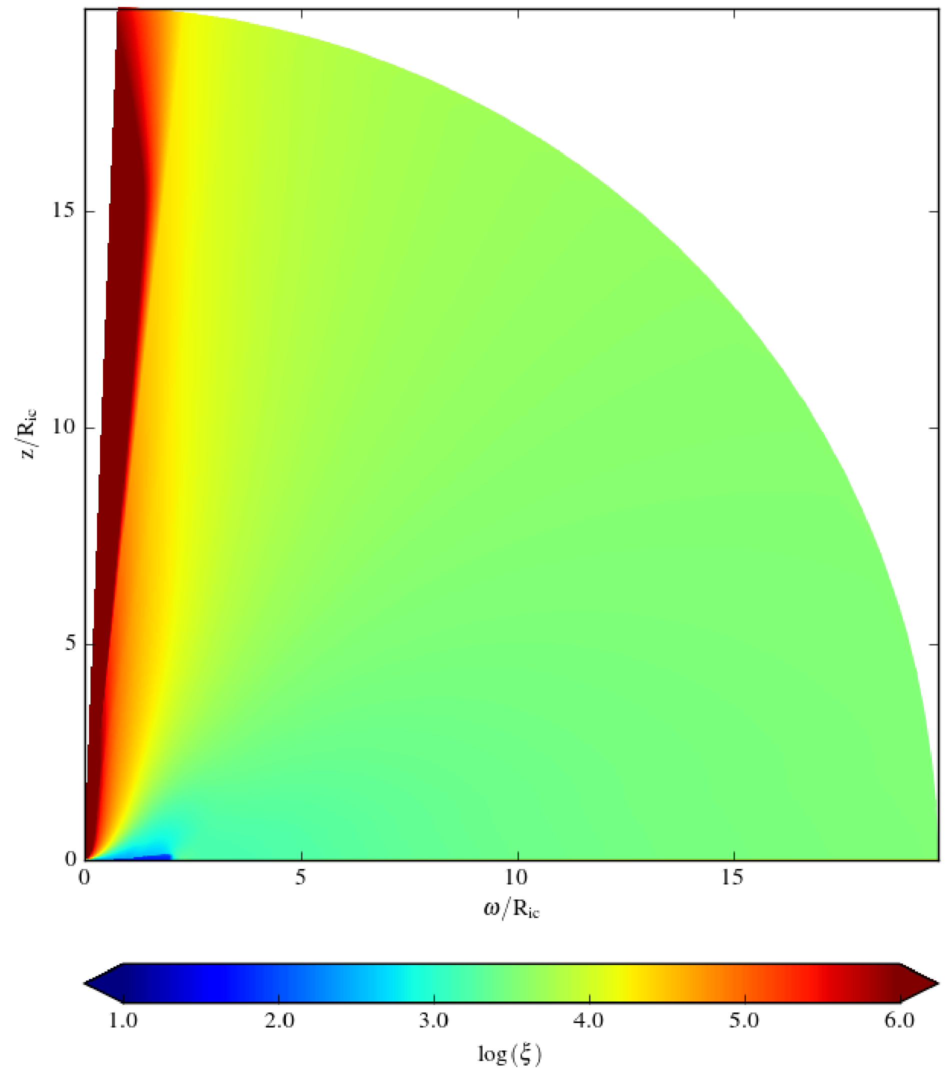
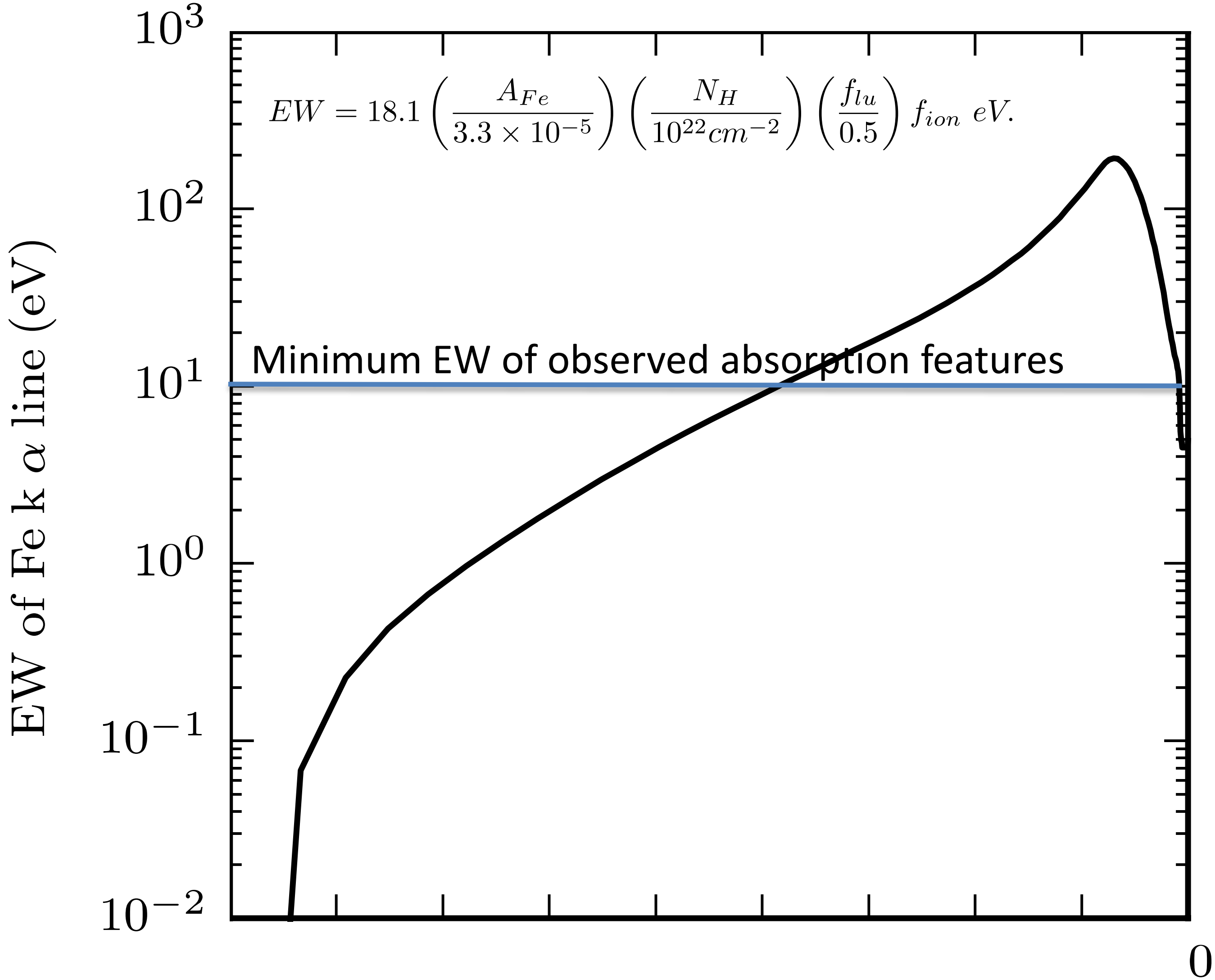
Observables 2 : Ionization parameter

- The value inferred from observations is log(ξ)≈3





Observables 3 : Equivalent widths



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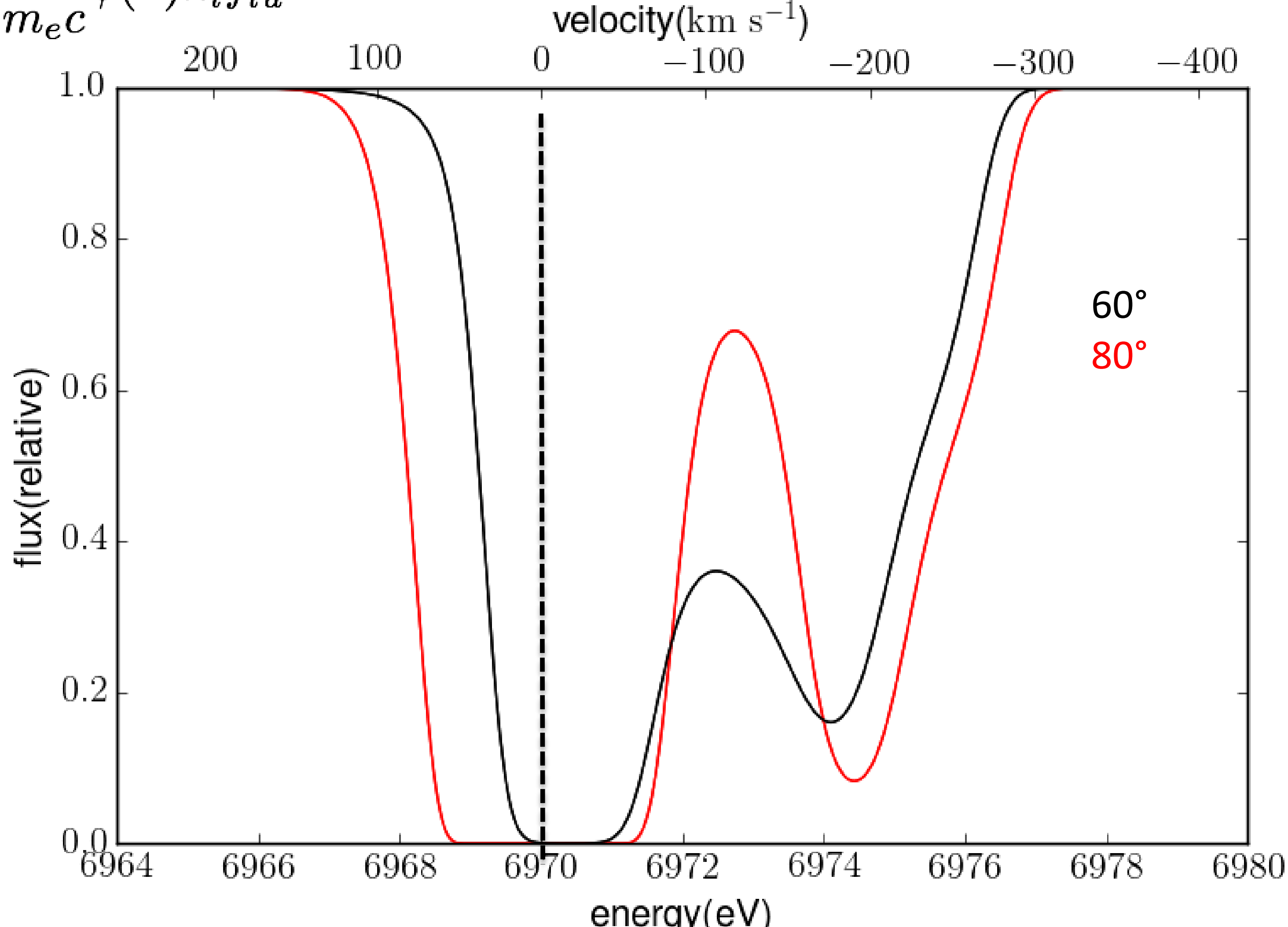
Observables 4: Synthetic Fe Kα Absorption line

$$\alpha(\nu) = \frac{\pi e^2}{m_e c} \phi(\nu) n_l f_{lu}$$



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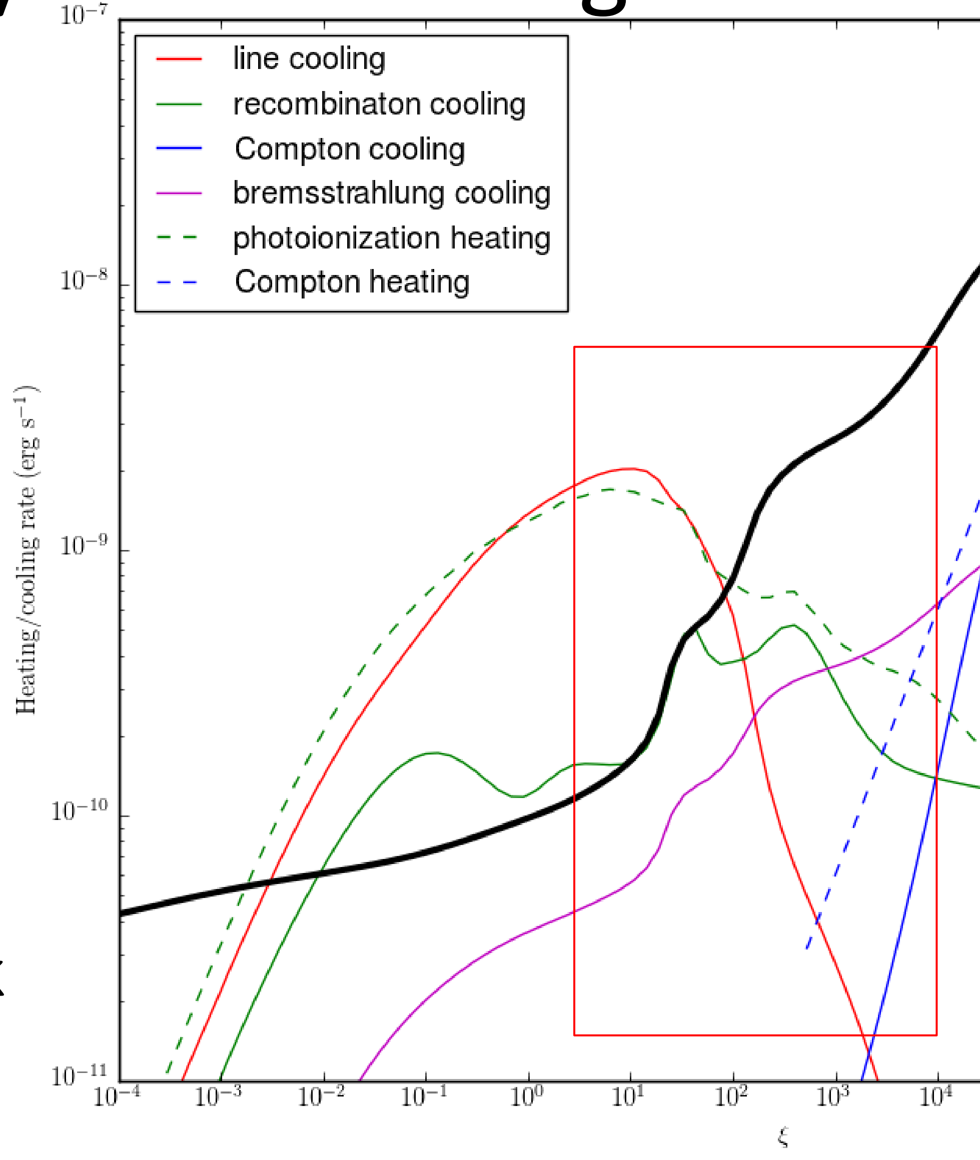
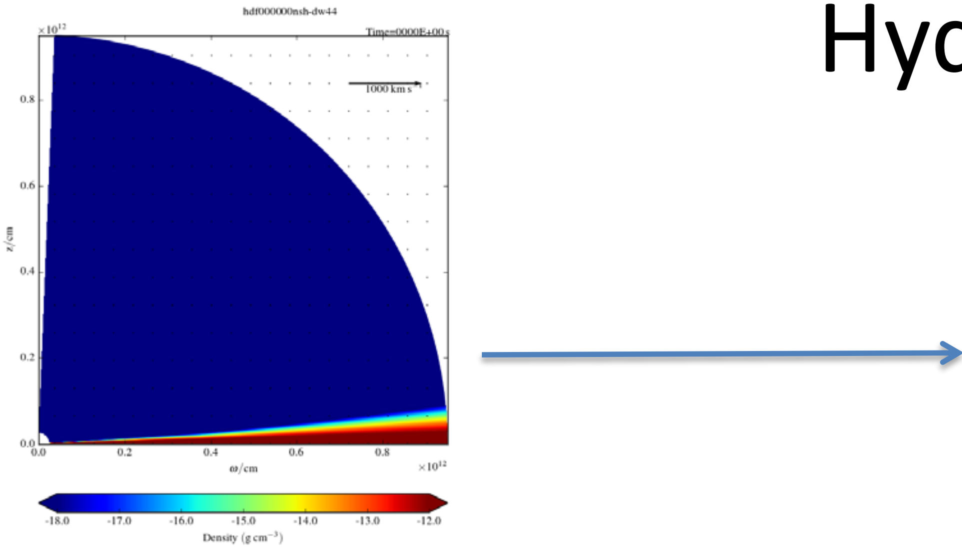
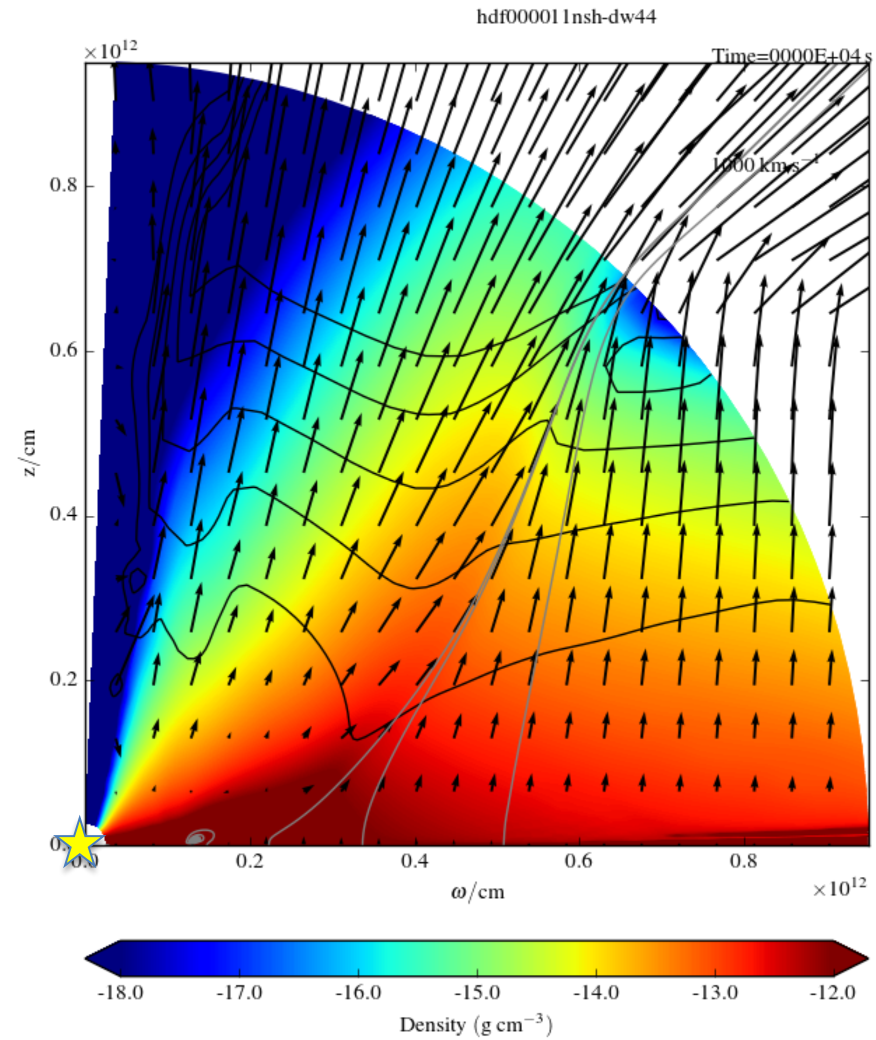
The next step – full Radiation Transport / Hydro modelling

- Onset of thermal instability drives the outflow
- The precise form of the transition defines the properties of the wind.
- The mechanisms responsible are highly sensitive to SED/RT
- Must include RT to check the effect



An operator splitting method for RT-Hydro





- Run initial simulation for a short while
- Import geometry (v,T,ρ) into our Monte Carlo RT code
- Compute ionization state and hence heating/cooling rates
- Import updated estimates of H/C rates and apply correction factors in hydro.
- Repeat to convergence.

Summary

- Thermal winds generated from accurate heating and cooling rates are currently:
  - Moderately dense (optically thick at the base)
  - Slow (Less than typically observed blue shifted absorption line velocity)
  - Have mass loss rates just about sufficient to destabilize the disk (state change?)
  - Arise at large radii (Need long period systems)
- Next step – full radiative transfer treatment.
  - Different SEDs? (Dyda+ 16)
  - Then line driving simulations for AGN.