Warm absorbers from torus evaporative flows(??)

Tim Kallman (NASA/GSFC)
+
A. Dorodnitsyn (GSFC)
+
D. Proga (UNLV)

..

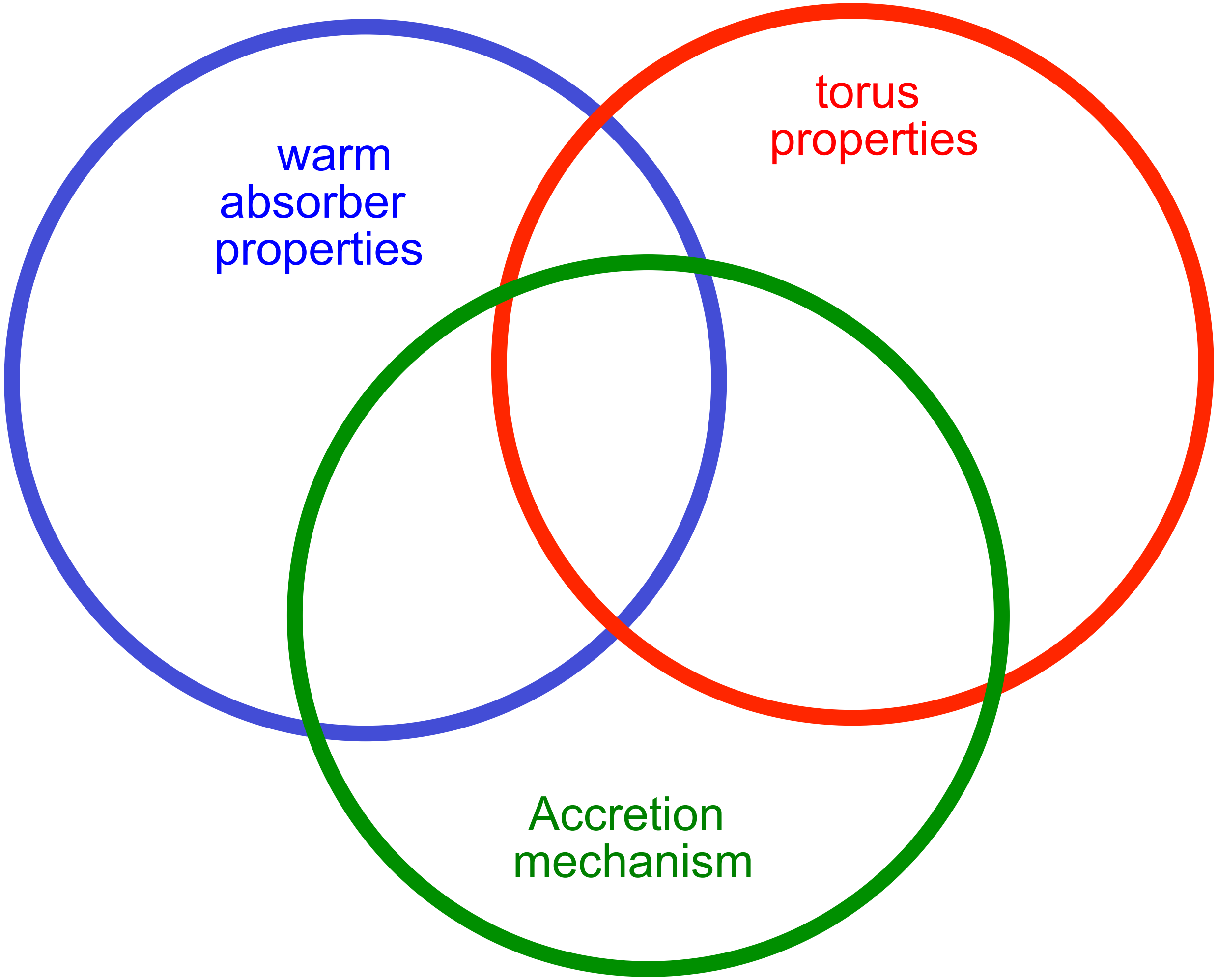
Why should we care about warm absorbers…

- Mass loss rate in wind $< 0.1\ M_{sun}/yr$
- Mass accretion rate $\sim 0.01\ L_{44}\ M_{sun}/yr$
- → warm absorber flows are important in the AGN mass budget
- Suggests that accretion inside warm absorber launching may be easily disrupted: what determines how much gas makes it inward, past the torus?
- Torus origin consistent with warm absorber speeds, dust sublimation.

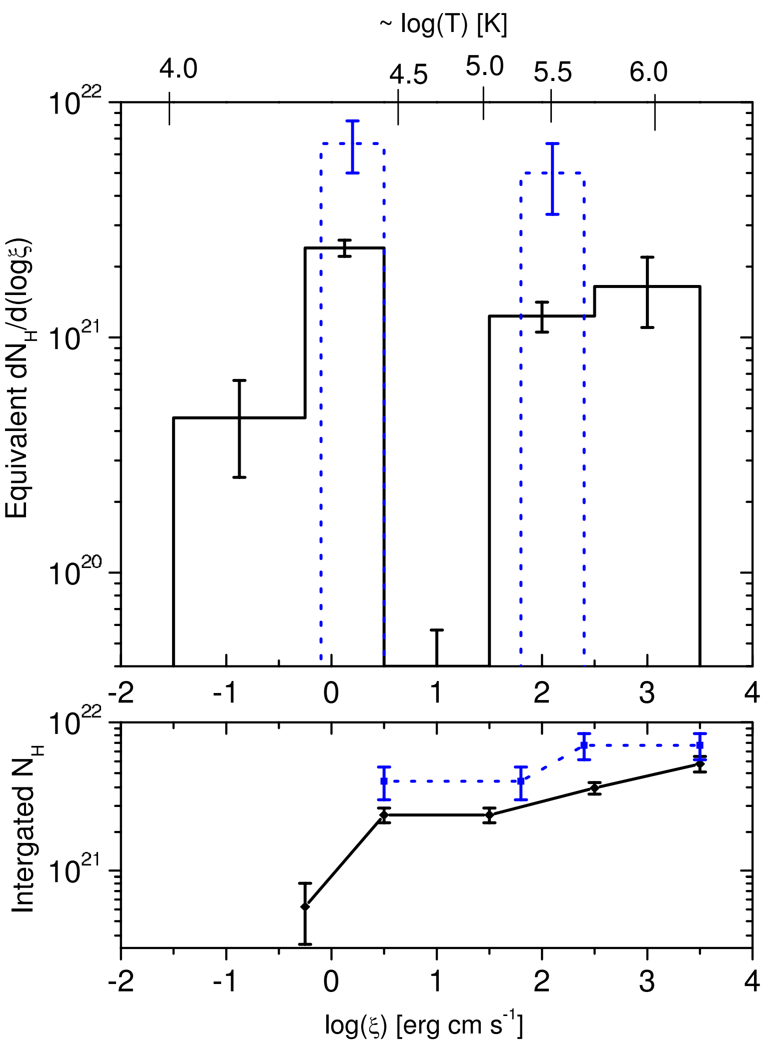
Questions..

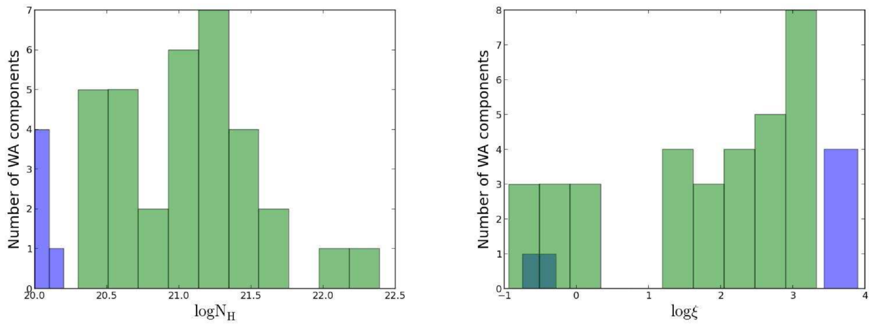
- Can the (relatively) simple scenario, torus evaporation, explain warm absorber observed properties?
- To what extent does warm absorber modeling force us to understand (everything else about) the gas flows in AGN central regions?
- What are the key observed quantities (i.e. how can we tailor future efforts to maximize progress)

The challenge of understanding torus origin of warm absorbers



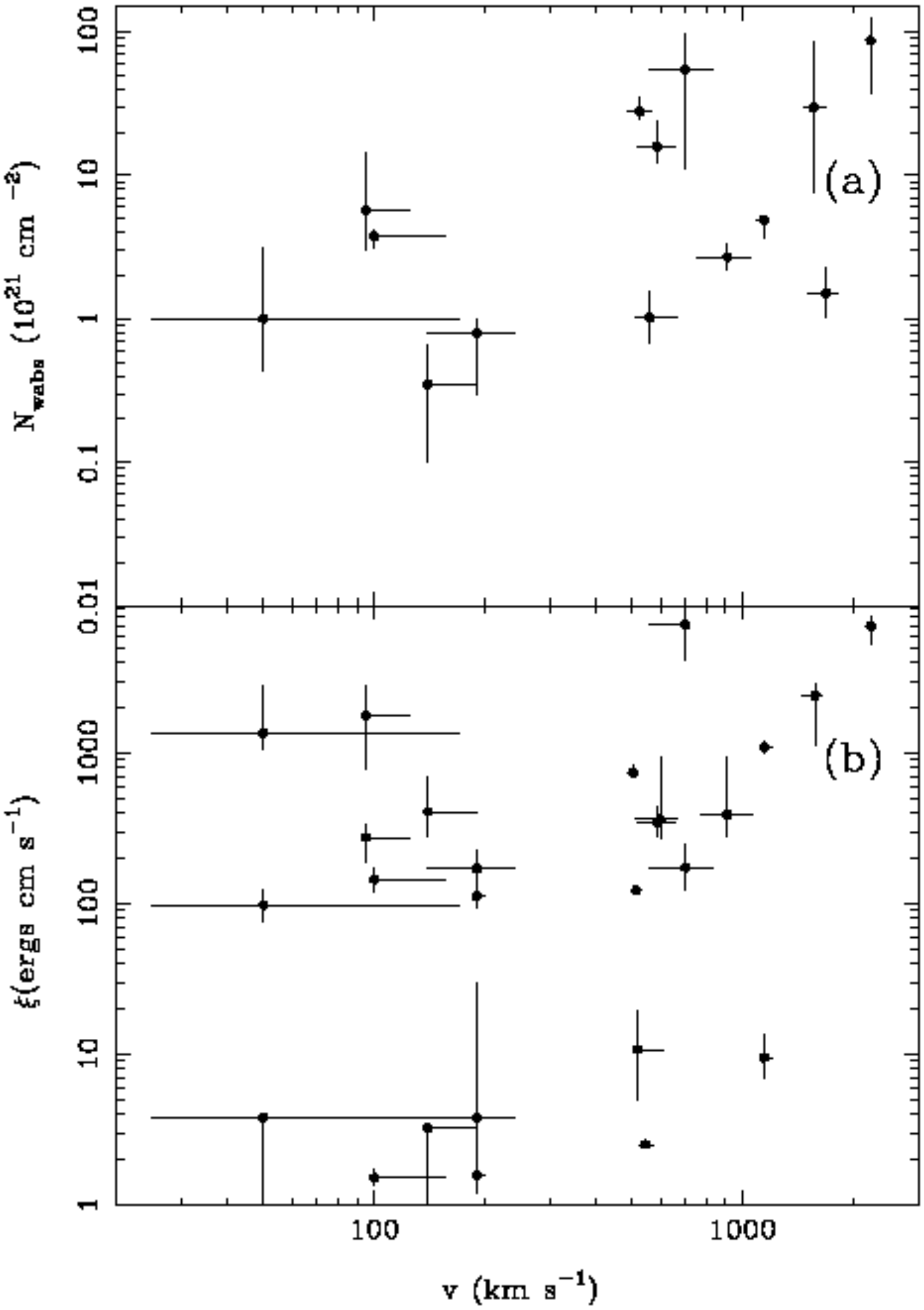
Observational situation





This behavior seems to be common to many objects:

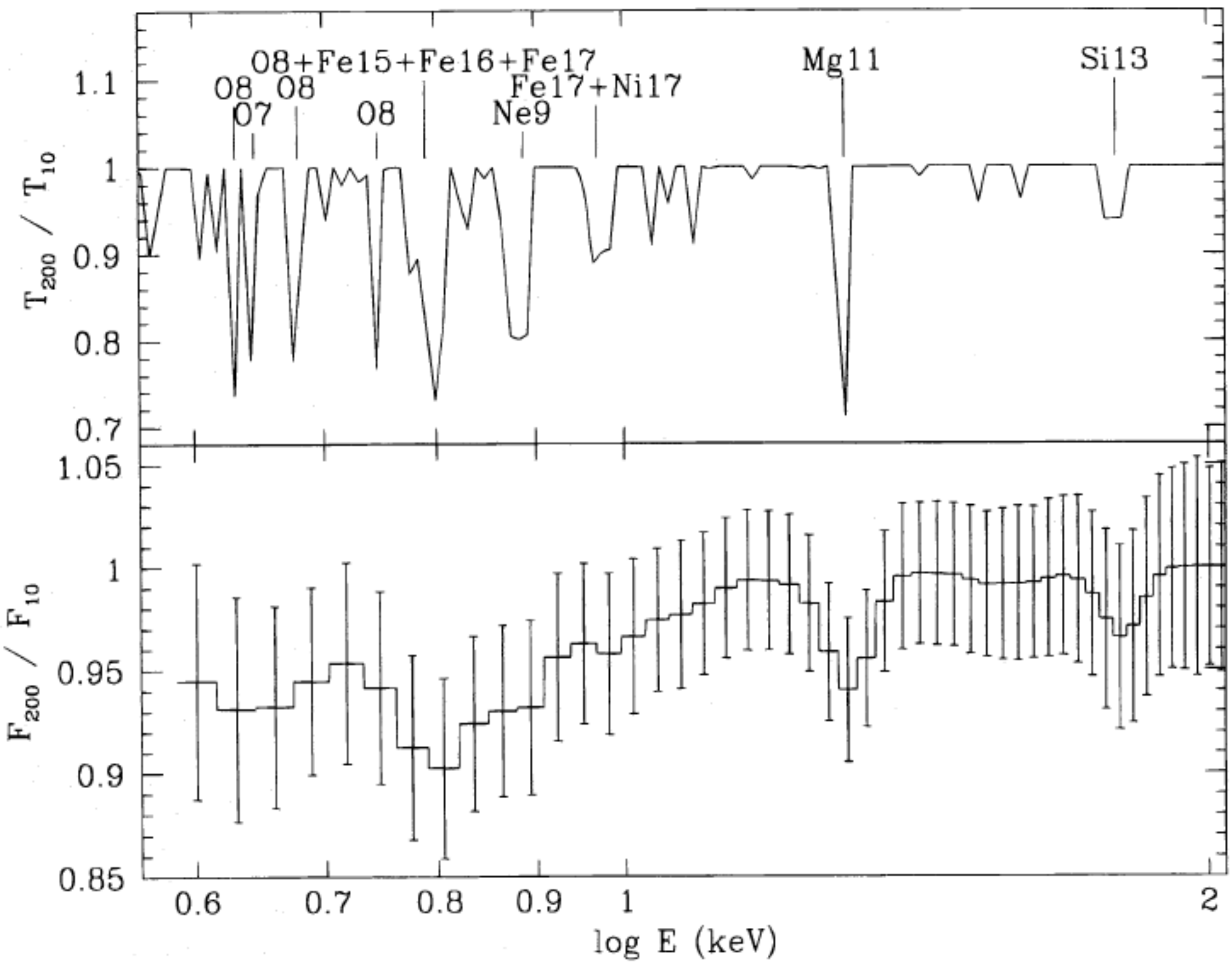
- Ionization parameter: apparently bimodal
- V<2000 km/s
- Column ~anticorrelated with ionization



McKernan et al. 2007

Lines in warm absorbers were predicted before their discovery..

- Photoelectric absorption should be accomanied by line photoexcitation
- This will result in absorption features if the gas is non-spherical, or moving radially
- The ratio of line/ continuum depends on the line widths



Kriss et al. 1996

The torus

- To make obscuration:

$$R \sim 1 \text{ pc}$$

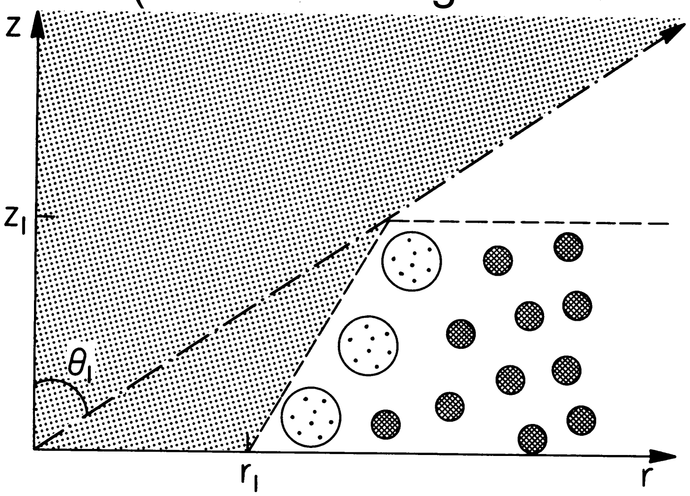
$$\tau_{Th} = 10$$

$$n_{Torus} \simeq 10^5 \text{ cm}^{-3}\ \tau_{Th} R_{pc}^{-1}$$

$$M_{Torus} \simeq 10^6 M_\odot \tau_{Th} R_{pc}^2$$

$$T_{vir} = 5 \times 10^5 \text{ K } M_6 R_{pc}^{-1}$$

(Krolik and Begelman 1986)

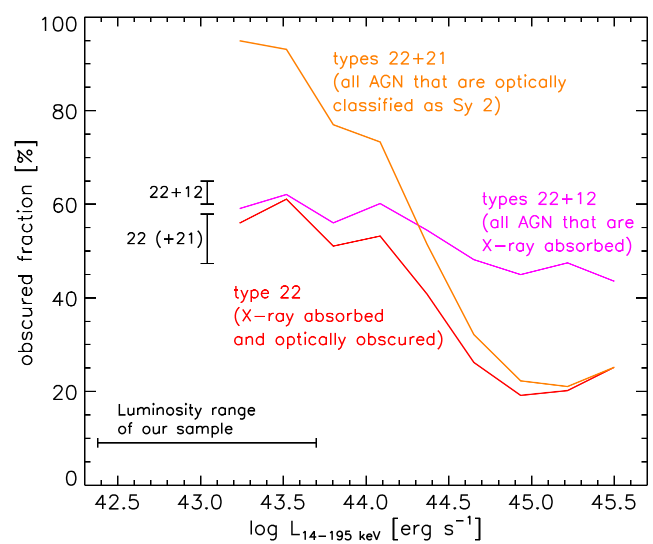


- Vertical Support:

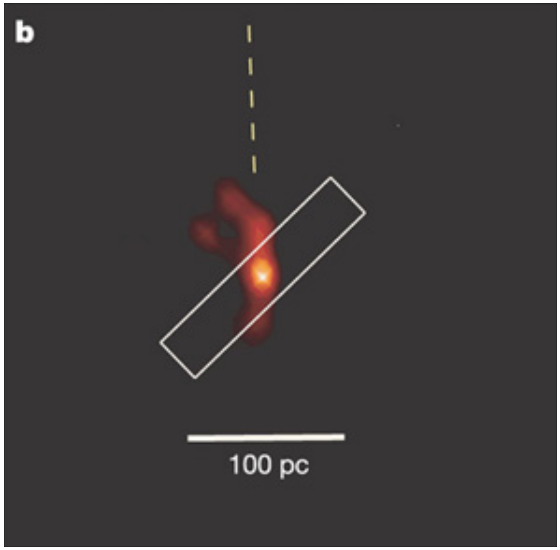
$$\frac{H}{R} = \sqrt{\frac{T}{T_{Vir}}}$$

$$\frac{H}{R} = \sqrt{\frac{aT^4}{nkT_{Vir}}}$$

(Davies et al. 2015)



(Jaffe et al. 2004)



Torus Evaporation:

In a heated hydrostatic atmosphere, gas is expected to remain in warm/cold phase when pressure exceed P_{min}
At lower pressure gas heats toward Compton temperature, ~ 10^7K

$$P_{min} \simeq \frac{L}{4\pi R^2 \Xi_c^* c}$$

$$\dot{m} \sim \frac{P_{min}}{c_s} \simeq 10^{-13}\ \mathrm{gm\ s^{-1}\ cm^{-2}}\ L_{44} R_{pc}^{-2} T_7^{-1} \Xi$$

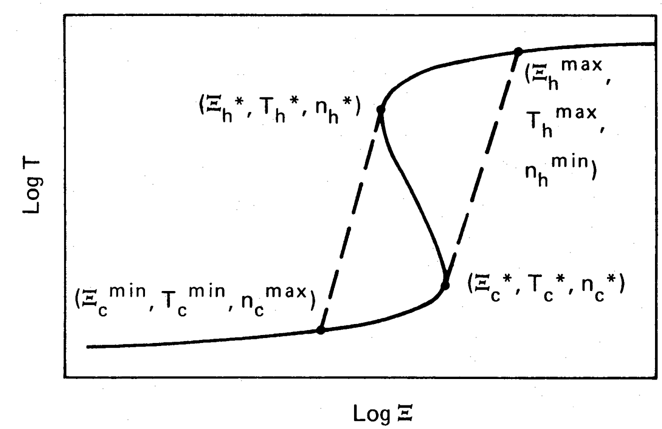
$$\dot{M} \simeq 0.1 M_\odot\ \mathrm{yr}^{-1}\ L_{44} T_7^{-1} \Xi$$

$$t_{evap} = \frac{M_{Torus}}{\dot{M}} \simeq 10^7\ \mathrm{yrs}$$

$$t_{dyn} = \sqrt{\frac{R^3}{2GM_{BH}}} \simeq 10^4\ \mathrm{yrs}\ R_{pc}^{3/2} M_6^{-1/2}$$

$$t_{Heat} \simeq 2 \times 10^4\ \mathrm{yrs}\ \frac{T}{T_{IC}} R_{pc}^2 L_{44}^{-1}$$

(Krolik McKee Tarter 1982)



→ X-ray heating will produce a thermally driven outflow in approximate equilibrium with the illuminating radiation

Wind/warm absorber

Mean density, ionization parameter, column density:

$$n_{wind} \sim \frac{\dot{M}/m_H}{4\pi R^2 v} \simeq 2 \times 10^3 \ \mathrm{cm}^{-3} \dot{M}_{0.1} R_{pc}^{-2} v_7^{-1}$$
$$\xi_{wind} = \frac{L}{nR^2} \simeq 10^4 \ \mathrm{erg\ cm\ s}^{-1} \ L_{44} \dot{M}_{0.1}^{-1} v_7$$
$$N_{wind} = nR \simeq 5 \times 10^{21} \ \mathrm{cm}^{-2} \ L_{44} \dot{M}_{0.1}^{-1} v_7 R_{pc}$$

Density is slightly low and ionization parameter is slightly greater than needed to produce warm asorbers
But geometric effects may change the quantitative results

Dynamical calculations

- Assume a torus at ~1 pc about a $10^6 M_{sun}$ black hole
- Initial structure is constant angular momentum adiabatic (cf. Papaloizou and Pringle 1984)
- This structure is stable (numerically) for >20 rotation periods
- Choose $T \sim T_{vir}$, $n \sim 10^8$ cm^{-3} for unperturbed torus
- Calculate hydrodynamics in 2.5d (2d + axisymmetry) (Zeus2d)
- Add illumination by point source of X-rays at the center
- Include physics of X-ray heating, radiative cooling --> evaporative flow (cf. Blondin 1994)
- Also radiative driving due to UV lines (cf. Castor et al. 1976; Stevens & K. 1986)
- Formulation similar to Proga et al. 2000, Proga & K. 2002, 2004

goals

- Understand divergence of flow, i.e. geometry

→ accurate determination of ξ, N

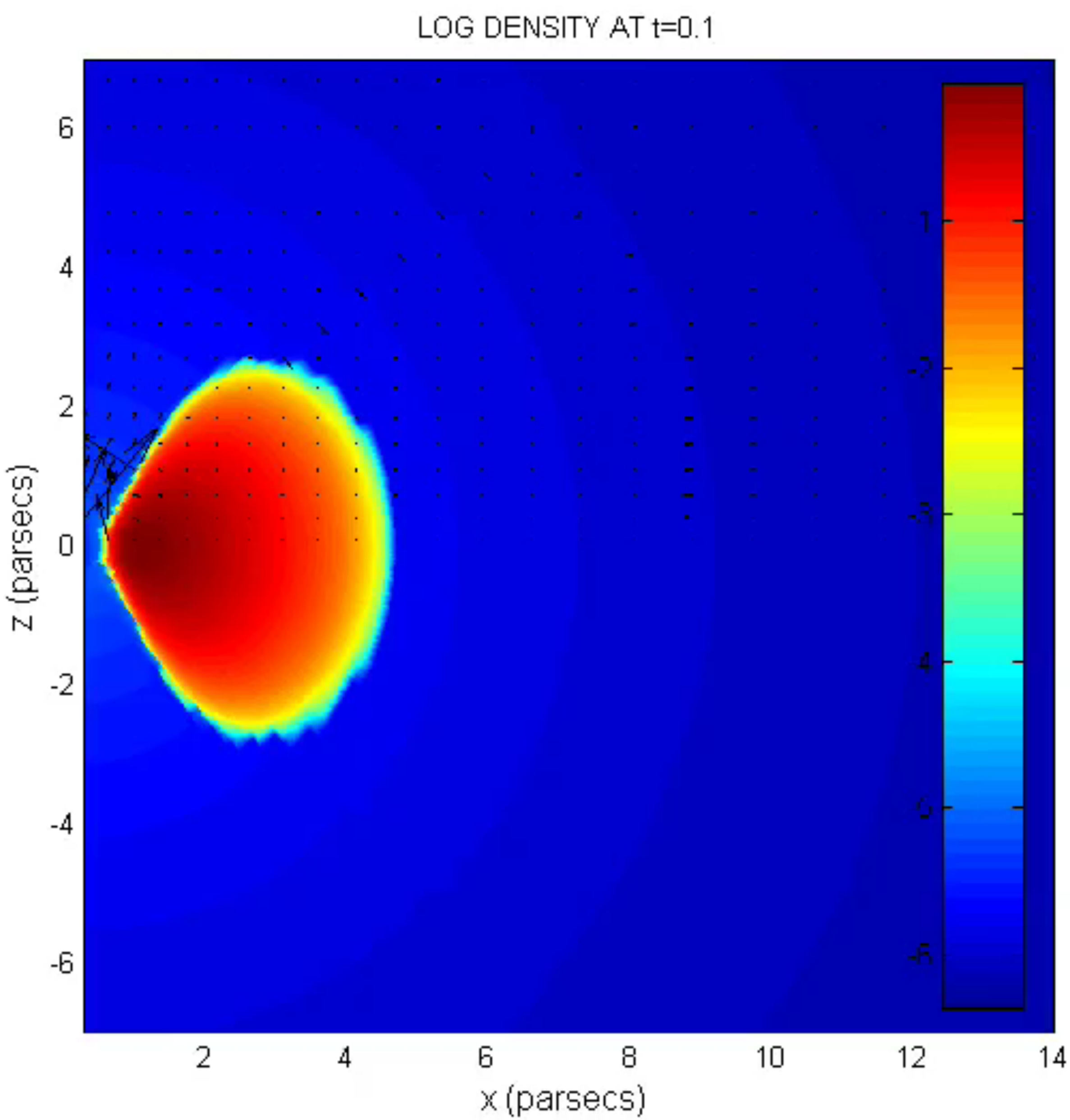
- Understand thermodynamics of flow

→ What does T-Ξ curve look like?

- Feedback of flow on torus

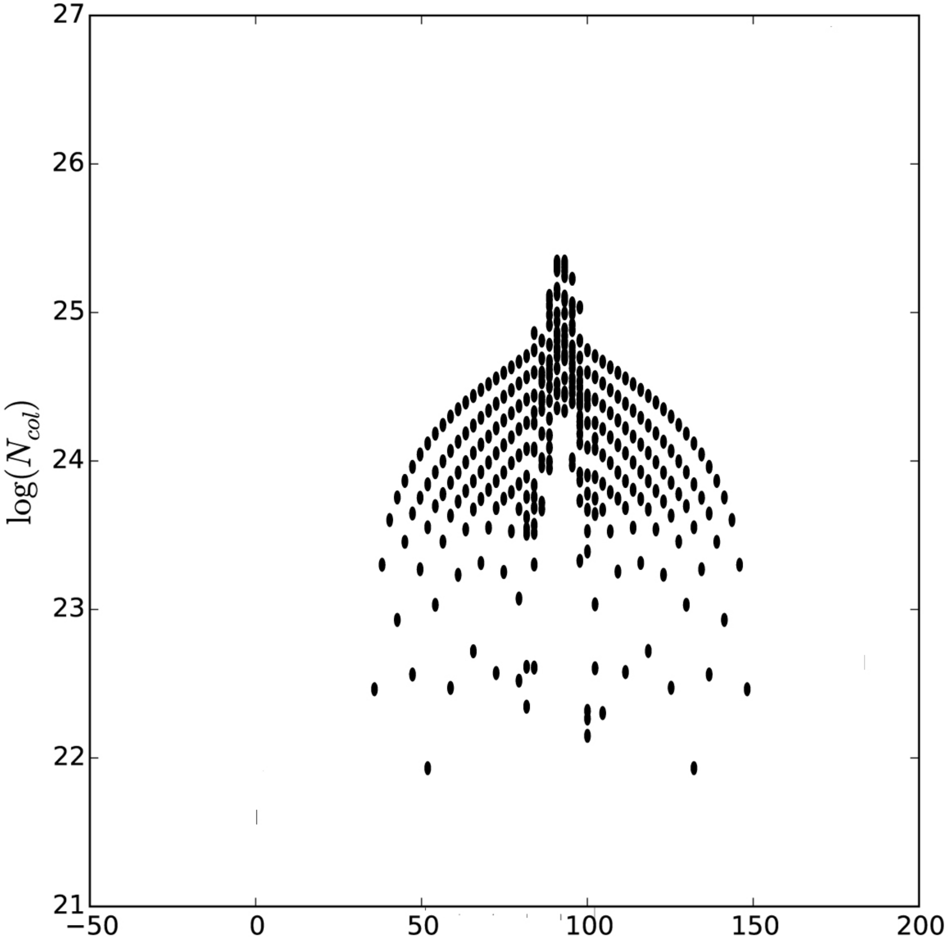
→ can we learn anything about the torus from the warm absorbers?

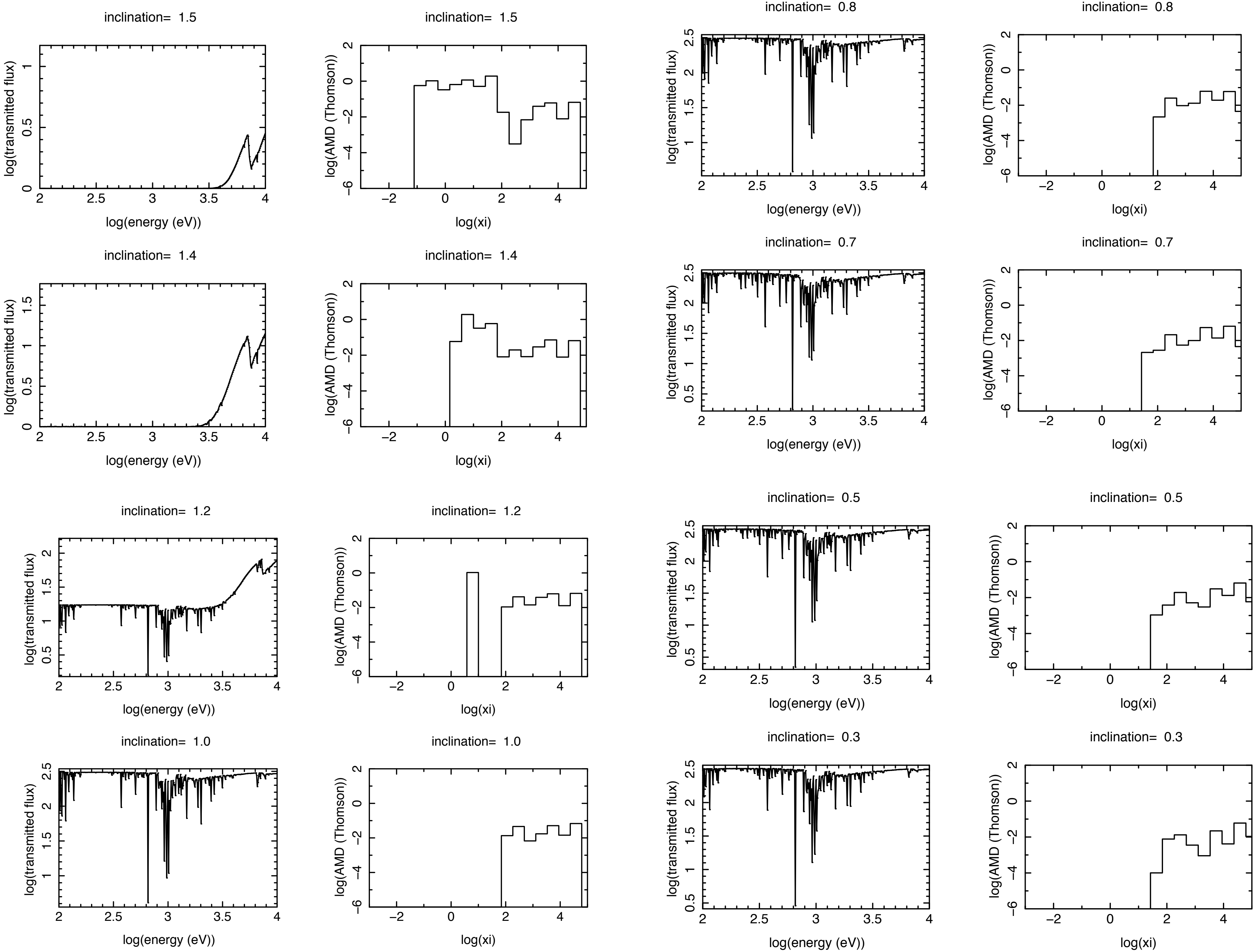
Gas pressure dominated torus



Column density vs. inclination

- Column is ~10^{24} cm^{-3} for inclinitions >45 initially
- Torus thins with time
- Very rapid transition from thick to thin at most times



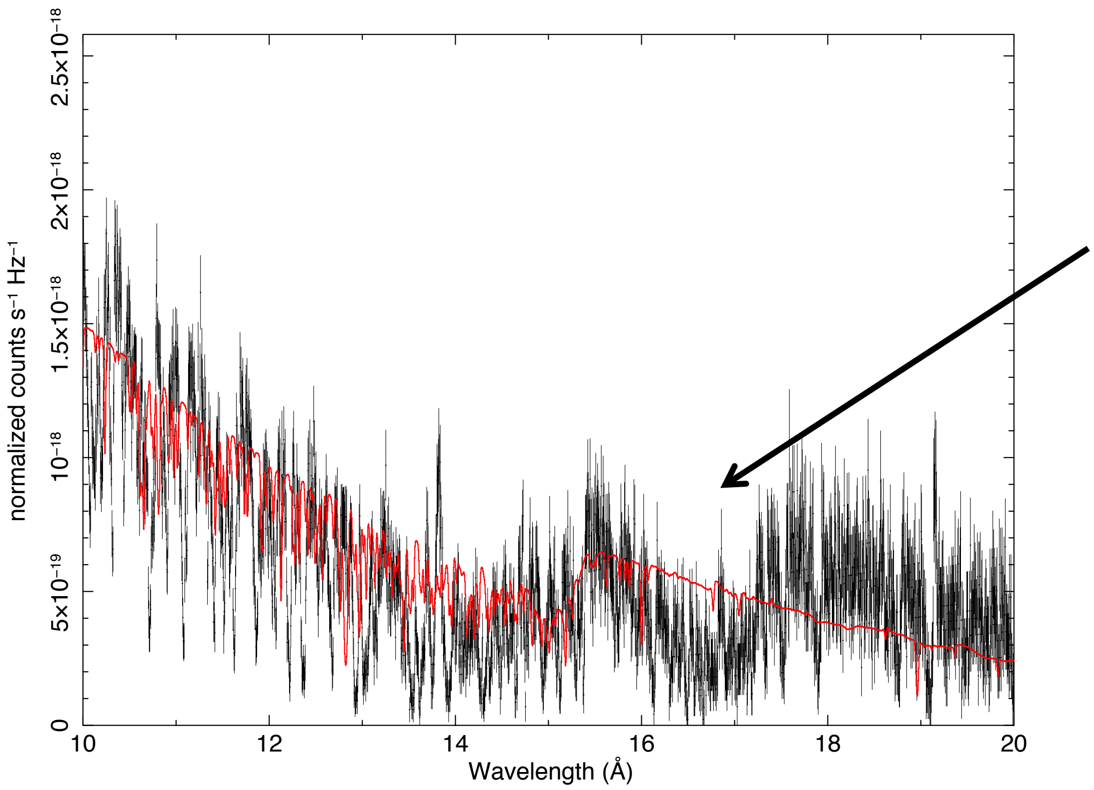


inclination= 1.5
log(transmitted flux)
log(energy (eV))
inclination= 1.5
log(AMD (Thomson))
log(xi)
inclination= 0.8
log(transmitted flux)
log(energy (eV))
inclination= 0.8
log(AMD (Thomson))
log(xi)
inclination= 1.4
log(transmitted flux)
log(energy (eV))
inclination= 1.4
log(AMD (Thomson))
log(xi)
inclination= 0.7
log(transmitted flux)
log(energy (eV))
inclination= 0.7
log(AMD (Thomson))
log(xi)
inclination= 1.2
log(transmitted flux)
log(energy (eV))
inclination= 1.2
log(AMD (Thomson))
log(xi)
inclination= 0.5
log(transmitted flux)
log(energy (eV))
inclination= 0.5
log(AMD (Thomson))
log(xi)
inclination= 1.0
log(transmitted flux)
log(energy (eV))
inclination= 1.0
log(AMD (Thomson))
log(xi)
inclination= 0.3
log(transmitted flux)
log(energy (eV))
inclination= 0.3
log(AMD (Thomson))
log(xi)

Warm absorber spectra

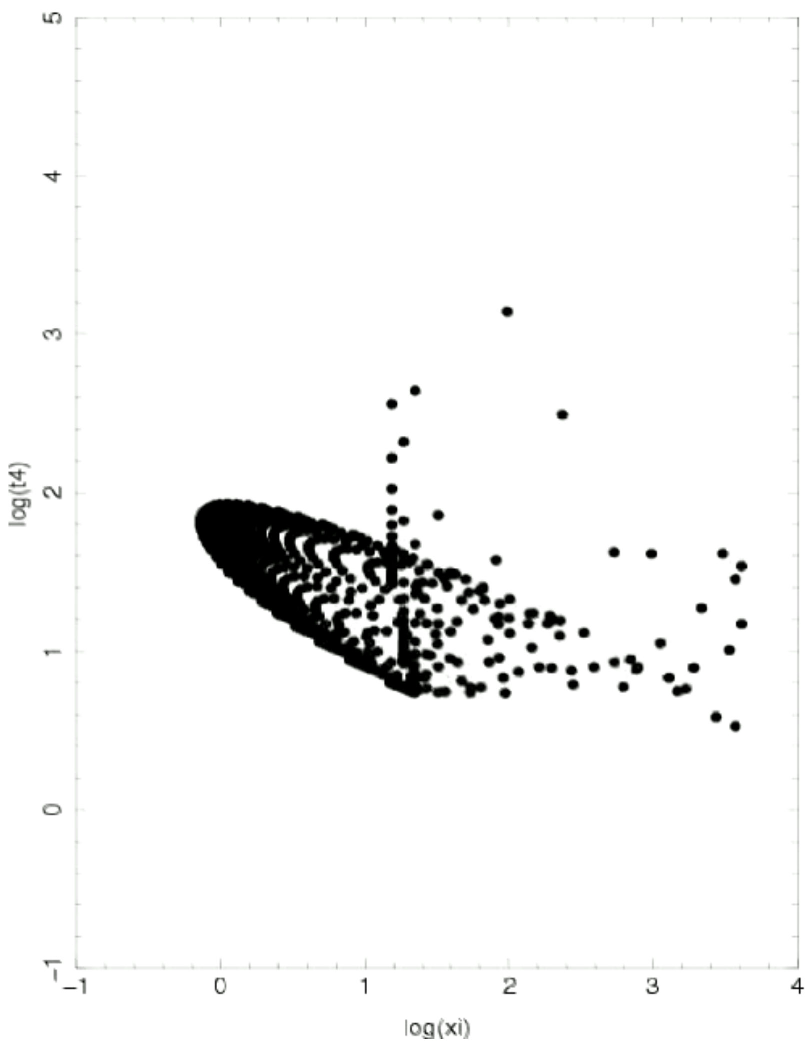
- Spectra shown at intermediate time
- At i~90^o see AMD~few x Thomson across many ionization parameters
- Obscuration angle ~+-30^o
- at lower angles see weak, highly ionized warm absorber
- Plausible warm absorber only in narrow range of angles near ~30^o
- weak evidence for thermal instability/2 phase behavior

Fit to Chandra HETG spectrum of NGC 3783



Misses UTA due to absence of low ionization gas

What happens to gas in the T-ξ/T plane in such a model..



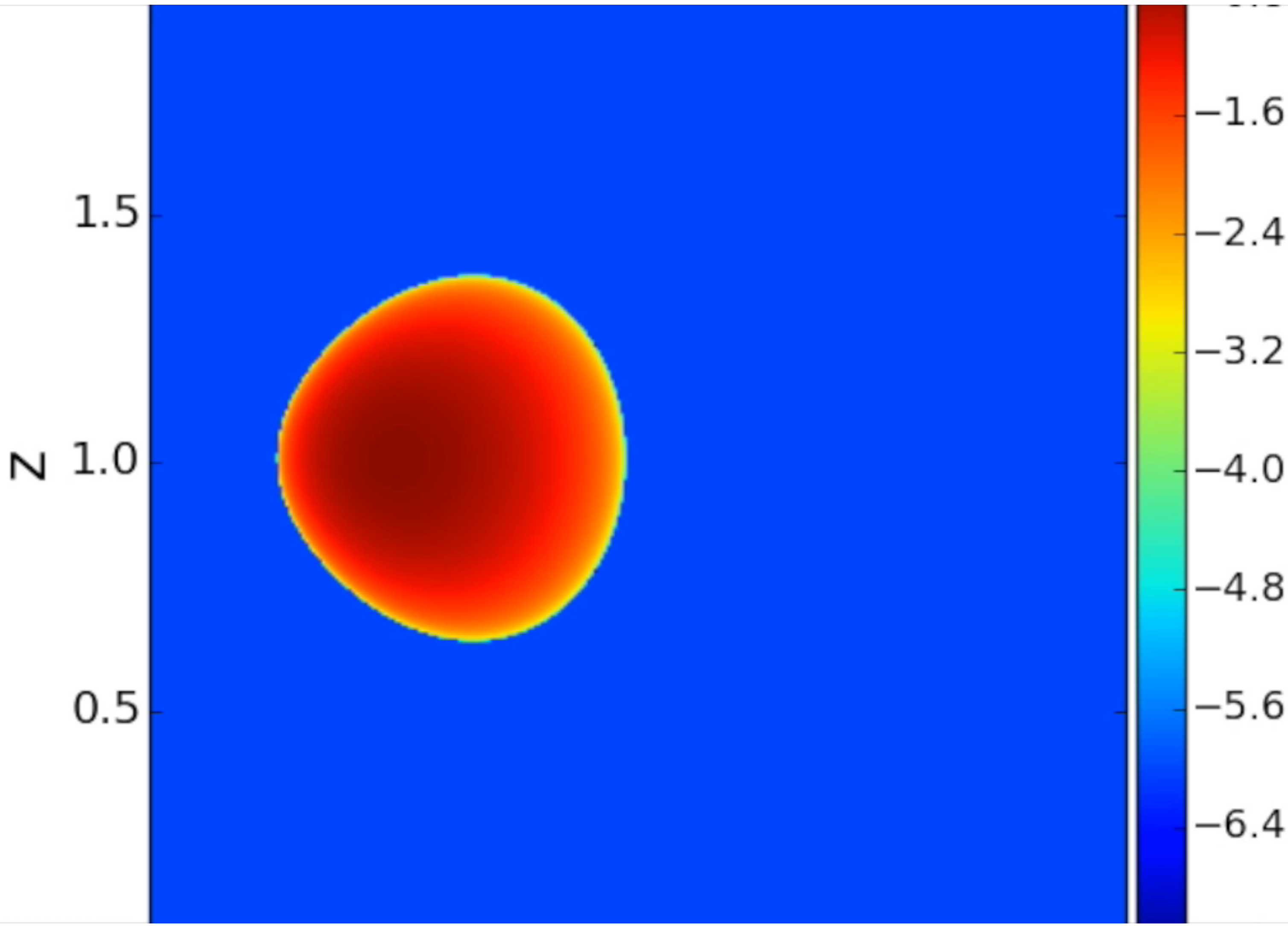
Lessons from gas-pressure dominated torus models

- Outflow mass loss rate is comparable to estimates, it shapes the torus
- Line profiles, ionization, blueshift ~consistent with observations.
- Density in torus throat is similar to spherically diverging flow → warm absorbers are seen for relatively narrow range of viewing angles
- Adiabatic cooling is important → no obvious 2 phase behavior
- Outflow depends on torus structure; unphysical gas pressure dominated torus does not fit with standard unification.

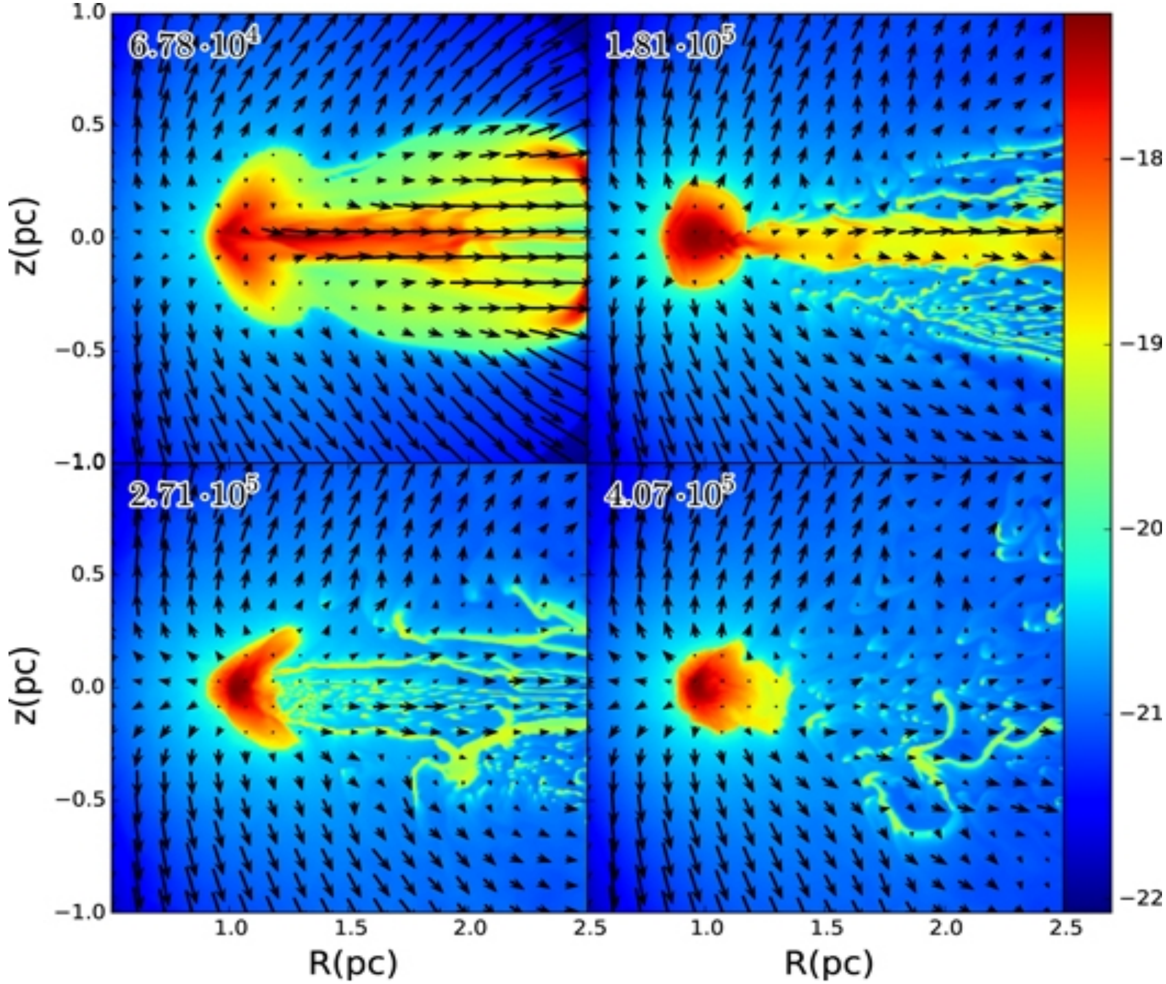
Model with IR radiation pressure

- IR generated by reprocessing of X-rays according to simple prescription
- IR transfer uses flux limited diffusion
- Include all X-ray thermal and pressure effects from gas-pressure models
- Models are 2.5D axisymmetric (zeusmp)
- Hydrodynamic viscosity is also included to maintain balance with radiation pressure
- X-ray excited wind contributes to accretion
- Cf. Krolik 2007, Shi and Krolik 2008, Chan and Krolik 2016…

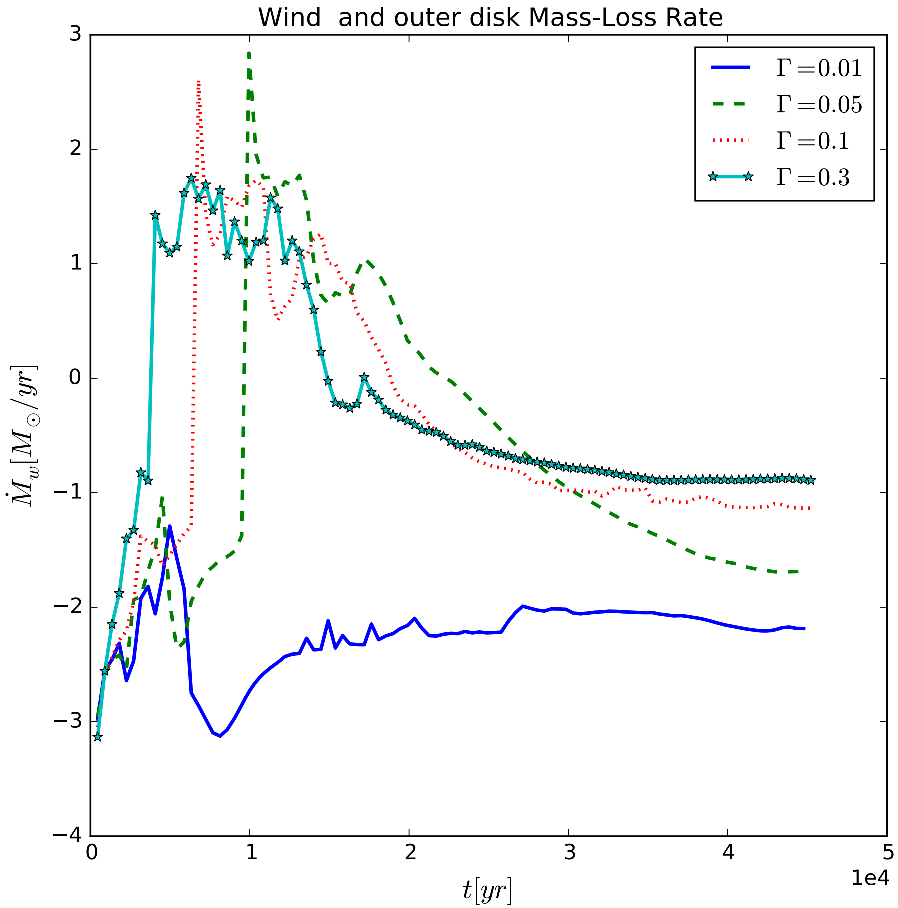
Model with IR radiation pressure



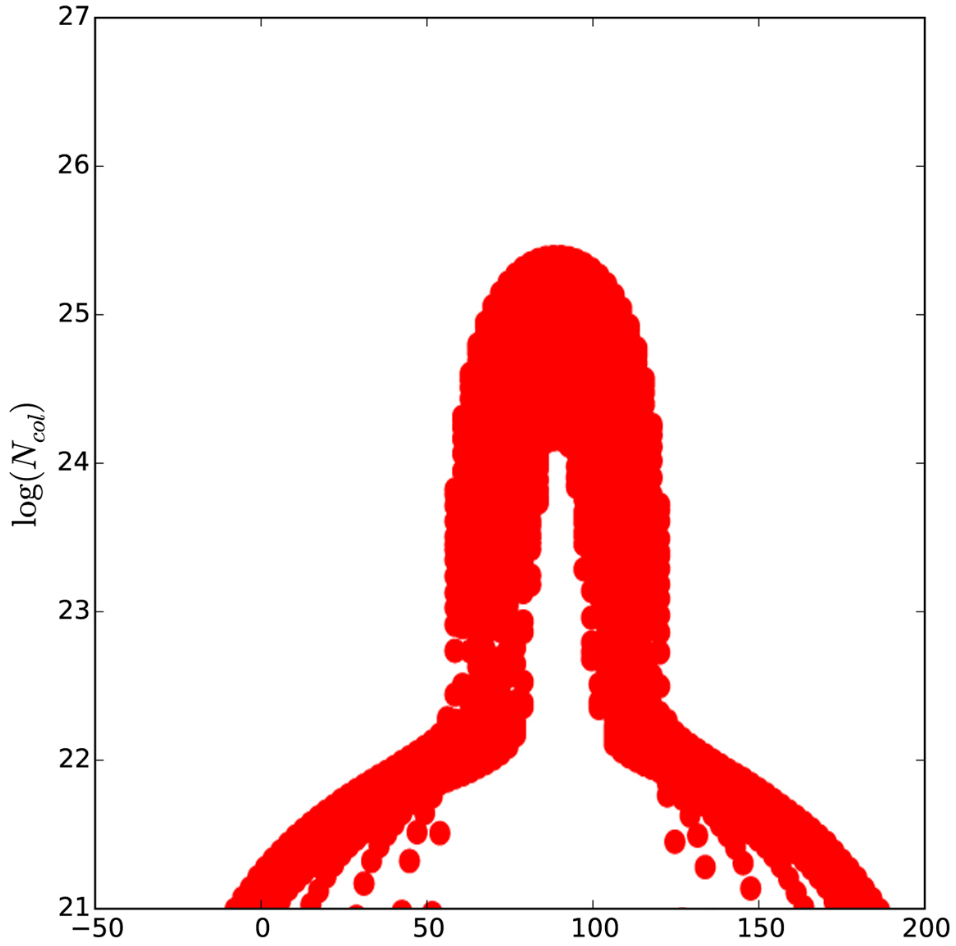
Model with IR radiation pressure



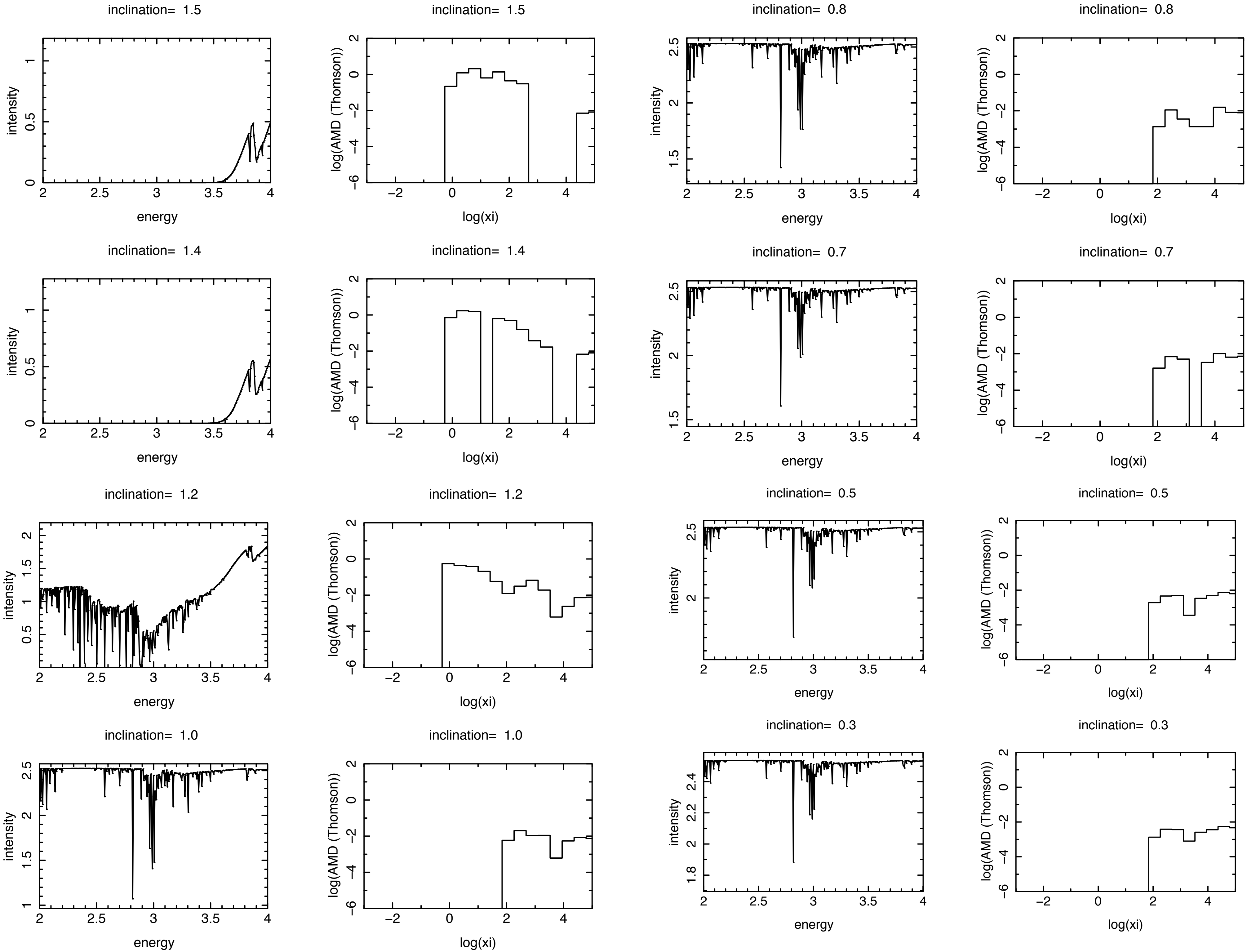
Wind mass loss rate vs. time



Column density vs. inclination



Model with
IR radiation pressure


inclination= 1.5
intensity
energy
inclination= 1.5
log(AMD (Thomson))
log(xi)
inclination= 0.8
intensity
energy
inclination= 0.8
log(AMD (Thomson))
log(xi)
inclination= 1.4
intensity
energy
inclination= 1.4
log(AMD (Thomson))
log(xi)
inclination= 0.7
intensity
energy
inclination= 0.7
log(AMD (Thomson))
log(xi)
inclination= 1.2
intensity
energy
inclination= 1.2
log(AMD (Thomson))
log(xi)
inclination= 0.5
intensity
energy
inclination= 0.5
log(AMD (Thomson))
log(xi)
inclination= 1.0
intensity
energy
inclination= 1.0
log(AMD (Thomson))
log(xi)
inclination= 0.3
intensity
energy
inclination= 0.3
log(AMD (Thomson))
log(xi)

Warm absorber spectra

- Spectra shown at intermediate time
- At $i=\pi/2$ see AMD~few across many ionization parameters
- Results for obscuration angle and range of warm absorber observations are similar to gas pressure dominated case
- Mass requirement is lower due to pressure support

Lessons from radiation-pressure dominated torus models

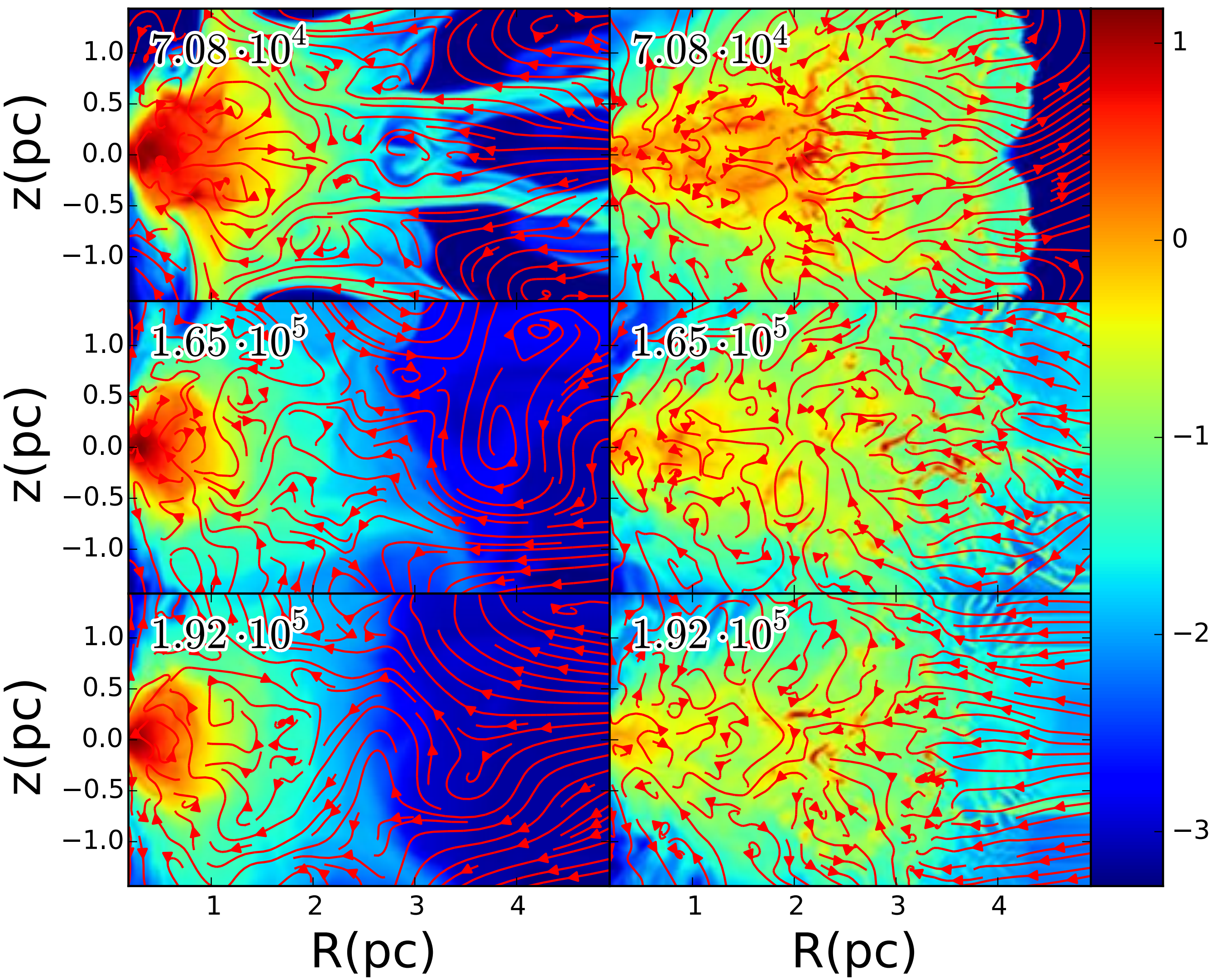
- Internal IR from X-ray heating provides sufficient pressure support even with cold gas temperature
- Density in torus throat is similar to gas pressure torus → warm absorbers are seen for relatively narrow range of viewing angles
- Weak 2-phase behavior is found
- Radiation pressure affects the torus bulk properties (even at low L/L_{edd}) → angular momentum loss mechanism is needed to produce quasi-steady torus

Mhd torus

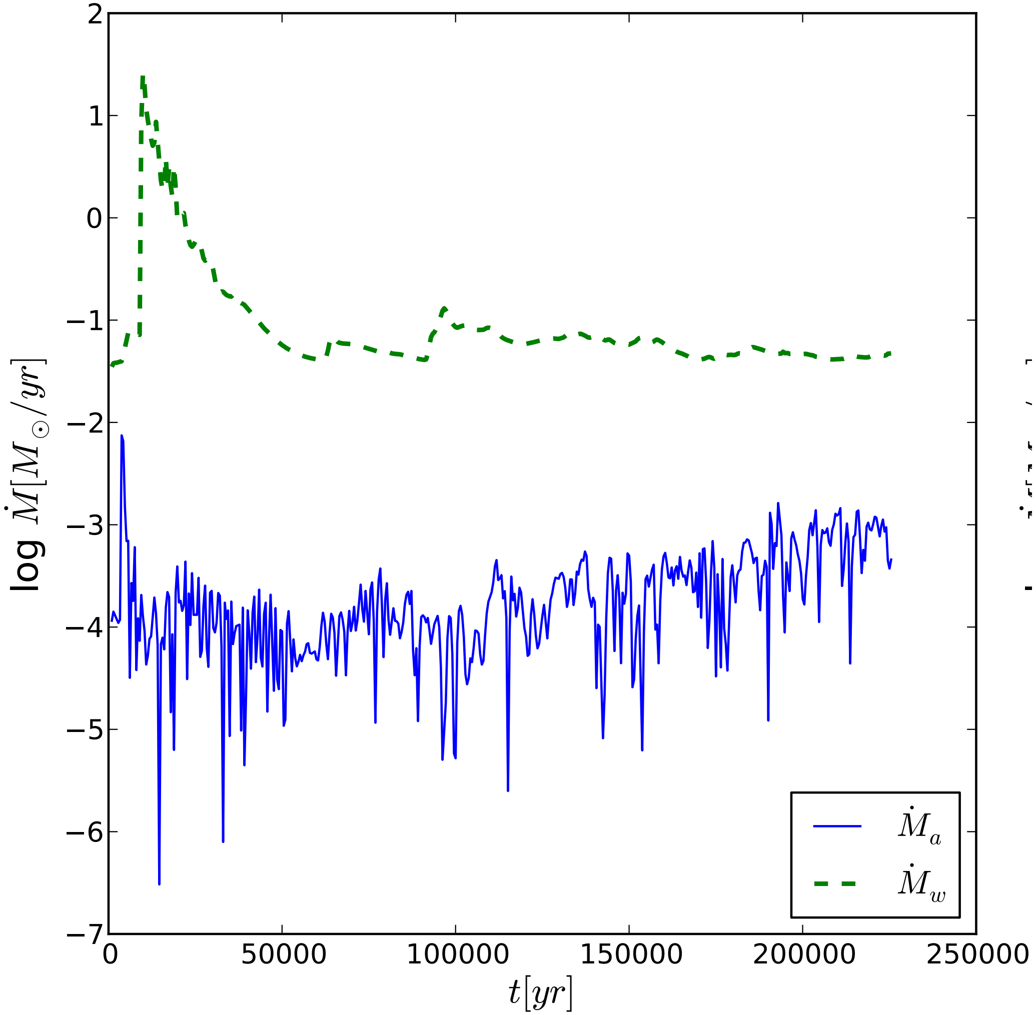
I

- 3d MHD models (Athena)
- X-ray heating included
- No IR radiation pressure
- Two different initial magnetic field configurations considered
  - configuration based on tokamak solution → strong initial poloidal field both inside and outside torus (SOL)
  - Configuration with field proportional to gas density (TOR)

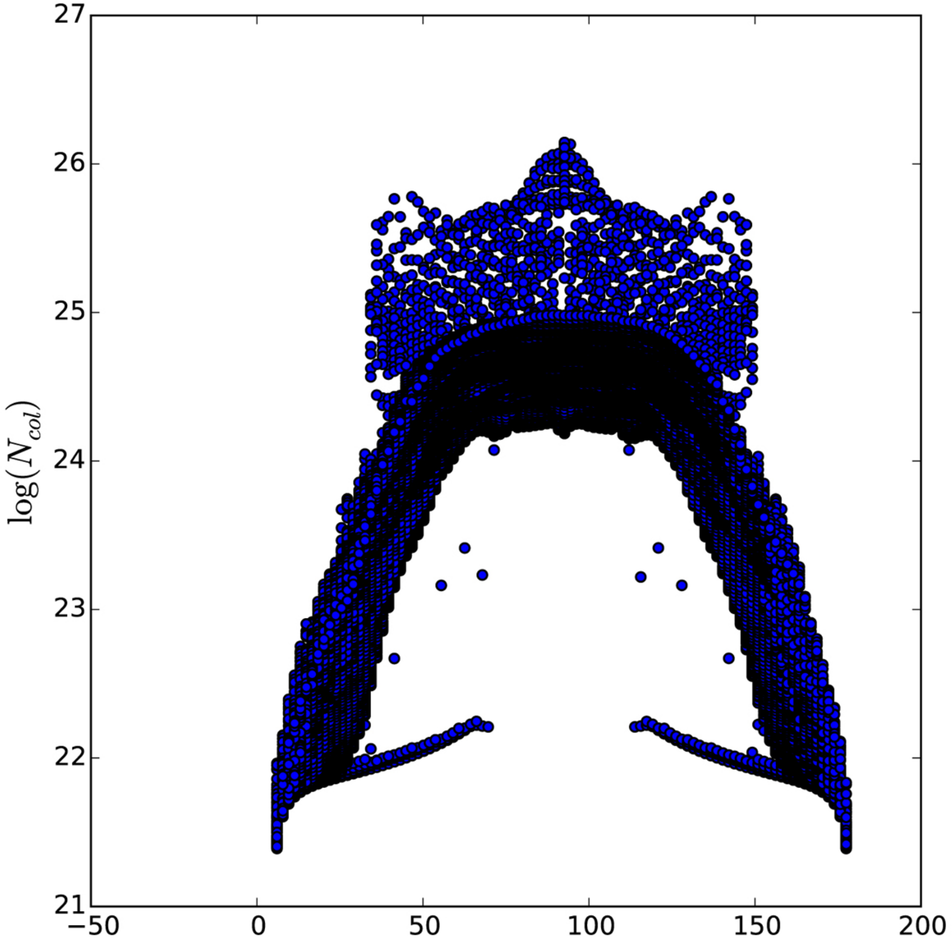
Mhd torus density structure and streamlines



Accretion rate and mass loss rate: SOL model



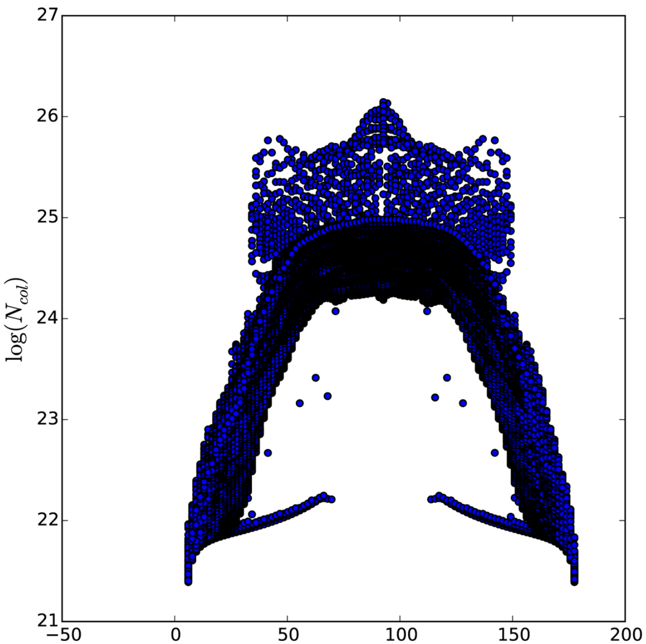
Column density vs. inclination



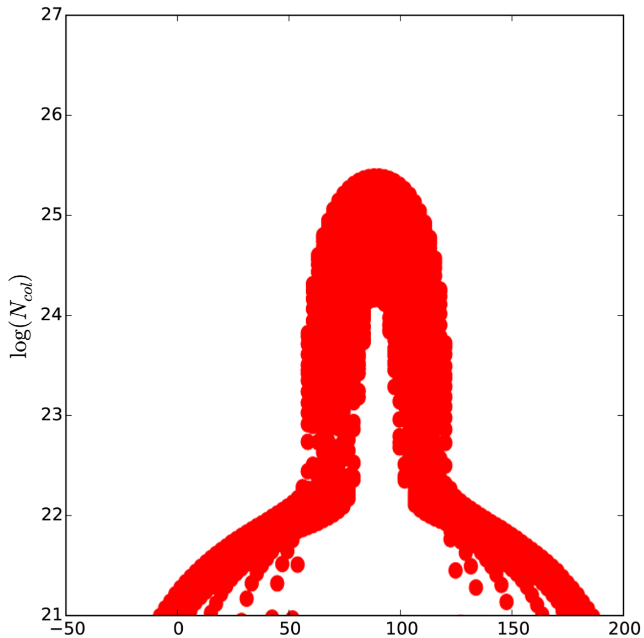
MHD model

Column density vs. inclination

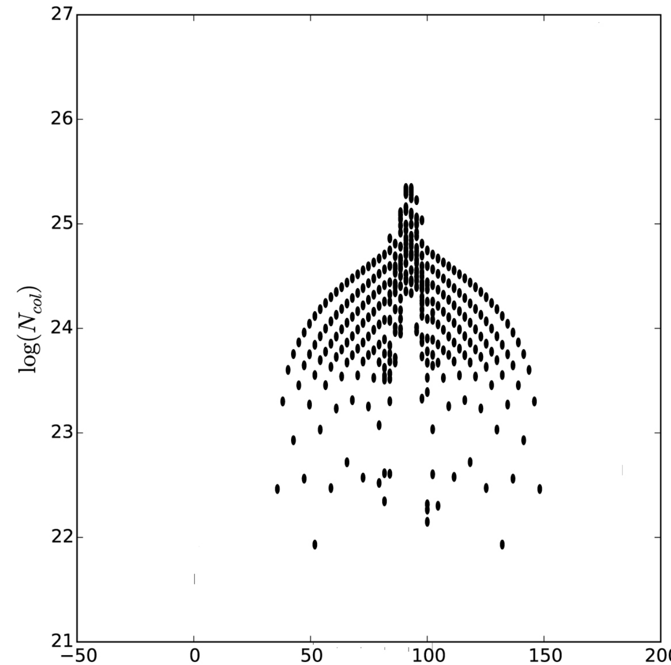
MHD model

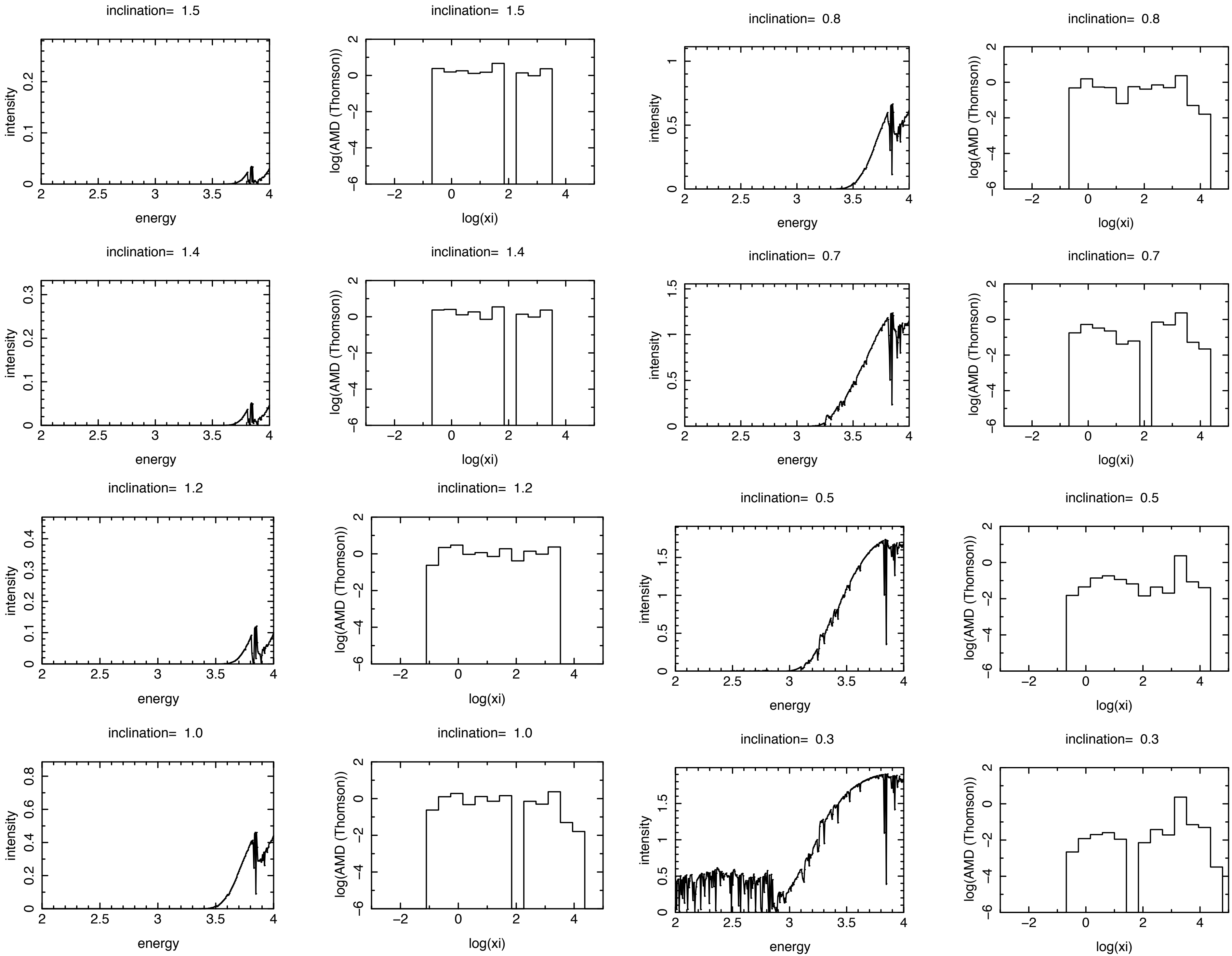


Model with
IR radiation pressure

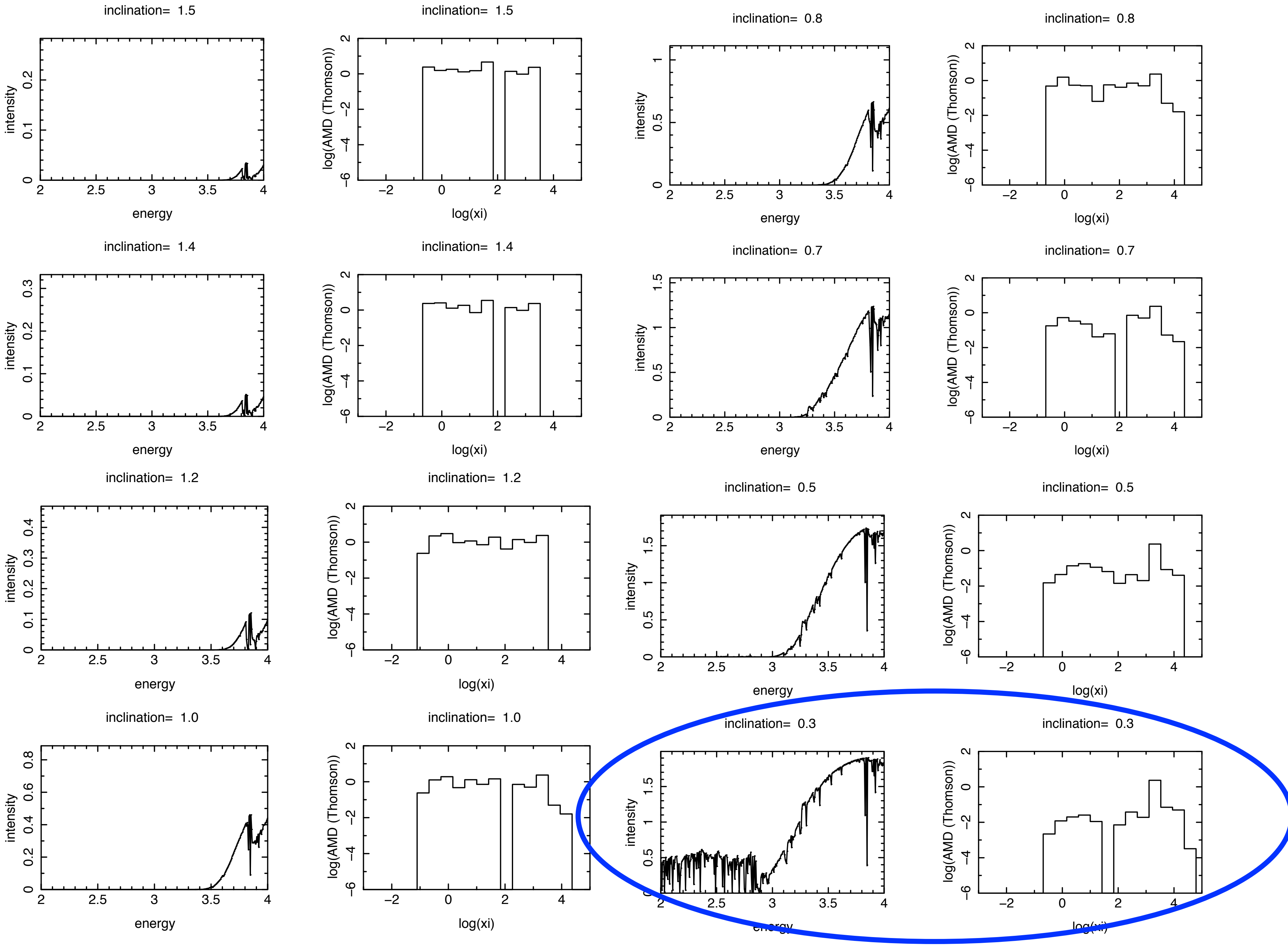


Gas pressure
dominated model





inclination= 1.5
intensity
energy
inclination= 1.5
log(AMD (Thomson))
log(xi)
inclination= 0.8
intensity
energy
inclination= 0.8
log(AMD (Thomson))
log(xi)
inclination= 1.4
intensity
energy
inclination= 1.4
log(AMD (Thomson))
log(xi)
inclination= 0.7
intensity
energy
inclination= 0.7
log(AMD (Thomson))
log(xi)
inclination= 1.2
intensity
energy
inclination= 1.2
log(AMD (Thomson))
log(xi)
inclination= 0.5
intensity
energy
inclination= 0.5
log(AMD (Thomson))
log(xi)
inclination= 1.0
intensity
energy
inclination= 1.0
log(AMD (Thomson))
log(xi)
inclination= 0.3
intensity
energy
inclination= 0.3
log(AMD (Thomson))
log(xi)



inclination= 1.5
intensity
energy
inclination= 1.5
log(AMD (Thomson))
log(xi)
inclination= 0.8
intensity
energy
inclination= 0.8
log(AMD (Thomson))
log(xi)
inclination= 1.4
intensity
energy
inclination= 1.4
log(AMD (Thomson))
log(xi)
inclination= 0.7
intensity
energy
inclination= 0.7
log(AMD (Thomson))
log(xi)
inclination= 1.2
intensity
energy
inclination= 1.2
log(AMD (Thomson))
log(xi)
inclination= 0.5
intensity
energy
inclination= 0.5
log(AMD (Thomson))
log(xi)
inclination= 1.0
intensity
energy
inclination= 1.0
log(AMD (Thomson))
log(xi)
inclination= 0.3
intensity
inclination= 0.3
log(AMD (Thomson))

Warm absorber spectra

- Spectra shown at intermediate time
- Model provides obscuration over many lines of sight
- Much more obscuration compared with previous models
- Warm absorber produced only for lines of sight close to axis

Lessons from MHD torus models

- With strong poloidal initial field, evaporation rate is suppressed by large factor
- 2-phase behavior is apparent
  - Due to impeded flow/dilution?
  - Or?
- Long-lived torus provides obscuration over large range of viewing angles for longer time
- Torus structure/evolution depends strongly on field topology

Model comparison

	M_{torus}	M_{BH}	L/Ledd	t_{max}/t_{dyn}	t_{dyn}	Mdot	M_{torus}/ Mdot	M_{torus}/Mdot /t_{dyn}
units	10^6 M_{sun}	10^6 M_{sun}			10^6 yrs	M_{sun}/yr	10^6 yrs	
gas (B6)	0.93	1.00	0.50	5.00	0.0150	0.07	13.29	885.71
radiation	0.50	10.00	0.30	100.00	0.0004	0.10	5.00	11627.91
magnetic (sol)	1.00	10.00	0.50	60.00	0.0016	0.05	10.00	12500.00
magnetic (tor)	1.00	10.00	0.50	60.00	0.0016	10.00	0.10	62.50

summary

- Models show evaporative wind from torus ‘throat’, mass loss rate comparable to estimates

  → What is the torus?

- Ionization parameter and column are outside observed range for lines of sight close to axis
- Plausible warm absorbers are produced within a $\sim 10^{o}$ cone near the torus

  → what is the true incidence of warm absorbers?

- Trapped IR radiation pressure produces a torus with lower mass, comparable obscuration

  → long term survival?

- A strong ($\beta \sim 100$) poloidal magnetic field can retard torus evaporation

  → self-gravity?