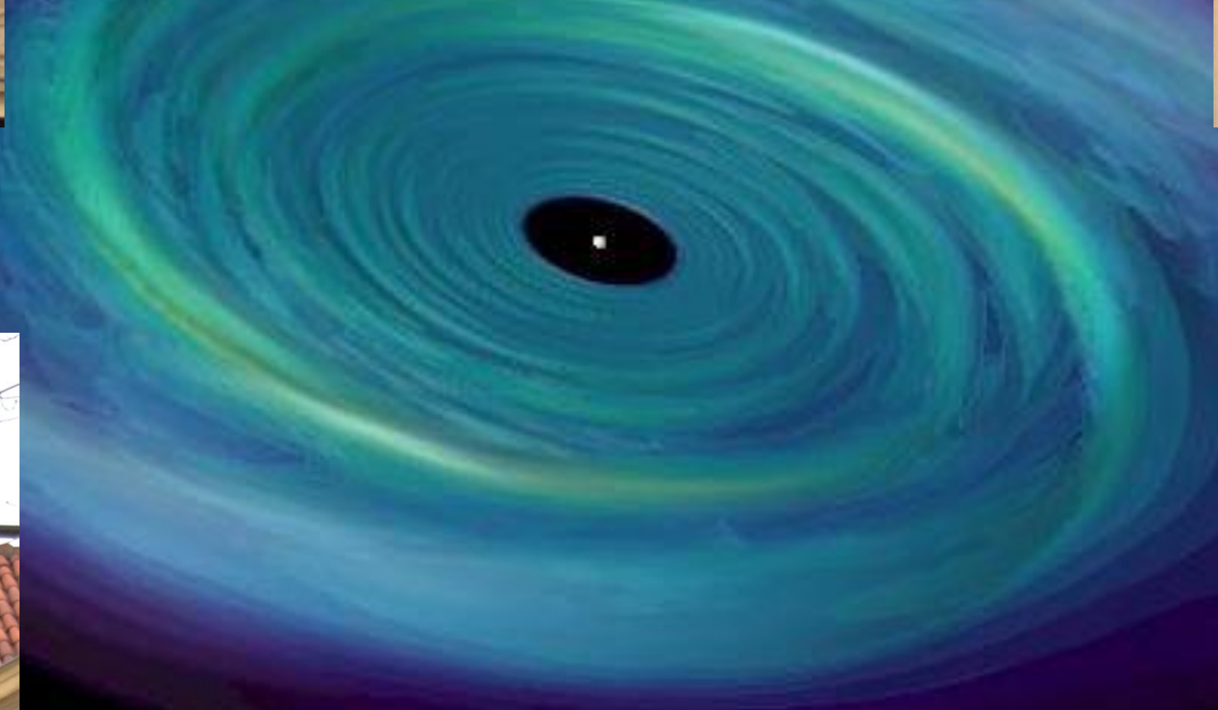
Theory of Accretion Disc Winds



Stuart Sim

ANU
THE AUSTRALIAN NATIONAL UNIVERSITY

Overview

1. How to launch a disc wind

- **Thermal wind (hot, bright central source)**
- **Line-driven wind (UV bright, modest ionization)**
- **MHD wind (significantly magnetized flow)**

Launching physics + hydrodynamical simulations

2. Observable properties

- **Blue-shifted absorption lines (UV / X-ray)**
- **X-ray photoelectric absorption and “warm absorbers”**
- **Broad emission lines**

Radiative transfer simulations + complex geometries

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AGN bias
See Proga 2007

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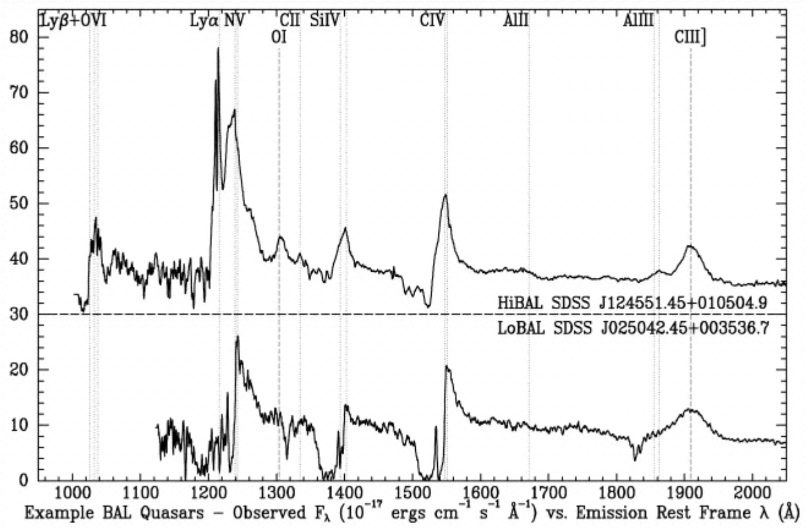
For another time....

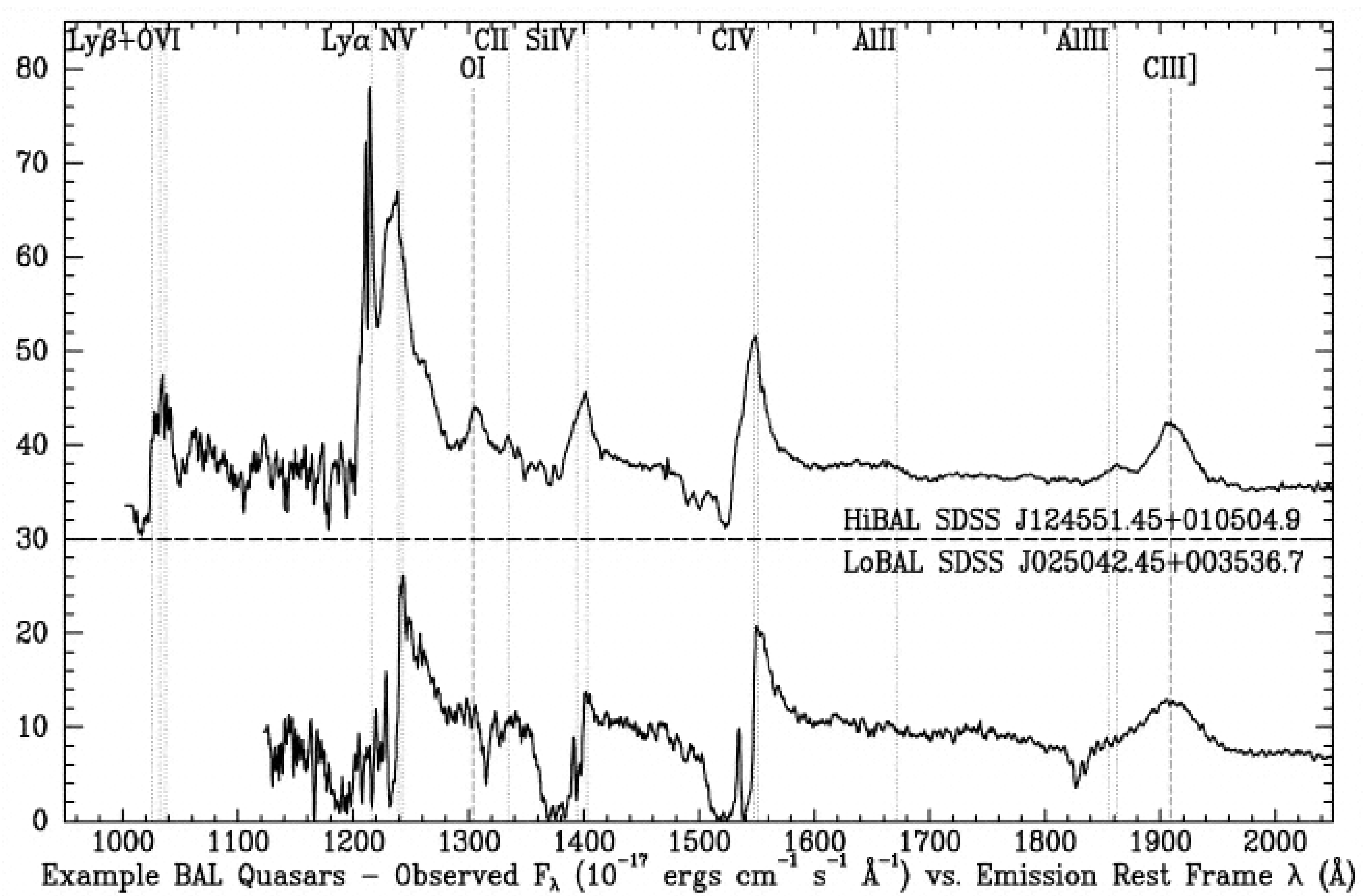
1. **Review of observational arguments in favour/against presence of winds in AGN**



BAL QSOs
(from Hall et al. 02)

2. **Empirically constructed wind models**

3. **Fate of wind material (feedback etc.)**



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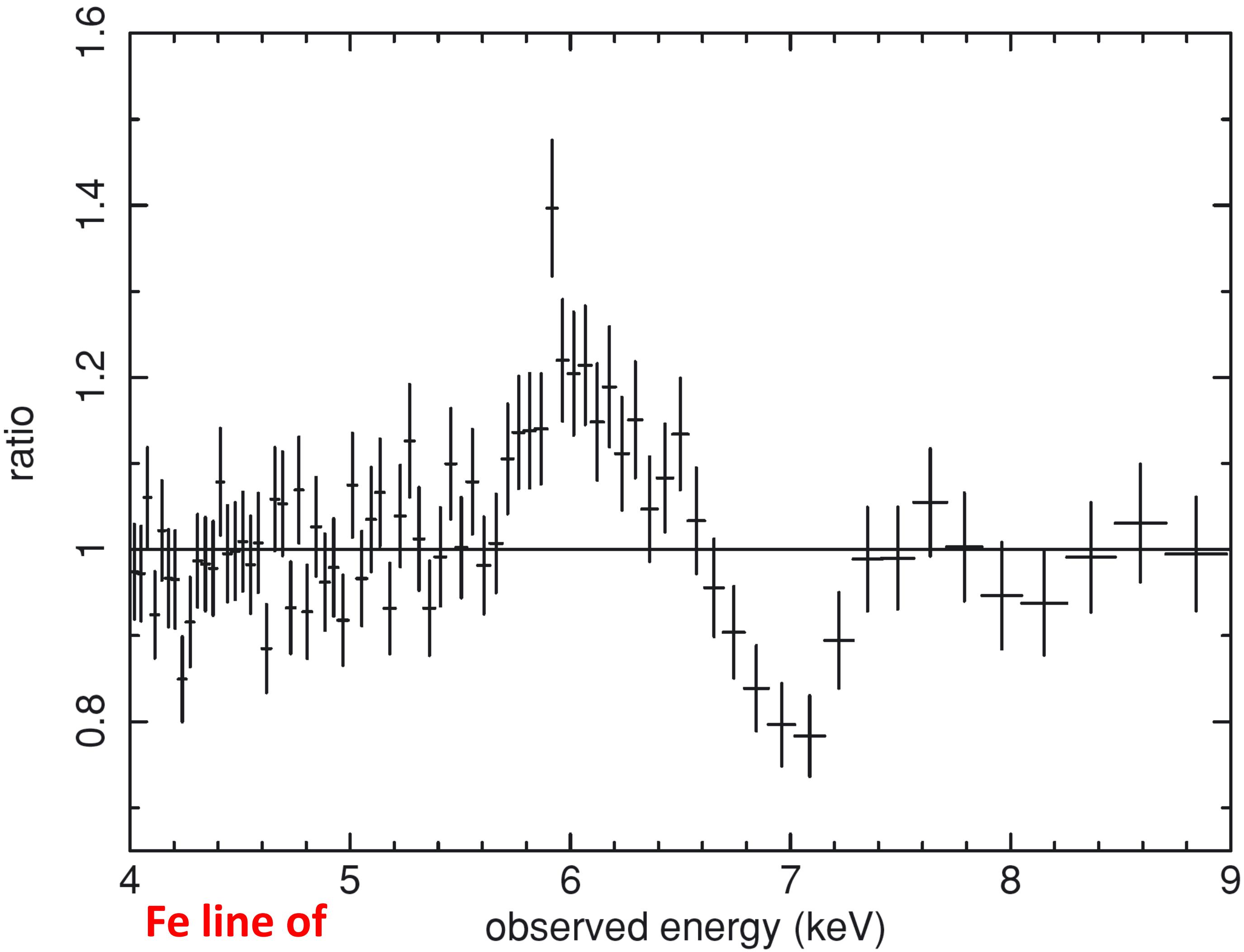

Fe line of
PG1211+143
(Pounds et al. 2009)

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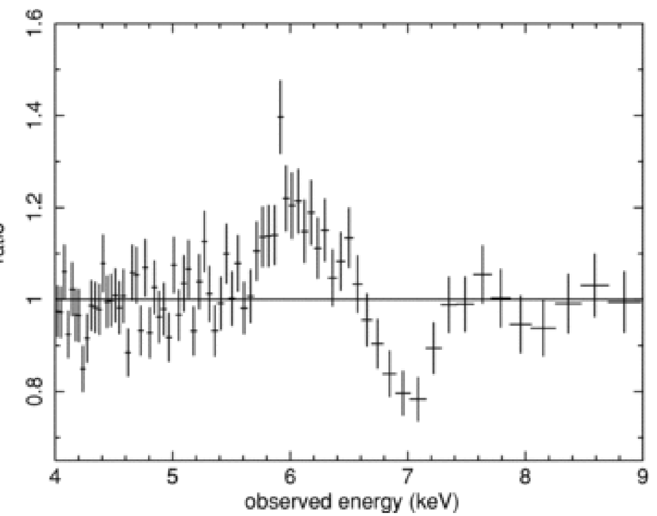

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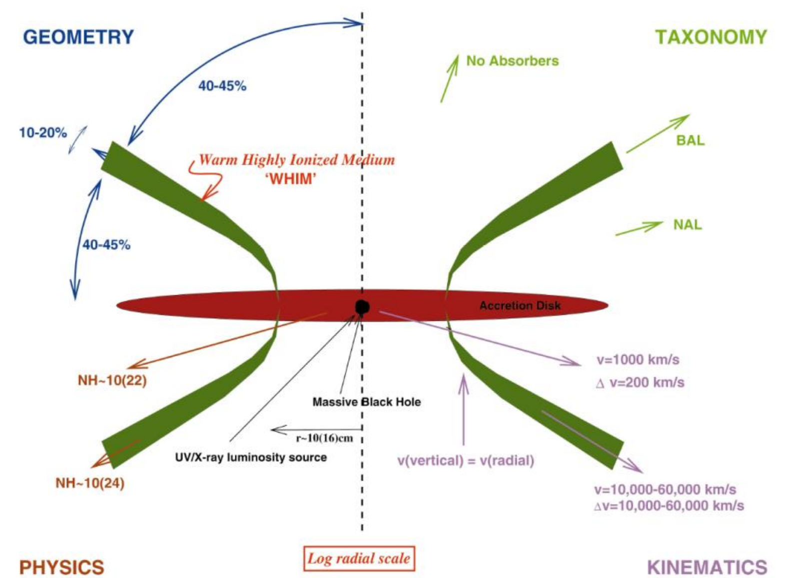
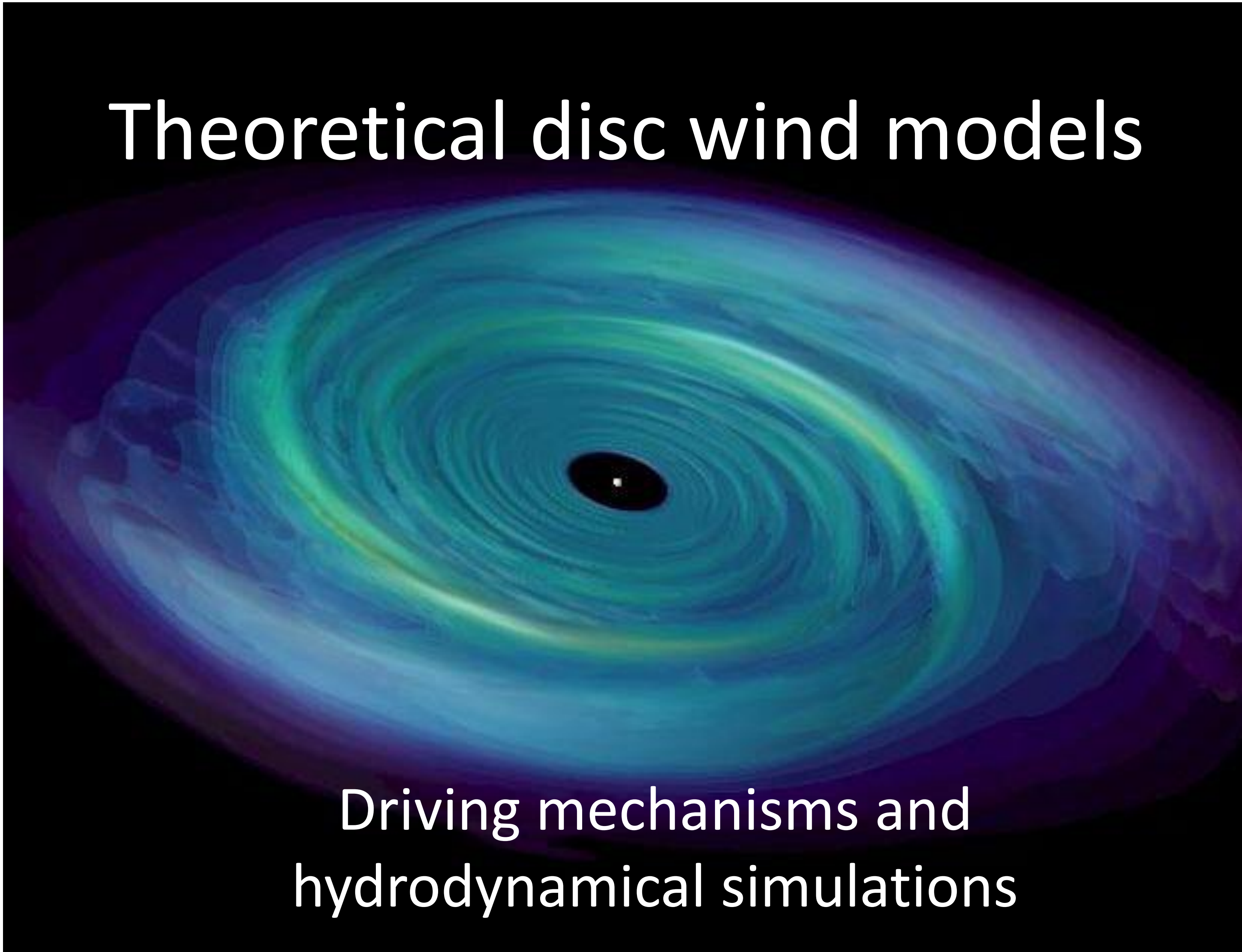


Model based on observed BAL/NAL properties (Elvis 2000)

3. **Fate of wind material (feedback etc.)**

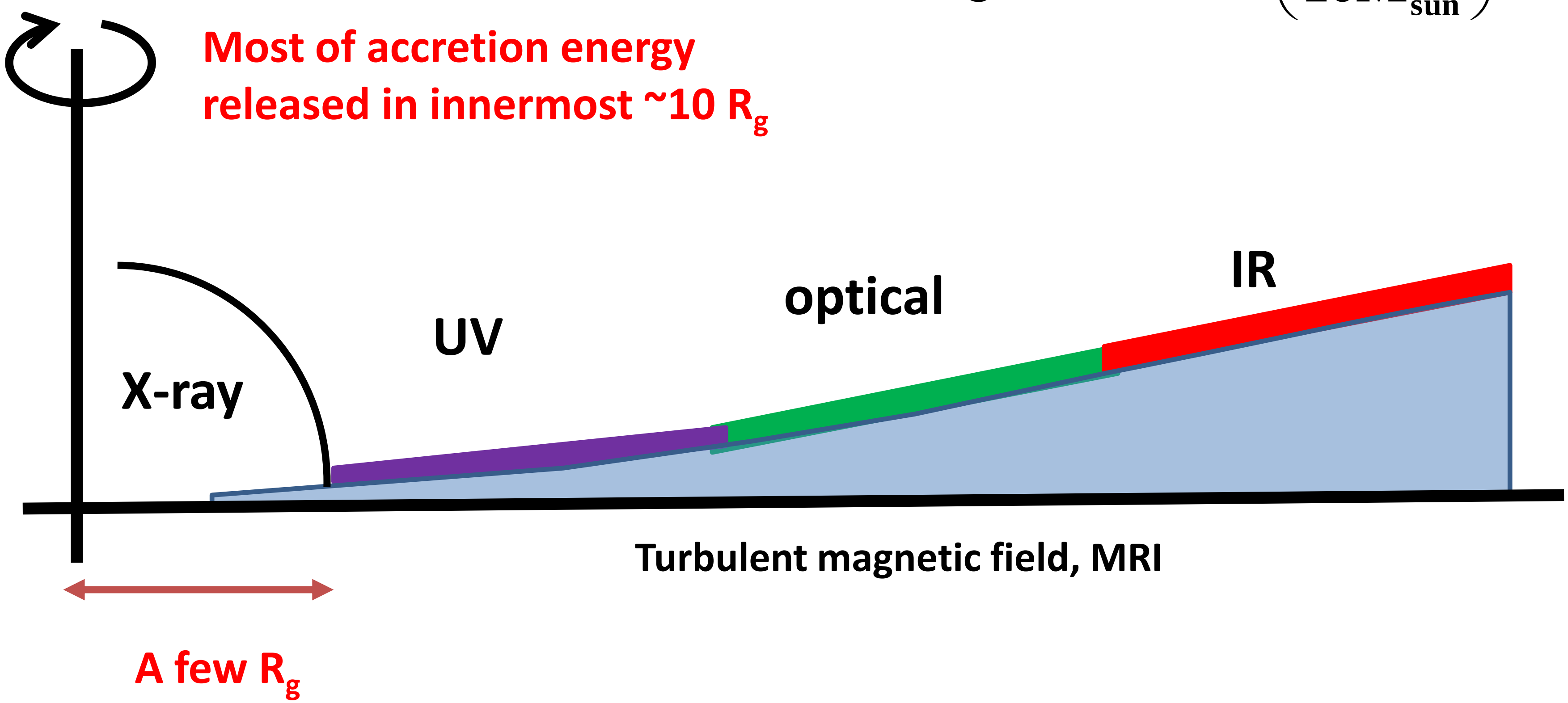

Theoretical disc wind models
Driving mechanisms and
hydrodynamical simulations

A little background...

Disc structure (AGN)

$$R_g = \frac{GM}{c^2} \approx 1.5 \times 10^6 \left(\frac{M}{10 M_{sun}} \right) cm$$

Most of accretion energy released in innermost ~10 R_g



Equations of hydrodynamics

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

Mass conservation

$$\rho \frac{D\mathbf{v}}{Dt} = -\nabla P + \rho \mathbf{g}$$

Momentum equation with gravity

$$\rho \frac{D}{Dt}\left(\frac{e}{\rho}\right) = -P \nabla \cdot \mathbf{v}$$

$$P = (\gamma - 1)e$$

Energy equation and equation of state

Thermal disk winds

"energy driven"

Notus; the South Wind

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Net cooling/heating rate

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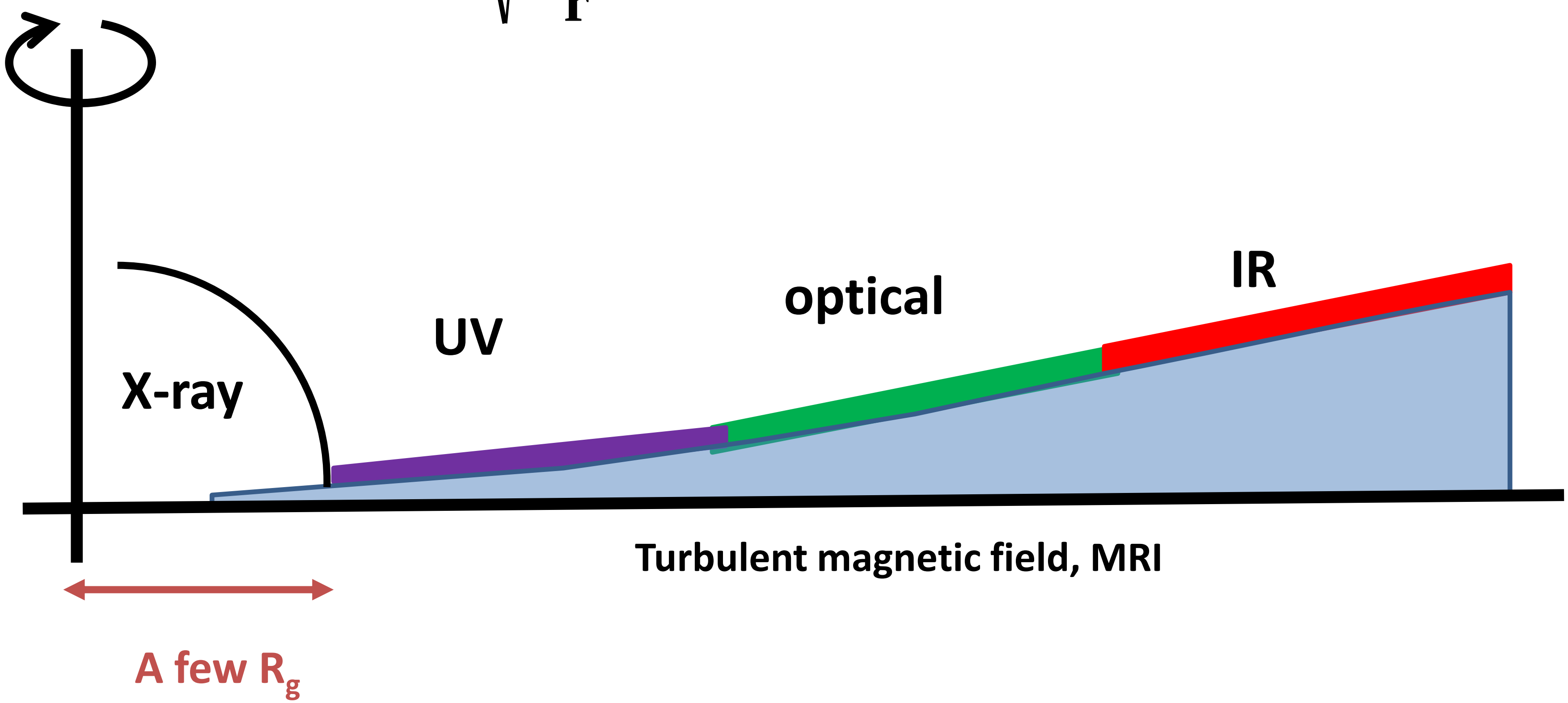
Heating leads to thermal pressure (temperature) sufficient for matter to escape the object = thermal wind

Net cooling/heating rate

Thermal wind regime

$$v_{esc} = \sqrt{\frac{GM}{r}} \Rightarrow T_{esc} \propto r^{-1}$$

Most easily realised in outer regions



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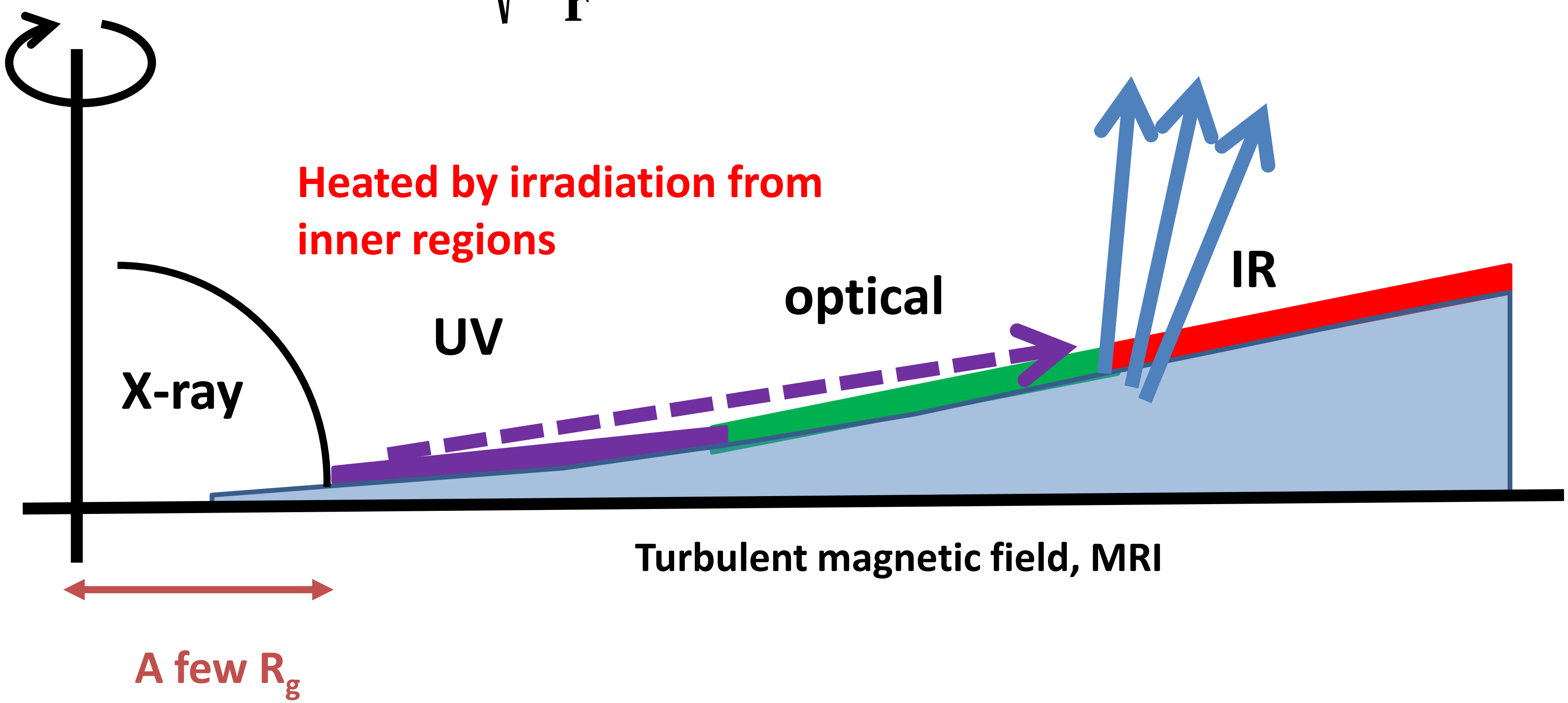
Heated by irradiation from inner regions



Thermal wind regime

Can estimate roughly where the wind can rise:

$$\frac{GM}{r}\mu m_H = kT_{esc} \approx kT_c$$

Compton temperature, Tc

$$\frac{r}{R_g} = \frac{\mu m_H c^2}{kT_c} \approx 6\times 10^5 \left(\frac{10^7\,K}{T_c}\right)$$

r = 10^{12} cm for 10 M_{sun}

r = 10^{18} cm for 10^8 M_{sun}

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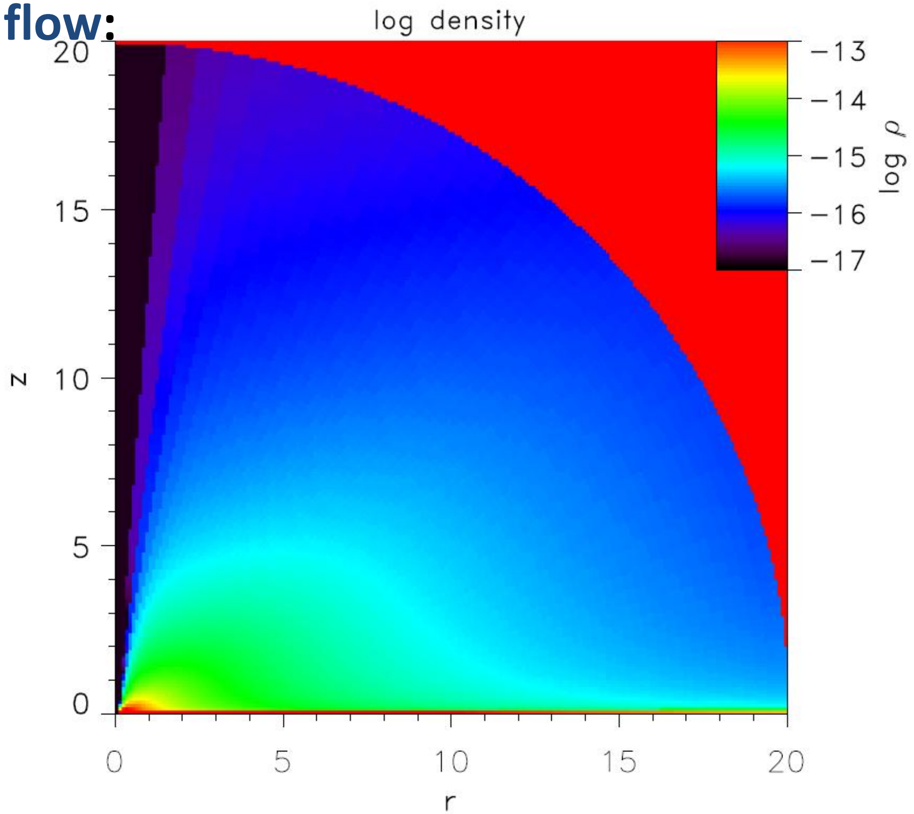
To be quantitative about where it's launched and how much mass can be expelled use numerical simulations...

Numerical simulations

2D numerical simulations of a thermal wind: e.g. Woods et al. 96 (AGN) and Luketic et al. 10 in an X-ray binary system (targeting GRO J1655-40).

Luketic:

- **Non-spherical but roughly steady-state flow:**
  - **Equatorially concentrated**
  - **Self-similar outer regions**



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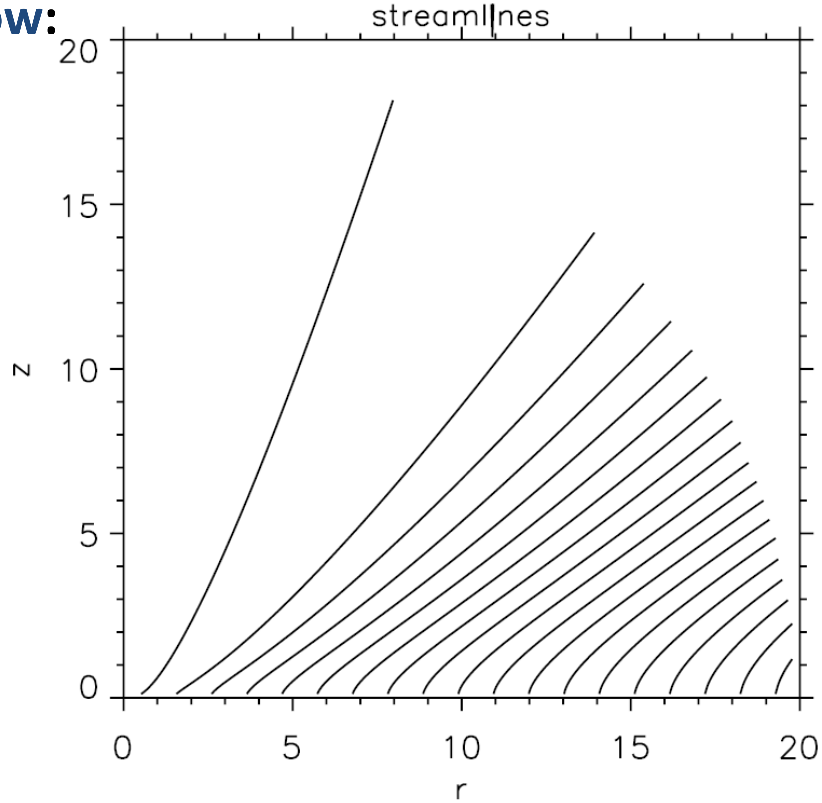

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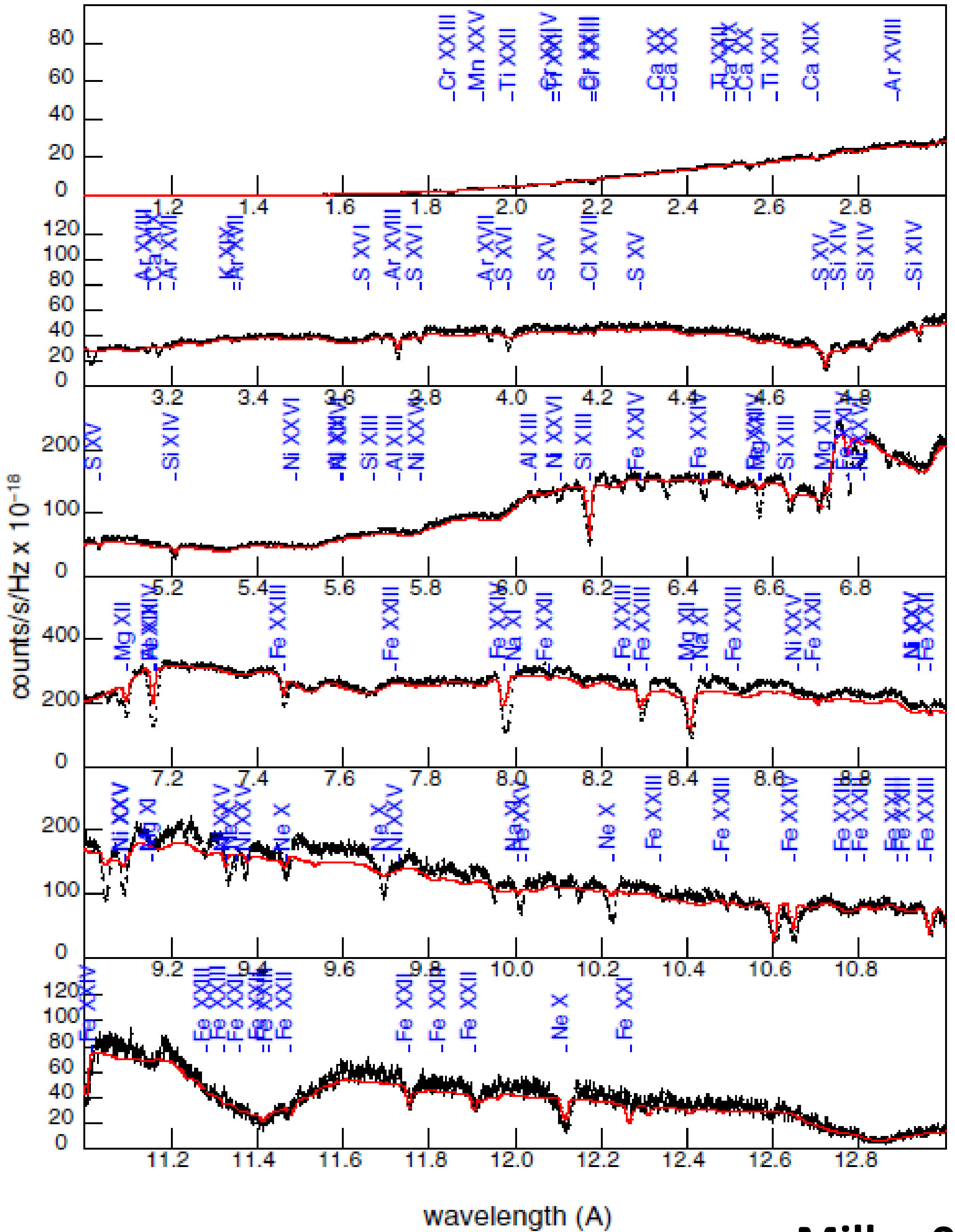

Miller 06; Luketic et al. 11

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- Too low-density to reproduce obs. spectrum
  - ...but makes many of the right features
- Mass-loss of 7 M_{acc}! (Woods also > 1.)

$$M_{wind} \approx 7M_{acc}$$

Thermal winds

Expected for both AGN and X-ray binaries but likely not the whole story...
Even if they don't dominate observable features could carry a large mass flux!

See also work by:

1. Dorodnitsyn & Kallman (2009) AGN torus wind
2. Kurosawa & Proga (2009) outflows from accretion flow

Line-driven disk winds

“momentum driven”

Boreas; the South Wind

Equations of hydrodynamics

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

$$\rho \frac{D\mathbf{v}}{Dt} = -\nabla P + \rho \mathbf{g} + \rho \mathbf{F}_{rad}$$

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Radiation pressure

$$F_{rad}^{electrons} = \frac{\sigma_T}{c} f_{rad}$$

Radiation force (F_{rad}) due to electron scattering of flux (f_{rad})

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Radiation force (F$_{rad}$) due to electron scattering of flux (f$_{rad}$)

$$F_{rad}^{lines} = M \frac{\sigma_T}{c} f_{rad}$$

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Force multiplier M depends on:

- Flow properties
- Composition (number/strength of lines)
- Ionization state

See Castor, Abbott & Klein (1975)

(CAK theory)

Radiation pressure

$$F_{rad}^{electrons} = \frac{\sigma_T}{c} f_{rad}$$

Radiation force **(F_{rad})** due to **electron scattering** of flux **(f_{rad})**

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Force multiplier M depends on:

- **Flow properties**
- **Composition (number/strength of lines)**
- **Ionization state**

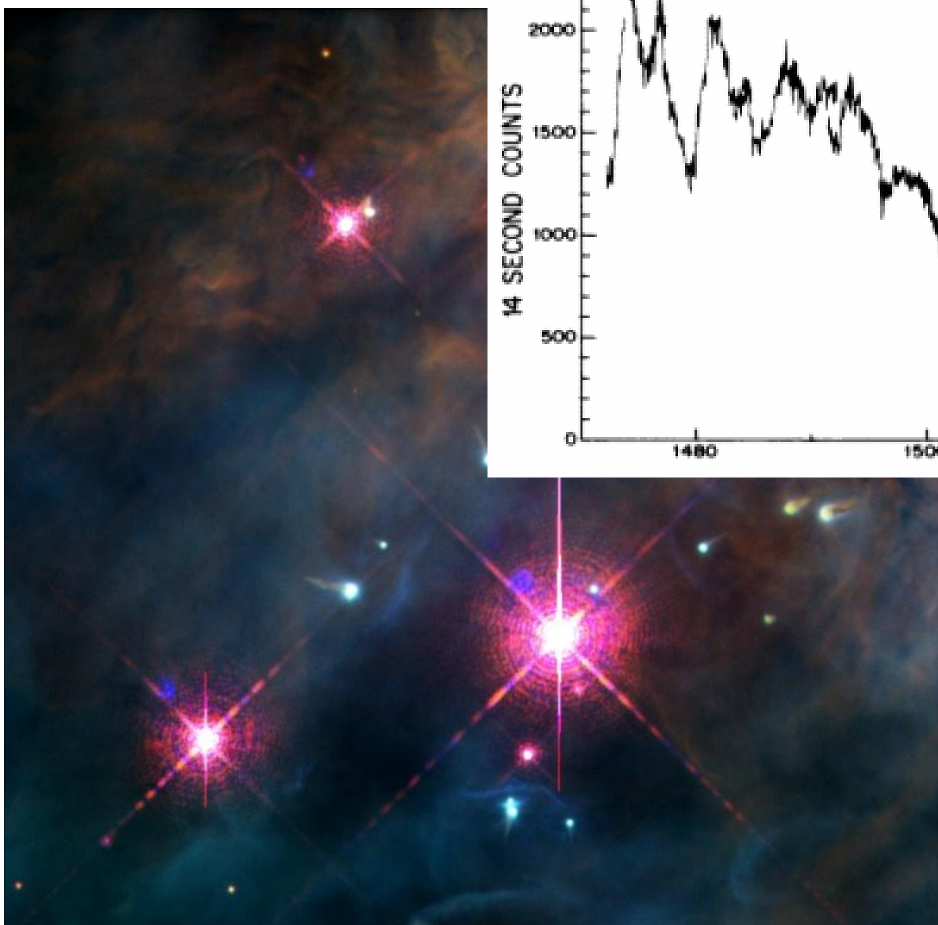
For conditions of moderate ionization and modest optical depth, radiation pressure on spectral lines can exceed electron scattering by:

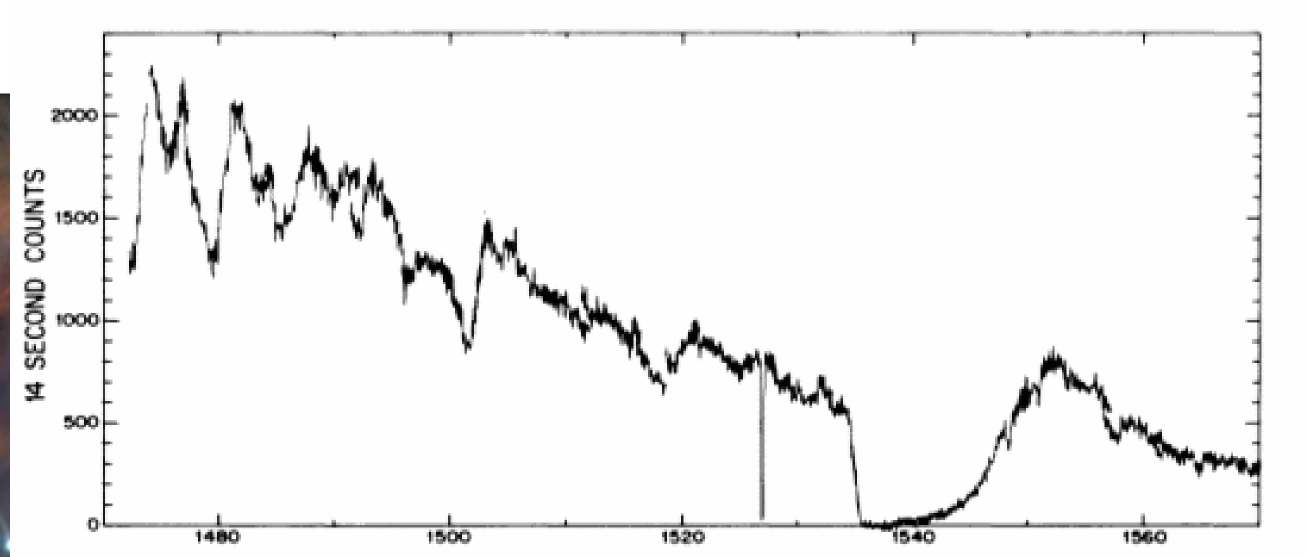
$$M_{max} \approx 2000$$

Radiation pressure: OB stars

Radiating at few percent of Eddington limit but show strong winds: radiatively driven by pressure on spectral lines (CAK75).

Radiation pressure: OB stars





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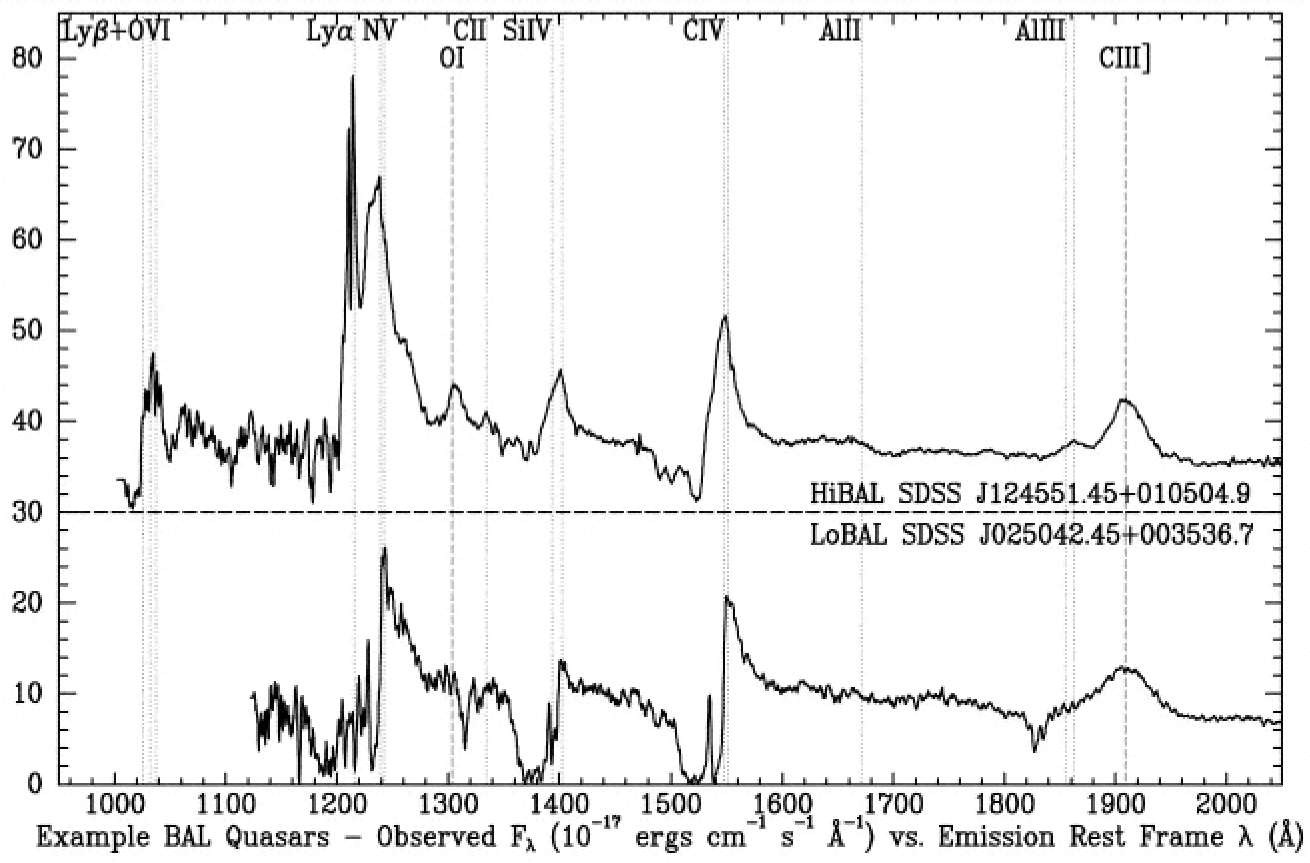
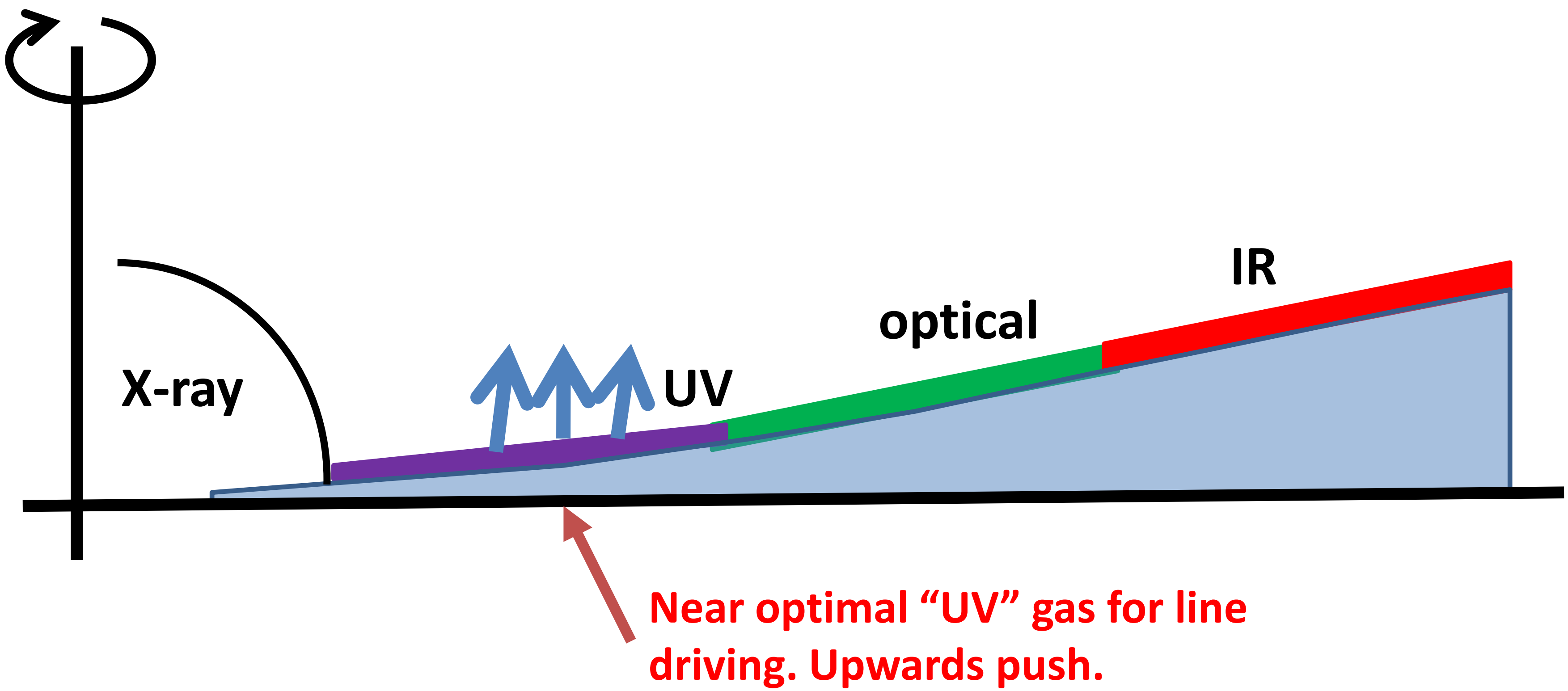
Radiation pressure: BAL QSOs?



SDSS quasars, from Hall et al. 02

Line-driven wind regime (AGN)



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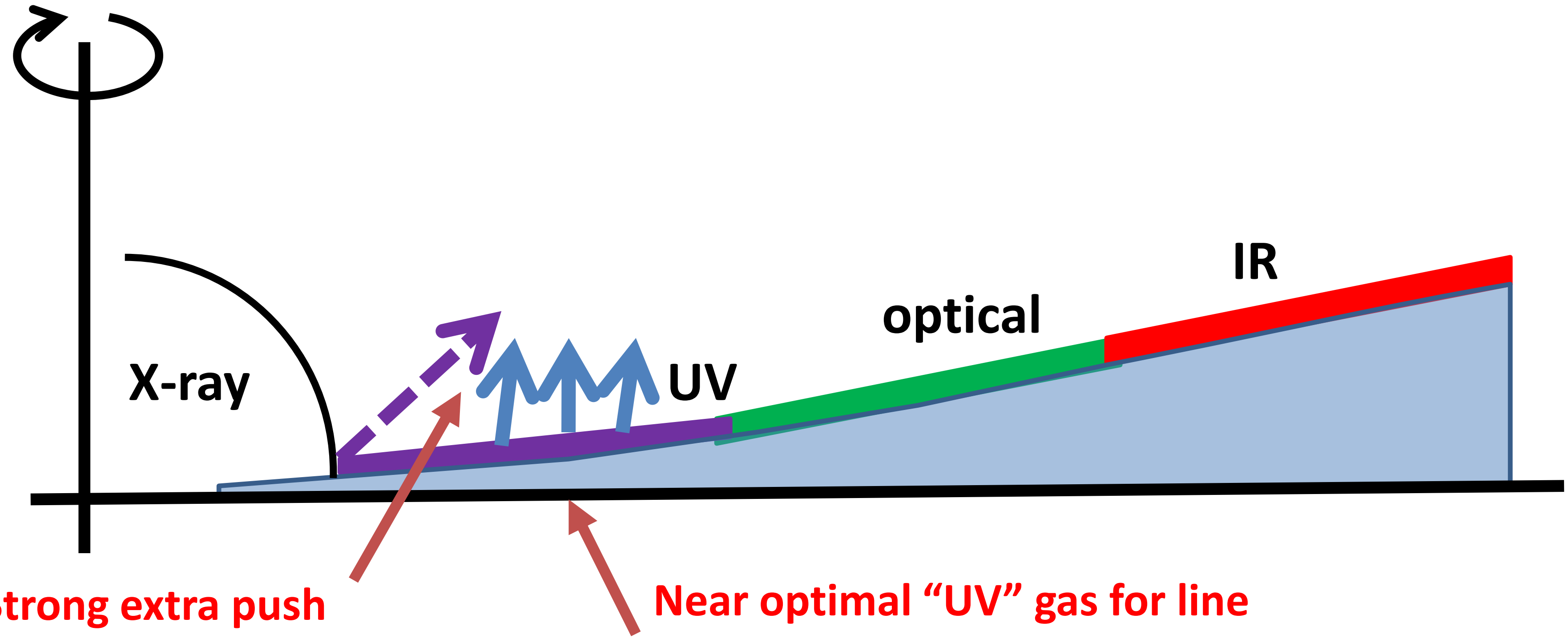
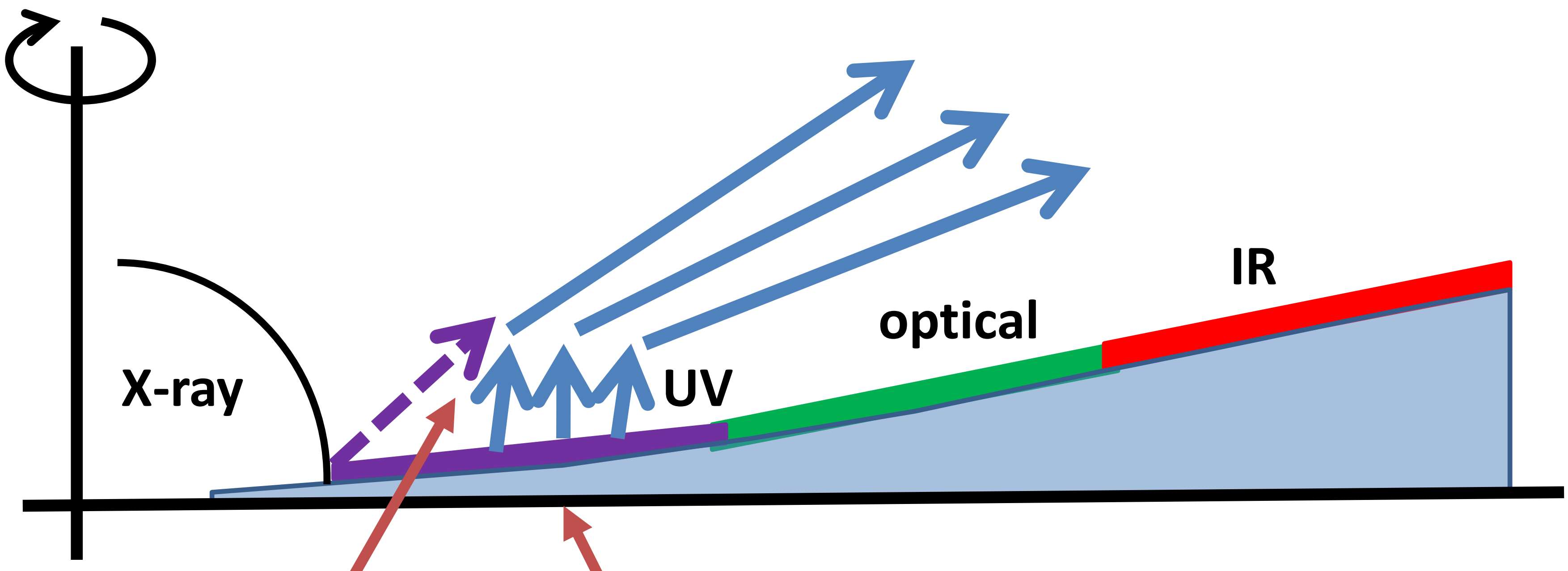


Strong extra push outwards from bright inner UV disk

Near optimal "UV" gas for line driving. Upwards push.

Line-driven wind regime (AGN)



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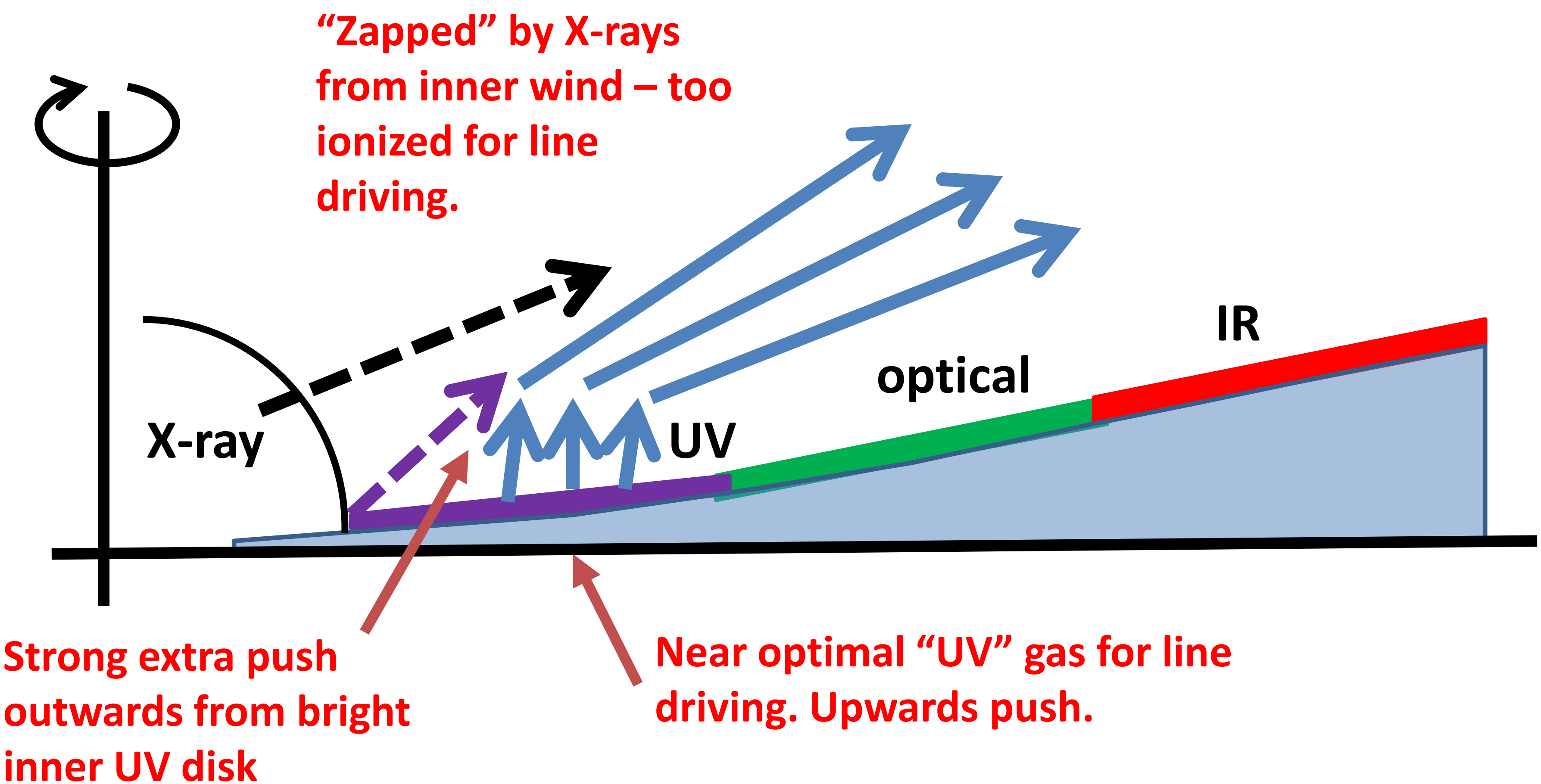
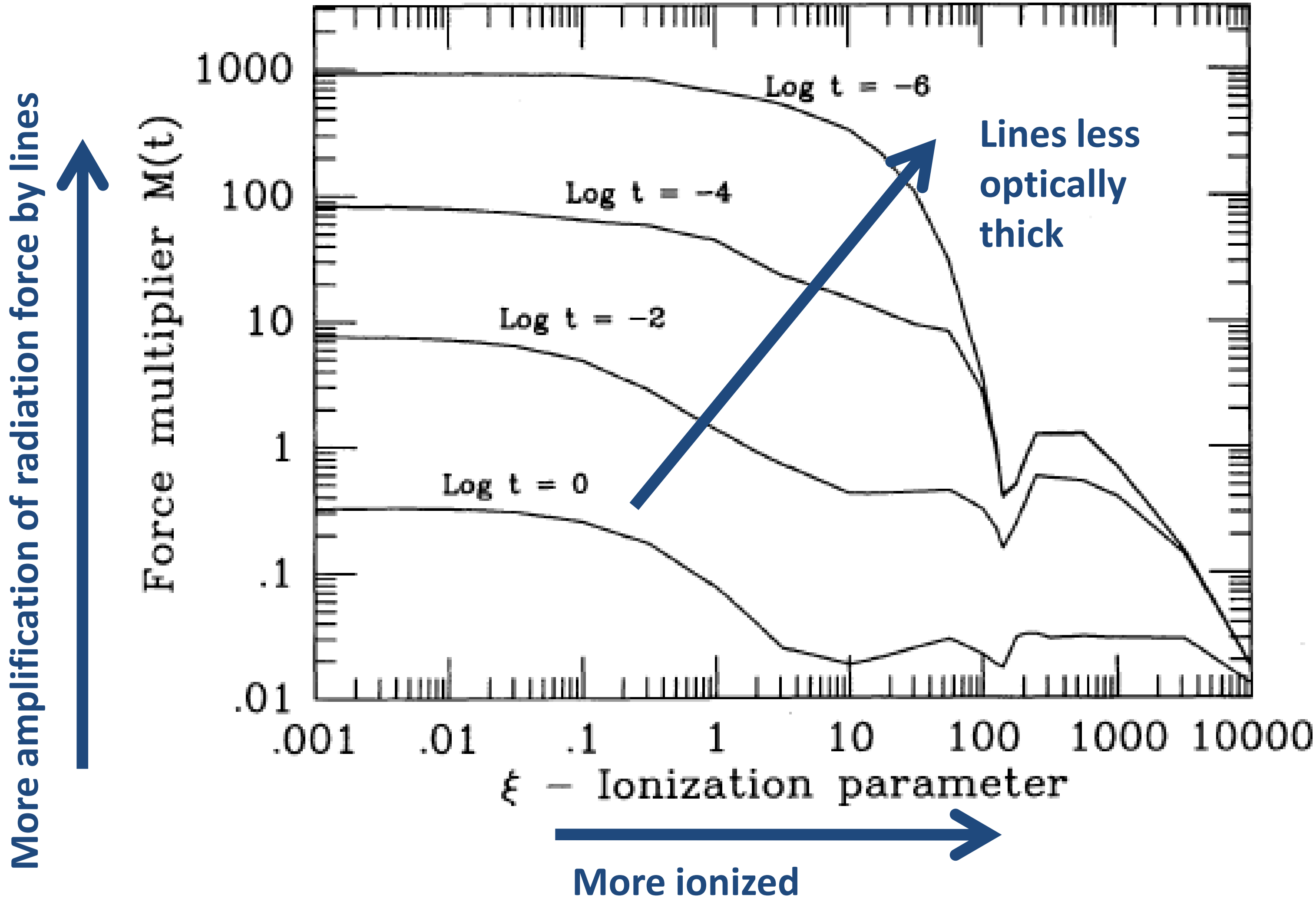


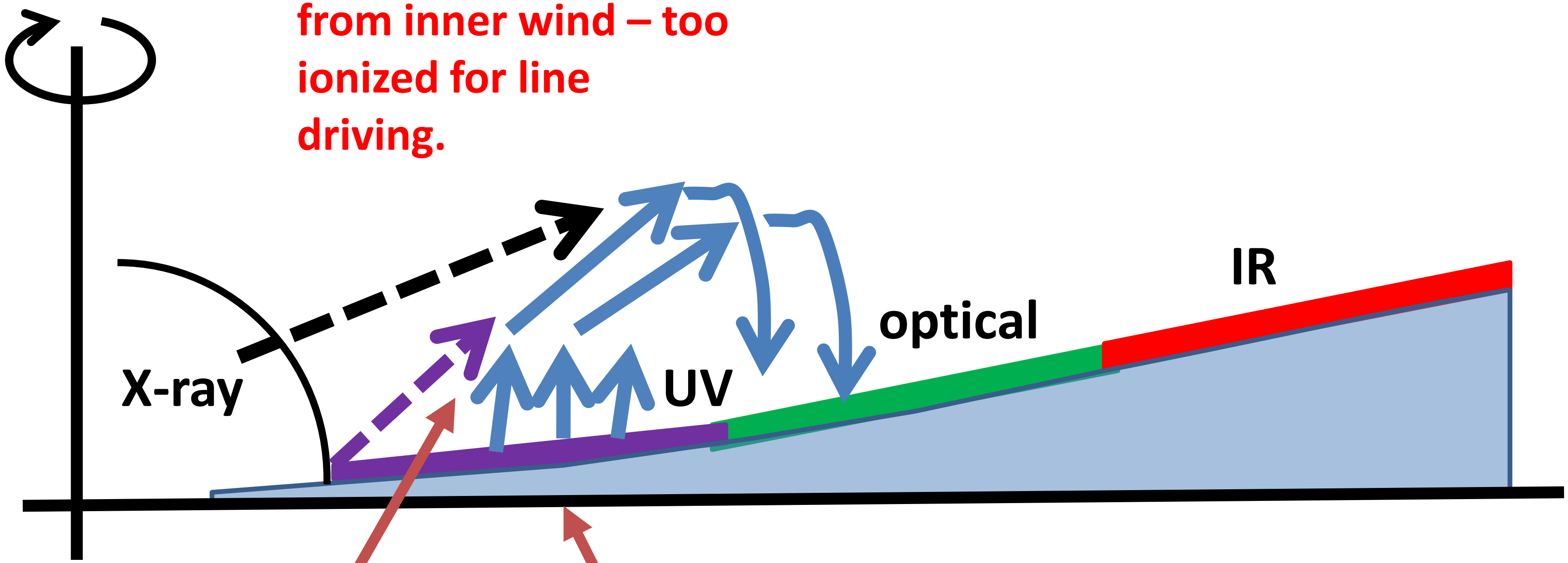
Radiation pressure



Stevens & Kallman 1995

Line-driven wind regime (AGN)

“Zapped” by X-rays from inner wind – too ionized for line driving.



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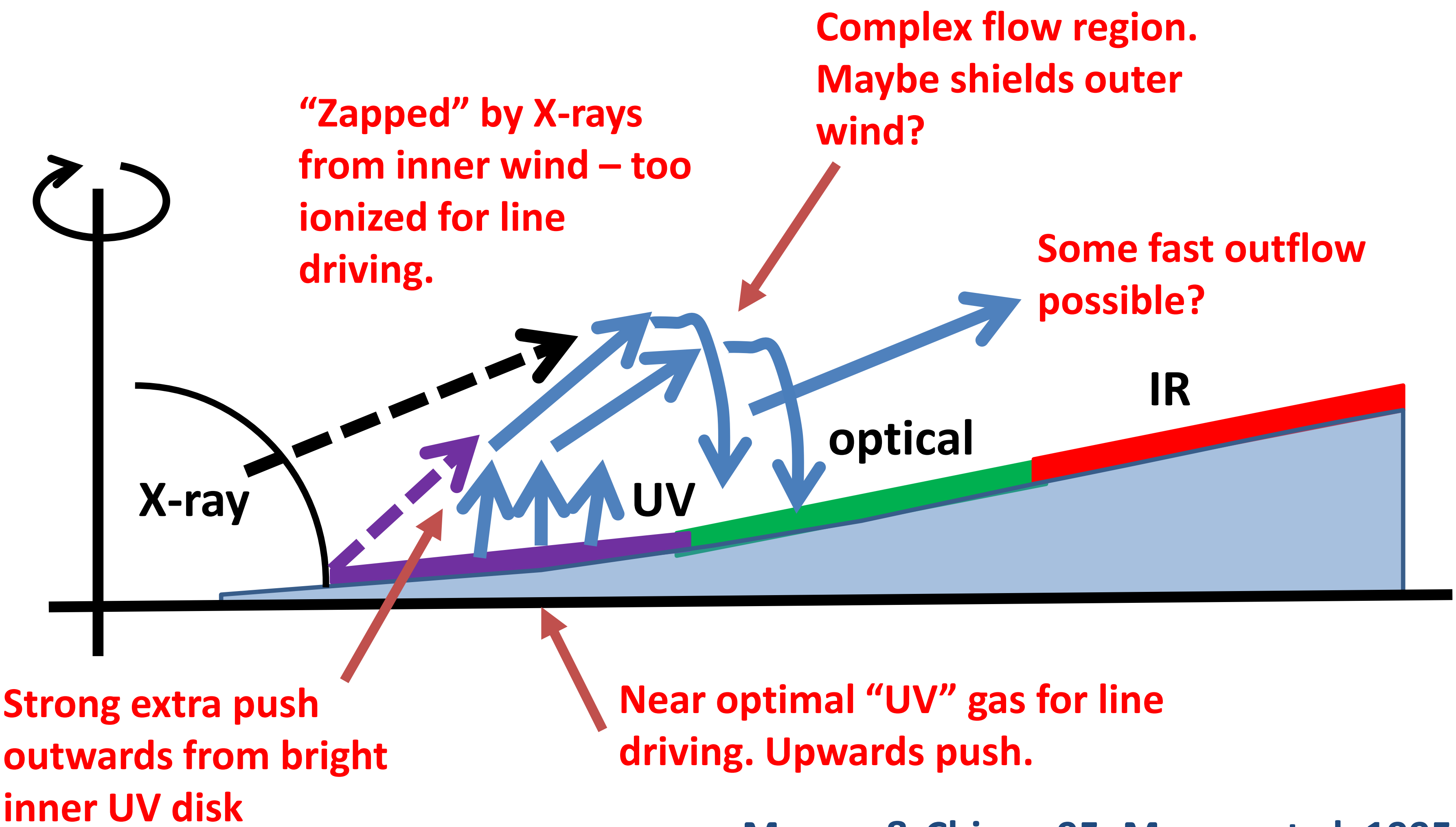

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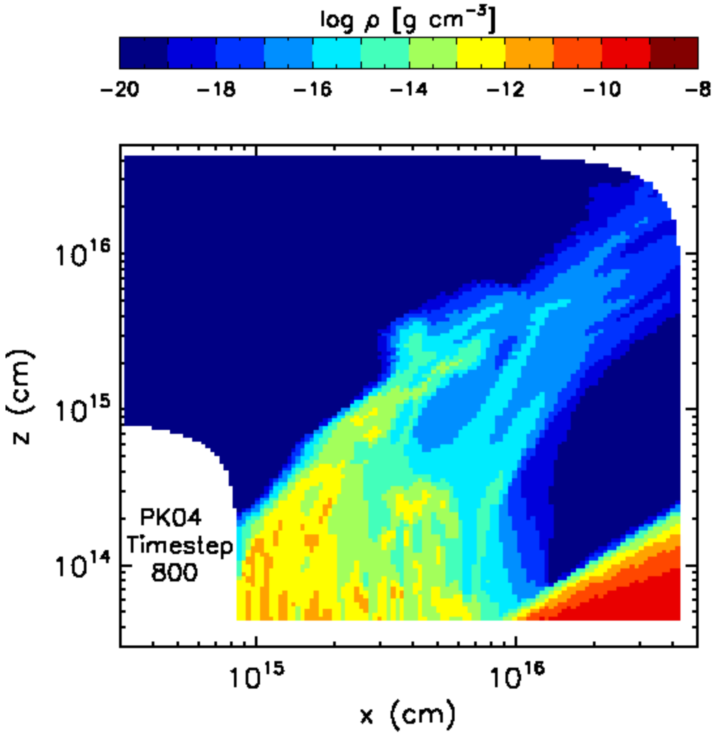
Numerical simulations

Radiation hydrodynamics simulations study over-ionization problem and shielding:

- target region above UV disc
- CAK line force
- central power source X-ray
- central + disc UV sources
- pure attenuation RT
- disc atmosphere boundary condition



Proga et al. 2000, 2004

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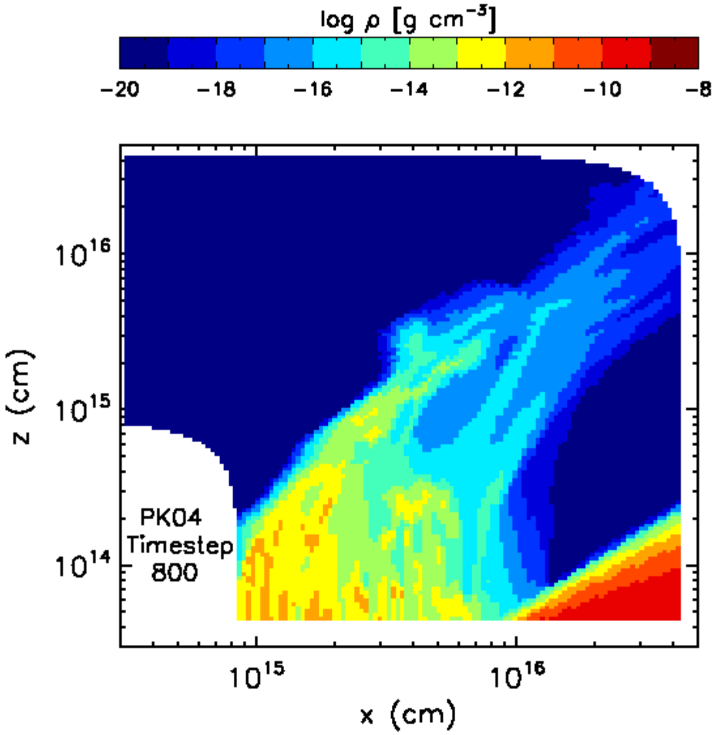
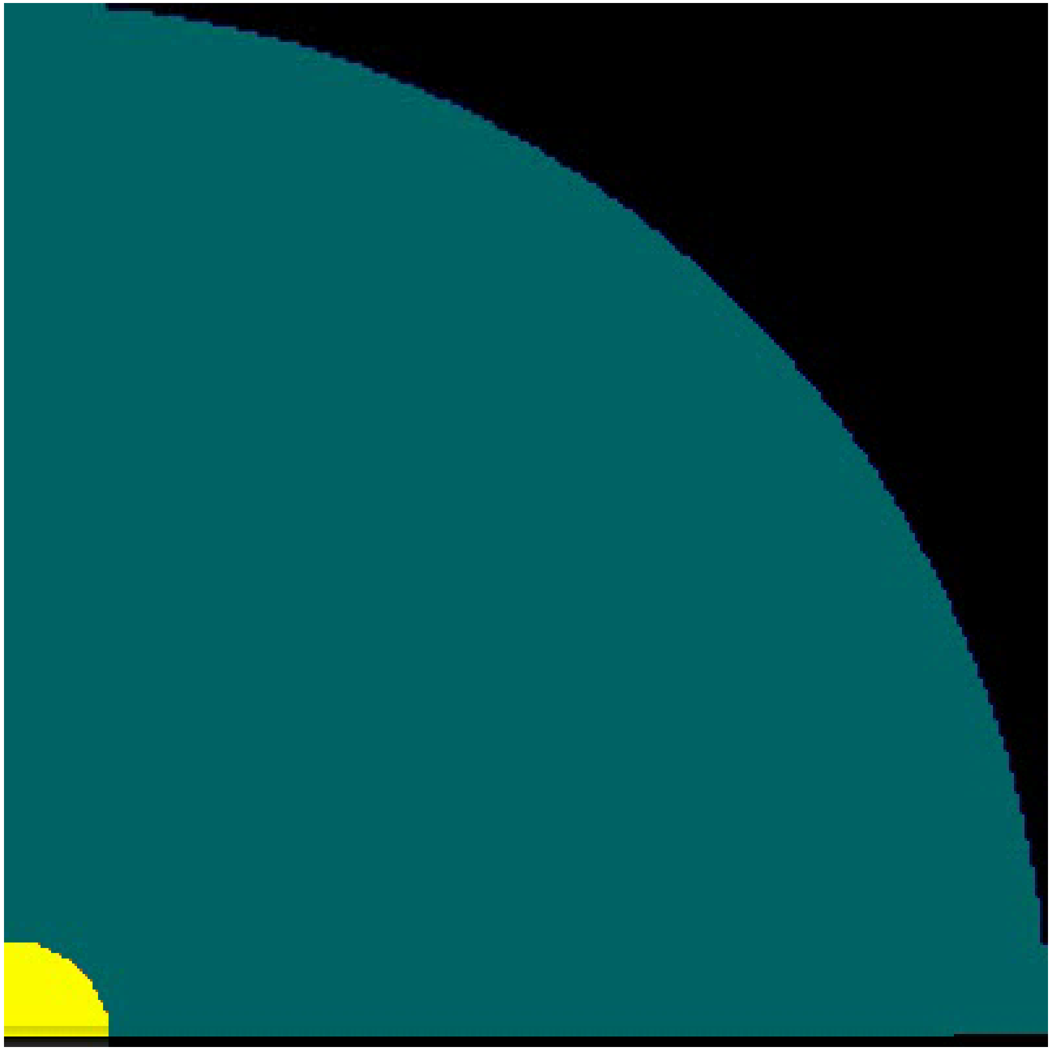


MOVIE!

Simulation for 10^8 M_{sun} BH
Accreting at 0.5 L_{edd}
Simulated 600 – 6000 R_g

Proga et al. 2000, 2004

Numerical simulations

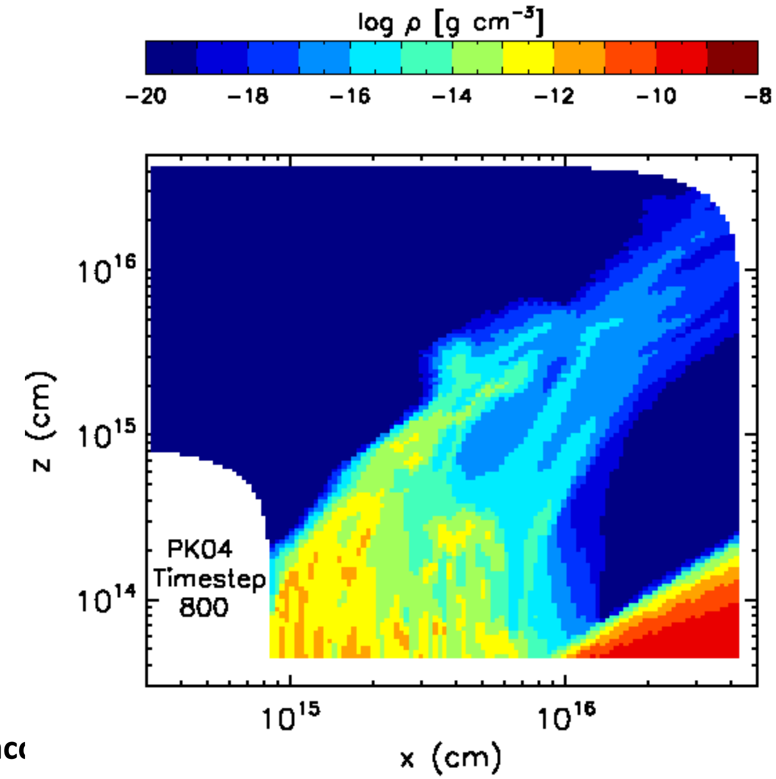


Proga et al. 2000, 2004

Numerical simulations

Results:

- Shielding can work
- Multi-component flow:
  - Low density polar flow
  - Slow equatorial outflow
  - Fast stream at intermediate angles (mildly relativistic)
  - Inner “failed wind” region – the shield
- Time variable flow
- Significant mass loss for luminous objects
  - For 0.5 L_{edd} sim., mass loss about 0.1 M_{acc}
- Wind not present for < 0.1 L_{edd}
  - Still develop failed wind region



Proga et al. 2000, 2004

Line-driven winds

For luminous AGN (>0.1 L_{edd}) with massive BHs (>10^7 M_{sun}) line driving from the UV radiation field may be able to produce an outflow.

- **Unlikely to be very effective for low mass black holes (e.g. Proga & Kallman 02)**

- **Mass loss from pure line-driving difficult below 0.1 L_{edd}...but complex flow above UV disk expected.**

MHD disk winds

"magnetic driving"

Zephyrus; the West Wind

Equations of hydrodynamics

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

$$\rho\frac{D\mathbf{v}}{Dt} = -\nabla P + \rho \mathbf{g} + \frac{1}{c}\mathbf{J}\times\mathbf{B}$$

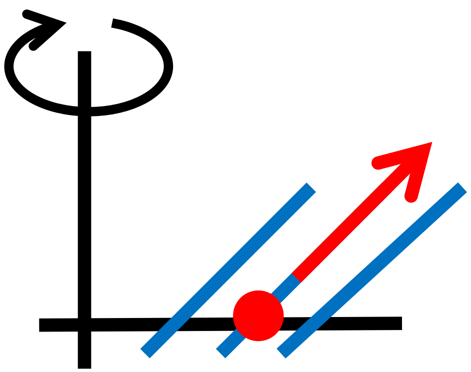
$$\rho\frac{D}{Dt}\left(\frac{e}{\rho}\right) = -P\nabla \cdot \mathbf{v}$$

$$P = (\gamma - 1)e$$

MHD driving

1. Magnetocentrifugal winds

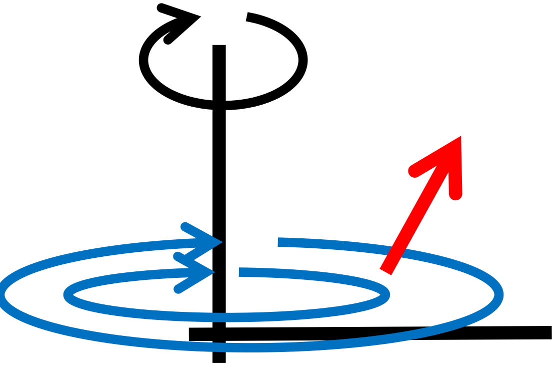
e.g. Blandford & Payne 82, Contopoulos & Lovelace 94, Konigl & Kartje 94, Fukumura et al. 10



Model involving ordered poloidal field just above disk. If it can be loaded then wind can be launched.

2. Magnetic pressure driven

e.g. Uchida & Shibata 85, Pudritz & Norman 86, Konigl 93, Proga 03



Model with toroidal field supplied by accretion disk. If it can be supplied fast enough then wind can be driven by magnetic pressure.

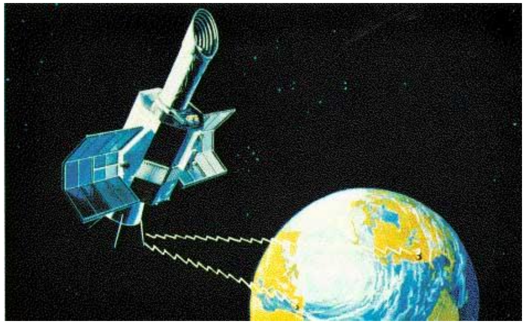
MHD driving

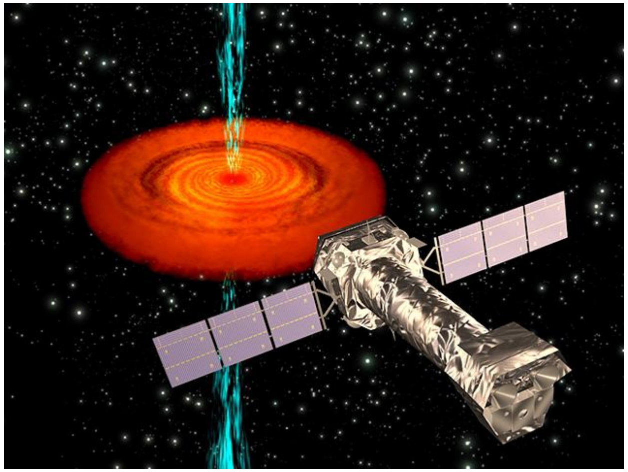
Magnetic forces could accelerate and launch winds...but depends on field geometry (boundary conditions in simulations).

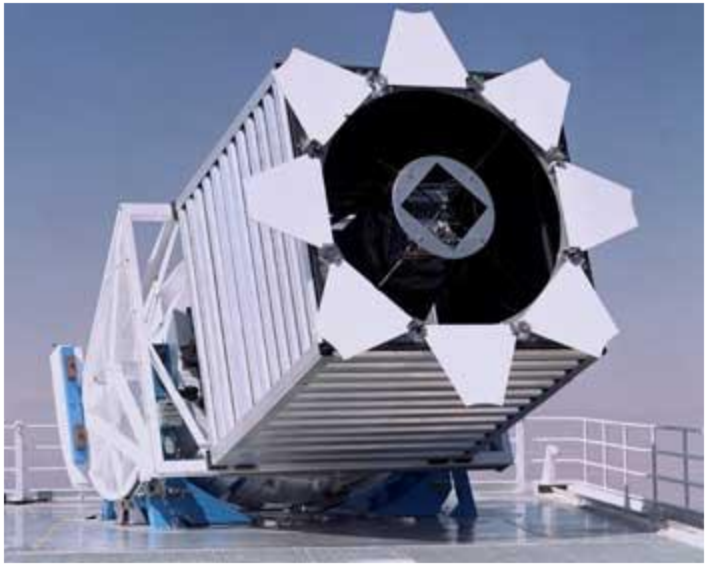
Lots to do in this field...

Observable properties

Radiative transfer and synthetic spectra

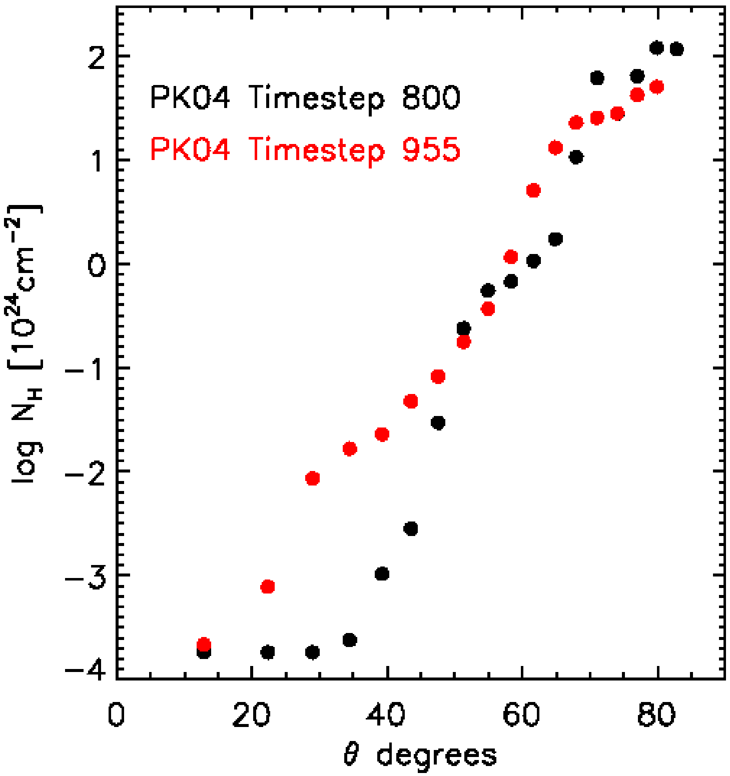






Observable signatures

If winds have high enough column density, they will imprint signatures on spectra.



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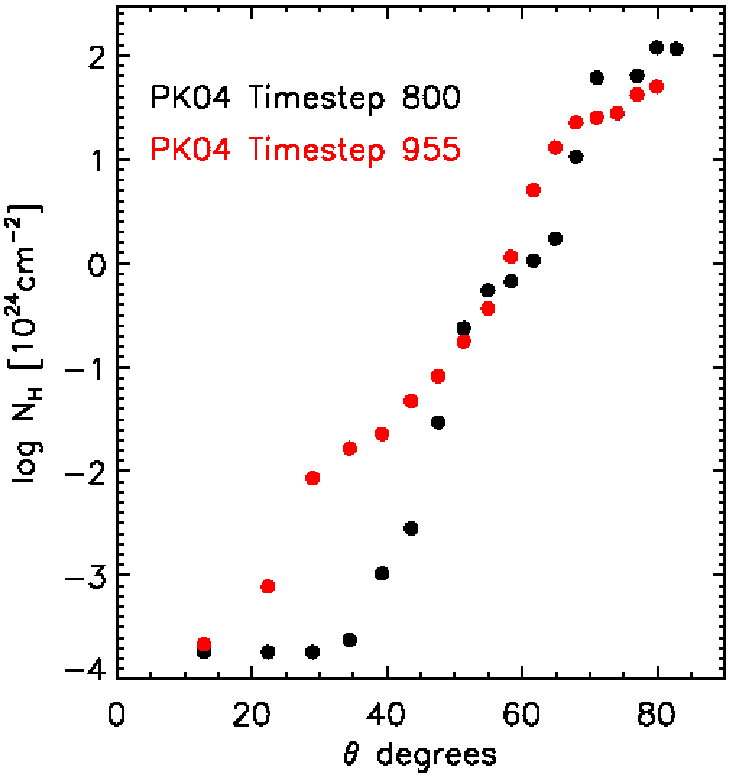
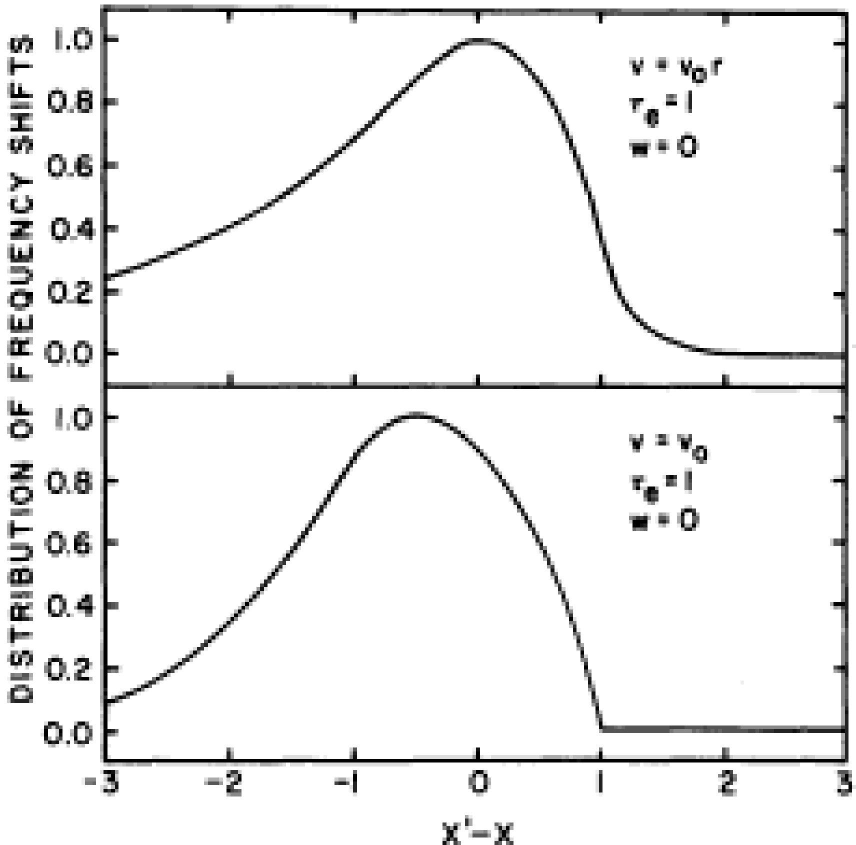


1. Blue-shifted absorption lines
   - Best outflow signature
   - Known in UV/X-ray (e.g. BAL QSOs)
   - Geometry/orientation?
2. Continuum absorption
   - Photoelectric absorption in X-ray
   - Range of ionization parameters
3. Emission lines and red-skewed line wings
   - Wind are not pure absorbing structures
   - Broad line emission expected
   - Scattering in outflow = red tail

Red wings from scattering in a flow



First order **v/c-effect** caused by scattering in **divergent velocity flow**. Preferential **red-shifting of photons** as seen by observer.

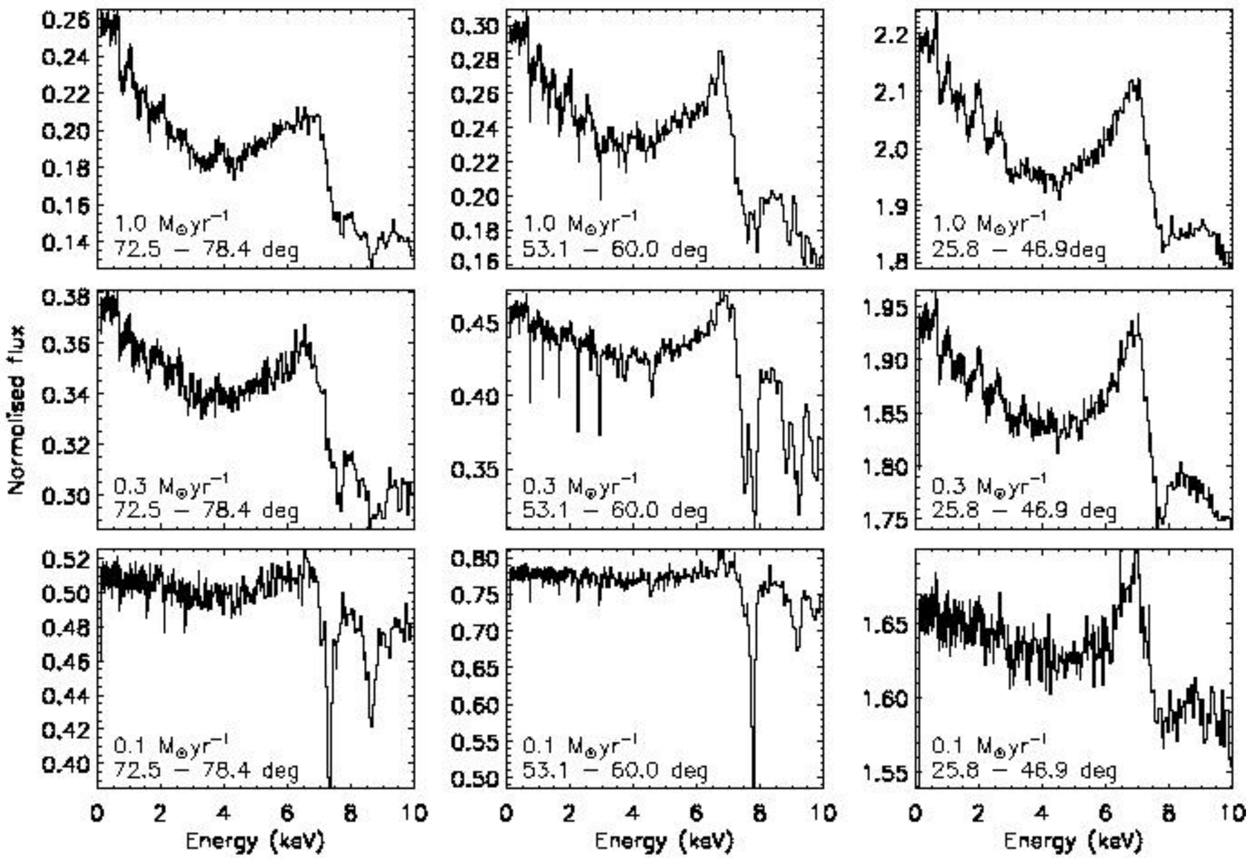
Happens even for coherent, isotropic scattering. **Not just Compton downscattering!**

Requires high velocity flow.

Auer & van Blerkom 1972

See also papers by Titarchuk et al. 2003, 2009

Grids of models: broad Fe K emission



A wide range of emission line shapes:

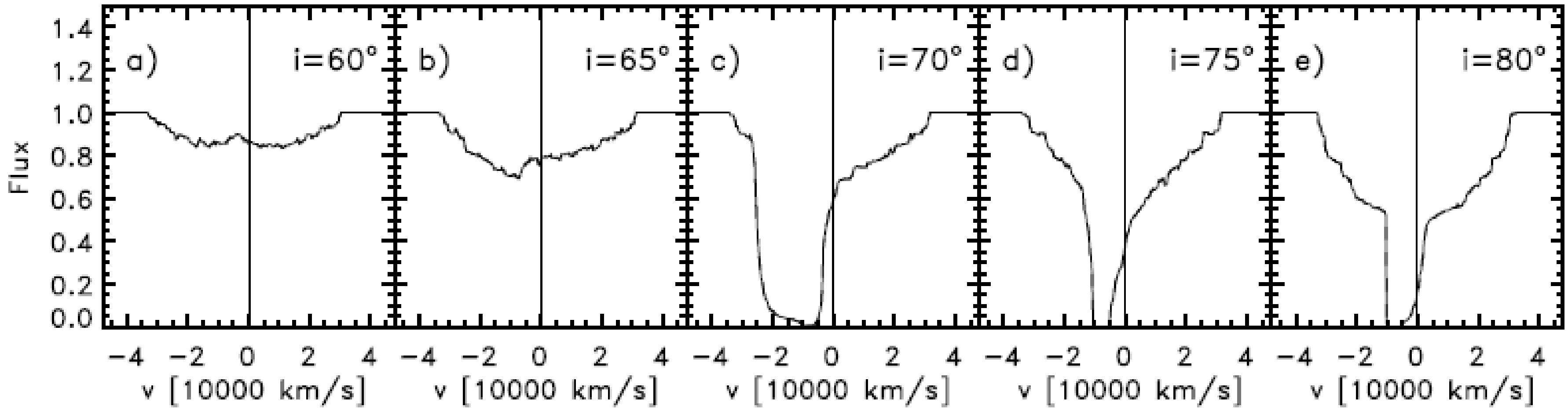
- **P Cygni profiles**
- **extended red wings**

Sim et al. 2008

Proga 2004 line-driven wind

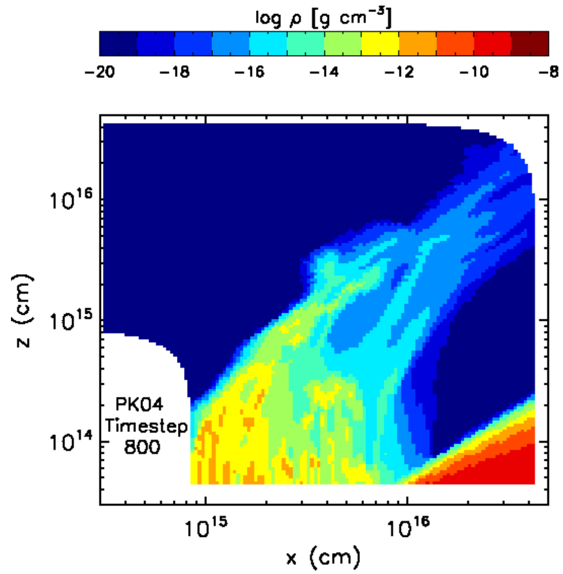
(Quasi-) 1D RT and absorption

Proga 2004 line-driven wind

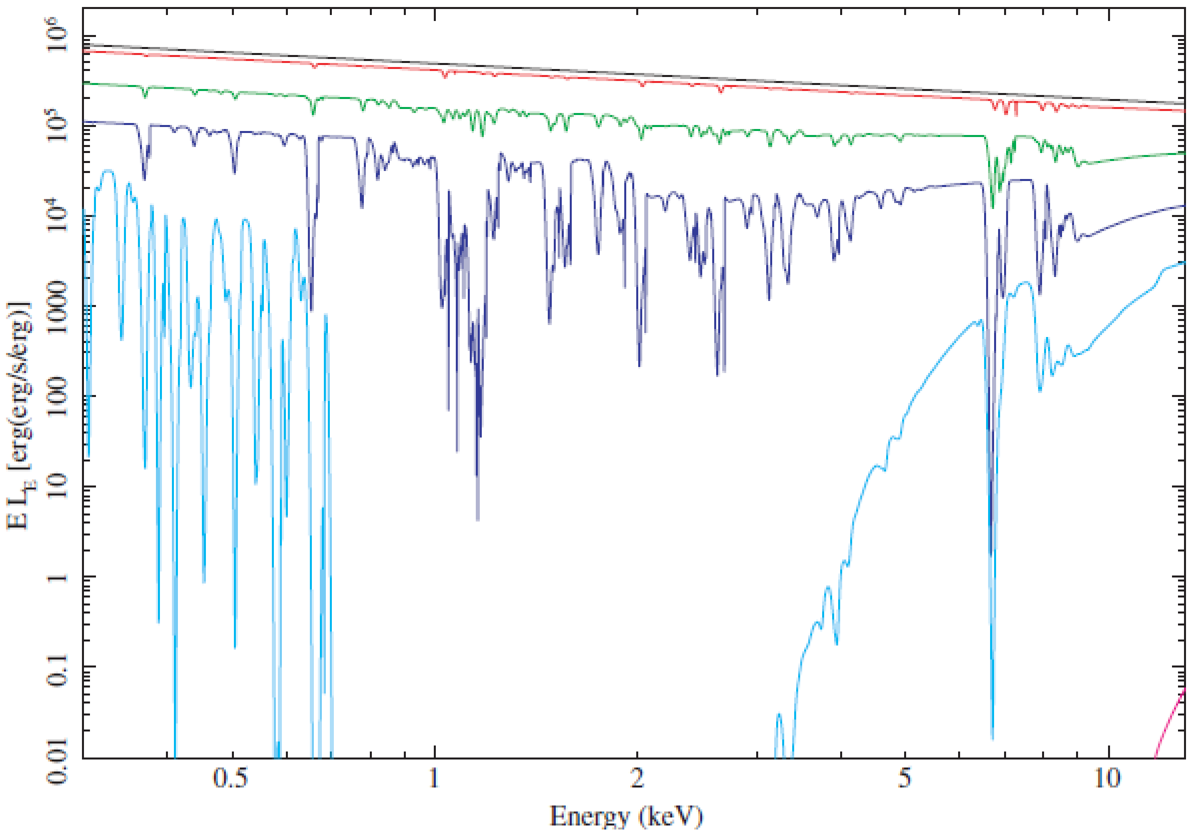


Synthetic absorption profiles for UV absorption line

- Absorption present for modest fraction of equatorial lines-of-sight
- Broad and blueshifted
- Deepest absorption not at v=0
- Strongly angle dependent
- Similar to known properties of BAL QSOs (Korista et al. 93, Hall et al. 2002)



X-rays; Schurch, Done & Proga 2009



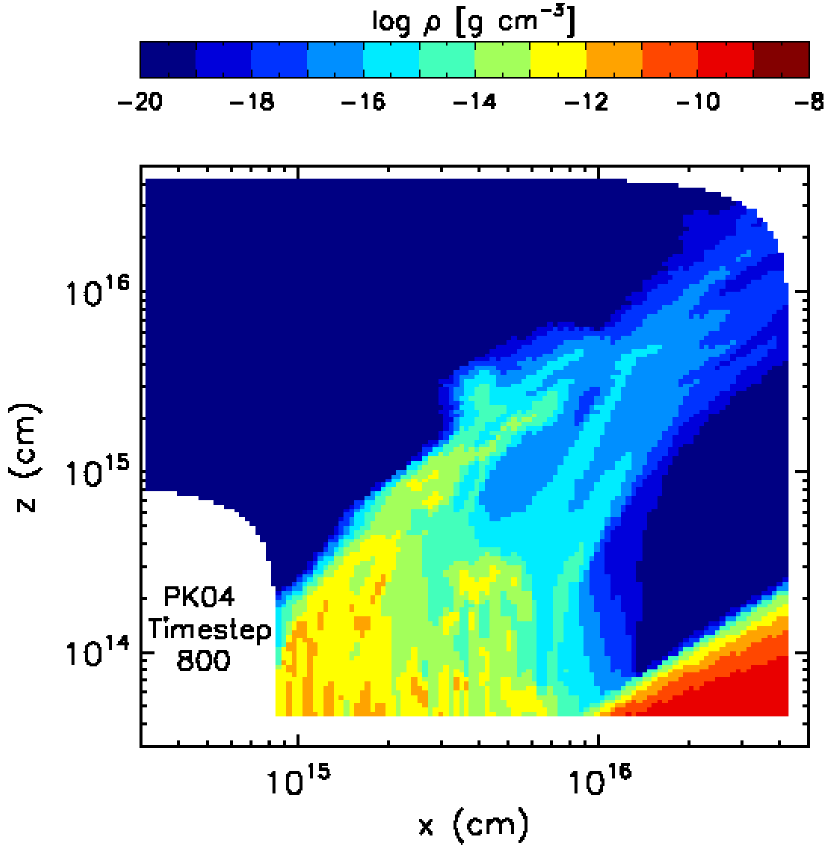
Synthetic X-ray absorption spectra

- 50, 57, 62, 65 and 67 degree orientations
- XSCORT spectra

Proga 2004 line-driven wind

2D RT: a more complete picture

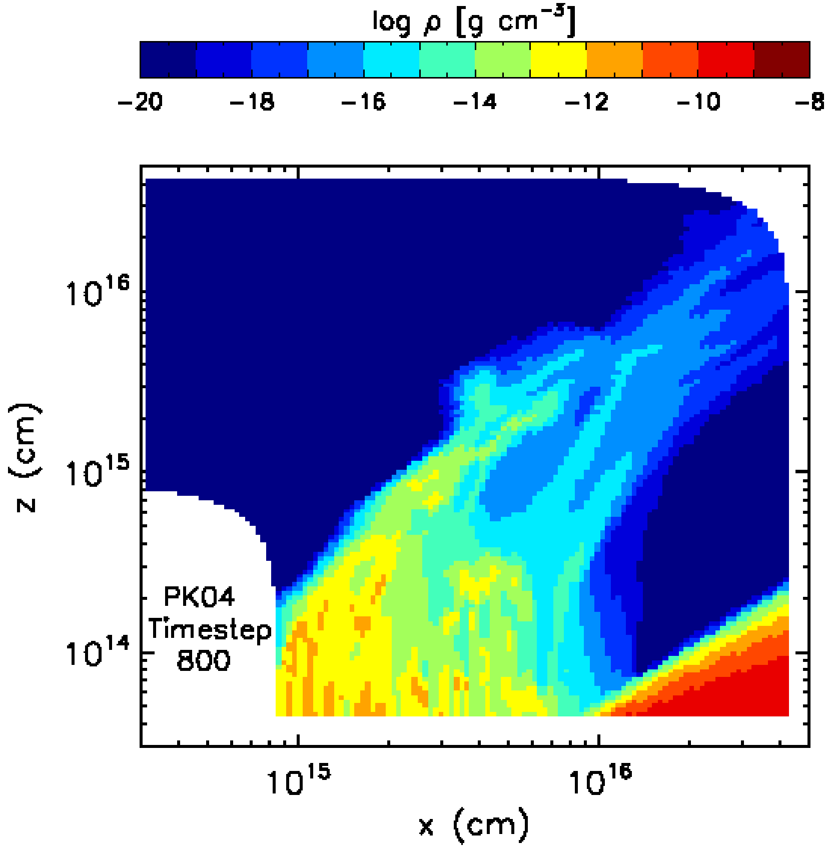
Multi-D radiative transfer needed



1D methods maybe ok for pure absorption spectra (cf. Warm absorbers) but:

To compute synthetic spectra for realistic (disk wind) geometries.... need multi-D rad. Trans.

Multi-D radiative transfer needed



1D methods maybe ok for pure absorption spectra (cf. Warm absorbers) but:

1. **Compton scattering (dominant in most strongly radiated regions)**
2. **Line absorption leads to excited atoms...they want to re-emit**
3. **Photo electric/free-free absorption heats material...will try to cool**

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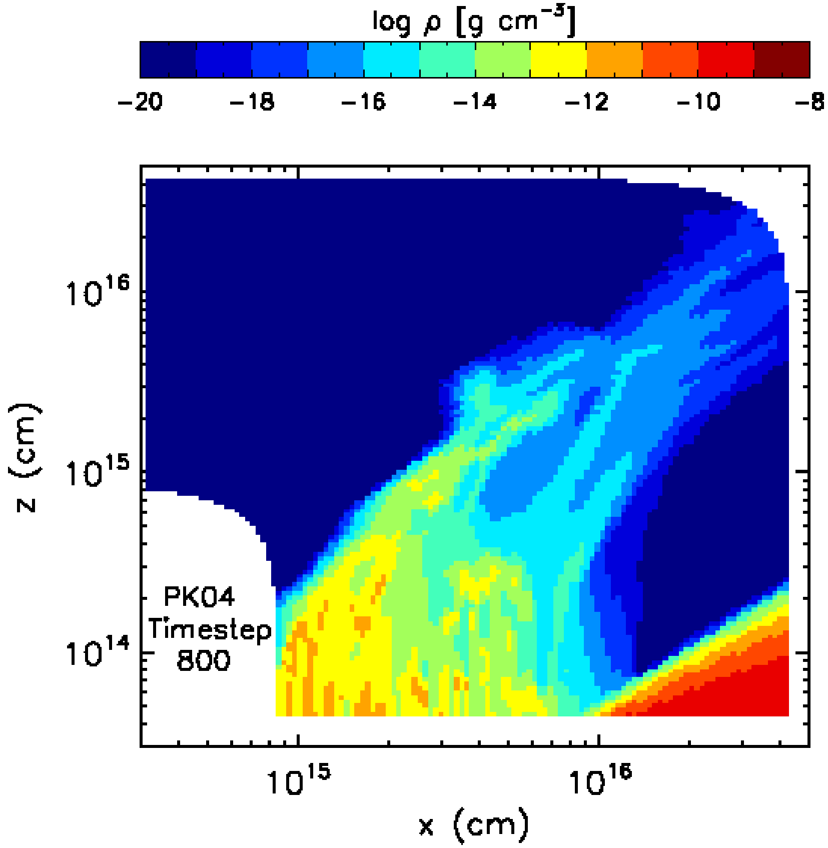
Multi-D radiative transfer needed



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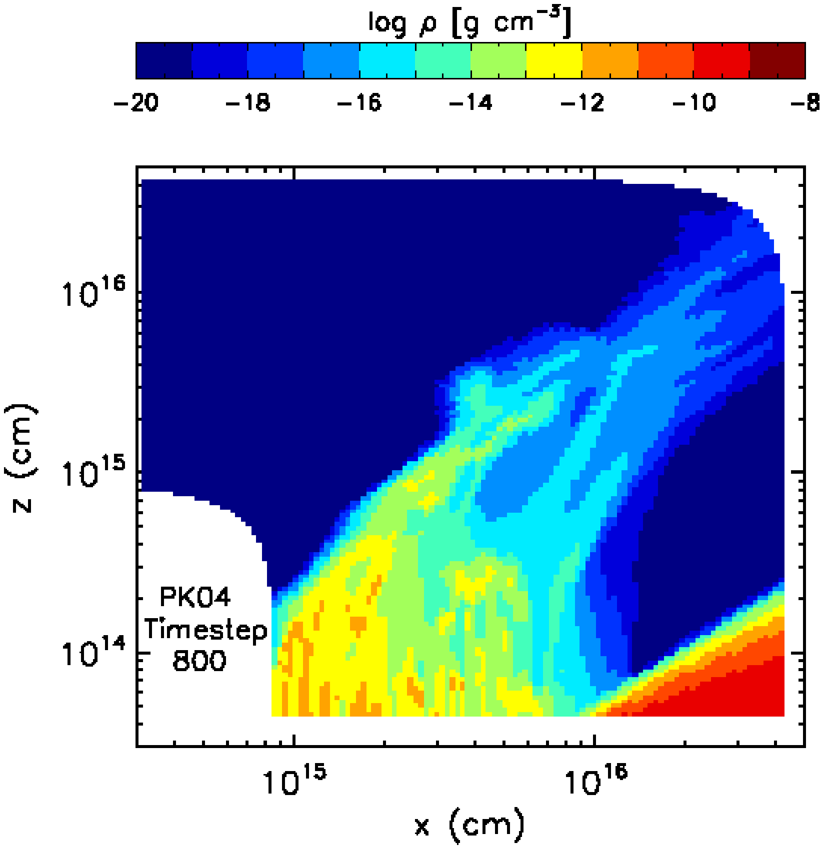
Relatively easy to do accurately with Monte Carlo methods (Sim 05, 08, 10). (See Higginbottom poster.)

To compute synthetic spectra for realistic (disk wind) geometries.... need multi-D rad. Trans.

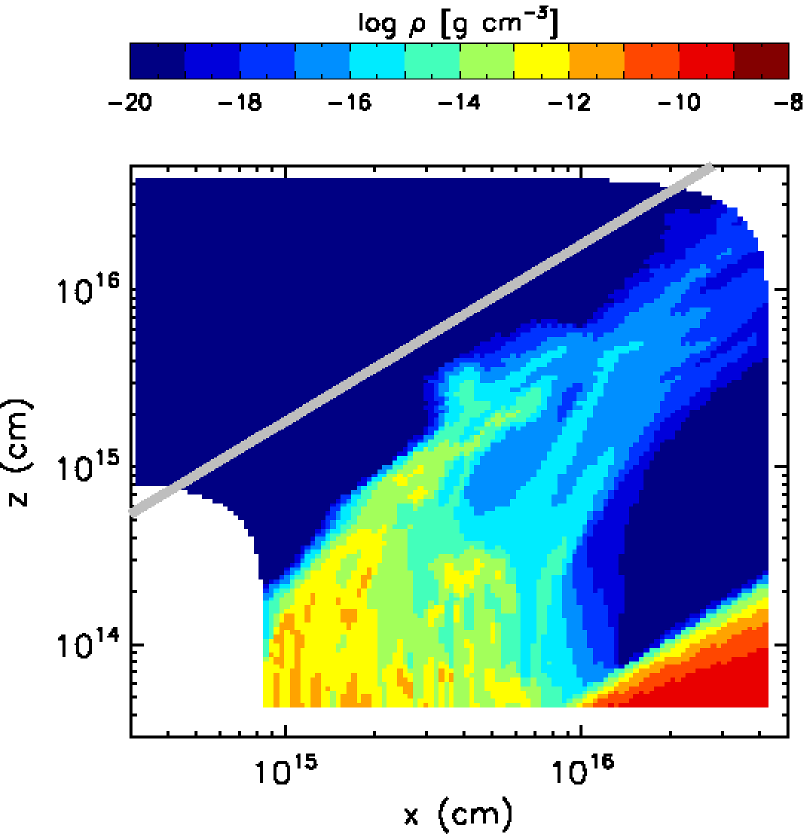
Proga 2004 line-driven wind

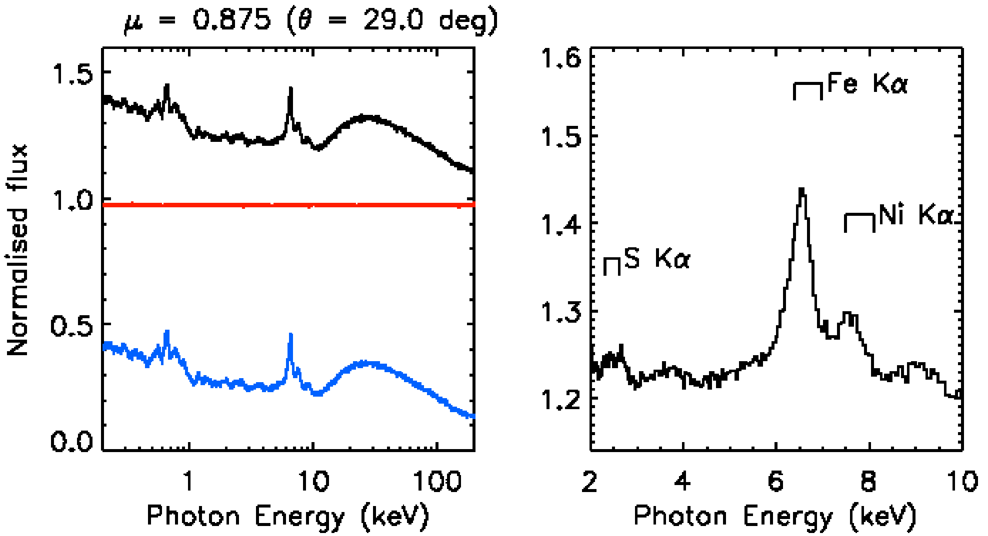


Compute synthetic spectra:

- Central power-law X-ray source
- Compute ionization state
- Spectra for multiple orientations
- Broadly, 3 classes of spectra

Proga 2004 line-driven wind

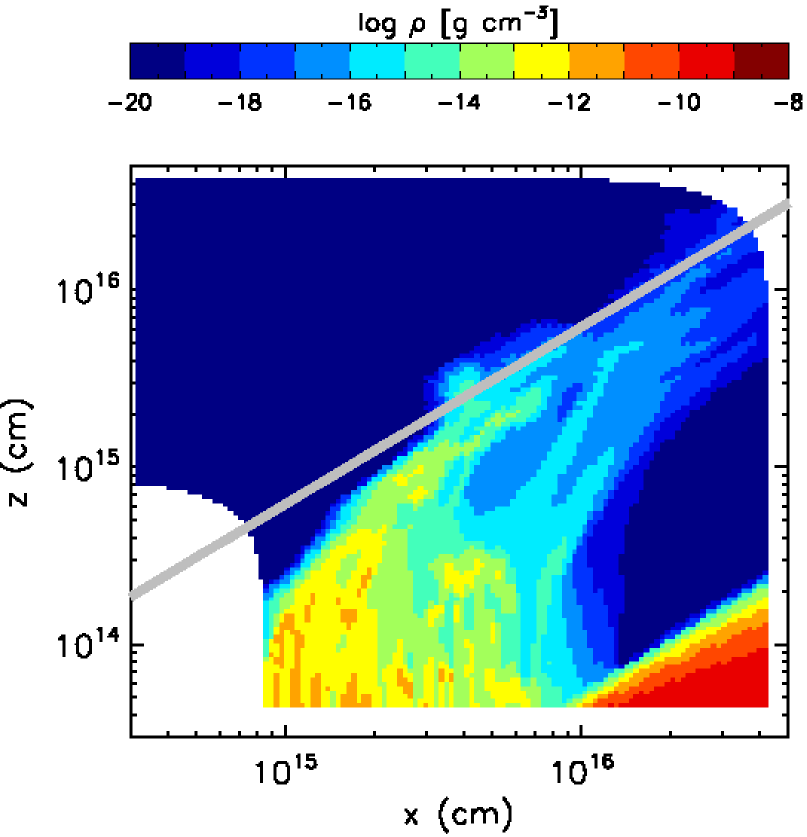


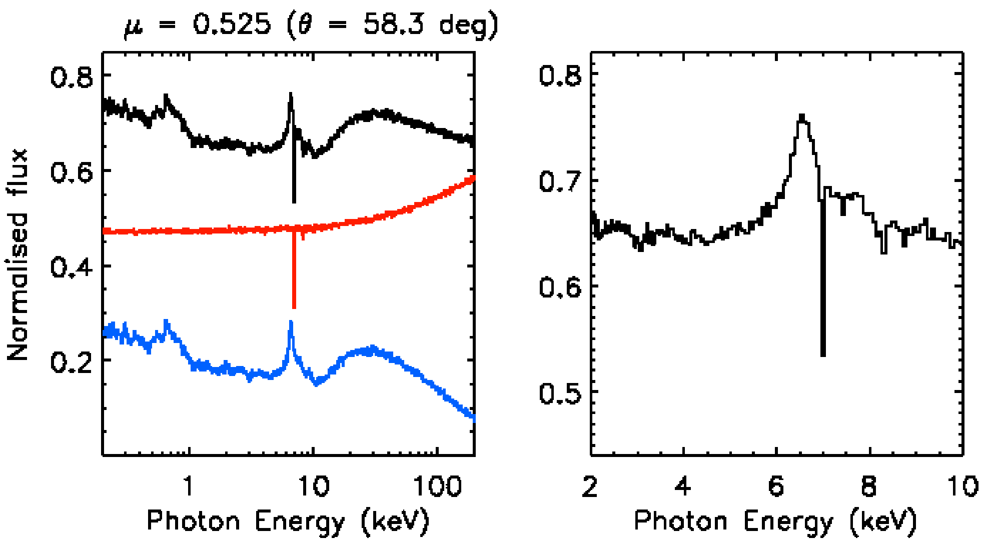


Polar observer:

- Direct continuum + Reflection
- Fe Ka emission + weak Comp. hump

Proga 2004 line-driven wind

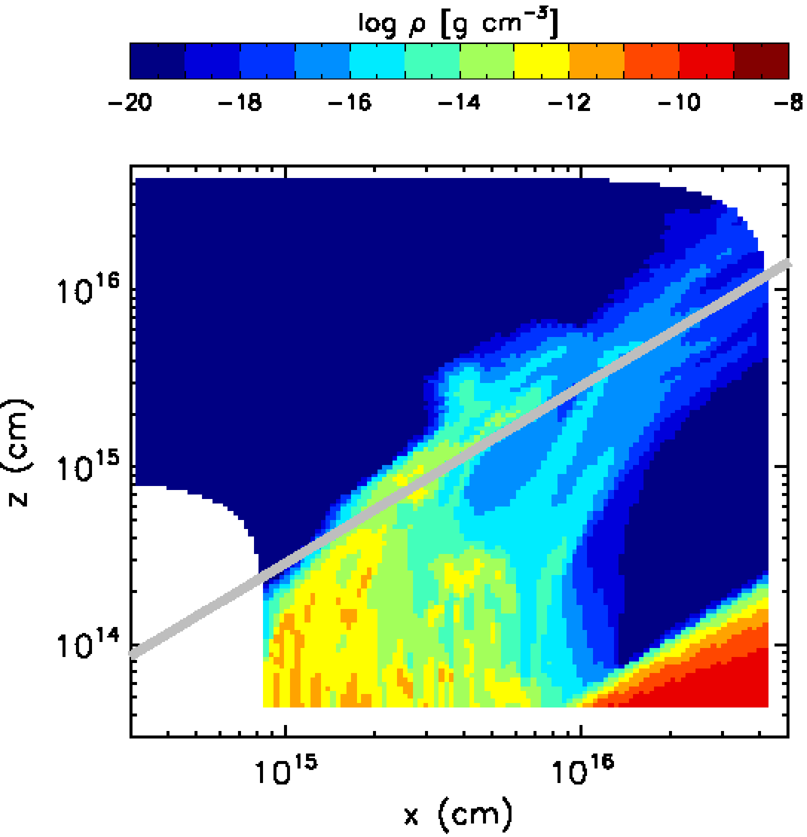


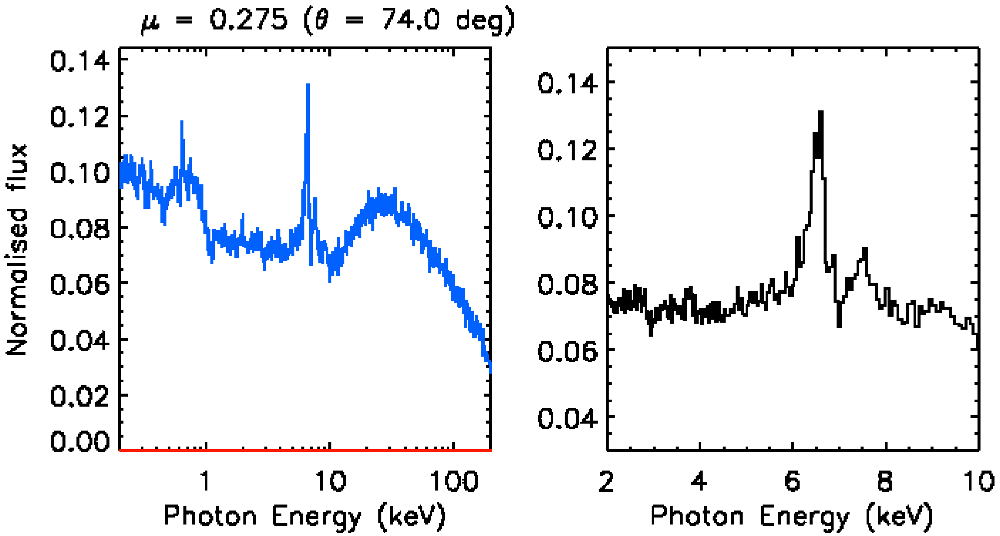


Intermediate orientation observer:

- Weaker continuum + Reflection
- Broad Fe Ka + weak Comp. Hump
- Narrow absorption lines

Proga 2004 line-driven wind





High orientation observer:

- Scattered/reprocessed spectrum
- Complex features
- No narrow absorption

Proga 2004 line-driven wind RT

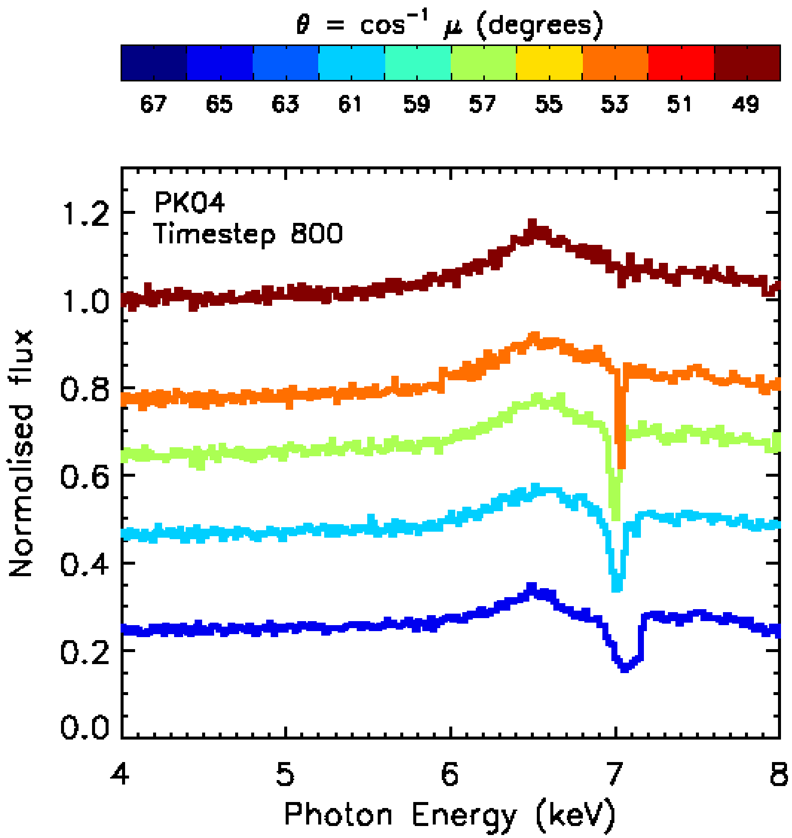
Summary (Sim et al. 2010):

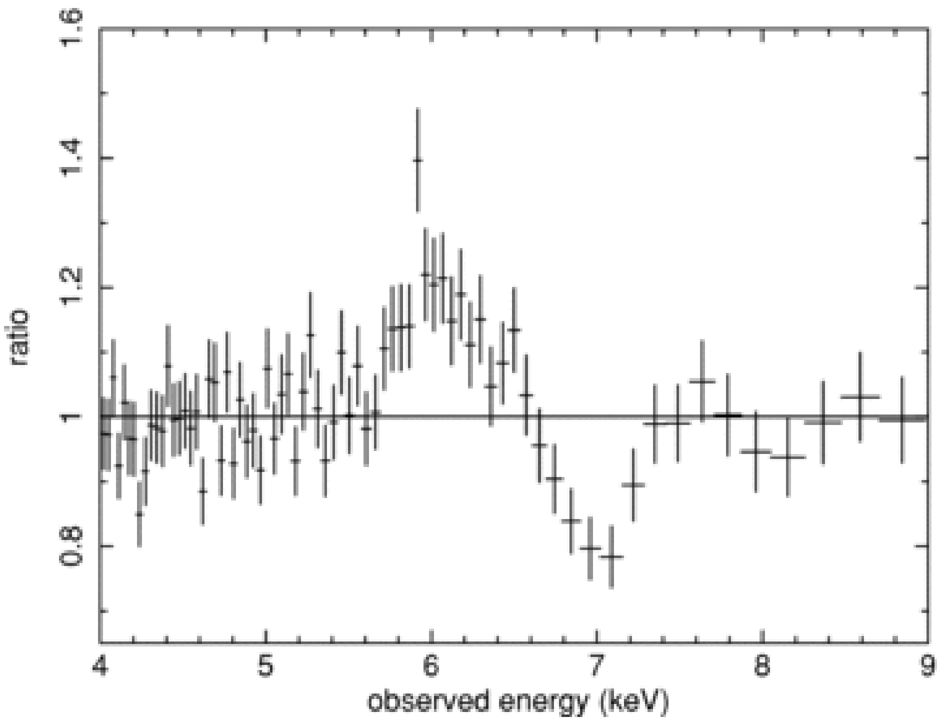
- Fe Ka emission for all orientations
  - Significant EW (~150 eV up to ~400 eV)
  - Broad (FWHM > 700 eV; cf. MCG 5-23-115, Braito et al. '07)
  - Red-skewed wings (cf. Auer '72, Titarchuck et al. '03)
- Narrow Ka absorption lines
  - Up to EW ~70 eV and v ~0.06 c
  - Significant variability: ~5 year time scale
  - Present for ~ 5 – 12 deg range (3 – 15 %, isotropic)
- Compton hump/soft emission lines
- Scattered/reprocessed light critical – multi-D necessary!

Note:

- No tuning (also no improvement to model)
- Still 2D – no realistic clumping

The need to explore...



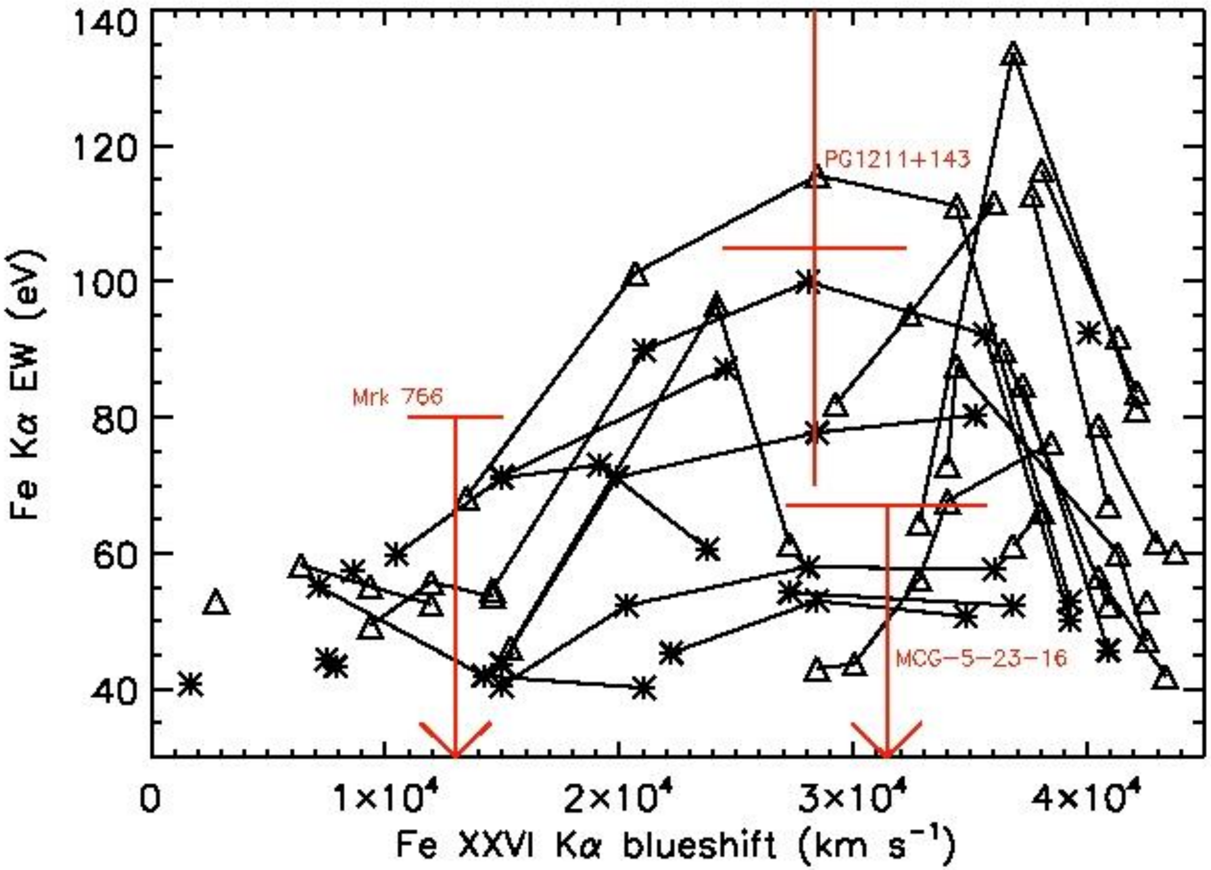


Fe line of
PG1211+143
(Pounds et al. 2009)

Summary

- **Accretion discs can launch winds:**
  - **Thermal: launched far out/slow: might be observationally too "puny" but huge mass-loss**
  - **Line-driven: launched from UV disk/fast+slow: can work for AGN (important spectral influence)**
  - **Magnetic fields can help both accelerate and launch (need to understand field geometry)**
  - **Nothing exclusive between the mechanisms...all can work together! (Proga 2007).**
- **Important consequences:**
  - **Mass (angular momentum?) budget**
  - **Blue-shifted absorption (the smoking gun); but beware projection/geometry**
  - **Broad emission (perhaps with red-skewed wings...electron scattering)**
  - **Modelling spectra: they are not just absorbing slabs**
- **Lots to do:**
  - **Many missing elements of simulations: scattering in line-driven model, field geometry (MHD)**
  - **3D structure, clumps etc.**
  - **Timing constraints**

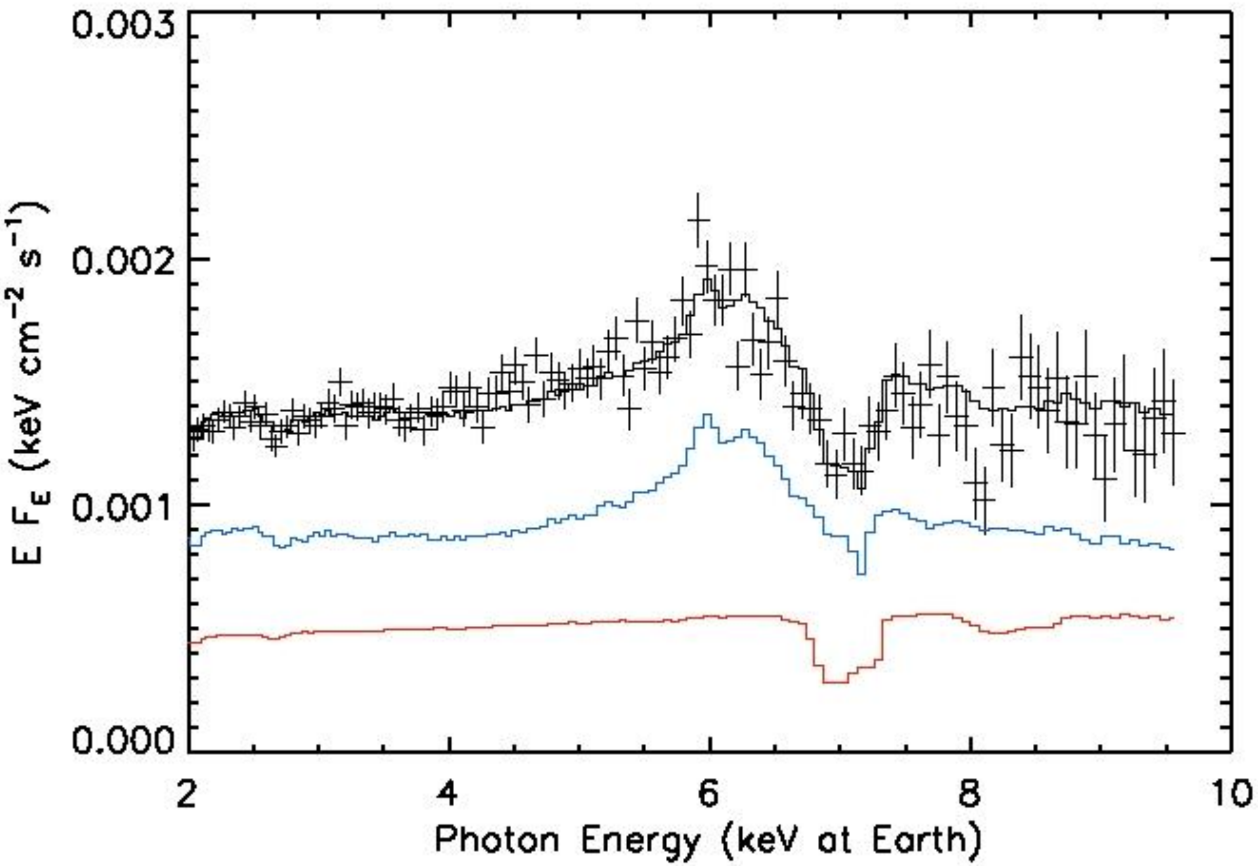
Grids of models: blue-shifted Fe K absorption line



Models showed wide range of EWs and blueshifts

Pounds et al. 2003
Turner et al. 2007
Braito et al. 2007

Our attempt to fit: PG1211



Sim et al. 2010

Imperfect but good fit:

- ❑ P Cygni profile
- ❑ red wing
- ❑weak S XVI

Broadly supports conclusions of Pounds & Reeves:

- ❑wide angle flow