PHYSICS OF ACTIVE GALACTIC NUCLEI

活動銀河核の物理学

Isaac Shlosman
University of Kentucky, Lexington, USA
and
Theoretical Astrophysics
Osaka University, Japan

October 27, 2015

LECTURE 3
AGN: INFLOWS VERSUS OUTFLOWS

Accretion and AGN power

Winds from accretion disks and driving mechanisms

Broad-line regions in AGN and outflows

AGN tori and outflows

Collimated winds: jets

Where is accretion and where is an outflow

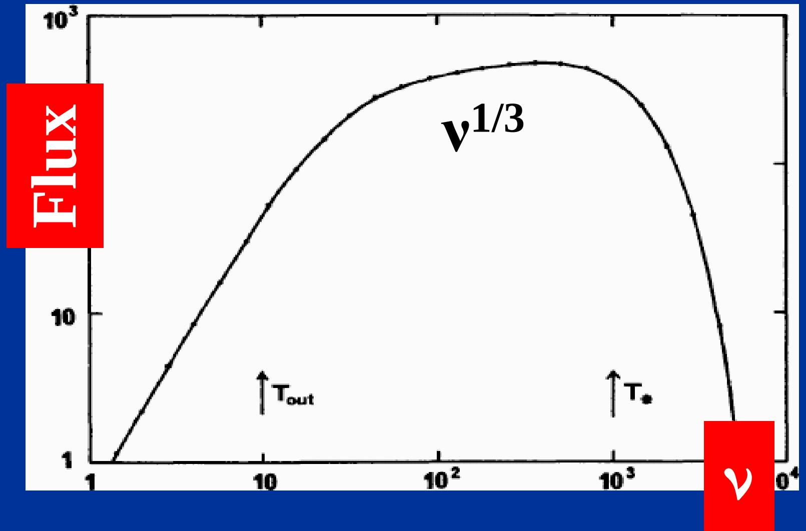
OBSERVATIONAL EVIDENCE FOR INFLOWS AND OUTFLOWS IN AGN

- Review of AGN energetics

$$L = \eta \dot{M} c^2 \sim 6\text{x}10^{45} \left(\frac{\eta}{0.1}\right)\left(\frac{\dot{M}}{1\,M_{\odot}/\text{yr}}\right) \text{erg/s}$$ accretion luminosity

$$L = \frac{4\pi G c m_p}{\sigma_T} M_{\bullet} \sim 1.3 \text{ x } 10^{46} \left(\frac{M_{\bullet}}{10^8 M_{\odot}}\right) \text{erg/s}$$ the Eddington luminosity

$$T_{bb} \sim \left(\frac{L}{\pi R^2 \sigma}\right)^{1/4} \sim 10^5 \left(\frac{L}{10^{46}\text{erg/s}}\right)^{1/4}\left(\frac{R}{1\text{ light-day}}\right)^{-1/2} \text{K}$$ effective temperature of blackbody accretion disk emission → peaks at ~ 10^{16} Hz



accretion disk continuum

OBSERVATIONS: INFLOWS AND OUTFLOWS IN AGN

❖ Analogy with hot stars

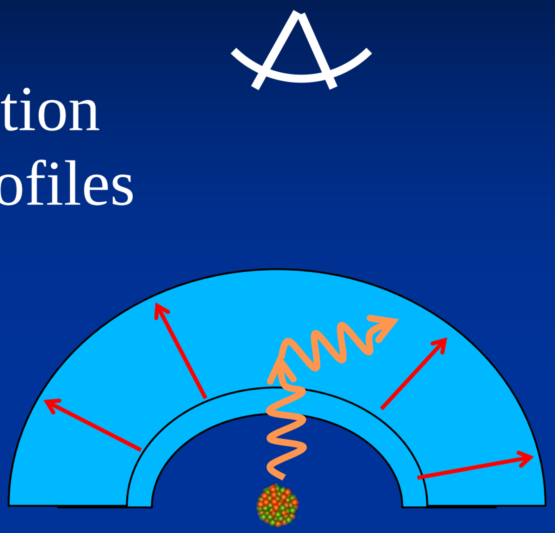
Optical/UV spectroscopy: blueshifted absorption or P Cygni line profiles

$$a_{rad} = \int d\nu \frac{\kappa_\nu F_\nu}{c}$$

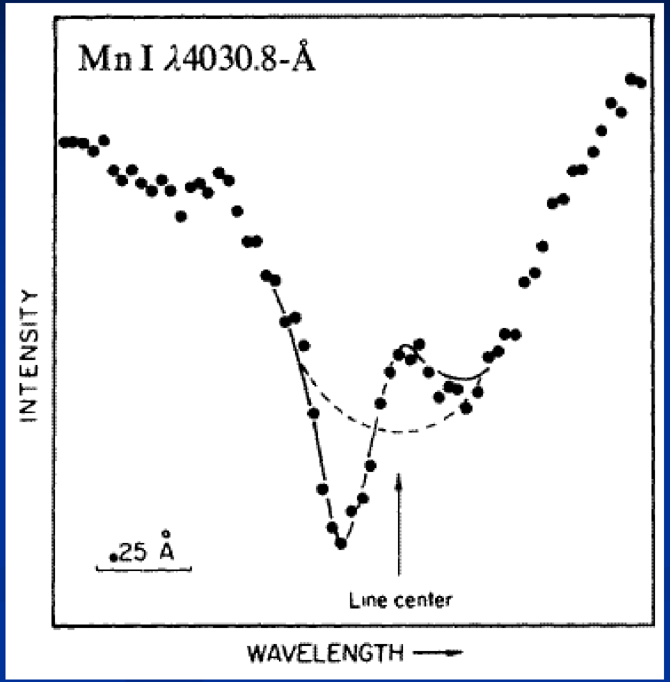
F_ν -- stellar radiation flux

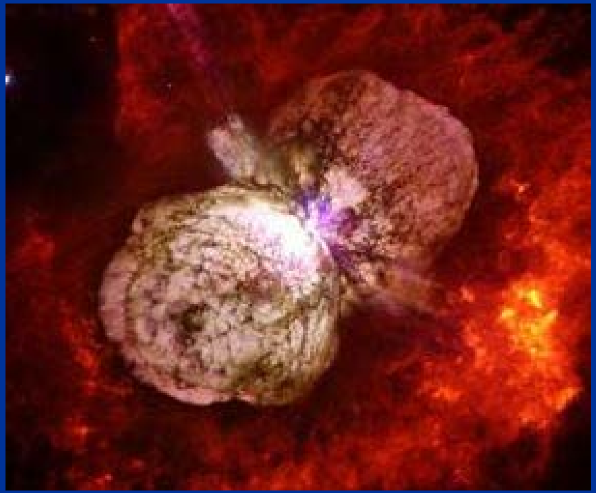
a_{rad} – radiative acceleration

κ_ν – opacity coeff.

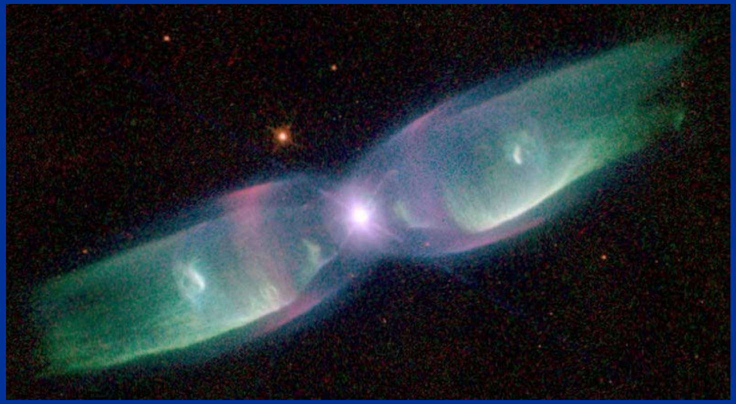


wind from an O star





Eta Carina



OBSERVATIONS: INFLOWS AND OUTFLOWS IN AGN

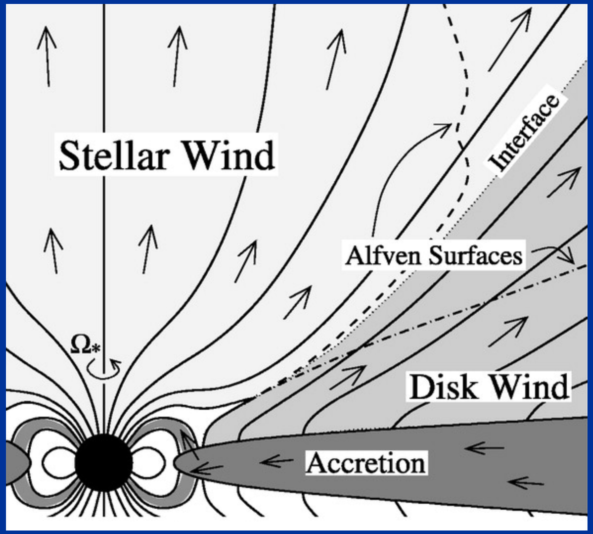
❖ Analogy with solar (Parker) wind

What triggers the solar wind:
waves and turbulence,
or magnetic reconnection?

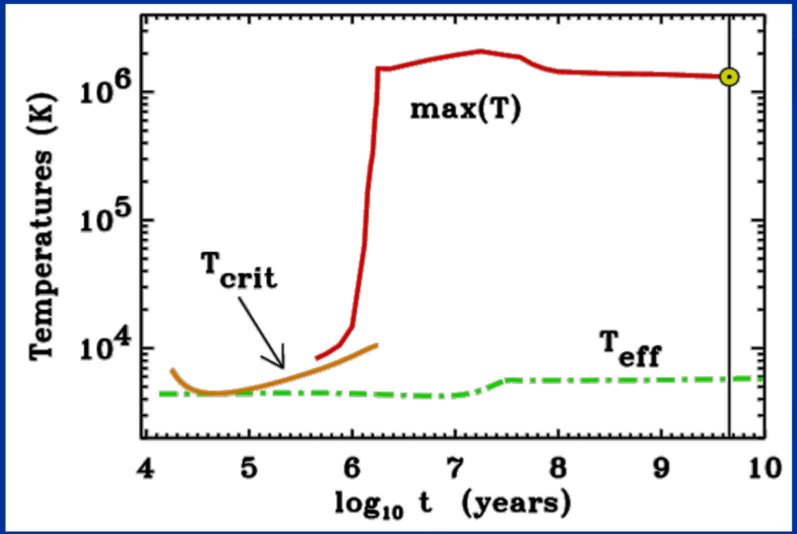
$$\dot{M} \propto F_{\rm heat} \propto F_{\rm X}$$

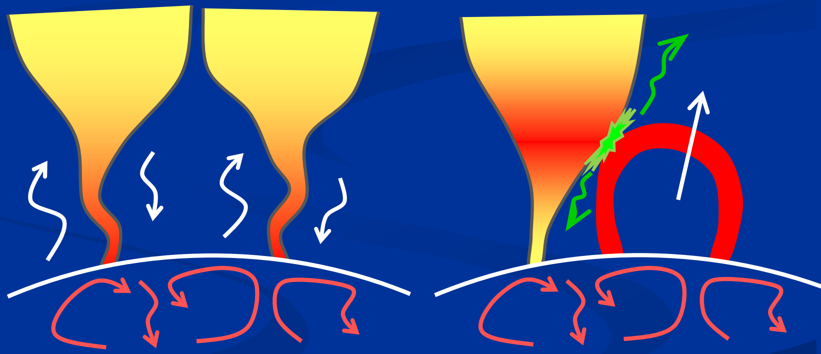
solar wind

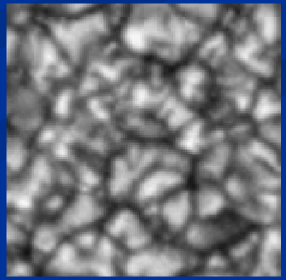
Some stars have disks (T Tauri) and winds



(Matt & Pudritz 2005)







MHD turbulence
→ granulation

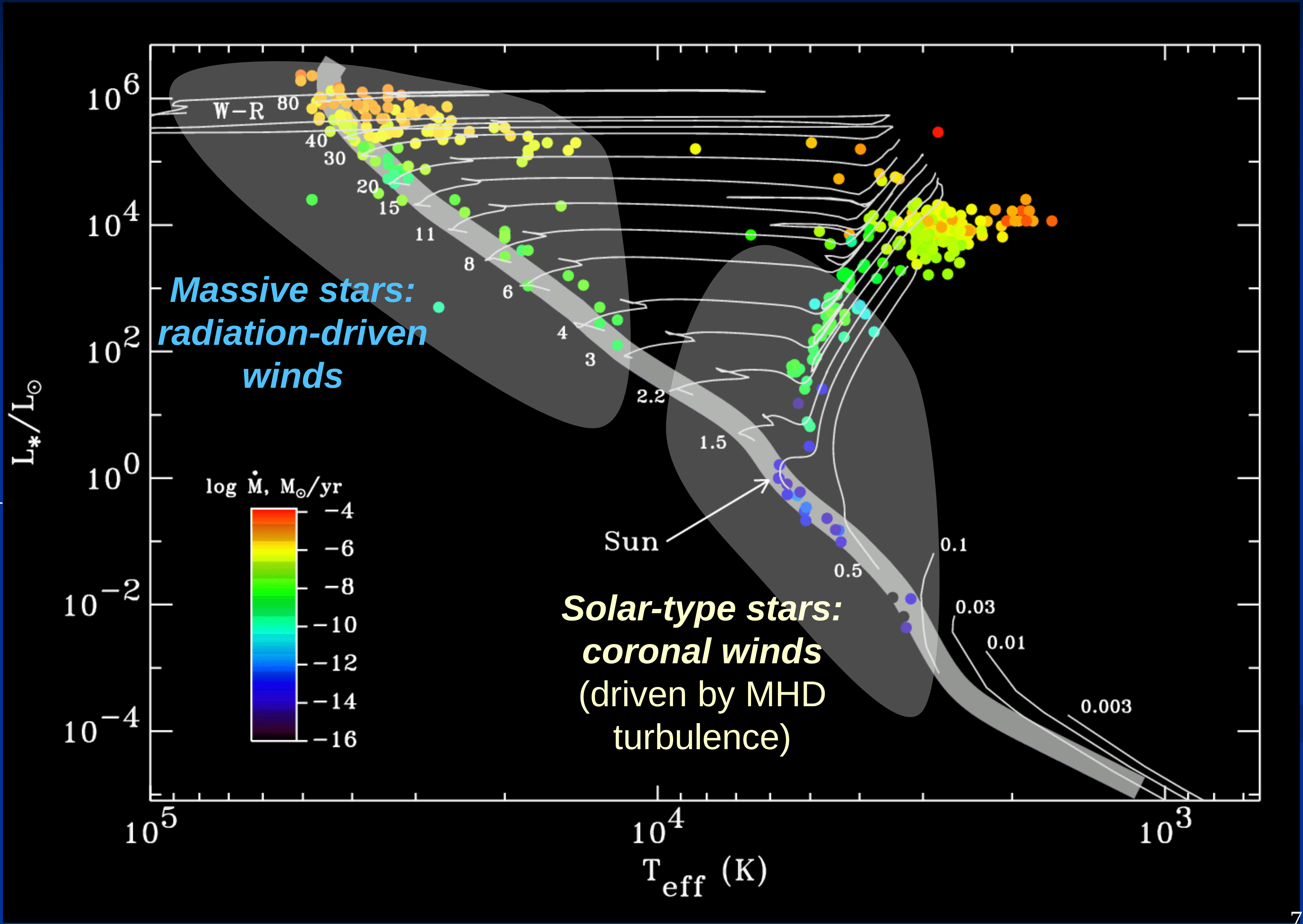
OBSERVATIONS: INFLOWS AND OUTFLOWS IN AGN

- Analogy with hot stars

T-range for radiation-driven and coronal stellar winds

T-range for geometrically-thin accretion disks in AGN is similar to stellar range!

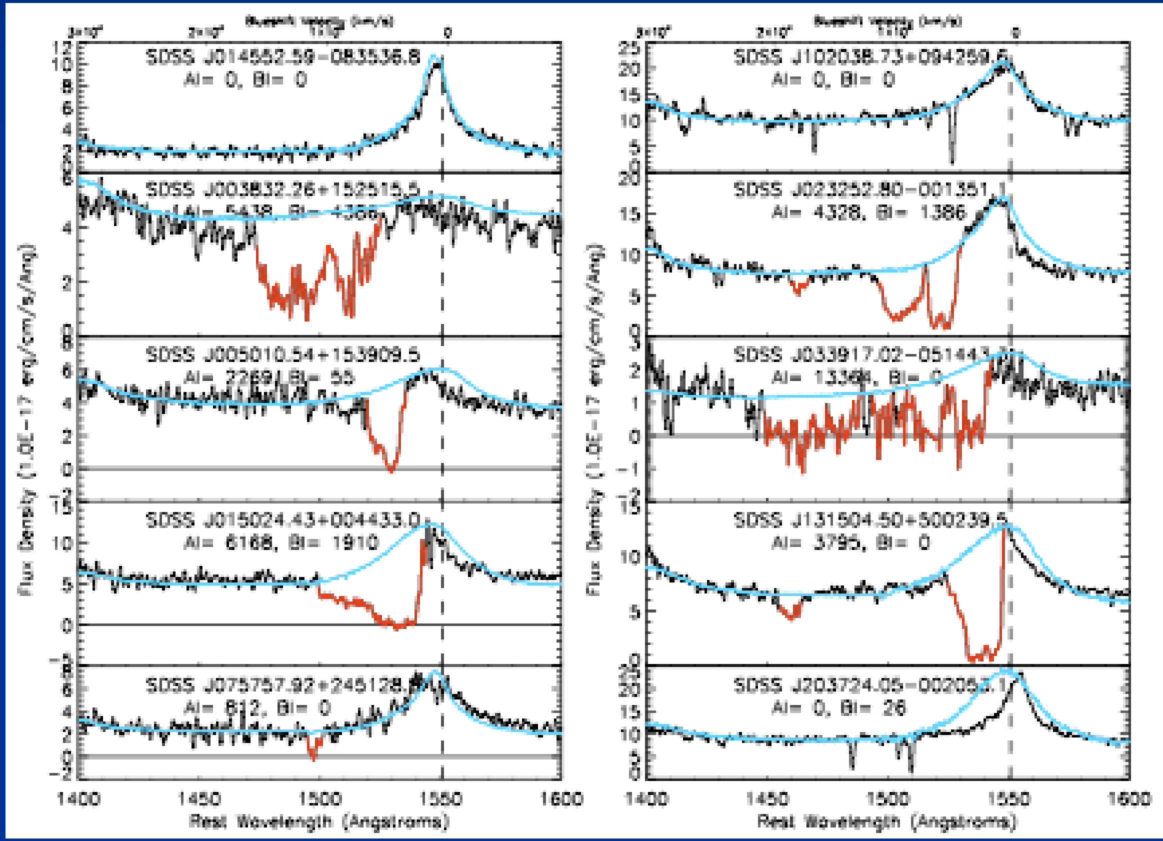
AGN winds can be radiation-driven!



OBSERVATIONS: INFLOWS AND OUTFLOWS IN AGN

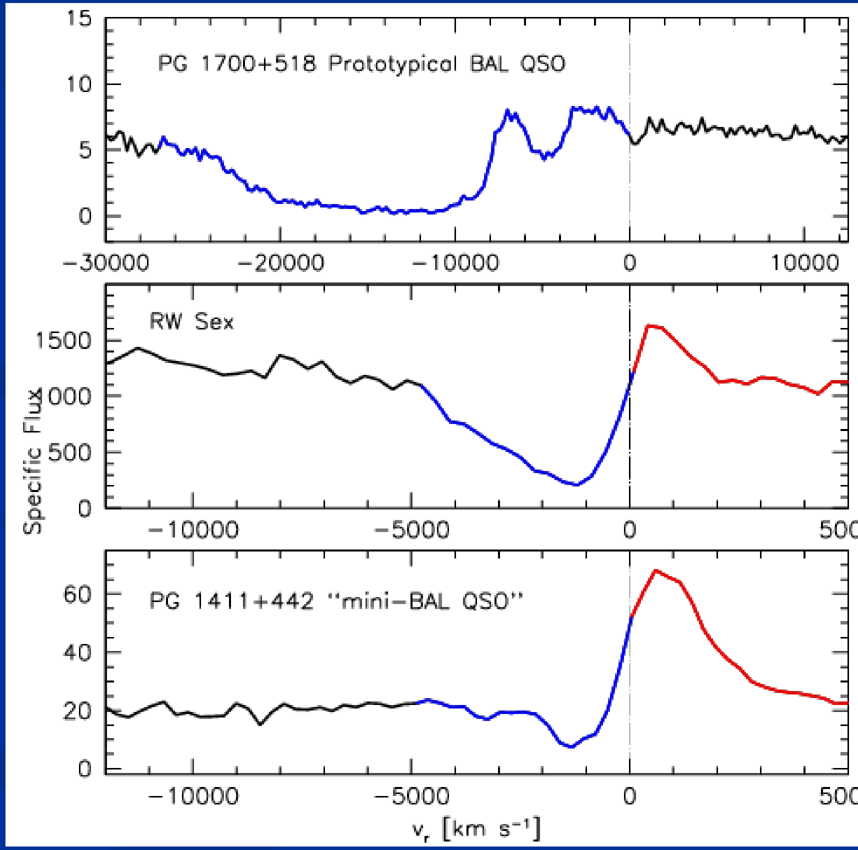
- Evidence for outflows: BAL QSOs

7 BAL QSOs (red throughs), 2 non-BAL QSOs



Trump et al. 2006

Similarity of the CIV line profile of the nova-like variable RW Sex with those of BAL QSOs



All BALQSOs absorption lines are blueshifted →outflows !

OBSERVATIONS: INFLOWS AND OUTFLOWS IN AGN

- Evidence for outflows: high-ionization UV emission lines (HILs) in QSOs

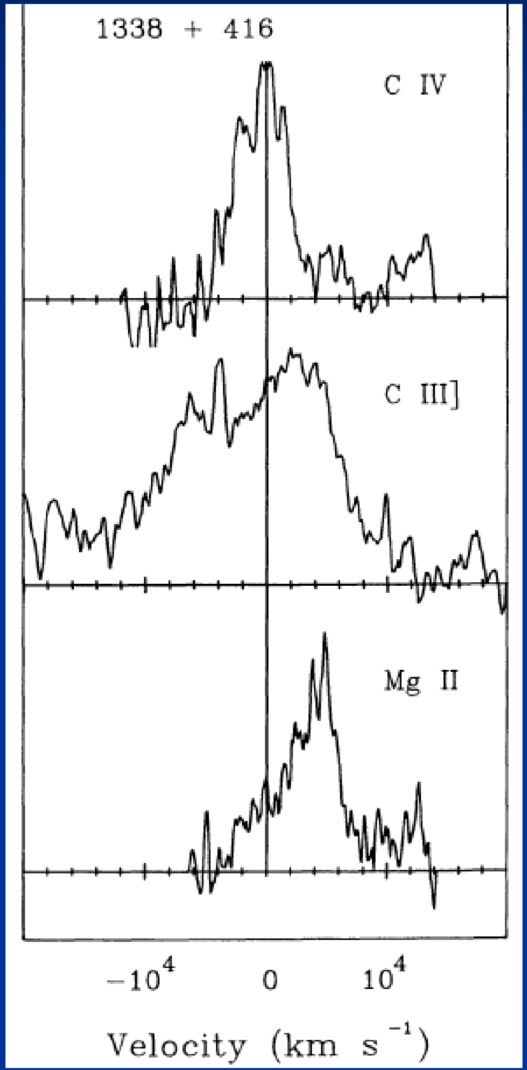


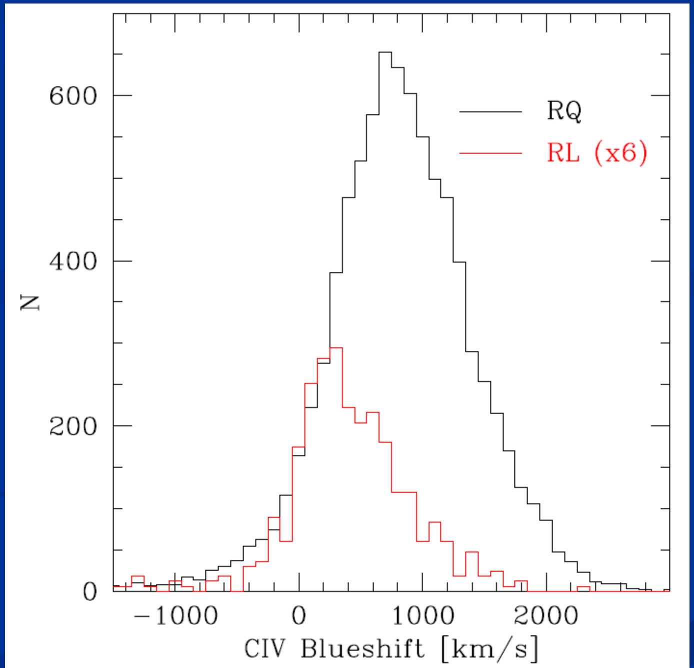
TABLE 1

REDSHIFT DIFFERENCES

Object	Velocity of Mg II relative to C IV (km s^{-1})	Velocity of C III] relative to C IV (km s^{-1})
BQS		
0117+213	1200	900
1008+133	2500	1300
1241+176	1200	900
1338+416	4400	2500
1352+011	1500	500
1522+101	1600	200
1630+377	1400	100
1634+706	200	200
Mean	1750 ± 439	825 ± 282

Corbin et al. (1990)

blueshifted CIV emission line in luminous radio-quiet and radio loud QSOs



Richards et al. (2011)

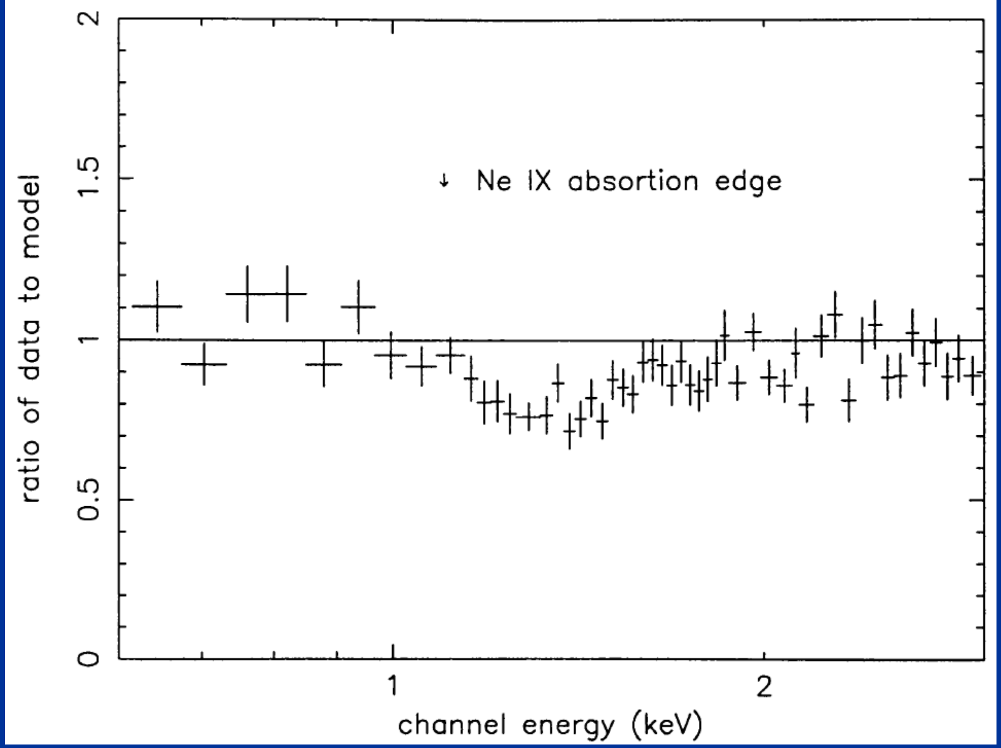
HILs in QSOs are blueshifted
By ~few x 100 – 1000 km/s → these broad line produced in winds !

Observations: Inflows and Outflows in AGN

❖ Evidence for outflows: warm absorbers in Seyfert galaxies

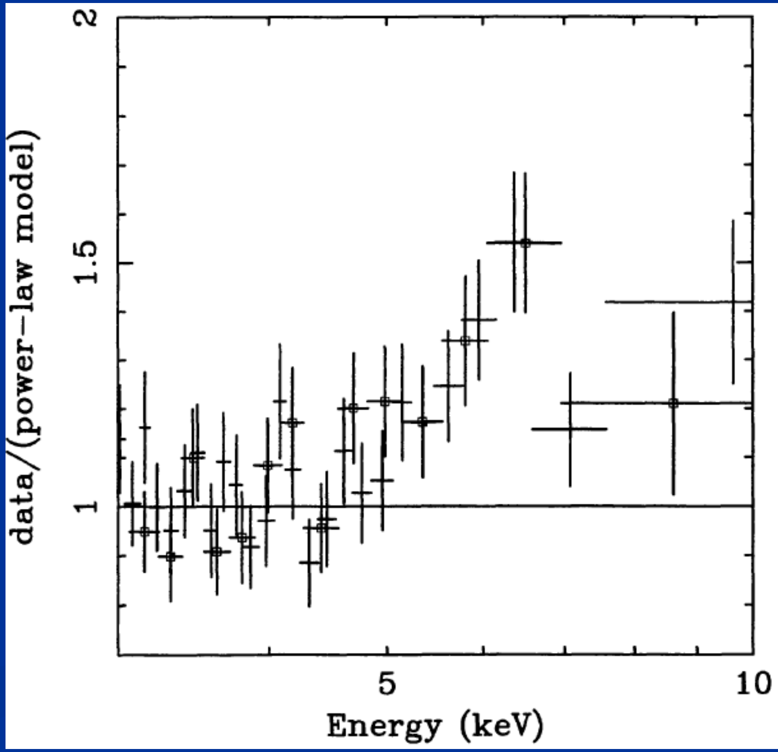
Covering factors can be as high as 0.5 ← about 50% of Seyferts show warm absorber

warm absorber fit to the ASCA satellite spectrum of NGC 3783 → Ne IX absorption line



Mushotzky (1997)

Fe K line in Fairal 9 from ASCA



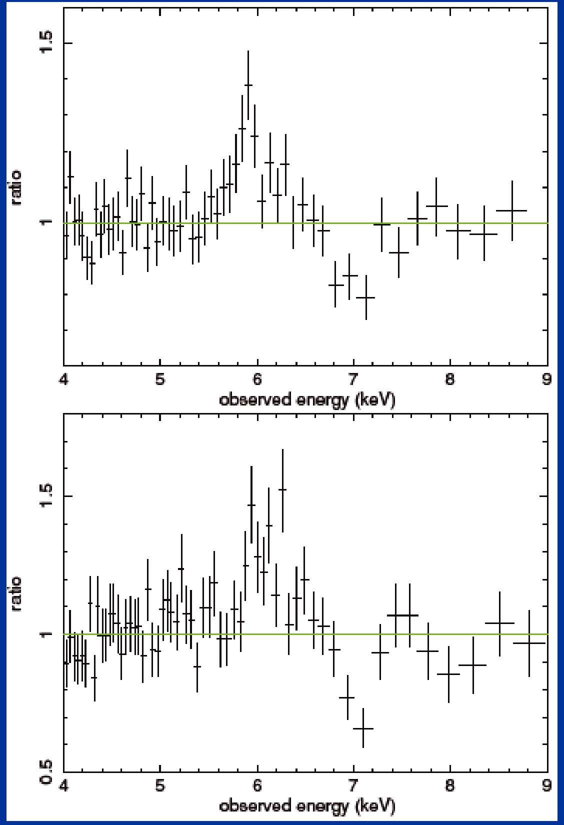
Reynolds (1997)

OBSERVATIONS: INFLOWS AND OUTFLOWS IN AGN

- Evidence for outflows: ultra-fast X-ray outflows (UFOs)

Very fast outflows of highly ionized material by XMM/Newton in absorption lines of highly ionized Fe, S, Mg → warm absorbers?

Fe Kα line normalized by continuum emission:
absorption line well defined, but emission line much less defined



PG 1211+143; Pounds & Reeves (2009)

L_{kin}~0.1 L_{bol}, v~ 0.13c !

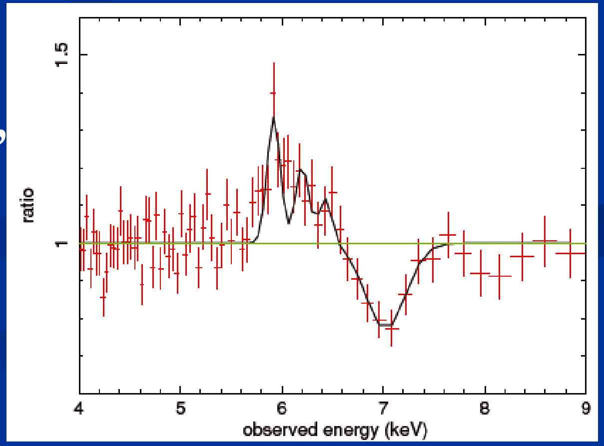
The physical implications are:

persistent (>6-7 yrs), massive wide-angle wind, covering 0.3-0.6, $\dot{M}$ (wind) ~ $\dot{M}$ (accretion), column density $N_H \sim 8 \times 10^{23}$ cm^{-2} , *super*-Eddington → Compton-thick wind?

BUT:

Often only one line is detected: unsure identification, ionization/column density

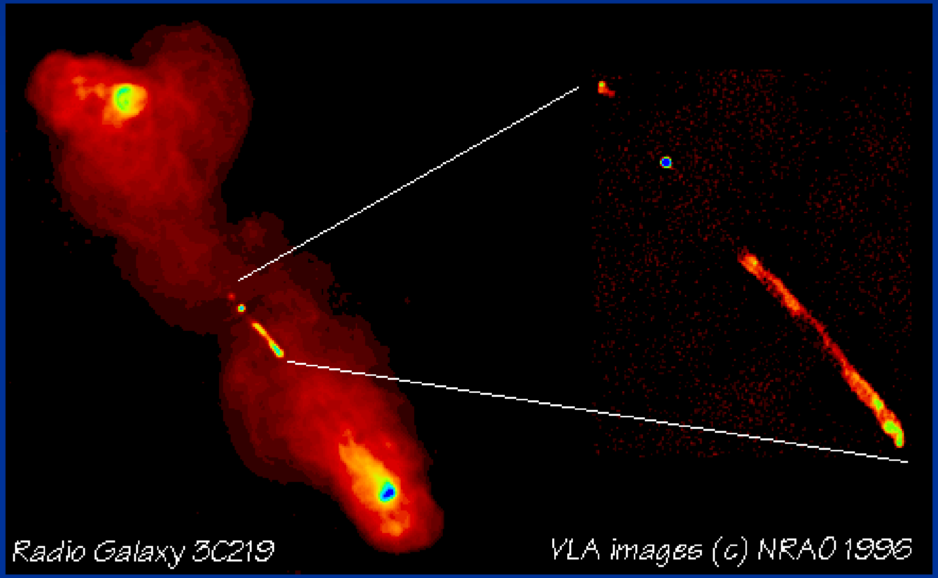
Region strongly influenced by:
background subtraction, continuum modelling, lower effective area/resolution

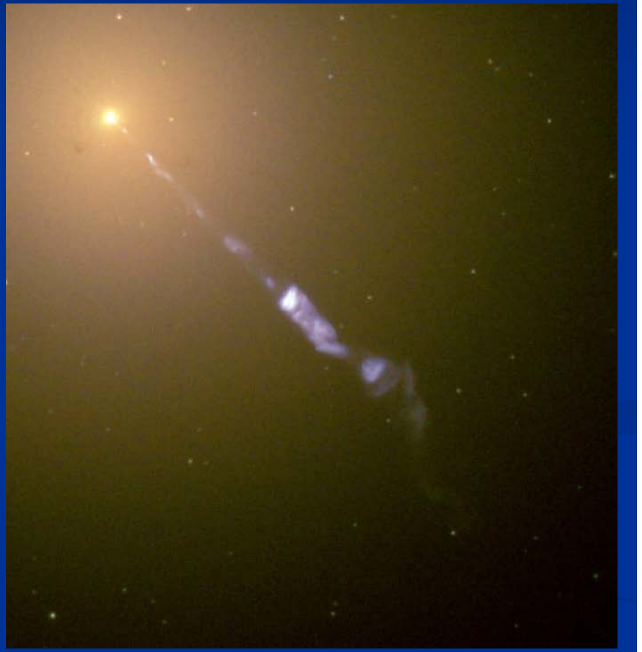


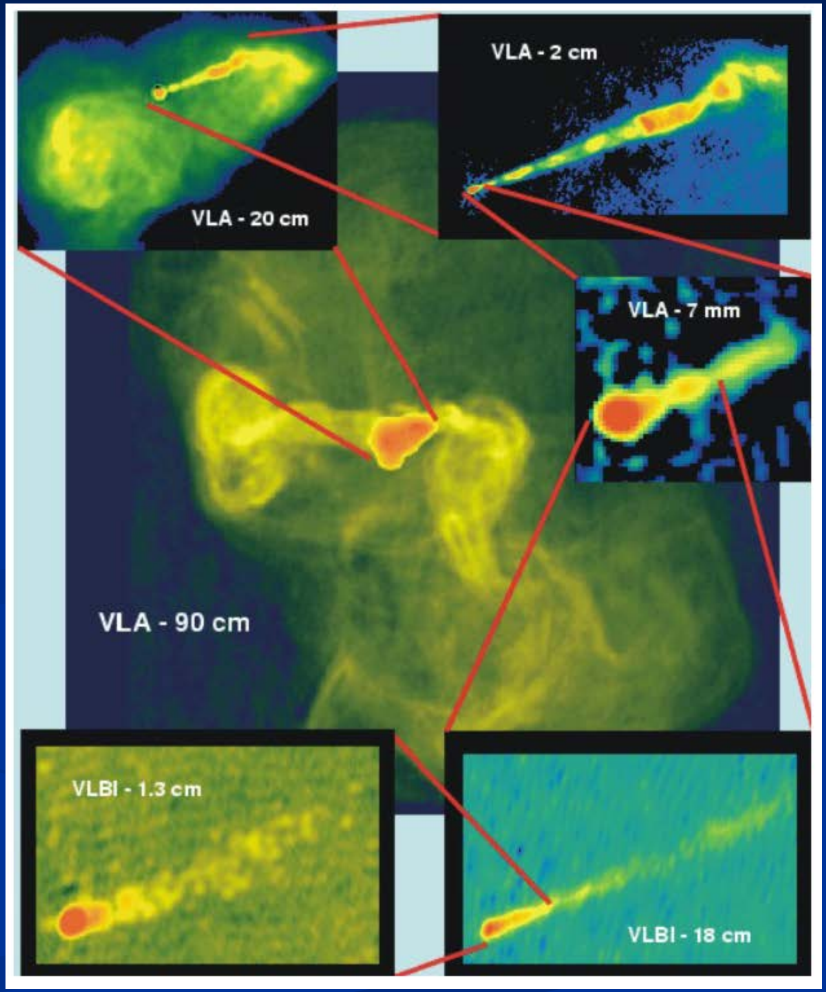
P Cygni line profile

OBSERVATIONS: INFLOWS AND OUTFLOWS IN AGN

- Evidence for outflows: jets in radio and other (AGN) galaxies







Jet in M87 → optical emission is synchrotron mechanism (electrons accelerated in B-field)

OBSERVATIONS: INFLOWS AND OUTFLOWS IN AGN

- Evidense for outflows: summary

Uncollimated or partially collimated winds:

UV resonance lines in QSOs and Seyferts (line-driven winds)

BAL QSOs

UV absorbers: warm absorbers, UFOs (X-ray Ultra-Fast Outflows)

Super-Eddington winds?

Collimated winds (jets)

Powerful and not so powerful radio galaxies

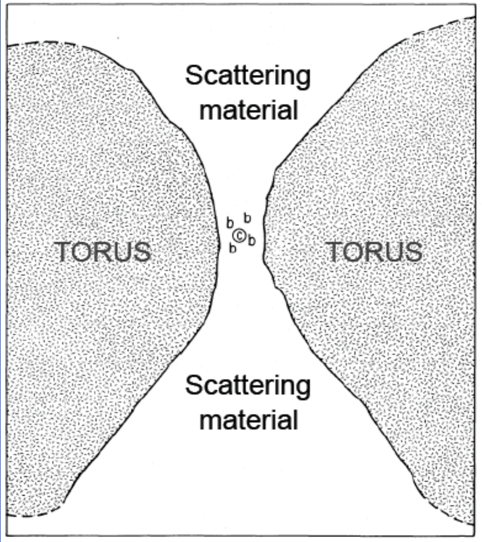
(RLQ, FR II, FR I), Seyferts

LLAGN (XRB hard state compact jets)

THEORY: INFLOWS AND OUTFLOWS IN AGN

❖ Summary: radiation-driven winds

To drive a wind by radiation → need opacity → $F_{rad} > F_{grav}$



resonance lines
e.g., C IV
↓
wind T < 10,000 K

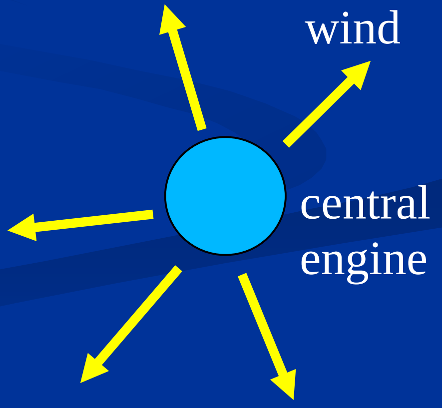
dust
↓
wind T < 2,000 K

electron scattering
↓
wind fully ionized
T > 10,000 K
↓
super-Eddington wind?

?

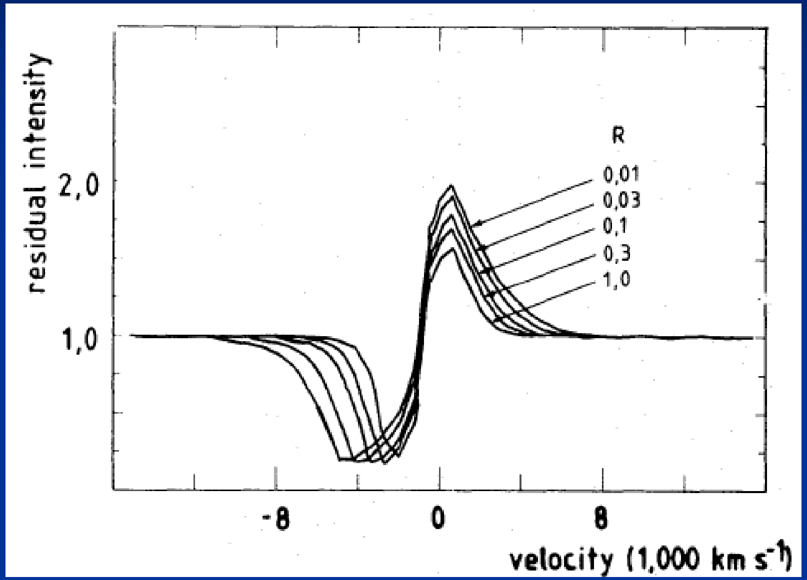
- **But linewidth ~ 10^4 km/s**
  →T_{gas} ~ 10^{10} K !
  No lines! No dust!
- **What is the geometry of the wind?**

BLR must be clumpy
but
what about wind ?



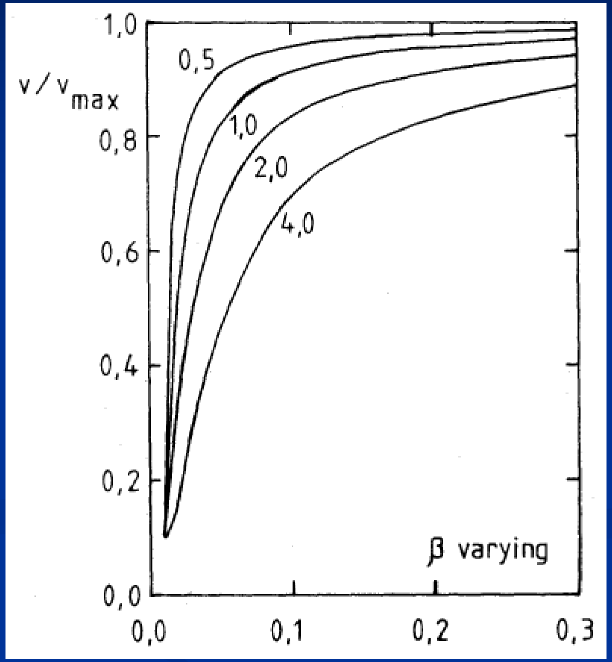
THEORY: INFLOWS AND OUTFLOWS IN AGN

❖ Radiation-driven disk winds: driving spherical wind by resonance lines



line profiles similar
to stellar line profiles

$$v(r)/v_{\rm max} = w_c + (1 - w_c)(r/r_{\rm max})^{\beta}$$



Drew & Giddings (1982)

dependence beyond the Lyman limit, down to X-ray wavelengths. In the optically thin approximation, even when the spectral index is increased to $\alpha = 3$ in the ultraviolet and X-ray part of the spectrum, the mass-loss rate needs to be of the order of $\sim 1000 M_\odot\, {\rm yr}^{-1}$, if the visual luminosity of the QSO is comparable with that of 3C 273. It is anticipated that,

Such mass loss is not achievable in AGN!

THEORY: INFLOWS AND OUTFLOWS IN AGN

❖ Radiation-driven disk winds: driving by resonance lines (Shlosman et al. 1985)

$$F_{l,\mathrm{tot}} = \sum_l \frac{\mathscr{F}(R;\nu_l)}{c} k_l \rho \frac{1-e^{-\tau_l}}{\tau_l}$$

radiation force (Sobolev) per unit volume summed over lines (C, N, O lines)

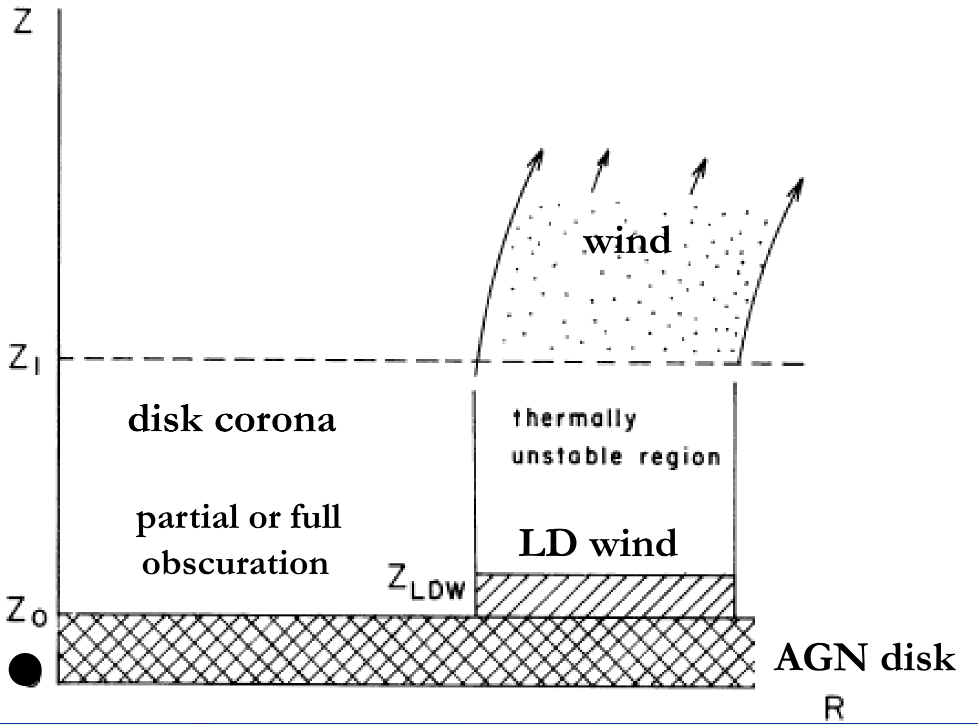
$$\tau_l = \frac{k_l \rho c}{\nu_l} \left| \frac{dv}{dz} \right|^{-1}$$

optical depth in line *l* depends on v-gradient!

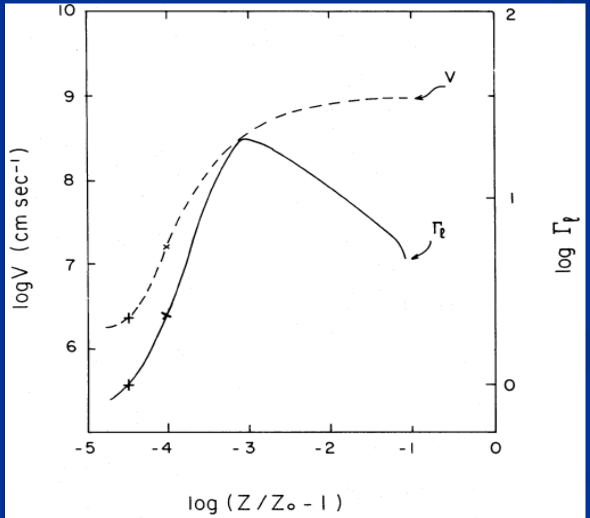
$$\rho v_z g = \dot{\mathscr{M}}$$

$$(v_z^2 - v_s^2)\frac{dv_z}{dz} = \frac{v_z}{z}\left[\frac{2v_s^2 z^2}{gR_0^2} - z\frac{dv_s^2}{dz} - \frac{GM_{\mathrm{BH}} z^2}{g^{3/2} R_0^3}(1-\Gamma_{es}-\Gamma_l)\right]$$

$$\frac{dT}{dz} = \frac{2}{3}\frac{1}{v_z}\left[\frac{H-\Lambda}{k_B n} - T\left(\frac{dv_z}{dz} + \frac{2zv_z}{gR_0^2}\right)\right]$$



Shlosman, Vitello & Shaviv (1985)



vertical velocity and line radiation force profiles (normalized by gravity)

disk wind fits, But what about line profiles?

THEORY: INFLOWS AND OUTFLOWS IN AGN

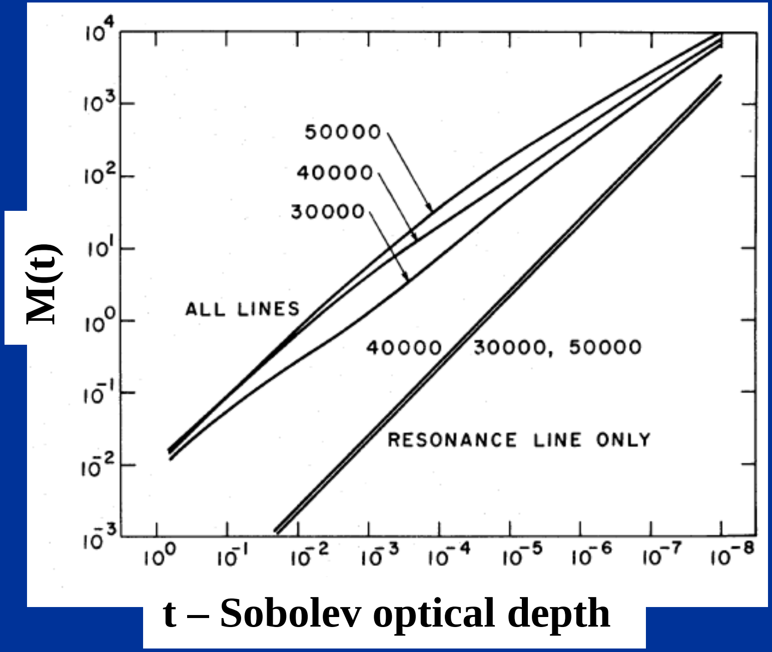
❖ Radiation-driven disk winds: driving by resonance lines (Proga et al. 2000)

$$F^{\mathrm{rad},l}(r) = \oint_{\Omega} M(t)\left[\hat{n}\frac{\sigma_e I(r,\hat{n})d\Omega}{c}\right]$$

electron scattering force

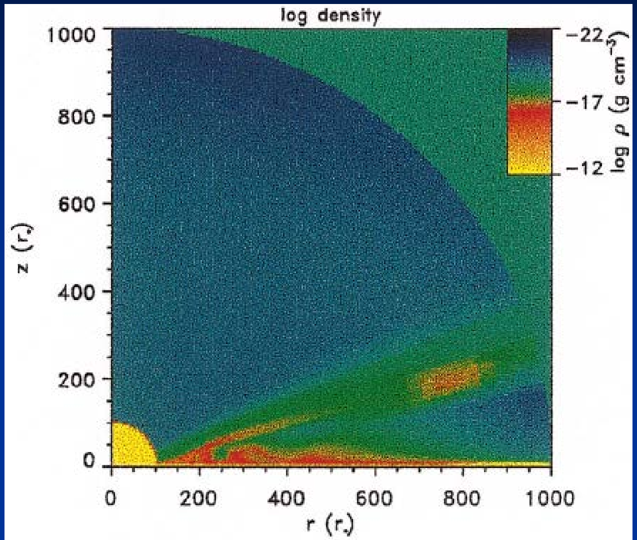
radiation force (Sobolev) per unit mass approximated by force multiplier M(t)

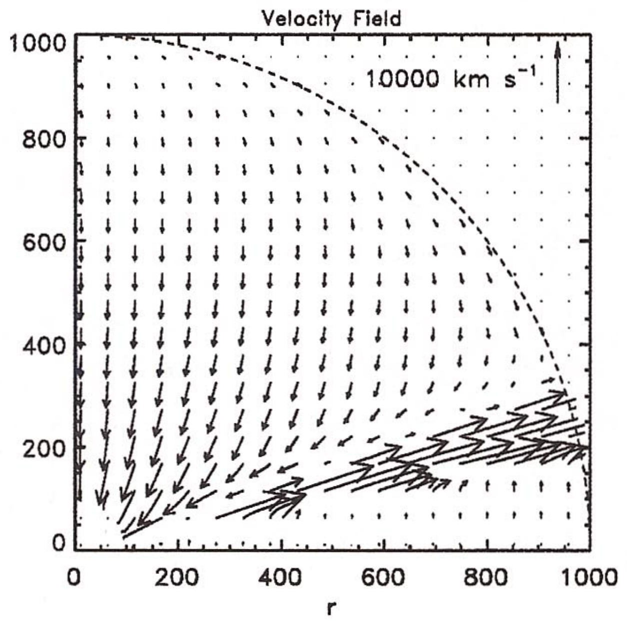
Force multiplier has been calculated for stellar case only !



Castor, Abbott & Klein (1973)

$$M(t) = \sum_{\mathrm{lines}} \frac{F_c \Delta\nu_D}{F} \min\left(\frac{1}{\beta}, \frac{1}{t}\right)$$





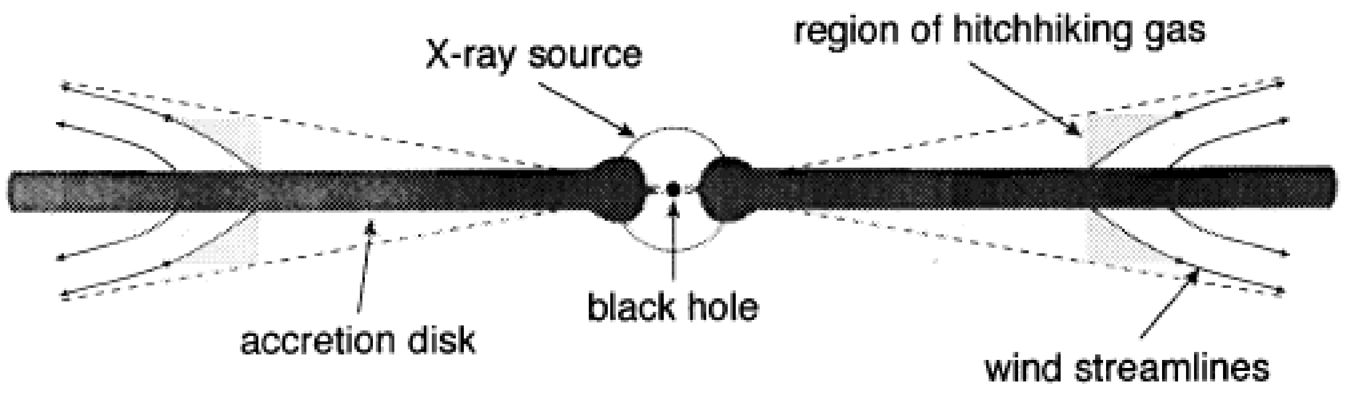
Proga et al. (2000)

THEORY: INFLOWS AND OUTFLOWS IN AGN

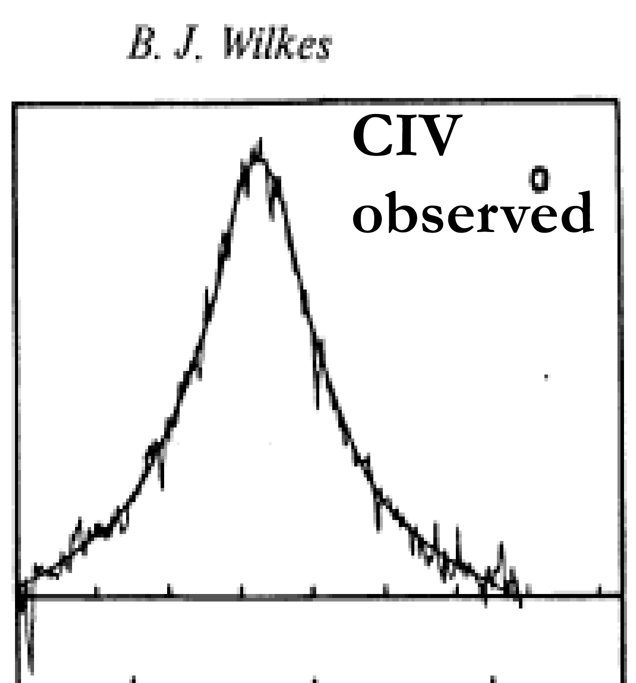
❖ Radiation-driven disk winds: driving by resonance lines (Murray et al. 1995)

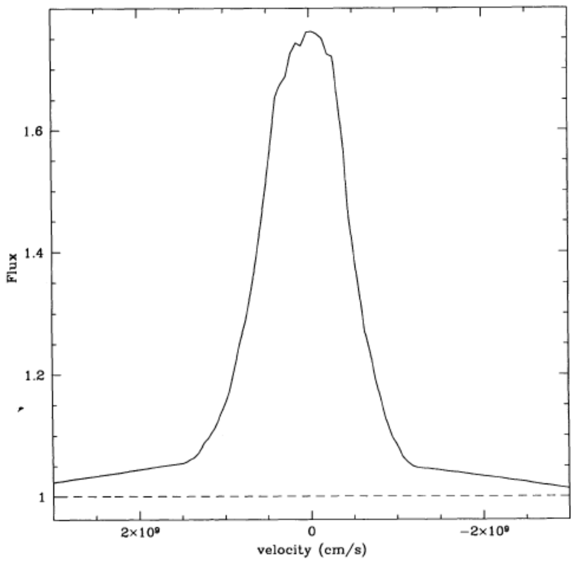
Continuous wind → no clumps

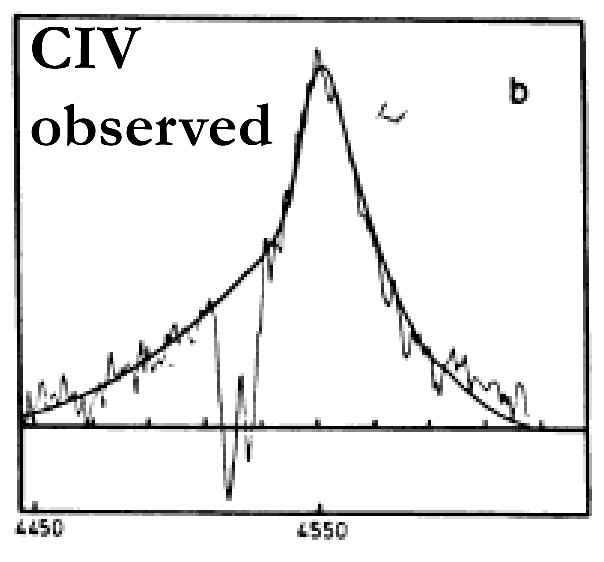
Radiation force (Sobolev)
per unit mass approximated
by force multiplier M(t)
as in Proga et al. (2000)



Wind streamlines make 5^{o} with the disk surface







CIV line shapes don’t fit…. geometry wrong?

THEORY: INFLOWS AND OUTFLOWS IN AGN

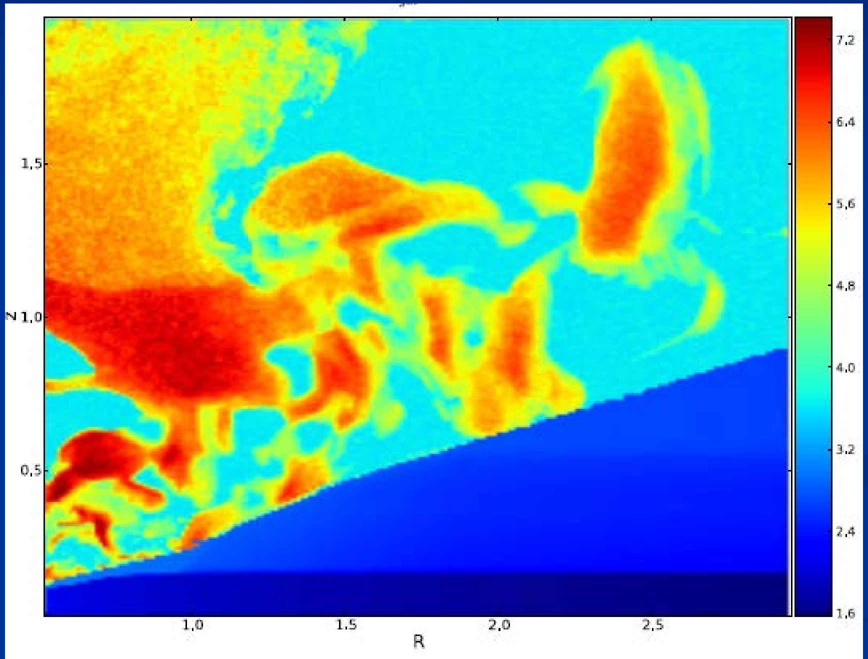
❖ Radiation-driven disk winds: driving by dust

Single fluid approximation → no dust evolution

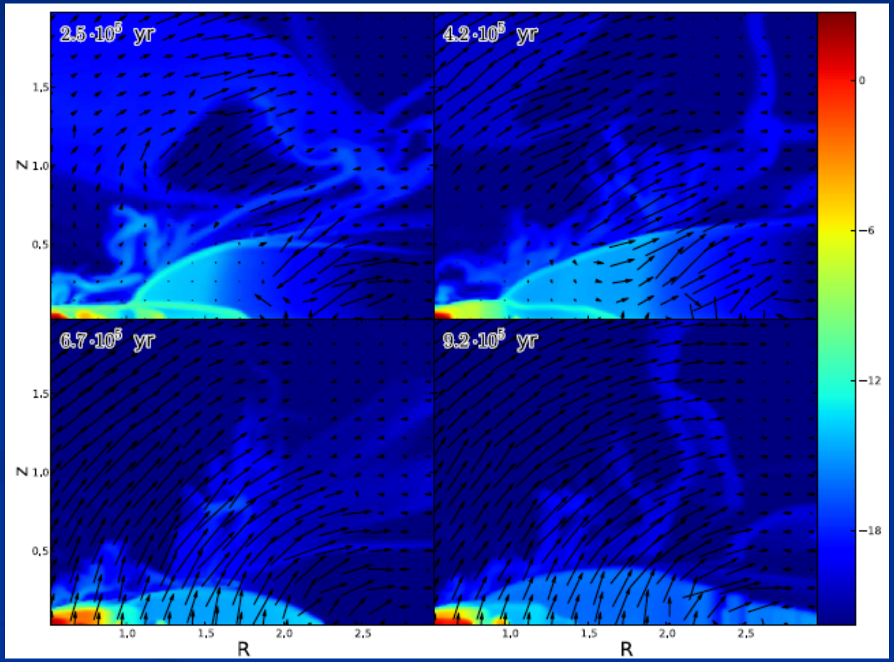
$$\mathbf{F} = -D\,\nabla E$$

Radiation flux calculated using flux-limited diffusion approximation

color → gas *T*



color → gas density



Dorodnitsyn & Kallman (2012)

But do dust grains survive both the acceleration and associated temperature? → need self-consistent treatment!

THEORY: INFLOWS AND OUTFLOWS IN AGN

- Theory: summary of MHD

Mass conservation

$$\nabla \cdot (\rho \mathbf{v}) = 0$$

z- component of momentum conservation (Euler eq.)

$$\rho (\mathbf{v} \cdot \nabla)\, v_z = -\frac{\partial p}{\partial z} - \frac{\rho \partial \Phi}{\partial z} - \frac{1}{8\pi}\frac{\partial B^2}{\partial z} + \frac{1}{4\pi}(\mathbf{B} \cdot \nabla) B_z$$

Energy

$$\rho T \left(\frac{dS}{dt}\right) = \rho T v_p \bullet \nabla S = Q$$

Perfect gas

$$P = \rho \frac{k_B}{\mu m_p} T$$

Ohm's law

$$\eta_m J_\varphi e_\varphi = \mathbf{v}_p \times \mathbf{B}_p$$

Induction

$$\nabla \cdot \left(\frac{\nu'_m}{r^2} \nabla r B_\phi\right) = \nabla \cdot \frac{1}{r}(B_\phi \boldsymbol{u_p} - \boldsymbol{B_p} \Omega r)$$

THEORY: INFLOWS AND OUTFLOWS IN AGN

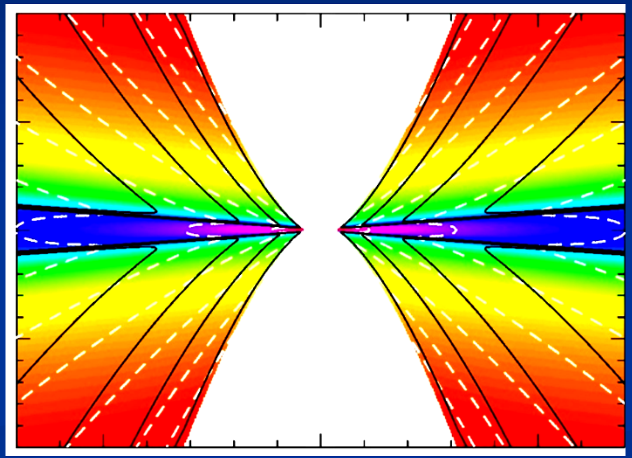
- Outflows: magneto-centrifugal winds → Blandford & Payne (1982) solution ($\rho_{disk} \sim r^{-3/2}$)

Include inertia and assume MHD conditions $\mathbf{E} + (1/c)\mathbf{v} \times \mathbf{B} = 0$

Stationary axisymmetric MHD flow

Euler equation

$$\rho(\mathbf{v}\cdot\nabla)v_z = -\frac{\partial P}{\partial z} - \rho\frac{\partial \Phi}{\partial z} - \frac{1}{8\pi}\frac{\partial B^2}{\partial z} + \frac{1}{4\pi}(\mathbf{B}\cdot\nabla)B_z$$



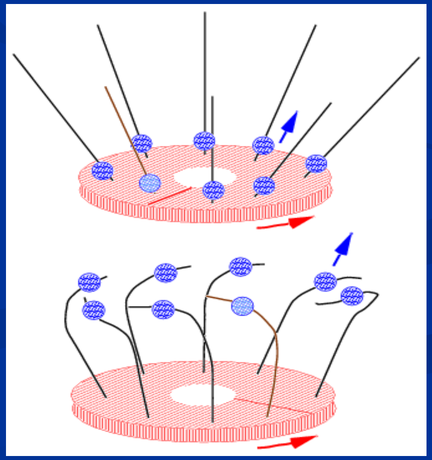
Self-similar solution $\mathbf{r} = [r_0\xi(\chi), \phi, r_0\chi]$ $\mathbf{v} = [\xi'(\chi)f(\chi), g(\chi), f(\chi)](GM/r_0)^{1/2}$

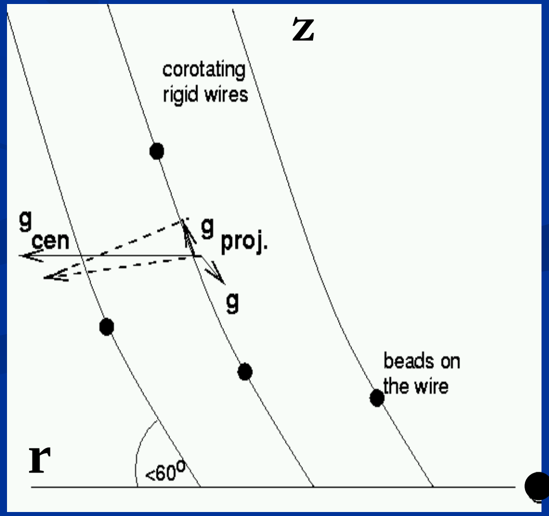
Solutions scale with spherical radius along a given direction

Centrifugal acceleration (gas clouds on B-lines act as "beads on a wire"): a wind is launched when the inclination angle of magnetic lines to the disk is < 60°

After launch the flow is dominated by the toroidal magnetic field imposed by rotation

Collimation along the magnetic axis





THEORY: INFLOWS AND OUTFLOWS IN AGN

❖ Outflows: magneto-centrifugal winds → Blandford & Payne (1982) solution ($\rho_{disk} \sim r^{-3/2}$)

Disk winds: 2D → remove one degree of freedom → 1D ordinary differential equation

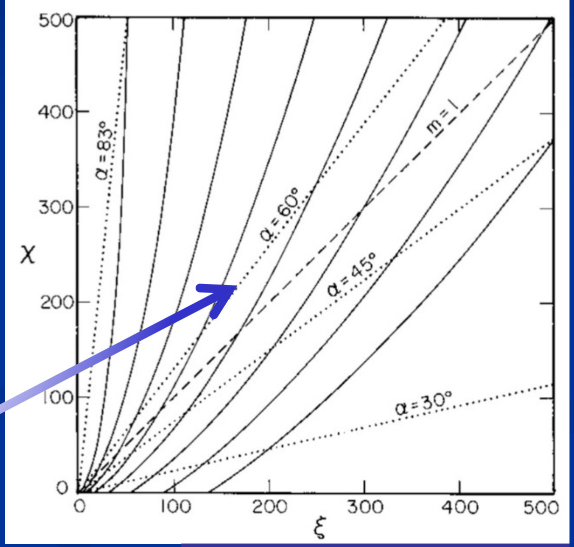
Self-similarity assumptions:

cylindrical *z*: pre-supposes a collimated vertical jet structure

cylindrical *r*: accretion disk structure, not jets

spherical θ: spherical wind (NO collimation)

spherical *r*: only choice with equations that allow collimation



$$\mathbf{r} = [r_0 \xi(\chi), \phi, r_0 \chi]$$

Blandford & Payne (1982): *r*-self-similarity; θ structure same for every field line

reduces MHD to only two ordinary differential equations

THEORY: INFLOWS AND OUTFLOWS IN AGN

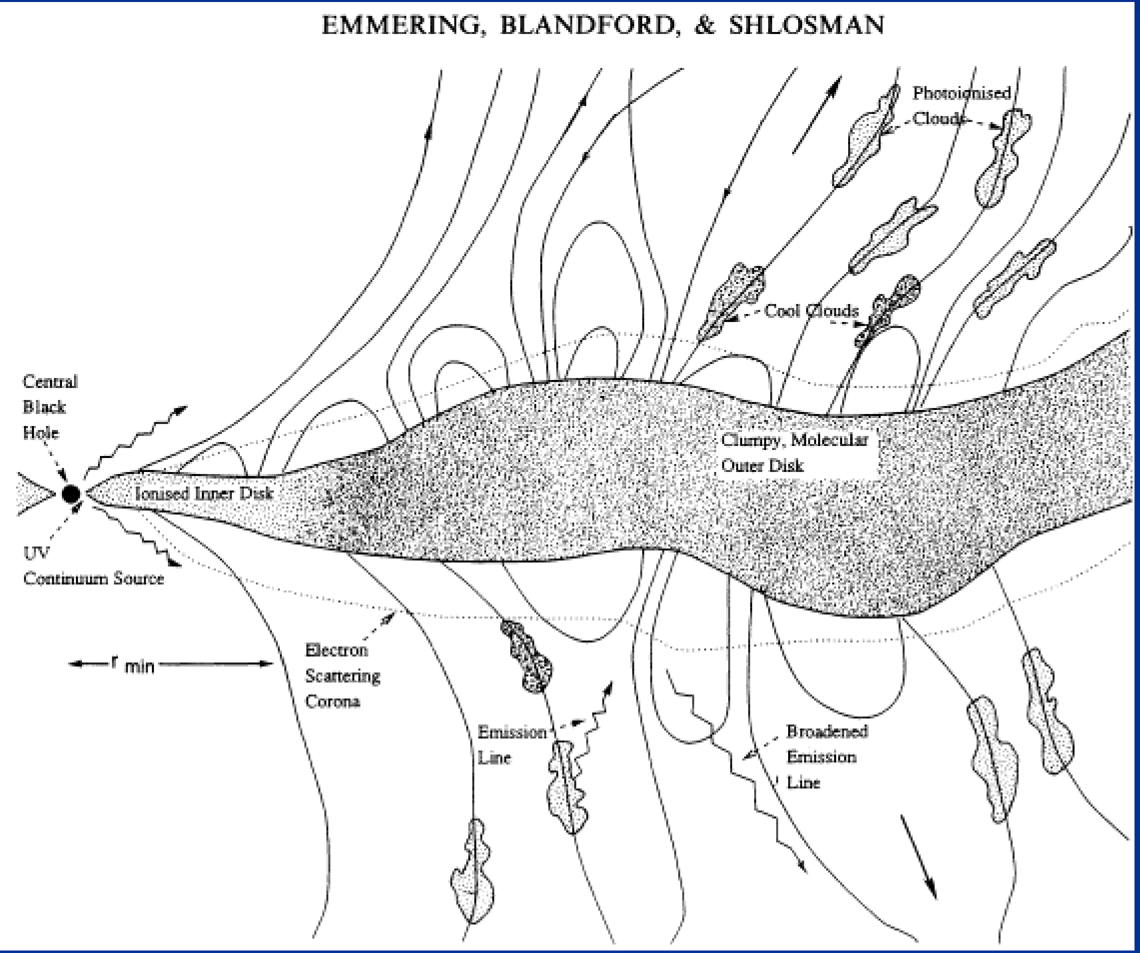
- Outflows: magneto-centrifugal winds → merging radiation & MHD winds
  generalized Blandford/Payne model (Emmering, Blandford & Shlosman 1992 solution)

$\rho_{disk} \sim r^{-\alpha}$

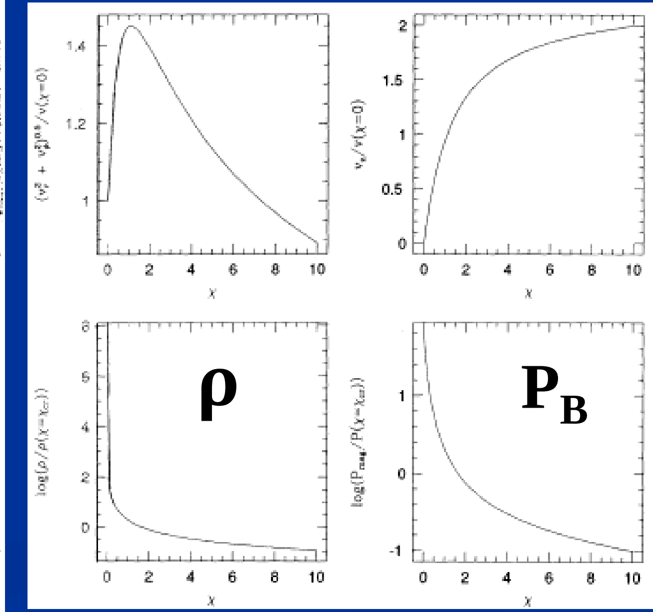
$\dot{M} r_0 v_0 \sim K B_A^2 r_A^3$

B-field extracts angular momentum→ low $\dot{M}$ wind !

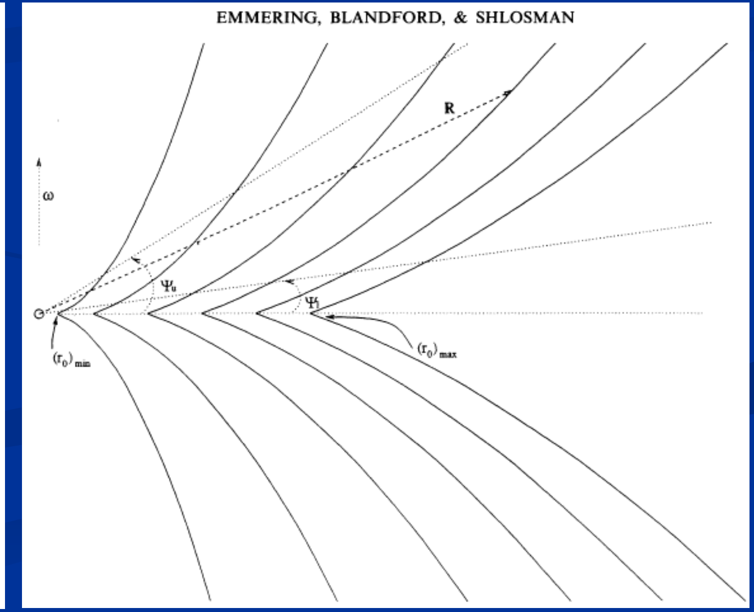
Electron-scattering corona widens the line wings



v ⊥ z axis v || z axis



self-similarity of *B*-lines and *r*



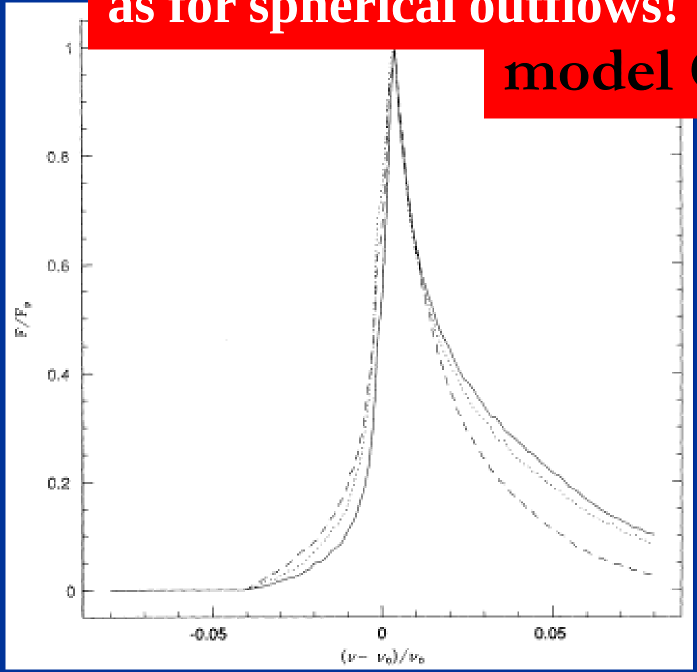
THEORY: INFLOWS AND OUTFLOWS IN AGN

- Outflows: magneto-centrifugal winds → merging radiation & MHD winds

Generalized Blandford/Payne model (Emmering, Blandford & Shlosman 1992 solution)

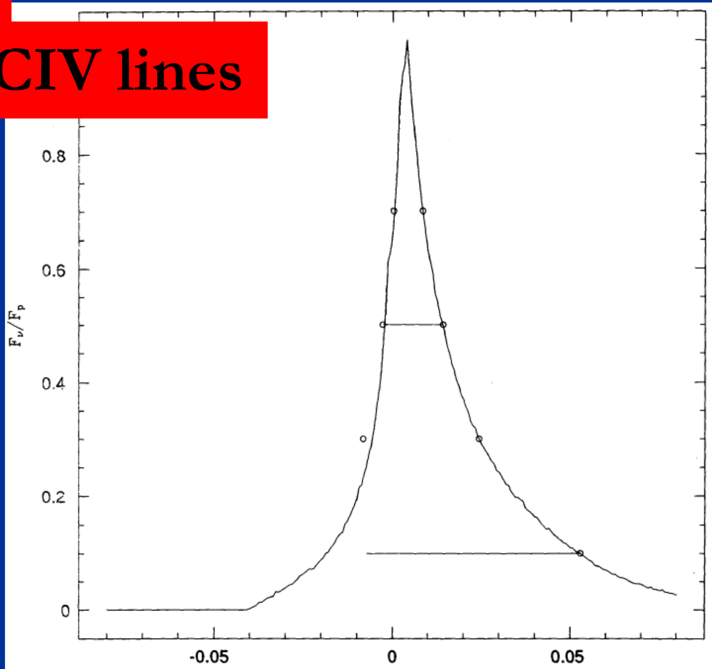
So, disk winds produce characteristic triangular shapes of emission lines in AGN → match as good as for spherical outflows!

CIV emission line profiles for various inclinations to z-axis

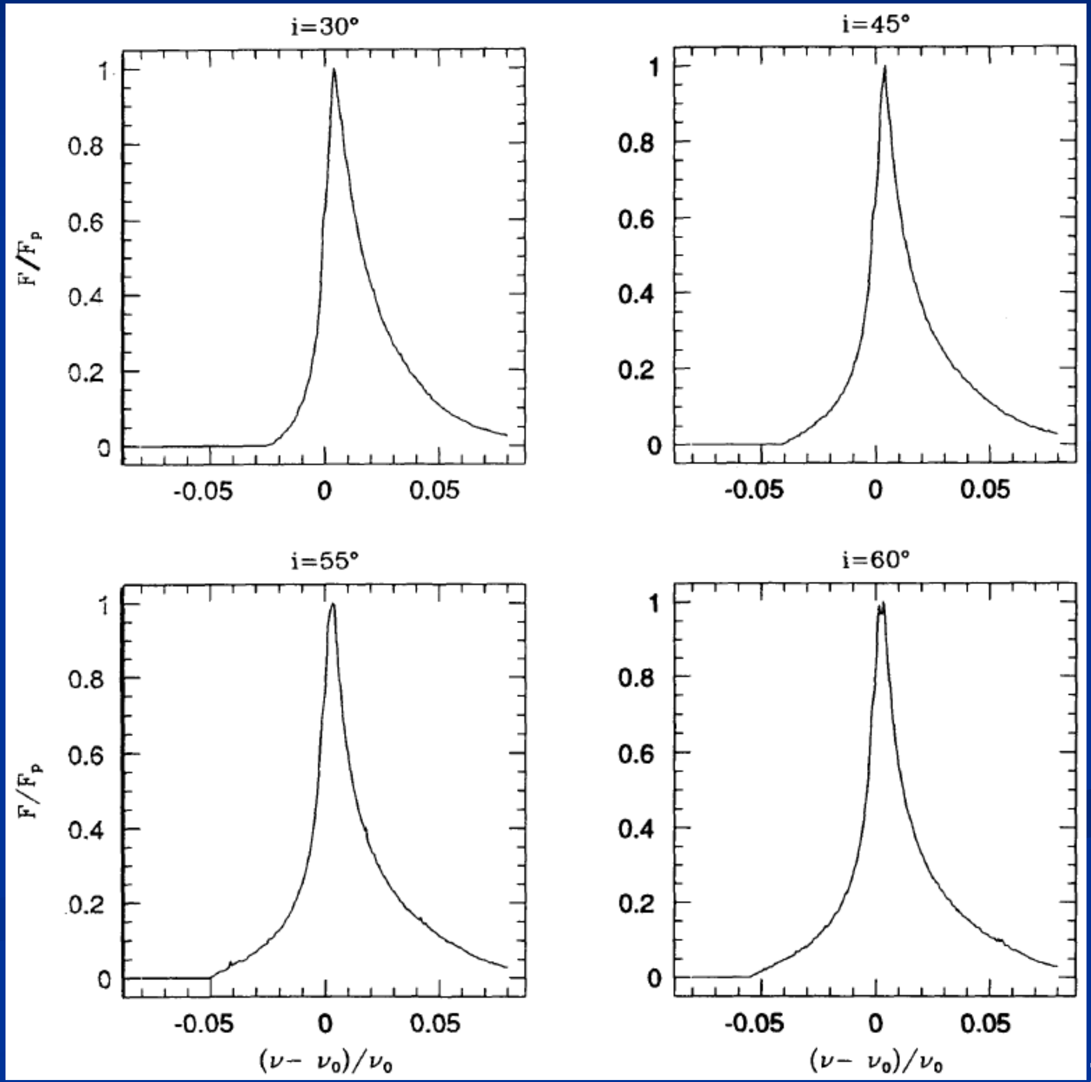


CIV emission line profiles for various gas emissivities

model CIV lines



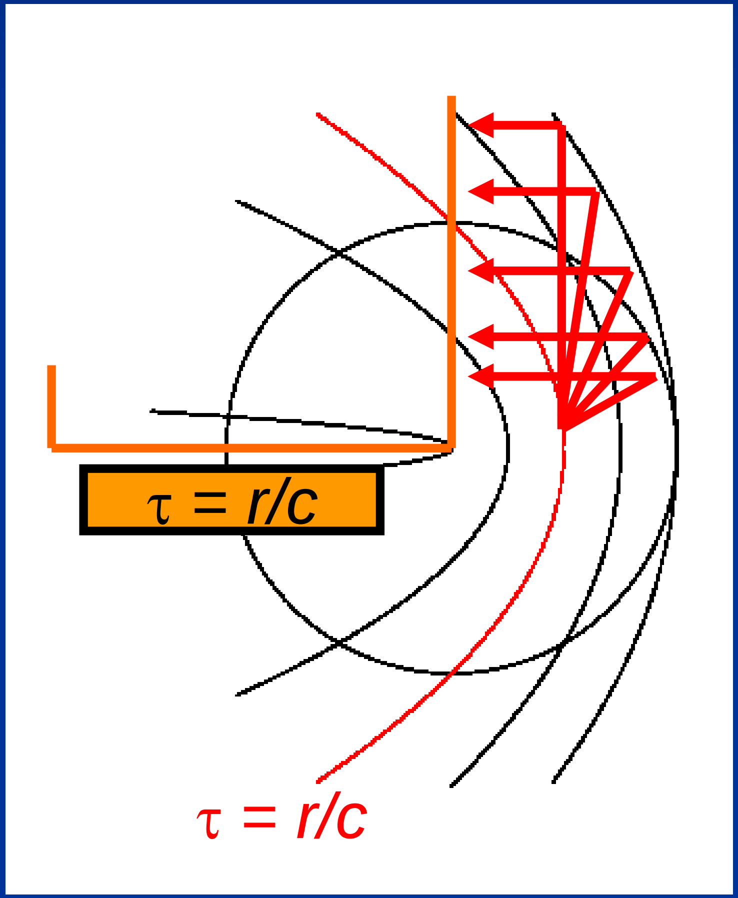
CIV emission line profiles with observed asymmetry



THEORY: INFLOWS AND OUTFLOWS IN AGN

❖ Outflows: magneto-centrifugal winds → reverberation mapping of BLR

Formation of the broad line region (BLR)



isodelay surfaces

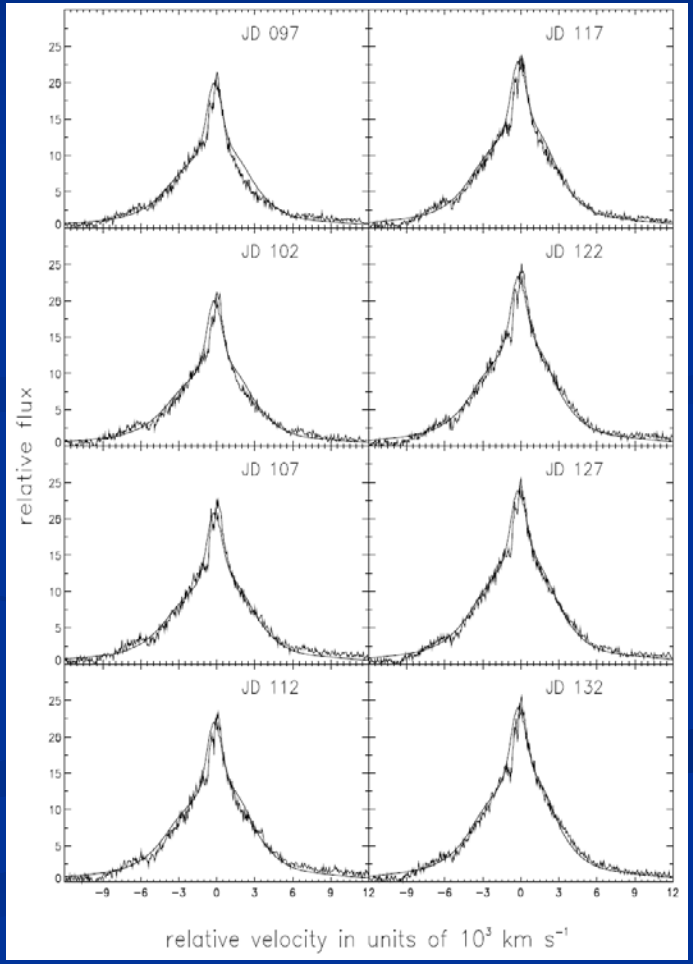
All points on an "isodelay surface" have the same extra light-travel time to the observer, relative to photons from the continuum source.

echo mapping

$M_{\bullet} \sim 3 \times 10^7\ M_{\odot}$

in Seyfert 1 galaxy NGC5548

C IV emission line profile evolution in Seyfert 1 galaxy NGC5548

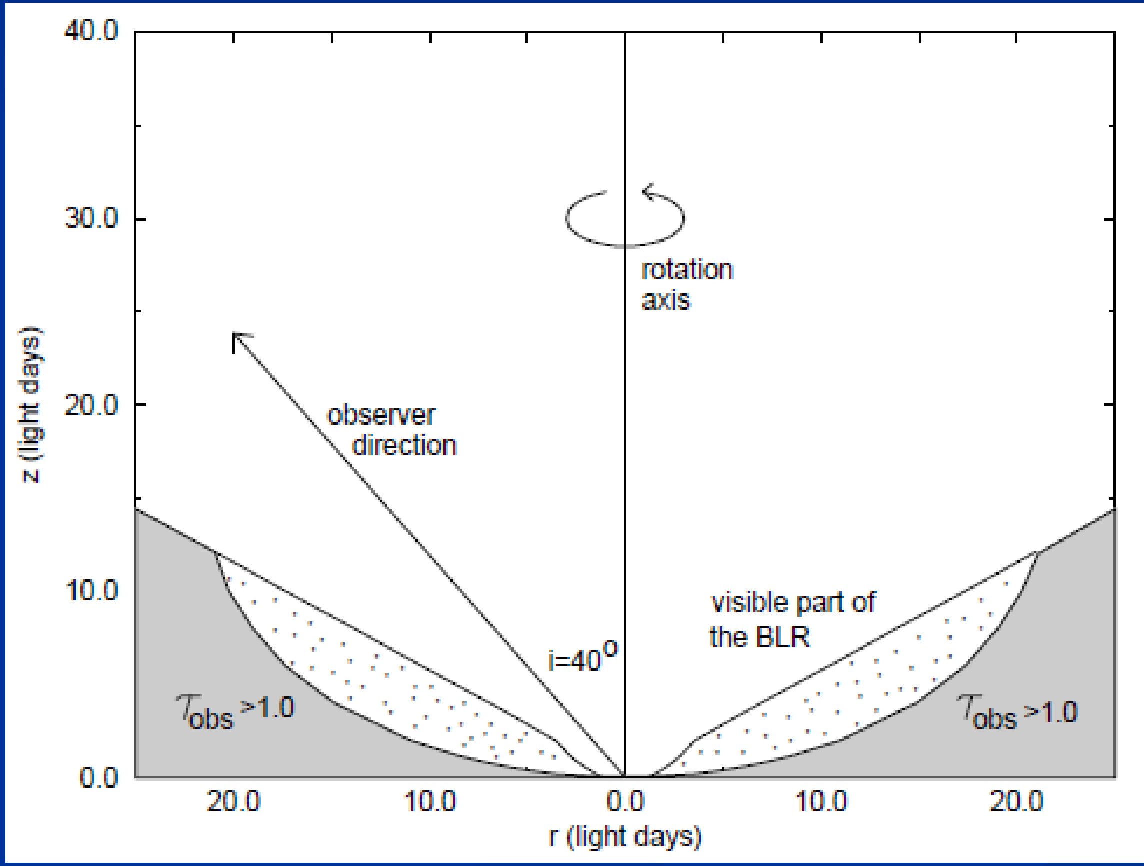


Bottorff, Korista, Shlosman & Blandford (1997)

THEORY: INFLOWS AND OUTFLOWS IN AGN

- Outflows: magneto-centrifugal winds

Formation of the broad line region (BLR)



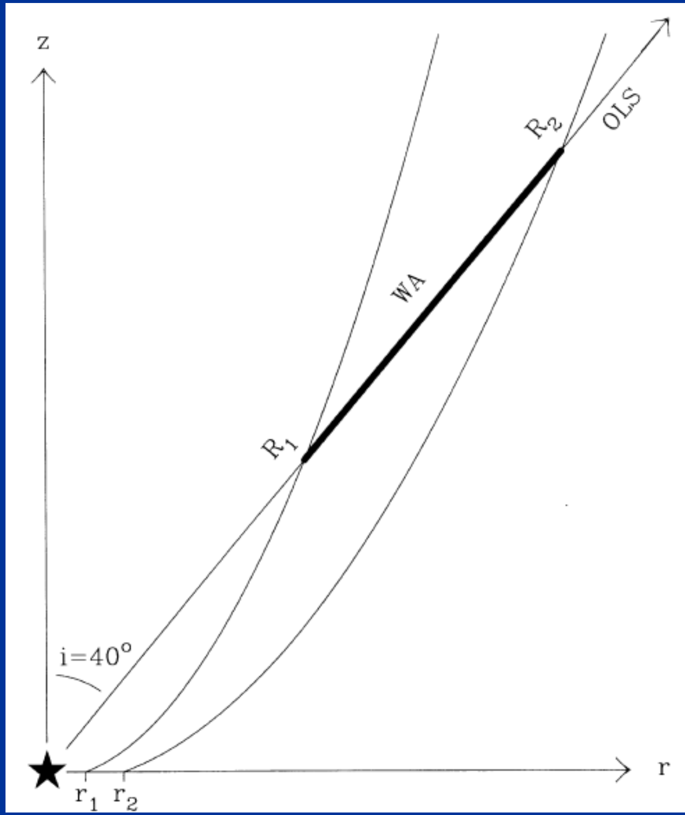
Bottorff, Korista, Shlosman & Blandford (1997)

THEORY: INFLOWS AND OUTFLOWS IN AGN

- Outflows: magneto-centrifugal winds

Multi-component warm absorbers in NGC 5548

observer's orientation in NGC 5548

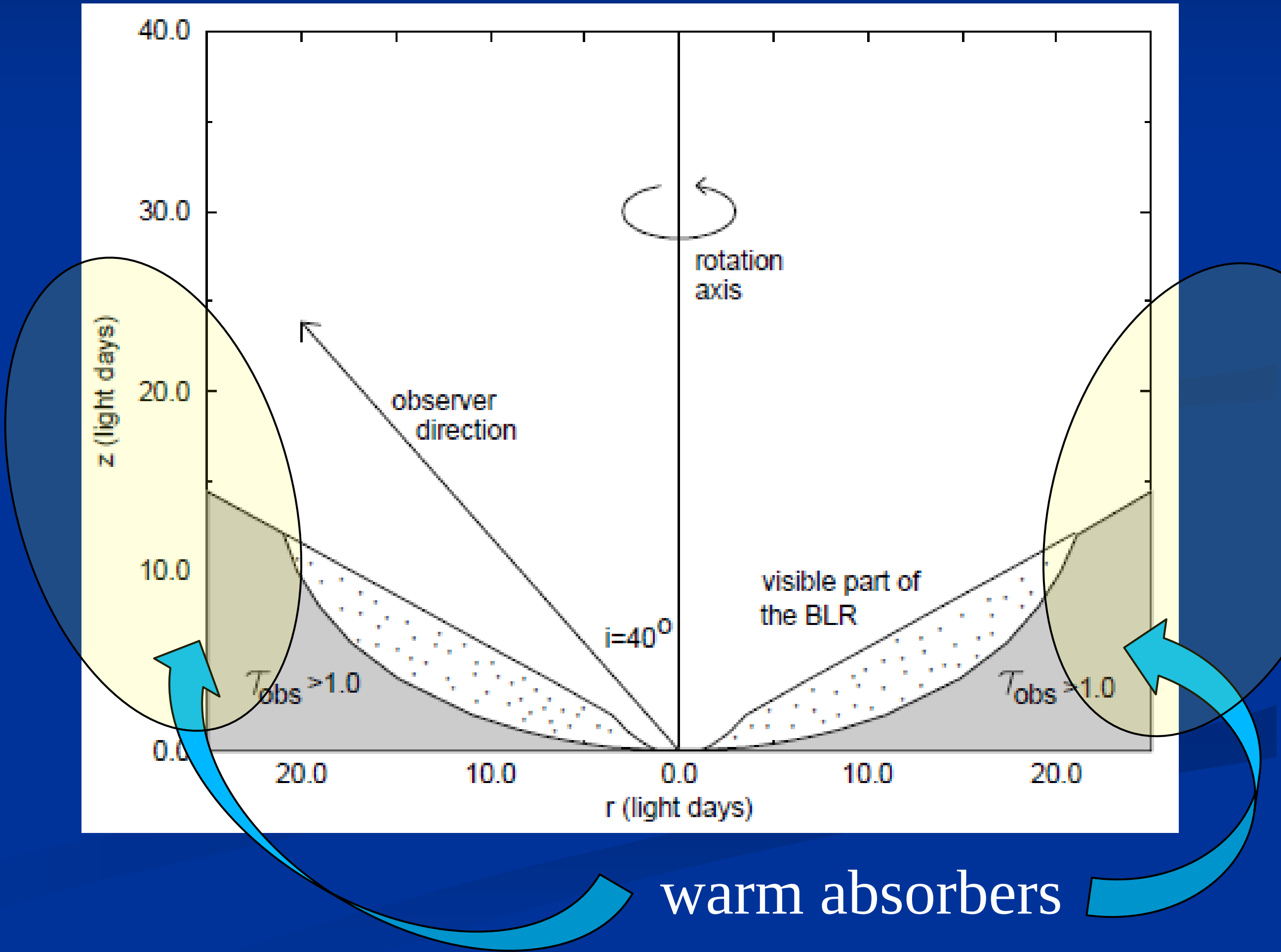


Parameter	log(value)[a]
R_{min}	17.75
R_{max}	20.59
n_{min}	6.455
n_{max}	2.253
N(H)	21.76
N(H I).........	15.94
N(C IV)	14.70
N(N V)........	15.13
N(O VII)	17.94
N(O VIII)......	18.22
ϵ	−2.716

Model Solution for the Continuously Distributed Warm Absorber in NGC 5548

[a] Values in cgs units.

Bottorff, Korista & Shlosman (2000)

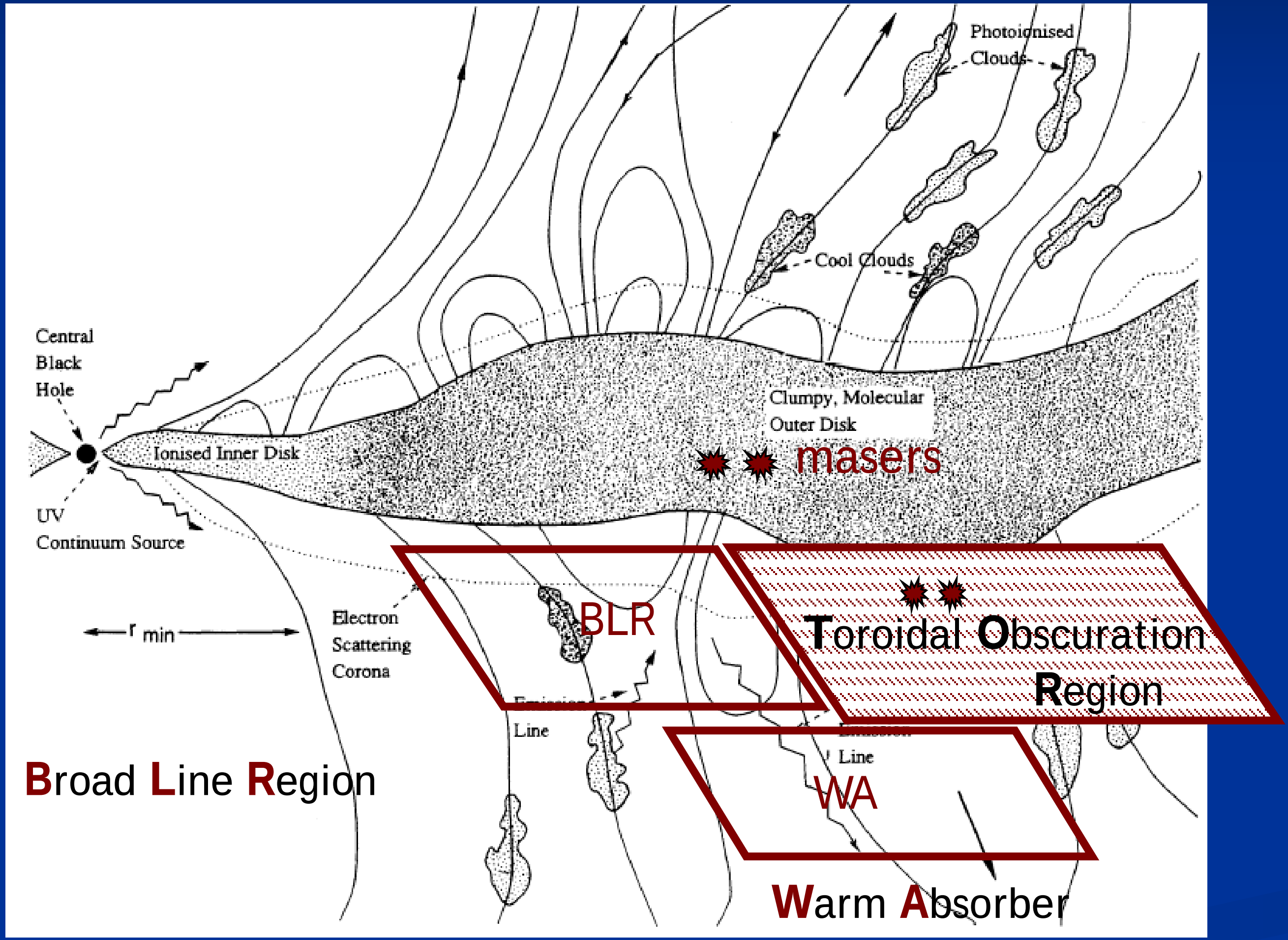


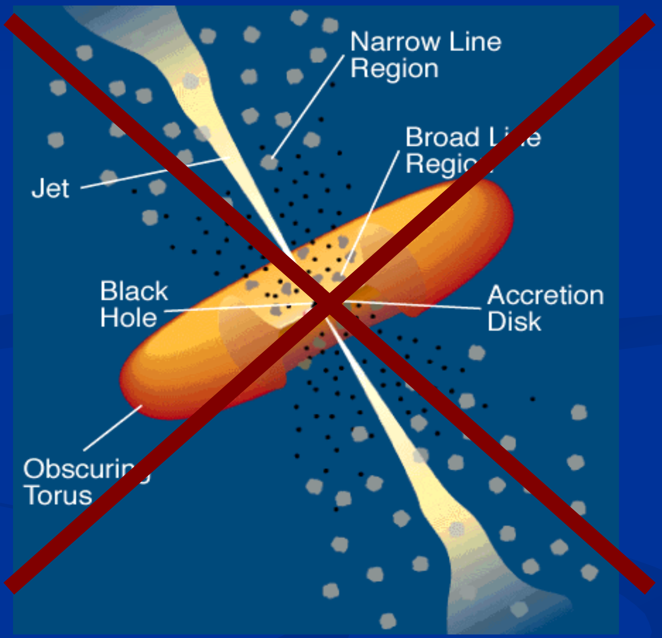
warm absorbers

THEORY: INFLOWS AND OUTFLOWS IN AGN

❖ Outflows: The end of the torus paradigm (Elitzur & Shlosman 2006; Nenkova, Elitzur & Ivezic 2008)

IR radiation transfer in clumpy wind



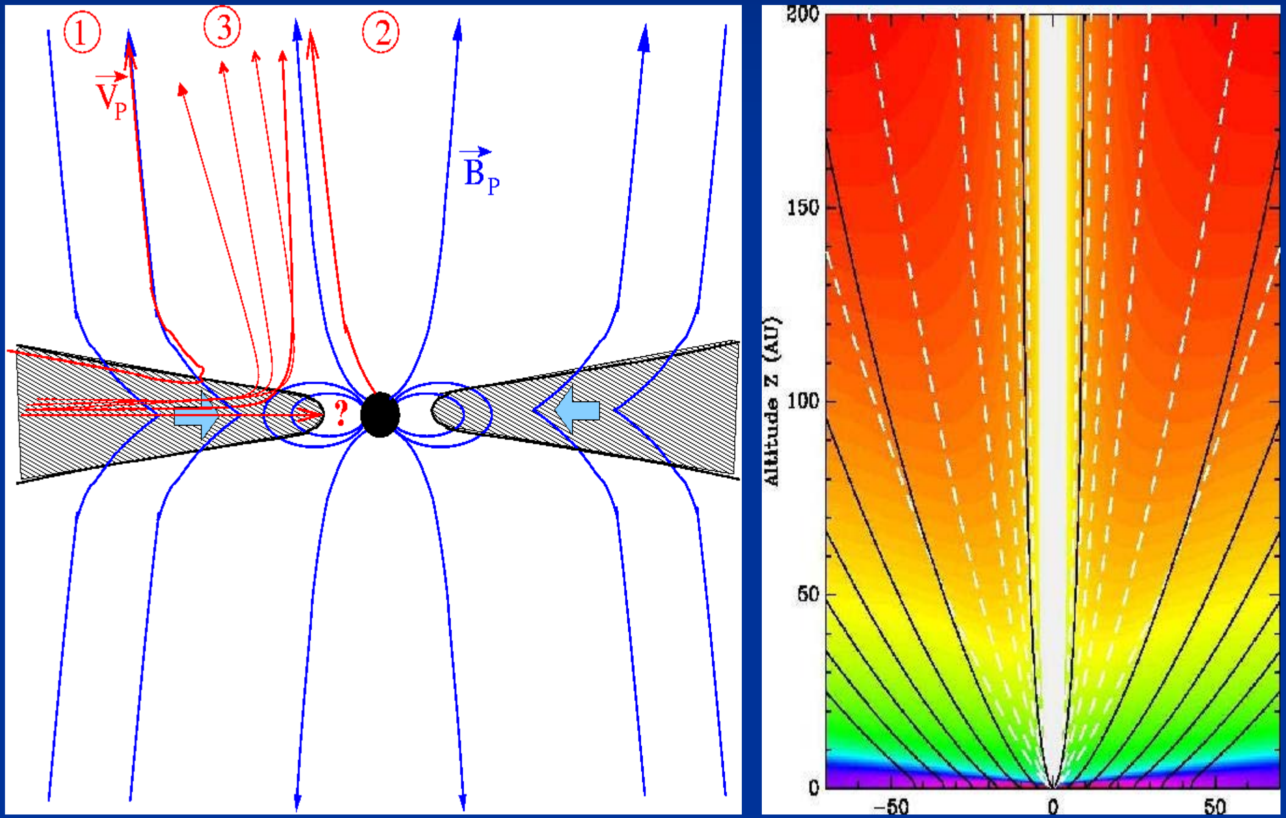


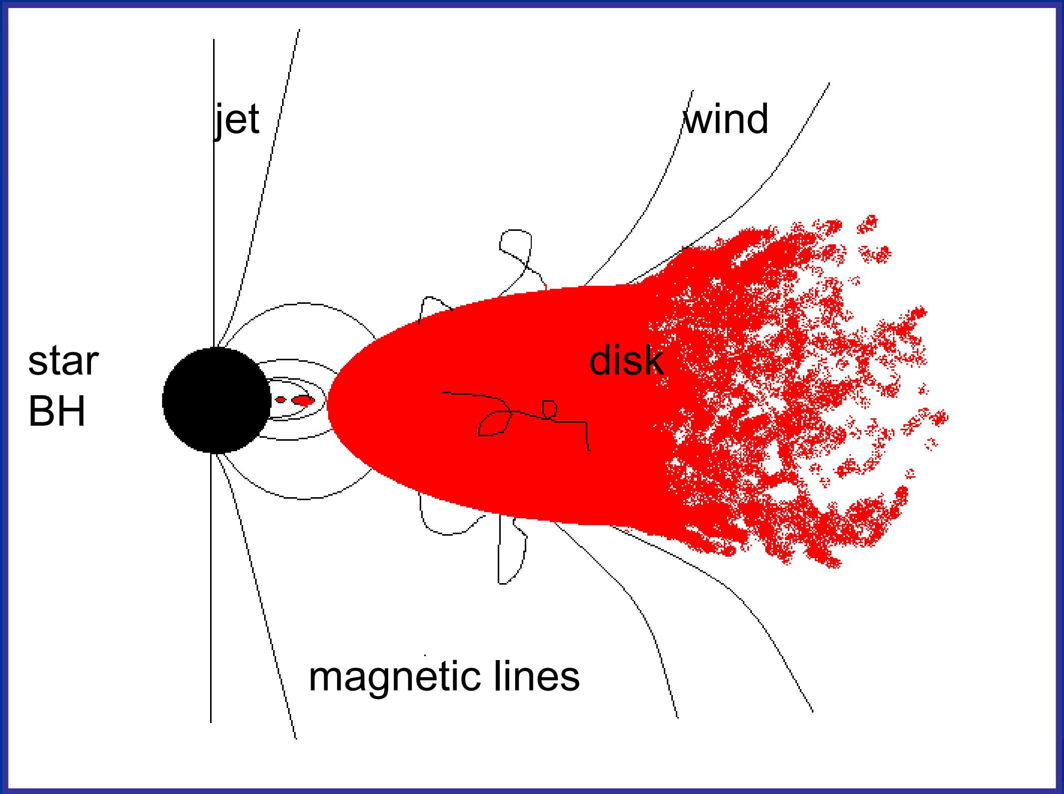
Toroidal Obscuration region is an outflow and it disappears at $L \leq 10^{42}$ erg/s !

THEORY: INFLOWS AND OUTFLOWS IN AGN

- Outflows: collimated MHD winds → jets

Accretion disk-driven jets





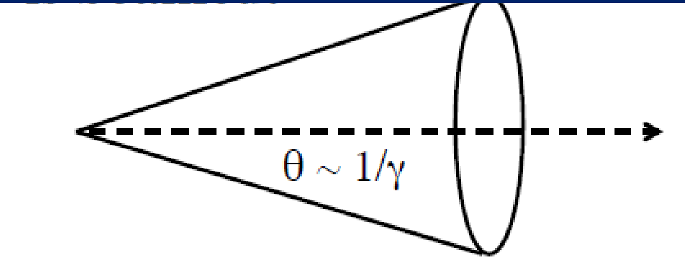
Accretion disk driven jets → velocity distribution at the wind base is that of a Keplerian disk

Blandford & Payne model: inertia→ poloidal B→ toroidal B

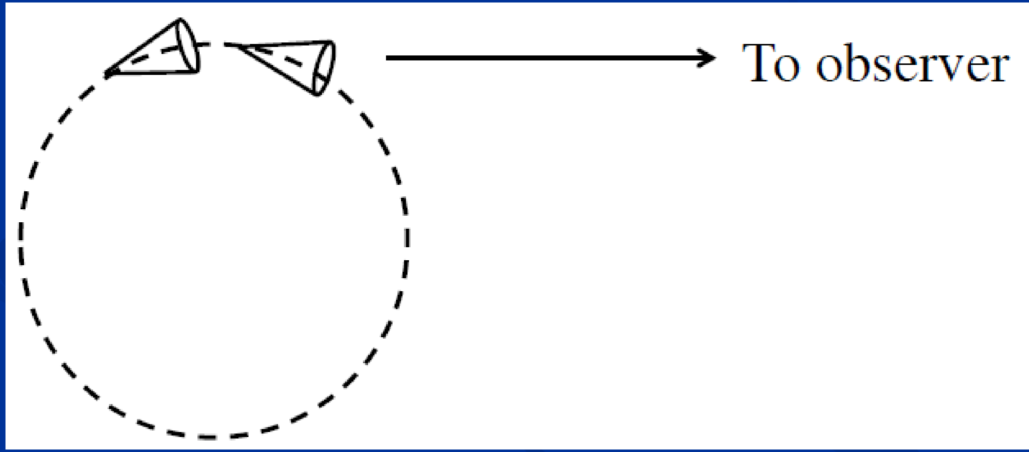
THEORY: INFLOWS AND OUTFLOWS IN AGN

- Outflows: emission mechanism in jets → synchrotron radiation

If electrons are moving at v~c → radiation is beamed



Particle moving with Lorentz factor γ toward observer emits Into cone of opening angle $\boldsymbol{\theta \sim \gamma^{-1}}$



We only see radiation from a small portion of the orbit, when the cone points toward us
→ but many electrons!

THEORY: INFLOWS AND OUTFLOWS IN AGN

- Outflows: collimated MHD winds → jets

Alternative acceleration mechanisms:

Twin-exhaust scheme
(Blandford & Rees 1972)

Radiation pressure in accretion funnels
(FRT 1985)

Electrodynamic effects in accretion funnels and Poynting flux jets
(Lovelace 1976, Blandford 1976)

Magneto-centrifugal acceleration
(Blandford & Payne 1982)

THEORY: INFLOWS AND OUTFLOWS IN AGN

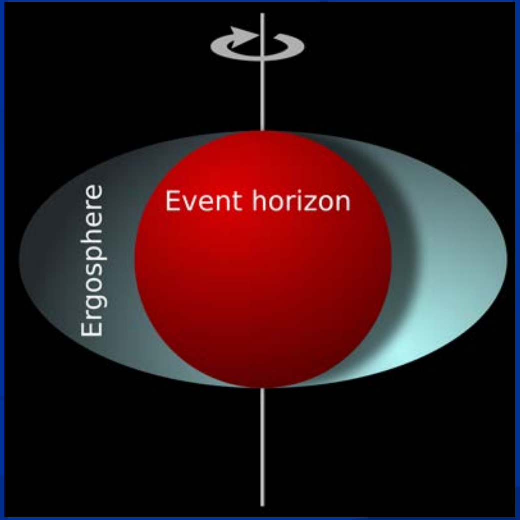
- Outflows: collimated MHD winds → jets

Alternative acceleration mechanisms: tapping the rotational energy of black hole

Blandford & Znajek (1977)

> Blandford and Znajek(1977) found a *stationary solution* for monopole magnetospheres of slowly rotating black holes. It exhibited outflows of energy and angular momentum

Black hole rotational energy (*a* =1): $E_b = 0.29 M_b c^2 \simeq 10^{54} \left(\frac{M_b}{2M_\odot}\right) \text{erg}$



Kerr black hole

Power of the Blandford-Znajek mechanism: $L_{BZ} \simeq 3.6\times 10^{50} a^2 \left(\frac{M}{2M_\odot}\right)^2 \left(\frac{\Psi}{10^{27}}\right)^2 \text{erg/s}$

a - spin parameter of the black hole ($0 < a < 1$),

Ψ - the magnetic flux of black hole.

$\Psi = 10^{27}$ G cm^2 is the highest value observed in magnetic stars:

Ap, white dwarfs, neutron stars (magnetars).

Efficiency of Blandford-Znajek mechanism ?

THEORY: INFLOWS AND OUTFLOWS IN AGN

- Outflows: collimated MHD winds → jets

Tapping the rotational energy of black hole: Blandford & Znajek (1977)

What is the condition for activation of the BZ-mechanism with finite inertia of plasma?

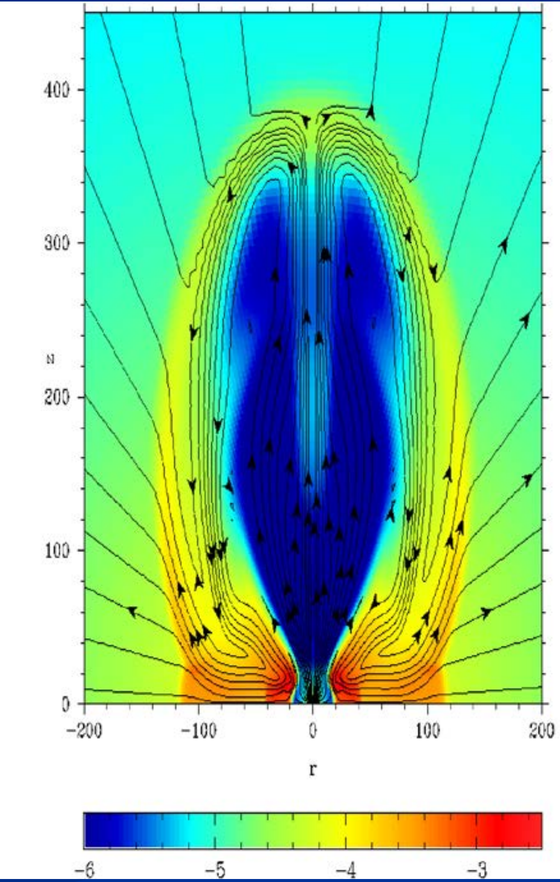
MHD waves must be able to escape from the black hole ergosphere !?

Alfven speed $v_a > v_{ff}$ free fall

$$c_a^2 = B^2/4\pi\rho,$$

$$v_{ff}^2 = 2GM/r$$

Apply at the ergosphere, **$r = 2r_s = 2GM/c^2$** → $B^2 > 4\pi\rho c$



The energy density of magnetic field must exceed that of matter for the BZ-mechanism to be activated!

OBSERVATIONAL EVIDENCE FOR INFLOWS AND OUTFLOWS IN AGN

Evidense for inflows:

To be discussed on Thursday as a FUELING issue

CONCLUSIONS FOR LECTURE 3

- Active Galactic Nuclei (AGN) are powered by accretion processes, but there are clear and objective difficulties to detect this accretion flow

- On the other hand, UV and some X-ray emission and absorption lines point to powerful and diverse outflows from the accretion disks in AGN

- There is a clear preference, both observationally and theoretically to the presence of accretion disks in AGN, as opposite to spherical outflows

- MHD winds have preference over radiation-driven winds in AGN, because they are capable of extracting angular momentum, which radiation is inefficient in this process

- MHD is probably collimates some of the wind into powerful jets, sometimes relativistic