Relativistic Emission Lines of Accreting Black Holes

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21. Mai 2003

Quasare und früher Kosmos

Forschungsseminar LSW

Overview

- Motivation
- AGN paradigm
- AGN X-ray spectra
- X-ray fluorescence
- Coronal irradiation
- Rotating black holes and Kerr ray tracing
- Plasma kinematics
- Accretion theory and radiation
- Radial drift model: disk truncation
- Simulated disk images: g-factor, emission
- Emission line calculation
- Emissivity models
- Emission lines: calculation, studies, criteria, classification, observation

Note:

All radius declaration were in units of the gravitational radius

$$1\ r_g = GM/c^2$$

In general, relativistic units were used G=M=c=1

$$1\ r_g := 1.0$$

Motivation

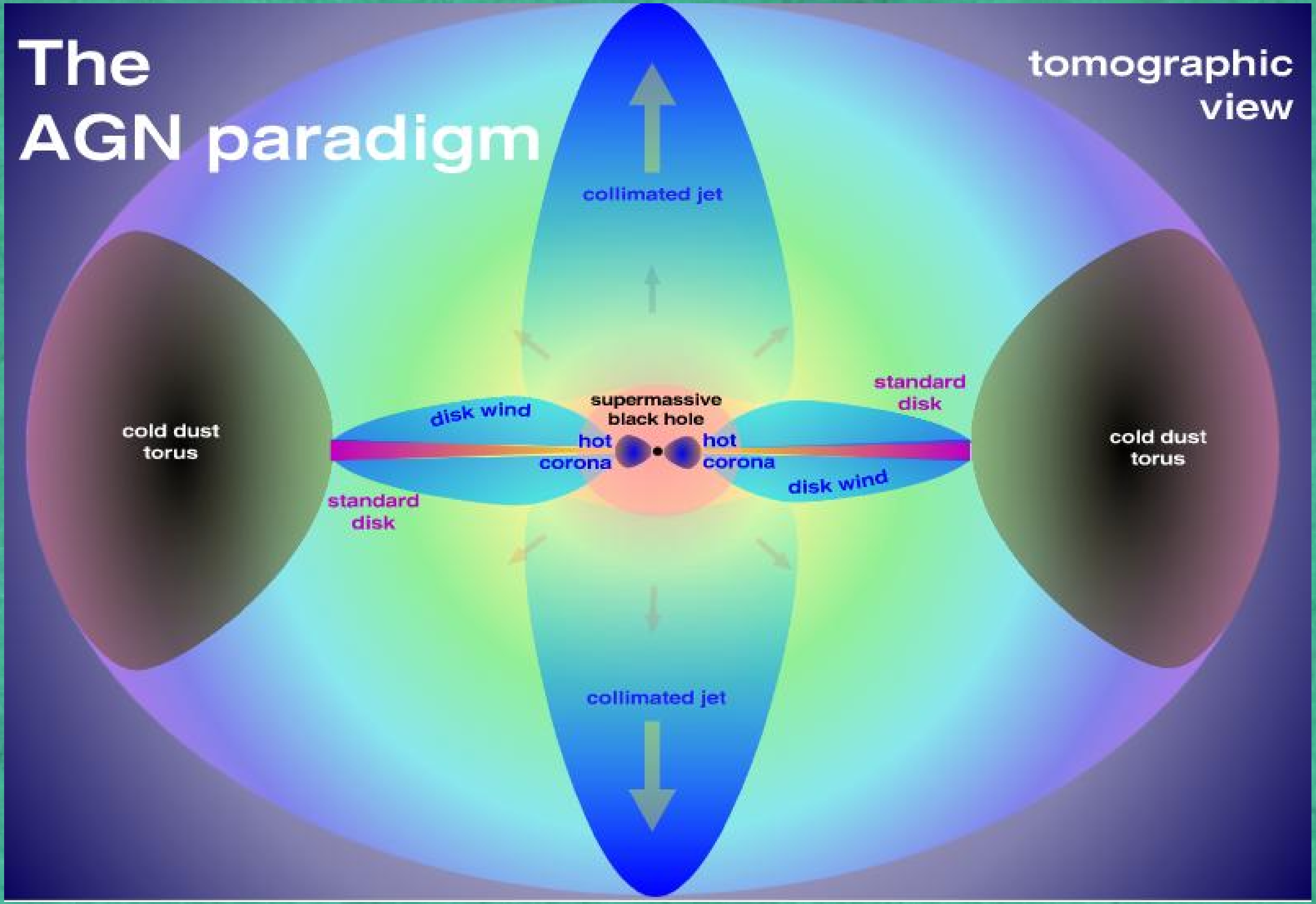
In general

- probing strong gravity
- verify or falsify event horizon?
  Black Holes vs. ***Gravastars***
  (few hope because strong redshift suppresses *any* information)
- measure parameters in accreting black hole systems
  (AGN, microquasars, globular clusters)

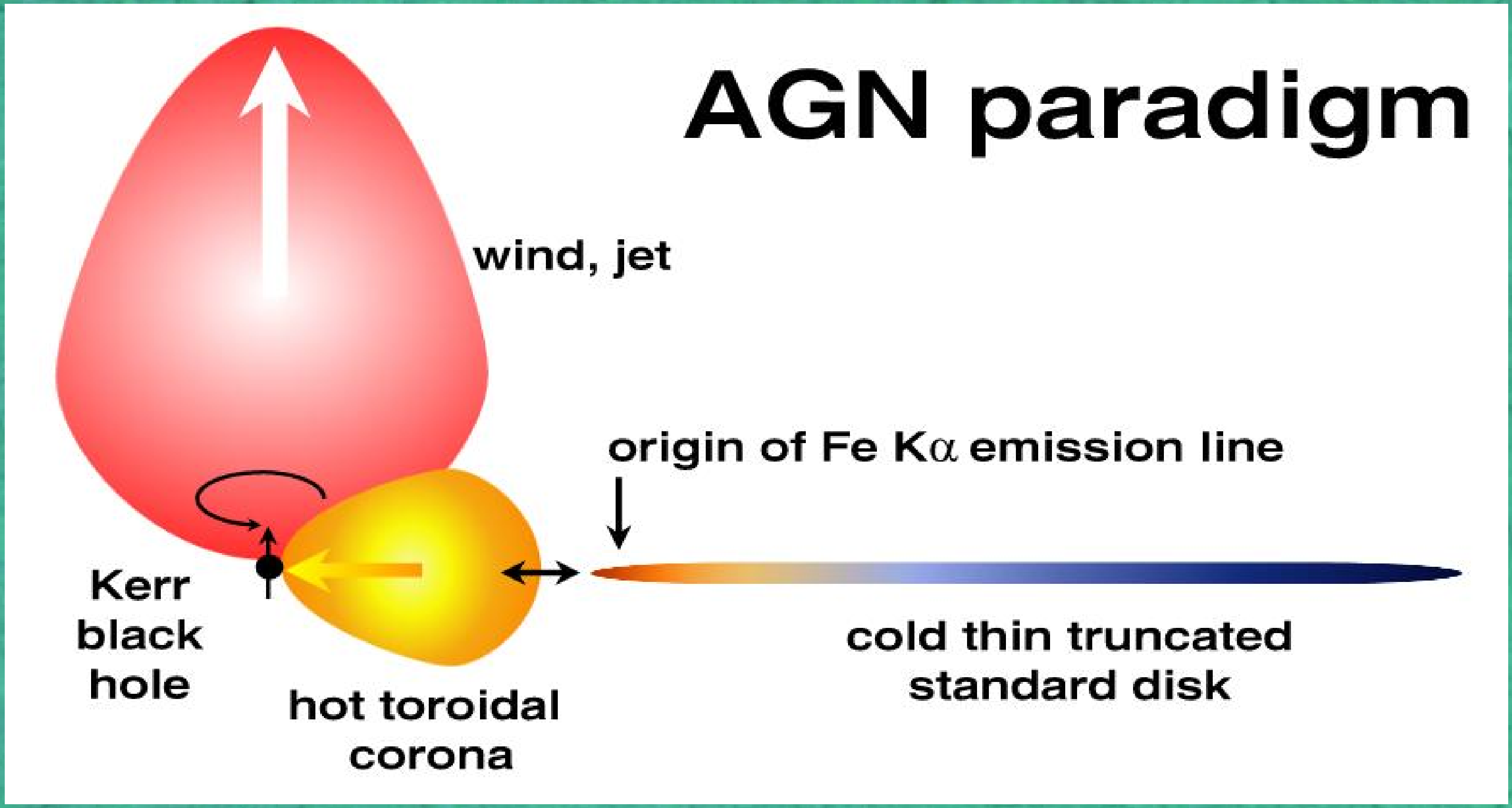
Cosmological

- emission line diagnostics for **Quasars** feasible
- highest redshift today: z ~ 0.16 (3C 273)
- extension to **Early Universe** expected

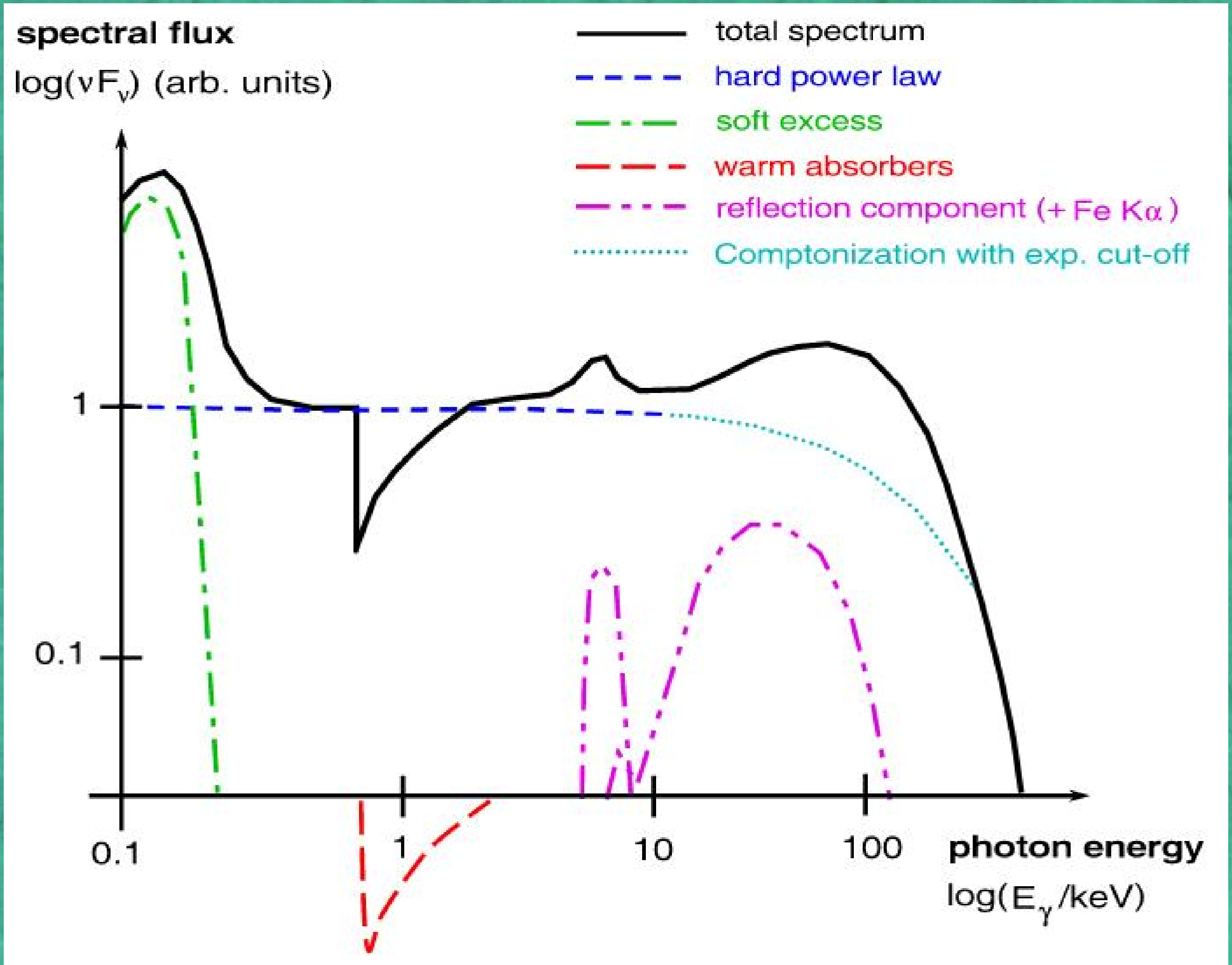
The AGN paradigm
Global topology: kpc-scale



X-ray emitter
Accreting black holes: pc-scale

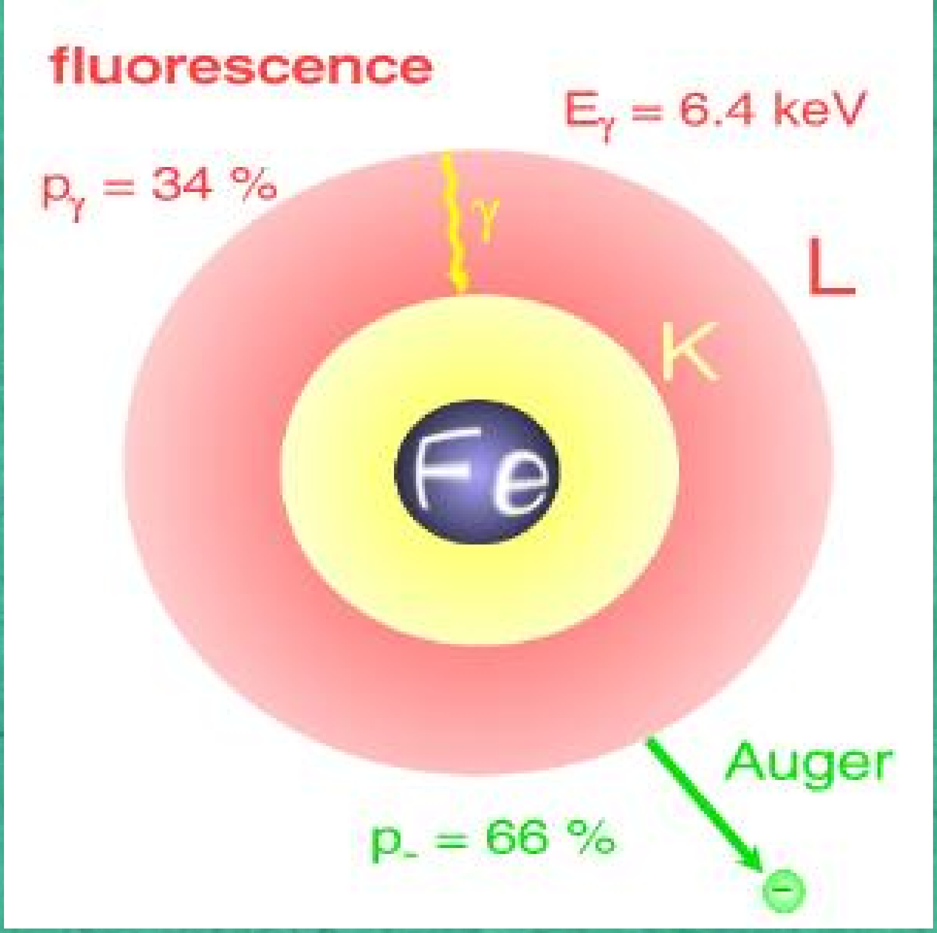


X-ray AGN spectra
Spectral components



(**plot idea** by
A. Fabian 1998)

X-ray fluorescence
Fe Kα



X-ray fluorescence
Prominent species

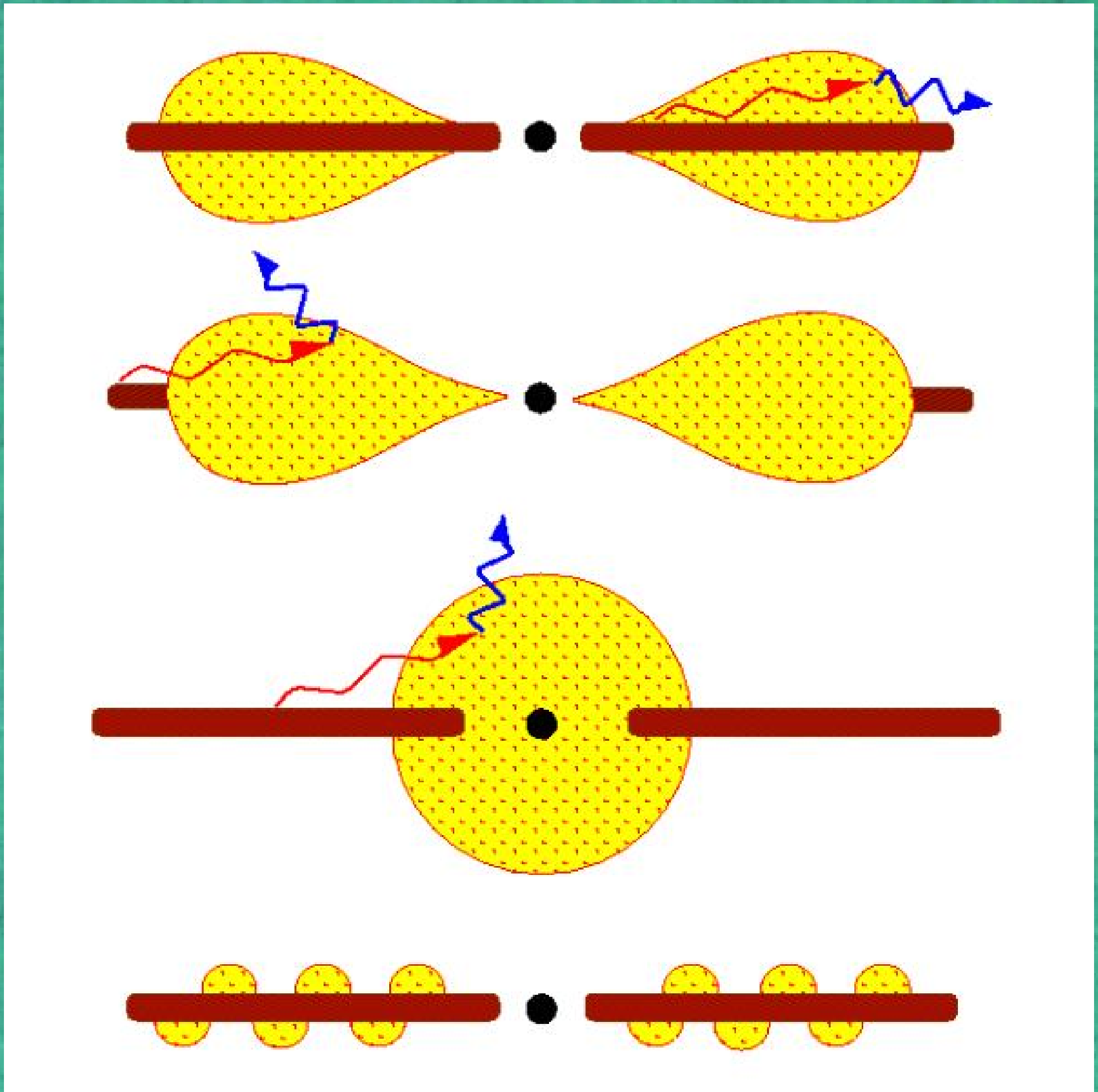
Fe Kα	6.40	keV
Fe Kβ	7.06	keV
Ni Kα	7.48	keV
Cr Kα	5.41	keV

↓ decreasing relative line strength

Dependency of these rest frame energies on ionization state!

(Reynolds 1996)

X-ray illumination
Corona geometries



slab, sandwich

sphere+disk geometry

patchy, pill box

(Reynolds & Nowak 2003)

X-ray illumination
The corona problem

- corona geometry and location still **open question**!
- models:
  - slab corona (SSD, slim disk)
  - patchy corona
  - sphere+disk geometry (ADAF)
  - on-axis point-source (jet)
- observational technique: ***reverberation mapping***
- theory: ***radiative GRMHD in 3D***

Rotating Black Holes
Kerr geometry

$$ds^2 = -\alpha^2 dt^2 + \tilde{\omega}^2 (d\Phi - \omega dt)^2 + \rho^2/\Delta dr^2 + \rho^2 d\Theta^2$$

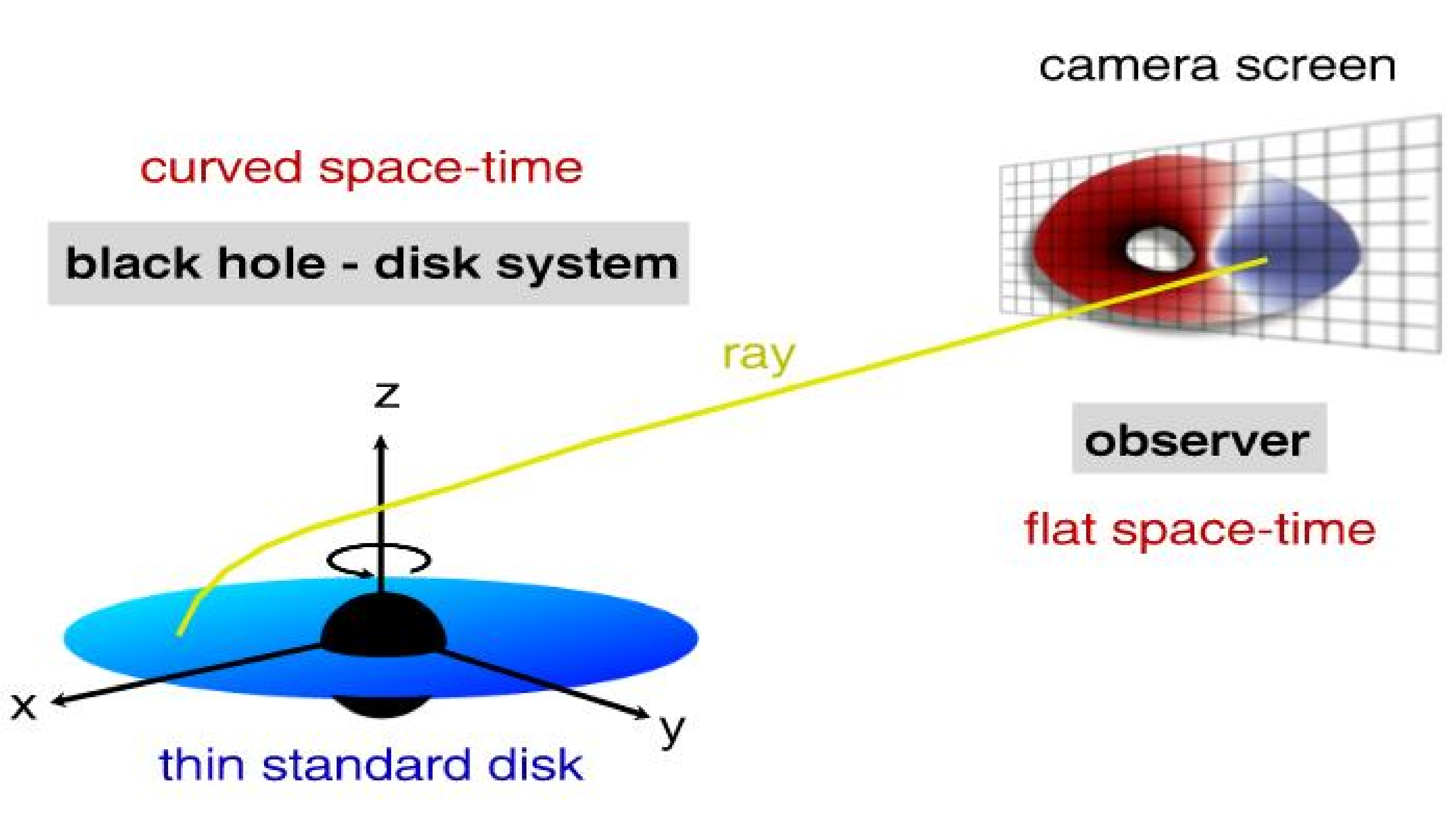
Kerr metric in Boyer-Lindquist co-ordinates $\{t, r, \Theta, \Phi\}$

$$\mathbf{g}_{\mu\nu} = \begin{pmatrix} g_{tt} & 0 & 0 & g_{t\Phi} \\ 0 & g_{rr} & 0 & 0 \\ 0 & 0 & g_{\Theta\Theta} & 0 \\ g_{\Phi t} & 0 & 0 & g_{\Phi\Phi} \end{pmatrix} = \begin{pmatrix} -\alpha^2 + \omega^2\tilde{\omega}^2 & 0 & 0 & -\omega\tilde{\omega}^2 \\ 0 & \rho^2/\Delta & 0 & 0 \\ 0 & 0 & \rho^2 & 0 \\ -\omega\tilde{\omega}^2 & 0 & 0 & \tilde{\omega}^2 \end{pmatrix}$$

$$\mathbf{g}^{\mu\nu} = \begin{pmatrix} g^{tt} & 0 & 0 & g^{t\Phi} \\ 0 & g^{rr} & 0 & 0 \\ 0 & 0 & g^{\Theta\Theta} & 0 \\ g^{\Phi t} & 0 & 0 & g^{\Phi\Phi} \end{pmatrix} = \begin{pmatrix} -1/\alpha^2 & 0 & 0 & -\omega/\alpha^2 \\ 0 & \Delta/\rho^2 & 0 & 0 \\ 0 & 0 & 1/\rho^2 & 0 \\ -\omega/\alpha^2 & 0 & 0 & \frac{\alpha^2 - \omega^2\tilde{\omega}^2}{\alpha^2\tilde{\omega}^2} \end{pmatrix}$$

(Chandrasekhar 1983)

Numerical technique
Kerr ray tracing



Numerical technique
Geodesics equations in Kerr

- GR Lagrangian in Boyer-Lindquist co-ordinates
- Legendre transformation to Hamiltonian
- separability ansatz for Hamilton-Jacobi differential equation
- photon momenta follow from derivatives of action
- 4 conservatives:
  - energy E,
  - mass μ,
  - angular momentum J,
  - Carter constant **C** (Kerr-specific!)
- reduction to set of 4 1st order differential equations
- integraton of geodesics equations by
  - Runge-Kutta scheme (direct method)
  - elliptical integrals (*Fanton et al. 1997, A. Müller 2000*)
  - transfer functions (*Cunningham 1975, Bromley et al. 1997*)

(Chandrasekhar 1983)

Generalized Doppler factor g-factor

$$g \equiv \frac{\nu_{obs}}{\nu_{em}} = \frac{\hat{p}^t_{obs}}{\hat{p}^t_{em}}$$

definition in rest-frame

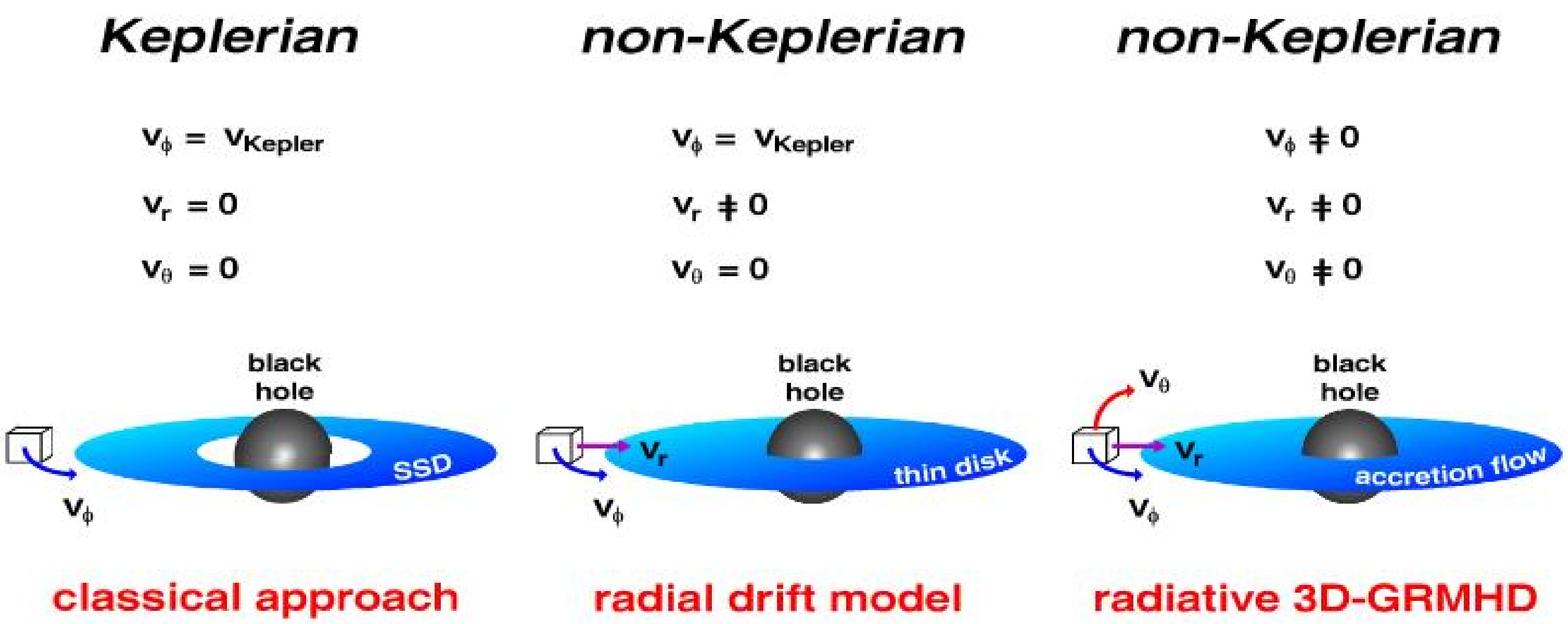
Carter momenta in ZAMO (1968)

$$\hat{p}^t = \gamma \left[p^{(t)} - v^{(j)} p_{(j)} \right]$$

Lorentz boost from ZAMO to rest frame

$$\begin{aligned} g &= \frac{\alpha}{\gamma \left[(1 - \omega\lambda) - \alpha v^{(r)} \frac{\sqrt{\mathcal{R}_0}}{\rho\sqrt{\Delta}} - \alpha v^{(\theta)} \frac{\sqrt{\Theta}}{\rho} - \alpha v^{(\Phi)} \frac{\lambda}{\tilde{\omega}} \right]} \\ &= \frac{\alpha}{\gamma \left[1 - \alpha v^{(r)} \frac{\sqrt{\mathcal{R}_0}}{\rho\sqrt{\Delta}} - \alpha v^{(\theta)} \frac{\sqrt{\Theta}}{\rho} - \lambda\Omega \right]} \end{aligned}$$

Plasma kinematics



Accretion theory
Hydrodynamics and MHD

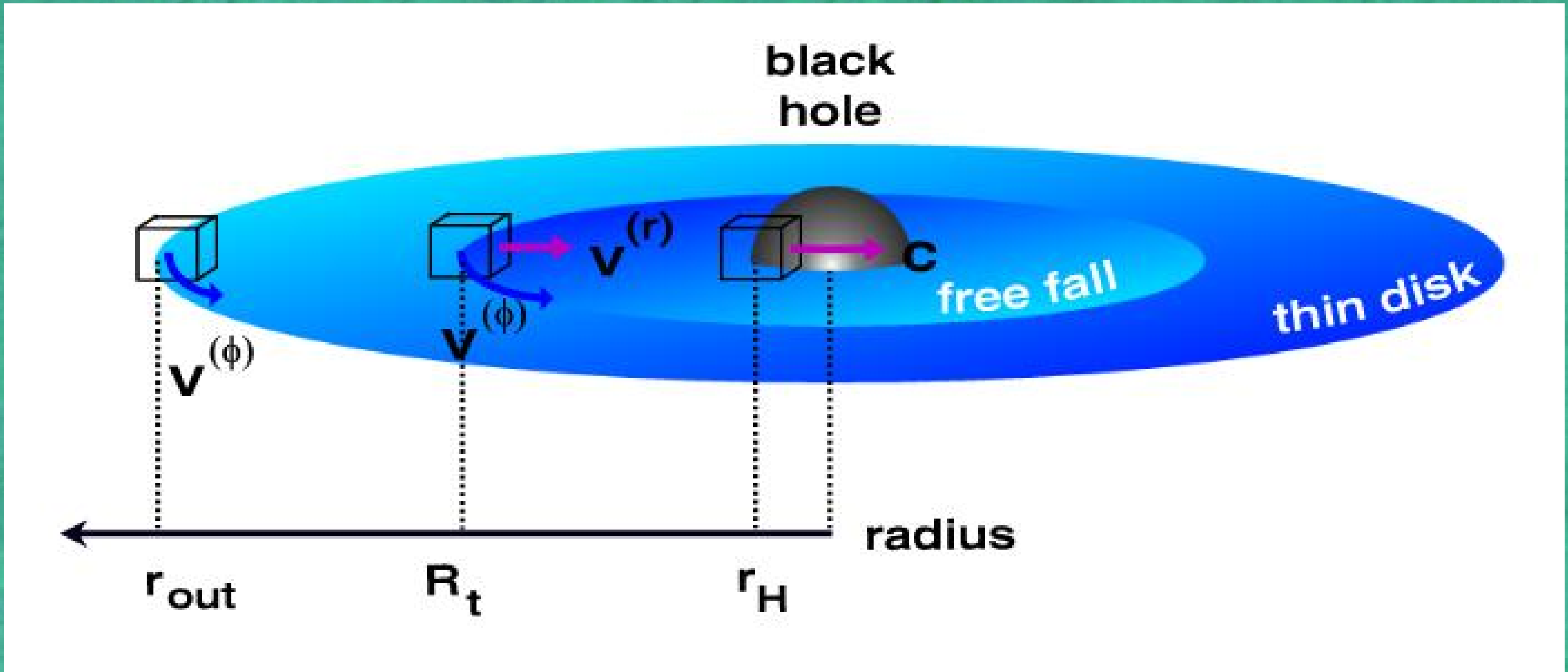
- co-existent and overlapping solutions available:
  - **ADAF** (*Advection-Dominated Accretion Flow*)
    Narayan & Yi 1994
  - **ADIOS** (*Advection-Dominated Inflow-Outflow Solution*)
    Blandford & Begelman 1999
  - **CDAF** (*Convection-Dominated Accretion Flow*)
    Quataert & Gruzinov 2000
  - **ISAF** (*Ion-Supported Accretion Flow*)
    Spruit & Deufel 2001
  - **TDAT** (*Truncated Disk – Advective Tori*)
    Hujeirat & Camenzind 2001
  - **NRAF** (*Non-Radiative Accretion Flow*)
    Balbus & Hawley 2002
- α- and β-disks
- complete parameter space investigation
- need for covariant radiative generalization!

Radiation mechanisms

- **thermal emission**
  - single black body
  - multi-color black body (SSD)
- **Comptonization** (Kompaneets equation)
  - dominant global X-ray component
  - reprocessed soft photons from environment
  - corona: seed photon production for fluorescence
- **Synchrotron radiation**
  - radio emission
  - fast cooling of hot accretion flow on ms-scale
  - SSC (sub-mm bump)
  - SSA (dip feature)
- **bremsstrahlung**
  - launch of outflow (disk wind, Poynting flux)

→ **Covariant generalization: GR radiation transfer**!

Radial drift model
Truncation and free-fall



Truncated Standard accretion Disks (TSD) due to efficient radiative cooling. Disk cuts off at R_t, not at r_{ms} (cp. SSD) depending on radiative accretion theory (accretion rate, cooling, conduction).
(Hujeirat & Camenzind 2000)

Radial drift model
Velocity field in ZAMO frame

ZAMO velocities

$$v^{(\Phi)} = \tilde{\omega}\left(\frac{\Omega - \omega}{\alpha}\right)$$

$$v^{(r)} = \frac{\sqrt{\mathcal{R}}}{\Sigma(1 - \omega\lambda)}$$

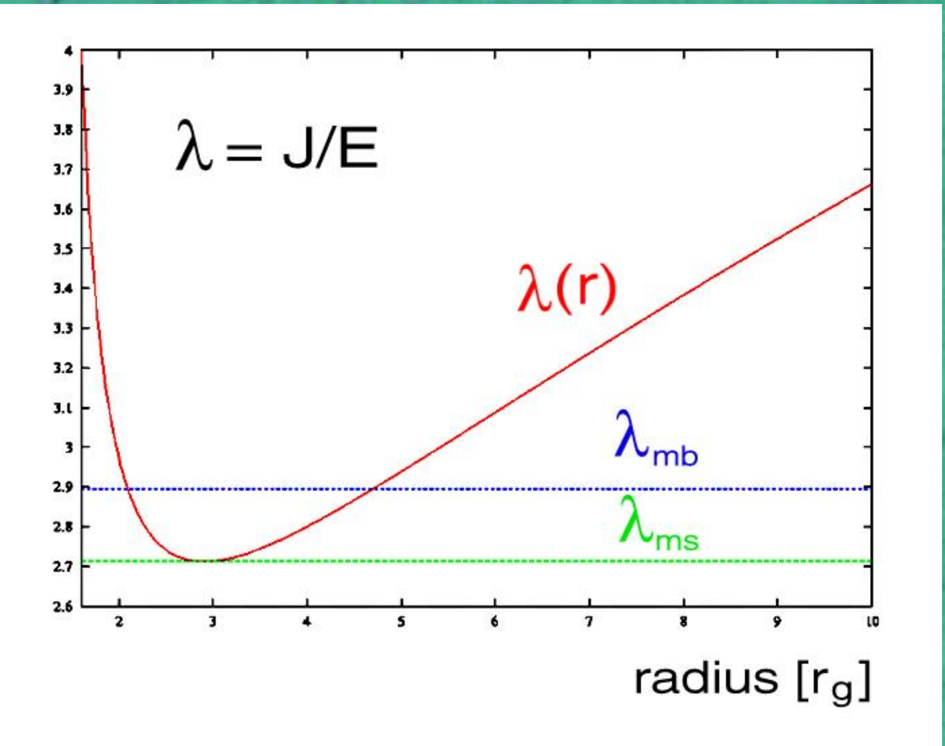
angular frequencies

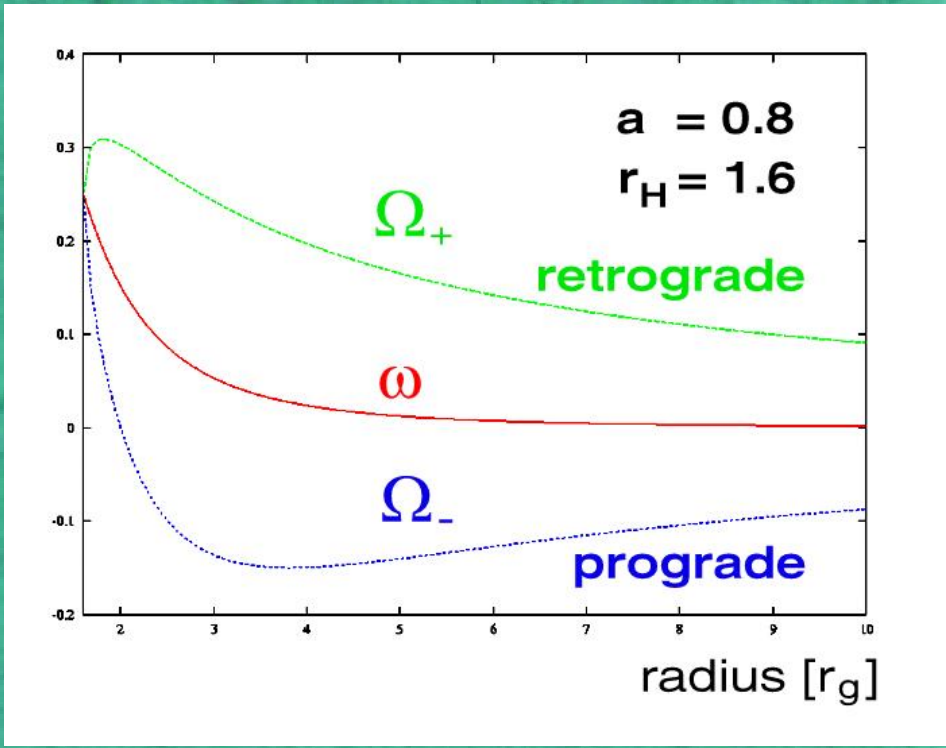
$$\Omega_K = \pm\frac{\sqrt{M}}{\sqrt{r^3} \pm a\sqrt{M}}$$

$$\Omega = \Omega_{in} = \omega + \frac{\alpha^2}{\tilde{\omega}^2}\frac{\lambda_{ms}}{1 - \omega\lambda_{ms}}$$

$$\lambda_{ms} = \frac{\tilde{\omega}^2_{ms}\left(\Omega_{K,ms} - \omega_{ms}\right)}{\alpha^2_{ms} + \omega_{ms}\tilde{\omega}^2_{ms}\left(\Omega_{K,ms} - \omega_{ms}\right)}$$

Radial drift model
Parameter restrictions

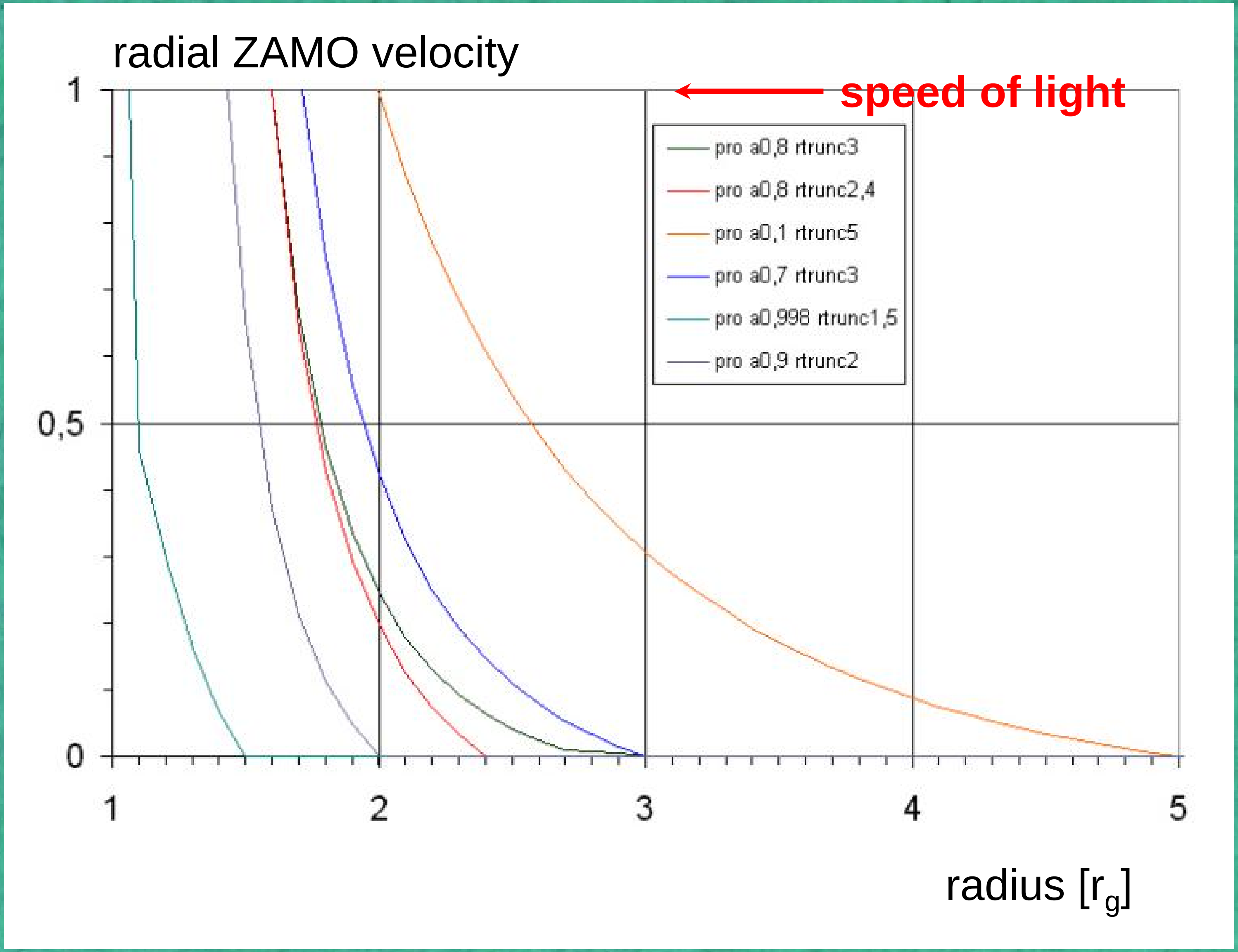




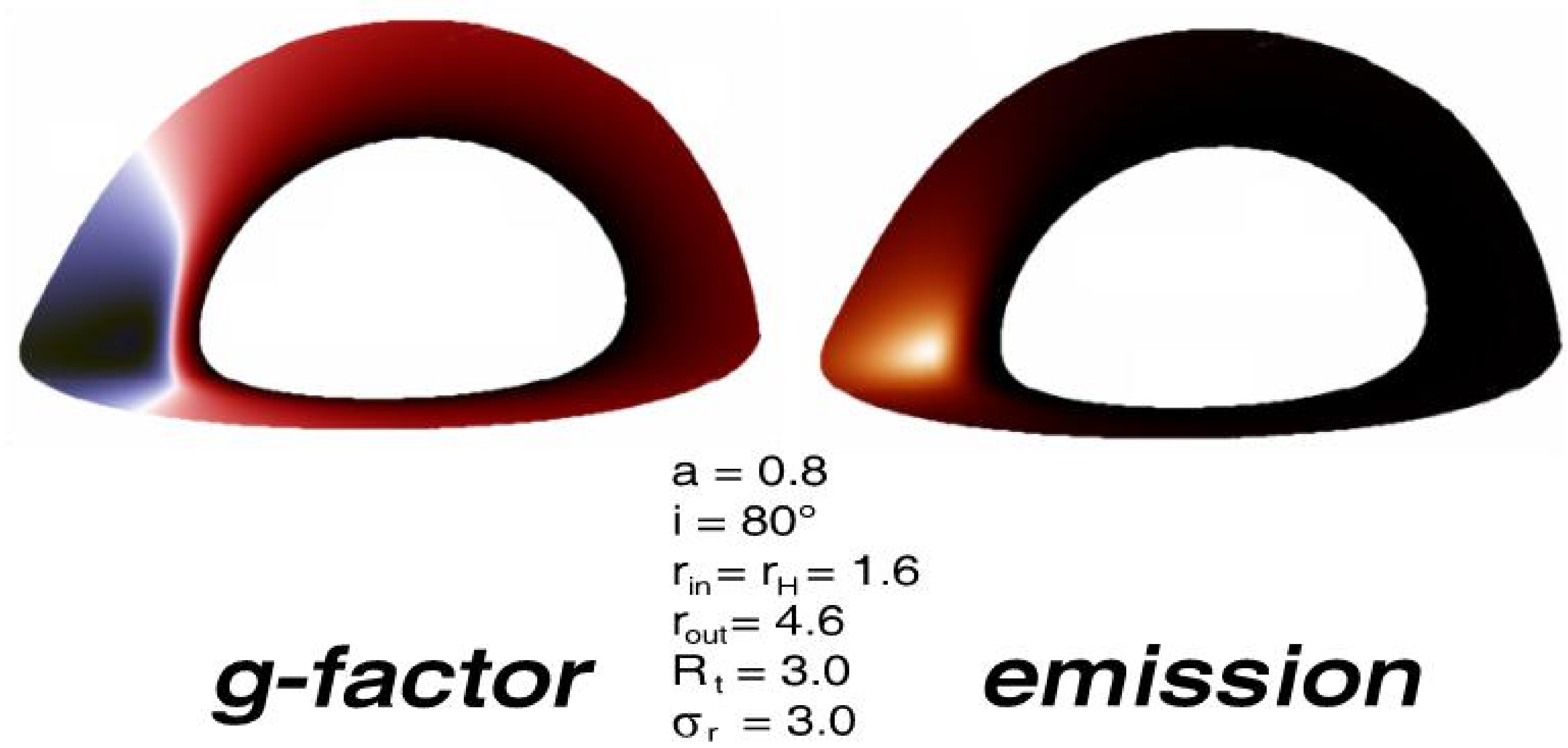
Specific angular momentum λ
has chosen between λ_{ms} and λ_{mb} .

Only region between Ω_+ and Ω_-
is allowed (time-like trajectories).

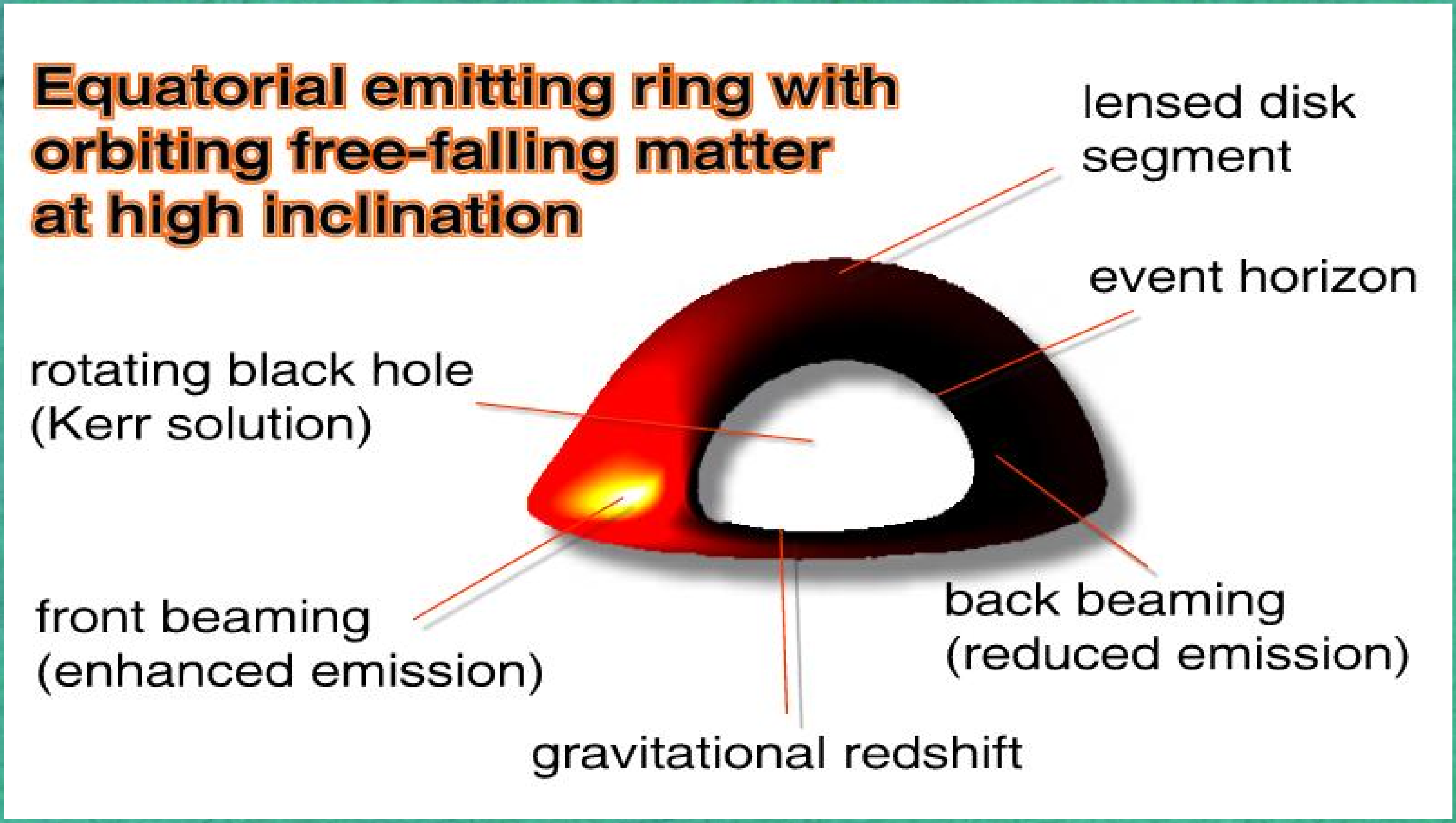
Radial drift models



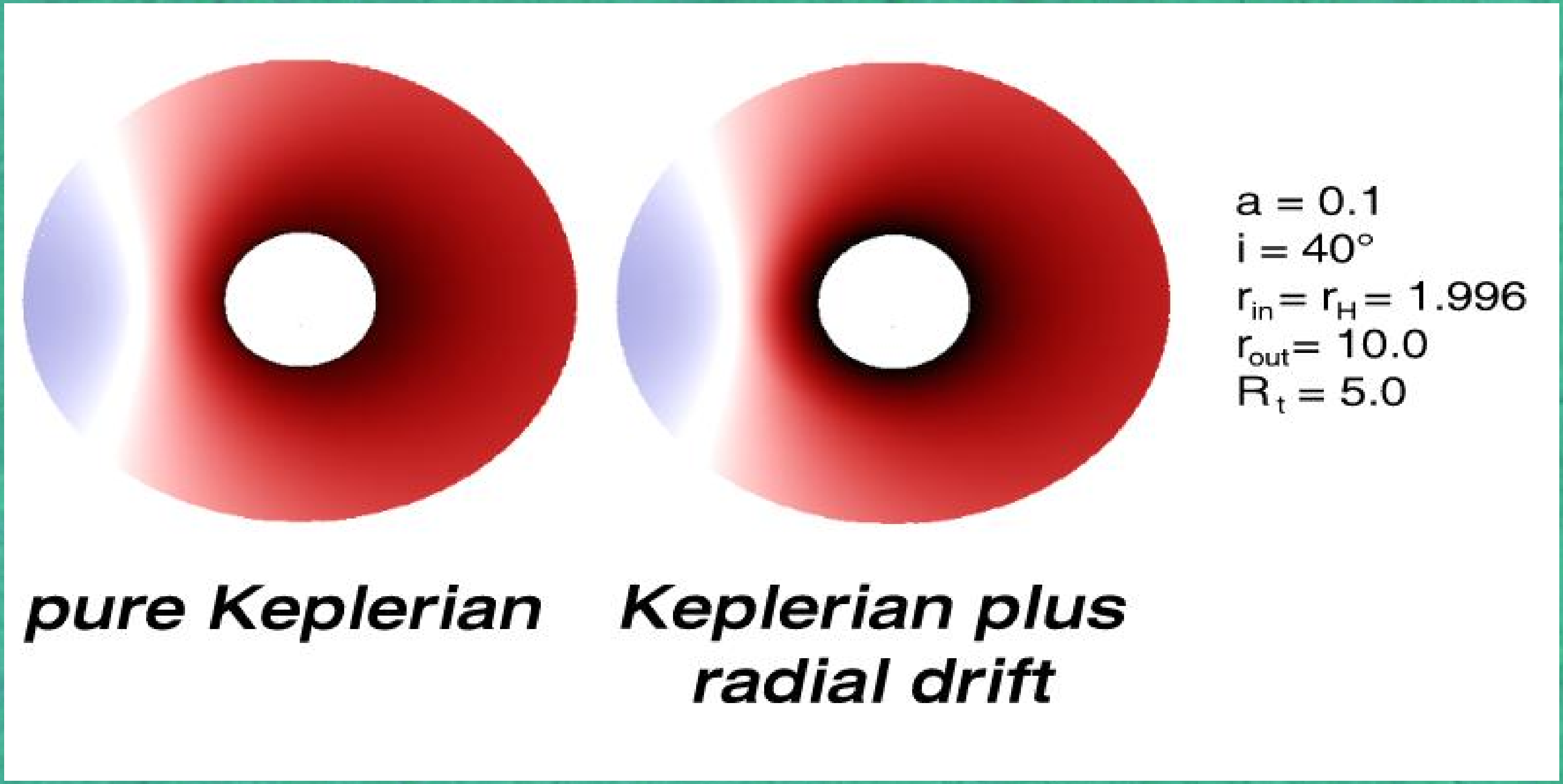
Rendered disk images
g-factor and emission



Disk emission
Relativistic effects



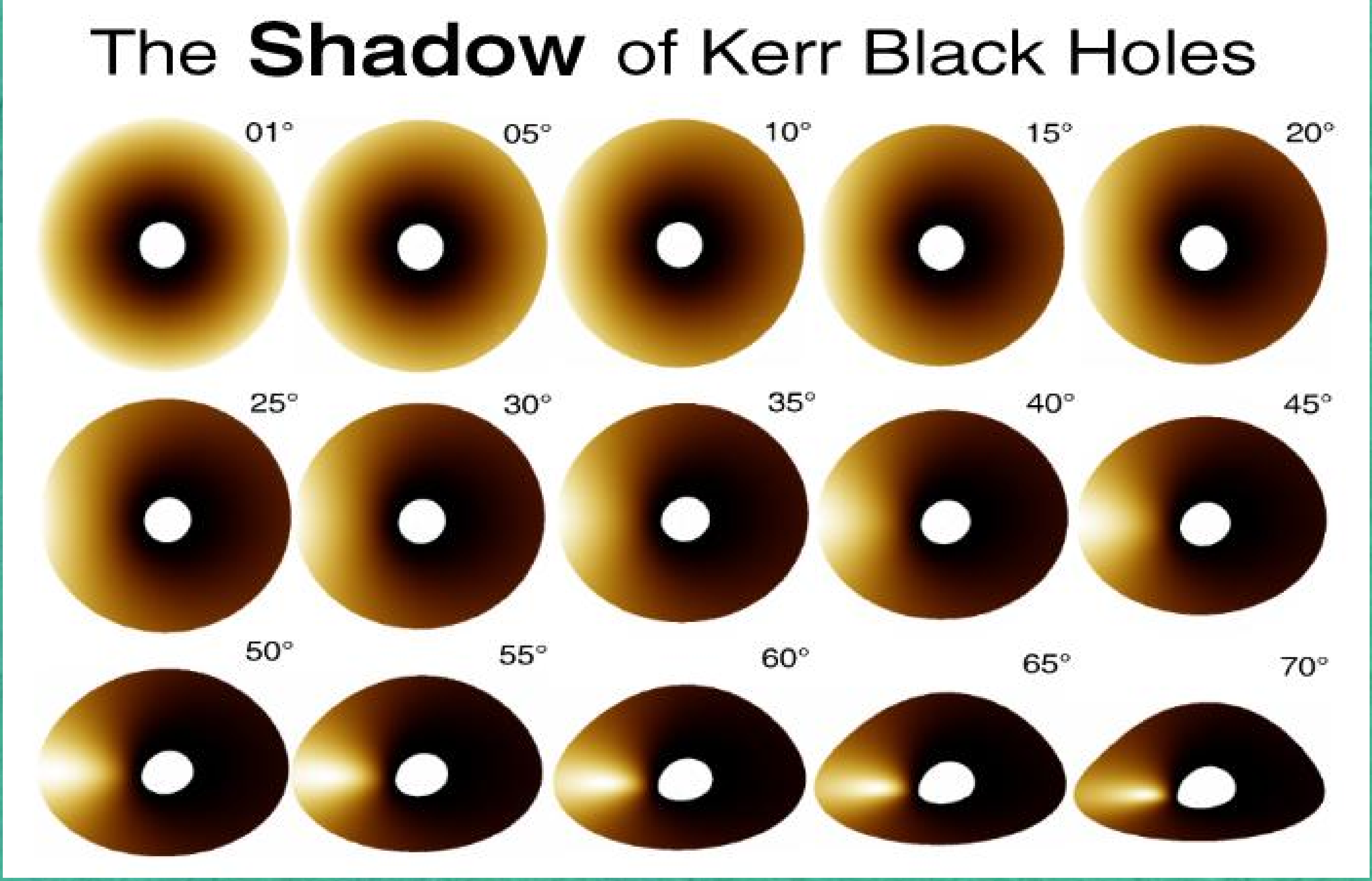
Radial drift model
g-factor: Keplerian vs. Drift



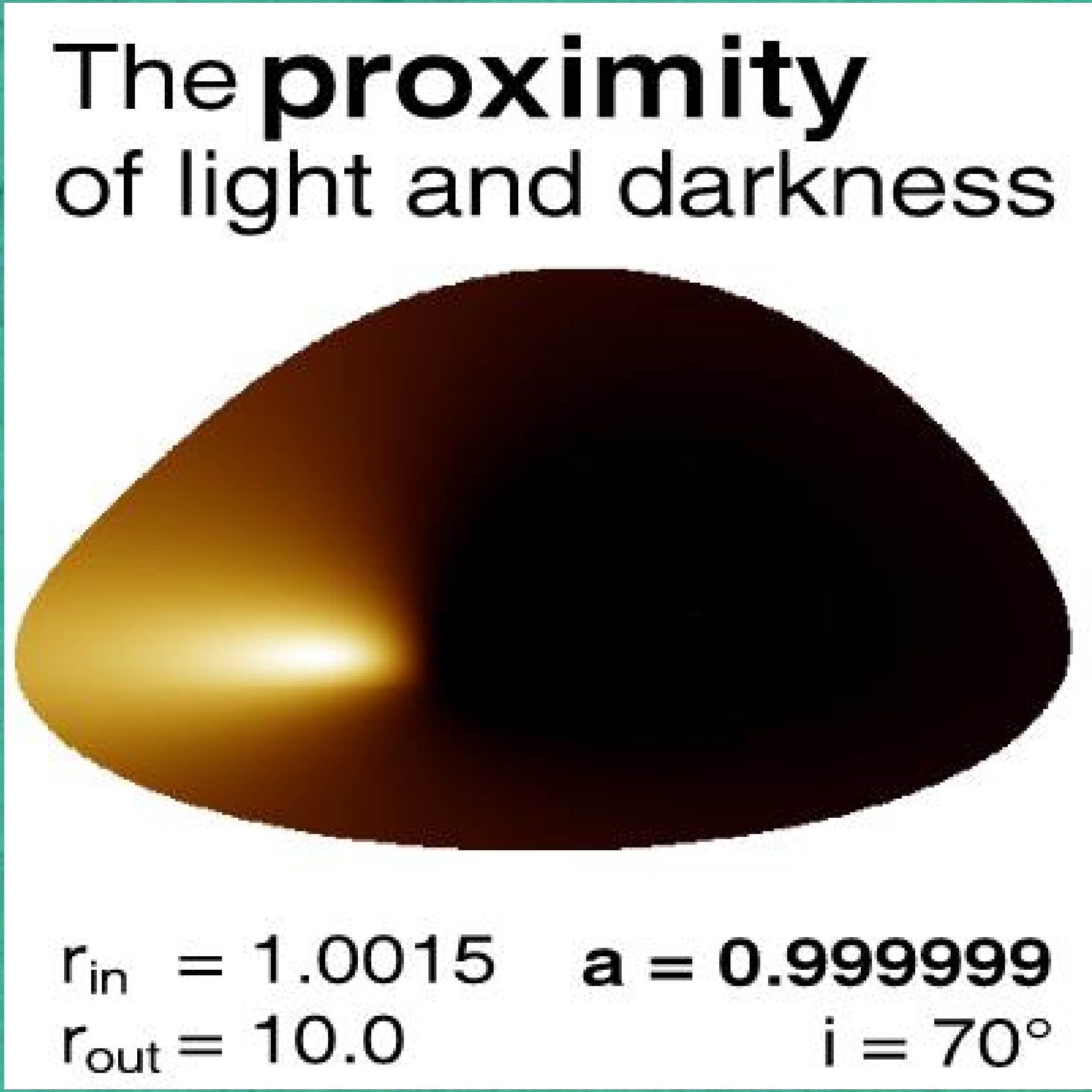
Radial drift model
Implications

- adequate consideration of **accreted inflow**
- **truncation** softens the „*evidence for Kerr*"- argument, because R_t replaces r_{ms}. Coupling between r_{in} and r_{ms} is lost!
- **gravitational redshift** is enhanced!
- emission line shape does not change dramatically compared with pure Keplerian: only ***red wing effects***
- **poloidal motion** still neglected!
- awaiting new accretion theory: **covariance**
- follow *Armitage & Reynolds (2003)* approach: **couple** line emission to accretion model

Disk emission
Inclination study with g^4



Black hole shadow



Strong gravitational redshift

horizon:

g = 0

Flux integral folds g in high power with emissivity.

g^4 – distribution suppresses *any emission* near black holes!

„*Shadow*“ by *Falcke et al. 2000*

Relativistic emission line
Calculation

$$F^{obs} = \int_{image} d\Xi \; I_\nu^{obs}$$

general spectral flux integral

$$I_\nu^{obs} = g^3 \, \hat{I}_\nu^{em}$$

using Lorentz invariant
(Misner 1973)

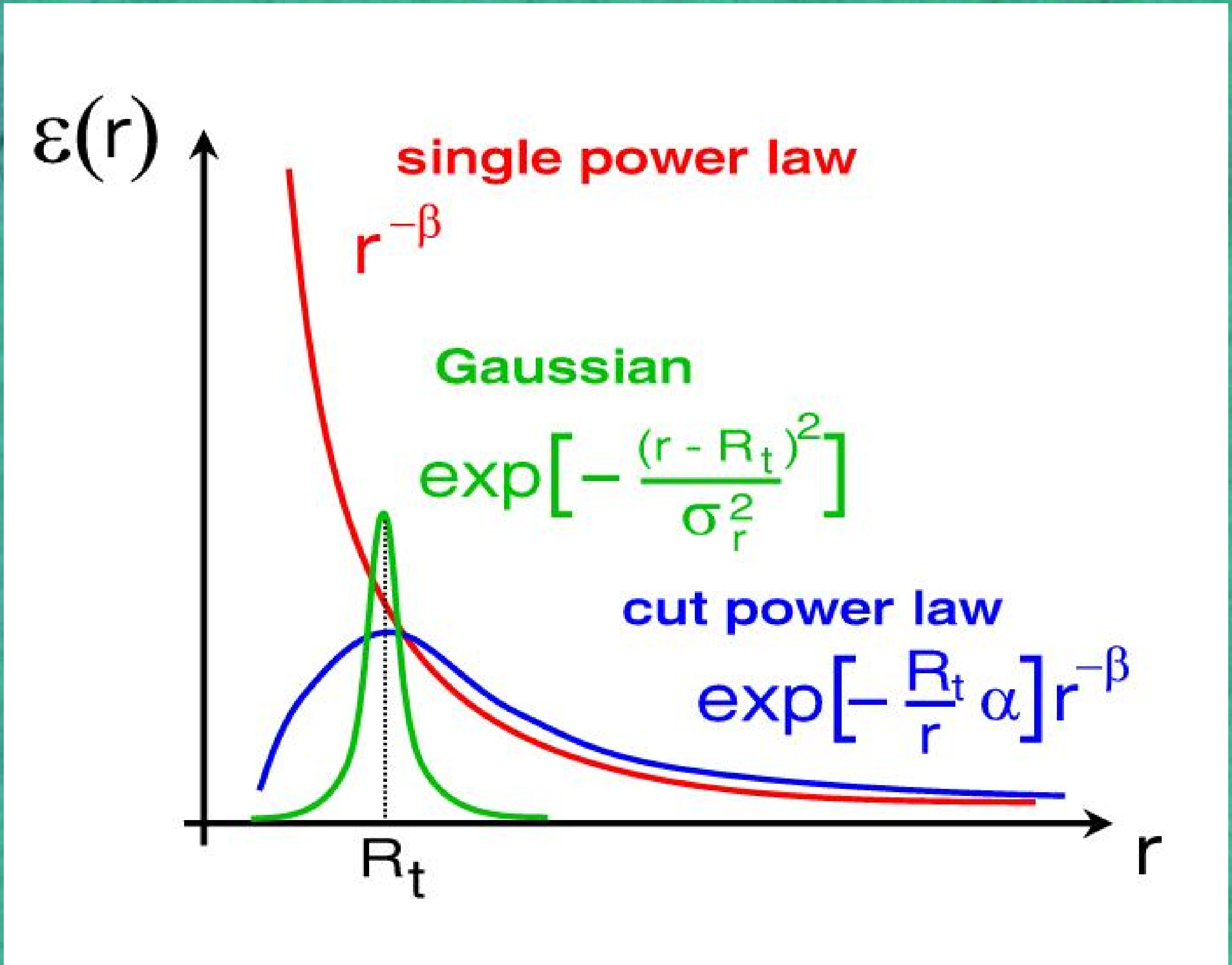
$$\hat{F}_\nu^{em} = \pi \hat{I}_\nu^{em} = \epsilon(r)\delta\left(\nu_{em} - \nu_0\right)$$

assume line shape in rest frame:
δ-distribution
fold radial emissivity profile
- single power law
- double or broken power law
- Gaussian
- cut-power law

$$F_{obs}(E_{obs}) = \int_{image} \epsilon(r) g^4 \delta(E_{obs} - gE_0) d\Xi$$

evaluate tuple {g, $\Delta\Omega$, r} on
each pixel and sum over pixels!

Radial emissivity profiles



emissivities

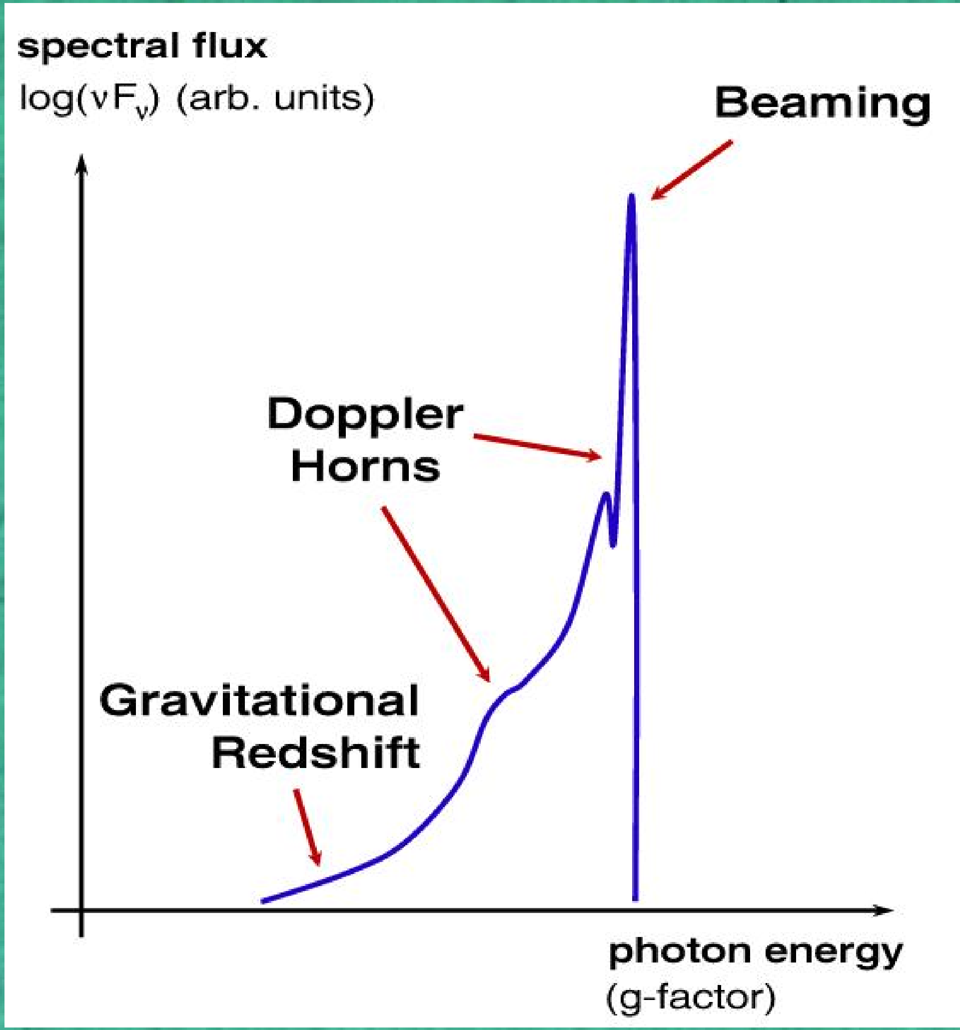
single power law
(Page & Thorne 1974)

double or broken power law

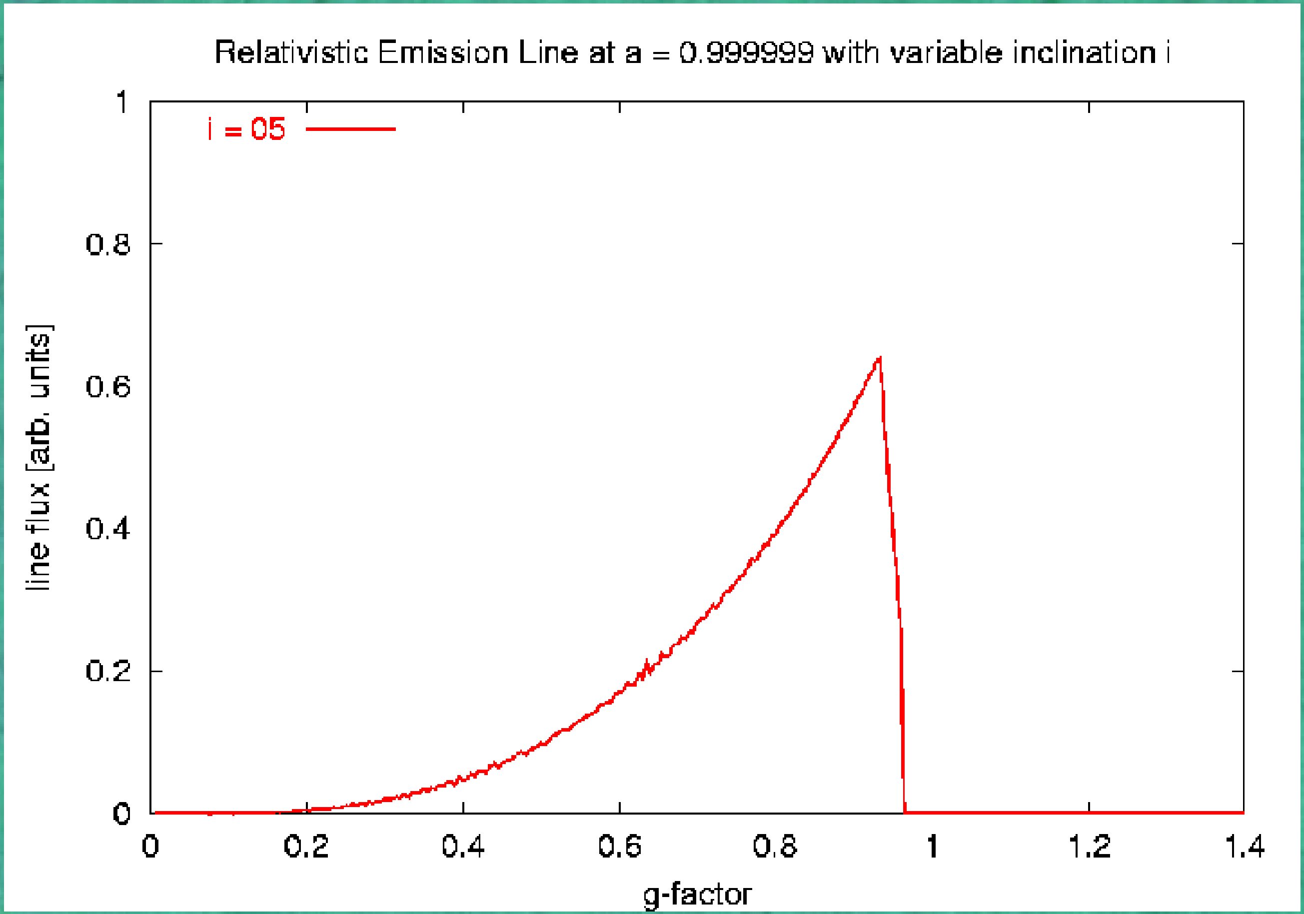
Gaussian,
cut-power law
(Müller & Camenzind 2003)

Line features
Imprints of relativistic effects

- Doppler (Newtonian)
- Beaming (SR)
- Gravitational redshift (GR)



Line studies
Inclination



Parameters:

a = 0.999999

i = 5°....70°

r_{in} = r_{ms} = 1.0015

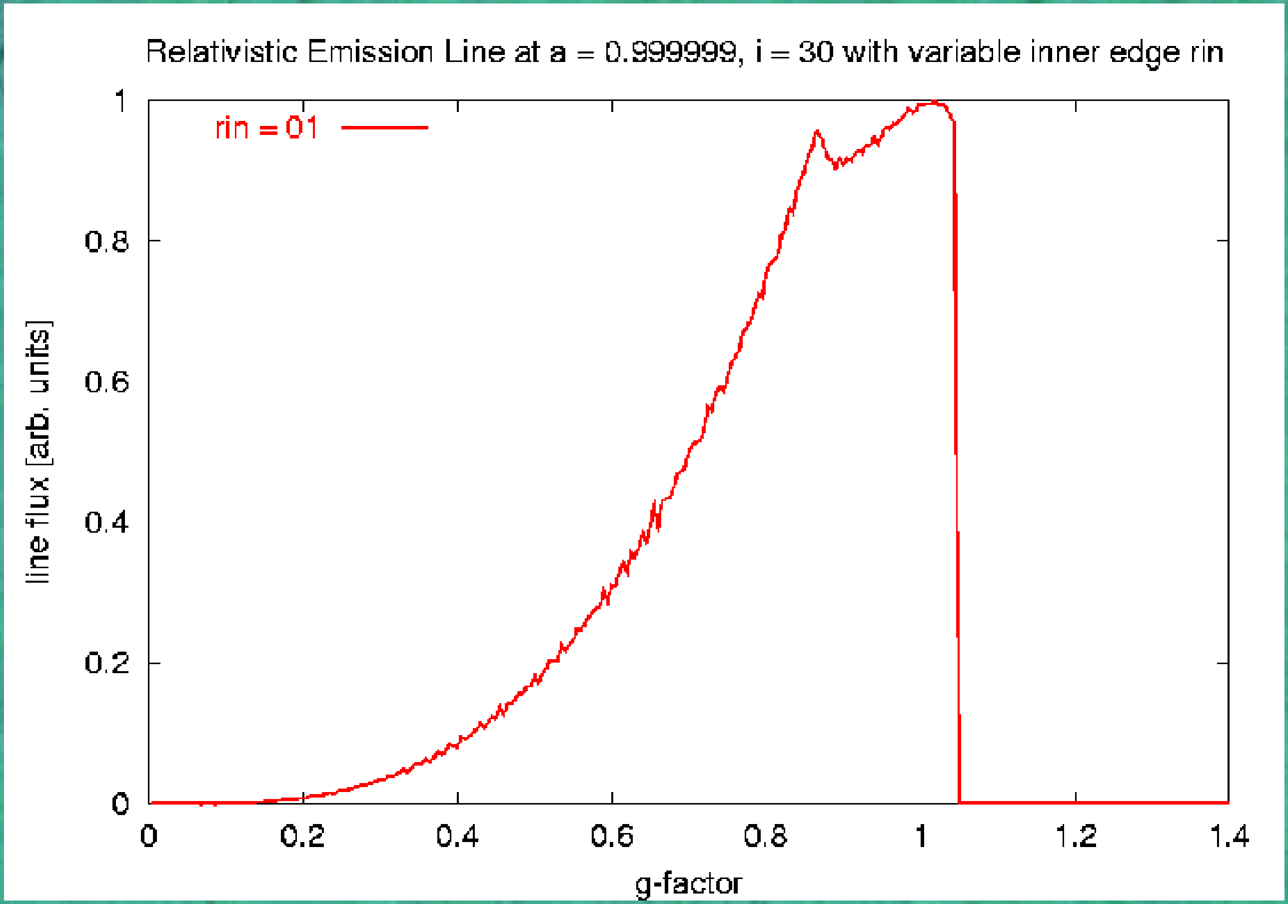
r_{out} = 30.0

single power law emissivity

pure rotation, no drift

Blue edge shifts!
Enhanced Beaming!
Doppler effect

Line studies
Inner disk edge



Parameters:

a = 0.999999

i = 30°

r_{in} = 1...28

r_{out} = 30.0

single power law emissivity

pure rotation, no drift

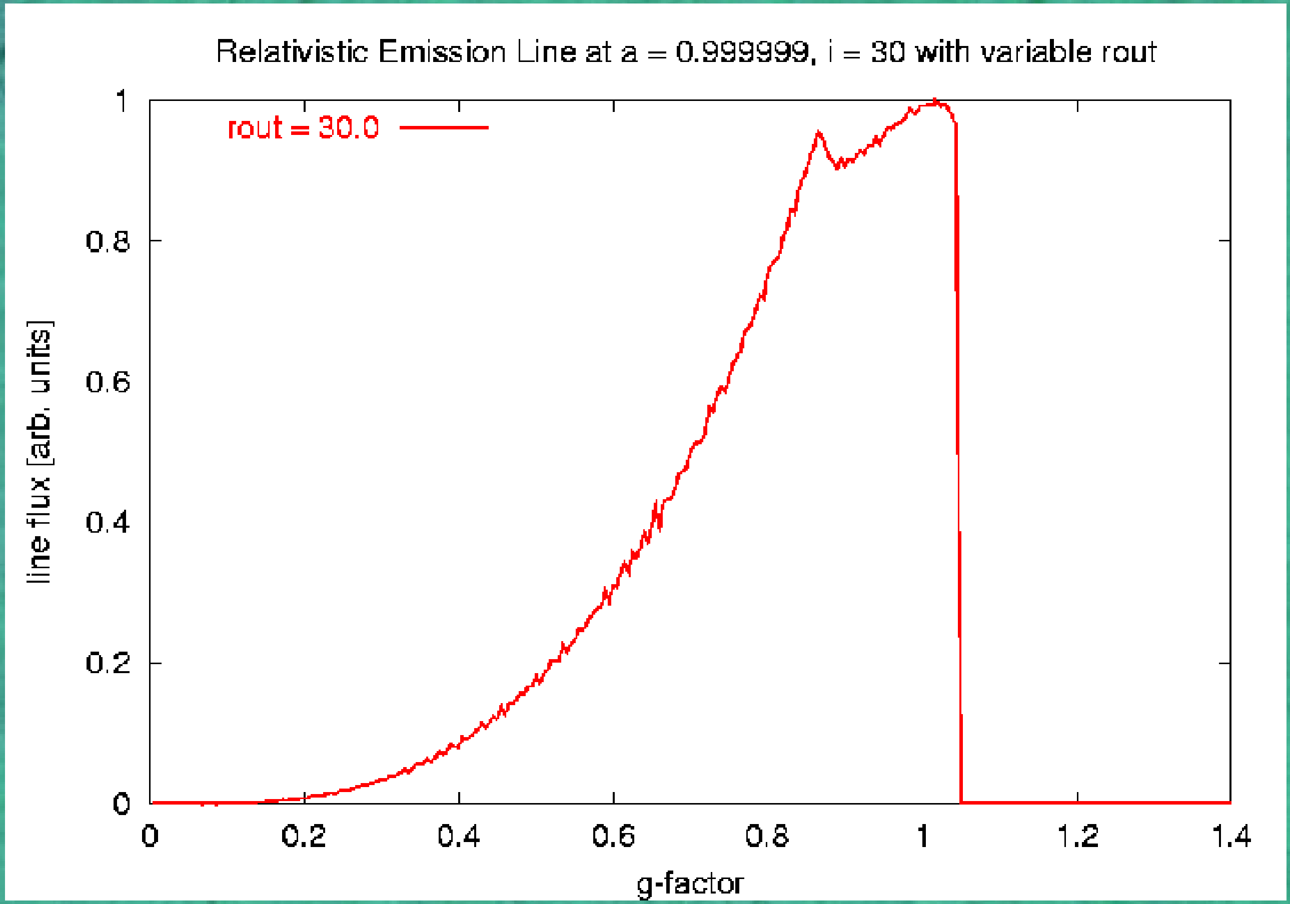
Static blue edge!

Red wing vanishes!

Doppler effect end: Newtonian

Space-time curvature is negligible at radii ~ 20 r_g!!!

Line studies
Outer disk edge



Parameters:

a = 0.999999

i = 30°

r_{in} = 1.0015

r_{out} = 30...1.5

single power law emissivity

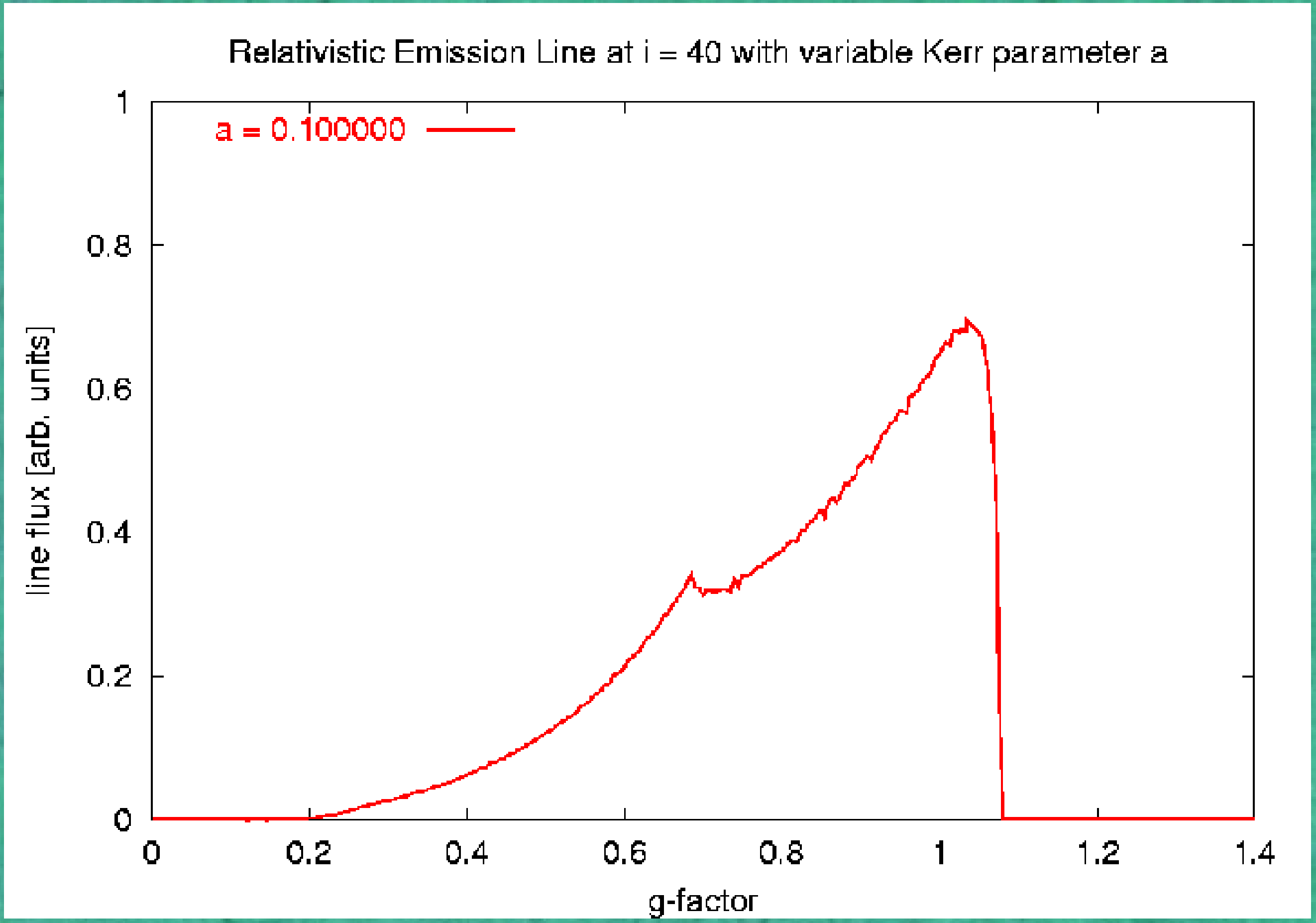
pure rotation, no drift

Static red edge!

Beaming vanishes!

Doppler effect

Line studies
Kerr parameter



Parameters:

a = 0.1....0.999999

i = 40°

r_{in} = r_{ms}

r_{out} ~ 10.0 decreasing

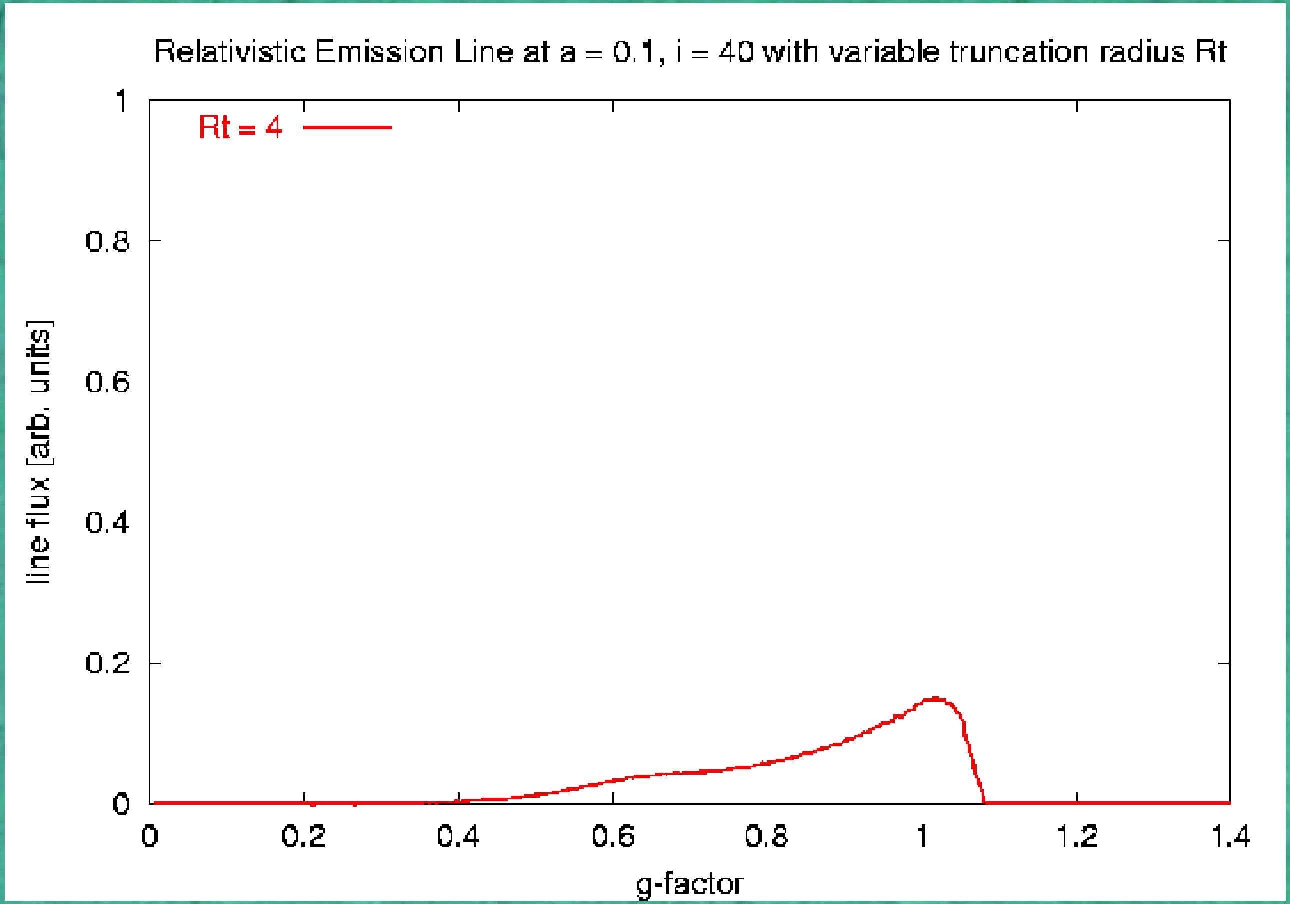
constant emitting area!

single power law emissivity

pure rotation,
no drift

Beaming increases due to increasing *frame-dragging effect*!

Line studies
Truncation radius



Parameters:

a = 0.1

i = 40°

r_{in} = r_H = 1.995

r_{out} = 30.0

R_t = 4....8

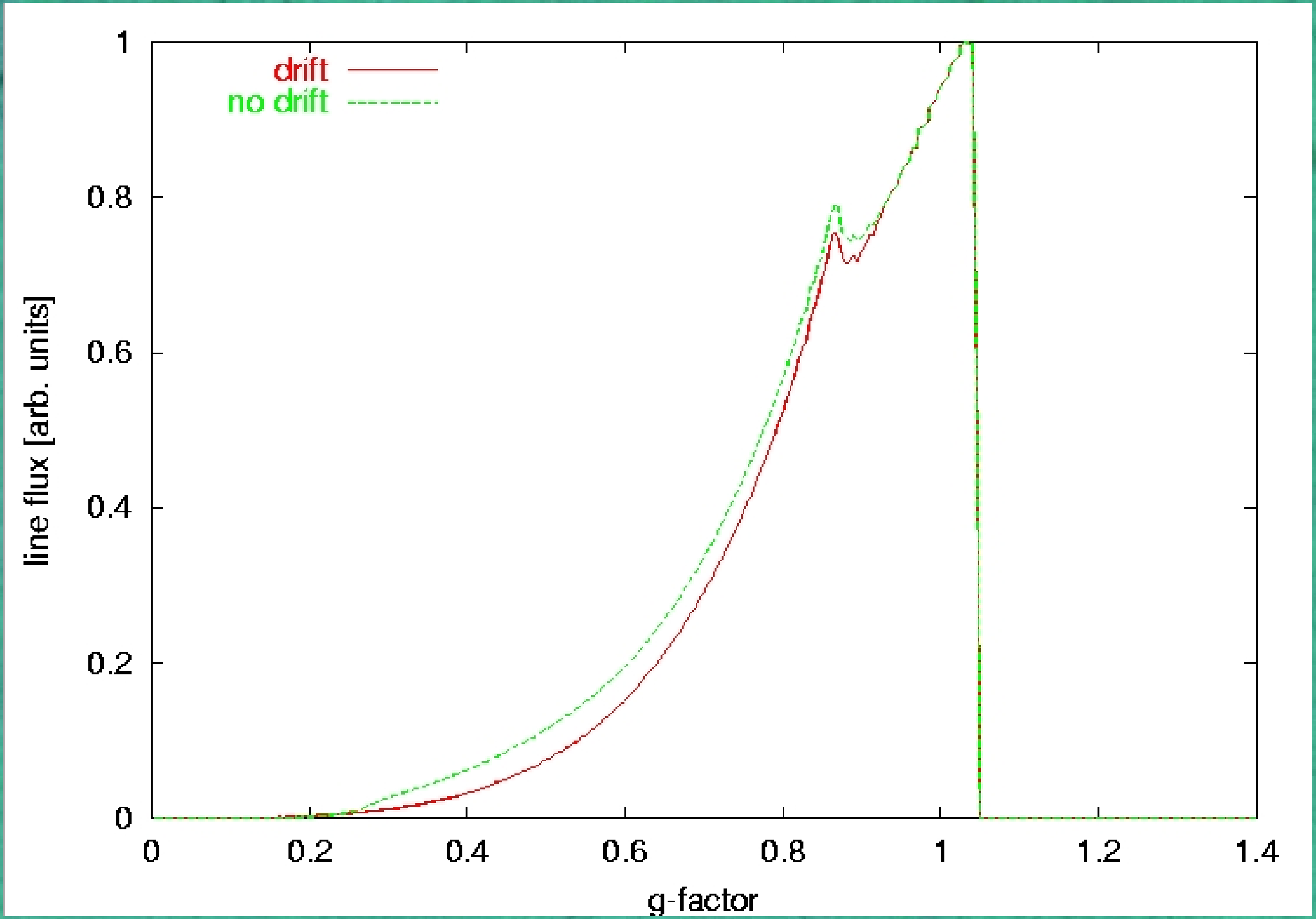
σ_r = 0.4 R_t

Gaussian emissivity couples to R_t

non-Keplerian: rotation plus drift!

Gravitational redshift decreases with radius!
Enhanced Beaming!
Doppler effect

Line studies
Drift + rotation vs. pure rotation



Parameters:

a = 0.001

i = 30°

r_{in} = r_H = 2.0

r_{out} = 30.0

R_t = 6

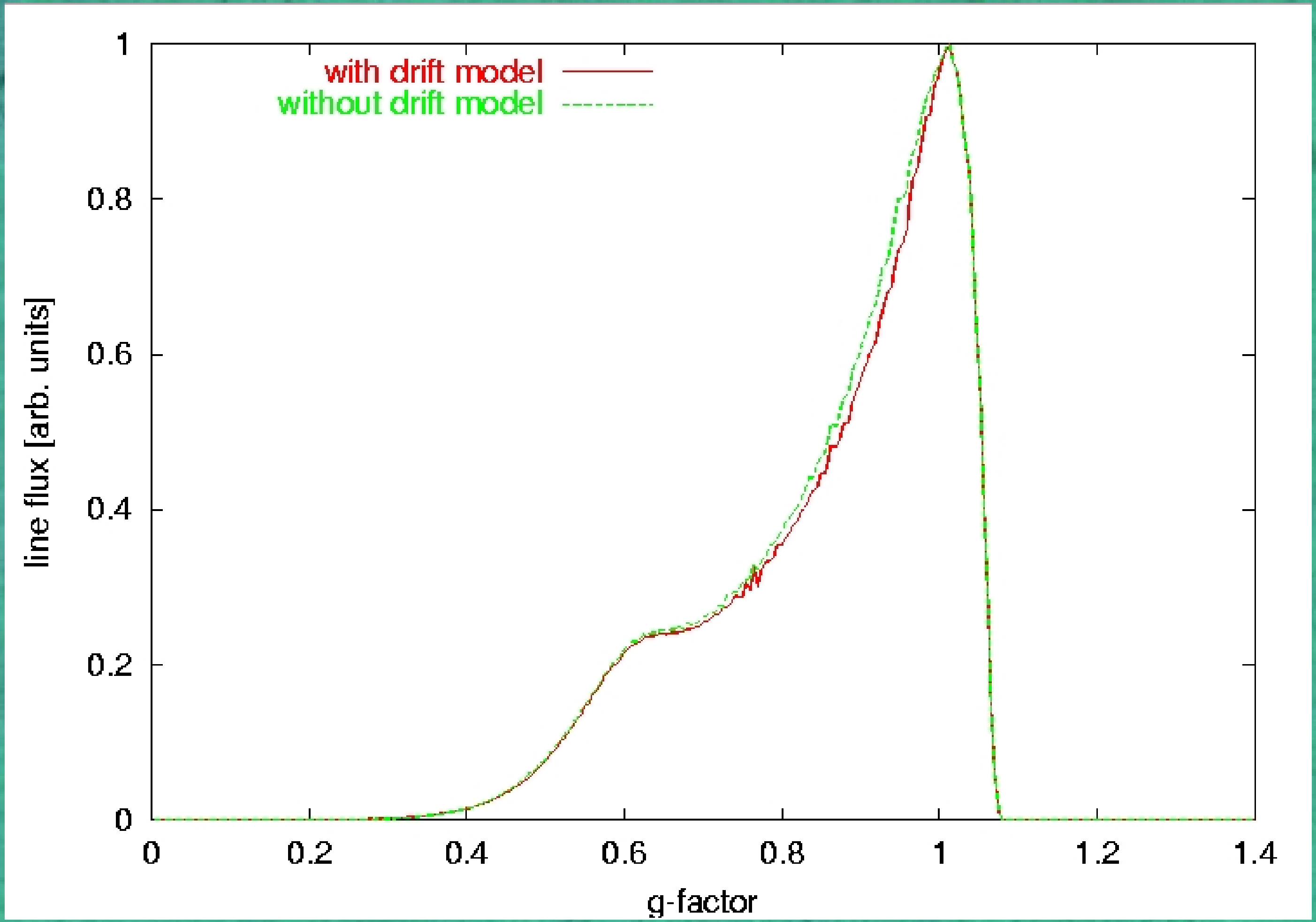
single power law emissivity

pure Keplerian

non-Keplerian: rotation plus drift!

Drift causes enhanced gravitational redshift and reduces red wing flux!

Line studies
Drift + rotation vs. pure rotation



Parameters:

a = 0.1

i = 40°

r_{in} = r_H = 1.995

r_{out} = 10.0

R_t = 5

σ_r = 0.4 R_t

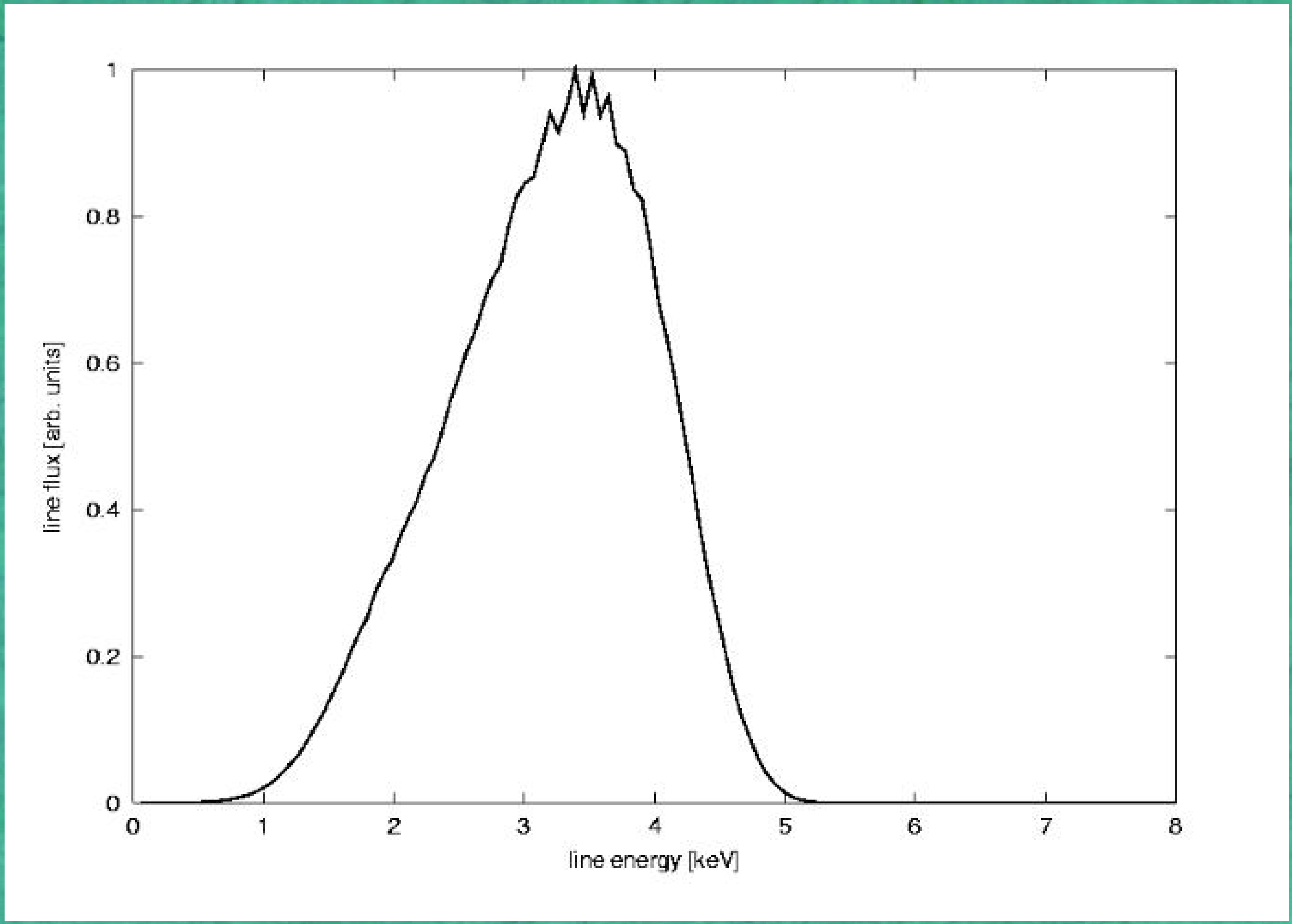
Gaussian emissivity couples to R_t

pure Keplerian

non-Keplerian: rotation plus drift!

Gravitational redshift causes red wing differences!

Line suppression
„Shadowed lines“



Parameters:

a = 0.998

i = 30°

r_{in} = r_H = 1.06

r_{out} = 30.0

R_t = 1.5

σ_r = 0.4

Gaussian emissivity

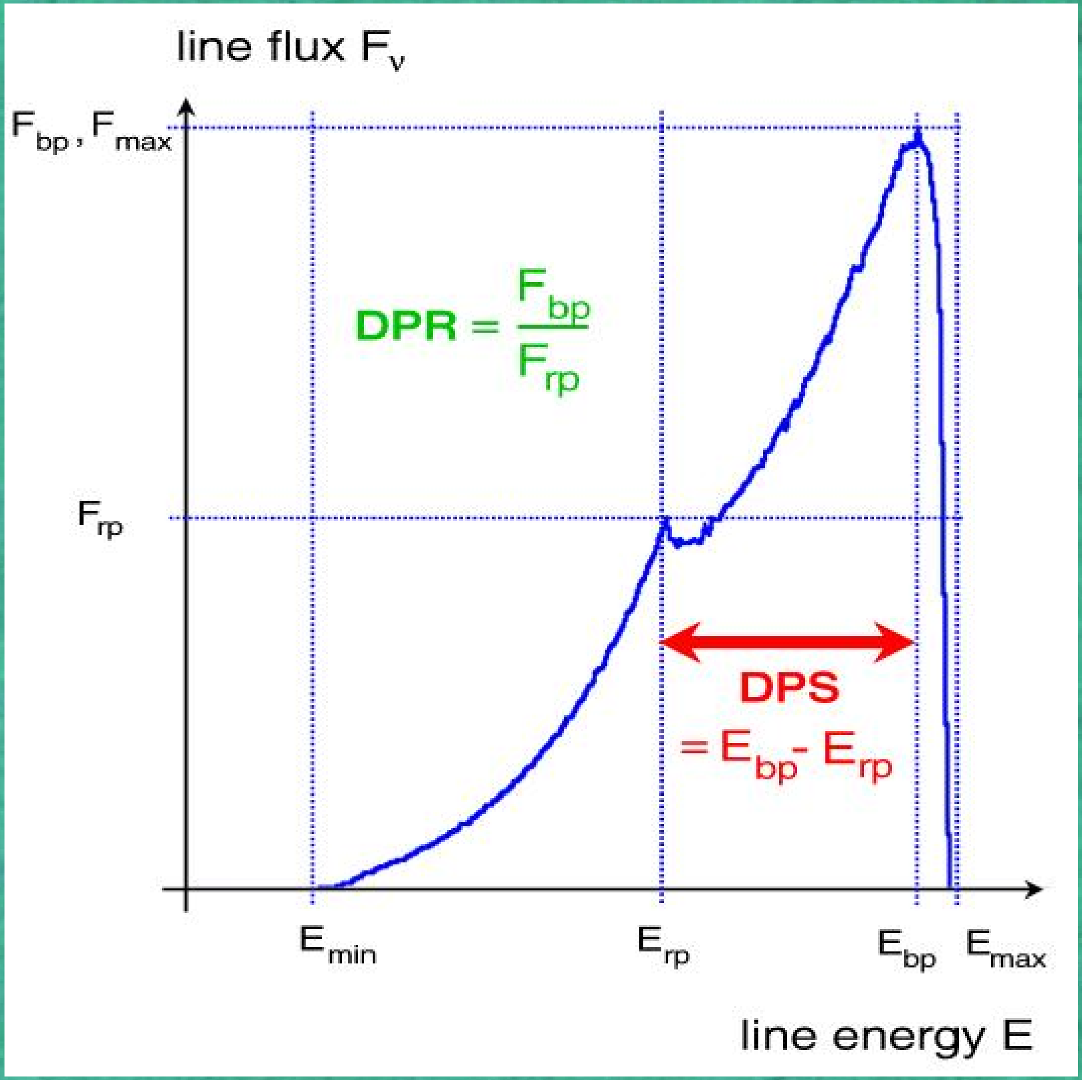
non-Keplerian: rotation + drift

peak at ~ 3 keV

high redshift!

(**„unphysical“ line**: consider fluorescence restrictions)

Line criteria



DPR

Doppler Peak Ratio

DPS

Doppler Peak Spacing

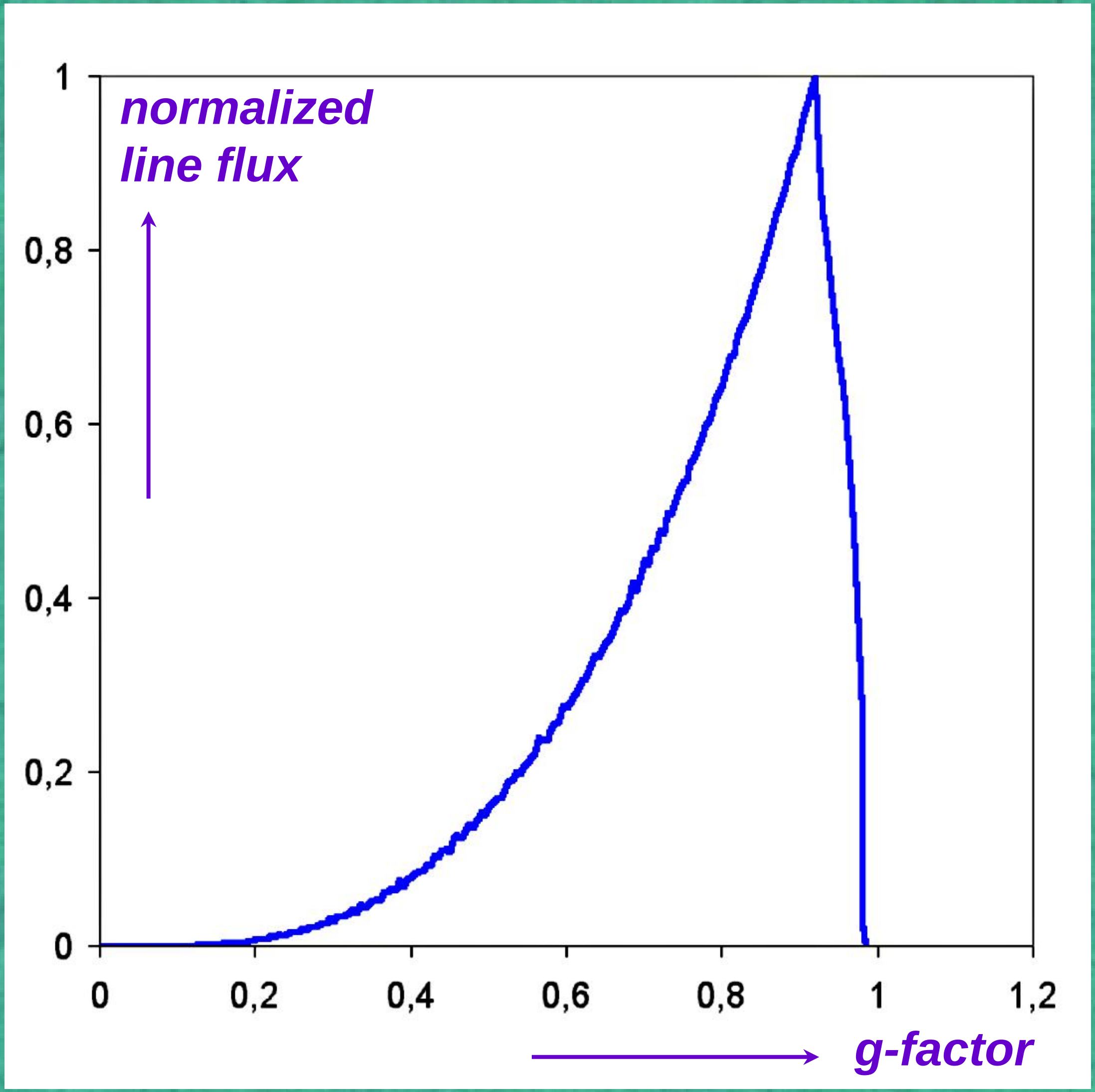
(relative quantities!)

(Müller & Camenzind 2003)

Line classification
Proposed nomenclature

- topological criterion:
  - triangular
  - bumpy
  - double-horned
  - double-peaked
  - shoulder-like
- pre-selection of parameters possible
- pre-classification of observed lines
- unification scheme of AGN

Line classification
Triangular



Parameters:

a = 0.999999

i = 10°

r_{in} = 1.0015

r_{out} = 30.0

β = 3.0

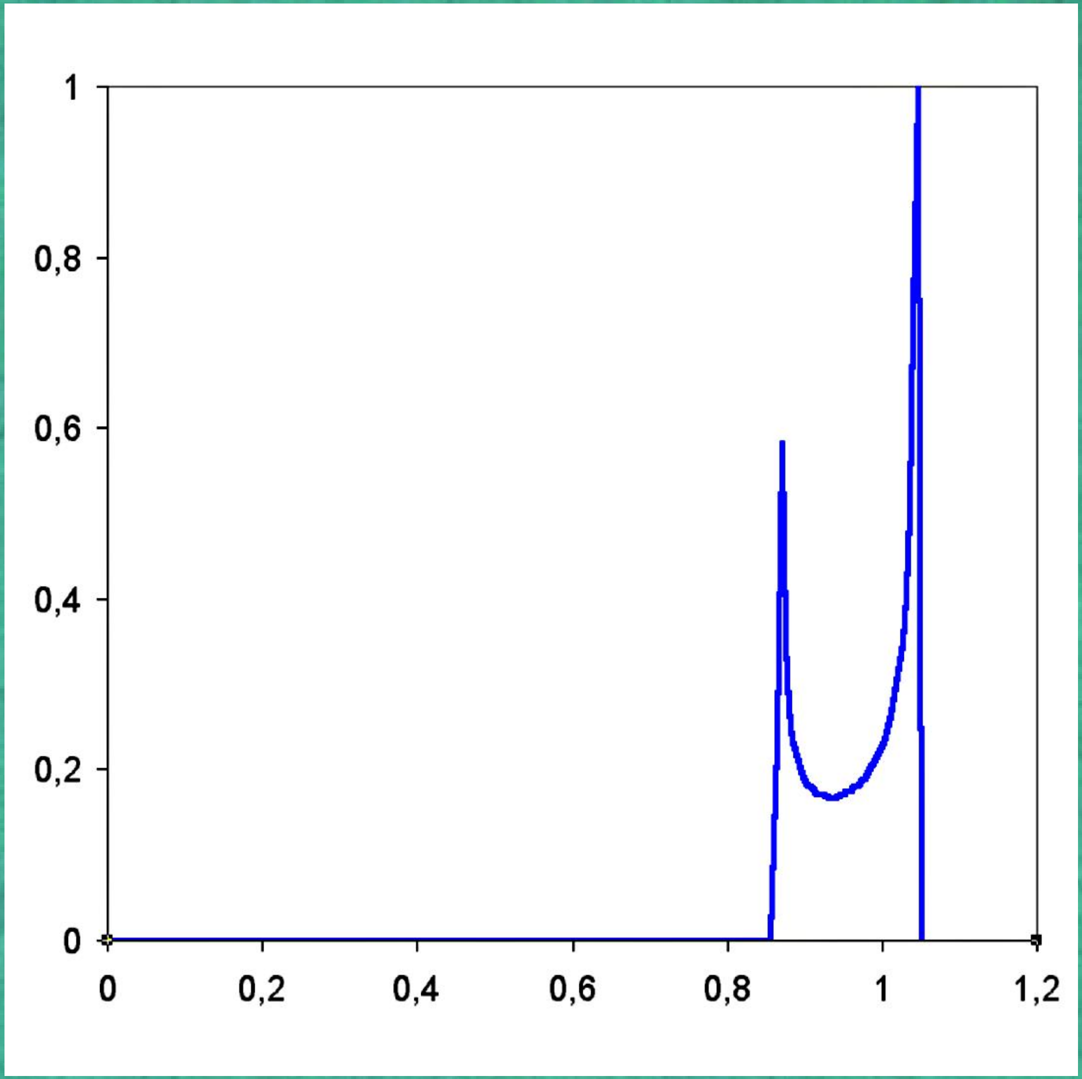
single power law

Keplerian

typical:

low inclination, Doppler reduced

Line classification
Double-peaked



Parameters:

a = 0.999999

i = 30°

r_{in} = 28.0

r_{out} = 30.0

β = 3.0

single power law

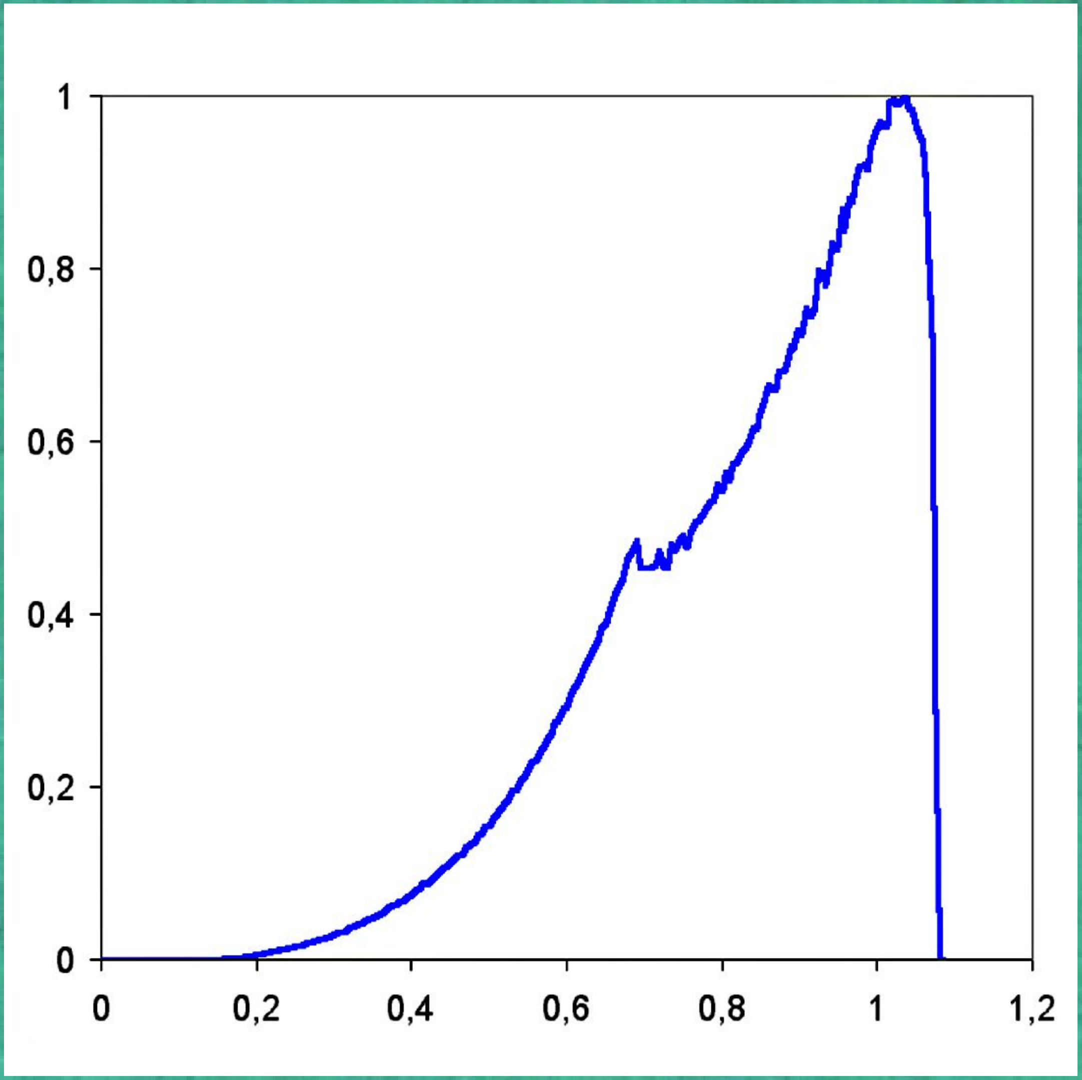
Keplerian

typical:

medium2high inclination, asymptotically

flat metric, no GR effects

Line classification
Double-horned



Parameters:

a = 0.4

i = 40°

r_{in} = 1.9165

r_{out} = 9.9846

β = 3.0

single power law

Keplerian

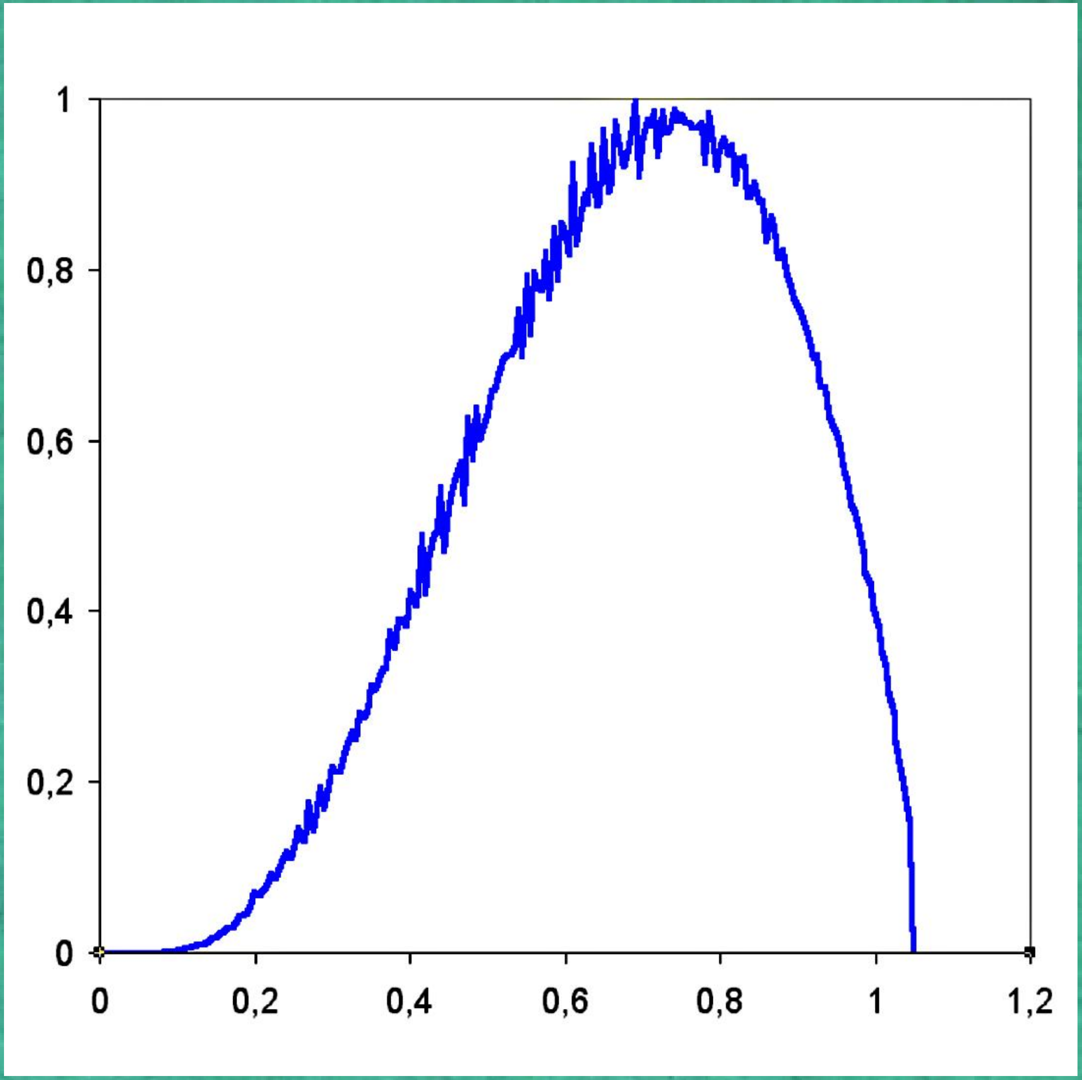
typical:

medium inclination,

standard emissivity,

2 relic Doppler peaks

Line classification
Bumpy



Parameters:

a = 0.998

i = 30°

r_{in} = r_{ms} = 1.23

r_{out} = 30.0

β = 4.5

single power law

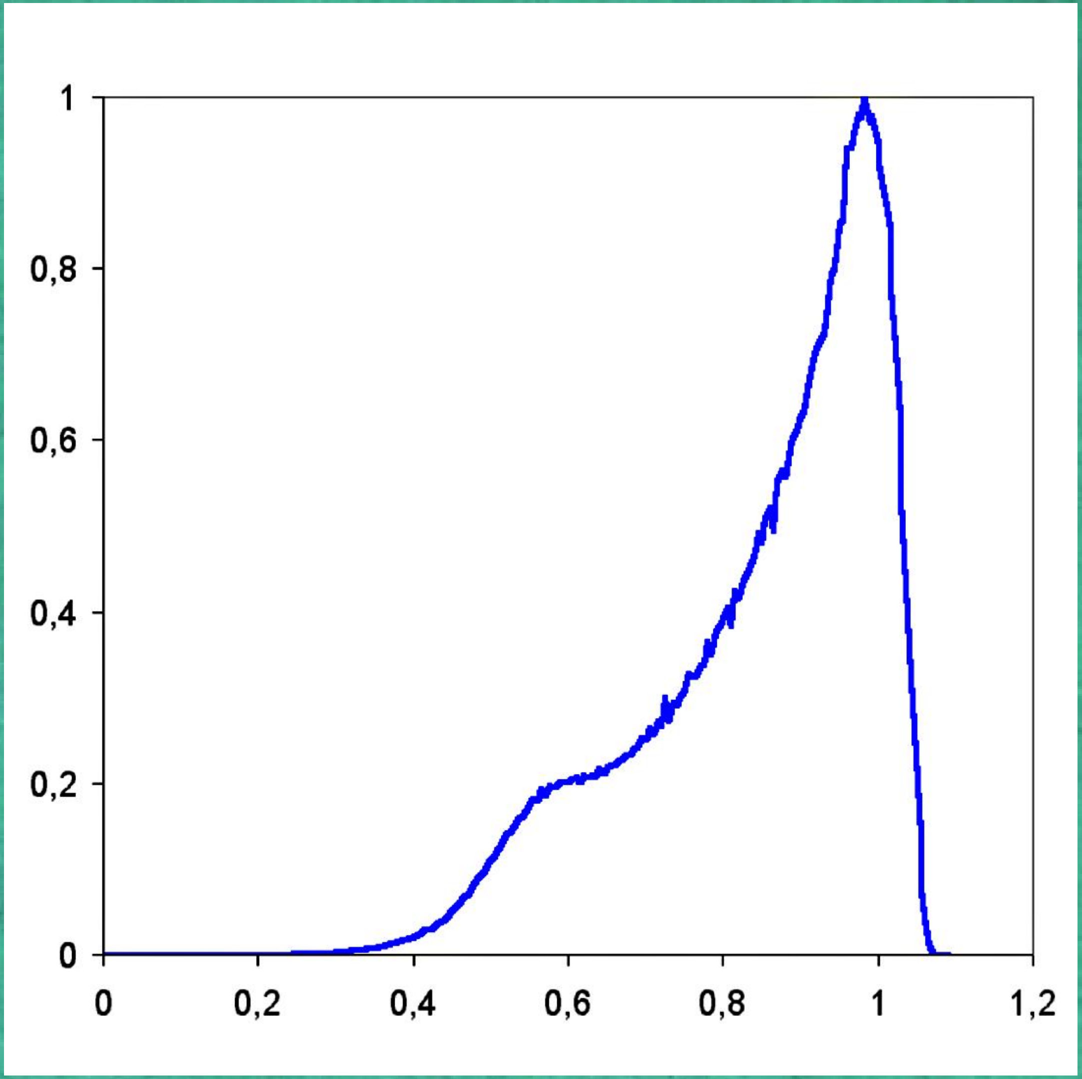
Keplerian

typical:

steep emissivity,

beaming lack

Line classification
Shoulder-like



Parameters:

a = 0.8

i = 40°

r_{in} = 1.6

r_{out} = 30.0

R_t = 4.0

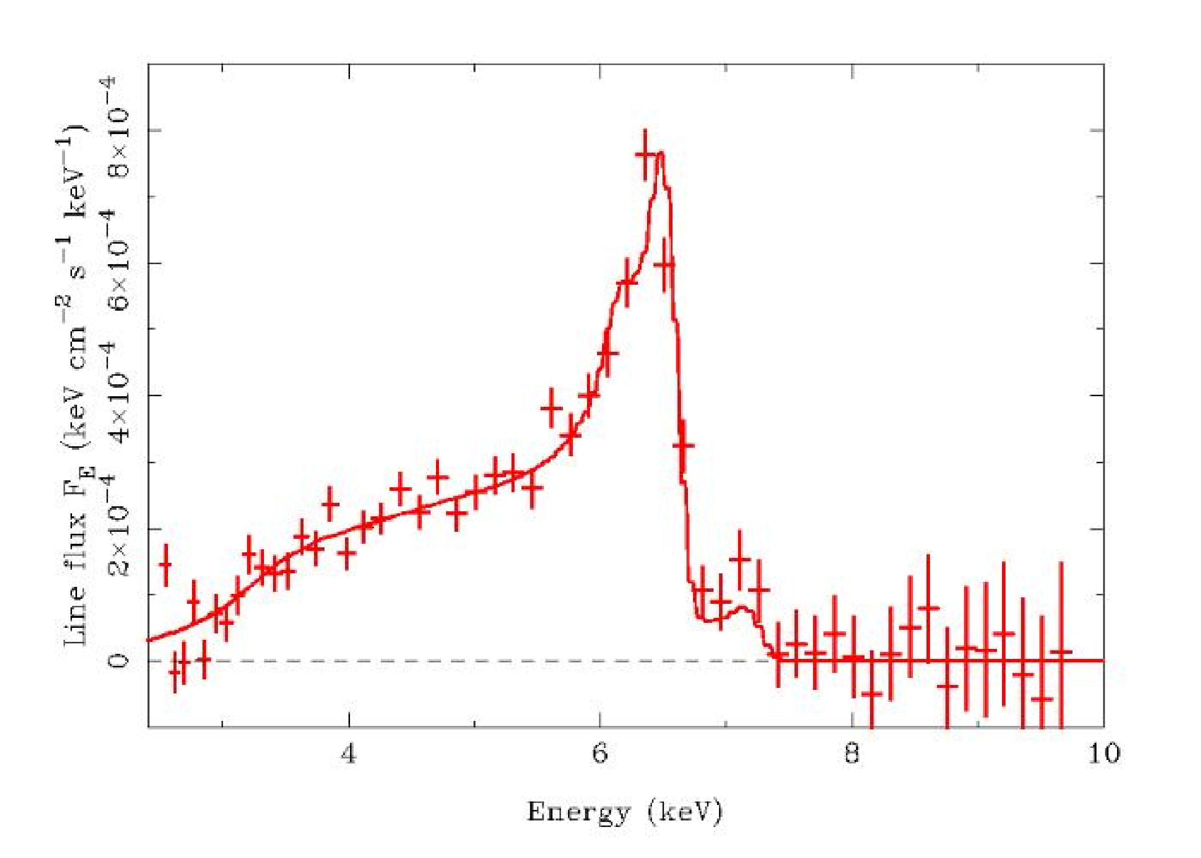
Gaussian emissivity

Keplerian + drift

typical:
localized emissivity,
Medium inclination,
very sensitive!

Line observations

Seyfert 1 MCG-6-30-15, z = 0.008



XMM EPIC MOS

broad Fe Kα 6.5 keV

+

broad Fe Kβ 7.05 keV

i = 27.8°

R_{in} = 2.0

R_{br} = 6.5

q_{in} = 4.8 broken

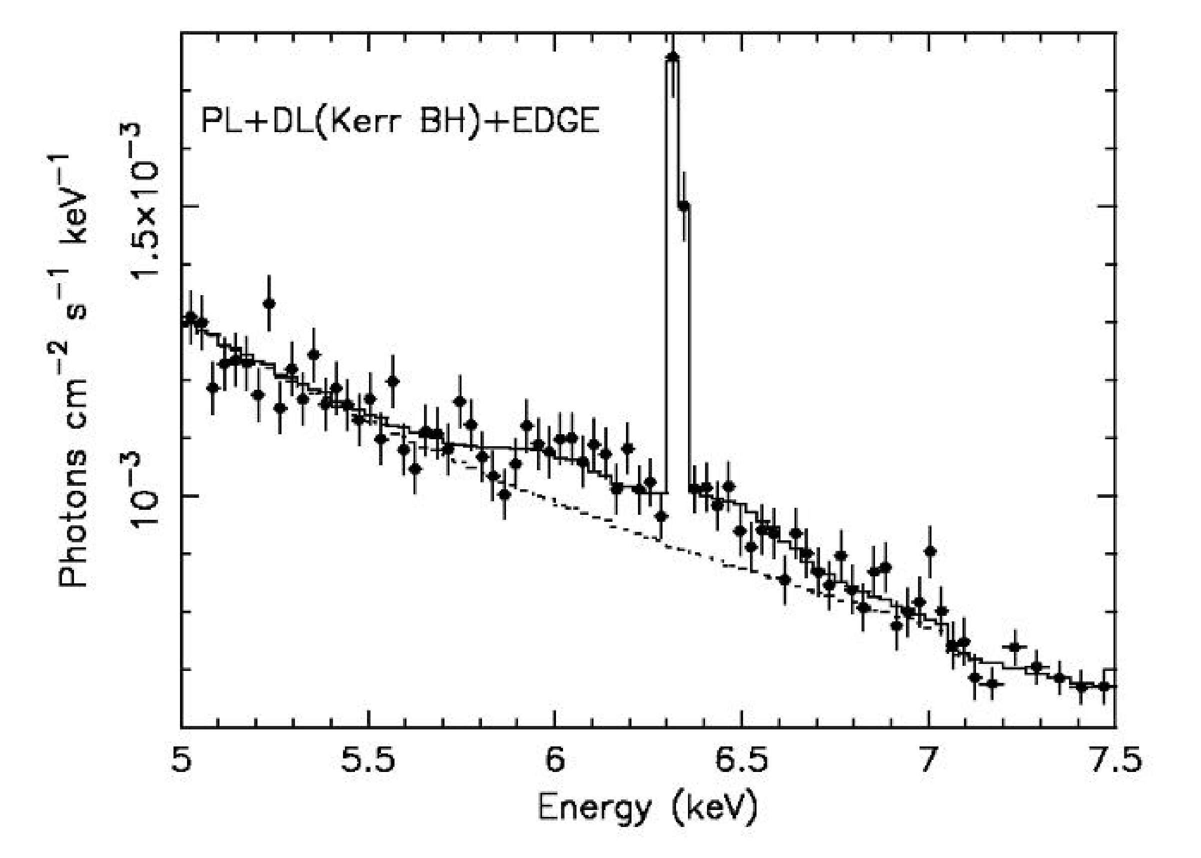
q_{out} = 2.5 emissivity

Γ = 1.95

shoulder-like line topology

(Fabian et al. 2002)

Line observations
Seyfert 1.9 MCG-5-23-16, z = 0.0083



XMM EPIC PN

broad Fe Kα 6.4 keV

+

narrow Gaussian

(torus reflection)

i ~ 46°

absorption feature

at 7.1 keV

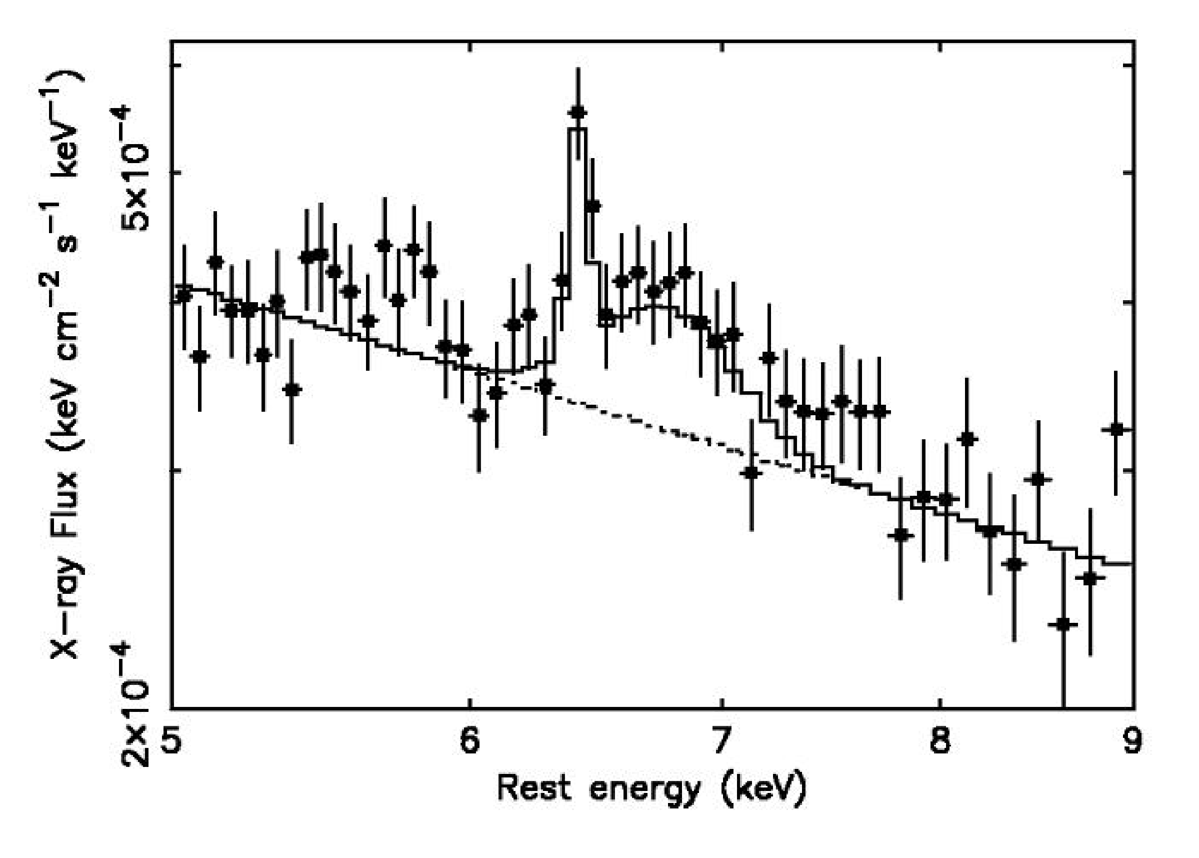
flattening continuum

⟷

line weakening

(Dewangan et al. 2003)

Line observations
Quasar Mrk 205, z = 0.071



XMM EPIC PN

broad Fe Kα 6.7 keV

+

narrow Gaussian

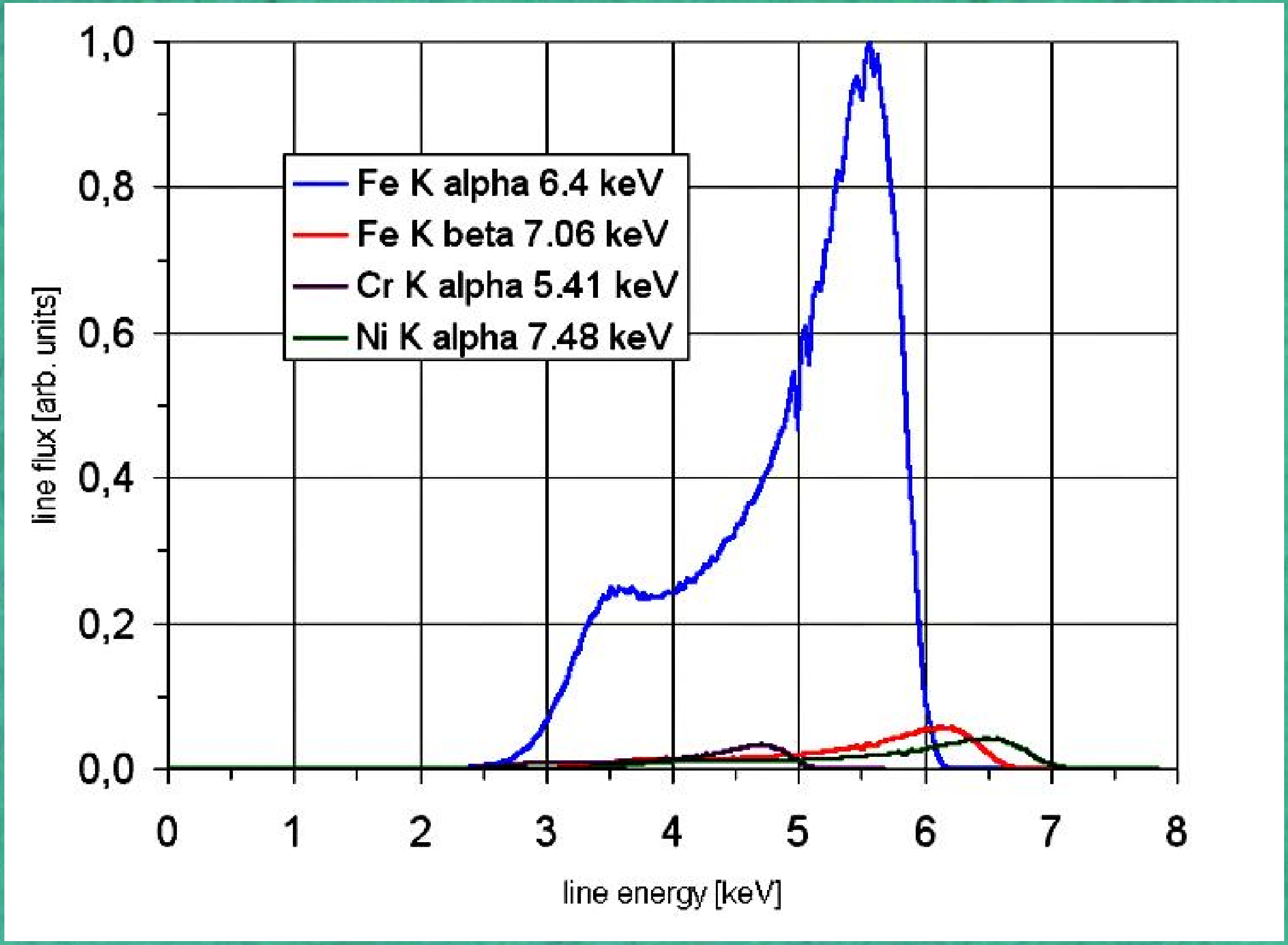
6.4 keV (neutral component)

i ~ 75...90°

low luminosity, radio-quiet QSO

(Reeves et al. 2000)

X-ray spectroscopy
Multi-species emission line complex



Parameters:

$a = 0.998$

$i = 30°$

$r_{in} = r_{ms} = 1.23$

$r_{out} = 30.0$

$R_t = 4.0$

$\sigma_r = 0.8$

Gaussian emissivity

(relative line strengths from *Reynolds 1996*)

Coming soon on the web...

paper version of this talk

A. Müller & M. Camenzind (2003)

powerpoint and postscript version of this talk available under

http://www.lsw.uni-heidelberg.de/~amueller/astro_ppt.html

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