PROCESSES CLOSE TO THE CENTRAL ENGINE OF AGN

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OVERVIEW

- Theoretical Framework
  1.1 Radiative Processes
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  1.3 Black hole accretion
  1.4 Relativistic effects
- Observations
  2.1 The X-ray continuum source
  2.2 The iron Kα line and Compton reflection
  2.3 Absorption
  2.4 The soft excess

PART 1: THEORETICAL FRAMEWORK

1.1 RADIATIVE PROCESSES

- Blackbody Radiation
- Electron Scattering
- Line Emission and Absorption

BLACKBODY RADIATION

For matter and radiation in thermal equilibrium, radiation has the Planck spectrum:

$$I(E) = \left(\frac{2}{h^2c^2}\right)\left(\frac{E^3}{e^{E/k_BT}-1}\right)d\nu$$

for $E = h\nu << kT$ we have the Rayleigh-Jeans spectrum:

$$I(\nu) \propto \nu^2$$

for $E = h\nu >> kT$ we have the Wien spectrum:

$$I(\nu) \propto \nu^3 \exp(-h\nu/kT)$$

Example in AGN physics: accretion disks

BLACKBODY EMISSION

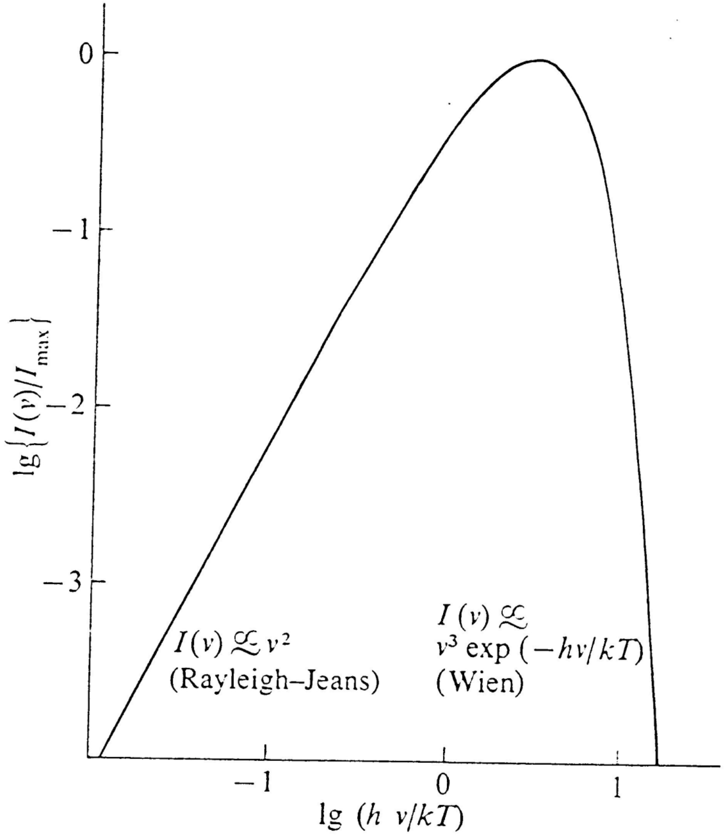


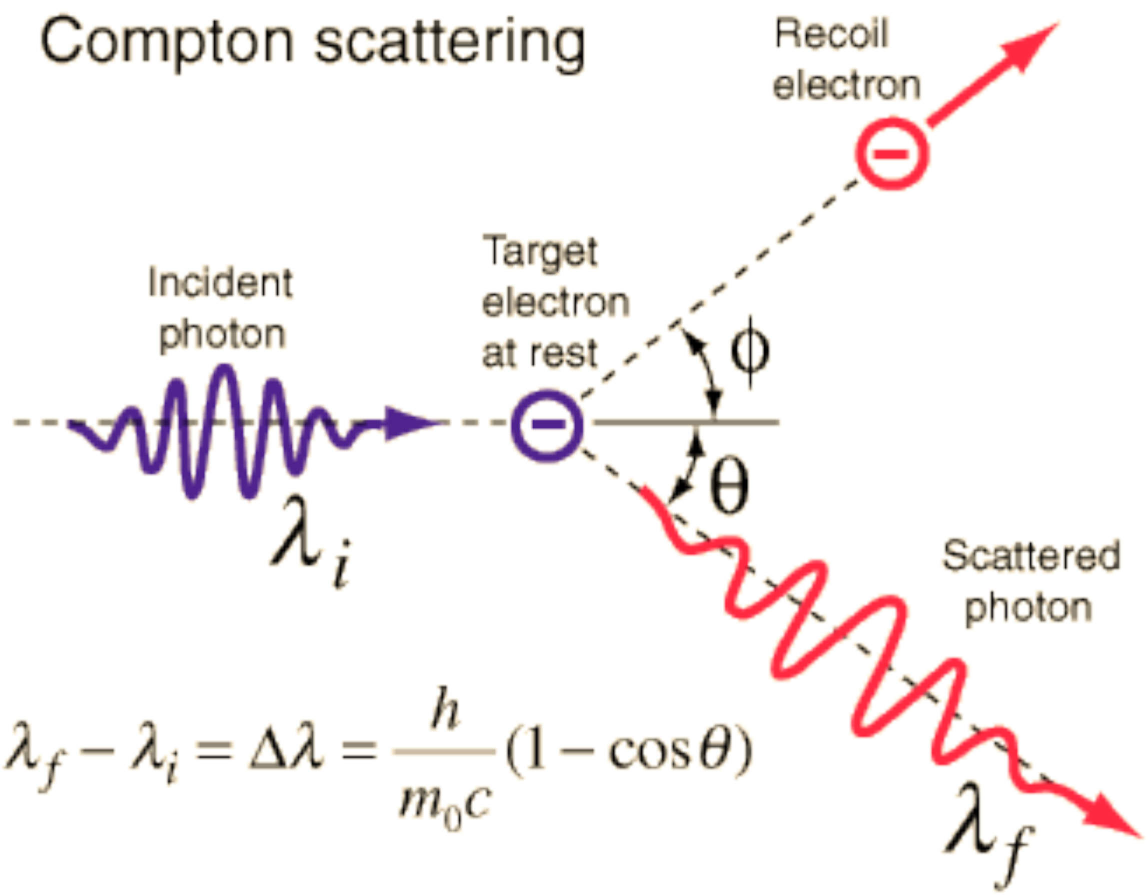
Fig. 1.9 The Planck blackbody spectrum. The intensity is given in units of the peak intensity. $I_{\max} = 1.9 \times 10^{-19}\, T^3\ \mathrm{Wm^{-2}\,sr^{-1}\,Hz^{-1}}$.

Peak frequency: $\nu_m = 2.821 \frac{k_B T}{h}$

Energy density:

$$u_{\mathrm{rad}} = \int_0^\infty \frac{4\pi}{c} I(\nu) d\nu = aT^4 \qquad \text{where}$$

$$a = \left(\frac{8\pi^5 k_B^4}{15 h^3 c^3} \right) = 7.565 \times 10^{-16}\,\mathrm{Jm^{-3}K^{-4}}$$



$$\lambda_f - \lambda_i = \Delta\lambda = \frac{h}{m_0 c}(1 - \cos\theta)$$

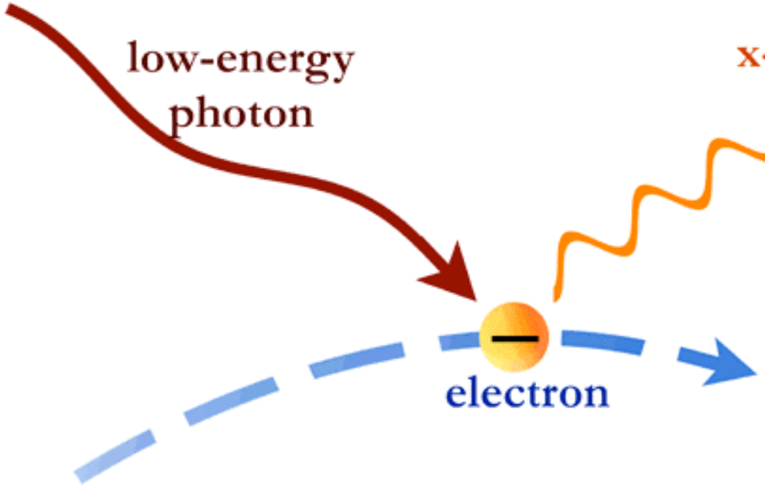
Thomson cross section: $\sigma_T = 6.65\times10^{25}$ cm^{-2}
Thomson optical depth: $\tau_T = \sigma_T N(H)$
“Optically thick”: $\tau_T > 1$

Example in AGN physics: reflection continuum

Credit: GSU Hyperphysics

INVERSE COMPTON EMISSION

- Photon $E_0 = h\nu$ boosted in energy by hot e^- at kT to e.g. X-rays

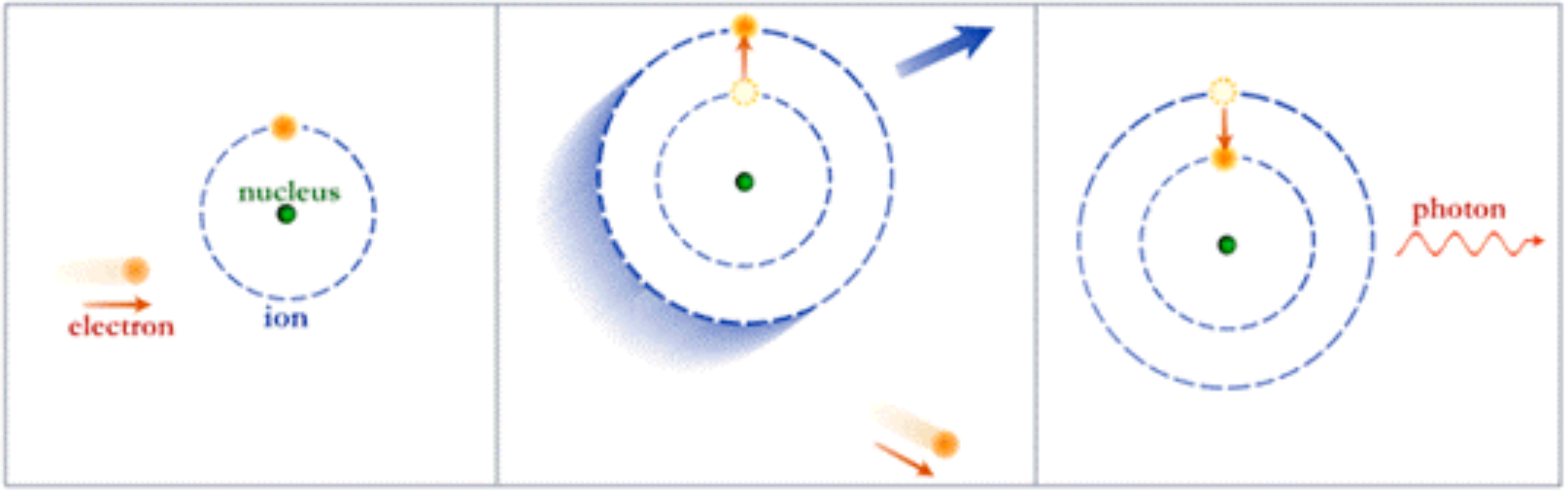


$$\frac{\Delta E}{E_0} = \frac{1}{m_e c^2}\left(4kT - E_0\right)$$

Example in AGN physics: Primary X-ray continuum

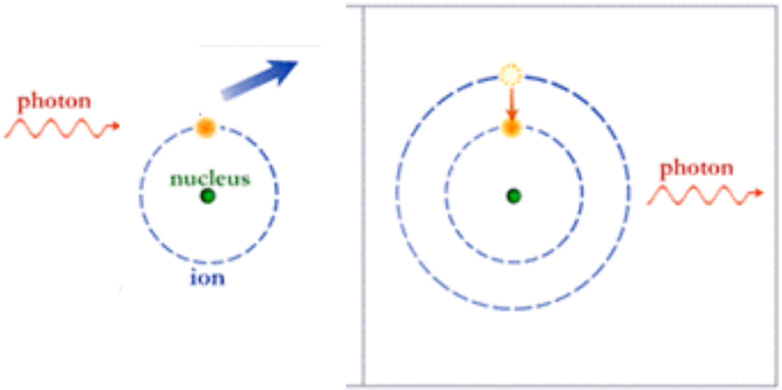
LINE EMISSION

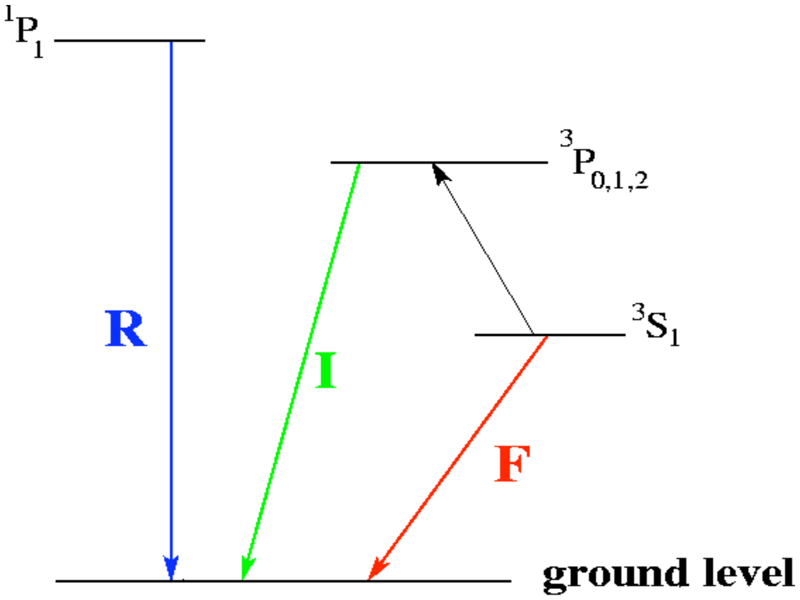
- Excitation of atoms by:
  - Thermal collisions
  - Radiative excitation
- Then radiative de-excitation



TYPES OF LINE EMISSION

- Fluorescence:
  - Needs L-shell electrons
  - Photoionization, then either:
  - 2p->1s radiative transition
  - *or* Auger ionization
  - **Fluorescence yield** measures ratio
- Recombination (ionized)
  - He and H-like are most important
  - Triplet: forbidden, resonance, intercombination





From R. Smith

STRONG X-RAY LINES (NEUTRAL)

Element	**Transition**	**Energy (keV)**
Carbon	C I Kα_1	0.277
Nitrogen	N I Kα_1	0.3924
Oxygen	O I Kα_1	0.525
Neon	Ne I Kα_1, Kα_2	0.849, 0.849
Magnesium	Mg I Kα_1, Kα_2, Kβ_1	1.253, 1.253, 1.302
Silicon	Si I Kα_1, Kα_2, Kβ_1	1.740, 1.740, 1.836
Sulphur	S I Kα_1, Kα_2, Kβ_1	2.308, 2.307, 2.464
Iron	**Fe I Kα_1, Kα_2, Kβ_1** Fe I Lα_1, Lα_2, Lβ_1	**6.403, 6.391, 7.058** 0.705, 0.705, 0.719
Nickel	Ni I Kα_1, Kα_2, Kβ_1 Ni I Lα_1, Lα_2, Lβ_1	7.478, 7.461, 8.265 0.852, 0.852, 0.869

From Bearden (1979)

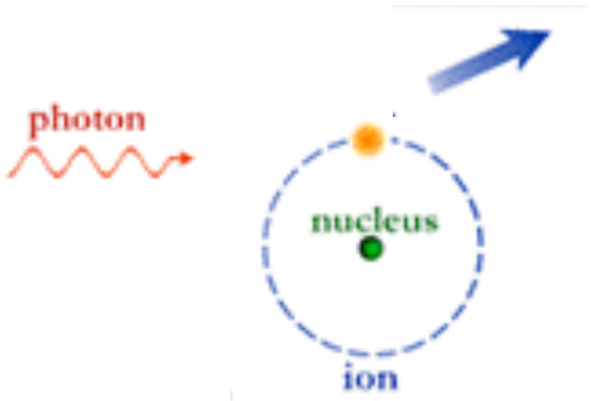
STRONG X-RAY LINES (IONIZED)

Element	**Transition**	**Energy (keV)**
Nitrogen	N VII	0.3924
Oxygen	O VII O VIII	0.666, 0.698 0.816, 0.837, 0.846
Iron	**Fe XXVI** **Fe XXVI Lyα**	**6.63(f), 6.67(i), 6.70(r)** **6.89, 6.97**
Nickel	Ni XXVII Ni XXVIII Lα	7.75(f), 7.80(i), 7.80(r) 7.95

From XSTAR list (T. Kallman NASA/GSFC)

PHOTOELECTRIC ABSORPTION

- Bound-free ionization of e^- by photon
- Threshold energy $E_{th}=h\nu$ depending on ionziation potential of atom (i.e. on Z)
- Abundant elements (C,N,O) are light: absorption dominant at soft (<1 keV) X-rays



Continuum ⇒

⇐ Observer

PROMINENT X-RAY ABSORPTION EDGES

Element	**Transition**	**Energy (keV)**
Carbon	C I V, VI K	0.282, 0.392, 0.490
Nitrogen	N I, VI, VII K	0.397, 0.552, 0.667
Oxygen	O I, VII, VIII K	0.533, 0.739 0.871
Neon	Ne I, IX, X K	0.876, 1.196, 1.362
Magnesium	Mg I, XI, XII K	1.309, 1.762, 1.963
Silicon	Si I, XIII XIV K	1.840, 2.432, 2.673
Sulphur	S I, XV, XVI K	2.471, 3.214, 3.494
Iron	Fe I, XXV, XXVI K Fe I M2, L2, L3	7.112, 8.755, 9.278 0.538, 0.721, 0.707
Nickel	Ni I XXVII, XXVIII K	8.339, 10.19, 10.66

From T. Kallmann (GSFC) compilation

PHOTOELECTRIC ABSORPTION

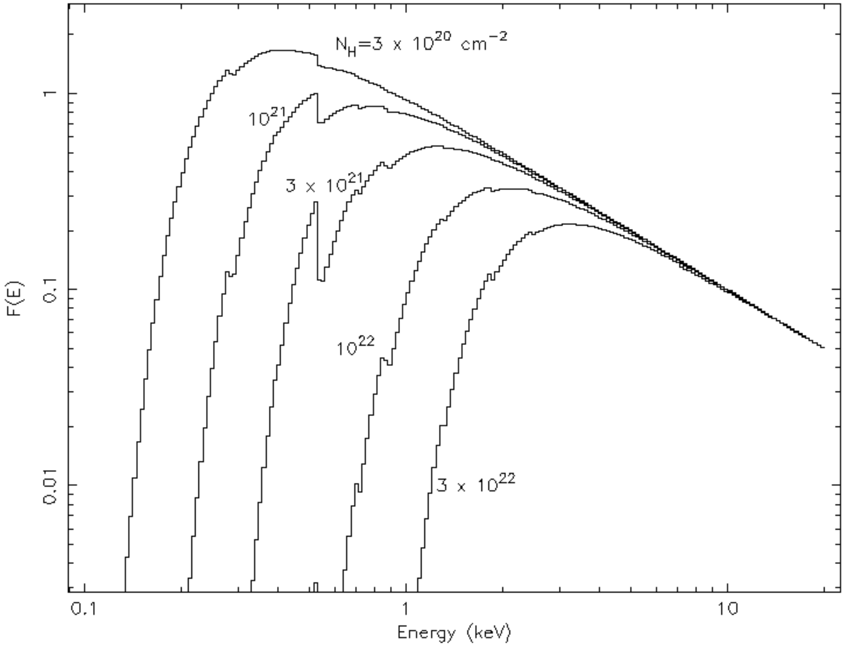
$N_H =$ Equivalent hydrogen column density (cm^{-2})

$\sigma(E) =$ cross section (cm^2)

$\tau = \sigma(E) N_H =$ optical depth

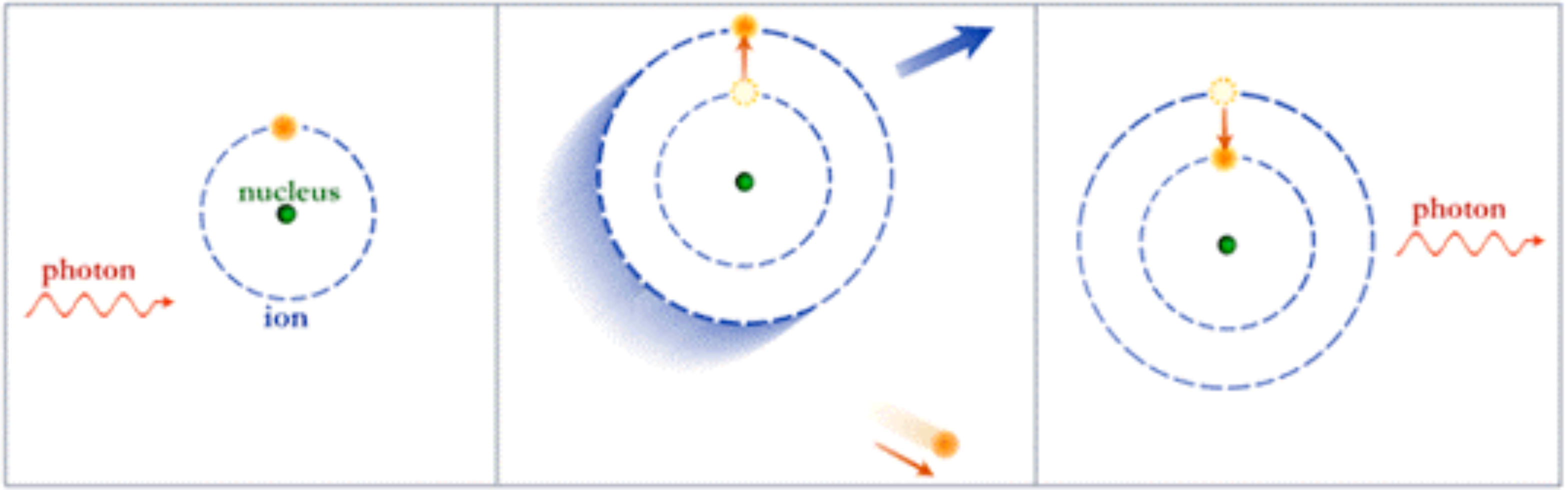
$F(E) = A E^{-\Gamma} e^{-\sigma(E) N_H}$

$\sigma(E) \approx E^{-3}$



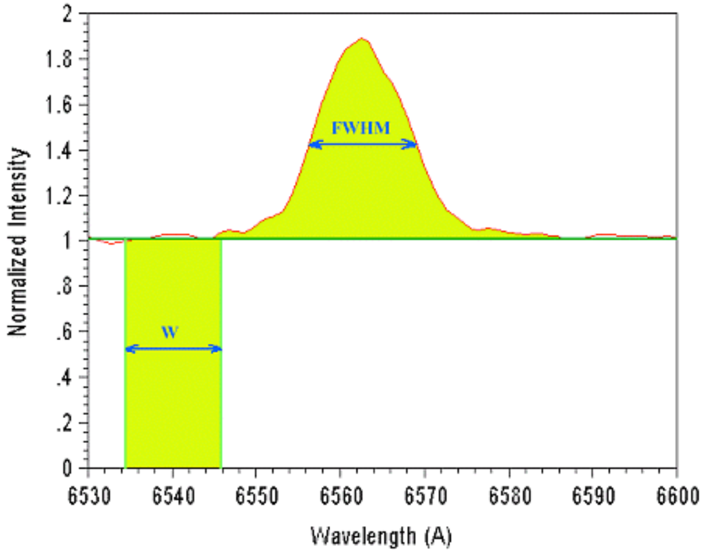
Profile dominated by bound-free edges of abundant elements

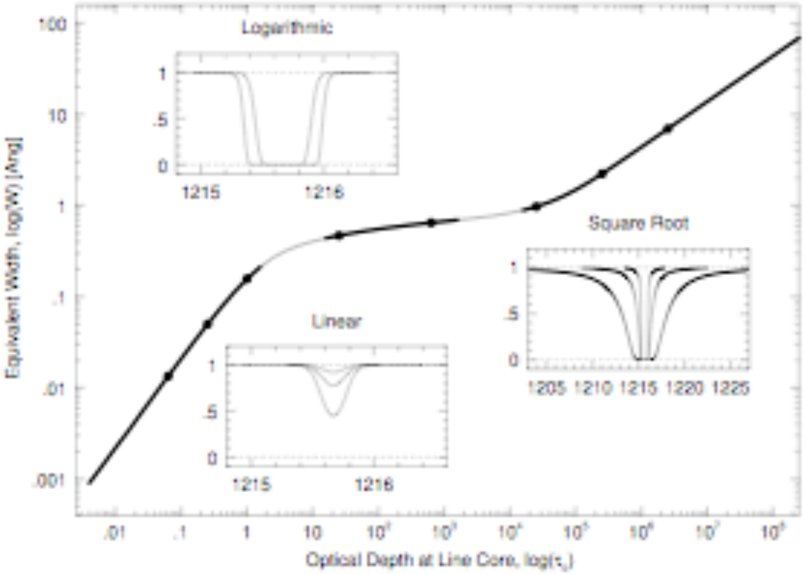
ABSORPTION LINES



- Absorption by a specific transition in atom
- Cross-sections larger than photoelectric
- But only over a small wavelength range
- Strength depends on Doppler parameter b
- Can measure N_H, U, velocity etc.

ABSORPTION LINES





Equivalent width:

$$EW = \frac{\int_{-\infty}^{\infty} F_l(E)\,dE}{F_c(E_l)}$$

F_l = line flux, F_c = continuum flux,

E_l = line energy

Curve of growth:

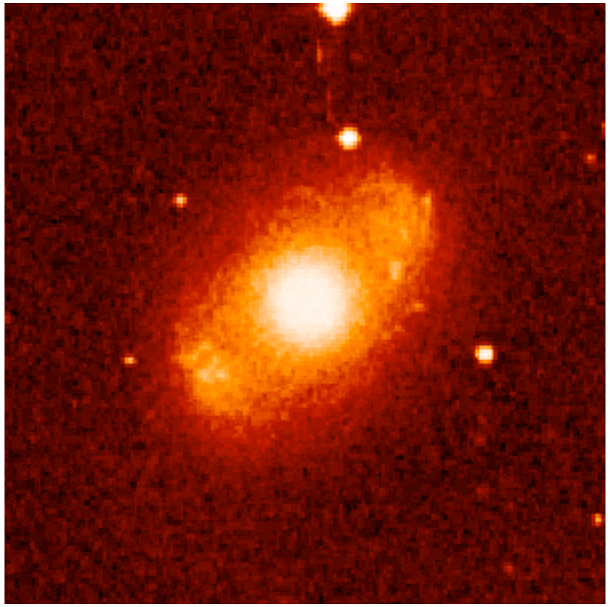
$\tau < 1 \quad EW \propto N$ (linear)

$10 < \tau < 10^3 \quad EW \approx const$ (saturated)

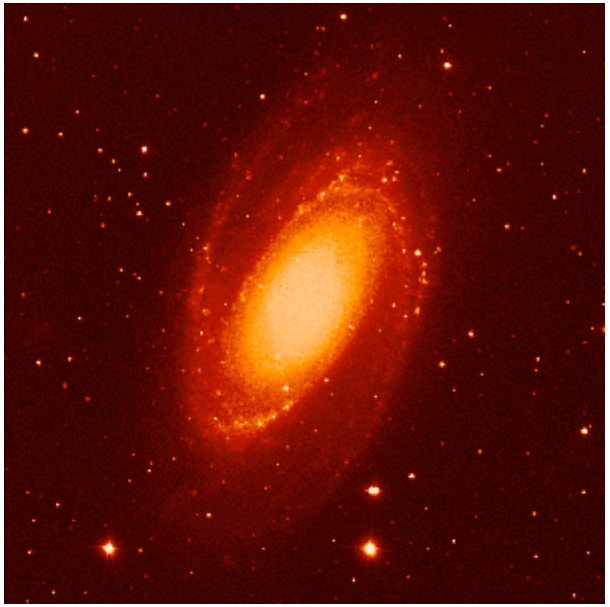
$\tau >> 10^4 \quad EW \propto \sqrt{N}$ (damping wings)

1.2 BASIC AGN PROPERTIES

ACTIVE: NGC 4151

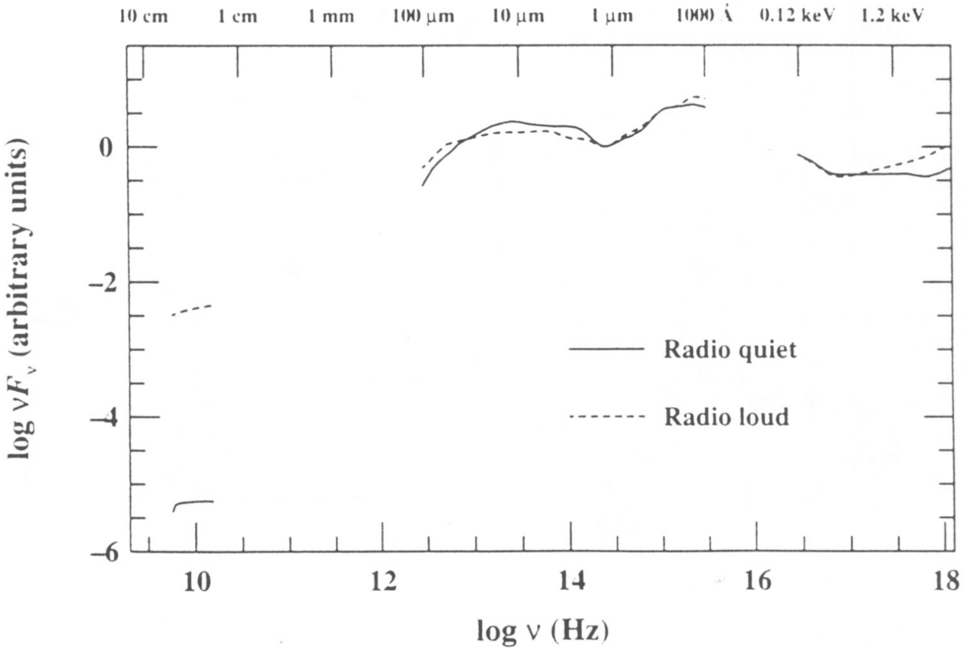


LINER: NGC 3031



RADIATIVE PROPERTIES

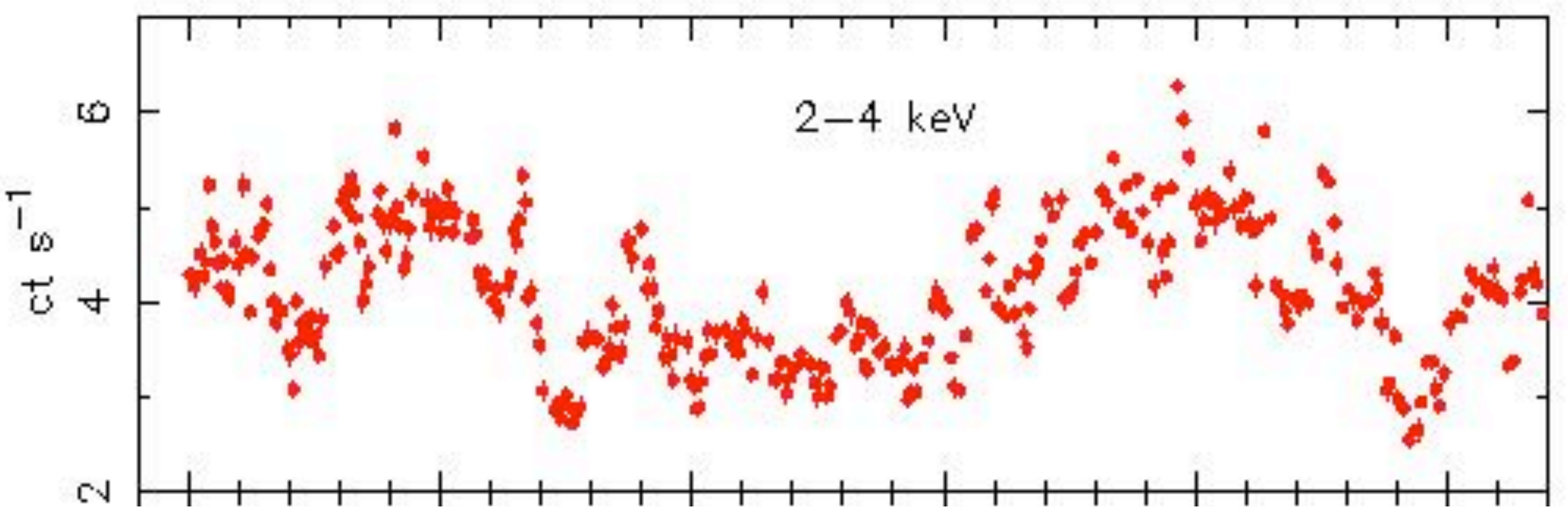
- AGN emit over a wide spectral range
- L_{bol} can exceed 10^{49} erg s^{-1}
- …or be as little as 10^{39} (50% of galaxies?)
- Strongly variable, thus **compact** (L/R)



Spectral Energy Distribution (SED)

Elvis et al. 1994

VARIABILITY



Time (30d duration)

X-ray variability is the most extreme (NGC 7469 RXTE)

X-RAY COMPACTNESS LEAGUE TABLE

	L_X erg s^{-1}	R(cm)	$L_x/L_{¤}$	R(AU)	L/R
AGN	10^{40}-10^{47}	10^{14}-10^{16}	10^{7}-10^{14}	2-200	10^{4}-10^{13}
Galaxy Clusters	10^{43}-10^{46}	10^{24}-10^{26}	10^{10}-10^{13}	10^{10}-10^{12}	10^{-2}-10^{3}
Normal Galaxies	10^{38}-10^{40}	10^{22}-10^{23}	10^{5}-10^{7}	10^{9}-10^{10}	10^{-5}-10^{-2}
Supernovae	10^{35}-10^{37}	10^{17}-10^{19}	10-10^{4}	10^{4}-10^{6}	10^{-5}-1
Stars, X-ray binaries	10^{30}-10^{37}	10^{6}-10^{11}	10^{-3}-10^{4}	10^{-7}-10^{-2}	10^{-1}-10^{11}

EFFICIENCY ARGUMENT

(e.g. Fabian 1979; Brandt et al. 1998)

Outburst of accreted mass M, luminosity ΔL in time Δt

$\Delta L \Delta t = \eta M c^2$ η = radiative efficiency

$M \approx m_p n V$ n = number density, V = volume

Source variability slowed down by scattering (photon diffusion):

$\Delta t \geq (1+\tau_T)\frac{R}{c}$ Thomson optical depth $\tau_T = n\sigma_T R$

Hence: $\eta \geq \frac{\Delta L}{\Delta t} f(\tau_T)$ $f(\tau_T) \propto \frac{(1+\tau_T)^2}{\tau_T}$

So η has a minimum value for a given $\Delta L/\Delta t$ of:

$$\eta \geq 4.8 \times 10^{-43} \Delta L / \Delta t$$

AGN variations typically exceed η =0.007, max for nuclear fusion

➔ACCRETION POWERED SOURCES

BASIC PARAMETERS

Eddington limit:

$$F_{rad} = F_{grav}$$

$$L_{Edd} = \frac{4\pi G M_{\bullet} m_p}{\sigma_T} = 1.26 \times 10^{38} \left(\frac{\mathrm{M}}{\mathrm{M}_{\Theta}} \right) \text{ erg s}^{-1} \text{ (H only)}$$

$$= 1.52 \times 10^{38} \left(\frac{\mathrm{M}}{\mathrm{M}_{\Theta}} \right) \text{erg s}^{-1} \text{ (including He)}$$

Accretion Luminosity:

$$L = \eta \dot{M} c^2 \quad \dot{m} = \frac{L}{L_{Edd}} = \frac{\dot{M}}{\dot{M}_{Edd}}; \quad \dot{M}_{Edd} = \frac{L_{edd}}{\eta c^2}$$

efficiency depends on compact object (NS, BH, spinning BH)

1.3 BLACK HOLE ACCRETION

- Rapid variability: trillions of solar luminosities are generated in a region $<10^{13\text{-}15}$ cm.
- Source is extremely compact and highly efficient – usually too efficient for stellar processes.
- Implied efficiency $\eta>0.1$ (10-100 x fusion)
- Eddington limit implies mass $M>8 \times 10^5\ L_{44}\ M_\odot$
- Dynamical studies show masses of $\sim 10^6\text{-}10^9\ M_\odot$
- ⇒ Compact object is a supermassive black hole

DISK ACCRETION

- Accreting material will have angular momentum ⇒ **ACCRETION DISK**

Accretion rate required to generate $L = \eta \dot{m} c^2$

$\dot{m} \approx 1.8 \times 10^{-3} L_{44} M_8 \text{ yr}^{-1}$

Radial temperature profile

$L \propto GM\dot{m}/R \propto 2\pi R^2 T^4$ (local blackbody assumption)

Hence :

$T(R) = M^{-0.25} \dot{m}^{0.25} R^{-0.75}$

Typical characteristic temperature is $T_{bb} = 5\ 10^5\ M_8^{-0.25}$ K

ALPHA DISKS

The classic solution for accretion disks was given by Shakura & Sunyaev (1973). SS disks can be either *gas pressure* or *radiation pressure* dominated.

Temperature, Flux and Density for Radiation dominated (small *R*):

$$T = 3.1\times10^{5}\alpha^{-1/4}M_8^{-1/4}\left(\frac{R}{R_g}\right)^{-3/8} K$$

$$F = 8.3\times10^{17}\left(\frac{R}{R_g}\right)^{-3}\left(\frac{\dot{M}}{M_{edd}}\right)M_8^{-1}\left(1-\left[\frac{R_{in}}{R}\right]^{1/2}\right)\mathrm{erg\ cm^{-2}\ s^{-1}}$$

$$n = 5.7\times10^{10}\alpha^{-1}\left(\frac{R}{R_g}\right)^{-3/2}\left(\frac{\dot{M}}{M_{edd}}\right)^{-2}M_8^{-1}\left(1-\left[\frac{R_{in}}{R}\right]^{1/2}\right)^{-2}$$

Viscosity parameter α encompasses unknown physics!

(Treves, Maraschi & Abramowicz, PASP, 1988)

MAGNETO-ROTATIONAL INSTABILITY

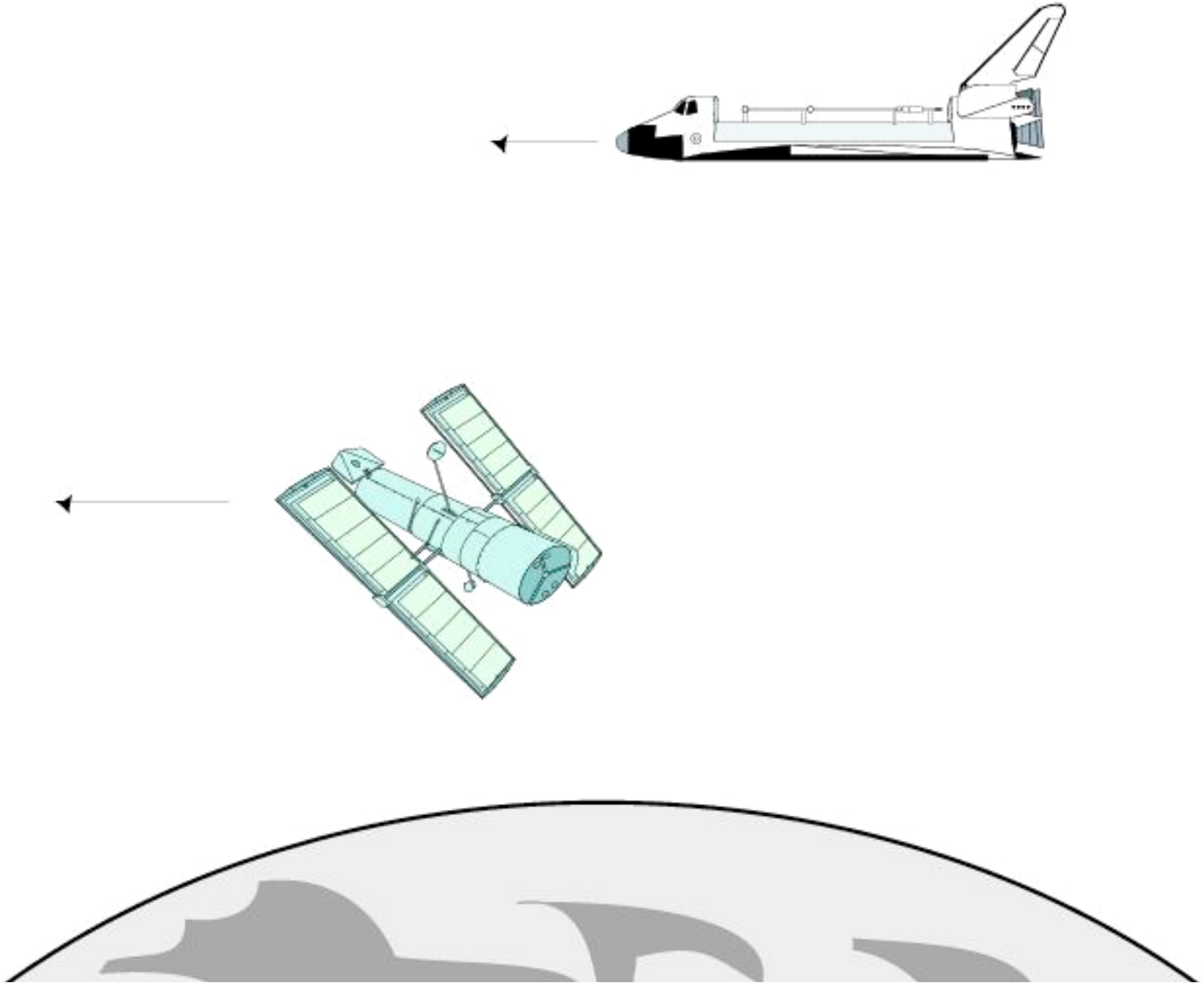
- Disk threaded by weak magnetic field
- Radial fluid elements coupled by magnetic tension (like a spring)
- Outer element speeds up, moves out
- Inner element slows down, moves in – accretion happens!
- Provides angular momentum transport
- Unstable ⇒ turbulence

(Balbus & Hawley 1991)

Orbital Dynamics

Higher angular momentum = lower angular velocity

Slide: J. Hawley



Orbital Dynamics

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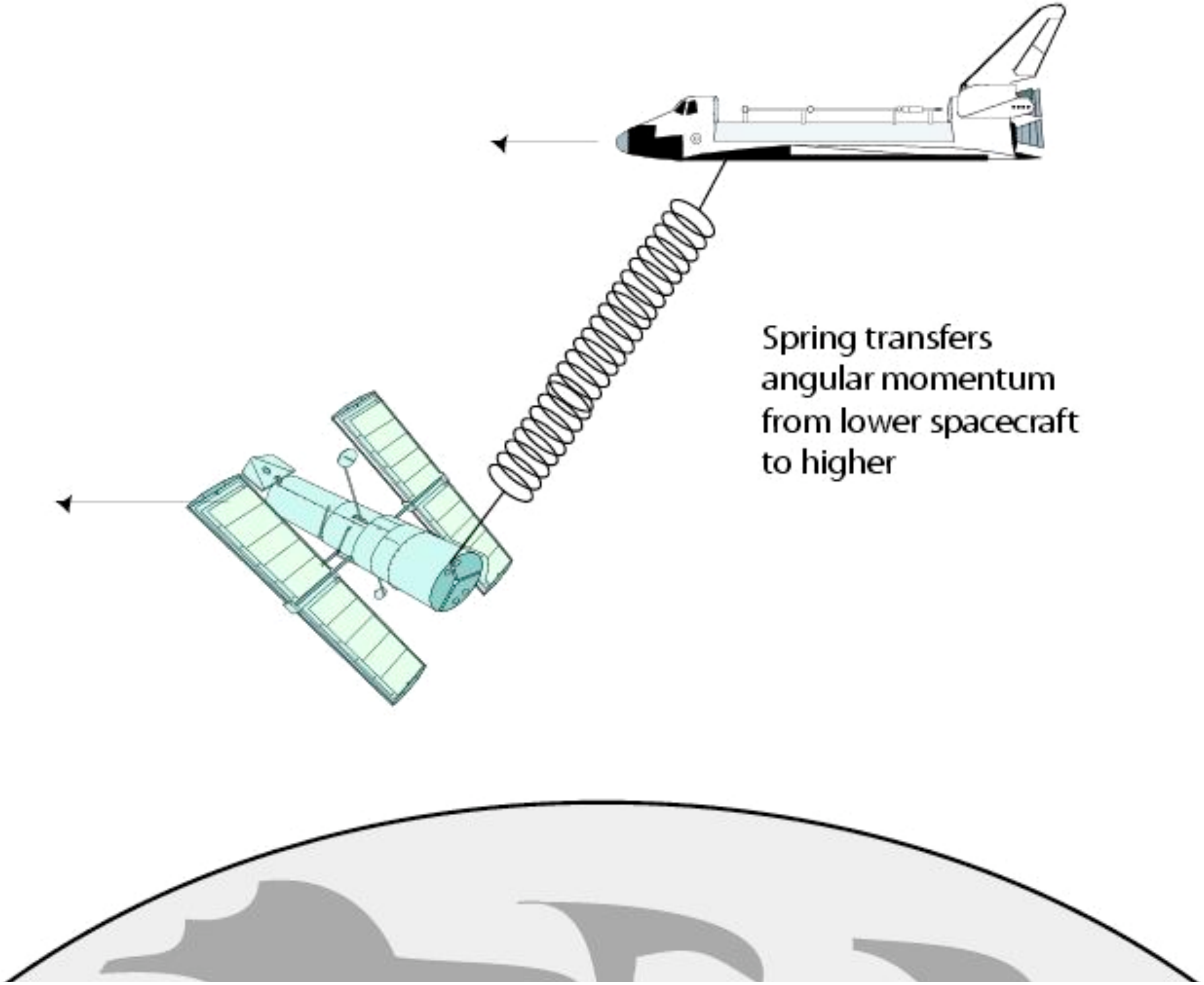
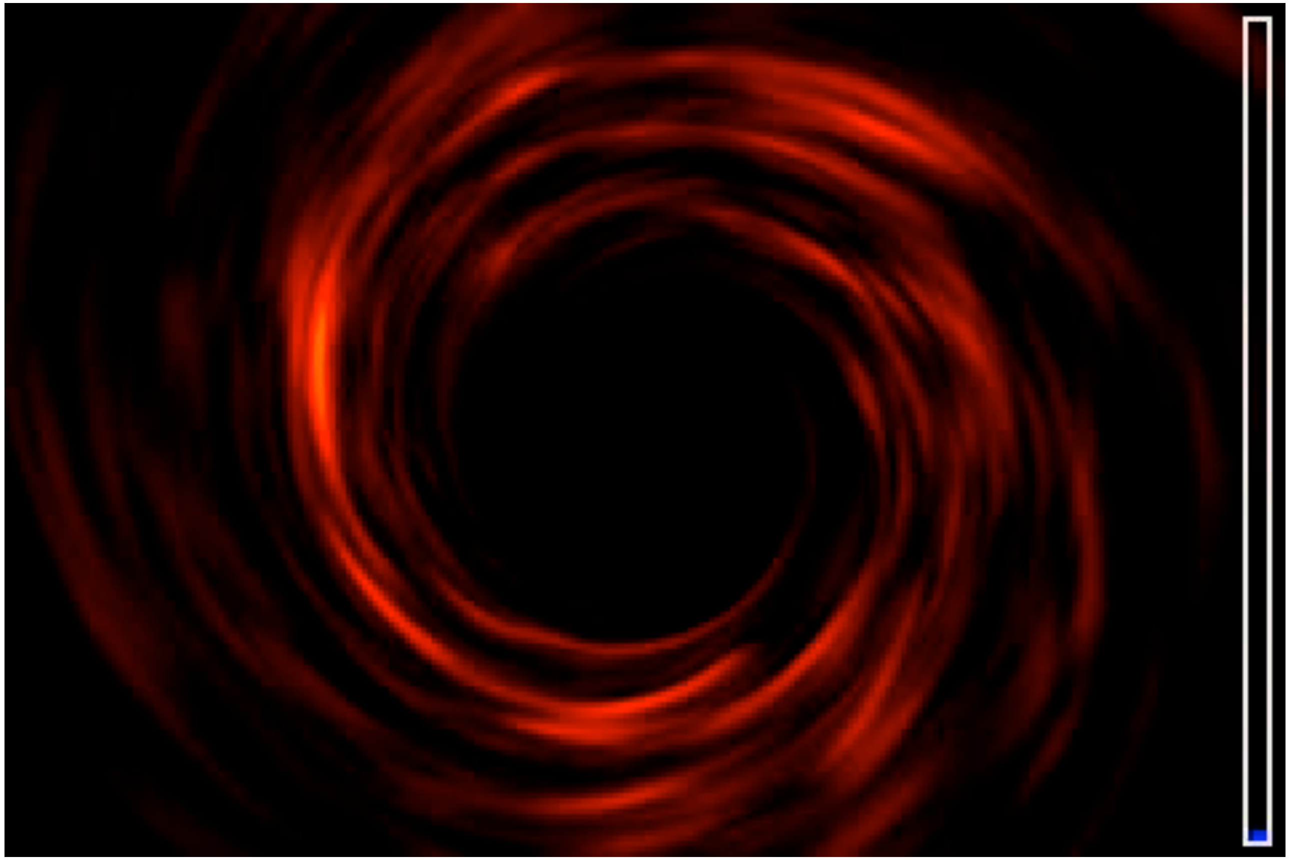


Spring transfers angular momentum from lower spacecraft to higher

MHD SIMULATIONS



Armitage & Reynolds (2003)

1.4 RELATIVSTIC EFFECTS

- Black hole important at small radii
- Doppler shifts due to large velocities
- Gravitational redshift
- Time dilation
- Light bending/focussing

BLACK HOLE FUNDAMENTALS

Schwarzschild Metric (non-rotating BH):

$$ds^2 = -\left(1 - \frac{R_s}{r}\right)c^2 dt^2 + \left(1 - \frac{R_s}{r}\right)^{-1} dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2$$

$$E_{obs} = E_{em}\sqrt{1 - \frac{2R_g}{R}}$$ (Gravitational redshift)

$$R_s = 2R_g = \frac{2GM}{c^2} = 2.96 \times 10^{13} M_8 \text{ cm}$$ (Schwarzschild radius)

$$R_{ms} = 6R_g \quad (\sim 20\% \text{ shift})$$

Infinite gravitational redshift at R=R_s (event horizon)

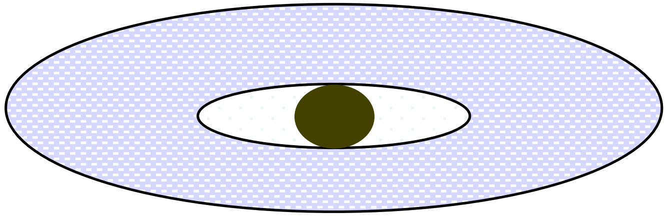
Kerr metric describes rotating black hole
Event horizon at R~R_g

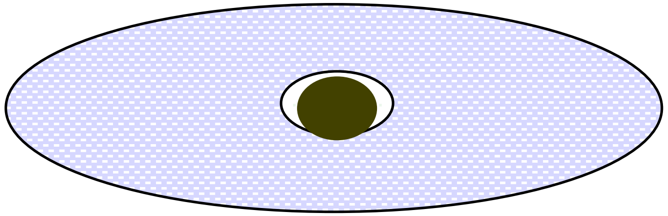
Spin parameter a/M=0-1
Schwarzschild ➔Maximal Kerr

THE ISCO

- Stable orbits cannot exists arbitrarily close to the BH
- Radius of marginal stability r_{ms} or Innermost Stable Circular Orbit (ISCO)
- Depends on black hole spin:

Schwarzschild (a=0): $r_{ms} = 6\ r_g$
Maximal Kerr (a~1) prograde: $r_{ms} \sim r_g$
Maximal Kerr (a~1) retrograde: $r_{ms} \sim 9r_g$
Measuring ISCO can constrain spin**

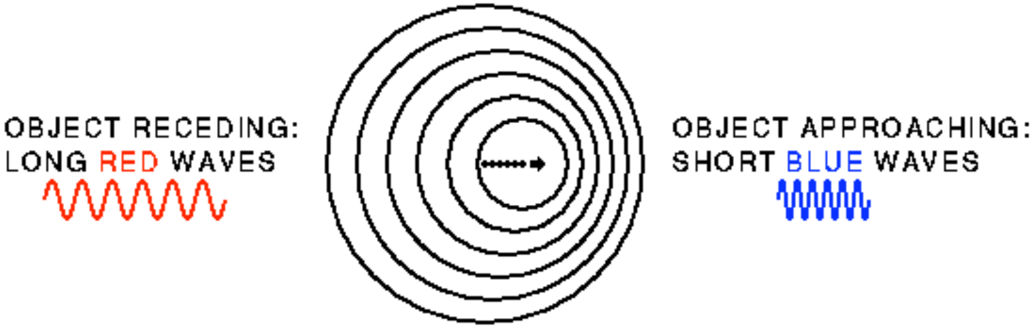

SCHWARZSCHILD = NON-ROTATING


KERR = ROTATING

***But emission within r_{ms} possible for Schwarzschild (Reynolds & Begelman 1997)*

ENERGY SHIFTS

$$z = \frac{\Delta\nu}{\nu_0} = \frac{\nu_e - \nu_0}{\nu_0} \approx \frac{\upsilon}{c}$$ for $\upsilon << c$ (Classical Doppler)



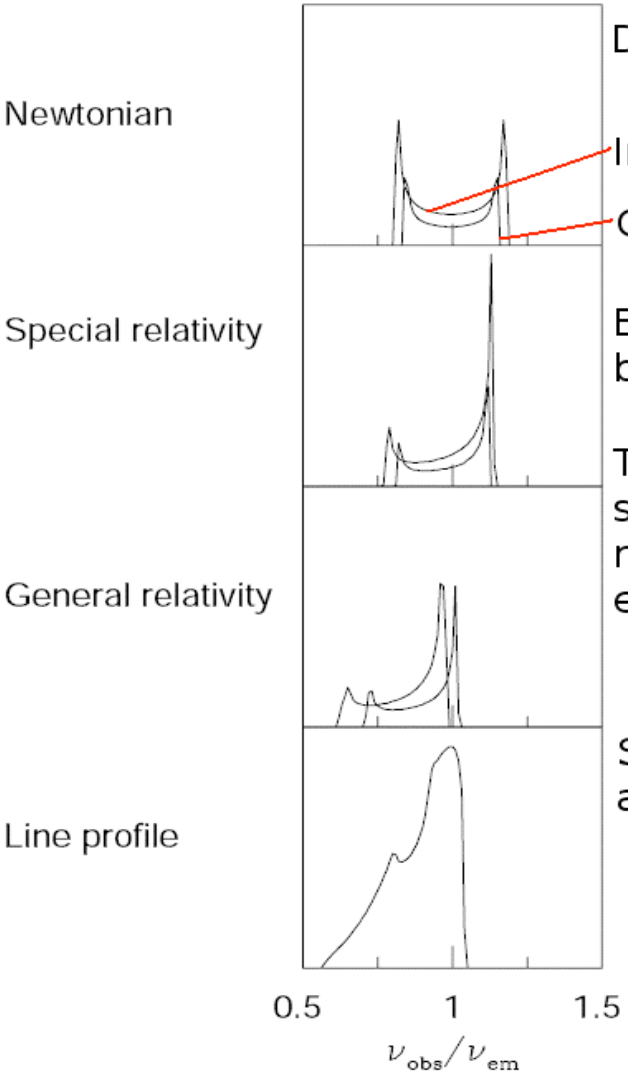
$$z = 1 - \sqrt{\frac{1+\upsilon/c}{1-\upsilon/c}}$$ (SR: v≈c + beaming/aberration)

$$E_{obs} = E_{em}\sqrt{1 - \frac{2R_g}{R}}$$ (gravitational redshift)

$$R_g = \frac{GM}{c^2} = 1.48 \times 10^{13} M_8 \text{ cm}$$

$$R_{ms} = 6R_g \quad (\sim 20\% \text{ shift})$$

LINES FROM A RELATIVISTIC DISK



Doppler shift

Inner annulus

Outer annulus

Beaming enhances blue peak

Transverse Doppler shift and gravitational redshift decrease emission energy

Sum emission from all radii