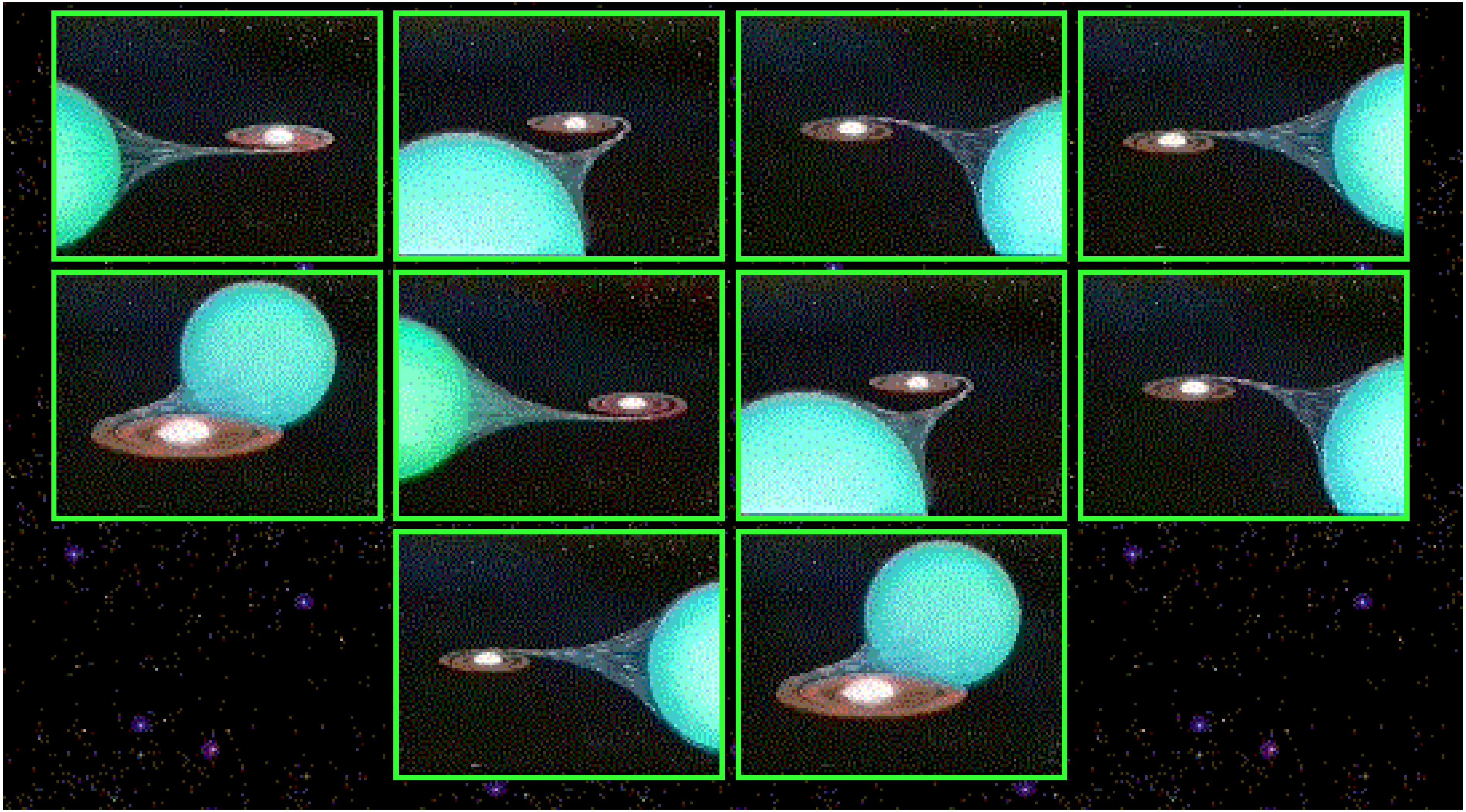


Accretion and Accretion Disks

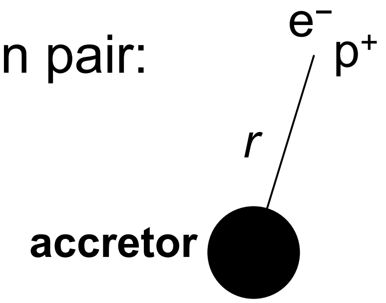
- Spherical accretion (Bondi Hoyle)
- Standard accretion (Shakura&Sunyaev)
- Advection dominated accretion (ADAF)
- ADIOS
- Corona
- Distortions (ionisation, relativistic effects)

Spherical Accretion (Bondi Hoyle)

The radiation pressure is $P_{\mathrm{rad}} = \frac{F}{c} = \frac{L}{4\pi r^2 c}$, so that $\vec{F}_{\mathrm{rad}} = \sigma_e \frac{L}{4\pi r^2 c}\hat{r}$,

where σ_e is the Thompson cross-section.

This has to balance the gravity exerted over an electron-proton pair:



$$\vec{F}_{\mathrm{grav}} = -\frac{GM_\bullet(m_p + m_e)}{r^2}\hat{r}$$

The condition $\vec{F}_{\mathrm{rad}} \le \vec{F}_{\mathrm{grav}}$ then implies that

$$L \le \frac{4\pi G c m_p}{\sigma_e} M_\bullet \approx 6.31\times10^4 M_\bullet \ \mathrm{erg\,s^{-1}} \approx 1.26\times10^{38} (M_\bullet / M_\odot) \ \mathrm{erg\,s^{-1}}$$

This is known as the Eddington limit.

The Eddington luminosity is the maximum luminosity emitted by a body of mass $M_\bullet$ that is powered by spherical accretion.

$$\boxed{L_{\mathrm{E}} = \frac{4\pi G c m_p}{\sigma_e} M_\bullet}$$

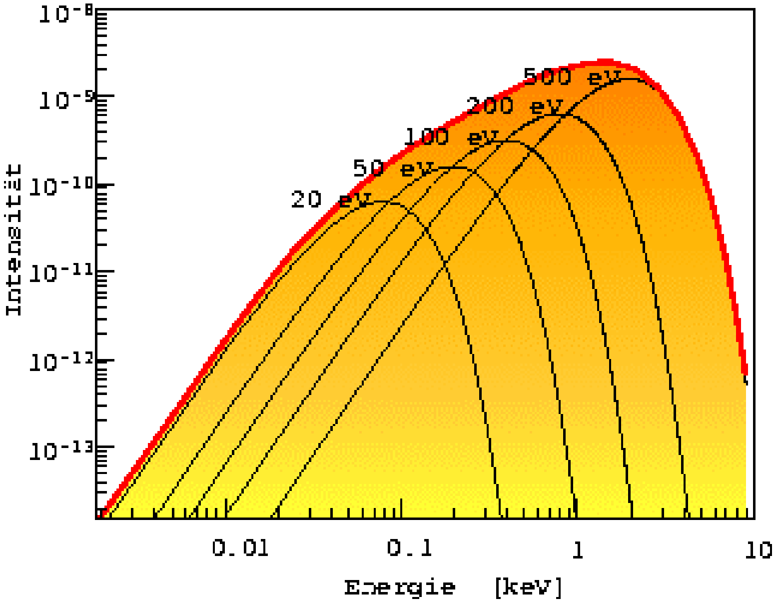
Standard Accretion (Shakura&Sunyaev 1973)

- virial theorem: half of potential is radiated away, other half heats gas

$$L = \frac{1}{2}\dot{U} = \frac{GM_\bullet \dot{M}_\bullet}{2r} = 2\pi r^2 \sigma T^4 \;\Rightarrow\; T = \left(\frac{GM_\bullet \dot{M}_\bullet}{4\pi\sigma r^3}\right)^{1/4}$$

- Temperature distribution

$$T(r) \approx \left[\frac{3GM_\bullet \dot{M}_\bullet}{8\pi\sigma R_S^3}\right]^{1/4} \left(\frac{r}{R_S}\right)^{-3/4} = 6.3\times 10^5\,\mathrm{K} \left(\frac{\dot{M}_\bullet}{\dot{M}_E}\right)^{1/4} M_8^{-}$$



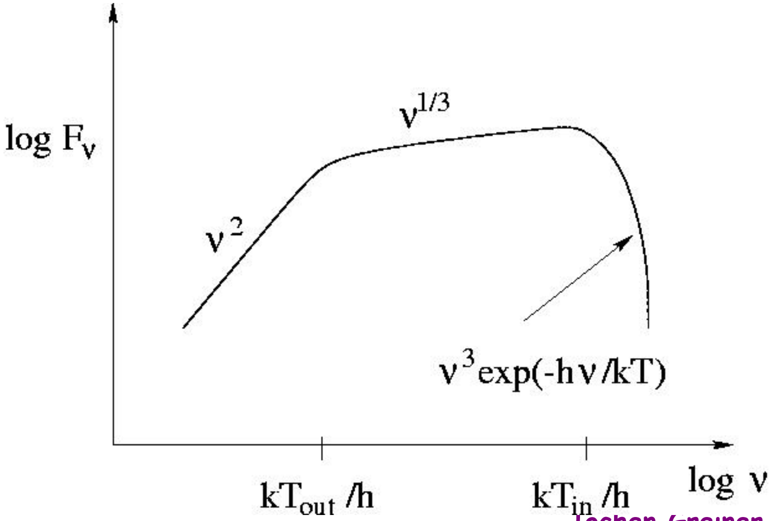
- 2 regions:

  radiation pressure > gas pressure

  inner region; torus-like

  gas pressure > radiation pressure

  optically thin, geometrically thick disk
- Innermost radius = 6 R_g = 6 GM/c^2



Thin Accretion Disk Models

- Cooling-Dominated Flows: **viscous heating of the gas is balanced by local radiative cooling.**

- Advection-Dominated Flows (ADAF):

  electrons decouple from protons: radiative cooling is very inefficient and most of the dissipated energy is advected into the black hole.

- Advection-Dominated Flows with Inflow and Outflow (ADIOS): **outflow is possible based on the Bernoulli number.**

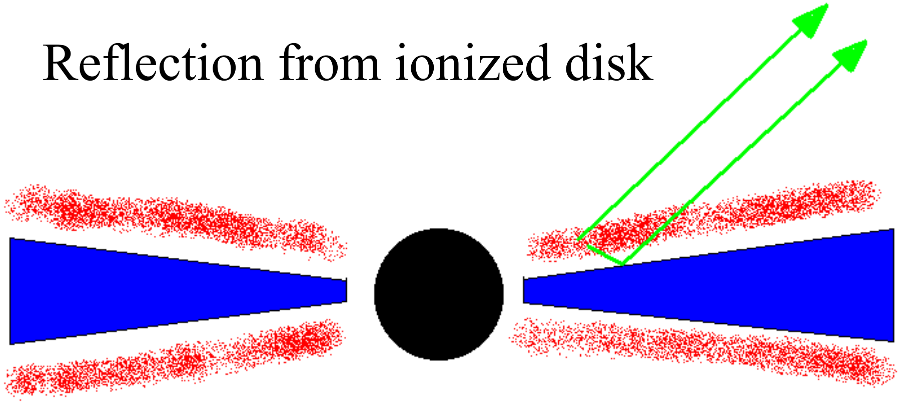
  is interesting as it may describe jets

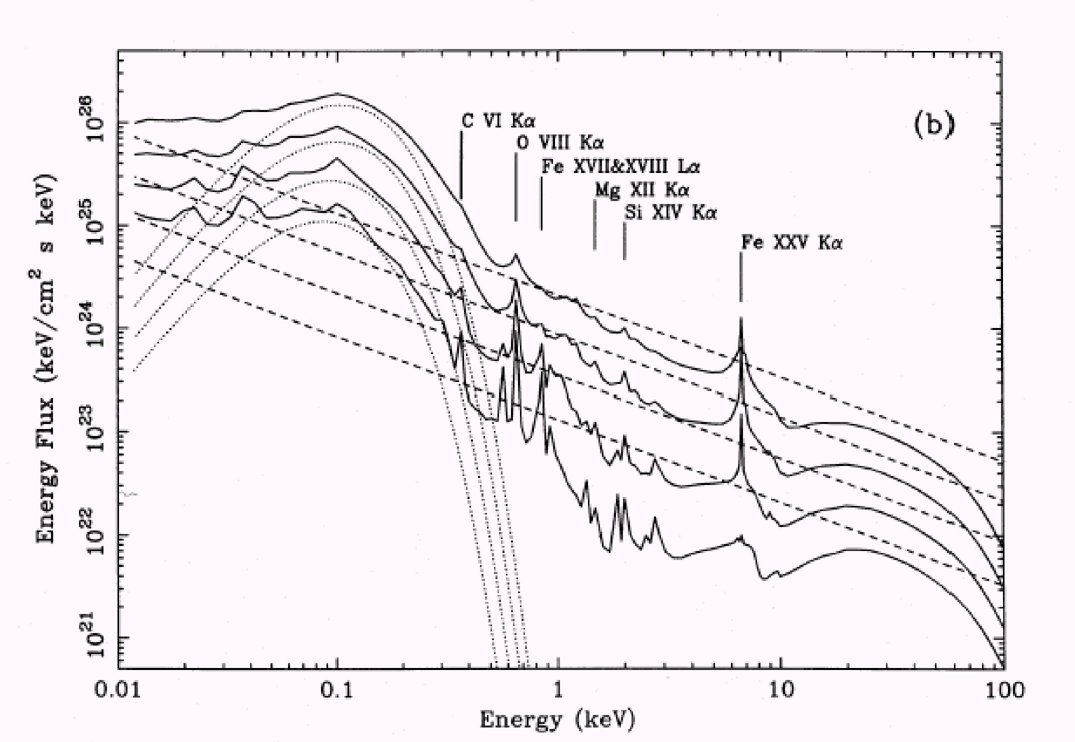
Main Properties of Accretion Disk

- Inflow of Matter
    - ☞coming through Lagrange point from companion
    - ☞being gas and/or stars from galaxy
- Outwards Transport of Angular Momentum
    - ☞through viscous stress
    - ☞through hydromagnetic winds
    - ☞through amplification of local viscous stress through the onset of turbulence resulting from possible hydromagnetic, convective, or shear flow instabilities
    - ☞through propagating waves
    - ☞through torque resulting from the presence of nonaxisymmetric unstable modes in self-gravitating and geometrically thick disks
- Electron Corona
    - ☞either spherical around central object
    - ☞or in two slabs (sandwich-like) above/below disk
- Matter Outflow
    - ☞either spherical wind
    - ☞or directed outflow (jet)

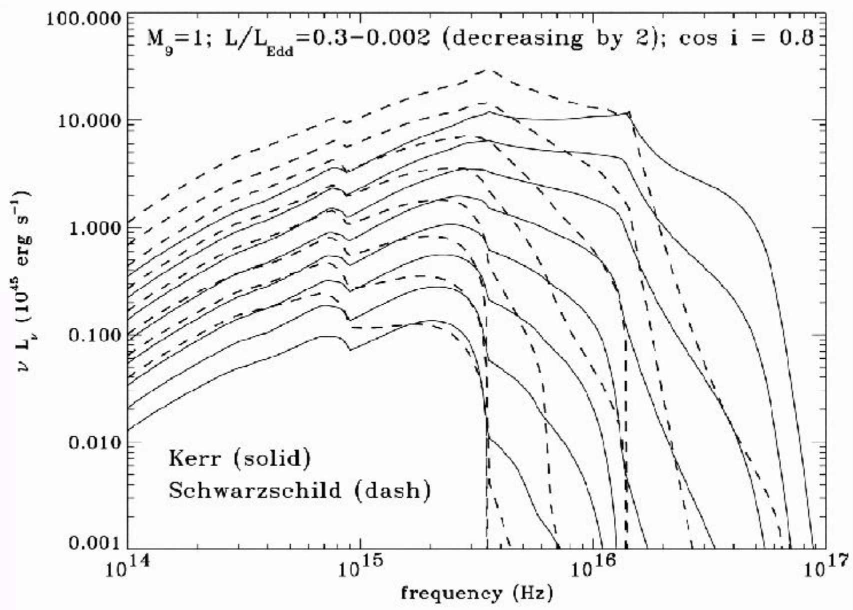
Accretion Disk: Other Complications (I)

Reflection from ionized disk



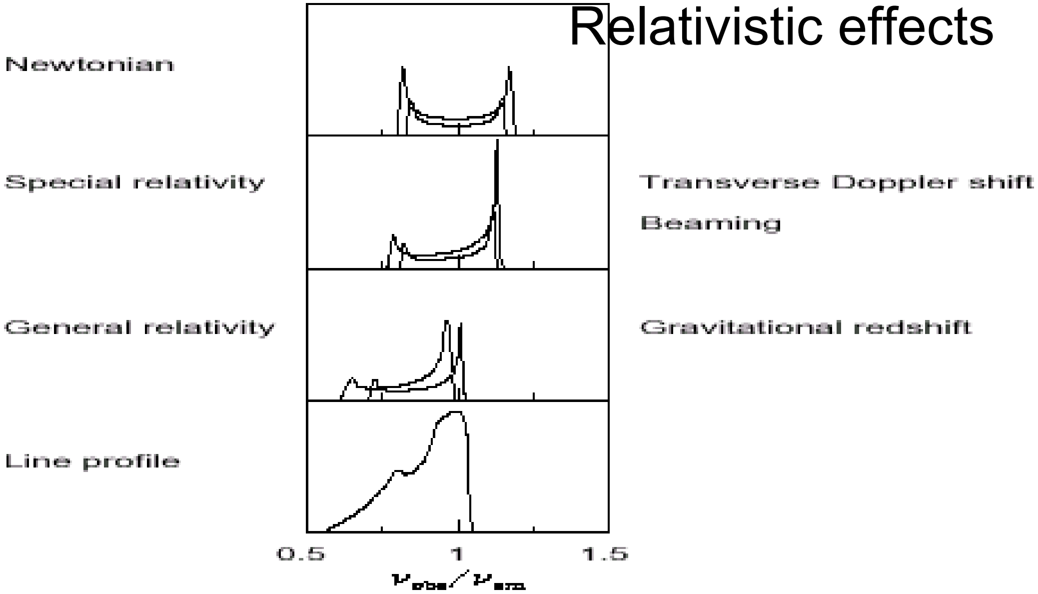


Rotating vs. non-rotating BH

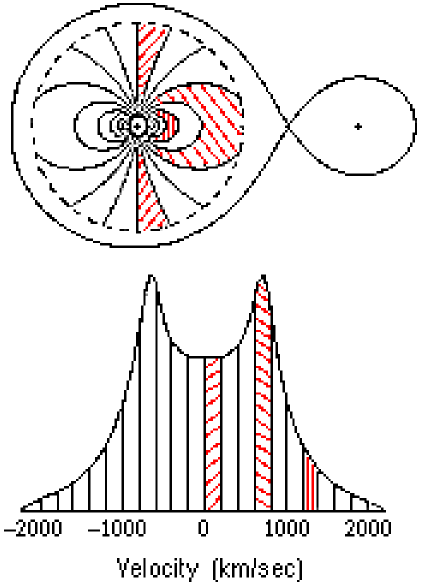


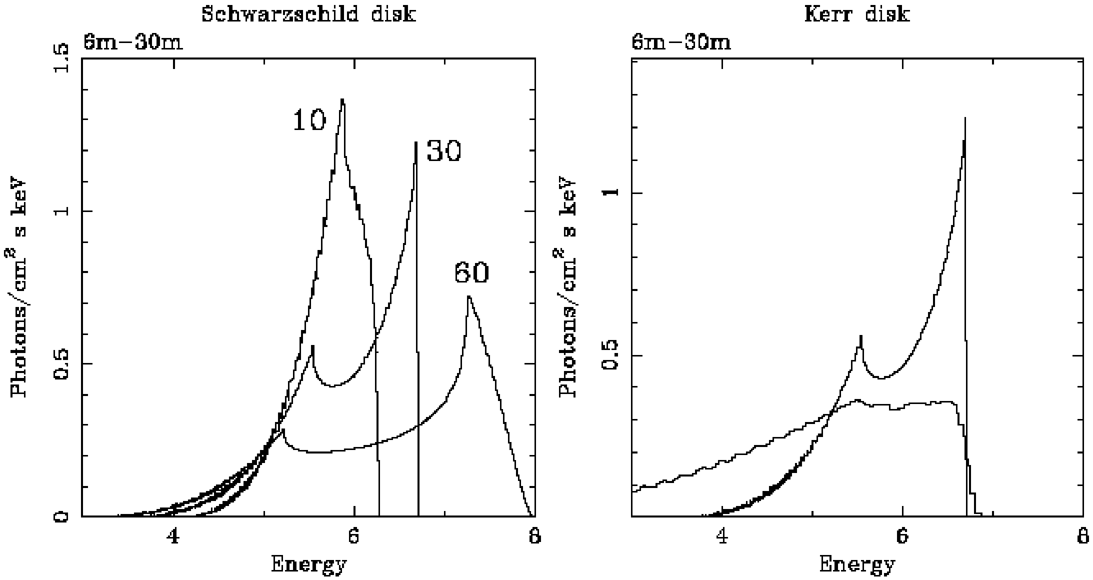
Accretion Disk: Other Complications (II)

Relativistic effects



classical





Accretion Disk: Observable Properties

- mass, mass accretion rate (luminosity) → spectral shape determined

Maximum disk color temperature

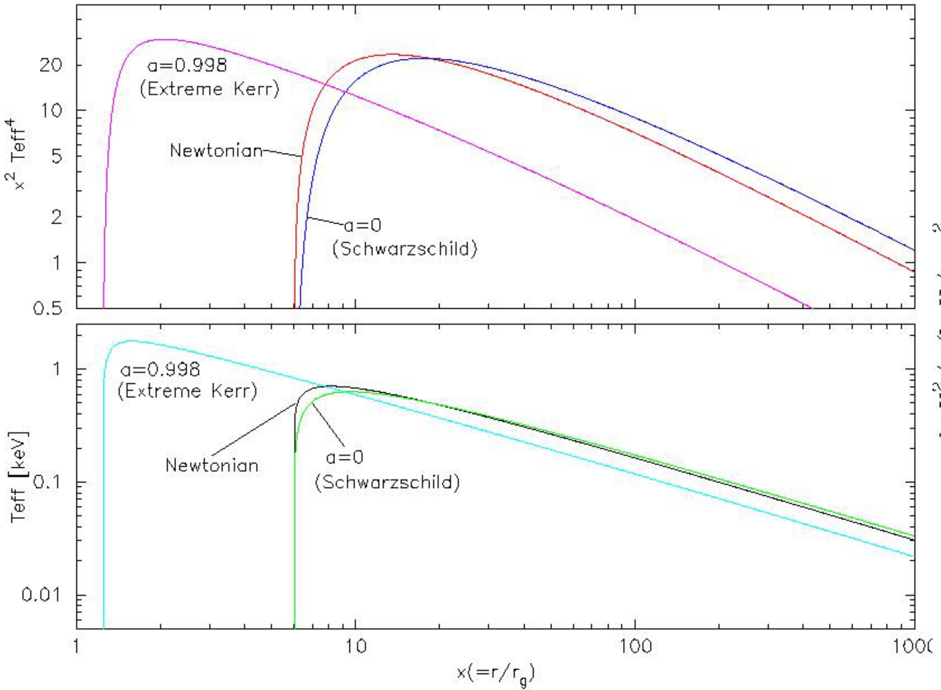
$T^{(max)}_{col} \sim 1.2$ keV $((T_{col}/T_{eff})/1.7)\ (M/M_{Edd})^{1/4}\ (M/7M_\odot)^{-1/4}$

is directly measured from observed X-ray spectral shape

Kerr disk can be much hotter, as innermost radius →1.24 Rg

Disk temperature and emissivity

10 solar mass black hole at the Eddington limit

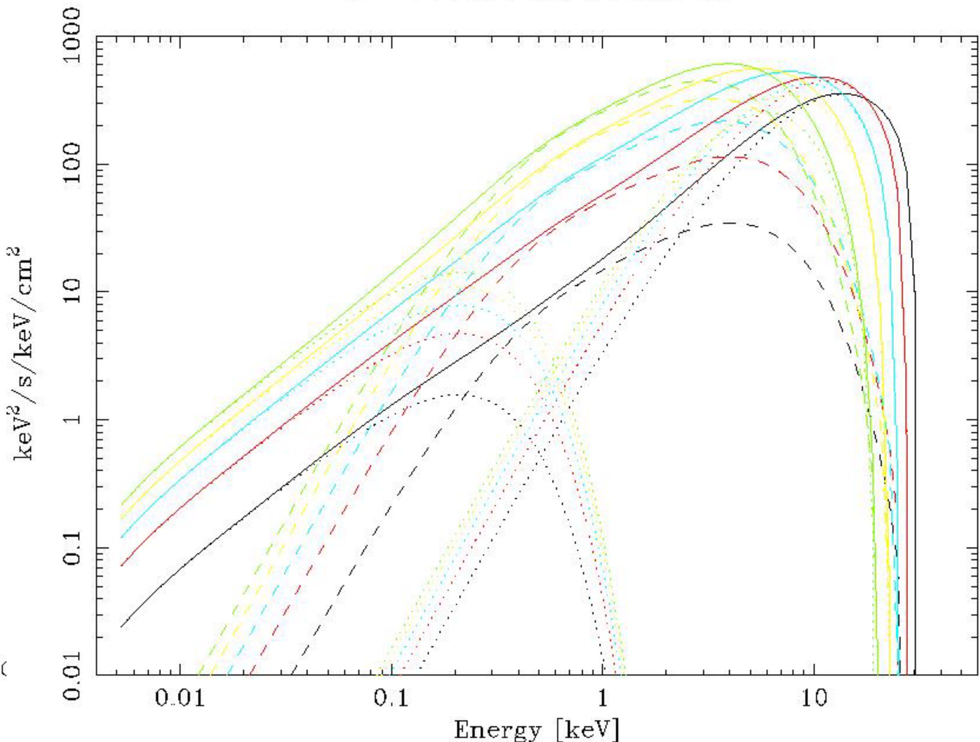


Hard emission from very inner parts ($1.26\ r_g < r < 7\ r_g$) is enhanced for inclined Kerr disks (due to Doppler boost)

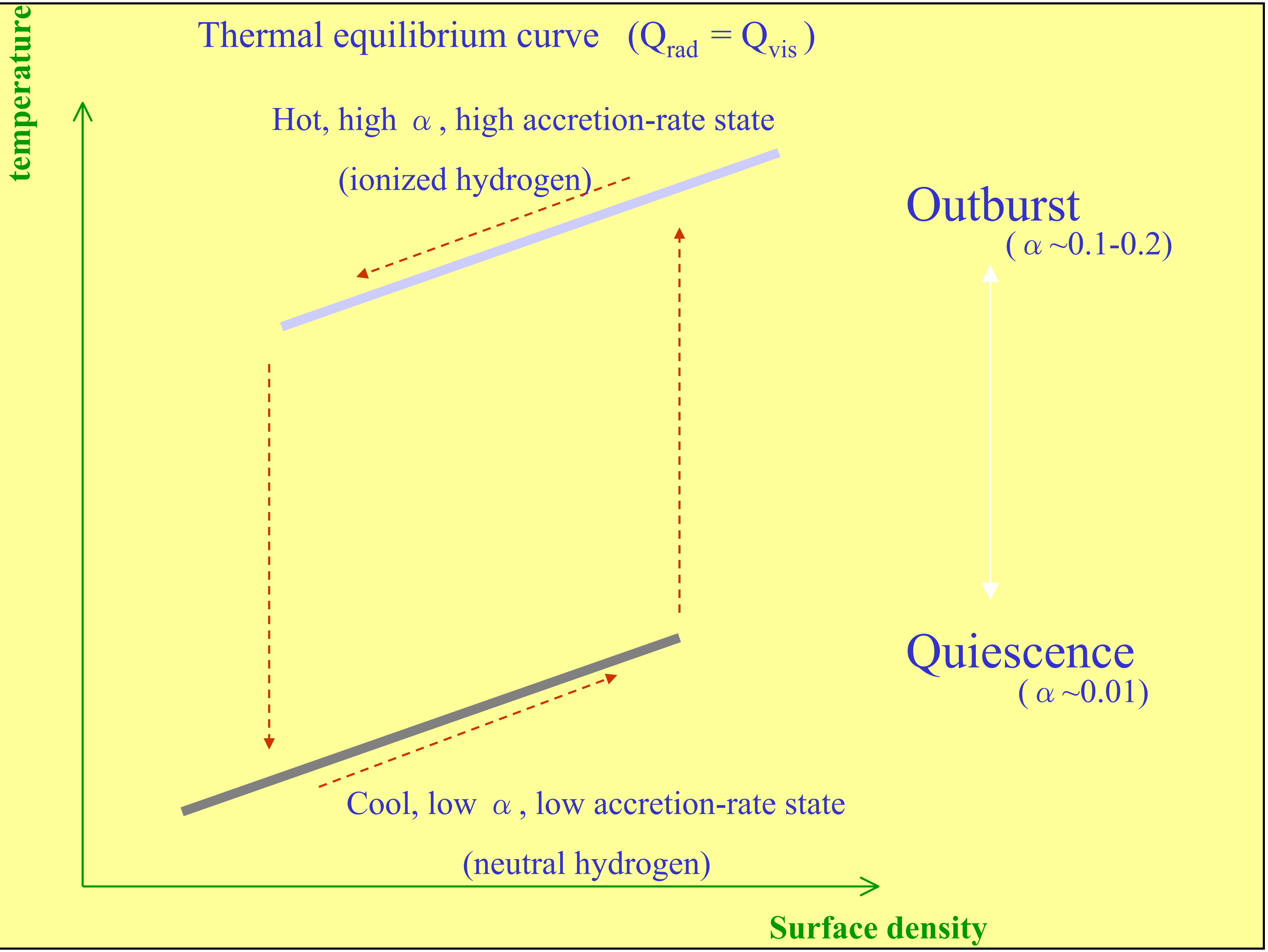
When the disk is face-on, emission from inner part is weak, and the spectrum is not very different from the Schwarzschild case

Kerr disk at d = 1 kpc, M= 1 $M_\odot$, Eddington limit

μ = 0.9, 0.7, 0.5, 0.3 and 0.1



Thermal equilibrium curve $(Q_{rad} = Q_{vis})$



temperature

Hot, high α, high accretion-rate state

(ionized hydrogen)

Outburst

$(\alpha \sim 0.1\text{-}0.2)$

Quiescence

$(\alpha \sim 0.01)$

Cool, low α, low accretion-rate state

(neutral hydrogen)

Surface density

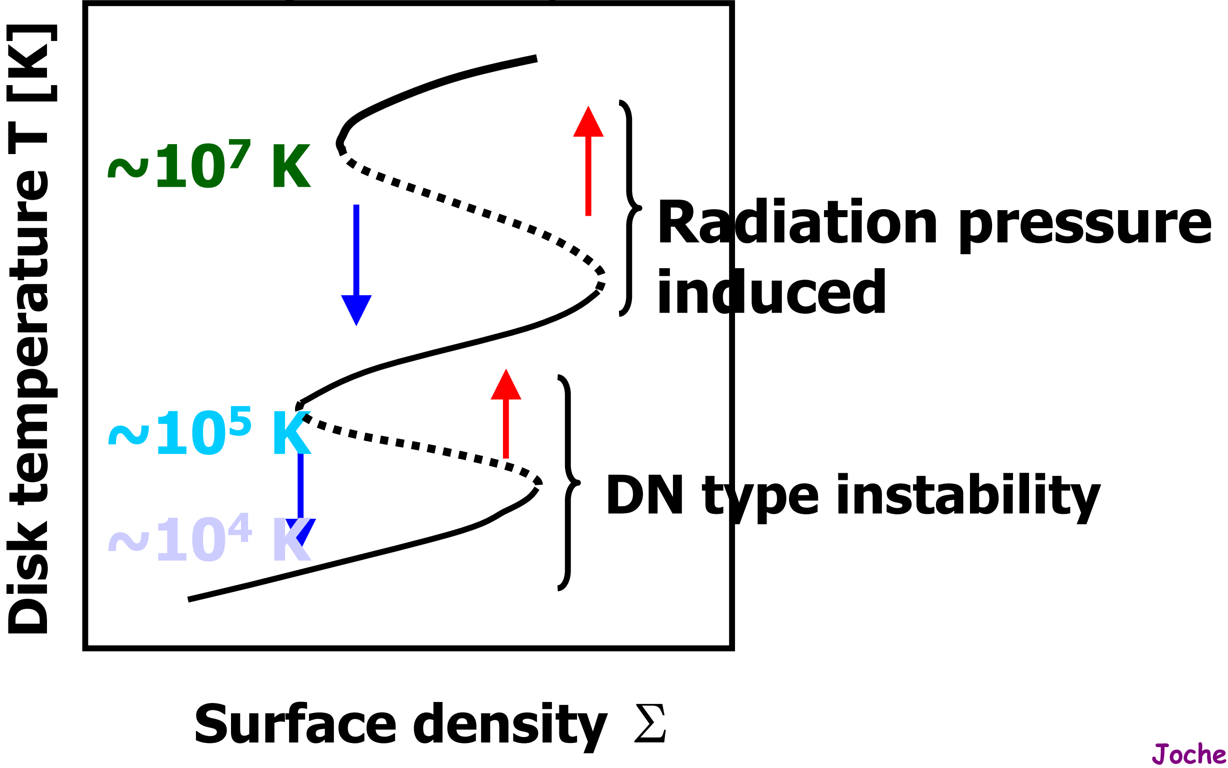
Time-dependent Properties of Accretion Disk

- Disk instability ($Q_{vis} > Q_{rad} >\sim Q_{adv}$, $P \sim P_{rad} \propto T^4$)
- Dwarf Nova type instability
- Different ignition mechanism for radiation pressure-induced instability

"S-shaped curve (thermal equilibrium)"

thermal instability condition.

$$\left(\frac{\partial Q^{+}_{vis}}{\partial T}\right)_{\Sigma} > \left(\frac{\partial Q^{-}_{rad}}{\partial T}\right)_{\Sigma}$$



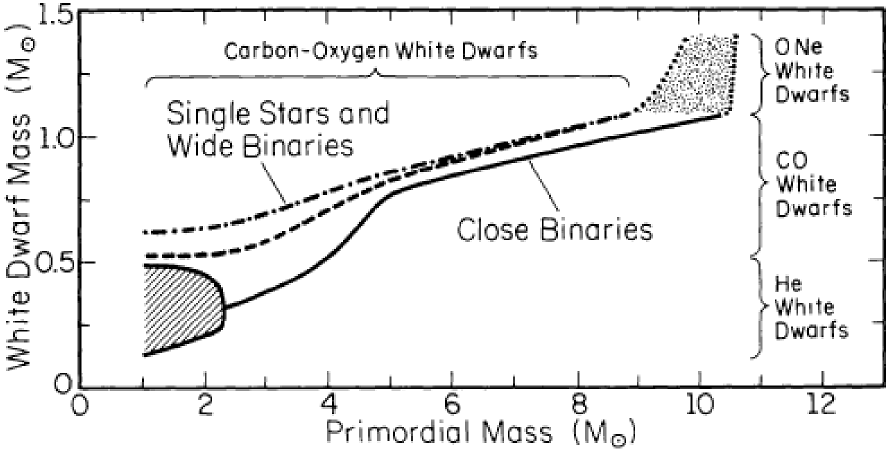
Compact Sources (WD, NS, BH)

- As Single Stars
  - ☞Equation of State
  - ☞Density/Size
  - ☞Rotation
  - ☞Magnetic Field

- In Binary Systems
  - ☞Types according to Central Object
  - ☞Types according to Companion

Singles: Only neutron stars observable at X/Gamma-rays.
Binaries: All 3 types observable at X/Gamma-rays.

Formation of Compact Objects



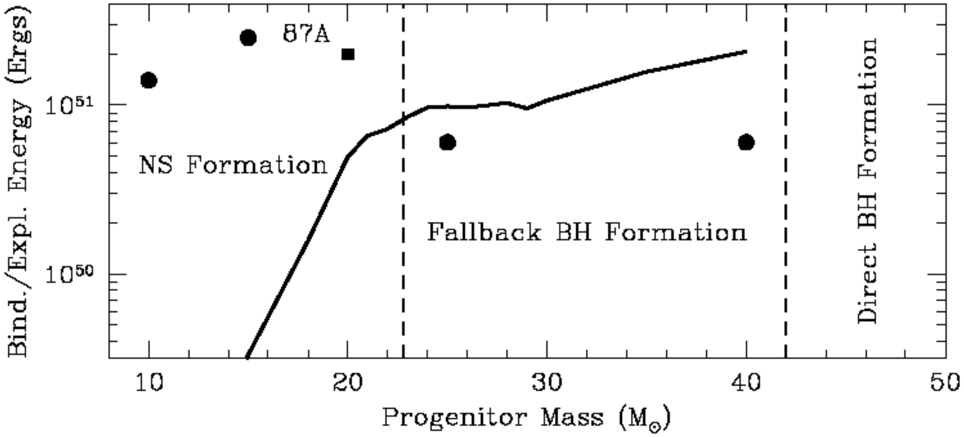


Figure 3. Binding energy/explosion energy *vs.* progenitor mass assuming no mass loss. The solid line is the binding energy of all but the inner 3 $M_\odot$ of the stellar core. If the explosion energy is not at least this powerful, the star will collapse to a black hole. The four circular dots denote the explosion energies from core-collapse simulations and the square is the predicted explosion energy observed from SN 1987A.

- **Type Depends on Mass of Companion star**
  - ☞1-8 $M_\odot$ ➡ White Dwarf <1.4 $M_\odot$
  - ☞8-22 $M_\odot$ ➡ Neutron Star 1.4-3 $M_\odot$
  - ☞>22 $M_\odot$ ➡ Black Hole >3 $M_\odot$
- **WD Mass Spectrum**
  - ☞Peak at ~0.5-0.6 $M_\odot$

Properties of Compact Objects

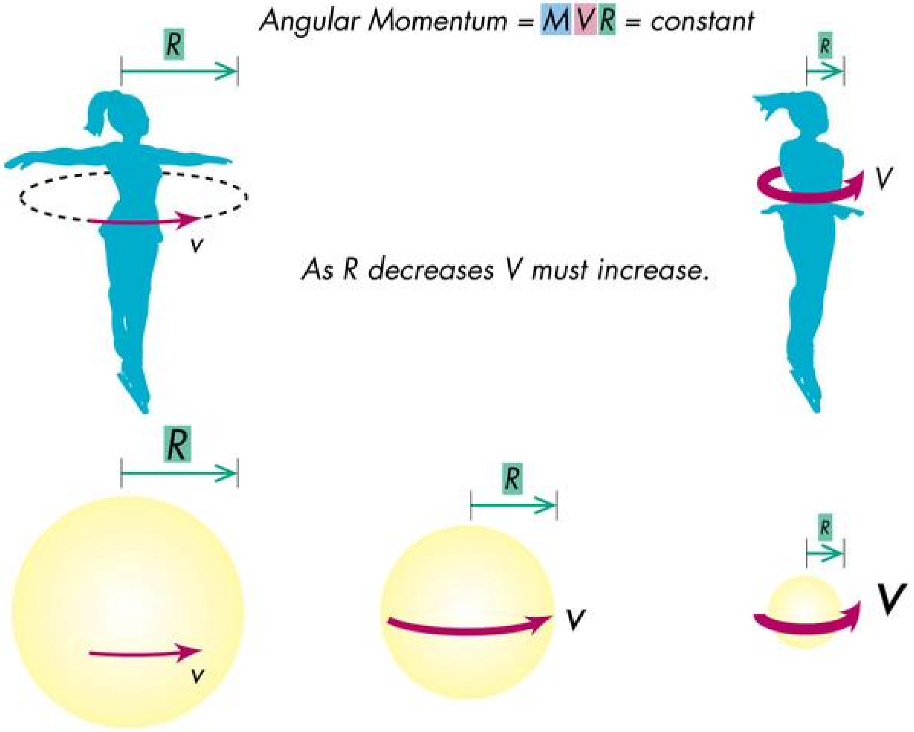
	White dwarf	Neutron Star	Black Hole
Mass	0.4-1.4	1.4 (-3)	>3
Pressure	>electron pressure	>neutron pressure $p + e^- \rightarrow n + \nu_e$	
Density	10^6 g/cm^3	10^{14} g/cm^3	arbitrary
Radius	1000 km	10 km	horizon
Surface T	$<10^5$ K	10^6 K	disk size
Moment of Inertia	10^{51} g cm^2	10^{45} g cm^2	
Spin Period	10-1000 sec	0.001 sec	mass
Magnetic Field	10^8 - 10^9 G	10^{10} - 10^{14} G	none

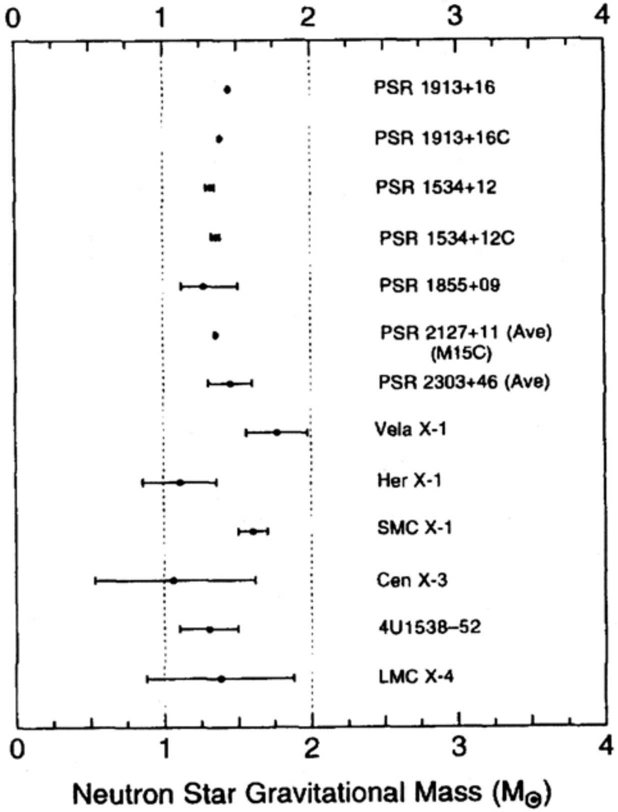
What is a Neutron Star?

Angular momentum conservation => period P is proportional to the square of the radius.

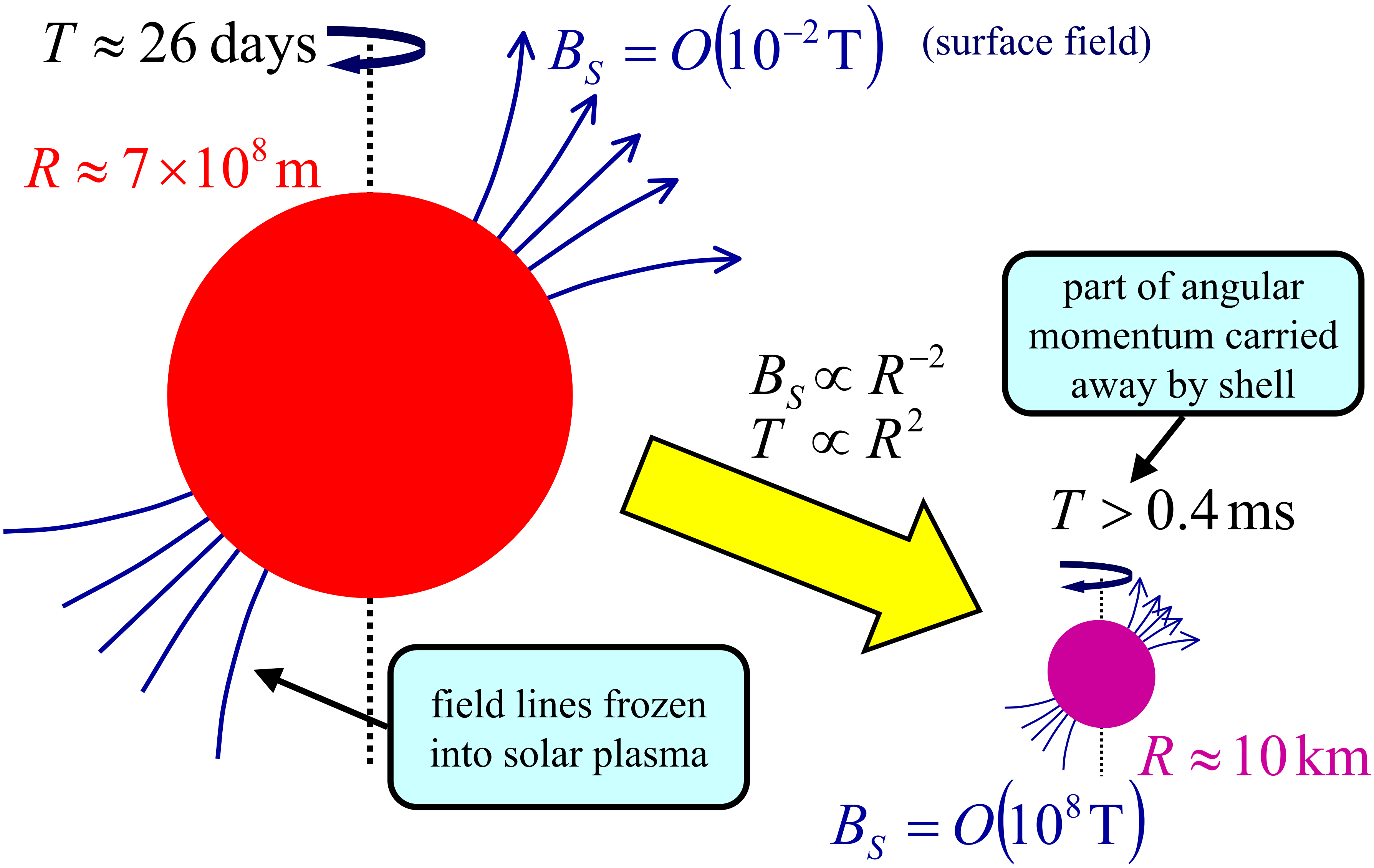
=> Collapse from R = 1000 km → 10 km will speed the rotation up by a factor of 100^2 = 10,000

=> P decreases from minutes to milliseconds.





Supernova Explosion => Neutron Stars



$T \approx 26\,\text{days}$

$B_S = O\left(10^{-2}\,\text{T}\right)$ (surface field)

$R \approx 7 \times 10^{8}\,\text{m}$

$B_S \propto R^{-2}$
$T \propto R^{2}$

part of angular momentum carried away by shell

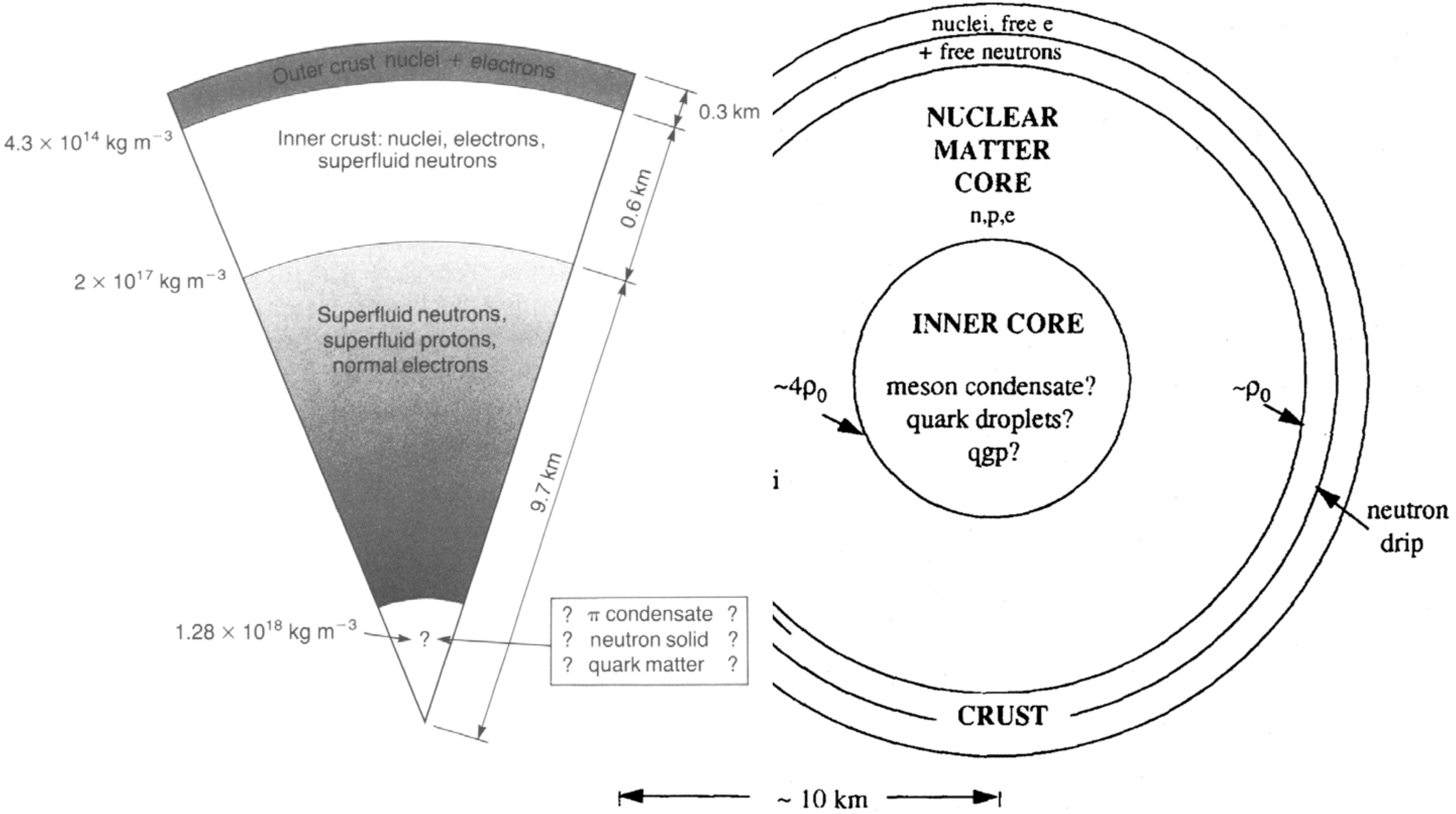
$T > 0.4\,\text{ms}$

field lines frozen into solar plasma

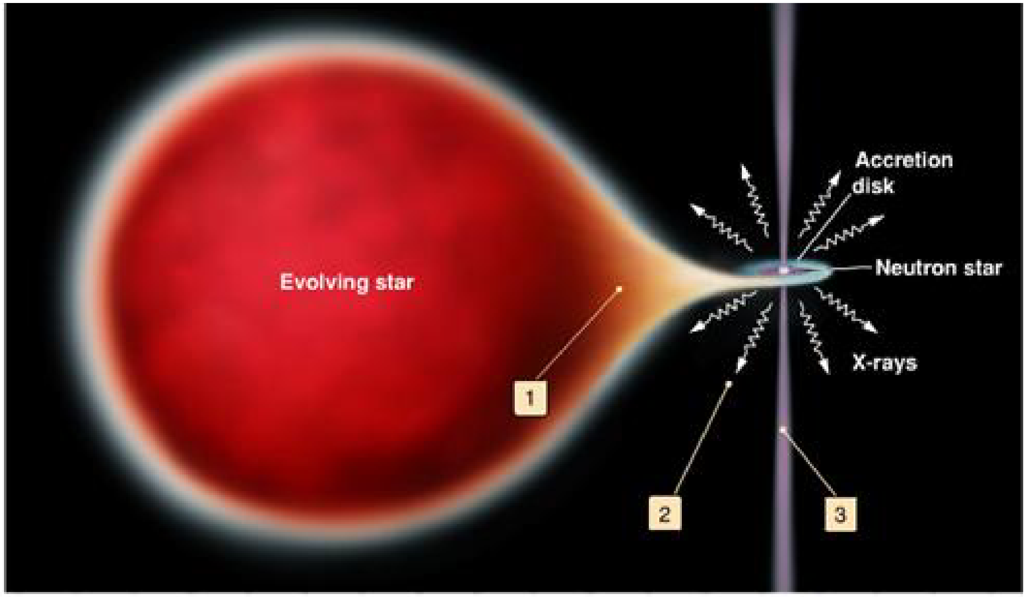
$R \approx 10\,\text{km}$

$B_S = O\left(10^{8}\,\text{T}\right)$

Structure


Outer crust nuclei + electrons
Inner crust: nuclei, electrons, superfluid neutrons
Superfluid neutrons, superfluid protons, normal electrons
4.3 × 10^14 kg m^−3
2 × 10^17 kg m^−3
1.28 × 10^18 kg m^−3
?
0.3 km
0.6 km
9.7 km
? π condensate ?
? neutron solid ?
? quark matter ?
nuclei, free e
+ free neutrons
NUCLEAR MATTER CORE
n,p,e
INNER CORE
meson condensate?
quark droplets?
qgp?
~4ρ0
~ρ0
i
neutron drip
CRUST
~ 10 km

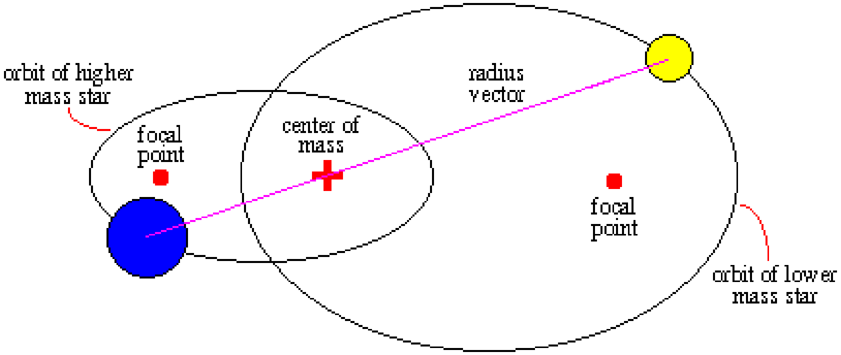
X-ray Binary



- When a compact object is part of a binary system
- Compact object can be neutron star, white dwarf or black hole
- When the other star fills its Roche limit
  - ☆ starts feeding matter to neutron star
- The compact object has an accretion disk
  - ☆ heated by matter falling onto it
- The accretion disk heats enough to glow in the x-ray part of the spectrum

X-ray Binary

Binary Star Orbit



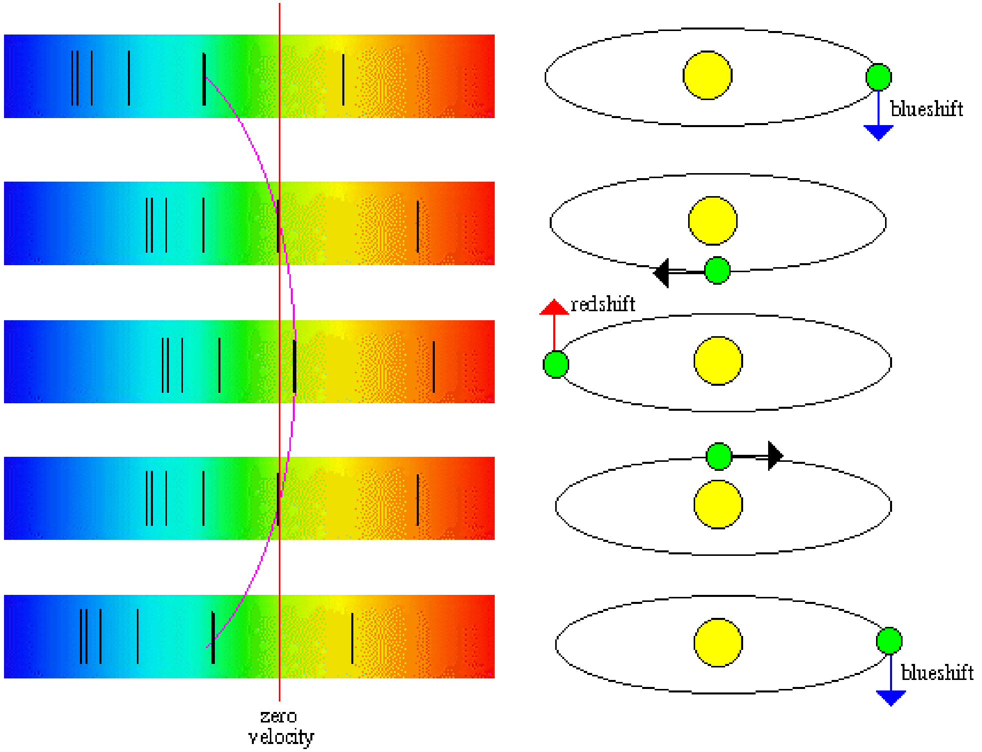
Spectral lines of companion allow velocity and period determination

Mass function

$$f(M) = \frac{K^3 P}{2\pi G} = \frac{M_2^{\,3} \sin^3 i}{(M_1 + M_2)^2}$$

Spectroscopic Binary

A spectroscopic binary is where there is evidence of orbital motion in the spectral features due to the Doppler effect



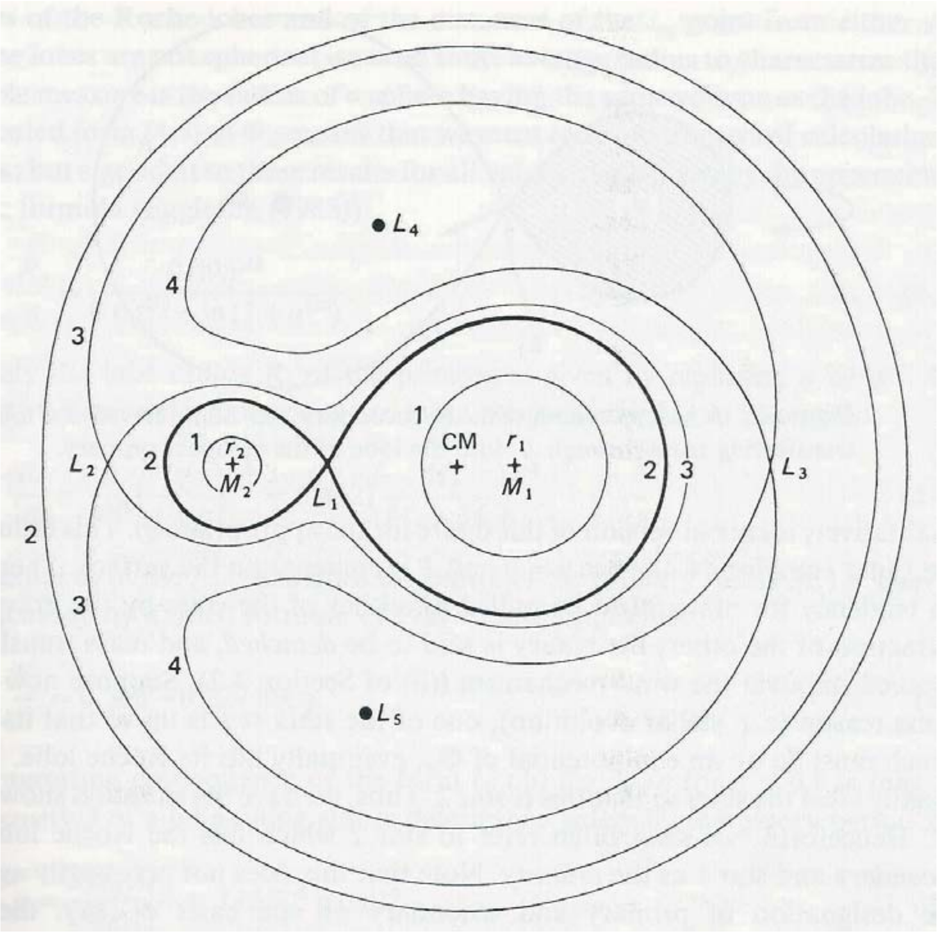
Properties of the Roche Lobe

Roche lobe Potential:

$$\Phi_R(r) = \frac{-GM_1}{|r-r_1|} - \frac{GM_2}{|r-r_2|} - \frac{1}{2}(\omega \times r)^2$$

where r_1 and r_2 are the position vectors of the centers of the two stars and ω is the angular velocity of the binary.

Equipotential surfaces: shape of the plot is completely dependent on the mass ratio q (= M_2/M_1), while the scale is dependent on a.



Types of X-ray Binaries

White Dwarf:

CV (cataclysmic variable):

Dwarf novae, polars, VY Scl stars, supersoft X-ray sources, novae

Neutron Star or Black Hole:

HMXB	LMXB
Luminous (early OB star)	Optically faint (blue) counterpart
high-mass companion	*low-mass companion*
wind accretion	disk accretion
(strong winds for $M>10\ M_\odot$)	(RLOF instable for $M>1.4M_\odot$)
hard X-ray spectra	soft X-ray spectra
($T>100$ million K)	*($T\sim30-80$ million K)*
often pulsating	non-pulsating
X-ray eclipses	*no X-ray eclipses*
Galactic plane	Gal. Centre + bulge
Population I	*older, population II*

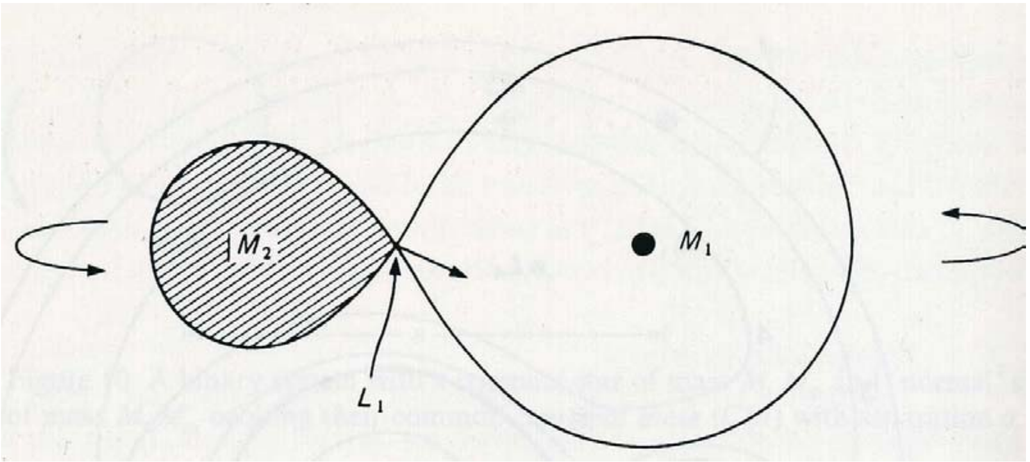
What is a CV?

A CV is a binary system in which one star (designated the primary) accretes matter from a secondary star that, for whatever reason, has exceeded its Roche lobe. More specifically, it is a semi-detached binary with a white dwarf primary and a secondary that is typically a late-type main sequence star.

Miscellaneous Facts

- ≈ 1 million in our galaxy
- ***a*** is typically a few times the Earth-Moon separation
- Typical orbital periods ***P*** range from 1-10 hours

Geometry of a CV:



The Roche lobe becomes filled in CV's most typically by a decreasing semi-major axis. The driving mechanism for the shrinkage is driven by magnetic breaking of the secondary if ***P*** > 3 hours or gravitational radiation if ***P*** < 2.

Differences between NS/BH Accretion

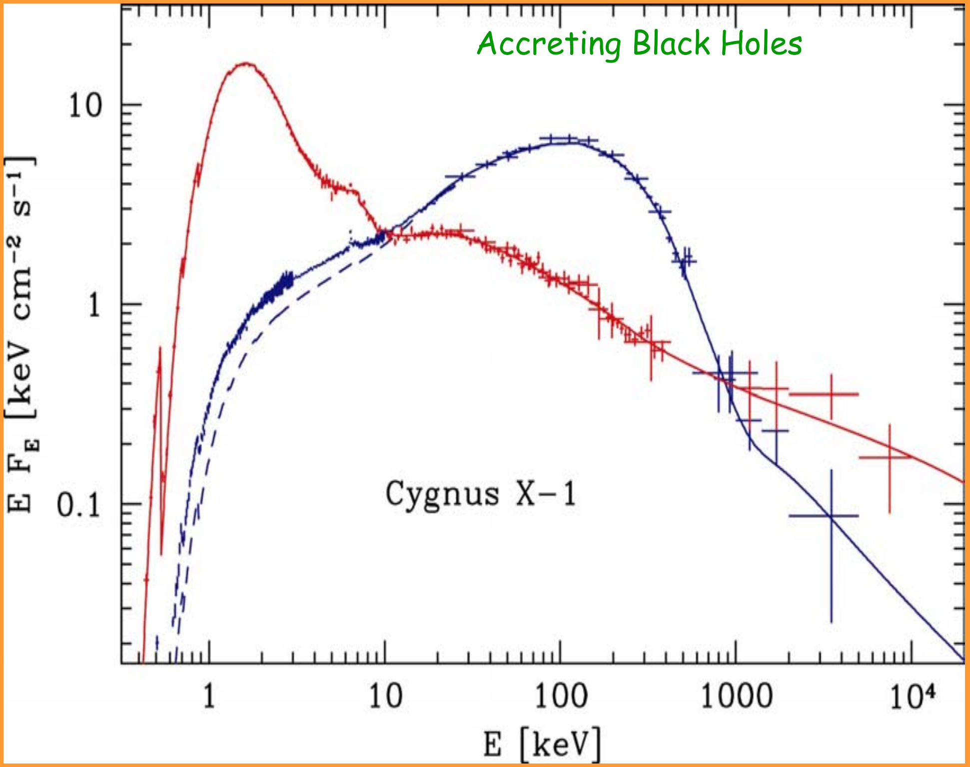
	Neutron star	Black Hole
Magnetic field	*yes*	*no*
Solid surface	*yes*	*no*
Disk extends	*down to NS surface (depending on B)*	*innermost stable orbit*
Spin	*does not matter*	*strong dependence*

⇒ **spectra of NS accretors should be more complicated!**

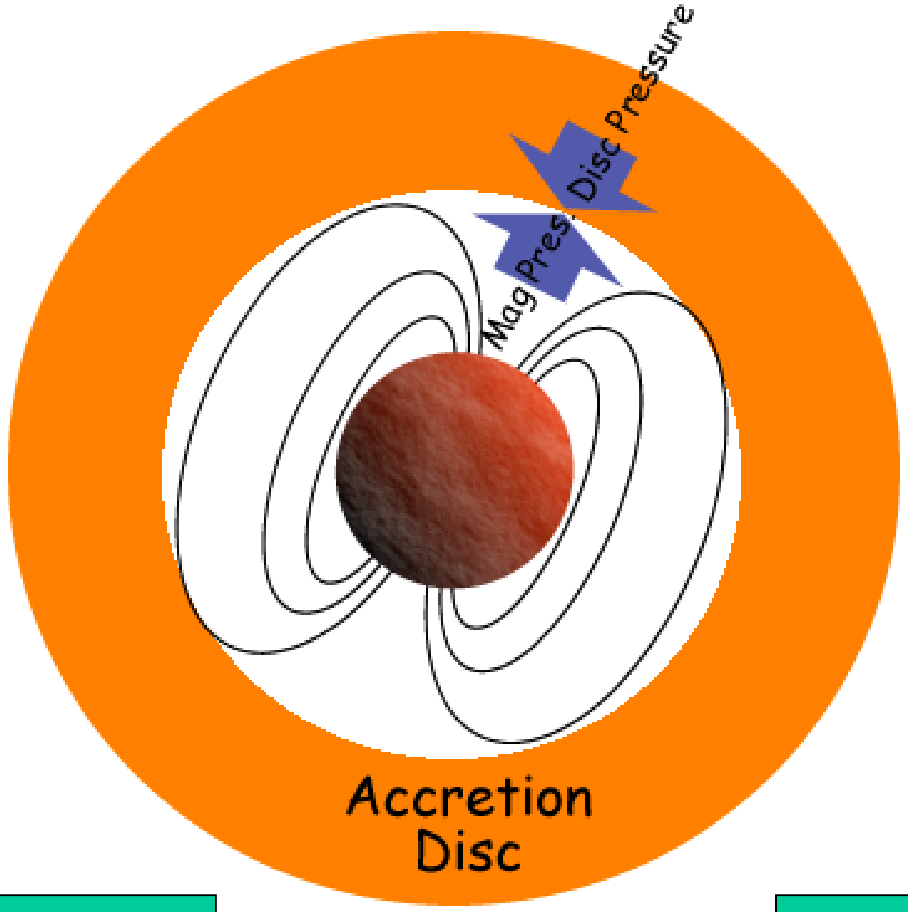
Observations: spectra rather similar!!! Why?

Typical-Source Energy Spectra

- **Thermal Components**
  - ☞ Stellar Surfaces
  - ☞ Accretion Disks
  - ☞ Plasma Bubbles
- **Non-Thermal Components**
  - ☆ Accelerated Particles
    - ☞ Synchrotron Radiation
    - ☞ Bremsstrahlung
    - ☞ Inverse Comptonization



Disc – Magnetic Field Interaction



$$B^2/8\pi \sim 1/2 \rho v_{ff}^2$$

$$\mu = B r^3$$

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

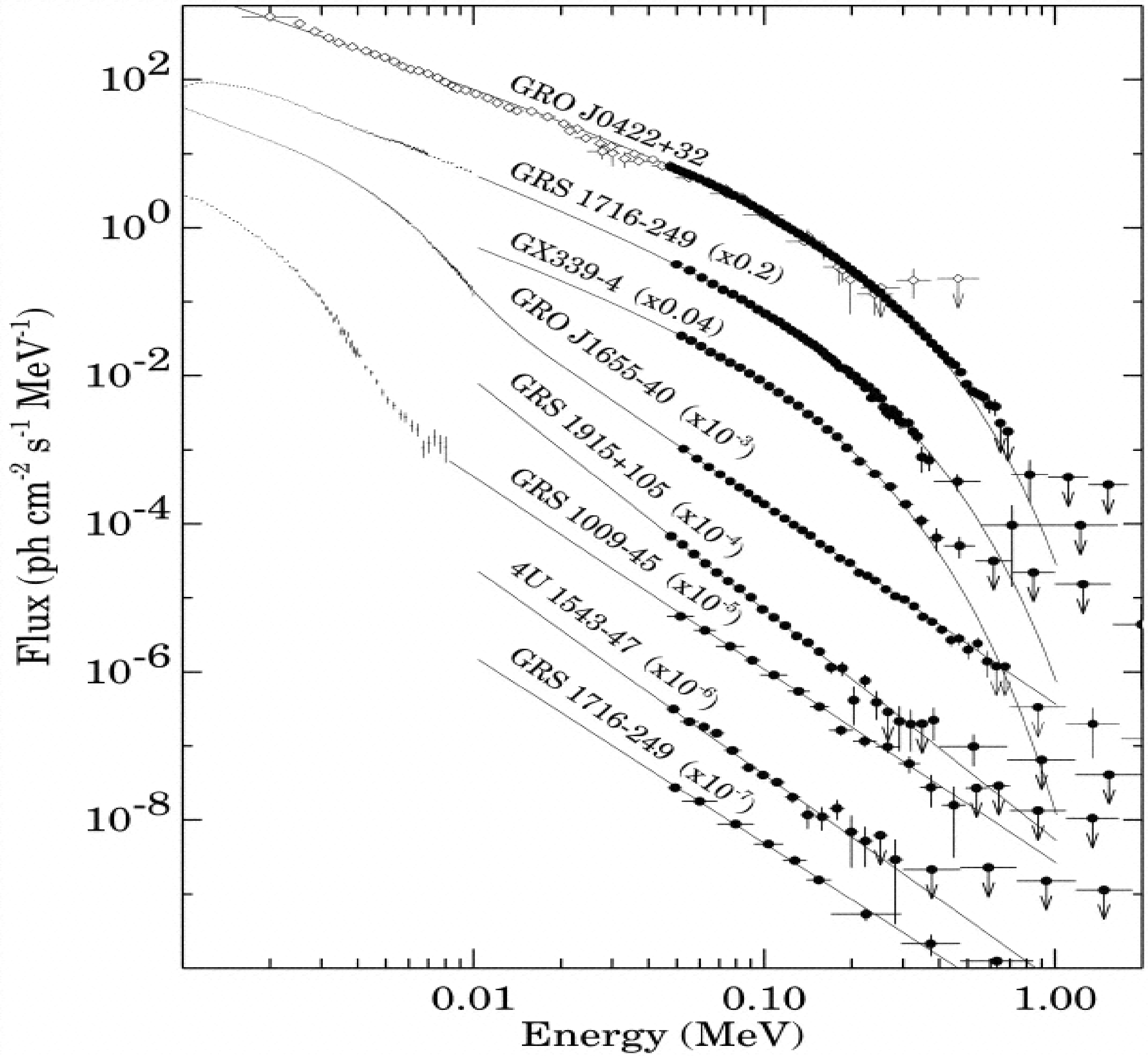
$$\dot{M} \sim 4\pi r^2 \rho v_{ff}$$

Disc Pressure proportional to $\dot{M}$

Magnetic Pressure Proportional to B^2

X/Gamma-Ray Spectra of Black Hole Binaries

GRO (Grove et al 98)



DIFFERENT FROM SPECTRA OF NEUTRON STAR X-RAY BINARIES

BUT NOT MUCH!!!

Dynamically Established BH Systems

Measure mass of candidate black hole via mass function
This constitutes the strongest evidence for the existence of stellar-mass black holes in binary systems. Currently there are at least 10 systems for which dynamical mass determinates result in the compact object having mass greater than 3 M_0, the theoretical upper limit of a neutron star.

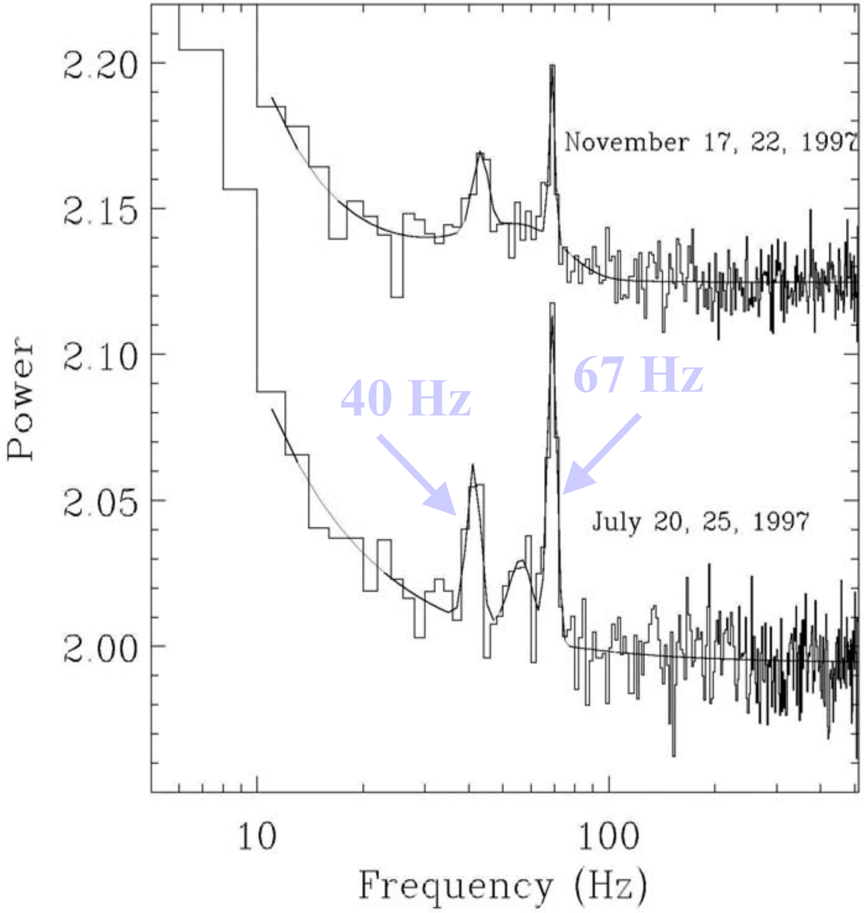
Source Name	Alternate Name	BH Mass (M_{sun})
GRS 1915+105	–	10 –18
0538–641	LMC X-3	7 – 14
0540–697	LMC X-1	4 – 10
GRO J 0422+32	XN Per 1992	3.57 ± 0.34
A0620–00	XN Mon 1975	4.9 – 10
GRS1124–683	XN Mus 1991	5.0 – 7.5
GRO J1655–40	XN Sco 1994	7.02 ± 0.22
H 1705–250	XN Oph 1977	4.9 ± 1.3
1956+350	Cyg X-1	7 – 20
GS2000+25	XN Vul 1988	8.5 ± 1.5
GS2023+338	V404 Cyg	12.3 ± 0.3

Accretion Disks Exhibit "Quasi-Periodic" Oscillations (QPO)

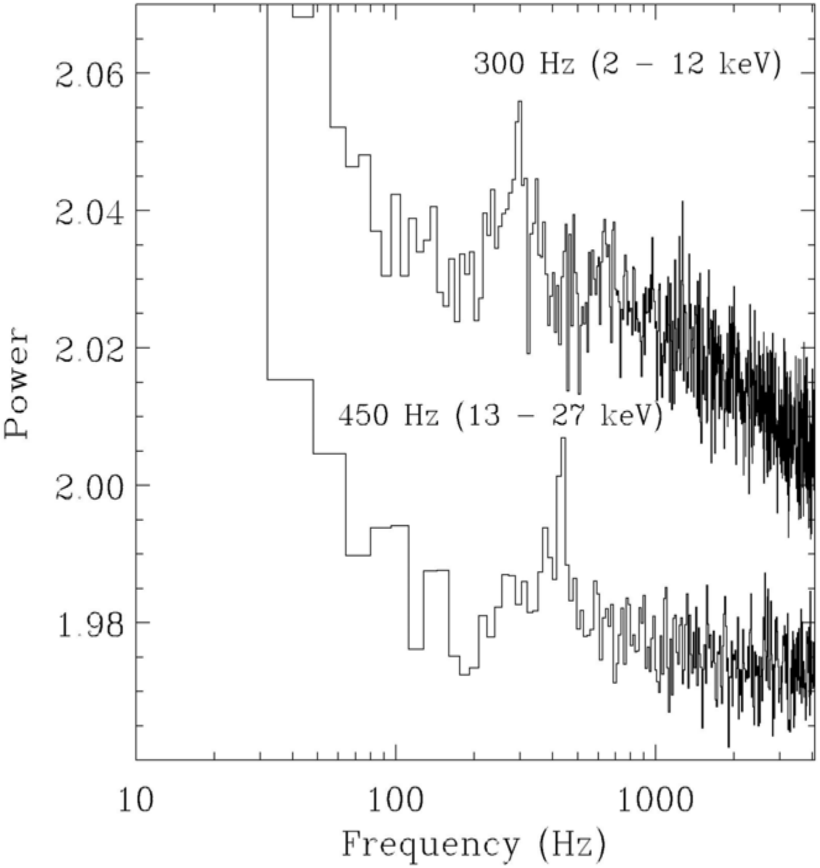
- Rich spectrum of modes: coherence up to Q ~20
- Highest frequency QPOs must come from close to horizon - tied to marginally stable orbit?
- Detailed origins of different modes still unclear
  - ☆ Period of circular orbits
  - ☆ Precessional modes
    - ☞ Lense-Thirring precession tied to BH spin - dragging of inertial frames
    - ☞ Precession of periastron
  - ☆ Pulsational modes: "diskoseismology"
    - ☞ Disk acts as resonant cavity under influence of GR effects
  - ☆ Bending modes
- Redundant probes of spacetime structure

… all depend on metric in different ways

QPOs in two Microquasars



GRS 1915+105



GRO J1655-40

Transient Phenomena

- **Different causes**
  - ☞ Accretion disk instabilities (Dwarf novae, BH transients)
  - ☞ Variable mass overflow (VY Scl stars)
  - ☞ Variable density (NS/Be systems)
  - ☞ Variable irradiation

- **Various types of transient sources**
  - ☞ NS/Be systems
  - ☞ Dwarf novae
  - ☞ BH transients
  - ☞ Microquasars

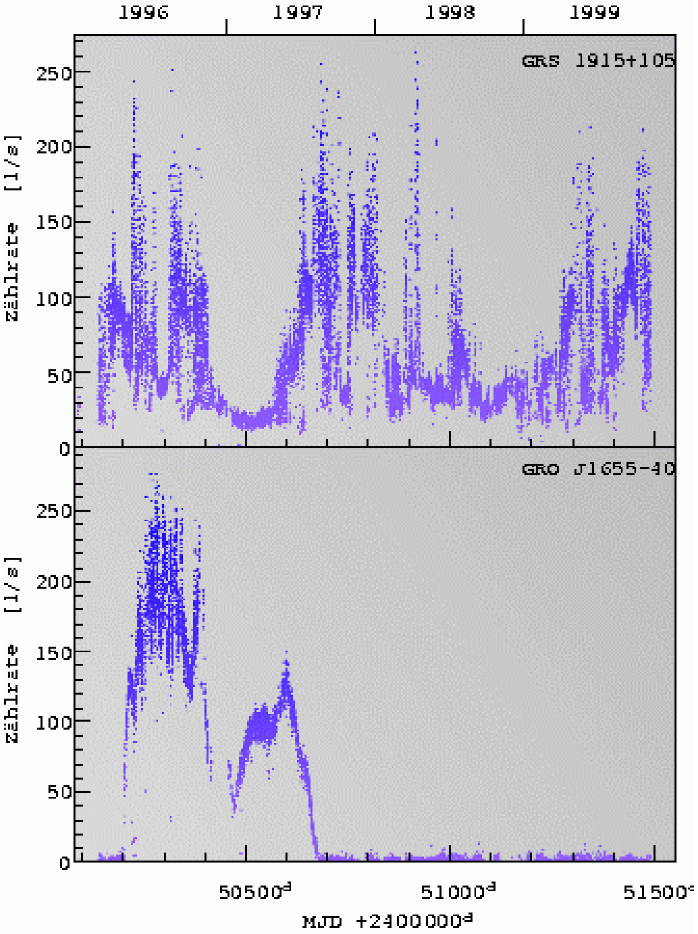
⇒ **Complicated: time dependent phenomena in accretion disk**

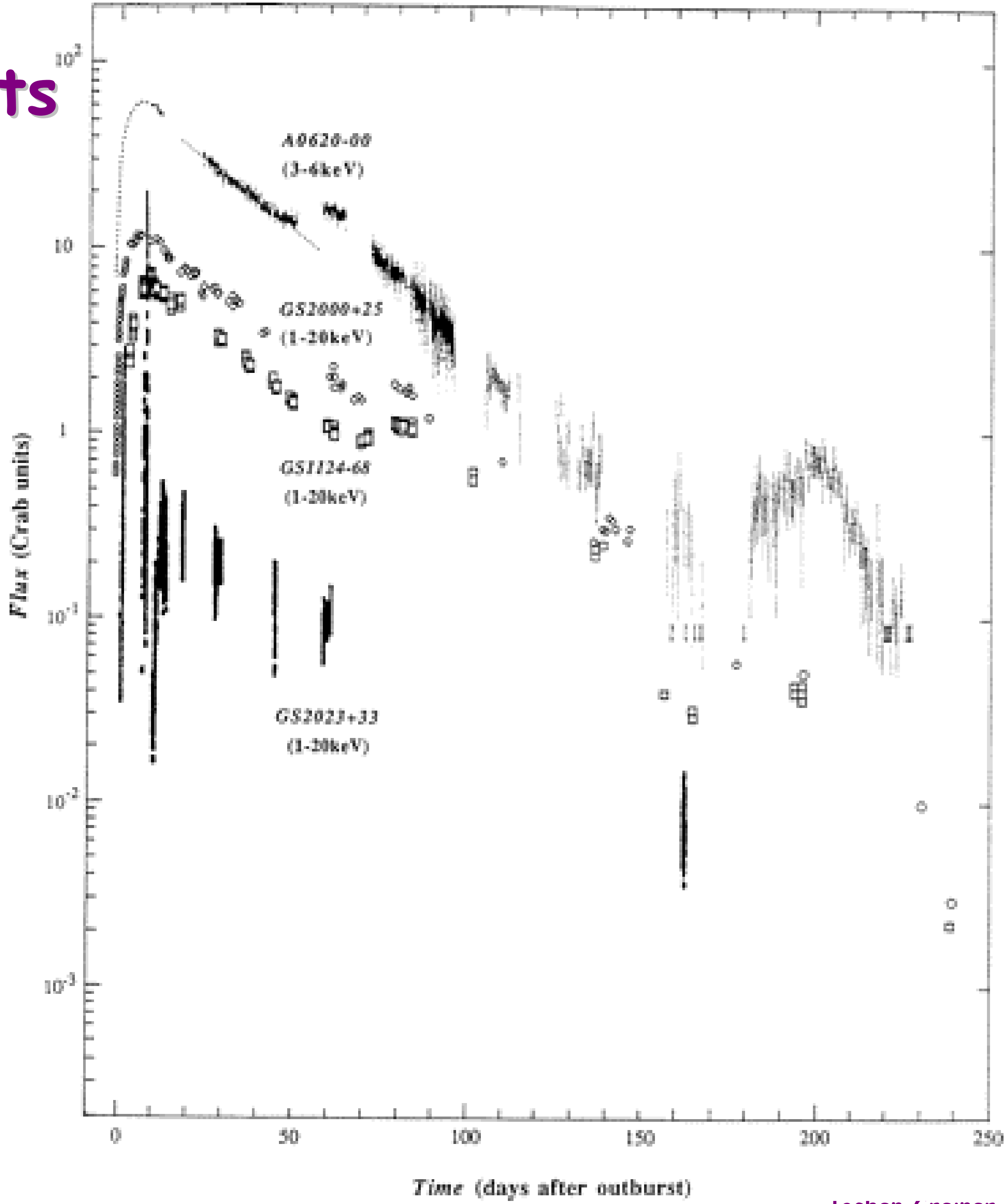
Short-lived: can investigate certain states only ones

Black Hole Transients

Sudden rise in X-ray intensity

Decay with e-folding time of
about 30 days





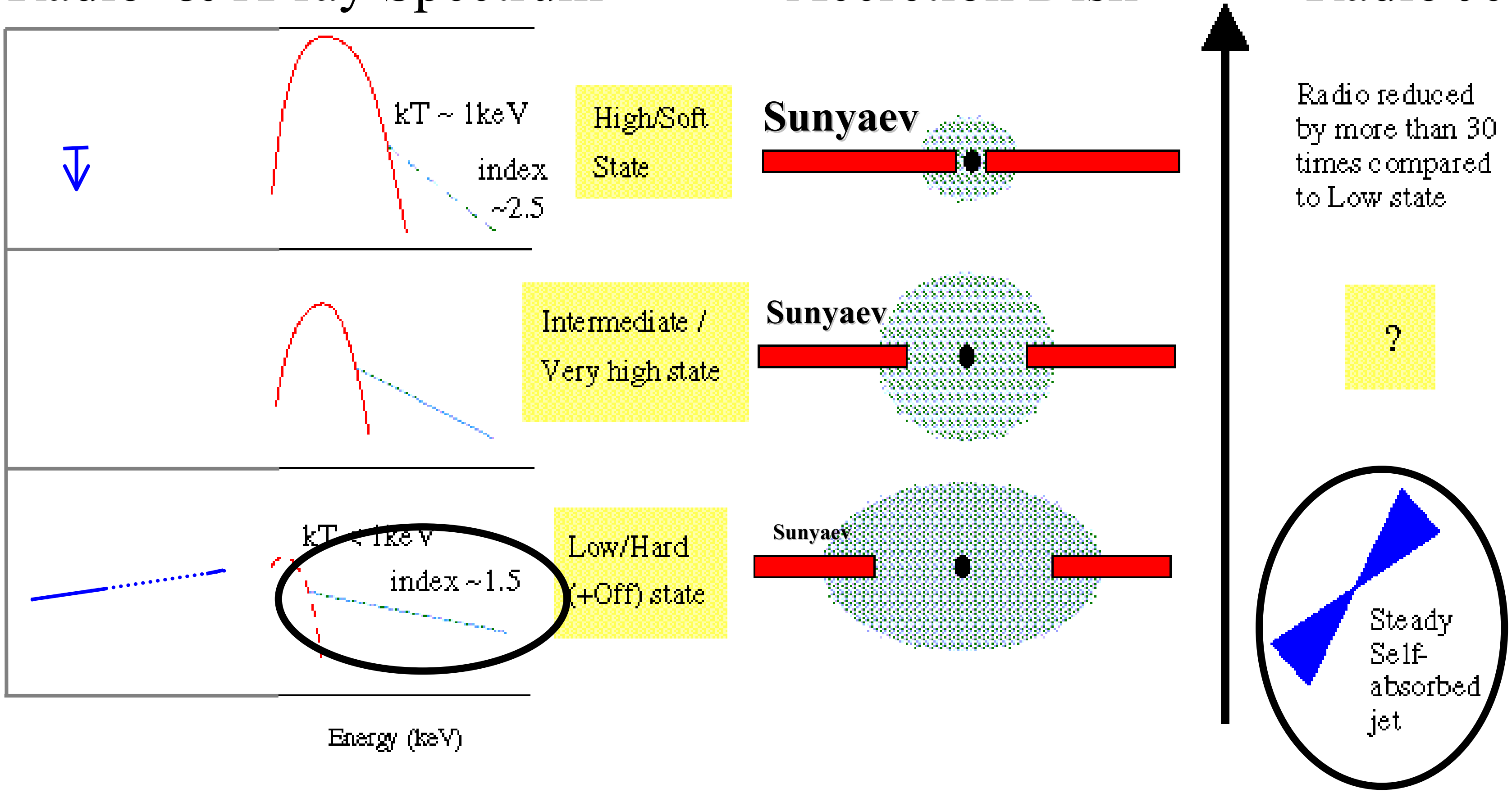
The Power-Evolution of Black Hole Transients

Radio & X-ray Spectrum

Accretion Disk

$\dot{M}$

Radio Jet



High/Soft State

Radio reduced by more than 30 times compared to Low state

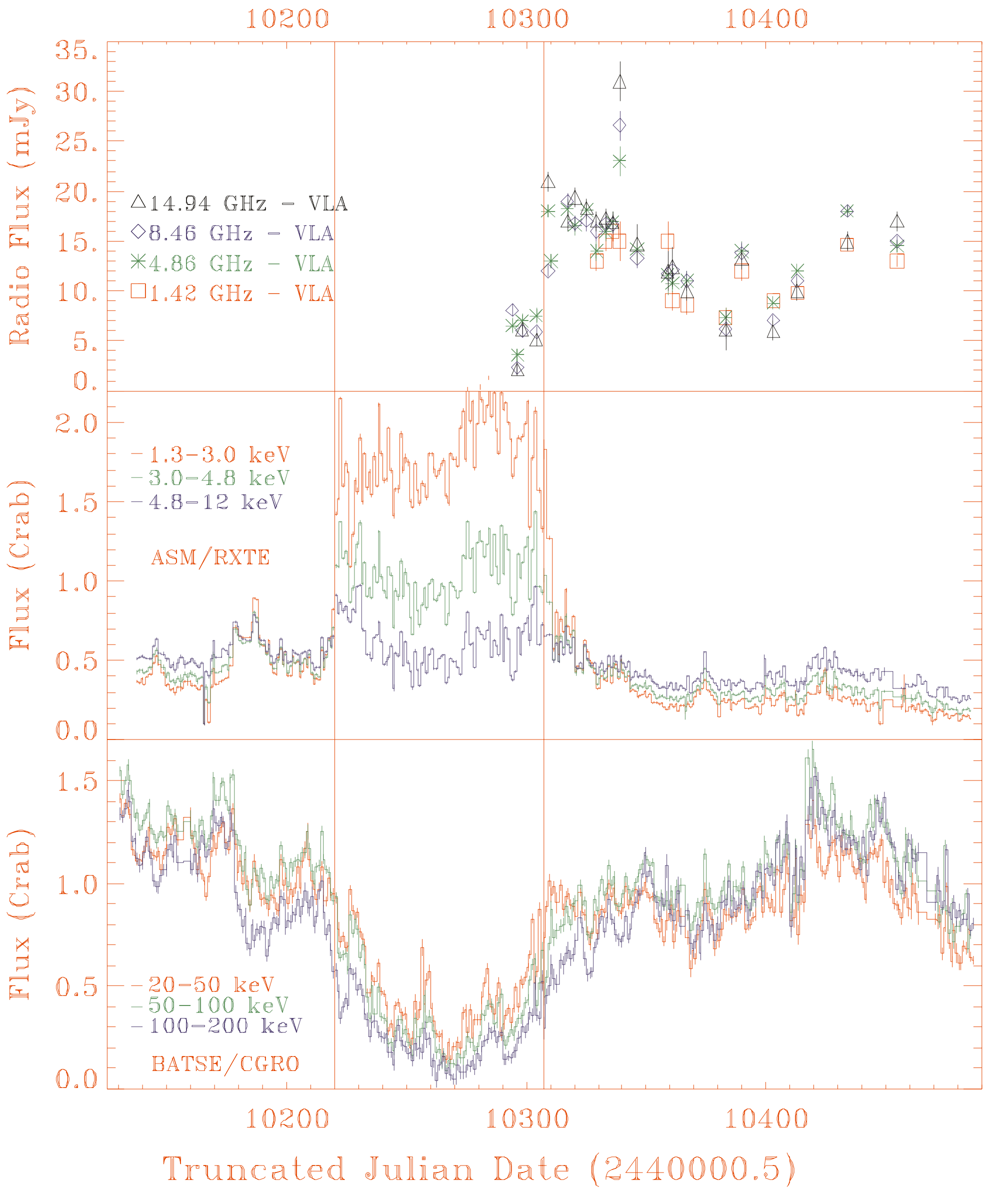
Intermediate / Very high state

?

Low/Hard (+Off) state

Steady Self-absorbed jet

High-/Low States

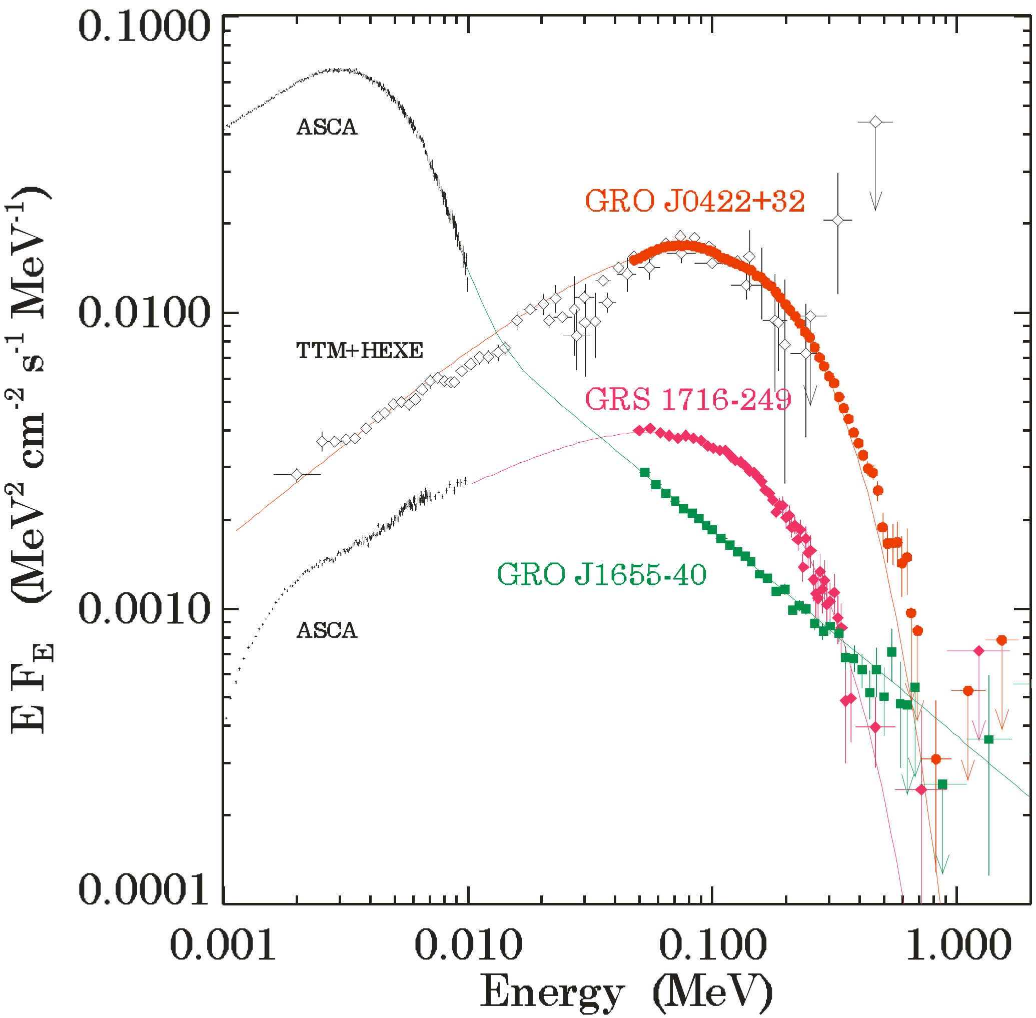


Spectral state changes in the persistent source Cyg X-1. Soft X-ray emission is anti-correlated with hard X-ray and gamma-ray emission. The transition from the X-ray high state is marked by a radio flare.

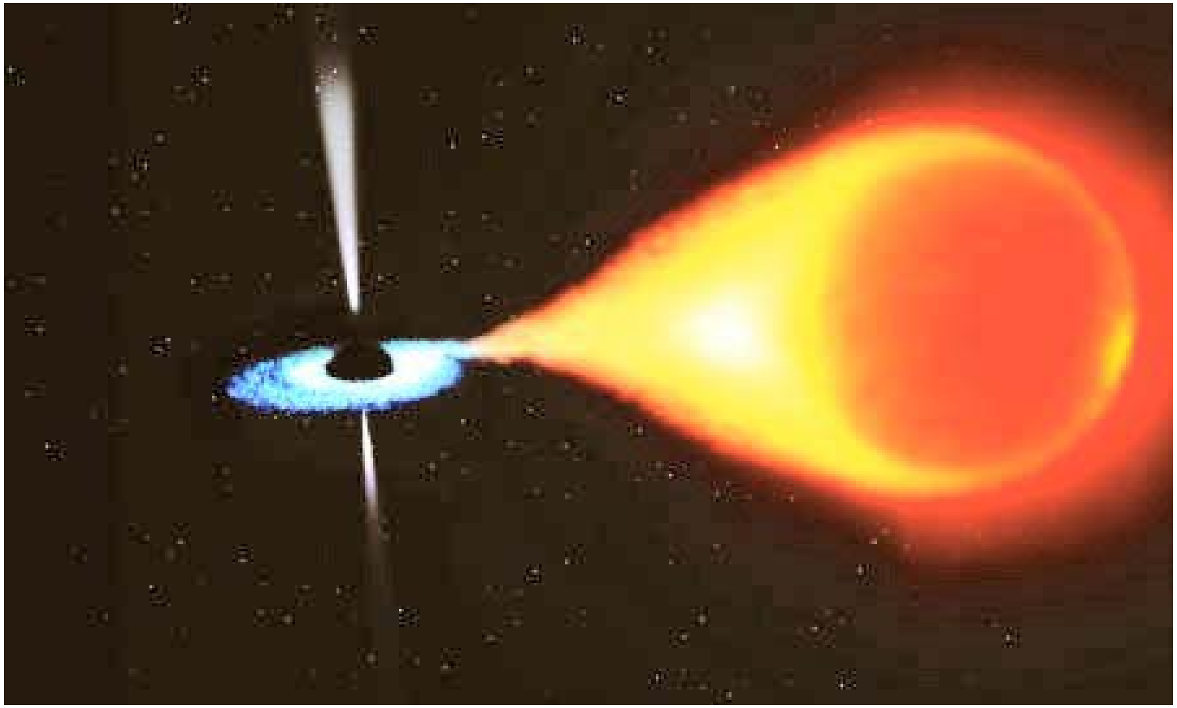
High-Energy Emission during High-/Low States

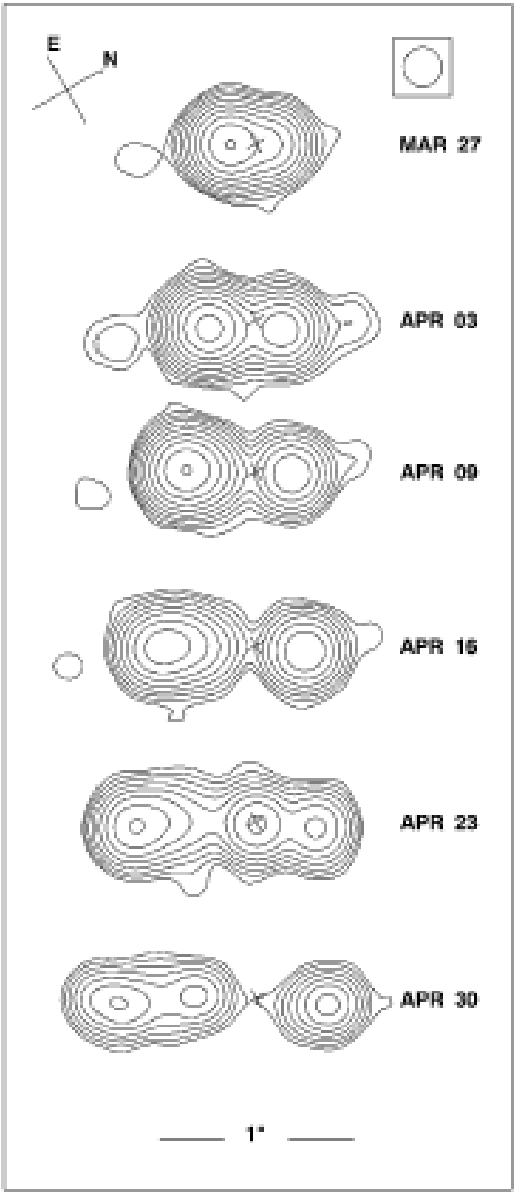
Several high-energy states:

- "X-ray high/soft" state, the soft component is dominant. It is emitted from the inner accretion disk and can be well modeled by a multi-color disk black-body spectrum, where the temperature falls as radius $r^{-3/4}$. The hard component is a simple power law and may be the signature of inverse-Compton scattering from a non-thermal relativistic electron population.
- "X-ray low/hard" state, the black-body component is weak or absent, having been Compton up-scattered to gamma-ray energies by a thermal plasma with temperature ~100 keV. The plasma likely exists either as a hot inner disk or as a patchy corona above a cold disk.



Plasma Jets from Accreting Compact Stars

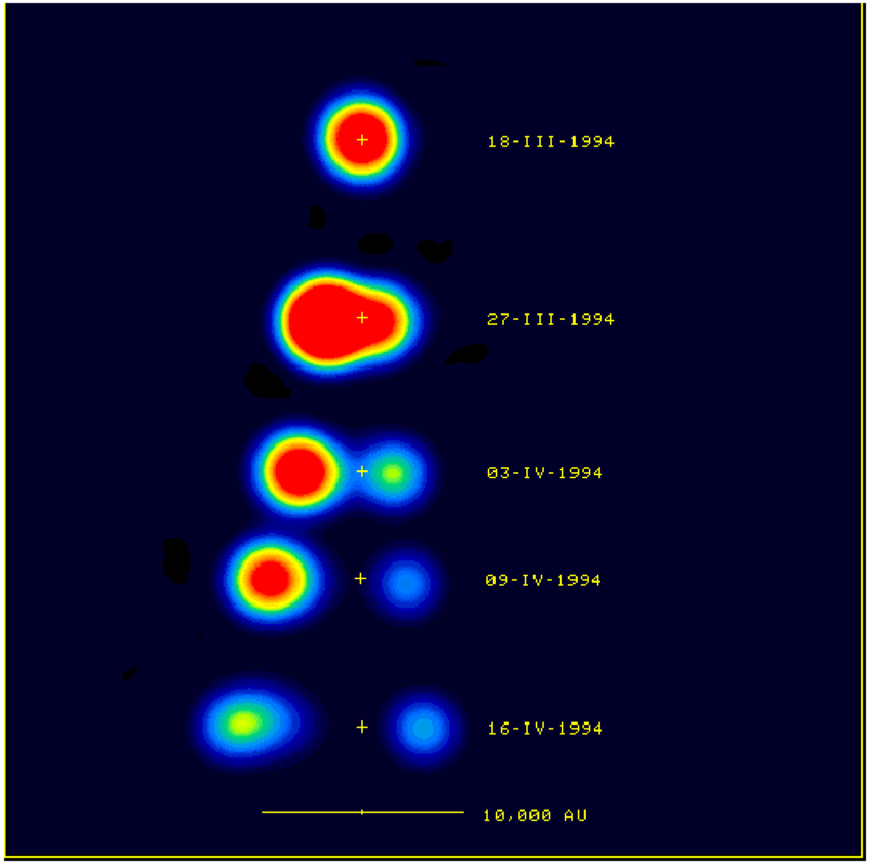


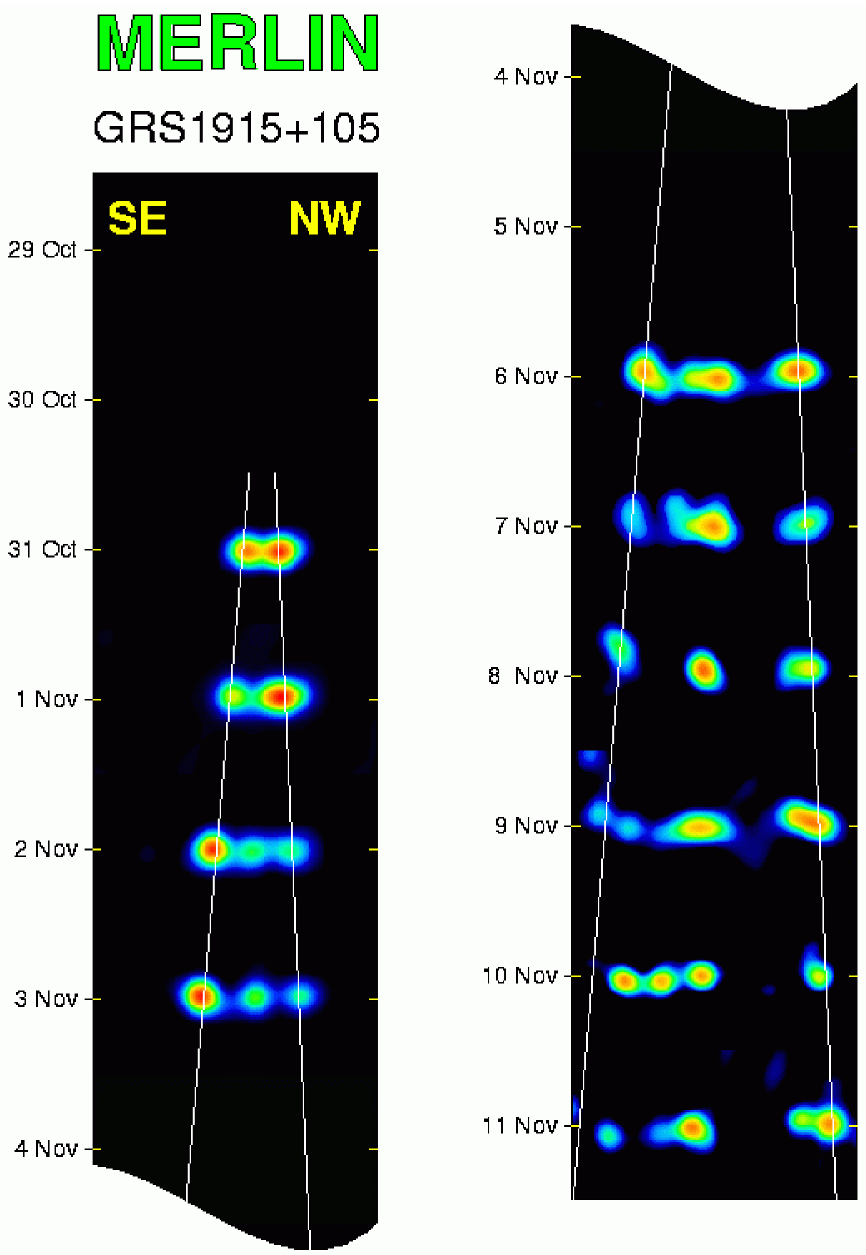


- "Micro-Quasars": Jets from Accreting Stellar-Mass Compact Objects (NS + BH)
- X-Ray and Radio/γ Emission from Hot Plasma & Relativistic Particles
- "Superluminal" Plasma Blobs Traced in Radio Emission

Superluminal Motion

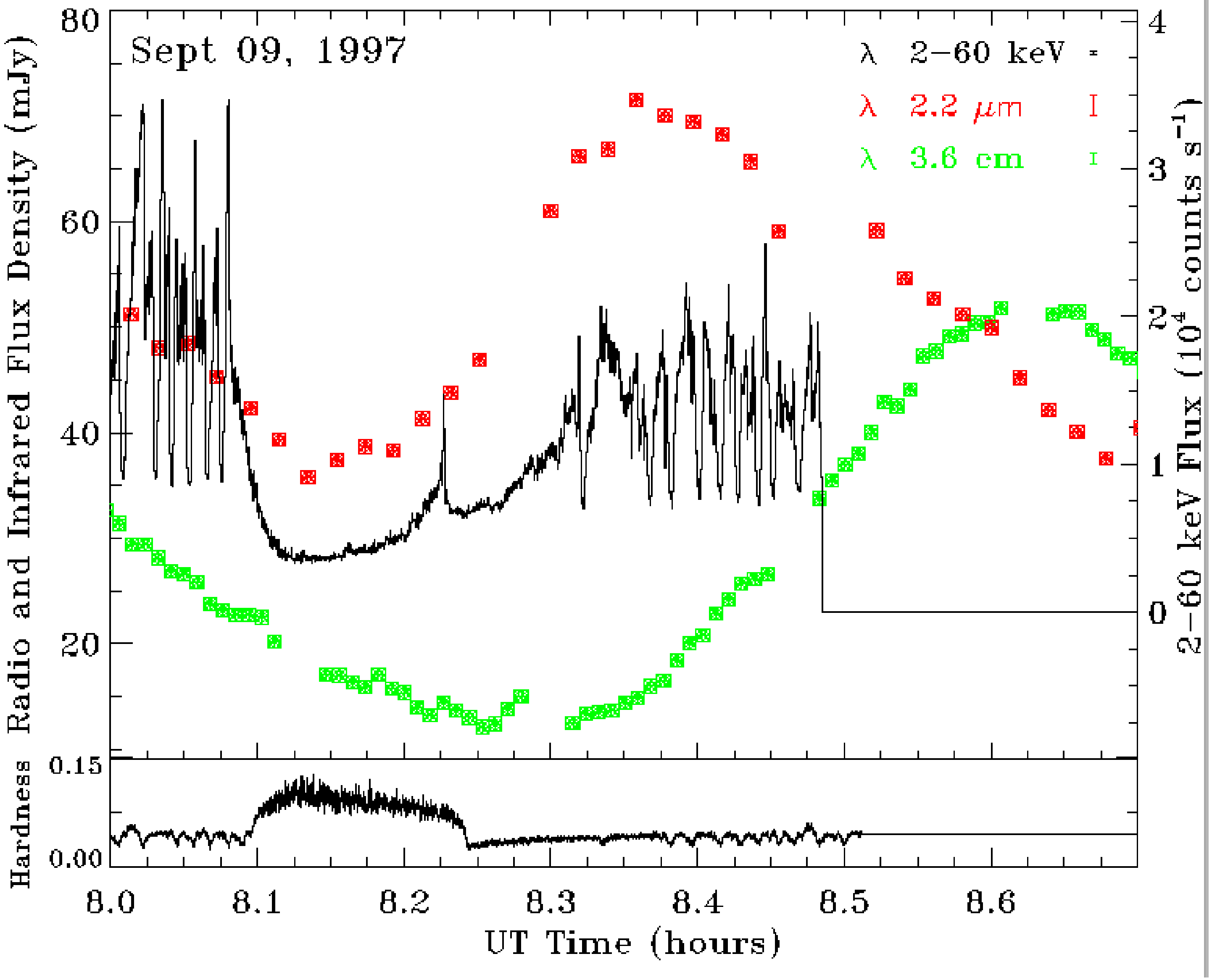
Relativistic, radio-loud jets from the cores of external Active Galaxies have been known for some years. Recently, such apparent superluminal motion has been detected from several objects within our Galaxy for the first time. A sequence of 3.6-cm radio images from the black hole candidate GRS 1915+105 shows radio-luminous ejecta moving in the sky. The images were taken with the Very Large Array with an angular resolution of 0.2 arc seconds. The illusion of **superluminal** motion arises when a relativistic blob of emitting matter is ejected close to our line of sight to the object.



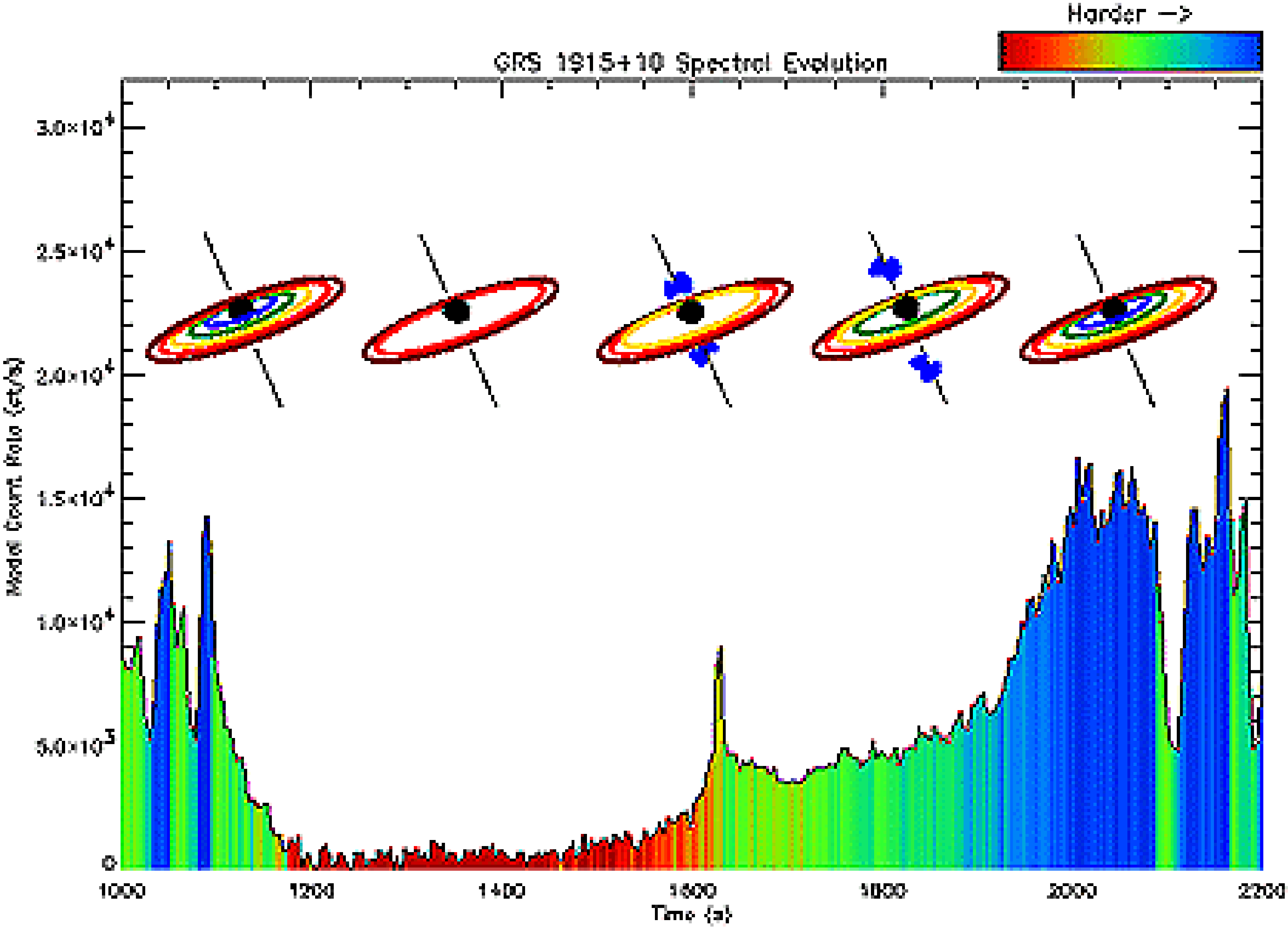


The radio jets of the Galactic black-hole candidate GRS 1915+105

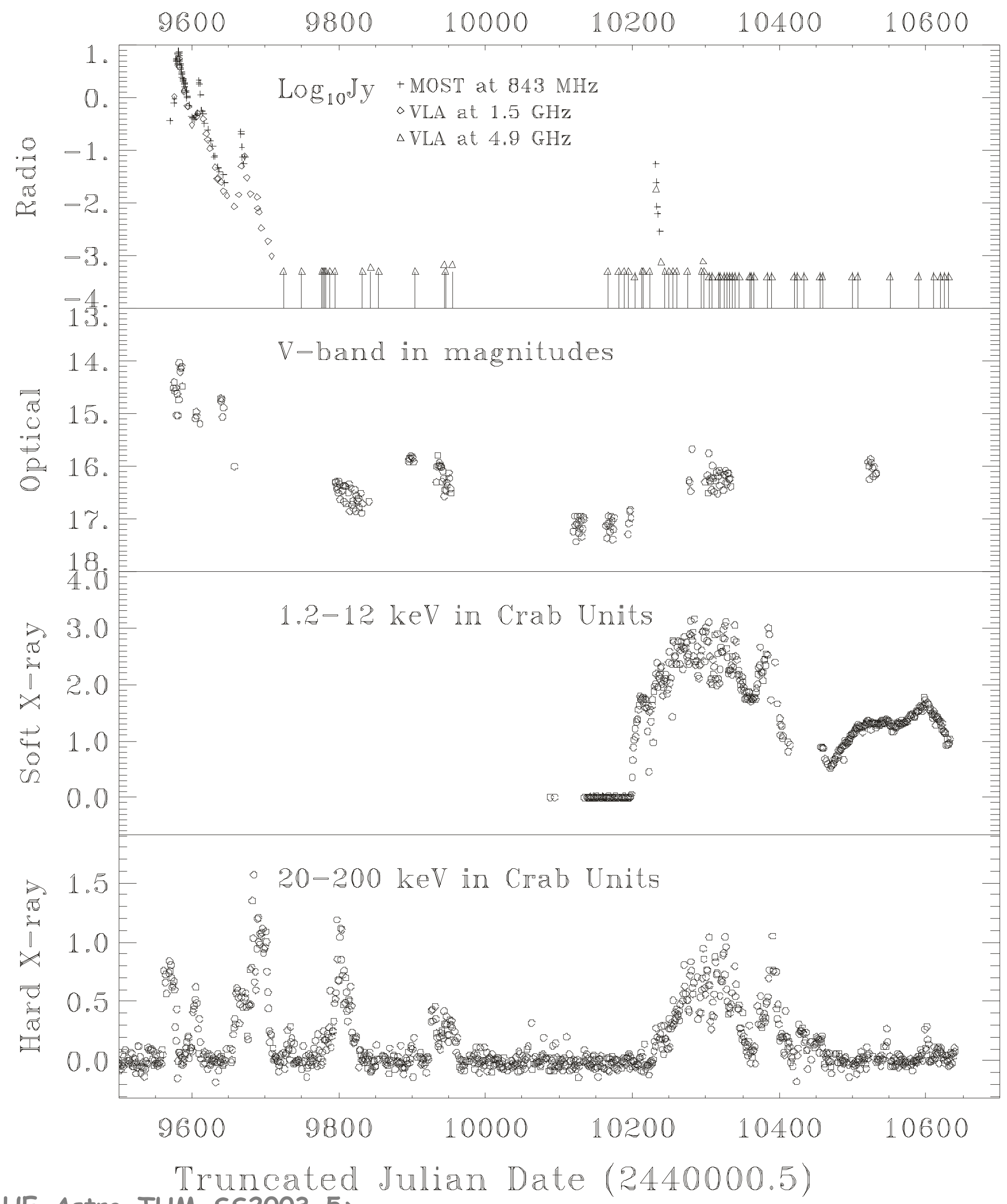
Disk-Jet Connection (I)



Disk-Jet Connection (II)



Multifrequency Observations



Flaring episodes of the transient GRO J1655-40, which exhibits super-luminal radio jets. Strong hard X-ray and gamma-ray flares not accompanied by radio flares indicate that the high-energy emission is not produced in the jets.