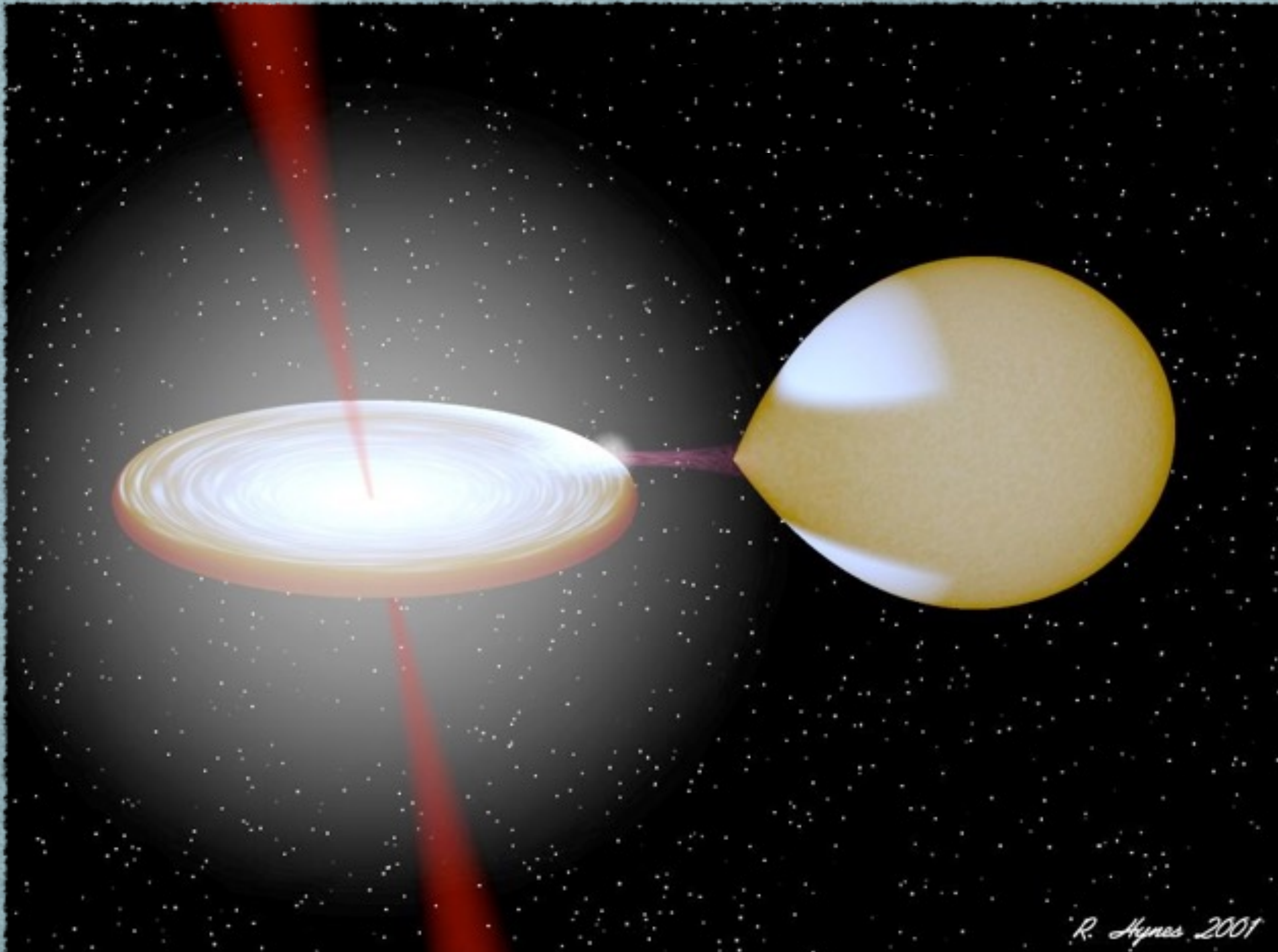

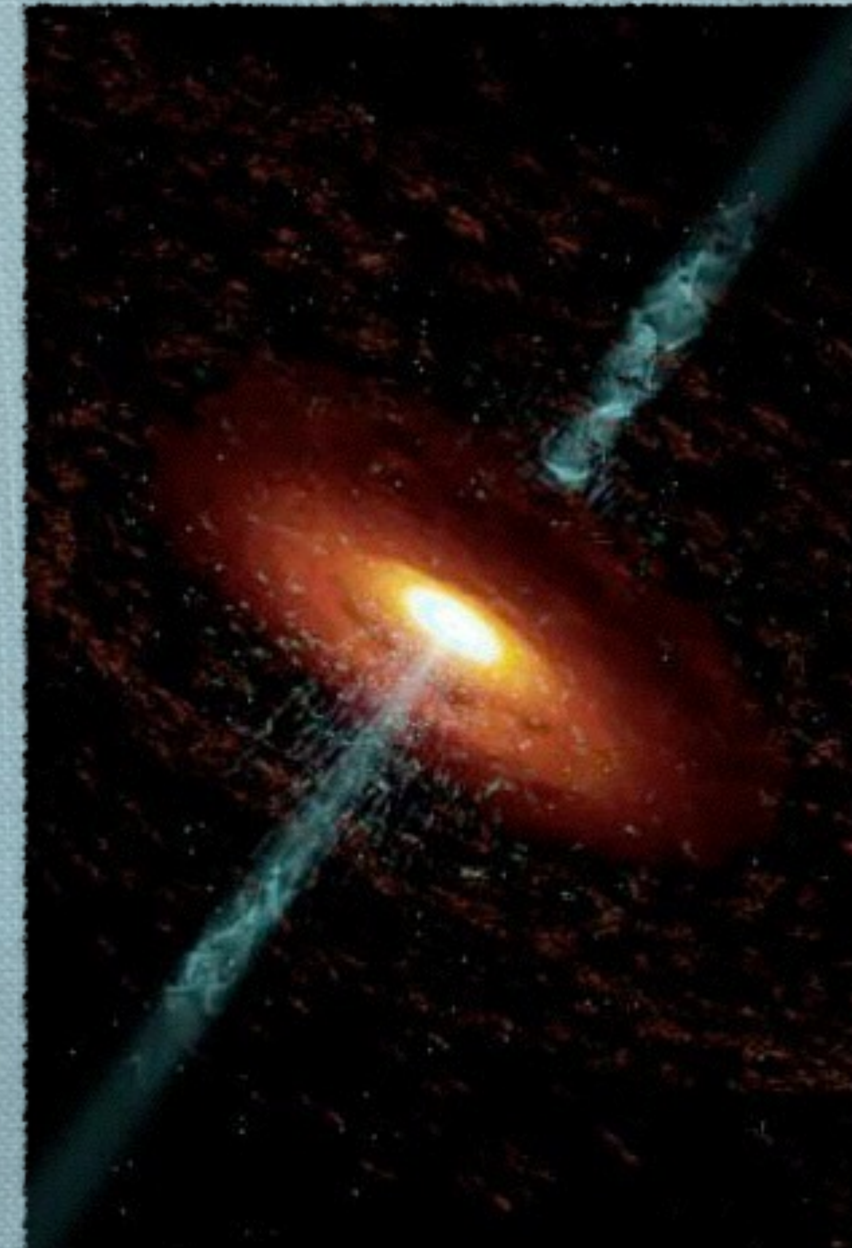

X-ray observations of X-ray binaries and AGN

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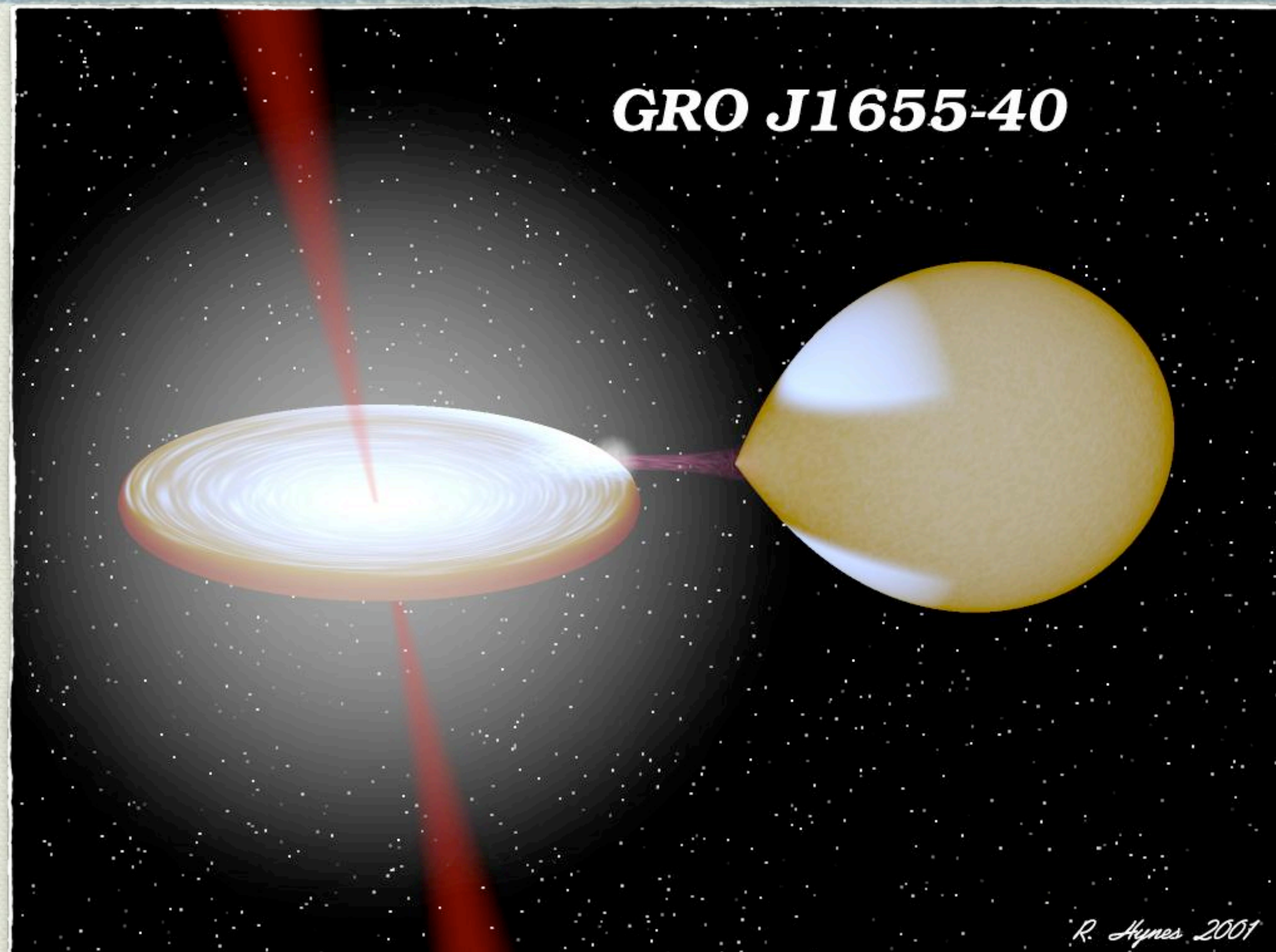
(Visiting Professor, Univ. of Southampton)

OUTLINE

- **Lecture I: Accretion onto compact objects, X-ray binaries, black hole candidates, X-ray pulsars**
- Lecture II: High-energy emission and spectra
- Lecture III: Time variability on all scales
- Lecture IV: Radio emission, jets, accretion/ejection
- Lecture V: BH parameters & GR, AGN connection
- Lecture VI: Neutron-Star binaries + ULX + more

X-ray binaries



Accretion power

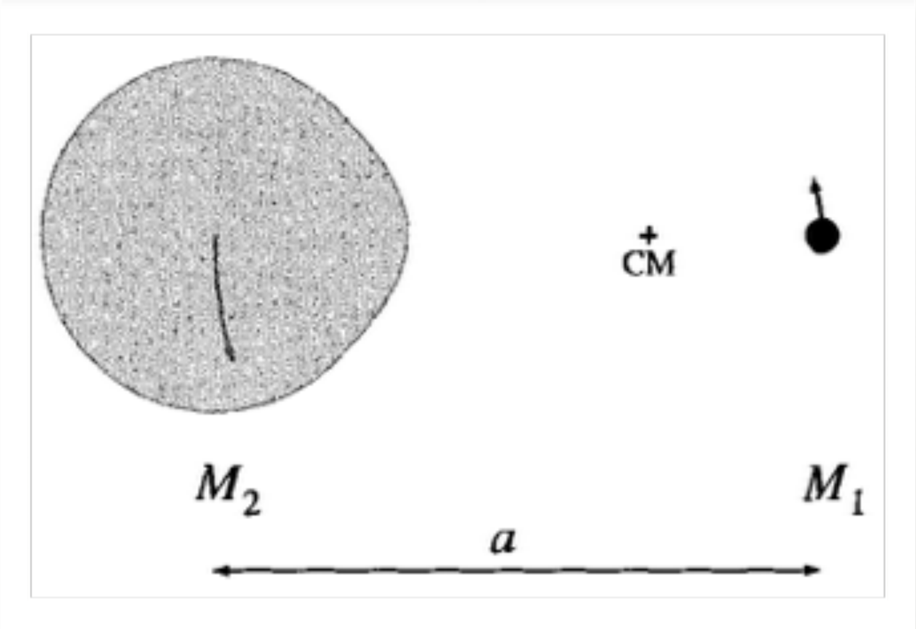
- Extraction of gravitational potential energy
- Main source of power of several astronomical objects
- Natural and powerful mechanism for production of X/γ rays
- Provides emission at all wavelengths
- Double-game: GR effects and accretion/ejection
- Variability on all scales from ms to years/centuries

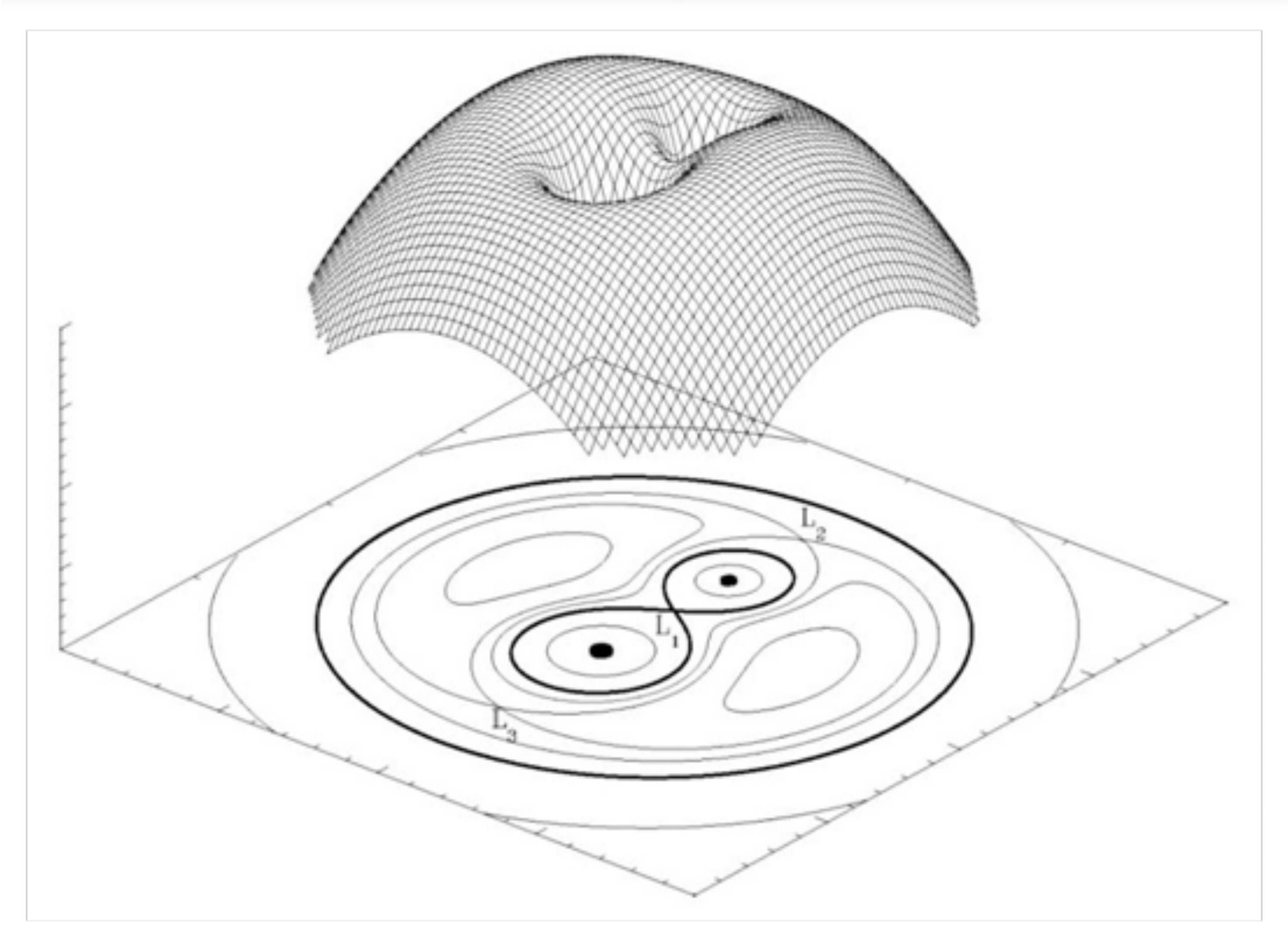
Accretion in binaries

- Transfer of matter from a star to a compact object
- Two possible scenarios:
  - Gravitational force from BH/NS strips gas
  - Strong stellar wind loss captured by BH/NS
- Dependence on binary and evolution

Roche geometry

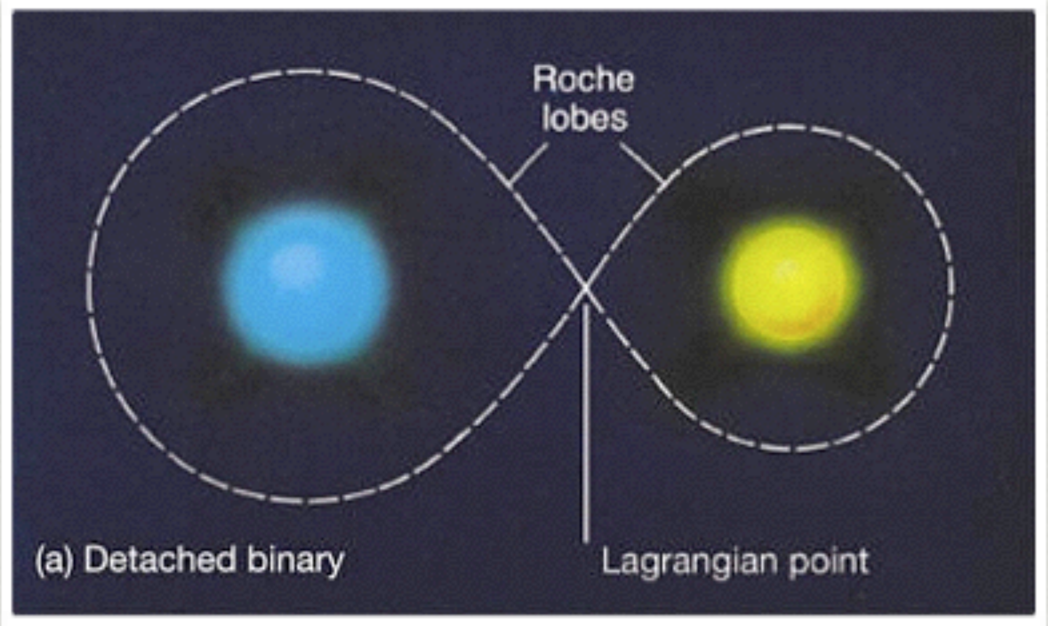
- Roche geometry of the binary
- Lagrangian points
- Mass ratio $q=M_2/M_1$

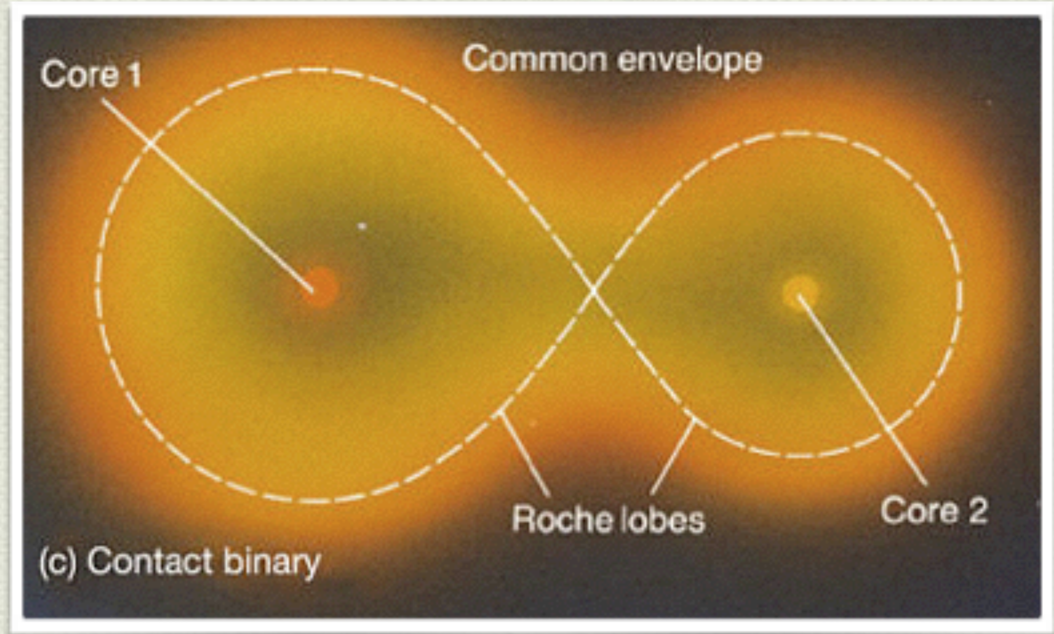


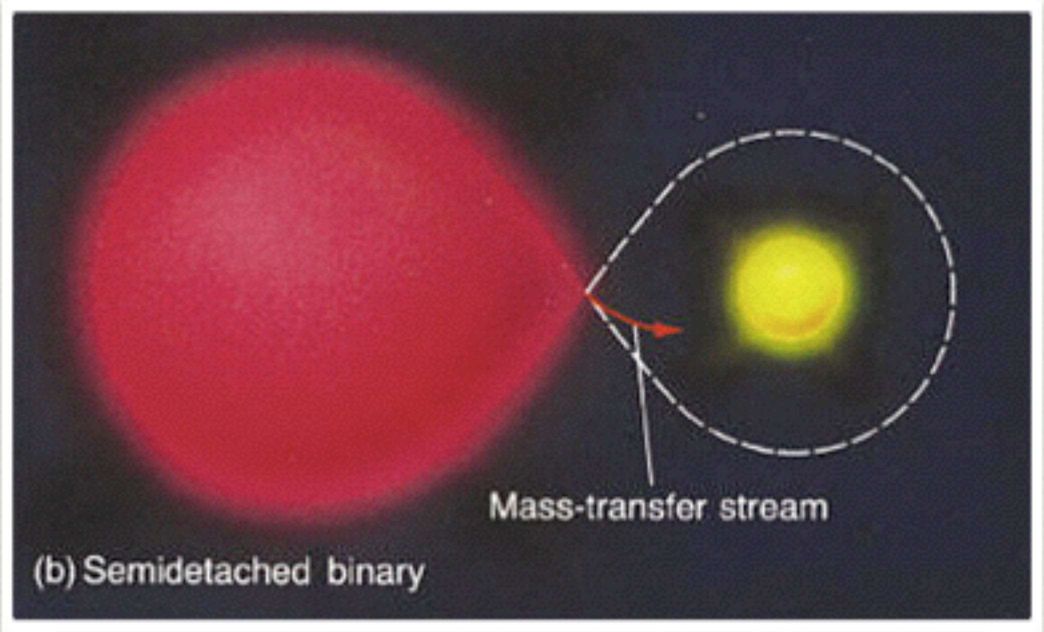


Roche-lobe overflow

- Three possible geometries
- Filling star: secondary
- Compact object: primary

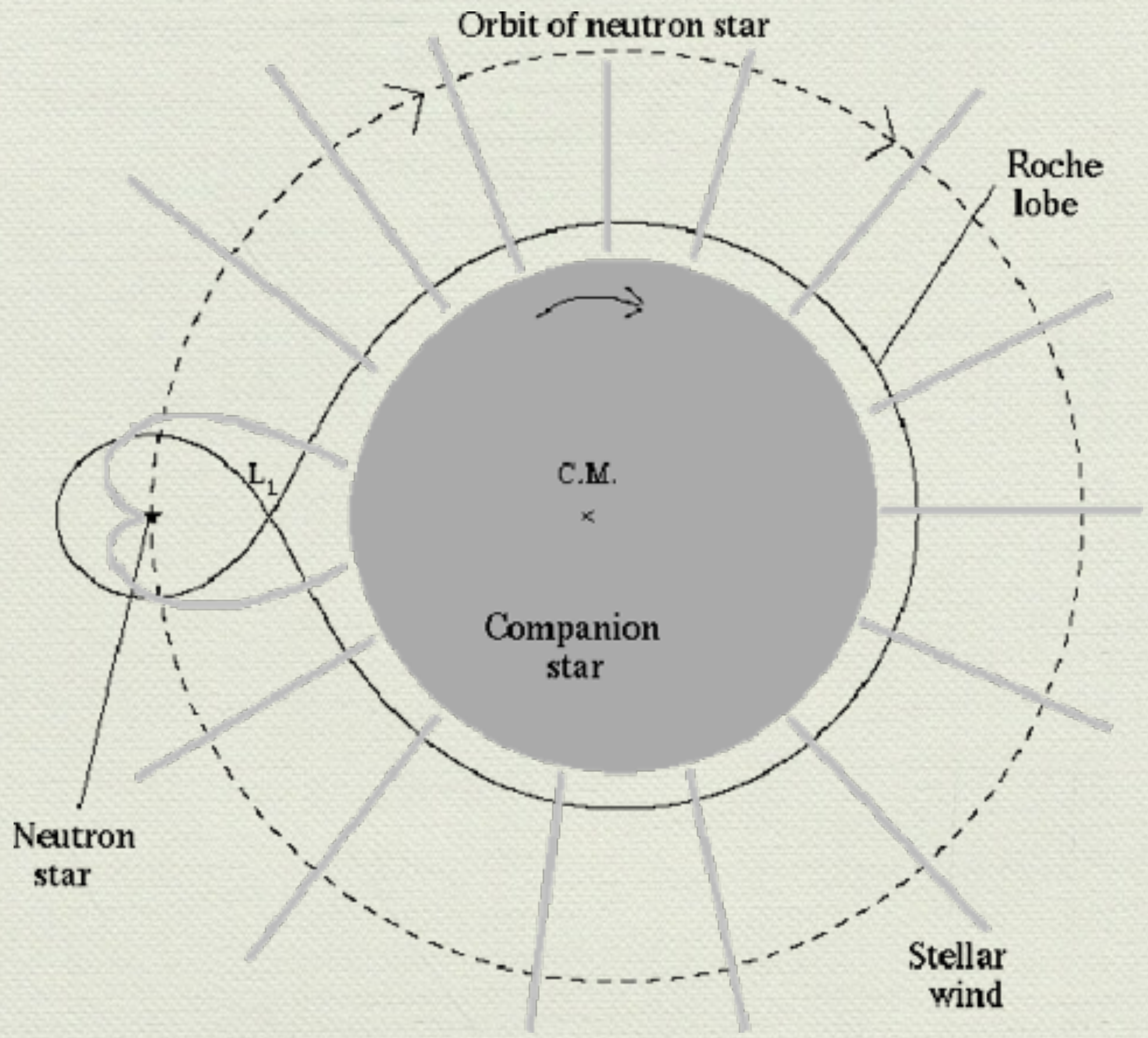




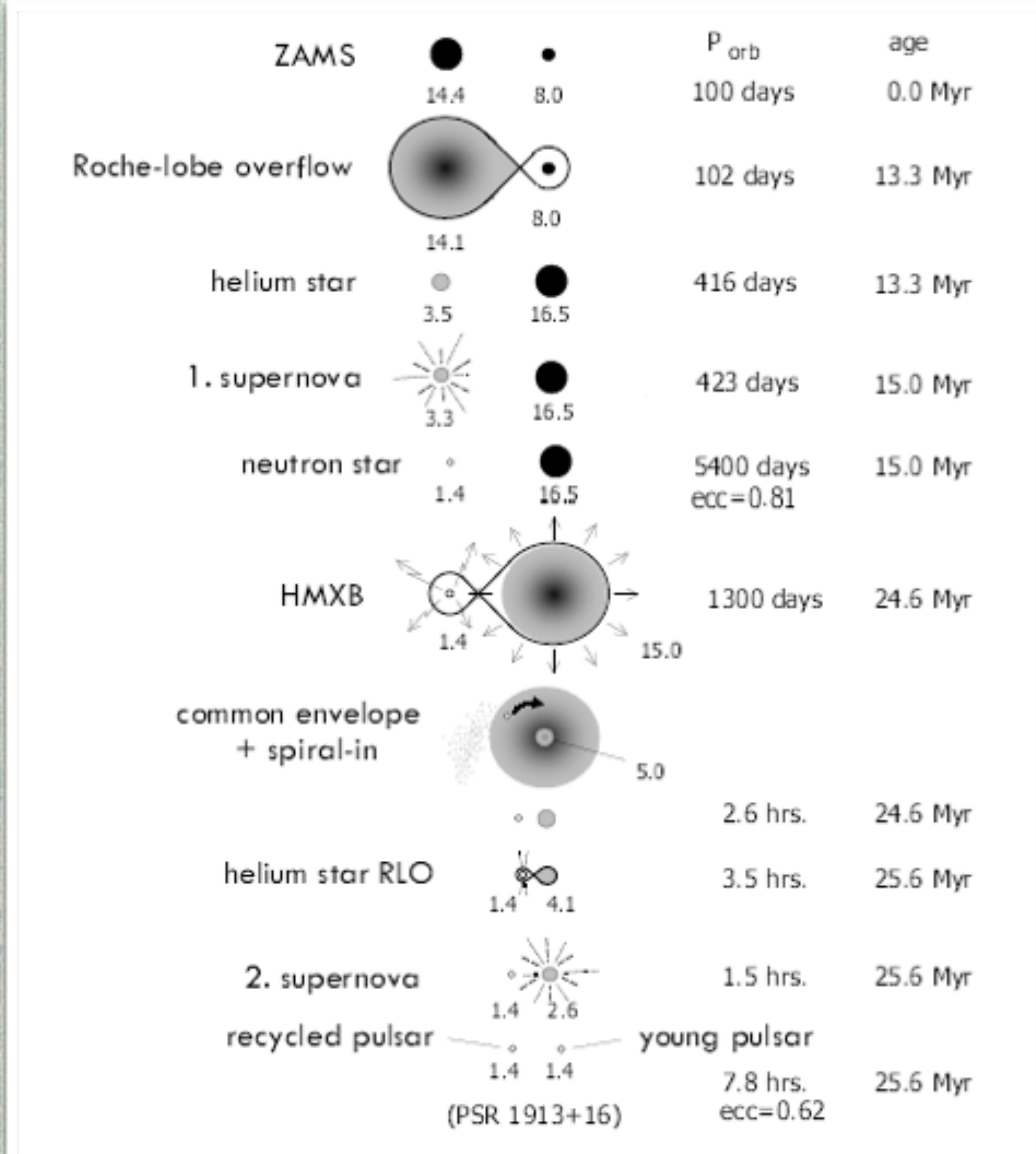


Wind / RL accretion

- No Roche-lobe overflow
- Strong stellar wind
- Very different systems
  - LMXB
  - HMXB

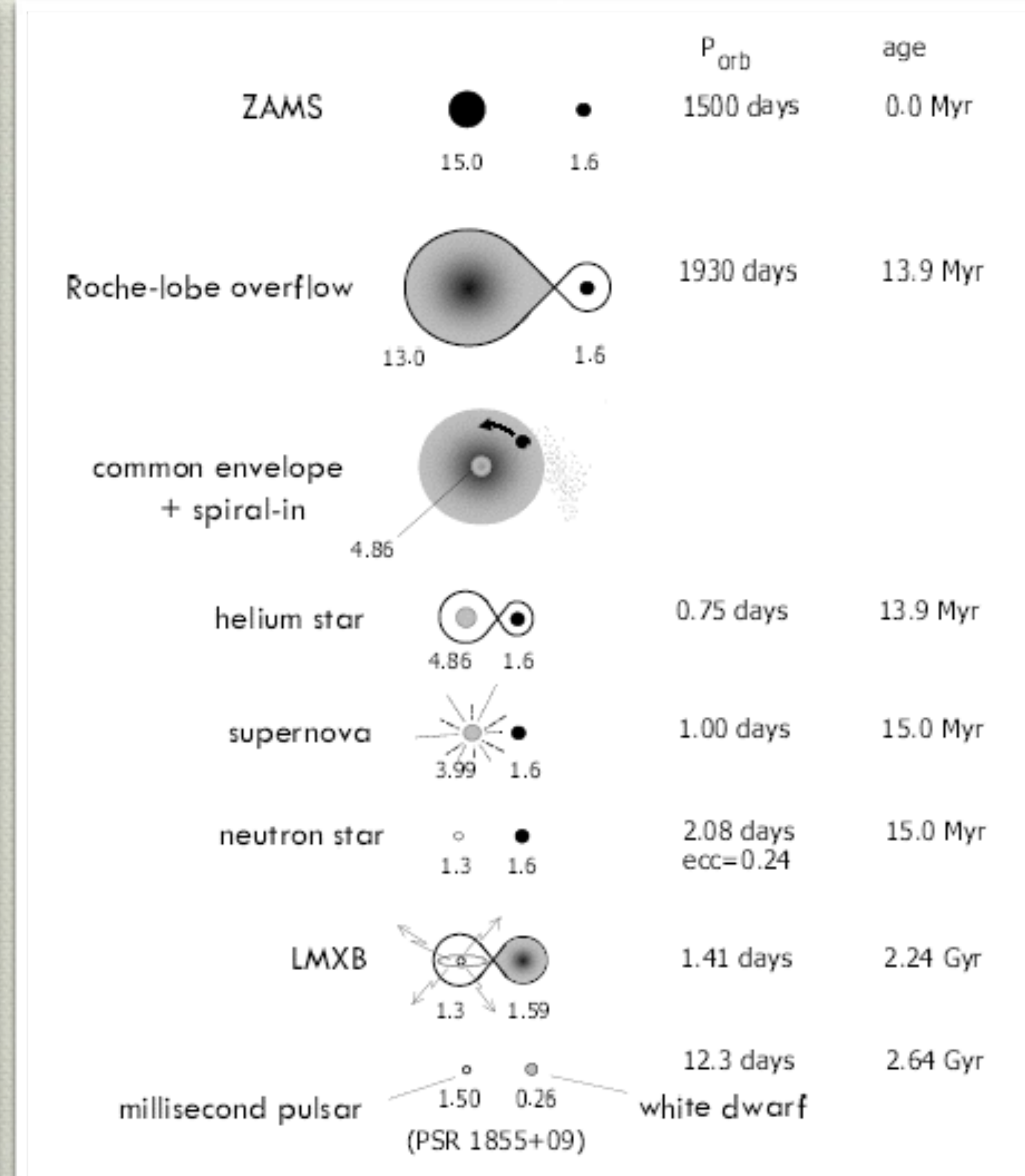


HMXB



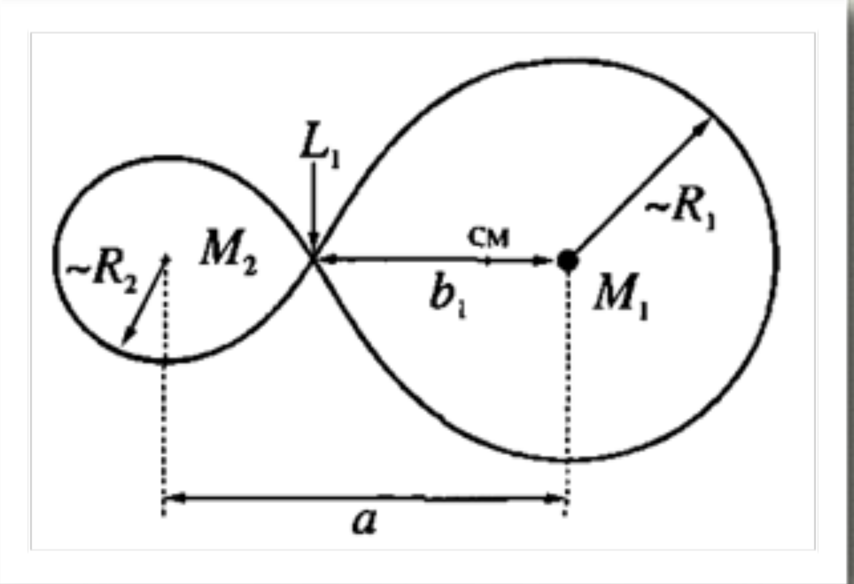
P orb
age
ZAMS
14.4
8.0
100 days
0.0 Myr
Roche-lobe overflow
14.1
8.0
102 days
13.3 Myr
helium star
3.5
16.5
416 days
13.3 Myr
1. supernova
3.3
16.5
423 days
15.0 Myr
neutron star
1.4
16.5
5400 days
ecc=0.81
15.0 Myr
HMXB
1.4
15.0
1300 days
24.6 Myr
common envelope
+ spiral-in
5.0
2.6 hrs.
24.6 Myr
helium star RLO
1.4
4.1
3.5 hrs.
25.6 Myr
2. supernova
1.4
2.6
1.5 hrs.
25.6 Myr
recycled pulsar
young pulsar
1.4
1.4
7.8 hrs.
ecc=0.62
25.6 Myr
(PSR 1913+16)

LMXB



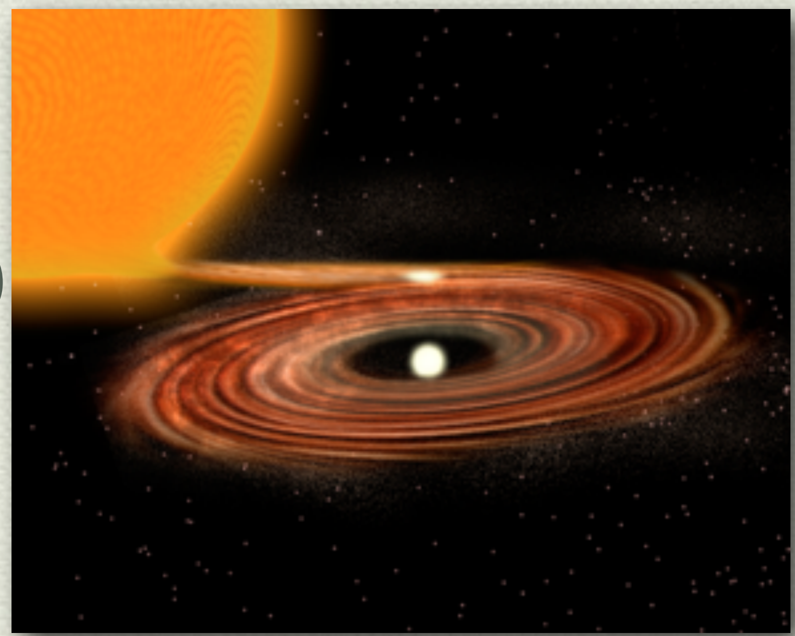
P orb
age
ZAMS
15.0
1.6
1500 days
0.0 Myr
Roche-lobe overflow
13.0
1.6
1930 days
13.9 Myr
common envelope
+ spiral-in
4.86
helium star
4.86
1.6
0.75 days
13.9 Myr
supernova
3.99
1.6
1.00 days
15.0 Myr
neutron star
1.3
1.6
2.08 days
ecc=0.24
15.0 Myr
LMXB
1.3
1.59
1.41 days
2.24 Gyr
millisecond pulsar
1.50
0.26
white dwarf
12.3 days
2.64 Gyr
(PSR 1855+09)

Disk formation



- L_1 rotates: angular momentum
- Orbit @ circularization radius
- Single particle vs. stream
- Friction - loss of energy - spiral in
- Angular momentum goes out
- Matter spreads in and out through near-circular orbits
- A disk is formed with $$L_{disk} = \frac{GM\dot{M}}{2R_\star} = \frac{1}{2}L_{acc}$$

Accretion disk



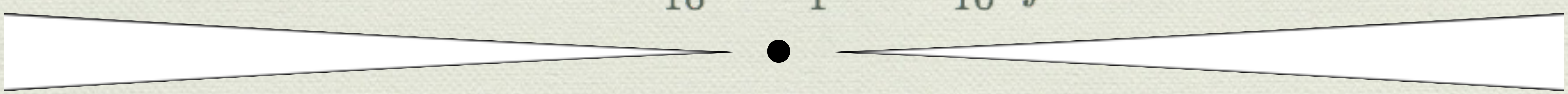
- Conversion of energy into heat
- Viscosity in the disk (differential rotation)
- Nature of viscosity is not clear
    - Turbulent eddies cannot be larger than the disk thickness
    - They cannot be supersonic (shock thermalization)
- Therefore $\nu = \alpha c_s H$ with $\alpha \leq 1$
- It's the carpet

Accretion disk

$$f = \left[1 - \left(\frac{R_\star}{R}\right)^{1/2}\right]^{1/4}$$

- Model for thin disks (1973)
- Algebraic solution with thickness

$$H = 1.7 \times 10^8 \alpha^{-1/10} \dot{M}_{16}^{3/20} m_1^{-3/8} R_{10}^{9/8} f^{3/5} \mathrm{cm}$$



- At large radii: $H/R \propto \alpha^{-10} R^{1/8}$
- Inner regions (rad. pressure dominated): H~const * f
- Close to L_{edd}: $H \sim \frac{3R_\star}{4\eta} \frac{\dot{M}}{\dot{M}_{Edd}} \left[1 - \left(\frac{R_{star}}{R}\right)^{1/2}\right]$
- Thin disk approximation can breakdown

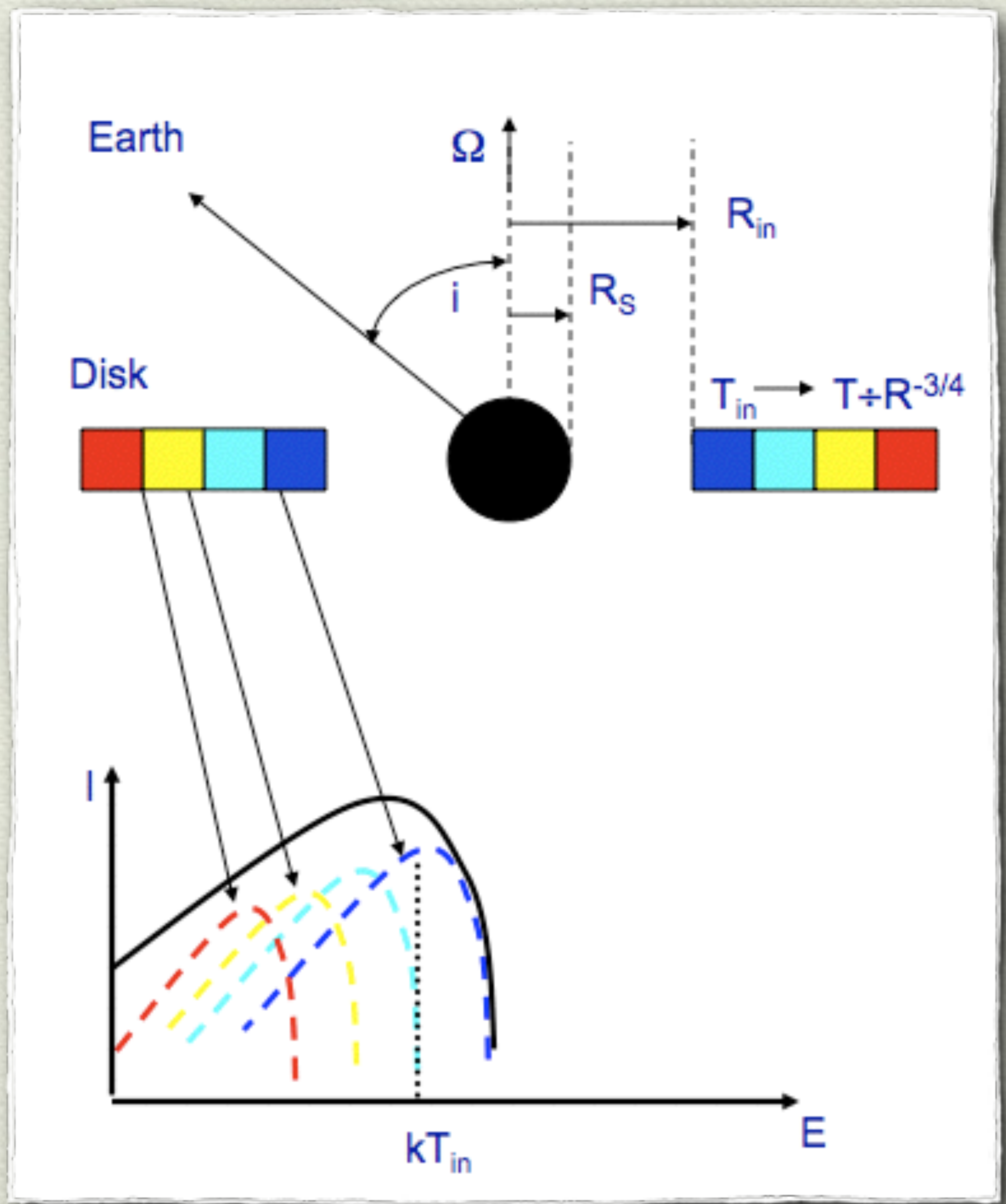
Thin disk spectrum

- Model for thin disks (1973)
- Optically thick disk
- Each radius a blackbody with

$$T(R) = \left\{ \frac{3GM\dot{M}}{8\pi R^3 \sigma} \right\}^4 f$$

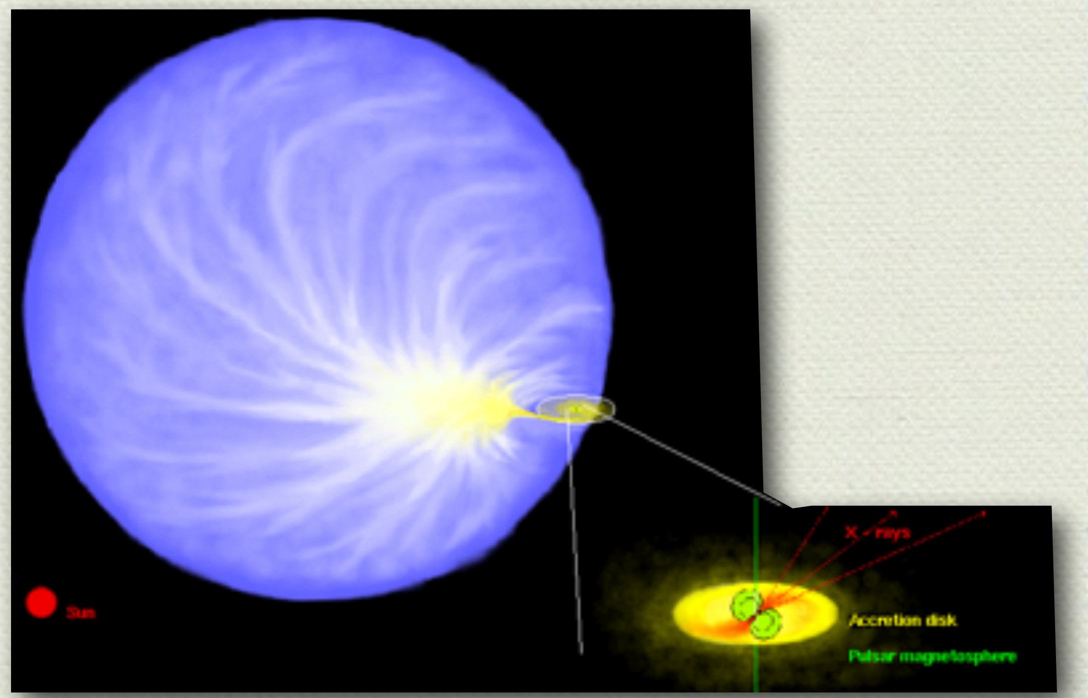
- *T(R)* as effective temperature
- Total spectrum is

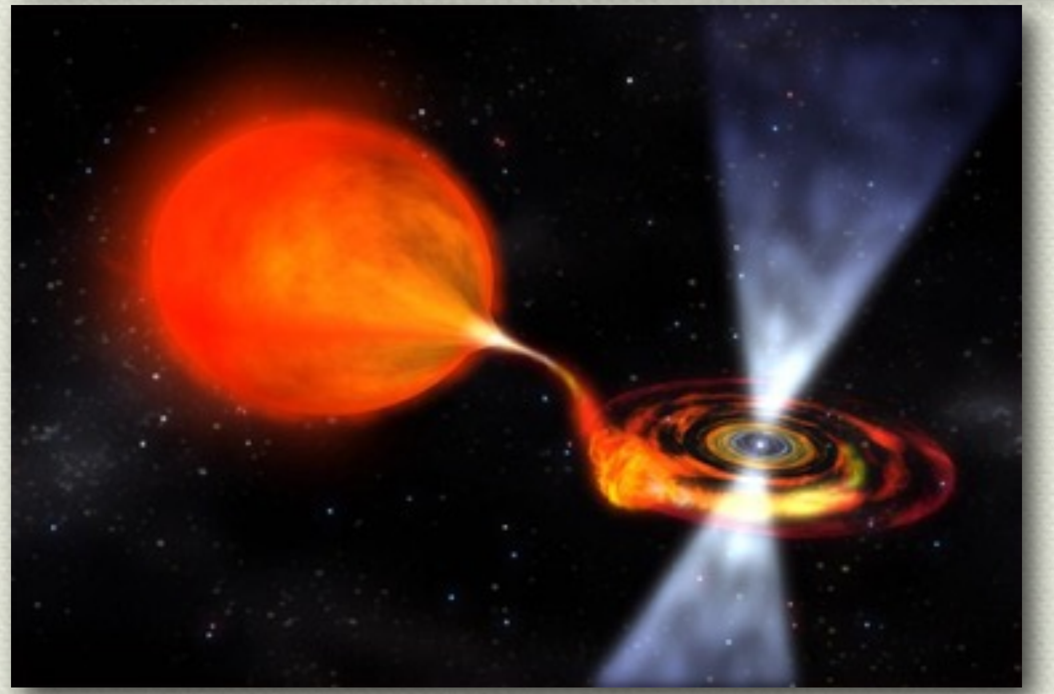
$$F_\nu = \frac{4\pi h \cos i \nu^3}{c^2 D^2} \int_{R_\star}^{R_{out}} \frac{R dR}{e^{h\nu/kT(R)} - 1}$$



Classes of X-ray binaries

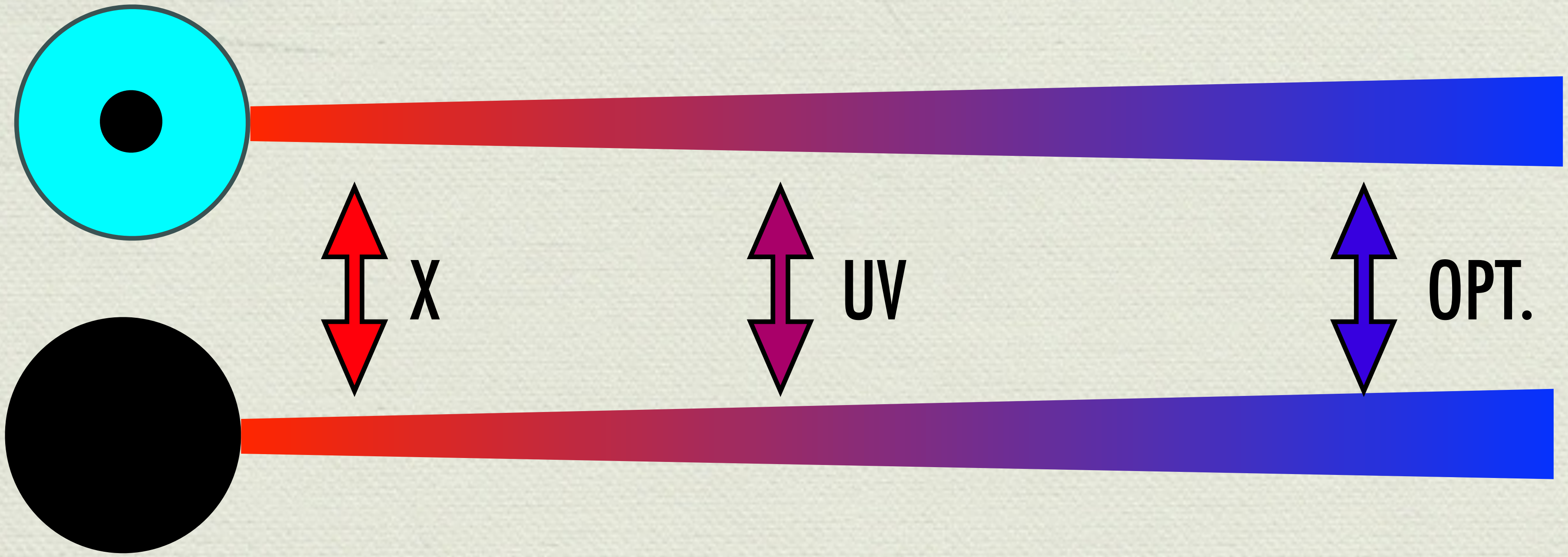
- Neutron star
  - High B field: HMXB/pulsars
  - Low B field: LMXB/ms pulsars
- Black hole
  - LMXB: transients
  - HMXB: persistent





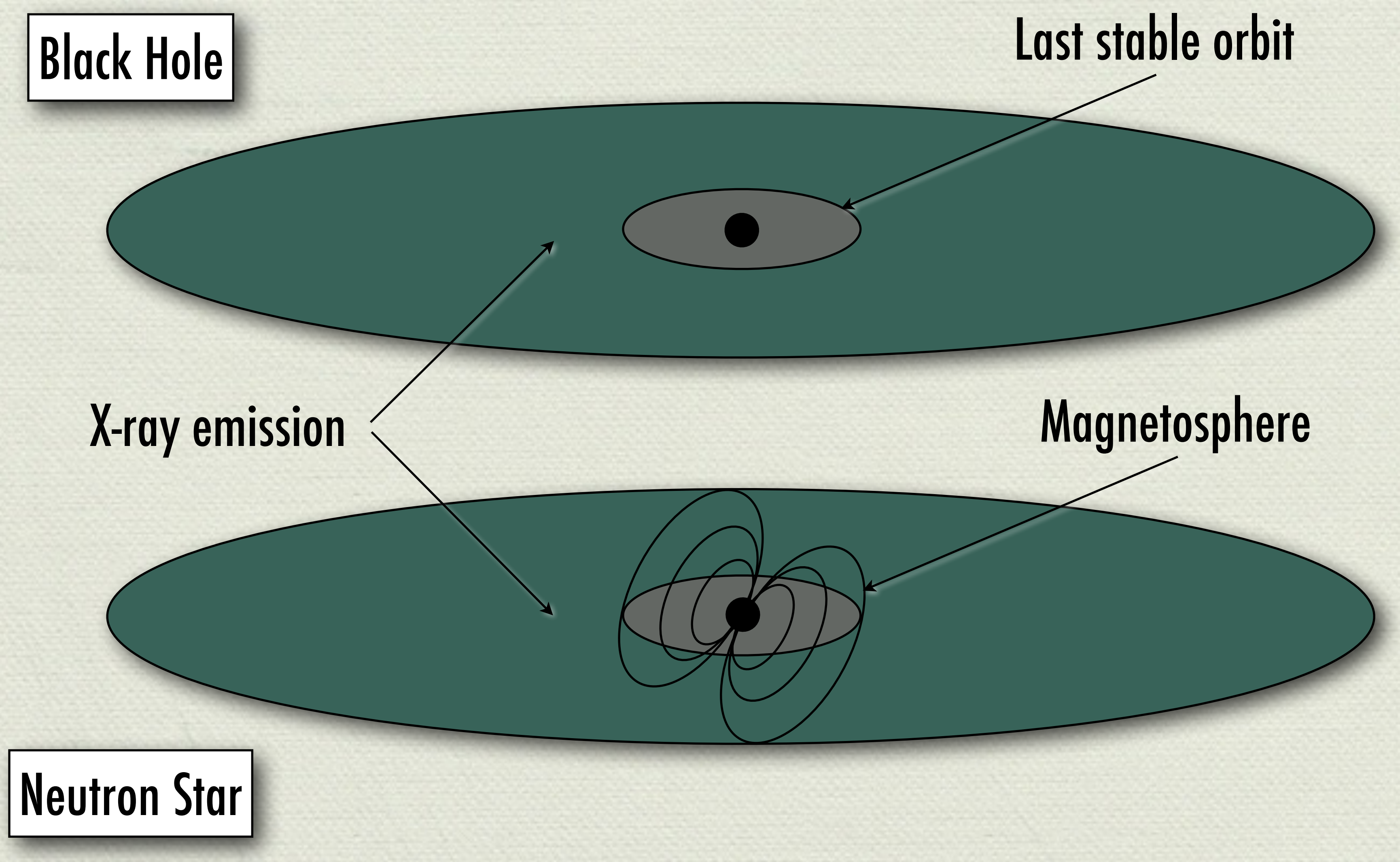
BH versus low-B NS

- Same sizes, same components



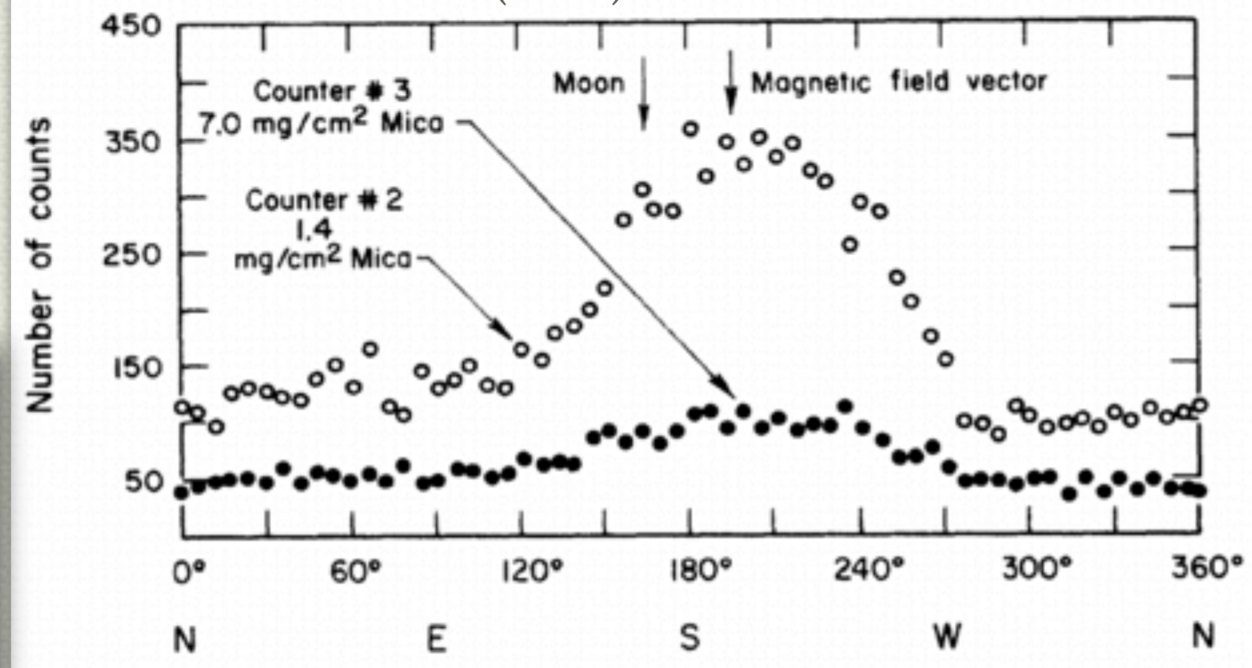
BH versus low-B NS

- Same sizes, same components

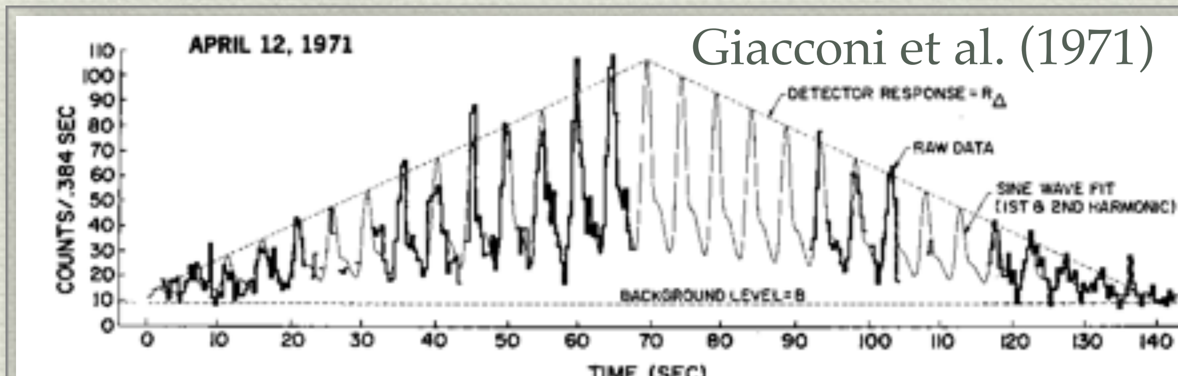


And observations?

- First X-ray source: Sco X-1 (the brightest)
- First X-ray pulsar: Cen X-3
- Pulsations & not…



Giacconi et al. (1962)



Giacconi et al. (1971)

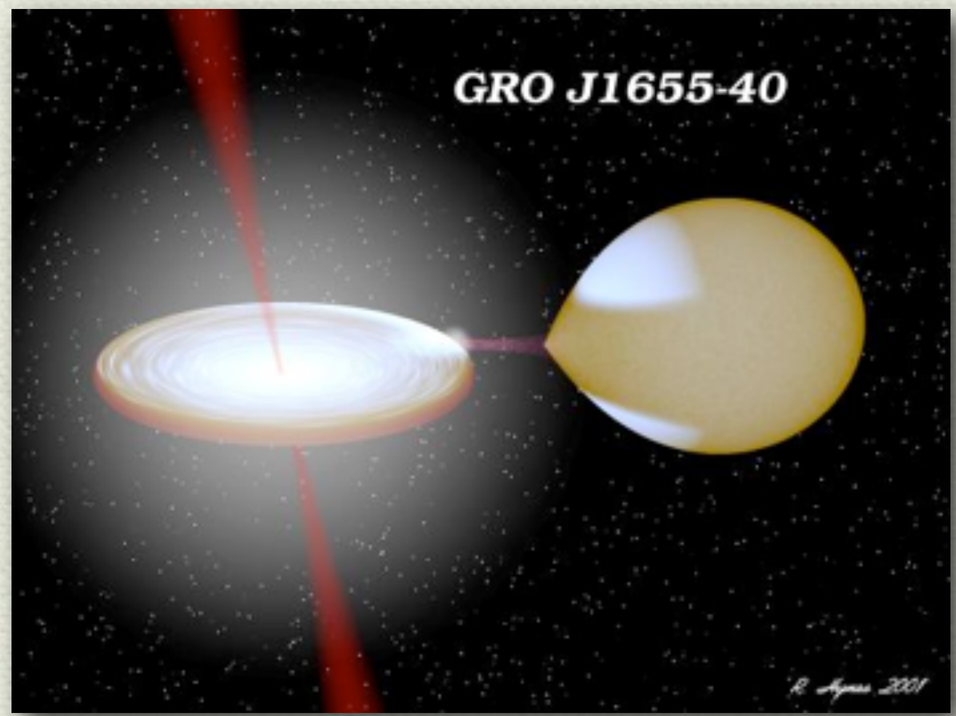
DATA ON X-RAY PULSARS

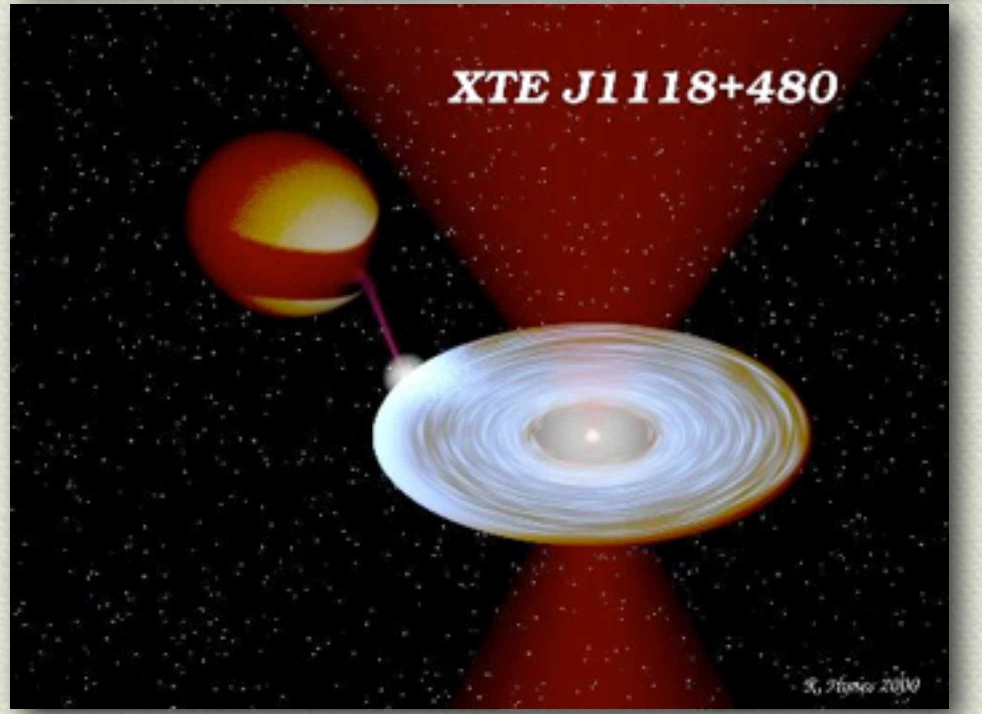
Parameter	Star: NP 0532*	Cygnus X-1†	Centaurus X-3
Period τ (seconds).......	0.033	0.073 or 0.292 1.1 or 1.3 Possibly >5	4.87

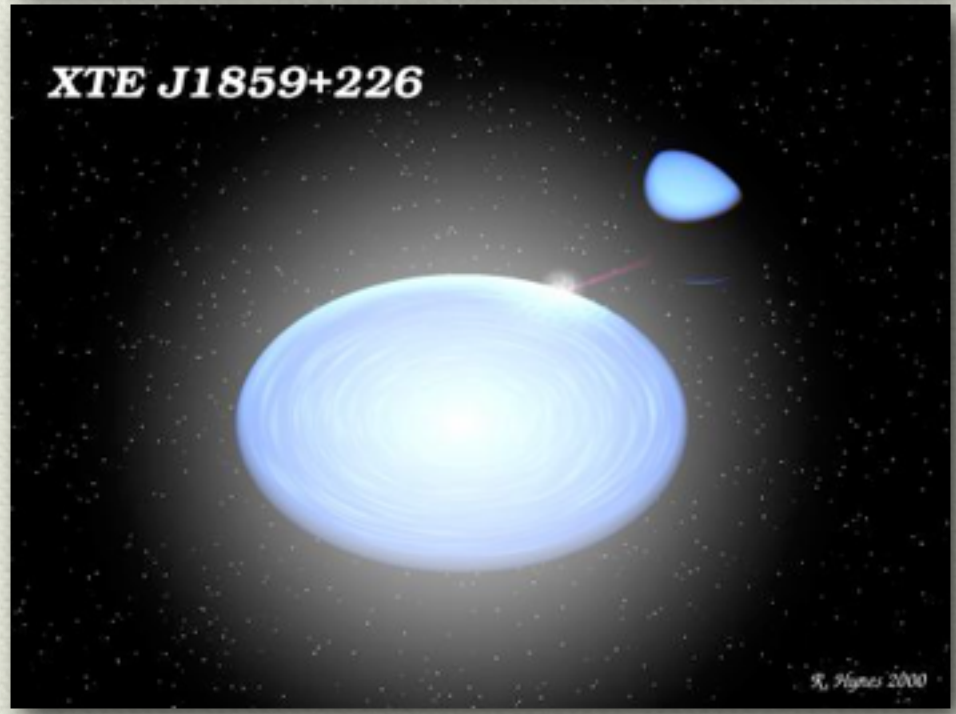
And observations?

- Historically, first black-hole candidate was Cygnus X-1
- Bright O9.7Iab star (V=8.95) - HDE 226868 a.k.a LS II +35 8
- Rocket flight in 1964: discovery of X-ray sources
- 1972: Webster & Murdin + Bolton find evidence of binarity (P=5.6d) and estimated the companion's mass
- A HMXB
- Mass function is 0.244 - mass of compact object ~10 $M_\odot$

Black-hole binaries





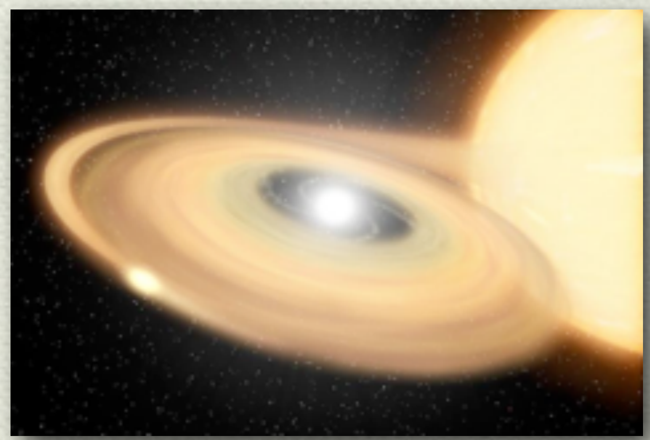


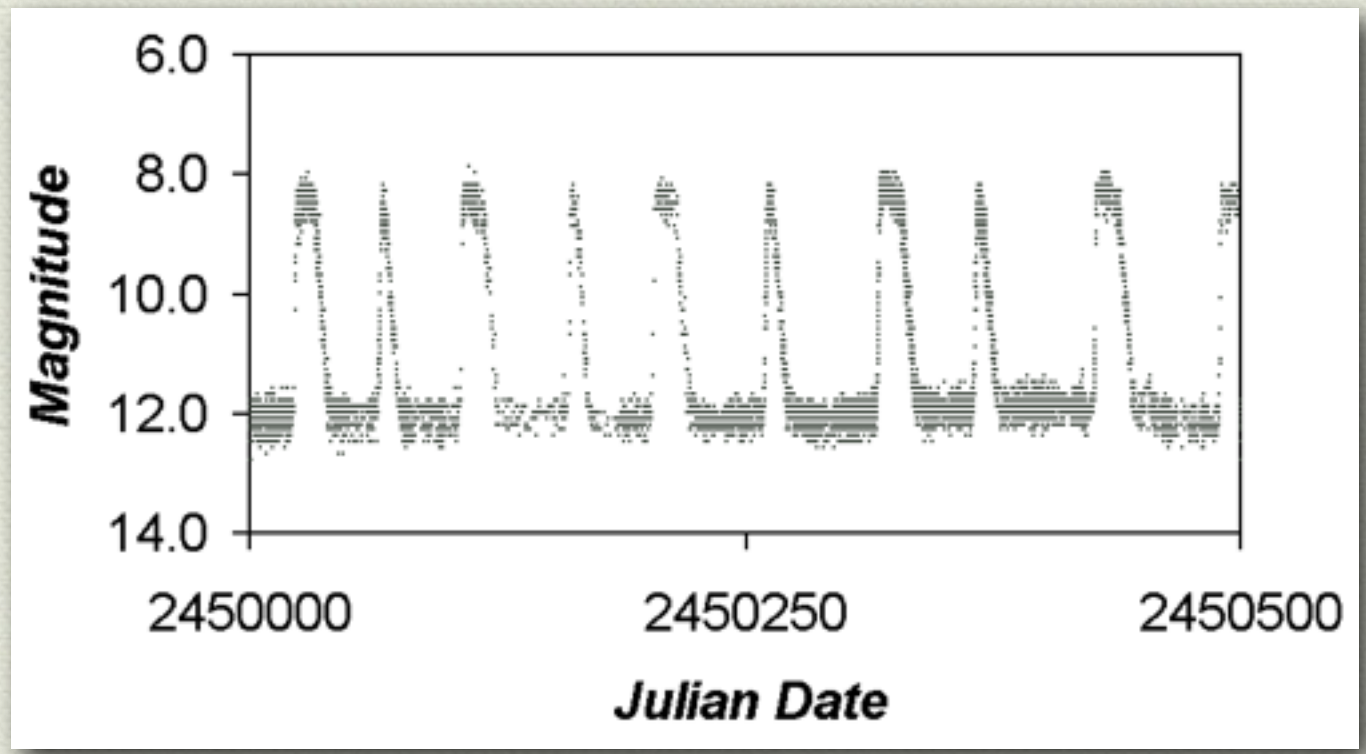
Black hole binaries?

- Black-hole candidates: dynamical mass
- Quest for a direct signature: not found (yet)
- Lots of circumstantial evidence
- “The jury” reached a verdict
- Now we know the masses: black-hole binaries
- We go for the spinFollow the information flow

Transient vs. persistent

- First, the dwarf-nova case (simplest)
- Accreting white dwarf from low-mass star
- Alternate outbursts and quiescences
- Surges of accretion rate
- What is the origin?



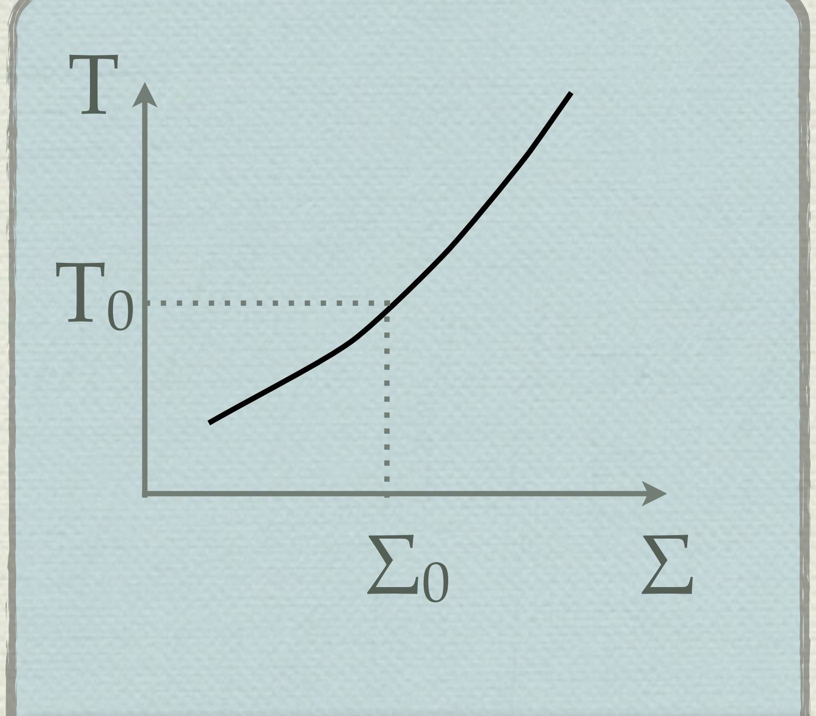


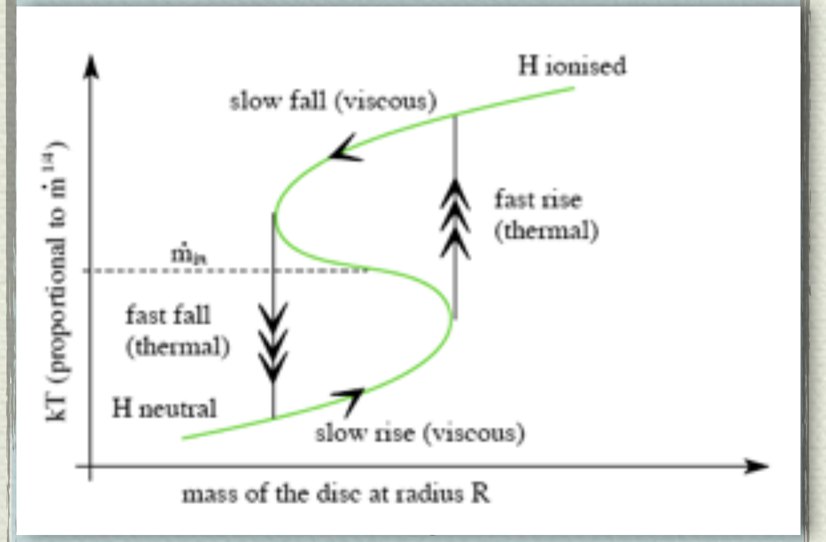
Dwarf novae

- Two possibilities:
  - The companion gives more mass (unstable envelope)
    - Too slow declines; why some systems do not?
  - The viscosity changes
    - Disk-instability model
    - Stems from accretion disk models

Disk instability

- Disk hydrogen can be neutral or ionized
- Properties change
- Instability region
- Domino effect: high accretion
- Cooling front: back to quiescence
- Condition: $\dot{M}_{DN} < 3 \times 10^{-9} P_{3hr}^{2} \, M_{\odot} \, \mathrm{yr}^{-1}$
- For NS/BH binaries?

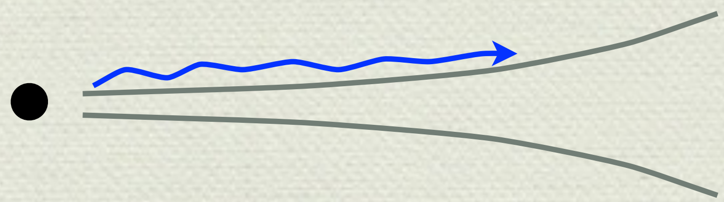




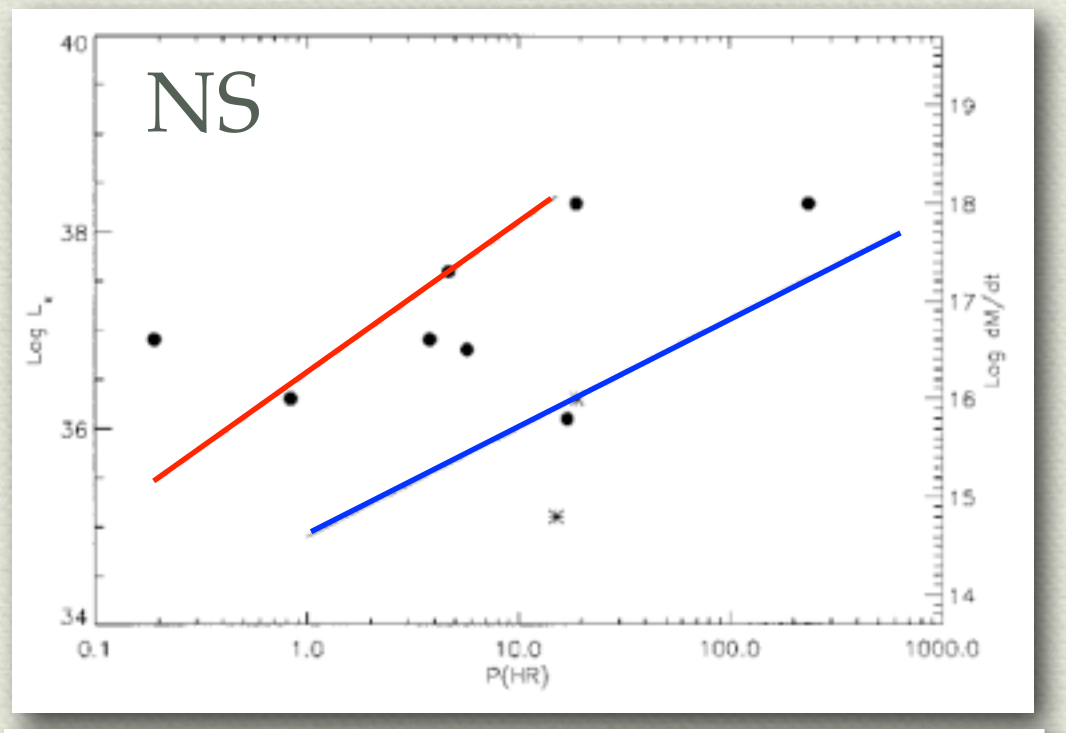
Disk instability for LMXB

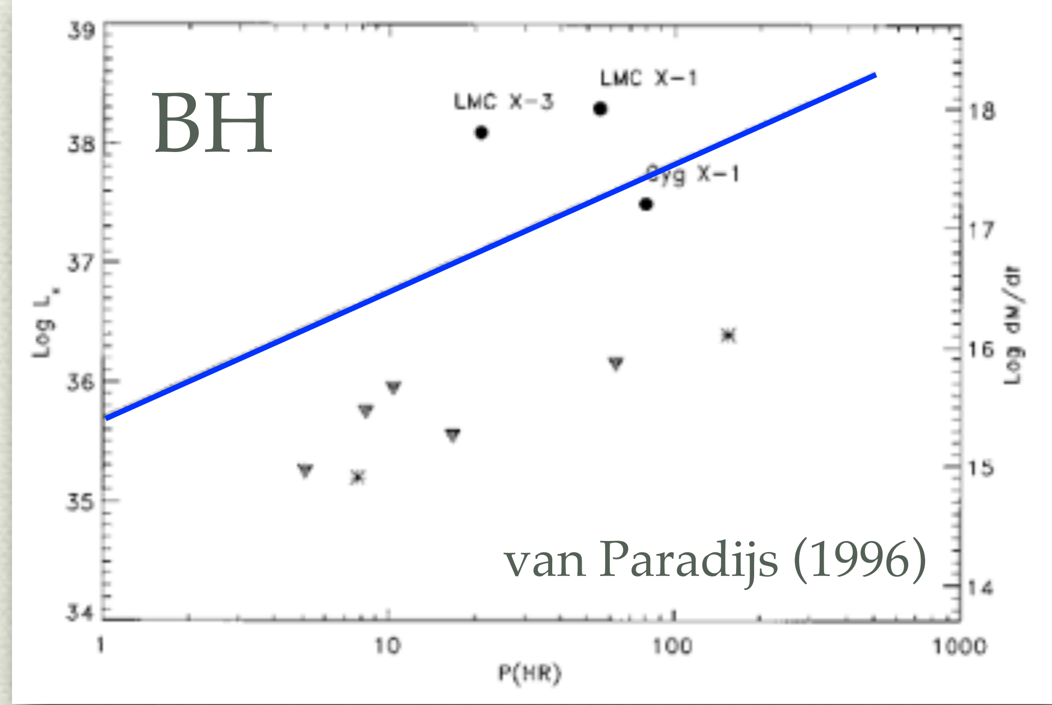
- Apparently it does not work
- However, disk is irradiated:

~~$T \propto R^{-3/4}$~~ $T \propto R^{-3/7}$



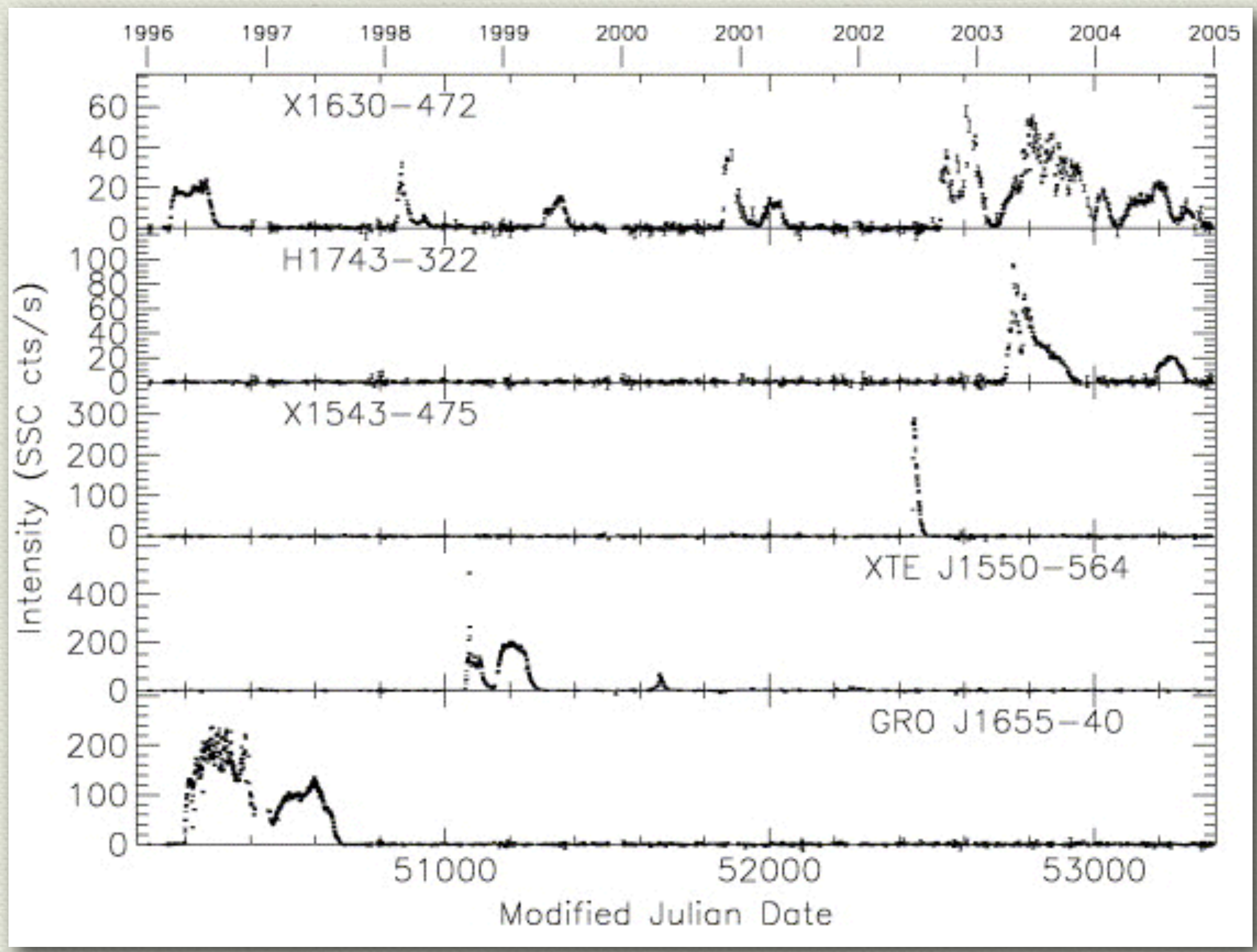
- This changes the relation





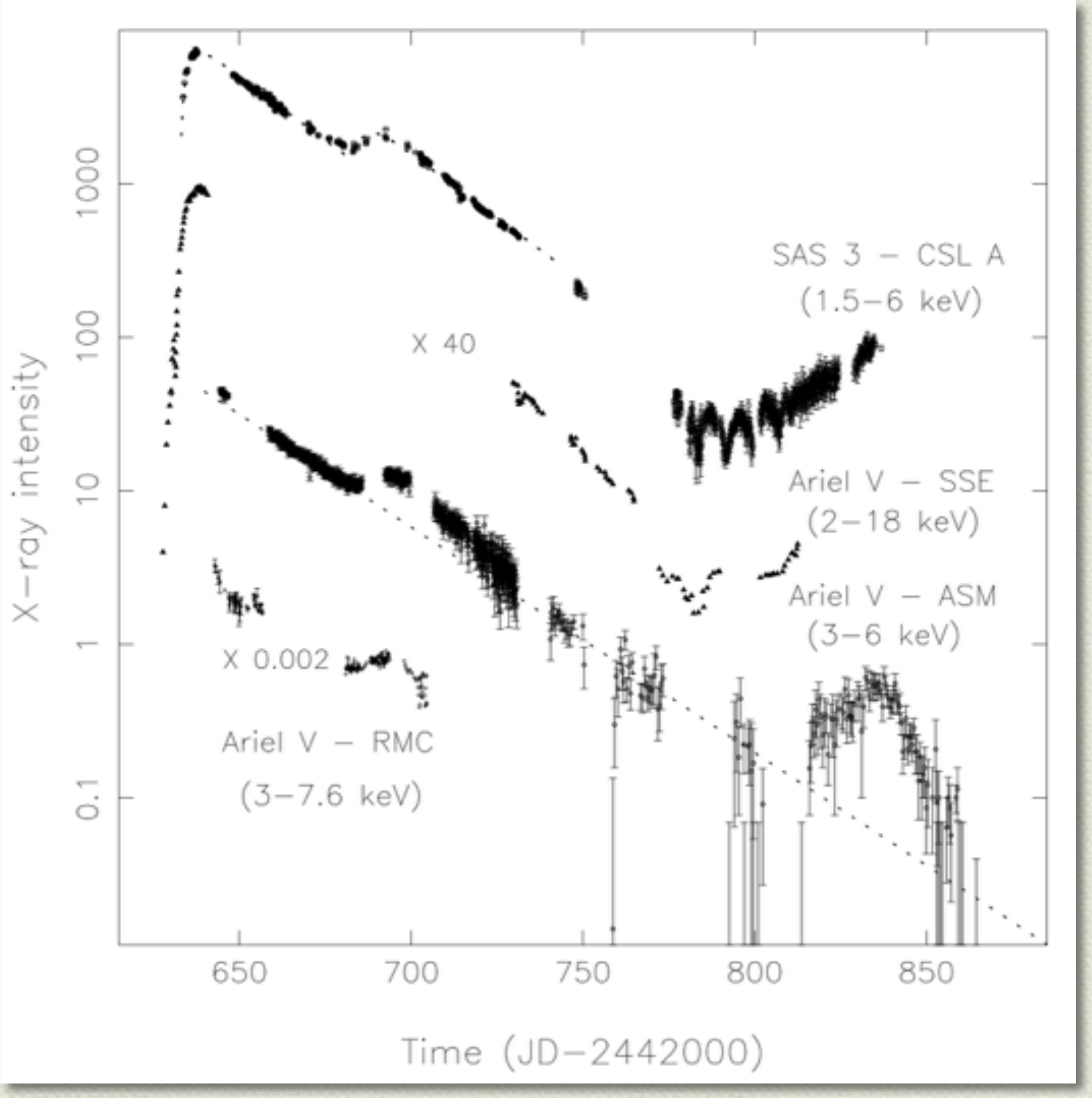
Black-hole transients

Levine et al. (2006)



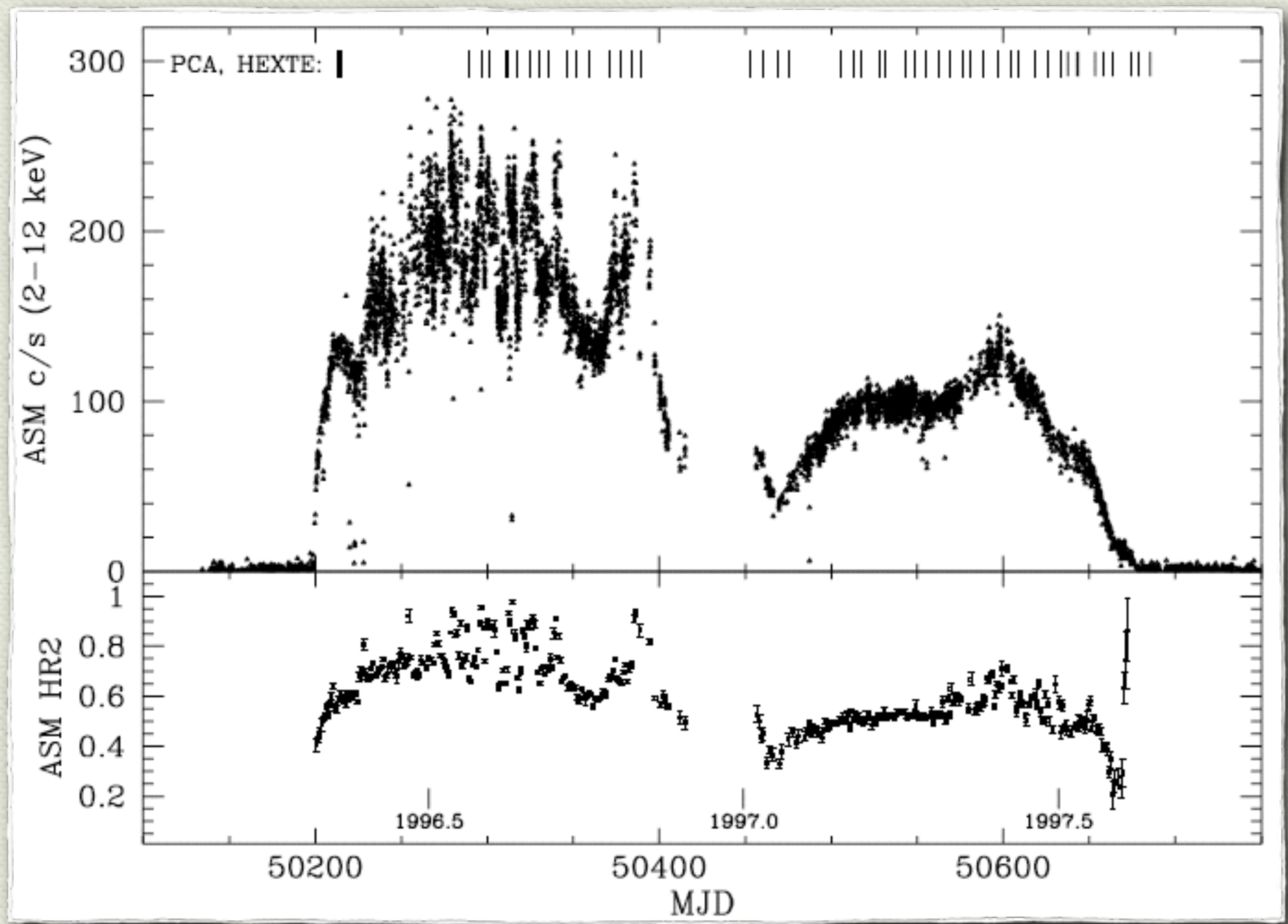
Very different shapes

Kuulkers
(1998)



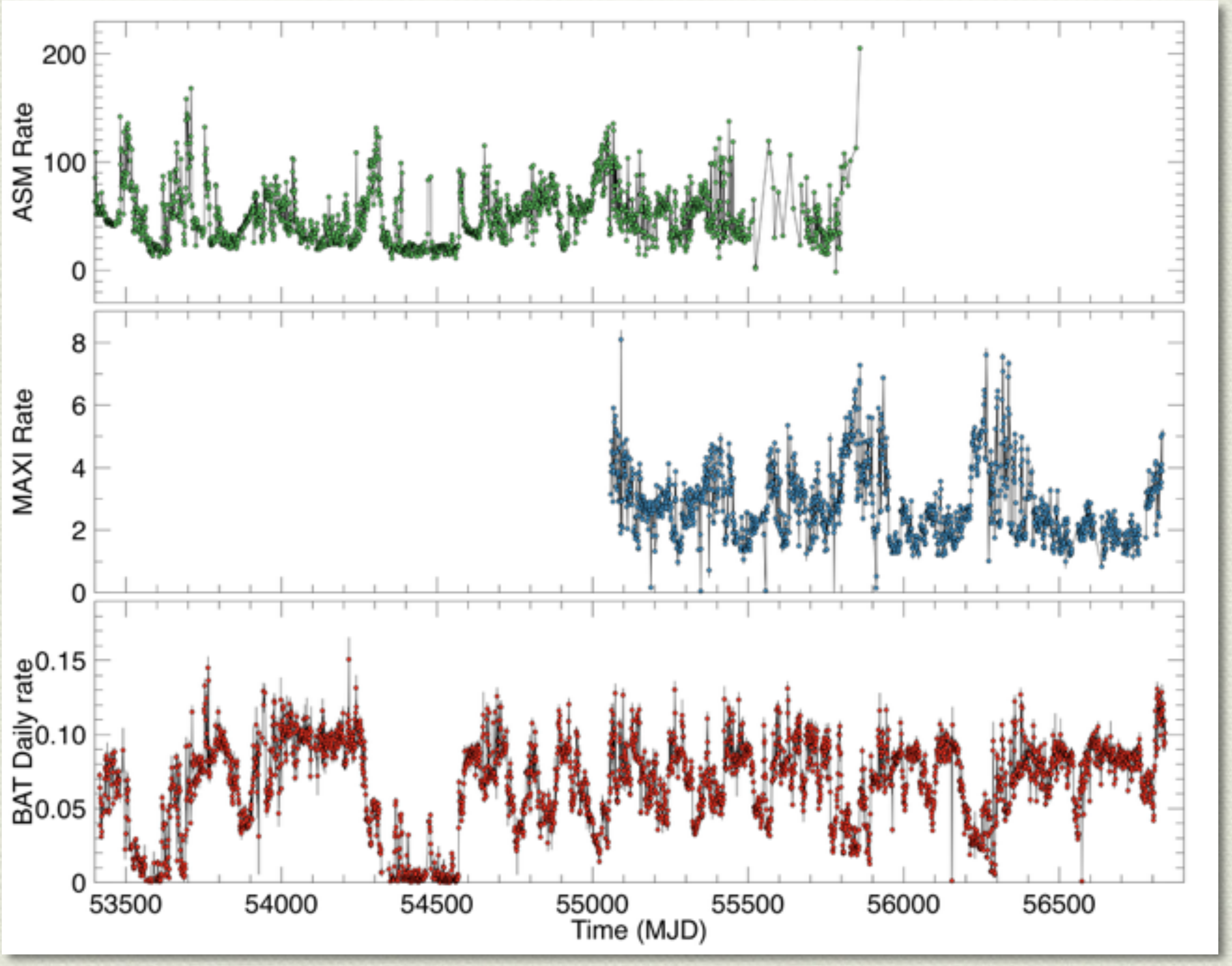
Very different shapes

Sobczak et al. (1999)



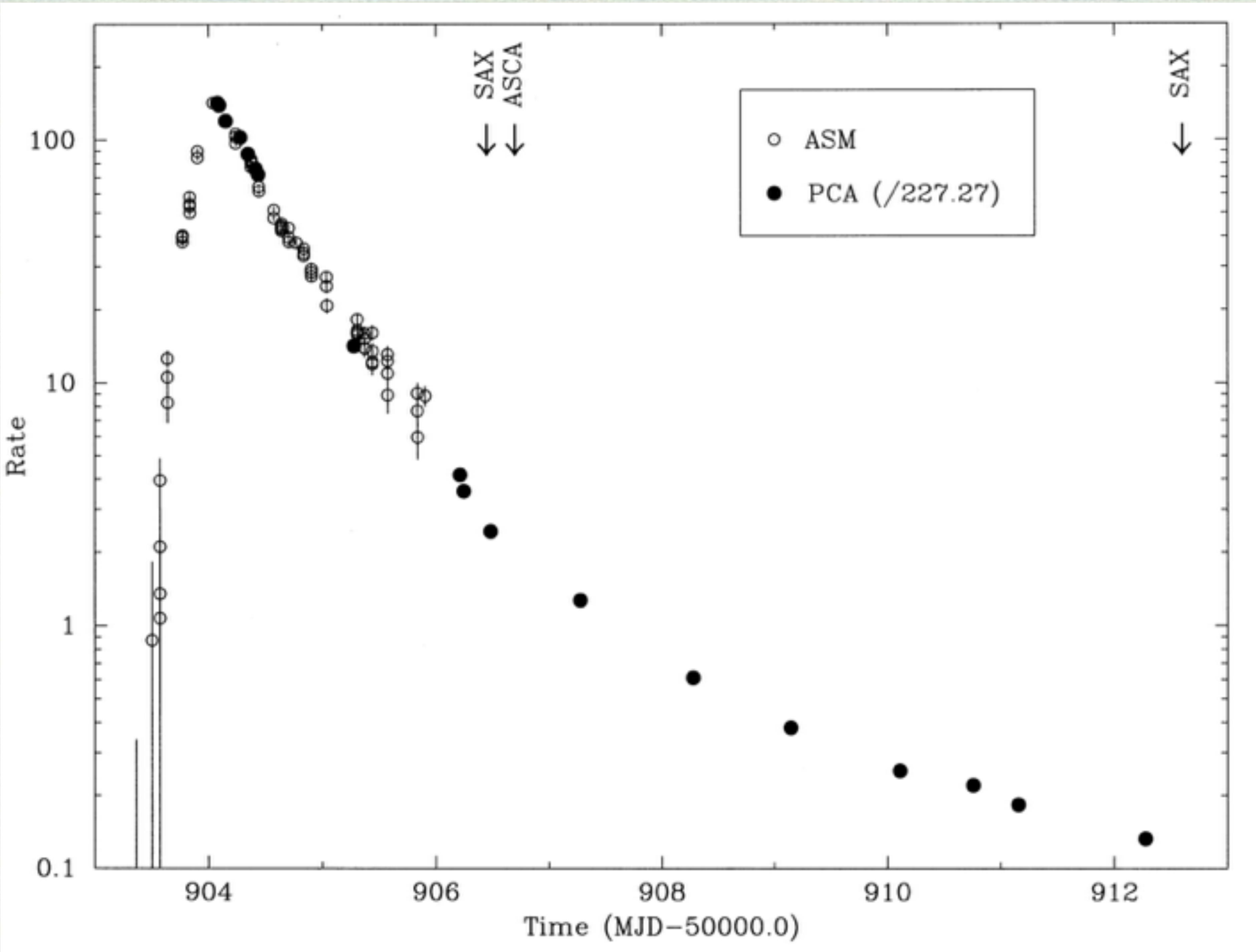
Very different shapes

GRS 1915+105



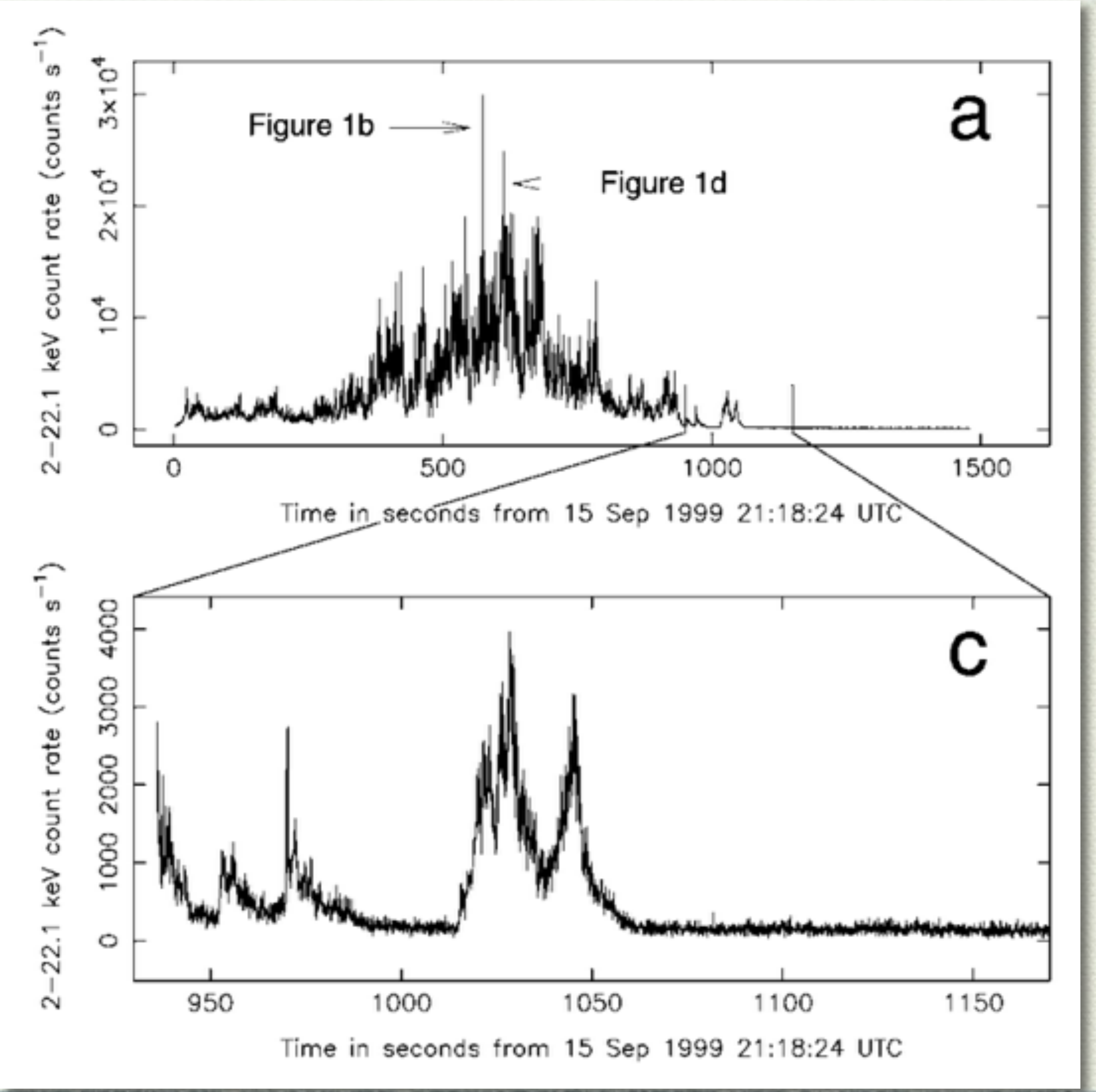
Very different shapes

Belloni et al. (1999)

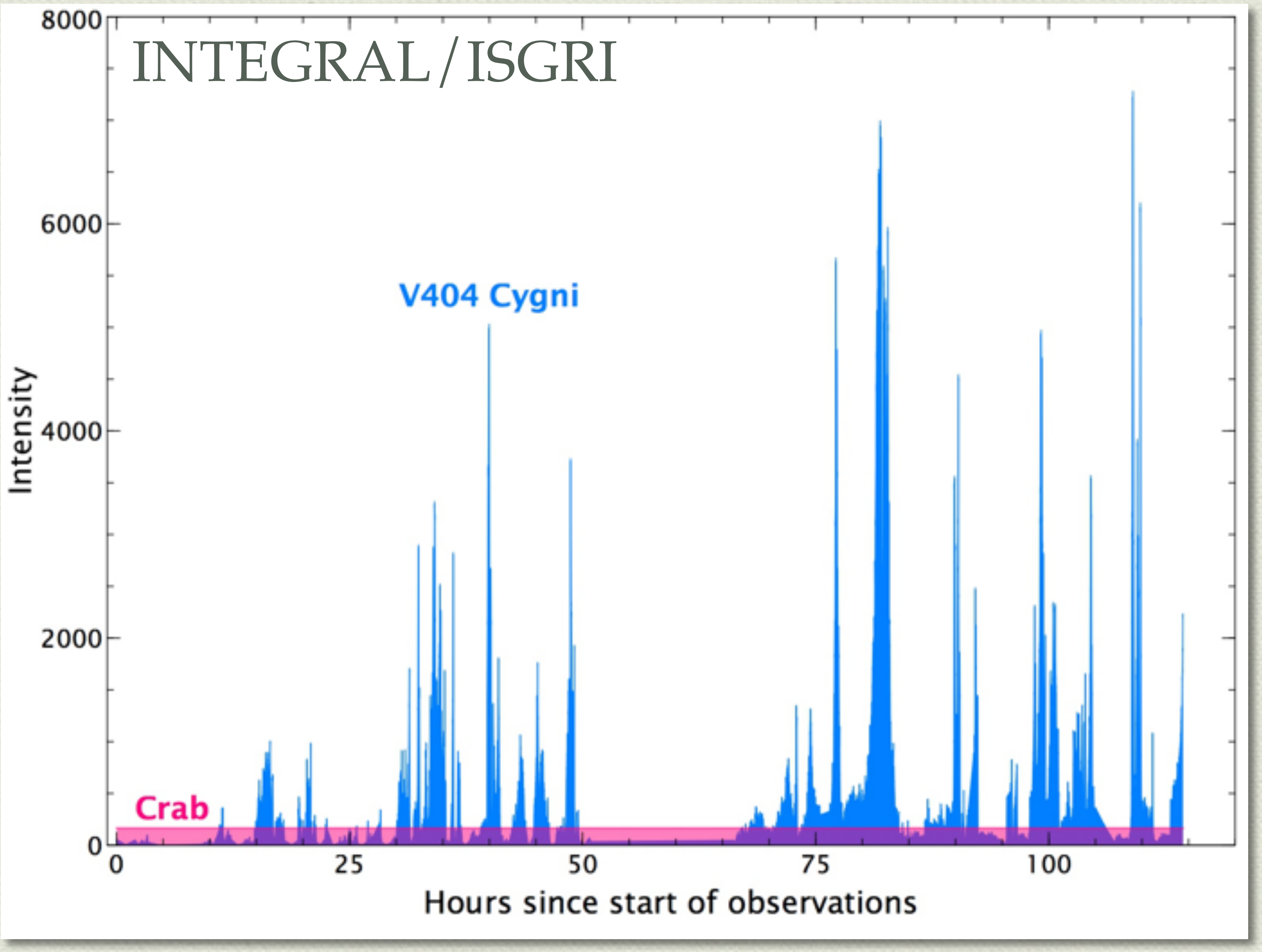


Very different shapes

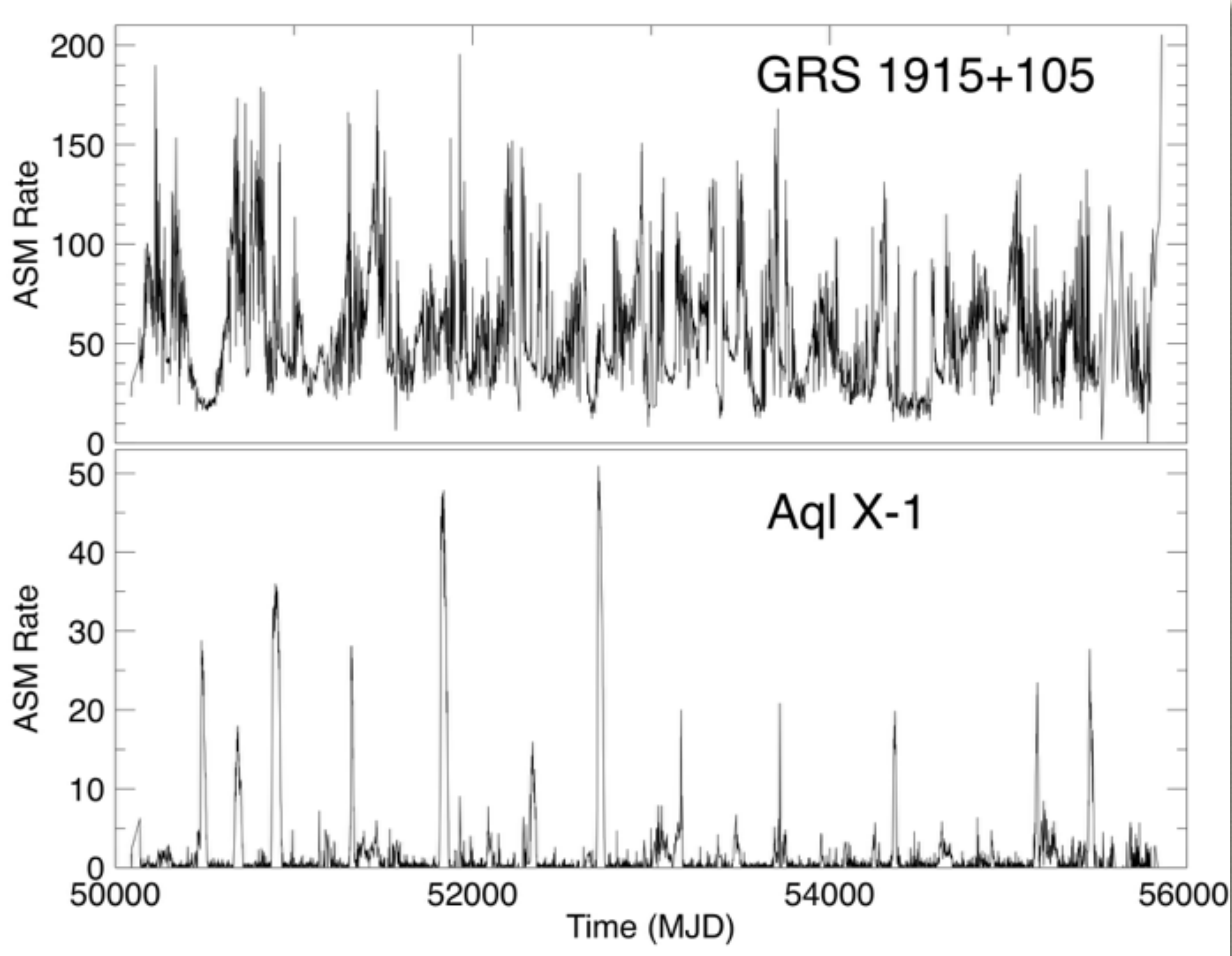
Wijnands & van der Klis (2000)



V404 Cyg in 2015

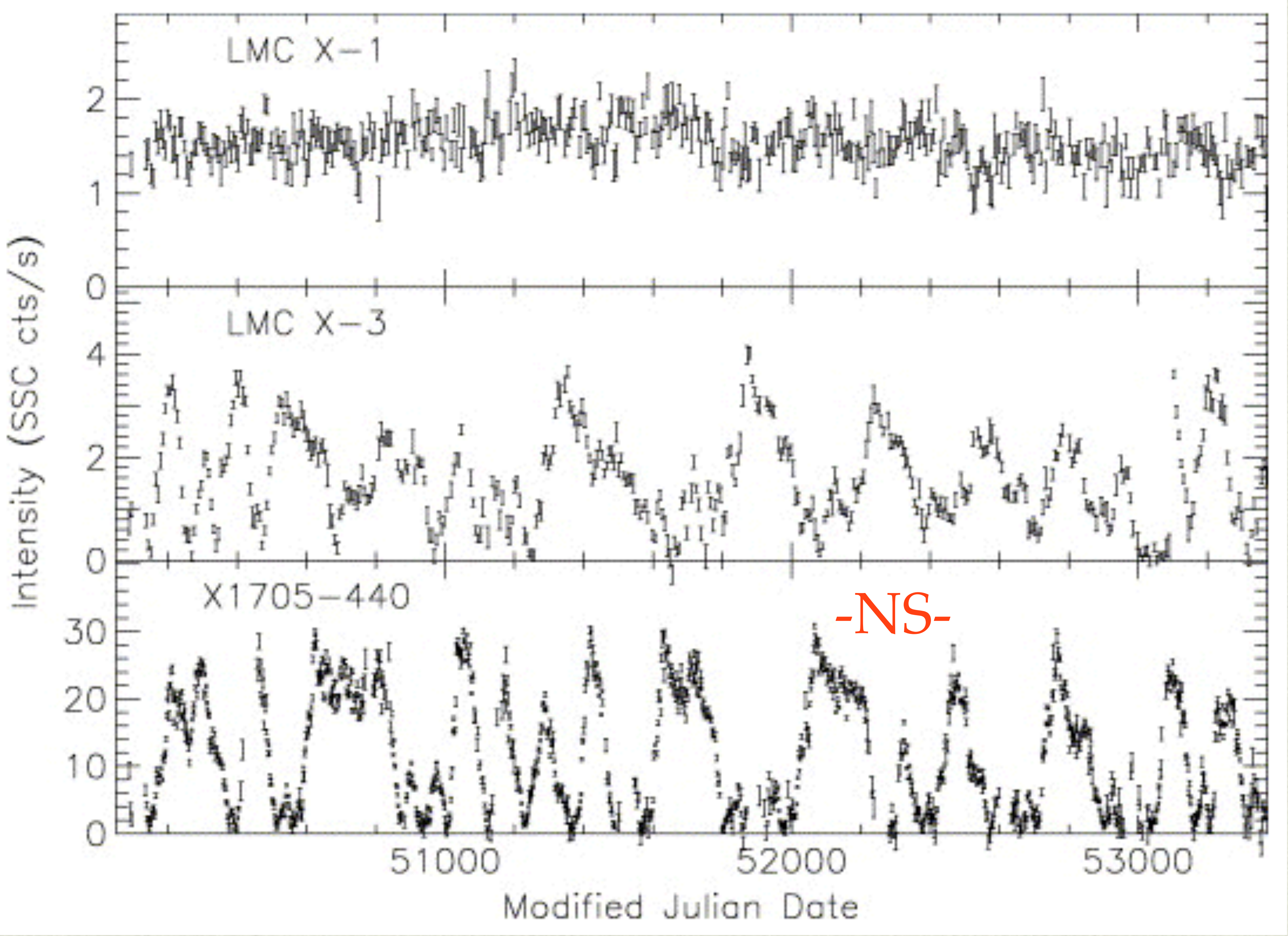


Other examples



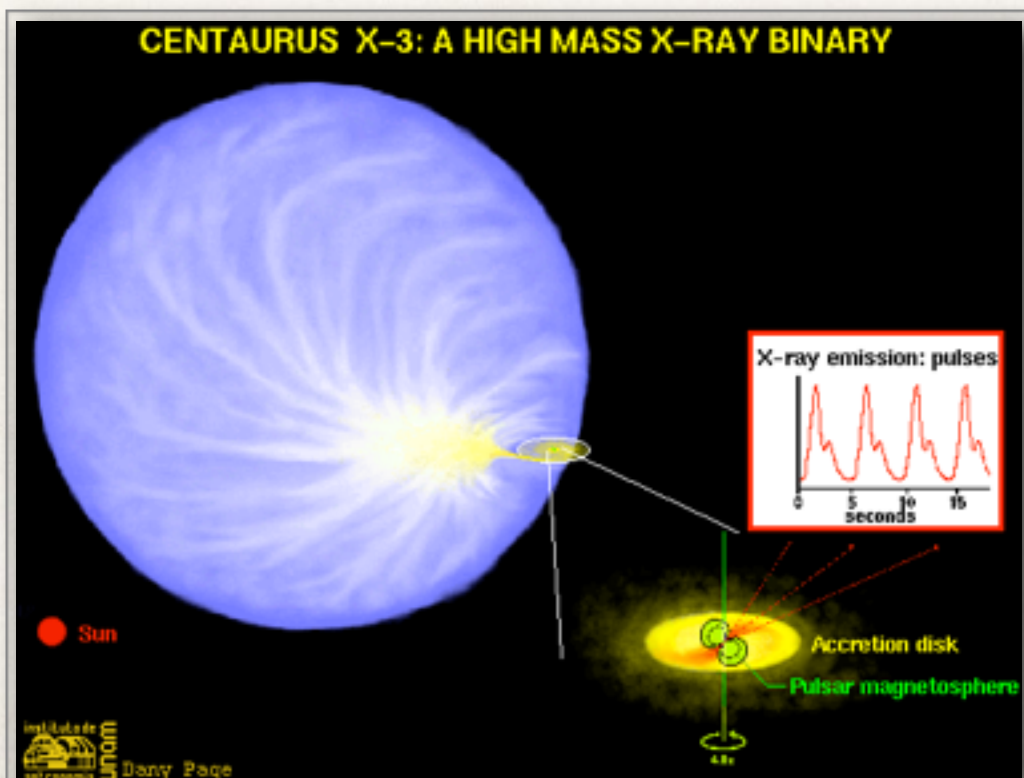
Persistent systems

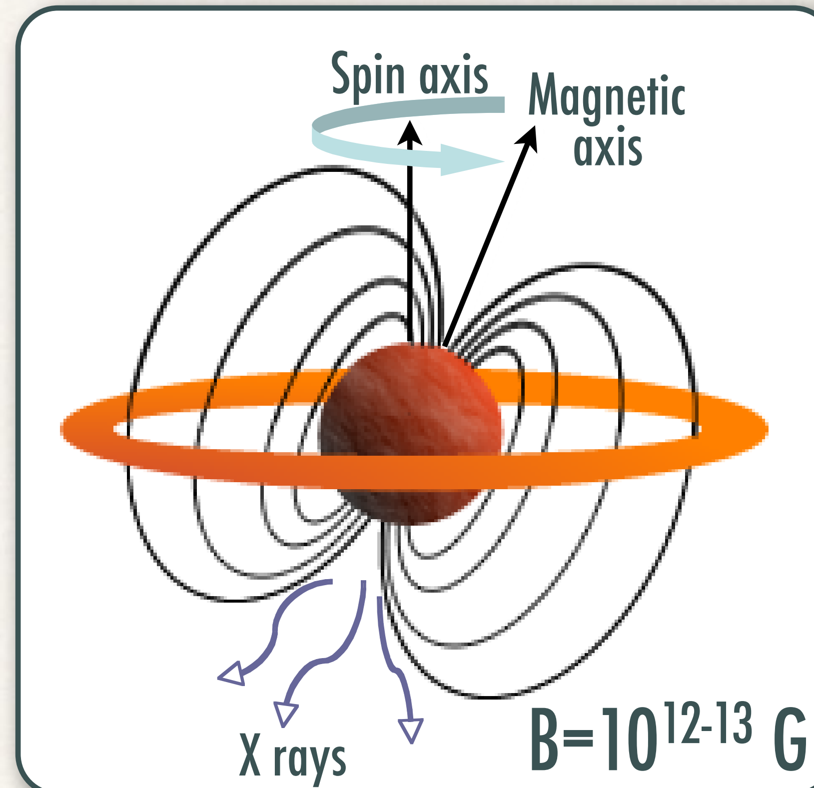
Levine et al. (2006)



Accreting X-ray pulsars

- Magnetized NS accreting from a non-collapsed star
- A fraction of the X rays are modulated at the spin period

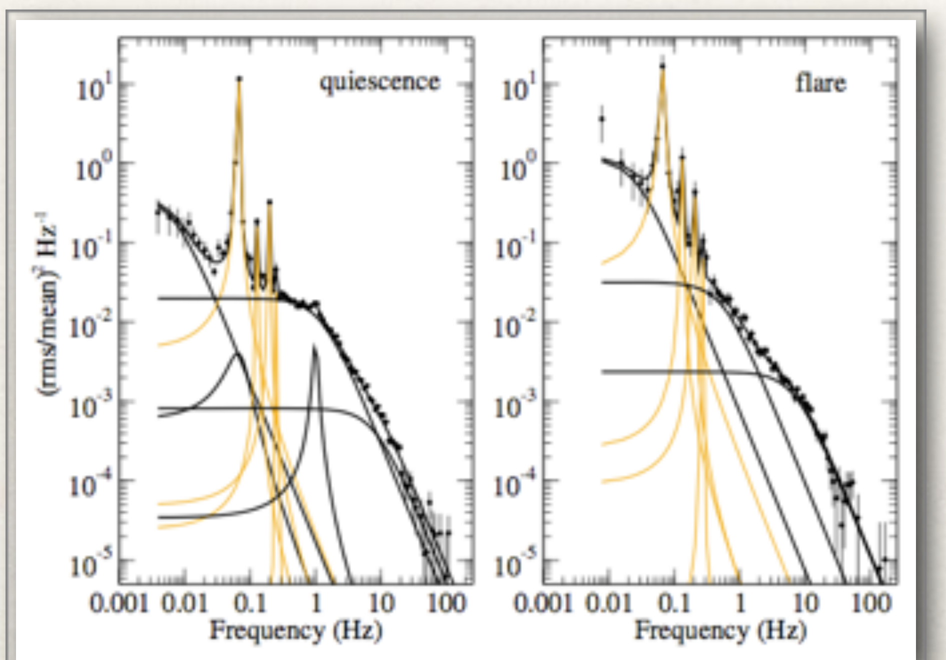


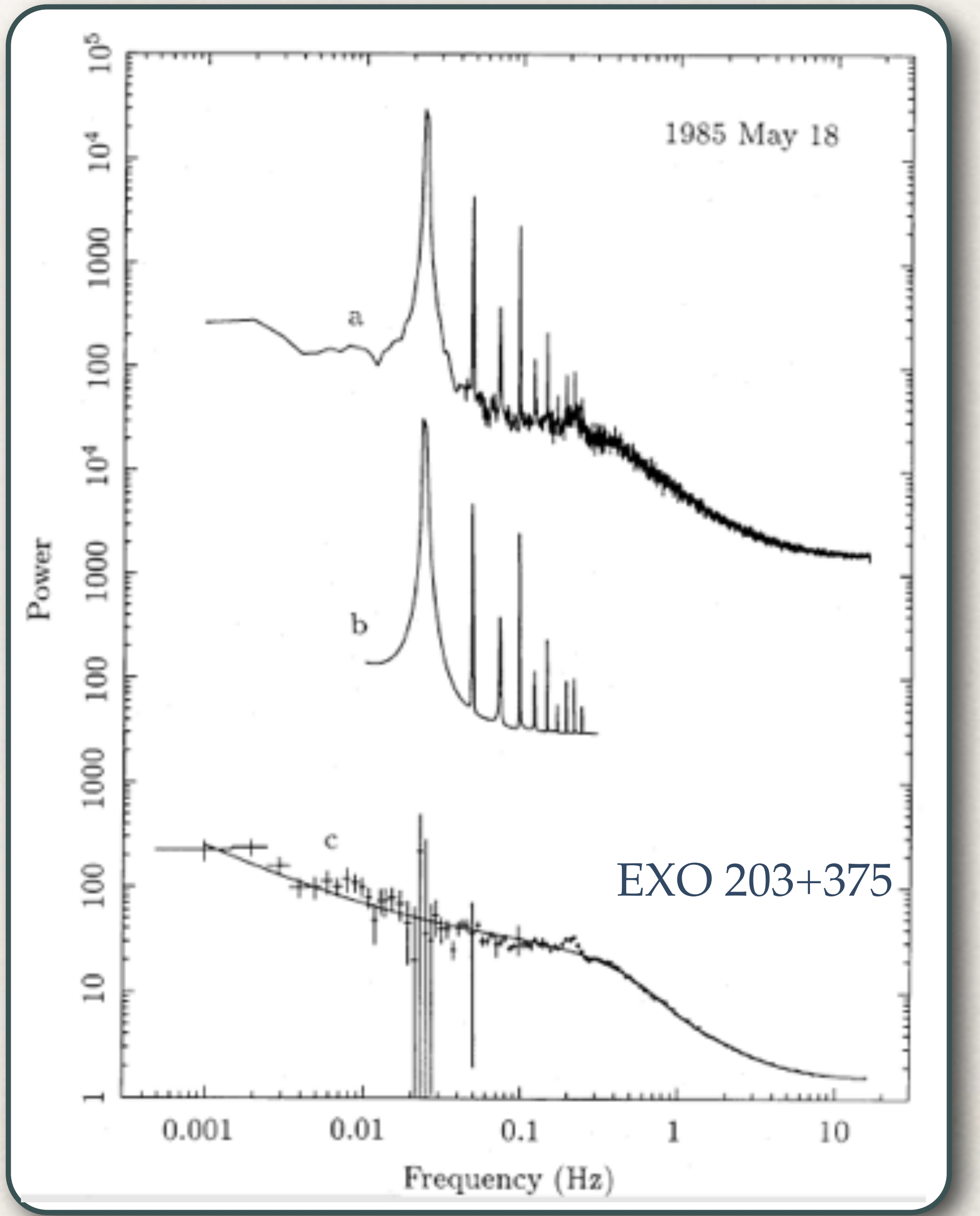


Pulse periods from 69 ms to 3 hr

Accreting X-ray pulsars

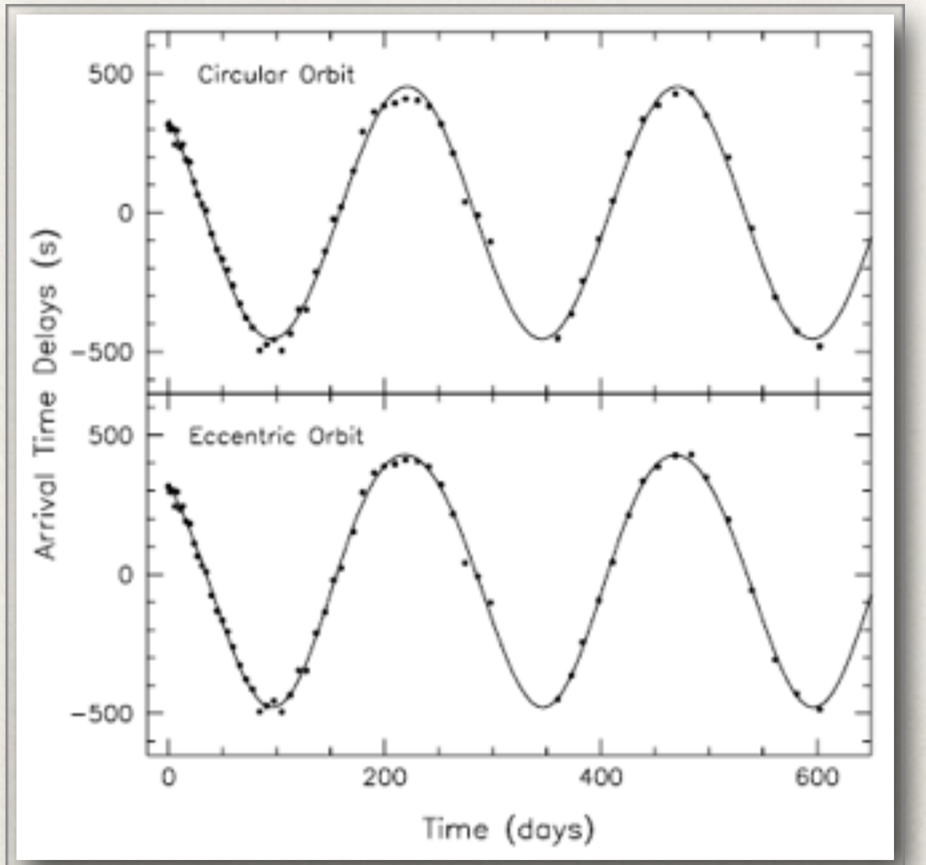
- Periodic signal
- Higher armonics: non-sinusoidal
- Broad noise
- Even Quasi-Periodic Oscillations (QPO)

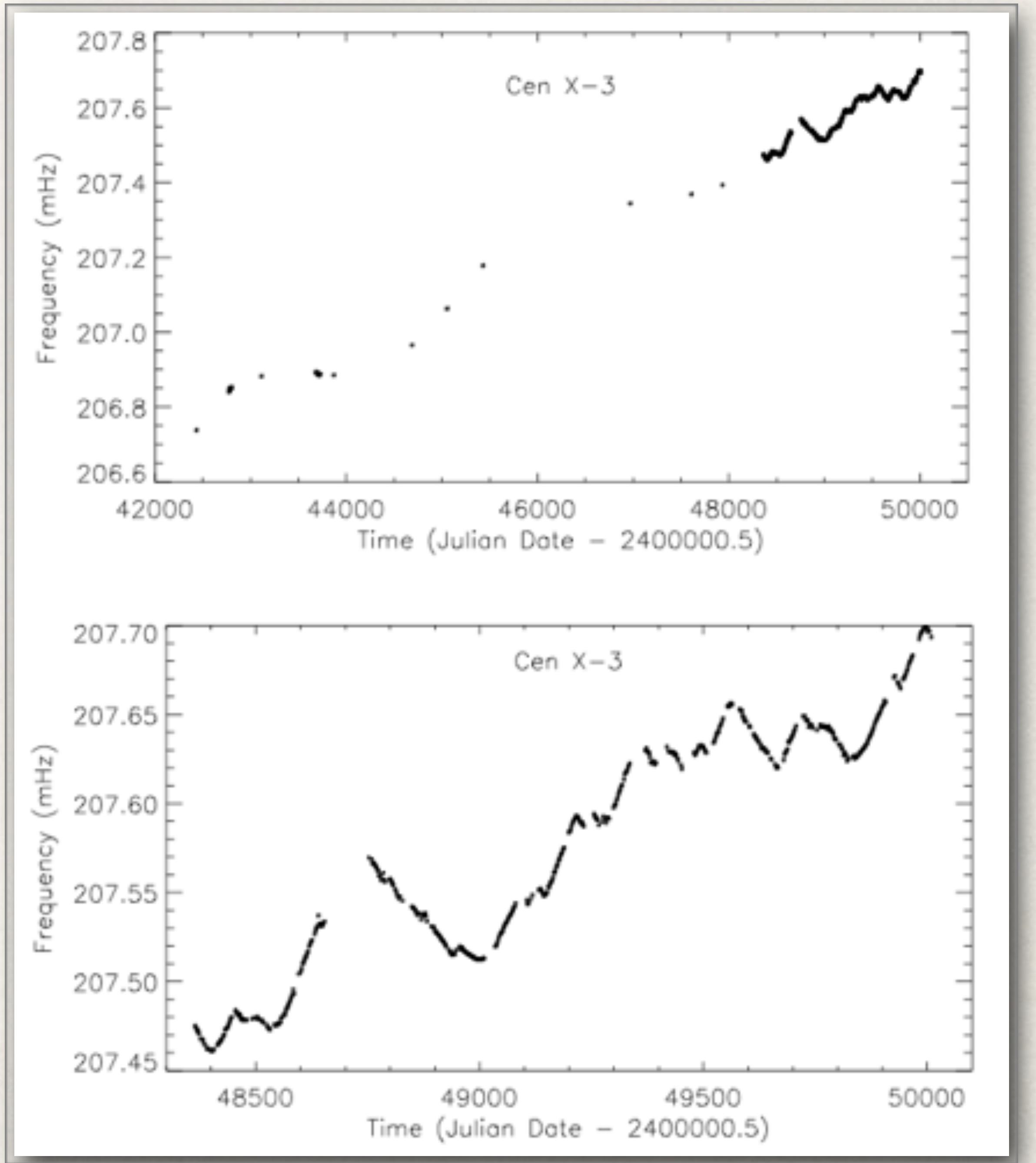




Folding and pulse shape

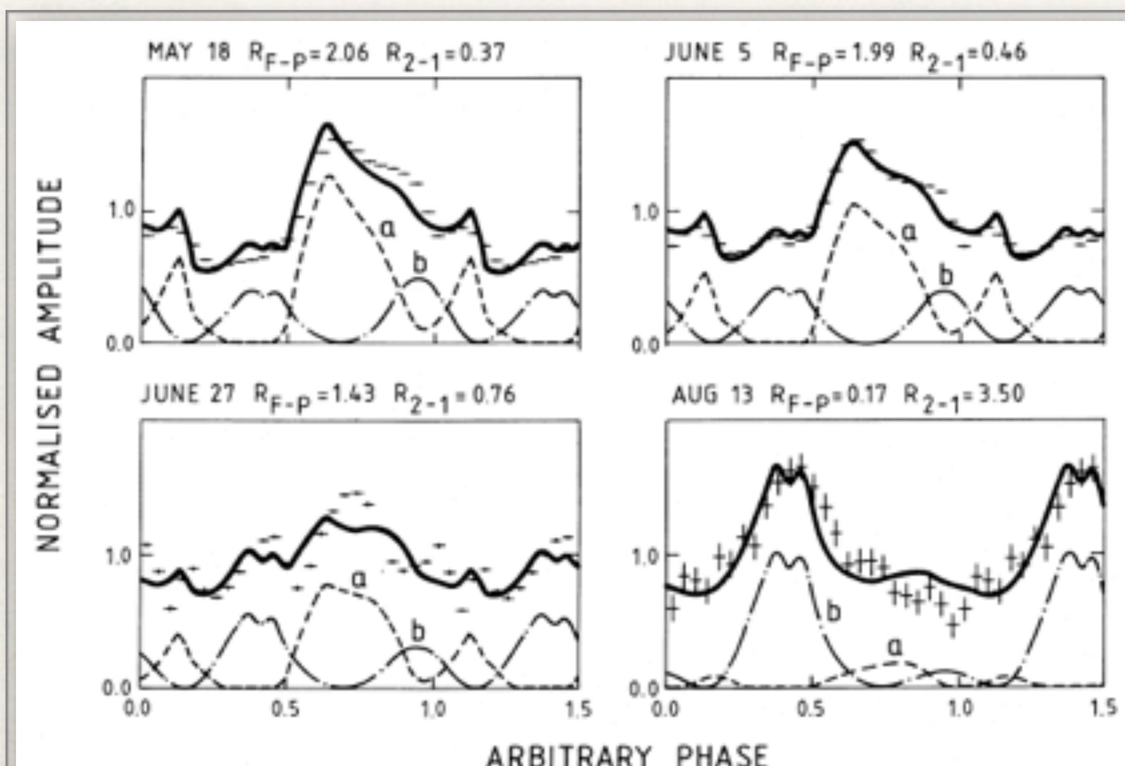
- Orbital variations
- Spin-up due to accretion
- Not steady as expected

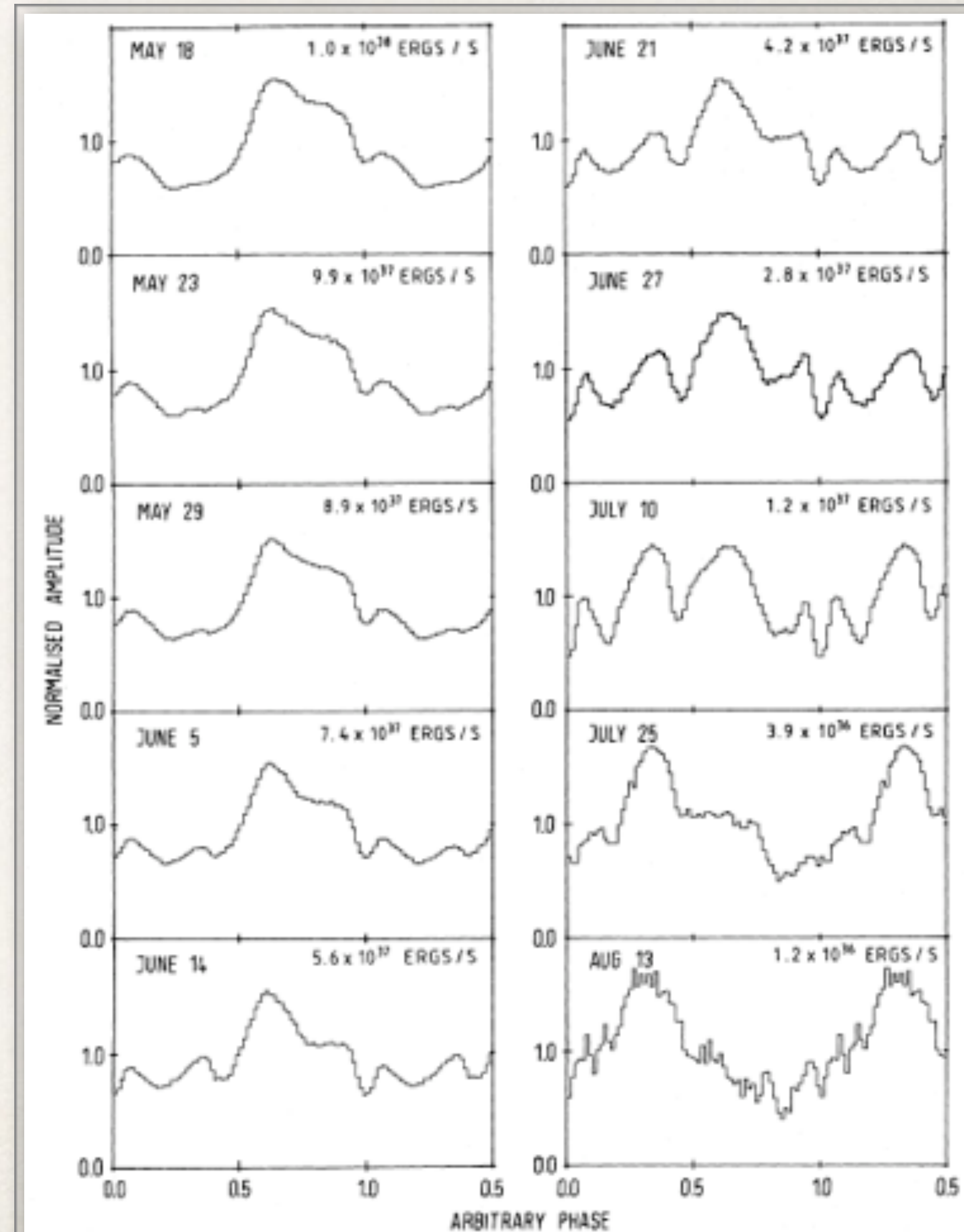




Pulse shapes

- Pulsations as a function of energy
- Complicated pulse shapes





Peculiar objects

- 15s pulsar with