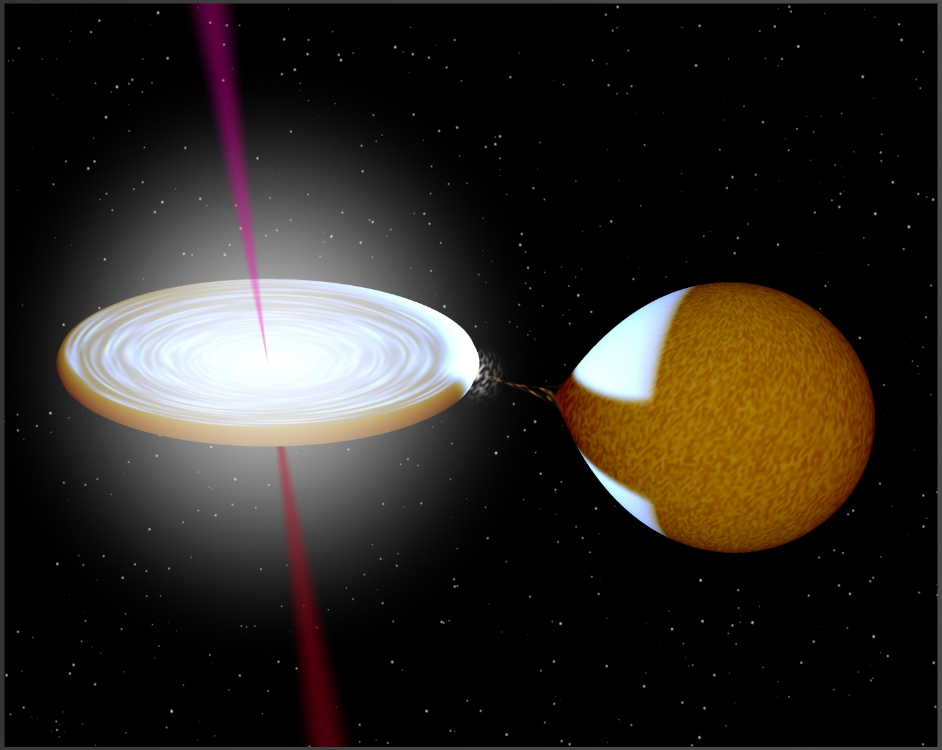
Galactic Black Hole and Neutron Star Systems Part I

Jack Steiner

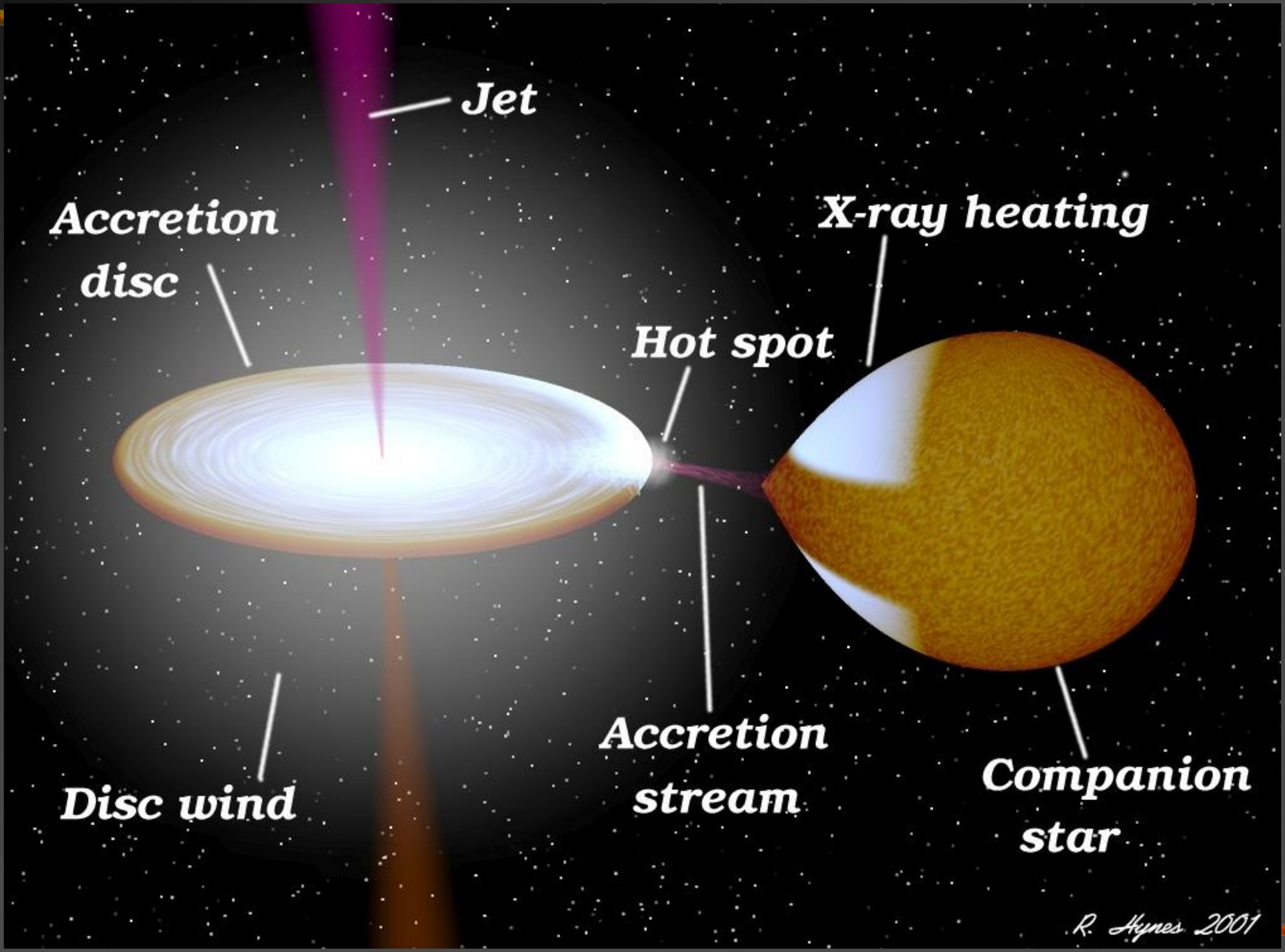
Harvard-Smithsonian Center for Astrophysics

Talk Overview



- XRB Overview and Characterization
- Formation & Discovery
- Masses & Mass Measurements
- Accretion, States, and Jets

XRB Blueprint



1,000,000 km

Dichotomies:

- NSs vs BHs
- High-mass (HMXBs) vs Low-mass (LMXBs)
- Wind-Fed vs Roche-Lobe Overflow
- Persistent vs Transient

Dichotomies:

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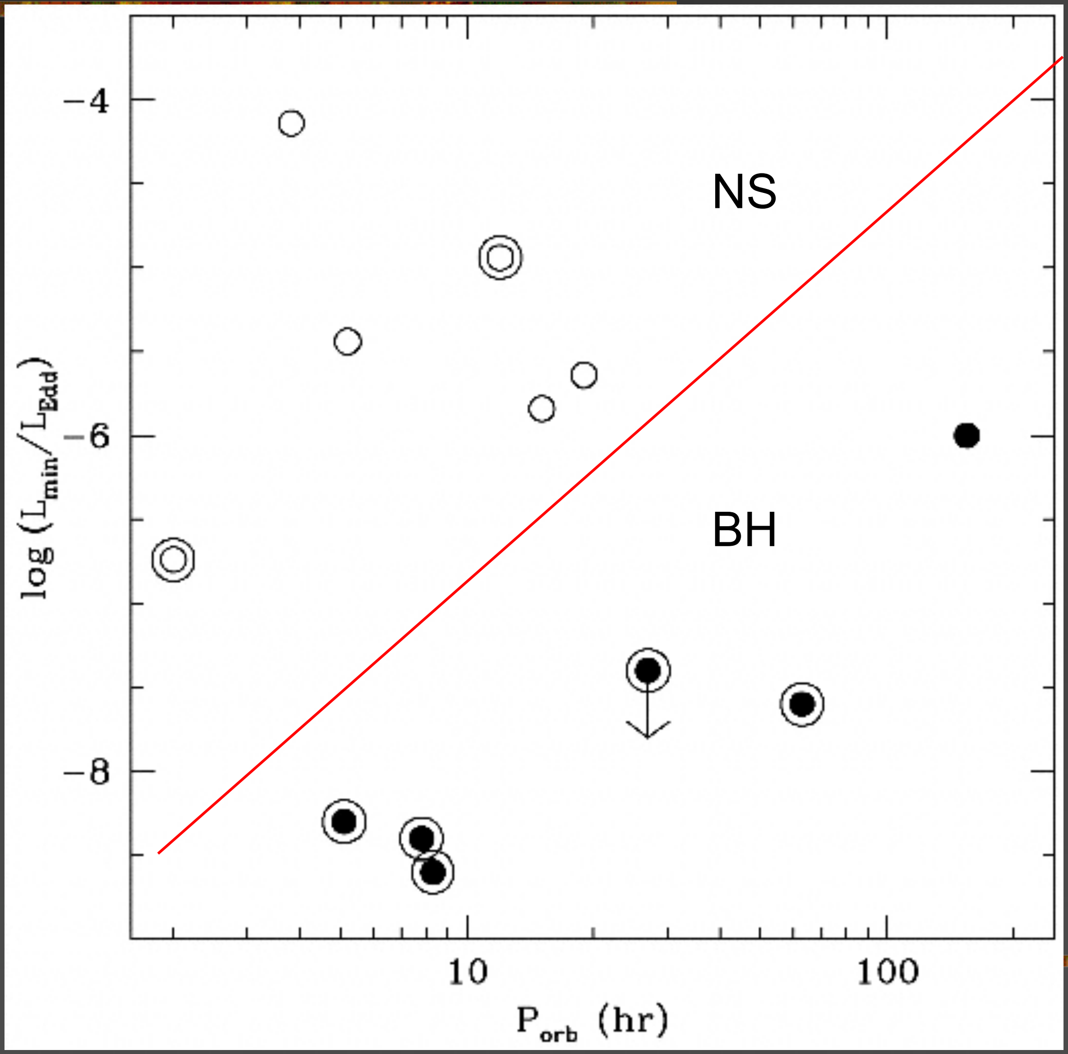
(coloring indications *correlative*, but note the mapping is not absolute)

Distinguishing Characteristics of NSs vs BHs

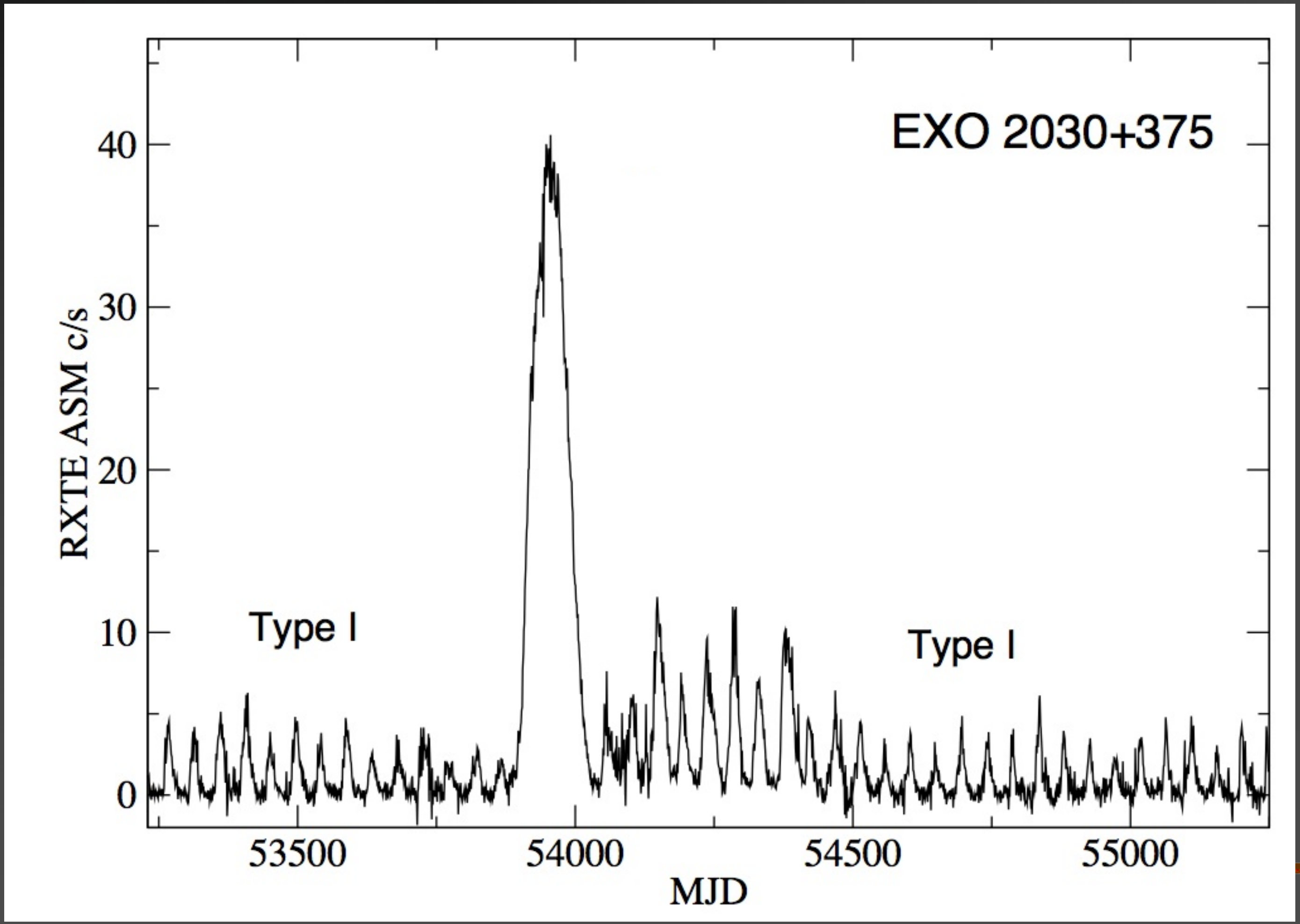
- NSs have surfaces which means they
  - Can contain (strong) magnetic fields
  - Can produce extra thermal emission
  - Can produce thermonuclear bursts
  - Can produce pulsations
  - Emit more than a black hole for a given mass-accretion rate!
- BHs can have very high spin-rates, beyond reach for a NS
  - NS limit ~1500 Hz ⟺ a*~0.7 (Lo & Lin 2011)

A Comparison In Quiescence



Garcia et al. 2001

NS X-ray Bursts

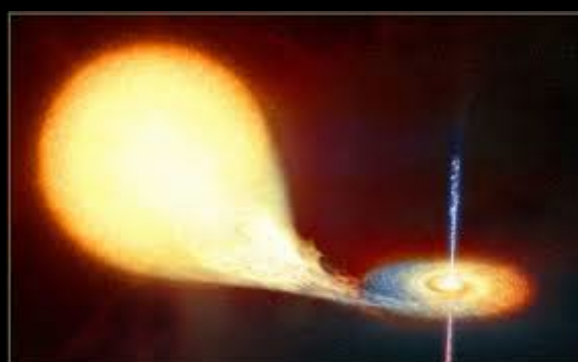


High-Mass vs Low-Mass XRBs

- Distinguished based on the mass of the *companion* star
- A and hotter stellar types are considered HMXB, F and cooler are LMXBs
- Some systems with companion mass = several M_{O} straddle this boundary (e.g., LMC X-3, 4U1543-47, Her X-1)

HMXB and LMXB archetypes

Illustrations by NASA



1) Wind-fed (persistent, HMXB)

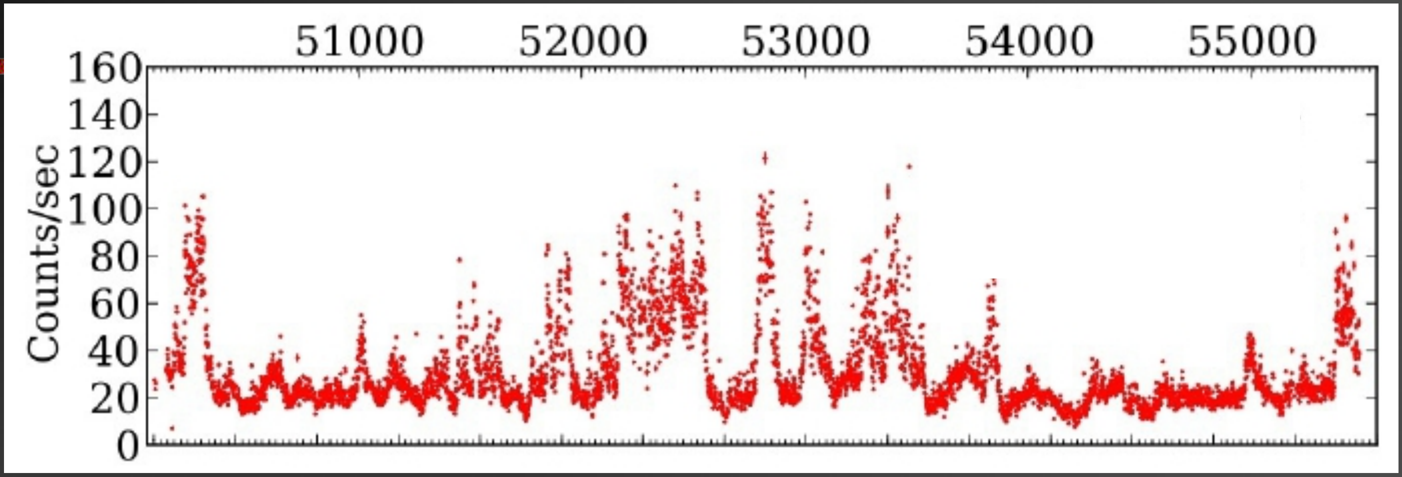
- O-B giants
- $L_{opt}/L_X \sim 10$

2) Roche-lobe overflow (transient, LMXB)

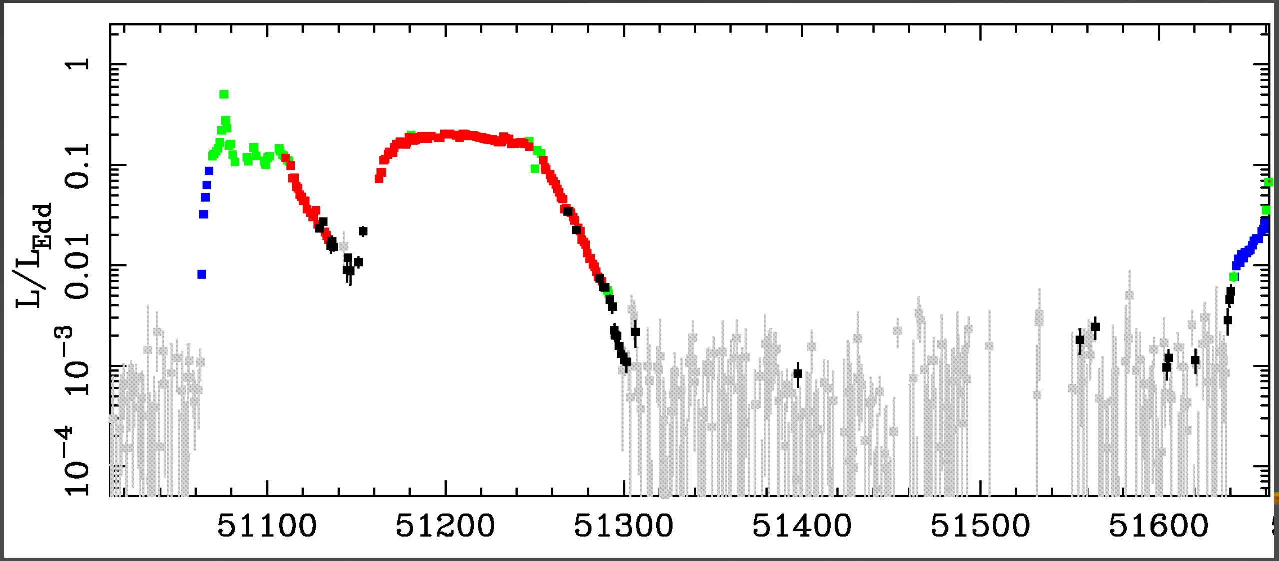
- K-M dwarf
- $L_{opt}/L_X \sim 10^{-2}$

X-ray activity

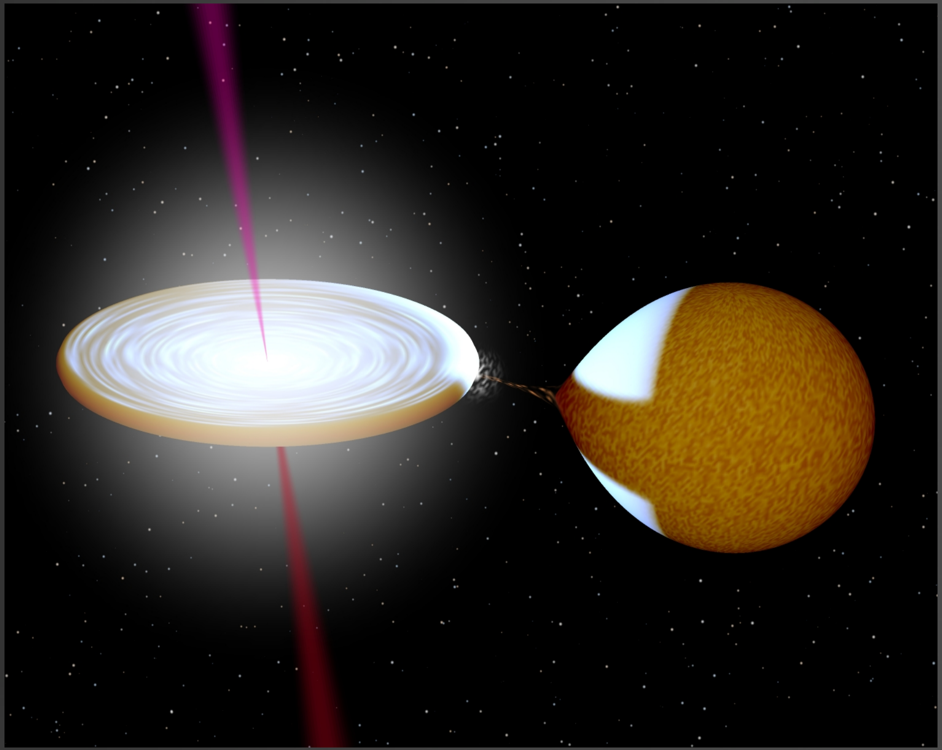
- Persistent



- Transient



Talk Overview



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The birth of an X-ray binary in a stellar nursery

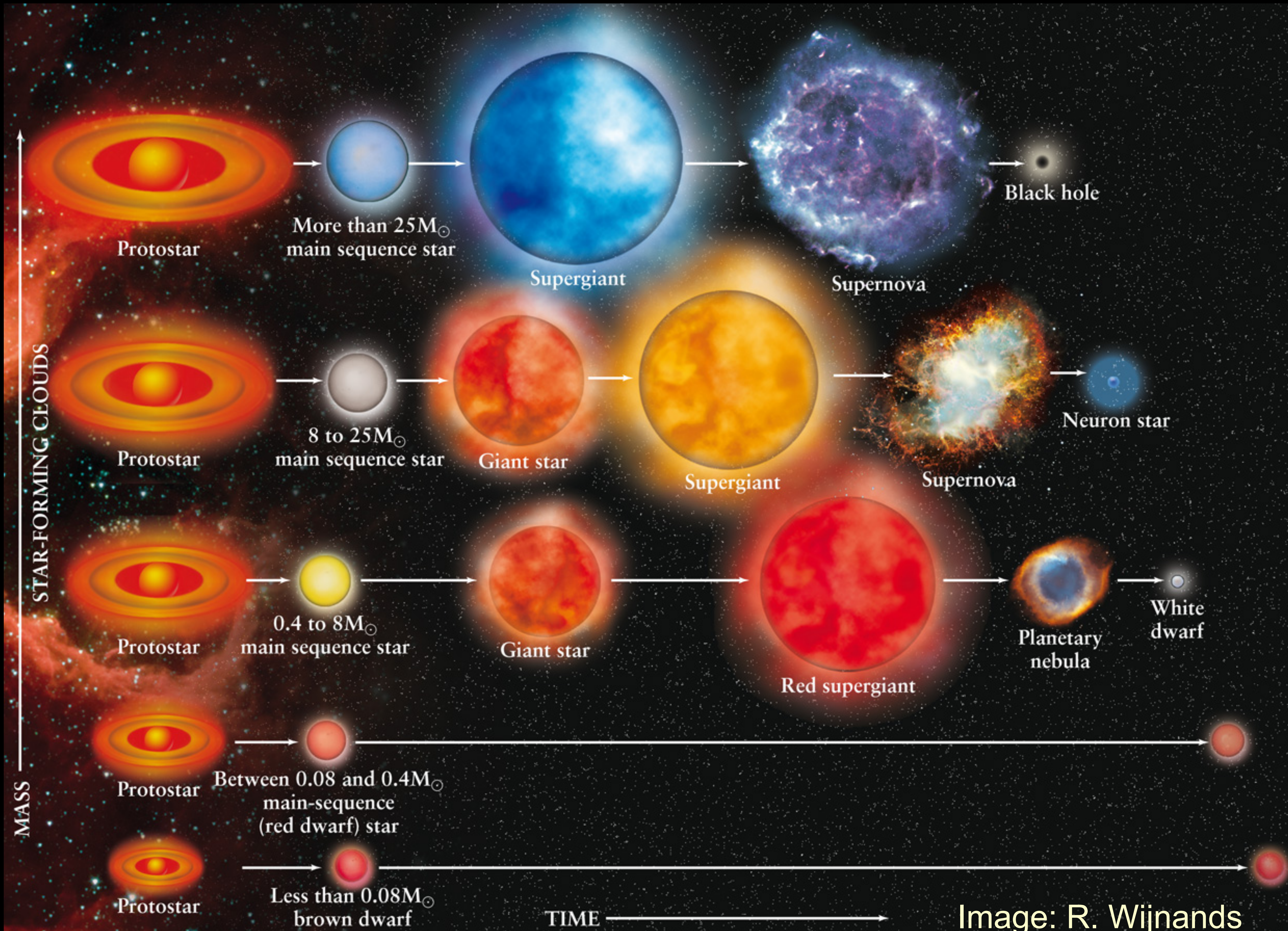


Image: R. Wijnands

Why should a high-enough mass star forms a BH? *It's inevitable*

Newtonian physics: if pressure increases rapidly enough towards the interior, an object can counteract its self-gravity

$$\frac{1}{\rho}\frac{dP}{dr} = -\frac{GM(r)}{r^2}, \quad P = P(\rho), \quad \frac{dM}{dr} = 4\pi r^2 \rho$$

General relativity: pressure does not help

$$\frac{1}{\rho}\frac{dP}{dr} = -\frac{GM}{r^2}\frac{\left(1+P/\rho c^2\right)\left(1+4\pi \mathrm{P}r^3/Mc^2\right)}{\left(1-2GM/c^2 r\right)}$$

Pressure=energy=mass=gravity

Credit: R. Narayan

Example Binary Evolution / XRB formation

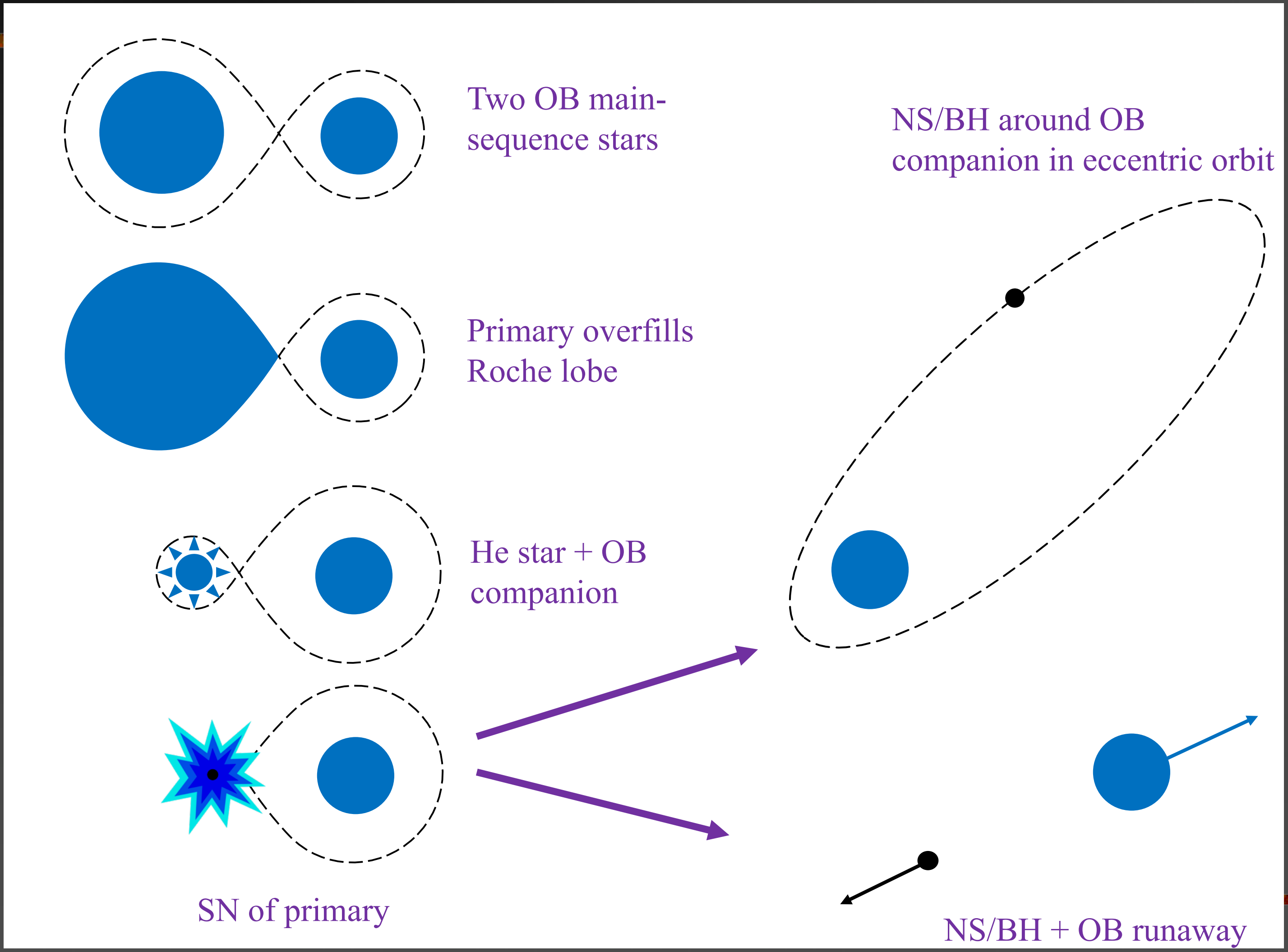


Image: R. Wijnands

Globular clusters, XRB cities

- Globular clusters filled with XRBs
- ~10% of LMXBs in GCs (~100x over-represented)
- Mostly NSs, BH XRBs scarce in MW GCs

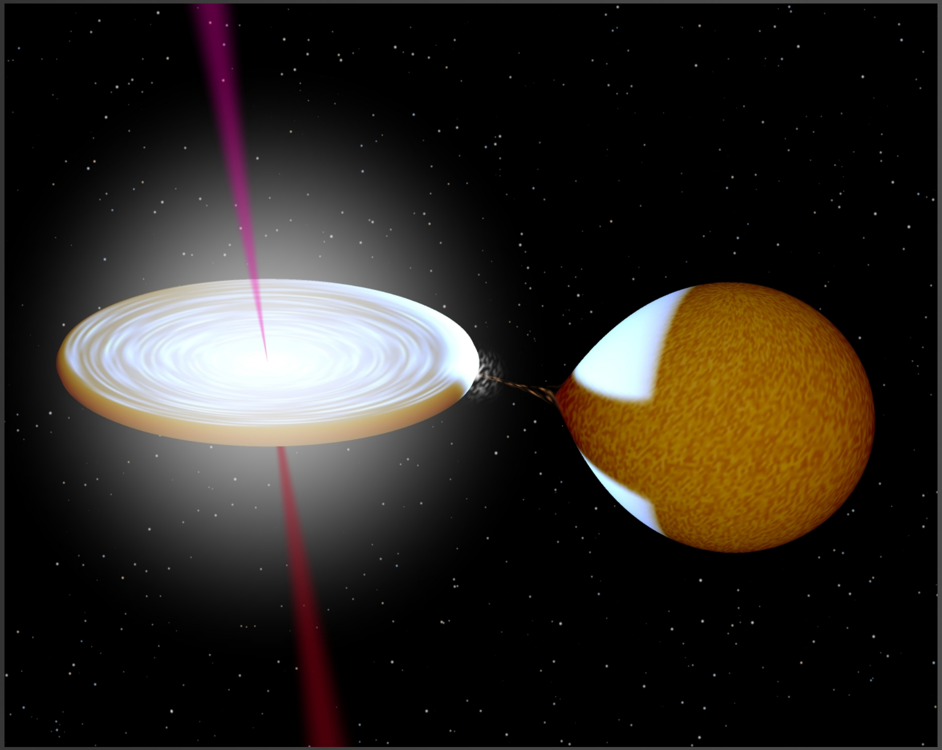
Discovery: How we find new XRBs

- Wait for new X-ray transient (1-2 /yr)
- Pulsations or bursts → NS; otherwise a BH candidate
- Identify optical counterpart
- Wait for quiescence
- Dynamical mass measurement distinguish between BH vs NS, i.e. ($M > 3\ M_{\odot}$ → BH; we don't know of nature making any BHs less massive than this.

Transient Systems

- ~70% BH Candidates
- Typical Outburst
  - Rise time: days
  - Decay time: months
  - Recurrence time: decades
  - Peak luminosity: >100 mCrab (among brightest objects in X-ray sky)
- Quiescence: barely detectable in X-rays

Talk Overview



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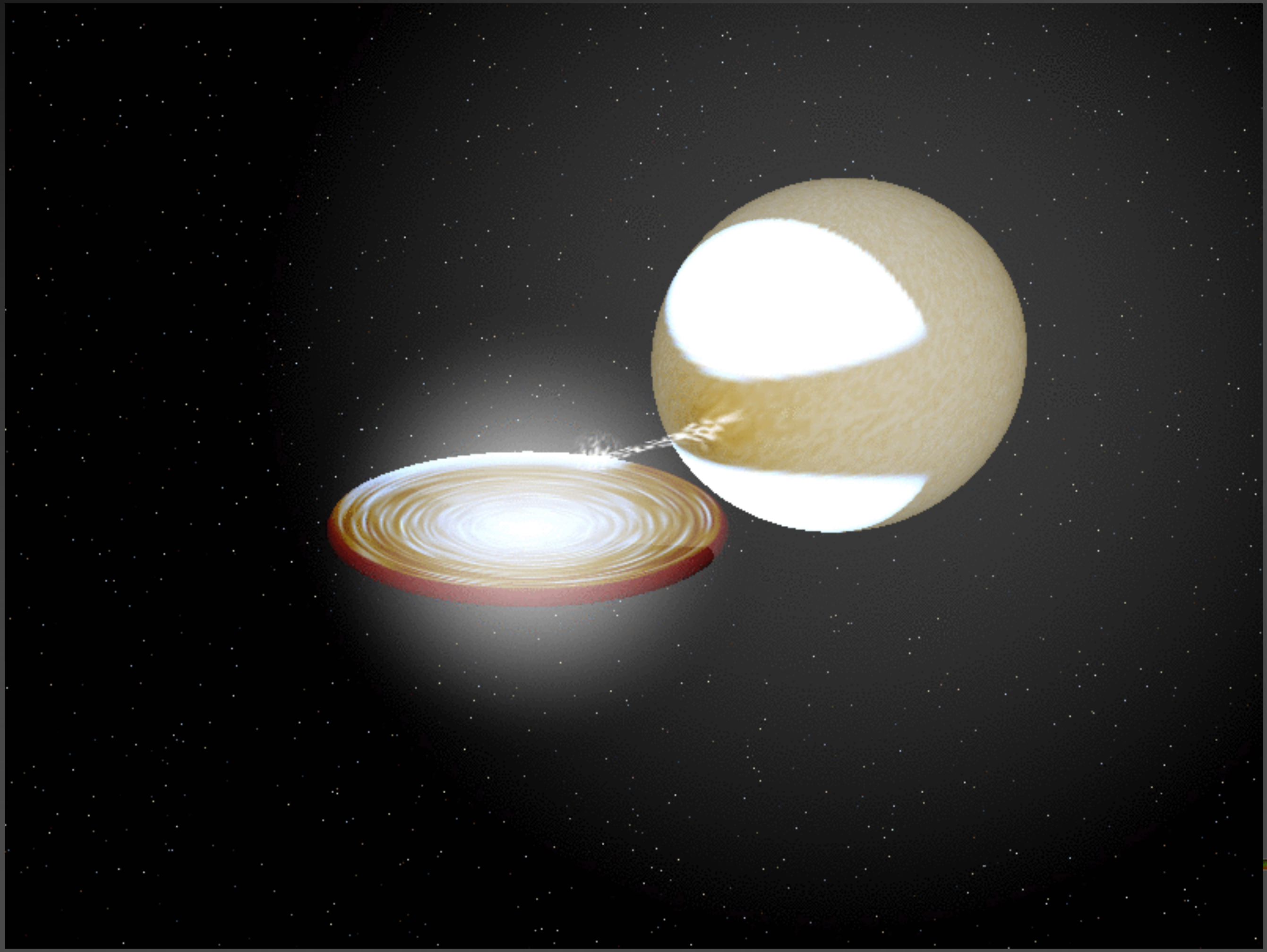
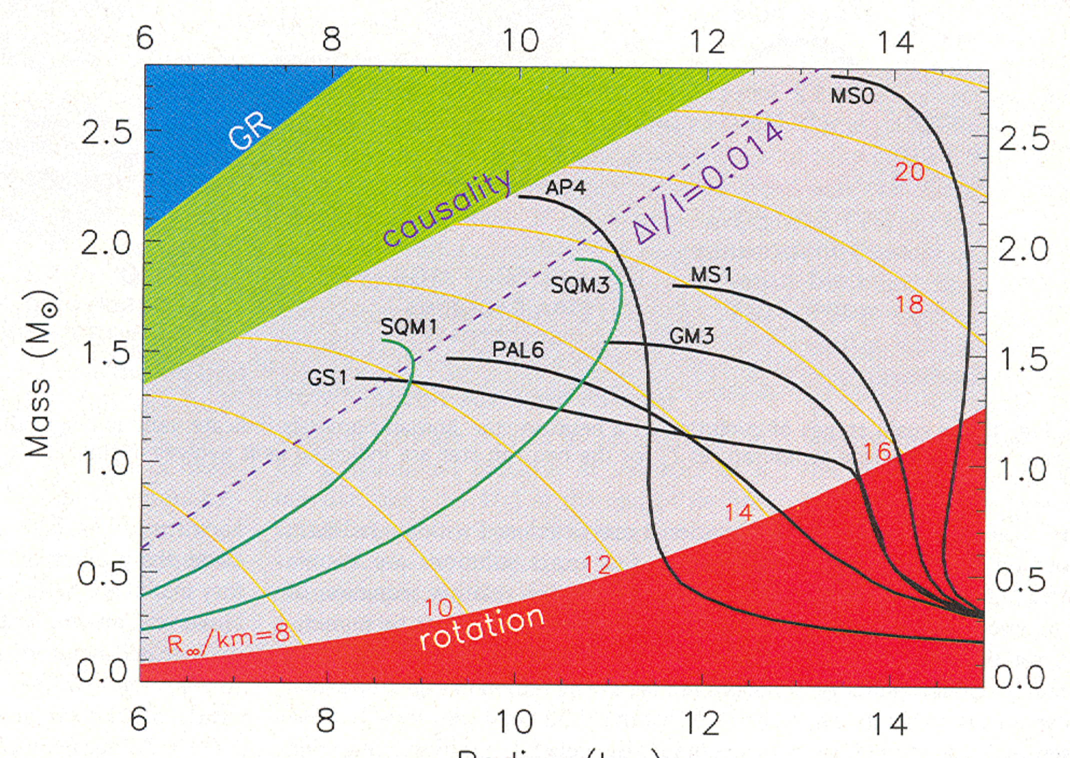
Dynamical Mass Measurements



EoS of Neutron Stars

Oppenheimer & Volkoff (1939): maximum mass for NS stable against gravitional collapse



Lattimer & Prakash (2004)

Widely accepted upper limit to NS mass ~3 $M_\odot$
(Kalogera & Baym 96, Rhoades & Ruffini 74,etc.)

XRBs Masses – Ingredient List

1) $$f(M) = \frac{M_X \sin^3 i}{(1 + M_C / M_X)^2}$$

2) Measure $V_{rot} \sin$ i

$$\frac{V_{rot} \sin \ i}{K} = 0.462\ q^{1/3} (1+q)^{2/3}$$

$$q = M_C / M_X$$

3) Fit ellipsoidal modulation

Amplitude is strong
function of inclination

A quick derivation of f(M)

$$a^3 = GM_{\rm tot}P^2/4\pi^2$$

Important Note!
P (period) and K
(v sini semi-amplitude) are
direct observables

$$(2\pi a/P)^3 P/2\pi G = M_{\rm tot}$$

$$(v(1+q))^3 P/2\pi G = M_X(1+q)$$

$$P(K/{\rm sin}i)^3/2\pi G = M_X/(1+q)^2$$

$$f(M) \equiv \frac{P\ K^3}{2\pi G} = \frac{M_X \sin^3\ i}{(1+q)^2} < M_X$$

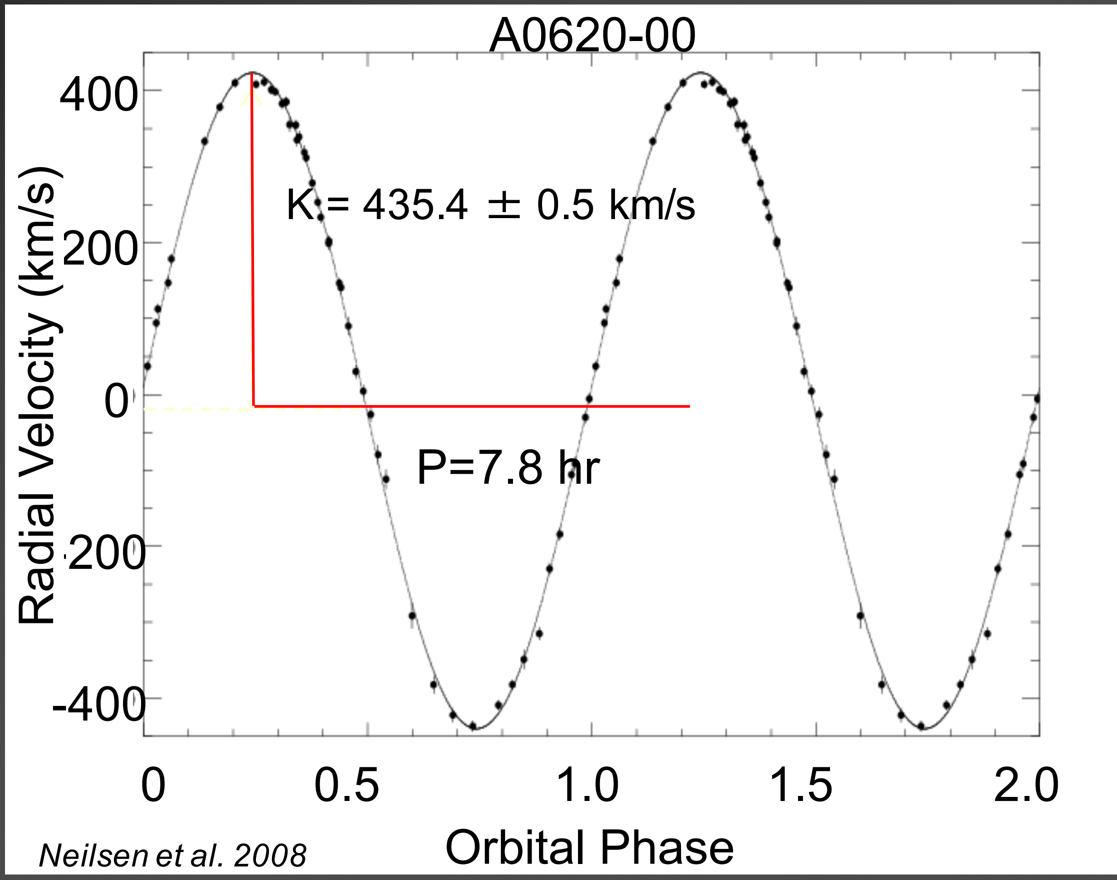
Dynamical Masses

1) Mass function, determined from radial velocities
- a compact-object mass lower limit

$$f(M) = \frac{P_{orb} K^3}{2\pi G} = \frac{M_X \sin^3 i}{(1+q)^2}$$

$M_X > f(M)$

$R = \lambda/\Delta\lambda \geq 1500$ required

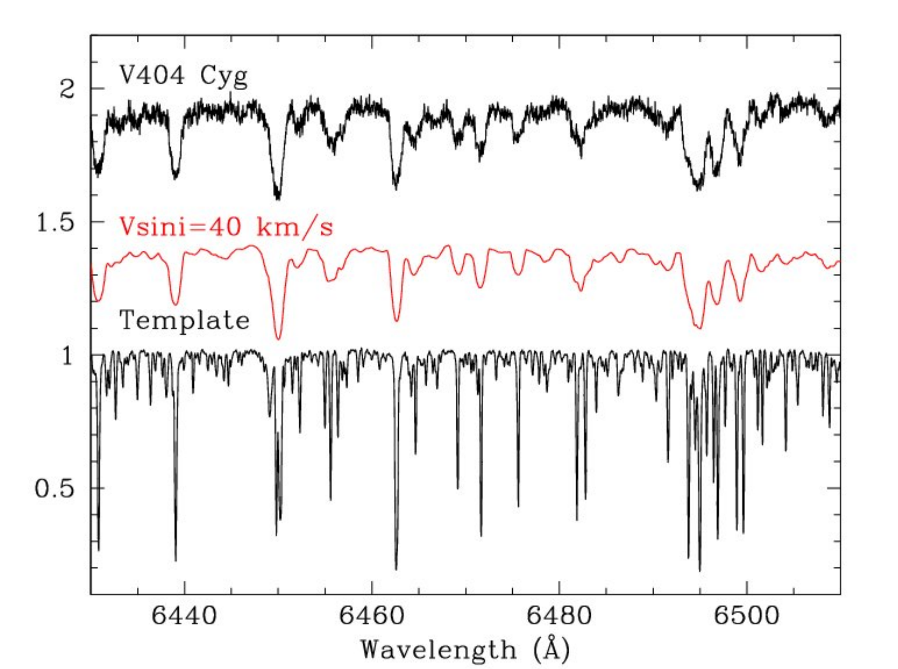


Dynamical Masses

2) Measure q by $V_{rot} \sin i$

$$\frac{V_{rot} \sin\ i}{K} = 0.462\ q^{1/3}(1+q)^{2/3}$$

$$q = M_C / M_X$$



Casares et al.

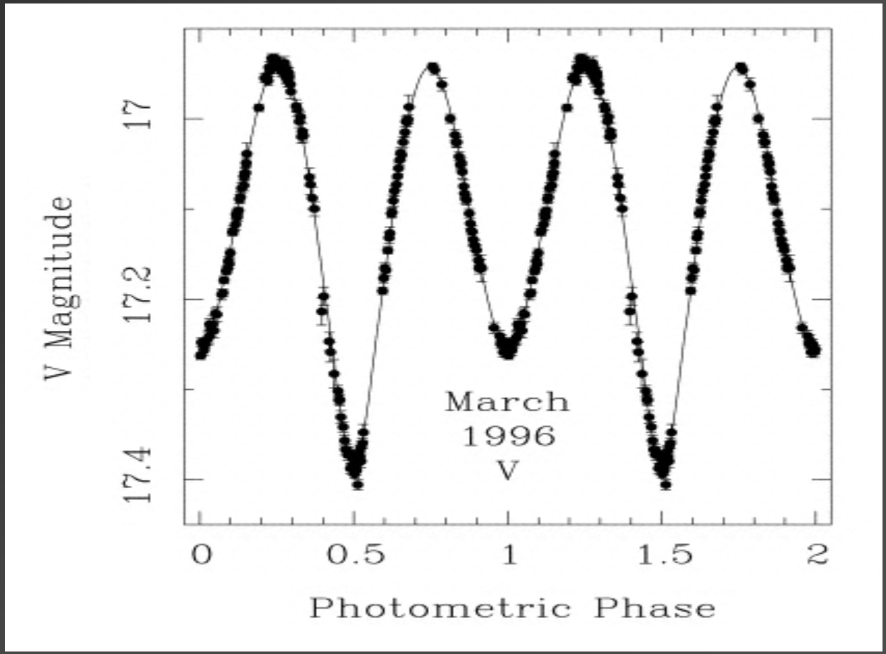
Mass ratio q measured using Eggleton approximation for Roche potential

R=λ/Δλ≥5000 required

Dynamical Masses

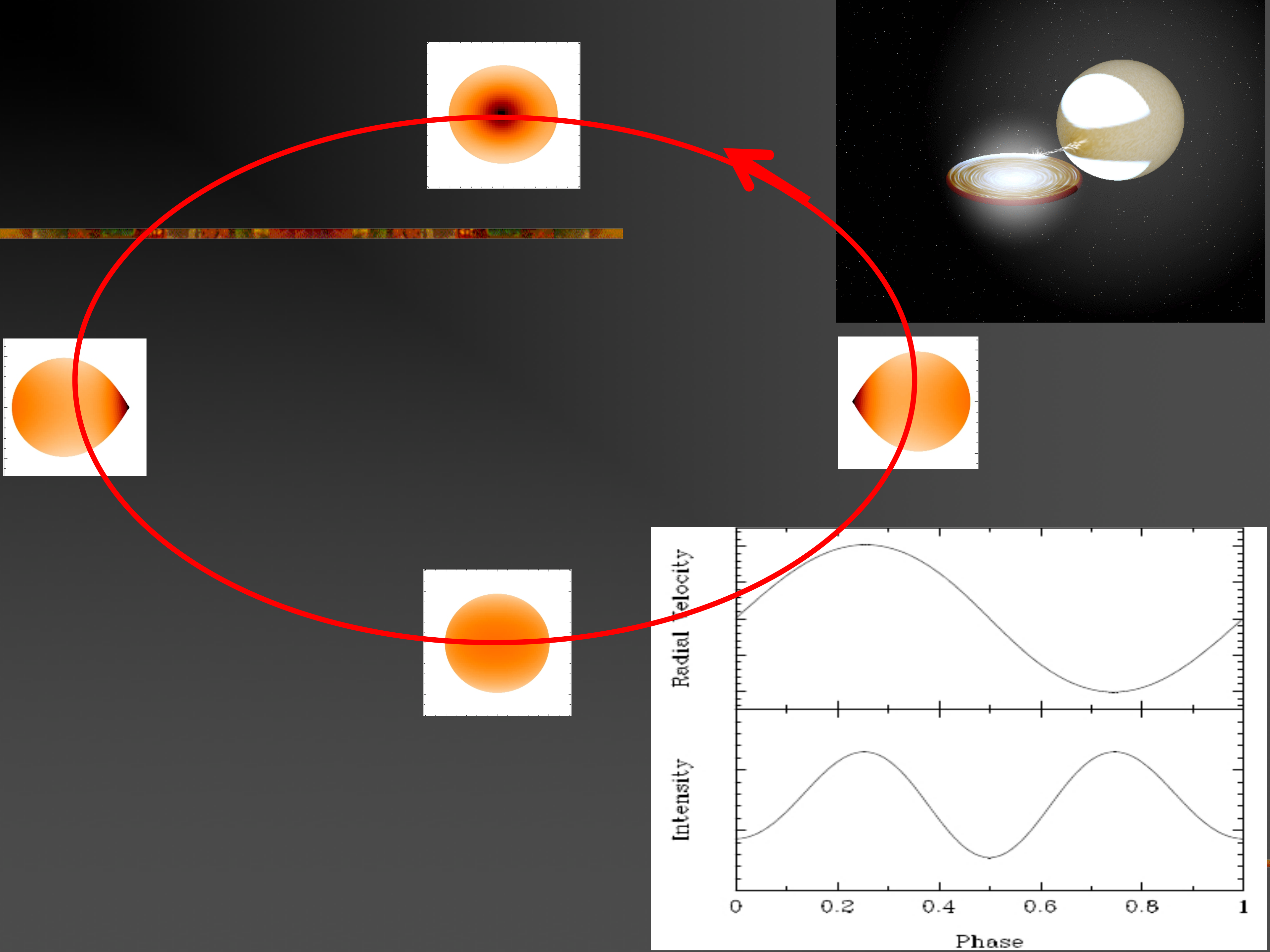
3) Fit ellipsoidal modulation

GRO J1655-40 (Orosz & Bailyn. 97)

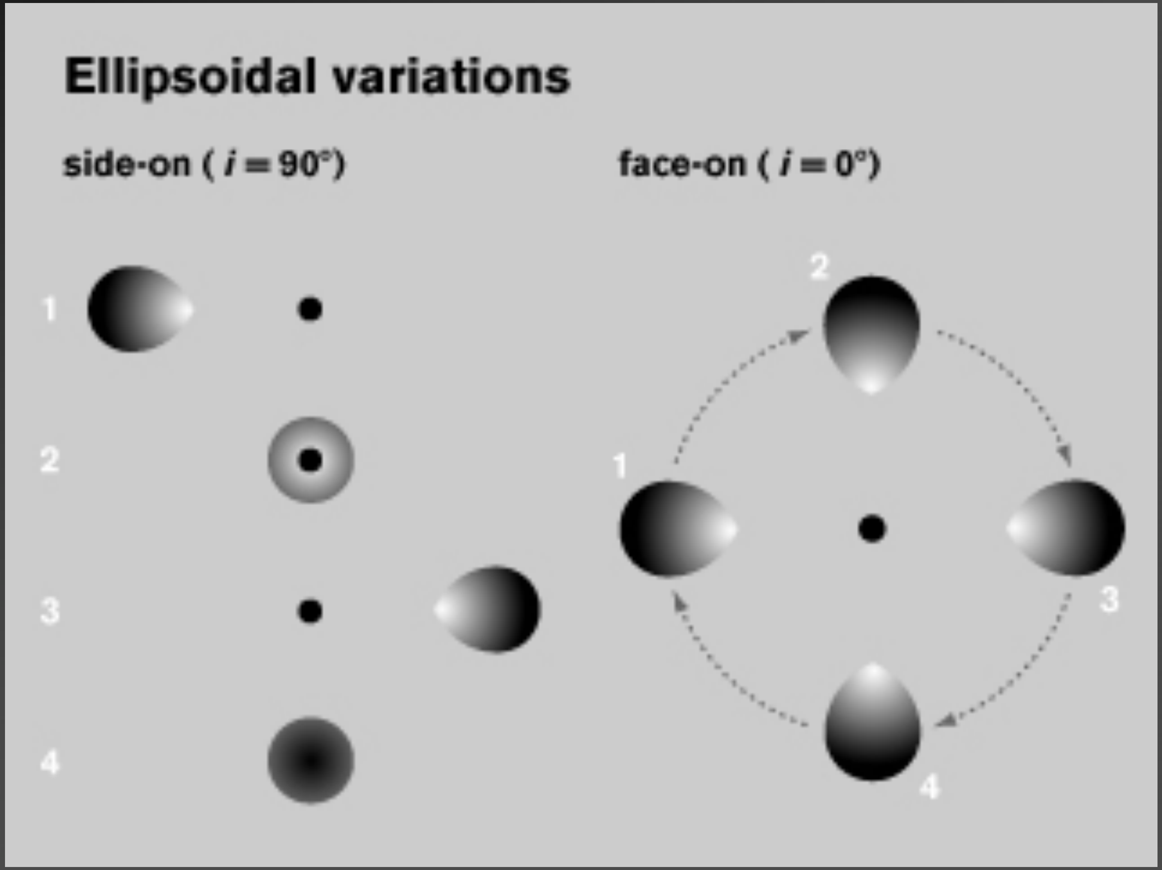


Determines inclination

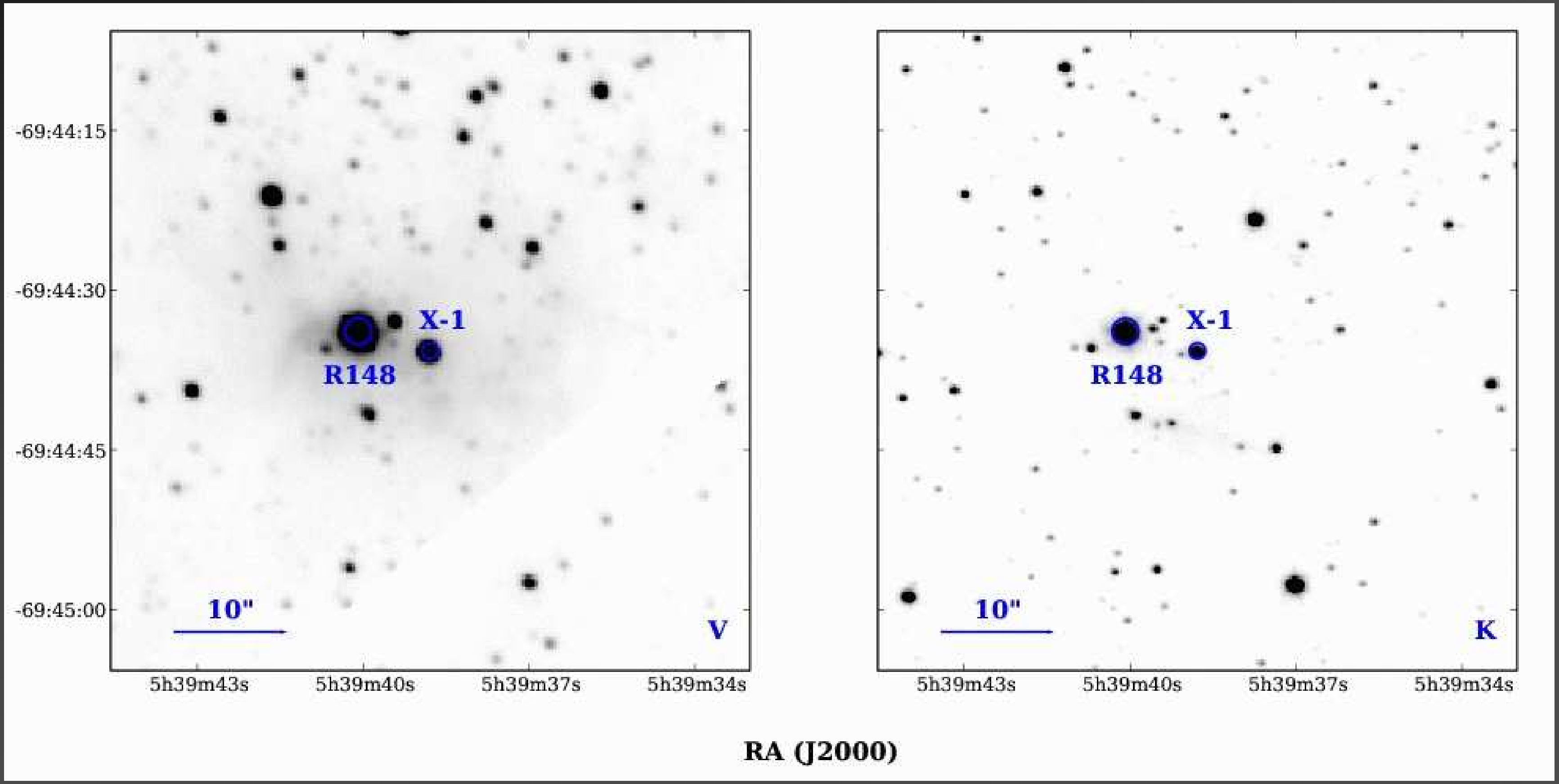
***f(M)* + *q* + *i* ➔** complete solution


Radial Velocity
Intensity
0
0.2
0.4
0.6
0.8
1
Phase

Ellipsoidal Variations

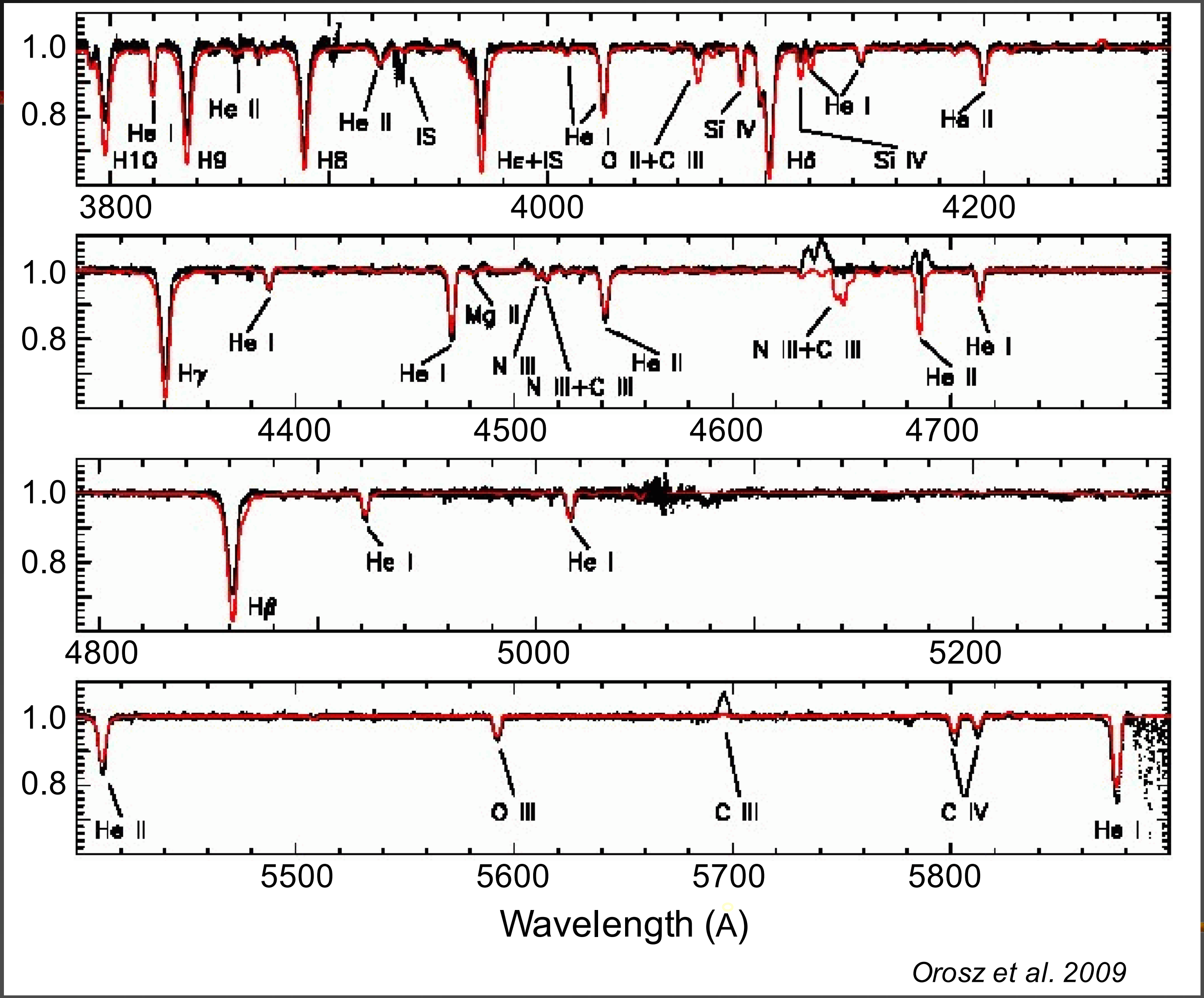


Putting it all together: Case study LMC X-1

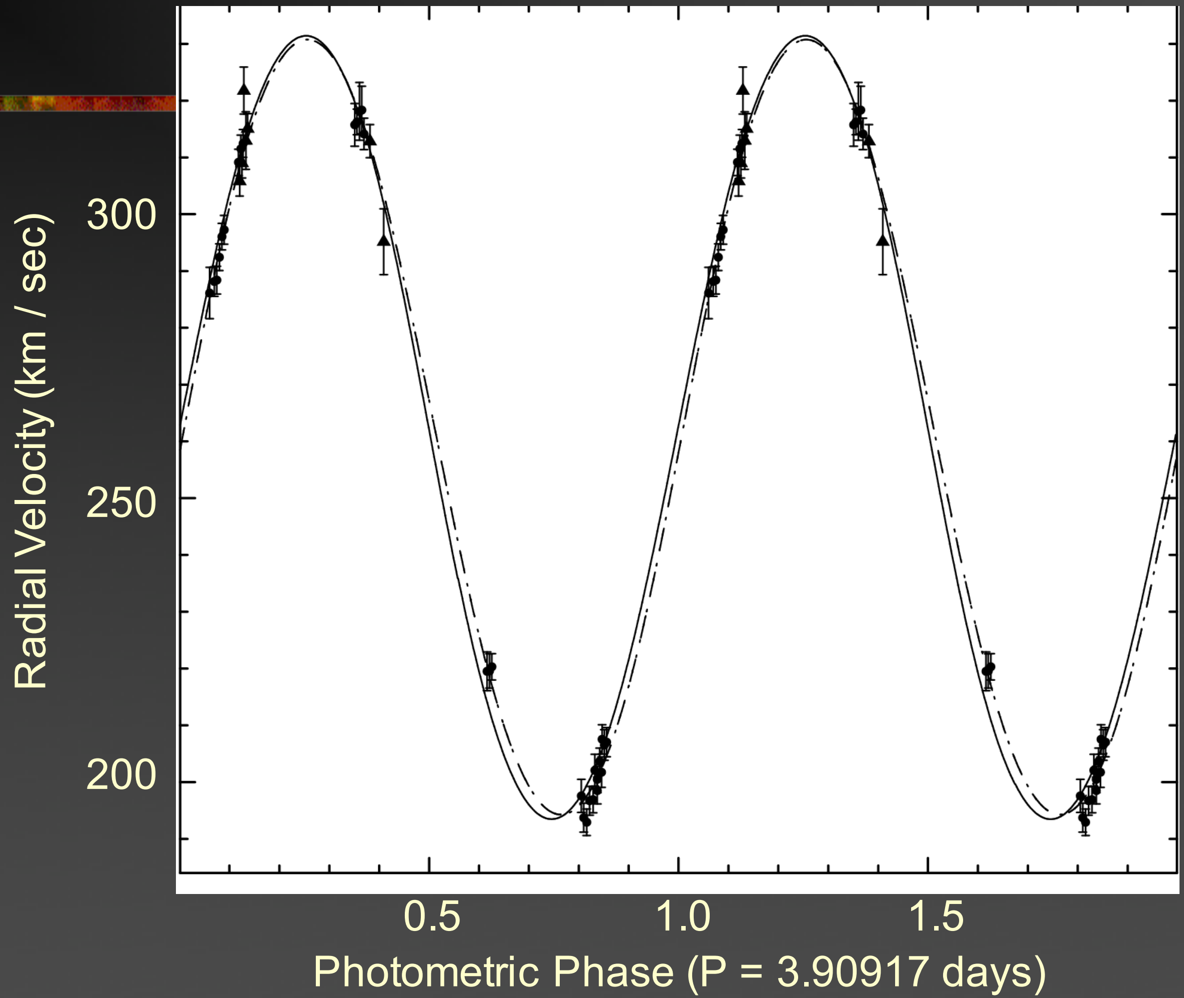


-69:44:15
-69:44:30
-69:44:45
-69:45:00
X-1
R148
10"
V
5h39m43s
5h39m40s
5h39m37s
5h39m34s
X-1
R148
10"
K
5h39m43s
5h39m40s
5h39m37s
5h39m34s
RA (J2000)

MIKE Spectrum: T_{eff}=33,225 & log(g) = 3.49

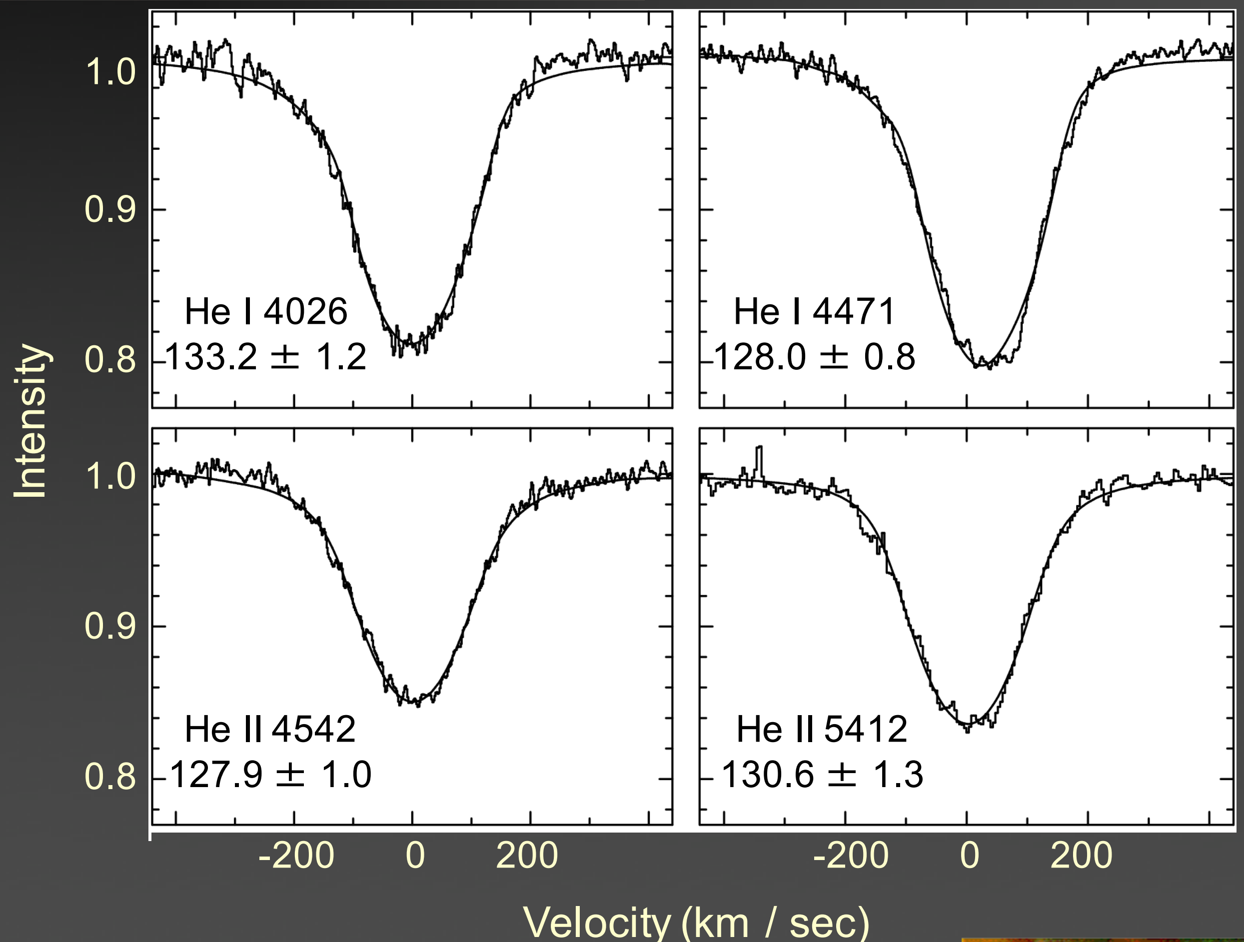


MIKE Radial Velocities: K = 69.2 ± 0.9 km/sec

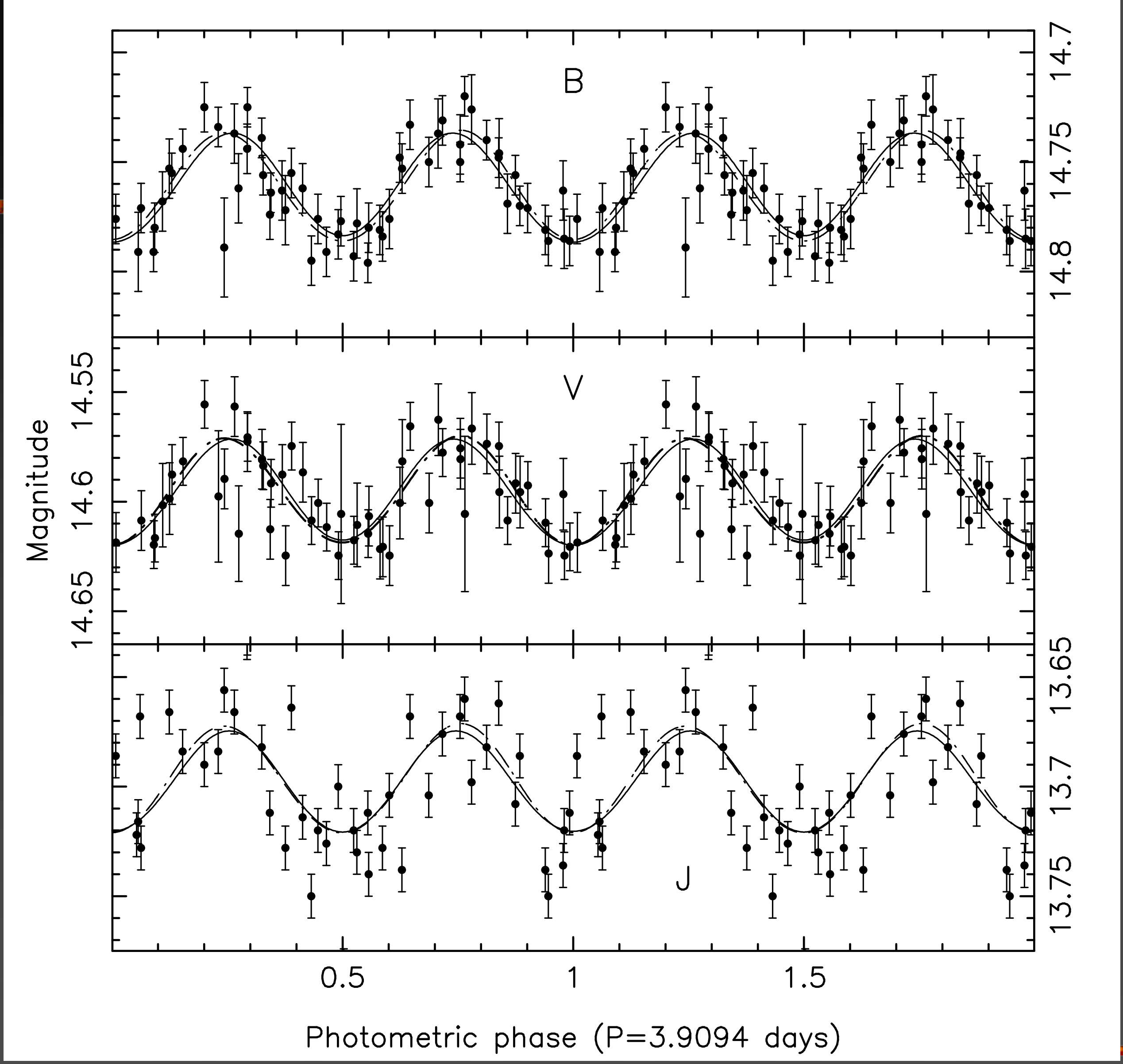


Orosz et al. 2009

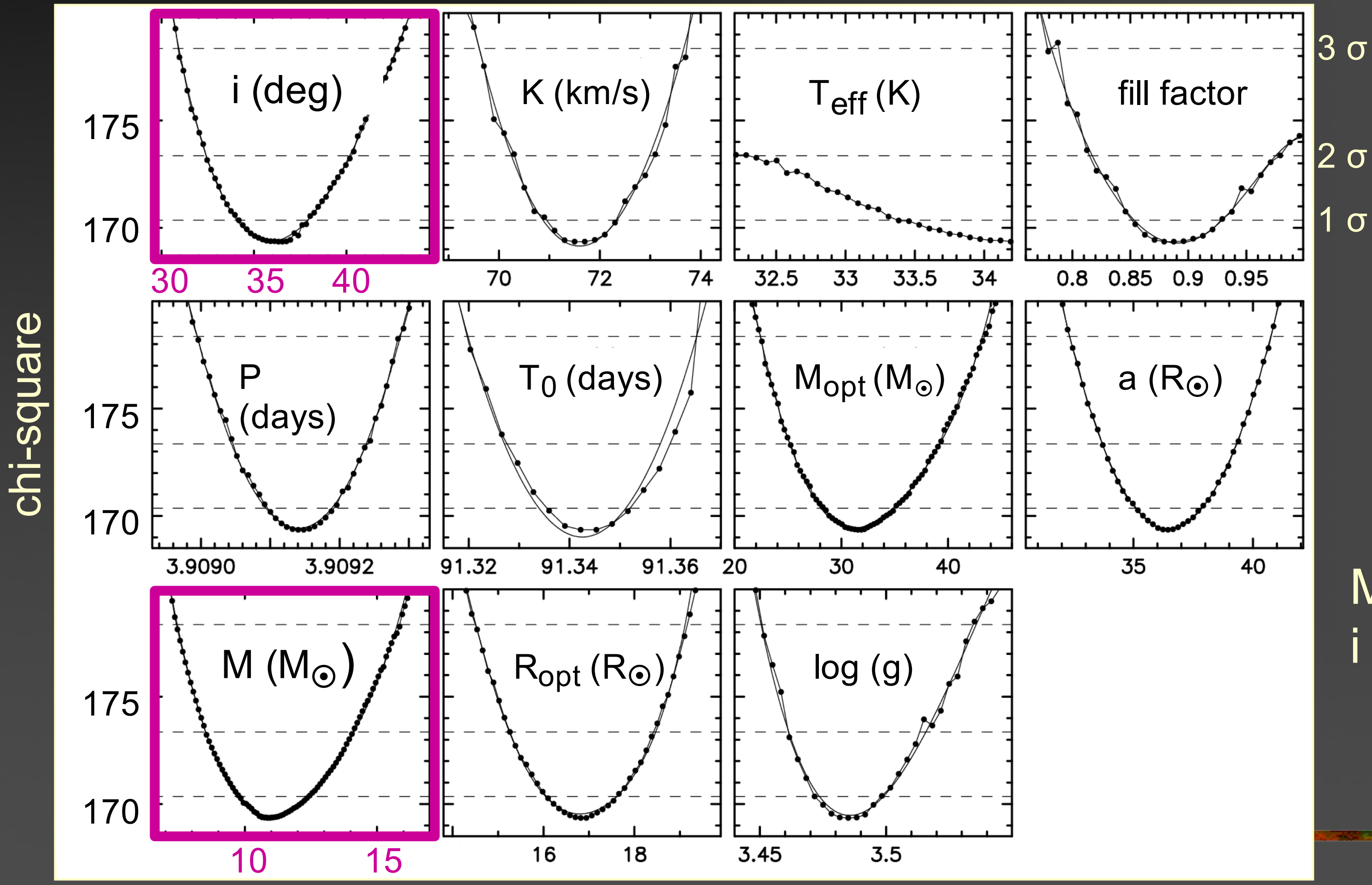
MIKE Rotational Velocity of Secondary: Vsin i = 129.9 ± 2.2 km/sec



Orosz et al. 2009


B
V
J
Magnitude
14.7
14.75
14.8
14.55
14.6
14.65
13.65
13.7
13.75
0.5
1
1.5
Photometric phase (P=3.9094 days)

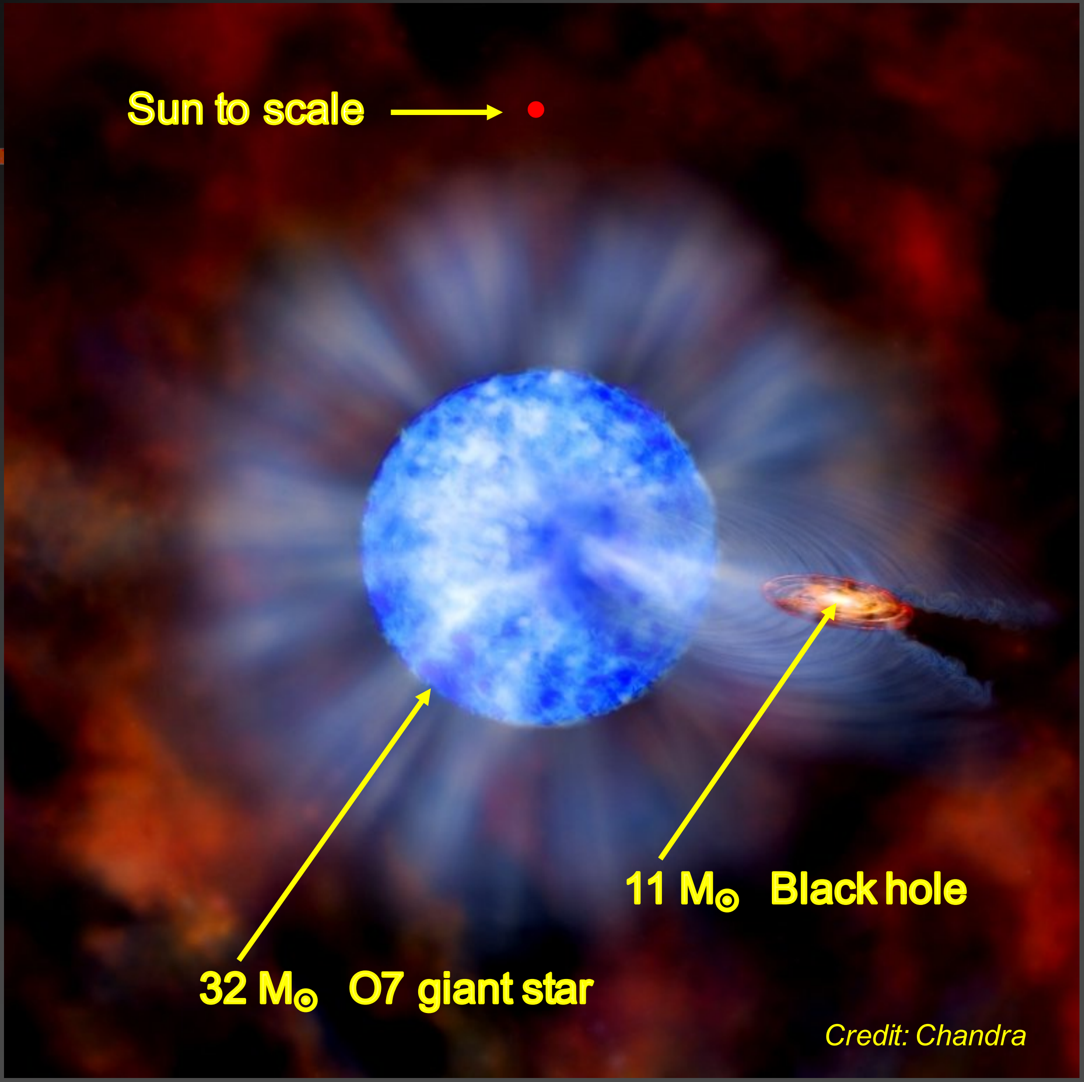
Curves of χ^2 vs. Parameters



$M = 10.9 \pm 1.4\ M_\odot$
$i = 36.4 \pm 1.9$ deg

Orosz et al. 2009

LMC X-1



Black-Belt Topic -

X-ray heated systems: Bowen-line emission

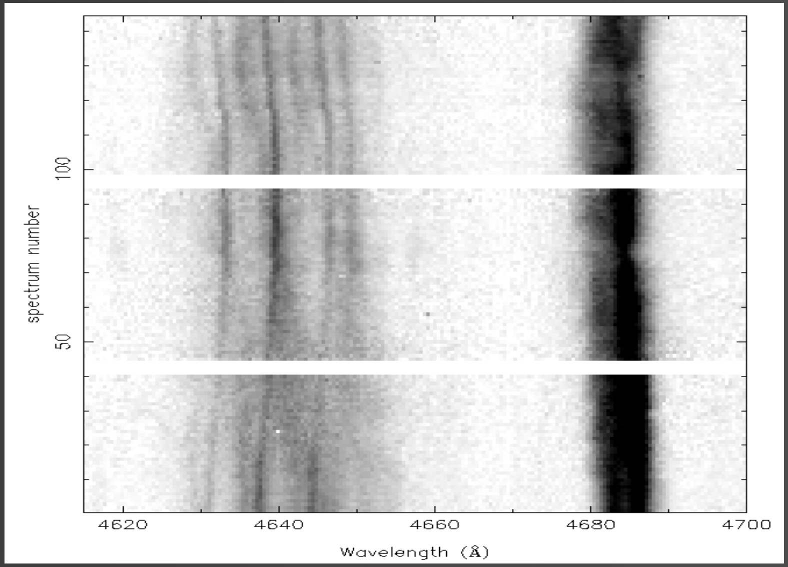
Detection of sharp high excitation emission lines

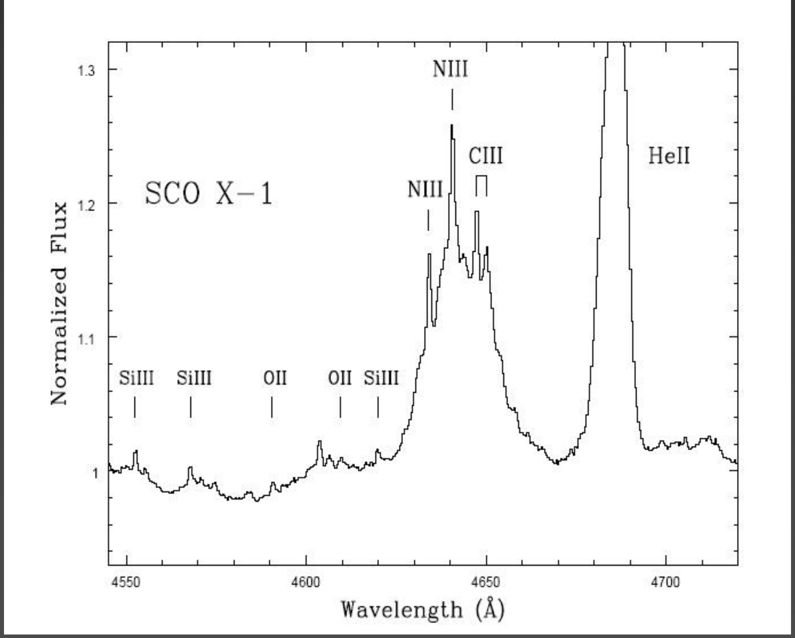
Most prominent are CIII/NIII at λλ4630-40

NIII powered by fluorescence

Doppler shift traces orbit of heated companion

NIII/CIII HeII



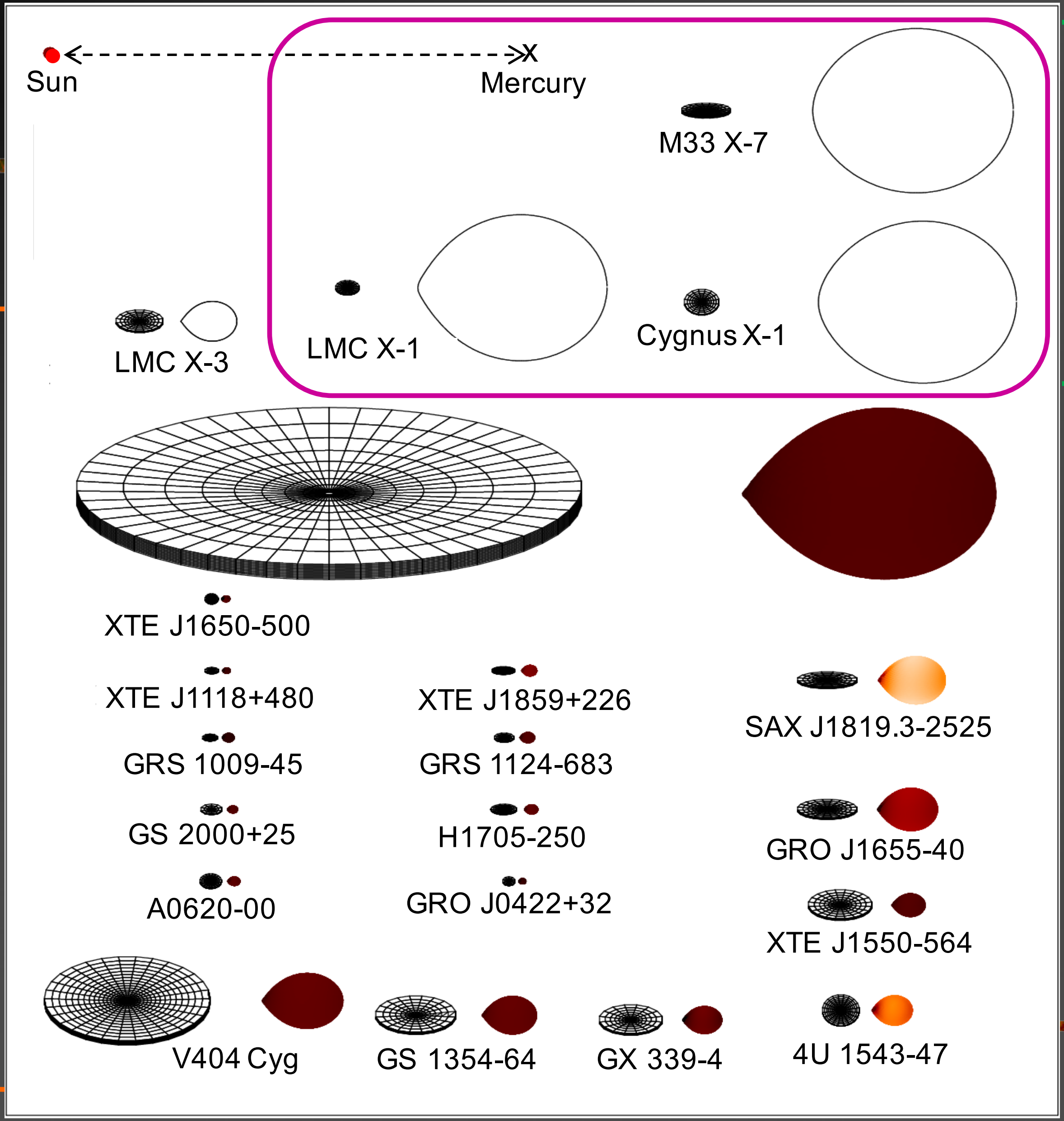


Steeghs & Casares 2002

Credit: J. Casares

The Black Hole Binary Zoo

Courtesy: J. Orosz

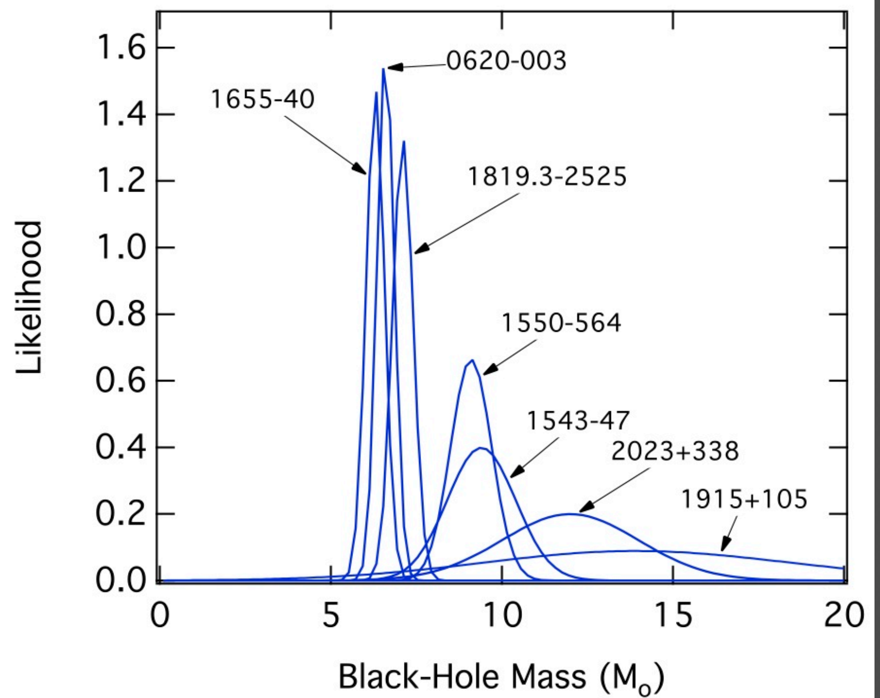


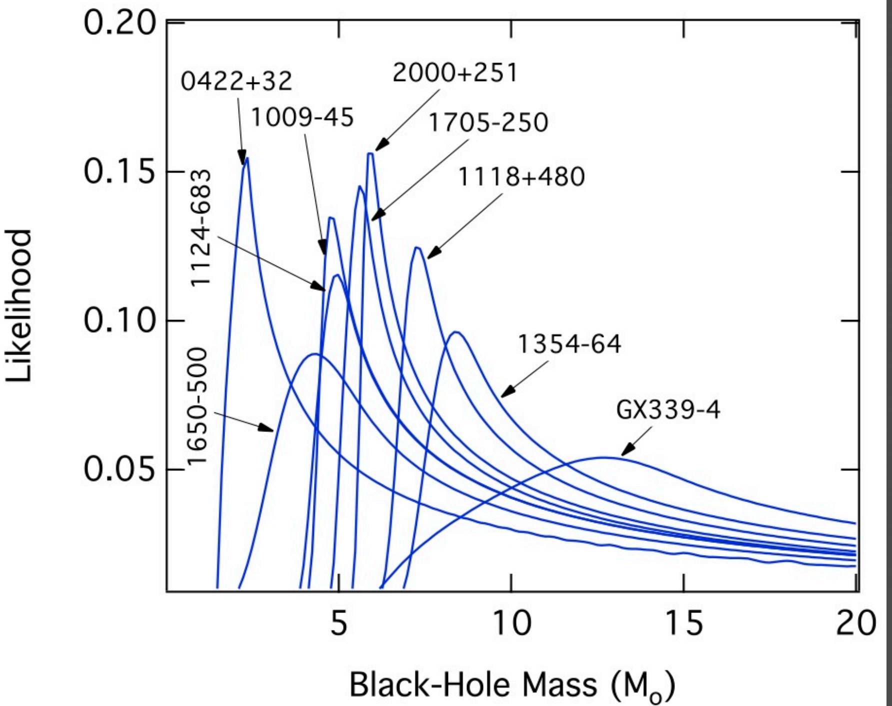
Three persistent systems

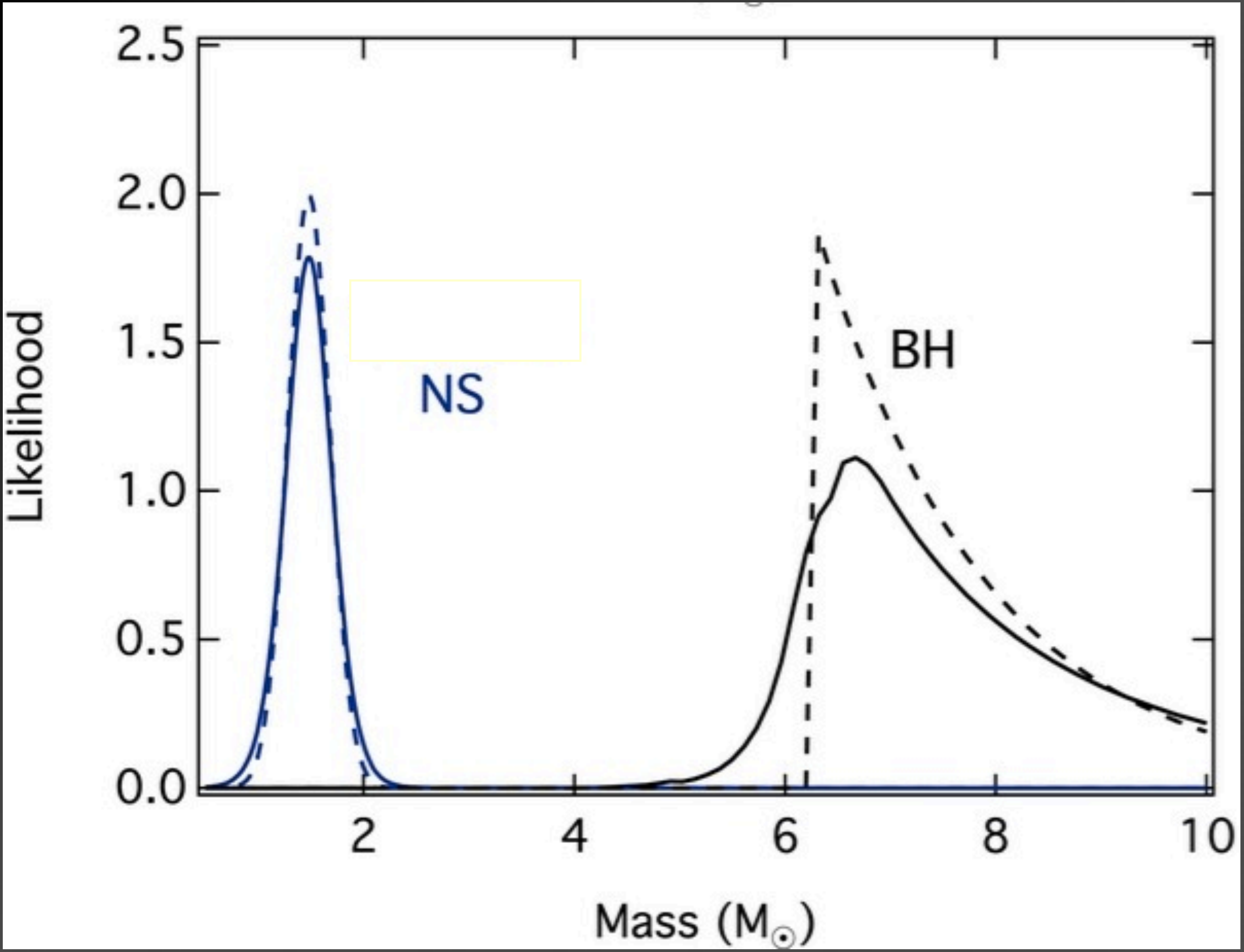
18 transient systems

Results: Masses of BH Transients

Özel, Psaltis, Narayan,
& McClintock 2010





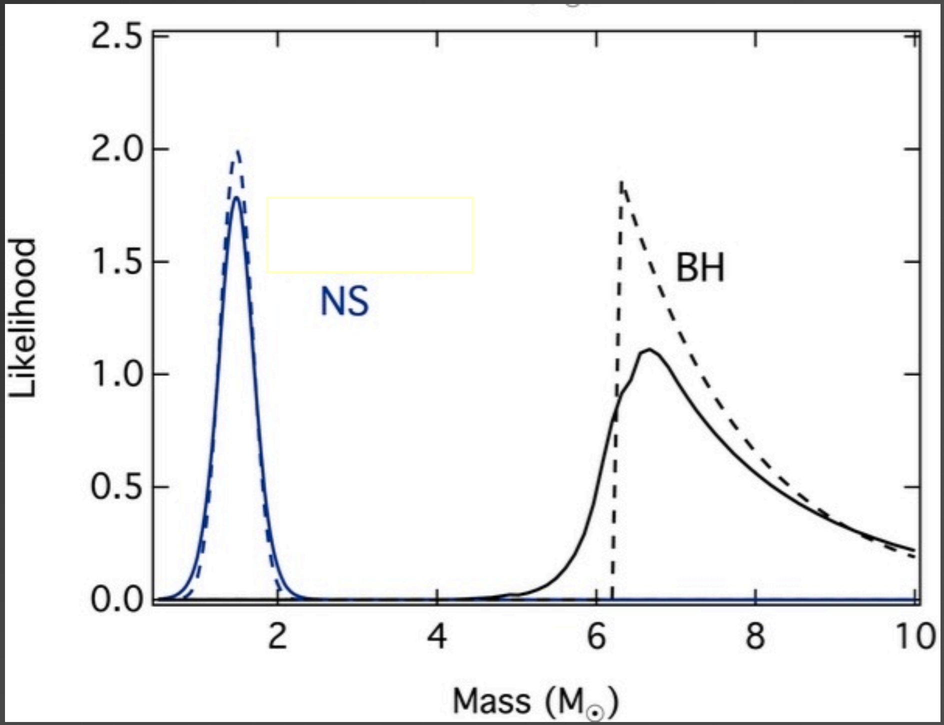


Minimum BH mass **~ 5M_0** Recall: maximum NS mass **~ 2M_0**

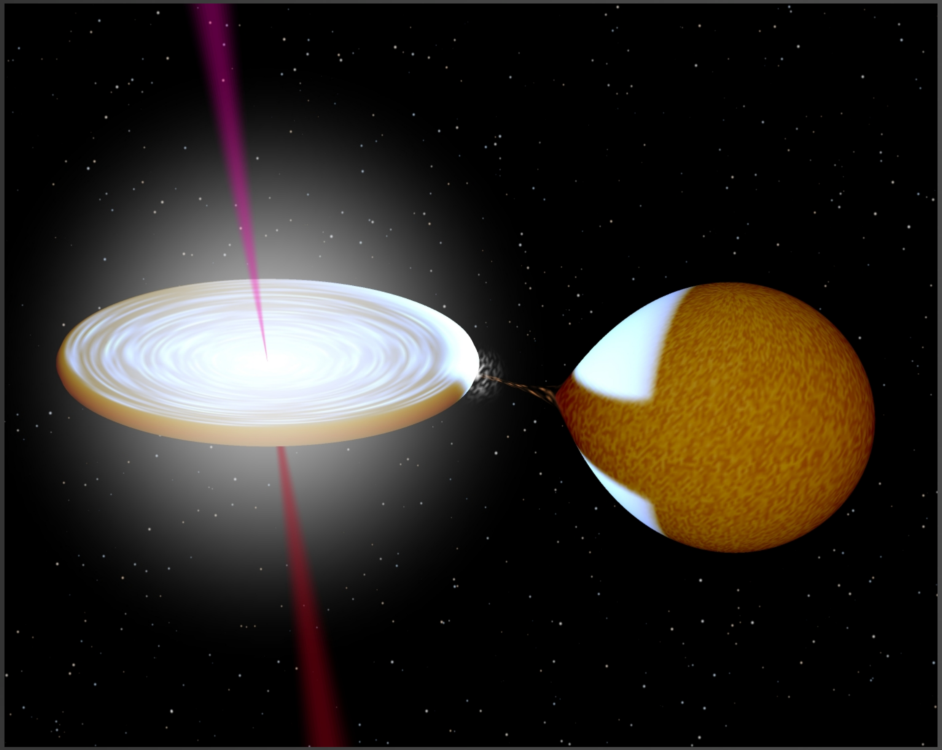
Özel et al. (2010, 2012); Bailyn et al. (1998)

Mind the Mass Gap

- Unexpected, because main-sequence mass distribution **rising** at low M. (Özel et al 2010)
- Not predicted by evolutionary theory (Freyer & Kalogera 2001)
- Perhaps this is offers a clue about SNe? (Belczynski et al 2011)
- Alternatively: indirect hints (not confirmed) of low-mass BHs in 4U 1957+11, IGR J17091-3624



Talk Overview



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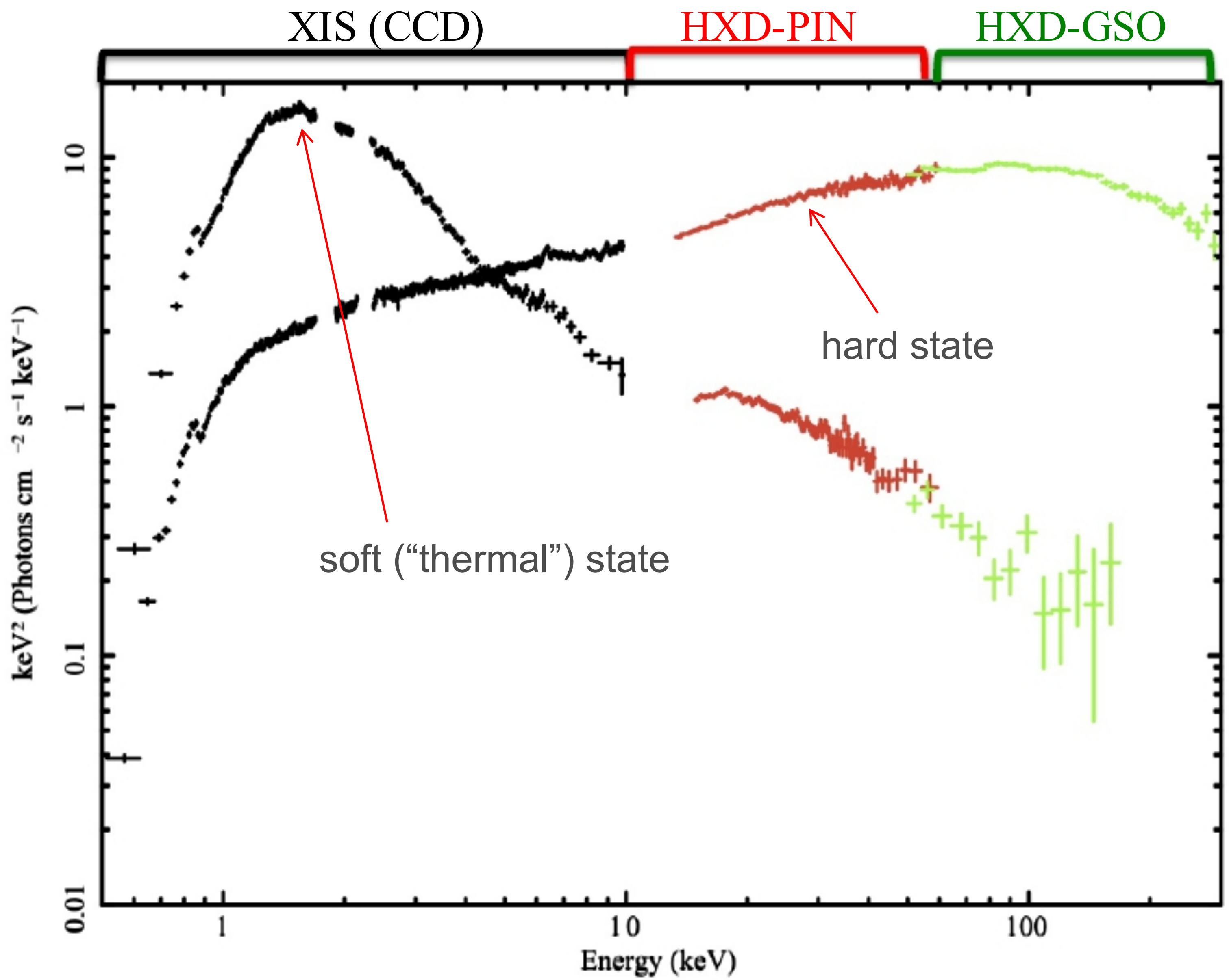
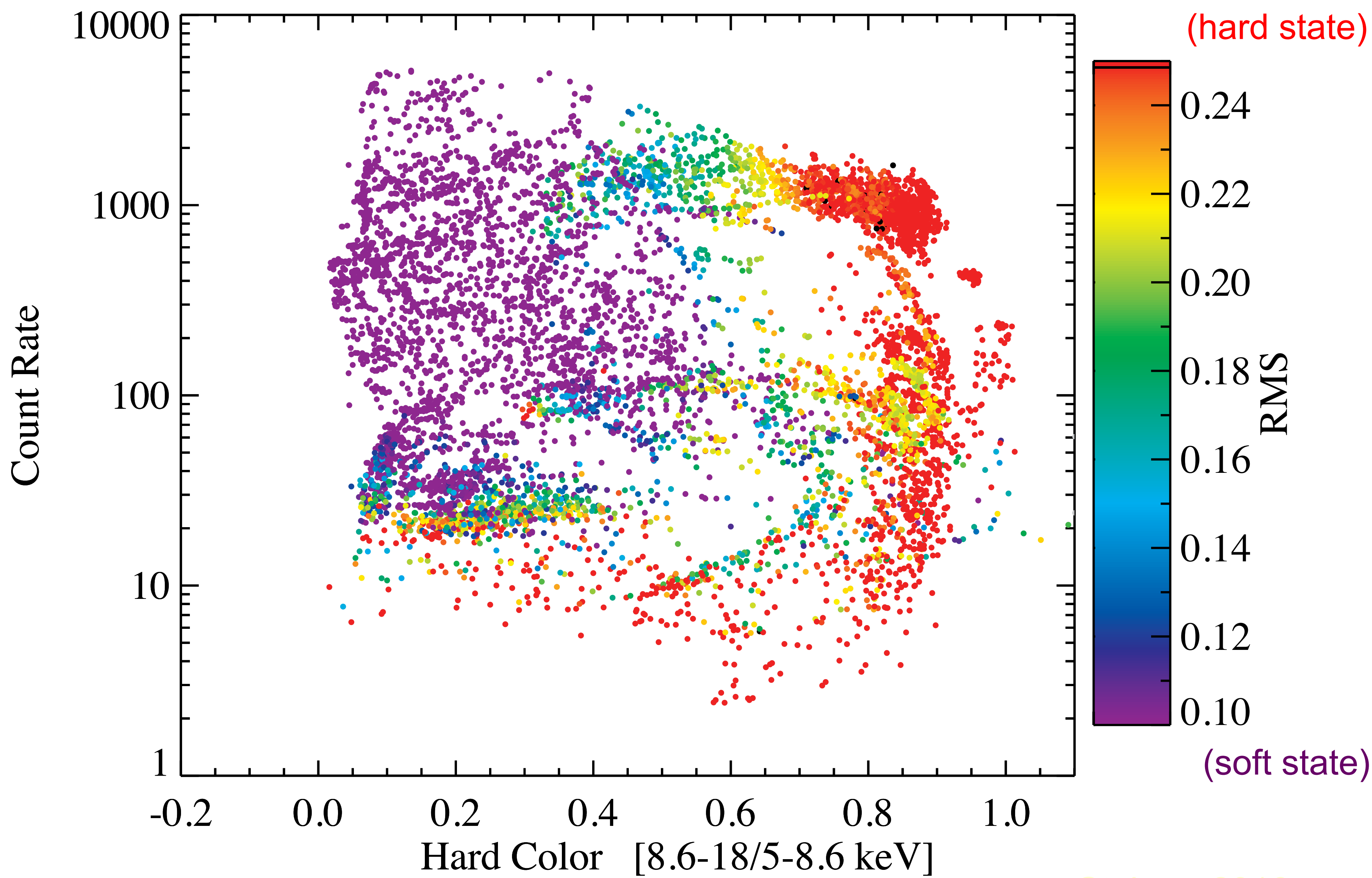
Canonical States of Cyg X-1

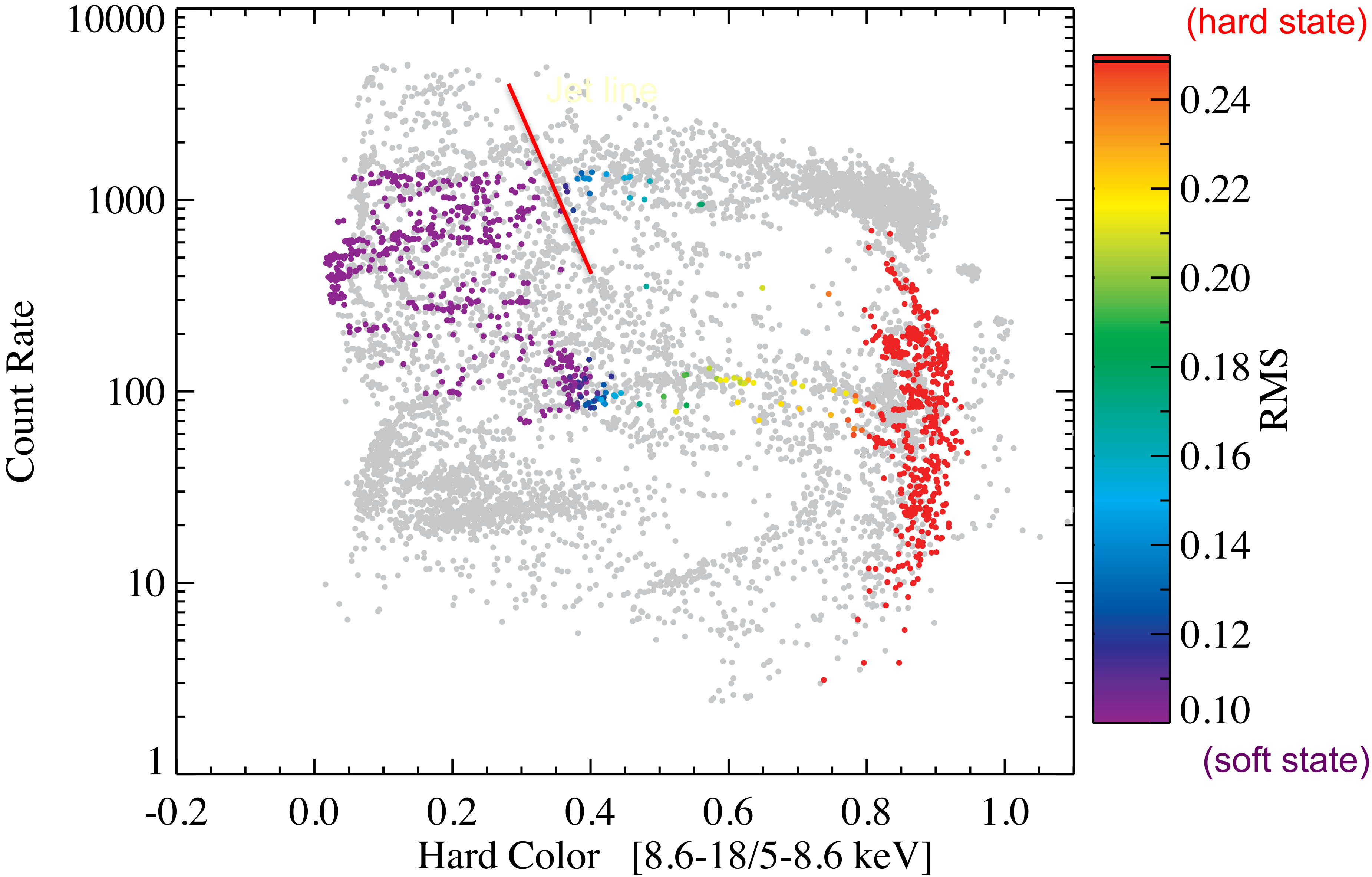


The RXTE View of BHs

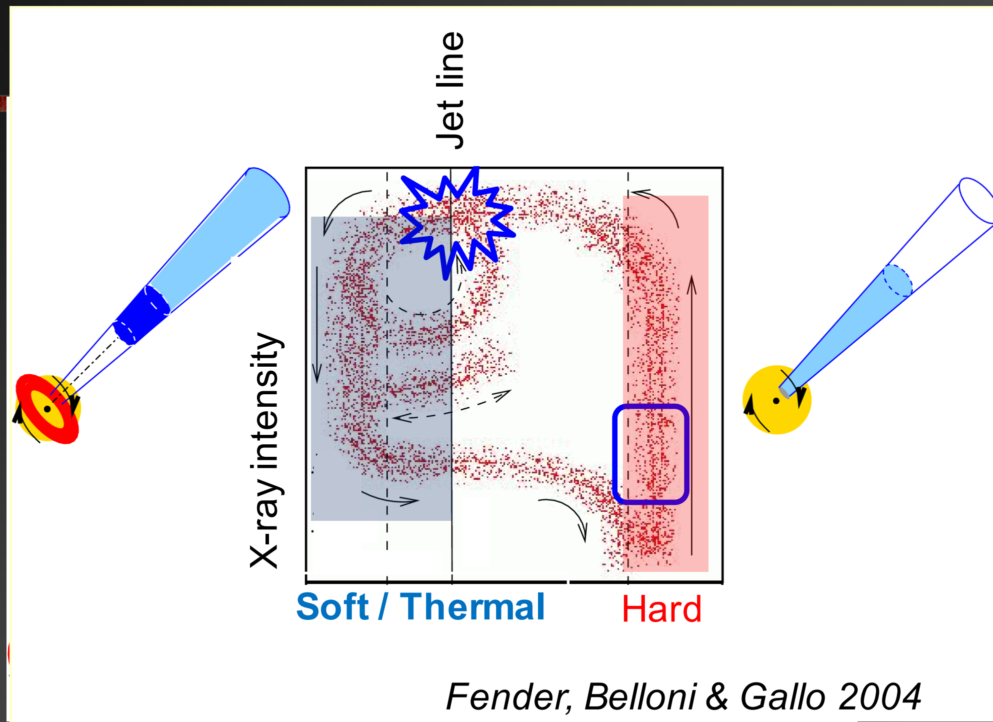


Steiner+2016

GX 339-4 as template



States, Turtles, and Jets



Type 1

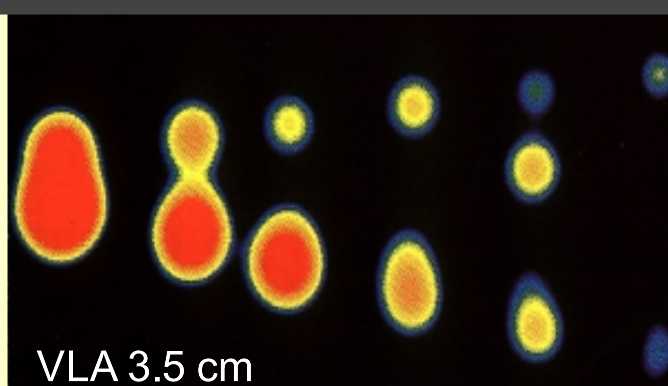
Pc-scale ballistic jets: Seen episodically near X-ray maximum at $L_X \sim L_{Edd}$

Type 2

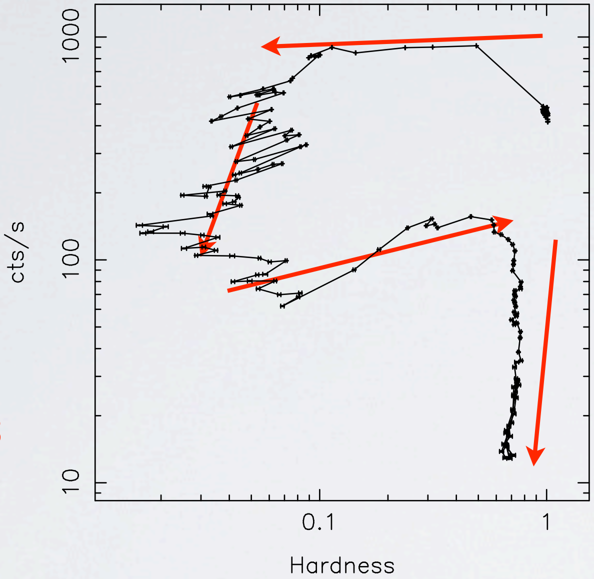
AU-scale steady jets: Seen continuously in low hard sate at $L_X \sim$ few% L_{Edd}

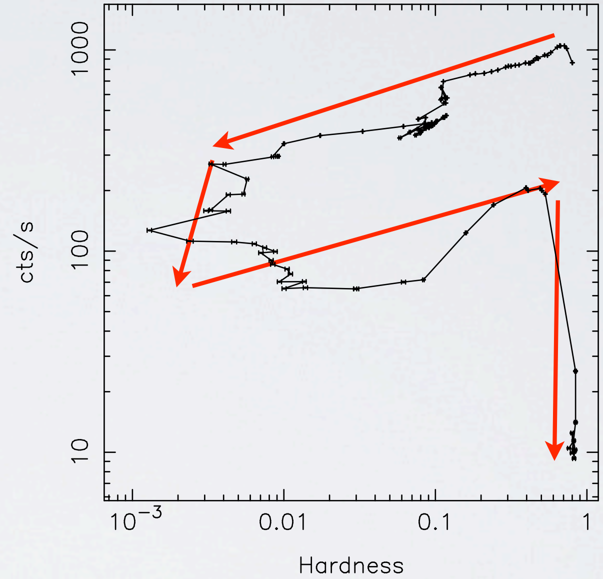
GRS 1915 +105

Mirabel & Rodriguez 1994



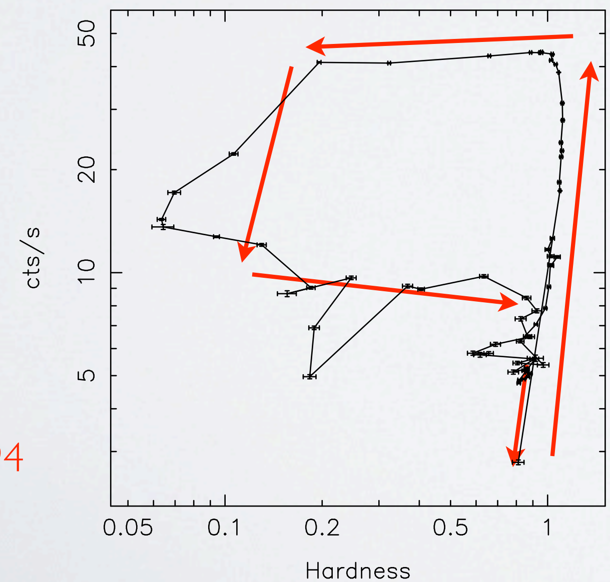
XTE J1752-223

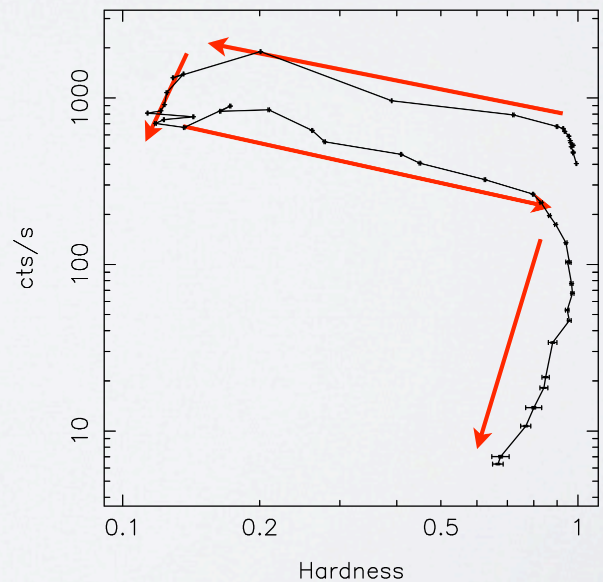




XTE J1650-500

XTE J1908+094





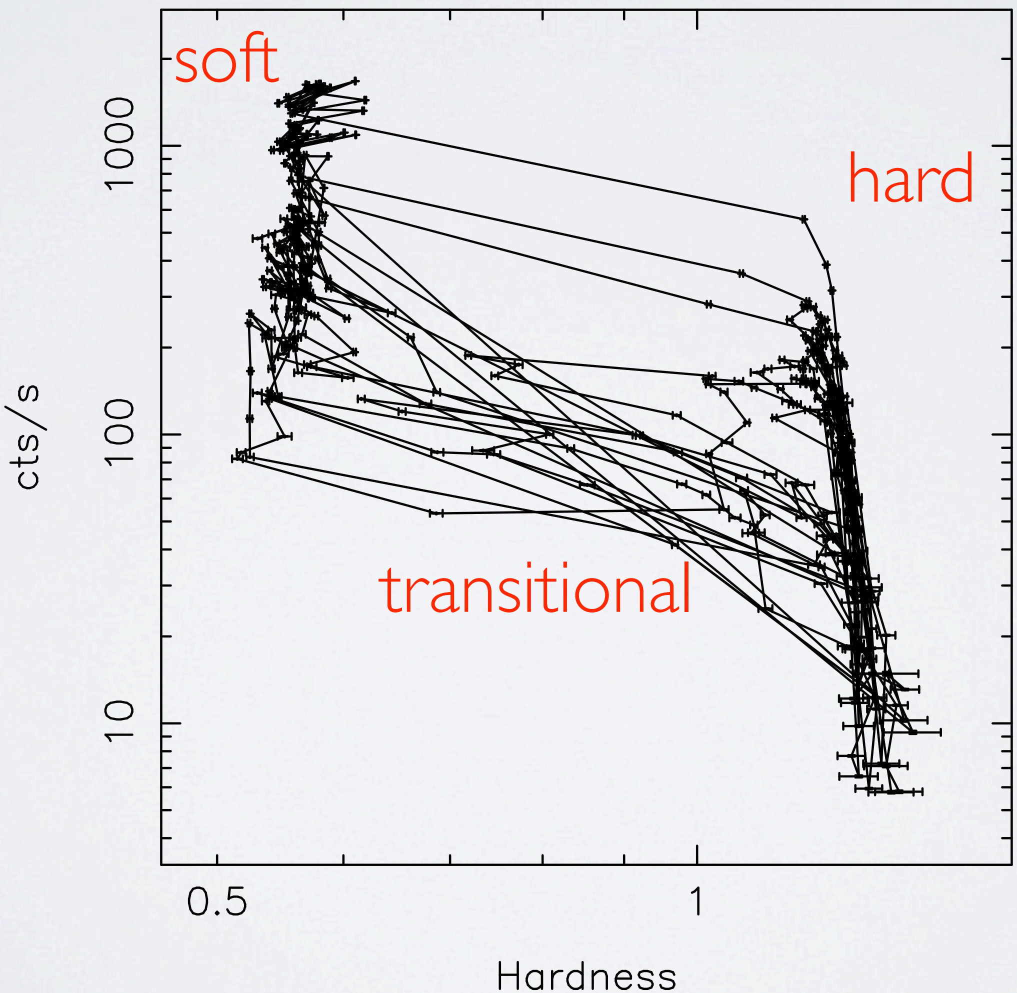
XTE J1550-564

Credit: J. Homan

NEUTRON STARS

hard - soft - transitions

Aql X-1

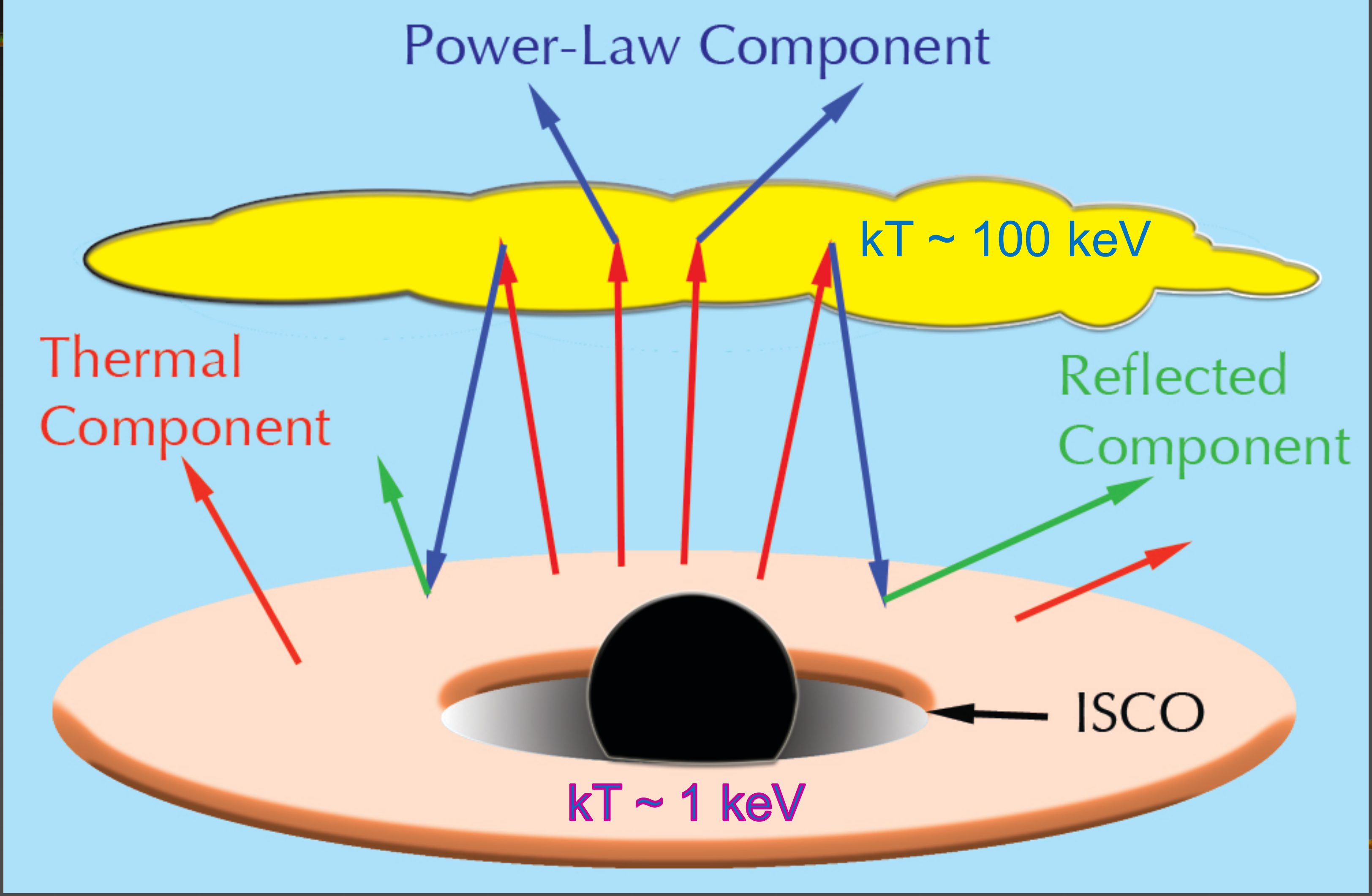


q-shaped

anti-clockwise motion

Credit: J. Homan

The physics of states: the X-ray Corona interacting with the Cold Accretion Disk



State Spectral and Timing General Properties

- Hard State –
  - Generally at lower luminosities
  - Dominated by nonthermal emission from corona (Comptonization and associated reflection).
  - QPOs common (more on this tomorrow).
  - Compact radio jet is present
  - High rms timing noise
- Soft State –
  - Generally at higher luminosities
  - Dominated bythermal blackbody emission from the disk and/or surface (for NS only of course)
  - No jet
  - Low RMS timing noise

State Spectral and Timing Properties

- Intermediate States –
  - Transitional between hard and soft and usually short lived.
  - Changing mixture of thermal and nonthermal components.
  - QPOs common
  - Ballistic jets can be launched crossing jet line
  - RMS varies, coupled to hardness

- Quiescence –
  - An extreme extension of the hard state to vanishingly small mass-accretion rate / luminosity

Takeaways

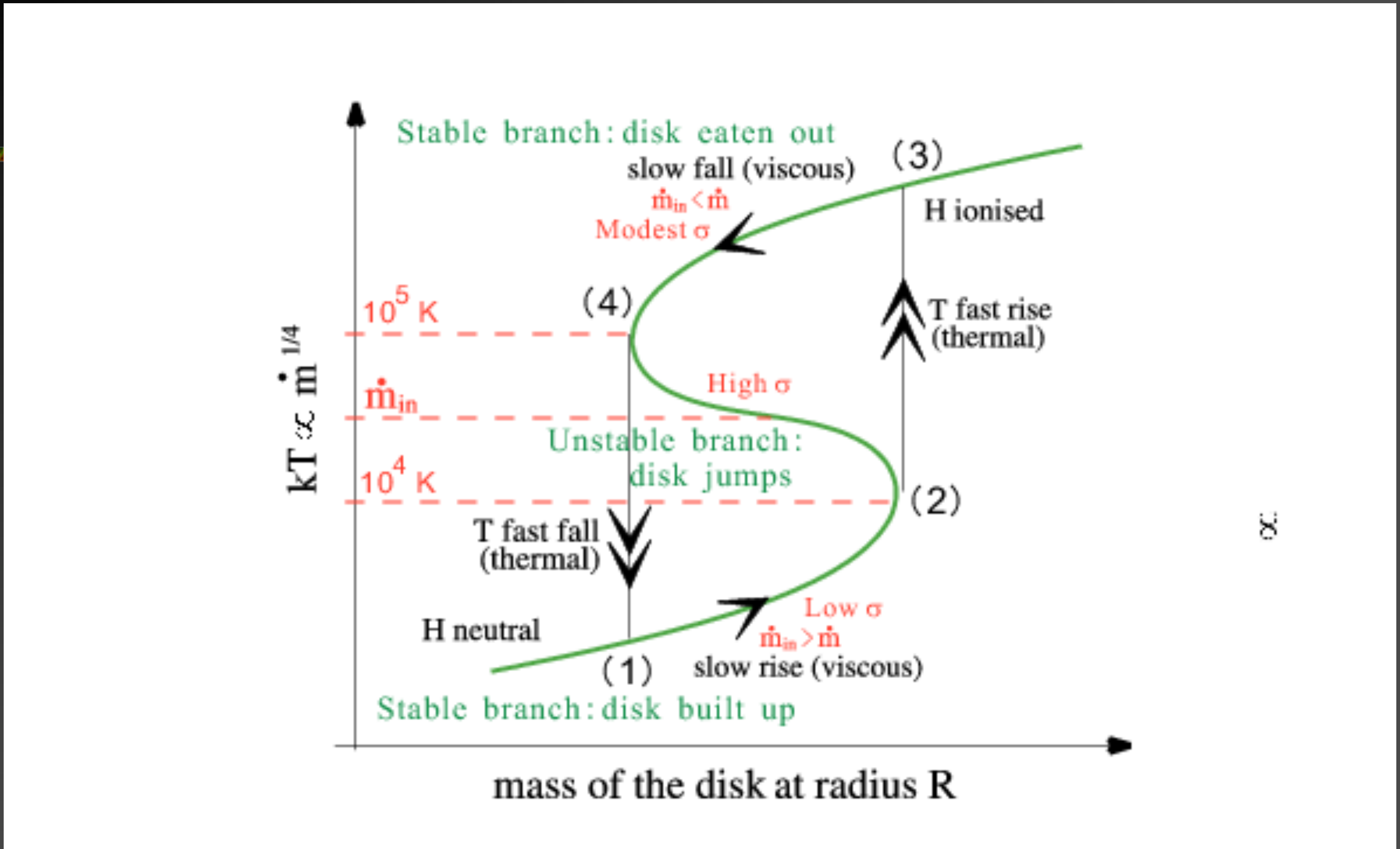
- Taxonomy of XRBs (HMXB, LMXB), basics of each
- Quiescent observations provide a mass function from radial velocity measurements (spectroscopy)
- Light curves are used to determine inclination from ellipsoidal variability (photometry)
- A mass gap between NSs and BHs
- “Q”-shape of BH (and NS) HID
- Coupling of spectral states and timing noise (spectral-timing states)

For Tomorrow

- Physical models of spectral states
  - Continuum and reflection spectral modeling
  - QPOs and state evolution
  - Black-hole spin

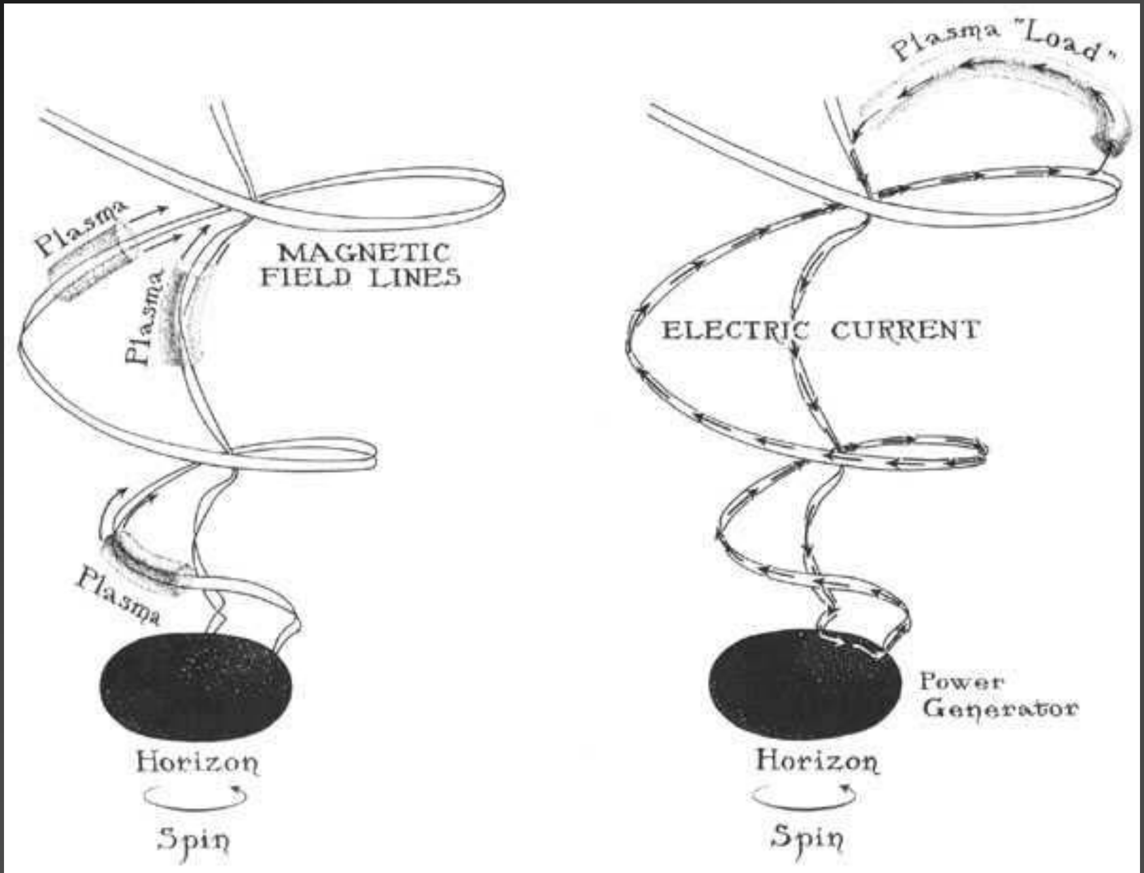
- Z- atoll- NS systems, X-ray pulsars
- NS Equation of state

Extra Slides


Stable branch: disk eaten out
slow fall (viscous)
(3)
$\dot{m}_{in} < \dot{m}$
Modest σ
H ionised
(4)
10^5 K
T fast rise
(thermal)
$kT \propto \dot{m}^{1/4}$
$\dot{m}_{in}$
High σ
Unstable branch:
disk jumps
10^4 K
(2)
T fast fall
(thermal)
Low σ
H neutral
$\dot{m}_{in} > \dot{m}$
(1)
slow rise (viscous)
Stable branch: disk built up
mass of the disk at radius R

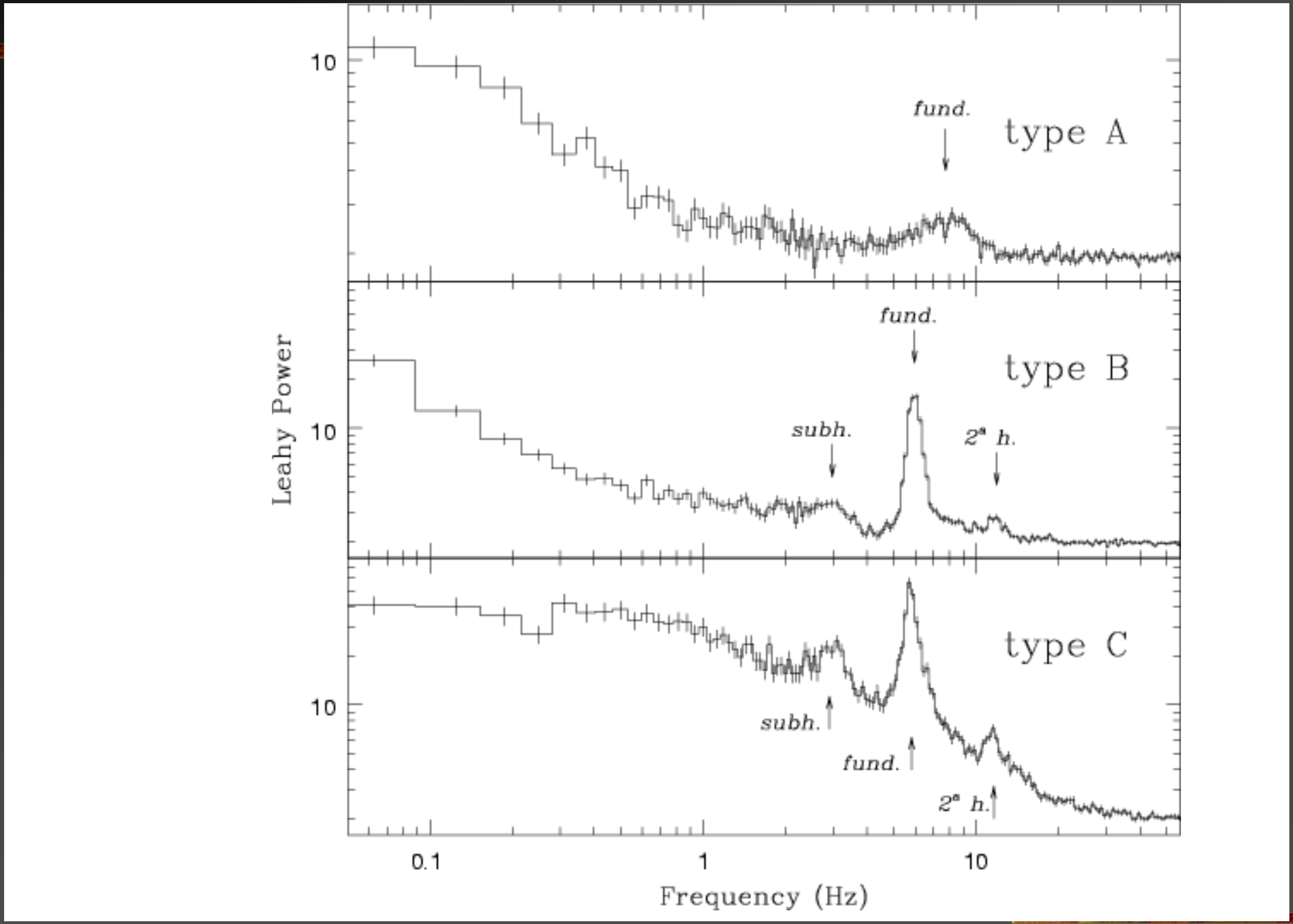
Zhang 2013

B-Z Mechanism



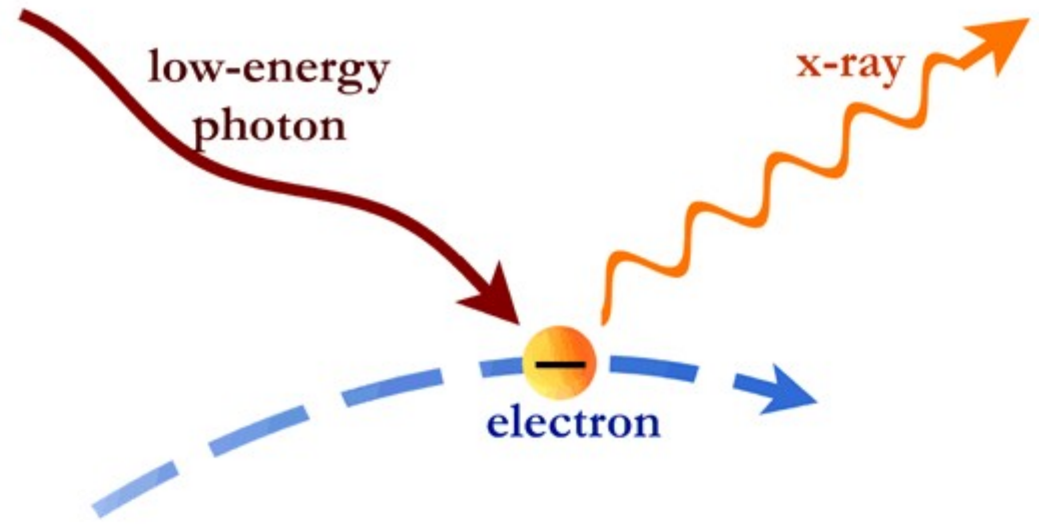
Thorne 1994

BH QPOs



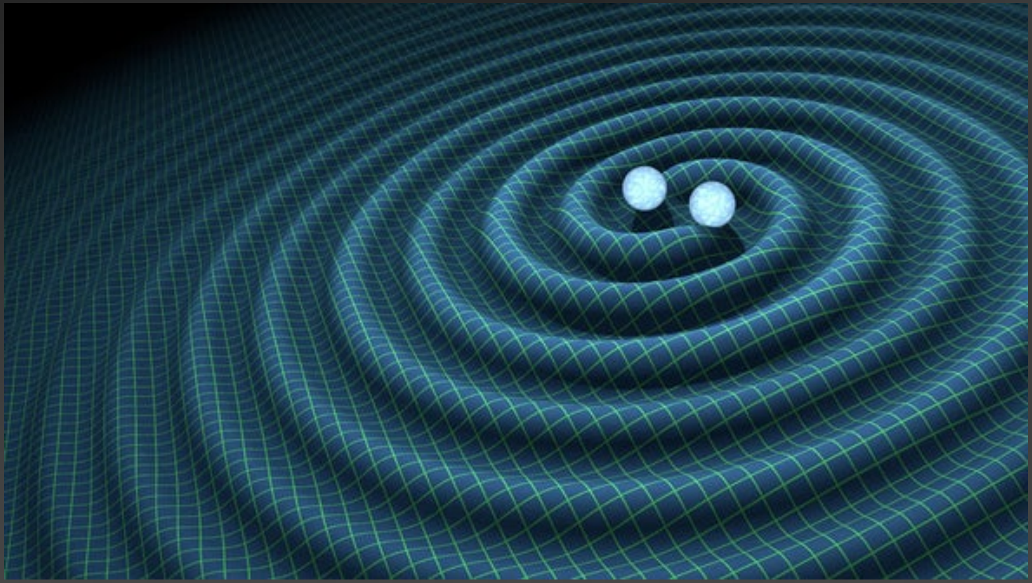
Casella et al. 2004

Comptonization and cutoff power laws



Credit: T. Maccarone

Gravitational Waves – LIGO & VIRGO



”Equivalent to measuring the distance to the nearest star (some 4.2 light years away) to an accuracy smaller than the width of a human hair!”

LIGO / GW BHs


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
LIGO-Virgo Neutron Stars