Constraining the neutron star equation of state

some current and future methods and observations

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Why is the neutron star equation of state so important?

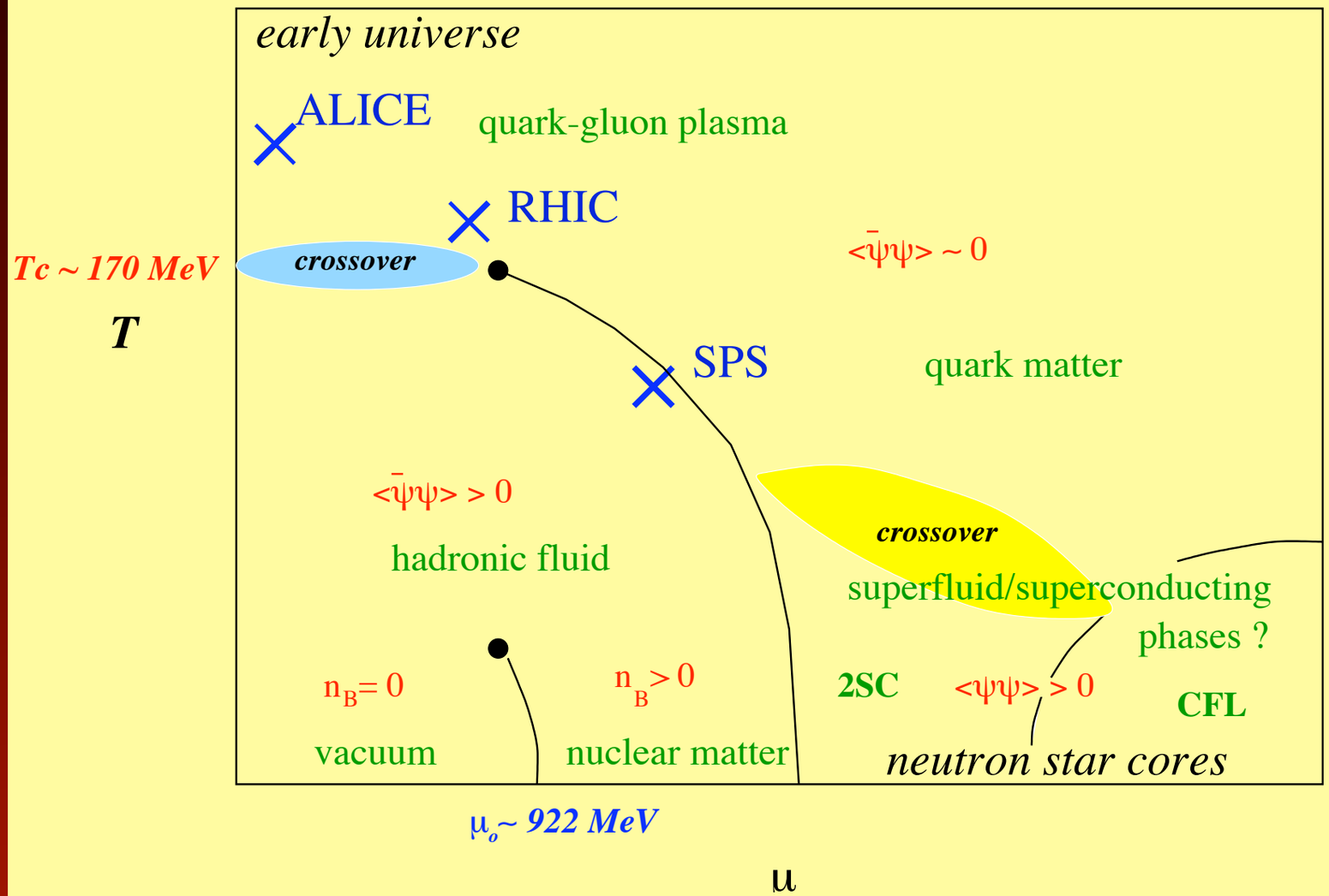
radius ~10 km

mass ~1.4 Msun

extreme density

10^{14} times of water

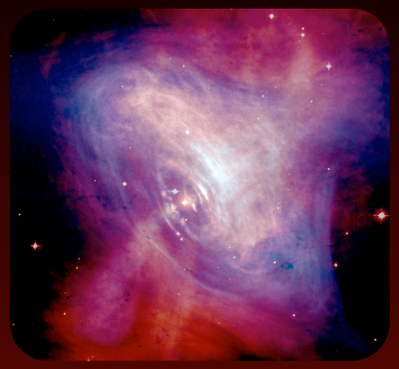
Neutron star's special place in QCD



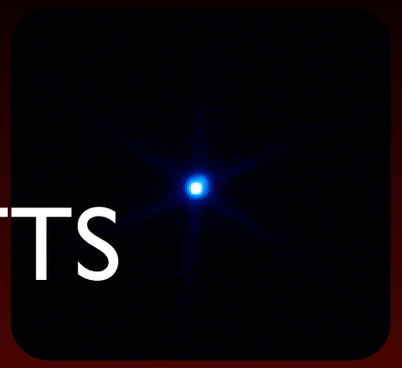
Hands 2001

Neutron stars in astronomy:

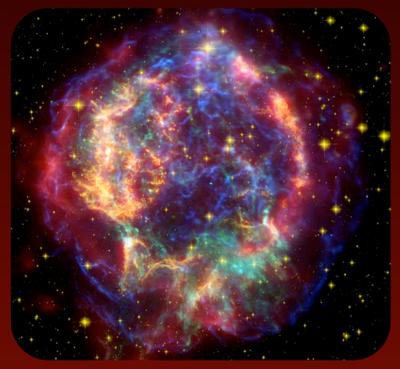
Pulsars



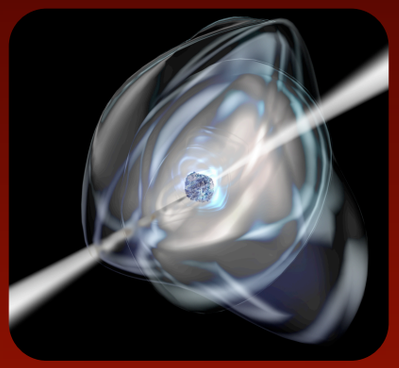
DINS
& RATTS



Compact Central Objects

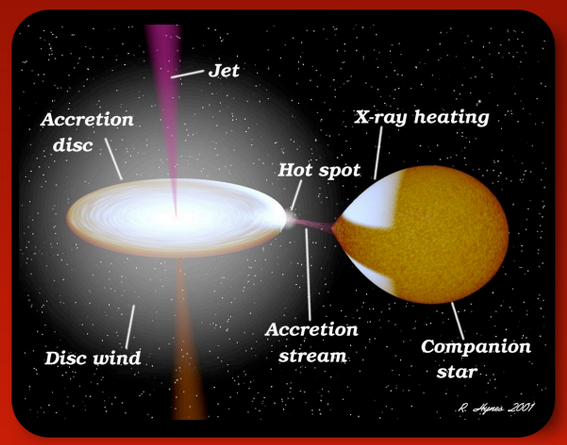


AXPs & SGRs



In HMXBs

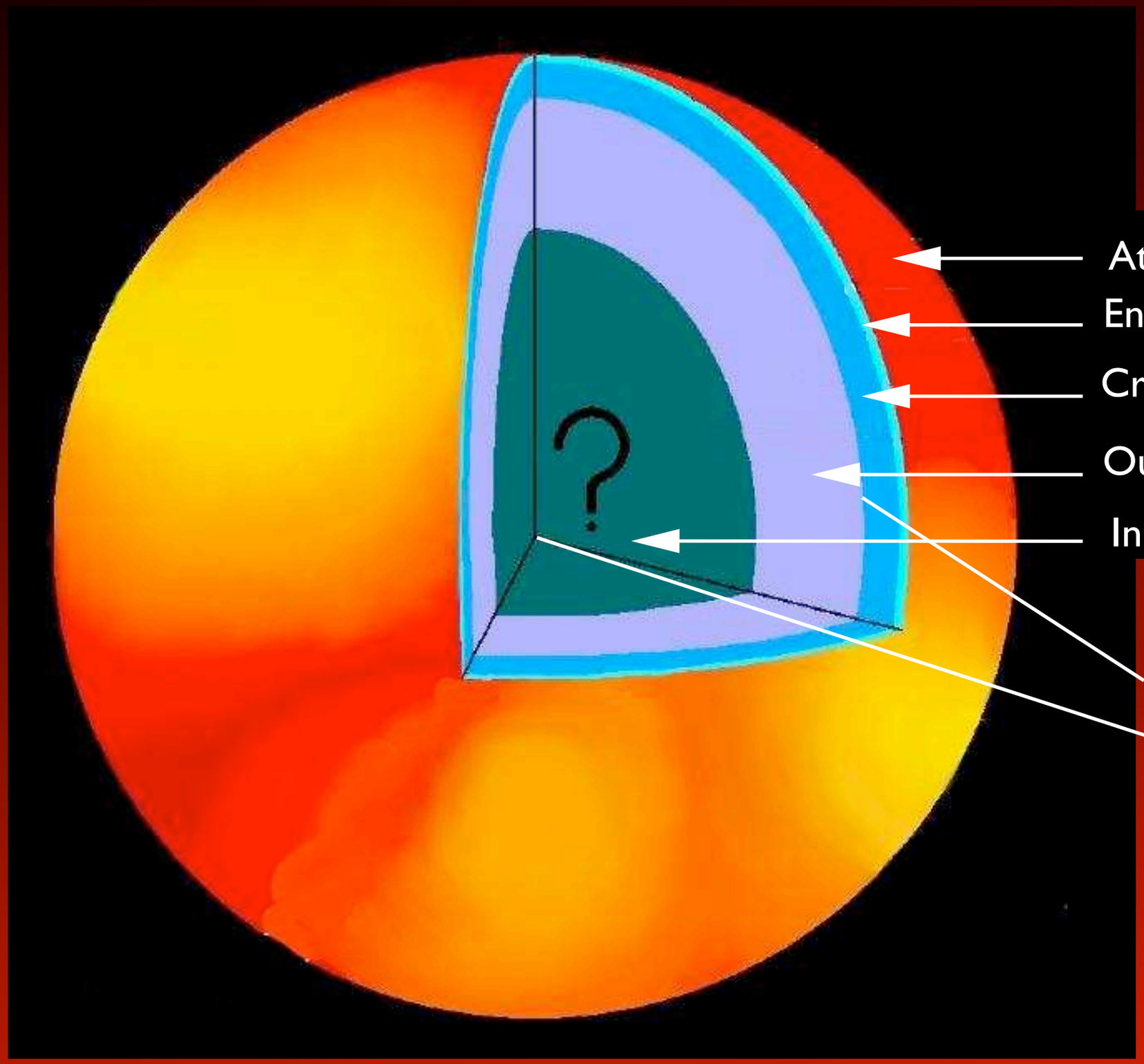
In LMXBs



In short γ-ray bursts (?)

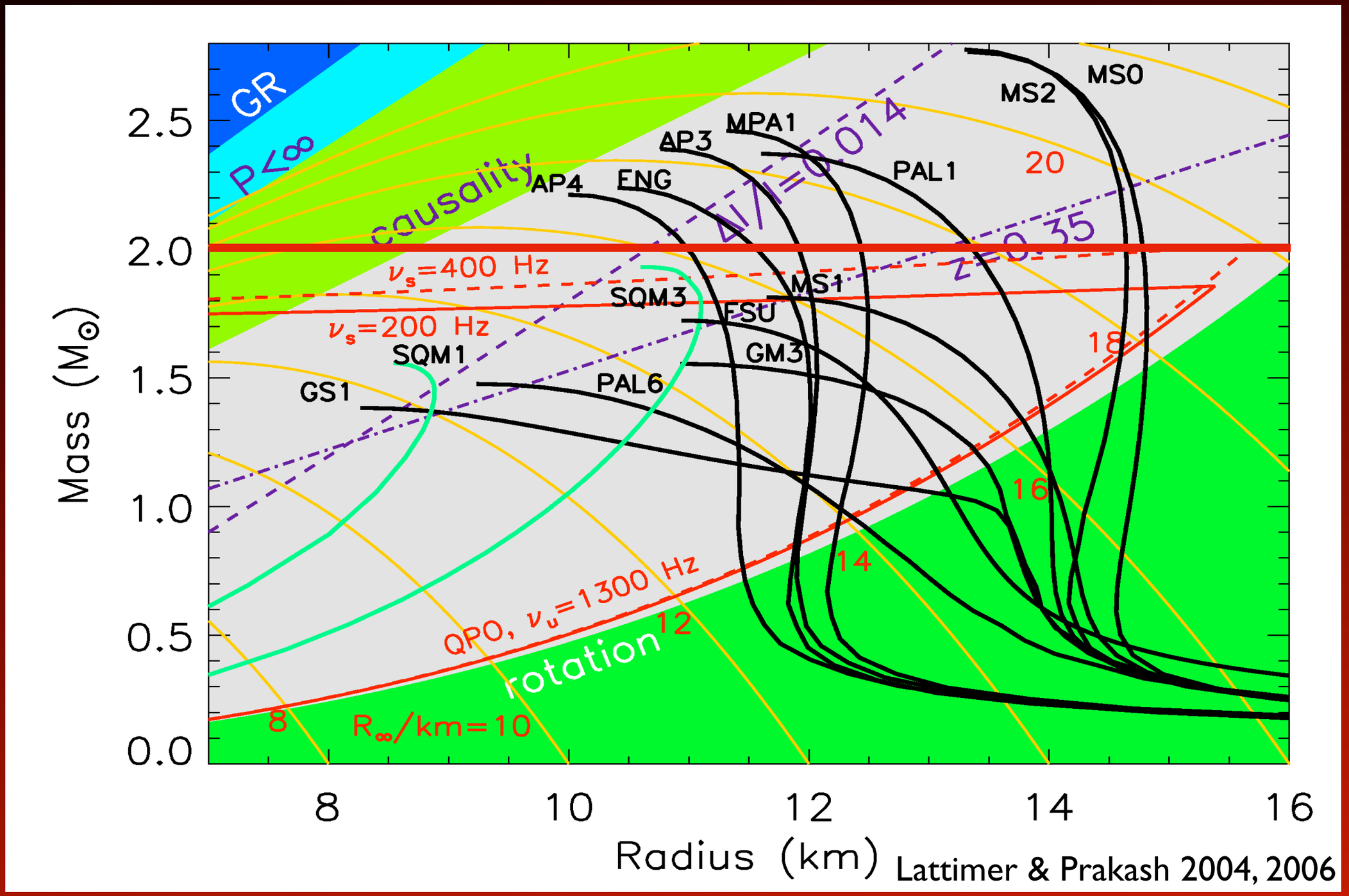
Detection of grav. wave rad.

Neutron stars and their EoS



Page 2004; Lattimer & Prakash 2001, 2004

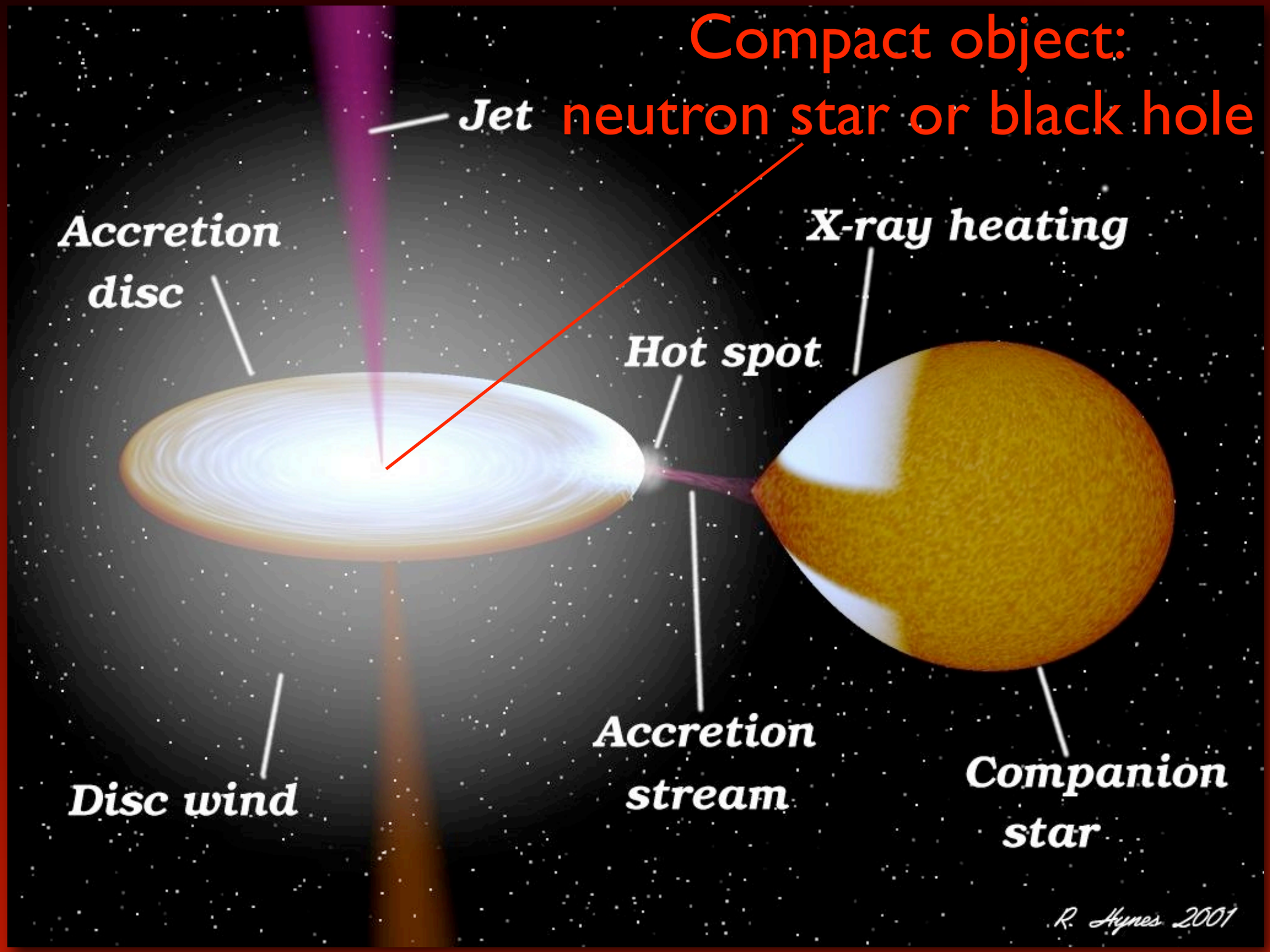
Differentiate between various EoS



Lattimer & Prakash 2004, 2006

Measure at least 2 of:
mass, radius, spin frequency, gravitational redshift

Cartoon image of a low-mass X-ray binary

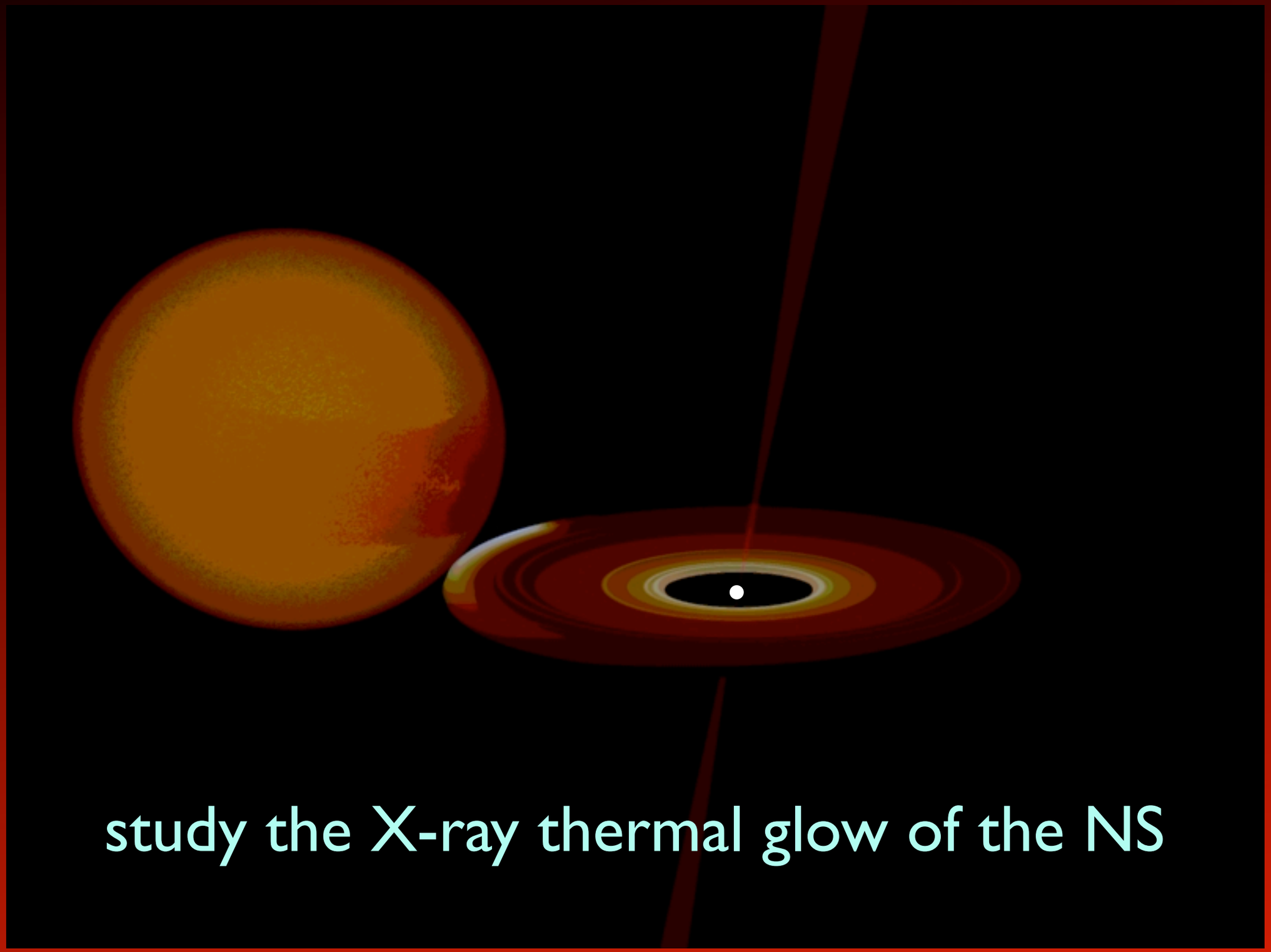


BinSim R. Hynes

Transient sources near the Galactic Center

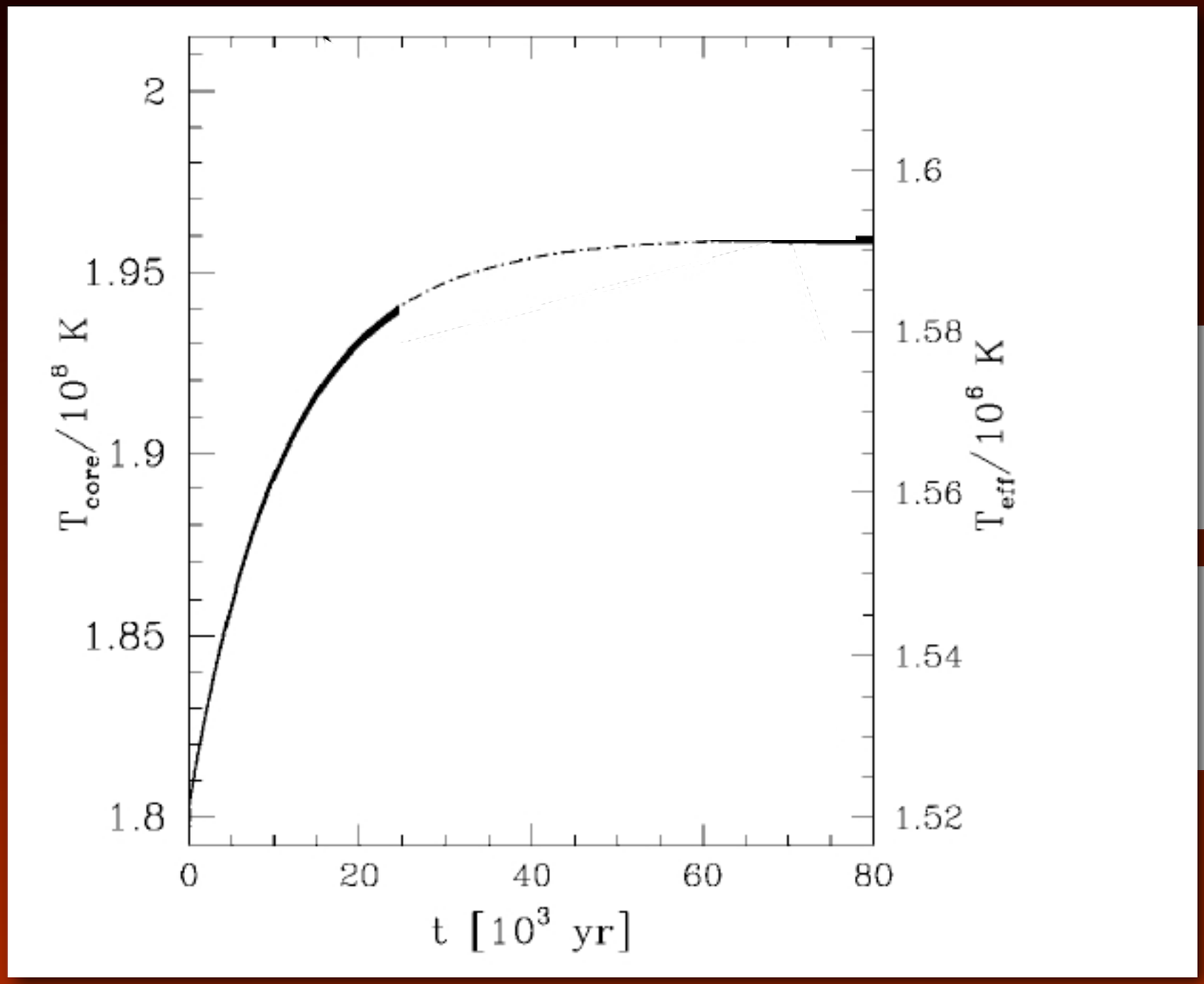
Wang et al. 2000, Muno et al. 2002

Quiescent low-mass X-ray binaries



study the X-ray thermal glow of the NS

Masses from NS X-ray transients in quiescence



$^{34}\mathrm{Ne} + {}^{34}\mathrm{Ne} \rightarrow {}^{68}\mathrm{Ca}$

$^{48}\mathrm{Mg} + {}^{48}\mathrm{Mg} \rightarrow {}^{96}\mathrm{Cr}$

$\mathrm{M_{NS}} = 1.4\,\mathrm{M_\odot}$

$\langle \dot{\mathrm{M}} \rangle = 1.46 \times 10^{-10}\,\mathrm{M_\odot\,yr^{-1}}$

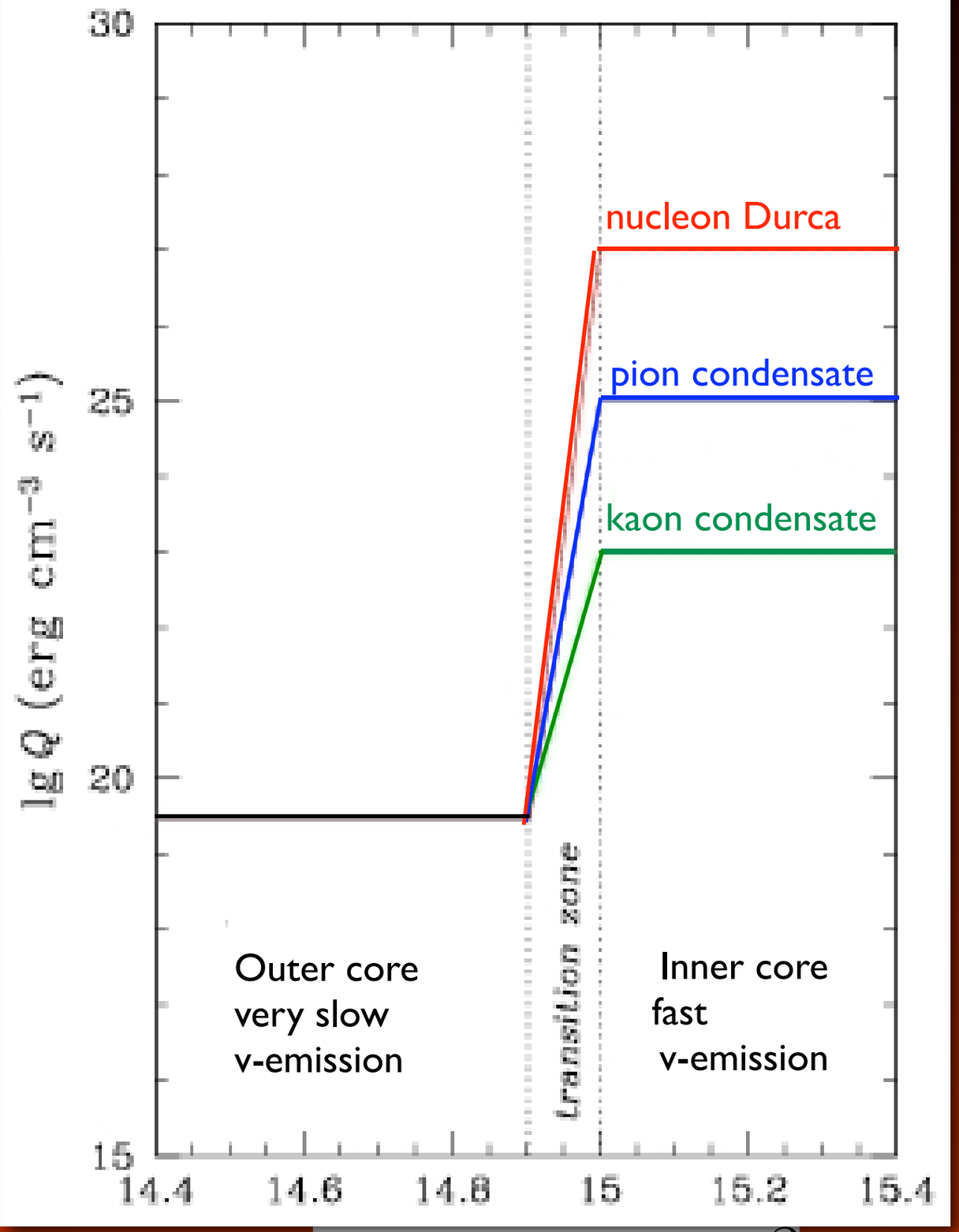
Pycnonuclear reactions: Salpeter& van Horn 1969, Kitamura 2000

Heating of neutron stars: Colpi et al. 2001, Brown et al. 1998

~1 MeV per accreted nucleon

Neutrino cooling processes: fast or slow?

Yakovlev & Pethick 2004 c.f. Page et al 2005



Direct URCA

Nucleon matter $n \longrightarrow pe\bar{\nu}$ $pe \longrightarrow n\nu$

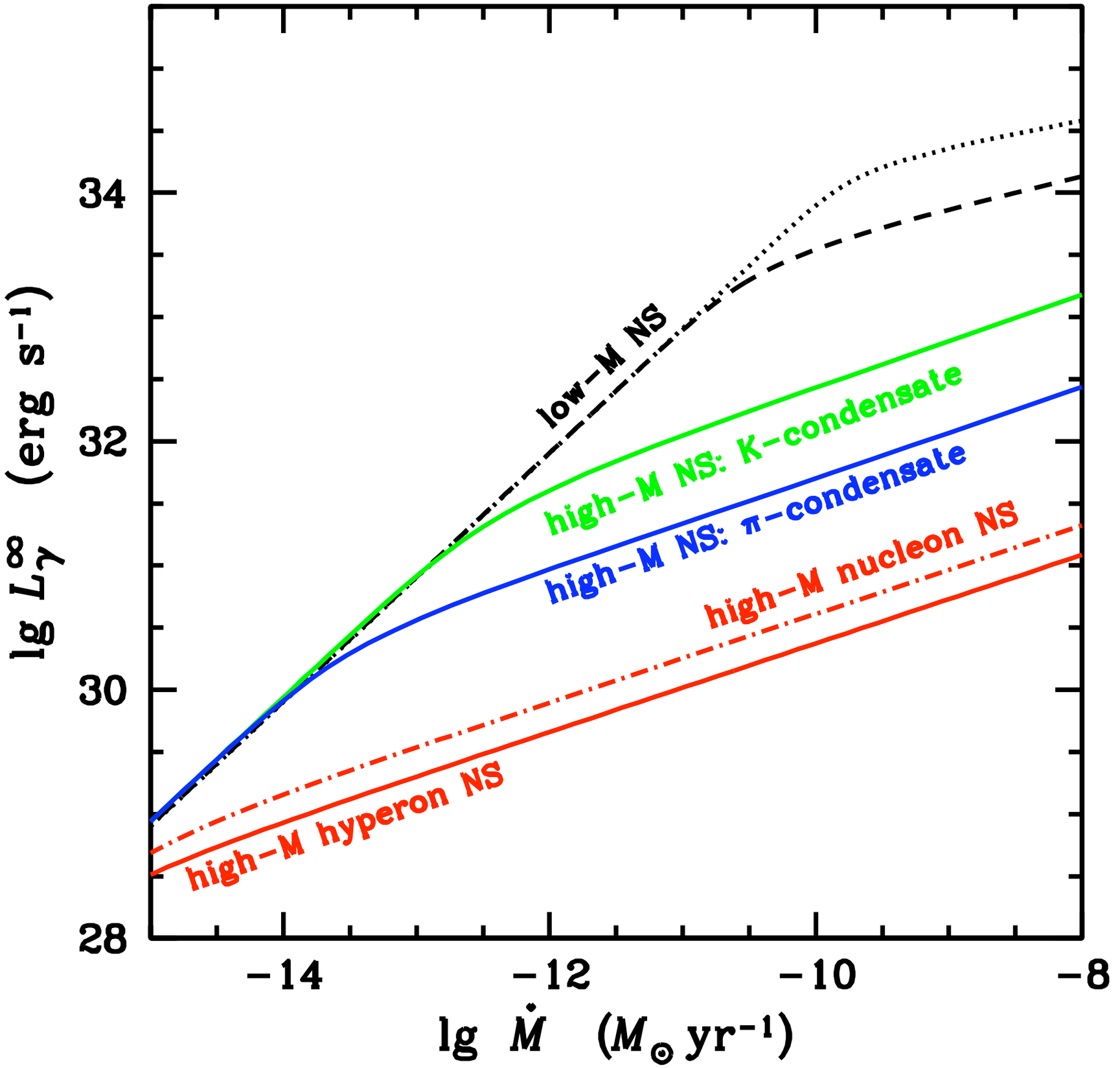
Quark matter $d \longrightarrow ue\bar{\nu}$ $ue \longrightarrow d\nu$

Modified URCA

Nucleon matter $nS \longrightarrow Spe\bar{\nu}$ $Spe \longrightarrow Sn\nu$

etc

Resulting NS temperature/luminosity



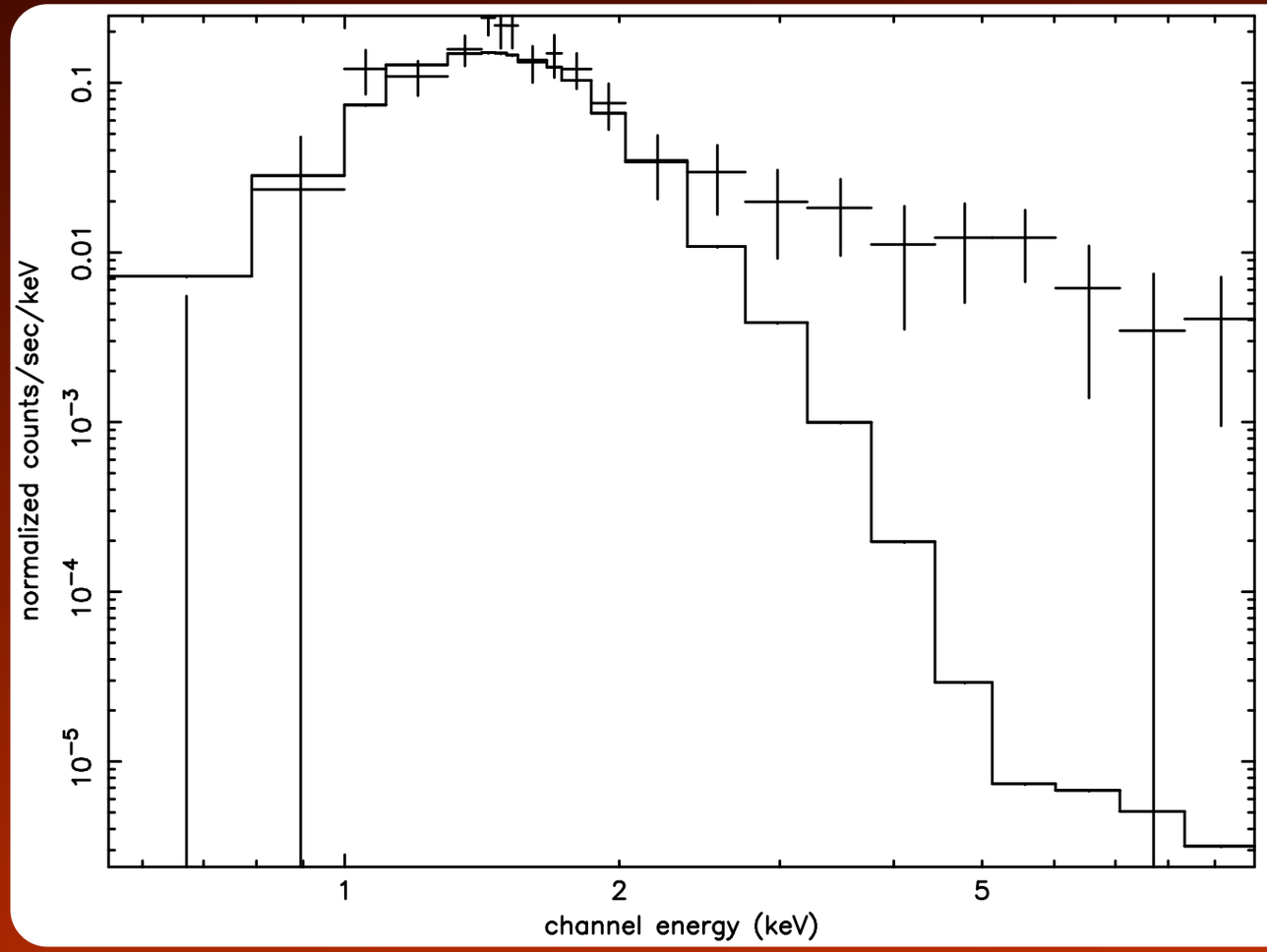
Yakovlev & Pethick 2004

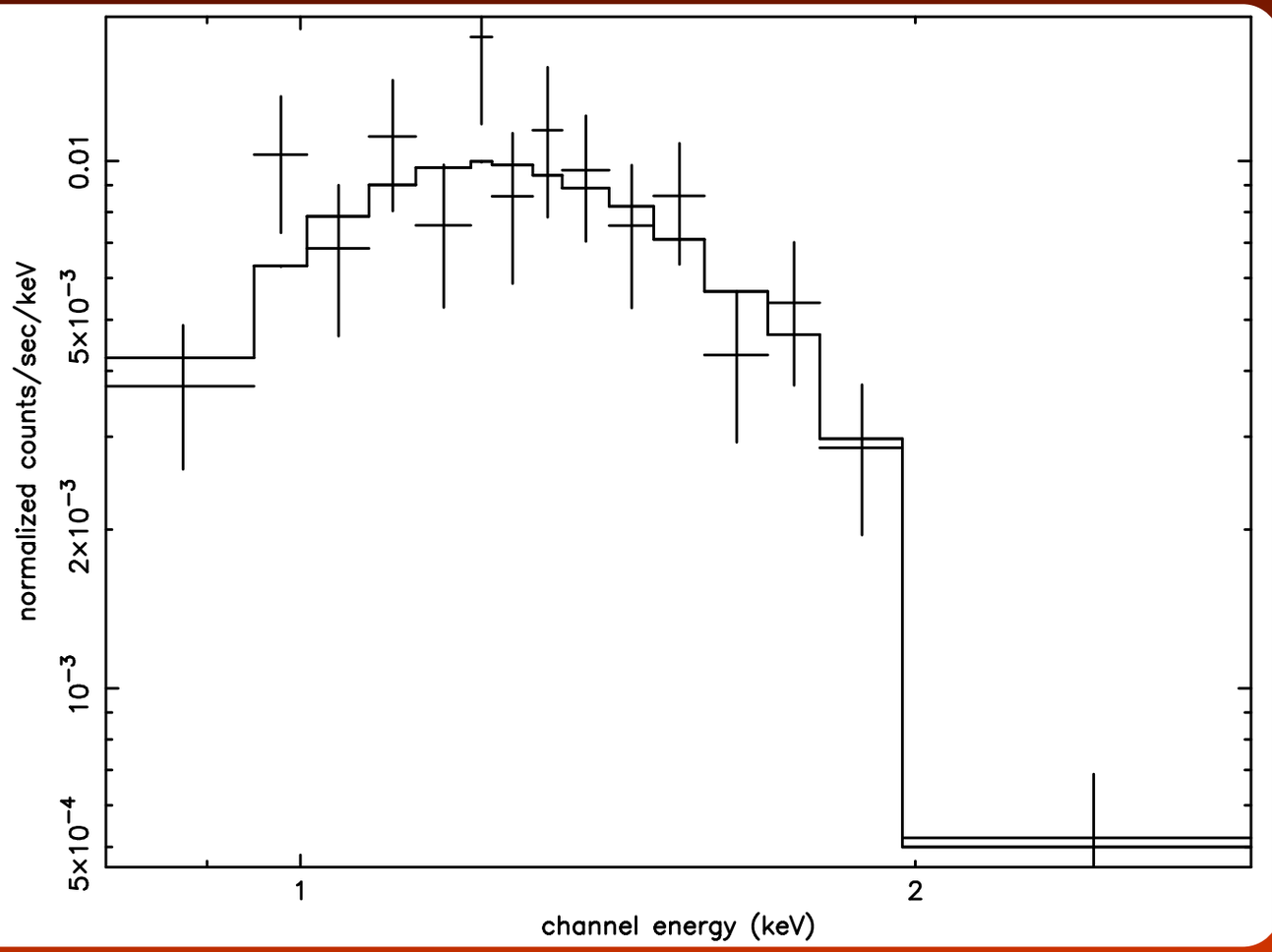
XMM-Newton and Chandra X-ray observations of quiescent LMXBs:

4U 1608-52

Absorbed NSA fit

IH 1715-321





T~1.26 million K

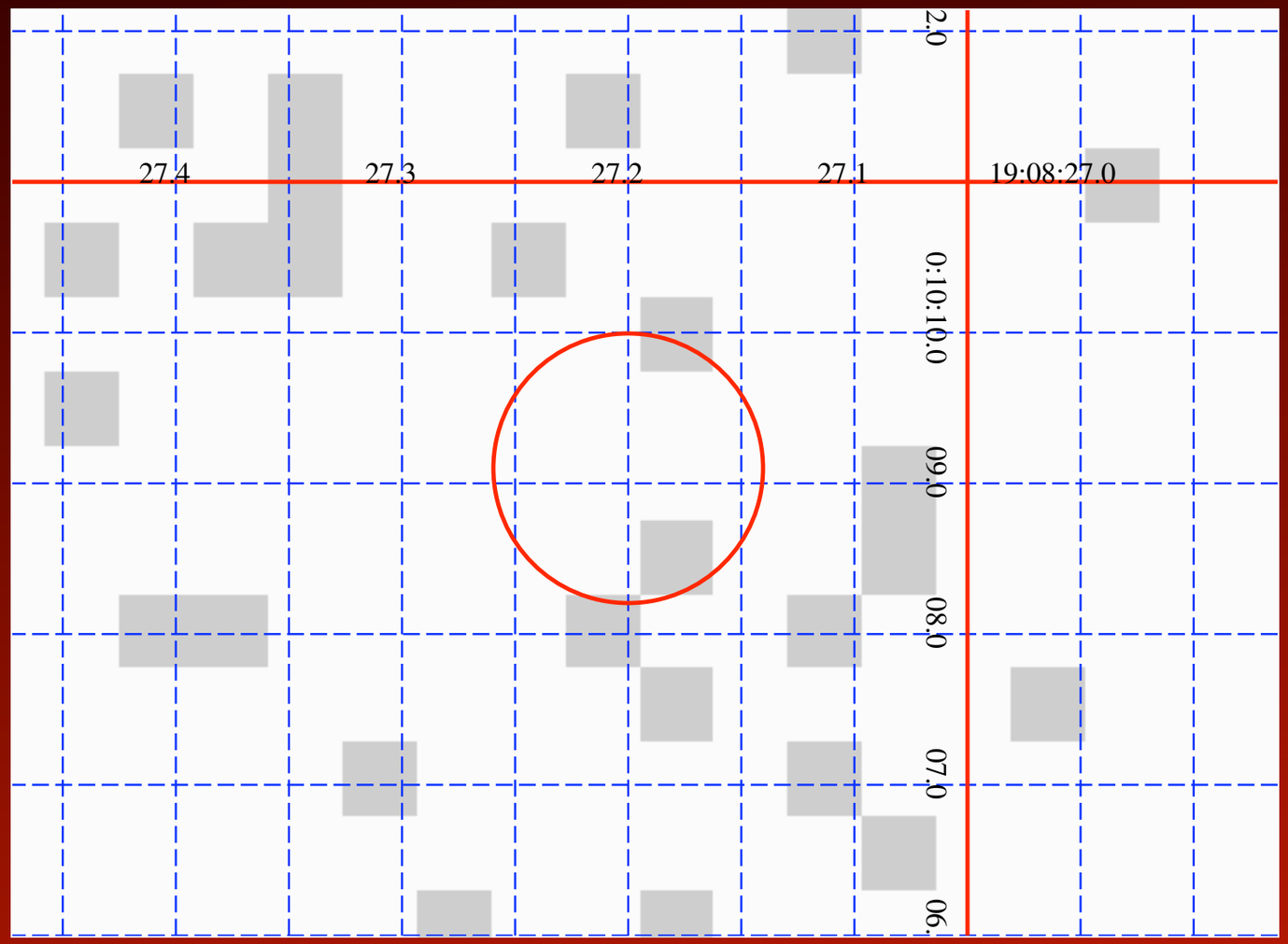
Altamirano et al. in prep.

T~1.2 million K

Jonker, Bassa & Wachter 2007

e.g. Heinke et al. 2003, Webb & Barret 2007

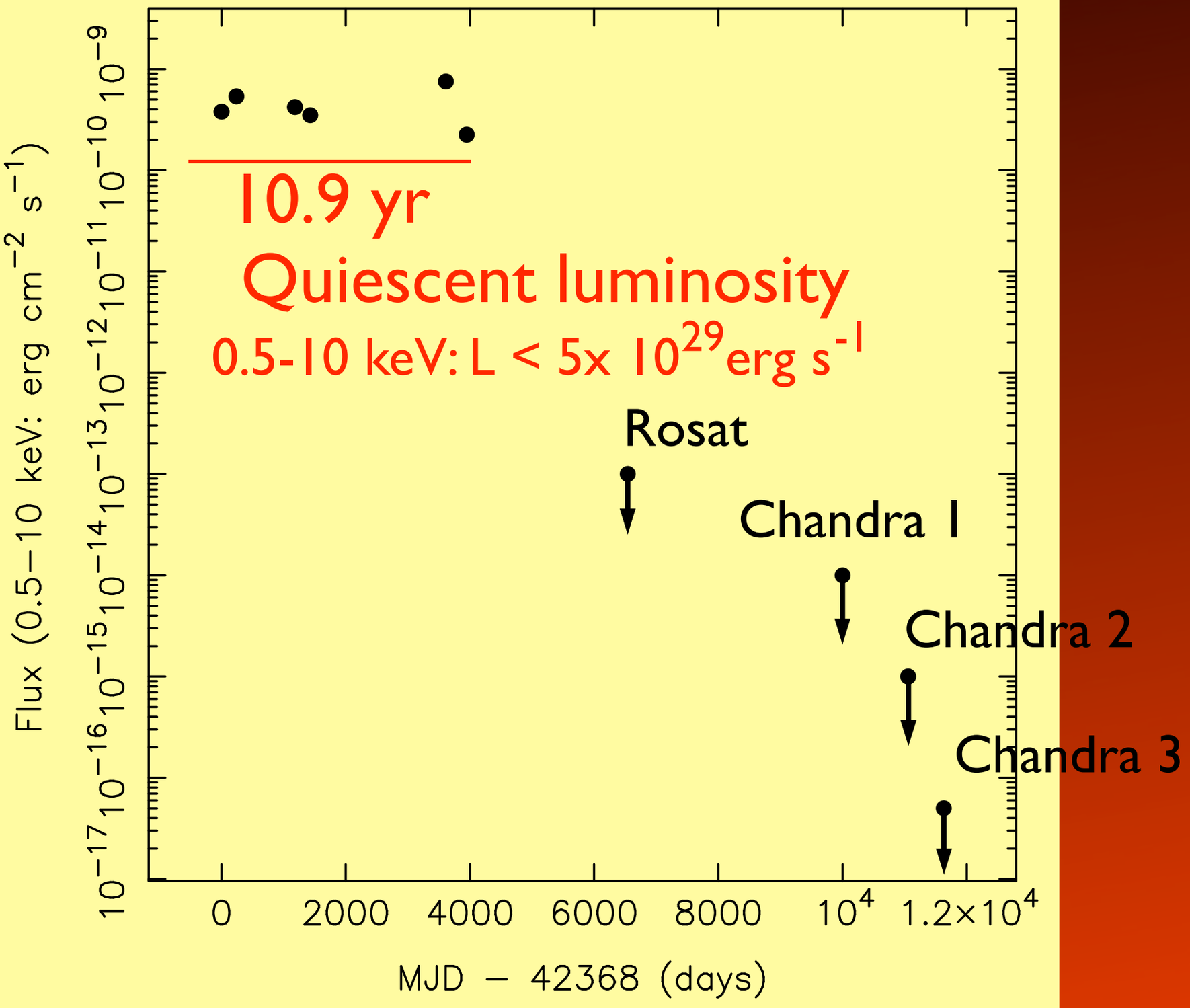
An extremely weak NS transient: 1H 1905+000



300 ksec Chandra observation:
source 0.5-10 keV luminosity <2E30 erg/s

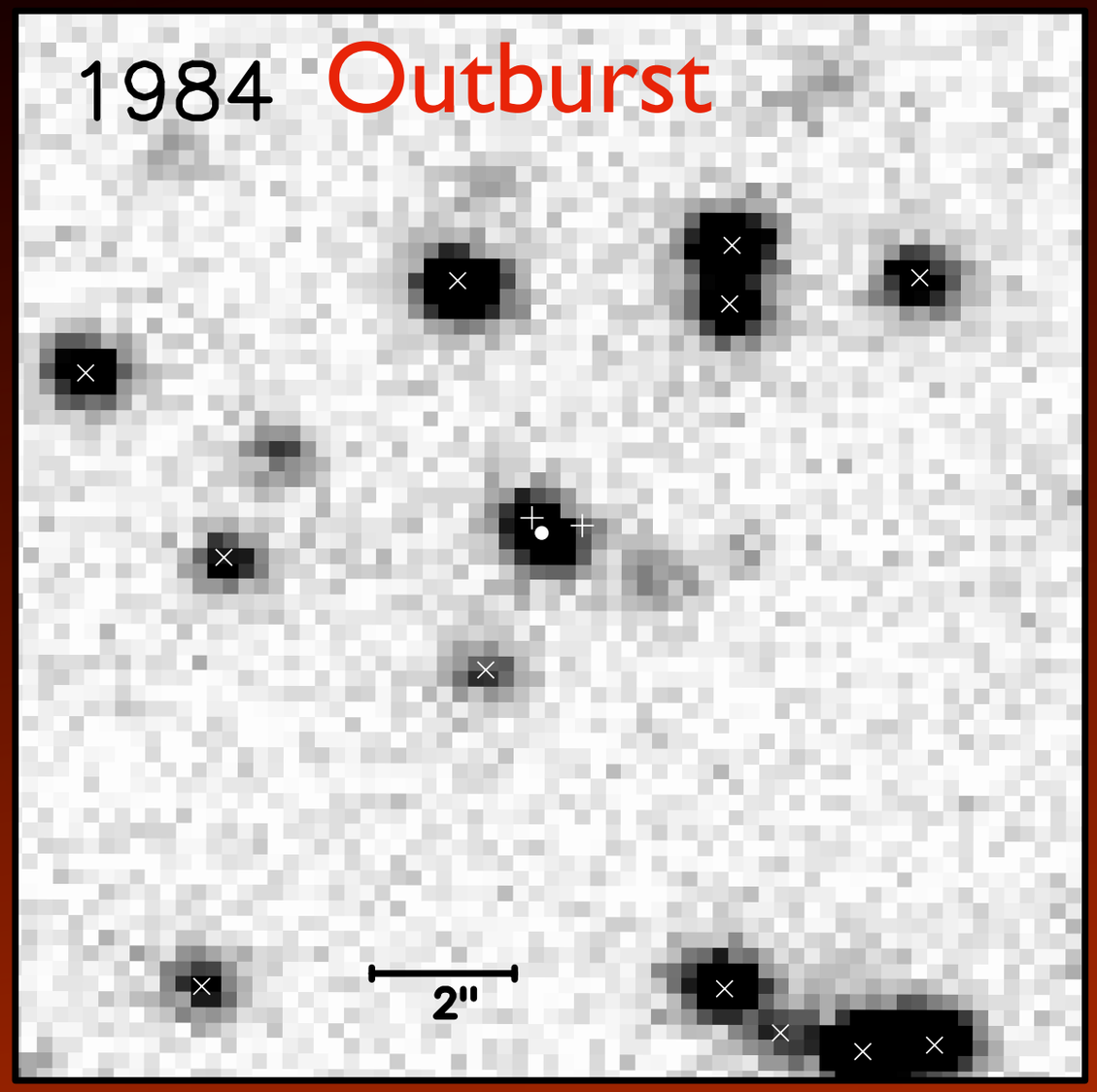
Ariel-5, SAS-3, HEAO-1, Einstein, EXOSAT,

Persistent $L \sim 4 \times 10^{36}$ erg s^{-1}

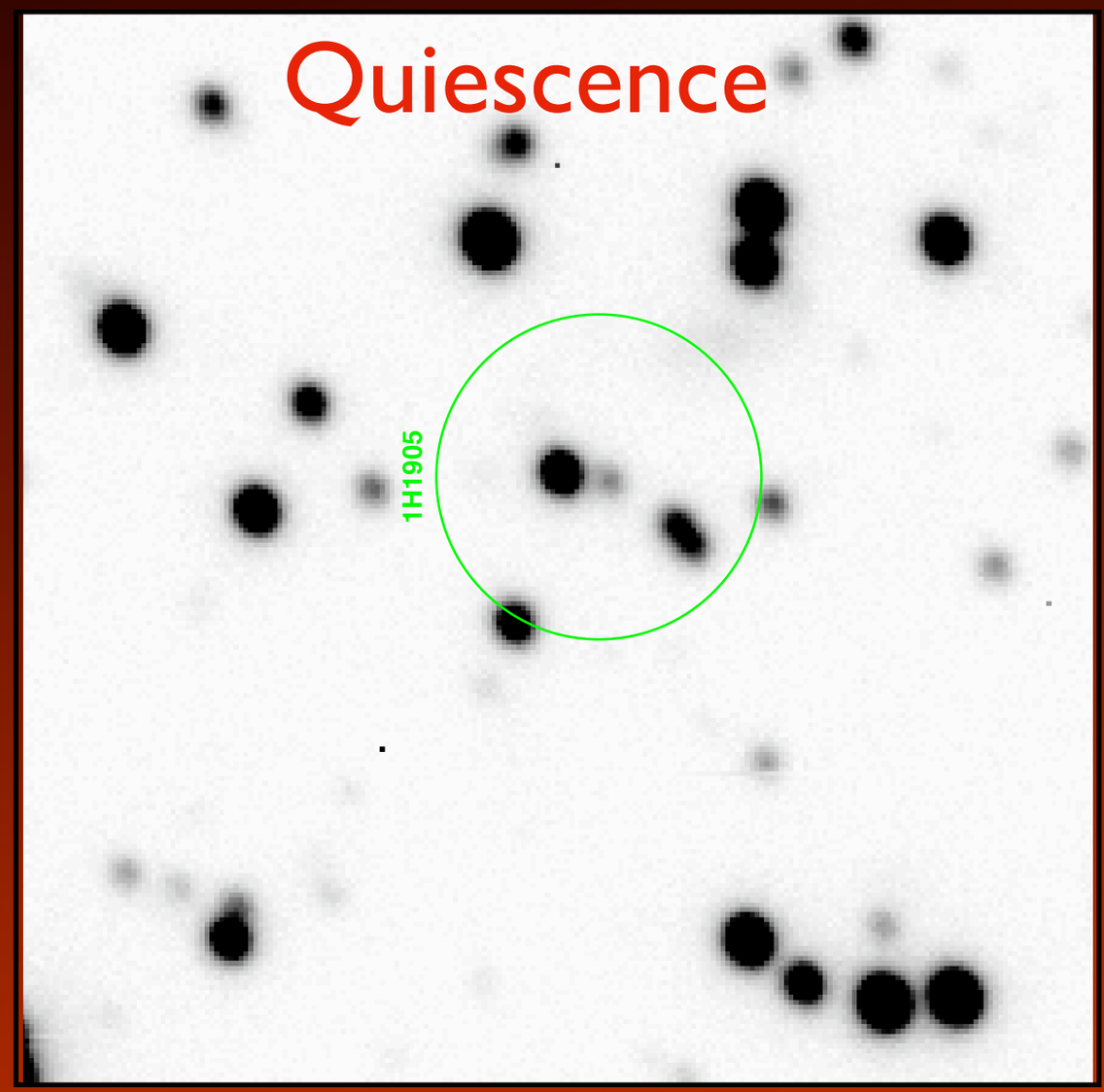


Jonker et al. 2006 & 2007

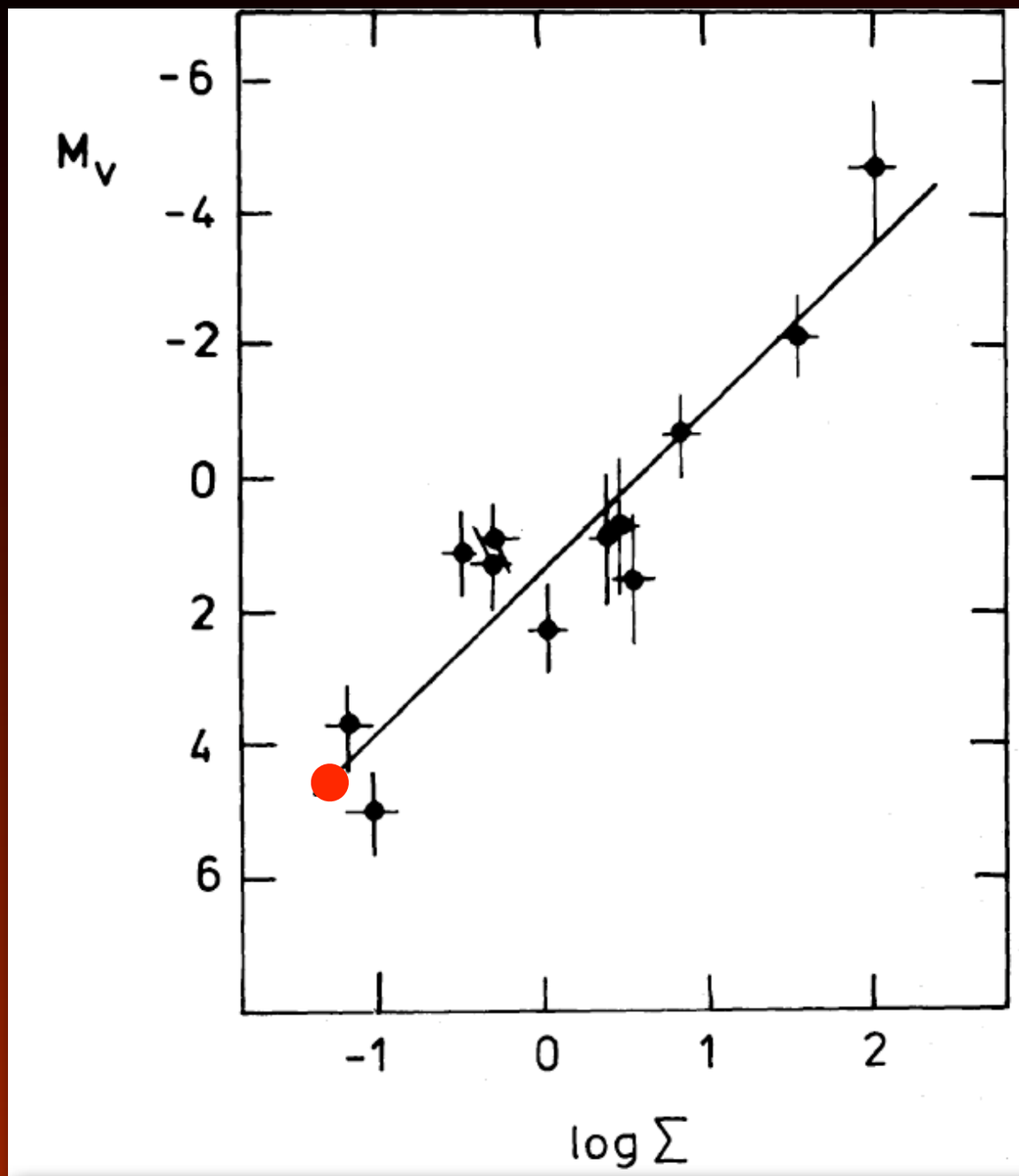
Optical observations of 1H1905+000



1984 CFHT V band outburst image
Chevalier & Ilovaisky 1990
figure from Jonker et al. 2006



2006 Magellan MAGic
seeing 0.4", no CP i'<25.3
Jonker et al. 2007, ApJL, accepted
tomorrow on Astro-ph!



van Paradijs & McClintock 1994

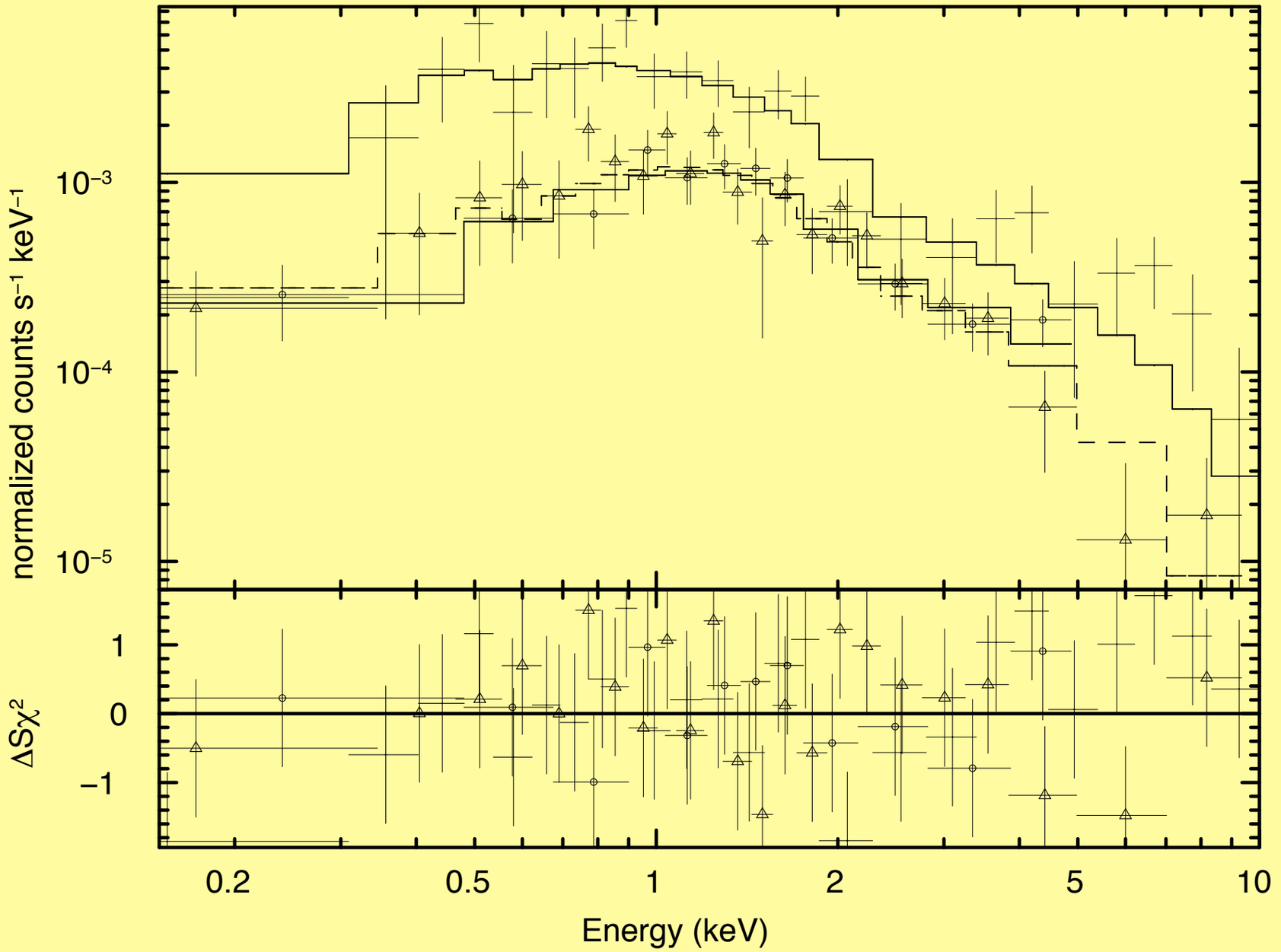
$$\Sigma = (\frac{L_X}{L_{Edd}})^{1/2}(P_{orb}/1hr)^{2/3}$$

Porb 1H1905+000 ~ 20-30 min

From binary evolution models $\dot{M} \gtrsim 10^{-12 \text{ or } -13} M_\odot/yr$

cf. Deloye & Bildsten 2003

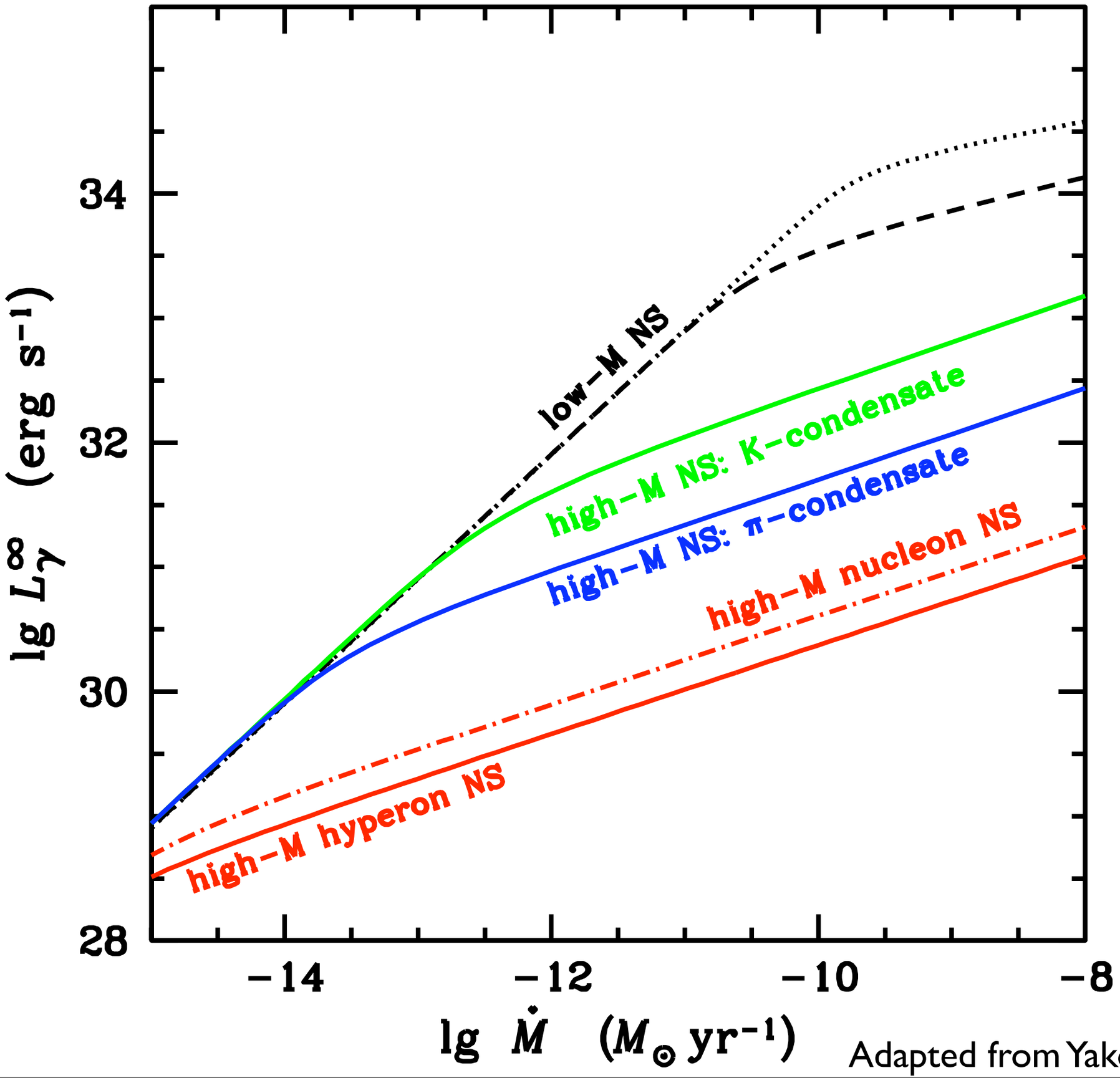
SAX J1808.4-3658



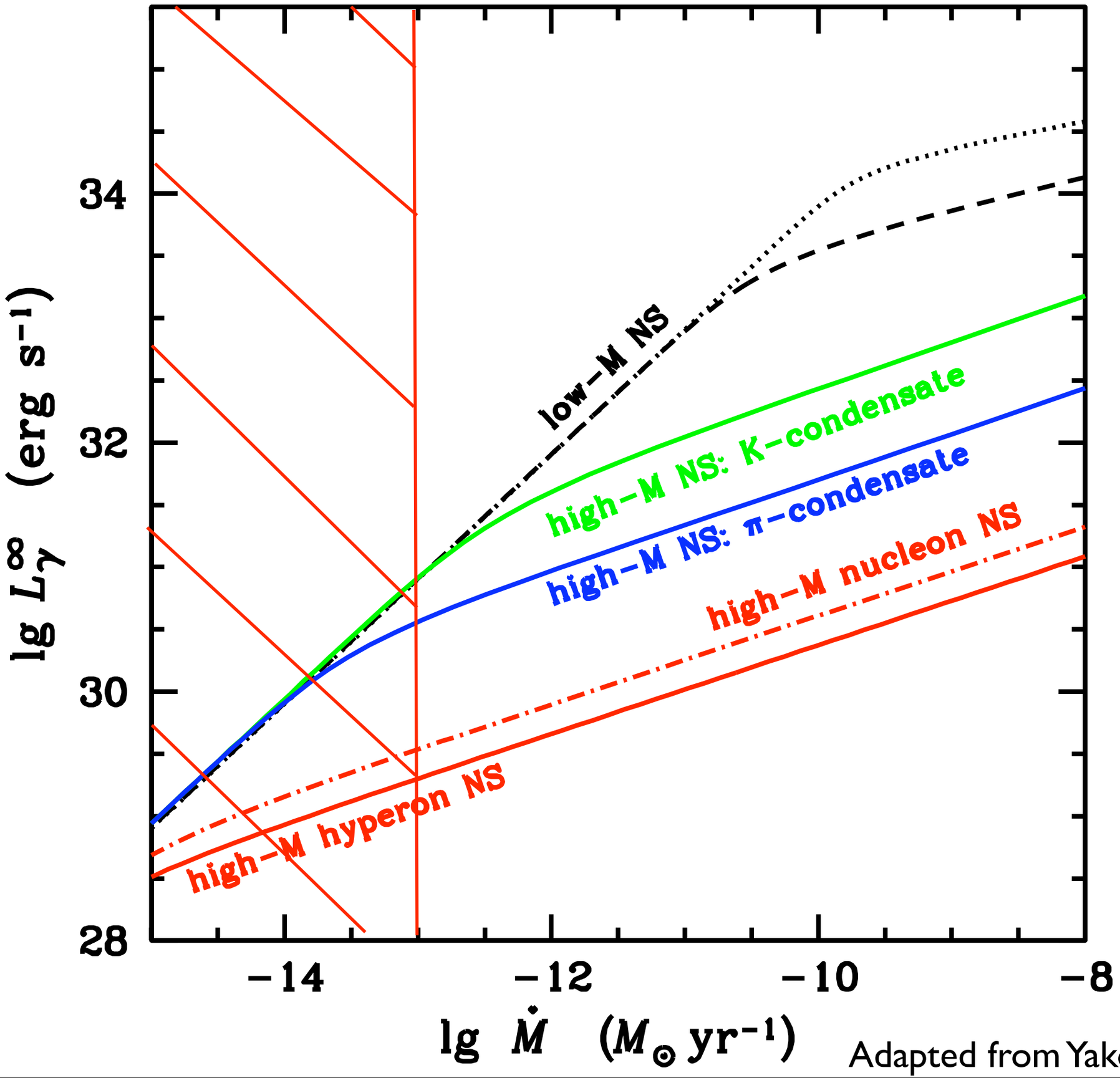
XMM-Newton: $L_X < 1.1 \times 10^{31}$ erg s^{-1}

mass accretion rate $\sim 10^{-11} M_\odot$ yr^{-1}

Heinke, Jonker, Wijnands & Taam 2007



Adapted from Yakovlev & Pethick 2004



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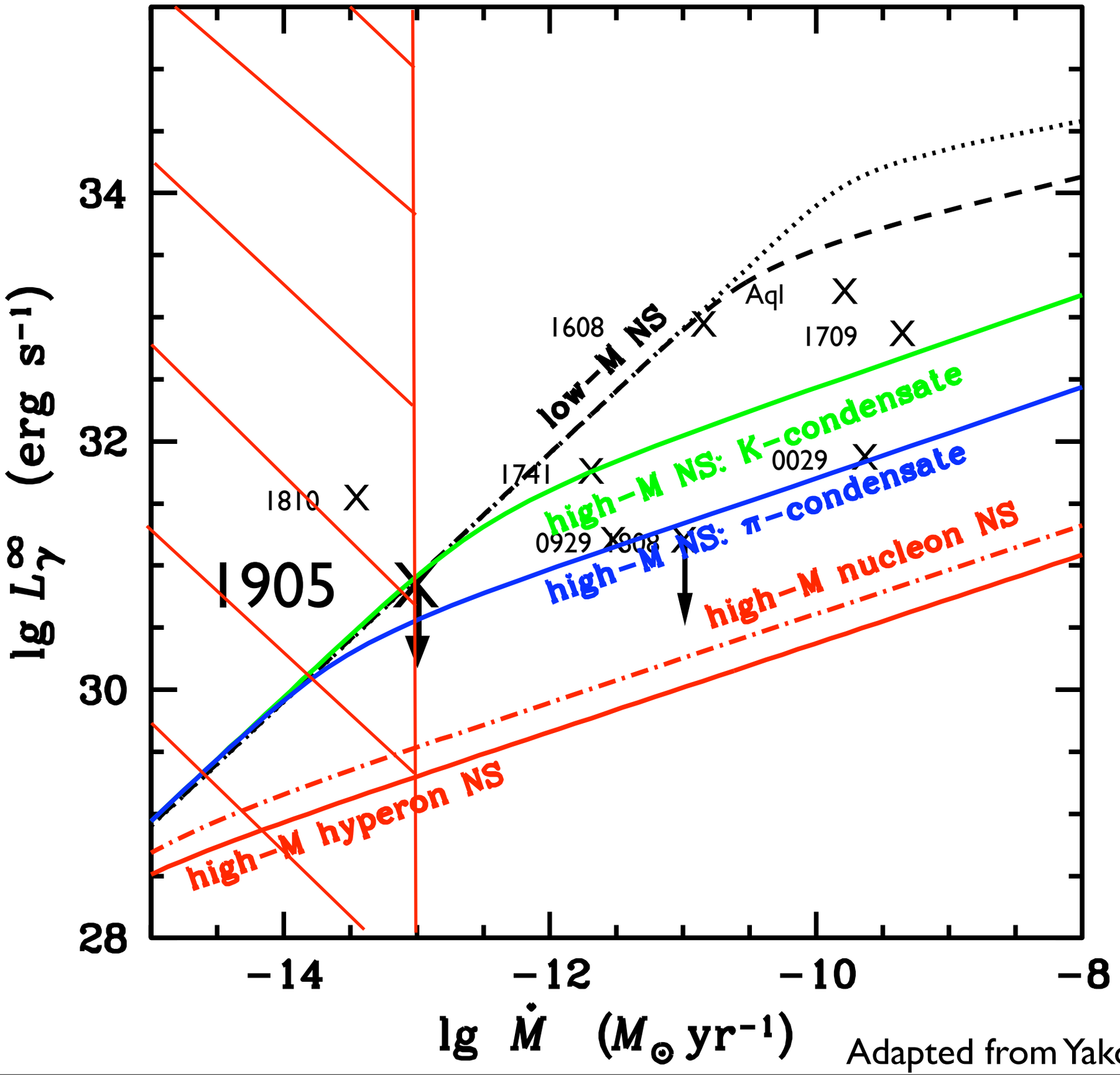

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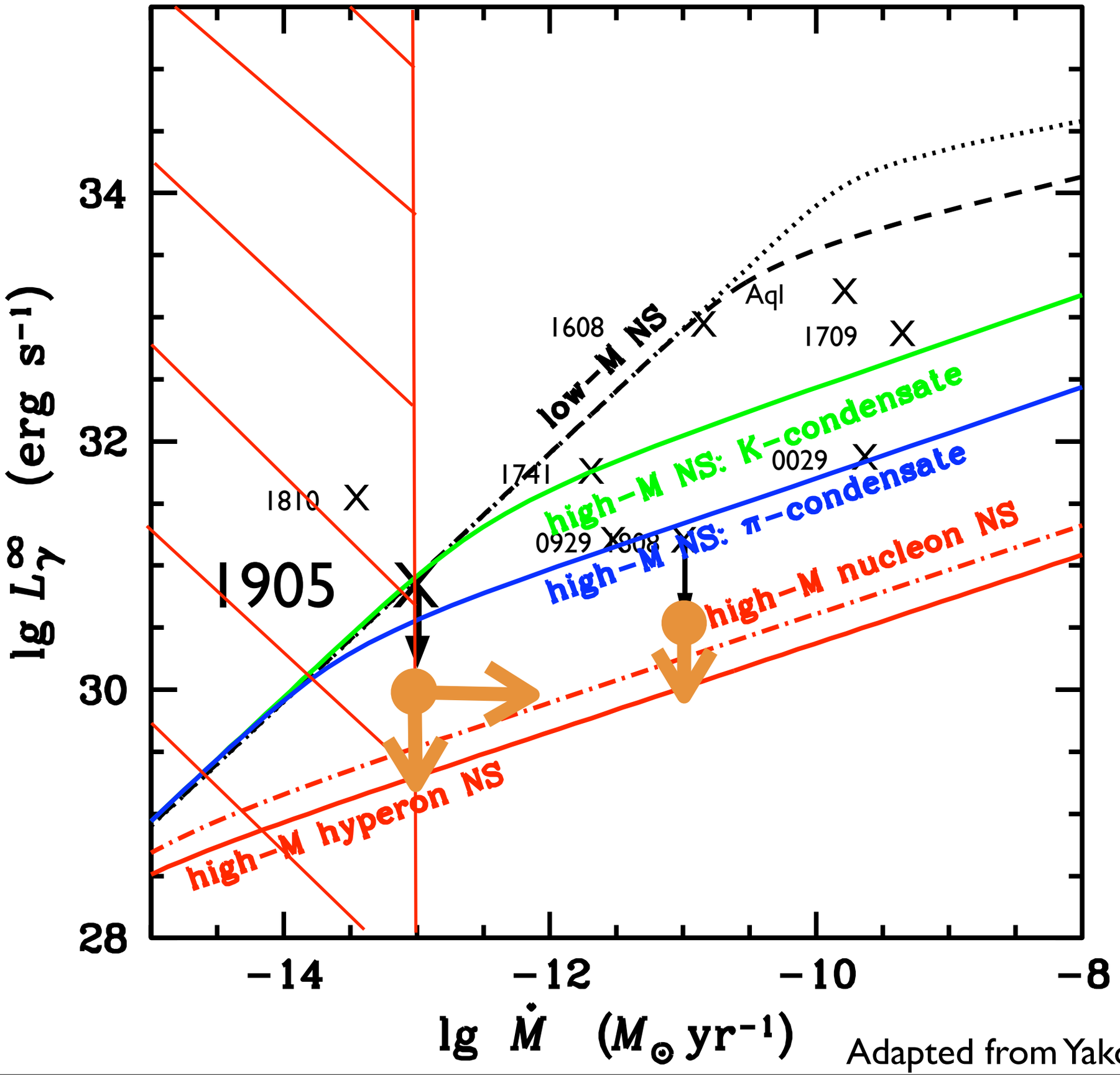
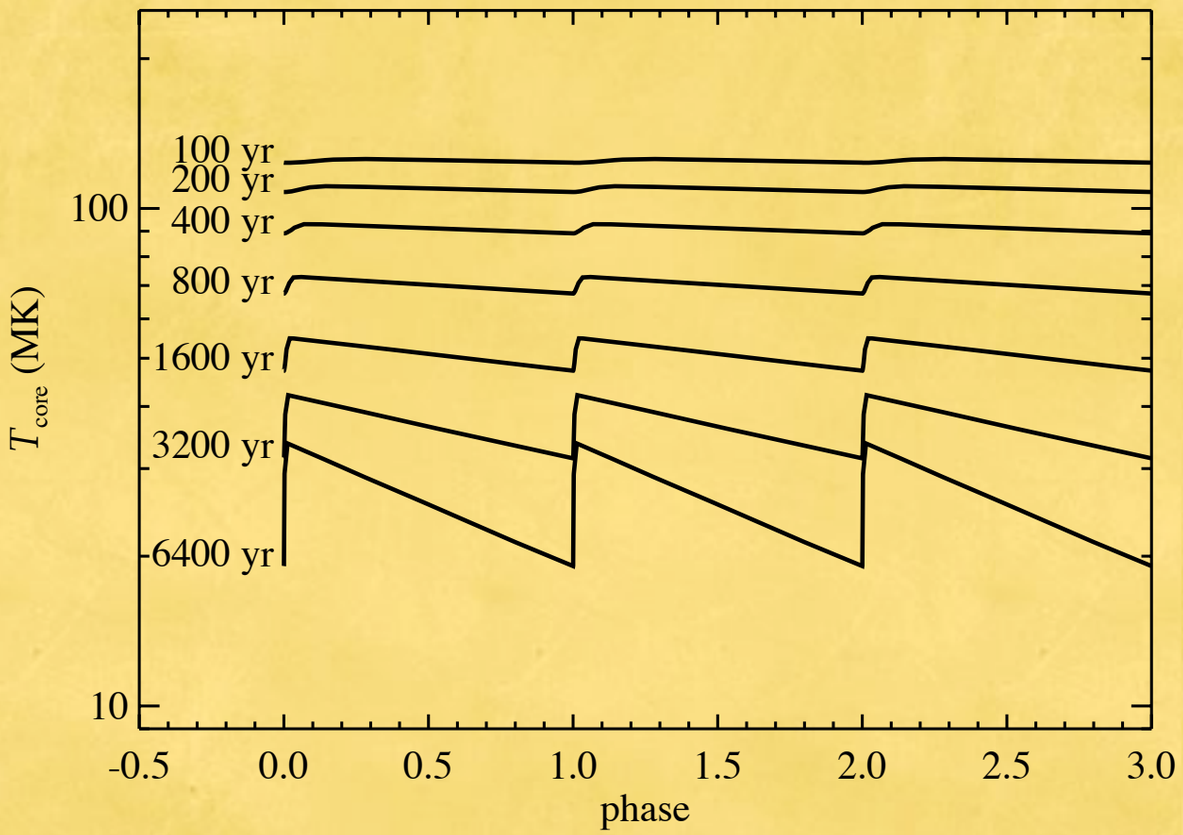


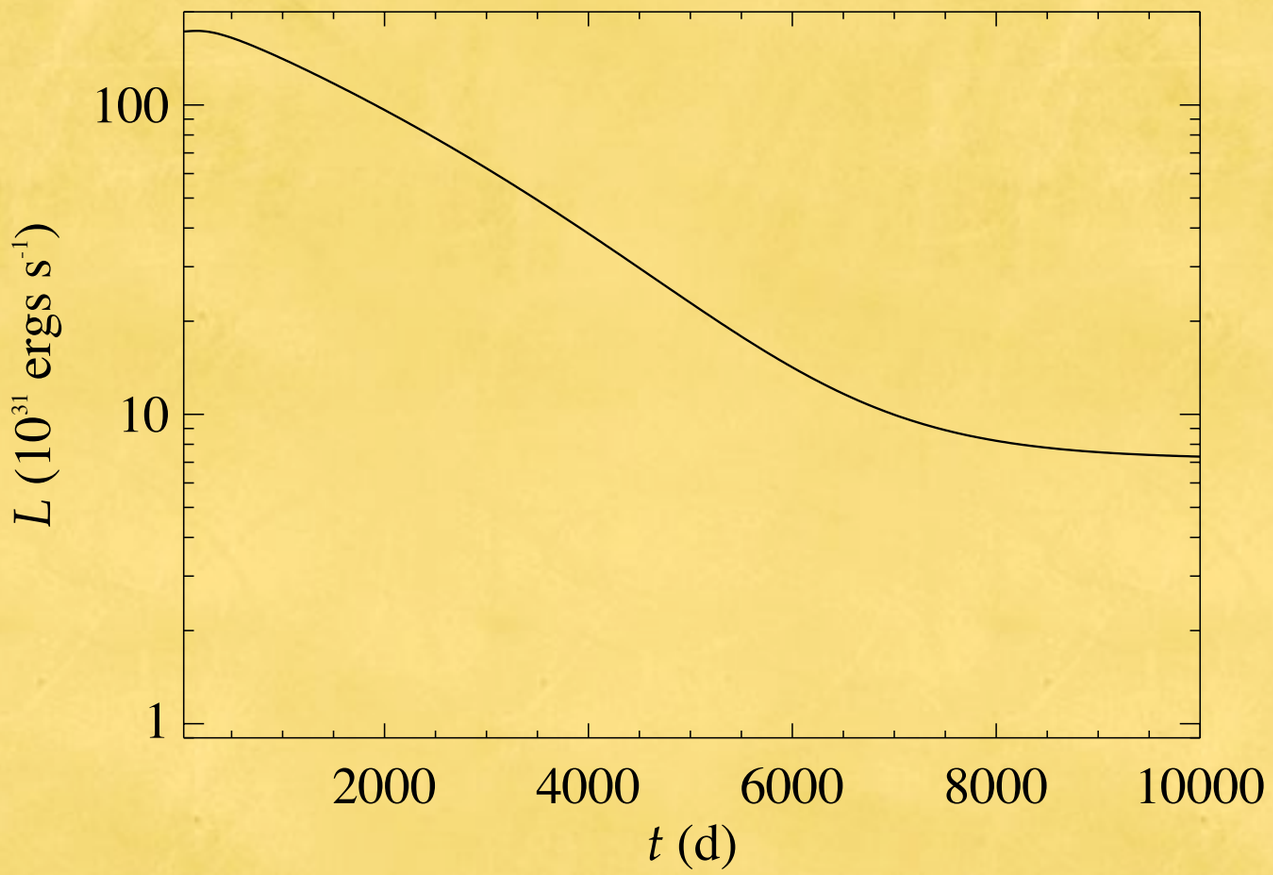
Adapted from Yakovlev & Pethick 2004

Modelling 1905 from Ed Brown

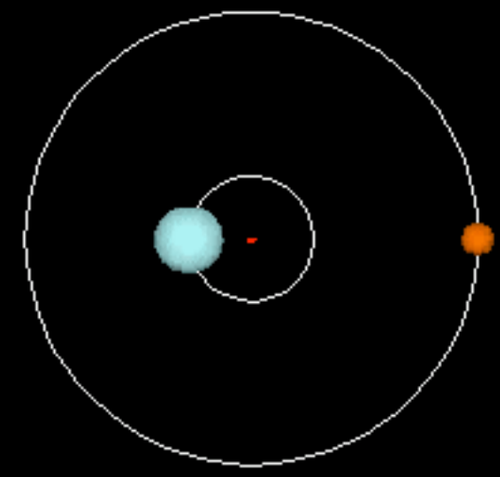
An extreme recurrence time?

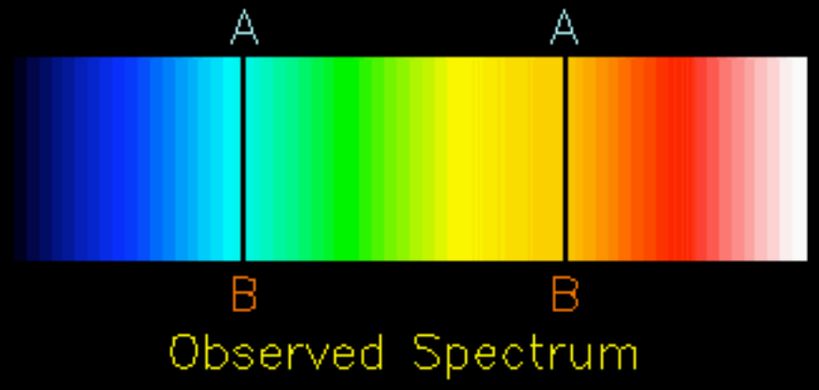


Using Modified URCA only



Quiescent low-mass X-ray binaries





study the NS via the motion of the small companion star

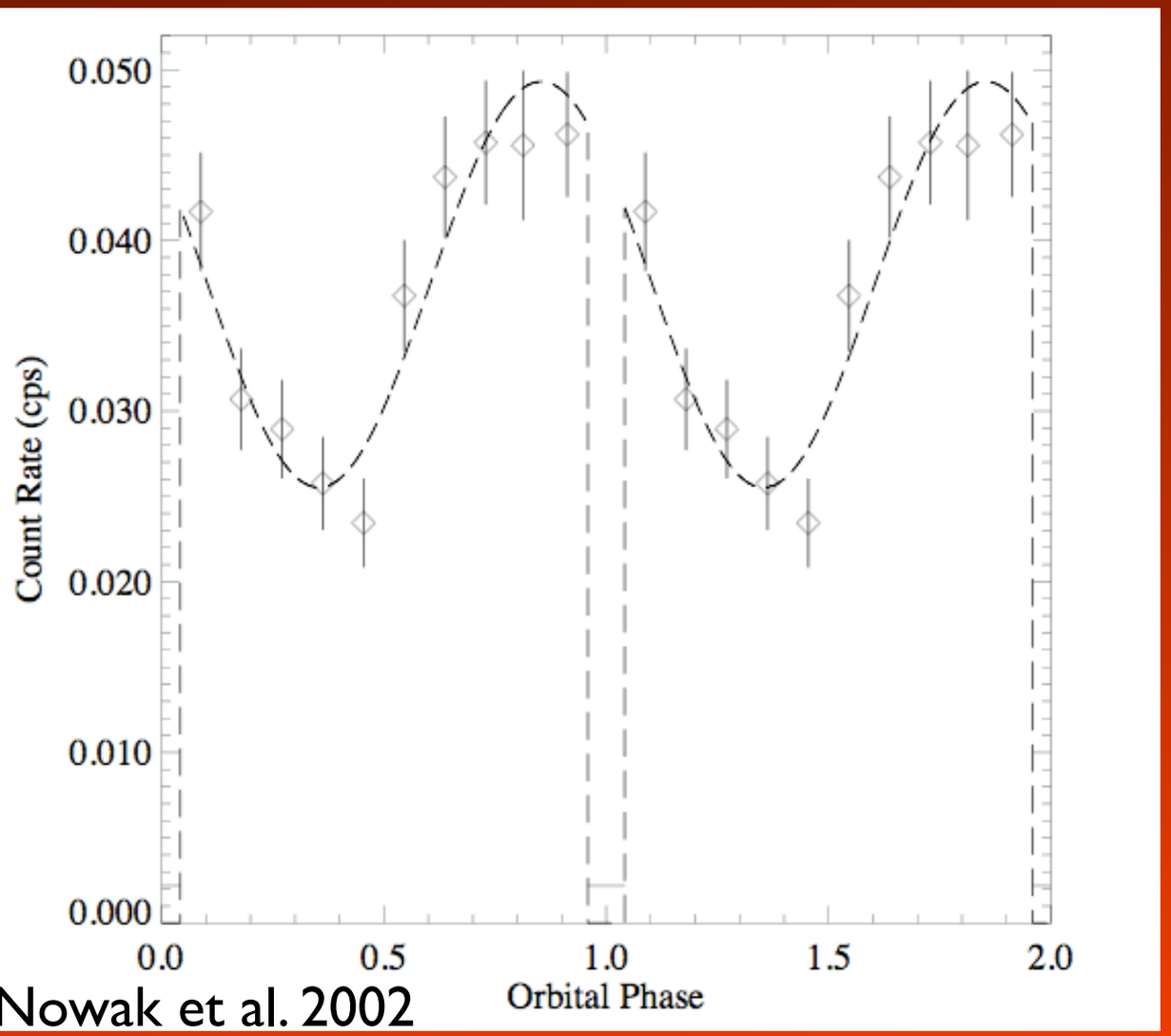
Determine inclination from eclipses in the X-ray light curve
Optical (VLT + X-shooter) + X-ray XMM or Chandra

$$\frac{P_{orb}K^3}{2\pi G} = \frac{M_{NS}\,sin^3 i}{(1+q)^2}$$

$$\frac{v\ sin\ i}{K} = 0.46[(1+q)^2 q]^{1/3}$$

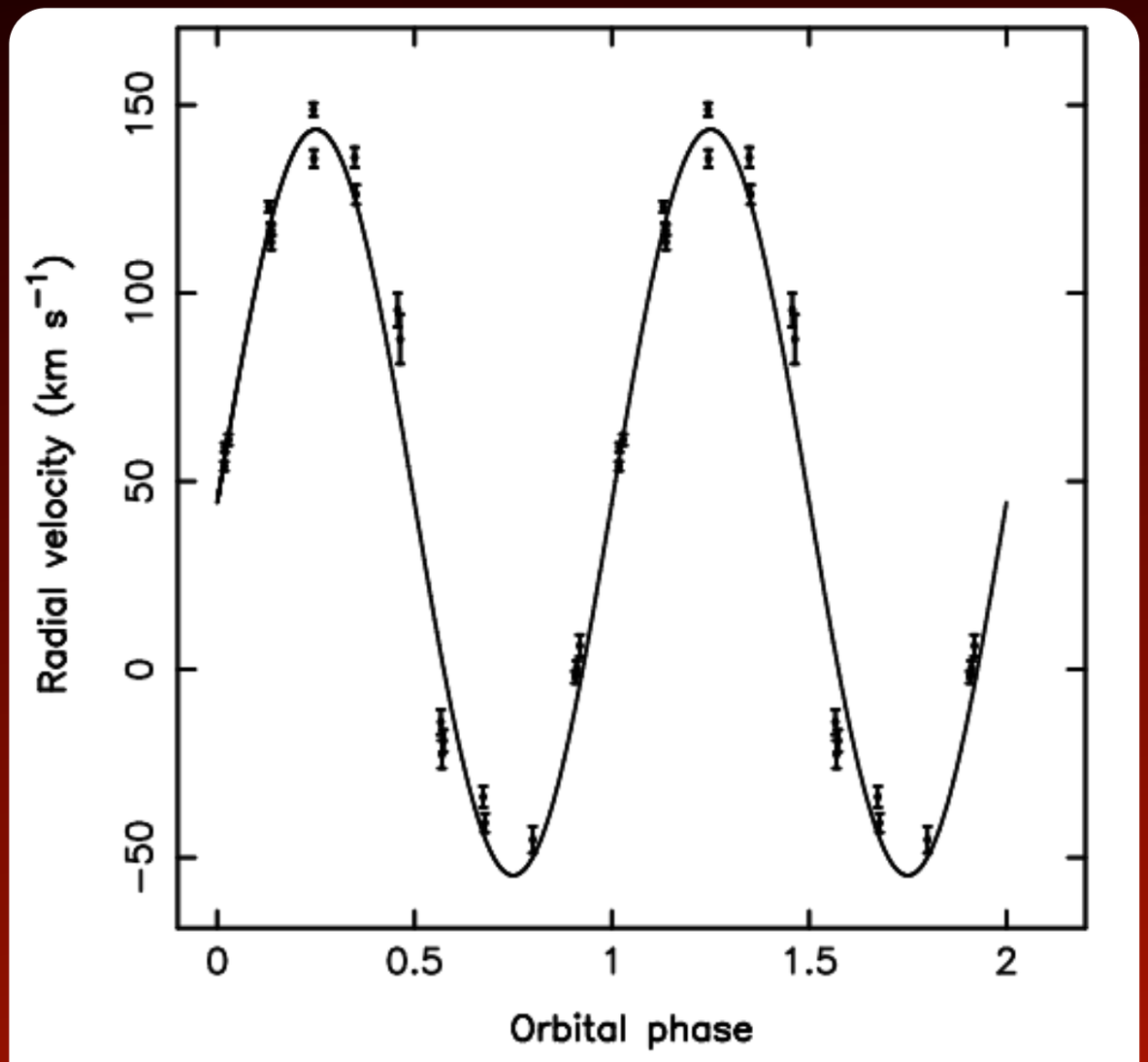
$$\Delta\phi^2 = \left(\frac{0.49\,q^{2/3}}{0.6\,q^{2/3}+\ln(1+q^{1/3})}\right)^2 - \left(\frac{\cos i}{1+q}\right)^2$$

Horne 1985



Nowak et al. 2002

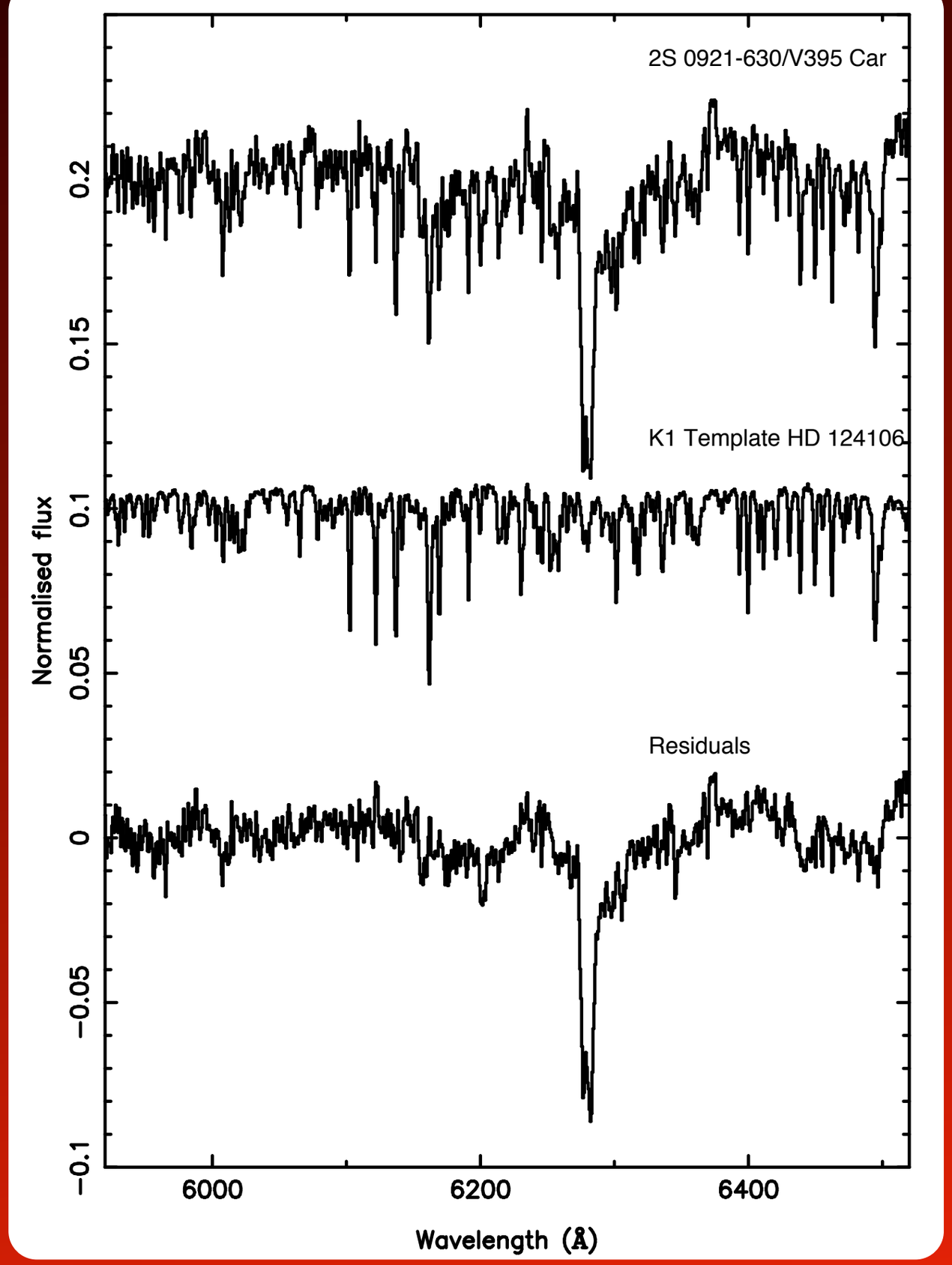
VLT optical spectroscopic observations



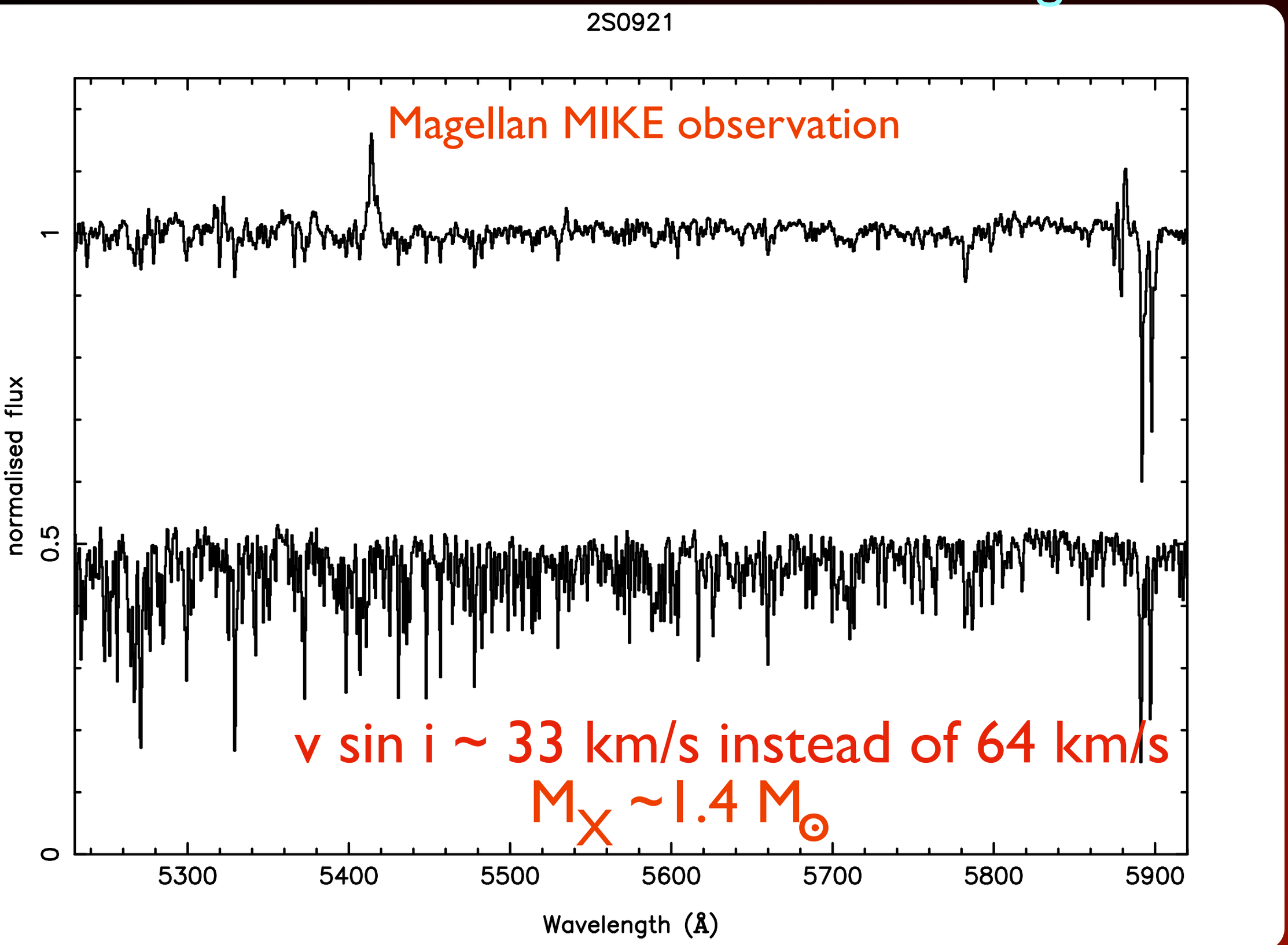
Jonker et al. 2005

v sin i =64 km/s: Shahbaz et al. 1999

$2<M_X<3\ M_\odot$



Measure rotational line broadening



Steeghs & Jonker in prep.

Currently known eLMXBs in quiescence too faint

Find more eLMXBs

Wang et al. 2000, Muno et al. 2002

Galactic Bulge Survey

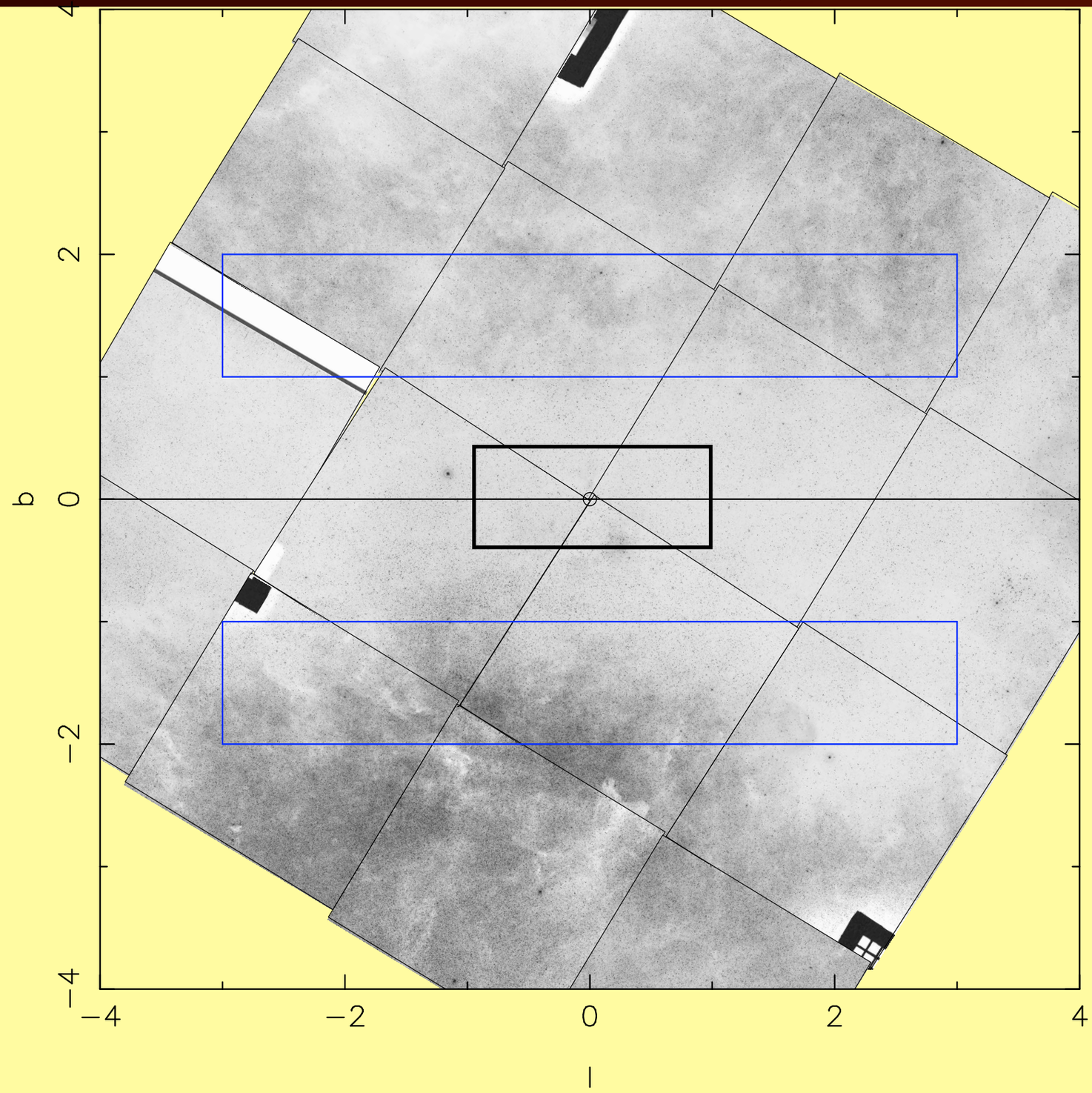
PI: Jonker, Co-I's: Bassa, Maccarone, Nelemans, In 't Zand eo

Predictions:

500 LMXBs
detectable in optical!
≳10 eclipsing qLMXB

500 CVs
detectable in optical!

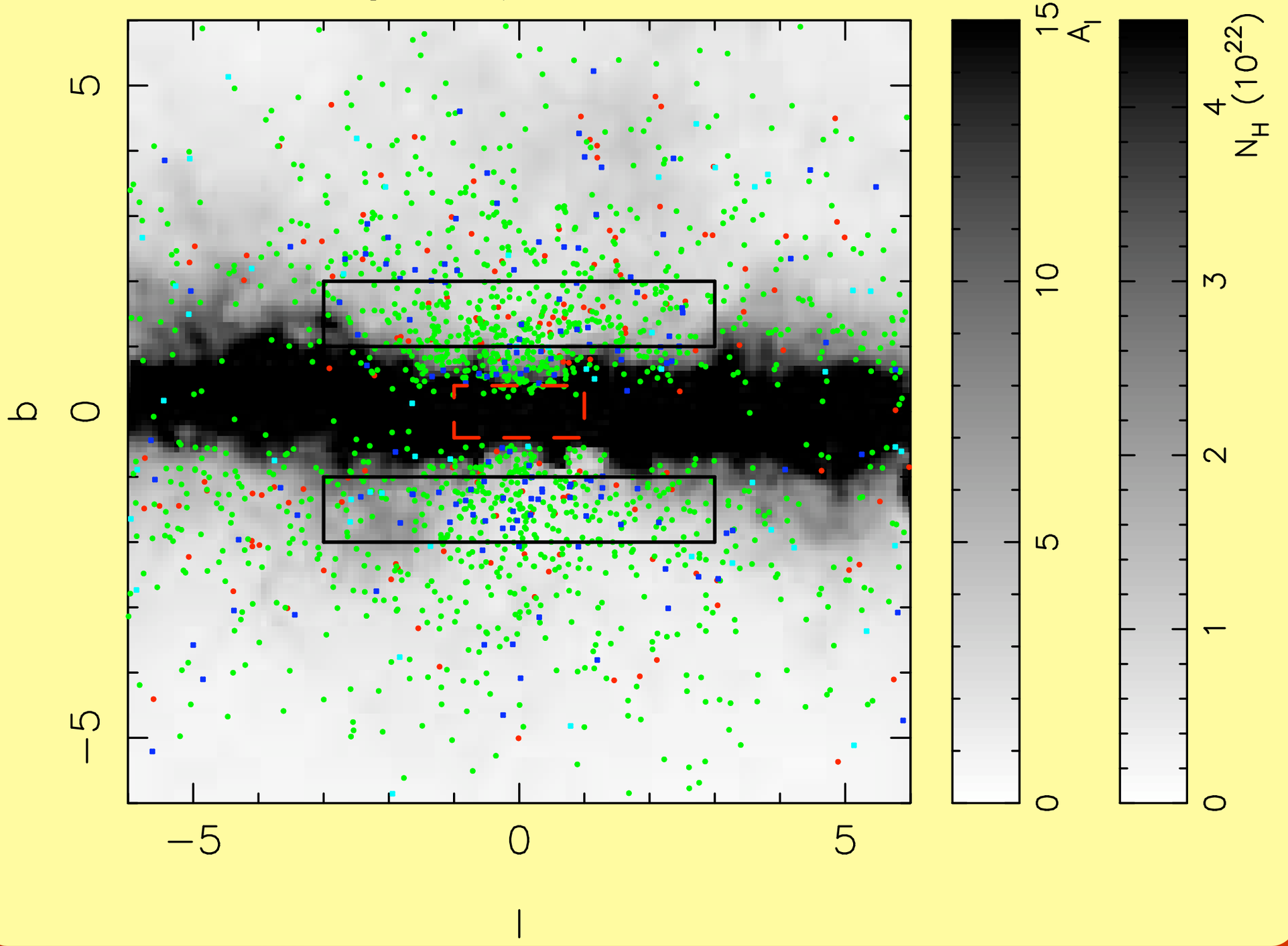
Much more science:
PNe, star clusters...



Search for quiescent, eclipsing LMXBs with the Galactic Bulge Survey or eRosita

Galactic Bulge Survey:

www.sron.nl/~peterj



Optical images in hand: area covered with VISTA, UKIDDS, EGAPS (optical/NIR)

Conclusions:

- From optical mass measurements:
  NS in 2S 0921-630 ~1.4 Msun

- Evidence from cooling NSs such as SAXJ 1808 & 1H 1905 suggest that EoS with condensates can be excluded

- Ideally one would like to have a system where both methods can be used → Galactic Bulge Survey

- Optical spectroscopy together with X-ray light curves of eclipsing systems will provide (virtually) model independent mass measurements and hopefully constrain the neutron star equation of state