X-ray bursts as probes of nuclear physics

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Artwork courtesy T. Piro, Caltech

DISCOVERY OF INTENSE X-RAY BURSTS FROM THE GLOBULAR CLUSTER NGC 6624

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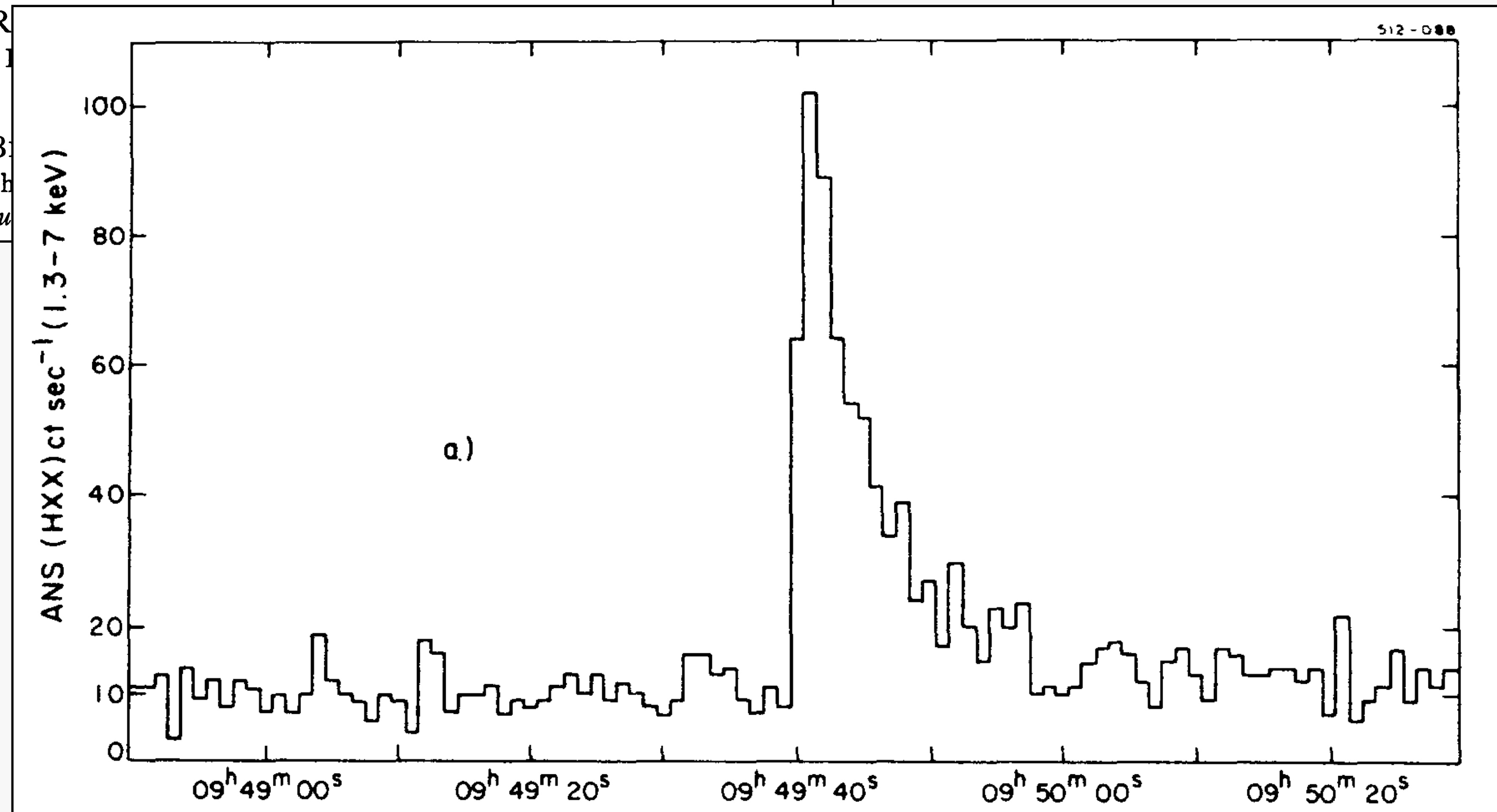
Received 1976 Janu

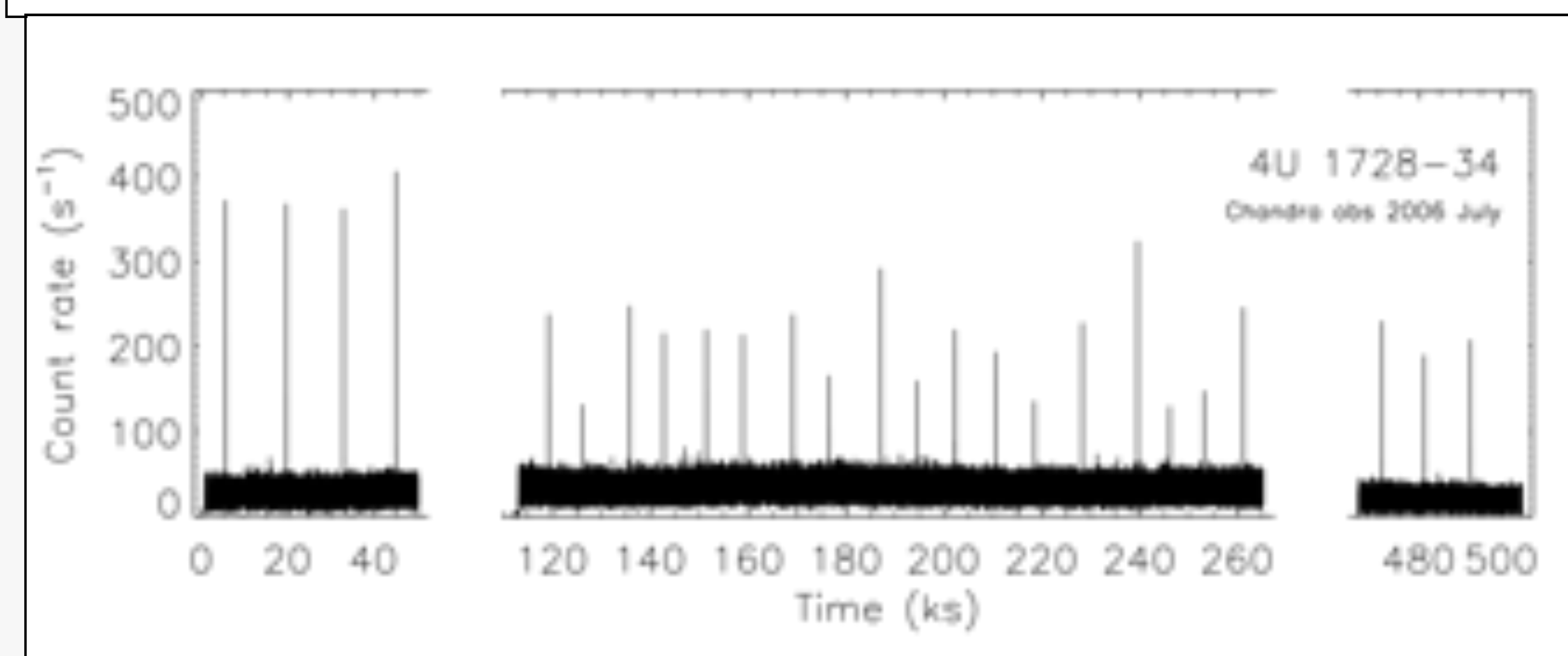


fast rise ~ 1 second

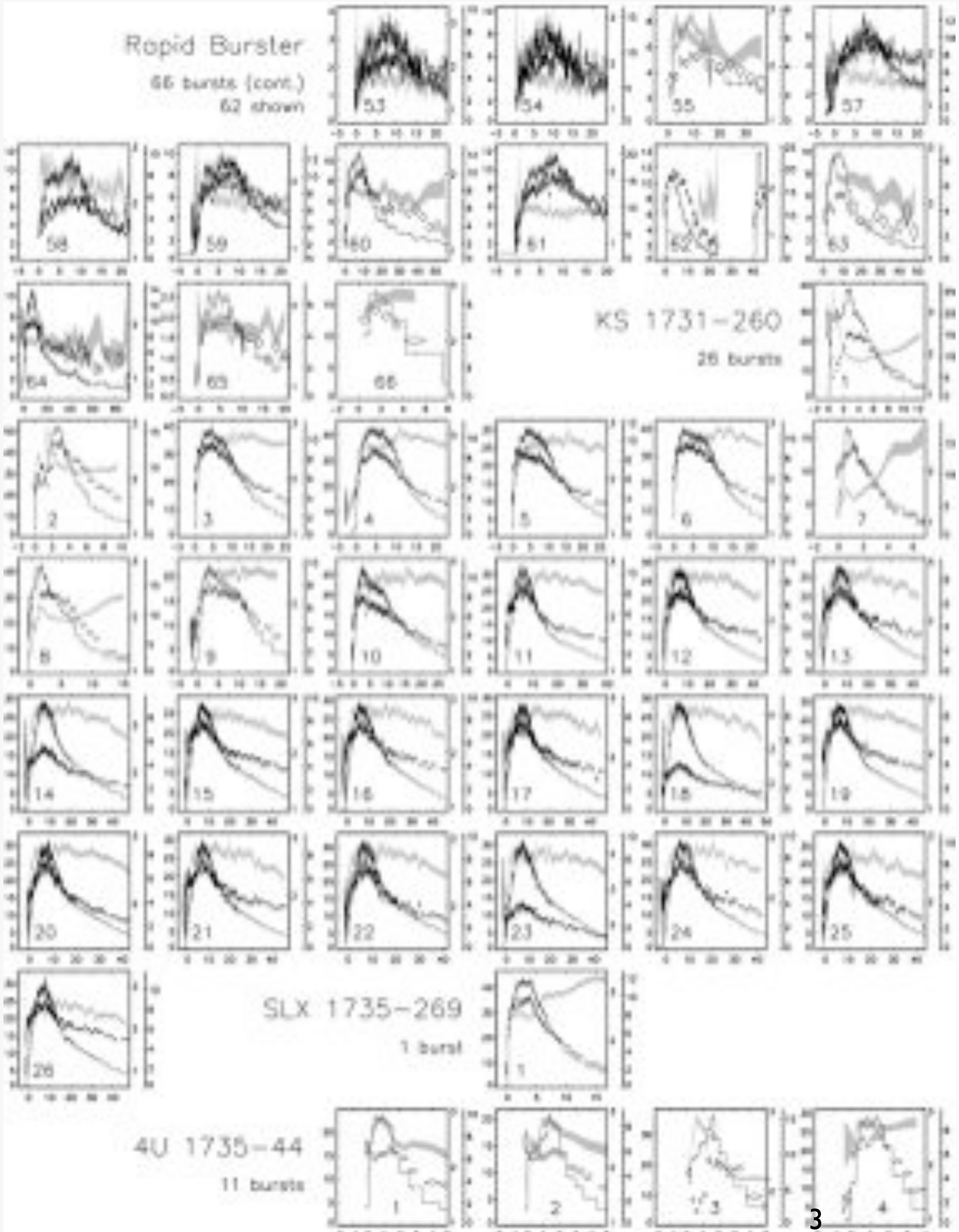
slow, roughly exponential decay ~ 10–100 s

for most bursts, spectral cooling in tail observed

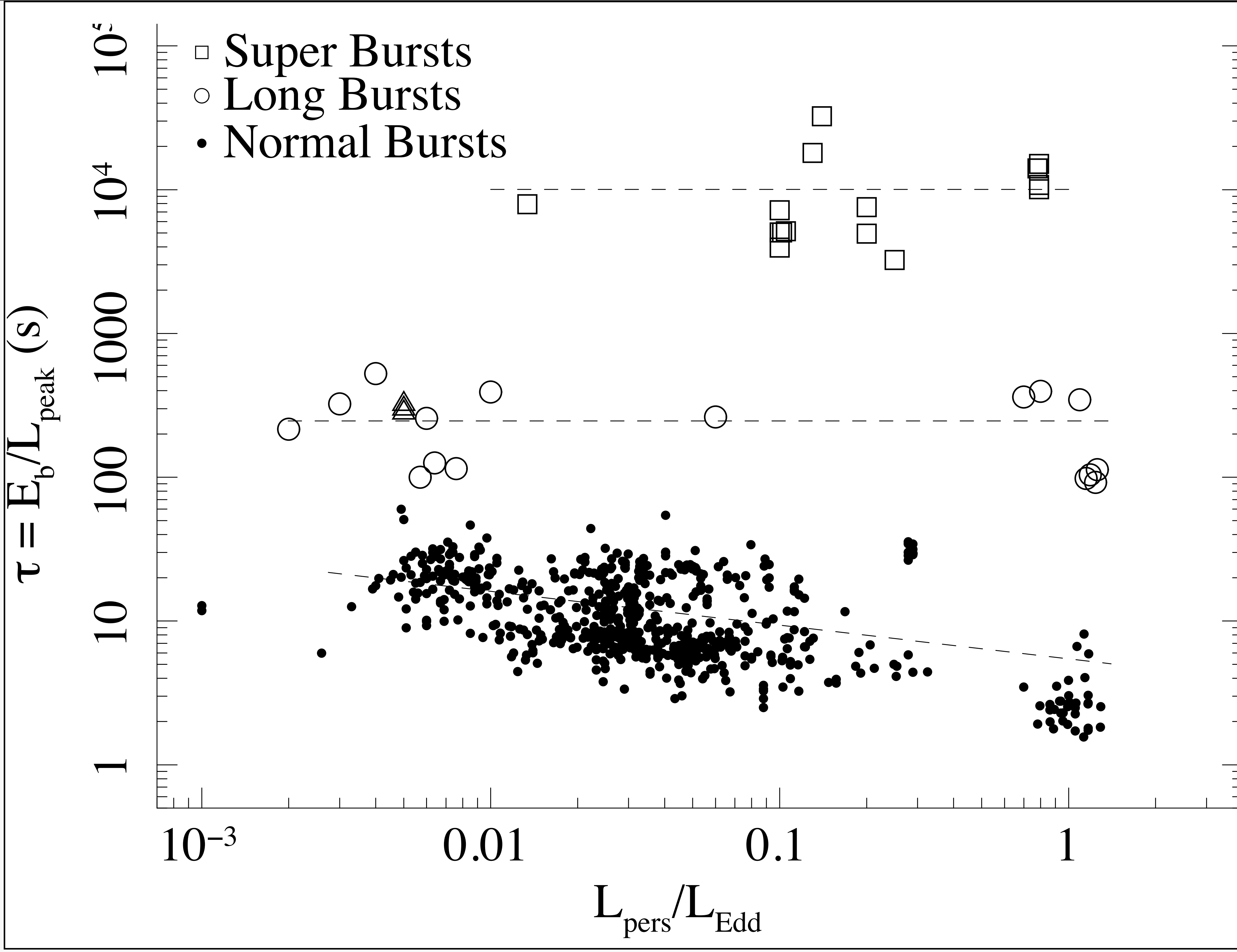
$$\alpha \equiv \frac{\int dt\,\{\text{persistent flux}\}}{\int dt\,\{\text{burst flux}\}} \sim 30\text{–}100$$



Observe trains of bursts from many sources: a diagnostic of the underlying neutron star



Galloway et al. 2008
A sample of 1187 X-ray bursts from 48 sources



Falanga et al. 2008: A diversity of bursting regimes

X-ray bursts as probes of nuclear physics

- Basic scenario
  - Thin-shell instability in accreted envelope
  - Regimes of burning
  - Successes and failures of models
- Probing the physics of dense matter
  - Mass and radius constraints from X-ray bursts
  - Mass and radius constraints from quiescent transients
  - Successes and challenges for more precise measurements
- Concluding remarks

Thin-shell instability

Hansen & van Horn Fujimoto et al., many others; see also Narayan & Heyl, Cooper & Narayan

For a thin shell, thermal instability develops where

$$\left.\frac{\partial \ln \varepsilon_{nuc}}{\partial T}\right|_P > \left.\frac{\partial \ln \varepsilon_{cool}}{\partial T}\right|_P ,$$

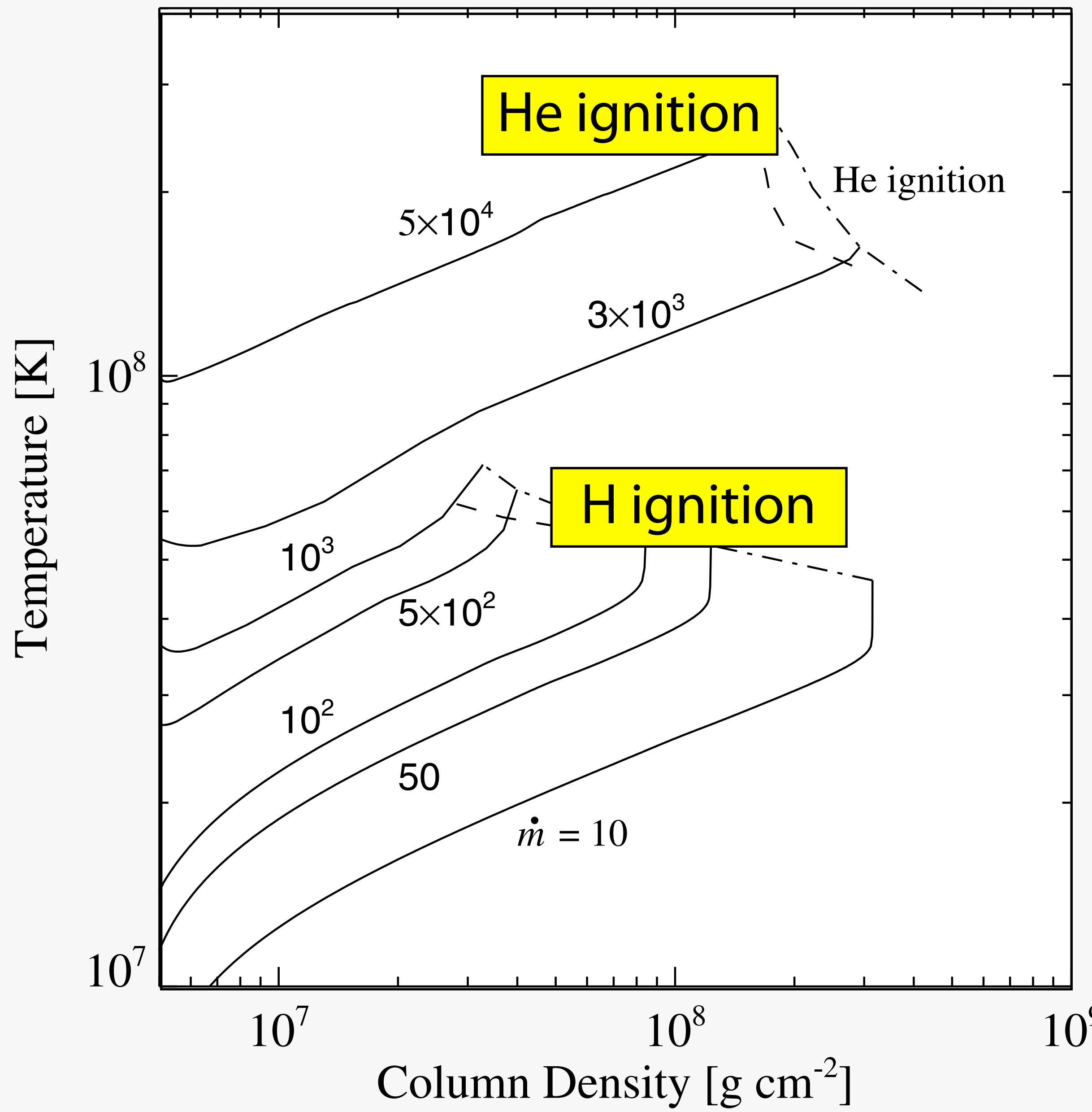
with

$$\varepsilon_{cool} \sim -\chi\nabla^2 T.$$

A thermal runaway occurs and rapidly consumes available fuel; if

$$t_{cool} \ll t_{accrete}$$

a limit cycle develops.



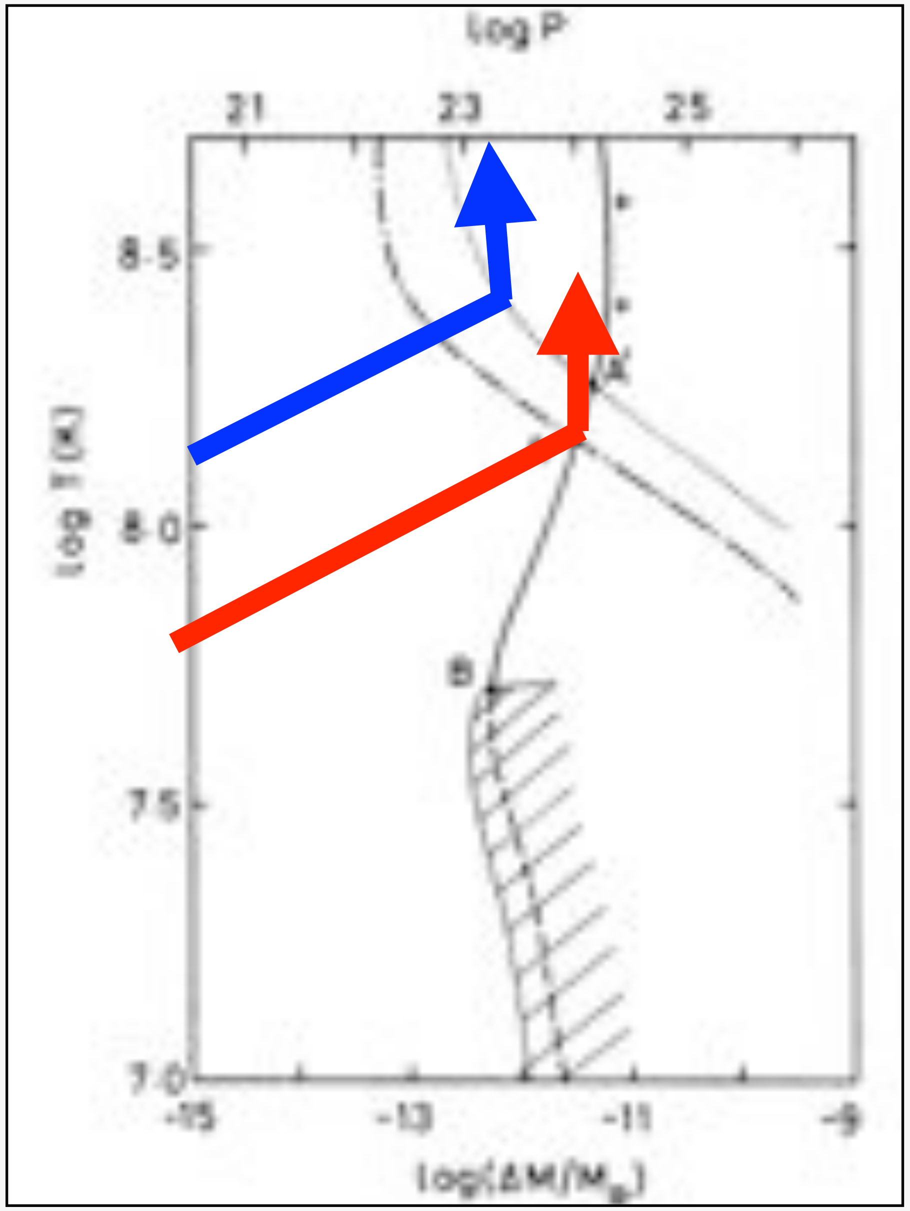
Peng et al. 2007

Burst behavior controlled by consumption of hydrogen

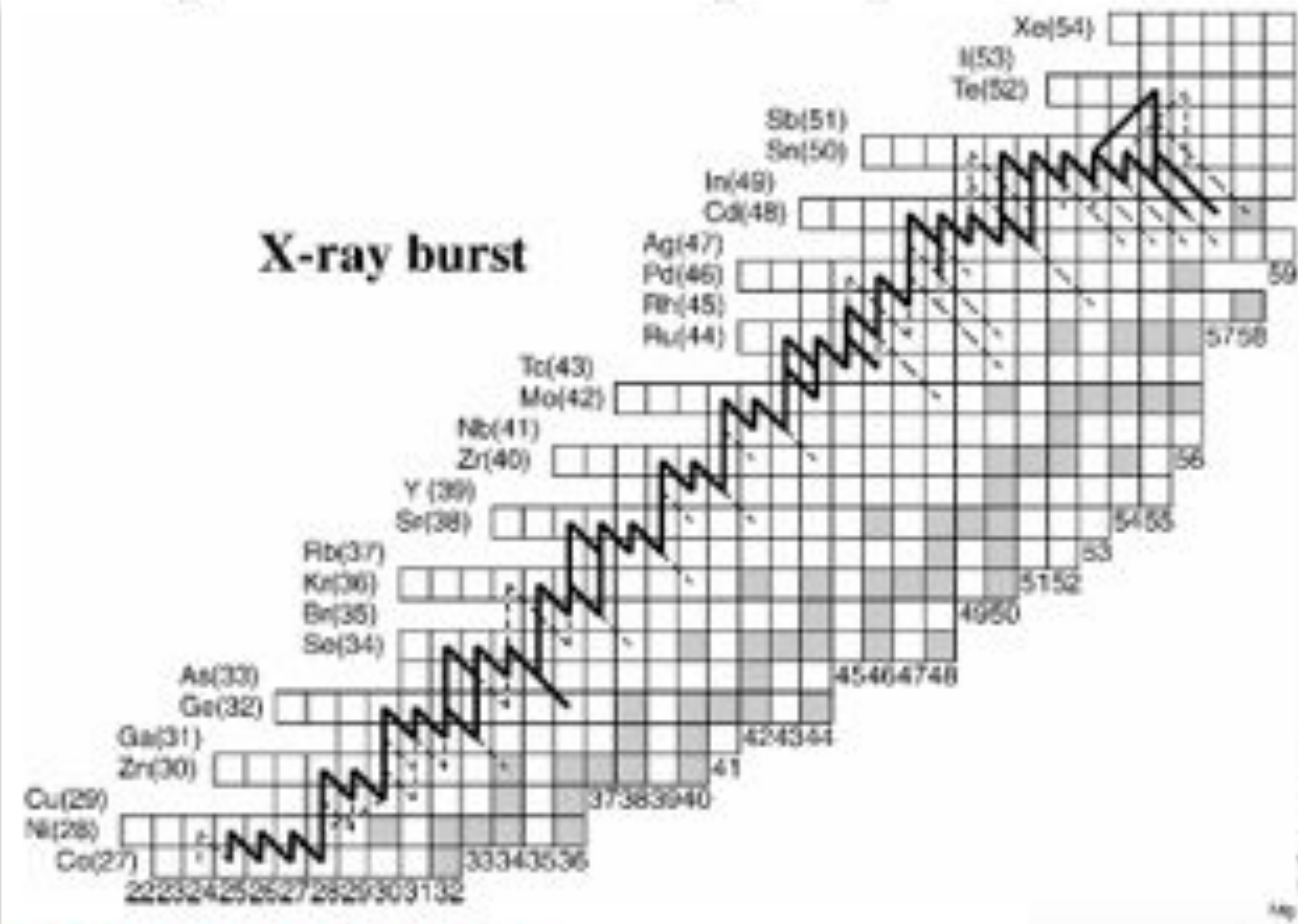
Fujimoto et al.

Assume all H consumed stably via HCNO cycle. Time to consume H set by β-decay of ^{14}O ($t_{1.2} = 71$ s) and ^{15}O ($t_{1/2} = 122$ s).

$$t_H = \frac{1}{4}\frac{Y_H}{Y_{CNO}}\frac{193\ \mathrm{s}}{\ln 2} \approx 18\ \mathrm{hr}\left(\frac{X_H}{0.7}\right)\left(\frac{0.01}{X_{CNO}}\right).$$

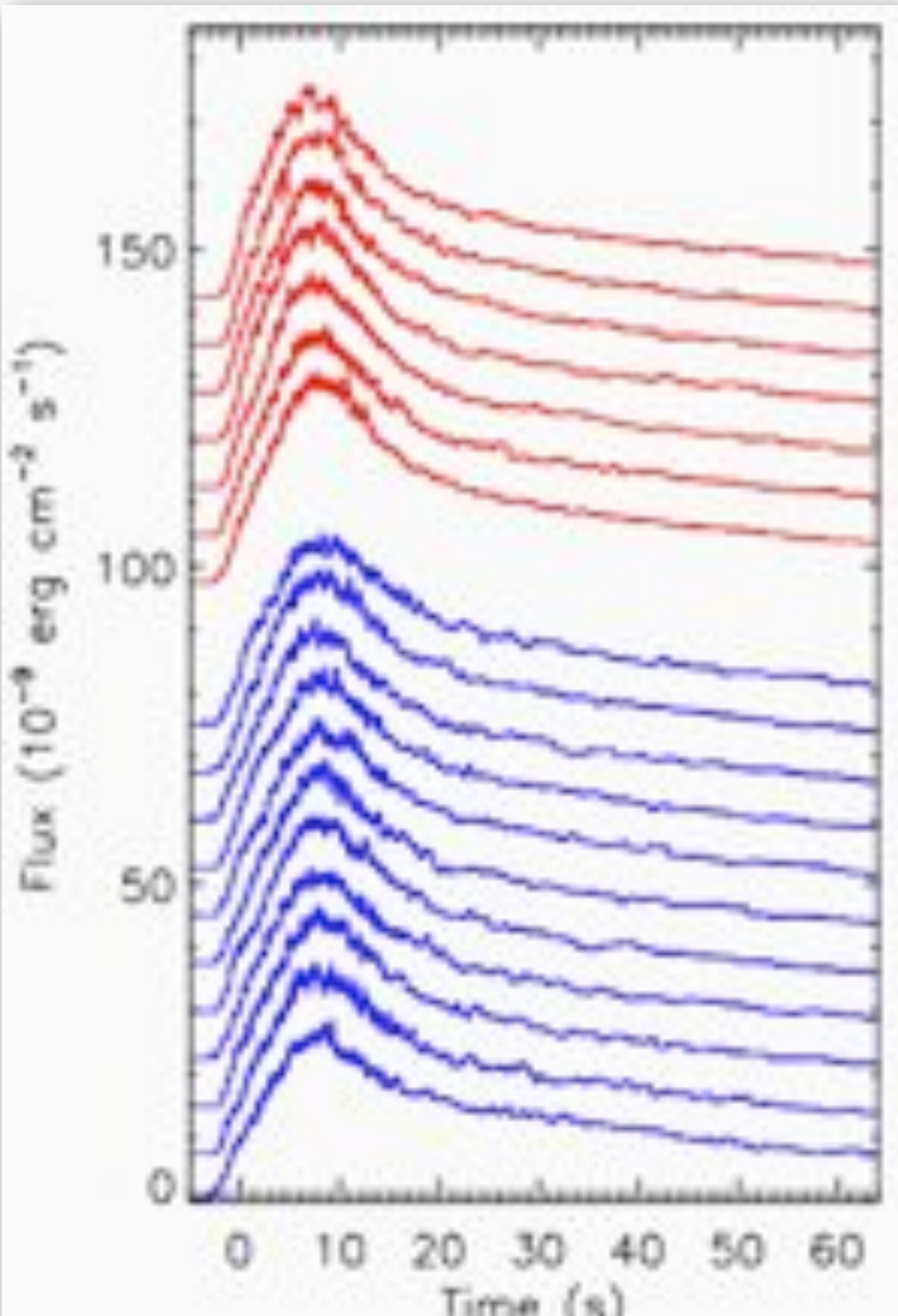


$$^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}(p,\gamma)^{14}\mathrm{O}(\beta^+)^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}(\beta^+)^{15}\mathrm{N}(p,{}^4\mathrm{He})^{12}\mathrm{C}$$

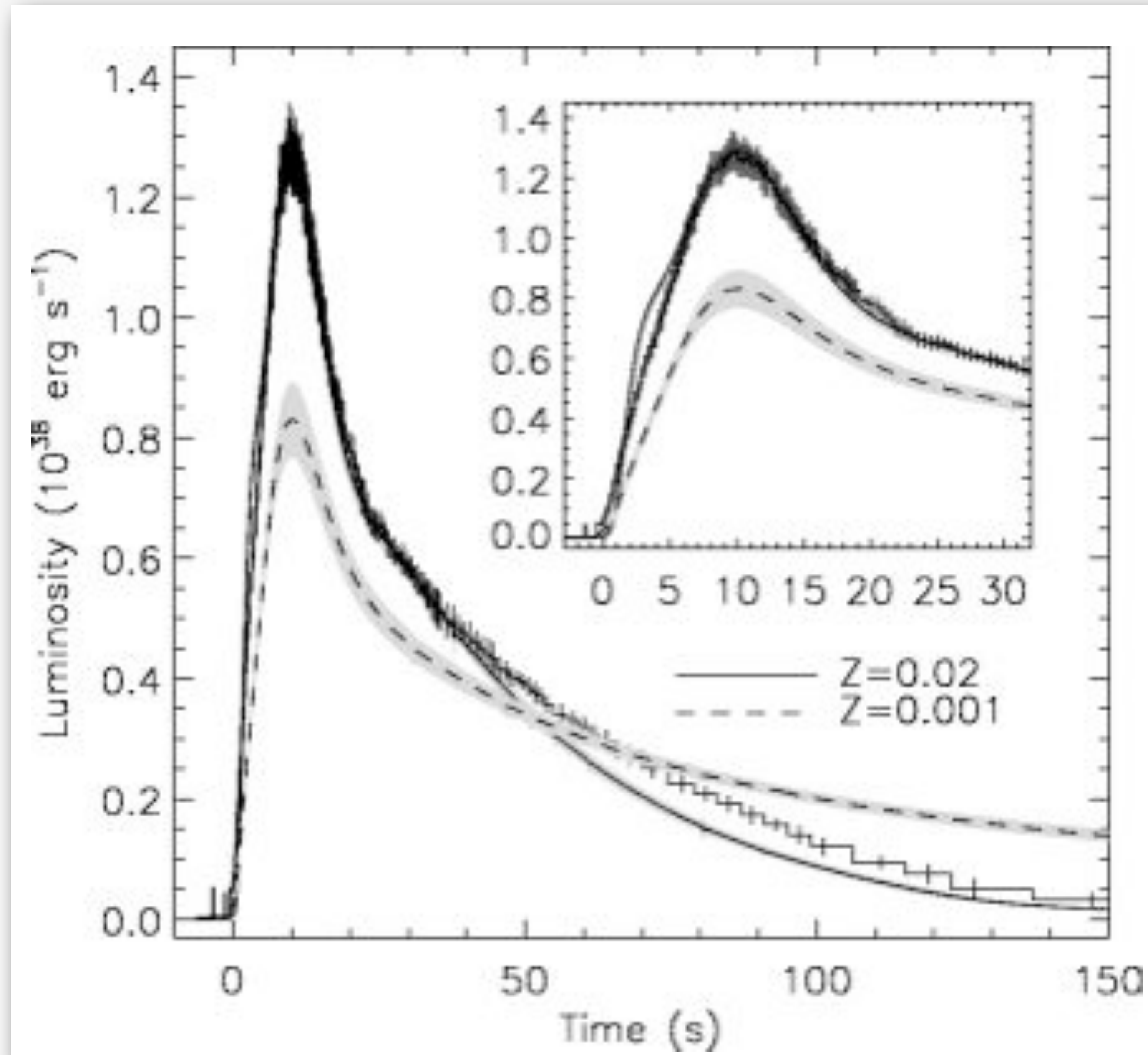


Schatz et al. 2001: consumption of H via rp-process

For GS1826–24, 1-d models do remarkably well!



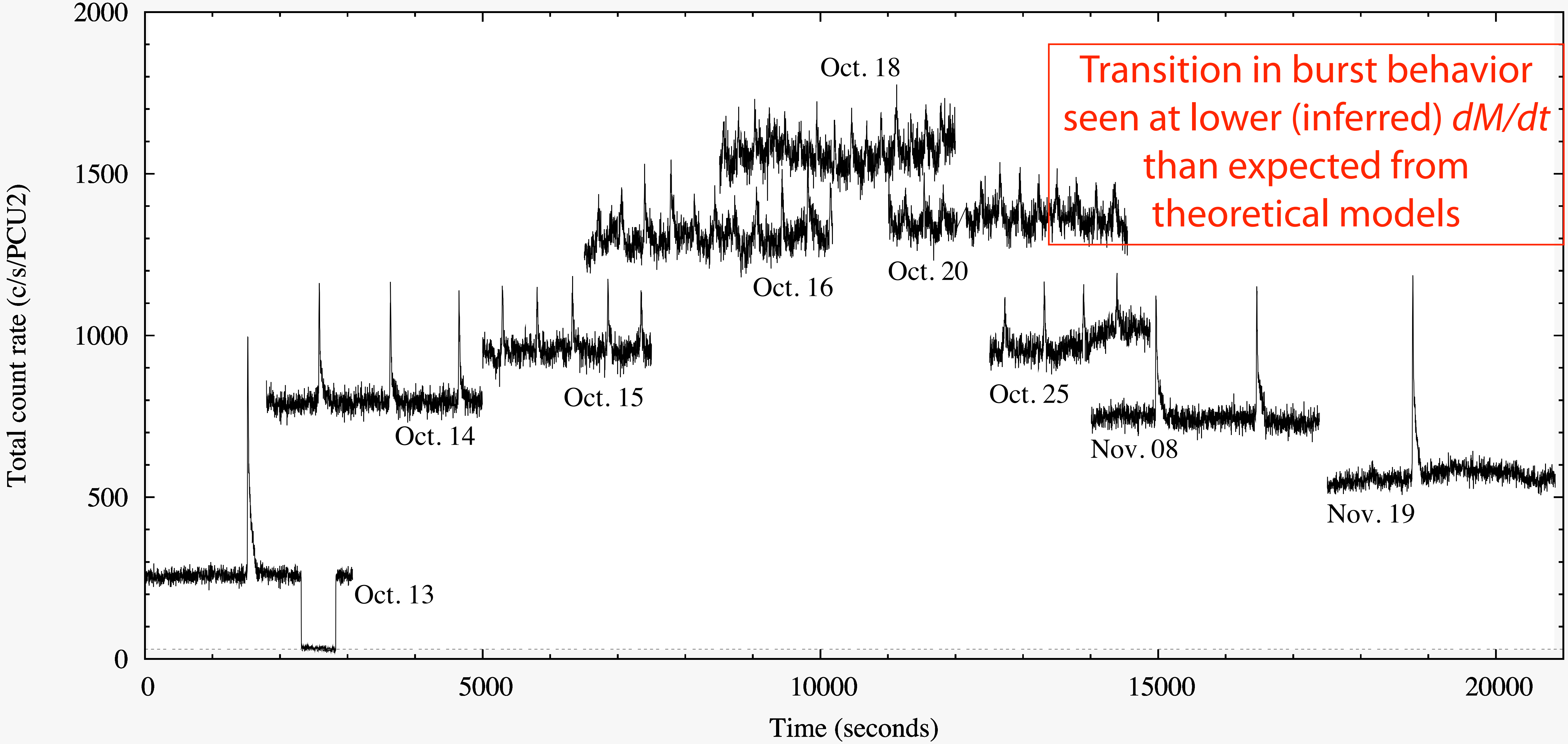
Galloway et al.



Heger et al. 07

Different bursting regimes: Terzan 5

Linares et al.



Challenges

Most systems are not like GS1826–24!

Above 0.1 Eddington accretion rate, evidence for some stable burning from many systems: for example,

- burst frequency decreases (model predicts an increase)
- bursts become shorter, indicating less H, not more

Some groups come in “clusters”: a group of up to 4 bursts, separated by waits of a few minutes (see Keek et al. 2010)

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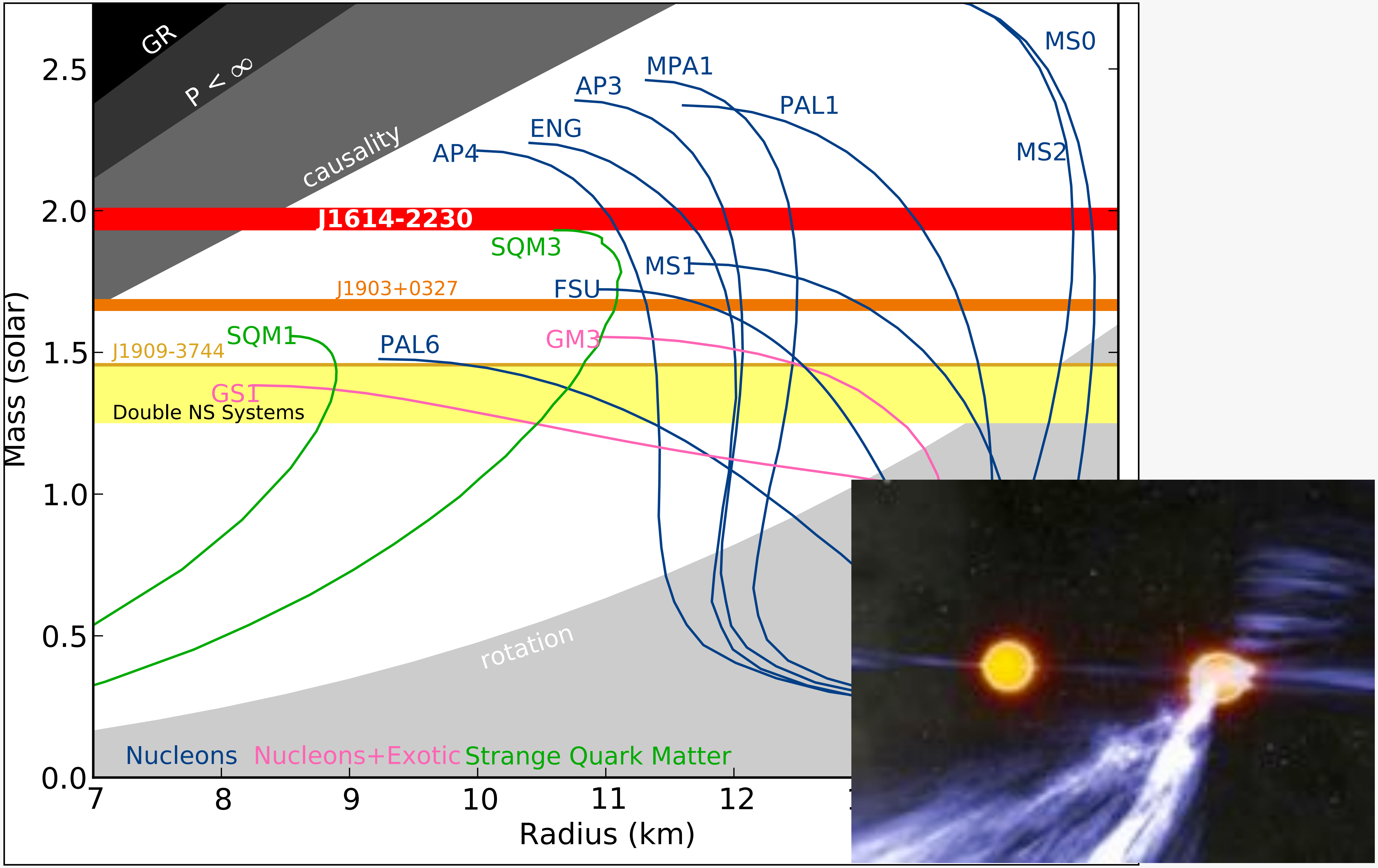
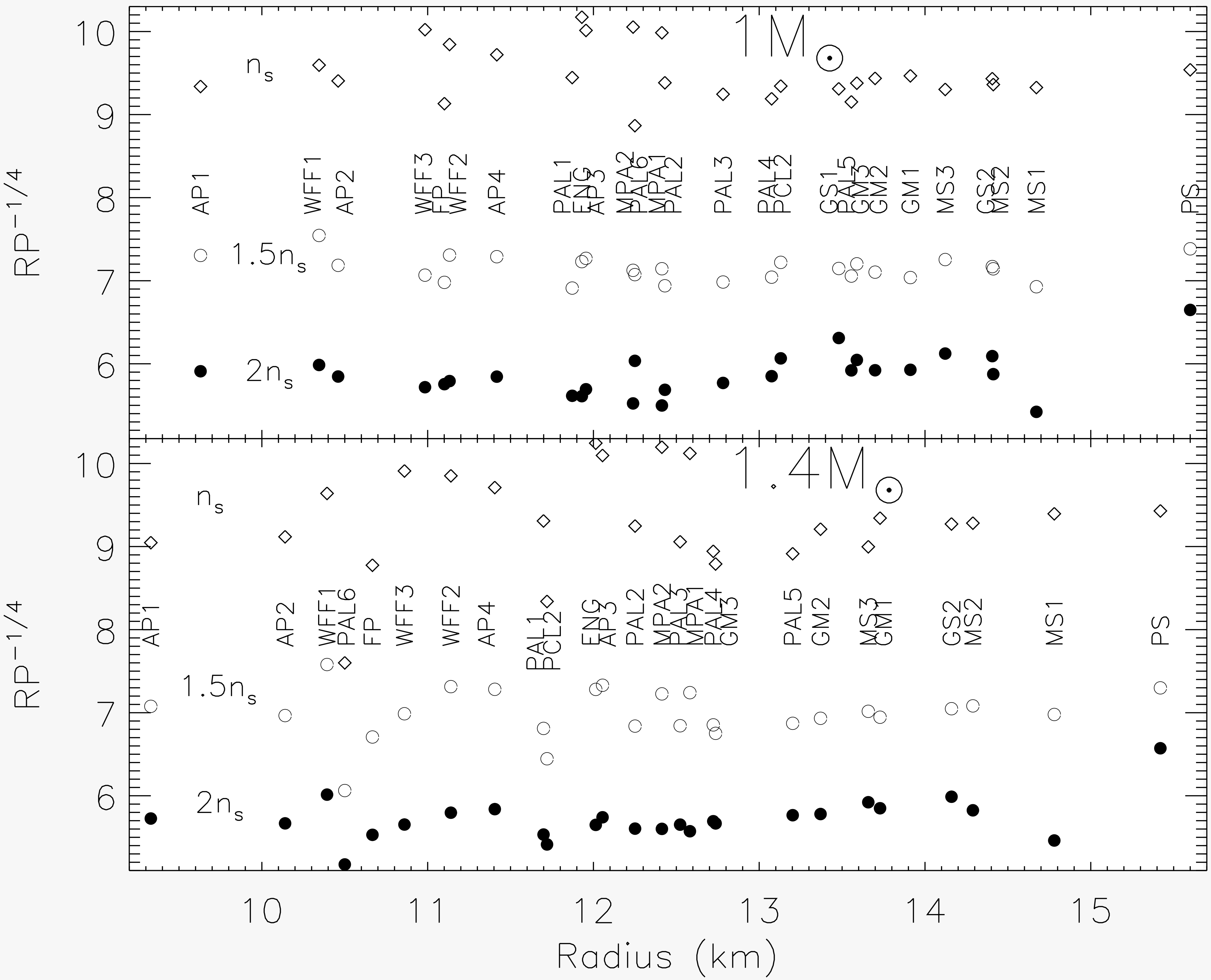
Pulsars: about 50 are in binaries with information on masses



Demorest et al. 2010

PSR J0737-3039A/B
John Rowe Animation/Australia Telescope
National Facility, CSIRO



Radius correlated with pressure of nuclear matter

Lattimer & Prakash 2001

Using X-ray bursts to determine *M, R*

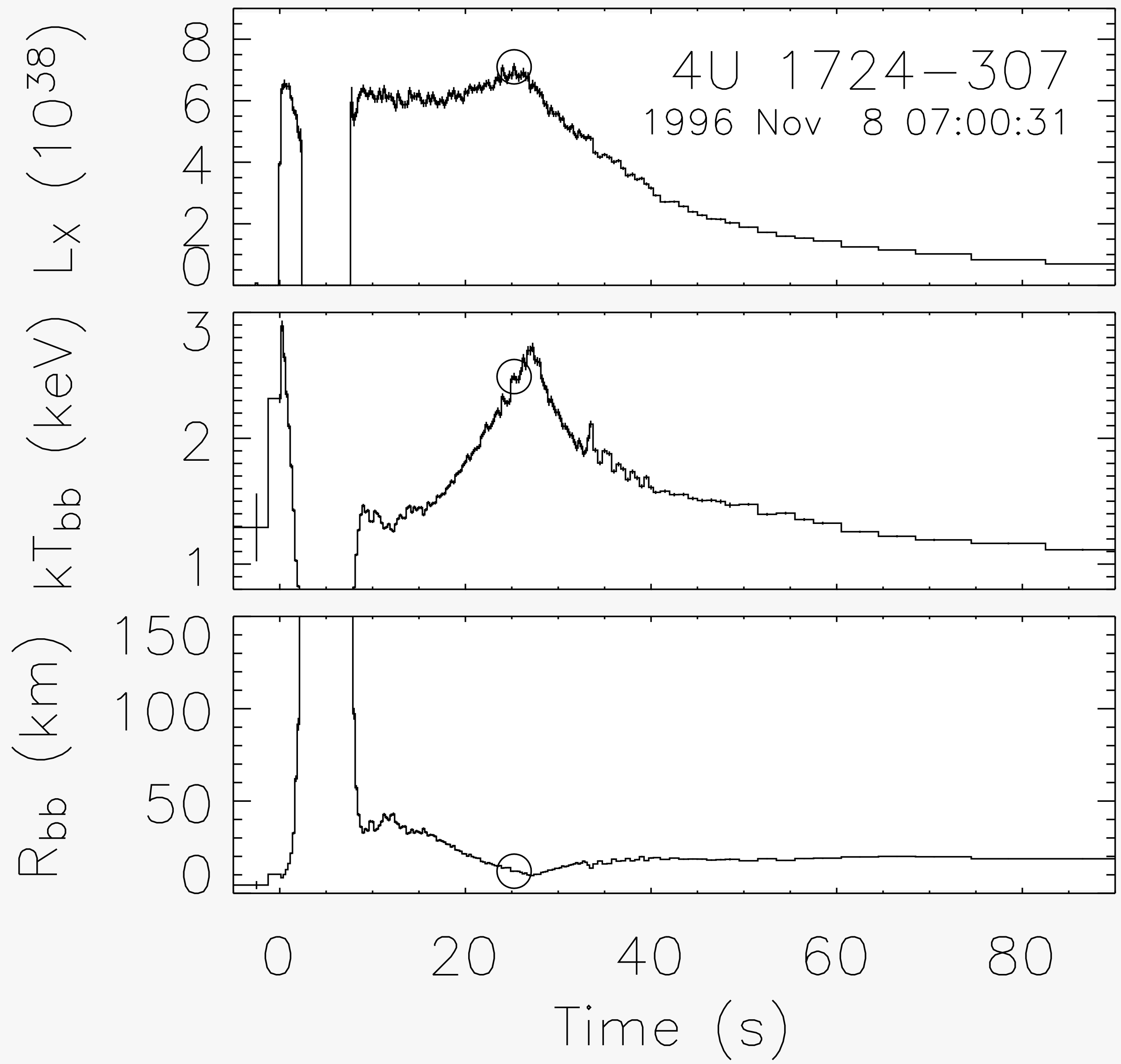
Marshall; van Paradijs et al.; Özel et al; Steiner et al.

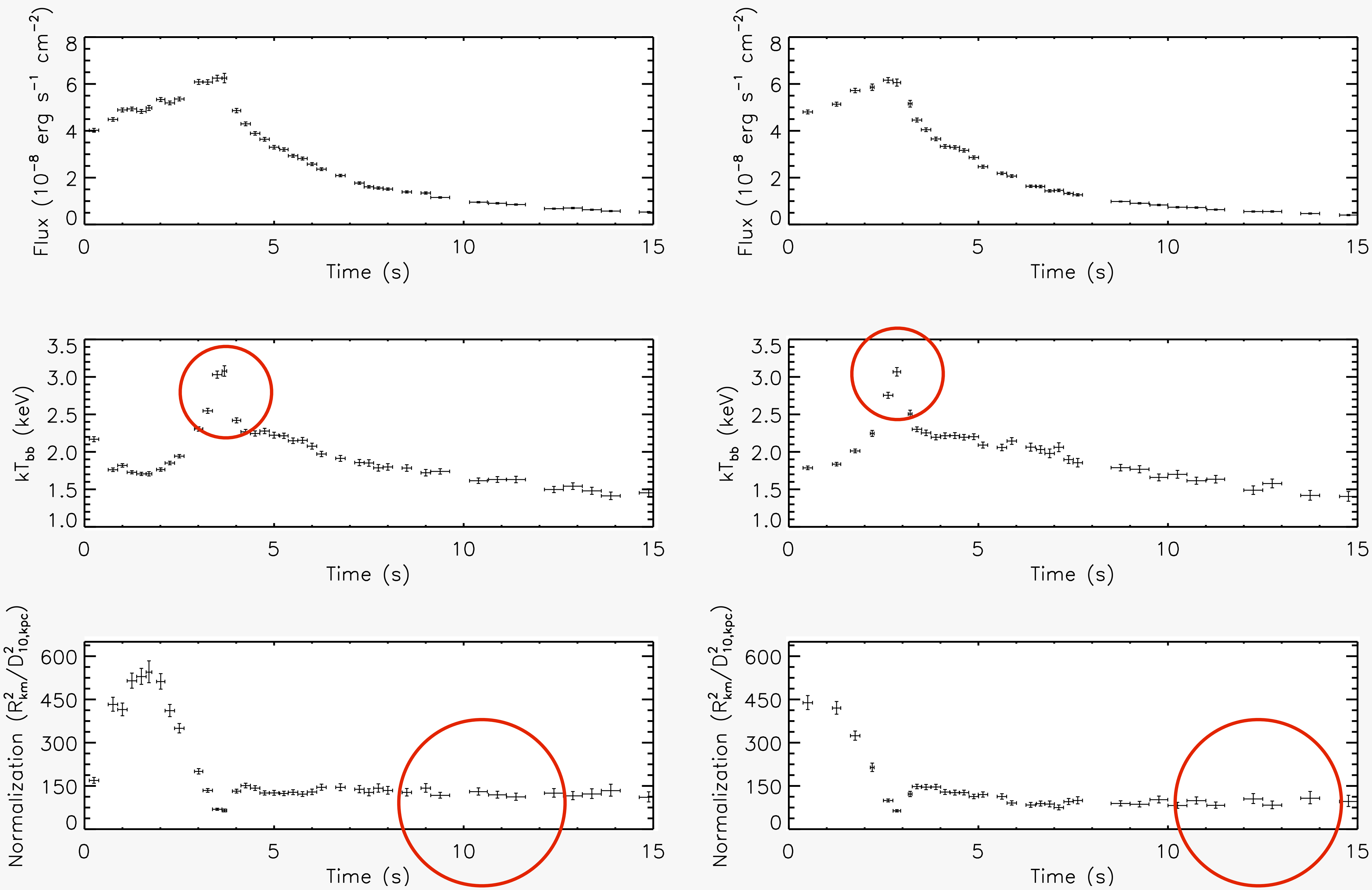
RXTE observations; Galloway et al. '08

From X-ray bursts with *photospheric radius expansion*

$$F_{Edd} = \frac{GMc}{\kappa D^2}\left(1 - 2\frac{GM}{r_{ph}c^2}\right)^{1/2}$$

$$\frac{F}{\sigma T_{eff}^4} = \left(\frac{R}{D}\right)^2\left(1 - 2\frac{GM}{Rc^2}\right)^{-1}$$





X-ray burst profiles (Özel et al. 2009)

Is the model correct?

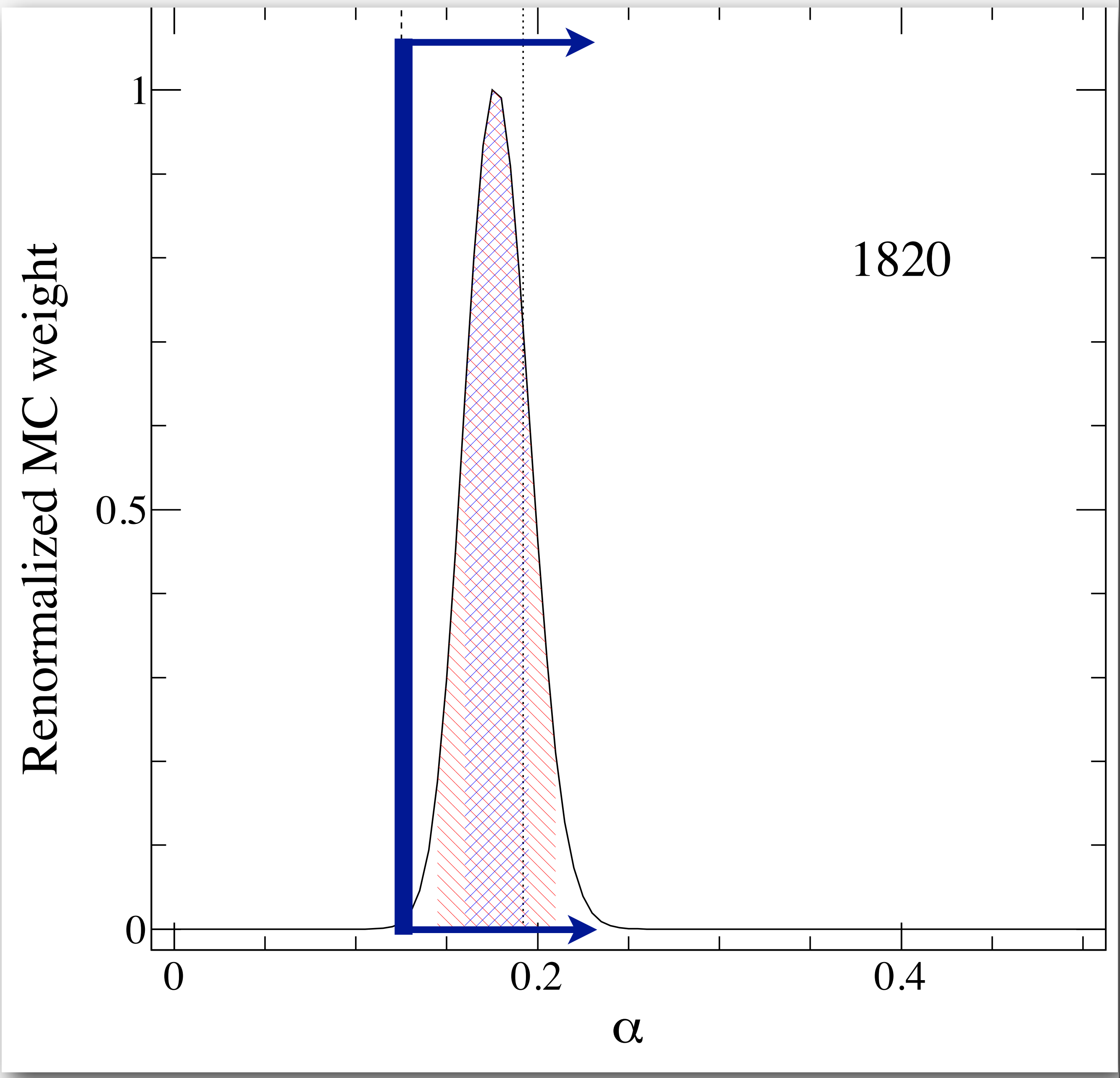
Central values of f_c, D, X_H do not produce solutions for M, R

$$\frac{GM}{Rc^2} = \frac{1}{4} \pm \frac{1}{4}\sqrt{1-8\alpha}$$

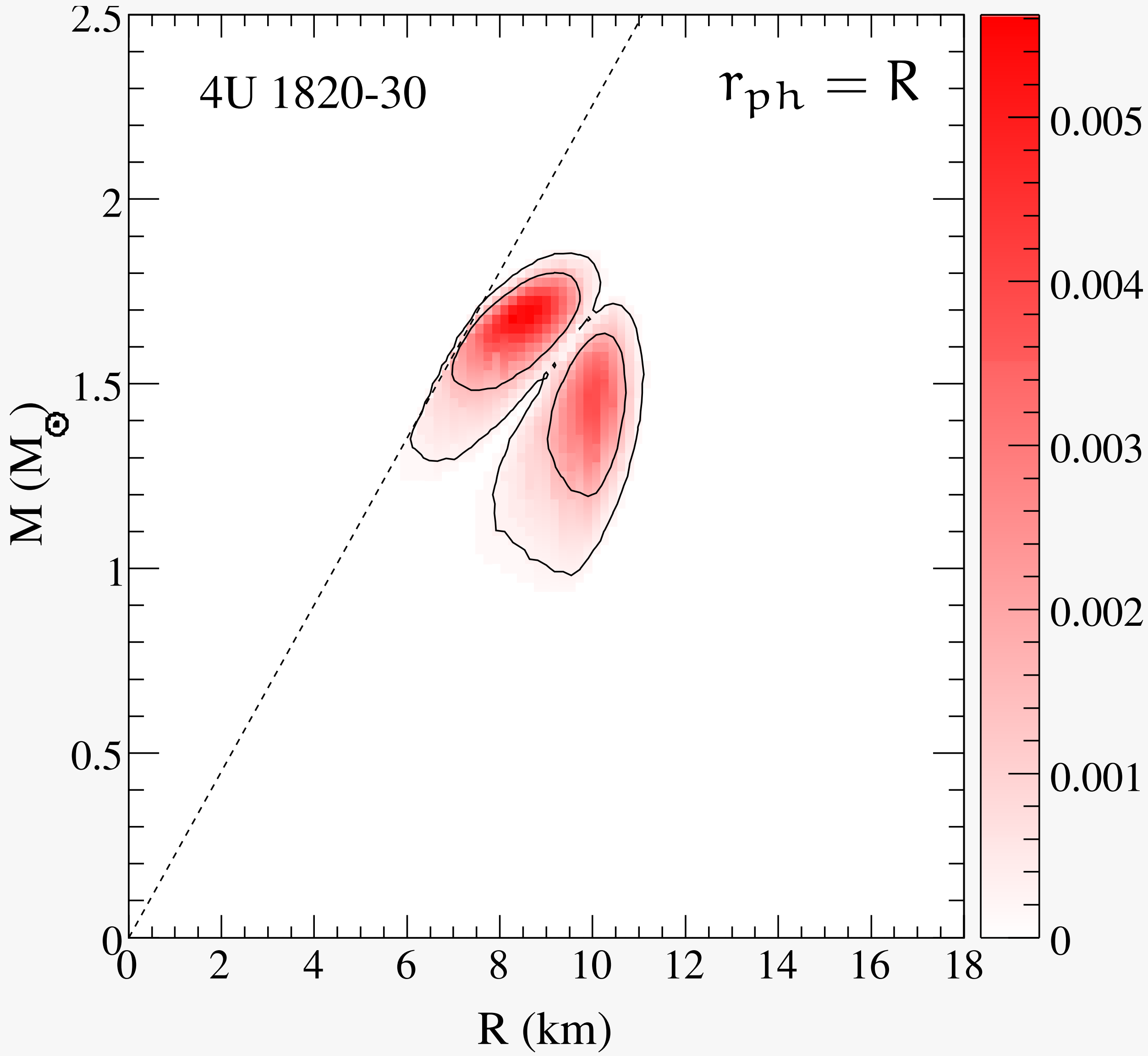
$$\alpha = \frac{F_{TD,\infty}}{\kappa D} c^3 f_c^2 \sqrt{\frac{\sigma T_{bb,\infty}^4}{F_{tail,\infty}}}$$

For a real-valued solution, $\alpha < 1/8$.

NB. $f_c \equiv \frac{T_{bb}}{T_{eff}}$

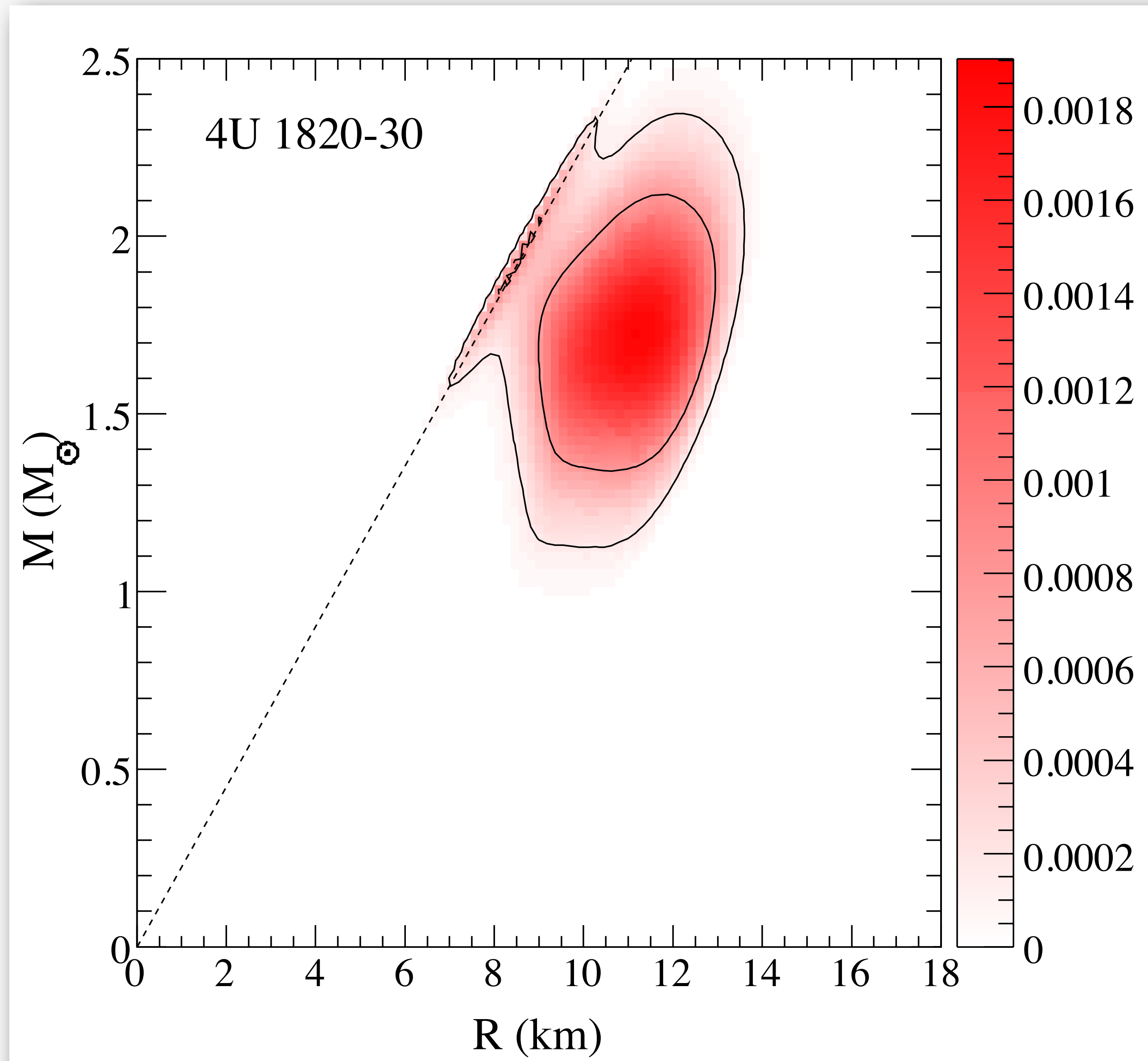


neutron star mass, radius constraints



Steiner et al., following Özel et al.

uniform prior in $h = 2R/r_{ph}$

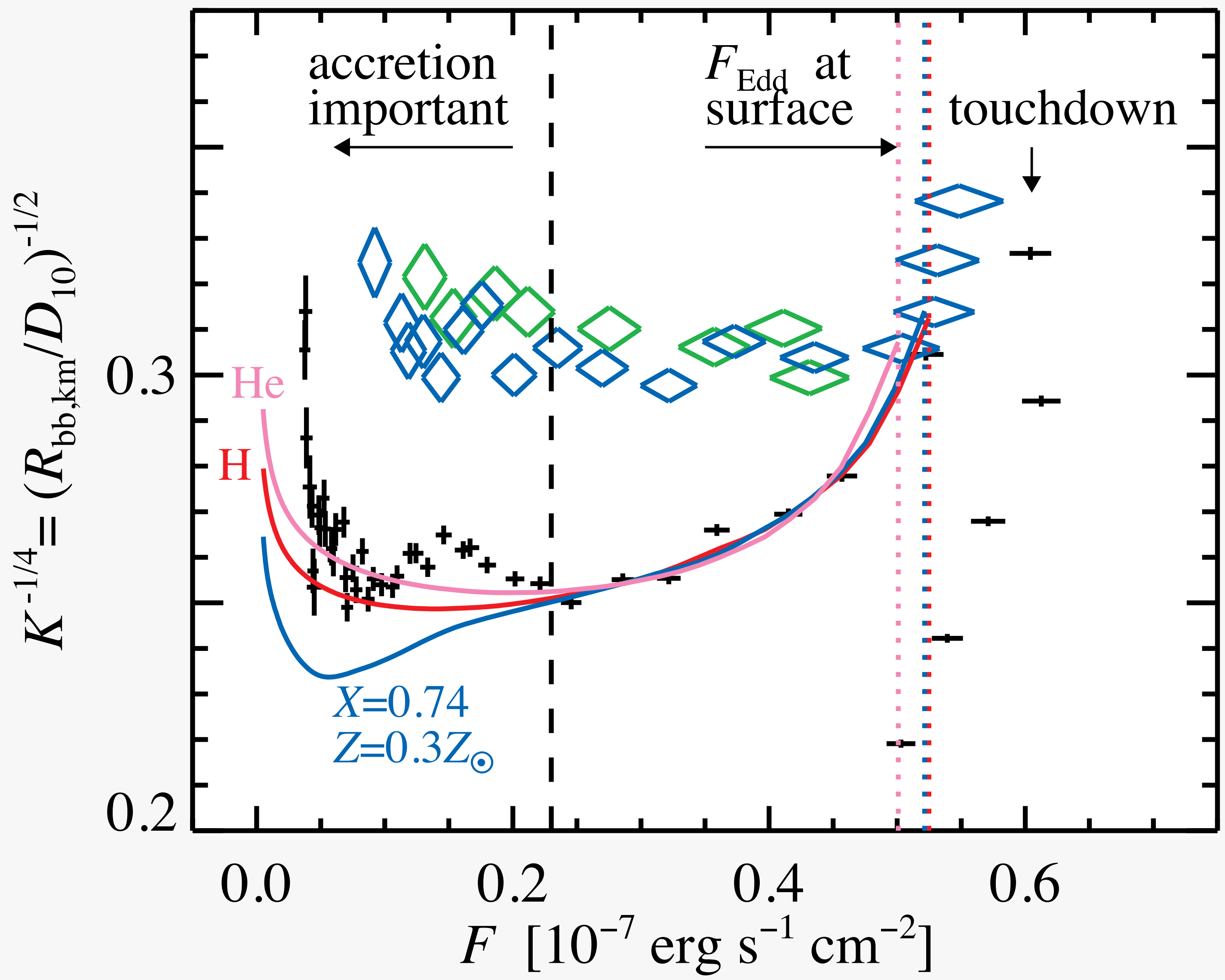


Steiner et al.; data from Guver et al. '10

Systematic uncertainties (Suleimanov et al.)

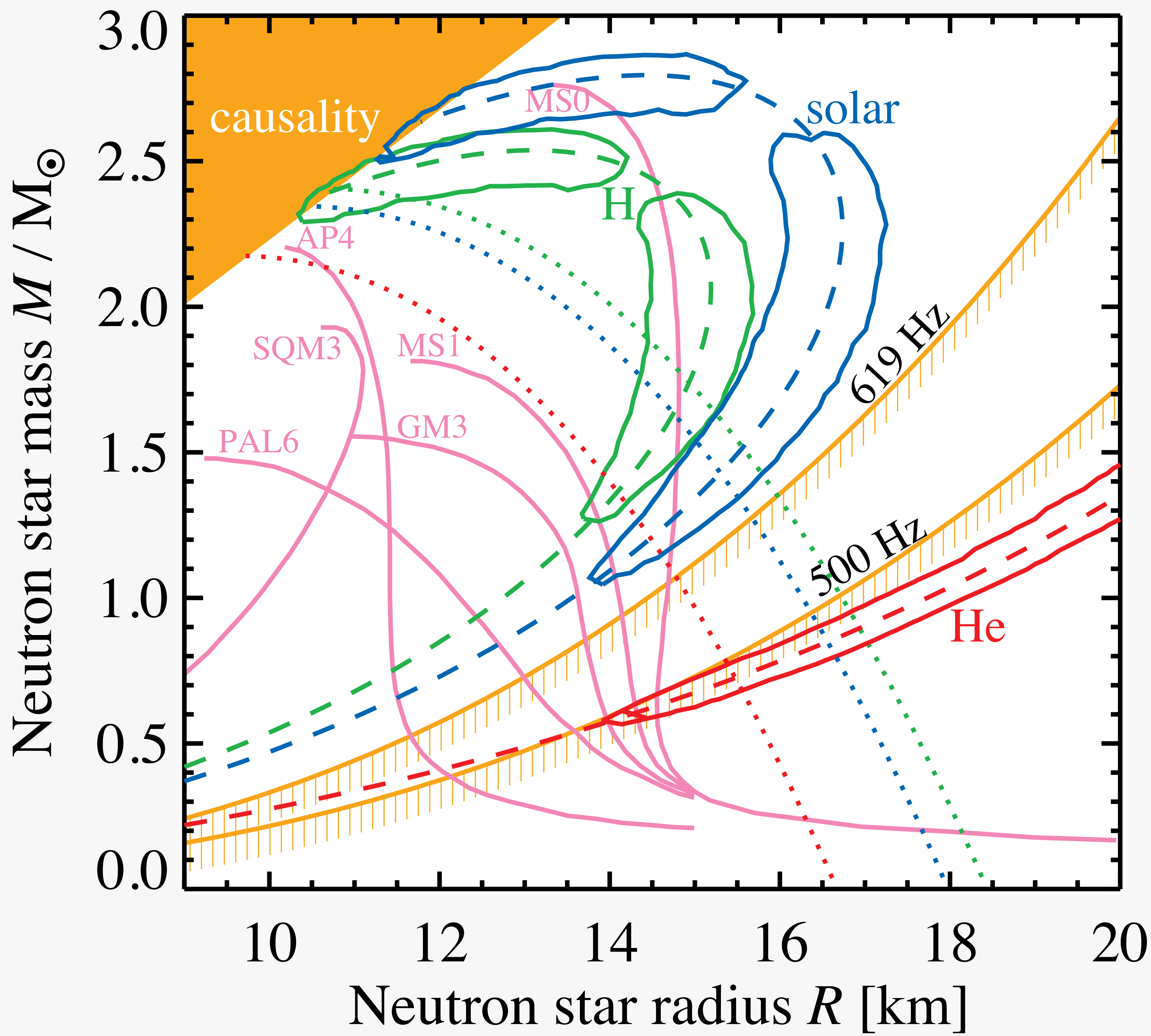
model spectral evolution over entire burst (for 1724-307): check on whether model matches burst behavior

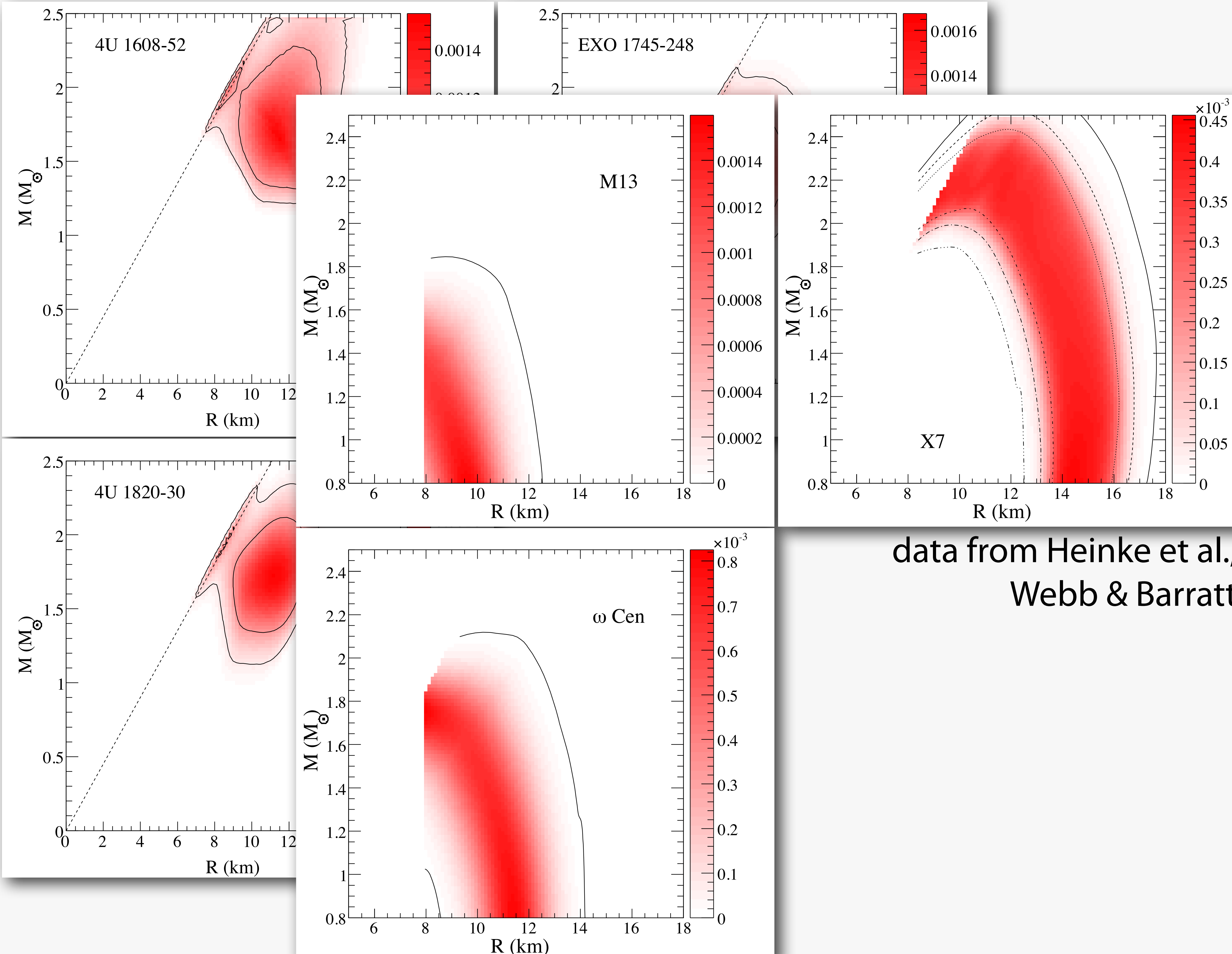
- touchdown flux > Eddington
- color correction factor f_C is not constant, and it depends on composition



results of fitting long bursts from 1724–307

Suleimanov et al. 2011





data from Heinke et al.,
Webb & Barratt

Fitting a dense EOS: 3 components

Steiner et al. 2010

A general equation of state

low-density: expansion in $u=n/n_0$ with priors (K, K', S_v, γ) constrained from experiment

$$\varepsilon = n_B \left\{ m_B + B + \frac{K}{18}(u-1)^2 + \frac{K'}{162}(u-1)^3 + (1-2x)^2 \left[S_k u^{2/3} + S_p u^\gamma \right] + \frac{3}{4}\hbar c x (3\pi^2 n_b x)^{1/3} \right\}$$

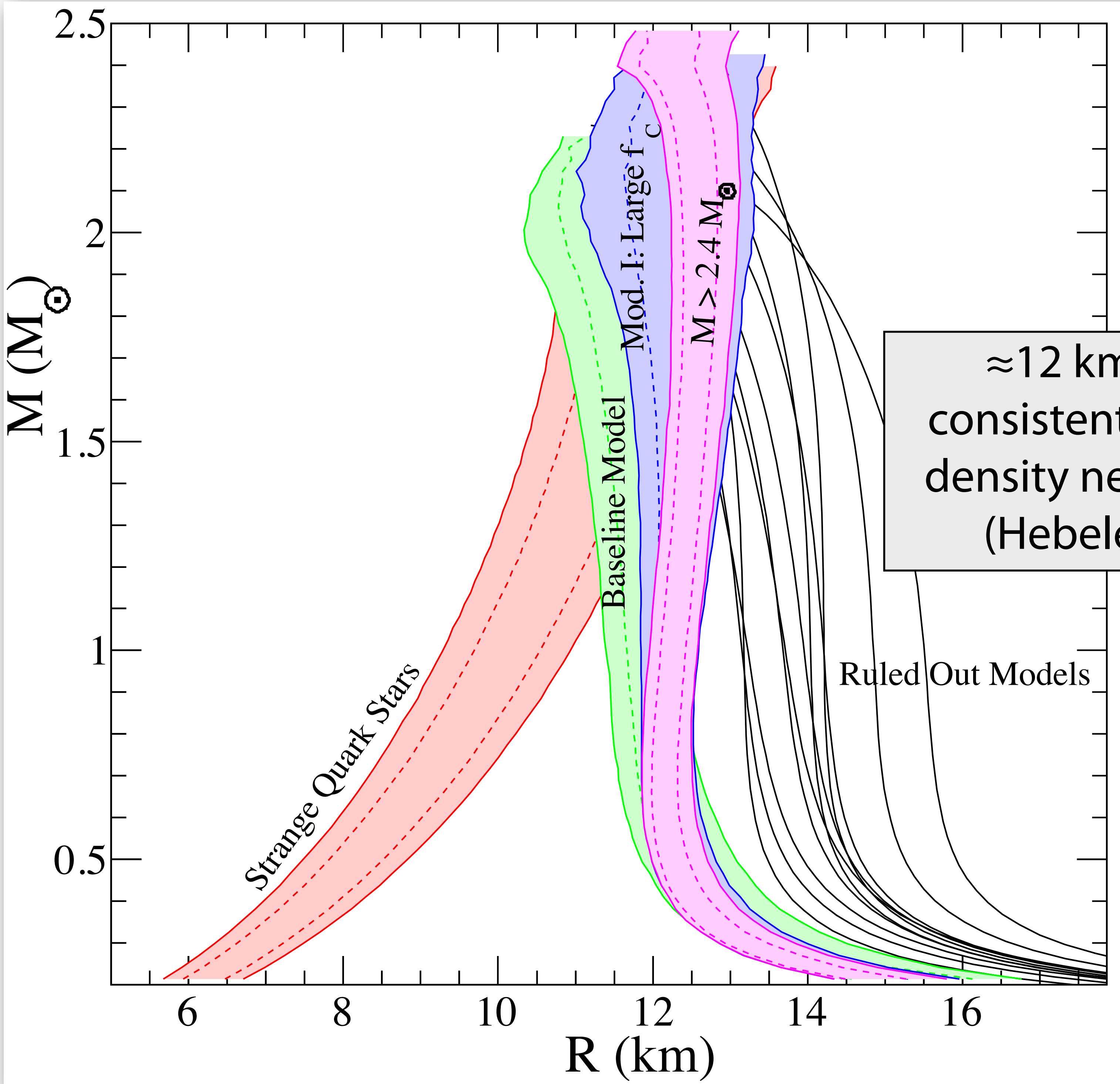
high-density: two matched polytropes ($P = K\rho^{1+1/n}$); covers wide-range of models (Read et al. '09)

masses of individual neutron stars

Markov Chain Monte Carlo

for each set {EOS parameters, NS masses} compute the likelihood of a point

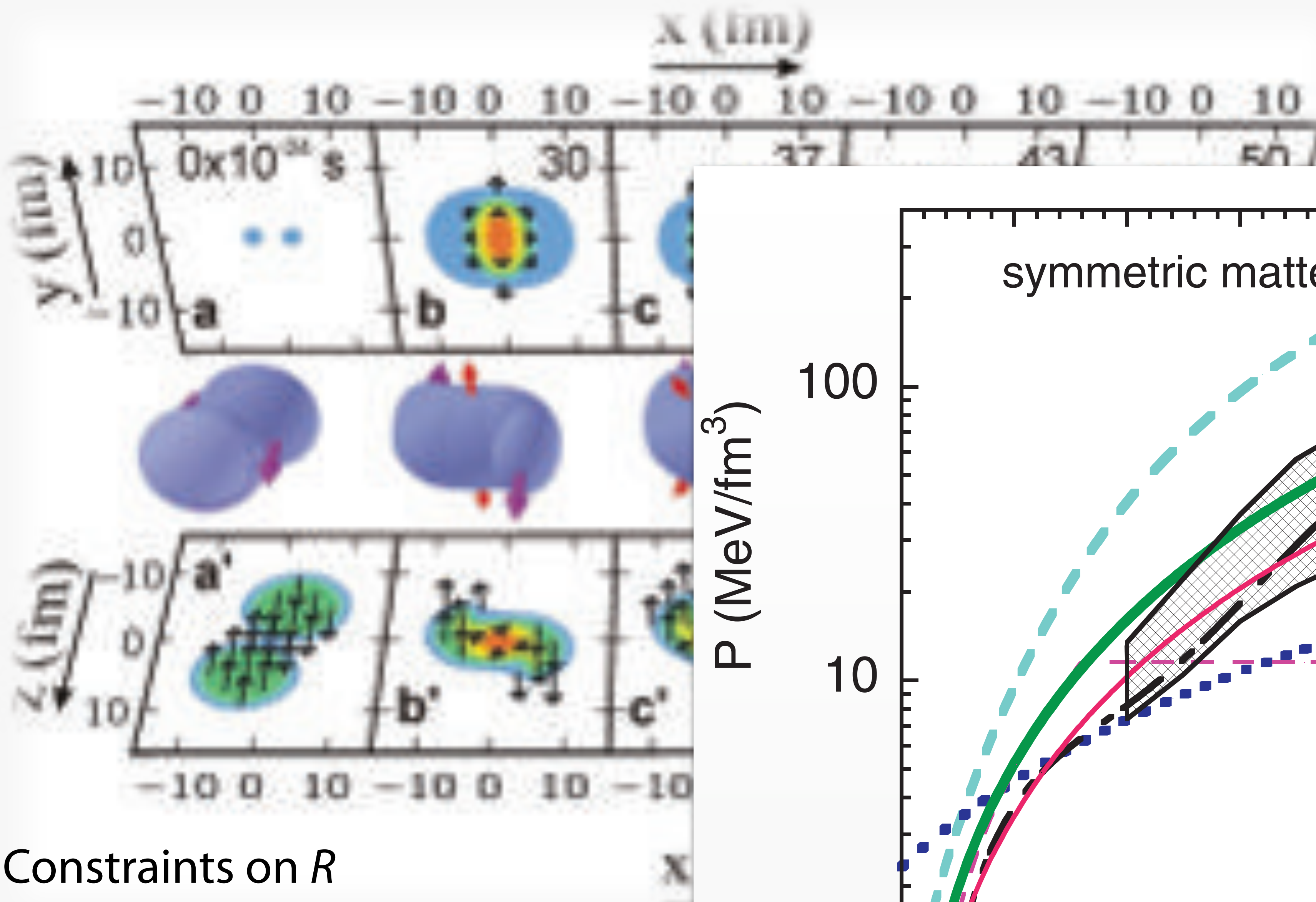
accept or reject that point via Metropolis algorithm

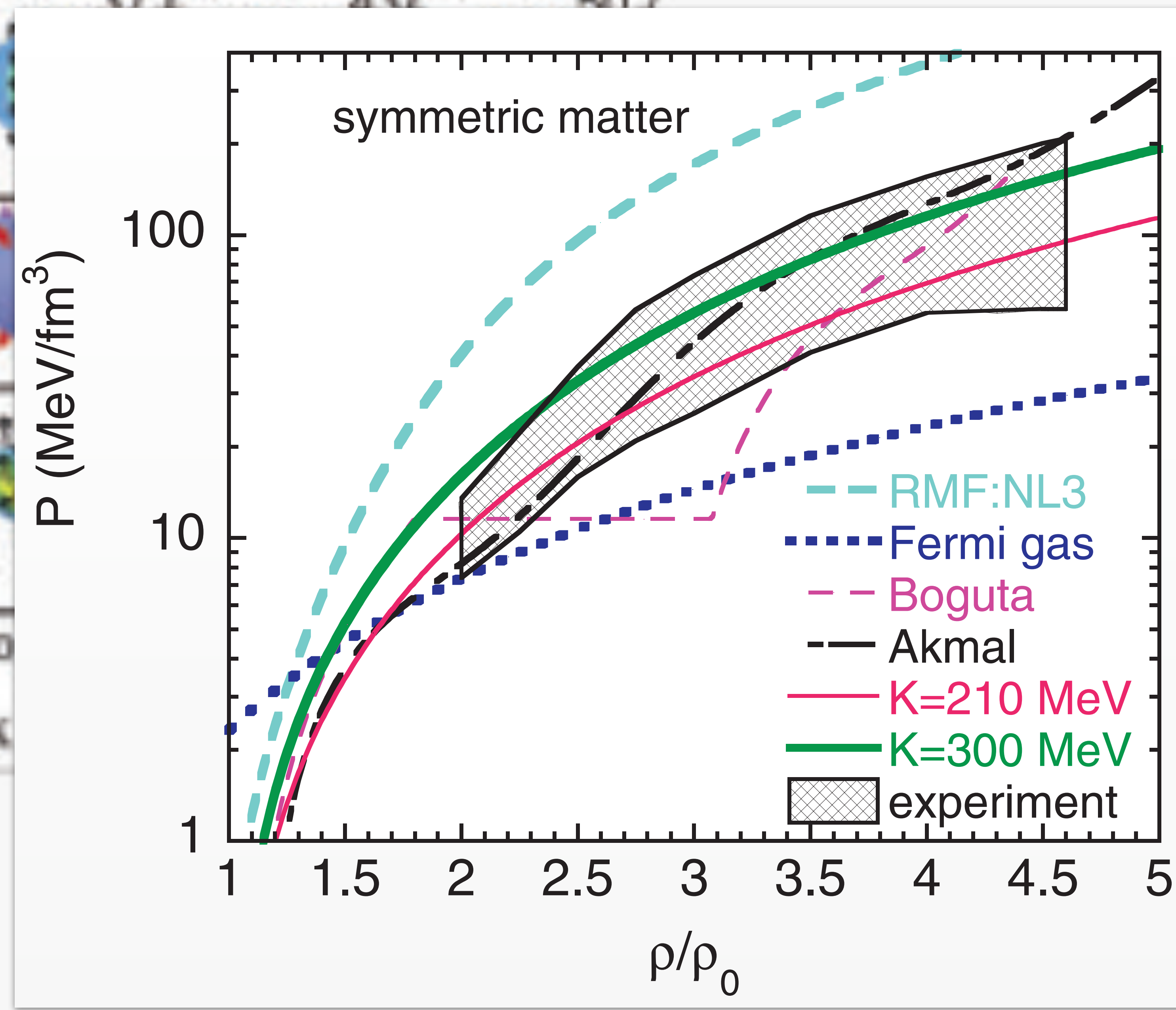


≈12 km radius consistent with low-density neutron EOS (Hebeler et al.)

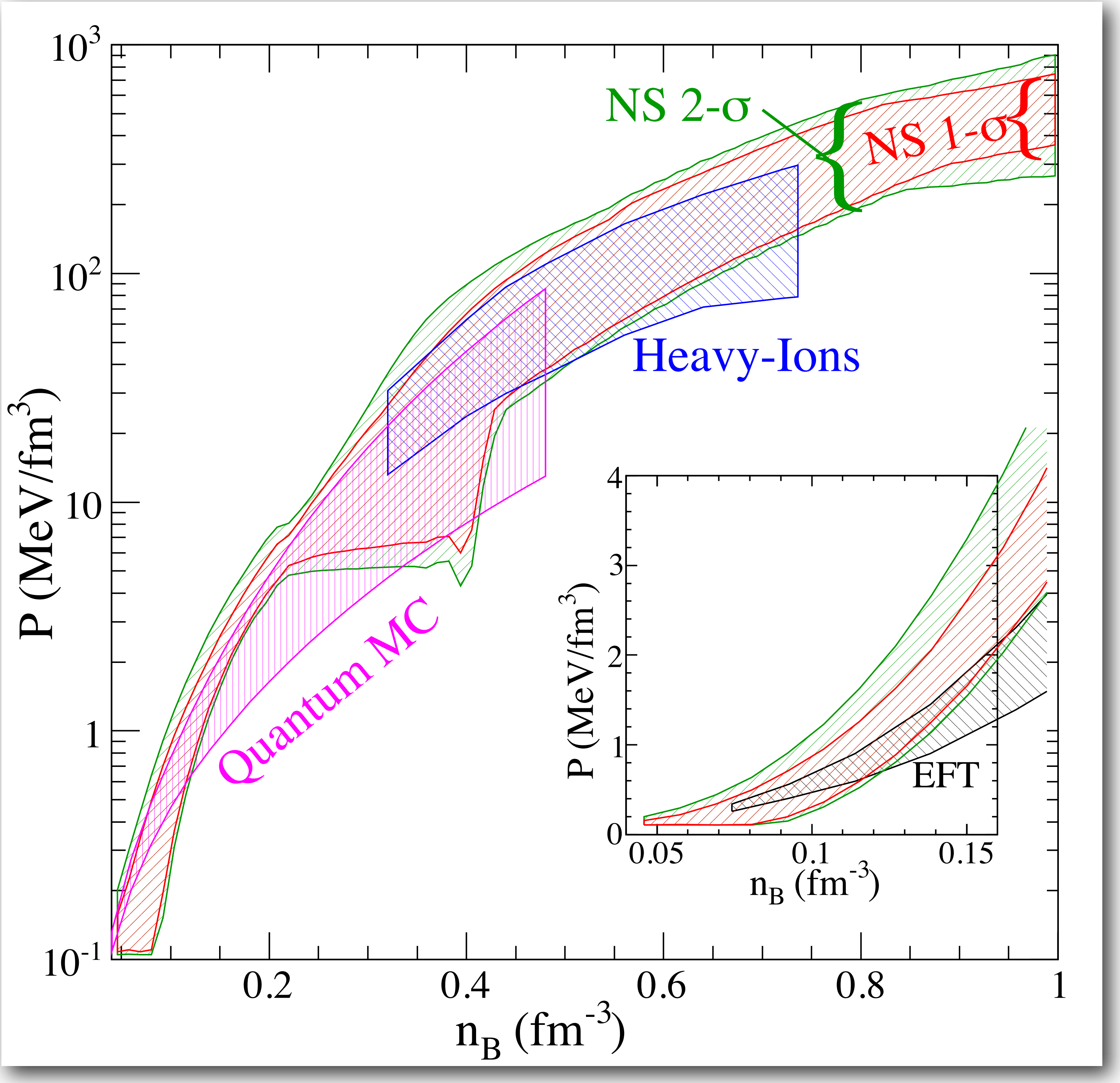
An empirical *M-R* relation Steiner et al., in prep.

equation of state from heavy nucleus collisions
Danielewicz et al. (2002) *Science*





Constraints on *R* possible from measurements on neutron "skin" thickness of ^{208}Pb (Abrahamyan et al. 2012, PRL)



Comparison with nuclear experiment, theory

Steiner et al., in prep.

Summary

- Well-developed analytical and numerical theory of nuclear burning in neutron star envelopes
  - Successfully reproduces bursting behavior in some sources
  - For most sources, burning appears to stabilize at too low an accretion rate
- Bursts with photospheric radius expansion can be used to constrain masses, radii
  - Is the touchdown flux Eddington (for the quiescent photosphere)?
  - Why is the normalization constant for some bursts (no evolution of color correction factor)?
- Potential for learning about dense matter EOS from both astronomical observations, nuclear experiment and theory (and gravitational waves?)
  - Challenge: fitting a heterogeneos dataset (different phenomena and instruments)

neutron stars and nuclear physics

Connecting Quarks with the Cosmos (2006)

"What is the nature of dense matter?" is one of the top unanswered questions for the 21st century

New Worlds, New Horizons in Astronomy and Astrophysics

"Measuring neutron star masses and radii yields direct information about the interior composition [of neutron stars] that can be compared with theoretical predictions."

Scientific Opportunities with a Rare-Isotope Facility in the United States, National Research Council (2006)

There are roughly one billion neutron stars in our galaxy, yet their internal structure and the composition of their crusts are poorly understood. ... a [**Facility for Rare-Isotope Beams**] can study the central questions concerning the composition and energetics of their upper mantles.

http://www.frib.msu.edu/