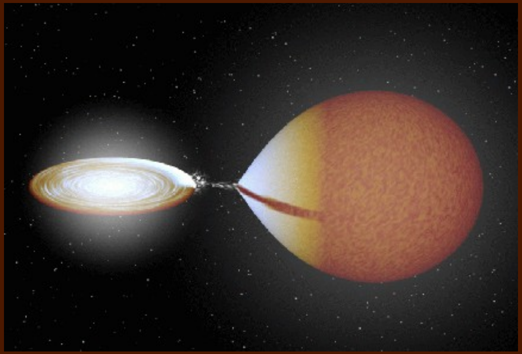
# HOW STRANGE IS THE RAPID BURSTER?
# CONSTRAINTS ON THE MASS AND RADIUS OF MXB 1730-335

## or measuring the neutron star of the Rapid Burster from a type I (thermonuclear) X-ray burst with Photospheric Radius Expansion

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# CONSTRAINTS ON THE MASS AND RADIUS OF MXB 1730-335

***Matter under extreme conditions:***
***what is the equation of state of matter in neutron stars?***

Observational answer through determination of mass and radius of neutron stars via

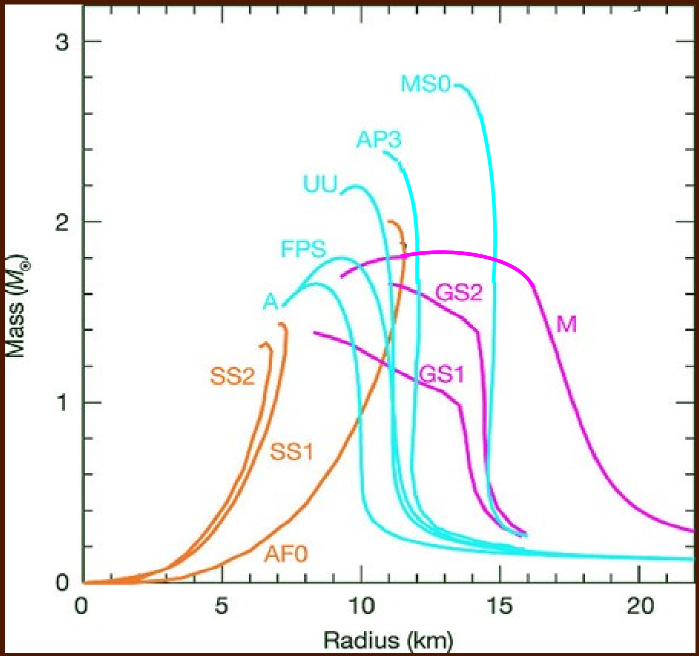
- Pulsations during type I X-ray bursts

- Oscillations in magnetars

- Coherent pulsations

- NS spin frequency

**- Eddington limited type I X-ray bursts, i.e., with Photospheric Radius Expansion**




- Gravitational redshift of absorption lines during type I X-ray bursts

## The Rapid Burster

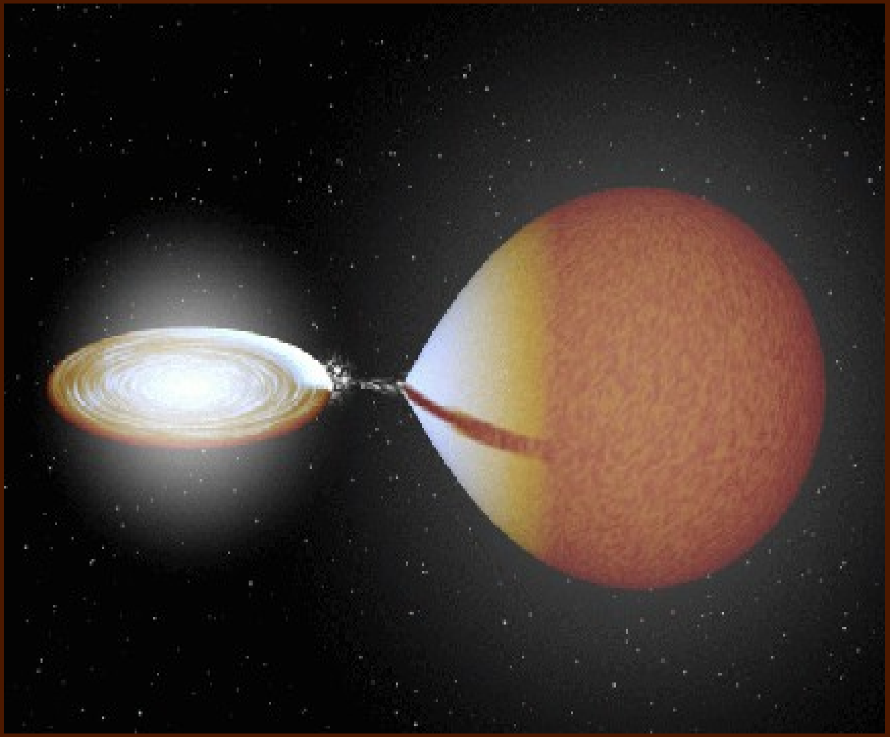
Peculiar LMXB, accreting neutron star, one of the first X-ray bursters discovered (Lewin 1976)

Unique object showing both

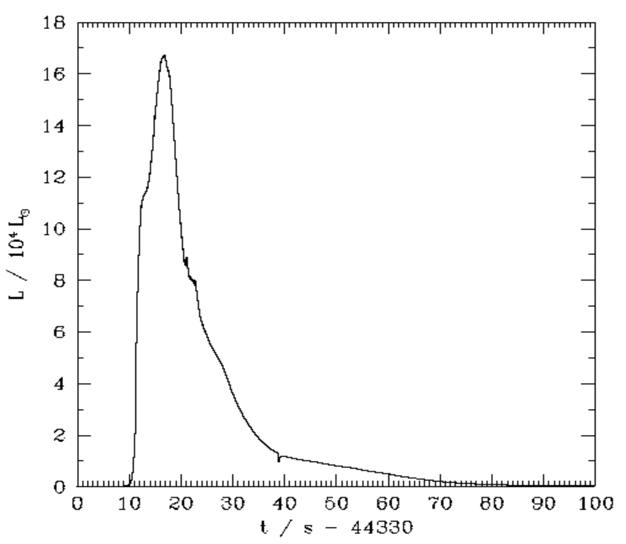
type I X-ray bursts (thermonuclear events)

and

type II X-ray bursts (spasmodic accretion events)



**type I X-ray bursts**
(thermonuclear events)




=> softening during decline

=> burst fluence ~ time since previous burst

=> recurrence times of several hours

=> envelope enriched with metals during burst

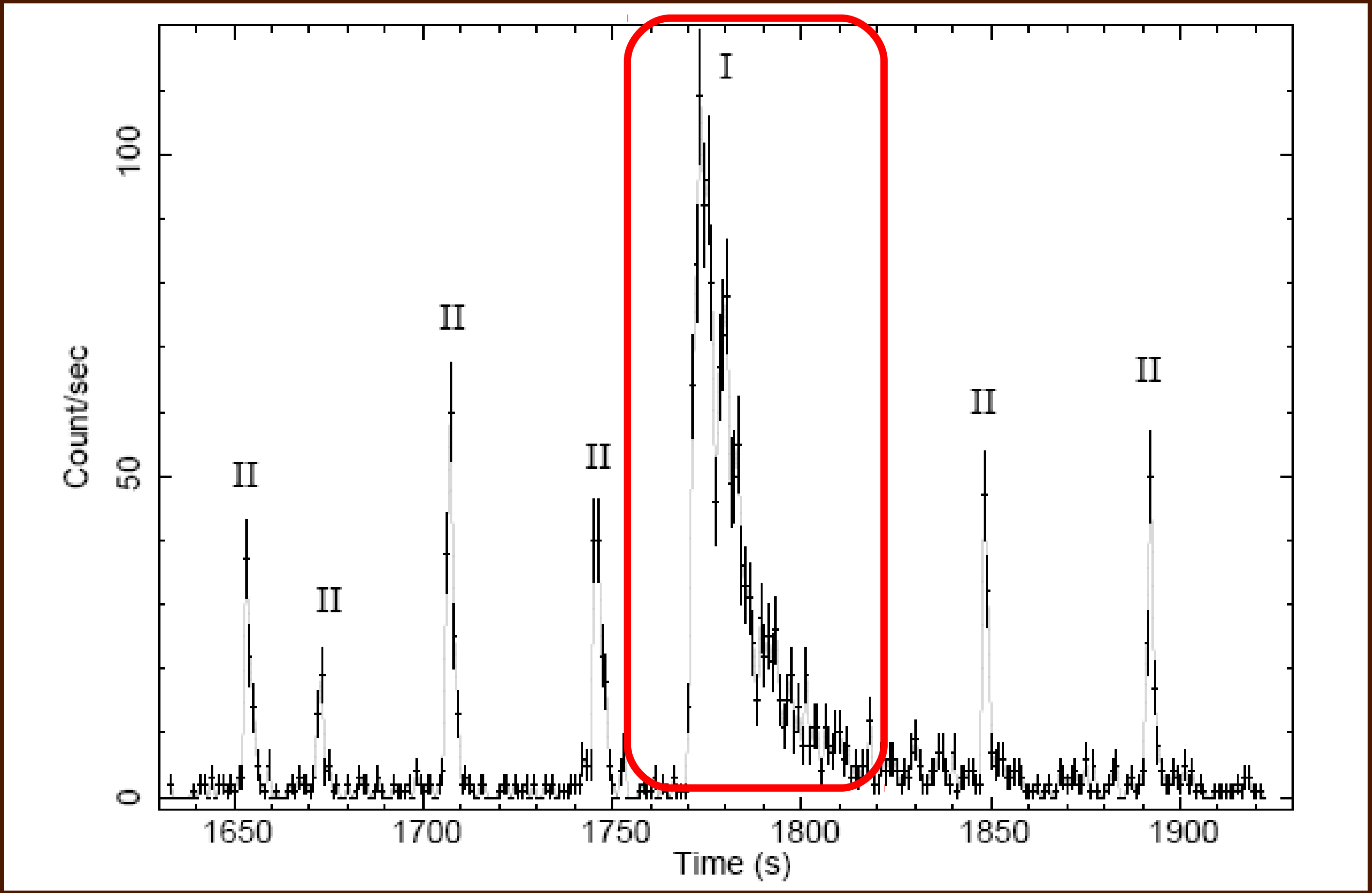
*=> recent hydrodynamic models with detailed nucleosynthesis by José et al 2010: "Hydrodynamic models of type I X-ray bursts: metallicity effects" ApJS 189, 204*

*see also Fisker et al 2008; Woosley et al 2004*

# CONSTRAINTS ON THE MASS AND RADIUS OF THE RAPID BURSTER

The Rapid Burster as LMXB,
outbursts occur every 100-200 days, last 2-4 weeks.
During outburst: increased persistent emission, type I and II X-ray bursts.

Swift /XRT observation on 2009 March 5




Sala et al. 2011 (ApJ submitted)

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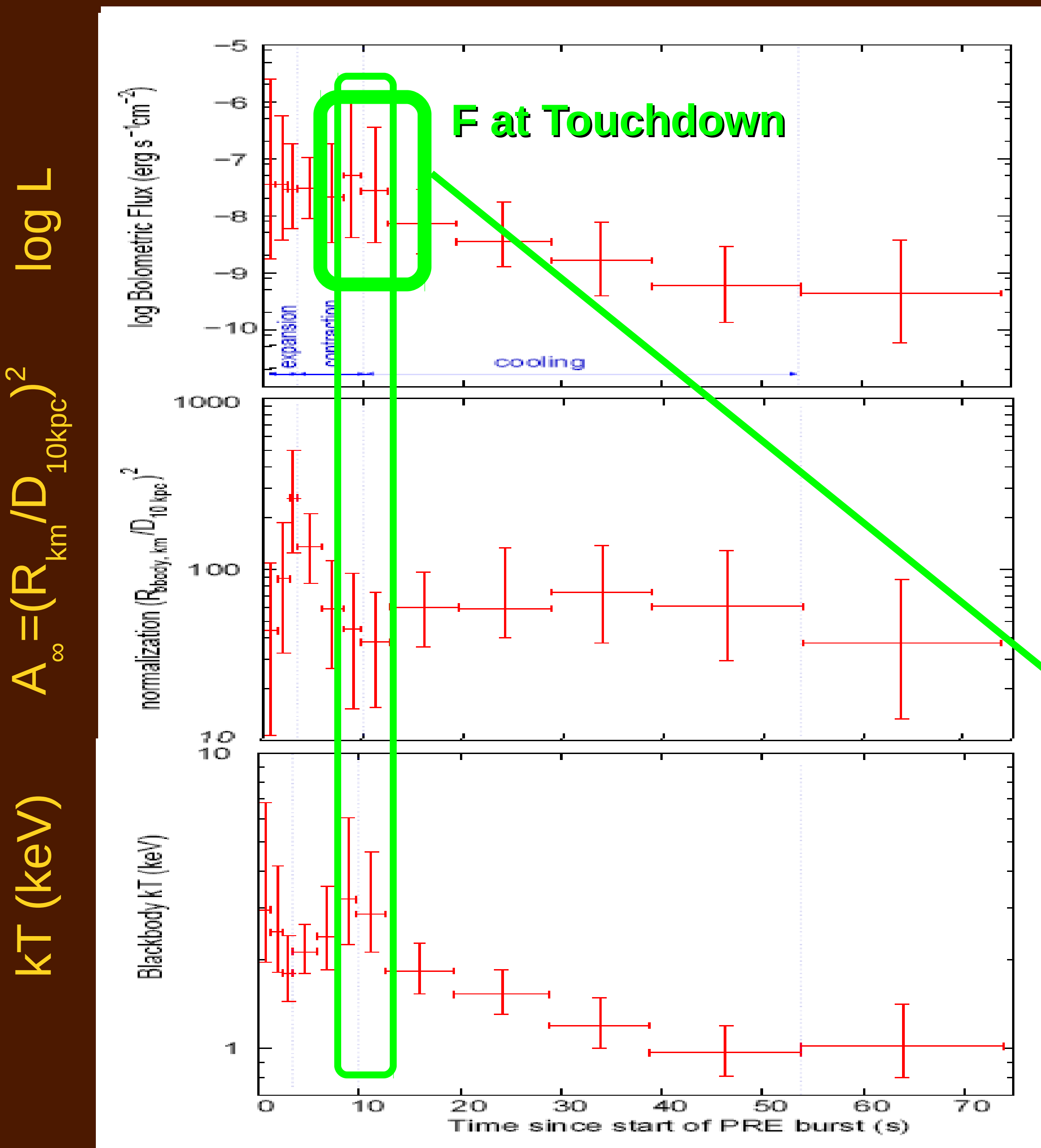



Photospheric Radius Expansion

↓

Luminosity at Eddington limit

↓

Constraint on the mass

$$F_\infty = \frac{GMc}{0.2(1+X)D^2}\left(1 - \frac{2GM}{Rc^2}\right)^{1/2}$$

with
D: distance
X: hydrogen mass fraction

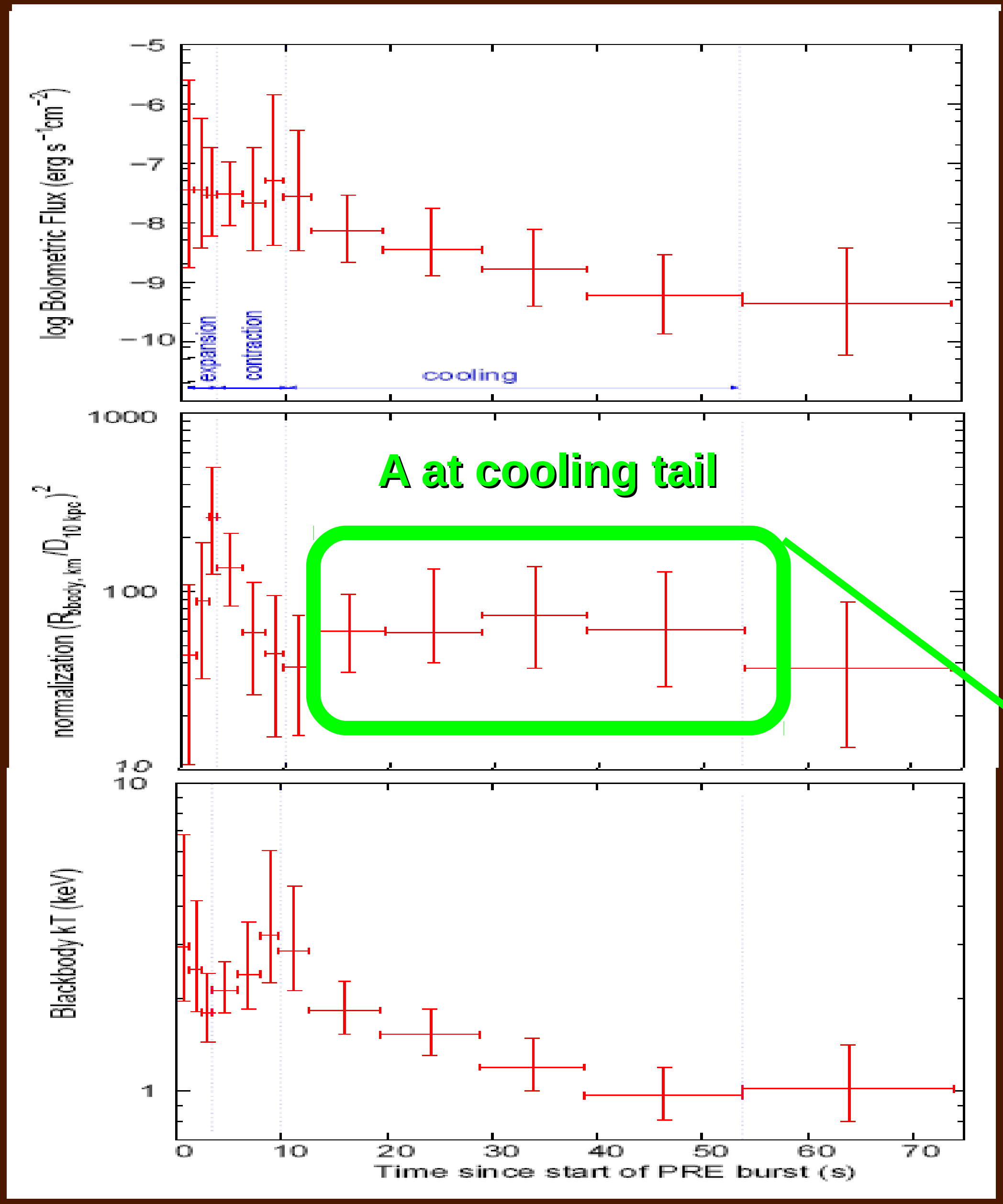
# CONSTRAINTS ON THE MASS AND RADIUS OF THE RAPID BURSTER

Sala et al. 2011 (ApJ submitted)

log L

$A_\infty = (R_{km}/D_{10kpc})^2$

kT (keV)




Photosphere recedes to NS surface

Emitting area during cooling tail

Constraint on the NS radius

$$A_\infty = \frac{R^2}{D^2 f_c^4}\left(1 - \frac{2GM}{Rc^2}\right)^{-1}$$

with

D: distance

$f_c = T_{bbody}/T_{eff}$: color correction factor

# CONSTRAINTS ON THE MASS AND RADIUS OF THE RAPID BURSTER

Mass and radius of neutron star can be determined from

Eddington flux ($F_\infty$) and Emitting area ($A_\infty$) by solving

$$F_\infty = \frac{GMc}{0.2(1+X)D^2}\left(1 - \frac{2GM}{Rc^2}\right)^{1/2}$$

$$A_\infty = \frac{R^2}{D^2 f_c^4}\left(1 - \frac{2GM}{Rc^2}\right)^{-1}$$

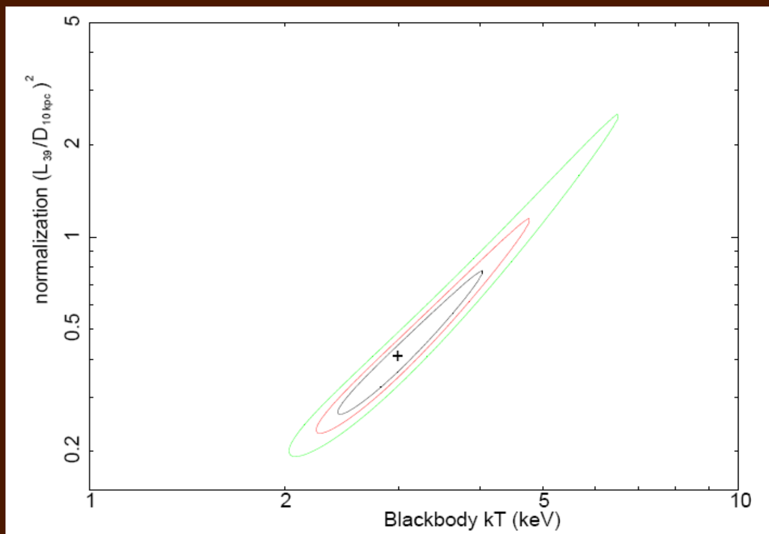
for given distance **D**, hydrogen abundance **X** and color correction factor. BUT

- X-ray data results ($F_\infty$, $A_\infty$) have a statistical uncertainty
- **D**, **X** and **$f_c$** are not well determined, a range of values is possible

## Bayesian approach (first used by Özel 2006):

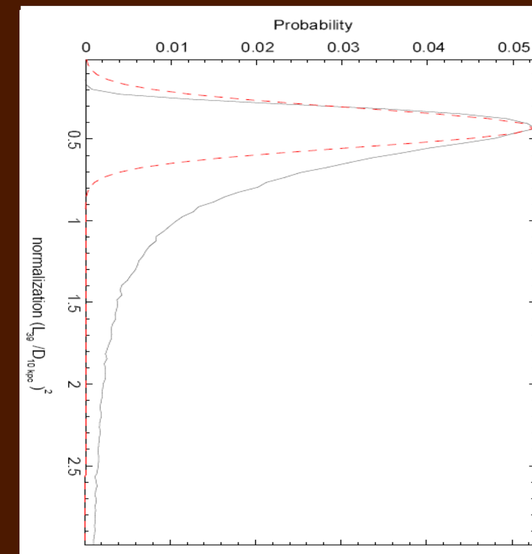
1 - Determine Probability Distribution Function (PDF) for results $F_\infty$, $A_\infty$

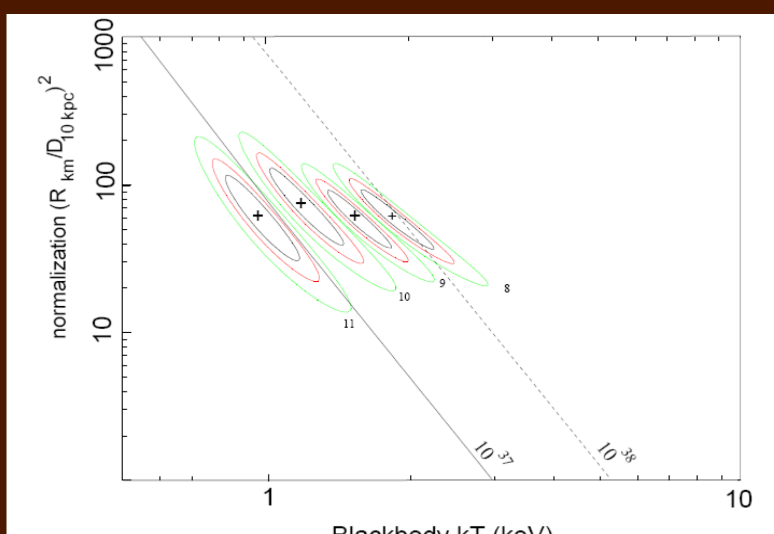
**a)** run MCMC on blackbody fit to touchdown and cooling tail spectra




**b)** marginalize over kT to have Probability Density Function of Eddington Flux,

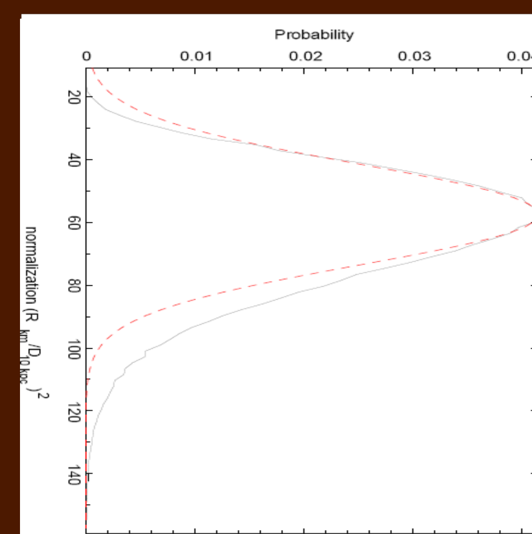
$P(F_\infty)dF_\infty$




and emitting area

$P(A_\infty)dA_\infty$




Sala et al. 2011 (ApJ submitted)

# CONSTRAINTS ON THE MASS AND RADIUS OF THE RAPID BURSTER

Bayesian approach:

1 - Determine Probability Distribution Function (PDF) for results,

$P(F_\infty)dF_\infty$ and $P(A_\infty)dA_\infty$

2 - Assign box-car PDF for **D**, **X** and **$f_c$** for all possible values

**D:** 5.8-10 kpc (Ortolani et al 2007)

**X:** 0 – 0.7

**$f_c$:** 1.3-1.4 (Suleimanov et al 2011, Madej et al 2004, Majczyna et al 2005. **SEE POSTER 51 by V. Suleimanov**).

Sala et al. 2011 (ApJ submitted)

Bayesian approach:

1 - Determine Probability Distribution Function (PDF) for results,

$$P(F_\infty)dF_\infty \text{ and } P(A_\infty)dA_\infty$$

2 - Assign box-car PDF for **D**, **X** and $\mathbf{f_c}$ for all possible values

3 - Determine PDF of NS mass P(M)dM and radius P(R)dR by

$$\mathbf{P(M)P(R)}\ \ P(D)P(X)P(f_C)\ \ dMdRdDdXdf_C =$$

$$\mathbf{J(MR}\mathit{DXf_C}\mathbf{|FA}\mathit{DXf_C}\mathbf{)}\ \mathbf{P(A_\infty)P(F_\infty)}\ \ P(D)P(X)P(f_C)\ dA_\infty dF_\infty dDdXdf_C$$

where $\mathbf{J(MR}\mathit{DXf_C}\mathbf{|FA}\mathit{DXf_C}\mathbf{)}$ is the Jacobian of the variable change

4 - marginalize over **D**, **X** and $\mathbf{f_c}$

Sala et al. 2011 (ApJ submitted)

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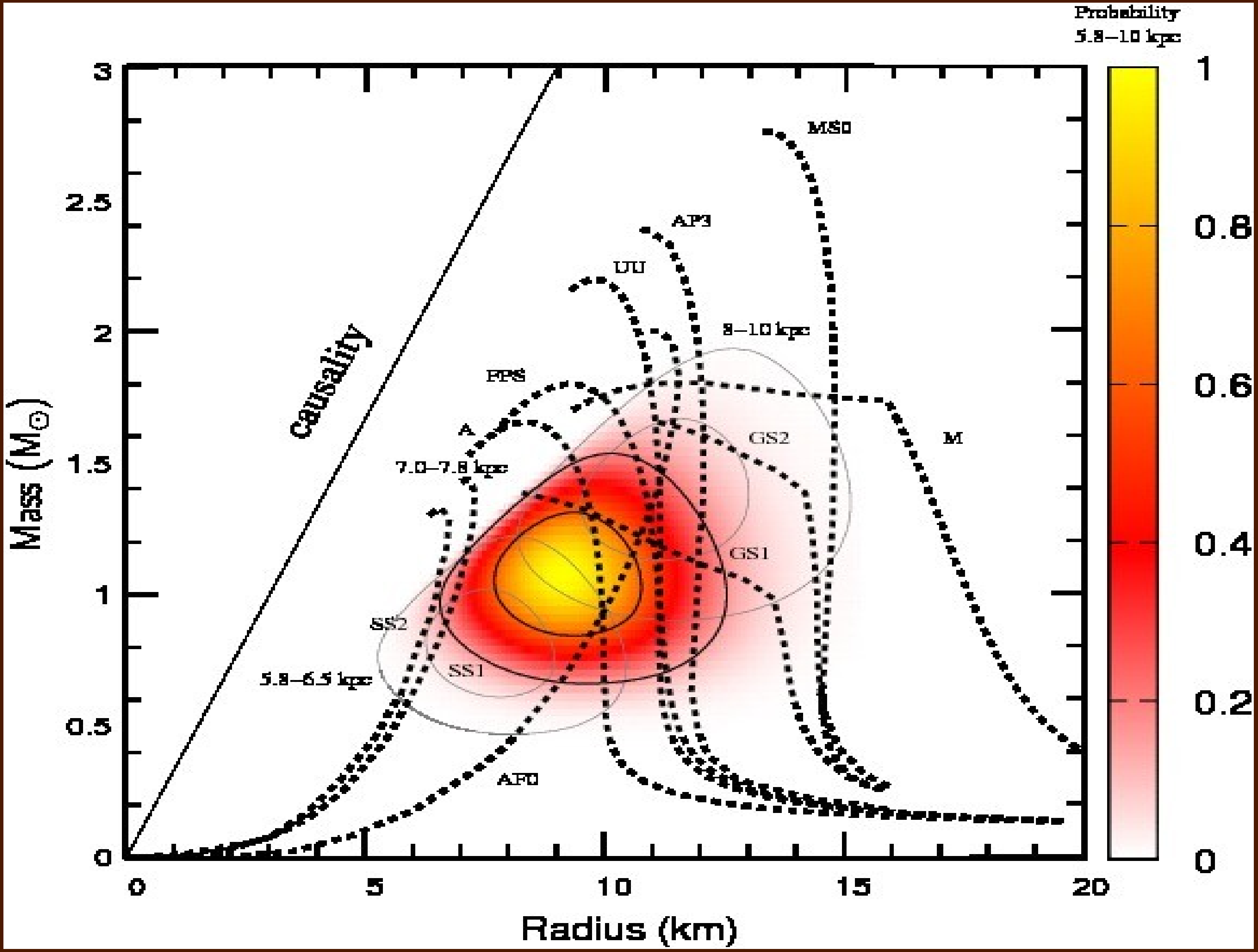


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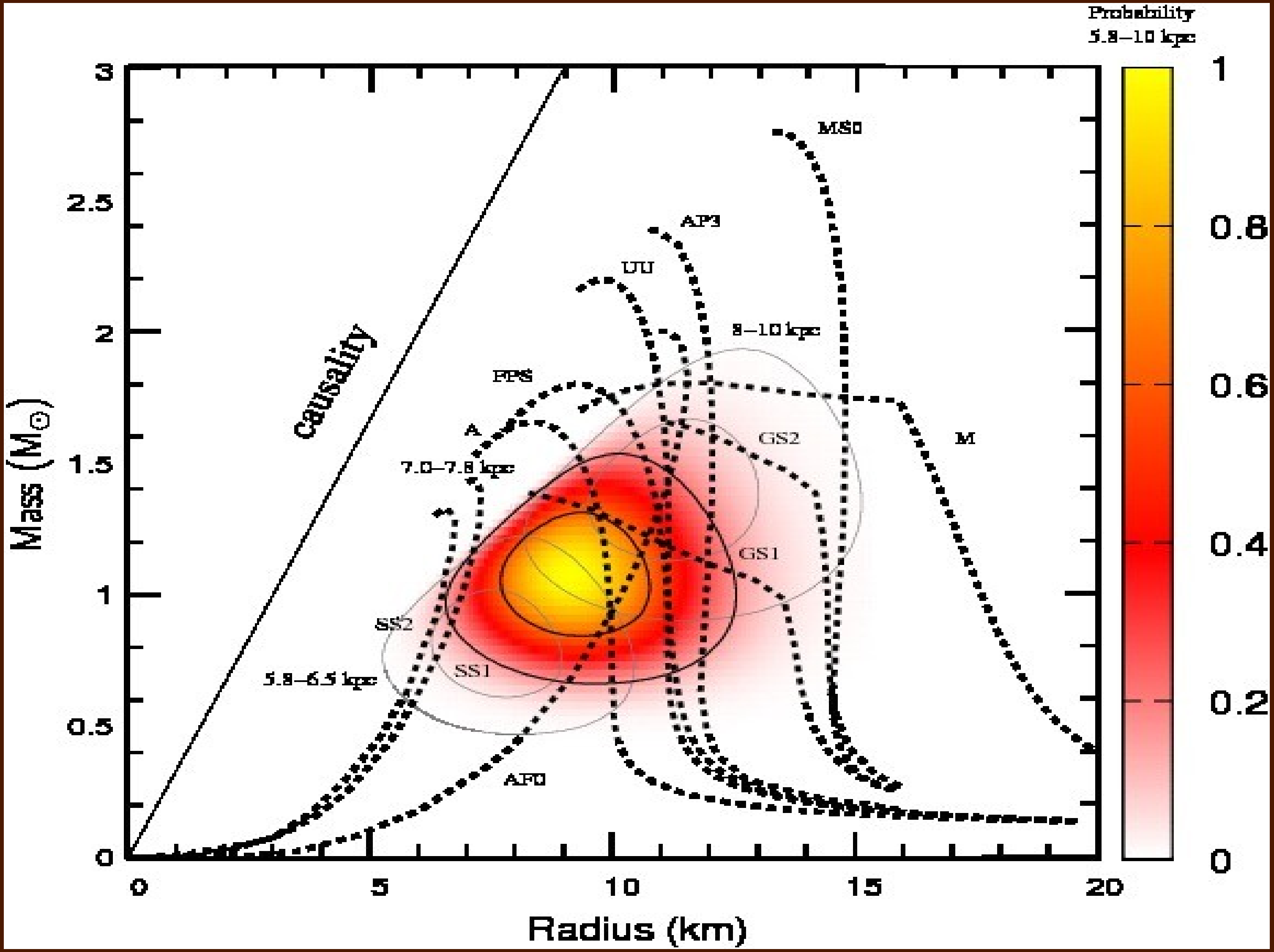
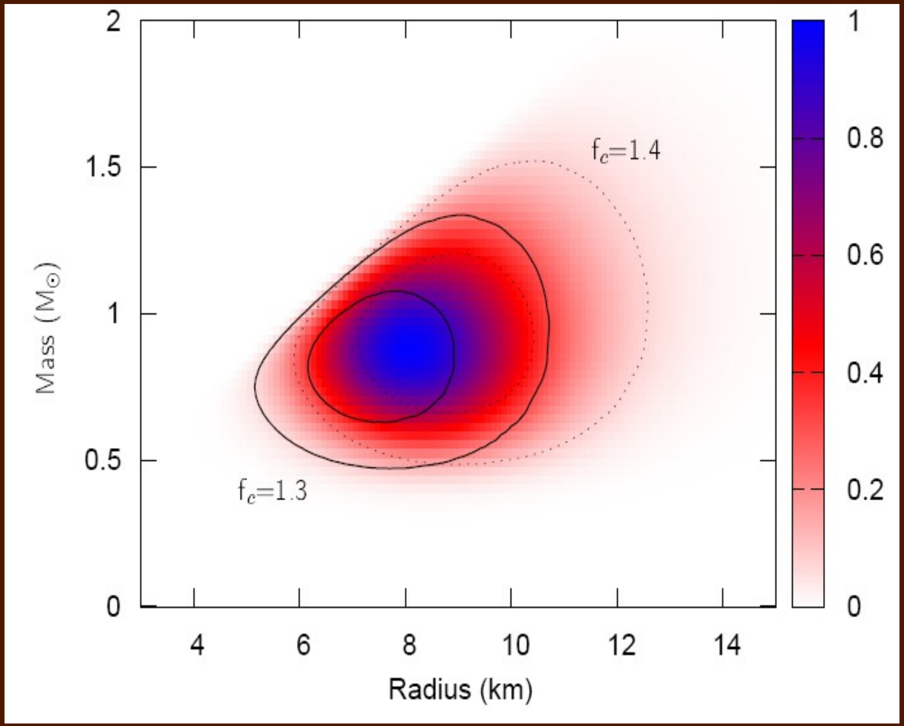


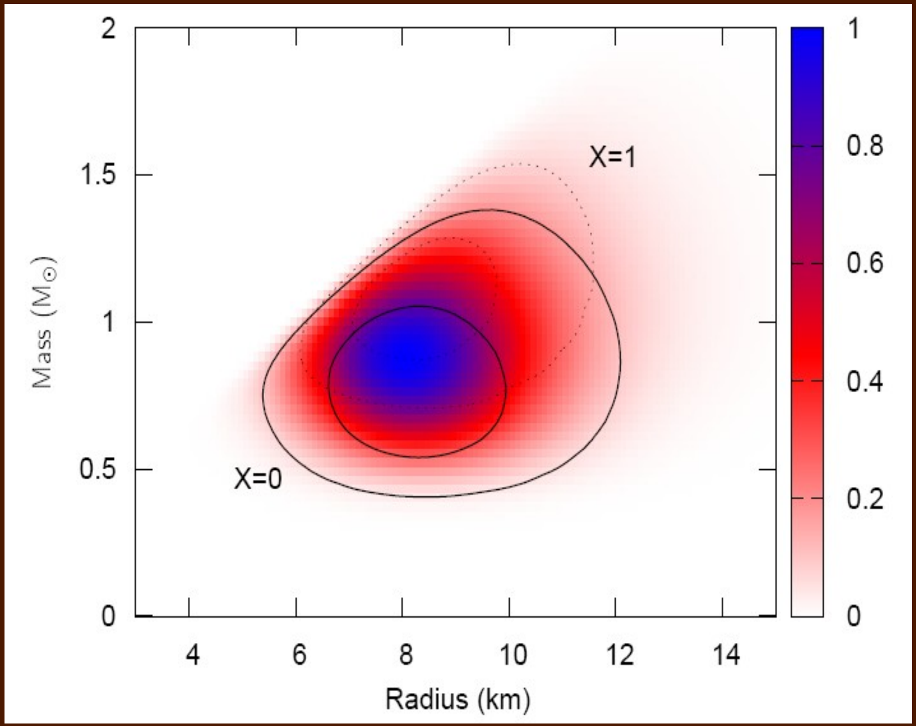

Sala et al. 2011 (ApJ submitted)

**Test on sensitivity** of results to different distances
(Ortolani et al 2007 with different calibration systems, Valenti et al 2010)

# CONSTRAINTS ON THE MASS AND RADIUS OF THE RAPID BURSTER

With statistical uncertainties of this case, **small sensitivity** of results to **X** and $\mathbf{f_c}$




Sala et al. 2011 (ApJ submitted)

- Eddingotn limited bursts =>
**smaller** statistical **uncertainties** in M & R determination.

*Then results more sensitive to X and colour correction factor =>*
*more **important** role of **modeling** of **nucleosynthesis** and **atmospheres***

*Note systematic uncertainites remain but are small enough to distinguish EOS,*
*according to Güver et al 2011a,arXiv: 1103.5767: 3-7 % in NS radii*
*2011b, arXiv:1104.2602: 5-10% in Eddington luminosity*

- Absoprtion features in X-ray bursts => measure gravitational redshift

- Discovery of **new** X-ray bursters during survey phase

# SUMMARY

- From Eddington limited X-ray burst of the Rapid Burster we determine

$$M = 1.1 +/- 0.2\ M_o$$
$$R = 9.6 +/- 1.5\ \text{km}$$

- Within statistical uncertainties, results sensitive to **distance** but not to **X** or $\mathbf{f_c}$

*For eROSITA results with smaller uncertainties, more relevant modeling giving **X** and $\mathbf{f_c}$*

- ***Small mass for the NS in the Rapid Burster.***

*Canonical 1.4 $M_o$ only for D> 8 kpc. But extinction and metalicity of cluster hosting RB argue against large distance => not behind the Galactic Center*

- Rapid Burster NS **compatible** with **strange quark matter EOS** for shortest distances.

**More details in Sala et al. 2011 (ApJ submitted)**