

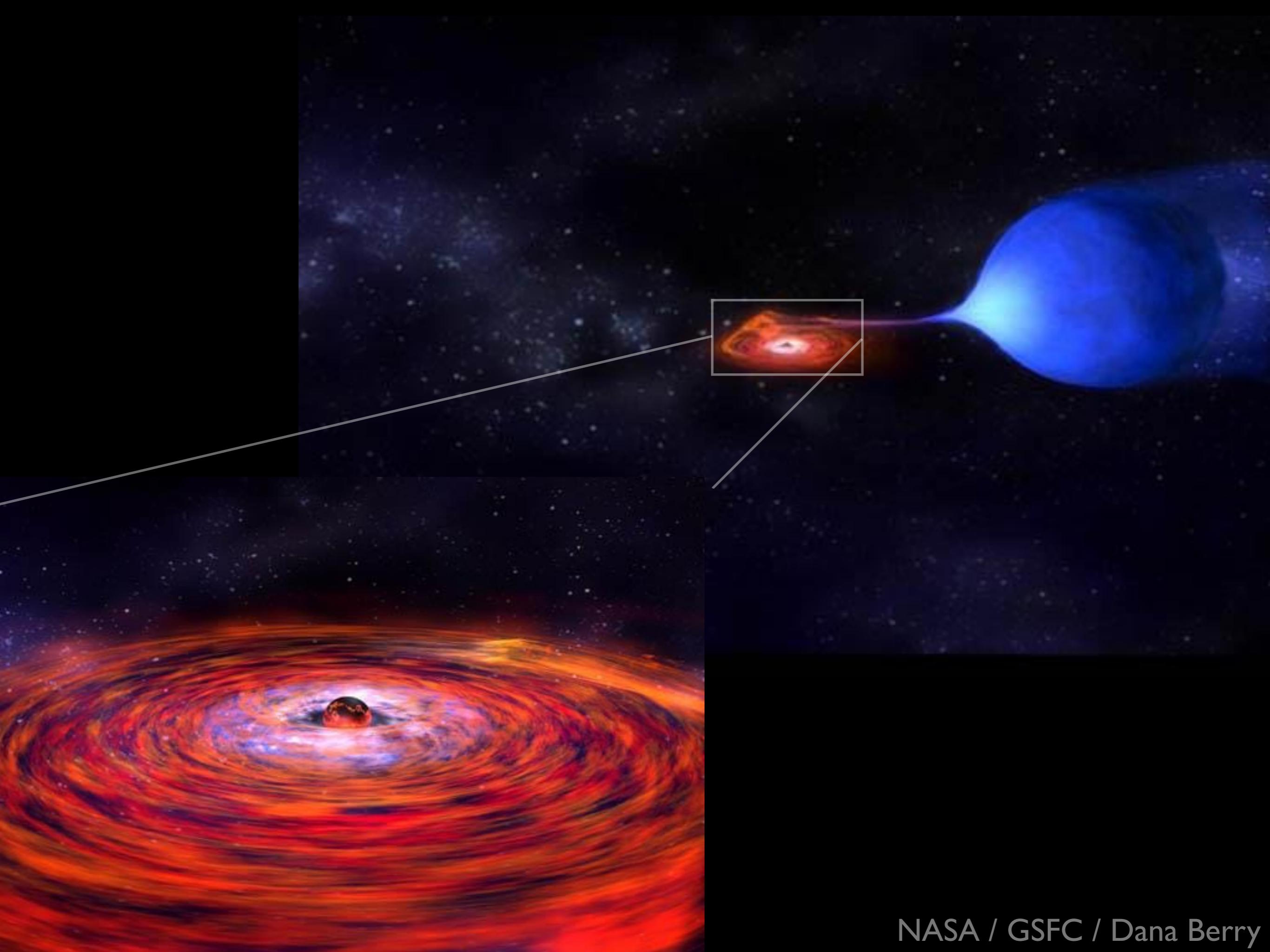


# Direct atmosphere model fits of X-ray bursts: New neutron star radius constraints

**Joonas Nättilä**

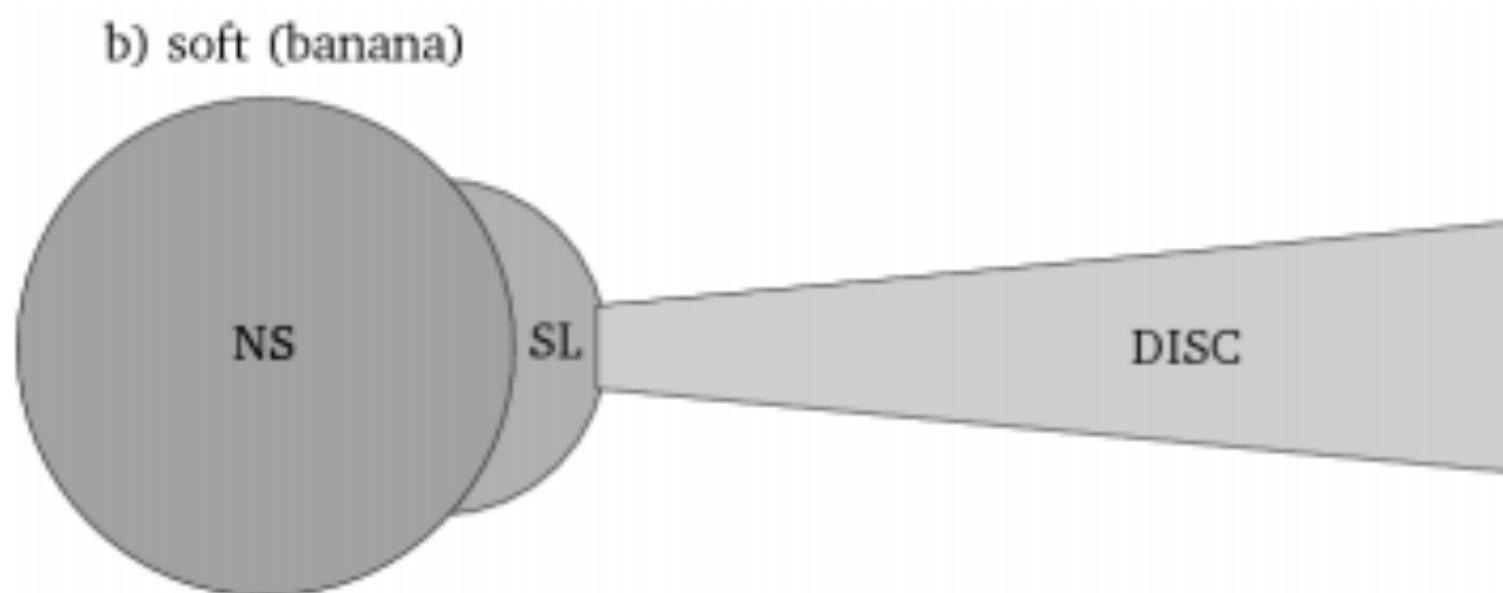
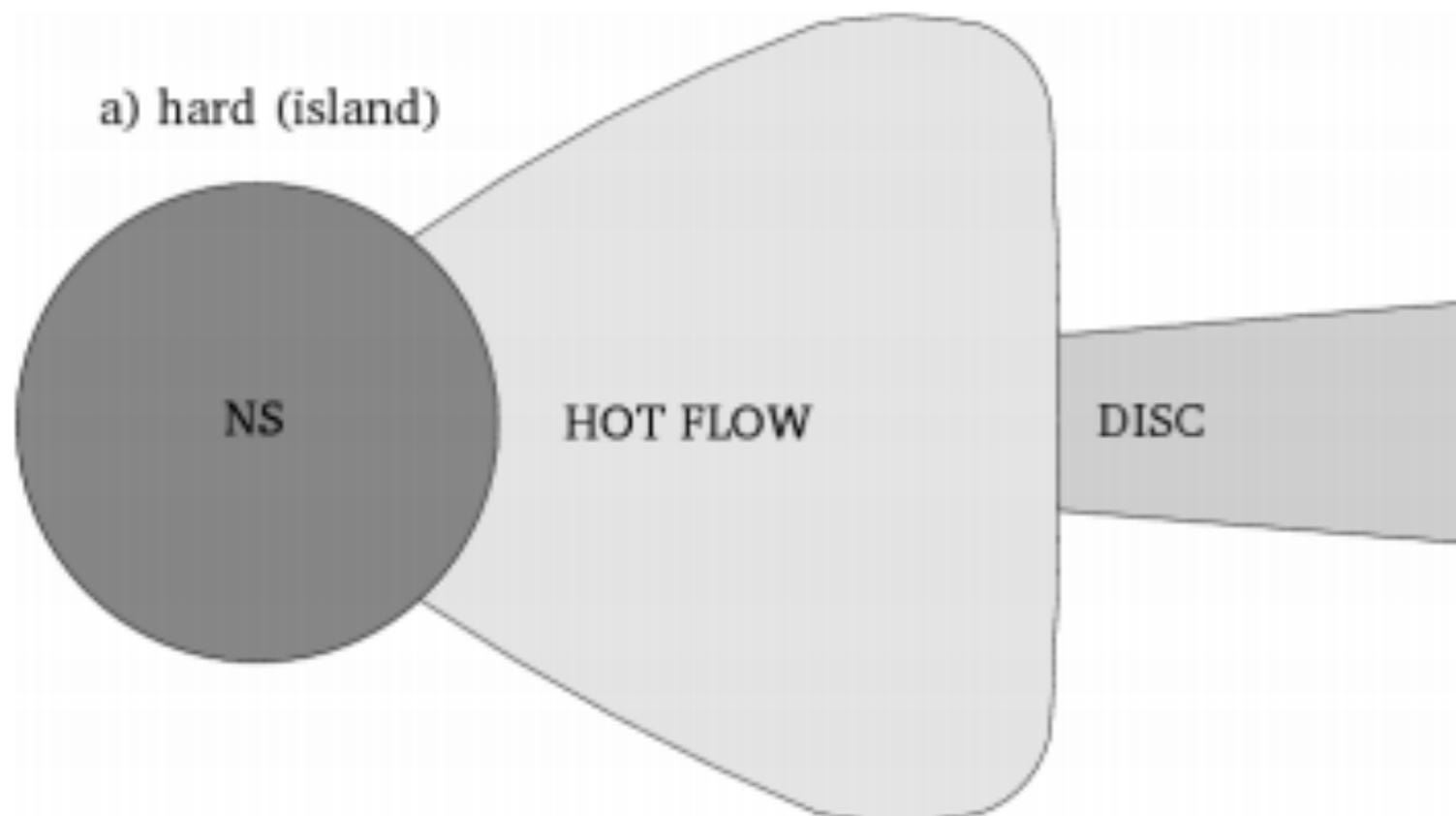
Tuorla Observatory, Univ. Turku  
Nordita, KTH & Univ. Stockholm

J. Kajava, A.W. Steiner, M.C. Miller, E. Annala,  
A. Vuorinen, A. Kurkela, V.F. Suleimanov, J. Poutanen



NASA / GSFC / Dana Berry

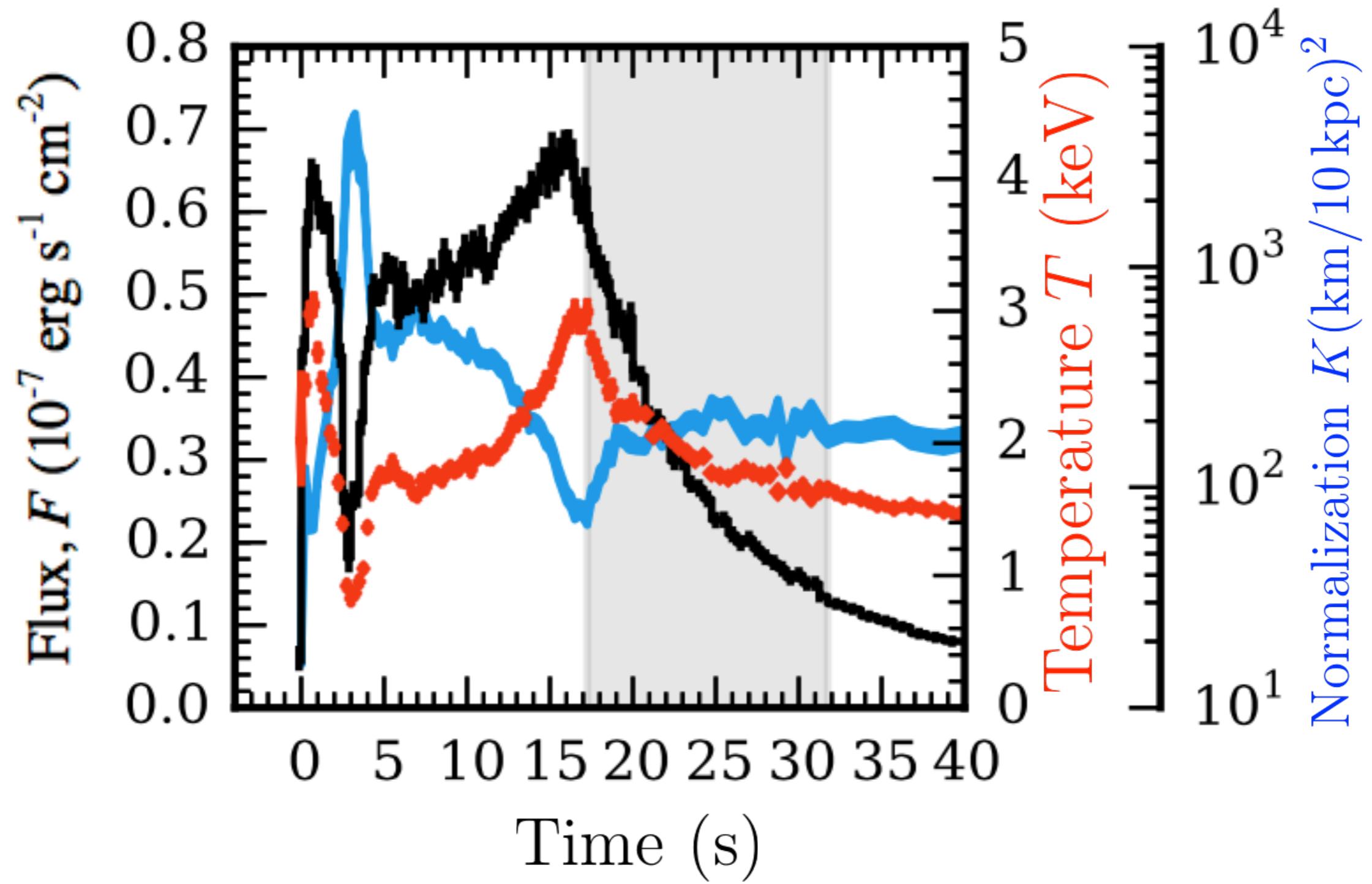
# Physical setup



**Hard state**  
Low accretion rate

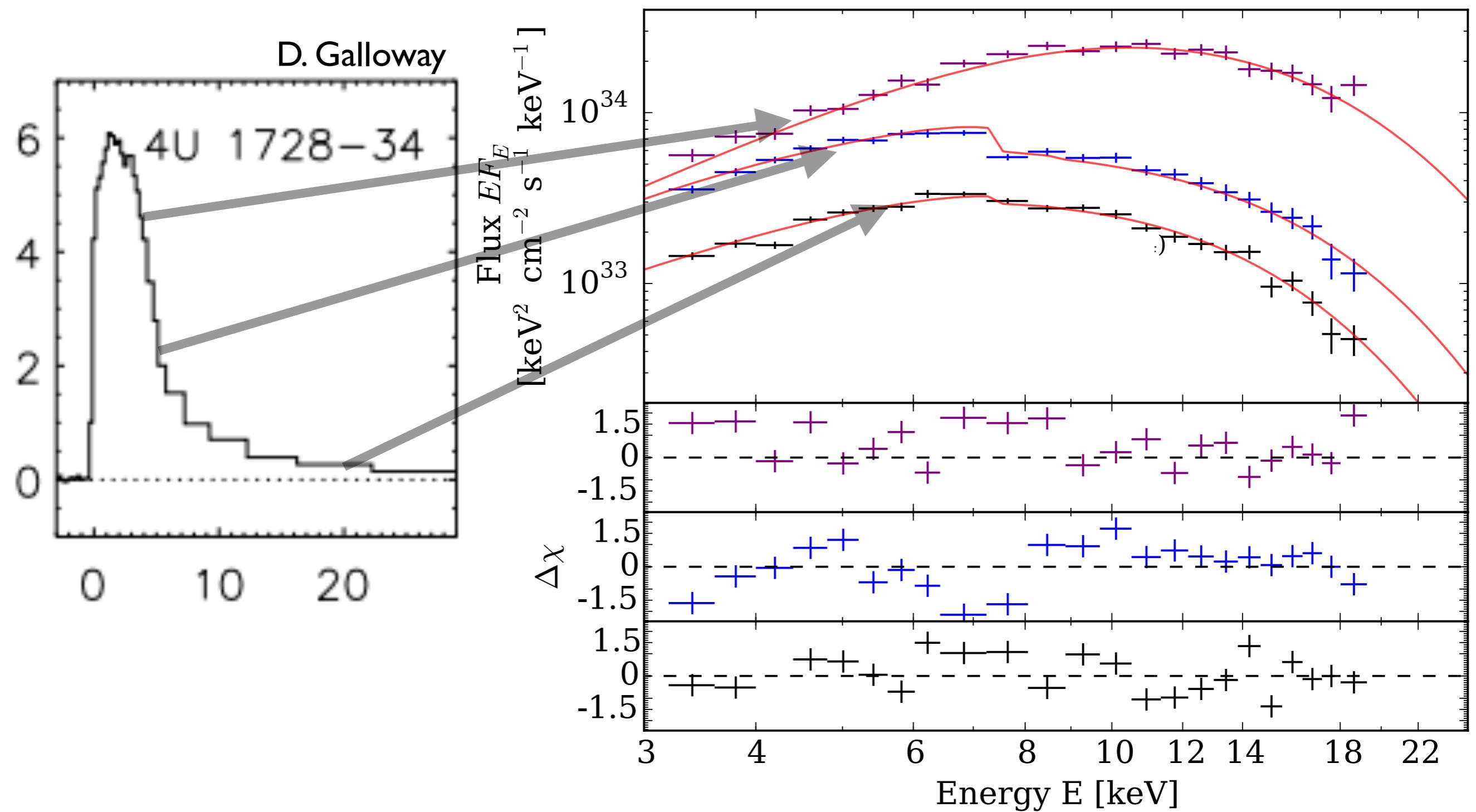
**Soft state**  
High accretion rate

# Thermonuclear X-ray bursts



# Thermonuclear X-ray bursts

## Time-resolved spectroscopy



# Atmosphere models

$$\frac{dP_g}{dm} = g - g_{\text{rad}}, \quad dm = -\rho ds,$$

Hydrostatic equilibrium

$$\mu \frac{dI(x, \mu)}{d\tau(x, \mu)} = I(x, \mu) - S(x, \mu),$$

Radiative transfer

$$\sigma(x, \mu) = \kappa_e \frac{1}{x} \int_0^\infty x_1 dx_1 \int_{-1}^1 d\mu_1 R(x_1, \mu_1; x, \mu) \left( 1 + \frac{C I(x_1, \mu_1)}{x_1^3} \right), \quad \text{Electron opacity}$$

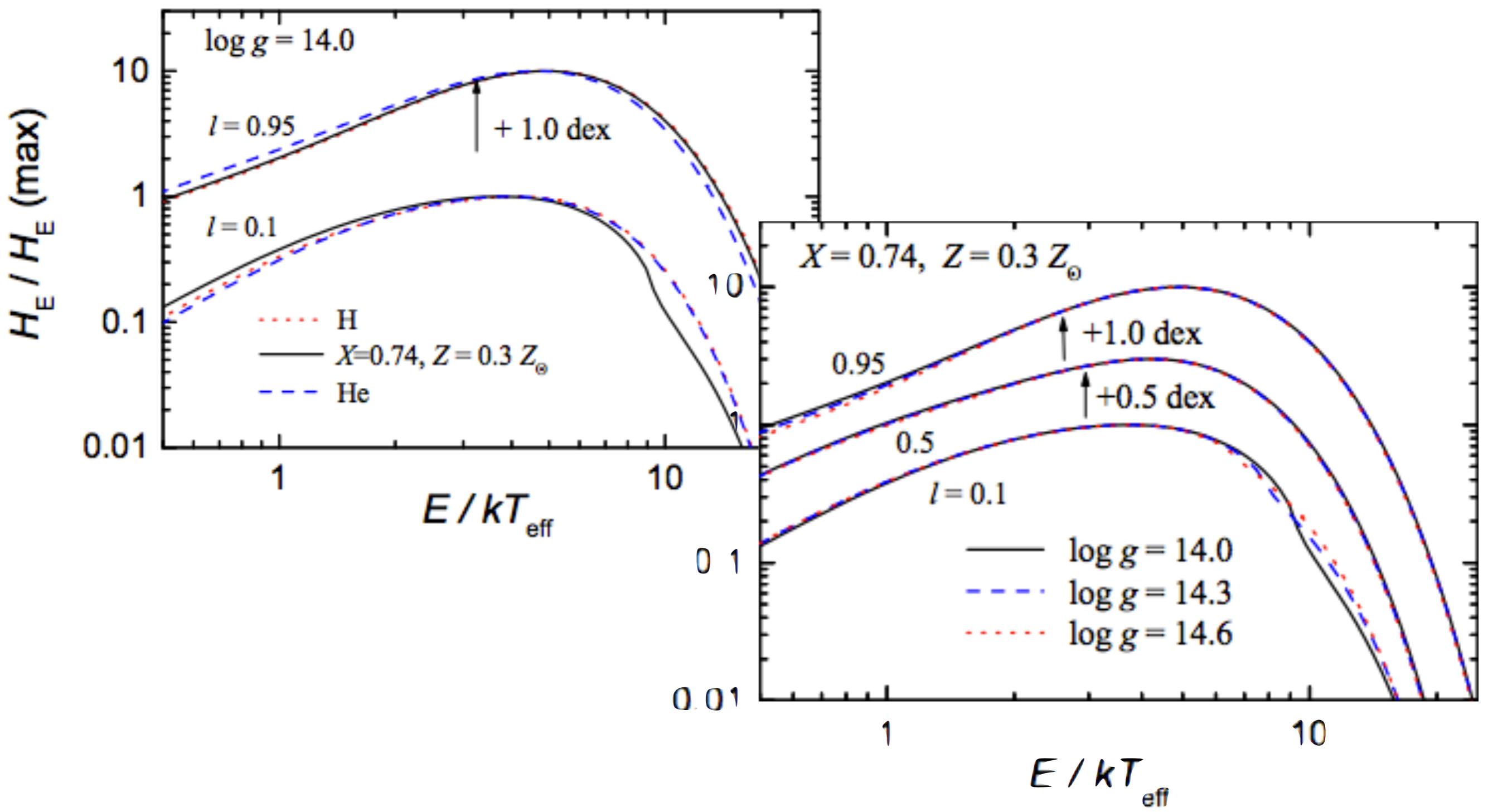
$$\int_0^\infty dx \int_{-1}^{+1} [\sigma(x, \mu) + k(x)] [I(x, \mu) - S(x, \mu)] d\mu = 0,$$

Energy balance

$$P_g = N_{\text{tot}} kT,$$

Ideal gas law

# Atmosphere models



# Time-resolved spectroscopy

## Old observationally driven method:

- Describe spectra with black bodies
  - Temperature
  - Area normalization

Degrees of freedom = #(of parameters)  $\times$   
                                  #(of spectra)

$= \sim 200$

# Time-resolved spectroscopy

## New physically driven method

Describe spectra with atmosphere models

- Temperatures +
  - NS radius
  - NS mass
  - Composition
  - Distance

Degrees of freedom = #(of parameters)  $\times$  #(of spectra)  
+ #(global parameters)  
 $\approx 100 + 4$

# The problem

$$P(p_j|\mathcal{D})(p_j) \propto \int \int \int \int \dots \int \int \int P(\mathcal{D}|\mathcal{M}) dp_1 \dots dp_{j-1} dp_{j+1} \dots dp_N$$



x100 - 300

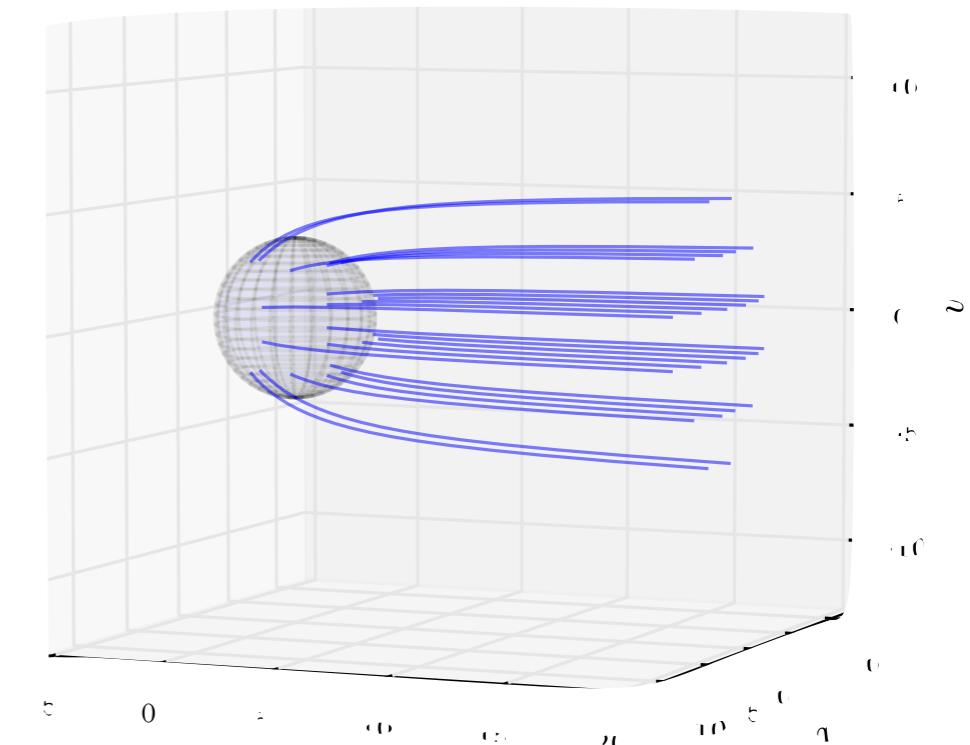
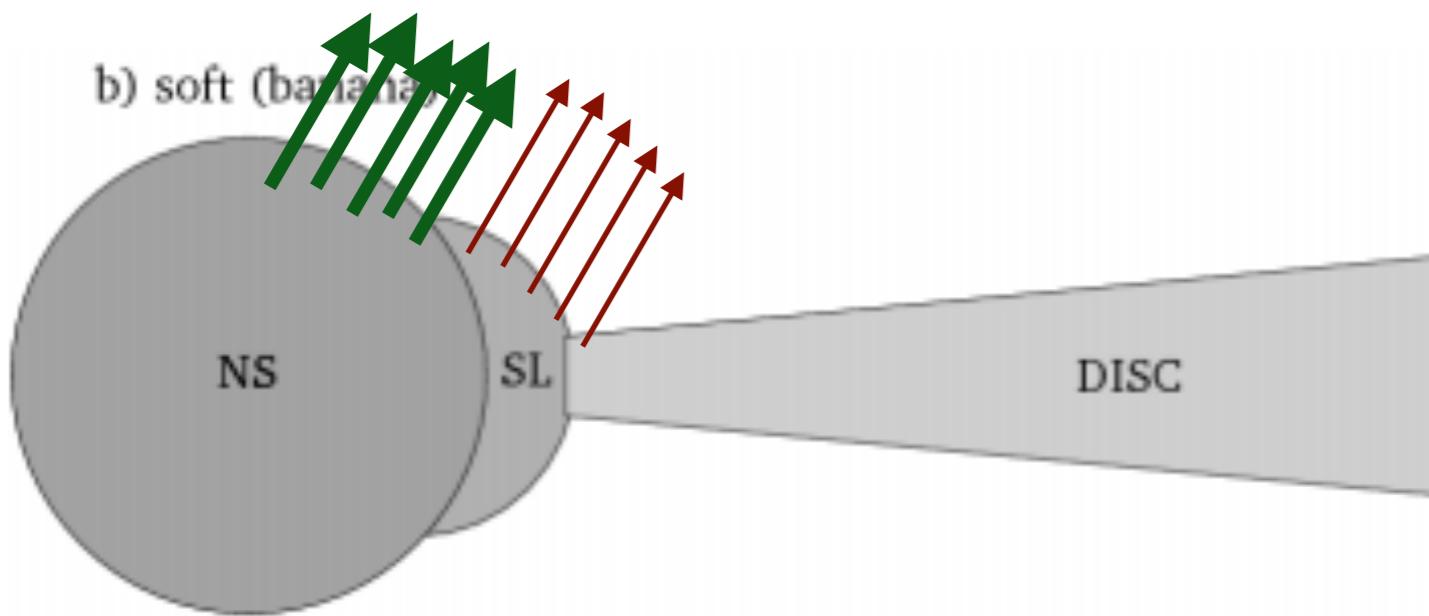
# The solution



Thanks to Finnish super computing center,  
we can just bruteforce it!

# Assumptions

- Low B field
  - should be ok
- Isotropic emission from passively cooling NS
  - ok sometimes!
  - starting to be ok
- Rotation
  - no assumptions
- Touchdown/Edd. limit

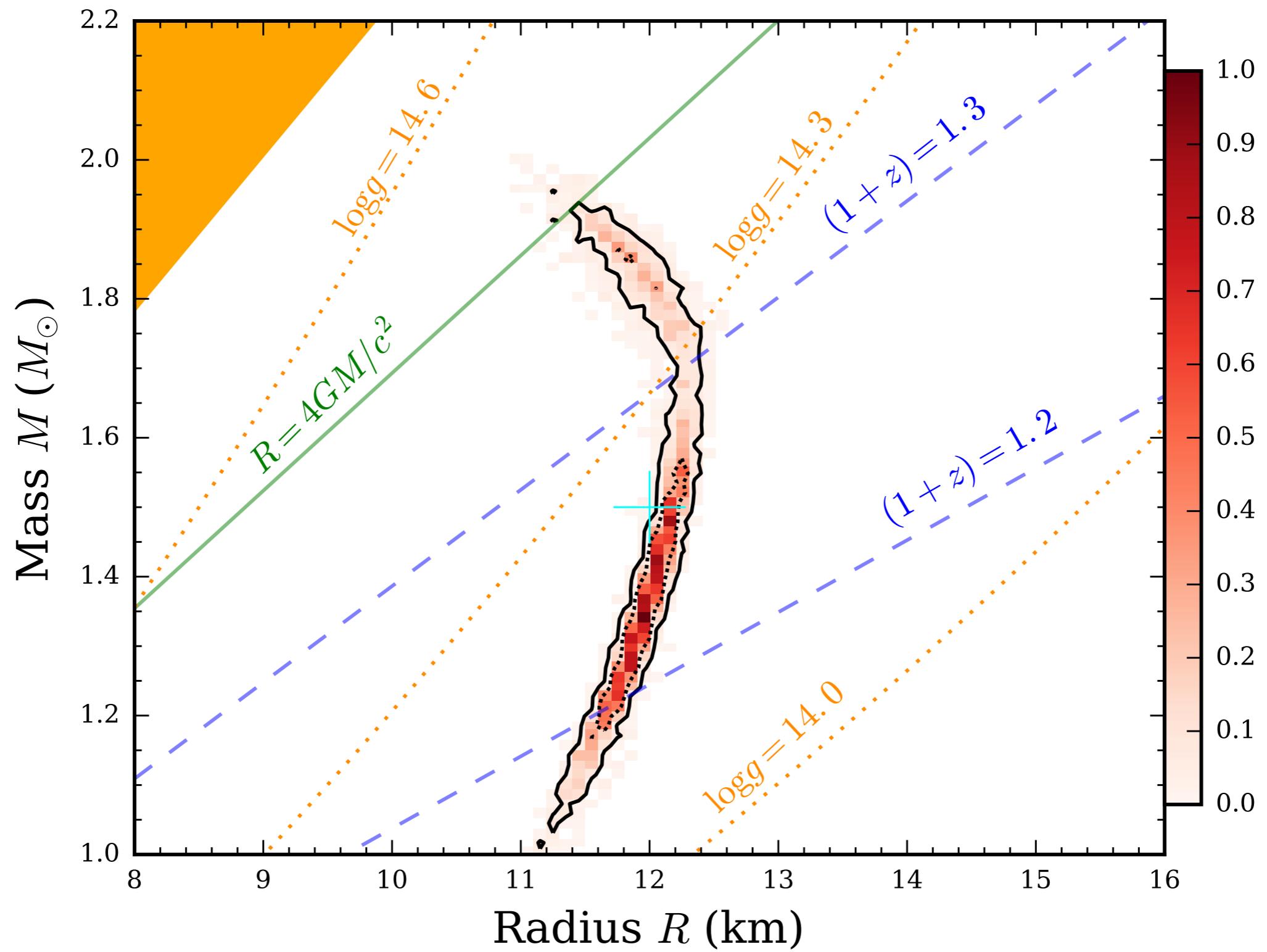


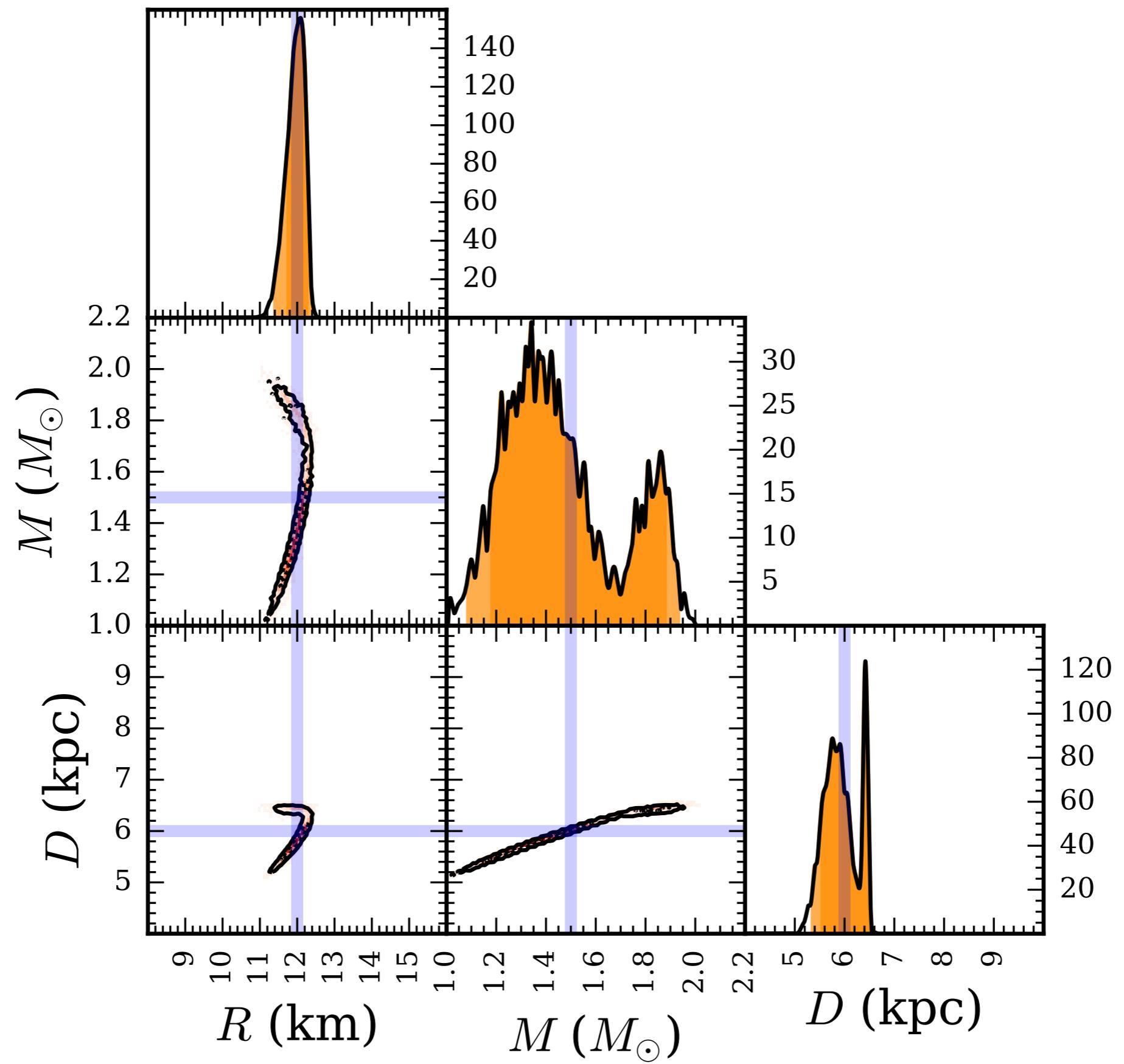
# Synthetic data

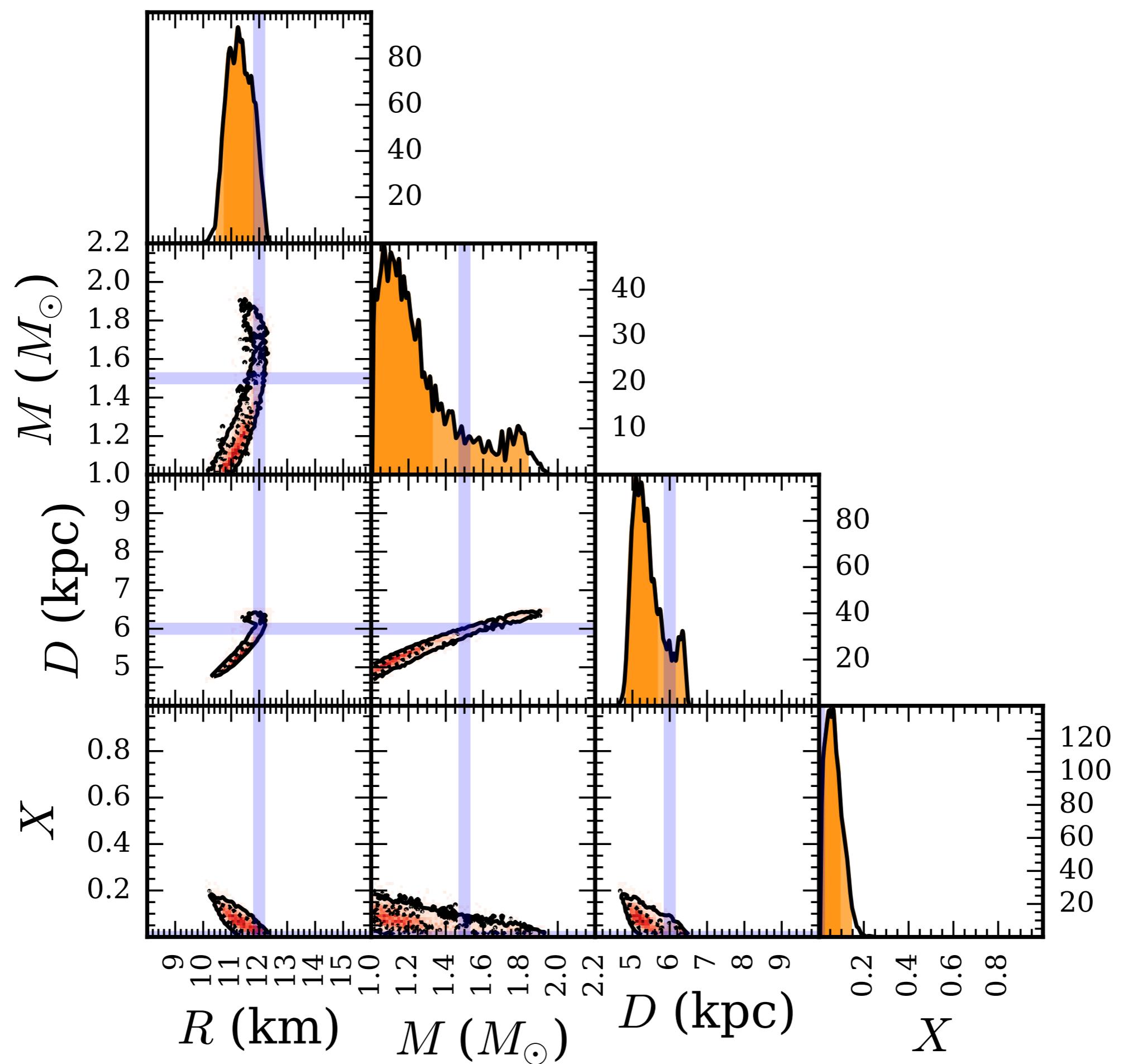
What is the ideal case for us?

How precise can we hope to measure  
things?

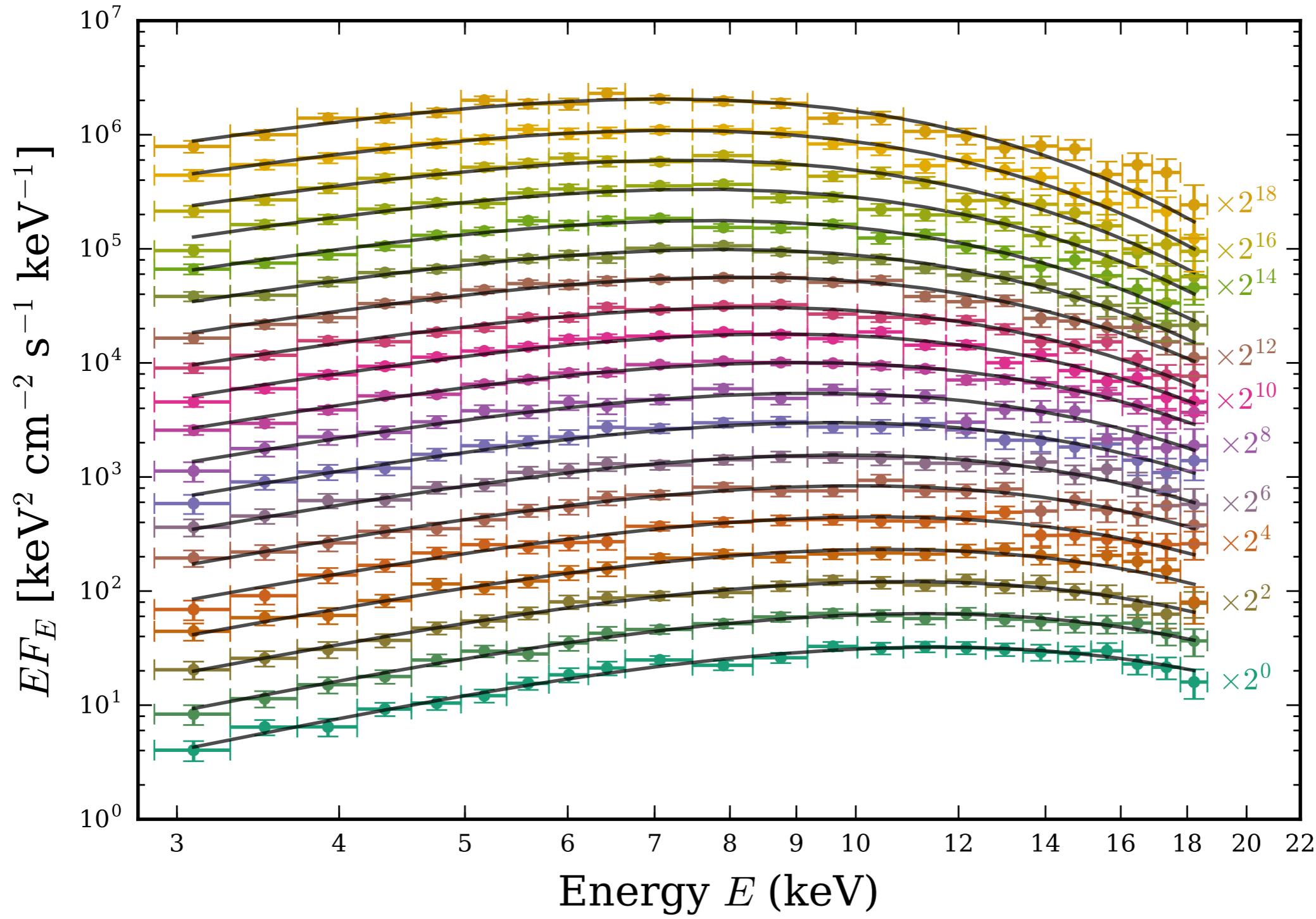
# Synthetic data



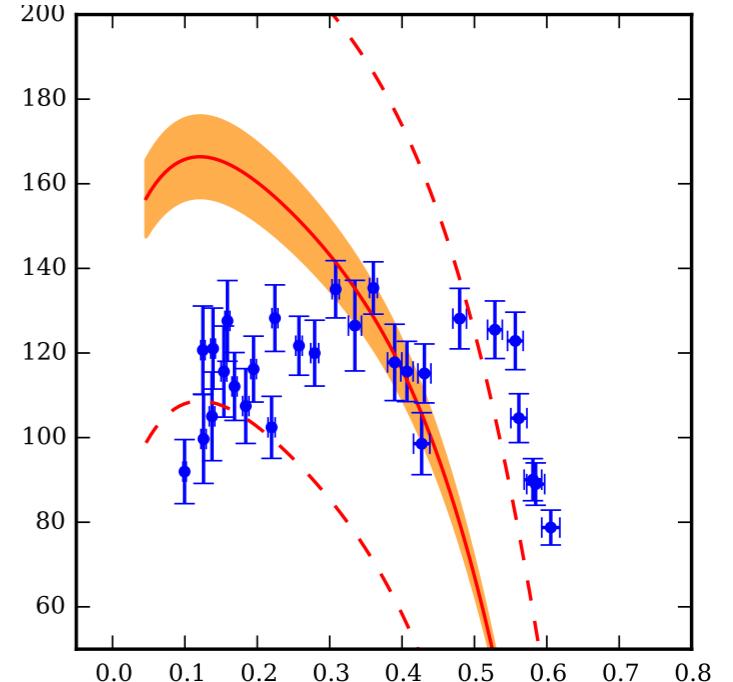
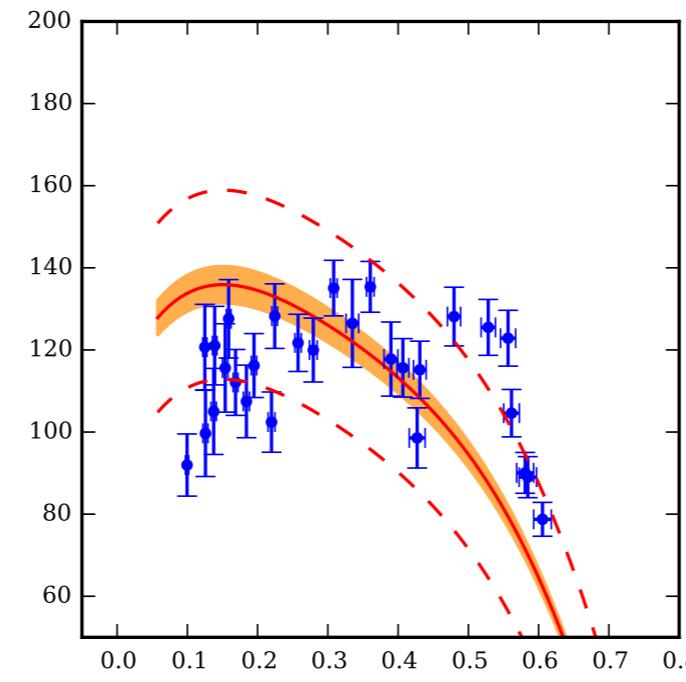
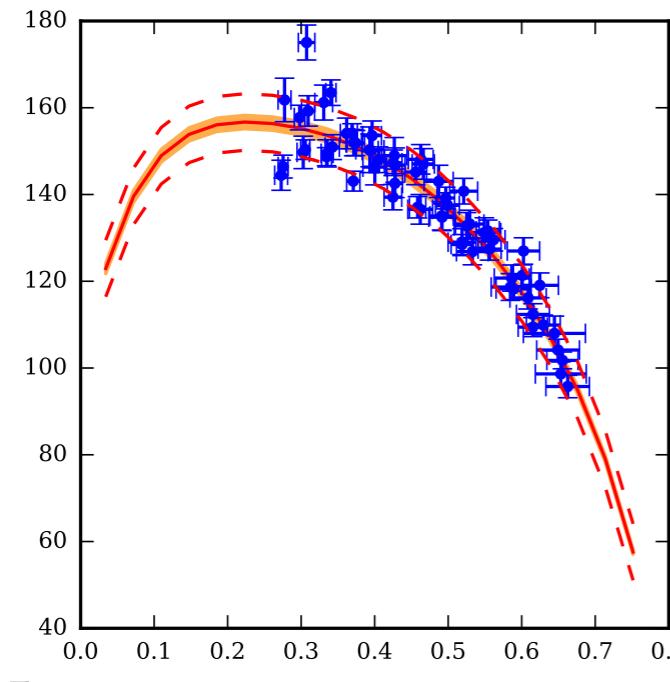
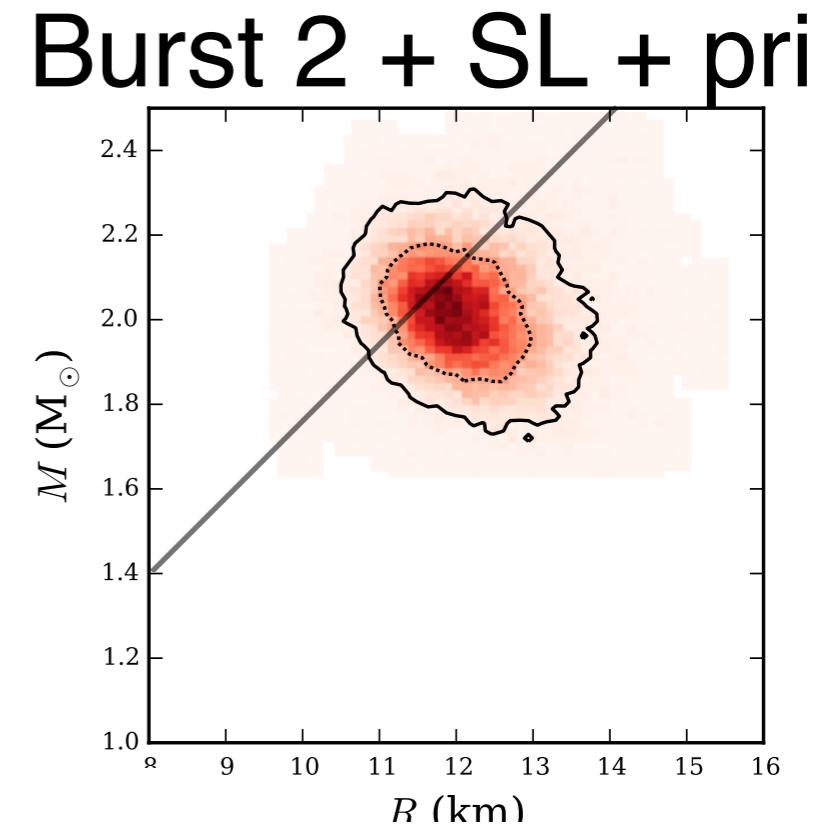
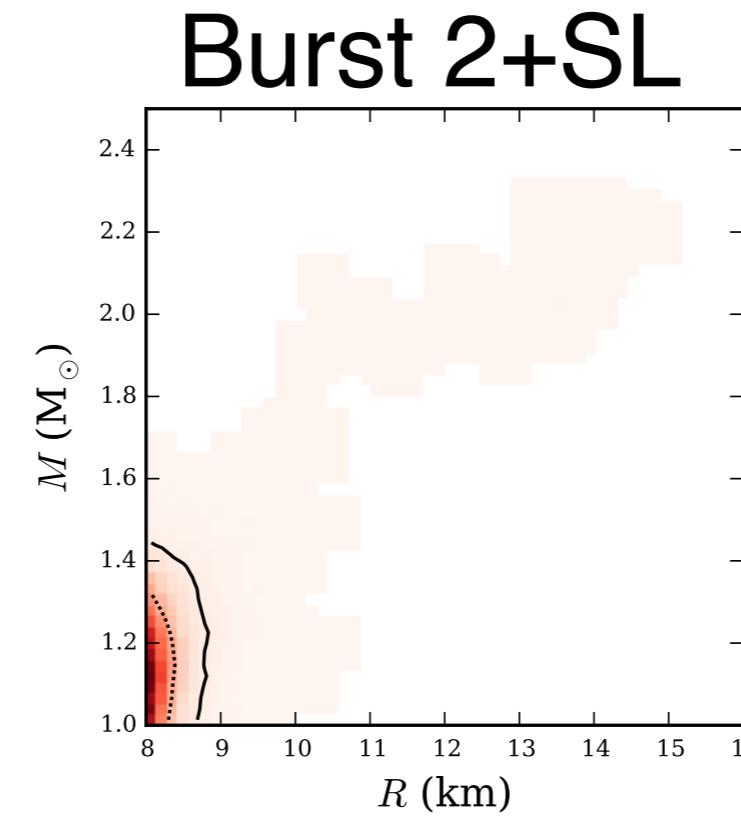
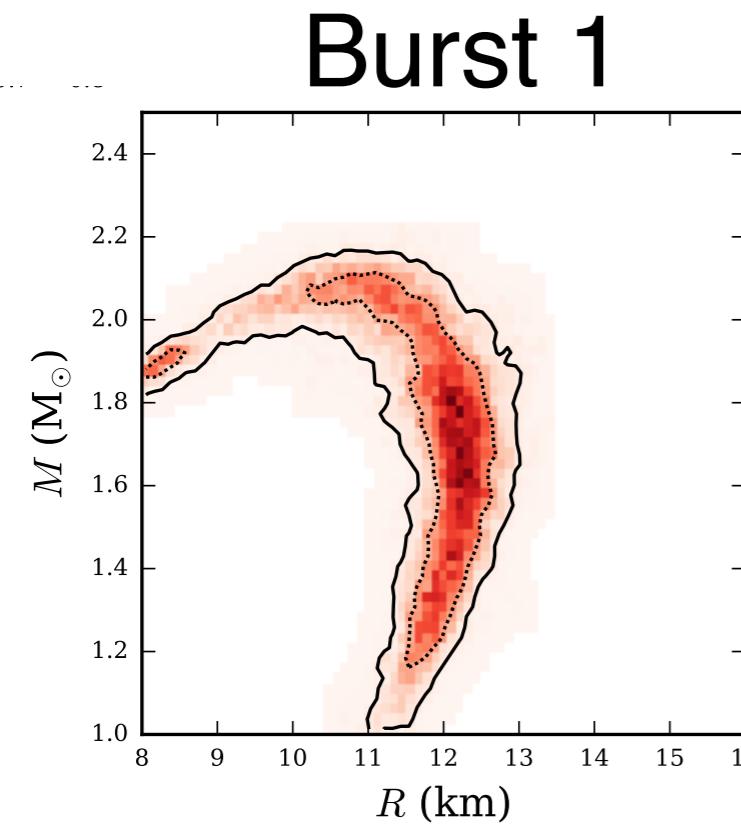




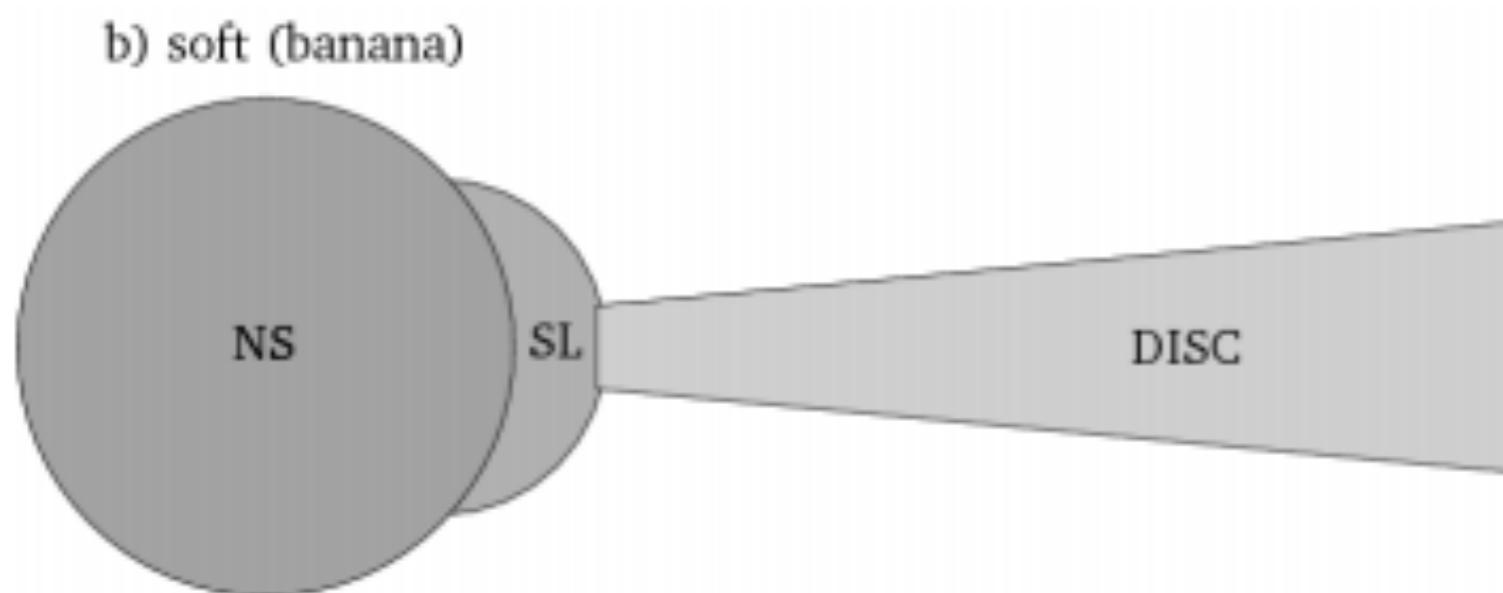
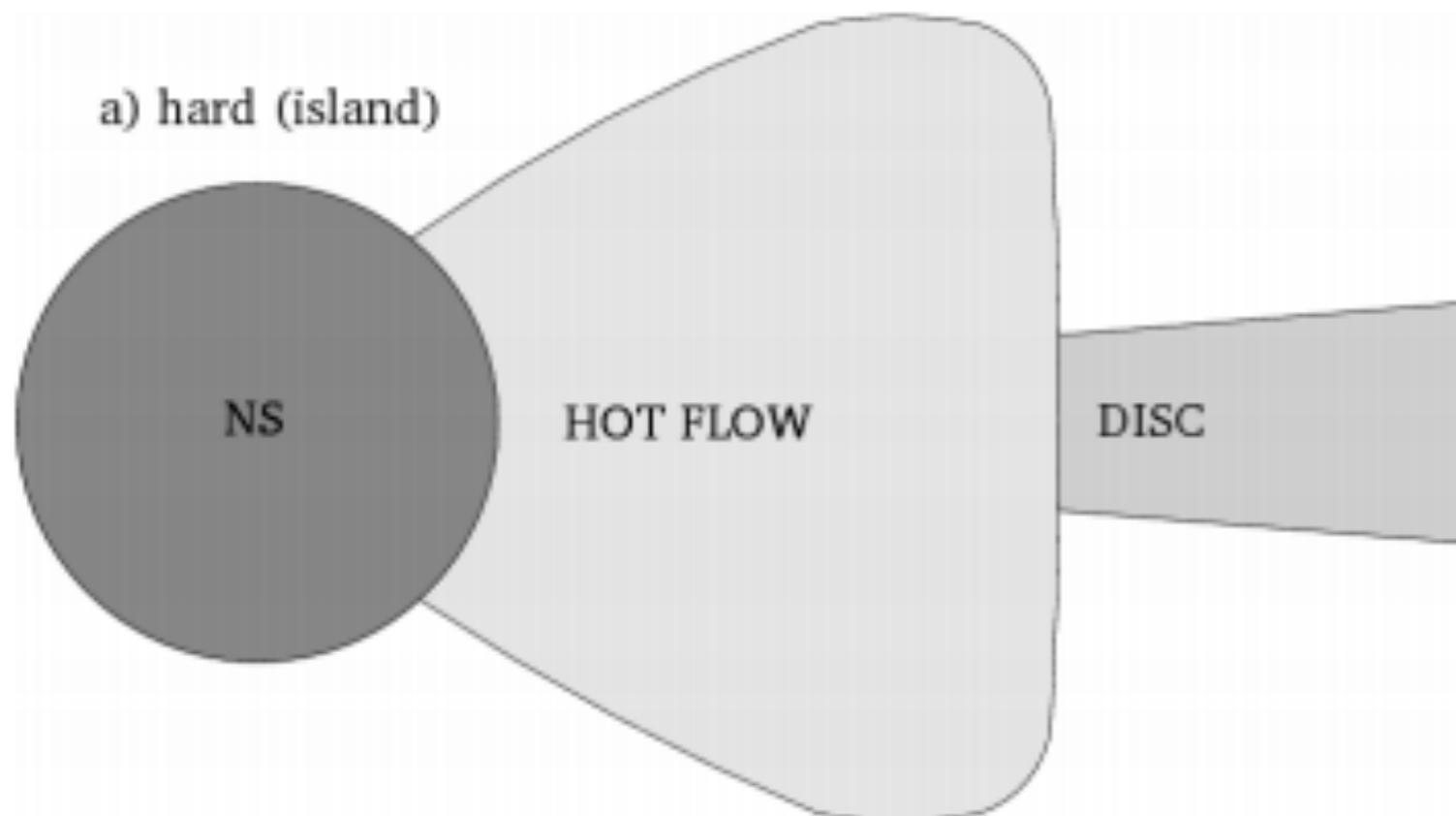
# Real data...



...turns out to be not so simple!



# Remember the physical setup



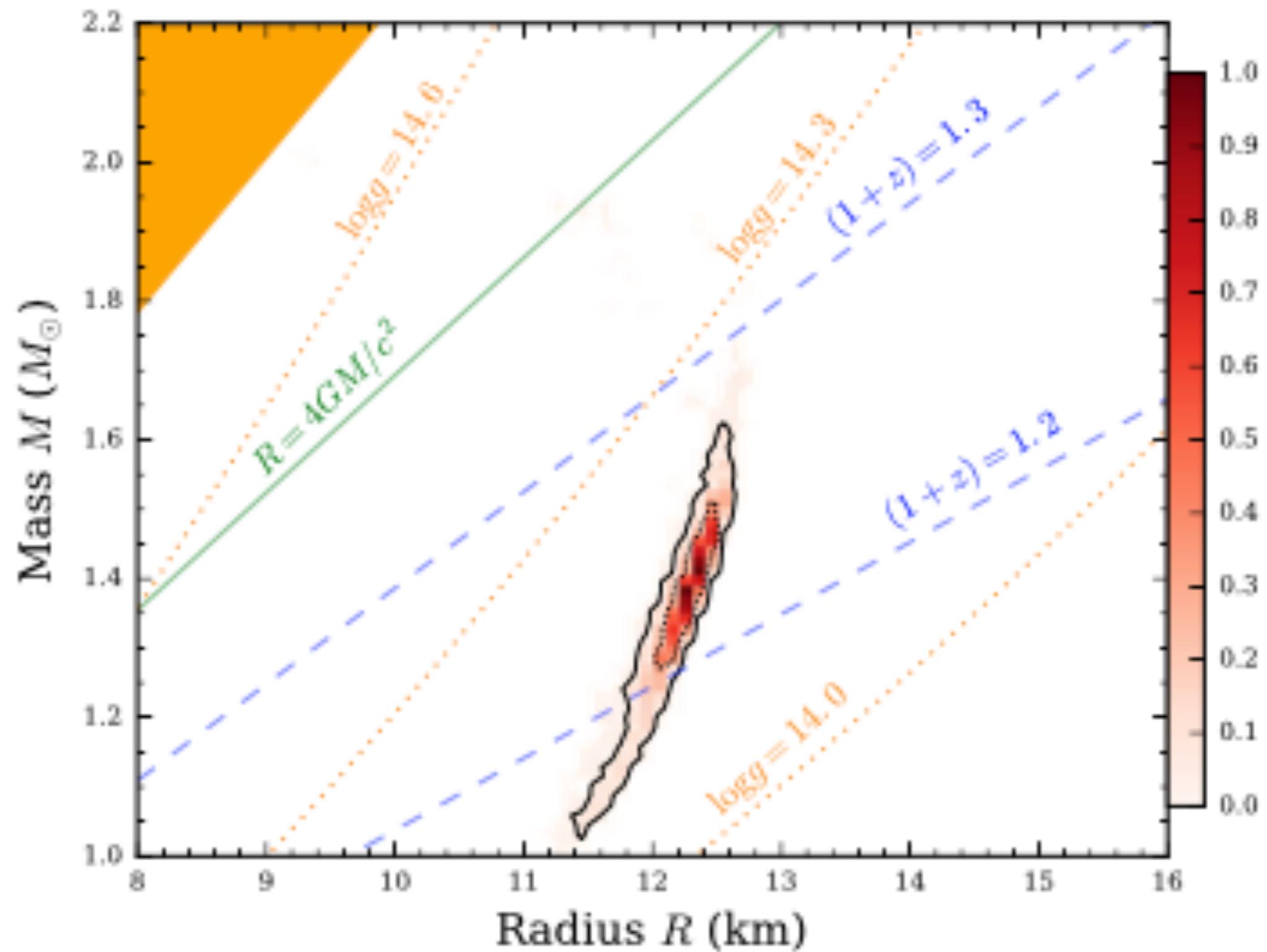
**Hard state**

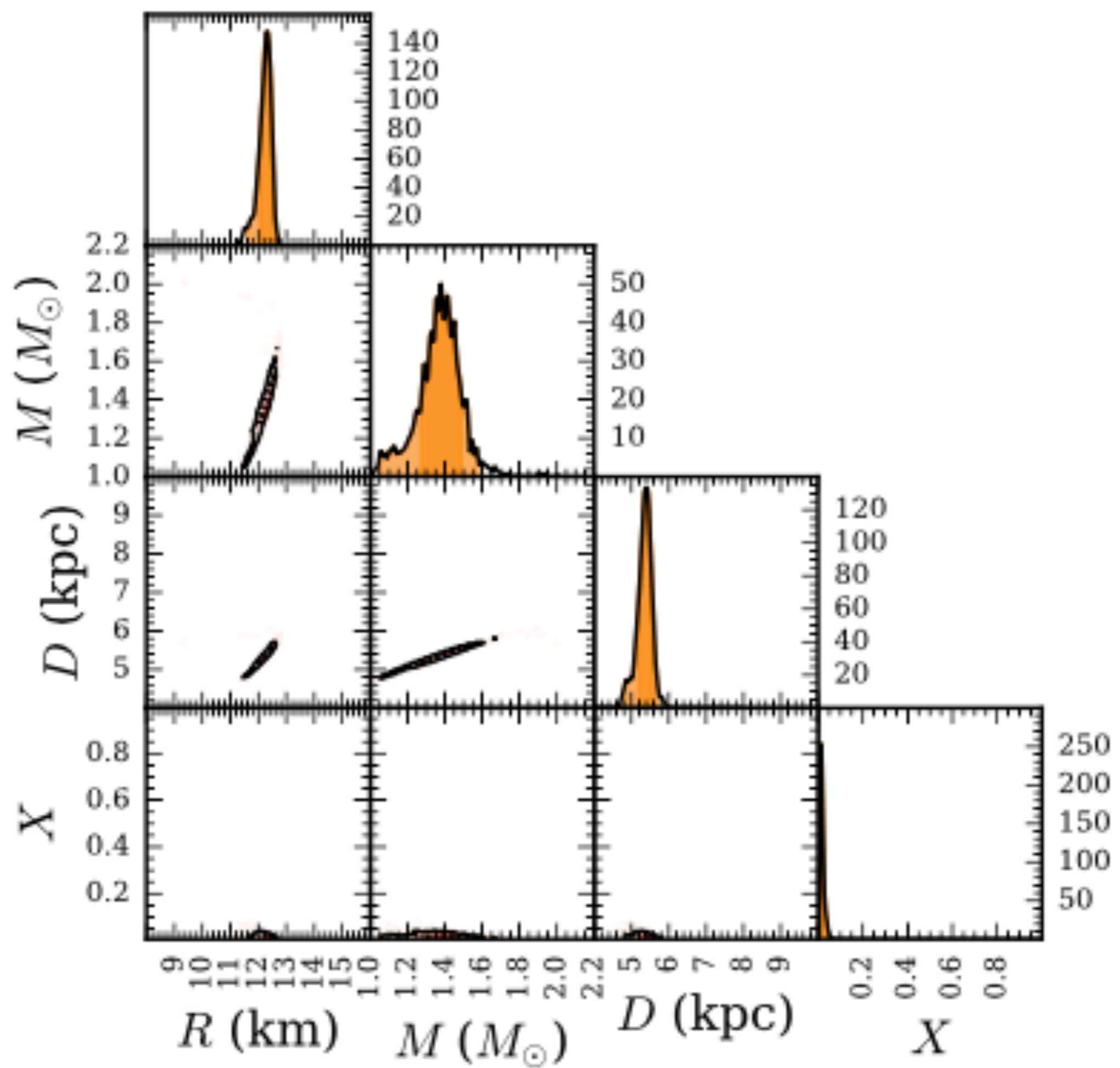
Low accretion rate

**Soft state**

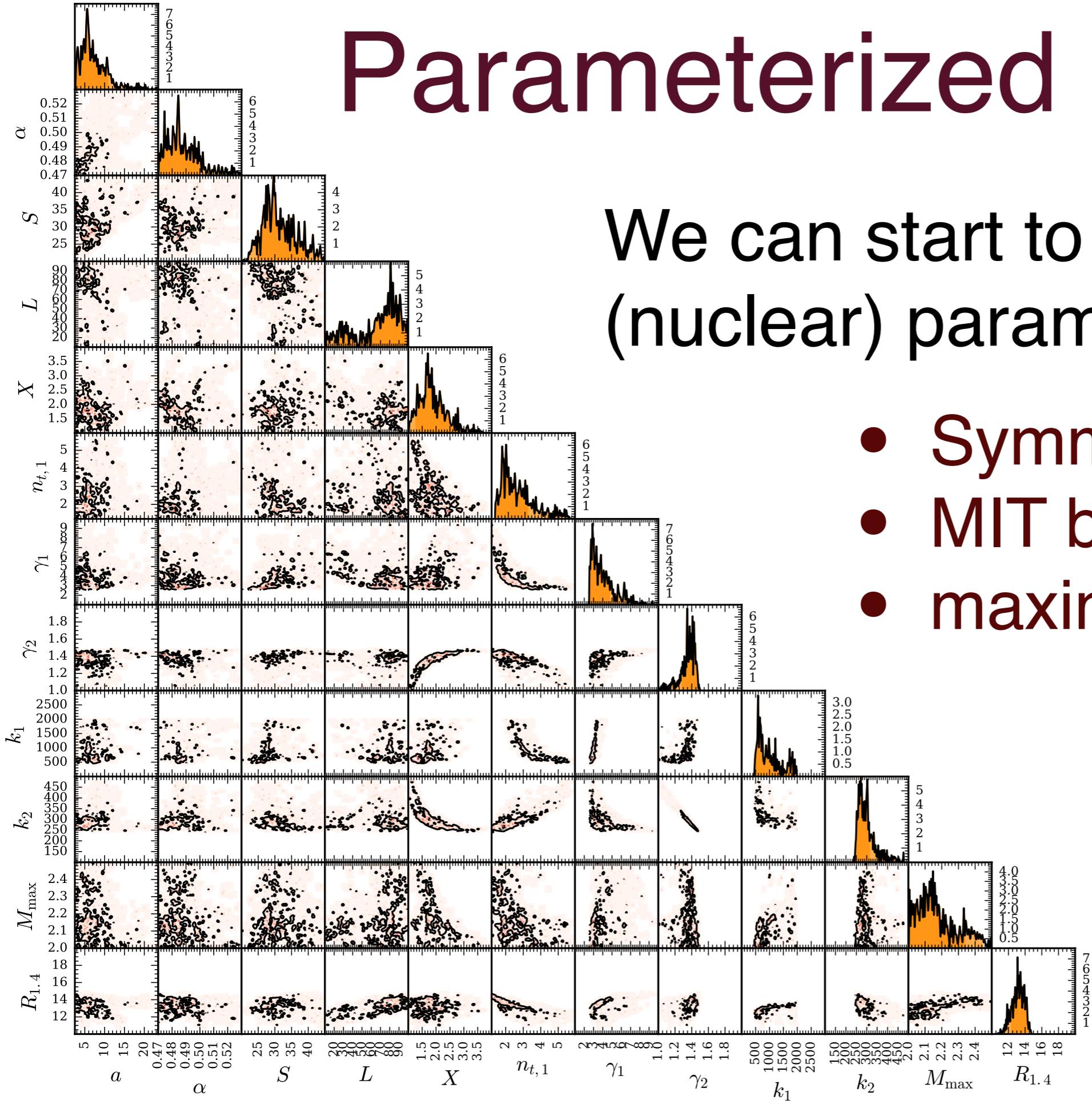
High accretion rate

# Neutron star in 4U 1702-429





# Parameterized EoS



We can start to probe  
(nuclear) parameters such as

- Symmetry energy
- MIT bag constant
- maximum NS mass

See upcoming  
Annala *et al* (2017)

# Summary

- Thermonuclear X-ray bursts can be a great tool to constrain  $M$ - $R$

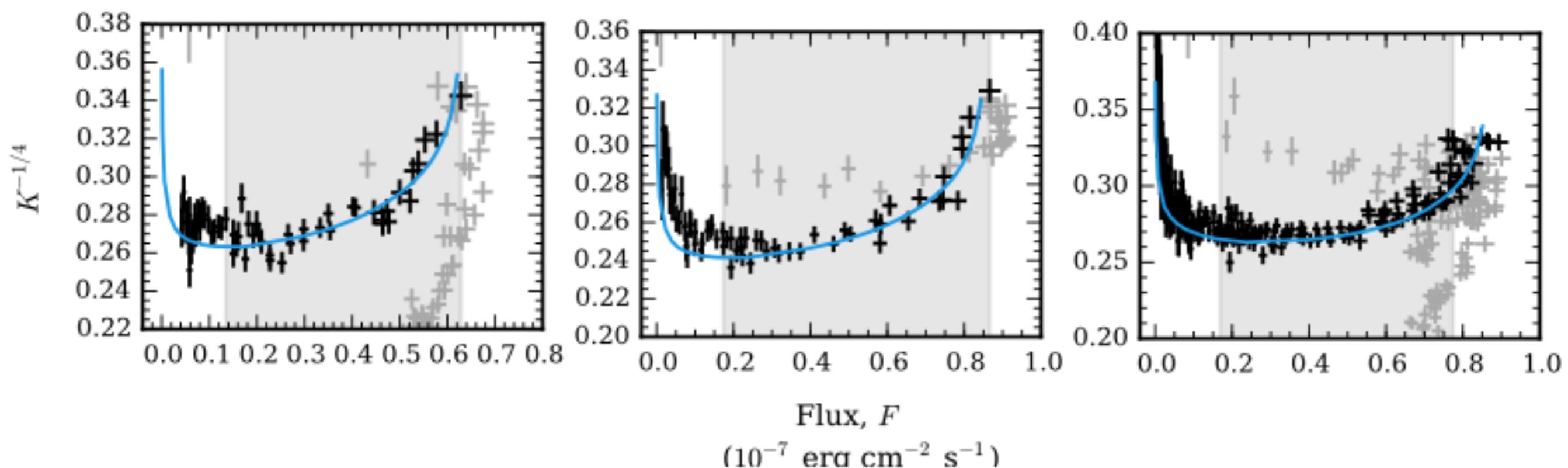
...If one is cautious!

- Hard state bursts give:

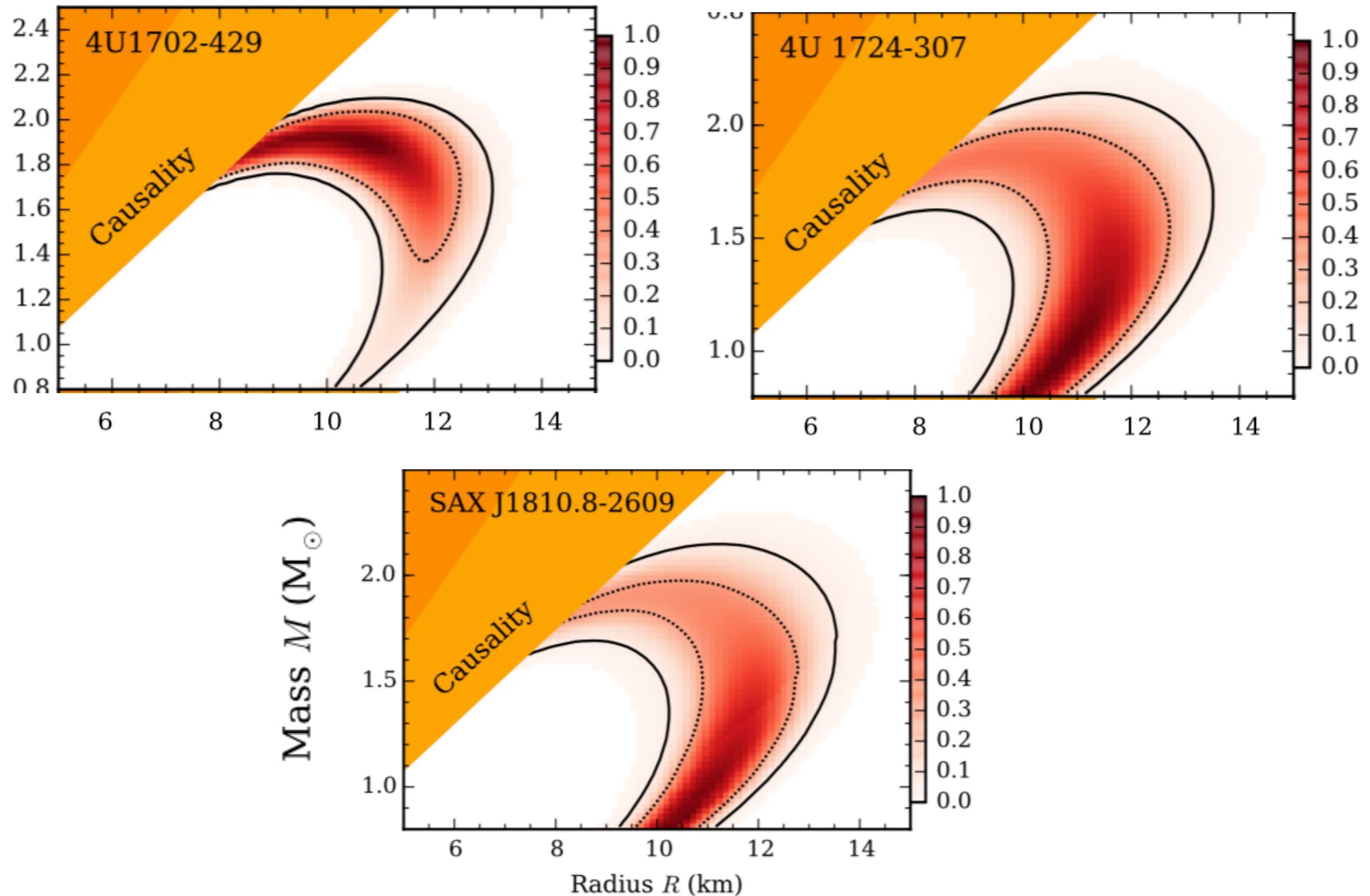
$12 < R < 13$  km for  $M = 1.4 \text{ Msun}$

Extra:

# $M$ - $R$ constraints from hard state bursts

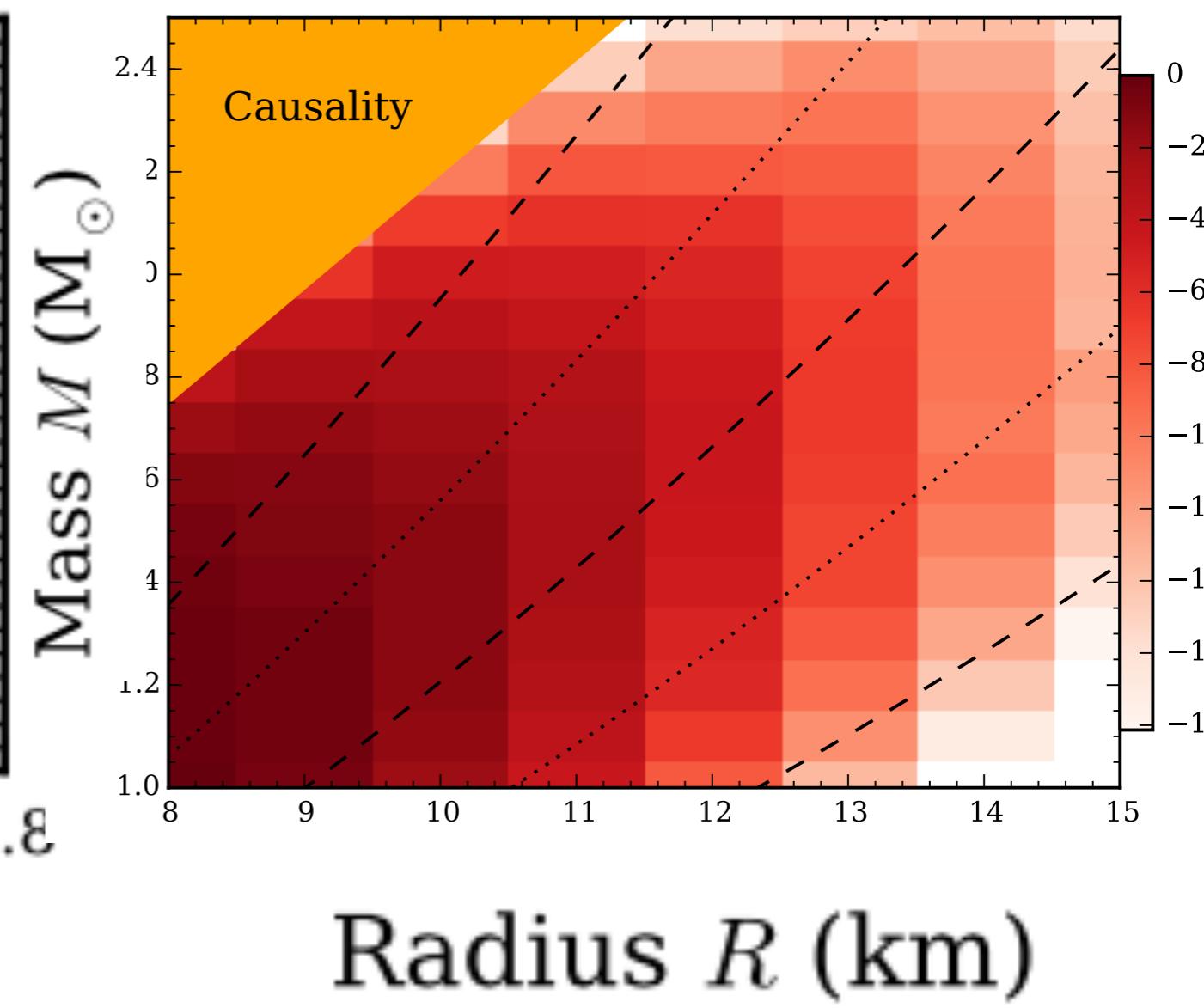
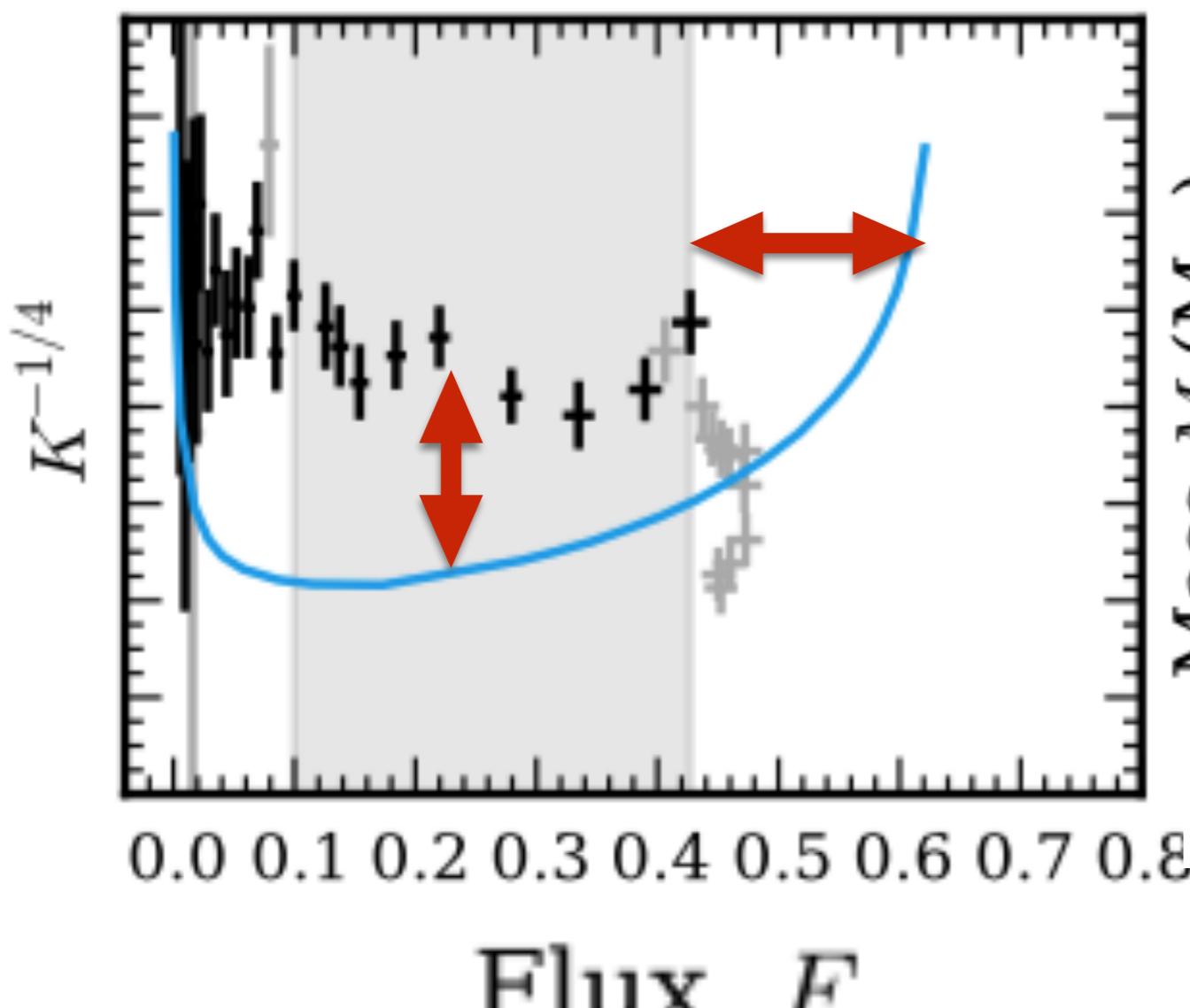


# $M$ - $R$ constraints from hard state bursts



# 4U 1724-307

Soft state



# 4U 1724-307

Hard state

Soft state

