Through the atmosphere into the core of the neutron star

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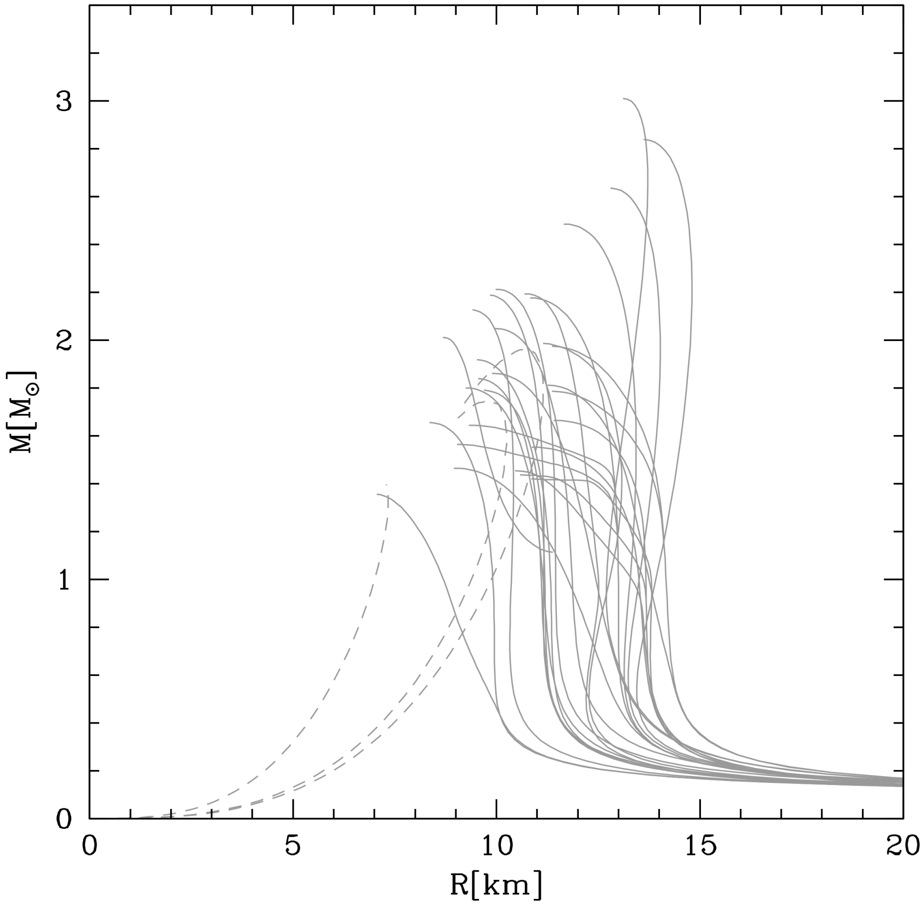
Equations of state (EOS) of the neutron star



An example of different equations of state of the super dense matter.

- **matter, such as in neutron star - we are unable to obtain it in any Earth laboratory**
- there are several methods of determination of basic parameters of NS (review eg. Bhattacharyya (2010), Miller (2013), Özel & Freire (2016))
- to strongly constrain EOS we need accurate and simultaneous mass and radius determination for neutron stars
- we develop such method based on the fitting of observed X-ray spectra of NS
- very important issue is an estimation of the accuracy of the mass and radius determination

Model atmospheres of hot neutron star (ATM24)

- equation of the radiative transport

$$\mu \frac{\partial I_\nu}{\partial \tau_\nu} = I_\nu - \epsilon_\nu B_\nu - (1-\epsilon_\nu) J_\nu + (1-\epsilon_\nu)(J_\nu - B_\nu) \int_0^\infty \Phi_1(\nu, \nu') d\nu'$$
$$-(1-\epsilon_\nu) \int_0^\infty (J_{\nu'} - B_{\nu'}) \Phi_2(\nu, \nu') d\nu'$$

- hydrostatic equilibrium

$$\int_0^\infty (\kappa_\nu + \sigma_\nu) J_\nu d\nu = \int_0^\infty (\kappa_\nu + \sigma_\nu) S_\nu d\nu$$

atmosphere does not collapse, expand or pulsate

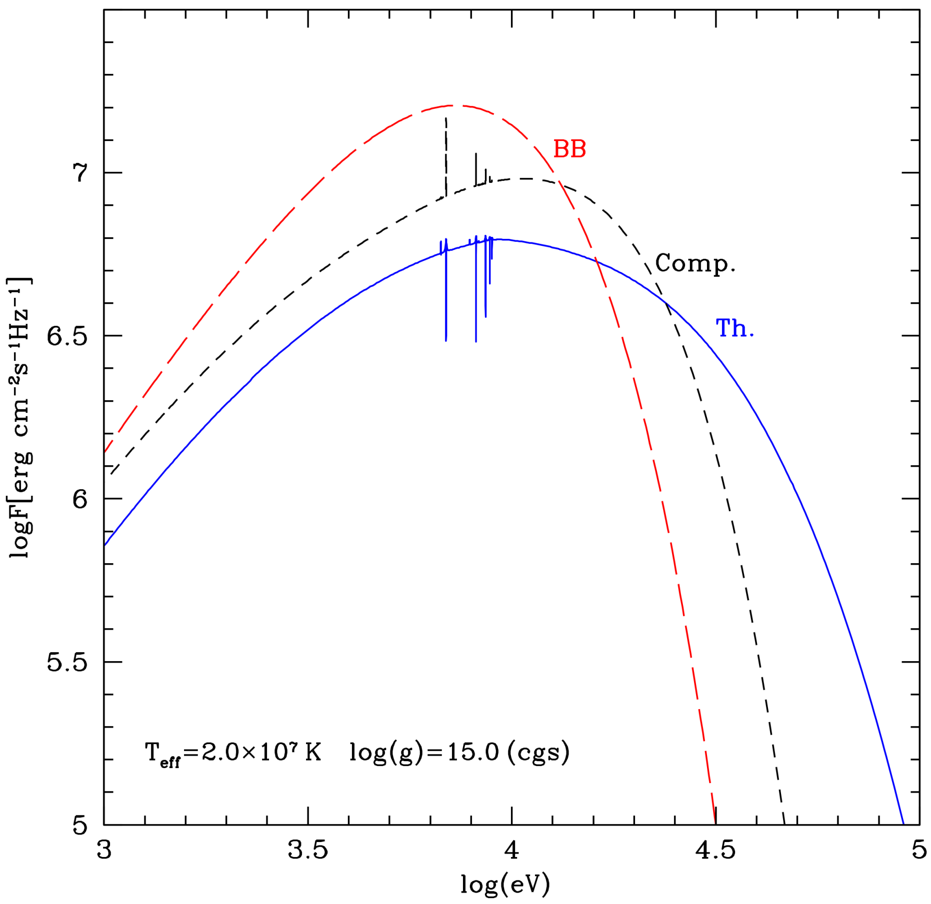
- radiative equilibrium

$$\frac{dP_{gas}}{dz} + \frac{dP_{rad}}{dz} = -\rho g$$

only photons transport the energy
- no energy sources
- no convection

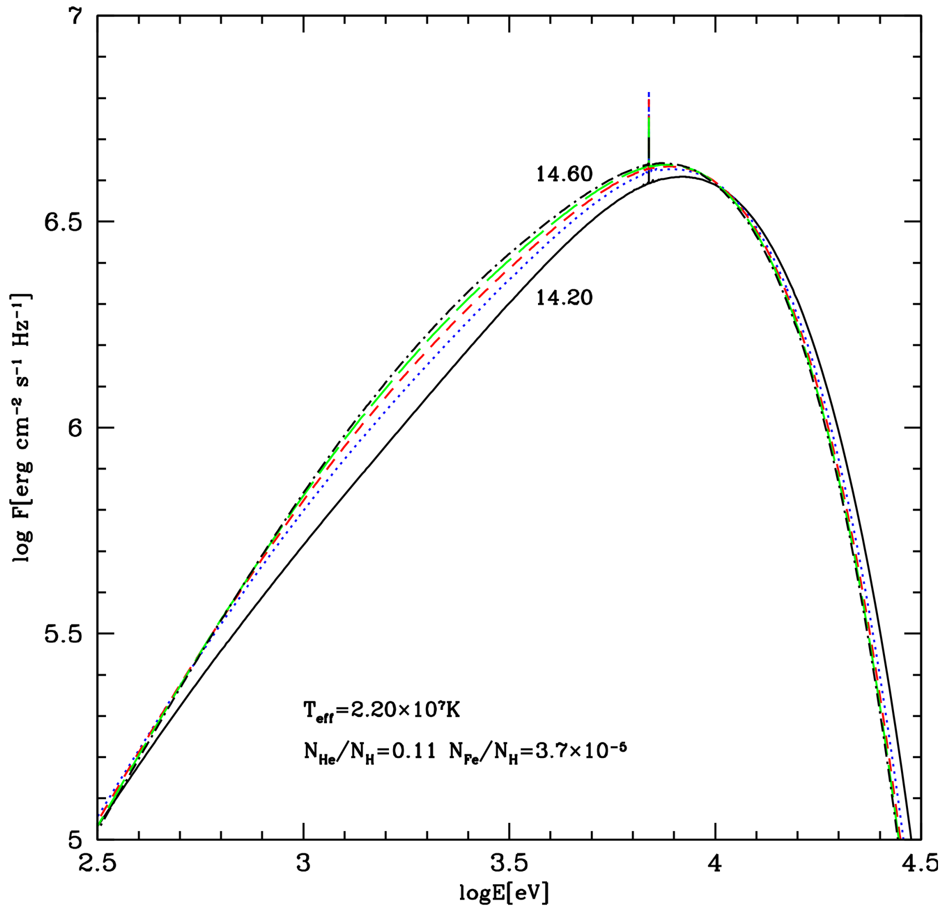
- for detailed description of the model see eg. Madej (1991); Majczyna et. al. (2005); Madej et al. (2017); Majczyna et. al. (2020)

Our theoretical spectra



- comparison of the black body spectrum with spectra with Thomson and Compton scattering
- spectrum of the atmosphere dominated by Compton scattering is harder than the black body spectrum
- maximum of our spectrum is shifted toward higher energies

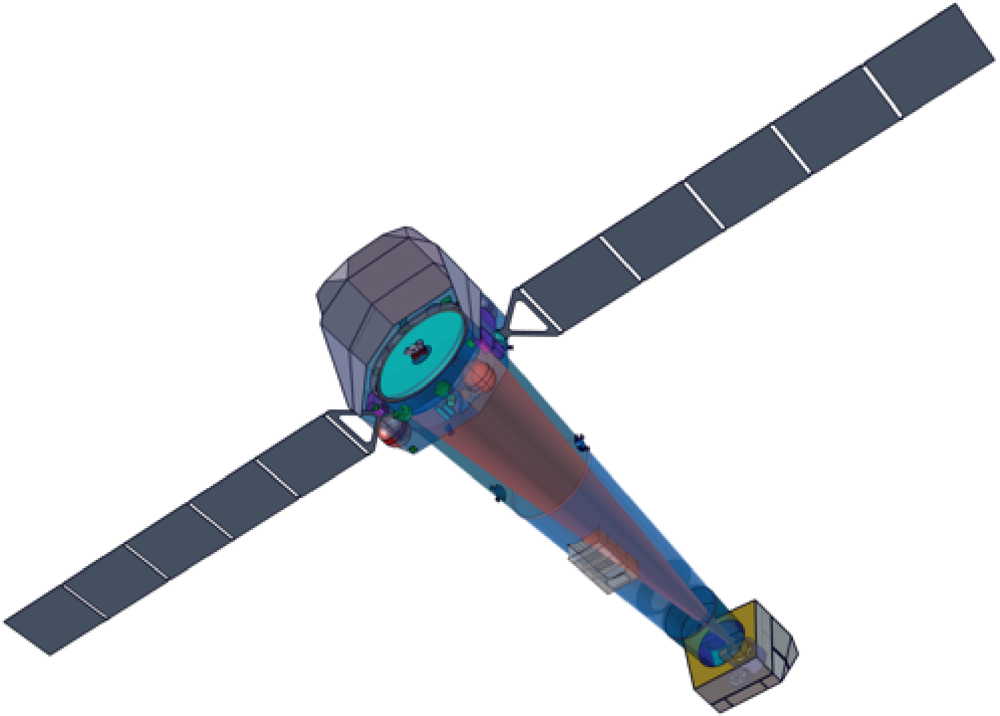
Our theoretical spectra



- surface gravity modifies outgoing spectra
- spectrum for the lowest gravity is harder than this for higher gravity
- strong iron line at ~6.9 keV is clearly visible
- for lower log(g) maximum of spectrum is shifted toward higher energies

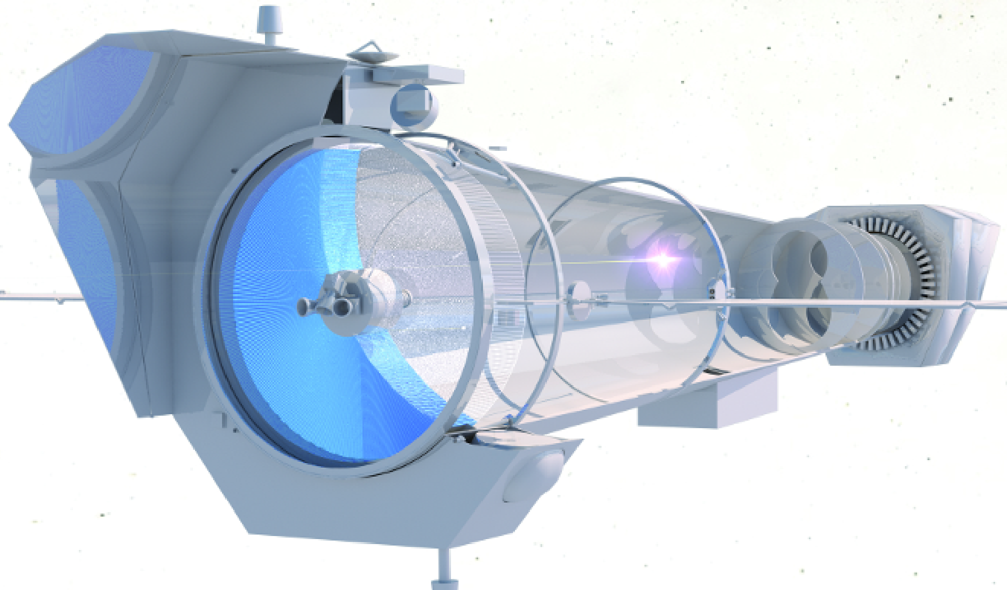
Our method of mass and radius determination

- our method is based on the fitting observed spectra by theoretical one
- we are able to determine mass and radius simultaneously
- our method is independent on the distance, which could be use to reduce errors
- this method was applied to spectra observed by RXTE eg. Kusmierek et al. (2011)
- we use WFI/ATHENA fake spectra to show, how accurate is our method (Majczyna et al. 2020)



Athena (Advanced Telescope for High Energy Astrophysics)

It is due for launch in 2030



X-ray Integral Field Unit (X-IFU)

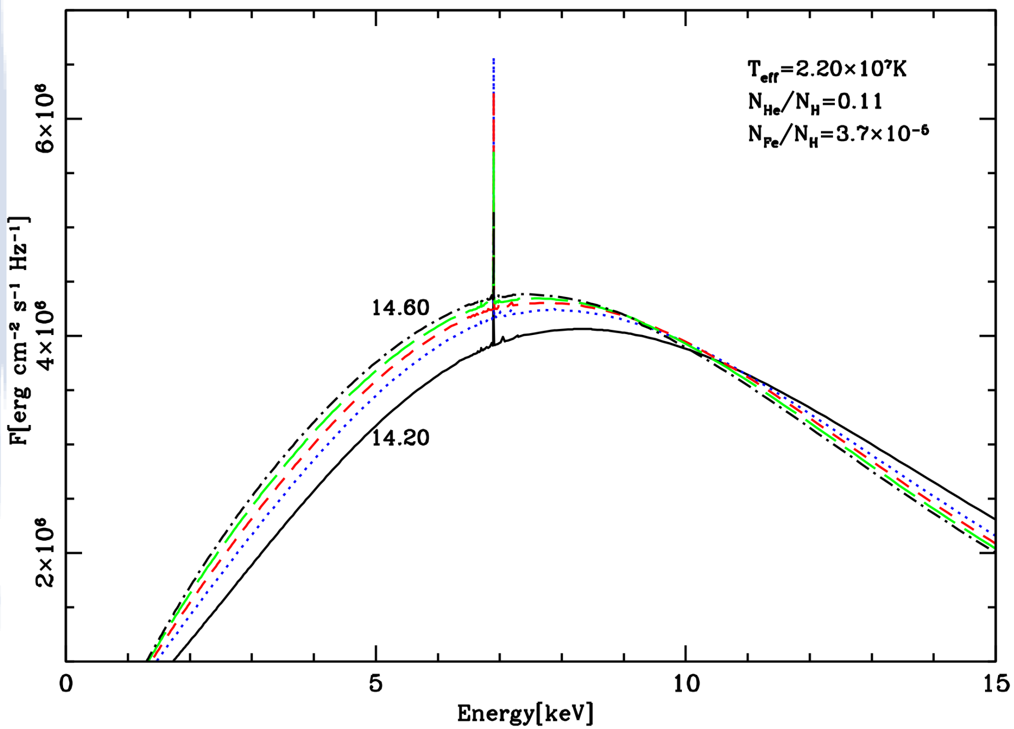
- energy range: 0.2-12 keV
- energy resolution: 2.5 eV (<7 keV)
- field of view: 5'
- time resolution: 10 μsec
- effective area: 1500 cm^2 (@7 keV)

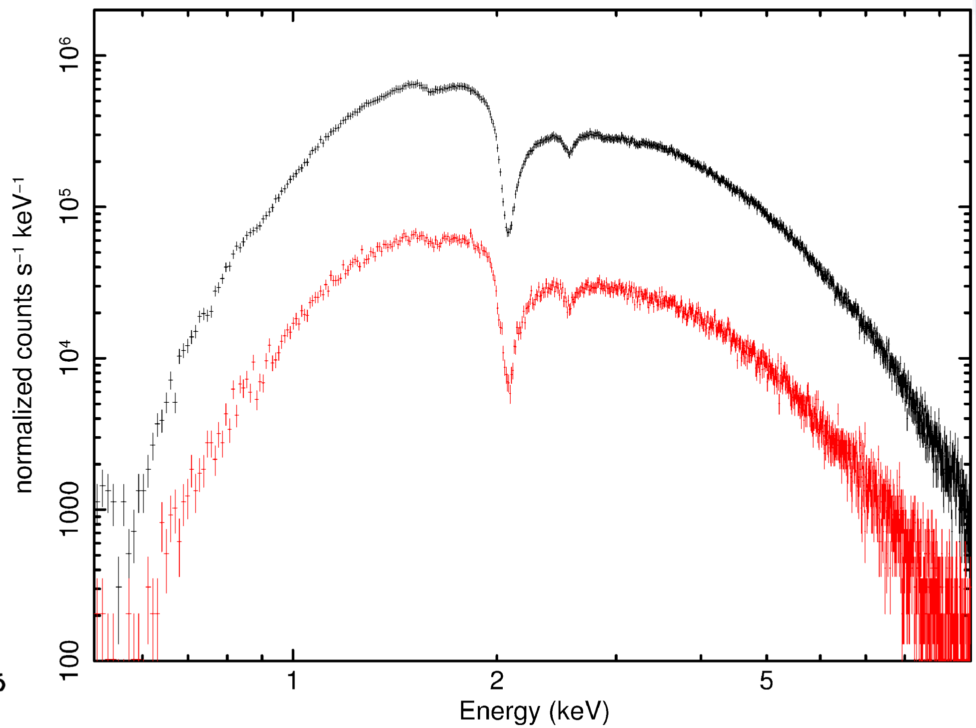
Wide Field Imager (WFI)

- energy range: 0.2-15 keV
- energy resolution: <170 eV (@7 keV)
- time resolution: <5 msec
- angular resolution: 5”
- field of view: 40'×40'

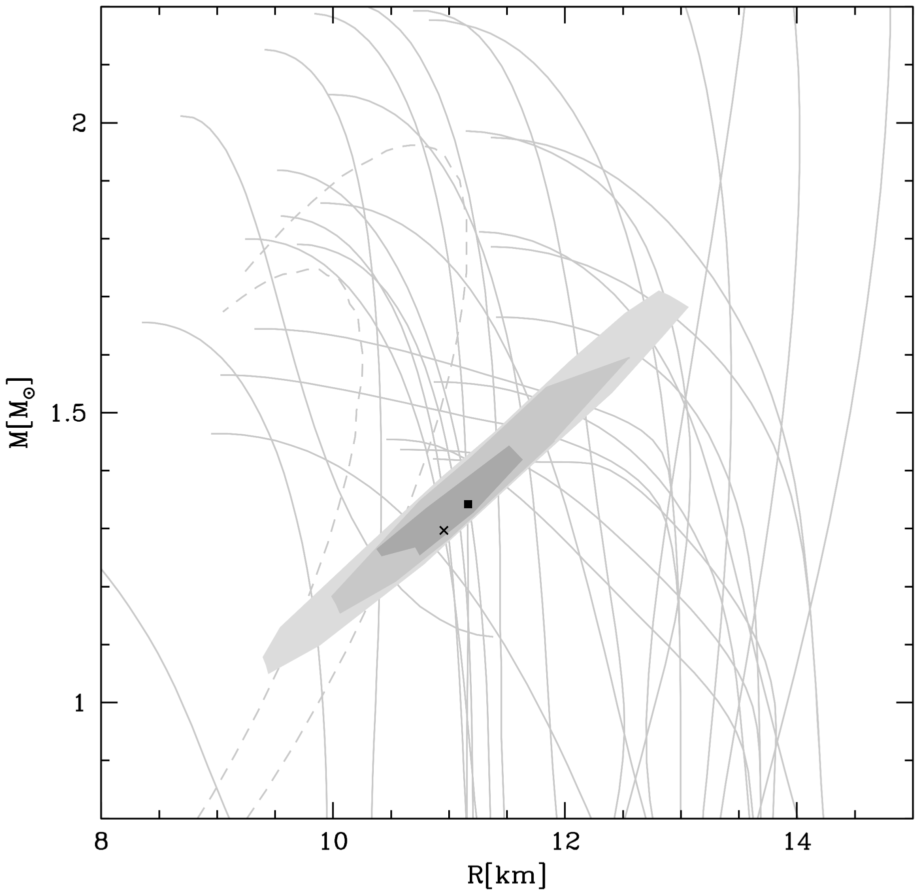
Athena's fake spectrum

- our theoretical spectra with chosen parameters (M, R, T_{eff}) were convolved with the *Athena* response matrix
- these fake spectra were fitted by large grid of our theoretical models
- we expected that this fitting procedure reproduce assumed parameters
- we are able to estimate accuracy of mass and radius determination in our method

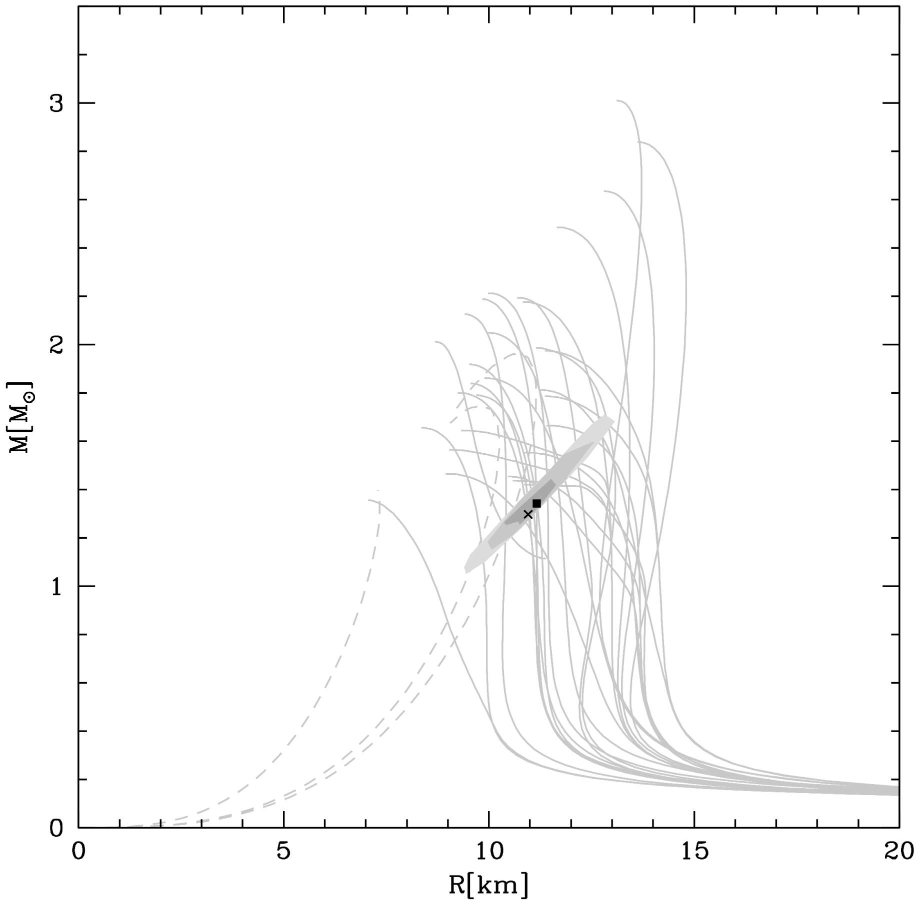




Accuracy of mass and radius determination



- 1σ, 2σ, and 3σ confidence contours
- black cross denotes assumed value of M and R, whereas black point our best fit



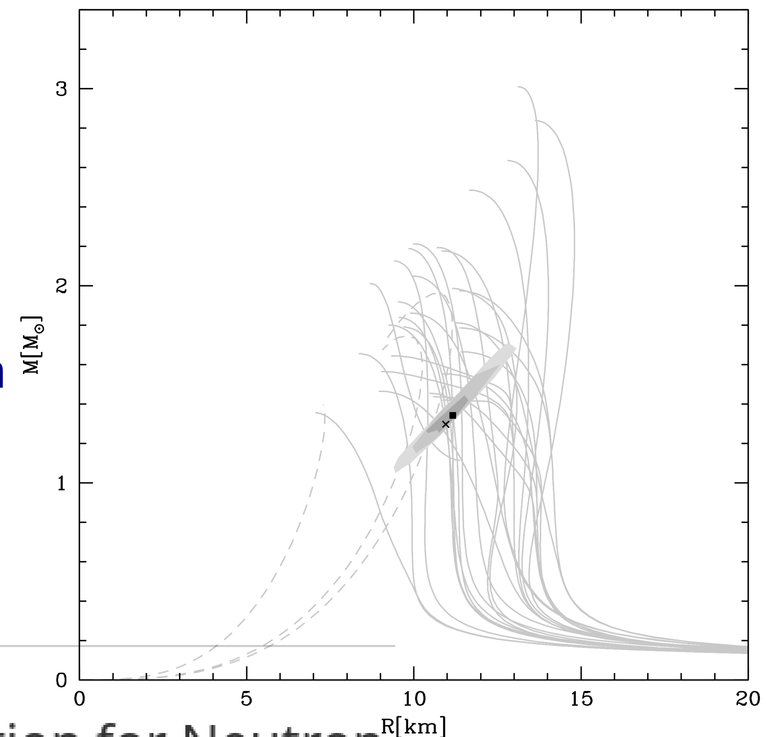
Majczyna et al. (2020)
ApJ 888, 123

Accuracy of mass and radius determination

- based on the method of fitting continuum spectra we determined the mass and the radius of the neutron star with the accuracy:

δM = 3-10 %
δR = 2-8 %

- that means that **we are able to constrain** the equation of state of super dense matter in the neutron star interior



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Precision of Mass and Radius Determination for Neutron Stars from the *ATHENA* Mission

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Summary

- after about 90 years after postulating the existence and about 70 years after discovery of the neutron star, the equation of state is still open question
- in any Earth laboratory we are unable to obtain matter, which build up neutron star
- the only way to know properties of the super dense matter are astronomical observations
- only accurate and simultaneous determination of mass and radius of the neutron star could constrain equation of state of neutron star matter
- we created and develop model atmospheres of hot neutron star (ATM24)
- we develop method of mass and radius determination based on the fitting of the theoretical spectra to the observed X-ray spectra
- we shown that we are able to determine mass with ~3-10 % accuracy and the radius with 2-8 % accuracy
- therefore we are able to strongly constrain equation of state of neutron star matter

Thank you