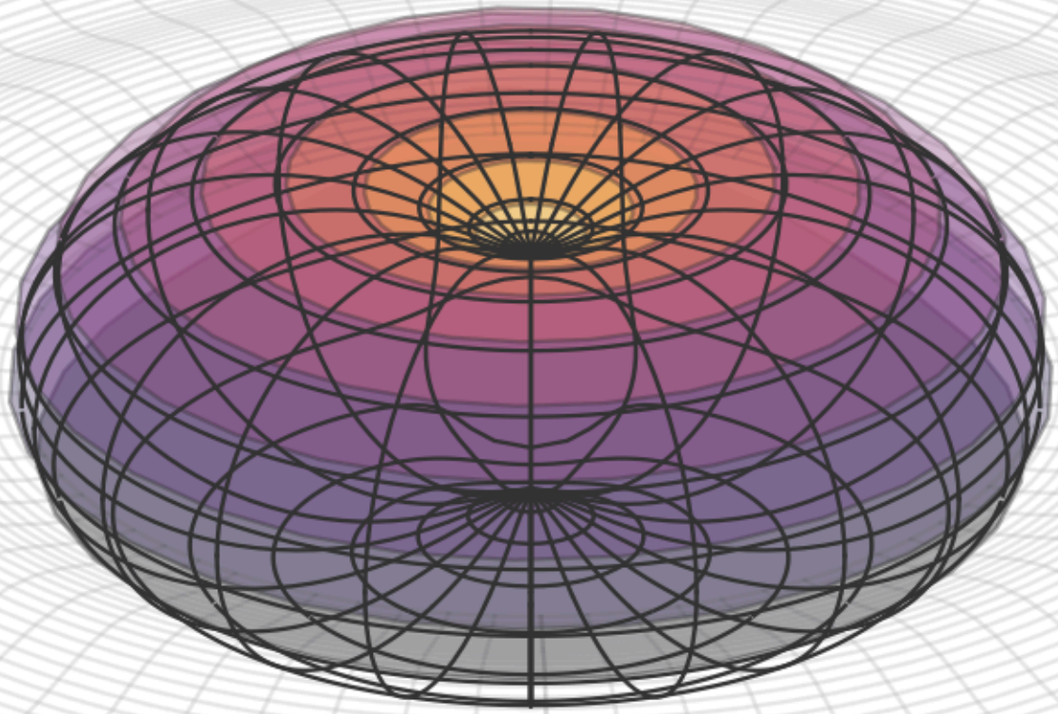
NORDITA
Nordic Institute for Theoretical Physics

Understanding the nuclear physics of neutron stars with astrophysics



Joonas Nättilä

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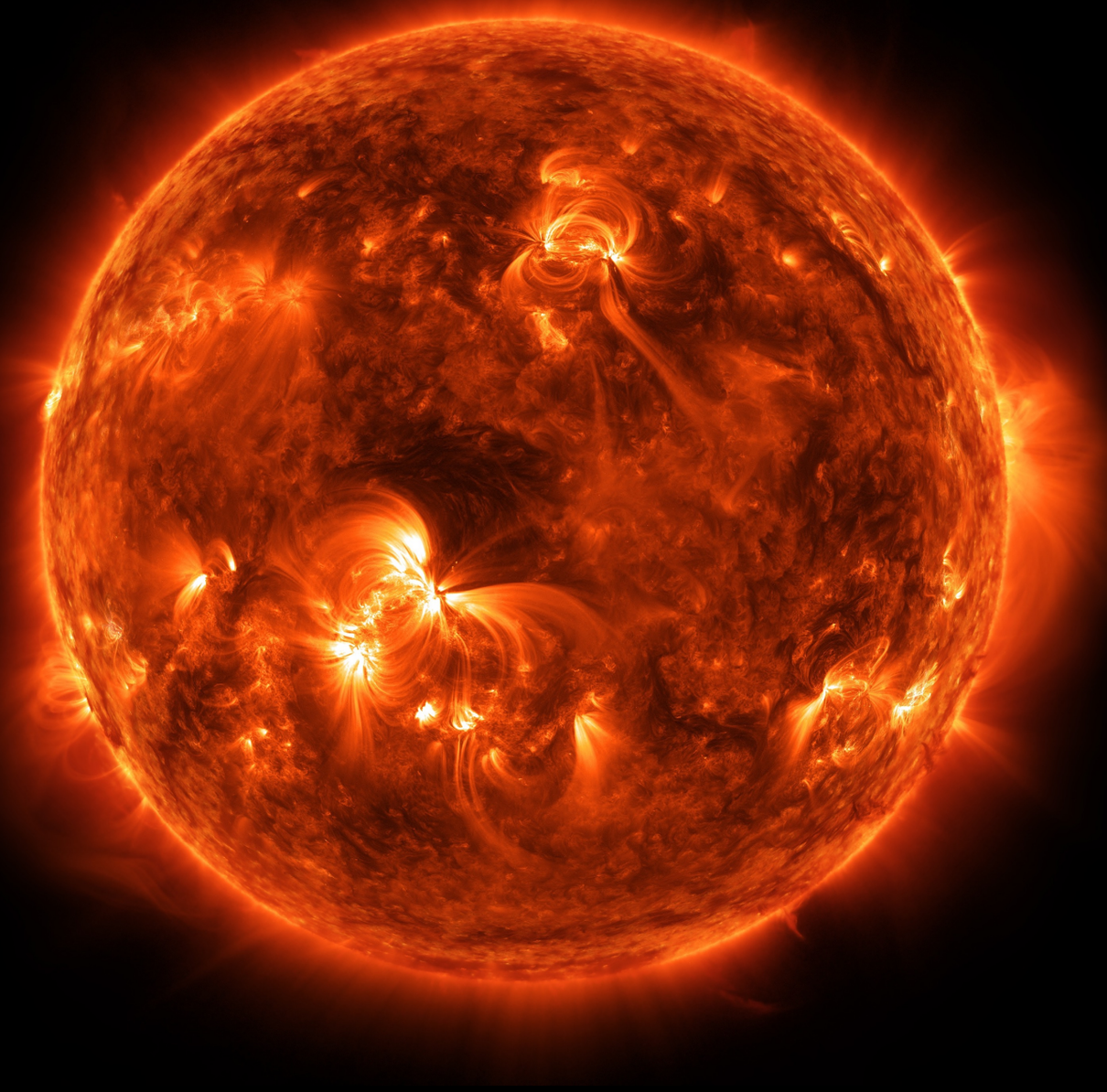
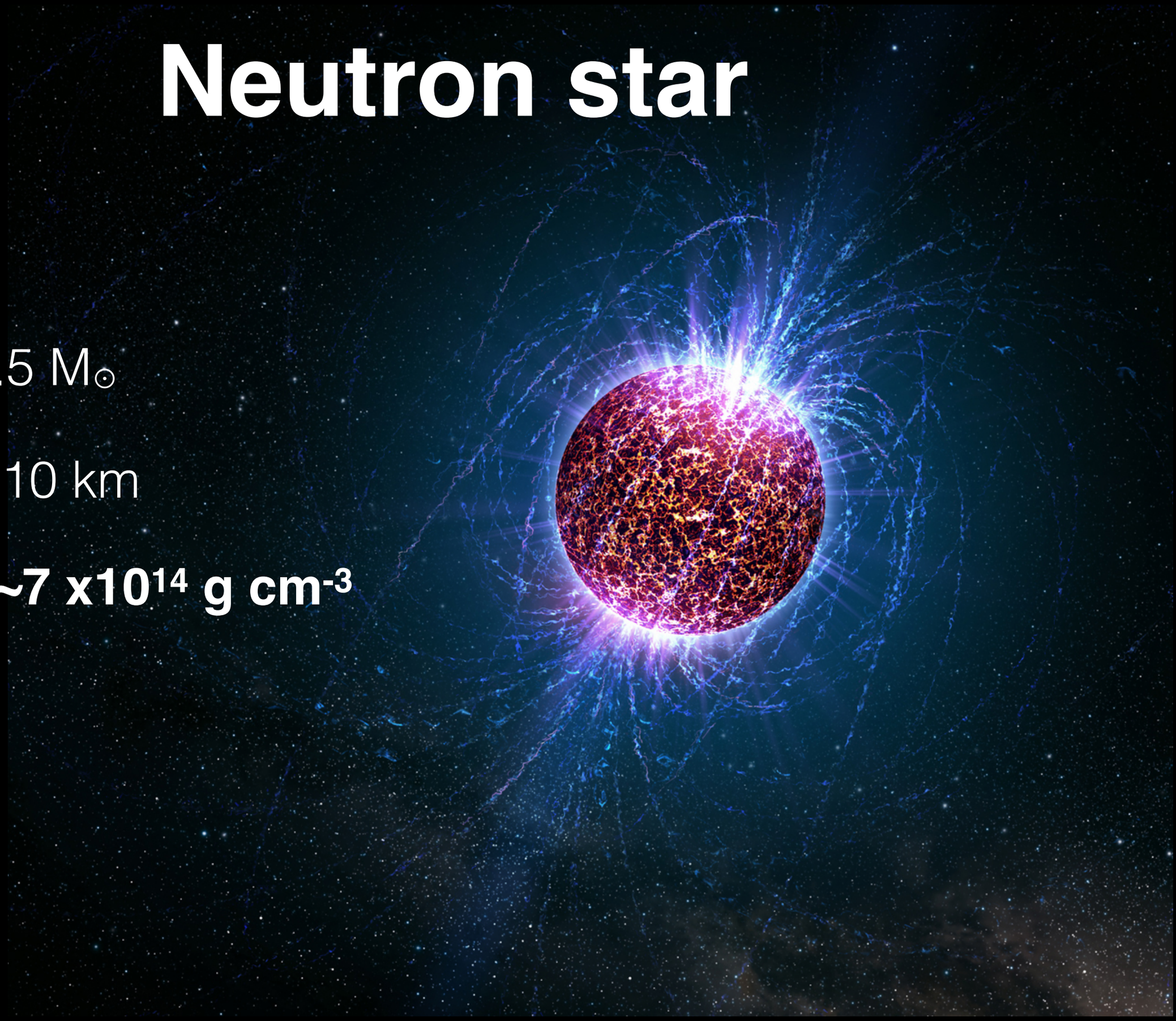
Our Sun

- Mass ~1 $M_\odot$ (2×10^{30} kg)
- Radius ~1 $R_\odot$ (7×10^5 km)
- **Density ~1.4 g cm^{-3}**

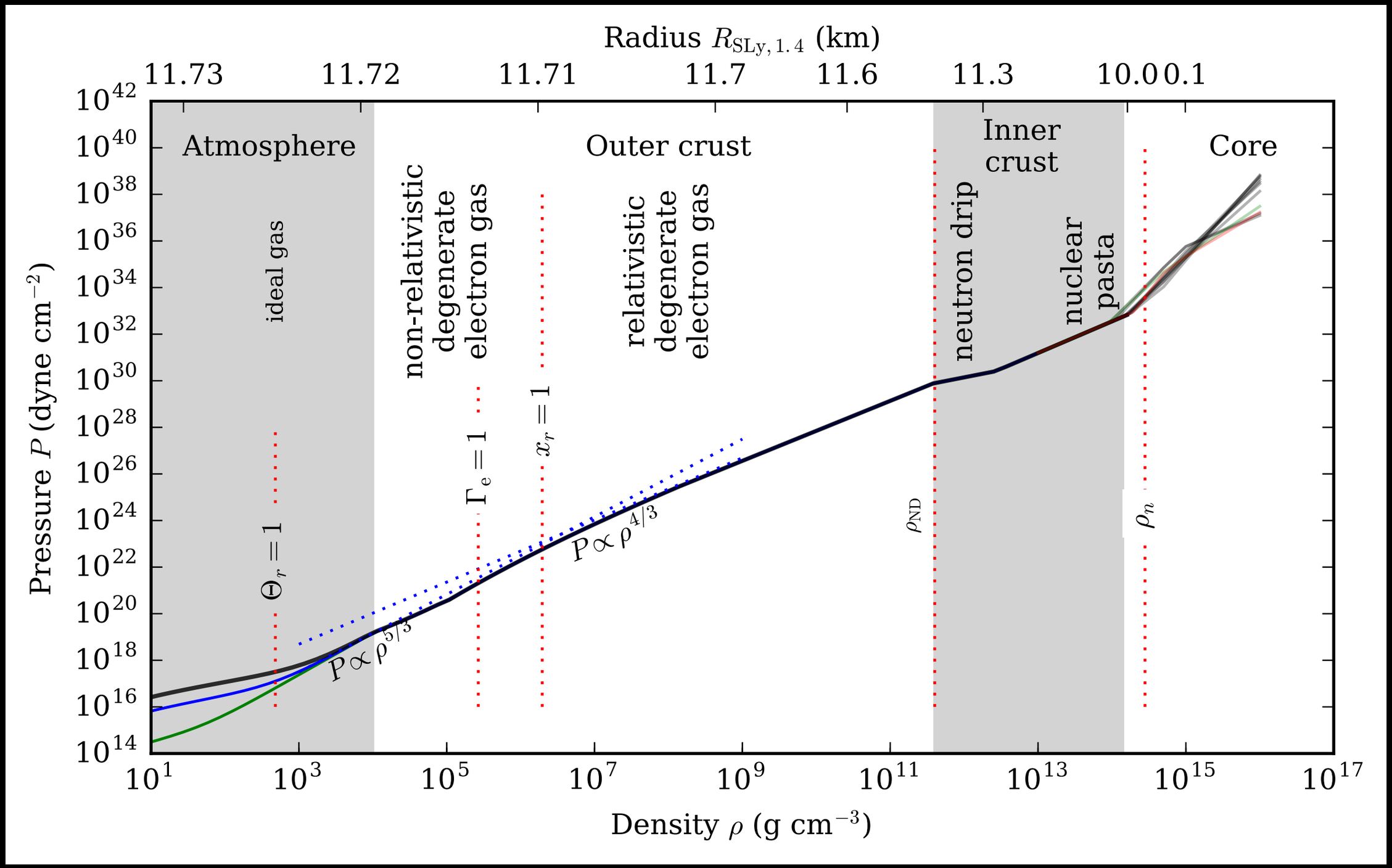


Neutron star

- Mass ~1.5 $M_\odot$
- Radius ~10 km
- **Density ~7 x10^{14} g cm^{-3}**



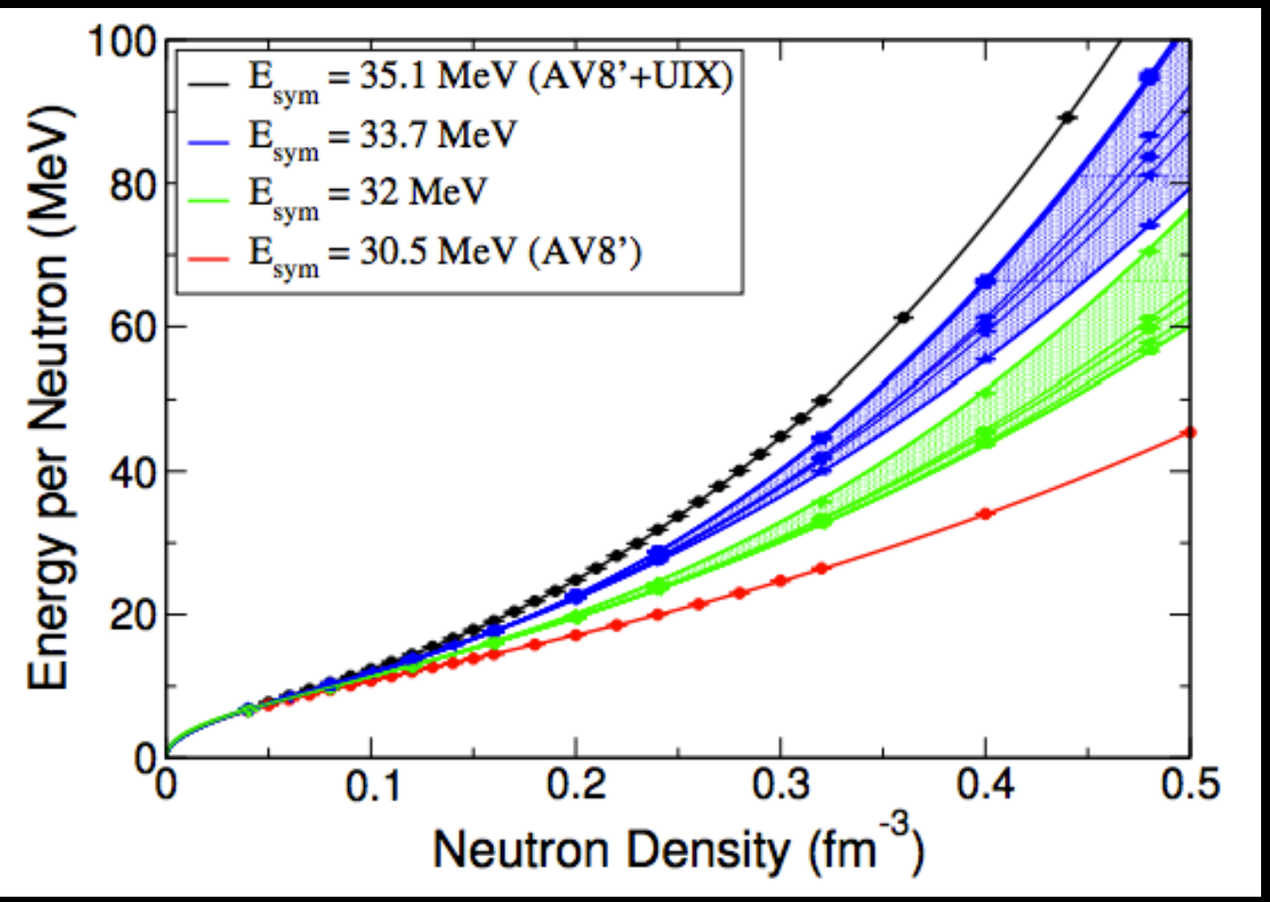
Neutron stars as seen by nuclear physicist



So what do we actually know?

Low and high densities

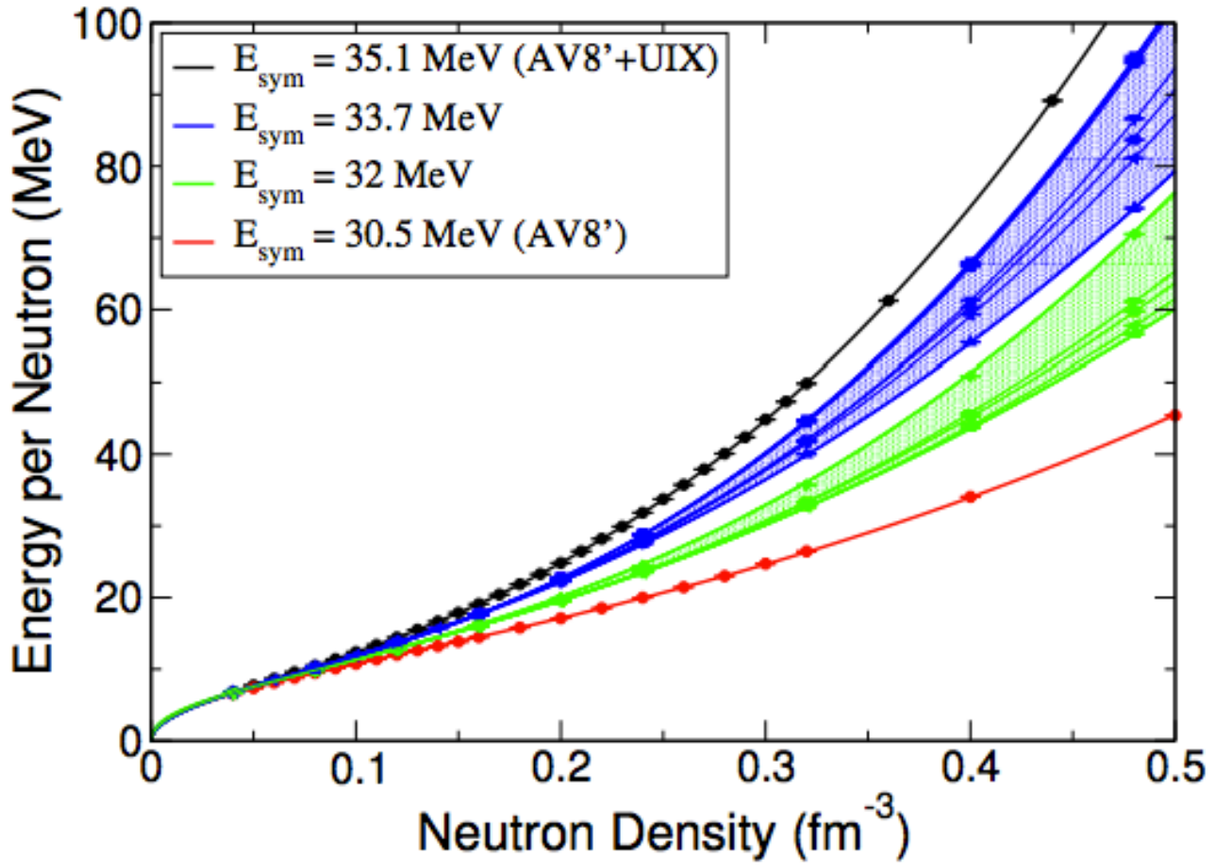
Quantum Monte Carlo simulations



Gandolfi+2014

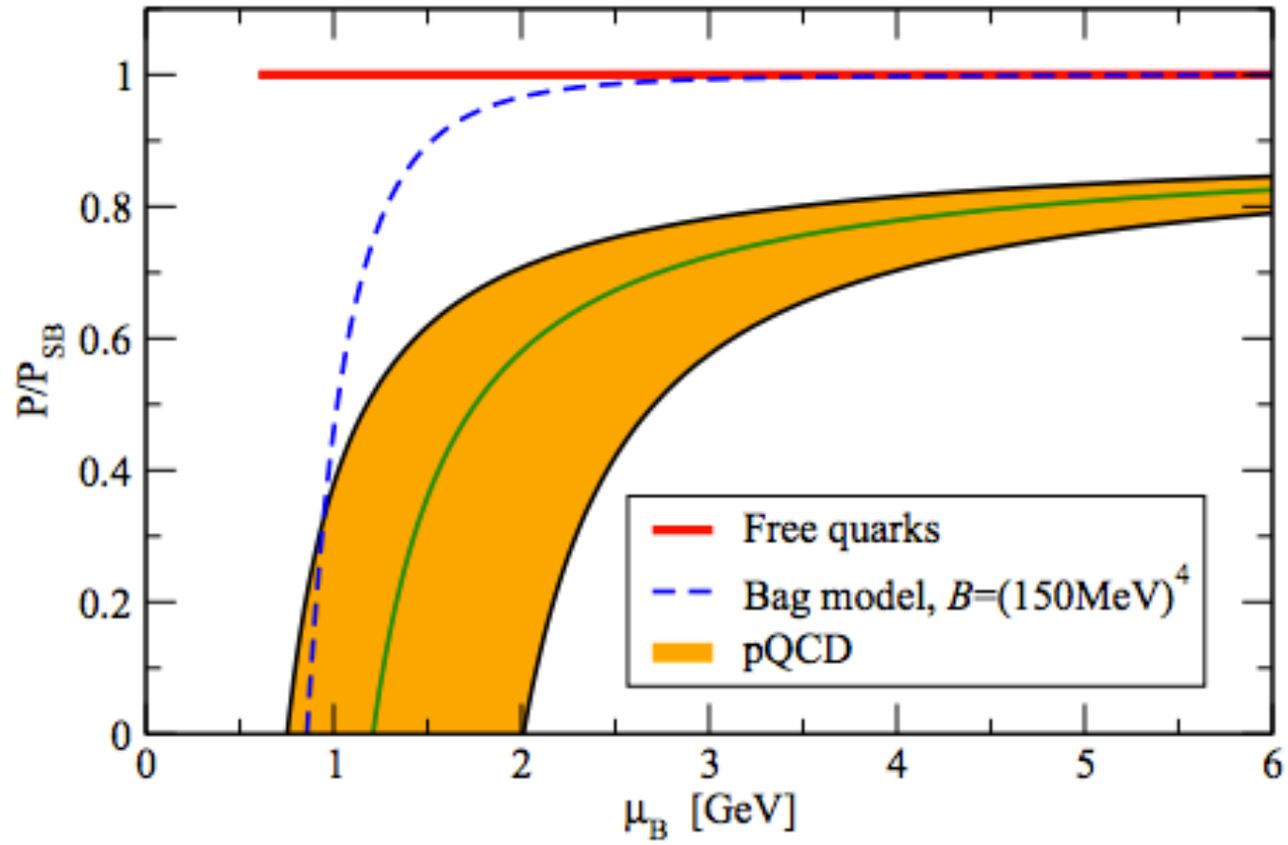
Low and high densities

Quantum Monte Carlo simulations



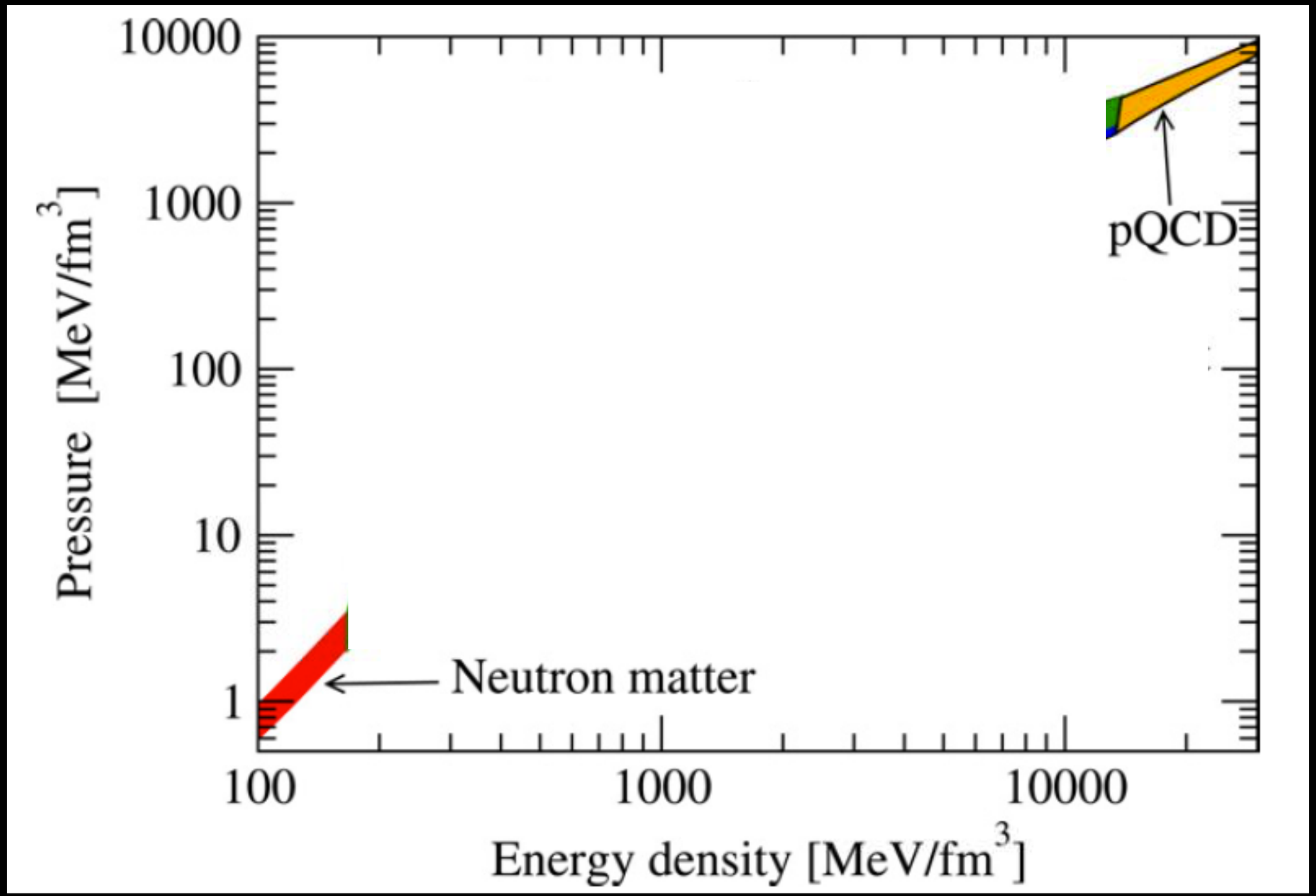
Gandolfi+2014

Perturbative Quantum Chromodynamics (pQCD)



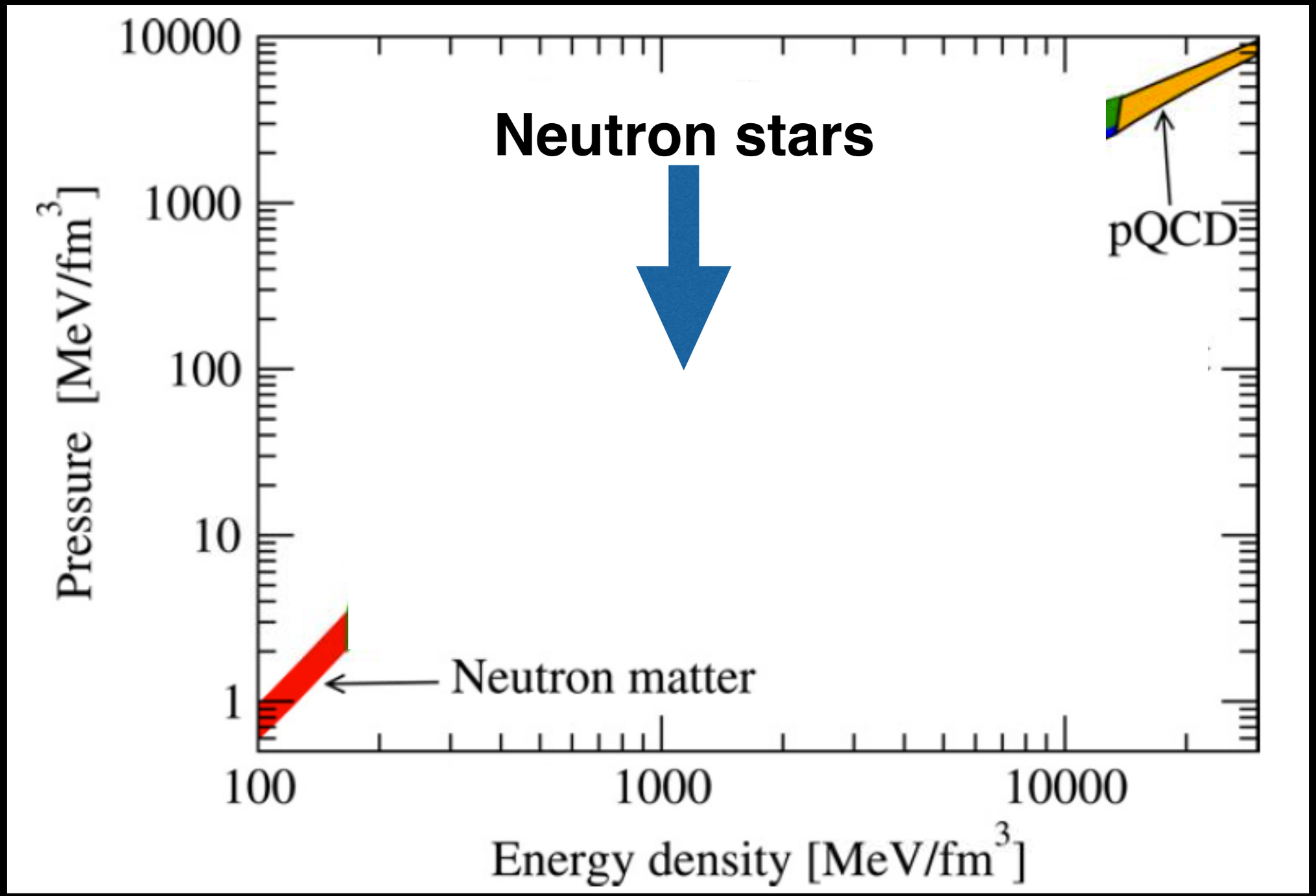
Kurkela+2010

Low and high densities



Kurkela+2014

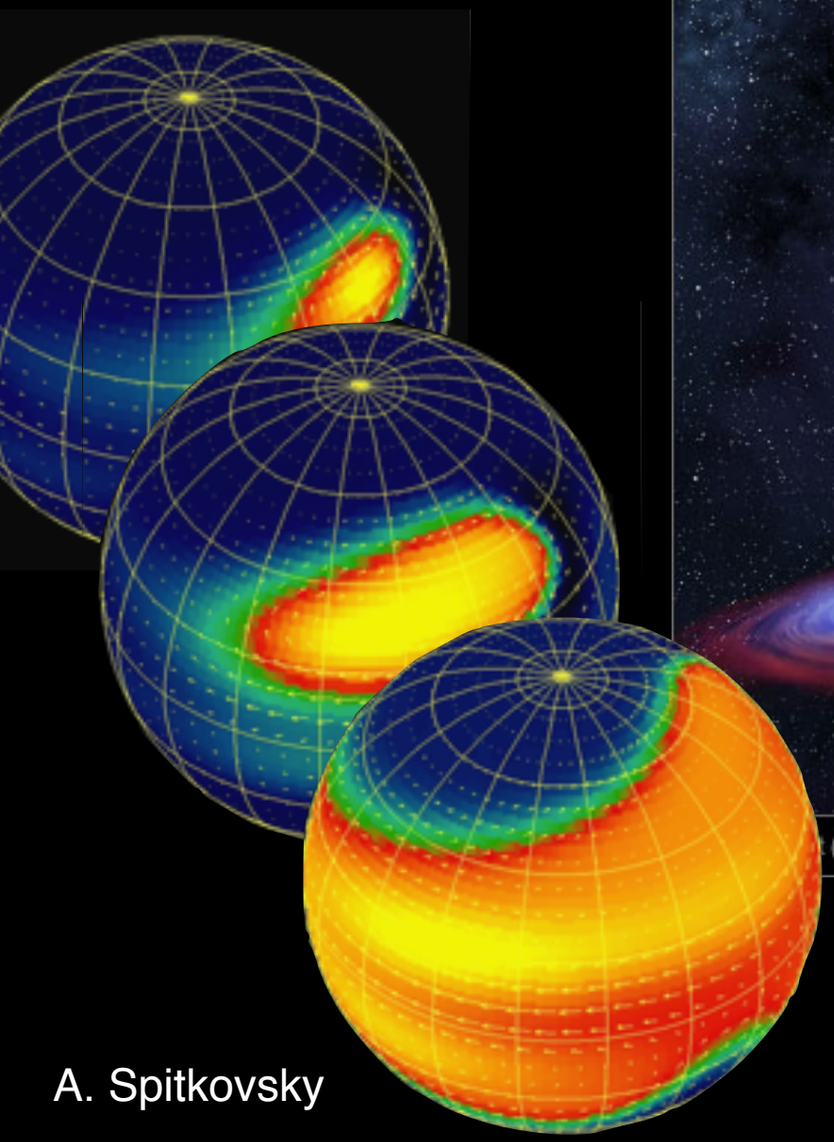
Low and high densities



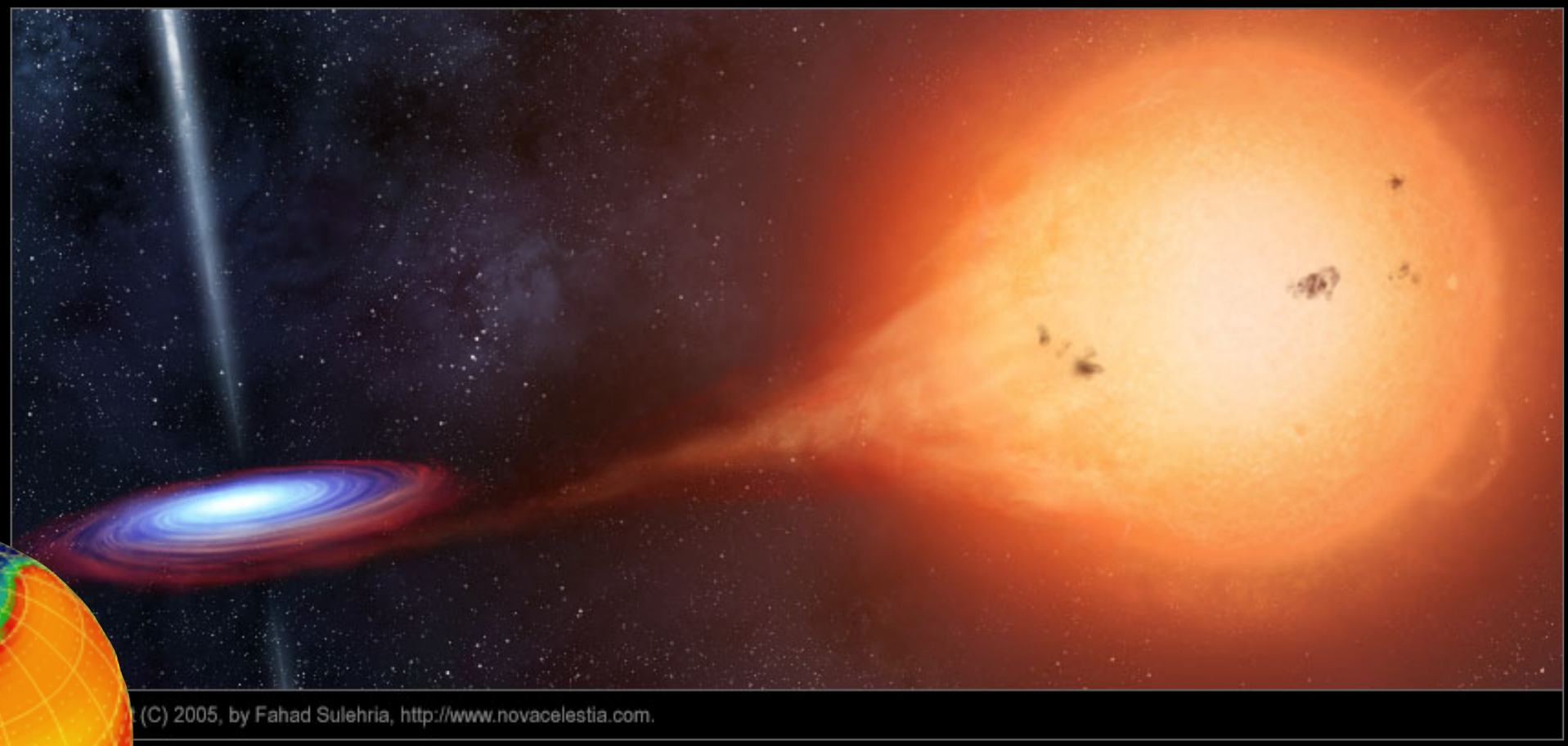
Kurkela+2014

Astrophysical measurements

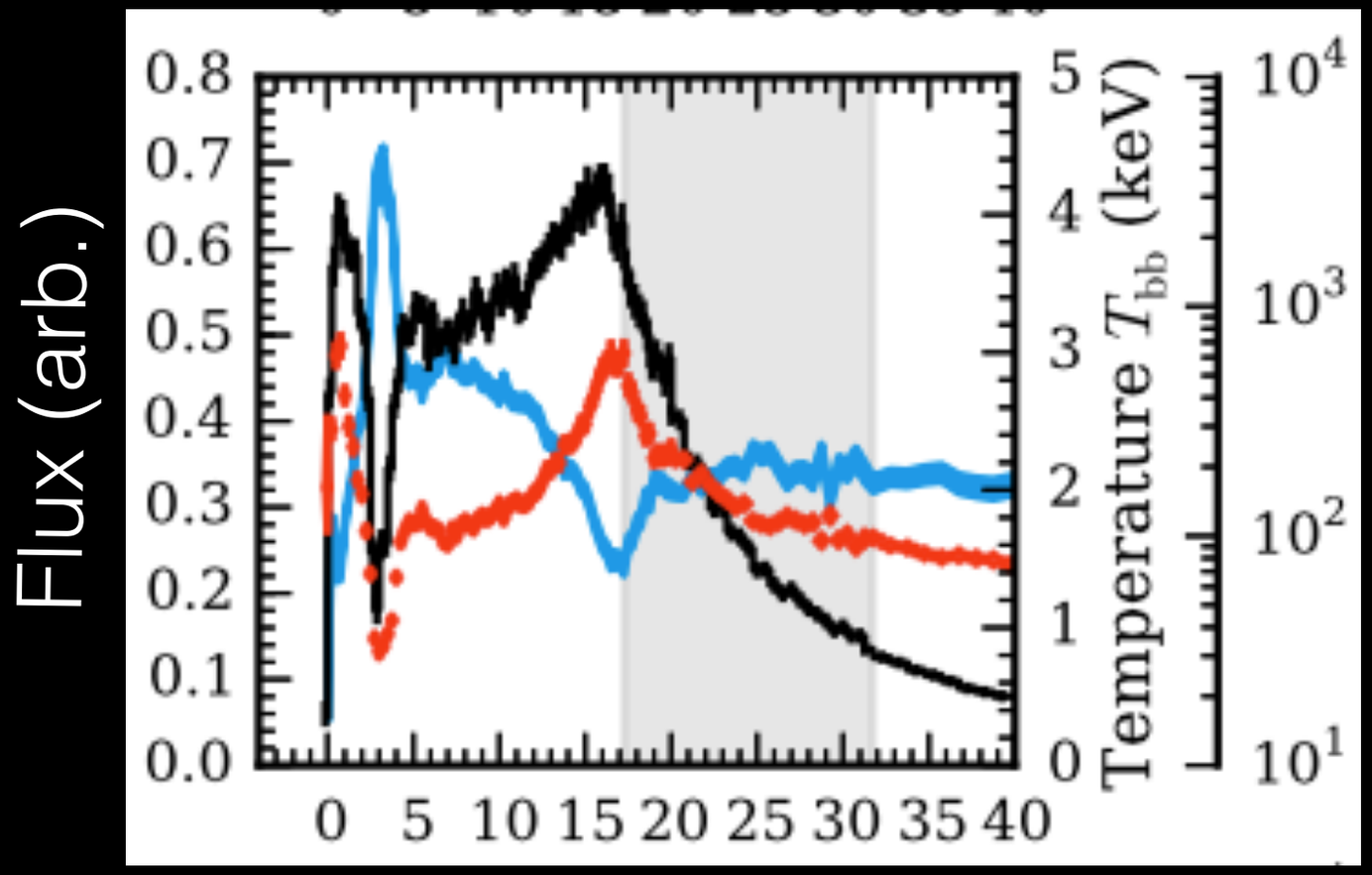
- Thermonuclear explosions on top of neutron stars



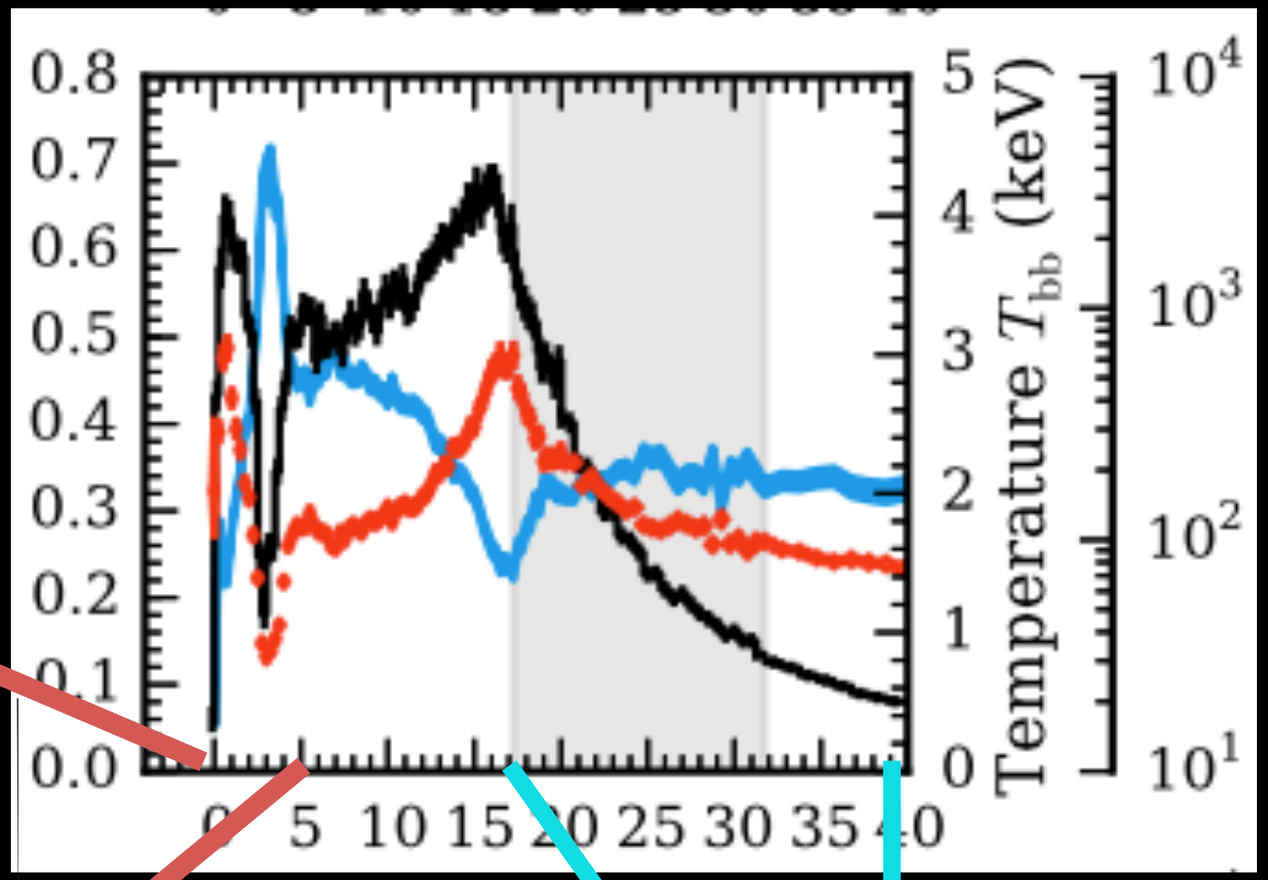
A. Spitkovsky



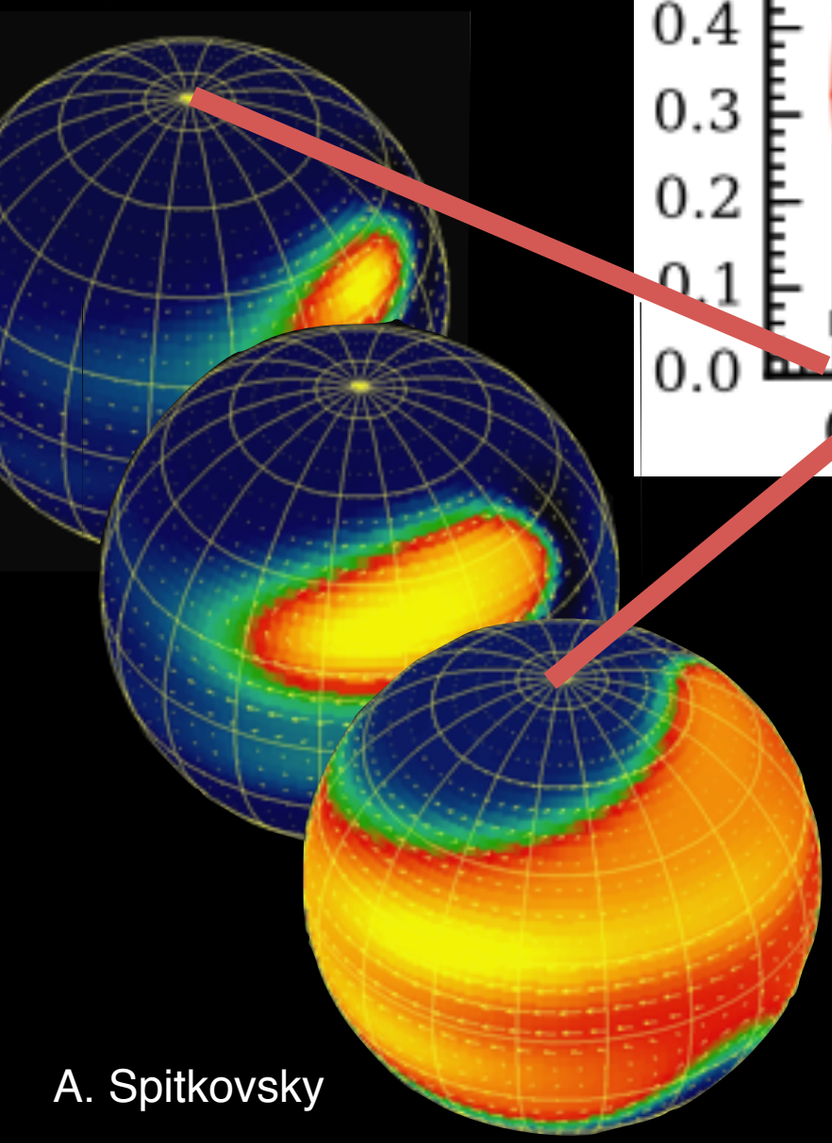
X-ray burst evolution



X-ray burst evolution



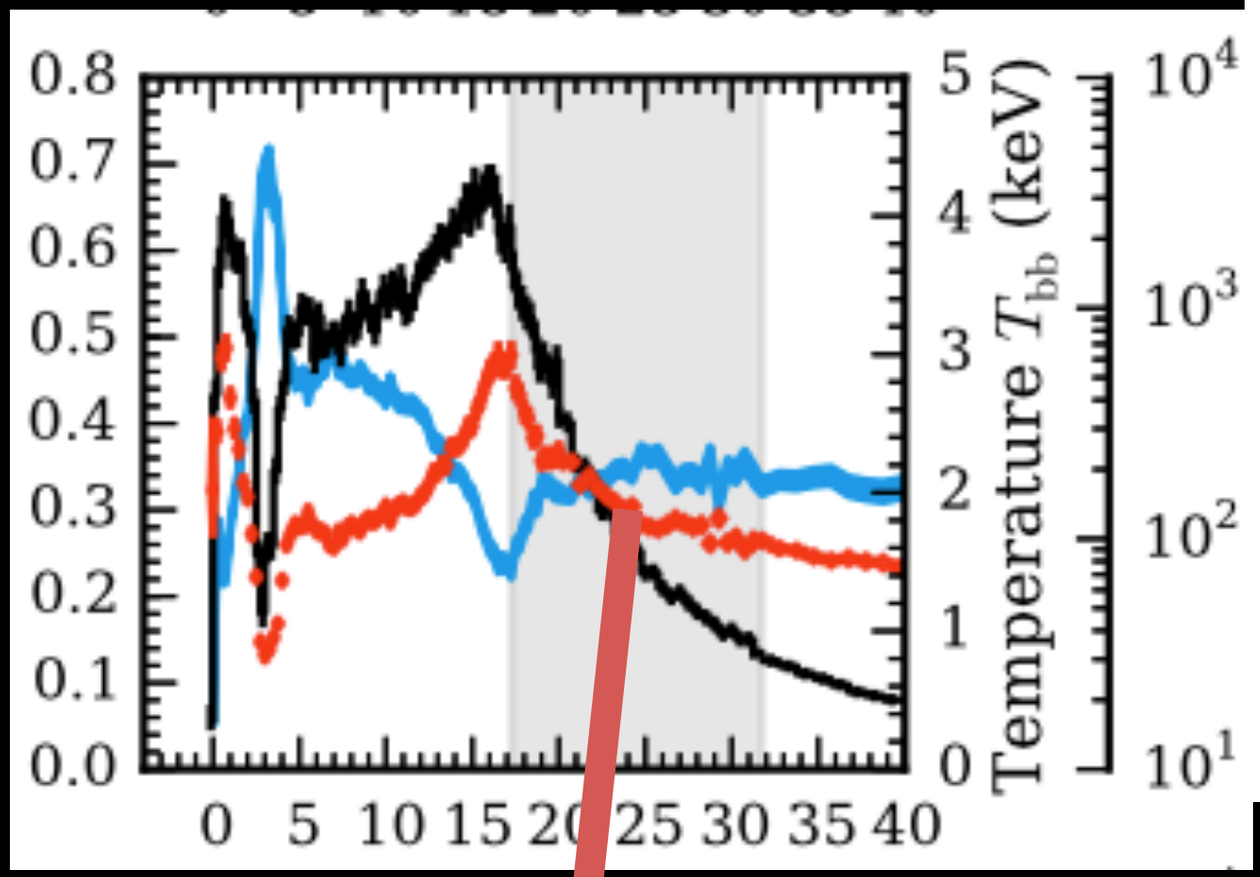
Ignition

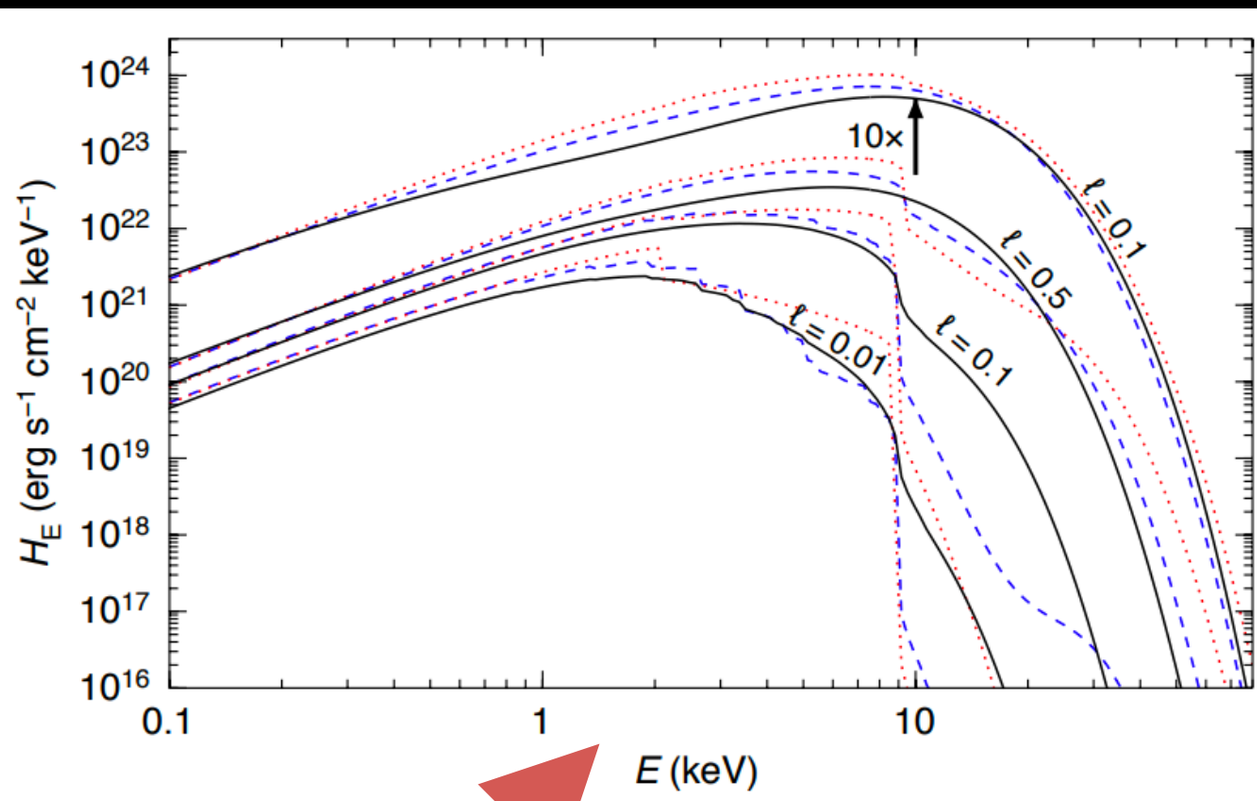


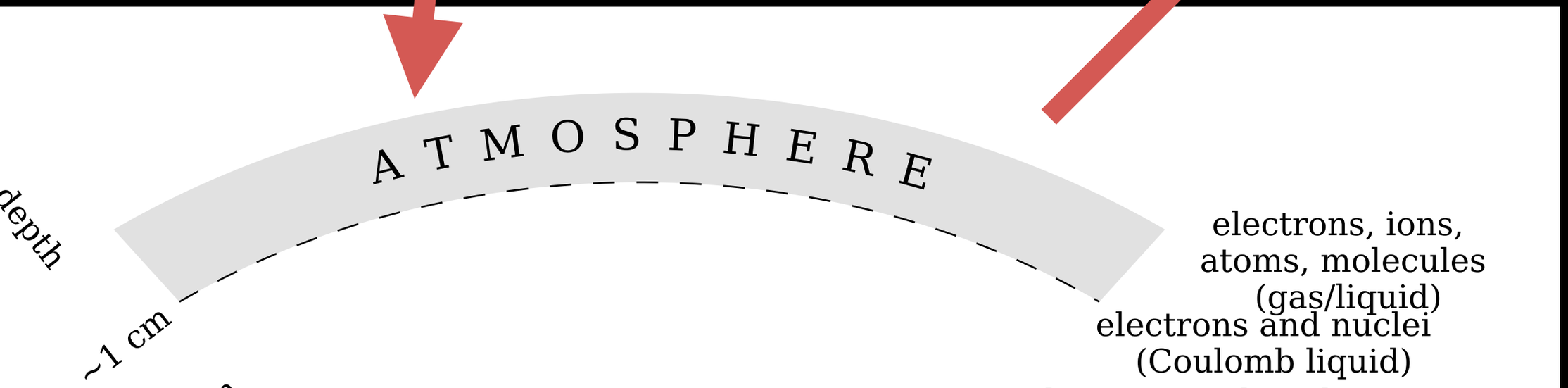
Cooling

A. Spitkovsky

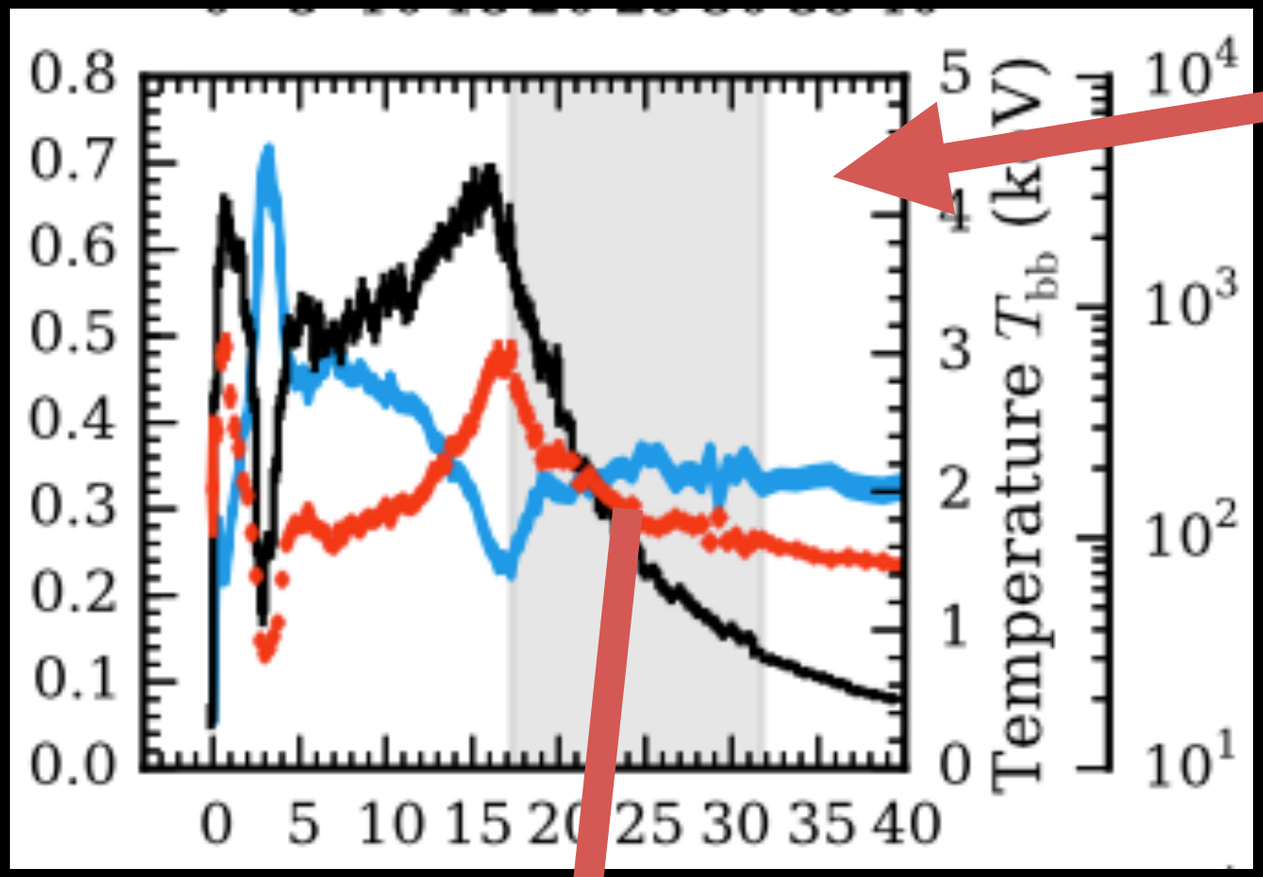
Atmosphere models

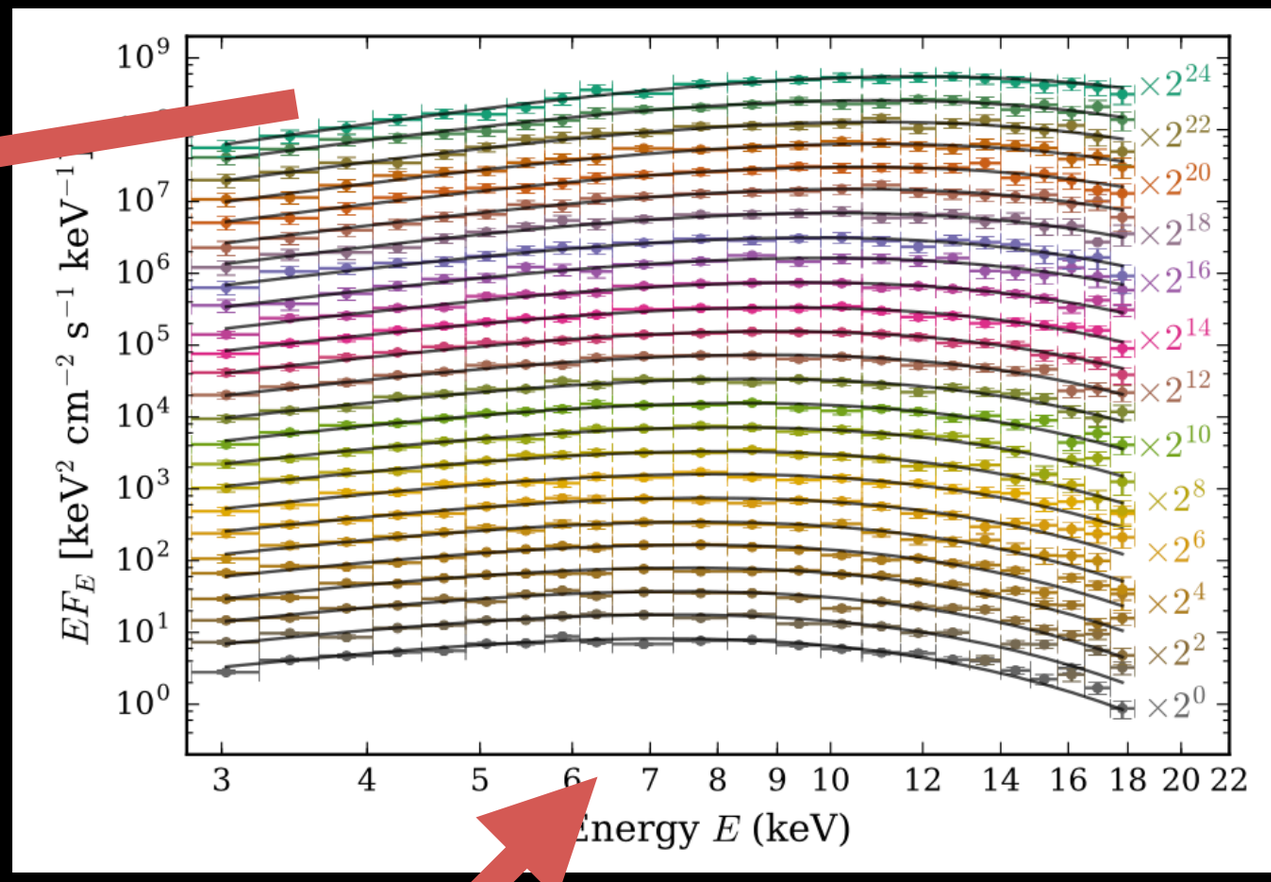


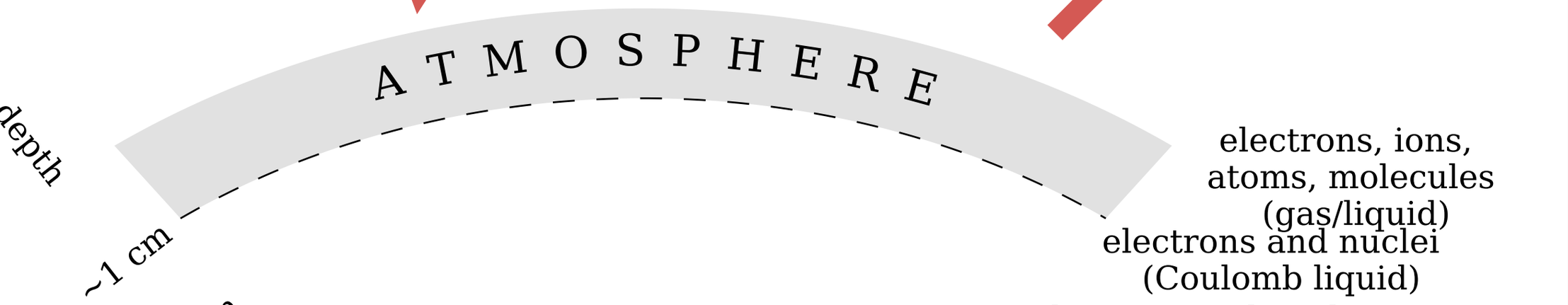




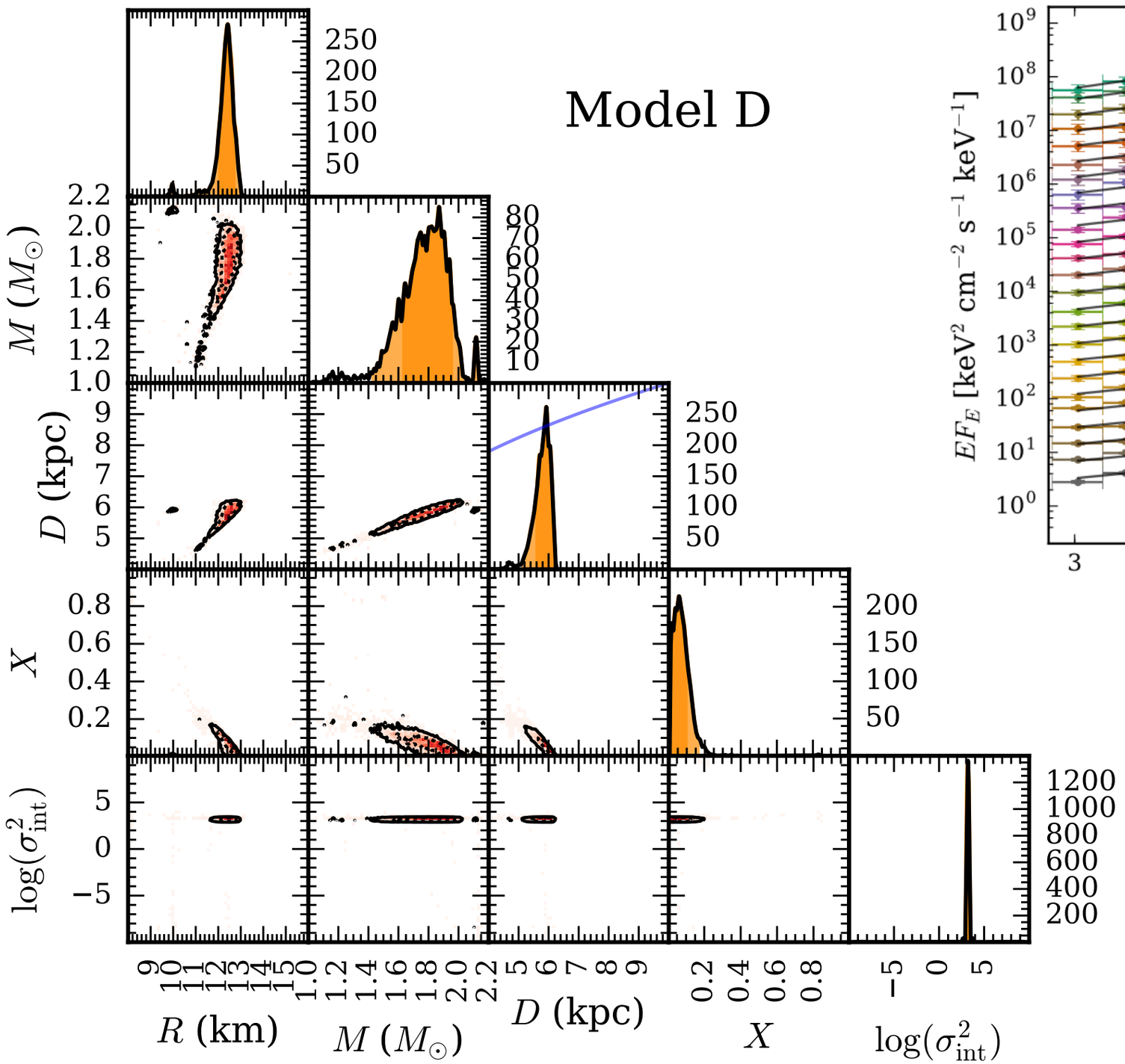
Atmosphere models

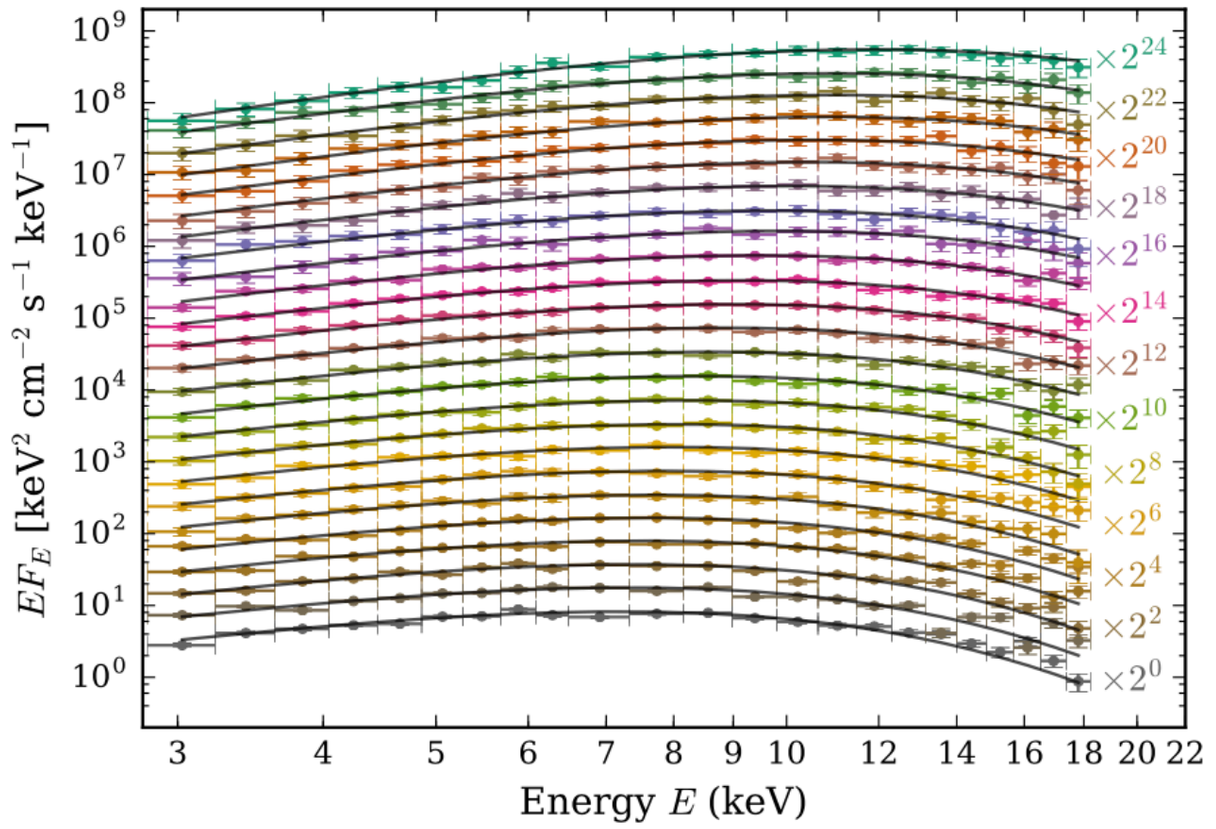




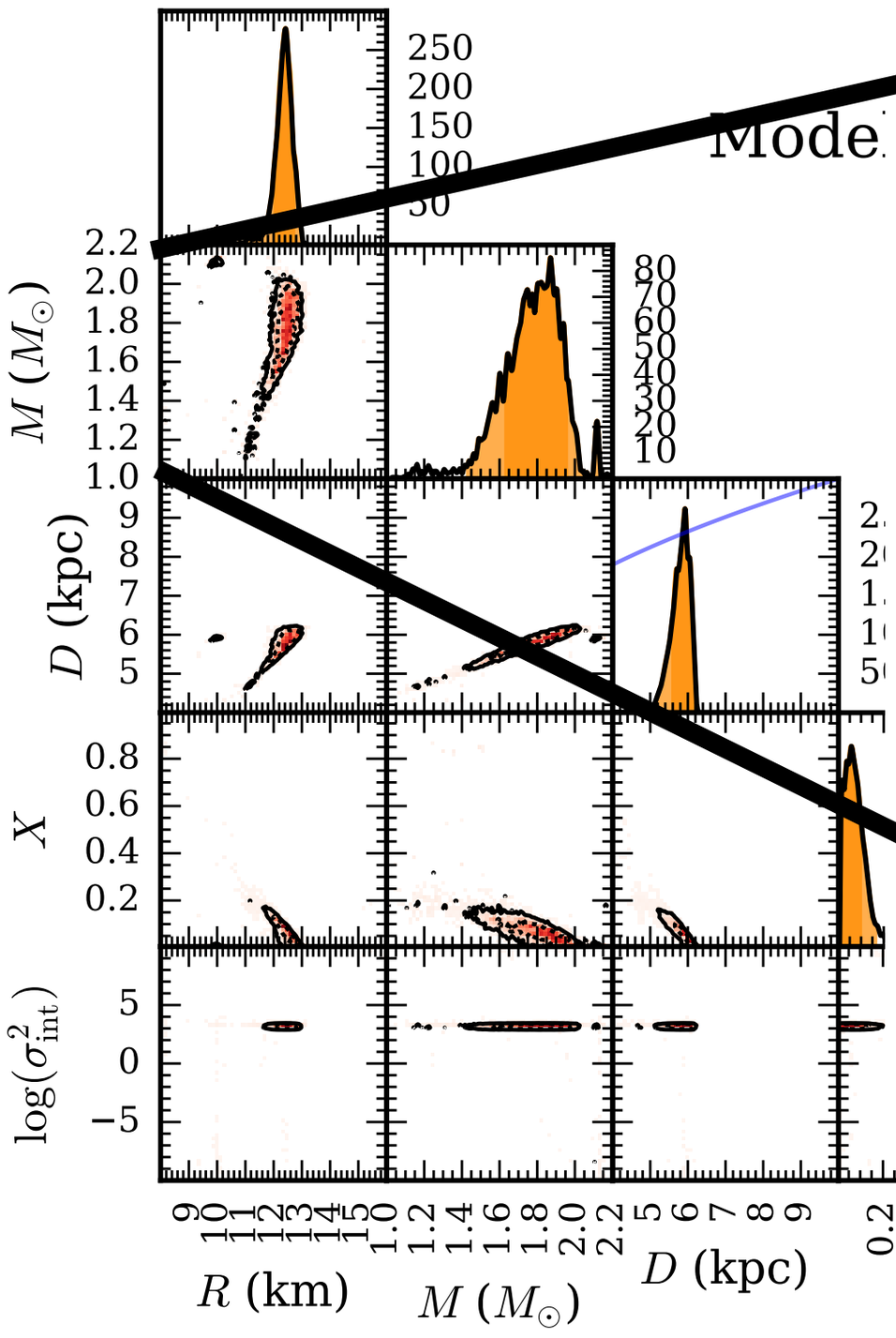


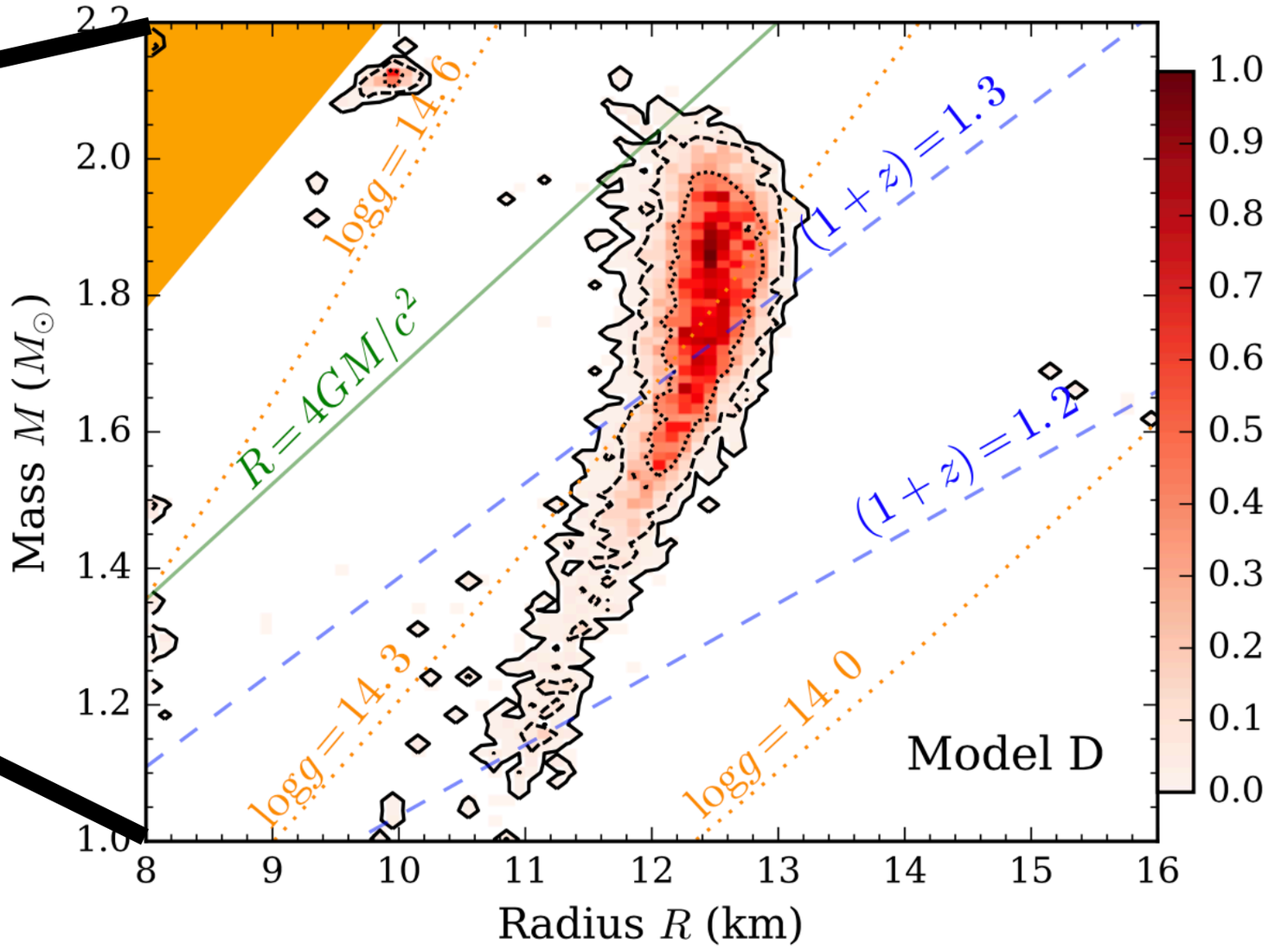
Posteriors


Model D
R (km)
M ($M_\odot$)
D (kpc)
X
$\log(\sigma^2_{\rm int})$


EF_E [keV^2 cm^{-2} s^{-1} keV^{-1}]
Energy E (keV)

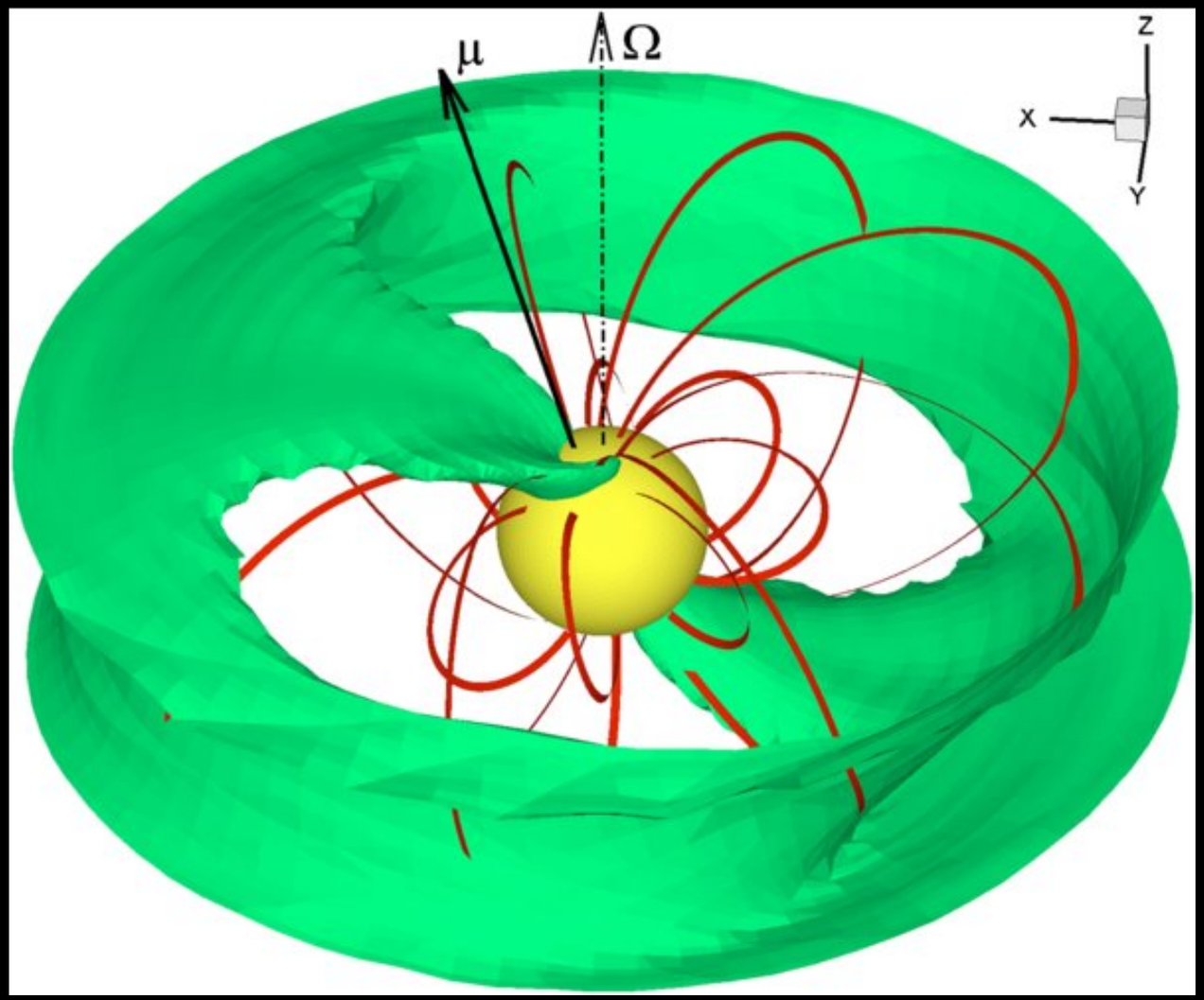
Posteriors


Mode
R (km)
M ($M_\odot$)
D (kpc)
X
$\log(\sigma^2_{\rm int})$

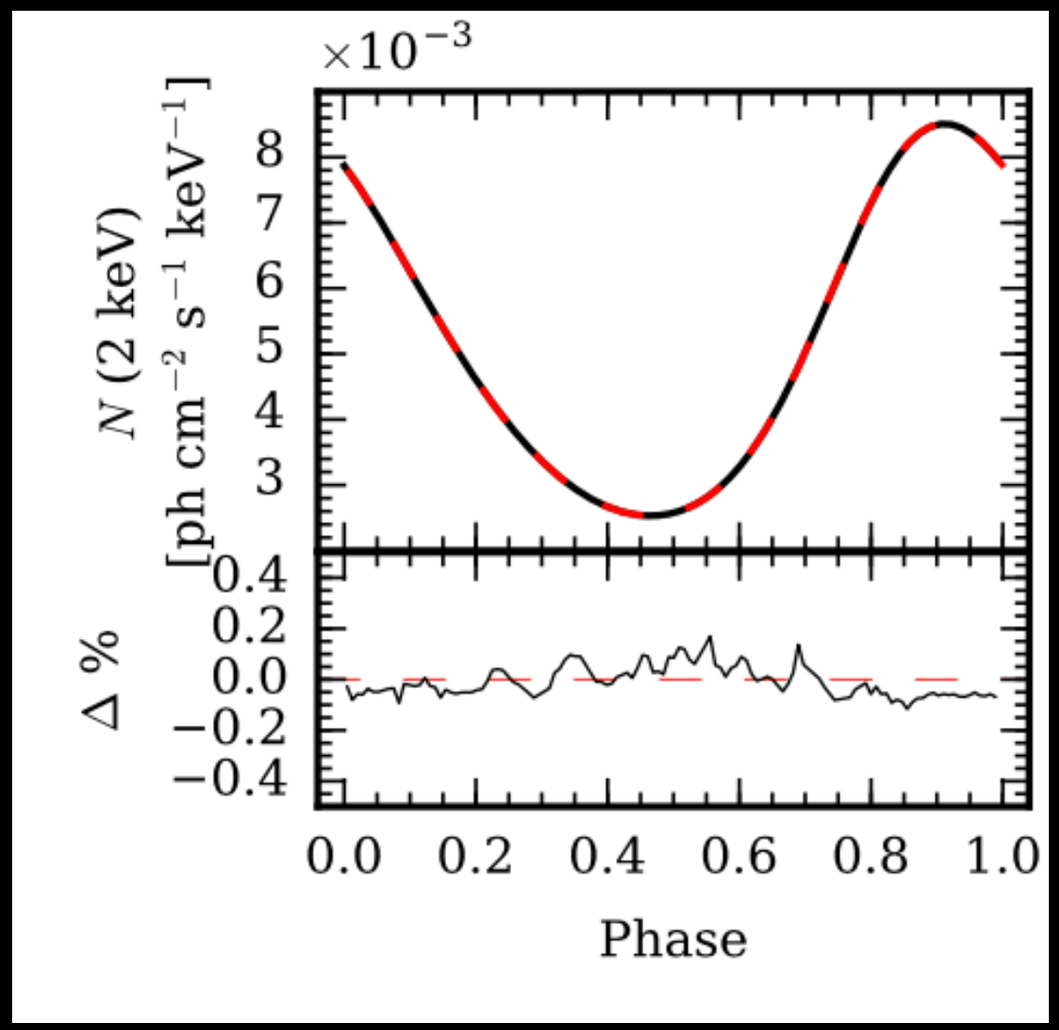

Mass M ($M_\odot$)
Radius R (km)
$\log g = 14.6$
$R = 4GM/c^2$
$(1+z) = 1.3$
$(1+z) = 1.2$
$\log g = 14.3$
$\log g = 14.0$
Model D

Astrophysical measurements

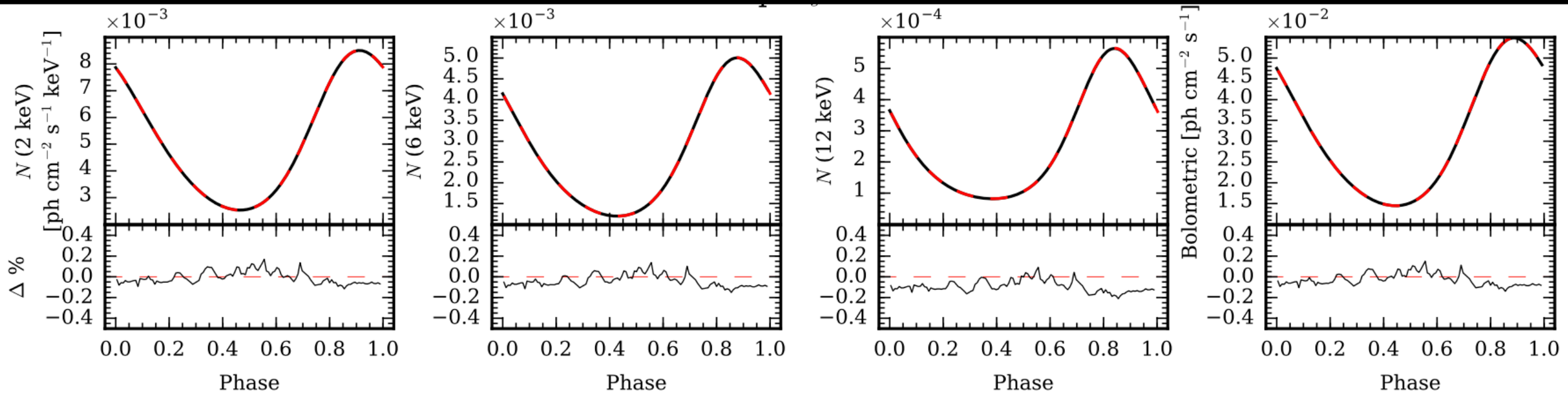
- Pulse profiles of millisecond X-ray pulsars



Romanova et al.

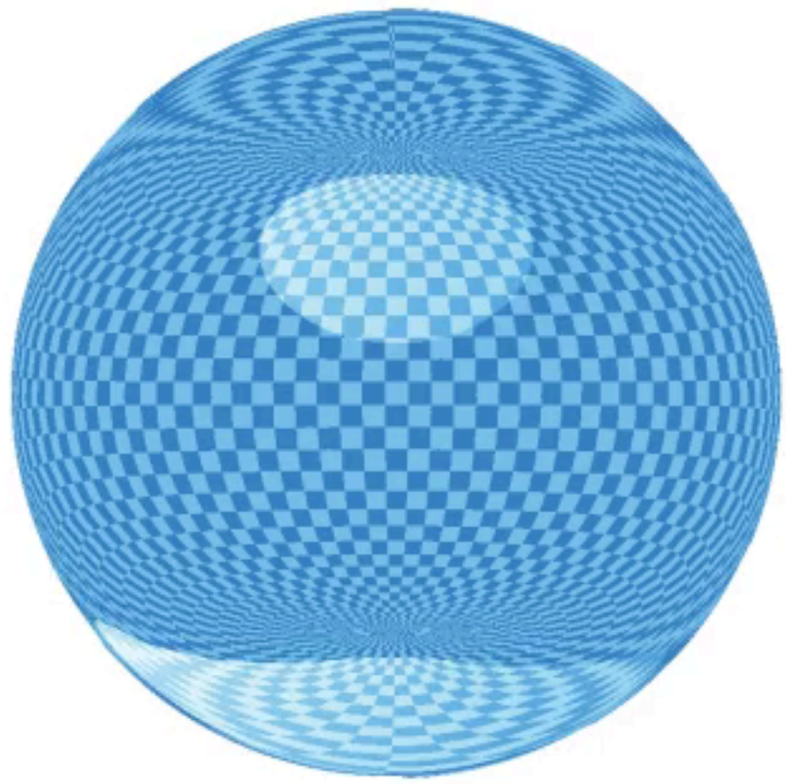


Pulse profiles

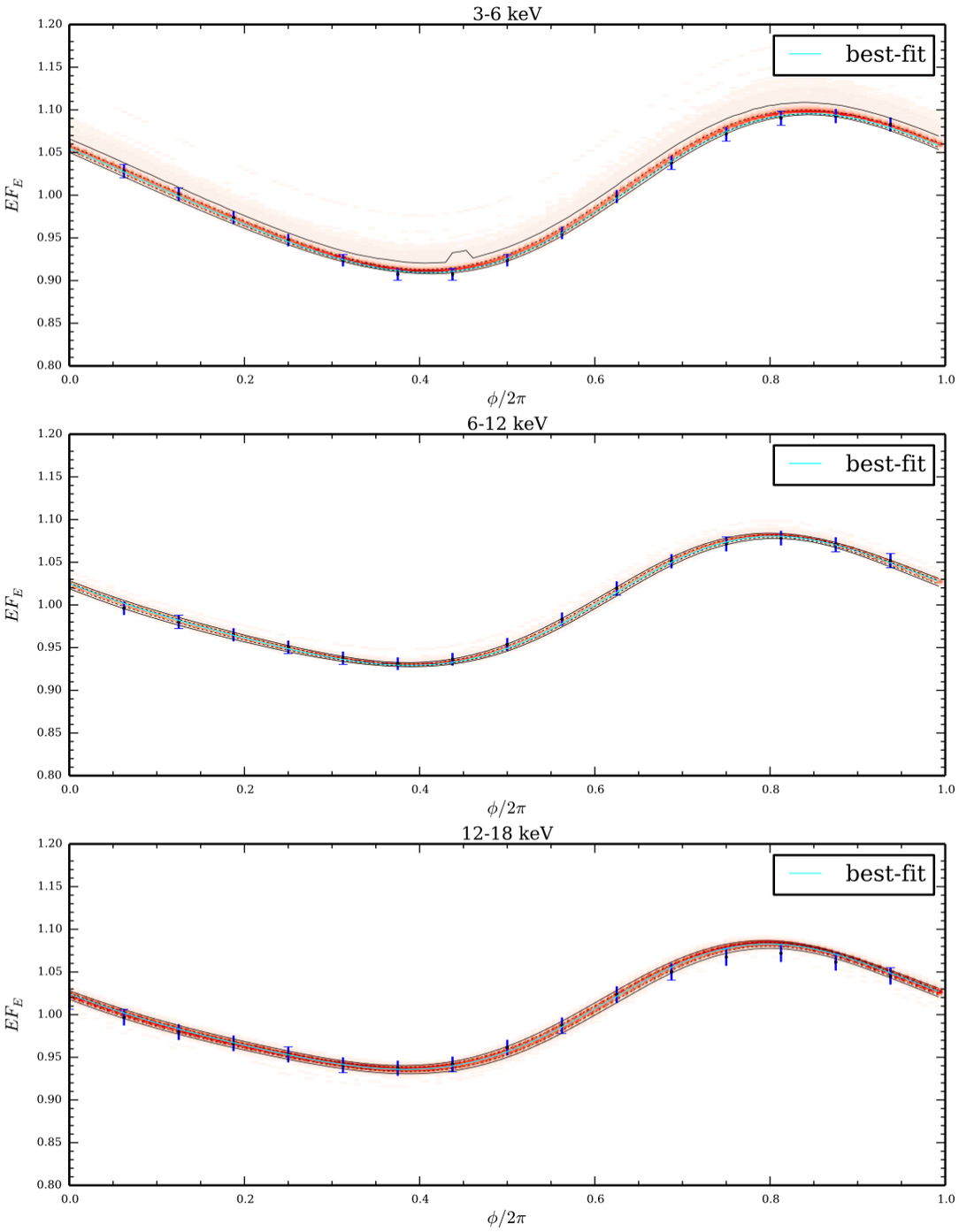


$$F_E(t) = \int I_E(t)\, d\Omega_o = \int\int \frac{I'_{E'}(t_*, \alpha')}{(1+z)^3}\, \frac{b db\, d\chi}{D^2}$$

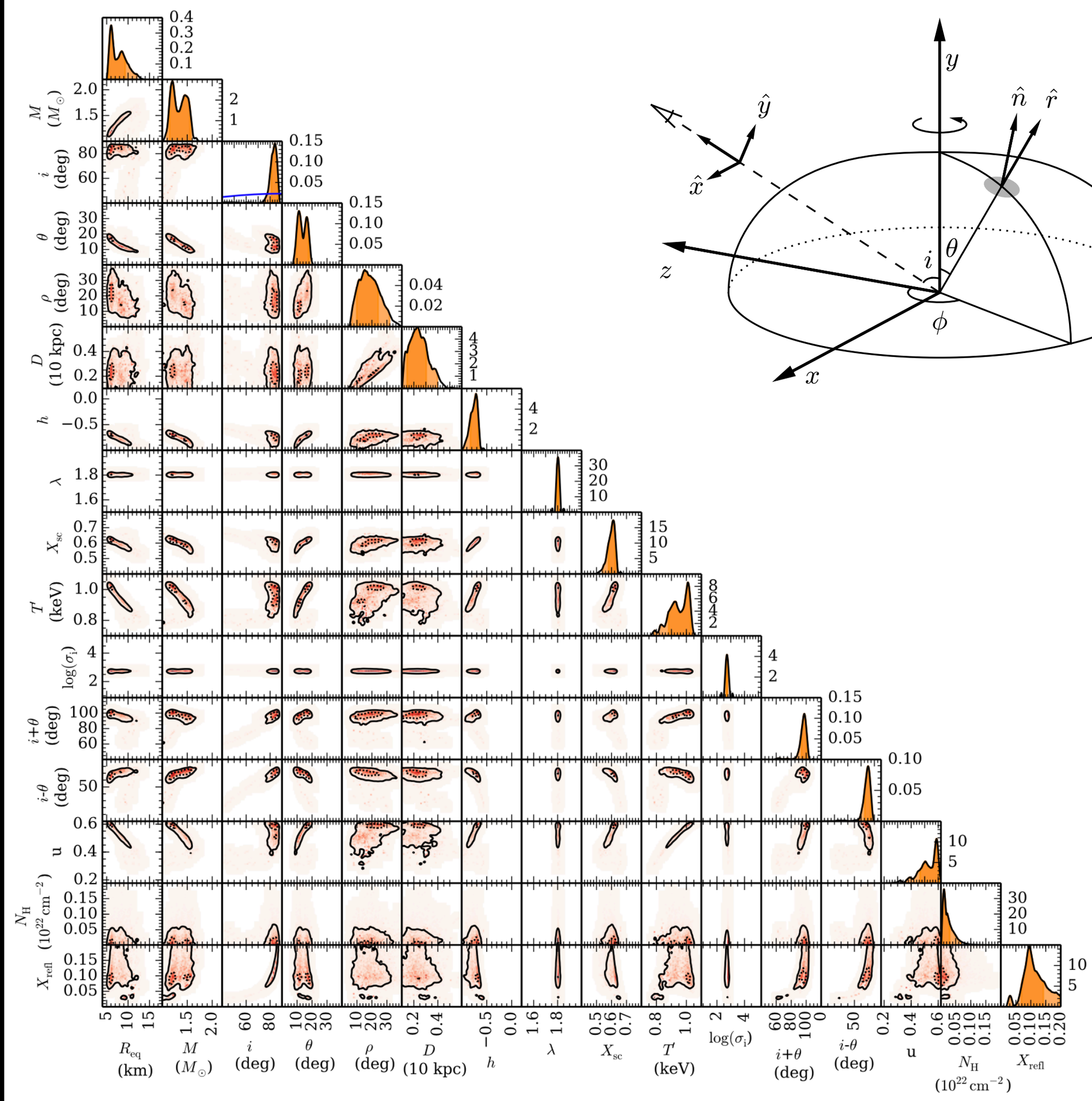
Nättilä & Pihajoki 2018



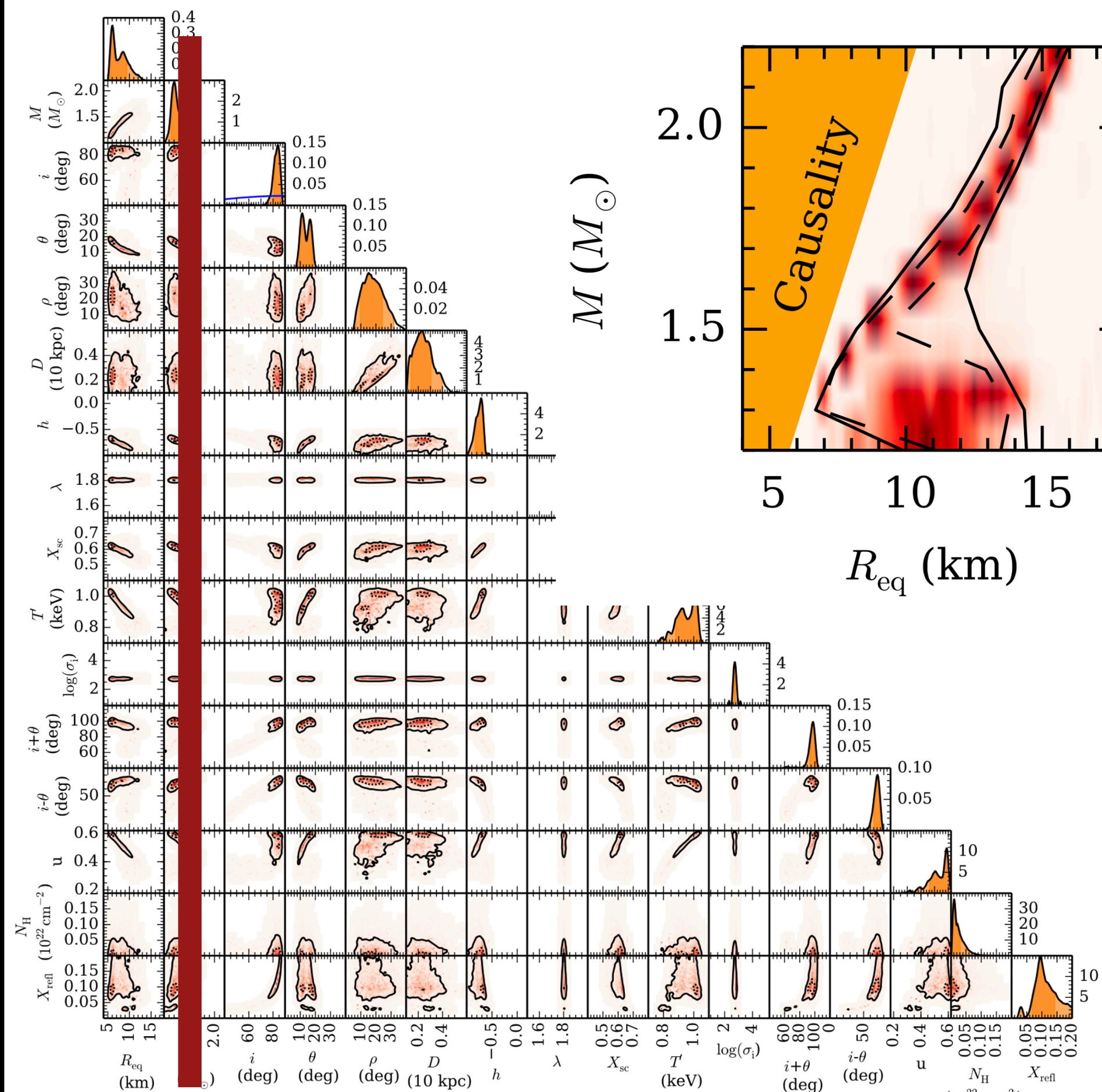
Pulse profiles vs. data



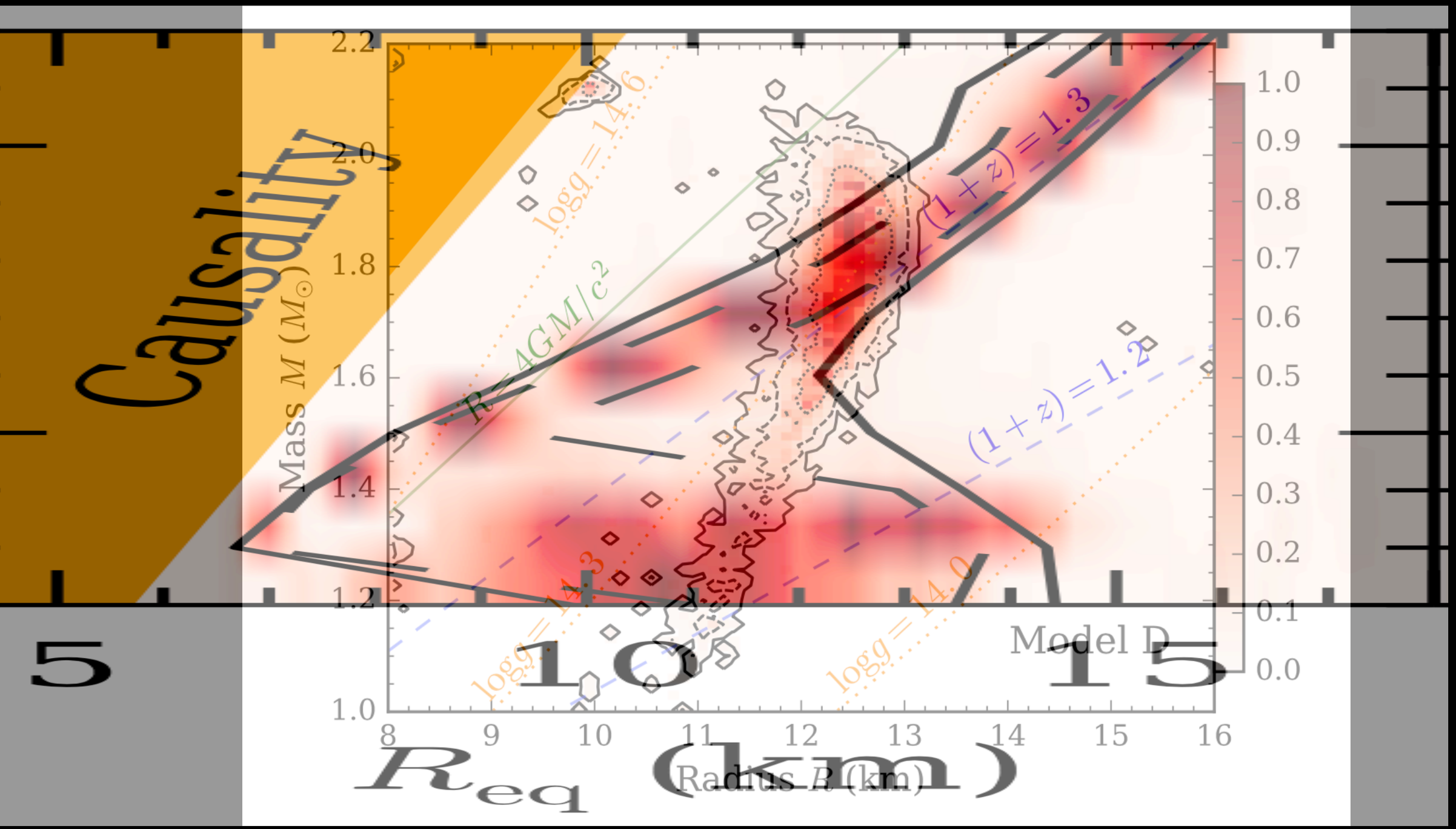
- **SAXJ 1808.4-3658**
- millisecond period
- 16 Phase bins
- 24 Energy bins
- ~1 week of data


$R_{\rm eq}$ (km)
M ($M_\odot$)
i (deg)
θ (deg)
ρ (deg)
D (10 kpc)
h
λ
$X_{\rm sc}$
T' (keV)
$\log(\sigma_{\rm i})$
i+θ (deg)
i-θ (deg)
u
$N_{\rm H}$ ($10^{22}\,{\rm cm}^{-2}$)
$X_{\rm refl}$

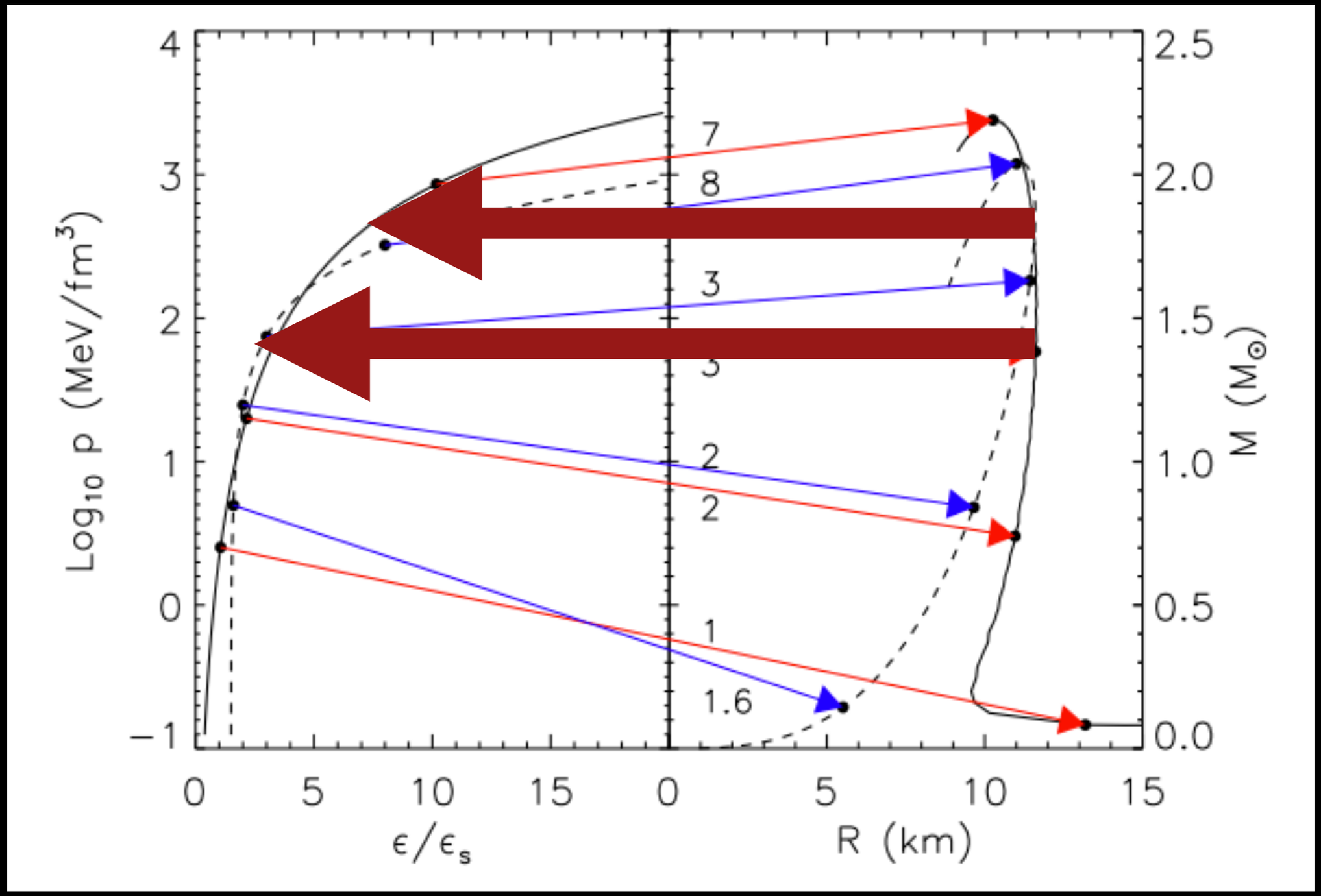
y
$\hat{y}$
$\hat{n}$
$\hat{r}$
$\hat{x}$
z
i
θ
ϕ
x


Causality
$M\ (M_\odot)$
$R_{\rm eq}$ (km)
2.0
1.5
5
10
15

Combining our knowledge

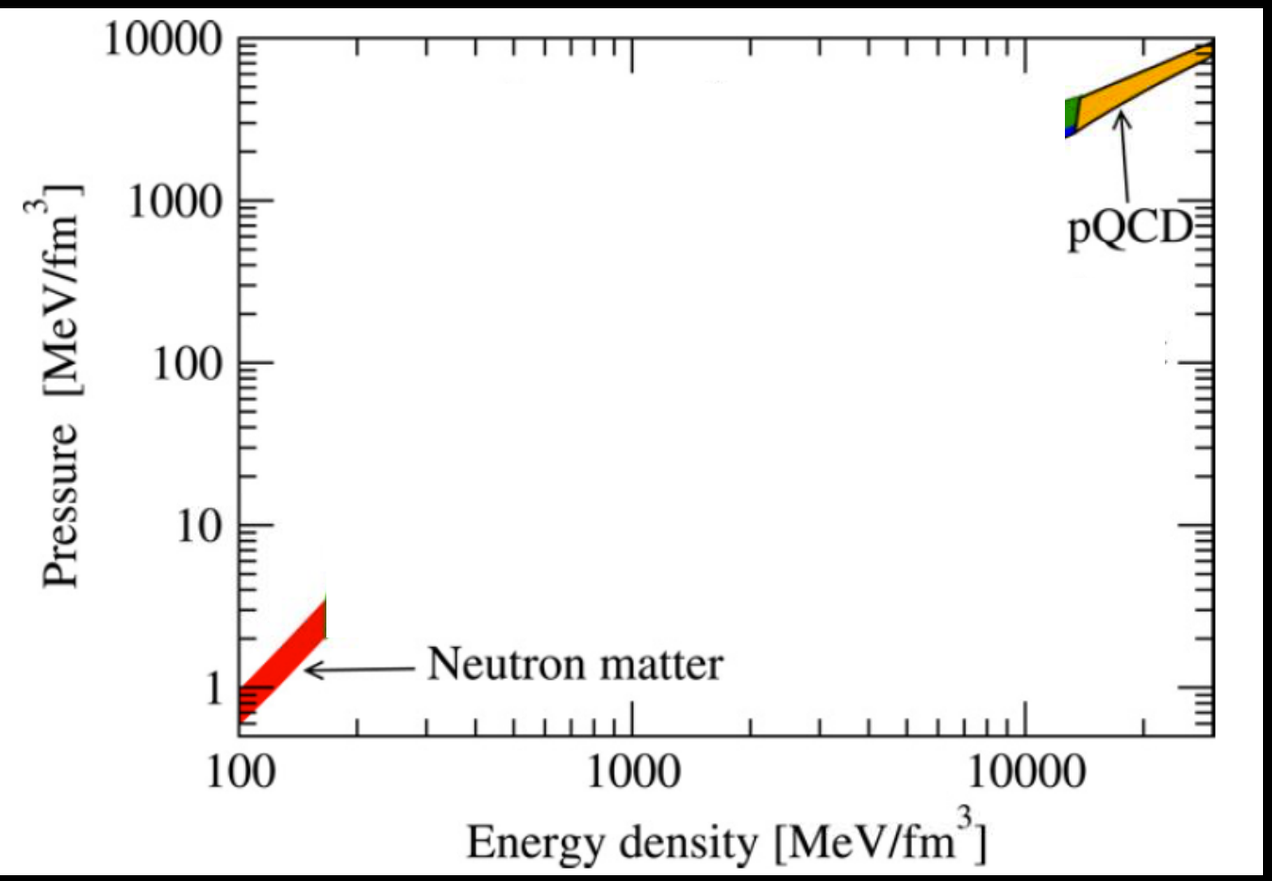


Astrophysical measurements



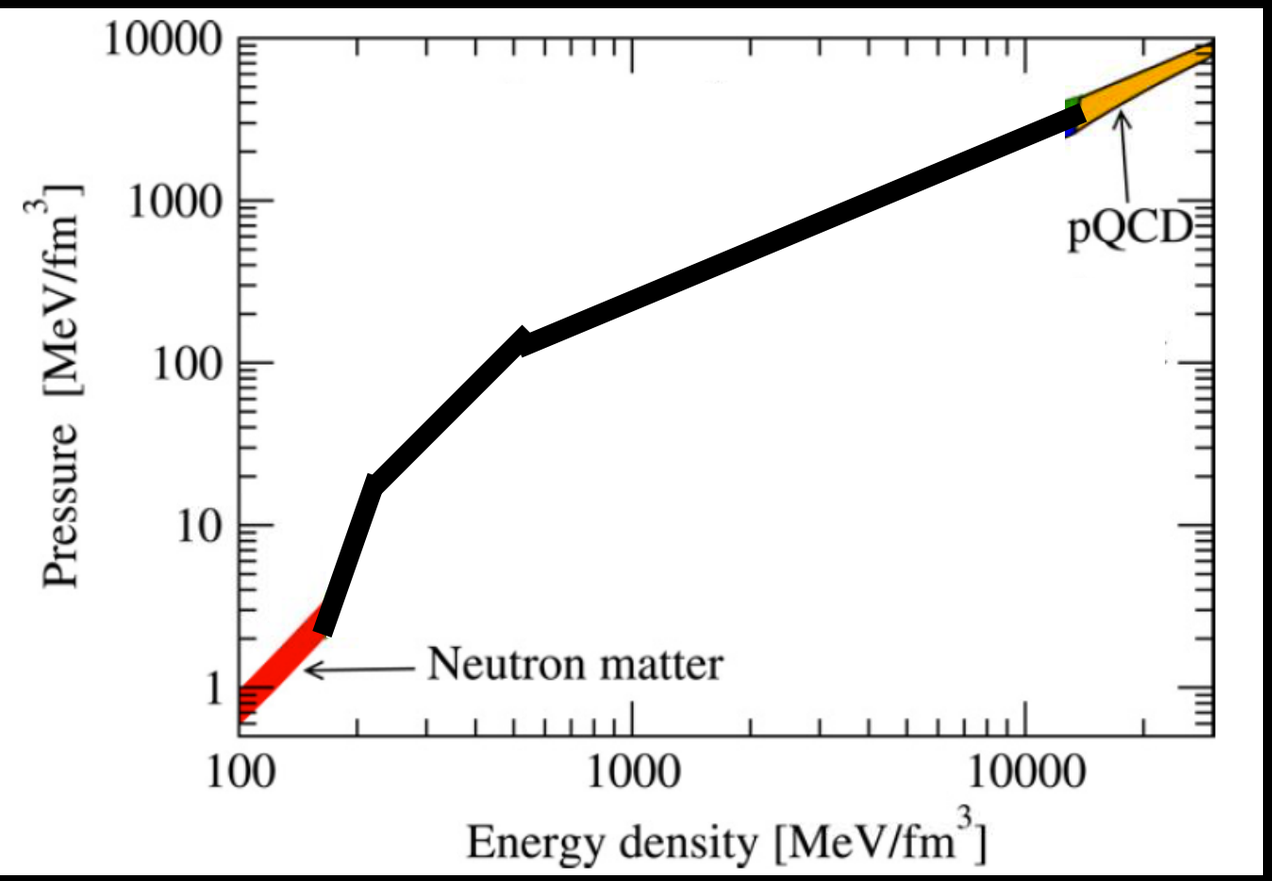
Lattimer+2012

EoS reconstruction



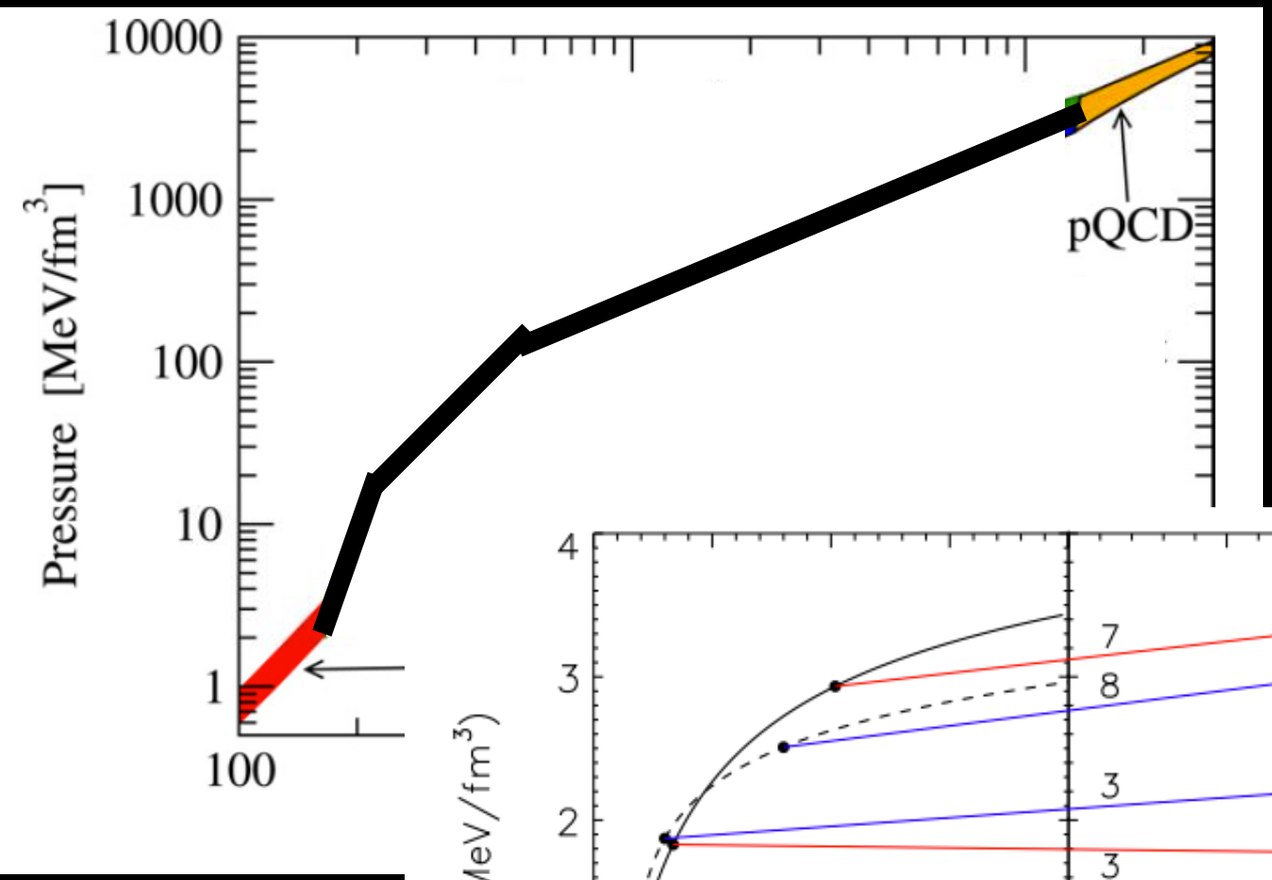
Step 0.

EoS reconstruction



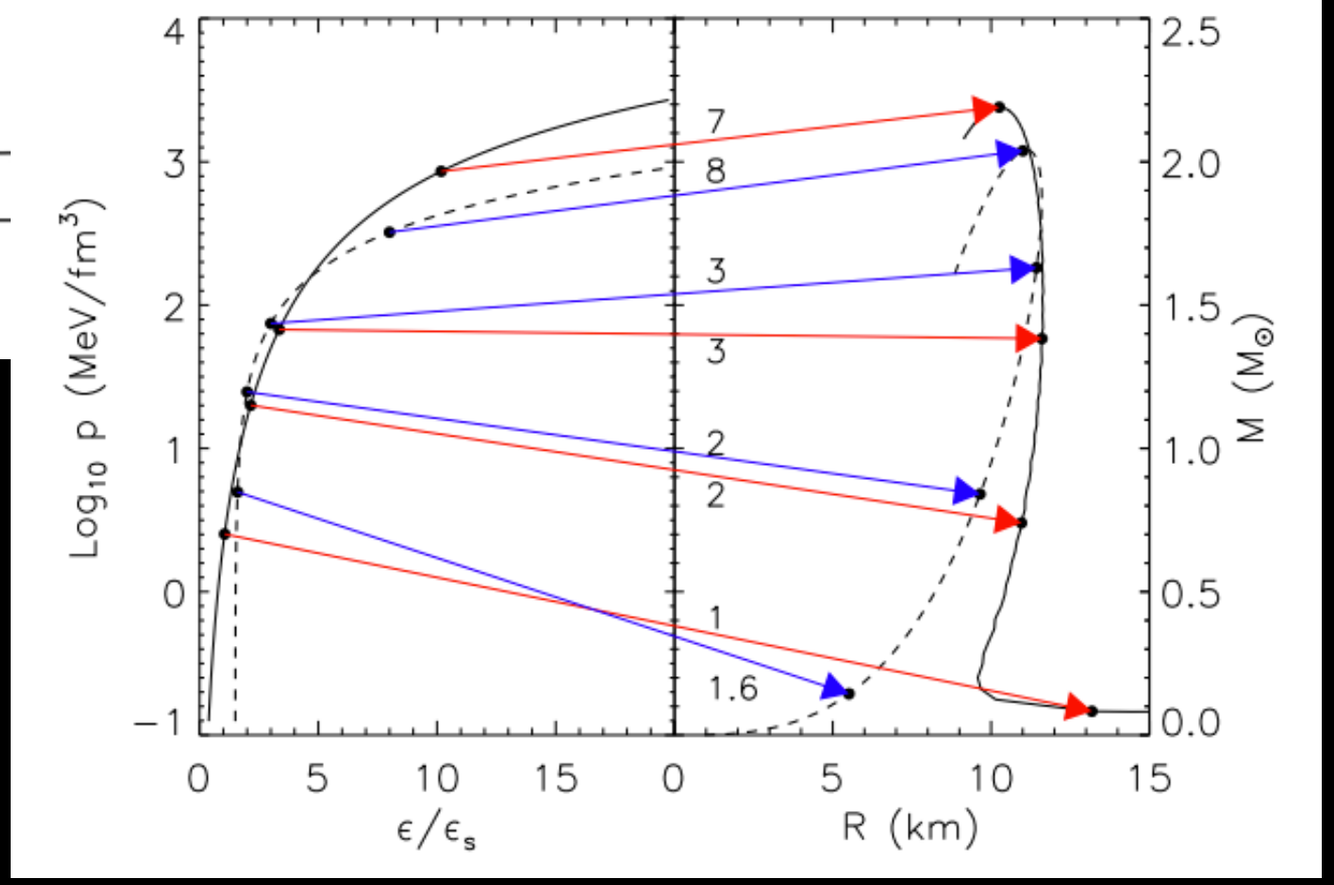
Step 1.

EoS reconstruction

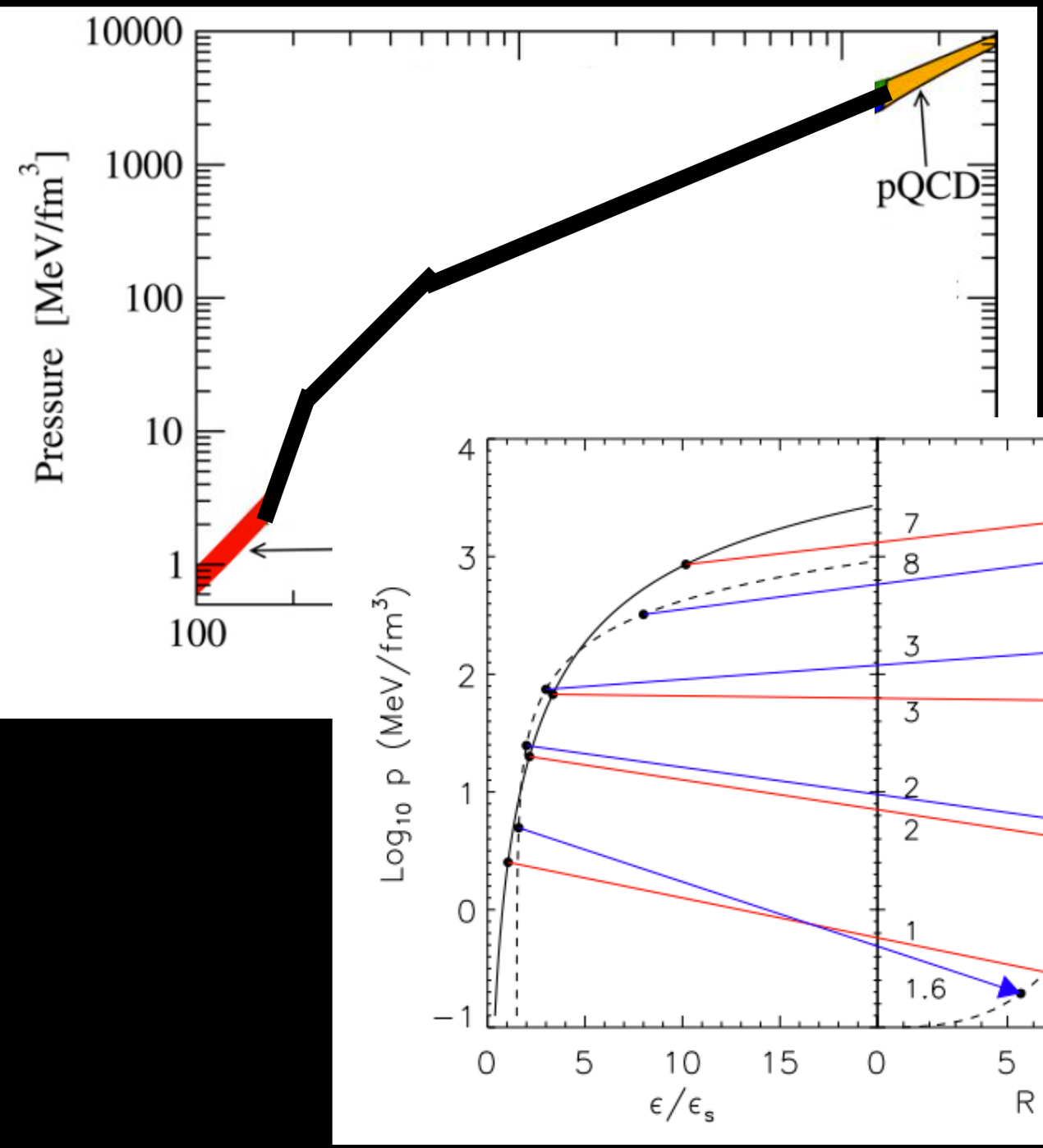


Step 1.

Step 2.



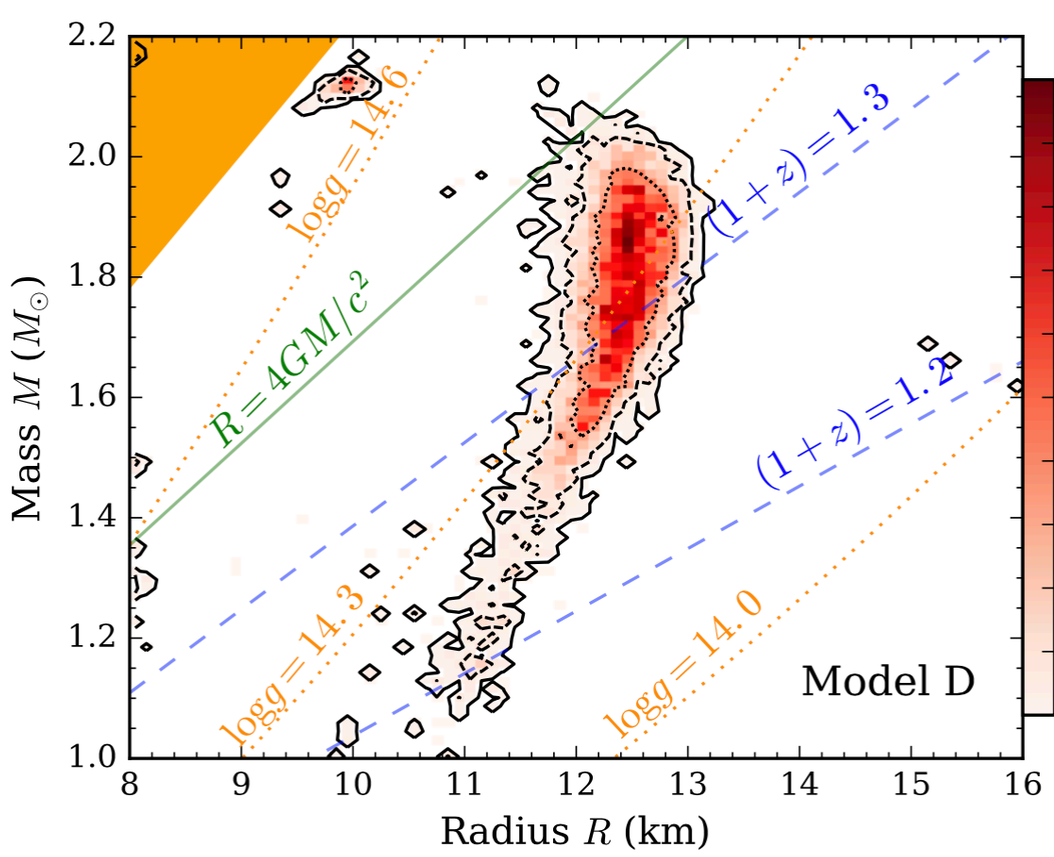
EoS reconstruction



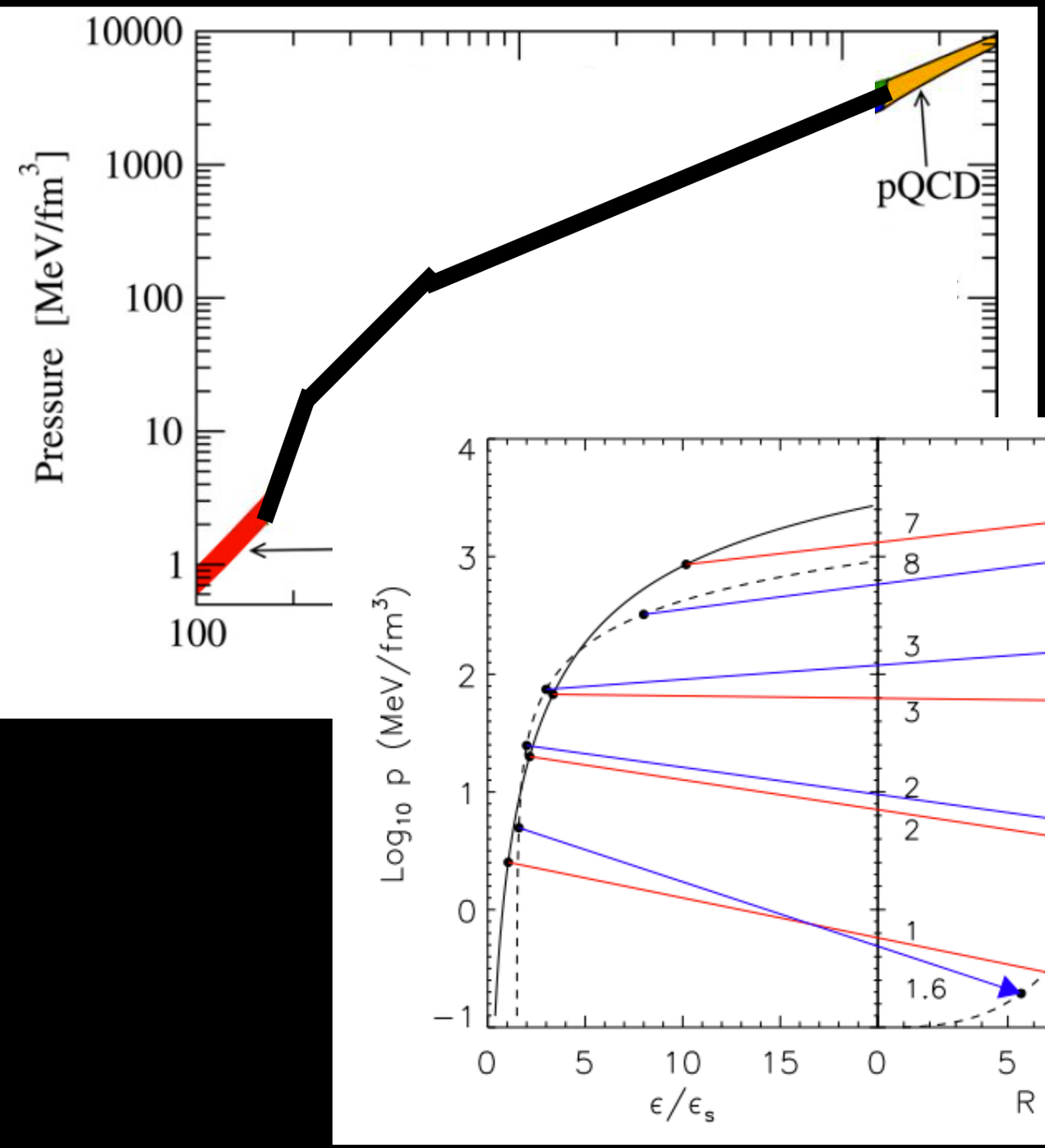
Step 1.

Step 2.

Step 3.



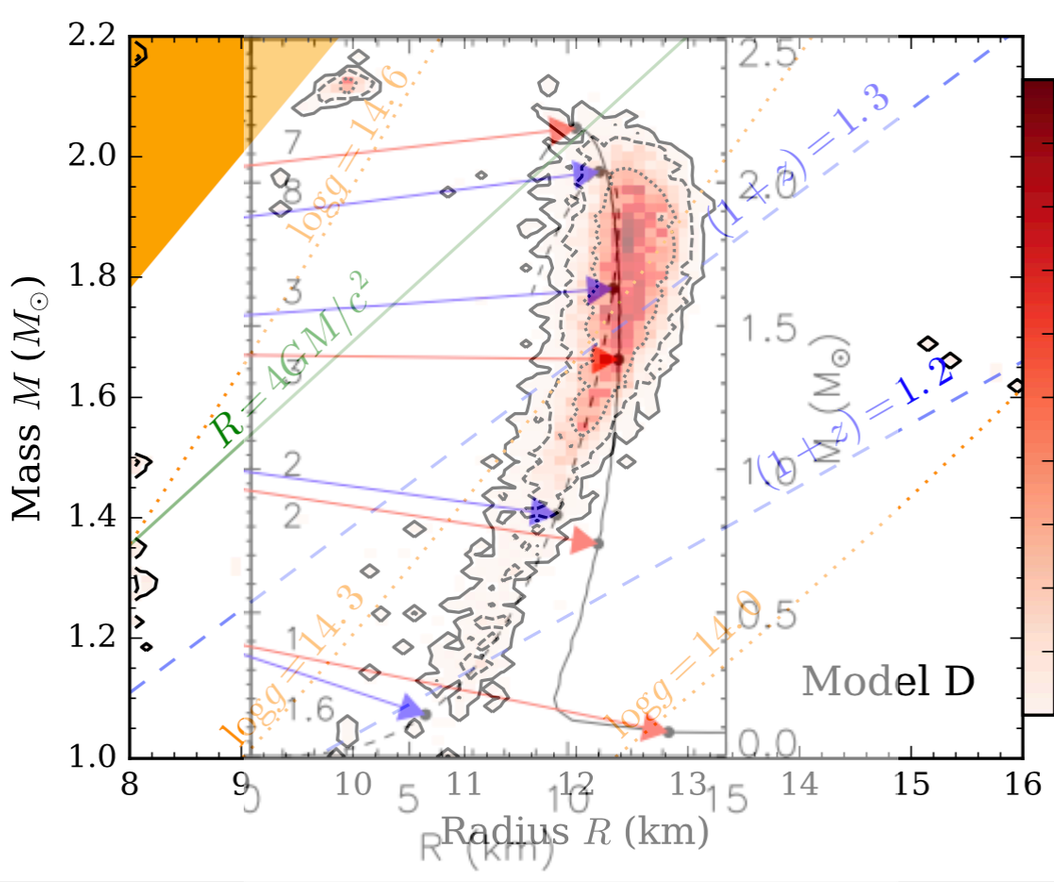
EoS reconstruction



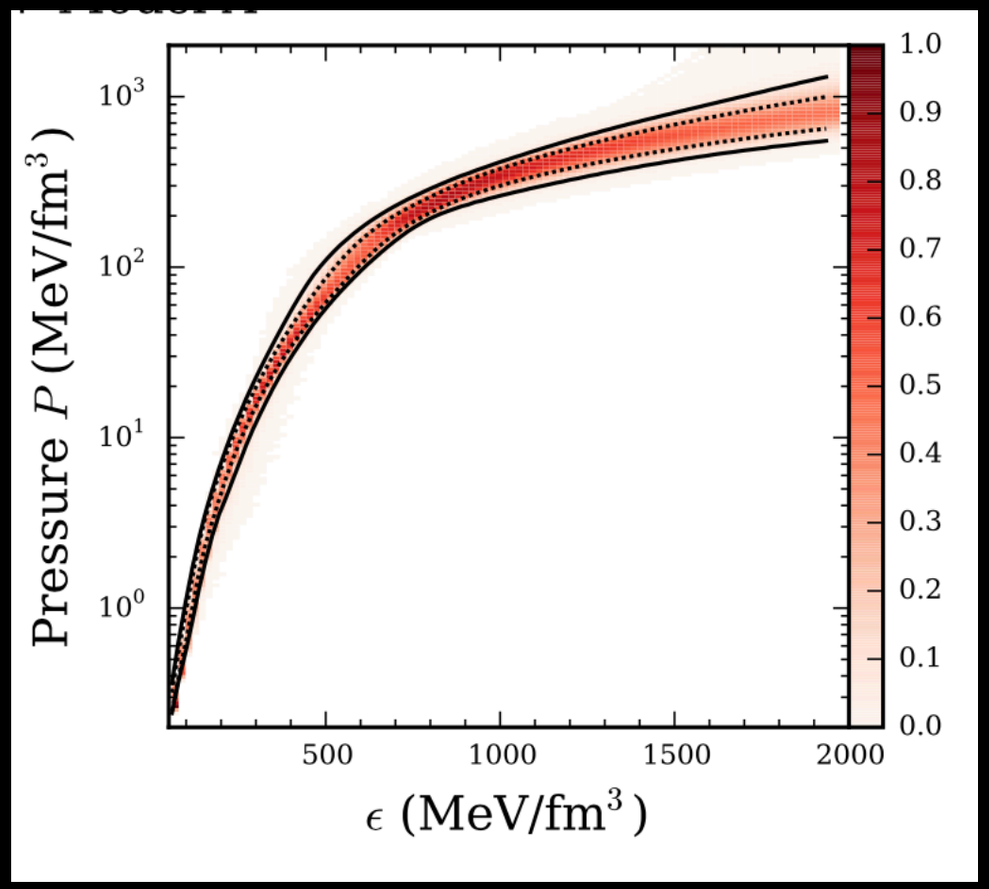
Step 1.

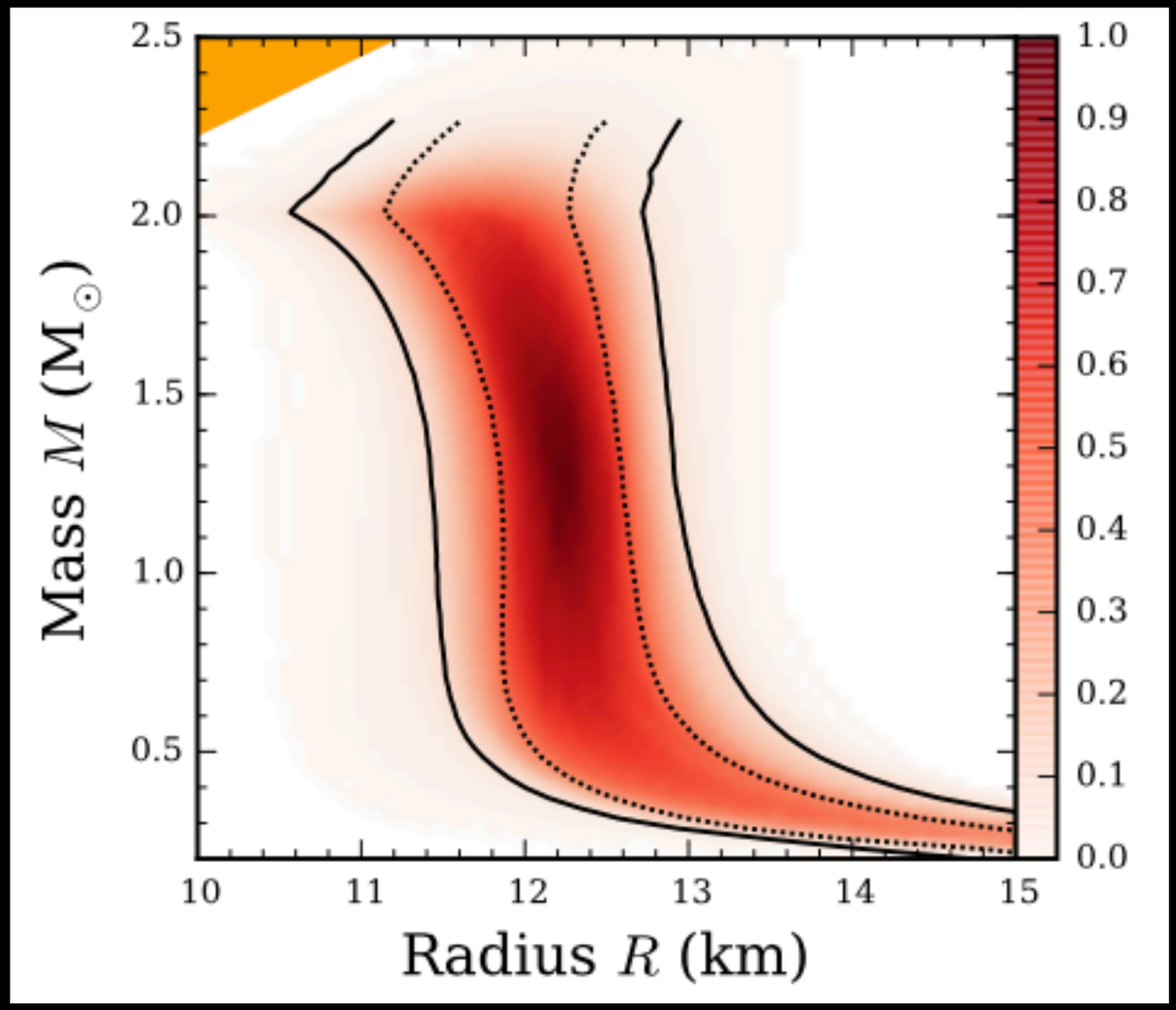
Step 2.

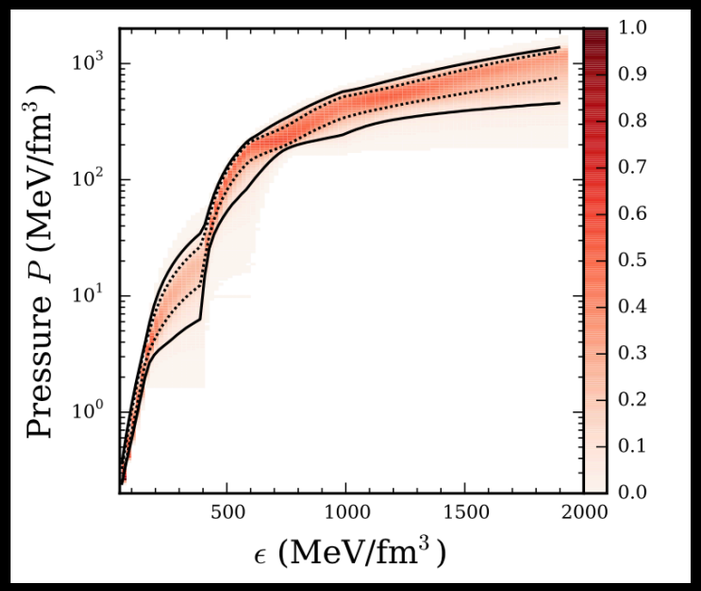
Step 3.



Reconstructed EoS

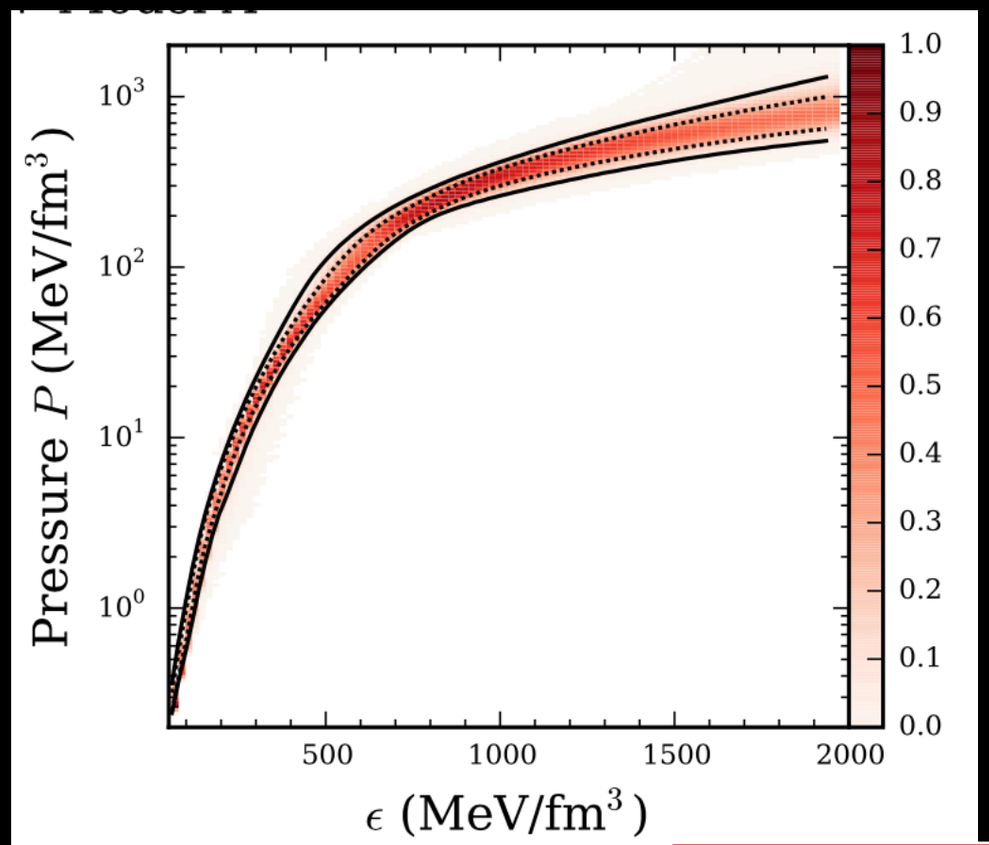


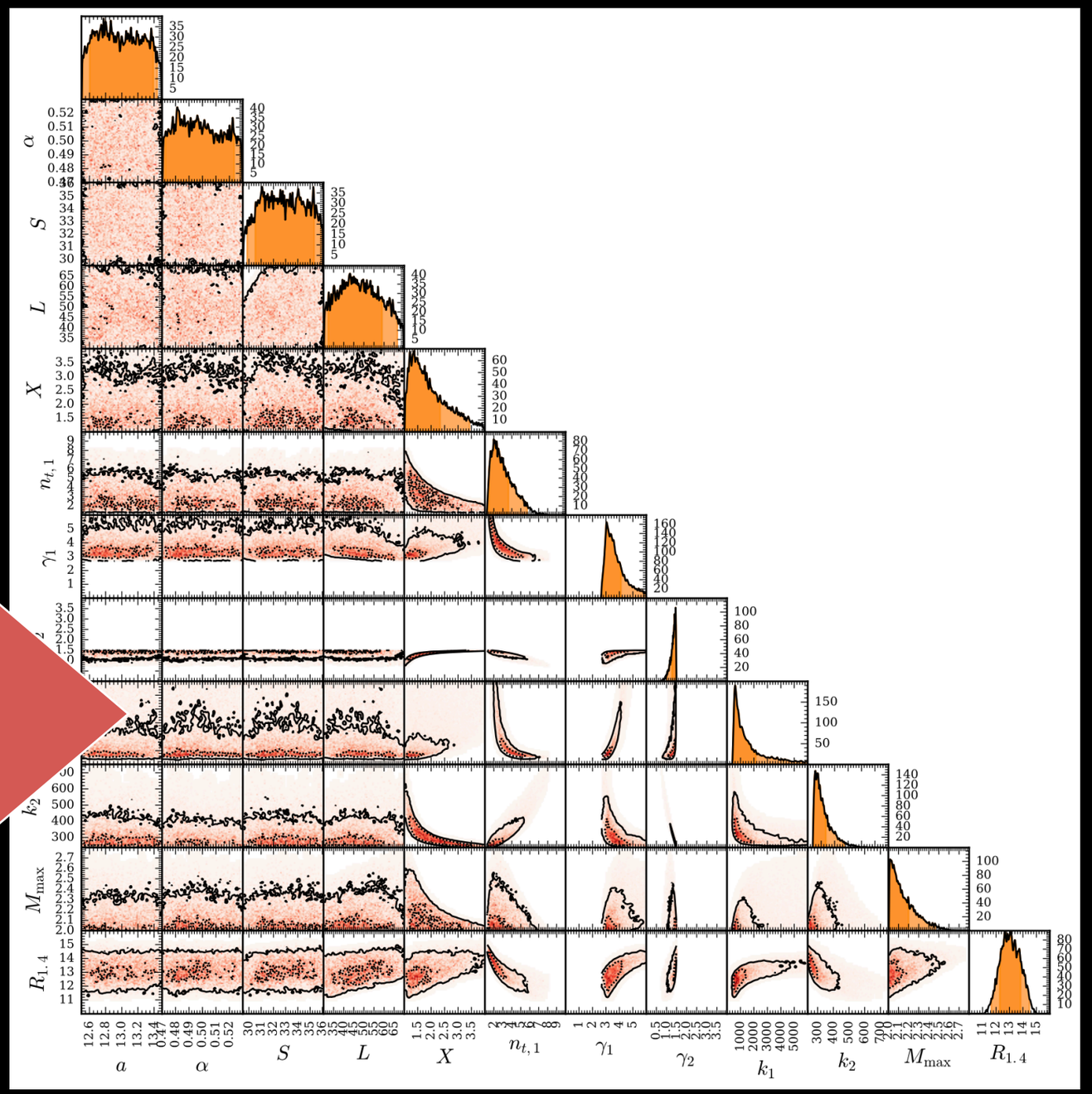


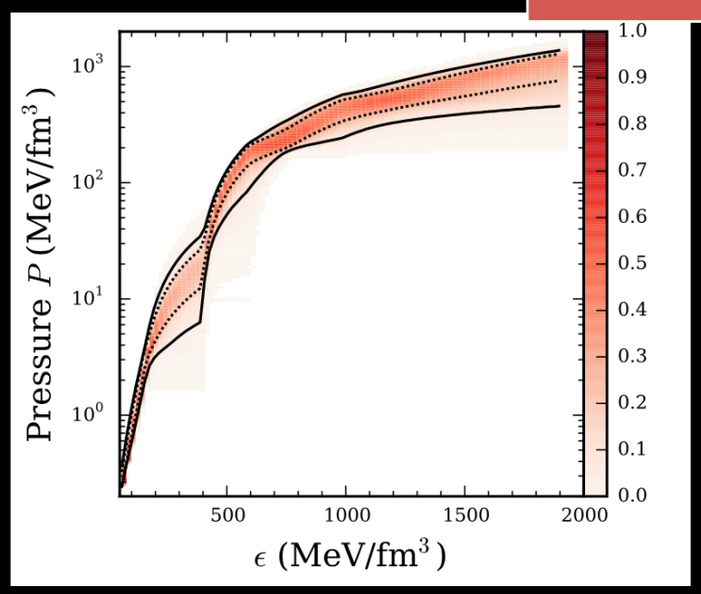


Nättilä+2016

…and nuclear physics







EoS + pQCD constraints

Annala, Nättilä+ 2018 (in prep.)

Simple questions from kindergarden:

how big are neutron stars?

What is inside them?

How does matter behave under immense pressure?