# Neutron-Mirror Stars

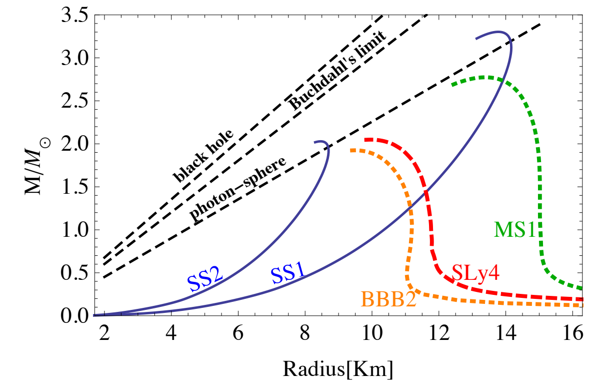
**Massimo Mannarelli**
**INFN-LNGS**
**massimo@lngs.infn.it**

**work in progress with Z. Bherezhiani, R. Biondi and F. Tonelli**

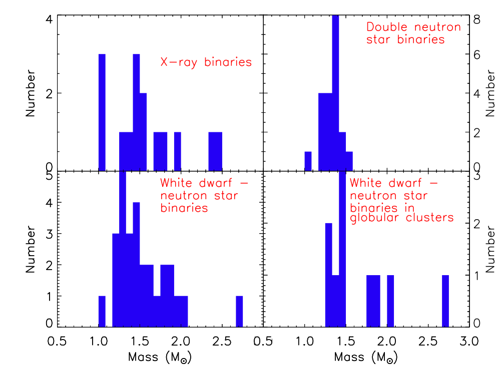
*Particle Physics with Neutrons at the ESS*
*Stockholm, Dec 14, 2018*

# Outline

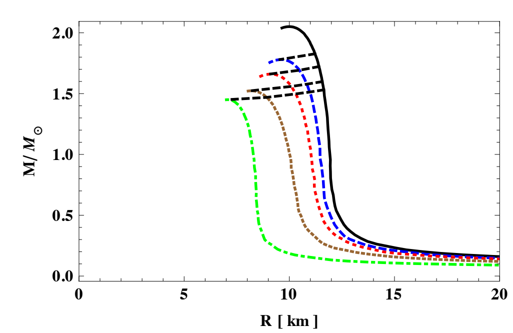
- Introduction




- Mass distribution of NSs




- Neutron-mirror stars

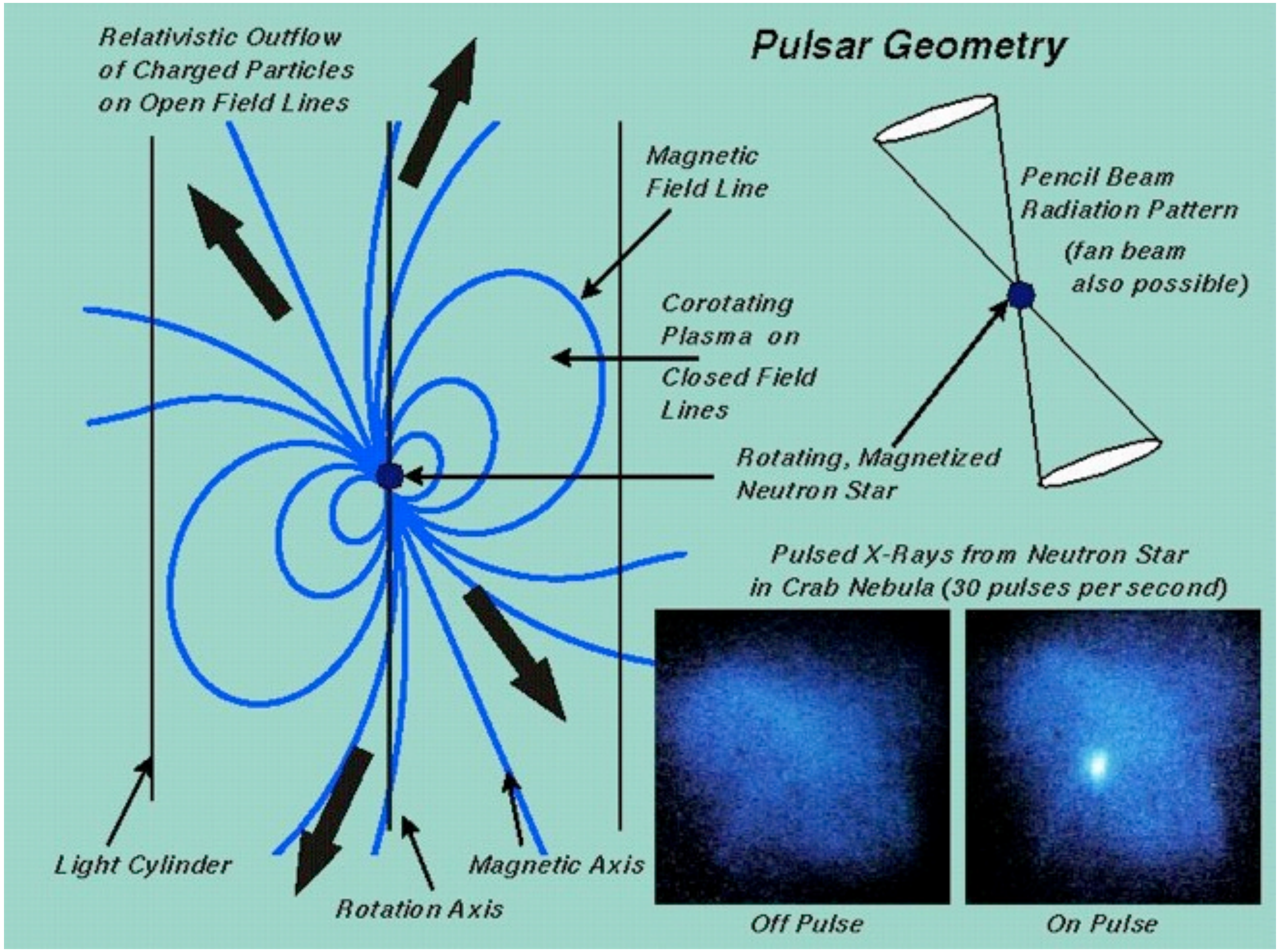



- Conclusions

# Introduction

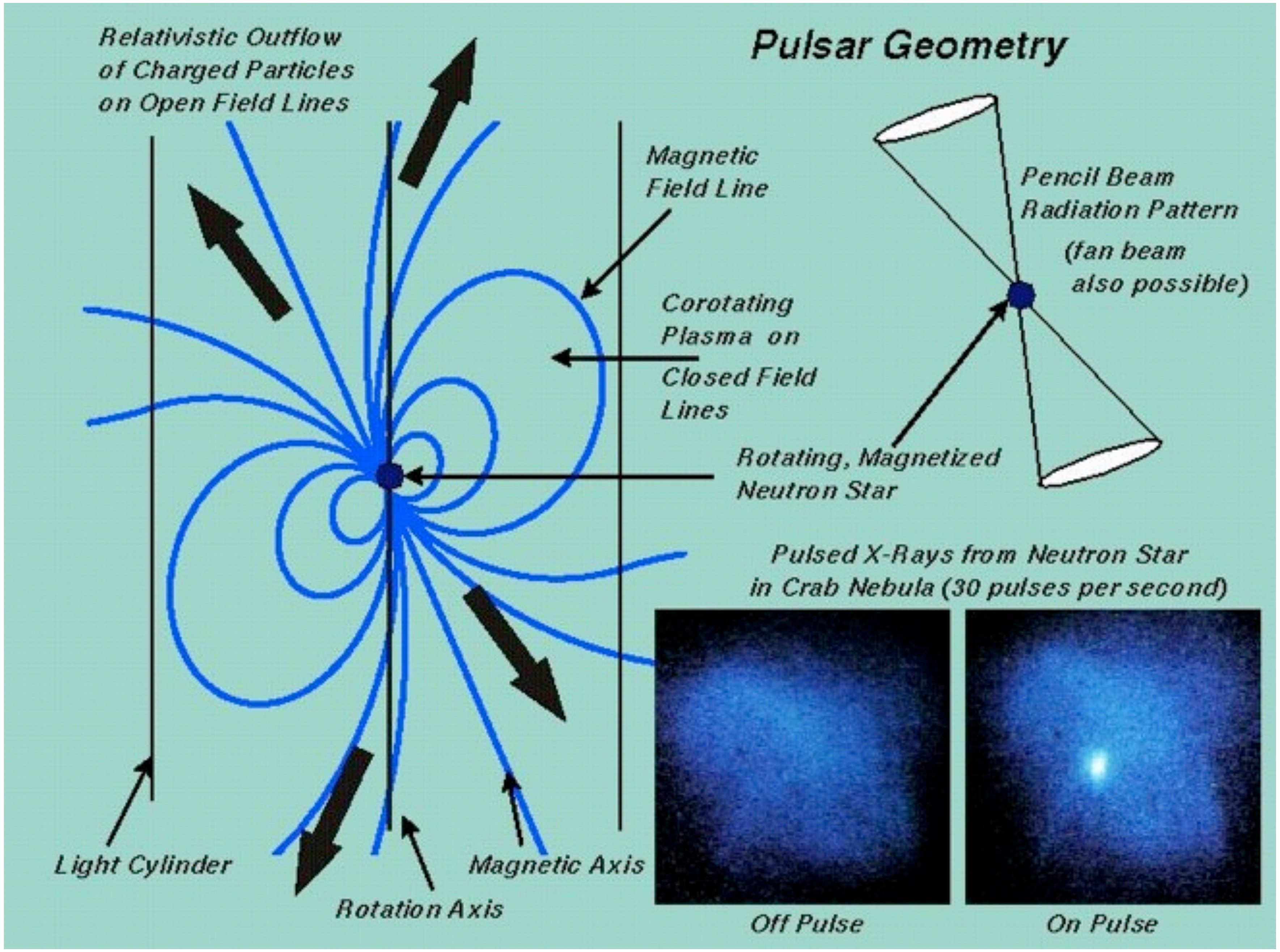
# Pulsars

**Compact stars are typically observed as pulsars**



# Pulsars

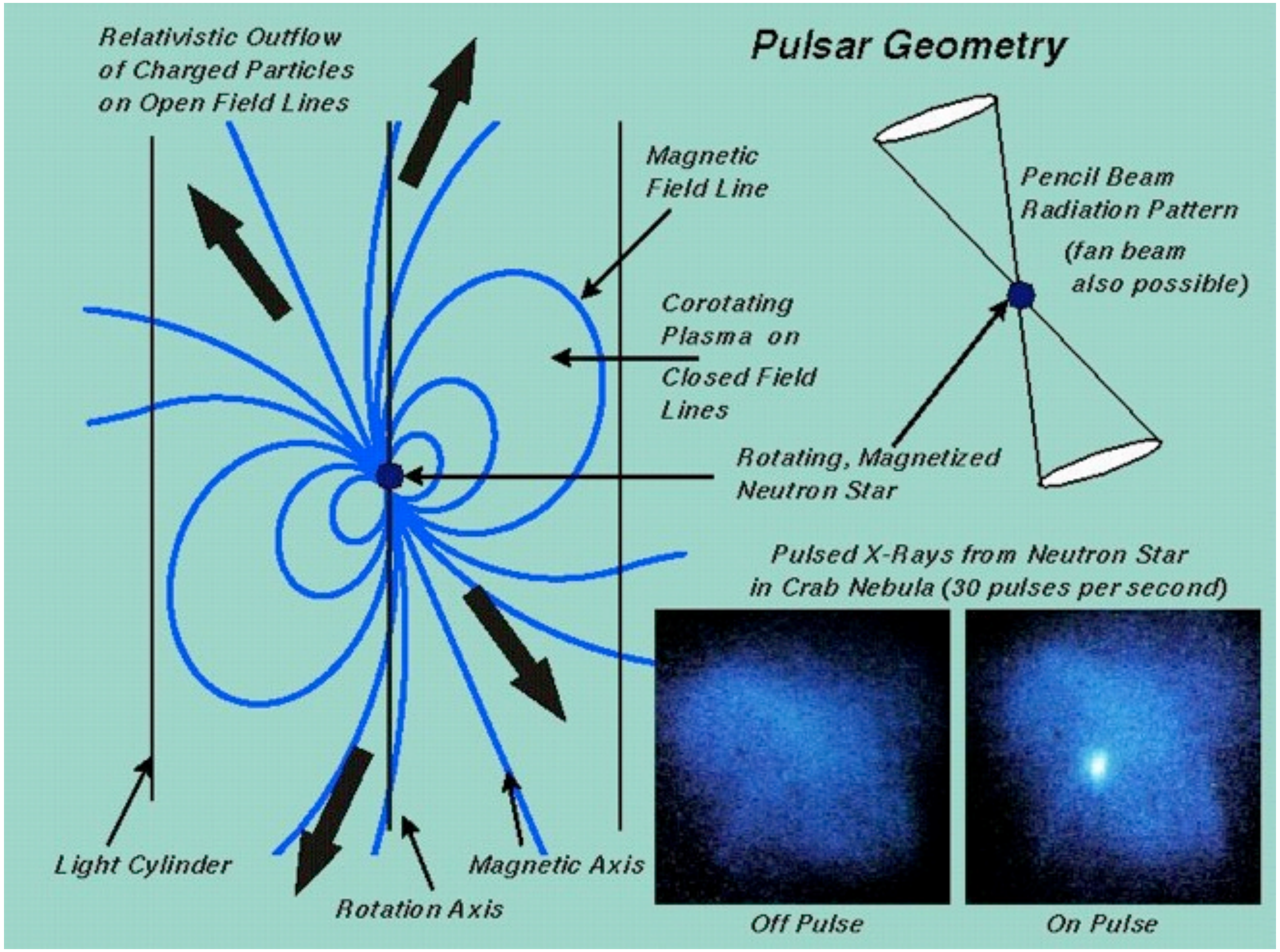
**Compact stars are typically observed as pulsars**




**Vela**
**P~89ms**

# *Pulsars*

**Compact stars are typically observed as pulsars**

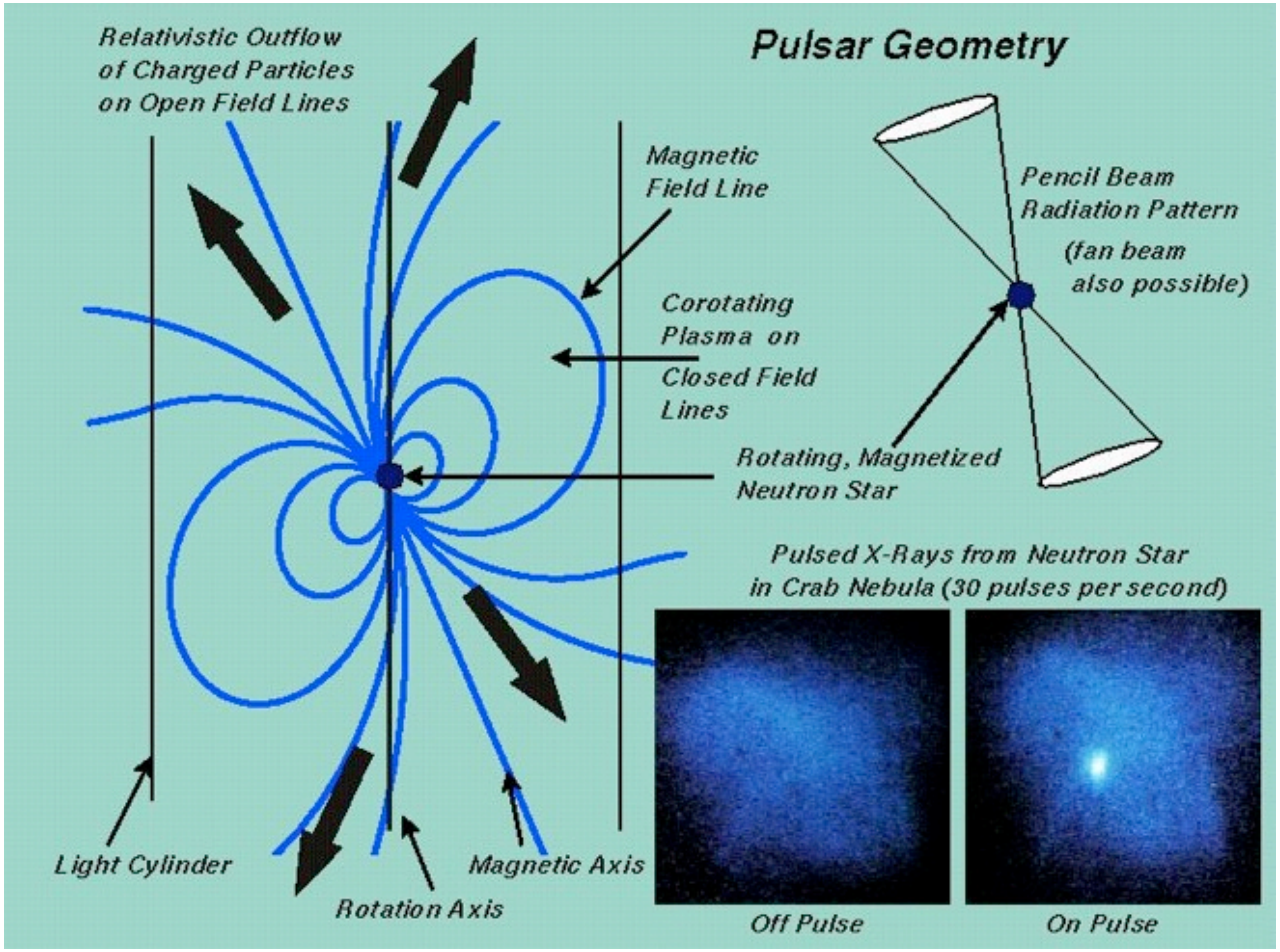



**Vela**
**P~89ms**

**Crab**
**P~33ms**

# Pulsars

**Compact stars are typically observed as pulsars**



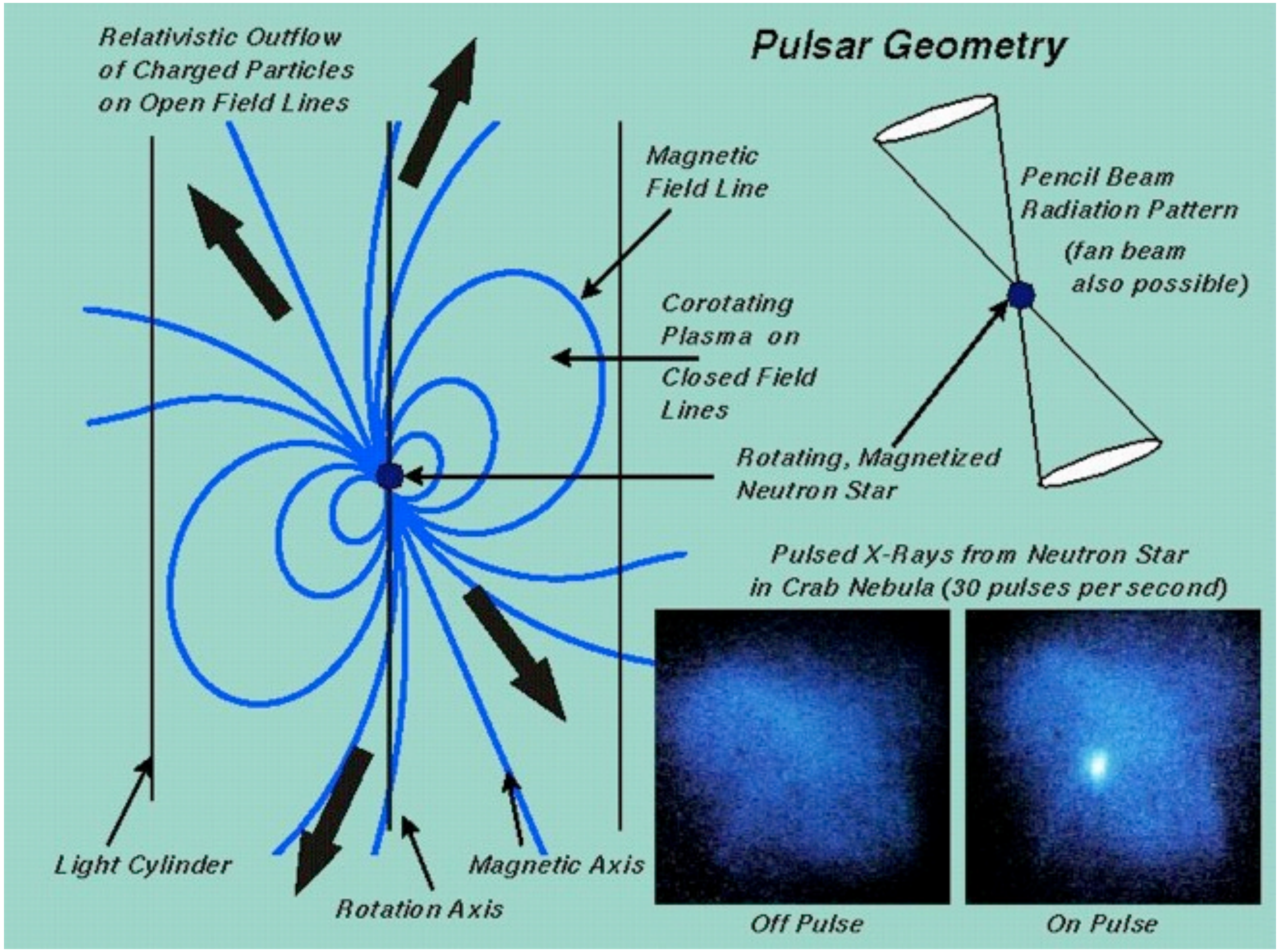

**Vela**
**P~89ms**

**Crab**
**P~33ms**

**PSR J1748 –2446ad**
**P~1.4ms**

# *Pulsars*

**Compact stars are typically observed as pulsars**




**Vela**
**P~89ms**

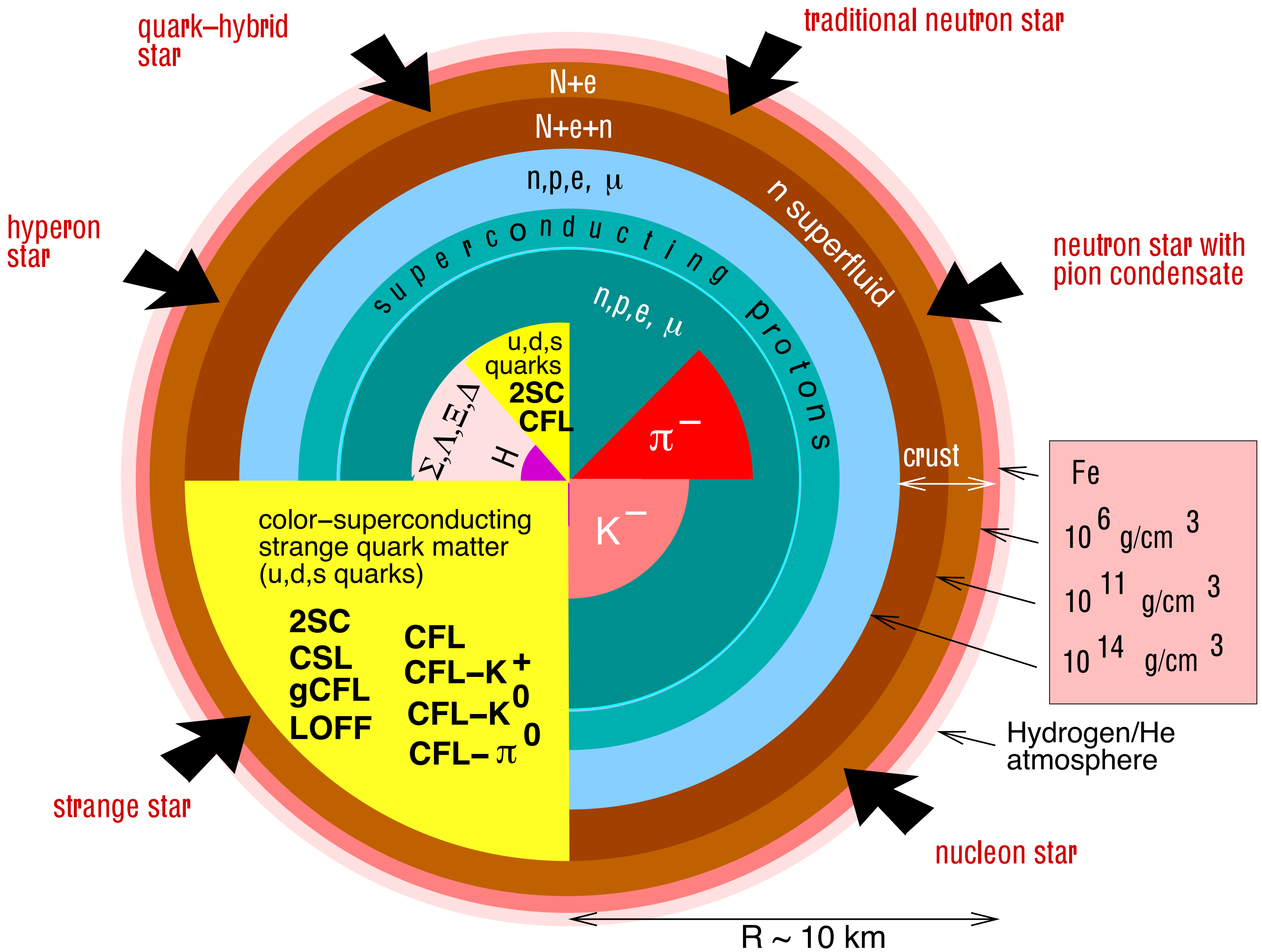
**Crab**
**P~33ms**

**PSR J1748 –2446ad**
**P~1.4ms**

**Modern washing machines about 30 rounds/s thus P~33 ms as the Crab pulsar**

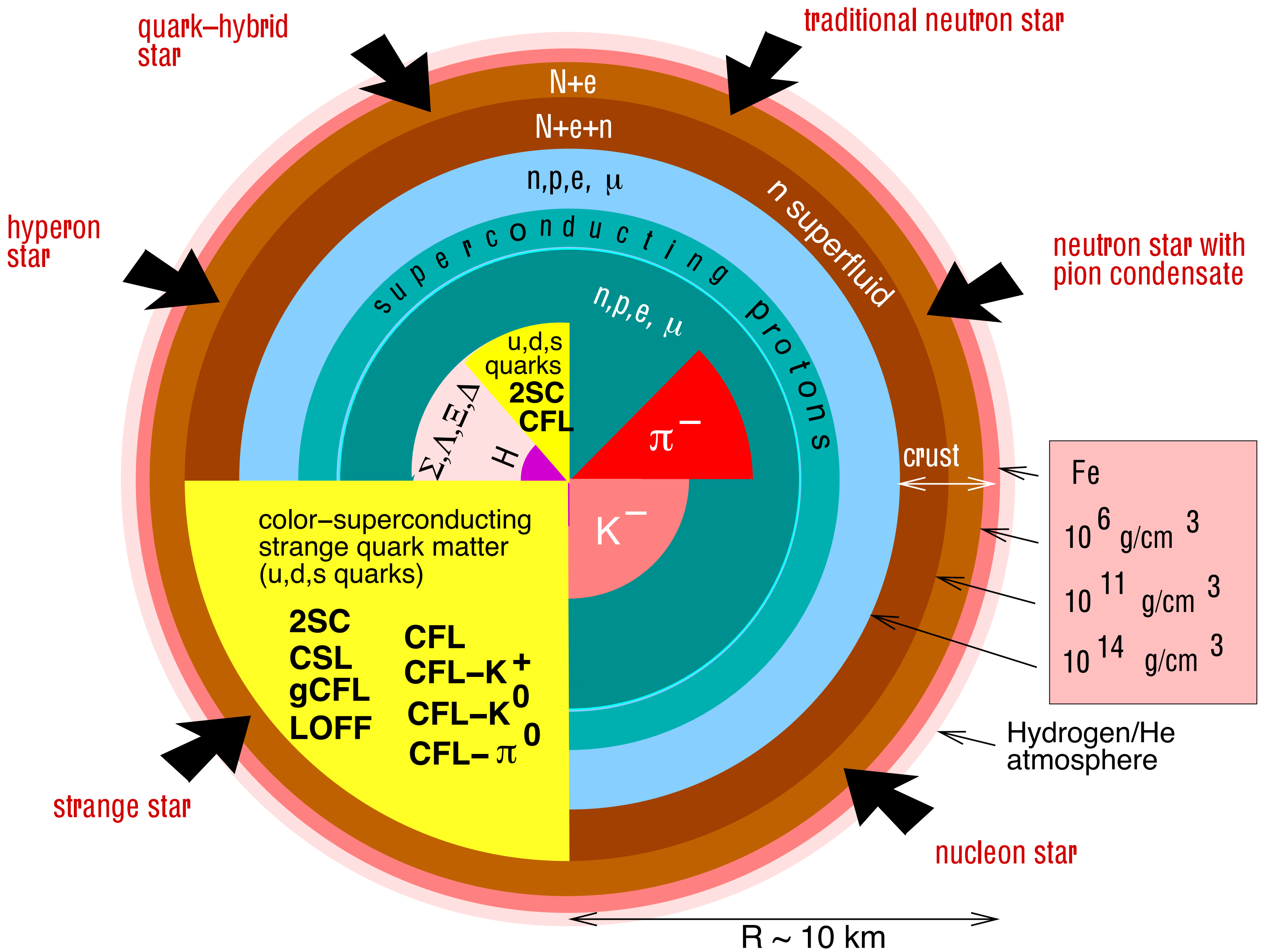
**Ferrari Engine F2004 (F1 world champion 2004) P~3.16 ms**

# *Compact stellar objects*




**F. Weber, Prog.Part.Nucl.Phys. 54 (2005) 193**

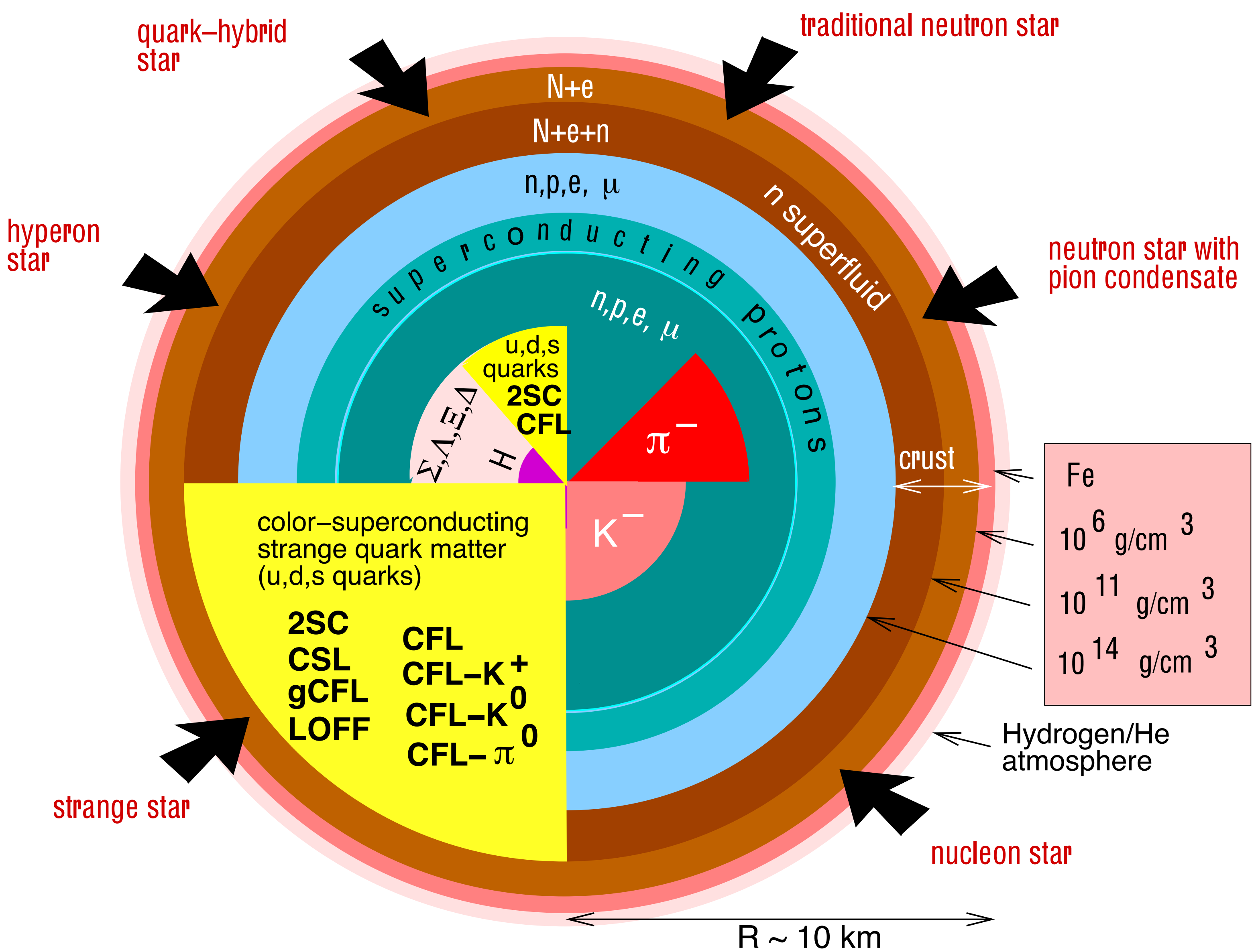
# Compact stellar objects




**"Probes"**
**cooling**
**glitches**
**instabilities**
**mass-radius**
**magnetic field**
**GWs**
**……**

F. Weber, Prog.Part.Nucl.Phys. 54 (2005) 193

# Compact stellar objects




"Probes"
cooling
glitches
instabilities
mass-radius
magnetic field
GWs
……

F. Weber, Prog.Part.Nucl.Phys. 54 (2005) 193

Compact stars can have an age comparable to the age of the Universe.
However, pulsars can be observed for a limited time… of tens of millions of years (as far as they are active)

# *Simplified Netron Star model*

**Catalysed nuclear matter**

**Neutron decay n → p + e + $\overline{\nu}_e$**
**Electron capture p + e → n + $\nu_e$** ⇒ $\mu_n = \mu_p + \mu_e$

**Electric charge neutrality** ⇒ $N_p = N_e$

**Dynamical equilibrium: nuclear matter cools down by neutrino emission**

# *Simplified Netron Star model*

**Catalysed nuclear matter**

**Neutron decay** $n \to p + e + \overline{\nu}_e$
**Electron capture** $p + e \to n + \nu_e$ → $\mu_n = \mu_p + \mu_e$

**Electric charge neutrality** → $N_p = N_e$

**Dynamical equilibrium: nuclear matter cools down by neutrino emission**

**In Neutron stars, nuclear matter is mainly made of neutrons:**

$$N_p/N_n \sim 1/10$$

**For our purposes we can roughly assume that a NS is a Fermi liquid of neutrons (neglect neutron superfluidity etc.) filling a Fermi sphere**

# *Equilibrium configurations*

**In general one solves the TOV's equations of hydrostatic equilibrium**

$$\frac{dm}{dr} = 4\pi\rho r^2$$
$$\frac{dp}{dr} = (\rho + p)\frac{m + 4\pi p r^3}{2mr - r^2}$$

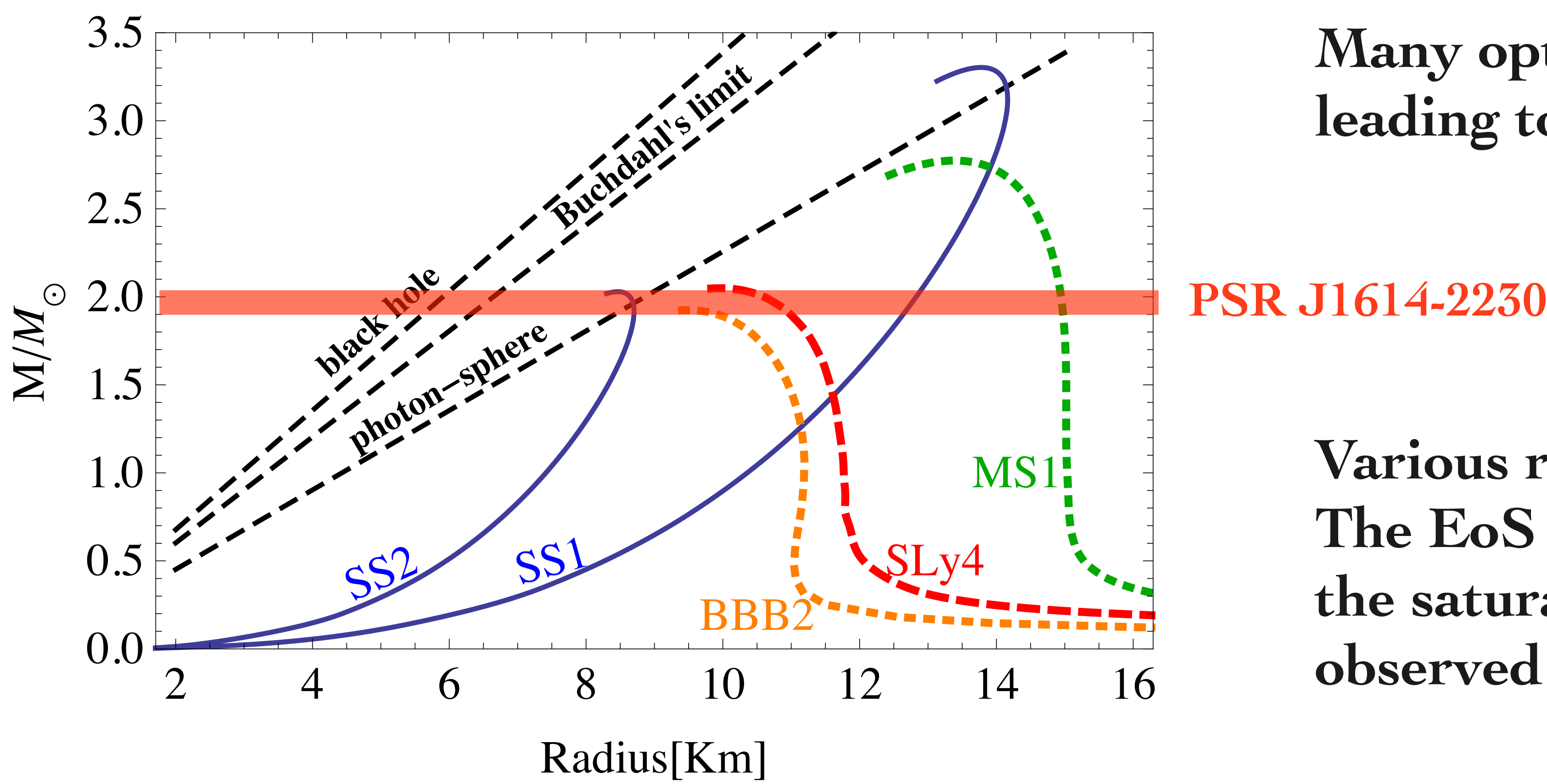
**to solve these equations one needs an EoS, i.e. a relation between the pressure and the density.**

# *Equilibrium configurations*

**In general one solves the TOV's equations of hydrostatic equilibrium**

$$\frac{dm}{dr} = 4\pi\rho r^2$$
$$\frac{dp}{dr} = (\rho + p)\frac{m + 4\pi p r^3}{2mr - r^2}$$

**to solve these equations one needs an EoS, i.e. a relation between the pressure and the density.**



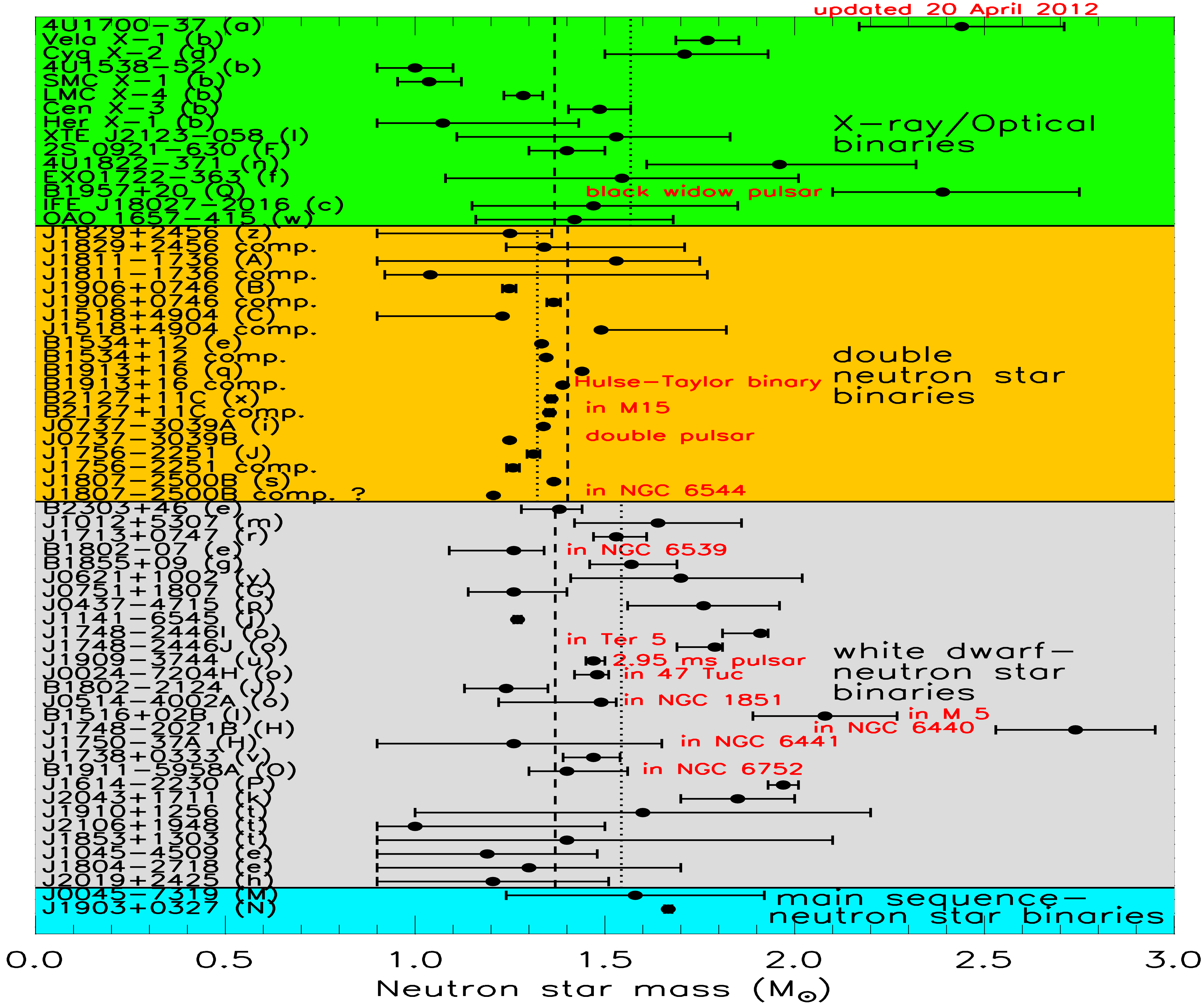

**Many options for the EoS, leading to different mass and radii.**

**Various requirements:**
**The EoS should describe matter above the saturation point, reproduce the observed NSs masses etc.**

[7] MM and F. Tonelli, Phys.Rev. D97 (2018) no.12, 123010

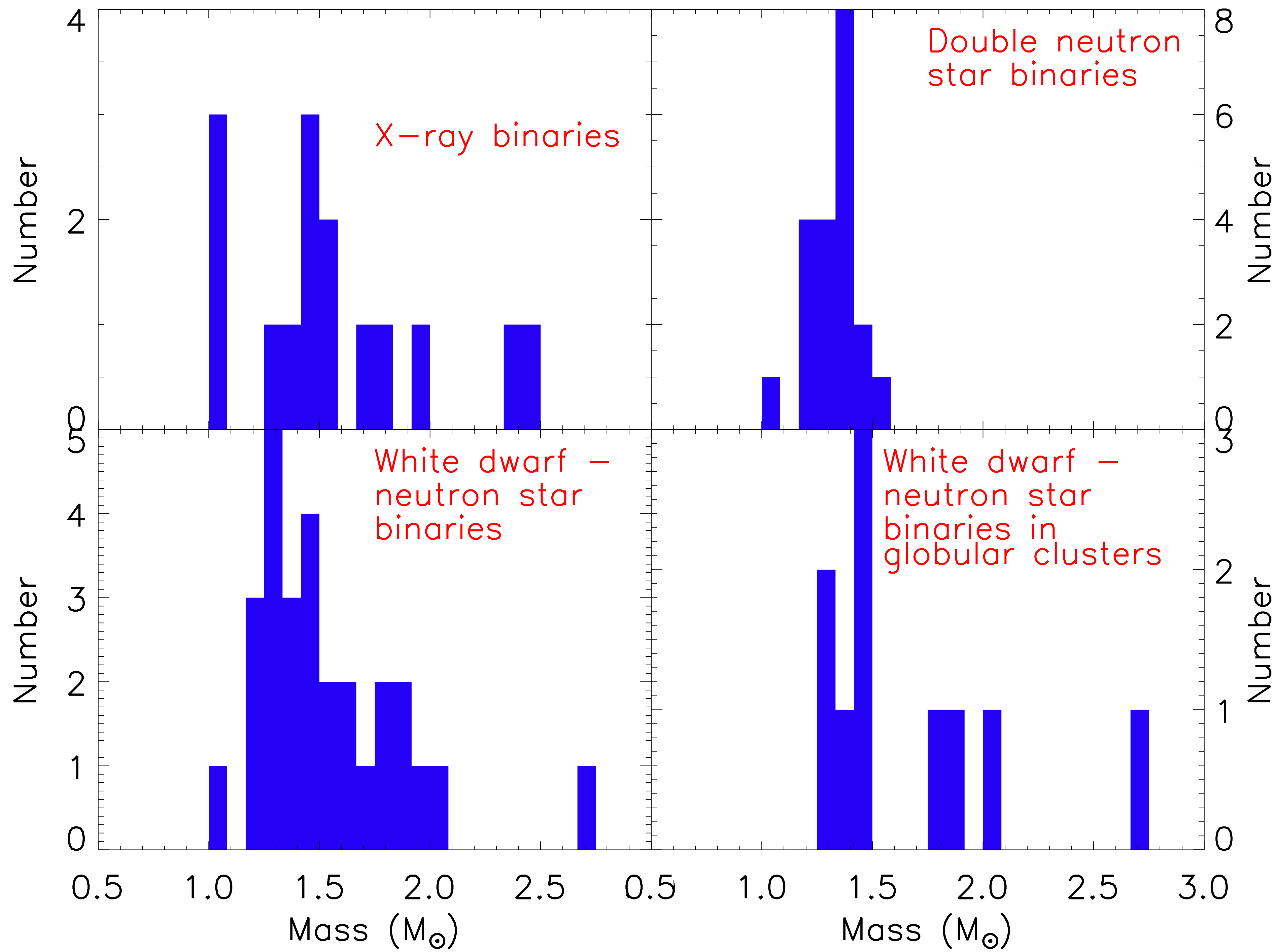
# Mass distribution
# of
# Neutron Stars

# *Masses of known NSs*




J. Lattimer, Annu. Rev. Nucl. Part. Sci. 62, 485 (2012)

# *Mass distribution of known NSs*

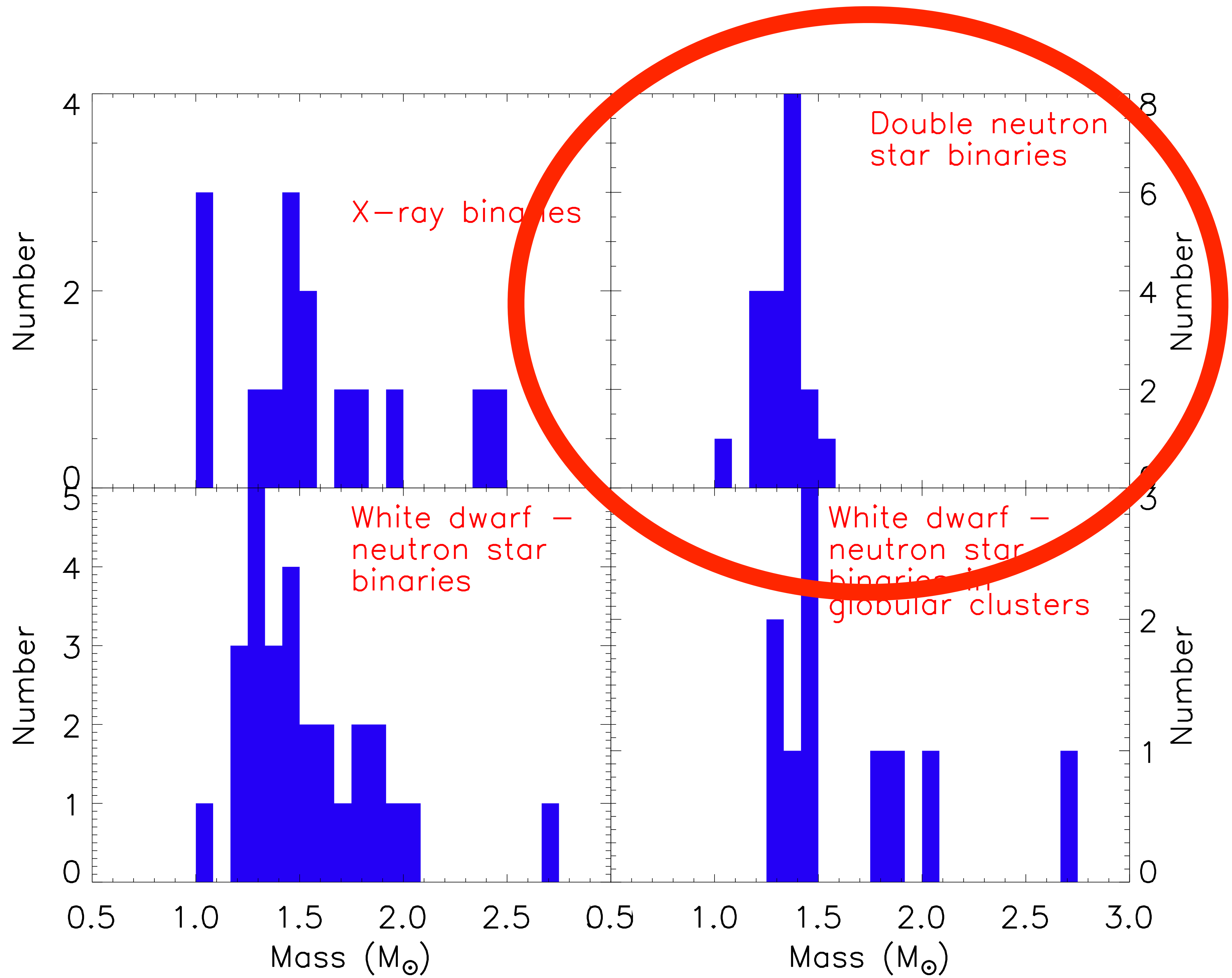



**The reason of this peculiar distributions is unknown**

**No large mass NSs in double NS binaries!**

J. Lattimer, Annu. Rev. Nucl. Part. Sci. 62, 485 (2012)

# *Mass distribution of known NSs*




**The reason of this peculiar distributions is unknown**

**No large mass NSs in double NS binaries!**

J. Lattimer, Annu. Rev. Nucl. Part. Sci. 62, 485 (2012)

# *Conversion of neutrons in mirror neutrons*

**We assume that inside the NS neutrons are slowly converted in mirror neutrons** → **The star will (slowly) modify its equilibrium configuration.**

**Any small mass difference** $m_n - m_{n'}$ **is irrelevant, as far as neutrons fill the Fermi sphere.**

$$H \simeq \begin{pmatrix} \mathcal{E}_F & \epsilon \\ \epsilon & \mathcal{E}'_F \end{pmatrix} \quad \rightarrow \quad \overline{P}_{nn'} = \left( \frac{\epsilon}{\mathcal{E}_F - \mathcal{E}'_F} \right)^2$$

# *Conversion of neutrons in mirror neutrons*

**We assume that inside the NS neutrons are slowly converted in mirror neutrons** → **The star will (slowly) modify its equilibrium configuration.**

**Any small mass difference** $m_n - m_{n'}$ **is irrelevant, as far as neutrons fill the Fermi sphere.**

$$H \simeq \begin{pmatrix} \mathcal{E}_F & \epsilon \\ \epsilon & \mathcal{E}'_F \end{pmatrix} \quad \longrightarrow \quad \overline{P}_{nn'} = \left( \frac{\epsilon}{\mathcal{E}_F - \mathcal{E}'_F} \right)^2$$

**The collision rate between neutrons is** $\Gamma = \langle \sigma_{nn} v N \rangle \simeq 10^{24} \times (N/N_{\rm nuc})^{4/3} \mathrm{s}^{-1}$

# *Conversion of neutrons in mirror neutrons*

**We assume that inside the NS neutrons are slowly converted in mirror neutrons** $\Rightarrow$ **The star will (slowly) modify its equilibrium configuration.**

**Any small mass difference** $m_n - m_{n'}$ **is irrelevant, as far as neutrons fill the Fermi sphere.**

$$H \simeq \begin{pmatrix} \mathcal{E}_F & \epsilon \\ \epsilon & \mathcal{E}'_F \end{pmatrix} \Rightarrow \overline{P}_{nn'} = \left( \frac{\epsilon}{\mathcal{E}_F - \mathcal{E}'_F} \right)^2$$

**The collision rate between neutrons is** $\Gamma = \langle \sigma_{nn} v N \rangle \simeq 10^{24} \times (N/N_{\rm nuc})^{4/3} {\rm s}^{-1}$

**In each collision a neutron is turned in a mirror neutron with probability** $\overline{P}_{nn'}$

# *Conversion of neutrons in mirror neutrons*

**We assume that inside the NS neutrons are slowly converted in mirror neutrons** → **The star will (slowly) modify its equilibrium configuration.**

**Any small mass difference** $m_n - m_{n'}$ **is irrelevant, as far as neutrons fill the Fermi sphere.**

$$H \simeq \begin{pmatrix} \mathcal{E}_F & \epsilon \\ \epsilon & \mathcal{E}'_F \end{pmatrix} \quad \rightarrow \quad \overline{P}_{nn'} = \left( \frac{\epsilon}{\mathcal{E}_F - \mathcal{E}'_F} \right)^2$$

**The collision rate between neutrons is** $\Gamma = \langle \sigma_{nn} v N \rangle \simeq 10^{24} \times (N/N_{\rm nuc})^{4/3} {\rm s}^{-1}$

**In each collision a neutron is turned in a mirror neutron with probability** $\overline{P}_{nn'}$

**The conversion rate is therefore** $\Gamma_{n'} \simeq \left( \frac{\epsilon}{10^{-11}{\rm eV}} \right)^2 \times 10^{-6} {\rm yr}^{-1}$

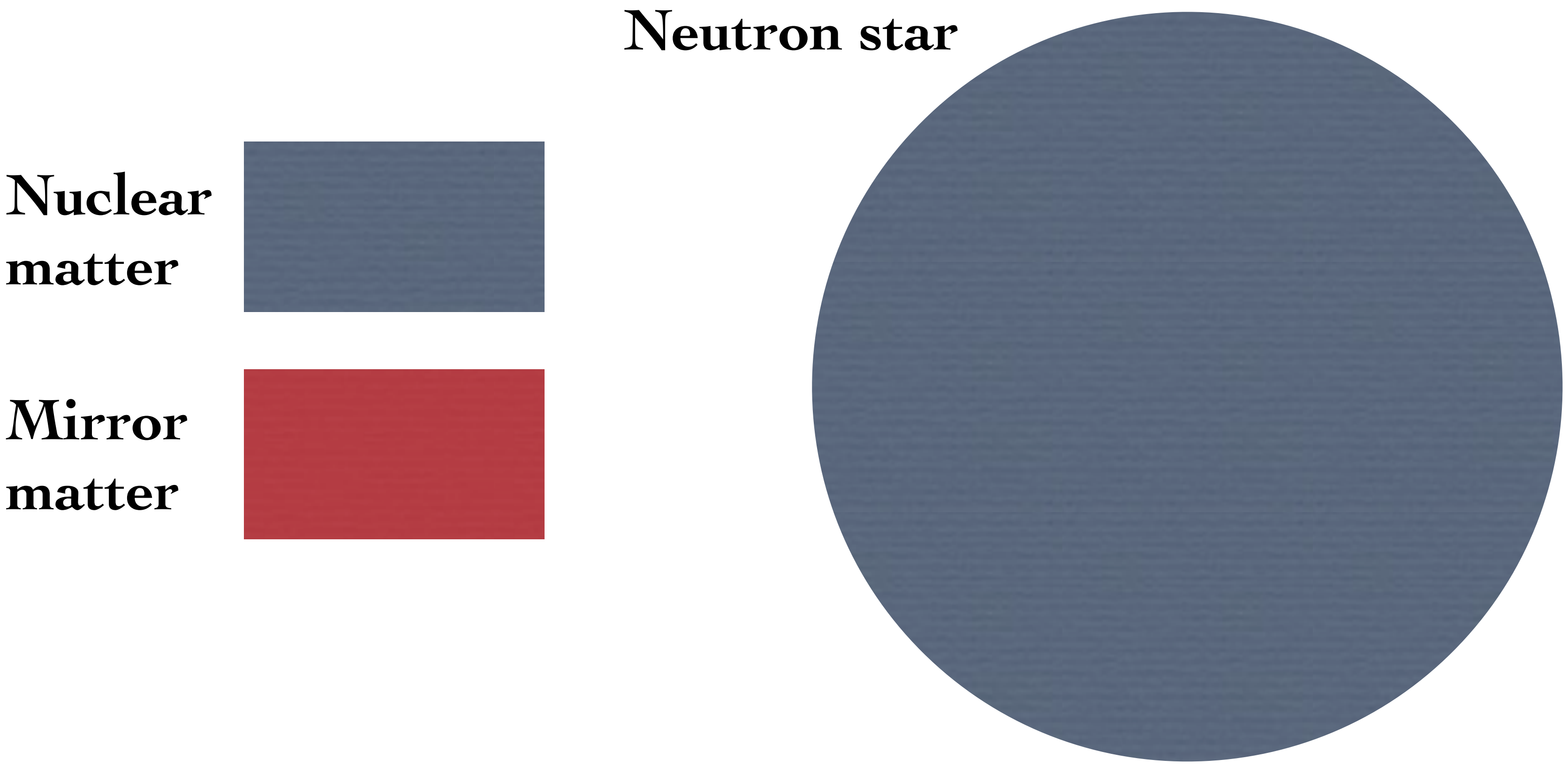
# *Conversion of neutrons in mirror neutrons*

**For the stellar evolution we also assume**

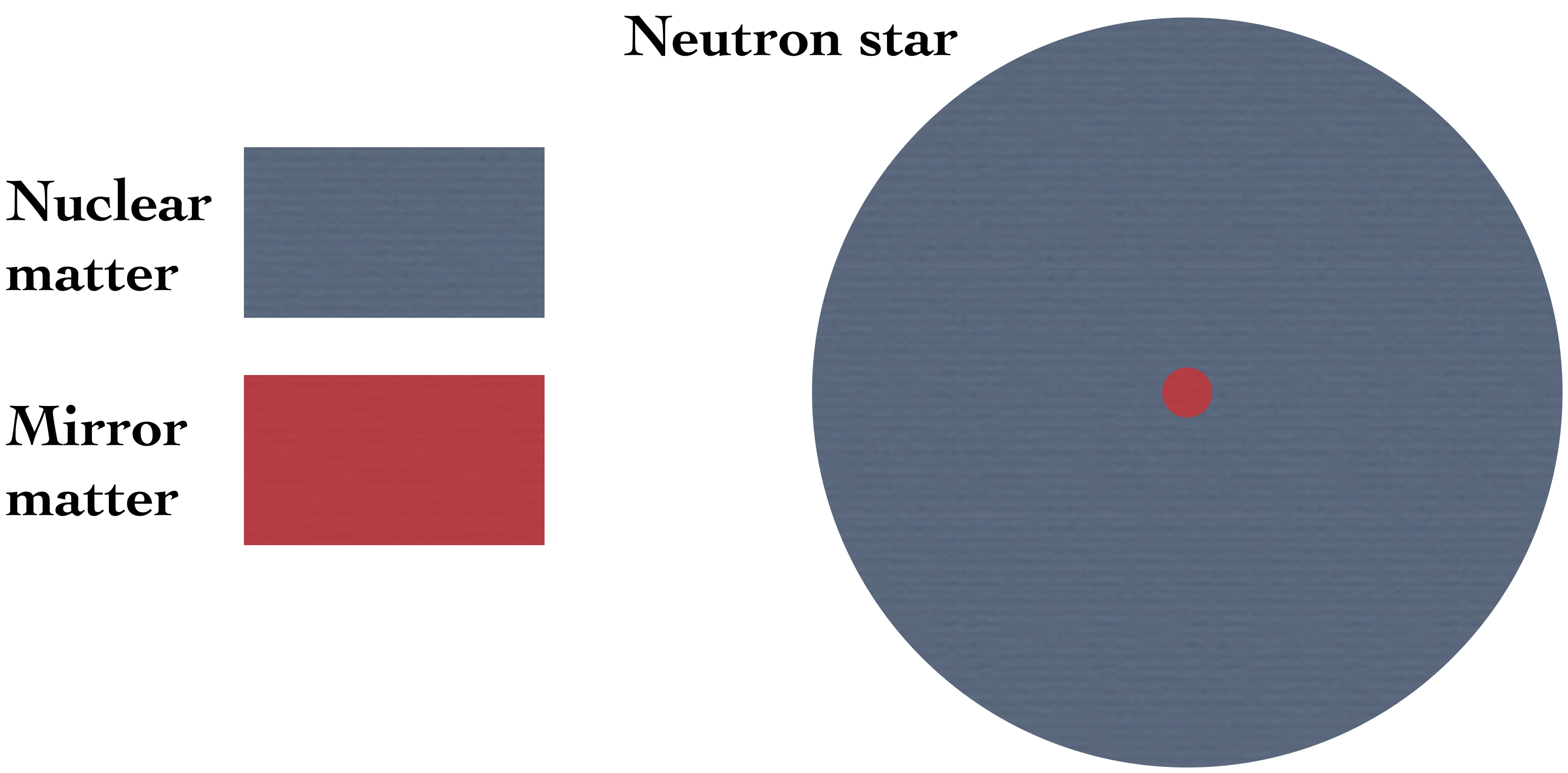
- **NM and MM behave as independent fluids only coupled by gravity**
- **NM and MM are not, in general, in chemical equilibrium**
- **NM and MM have the same equation of state (EoS)**
- **NM and MM form two concentric stars**

**In other words:**
**MM is gravitationally trapped and the system is approximated as a two fluid noninteracting system**

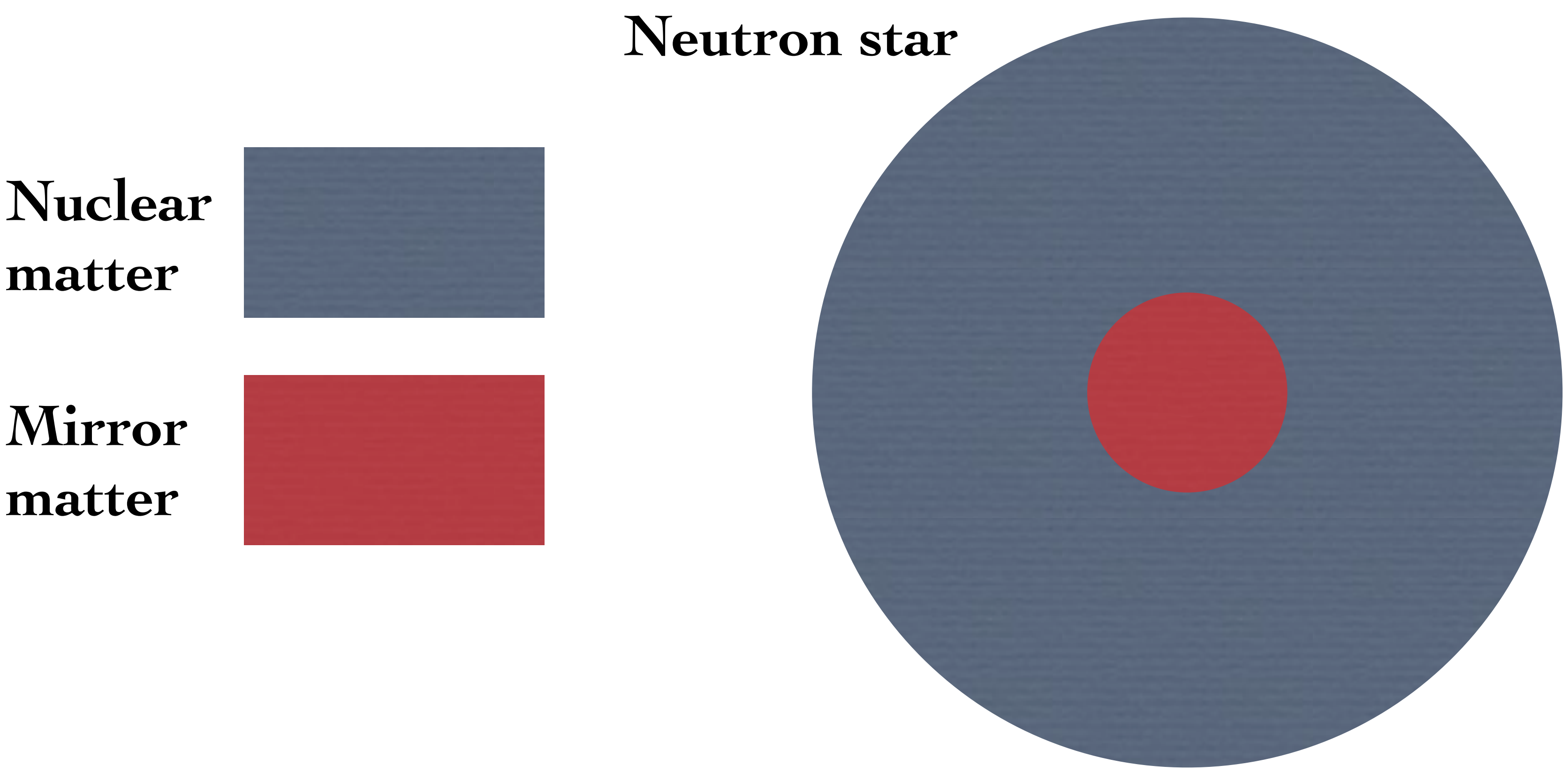
# *Qualitative expectations*



# *Qualitative expectations*



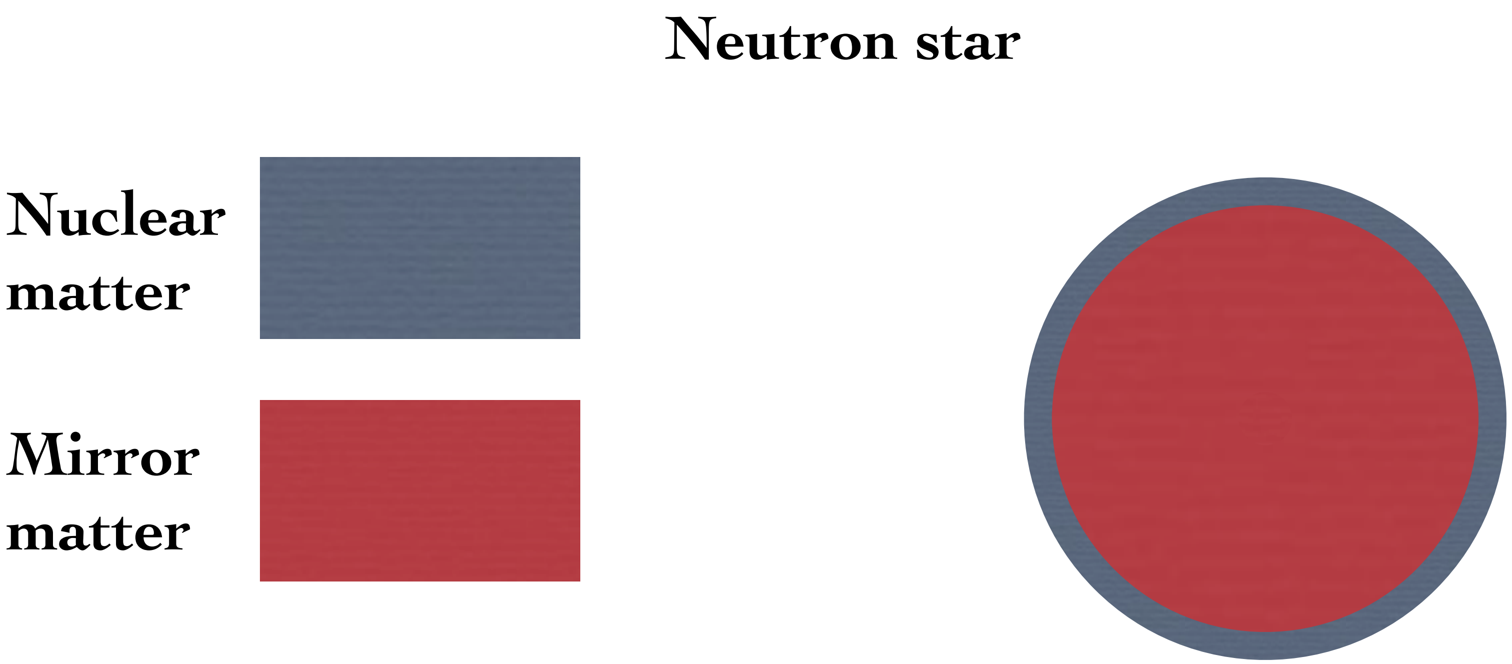
# *Qualitative expectations*



# *Qualitative expectations*

**Neutron star**

# *Qualitative expectations*



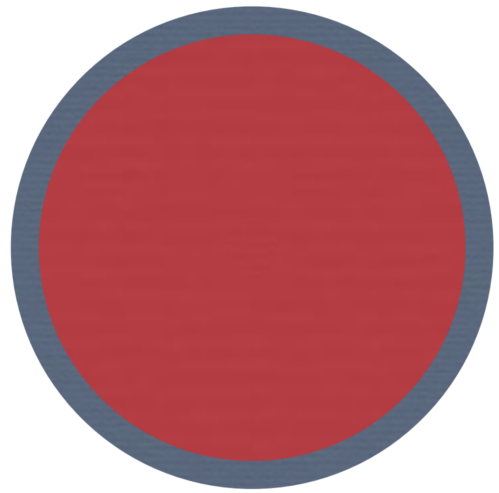

The conversion speed depends on many factors.
We expect to be slow, but comparable with typical NS life-time

# *Qualitative expectations*

Neutron star

Nuclear matter

Mirror matter



The conversion speed depends on many factors.
We expect to be slow, but comparable with typical NS life-time

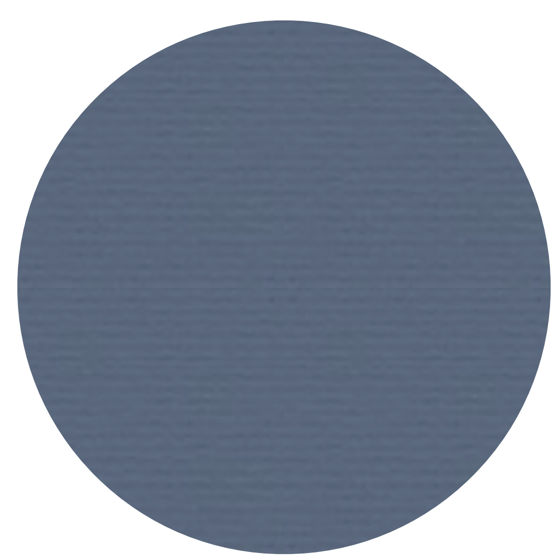
The final configuration is a NS with smaller radius and a smaller mass, or...

# *Qualitative expectations*

**Neutron star**


**The conversion speed depends on many factors.**
**We expect to be slow, but comparable with typical NS life-time**

**The final configuration is a NS with smaller radius and a smaller mass, or…**

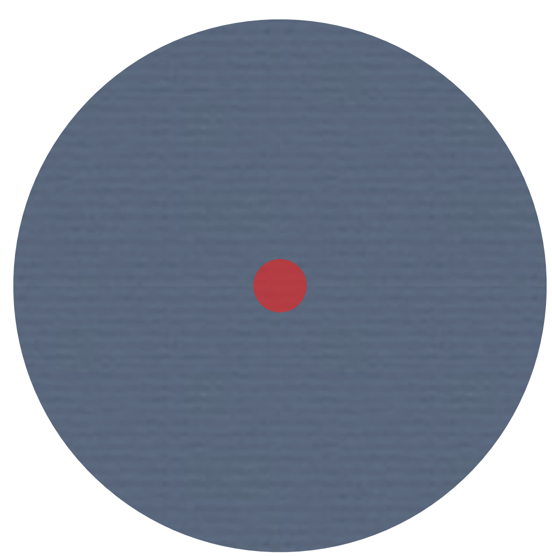


# *Qualitative expectations*

Neutron star


The conversion speed depends on many factors.
We expect to be slow, but comparable with typical NS life-time

The final configuration is a NS with smaller radius and a smaller mass, or...

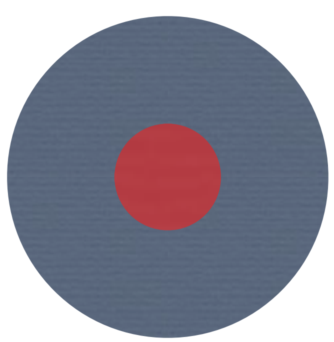


# *Qualitative expectations*

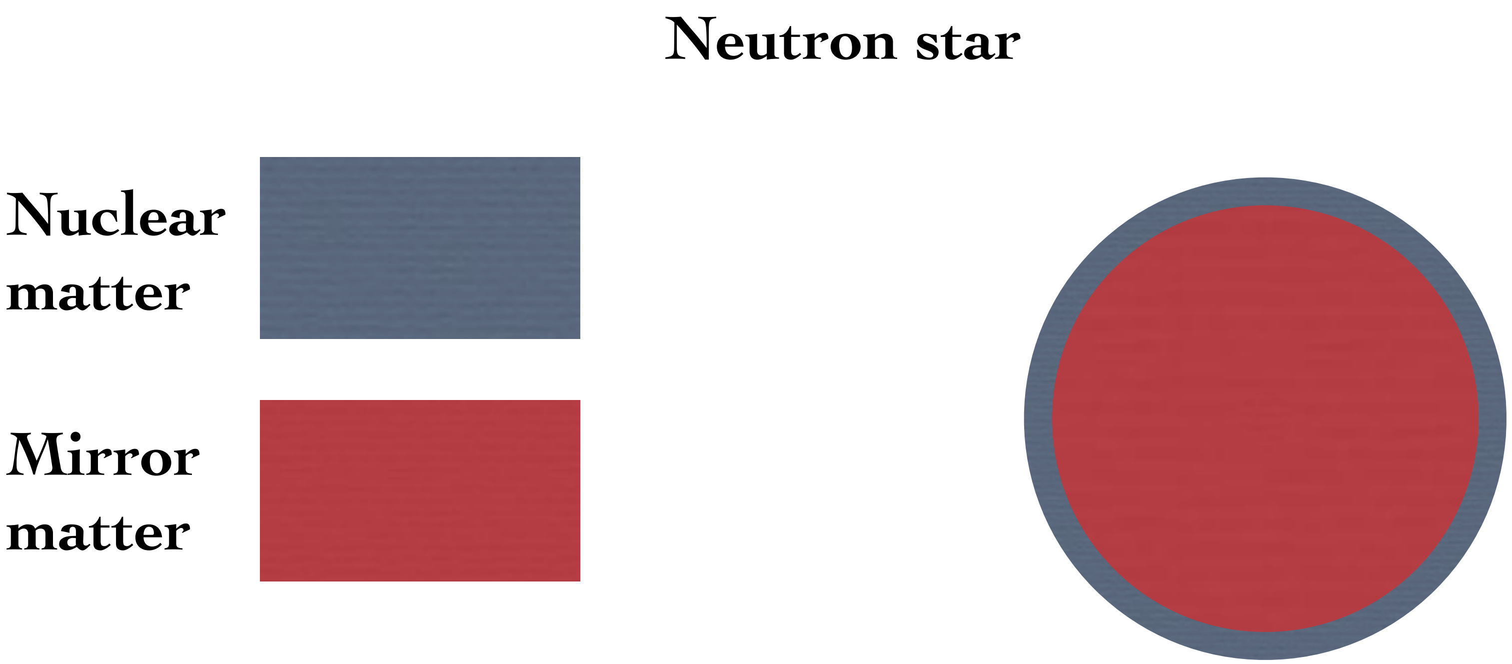
Neutron star


The conversion speed depends on many factors.
We expect to be slow, but comparable with typical NS life-time

The final configuration is a NS with smaller radius and a smaller mass, or...

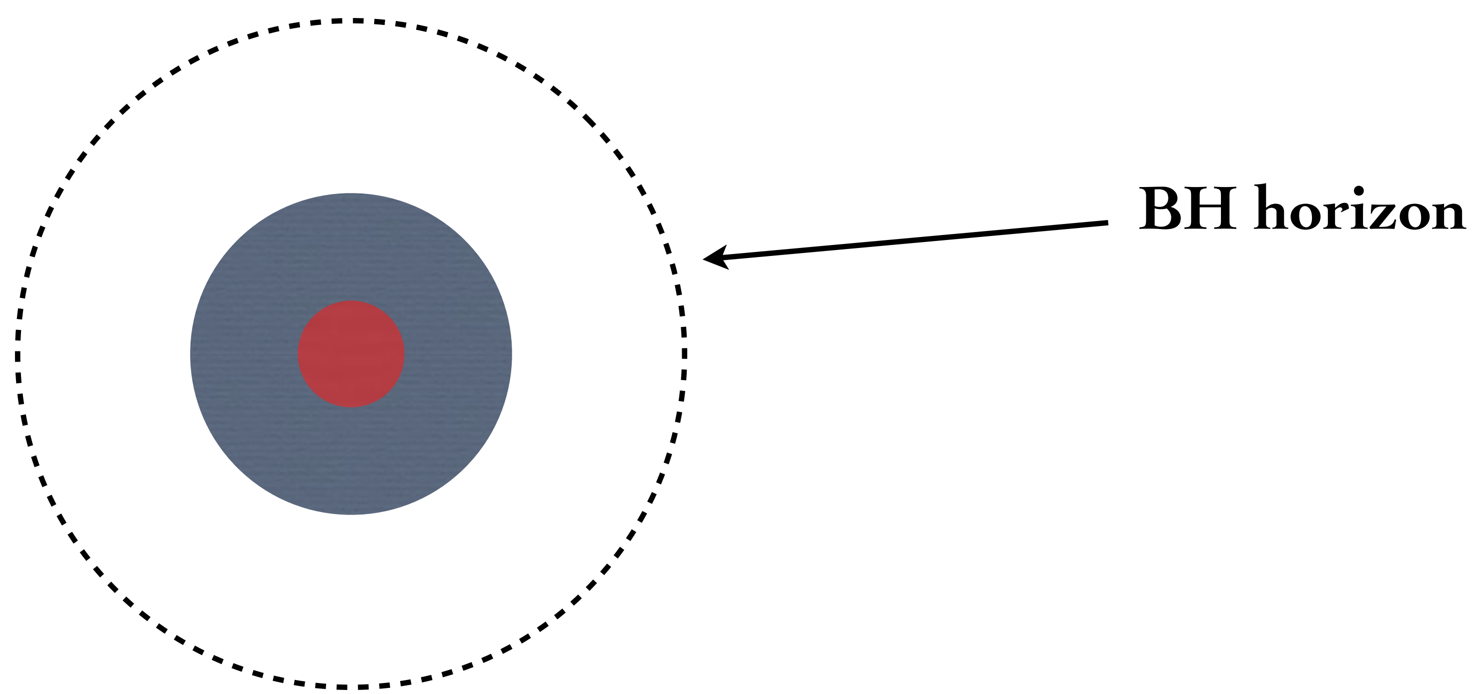


# *Qualitative expectations*




**The conversion speed depends on many factors.**
**We expect to be slow, but comparable with typical NS life-time**

**The final configuration is a NS with smaller radius and a smaller mass, or...**

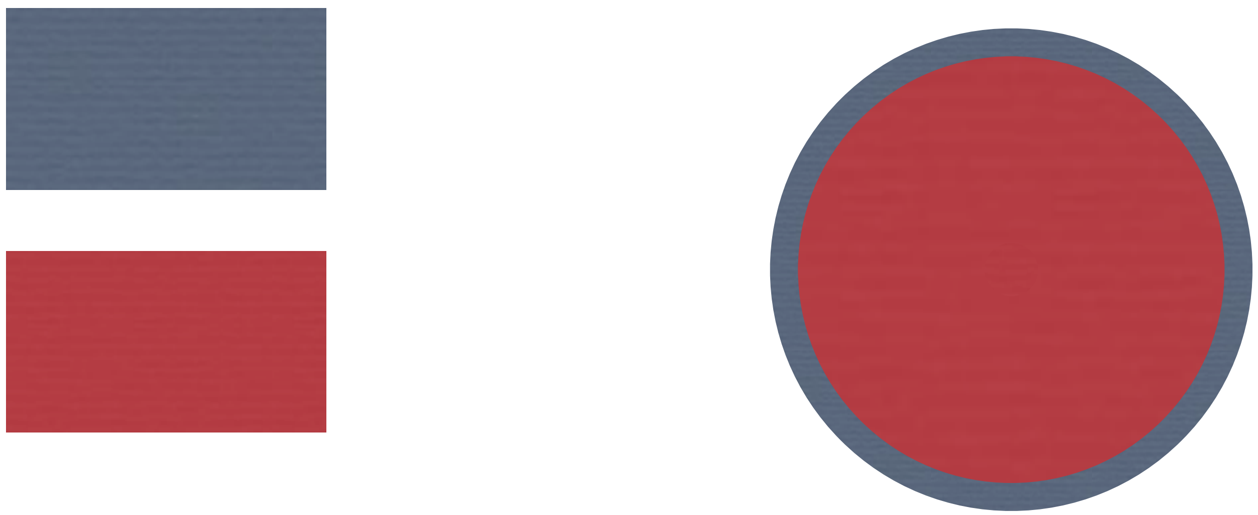


# *Qualitative expectations*

Neutron star

Nuclear matter

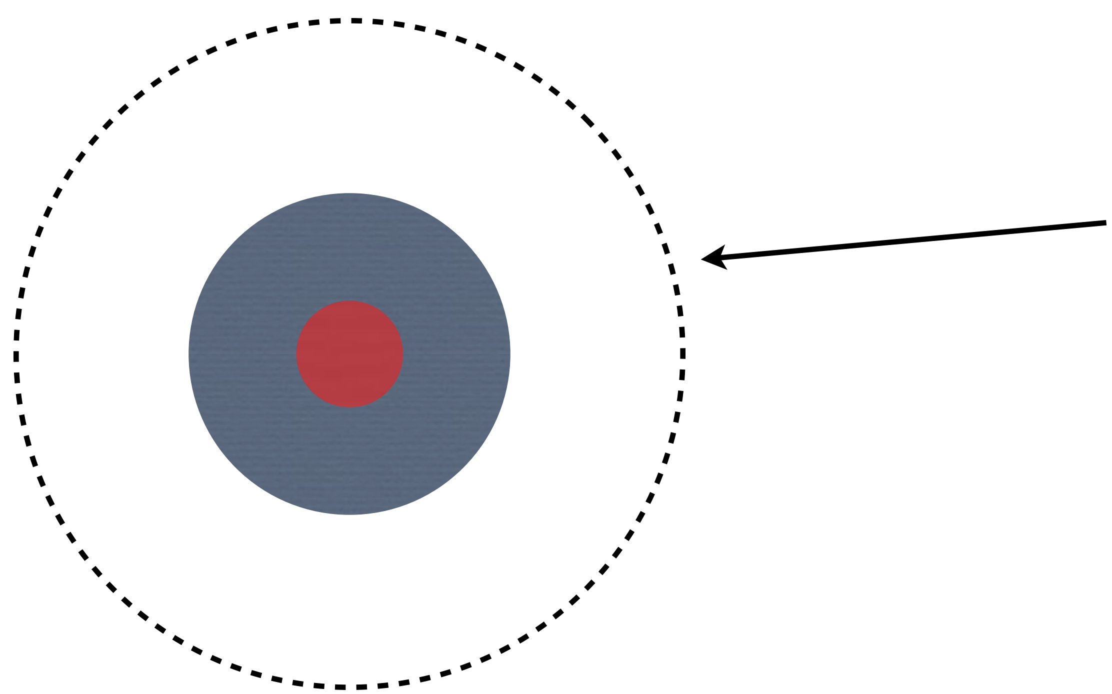
Mirror matter



The conversion speed depends on many factors.
We expect to be slow, but comparable with typical NS life-time

The final configuration is a NS with smaller radius and a smaller mass, or...

A black hole (BH) triggered by radial unstable oscillations



BH horizon

# *Equilibrium configurations*

**The TOV's equations of hydrostatic equilibrium for one fluid**

$$\frac{dm}{dr} = 4\pi\rho r^2$$
$$\frac{dp}{dr} = (\rho + p)\frac{m + 4\pi p r^3}{2mr - r^2}$$

# *Equilibrium configurations*

**The TOV's equations of hydrostatic equilibrium for one fluid**

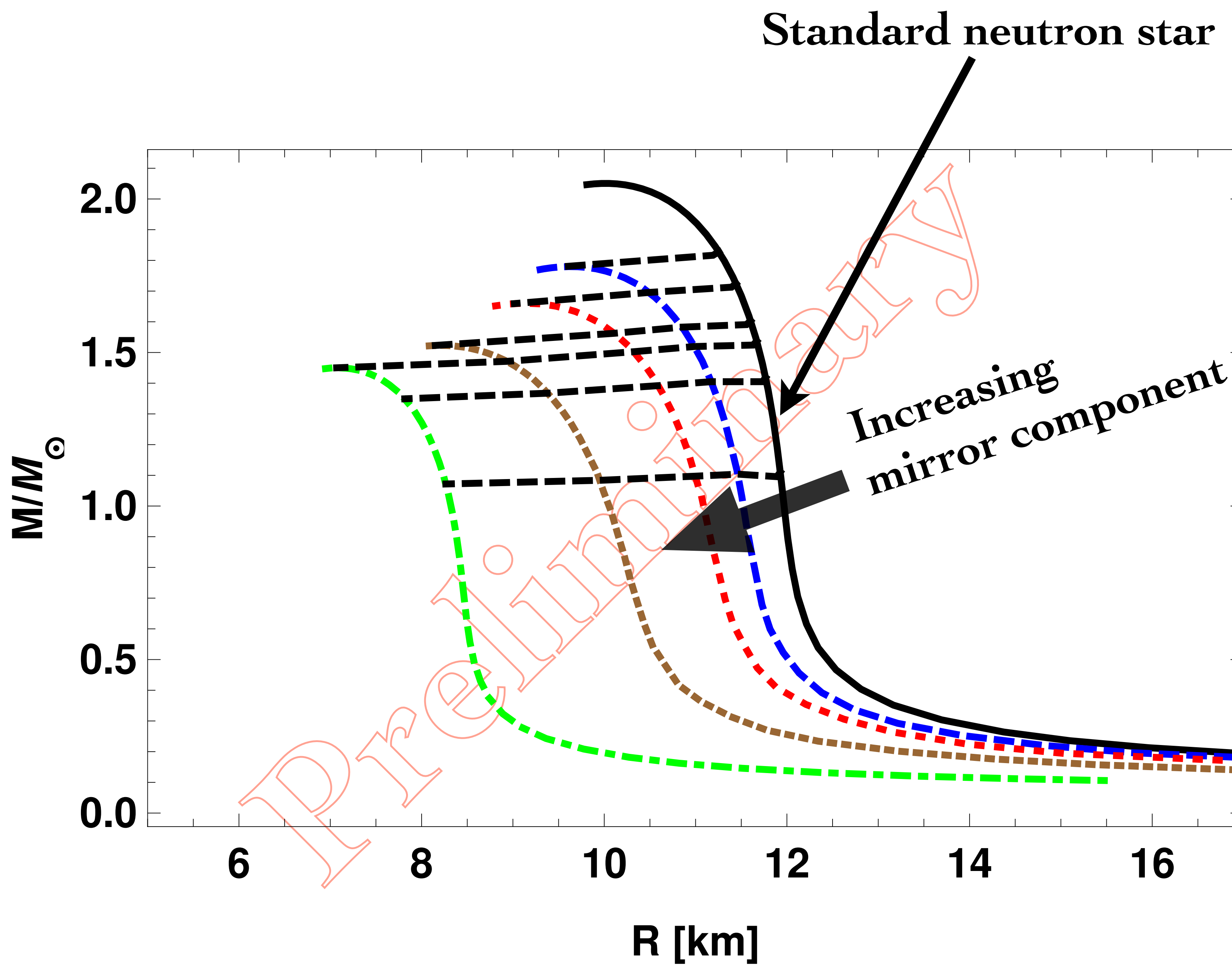
$$\frac{dm}{dr} = 4\pi\rho r^2$$
$$\frac{dp}{dr} = (\rho + p)\frac{m + 4\pi p r^3}{2mr - r^2}$$

**are modified to include coupled (by gravity) TOV's equations for a two fluid system**

$$\frac{dm_1}{dr} = 4\pi\rho_1 r^2 \qquad \text{for} \qquad r \leq R_1$$
$$\frac{dm_2}{dr} = 4\pi\rho_2 r^2$$
$$\frac{dp_2}{dr} = (\rho_2 + p_2)\frac{m_1 + m_2 + 4\pi(p_1 + p_2)r^3}{2(m_1 + m_2)r - r^2}$$
$$\frac{dp_1}{dr} = \frac{\rho_1 + p_1}{\rho_2 + p_2}\frac{dp_2}{dr} \qquad \text{for} \qquad r \leq R_1$$

# *Conversion of neutrons in mirror neutrons*

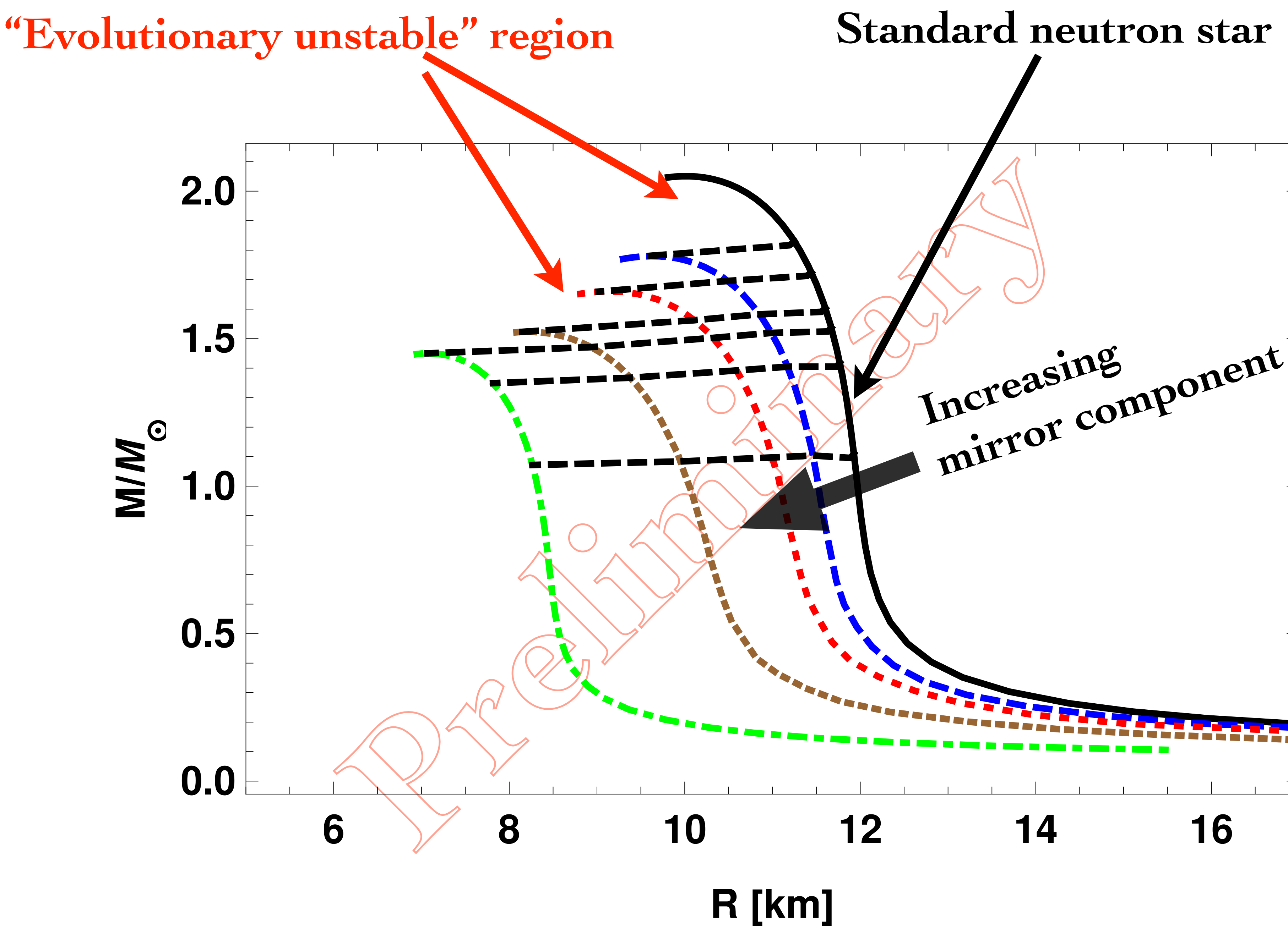
**Solving the coupled TOV's equations we determine the equilibrium configurations**




**Dashed line correspond to constant baryonic + mirror matter number**

# *Conversion of neutrons in mirror neutrons*

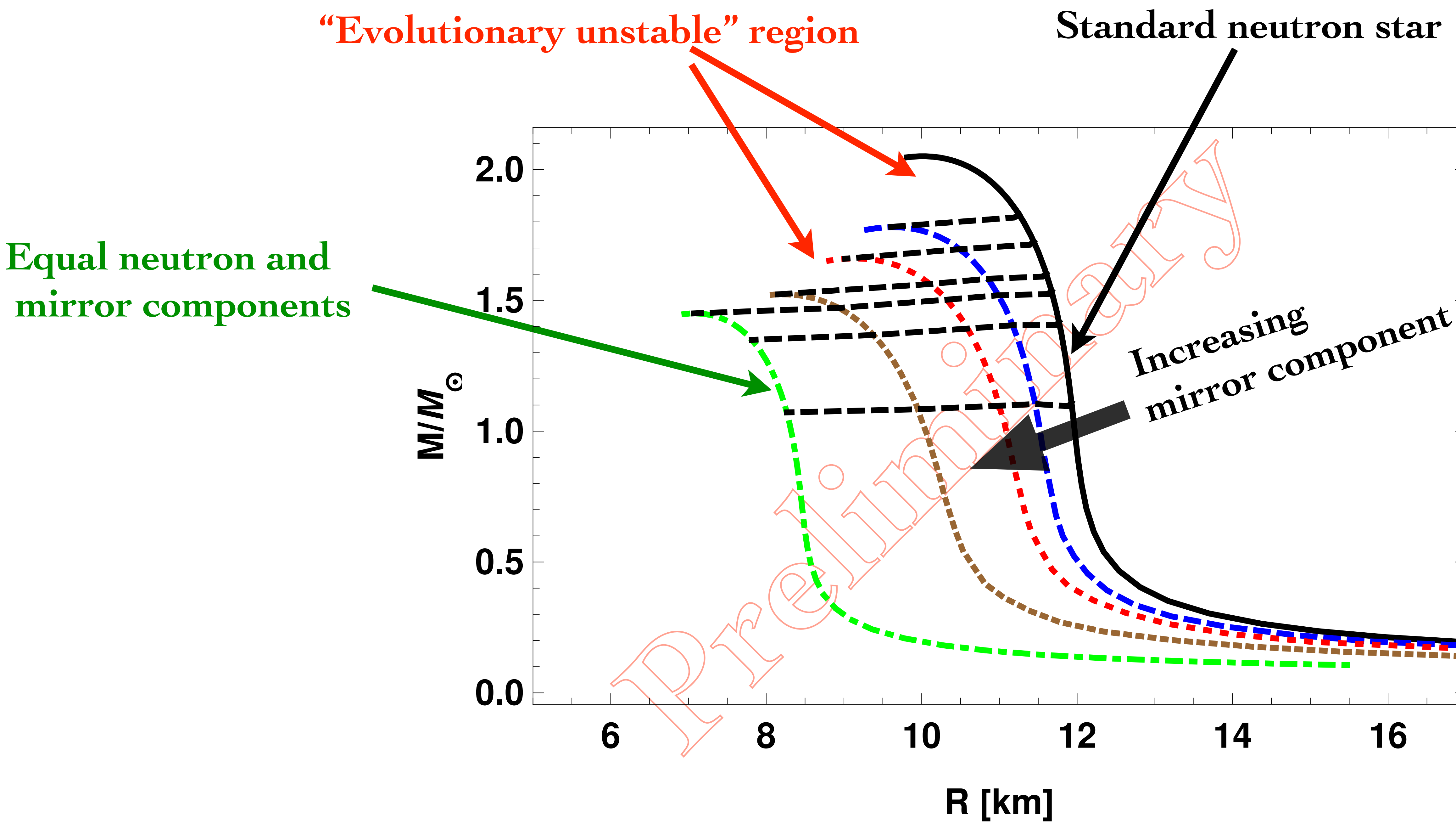
**Solving the coupled TOV's equations we determine the equilibrium configurations**




**Dashed line correspond to constant baryonic + mirror matter number**

# *Conversion of neutrons in mirror neutrons*

**Solving the coupled TOV's equations we determine the equilibrium configurations**

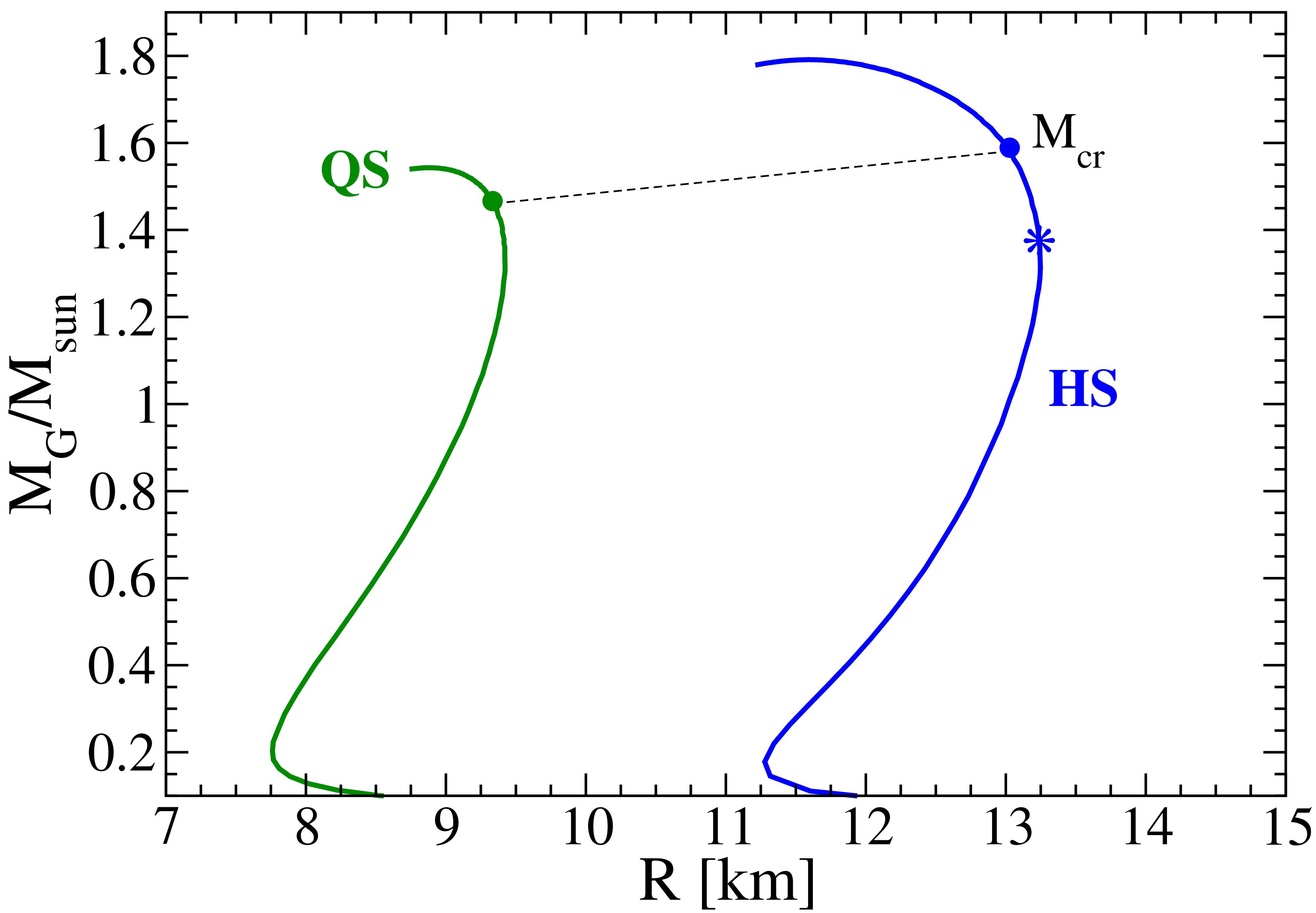



**Dashed line correspond to constant baryonic + mirror matter number**

# *Twin stars*

**Assuming that during the stellar evolution the standard hadronic matter is converted in a different kind of matter one can obtains twin stars**

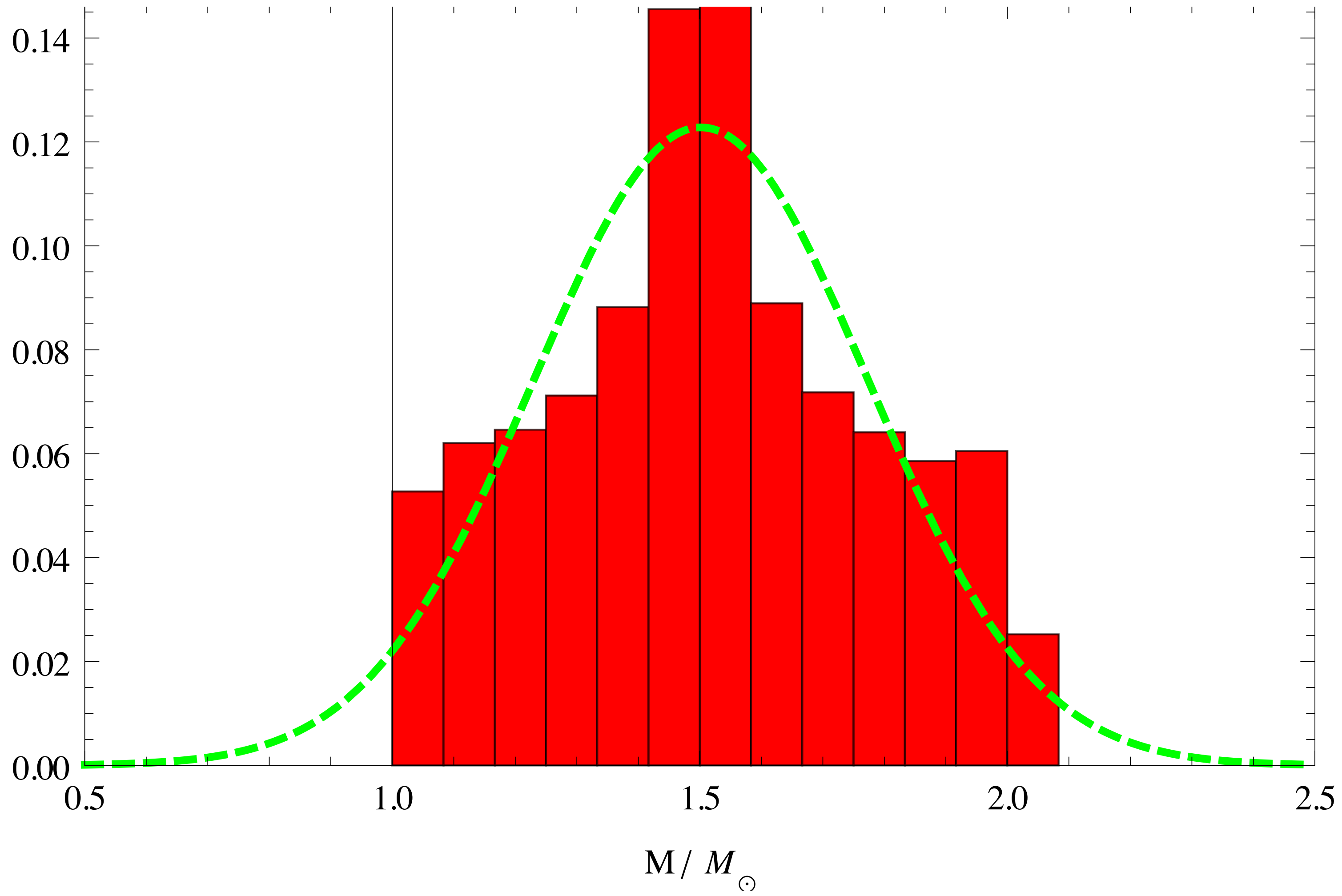
**Example: conversion of Neutron Stars in Hybrid Stars (with a deconfined quark core)**




I. Bombaci et al., Eur.Phys.J. A52 (2016) no.3, 58

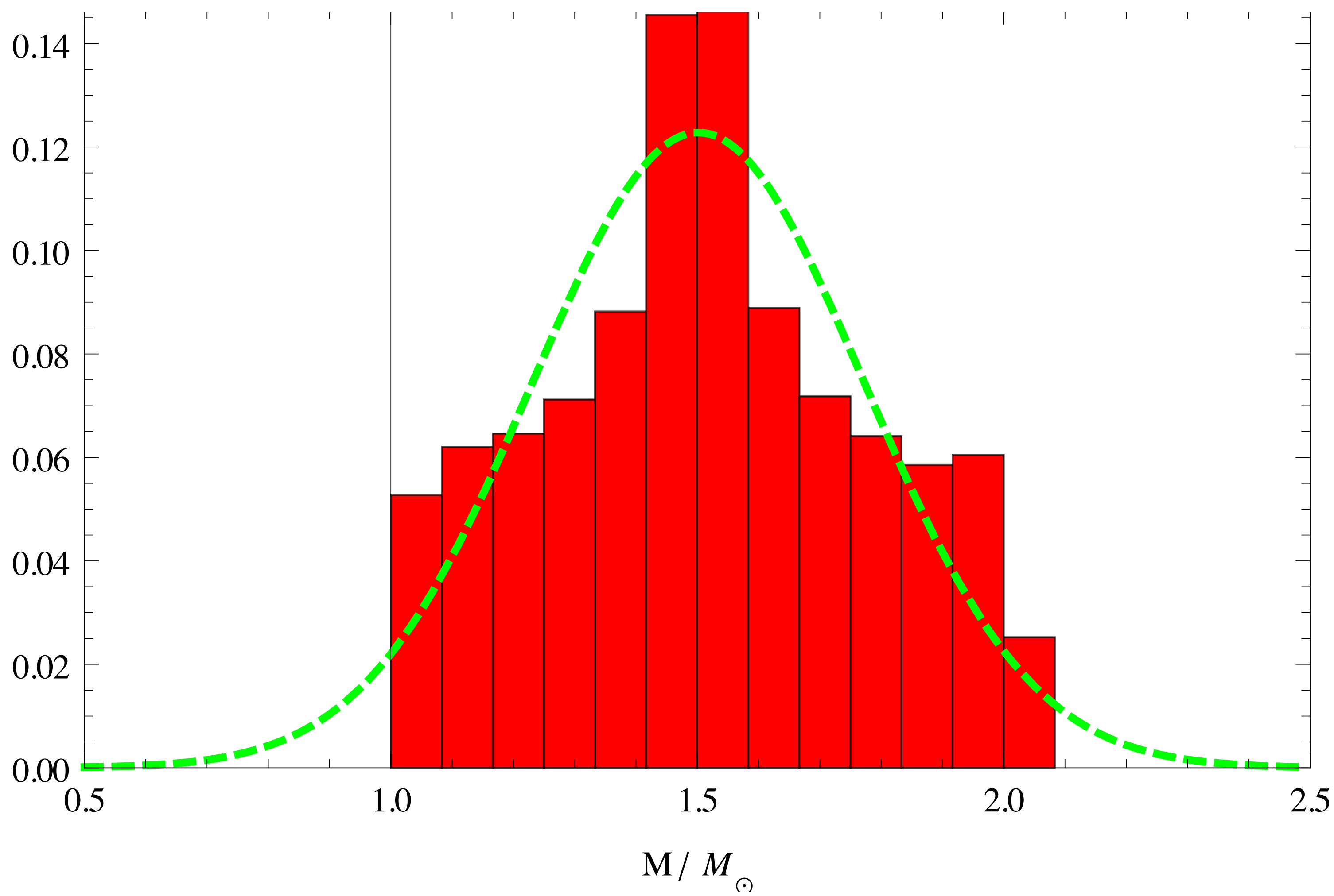
# *Procedure*

**We generate NSs at a constant rate with an initial mass distribution:**



# Procedure

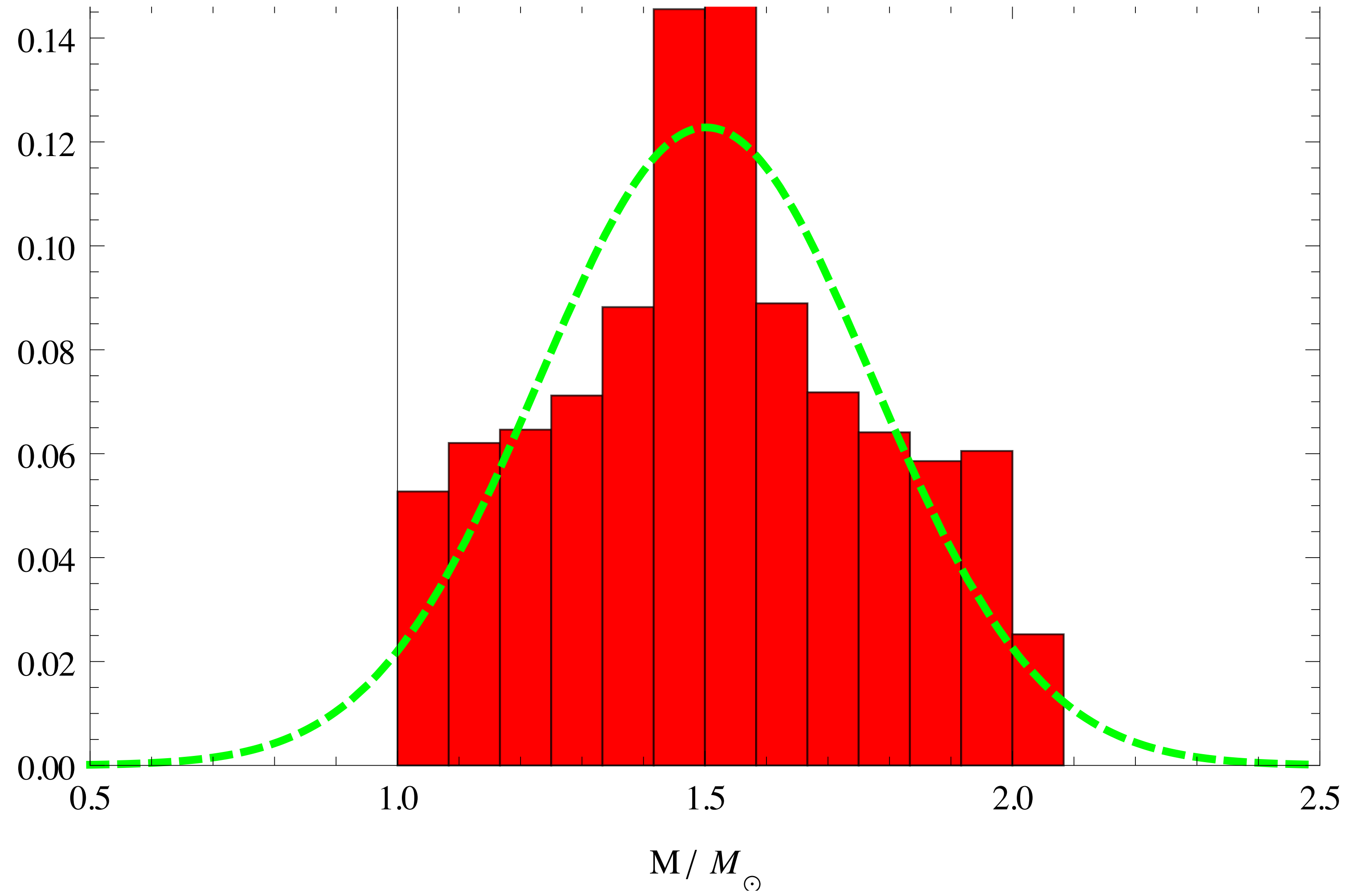
**We generate NSs at a constant rate with an initial mass distribution:**




**Time evolution:**
**1) At every time step a certain number of NSs is created and evolves along a total constant baryonic number line.**
**2) We turn off the creation rate and allow the system to evolve.**

# Procedure

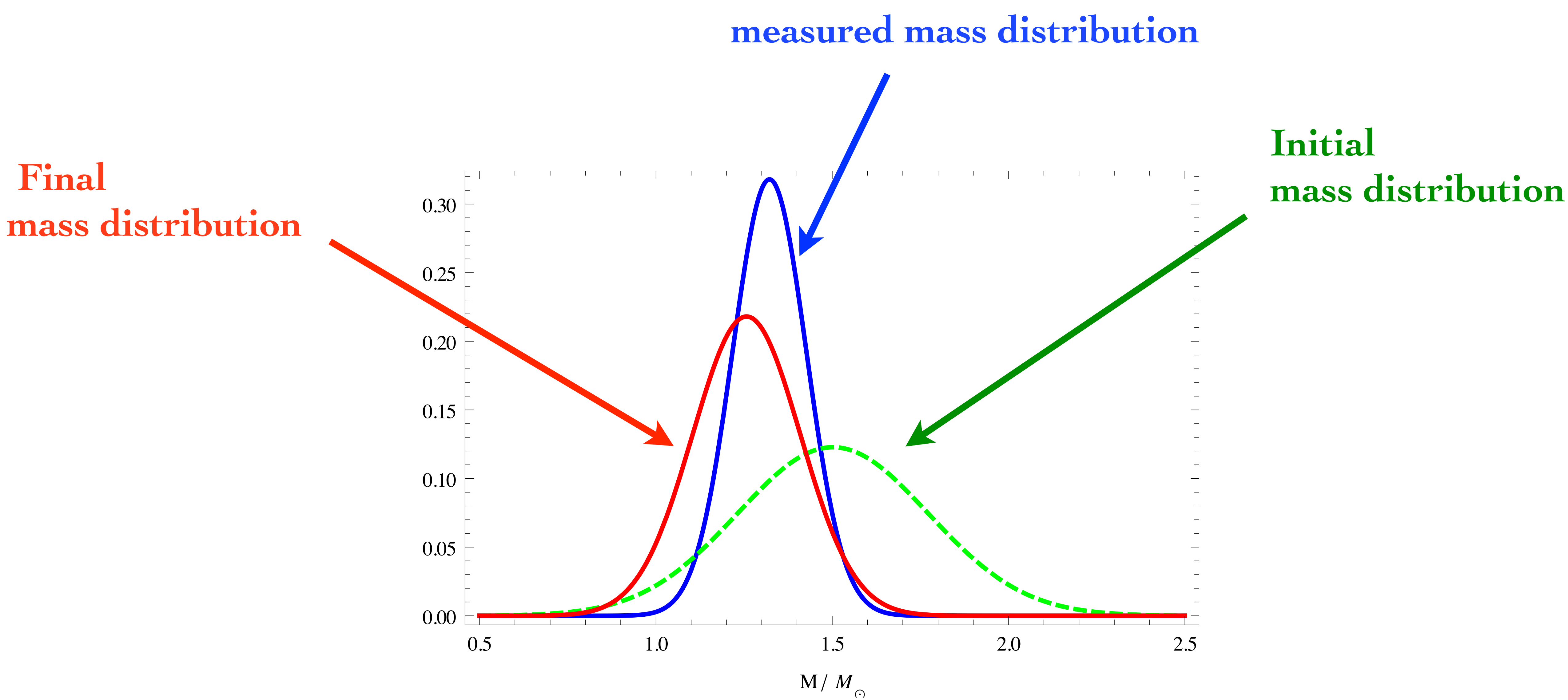
**We generate NSs at a constant rate with an initial mass distribution:**




**Time evolution:**
**1) At every time step a certain number of NSs is created and evolves along a total constant baryonic number line.**
**2) We turn off the creation rate and allow the system to evolve.**

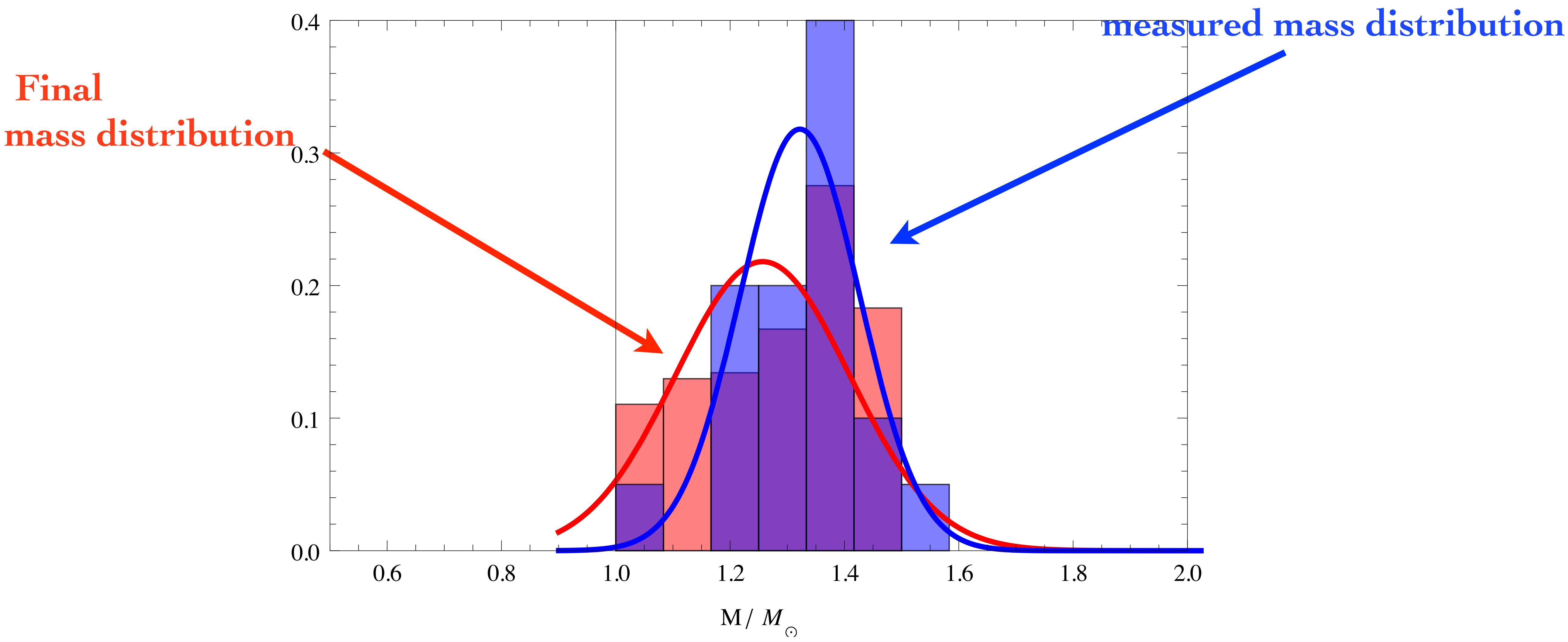
**We tried different initial distributions and creation rates, obtaining similar results.**

# *Mass distribution of NSs*




**Thanks to the "decay" of massive NSs, the peak moves to the left and shrinks**

# *Mass distribution of NSs*




**One interesting aspect is that both the measured mass distribution and our Final mass distribution cannot be well fitted by a Gaussian. They have a similar asymmetry: in both distributions the high mass NSs are suppressed.**

# *Conclusions*

- **Neutron star masses are distributed in a peculiar way**

- **Assuming that standard baryonic matter inside NSs slowly evolves suppresses the large mass NSs**

- **The NSs mass distribution then shrinks and is asymmetric**

- **NSs born with a mass close to two solar masses may become unstable by the conversion of neutrons in mirror neutrons**

# BACKUP

# *Taxonomy of compact stars*

**Neutron star**

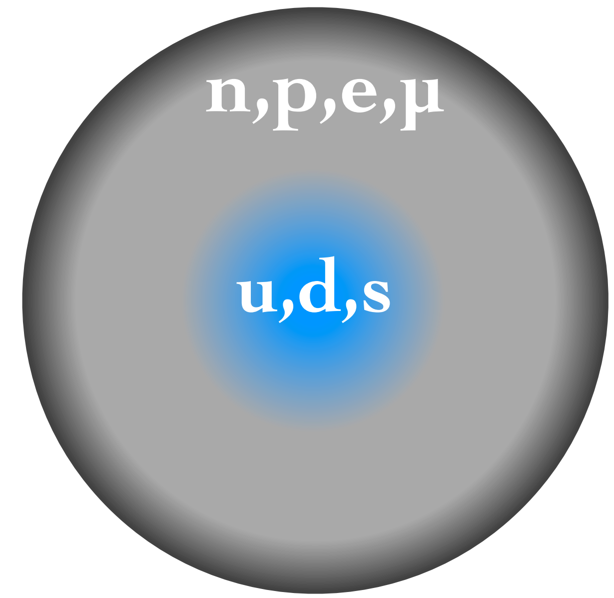

$R \sim 10$ km $M = 1 - 2\, M_{\odot}$

# *Taxonomy of compact stars*

**Neutron star**


$R \sim 10 \text{ km} \;\; M = 1 - 2\, M_\odot$

**Hybrid star**



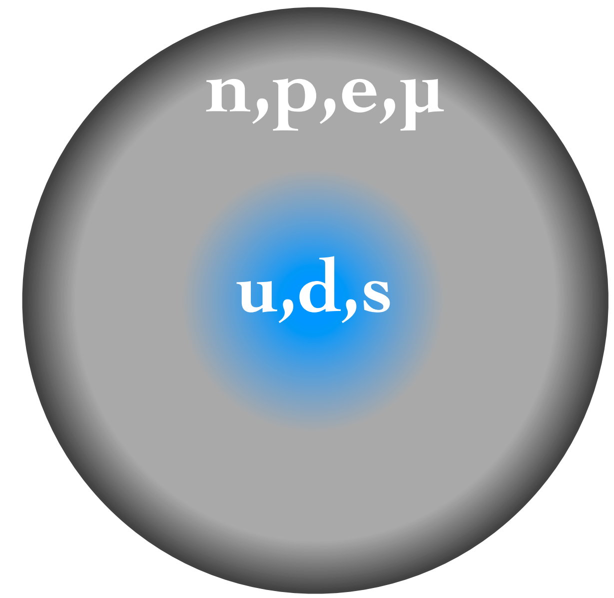

$R \sim 10 \text{ km} \;\; M = 1 - 2\, M_\odot$

# *Taxonomy of compact stars*

**Neutron star**

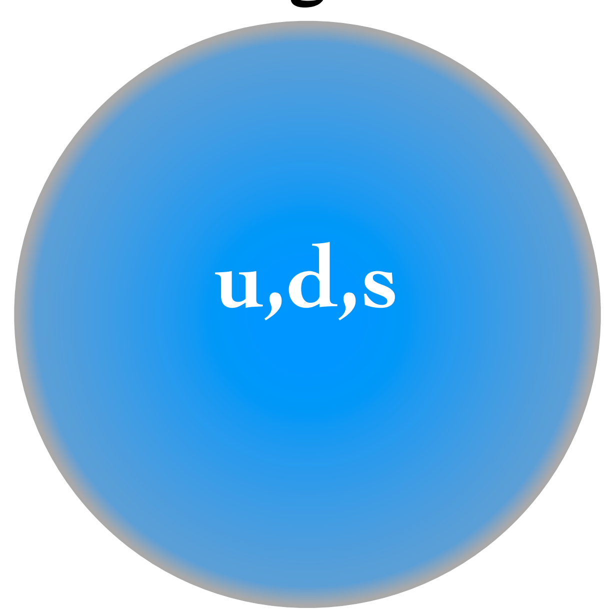

$R \sim 10\ \text{km} \quad M = 1 - 2\, M_{\odot}$

**Hybrid star**



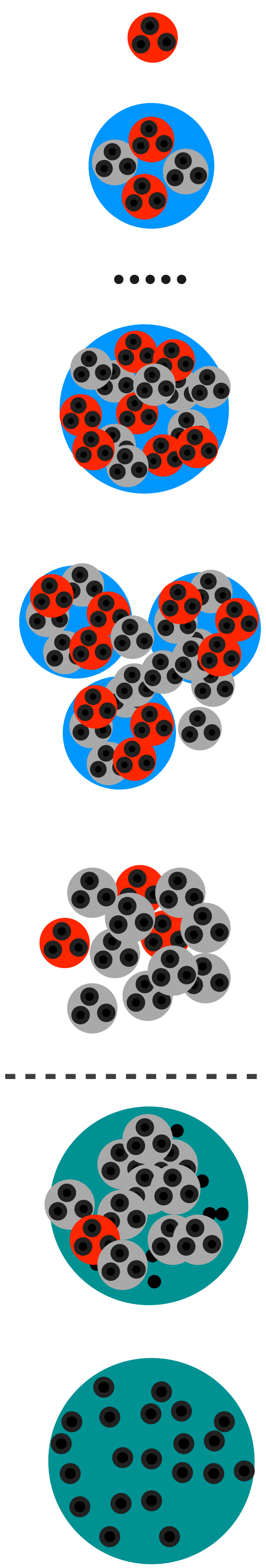

$R \sim 10\ \text{km} \quad M = 1 - 2\, M_{\odot}$

**Strange star**




$R \sim 0 - 10\ \text{km} \quad M < 3\, M_{\odot}$

# *Increasing baryonic density*



| | Density | CSO part | $\alpha_s \equiv \alpha_s(\mu)$ | Degrees of freedom |
|---|---|---|---|---|
| H | | | | |
| He | ...... | atmosphere | | light nuclei |
| ...... | | | | ..... |
| Fe | 10 g cm$^{-3}$ | outer crust | confining | heavy nuclei |
| neutron drip | 10 $^{11}$ g cm$^{-3}$ | | | |
| | | inner crust | | |
| neutron proton soup | 10 $^{14}$ g cm$^{-3}$ | | | neutrons and protons |
| | | core | | |
| quark drip | very large | | strong coupling | quarks and gluons<br>Cooper pairs of quarks? |
| quark soup | extreme | | weak coupling | Cooper pairs of quarks<br>NGBs |

$\rho$