The cooling processes and mass distribution of neutron stars

Harish Chandra Das

INFN Catania, Italy

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Neutron star cooling and mass distributions

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H. C. Das, Jin-Biao Wei, G. F. Burgio, and H. -J. Schulze

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ABSTRACT

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We study the cooling of isolated neutron stars, employing different nuclear equations of state with or without active direct Urca process, and investigate the interplay with the nuclear pairing gaps. We find that a consistent description of all current cooling data requires fast direct Urca cooling and reasonable proton 1S0 gaps, but no neutron 3P2 pairing. We then deduce the neutron star mass distributions compatible with the cooling analysis and compare with current theoretical models. Reduced 1S0 gaps and unimodal mass distributions are preferred by the analysis. The importance of statistical and systematic errors is also investigated.

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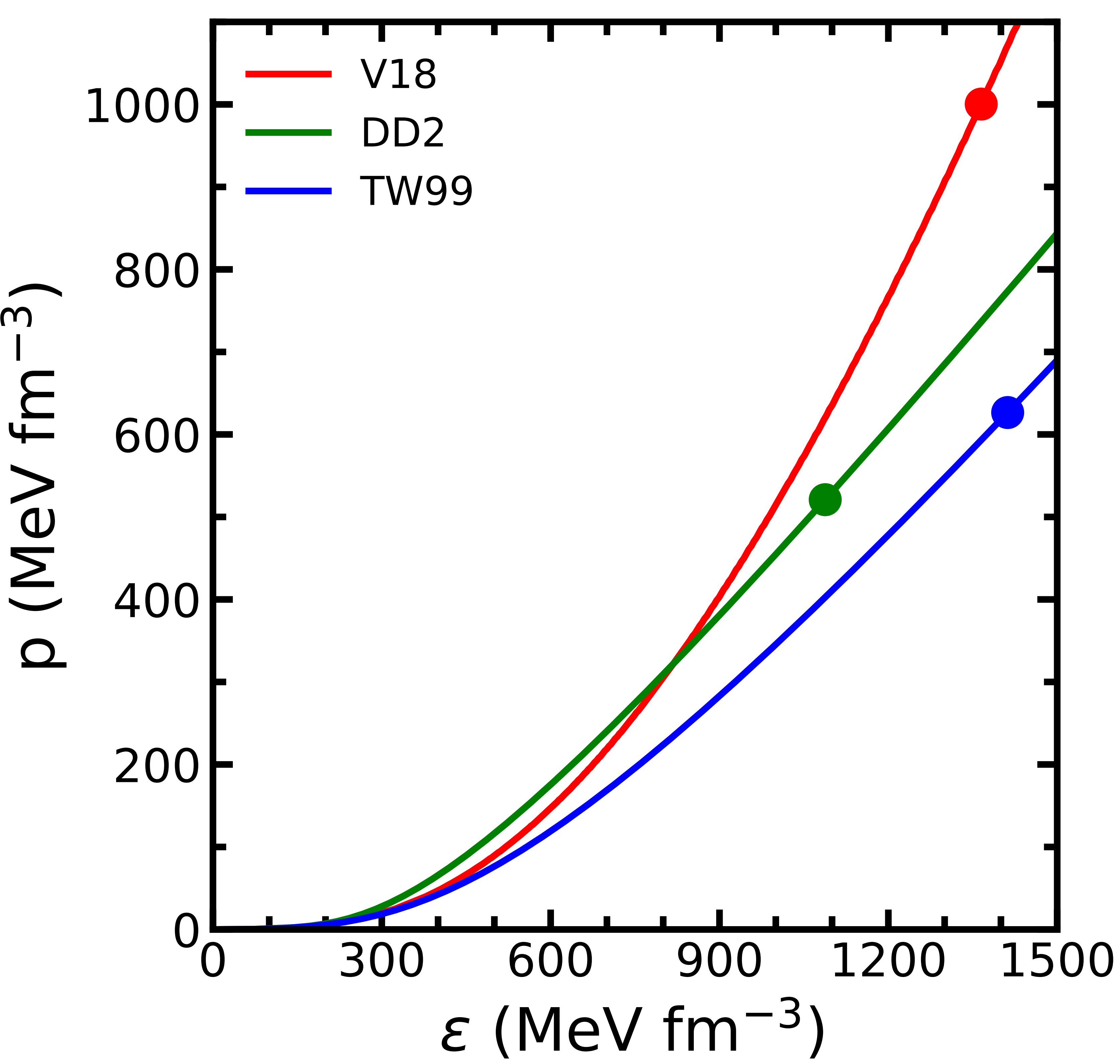
Introduction

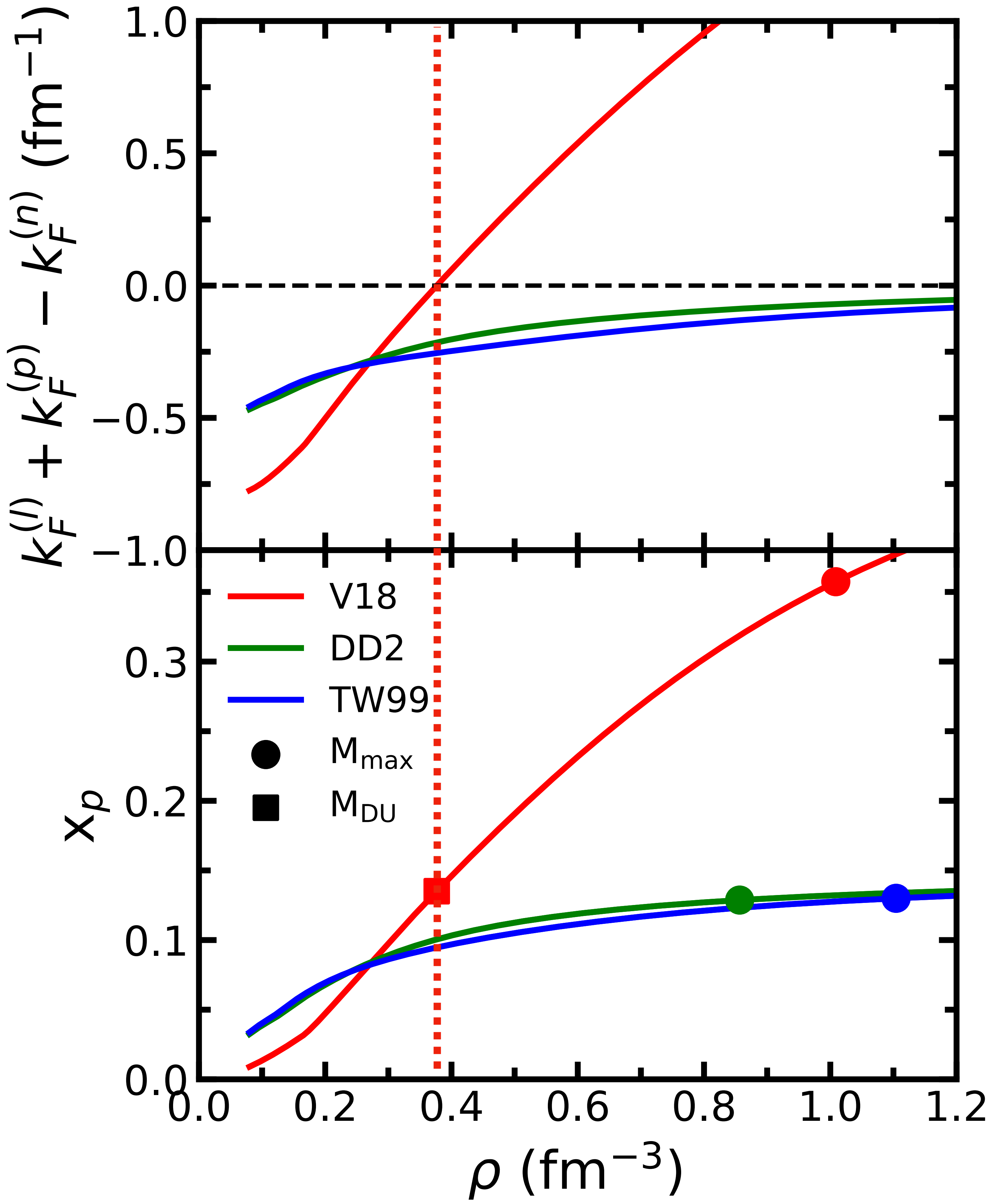
- Star of mass $(8 - 20\ M_\odot)$ collapse → newly formed Neutron Star ($\sim 10^{10-11}\ K)$.
- It cools very fast due to huge amount of neutrino emission .
- NS cooling is over vast domain of time $(10^{-10} - 10^{5}\ \text{yr})$ dominated by several macroscopic processes.
- Processess → (i) URCA $(n \to p + e + \bar{\nu}_l, \ldots)$

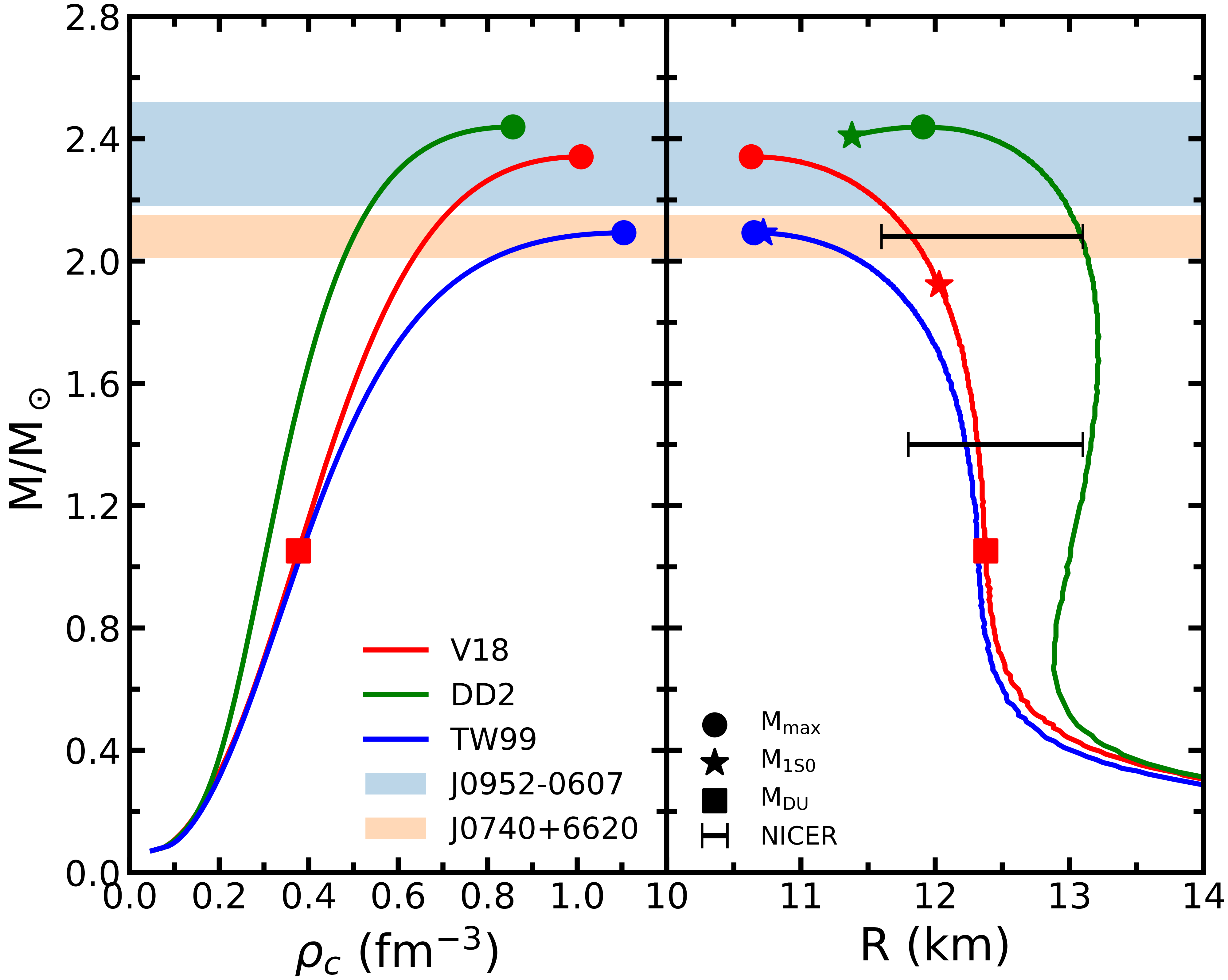
  (ii) modified URCA $(n + N \to p + N + l + \bar{\nu}_l, \ldots)$

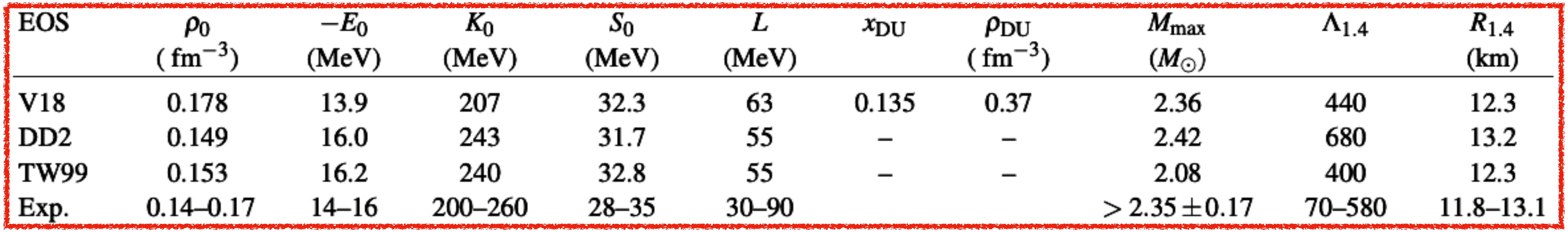
  (iii) Bremsstrahlung $(N + N \to N + N + \nu + \bar{\nu})$ …
- Like mass and radius; the temperature at the surface of the NS can be detectable.
- The emitted surface temperature depends on the internal structure, density profiles, particle types, …
- One of the main ingredient is the equation of state $p(\rho), \epsilon(\rho)$.

Equation of states, URCA process, M-R relations









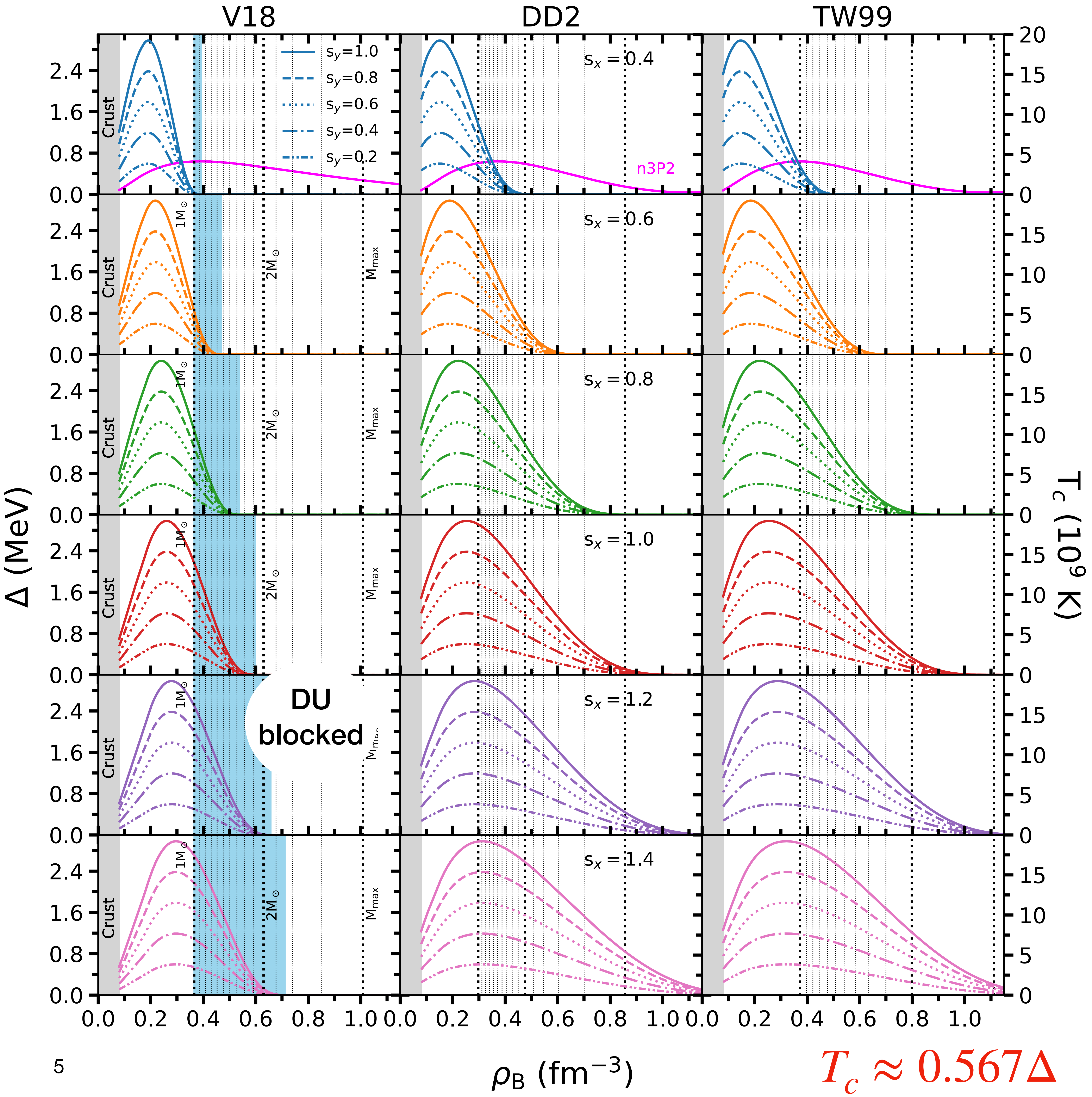
EOS	ρ_0 (fm^{-3})	$-E_0$ (MeV)	K_0 (MeV)	S_0 (MeV)	L (MeV)	x_{DU}	ρ_{DU} (fm^{-3})	M_{max} ($M_\odot$)	$\Lambda_{1.4}$	$R_{1.4}$ (km)
V18	0.178	13.9	207	32.3	63	0.135	0.37	2.36	440	12.3
DD2	0.149	16.0	243	31.7	55	–	–	2.42	680	13.2
TW99	0.153	16.2	240	32.8	55	–	–	2.08	400	12.3
Exp.	0.14–0.17	14–16	200–260	28–35	30–90			$> 2.35 \pm 0.17$	70–580	11.8–13.1

Super fluidity, Pairing gaps and Scaling factors

- Superfluids are created by the formation of pp and nn Cooper pairs (attractive NN potential)
- The most important are p1S0 and n3P2 pairing channels, while the n1S0 gap (crust only) is much less relevant, and the p3P2 gap is disregarded due to its uncertain properties at extreme densities.
- For simplest approx., $\Delta_{\mathrm{BCS}}(\rho)$ is universal for any EOS, independent of the used V_{NN} .
- In medium effects might strongly affect the BCS results due to 3-body force and polarization corrections, which suppress the magnitude and density domain of the BCS gap.
- The suppression can be taken care with the scaling factors s_x and s_y

$$\Delta(\rho) \equiv s_y \Delta_{\mathrm{BCS}}(\rho/s_x)$$

PRC **70**, 048802 (2004)



$T_c \approx 0.567\Delta$

Cooling of Neutron Star

$$\boxed{\begin{aligned} \frac{\partial}{\partial r}(Le^{2\phi(r)}) &= -\frac{4\pi r^2 e^{\phi(r)}}{\sqrt{1-\frac{2GM}{c^2 r}}}\left(C_V\frac{\partial T}{\partial t} - e^{\phi(r)}(Q_\nu + Q_h)\right) \\ \frac{\partial}{\partial r}(Te^{\phi(r)}) &= -\frac{L}{\kappa 4\pi r^2}\frac{e^{\phi(r)}}{\sqrt{1-\frac{2GM}{c^2 r}}} \end{aligned}}$$

Thorne+1977

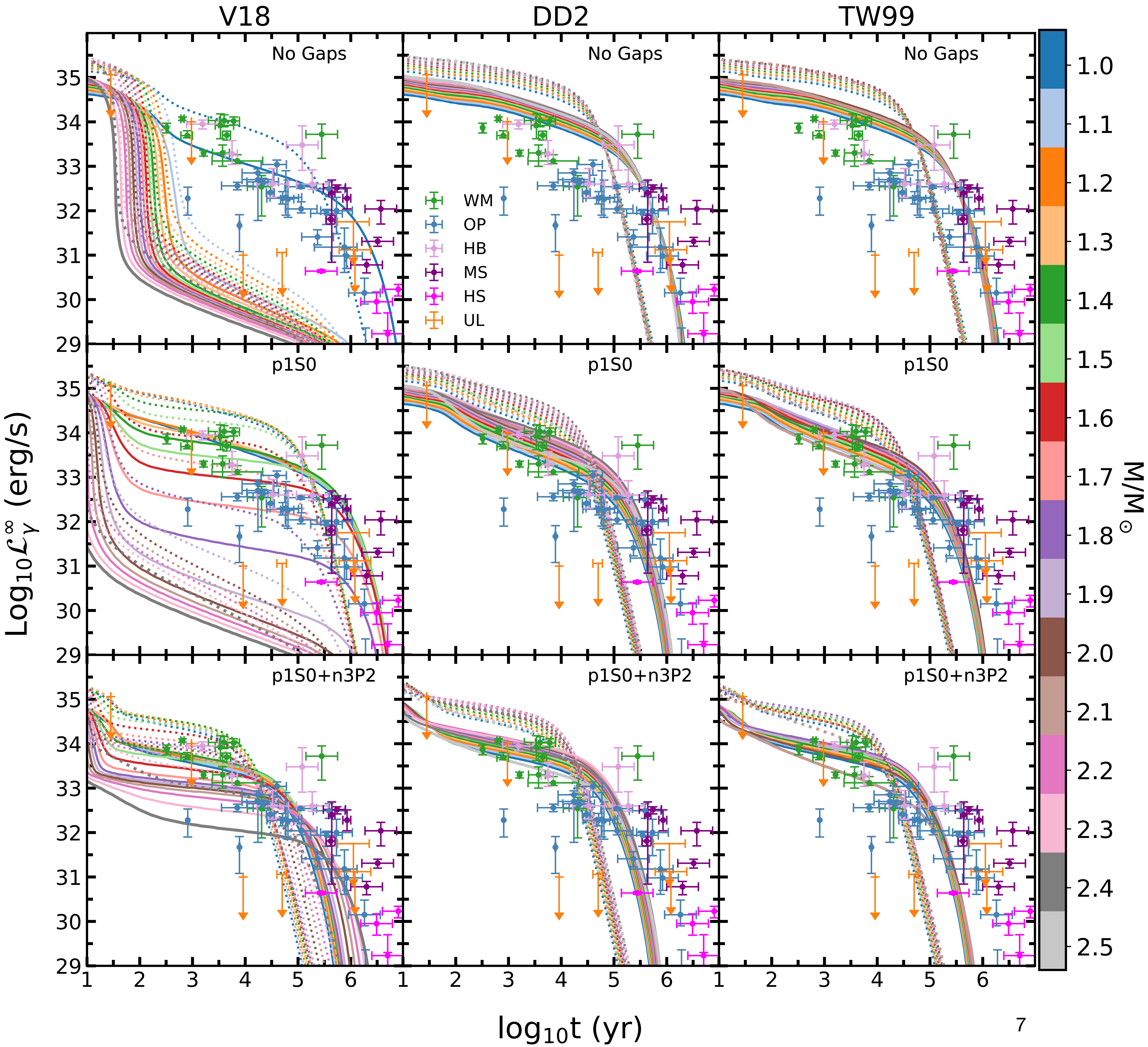
$L \rightarrow$ Luminosity $t, \phi(r) \rightarrow$ time and gravitational potential

$C_v \rightarrow$ Specific heat (heating of the electron gas and nucleon), $C_v = \sum_i \frac{M_i^* n_i}{k_{Fi}^2}\pi^2 k_B T$

$Q_\nu, Q_h \rightarrow$ Neutron emissivity for neutrino and heat production per uni volume (ignored in this study)
(URCA, mURCA, Plasmon decay, Bremsstrahlung etc.)

$\kappa \rightarrow$ Thermal conductivity, $\kappa_i = \frac{\pi^2 k_B^2 n_i T \tau_i}{3M_i^*}$

Cooling curves and observational data



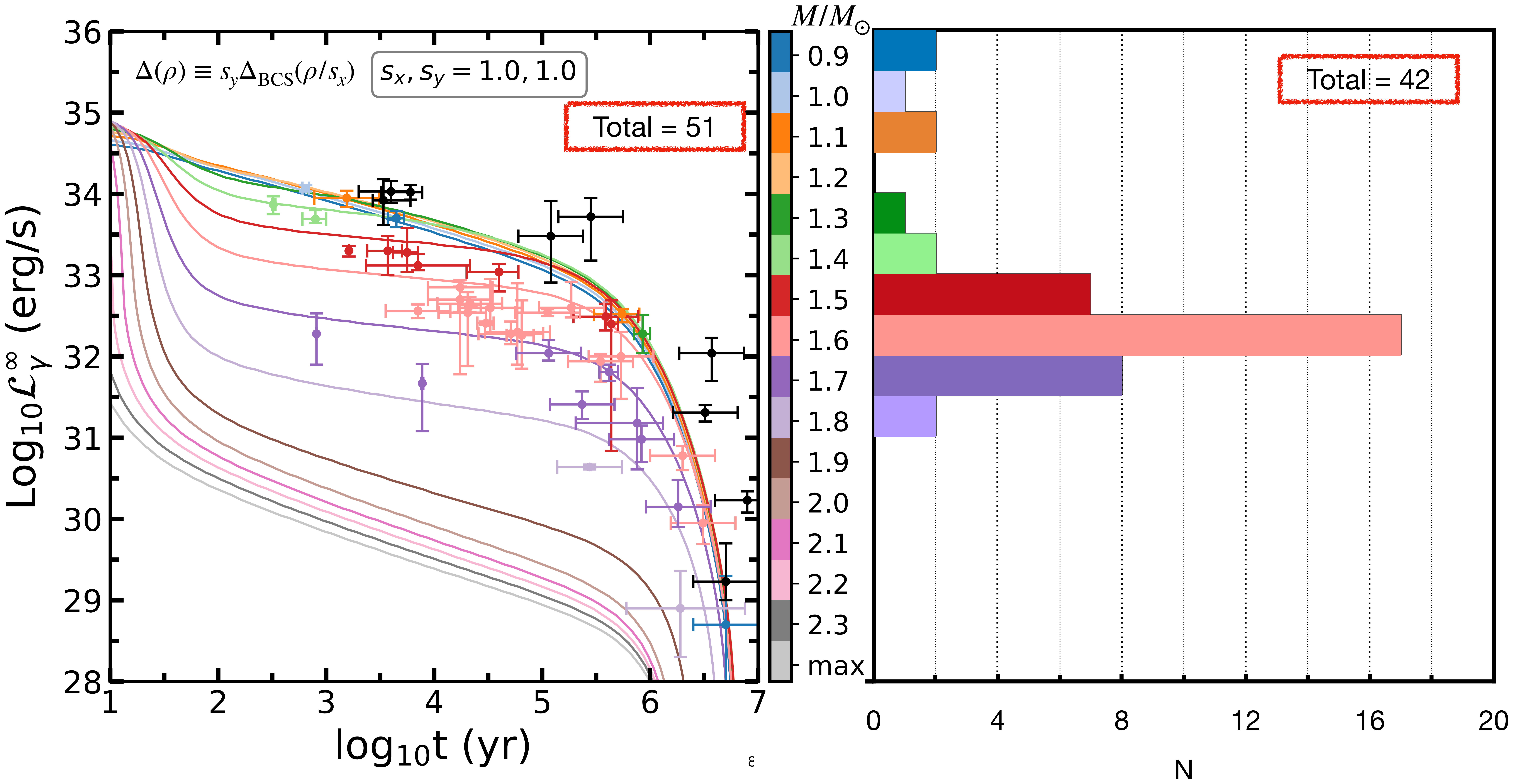
Type of Neutron Stars

- Weakly Magnetized (WM): 12
- Ordinary Pulsars (OP): 22
- High-B Pulsars (HB): 5
- The Magnificent Seven (MS): 7
- Small Hot Spots (HS): 5
- Upper Limits (UL): 6

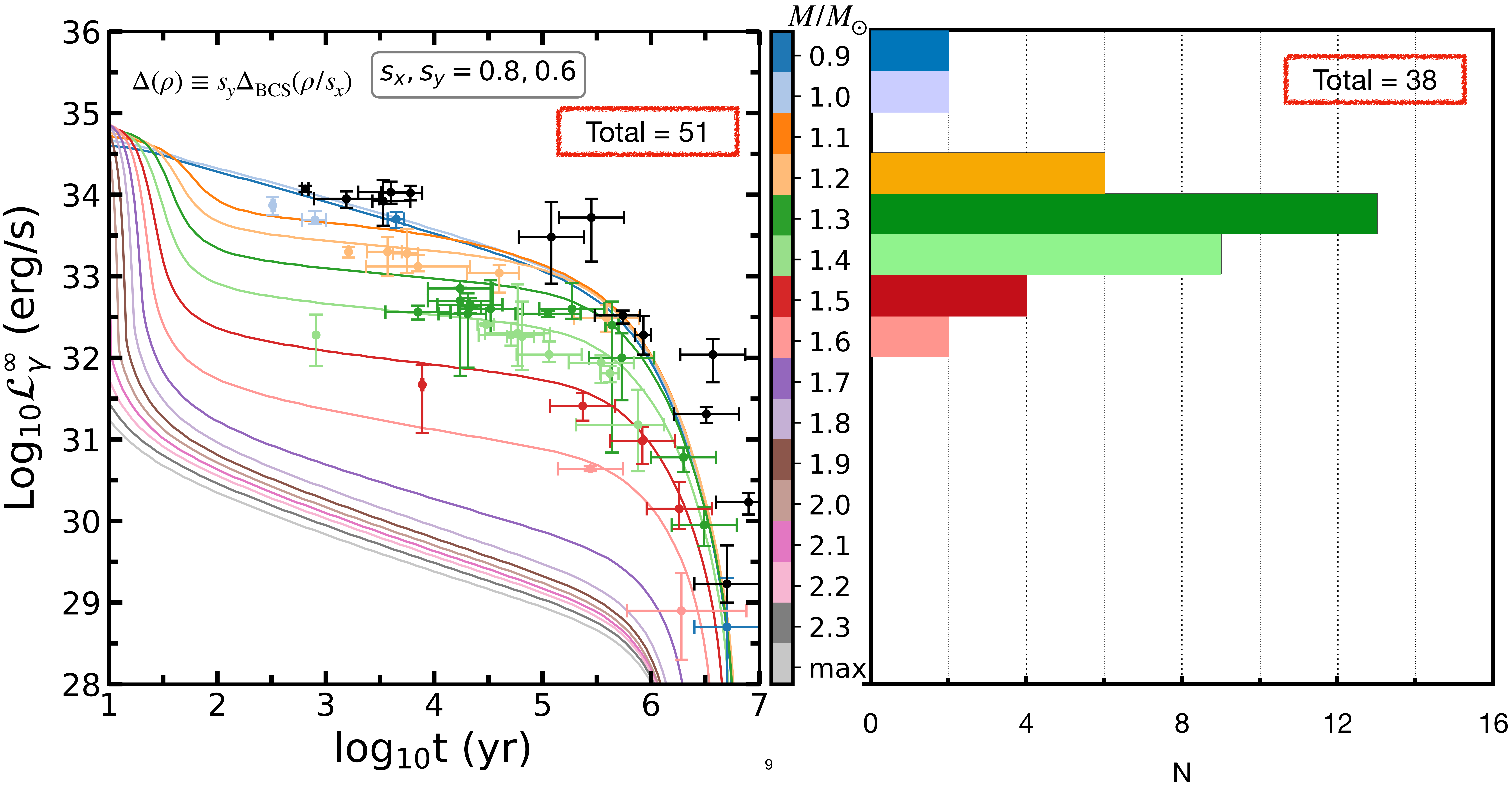
Total = 57

https://www.ioffe.ru/astro/NSG/thermal/cooldat.html

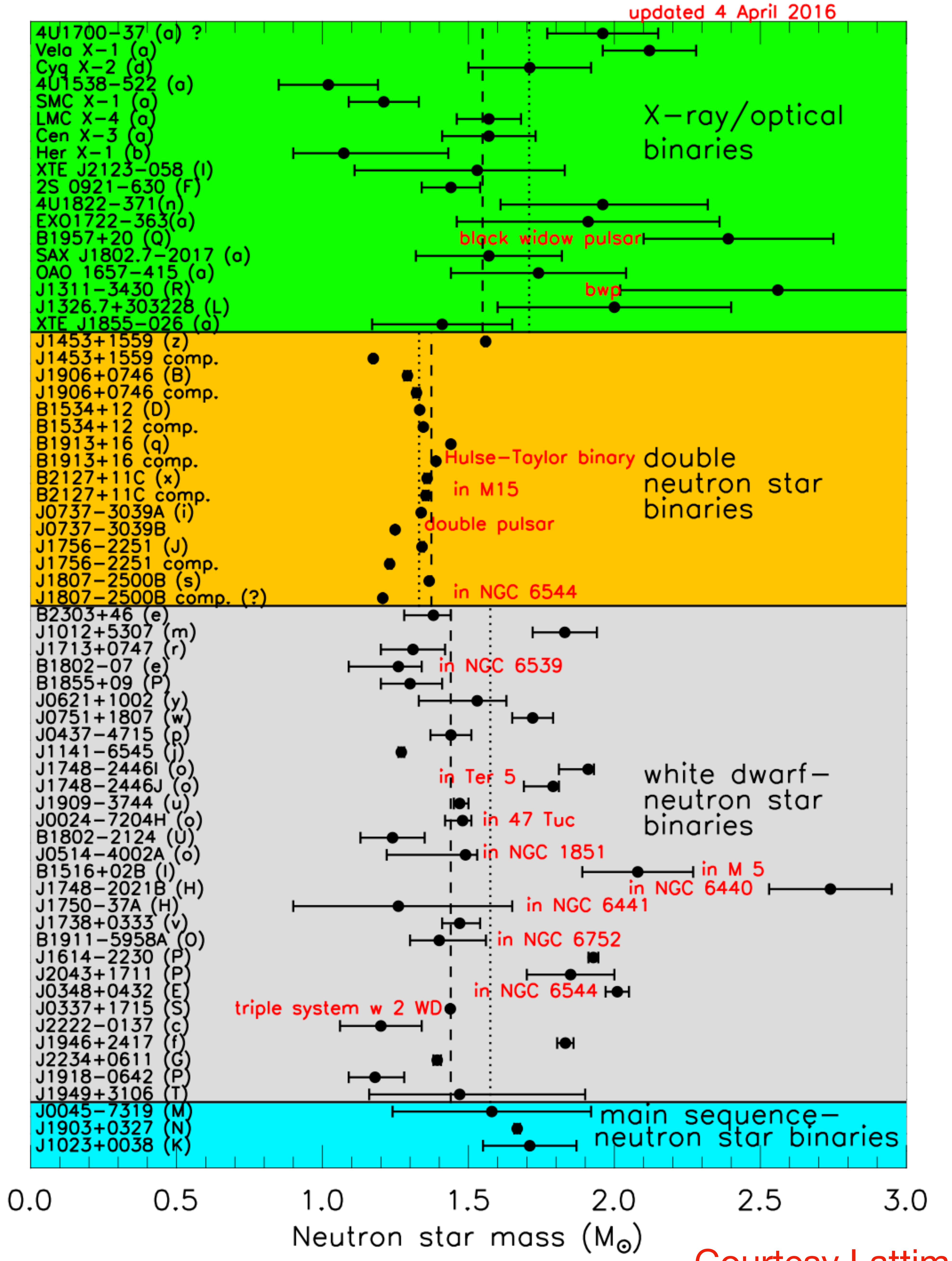
Cooling curves and mass histograms



Cooling curves and mass histograms



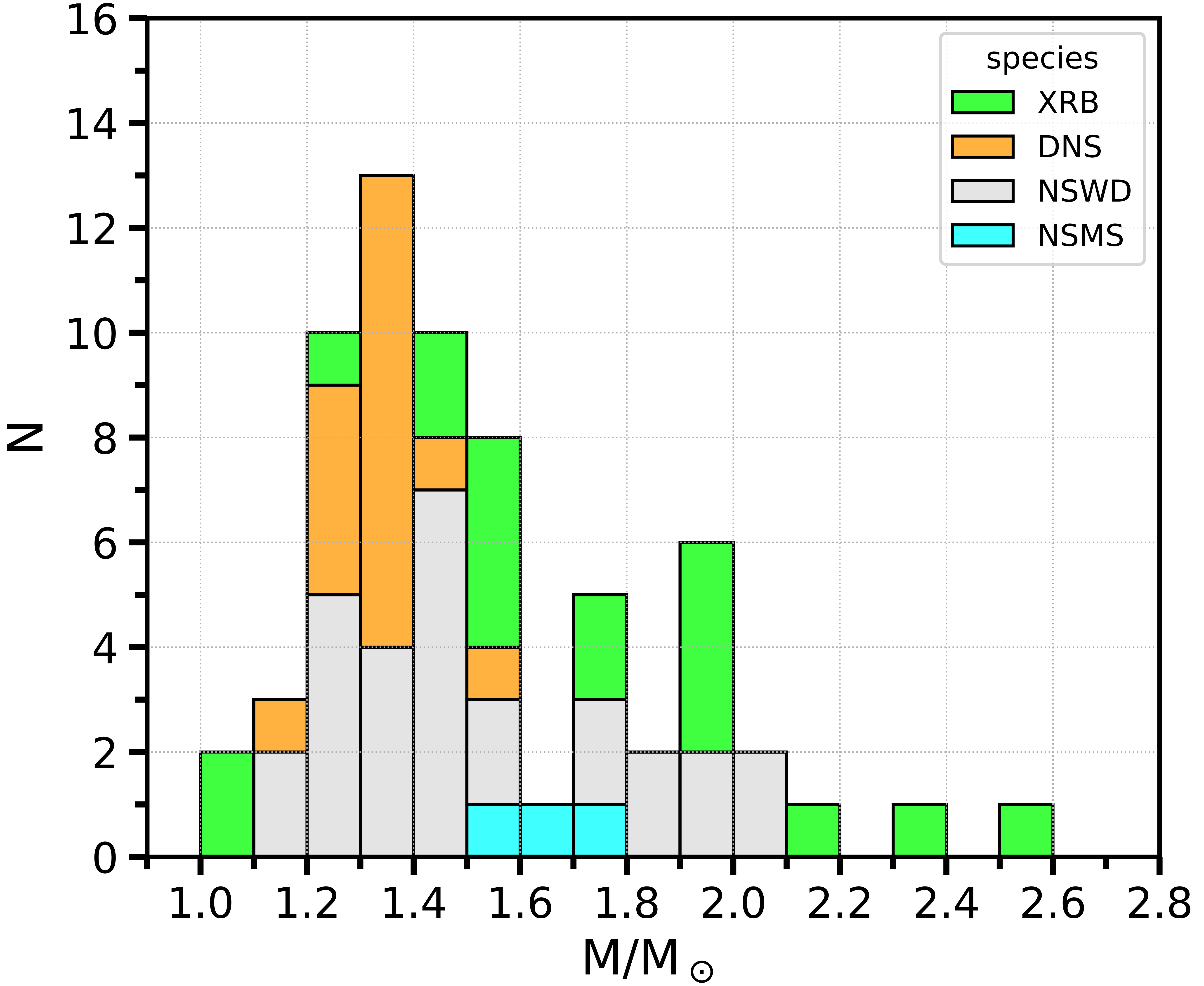
Theoretical mass distributions and histograms



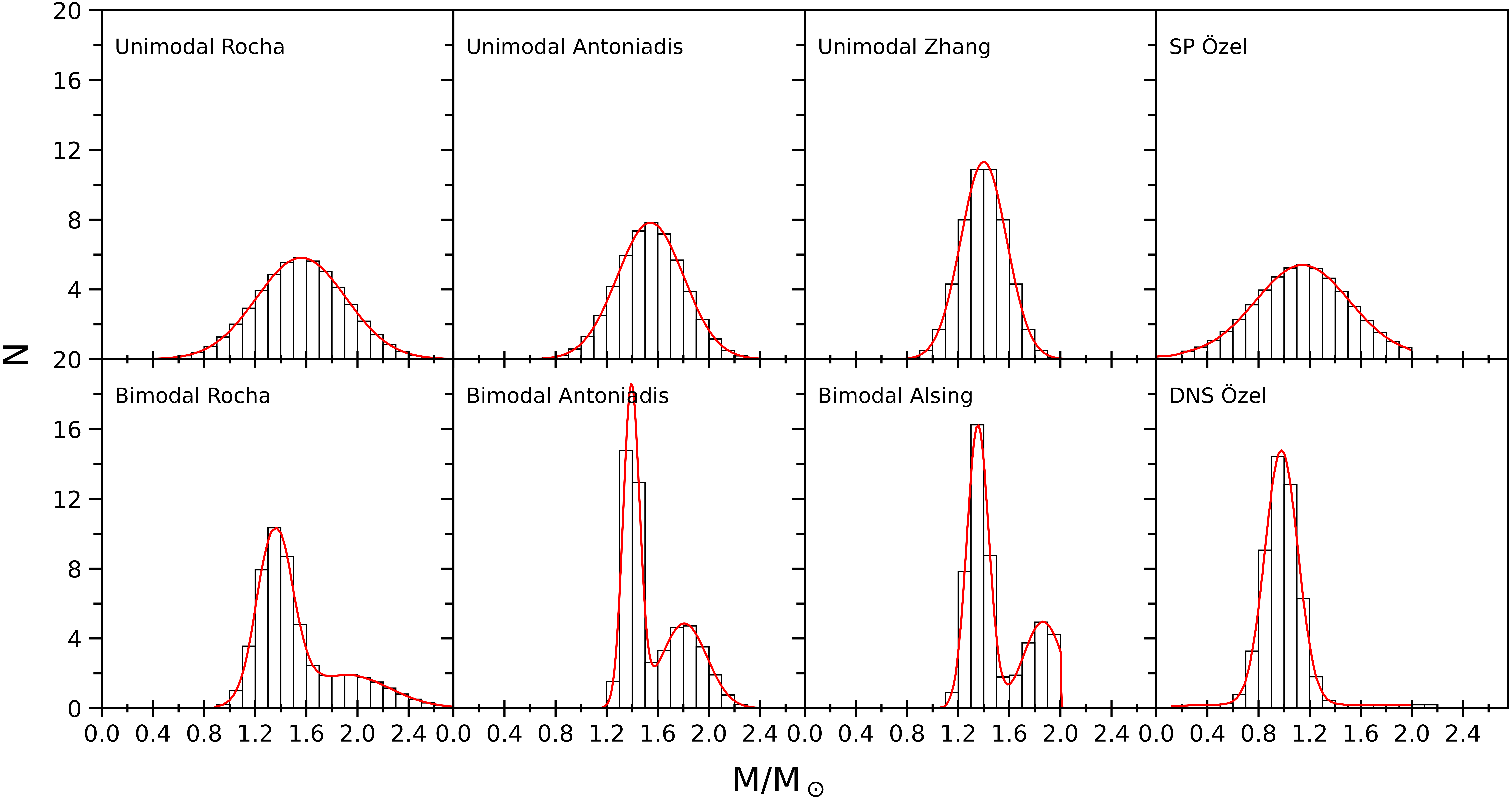
Courtesy Lattimer

Source

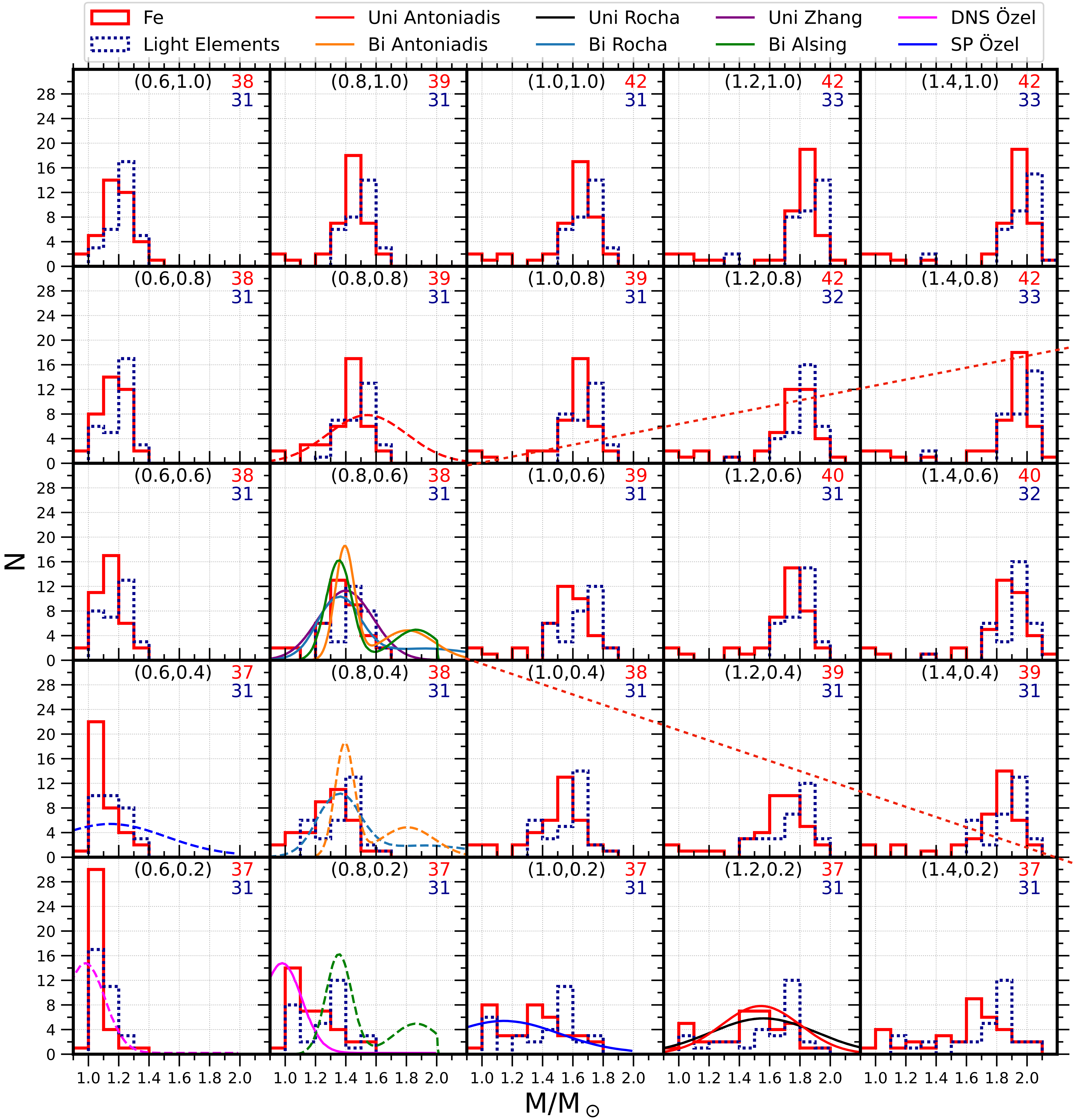
1. https://stellarcollapse.org/nsmasses.html
2. https://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html



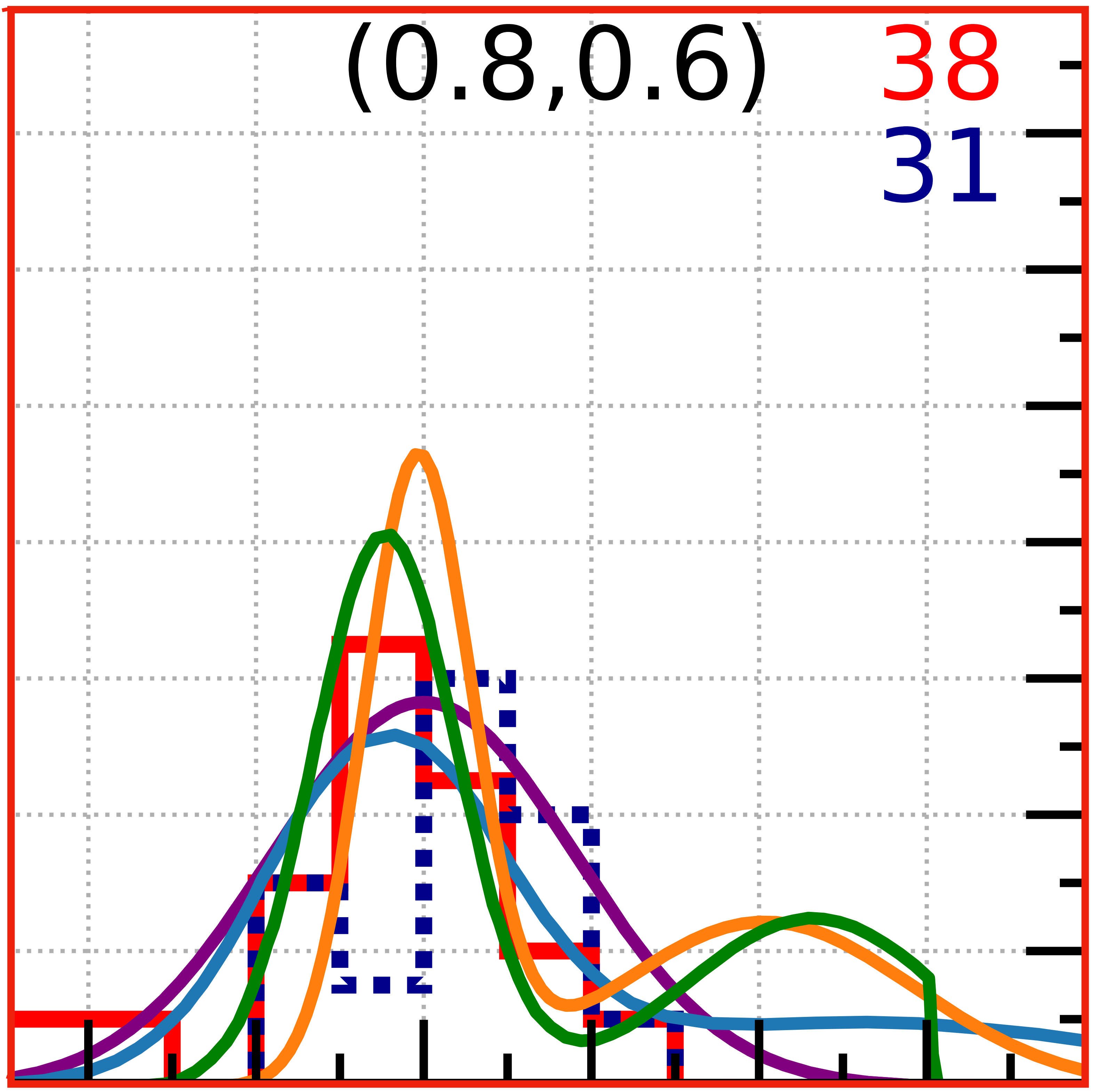
Theoretical mass distributions and histograms



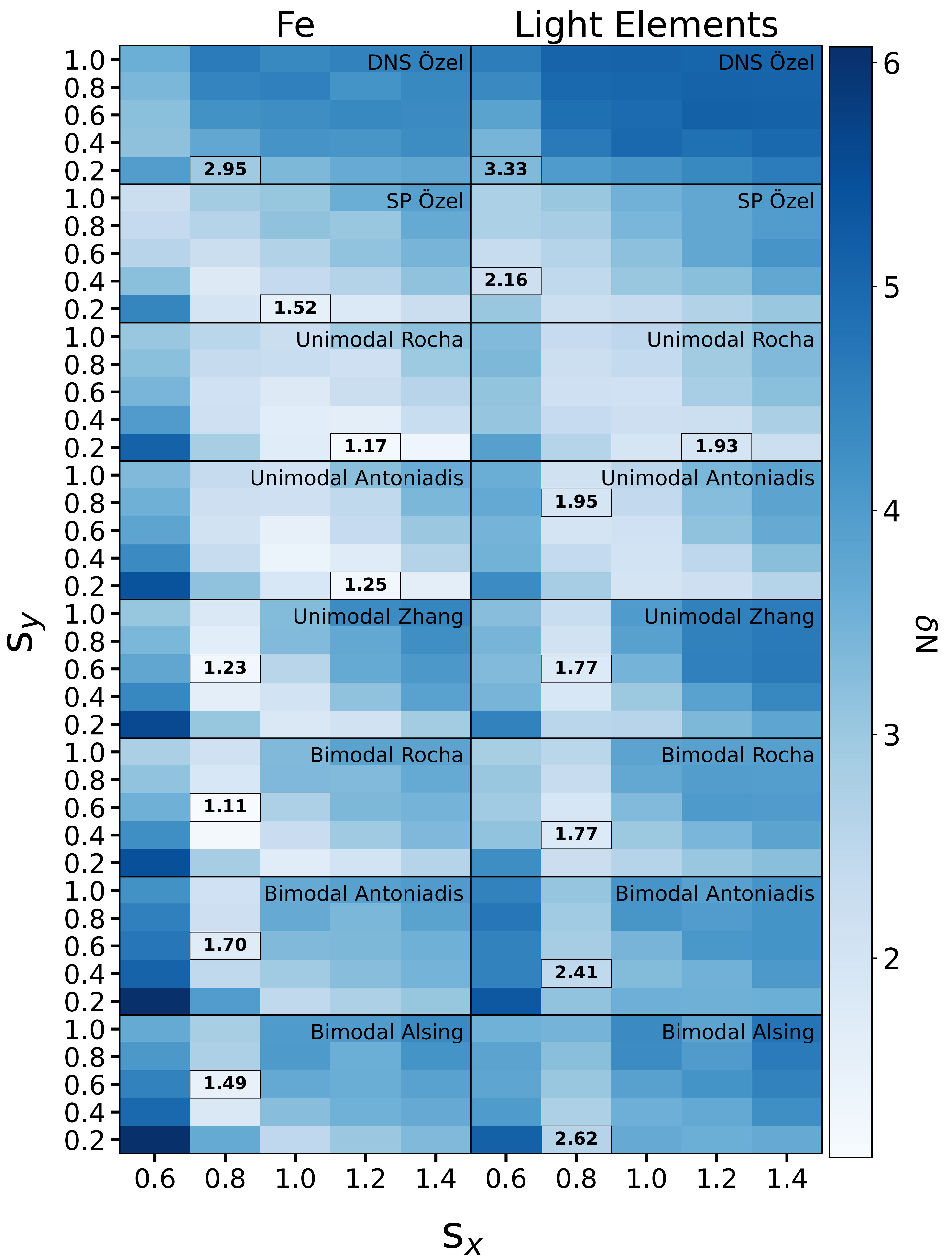
Mass histograms with different scaling factors



$$\Delta(\rho) \equiv s_y \Delta_{\mathrm{BCS}}(\rho/s_x)$$

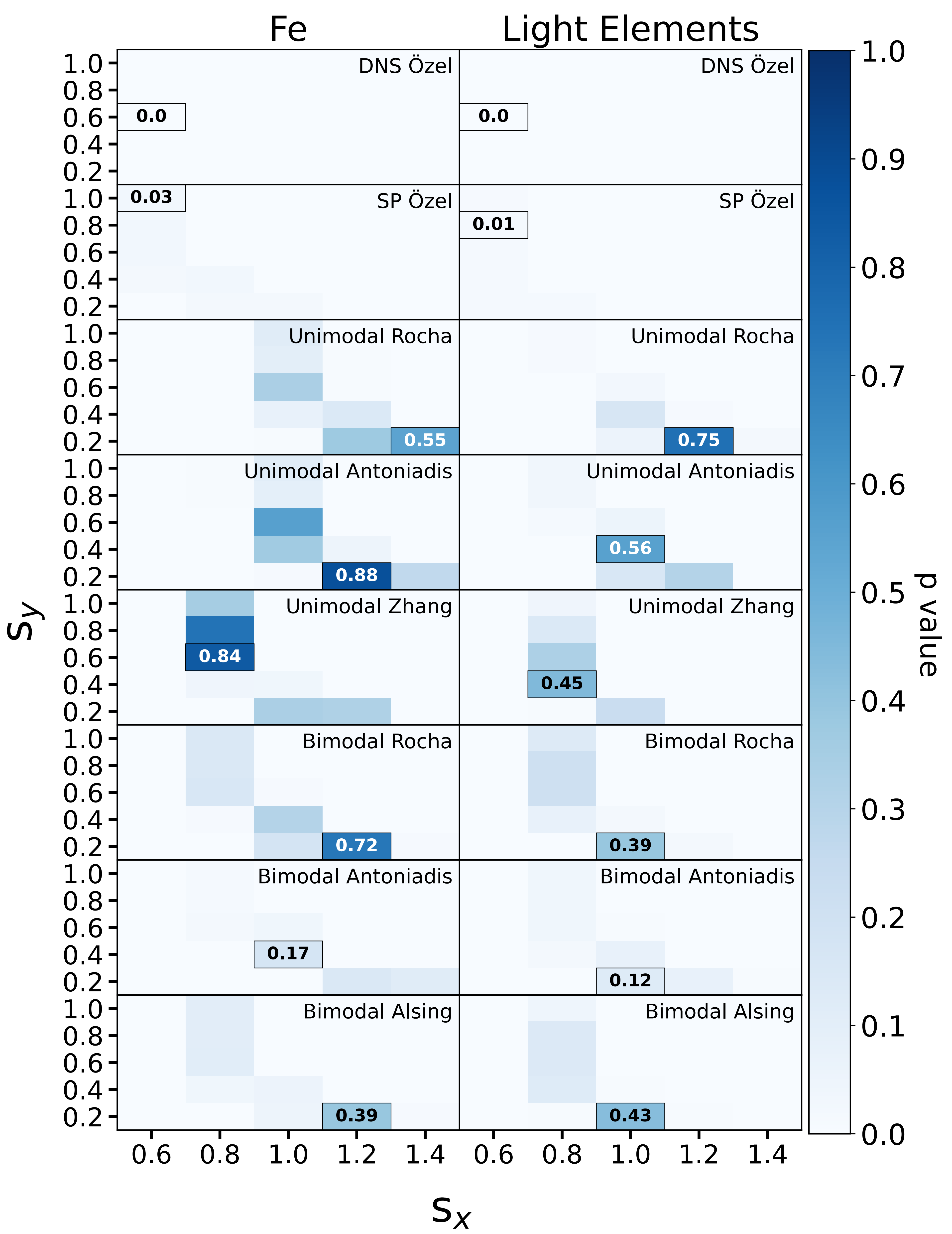


RMS deviation, Kolmogorov-Smirnov (KS) test



$$\delta N \equiv \sqrt{\frac{1}{N^{\rm dat}}\sum_i \left(N_i^{\rm dat} - N_i^{\rm theo}\right)^2}$$

(b) KS



Mass histogram with Montecarlo method

Conclusion

- Neutron star cools very fast due to emission of huge amount of neutrinos.
- Cooling of the NS is calculated with/without direct URCA active models.
- The rate of cooling is highly impacted by the URCA process and superfluidity gaps.
- Different scaling factor of the 1S0 gap are chosen to explore the cooling diagrams and the corresponding mass histograms are estimated with cooling observational data.
- The comparison between theoretical mass distributions and obtained one, provides the optimal values of scaling factor $(s_x, s_y = 0.8{,}0.6)$ for pairing gaps.
- The randomly generated false data with Montecarlo simulation also predicts the same distribution with original observational case.

T H A N K Y O U