

Fast neutrino cooling in the accreting neutron star MXB 1659-29

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Farrukh J. Fattoyev

Manhattan College, Riverdale

In collaboration with Melissa Mendes, Andrew Cumming, Charles Gale

Image Credit: Chandra Harvard



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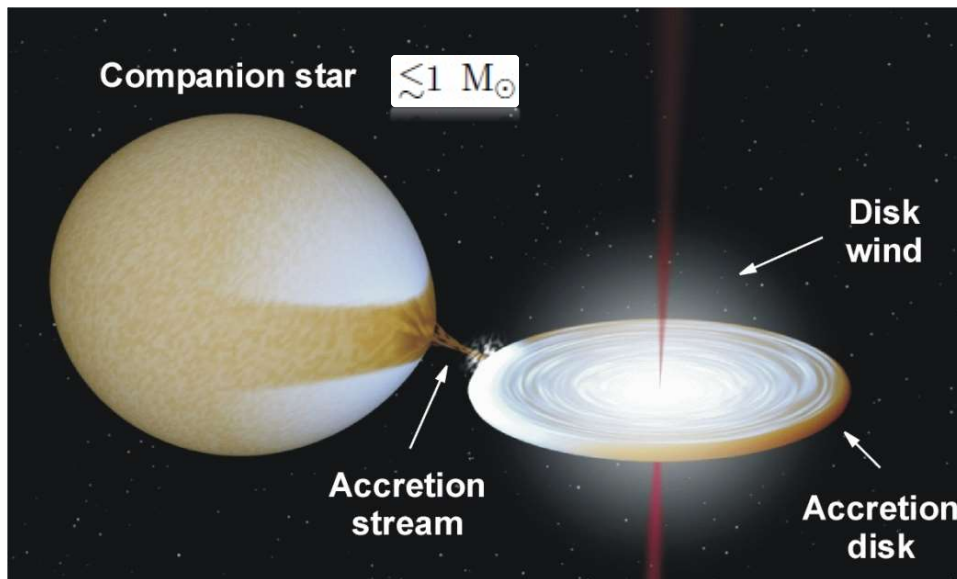
Neutron Rich Matter on Heaven and Earth

June 25 - July 1, 2023, Institute for Nuclear Theory, Seattle, WA

Introduction

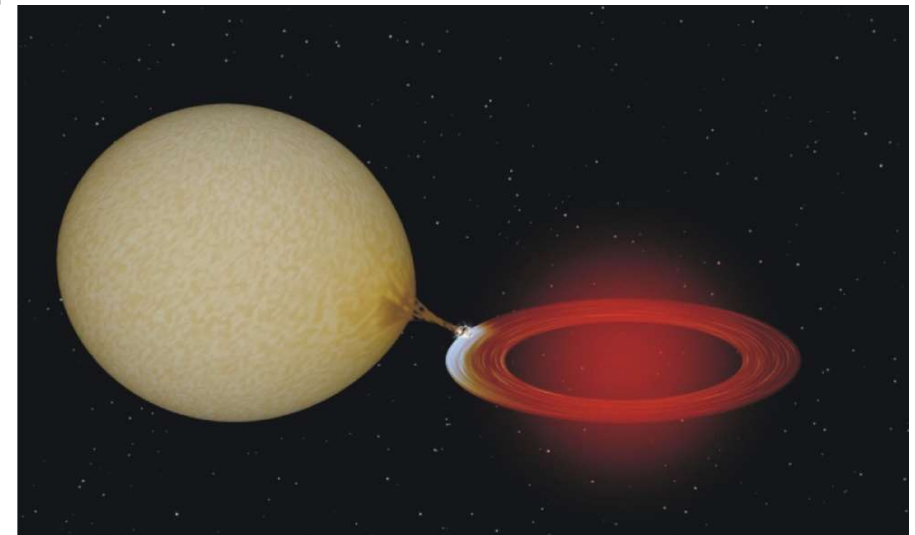
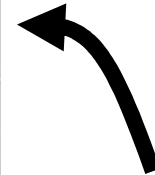
- ❑ Neutron star cooling data in low-mass X-ray binaries (LMXB) can constrain equation of state (EOS) properties, such as particle composition and hence the symmetry energy.
- ❑ Modeling of the crust cooling and heating in MXB 1659-29 across multiple outbursts indicates that $\sim 1\%$ of the core volume is involved in direct Urca reactions. Brown et al. Phys. Rev. Lett., 120, 182701 (2018).
- ❑ In this study we use models incorporating a detailed EOS, characterized by the nuclear symmetry energy slope L , that encompasses various neutron and proton superfluid gaps.
- ❑ In particular, we study the sensitivity of the NS mass on both L and the gap model.

Neutron Stars in Transient Low-Mass X-ray Binaries



Quiescence:
no or little accretion,
faint X-ray emission,
crust cools down,
(lasts from years to decades)

$$L_X \simeq 10^{31-34} \text{ erg s}^{-1}$$



Accretion outburst:
rapid accretion,
matter compresses crust,
nuclear reactions: e-capture, fusion
energy release in bright X-ray emission
(lasts for months/sometimes years)

$$L_X \simeq 10^{36-38} \text{ erg s}^{-1} \text{ (0.5-10 keV)}$$

The Effect of Accretion

Large amount of gravitational energy is released raising temperatures to $\sim 10^7$ K;
 Heat flows (if the core is colder) into the core; Fujimoto et al. 1984, ApJ, 278, 813
 Compression of materials causes nuclear reactions in the crust which heat the core;
 In quiescent phase, the NS surface temperature can be measured;
 This in turn gives an estimation of the core temperature. Brown, et al. 1998, ApJL, 504, L95

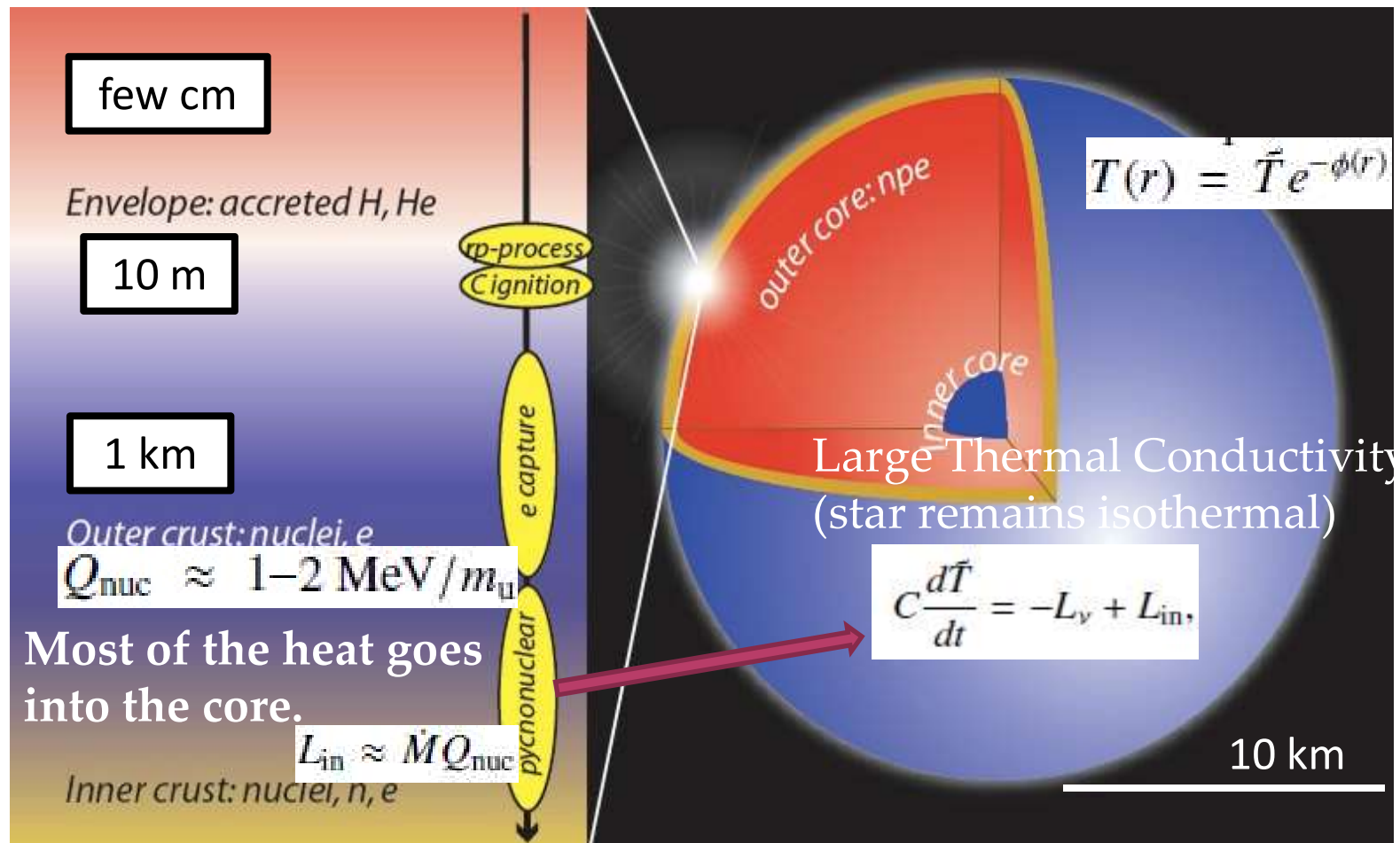


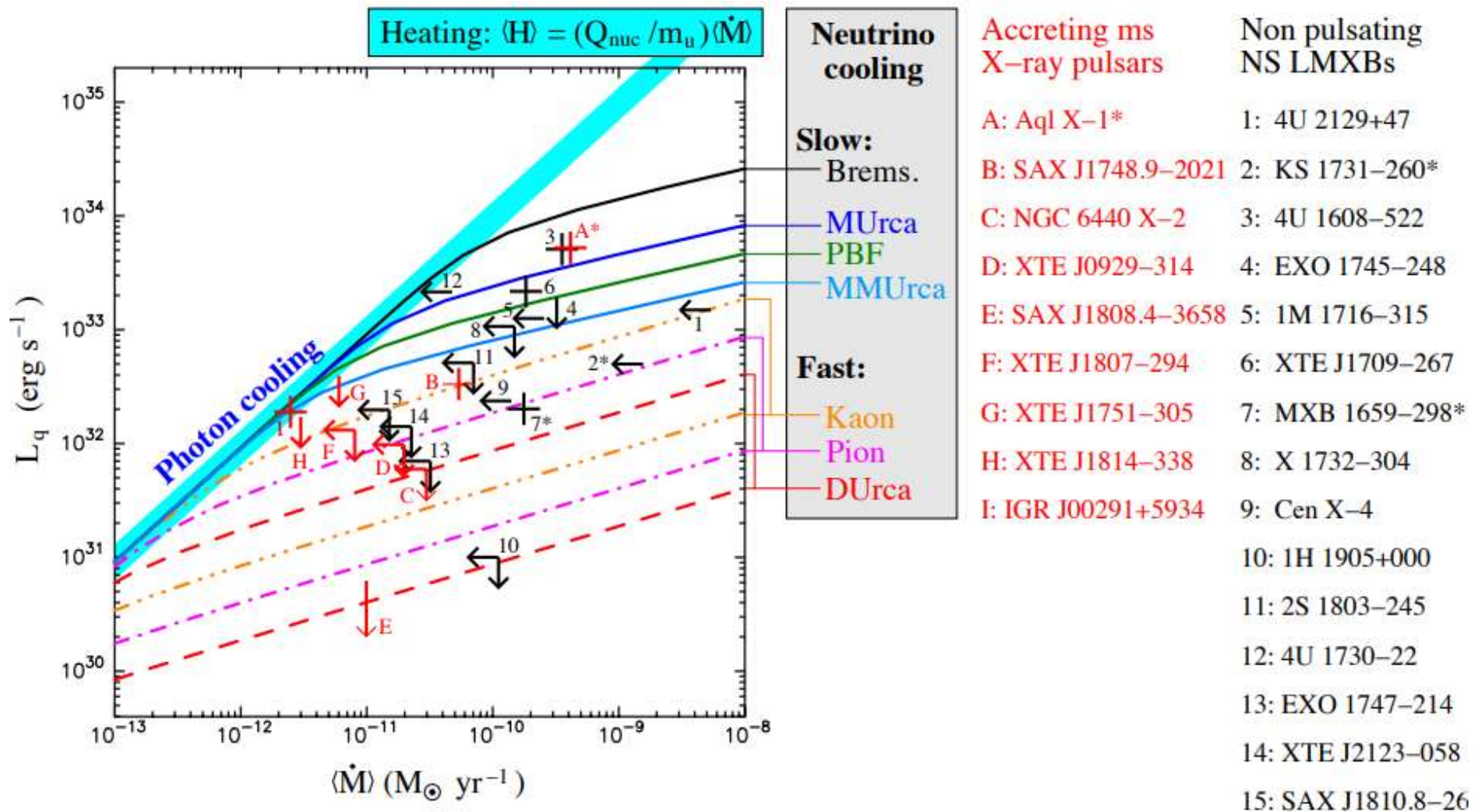
Image Credit: E. F. Brown

Quiescent Luminosities

The observed quiescent luminosity will depend on the time-averaged accretion rate and the neutrino emission processes active in the core.

The L_q versus $\langle \dot{M} \rangle$ for a sample of transient NS LMXBs as well as several cooling scenarios

Wijnands et al. 2017, Journal of Astrophysics and Astronomy 38, 49



Main neutrino processes

(I) Baryon direct Urca	$Q \sim (10^{23}-10^{27}) T_9^6 \text{ erg cm}^{-3} \text{ s}^{-1}$	
(1) $n \rightarrow pl\bar{\nu}_l$ $pl \rightarrow n\nu_l$	(2) $\Lambda \rightarrow pl\bar{\nu}_l$ $pl \rightarrow \Lambda\nu_l$	
(3) $\Sigma \rightarrow nl\bar{\nu}_l$ $nl \rightarrow \Sigma\nu_l$	(4) $\Sigma \rightarrow \Lambda l\bar{\nu}_l$ $\Lambda l \rightarrow \Sigma\nu_l$	
(II) Baryon modified Urca	$Q \sim (10^{18}-10^{21}) T_9^8 \text{ erg cm}^{-3} \text{ s}^{-1}$	
(1) $nB \rightarrow pBl\bar{\nu}_l$ $pBl \rightarrow nB\nu_l$	(2) $\Lambda B \rightarrow pBl\bar{\nu}_l$ $pBl \rightarrow \Lambda B\nu_l$	
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(III) Baryon bremsstrahlung	$Q \sim (10^{16}-10^{20}) T_9^8 \text{ erg cm}^{-3} \text{ s}^{-1}$	
(1) $nn \rightarrow nn\nu\bar{\nu}$	(2) $np \rightarrow np\nu\bar{\nu}$	(3) $pp \rightarrow pp\nu\bar{\nu}$
(4) $\Sigma\Sigma \rightarrow \Sigma\Sigma\nu\bar{\nu}$	(5) $\Sigma n \rightarrow \Sigma n\nu\bar{\nu}$	(6) $\Sigma p \rightarrow \Sigma p\nu\bar{\nu}$
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(IV) Lepton modified Urca	$Q \sim (10^{13}-10^{15}) T_9^8 \text{ erg cm}^{-3} \text{ s}^{-1}$	
(1) $\mu p \rightarrow ep\bar{\nu}_e\nu_\mu$ $ep \rightarrow \mu p\bar{\nu}_\mu\nu_e$	(2) $\mu\Sigma \rightarrow e\Sigma\bar{\nu}_e\nu_\mu$ $e\Sigma \rightarrow \mu\Sigma\bar{\nu}_\mu\nu_e$	
(3) $\mu e \rightarrow ee\bar{\nu}_e\nu_\mu$ $ee \rightarrow \mu e\bar{\nu}_\mu\nu_e$	(4) $\mu\mu \rightarrow e\mu\bar{\nu}_e\nu_\mu$ $e\mu \rightarrow \mu\mu\bar{\nu}_\mu\nu_e$	
(V) Coulomb bremsstrahlung	$Q \sim (10^{13}-10^{15}) T_9^8 \text{ erg cm}^{-3} \text{ s}^{-1}$	
(1) $lp \rightarrow lp\nu\bar{\nu}$	(2) $l\Sigma \rightarrow l\Sigma\nu\bar{\nu}$	(3) $ll \rightarrow ll\nu\bar{\nu}$

*) Σ means Σ^- ; l stands for e or μ ; B stands for n , p , Σ or Λ .

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Direct Urca cooling in npe μ matter

History: Gamow and Schoenberg (1941), Casino da Urca, Rio de Janeiro (closed in 1955) – rapid disappearance of thermal energy from the interior of a star = rapid disappearance of money from the pockets of the gamblers.

If *Physical Review* ever asked, an explanation was ready: **U**n**R**ecordable **C**ooling **A**gent = URCA – it was never asked.

Nucleons at the top of the Fermi sea beta decay:



Beta equilibrium guarantees energy conservation: $\mu_n - \mu_p = \mu_e$
 Momentum conservation is also required: $|\mathbf{k}_{Fn}| \leq |\mathbf{k}_{Fp}| + |\mathbf{k}_{Fe}|$
 Total luminosity is found by evaluating:

$$L_{\nu_{dUrca}}^{\infty} = \int_0^{R_{\text{core}}} \frac{4\pi r^2 \epsilon_0^{\text{dUrca, total}} e^{2\phi(r)}}{(1 - 2Gm(r)/c^2 r)^{1/2}} dr,$$

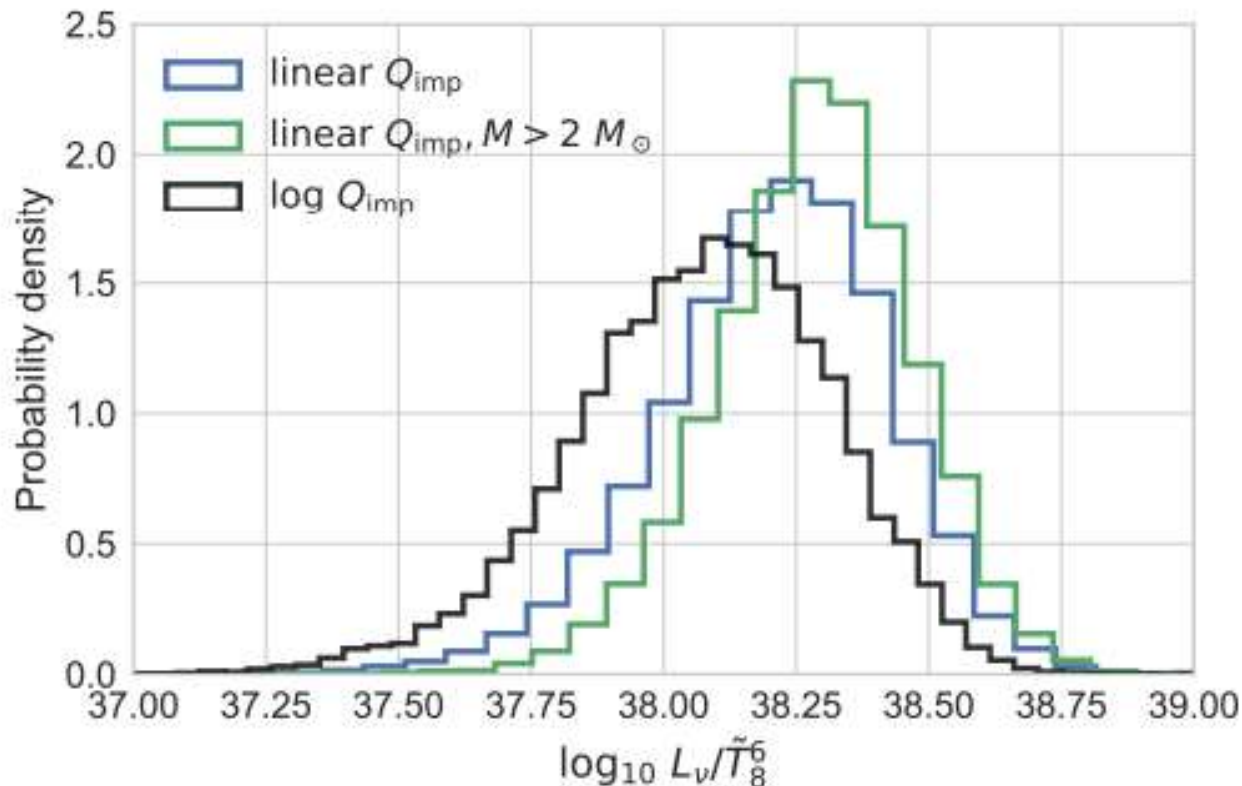
where

$$\begin{aligned} \epsilon_0^{\text{dUrca, total}} &= \epsilon_0^{\text{dUrca, } e^-} + \epsilon_0^{\text{dUrca, } \mu^-} & \epsilon_0^{\text{dUrca, } \mu^-} &= \epsilon_0^{\text{dUrca, } e^-} \Theta_{np\mu} \\ \epsilon_0^{\text{dUrca, } e^-} &= \frac{457\pi}{10080} G_F^2 \cos^2 \theta_C (1 + 3g_A^2) \frac{m_n^* m_p^* m_e}{h^{10} c^3} (k_B T)^6 \Theta_{npe} \end{aligned}$$

The case of MXB 1659-29

E. F. Brown et al. PRL 2018, 120 (18), 182701

Physics See Viewpoint: A Rapidly Cooling Neutron Star



Observations of the thermal relaxation of the neutron star crust following 2.5 years of accretion allowed to measure the energy deposited into the core during accretion, which is then reradiated as neutrinos.

Posterior distribution of the neutrino cooling prefactor from the MCMC fits to the MXB 1659-29 cooling curve.

Conclusion: If the NS-matter is normal, then Direct Urca reactions occur in $\sim 1\%$ of the neutron star core.

The effects of superfluidity and superconductivity

Local neutrino emissivity is exponentially reduced by a reduction factor:

$$\epsilon^{dUrca} = \epsilon_0^{dUrca} R$$

For example, for a neutron triplet:

$$R_L = \left[0.2546 + \sqrt{(0.7454)^2 + (0.1284 v_T)^2} \right]^5 \exp \left(2.701 - \sqrt{(2.701)^2 + v_T^2} \right)$$

$$v_T = \sqrt{1 - \tau} \left(0.7893 + \frac{1.188}{\tau} \right)$$

$$\tau = T/T_c$$

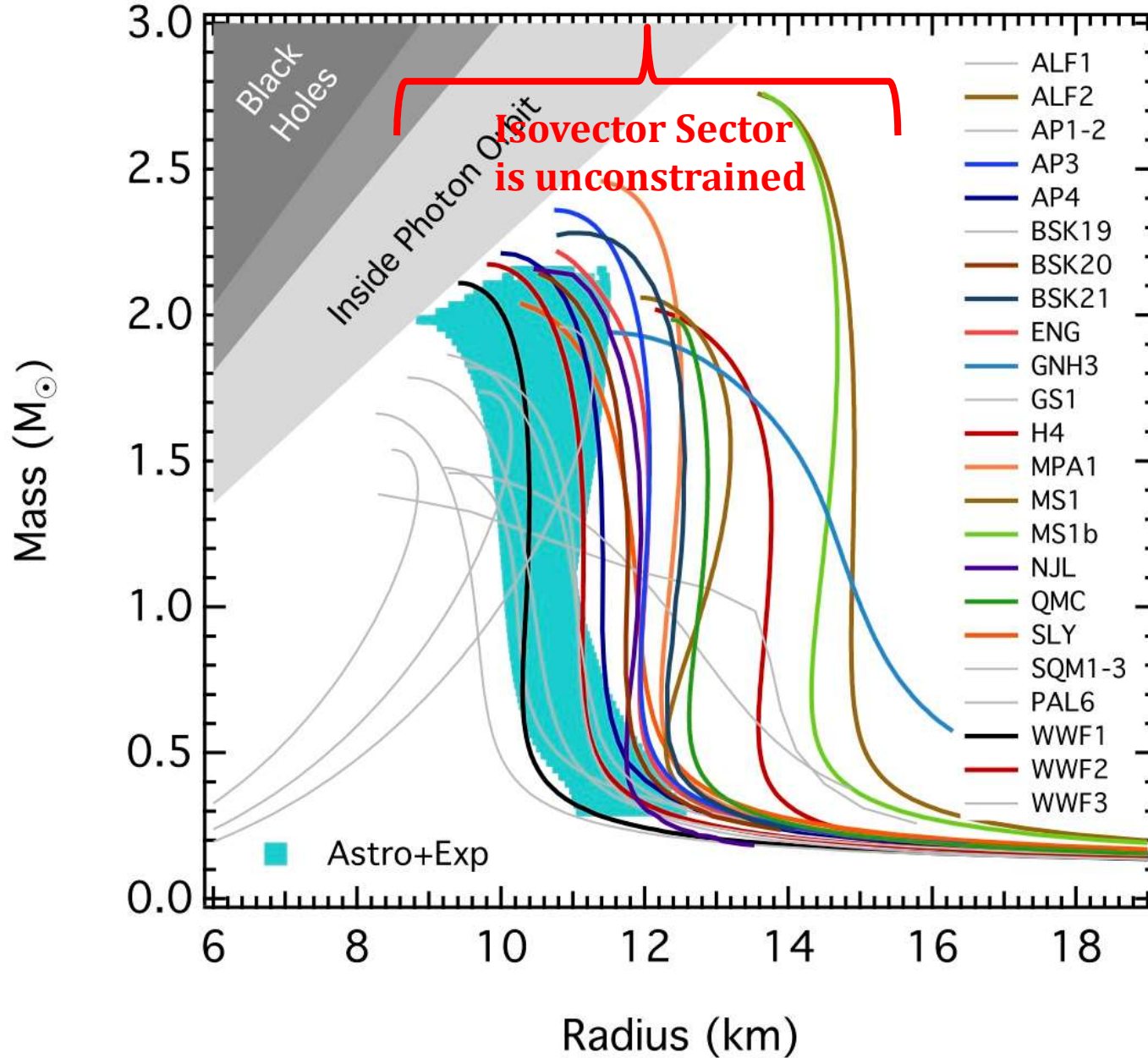
If proton singlet and neutron triplet are simultaneously present then:

$$R_L \sim \min (R_{L \text{ singlet}}, R_{L \text{ triplet}})$$

See, e.g., D. G. Yakovlev et al. 2001, Phys. Rep., 354, 1

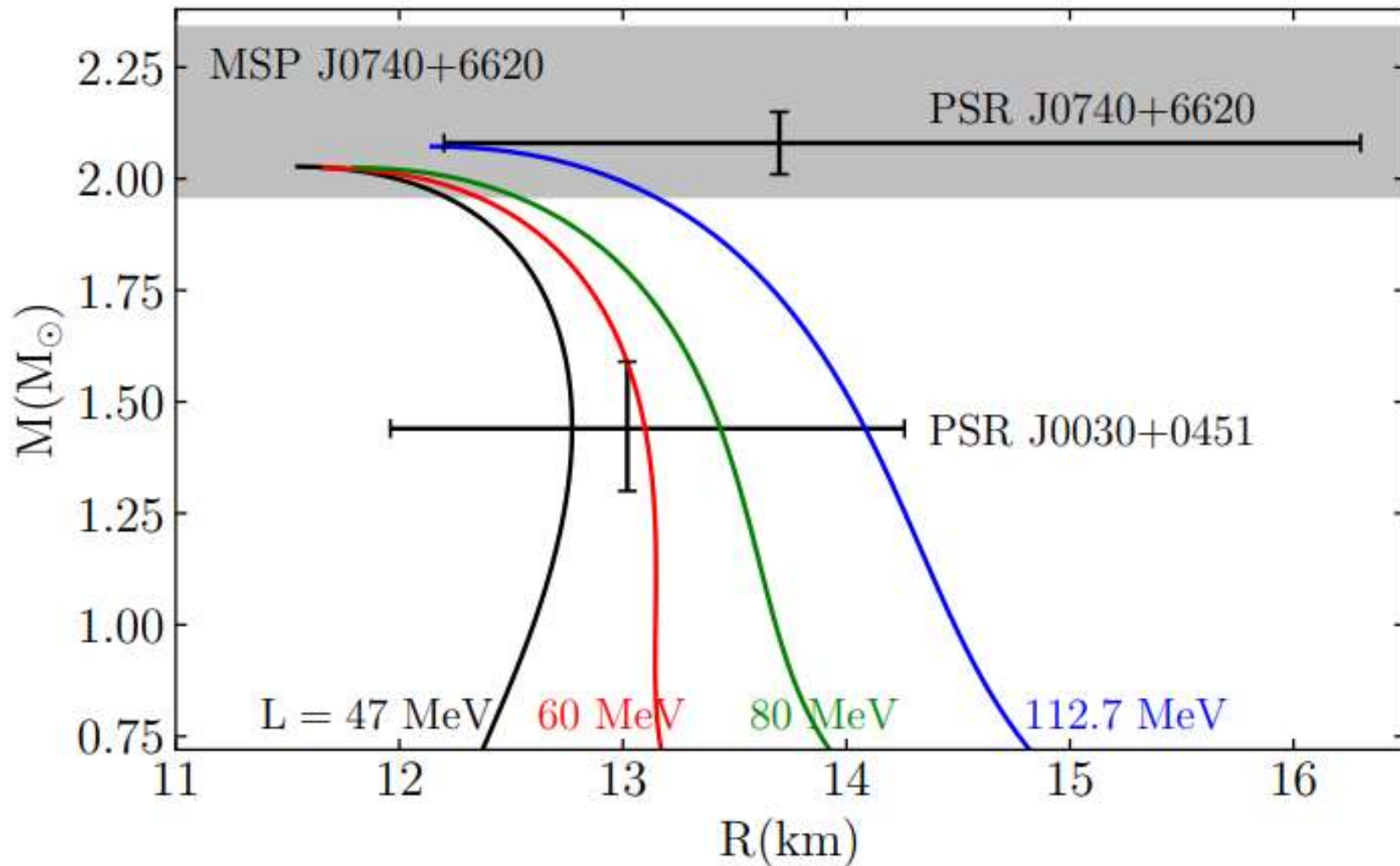
Uncertainties in the neutron-star EOS

F. Ozel, <http://xtreme.as.arizona.edu/NeutronStars/index.php/neutron-star-radii/>



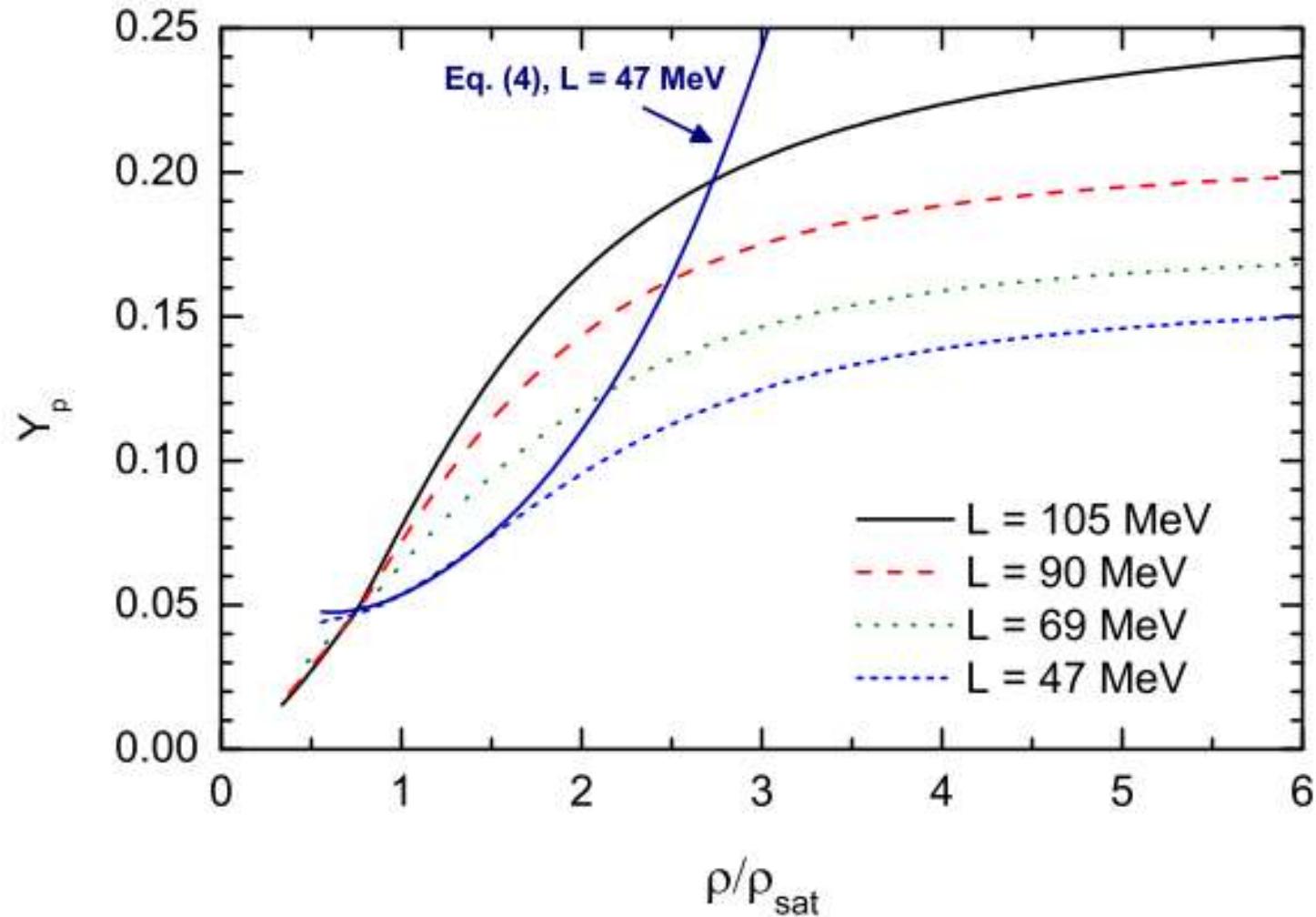
NS EOS: FSUGold2 Family

The largest uncertainty is the density slope of the symmetry energy: L



Proton Fractions

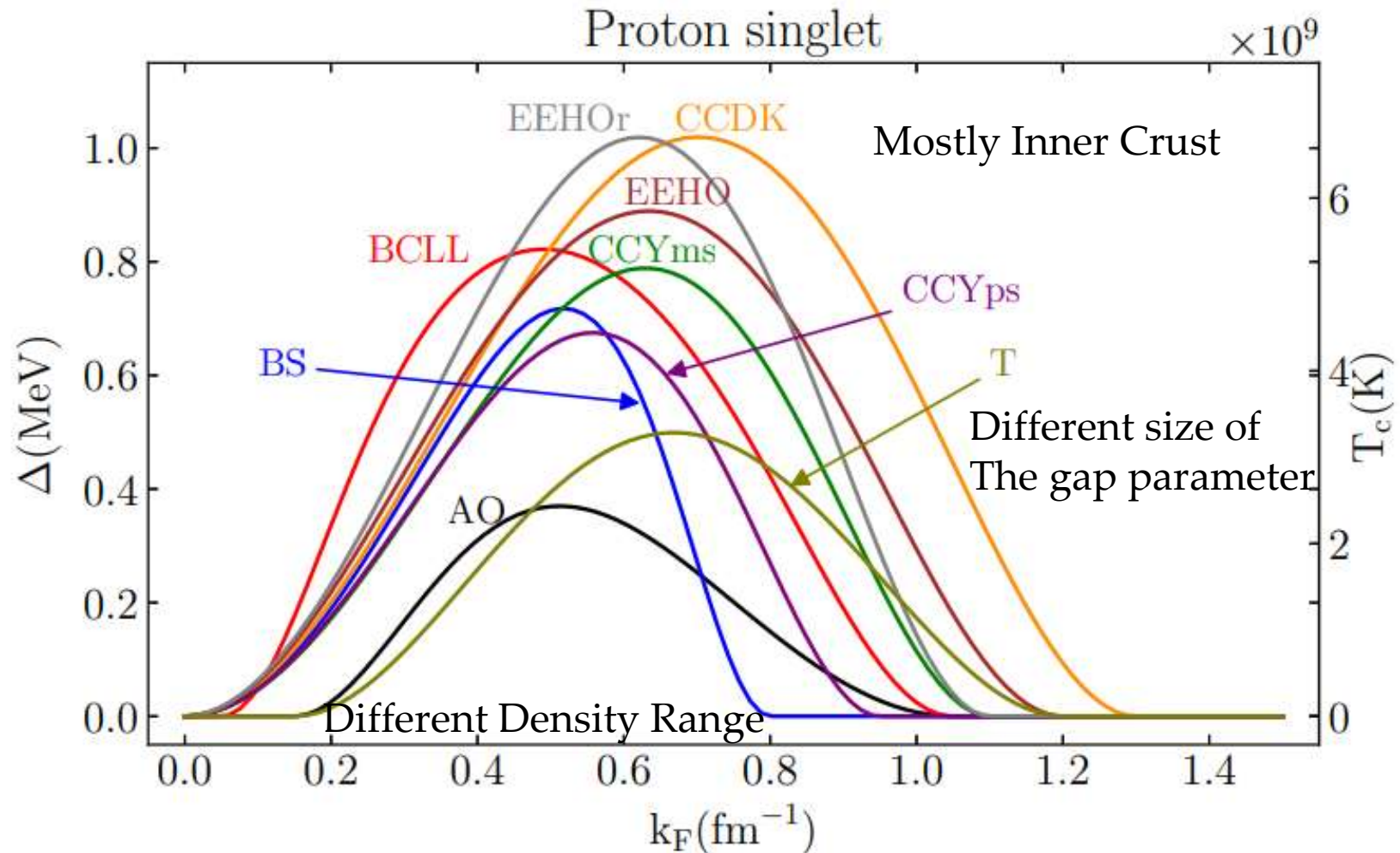
Proton fractions are highly sensitive to the density slope.



Mendes et al. 2021, XVI Marcel Grossmann Meeting, arXiv:2110.11077

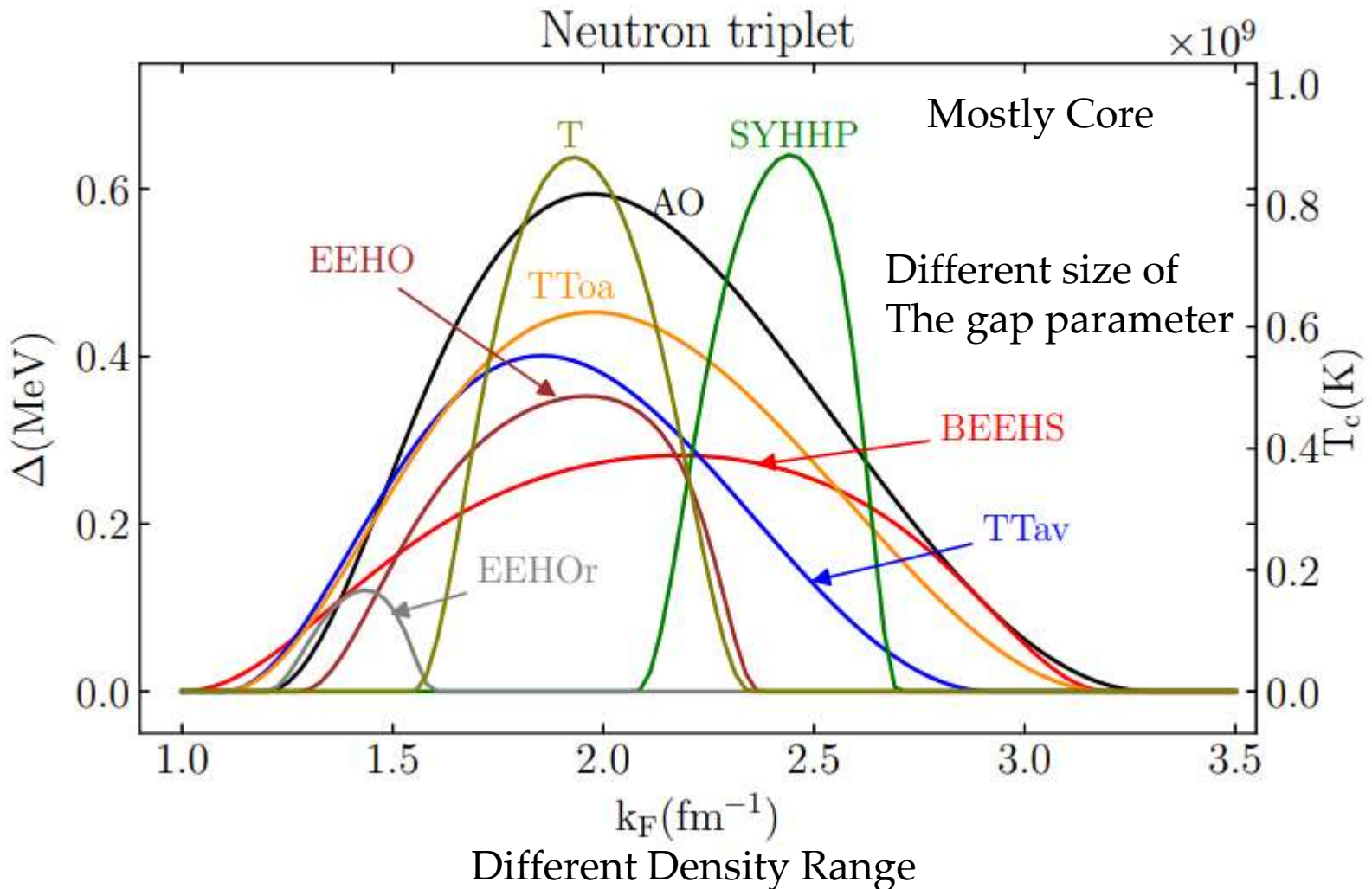
Gap Models

We explore a range of different superfluid gap models. For easy integration, we use the analytic fits of Ho et al. (2015) (See W. C. G. Ho et al. 2015, Phys. Rev. C: Nucl. Phys., 91, 015806 and References therein)



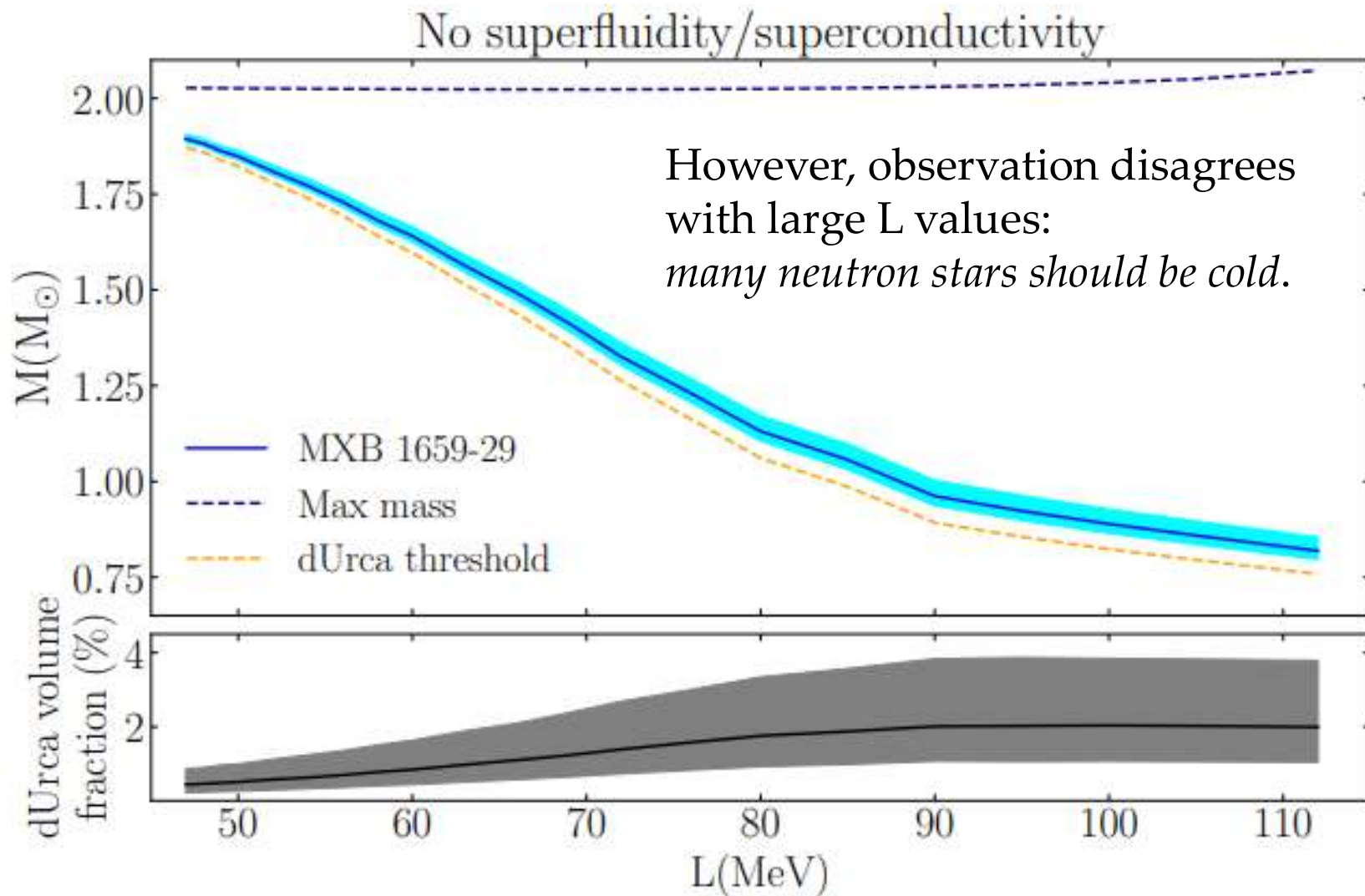
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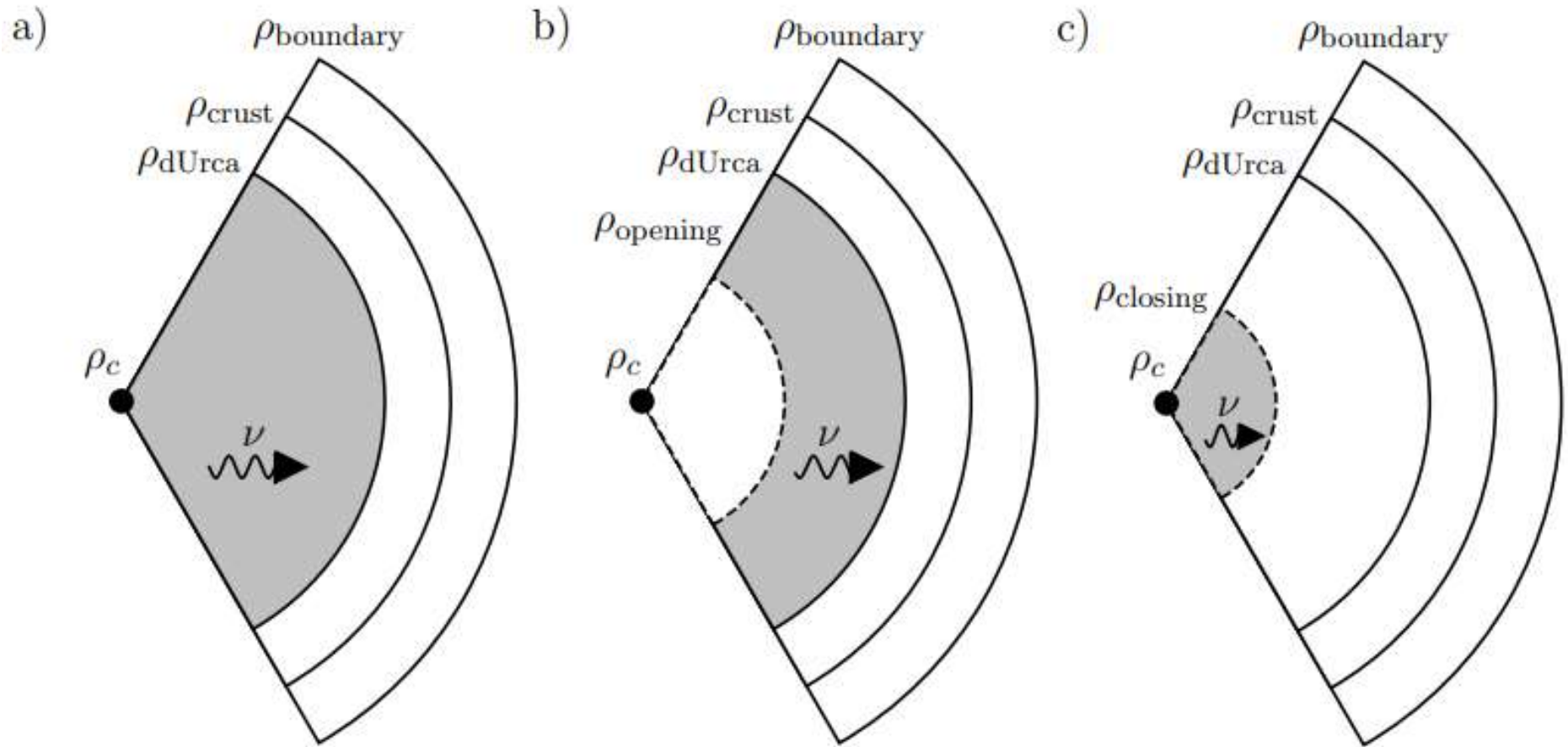


MXB 1659-21: models with no pairing

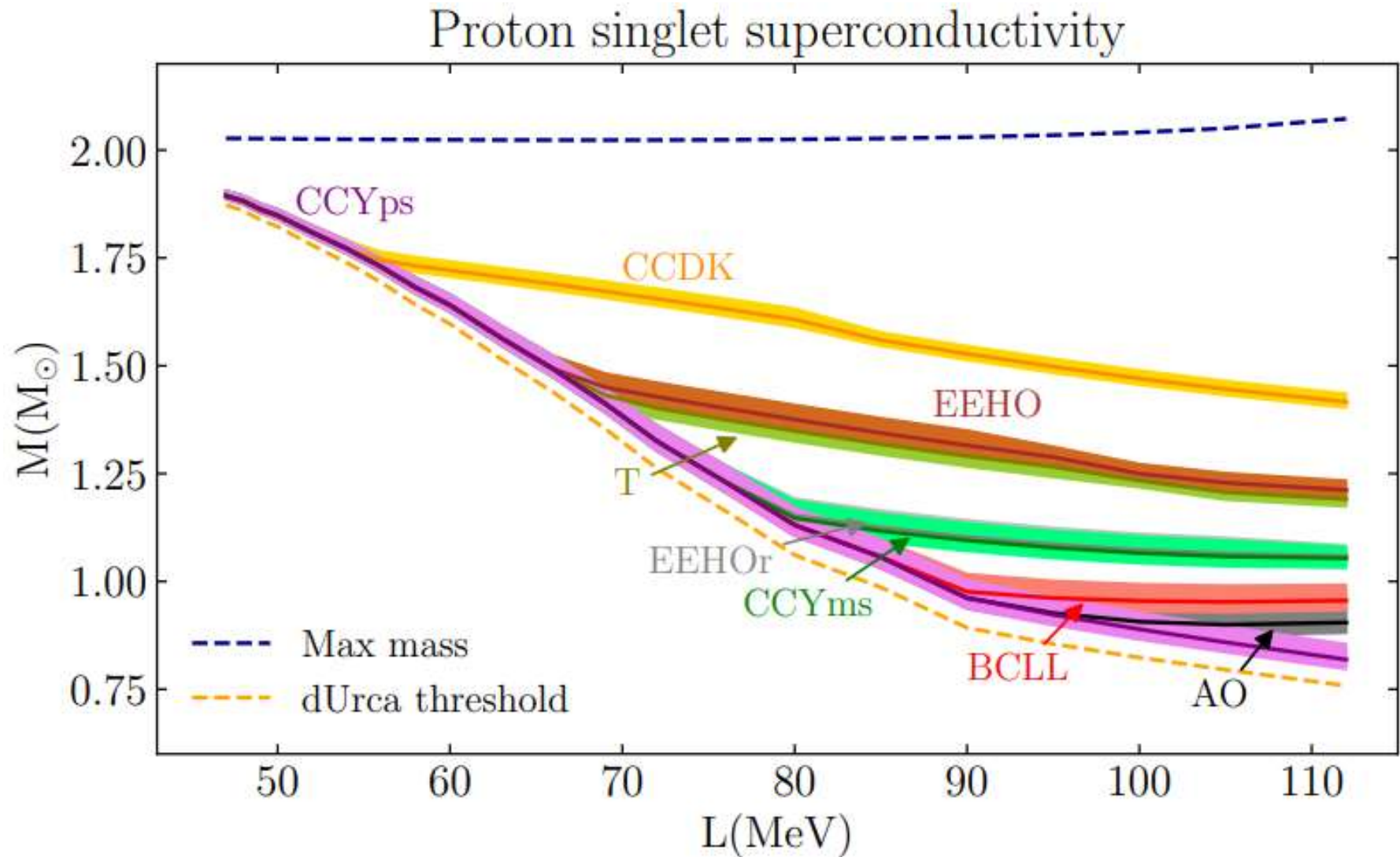
The required luminosity is achieved within a short density gradient in the core where Direct Urca is active.



Schematic effects of superfluidity and superconductivity

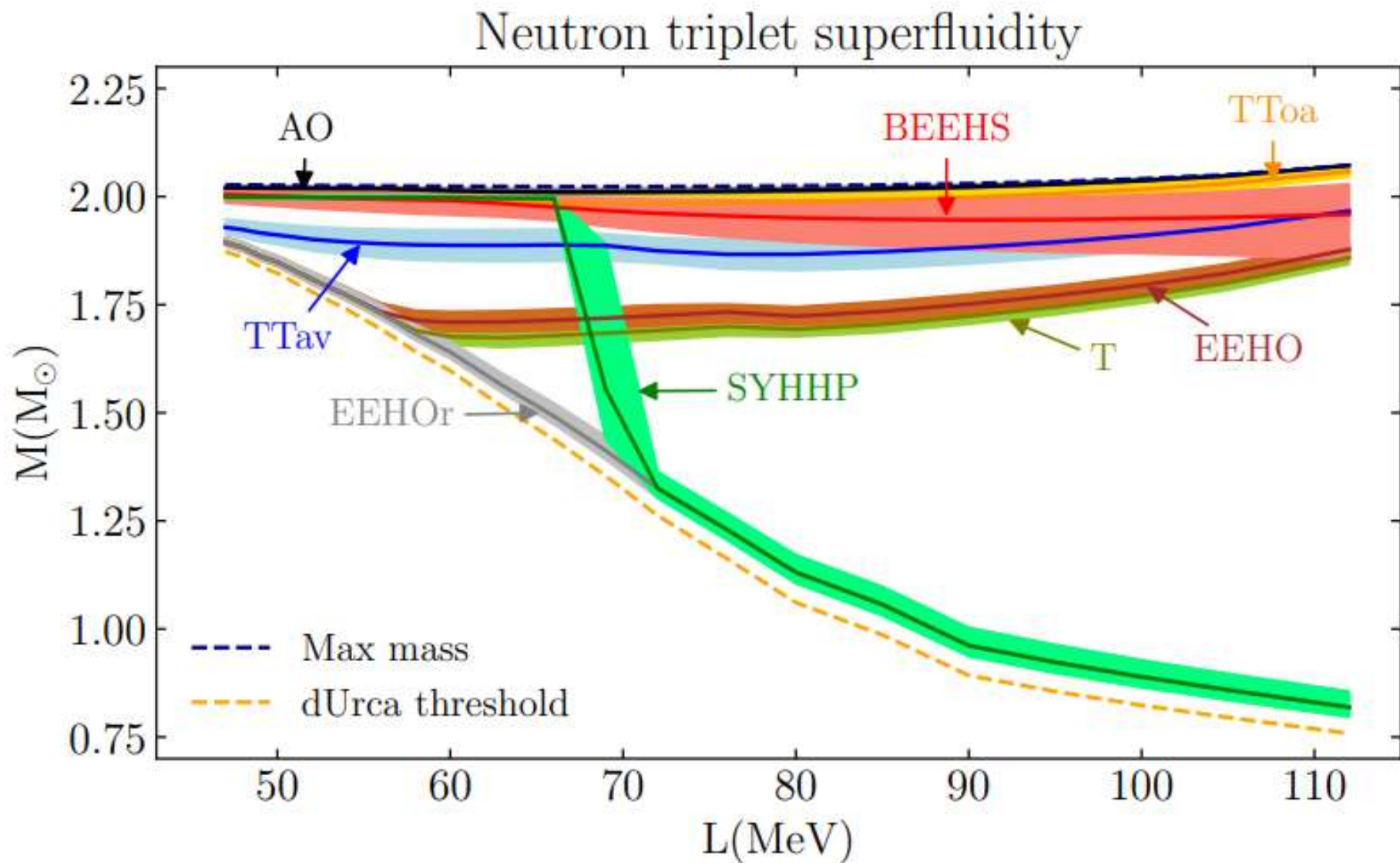


Effects of proton superconductivity



Solution exist for all gap models.

Effects of neutron superfluidity

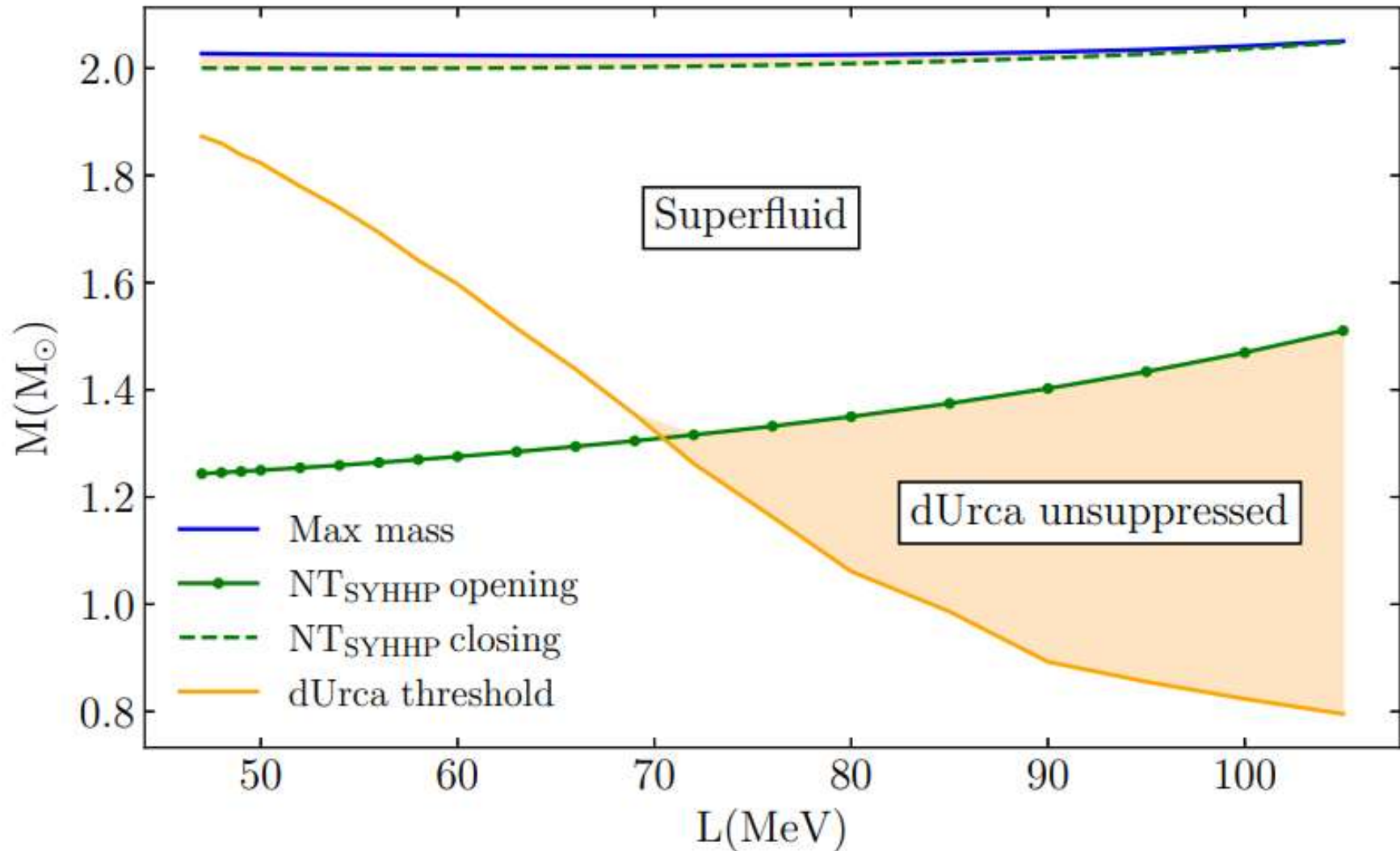


Solution exist for all gap models, except for **gap model NT AO (large amplitude)** and **$L > 110 \text{ MeV}$** .

The case of a NT SYHHP model

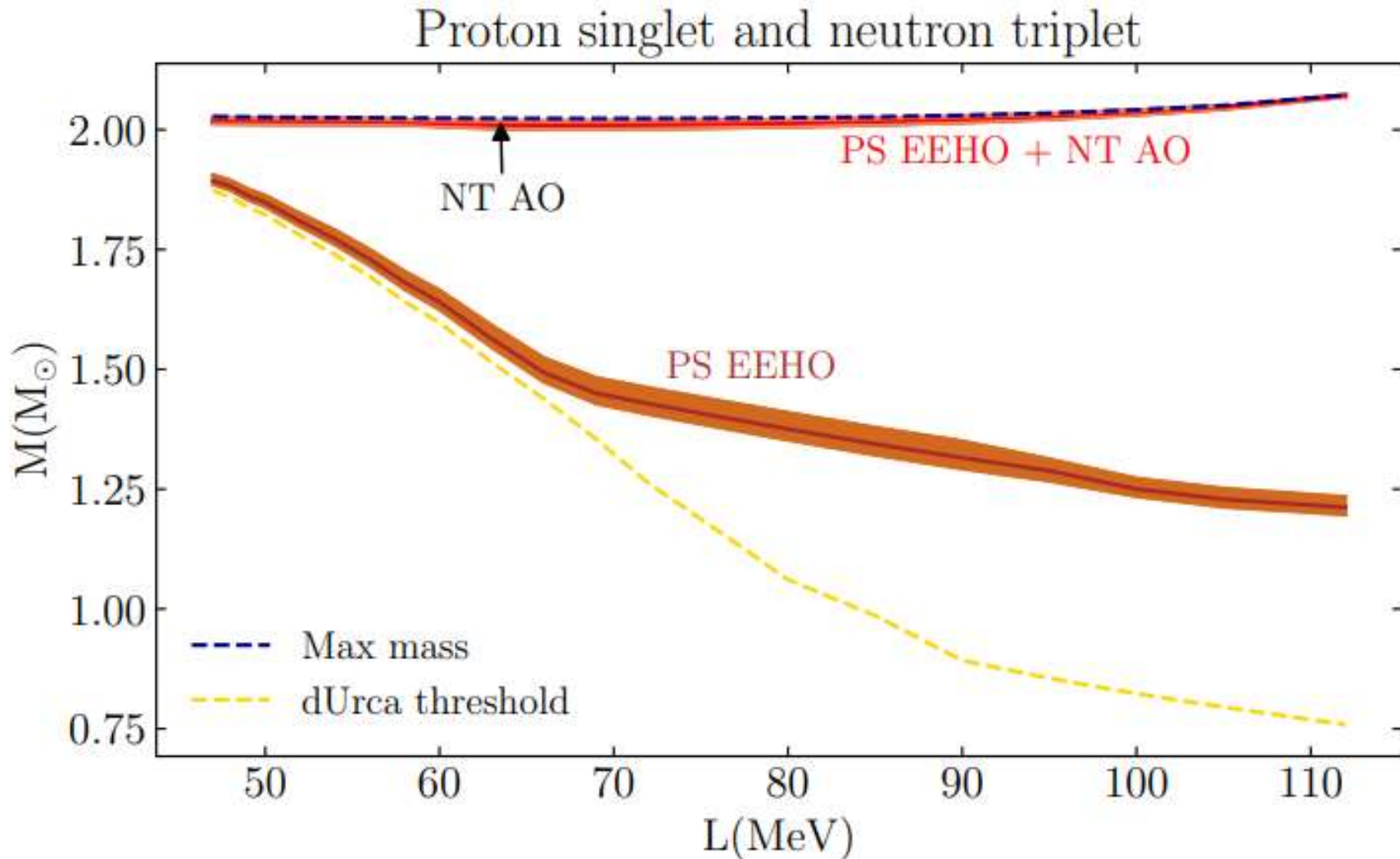
A phenomenological model developed to fit the observed cooling of Cas A

P. S. Shternin et al.2011, MNRAS Letters, 412, L108



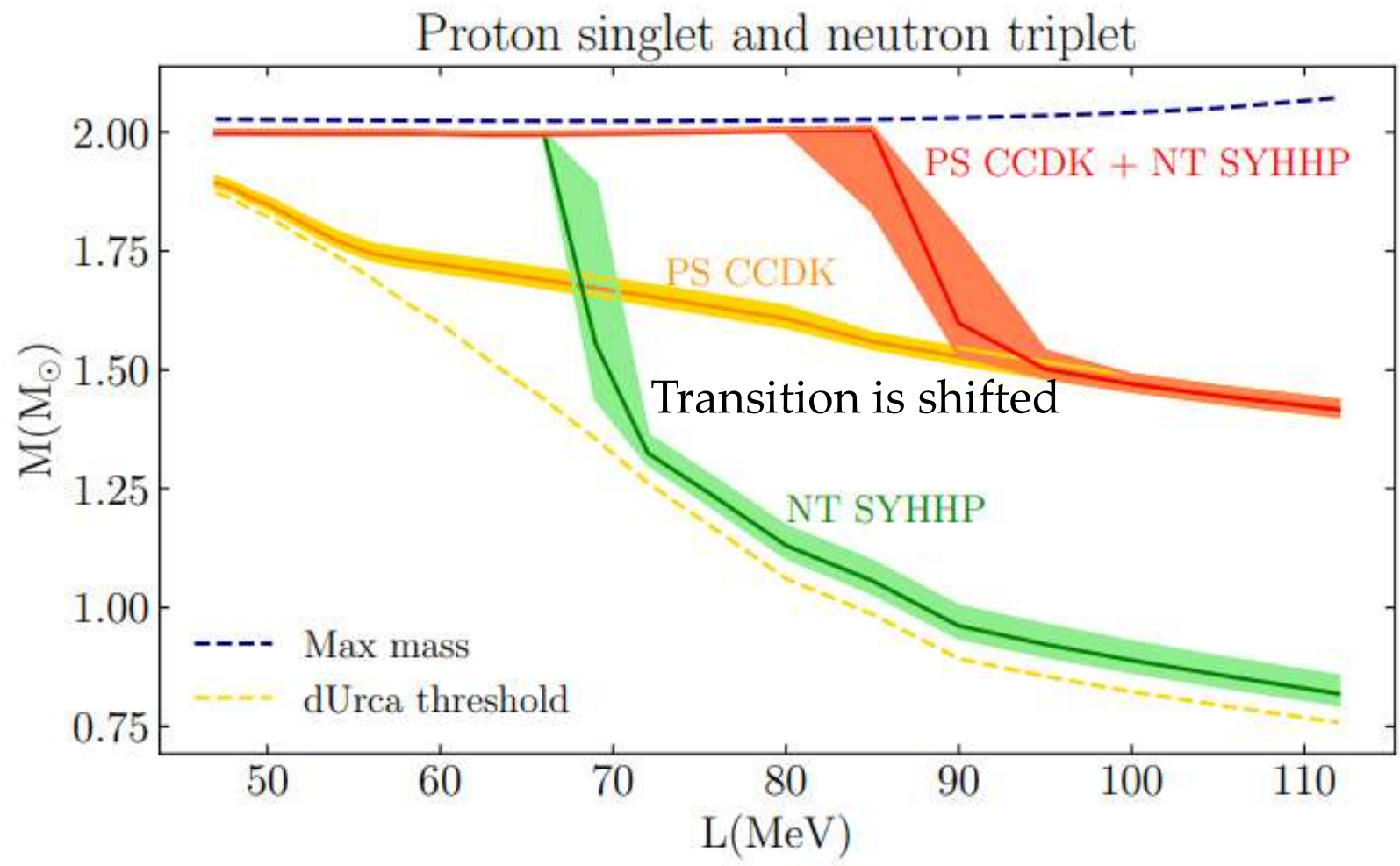
Combined PS + NT

For most combinations of the NT and PS pairings, the neutron superfluid suppression dominates and the effect of proton superconductivity is negligible. (same conclusion reached by S. Han & A. W. Steiner, 2017, PRC, 96, 035802)



Combined PS + NT

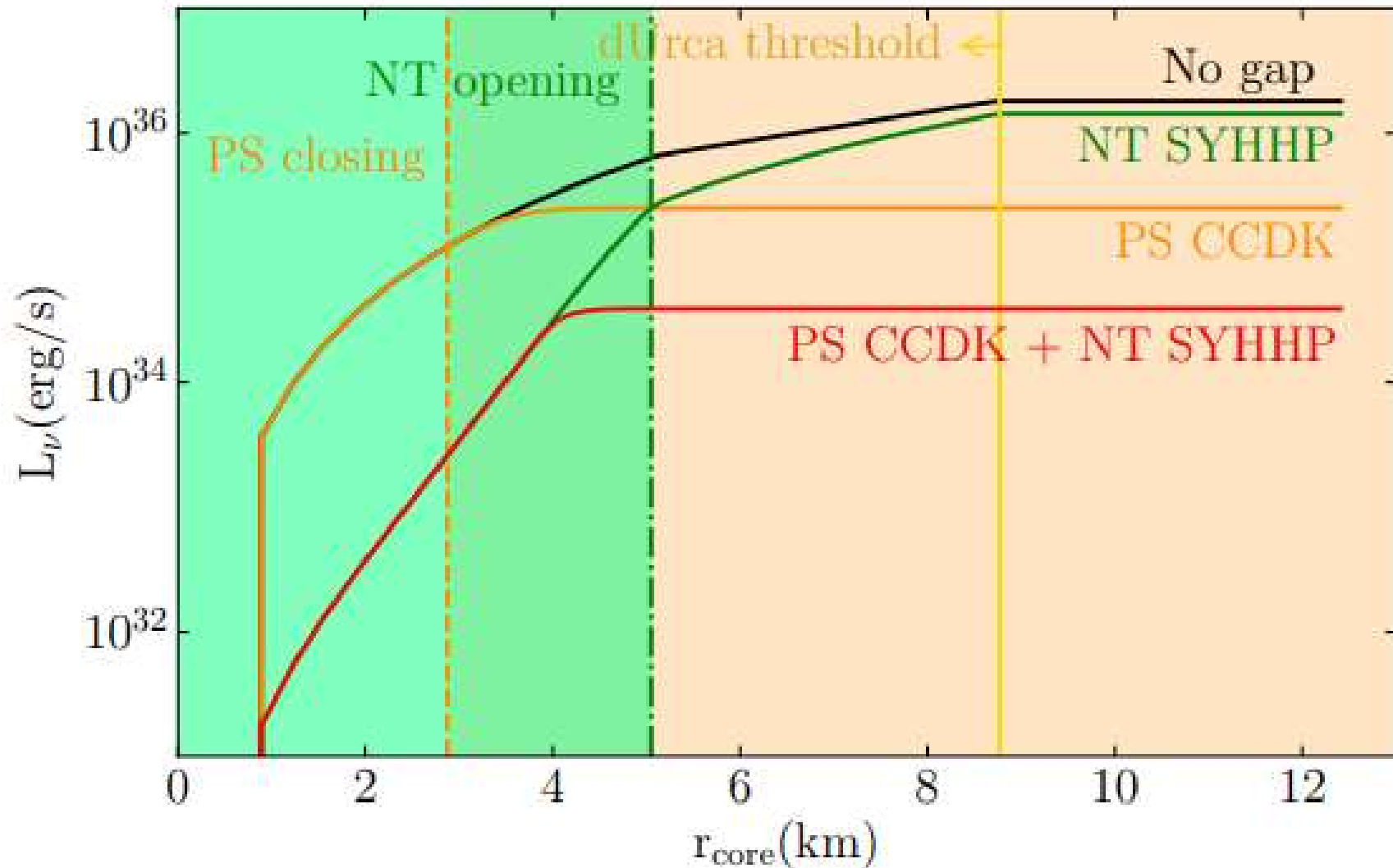
In some cases, PS pairing affects the outcome.



Combined PS + NT

An example: A 1.60 solar mass neutron stars cumulative luminosity profile.

Cumulative neutrino luminosity - $L=90$ MeV



Neutron stars as calorimeters: Heat Capacity

The neutron star's total heat capacity is

$$C = \int_0^R \frac{4\pi r^2 \sum_i c_i dr}{\sqrt{1 - 2GM(r)/(c^2 r)}} .$$

Here the “i” specie can be fermions as well as ions in the crust.

$$C_f = \frac{k_B^2 T}{3\hbar^3 c} p_f^F \sqrt{(m_f^* c)^2 + (p_f^F)^2} \quad m_{\pi}^* = m - g_s \phi$$

$$C_{\text{ion}} = \begin{cases} \frac{3}{2} n_i k_B & \text{if } \Gamma \leq 1 \quad (\text{Gas Phase}) \\ \frac{3}{2} n_i k_B - n_i k_B \Gamma^2 \frac{\partial}{\partial \Gamma} \left(\frac{1}{\Gamma} \frac{U}{n_i k_B T} \right) & \text{if } 1 < \Gamma \leq 178 \quad (\text{Liquid Phase}) \\ 3 n_i k_B f_D(T/\theta_D) & \text{if } \Gamma > 178 \quad (\text{Solid Phase}) \end{cases}$$

The lower limit on the heat capacity

A. Cumming et al. 2017, PRC 95, 025806

Combining the observed core T with the energy release during the outburst it was found that:

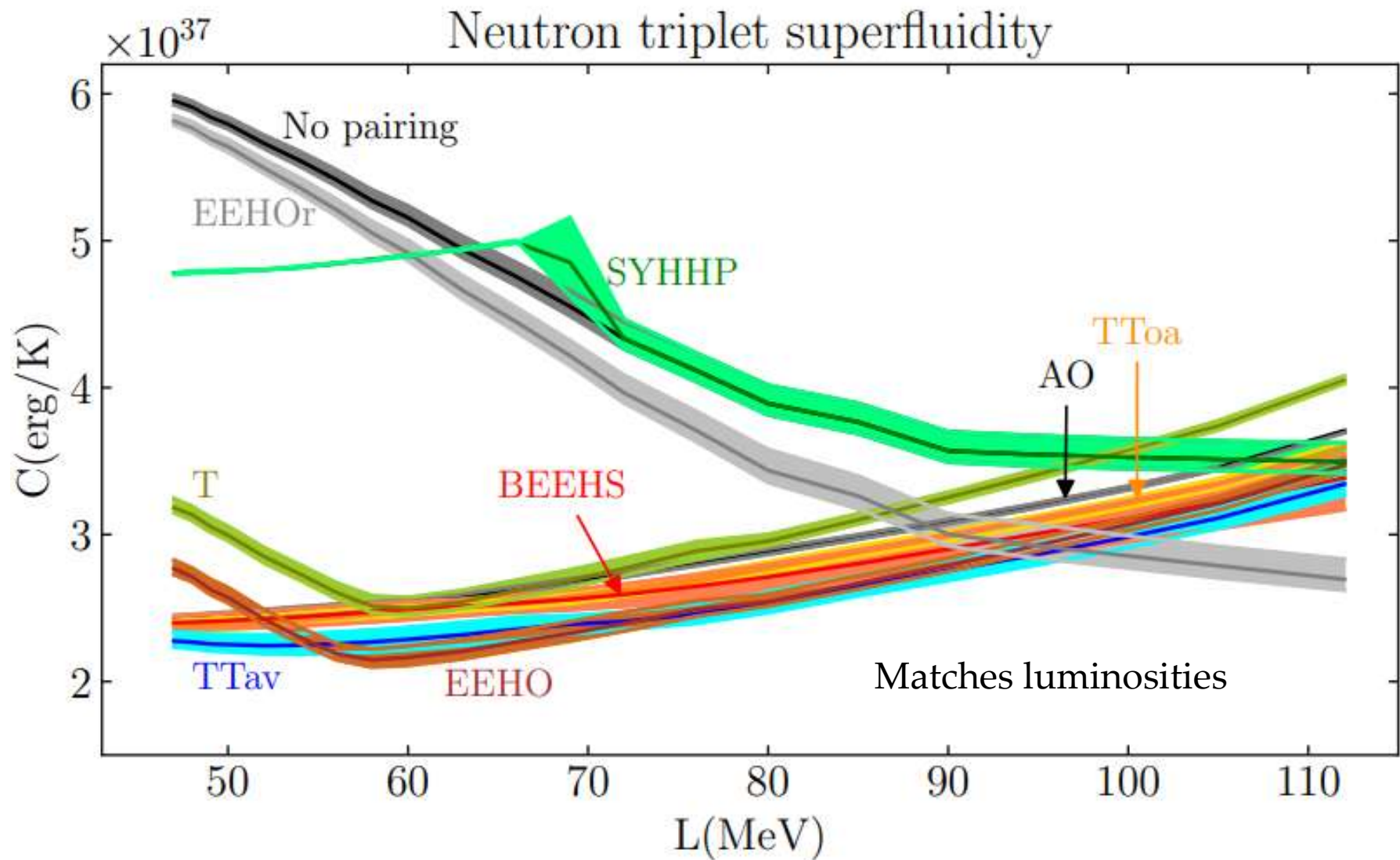
Source	\dot{M} [10^{18} g s^{-1}]	t_0 [yr]	E_{43}	T_{eff}^{∞} [eV]	\tilde{T}_8	Envelope composition	C [$\tilde{T}_8 10^{36} \text{ erg K}^{-1}$]
KS 1731-260	0.1	12	7.2	63.1	0.7	Fe	2.9
MXB 1659-29	0.1	2.5	1.5	55	0.25	He	4.8
XTE J1701-462	1	1.6	9.6	121.9	0.92	He	2.2

The lower limits to the core heat capacity for the sources KS 1731-260, MXB 1659-29, and XTE J1701-462 were found, which was a factor a 2–3 below the heat capacity expected from electrons.

The most constraining one was from MXB 1659-29.

This rules out a core dominated by the CFL phase.

The heat capacity of MXB 1659-29



Temperature variation and heat capacity

When the core is isothermal, a neutron star in quiescence has

$$C \frac{d\tilde{T}}{dt} = -L_\gamma(\tilde{T}) - L_\nu(\tilde{T}),$$

neglecting $L_\gamma(\tilde{T})$ and knowing $C \propto \tilde{T}$ and $L_\nu(\tilde{T}) \propto \tilde{T}^6$, for dUrca processes, it can be shown that

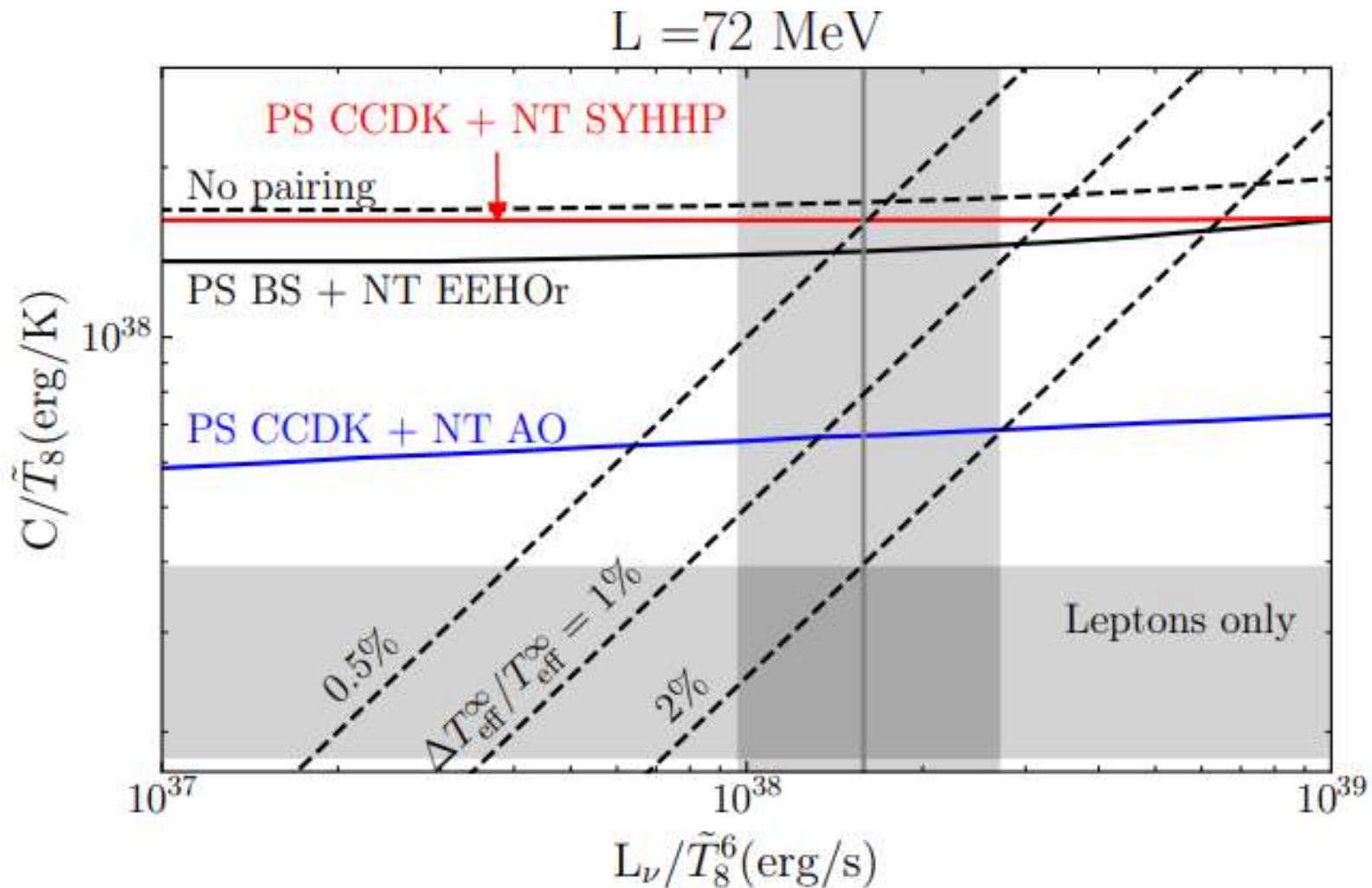
$$\left(\frac{\tilde{T}_i}{\tilde{T}_f} \right)^4 - 1 = 4 \frac{\Delta t L_\nu}{C \tilde{T}}.$$

for $\Delta t \ll C \tilde{T} / L_\nu$, we expand in first order to get

$$\frac{C_{38}}{L_{\nu,35}} = \left(\frac{\Delta \tilde{T} / \tilde{T}}{0.3\%} \right)^{-1} \left(\frac{t_q}{10 \text{ yr}} \right) \tilde{T}_8^{-1}$$

Temperature variation and heat capacity

Knowing this source's temperature to a better accuracy, we could better constraint its heat capacity (also see Brown et al. 2018)



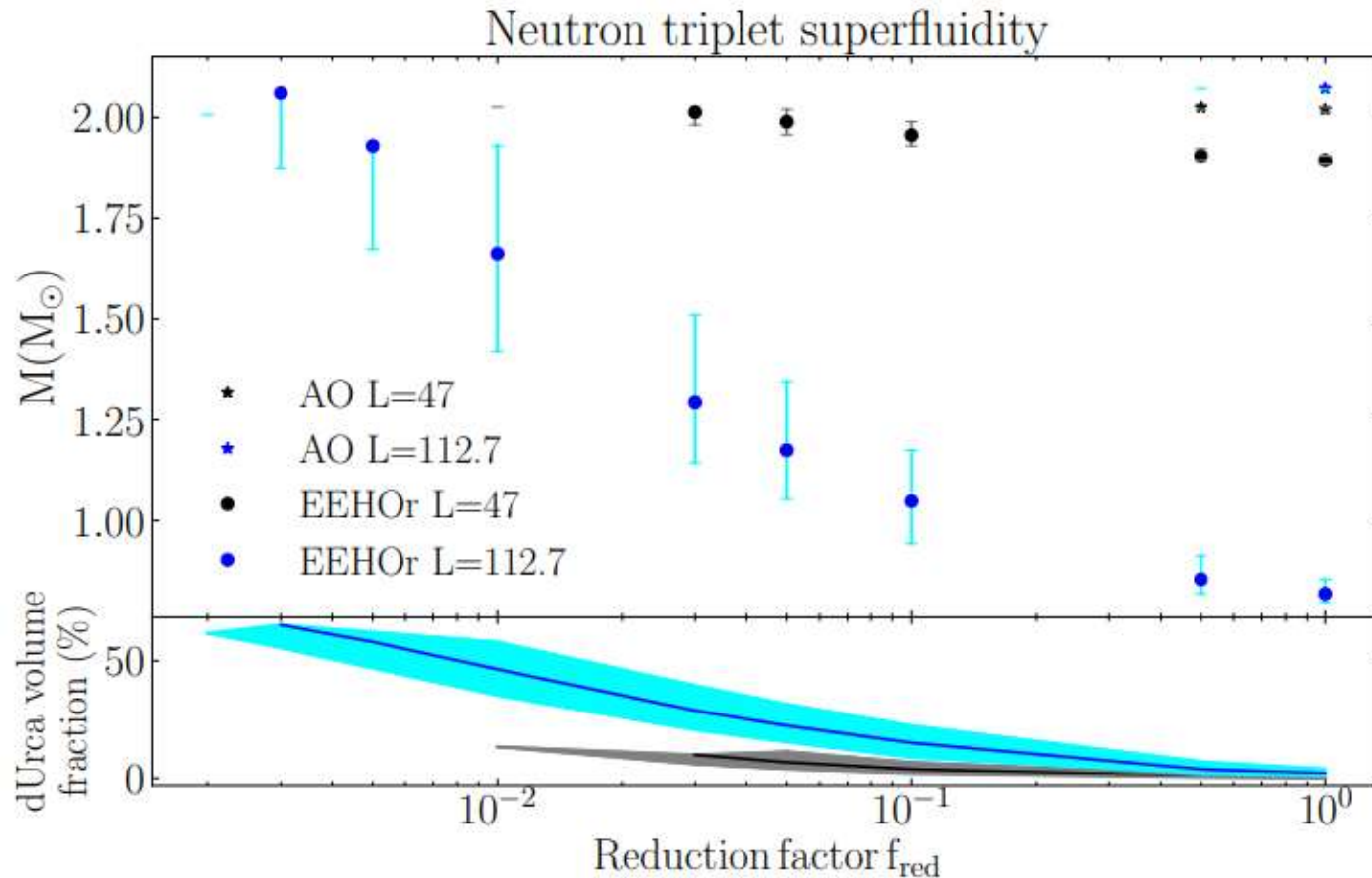
Modeling Uncertainties

1. Concern: Allowed range of neutron star masses is rather small <5%. For some specific EOS and gap model combinations, we can have up to 10% mass range. This creates a fine tuning problem.
2. Assumption: It is assumed that the average accretion rate over the last 30 years of observations of MXB 1659-29 are representative of the longer term average accretion rate. This assumption can be relaxed.
3. Distance uncertainties are not included in the marginalization.
4. Assumption: A fixed value of the core temperature of 2.5×10^7 K was used. For a given surface temperature, the inferred core temperature depends on the envelope model and assumed neutron star mass and radius. This may give a factor of 2-3 error.

Alternative fast emission processes

(work in progress led by Melissa Mendes)

The small emitting volume for dUrca provides motivation for considering a **less efficient fast process (but more than 0.001 of nucleonic Direct Urca)** that would result in a larger emission volume and therefore might give a more natural explanation for the observations of MXB 1659-29. A work is in progress (Melissa Mendes, Andrew Cumming, Charles Gales, Jan-Erik Christian, Jürgen Schaffner-Bielich.)



Some concluding remarks

1. Calculations of the neutron star total heat capacity, combined with its inferred neutrino luminosity show that a future measurement of surface temperature variation in a long time interval could help discriminate between core nuclear pairing models.
2. We have taken M and L as free parameters. Constraints on L can further constrain cooling models. For example, if $L > 80$ MeV, certain gap model combinations would be ruled out for MXB 1659-29, as we need the gap to close at higher density to delay the transition to Direct Urca.
3. The mass of MXB 1659-29 is currently unknown, but future X-ray spectroscopy of the accretion disk or spectral fitting of its thermal spectrum may provide a potential means to measure it with an uncertainty of about 5%, though these methods still have significant systematic uncertainties.

G. Ponti et al. 2018, MNRAS, 481, L94; F. Özel, & P. Freire 2016, Ann. Rev. A&A, 54, 401

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My Collaborators:

J. Piekarewicz, W.-C. Chen (FSU)

B.-A. Li, W. G. Newton (Texas A&M U-Commerce)

J. Carvajal (FIU)

B. T. Reed, **C. J. Horowitz**, A. Deibel (IU)

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C. Y. Tsang, M. B. Tsang, P. Danielewicz, W. G. Lynch, **E. F. Brown**, B. Schuetrumpf (NSCL/MSU)

S. Gandolfi, I. Sagert (Los Alamos)

M. Mendes, **A. Cumming**, **C. Gale** (McGill U.)

S. Reddy (UW)

D. Page (UNAM)

J. Xu (SINAP)

X.-H. Li (U. South China)

C. Xu (Nanjing U)

L.-W. Chen (Shanghai Jiao Tong U.)

W.-Z. Jiang (Southeast U.)

X.-T. He (Nanjing U. Aeronautics and Astronautics)

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Thank You!



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