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Thermal States of Transiently Accreting Neutron Stars in Quiescence

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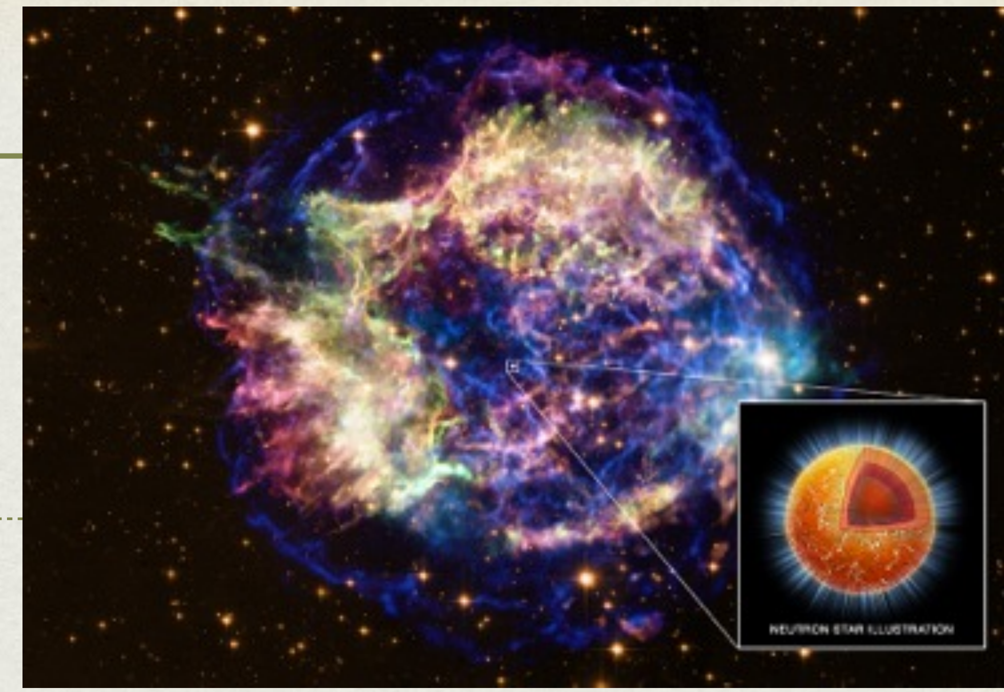
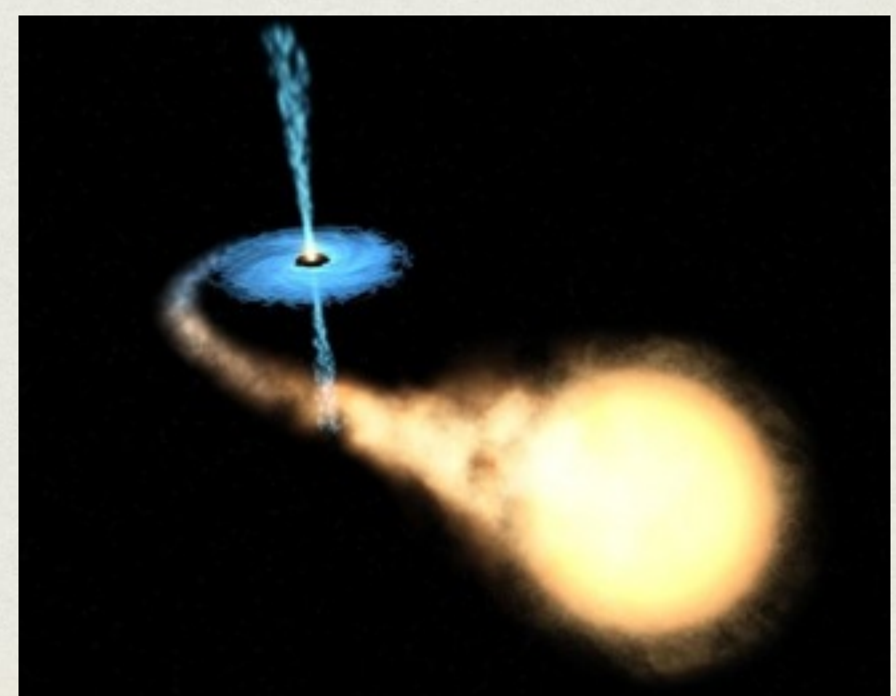
Dense matter in neutron stars

Properties	Observables
equations of state	mass, radius, moment of inertia...
thermal & transport properties, vortex pinning	cooling, spin-down, glitches, neutrinos, GW, magnetic field...





Thermal States of

-Cooling isolated neutron stars

-Transiently accreting neutron stars

Soft X-ray transients

A class of low-mass X-ray binaries (LMXBs)

-outburst state: weeks to months of high accretion; bright in X-rays & optical $L \sim 10^{36} - 10^{39} erg \cdot s^{-1}$

-quiescent state: decades or longer; very faint or even unobservable

$L < 10^{34} erg \cdot s^{-1}$

Eventually a thermal steady-state for the system is reached

-regulator: deep crustal heating; Brown, Bildsten & Rutledge (1998)

-heat per one accreted nucleon deposited in the crust ~1-2 MeV: Haensel & Zdunik (1990), Haensel & Zdunik (2003)

Global thermal balance

-X-ray luminosity in quiescence (after reaching a stationary state, heating = cooling) depends on the time-averaged accretion rate

$$L^{\infty}_{\rm dh}(\dot{M}) = L^{\infty}_{\gamma}(T_s) + L^{\infty}_{\nu}(T_i),\ T_s = T_s(T_i)$$

$$\dot{M} \equiv t_a \dot{M}_a/(t_a + t_q) \ll \dot{M}_a$$

$$L_{\rm dh} = Q \times \frac{\dot{M}}{m_{\rm N}} \approx 6.03 \times 10^{33} \left(\frac{\dot{M}}{10^{-10}\,{\rm M}_{\odot}\,{\rm yr}^{-1}} \right) \frac{Q}{\rm MeV}\ erg\ s^{-1}$$

-Exception: quasi-persistent X-ray transients e.g. KS 1731-260 with accretion period ~ years to decades instead of weeks to months

$\rightarrow$ during accretion stellar interiors are heated out of thermal equilibrium

significant late crust cooling observed after outburst

Heat-blanketing envelope

-NS interior assumed isothermal $T_i = T(r)e^{\Phi(r)} = T_b$

insulating envelope extends to the density

$$\rho_b \simeq 10^{10-11}\,\mathrm{g\,cm}^{-3}$$

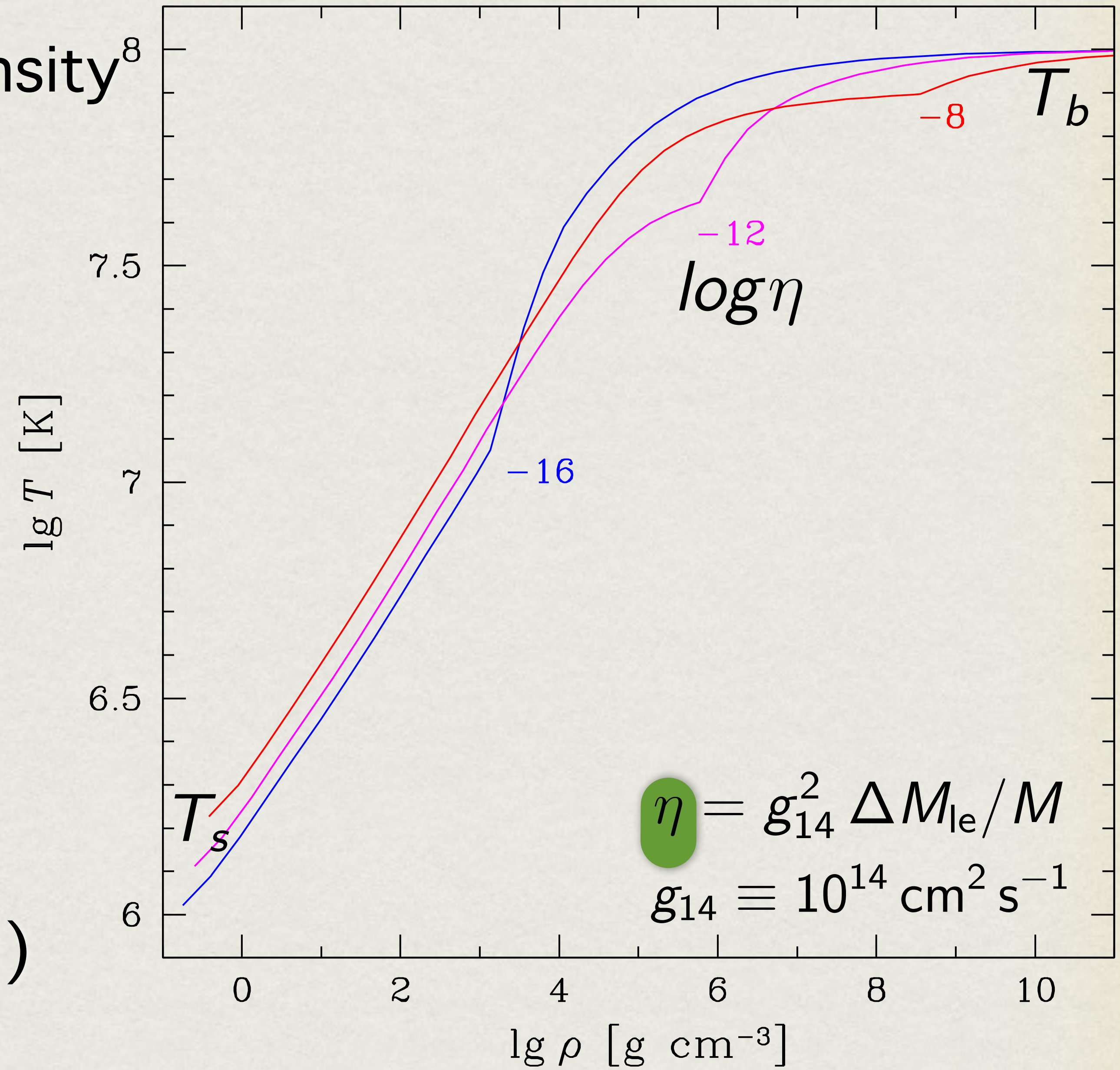
-temperature gradient near surface

$$T_s \simeq 10^6 K \times \left(\frac{T_b}{10^8 K}\right)^{0.5+\alpha}$$

-light-element (H/He) amount

thicker light-element layer $\Longleftrightarrow$ higher surface temperature and emitted flux

-this work: NSCool code (Page 2009) applying standard PCY envelope (Potekhin et al. 1997)



Yakovlev et al. (2004)

Simple approximation

$$L_{\rm dh}^{\infty}(\dot{M}) = L_{\gamma}^{\infty}(T_s) + L_{\nu}^{\infty}(T_i)$$

$L_{\rm dh}^{\infty} \propto \dot{M}$ $\qquad L_{\gamma}^{\infty} \propto (T_s)^4 \qquad T_s \propto (T_i)^{1/2}$

$$L_{\gamma}^{\infty} \propto (T_i)^2$$

-if neutrino luminosity is negligible $L_{\rm dh}^{\infty} \approx L_{\gamma}^{\infty} \propto \dot{M}$

-when neutrino luminosity takes over $L_{\rm dh}^{\infty} \approx L_{\nu}^{\infty} \propto \dot{M}$

$$L_{\nu}^{\infty}(T_i) = \begin{cases} L_{\nu}^{\rm slow} \approx \frac{3}{4}\pi R^3 \cdot Q^{\rm slow} T_9^8 \equiv N^{\rm slow} T_9^8 \\ L_{\nu}^{\rm fast} = \frac{3}{4}\pi R_p^3 \cdot Q^{\rm fast} T_9^6 \equiv N^{\rm fast} T_9^6 \end{cases} \rightarrow \begin{cases} (L_{\gamma}^{\infty})^4 \propto \dot{M} \\ (L_{\gamma}^{\infty})^3 \propto \dot{M} \end{cases}$$

Simple approximation

$$L^{\infty}_{\text{dh}}(\dot{M}) = L^{\infty}_{\gamma}(T_s) + L^{\infty}_{\nu}(T_i)$$

$L^{\infty}_{\text{dh}} \propto \dot{M}$ $\quad L^{\infty}_{\gamma} \propto (T_s)^4$ $\quad T_s \propto (T_i)^{1/2}$

$$L^{\infty}_{\gamma} \propto (T_i)^2$$

On the $L^{\infty}_{\gamma} - \dot{M}$ diagram, two limiting cases

i) linear behavior

ii) power law; sensitive to neutrino emissivity

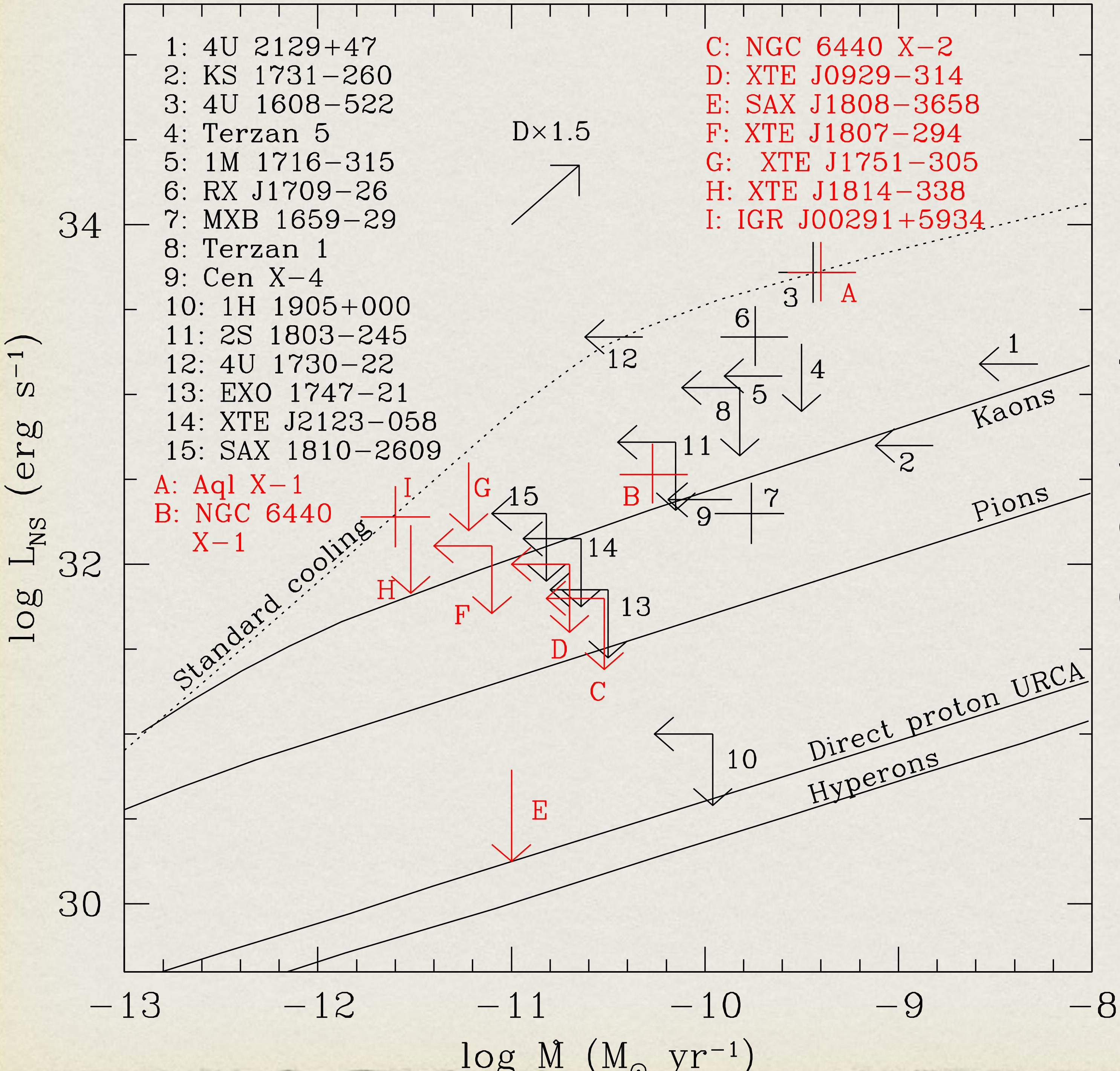
-if neutrino luminosity is negligible $L^{\infty}_{\text{dh}} \approx L^{\infty}_{\gamma} \propto \dot{M}$

-when neutrino luminosity takes over $L^{\infty}_{\text{dh}} \approx L^{\infty}_{\nu} \propto \dot{M}$

$$L^{\infty}_{\nu}(T_i) = \begin{cases} L^{\text{slow}}_{\nu} \approx \frac{3}{4}\pi R^3 \cdot Q^{\text{slow}} T_9^8 \equiv N^{\text{slow}} T_9^8 \\ L^{\text{fast}}_{\nu} = \frac{3}{4}\pi R_p^3 \cdot Q^{\text{fast}} T_9^6 \equiv N^{\text{fast}} T_9^6 \end{cases} \rightarrow \quad \begin{matrix} (L^{\infty}_{\gamma})^4 \propto \dot{M} \\ (L^{\infty}_{\gamma})^3 \propto \dot{M} \end{matrix}$$

Heating curves

Heinke et al. (2010)



-Thermal equilibrium

$$L^{\infty}_{\rm dh}(\dot{M}) = L^{\infty}_{\gamma}(T_s) + L^{\infty}_{\nu}(T_i)$$

observables

-Theoretical prediction

specify EoS, composition, light element amount, superfluidity gaps and NS mass

-Observation

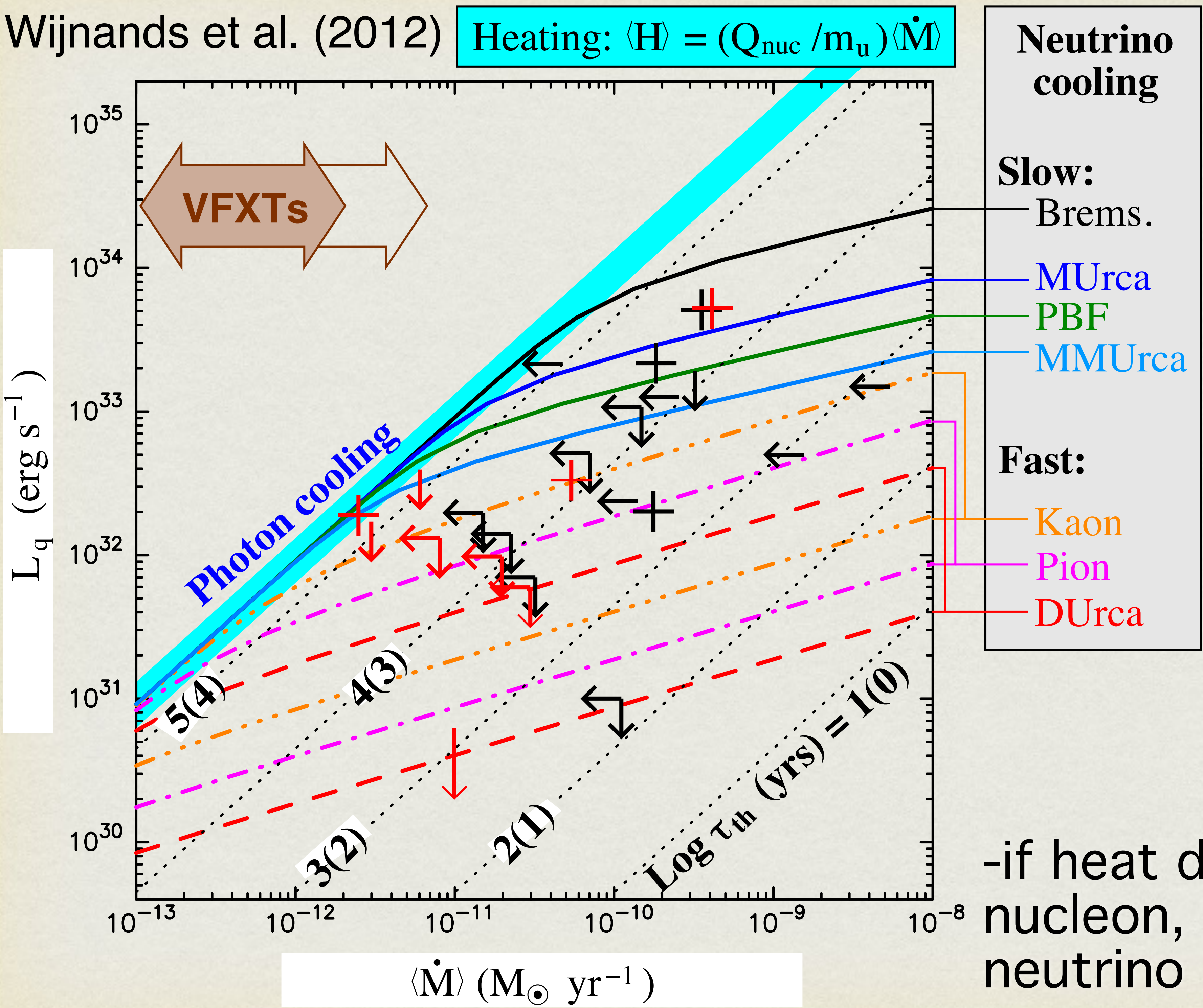
lower surface luminosity at the same accretion rate

⇔

heavy stars cool more efficiently

Photon vs. neutrino cooling

Wijnands et al. (2012)



-photon emission regime: faint NSs, ind. of internal structure

-neutrino emission regime: warmer NSs

$$L_\nu \approx L_{dh} \gg L_\gamma$$

1) slow neutrino emission in low- and intermediate-mass NSs

2) fast emission mechanisms dominate in high-mass NSs

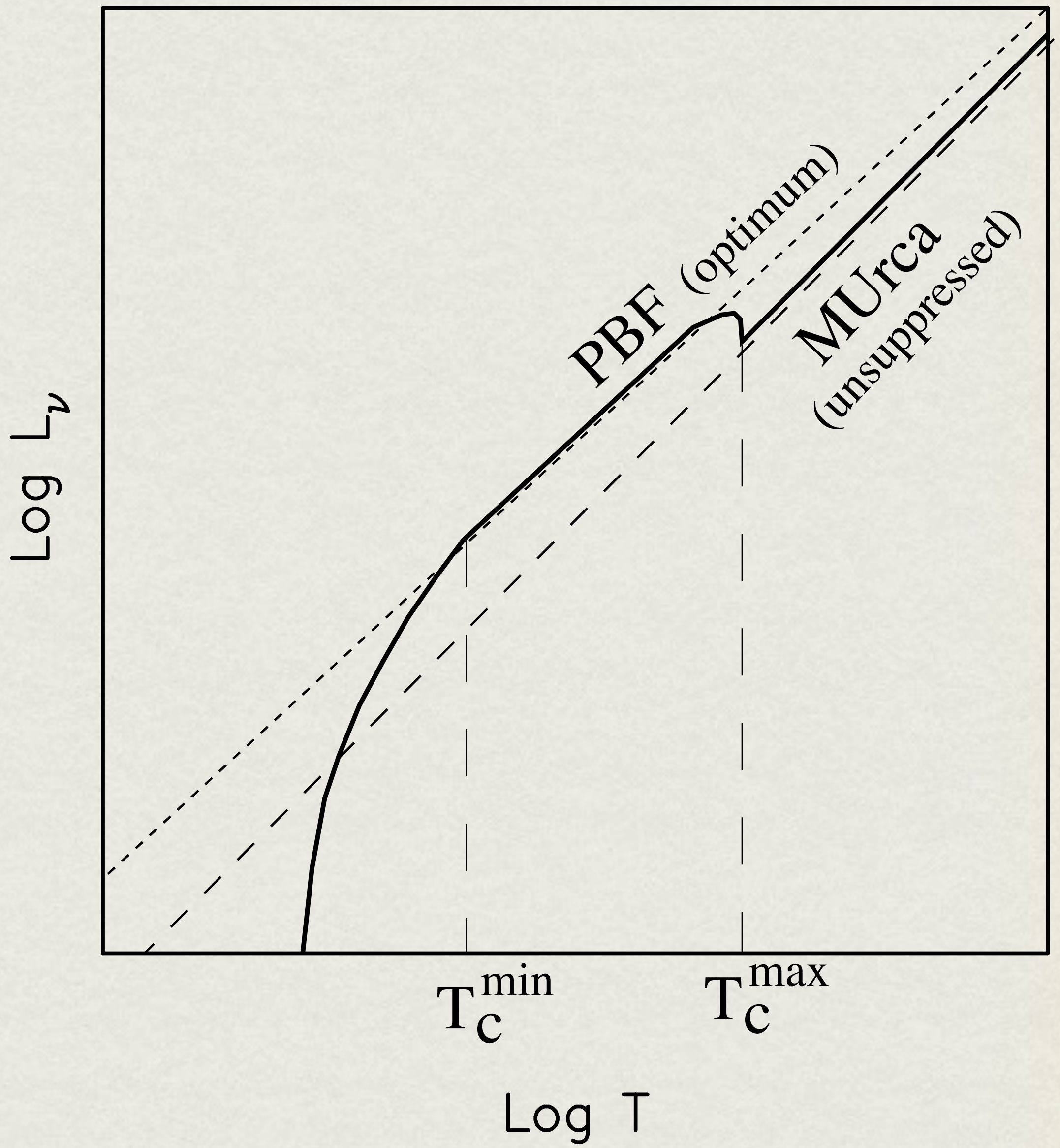
-if heat deposited as 1~2 MeV/ nucleon, most SXRTs are at the neutrino stage: probe interior

Neutrino emission mechanism

-Hadronic matter

Process	Neutrino Emissivity $(\mathrm{erg\,cm^{-3}\,s^{-1}})$
mUrca	$\sim 10^{21}\ T_9^8$
brems.	$\sim 10^{19} - 10^{20}\ T_9^8$
dUrca	$\sim 10^{27}\ T_9^6$
pair-breaking formation	$\sim 10^{19} - 10^{21}\ T_9^7$

Page et al. (2009)



-Pairing in nucleonic SF: suppresses Urca processes but trigger PBF

Equations of state

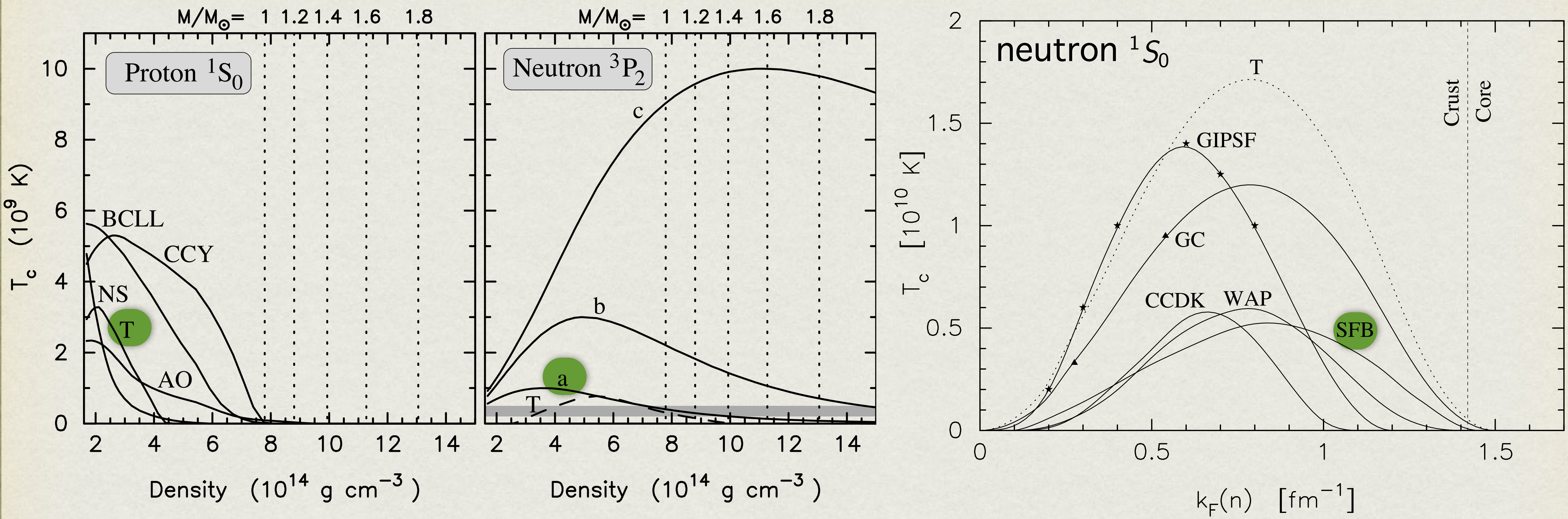
-Within nucleons-only model

Property	APR	HHJ	SLy4	NL3
symmetry energy S_0 (MeV)	32.6	32.0	32.0	37.3
$L = 3n_0 \left[dS_0/dn\right]_{n_0}$ (MeV)	60	67.2	45.9	118.2
dUrca threshold n_B^{dU} (fm^{-3})	0.77	0.57	1.42	0.21
maximum density n_{max} (fm^{-3})	1.12	1.02	1.21	0.68
dUrca onset mass ($M_\odot$)	2.01	1.87	2.03	0.82
maximum mass ($M_\odot$)	2.18	2.17	2.05	2.77
radius of heaviest star (km)	10.18	10.98	9.96	13.65

-Given EoS, specifying the mass designates possible cooling channels

Stellar superfluids

outer core inner core Page et al. (2009)



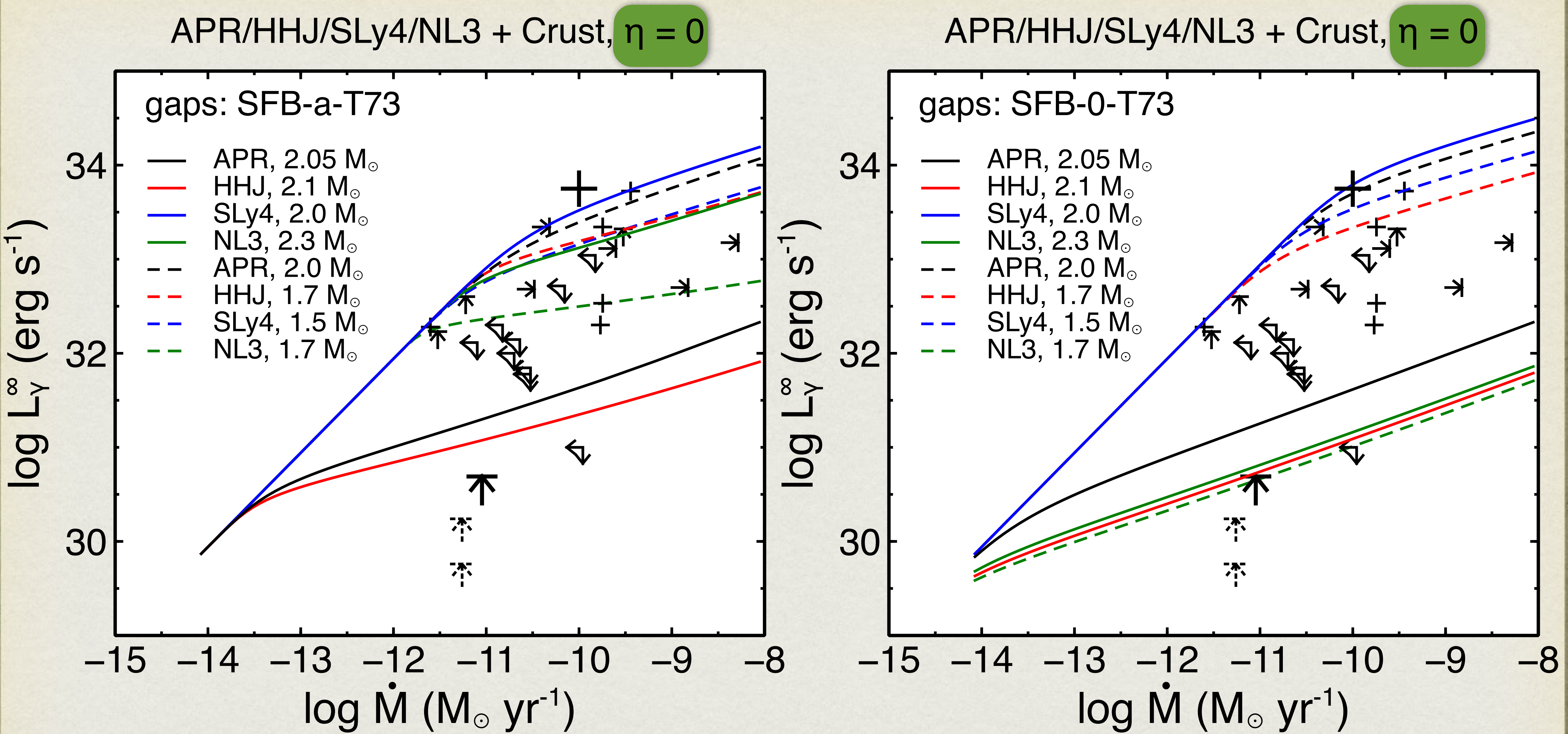
-density/radial profiles of the SF critical temperature remain uncertain

inside the star, regions where $T_i \leq T_{\rm crit}(r)$ undergo pairing-induced suppression of Urca neutrinos

PBF neutrino emissions: most noticeable at $T_i \approx T_{\rm crit}(r)$

$\longrightarrow$ presence of SF alters the <u>dominant</u> neutrino emission mechanism

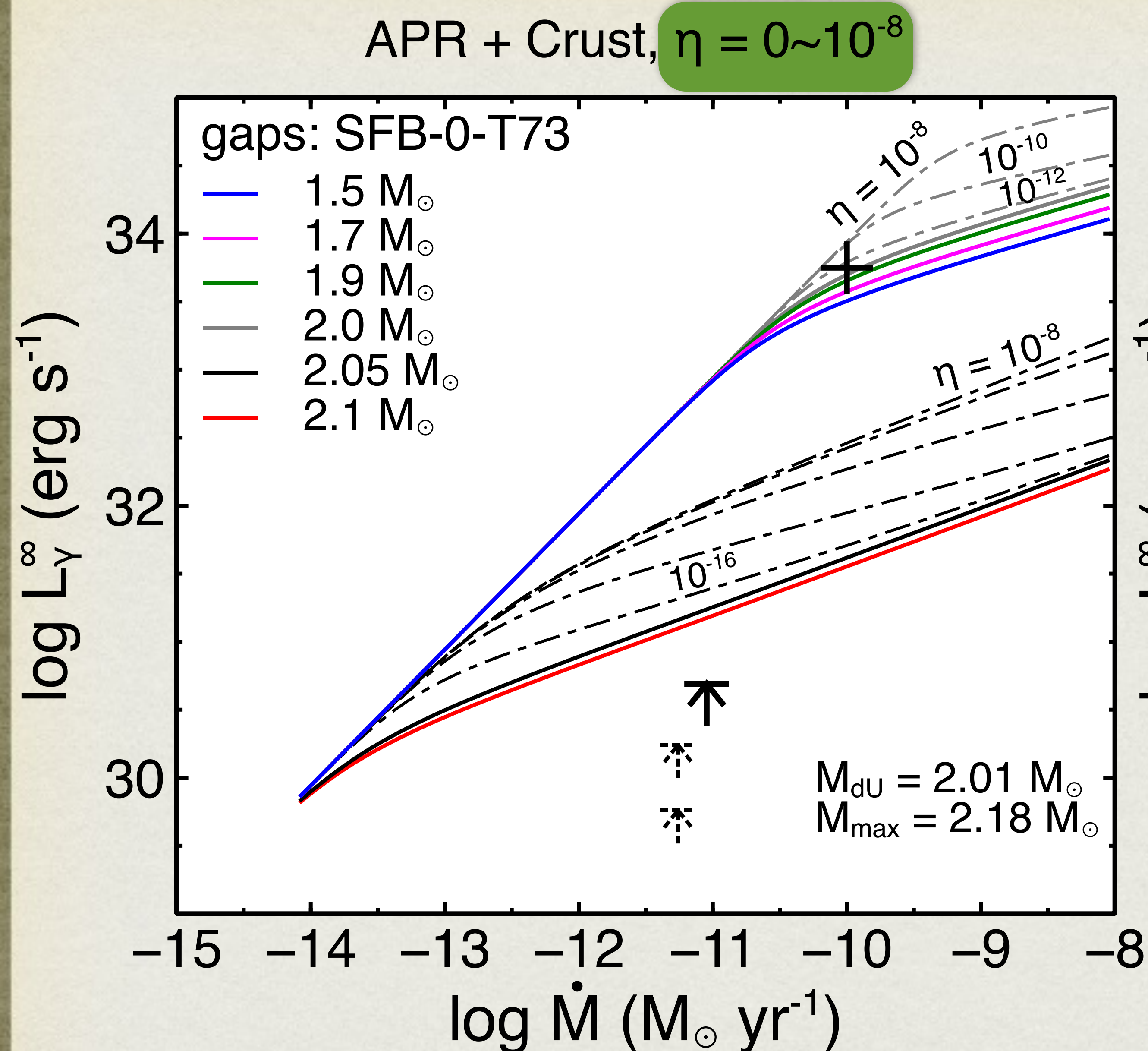
Theoretical prediction

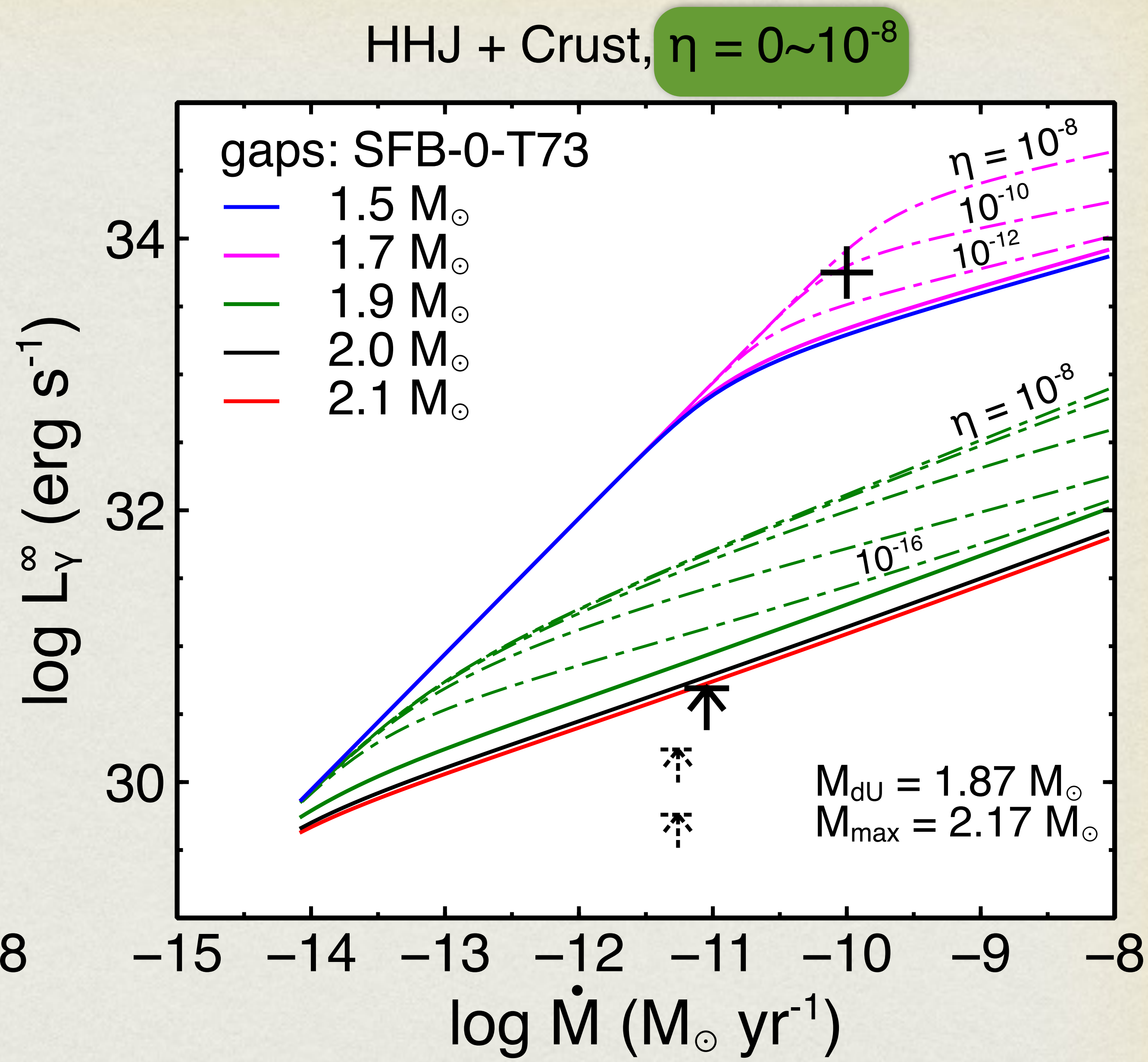


-dichotomy of thermal states of SXRTs: separated by dUrca onset mass

-PBF: test between mild and vanishing neutron $^3P_2$ triplet superfluidity

Light-element residue



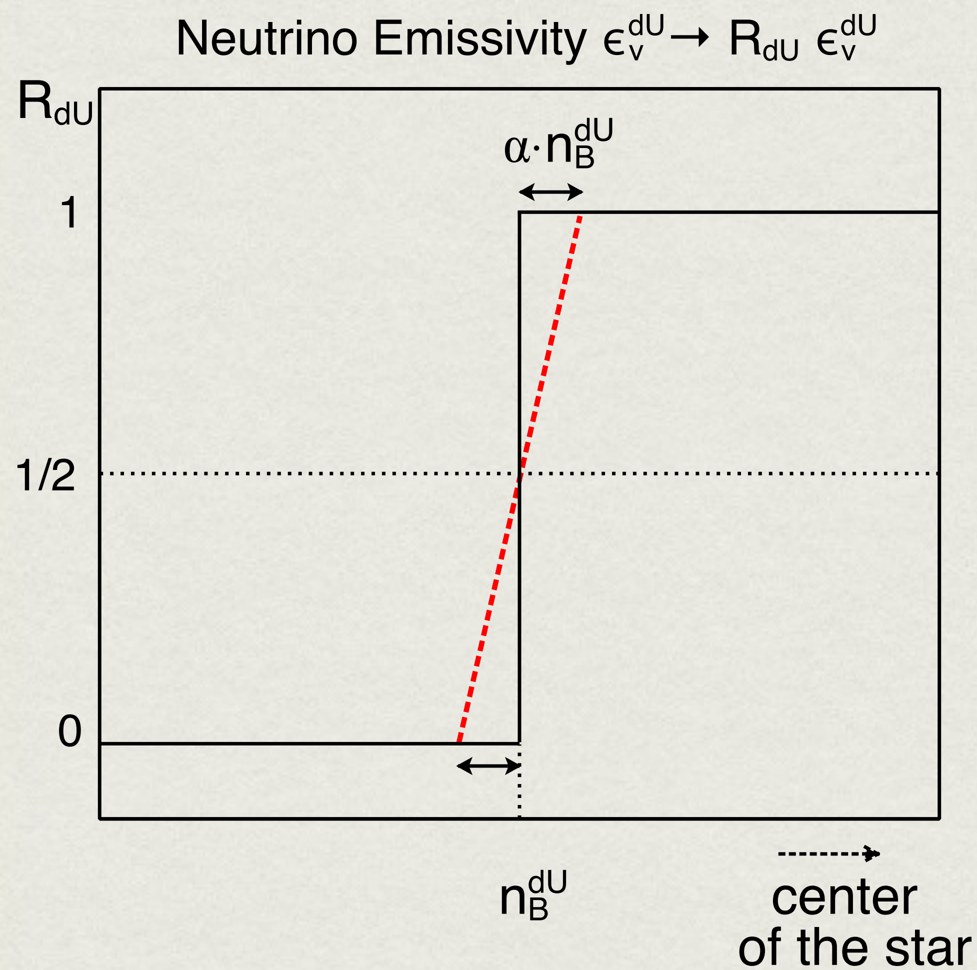


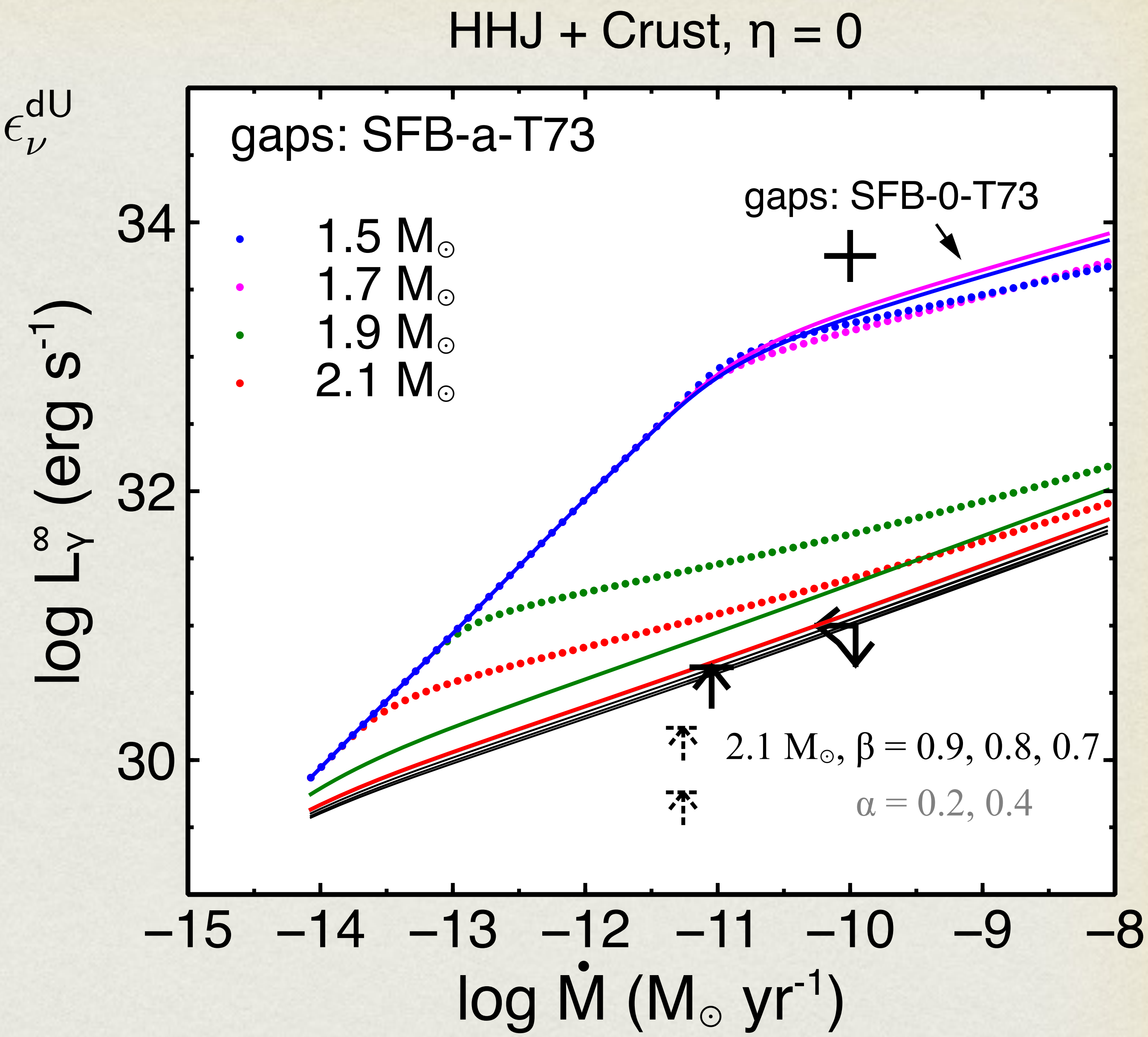
-APR/HHJ EoS; vanishing neutron $^3P_2$ gap; dUrca in massive stars (cold)

-tune light-element layer thickness
- i) cover more luminosity range
- ii) help explain hottest Aquila X-1

Stringent constraints

-dUrca: phenomenological shifting $n_B^{dU} \to \beta n_B^{dU}$ and broadening $\epsilon_\nu^{dU} \to R_{dU}\, \epsilon_\nu^{dU}$ effects





-need early dUrca onset + small SF gaps to explain extremely cold sources in SAX J1808.4-3658 (arrow) and 1H 1905+000 (double arrows)

Statistical analysis

-Fit to luminosity data of the hottest and coldest source $(L_{1808}, L_{\rm Aql})$

-Input parameters

two NS masses $(M_{1808}, M_{\rm Aql})$

dUrca onset characterization $n_{\rm B}^{\rm dU}(1-\alpha) \geq n_{\rm sat}$

EoS: nuclear model + polytropes above twice saturation density (K, Γ)

$$P(\varepsilon) = P_{\rm NM}(\varepsilon) + \Theta(\varepsilon - 2\varepsilon_0) K \left[\varepsilon^\Gamma - (2\varepsilon_0)^\Gamma\right]$$

light-element layer thickness

(for Aql X-1, set to zero for SAX J1808) $(\eta_{\rm Aql}, Q)$

energy release per nucleon in deep crustal heating

Gaussian functions $n\,^3P_2 : [T_{\rm cnt}^{\rm max}, k_{F\rm n}^{\rm peak}, \Delta k_{F\rm n}]$ $\quad p\,^1S_0 : [T_{\rm cps}^{\rm max}, k_{F\rm p}^{\rm peak}, \Delta k_{F\rm p}]$

Results & connections to…

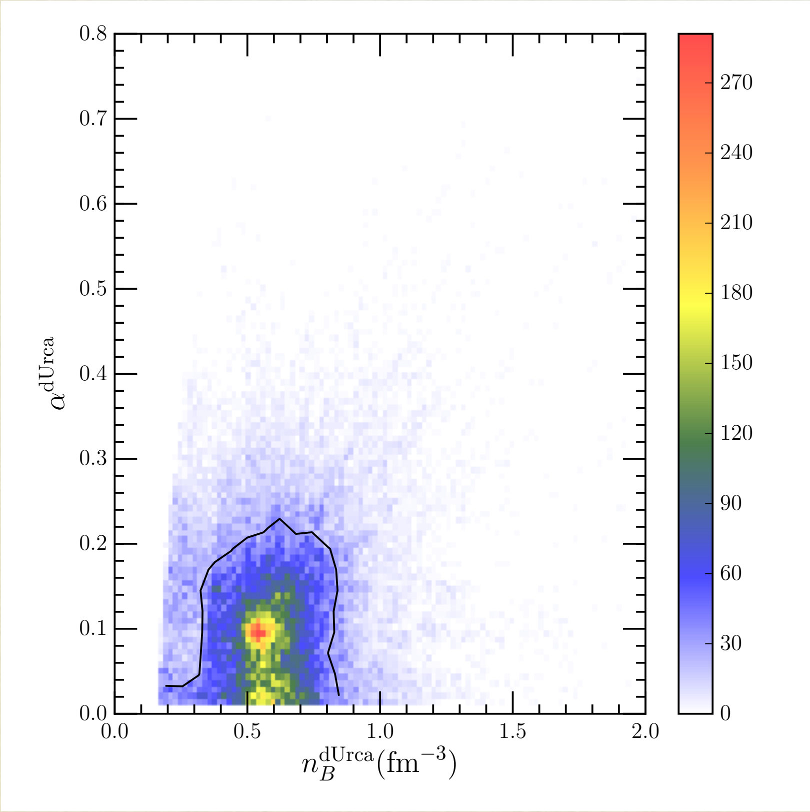
-Example: SLy4 EoS + polytropes; fit to data $(L_{1808}, L_{\rm Aql})$

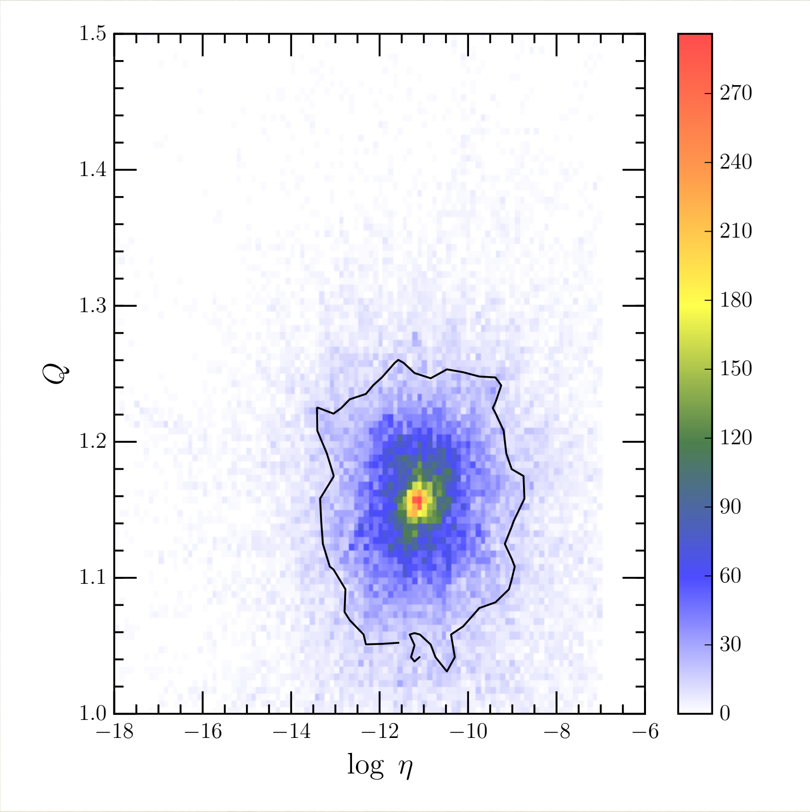
nuclear physics

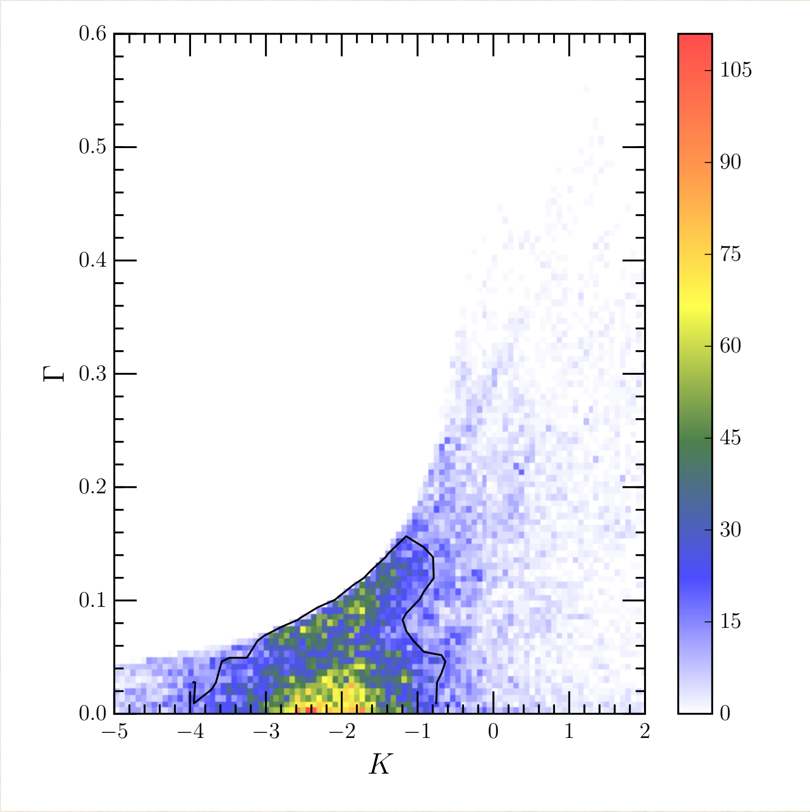
dUrca threshold $n_{\rm B}^{\rm dU}(1-\alpha) \sim 3n_{\rm sat}$, anti-correlated with derivative of Esym

deep crustal heating energy $Q = 1 \sim 1.3\,{\rm MeV}$, can vary with multicomponent

softening at higher densities $\Leftrightarrow$ lower L, or other degrees of freedom?







Results & connections to…

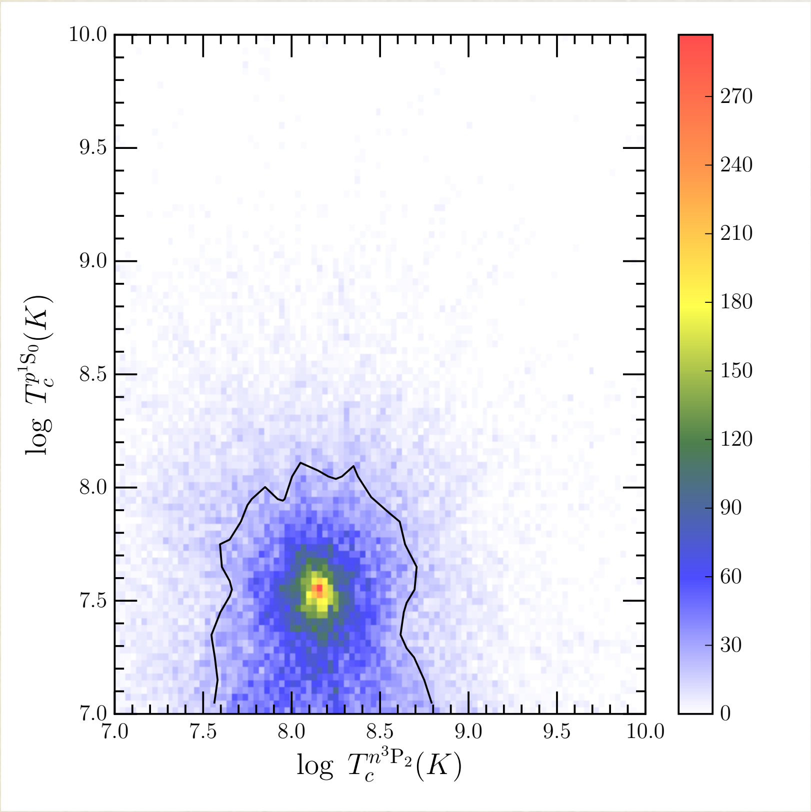
-Example: SLy4 EoS + polytropes; fit to data (L_{1808}, L_{Aql})

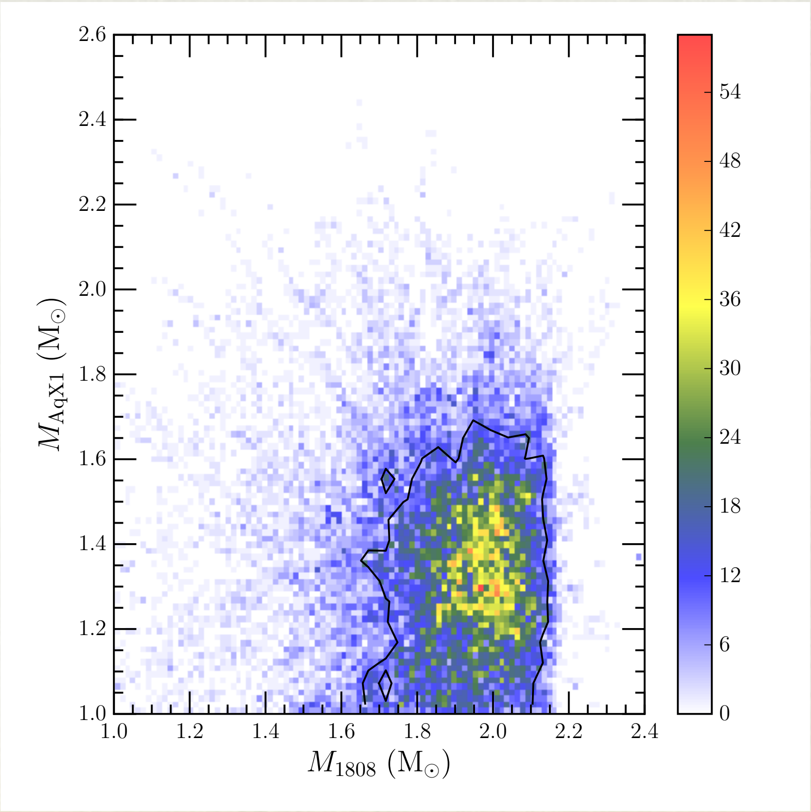
observation

jointly test SF from cooling isolated neutron stars

constraints from mass estimate, in particular 1808

update surface luminosity and mean accretion rate





other studies

pion condensation

(Matsuo et al. 2016)

analytical approx.

(Ofengeim et al. 2016)

NS mass distribution

(Beznogov et al. 2015)

...future work

Summary

Thermal states of accreting NSs in SXRTs

-surface luminosity at given accretion rate; same physics tested as in isolated stars

-observational constraint: hottest/coldest star; possible mass & radius measurement

Probe properties of dense matter

-nuclear matter EoSs; direct Urca threshold

-neutron star crust composition and heating

-light-element accreted envelope

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-proton and neutron superfluidity

-exotic matter (future work)

THANK YOU!

Q & A