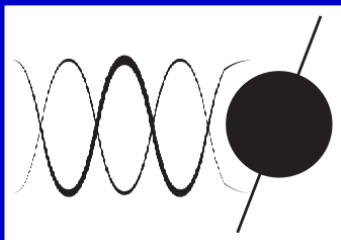


Ioffe Institute
Department of Theoretical Astrophysics
N. Copernicus Astronomical Center



Bulk Viscosity in Neutron Star Cores with Hyperonic Equations of State

**Dmitry OFENGEIM, Mikhail GUSAKOV,
Pawel HAENSEL, Morgane FORTIN**

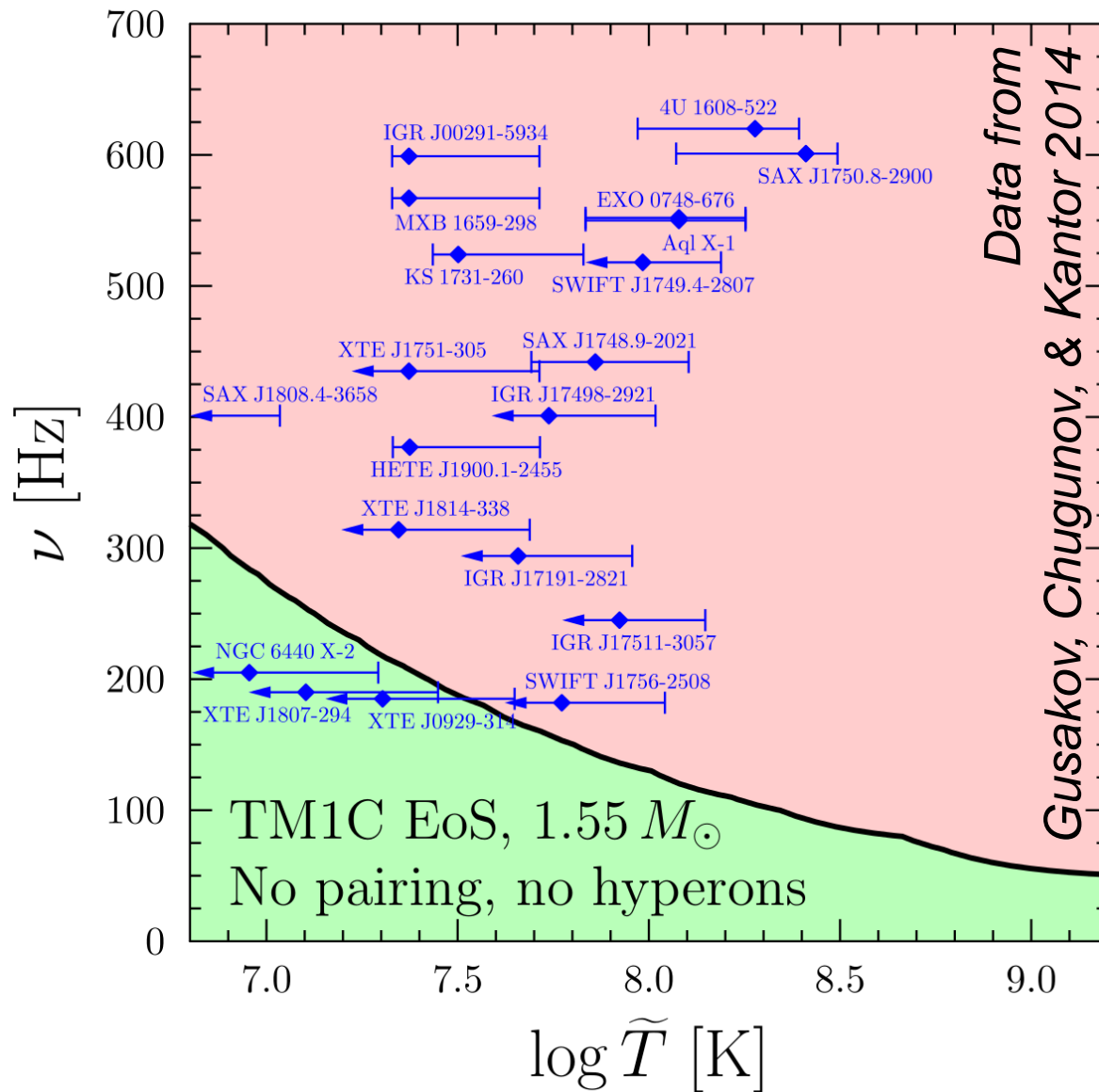


PHAROS WG1+WG2 meeting
*Neutron stars: the equation of state,
superconductivity/superfluidity and transport coefficients*

University of Coimbra, 27 September 2018



R-modes Instability Window



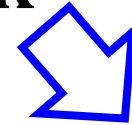
Stability criterion for r-modes

$$\tau_{\text{GW}}^{-1} + \tau_{\text{shear}}^{-1} + \tau_{\text{bulk}}^{-1} > 0$$

\wedge \vee \vee
 0 0 0

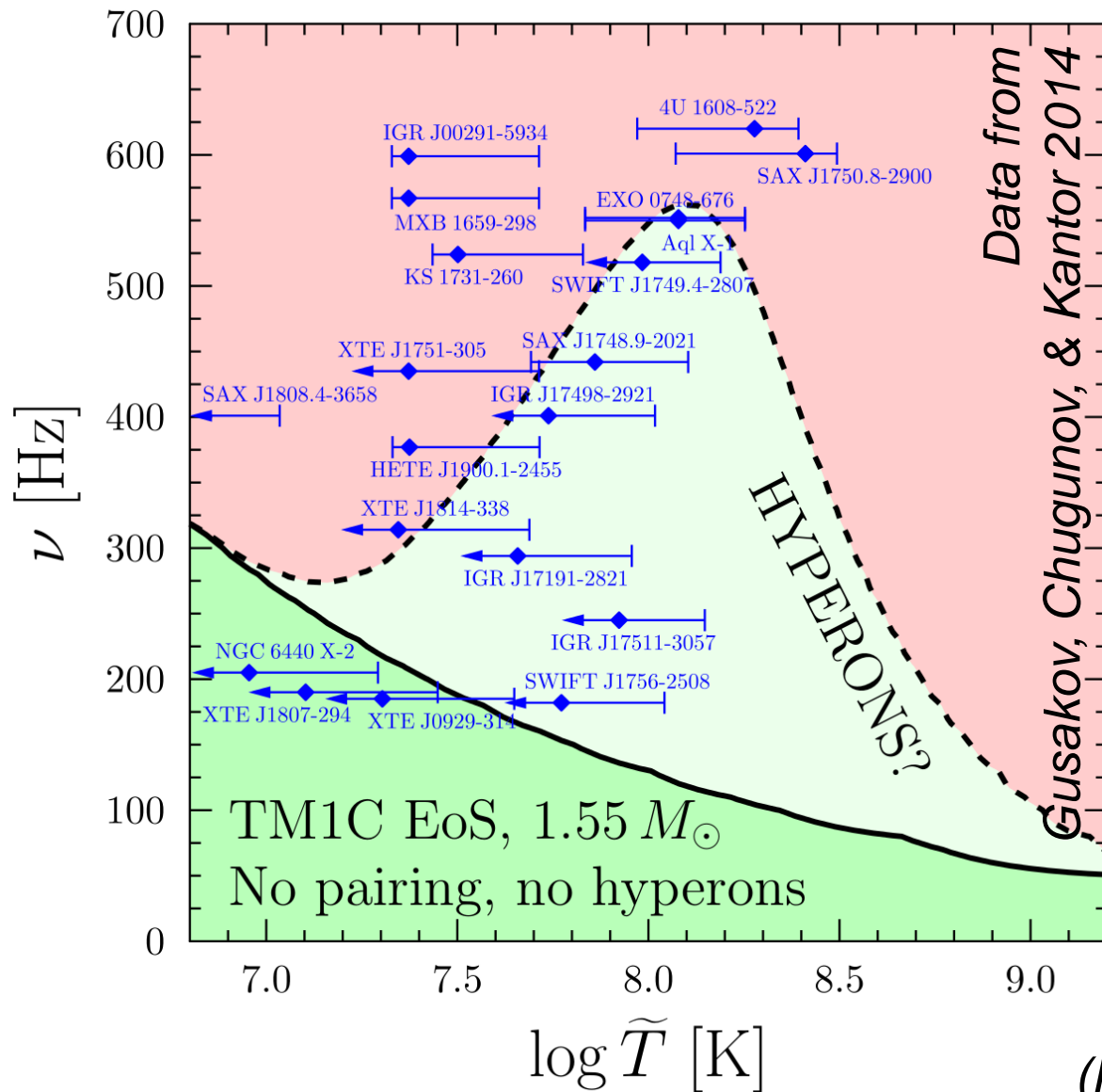
$n\rho e\mu$ NS:

$$\tilde{T} \lesssim 10^9 \text{ K}$$



$$1/\tau_{\text{shear}} \gg 1/\tau_{\text{bulk}}$$

R-modes Instability Window

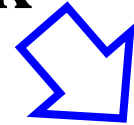


Stability criterion for r-modes

$$\tau_{\text{GW}}^{-1} + \tau_{\text{shear}}^{-1} + \tau_{\text{bulk}}^{-1} > 0$$

\wedge \vee \vee
 0 0 0
npeμ NS:

$$\tilde{T} \lesssim 10^9 \text{ K}$$



$$1/\tau_{\text{shear}} \gg 1/\tau_{\text{bulk}}$$

Hyperons:

$$1/\tau_{\text{bulk HYP}} \gg 1/\tau_{\text{bulk NUC}}$$

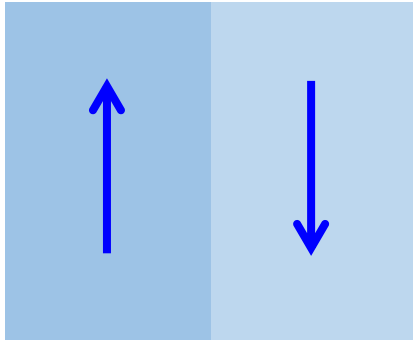


Stabilization at $\tilde{T} = ?$

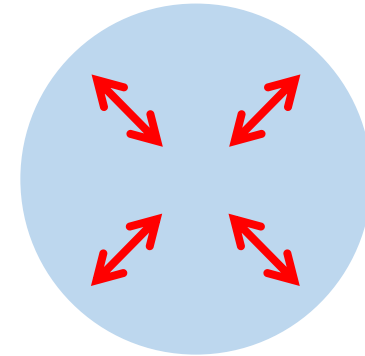
(Nayyar & Owen'06; Vidana'15)

Viscosity in Neutron Star Cores

Shear



Bulk



$$\sigma_{jk} = \eta \left(\partial_j v_k + \partial_k v_j - \delta_{jk} \frac{2}{3} \text{div } \vec{v} \right) + \delta_{jk} \zeta \text{div } \vec{v}$$

momentum diffusion

non-equilibrium reactions

npeμ NS:

Urca processes



rate $\propto T^{4\dots 6} \Delta\mu$

Hyperonic NS:

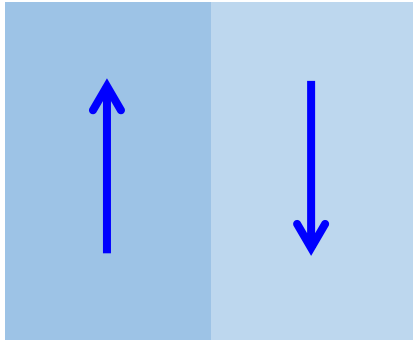
nonleptonic weak reactions



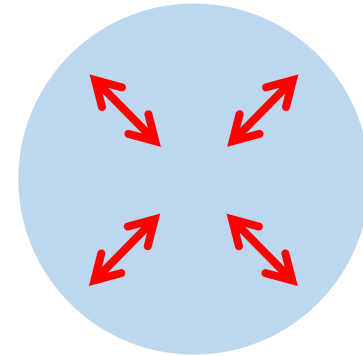
rate $\propto T^2 \Delta\mu$

Viscosity in Neutron Star Cores

Shear



Bulk



$$\sigma_{jk} = \eta \left(\partial_j v_k + \partial_k v_j - \delta_{jk} \frac{2}{3} \text{div } \vec{v} \right) + \delta_{jk} \zeta \text{div } \vec{v}$$

momentum diffusion

non-equilibrium reactions

npeμ NS:

Urca processes



rate $\propto T^{4\dots 6}$ **effective at low T**

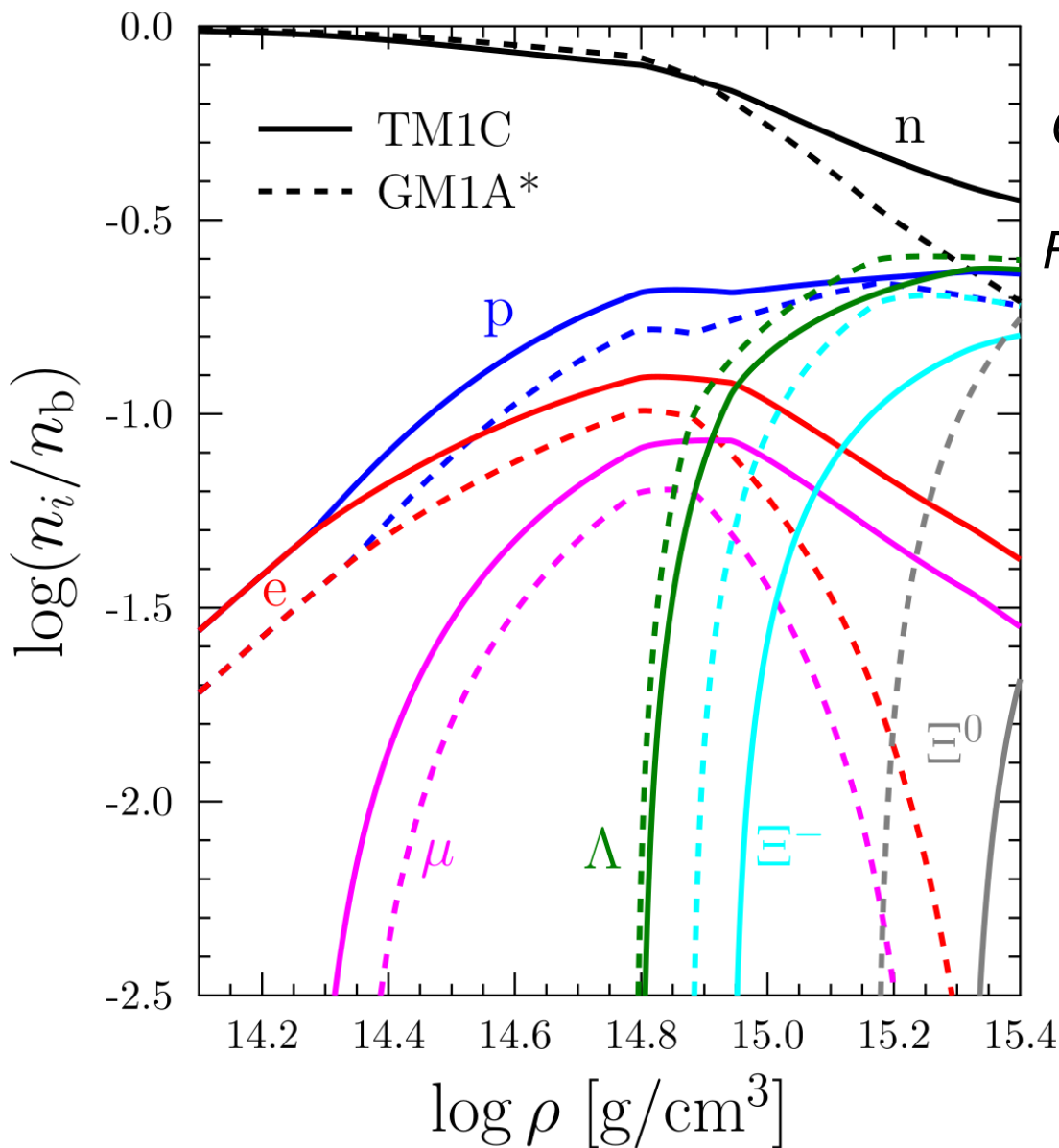
Hyperonic NS:

nonleptonic weak reactions



rate $\propto T^2 \Delta\mu$

Hyperonic NS: modern composition



$n, p, e, \mu, \Lambda, \Xi^-, \dots$

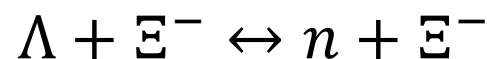
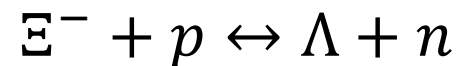
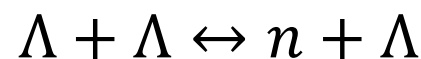
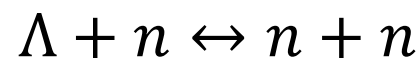
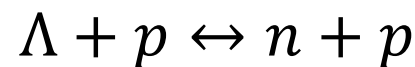
Gusakov, Haensel, & Kantor 2014

Fortin+2017

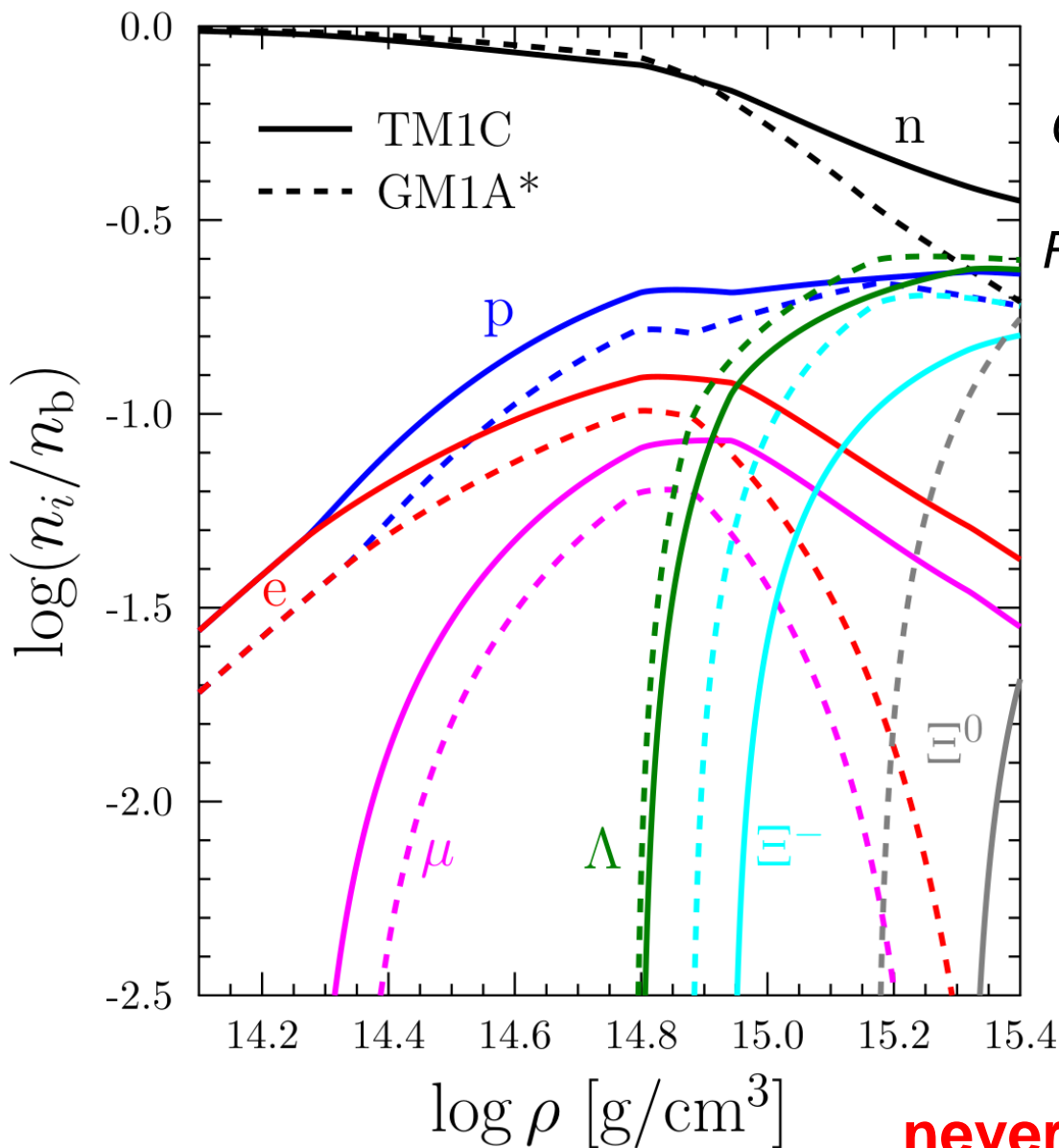
Raduta, Sedrakian, & Weber 2018

Nonleptonic Reactions

($\Delta S = 1$)



Hyperonic NS: modern composition



$n, p, e, \mu, \Lambda, \Xi^-, \dots$

Gusakov, Haensel, & Kantor 2014

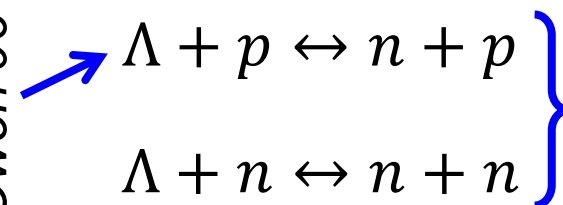
Fortin+2017

Raduta, Sedrakian, & Weber 2018

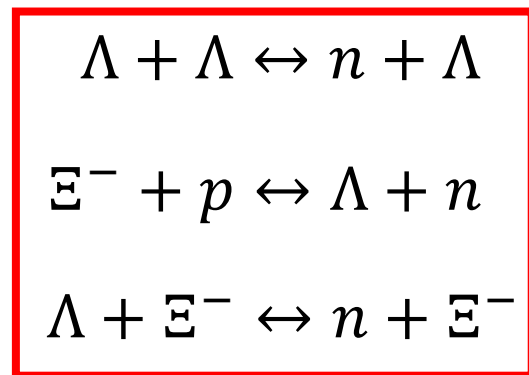
Nonleptonic Reactions

$(\Delta S = 1)$

Nayyar&Owen'06

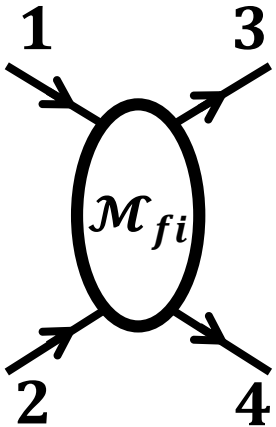


van Dalen & Dieperink'04



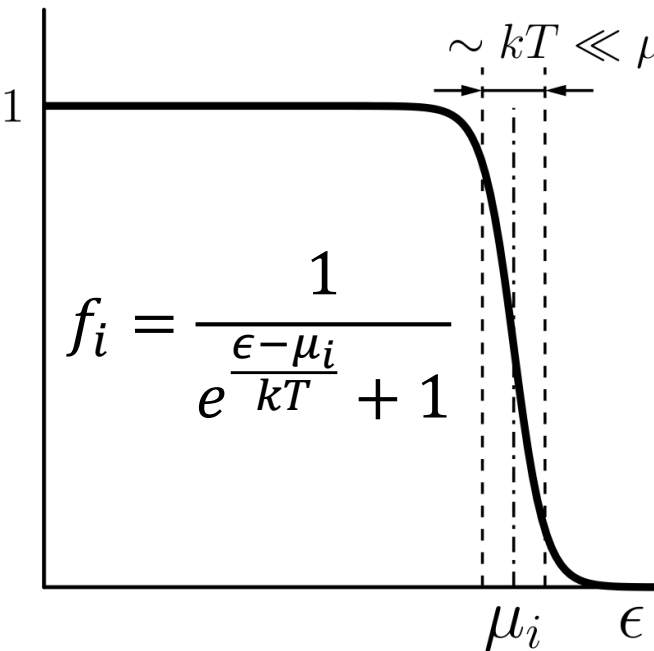
never considered before in NSs

Reaction Rates



$$\Gamma_{12 \rightarrow 34} = \frac{1}{(2\pi)^8 S} \int \prod_{i=1}^4 \frac{d^3 \vec{p}_i}{2m_{Li}^*} \delta^{(4)}(k_1 + k_2 - k_3 - k_4) \times \sum_{\text{spins}} |\mathcal{M}_{fi}|^2 f_1 f_2 (1 - f_3)(1 - f_4)$$

Strongly degenerate matter + RMF approach:



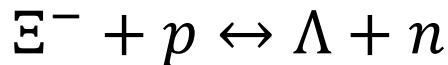
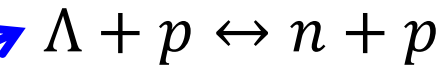
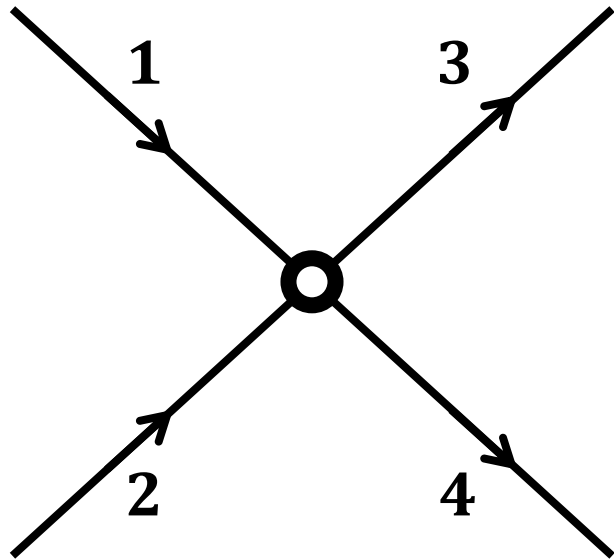
$$k_i^0 = \mu_i, \quad |\vec{k}_i| = k_{Fi}, \quad \psi_i = \frac{u_i}{\sqrt{2m_{Li}^*}} e^{ik^\mu x_\mu}$$

$$\sum_{\text{spin}} u_i \bar{u}_i = \underbrace{m_{Di}^*}_{\text{Dirac eff. mass}} + \underbrace{\gamma^0 m_{Li}^* - \vec{\gamma} \cdot \vec{k}_i}_{\text{Landau eff. mass}}$$

known for RMF EoSs

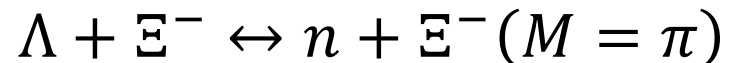
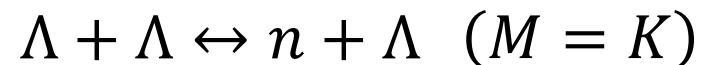
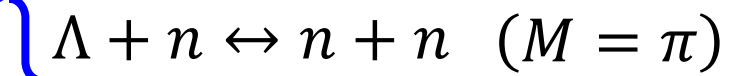
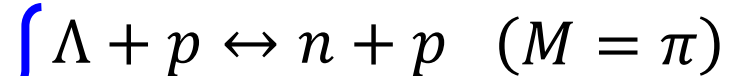
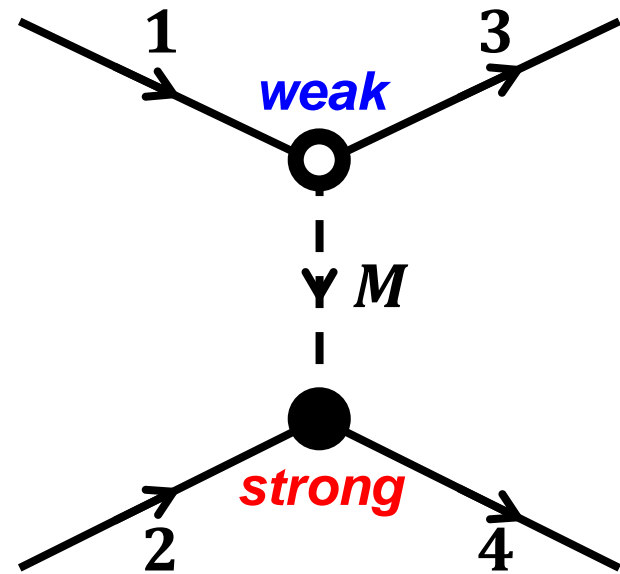
Reaction Rates: Matrix Element

weak contact



(no 'ds' weak current)

one-meson exchange

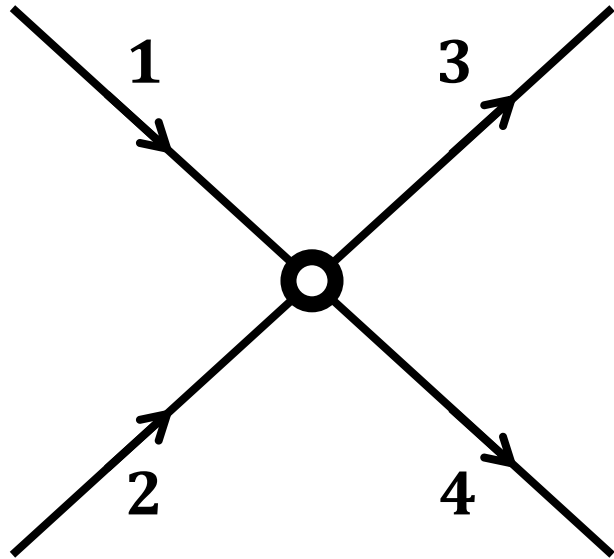


Nayyar&Owen'06

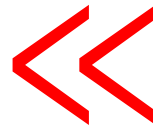
van Dalen & Dieperink'04

Reaction Rates: Matrix Element

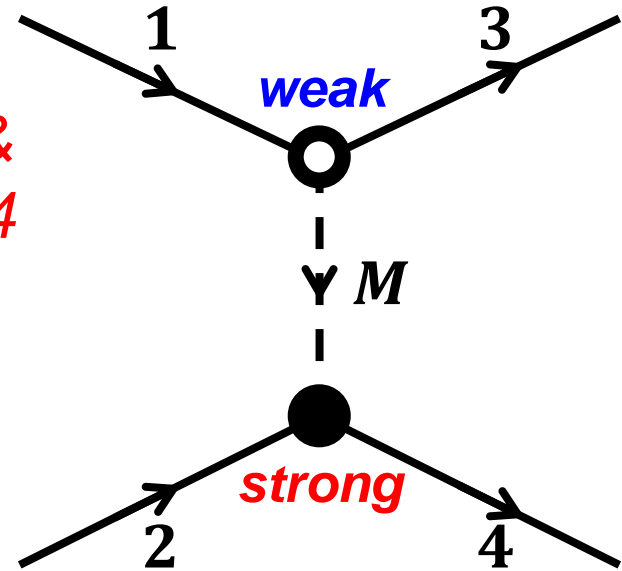
weak contact



van Dalen & Dieperink'04

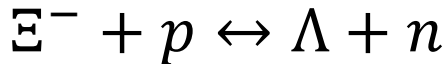


one-meson exchange



van Dalen & Dieperink'04

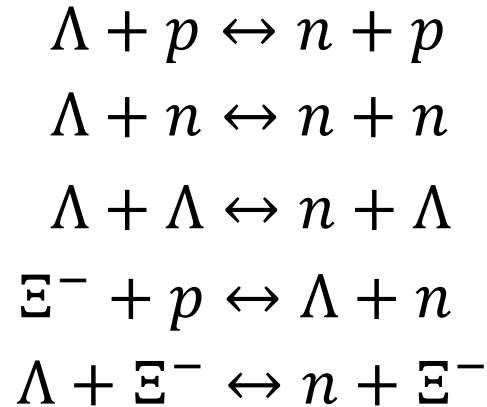
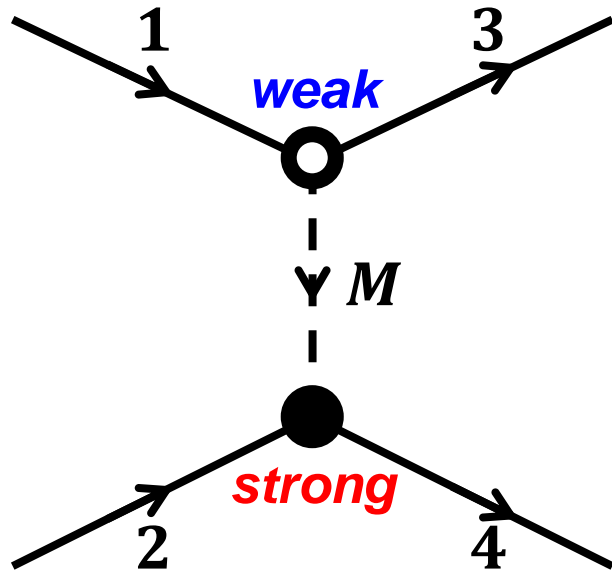
- $\Lambda + p \leftrightarrow n + p \quad (M = \pi)$
- $\Lambda + n \leftrightarrow n + n \quad (M = \pi)$
- $\Lambda + \Lambda \leftrightarrow n + \Lambda \quad (M = K)$
- $\Xi^- + p \leftrightarrow \Lambda + n \quad (M = \pi)$
- $\Lambda + \Xi^- \leftrightarrow n + \Xi^- \quad (M = \pi)$



(no 'ds' weak current)

Nayyar & Owen'06

Reaction Rates: Matrix Element



Vertex	Strong g	Weak A	Weak B
$pp\pi$	13.3	—	—
$np\pi$	$13.3\sqrt{2}$	—	—
$nn\pi$	-13.3	—	—
$\Lambda n\pi$	—	-1.07	-7.19
$\Lambda p\pi$	—	1.46	9.95
ΛnK	-14.1	—	—
$\Lambda\Lambda K$	—	0.67	12.72
$\Xi^-\Lambda\pi$	—	2.04	-7.5
$\Xi^-\Xi^-\pi$	-5.4	—	—

$$\mathcal{M}_{fi} = G_F m_\pi^2 \cdot \overline{u}_3 (A_{13} + B_{13} \gamma^5) u_1 \cdot D_M \cdot \overline{u}_4 (g_{24} \gamma^5) u_2 - \text{exch.}$$

$$D_M^{-1} = (\vec{k}_1 - \vec{k}_3)^2 + \tilde{m}_M^2,$$

$$\tilde{m}_M^2 = m_{M\text{bare}}^2 + \Pi - (\mu_1 - \mu_3)^2 > 0$$

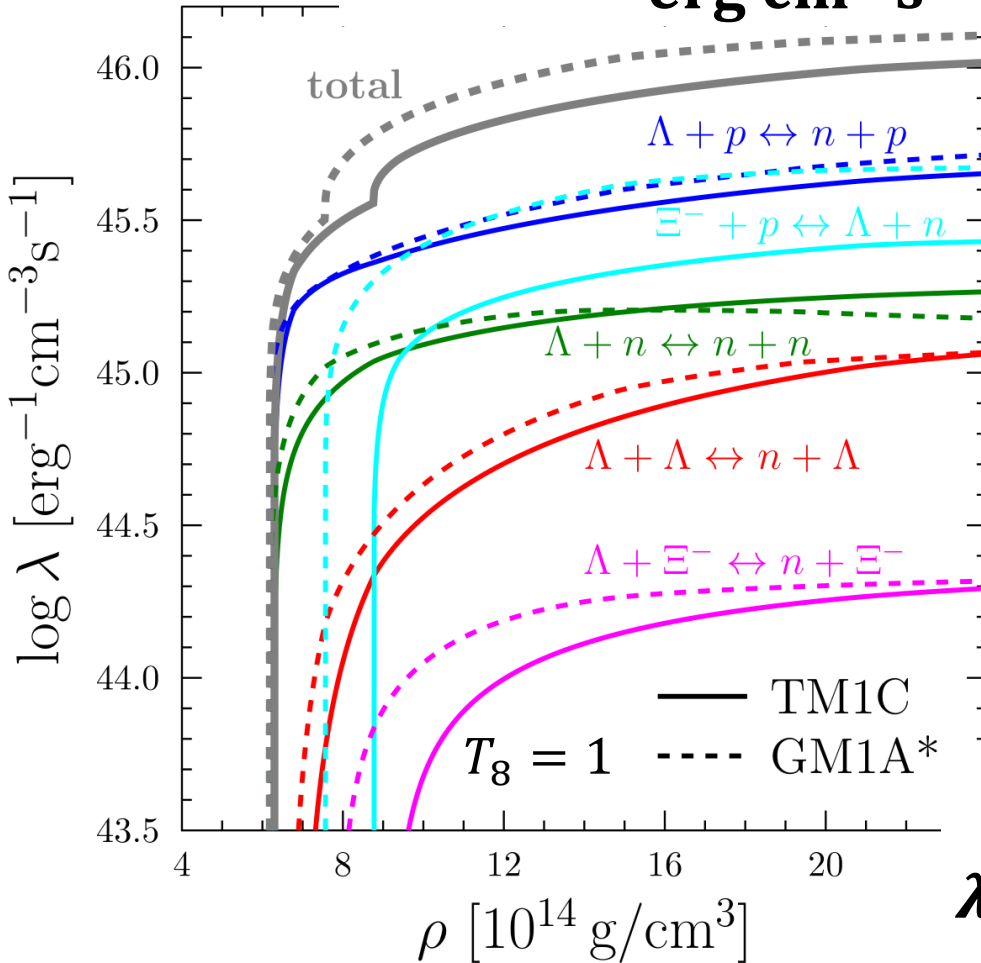
this talk: $\tilde{m}_M = m_{M\text{bare}}$

avoid meson condensation

Reaction Rates: Results

$$\Delta\Gamma_{12\leftrightarrow 34} = \Gamma_{12\rightarrow 34} - \Gamma_{34\rightarrow 12} = \lambda_{12\leftrightarrow 34}(\mu_1 + \mu_2 - \mu_3 - \mu_4)$$

$$\lambda_{12\leftrightarrow 34} = \frac{1.7 \times 10^{45}}{\text{erg cm}^3 \text{ s}} \cdot \frac{k_{\max} - k_{\min}}{(3\pi^2 n_0)^{1/3}} T_8^2 \cdot \mathcal{W}_{12\leftrightarrow 34}$$



$$k_{\max} = \min\{k_{F1} + k_{F3}, k_{F2} + k_{F4}\}$$

$$k_{\min} = \max\{|k_{F1} - k_{F3}|, |k_{F2} - k_{F4}|\}$$

- may be evaluated analytically
- flat function of ρ

Simple fitting formula

$$x = \frac{\rho}{\rho_{\text{start}}} - 1$$

$$\lambda_{12\leftrightarrow 34} \approx \lambda_0 x^{p1} \left(1 + \left(\frac{x}{a} \right)^{p2} \right)^{\frac{p3-p1}{p2}}$$

Bulk Viscosity & Reaction Rates

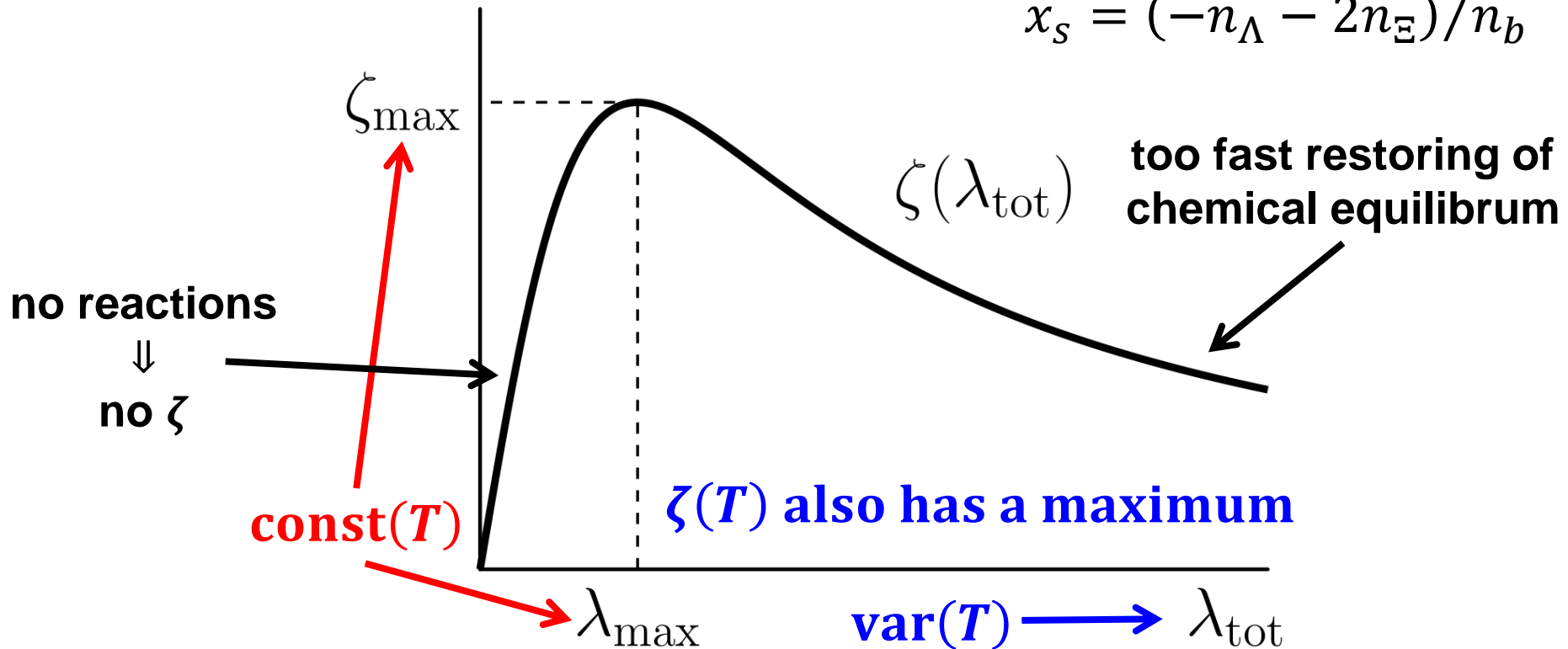
$$\zeta = \zeta_{\max} \frac{2 \lambda_{\text{tot}} / \lambda_{\max}}{1 + (\lambda_{\text{tot}} / \lambda_{\max})^2}$$

(Lindblom & Owen'02;
Gusakov & Kantor'08)

$$\zeta_{\max} = \frac{n_b}{2\omega} \frac{\partial P}{\partial x_s} \frac{\partial \Delta\mu}{\partial n_b} \left(\frac{\partial \Delta\mu}{\partial x_s} \right)^{-1}$$

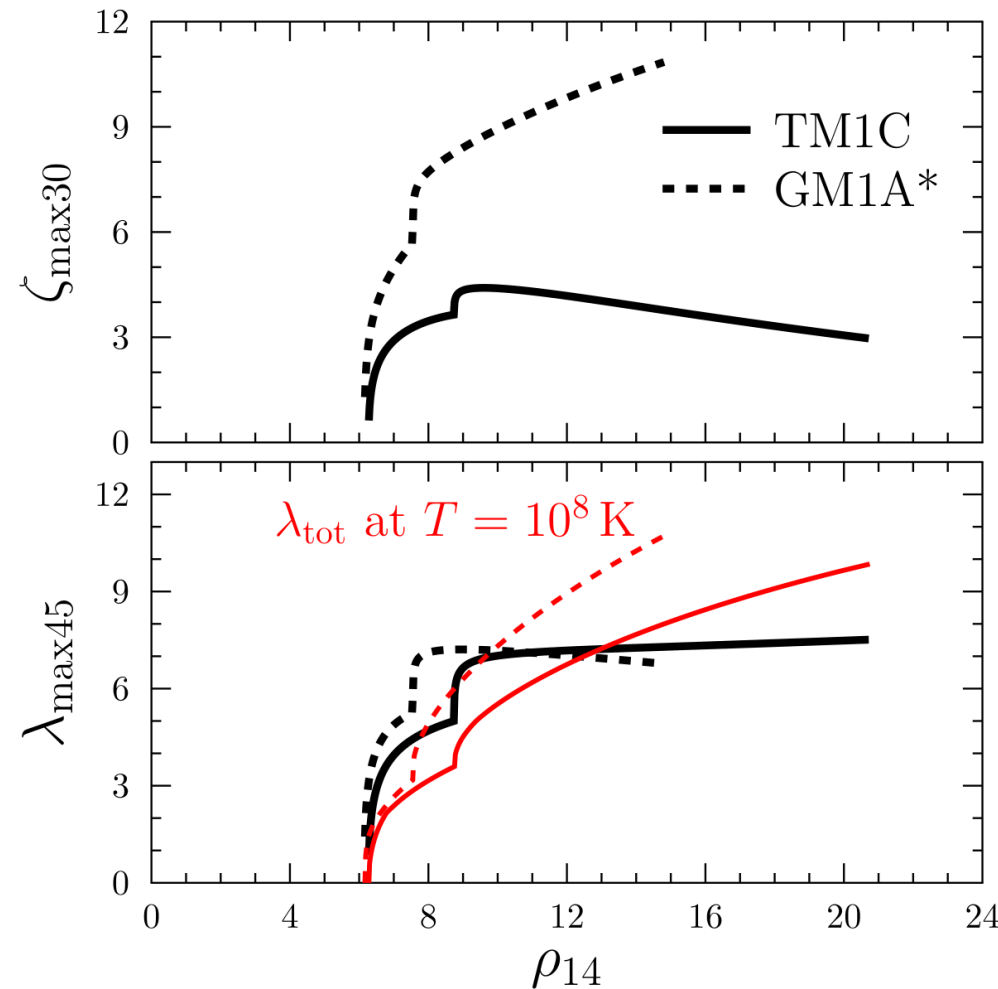
$$\lambda_{\max} = \omega n_b \left(\frac{\partial \Delta\mu}{\partial x_s} \right)^{-1}$$

$$x_s = (-n_\Lambda - 2n_\Xi) / n_b$$



Bulk Viscosity & Reaction Rates

$$\zeta_{\max} = \frac{n_b}{2\omega} \frac{\partial P}{\partial x_s} \frac{\partial \Delta\mu}{\partial n_b} \left(\frac{\partial \Delta\mu}{\partial x_s} \right)^{-1} \quad \lambda_{\max} = \omega n_b \left(\frac{\partial \Delta\mu}{\partial x_s} \right)^{-1} \quad x_s = \frac{-n_\Lambda - 2n_\Xi}{n_b}$$



- non-equilibrium thermodynamic derivatives

• \leftrightarrow Landau f_{ij}^0

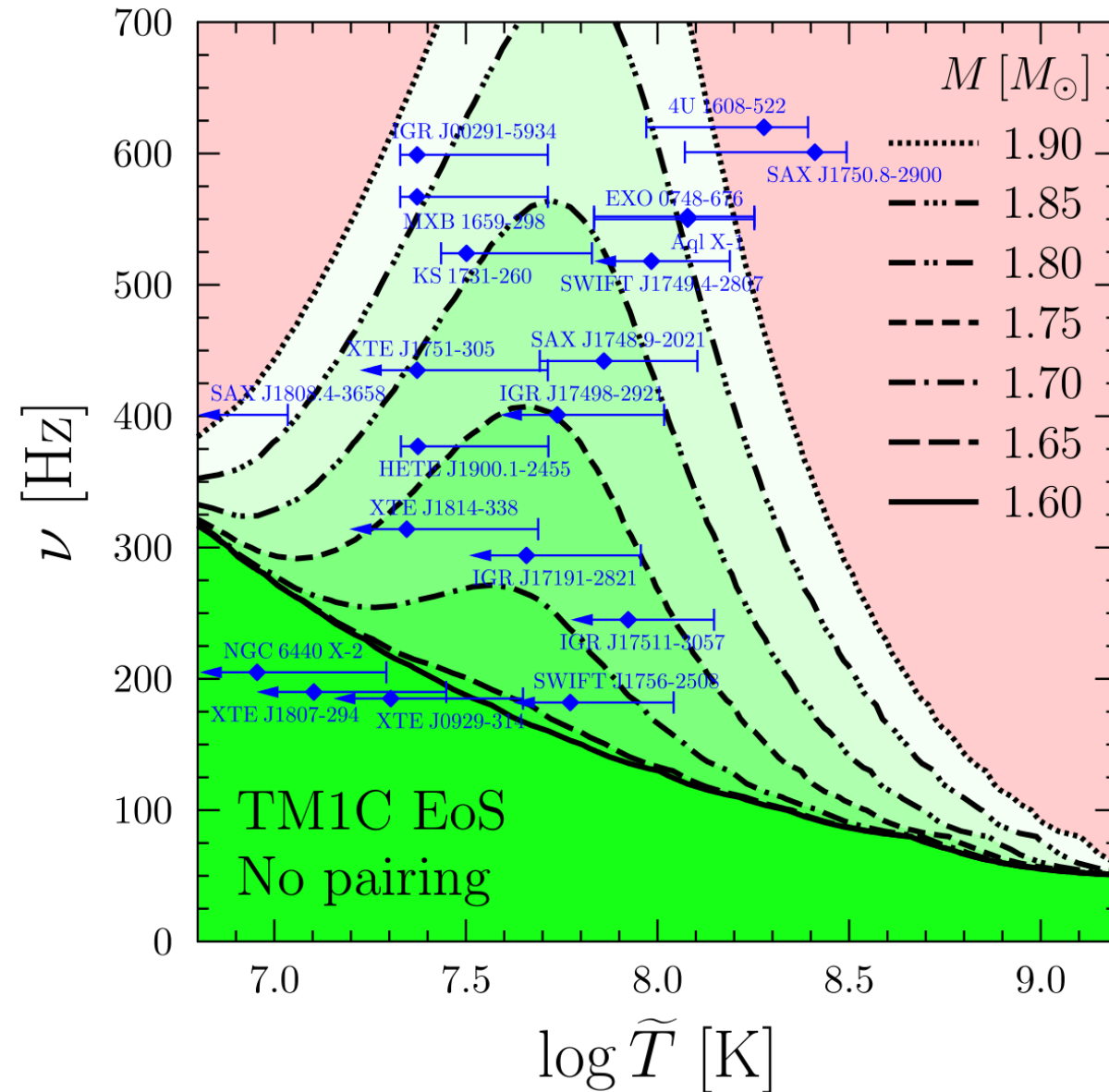
derivable for RMF EoSs

(Gusakov, Haensel, & Kantor'14)

- handy analytical fits $\zeta_{\max}(\rho)$ and $\lambda_{\max}(\rho)$ are built

$$\lambda_{\max} \sim \lambda_{\text{tot}}(T = 10^8 \text{K})$$

Instability Window with Hyperons



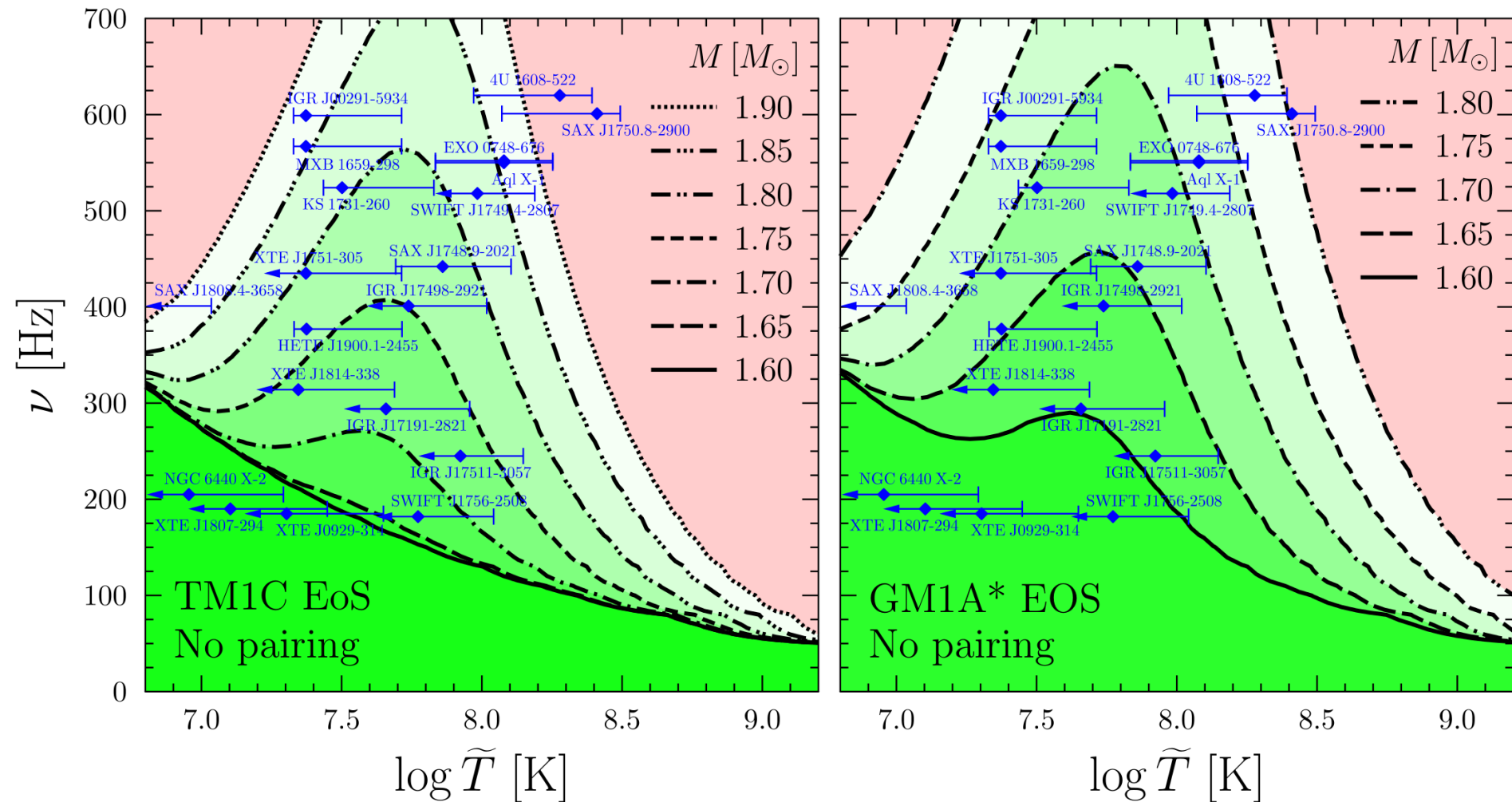
$$\tau_{\text{GW}}^{-1} + \tau_{\text{shear}}^{-1} + \tau_{\text{bulk}}^{-1} > 0$$

Stabilized $\tilde{T} <$ than in
Nayyar&Owen'06

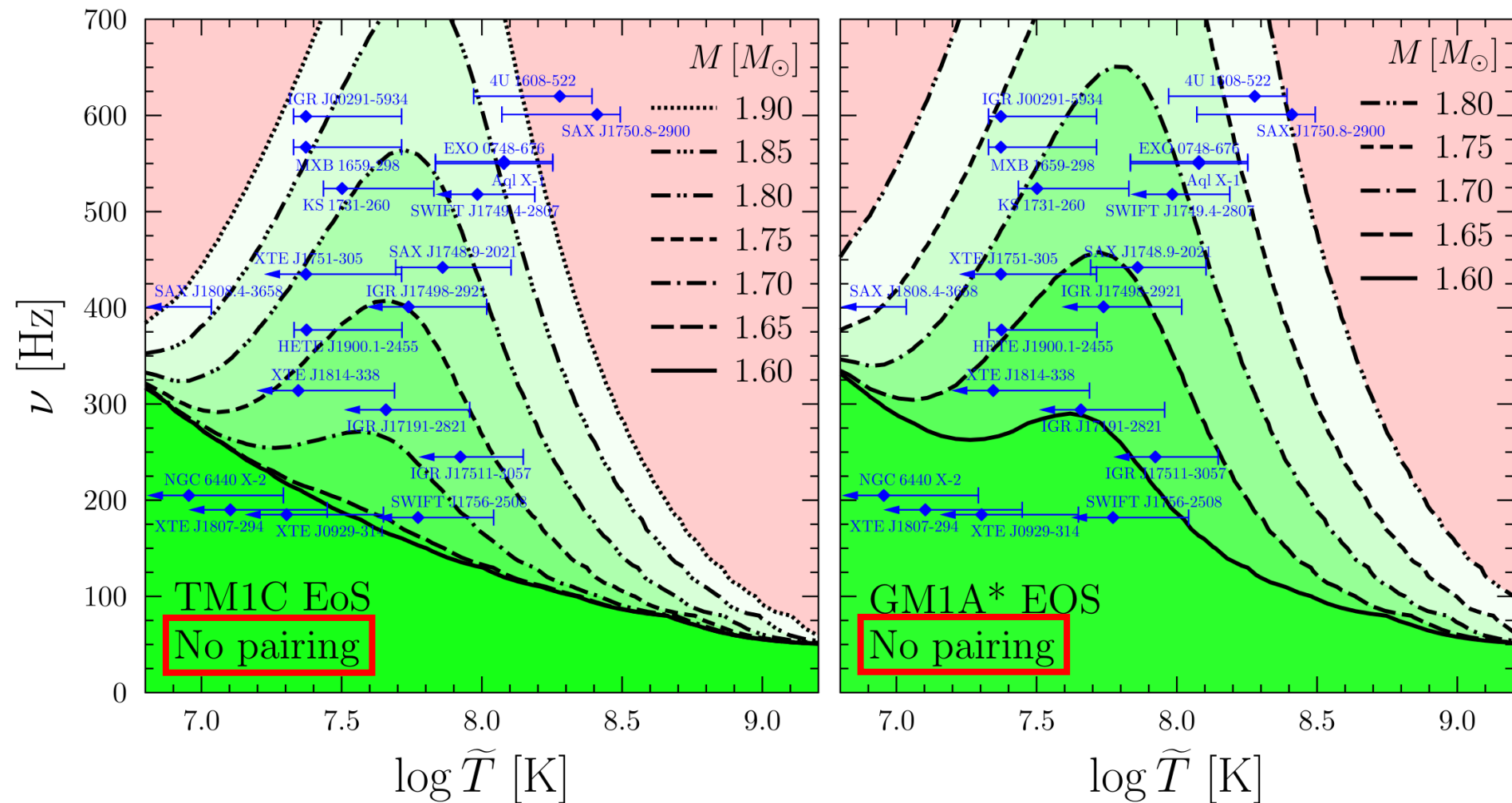
Reasons:

- different EoS
- more reactions
- OME channel
- pairing off ☹️

Instability Window with Hyperons



Instability Window with Hyperons



normal $p, \mathbb{E}^- \Rightarrow$ DURCA cooling $\Rightarrow \tilde{T} \sim 10^8$ K is too hot

Including Pairing

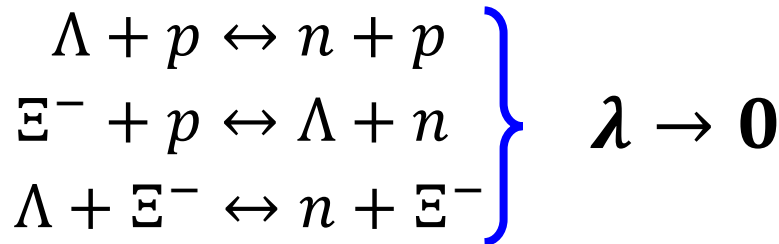
(e.g. Sedrakian & Clark'18)

$p, \Xi^-: T_c \gtrsim 10^9 \text{K} \longrightarrow$ adopt **all p, Ξ^- strongly paired**
 (cf. Nayyar&Owen'06: $T_{cp} \rightarrow 0$ in centers of high- M NSs)

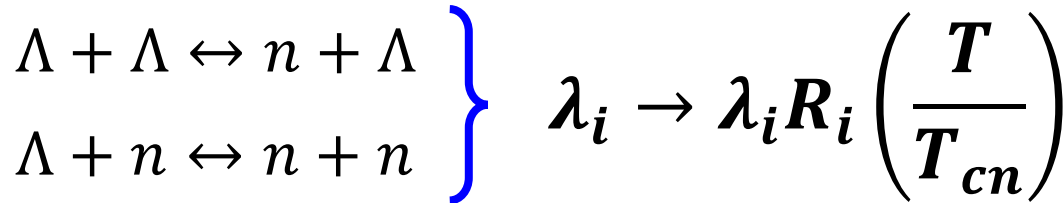
$n: T_c \sim 10^8 \text{K} \longrightarrow$ moderately paired n with some $T_{cn}(n_n)$

$\Lambda: T_c \lesssim 10^8 \text{K} \xrightarrow[\text{Takahashi+'08}]{\text{'Nagara event' (Takahashi+'01)}} \text{adopt all } \Lambda \text{ normal}$

$R(1n)$ is known
 (Haensel, Levenfish,
 & Yakovlev'02)



$R(3n)$ is calculated
 in this work

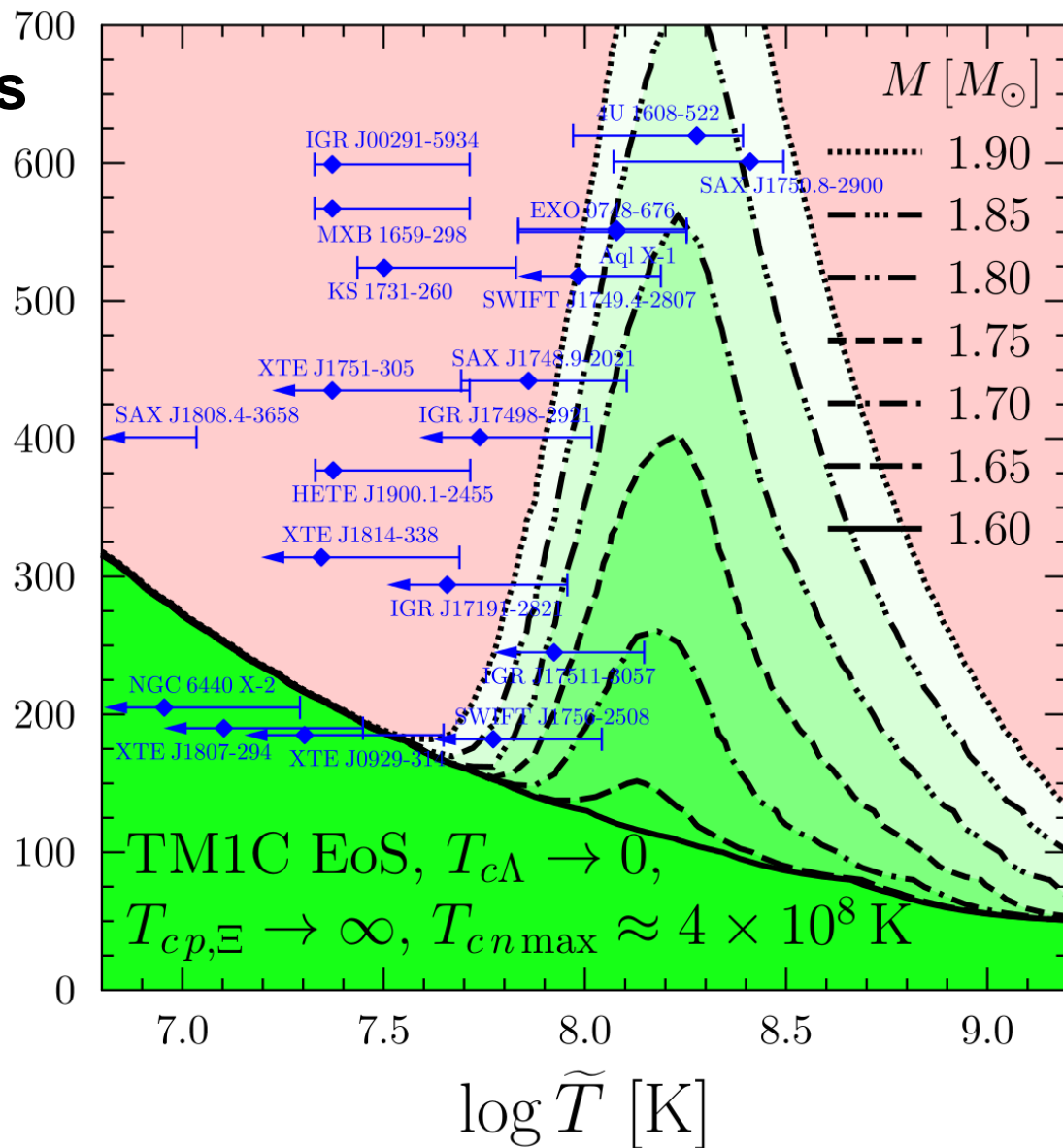
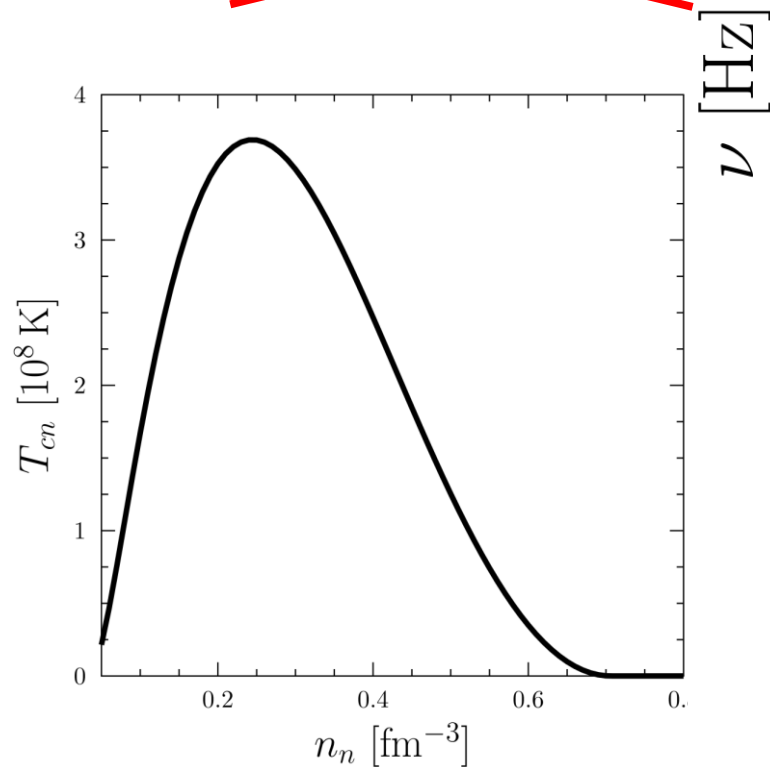


Hyperons + Pairing

- still explain some points

- p, Ξ^- off

~~DURCA cooling~~



Conclusions

- The bulk viscosity of the hyperonic NS cores is calculated self-consistently for several modern EoSs; all reactions for the $npe\mu\Lambda E^-$ composition are considered
- At least several LMXB's can be explained by the hyperonic bulk viscosity even within conservative pairing models
- The reactions with neutral particles ($\Lambda n \leftrightarrow nn$ and $\Lambda\Lambda \leftrightarrow n\Lambda$) are especially important for the r-mode instability window calculations
- Handy analytical fits for the reaction rates and the bulk viscosity are given; they are approximately valid for a number of EoS models

Further work

- more pairing reduction factors
- detailed effective pion mass
- superfluid hydrodynamics
- more calibrated EoSs
- fits for pairing reduction factor

Thank you!

Effect of pion mass renormalization

