Ioffe Institute

Department of Theoretical Astrophysics

Spectral Analysis of the Vela Pulsar and its Neutrino Cooling Rate

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The Modern Physics of Compact Stars and Relativistic gravity

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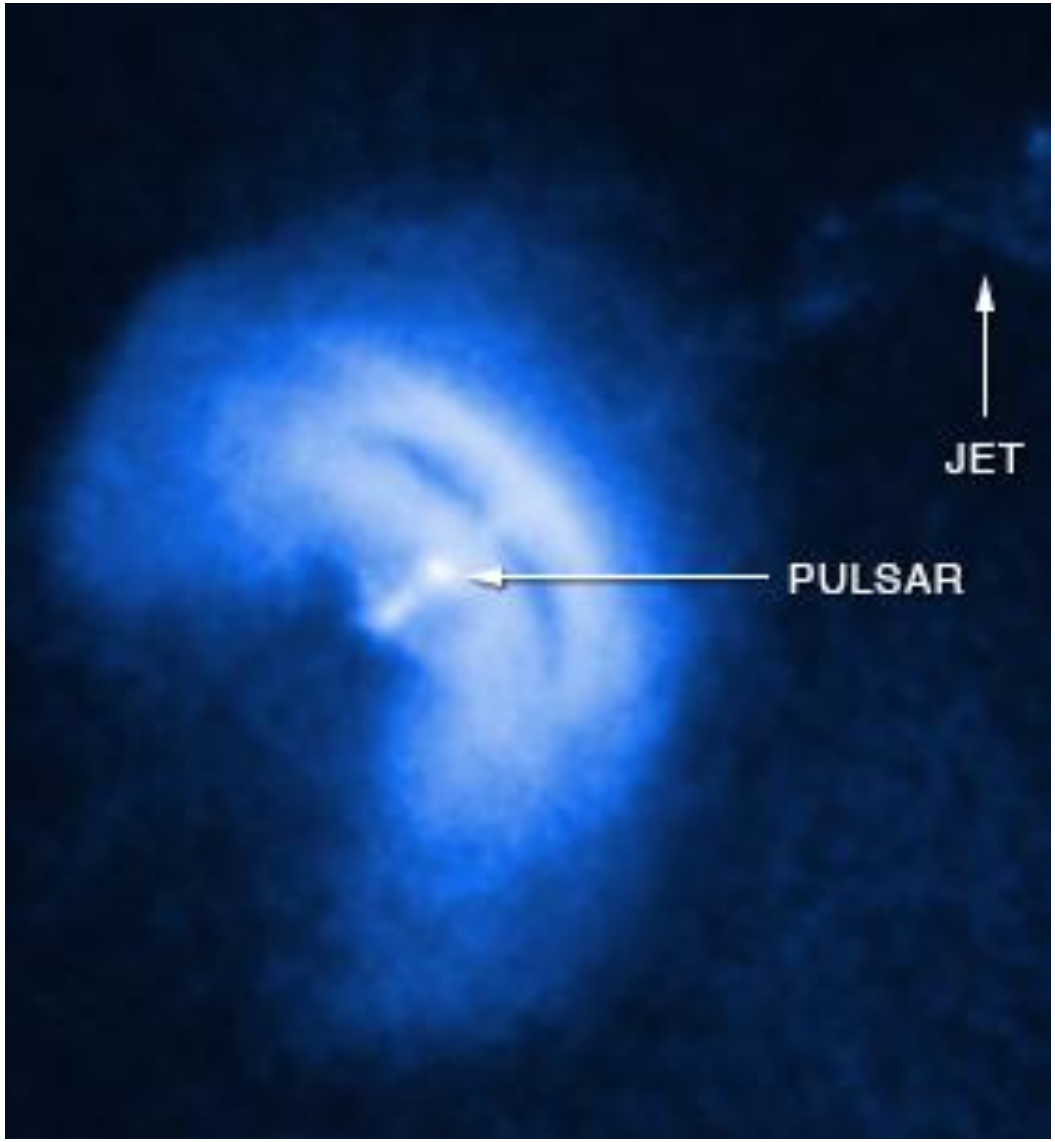
Plan

1) **Introduction: the Vela pulsar as a cooling neutron star**
2) **X-ray spectral analysis of the Vela pulsar**
   a. ***T_s measurement***
   b. ***M, R constraints***
3) **Cooling analysis with the Minimal Cooling Paradigm**
   a. ***Neutron star cooling***
   b. ***Minimal cooling & its simplifications***
   c. ***Vela cooling analysis***
   d. ***Possible M, R constraints***
4) **Another solutions to the Vela cooling problem**
5) **Conclusions**

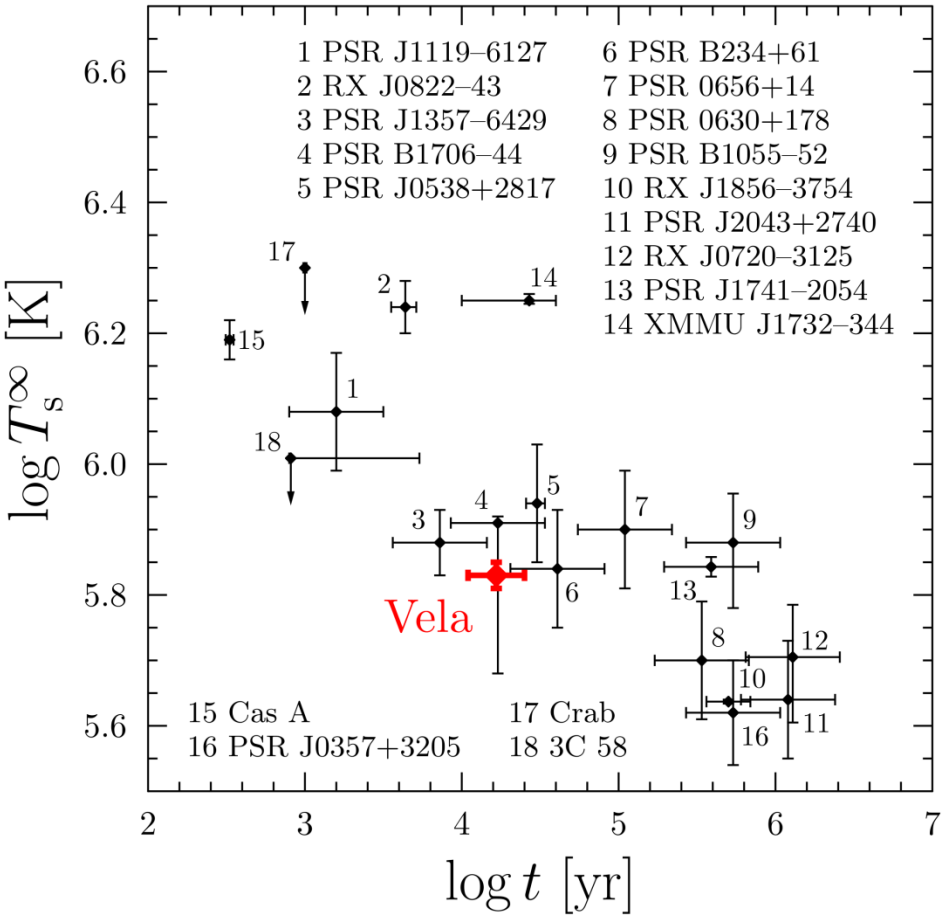
Vela Pulsar

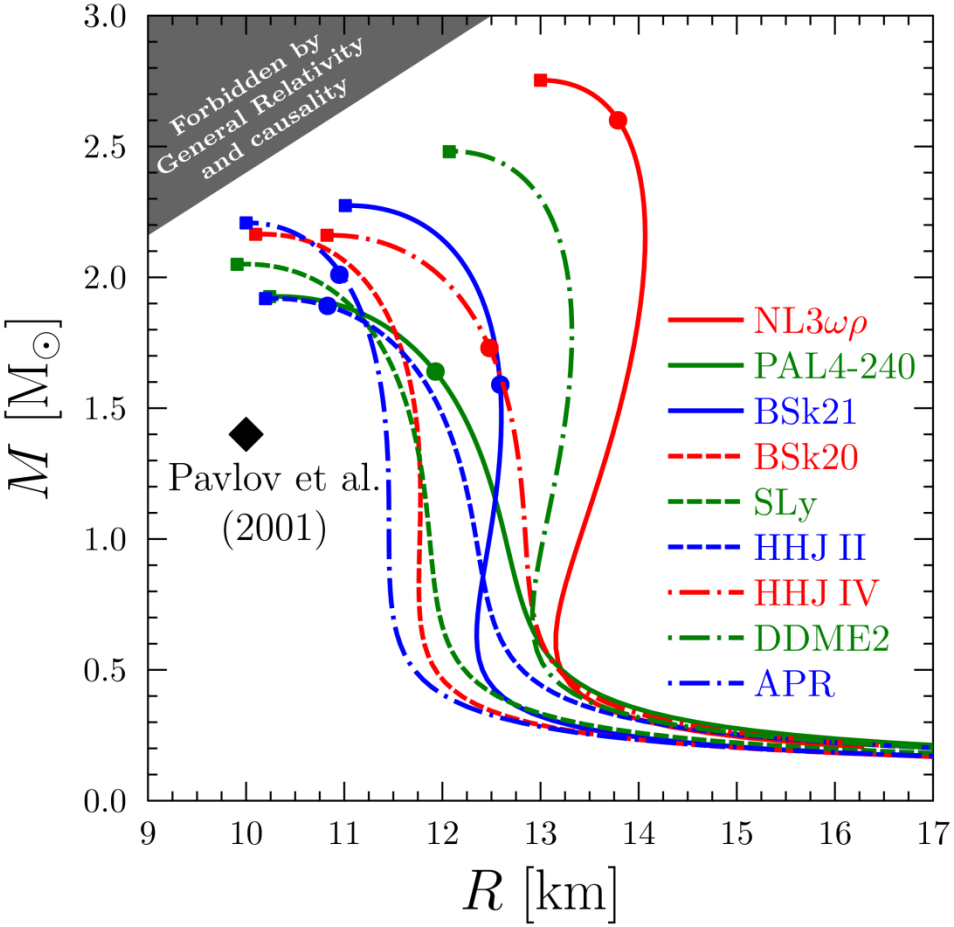


http://chandra.harvard.edu/photo/2013/vela/

- **PSR B0833-45**
- $d = 287^{+19}_{-17}$ pc
  (Dodson et al. 2003)
- $t = 11 - 25$ kyr
- $B_{\rm surf} = 3.38 \times 10^{12}$ G
  (ATNF catalogue)
- ***Spectral analysis Pavlov et al. (2001)***
  - $H + B +$ p. l. atm. model
  - $M = 1.4 M_\odot$
  - $R = 10$ km
  - $T_s^\infty = 0.68 \pm 0.03$ MK, $d = 210 \pm 10$ pc

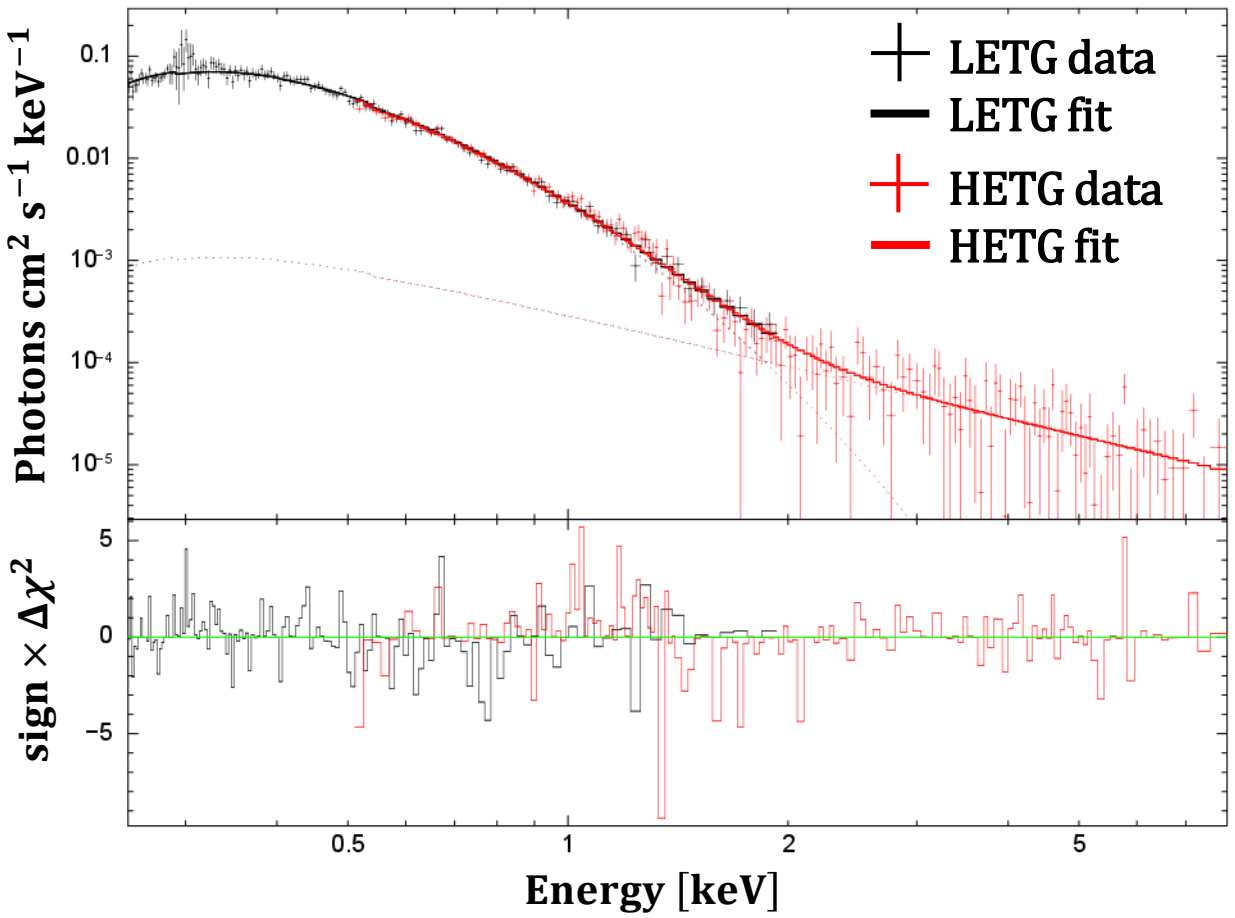
Reasons for New Analysis





- **One of the coldest for its age**
- **New observations appeared**
- **M and R should be different**
- **The distance became known**

Chandra Observations and Vela Spectral Analysis



Observations

- 12 oct 1999
- 28 jan 2000

} Pavlov et al. (2001)

- 12 jan 2001

Atmosphere model

$H + B +$ power law

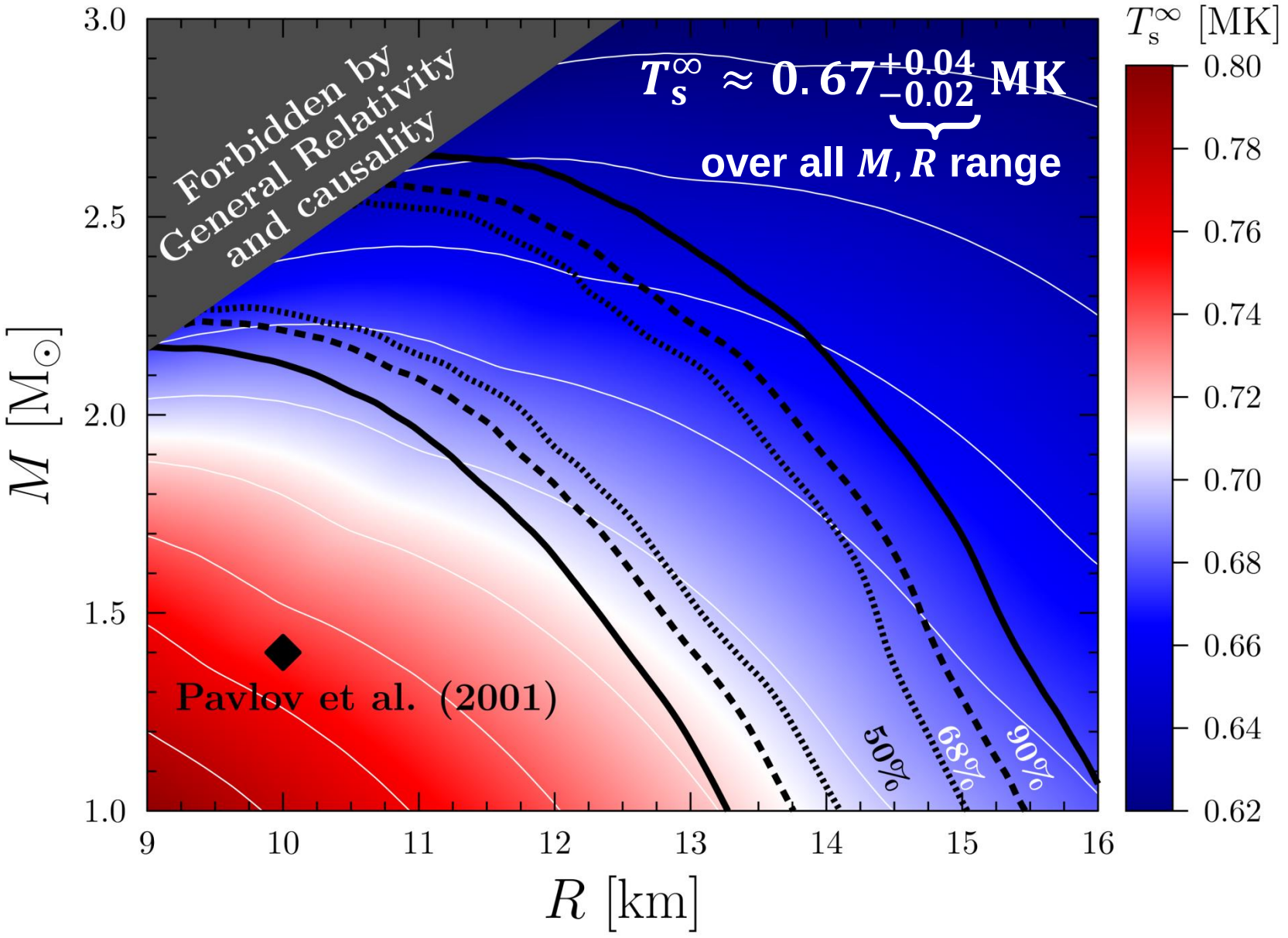
$d = 290$ pc

$M = 1 \ldots 3\ \mathrm{M}_\odot$

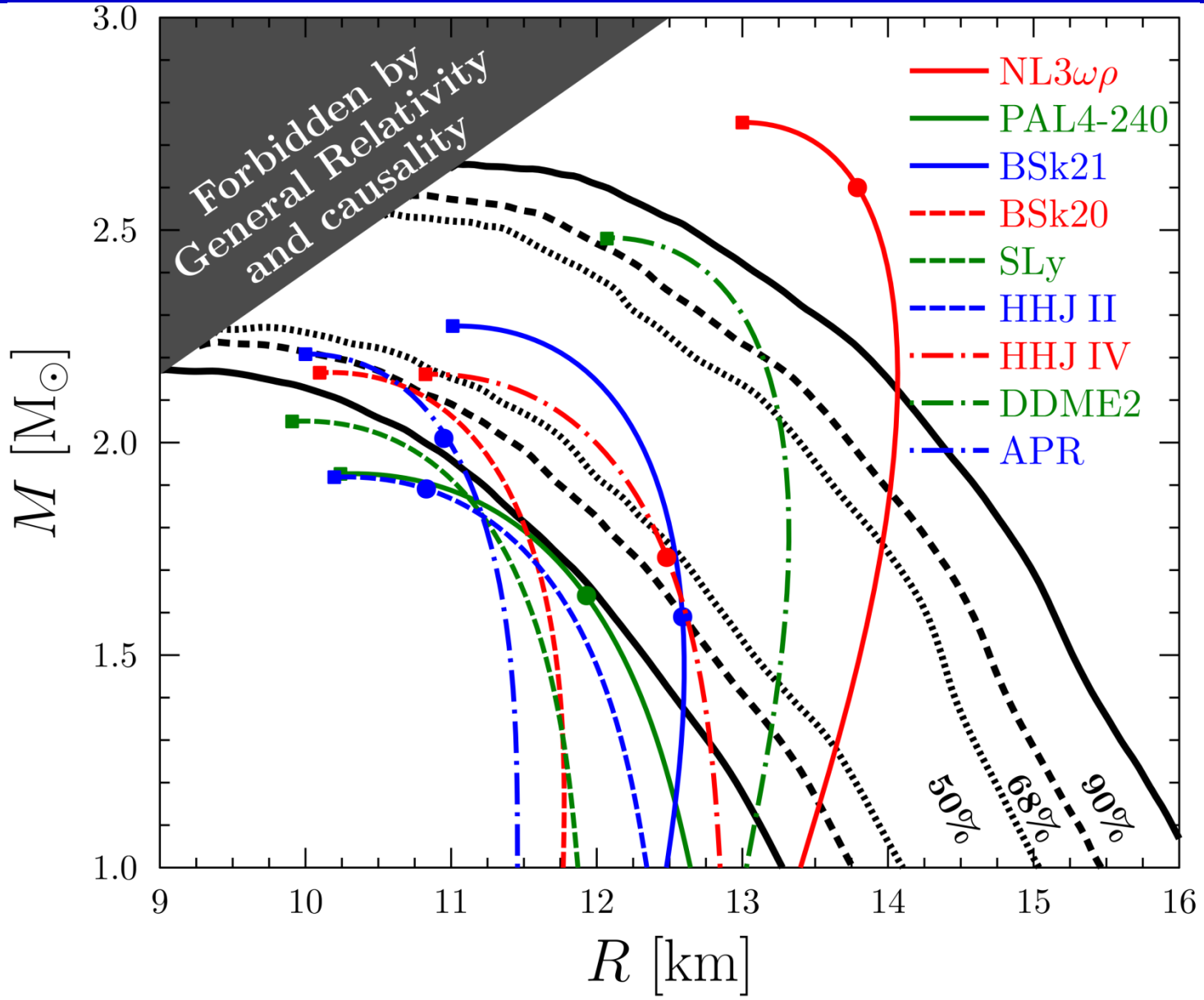
$R = 9 \ldots 16$ km

Each (M, R) ⟶ min χ^2, best-fit T_s^∞

Results of Spectral Analysis



Results of Spectral Analysis



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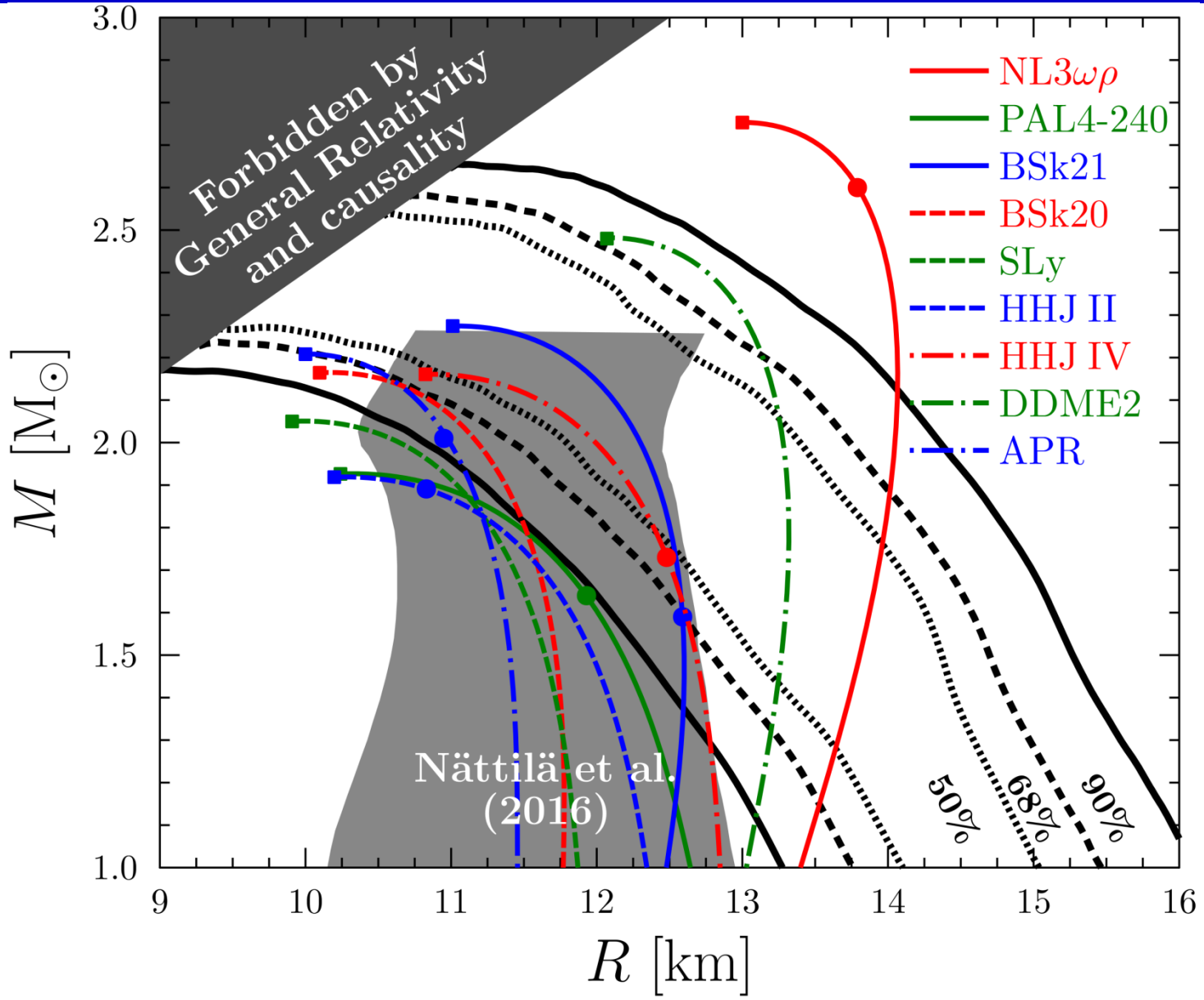
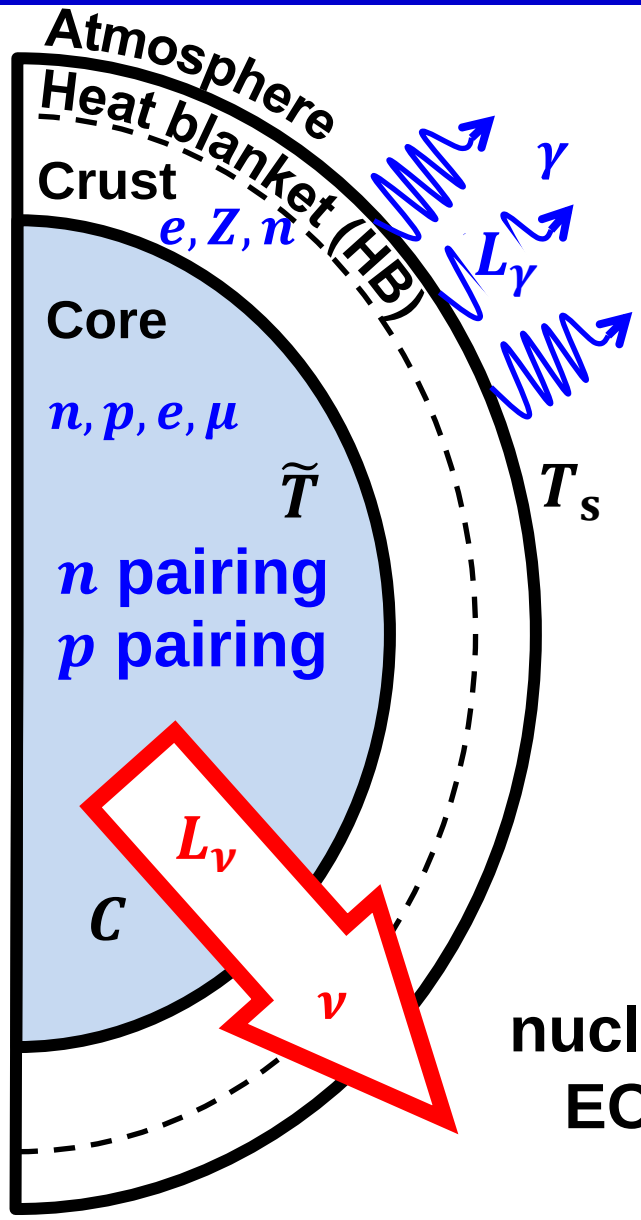


Cooling of Neutron Stars



- *Blaschke, Gigorian & Voskresensky (2004)*
  Yakovlev & Pethick (2004)
- $t \gtrsim 100\ \mathrm{yr} \Longrightarrow \widetilde{T} = T\sqrt{g_{00}} = \mathrm{const}$
- $\mathrm{depth} \lesssim 10\ \mathrm{m} \Longrightarrow$ heat blanket

$$T_s \xleftrightarrow[\text{Potekhin et al. (2003)}]{\Delta M_{\mathrm{acc}},\, B_{\mathrm{surf}}} \widetilde{T}$$

- $t \lesssim 100\ \mathrm{kyr} \Longrightarrow L_\gamma \ll L_\nu$

Vela is ν-cooling

- $B \lesssim 10^{14}\ \mathrm{G}$ does not affect ν-cooling
- MINIMAL COOLING PARADIGM
  (Gusakov et al. 2004, Page et al. 2004)

nucleon EOS

full $1S_0$ p pairing

~~MUrca~~, ~~DUrca~~, ~~C_{proton}~~

$3P_2$ n pairing

L_ν from Cooper pairing

Cooling via Cooper Pairing

$$L_{\nu \mathrm{CP}} = \int_{\mathrm{core}} Q_0 \frac{m_n^*}{m_n} \frac{p_{\mathrm{F}n}}{m_n c} T^7 F\left(\frac{T}{T_{\mathrm{crit}}}\right) \mathrm{g}_{00} \mathrm{d}V$$

(Leinson 2010)

$$C = \sum_{j=n,p} \int_{\mathrm{core}} C_{0j} \frac{m_j^*}{m_j} \frac{p_{\mathrm{F}j}}{m_j c} T R_j\left(\frac{T}{T_{\mathrm{crit}}}\right) \mathrm{d}V + C_{e\mu}$$

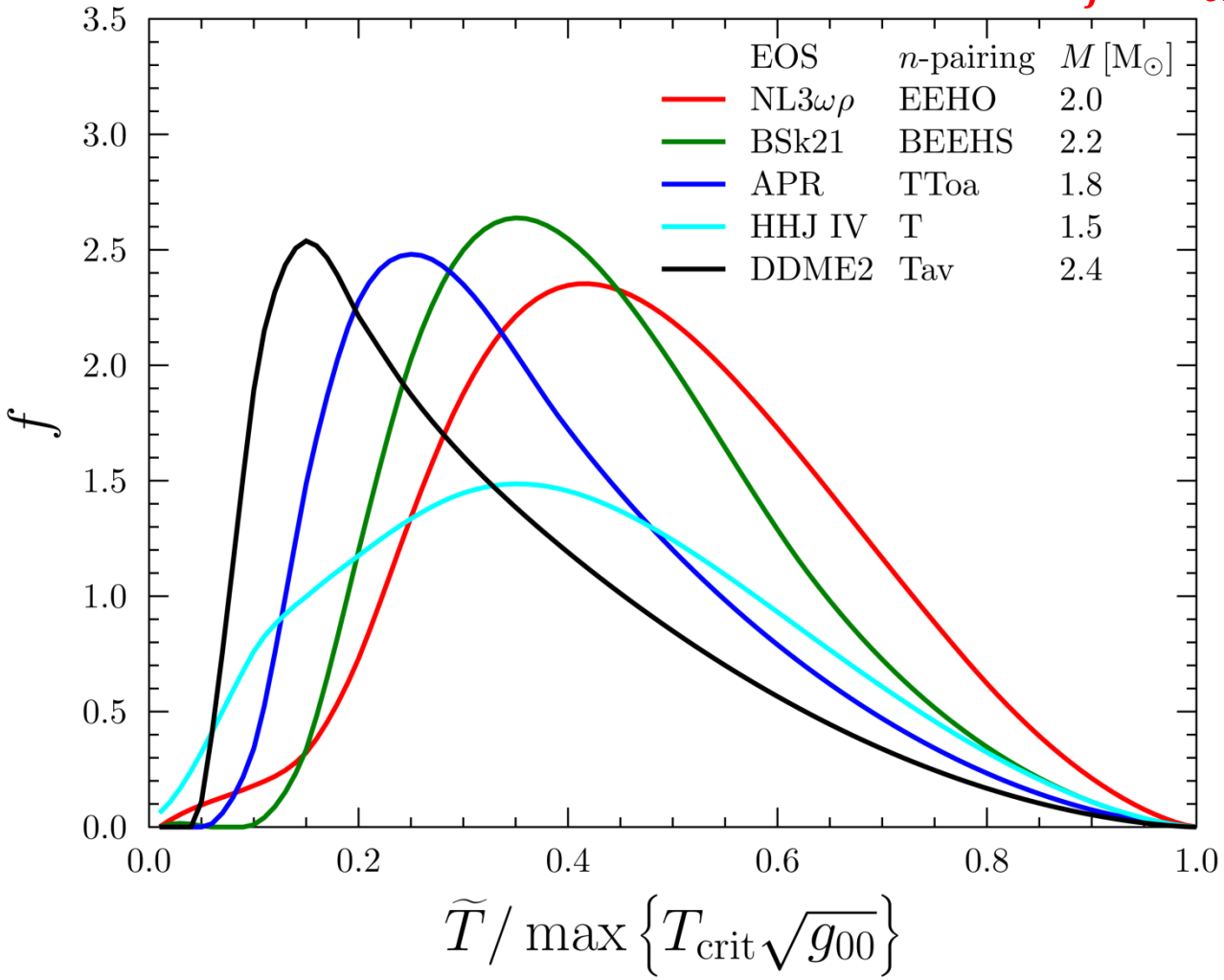
(Levenfish & Yakovlev 1994)

$$\frac{\mathrm{d}\tilde{T}}{\mathrm{d}t} = -\frac{L_{\nu \mathrm{CP}}}{C} = \underbrace{-f\left(\frac{\tilde{T}}{\max\{T_{\mathrm{crit}}\sqrt{g_{00}}\}}\right)}_{} \times \frac{L_{\nu \mathrm{CP}}|_{F(T/T_{\mathrm{crit}})=1}}{C|_{R_j(T/T_{crit})=1}}$$

includes all T/T_{crit} dependence

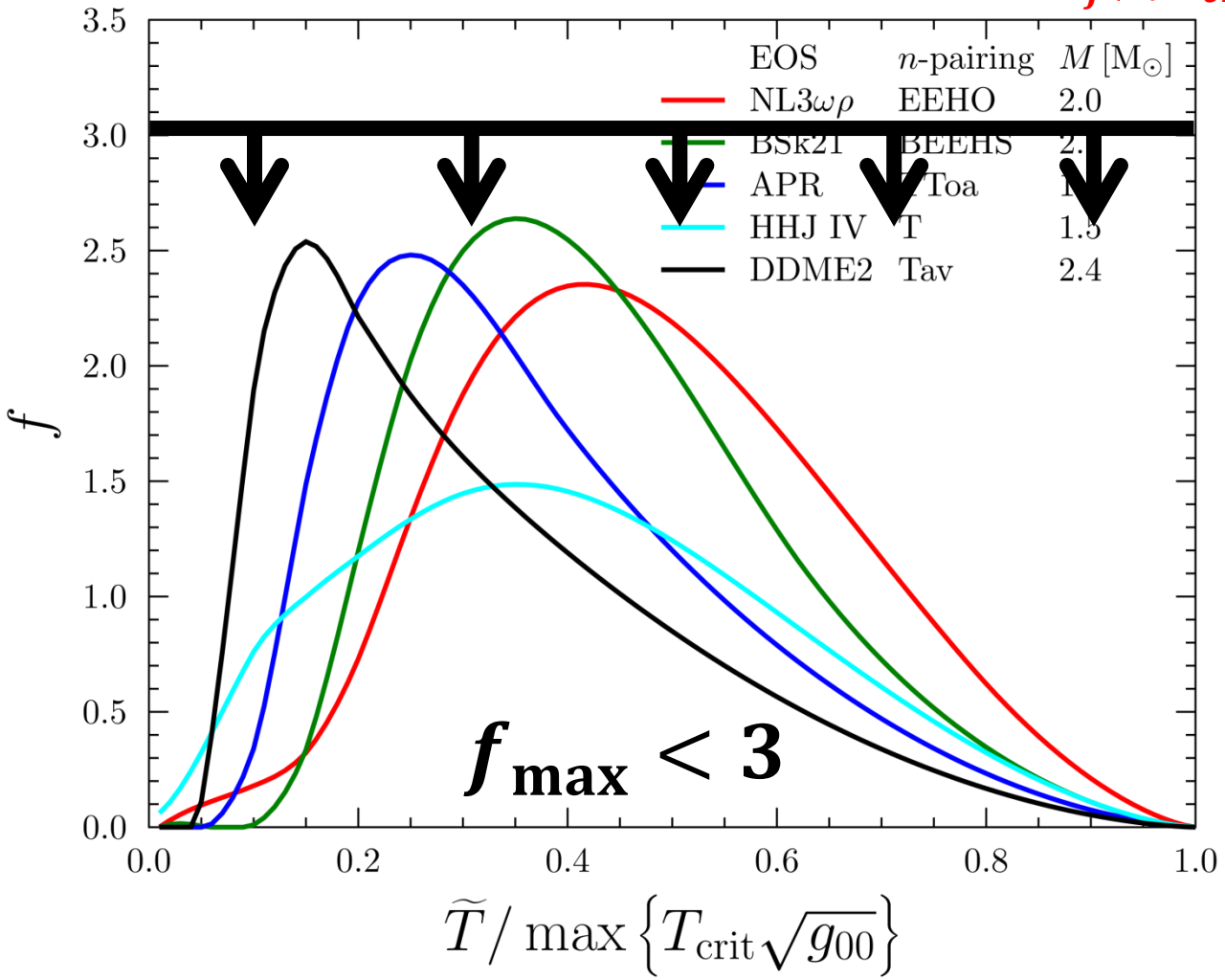
Simplified Cooling

$$\frac{d\widetilde{T}}{dt} = -\frac{L_{\nu CP}}{C} = -f\left(\frac{\widetilde{T}}{\max\{T_{crit}\sqrt{g_{00}}\}}\right) \times \frac{L_{\nu CP}|_{F(T/T_{crit})=1}}{C|_{R_j(T/T_{crit})=1}}$$



Simplified Cooling

$$\frac{d\tilde{T}}{dt} = -\frac{L_{\nu CP}}{C} = -f\left(\frac{\tilde{T}}{\max\{T_{crit}\sqrt{g_{00}}\}}\right) \times \frac{L_{\nu CP}|_{F(T/T_{crit})=1}}{C|_{R_j(T/T_{crit})=1}}$$



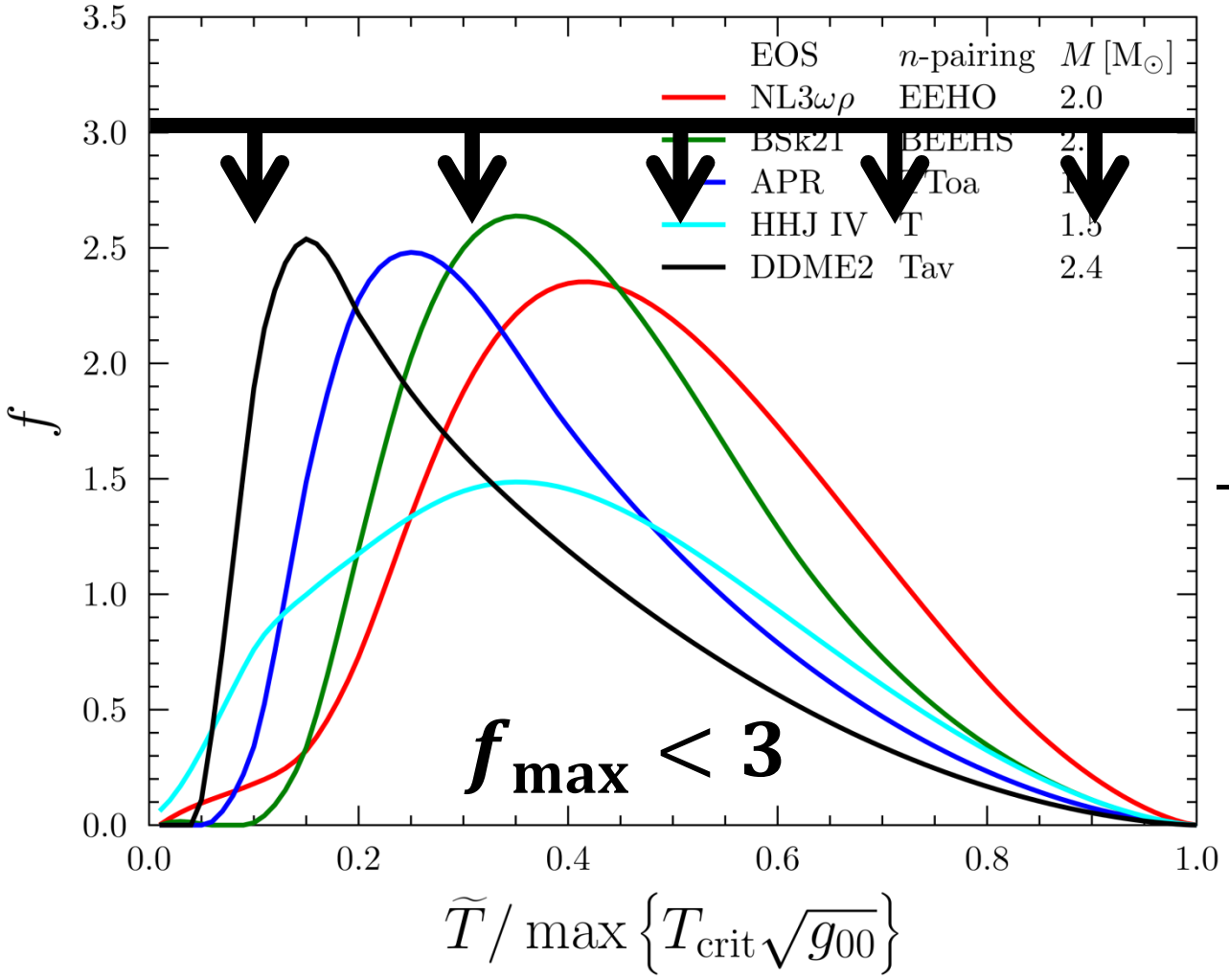
Simplified Cooling

$$\frac{d\tilde{T}}{dt} = -\frac{L_{\nu CP}}{C} = -f\left(\frac{\tilde{T}}{\max\{T_{crit}\sqrt{g_{00}}\}}\right) \times \underbrace{\frac{L_{\nu CP}|_{F(T/T_{crit})=1}}{C|_{R_j(T/T_{crit})=1}}}$$

$$\approx q(M,R)\tilde{T}^6$$

Universal for the wide range of EOSs

max error ~ 10%



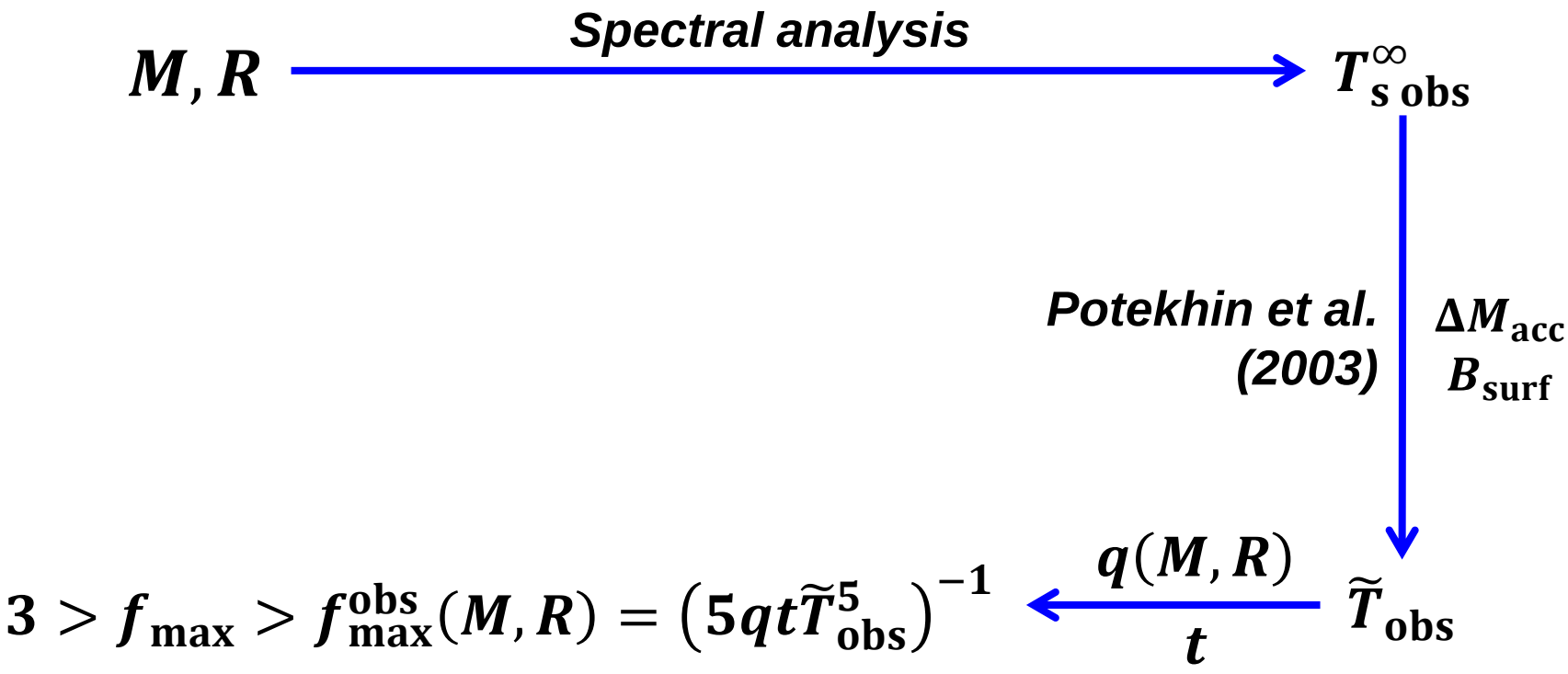
$$-\frac{d\tilde{T}}{dt} \le f_{max} q(M,R)\tilde{T}^6$$

$t \gg t_{pairing}$

$$\tilde{T} \gtrsim (5 f_{max} q t)^{-1/5}$$

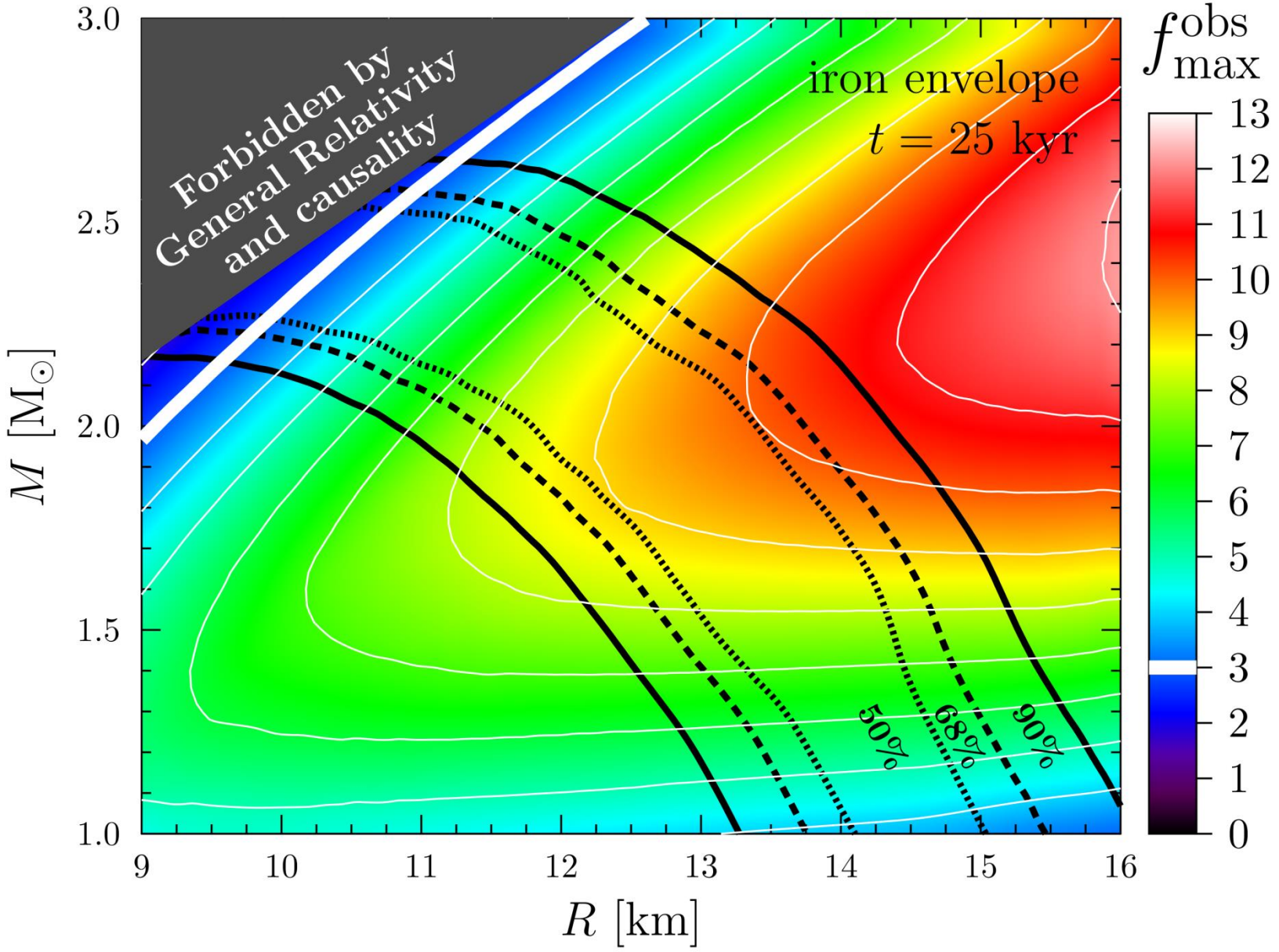
$$f_{max} \gtrsim \left(5 q t \tilde{T}^5\right)^{-1}$$

Vela Cooling Analysis

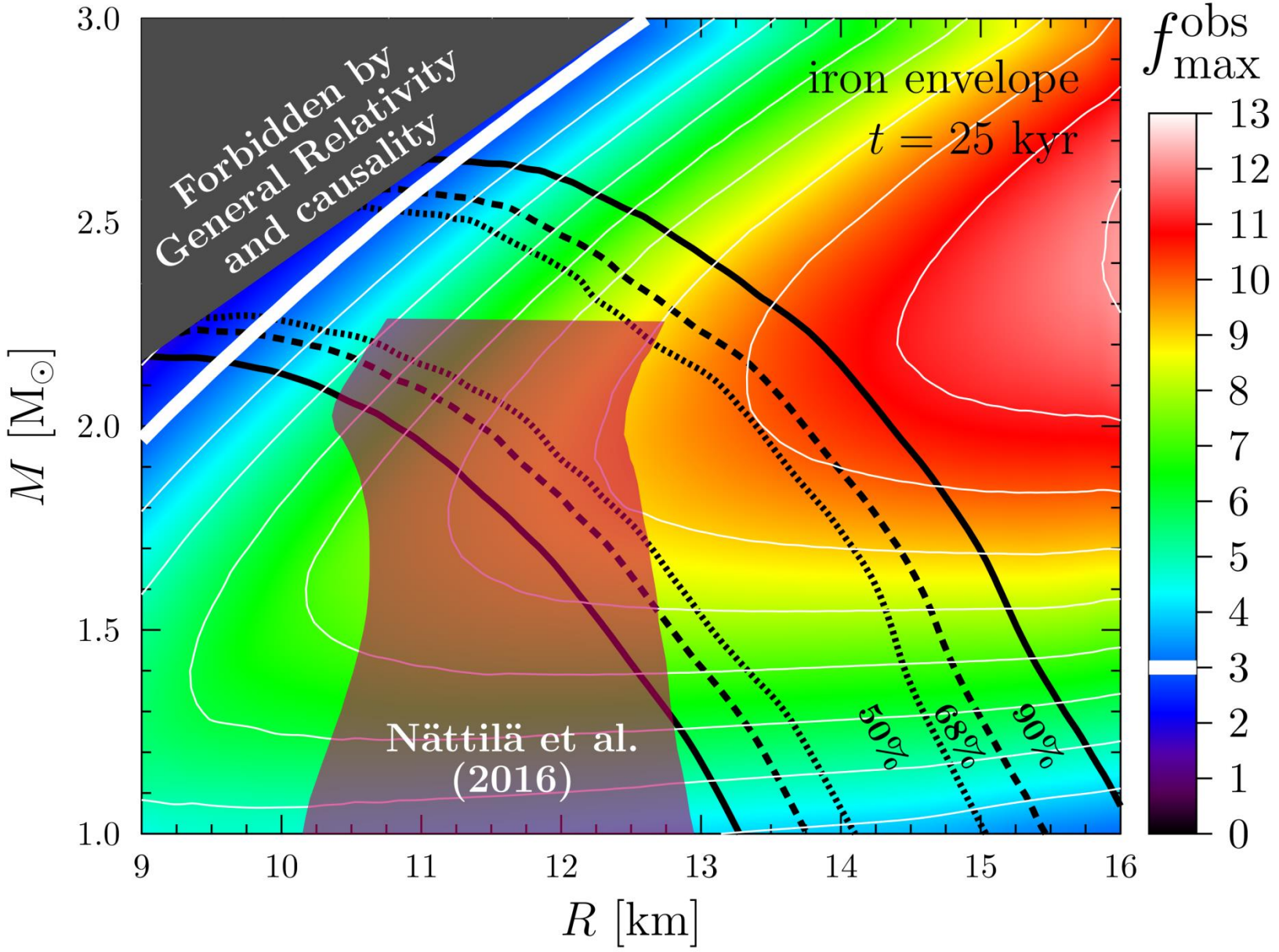


Restriction on Vela's M and R

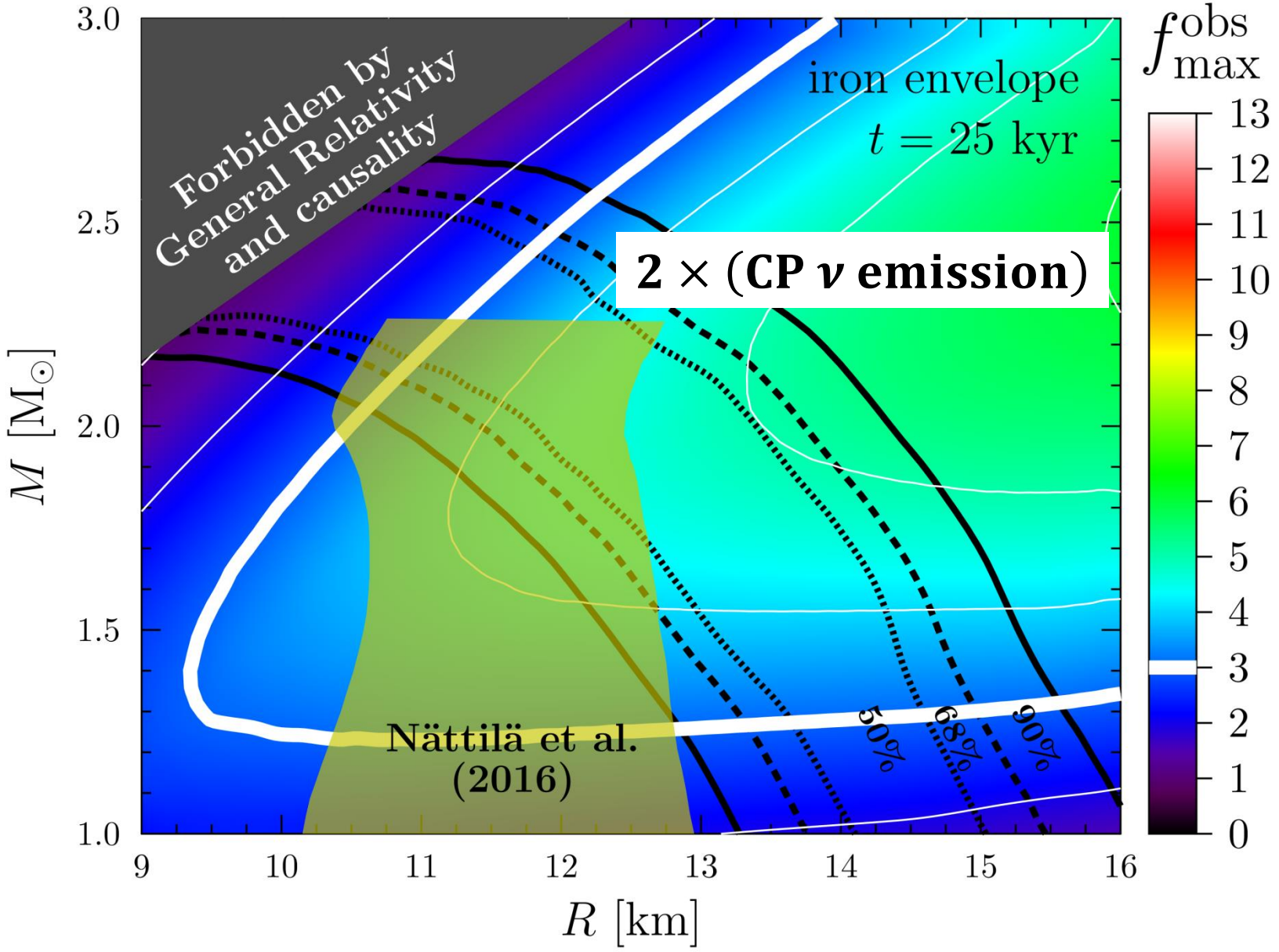
Vela Cooling Analysis



Vela Cooling Analysis

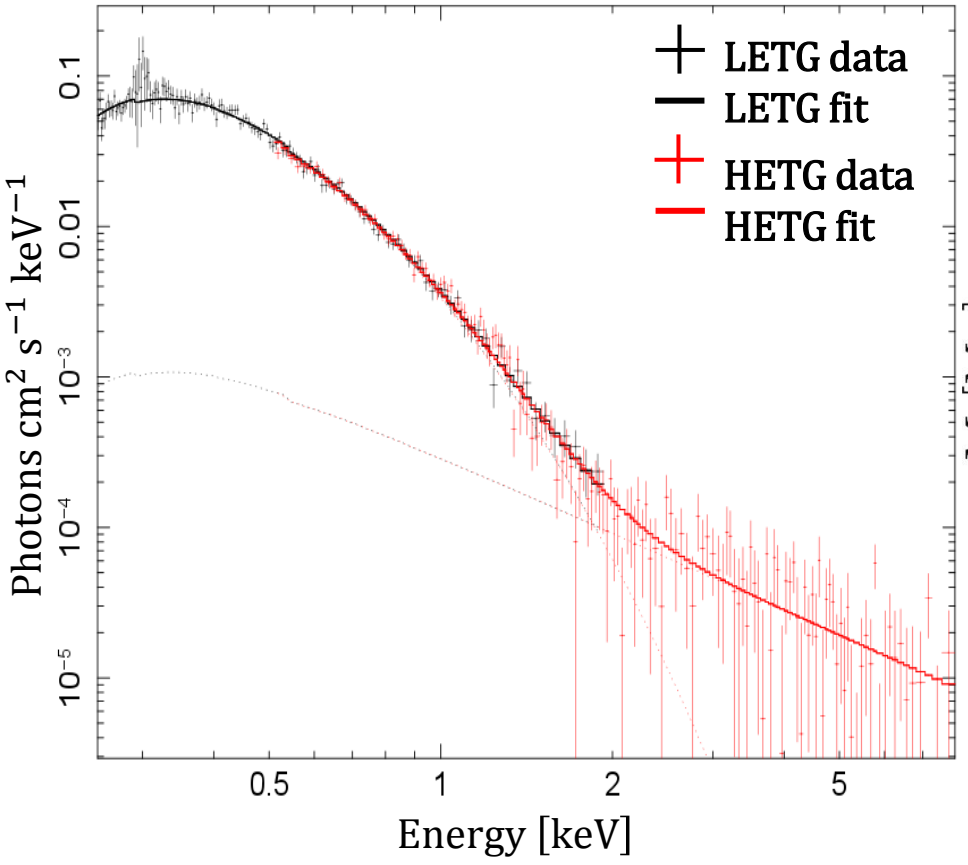


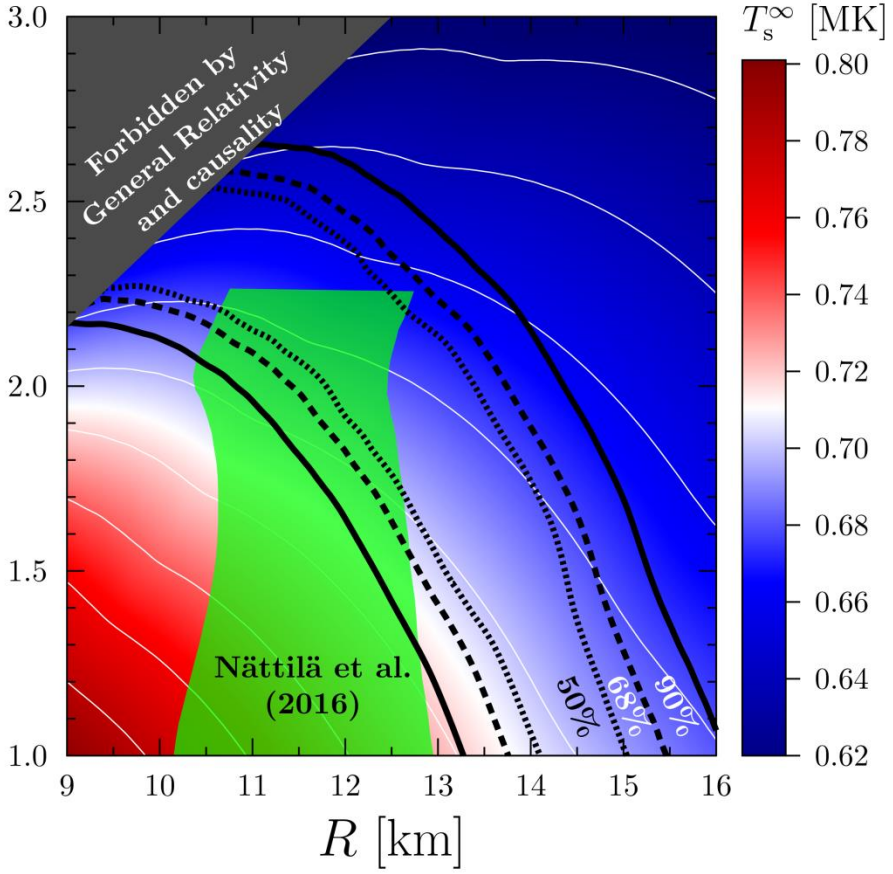
Vela Cooling Analysis



Another Solutions for Vela Cooling Problem

- **Another atmosphere model**
- **$3P_2$ proton pairing**
- **Hyperons**
- **Medium modified cooling**





Conclusions

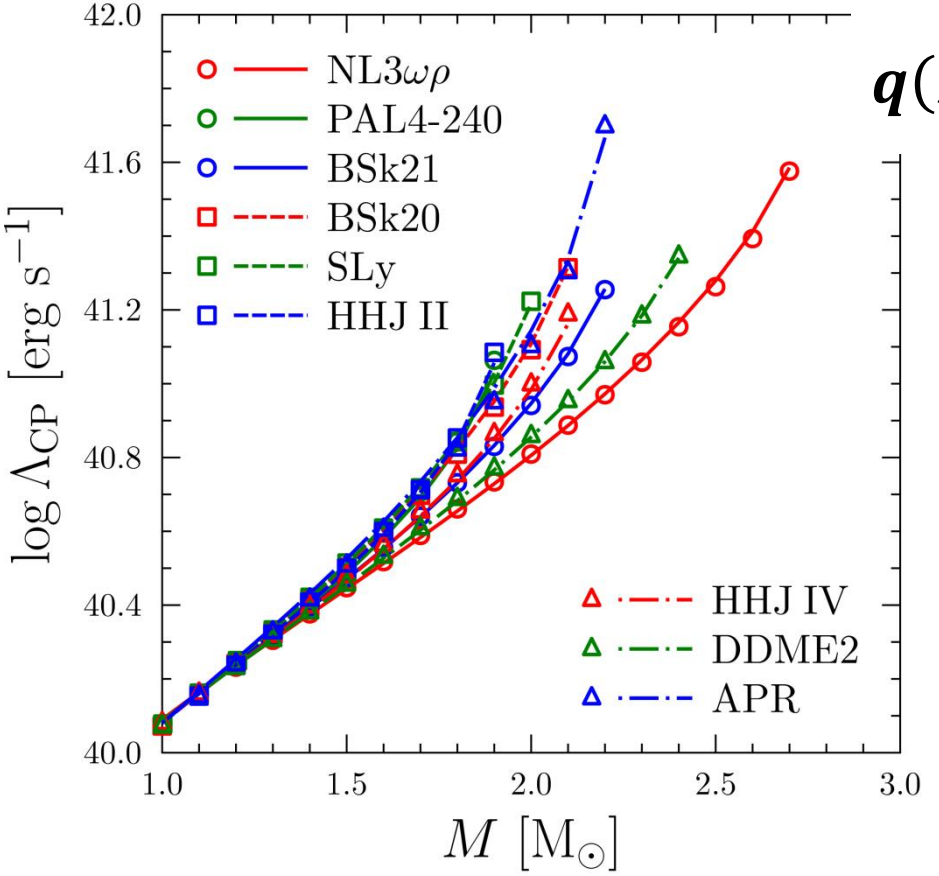
- The new spectral analysis of the Vela pulsar is performed. It shows that, while the Vela's T_s is consistent with earlier results, the star has likely either larger mass or larger radius.
- We analyze the Vela pulsar using the Minimal cooling paradigm. Our analysis represents properties of a wide range of EOS and $3P_2$ n superfluidity models.
- Under the Minimal cooling paradigm the observed Vela's T_s and t can be explained by employing an iron heat blanketing envelope model only.
- Restrictions coming from the properties of $3P_2$ n pairing models allow us to make additional stringent constraints on Vela's M and R. These constraints may be so stringent that the Minimal cooling paradigm meets with difficulties.

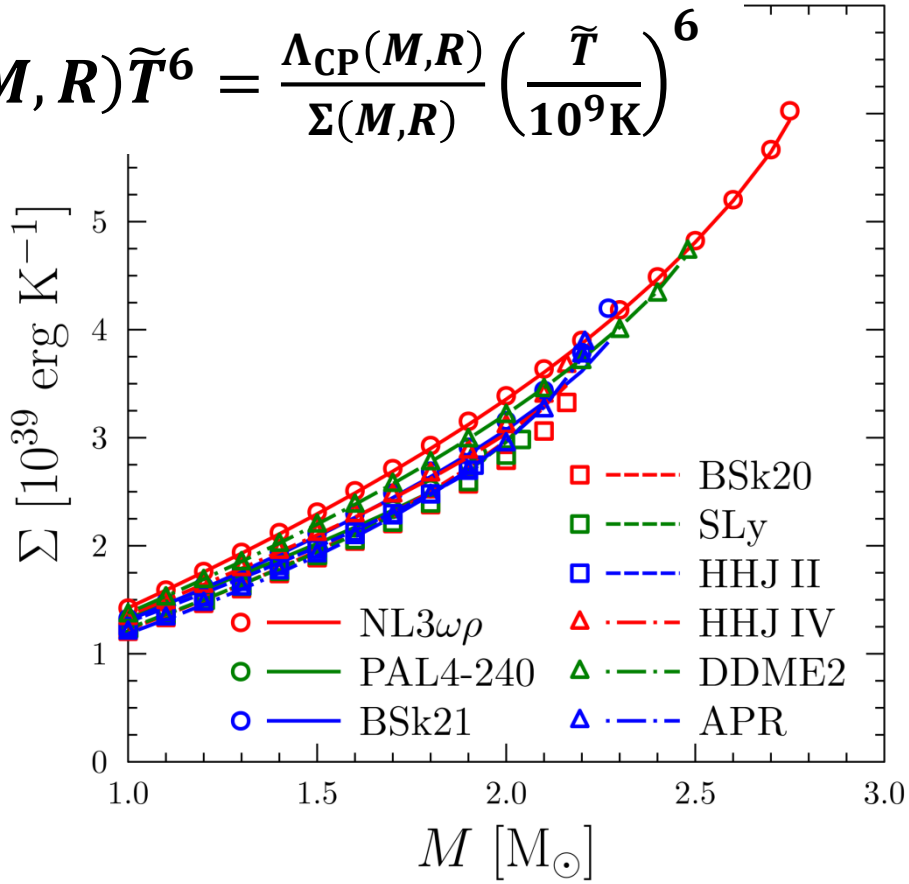
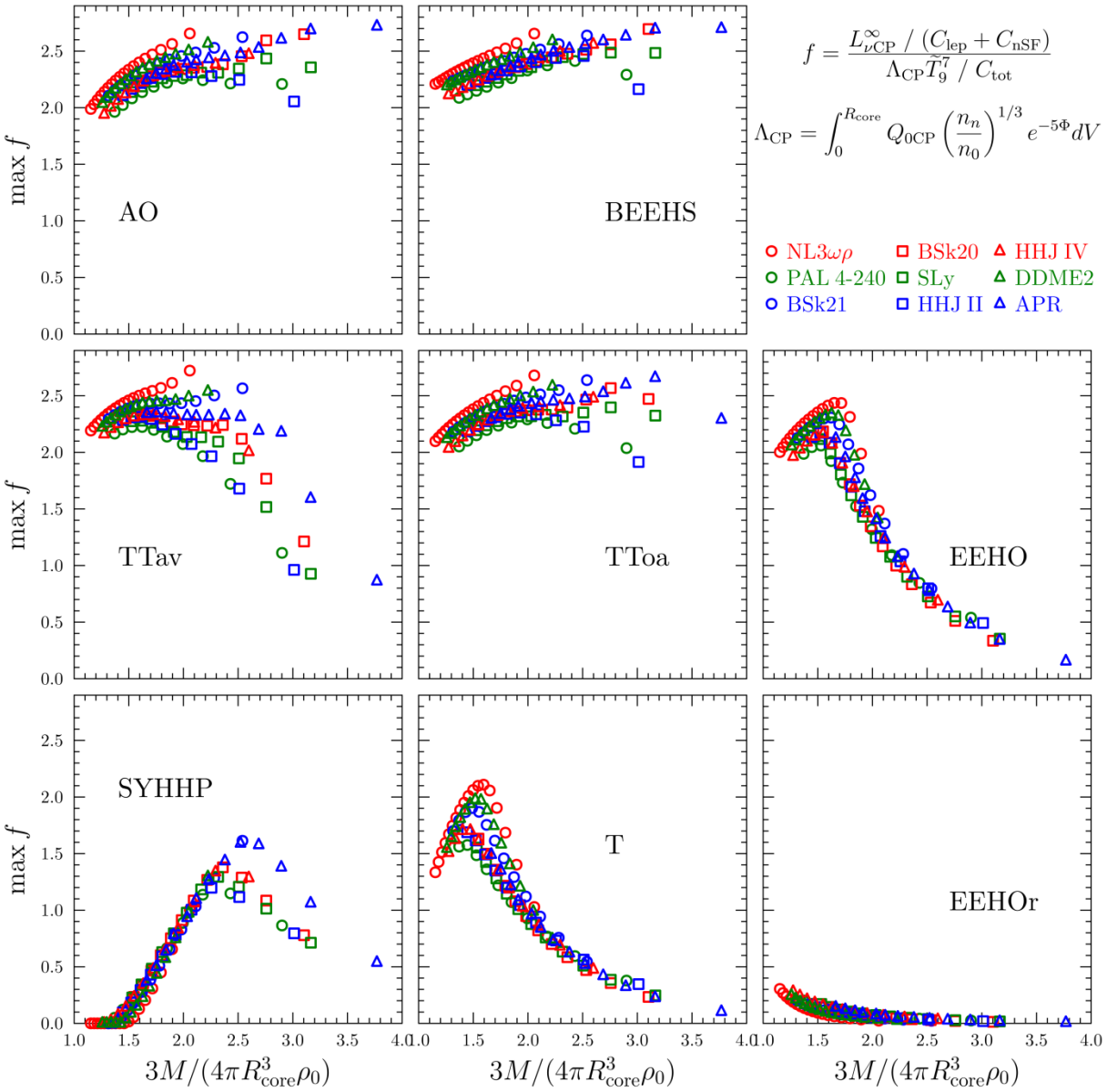
Thank you!

Approximate cooling function $q(M,R)$

$$L_{\nu CP}\Big|_{F(T/T_{crit})=1} \approx \Lambda(M,R)\left(\frac{\widetilde{T}}{10^9\mathrm{K}}\right)^7 \qquad C\Big|_{R_j(T/T_{crit})=1} \approx \Sigma(M,R)\frac{\widetilde{T}}{10^9\mathrm{K}}$$

$$q(M,R)\widetilde{T}^6 = \frac{\Lambda_{CP}(M,R)}{\Sigma(M,R)}\left(\frac{\widetilde{T}}{10^9\mathrm{K}}\right)^6$$





Exploring $f_{\max}$