Structure and Cooling of Compact Stars obeying Modern Constraints

David Blaschke (Wroclaw University, JINR Dubna)

compstar

Facets of Strong Interaction Physics, Hirschegg, January 17, 2012

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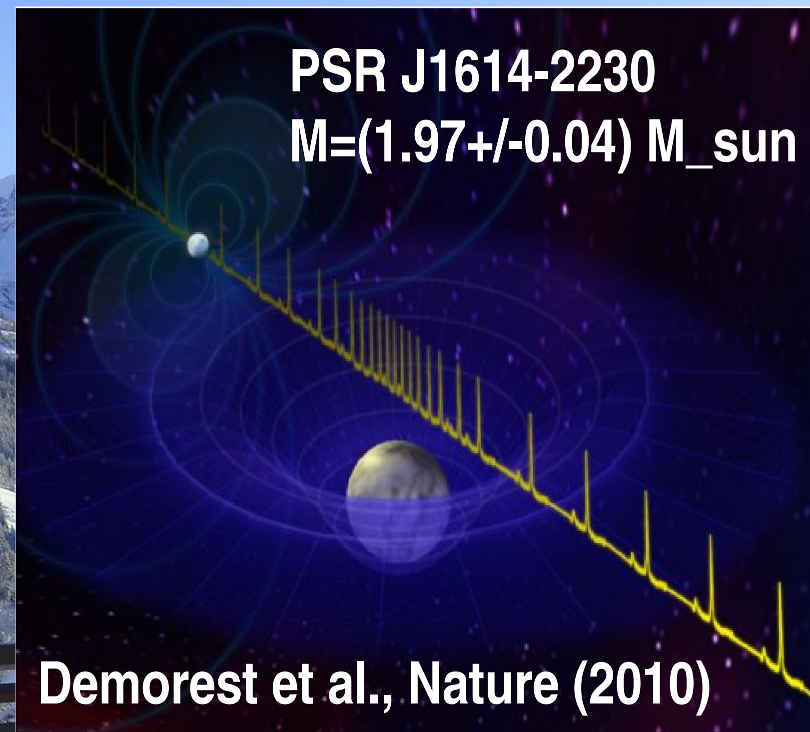

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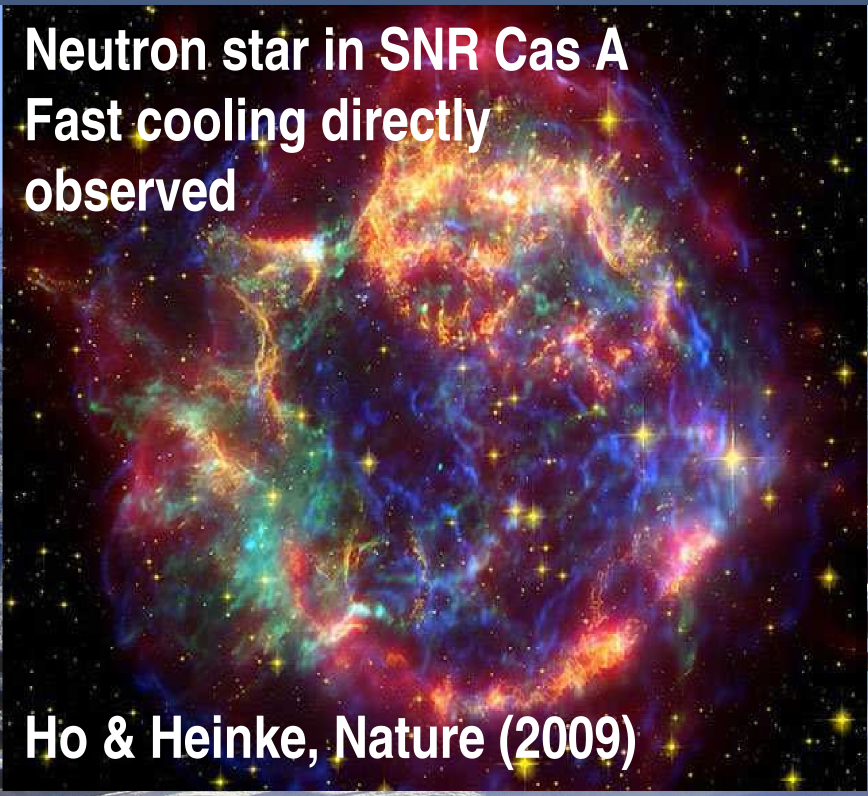

Facets of Strong Interaction Physics, Hirschegg, January 17, 2012

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Thanks to 'cool' coauthors: Hovik Grigorian, Fridolin Weber, Dima Voskresensky
and 'dense' ones: Thomas Klaehn, Rafal Lastowiecki, Fredrik Sandin, Daniel Zablocki

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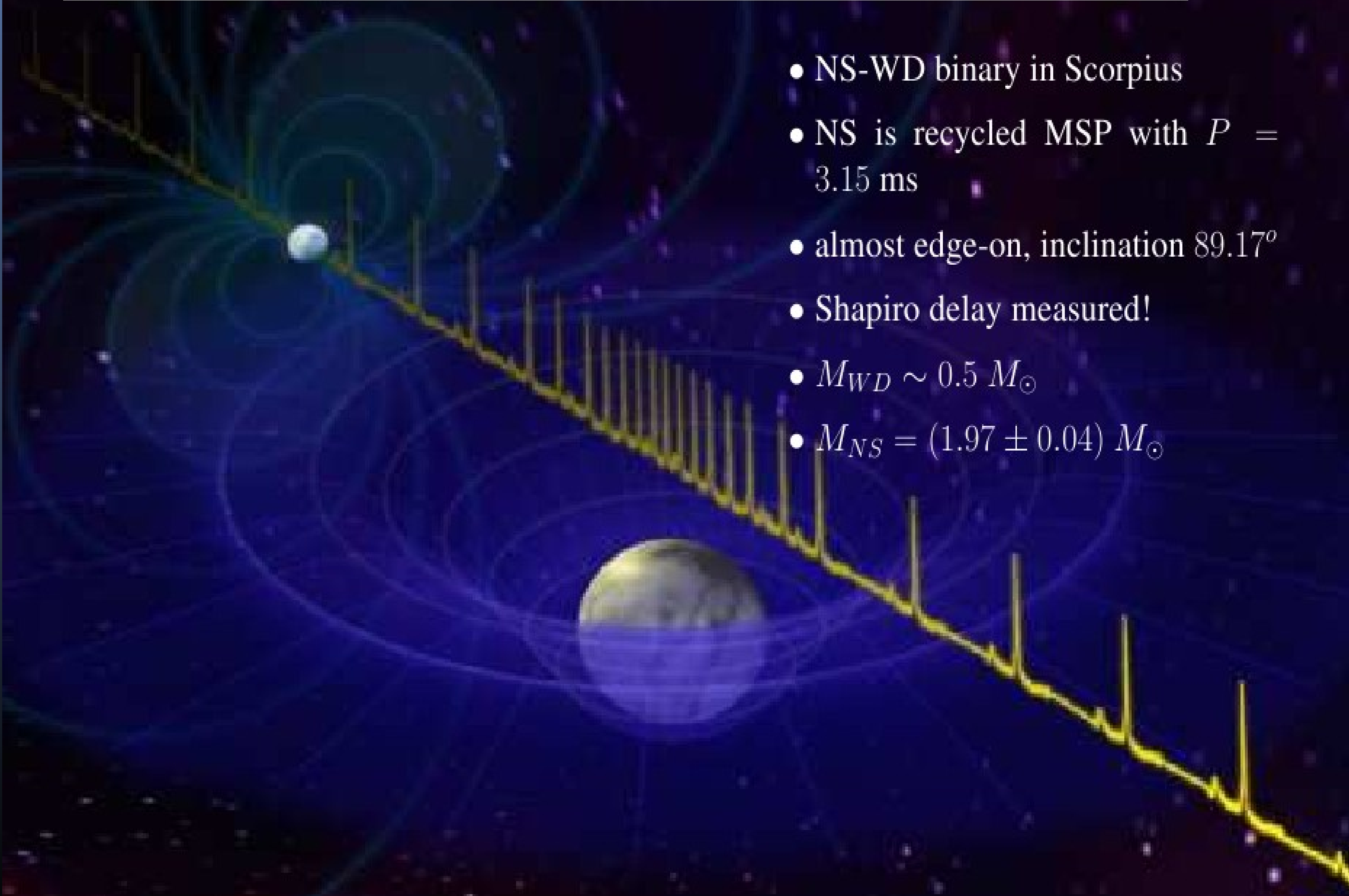
PSR J1614-2230 - A new constraint for the Compact Star EoS



- NS-WD binary in Scorpius
- NS is recycled MSP with $P = 3.15$ ms
- almost edge-on, inclination 89.17^o
- Shapiro delay measured!
- $M_{WD} \sim 0.5\ M_\odot$
- $M_{NS} = (1.97 \pm 0.04)\ M_\odot$

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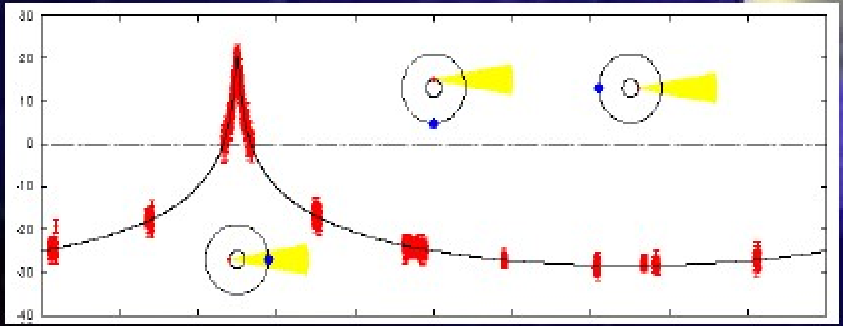

Demorest et al., Nature 467, 1081 (2010)

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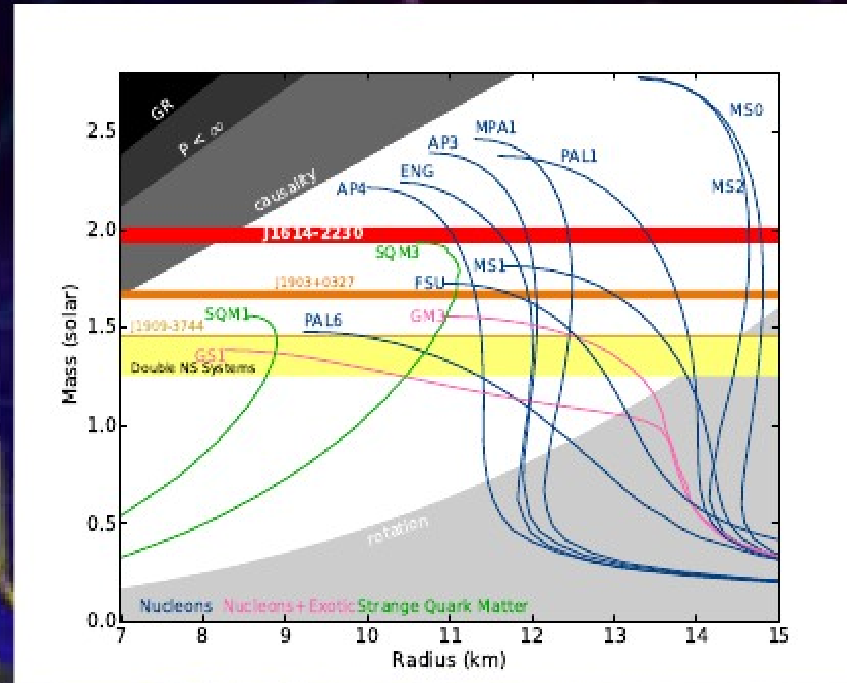

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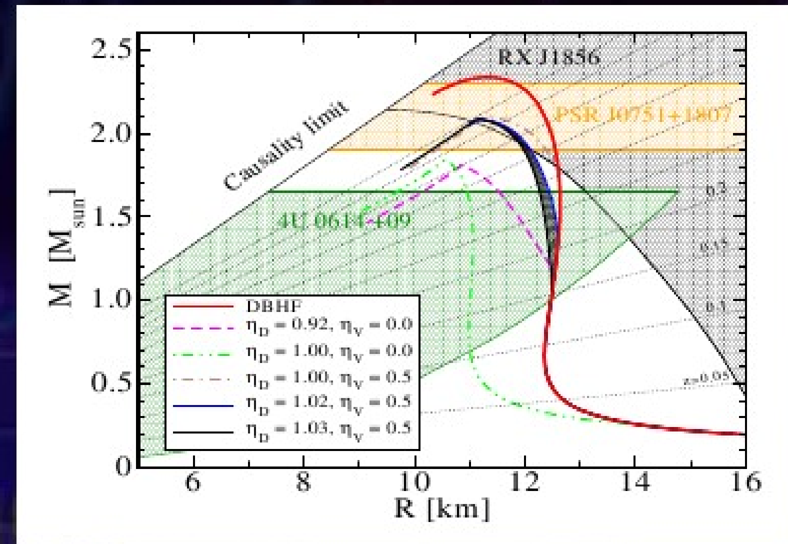
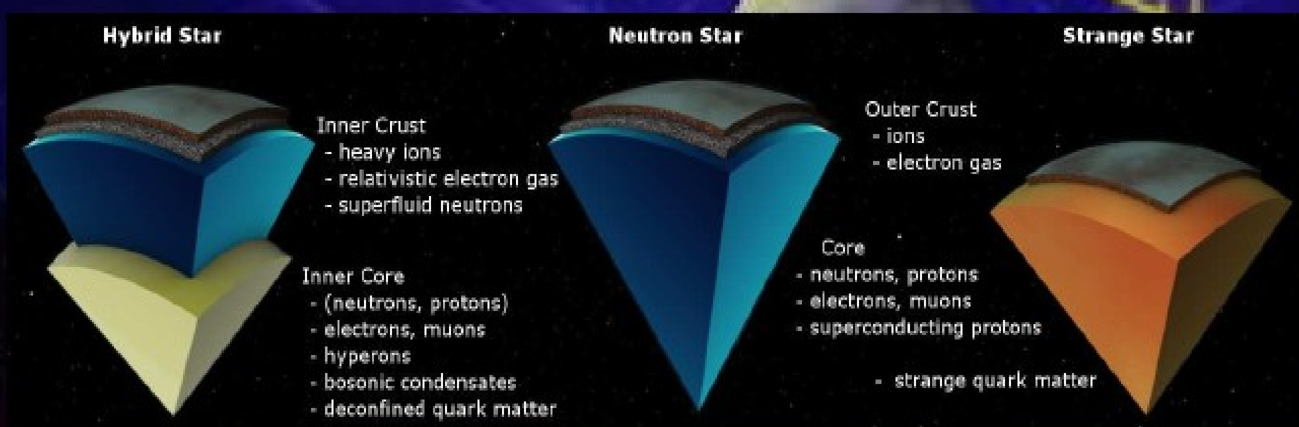


Klähn et al., PLB 654, 170 (2007)



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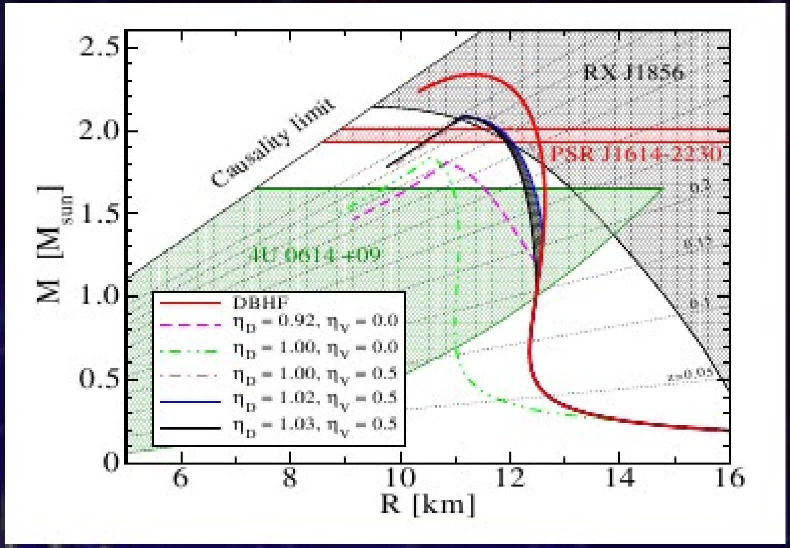

CompStar, in preparation (2010)

State-of-the-art hybrid EoS model:

- Chiral symmetry restoration
- Color superconductivity
- Vector meanfield “stiffening”

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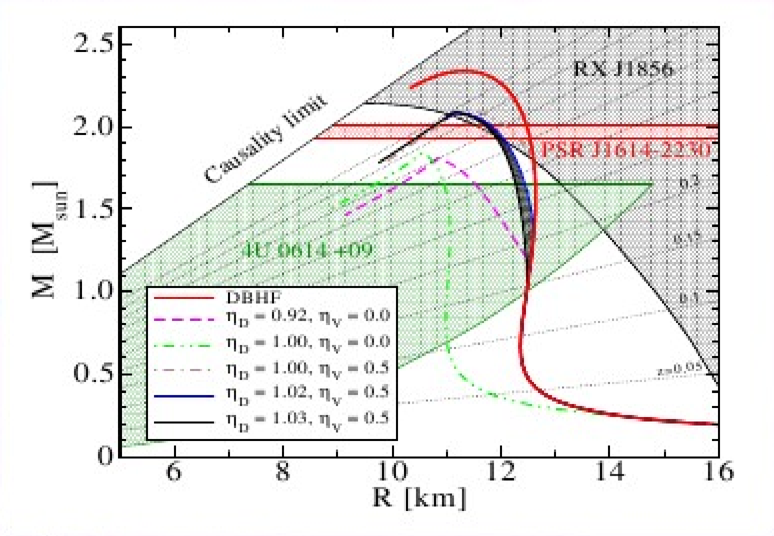


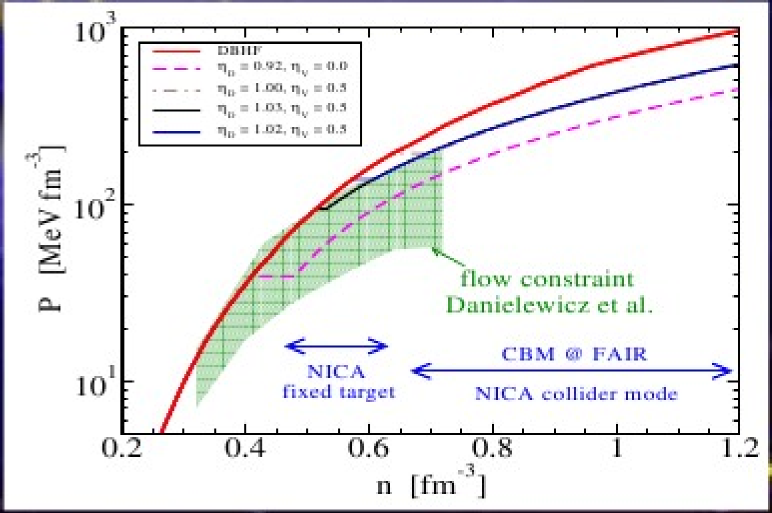
State-of-the-art hybrid EoS model:

- Chiral symmetry restoration
- Color superconductivity
- Vector meanfield "stiffening"

Constraints from heavy-ion collisions:

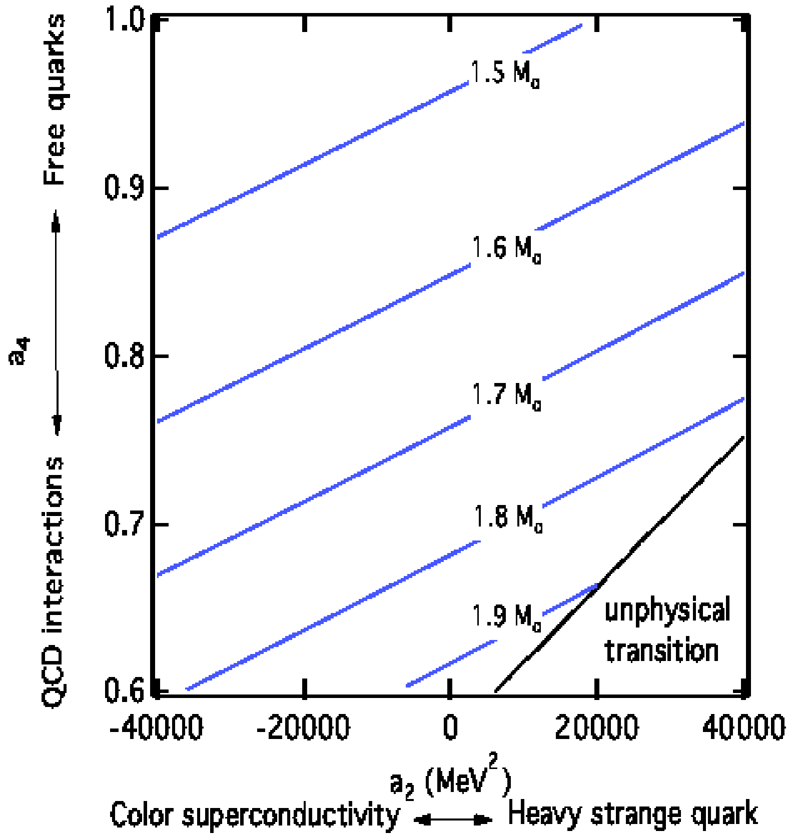
- Flow constraint at high densities
- Not too early onset of quark matter

⟹ **QCD phase diagram**



Klähn et al., PLB (2007), arxiv:1101.6061

CONSTRAINTS FROM PSR J1614-2230 FOR QUARK MATTER EOS



Özel, Psaltis, Ransom, Demorest, Alford, arxiv:1010.5790 [astro-ph] (2010)

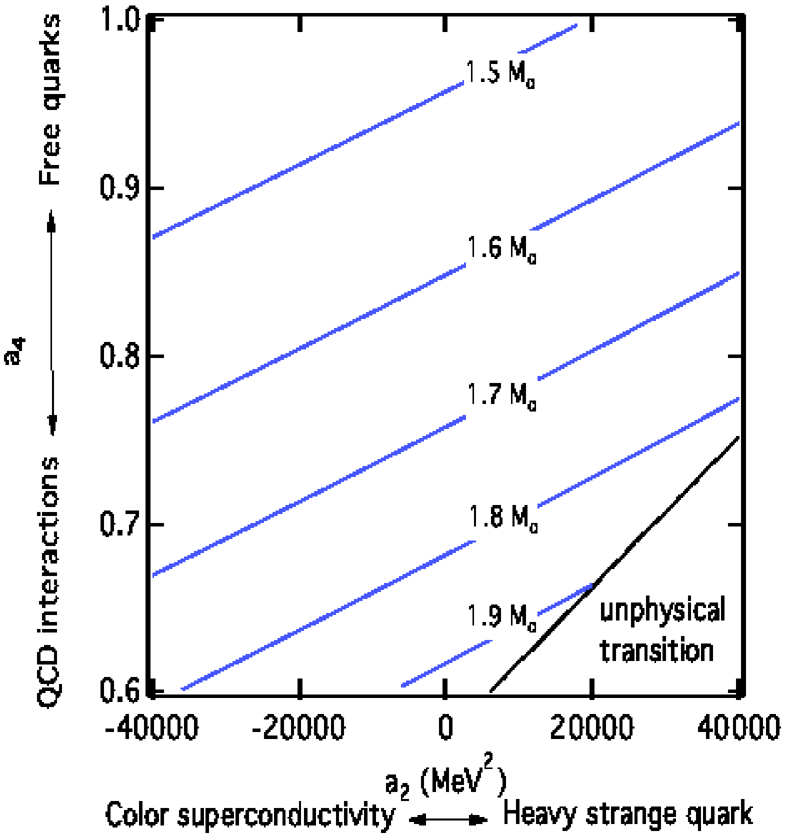
Phenomenological Quark Matter EoS:

$$\Omega_{\rm QM} = -\frac{3}{4\pi}a_4\mu^4 + \frac{3}{4\pi^2}a_2\mu^2 + B_{\rm eff}$$

If the critical density for chiral restoration/deconfinement is reached in the compact star core, then $M_{J1614} = 1.97 \pm 0.04\ M_\odot$ implies the following:

- Quark matter is strongly interacting, QCD corrections (a_4) important
- Quark matter is color superconducting: $a_2 \leq 0$

Constraints from PSR J1614-2230 for Quark Matter EoS



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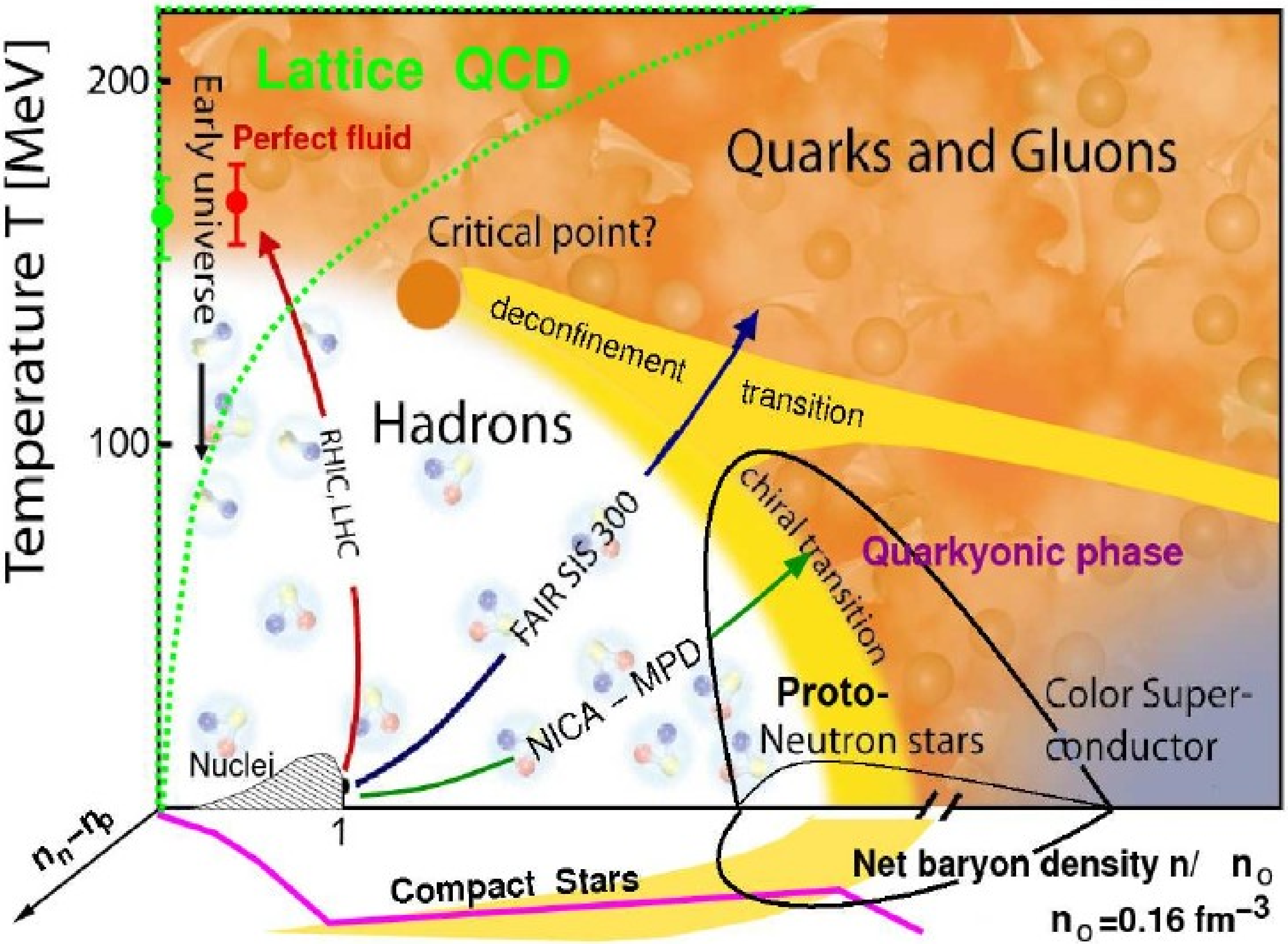
Recent systematic studies: S. Weissenborn et al., ApJ Lett. 740 (2011)
L. Bonanno & A. Sedrakian, 1108.0559 (2011)
T. Klahn et al., 1111.6889; R. Lastowiecki et al. (in preparation)

Extreme States of Matter - The Phase Diagram



NICA White Paper, http://theor.jinr.ru/twiki-cgi/view/NICA/WebHome

Chiral Model Field Theory for Quark Matter

- Partition function as a Path Integral (imaginary time $\tau = i\,t$)

$$Z[T,V,\mu] = \int \mathcal{D}\bar{\psi}\mathcal{D}\psi \exp\left\{ -\int^{\beta} d\tau \int_V d^3x [\bar{\psi}[i\gamma^\mu\partial_\mu - m - \gamma^0(\mu + \lambda_8\mu_8 + i\lambda_3\phi_3]\psi - \mathcal{L}_{\rm int} + U(\Phi)] \right\}$$

Polyakov loop: $\Phi = N_c^{-1}{\rm Tr}_c[\exp(i\beta\lambda_3\phi_3)]$ Order parameter for deconfinement

- Current-current interaction (4-Fermion coupling) and KMT determinant interaction

$$\mathcal{L}_{\rm int} = \sum_{M=\pi,\sigma,\dots} G_M(\bar{\psi}\Gamma_M\psi)^2 + \sum_D G_D(\bar{\psi}^C\Gamma_D\psi)^2 - K[{\rm det}_f(\bar{q}(1+\gamma_5)q) + {\rm det}_f(\bar{q}(1-\gamma_5)q)]$$

- Bosonization (Hubbard-Stratonovich Transformation)

$$Z[T,V,\mu] = \int \mathcal{D}M_M\mathcal{D}\Delta_D^\dagger\mathcal{D}\Delta_D\, {\rm e}^{-\sum_{M,D}\frac{M_M^2}{4G_M} - \frac{|\Delta_D|^2}{4G_D} + \frac{1}{2}{\rm Tr}\,\ln S^{-1}[\{M_M\},\{\Delta_D\},\Phi] + U(\Phi) + V_{\rm KMT}}$$

- Collective quark fields: Mesons (M_M) and Diquarks (Δ_D); Gluon mean field: Φ
- Systematic evaluation: Mean fields + Fluctuations
  - Mean-field approximation: order parameters for phase transitions (gap equations)
  - Lowest order fluctuations: hadronic correlations (bound & scattering states)
  - Higher order fluctuations: hadron-hadron interactions

NJL model for neutral 3-flavor quark matter

Thermodynamic Potential $\Omega(T,\mu) = -T\ln Z[T,\mu]$

$$\Omega(T,\mu) = \frac{\phi_u^2+\phi_d^2+\phi_s^2}{8G_S} + \frac{|\Delta_{ud}|^2+|\Delta_{us}|^2+|\Delta_{ds}|^2}{4G_D} + \frac{K\ \phi_u+\phi_d+\phi_s}{16G_S^3} - \frac{(\mu^*-\mu)^2}{4G_V}$$
$$- T\sum_n \int \frac{d^3p}{(2\pi)^3}\frac{1}{2}\mathrm{Tr}\ln\left(\frac{1}{T}S^{-1}(i\omega_n,\vec{p})\right) + U(\Phi) + \Omega_e - \Omega_0.$$

$$\mathrm{InverseNambu-GorkovPropagator} \quad S^{-1}(i\omega_n,\vec{p}) = \begin{bmatrix} \gamma_\mu p^\mu - M(\vec{p}) + \mu\gamma^0 & \widehat{\Delta}(\vec{p}) \\ \widehat{\Delta}^\dagger(\vec{p}) & \gamma_\mu p^\mu - M(\vec{p}) - \mu\gamma^0 \end{bmatrix},$$

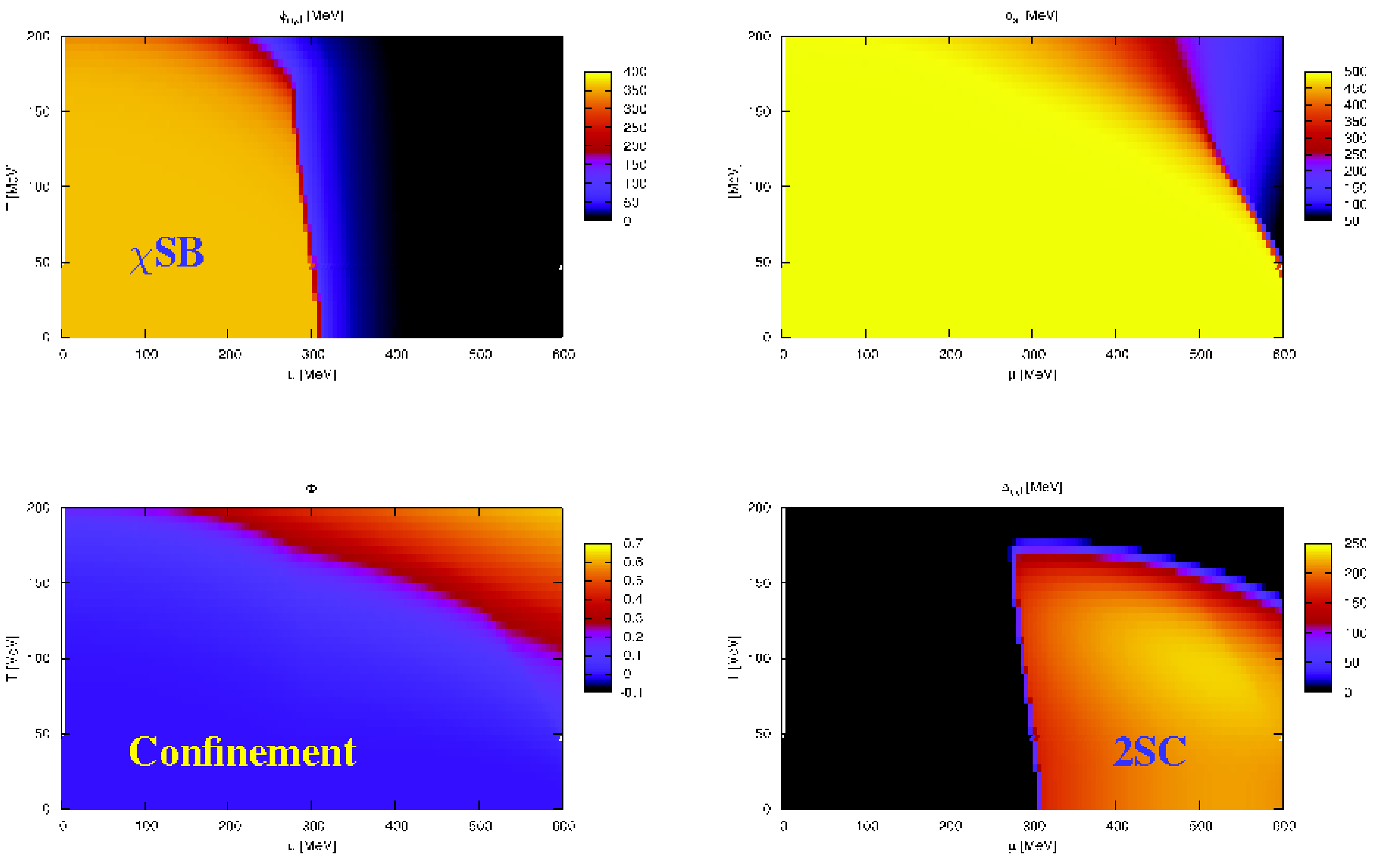
Fermion Determinant (Tr ln D = ln det D): $\ln\det[\beta\ S^{-1}(i\omega_n,\vec{p})] = 2\sum_{a=1}^{18}\ln\{\beta^2[\omega_n^2+\lambda_a(\vec{p})^2]\}$.

Result for the thermodynamic Potential (Meanfield approximation)

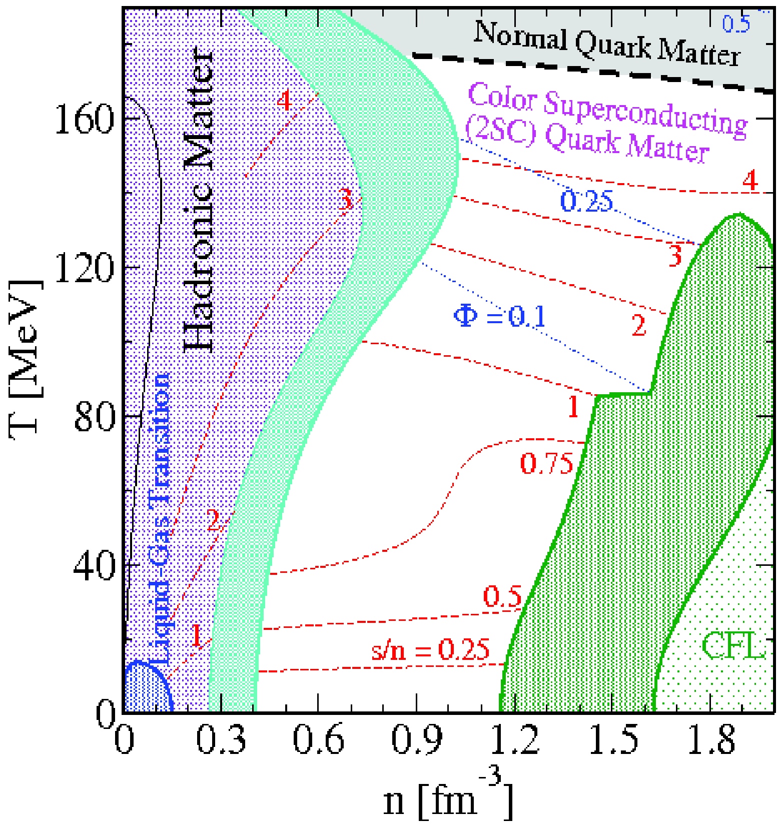
$$\Omega(T,\mu) = \frac{\phi_u^2+\phi_d^2+\phi_s^2}{8G_S} + \frac{|\Delta_{ud}|^2+|\Delta_{us}|^2+|\Delta_{ds}|^2}{4G_D} + \frac{K\ \phi_u+\phi_d+\phi_s}{16G_S^3} - \frac{(\mu^*-\mu)^2}{4G_V}$$
$$- \int \frac{d^3p}{(2\pi)^3}\sum_{a=1}^{18}\left[\lambda_a + 2T\ln\left(1+e^{-\lambda_a/T}\right)\right] + U(\Phi) + \Omega_e - \Omega_0.$$

Color and electric charge neutrality constraints: $n_Q = n_8 = n_3 = 0$, $n_i = -\partial\Omega/\partial\mu_i = 0$,
Equations of state: $P = -\Omega$, etc.

Phases of QCD @ Extremes: no Color Neutrality



PHASE DIAGRAM FOR SYMMETRIC MATTER (HIC)



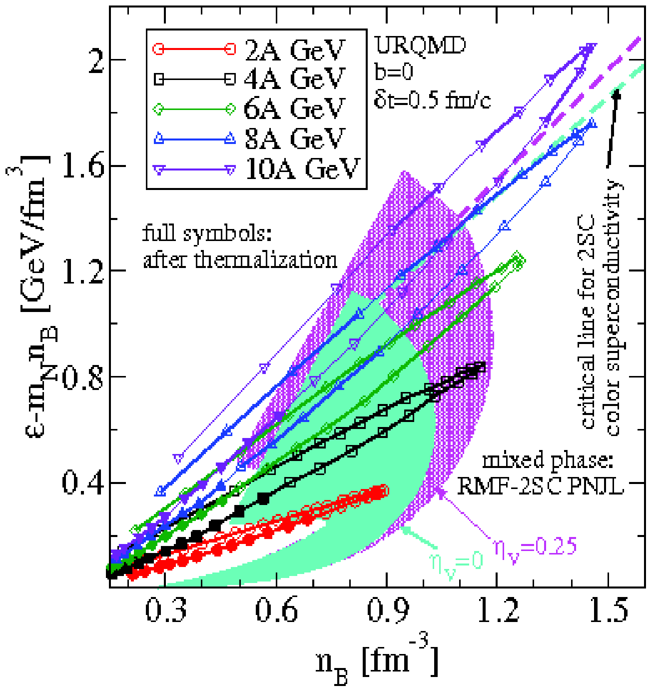
DB, Sandin, Skokov, NICA WhitePaper (2009)

- Critical density for chiral restoration $n_\chi \geq 1.5\, n_0$ increasing (!) with low T
- Almost crossover (masquerade!), i.e. small density jump, small latent heat/ time delay in heavy-ion coll.!
- High $T_c \approx 0.9 T_d$ for 2SC phase due to Polyakov loop.
- 2SC - CFL phase transition at $n \geq 6\ n_0$ with density jump and latent heat/ time delay!
  Provided the temperature can be kept low $T \leq 100$ MeV

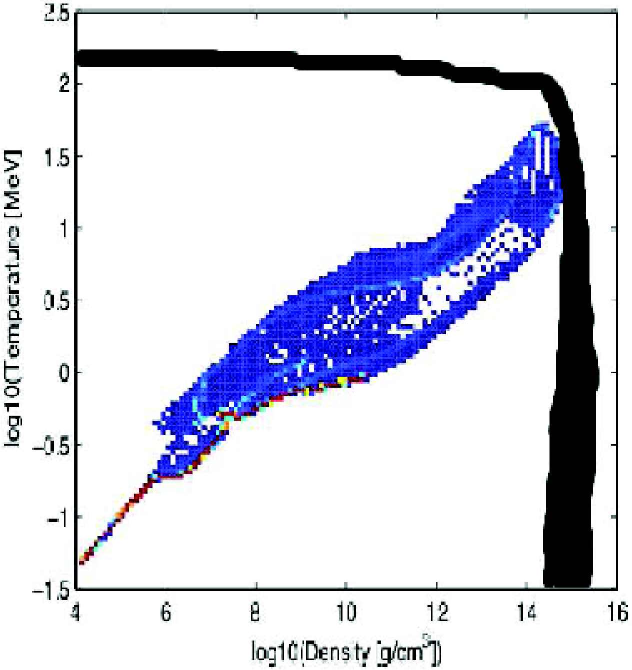
Acta Phys. Pol. Suppl. 3, 641 (2010); arxiv:1004.4375 [hep-ph]

Exploring the QCD Phase Diagram: Trajectories

Heavy-Ion Collisions:



Supernova Explosions (15 $M_\odot$):



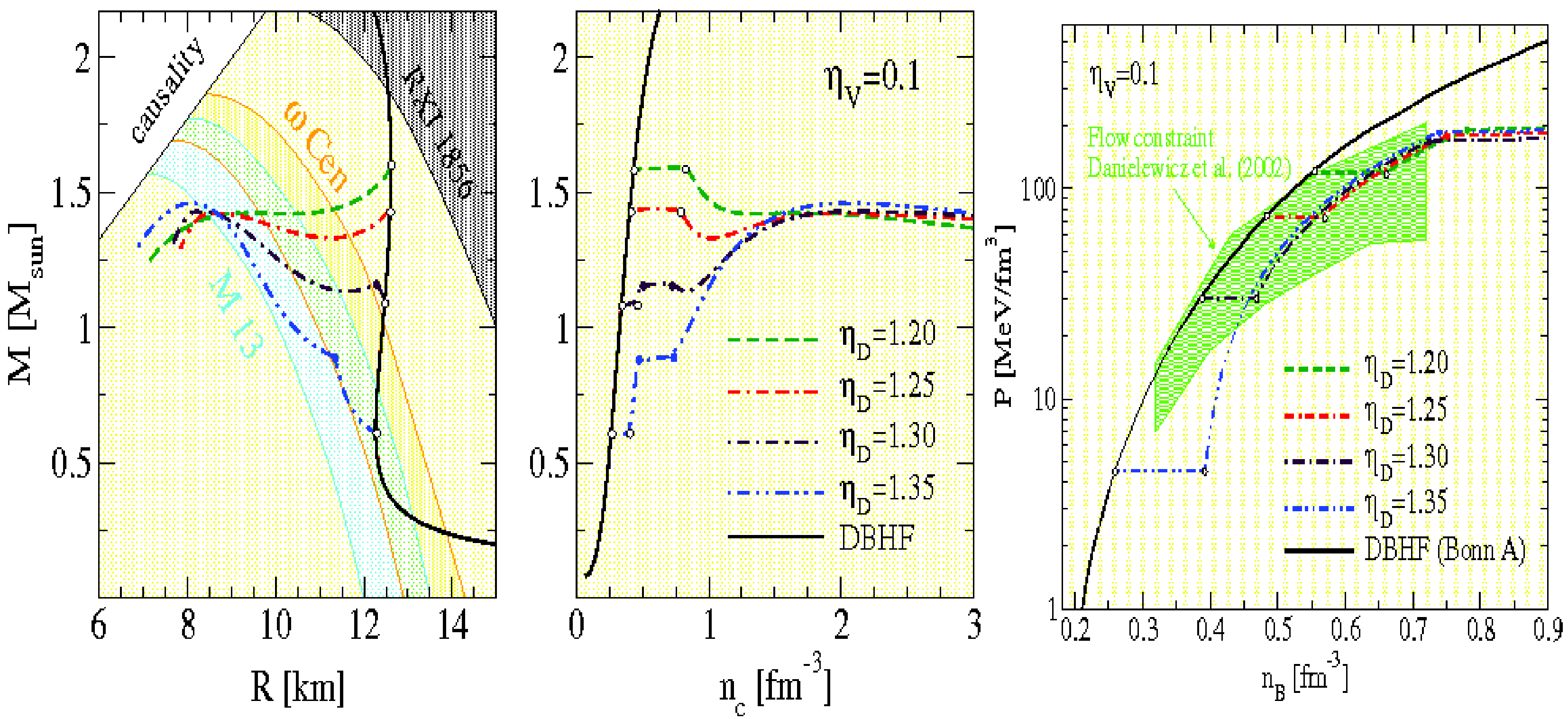
D.B.,Skokov, Sandin, NICA WhitePaper (2009)

Liebendoefer et al. (2005)

Sagert et al., PRL 102 (2009)

Fischer et al., arxiv: 1103.3004

HYBRID-EOS ROBUST? ROLE OF KMT DET - TWINS!



- Mass - radius constraints from quiescent LMXB's and RXJ 1856 ⇒ Small AND large stars? NJL with KMT allows for mass twins! Direct transition DBHF-CFL possible!
- Flow constraint ⇒ PT not too early! No direct DBHF-CFL trans.!

D.B., Klähn, Łastowiecki, Sandin, J. Phys. G 37, 094063 (2010); arxiv:1002.1299 [nucl-th]

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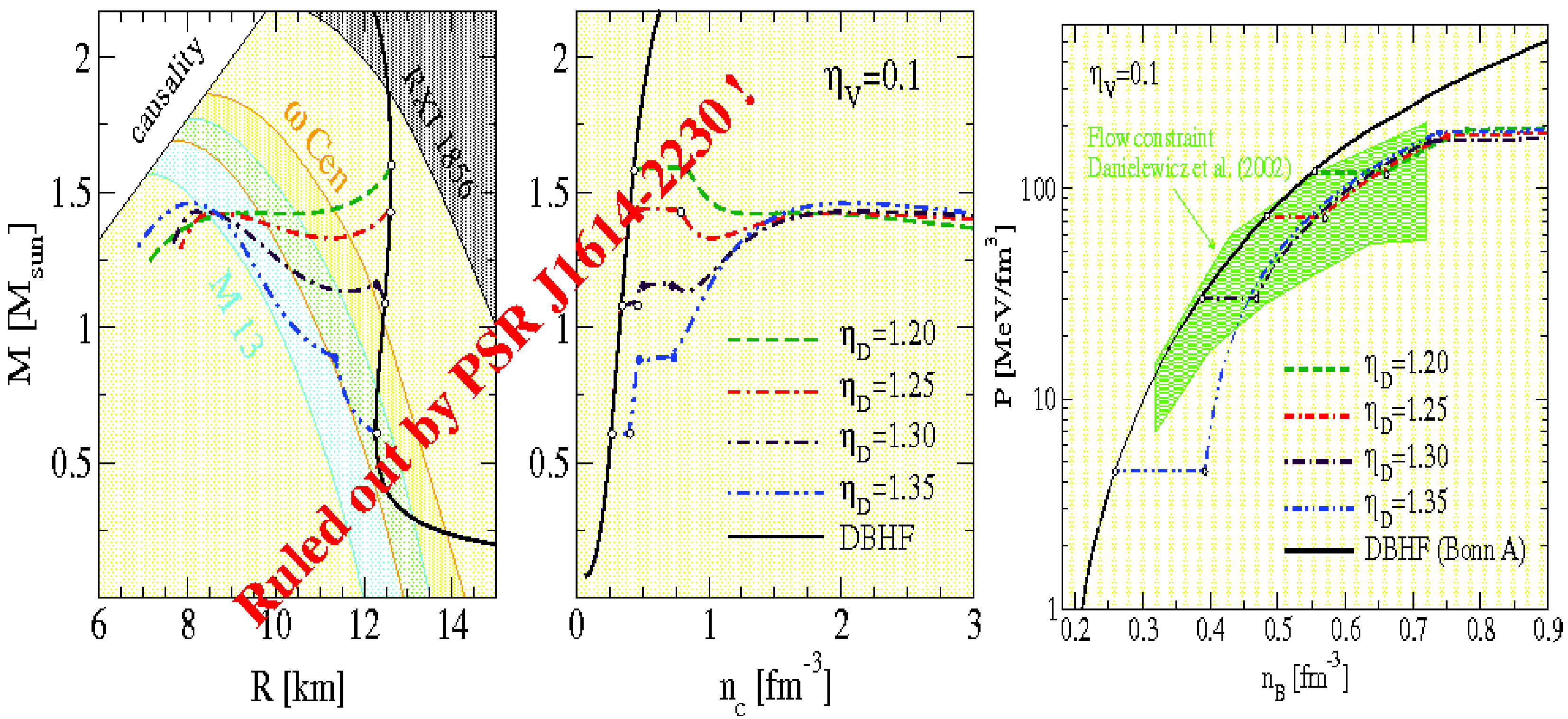

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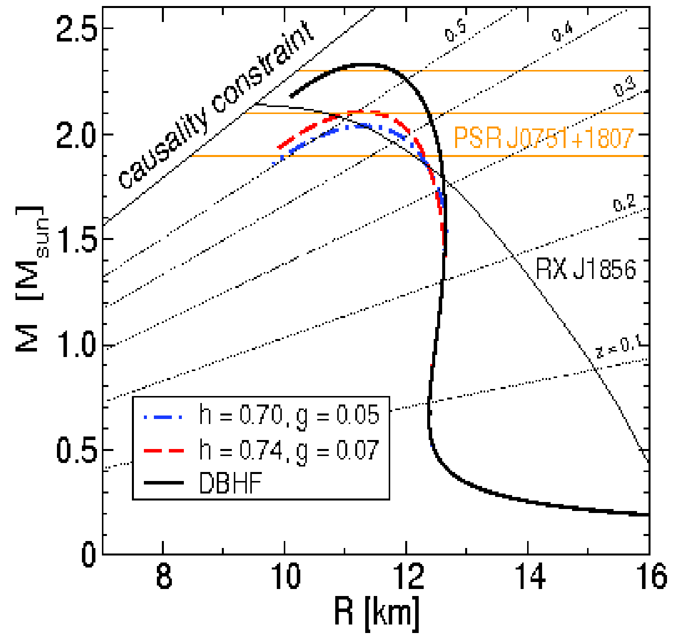
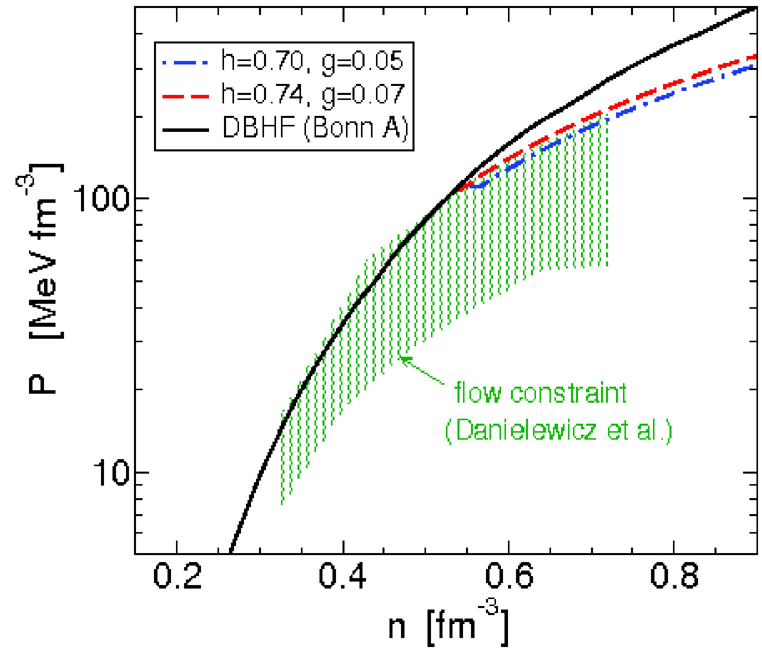
HYBRID-EOS ROBUST? CONSTRAINTS & COVARIANT NCQM





- Covariant, nonlocal interaction model:

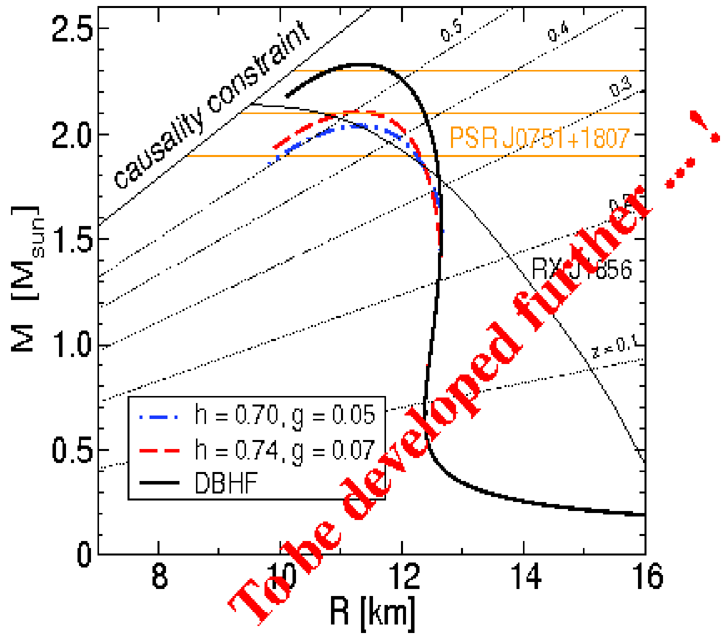
$$\mathcal{L}_{\rm int} = -\int d^4x \, \left\{ \frac{G_S}{2} j_S^f(x) j_S^f(x) + \frac{H}{2} \left[j_D^a(x) \right]^\dagger j_D^a(x) + \frac{G_V}{2} j_V^\mu(x) \, j_V^\mu(x) \right\}$$

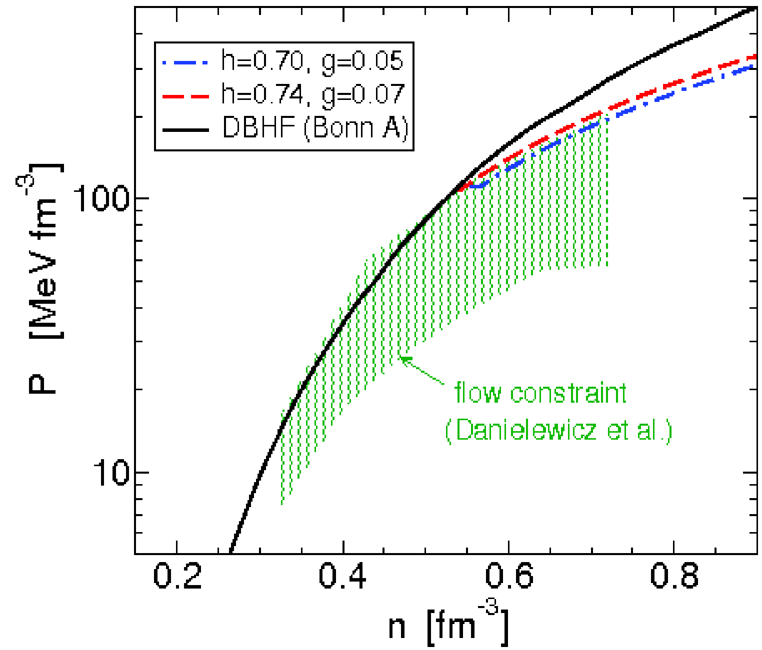
- Nonlocal currents, e.g.

$$j_S^f(x) = \int d^4z \, g(z) \, \bar{\psi}(x + \tfrac{z}{2}) \, \Gamma_f \, \psi(x - \tfrac{z}{2}) \, ,$$

D.B., Gomez-Dumm, Grunfeld, Klähn, Scoccola, PRC 75, 065804 (2007); [arxiv:nucl-th/0703088]
Recent developments: Radzhabov et al., arxiv:1012.0664; Horvatic et al., arxiv:1012.2113

Hybrid-EoS Robust? Constraints & Covariant NCQM





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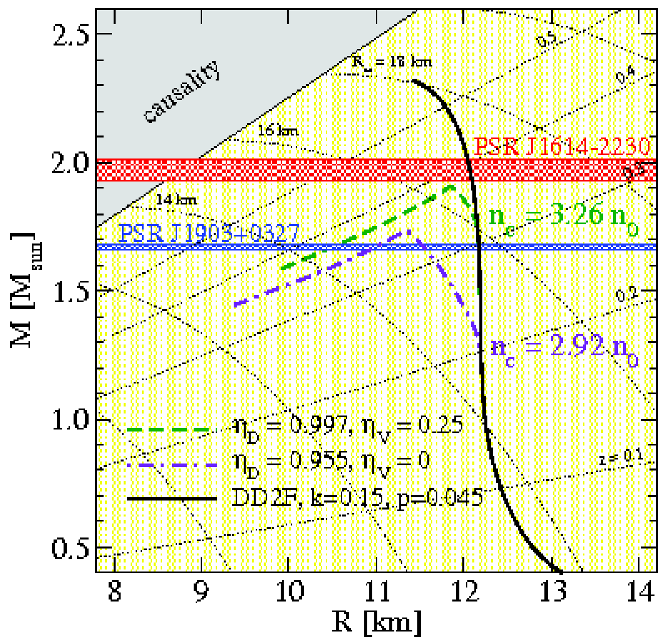
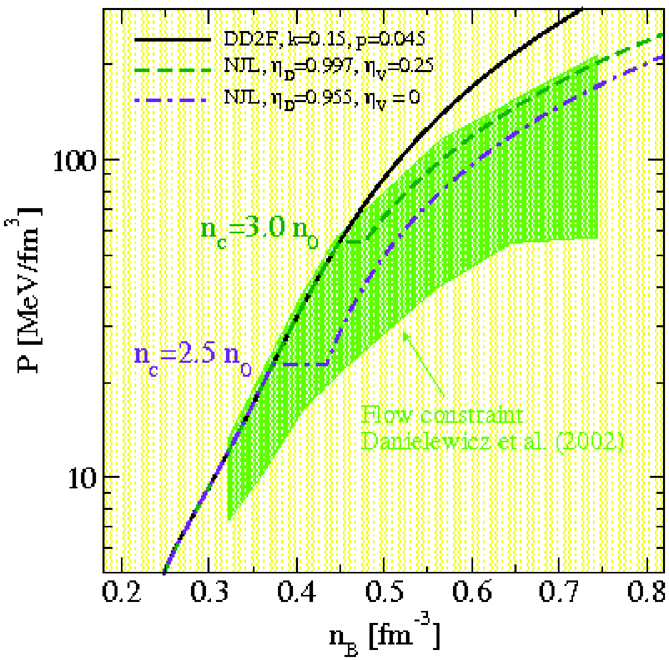
Mass-Radius constraint and Flow constraint

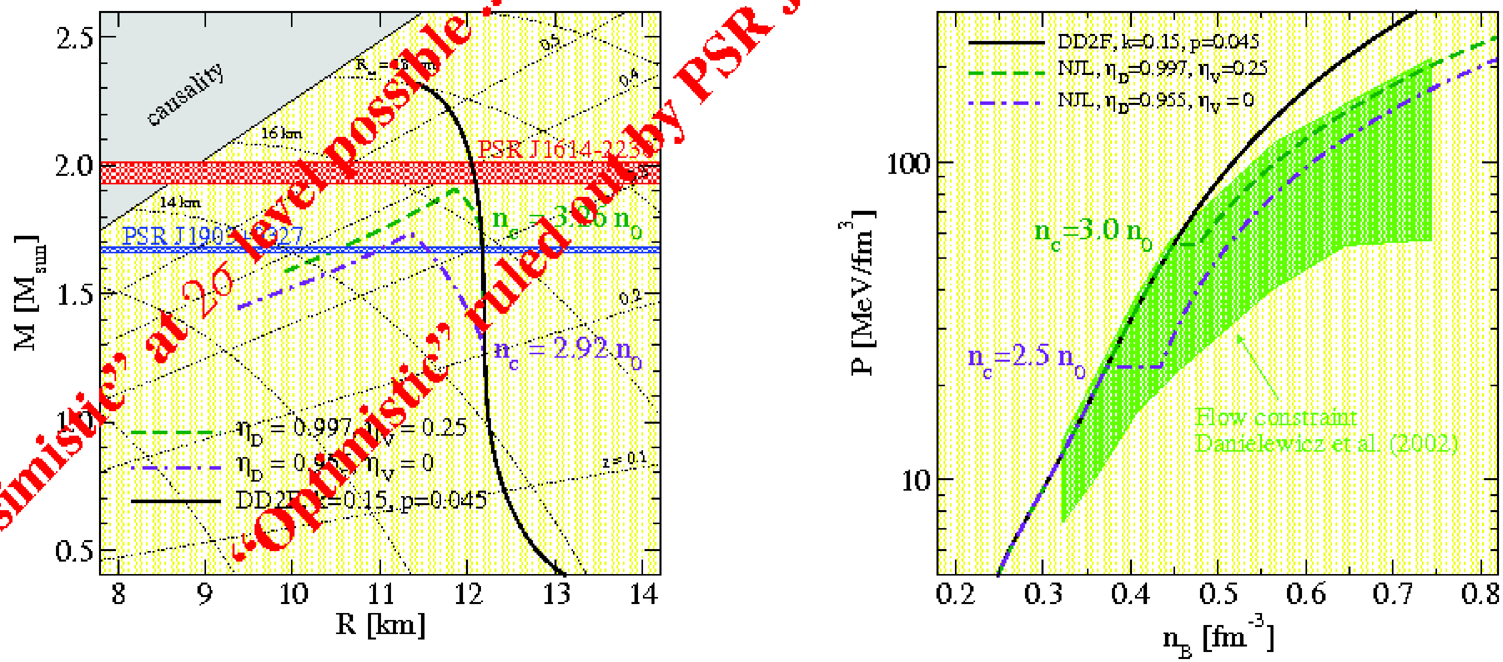




- Large Mass ($\sim 2\ M_\odot$) and radius ($R \geq 12$ km) $\Rightarrow$ stiff EoS;
- Flow in Heavy-Ion Collisions $\Rightarrow$ not too stiff EoS !

Sandin et al., CompOSE project (2009-10); See also:
Klähn, D.B., Sandin, Fuchs, Faessler, Grigorian, Röpke, Trümper, PLB 654, 170 (2007)

MASS-RADIUS CONSTRAINT AND FLOW CONSTRAINT



"Pessimistic" at 2σ level possible ...

"Optimistic" ruled out by PSR J1614-2230 !

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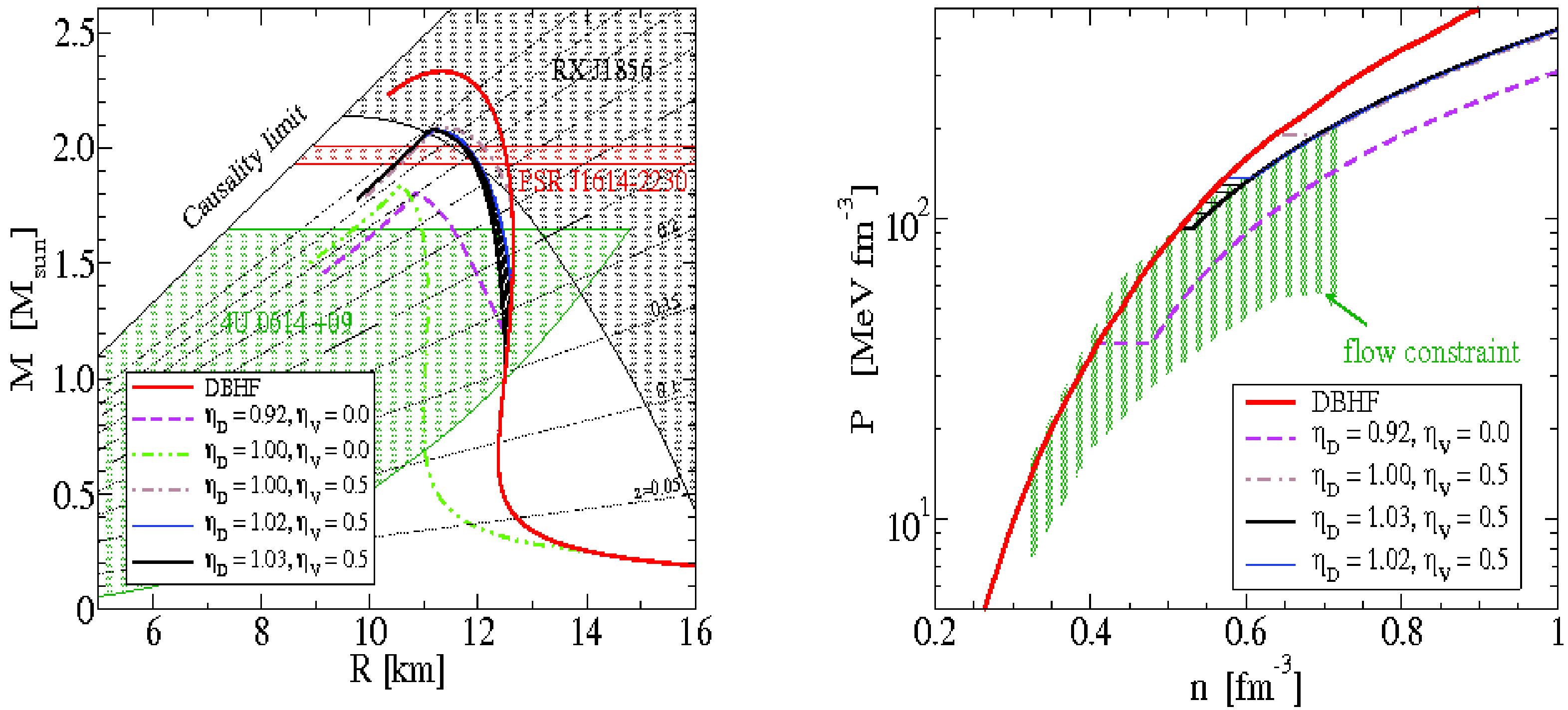

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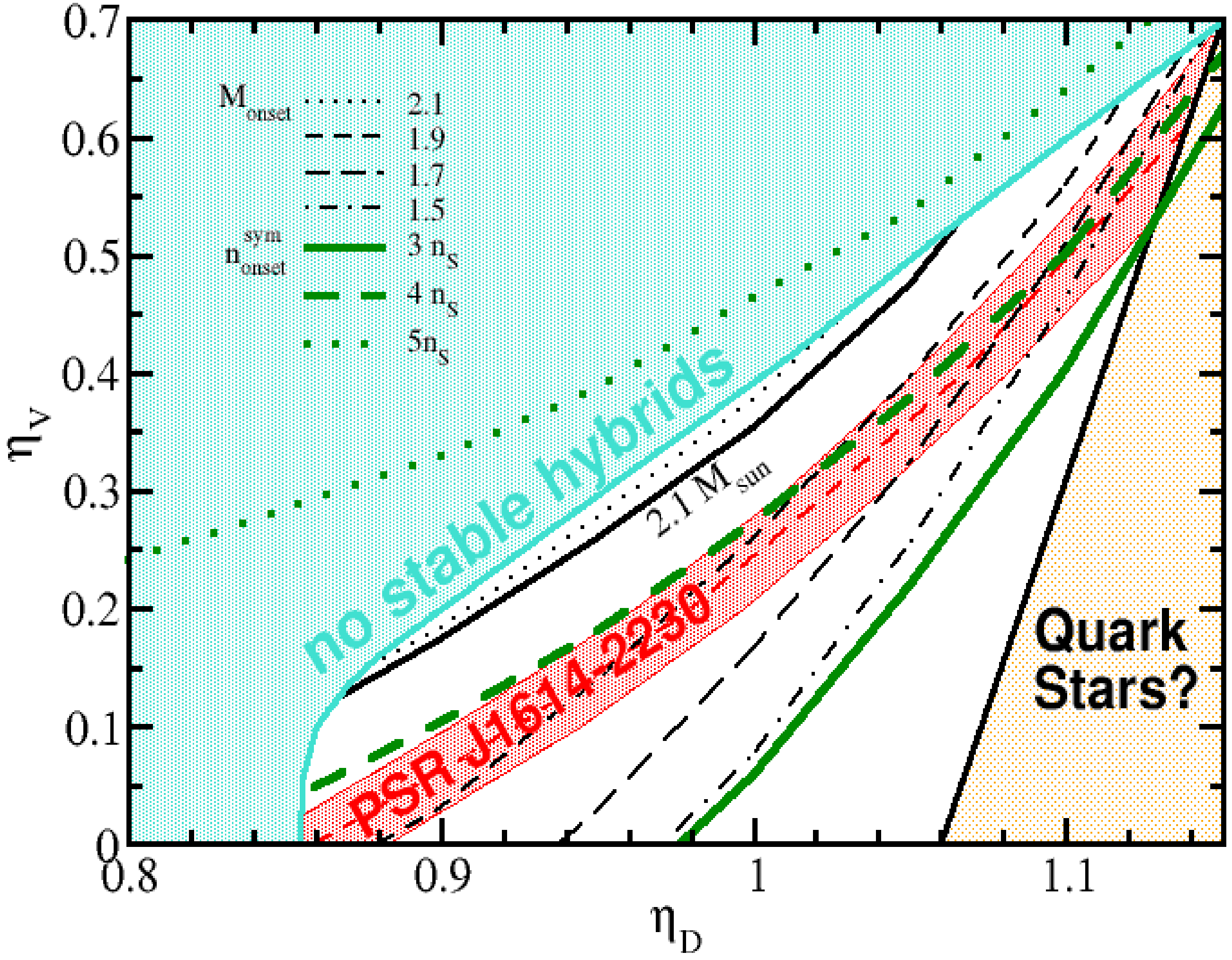
Implications from PSR J1614-2230 within 3fCS NJL – DBHF model

T. Klahn et al., Acta Phys. Pol. (to appear); arxiv: 1111.6889



If hybrid star, Then:

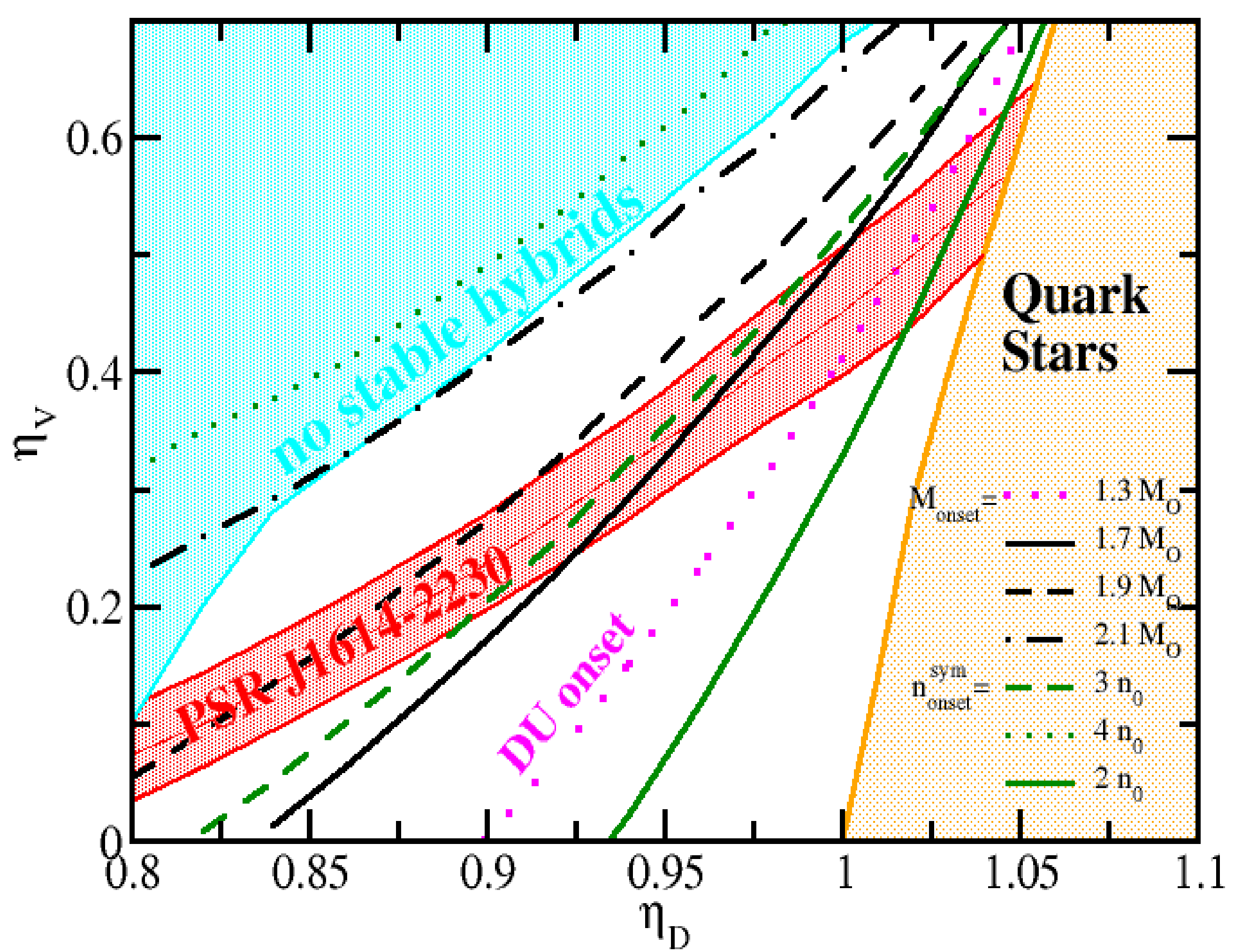
- 2SC QM
- Vector MF
- HIC: n_c ~ 4n_0

If no hybrid star, then:

- small (<0.85) diquark coupl.
- HIC: n_c > 4.5 n_0

Same hybrid model (3fCS NJL – DBHF) , smaller chiral condensate (quark mass)

R. Lastowiecki et al., in preparation



If hybrid star, Then:

- 2SC QM
- Vector MF
- HIC: n_c ~2-3 n_0

If no hybrid star, then:

- small (<0.85) diquark coupl.
- HIC: n_c > 2 n_0

The question of hyperons …
… and quark-hyperon hybrids

$$p_{\text{quark}}(\mu) = p_{\text{NJL}}(\mu) - B(\mu)$$

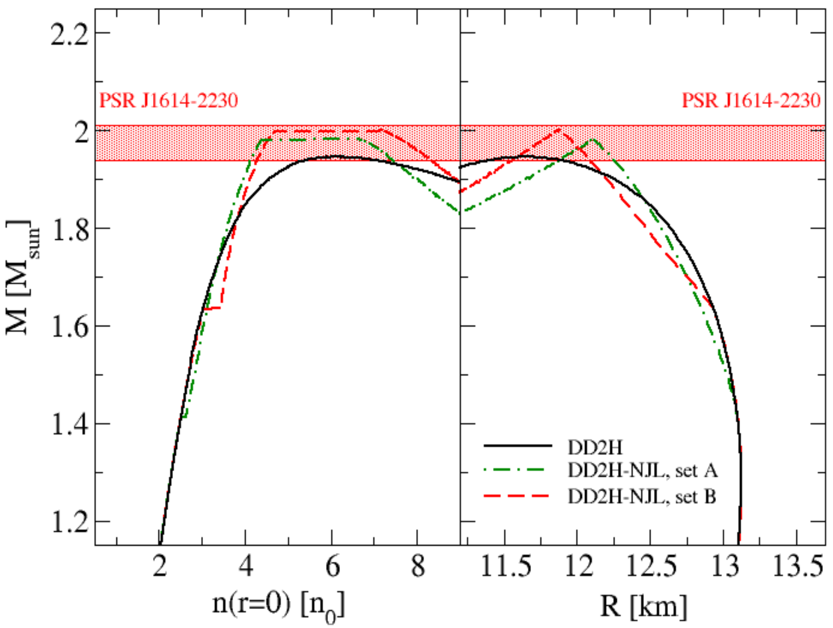
$$B(\mu) = B_0\left[\exp\left(-\frac{\mu-\mu_c}{\delta\mu}\right) - 1\right] \quad , \quad \mu > \mu_c$$

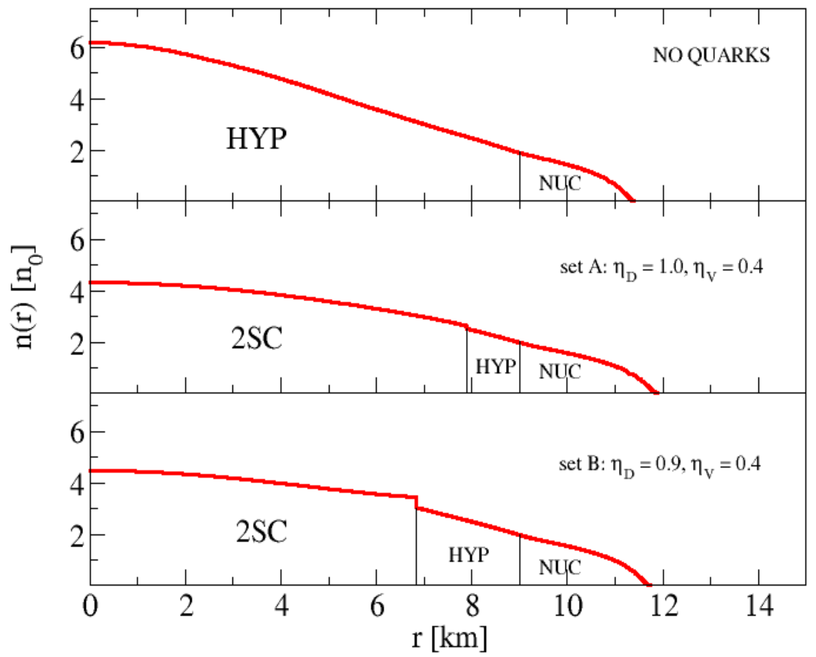
$$\Delta n(\mu) = -\frac{\partial B(\mu)}{\partial \mu} = \frac{B_0 + B(\mu)}{\delta\mu}$$

- Hyperonic matter without strange vector meson Repulsion → too soft; Demorest constraint failed
- Inclusion of phi-meson repulsion → OK
- Phase transition: "masquerade" problem …
- Density dependence of gluon sector (bag) !

$$\Delta\varepsilon(\mu) = \varepsilon_{\text{quark}}(\mu) - \varepsilon_{\text{NJL}}(\mu) = B(\mu) + \mu\Delta n(\mu)$$

Lastowiecki et al., 1112.6430 [nucl-th]



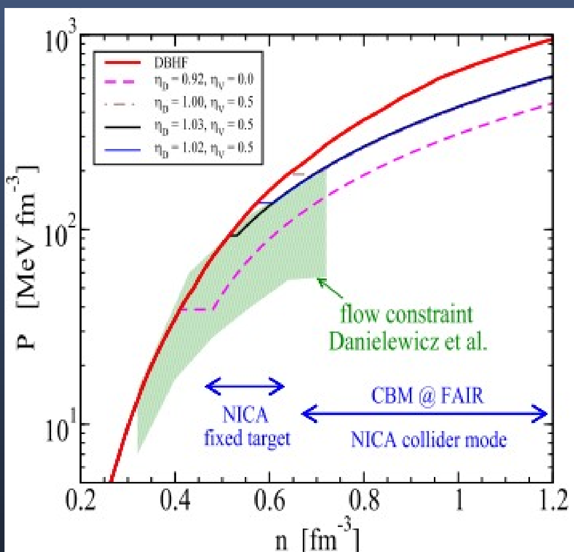


NICA White Paper

Exploring hybrid star matter at NICA & FAIR

T.Klähn (1), D.Blaschke (1,2), F.Weber (3)
(1) Institute for Theoretical Physics, University of Wroclaw, Poland
(2) Joint Institute for Nuclear Research, Dubna
(3) Department of Physics, San Diego State University, USA

Heavy-Ion Collisions ⟷ Compact Stars



- stiff EoS
(at flow limit)

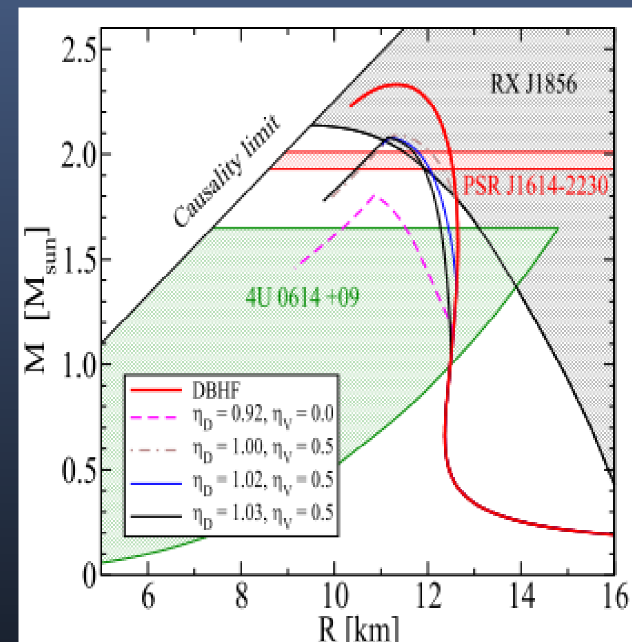
- low n_{crit}
(at NICA fixT)

- soft EoS
(dashed line)

- high M_{max}
(J1614-2230)

- low M_{onset}
(all NS hybrid)

- excluded
(J1614-2230)



Proposal:

1. Measure transverse and elliptic flow for a wide range of energies (densities) at NICA and perform Danielewicz's flow data analysis ---> constrain stiffness of high density EoS
2. Provide lower bound for onset of mixed phase ---> constrain QM onset in hybrid stars

„The CBM Physics Book“, Springer LNP 841 (2011), pp.158-181; arxiv:1101.6061

Conclusions I

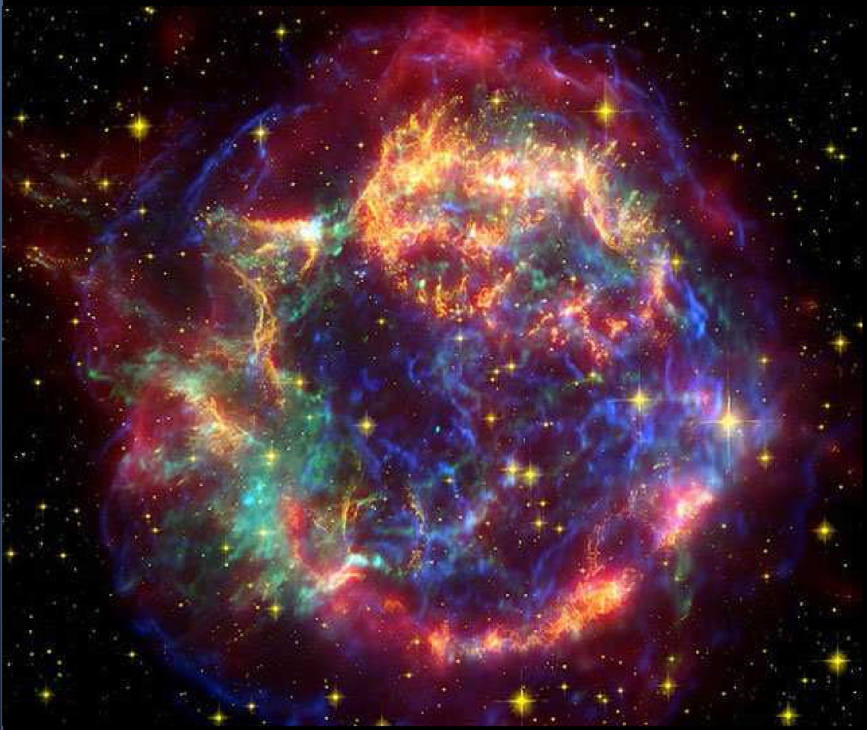
- PSR 1614-2230 (“Demorest-pulsar”) puts strong constraints to dense matter EoS
- Both alternatives for the inner structure, hadronic and hybrid star, are viable for the Demorest pulsar; HIC favors hybrid model
- If Demorest pulsar has a quark matter (QM)core, then QM must:

  - be color superconducting

  - have a strong (vector-field) repulsion

  - occur at >2 n_0 in HIC, depending on $\langle \bar{q}q \rangle$
- Discriminating test? Measure M-R relation !!

Neutron Star in Cassiopeia A (Cas A)



- 16.08.1680 John Flamsteed
  6m star 3 Cas
- 1947 re-discovery in radio
- 1950 optical counterpart
- T ~ 30 MK
- $V_{exp} \sim 4000 - 6000$ km/s
- distance 11.000 ly = 3.4 kpc

picture: spitzer space telescope

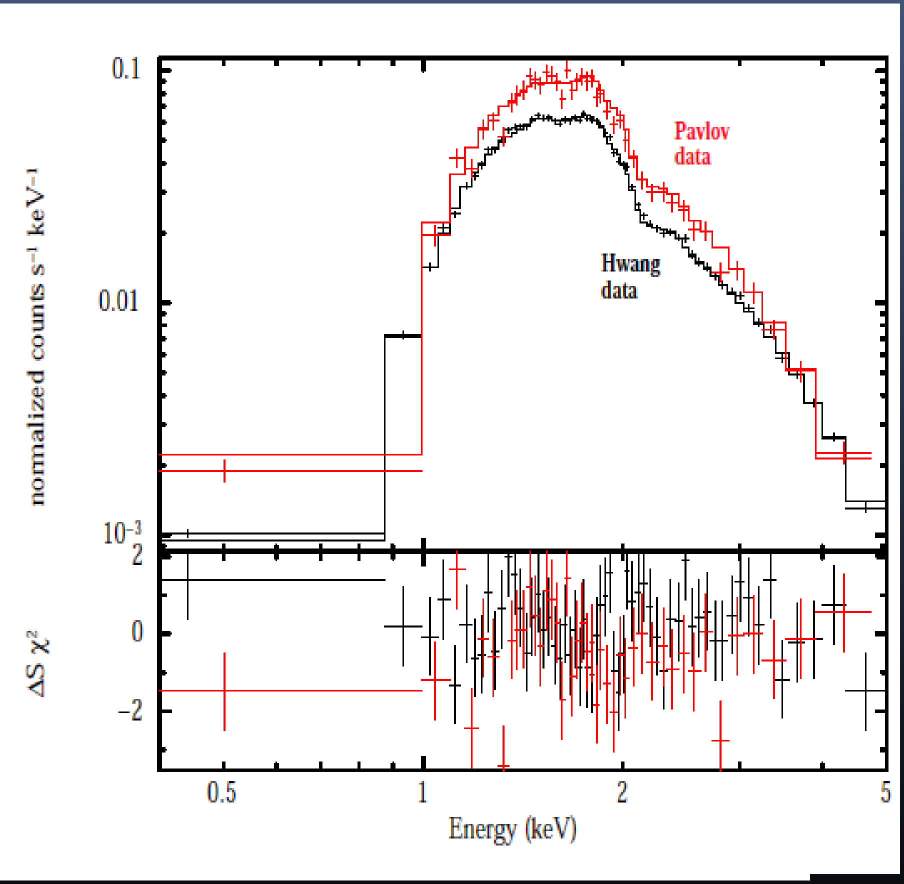
Ho & Heinke, Nature 462 (2009) 71, Heinke & Ho, arxiv:1007.4719

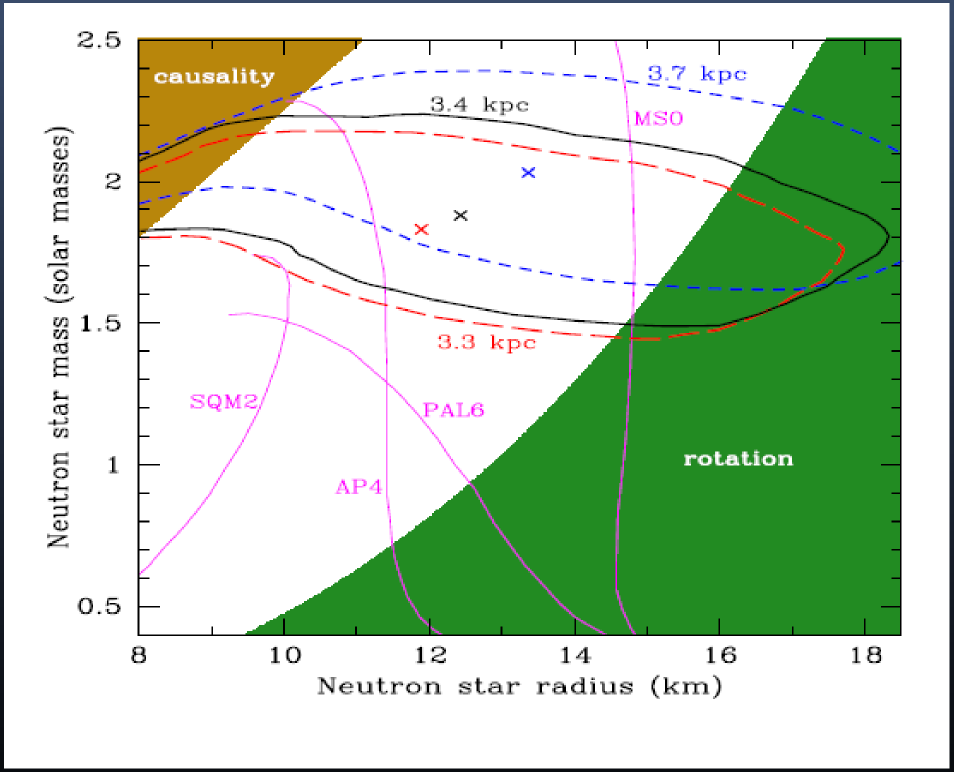
Page, Prakash, Lattimer, Steiner, PRL (2011); arxiv:1011.6142
Shternin, Yakovlev, Heinke, Ho, Patnaude, MNRAS (2011); arxiv:1012.0045

D.Blaschke, H. Grigorian, D. Voskresensky, F. Weber, arxiv:1108.4125

Cas A Cooling Observations

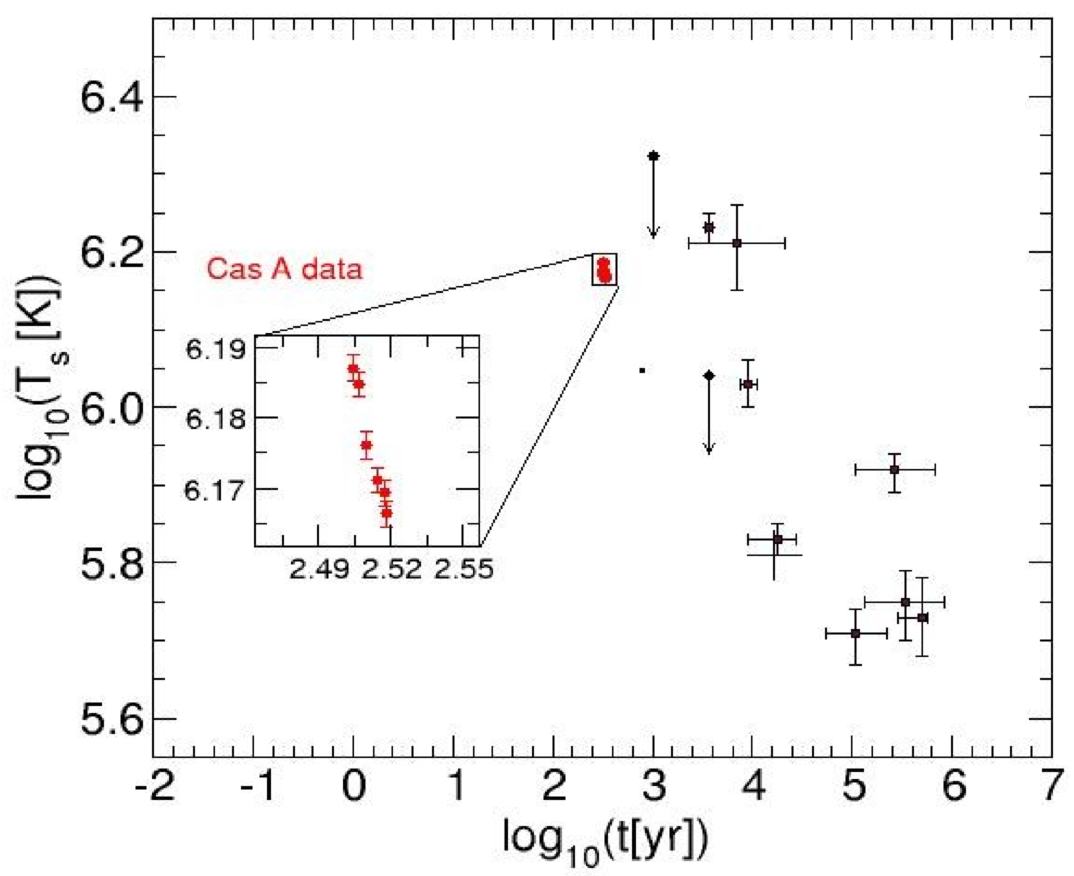
Cas A is a rapidly cooling star –
Temperature drop ~4% in 10 years



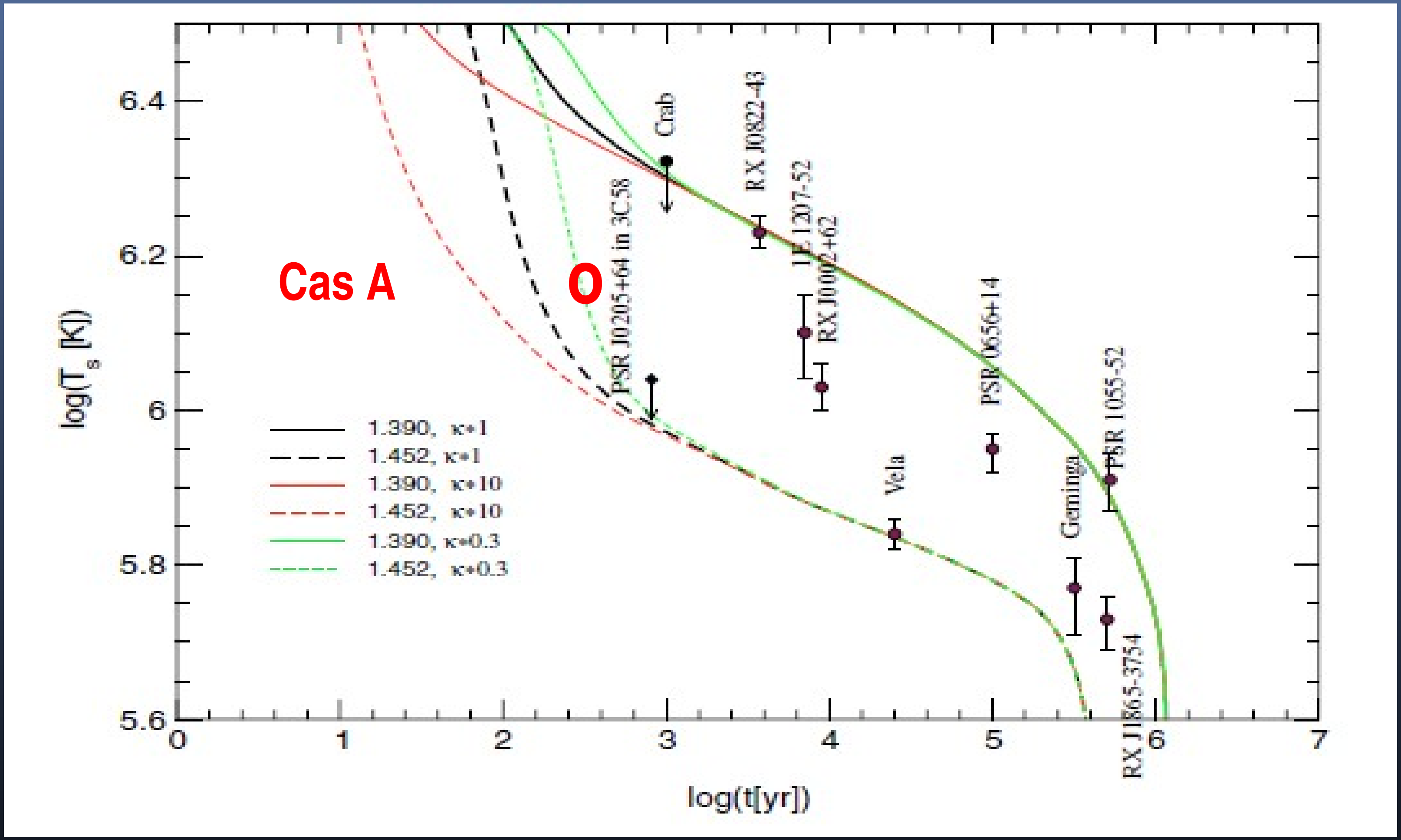


W.C.G. Ho, C.O. Heinke, Nature 462, 71 (2009)

Cas A Cooling Observations



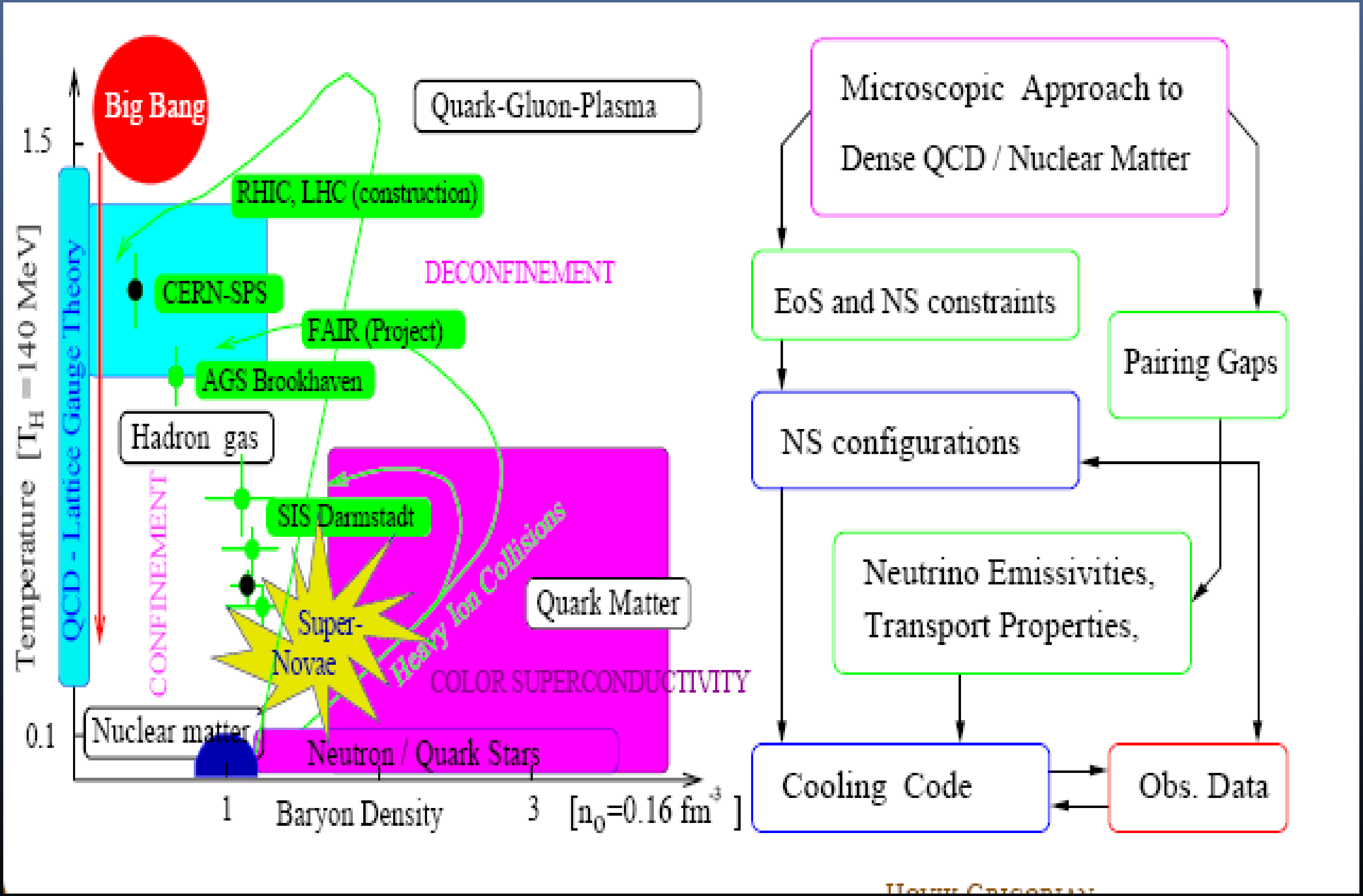
The influence of the (core) heat conductivity



Blaschke, Grigorian, Voskresensky, A&A 424, 979 (2004)

http://www.nature.com/news/2011/110201/full/news.2011.64.html?s=news_rss#comment-id-18186

Phase Diagram & Cooling Simulation



Cooling Mechanism

$$\frac{dU}{dt} = \sum_i C_i \frac{dT}{dt} = -\varepsilon_\gamma - \sum_j \varepsilon_\nu^j$$

Cooling Processes

- Direct Urca: $n \rightarrow p + e + \bar{\nu}_e$
- Modified Urca: $n + n \rightarrow n + p + e + \bar{\nu}_e$
- Photons: $\rightarrow \gamma$
- Bremsstrahlung: $n + n \rightarrow n + n + \nu + \bar{\nu}$

Cooling Evolution

The energy flux per unit time $l(r)$ through a spherical slice at distance r from the center is:

$$l(r) = -4\pi r^2 k(r) \frac{\partial (T e^{\Phi})}{\partial r} e^{-\Phi} \sqrt{1 - \frac{2M}{r}}.$$

The equations for energy balance and thermal energy transport are:

$$\frac{\partial}{\partial N_B}(l e^{2\Phi}) = -\frac{1}{n}(\epsilon_\nu e^{2\Phi} + c_V \frac{\partial}{\partial t}(T e^{\Phi}))$$

$$\frac{\partial}{\partial N_B}(T e^{\Phi}) = -\frac{1}{k} \frac{l e^{\Phi}}{16\pi^2 r^4 n}$$

where $n = n(r)$ is the baryon number density, $NB = NB(r)$ is the total baryon number in the sphere with radius r

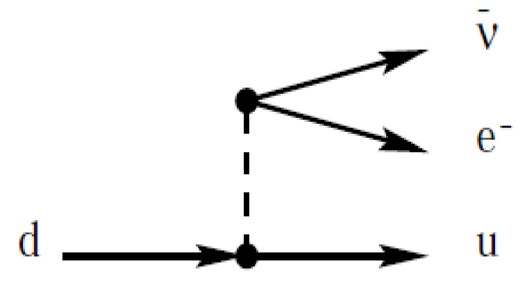
$$\frac{\partial N_B}{\partial r} = 4\pi r^2 n (1 - \frac{2M}{r})^{-1/2}$$

F.Weber: Pulsars as Astro. Labs ... (1999);

D. Blaschke Grigorian, Voskresensky, A& A 368 (2001)561.

Neutrino Emissivities in Quark Matter

- Quark direct Urca (QDU) the most efficient process

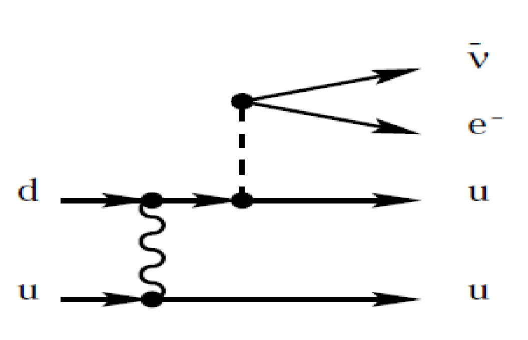


$d \to u + e + \bar{\nu}$ and $u + e \to d + \nu$

$$\epsilon_\nu^{\rm QDU} \simeq 9.4 \times 10^{26} \alpha_s u Y_e^{1/3} \zeta_{\rm QDU}\, T_9^6 \text{ erg cm}^{-3}\text{ s}^{-1},$$

Compression n/n0 ≃ 2, strong coupling $\alpha_s \approx 1$

- Quark Modified Urca (QMU) and Quark Bremsstrahlung



$d + q \to u + q + e + \bar{\nu}$ and $q_1 + q_2 \to q_1 + q_2 + \nu + \bar{\nu}$

$$\epsilon_\nu^{\rm QMU} \sim \epsilon_\nu^{\rm QB} \simeq 9.0 \times 10^{19} \zeta_{\rm QMU}\, T_9^8 \text{ erg cm}^{-3}\text{ s}^{-1}.$$

- Suppression due to the pairing

QDU : $\zeta_{\rm QDU} \sim \exp(-\Delta_q/T)$

QMU and **QB** : $\zeta_{\rm QMU} \sim \exp(-2\Delta_q/T)$ for $T < T_{{\rm crit},q} \simeq 0.57\, \Delta_q$

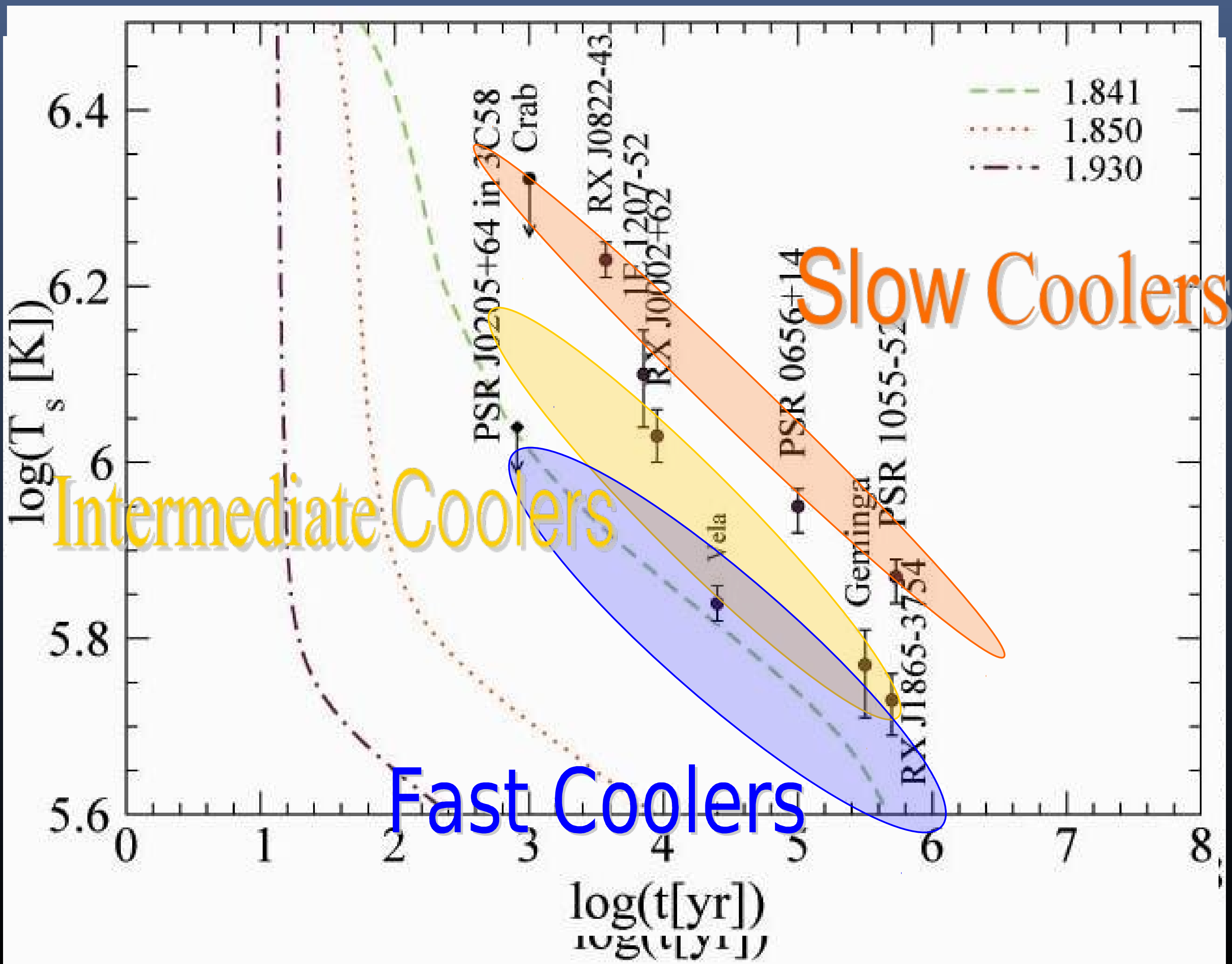
- Enhanced cooling due to the pairing

- $e + e \to e + e + \nu + \bar{\nu}$ (becomes important for $\Delta_q/T >> 1$)

$$\epsilon_\nu^{ee} = 2.8 \times 10^{12} Y_e^{1/3} u^{1/3} T_9^8 \text{ erg cm}^{-3}\text{ s}^{-1},$$

Quark PBF

Surface Temperature & Age Data



Crust Model

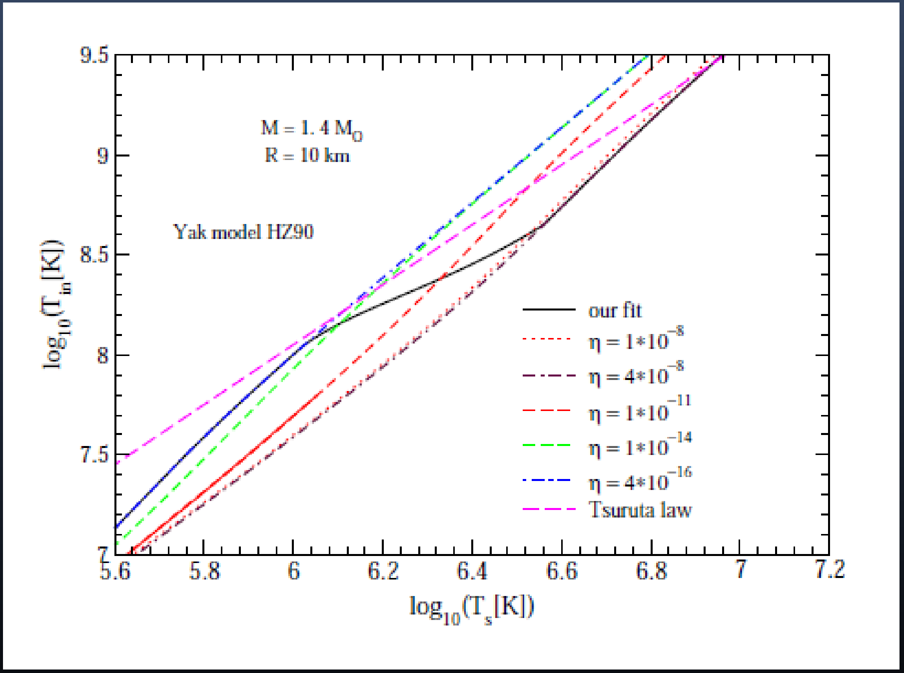
Time dependence of the light element contents in the crust

$$\Delta M_{\mathrm{L}}(t) = e^{-t/\tau}\Delta M_{\mathrm{L}}(0)$$

Page,Lattimer,Prakash & Steiner, Astrophys. J. 155, 623 (2004)

Yakovlev, Levenfish, Potekhin, Gnedin & Chabrier , Astron. Astrophys , 417, 169 (2004)

Blaschke, Grigorian, Voskresensky, A& A 424 (2004) 979

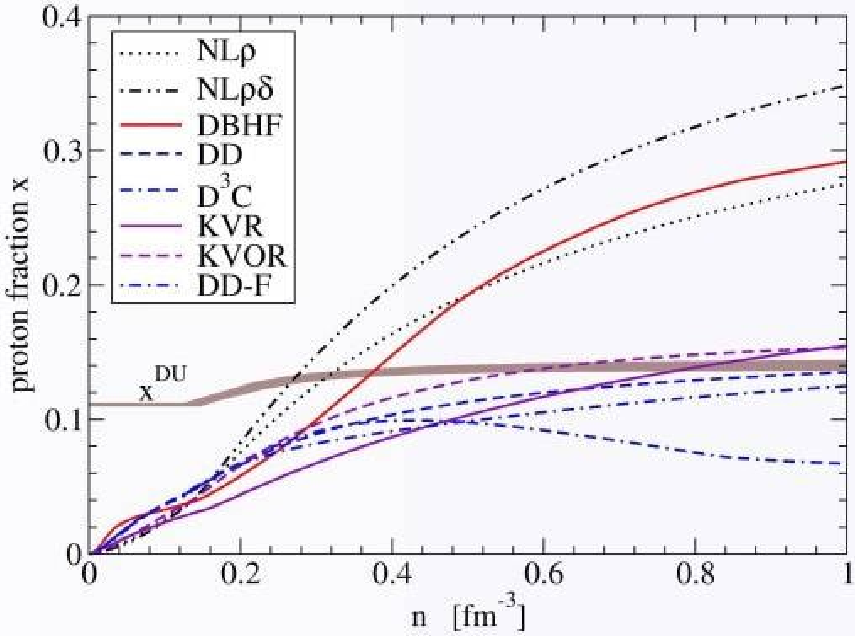


DU constraint

$n \to p + e + \bar{\nu}_e$ implies $p_n \leq p_p + p_e$, charge neutrality results in

$$x_{DU}(x_e) \geq \frac{1}{1 + (1 + x_e^{1/3})^3} \qquad x_e = n_e/(n_e + n_\mu)$$

- no muons: $x_{DU} = 11.1\%$
- relativistic limit ($n_e = n_\mu$): $x_{DU} = 14.8\%$



NLρ, NL$\rho\delta$, DBHF :

DU occurs below $2.5 n_0$

DU Thresholds

DU critical densities

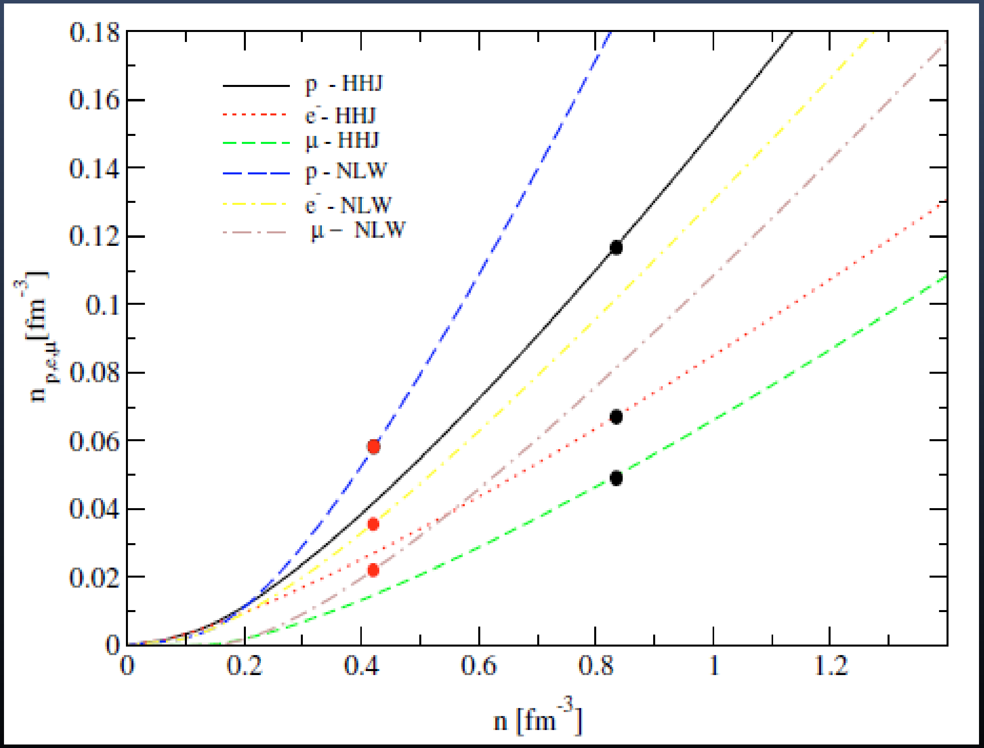
nc = 2.7 n0 NLW (RMF)

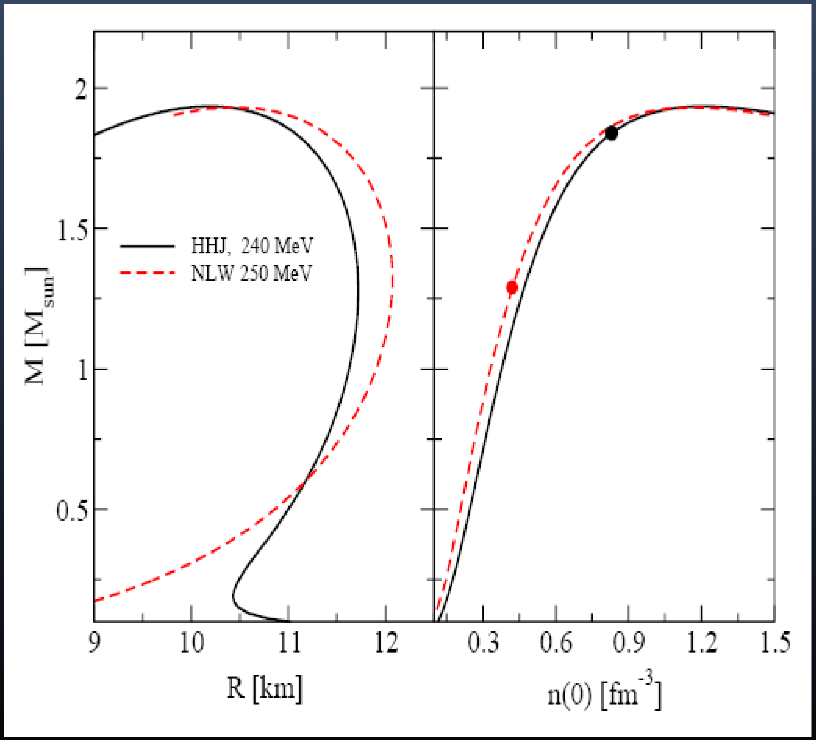
nc = 5.0 n0 HHJ (APR)

DU critical masses

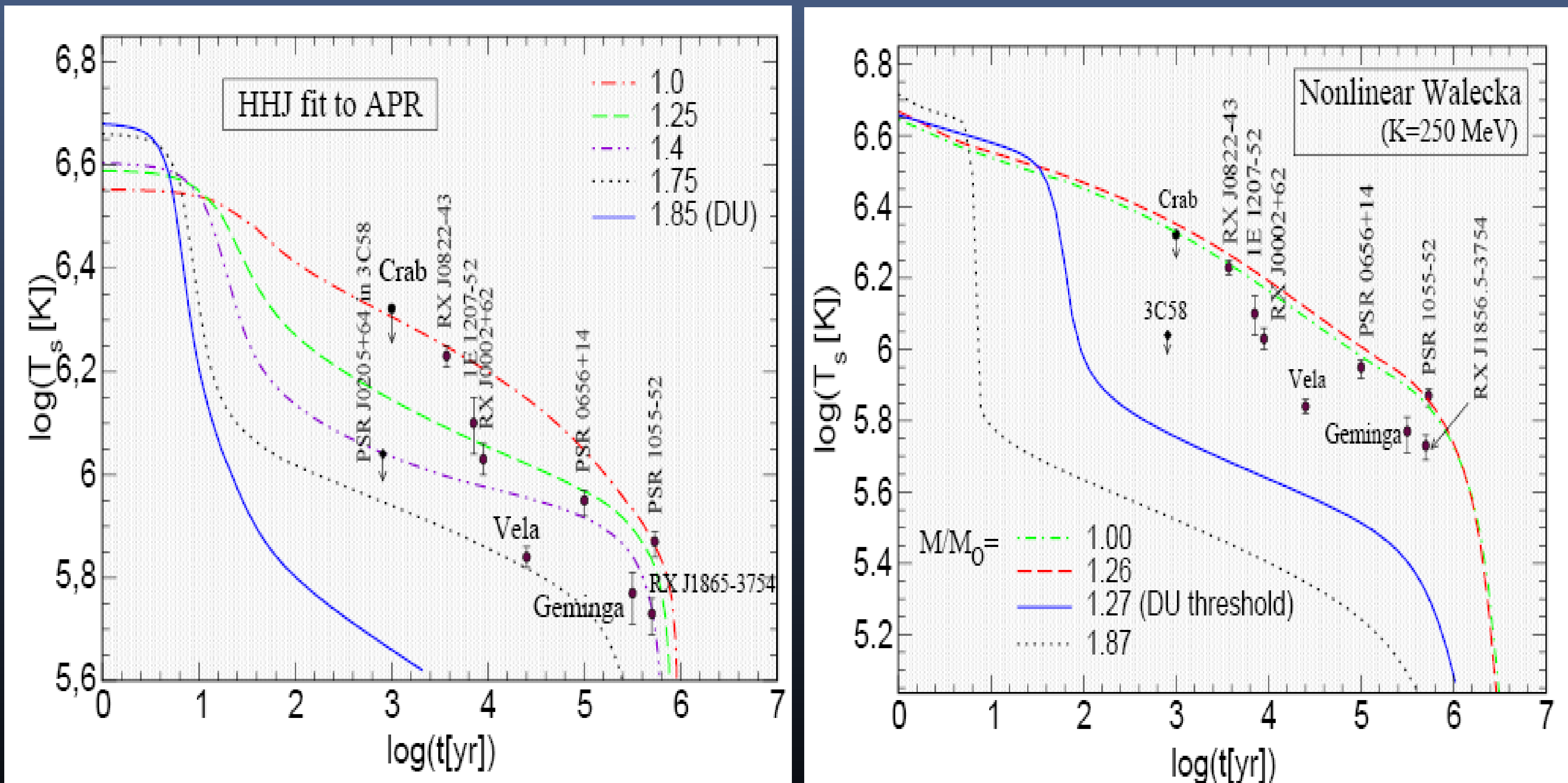
Mc = 1.25 Msun – NLW

Mc =1.84 Msun - HHJ





DU problem & constaint



SC pairing gaps – hybrid stars

2SC phase: 1 color (blue) is unpaired (mixed superconductivity)

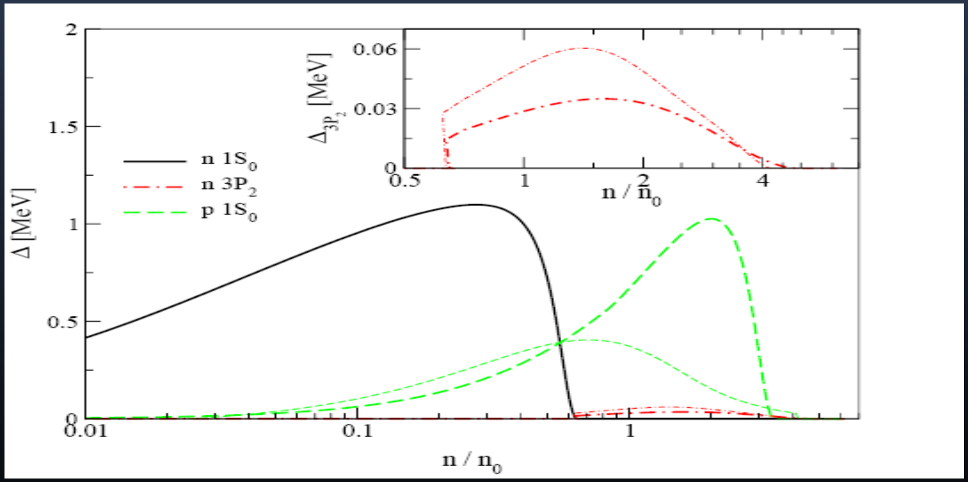
Ansatz   2SC + X phase:

$$\Delta_0^X = \Delta_0 \exp -\alpha \left(\frac{\mu - \mu_c}{\mu_c}\right)$$

Model	Δ_0 [MeV]	α
I	1	10
II	0.1	0
III	0.1	2
IV	5	25

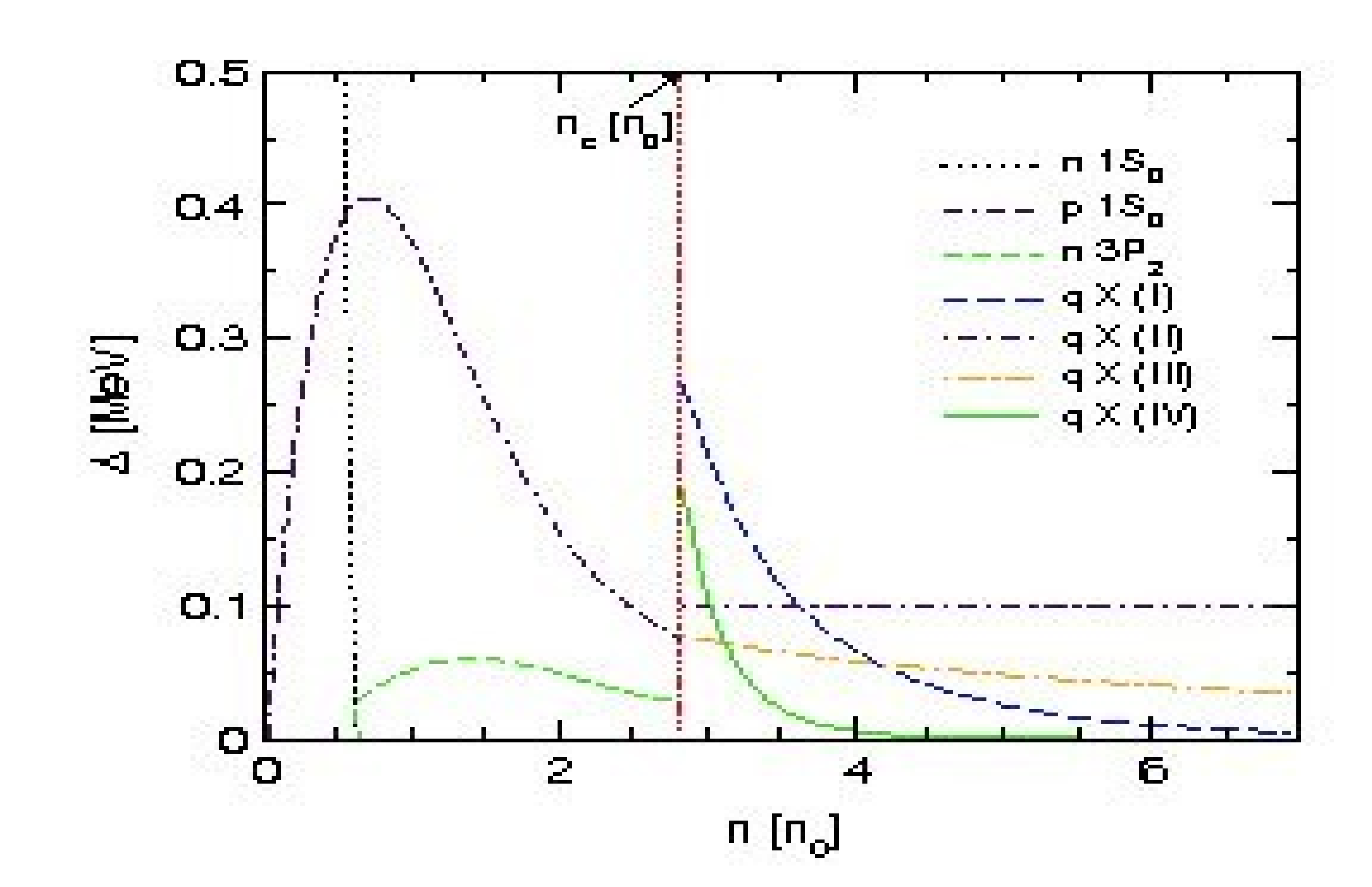
Grigorian, DB, Voskresensky , PRC 71 (2005) 045801

Pairing gaps for hadronic phase (**AV18 - Takatsuka et al. (2004)**)



Blaschke, Grigorian, Voskresensky , A&A 424 (2004) 979

SC pairing gaps – hybrid stars

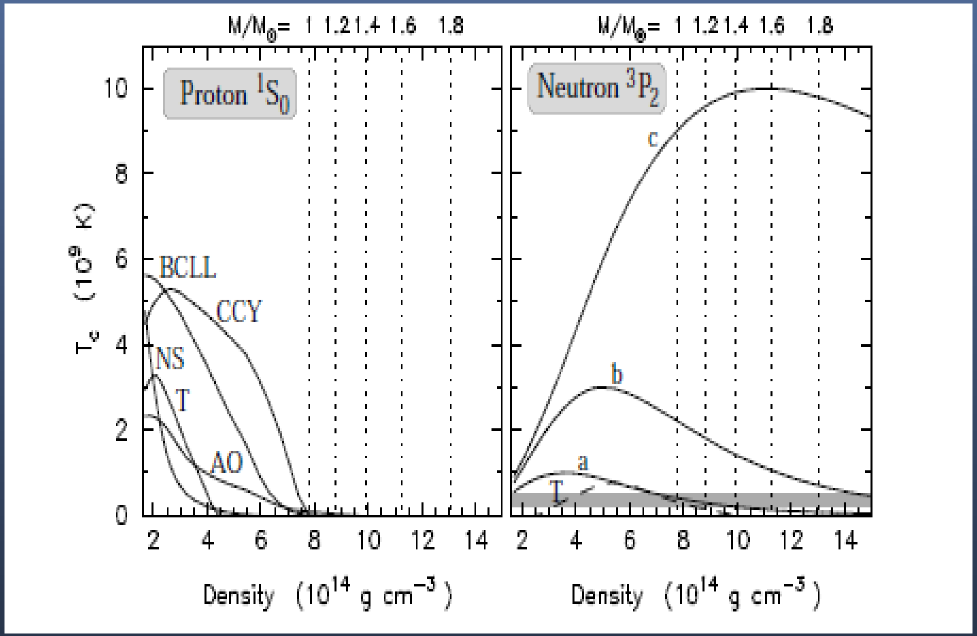


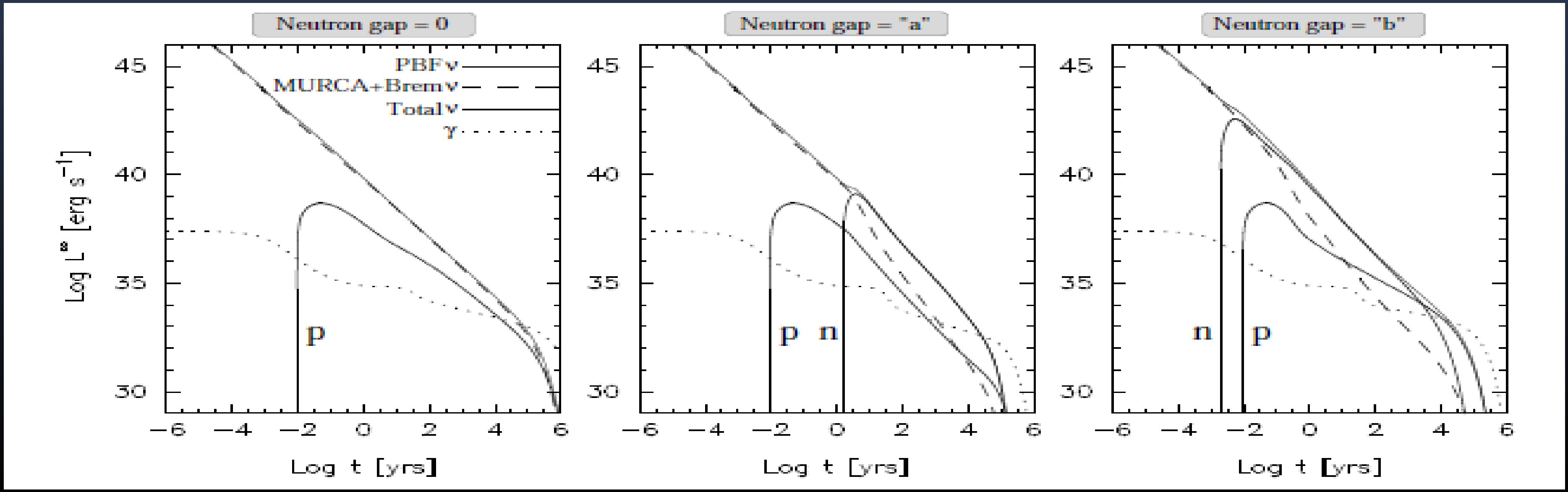
Popov, Grigorian, Blaschke, PRC 74 (2006)

Influence of SC on luminosity

Critical temperature Tc, for the proton $^1S_0$ and neutron $^3P_2$ gaps, used in

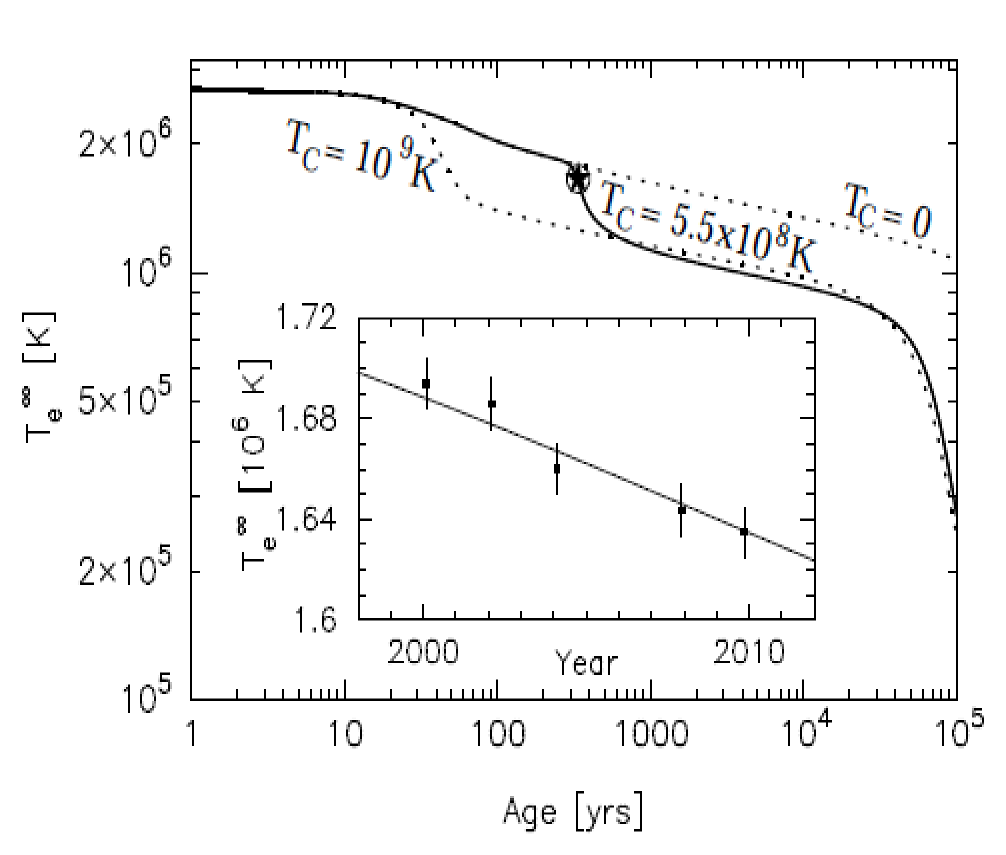
Page, Lattimer, Prakash & Steiner, Astrophys. J. 707 (2009) 1131

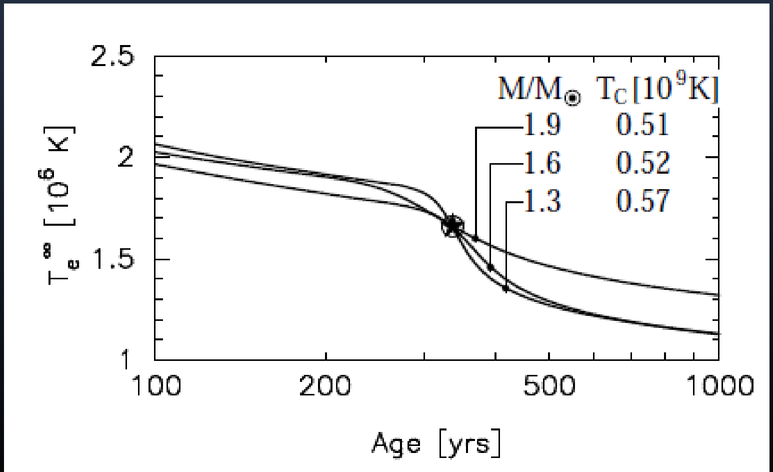




T_c 'measurement' from Cas A

- 1.4 M⊙ star built from the APR EoS
- Rapid cooling at ages ~30-100 yrs due to the thermal relaxation of the crust
- Mass dependence

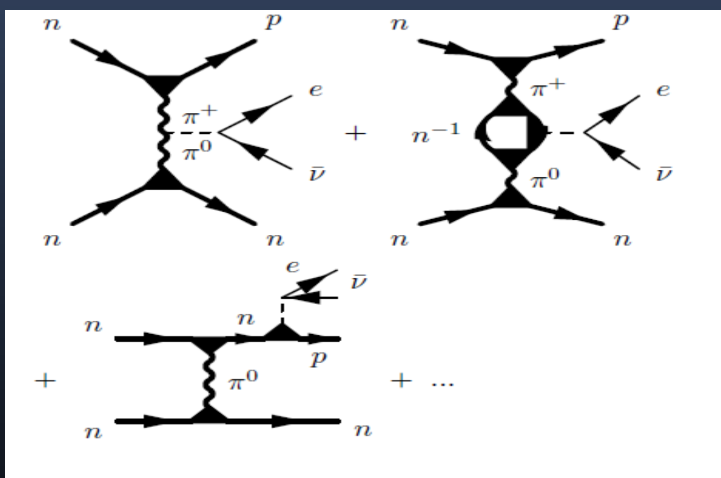




Page, Lattimer, Prakash & Steiner,
Phys. Rev. Lett. 106 (2011) 081101

Medium effects in cooling of neutron stars

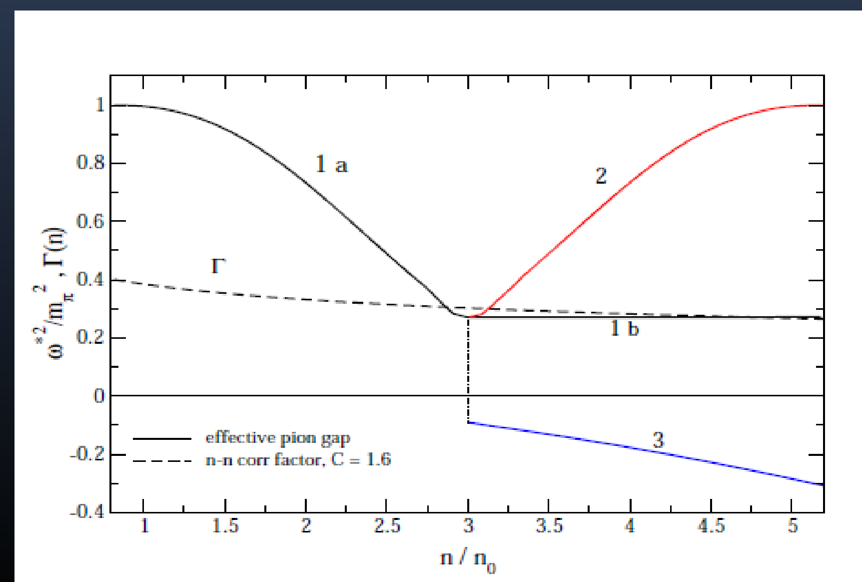
- Based on Fermi liquid theory: Landau (1956), Migdal (1967), Migdal et al. (1990)
- MMU – instead of MU



$$\frac{\varepsilon_\nu[\mathrm{MMU}]}{\varepsilon_\nu[\mathrm{MU}]} \sim 10^3 \; (n/n_0)^{10/3} \frac{\Gamma^6(n)}{[\omega^*(n)/m_\pi]^8},$$

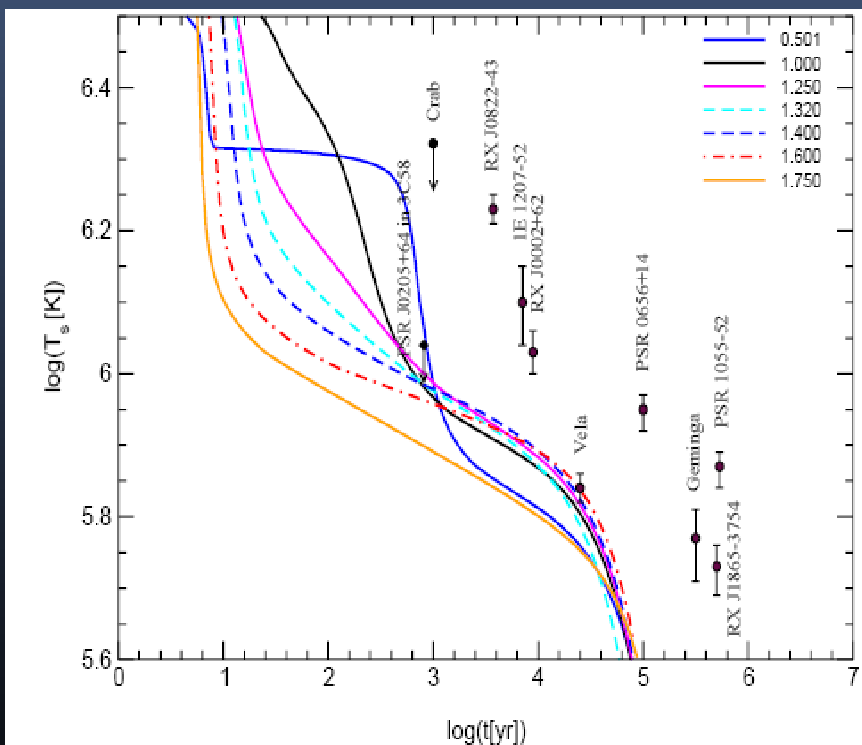
- PBF – fast cooling process for $T<T_c$

$$\varepsilon_\nu[\mathrm{MpPBF}] \sim 10^{29} \, \frac{m_N^*}{m_N} \left[\frac{p_{Fp}}{p_{Fn}(n_0)}\right] \left[\frac{\Delta_{pp}}{\mathrm{MeV}}\right]^7 \times \left[\frac{T}{\Delta_{pp}}\right]^{1/2} \xi_{pp}^2 \; \frac{\mathrm{erg}}{\mathrm{cm}^3\ \mathrm{sec}}\,, \quad T < T_{cp}.$$

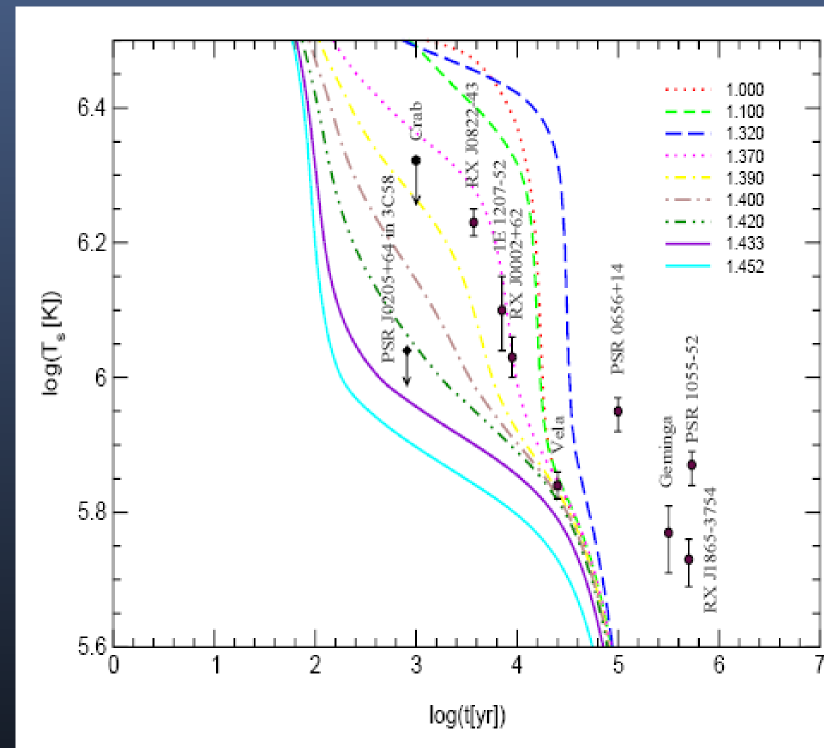


Anomalies because of PBF proccess

AV18 gaps, pi-condensate, without suppression of 3P2 neutron pairing - Enhanced PBF process



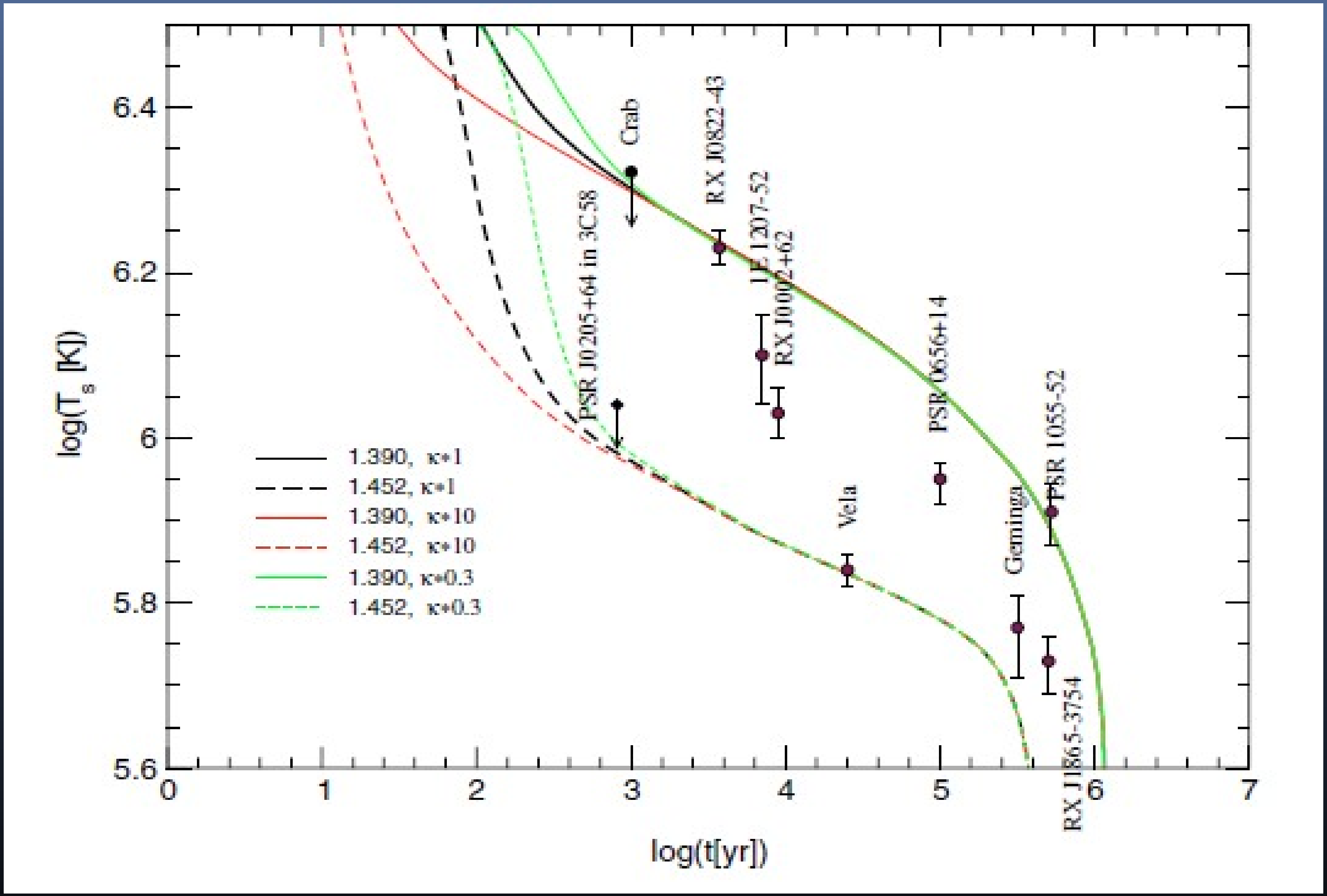
Gaps taken from Yakovlev at al. (2003)



n 3P2 gap **strongly suppressed:** Friman&Schwenk, PRL (2004)

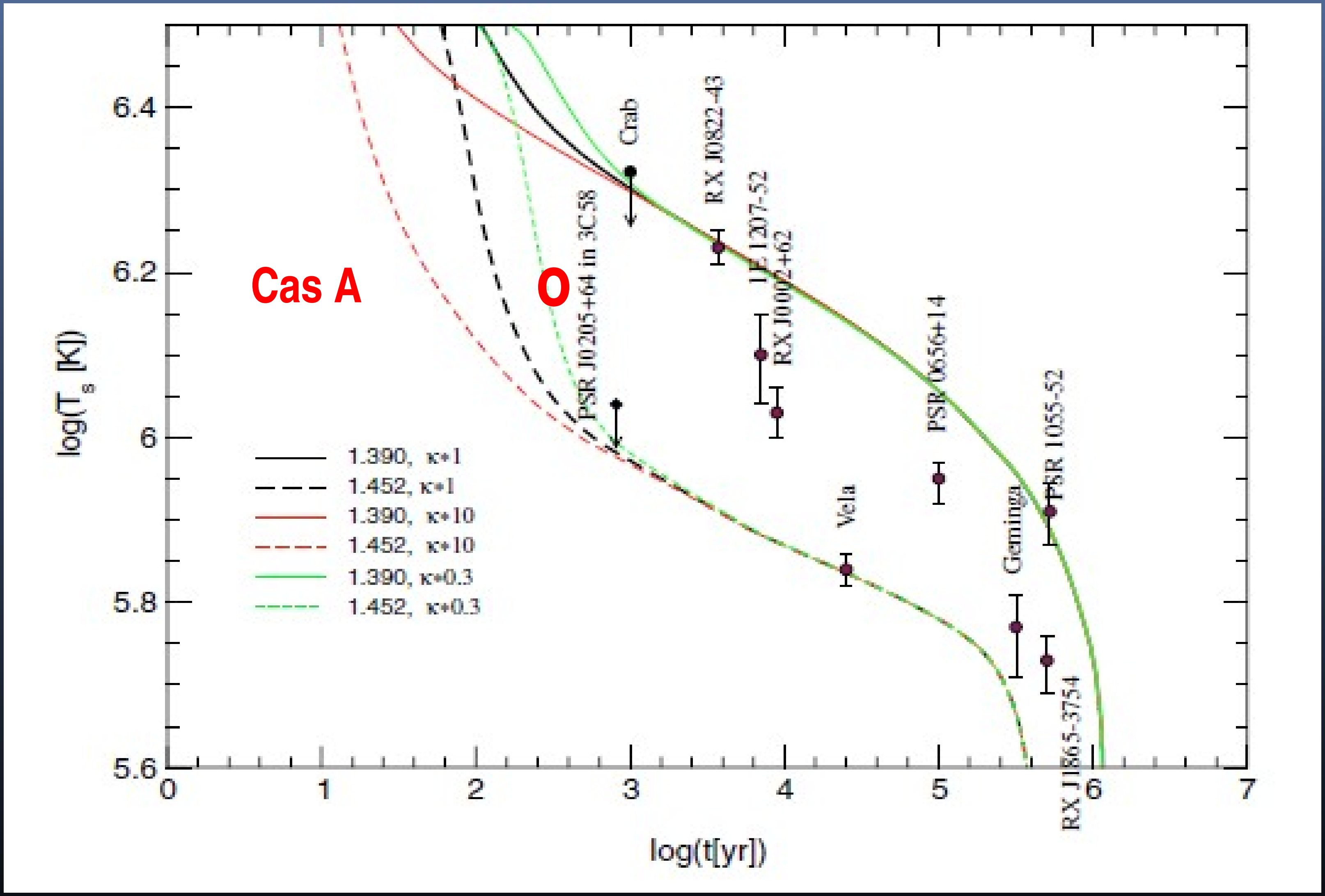
Grigorian, Voskresensky Astron.Astrophys. 444 (2005)

The influence of the (core) heat conductivity



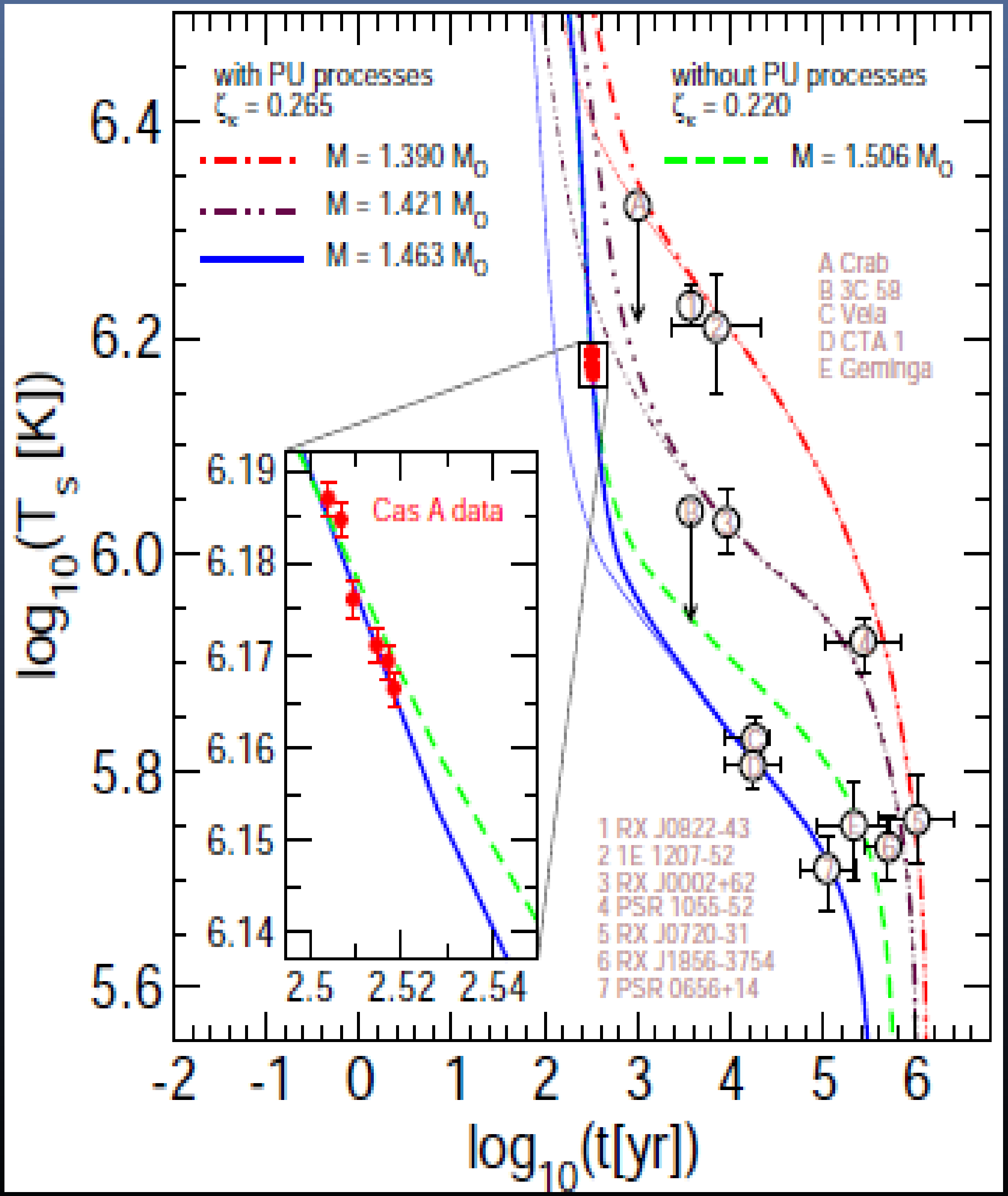
Blaschke, Grigorian, Voskresensky, A&A 424, 979 (2004)

The influence of the (core) heat conductivity

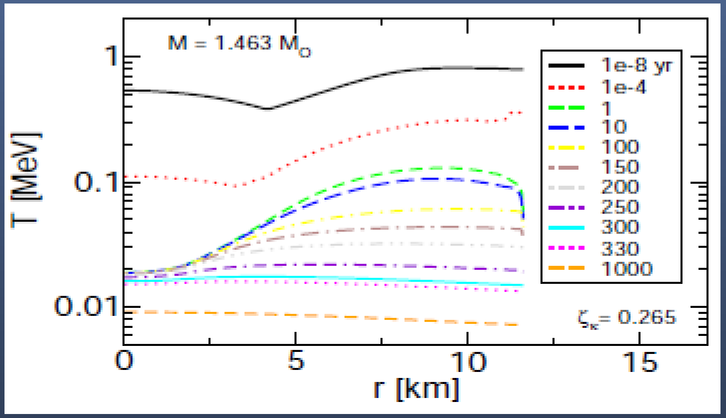


Blaschke, Grigorian, Voskresensky, A&A 424, 979 (2004)

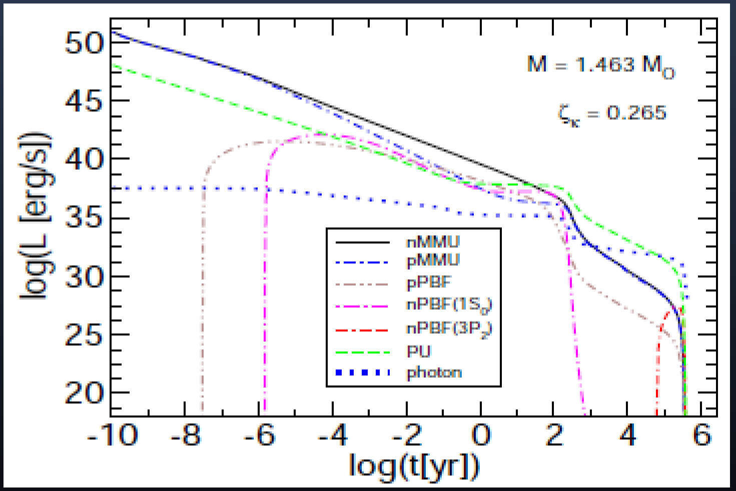
Cas A as a Hadronic Star – arxiv:1108.4125



Evolution of T - profiles



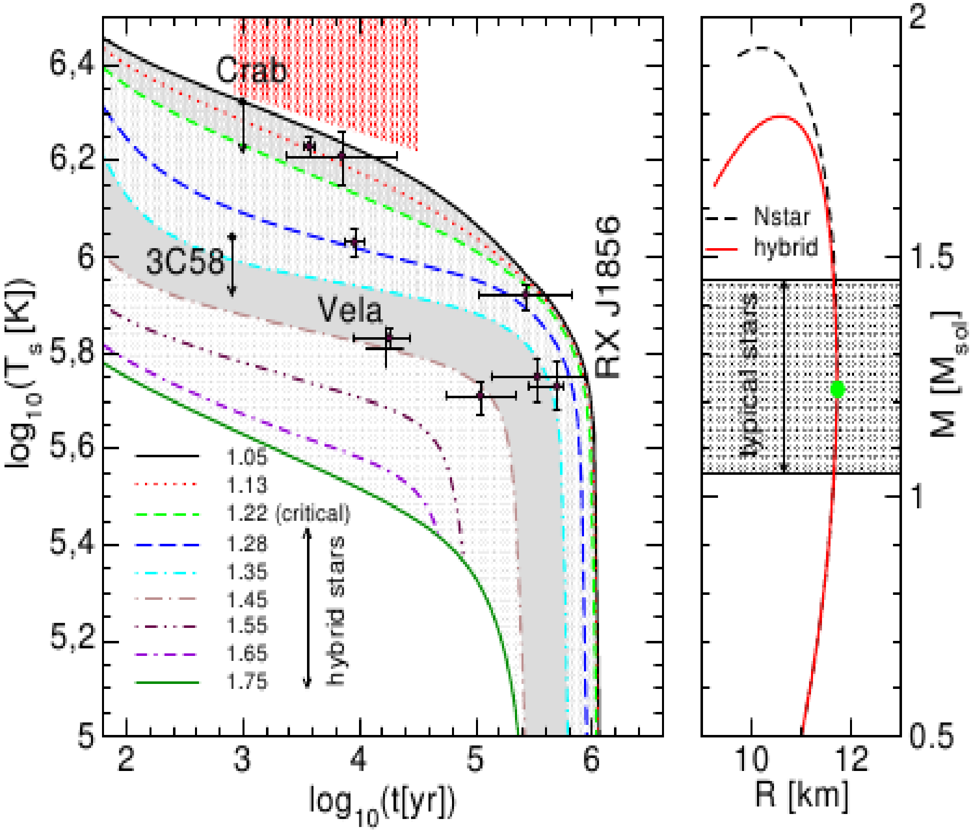
Partial contributions to L



Pion Urca? See in 10 - 50 years !

Quark matter in compact stars: Cooling constraint

Quark matter in compact stars: color superconducting

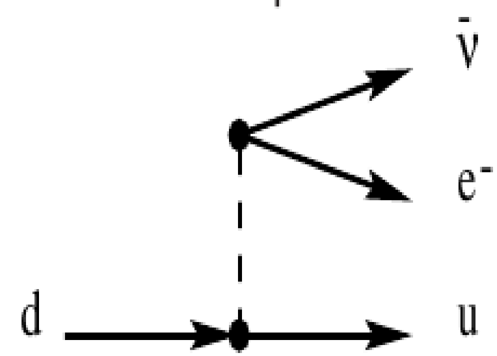


Popov et al: Neutron star cooling constraints ...
PRC 74, 025803 (2006); [nucl-th/0512098]

- Neutrinos carry energy off the star, Cooling evolution (schematic) by

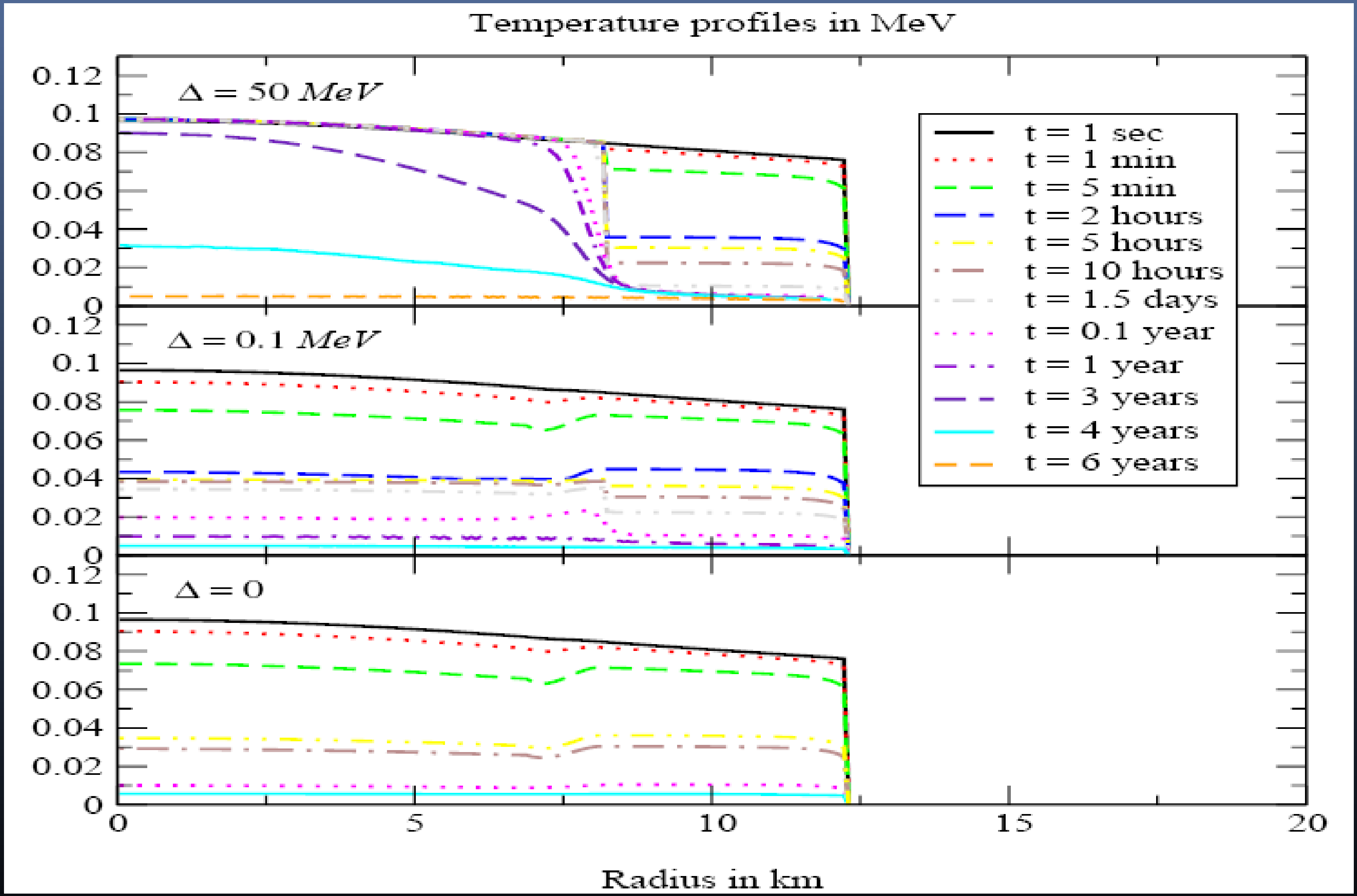
$$\frac{dT(t)}{dt} = -\frac{\epsilon_\gamma + \sum_{j=Urca,\dots} \epsilon_\nu^j}{\sum_{i=q,e,\gamma,\dots} c_V^i}$$

- Most efficient process: Urca



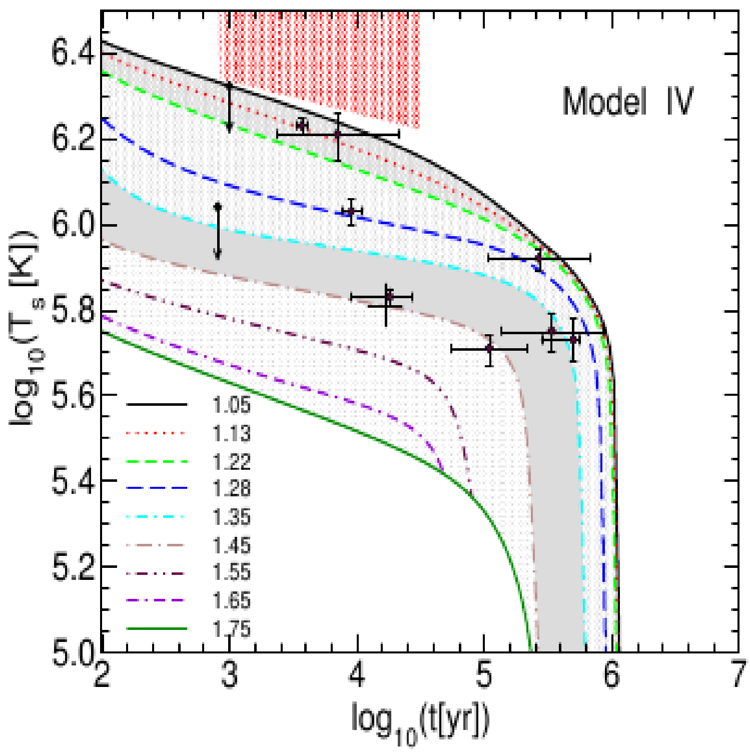
- Exponential suppression by pairing gaps! $\Delta \sim 10 \dots 100$ keV

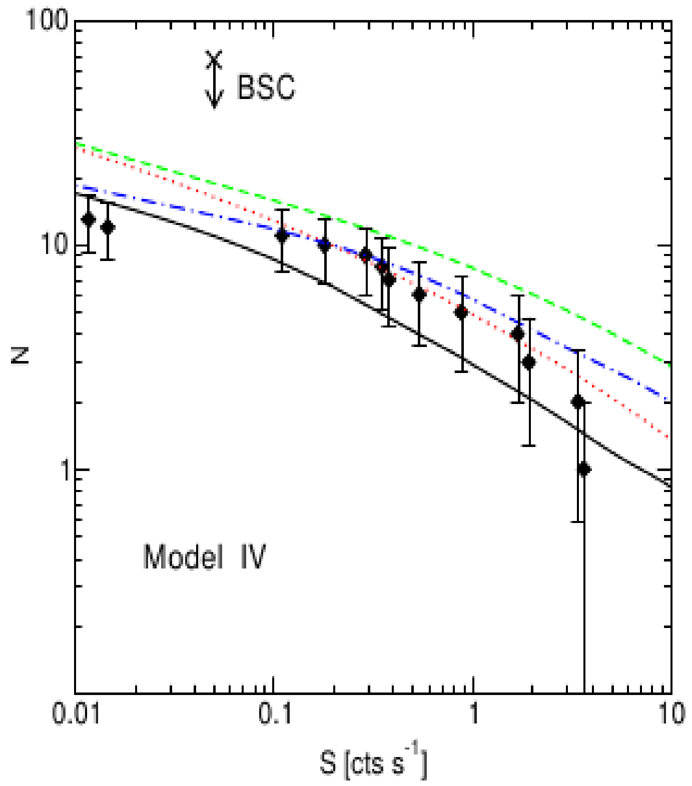
Temperature in the Hybrid Star Interior



Blaschke, Grigorian, Voskresensky, A& A 368 (2001) 561

Hybrid Star Cooling with 2SC Quark Matter (III)





2SC + X phase, $\Delta_0 = 5$ MeV, $\alpha = 25$

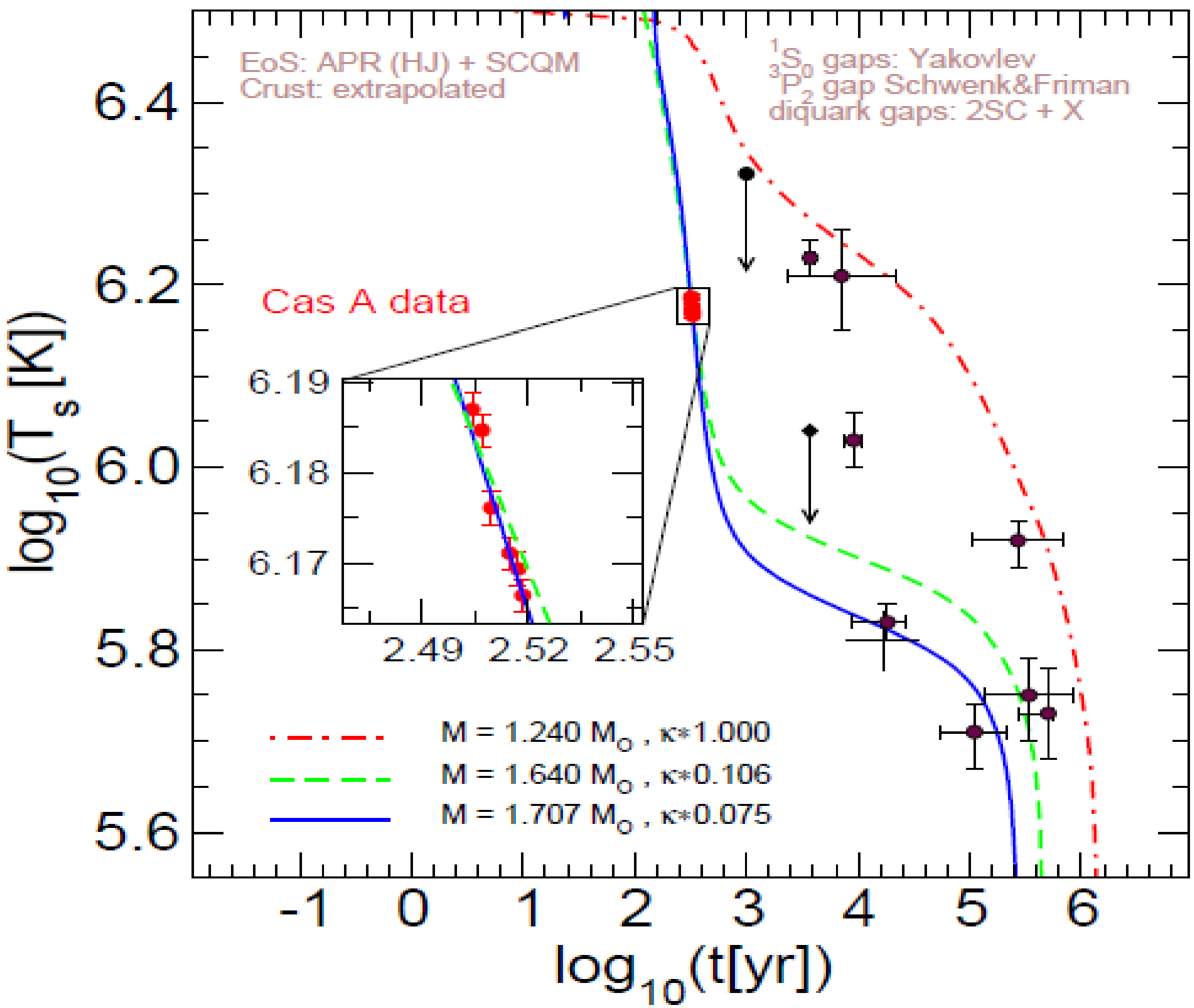
Temperature-age and Vela mass OK

Log N - Log S test passed

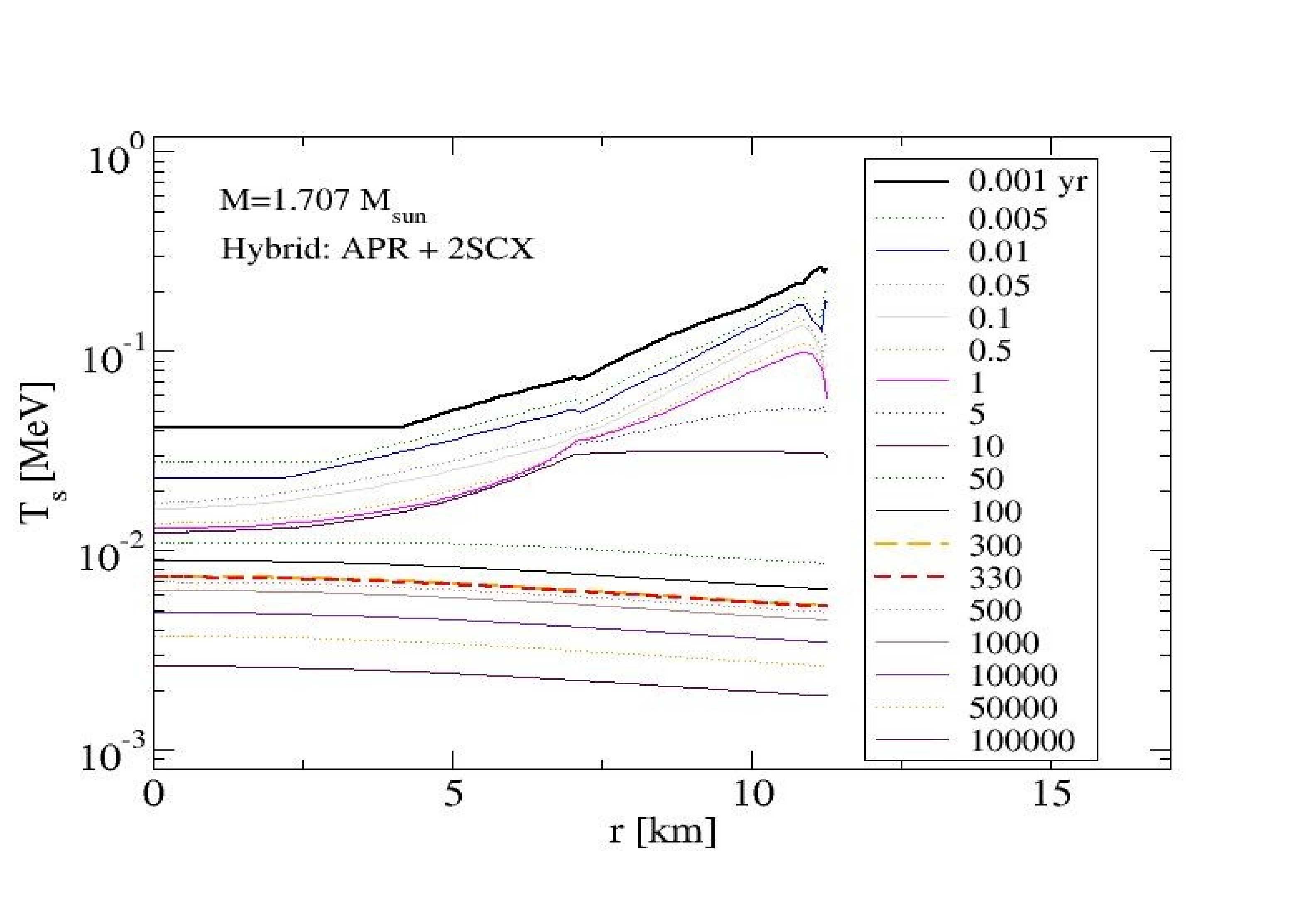
Popov, Grigorian, D.B., PRC 74 (2006)

Cas A as an Hybrid Star

H. Grigorian, D. Blaschke, D.N. Voskresensky, Phys. Rev. C 71, 045801 (2005)



Cas A as Hybrid Star: T-profile evolution



Conclusions II

- Cas A rapid cooling consistently described by the nuclear medium cooling model as a "first drop", delayed by low conductivity
- Both alternatives for the inner structure, hadronic and hybrid star, are viable for Cas A; a higher star mass favors the hybrid model
- In contrast to the minimal cooling scenario, our approach is sensitive to the star mass and thermal conductivity of superfluid star core matter
- Discriminating test? Log N – Log S !! (?)

It's cool to be a CompStar member!

Upcoming School and Conference ...

Thanks for Your attention!