Strangeness in Compact Stars

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HGSFP

EMMI

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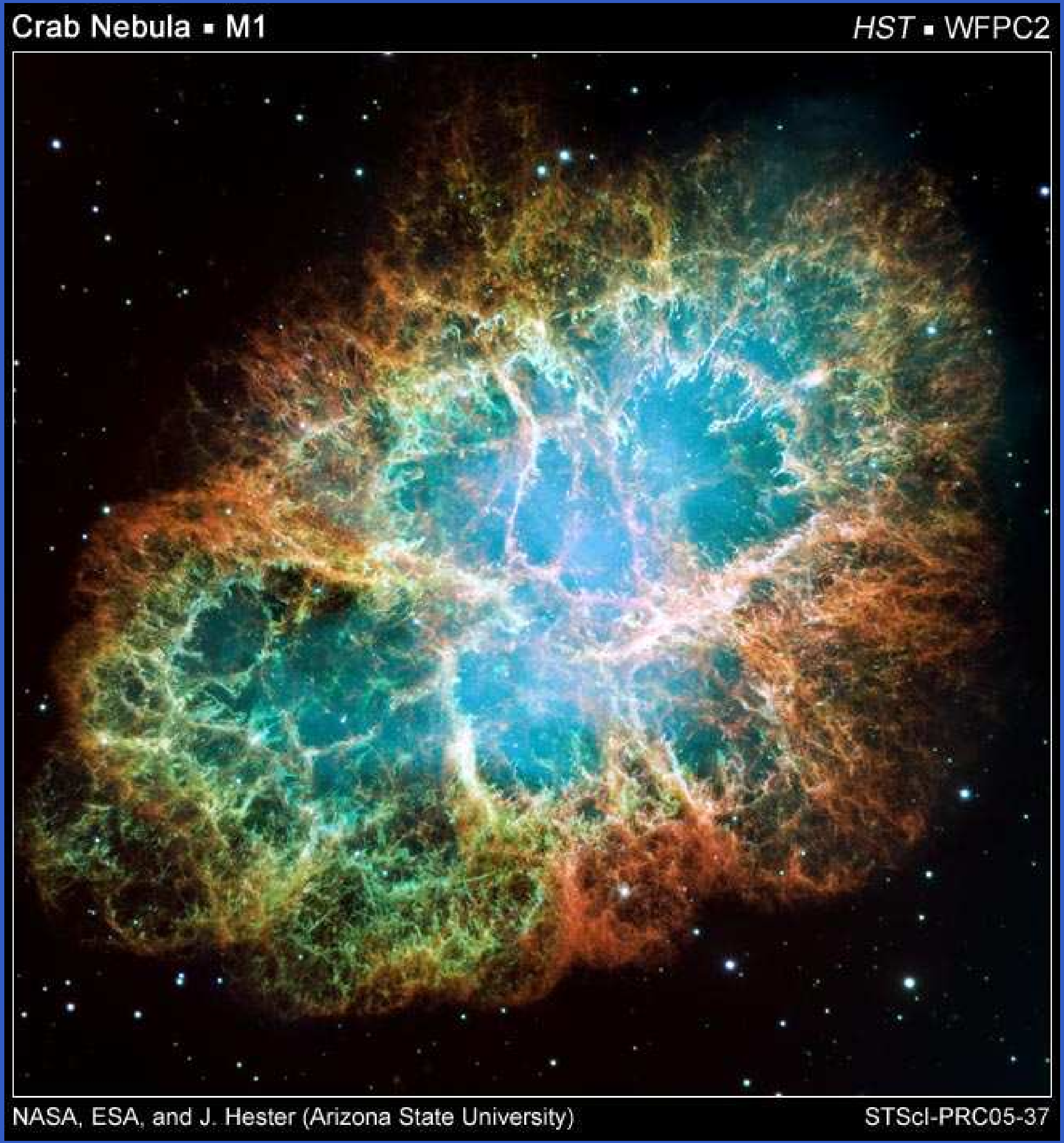
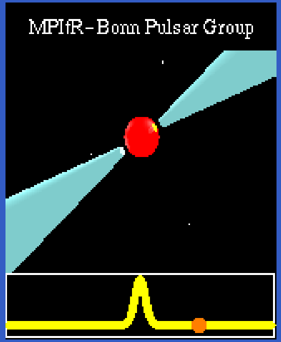
Outline

- Observations of neutron stars
- Composition of neutron stars: they are giant hypernuclei
- Masses of neutron stars: controlled by three-body force involving hyperons
- Maximum mass of neutron stars: new limit determined from kaon production in heavy-ion collisions
- Neutron star cooling: fast cooling with hyperons
- Gravitational wave emission from rotating neutron stars: stabilized with nonmesonic weak processes involving hyperons
- Supernova matter: presence of hyperons can trigger the phase transition to quark matter
- Summary

Observations of neutron stars

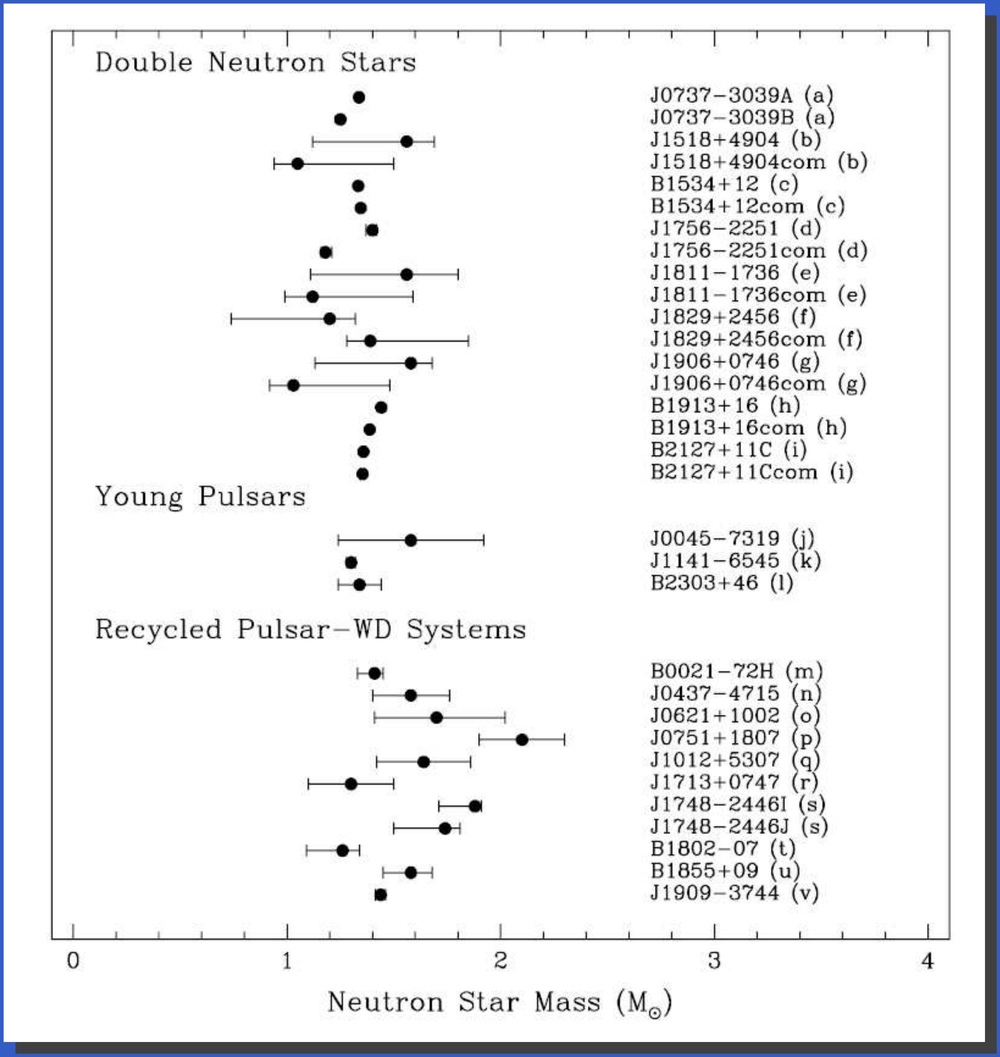
Neutron Stars





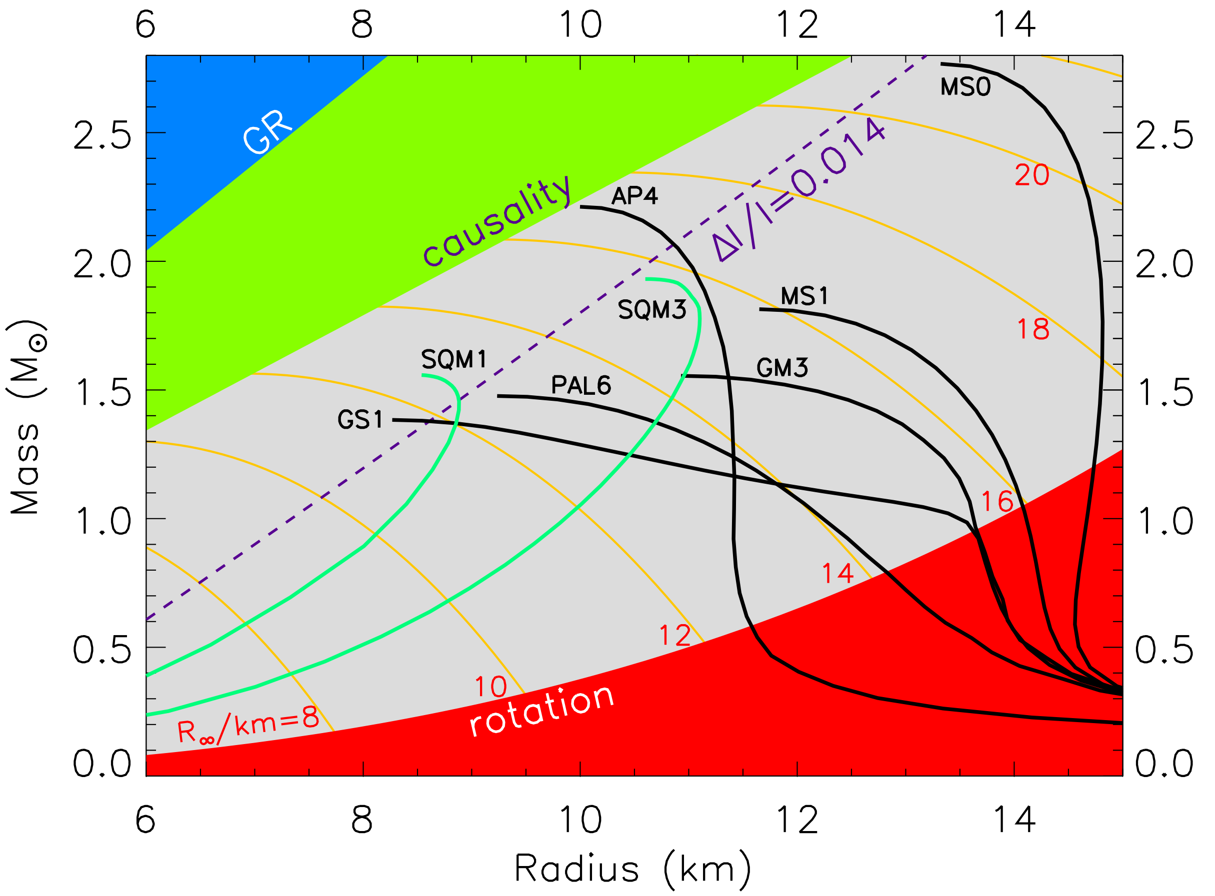
- produced in core collapse supernova explosions
- compact, massive objects: radius ≈ 10 km, mass $1 - 2M_\odot$
- extreme densities, several times nuclear density: $n \gg n_0 = 3 \cdot 10^{14}$ g/cm^3
- in the middle of the crab nebula: a pulsar, a rotating neutron star!

Masses of Pulsars (Stairs, 2006)



- >1700 pulsars known
- best determined mass: $M = (1.4414 \pm 0.0002) M_\odot$ for the Hulse-Taylor pulsar (Weisberg and Taylor, 2004)
- mass of PSR J0751+1807 corr. from $M = (2.1 \pm 0.2) M_\odot$ to $M = (1.14 - 1.40) M_\odot$ (Nice et al. 2008)
- mass of PSR J1903+0327 (not finalized yet): $M = (1.67 \pm 0.01) M_\odot$ (Freire et al. 2009)

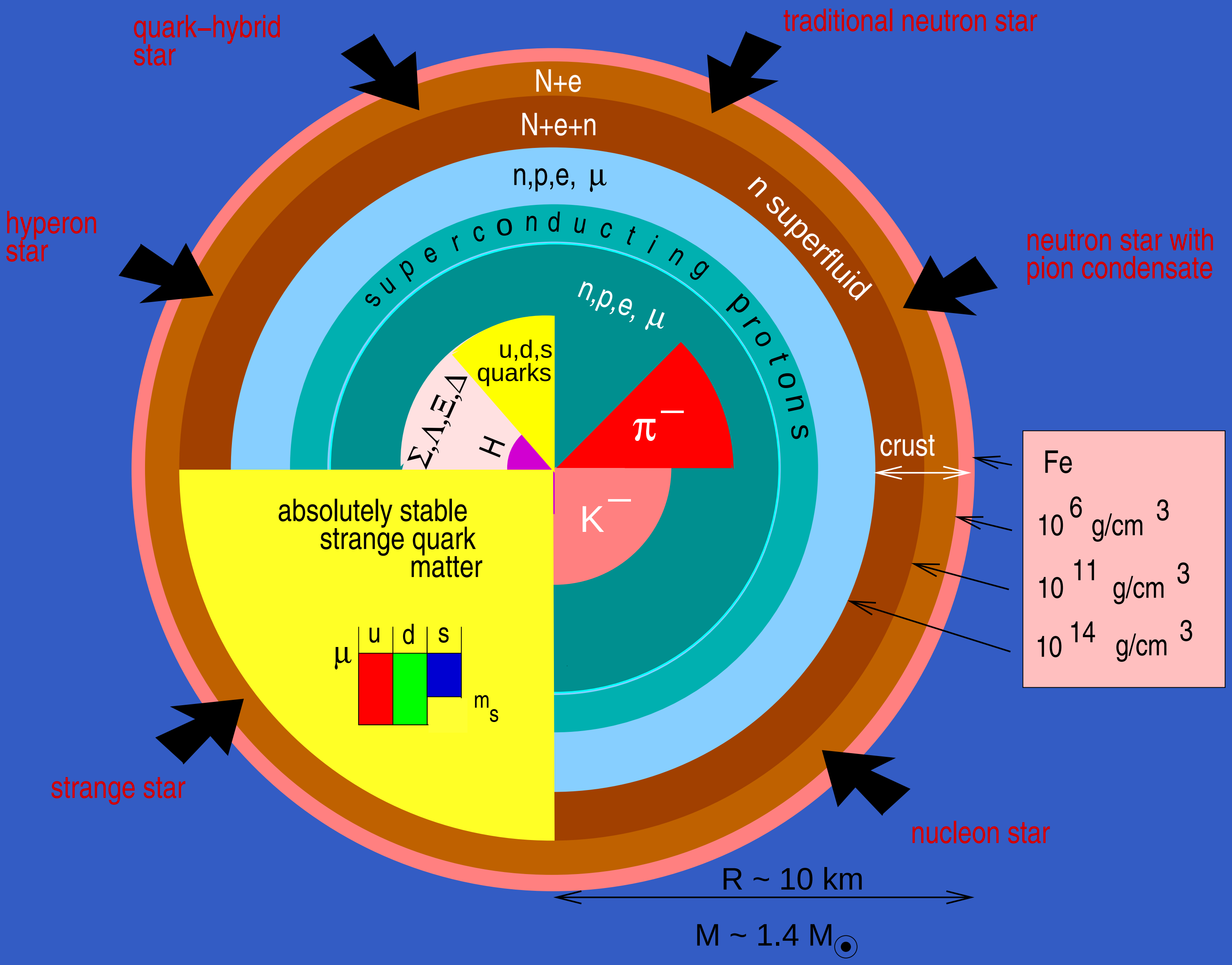
Constraints on the Mass–Radius Relation (Lattimer and Prakash (2004))



- spin rate from PSR B1937+21 of 641 Hz: $R < 15.5$ km for $M = 1.4M_\odot$
- Schwarzschild limit (GR): $R > 2GM = R_s$
- causality limit for EoS: $R > 3GM$

Composition of Neutron Stars

Structure of a Neutron Star — the Core (Fridolin Weber)



Neutron Star Matter and Particle Composition

general critical condition: chemical potential = in-medium energy

β-equilibrium: weak decays are Pauli-blocked

for a free gas (Ambartsumyan and Saakyan, 1960):

Hadron	p,n	Σ^-	Λ	others
appears at:	$\ll n_0$	$4n_0$	$8n_0$	$> 20n_0$

note: no pion or kaon condensation (for s-wave: $\mu_K = \mu_e$)

but the corresponding equation of state results in a maximum mass of only (Oppenheimer and Volkoff, 1939):

$$M_{\mathrm{max}} \approx 0.7 M_\odot < 1.44 M_\odot$$

$\Longrightarrow$ effects from strong interactions are essential to describe neutron stars!

Onset of Hyperons in Neutron Star Matter

Hyperons appear at $n \approx 2n_0$! (based on hypernuclear data!)

- relativistic mean–field models

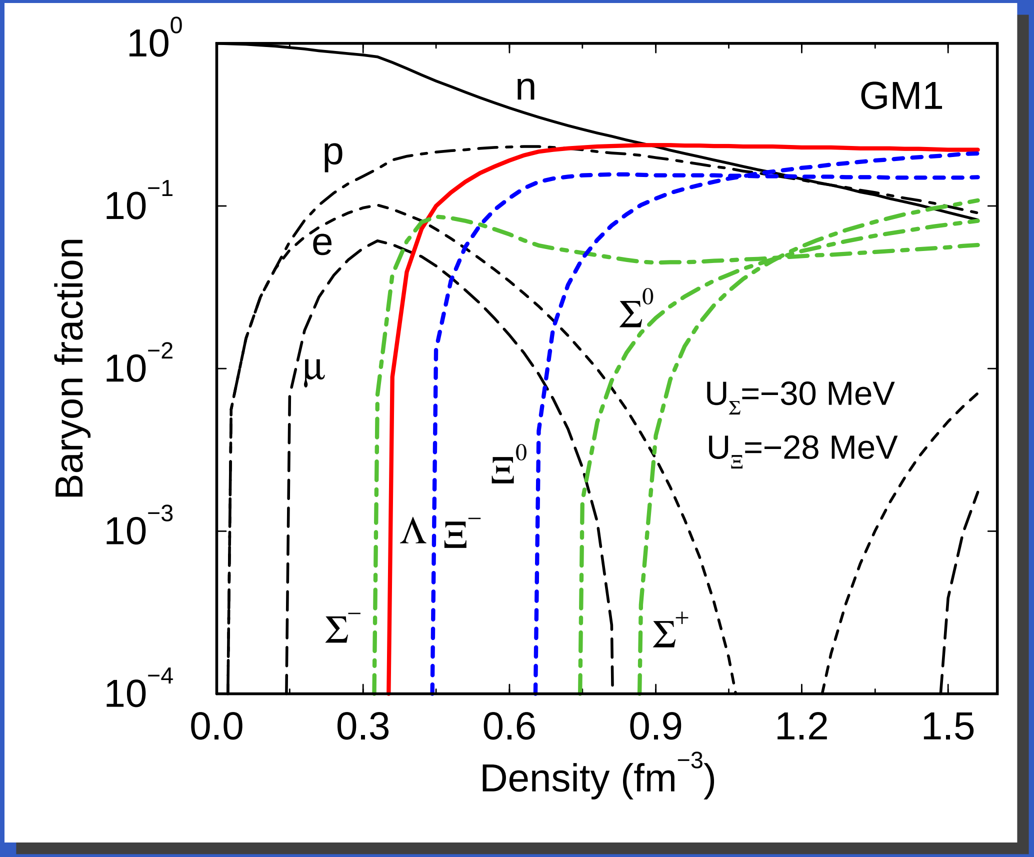
  (Glendenning 1985; Knorren, Prakash, Ellis 1996; JS and Mishustin 1996)
- nonrelativistic potential model (Balberg and Gal 1997)
- quark-meson coupling model (Pal et al. 1999)
- relativistic Hartree–Fock (Huber, Weber, Weigel, Schaab 1998)
- Brueckner–Hartree–Fock

  (Baldo, Burgio, Schulze 1998, 2000; Vidana et al. 2000; Schulze, Polls, Ramos, Vidana 2006)
- chiral effective Lagrangian using SU(3) symmetry

  (Hanauske et al. 2000; Schramm and Zschiesche 2003; Dexheimer and Schramm 2008)
- density-dependent hadron field theory (Hofmann, Keil, Lenske 2001)
- G-matrix calculation (Nishizaki, Takatsuka, Yamamoto 2002)
- RG approach with $V_{\mathrm{low\ k}}$ (Djapo, Schäfer, Wambach 2008)

$\Rightarrow$ neutron stars are giant hypernuclei !!!

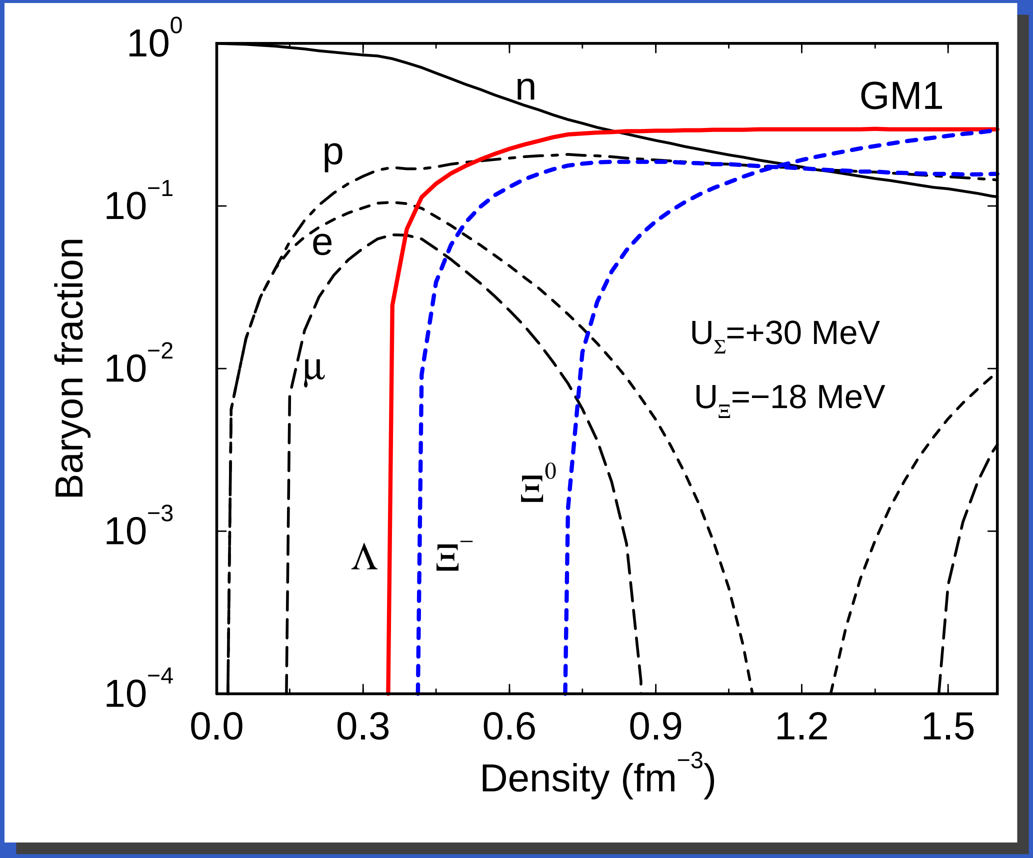
Composition of Neutron Star Matter



(JS and Mishustin 1996)

- hyperon potentials fixed to hypernuclear data
- attractive potential for Σs and Ξs
- Σ^- appear shortly before Λs around $n = 2n_0$
- Λs present in matter at $n = 2.5n_0$, Ξ^- before $n = 3n_0$

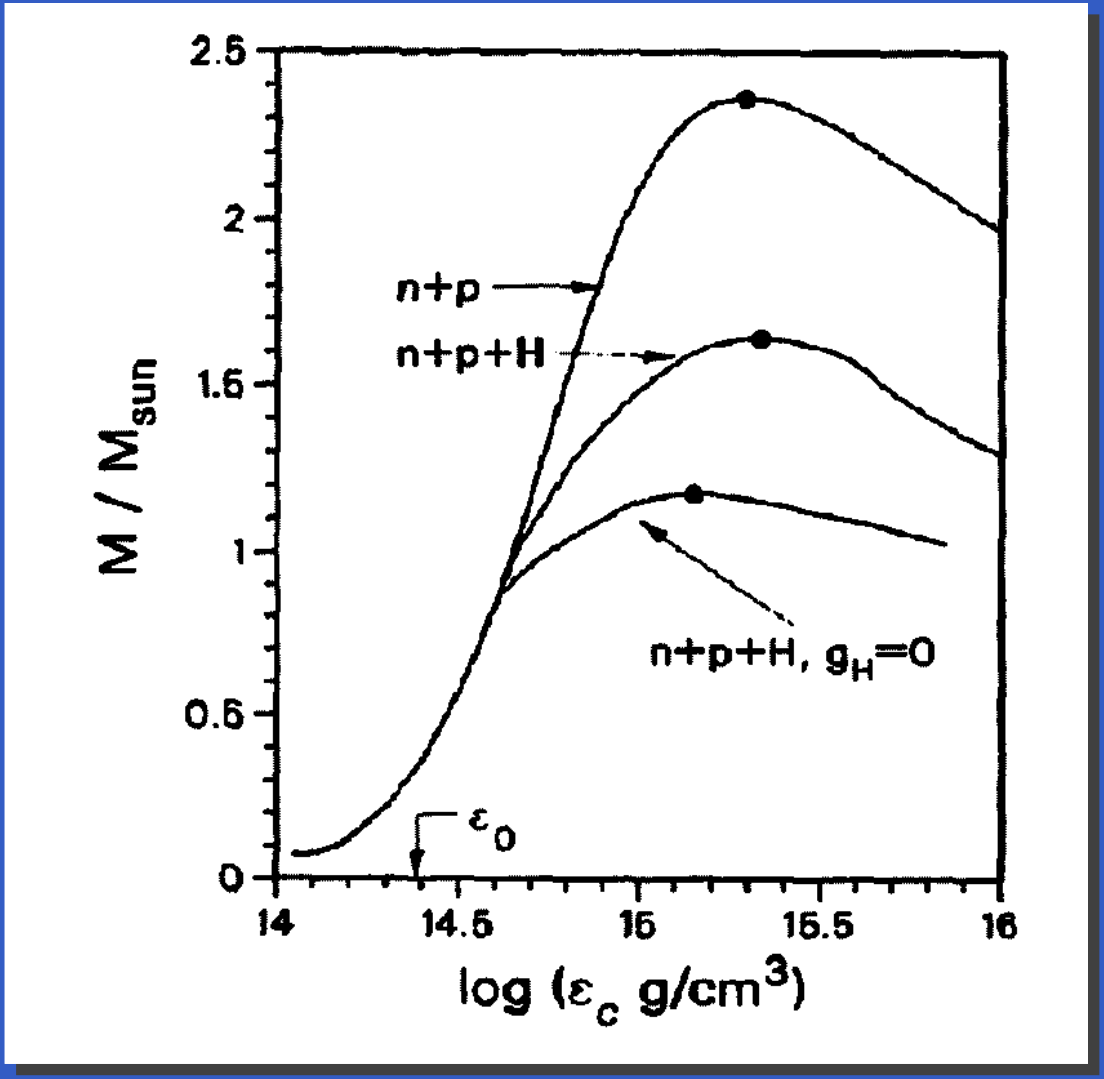
Composition of Neutron Star Matter



- Λs are present close to $n = 2n_0$
- repulsive potential for Σs: Σ hyperons do not appear at all!
- population is highly sensitive to the in-medium potential!

Masses of Neutron Stars

Impact of hyperons on the maximum mass of neutron stars



(Glendenning and Moszkowski 1991)

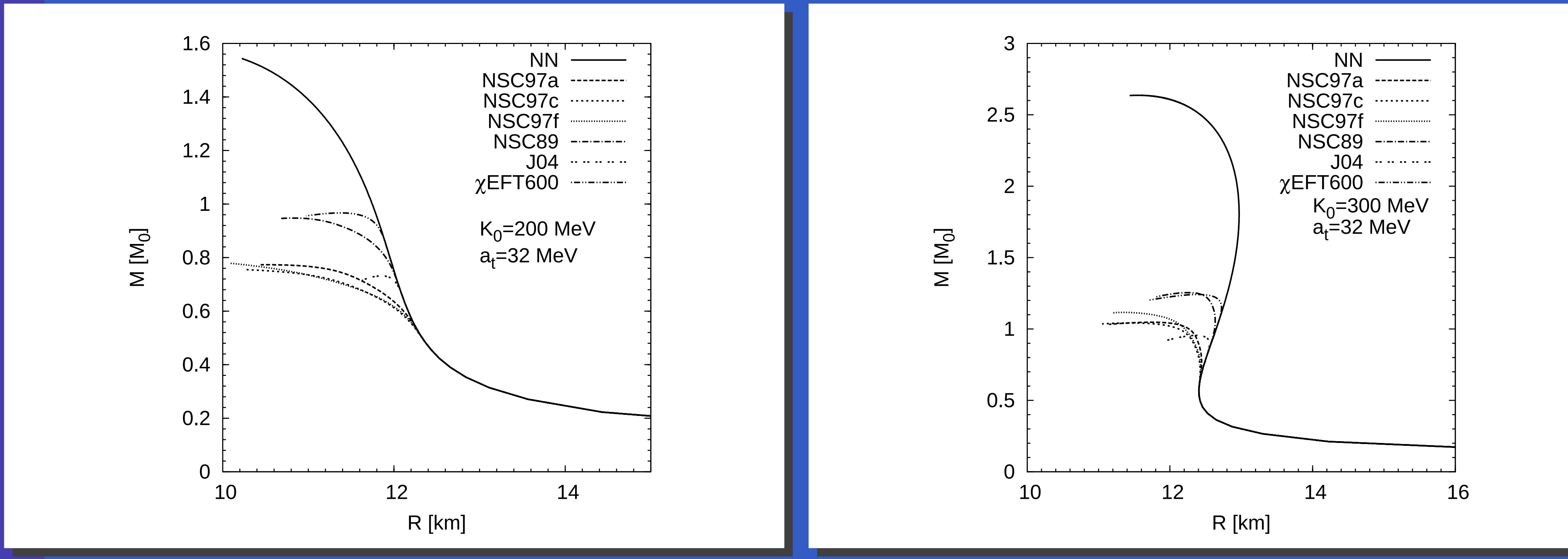
- neutron star with nucleons and leptons only: $M \approx 2.3 M_\odot$
- substantial decrease of the maximum mass due to hyperons!
- maximum mass for “giant hypernuclei”: $M \approx 1.7 M_\odot$
- noninteracting hyperons result in a too low mass: $M < 1.4 M_\odot$!

Maximum mass and modern many-body approaches

modern many-body calculations
(using Nijmegen soft-core YN potential)

- Vidana et al. (2000): $M_{\mathrm{max}} = 1.47 M_\odot$ (NN and YN interactions), $M_{\mathrm{max}} = 1.34 M_\odot$ (NN, NY, YY interactions)
- Baldo et al. (2000): $M_{\mathrm{max}} = 1.26 M_\odot$ (including three-body nucleon interaction)
- Schulze et al. (2006): $M_{\mathrm{max}} < 1.4 M_\odot$
- Djapo et al. (2008): $M_{\mathrm{max}} < 1.4 M_\odot$
- too soft EoS, too low masses!
- missing three-body force for hyperons (YNN, YYN, YYY): neutron stars can not live without it!
- more input needed from hypernuclear physics!

Mass-radius relation with $V_{\text{low k}}$ potential



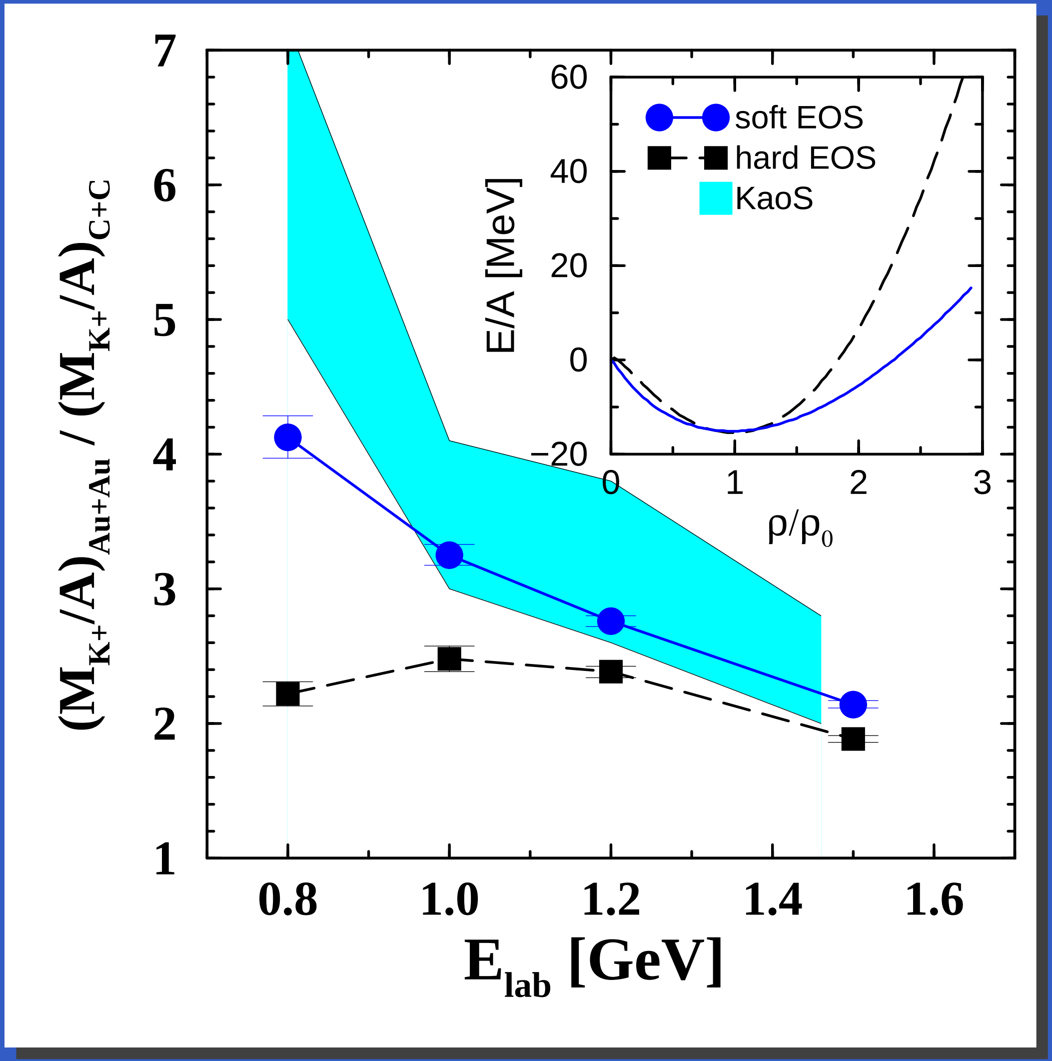
(Djapo, Schäfer, Wambach 2008)

- RG approach with $V_{\text{low k}}$ potential from various models
- presence of hyperons substantially reduces the maximum mass
- in contradiction with pulsar data: $M_{\max} < 1.44 M_\odot$

Maximum mass of neutron stars: new limit from heavy-ion data

(Irina Sagert, JSB, Christian Sturm, 2009)

Kaon production in heavy-ion collisions

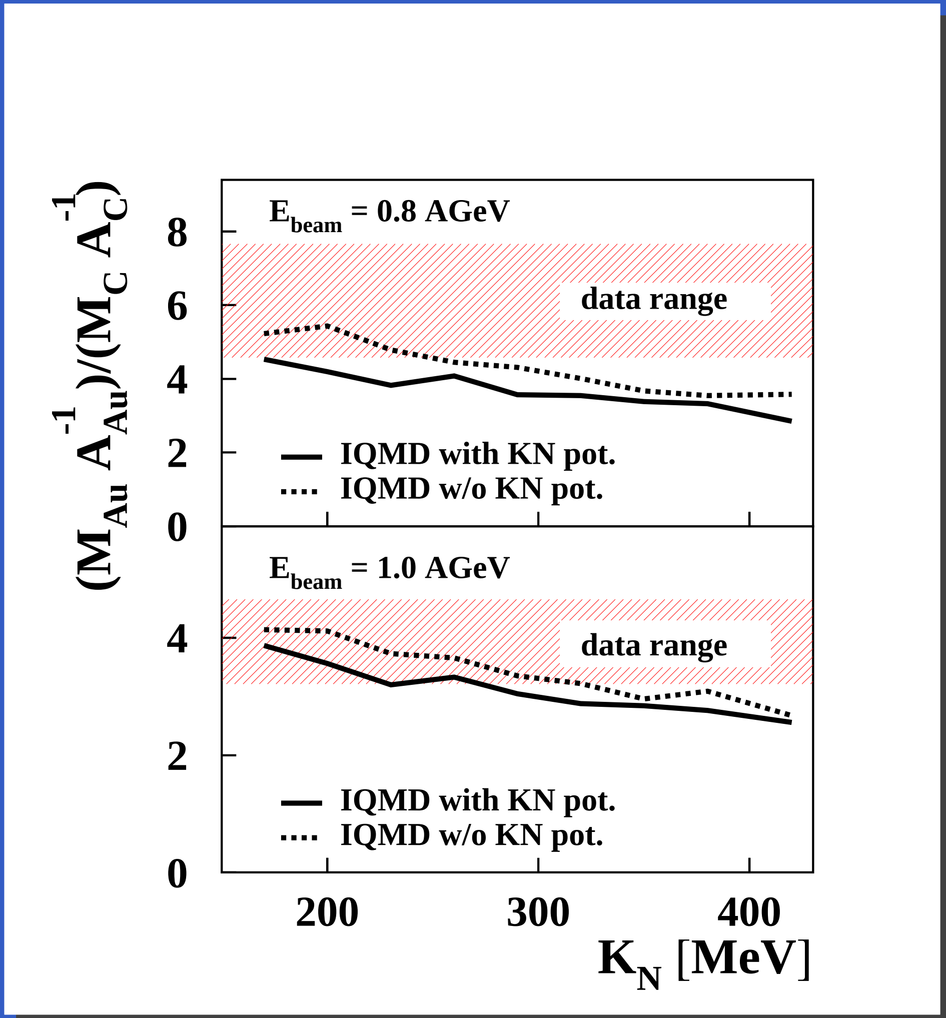


Sturm et al. (KaoS collaboration), PRL 2001

Fuchs, Faessler, Zabrodin, Zheng, PRL 2001

- Kaons produced by associated production: NN$\rightarrow$ NΛK, NN$\rightarrow$NNK$\overline{\mathrm{K}}$
- in-medium processes (rescattering): $\pi\mathrm{N} \rightarrow \Lambda$K, $\pi\Lambda \rightarrow \mathrm{N}\overline{\mathrm{K}}$
- nuclear matter is compressed up to $3n_0$!
- long mean-free path of kaons: kaons can escape high density matter

Confirmed KaoS data analysis: the nuclear EoS is soft!

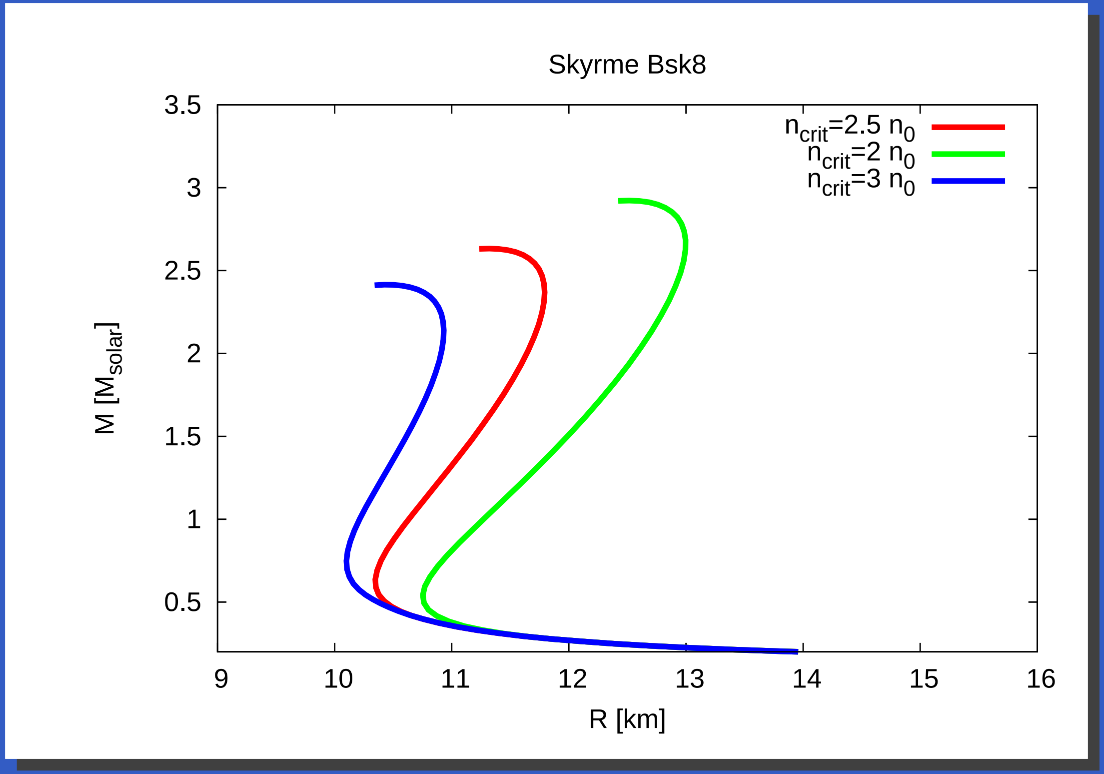


The KΛOS Collaboration

- kaon production (K^+) in heavy-ion collisions at subthreshold energies
- double ratio: multiplicity per mass number for C+C collisions and Au+Au collisions at 0.8 AGeV and 1.0 AGeV (rather insensitive to input parameters)
- only calculations with a compression modulus of $K_N \approx 200$ MeV can describe the data (Hartnack, Oeschler, Aichelin, PRL 2006; KaoS collaboration, 2007)

$\Longrightarrow$ the nuclear equation of state is SOFT!

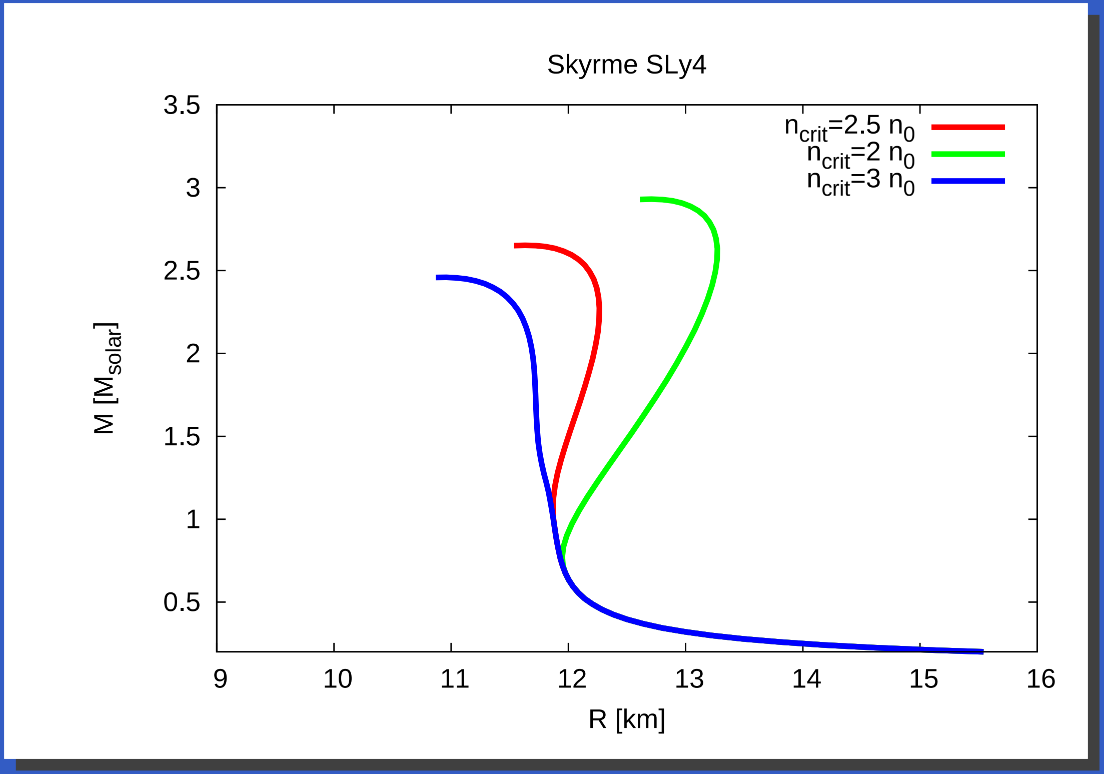
Maximum Masses of Neutron Stars – Causality



(Irina Sagert)

- Skyrme parameter set BSK8: fitted to masses of all known nuclei
- above a fiducial density (determined from the data analysis of the KaoS data) transition to stiffest possible EoS
- causality argument: $p = \epsilon - \epsilon_c$ above the fiducial density ϵ_f
  Rhoades, Ruffini (1974), Kalogera, Baym (1996): $M_{\max} = 4.2 M_\odot (\epsilon_0/\epsilon_f)^{1/2}$
- $\Longrightarrow$ new upper mass limit of about $2.7 M_\odot$ from heavy-ion data!

Maximum Masses of Neutron Stars – Causality



(Irina Sagert)

- Skyrme parameter set Sly4: fitted to properties of spherical nuclei
- above a fiducial density (determined from the data analysis of the KaoS data) transition to stiffest possible EoS
- causality argument: $p = \epsilon - \epsilon_c$ above the fiducial density ϵ_f
  Rhoades, Ruffini (1974), Kalogera, Baym (1996): $M_{\rm max} = 4.2 M_\odot (\epsilon_0/\epsilon_f)^{1/2}$
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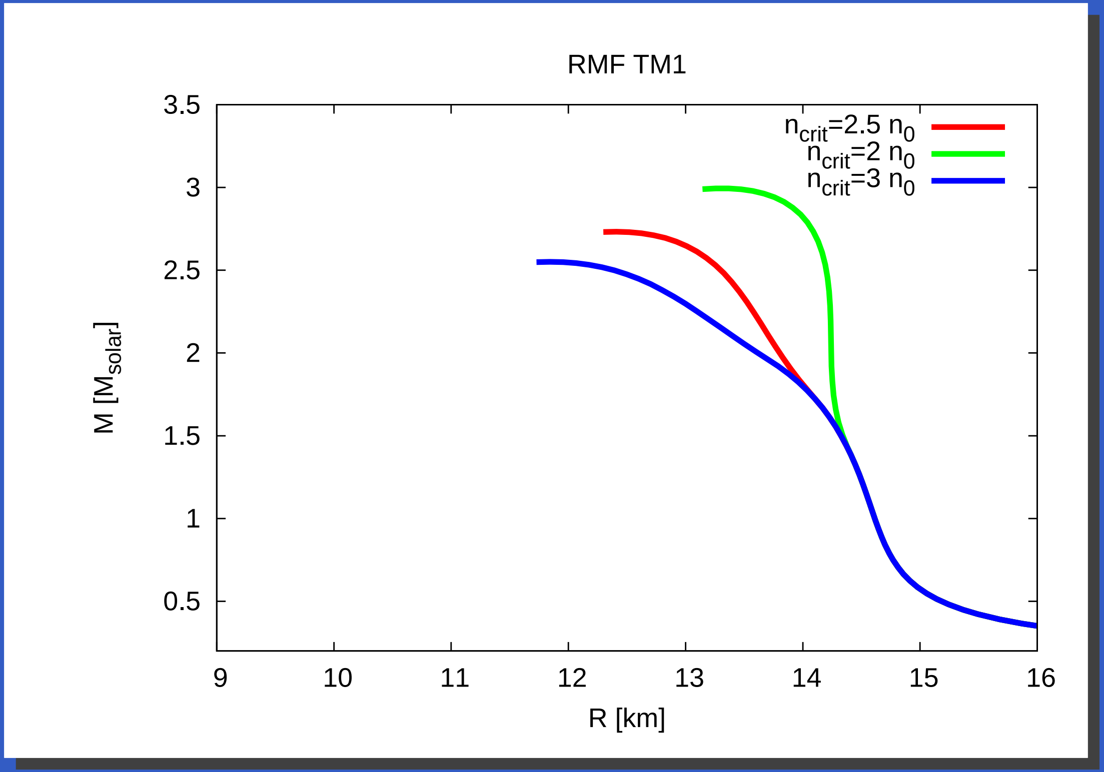
Maximum Masses of Neutron Stars – Causality



(Irina Sagert)

- RMF parameter set TM1: fitted to properties of spherical nuclei
- above a fiducial density (determined from the data analysis of the KaoS data) transition to stiffest possible EoS
- causality argument: $p = \epsilon - \epsilon_c$ above the fiducial density ϵ_f
  Rhoades, Ruffini (1974), Kalogera, Baym (1996): $M_{\max} = 4.2 M_\odot (\epsilon_0/\epsilon_f)^{1/2}$
- $\Longrightarrow$ new upper mass limit of about $2.8 M_\odot$ from heavy-ion data!

Neutron star cooling with hyperons

Cooling processes with neutrinos

modified URCA process (slow):

$$N + p + e^- \longrightarrow N + n + \nu_e \qquad N + n \longrightarrow N + p + e^- + \bar{\nu}_e$$

direct URCA process (fast):

$$p + e^- \longrightarrow n + \nu_e \qquad n \longrightarrow p + e^- + \bar{\nu}_e$$

can only proceed for $p_F^p + p_F^e \geq p_F^n$! Charge neutrality implies:

$$n_p = n_e \hookrightarrow p_F^p = p_F^e \hookrightarrow 2p_F^p = p_F^n \hookrightarrow n_p/n \geq 1/9$$

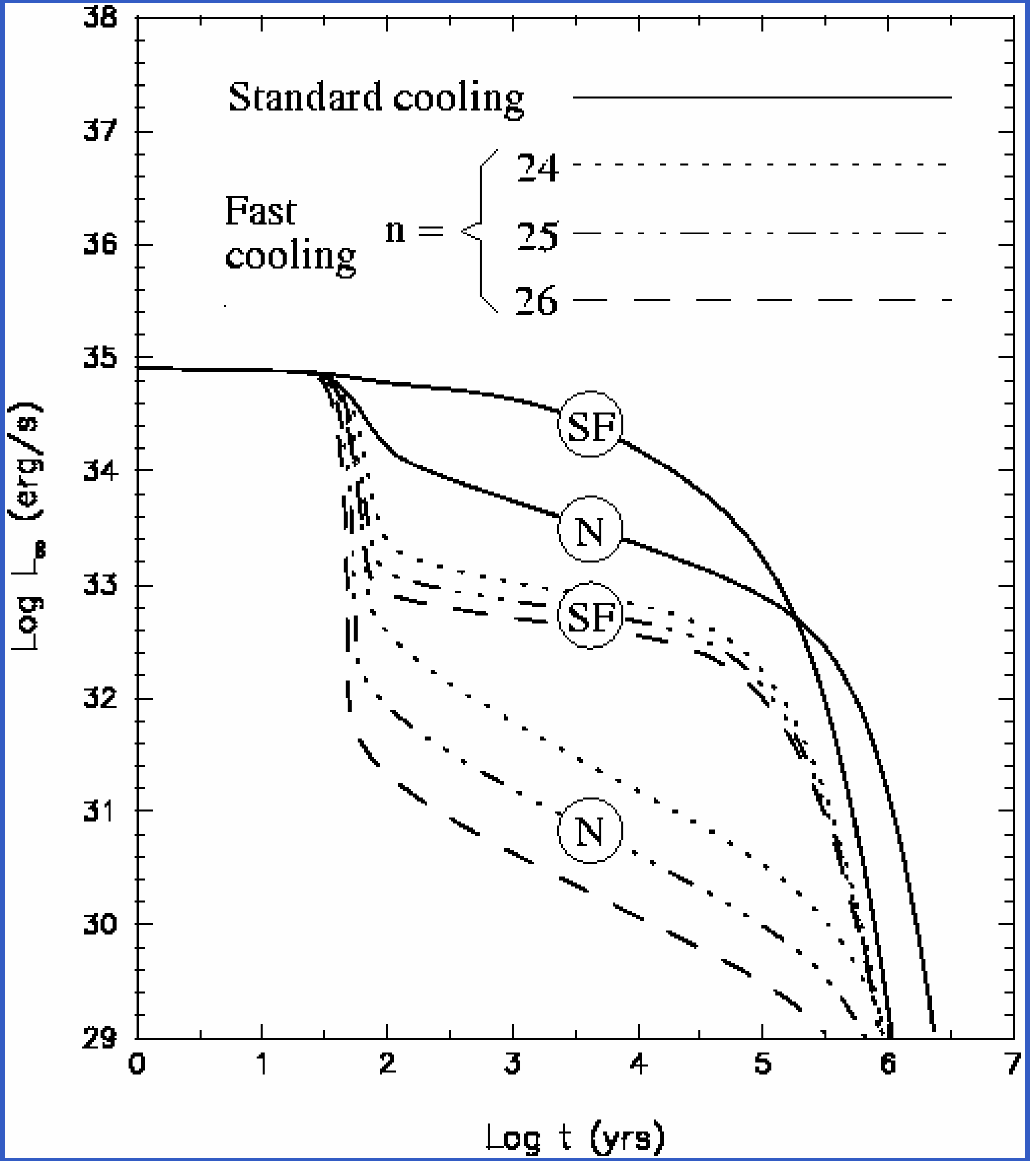
nucleon URCA only for large proton fractions, but hyperon URCA process:

$$\Lambda \longrightarrow p + e^- + \bar{\nu}_e \quad , \quad \Sigma^- \longrightarrow n + e^- + \bar{\nu}_e \quad , \quad \ldots$$

happens immediately when hyperons are present!

only suppressed by hyperon pairing gaps!

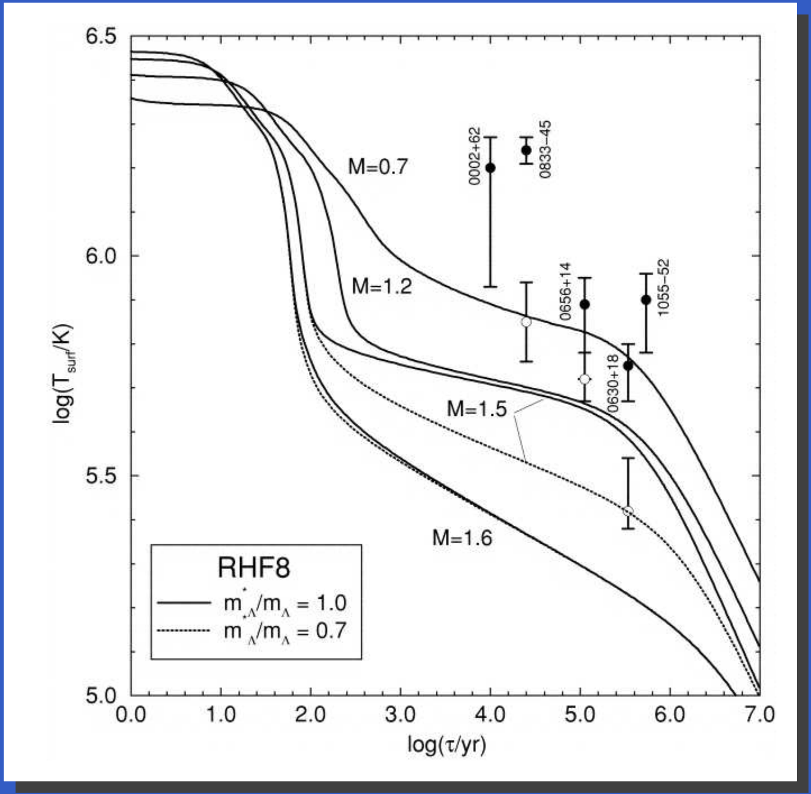
Basic cooling of neutron stars (Page and Reddy (2006))



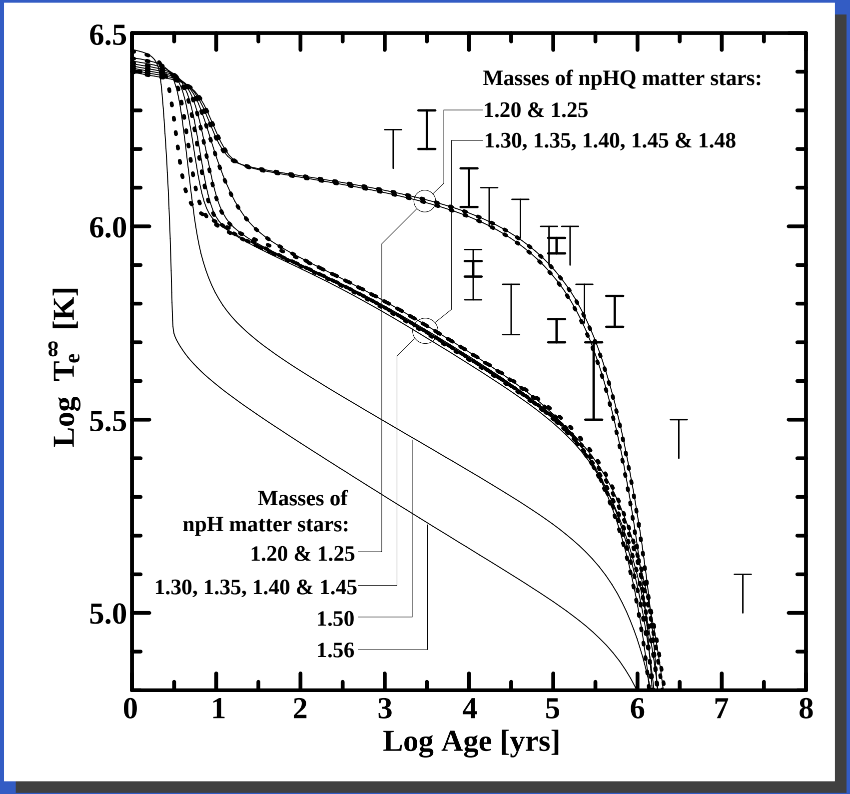
- slow standard cooling via the modified URCA process versus fast neutrino cooling (emissivities of $\epsilon_\nu = 10^n \times T_9^6 \text{ erg cm}^{-3} \text{ s}^{-1}$)
- normal neutron matter: N, superfluid neutron matter: SF
- fast cooling due to 'exotic' processes as nucleon direct URCA or kaon condensation

Cooling with hyperons: fast cooling and hyperon gaps

(Schaab, JSB, Balberg 1998)



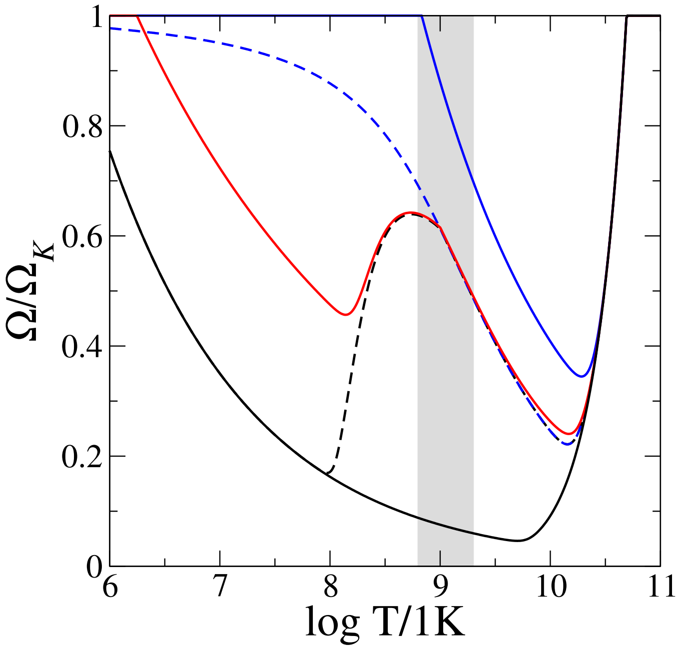
(Page, Lattimer, Prakash, Steiner 2000)



- slow cooling for low mass neutron stars
- fast cooling for heavier ones due to direct nucleon URCA
- hyperon cooling suppressed by pairing gaps (left) and unsuppressed (right)
- two-body YY interactions as input needed!
- pairing of Σ hyperons and cooling: Vidana and Tolos (2004)

Gravitational wave emission from rotating neutron stars

R-mode instability for rotating neutron stars



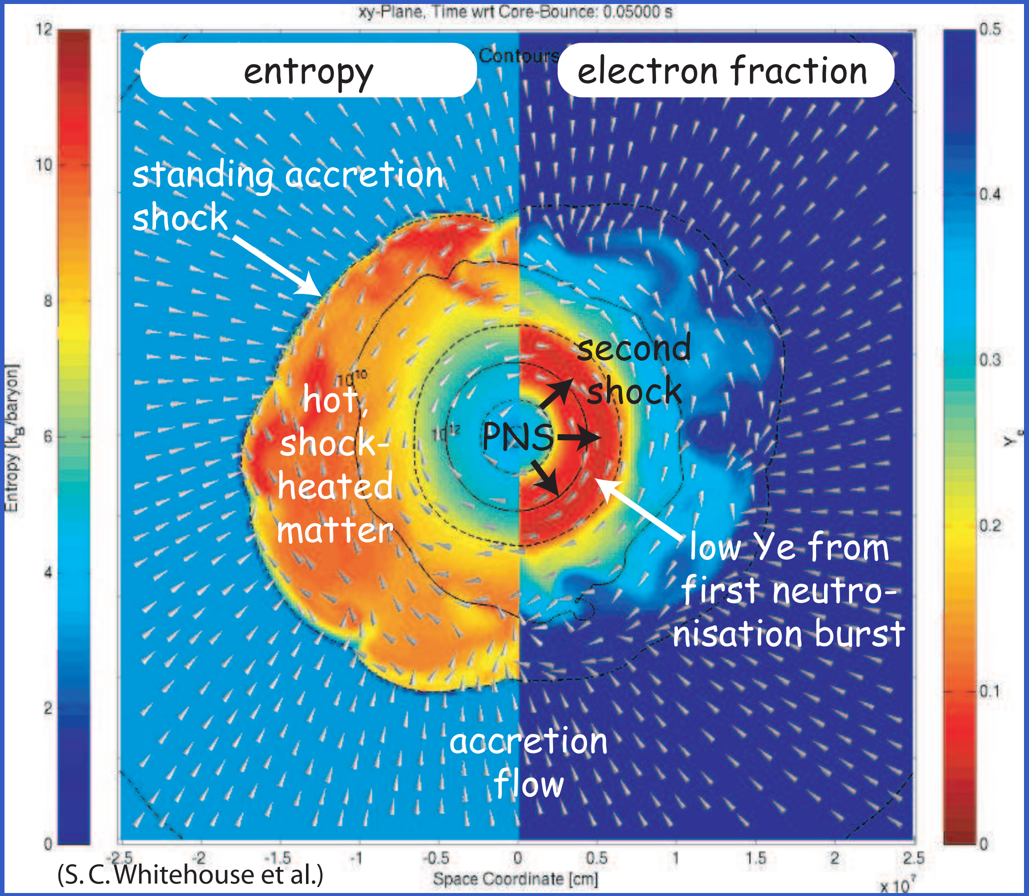
- oscillations brings the matter out of β-equilibrium
- dominating effect to restore equilibrium: weak nonmesonic processes $NN \leftrightarrow \Lambda N$ and $NN \leftrightarrow \Sigma N$
- substantial increase of the stability window (blue line)
- depends crucially on hyperon superfluidity (dashed lines)

QCD phase transition in supernovae

Irina Sagert, Matthias Hempel, Giuseppe Pagliara, JSB, Tobias Fischer, Anthony Mezzacappa, Friedel Thielemann, Matthias Liebendörfer, PRL 102, 081101 (2009)

Supernova Explosions

(Liebendörfer et al.)



- stars with a mass of more than 8 solar masses end in a (core collapse) supernova (type II)
- new generation of simulation codes: 3D, Boltzmann neutrino transport
- Improved Models of Stellar Core Collapse and Still no Explosions: What is Missing? (Buras, Rampp, Janka, Kifonidis, PRL 2004)

’. . . the models do not explode. This suggests missing physics, possibly with respect to the nuclear equation of state . . . ’ !

Supernova Explosions

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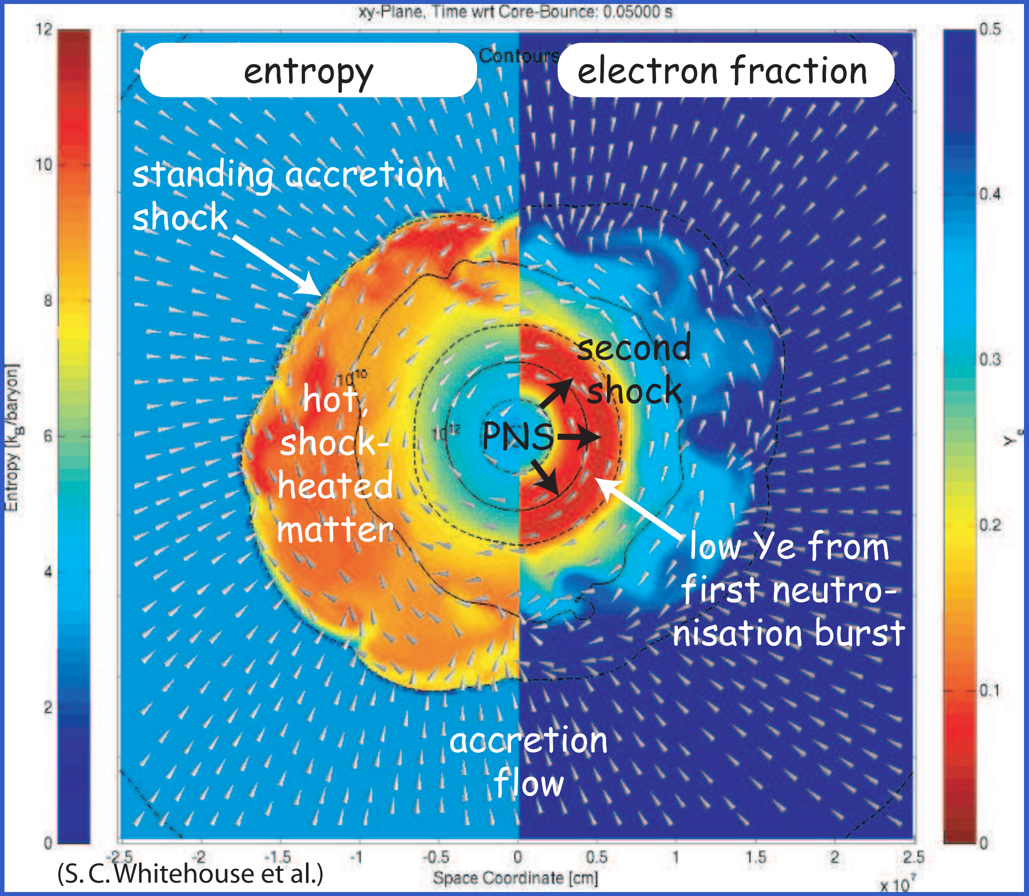

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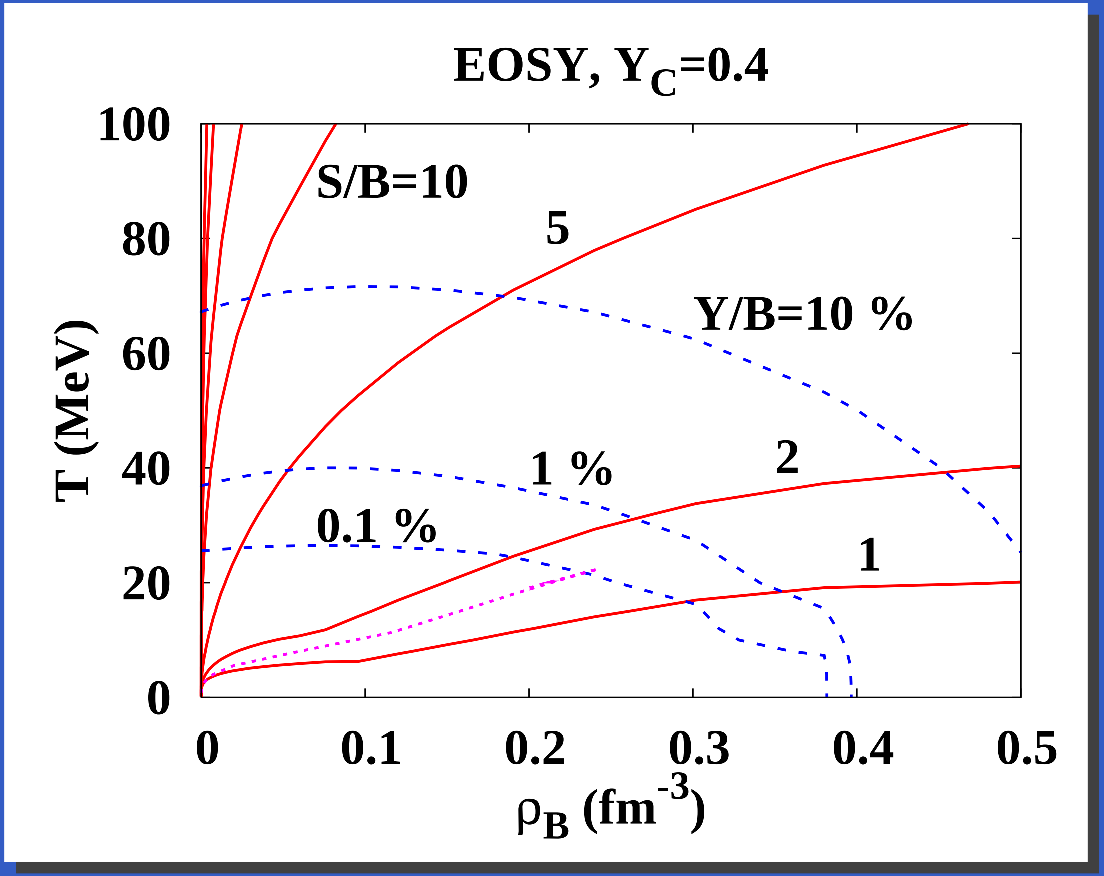
SASI: standing accretion shock instability, the models *do* explode after 600ms! (Marek and Janka, 2009)

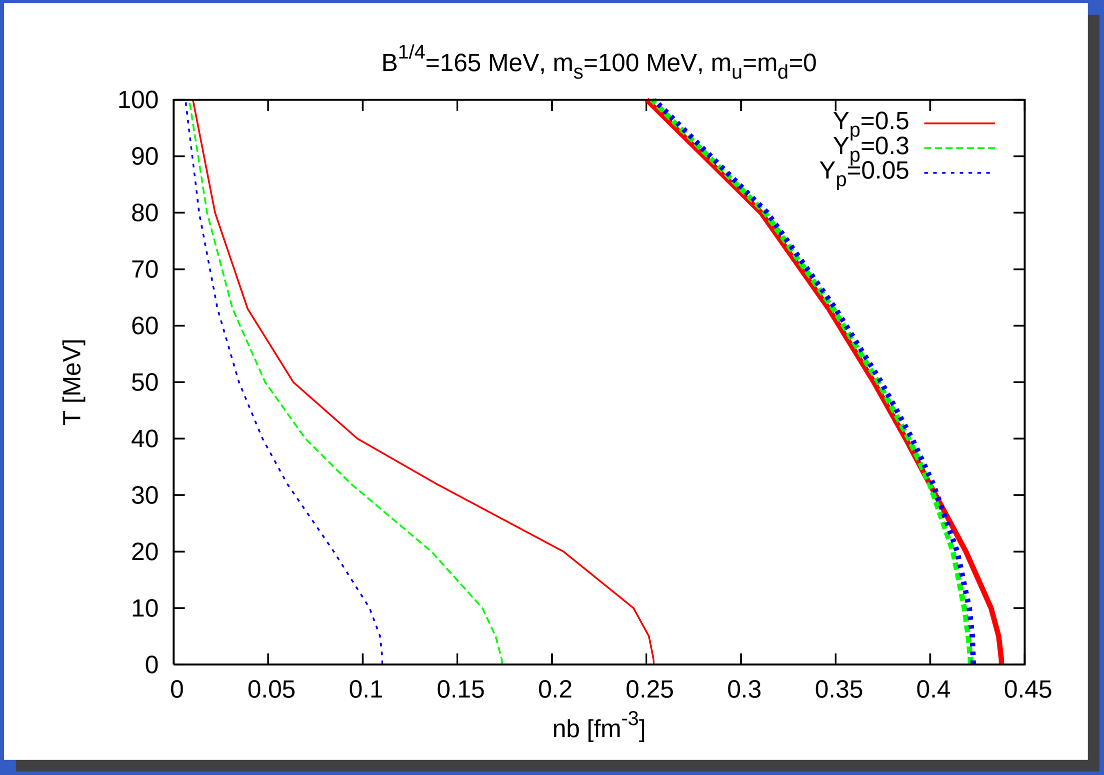
Strangeness in Supernova Matter: Hyperons



C. Ishizuka, A. Ohnishi, K. Tsubakihara, K. Sumiyoshi, S. Yamada 2008

- supernova matter for $Y_c = 0.4$ with constant entropy/baryon ratio S/B
- hyperon fraction at bounce $T \sim 20$ MeV: about 0.1%
- thermally produced strangeness, hyperons are in β-equilibrium!

Phase Transition to Strange Quark Matter for Astros



(Irina Sagert and Giuseppe Pagliara)

- quark matter appears at low density due to β-equilibrium
- low critical density for low proton fraction (Y_p) due to nuclear symmetry energy
- quark matter favoured at finite temperature
- supernova matter at bounce: $T = 10 - 20$ MeV, $Y_p = 0.2 - 0.3$, $\epsilon \sim (1 - 1.5)\epsilon_0$

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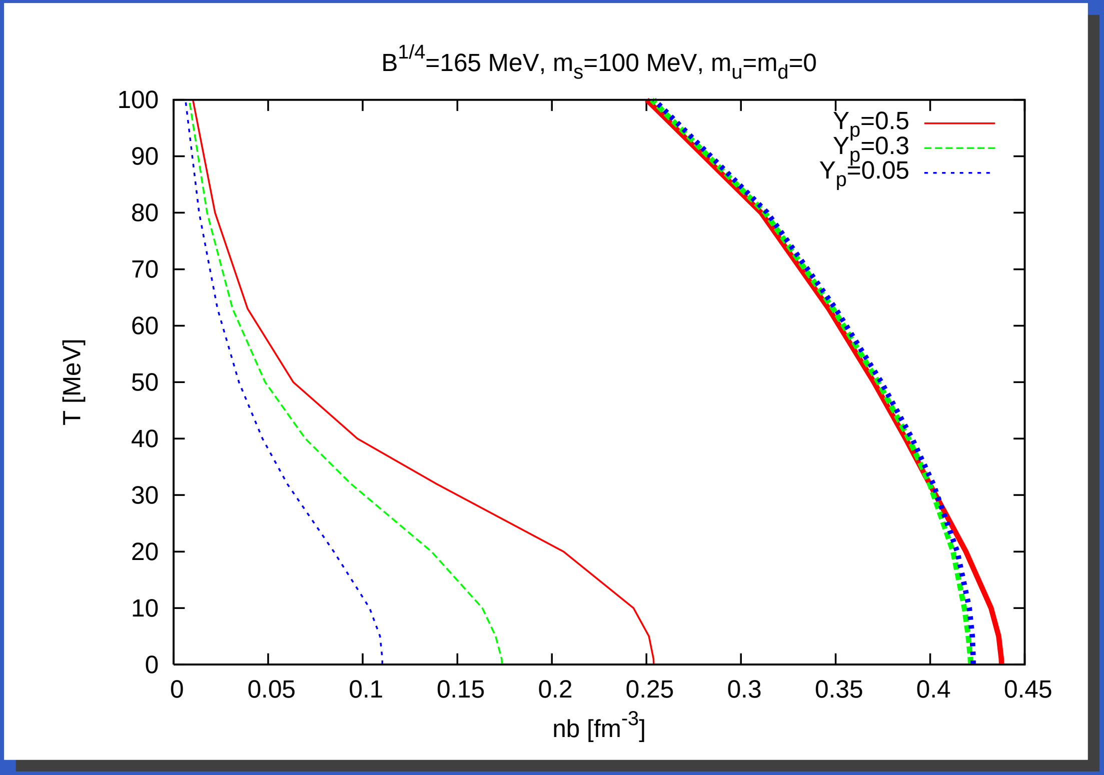

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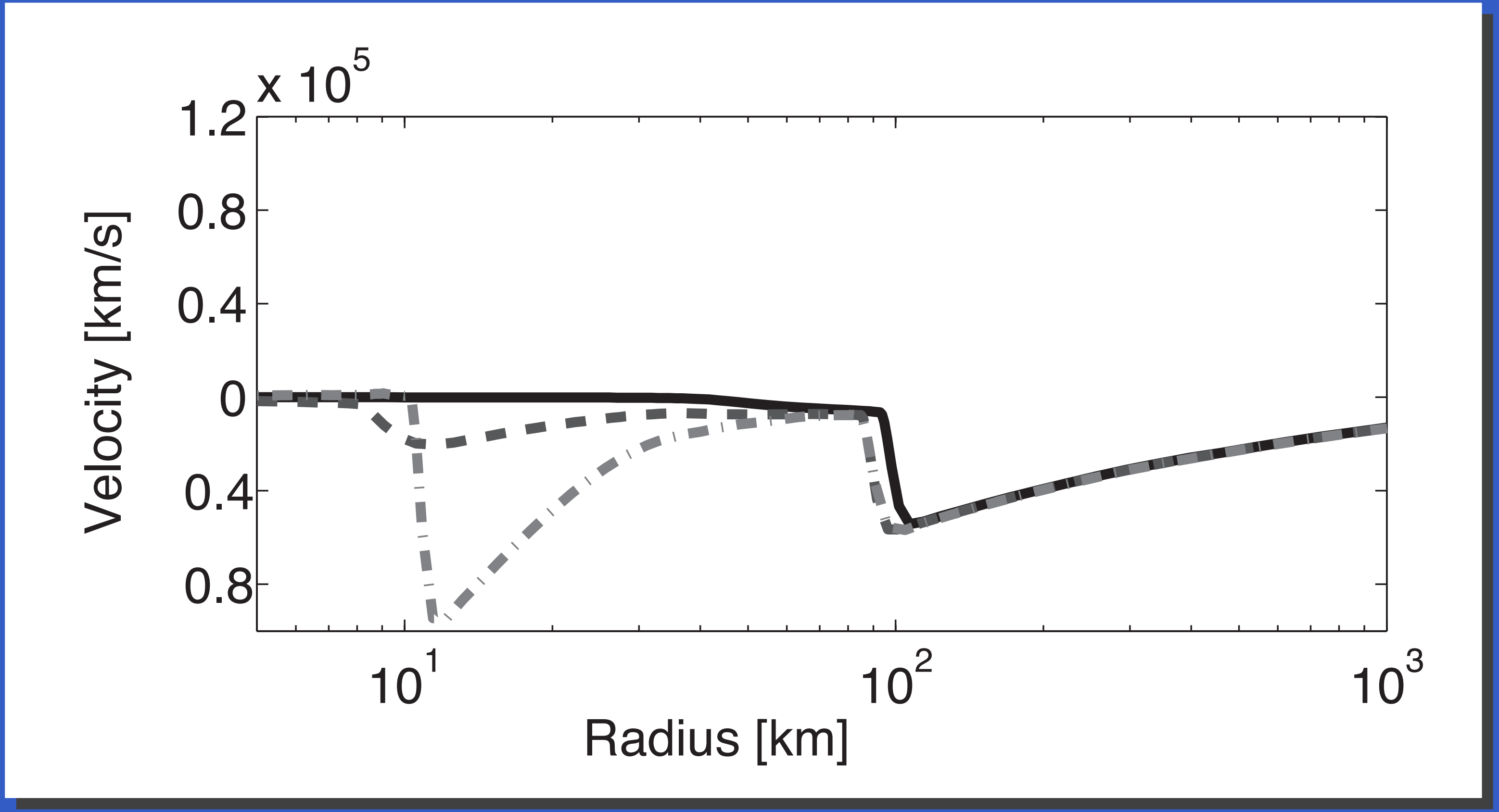
- supernova matter at bounce: $T = 10 - 20$ MeV, $Y_p = 0.2 - 0.3$, $\epsilon \sim (1 - 1.5)\epsilon_0$
- production of quark matter in supernovae at bounce possible!

Implications for Supernovae – Explosion!



(Sagert, Hempel, Pagliara, JSB, Fischer, Mezzacappa, Thielemann, Liebendörfer, 2009)

- velocity profile of a supernova for different times (around 250ms)
- formation of a core of pure quark matter produces a second shock wave

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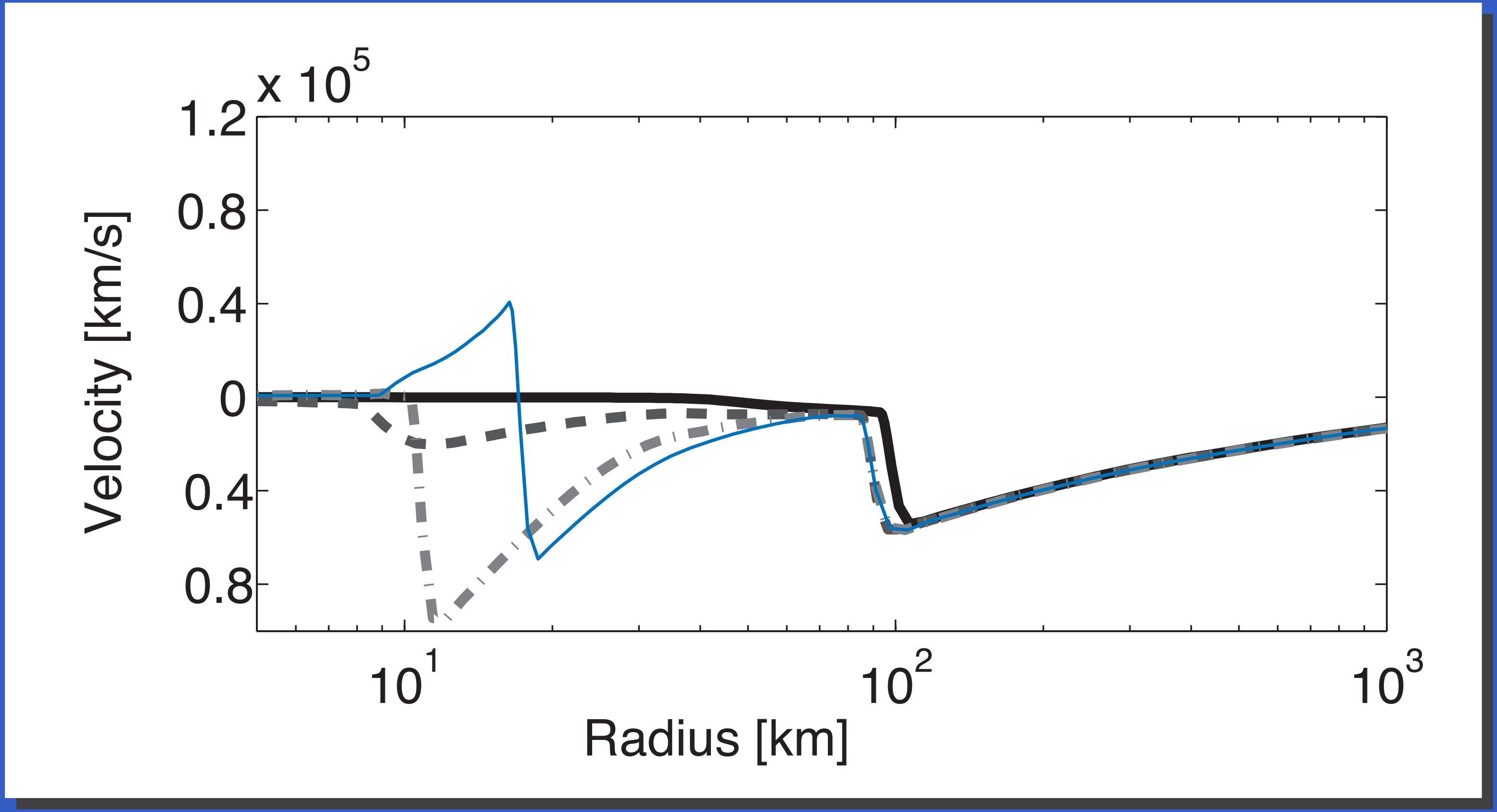

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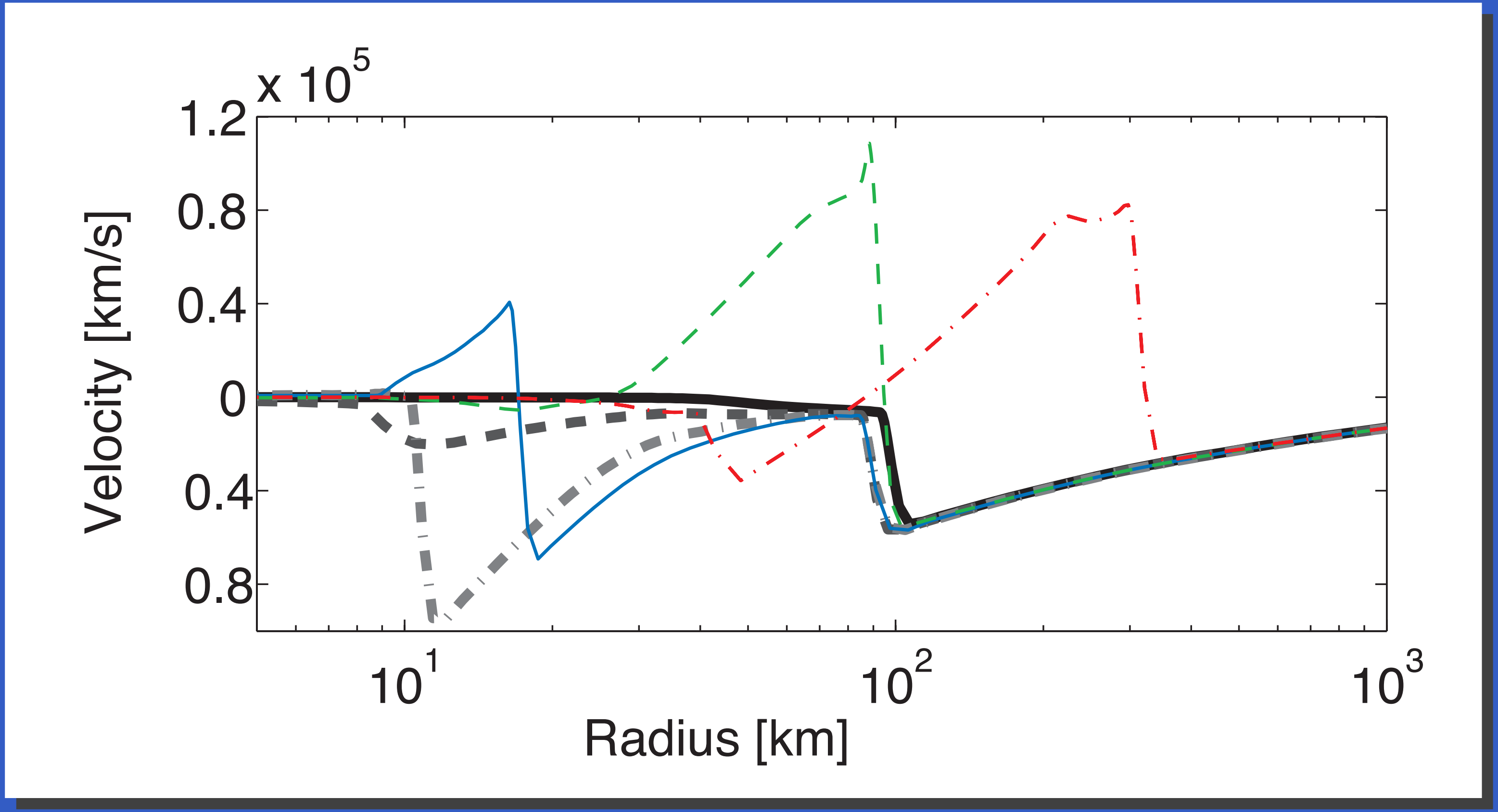

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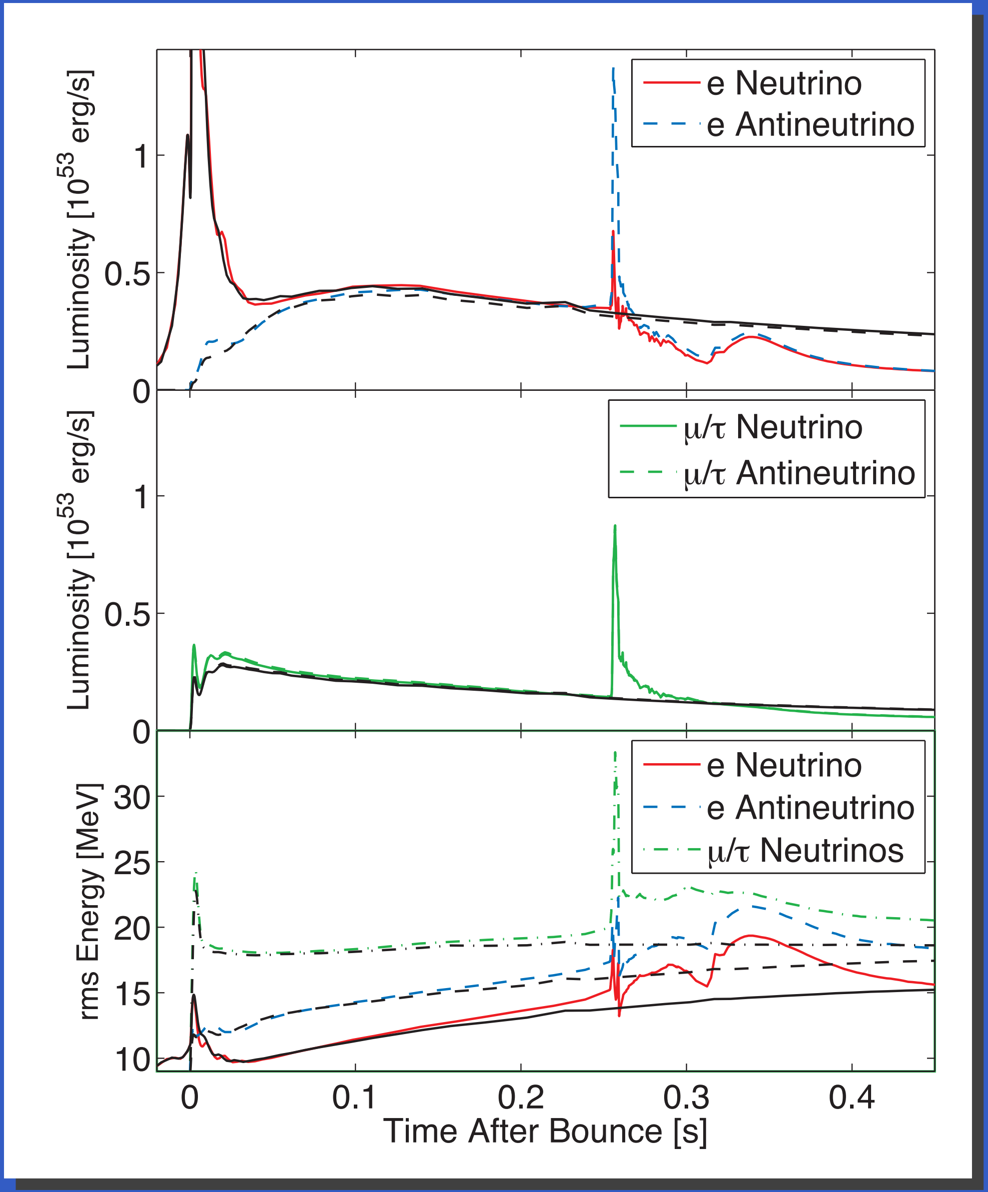
- velocity profile of a supernova for different times (around 250ms)
- formation of a core of pure quark matter produces a second shock wave
- leads to an explosion!

Implications for Supernova – Neutrino-Signal!



(Sagert, Hempel, Pagliara, JSB, Fischer, Mezzacappa, Thielemann, Liebendörfer, 2009)

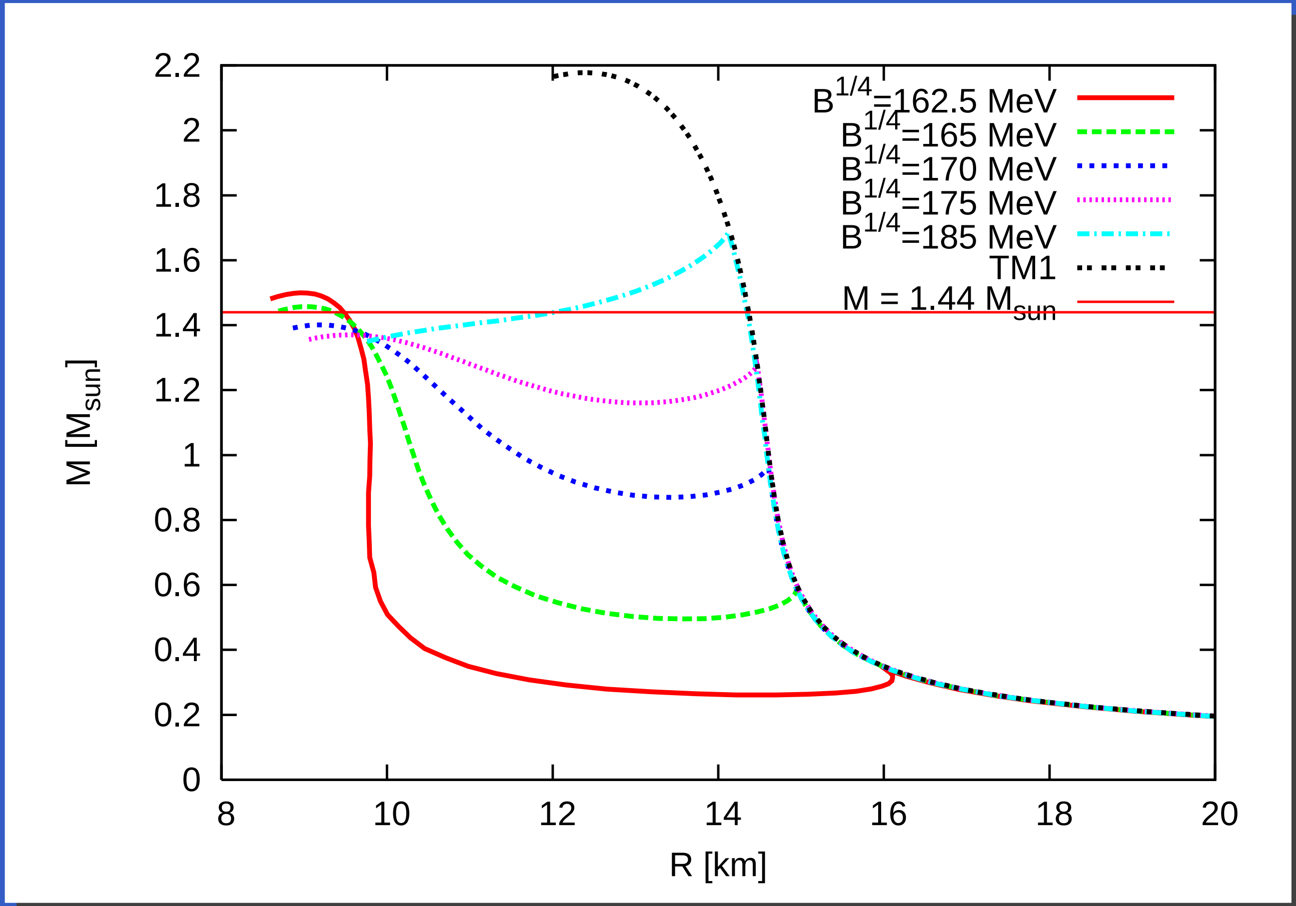
- temporal profile of the emitted neutrinos out of the supernova
- thick lines: without, thin lines: with a phase transition
- pronounced second peak of anti-neutrinos due to the formation of quark matter
- peak location and height determined by the critical density and strength of the QCD phase transition!!

Summary

Hypernuclear physics has a substantial impact on neutron star properties!

- Two-body YN interaction: controls composition and cooling
  $\Longrightarrow$ hyperons are most likely the first exotic phase to appear in the core
  $\Longrightarrow$ hyperons can cool neutron stars rapidly (hyperon gaps!)
- Three-body YNN and YYN force: controls the maximum mass
  $\Longrightarrow$ low maximum masses below $1.4M_\odot$ without three-body force
- Kaon production in heavy-ion collision: probe of the nuclear EoS
  $\Longrightarrow$ sets a new upper limit on the maximum mass allowed by causality
- Nonmesonic weak nonmesonic reactions with hyperons
  $\Longrightarrow$ damps the r-mode instability of rotating neutron stars (pulsars) and their gravitational wave emission
- YN potentials control amount of strangeness present supernova matter
  $\Longrightarrow$ presence of hyperons trigger the phase transition to quark matter

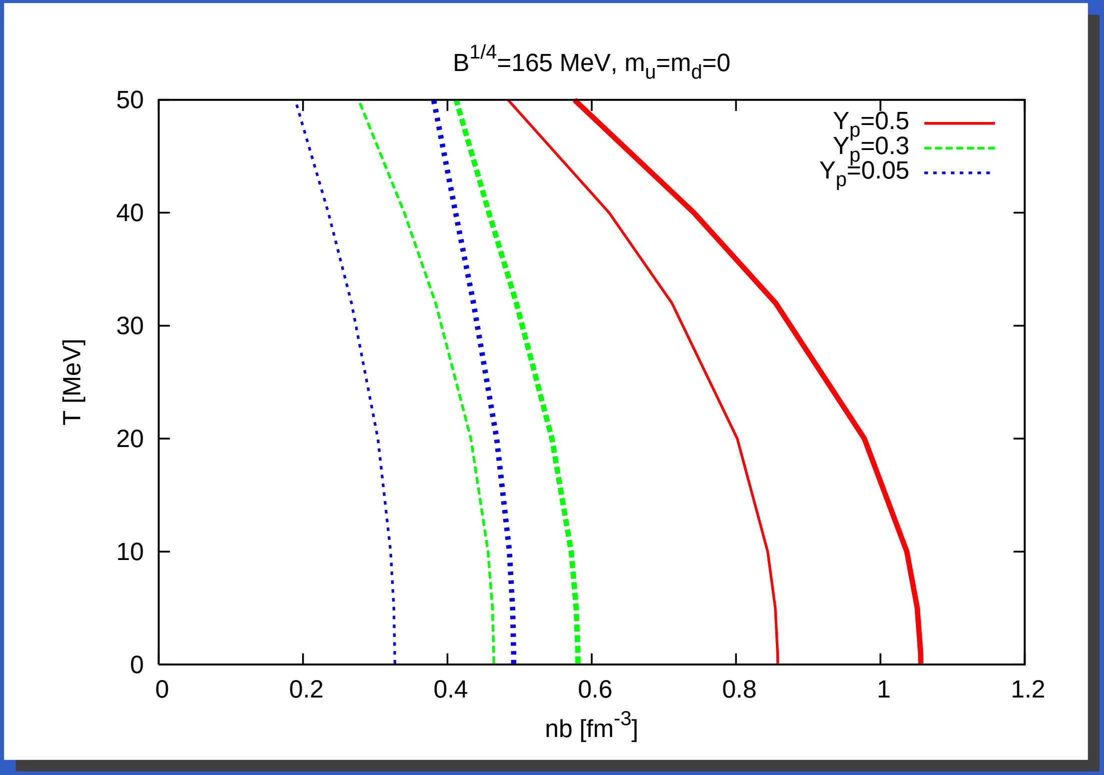
Check: Mass-Radius Diagram of Cold Neutron Stars



(Irina Sagert and Giuseppe Pagliara)

- presence of quark matter can change drastically the mass-radius diagram
- third family of solution for certain bag constants
- maximum mass: $1.56M_\odot$ ($B^{1/4} = 162$ MeV), $1.5M_\odot$ ($B^{1/4} = 165$ MeV)

Check: Phase Transition for Heavy-Ion Collisions



(Irina Sagert and Giuseppe Pagliara)

- no β-equilibrium (just up-/down-quark matter)
- large critical densities in particular for isospin-symmetric matter (proton fraction $Y_p = 0.5$)
- production of ud-quark matter unfavoured for HICs at small T and high density
- no contradiction with heavy-ion data!