Strangeness Condensation and Neutron Stars

2005 Summer Workshop Experimental Hall C

Jefferson Lab

August 18, 2005

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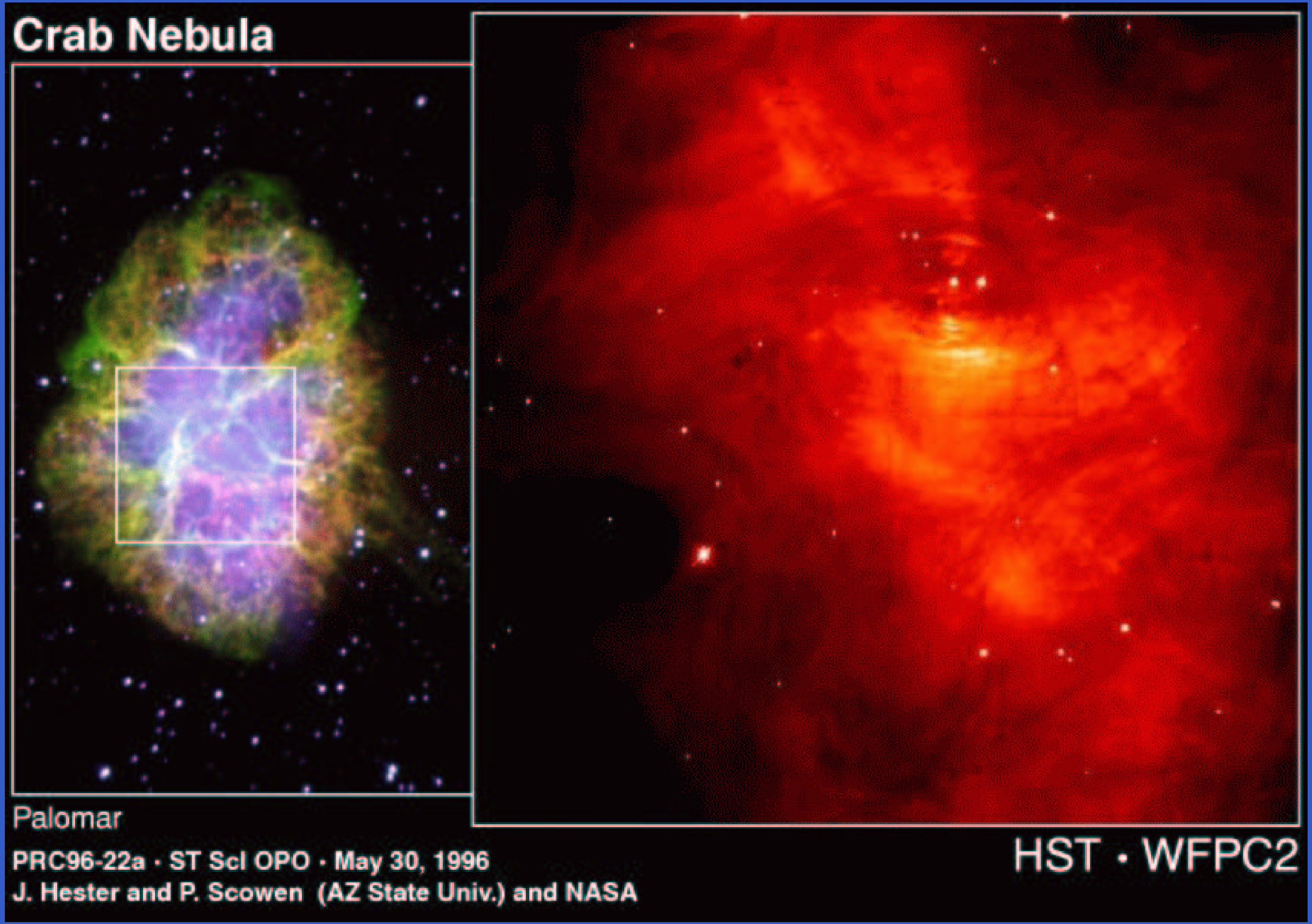
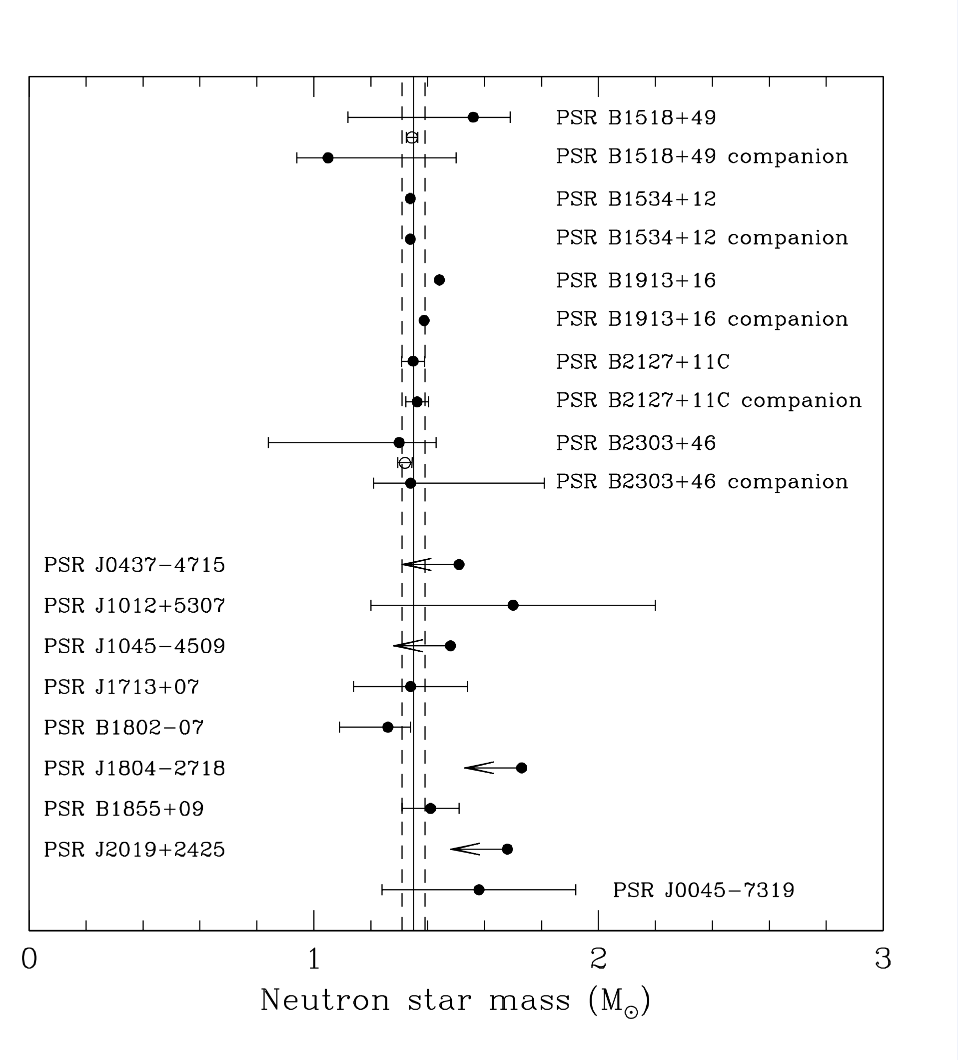
Neutron Stars



PRC96-22a · ST ScI OPO · May 30, 1996
J. Hester and P. Scowen (AZ State Univ.) and NASA

- produced in supernova explosions (type II)
- compact, massive objects: radius $\approx$ 10 km, mass $1-2M_\odot$
- extreme densities, several times nuclear density: $n \gg n_0 = 3 \cdot 10^{14}$ g/cm^3

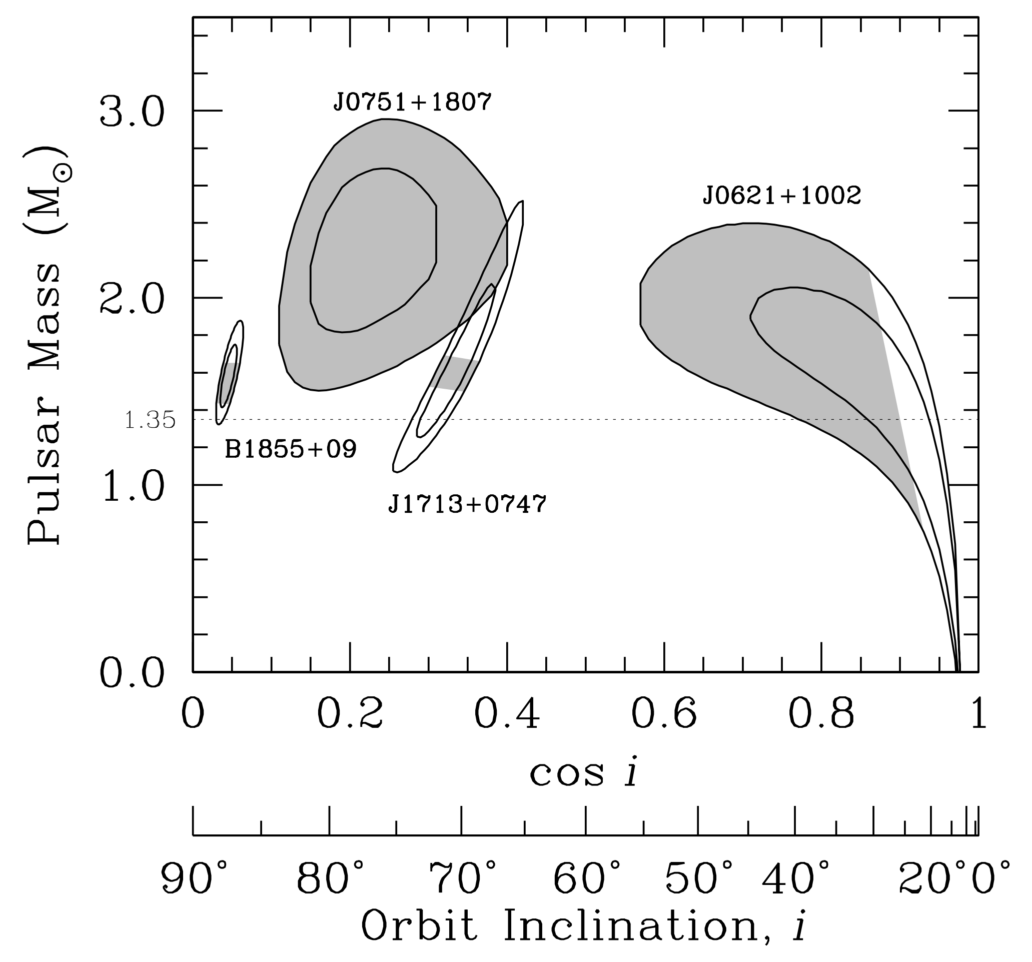
Masses of Pulsars (Thorsett and Chakrabarty (1999))



- more than 1500 pulsars known
- best determined mass: $M = (1.4411 \pm 0.00035) M_\odot$ (Hulse-Taylor-Pulsar)
- shortest rotation period: 1.557 ms (PSR 1937+21)

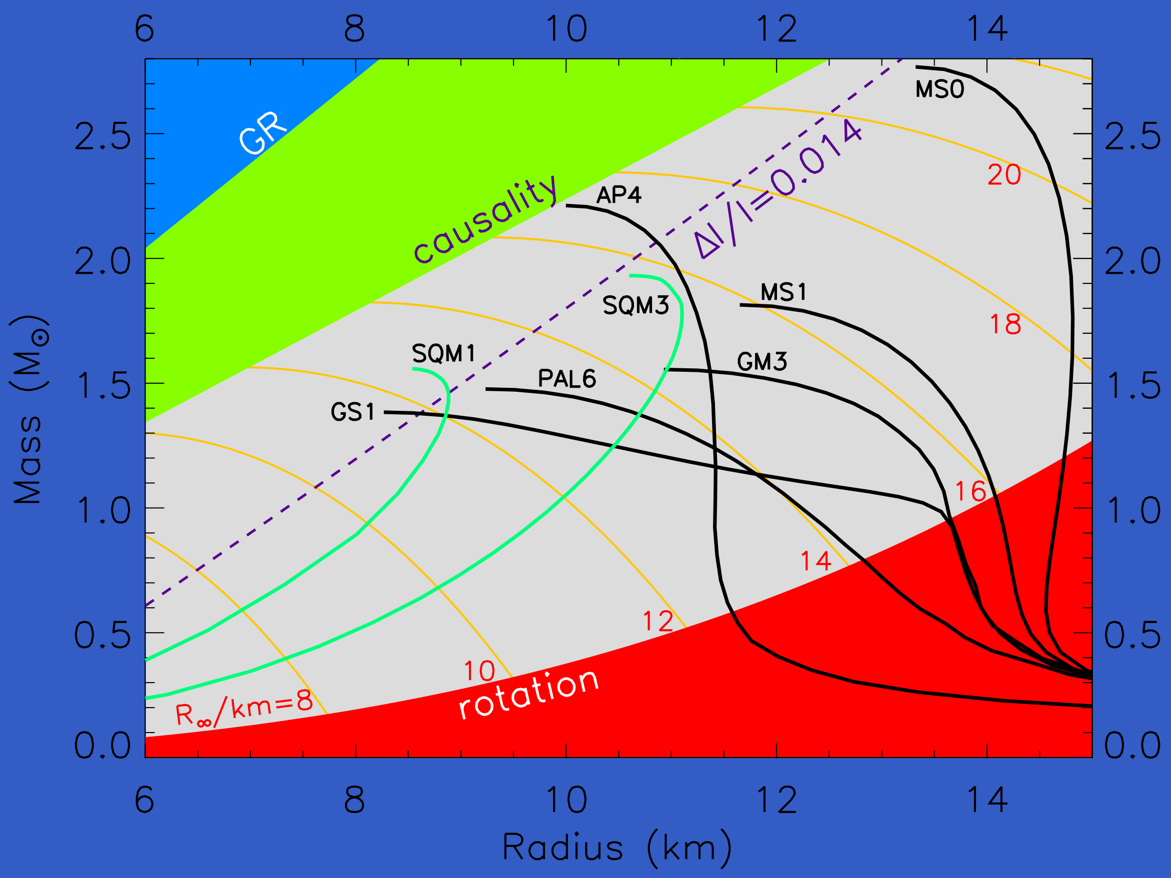
Heavy Neutron Stars in Pulsar–White Dwarfs Systems?

(Nice, Splaver, Stairs (2003))



- four pulsars with a white dwarf companion
- measure masses by changes in the pulsar signal
- shaded area: from theoretical limits for white–dwarf companion
- massive pulsar J0751+1807: $M = 1.6 - 2.8 M_\odot$ (2σ!)
- Nice et al. (2005): $M = 2.1 \pm 0.2 M_\odot$ (1σ) and $M = 1.6 - 2.5 M_\odot$ (2σ)!!!

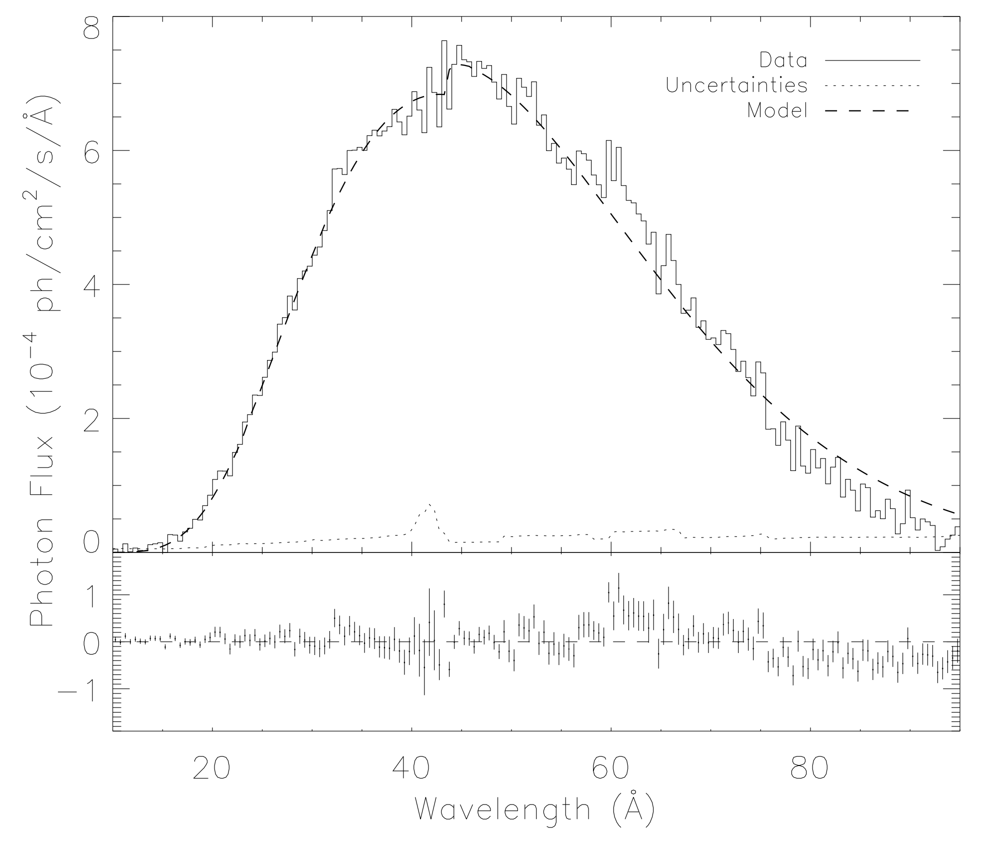
Constraints on the Mass–Radius Relation



(Lattimer and Prakash (2004))

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

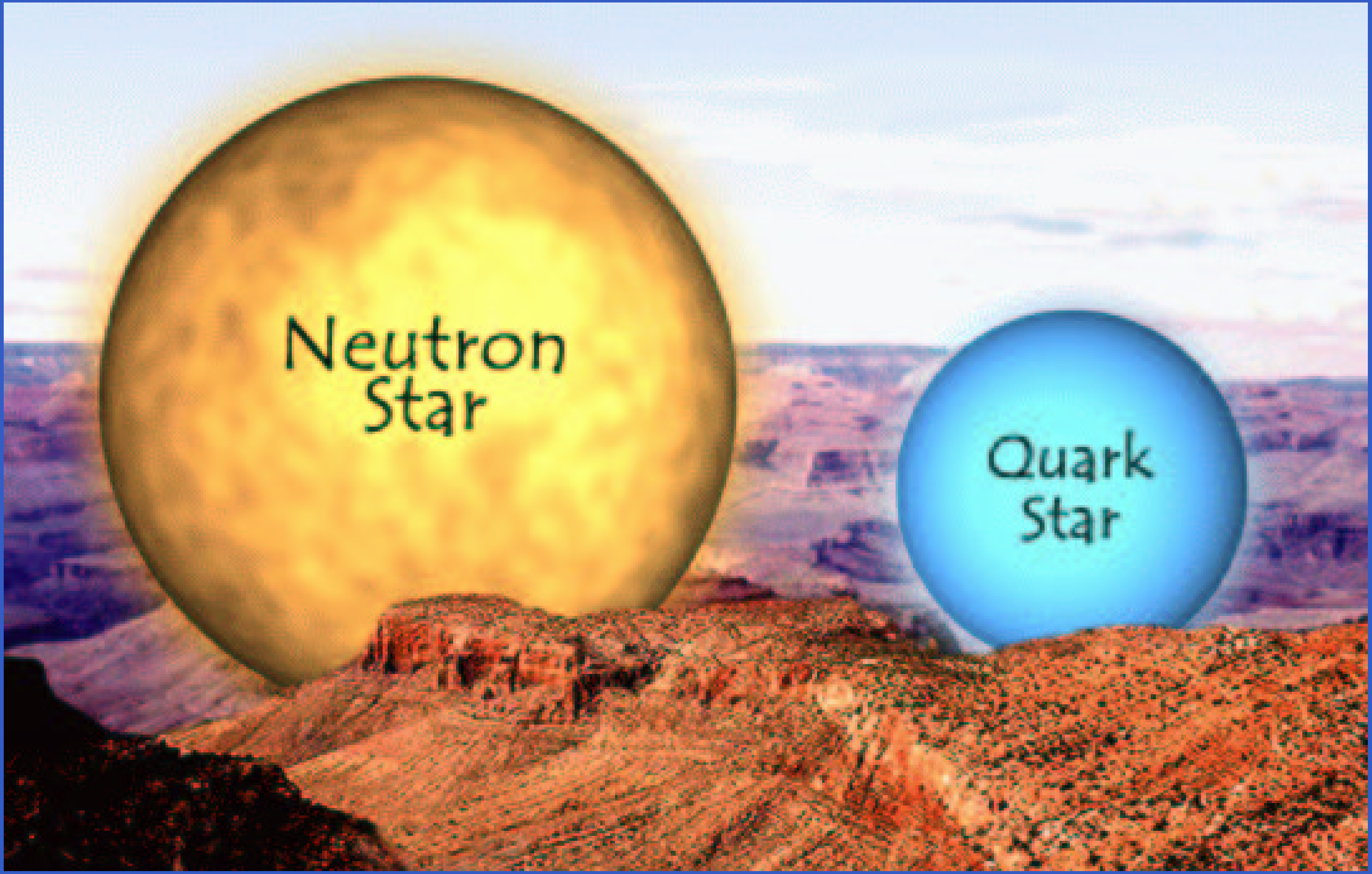
Isolated Neutron Star RX J1856



(Drake et al. (2002))

- closest known neutron star
- perfect black–body spectrum, no spectral lines!
- for black-body emission: $T = 60$ eV and $R_\infty = R\sqrt{1 - 2GM/R} = 4 - 8$ km!

A Quark Star? (NASA press release 2002)

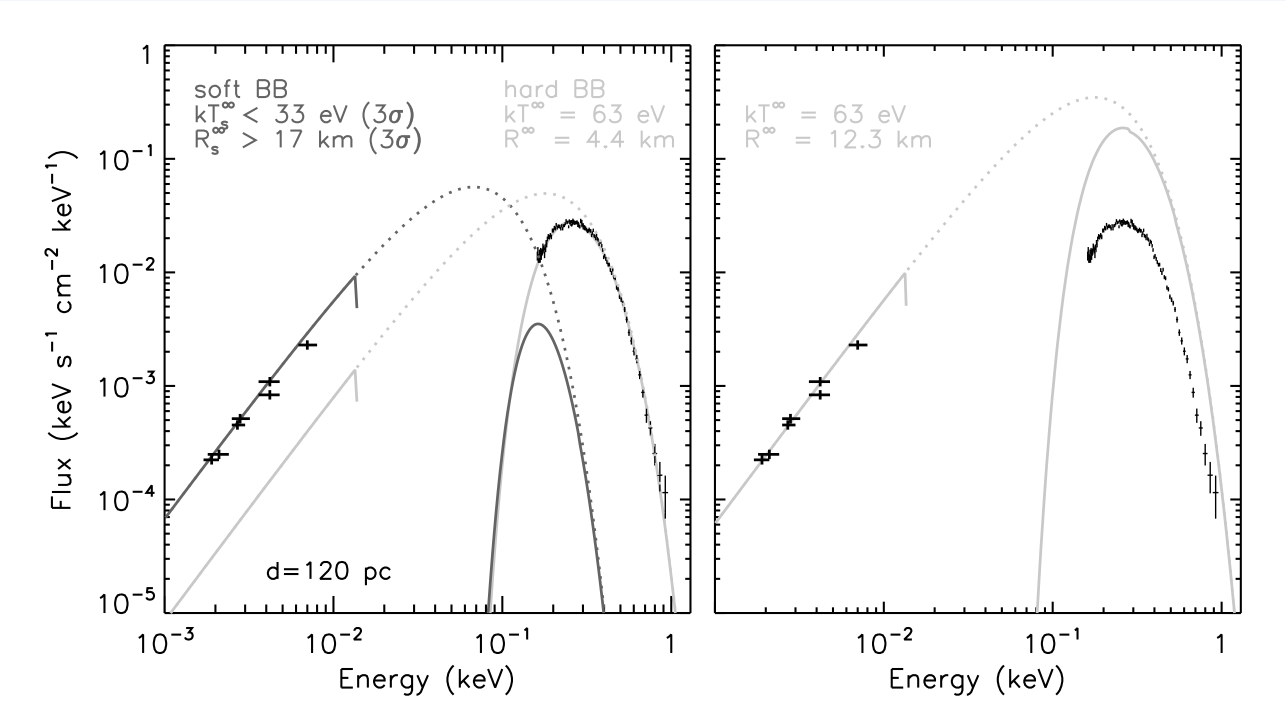


NASA news release 02-082:

“Cosmic X-rays reveal evidence for new form of matter”

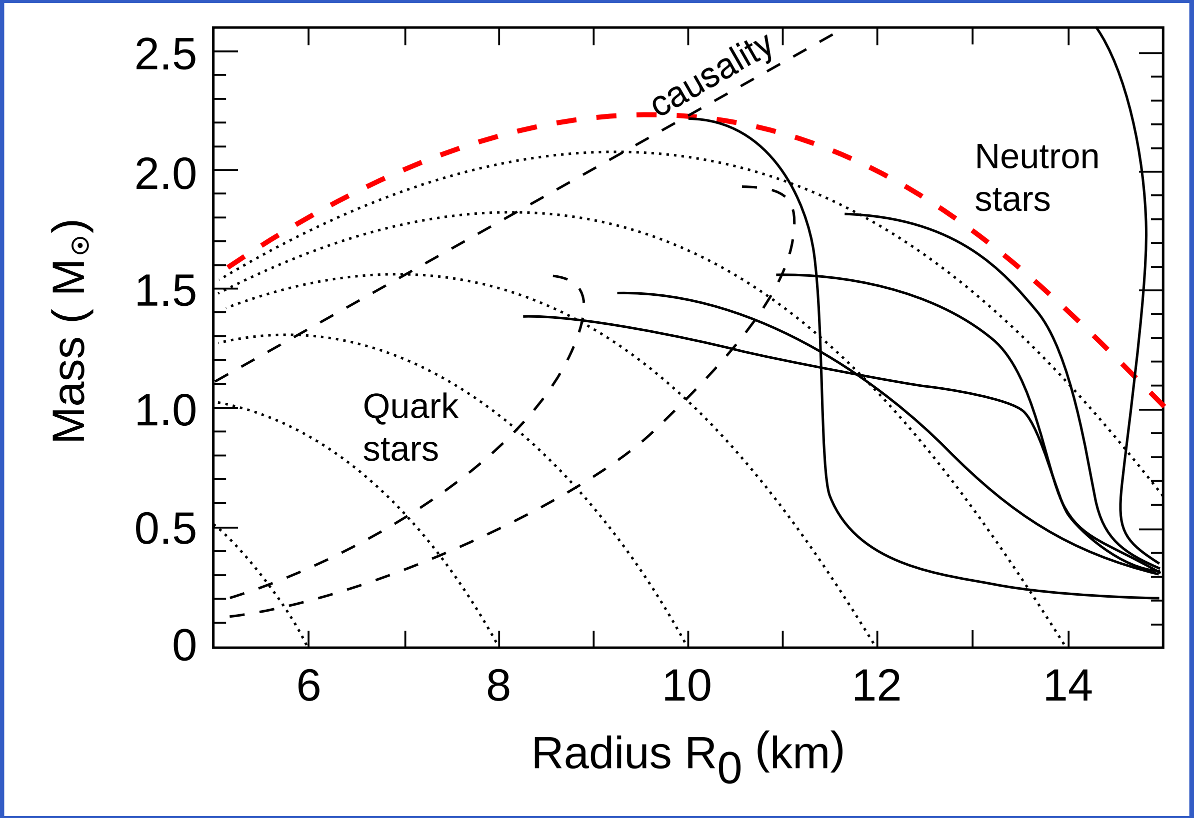
— a quark star?

Modelling the Atmosphere of Neutron Stars (Burwitz et al. (2003))



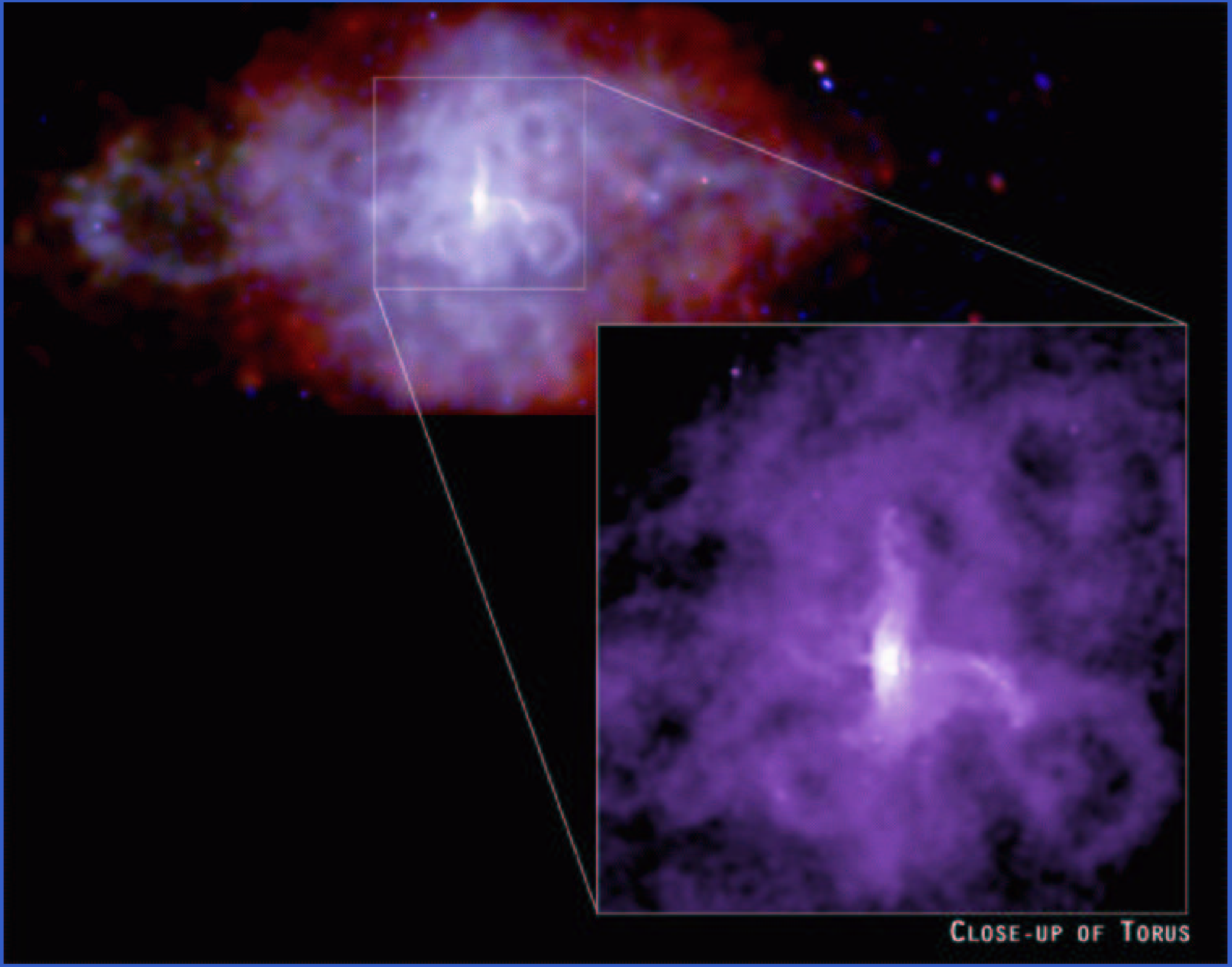
- H atmospheres ruled out, they over-predict the optical flux!
- heavy element atmospheres ruled out, as there are no spectral lines!
- all classic neutron star atmosphere models fail!
- alternatives: two-component blackbody model (left plot)
- or condensed matter surface for low $T < 86$ eV and high $B > 10^{13}$ G (right plot) — grey body with a suppression of a factor 7!

RXJ 1856: Neutron Star or Quark Star? (Trümper et al. (2003))



- two-component blackbody: small soft temperature, so as not to spoil the x-ray band
- this implies a rather LARGE radius so that the optical flux is right!
- conservative lower limit: $R_\infty = 16.5$ km (d/117 pc)
- excludes quark stars and even neutron stars with a quark core!?

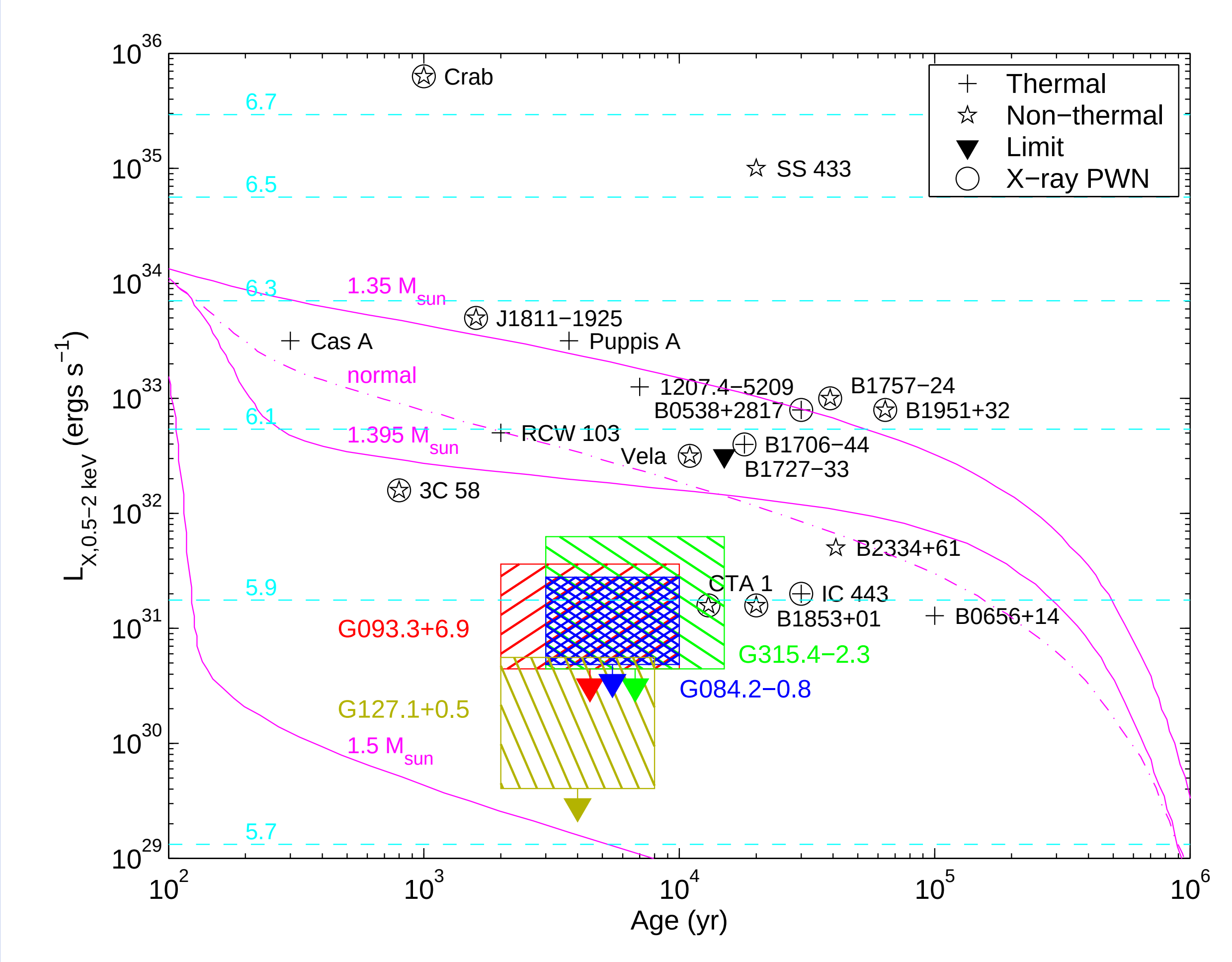
Supernova remnant 3C58 from 1181 AD (Slane et al. 2004)



CHANDRA press release 04-13:

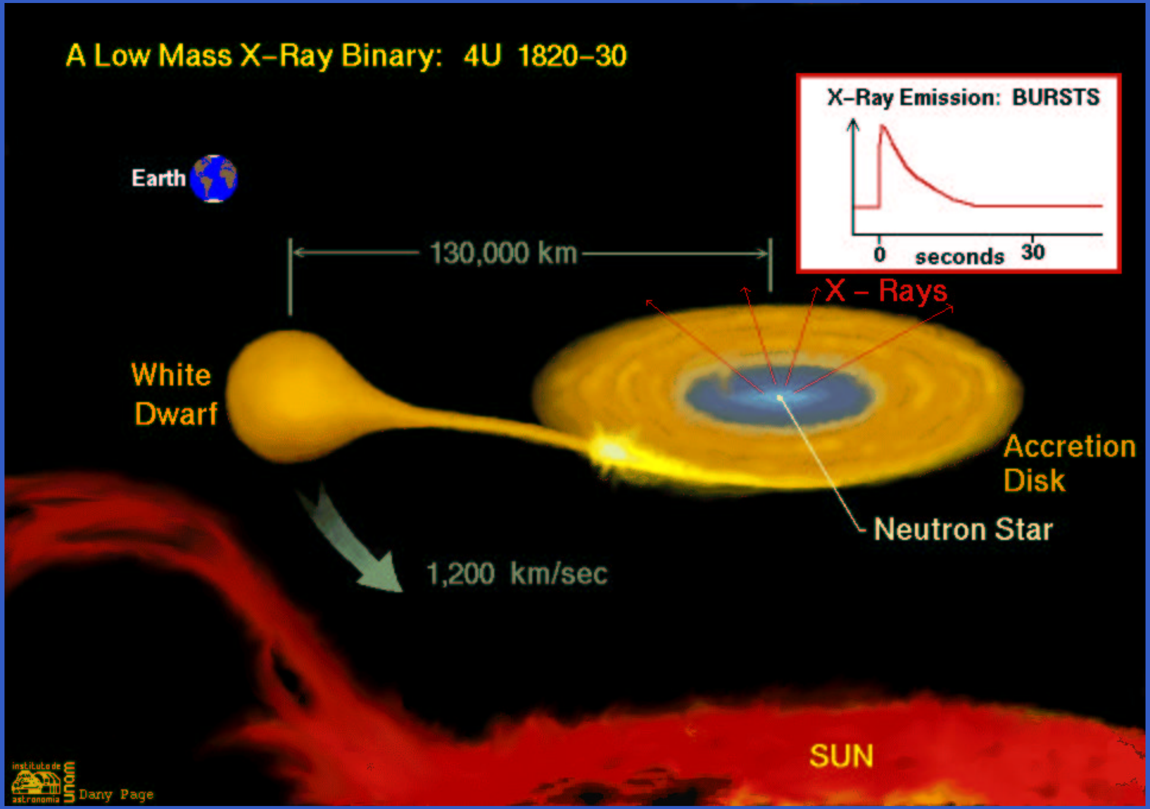
“Going to Extremes: Pulsar Gives Insight on Ultra Dense Matter and Magnetic Fields” — rapid cooling due to unexpected conditions in the neutron star!

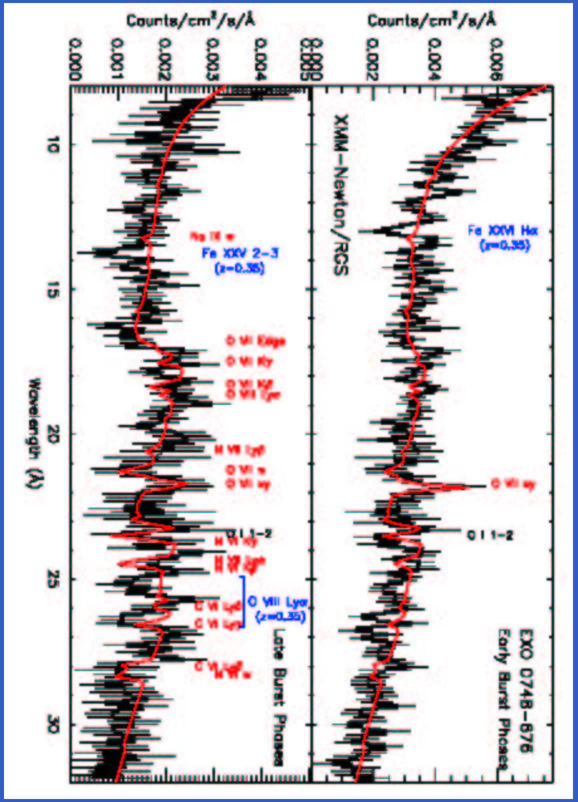
Cooling of Supernova Remnants (Kaplan et al. (2004))



- newest data from four neutron stars suggest fast cooling (direct URCA)
- standard cooling curves are too high!
- large nuclear asymmetry energy generates fast cooling!
- strange particles (exotic matter) generate fast cooling!

X-Ray burster (Cottam, Paerels, Mendez (2002))



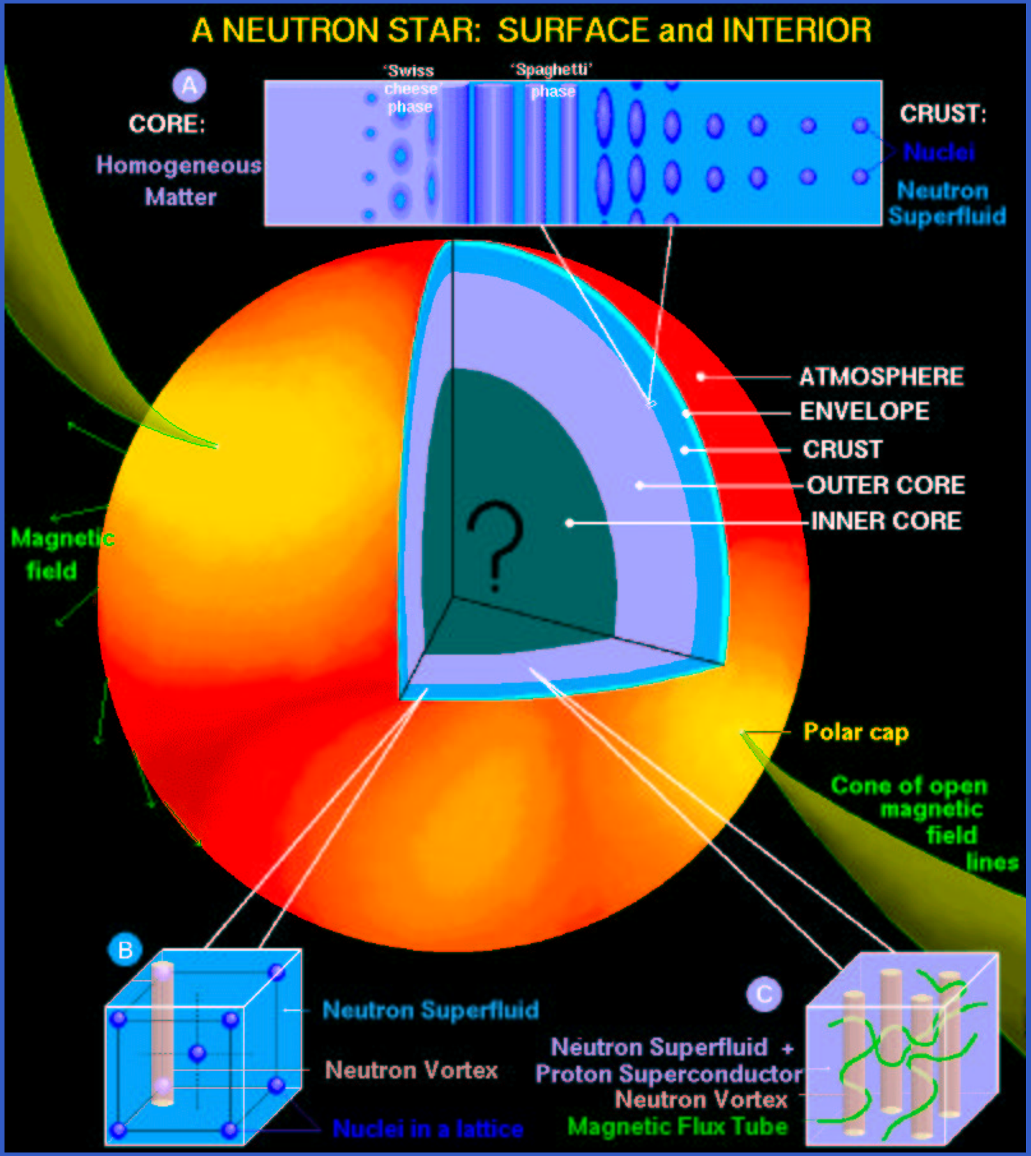


- binary systems of a neutron star with an ordinary star
- accreting material on the neutron star ignites nuclear burning
- explosion on the surface of the neutron star: x-ray burst
- red shifted spectral lines measured! ($z = 0.35 \rightarrow M/M_\odot = 1.5$ (R/10 km))

movie

Modelling the Neutron Star Crust

Structure of Neutron Stars — the Crust (Dany Page)



- $n \leq 10^4$ g/cm^3: atmosphere (atoms)

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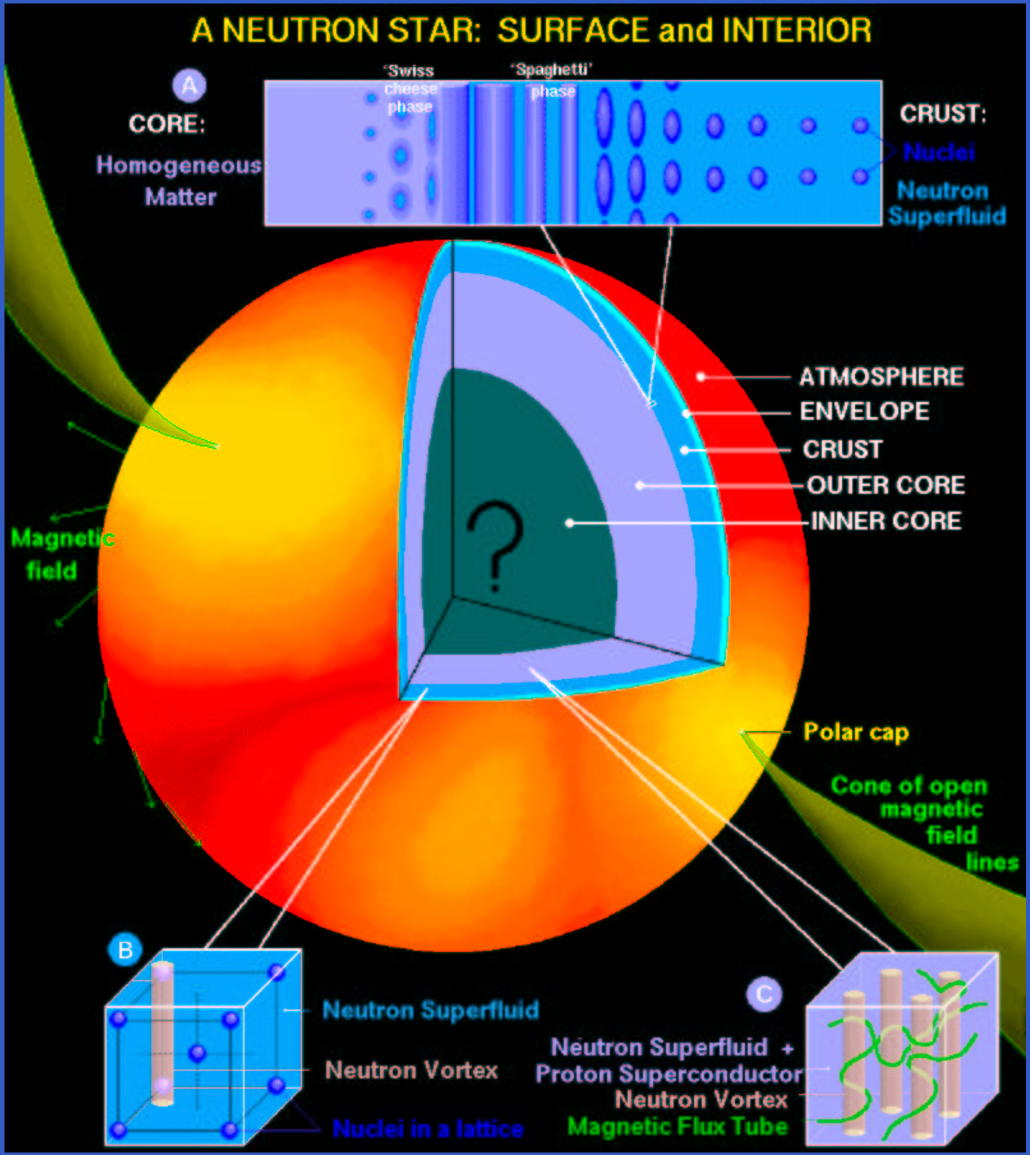

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- $n = 10^4 - 4 \cdot 10^{11}$ g/cm^3: outer crust or envelope (free e^-, lattice of nuclei)

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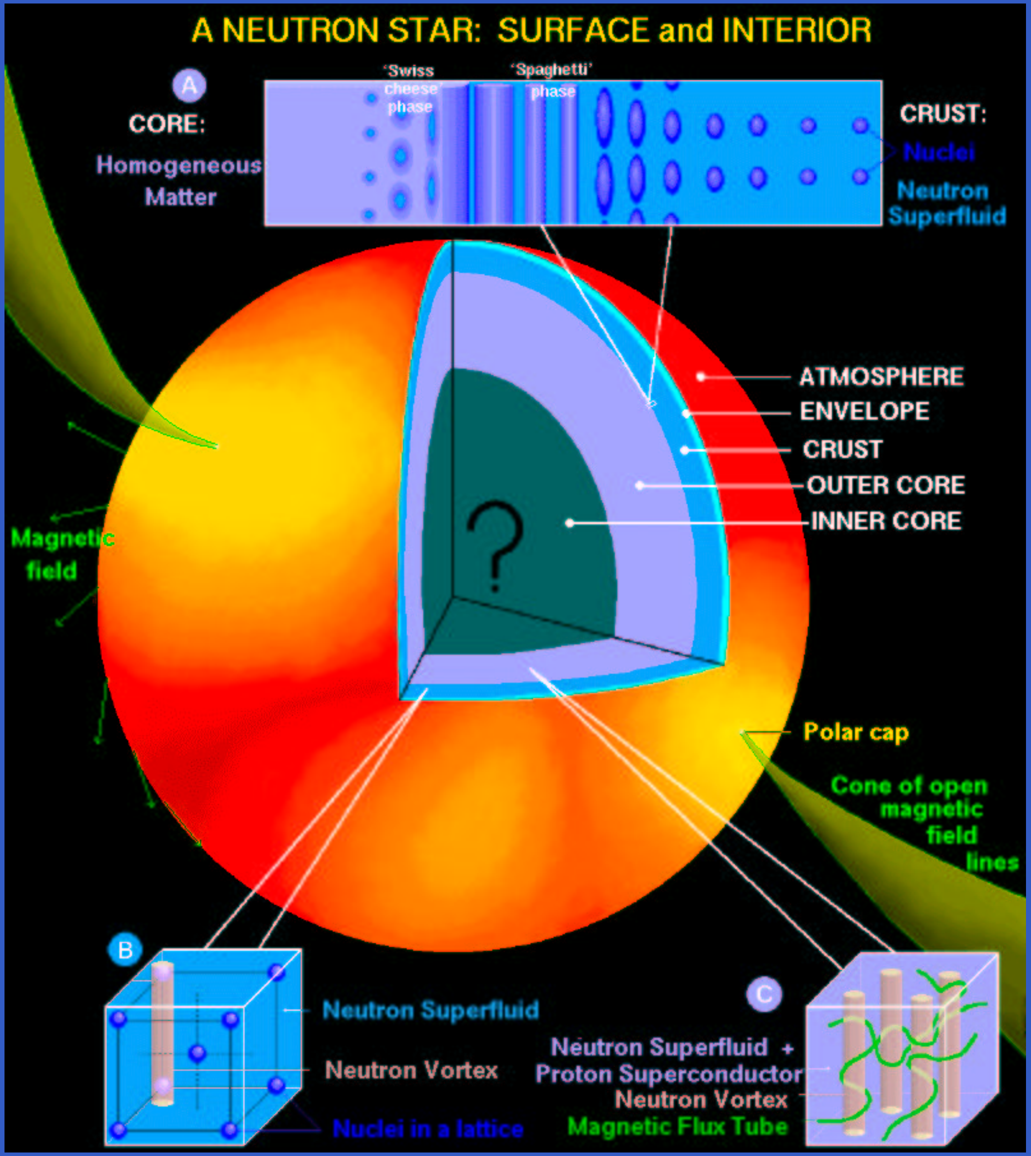
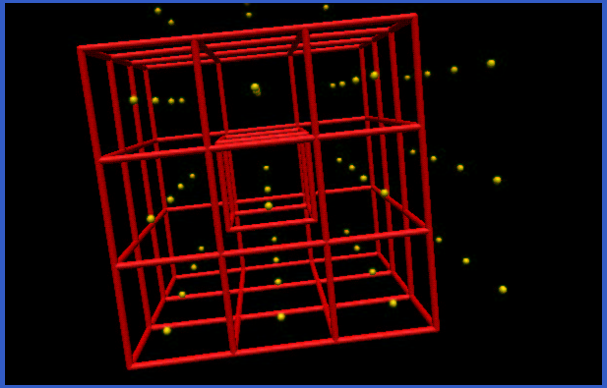


- $n \leq 10^4$ g/cm^3: atmosphere (atoms)
- $n = 10^4 - 4 \cdot 10^{11}$ g/cm^3: outer crust or envelope (free e^-, lattice of nuclei)
- $n = 4 \cdot 10^{11} - 10^{14}$ g/cm^3: Inner crust (lattice of nuclei with free neutrons and e^-)

Composition of the crust of a neutron star

lattice of nuclei surrounded by free electrons



- Wigner–Seitz–cell, lattice structure is bcc
- minimize $E = E_{\text{nuclei}} + E_{\text{lattice}} + E_{\text{electrons}}$
- loop over all particle stable nuclei (up to 14.000)
- use atomic mass evaluation of 2003 by Audi, Wapstra, and Thibault
- extrapolate to the drip–line with various models
- $\Longrightarrow$ sequence of nuclei ^{A}Z as a function of density

Nuclear Models

- Nonrelativistic nuclear models:
  - Skyrme Hartree-Fock plus BCS pairing (MSk7)
  - Skyrme Hartree-Fock-Bogoliubov (SLy4, SkP, SkM*, BSk8)
  - Extended Thomas-Fermi models plus BCS pairing (SkSC4, SkSC18)
- Relativistic nuclear models:
  - Relativistic Mean–Field (NL3, NL-Z2)
  - Relativistic Point–Coupling (PCF1)
  - Chiral Effective Lagrangian (Chiral)

nuclear data tables generated “in-house” or taken from home-pages of BRUSLIB and Dobaczewski

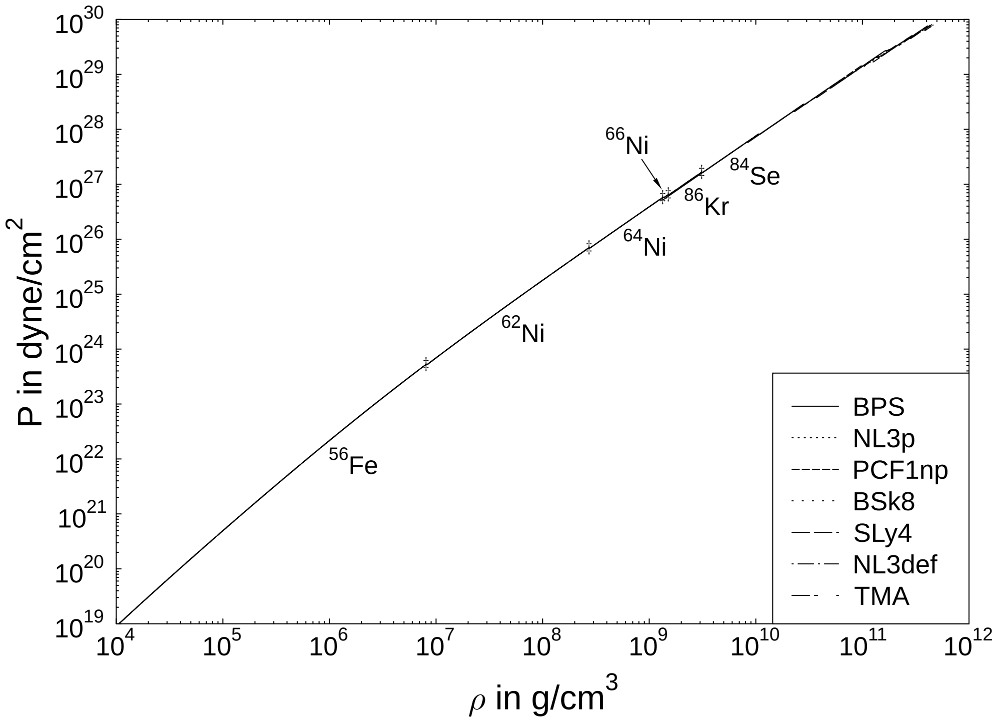
Chiral Effective Lagrangian

(Papazoglou, Zschiesche, JSB, Schramm, Stöcker, Greiner, PRC 59, 411 (1999))

- invariant under $SU(3)_L \times SU(3)_R$ chiral symmetry
- with scalar + pseudoscalar, vector + axial-vector meson–nonet
- with baryon octet (and baryon decuplet)
- with explicit and spontaneous symmetry breaking
- fit to hadron masses, nuclei and hypernuclei (~ 10 parameters)

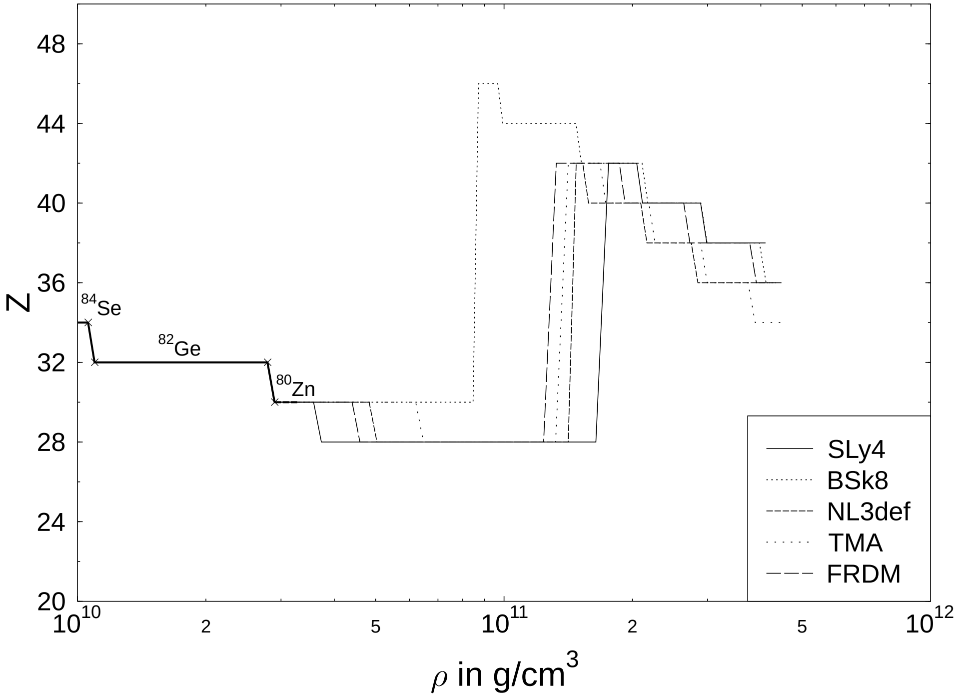
good description of hadron masses, nuclear matter, nuclei and hypernuclei

Sequence to the Dripline (Hempel, Rüster, JSB 2005)



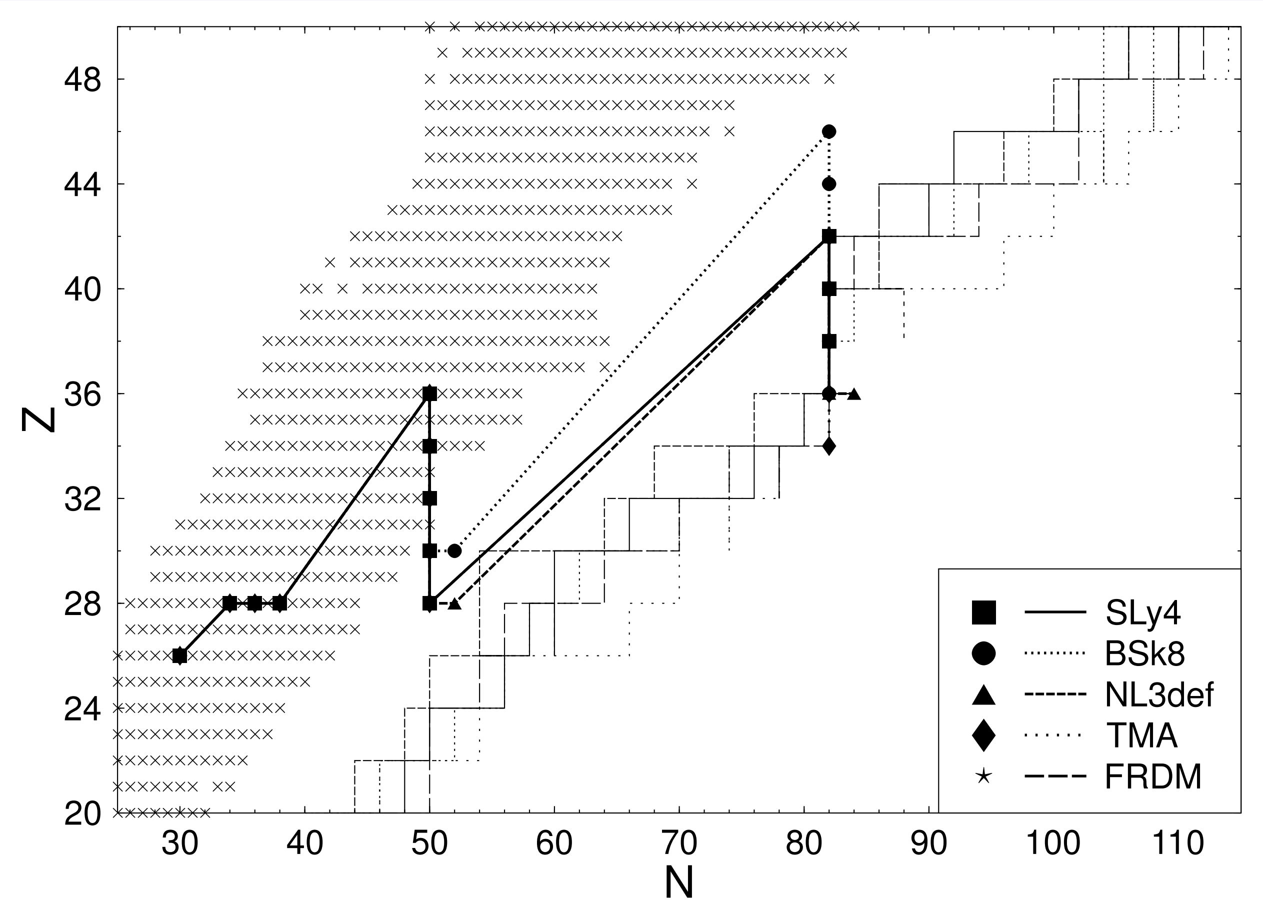
- outer crust starts with iron (^{56}Fe) up to $\rho \approx 10^7$ g/cm^3
- continues along nickel isotopes ($Z = 28$), then Kr, Se ($N = 50$)
- initial sequence at low densities independent of parameter set (data)!
- equation of state (nearly) independent of parameter set!

Sequence to the Dripline II (Hempel, Rüster, JSB 2005)



- selection of state-of-the-art mass tables (deformed calculations)
- intial sequence of nuclei: Se, Ge, Zn (data)
- overall narrow range in Z
- neutron drip around $5 \cdot 10^{11}$ g/cm^3

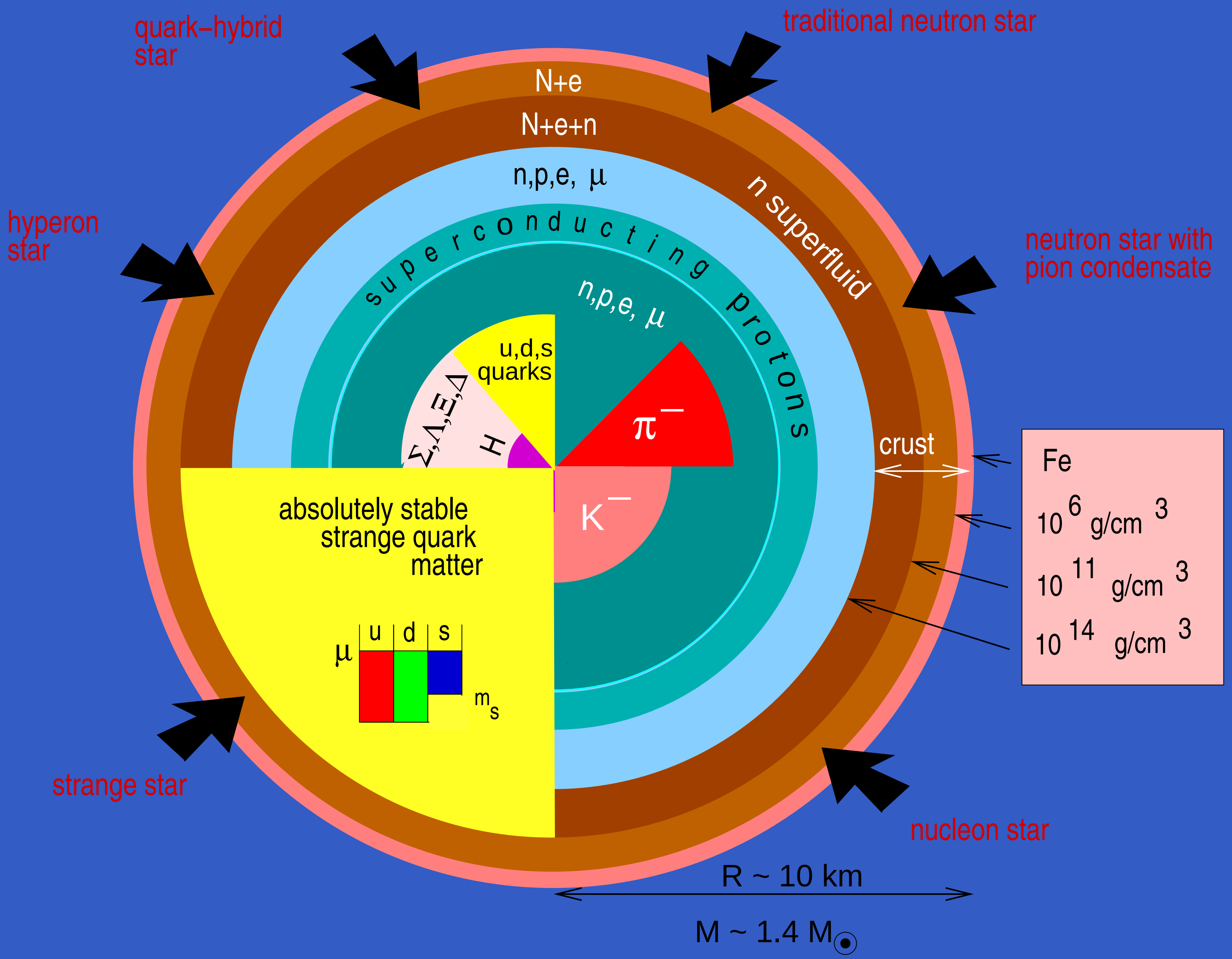
Nuclei in the crust (Hempel, Rüster, JSB 2005)



- sequence of nuclei: along $N = 50$ then along $N = 82$ with $Z = 46 - 34$
- common endpoint around $N = 82$ and $Z = 36$ (!)
- common location of the dripline at N$= 82$ (!)
- updates classic work of Baym, Pethick, Sutherland from 1971!

Modelling the Neutron Star Core

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



Neutron Star Matter for a Free Gas

(Ambartsumyan and Saakyan, 1960)

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

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

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

Baryon–Baryon Interactions

NΛ: attractive $\rightarrow$ Λ-hypernuclei for $A = 3 - 209$
$U_\Lambda = -30$ MeV at $n = n_0$

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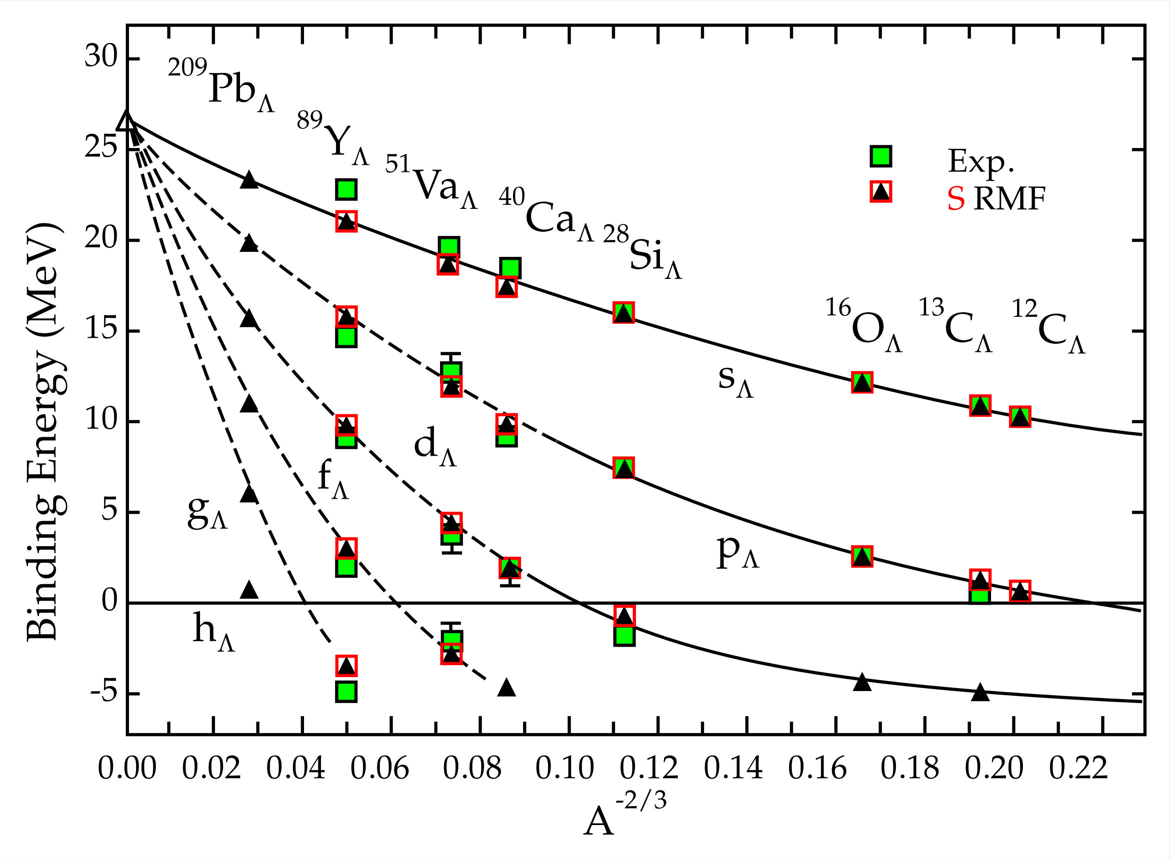
YY: Y$= \Lambda, \Sigma, \Xi$, unknown!

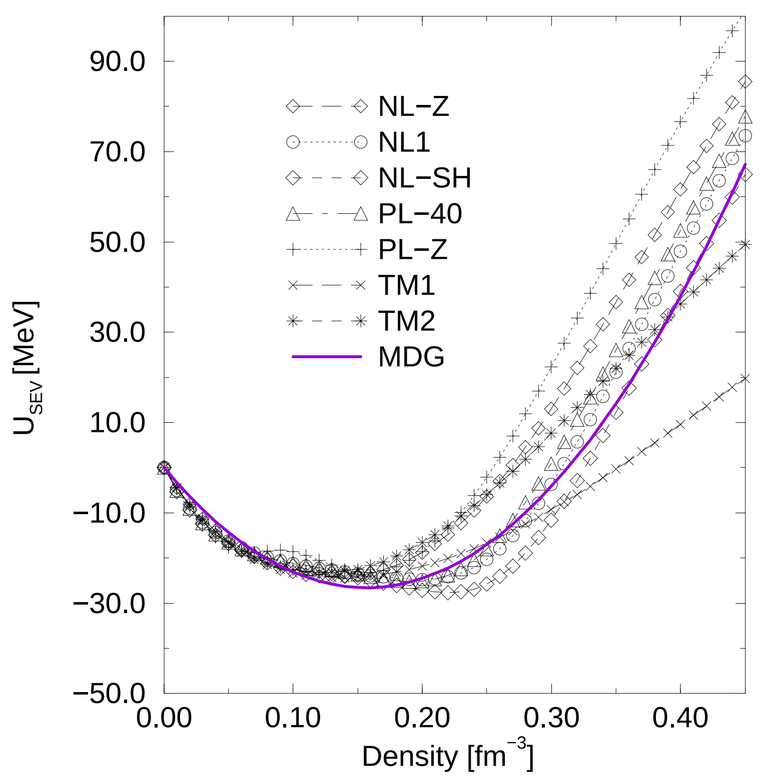
Λ Single–Particle Energies



(Rufa, JS, Maruhn, Stöcker, Greiner, Reinhard (1990))

- measured in (π^+, K^+) reactions
- spin–orbit splitting smaller than experimental resolution
- fit to single particle energies: $U_\Lambda = -27$ MeV for $A \to \infty$

Λ potential in nuclear matter (JSB, Bondorf, Mishustin 1997)



- hyperon potential in various (relativistic) parameterizations
- hyperon potential becomes repulsive above $2n_0$
- compatible with hypernuclear data, three-body interactions for hyperons (MDG: Millener, Dover, Gal 1988)

$\Lambda\Lambda$ Hypernuclei

two Λs bound in a nucleus, produced by Ξ^- capture

1963 Danysz et al.: ${}^{10}_{\Lambda\Lambda}\mathrm{Be} \to {}^{9}_{\Lambda}\mathrm{Be} + \mathrm{p} + \pi^-$

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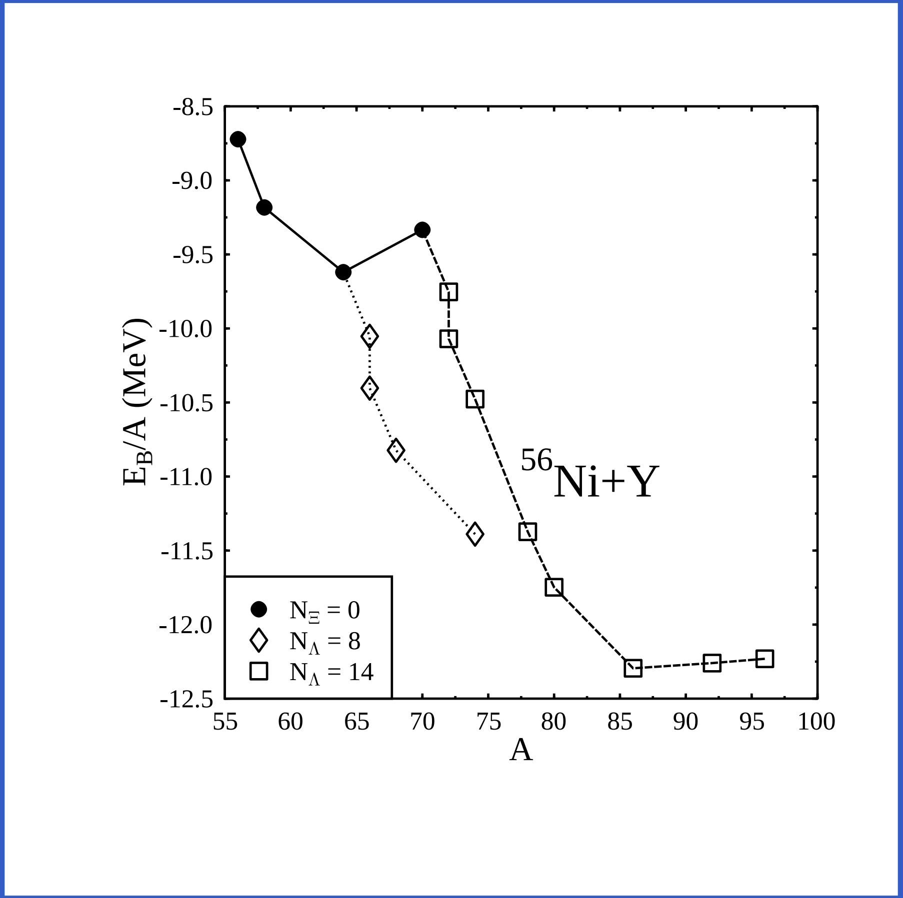
- $\Lambda\Lambda$ interaction is attractive
- no strong decay to the H-dibaryon seen
  $\Lambda + \Lambda \rightarrow H \rightsquigarrow m_H > 2m_\Lambda - B_{\Lambda\Lambda} \sim 2220$ MeV

Systems of Nucleons and Hyperons



(JS, Dover, Gal, Greiner, Stöcker (1993))

- Pauli–blocking of the reactions: $\Lambda + \Lambda \leftrightarrow \Xi + N$, $Q \approx -25$ MeV
- Σs are not stable: $\Sigma + N \to \Lambda + N$, $Q \approx -80$ MeV
- nuclear binding energy with Λs and Ξs increases to $E/A = -12$ MeV!

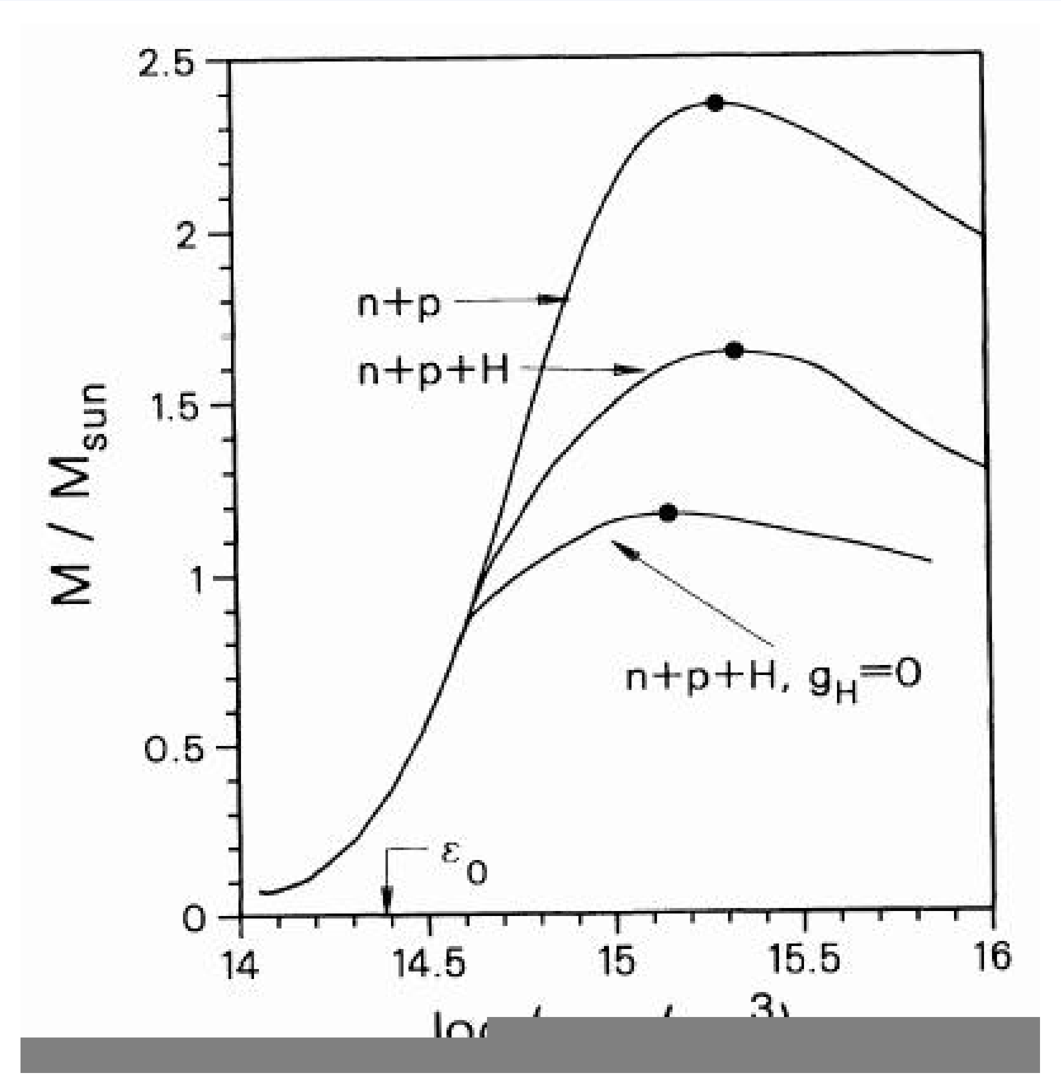
Neutron Star Matter and Hyperons

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

- nonrelativistic potential model (Balberg and Gal, 1997)
- quark-meson coupling model (Pal et al., 1999)
- relativistic mean–field models (Glendenning, 1985; Knorren, Prakash, Ellis, 1995; JS and Mishustin, 1996)
- relativistic Hartree–Fock (Huber, Weber, Weigel, Schaab, 1998)
- Brueckner–Hartree–Fock (Baldo, Burgio, Schulze, 2000; Vidana et al., 2000)
- chiral effective Lagrangian's (Hanauske et al., 2000)
- density-dependent hadron field theory (Hofmann, Keil, Lenske, 2001)

$\Rightarrow$ neutron stars are strange !!!

Impact of hyperons on the maximum mass of neutron stars



[redacted]

(Glendenning and Moszkowski 1991)

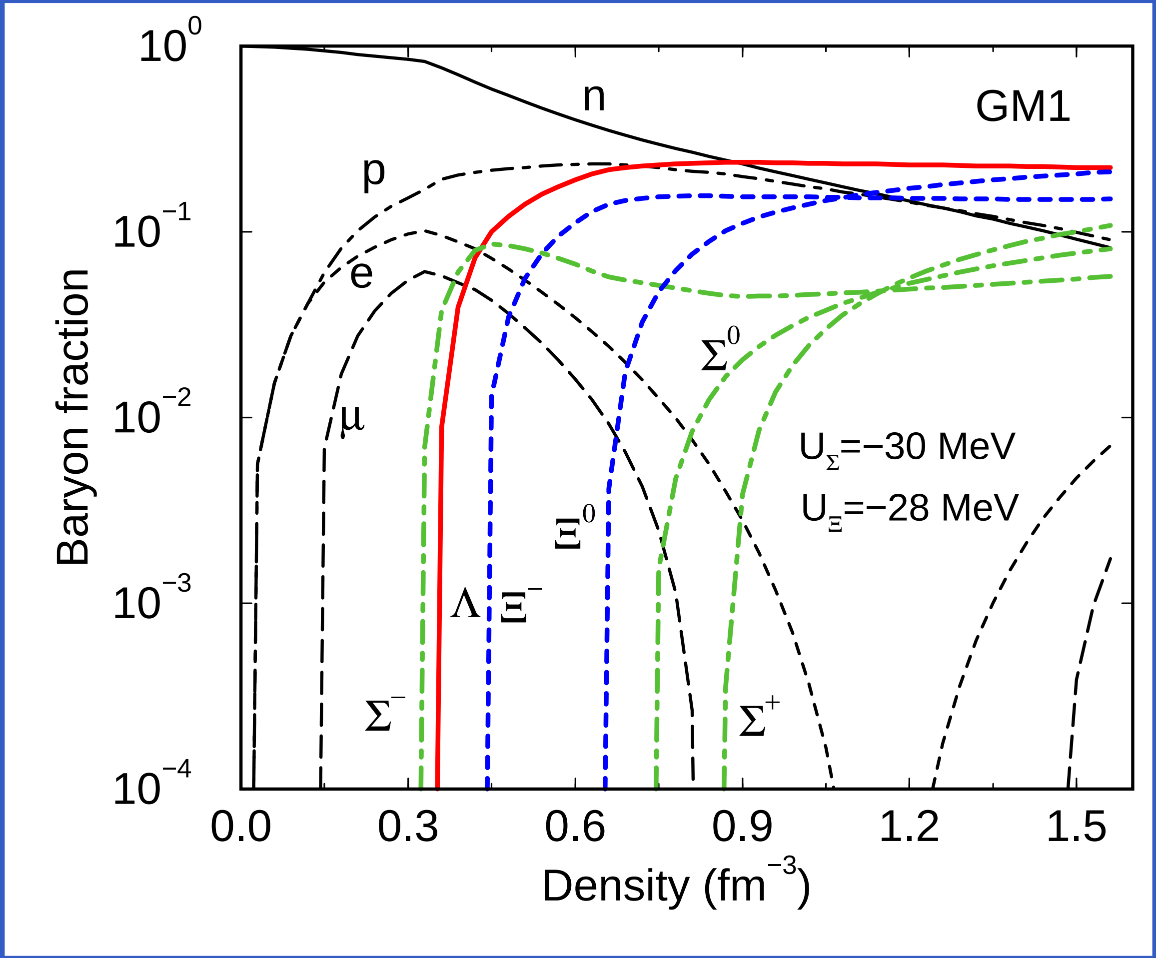
- neutron star with nucleons and leptons only: $M \approx 2.3 M_\odot$
- substantial decrease of the maximum mass due to hyperons!
- maximum mass for “giant hypernuclei”: $M \approx 1.7 M_\odot$
- noninteracting hyperons result in a too low mass: $M < 1.4 M_\odot$!

Modern many-body approaches to neutron stars

beyond mean-field . . .

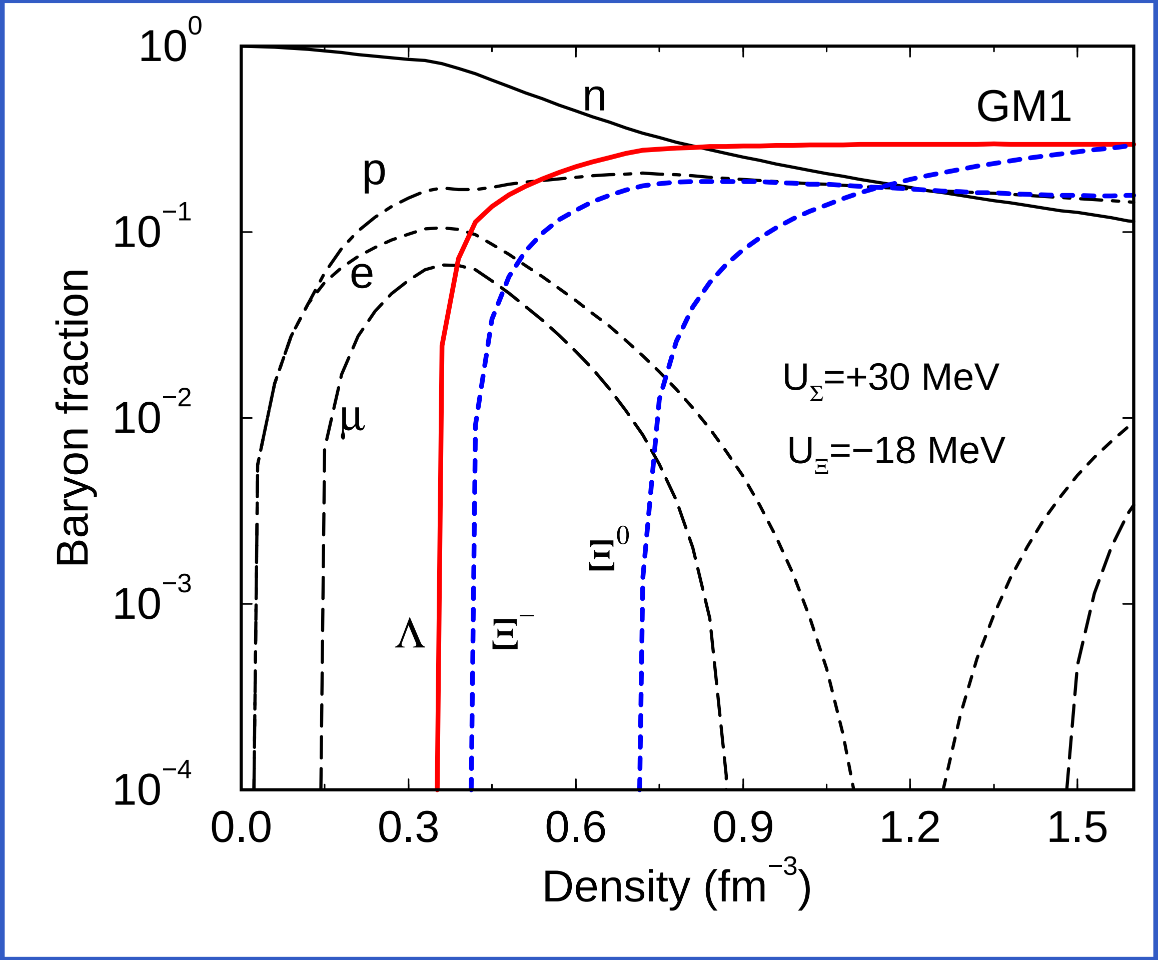
- Relativistic Hartree-Fock (Huber et al. 1998): $M_{\rm max} = 1.3 - 1.6 M_\odot$ depending on hyperon coupling strength
- Brueckner-Hartree-Fock: using Nijmegen soft-core YN potential
- Vidana et al. (2000): $M_{\rm max} = 1.47 M_\odot$ (NN and YN interactions), $M_{\rm max} = 1.34 M_\odot$ (NN, NY, YY interactions)
- Baldo et al. (2000): $M_{\rm max} = 1.26 M_\odot$ including three-body forces
- too soft EoS, too low masses!
- three-body force for hyperons? momentum dependence? typically $p = 300 - 600$ MeV

Composition of Neutron Star Matter



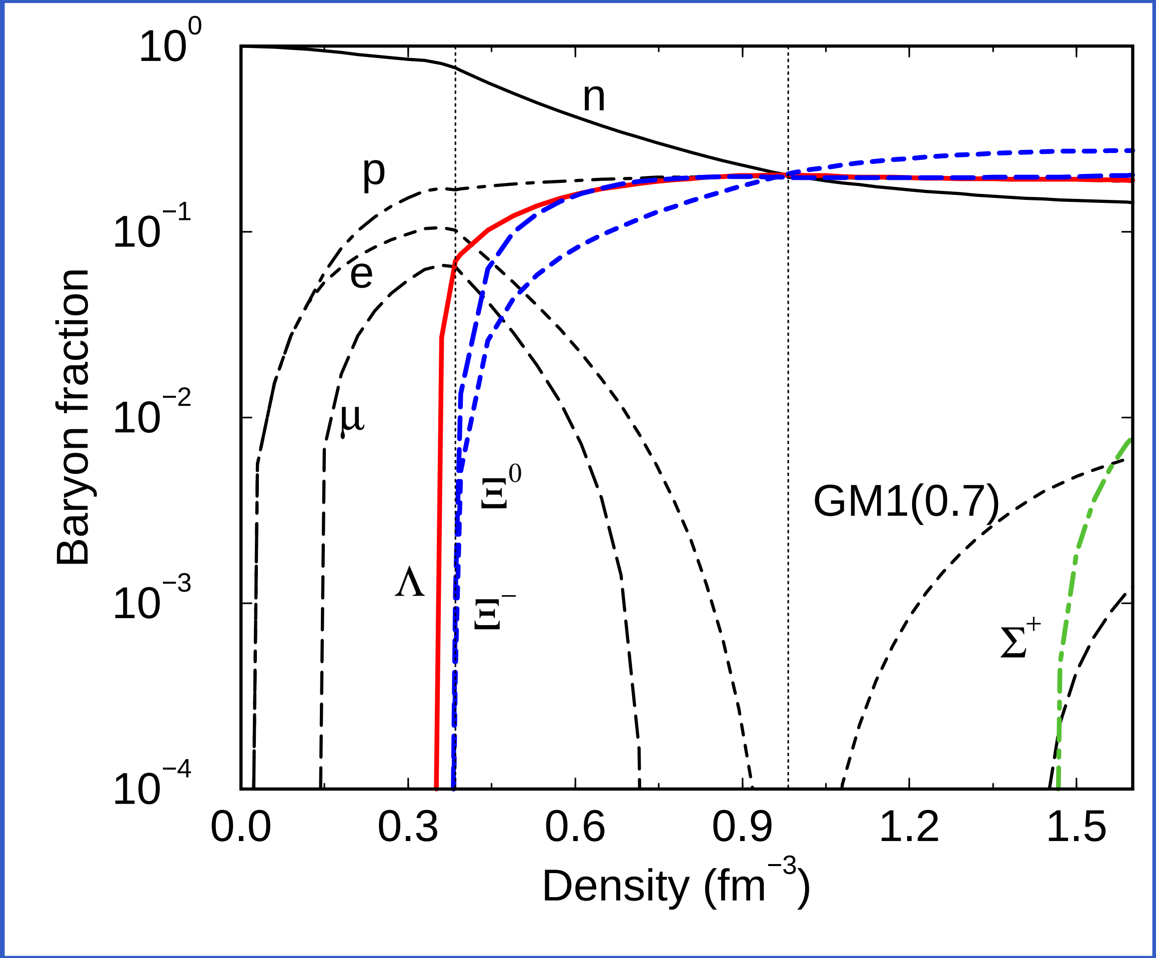
- attractive potential for Σs and Ξs
- Σ^- appear shortly before Λs around $n = 2n_0$
- Λs present in matter at $n = 2.5n_0$, Ξ^- before $n = 3n_0$

Composition of Neutron Star Matter II



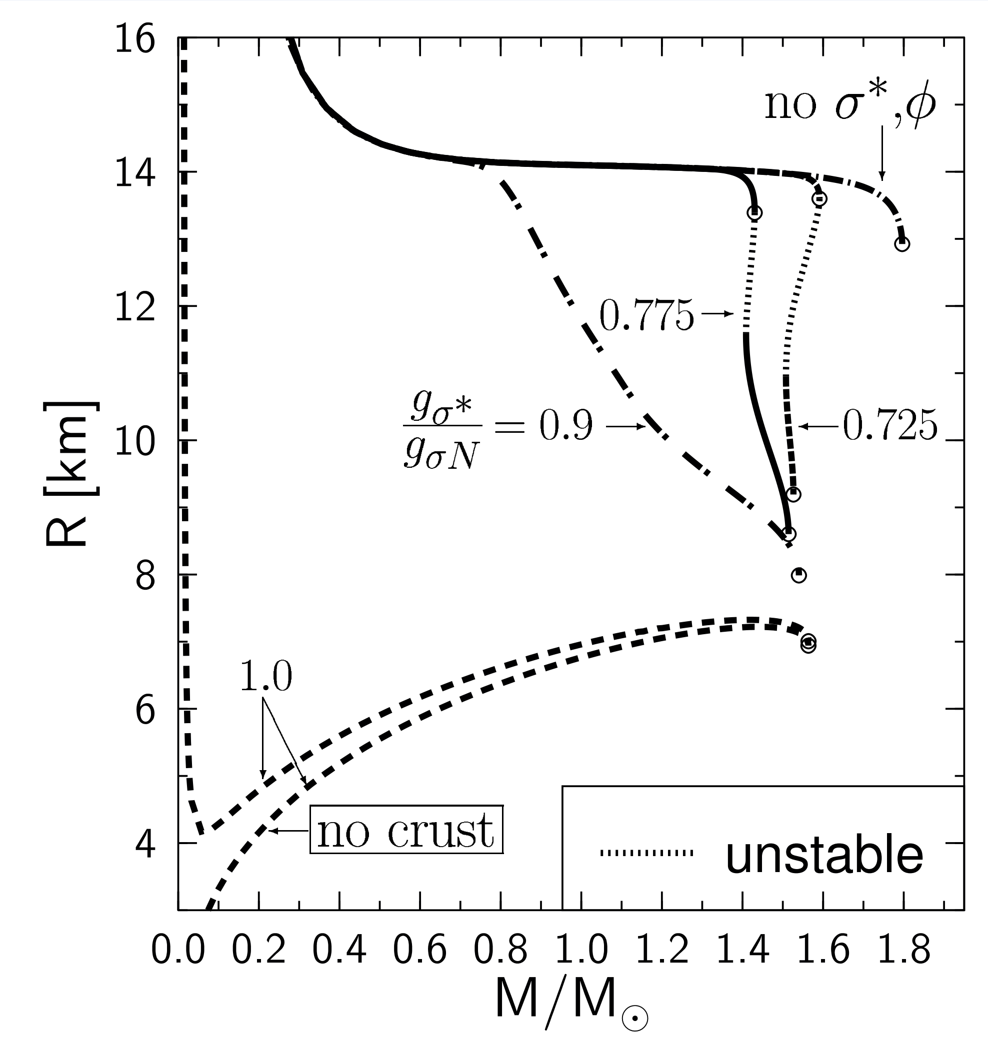
- Λs are present close to $n = 2n_0$
- repulsive potential for Σs: Σ hyperons do not appear at all!
- Ξ^- present in matter before $n = 3n_0$

Phase Transition to Hypermatter



- increase strength of YY interactions
- first order phase transition, mixed phase for a wide range of densities
- all hyperons (Λ, Ξ^0, Ξ^-) appear at the start of the mixed phase

Ultracompact Neutron Stars with Hyperons — Hyperon Stars

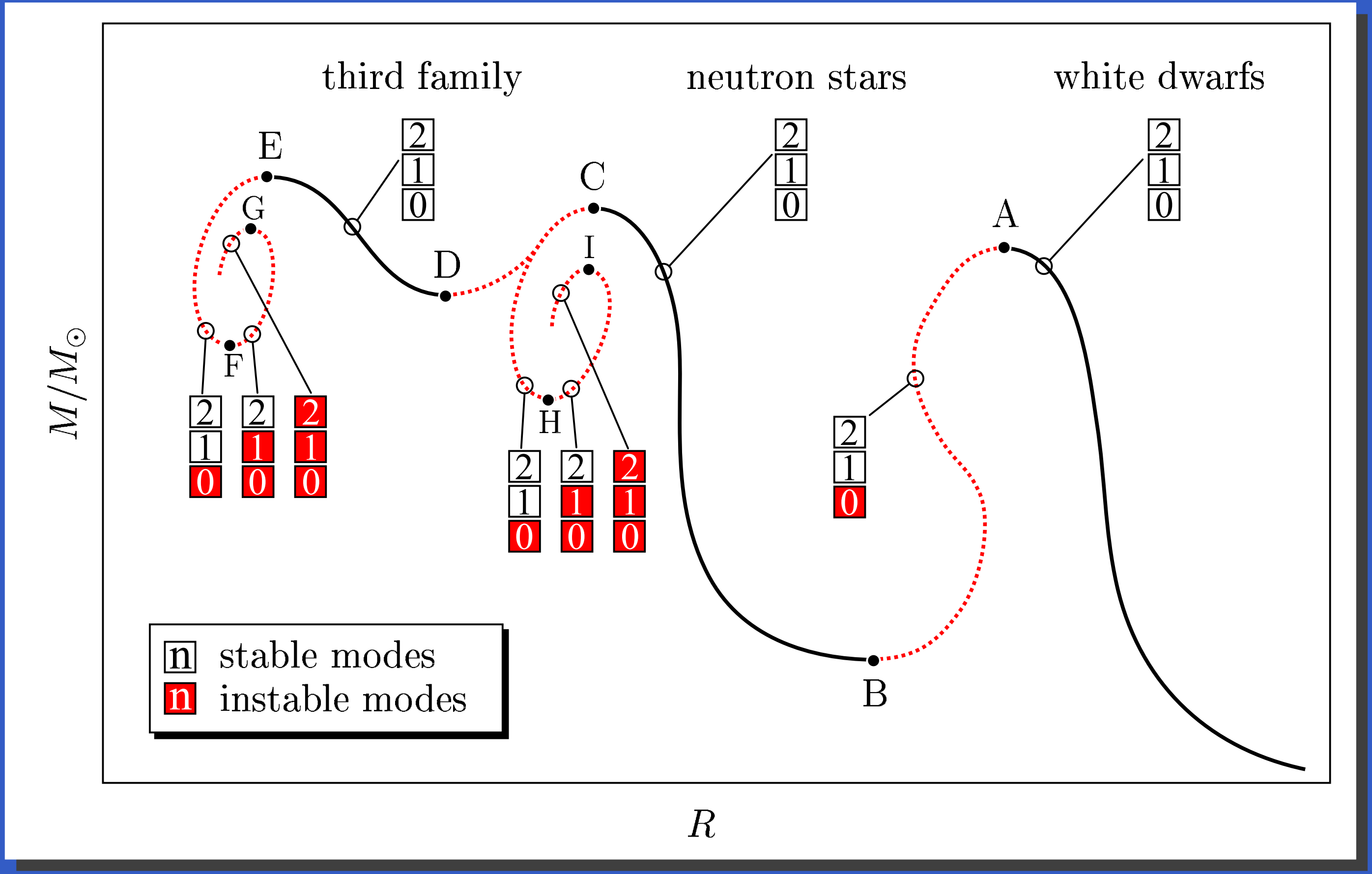


(JSB, Hanauske, Stöcker, Greiner, PRL 89, 171101 (2002))

- new stable solution in the mass–radius diagram!
- neutron star twins: $M_{\text{hyp}} \sim M_n$ but $R_{\text{hyp}} < R_n$
- selfbound compact stars for strong attraction with $R = 7 - 8$ km

Third Family of Compact Stars

(Glendenning, Kettner 2000; Schertler, Greiner,JSB, Thoma 2000)



- third solution to the TOV equations besides white dwarfs and neutron stars, solution is stable!
- generates stars more compact than neutron stars!
- possible for any first order phase transition!

Signals for a Third Family/Phase Transition?

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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 possible for a large fraction of protons!

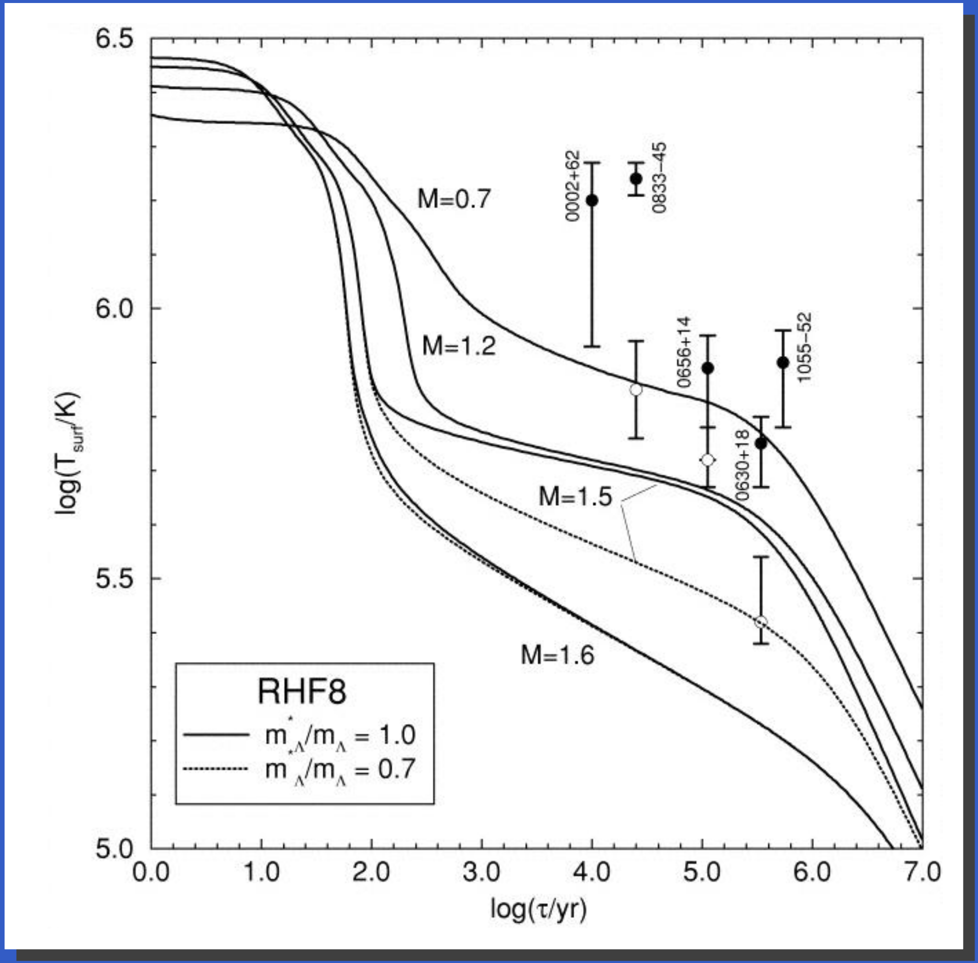
hyperon URCA process:

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

happens immediately when hyperons are present!

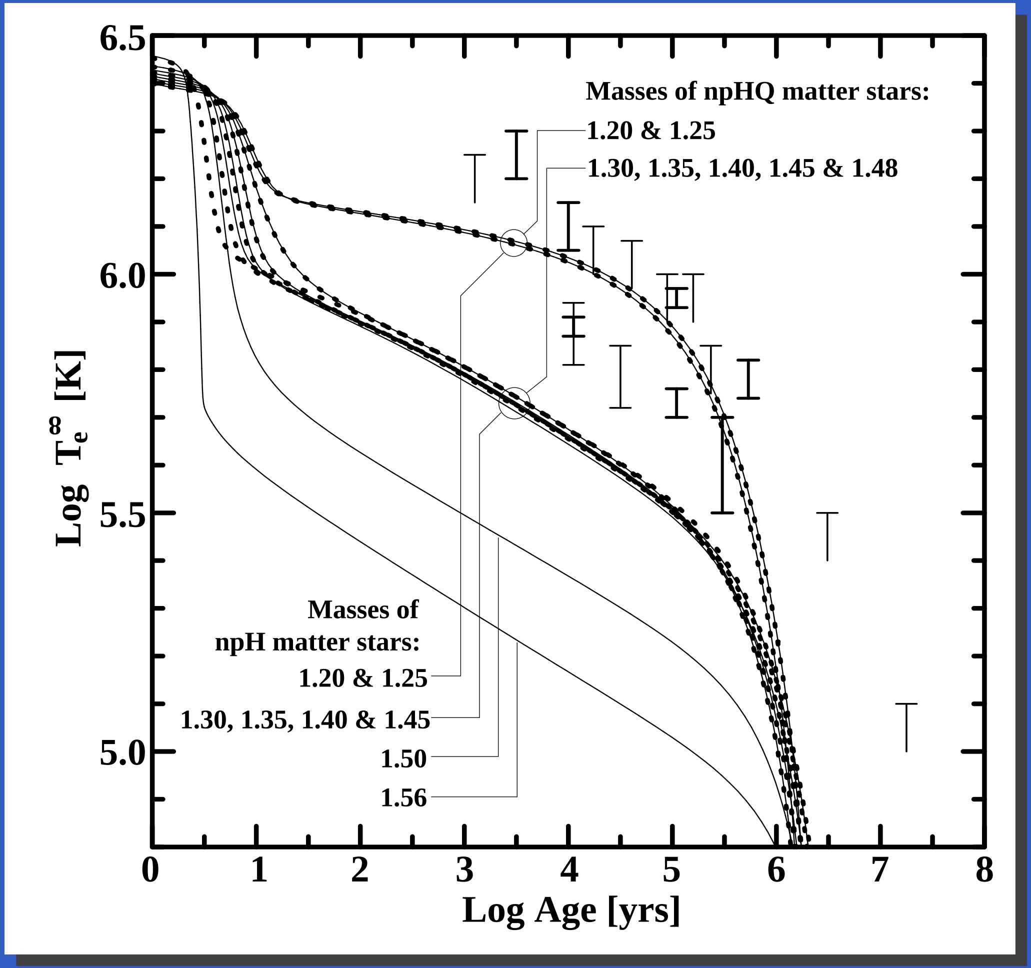
only suppressed by hyperon pairing gaps!

Hyperon cooling with gaps (Schaab, JSB, Balberg 1998)



- slow cooling for low mass neutron stars
- fast cooling for heavier ones (direct nucleon URCA)
- hyperons are present in the core for $M \geq 1.35 M_\odot$
- hyperon cooling suppressed by pairing gaps (same curve for $M = 1.6 M_\odot$)

Hyperon cooling with gaps II (Page, Lattimer, Prakash, Steiner 2000)



- fast cooling for $M \geq 1.3 M_\odot$ stars via direct nucleon URCA
- even faster cooling for heavier stars via hyperon direct URCA
- hyperon cooling not suppressed by pairing gaps!
- tiny density range of unpaired Λ hyperons present as Σ hyperons appear later!

Future of Pulsar Physics: Square Kilometer Array (SKA)

- receiving surface of 1 million square kilometers
- 1 billion dollar international project
- potential to discover:
  - 10,000 to 20,000 new pulsars
  - more than 1,000 millisecond pulsars
  - at least 100 compact relativistic binaries!
- probing the equation of state at extreme limits!
- cosmic gravitational wave detector by using pulsars as clocks!

movie

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- hyperon cooling can be suppressed by hyperon pairing, depends on Σ hyperon composition!