Strangeness in Neutron Stars

Jürgen Schaffner-Bielich

Institut für Theoretische Physik

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Laboratori Nazionali di Frascati, Italy, March 28, 2013

GEFÖRDERT VOM Bundesministerium für Bildung und Forschung

EMMI

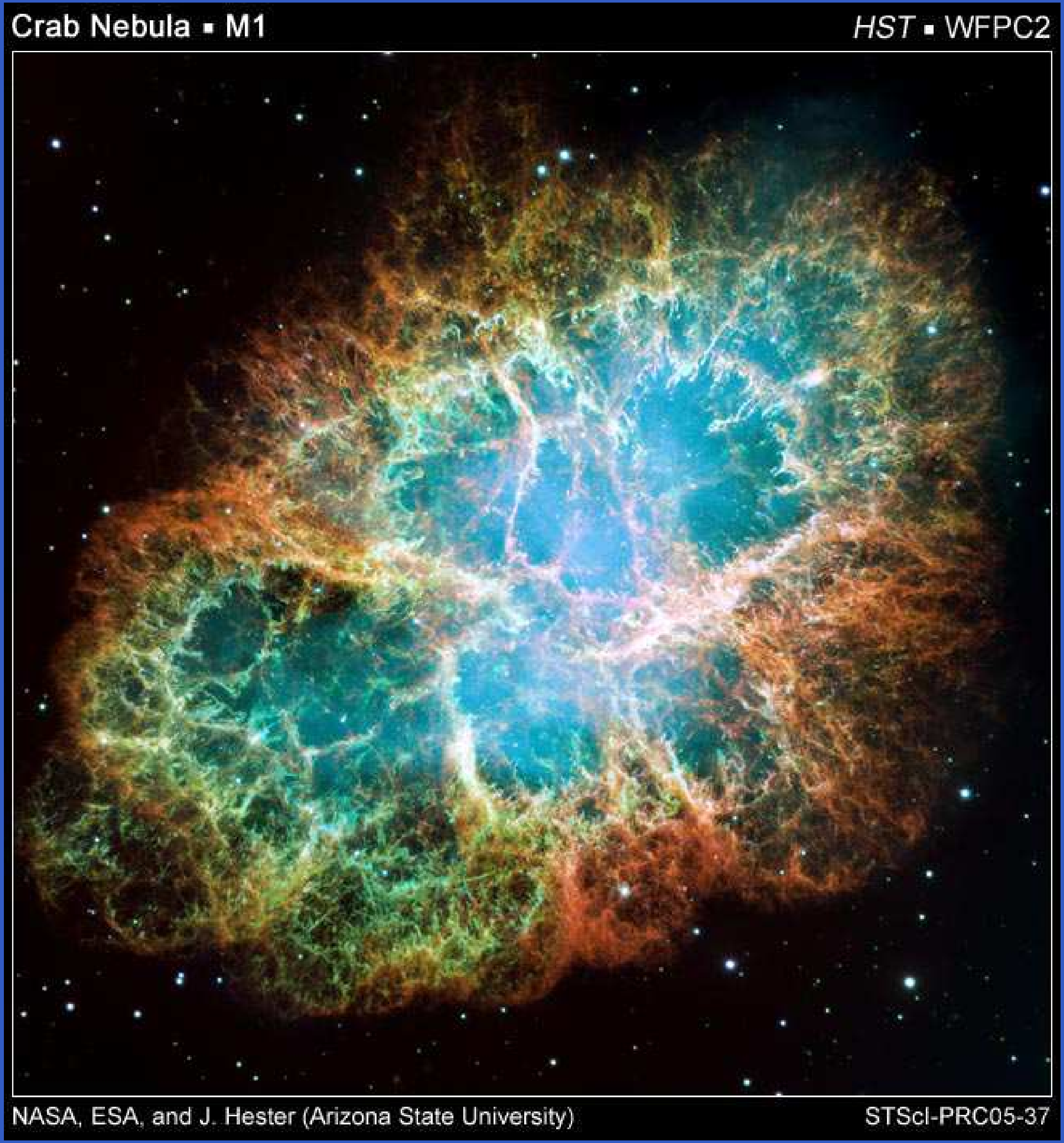
HIC for FAIR Helmholtz International Center

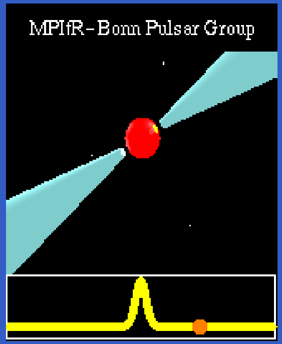
HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research

Outline

- Introduction: measuring neutron star masses
- Hyperons in Neutron Stars: incompatible with massive pulsars?
  - Rescue the hyperons I: change hyperon potentials
  - Rescue the hyperons II: going from SU(6) to SU(3) symmetry
  - Rescue the hyperons III: add quark matter
- What is the maximum possible neutron star mass?
  - Constraints from causality
  - Constraints from subthreshold production of kaons in heavy-ion collisions
- Summary

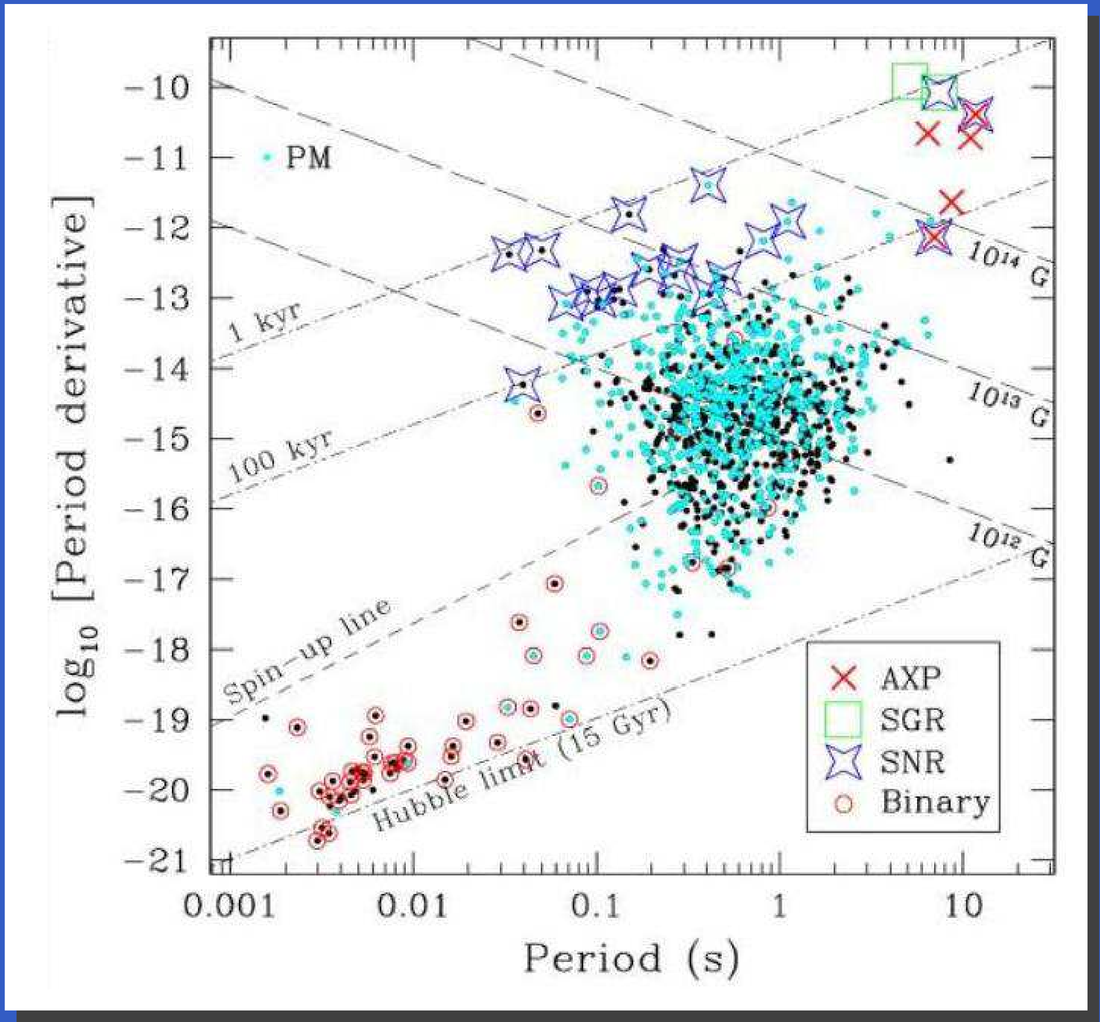
Neutron Stars





- produced in core collapse supernova explosions
- 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
- in the middle of the crab nebula: a pulsar, a rotating neutron star!

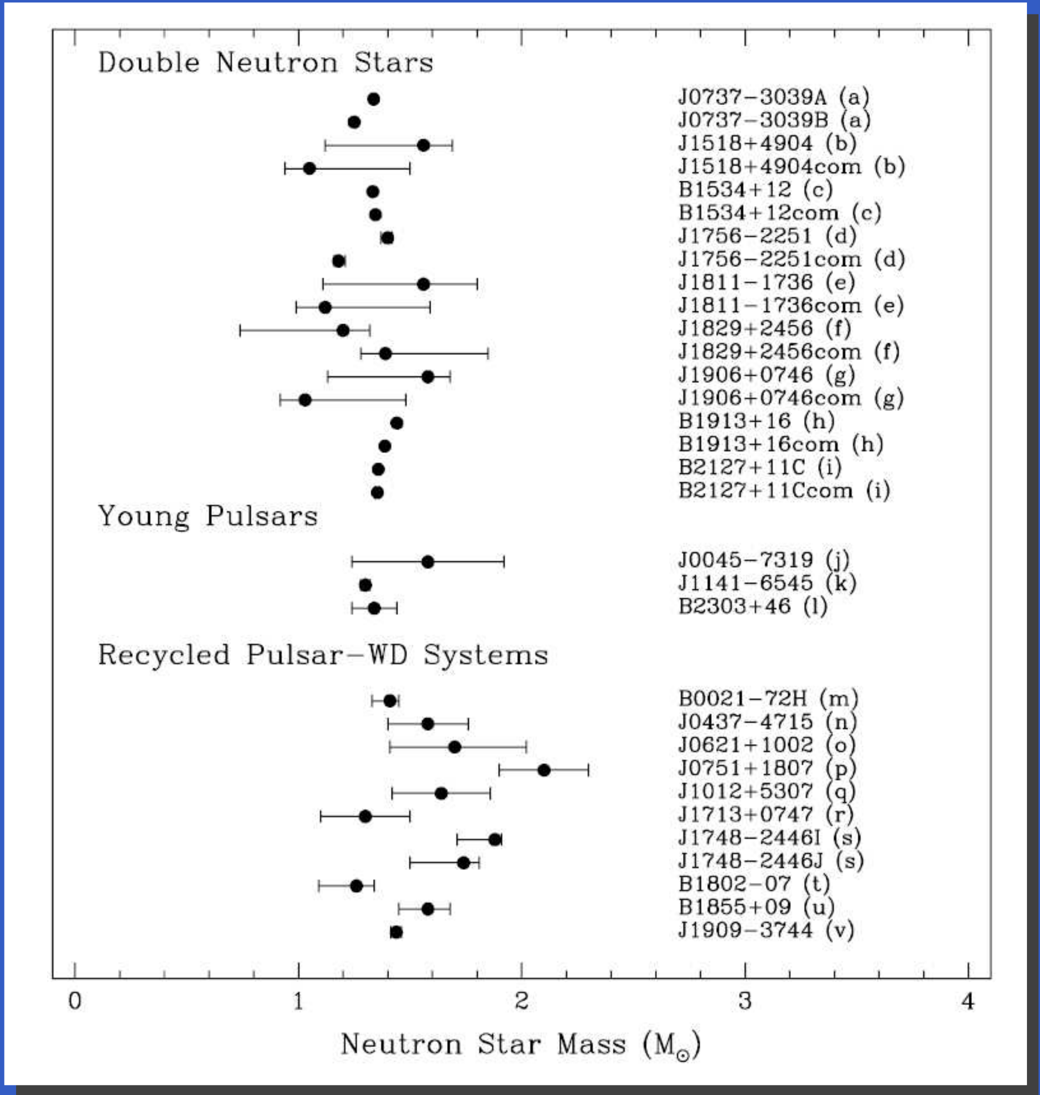
The Pulsar Diagram



(ATNF pulsar catalog)

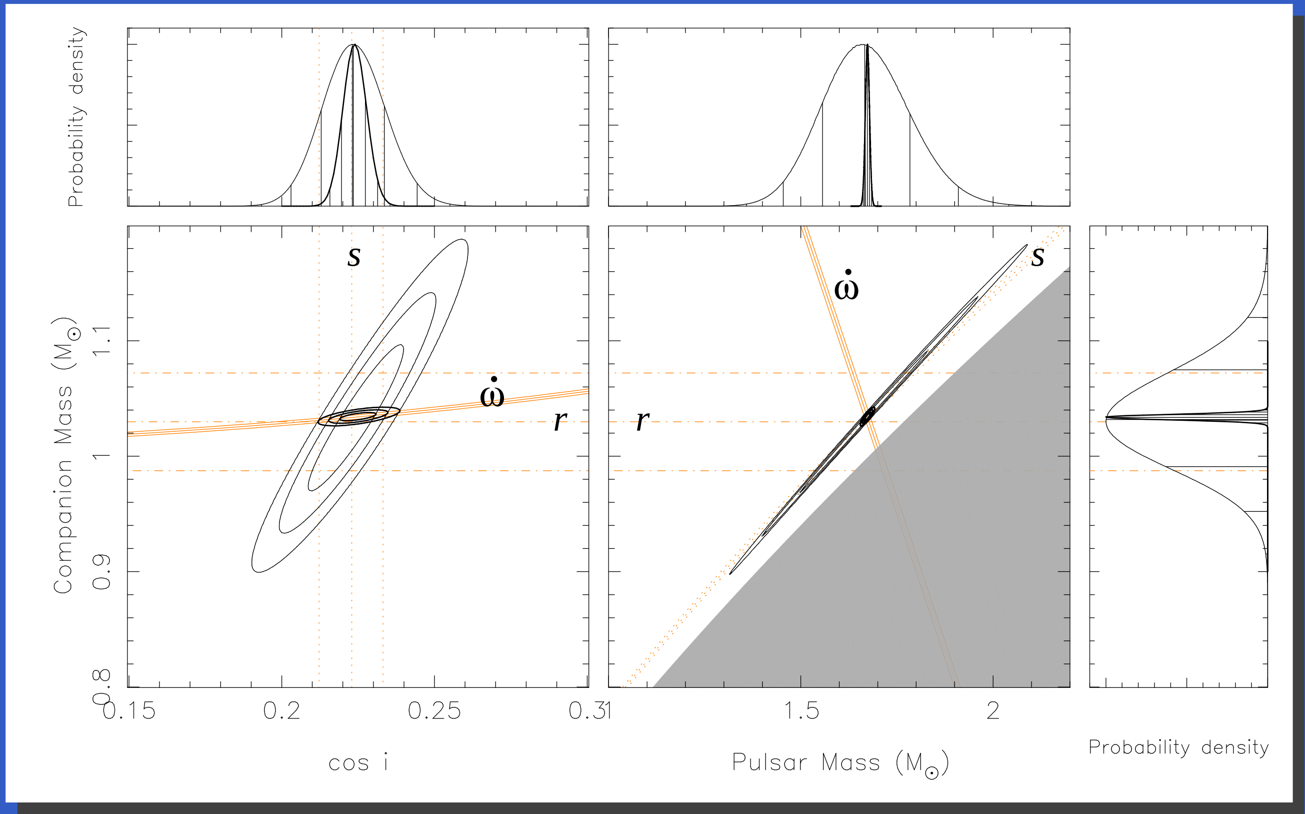
- the diagram for pulsars: period versus period change (P-Ṗ)
- dipole model for pulsars: characteristic age: $\tau = P/(2\dot{P})$ and magnetic field $B = 2 \cdot 10^{19}(P \cdot \dot{P})^{1/2}$ Gauss
- anomalous x-ray pulsars: AXP, soft-gamma ray repeaters: SGR, young pulsars in supernova remnants: SNR
- rapidly rotating pulsars (millisecond pulsars): mostly in binary systems (old recycled pulsars!)

Masses of Pulsars (Stairs 2006)



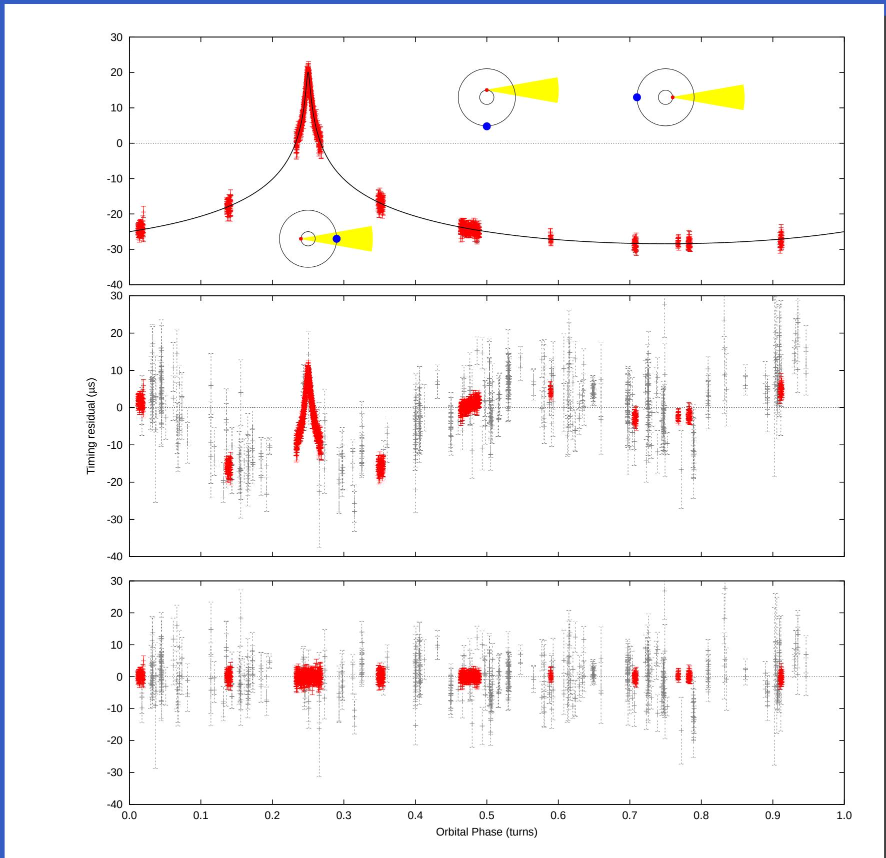
- nearly 2000 pulsars known with 140 binary pulsars
- best determined mass: $M = (1.4414 \pm 0.0002) M_\odot$ Hulse-Taylor pulsar (Weisberg and Taylor, 2004)
- mass of PSR J0751+1807 corr. from $M = (2.1 \pm 0.2) M_\odot$ to $M = (1.14 - 1.40) M_\odot$ (Nice et al. 2008)
- extremely rapid rotations: up to 716 Hz (1.397 ms) (PSR J1748-2446ad)

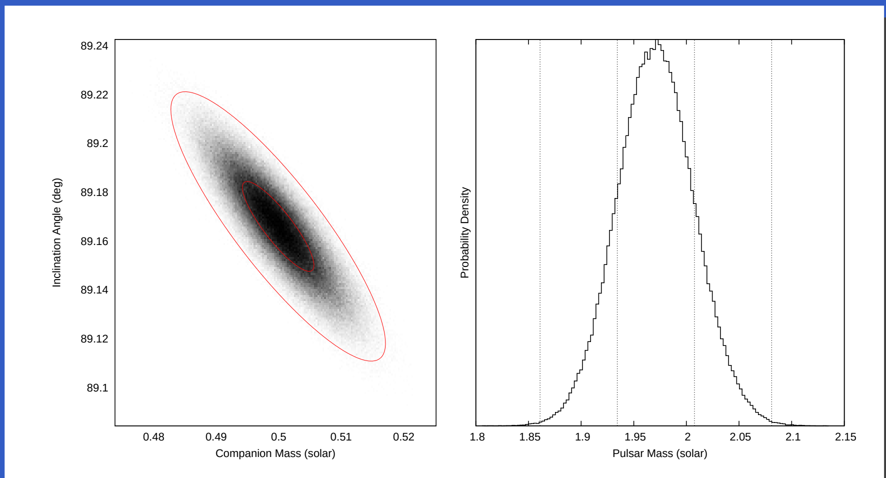
Mass measurement of pulsar PSR J1903+0327 (Freire 2009)



- measure post-Keplerian parameters from pulsar timing
- Shapiro delay parameters r and s alone constrain $M = (1.67 \pm 0.11) M_\odot$
- combined with periastron advance $\dot{\omega}$: $M = (1.67 \pm 0.01) M_\odot$
- rotation of the companion star could influence $\dot{\omega}$
  (follow-up observation with Hubble planned)

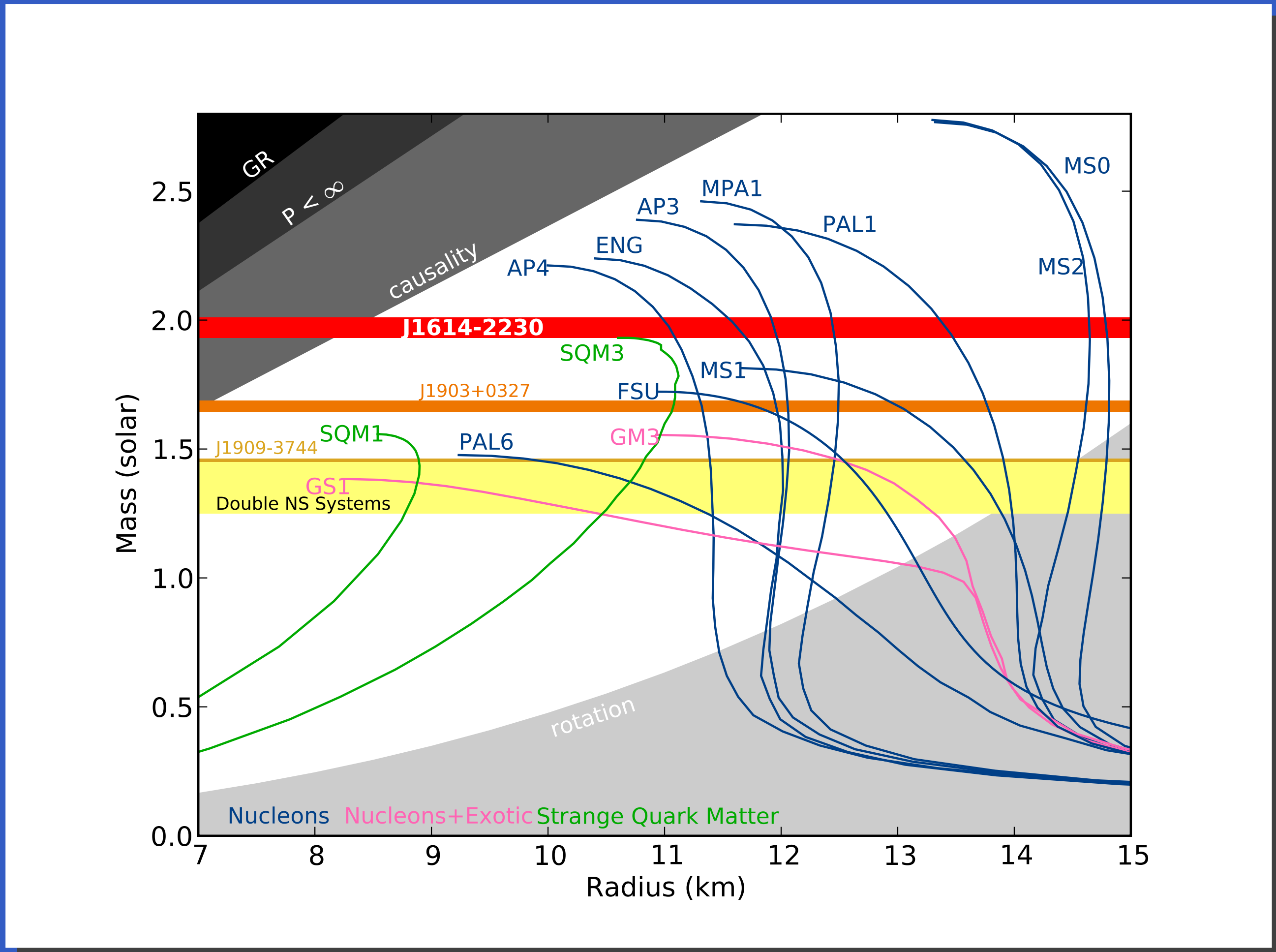
Mass measurement of pulsar PSR J1614-2230 (Demorest et al. 2010)





- extremely strong signal for Shapiro delay
- Shapiro delay parameters r and s alone give $M = (1.97 \pm 0.04) M_\odot$ - new record!
- by far the highest precisely measured pulsar mass!
- considerable constraints on neutron star matter properties!

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



- spin rate from PSR B1937+21 of 641 Hz: $R < 15.5$ km for $M = 1.4 M_\odot$
- Schwarzschild limit (GR): $R > 2GM = R_s$
- causality limit for EoS: $R > 3GM$
- mass limit from PSR J1614-2230 (red band): $M = (1.97 \pm 0.04) M_\odot$

Hyperons in Neutron Stars

Neutron Star Matter for a Free Gas

(Ambartsumyan and Saakyan, 1960)

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

but the corresponding equation of state results in a maximum mass of only

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

(Oppenheimer and Volkoff, 1939)

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

Experimental Status of Hypernuclear Systems

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

NΣ: $^4_\Sigma$He hypernucleus bound by isospin forces
Σ^- atoms: potential is repulsive

NΞ: attractive $\rightarrow$ 7 Ξ hypernuclear events
$U_\Xi = -28$ MeV at $n = n_0$
quasi-free production of Ξ: $U_\Xi = -18$ MeV

$\Lambda\Lambda$: attractive $\rightarrow$ 3 $\Lambda\Lambda$ hypernuclei measured

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

hypernuclear programs: JLab, J-PARC, and PANDA, HYPHI @FAIR!
CBM@FAIR: access to strange dibaryons, multi-hypernuclei!

Onset of Hyperons in Neutron Star Matter

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

- relativistic mean–field (RMF) 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)

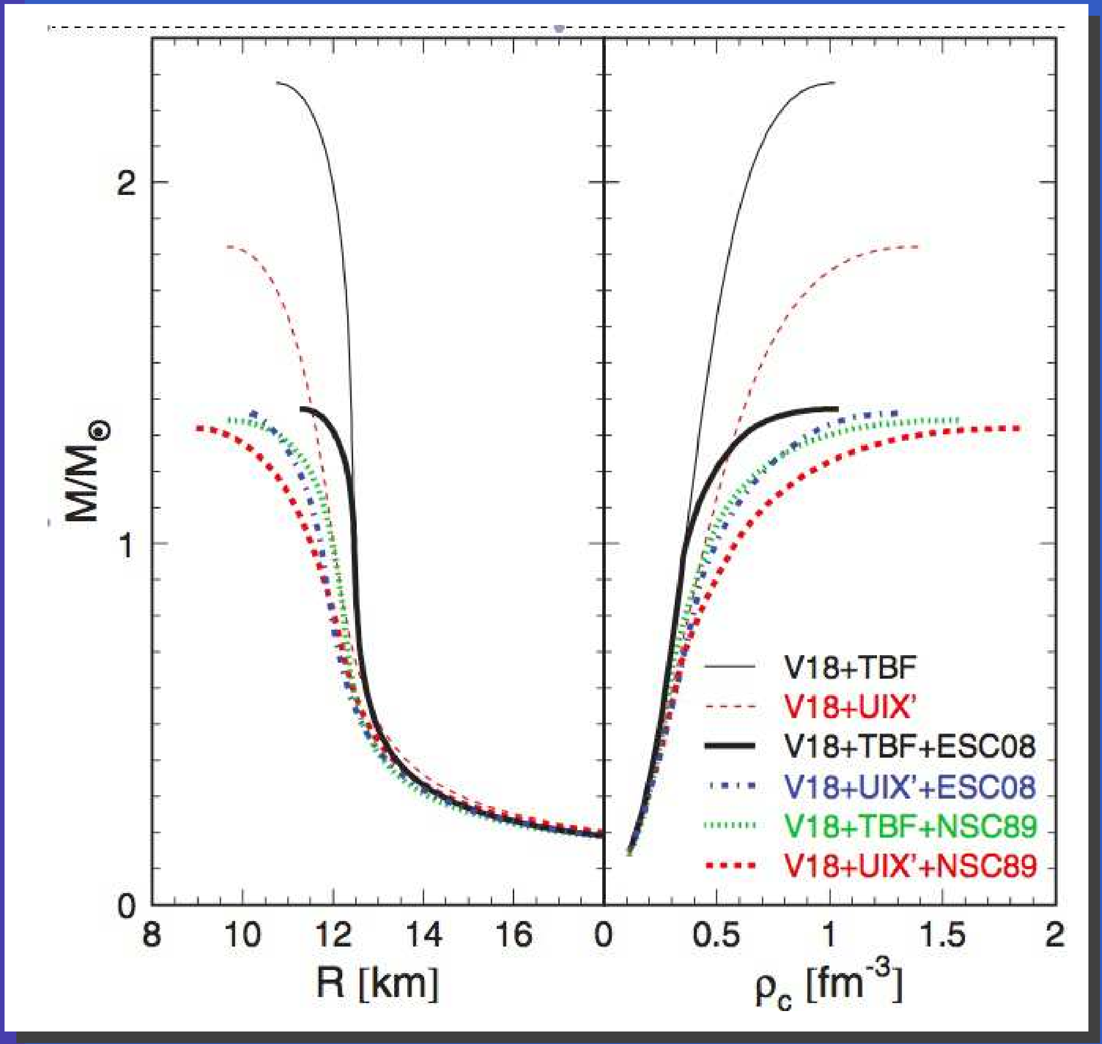
$\Rightarrow$ neutron stars are giant hypernuclei !!!

Maximum mass and modern many-body approaches

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

- Vidana et al. (2000): $M_{\text{max}} = 1.47 M_{\odot}$ (NN and YN interactions), $M_{\text{max}} = 1.34 M_{\odot}$ (NN, NY, YY interactions)
- Baldo et al. (2000): $M_{\text{max}} = 1.26 M_{\odot}$ (including three-body nucleon interaction)
- Schulze et al. (2006): $M_{\text{max}} < 1.4 M_{\odot}$
- Djapo et al. (2008): $M_{\text{max}} < 1.4 M_{\odot}$ ($V_{\text{low}-\text{k}}$)
- Schulze and Rijken (2011): $M_{\text{max}} < 1.4 M_{\odot}$ (ESC08)
- EoS too soft, too low masses!

Maximum masses of neutron stars with hyperons

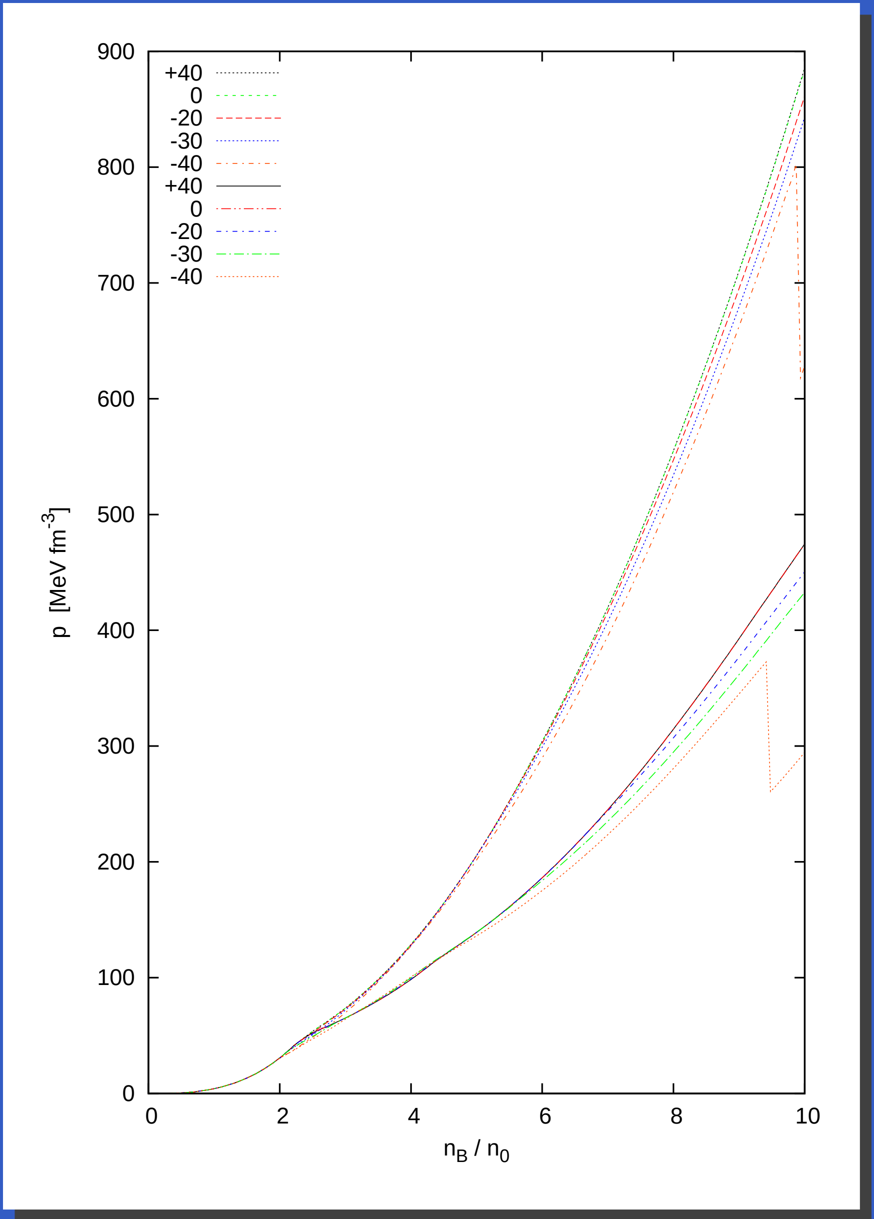


(Schulze and Rijken 2011)

- Brueckner-Hartree-Fock calculation with most recent soft core Nijmegen potential ESC08
- includes repulsive three-body forces (TBF, UIX')
- overall findings: $M < 1.4 M_\odot$ when hyperons are included
- their conclusion: need a stiff quark matter core!
- is it really necessary? And does it really work?

Rescue the hyperons I: change hyperon potentials

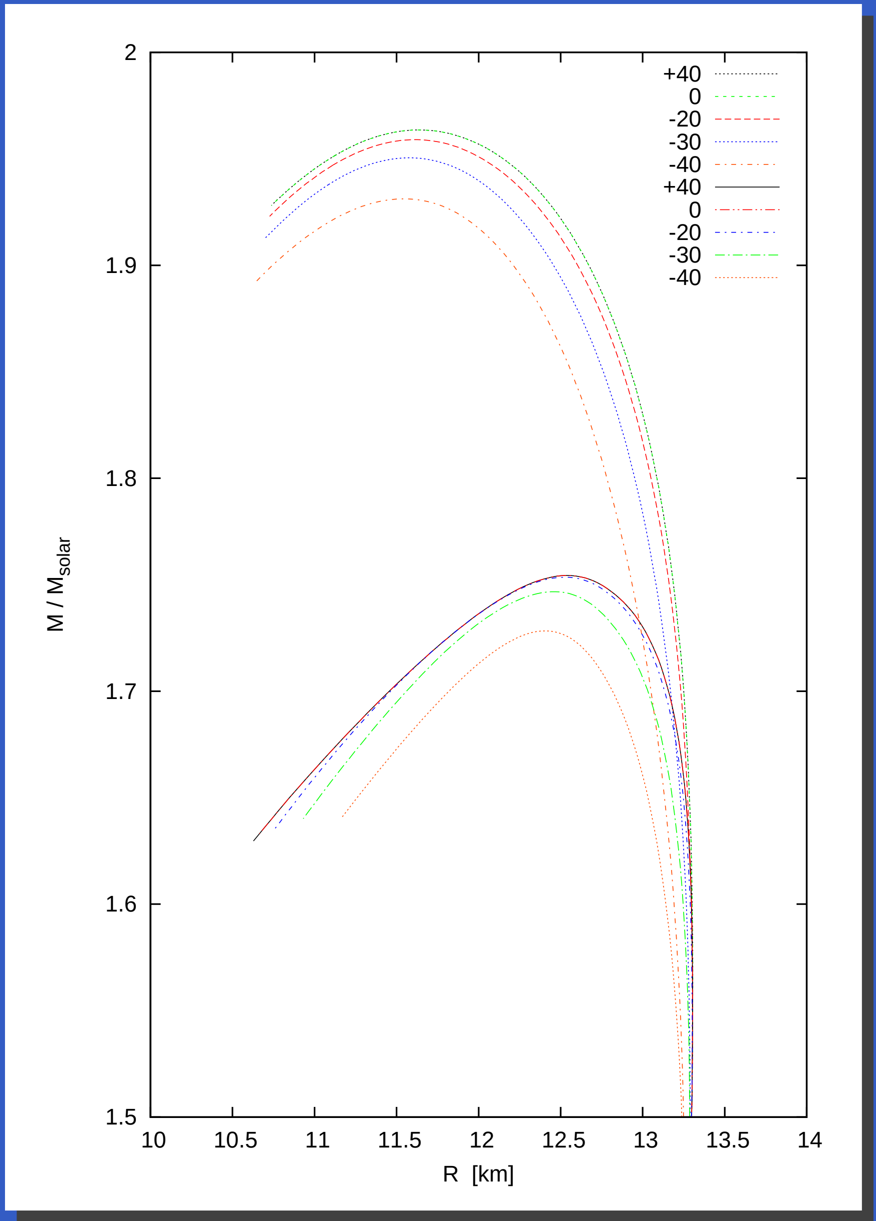
Varying the Σ potential for neutron stars: EoS



(Weissenborn, Chatterjee, JSB 2011)

- use RMF model with set GM1
- EoS for different $U_\Sigma = -40, \ldots 40$ MeV
- lower curves: model 1 (without ϕ meson)
- upper curves: model 1 + ϕ meson
- set $U_\Xi = -28$ MeV
- Σ baryons do not soften the EoS for repulsive potentials

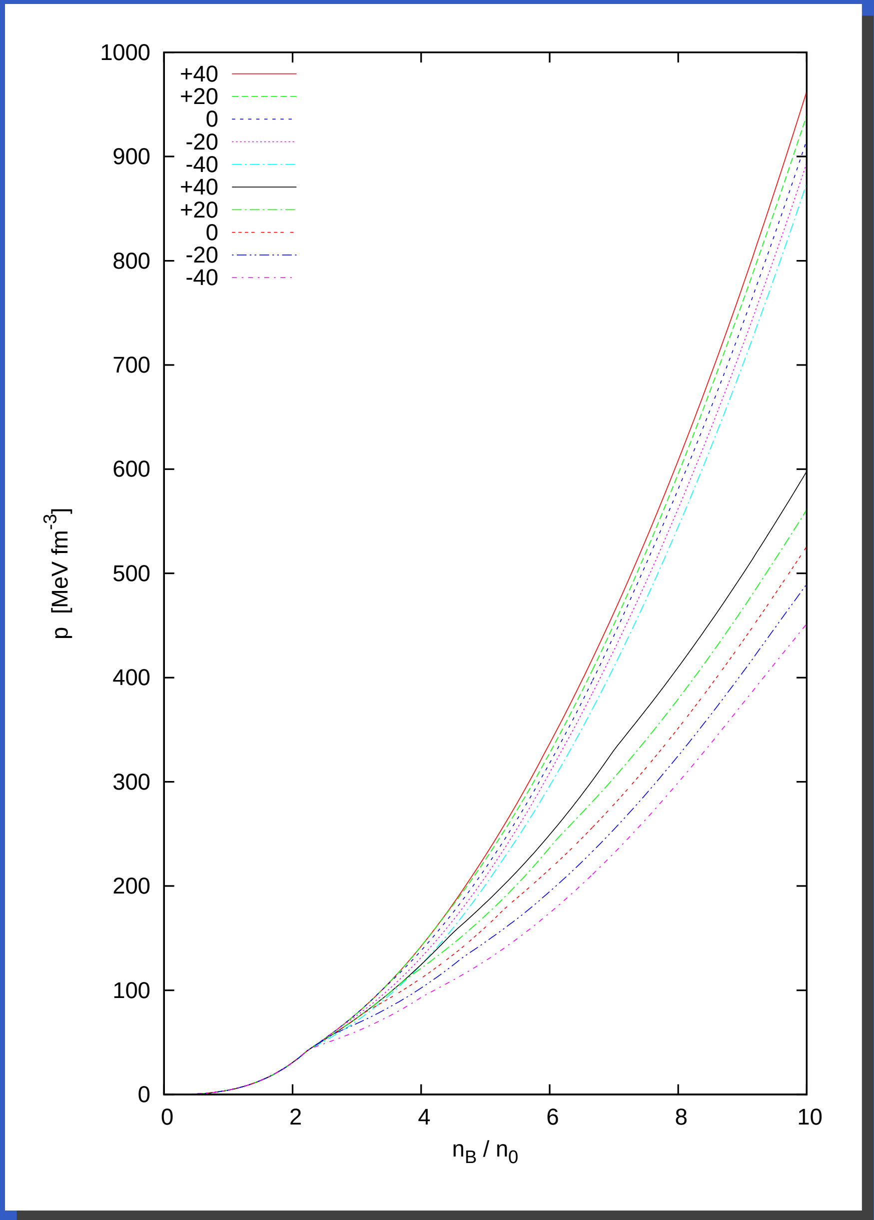
Varying the Σ potential for neutron stars: masses



(Weissenborn, Chatterjee, JSB 2011)

- mass-radius relation for different $U_\Sigma = -40, \ldots 40$ MeV
- lower curves: model 1 (without ϕ meson)
- upper curves: model 1 + ϕ meson
- Σ baryons do not change the mass-radius relation for repulsive potentials
- moderate increase in maximum mass for repulsive Σ potential

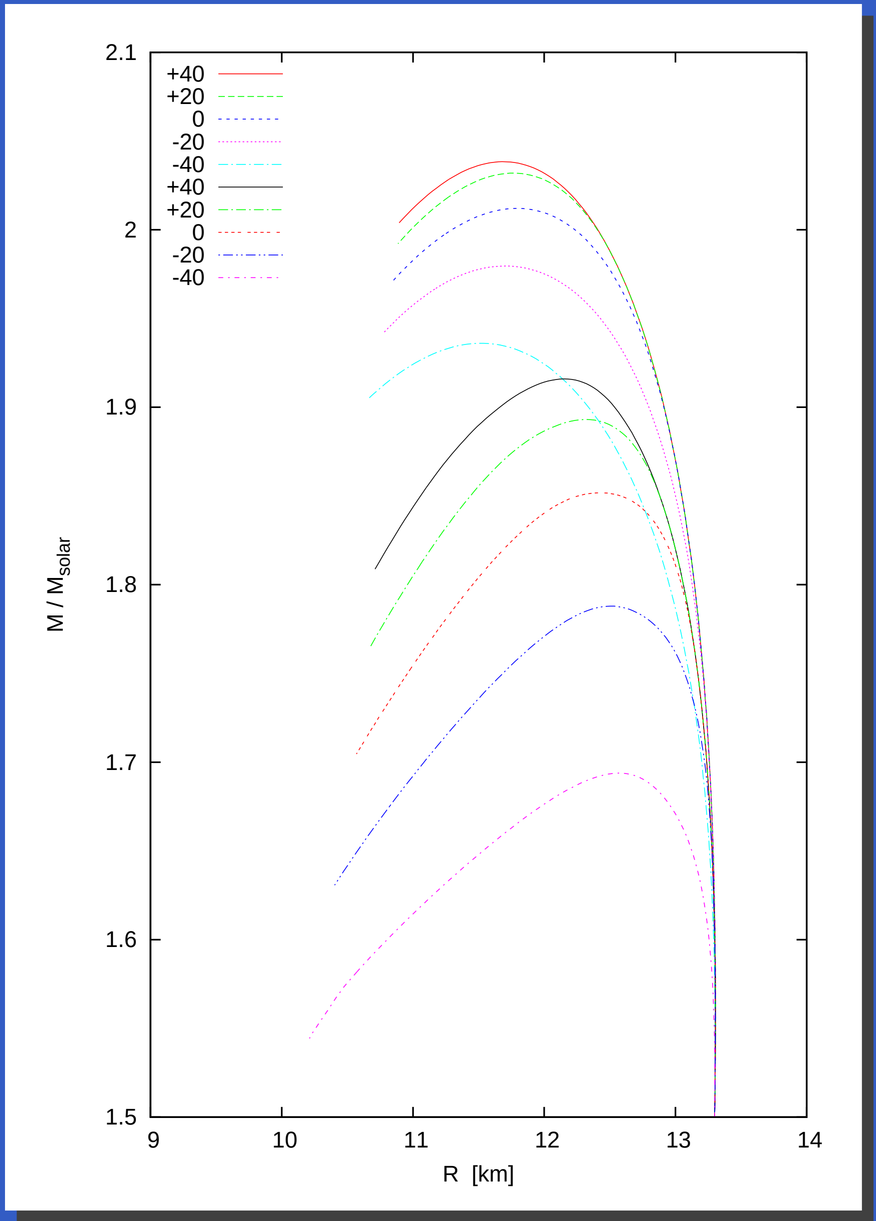
Varying the Ξ potential for neutron stars: EoS



(Weissenborn, Chatterjee, JSB 2011)

- use RMF model with set GM1
- mass-radius relation for different $U_\Xi = -40, \ldots 40$ MeV
- lower curves: model 1 (without ϕ meson)
- upper curves: model 1 + ϕ meson
- repulsive Ξ potential stiffens the EoS at high densities
- set $U_\Sigma = +30$ MeV

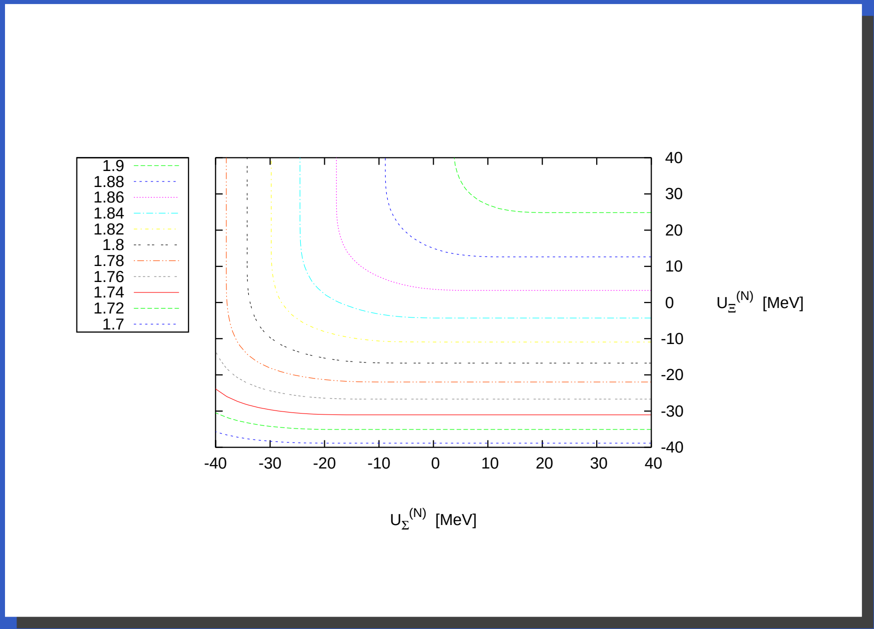
Varying the Ξ potential for neutron stars: masses

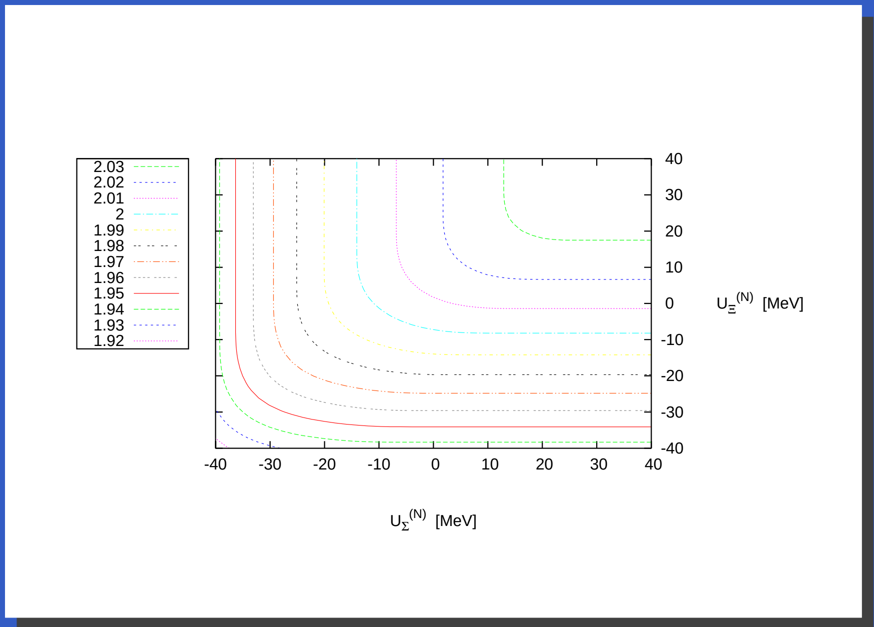


(Weissenborn, Chatterjee, JSB 2011)

- use RMF model with set GM1
- mass-radius relation for different $U_\Xi = -40, \ldots 40$ MeV
- lower curves: model 1 (without ϕ meson)
- upper curves: model 1 + ϕ meson
- repulsive Ξ potential helps to increase maximum mass

Varying hyperon potentials for neutron stars





(Weissenborn, Chatterjee, JSB 2011)

- contour plots for different Σ and Ξ potentials
- upper plot: model 1 (without ϕ meson)
- lower plot: model 1 + ϕ meson
- new mass limit only compatible with (repulsive) ϕ meson

Rescue the hyperons II: going from SU(6) to SU(3) symmetry

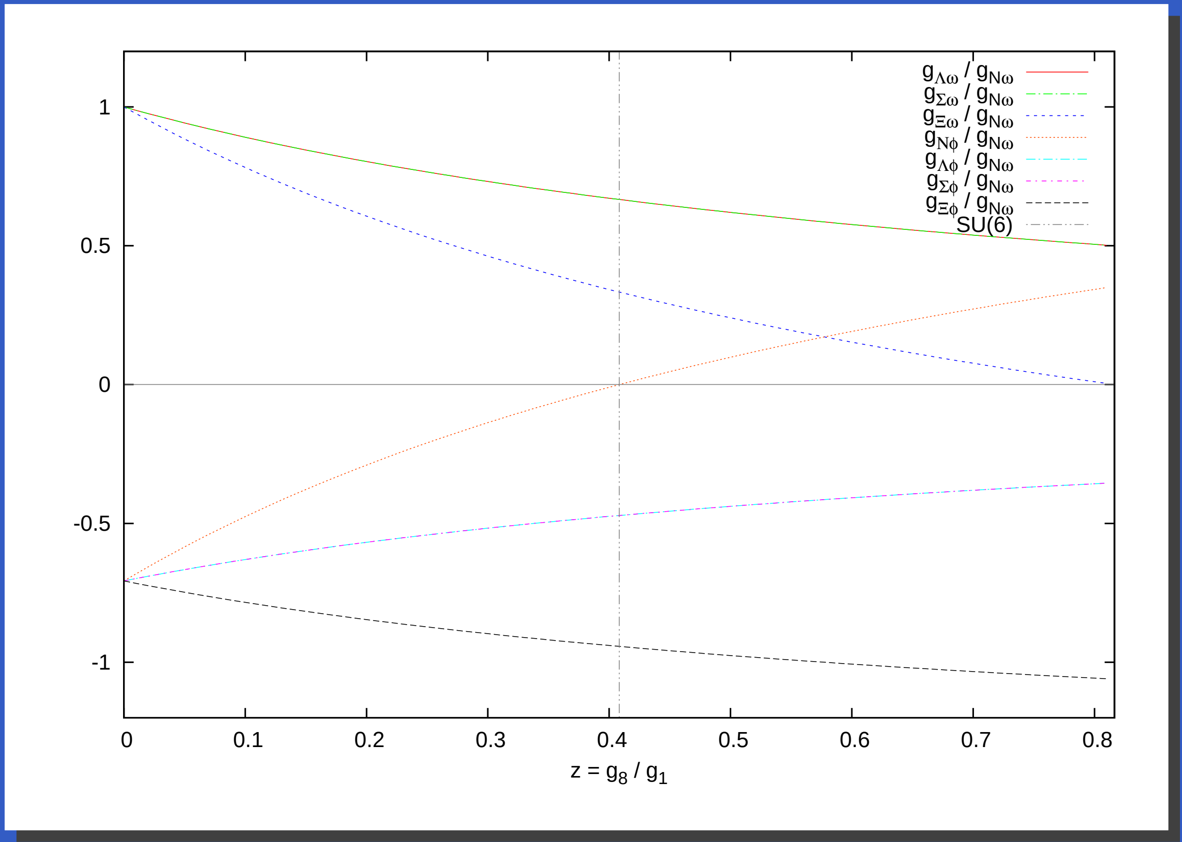
SU(3) symmetry

- consider Yukawa coupling of baryons with mesons in SU(3):
  coupling of two octets: $8 \otimes 8 = 1 \oplus 8_S \oplus 8_A \oplus 10 \oplus 10^* \oplus 27$
- general coupling scheme for baryon octet with mesons:

$$\mathcal{L}_{\mathrm{SU(3)}} = -g_8 \alpha \mathrm{Tr}([\bar{B}, B]M) + g_8(1-\alpha)\mathrm{Tr}(\{\bar{B}, B\}M) - g_1 \mathrm{Tr}(\bar{B}, B)\mathrm{Tr}(M)$$

- parameters: octet coupling constant g_8,
  $\alpha = F/(F+D)$ ratio (F: antisymmetric, D: symmetric coupling),
  singlet coupling constant g_1, meson nonet mixing angle θ
- SU(6) model: SU(3) flavour plus SU(2) spin symmetry
- spin independence of Λ and Σ vector coupling: $\alpha_V = 1$
- for vector nonet: ideal mixing $\tan\theta_V = 1/\sqrt{2}$ (ϕ meson: pure $s\bar{s}$ state)
- nucleon does not couple to ϕ mesons: $g_1 = \sqrt{6} g_8$
- everything fixed in terms of one (nucleon) coupling constant in SU(6)

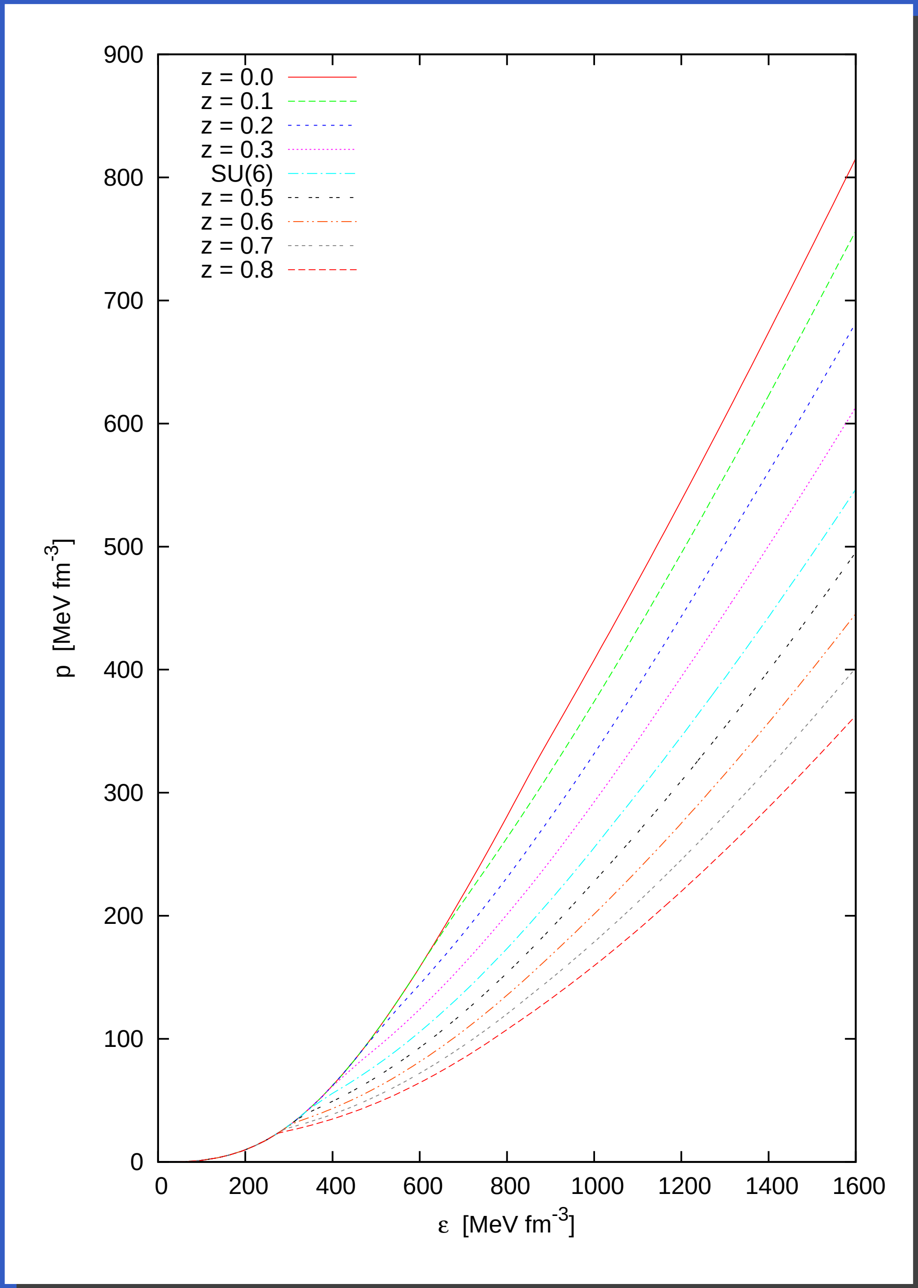
Varying hyperon coupling z: coupling constants



(Weissenborn, Chatterjee, JSB 2011)

- baryon coupling constants for different $z = g_8/g_1 = 0, \ldots 2/\sqrt{6}$
- SU(6) value: $z = 1/\sqrt{6} \approx 0.408$, equal coupling for $z = 0$
- always repulsive vector interactions except for $g_{N\phi}$
- Λ and Σ coupling constants are always equal

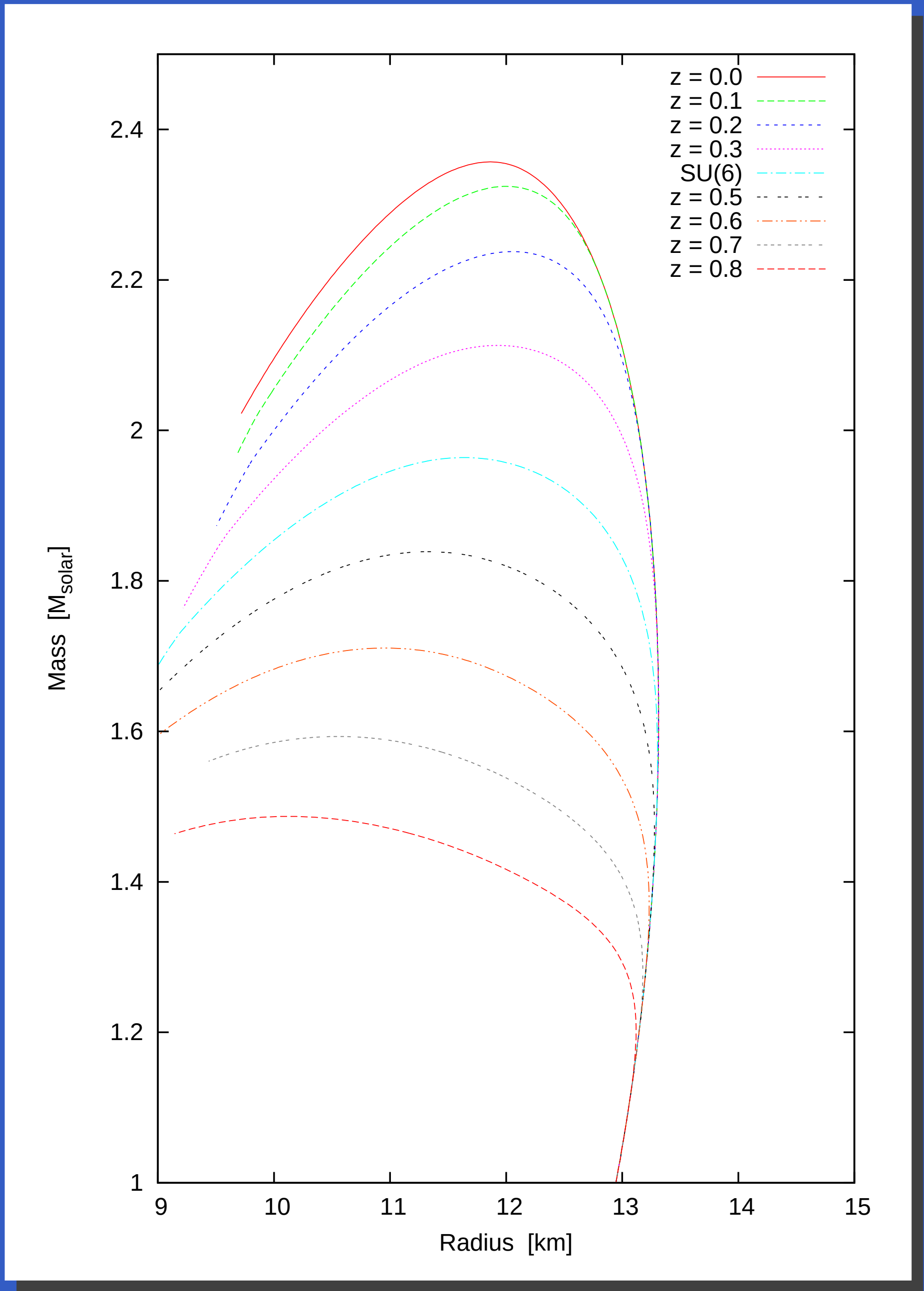
Varying hyperon coupling z: EoS



(Weissenborn, Chatterjee, JSB 2011)

- varying $z = 0, \ldots 2/\sqrt{6}$
- use set GM1 with model 1 + ϕ
- adjust scalar couplings to $U_\Sigma = +30$ MeV, $U_\Xi = -28$ MeV
- SU(6) value: $z = 1/\sqrt{6} \approx 0.408$
- always repulsive vector interactions except for $g_{N\phi}$

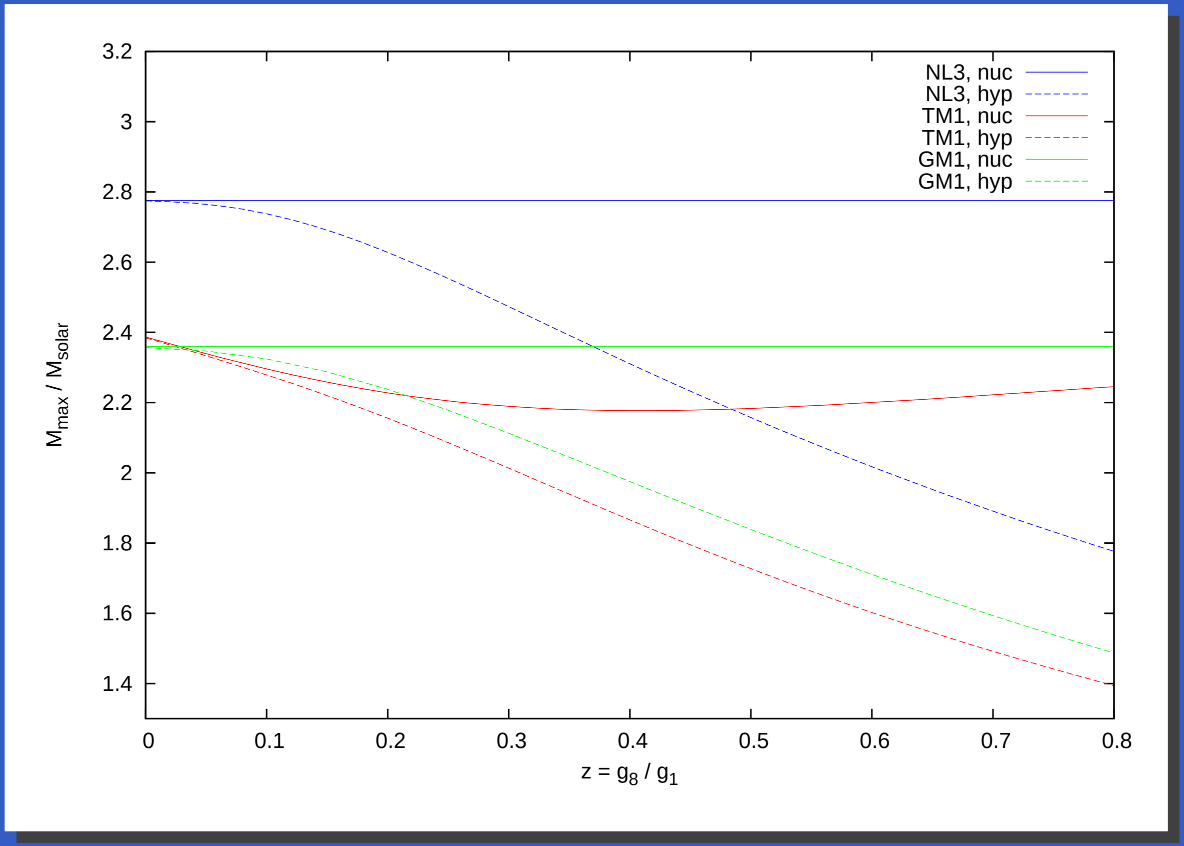
Varying hyperon coupling z for neutron stars



(Weissenborn, Chatterjee, JSB 2011)

- allow $z = g_8/g_1$ to vary
- use set GM1 with model 1 + ϕ
- mass-radius relation for different $z = 0, \ldots 2/\sqrt{6}$ (repulsive vector interactions except for $g_{N\phi}$)
- SU(6) value: $z = 1/\sqrt{6} \approx 0.408$
- drastic difference in maximum mass

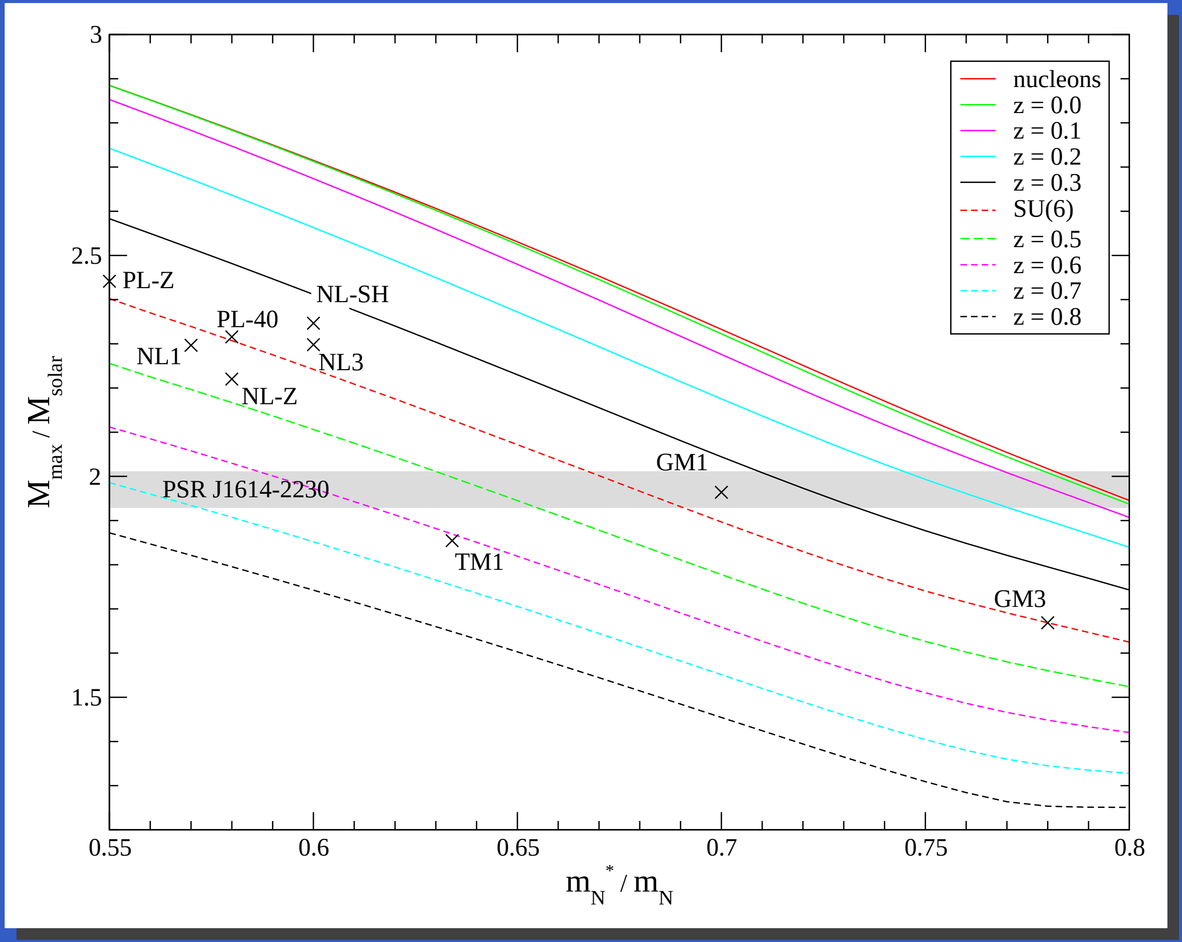
Maximum mass with hyperons for different z



(Weissenborn, Chatterjee, JSB 2011)

- maximum mass with varying hyperon couplings $z = g_8/g_1$
- different RMF parameter sets
- continous drop in maximum mass with increasing z
- values of $M > 2M_\odot$ possible

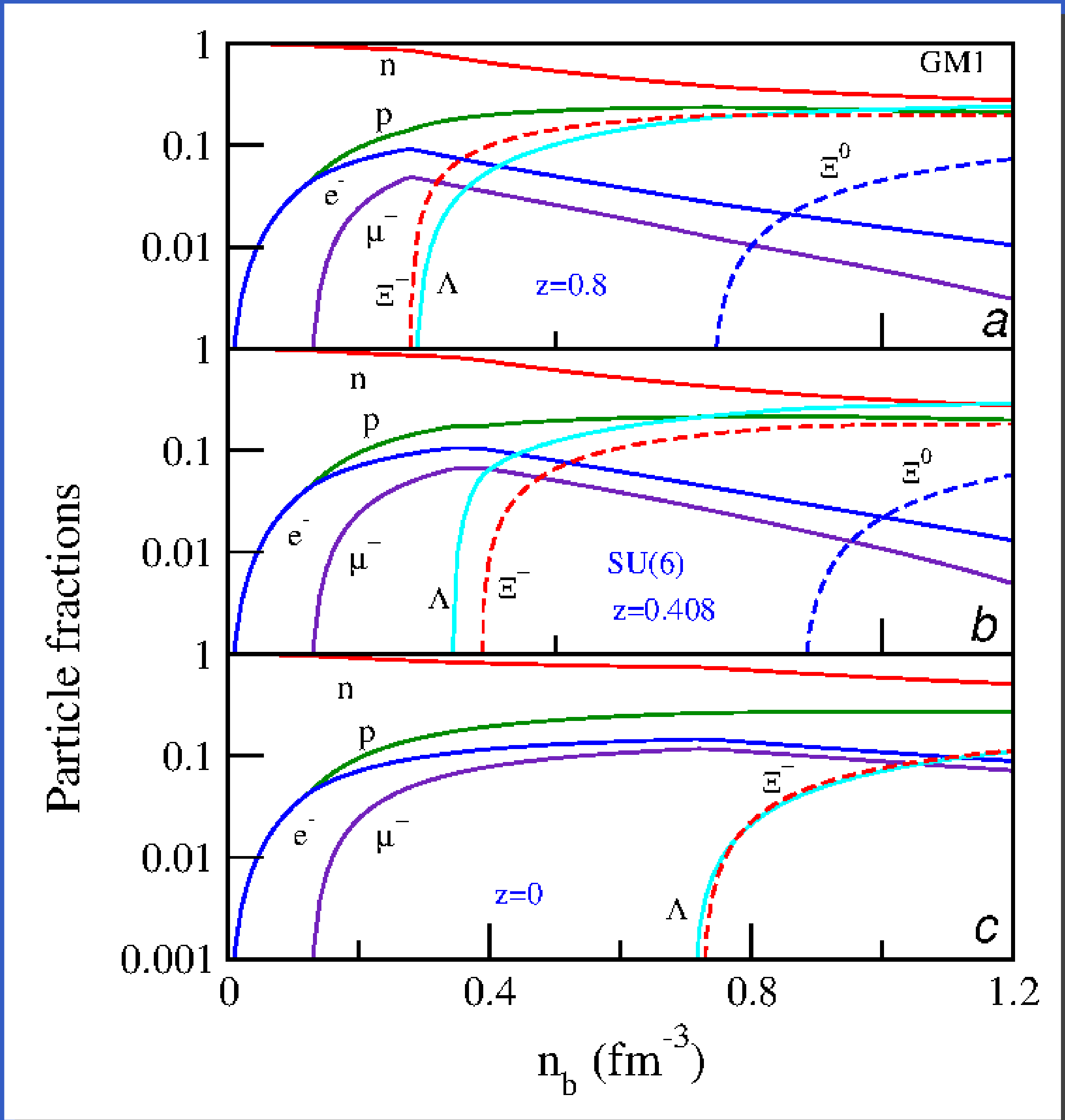
Maximum mass with hyperons



(Weissenborn, Chatterjee, JSB 2011)

- maximum mass for different effective masses of RMF parameter sets
- crosses: parameter sets with standard SU(6) baryon couplings
- values of $M > 2M_{\odot}$ possible with hyperons for stiff nuclear EoS

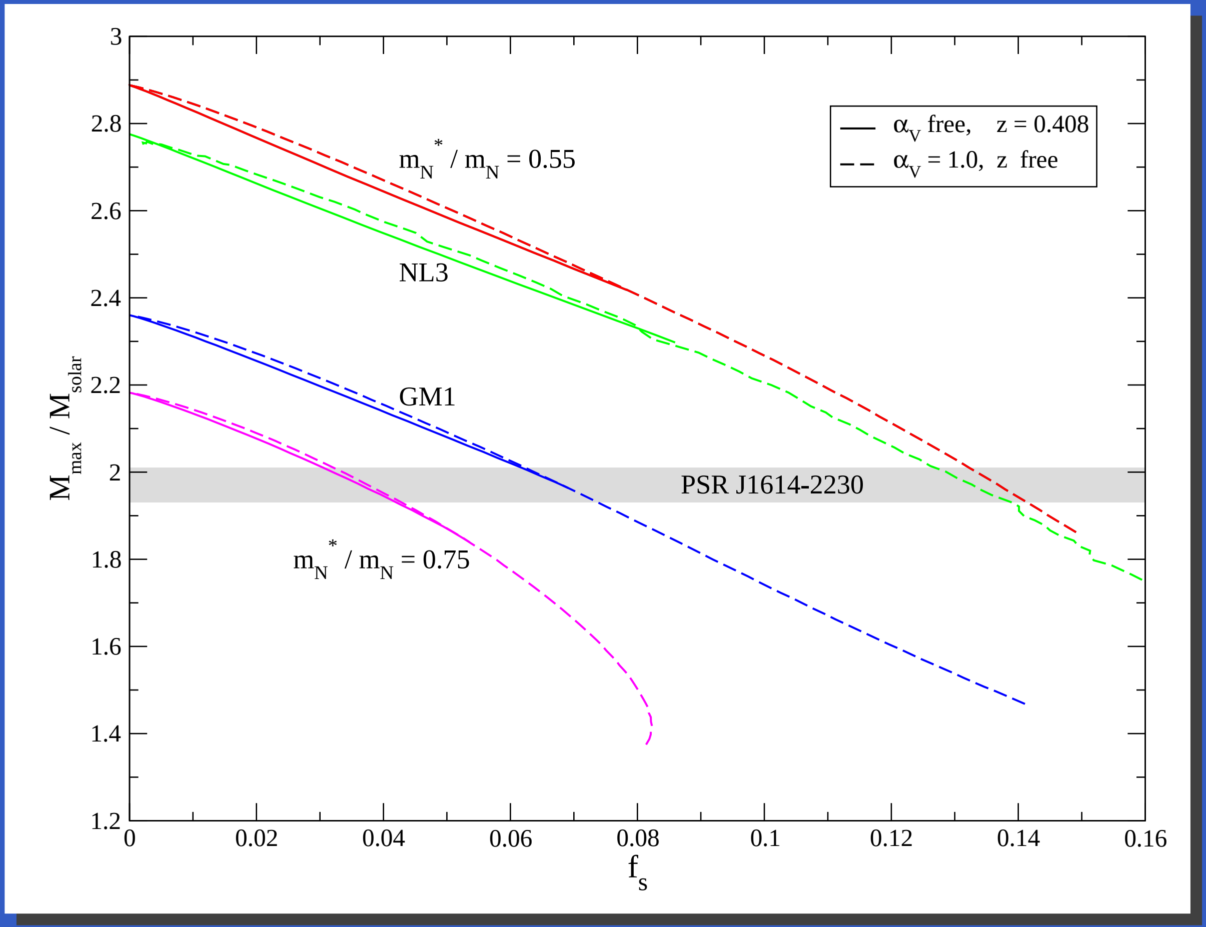
Neutron Stars with Hyperons: Composition



(Weissenborn, Chatterjee, JSB 2012)

- hyperons within RMF model: couples to scalar and vector fields
- scalar coupling: fixed by hyperon potential depths (hypernuclei)
- vector coupling: controlled by SU(3) symmetry, vary singlet to octet strength: $z = g_8/g_1$

Neutron Star Masses and Strangeness Fraction

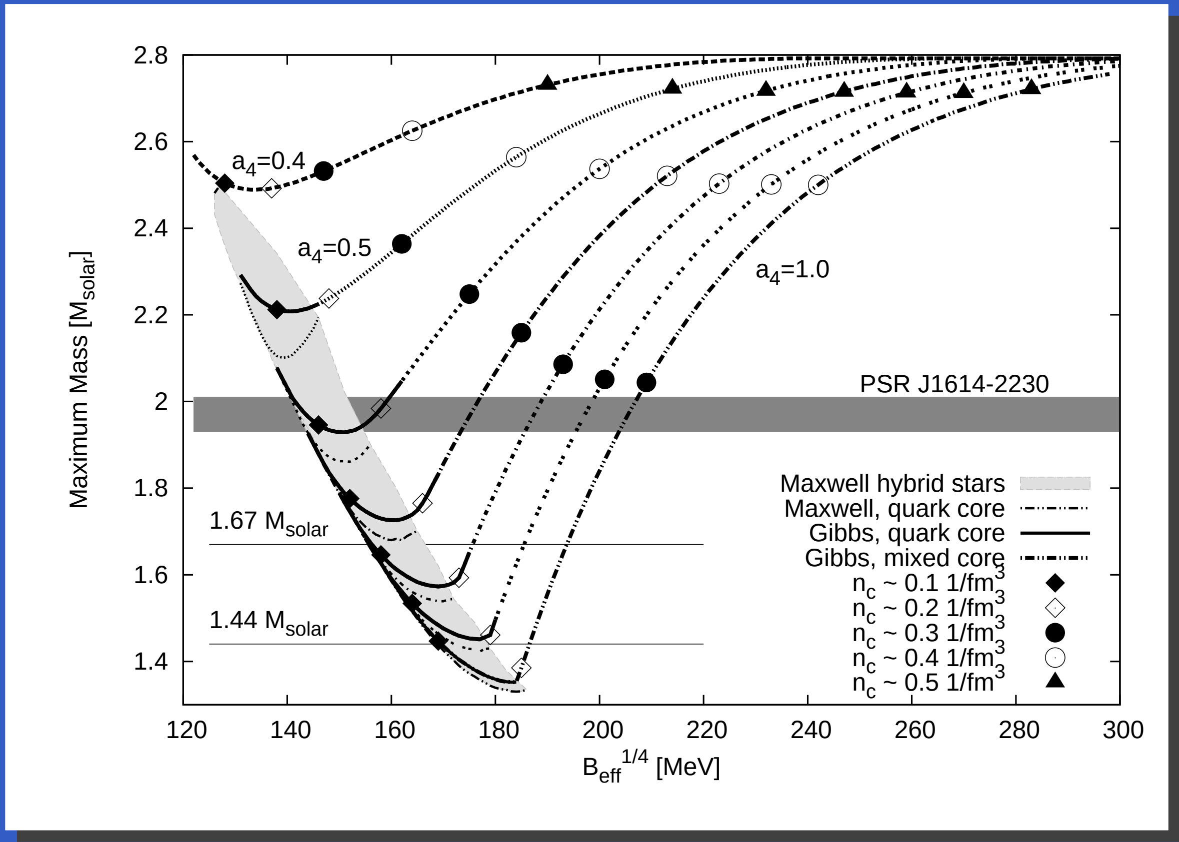


(Weissenborn, Chatterjee, JSB 2012)

- RMF model for different nuclear parameter sets and hyperon coupling
- neutron star maximum mass versus the strangeness fraction f_s
- unique relation: $M_{\max}(f_s) = M_{\max}(0) - 0.6 M_\odot (f_s/0.1)$

Rescue the hyperons III: add quark matter?

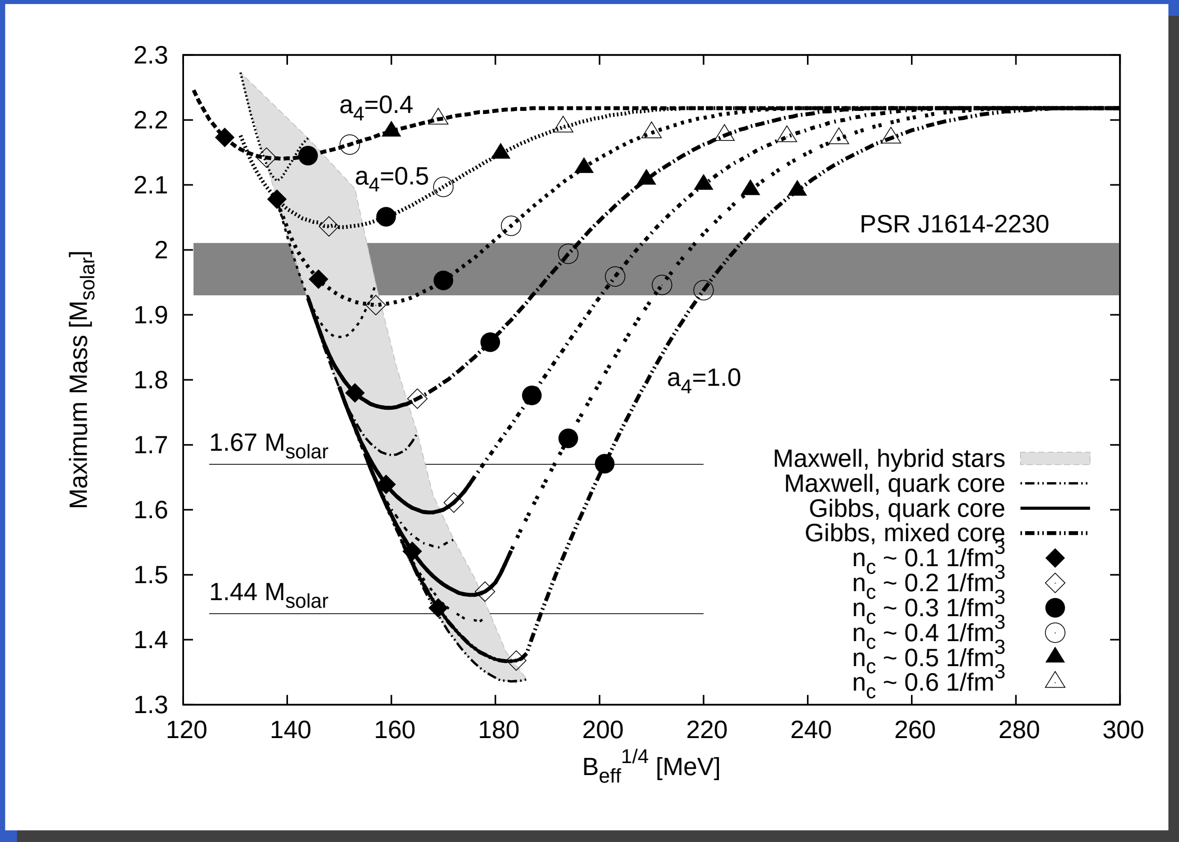
Hybrid Stars with a stiff nuclear EoS



(Weissenborn, Sagert, Pagliara, Hempel, JSB 2011)

- nuclear phase: relativistic mean field model with parameter set NL3 (fitted to properties of nuclei)
- match with Gibbs (lines) or Maxwell construction (shaded area)
- solid lines: pure quark matter cores, dashed lines: mixed phase cores

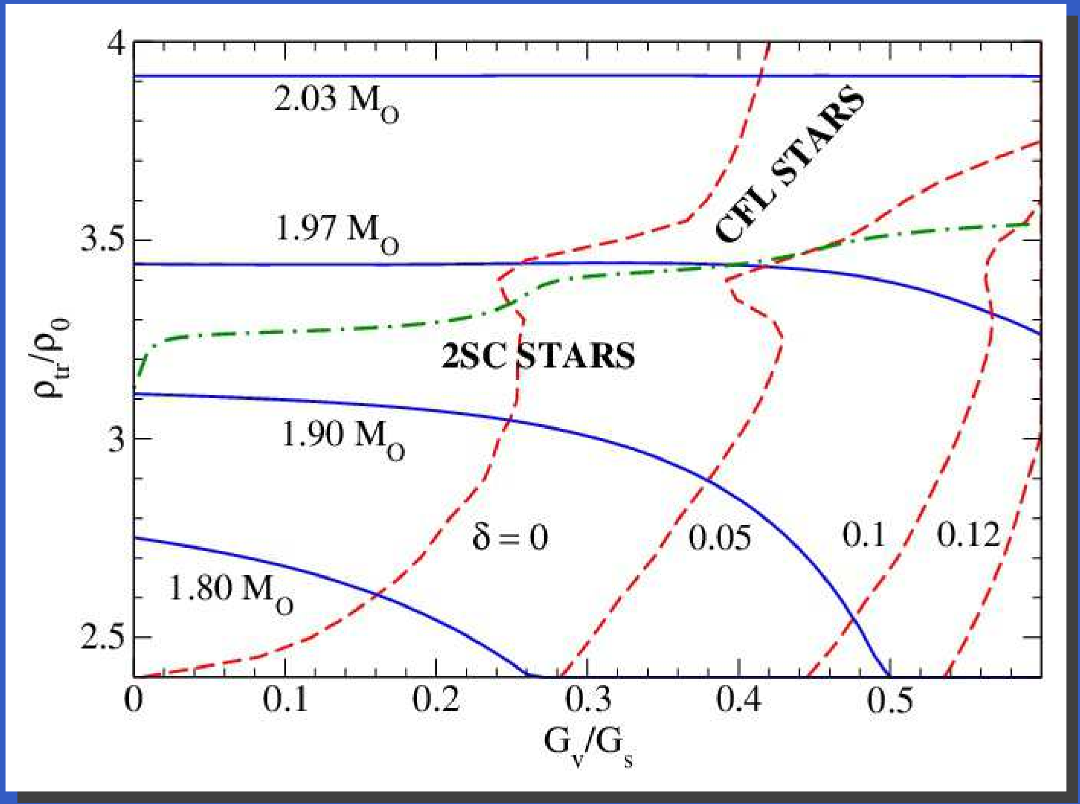
Hybrid Stars with a soft nuclear EoS



(Weissenborn, Sagert, Pagliara, Hempel, JSB 2011)

- nuclear phase: relativistic mean field model with parameter set TM1 (fitted to properties of nuclei)
- match with Gibbs (lines) or Maxwell construction (shaded area)
- solid lines: pure quark matter cores, dashed lines: mixed phase cores
- no pure quark cores compatible with data for a soft nuclear EoS

Hybrid Stars with a NJL model

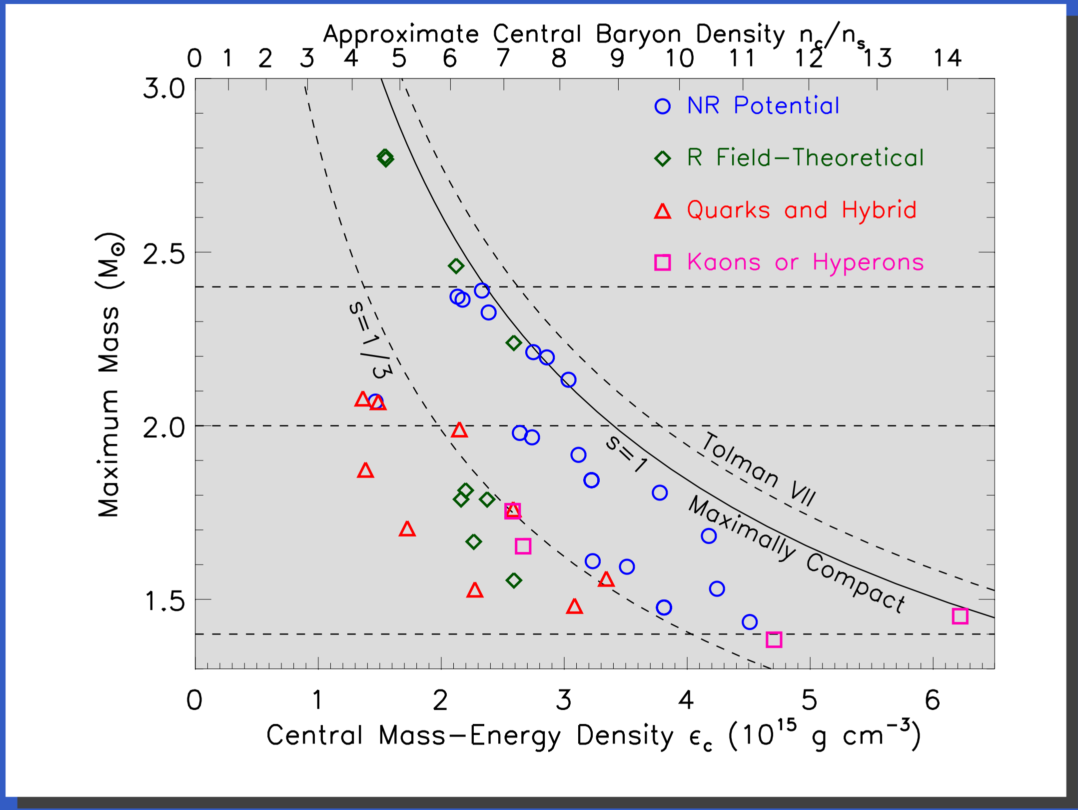


(Bonanno and Sedrakian 2011)

- uses Nambu-Jona-Lasinio model for quark matter
- matches to nuclear EoS with hyperons (RMF with set NL3)
- 2SC quark matter below green line
- $\delta = R_{\mathrm{CFL}}/R$: amount of CFL quark matter

What is the maximum possible neutron star mass?

Maximum central density of a compact stars

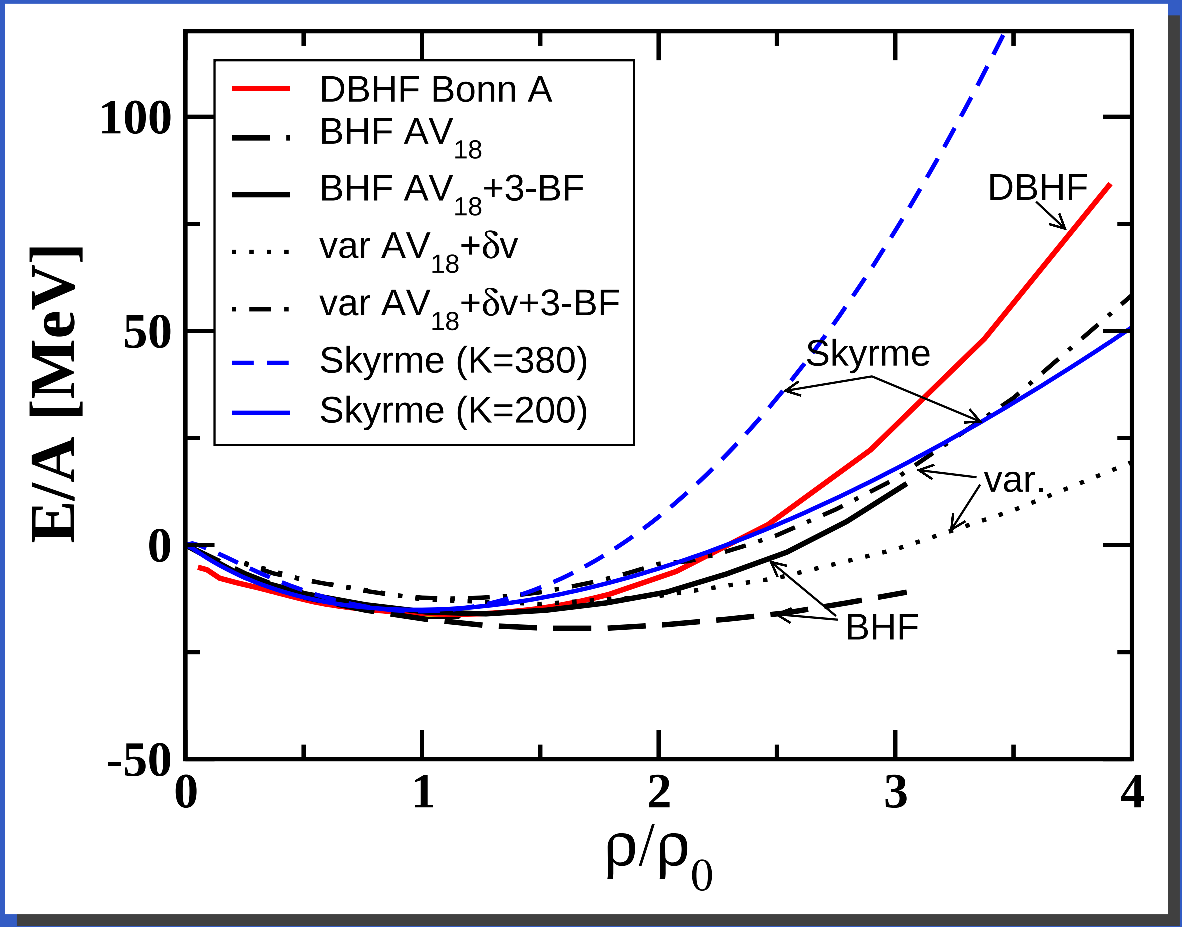


(Lattimer and Prakash 2011)

- maximally compact EoS: $p = s(\epsilon - \epsilon_c)$ with $s = 1$
- stiffest possible EoS (Zeldovich 1961)
- gives upper limit on compact star mass: $M_{\max} = 4.2 M_\odot (\epsilon_{\mathrm{sat.}}/\epsilon_f)^{1/2}$

  (Rhoades and Ruffini 1974, Hartle 1978, Kalogera and Baym 1996, Akmal, Pandharipande, Ravenhall 1998)

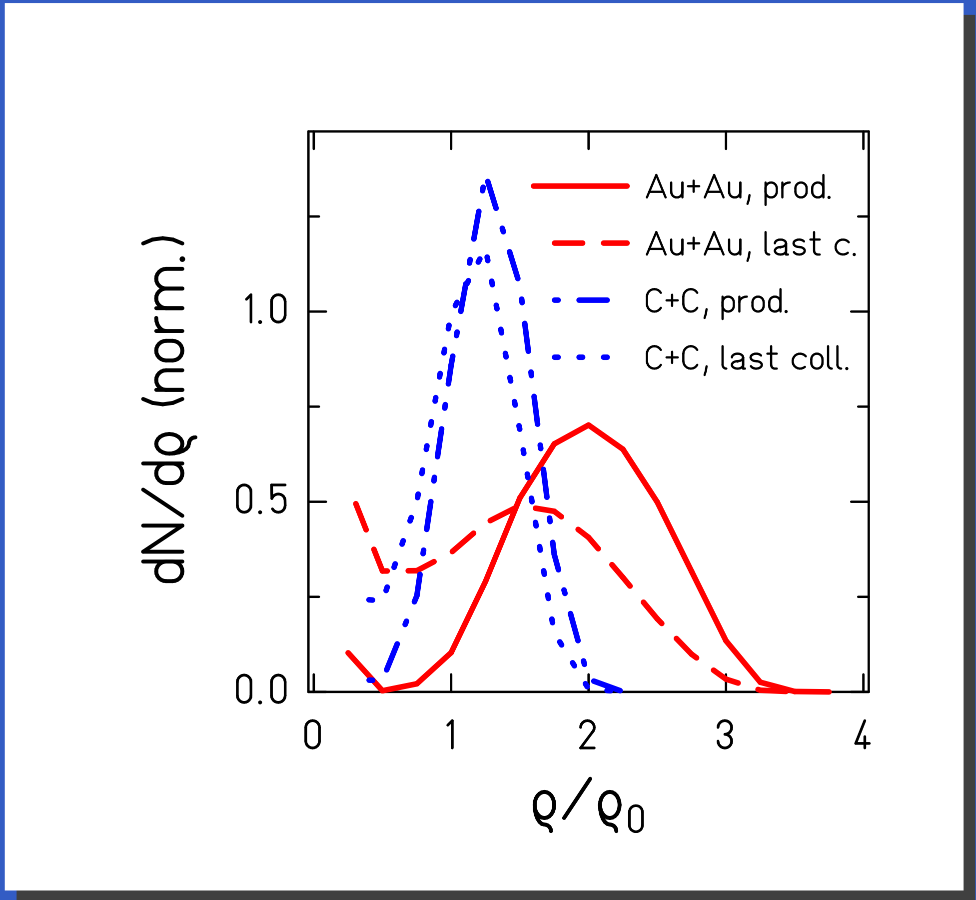
Input to transport models: the nucleon potential



(Fuchs 2006)

- crucial input to control the amount of compression: the nucleon potential
- study two extreme cases using the Skyrme model
- hard EoS: stiffness parameter $K = 380$ MeV, soft EoS: $K = 200$ MeV

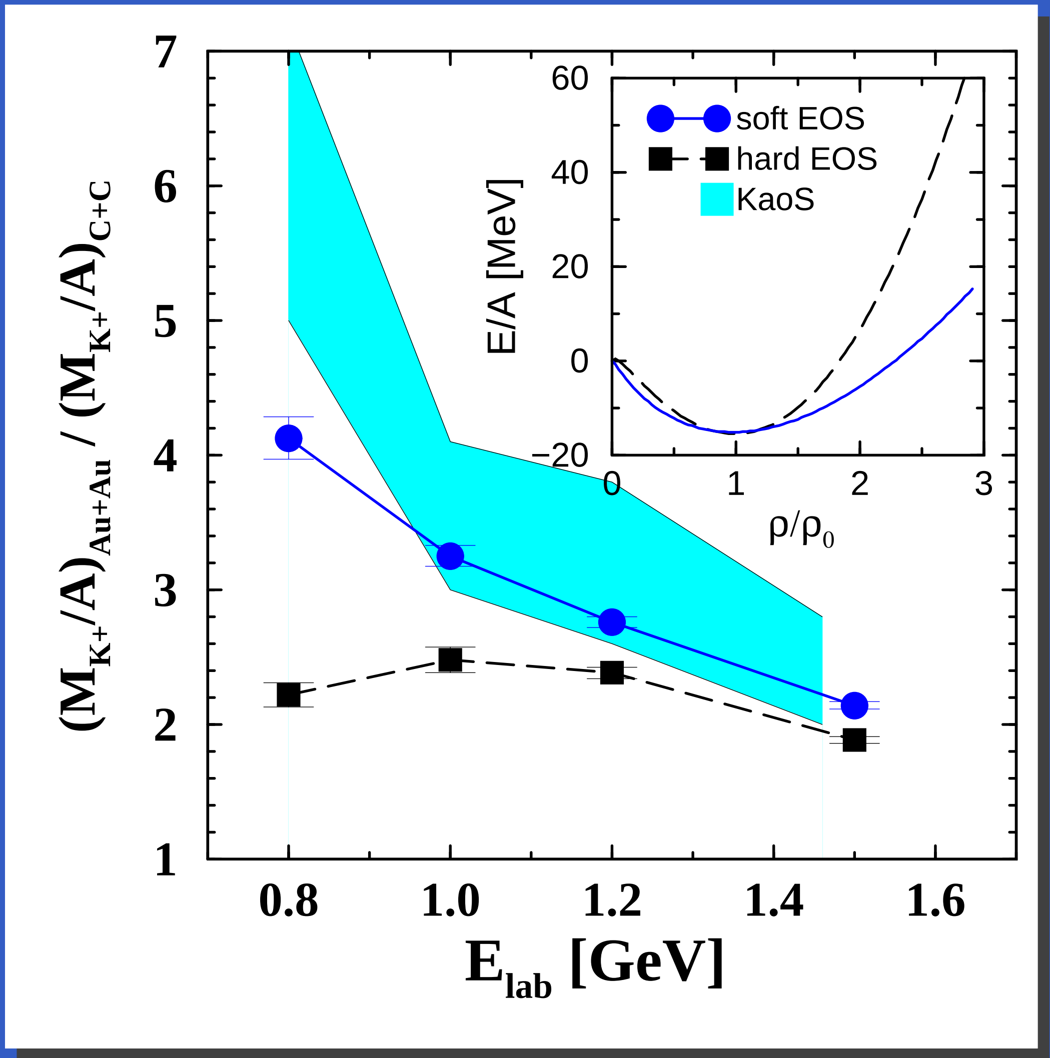
Heavy-ion collisions: density range probed with kaons



(Hartnack, Oeschler, Leifels, Bratkovskaya, Aichelin 2012)

- kaon production by associated production: NN$\rightarrow$ $\mathrm{N\Lambda}$K, NN$\rightarrow$NNK$\overline{\mathrm{K}}$
- produced in a baryon-rich medium at densities of $2n_0$ up to $3n_0$
- long mean-free path of kaons: escape from the high-density region

Kaon production in heavy-ion collisions

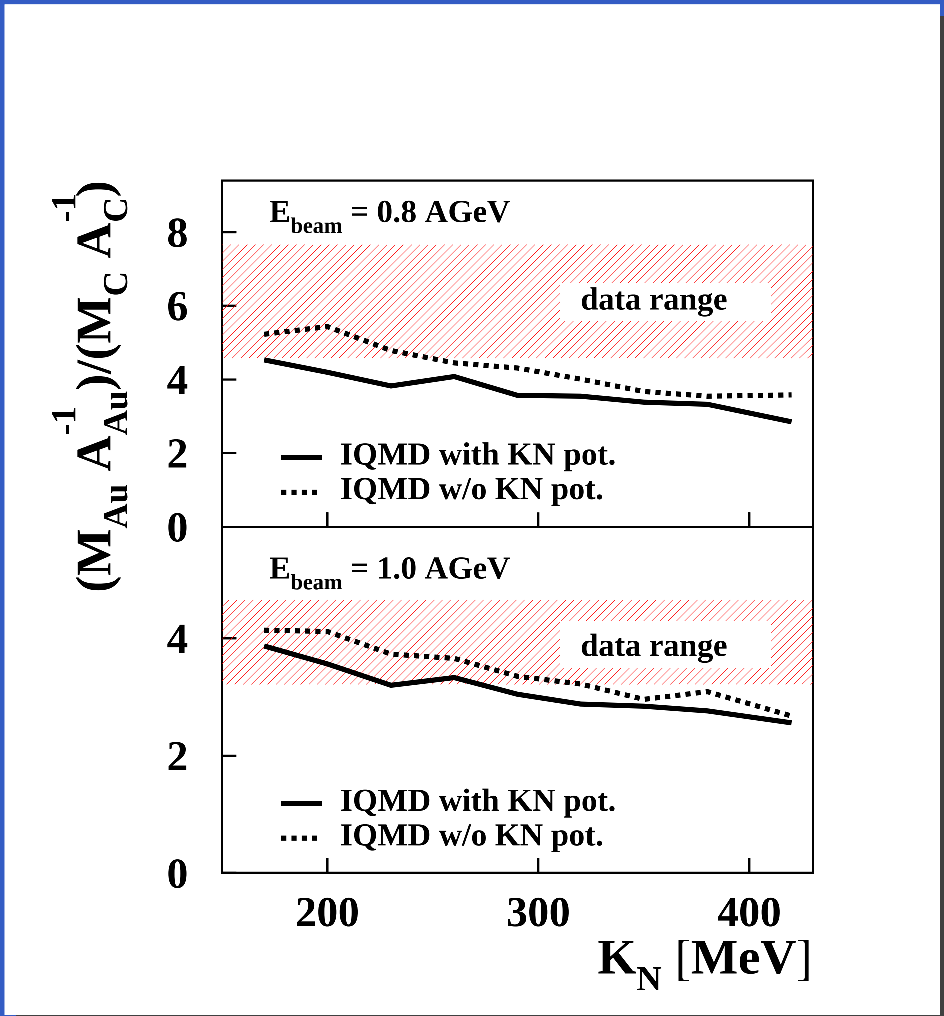


Sturm et al. (KaoS collaboration), PRL 2001

Fuchs, Faessler, Zabrodin, Zheng, PRL 2001

- nuclear matter is compressed up to $2 - 3n_0$!
- long mean-free path of kaons: kaons can escape high density matter
- clear trend indicating high compression
  $\rightarrow$ a soft EoS

Confirmed KaoS data analysis: the nuclear EoS is soft!



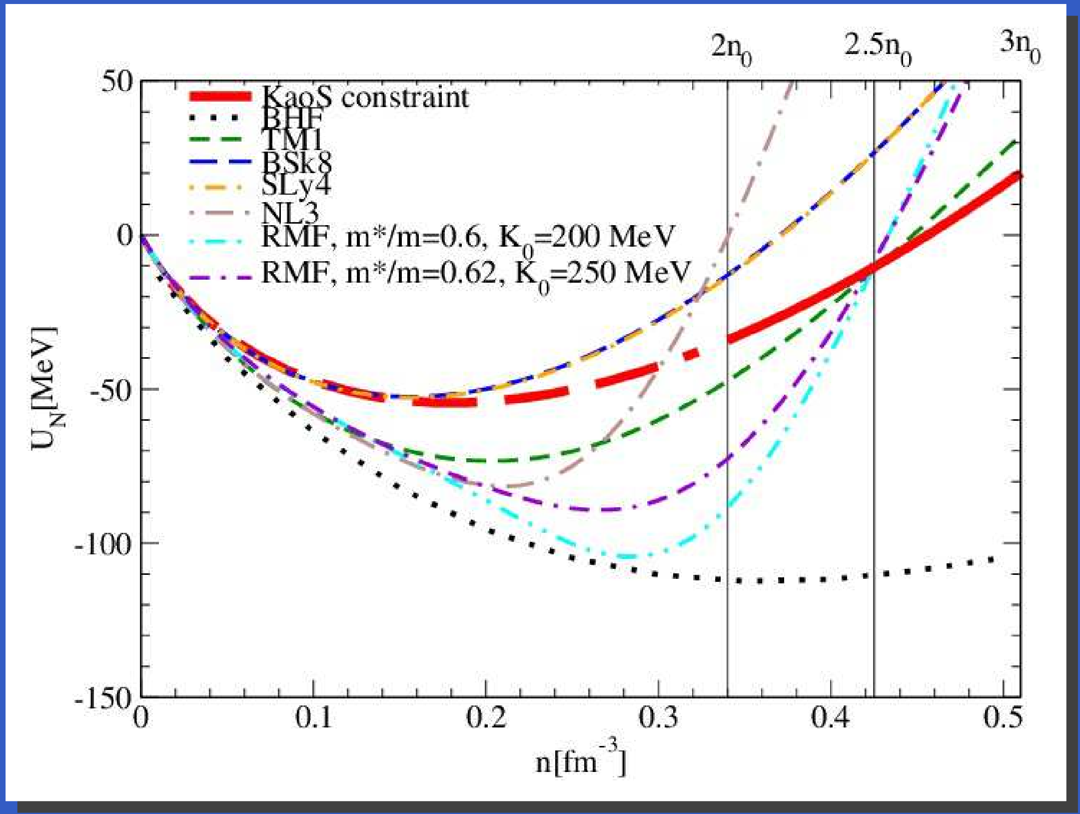
Forster et al. (KaoS collaboration) 2007

Hartnack, Oeschler, Aichelin, 2006

- kaon production (K^+) far below threshold
- double ratio: multiplicity per mass number for C+C collisions and Au+Au collisions at 0.8 AGeV and 1.0 AGeV
- only calculations with a compression modulus of $K_N \approx 200$ MeV and smaller can describe the data

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

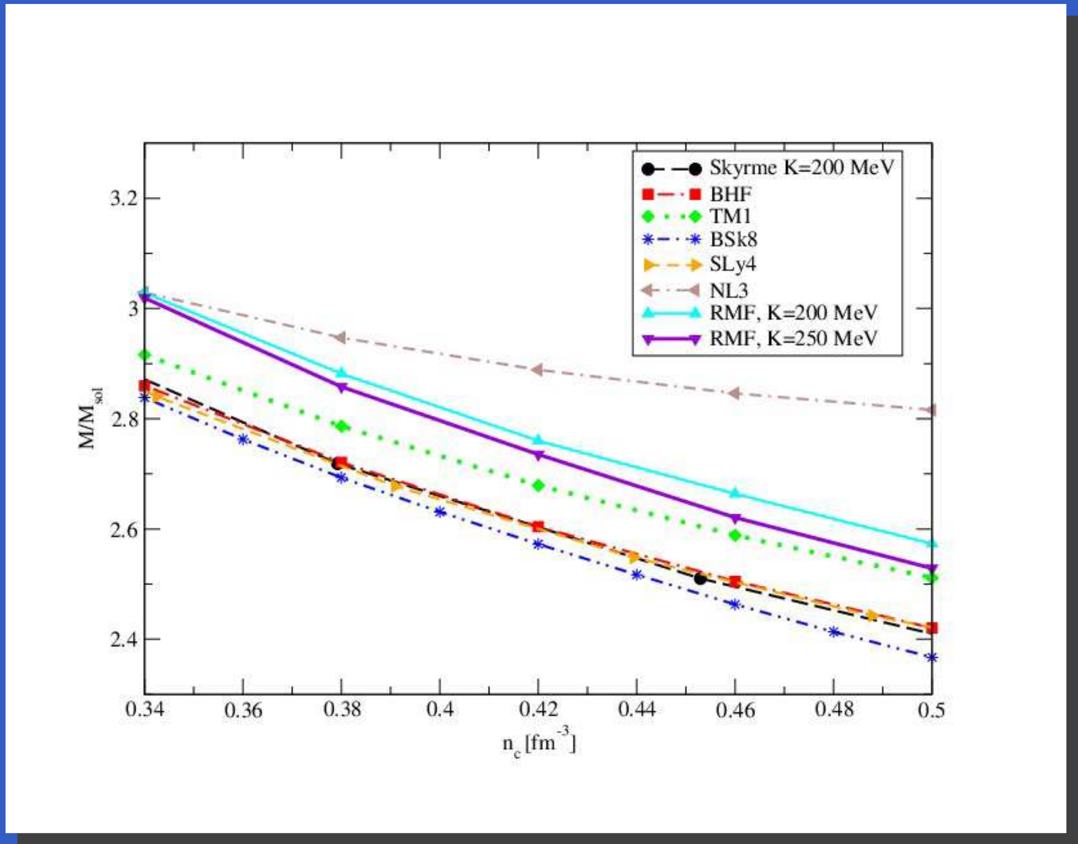
Constraint from heavy-ion data: nucleon potential at $2 - 3n_0$



(Sagert, Tolos, Chatterjee, JSB, Sturm 2012)

- input to transport simulations: nucleon potential
- kaon production is sensitive to densities of $n = 2 - 3n_0$ ($n_0 = 0.17$ fm^{-3})
- constraint: nucleon potential must be below the curve for the Skyrme model with $K = 200$ MeV at a fiducial density of $n_f = 2 \ldots 3n_0$

Constraint for neutron stars: causality plus heavy-ion



(Sagert, Sturm, Chatterjee, Tolos, JSB 2011)

- maximum mass for neutron stars versus the fiducial density
- same trend for the various nuclear models
- main difference: the density dependence of the asymmetry energy
- upper limit of a maximum mass of $M_{max} = 3M_\odot$ for $n_f = 2n_0$

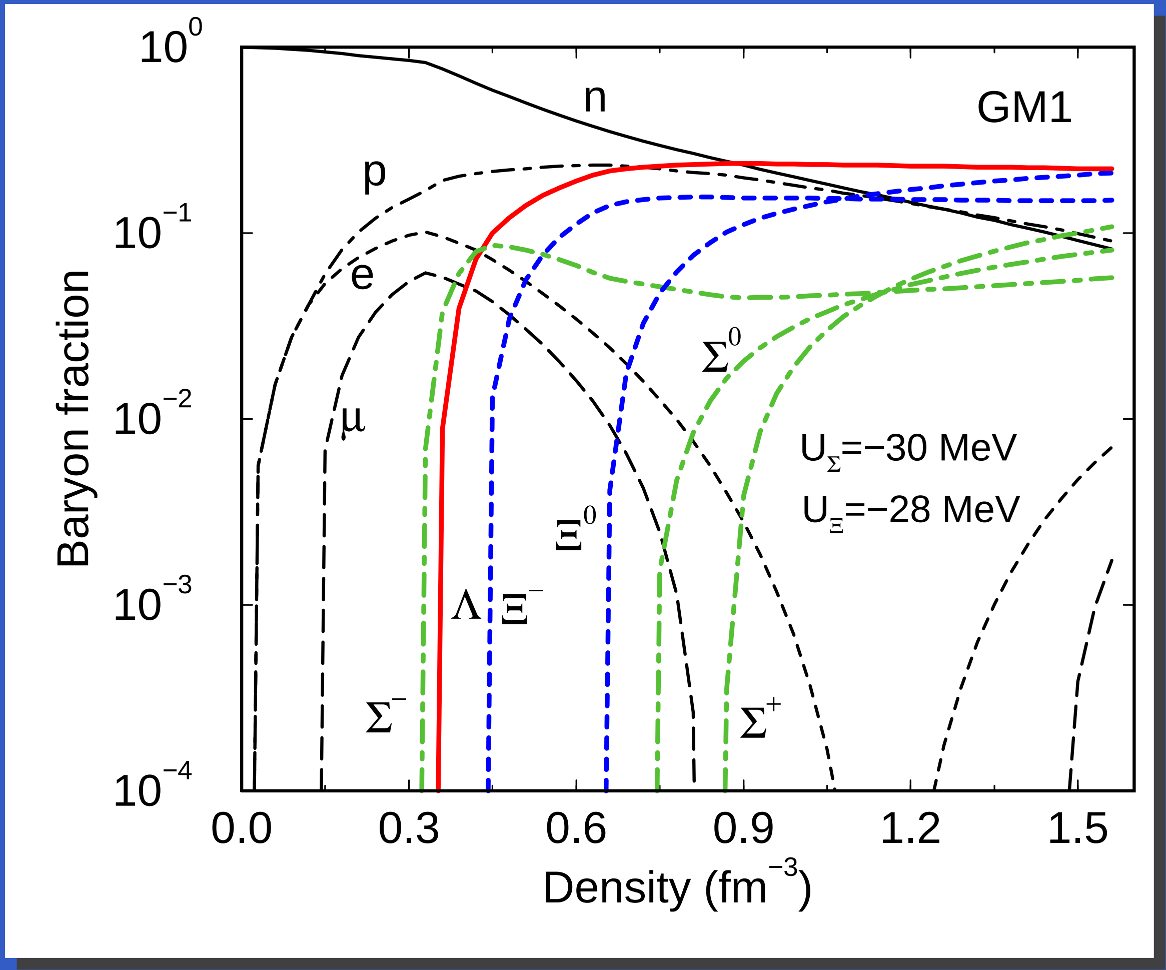
Summary:

- hyperons can substantially soften the EoS
- hyperons can substantially reduce the maximum mass of neutron stars
- too low masses in modern many-body models
- rescue the hyperons in neutron stars:
  - make hyperon potentials repulsive: does not really work
  - add ϕ mesons and break SU(6) symmetry: works
    $\Longrightarrow$ limits on the amount of hyperons in neutron stars
  - add quark matter in the core: works
    $\Longrightarrow$ both nuclear and quark matter must be stiff
- constraints from causality and heavy-ion data: new firm upper mass limit for neutron stars of $3M_\odot$!

Thanks to:

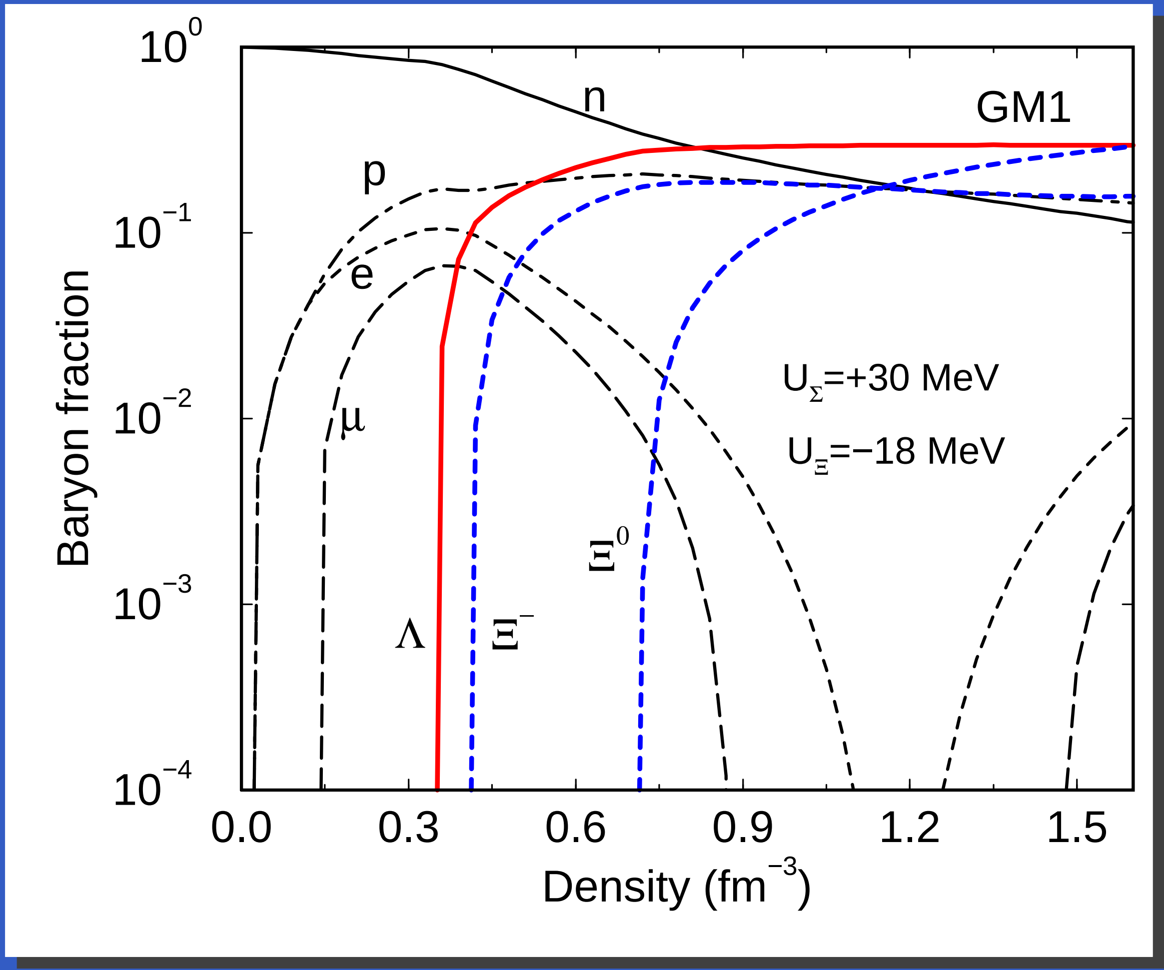
- Simon Weissenborn (Heidelberg)
- Debarati Chatterjee (Heidelberg)
- Giuseppe Pagliara (Ferrara)
- Matthias Hempel (Basel)
- Irina Sagert (Michigan State)
- Christian Sturm (GSI Darmstadt)
- Laura Tolos (Barcelona)

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



- 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!

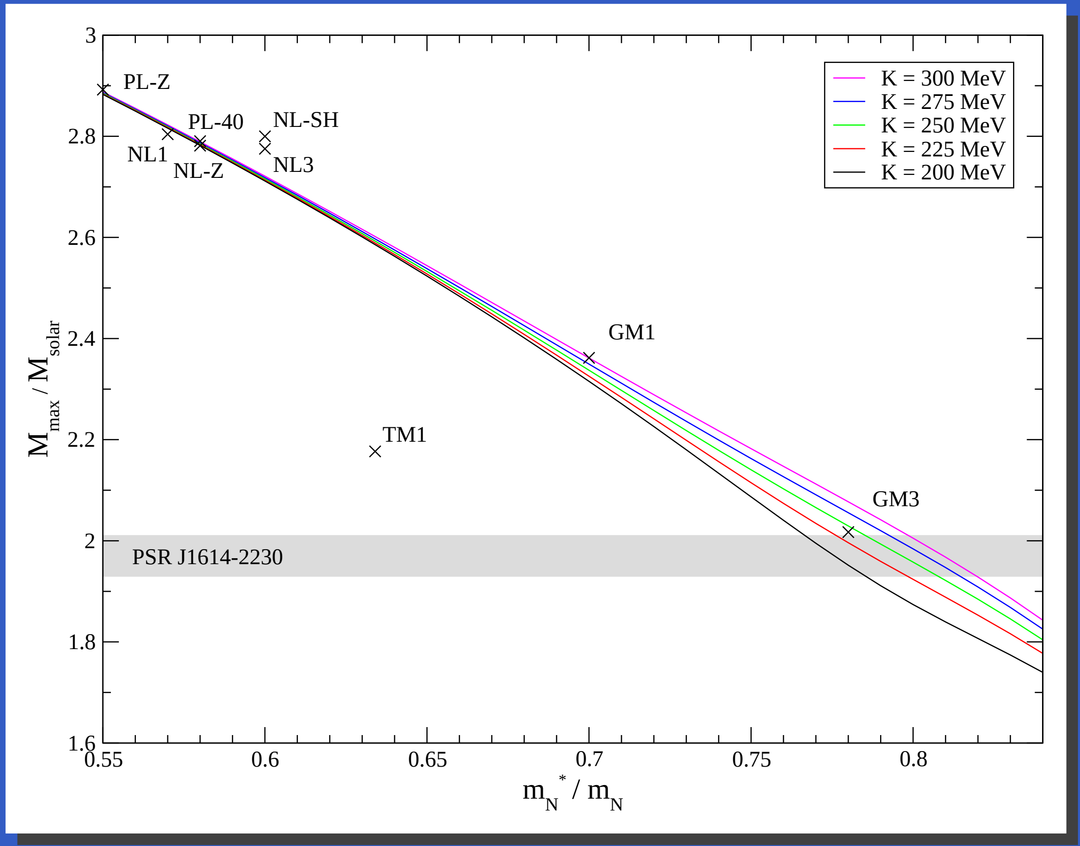
Spin–orbit splitting of hypernuclei: theory

Simple Quark Model (SU(6) symmetry):

- in quark picture: $\Lambda = (uds)$, where the u- and d-quark couple to spin zero
- nucleon couples only to u- and d-quarks: no spin-orbit term!
- for $\Sigma^0 = (uds)$ u- and d-quarks couple to spin one $\rightarrow$ big spin-orbit splitting!
- for $\Xi^- = (dss)$ or $\Xi^0 = (uss)$ nucleon couples to one light quark only $\rightarrow$ same spin-orbit strength as for nucleons
- summary: spin-orbit strength goes as $N : \Lambda : \Sigma : \Xi = 1 : 0 : 2 : 1$

Relativistic potentials and SU(6) symmetry: cancellation effect due to large tensor term for Λs (Jennings 1990)

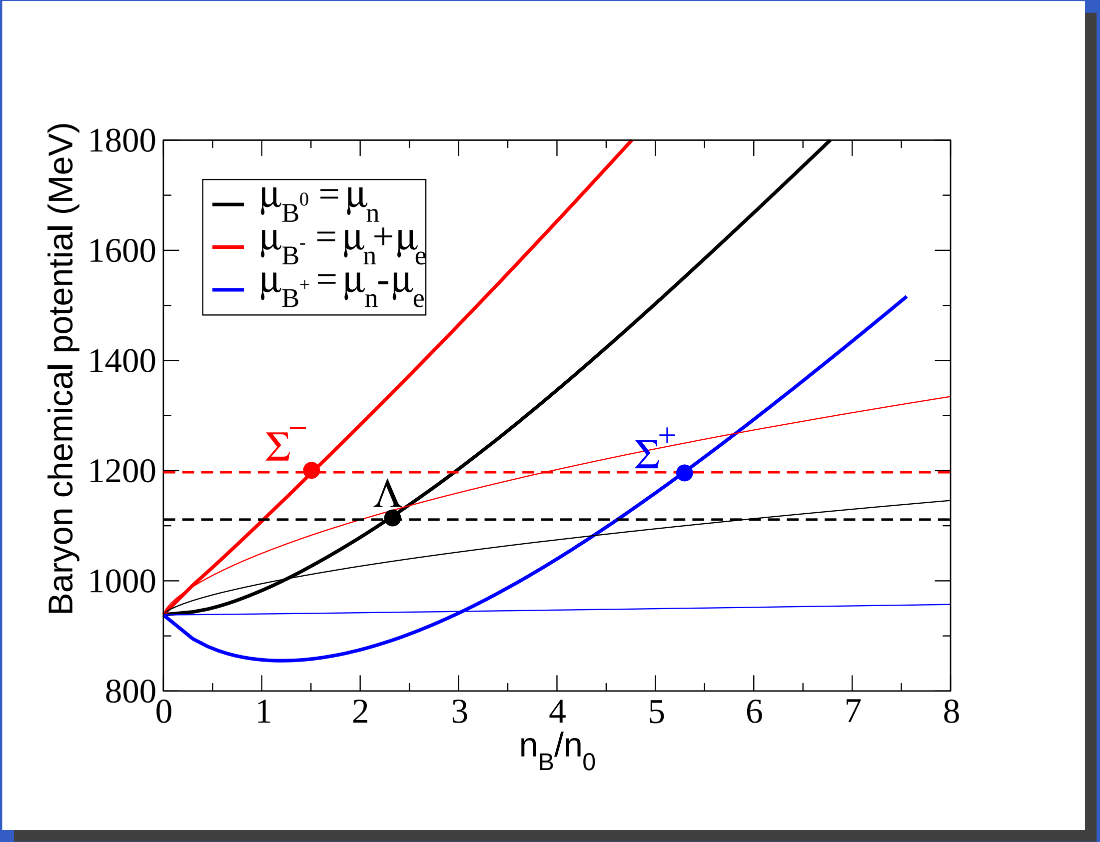
Maximum mass without hyperons (nucleons only)



(Weissenborn, Chatterjee, JSB 2011)

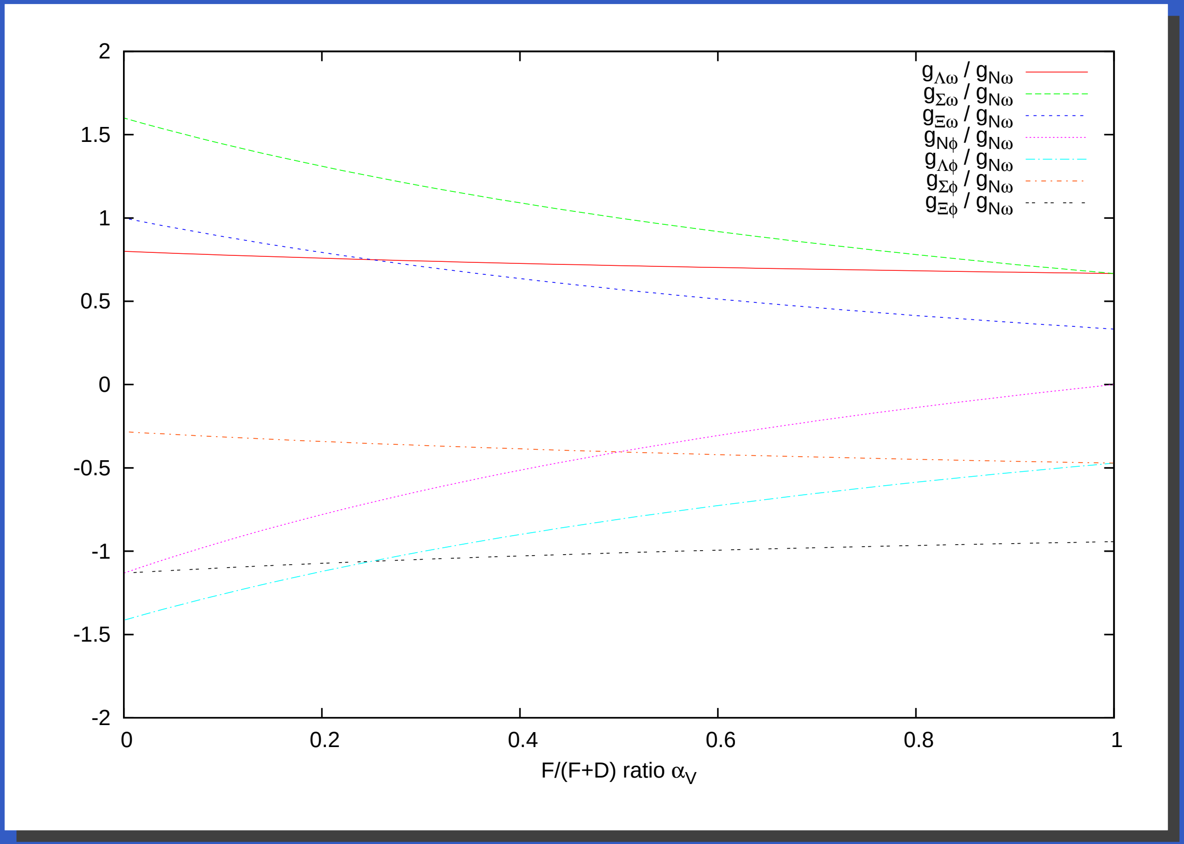
- maximum mass for different effective masses m^*/m and compressibility K
- change in maximum mass for different compressibilities: at most $0.1 M_\odot$
- change in maximum mass for different m^*/m: up to $1 M_\odot$!
- values of $M > 2M_\odot$ possible for reasonable values of m^*/m

At which density do new particles appear? (Page and Reddy (2006))



- hyperons appear, when its in-medium energy equals its chemical potential:
  $\mu(Y) = \omega(Y) = m_Y + U_Y(n)$ with $\mu(Y) = B(Y) \cdot \mu_n - Q(Y) \cdot \mu_e$
- thin lines: free gas, thick lines: with mean-field NN potential
- note: horizontal lines are hyperon vacuum masses, onset of hyperons will change due to YN potentials

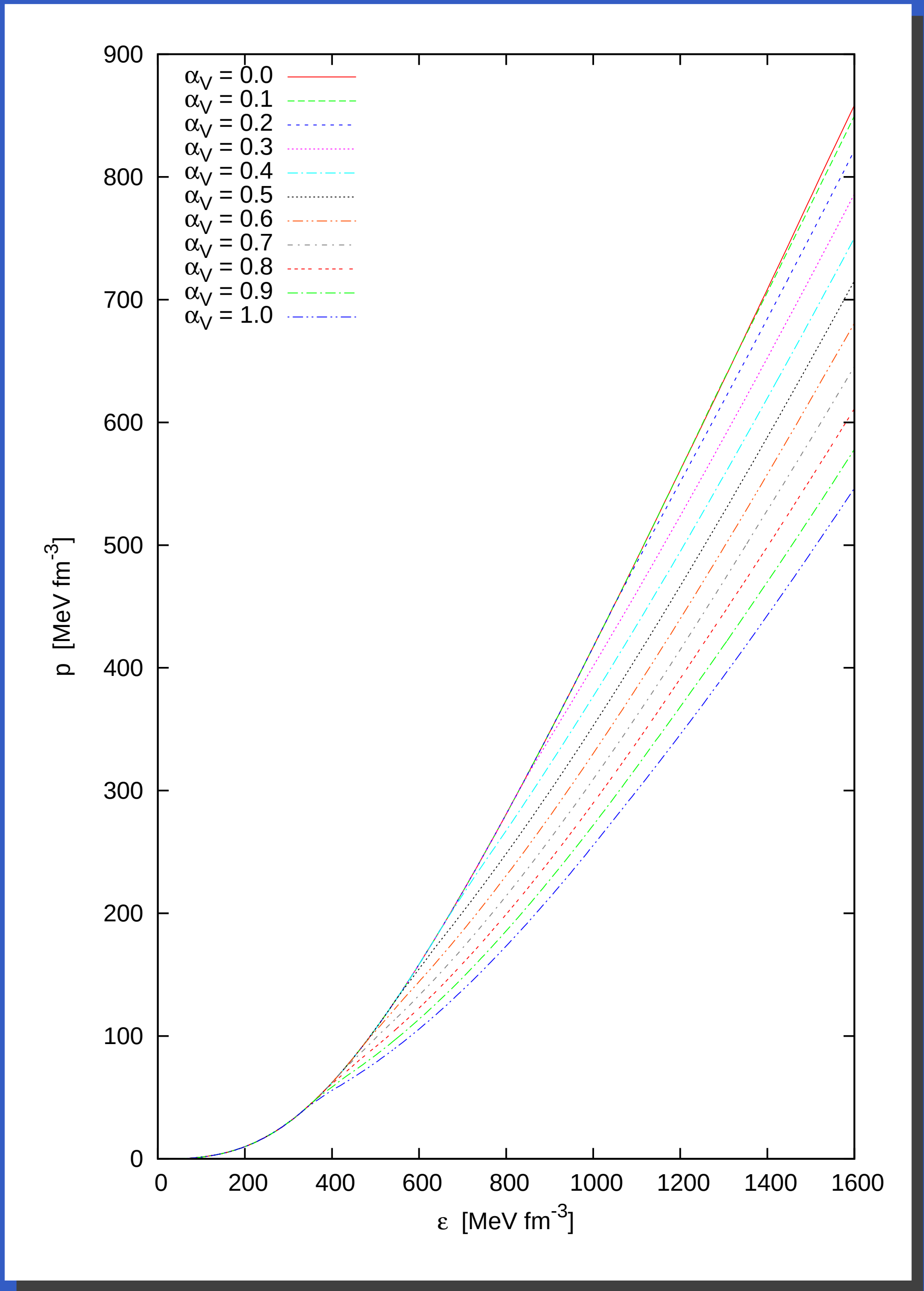
Varying hyperon coupling α_v: coupling constants



(Weissenborn, Chatterjee, JSB 2011)

- baryon coupling constants for different $\alpha_v = 0, \ldots 1$
- SU(6) value: $\alpha_v = 1$
- always repulsive vector interactions
- $\Lambda\omega$ coupling constant does not change

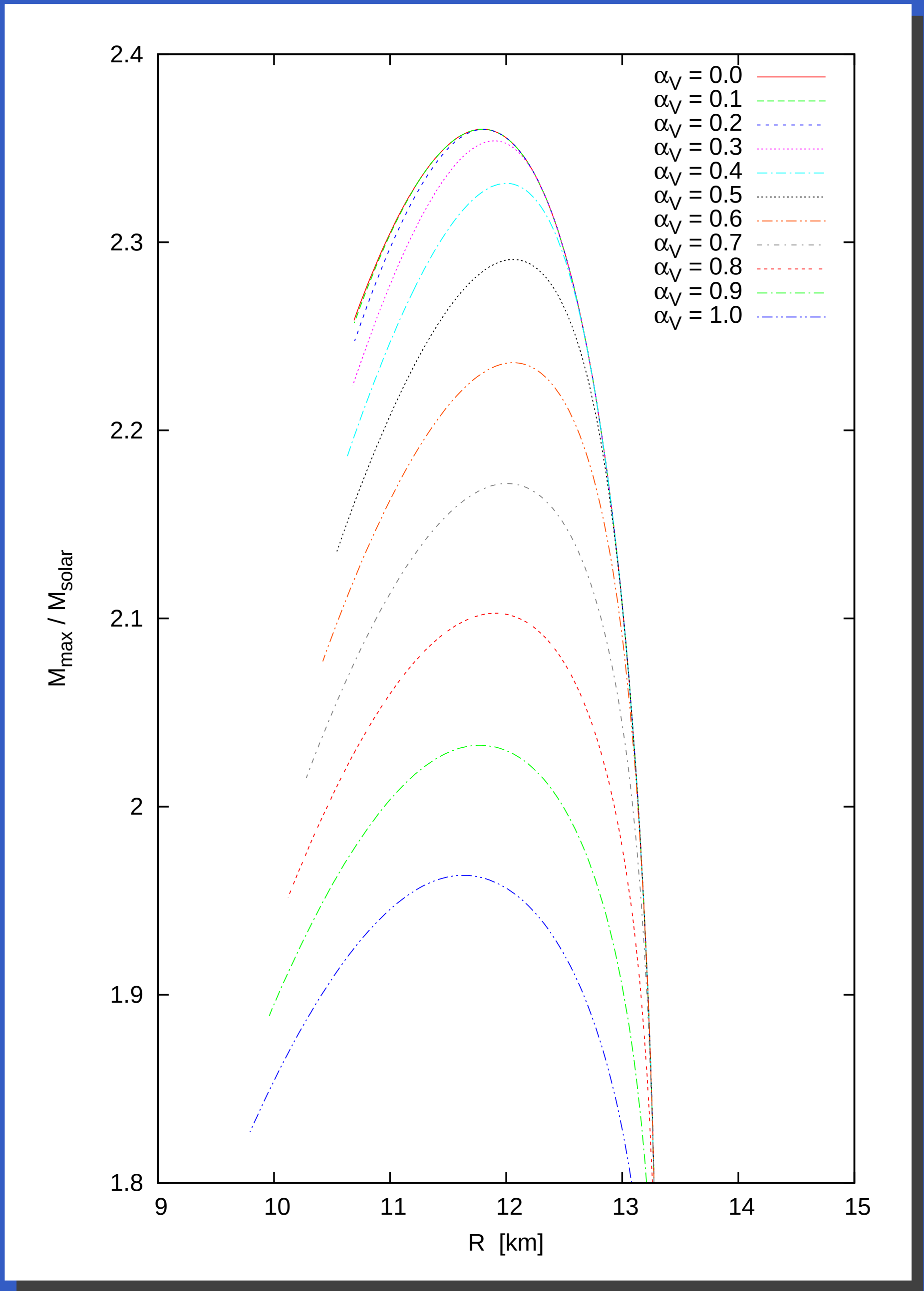
Varying hyperon coupling α_v: EoS



(Weissenborn, Chatterjee, JSB 2011)

- RMF set GM1, model 1 + ϕ
- adjust scalar couplings to $U_\Sigma = +30$ MeV, $U_\Xi = -28$ MeV
- varying $\alpha_v = 0, \ldots 1$
- use set GM1 with model 1 + ϕ
- SU(6) value: $\alpha_v = 1$
- softest EoS for SU(6) case

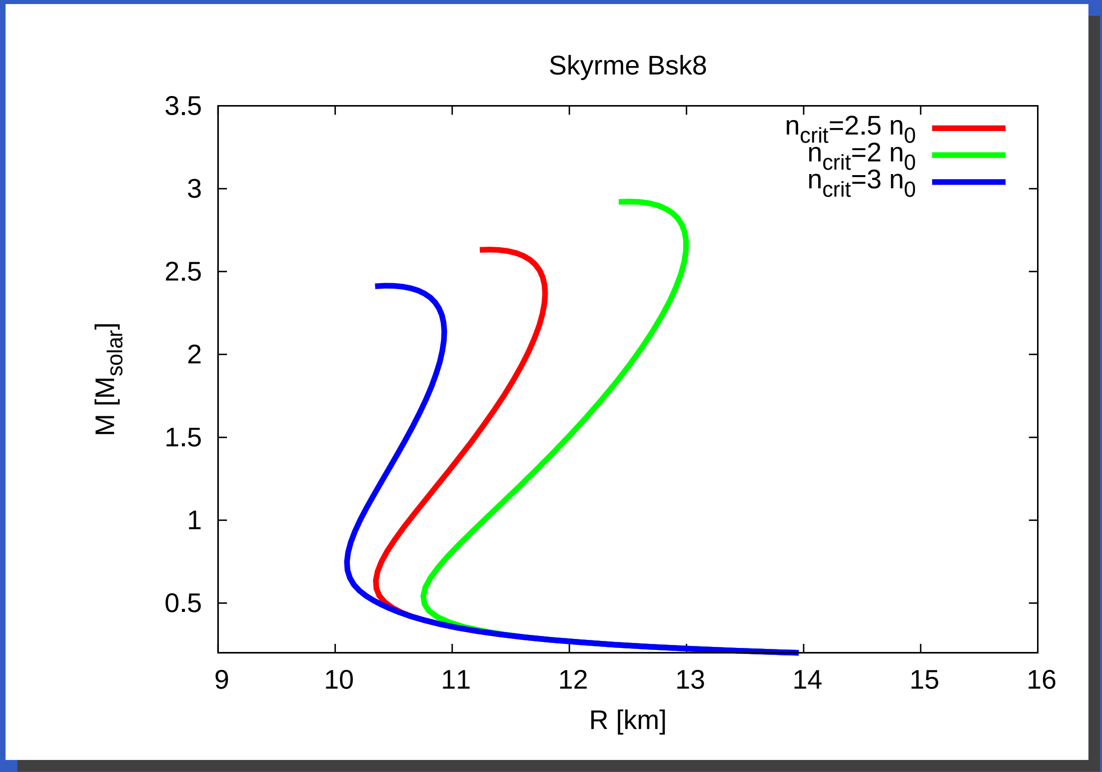
Varying hyperon coupling α_v for neutron stars



(Weissenborn, Chatterjee, JSB 2011)

- varying $\alpha_v = 0, \ldots 1$
- use set GM1 with model 1 + ϕ
- adjust scalar couplings to $U_\Sigma = +30$ MeV, $U_\Xi = -28$ MeV
- mass-radius relation for different α_v, SU(6) value: $\alpha_v = 1$
- substantially increasing mass with decreasing α_v

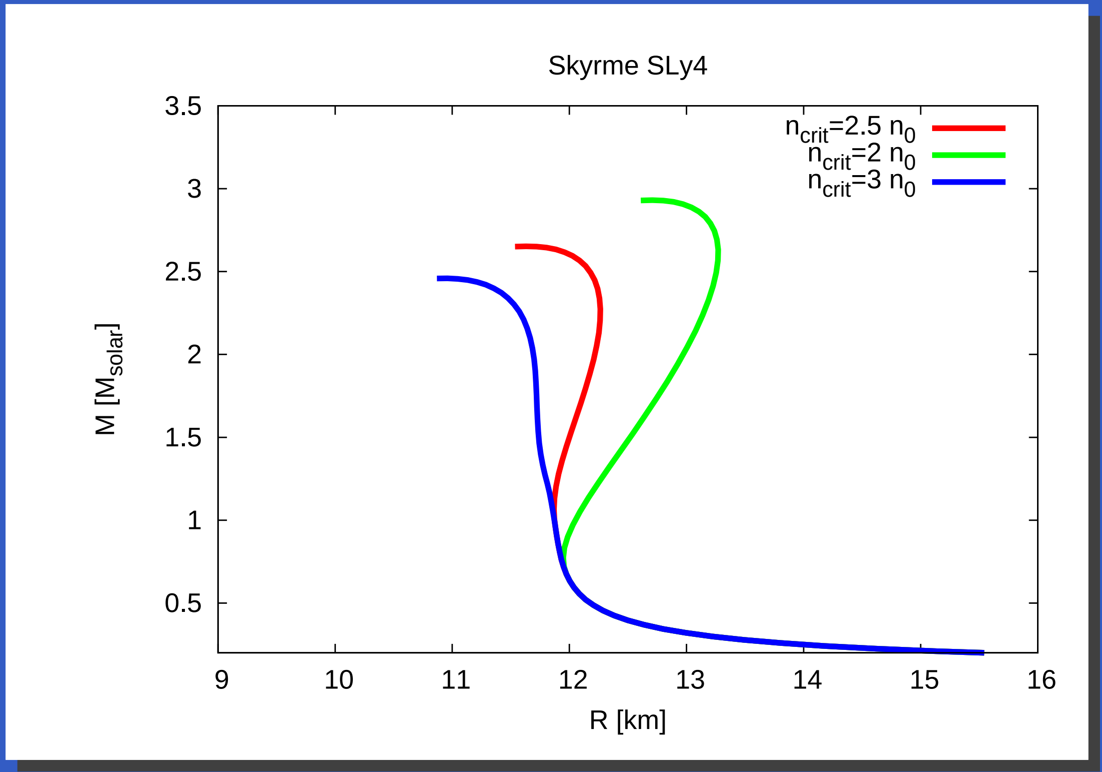
Maximum Masses of Neutron Stars – Causality



(Sagert, Sturm, Chatterjee, Tolos, JSB 2011)

- Skyrme parameter set BSK8: fitted to masses of all known nuclei
- above a fiducial density (determined from the analysis of the KaoS heavy-ion data) transition to stiffest possible EoS
- causality argument: $p = \epsilon - \epsilon_c$ above the fiducial density ϵ_f
  Rhoades, Ruffini (1974), Kalogera, Baym (1996): $M_{\rm max} = 4.2 M_\odot (\epsilon_0/\epsilon_f)^{1/2}$
- $\Longrightarrow$ new upper mass limit of about $2.8 M_\odot$ from heavy-ion data!

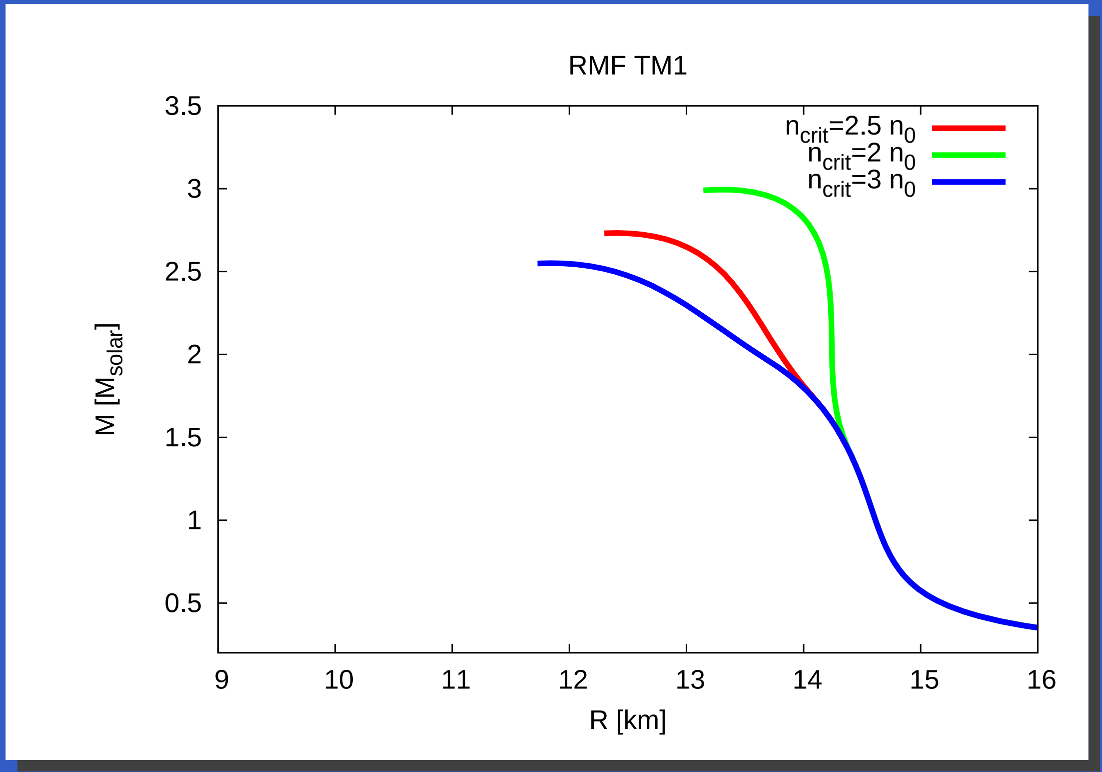
Maximum Masses of Neutron Stars – Causality



(Sagert, Sturm, Chatterjee, Tolos, JSB 2011)

- Skyrme parameter set Sly4: fitted to properties of spherical nuclei
- above a fiducial density (determined from the analysis of the KaoS heavy-ion data) transition to stiffest possible EoS
- causality argument: $p = \epsilon - \epsilon_c$ above the fiducial density ϵ_f
  Rhoades, Ruffini (1974), Kalogera, Baym (1996): $M_{\rm max} = 4.2 M_\odot (\epsilon_0/\epsilon_f)^{1/2}$
- $\Longrightarrow$ new upper mass limit of about $2.8 M_\odot$ from heavy-ion data!

Maximum Masses of Neutron Stars – Causality



(Sagert, Sturm, Chatterjee, Tolos, JSB 2011)

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