Nuclear Constraints on EoS and Supramassive Neutron Stars?

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Yerevan, Sep 2013

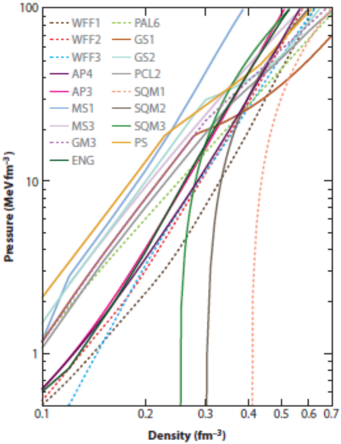
content

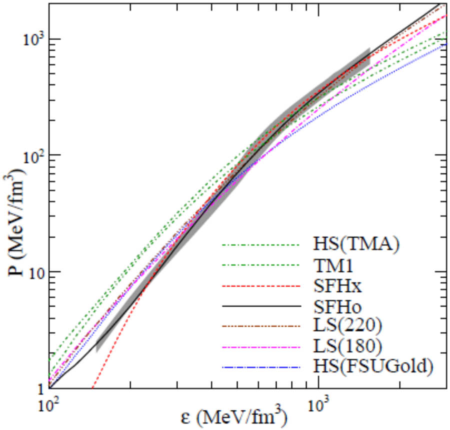
1. Improve Nuclear Constraints on EoS
2. Supramassive Neutron Stars?

Part I

Nuclear Constraints on EoS using Charge Radii

EoS last decade





from Lattimer 2000...2012

various models for EoS

spread in $P(\rho = \rho_s)$ is factor 6

from Steiner et al., astro-ph/1207.2184

various Relativ. Mean Field

L varies between 23 and 111 MeV

EoS

Pressure in terms of energy density $P(\rho) = \rho \frac{d\epsilon}{d\rho} - \epsilon$

In neighborhood of saturation density ρ_s , $u = \rho/\rho_s$

$$\epsilon(u, x) = B + K/18(u-1)^2 + S_A(u)(1-2x)^2 + ..$$

K : compressibility, S_A: symmetry energy, x: proton fraction

$$P \sim u^2 \rho_s [K/9(u-1) + \frac{dS_A}{du}(1-2x)^2 + ..]$$

In practice $P(\rho \sim \rho_s)$ dominated by 2nd term,
$L \equiv \frac{dS}{du}$, will be subject on next slides

Nuclear constraints: Symmetry energy and neutron skin

The symmetry energy in LDM has 2 par's
S_s (surface) and S_v (volume) SE

$$S_A = \frac{(N-Z)^2}{A} \frac{S_v}{1+yA^{-1/3}} \qquad y = S_s/S_v$$

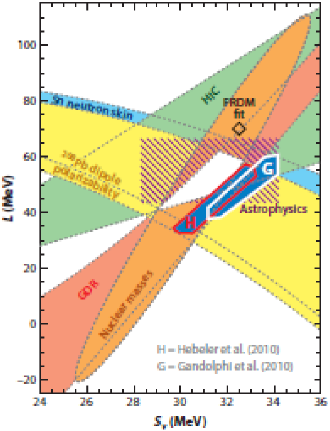
Wanted: $L = dS/d\rho$, (Lattimer)

$$y \sim 0.65 + S_v/98\text{MeV} + 0.44 L/S_v + ..$$

S_v, y from fit to masses strongly correlated
same for L, S_v (orange 1-σ confid. ellips)

similar correlation in microscopic (MF) models

info from radii is orthogonal to masses
but blue band ("skins of Sn") model dependent
(e.g. anti-p atoms)



L vs S_v
Lattimer,Ann.Rev.NP.Sci62(2012)

Information from Masses

Liquid Drop Model: (Equivalent to Energy Density Functional (EDF) for $A \to \infty$ after averaging over shell effects)

$$B(N,Z) = a_v A + a_a A^{2/3} + a_{sym}\frac{(N-Z)^2}{A} + Coulomb + pairing + \ldots.$$

$$S_A = \frac{(N-Z)^2}{A}\frac{S_v}{1+yA^{-1/3}} \qquad y = S_s/S_v$$

variation of $A^{1/3}$ between A=27 and A=216 is only factor 2
hence global fit leads to strong correlation between S_s and S_v

But there are remedies...

Idea: By taking differentials, eg $E(N+i, Z-i) - E(N,Z)$
one can isolate Symmetry energy from A- dependent terms

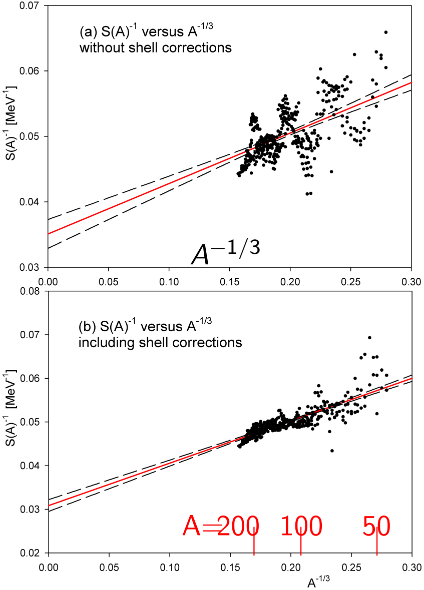
Improved fit, remove shell effects

step (1) isolate symmetry energy
by taking differences with same A

fit par's in $S = \frac{S_v}{1+yA^{1/3}}$ to masses
by plotting $1/S$ vs $A^{-1/3}$
crossing of line with y-axis ($A = \infty$)
gives $1/S_v$, slope $y = 2.6 \pm 0.8$

step (2)
remove shell effects (see Duflo-Zucker)
improves fit $S_v = 31 \pm 0.6\text{MeV}$
$y = 2.5 \pm 0.40$ correlated

L.D and P. van Isacker, Eur.J.Phys. A32 11



Alternative: Double Differences

use Double Differences e.g.

$\Delta_{ij} = E(Z,N) + E(Z-i,N-j) - E(Z,N-j) - E(Z-i,N)$ (i,j=1,2,..)
Jiang, Arima et al. PRC85 024301(2012)

Result $S_v = 32.1 \pm 0.3$ MeV and $S_s = 58.9 \pm 1.1$ MeV $y = 1.9 \pm ..?$

errors smaller than in literature, no correlation given
however dependence on form Wigner energy (=binding correction for $N = Z$)

Some recent results

S_v	S_s/S_v	L(MeV)	ref	model
		masses		
32.5	1.98	70 ± 15	Möller etal PRL108 052501	FRLDM
32.1	1.9		Jiang et al PRC85 024301	double diff
31.1	2.31	66 ± 13	Liu et al PRC82 064306	LDM
32	3.0	113	Danielewicz IntJMP 18 892	analysis IAS
31	$2.5 \pm .4$	80 ± 15	L.D. etal EurJPhysA32 11	LDM+shell co
		Microsc		
30		58 ± 18	L-W. Chen, PRC82 024321	Skyrme+skin
31 ± 1		$31 - 60$	Gandolfi etal,PRC85 032801	QMC
31 ± 1	$1.85 \pm .25$	46 ± 10	Hebeler,PRL105 161102	EFT
31 ± 1		59 ± 13	Agrawal, NT/1305.5336	EDF

Step(3): Information from Radii is Complementary

In LDM one distinguishes proton and neutron radii

$$R_i(N,Z) = R_0(N,Z) \pm \frac{N-Z}{2A} R_1(N,Z) \pm \frac{1}{2}\delta R_{\mathrm{C}}(N,Z) \quad \text{i=p,n}$$

isoscalar term $R_0 = (NR_n + ZR_p)/A \sim r_0 A^{1/3}$

isovector term (neutron skin) $R_n - R_p = \frac{2r_0}{3}\frac{N-Z}{A}(\frac{1}{1+A^{1/3}/y}) + \delta R_C$

depends only on $y = S_s/S_v$ (apart from Coulomb)

scenarios:

(i) measure neutron skin in pv electron scatt.[PREX: Pb Radius Exp]

PRL 108 112502 (2012): $R_{np} \sim 0.33 \pm 0.17$ fm, improved at PREX-II?

more promising:Atomic parity violation, in progress, aim $R_{np} = .. \pm 0.04$

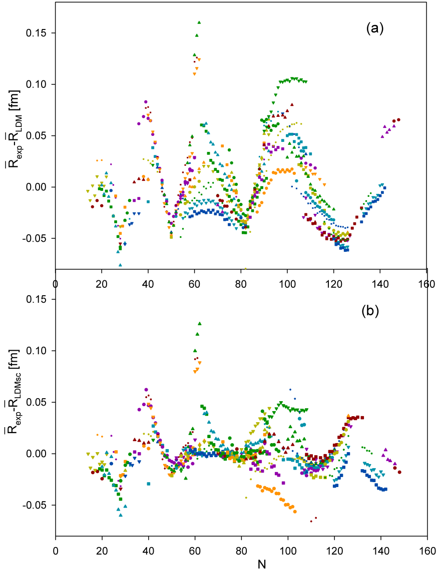
(ii) fit to observed charge charge radii

can be improved by considering isobar shifts (same A)

$R_p(N,Z) - R_p(N-i, Z+i)$, independent of R_0

best strategy: combined fit to radii and masses

Charge Radii in LDM, shell corrected



fit “database” of 700 radii

Residuals $R_{exp} - R^{fit}_{LDM}$ vs N
(same color for isotopic chain)
note shell effects at N=50,82,126

rms dev $= 0.036$ fm $\quad y = 2.6 \pm 0.3$

Remove shell effects (method: Duflo-Zucker, mod:LD)
rms dev$= 0.019$ fm $\quad y = 2.25 \pm 0.13$

long chains of accurate isotope shifts, except overall normalization

remaining variations due to effects of deformation etc

Neutron Skin

- pv electron scatt. [PREX: Pb Radius Exp]
  PRL 108 112502 (2012): $R_{np} \sim 0.33 \pm 0.17$ fm,
  will be improved at PREX-II
- atomic parity violation, primary aim: to determine Weinberg angle

  $$\langle H \rangle = \frac{G}{2\sqrt{2}} \int d^3r[-N\rho_n(r) + Z(1 - 4\sin^2\theta_W)\rho_p(r)]\psi^\dagger\gamma_5\psi$$

  can be turned around, assume weak force OK
  determine R_{np} and slope within 1%
  available for Cs (Wieman, 1990) not accurate enough
  in progress on Ra isotopes, expected accuracy 1%
- anti-protonic atoms; analysis model dependent

Result for L and Skin

Combined fit to masses and radii

model	y	L(MeV)	$R_{np}(^{208}\mathrm{Pb})$ (fm)
present	2.25 ± 0.20	$65 < L < 90$	0.185 ± 0.015
χEFT	1.85 ± 0.25	$36 < L < 56$	0.17 ± 0.03
QMC		$41 < L < 64$	
EDF		$46 < L < 72$	0.195 ± 0.02

Phenomenology favours larger L values than most microscopic models

Need to understand that

Microscopic developments: use χEFT

For long time microscopic calculations of group of Pandharipande was considered most realistic, based upon realistic NN force plus phenomenological 3-body force using var. approach and correlated basis functions

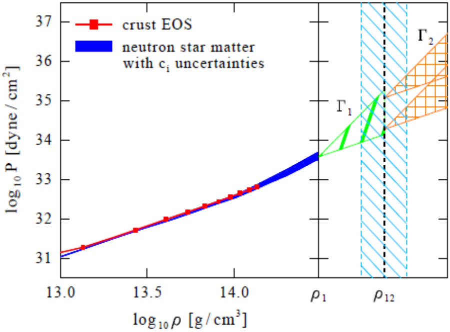
Later: SCGF, RMF, Bruckner+3BF...)

Recent development: use of chiral effective field theory for low density neutron matter, with extrapolation to beta equilibrium

Claim: uncertainty in $P(\rho_s)$ reduced from factor 6 to 1.5

all many-body effects included?

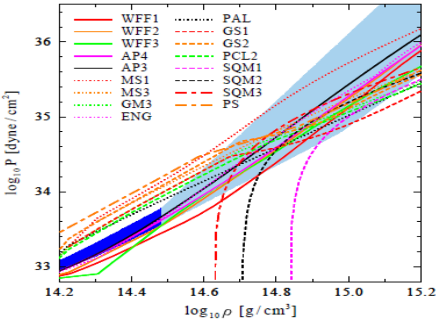
saturation density predicted correctly?



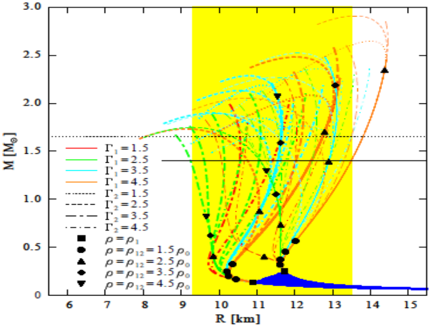
EoS; polytropes added for $\rho > \rho_s$

Hebeler, PRL 105 161102 (2010)

Results



Hebeler et al, EoS



$MvsR$ for various polytropes $\rho > \rho_s$
$P = K\rho^\Gamma$

Part II: Rotating Neutron Star

- Several energetic observations can be associated with formation of NS's or BH's: Supernovae, Gamma Ray Bursts....
  Some short GRB (∼1s) have been attributed to NS mergers
- New: observed short (ms) radio bursts
  Suggestion: collapse of supramassive rotating NS

"supramassive": M_{rot} larger than $M_{max}(0)$ of non-rotating NS

Radio Bursts

A population of fast radio bursts at cosmological distances
D. Thornton *et al.*, Science 341 53 (2013)

". . . Host galaxy and intergalactic medium models suggest that they have redshifts of 0.5 to 1 and distances of up to 3 gigaparsecs. No temporally coincident x- or gamma-ray signature was identified in association with the bursts . . . . "

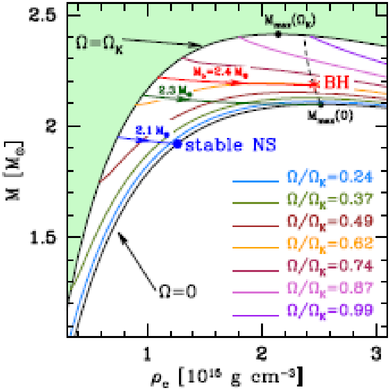
Fast Radio Bursts: last sign of Supramassive Rotating Neutron Stars (Blitzars)
Heino Falcke and Luciano Rezzolla, arXiv:astro-ph/1307.1409

Millisecond extragalactic radio bursts as magnetar flares
S.B. Popov , K.A. Postnov astro-ph/1307.4924

Fast Radio Burst explained by F-R

- Observation: bright radio pulse $\Delta T \leq 1$ms
  does not repeat, no $\gamma-$ or x-ray seen
  radio flux $\sim$ Jy at GHz freq.; dispersive
  several ones have been observed since 2007
- Interpretation by F-R: final farewell greetings of supramassive rotating NS, e.g. created by accretion in binary system
  at critical point: collapsing into Kerr BH after slowing down due to magnetic braking
  - Event horizon will hide stars surface, only emission from detached magnetosphere is seen
  - Timescale for collapse: (freefall) $\tau \sim 0.04 R_{10}^{3/2} M_2^{-1/2}$ ms

Scenario of Falcke-R



grav. mass *vs* central density for various ratios $f = \Omega/\Omega_K$

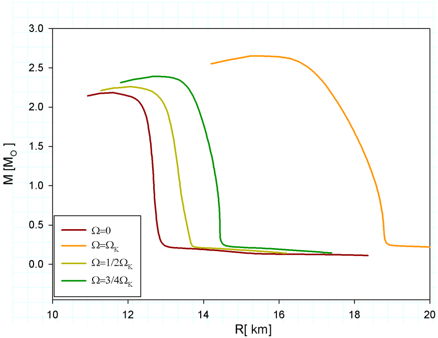
- EoS: polytrope $P = K\rho^\gamma$ $\gamma = 2$, K adjusted such that $M(0)_{max} = 2.1M_\odot$
- computed critical spin (Keppler or mass shedding limit) $\Omega_K = 2\pi/\tau$ $(\sim 1\mathrm{ms}^{-1})$
- arrows: tracks of NSs slowing down due to magnetic braking (depends on f, $B \sim 10^{12}$G ?) green: 10^6y, red: 3000y
- dashed line: stability line (collapse to Kerr BH)

Event horizon hides stars surface, only emission from detached magnetosphere is seen; timescale: (freefall) $\tau \sim 0.04 R_{10}^{3/2} M_2^{-1/2}$ ms

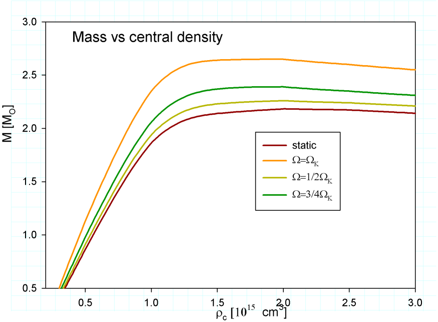
Questions

- Rates: F-R claim: only few % of NS's need to be supramassive
  to explain observations
  finding a NS with $\tau \sim 1$ms, $M > M_{max}(0)$ and $B \sim 10^{12}$G seems extremely rare (using info pulsars)
  e.g. $\tau_K \sim$1ms; observed $< 1\%$
- Magnetic field: plays role in "braking" as well in "bursts"
  is a "unknown parameter"
  if spin-up comes from companion will it suppress magnetic field?
  Isotropic or directional emission?
- EoS: F-R use single polytrope $P = K\rho^{\gamma}$
  $\gamma = 2$, K adjusted to $M_{max} = 2.1 M_{\odot}$
  Note: is simplistic, plenty of realistic EoS exist
  is there a sensitivity to EoS ?

M vs R for realistic EoS



Mass vs Radius

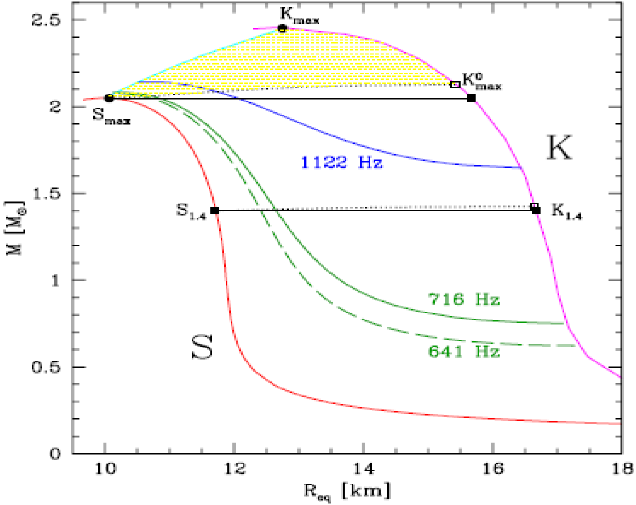


Mass vs Central density

Qualitatively we confirm plot of Falcke-Rezzolla,
i.e. $M(\Omega_K)$ increases by 20% $R(\Omega_K)$ increases by 50%

EoS based on 3-polytrope fit to Steiner et al $(M(0)_{max} = 2.2 M_\odot)$

Other results for M vs R

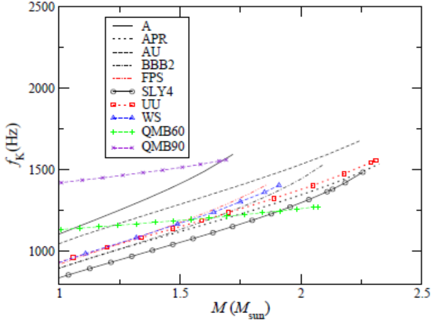


from Haensel et al., astro-ph/0901.1268

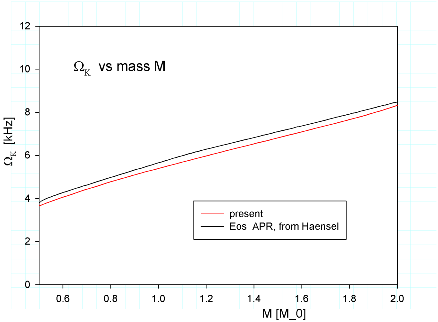
based on EoS of Douchy-Haensel, $M_{max} = 2.05 M_\odot$

Dependence ν_K on EoS (2)

Critical frequency is sensitive to EoS



from Lo and Lin, Astroph.J.728 12 (2011)



comparison of present EoS and APR

Approximation for mass shedding (Kepler) frequency

Newtonian uniformly rotating rigid star with M, R (mass shedding limit)

$$\tau_{min} = 2\pi\sqrt{\frac{R^3}{GM}} = 0.545(M_\odot/M)^{1/2}(R/10\mathrm{km})^{3/2}\ \text{ms}$$

General relativity Lattimer, Haensel derived empirical relation (valid for $M < 0.9M_{max}(0)$; M, R of static star, depending on EoS)

$$\tau_{min} = 0.92 \pm 0.04(M_\odot/M)^{1/2}(R/10\mathrm{km})^{3/2}\ \text{ms}$$

Relevance

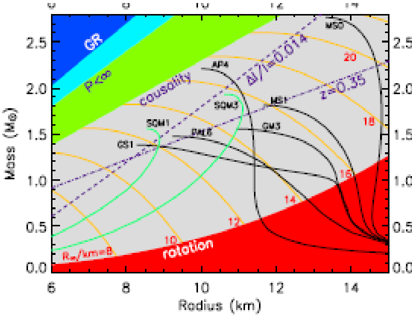
observed max spin $\nu_{obs} = 1/\tau_{obs}$ (using $\nu_K \geq \nu_{obs}$) puts bound on M *vs* R

Observed 716 Hz pulsar

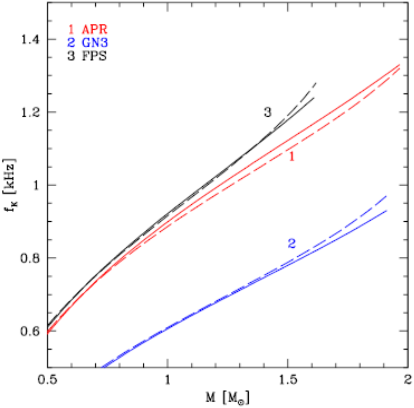
$$R < 10.4(1000\mathrm{Hz}/\nu_{obs})^{2/3}(M/M_\odot)^{1/3}\ \text{km}$$

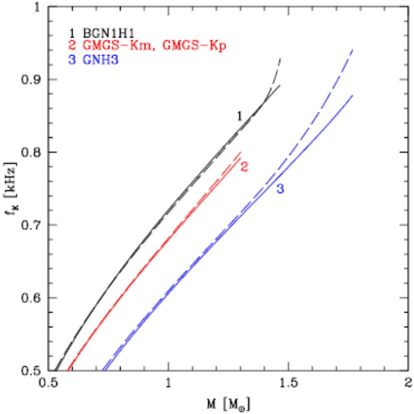
excludes red area in figure

fairly insensitive to EoS



Dependence ν_K on EoS





$\nu_K = \Omega_K/(2\pi)$ vs M from Haensel et al.

neutron skin in LDM

options:

1. from isovector term in R: $\frac{R_{np}}{R} = \frac{N-Z}{A}\left(\frac{1}{1+A^{1/3}/y}\right) b + \delta R_C$

   fit to charge radii, $y = S_v/S_s$
   e.g. ^{208}Pb: (no shell corr!) $R_{np} = 0.18 \pm 0.03$ fm $y = \ldots$
2. from relation between R_{np} and μ_a (=isovector chem pot)

$$\mu_a = S_n - S_p = B(N-1,Z) - B(N,Z-1) = \frac{dE}{dN} - \frac{dE}{dZ} \sim \frac{N-Z}{A} S_A + ..$$

$$= \frac{4(N-Z)}{A} \frac{S_v}{1+yA^{-1/3}} - \frac{5a_c}{6} \frac{Z}{A^{1/3}}$$

combining (i)+(ii) $\frac{R_{np}}{R_0} = \frac{\mu_a}{24 S_s} \frac{A^{5/3}}{NZ} + \frac{5a_c}{72 S_s} \frac{A^{4/3}}{N}$

take $\mu_a(N,Z)$ from exp (hence shell effects implicitly included)
overall uncertainty in R_{np} from error in S_s (15%)
One accurate measurement (PREX) on ^{208}Pb will fix that

Note: scaling in (1) but not in (2)