Constraining the Skewness Parameter of Symmetric Nuclear Matter in Nonlinear Relativistic Mean Field Model

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my plan

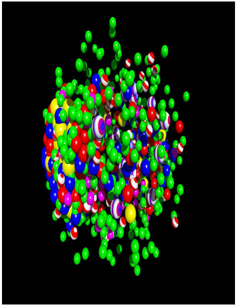
α). EoS of ANM and what we have known ?

β). constraining J_0 using nonlinear RMF model

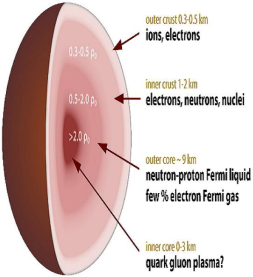
γ). a possible new RMF interaction

why EoS of asymmetric nuclear matter (ANM) is important ?

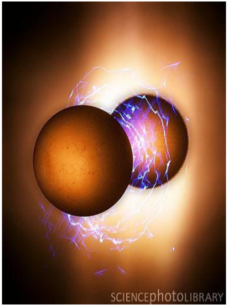
Heavy Ion Collisions



Neutron Stars



Nuclear Forces



$$\frac{\mathcal{E}_{\text{tot}}}{A} \equiv E = E(\rho, \delta, T) \xrightarrow{T=0} E = E(\rho, \delta), \quad \delta = \frac{\rho_{\text{n}} - \rho_{\text{p}}}{\rho_{\text{n}} + \rho_{\text{p}}}$$

$$p(\rho, \delta) = \rho^2 \frac{\partial E(\rho, \delta)}{\partial \rho}, \quad K(\rho, \delta) = 9 \frac{\partial p(\rho, \delta)}{\partial \rho}$$

equation of state (energy per nucleon) for asymmetric nuclear matter is,

$$E(\rho,\delta) \simeq \underbrace{E(\rho,0)}_{\equiv E_0(\rho)} + \boxed{\underbrace{E_{\rm sym}(\rho)}_{\text{symmetry energy}} \delta^2} + E_{{\rm sym},4}(\rho)\delta^4 + \mathcal{O}(\delta^6), \quad \delta \equiv \frac{\rho_{\rm n}-\rho_{\rm p}}{\rho_{\rm n}+\rho_{\rm p}}$$

go a step further, every energy term can be expanded at $\rho = \rho_0$,

$$E_0(\rho) \simeq E_0(\rho_0) + \frac{K_0}{2!}\chi^2 + \frac{J_0}{3!}\chi^3 + \frac{I_0}{4!}\chi^4 + \mathcal{O}(\chi^5), \quad \chi = \frac{\rho-\rho_0}{3\rho_0}$$

$$E_{\rm sym}(\rho) \equiv \frac{1}{2}\frac{\partial^2 E(\rho,\delta)}{\partial\delta^2}\bigg|_{\delta=0}$$

$$\simeq E_{\rm sym}(\rho_0) + L\chi + \frac{K_{\rm sym}}{2!}\chi^2 + \frac{J_{\rm sym}}{3!}\chi^3 + \frac{I_{\rm sym}}{4!}\chi^4 + \mathcal{O}(\chi^5)$$

we want to know

$$\boxed{\rho_0,\ E_0(\rho_0),\ K_0,\ J_0,\ E_{\rm sym}(\rho_0),\ L,\ K_{\rm sym},\ \cdots}$$

what we have known now ? $J_0 =$ skewness

$$\rho_0 = 0.16 \pm 0.02\,\mathrm{fm}^{-3}$$

$$E_0(\rho_0) = -16 \pm 1\,\mathrm{MeV}$$

$$K_0 \equiv 9\rho_0^2 \left.\frac{\partial^2 E_0(\rho)}{\partial \rho^2}\right|_{\rho_0} = 230 \pm 20\,\mathrm{MeV}$$

$$E_{\mathrm{sym}}(\rho_0) = 30 \pm 3\,\mathrm{MeV}$$ ⟵ lots of studies, but why not J_0 ?

$$L \equiv 3\rho_0 \left.\frac{\partial E_{\mathrm{sym}}(\rho)}{\partial \rho}\right|_{\rho_0} = 50 \pm 20\,\mathrm{MeV},$$ order $= \chi^1 \delta^2$ (3)

$$J_0 \equiv 27\rho_0^3 \left.\frac{\partial^3 E_0(\rho)}{\partial \rho^3}\right|_{\rho_0}$$ → almost unknown, order $= \chi^3 \delta^0$ (3)

$$K_{\mathrm{sym}} \equiv 9\rho_0^2 \left.\frac{\partial^2 E_{\mathrm{sym}}(\rho)}{\partial \rho^2}\right|_{\rho_0}$$ → almost unknown, order $= \chi^2 \delta^2$ (4)

THIS TALK WILL SAY SOMETHING ABOUT J_0

why J_0 is important ? naive consideration

$$E_0(\rho) \simeq E_0(\rho_0) + \frac{1}{2}K_0\chi^2 + \underbrace{\frac{1}{6}J_0\chi^3}_{} \longleftarrow \boxed{\text{anharmonic effect}}$$

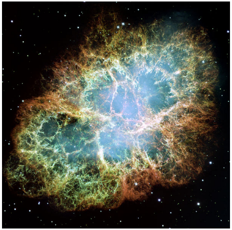
when $\rho \simeq 3 \sim 4\rho_0, \chi \simeq 1, \rightarrow$ neutron star

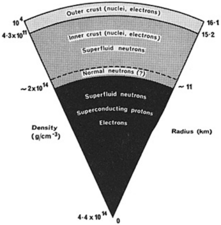
$J_0 \longleftrightarrow$ gravitational instability, r-mode ? $\Downarrow$ N. Andersson, 2000

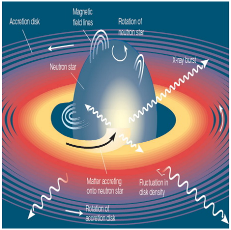
$$E_0(\rho) \simeq E_0(\rho_0) + \frac{1}{2}K_0\left(1 + \frac{1}{3}\frac{J_0}{K_0}\right) \simeq E_0(\rho_0) + \frac{1}{2}K_0\left(1 - \frac{2}{3}\right)$$

$\Downarrow$

the effect of J_0 is comparable of K_0 $\longrightarrow$ mass, GW, merge process, supernovae explosion, $\cdots$

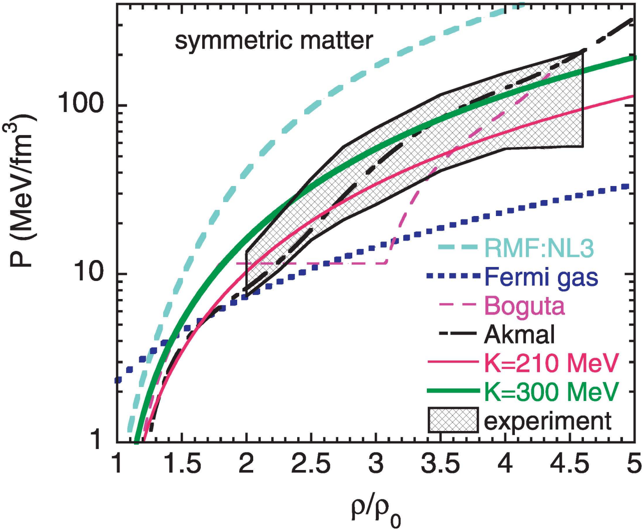






how to constrain J_0 ?

flow data from heavy ion collision — soft EoS — small J_0



P. Danielewicz, *et.al*, Science, 2002

$$\text{J0348} + 0432, \quad M_{\rm NS}^{\rm max} \simeq 2.01 \pm 0.04\, M_\odot$$

A Massive Pulsar in a Compact Relativistic Binary

John Antoniadis,* Paulo C. C. Freire, Norbert Wex, Thomas M. Tauris, Ryan S. Lynch, Marten H. van Kerkwijk, Michael Kramer, Cees Bassa, Vik S. Dhillon, Thomas Driebe, Jason W. T. Hessels, Victoria M. Kaspi, Vladislav I. Kondratiev, Norbert Langer, Thomas R. Marsh, Maura A. McLaughlin, Timothy T. Pennucci, Scott M. Ransom, Ingrid H. Stairs, Joeri van Leeuwen, Joris P. W. Verbiest, David G. Whelan

Introduction: Neutron stars with masses above 1.8 solar masses ($M_\odot$), possess extreme gravitational fields, which may give rise to phenomena outside general relativity. Hitherto, these strong-field deviations have not been probed by experiment, because they become observable only in tight binaries containing a high-mass pulsar and where orbital decay resulting from emission of gravitational waves can be tested. Understanding the origin of such a system would also help to answer fundamental questions of close-binary evolution.

Methods: We report on radio-timing observations of the pulsar J0348+0432 and phase-resolved optical spectroscopy of its white-dwarf companion, which is in a 2.46-hour orbit. We used these to derive the component masses and orbital parameters, infer the system's motion, and constrain its age.

Results: We find that the white dwarf has a mass of $0.172 \pm 0.003\, M_\odot$, which, combined with orbital velocity measurements, yields a pulsar mass of $2.01 \pm 0.04\, M_\odot$. Additionally, over a span of 2 years, we observed a significant decrease in the orbital period, $\dot{P}_b^{\rm obs} = -8.6 \pm 1.4$ μs year^{-1} in our radio-timing data.

J. Antoniadis, *et.al*, Science, 2013

model used (nonlinear RMF)

in my analysis, i use the following Lagrangian,

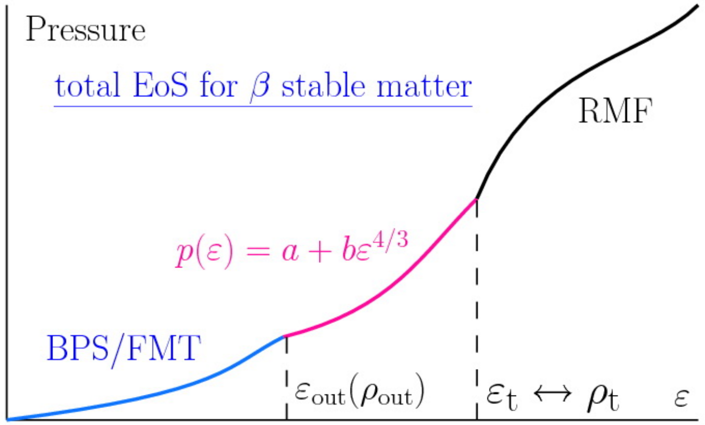
$$\begin{aligned}\mathcal{L} =& \overline{\psi}\left[\gamma_\mu(i\partial^\mu - g_\omega\omega^\mu - g_\rho\vec{\rho}^\mu\cdot\vec{\tau}) - (M - g_\sigma\sigma)\right]\psi \\ & - \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - U(\sigma) \\ & + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{4}c_\omega\left(g_\omega\omega_\mu\omega^\mu\right)^2 \\ & + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\cdot\vec{\rho}^\mu - \frac{1}{4}\vec{\rho}_{\mu\nu}\cdot\vec{\rho}^{\mu\nu} \\ & + \frac{1}{2}g_\rho^2\vec{\rho}_\mu\cdot\vec{\rho}^\mu\Lambda_{\mathrm{V}}g_\omega^2\omega_\mu\omega^\mu,\end{aligned}$$

where

$$\boxed{U(\sigma) = \frac{1}{3}b_\sigma M(g_\sigma\sigma)^3 + \frac{1}{4}c_\sigma(g_\sigma\sigma)^4}$$

using method of one to one correspondence

$$\underbrace{\boxed{\rho_0, E_0(\rho_0), M^*_{\mathrm{dirac}}, K_0, J_0, E_{\mathrm{sym}}(\rho_0), L}}_{\text{physical quantities}} \longleftrightarrow \underbrace{\boxed{g_\sigma, b_\sigma, c_\sigma, g_\omega, c_\omega, g_\rho, \Lambda_{\mathrm{V}}}}_{\text{interaction coulpings}}$$


Pressure
total EoS for β stable matter
RMF
$p(\varepsilon) = a + b\varepsilon^{4/3}$
BPS/FMT
$\varepsilon_{\mathrm{out}}(\rho_{\mathrm{out}})$
$\varepsilon_{\mathrm{t}} \leftrightarrow \rho_{\mathrm{t}}$
ε

values for constraining J_0

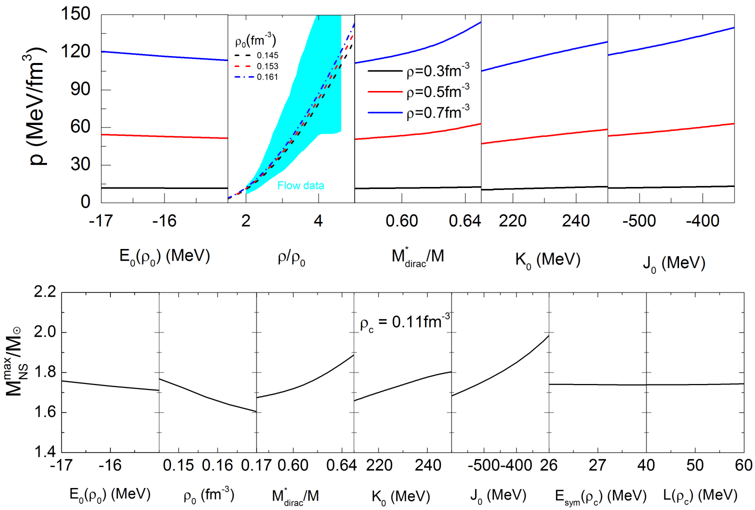
empirical values from finite nuclei studies,

$$\begin{aligned}
\rho_0 &= 0.153 \pm 0.008\,\mathrm{fm}^{-3} \\
E_0(\rho_0) &= -16.2 \pm 0.3\,\mathrm{MeV} \\
M^*_{\mathrm{dirac}}/M &= 0.61 \pm 0.04 \\
K_0 &= 230 \pm 20\,\mathrm{MeV} \\
E_{\mathrm{sym}}(\rho_{\mathrm{c}}) &= 27 \pm 1\,\mathrm{MeV} \\
L(\rho_{\mathrm{c}}) &= 50 \pm 10\,\mathrm{MeV},
\end{aligned}$$

and

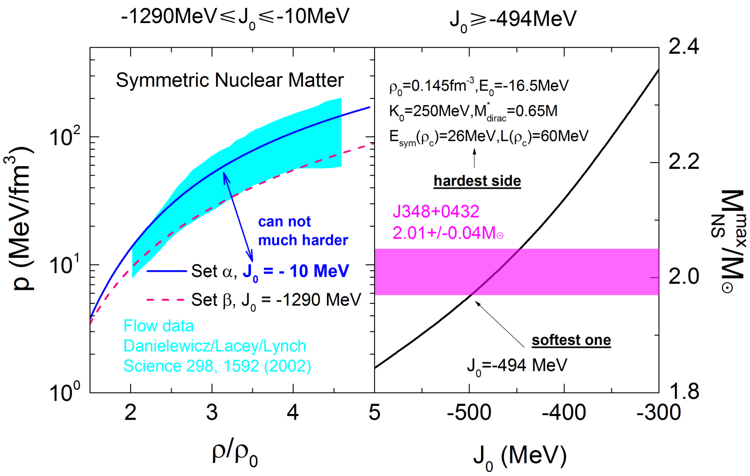
$$\rho_{\mathrm{c}} = 0.11\,\mathrm{fm}^{-3}.$$

monotonousness

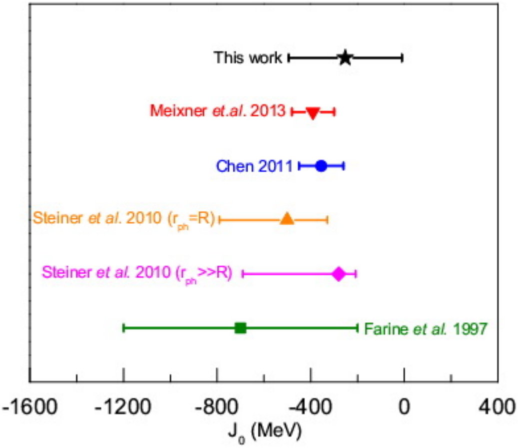


note: pressure from HIC and maximum mass for NS

constraints for skewness J_0



$$-494\,\mathrm{MeV} \leq J_0 \leq -10\,\mathrm{MeV}$$



B.J. Cai and L.W. Chen, in preparation

a new interaction needs what ?

if we want to construct a new RMF interaction, we should consider

α). correct binding energy for finite nuclei $B^{\rm finite}_{\rm nuclei}$, e.g., Pb208

β). correct charge rms for finite nuclei, $r^{\rm rms}_{\rm charge}$

γ). pass through constraint from flow data

δ). give as heavy neutron star as possible, at least $1.97M_\odot$

λ). $\cdots$

here, we give a new series of physical quantities (parameters)

$$\rho_0 = 0.151\,\mathrm{fm}^{-3},\ \ E_0(\rho_0) = -16.26\,\mathrm{MeV},\ \ \frac{M^*_{\rm dirac}}{M} = 0.64,\ \ K_0(\rho_0) = 230\,\mathrm{MeV},$$

$$J_0(\rho_0) = -435\,\mathrm{MeV},\ \ E_{\rm sym}(\rho_c) = 26.65\,\mathrm{MeV},\ \ L(\rho_c) = 46\,\mathrm{MeV},$$

B.J. Cai, L.W. Chen and W.Z. Jiang, in preparation; Z. Zhang and L.W. Chen, PLB, 2013

more values and figures

$$E_{\rm sym}(\rho_0) = 31.81\,\mathrm{MeV}, \quad L(\rho_0) = 52.95\,\mathrm{MeV},$$

$$M_{\rm NS}^{\rm max} = 1.97 M_{\odot}, \quad R_{\rm NS} = 11.08\,\mathrm{km},$$

$$\rho_{\rm t} = 0.062\,\mathrm{fm}^{-3}, \quad p_{\rm t} = 0.28\,\mathrm{MeV/fm}^3,$$

$$B^{\rm Pb208} = -7.868\,\mathrm{MeV}, \qquad (\mathrm{exp.} = -7.867\,\mathrm{MeV}),$$

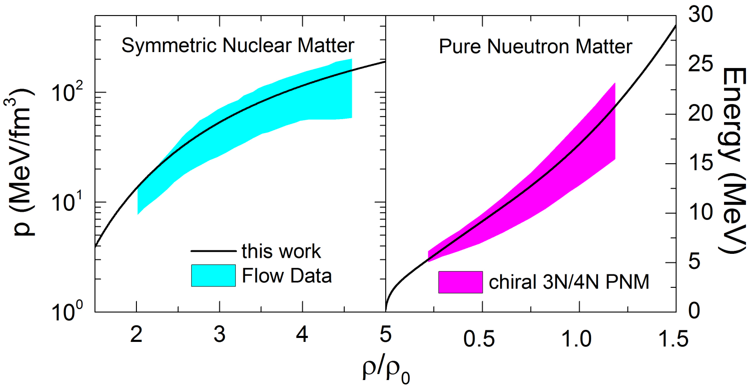
$$r_{\rm charge,rms}^{\rm Pb208} = 5.52\,\mathrm{fm}, \qquad (\mathrm{exp.} = 5.50\,\mathrm{fm}),$$

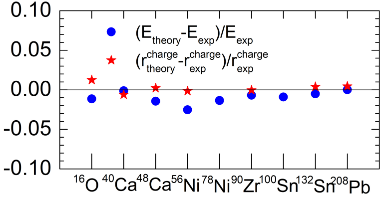
$$\Delta r_{\rm np}^{\rm Pb208} = 0.194\,\mathrm{fm}^{-3},$$

$$K_{\rm sym}(\rho_0) = -53.41\,\mathrm{MeV}, \quad K_{\rm sat,2} = -271\,\mathrm{MeV},$$

B.J. Cai, L.W. Chen and W.Z. Jiang, in preparation

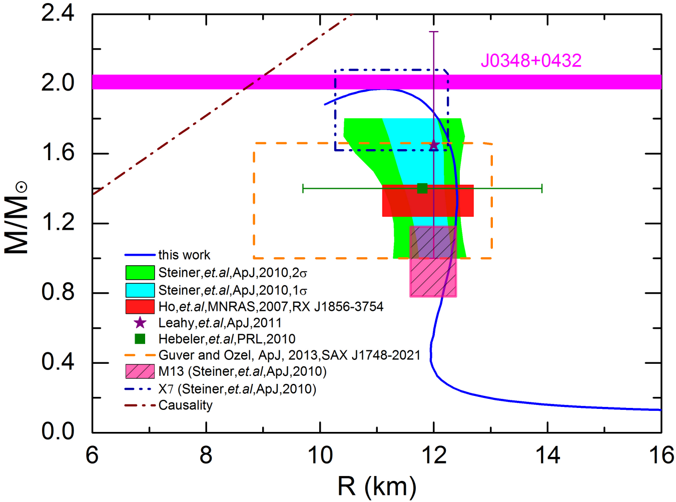
flow data again/PNM constraint from χPT/CRMS/Binding





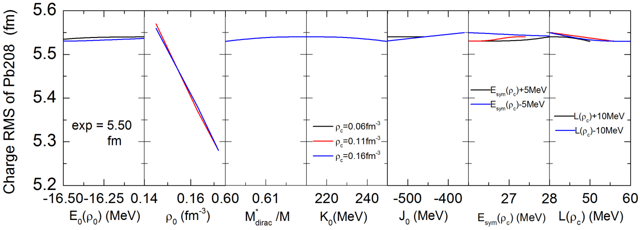
B.J. Cai, L.W. Chen and W.Z. Jiang, in preparation

mass — radius relation

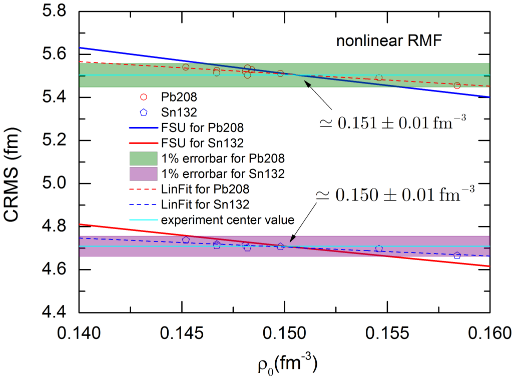


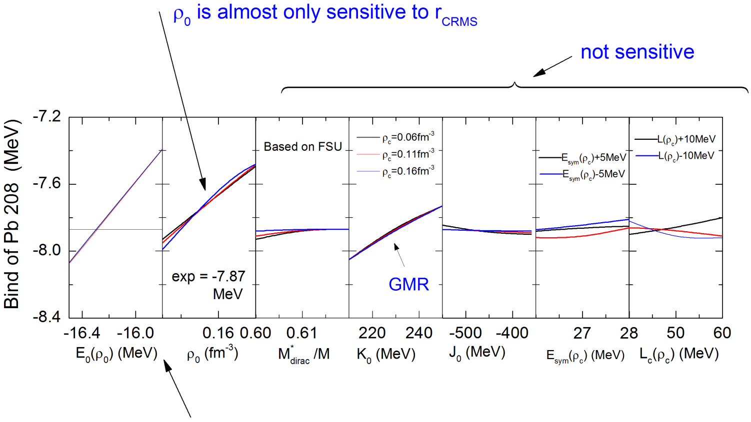
B.J. Cai, L.W. Chen and W.Z. Jiang, in preparation

thanks for your attention !



$$r_{\mathrm{CRMS}} \text{ ''} \simeq \text{'' } \rho_0$$



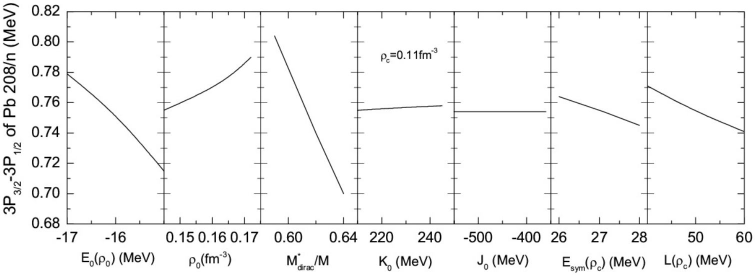


thus, $E_0(\rho_0)$ is almost determined by B

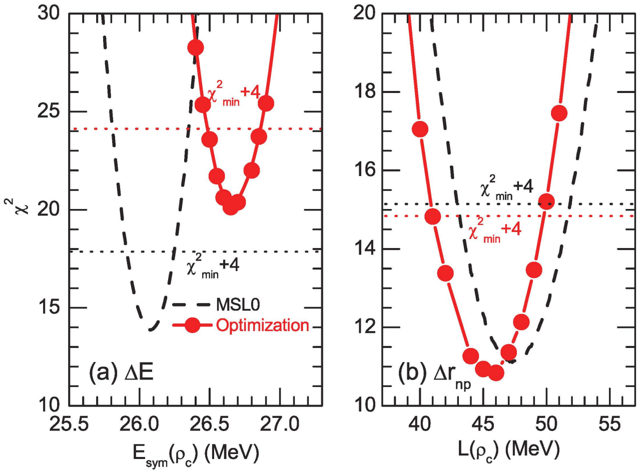
$$B = a_V + a_S A^{-1/3} + S_V \delta^2 + a_C Z^2/A^{4/3} + \cdots$$

$$\lim B = a_V,\ a_V = E_0(\rho_0)$$

spin-obit splitting is not only sensitive to M^*_{dirac}



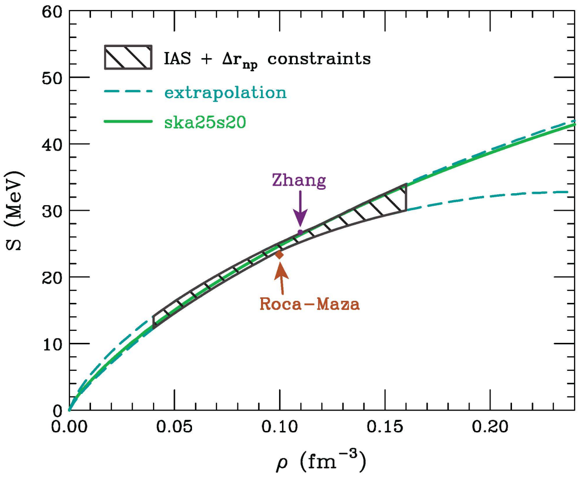
$E_{\mathrm{sym}}(\rho_{\mathrm{c}}) = 26.65 \pm 0.2\,\mathrm{MeV}, L(\rho_{\mathrm{c}}) = 46 \pm 4.5\,\mathrm{MeV}$



Optimization+SHF, $\rho_{\mathrm{c}} = 0.11\,\mathrm{fm}^{-3}$

Z. Zhang and L.W. Chen, PLB, 2013

constraints for E_{sym}



P. Danielewicz and J. Lee, NPA, 2014

$K_{\rm sym}$ effect, one more term $2^{-1} g_\rho^2 \vec{\rho}_\mu \cdot \vec{\rho}^\mu \Lambda_{\rm S} g_\sigma^2 \sigma^2 \rightarrow \Lambda_{\rm S}$