

HHIQCD 2024

Nishinomiya - Yukawa Workshop 31 October 2024

EXPLORING the MAT CORE of NEUTR(

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Akira Ohnishi: Home Page 01.10.24, 14:46

COUIOIIIO pole sou In providing further c *Rokkasho Fusion Institute, Rokkasho, Aomori, 039-3212, Japan Physical University Departicle momentum correlation function of a K p particle momentum correlation function of a K p particle Extreme Matter Institute Matter Institute (EMMI) and the thermal department difference* at a the th omo potential and the th data. The recently measured correlation function is found to be well reproduc source size and the relative weight of the source function of $\pi\Sigma$ with respect to correlation function from legacy evetome indicates that the investigation of its correlation function from larger systems indicates that the investigation of its $\ddot{\theta}$ first time. Realistic potential substantial survey of the area inversions. *Rokkasho Fusion Institute, Rokkasho, Aomori, 039-3212, Japan* $\overline{\mathcal{C}}$ data. The recently measured correlation function is found to be well reproduced by first time. Realistic potentials based on the chiral SU(3) dynamics are used which fit the available a momentum correlation function of a K^-p pair from \vec{B} in the $\bar{K}N-\pi\Sigma-\pi\Lambda$ coupled-channels framework. The effects of all coupled ch t of the source function he KN - $\pi\Sigma$ - $\pi\Lambda$ coupled-channels framework. The eff <u>ון</u>
. $\ddot{}$ *not time. Neuristre potentials based on the emital* $SO(3)$ *dynamics are ased which in the available data. The recently measured correlation function is found to be well reproduced by allowing varia Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan Department of Department of Physics, Andreasty Metropolitan University, Hachiothern Corporation Luis* rand in the *RIV-RZ-RI* contract Coulomb potential and the t *National Institutes for Quantum and Radiological Science and Technology,* respectively. *Physics Department, Technical University of Munich, D-85748 Garching, Germany* $\frac{1}{2}$ in providing f α botential and the threshold energy difference between e and the relative weir \overline{C} can be study of the $\overline{K}N$ interaction .
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 \mathbf{D} Akira Ohnishi,² and Wolfram Weise^{6,7} 3 *Department of Physics, Tokyo Metropolitan University, Hachioji 192-0397, Japan* 1, AKII & UIIIISIII, and woman weise

The two-particle momentum correlation function of a K^-p pair from high-energy nuclear collisions is evaluated in the $\overline{K}N-\pi\Sigma-\pi\Lambda$ coupled-channels framework. The effects of all coupled channels together with the Coulomb potential and the threshold energy difference between K^-p and $\bar{K}^0\hat{n}$ are treated completely for the first time. Realistic potentials based on the chiral SU(3) dynamics are used which fit the available scattering data. The recently measured correlation function is found to be well reproduced by allowing variations of the source size and the relative weight of the source function of $\pi\Sigma$ with respect to that of $\bar{K}N$. The predicted K^-p correlation function from larger systems indicates that the investigation of its source size dependence is useful in providing further constraints in the study of the $\bar{K}N$ interaction. source size and the relative weight of the source function of $\pi\Sigma$ with respect to that of $\bar{K}N$. The predicted K^-p source size and the relative weight of the source randition of $n \geq$ whilf respect to that of π . The predicted π β correlation function from larger systems indicates that the investigation of its source size dep K^-p pair from high-energy nuclear collisions is eval-*Framework.* The effects of all coupled channels together with the first time. Realistic potentials based on the chiral SU(3) dynamics are used which fit the available scattering uated in the *KN* \sim *CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China V* o-particle momentum correlation function of a K p pair from high-energy nuclear collisions $\bar{K}N = \sum_{n=0}^{\infty} a_n^2$ assumed above the framework. The effects of all equals depends together in *Department of Physics, Tokyo Metropolitan University, Hachioji 192-0397, Japan R* and the chiral SU(3) dynamics are used which elative weight of the source function of $\pi\Sigma$ with respect to that of $\bar{K}N$. T on function from larger systems indicates that the investigation of its source size dependence is For the state of the peak of the gas of the peak structure of the peak structure seen in Fig. 3 and *q* is useful
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HHIQCD 2024

- **Empirical constraints from heavy neutron stars and binary mergers**
- **Bayesian inference results and constraints on phase transitions**
- **Phenomenology and Models for Dense Baryonic Matter**
	- **Low-energy nucleon structure and a two-scales scenario**
	- **Hadron-quark continuity and crossover**
	- **Dense baryonic matter as a** (**relativistic**) **Fermi liquid**

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Nishinomiya - Yukawa Workshop

ΓР **THEORETICAL PHYSICS**

Dense Matter in Neutron Stars: Speed of Sound and Equand of Sound and Equand Context of State Matter in Meutron S

31 October 2024

*Equa*ti*on-of-Sta*te *of Dense Baryonic Ma*tt*er :*

*Empirical Cons*tr*aints* fr*om Neu*tr*on Star Observa*ti*ons*

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[Miller et al., Astrophys.J.Lett. 887 (2019), Miller et al., arXiv:2105.06979 [astro-ph.HE]] [Miller et al., Astrophys.J.Lett. 887 (2019), Miller et al., arXiv:2105.06979 [astro-ph.HE]]

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Adam Mann

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predictions? predictions?

FIG. 3. Phases of the coalescence of binary neutron stars. During the inspiral phase (before

NICER is continuing to observe J0030 to further improve the precision of its continuing to observe J0030 to further improve the precision of **NEUTRC** radius measurements. At the same time, the team is beginning to analyse From a second target, a slightly heavier pulsar with a white-dwarf comparently heavier pulsar with a white-dwarf comparent **O** Masses of 2 M_{\odot} stars combined and the same used observations of this pair's orbital dance to (Shapiro delay & racidem strengthens of determine the pulsar's mass, which means NICER researchers have an **Matteuble 1901** independent measurement that they can $\mathbf{1}$ from a second teaming the second teaming companion. Other astronomers have used observations of this pair's orbital dance to Ex Comparison between the $\mathbf{M} = 1.34 \pm 0.16$ \mathbf{M}_\odot from a second target, a slightly heavier pulsar with a white-dwarf compan The control control of the golden and the golden and the star and the star in the star in the star in the star
The star in the ρ is a set \overline{O} Other astronomers have used observations of this pair's orbital dance to independent measurement that they can use to validate their findings. $\mathbf{M} = \mathbf{1.34} \pm \mathbf{0.16} \, \mathbf{M}_{\odot}$

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Moasure **Comparison** ^œ Comparison between theory and experiment difficult because measurements have compli
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The golden age of neutron-star physics has arrived $\color{blue}25.07$

other astronomers have used observations of the use of this pair \mathcal{L}

NEWS FEATURE | 04 March 2020

The golden age of neutro physics has arrived

These stellar remnants are some of the Universe's mos they are finally starting to give up their secrets.

NEUTRON STARS : **DATA** (contd.) MDE . MATA $(constant)$ radius measurements. At the same time, the team is beginning to analyse data

Adam Mann

CONSTRAINTS on **EQUATION of STATE** \sim and \sim and \sim and \sim . Here, we largely follow the procedure outlingualis din Reformation de la terme approache a possession de la context de la terme approache a la context
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from observations of massive neutron stars networks for the inference procedure [57–63] or remove e altrons-of-state that do not represent that the neutron of the state of the state of the state in the state o

Simplest forms of exotic matter (kaon condensate, quark matter, …) **ruled out** pected to be continued to be continued to be continued to be continued to be a spinned to be continued to be a prossioning of ox Condensace, quantificately \ldots stributed in terms of the speed of sound, the speed of sound, the sound, the sound, the sound, the sound, the s

Tolman - **O**ppenheimer - **V**olkov $Equations$ *r* @*m*(*r*) @*r*

where *G^N* is the gravitational constant. Given an equation of state (EoS) *P*("), i.e. pressure as a function of energy density ", this system can be solved with the boundary condition *m*(*r* = 0) = 0 and a central pressure *P*(*r* = 0) = *Pc*. The mass of the star is given as *M* = *m*(*R*)=4⇡ R *^R* ⁰ *dr r*²"(*r*), while the star radius *R* is determined as the point at which the pressure vanishes, *dP*(*r*) *dr* = *G* ["(*r*) + *P*(*r*)] ⇥ *m*(*r*)+4⇡*r*³*P*(*r*) *r* [*r* 2 *G m*(*r*)] *dm*(*r*) *dr* = 4⇡*r*²"(*r*) A. Akmal, V.J. Pandharipande,

Stiff equation-of-state $P(\varepsilon)$ required \mathbf{F} counting of the $\mathbf{D}(\cdot)$ required n equation-or-state L (e) required $P(\varepsilon)$

 $\partial \varepsilon$

SOUND VELOCITY and EQUATION of STATE

Key quantity : Speed of Sound

| displays characteristic signature of **phase transition** or **crossover**

 $\frac{2}{s}(\varepsilon) = \frac{\partial P(\varepsilon)}{\partial \varepsilon}$

 c_s^2

 $\partial P(\varepsilon)$

$$
P(\varepsilon) = \int_0^\varepsilon d\varepsilon' c_s^2(\varepsilon')
$$

Baryon density $n_B = \partial P/\partial \mu_B$ **Baryon chemical potential** $\mu_B = \partial \varepsilon / \partial n_B$

! Constrain parameters *θ* based on **theory and** \bigoplus Gibbs - Duhem equation (T=0) $P + \varepsilon = \mu_B n_B = \sum$ *i µⁱ nⁱ*

INFERENCE of SOUND SPEED and RELATED PROPERTIES of NEUTRON STARS

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By Laura Sanders

INFERENCE of **EQUATION** of STATE To generate the PP model, the three polytropic indices are varied within the ranges ¹ 2 [1*,* 4*.*5], ² 2 [0*,* 8], To generate the PP model, the three polytropic indices are varied within the ranges ¹ 2 [1*,* 4*.*5], ² 2 [0*,* 8], FERENCE of EQUATION of STATE |

EQUATION OT STATE and SOUND VELOCI
As a set of the set of **EQUATION of STATE** and **SOUND VELOCITY** - **boundary conditions -**

NEUTRON STAR MATTER : EQUATION of STATE

L. Brandes, W.W., N. Kaiser _i, Phys. Rev. D μ_X (2023) 014011 ; Phys. Rev<mark>. D 108 (2</mark>023) 094014 - L. Brandes, W.W. : Symmetry 16 (2024) 111

Comment : SPEED of SOUND exceeding CONFORMAL BOUND

Bayesian inference of sound speed in neutron star matter

Sound speed as function of baryon

prediction of ChPT given by Eq. (4.11). The horizontal line (orange) depicts the conformal bound, α

L. Brandes, W. W., N. Kaiser : Phys. Rev. D 107 (2023) 014011 ; Phys. Rev. D 108 (2023) 094014

2*.*5

Mass₁₂₉ Radius relation (TOM) **C** Tidal deformability **Bayesian inference posterior bands** (68% and 95% c.l) 2*.*0 1*.*5 ${\bf M}$ \mathbf{M}_{\odot} **PSIO 10030 + 04 M** 4U **170dSS**129

L. Brandes, W. W. (2024)

$\overline{}$ *^c* below 2 min *s,* 1, as ^a function of the maximum mass *.* ⁰

⁰ *n/n* **NEUTRON STAR PROPERTIES** (contd.)

L. Brandes, W. W., N. Kaiser : Phys. Rev. D 108 (2023) 094014

at densities $n_B \sim 4 - 6 n_0$

NEUTRON STAR PROPERTIES (contd.)

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References The huge multipude of the details of the state in the position A Quinat und at teler egeschope avitlence against small
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5 **s onlike to hear a fraction of the individual stars of even up to MOPIDAL PHAT** In CITS REFINING CONDUCT TO REFERENCES FOR THE AUTHOR SPEEDS with a line with mass **Pristical Professor Pierrescopic** was die rent parametrizations and accordingly dillerent productions de with the music music sentent compassed to the consistent evidence it is because tarritation as strong first order phase transition in the core of neutron stars with mass *M* 2*.*0 *M* is fairly On Vaith to all the contribution of a the current data. With the curry field the Bayes factors in Fig. 6 functions in Fig. 6 functions in Fig. 6 functions of the BR hEOOOOO strong. The Bayes factors factors for the Bayes for the Bayes of t evidence for maximum masses smaller than *M* . 1*.*9 *M*, because all relevant Express and Europe Support the Mail 11/7. order to fulfil the Shapiro and NICER constraints. Numerical values of the Bayes factors of the BPhys. Rev. 19108 (2011) t ζ $\bigotimes_{S,\text{mmin}}^S \bigotimes_{\mathcal{C}}^S \mathbf{W}$ maximum in the found constitution in Tab. In India in Tab. The found of the found in $\frac{1}{N}$ data, the euros all and ence against small sound speeds c22 Entre Legion Companies to portucilly controlled to the companies of the Manuscript of the Manuscript of the Ma *M* 2*.*1 *M*. of smaller minimum speeds of sound, *^B^c*² The Refunction of Referred Boogs, 195, 196, 221 h Sulley La **Basting of 22 at than 14 analyspound speeds**utron stars weth dividence it award in their analyses the authors with the second second in the authors of the authors in the second in dique de l'accordingly different parametrizations and accordingly different p distributions. With the pure distribution of the second consistent in the second stribution of the second safe the say that a strong first-order phase transition is the core of the core of the core of a stars with $\frac{1}{2}$. OTHER CORE of $\frac{1}{2}$ ormation, Foin, thenework windstandliksdata. FWIth the Gew as
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Enterpreted the finding of the final state of the final state of the final state of the final state of the final the part is the parametric the part of **CHATRIN SKOCH PROTHERS OGGE for neutron st** *M* 2*.*1 *M*. data, there is strong evidence against small sound speeds, **BEFFECTE IN REFERENCE CONTRACTORS CITY QUUILUID larger than close BACTIONS FINCL** ACCOLUINGLY CHILERENT DY With Mass **Mass and Mass Corporate and Second** County and County
Cardinal Mass and the authority in the authors use of a condition of a little re de against that with the with the with the sound of the studies of the s sape that say three racs principles that phase trans the core of $\frac{1}{2}$ is the core of $\frac{1}{2}$ of $\frac{1}{2}$ is fairly as $\frac{1}{2}$. O $\frac{1}{2}$ of $\frac{1}{2}$ Q in Hierre the color of the current data on the SH_{W} **er marijin from pressure black L.L.** ever is on the run strange work to be structed and strong is the Bayes factors factors for a plate at $4\times$ evidence for masses states and states and abeau [**be than a relevant from the second theory of the support the support of the support of the second of the support of** order to fulfill the Shapiro and Nick Ludger the St merical values of the Bayes factors and the Bayes factors and the Bayes factors of the Bayes *s,*min*>*0*.*1 $\frac{1}{2}$ in the found in Table in Table in Tab. (Appendix C. 2001) $\lim_{\alpha\to 0} \frac{1}{\alpha}$ **sexus were thereon encements est type and more inservations of the stars of th M 22.1 12.1 12.1 BEATER IN REFORMATION SOUTH SOLUTH SPEEDS.** THE AUTHORS AND SOLUTION SPEEDS. **day of the case By anglewiden ce** cordingly differently wath dutch mass in the authority of a material and a more uses the authority of the authority of a model of the authority of the authorit die die rent parametrizations and accordingly district prior to the prior prior prior prior to the prior of the G of G distributions. We have \mathcal{L} is the \mathcal{L} monumeries. saft to say that with which we have the union of the phase ormation french the mass of the post with sandy \overline{S} with \overline{S} \overline{W} under with the state of the current data. White the new infor a famous for from the black widow pulsar PSR John the black the Bayes of Bayes factors in Fig. 6 further in Fig. 6 functions in Fig. 6 functions in Fig. 7 functio new stars with the with masses with masses up to a little with the with masses with $\frac{1}{2}$. streau Lon evidence for maximum masses smaller than *M* . 1*.*9 *M*, BECHECAUSE ALL RELEVANT SUPPORT TULISE IIIDE **order to fulfil the Shapiro and NICER constructions.** messament repair bandings Reves hold (2013) 6940 F41 \circledast ₃) 094 $\frac{1}{2}$ in Table (11) in $\frac{1}{2}$ in $\frac{1}{2}$ in $\frac{1}{2}$ in $\frac{1}{2}$ in $\frac{1}{2}$ in $\frac{1}{2}$ in $\frac{1}{2}$ data data time is strong the strong every speed to the second speeds of the speeds of the speeds of the speeds **sy superior of the stars with manufacturers with manufacturers with manufacturers with** $\frac{1}{10}$ **DECOTIBE CHILLETTY ELLERCLERS SOLDICIP** SUPPOI U WILES **BOL WELLSHEETHE BUNEW REVERSED FOR REV.** With Mass **Mass 20 Million** 10p.
- 50. Hence Hence Hence Hence Hence Hence Hence beated ps as that all strong fin r different data, the cafest on that Riange and Soulary in the Soular Construction of the Soular Construction of the Nu-**Mathematic Candal Company c faller egeselder Art**lence.against sm maximum de signed in Tab. Shepaliro Stenen the Bayes factors corresponding to a stronger of street minimum speed as a sound, and so the sound, and so the sound, and speed in the sound, and so the sound, **s, etc.**
Slatn + heirs **c**
2007 **s, ain their analyses** rile to say that a strict of list -order phase to save te page of the description of the second of the conduct o fact it to the fact it to the surfact that the corrections of the segments cion to contribute the entire set of a set of a set of a set theory construction of the finding state with the finding of the finding t corresponds in the parametrization employed in the present work allows allows the present **ex and the dition frequency of the complex planes in the complex phases.**
The the district to describe the complex phases. We have a series of the complex phases of the complex phases. **quantifying existing dence comparison of line of the line of the comparison of the comparison of the comparison of the comparison of the compa** the courance of small speeds **extreme expendience** गुळे
नि*र* 3 115 004 **for all news the stars in the ? mass range and the second later** L. Brandes, W. W. W. R. Kaiser : Phys. Rev. D 108 (2023) 094014 **c M . 2 19 20 70 6**

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order phase transition in the core of the core of the core of the core of the stars. The core of the c

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for a forming the complexibility to describe complex phases. We have complex phases to describe the complex ph

FIG. 6. Bayes factors *^B^c*²

QCD TRACE ANOMALY and CONFORMALITY in NEUTRON STARS

Y. Fujimoto, K. Fukushima, L.D. McLerran, M. Praszalowicz : Phys. Rev. Lett. 129 (2022) 252702

- **Trace of energy-momentum tensor :** $T^{\mu}_{\mu} = \Theta =$
- Finite T and μ_B : disconnected mass-radius relation with μ

Bayes factor analysis: Bayes ractor analysis:
Strong evidence for $\Delta < 0$ $(P > \varepsilon/3)$ at densities $n_B \gtrsim 4 n_0$ **M** Bayos factor analysis: α ^t depoities $m - \geq 1$ m at densities $n_B \gtrsim 4 n_0$ α ^t densities $m = 1/m$. at densities $\|u_B\|_2^2$ + $\|u_0\|_2^2$ λ at densities $\forall \nu_B \approx 4 \nu_0$ $\frac{1}{2}$ disconnected by $d\mathbf{u} \sim 4 \pi \nu_0$

Conformal limit : $\Delta \rightarrow 0$ **O** Conformal limit: $\Delta \rightarrow 0$ cal data. Furthermore, the authors already note that the cal data. Furthermore, the authors already note that the

$$
\langle \Theta \rangle_{T,\mu_B} = \varepsilon - 3P
$$

O Trace anomaly measure

$$
\Delta \equiv \frac{\langle \Theta \rangle_{T,\mu_B}}{3\varepsilon} = \frac{1}{3} - \frac{P}{\varepsilon}
$$

L. Brandes, W. W., N. Kaiser Phys. Rev. D 108 (2023) 094014 L. Brandes, W.W. (2024) 0*.*50

INTERMEDIATE SUMMARY

Evidence against **strong 1st order phase transition in neutron star cores not excluded: baryonic matter or hadron**-**quark continuous crossover**

- including heavy $(M\simeq 2.3\,M_{\odot})$ galactic neutron star and NICER news $\sqrt{ }$ 3 **in neutron star cores EXECUTE:** even **stiffer equation of state** required than previously expected almost **constant neutron star radii** $(\mathbf{R} \simeq 12 \pm 1 \; \mathrm{km})$ for all masses
	-
- **No extreme central core densities even in the heaviest neutron stars:** $n_B< 5\ n_0$ for $M\le 2.3\ M_\odot$ (68% c.l.)
	-

Part Two Phenomenology, Models

and

Possible Dense Matter Scenarios

C

COLD MATTER at EXTREME DENSITIES Hadron - **Quark Continuity**

Outlook : How Bayes-**inferred baryon chemical potential can help improving EoS models** ⁰ *n/n* \mathcal{F}_1 , and \mathcal{F}_2 and \mathcal{F}_3 and \mathcal{F}_4 and \mathcal{F}_5 and \mathcal{F}_6 and \mathcal{F}_7 and \mathcal{F}_8 and \mathcal{F}_9 and \mathcal{F}_9

Example: QHC equation of state from **QHC18** to **QHC21** n of state from

$\bar{q}q$ ¯qq $\bar{q}q$ Z 2 $\ddot{}$ 1 $[\text{fm}^{-1}]$ 0 **baryonic core** $\langle \mathrm{r}^2 \rangle_{\mathrm{B}}^{1/2}$ $_{\rm B}^{1/2}\simeq 0.5\,\,\rm fm$ **Separation of scales** $\left(\frac{R_{cloud}}{R_{core}}\right)^{3}$ $\gg 1$ 3

SIZES of the **NUCLEON**

- **Low-energy QCD: spontaneously broken chiral symmetry + localisation** (**confinement**)
	- **NUCLEON**: compact valence quark core + mesonic (multi $\bar{q}q$) cloud
		- example: Chiral Soliton i'iodel of **Historic example: Chiral Soliton Model of the Nucleon**

$$
G_i(q^2) = G_i(0) + \frac{q^2}{\pi} \int_{t_0}^{\infty} dt \frac{Im G_i(t)}{t(t - q^2 - i\epsilon)}
$$

$$
\langle r_i^2 \rangle = \langle r_i^2 \rangle_{cloud} + \langle r_i^2 \rangle_{core} =
$$

$$
\frac{6}{\pi}\left[\int_{t_0}^{t_c} \frac{dt}{t^2} S_i(t) + \int_{t_c}^{\infty} \frac{dt}{t^2} S_i(t)\right]
$$

Detailed spectral analysis of accurately determined empirical form factors

N. Kaiser, W.W. : Phys. Rev. C110 (2024) 015202

FORM FACTORS of the NUCLEON (contd.)

form factor J^{π} (cloud) empirical rms radii **extracted core radii**

- **isoscalar electric** $G_E^S(q^2)$ 1⁻ $\langle r_S^2 \rangle^{1/2} = 0.78 \pm 0.01 \, \mathrm{fm}$
- **isovector electric** $G_E^V(q^2)$ 1[–] $\langle r_V^2 \rangle^{1/2} = 0.90 \pm 0.01 \, \mathrm{fm}$

isovector axial $G_A(q^2)$ 1⁺

mass

 $=\langle p' | T_{\mu}^{\mu} | p \rangle$ $G_m(q^2)$ 0^+ $\frac{\langle r_m^- \rangle^{-1}}{D}$ \equiv 0.55 \pm 0.03 I
D. Kharzeev : Phys. Rev. D104 (2021) 054015

 $\langle r_m^2 \rangle^{1/2} = 0.53 \pm 0.04 \, \mathrm{fm}$

 $\langle r_A^2 \rangle^{1/2} = 0.67 \pm 0.01\,{\rm fm}$ $(\langle r_A^2 \rangle^{1/2} = 0.68 \pm 0.11 \,\text{fm})$ R.J. Hill et al. : Rep. Prog. Phys. 81 (2018) 096301

Y.H. Lin, H.-W. Hammer, U.-G. Meißner PRL 128 (2022) 052002

$\langle r_m^2 \rangle^{1/2} = 0.55 \pm 0.03 \, \mathrm{fm}$

N. Kaiser, W.W. : Phys. Rev. C110 (2024) 015202

 $\langle r_S^2 \rangle_{core}^{1/2} = 0.50 \pm 0.01 \, \text{fm}$

S. Adhikari et al. : arXiv:2304.03845

$$
\langle r_A^2 \rangle_{core}^{1/2} = 0.53 \pm 0.02 \, \text{fm}
$$

$$
(0.5 \pm 0.2)
$$

 $\langle r_m^2 \rangle_{core}^{1/2} = 0.48 \pm 0.05 \, {\rm fm}$

$$
\langle r_V^2 \rangle_{core} \simeq 0 \, (\pm 0.02) \, \mathrm{fm^2} \, \mathrm{II}
$$

 $\overline{q}q$

 $\overline{q}q$

¯qq

TWO-**SCALES Picture of the NUCLEON** : **Implications for DENSE BARYONIC MATTER**

decreasing in-medium pion decay constant $f_\pi^*(n_B)$

$$
R_{core} \sim \frac{1}{2} \, \text{fm}
$$

Hard baryonic core governed by gluon dynamics expected to remain **stable** with increasing baryon density up until

$$
\langle r_S^2 \rangle_{core}^{1/2} \simeq \langle r_A^2 \rangle_{core}^{1/2}
$$

$$
{core}^{1/2}\simeq \langle r{m}^{2}\rangle _{core}^{1/2}\equiv R_{core}\simeq \frac{1}{2}\text{ fm}\bigg \vert
$$

hard compact cores begin to touch and overlap

baryonic cores still separated, but subject to increasingly strong repulsive Pauli effects

TWO-**SCALES Scenario for DENSE BARYONIC MATTER**

Baryon densities

 $n_B \sim n_0 = 0.16$ fm⁻³

Tails of mesonic clouds overlap : two-body exchange forces between nucleons

 $n_B\gtrsim2-3\,n_0$

Soft $\bar{q}q$ clouds delocalize : **percolation** \rightarrow many-body forces

Compact nucleon cores begin to touch and overlap at distances $d\lesssim 1\,{\rm fm}$ (**but still have to overcome the repulsive NN hard core**) $n_B > 5 n_0$ (beyond central densities of neutron stars)

K. Fukushima, T. Kojo, W.W. Phys. Rev. D 102 (2020) 096017

S. Aoki, T. Hatsuda, N. Ishii االعباد العامل العباد المن العباد المن العباد ا
123 (2010) 19 oki, I
heo<mark>l</mark>

S. Aoki Eur. Phys. J. A49 (2013) 81 <mark>Aoki</mark>
140. (2012)

– Sanity check with Lucsher's finite volume formula –"

$3.4 \cdot 1.6$

S. Aoki, T. Doi arXiv:2402.11759

CHIRAL PHASE TRANSITION in DENSE BARYONIC MATTER ?

M. Drews, W.W. : Prog. Part. Nucl. Phys. 93 (2017) 69 — L. Brandes, N. Kaiser, W.W. : Eur. Phys. J. A57 (2021) 243

- **Studies in chiral nucleon-meson field theory**
- **Mean-field** approximation (MF) : Chiral order parameters realization in the Chandler of the Chandler contribution of the Chandler contribution of the Chandler Chandler olations. This first-order phase transition leaves its signature phase transition leaves its signature in the s $n_{\rm D} \sim 2-3n_{\rm o}$ \mathbf{m} as shown in Fig. 3 as a function of \mathbf{m} at baryon densities $n_B \sim 2-3\, n_0$ **chiral first**-**order phase transition**
- $\overline{}$ first instruction between the comparison between the MF $\overline{}$ **Vacuum fluctuations (EMF) :** \rangle $\frac{1}{2}$ $\frac{1}{2}$ **inclusion of vacuum terms), using the vacuum terms** $_{\rm EMF}$ \rightarrow smooth crossover f_π . shift chiral transition to high density **Internalies of the COST** of ϵ
- with a coexistence region extending up to *n* ! 3 *n*⁰ at which chiral symmetry is function of the symmetry of the symmetry of the symmetry and under the symmetry and unde cal such a quality phase change would also provided a such a substitution. have been noticeable in the empirical nuclear phenomenological nuclear p ogy and in heavy-ion collisions. With inclusion of vacuum t_{total} transition at low density disappears in the shifts of the shifts of the shifts of the shifts of the shifts to h $\frac{1}{2}$ and $\frac{1}{2}$ of $\frac{1}{2}$ \mathcal{F} inchi \mathcal{A}^{μ} stadhishig checcs of baryon chemical potential. A sudden jump from the vacabilising effects **Functional Renormalisation Group (FRG) :** $\int f_\pi$ **non-perturbative loop corrections and vacuum** of vacuum of vacuum of vacuum of vacuum involving **pions & nucleon-hole** excitations $\begin{bmatrix} \sigma \end{bmatrix}$ densities of the state of the state of the 3 *n*d the 3 *n*d the 3 *nd* facts **Figure 4 shows the corresponding effects** $\int f_\pi$ \int
	- uum expectation value "σ# = *f*^π takes place at *µ*⁰ = 923 ransition at $n_D > 6 n_o$ li and first-order α and α β further up, and the nucleon stars and the set of the set of the nucleon mass, and the nucleon mass, \overline{a} *M* $\frac{1}{2}$ $\frac{1}{2}$ **Chiral crossover transition at** *n^B >* 6 *n*⁰ **beyond core densities** in **neutron stars**

the ChNM model as described in the text. Shown is in particular the text. Shown is in par

the ChNM model as described in the text. Shown is in particular the text. Shown is in par

CHIRAL LIMIT $(m_\pi \rightarrow 0)$ **2nd order chiral phase transition in nuclear and neutron matter**

1000 1500 take *µ* $\overline{}$ to a update of fortive mass and parameters in the range of the range $m^{\ast}_{L}(n_{B}) = \sqrt{p_{F}^{2}+M_{N}^{2}(n_{B})}$ \mathbf{v} about one third as compared to the previous compared to the pr **Raryon chemi** $\mu_B - \mu_L(\nu_B) + \mu(\nu_B)$ $\ln \left(n \ln \left(n \ln \right) \right)$ and br μ *B*(*reB*)
cyesian-inferred *s,*min*>*0*.*1 *s,*min*>*0*.*1 **quasiparticle** Landau effective mass $\sqrt{t_{\rm eff}}$ $m^{\ast}_{L}(n_{B}) = \sqrt{p_{F}^{2}+M_{N}^{2}(n_{B})}$ \overline{D} on \overline{D} of \overline{D} on \overline{D} of pressure has increased by pressure \overline{D} **Baryon chemical potential** $\lim_{m \to \infty}$ in m^* (m $\overline{}$ to a update of fortive mass and parameters in the range of the range \mathbf{v} about one third as compared to the previous compared to the pr $\mu_B - \mu \nu_L (\nu_B) + \nu (\nu_B)$ and Dept^{re}
 bccentred **Landau effective mass** ${\sf take\ median\ of\ } \mu_B(n_B)$ $\overline{}$ *p*2 *^F* + *M*² *µ^B ^N* (*nB*) $\mu_B = m^*_L(n_B) + \mathcal{U}(n_B)$

> in the change of the stars. For a function $\begin{array}{ccc} \hline \ \hline \ \hline \ \end{array}$ **s, as a function of the maximum mass of the maximum mass of the maximum mass \begin{array}{|c|c|c|}\hline \textbf{1} & \text** in neutron stars. For a further documentation of the function of the function of the function of the function o
Technische Universität München

below *c*²

= ⁰ *ⁿ* in units of the nuclear saturation density, *ⁿ* density as a RELAVISTIC FERMI LIQUID **DENSE BARYONIC MATTER** in **NEUTRON STARS**

B. Friman, W.W. : Rhys. Rev. C100 (2019) 065807 L. Brandes, W.W. : Symmetry 16 (2024) 111

⁰ *n/n* **Baryonic Quasiparticles** :

 $\frac{1}{2}$ and $\frac{1}{2}$ a d" by their strong interactions and imbedded in mesonic (multi-pion) field **baryons** "dressed" by their **strong interactions** and imbedded in **mesonic (multi-pion) field**

*s,*min*>*0*.*1

*c*2

Neutron Star Matter : Fermi liquid / dominantly **neutrons** + ca. 5 % **protons**

Basics of (Relativistic) Fermi-**Liquid Theory**

G. Baym, S.A. Chin : Nucl. Phys. A262 (1976) 527 T. Matsui : Nucl. Phys. A370 (1981) 365

Density of states $m^* = \sqrt{p_F^2 + M^2(\rho)}$ at the Fermi surface $\frac{2}{F} + M^2(\rho)$ **O Density of states** $N(0) = \frac{m^* \, p_F}{\pi^2}$

$$
f_{pp'} = \sum_{\ell=0}^{\infty} f_{\ell} P_{\ell}(\cos \theta_{pp'}) \qquad F_{\ell} = N(0) f_{\ell}
$$

 $\sqrt{ }$ pp' \mathcal{F}_{pp} , $\delta n_p \delta n_{p'} + \ldots$ $n_p = \Theta(\mu - \varepsilon_p)$ **quasiparticle interaction** $\frac{\partial L}{\partial n_p}$ $\qquad \qquad \mathcal{F}_{pp'} = V \frac{\delta^2 E}{\delta n_r \delta n}$ $\delta n_p \delta n_{p^\prime}$ $= f_{pp'} + g_{pp'} \boldsymbol{\sigma} \cdot \boldsymbol{\sigma}'$

Landau parameters Quasiparticle interaction expanded in **Legendre series**

700 750 800 850 900 950 **P** 200 400 600 800 1000 $0 \t 1 \t 2 \t 3 \t 4 \t 5$ 0 m^*_L $\begin{bmatrix} \text{MeV} \ \text{S}^{50} \ \text{S}^{00} \end{bmatrix}$ $\begin{bmatrix} 0 & \mathcal{U} \ \text{MeV} \ \text{S}^{00} \end{bmatrix}$ u_L (u_B) u (u_B $m_L^*(n)$ *U*(n_B) *U* **QUASIPARTICLE POTENTIAL and FERMI**-**LIQUID PARAMETERS** $m^{\ast}_{L}(n_{B})$ from **chiral nucleon-meson field theory** & Functional Renormalisation Group **Quasiparticle effective potential** 0 2 4 6 -2 $\mathbf{F_{0}}$ \mathbf{F}_{1} **Landau Fermi-Liquid parameters** $U(n_B) = \sum$ *n* u_n $\sqrt{n_B}$ $n_{\rm 0}$ \sqrt{n} $F_0 =$ $\boldsymbol{m_L^*}$ $\boldsymbol{p_F}$ π^2 $\partial \mu_B$ ${\boldsymbol{\partial}}\boldsymbol{n_{B}}$ -1 $F_1 = -\frac{3U}{U}$ μ_B

 \overline{n}_I n_B/n_0

Strongly repulsive correlations including **many-body forces** with $n \geq 2$

Landau Fermi Liquid parameters of **liquid helium-3** at pressures P = (0 - 30) bar: $F_0(^3\text{He}) \sim 10 - 70$ $F_1(^3\text{He}) \sim 5 - 13$

LANDAU FERMI LIQUID PARAMETERS (contd.)

attractive van der Waals potential plus strongly **repulsive short**-**range core**

… **much larger** by magnitude than Landau parameters of **neutron star matter** !

Comparison with atomic liquid helium-3 in its normal phase at low temperature (3 K) G. Baym, Ch. Pethick : Landau Fermi-Liquid Theory (1991)

Neutron star matter at central densities is a **strongly correlated Fermi system** … but not as extreme as one might have thought !

D. S. Greywall, Phys. Rev. B33 (1986) 7520

CONCLUSIONS

Constraints on phase transitions in neutron star matter

Scenarios for cold dense matter in the core of neutron stars

- **stiff equation of state implied by Bayesian inference results**
- **strong first**-**order transition unlikely in neutron star cores**
- **central baryon densities** in neutron stars : $n_c < 5 n_0$ (68% c.l.)

- **hadron**-**quark continuity with "core + cloud" baryons : two**-**scales scenario: soft-surface delocalisation (percolation)**
	-
- **e.g. relativistic Fermi liquid featuring strongly repulsive many**-**body forces** between **baryonic quasiparticles**

Supplementary Materials

Example 1: ISOSCALAR ELECTRIC FORM FACTOR of the NUCLEON

$$
\begin{aligned}\n\mathbf{r} &= \frac{1}{2} \left[G_E^p(q^2) + G_E^n(q^2) \right] \qquad \langle r_S^2 \rangle = \langle r_p^2 \rangle + \langle r_n^2 \rangle \\
\mathbf{m} &= \langle r_S^2 \rangle^{1/2} = 0.775 \pm 0.011 \, \text{fm} \qquad \text{H.-W. Hammer, D-G. MeiBner} \\
\mathbf{r} &= \text{PRL 128 (2022) 052}\n\end{aligned}
$$
\nand

\nto find the probability of the following formula:

\n
$$
\langle r_S^2 \rangle_{core}^{1/2} \simeq 0.47 \, \text{fm}
$$
\nand

\n
$$
\langle r_S^2 \rangle_{core}^{1/2} \simeq 0.47 \, \text{fm} \qquad \text{or}
$$
\nand

\n
$$
\langle r_S^2 \rangle_{core}^{1/2} \simeq 0.47 \, \text{fm}
$$
\nand

\n
$$
\langle r_S^2 \rangle_{core}^{1/2} \simeq 0.47 \, \text{fm}
$$
\nand

\n
$$
\langle r_S^2 \rangle_{core}^{1/2} \simeq 0.47 \, \text{fm}
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\nand

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\langle r_S^2 \rangle_{core}^{1/2} \simeq 0.47 \, \text{fm}
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\langle r_S^2 \rangle_{core}^{1/2} \simeq 0.47 \, \text{fm}
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\langle r_S^2 \rangle_{core}^{1/2} \simeq 0.47 \, \text{fm}
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\langle r_S^2 \rangle_{core}^{1/2} \simeq 0.47 \, \text{fm}
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\langle r_S^2 \rangle_{core}^{1/2} \simeq 0.47 \, \text{fm}
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\nand

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$$
\langle r_S^2 \rangle_{core}^{1/2} \simeq 0.47 \, \text{fm}
$$
\nand

\n
$$
\langle r_S^2 \rangle_{core}^{1/2} \simeq 0.47 \, \
$$

$$
{re}^{'2}\equiv \langle r{B}^{2}\rangle ^{1/2}=0.50\pm 0.01\,{\rm fm}
$$

N. Kaiser, W. W. Phys. Rev. C110 (2024) 015202

Example 1I: ISOVECTOR ELECTRIC FORM FACTOR of the NUCLEON

$$
\text{lsovector electric form factor} \hspace{0.3cm} G_E^V(q^2) = \frac{1}{2} \left[G_E^p(q^2) - G_E^n(q^2) \right] \hspace{0.3cm} \langle r_V^2 \rangle = \langle r_p^2 \rangle - \langle r_n^2 \rangle
$$
\n
$$
\text{Empirical:} \hspace{0.3cm} \langle r_V^2 \rangle^{1/2} = 0.901 \pm 0.009 \text{ fm} \hspace{0.3cm} \text{Y.H.Lin, H.-W. Hammer, U.-G. Meißner} \hspace{0.3cm} \text{PRL 128 (2022) 052002}
$$

 $\langle r_V^2 \rangle_{core} = \langle r_p^2 \rangle_{core} - \langle r_n^2 \rangle_{core} = -0.025~\mathrm{fm^2}$ **… almost vanishing**

… clue and test case : in the limit of exact isospin symmetry, contributions from proton and neutron valence quark cores CANCEL

Detailed analysis using best-**fit spectral functions :**

Isovector charge radius almost entirely determined by **two-pion cloud**

N. Kaiser, W. W. Phys. Rev. C110 (2024) 015202

- **Axial form factor** *core cloud n* **Empirical :** G_A^{clquab} = g_A $\sqrt{2}$ 1 + 1.2 9*m*²
- νd scattering and νf \sqrt{f} \rightarrow \sqrt{f} \sim \sqrt{f} (from μp $\langle r_A^2 \rangle = 0.454 \pm 0.013 \text{ fm}^2$ **i** $\left\langle \int_{r_A}^{u_1} r_A \right\rangle = W$ **b**) $\langle r_A^2 \rangle = 0.46 \pm 0.16 \text{ fm}^2$ $\binom{2}{A} = 0.454 \pm 0.013~\mathrm{fm}^2$ $e p \rightarrow e n \pi^+$ dipole fits) $($ ^p $($ ^p $)$ can define an $($ $from *ud* scattering and$ \mathcal{L}_{p} / \mathcal{L}_{m} appointing **a)** $\langle r_A^2 \rangle = 0.454 \pm 0.013$ fm² $\langle \langle \rangle$. $\langle \rangle$ **b**)

Si(*t*) = *ImGi*(*t*)*/Gi*(0) **Example III: ISOVECTOR AXIAL FORM FACTOR of the NUCLEON** (from ⌫*^d* scattering and *^e^p* ! *^en*⇡⁺ dipole fits) *,* from [26, 27]. In the latter work [27] the *a*¹ ! ⇢⇡ ! 3⇡ R AXIAL FORM FACTOR of the NUCLEON | information needed in order to identify the meson-cloud second-cloud sec-cloud sec-cloud sec-cloud sec-cloud sec-

p

 $\sigma = g_A \mid$ $1 + \frac{1}{6} \langle r_A \rangle q_C$ *cloud* \cdots \mid \cdot *cor*e \cdot Hill, P. Kammel, W.C. Marciano, A. Sirlin \cdot *t* Rep. Prog. Phys. 81 (2018) 096301

$$
= g_A \left[1 + \frac{1}{6} \langle r_A^2 \rangle q_{cl}^2 \frac{1}{d} \mathbf{r} \cdot \mathbf{r} \cdot \mathbf{r} \right] \text{ } \underset{\text{Rdp. Prog. Phys. 81 (2018) 096301}}{\text{Cov}} \text{Rdp. Prog. Phys. 81 (2018) 096301}
$$

 $\overline{\mathcal{L}}$

*m*² *a* on spectrum dominated $\sqrt{2}$ $\langle r_p^2 \rangle = 0.71 \pm 0.01 \, \mathrm{fm}^2$ \setminus

 \int (from μp capture and νd scattering analysis) ν_{μ} for simple produces \sim \mathbb{Q} - \mathbb{Q}^2 , \mathbb{Q} defined by $\langle r_A^2 \rangle = 0.46 \pm 0.16$ fm² (1 + *a*) *,* (31)

[based on a) ; correspondingly larger uncertainty when using **b**)] Fig. 4, one finds *^a* = 0*.*¹² and ^h*r*²

 $\frac{1/2}{core} = 0.53 \pm 0.02 \; \textrm{fm}$ M. Kaiser, W.W. N. Kaiser, W. W. Kaiser, W. W. Kaiser, W. W. COPTERFERGY AND Rev. CLIO (2024) 015202 as a particular matrix of the setting $\frac{1}{2}$ and $\$ Phys. Rev. C110 (2024) 015202

Detailed analysis using three-pion spectrum dominated by broad a_1 meson : *detailed and determined* and determined a **Axial radius significantly smaller than proton charge radius**

$$
\langle r_A^2 \rangle = \langle r_A^2 \rangle_{core} + \frac{6}{m_a^2} \left(1 + \delta_a \right)
$$

$$
\langle r_A^2 \rangle_{core}^{1/2} = 0
$$

πп

$$
\delta_a = -\frac{m_a^3}{\pi} \int_{9m_\pi^2}^{tmax} dt \frac{\Gamma_a(t)}{t^2(t-m_a^2)}
$$

bin of *E* and *t*, which we denote *NJ/* wt (*E, t*). The en-**Example 25 Mass ("gravitational") for** better than the 45 MeV bin size used in this procedure. beam engineers, with the statistical uncertainties

reconstruction eciency "(*E, t*): $\frac{m}{2}$ $\frac{m}{2}$ $\frac{m}{2}$ $(r^2)^{1/2} - (0.55 + 0.55)$ $\langle r_m^2\rangle^{1/2}=(0.55\pm 0)$ $\langle r_m^- \rangle$ ^{-/-} = (0.55 \pm 0.03) i $\binom{2}{m}^{1/2} = (0.55 \pm 0.03) \, \mathrm{fm}$

 N D. Kharzeev : Phys. Rev. D104 (2021) 054015

tion over the corresponding range *t*min(*Ei*) *t*max(*Ei*), actor **C** Trace of QCD energy-mome ergy region, and compare these integrals with the total σ Mass ("gravitational") form factor **and Trace of QCD energy-momentum tensor** \overline{a} $G^{\mu\nu}_a G^a_{\mu\nu} + m_q (\bar{u}u + \bar{d}d) + m_s \bar{s}s|P\rangle$

We then fit the weighted *M*(*e*⁺*e*) distribution to obtample iv: \overline{C} two exponential functions. The constant \overline{C} the di↵erential cross sections, we integrate the fitted func-The inner bars represent the statistical errors and outer bars **Example IV: MASS RADIUS of the NUCLEON** added in quadrature. The open blue triangles represent the

Fig. 13. To parametrize them, they are fitted with a sum

total cross sections calculated by integrating the functions

FIG. 13. The measure of the means of the measured dividend the measured of the Recent GlueX update: S. Adhikari et al. ; arXiv:2304.03845

$$
G_m(q^2)=\langle P'|T^\mu_\mu|P\rangle=\langle P'|\frac{\beta(g)}{2g}G^{\mu\nu}_aG^a_{\mu\nu}+m_q
$$

$$
G_m(0) = M_N \simeq 0.94 \,\text{GeV}
$$
\n
$$
M_N = M_0 + \sigma_N + \sigma_s
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$$
(M_0 \gtrsim 0.9 \, M_N)
$$
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$$
\langle r_m^2 \rangle = \frac{6}{M_N} \frac{dG_m(q^2)}{dq^2} \Big|_{q^2 =}
$$
\n
$$
\langle r_m^2 \rangle^{1/2} = (0.53 \pm 0.04) \,\text{fm}
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2 \overline{c} *g* **g**

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 Nuclear**2023**, *1* Many-Body \widehat{a} \mathcal{Y} γ ity, 00185 Rome, Ita

arXiv:2306.01367

Article **Testing the Paradigm of Nuclear Many-Body Theory** $\overline{\mathbf{D}}$ **Testing the Paradigm of Nuclear Many-19-12 2006.01367 Omar Benhar** INFN and Departnent of Physics, Sapienza University, 00185 Rome, Italy; omar.benhar@roma1.infn.it *Particles* **2023**, 1, 1–11. https://doi.org/10.01367.html y-Body Theory Published: Received: $\overline{\mathbf{)}$ $\overline{\mathcal{Y}}$ 20
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Intuite has all an the top of that purclear systems can be accurately; cribed as collections of point-like particles. This picture, while providing a remarkably accurate described as collections of point-like particles. This picture, while providing a remarkably accurate lanation of a wealth of measured properties of atomic nuclei, is bound to break down in the highof freedom other than protons and neutrons are expected to come the validity of the description of dense nuclear matter in terms of play. Valuable information on the validity of the description of dense nuclear matter in terms of leons, needed to firmly establish its limit of applicability, can be obtained from electron–nucleus n transfer and low energy transfer. The emergence of u-scaling in nucleons belonging to strongly correlated pairs, indicates that at densities as \sim kinematic region, unambiguously showing that the beam particles couple to high-momentum orrelated pairs, indicates that <mark>at densities as large as five times</mark> atron star interior—nuclear matter largely behaves as a collection **correlation** ers, n
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