Astrophysical and Laboratory Studies on the Equation of State of Neutron Stars

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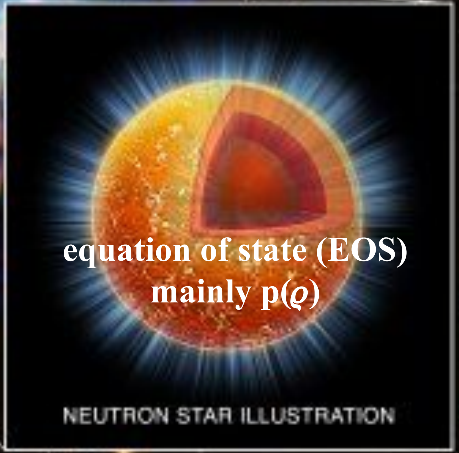


Many thanks for Invitation!

Workshop on Equation of State of Dense Nuclear Matter at RIBF and FRIB
RIKEN, 23-26 May 2023

Outline

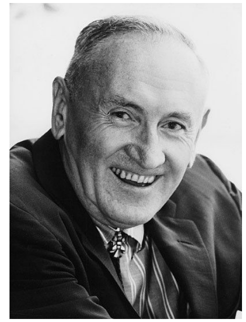
- **Basic** for neutron star structure and the EOS
- **Recent works** from connecting #consistently neutron star observations and nuclear experiments
- **What we learn** so far

What is the nature of the particles that make up neutron stars?

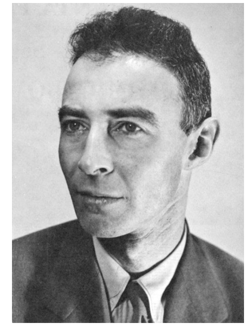
Lev Landau

James Chadwick

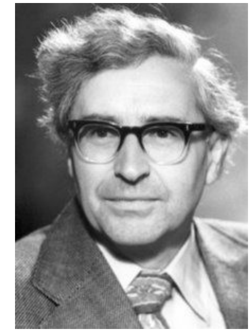
Walter Baade



Fritz Zwicky



J. Robert Oppenheimer



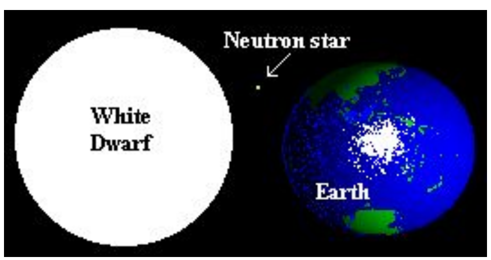
Antony Hewish

Dame Jocelyn Bell Burnell

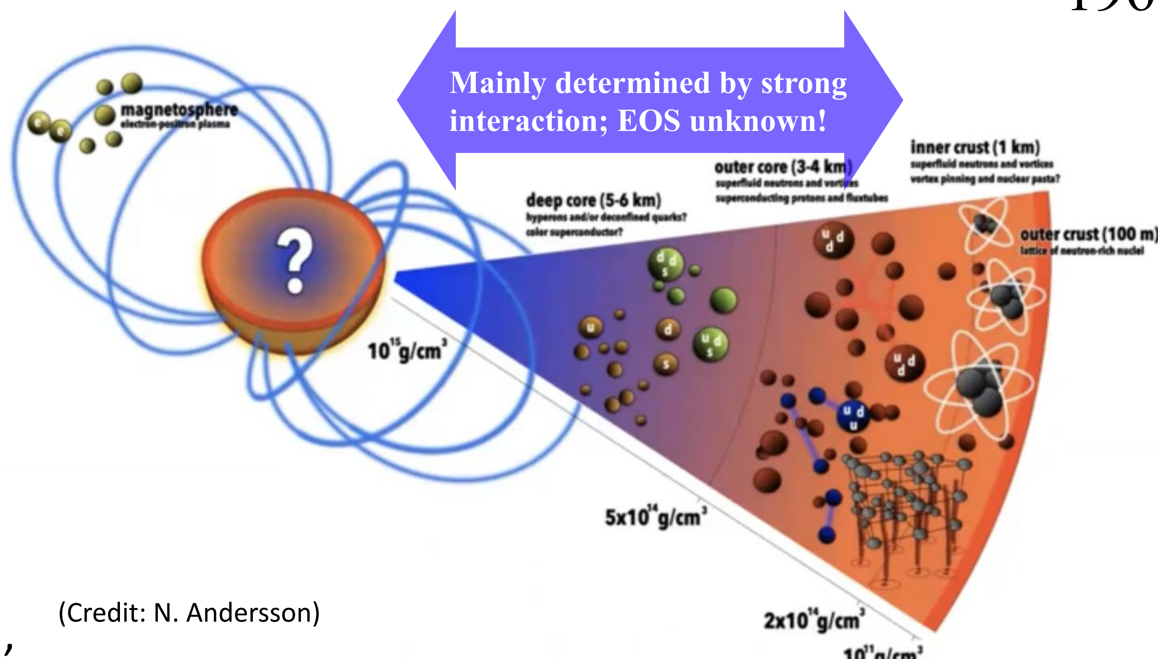
1967

1932-

"the density of matter becomes so great that atomic nuclei come in close contact, forming one gigantic nucleus."



A ~ 10^{57}; For R=10 km, M=1.4 $M_{\odot}$, average density ~6.9×10^{14} g/cm^3 ~(2-3) normal nuclear density ϱ_0



(Credit: N. Andersson)

Gravity, holds the star together (gravitational waves!)

Electromagnetism, makes pulsars pulse and magnetars flare

Strong interaction, determines the internal composition

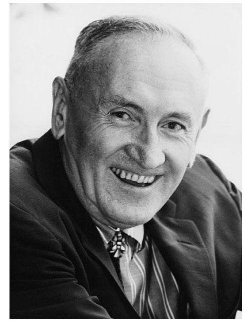
Weak interaction, affects reaction rates - cooling and internal viscosity

What is the nature of the particles that make up neutron stars?


Lev Landau


James Chadwick


Walter Baade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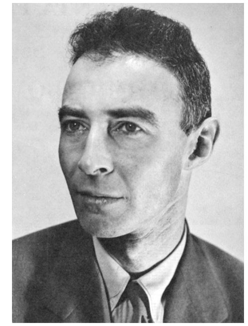
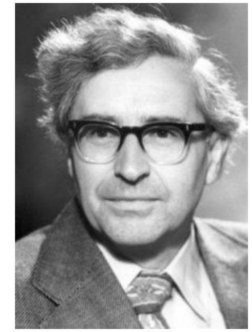

J. Robert Oppenheimer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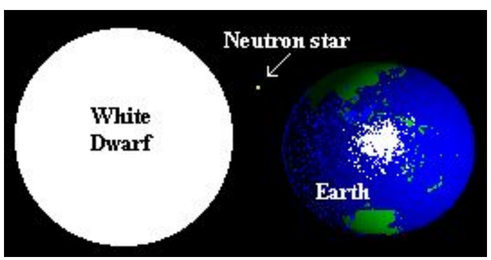
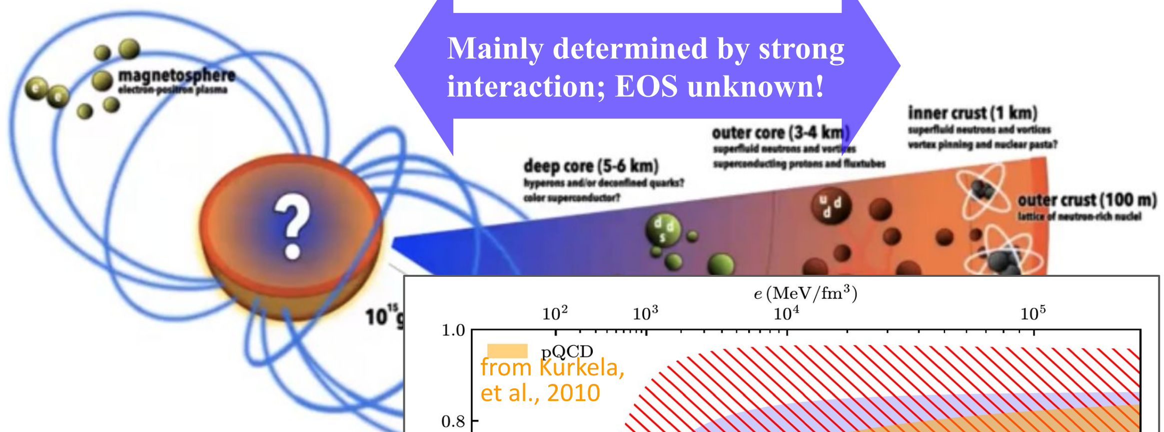
"the density of matter becomes so great that atomic nuclei come in close contact, forming one gigantic nucleus."



A ~ 10^{57}; For R=10 km, M=1.4 $M_{\odot}$,
average density ~6.9×10^{14} g/cm^3
~(2-3) normal nuclear density ϱ_0

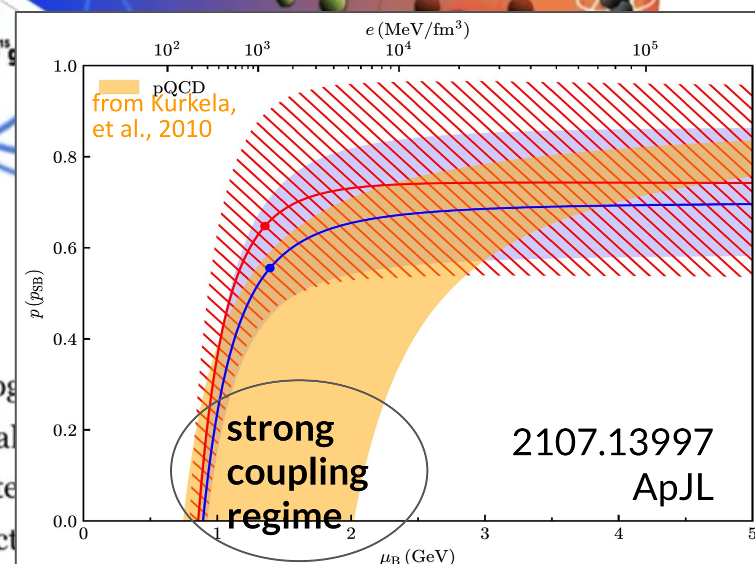
~several hundreds MeV;

Mainly determined by strong interaction; EOS unknown!



(Credit: N. Andersson)

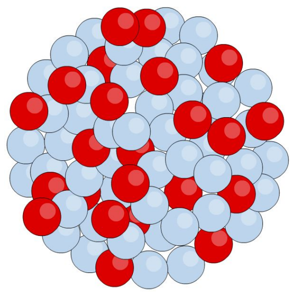
Gravity, holds the star tog
Electromagnetism, mai
Strong interaction, dete
Weak interaction, affect

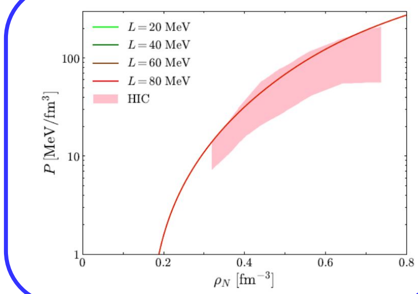


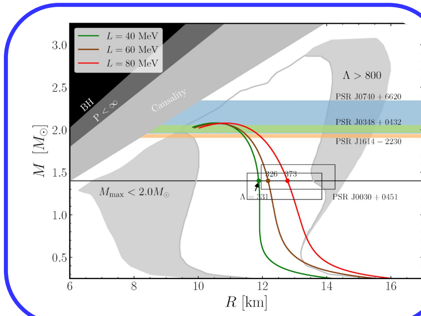
Exemplary QMF18 (Zhu et al.) neutron star EOS

-2020 Top Cited Paper Award

1. Model for interaction between particles → $\hat{\mathcal{H}}\Psi = E\Psi$ → **2. The EOS** → $G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$ → **3. NS observations (GW, photons, neutrinos)**

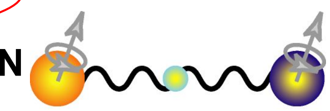






repeat!

$$\mathcal{L} = \overline{\psi}\left(i\gamma_\mu\partial^\mu - M_N^* - g_{\omega N}\omega\gamma^0 - g_{\rho N}\rho\tau_3\gamma^0\right)\psi - \frac{1}{2}(\nabla\sigma)^2 - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{3}g_2\sigma^3 - \frac{1}{4}g_3\sigma^4$$
$$+\frac{1}{2}(\nabla\rho)^2 + \frac{1}{2}m_\rho^2\rho^2 + \frac{1}{2}(\nabla\omega)^2 + \frac{1}{2}m_\omega^2\omega^2 + \frac{1}{2}g_{\rho N}{}^2\rho^2\Lambda_v g_{\omega N}{}^2\omega^2,$$



π,ρ,ω
(P, I, J symmetry)

L [MeV]	$g_{\sigma q}$	$g_{\omega q}$	$g_{\rho q}$	g_2 [fm^{-1}]	g_3	Λ_v
20	3.8620366	2.9174838	6.9588083	14.6179599	-66.3442468	1.1080665
40	3.8620366	2.9174838	5.4129448	14.6179599	-66.3442468	0.7693664
60	3.8620366	2.9174838	4.5830609	14.6179599	-66.3442468	0.4306662
80	3.8620366	2.9174838	4.0459574	14.6179599	-66.3442468	0.0919661

EOS contribution from isospin-asymmetry part:

$$\delta \equiv \frac{\rho_n - \rho_p}{\rho_n + \rho_p} \quad L \equiv 3\rho_0 \frac{dE_{sym}}{d\rho}(\rho_0)$$

$$E(\rho, \delta) = E_{SNM}(\rho) + E_{sym}(\rho)\delta^2 ,$$

ρ_0 [fm^{-3}]	E/A [MeV]	K [MeV]	E_{sym} [MeV]	L [MeV]	M_N^*/M_N /
0.16	-16	U(220,340)	U(28,45)	U(20,150)	U(0.55,0.80)

symmetry energy & slope

Zhu et al. ApJ 1802.05510

The unknown (high-density) neutron star (core) EOS

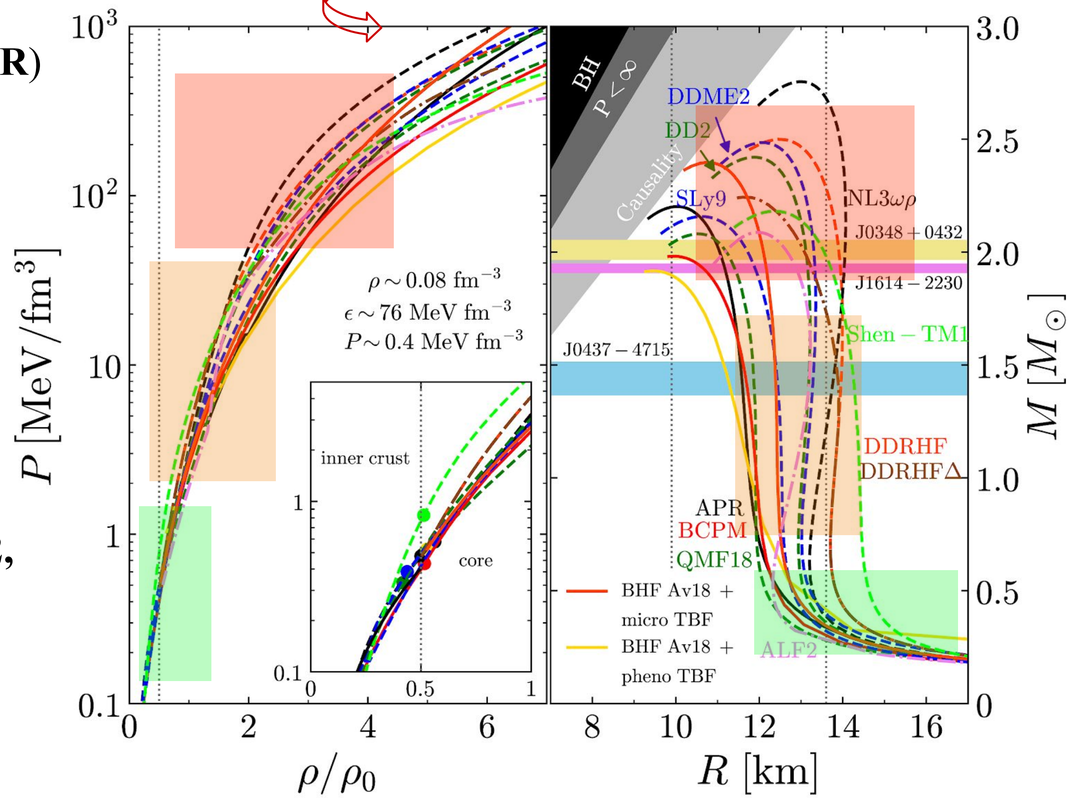
The problem is to find the EOS in a regime where laboratory measurements of particle interactions are inadequate and the necessary theories of multi-body interactions are still incomplete (LQCD, χEFT, etc).

a fan of different predictions on EOS: Better knowledge on uncertain nuclear symmetry energy (e.g., from neutron skin width) and non-nucleon df at high densities!?

Pheno

- Green's Function Monte Carlo
- Chiral Perturbation Theory (ChPT)
- Variational Many-Body (VMB; e.g., **APR**)
- V_{lowk} + Renormalization Group
- Relativistic Brueckner-Hartree-Fock (BHF)
- Dirac-Brueckner-Hartree-Fock (DBHF)
- Quark mean-field (QMF)
- Quark Meson Coupling (QMC)
- Relativistic mean-field (RMF; e.g., **DD2, NL3, TM1)**
- Skyrme energy density functional (e.g., **BSk20, Sly**)
- ...

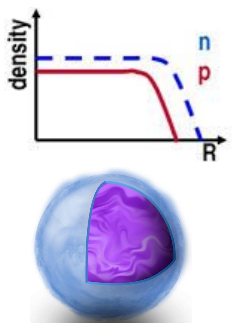
micro

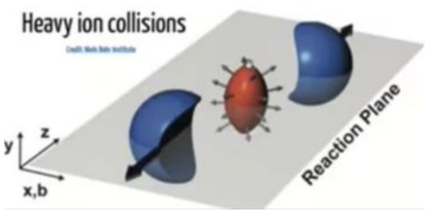


《致密物质状态方程：中子星与奇异星》李昂 胡金牛 鲍世绍 申虹 徐仁新, 2019 Nuclear Physics Review (in Chinese)

Experimental/Observational constraints on the EOS

- finite nuclei (especially neutron-rich, superheavy); ⇐ **mostly around saturation**
- collective flow/transport/meson production in heavy ion collision (HIC);





- PSR J0030+0451

$$M = 1.34^{+0.15}_{-0.16}\, M_\odot,\ \ R = 12.71^{+1.14}_{-1.19}\,\mathrm{km}$$

(Riley et al. 2019)

$$M = 1.44^{+0.15}_{-0.14}\, M_\odot,\ R = 13.02^{+1.24}_{-1.06}\,\mathrm{km}$$

(Miller et al. 2019)

- PSR J0740+6620 *(Cromartie et al. 2019)*

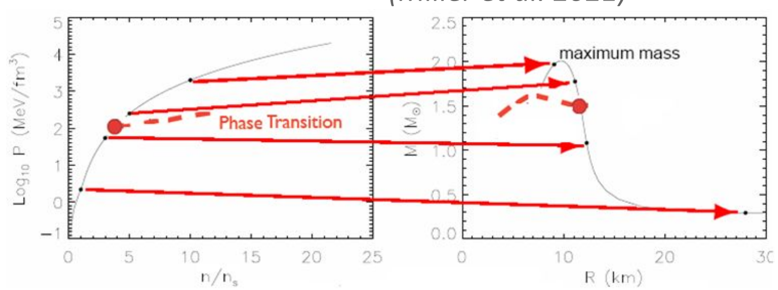
(currently most massive neutron star)

$$M = 2.072^{+0.067}_{-0.066}\, M_\odot,\ \ R = 12.39^{+1.30}_{-0.98}\,\mathrm{km}$$

(Riley et al. 2021)

$$M = 2.062^{+0.090}_{-0.091}\, M_\odot,\ R = 13.71^{+2.61}_{-1.50}\,\mathrm{km}$$

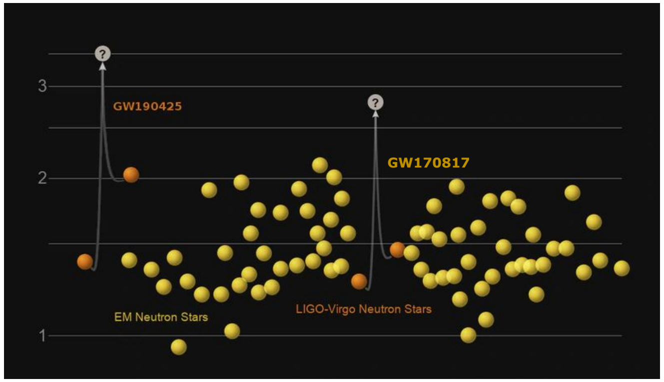
(Miller et al. 2021)



(Credit: J. Lattimer)

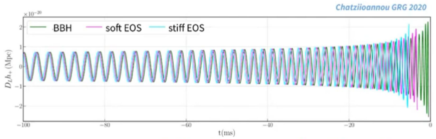
- neutron star binary:

GW+短伽玛暴SGRB+千新星kilonova



GW170817 (the 'golden' event)

GW190425



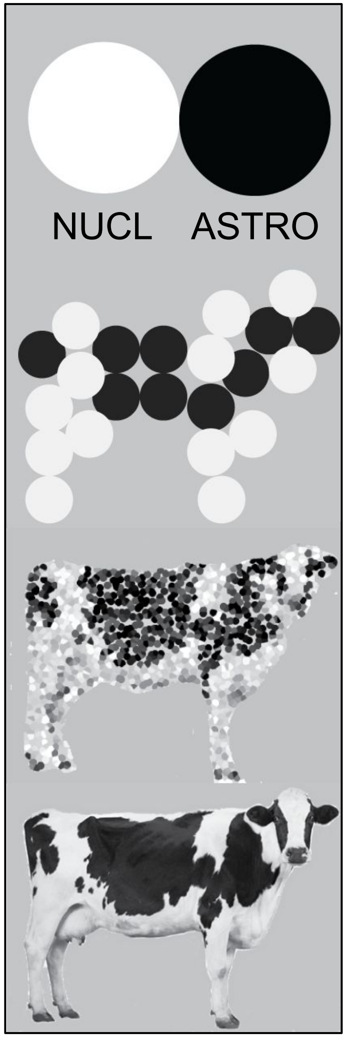
$$\mathcal{L}_{\rm NICER}(M,R|\boldsymbol{\theta}_{\rm EOS}\cup\{\varepsilon_c\},\mathbb{M}) = P_{\rm KDE}(M(\boldsymbol{\theta}_{\rm EOS};\varepsilon_c), R(\boldsymbol{\theta}_{\rm EOS};\varepsilon_c))$$

strain & waveform

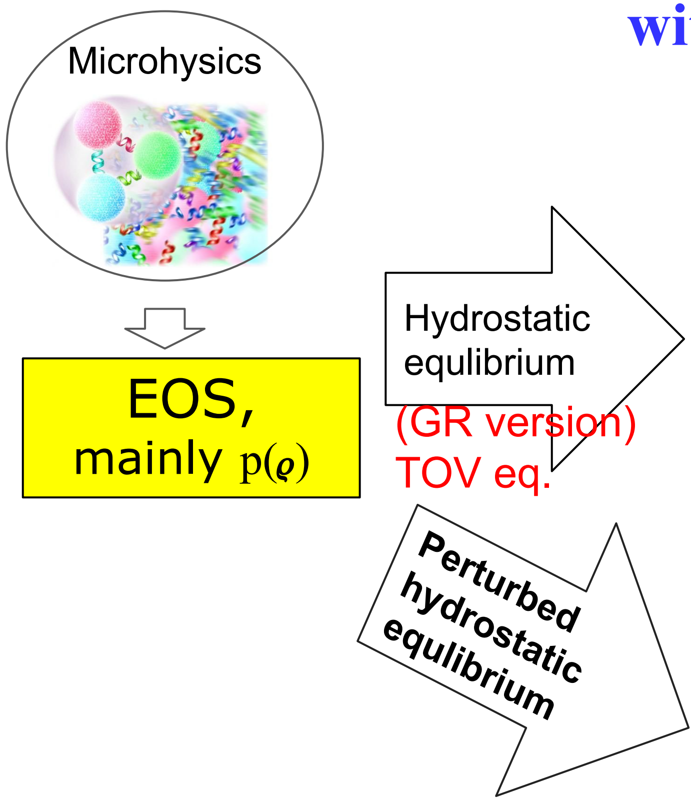
$$\mathcal{L}_{\rm GW}(d_{\rm GW}|\boldsymbol{\theta}_{\rm GW},\mathbb{M}) \propto \exp\left[-2\int_0^\infty \frac{|\tilde{d}(f)-\tilde{h}(f,\boldsymbol{\theta}_{\rm GW})|^2}{S_n(f)}df\right]$$

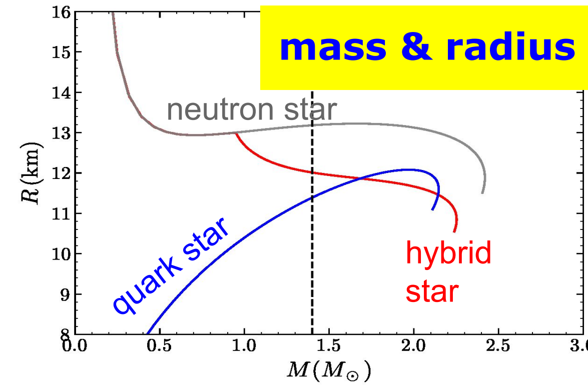
power spectral density

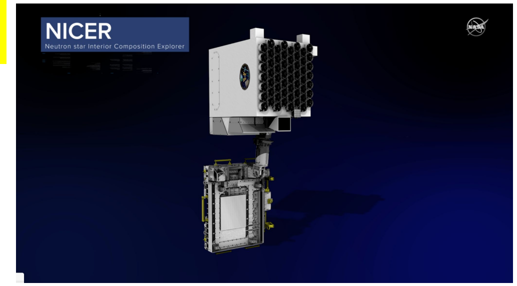
$$\boldsymbol{\theta}_{\rm GW} = \{M_1, M_2, \Lambda_1, \Lambda_2, \chi_{1z}, \chi_{2z}, \varphi, \Psi, \theta_{\rm jn}, t_c, d_L, \mathrm{R.A.}, \mathrm{Decl.}\}$$

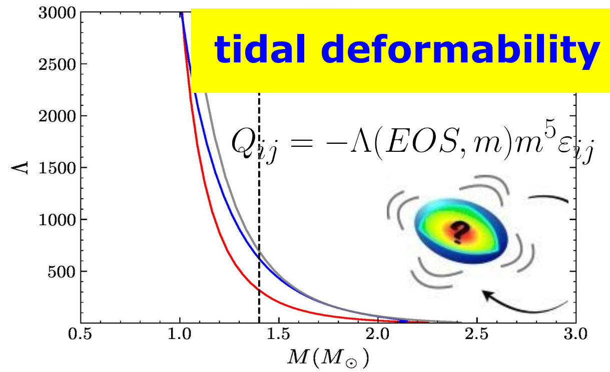


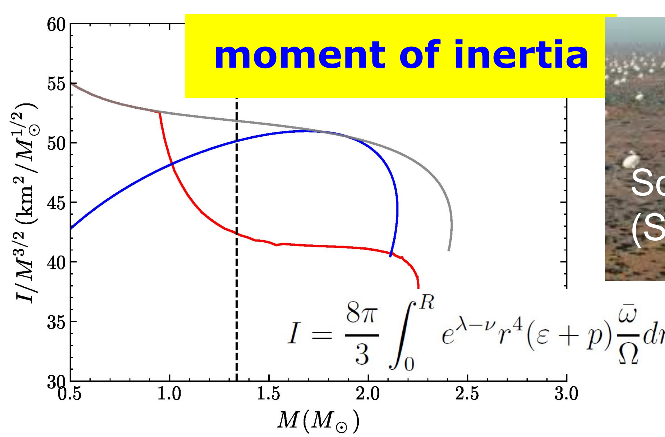
Macroscopic global properties of NSs have an intrinsic correlation with microphysical EOS











Very exciting future:

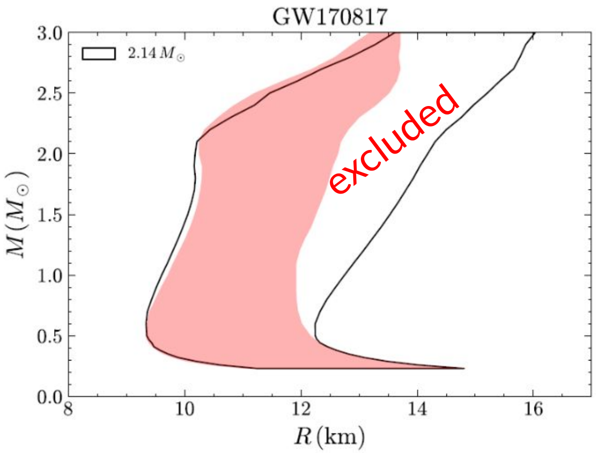
LIGO/Virgo/KAGRA, CE, ET;

HXMT, NICER, STROBE-X, eXTP;

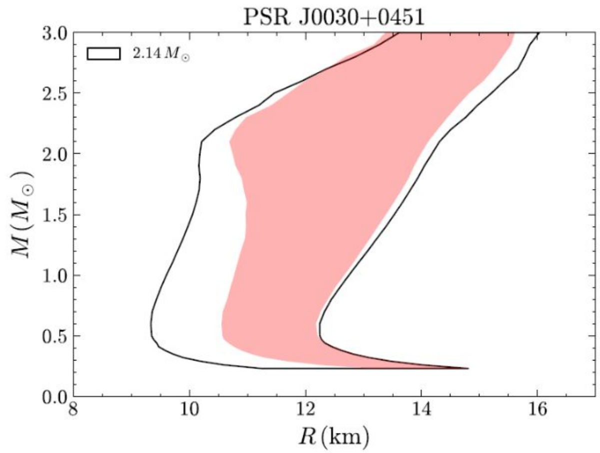
FAST, 平方公里阵列射电望远镜(SKA),...

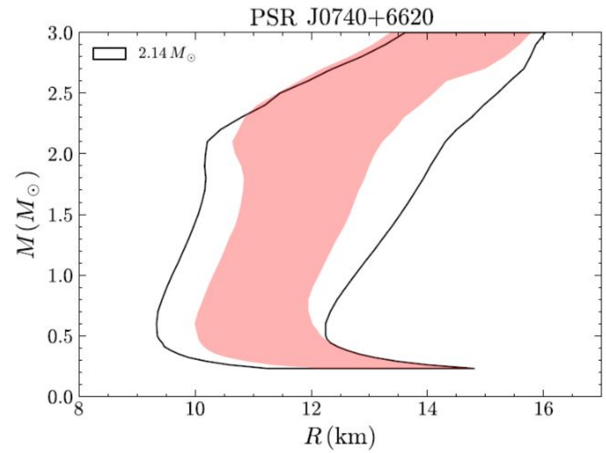
Important EOS constraints from neutron star observations

GW170817 Λ measurement

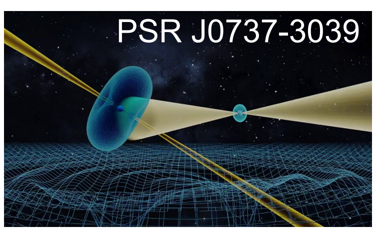


M & R measurements: light neutrons star vs. heavy neutrons star

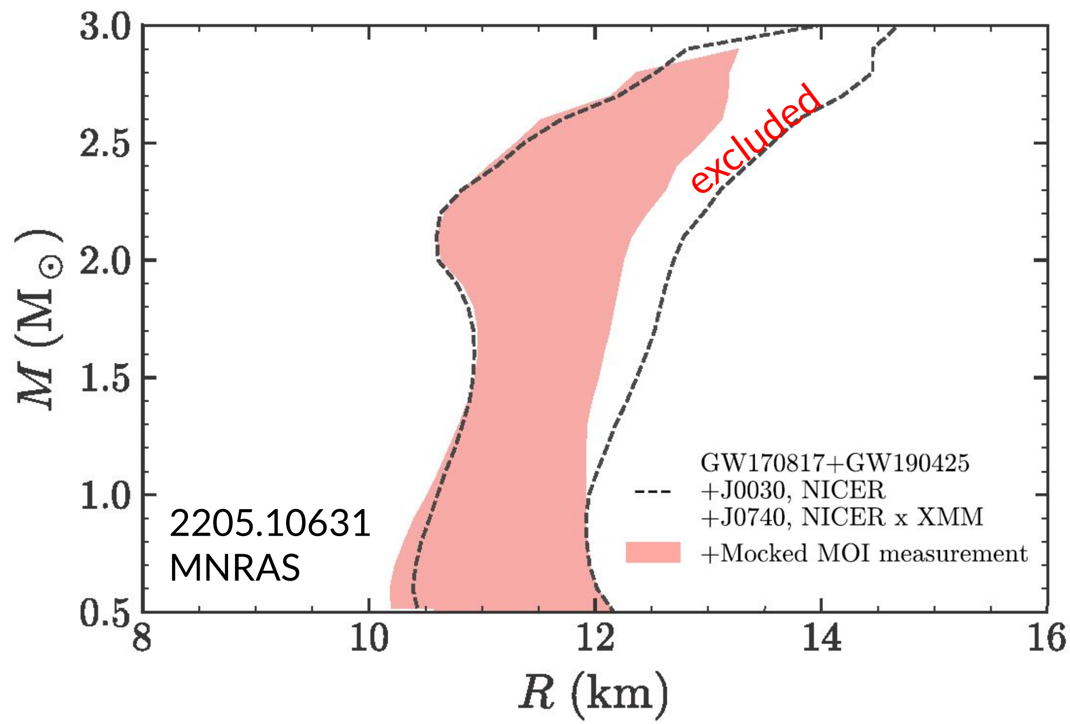




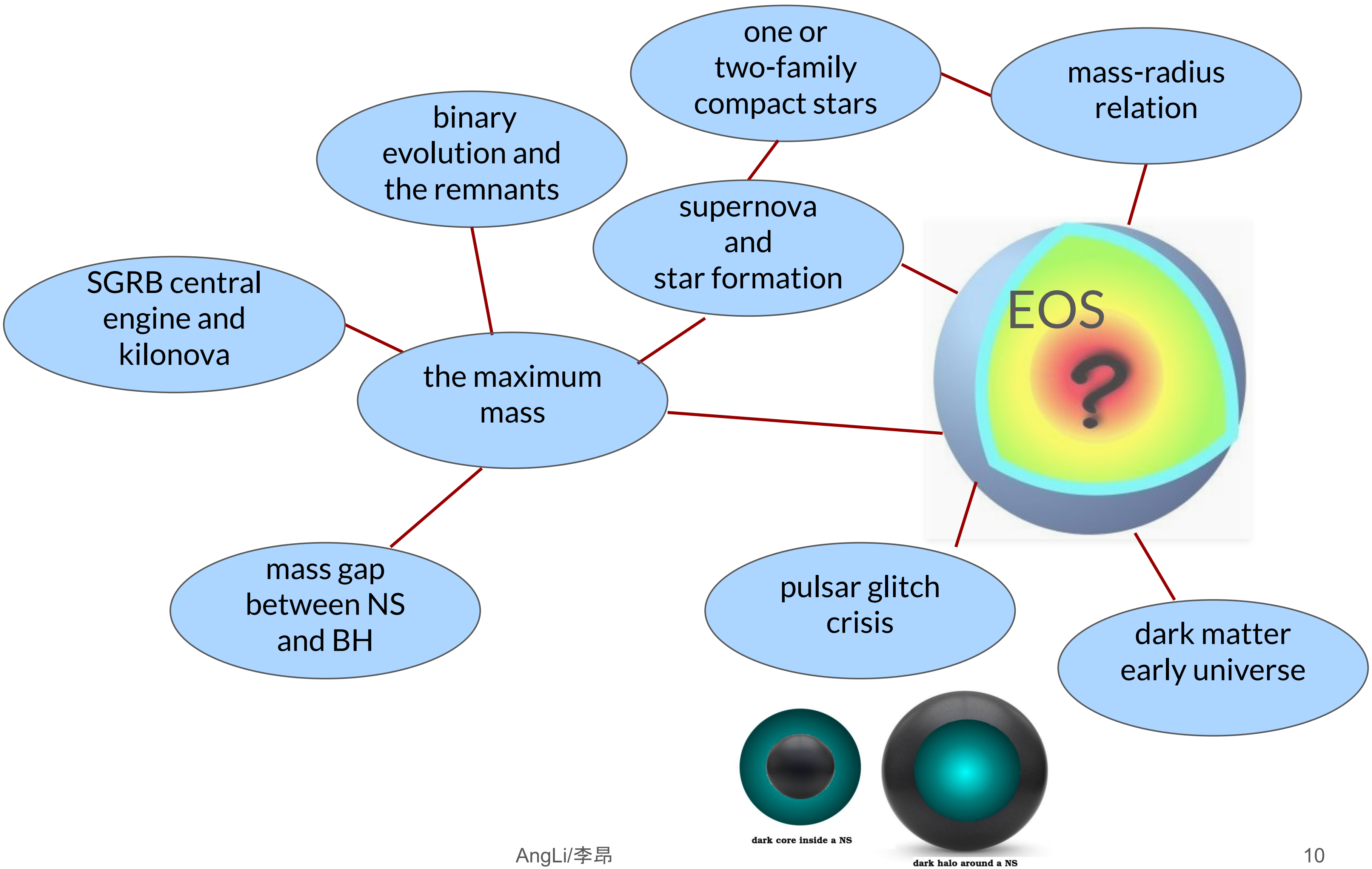
Future MOI measurement (from e.g., SKA)



检测GR Lense-Thirring效应



Why is understanding dense matter EOS important (for astrophysicists and astronomers)?



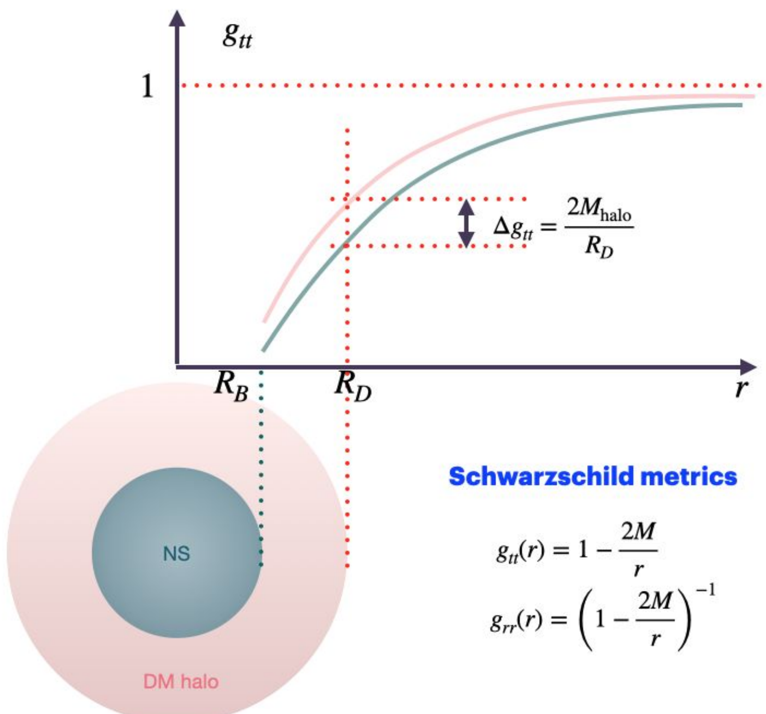
The Astrophysical Journal, 936:69 (10pp), 2022 September 1
https://doi.org/10.3847/1538-4357/ac8544

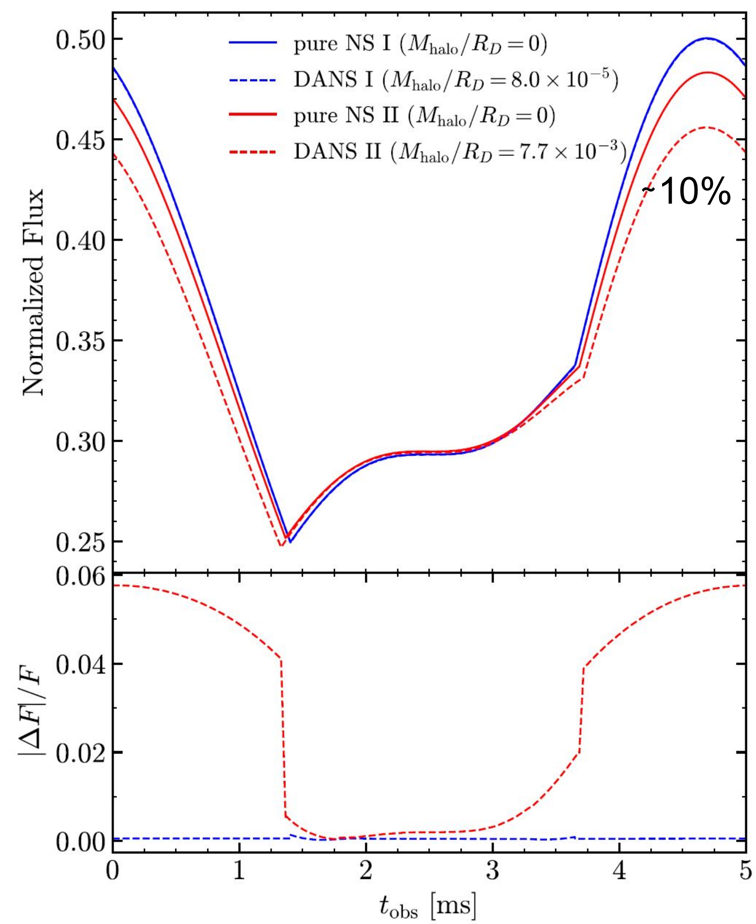
2204.05560

Dark Matter Admixed Neutron Star Properties in the Light of X-Ray Pulse Profile Observations

Zhiqiang Miao, Yaofeng Zhu, Ang Li, and Feng Huang
Department of Astronomy, Xiamen University, Xiamen, Fujian 361005, People's Republic of China; liang@xmu.edu.cn, fenghuang@xmu.edu.cn

Pulses emitted from the surface of the baryonic matter should suffer an additional gravitational potential due to DM halo;



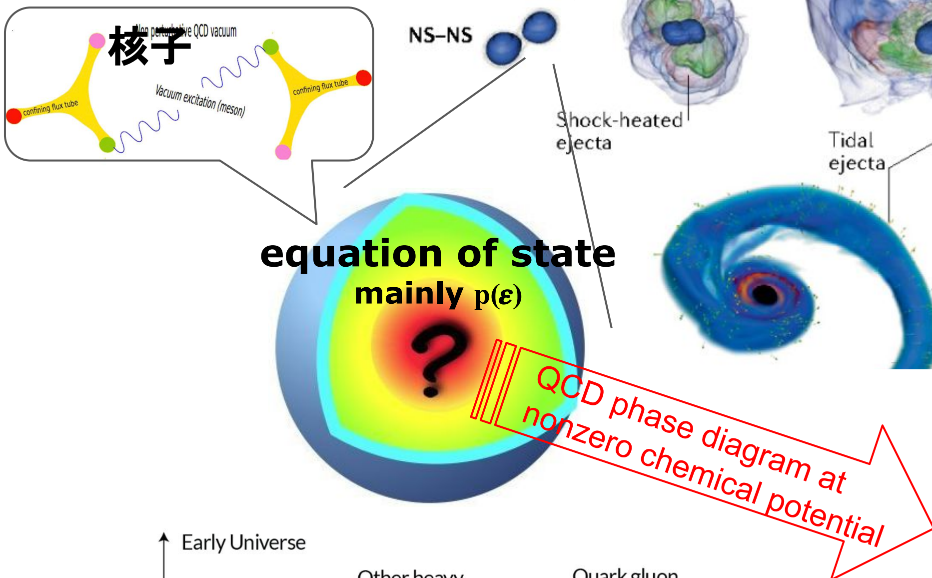


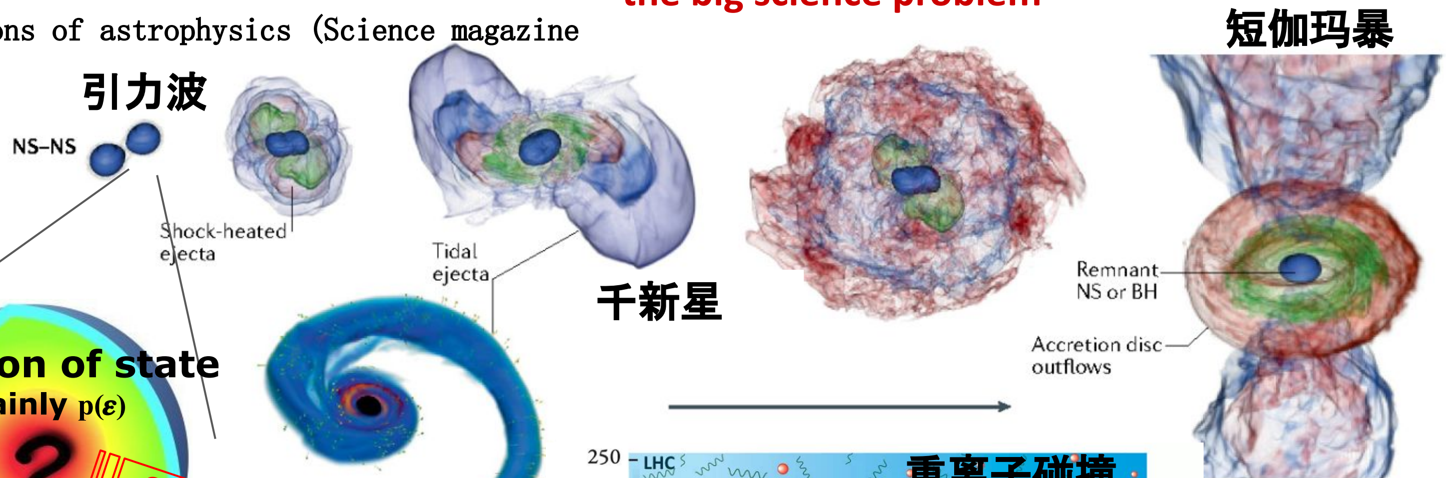
NICER, eXTP, ATHENA, STROBE-X,...

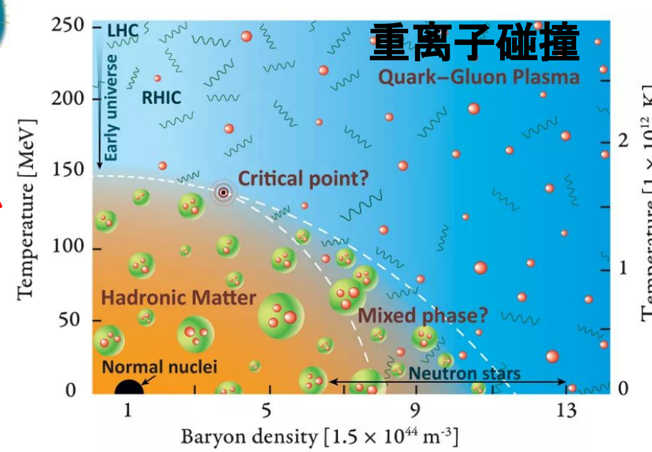
Is it possible to understand the structure of compact stars and matter?

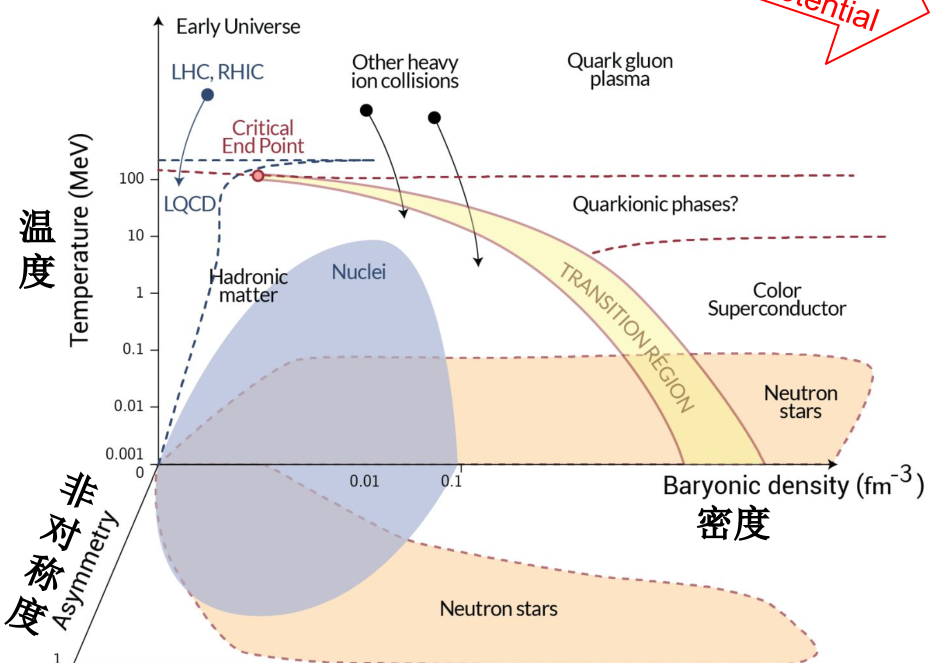
-One of 11 questions of physics (Discover magazine 2002)
-One of 21 questions of astrophysics (Science magazine 2021)

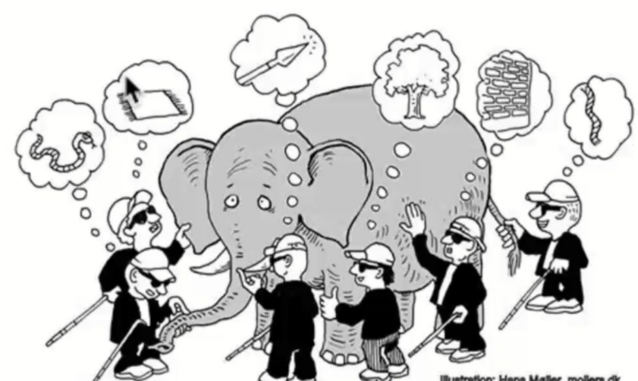
'the big science problem'









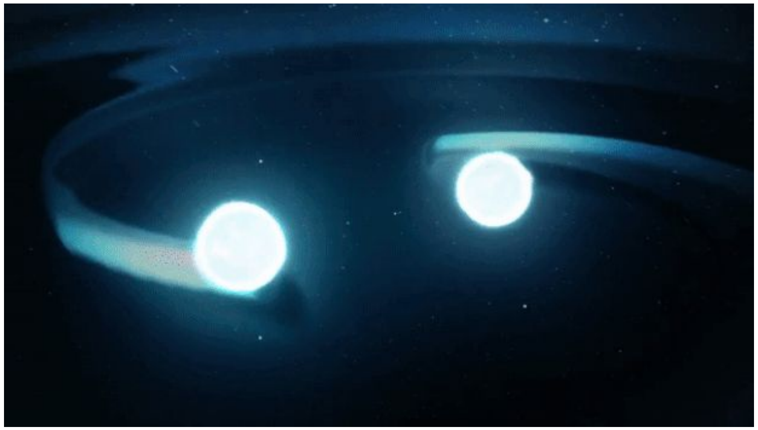


Outline

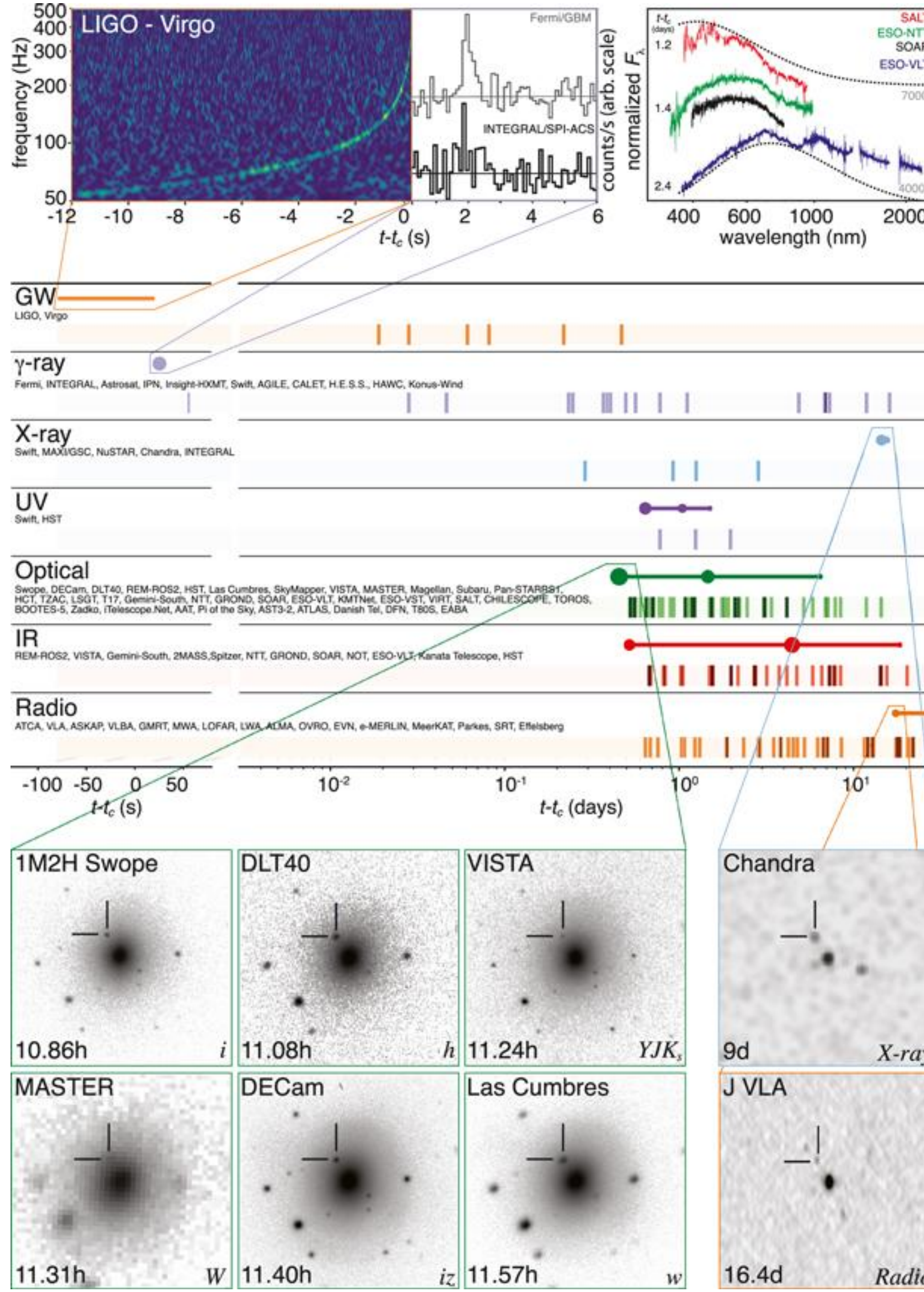
- Basic for neutron star structure and the EOS
- **Recent works** from connecting #consistently neutron star observations and nuclear experiments
  (Biased selected results; Highlighing work done by our group)
- What we learn so far

2017物理学十大突破

The **‘golden’** event of GW170817 brings the best time of neutron star physics!



- GW
- Neutrino: none
- γ-ray: 1.7 s
- X-ray: 9 days
- UV/Optical/IR (kilonova): 2 days
- Radio:16 days



AngLi/李昂

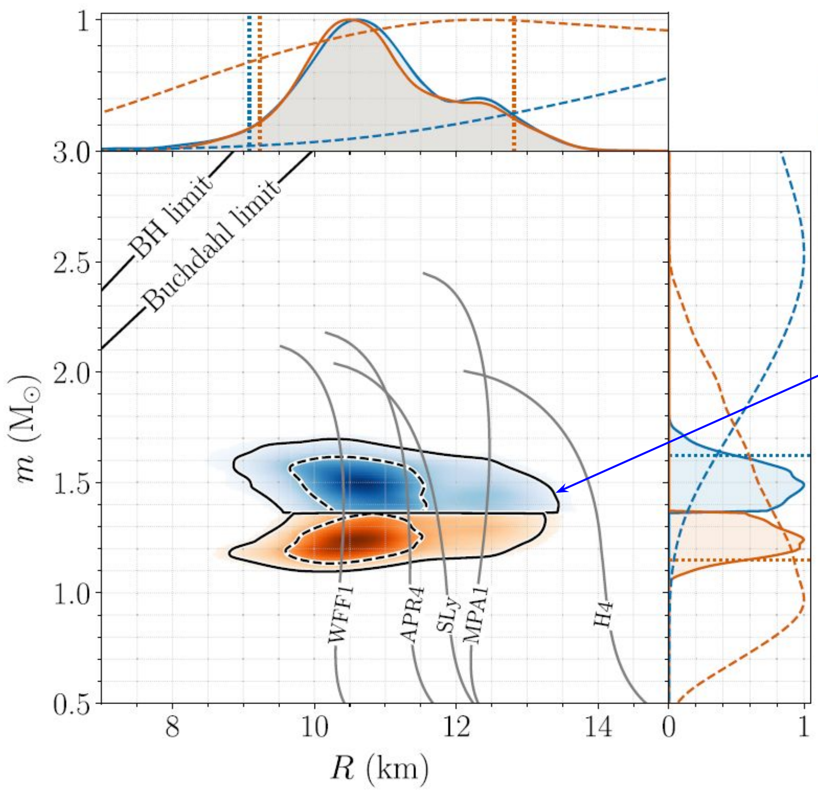
PHYSICAL REVIEW LETTERS **121**, 161101 (2018)

Editors' Suggestion

GW from a binary neutron star inspiral

GW170817: Measurements of Neutron Star Radii and Equation of State

B. P. Abbott *et al.**
(The LIGO Scientific Collaboration and the Virgo Collaboration)



Our results are comparable and consistent with studies that use the tidal measurement from [5] to obtain bounds on NS radii. Using our bound of $\Lambda_{1.4} < 800$ (the only tidal parameter in [5], which assumed a common EOS for both NSs) and different EOS parametrizations, several studies found $R_{1.4} \lesssim 13.5$ km [56,58,62,64].

[56] E.-P. Zhou, X. Zhou, and A. Li, Phys. Rev. D **97**, 083015 (2018). (2017/11/17 in 4 weeks, 1711.04312)

$$\Lambda = \frac{2}{3}k_2\left(\frac{R}{M}\right)^5$$

(1.36, 1.60) $M_\odot$
(1.16, 1.36) $M_\odot$

2017/10/16正式公布 (67 preprints):
http://blogs.cornell.edu/arxiv/2017/10/16/gw170817/

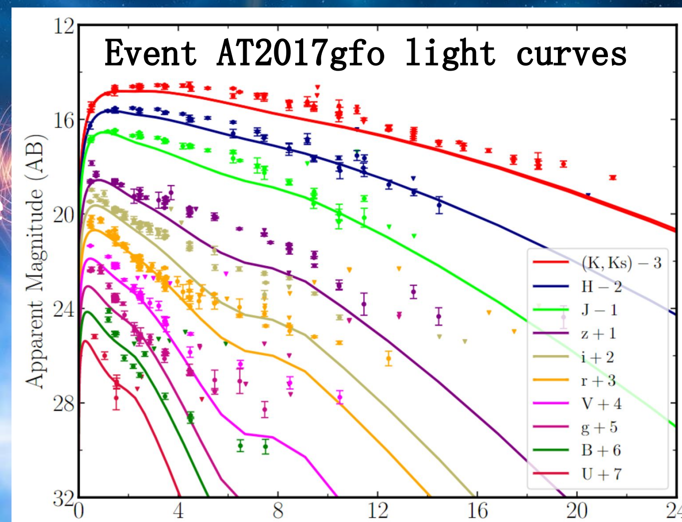
The Astrophysical Journal, 943:163 (11pp), 2023 February 1 https://doi.org/10.3847/1538-4357/acac1f

2211.02007

A Bayesian Inference of a Relativistic Mean-field Model of Neutron Star Matter from Observations of NICER and GW170817/AT2017gfo

Zhenyu Zhu[1], Ang Li[2], and Tong Liu[2]

Kilonova light curves connect with **the EOS** through the quasi-universal relations between the properties of the ejecta (the ejected mass, velocity, opacity, or electron fraction) and **binary** parameters (the mass ratio and reduced tidal deformability).

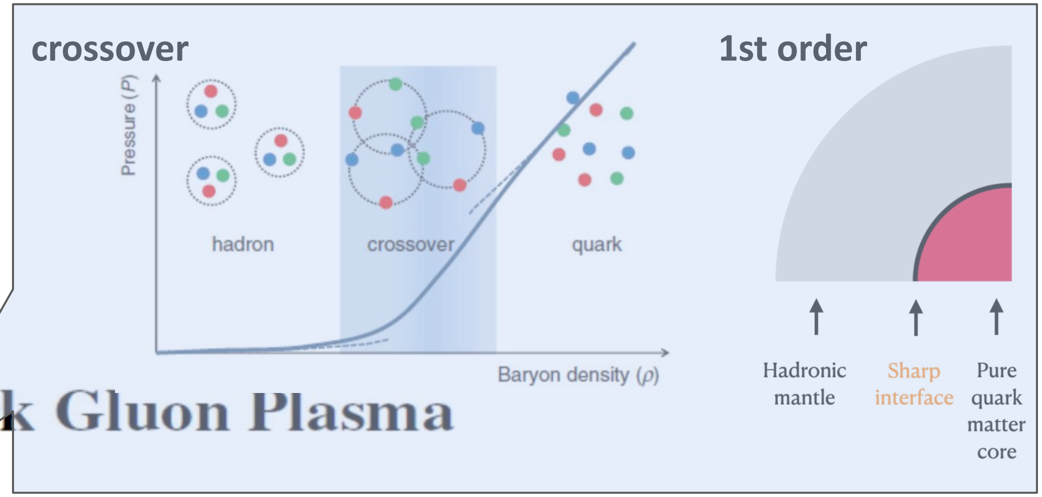


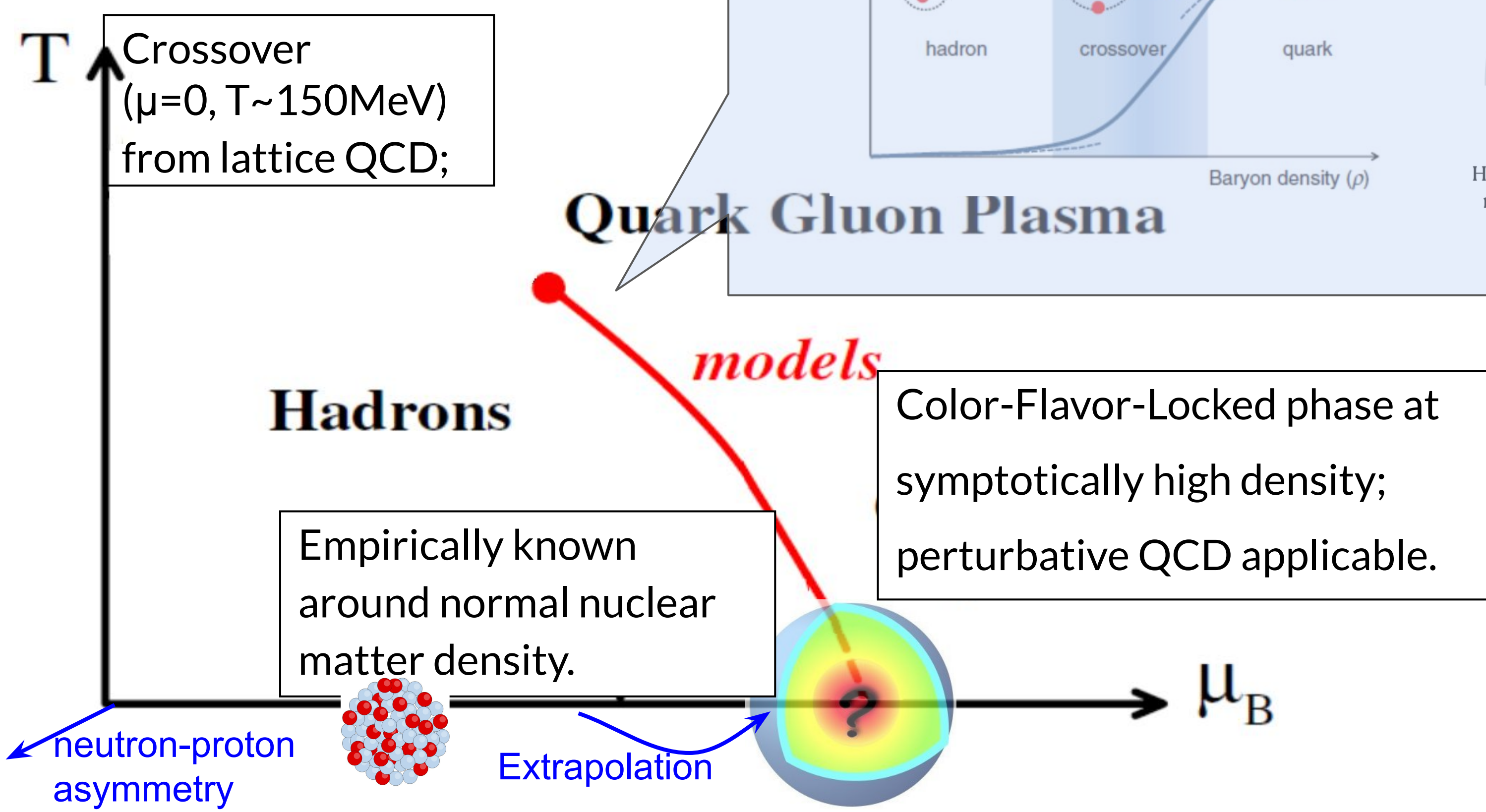
From the referee "The paper is very interesting and presents **new** strategies for studying the equation of state of dense matter. It is also one of the few papers performing a bayesian analysis in which the equation of state is computed within a model of **nuclear** interactions."

Parameters	AT2017gf	GW170817/AT2017gf	GW170817+NICER	GW170817/AT2017gf+NICER
J_0 (MeV)	$32.9321^{+1.8031}_{-2.3807}$	$33.0866^{+1.6679}_{-2.4922}$	$32.7278^{+1.9317}_{-2.1386}$	$33.0410^{+1.7229}_{-2.5494}$
K_0 (MeV)	$231.5976^{+27.6173}_{-10.1760}$	$230.5804^{+23.9437}_{-9.2084}$	$250.8818^{+25.1076}_{-27.2728}$	$230.2890^{+22.0389}_{-9.0966}$
L_0 (MeV)	$33.7546^{+19.8140}_{-11.6658}$	$35.3533^{+17.1443}_{-13.1968}$	$53.1642^{+26.3730}_{-24.9273}$	$34.4599^{+18.2543}_{-12.5515}$
M^*_N/M_N	$0.7887^{+0.0100}_{-0.0211}$	$0.7904^{+0.0083}_{-0.0172}$	$0.7166^{+0.0446}_{-0.0517}$	$0.7604^{+0.0250}_{-0.0198}$
$R_{1.4}$ (km)	$11.4107^{+0.2875}_{-0.2229}$	$11.3930^{+0.2364}_{-0.2123}$	$12.3821^{+0.5311}_{-0.5639}$	$11.6367^{+0.2121}_{-0.2312}$
$\Lambda_{1.4}$	$255.0494^{+41.1186}_{-26.4017}$	$251.2908^{+32.4407}_{-25.4602}$	$440.8698^{+123.4322}_{-107.7413}$	$300.2940^{+26.9738}_{-36.7643}$

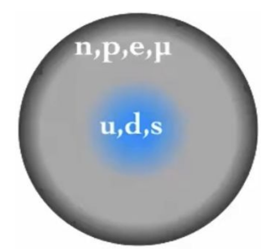
Massive PSRs + GW + kilonova + X-ray

Hadrons to quarks if too dense or too hot



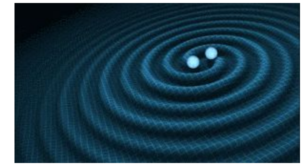


Credit: C. Sasaki



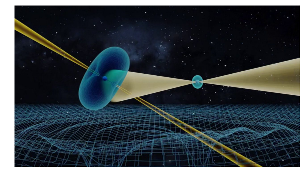
‘hybrid star’

Neutron star zoo



GW170817
GW190425

PSR J0030+0415
PSR J0740+6620



PSR J0737-3039

upcoming ~10% accuracy moment of inertia measurement

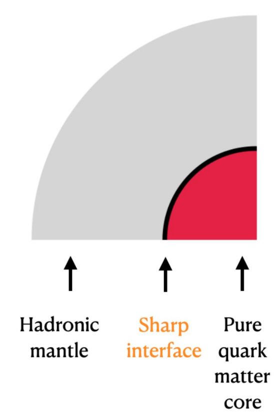
- Neutron star inner structure
  - Nuclear star
    - Nucleons
    - Nucleon excitations
    - Meson condensate
  - Hyperon star
    - Hypernuclei experiments
    - Hyperon scattering data
  - Hybrid star with deconfined quarks
    - EOS model for hadronic phase
    - Thermal, dynamic, chemical equilibrium
    - EOS model for quark phase
  - Quark star
    - Quark matter that can be self bound

In the following,

to appear in "The Equation of State of Pulsars": Contributed Chapter of upcoming book 《Pulsar Astronomy: State-of-the-Art of Chinese Instruments》

Where the phase transition happens?

(assuming assume nucleons and electrons, is in equilibrium with a gas of deconfined u, d, s quarks and leptons)



Interplay of nuclear symmetry energy with strangeness phase transition

THE ASTROPHYSICAL JOURNAL, 904:103 (12pp), 2020 December 1
https://doi.org/10.3847/1538-4357/abbd41

2006.00839

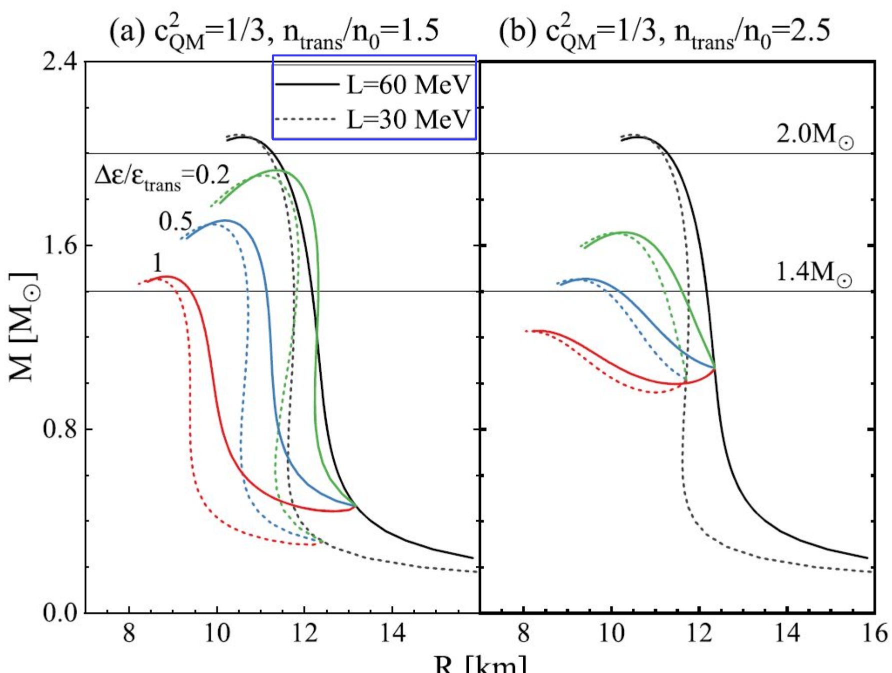
CrossMark

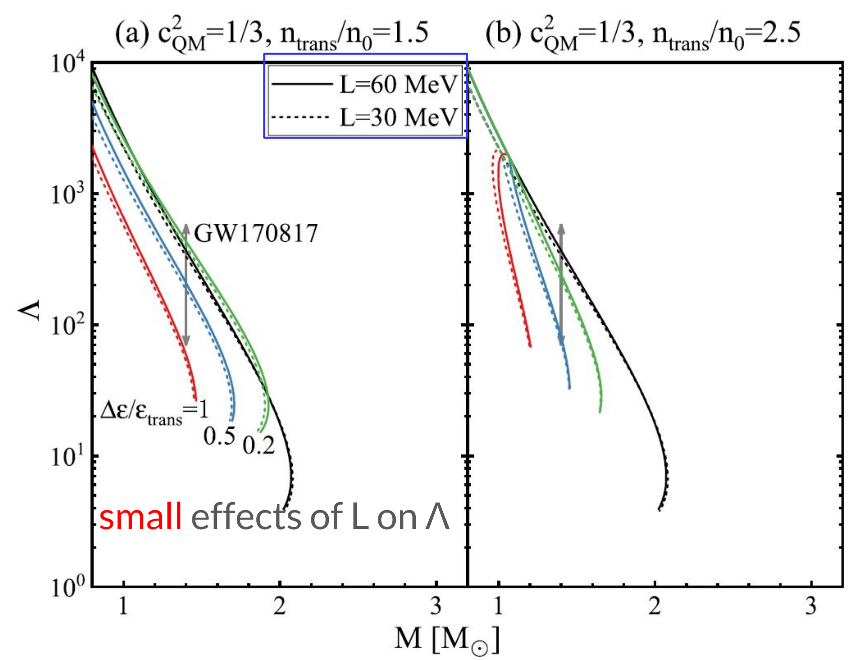
Constraining Hadron-quark Phase Transition Parameters within the Quark-mean-field Model Using Multimessenger Observations of Neutron Stars

Zhiqiang Miao[1], Ang Li[1,5], Zhenyu Zhu[1,2], and Sophia Han[3,4]

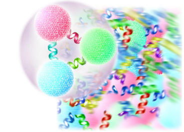
QMF hadronic EOS (symmetry energy slope L= 30-60) plus Constant-speed-sound (n_{trans}, $\Delta\mathcal{E}$, c_{QM}) paramtrization characterizing high-density (quark matter) phase;

Phase transition dominate when appear: Measuring Λ alone may NOT completely determine the density dependence of the symmetry energy.





Phase transitions are of central interest in physics



Open issues:

Order of transitions? Physics on interfaces? Finite T effects? hep-ph? nucl-th? cond-mat? astro-ph.HE?

New Neutron Star Equation of State with Quark–Hadron Crossover

Gordon Baym[1,2], Shun Furusawa[2,3], Tetsuo Hatsuda[4], Toru Kojo[5], and Hajime Togashi[6,7]

Published 2019 October 29 •

The Astrophysical Journal, Volume 885, Number 1

Tidal Deformations of Hybrid Stars with Sharp Phase Transitions and Elastic Crusts

Jonas P. Pereira[1], Michał Bejger[1], Nils Andersson[2], and Fabian Gittins[2]

Published 2020 May 21 •

The Astrophysical Journal, Volume 895, Number 1

Neutron stars with a crossover equation of state

J. I. Kapusta and T. Welle

Phys. Rev. C **104**, L012801 – Published 6 July 2021

Probing QCD critical point and induced gravitational wave by black hole physics

Rong-Gen Cai, Song He, Li Li, and Yuan-Xu Wang

Phys. Rev. D **106**, L121902 – Published 13 December 2022

g modes of neutron stars with hadron-to-quark crossover transitions

Constantinos Constantinou, Sophia Han (韩君), Prashanth Jaikumar, and Madappa Prakash

Phys. Rev. D **104**, 123032 – Published 22 December 2021

Differentiating between sharp and smoother phase transitions in neutron stars

Jonas P. Pereira, Michał Bejger, J. Leszek Zdunik, and Paweł Haensel

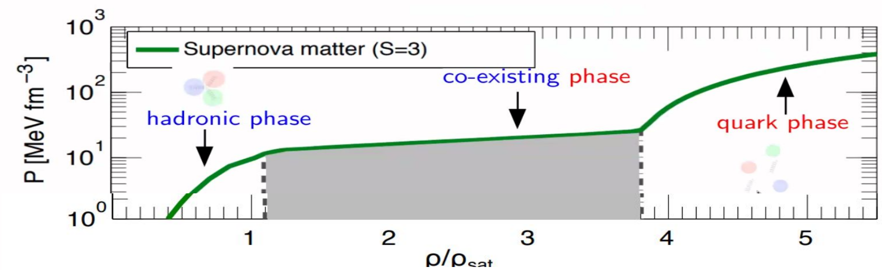
Phys. Rev. D **105**, 123015 – Published 15 June 2022

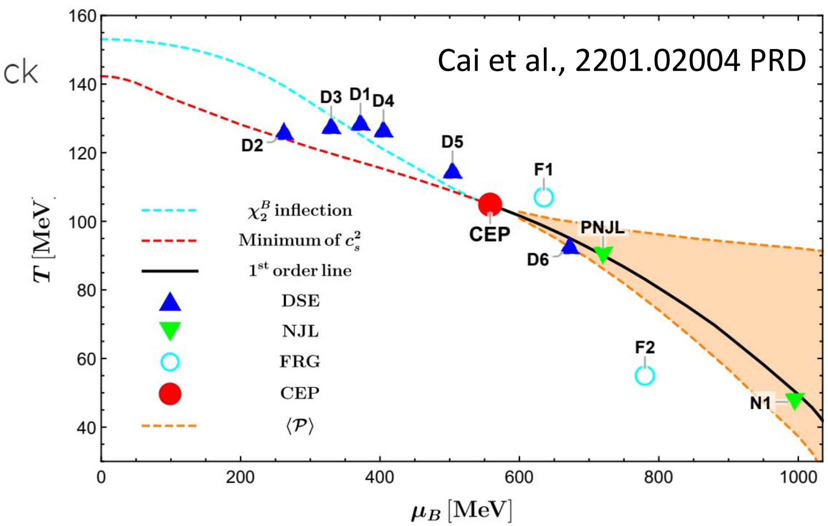
Article | Published: 22 October 2018

Quark deconfinement as a supernova explosion engine for massive blue supergiant stars

Tobias Fischer, Niels-Uwe F. Bastian, Meng-Ru Wu, Petr Baklanov, Elena Sorokina, Sergei Blinnikov, Stefan Typel, Thomas Klähn & David B. Blaschke

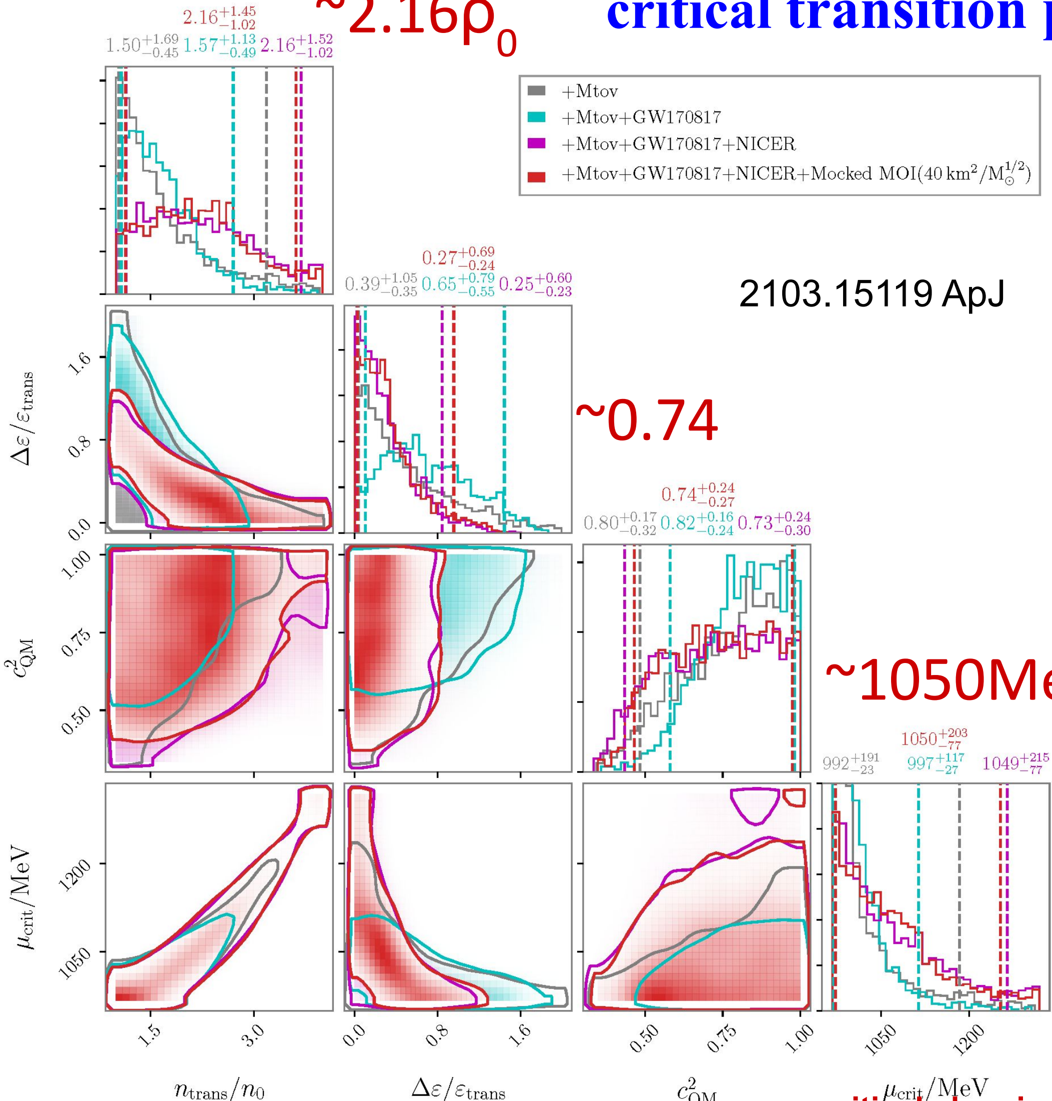
Nature Astronomy **2**, 980–986 (2018) | Cite this article





Using realistic EOS prior explicitly including phase transitions for the study of critical transition parameters

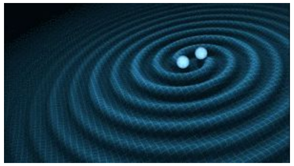
~2.16ρ_0



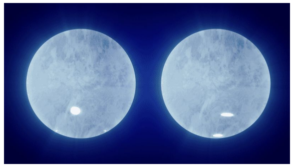
~0.74

~1050MeV

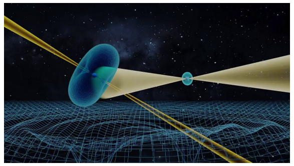
2103.15119 ApJ



GW170817
GW190425



PSR J0030+0415
PSR J0740+6620

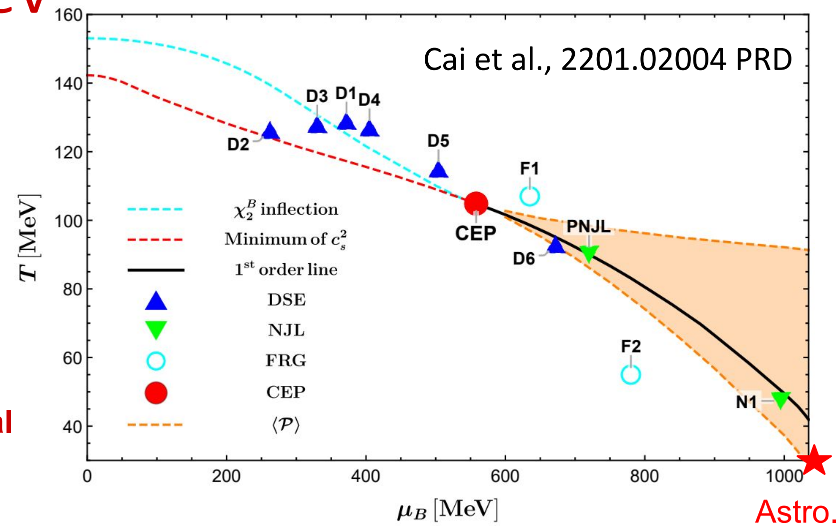


PSR J0737-3039

upcoming ~10% accuracy moment of inertia measurement

{transition density, transition strength, **sound speed squared in quark matter}**

critical chemical potential

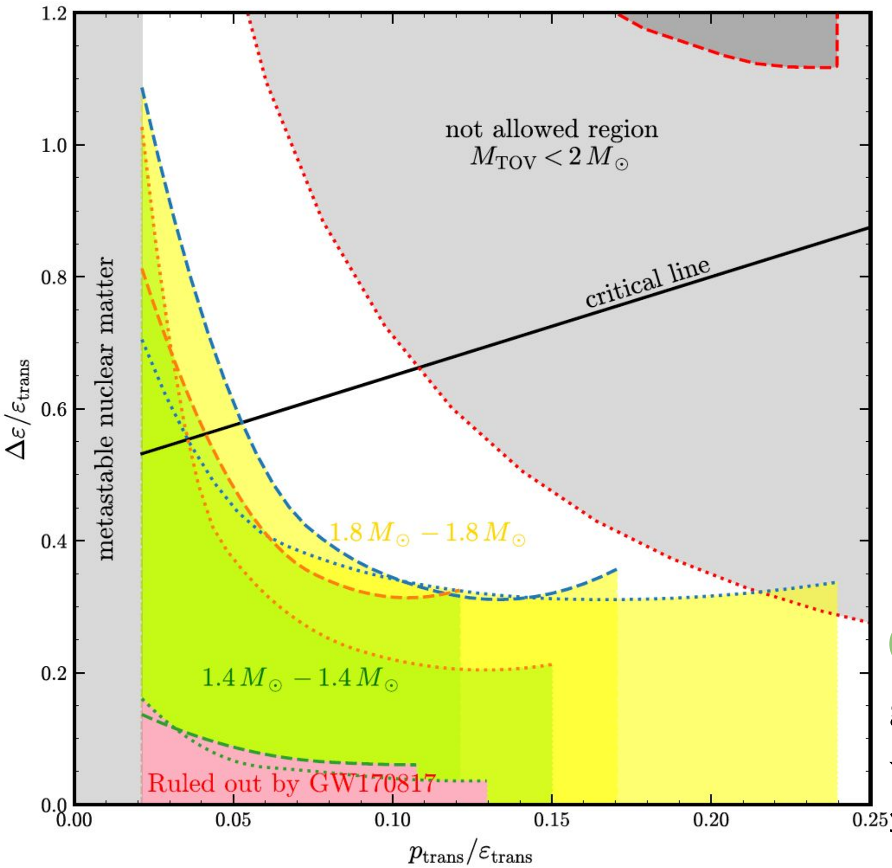


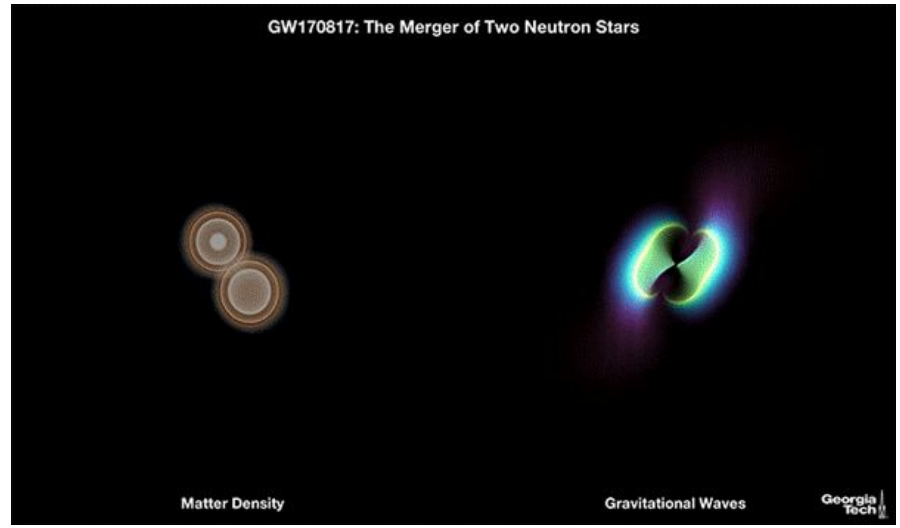
Astro.

prior: full parameter space from 1/sqrt(3) (the conformal limit in perturbative QCD matter) to 1 (the causal limit)

Static + Dynamic tide

- Static tidal: Quasi-equilibrium approximation, (i.e., the tidal field changes slowly); Tidal deformability
- Dynamic tidal: tidal-induced composition mode (or **i**nterfacial mode), discontinuity **g**-mode oscillation.
轨道运动与星体振荡将产生共振，加大被探测到的可能。



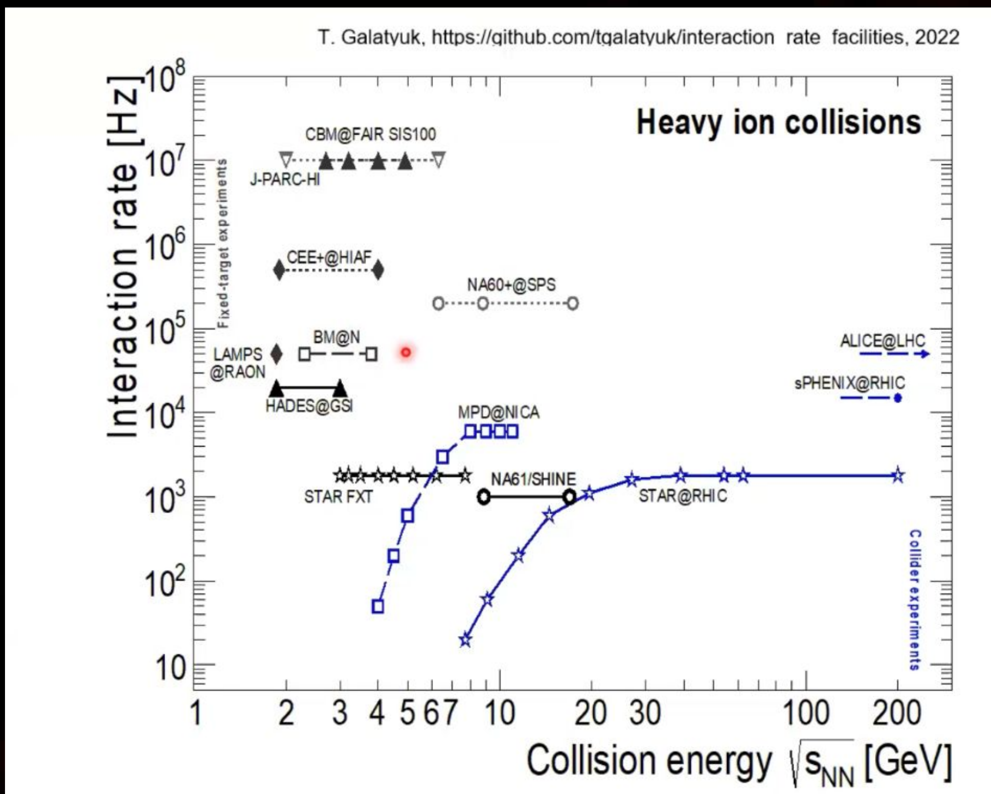


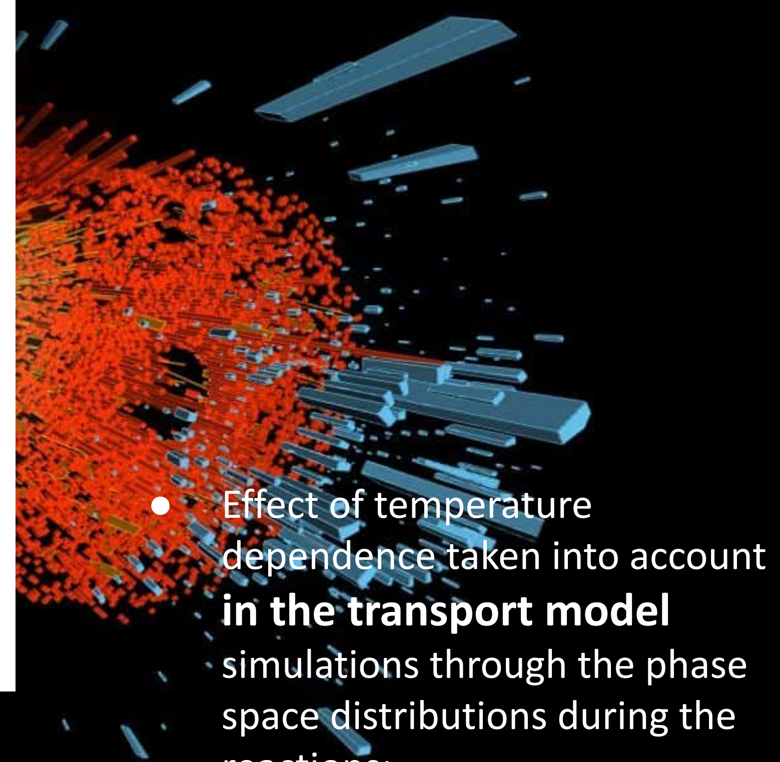
Green/Yellow: 3rd generation GW detectors 对于一个1.4/1.8$M_\odot$ 双星系统的可探测空间

- Available GW170817 data exclude low transition threshold (ptrans/ε trans ≲ 0.12) and weak transiton (Δ ε / ε trans ≲ 0.06)

Miao, Zhou, & Li, arXiv:2305.08401

Where & how the phase transition happens is a matter of recent debate not only in astrophysics but also within the theory of high energy (~GeV) heavy-ion collisions.





HIC: nearly symmetric hot matter

Neutron star matter: beta-stable cold matter

- Effect of temperature dependence taken into account **in the transport model** simulations through the phase space distributions during the reactions;
- Different EOS input->

PHYSICAL REVIEW D **107**, 043005 (2023)

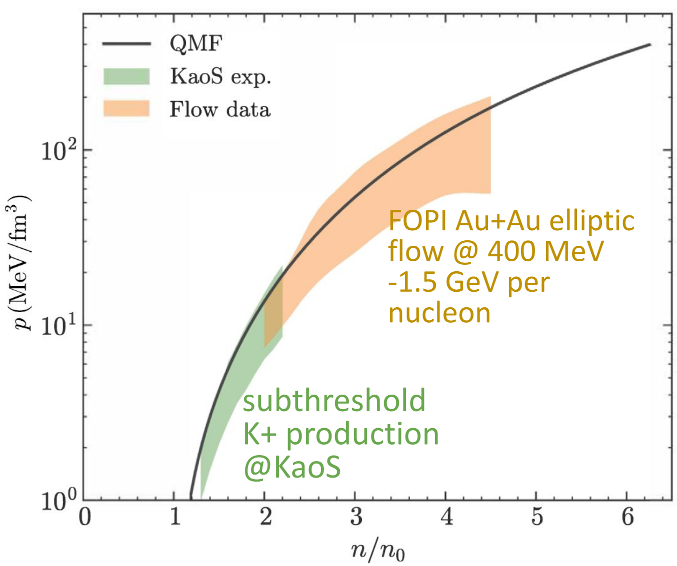
2211.04978

Testing the phase transition parameters inside neutron stars with the production of protons and lambdas in relativistic heavy-ion collisions

Ang Li,[1,*] Gao-Chan Yong,[2,3] and Ying-Xun Zhang[4,5]

- Input for HIC study via **AMPT**

$$\varepsilon(p) = \begin{cases} \varepsilon_{\rm HM}(p), & p < p_{\rm trans} \\ \varepsilon_{\rm HM}(p_{\rm trans}) + \Delta\varepsilon + c_{\rm QM}^{-2}(p - p_{\rm trans}), & p > p_{\rm trans}, \end{cases}$$

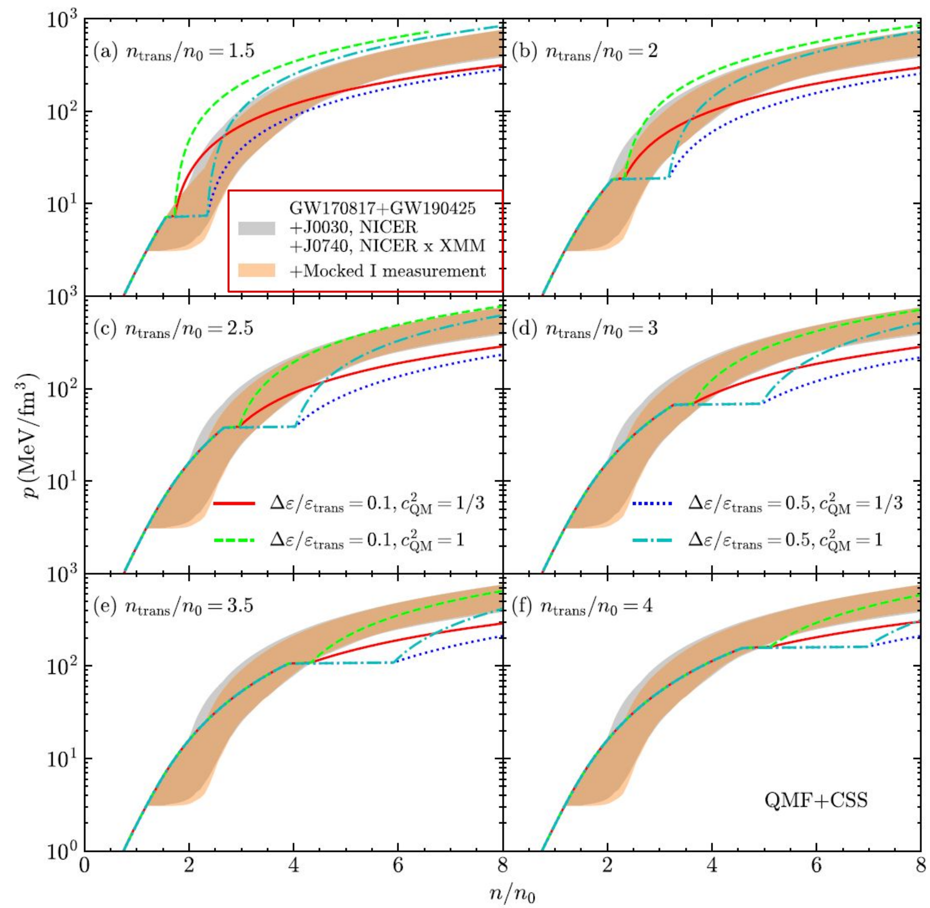


The single baryonic potential used in the transport model is derived from the QMF EOS:

$$U(n) = \partial\varepsilon_{\rm pot}/\partial n.$$

$$U_\Lambda(n) = \frac{2}{3}U(n)$$

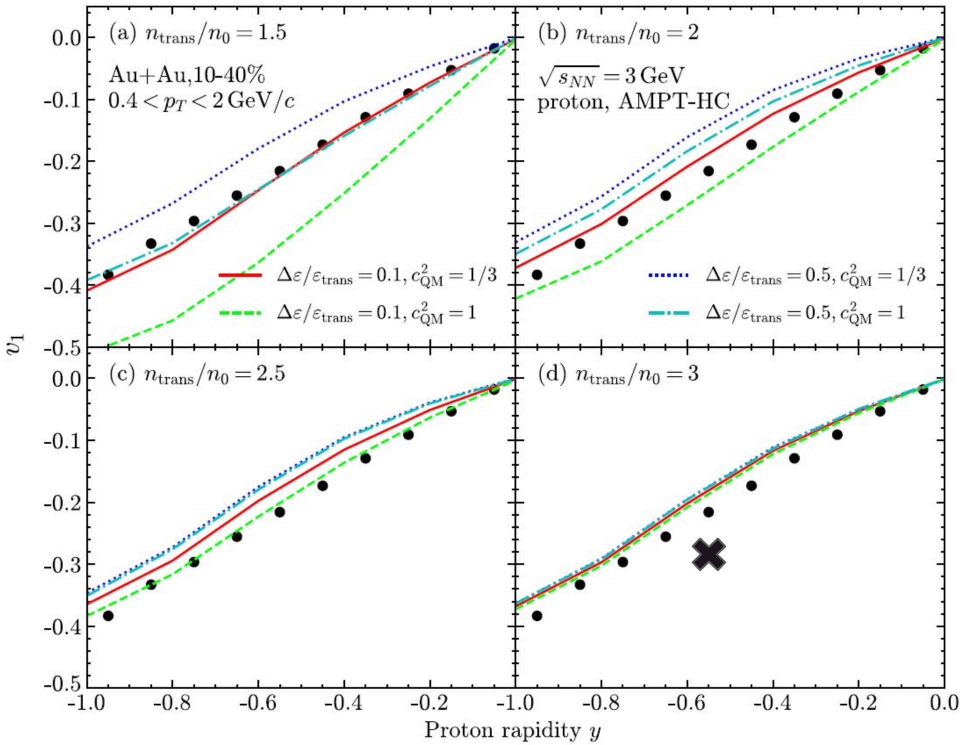
- Input for NS study

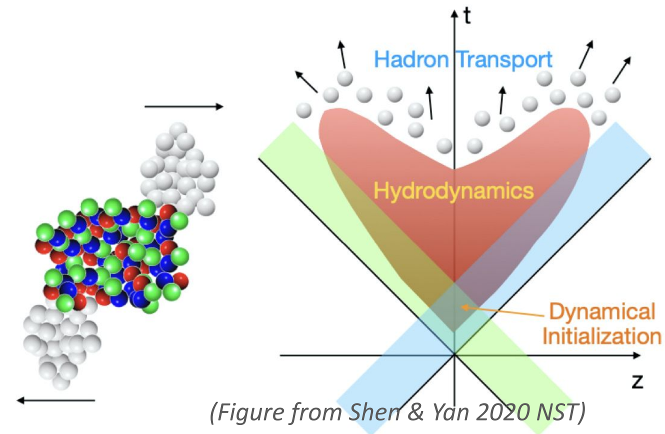


Proton directed/elliptic flow (3GeV): Transition density sensitive

- Two colliding nuclei produce collective motion of nucleons and fragments, depends sensitively on the gradient of pressure (i.e., soft/stiff EOS);

- STAR@RHIC 3GeV, 4.5GeV (Abdallah et al., PLB 2022; Abdallah et al., PRC 2021)





(Figure from Shen & Yan 2020 NST)

Favor a relatively low phase transition density <~2.5n_0, consistent with NS observations.

From the referee "The work presents an interesting and long-standing problem of creating a bridge between astrophysics, GW physics, and heavy-ion collisions."

2211.04978 PRD

Neutron star zoo

- Neutron star inner structure
  - Nuclear star
    - Nucleons
    - Nucleon excitations
    - Meson condensate
  - Hyperon star
    - Hypernuclei experiments
    - Hyperon scattering data
  - Hybrid star with deconfined quarks
    - EOS model for hadronic phase
    - Thermal, dynamic, chemical equilibrium
    - EOS model for quark phase
  - Quark star
    - Quark matter that can be self bound

In the following,

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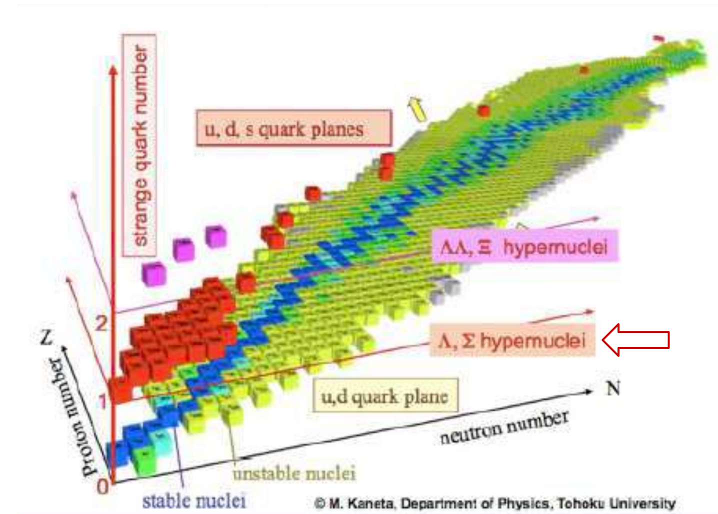
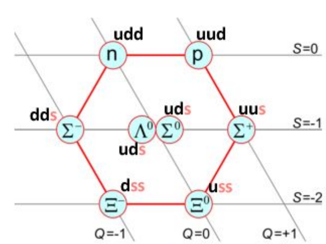
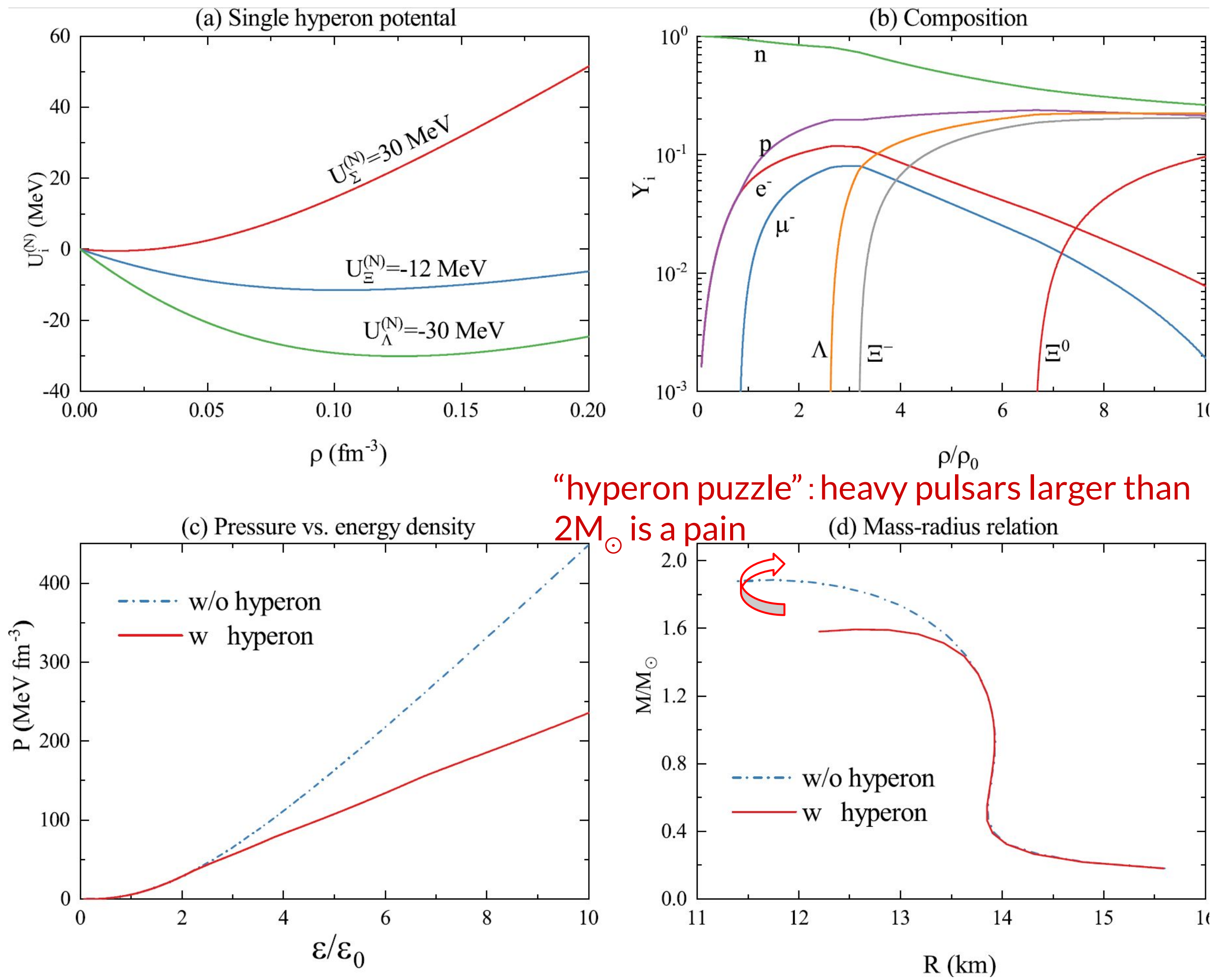




Many theoretical and experimental ambiguities regarding hyperon interaction (NY,YY,...)

- **Microscopic** scheme, e.g., BHF;
- Nijmegen soft-core NY potentials (NSC89/ESC08...) model, fitted to the available experimental NY scattering data: presently, 4233 NN data, 52 NY data;

- **Phenomenological** scheme, e.g., RMF/QMF;
- Dressed baryon-meson($\sigma\omega\varrho$...) coupling constants, fitted to hypernuclei data (>~40 Λ hypernuclei, a few ΛΛ hypernuclei, Ξ hypernuclei).



"hyperon puzzle": heavy pulsars larger than $2M_\odot$ is a pain

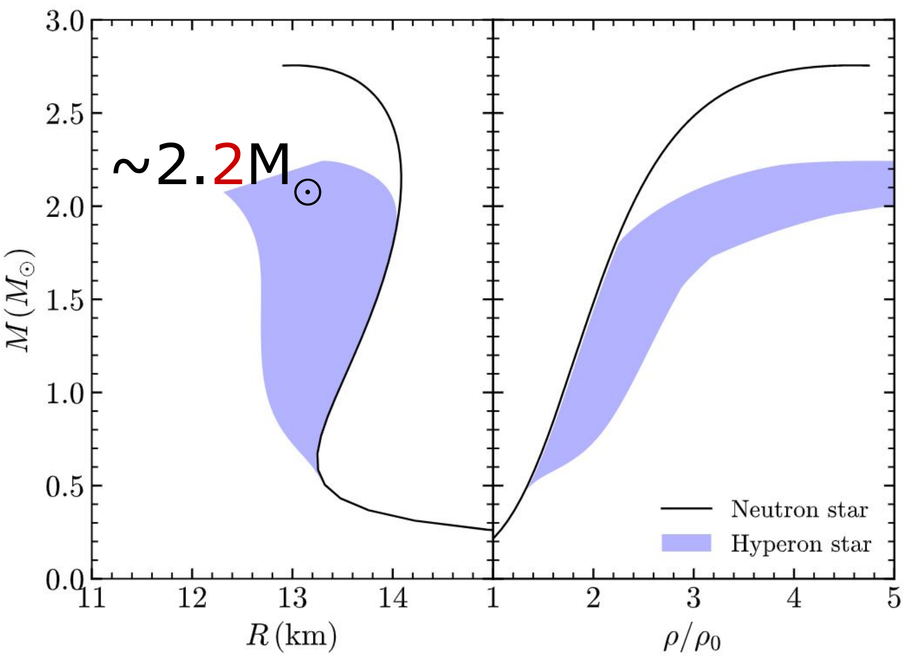
《Neutron star equation of state…》 AL, Zhu, Zhou, Dong, Hu, & Xia 2020 J. High Energy Astrophys (review)

THE ASTROPHYSICAL JOURNAL, 942:55 (13pp), 2023 January 1 https://doi.org/10.3847/1538-4357/ac9d9a

2205.10631

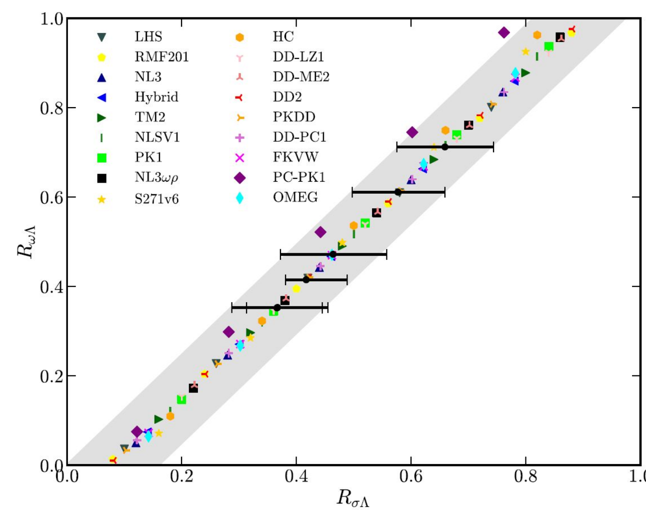
Astrophysical Implications on Hyperon Couplings and Hyperon Star Properties with Relativistic Equations of States

Xiangdong Sun[1], Zhiqiang Miao[1], Baoyuan Sun[2], and Ang Li[1]



Due to hyperons, the maximum mass is lowered by ~20%: $M_{\max} = 2.176^{+0.085}_{-0.202}\, M_{\odot}$ (68% credible interval).

correlation from fitting calculated Λ separation energies of **eleven A ≥ 12 Λ hypernuclei** (Rong et al., 2021)



From the referee "The present article addresses a long-standing issue in neutron star physics, namely the hyperon puzzle. The authors incorporate new information from hypernuclei calculations and treat the hyperon couplings in a more general way than what exists in the present literature. This is an **interesting work that can have important future implications.**"

The Astrophysical Journal, 942:55 (13pp), 2023 January 1
https://doi.org/10.3847/1538-4357/ac9d9a

2205.10631

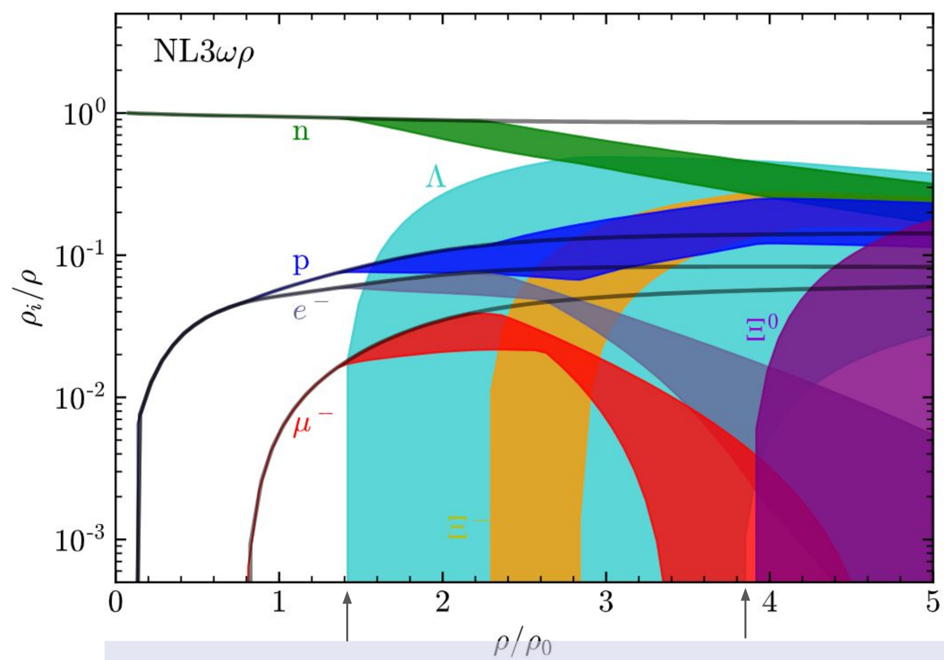
Astrophysical Implications on Hyperon Couplings and Hyperon Star Properties with Relativistic Equations of States

Xiangdong Sun[1], Zhiqiang Miao[1], Baoyuan Sun[2], and Ang Li[1]

an RMF with density dependent couplings. The authors of Sun et al. (2023) have recently developed a Bayesian inference approach, in the framework of several nuclear RMF, to determine how GW and NICER measurements constrain the $\Lambda-\sigma$ and $\Lambda-\omega$ couplings, while fixing the Σ and Ξ couplings to reasonable values. A major advantage of this methodology is the possibility, once the inference is completed, to discuss the possible composition of matter or the nuclear properties. In the present study, we will base our approach

A major advantage of this methodology is the possibility, once the inference is completed, to discuss the possible composition of matter or the nuclear properties.

Huang, Raaijmakers, Watts, Tolos, & Providência, 2303.17518

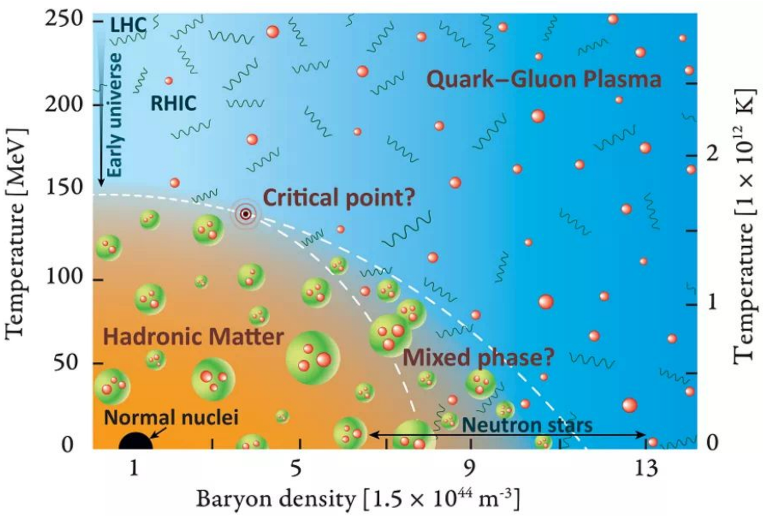


threshold density of Λ hyperons: ~1.4-3.8ρ_0

More hypernuclear data necessary to undersand hyperon interaction: theory+exp.+obs.!

Very exciting future for the study of neutron star EOS~!

强流重离子加速器装置 (HIAF), RIBF, FRIB, RHIC, FAIR, NICA, ROAN, …

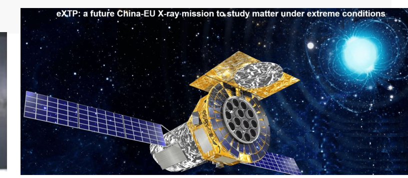


https://baas.aas.org/astro2020-science
面向2022-2032的天文和天体物理十年规划Astro2020

BAAS BULLETIN OF THE
HOME COMMUNITY REPORTS NEWS & COMMENTARY MEETING ABSTRACTS OBITUARIES ABOUT AAS PUBLISHING

Vol. 51, Issue 3 (Astro2020 Science White Papers) Published on May 31, 2019

Determining the Equation of State of Cold, Dense Matter with X-ray Observations of Neutron Stars



SCIENCE CHINA
Physics, Mechanics & Astronomy
CrossMark

• Invited Review • February 2019 Vol. 62 No. 2: 029503
Special Issue: The X-ray Timing and Polarimetry Frontier with eXTP

https://www.isdc.unige.ch/extp/
增强型X射线时变与偏振空间天文台卫星

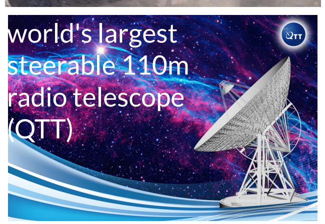
Dense matter with eXTP

eXTP Teams
- WG1 - Dense Matter
- WG2 - Strong Field Gravity
- WG3 - Strong Magnetism
- WG4 - Observatory Science
- WG5 - Synergy with GWs
- WG6 - Simulations
- Instrument Working Group
- Consortium

https://fast.bao.ac.cn/

FAST 早期科学 973

1. 脉冲星射电观测与理论研究
2. 从原子到恒星：星际介质及恒星形成的射电研究
3. 星系结构与星系演化
4. 宇宙学和暗物质
5. 射电光谱和脉泽源
6. 低频多波束接收机和VLBI的设计预研



PoS

https://www.skatelescope.org/
平方公里射电阵

Probing the neutron star interior and the Equation of State of cold dense matter with the SKA

https://psr.pku.edu.cn/qcs/qcs2023

Quarks and Compact Stars

Yangzhou University, Yangzhou, China; Sept. 23-26, 2023

Aiming at the puzzling state of cold matter at supra-nuclear density, the QCS series of meeting is to strengthen the researches and foster collaborations between China, Japan and Korea, especially for the younger generation of the East Asia.

QCS 2014 in Beijing https://psr.pku.edu.cn/rxx/conferences/qcs2014/index.htm

QCS 2017 in Kyoto http://journals.jps.jp/doi/book/10.7566/QCS2017

QCS 2019 in Busan https://old.apctp.org/plan.php/qcs2019

2023 YANGZHOU CHINA

International Advisory Committee

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Youngman	**Kim**	**(IBS, Korea)**
Kyujin	**Kwak**	**(UNIST, Korea)**
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Nobutoshi	**Yasutake**	**(Chiba Institute of Technology, Japan)**

Important Deadlines:

Early Registration: **June 30th, 2023**

Abstract Submission: August 31st, 2023

What we learn so far

-NS radius is controlled mainly by the density dependence of the nuclear symmetry energy around ρ_0, while the maximum mass is a reflection of the EOS stiffness at, e.g., $\gtrsim 5\rho_0$;

-The EOS is moderately stiff: Microscopic pure neutron stars theoretical upper limit ~2.4; maximum mass ~2.2 when including strangeness (also applied to quark stars);

-An enhancement in the sound speed is necessary to fulfill the two-solar-mass constraint of pulsars for neutron stars, not necessily the case for quark stars;

-NS observations can help with the parameters of phase transition and hyperon interaction;

-Consistency of the quark deconfinement phase transition parameters in NSs and in HICs;

-NSs provide effective & complementary approaches to cosmology!

-Gobal properties like mass, radius do not effectively distinguish various phase states with similar EOSs, not mentioned the nonperturbetive QCD; MANY things to be done theory+exp.+obs.!

Thank you

李昂 liang@xmu.edu.cn

astro.xmu.edu.cn/People/Faculty/la.htm

微信号:Nucl_Astrophys_xmu (厦大天文核天体物理小组)