HYPERON-NUCLEAR THREE-BODY FORCES
and
STRANGENESS in NEUTRON STARS

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- Brief Survey: Equation-of-State of Dense Matter in Neutron Stars
  - Observational constraints from $2\,\mathrm{M}_\odot$ neutron stars and mergers (GW signals)
  - Bayesian inference methods, deep learning strategies, and theoretical models

- Strangeness and Baryonic Matter
  - Hyperon-nucleon interactions, three-body forces and hypernuclei
  - Hyperons in the core of neutron stars ? Scenarios and the “hyperon puzzle”

1.

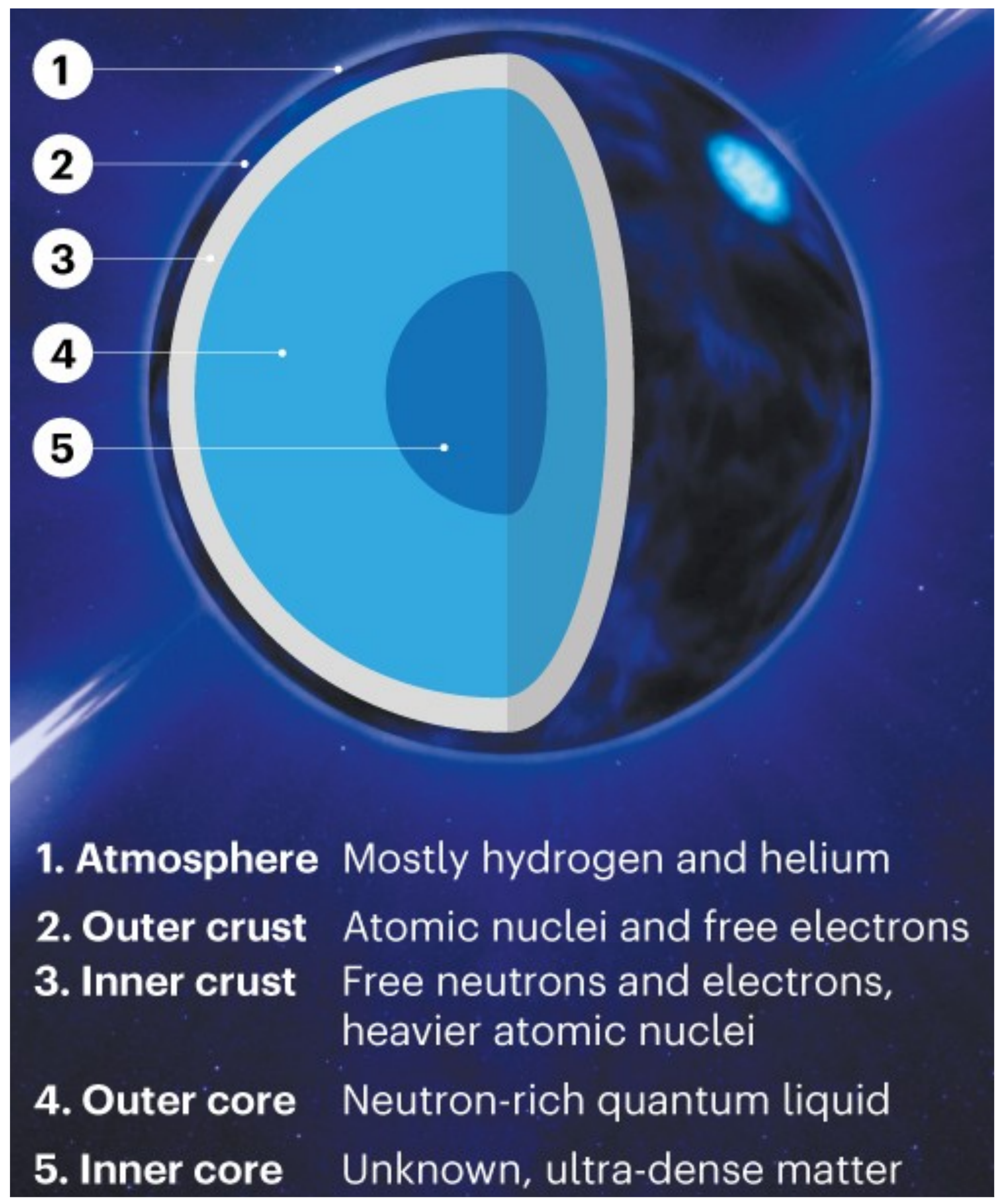
Equation-of-State of Dense Baryonic Matter :

Observational Constraints from Neutron Stars

. . . and possible Interpretations

NEUTRON STARS : EQUATION of STATE

- Constraints on **Equation-of-State** of baryonic matter at **HIGH DENSITY** and **LOW TEMPERATURE**
  - **Neutron star mass** measurements (Shapiro delay in n-star - white dwarf binaries)
  - **Gravitational wave** signals of **neutron star mergers** (LIGO and Virgo collaborations)
  - **Neutron star Interior Composition Explorer** (NICER telescope @ ISS)

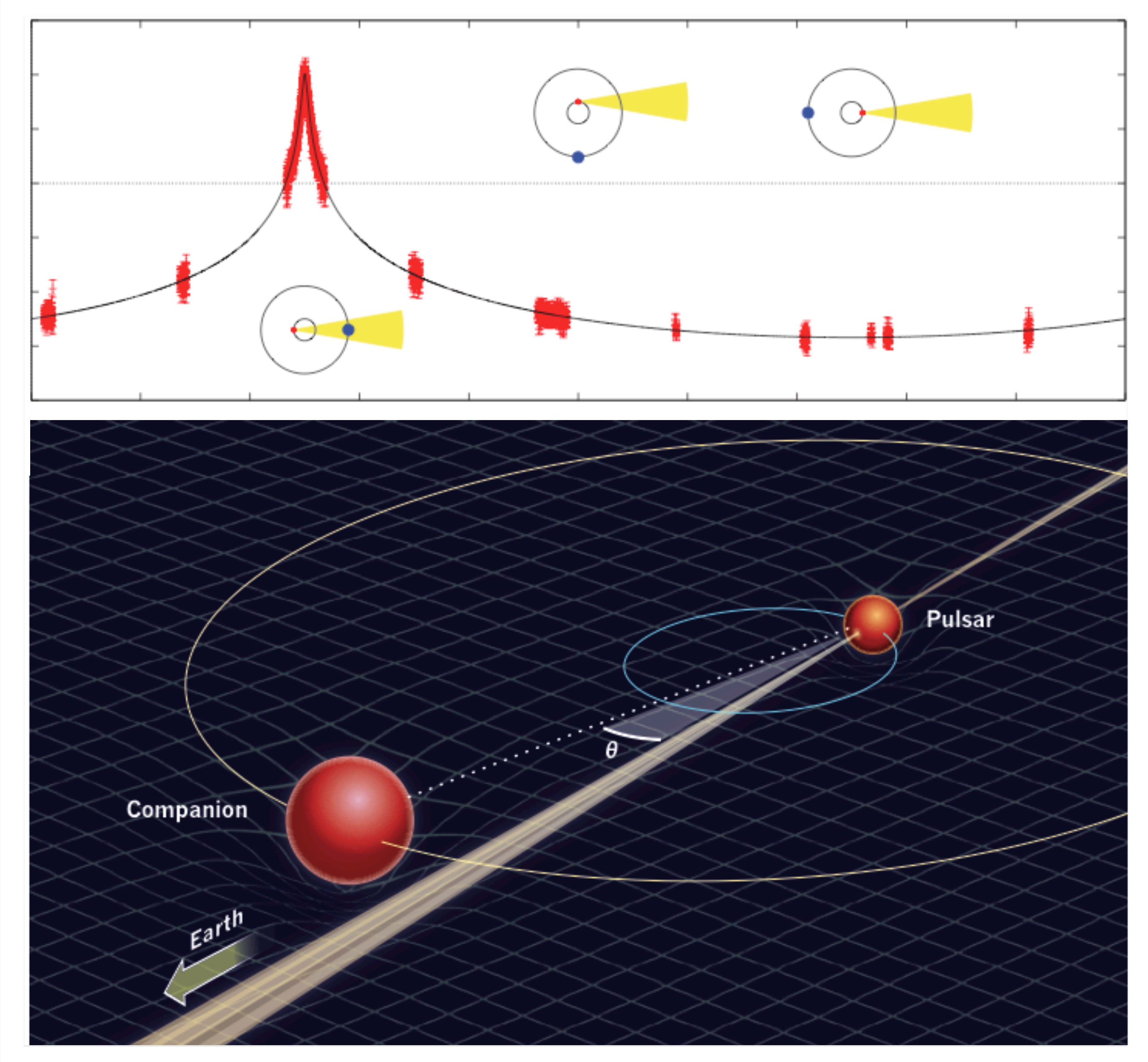


1. Atmosphere	Mostly hydrogen and helium
2. Outer crust	Atomic nuclei and free electrons
3. Inner crust	Free neutrons and electrons, heavier atomic nuclei
4. Outer core	Neutron-rich quantum liquid
5. Inner core	Unknown, ultra-dense matter

Layers of a **Neutron Star**

MASSIVE NEUTRON STARS

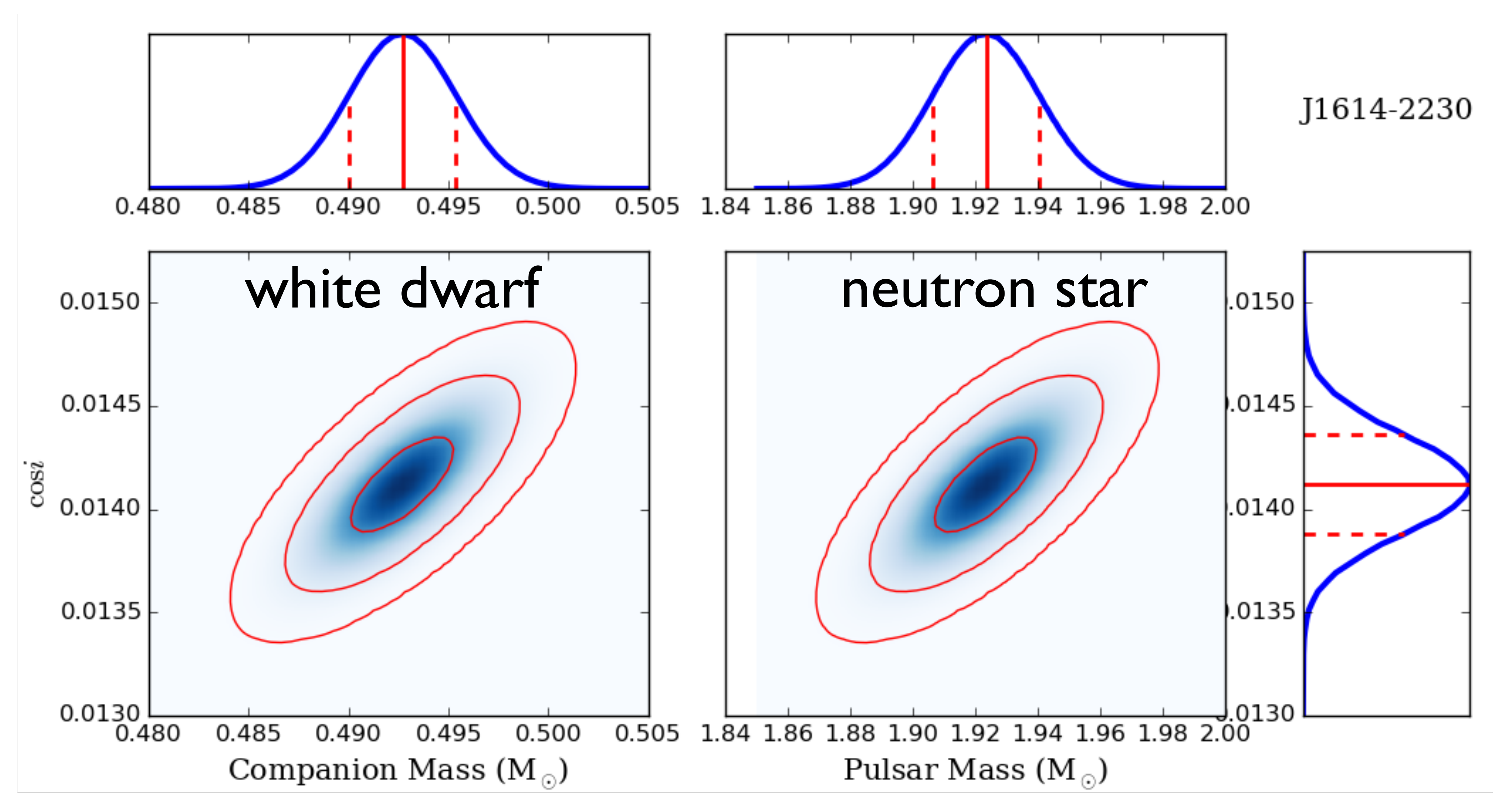
Shapiro delay measurements



P.B. Demorest et al. : Nature 467 (2010) 1081

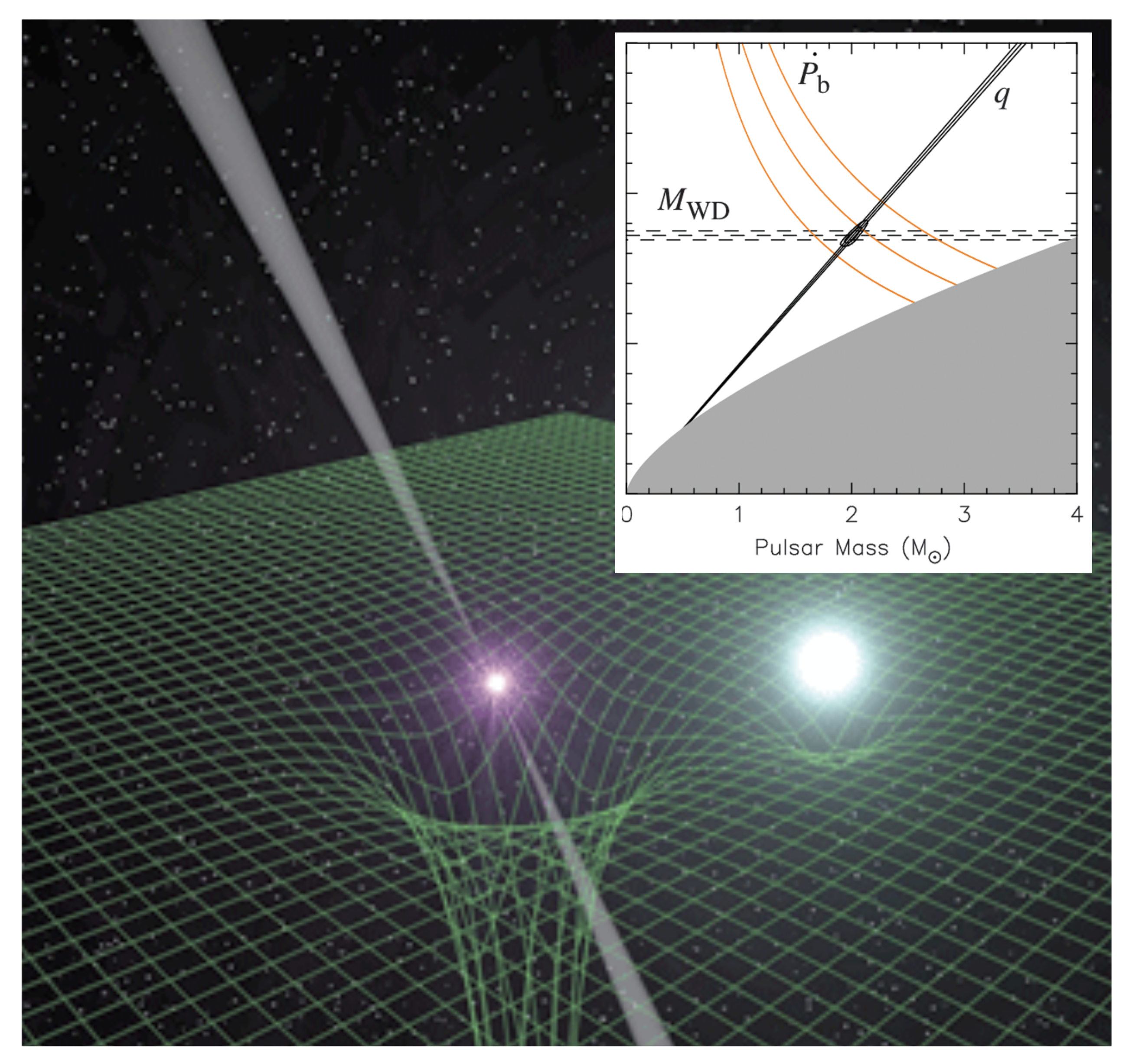
- Neutron star - white dwarf binaries

PSR J1614-2230



E. Fonseca et al. , Astrophys. J. 832 (2016) 167

PSR J0348+0432



PSR J1614-2230

$$\boxed{\mathrm{M} = 1.908 \pm 0.016\ \mathrm{M}_\odot}$$

Z. Arzoumanian et al. , Astrophys. J. Suppl. 235 (2018) 37

PSR J0348+0432

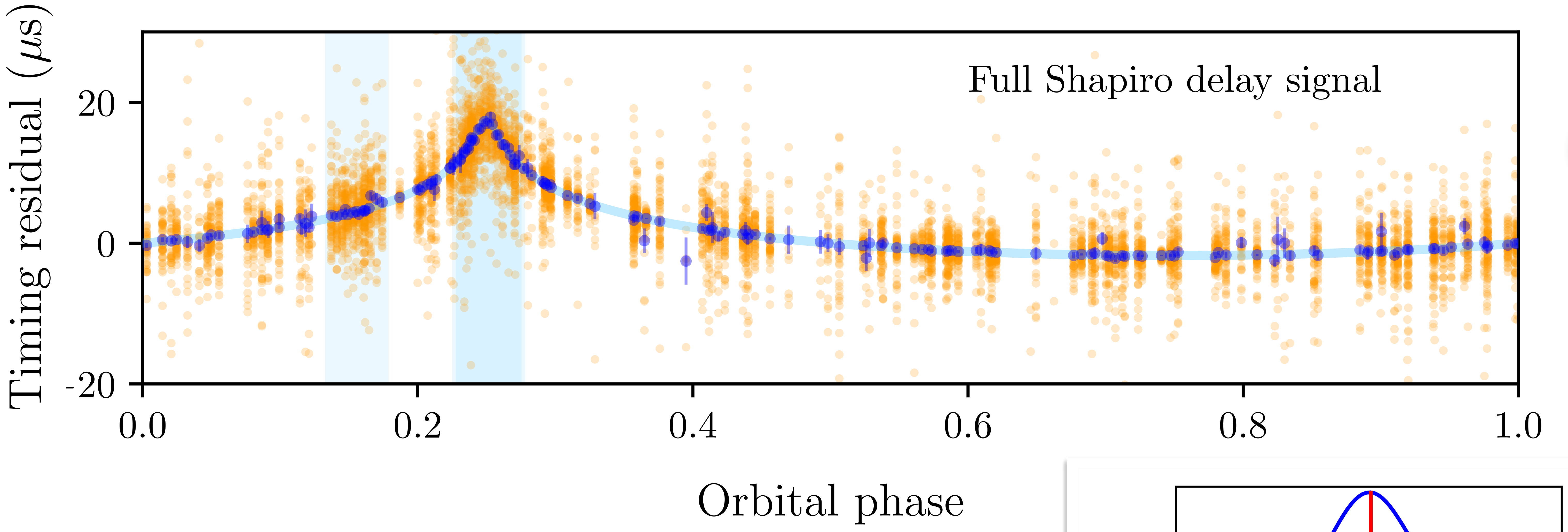
$$\boxed{\mathrm{M} = 2.01 \pm 0.04\ \mathrm{M}_\odot}$$

J. Antoniadis et al. : Science 340 (2013) 6131

- Strong constraints for the **stiffness of the Equation-of State** of cold & dense baryonic matter

MASSIVE NEUTRON STARS (contd.)

- Millisecond pulsar PSR J0740+6620 in neutron star - white dwarf binary



$$M = 2.14^{+0.10}_{-0.09}\ M_\odot$$

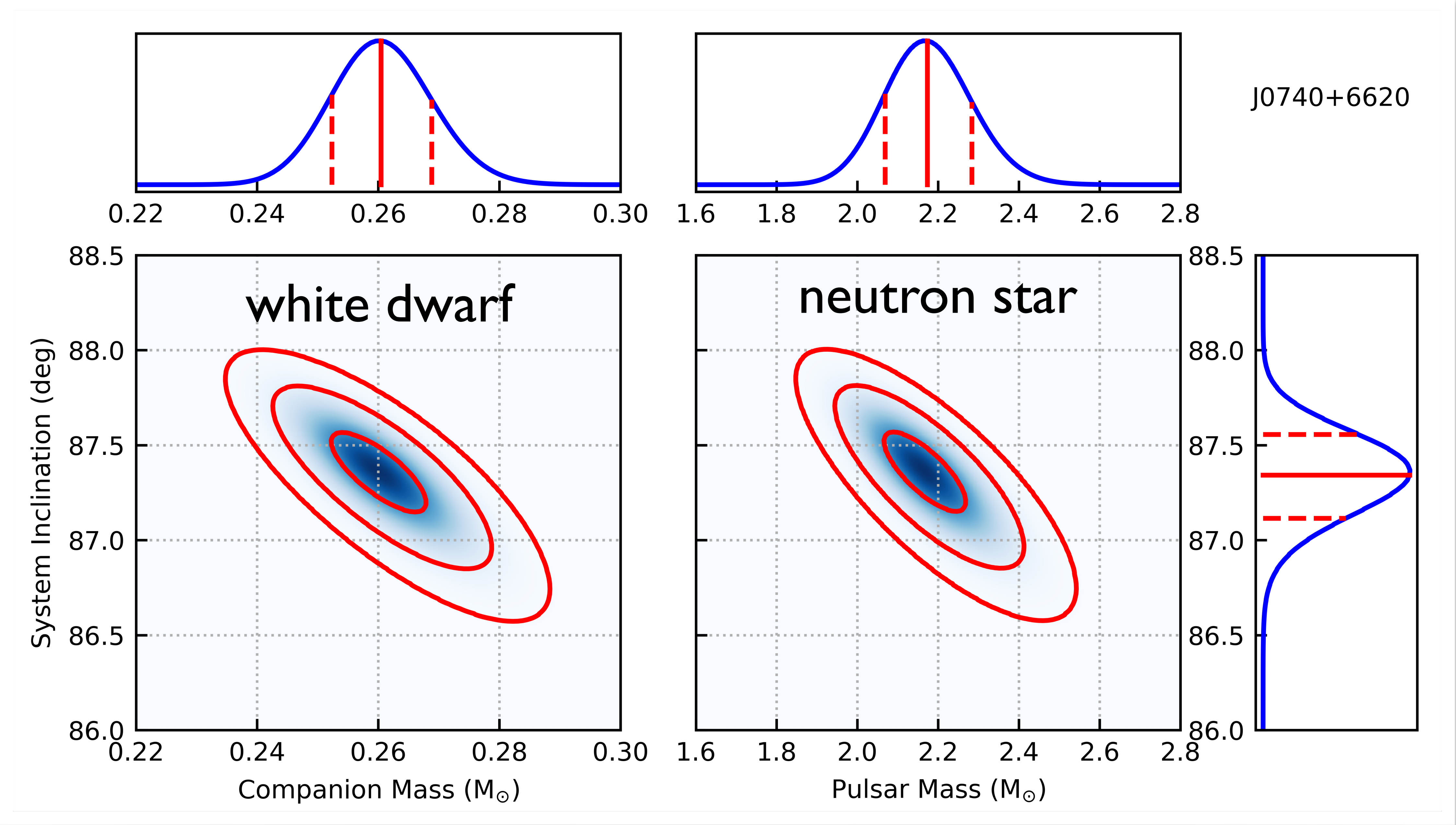
H.T. Cromartie et al., Nature Astron. 4 (2019) 72

- updated 1.5 years later:

$$M = 2.08 \pm 0.07\ M_\odot$$

E. Fonseca et al., Astrophys. J. Lett. 915 (2021) L12

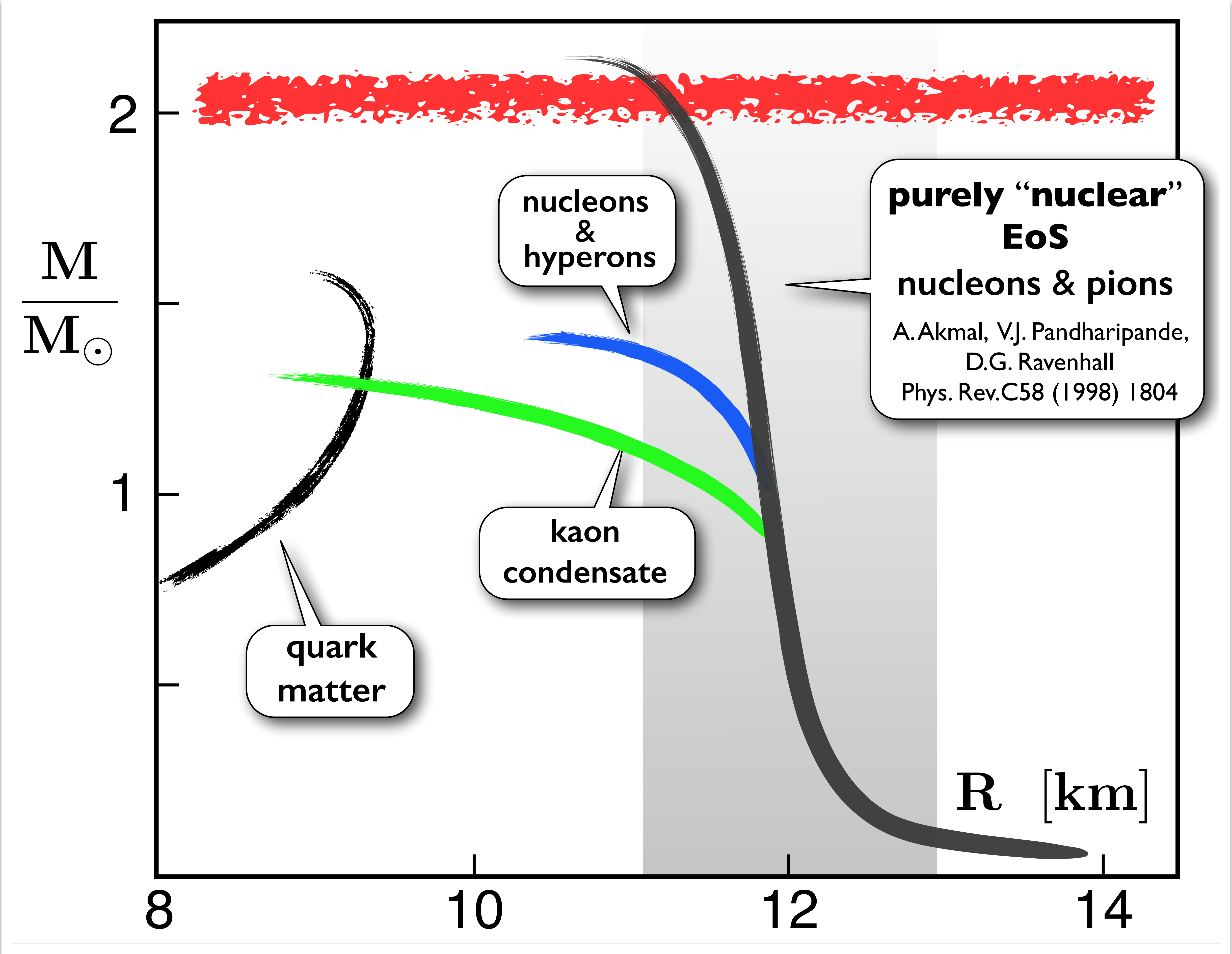
- Observations: Green Bank Telescope



CONSTRAINTS on EQUATION-of-STATE

- from observations of $2\,\mathrm{M}_\odot$ neutron stars

Mass-Radius Relation



Tolman - **O**ppenheimer - **V**olkov Equations

$$\frac{\mathrm{dP}}{\mathrm{dr}} = -\frac{\mathrm{G}}{\mathrm{c}^2}\frac{(\mathcal{E}+\mathrm{P})(\mathrm{M}+4\pi\mathrm{Pr}^3)}{\mathrm{r}(\mathrm{r}-2\mathrm{GM}/\mathrm{c}^2)}$$

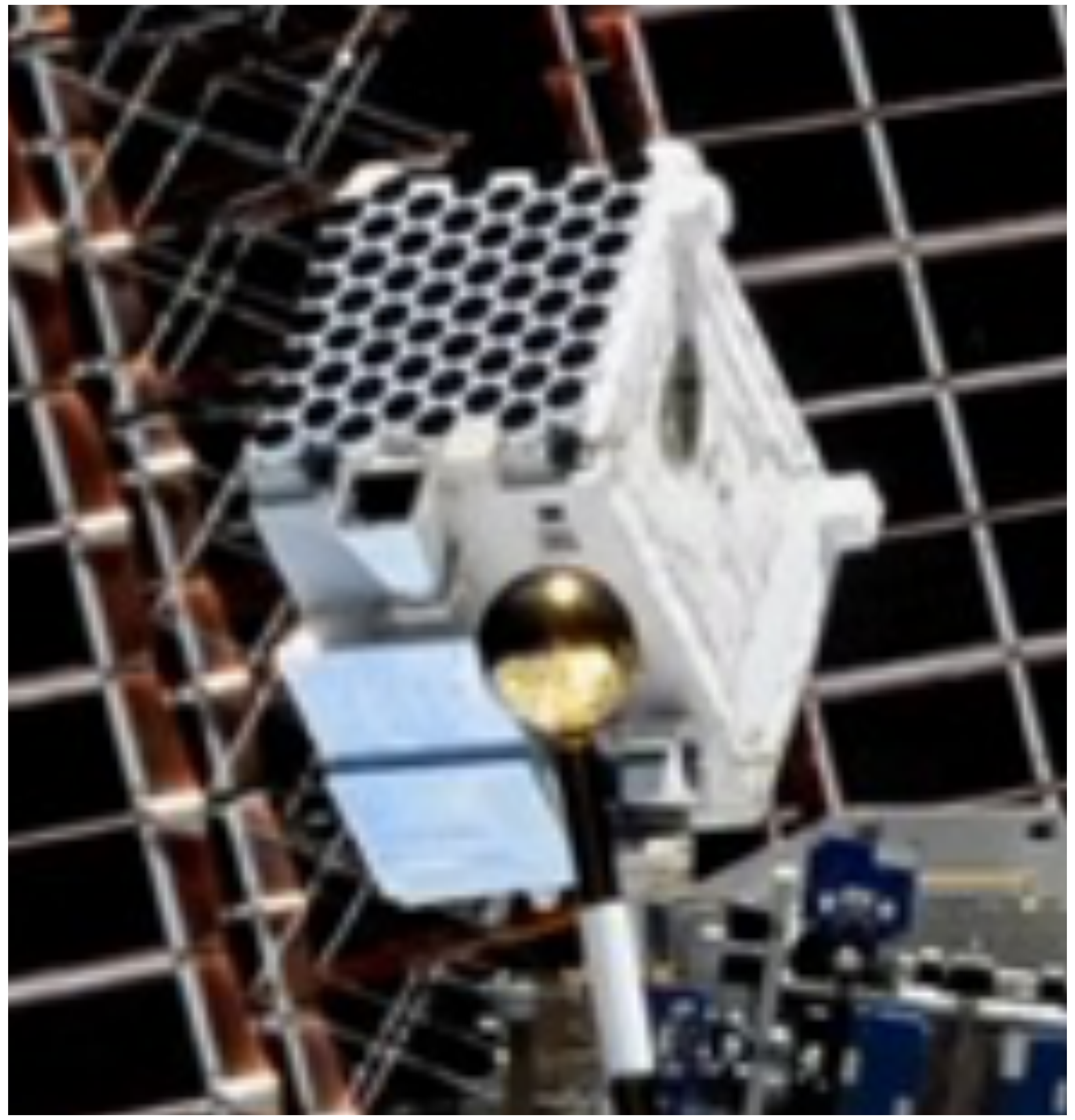
$$\frac{\mathrm{dM}}{\mathrm{dr}} = 4\pi\mathrm{r}^2\,\frac{\mathcal{E}}{\mathrm{c}^2}$$

- **Stiff equation-of-state $\mathrm{P}(\mathcal{E})$ required**
- **Simple forms of exotic matter**
  (kaon condensate, quark matter, ...)
  ruled out

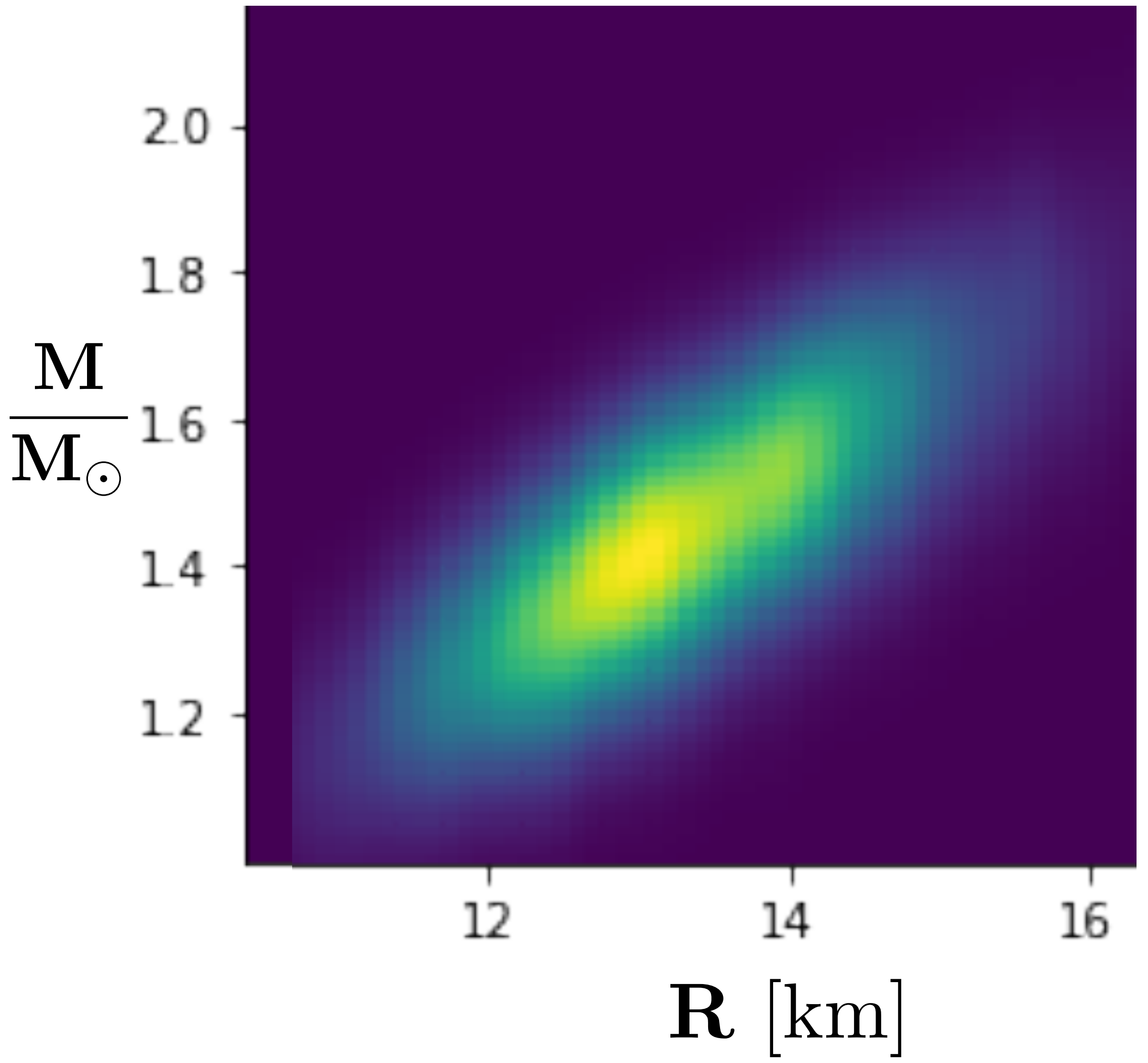
MASSES & RADII of NEUTRON STARS

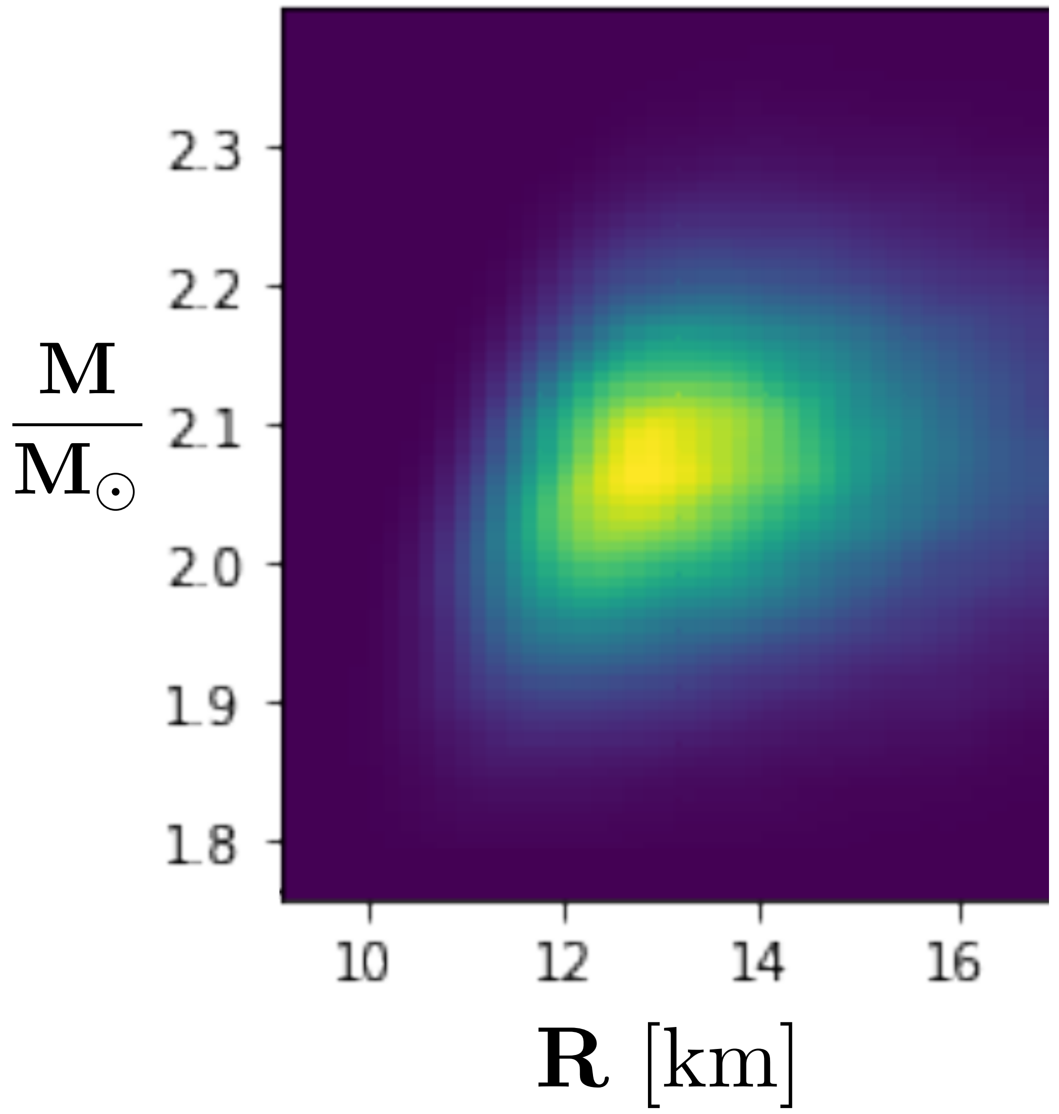
- **NICER** @ International Space Station

Neutron Star
Interior Composition Explorer



- X rays from hot spots at the surface of rotating neutron stars





- $PSR\,J0030+0451$

$$\mathbf{M = 1.44 \pm 0.15\, M_\odot}$$

$$\mathbf{R = 13.02^{+1.24}_{-1.06}\ km}$$

M.C. Miller et al. (NICER)
Astroph. J. Lett. 887 (2019) L24

$$\mathbf{R = 12.71^{+1.14}_{-1.19}\ km}$$

T.E. Riley et al. (NICER)
Astroph. J. Lett. 887 (2019) L21

- $PSR\,J0740+6620$

$$\mathbf{M = 2.08 \pm 0.07\, M_\odot}$$

$$\mathbf{R = 13.7^{+2.6}_{-1.5}\ km}$$

M.C. Miller et al. (NICER + XMM Newton)
Astroph. J. Lett. 918 (2021) L28

$$\mathbf{R = 12.39^{+1.30}_{-0.98}\ km}$$

T.E. Riley et al. (NICER + XMM Newton)
Astroph. J. Lett. 918 (2021) L27

GRAVITATIONAL WAVES from BINARY NEUTRON STAR MERGERS

LIGO and Virgo Collaborations 2017 - 2020

- Additional constraints on Equation-of-State:
  Binary tidal deformability

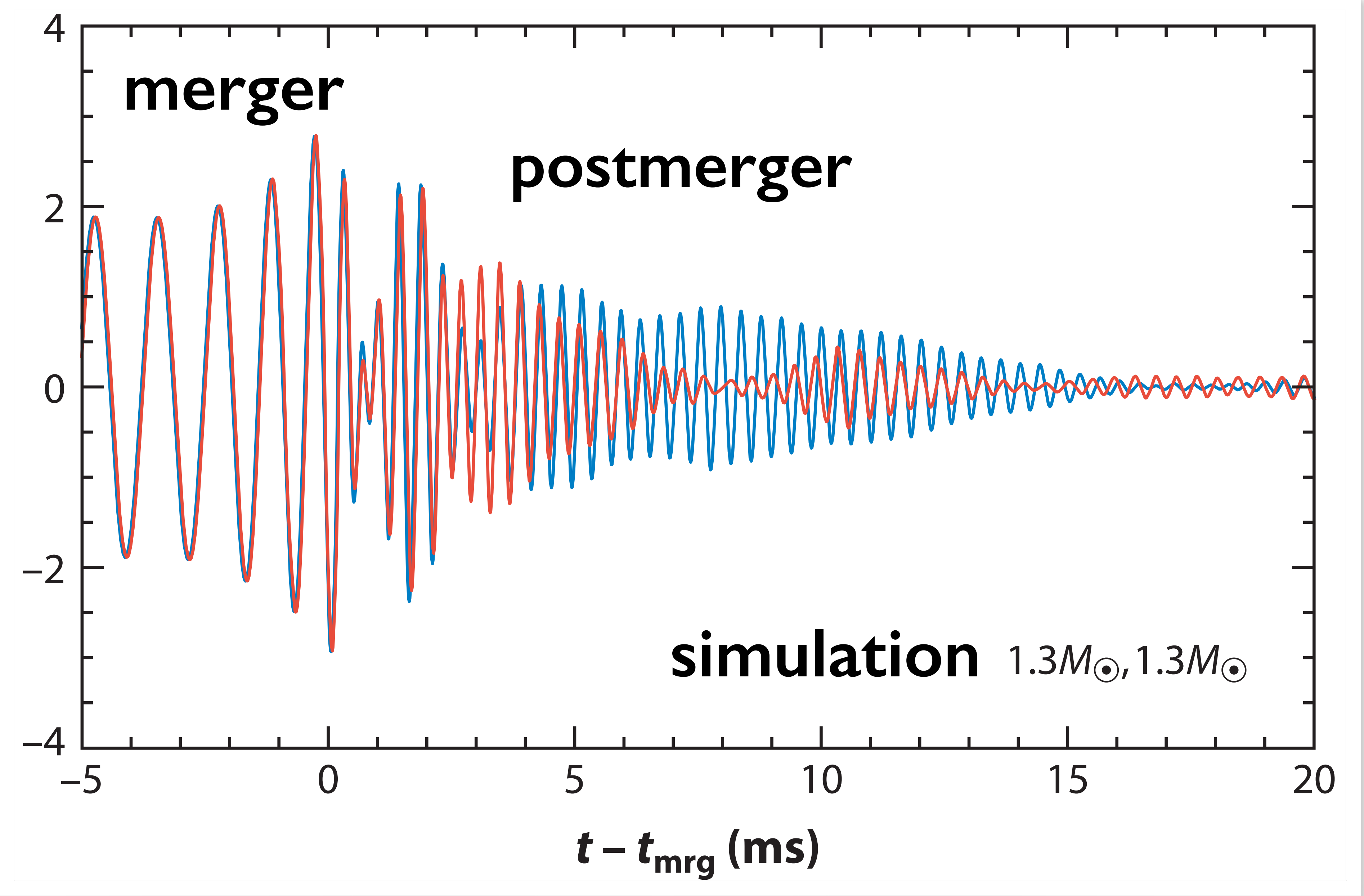
$$\tilde{\Lambda} = \frac{16}{13}\frac{(M_1 + 12\,M_2)M_1^4\Lambda_1}{(M_1+M_2)^5} + (1 \leftrightarrow 2)$$

- $\mathbf{GW\ 190425}\ :\ M = M_1 + M_2 = 3.3 \pm 0.1\ M_\odot$

B.P. Abbot et al. : Astroph. J. Lett. 892 (2020) L3

- $\mathbf{GW\ 170817}\ :\ M = M_1 + M_2 = 2.74^{+0.04}_{-0.01}\ M_\odot$

B.P. Abbot et al. : Phys. Rev. Lett. 119 (2017) 161101 Phys. Rev. X9 (2019) 011001



D. Radice, S. Bernuzzi, A. Perego : Ann. Rev. Nucl. Part. Sci, 70 (2020) 95

Individual neutron star masses and tidal deformabilities (GW170817)

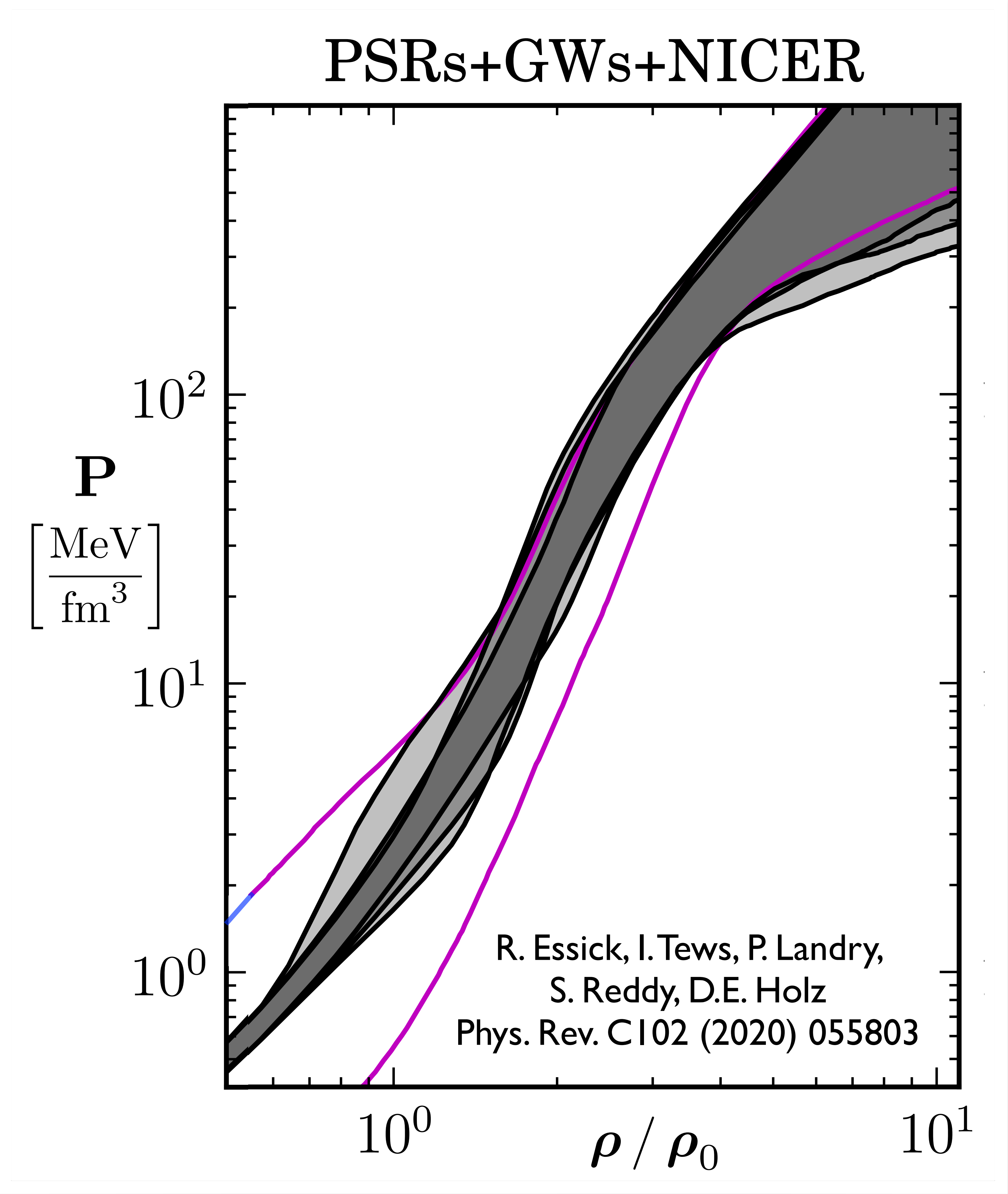
$$M_1 = 1.46^{+0.12}_{-0.10}\ M_\odot \qquad M_2 = 1.27 \pm 0.09\ M_\odot$$

$$\Lambda_1 = 255^{+416}_{-171} \qquad \Lambda_2 = 661^{+858}_{-375}$$

M. Fasano et al. : Phys. Rev. Lett. 123 (2019) 141101

NEUTRON STAR MATTER EQUATION-of-STATE

- Examples of recent **EoS analysis** based on **multimessenger data**

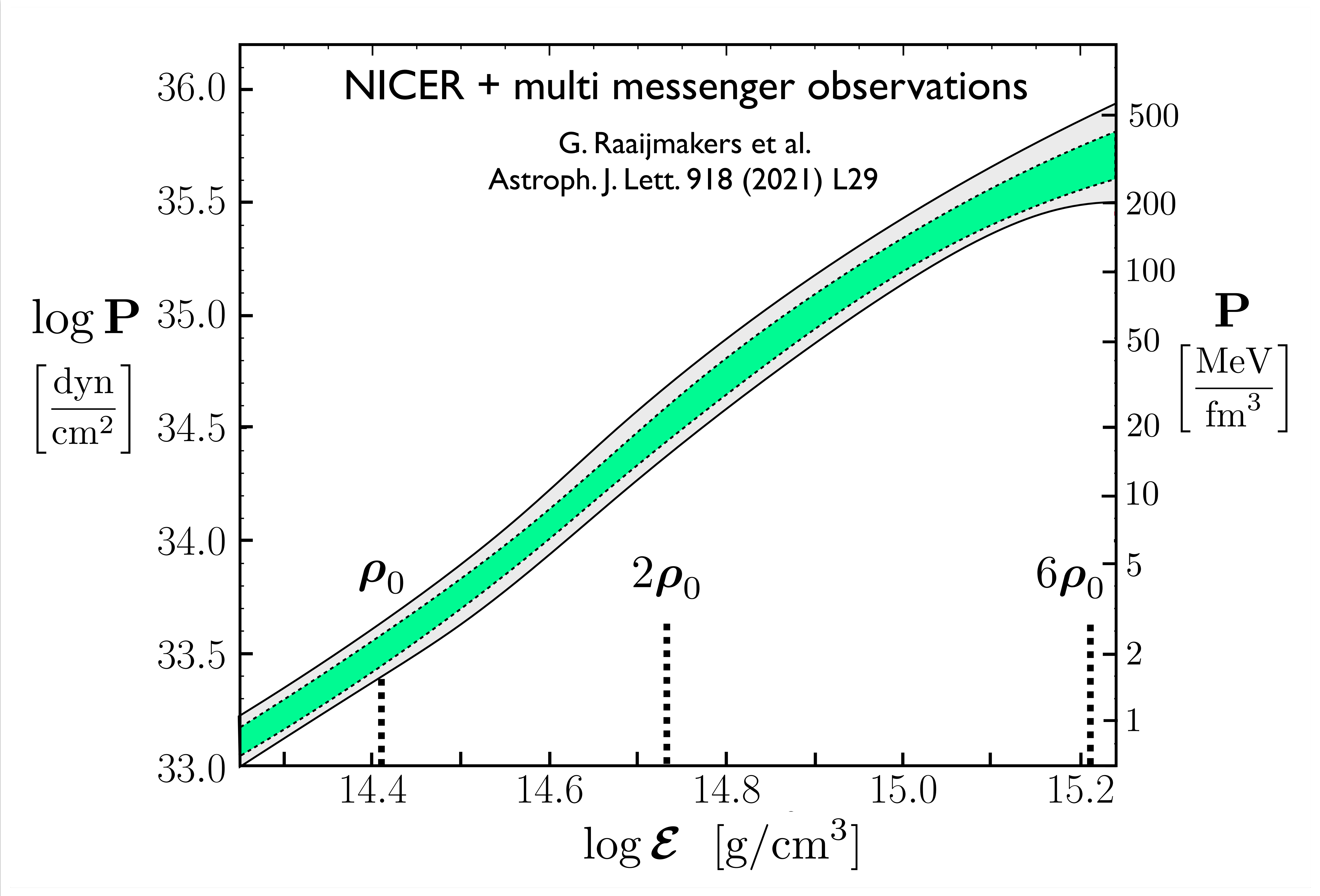


R. Essick, I. Tews, P. Landry, S. Reddy, D.E. Holz
Phys. Rev. C102 (2020) 055803

- **Bayesian statistical methods** : model $\mathcal{M}$, data $\mathcal{D}$

$$\mathcal{P}(\mathcal{M}|\mathcal{D}) \propto \mathcal{P}(\mathcal{D}|\mathcal{M})\mathcal{P}(\mathcal{M})$$

posterior likelihood prior



G. Raaijmakers et al.
Astroph. J. Lett. 918 (2021) L29

NEUTRON STAR MATTER EQUATION-of-STATE

- Example of recent **EoS analysis** :

  Bayesian Inference

  (68% and 95% confidence intervals)

  PSR masses, NICER & GW data
  low-density constraints (ChEFT)
  asymptotic constraints (pQCD)

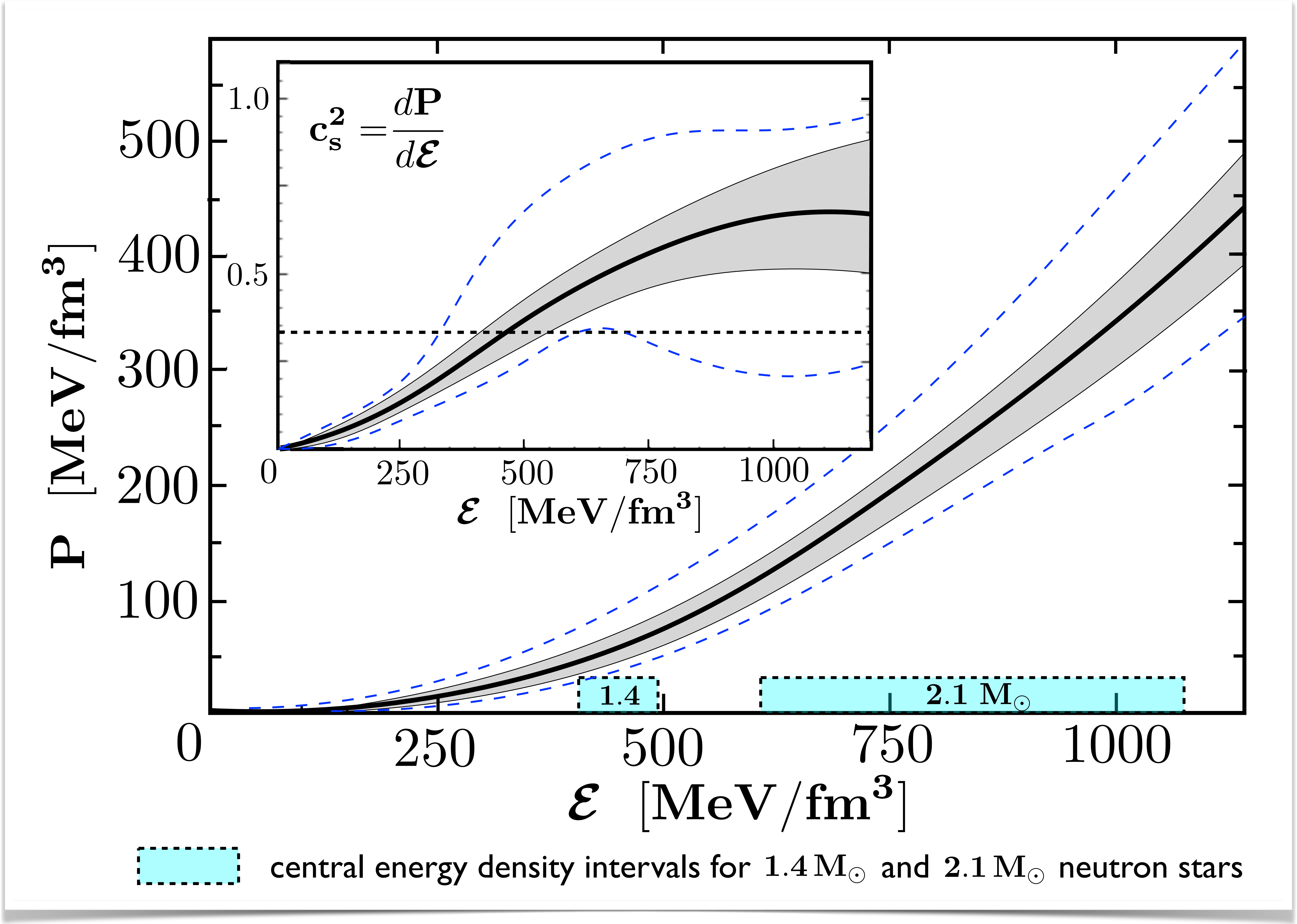
- Squared **speed of sound**

$$c_s^2 = \frac{dP}{d\mathcal{E}}$$

exceeds conformal limit $c_s^2 = \frac{1}{3}$
at densities $\rho > 3\rho_0$

- Strongly **repulsive correlations** at **high densities**

L. Brandes, N. Kaiser, W. W. (2022)



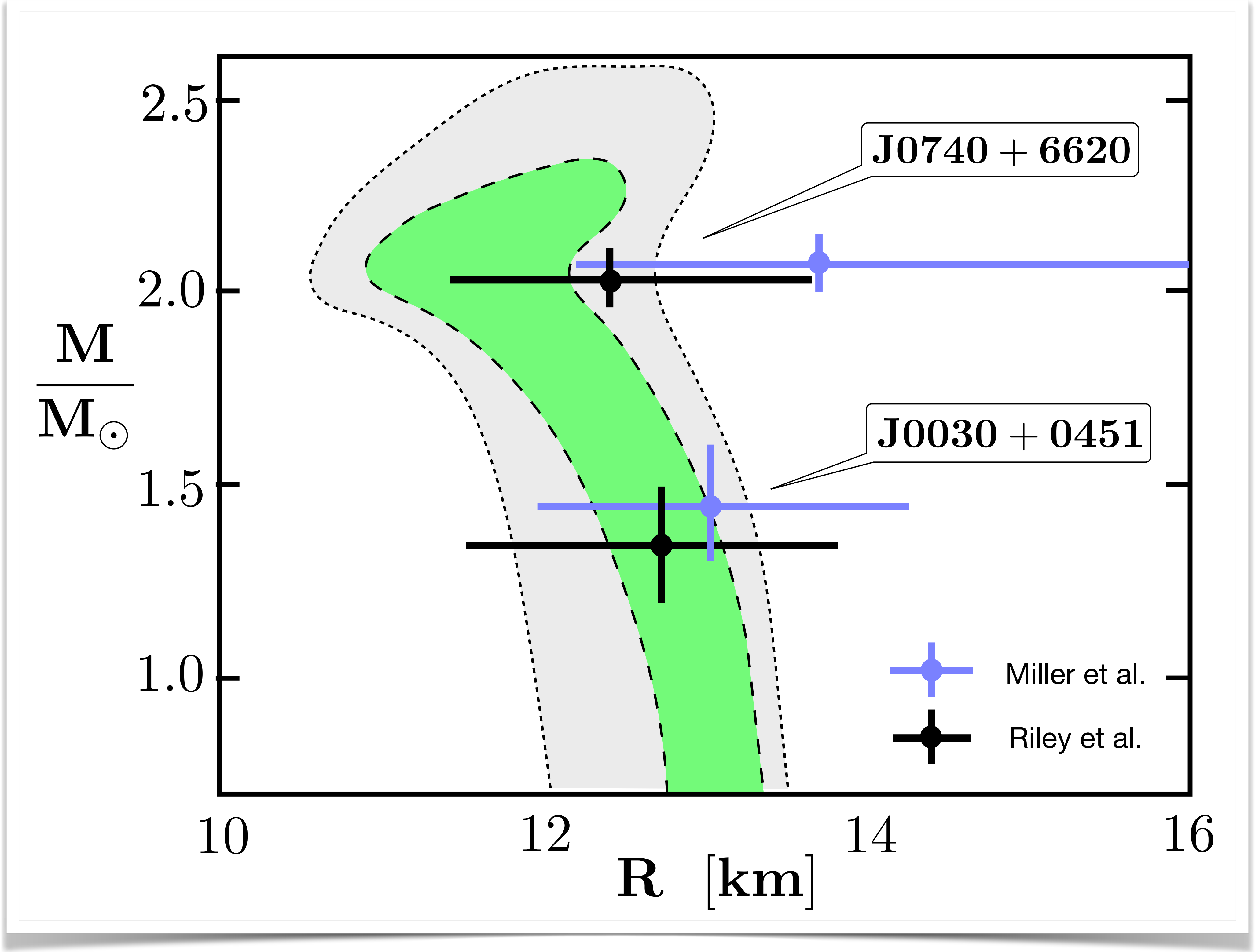
- **EoS** involving only **subconformal sound speeds** $(c_s^2 < 1/3)$ **in neutron star cores** is **unlikely**
  (only 0.03 % of studied samples)

S. Altiparmak, Ch. Ecker, L. Rezzolla arXiv:2203.14974

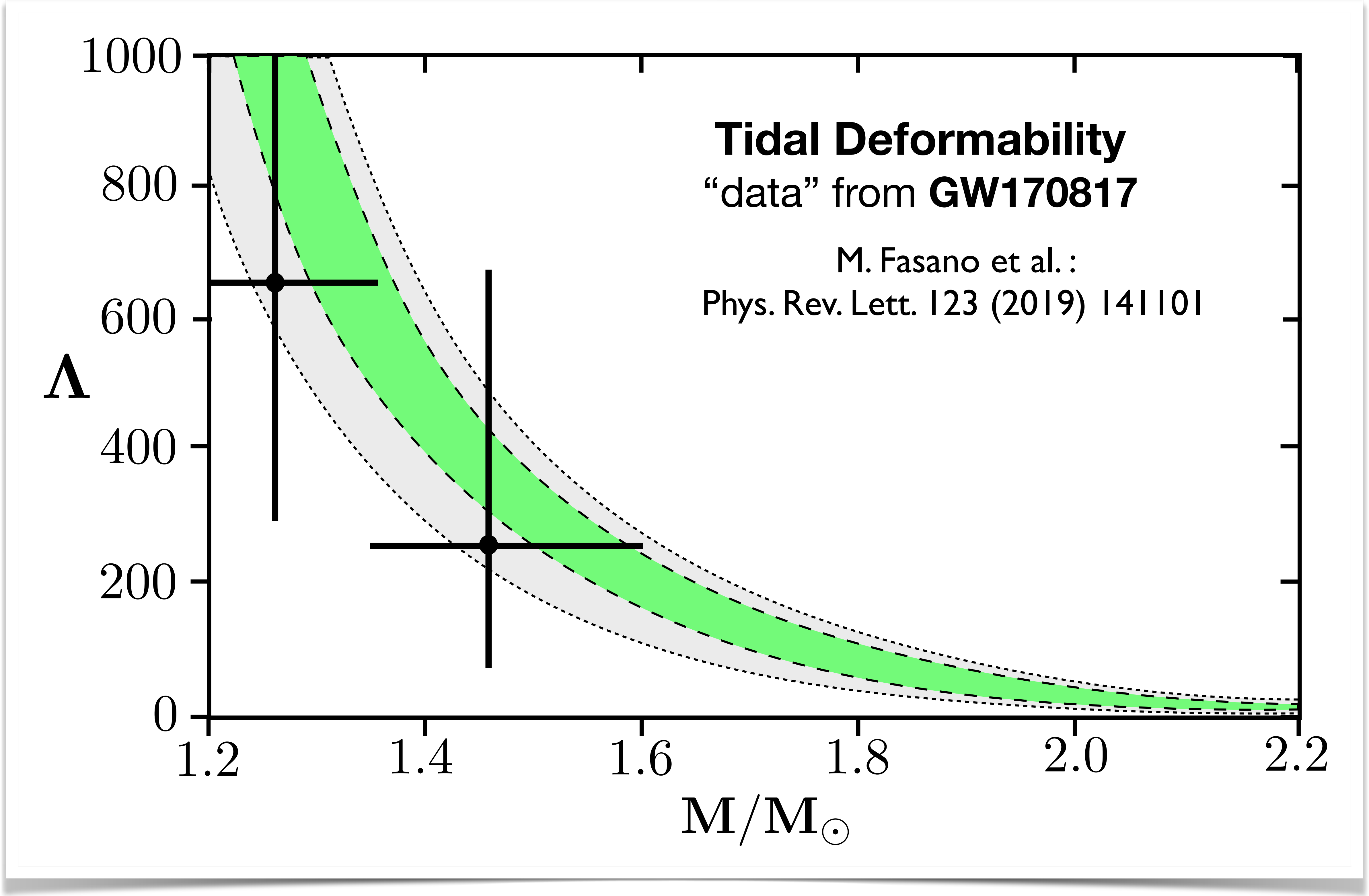
NEUTRON STAR MATTER EQUATION-of-STATE

L. Brandes, N. Kaiser, W. W. (2022)

- **Mass - radius relation** (from TOV) in comparison with **NICER** data



- **Tidal deformabilities** in comparison with those of two merging neutron stars observed in **gravitational wave signals**



Minimal Conditions to be satisfied by **Theories** of **Dense Baryonic Matter**

- **Vacuum :**
  - **Low-energy QCD and spontaneously broken CHIRAL SYMMETRY**
    Pion dynamics (theorems: Gell-Mann, Oakes, Renner ; Goldberger-Treiman ; …)
  - **Realistic nucleon-nucleon interaction (phase shifts)**

- **Low density** $(\rho \lesssim 2\,\rho_0)$ **:**
  - **Realistic EoS of symmetric nuclear matter and neutron matter**
  - **Asymmetric nuclear matter and symmetry energy**
  - **Nuclear thermodynamics : liquid-gas phase transition**

- **High density :**
  - **Neutron star maximum mass** $\mathrm{M}_{max} \gtrsim 2\ \mathrm{M}_\odot$
  - **Neutron star radii (NICER)** $11\,\mathrm{km} \lesssim \mathrm{R} \lesssim 14\,\mathrm{km}$
  - **Tidal deformability constraints from neutron star mergers (GW signals)**

Equation-of-State of **Dense Baryonic Matter**
- **Theoretical Frameworks** and **Models** -

- **Nuclear degrees of freedom** (nucleons + pions + s.r.c. / vector mesons)
  - **Many-body theory with realistic two- and three-nucleon interactions**
    (example: APR EoS - Akhmal, Pandharipande, Ravenhall (1998))
  - **Chiral EFT combined with Functional Renormalisation Group (FRG) methods**
    (reviews: Drischler, Holt, Wellenhofer (2021); Drews, W.W. (2017), …)
- **Nucleons + Hyperons**
  - **Many-body theory of baryonic matter with nucleons and hyperons**
    (examples: Djapo, Schaefer, Wambach (2010); Lonardoni, Pederiva, Gandolfi (2014), …)
  - **Baryon octet plus nonlinear meson couplings including three-body forces**
    (examples: Logoteta, Vidaña, Bombaci (2019); Motta, Guichon, Thomas (2021), …)
- **Hybrid models**
  - **Hadron - quark continuity (crossover) models:**
    from nucleonic matter at low densities to quark matter at high densities
    (examples: Baym, Hatsuda, Kojo et al. 2018-2021, Fukushima, Kojo, W.W. (2020), …)

NEUTRON STAR MATTER Equation-of-State

- **Included :**

  $$\mathrm{M}_{max} \gtrsim 2\,\mathrm{M}_{\odot}$$

  \+ GW constraints

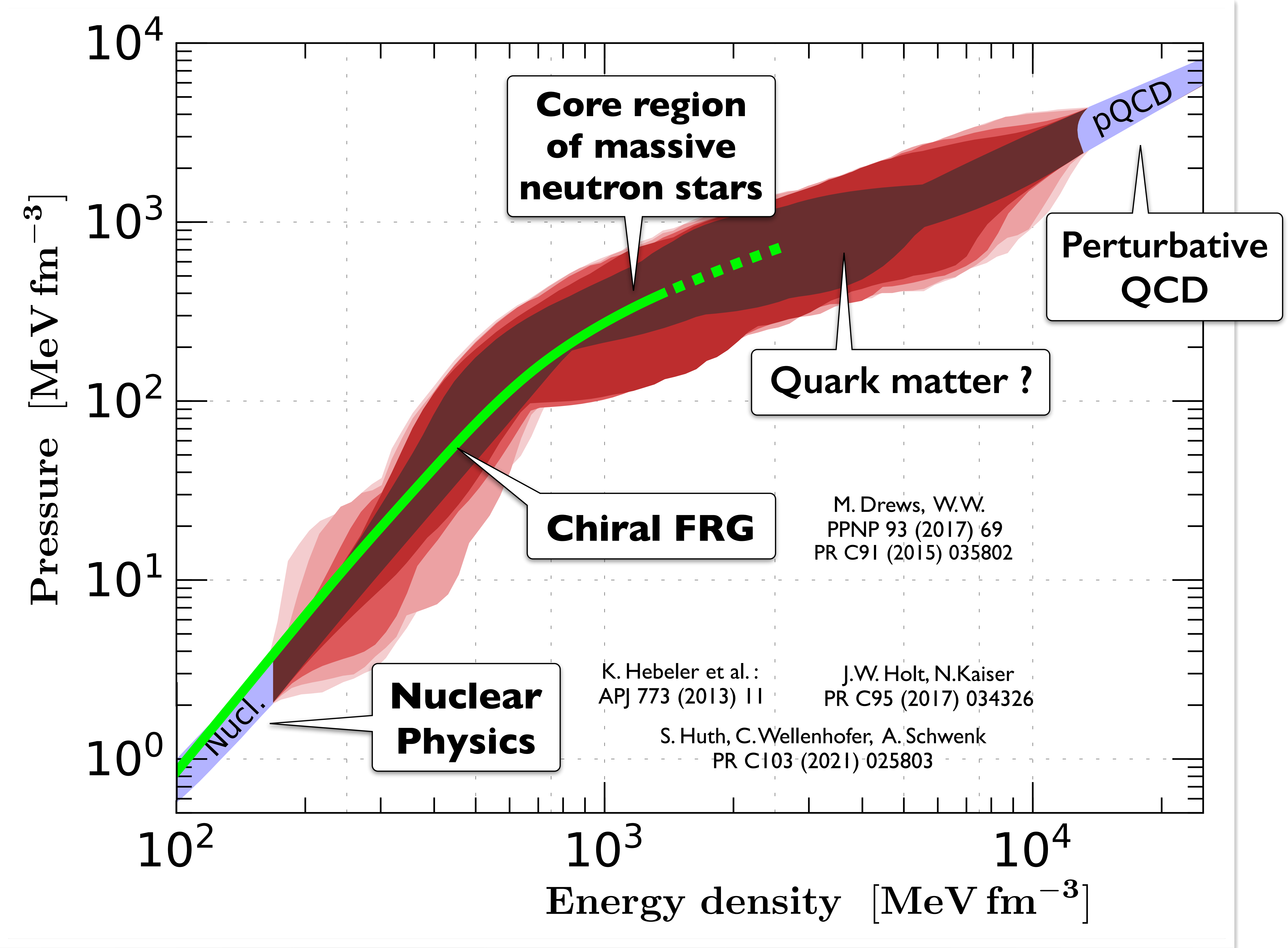
  \+ multi-messenger data

- Extrapolation to **perturbative QCD limit**

E. Annala, T. Gorda, A. Kurkela, J. Nättilä, A. Vuorinen : Nature Phys. 16 (2020) 907

… and a **neutron star EoS** based on **chiral meson-nucleon** theory combined with (non-perturbative) **F**unctional **R**enormalisation **G**roup

M. Drews, W.W. : PPNP 93 (2017) 69 ; PR C91 (2015) 035802



M. Drews, W.W.
PPNP 93 (2017) 69
PR C91 (2015) 035802

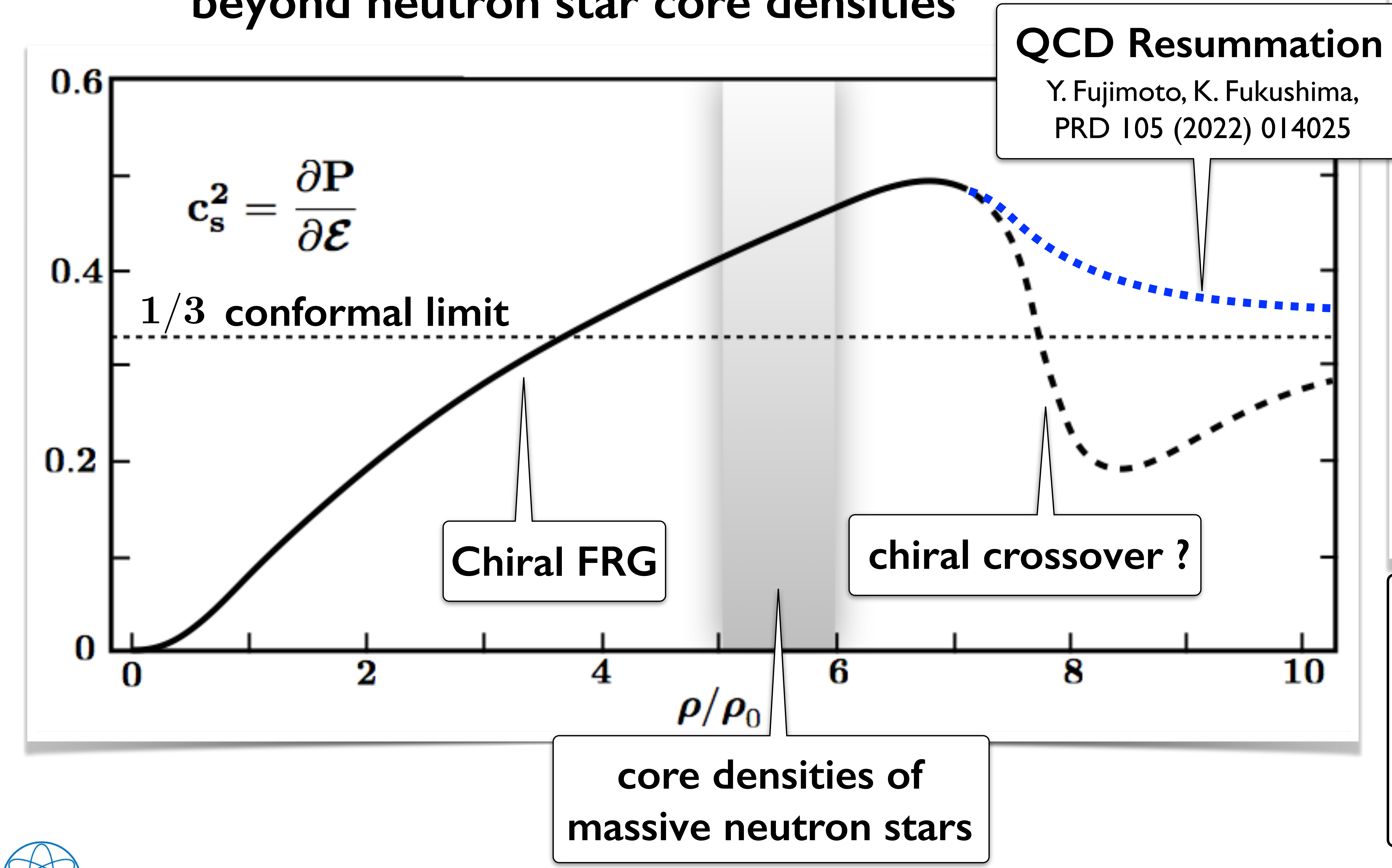
K. Hebeler et al. :
APJ 773 (2013) 11

J.W. Holt, N. Kaiser
PR C95 (2017) 034326

S. Huth, C. Wellenhofer, A. Schwenk
PR C103 (2021) 025803

VELOCITY of SOUND in NEUTRON STAR MATTER

- **Key quantity** to examine **phases, degrees of freedom** and **correlations in Fermi liquids**
- **Possible scenarios for extrapolation into regions beyond neutron star core densities**



$$c_s^2 = \frac{\partial P}{\partial \mathcal{E}}$$

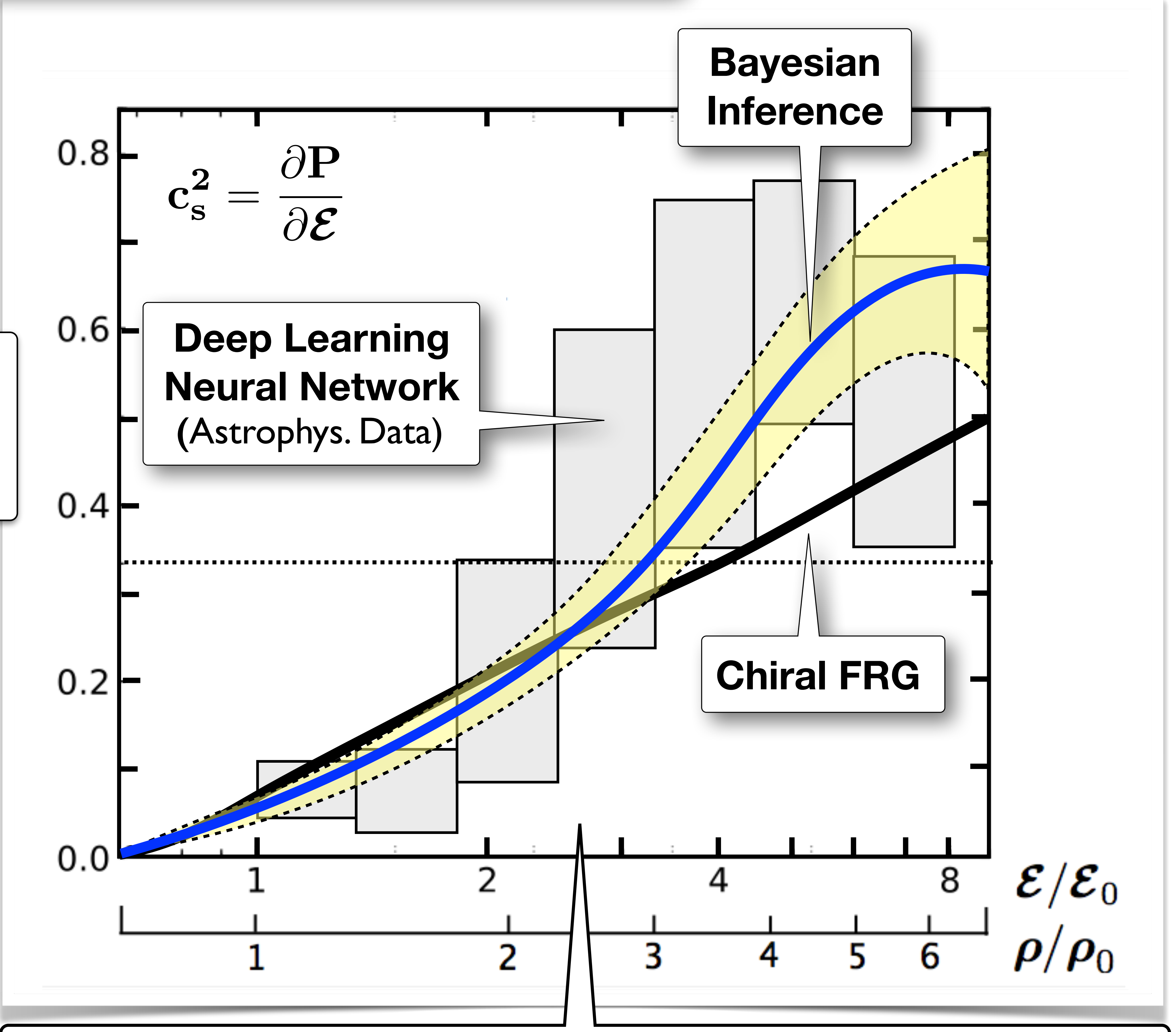
$1/3$ conformal limit

QCD Resummation
Y. Fujimoto, K. Fukushima,
PRD 105 (2022) 014025

Chiral FRG

chiral crossover ?

core densities of
massive neutron stars



$$c_s^2 = \frac{\partial P}{\partial \mathcal{E}}$$

Bayesian Inference

Deep Learning Neural Network
(Astrophys. Data)

Chiral FRG

deep neural network vs. **chiral FRG**

Y. Fujimoto, K. Fukushima, K. Murase
JHEP 03 (2021) 273

M. Drews, W.W.
Prog. Part. Nucl. Phys. 93 (2017) 69

vs. **Bayesian inference**
L. Brandes, N. Kaiser, W.W. (2022)

2.

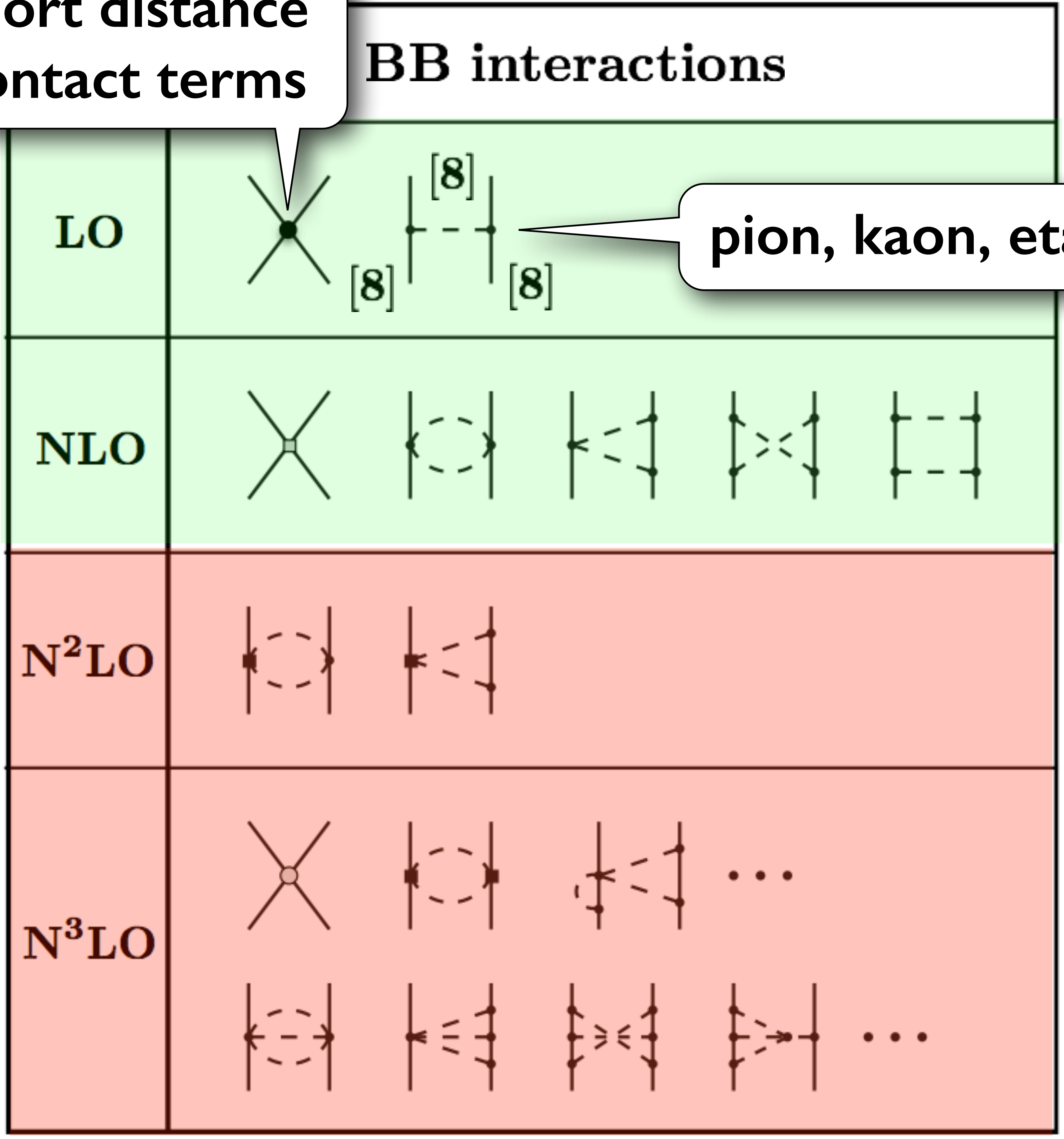
Strangeness (Part 1)

Chiral SU(3) Effective Field Theory of Hyperon - Nucleon Interactions
and
Hypernuclei

$$\begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}}+\frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}}+\frac{\Lambda}{\sqrt{6}} & n \\ -\Xi^- & \Xi^0 & -\frac{2\Lambda}{\sqrt{6}} \end{pmatrix}$$

BARYON-BARYON INTERACTIONS
from
CHIRAL $\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$ EFFECTIVE FIELD THEORY

$$\begin{pmatrix} \frac{\pi^0}{\sqrt{2}}+\frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}}+\frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2\eta}{\sqrt{6}} \end{pmatrix}$$



short distance contact terms

pion, kaon, eta exchange

- Systematically organized hierarchy in powers of $\mathbf{Q/\Lambda}$

  (Q: momentum, energy, pseudoscalar meson masses)

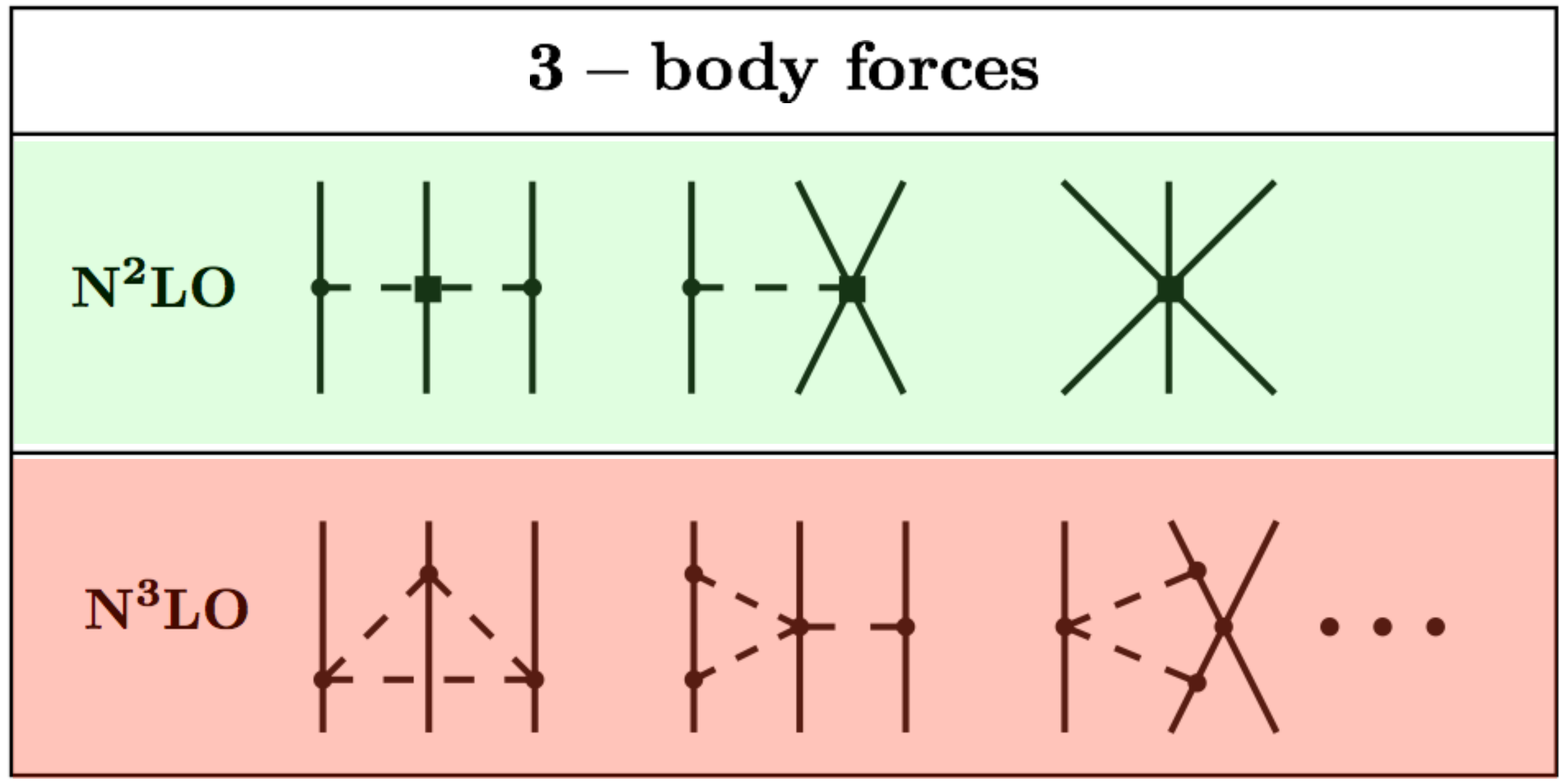
- **Hyperon-Nucleon interaction :**

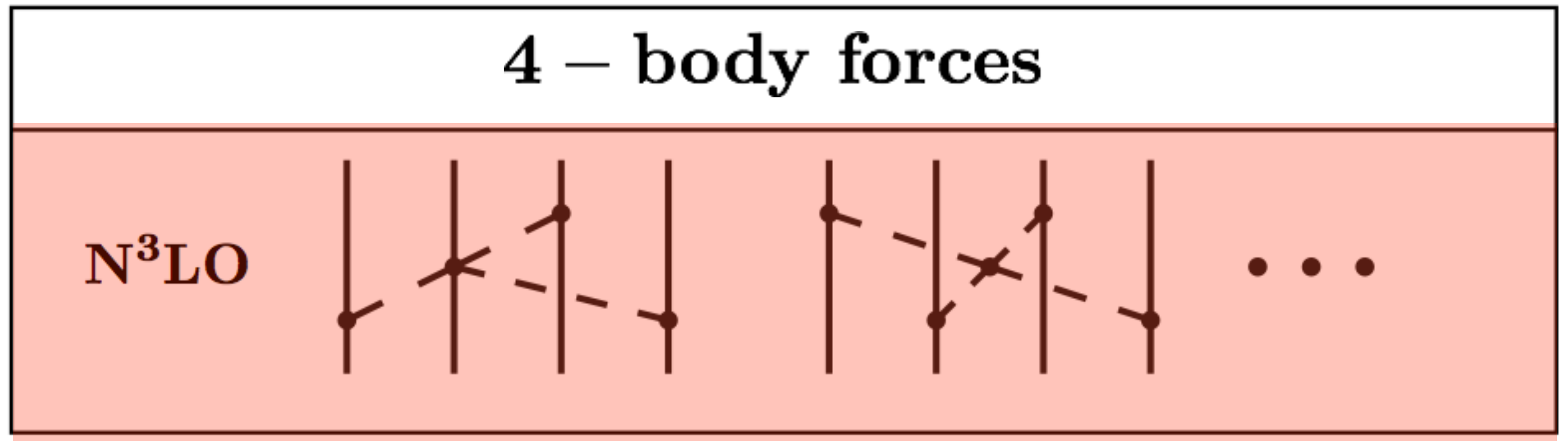
  still very limited scattering data base

  ⬇

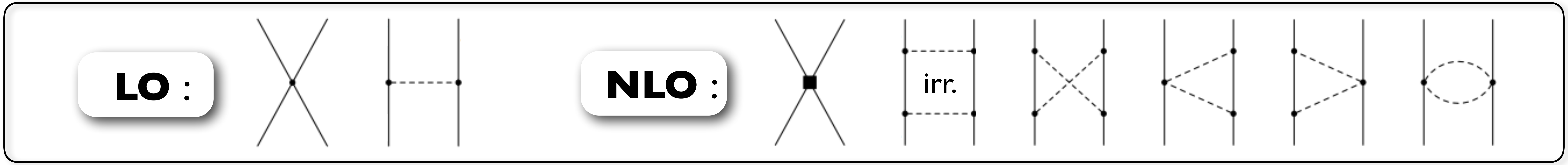
  Restriction in practice to

  NLO YN interactions plus three-body forces

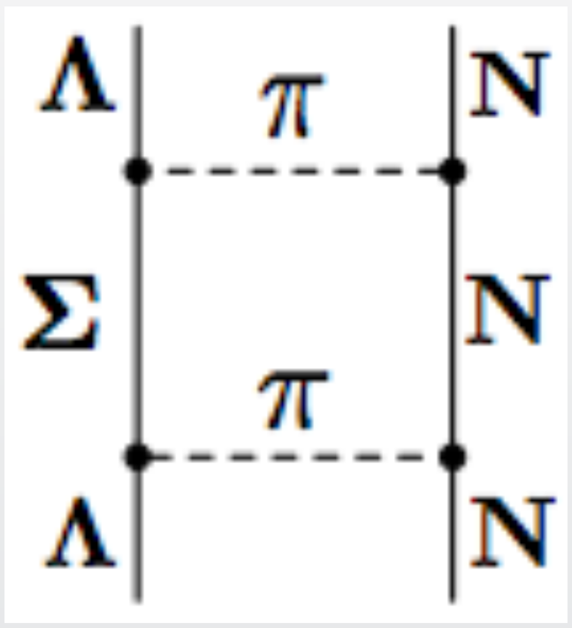




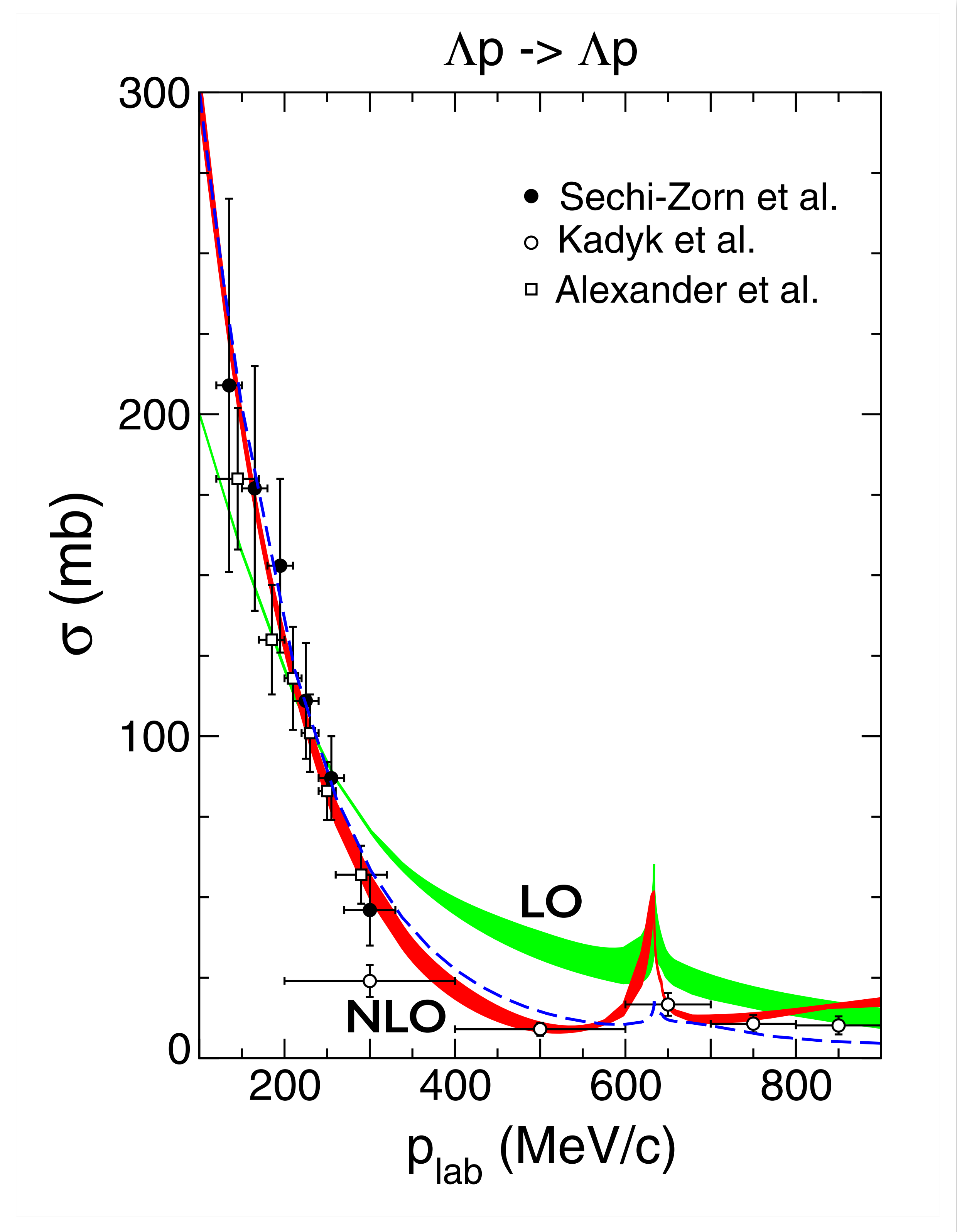
Hyperon - Nucleon Interaction
from **CHIRAL SU(3) Effective Field Theory**

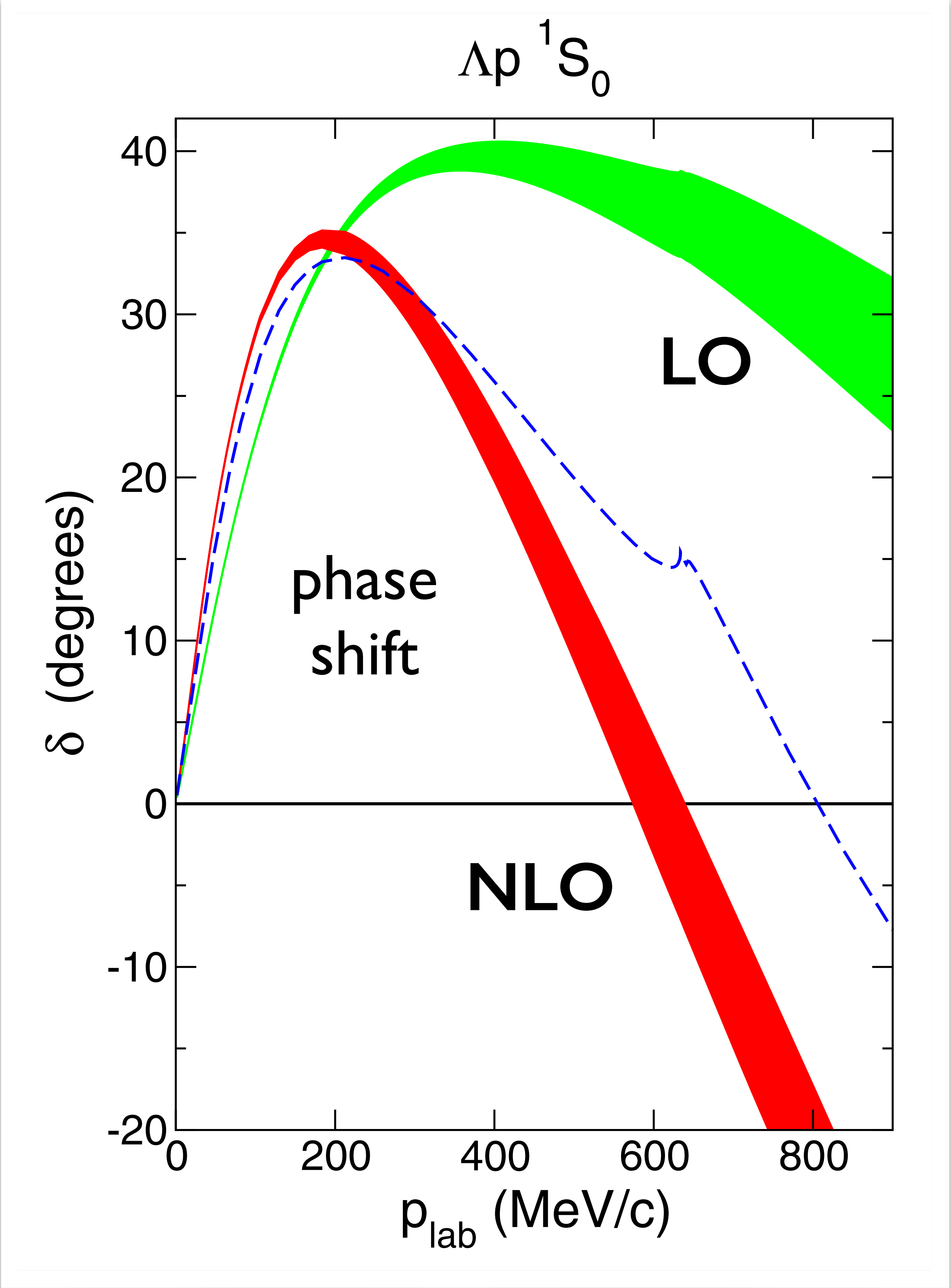


Example
ΛN scattering



Important role of
$\Lambda N \leftrightarrow \Sigma N$
coupled channels





- **moderate attraction** at low momenta
  → relevant for **hypernuclei**
- **increasing repulsion** at higher momenta
  → relevant for **dense baryonic matter**

J. Haidenbauer, S. Petschauer, N. Kaiser, U.-G. Meißner, A. Nogga, W.W.
Nucl. Phys. A 915 (2013) 24

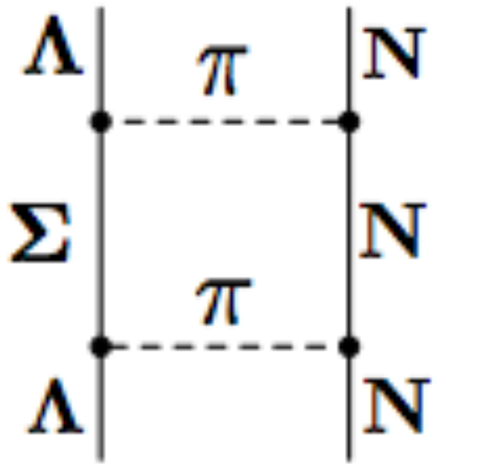
Λ Hyperon - Nucleon Interaction update

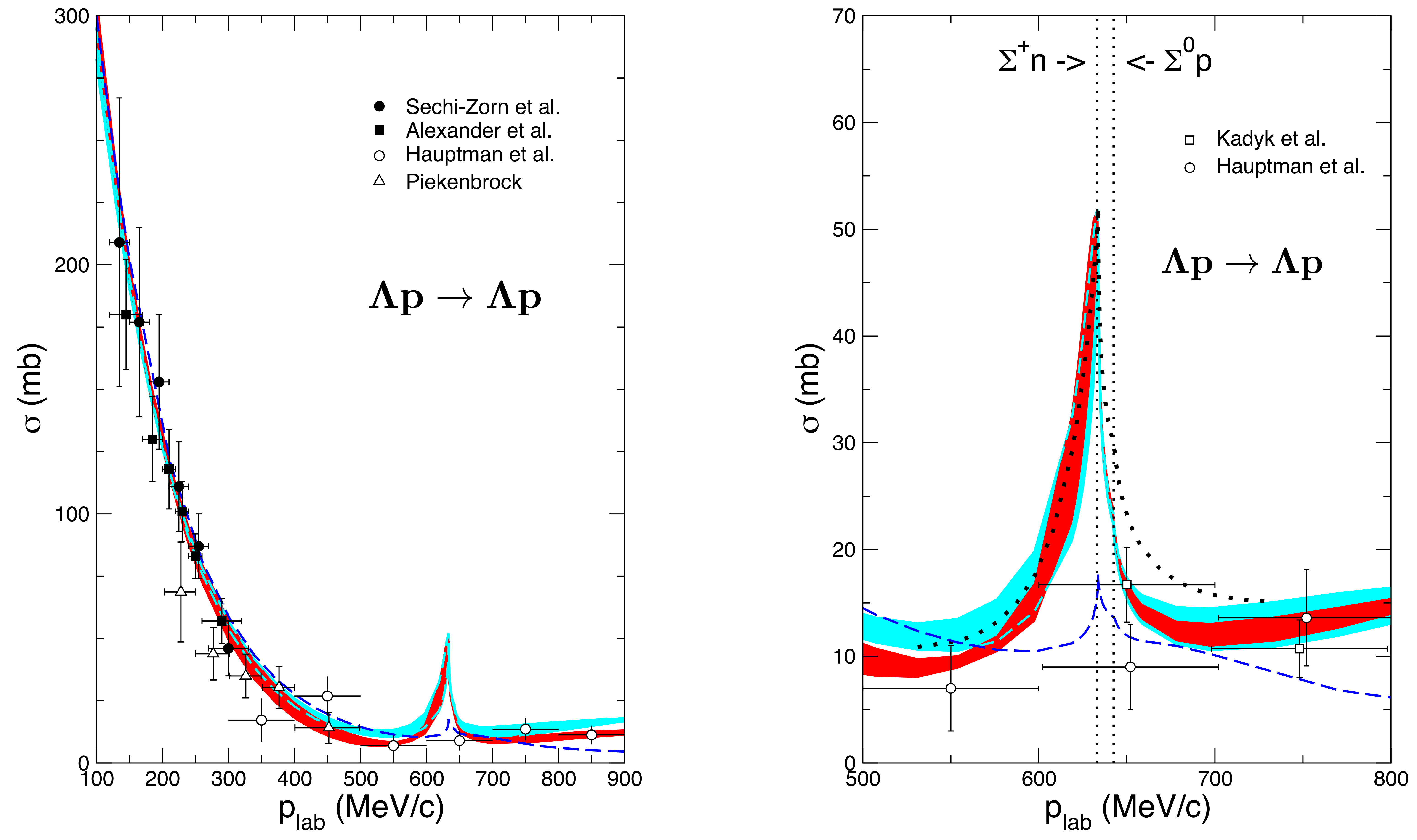
J. Haidenbauer, U.-G. Meißner, A. Nogga Eur. Phys. J. A56 (2020) 91

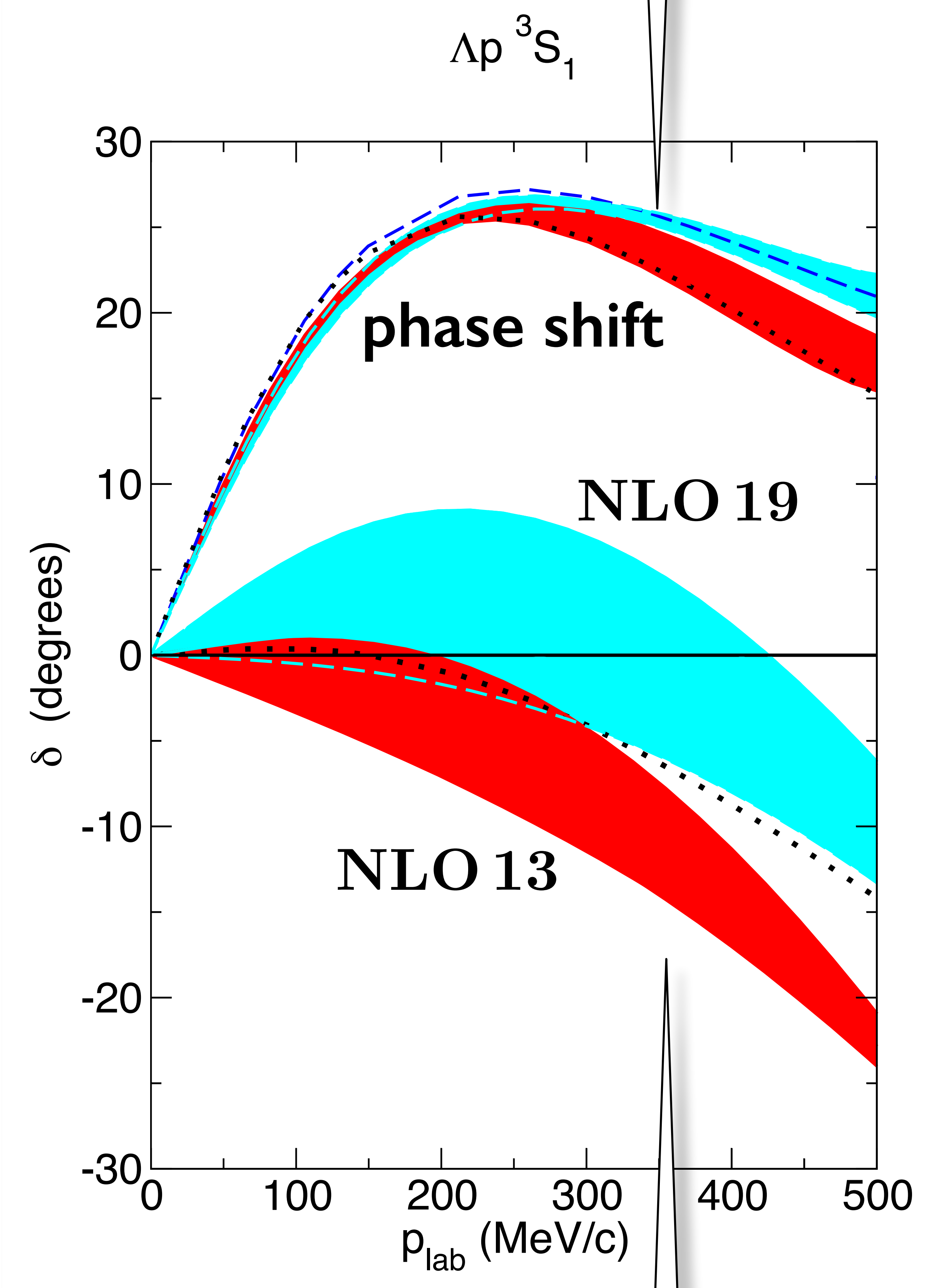
- Reduced no. of independent parameters (contact terms) at NLO by symmetries connecting NN and YN S-waves

blue : **NLO 19**
red : **NLO 13**

including $\Lambda N \leftrightarrow \Sigma N$ coupling



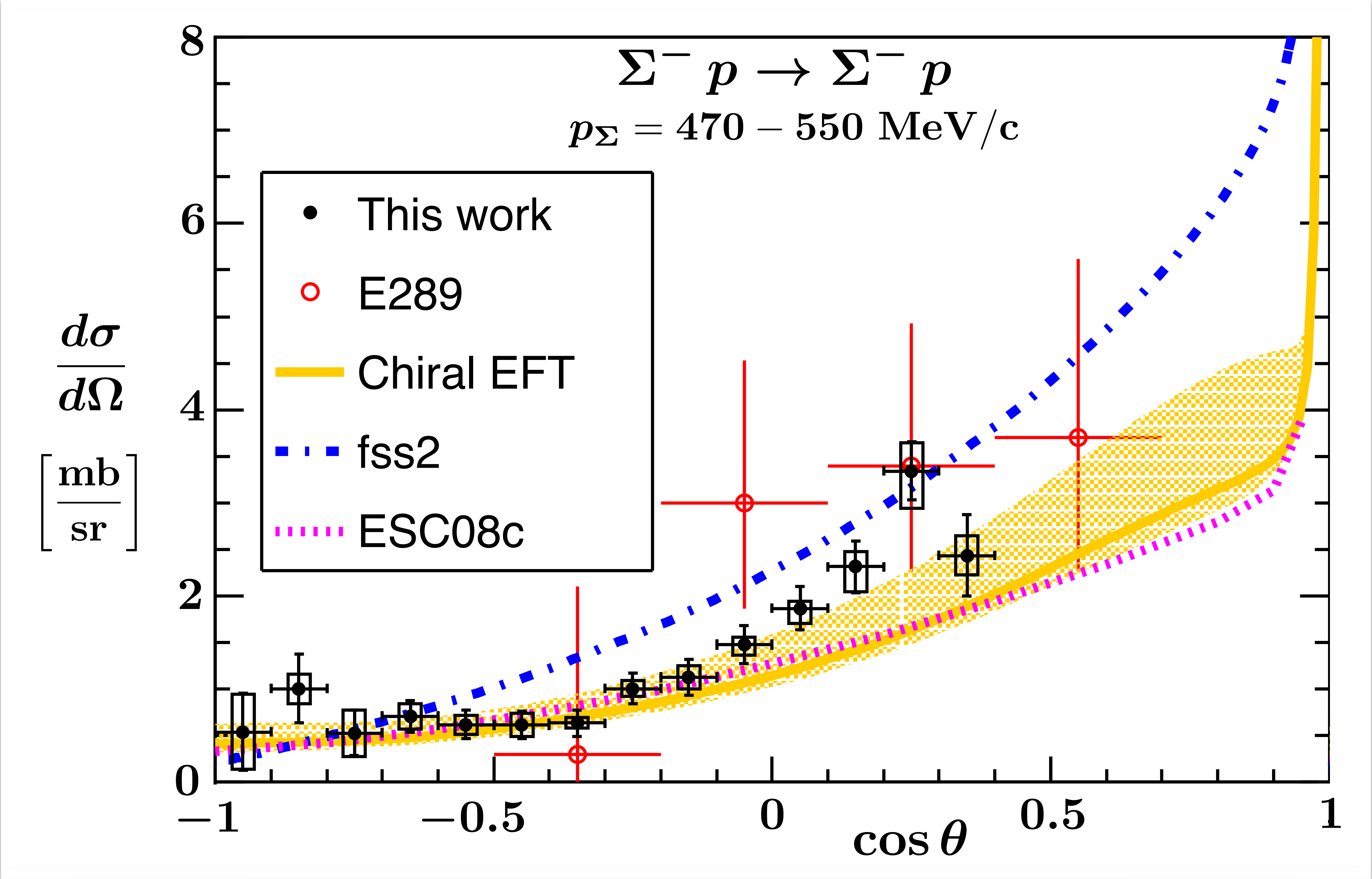




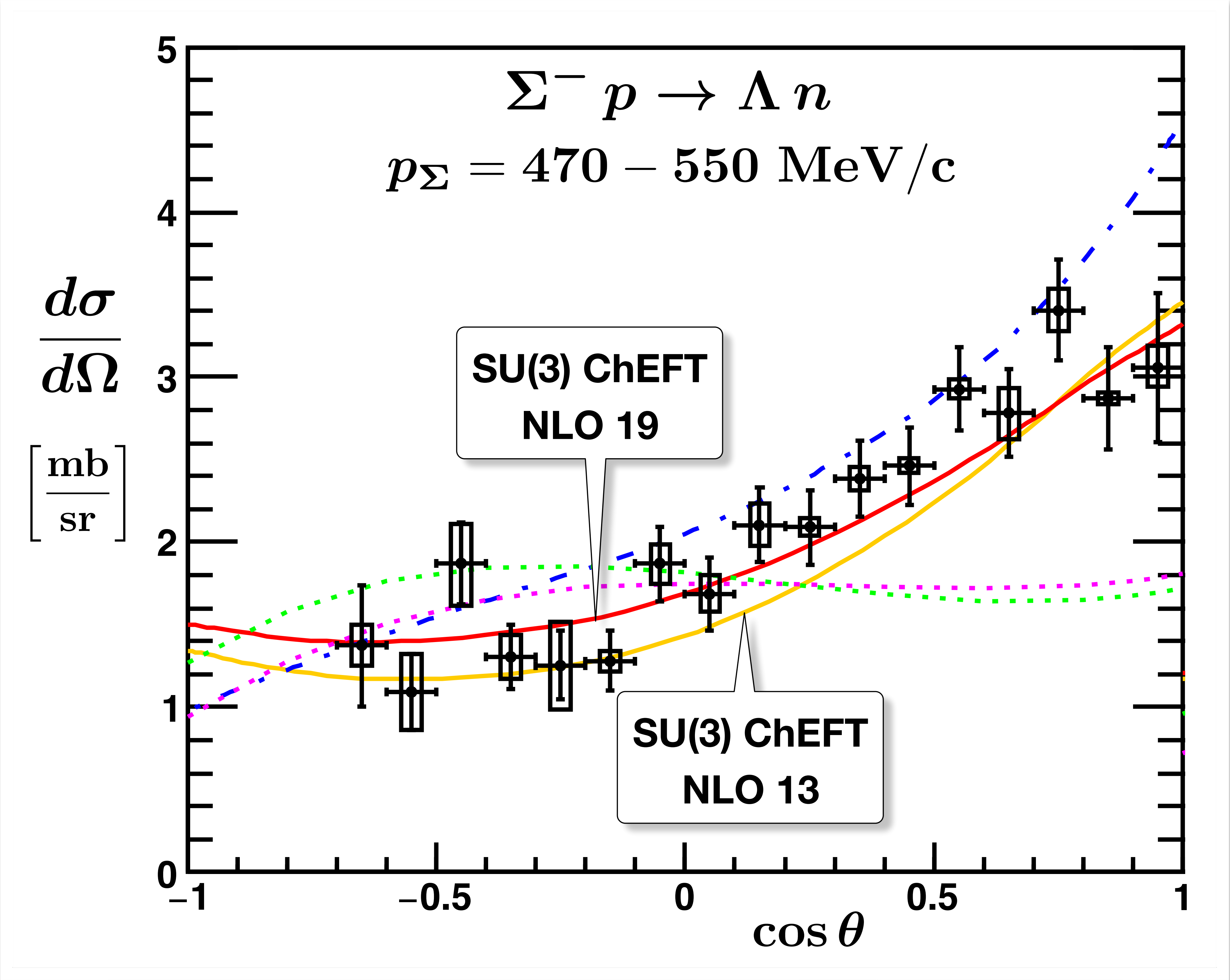
without $\Lambda N \leftrightarrow \Sigma N$ coupling

Hyperon - Nucleon Interaction
from **CHIRAL SU**(3) **Effective Field Theory** (contd.)

- $\Sigma^- p \rightarrow \Sigma^- p$ **elastic and** $\Sigma^- p \rightarrow \Lambda n$ **charge exchange scattering (J-PARC E40)**
- **Further important test of YN interactions based on ChEFT**



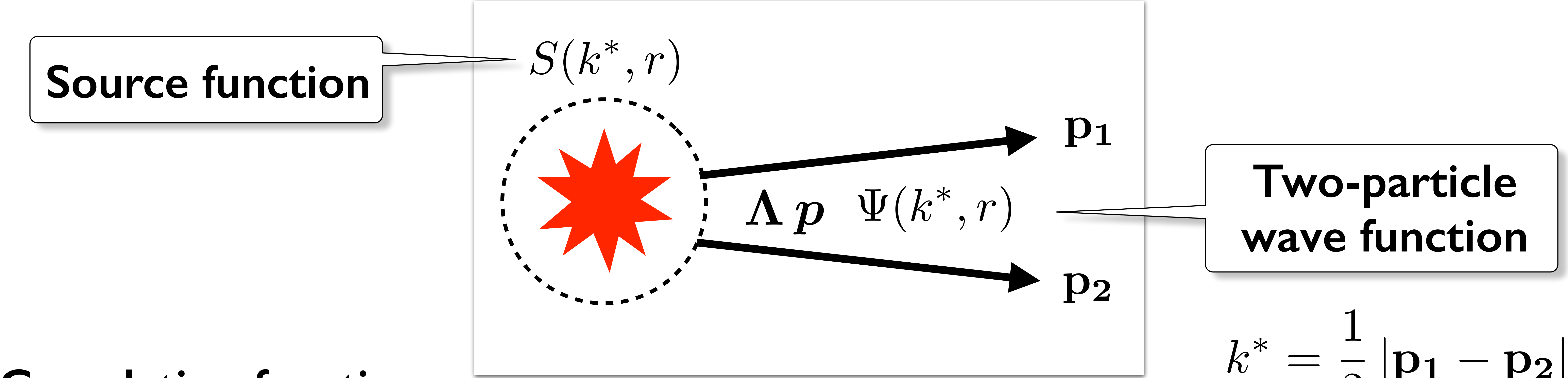
K. Miwa et al. (J-PARC E40 Collaboration) : Phys. Rev. C 104 (2021) 045204



K. Miwa et al. (J-PARC E40 Collaboration)
Phys. Rev. Lett. 128 (2022) 072501

New : $\Lambda - p$ CORRELATION FUNCTION

- **Femtoscopy two-particle correlation studies from p p collisions with ALICE @ LHC** L. Fabbietti, V. Mantovani Sarti, O.Vazquez Doce : Ann.. Rev. Nucl. Part. Sci. 71 (2021) 377



Source function

Two-particle wave function

$$k^* = \frac{1}{2}\,|\mathbf{p_1} - \mathbf{p_2}|$$

- **Correlation function**

$$C(k^*) = \frac{\langle \mathcal{P}_1(k^*)\mathcal{P}_2(k^*)\rangle}{\langle \mathcal{P}_1(k^*)\rangle\langle \mathcal{P}_2(k^*)\rangle} = \int d^3r\, S(k^*, r)|\Psi(k^* r)|^2$$

- **Accurate test of low-momentum $\Lambda\, p$ interaction**

$\Lambda - p$

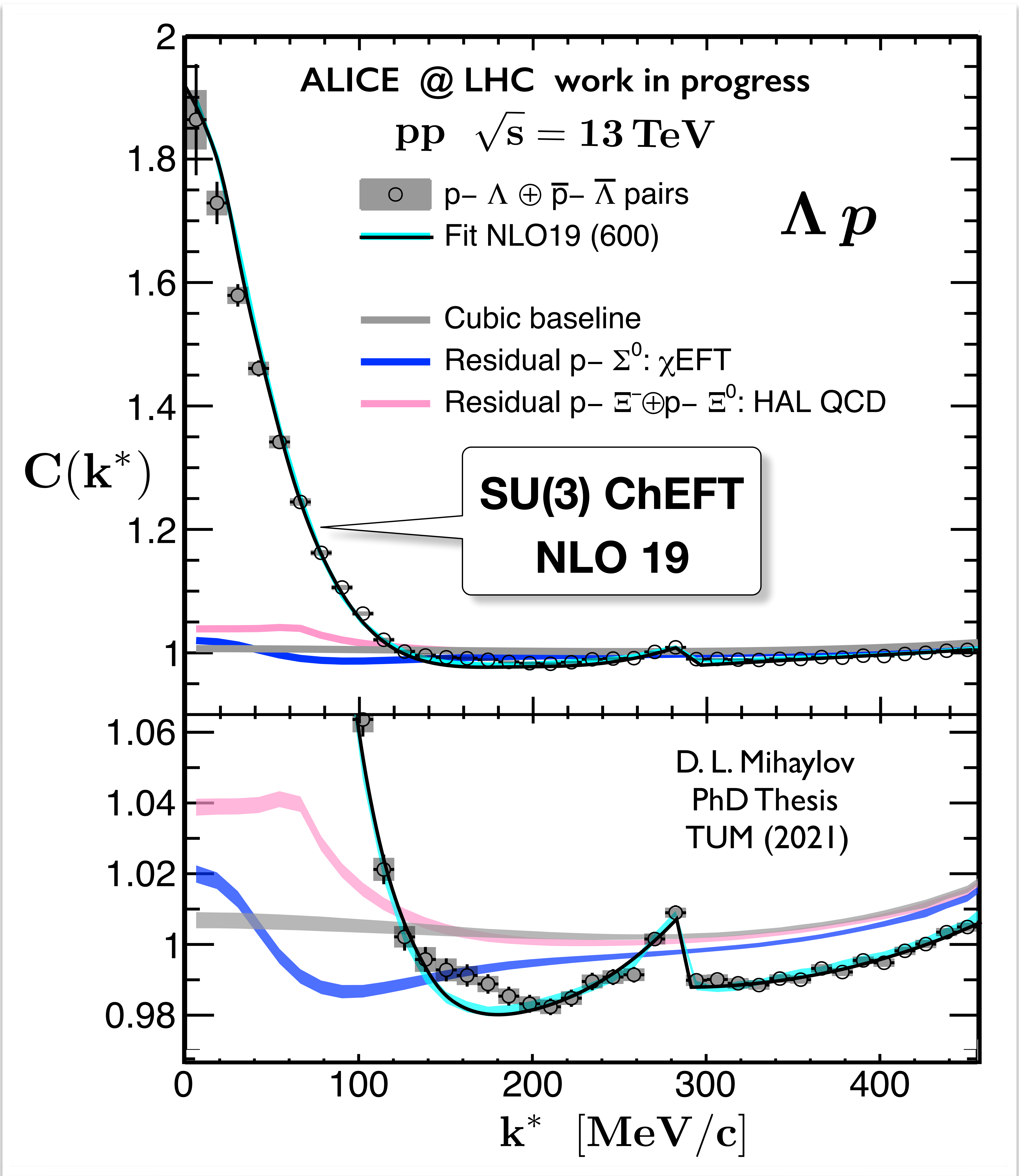
CORRELATION STUDIES

ALICE collaboration arXiv: 2104.04427

- Correlation function

$$C(k^*) = \frac{\langle \mathcal{P}_\Lambda(k^*)\mathcal{P}_p(k^*)\rangle}{\langle \mathcal{P}_\Lambda(k^*)\rangle\langle \mathcal{P}_p(k^*)\rangle}$$

- Accurate test of
  low-momentum $\Lambda\, p$ interaction
- Chiral SU(3) EFT (NLO 19) works
- Input for calculations of hypernuclei

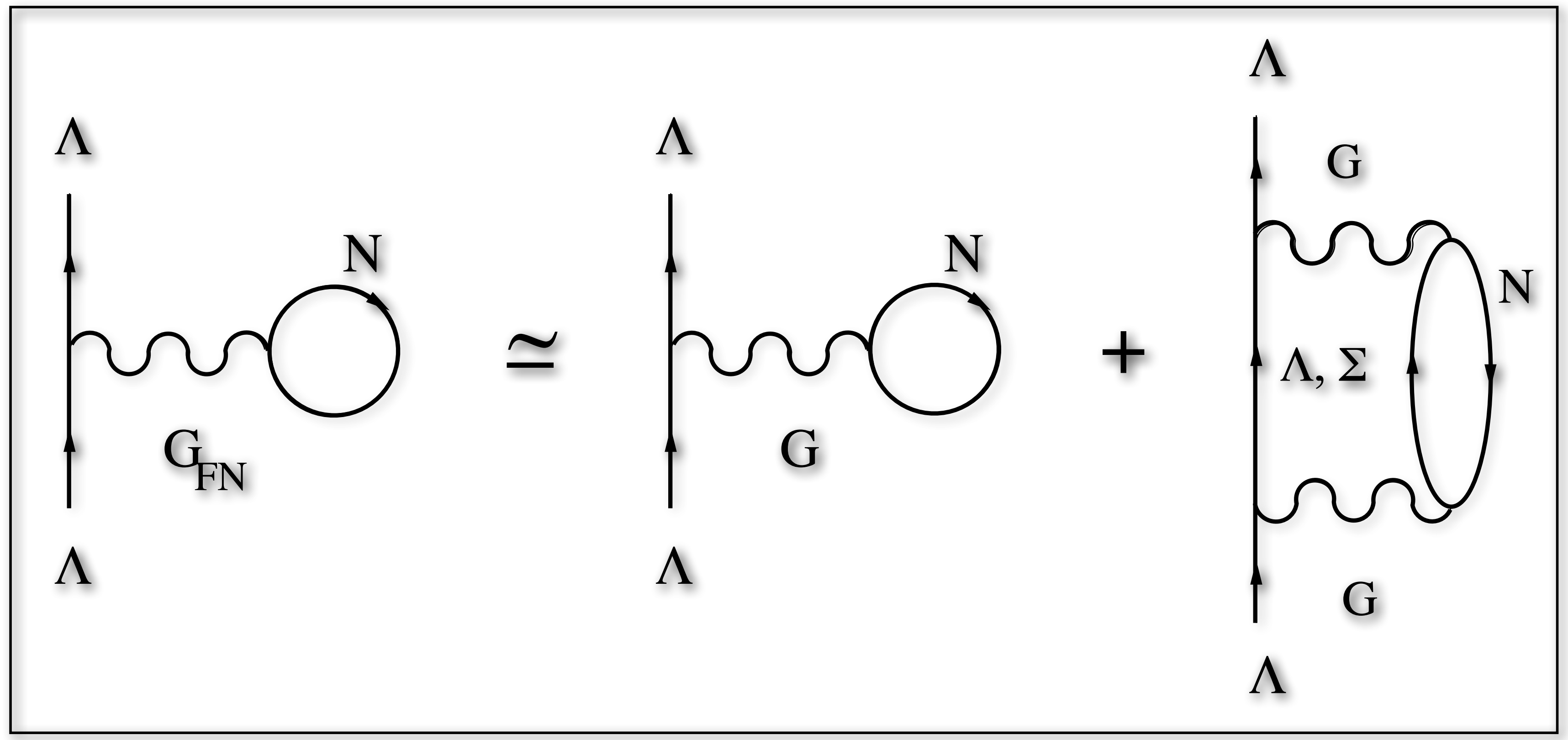


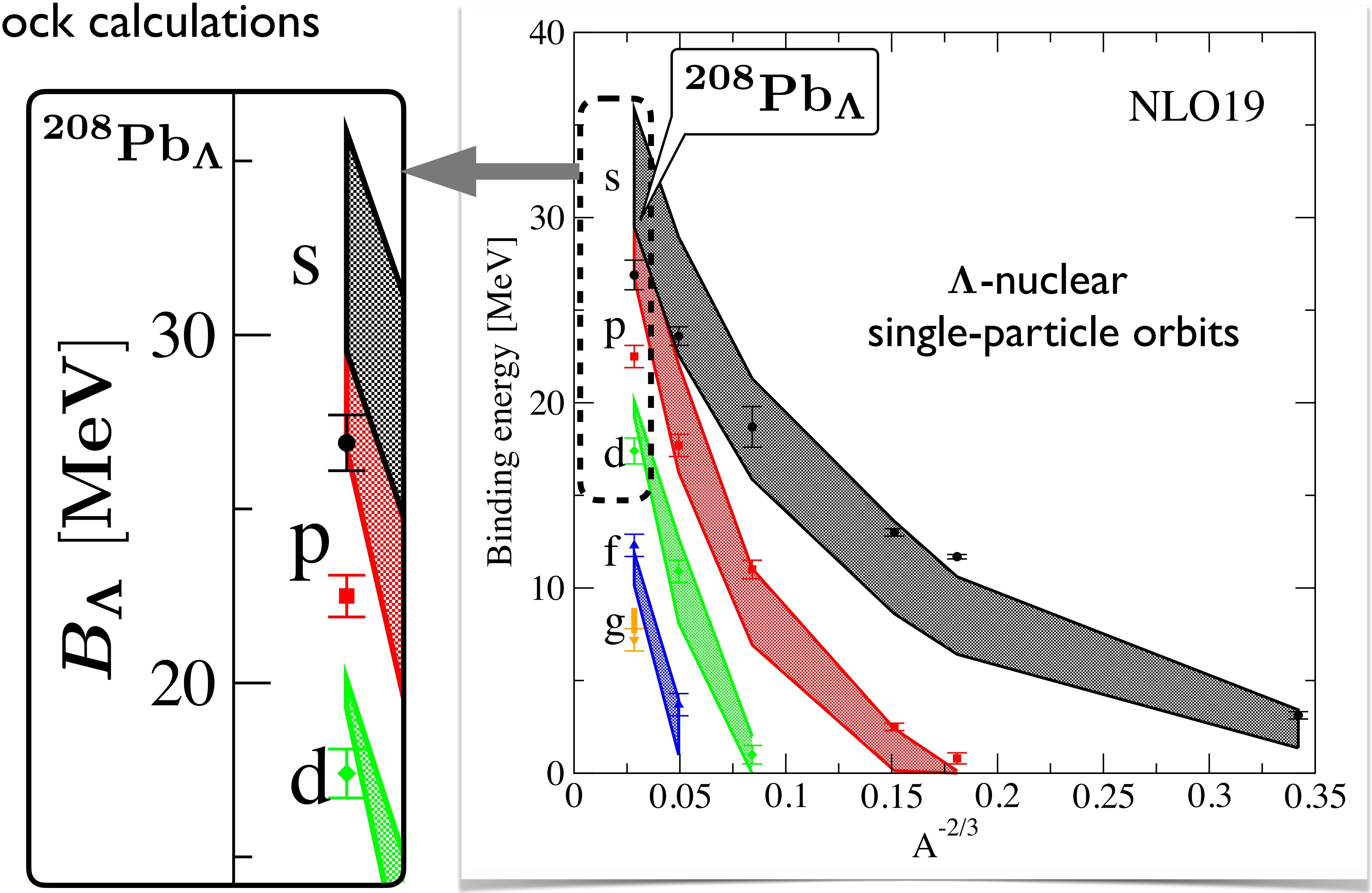
D. L. Mihaylov
PhD Thesis
TUM (2021)

Λ- HYPERNUCLEI with CHIRAL HYPERON-NUCLEON INTERACTION

J. Haidenbauer, I. Vidaña : Eur. Phys. J. A 56 (2020) 55

- 2nd order Brueckner-Hatrtree-Fock calculations





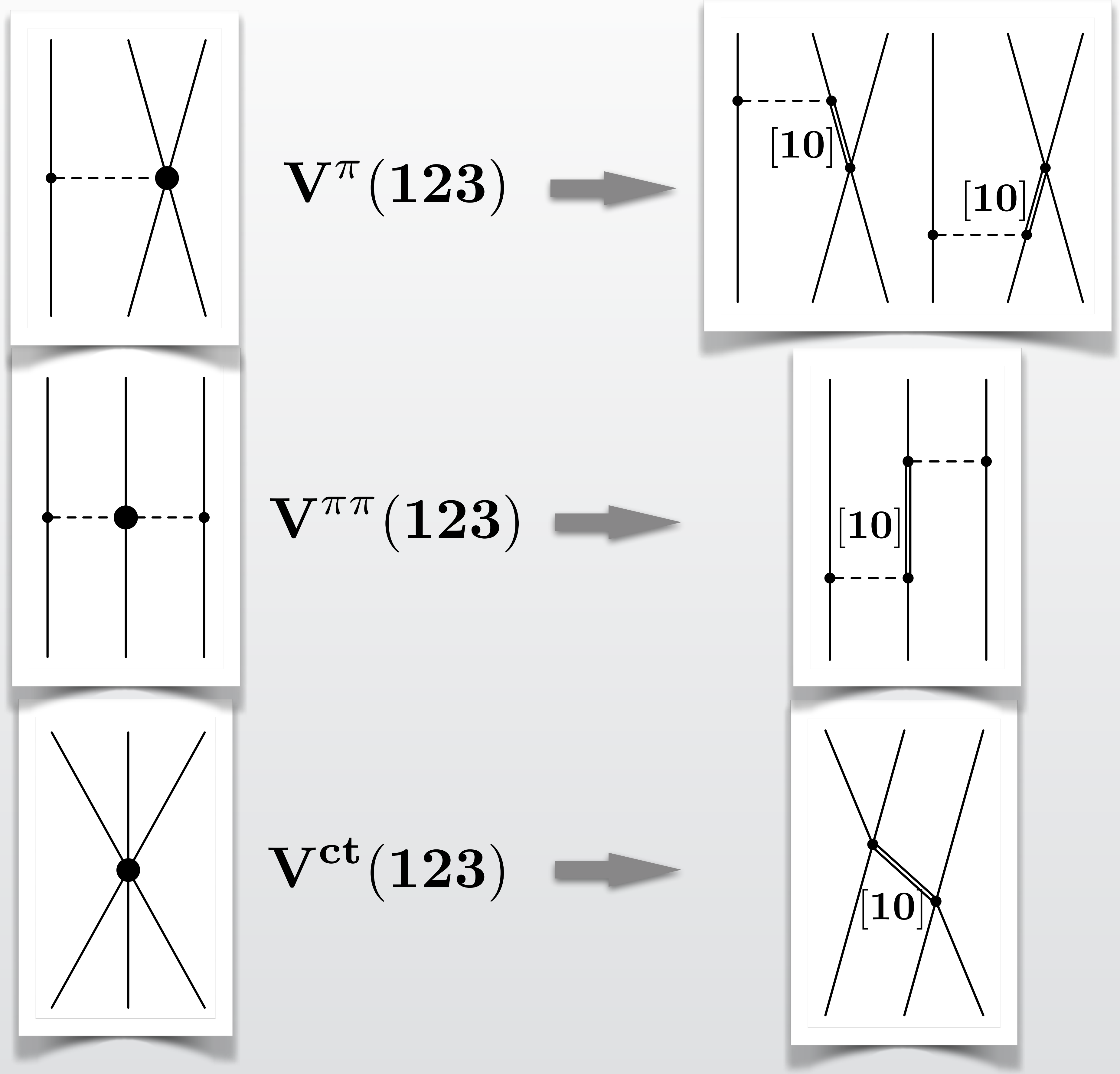
- With chiral hyperon-nucleon **two-body forces**:

  too much binding in lower (s, p and d) shell-model levels of **heavy hypernuclei** ($^{208}Pb_\Lambda$)

HYPERON - NUCLEON - NUCLEON THREE-BODY FORCES

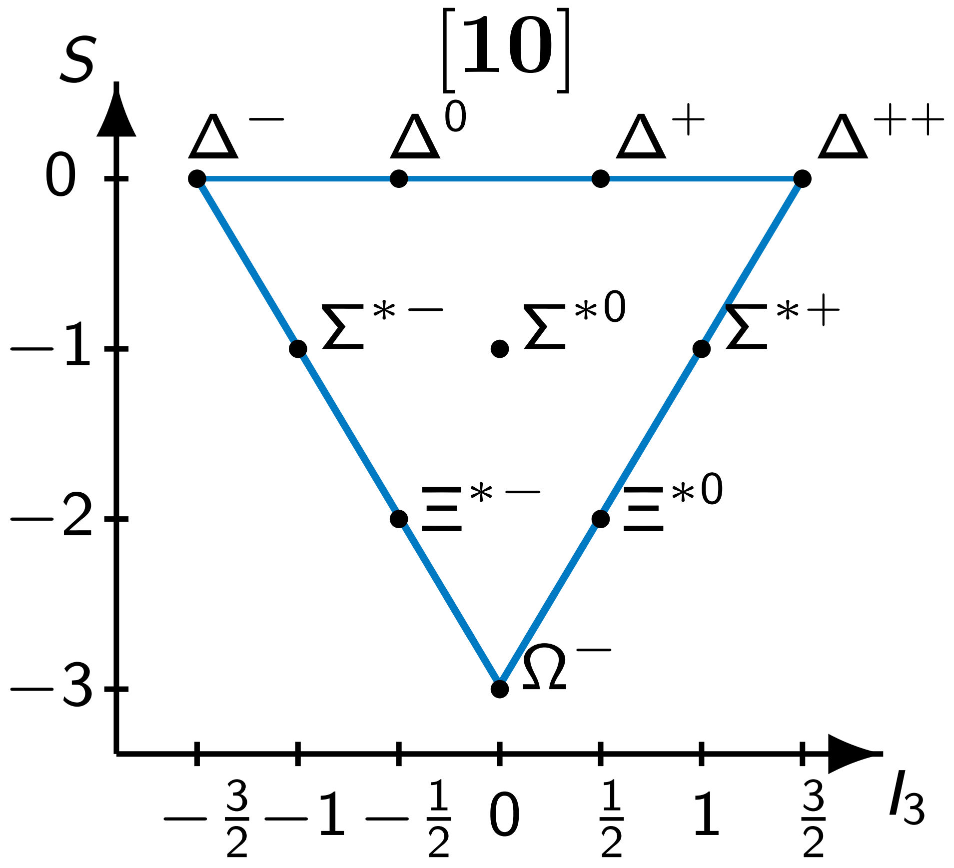
from Chiral $\mathbf{SU(3)_L \times SU(3)_R}$ Effective Field Theory

S. Petschauer, N. Kaiser, J. Haidenbauer, U.-G. Meißner, W.W. : Phys. Rev. C93 (2016) 014001

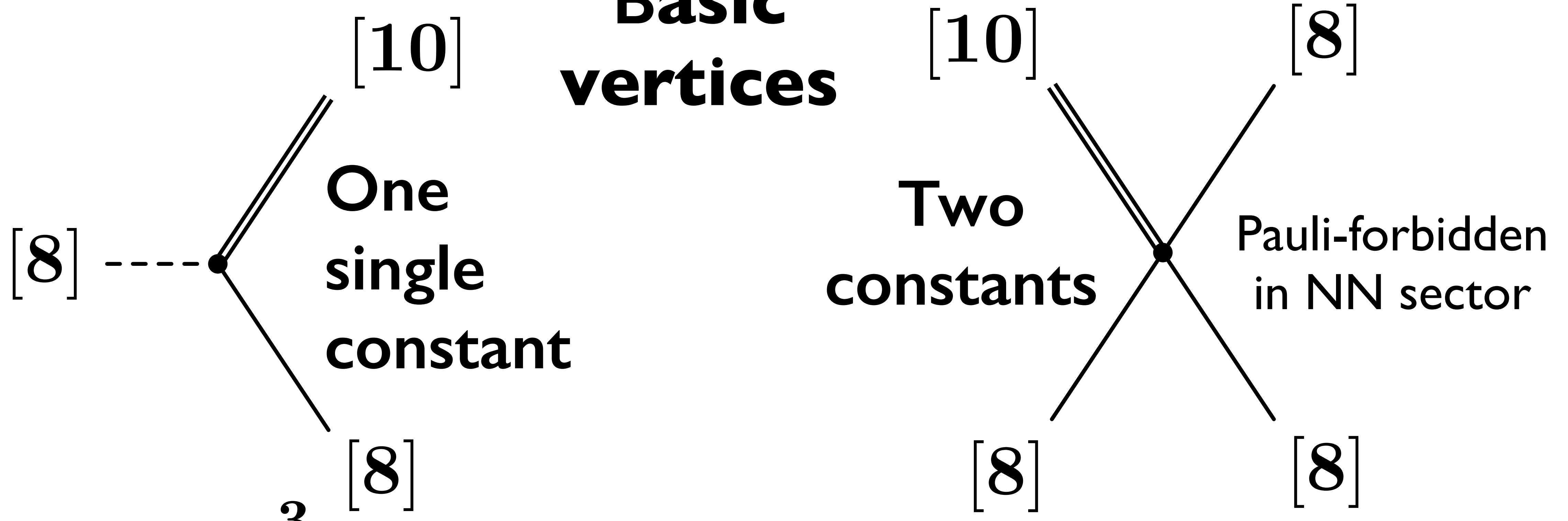


promotion from **NNLO** to **NLO**

- **Decuplet Dominance**
  in YNN three-body forces
- Estimates of **YNN** interactions assuming dominant $(\mathbf{\Sigma^*,\ \Delta})$ intermediate states



Basic vertices



One single constant

Two constants

Pauli-forbidden in NN sector

$\mathbf{C = \frac{3}{4} g_A \simeq 1}$

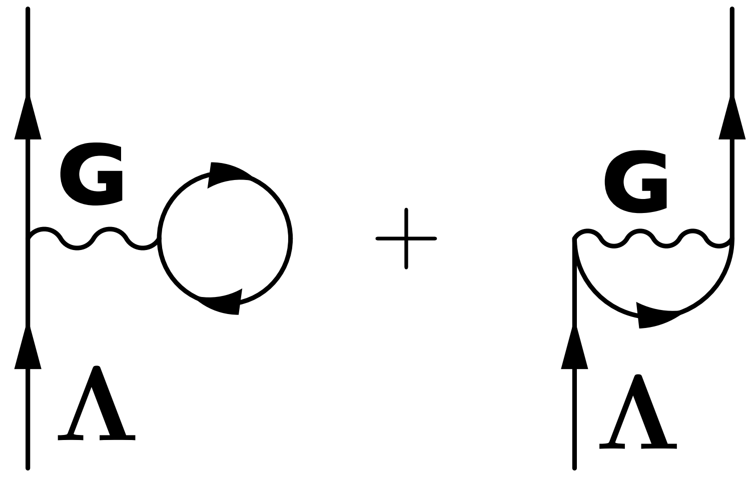
from $\mathbf{\Delta} \to \pi N$

$\mathbf{(H_1,\ H_2)}$ $\quad \mathbf{|H_i| \sim f_\pi^{-2}}$

Density dependence of Λ single particle potential

- Brueckner - Bethe - Goldstone calculations using chiral SU(3) interactions

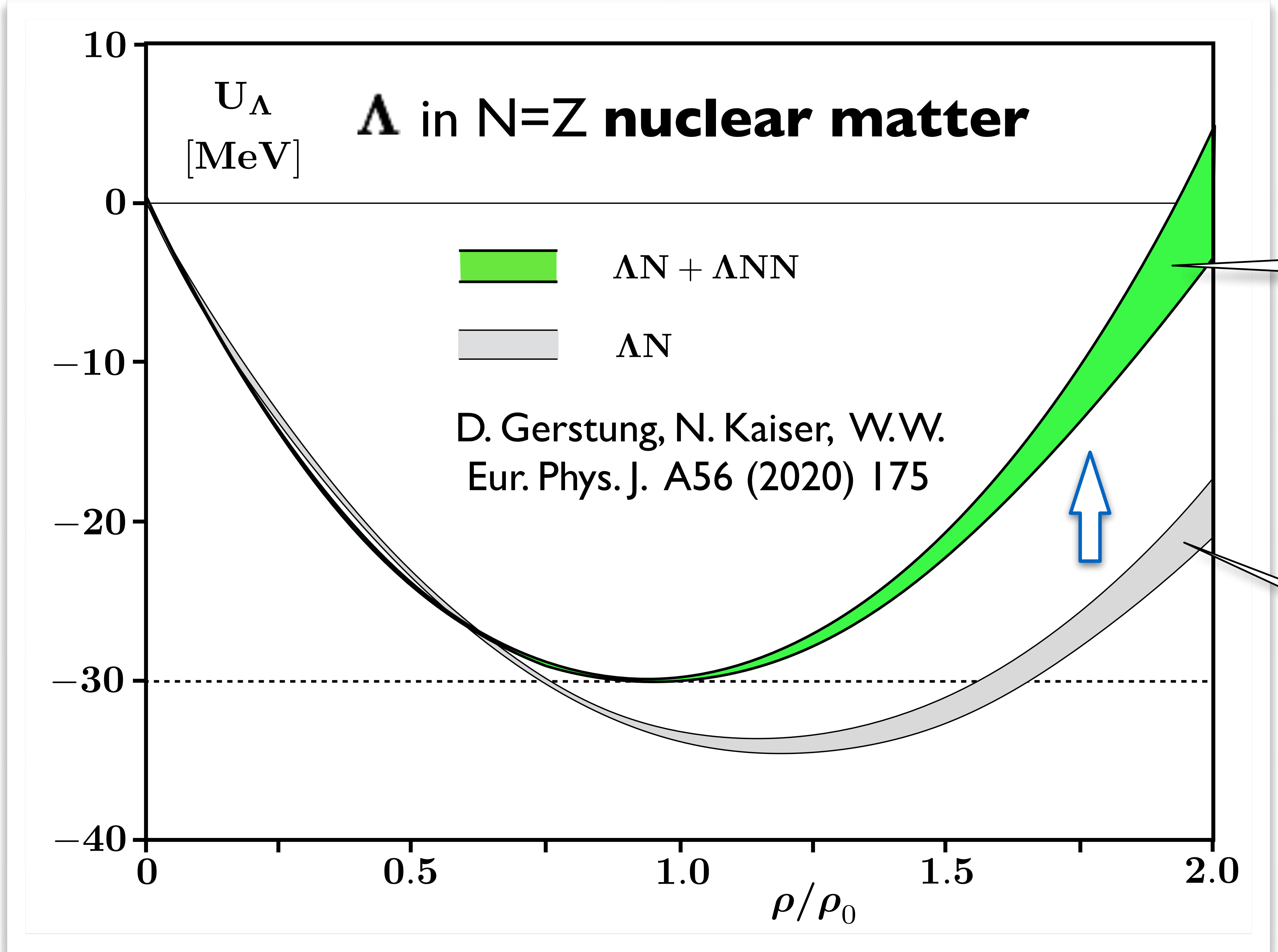
$$\mathbf{G}_{\alpha\beta}(\omega;\rho) = \mathbf{V}_{\alpha\beta}(\rho) + \mathbf{V}_{\alpha\gamma}(\rho)\frac{\mathbf{Q}}{\mathbf{e}(\omega)+\mathbf{i}\epsilon}\mathbf{G}_{\gamma\beta}(\omega;\rho)$$



- Coupled-channels G-matrix including explicit $\Lambda NN \leftrightarrow \Sigma NN$ three-body interactions treated as effective density-dependent 2-body forces

- Chiral NN (N3LO)
  +YN (NLO) interactions
  +NNN & YNN forces

Strong additional repulsion from YNN three-body forces



D. Gerstung, N. Kaiser, W.W.
Eur. Phys. J. A56 (2020) 175

2+3-body

$$-H_1 \in [2.2, 2.5]\ f_\pi^{-2}$$

$$H_2 \in [0, 1.2]\ f_\pi^{-2}$$

2-body only

- Constrained by hypernuclear physics : $U_\Lambda(\rho=\rho_0) \simeq -30\,\mathrm{MeV}$

A. Gal, E. Hungerford, D. Milner
Rev. Mod. Phys. 88 (2016) 035004

3.

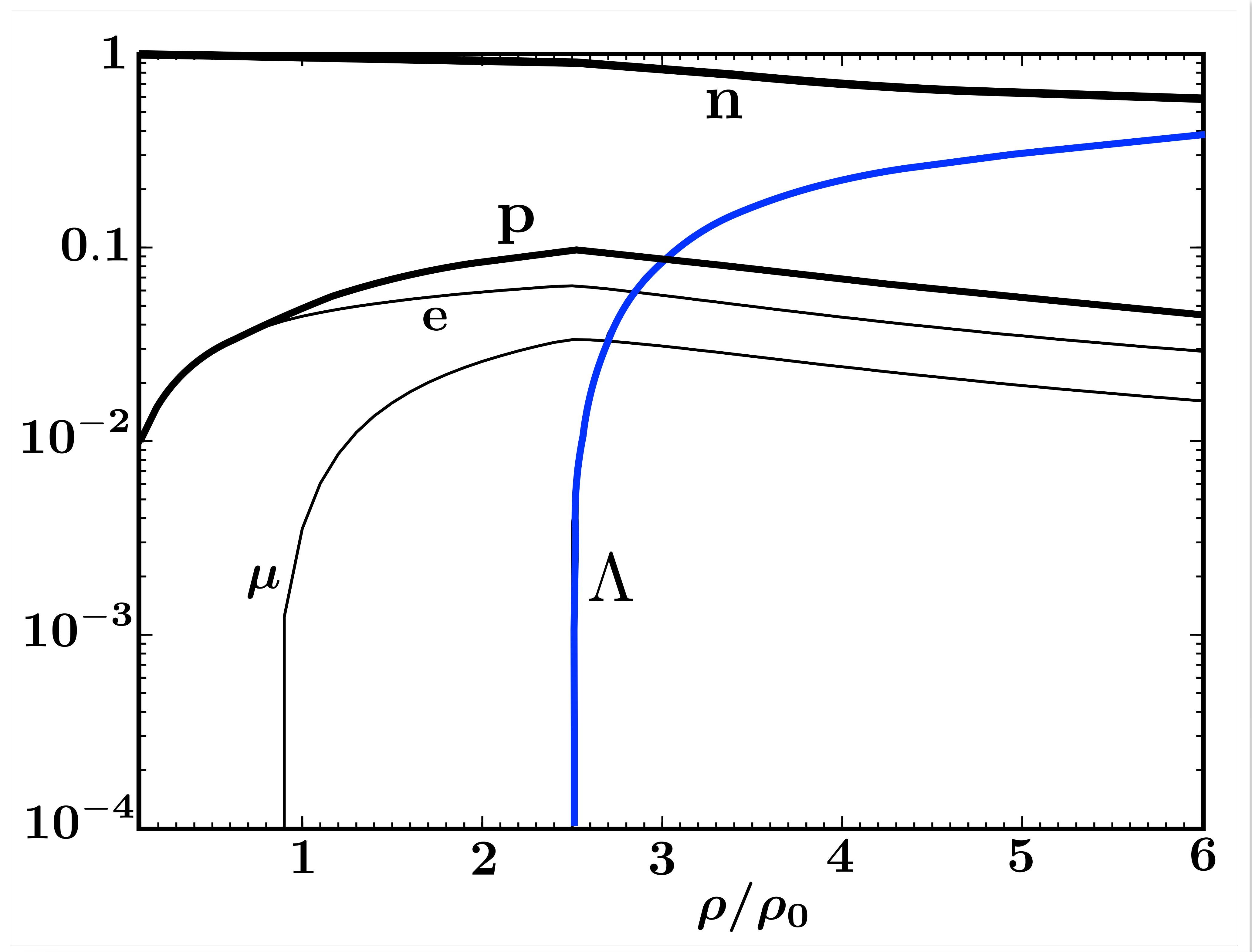
Strangeness (Part 2)

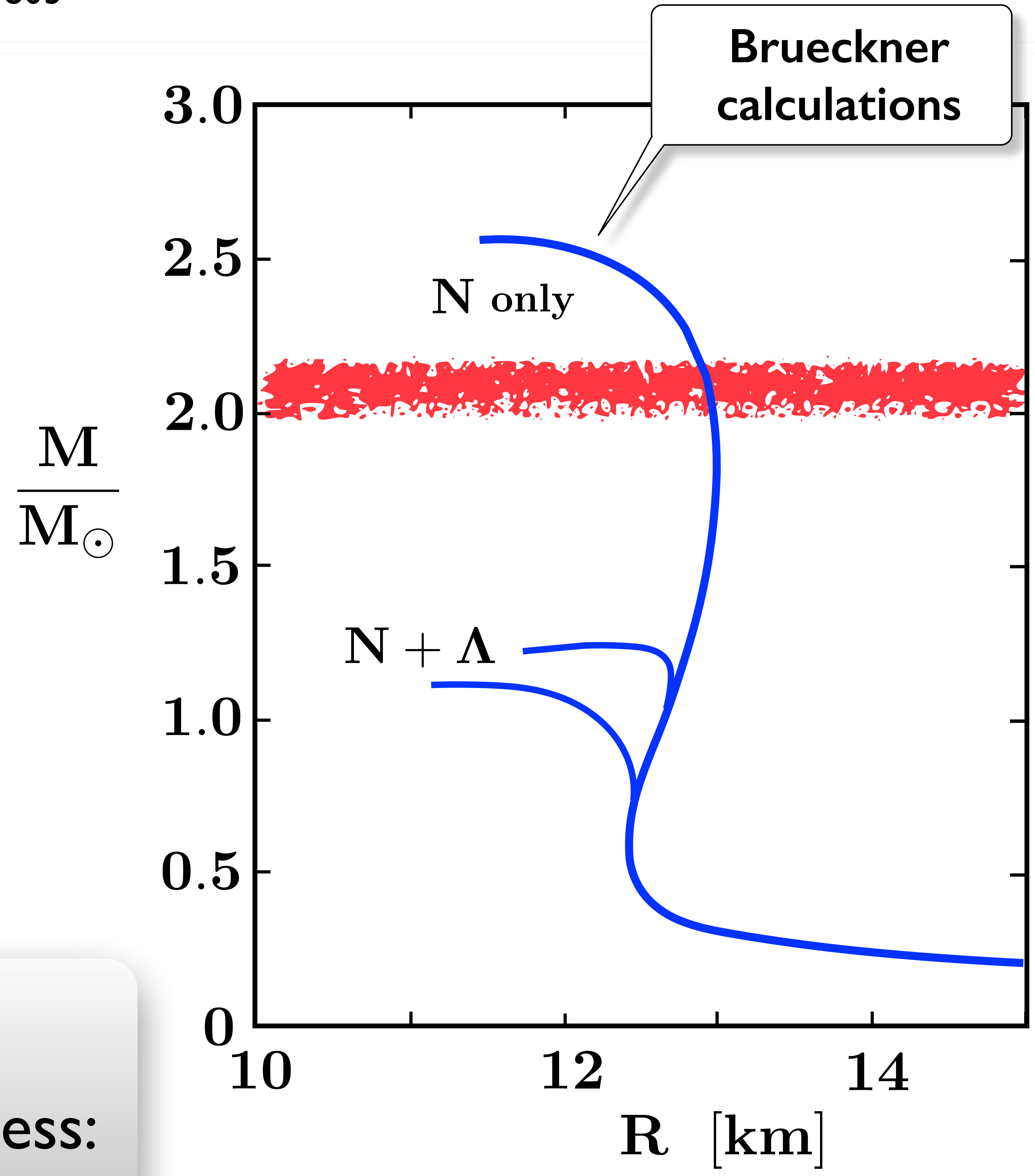
Hyperons in
Dense Baryonic Matter
and
Neutron Stars

NEUTRON STAR MATTER including **HYPERONS**

"Hyperon Puzzle"

H. Djapo, B.-J. Schaefer, J.Wambach : Phys. Rev. C81 (2010) 035803




Brueckner calculations

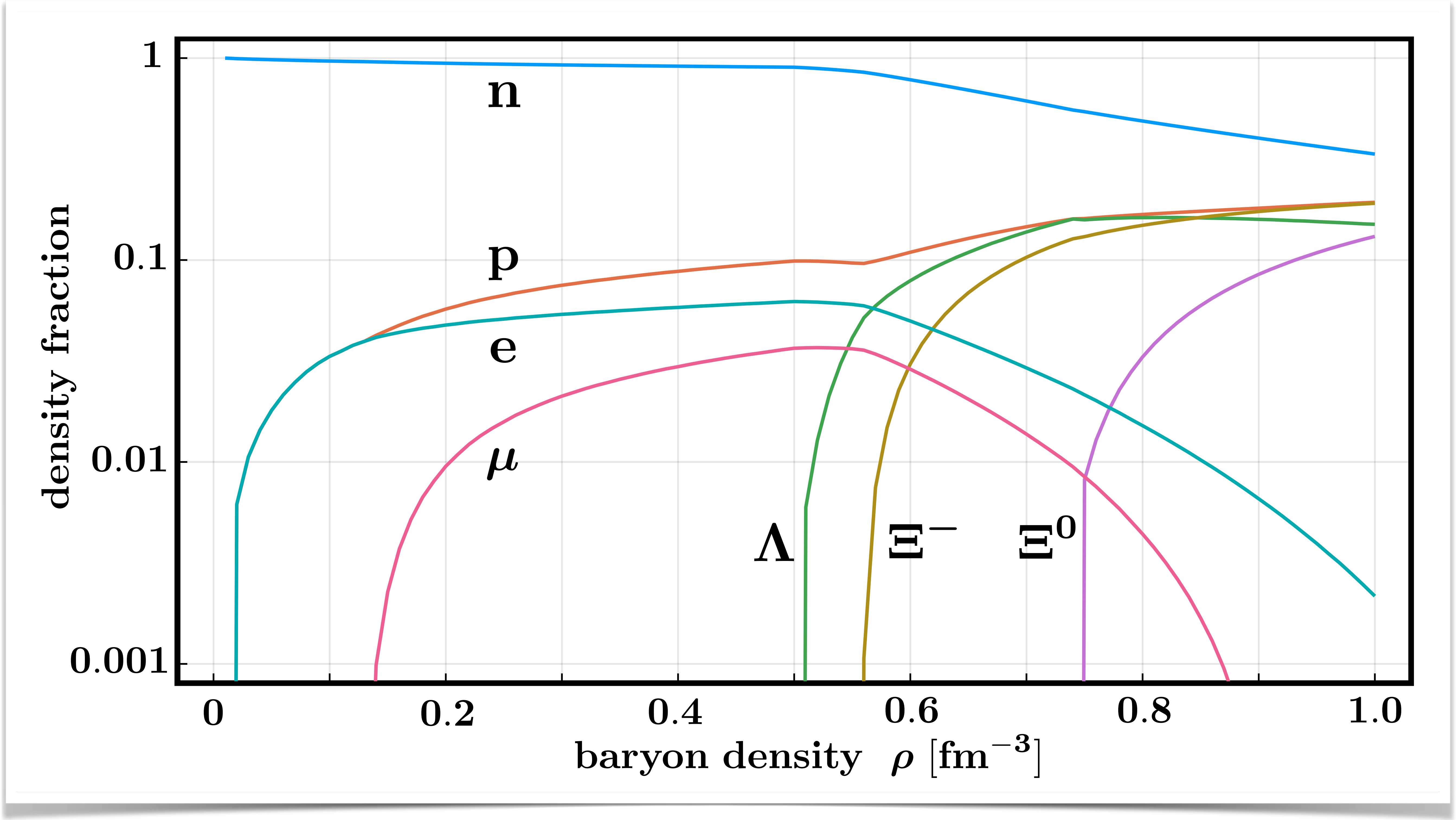
- Inclusion of **hyperons :**

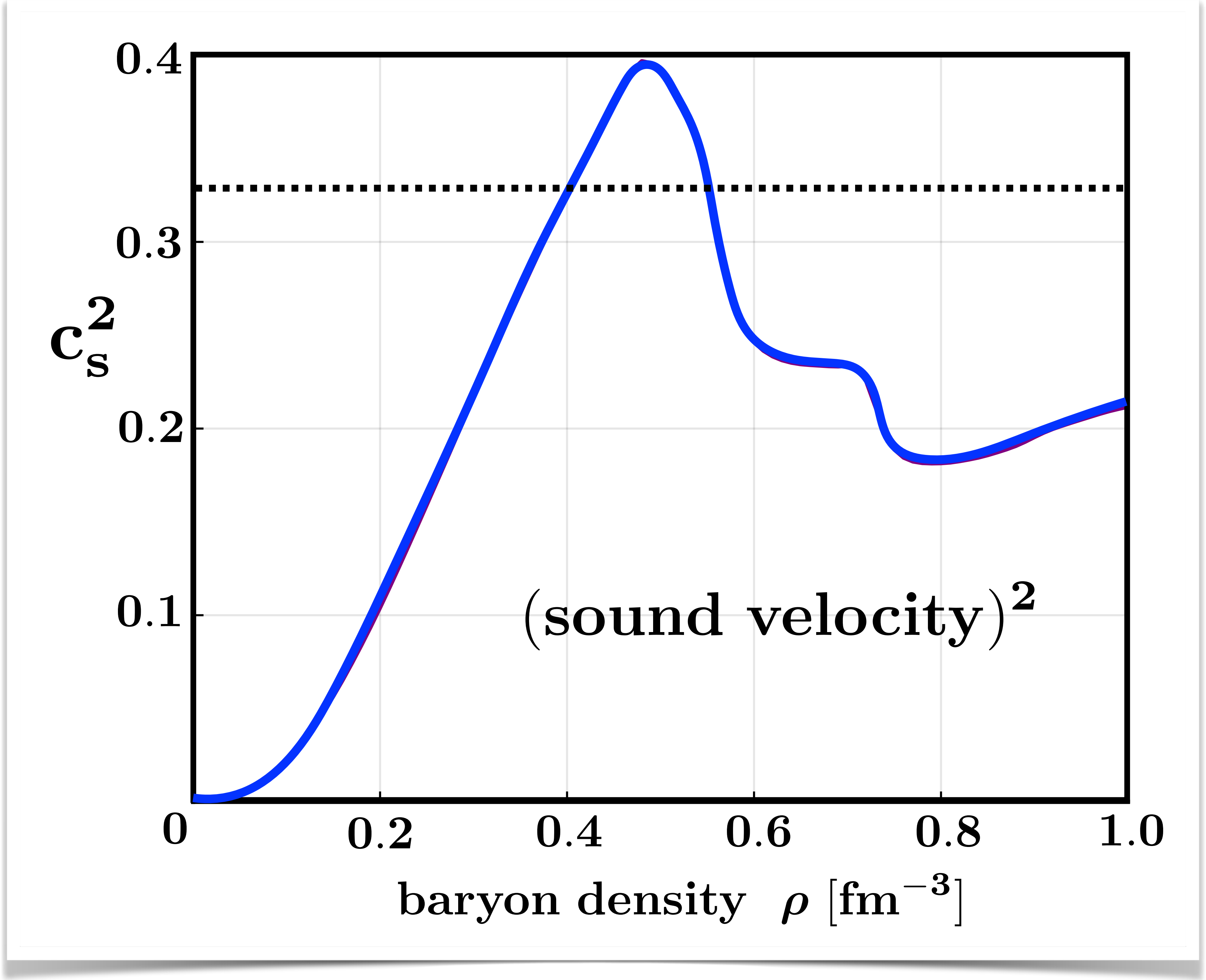
EoS too soft to support 2-solar-mass n-stars, unless:
strong repulsion in **YN** and/or **YNN** interactions

NEUTRON STAR MATTER including HYPERONS

NO "Hyperon Puzzle" ?

- **Quark - Meson Coupling model** T.F. Motta, P.A.M. Guichon, A.W. Thomas : Nucl. Phys. A1009 (2021) 122157

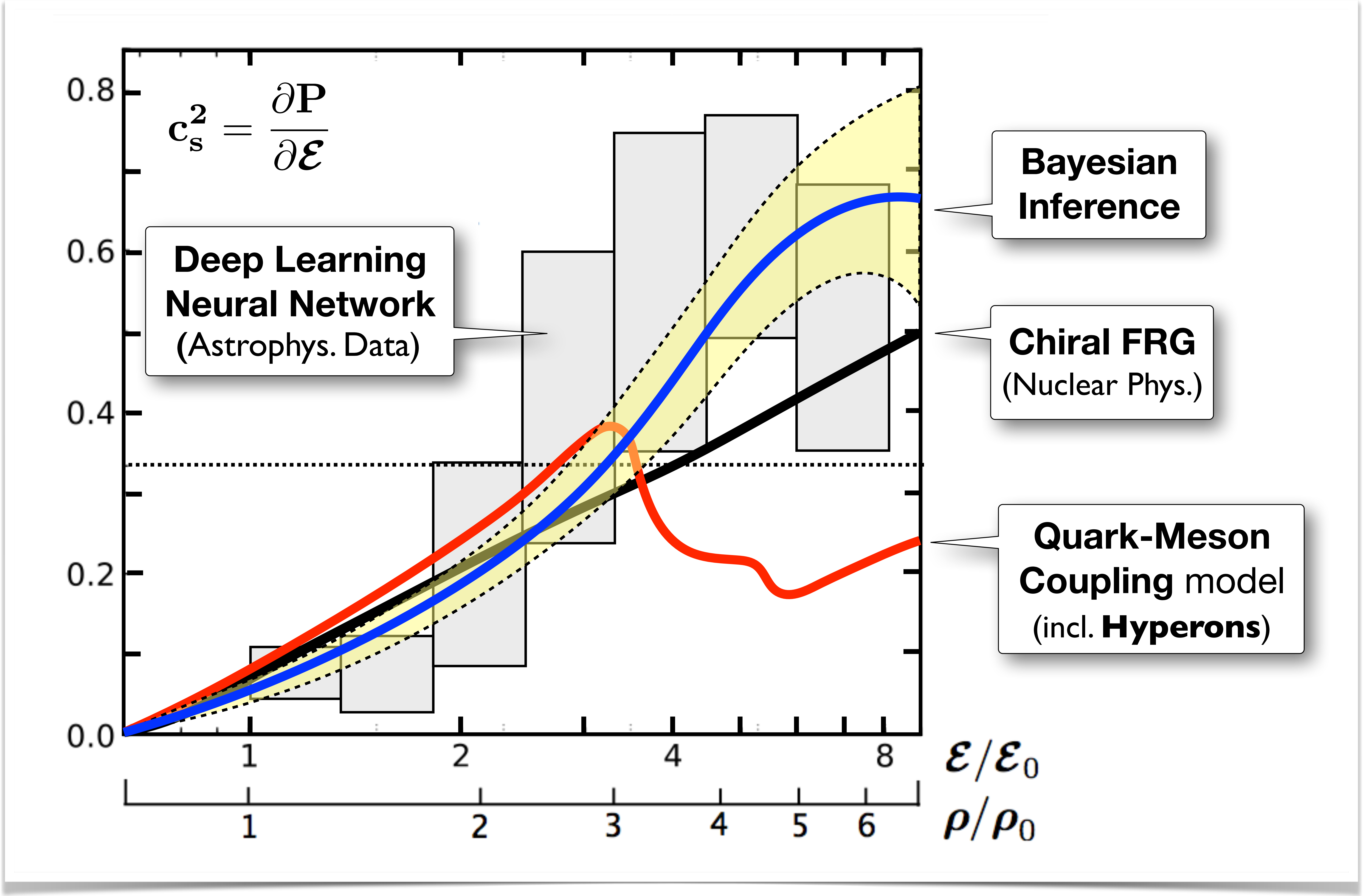




- Effective in-medium baryon masses including non-linear dependence on σ field, with **scalar polarizability** d_B representing e.g. effects of three-body forces :

$$M_B^* = M_B^{(0)} - g_B\,\bar{\sigma} + \frac{d_B}{2}\,(g_B\,\bar{\sigma})^2$$

Key Quantity : **SOUND VELOCITY** in the **NEUTRON STAR CORE MATTER**



Deep Learning Neural Network
(Astrophys. Data)

Bayesian Inference

Chiral FRG
(Nuclear Phys.)

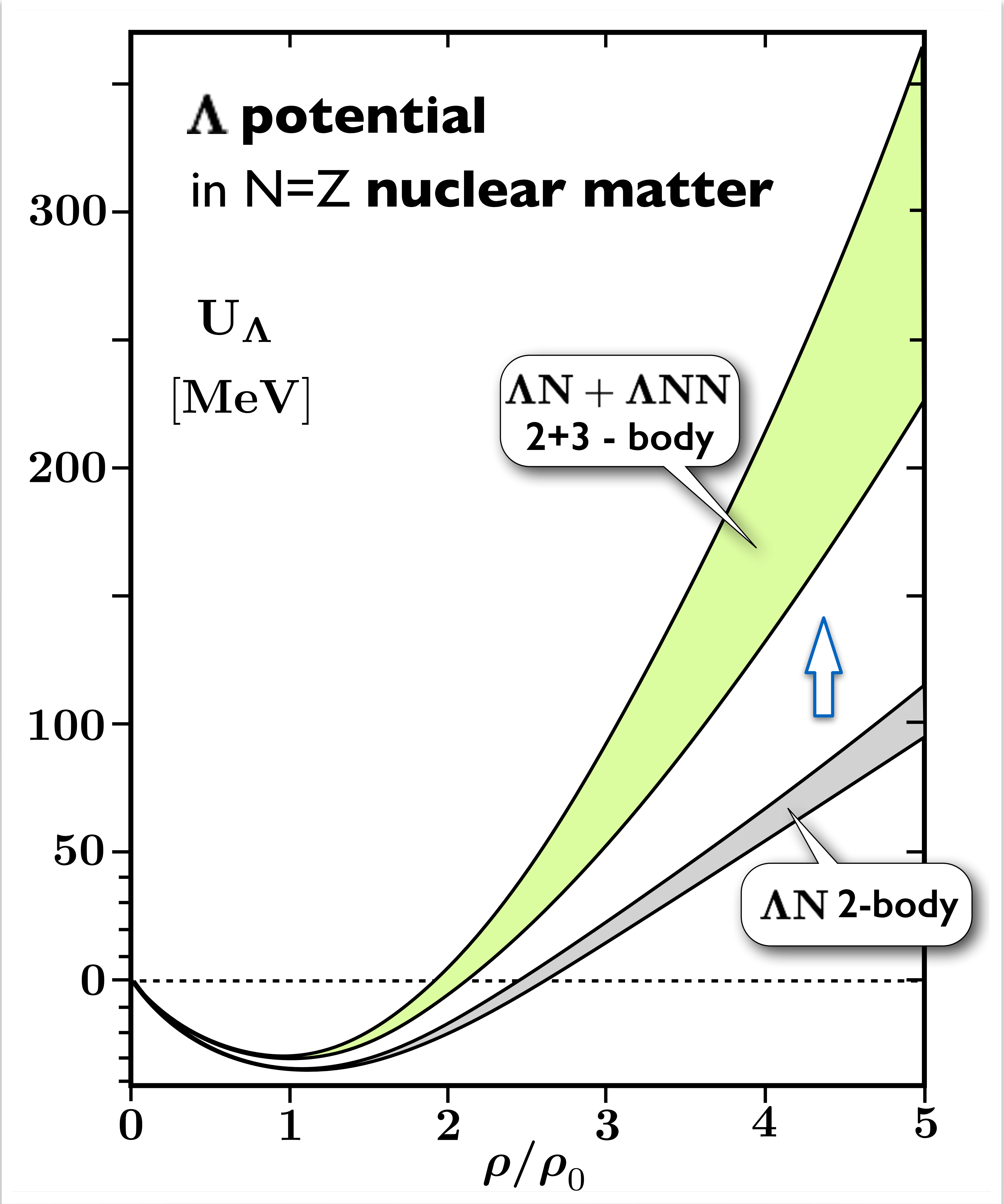
Quark-Meson Coupling model
(incl. **Hyperons**)

"Hyperon Puzzle" reiterated ?

- **Strong quest for further reduction of uncertainties in the astrophysical data base**

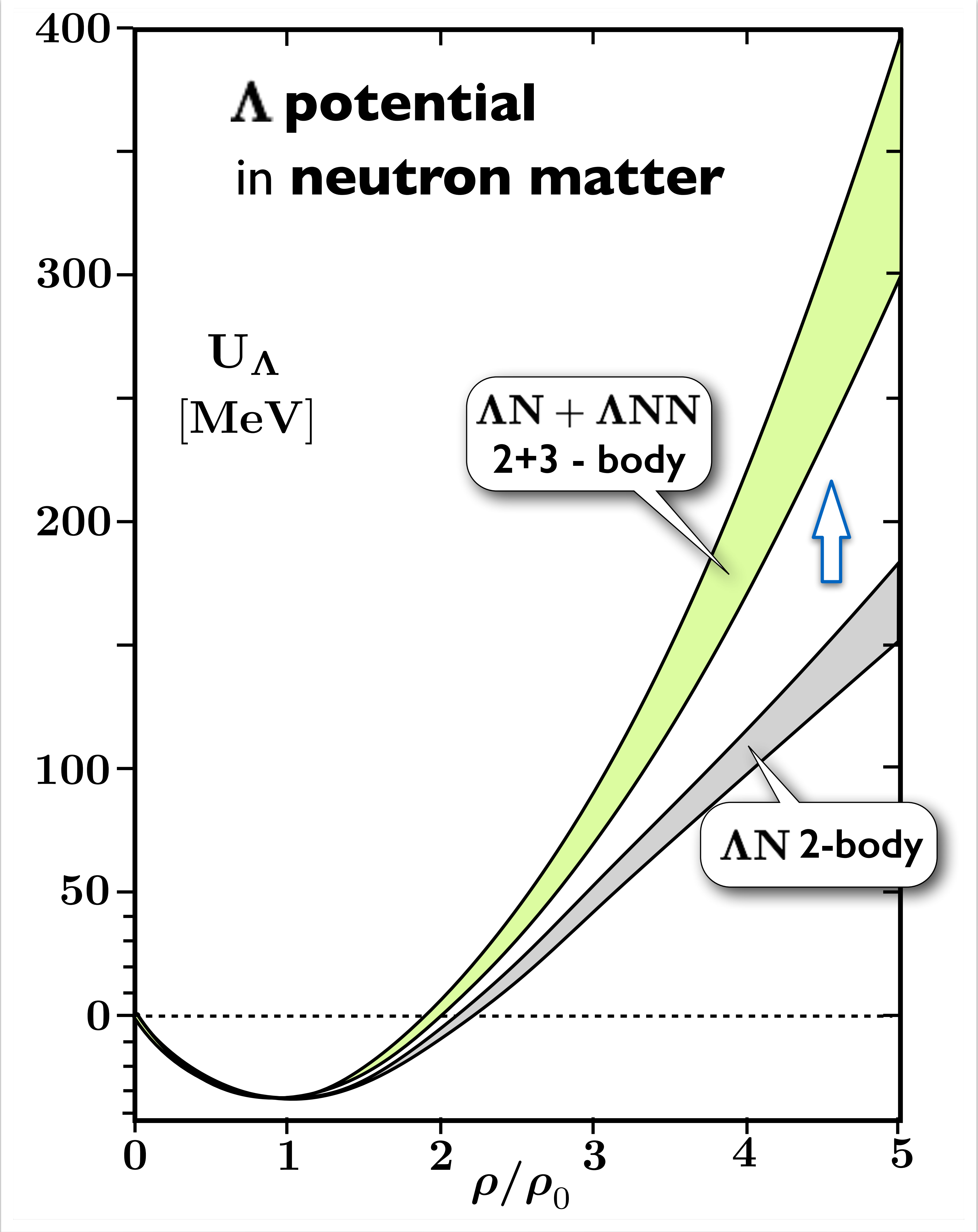
Density dependence of Λ single-particle potential (contd.)

- Extrapolations to high baryon densities
- Coupled-channels G-matrix including explicit 3-body interactions



Chiral
NN (N3LO)
+ YN (NLO)
+ NNN & YNN
interactions

Strong additional repulsion from YNN three-body forces



D. Gerstung, N. Kaiser, W.W.
Eur. Phys. J. A56 (2020) 175

Λ Hyperons in Neutron Stars ?

- Onset condition for appearance of Λ **hyperons in neutron stars :**

  Equality of **chemical potentials**

$$\mu_\Lambda = \mu_n$$

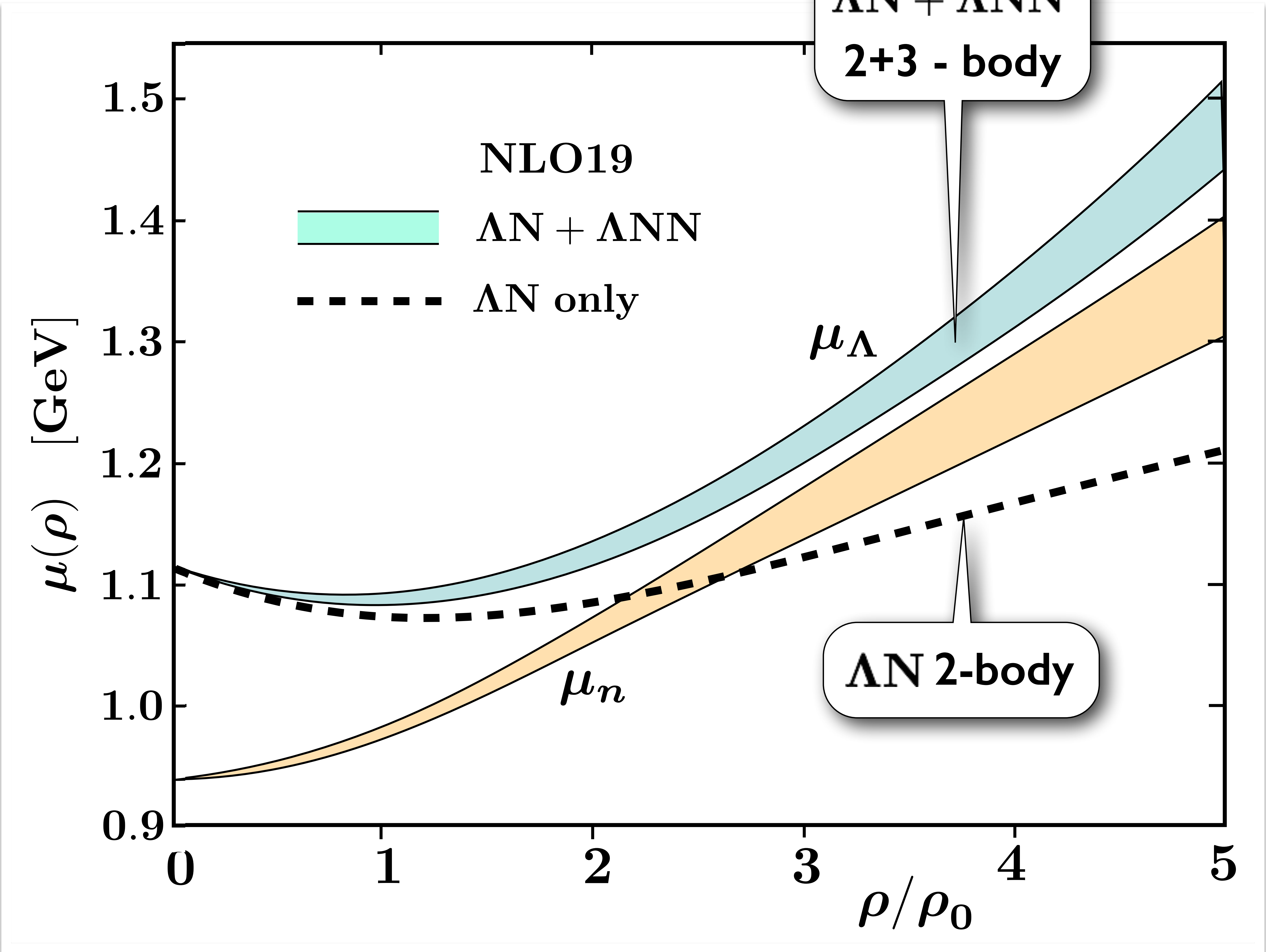
$$\mu_i = \frac{\partial \mathcal{E}}{\partial \rho_i}$$

- **Hyperon chemical potential** in **neutron star matter** from **Chiral SU(3) EFT** interactions

  D. Gerstung, N. Kaiser, W.W.
  Eur. Phys. J. A56 (2020) 175

- **Neutron chemical potential** in **neutron star matter** from **Chiral EFT + FRG EoS**

  M. Drews, W.W.
  Prog. Part. Nucl. Phys. 93 (2017) 69



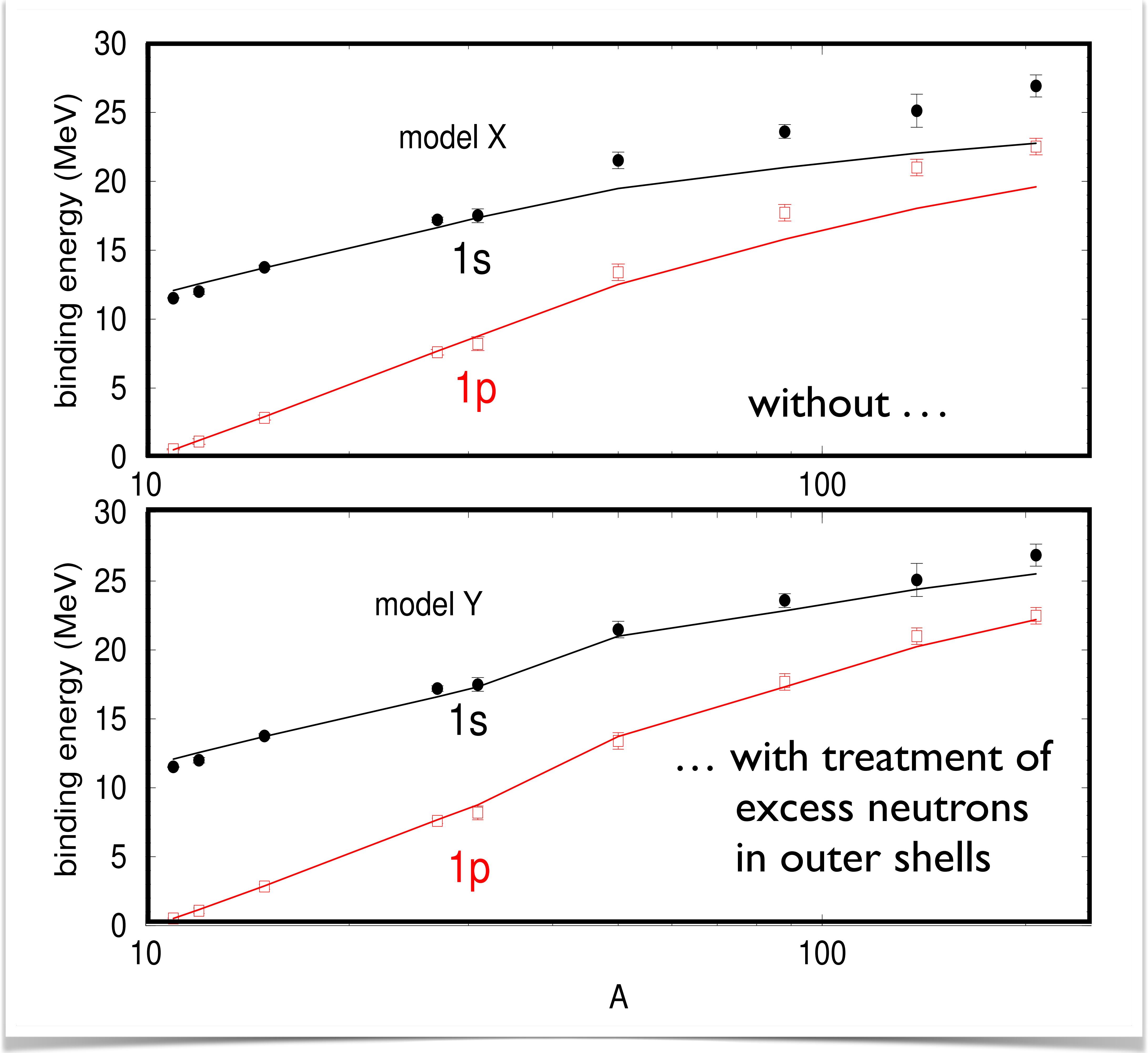
$\Lambda N + \Lambda NN$
2+3 - body

ΛN 2-body

Hypernuclear Phenomenology

- Recent update on Λ- **nuclear binding energies** including ΛNN **three-body forces**

E. Friedman, A. Gal arXiv: 2204.02264



- Two- and three-body **hyperon-nucleus potentials**

$$\mathbf{U}_{\boldsymbol{\Lambda}}(\rho) = \mathbf{U}_{\mathbf{0}}^{(\mathbf{2})} \frac{\rho(\mathbf{r})}{\rho_{\mathbf{0}}} + \mathbf{U}_{\mathbf{0}}^{(\mathbf{3})} \left(\frac{\rho(\mathbf{r})}{\rho_{\mathbf{0}}}\right)^{\mathbf{2}}$$

$$(\rho_0 = 0.17\,\mathrm{fm}^{-3})$$

with **realistic** (empirically constrained) **densities**

- **Pauli correlations** important (no good fit without)
- Detailed treatment of **excess neutrons** in **outer shells** of heavier hypernuclei (model Y)
- Best fit (model Y) : $\mathbf{U}_{\boldsymbol{\Lambda}}(\rho_{\mathbf{0}}) = -(\mathbf{26.5} \pm \mathbf{1.6})\,\mathbf{MeV}$

$$\mathbf{U}_{\mathbf{0}}^{(\mathbf{2})} = -(\mathbf{40.4} \pm \mathbf{0.6})\,\mathbf{MeV}$$
$$\mathbf{U}_{\mathbf{0}}^{(\mathbf{3})} = (\mathbf{13.9} \pm \mathbf{1.4})\,\mathbf{MeV}$$

- **Three-body** ΛNN **forces** of such repulsive magnitude are likely to solve the **hyperon puzzle**

CONCLUSIONS and OUTLOOK

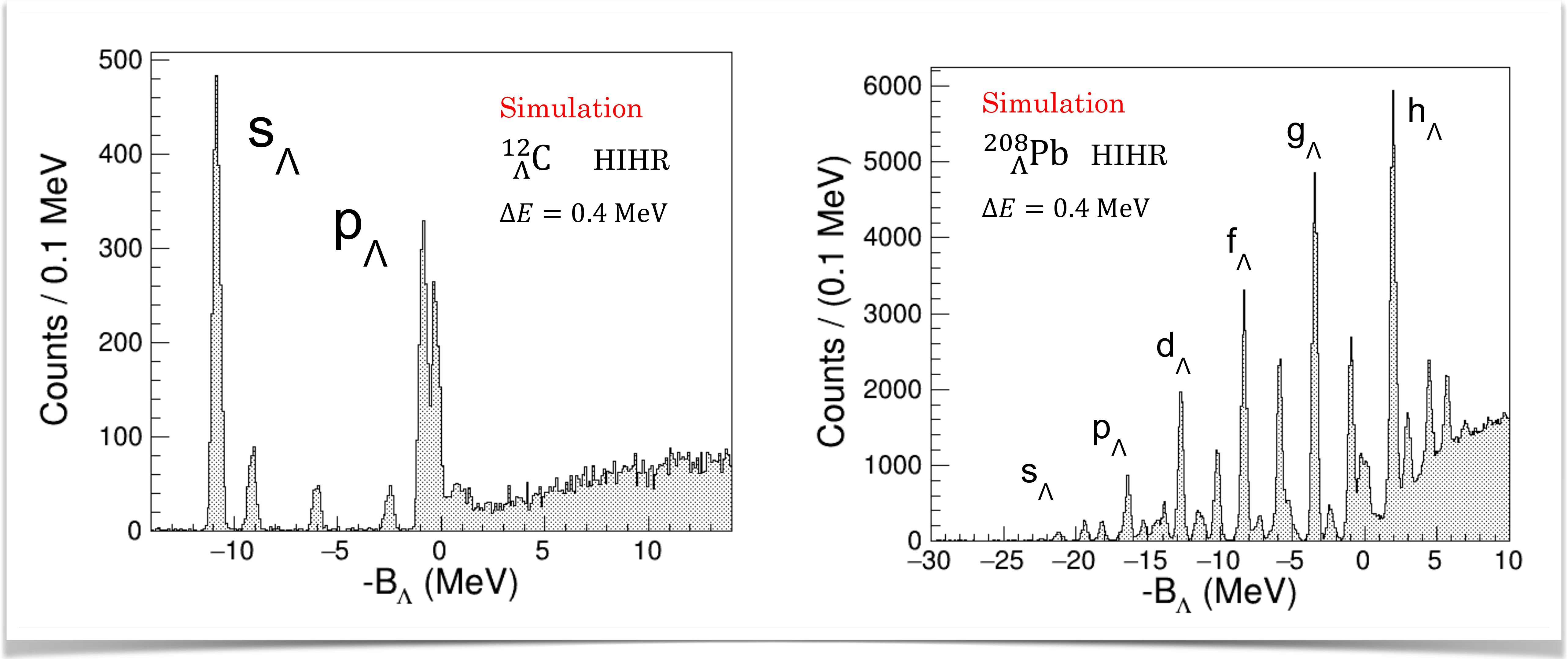
Understanding strangeness in **dense matter and neutron stars** requires detailed evaluation of the **quantitative balance** between **hyperon-nuclear two- and three-body forces**.

- Improved and expanded high-statistics **YN two-body data base** :
  YN scattering and reactions (e.g. J-PARC E40); **YN correlation functions** (e.g. Femtoscopy)

- Improved systematics of **high-resolution hypernuclear spectroscopy** :
  (π^+, K^+) at J-PARC, $(e, e'K^+)$ at JLab, MAMI, with **mass resolution better than 0.5 MeV**

Example:
simulation taken from
J-PARC HIHR beamline proposal
S. N. Nakamura et al. (2021)

expected **mass resolution :**
~ 0.33 MeV



- Increasing amounts of **astrophysical data** (focus on **speed of sound** in **neutron stars**)

Supplementary Materials

Density-dependent EFFECTIVE HYPERON - NUCLEON INTERACTION from CHIRAL THREE-BARYON FORCES

S. Petschauer, J. Haidenbauer, N. Kaiser, U.-G. Meißner, W.W. Nucl. Phys. A957 (2017) 347

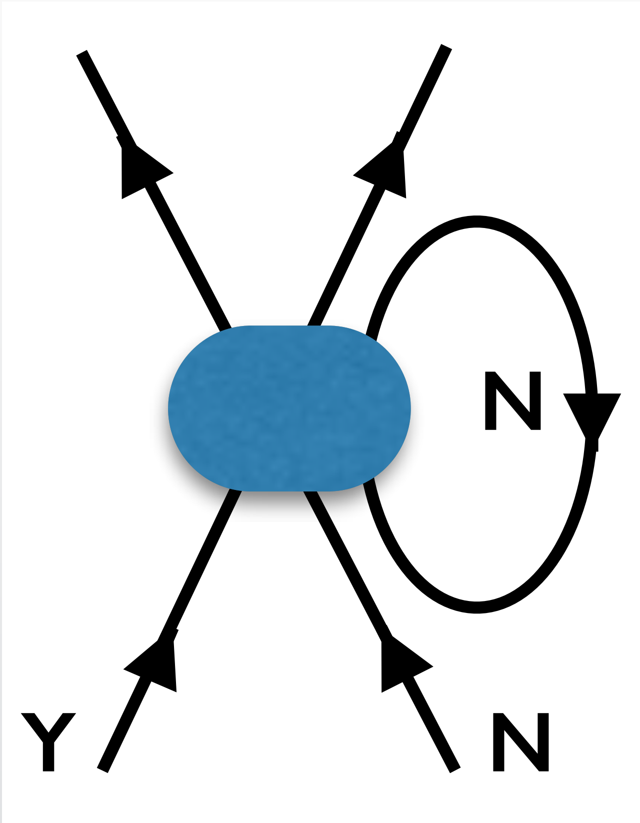
$$\mathbf{U}_{\mathbf{eff}}(12) = \sum_i \mathrm{tr}_{\sigma_3} \int_{|\vec{p}|\le p_F^i} \frac{d^3p}{(2\pi)^3} \mathbf{V}(123)$$

- Example: Λ**-neutron** density-dependent effective interaction in a nuclear medium (protons + neutrons)

$$\mathbf{U}^{\pi}_{\mathbf{eff}}(\Lambda n) = \frac{C\,H\,g_A^2}{2f_\pi^4\,\Delta}\left[\rho_n + 2\rho_p\right] + \mathcal{F}(p_F^p, p_F^n)$$ **+/-**

$$\mathbf{U}^{\pi\pi}_{\mathbf{eff}}(\Lambda n) = \frac{C^2\,g_A^2}{9f_\pi^4\,\Delta}\left[\rho_n + 2\rho_p\right] + \mathcal{G}(p_F^p, p_F^n)$$ **repulsive**

$$\mathbf{U}^{ct}_{\mathbf{eff}}(\Lambda n) = \frac{H^2}{18\,\Delta}\left[\rho_n + 2\rho_p\right]$$ **repulsive**



- **Decuplet-octet mass difference**

$$\Delta = \mathrm{M}_{[10]} - \mathrm{M}_{[8]} \simeq 270\,\mathrm{MeV} \qquad C = \frac{3}{4} g_A \simeq 1$$

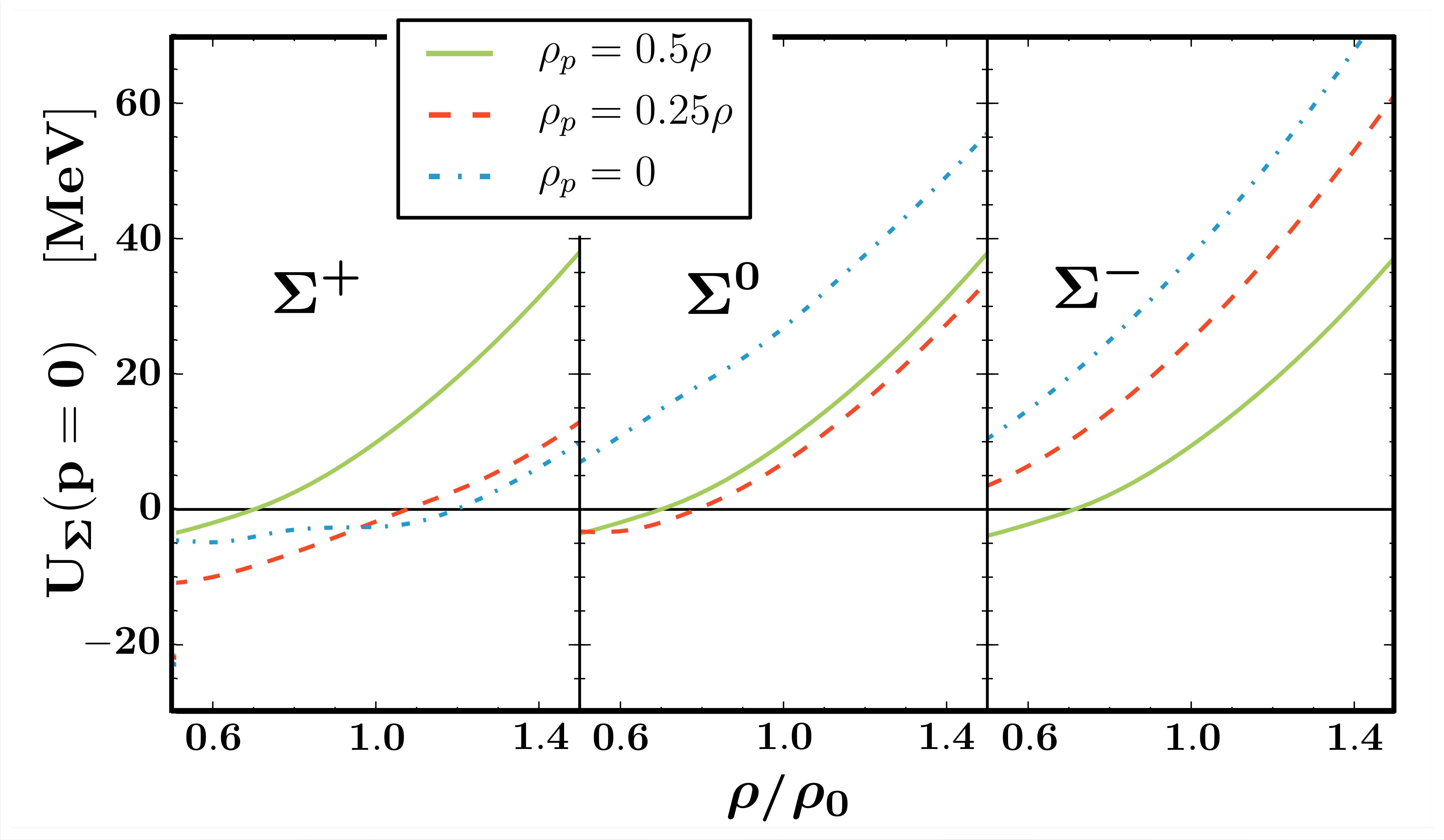
- **Coupling parameters :**

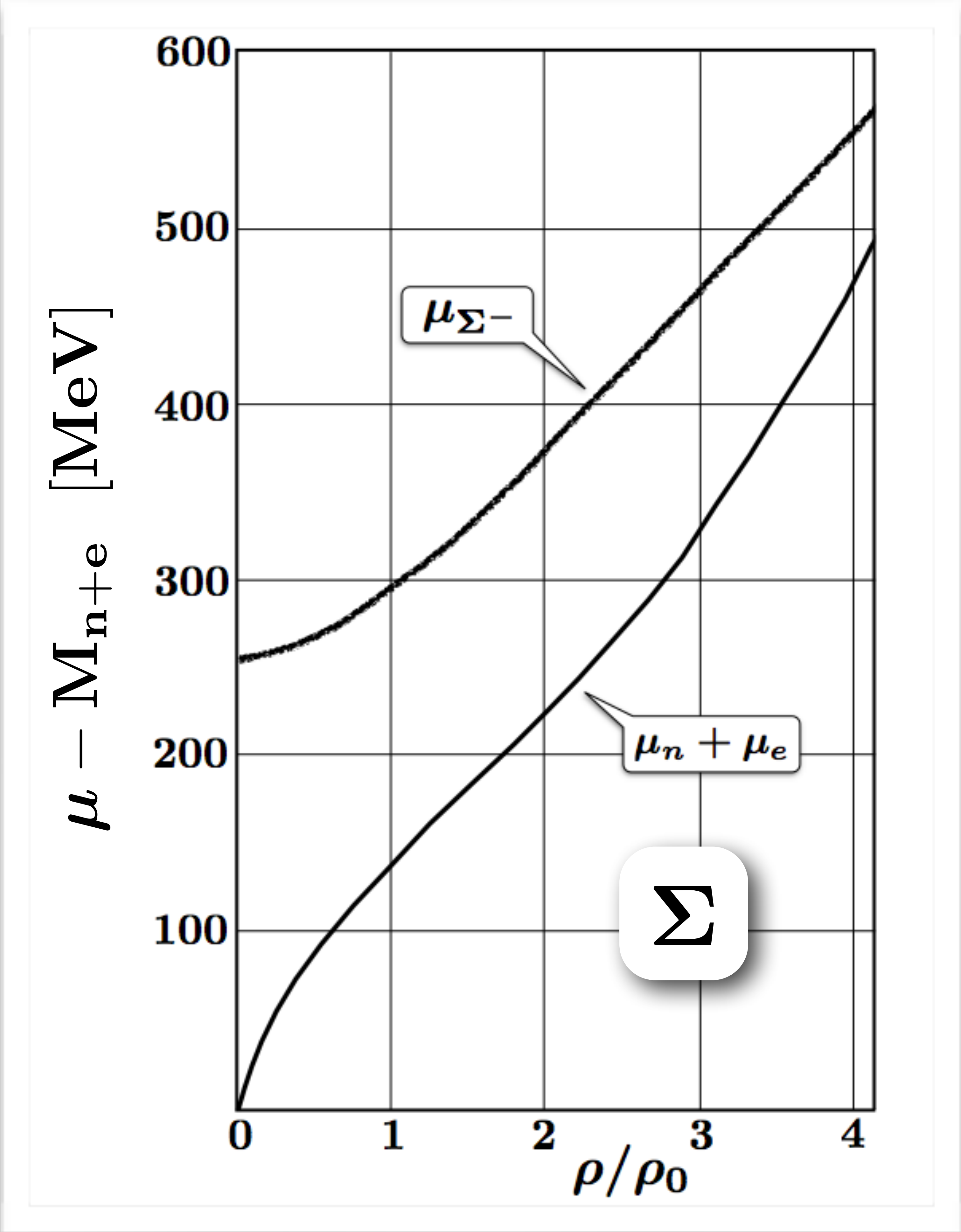
$$H = H_1 + 3H_2 \quad |H| \lesssim f_\pi^{-2}$$

Σ Hyperons in Neutron Stars ?

- Σ **hyperon potentials** from **Chiral SU(3) EFT** interactions

S. Petschauer, J.Haidenbauer, N. Kaiser,
U.-G. Meißner, W.W. : EPJ A52 (2016) 15





- Σ - nuclear potentials are **repulsive**
- Condition for appearance of Σ^- in neutron star matter :

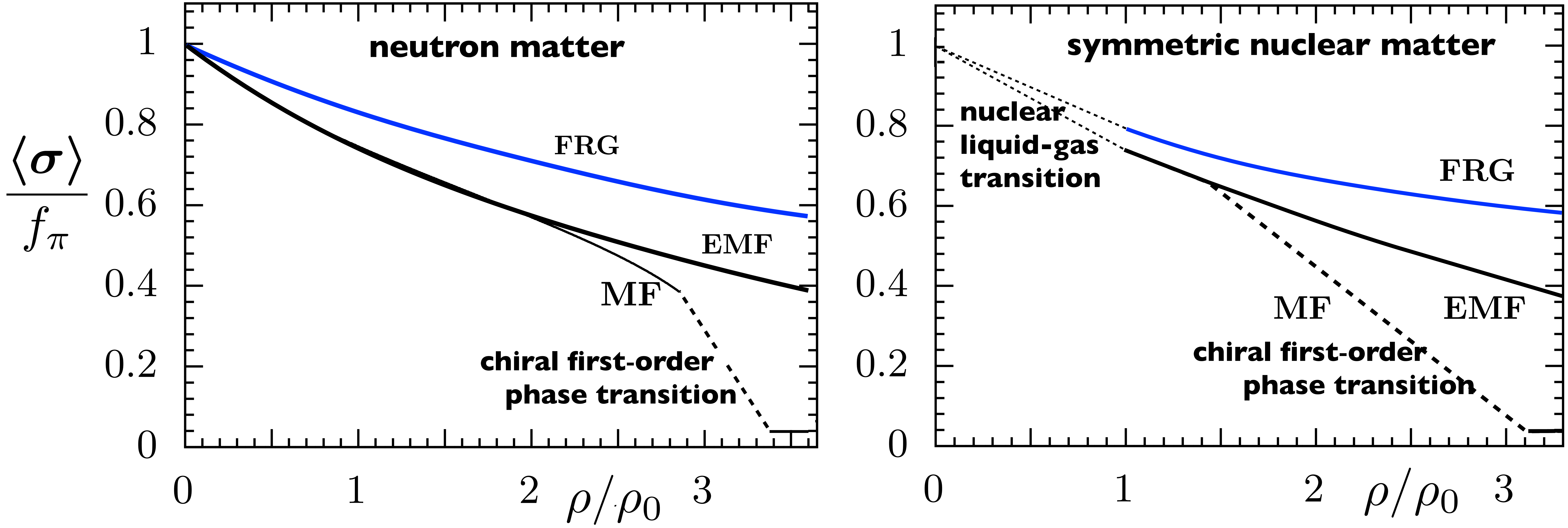
$$\mu_{\Sigma^-} = \mu_n + \mu_e = 2\mu_n - \mu_p \qquad \mu_i = \frac{\partial \mathcal{E}}{\partial \rho_i}$$

Technische Universität München

CHIRAL ORDER PARAMETER in NUCLEAR and NEUTRON MATTER (T = 0)

- Chiral phase transition in dense baryonic matter ? Studies in chiral meson-nucleon field theory

L. Brandes, N.. Kaiser, W.W.: Eur. Phys. J. A57 (2021) 243



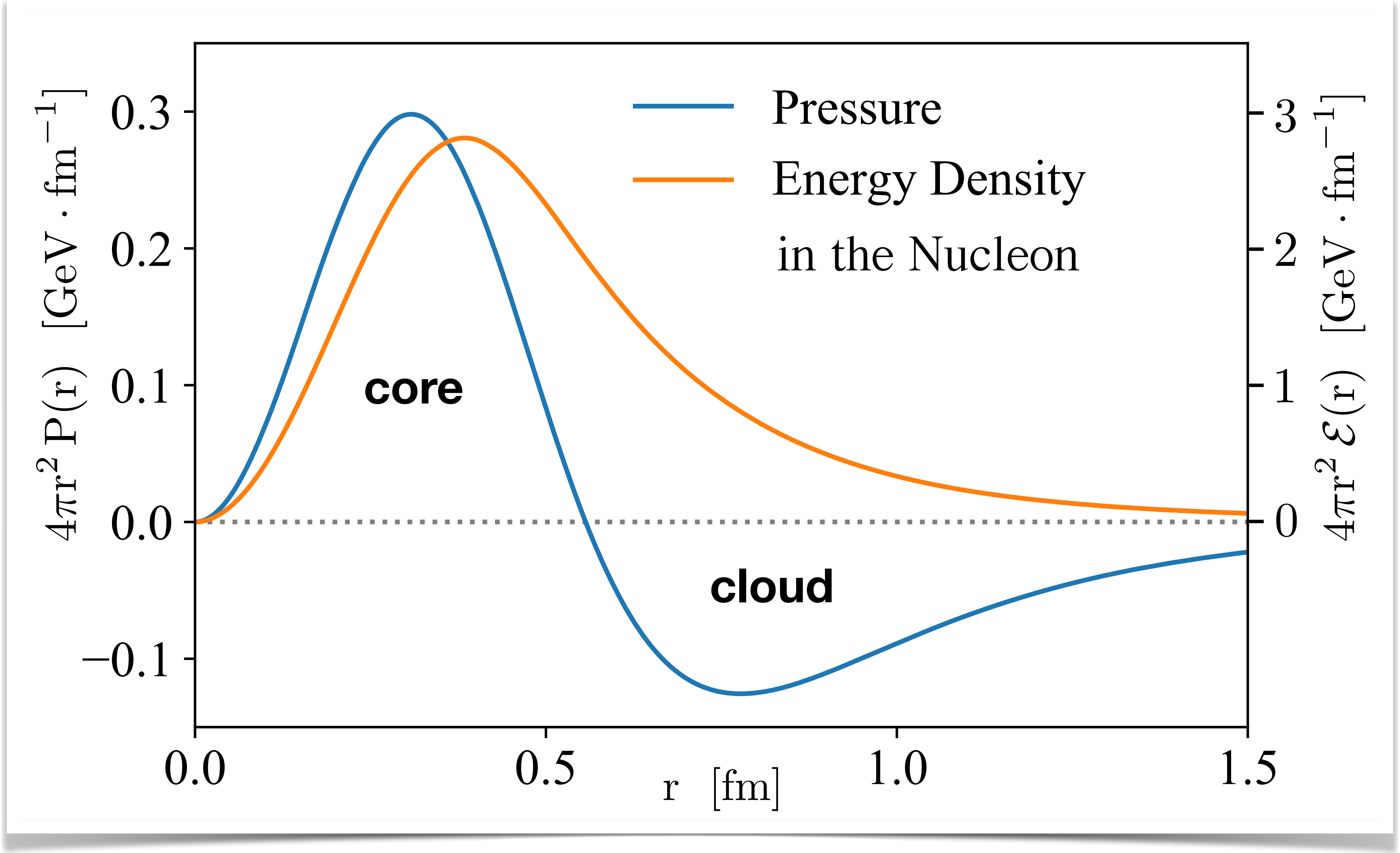
chiral **crossover** transition at baryon densities $\rho > 6\,\rho_0$

- **Mean-field** (MF) approximation (wrongly) features chiral 1st order transition at $\rho \sim 2 - 3\,\rho_0$
- **Vacuum fluctuations** (EMF) shift chiral transition to high density ➡ **smooth crossover**
- **FRG** (with non-perturbative **loop corrections** involving **pions** , **nucleons**) enhances this effect

Further **KEYWORDS** on **COLD MATTER** at **EXTREME DENSITIES**
Hadron - Quark Continuity

K. Fukushima, T. Kojo, W.W. : Phys. Rev. D102 (2020) 096017

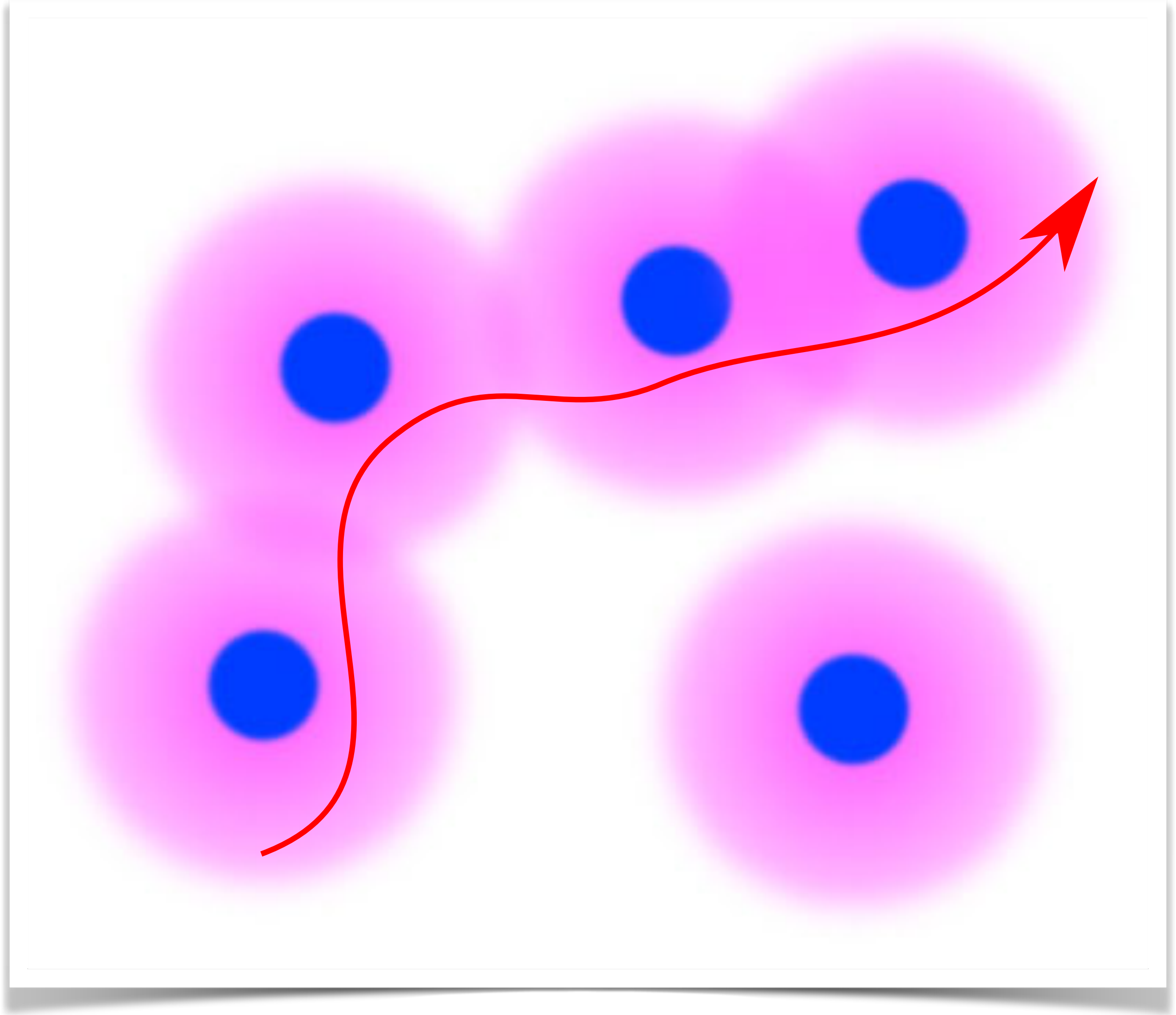
- Nucleonic scales : **HARD-CORE** deconfinement + **SOFT SURFACE** delocalisation



- Nucleon cores touch at baryon densities

$$\rho_B \sim 6\,\rho_0$$

- Percolation of mesonic clouds at lower densities inducing many-body correlations



F. Karsch, H. Satz
Phys. Rev.
D21 (1980) 1168

- Soft delocalisation and collective mobility of quark-antiquark pairs over larger distances
- No (first-order) phase transition expected at densities relevant to neutron stars