Constraints on phase transitions in neutron star matter

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Supervisors: Wolfram Weise and Norbert Kaiser

Dr. Klaus Erkelenz Prize Colloquium

Len Brandes

14.11.2023

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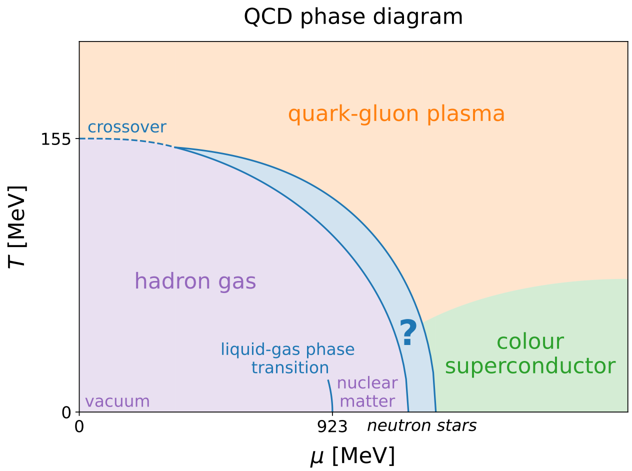
Phases of strongly interacting matter

- QCD vacuum:
  - Confinement of quarks and gluons in hadrons
  - Spontaneously broken chiral symmetry
- Crossover at $T \sim 155\,\text{MeV}$ to quark-gluon plasma
  [Bazavov *et al.*, Phys. Rev. D 90 (2014)]
- Nuclear liquid-gas phase transition at $\mu = 923\,\text{MeV}$
  [Elliott, Lake, Moretto and Phair, Phys. Rev. C 87 (2013)]
- Chirally restored phase at asymptotic densities
  [Schäfer and Wilczek, Phys. Rev. D 60 (1999)]

→ **Unknown transition from nuclear to quark matter**



Nucleon-nucleon potential

CURRENT STATUS OF THE RELATIVISTIC TWO-NUCLEON ONE BOSON EXCHANGE POTENTIAL

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Received April 1974

[Erkelenz, Phys. Rept. 13 (1974)]

- Describe nucleon-nucleon interactions via boson exchanges

  → Further developed into Bonn potential

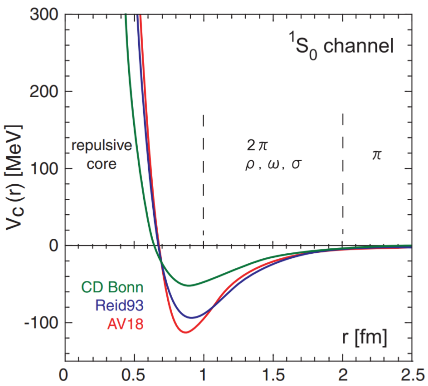
  [Machleidt and Holinde, Phys. Rept. 149 (1987)]

- Good agreement with nucleon-nucleon data

  [Machleidt, Phys. Rev. C 63 (2001)]

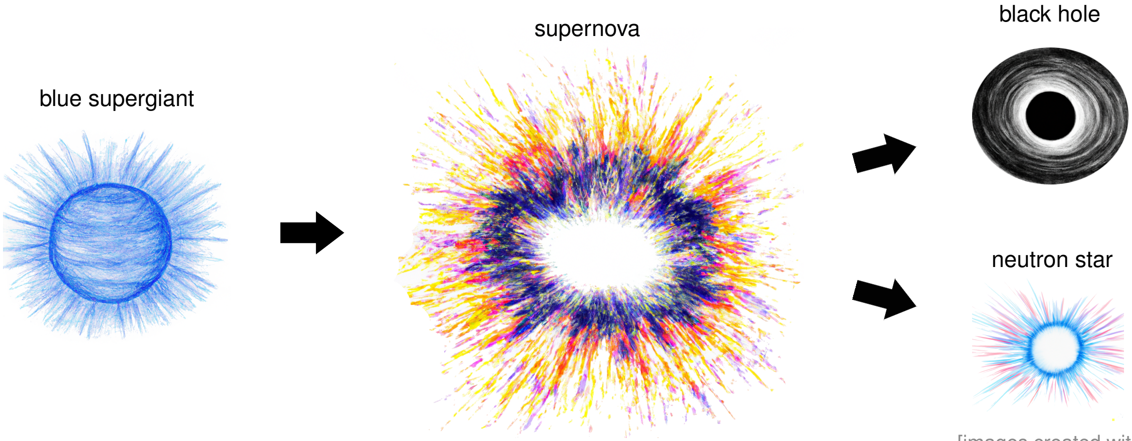
- **Repulsive core** at $r_{\text{hard-core}} \sim 0.5\,\text{fm}$

  → Relevance for dense baryonic matter in neutron stars
  average distance between baryons: $d \propto n^{-1/3}$



[Ishii, Aoki and Hatsuda, Phys. Rev. Lett. 99 (2007)]

Neutron stars

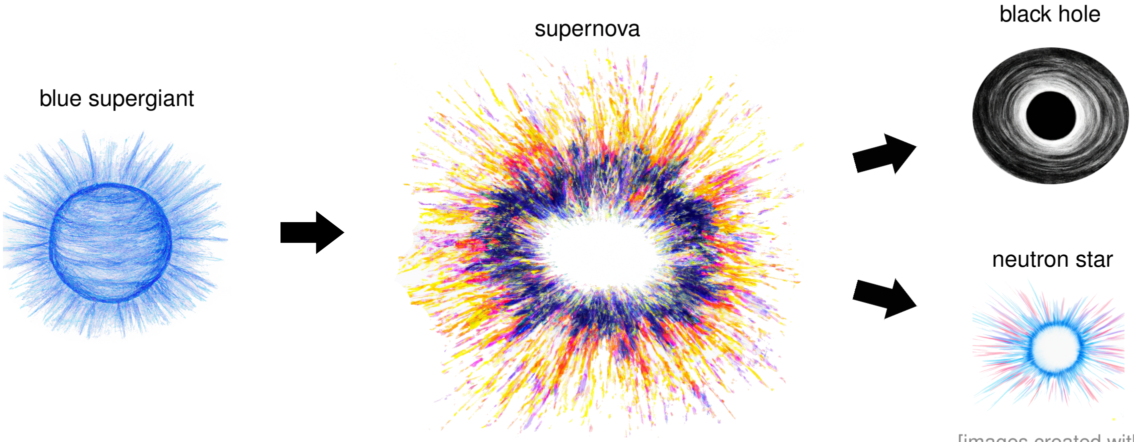


[images created with DALL·E, openAI]

- Stars remain stable by fusing light elements to heavier elements
- At some point no light elements left in core

  → Resulting implosion leads to supernova
- Collapsed core forms **neutron star**

Neutron stars



[images created with DALL·E, openAI]

- Masses $M \sim 1 - 2\,M_{\odot}$, radii $R \sim 11 - 13\,\text{km}$

  → **High baryon densities** in core beyond terrestrial experiments

- Recent substantial extension of observational data base
- **Phase transition** in dense neutron star matter?

Description of neutron stars

- Internal structure described by Tolman-Oppenheimer-Volkoff (TOV) equations

$$\frac{\partial P(r)}{\partial r} = -\frac{G_N}{r^2}\left(\varepsilon(r)+P(r)\right)\left(m(r)+4\pi r^3 P(r)\right)\left(1-\frac{2G_N m(r)}{r}\right)^{-1},$$

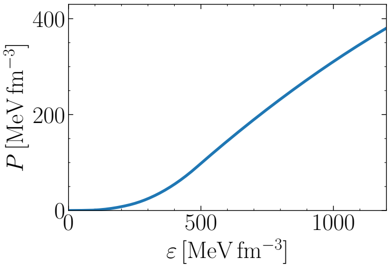
$$\frac{\partial m(r)}{\partial r} = 4\pi r^2 \varepsilon(r)$$

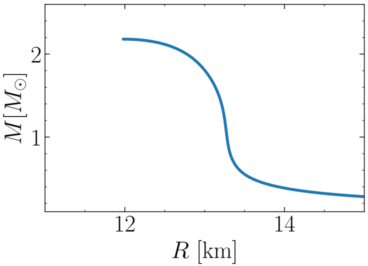
[Tolman, Phys. Rev. 55 (1939)] [Oppenheimer and Volkoff, Phys. Rev. 55 (1939)]

- Solved given **equation of state** (EoS) $P(\varepsilon)$ and central energy density $\varepsilon(r=0)=\varepsilon_c$

  → Solution for different ε_c yields (M,R)-relation

- Each EoS has maximum density $\varepsilon_{c,\max}$ corresponding to **maximum supported mass** M_{max}





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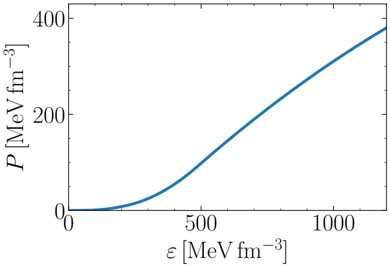
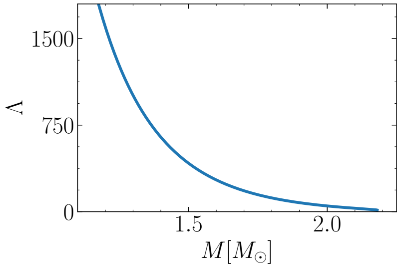
[Tolman, Phys. Rev. 55 (1939)] [Oppenheimer and Volkoff, Phys. Rev. 55 (1939)]

- Solved given **equation of state** (EoS) $P(\varepsilon)$ and central energy density $\varepsilon(r=0) = \varepsilon_c$
- Simultaneously solve for **tidal deformability** Λ

→ Relevant for neutron stars in binary systems





Speed of sound

- Determine EoS from **speed of sound**

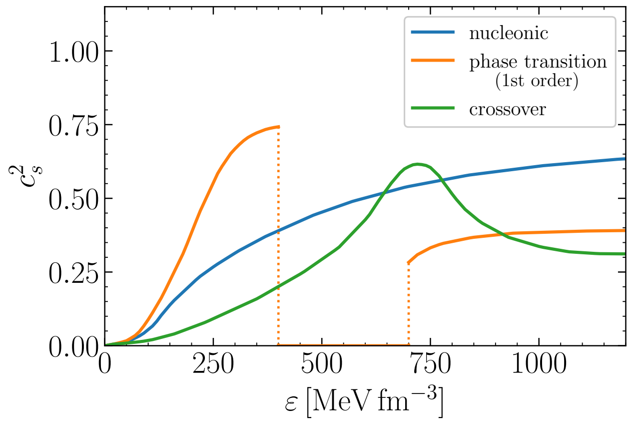
$$c_s^2(\varepsilon) = \frac{\partial P(\varepsilon)}{\partial \varepsilon}$$

- Causality & thermodynamic stability: $0 \leq c_s \leq 1$

- Measure of coupling strength in matter

$\rightarrow$ Characteristic signature of phase structure:

  - **Nucleonic**: monotonously rising sound speed
  - **First-order phase transition**: coexistence interval with zero sound speed $c_s^2 \sim 0$
  - **Crossover**: peaked behaviour



[McLerran and Reddy, Phys. Rev. Lett. 122 (2019)]

Parametrization

- Introduce **general parametrization** by segment-wise linear interpolations

$$c_s^2(\varepsilon,\theta) = \frac{(\varepsilon_{i+1}-\varepsilon)c_{s,i}^2 + (\varepsilon-\varepsilon_i)c_{s,i+1}^2}{\varepsilon_{i+1}-\varepsilon_i}$$

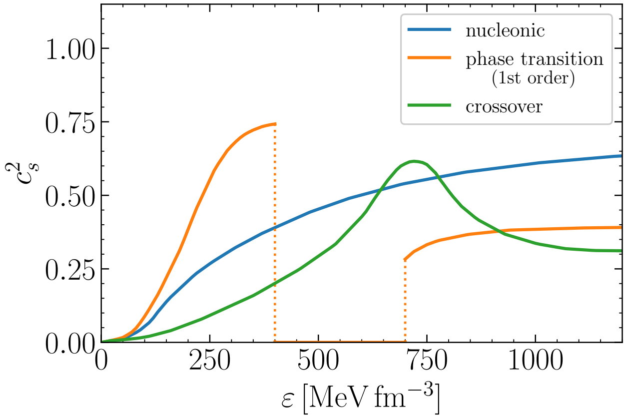
[Annala *et al.*, Nature Phys. 16, 907 (2020)]

- Can describe wide range of possible phase transitions and crossovers

- Previous analyses: similar results to non-parametric representations [Annala *et al.*, arXiv:2303.11356 (2023)]

- *Constrain parameters $\theta = (\varepsilon_i, c_{s,i}^2)$ based on available data*

→ Analyse for signatures of **possible phase transitions**



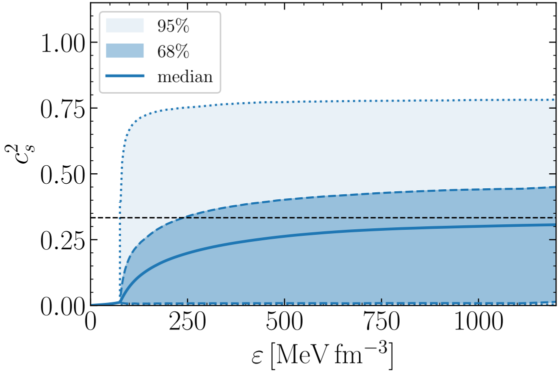
Bayesian inference

- Constrain parameters of $c_s^2(\varepsilon, \theta)$ via **Bayesian inference** based on **data** $\mathscr{D}$

$$\Pr(\theta|\mathscr{D}) \propto \Pr(\mathscr{D}|\theta)\,\Pr(\theta)$$

- Compute posterior probability $\Pr(\theta|\mathscr{D})$ for parameters θ:
    - Compute likelihood $\Pr(\mathscr{D}|\theta)$ for each data $\mathscr{D}$
    - Choose prior ranges for parameters $\Pr(\theta)$
- Compute median and **credible bands** at 68% or 95% level

→ Here: more prior support at small sound speeds to analyse phase transitions [LB, Weise and Kaiser, Phys. Rev. D 107 (2023)]



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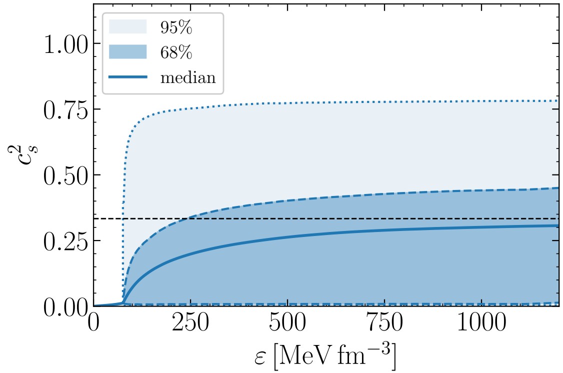


[LB, Weise and Kaiser, Phys. Rev. D 108 (2023)]

- Quantify evidence for hypothesis H_0 vs. H_1 with **Bayes factors**

$$\mathscr{B}^{H_1}_{H_0} = \frac{\Pr(\mathscr{D}|H_1)}{\Pr(\mathscr{D}|H_0)}$$

→ Comparison to classification scheme for statistical conclusions

[Lee and Wagenmakers, *Bayesian Cognitive Modeling* (Cambridge University Press, 2014)]

[Jeffreys, *Theory of Probability* (Oxford University Press, 1961)]

Perturbative QCD

- Strong coupling decreases at **high densities**

  → Perturbative QCD calculations in terms of quark and gluon degrees of freedom

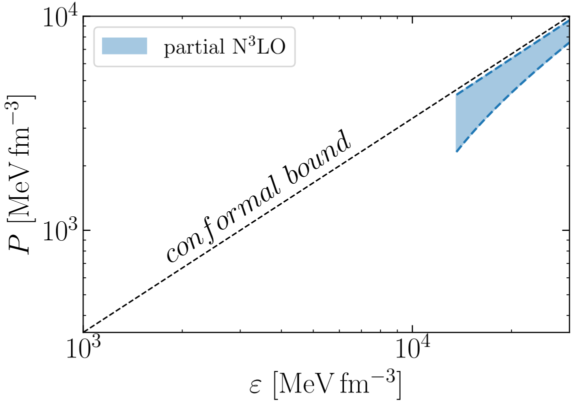
- Asymptotic boundary condition at $n \gtrsim 40\,n_0$ (with $n_0 = 0.16\,\mathrm{fm}^{-3}$)

- Speed of sound reaches **conformal limit** $c_s^2 = 1/3$ from below

  → Interpolation to asymptotic pQCD with $0 \leq c_s \leq 1$ constrains EoS at smaller densities

  [Komoltsev and Kurkela, Phys. Rev. Lett. 128 (2022)]

- Exclude EoS where **matching** to asymptotic pQCD is not possible



[Gorda *et al.*, Phys. Rev. Lett. 127 (2021)]

Chiral effective field theory

- ChEFT: systematic expansion of nuclear forces at low momenta with controlled uncertainties

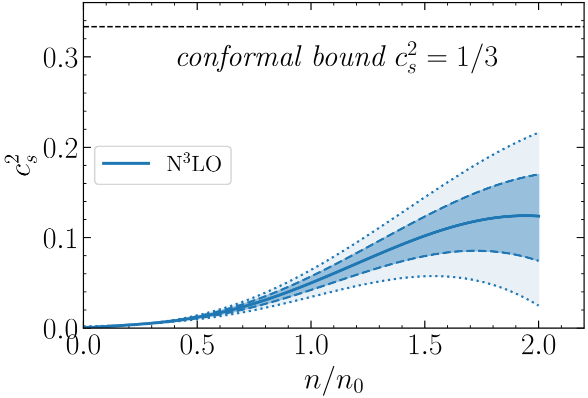
- Extended to finite densities using many-body methods

  → Good description of **low-density** nuclear phenomenology
  [Wellenhofer, Holt and Kaiser, Phys. Rev. C 92 (2015)]

- Combined uncertainties from many-body approximations and convergence errors [Drischler *et al.*, Phys. Rev. C 103 (2021)]

- N^3LO sound speed at $n \sim 2\,n_0$ **softer** compared to N^2LO

  → Employ only up to $n \leq 1.3\,n_0$ [Essick *et al.*, Phys. Rev. C 102 (2020)]



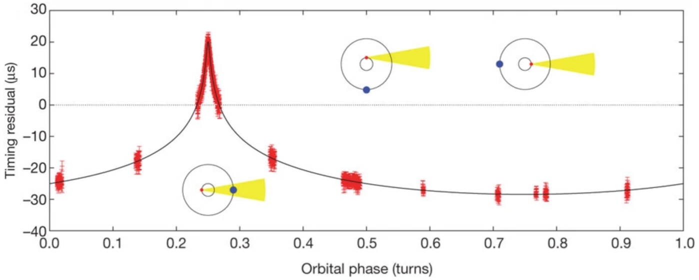
[Drischler, Han and Reddy, Phys. Rev. C 105 (2022)]

Shapiro time delay

- Neutron stars with strong magnetic fields emit synchroton radiation
- If magnetic and rotation axis not aligned, double cone of radiation rotates (→ pulsars)
- Binary systems: gravitational field of **companion changes pulsar signal**
- Extract **neutron star masses** with high precision (68% level):

PSR J0348+0432	$M = 2.01 \pm 0.04\, M_{\odot}$	[Antoniadis *et al.*, Science 340 (2013)]
PSR J0740+6620	$M = 2.08 \pm 0.07\, M_{\odot}$	[Fonseca *et al.*, Astrophys. J. Lett. 915 (2021)]

→ Matter must be sufficiently stiff to support such high masses



[Demorest *et al.*, Nature 467 (2010)]

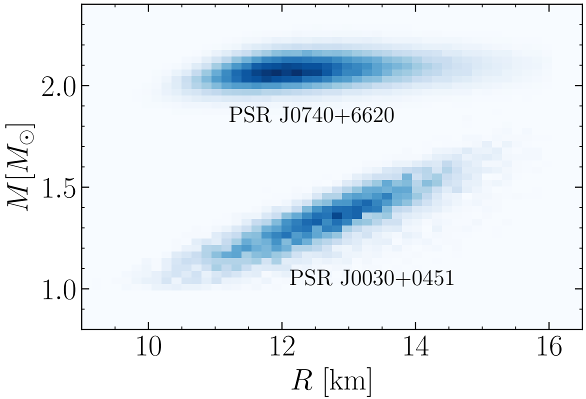
Pulse profile modelling

- **Hot spots** form on magnetic polar caps of rapidly rotating neutron stars
- Thermal X-ray emission modulated by gravitational effects

  → Measured by **NICER** telescope on ISS

- Model hot spots and neutron star atmosphere

  → Infer **mass and radius** from X-ray measurements (68% level):



PSR J0030+0451	$R = 12.71^{+1.14}_{-1.19}\,\mathrm{km}$	$M = 1.34^{+0.15}_{-0.16}\,M_\odot$	[Riley *et al.*, Astrophys. J. Lett. 887 (2019)]
PSR J0740+6620	$R = 12.39^{+1.30}_{-0.98}\,\mathrm{km}$	$M = 2.072^{+0.067}_{-0.066}\,M_\odot$	[Riley *et al.*, Astrophys. J. Lett. 918 (2021)]

→ Very similar radii for 1.34 and 2.07 $M_\odot$ neutron stars

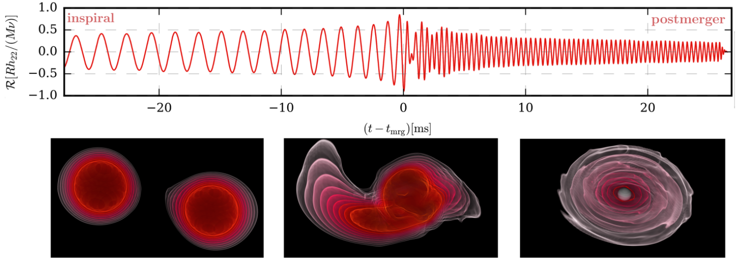
Neutron star mergers

- Binary neutron star mergers produce **gravitational waves**

- Compare observed LIGO and Virgo signal to waveform models

- Waveform depends on M_2/M_1 and combination of **tidal deformabilities**

$$\bar{\Lambda} = \frac{16}{13} \frac{(M_1 + 12M_2)M_1^4\Lambda_1 + (M_2 + 12M_1)M_2^4\Lambda_2}{(M_1 + M_2)^5}$$



[Dietrich, Hinderer and Samajdar, Gen. Rel. Grav. 53 (2021)]

- Two binary neutron star mergers detected so far (90% level):

GW170817 $\bar{\Lambda} = 320^{+420}_{-230}$ [Abbott *et al.* (LIGO and Virgo Collaborations), Phys. Rev. X 9 (2019)]

GW190425 $\bar{\Lambda} \leq 600$ [Abbott *et al.* (LIGO and Virgo Collaborations), Astrophys. J. Lett. 892 (2020)]

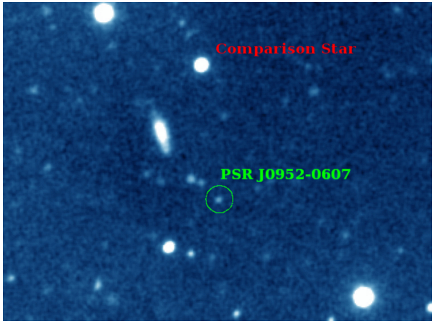
New data: black widow pulsar

- Black widow pulsars accrete most of mass from companion

  → Determine mass via observation of companion

- PSR J0952-0607 **heaviest neutron star** observed so far

  $M = 2.35 \pm 0.17\, M_\odot$ [Romani *et al.*, ApJL 934 (2022)]



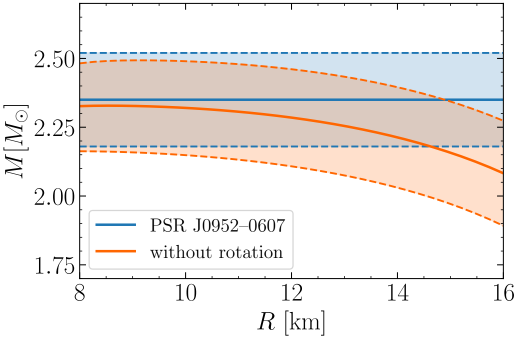
[W.M. Keck Observatory, Roger W. Romani, Alex Filippenko]

- Simpler heating model compared to other black widows

- Second fastest known pulsar $T = 1.41\,\mathrm{ms}$

  → **Rotation correction** via empirical formula

  [Konstantinou and Morsink, Astrophys. J. 934, 139 (2022)]



Speed of sound

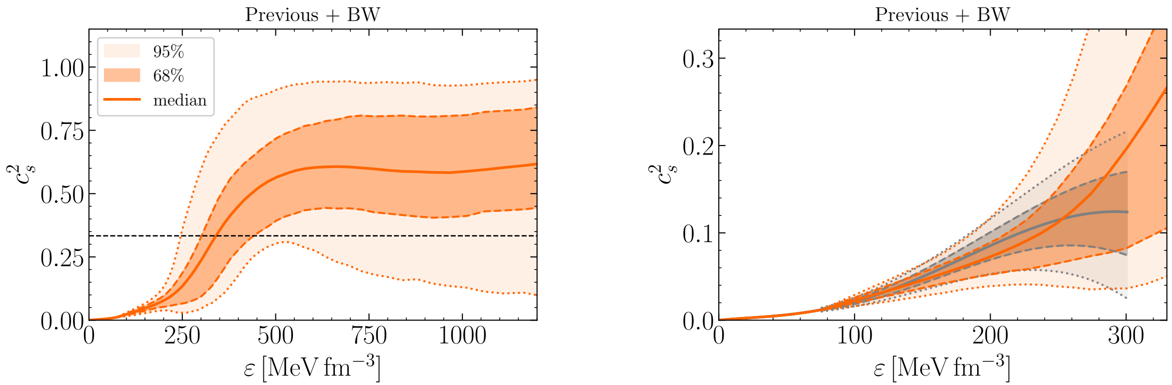
- **Steep increase** of speed of sound around $\varepsilon \sim 250 - 600\,\mathrm{MeV\,fm^{-3}}$

  → Required to support black-widow (BW) heavy mass measurement [LB, Weise and Kaiser, Phys. Rev. D 108 (2023)]

- Conformal bound $c_s^2 \leq 1/3$ exceeded inside neutron stars [Altiparmak, Ecker and Rezzolla, Astrophys. J. Lett. 939 (2022)] [Legred, Chatziioannou, Essick, Han and Landry, Phys. Rev. D 104 (2021)]

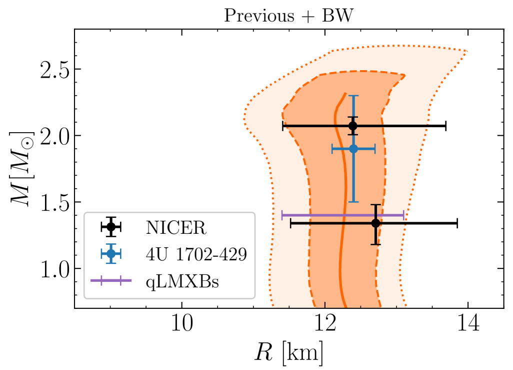
  → Strongly repulsive correlations at high densities

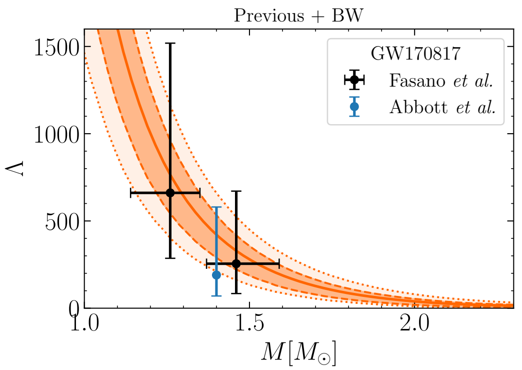
- Slight **tension** between ChEFT at $n \simeq 2\,n_0$ and astro data [Essick *et al.*, Phys. Rev. C 102 (2020)]



Mass-radius & tidal deformability

- Good agreement with data **not included** in Bayesian analysis:
  - Thermonuclear burster 4U 1702-429
    [Nättilä *et al.*, Astron. & Astrophys. 608 (2017)]
  - $R(M = 1.4\,M_\odot)$ from quiescent low mass X-ray binaries (qLMXBs)
    [Steiner *et al.*, Mon. Not. Roy. Astron. Soc. 476 (2018)]
- Median with **almost constant radius** $R \sim 12.3\,\mathrm{km}$
- Good agreement with other GW170817 analyses:
  - Masses and tidal deformabilities of two neutron stars
    [Fasano, Abdelsalhin, Maselli, and Ferrari, Phys. Rev. Lett. 123 (2019)]
  - $\Lambda(M = 1.4\,M_\odot)$ from universal relations
    [Abbott *et al.* (LIGO and Virgo Collaborations), Phys. Rev. Lett. 121 (2018)]





Pressure & coexistence interval

- Significantly increased pressure compared to previous EoS

- Maxwell construction of first-order phase transition: constant pressure in **phase coexistence region**

  → Width Δn measure of phase transition 'strength'

- **Maximum possible interval** within posterior credible band

$$\left(\frac{\Delta n}{n}\right)_{\max} \leq 0.2 \qquad \text{at 68\% level}$$

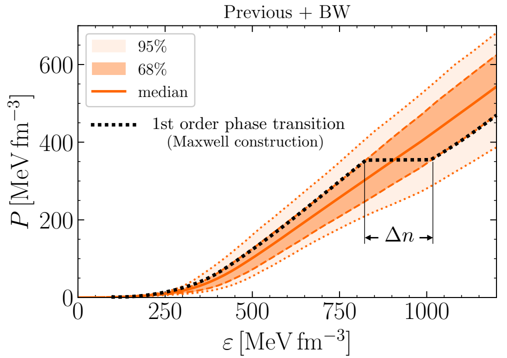
[LB, Weise and Kaiser, Phys. Rev. D 108 (2023)]

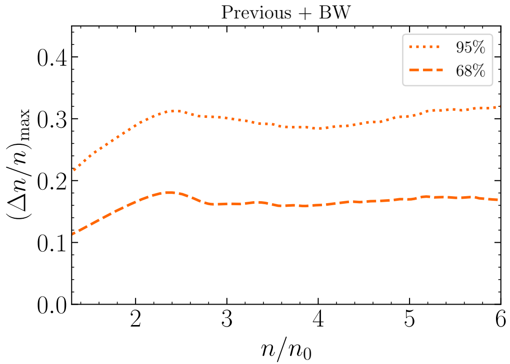
- Compare to 'strong' nuclear liquid-gas phase transition

$$\frac{\Delta n}{n} > 1$$

[Fiorilla, Kaiser and Weise, Nucl. Phys. A 880 (2012)]

→ Only **weak first-order phase transitions** possible





Small sound speeds

- Quantify **evidence of small sound speeds** inside neutron star cores with Bayes factor

$$\mathscr{B}^{c^2_{s,\mathrm{min}}>0.1}_{c^2_{s,\mathrm{min}}\leq 0.1}$$

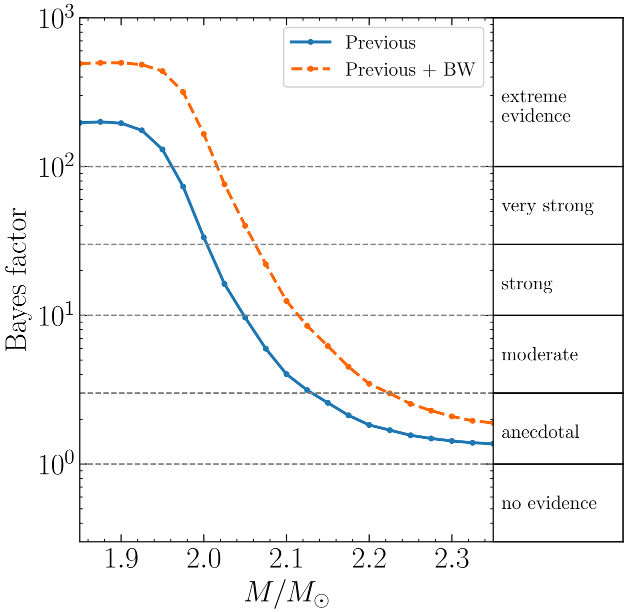
→ $c^2_{s,\mathrm{min}} \leq 0.1$ perquisite for first-order phase transition

- Previous analyses: $c_s^2 > 0.1$ in neutron stars with $M \leq 2\,M_\odot$
  [Ecker and Rezzolla, Astrophys. J. Lett. 939 (2022)] [Annala *et al.*, arXiv:2303.11356 (2023)]

- **Heavy mass measurement** increases Bayes factor

- Strong evidence against $c^2_{s,\mathrm{min}} \leq 0.1$ in cores of neutron stars with $M \leq 2.1\,M_\odot$ [LB, Weise and Kaiser, Phys. Rev. D 108 (2023)]

→ **Strong first-order phase transitions unlikely** based on empirical data



Possible interpretation

- **Central densities** in neutron stars (68%): $n_c < 5\,n_0$ for $M \leq 2.3\,M_\odot$

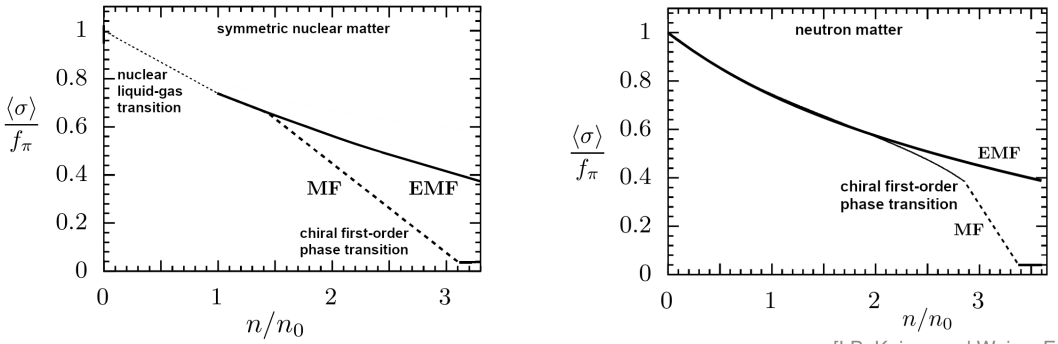
  → Average distance between baryons: $d > 1.0\,\mathrm{fm} \gg r_{\text{hard-core}} \sim 0.5\,\mathrm{fm}$

- **Chiral nucleon-meson model:** nucleons interacting via exchange of effective mesons

  [Floerchinger and Wetterich, Nucl. Phys. A 890–891 (2012)] [Drews and Weise, Prog. Part. Nucl. Phys. 93 (2017)]

- *Mean-field (MF)* approximation: first-order order phase transition to chirally restored phase

- *Extended mean-field (EMF):* fermionic vacuum fluctuations stabilize order parameter



[LB, Kaiser and Weise, Eur. Phys. J. A 57 (2021)]

Summary

- *Unknown transition from nucleons to quarks and gluons at high densities*
- **Bayesian inference** of sound speed in neutron star matter based on:
  - Shapiro time-delays
  - NICER X-ray measurements
  - Gravitational waves from binary neutron star mergers
  - ChEFT results at small densities
  - Perturbative QCD calculations at asymptotically high densities
  - (New) black widow pulsar $M = 2.35 \pm 0.17\, M_\odot$
- Maximum possible phase coexistence interval $(\Delta n/n)_{\max} \leq 0.2$
- Strong evidence against $c^2_{s,\min} \leq 0.1$ in cores of neutron stars with $M \leq 2.1\, M_\odot$
- Central densities $n_c < 5\, n_0$ for $M \leq 2.3\, M_\odot$: average distance between baryons still > 1 fm

→ **Strong first-order phase transitions unlikely** based on empirical data

→ Fluctuations stabilize hadronic phase?

Outlook

- Fourth observation run of LIGO, Virgo and KAGRA started on May 4th
- Four more objects to be measured by NICER telescope [Greif *et al.*, MNRAS 485 (2019)]
- Moment-of-inertia measurement of PSR J0737-3039 in next few years [Landry and Kumar, Astrophys. J. 868 (2018)]
- Extract more information with novel statistical tools from Machine Learning [Farrell *et al.*, arXiv:2305.07442 (2023)]

→ **Many more future measurements** will put even **tighter constraints** on phase structure at high densities

nature

NEWS FEATURE | 04 March 2020

The golden age of neutron-star physics has arrived

These stellar remnants are some of the Universe's most enigmatic objects – and they are finally starting to give up their secrets.

Adam Mann

Supplementary material

Twin stars

- Strong phase transitions can lead to mass-radius relations with **multiple stable branches** ('twin stars')

- Bayes factor gives **extreme evidence** against multiple stable branches
  [Gorda *et al.*, arXiv:2212.10576 (2022)]

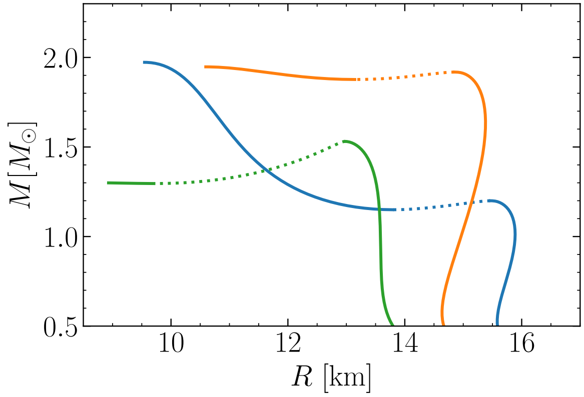
- Without likelihood from **ChEFT** 'only' strong evidence:

$$\mathscr{B}^{N_{\text{branches}}=1}_{N_{\text{branches}}>1} = 12.97$$

[Essick, Legred, Chatziioannou, Han and Landry, arXiv:2305.07411 (2023)]

- Disconnection takes place at $M \sim 0.8\,M_\odot$

→ Unlikely based on nuclear phenomenology

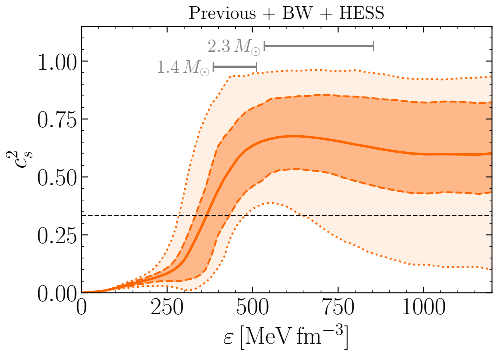


Possible impact of HESS J1731-347

- Central compact object within supernova remnant HESS J1731-347:

$$M = 0.77^{+0.20}_{-0.17}\, M_\odot$$
$$R = 10.4^{+0.86}_{-0.78}\,\mathrm{km}$$

[Doroshenko *et al.*, Nat. Astron. 6 (2022)]

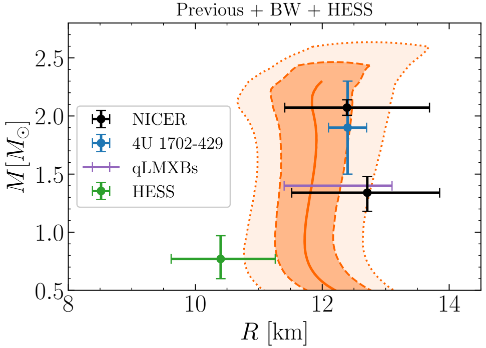


- Unusually **light neutron star** with very low radius

→ Neutron star mass $M < 1.17\, M_\odot$ in contradiction with known formation mechanisms

[Suwa *et al.*, MNRAS 481 (2018)]

→ Strange star?



- Systematic uncertainty: larger masses and radii might be possible

[Alford and Halpern, Astrophys. J. 944 (2023)]

- **Tension** between HESS and current astrophysical data

[Jiang, Ecker and Rezzolla, arXiv:2211.00018 (2022)]

General EoS parametrization

- Determine EoS from **speed of sound**

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

- Parametrize by **segment-wise linear interpolations**

$$c_s^2(\varepsilon,\theta) = \frac{(\varepsilon_{i+1} - \varepsilon)c_{s,i}^2 + (\varepsilon - \varepsilon_i)c_{s,i+1}^2}{\varepsilon_{i+1} - \varepsilon_i}$$

[Annala *et al.*, Nature Phys. 16, 907 (2020)]

- Matching to BPS crust at low densities $(c_{s,0}^2, \varepsilon_0) = (c_{s,\mathrm{crust}}^2, \varepsilon_{\mathrm{crust}})$ [G. Baym, C. Pethick, and P. Sutherland, Astrophys. J. 170 (1971)]
- Constant speed of sound $c_s^2(\varepsilon,\theta) = c_{s,N}^2$ beyond last point $\varepsilon > \varepsilon_N$
- Choose $N = 5$ corresponding to 7 segments and 10 free parameters
- **Priors** sampled logarithmically

$$c_{s,i}^2 \in [0,1] \quad \varepsilon_i \in [\varepsilon_{crust}, 4\,\mathrm{GeV\,fm^{-3}}]$$

- Parametrizations with only 4 segments leads to comparable results as non-parametric Gaussian process

[Annala *et al.*, arXiv:2303.11356 (2023)]

Bayesian inference

- Bayes theorem:

$$\mathrm{Pr}(\theta|\mathscr{D},\mathscr{M}) = \frac{\mathrm{Pr}(\mathscr{D}|\theta,\mathscr{M})\,\mathrm{Pr}(\theta|\mathscr{M})}{\mathrm{Pr}(\mathscr{D}|\mathscr{M})}$$

- Choose **Priors** for parameters $\mathrm{Pr}(\theta|\mathscr{M})$

- **Likelihood** $\mathrm{Pr}(\mathscr{D}|\theta,\mathscr{M})$: probability of data $\mathscr{D}$ to occur for θ and model $\mathscr{M}$

- (M, R, Λ) can be deterministically determined for θ

$$\mathrm{Pr}(\mathscr{D}|\theta,\mathscr{M}) = \mathrm{Pr}(\mathscr{D}|M,R,\Lambda,\mathscr{M})$$

→ For computational feasibility assume (valid for flat Priors in (M, R, Λ))

$$\mathrm{Pr}(\mathscr{D}|M,R,\Lambda,\mathscr{M}) \propto \mathrm{Pr}(M,R,\Lambda|\mathscr{D},\mathscr{M})$$

[Riley, Raaijmakers and Watts, Mon. Not. Roy. Astron. Soc. 478 (2018)] [Raaijmakers *et al.*, ApJL 918 (2021)]

Bayesian inference

- Bayes theorem:

$$\Pr(\theta|\mathscr{D},\mathscr{M}) = \frac{\Pr(\mathscr{D}|\theta,\mathscr{M})\Pr(\theta|\mathscr{M})}{\Pr(\mathscr{D}|\mathscr{M})}$$

- **Evidence** $\Pr(\mathscr{D}|\mathscr{M})$: determined via normalization of the posterior

$$\Pr(\mathscr{D}|\mathscr{M}) = \int d\theta \ \Pr(\mathscr{D}|\theta,\mathscr{M})\Pr(\theta|\mathscr{M})$$

→ High-dimensional integral, use sampling techniques

- **Credible bands**: determine $P(\varepsilon_i,\theta)$ on grid $\{\varepsilon_i\}$ for posterior samples to get $\Pr\left(P\middle|\varepsilon_i,\mathscr{D},\mathscr{M}\right)$

→ Compute credible interval $[a,b]$ with probability α at ε_i

$$\alpha = \int_a^b dP \ \Pr\left(P\middle|\varepsilon_i,\mathscr{D},\mathscr{M}\right)$$

→ Combine credible intervals at all ε_i to posterior credible band $P(\varepsilon)$

Trace anomaly measure

- Trace anomaly measure as signature of **conformality**

$$\Delta = \frac{g_{\mu\nu} T^{\mu\nu}}{3\varepsilon} = \frac{1}{3} - \frac{P}{\varepsilon}$$

[Fujimoto, Fukushima, McLerran and Praszałowicz, Phys. Rev. Lett. 129 (2022)]

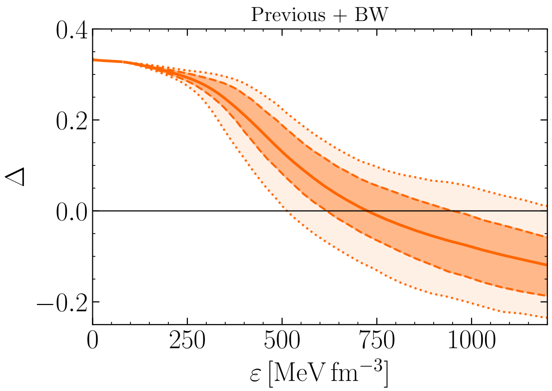
- Median becomes negative around $\varepsilon \sim 700\,\mathrm{MeV\,fm^{-3}}$

→ Moderate evidence for Δ turning **negative** inside neutron stars

Bayes factor $\mathscr{B}^{\Delta<0}_{\Delta\geq 0} = 8.11$

[Ecker and Rezzolla, Astrophys. J. Lett. 939 (2022)] [Annala *et al.*, arXiv:2303.11356 (2023)]
[Marczenko, McLerran, Redlich and Sasaki, Phys. Rev. C 107 (2023)]

- At higher energy densities again positive Δ to reach asymptotic pQCD limit



Impact of pQCD

- Matching to pQCD at $n_{c,\mathrm{max}}$ has only **negligible impact**
  [Somasundaram, Tews and Margueron, arXiv:2204.14039 (2022)]

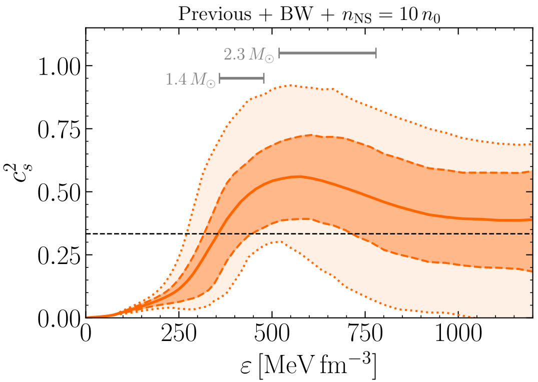
- **Change matching** to asymptotic pQCD from $n_{c,max}$ to $10\,n_0$

  → Much smaller c_s^2 at high energy densities
  [Gorda, Komoltsev, and Kurkela, arXiv:2204.11877 (2022)]
  [Komoltsev and Kurkela, Phys. Rev. Lett. 128 (2022)]

  → Few changes in mass-radius, properties of $2.3\,M_\odot$ neutron star change only slightly

- EoS beyond $n_{c,\mathrm{max}}$ no longer constrained by astrophysical data

  → Impact depends **unconstrained interpolation** to high densities
  [Essick, Legred, Chatziioannou, Han and Landry, arXiv:2305.07411 (2023)]



Perturbative QCD

- Connection of $(\mu_{\mathrm{NS}}, n_{\mathrm{NS}}, P_{\mathrm{NS}})(\theta)$ to $(\mu_{\mathrm{pQCD}}, n_{\mathrm{pQCD}}, P_{\mathrm{pQCD}})$

$$\int_{\mu_{\mathrm{NS}}}^{\mu_{\mathrm{pQCD}}} d\mu \; n(\mu) = P_{\mathrm{pQCD}} - P_{\mathrm{NS}} = \Delta P$$

- Causality and thermodynamic stability imply minimum and maximum values

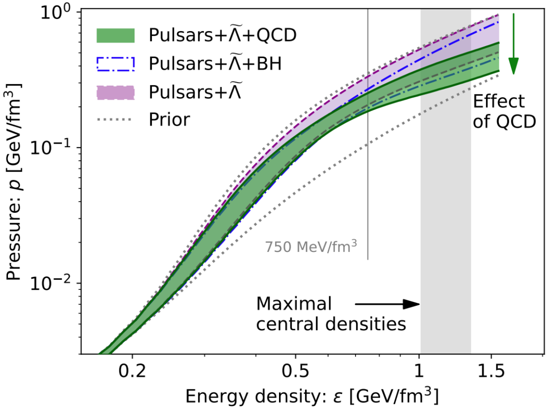
$$\Delta P_{\min} = \frac{\mu_{\mathrm{pQCD}}^2 - \mu_{\mathrm{NS}}^2}{2\mu_{\mathrm{NS}}} n_{\mathrm{NS}} \qquad \Delta P_{\max} = \frac{\mu_{\mathrm{pQCD}}^2 - \mu_{\mathrm{NS}}^2}{2\mu_{\mathrm{pQCD}}} n_{\mathrm{pQCD}}$$

- **Likelihood**

$$\Pr\left(\mathscr{D}_{\mathrm{pQCD}} \middle| \Delta P(\theta), \mathscr{M}\right) = \begin{cases} 1 & \text{if } \Delta P(\theta) \in [\Delta P_{\min}(\theta), \Delta P_{\max}(\theta)] \\ 0 & \text{else} \end{cases}$$

→ Take logarithmic average over renormalisation scale $X \in [1/2, 2]$

[Komoltsev and Kurkela, Phys. Rev. Lett. 128 (2022)]

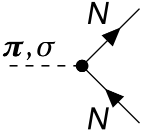


[Gorda, Komoltsev, and Kurkela, arXiv:2204.11877 (2022)]

Chiral nucleon-meson model

- Interactions of fermions via the **exchange of effective mesons**: Nambu-Goldstone boson $\boldsymbol{\pi}$ and heavy σ

$$\mathscr{L} = \bar{N}\gamma_\mu\partial_\mu N + \frac{1}{2}\left(\partial_\mu\sigma\partial_\mu\sigma + \partial_\mu\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi}\right) +$$



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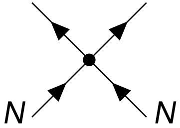
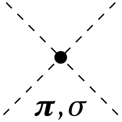


$$- \mathscr{U}(\boldsymbol{\pi}, \sigma)$$

→ Short distance dynamics modelled by massive vector fields [Floerchinger and Wetterich, Nucl. Phys. A 890–891 (2012)]

- Boson self-interactions and explicit symmetry breaking term

$$\mathscr{U}(\sigma, \boldsymbol{\pi}) =$$



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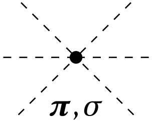


$$+ \cdots - m_\pi^2 f_\pi \left(\sigma - f_\pi\right)$$

- Expectation value $\langle\sigma\rangle$ dynamically creates nucleon mass

→ $\langle\sigma\rangle / \langle\sigma\rangle_{\text{vac}} = \langle\sigma\rangle / f_\pi$ **order parameter for chiral symmetry**

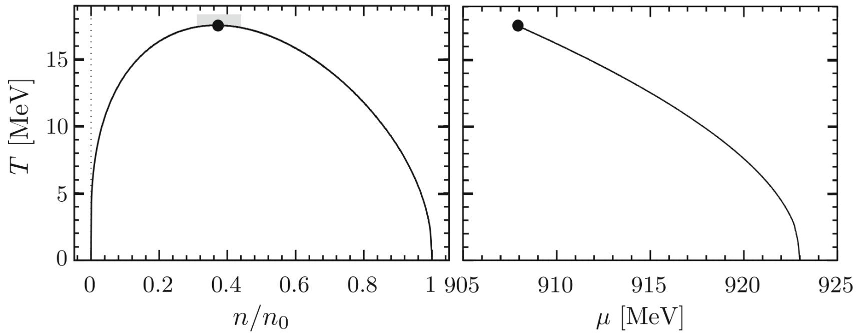
Mean-field approximation

- **Mean-field (MF)** approximation: replace chiral boson fields by expectation values $\langle\sigma\rangle$ and $\langle\boldsymbol{\pi}\rangle = 0$

  → Diverging fermionic vacuum contribution: $$\delta\Omega_{\text{vac}} = -4\int \frac{d^3p}{(2\pi)^3}\, E$$

- Compute with dimensional regularisation in **extended mean-field (EMF)** approach [Skokov et al., Phys. Rev. D 82 (2010)]

- Adjust model parameters to reproduce empirical nuclear properties, i.e., liquid-gas phase transition [Elliot et al., Phys. Rev. C 87 (2013)]



[LB, Kaiser and Weise, Eur. Phys. J. A 57 (2021)]

Functional Renormalization Group

- Additional fluctuations beyond vacuum contribution (chiral boson and nucleon loops)

  → Include using non-perturbative **Functional Renormalization Group (FRG)** approach

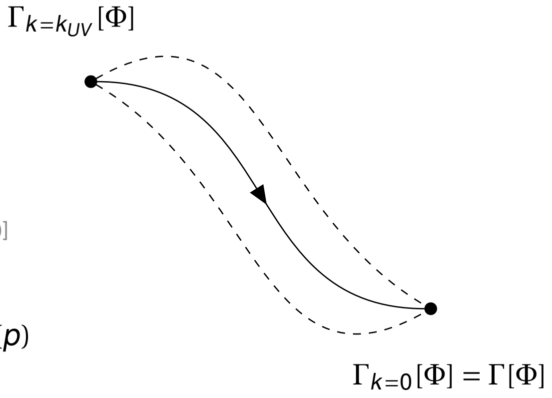
  [Drews and Weise, Prog. Part. Nucl. Phys. 93 (2017)]

- Initialize scale-dependent effective action $\Gamma_k[\Phi]$ at $k_{UV} \sim 4\pi f_\pi$

- Evolution $k \to 0$ governed by Wetterich's flow equation

$$k\frac{\partial \Gamma_k[\Phi]}{\partial k} = \frac{1}{2}\mathrm{Tr}\left[k\frac{\partial R_k}{\partial k}\cdot\left(\Gamma_k^{(2)}[\Phi]+R_k\right)^{-1}\right]$$

[Wetterich, Phys. Lett. B 301 (1993)]



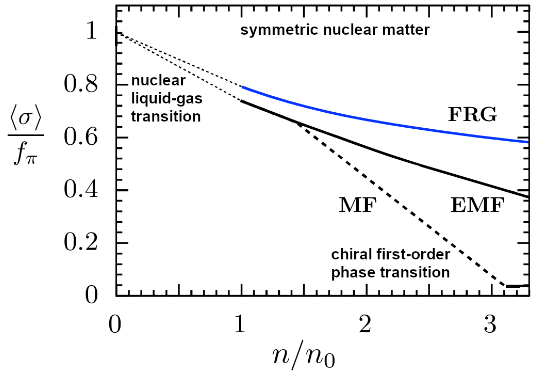
- $\Gamma_k[\Phi]$ contains all **fluctuations** with $p^2 \geq k^2$ through regulator $R_k(p)$

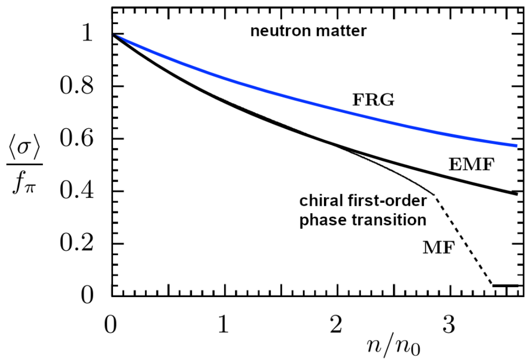
Phase structure

- *Mean-field:* unphysical **first-order order phase transition** to chirally restored phase
- *Extended mean-field:* vacuum contribution stabilizes order parameter
- *FRG:* further stabilization through additional fluctuations

$\rightarrow$ **Smooth crossover** at densities $n > 6\,n_0$ (with $n_0 = 0.16\,\mathrm{fm}^{-3}$)

$\rightarrow$ *No phase transition in neutron star matter?*





[LB, Kaiser and Weise, Eur. Phys. J. A 57 (2021)]

Likelihoods

- EoS supports masses between $M_{\rm min}$ and $M_{\rm max}(\theta)$
- Choose flat **mass prior** and $M_{\rm min} = 0.5\,M_\odot$

$$\Pr(M(\theta)) = \begin{cases} \frac{1}{M_{\rm max}(\theta) - M_{\rm min}} & \text{if } M \in [M_{\rm min}, M_{\rm max}(\theta)] \\ 0 & \text{else} \end{cases}$$

[Landry, Essick and Chatziioannou, Phys. Rev D 101 (2020)]

- When number of data increases incorporate mass population

→ Wrong population model causes a bias

[Mandel, Farr and Gair, Mon. Not. Roy. Astron. Soc. 486 (2019)]

- Assume **Shapiro** mass measurements Gaussian to compute likelihood

$$\Pr\big(M(\theta)\big|\mathscr{D}_{\text{Shapiro}}, \mathscr{M}\big) = \int_{M_{\rm min}}^{M_{\rm max}(\theta)} \mathrm{d}M\ \mathscr{N}\left(M, \langle M \rangle, \sigma_M\right) \Pr(M(\theta))$$

$$\approx \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{M_{\rm max}(\theta) - \langle M \rangle}{\sqrt{2}\sigma_M}\right)\right] \Pr(M(\theta))$$

Likelihoods

- Data available as samples, approximate underlying probability with Kernel Density Estimation (KDE)
- Solve TOV equations to obtain $R(M,\theta)$ and $\Lambda(M,\theta)$
- **NICER likelihood**:

$$\mathrm{Pr}\big((M,R)(\theta)\big|\mathscr{D}_{\mathrm{NICER}},\mathscr{M}\big) = \int_{M_{\min}}^{M_{\max}(\theta)} \mathrm{d}M\ \mathrm{KDE}\big(M,R(M,\theta)\big)\mathrm{Pr}(M(\theta))$$

- **GW likelihood**:

$$\mathrm{Pr}\big((M,\Lambda)(\theta)\big|\mathscr{D}_{\mathrm{GW}},\mathscr{M}\big) = \int \mathrm{d}M_1 \int \mathrm{d}M_2\ \mathrm{KDE}\big(M_1,M_2,\Lambda(M_1,\theta),\Lambda(M_2,\theta)\big)$$

- Do not assume neutron star-neutron star merger events

  → GW likelihood not weighted by mass prior and $\Lambda(M) = 0$ for black holes

- Do not assumed fixed chirp mass $M_{\mathrm{chirp}} = (M_1 M_2)^{3/5}(M_1 + M_2)^{-1/5}$

Conformal limit

- Derived from naive dimensional analysis and asymptotic limit

$$\mu \gg \Lambda_{\mathrm{QCD}} \qquad \Longrightarrow \qquad \begin{aligned} &P \propto \mu^{d+1} \\ &c_s^2 = \frac{\partial P}{\partial \varepsilon} \sim \frac{1}{d} \end{aligned}$$

[Hippert, Fraga and Noronha, Phys. Rev. D 104 (2021)]

- Expected to hold in all **conformal field theories** [Bedaque and Steiner, Phys. Rev. Lett. 114 (2015)]

- Recent Bayesian analyses found speeds of sound $c_s^2 > 1/3$ inside neutron stars
[Landry, Essick and Chatziioannou, Phys. Rev. D 101 (2020)] [Gorda, Komoltsev, and Kurkela, arXiv:2204.11877 (2022)]
[Altiparmak, Ecker, and Rezzolla, arXiv:2203.14974 (2022)] [Leonhardt *et al.*, Phys. Rev. Lett. 125 (2020)]

→ Also $c_s^2 > 1/3$ in recent $N_C = 2$ **lattice QCD** [Iida and Itou, PTEP 2022 (2022)]

- Hard Dense Loop resummation methods: conformal limit may be approached asymptotically from above
[Fujimoto and Fukushima, Phys. Rev. D 105 (2022)]

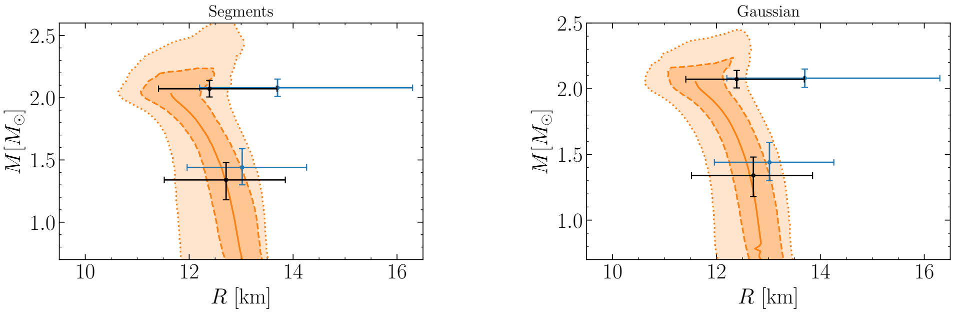
Parametrization dependence

- 'Old' segment-wise parametrisation: different ChEFT constraint, $c_s^2 = 1/3$ reached asymptotically from below
- Compared to skewed Gaussian plus logistic function to reach asymptotic limit $c_s^2 = 1/3$

$$c_s^2(x,\theta) = a_1 \exp\left[-\frac{1}{2}\frac{(x-a_2)^2}{a_3^2}\right]\left(1+\operatorname{erf}\left[\frac{a_6}{\sqrt{2}}\frac{x-a_2}{a_3}\right]\right) + \frac{1/3 - a_7}{1+\exp\left[-a_5(x-a_4)\right]} + a_7$$

[Greif *et al*,, MNRAS 485, 5363 (2019)] [Tews, Margueron and Reddy, EPJA 55, 97 (2019)]

- Very similar findings, results **robust against change** of parametrization and Prior



[LB, Weise and Kaiser, Phys. Rev. D 107 (2023)]