Quark cores in neutron stars

Aleksi Kurkela

July 2020, Theoretical Physics Colloquium

AK, Romatschke, Vuorinen PRD81 (2010)
AK, Fraga, Schaffner-Bielich, Vuorinen, Astrophys.J. 789 (2014)
AK, Fraga, Vuorinen, Astrophys.J.L 781 (2014)
AK, Vuorinen PRL 117 (2016)
Annala, Gorda, AK, Vuorinen PRL 120 (2018)
Gorda, AK, Vuorinen, Romatschke, Säppi, PRL 121 (2018)
Annala, Gorda, AK, Vuorinen, Nättilä, Nature Phys. (2020)

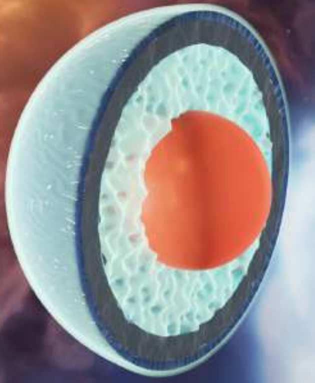
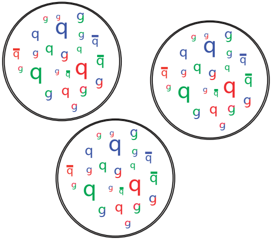


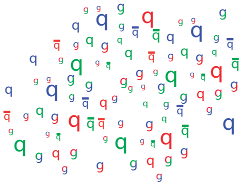
image credit: Jyrki Hokkanen CSC

Elementary particle matter:

- Matter in extreme conditions reveals its constituents



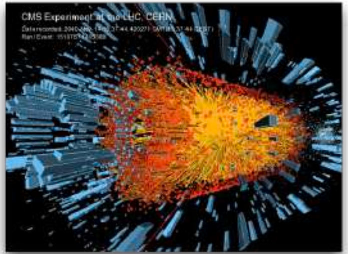
Nuclear matter



Quark matter

Elementary particle matter:

- Matter in extreme conditions reveals its constituents
- New era for matter in extreme conditions:

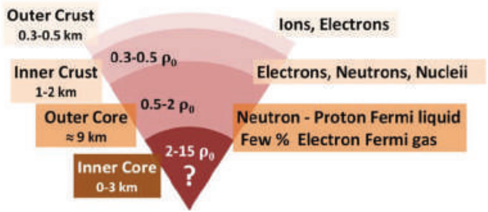


LHC Run 3-4, HL-LHC, FAIR, NICA, ...

LIGO+Virgo, NICER, eXTP, ...

Neutron stars

- Masses $\lesssim 2.0 M_{\odot}$
- Radii $\sim$ 10km
- $T \lesssim KeV \sim 10^7 K$
- $n \lesssim 15\rho_0 \quad (\rho_0 = 0.16\text{fm}^{-3})$



Can we understand these objects from 1st principles?

Structure

Competition:

- Gravity tries to pull the star into a black hole

$$\frac{dP}{dr} = -\frac{G\epsilon(r)M(r)}{r^2}\left[1+\frac{P(r)}{\epsilon(r)}\right]\left[1+\frac{4\pi r^3 P(r)}{M(r)}\right]\left[1-\frac{2GM(r)}{r}\right]^{-1}$$

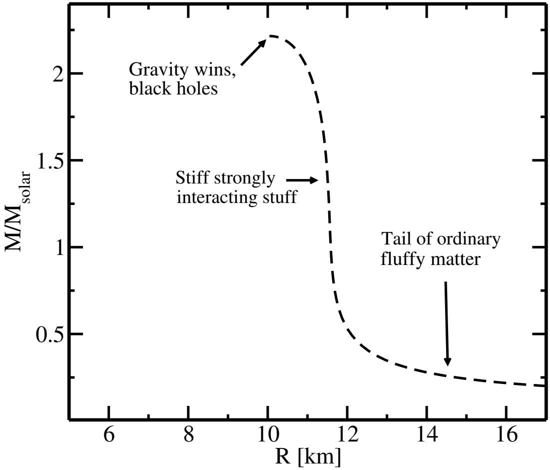
$$\frac{dM}{dr} = 4\pi r^2 \epsilon(r)$$

- Pressure of strong interactions resists the gravity

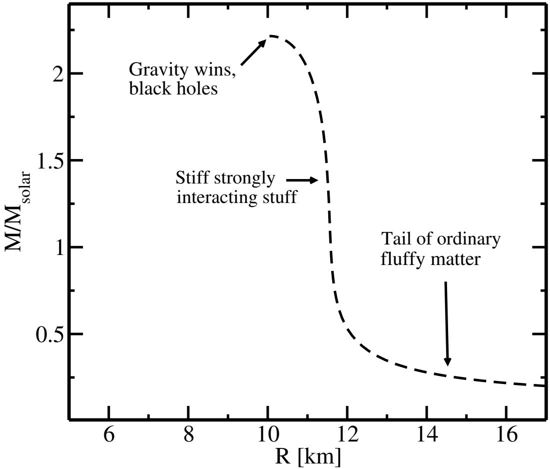
$$\epsilon(P)$$

or $P(\mu)$ ...

A map from micro to macro



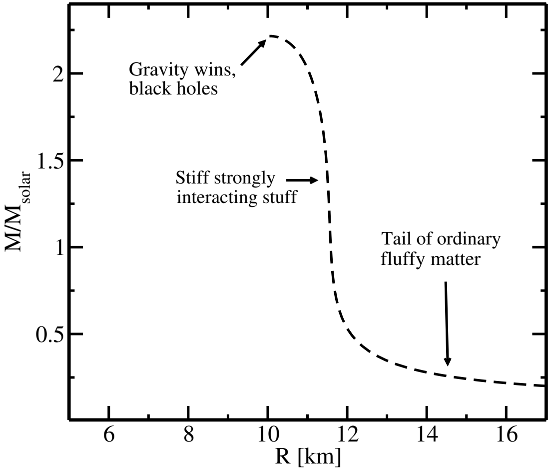
A map from micro to macro



Neutron stars are *femtoscopes*

$$10^{-15}\text{m} \rightarrow 10^{4}\text{m}$$

A map from micro to macro



Neutron stars are *femtoscopes*

$10^{-15}\mathrm{m} \to 10^{4}\mathrm{m}$

...but 10^{19}m away

The other femtoscope:

- Transition to hot quark matter around $\epsilon \sim 500\text{MeV}/\text{fm}^3$.

The other femtoscope:

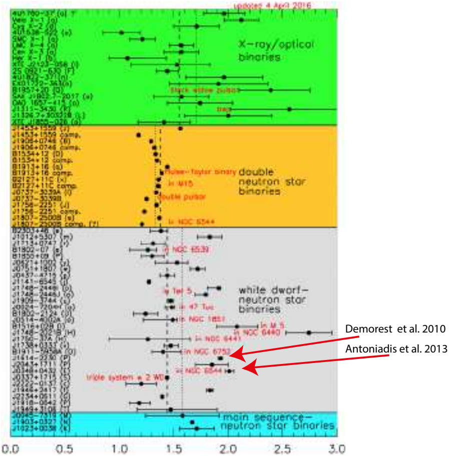
- Transition to hot quark matter around $\epsilon \sim 500\text{MeV/fm}^3$.
- The big question:

> Is there cold quark matter inside neutron stars?

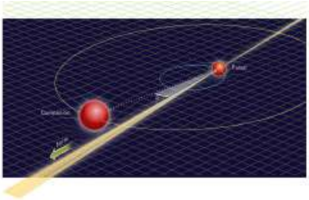
Outline

- Overview of neutron star observations
- What we know about the equation of state?
- Astrophysical constraints on the equation of state
- Is there quark matter in neutron stars?

Mass measurements



Lattimer Annu.Rev.Nucl.Part.Sci. 62 (2012)

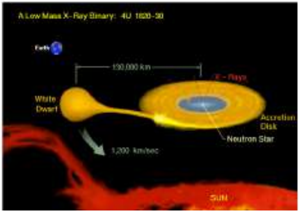


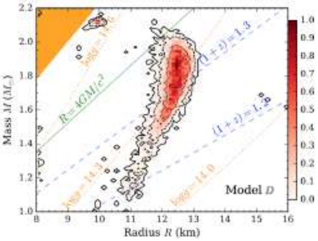
- Two accurate Shapiro-delay determinations of two-solar-mass stars

$$M_{\max} > \begin{cases} 1.908 \pm 0.016 & \text{J1614-2230} \\ 2.01 \pm 0.04 & \text{J0348+0432} \end{cases}$$

Demorest et al. Nature 467 (2010)
Antoniadis et al., Science 240 (2013)

Combined mass and radius measurements





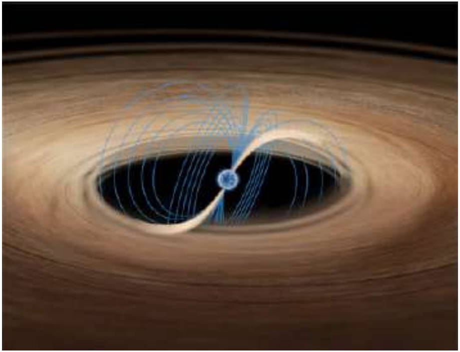
Nättilä et al.
Astron.Astrophys. 608 (2017)

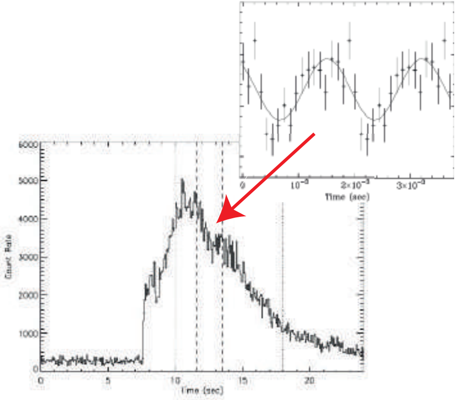
- NS accretes matter from a companion
- Ignition of the envelope generates thermonuclear explosion

$$A = \frac{F_\infty}{\sigma T_{bb}^4} = f_c^{-4} \left(\frac{R}{D}\right)^2 (1-2\beta)^{-1}$$

- Many challenges:
  PRE, distance, screening by accretion disk
  atmospheric composition
  interstellar absorption...

X-ray pulse profiling

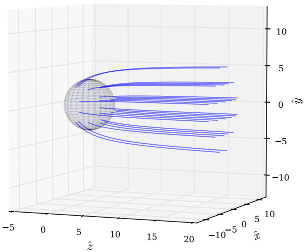




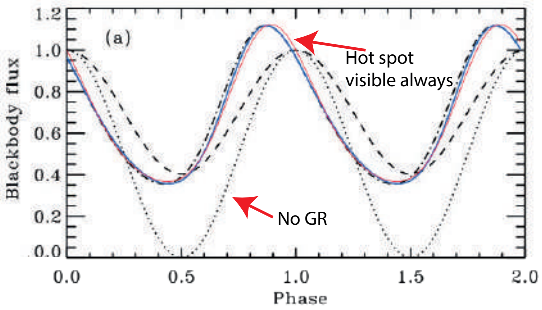
Rossi X-ray timing explorer
Strohmeyer et al. ApJ 486 (1997) 355

- Concentrated the accretion at magnetic poles
  $\rightarrow$ X-ray hot spot
- Rotation causes modulated X-ray emission

X-ray pulse profiling



Nättilä, Pihajoki A&A 615, A50 (2018)

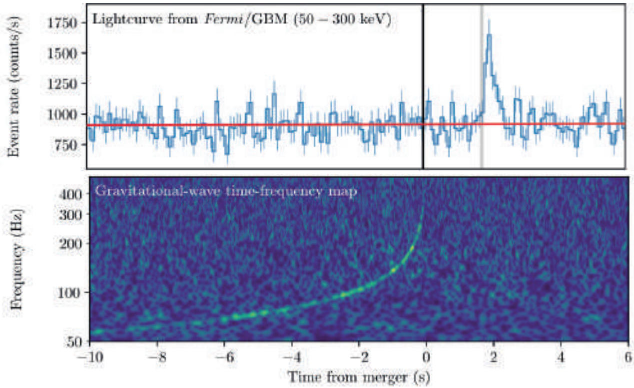


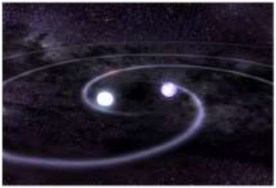
Poutanen & Beloborodov Mon.Not.Roy.Astron.Soc. 373 (2006)

- Light bends around neutron star, spot visible most of the time
- Pulse profile sensitive to compactness R/M.
- Missions:
  - NICER: First results, R/M to 6% precision
    Rotation powered, Riley et al. Astrophys.J.Lett. 887 (2019)
  - eXTP, STROBE-X ($\sim$ 2025): $\mathcal{O}(10)$ %-level radius measurements
    Sci.China Phys.Mech.Astron. 62 (2019)

Gravitational waves from neutron star mergers

Breakthrough in gravitational wave astronomy: GW170817





Gravitational waves: PRL. 119, 161101 (2017), γ-ray: APJ. 848 (2017)
Aslo: X-ray, UV, Optical, IR, Radio APJL, 848 (2017) L12

- New events since start of O3 (April 1st 2019)

GW190425, APJL 892 (2020) L3

How can mergers be used to teach us about QCD

1) Tidal deformability during inspiral

- A good measure of compactness

2) Associated electromagnetic signal

- Can tell about the nature of post-merger remnant

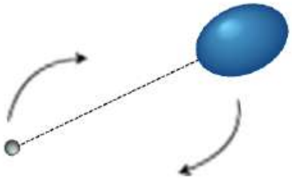
3) Post-merger hypermassive neutron star ringdown

- Sensitive to EoS at $T > 0$. Outside of current detector capability

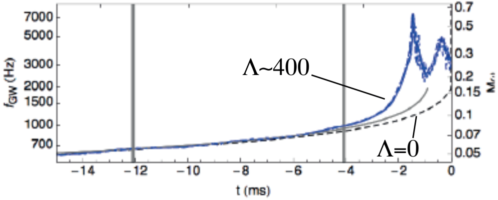
Gravitational waves from neutron star mergers

1) Tidal deformability during inspiral:

$$\Lambda = \frac{\text{(Quardupole moment) } Q_{ij}}{\text{(tidal field) } \mathcal{E}_{ij}}$$



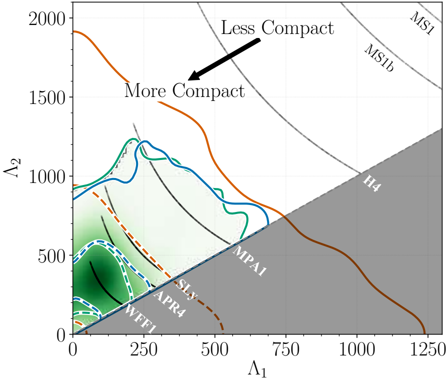
Linear response of the quadrupole moment to an external quadrupolar gravitational field



Read et al. PRD88 (2013) 044042

Gravitational waves from neutron star mergers

1) Tidal deformability during inspiral:



$$\text{LIGO/Virgo:} \quad 70 < \Lambda(1.4 M_\odot) < 580$$

Linearized framework, 90% credence, low spin prior
same EoS for both stars, LIGO+VIRGO PRL 121, (2018)

Outline

- Overview of neutron star observations
- What we know about the equation of state?
- Astrophysical constraints on the equation of state
- Is there quark matter in neutron stars?

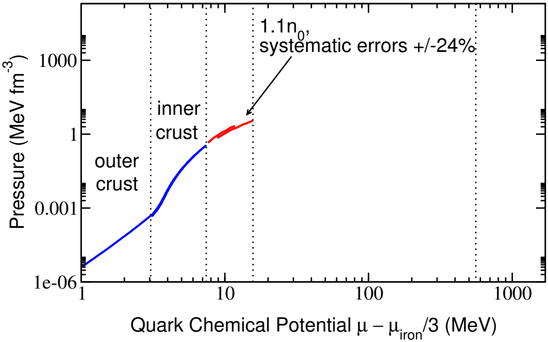
Equation of state:

$$P(\mu) = -\log \int \mathcal{D}\bar{\psi}\mathcal{D}\psi\mathcal{D}A_\mu e^{-\int d^4x \mathcal{L}_{QCD}}$$

$$\mathcal{L}_{QCD} = \frac{1}{4}F^a_{\mu\nu}F^a_{\mu\nu} + \bar{\psi}_i(\gamma_\mu D_\mu + m_i - \mu_i\gamma_0)\psi_i.$$

- At $T \neq 0$ and $\mu \lesssim T$: Lattice field theory
- At $\mu \gtrsim T$ simulations become unfeasible due to sign problem.
  - Low-energy effective theories at low densities
  - Perturbation theory at high densities $\alpha_s(\mu) \sim 1/\log(\mu^2)$

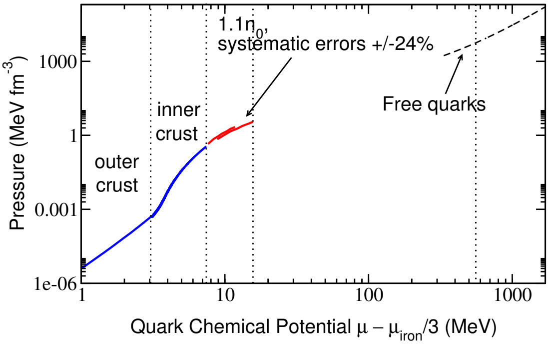
Equation of state:



- At low densities nuclear EFTs: Challenges at saturation density
  Relativistic Weinberg EFT, includes 3N, 4N, uncertainties from the low-energy constants dominate

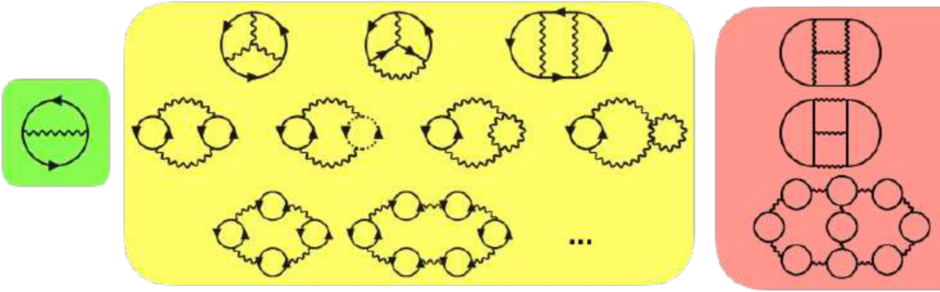
Tews et al. PRL. 110 (2013)
Hebeler et al. ApJ 773 (2013)

Equation of state



- At high densities: $\alpha_s(\mu_B) \approx 0$, free fermi gas of quarks

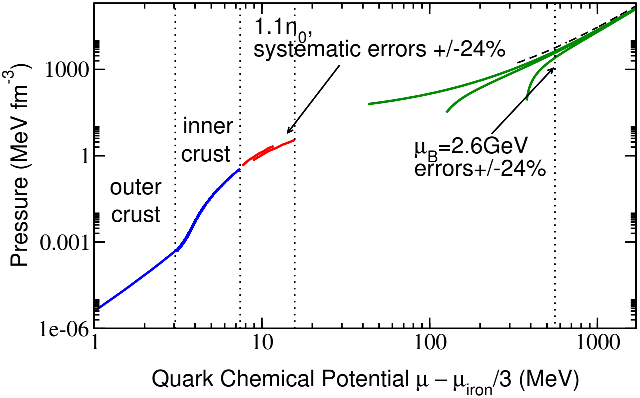
High-order QCD



$$P(\mu_B)/P_{\rm free} \sim 1 + \underbrace{c_1 g^2}_{NLO} + \underbrace{c_2 g^4 + c_2' g^4 \log g}_{NNLO} + \underbrace{c_3' g^6 \log^2 g + c_3'' g^6 \log g + \ldots}_{N^3LO}$$

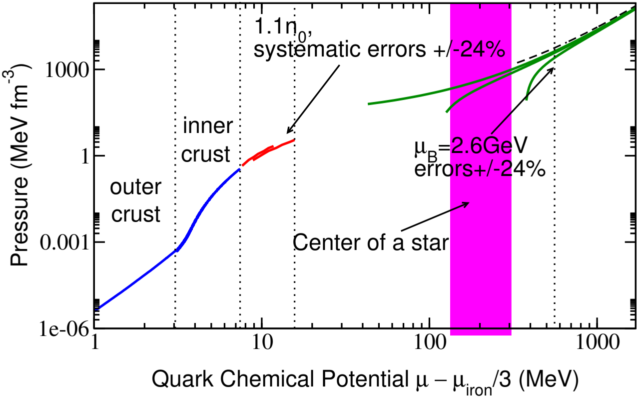
Full NNLO with full mass dependence: AK et al. PRD81 (2010)
Full T-dependence: AK, Vuorinen PRL 117 (2016)
Leading-log N^3LO: Gorda, AK, Vuorinen, Romatschke, Säppi, PRL 121 (2018)

State of the art in pQCD:



- Relative uncertainty $\pm 24\%$ at $\mu_B = 2.6\text{GeV}$, $n \approx 40 n_0$.

State of the art in pQCD:



- Relative uncertainty $\pm 24\%$ at $\mu_B = 2.6\text{GeV}$, $n \approx 40 n_0$.
- Cores lie in the poorly known no-man's-land

Phenomenological strategy: Interpolation

Strategy:

- Interpolate where EoS not reliably known.
- Find full set of reasonable* interpolations
- Constrain the set to be consistent with observations

- Thermod. consistency: $P(\mu_B)$ monotonic, match with nucleonic and pQCD EoS
- Subluminal: $c_s^2 < 1$ everywhere
- Smoothness: $P(\mu_B)$ and $\partial_{\mu_B} P = n(\mu_B)$ (mostly) continuous

allow also phase transitions

Phenomenological strategy: Interpolation

For example:

- Piecewise polytropes:

$$P_i(n) = \kappa_i n^{\gamma_i}, \text{ for } \mu_i < \mu_B < \mu_{i+1}$$

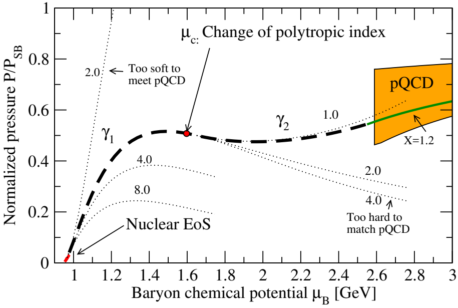
γ	EoS
∞	incompressible matter
~ 2.5	nuclear matter at n_0
2	asymptotically $c_s(\mu_B) = 1$
5/3	Non-relativistic degenerate fermi gas
4/3	Ultrarelativistic fermi gas
1	Ideal gas
0	1st order phase transition

Phenomenological strategy: Interpolation

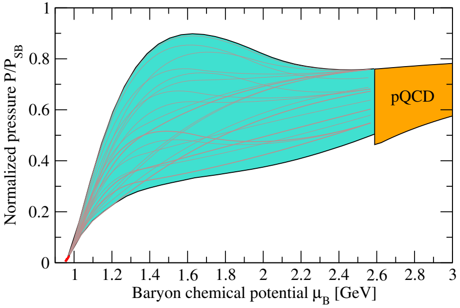
For example:

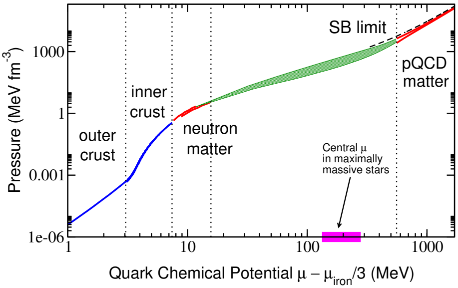
- Piecewise polytropes:

$$P_i(n) \;=\; \kappa_i n^{\gamma_i}, \text{ for } \mu_i < \mu_B < \mu_{i+1}$$



Complete set of interpolated EoSs

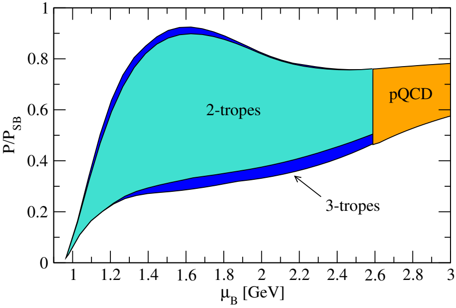




AK et al. Astrophys.J. 789 (2014) 127

- Complete set of EoS, quantifying our terrestrial understanding

Complete set of interpolated EoSs



AK et al. Astrophys.J. 789 (2014) 127

- Complete set of EoS, quantifying our terrestrial understanding
- Insensitivity enlargement of basis
- In the following: 4-tropes and different basis functions

ask for details

Outline

- Overview of neutron star observations
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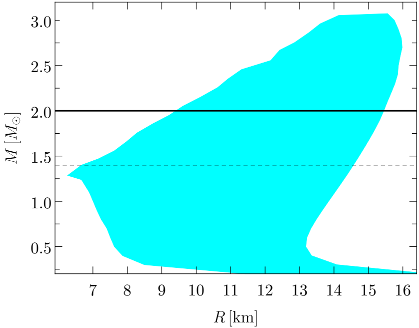
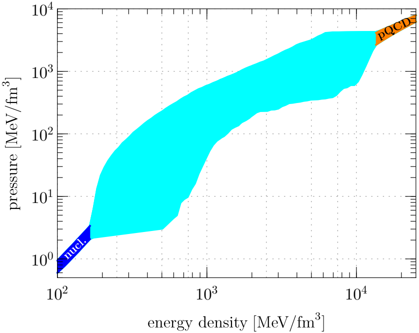
Constraining neutron star properties using QCD

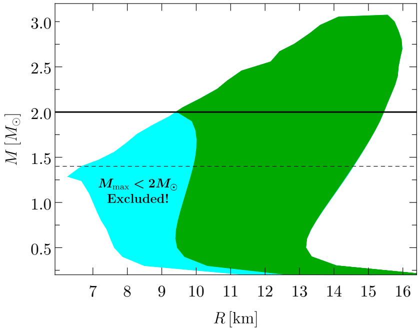


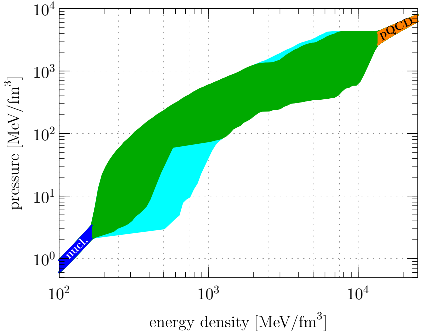


Annala et al. PRL 120 (2018)
Also: Most et. al PRL 120 (2018)

- 200’000 EoS with 4-tropes, no constraints on phase transitions, no constraints on parameter values

Constraining QCD using neutron star properties

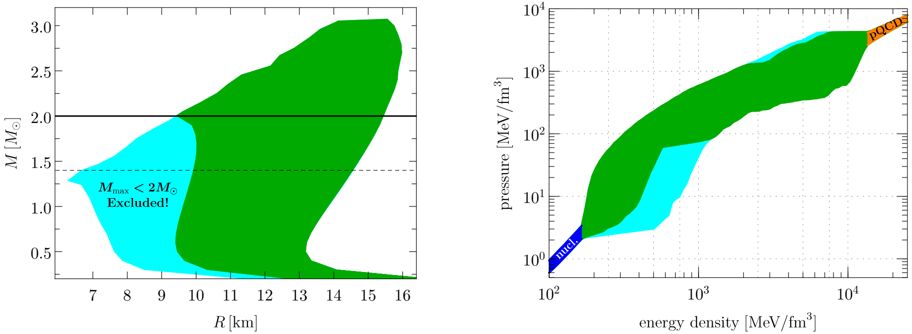




Annala et al. PRL 120 (2018)

- Requiring $2M_\odot$ implies that matter must be stiff enough

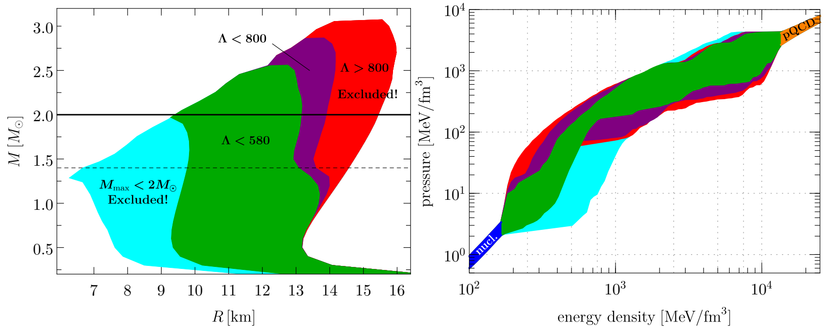
Constraining QCD using neutron star properties



Annala et al. PRL 120 (2018)

- Requiring $2M_\odot$ implies that matter must be stiff enough
- Lower limit for radius: $R(1.4M_\odot) > 10\text{km}$

Constraining QCD using neutron star properties



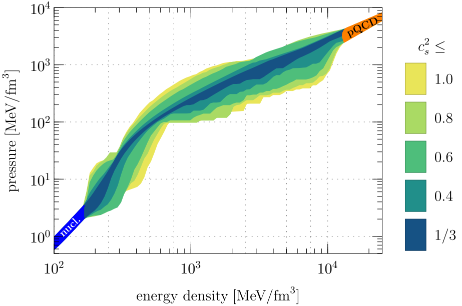
Annala et al. PRL 120 (2018)+LIGO update

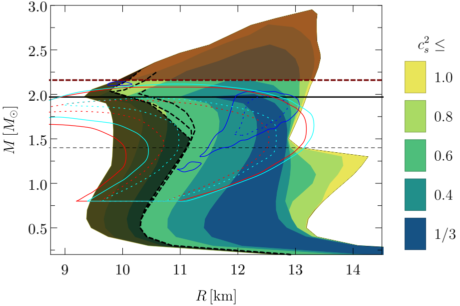
- Tidal deformability excludes too stiff equations of state
- Determination of radius from gravitational-wave measurements

$$\Lambda(1.4M_\odot) < 580 \quad \Rightarrow \quad 10\mathrm{km} < R(1.4M_\odot) < 13\mathrm{km}$$

LIGO+VIRGO, PRL 121 (2018): $10.5\mathrm{km} < R(1.4M_\odot) < 13.3\mathrm{km}$
Most et al. PRL 120 (2018): $8.5\mathrm{km} < R(1.4M_\odot) < 13.45\mathrm{km}$

Extremal EoSs are extreme





Annala, Gorda, AK, Nättilä, Vuorinen, Nat. Phys. (2020)
Measurements: Nättilä et al. Astron.Astrophys. 608 (2017)
Nättilä et al. Astron.Astrophys. A25 (2016)

- Boundaries are set by very extreme EoSs
- For pQCD $c_s^2 \lesssim 1/3$. Almost no known first principles calculations with $c_s^2 > 1/3$ Bedaque, Steiner, PRL 114 (2015)
- Current best radius measurements seem to favour low c_s^2

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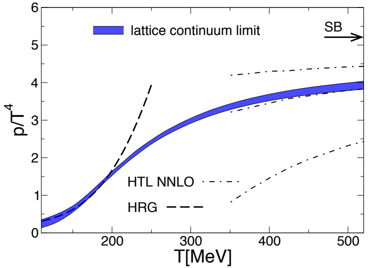
Quark matter in nuclear collisions



Borsanyi et al PLB 730 (2014)

- No true phase transition, but the the asymptotics understood in terms of hadronic and partonic calculations
- For $\epsilon \gtrsim 500$ MeV/fm^3, matter resembles nearly conformal quark matter:

$$\gamma \equiv \frac{d\log p}{d\log\epsilon} \sim 1, \qquad p/T^4 \sim \#_{d.o.f}, \qquad c_s^2 \lesssim 1/3$$

Also many others $\langle\bar\psi\psi\rangle$, P_L, correlators

Quark matter in nuclear collisions

- Measurement of energy flow gives estimate of density reached in heavy-ion collisions

$$\epsilon \sim \frac{dE_\perp}{d\eta}/(\text{volume of the collision system})$$

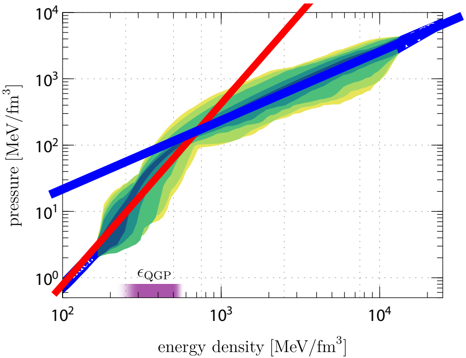
- Energy densities in the region of where EoS is roughly confromal

$$\epsilon \gg 500\text{MeV}/\text{fm}^3$$

Community asks: how we know that the matter is *thermalized*

How to repeat this logic with neutron stars?

Quark Matter cores in Neutron Stars?



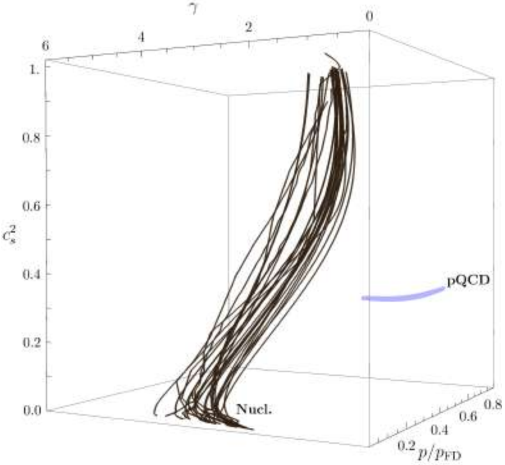
Annala, Gorda, AK, Nättilä, Vuorinen, Nat. Phys. (2020)

- Rapid softening hints to a phase transition to quark matter

$\epsilon \sim 500 - 750 \text{MeV/fm}^3$,

$$\gamma_{\rm nucl} \gtrsim 2.5 \quad vs. \quad \gamma_{\rm pQCD} \sim 1$$

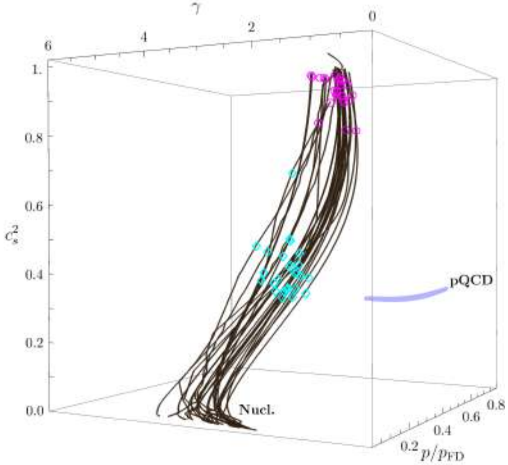
Quark Matter cores in Neutron Stars?



Annala, Gorda, AK, Nättilä, Vuorinen, Nat. Phys. (2020)

- Speed of sound c_s^2
- Polytropic index $\gamma = \frac{d\log p}{d\log \epsilon}$
- number of effective d.o.f: P/P_{free}

Quark Matter cores in Neutron Stars?



Annala, Gorda, AK, Nättilä, Vuorinen, Nat. Phys. (2020)

- Speed of sound c_s^2
- Polytropic index $\gamma = \frac{d\log p}{d\log\epsilon}$
- number of effective d.o.f: P/P_{free}

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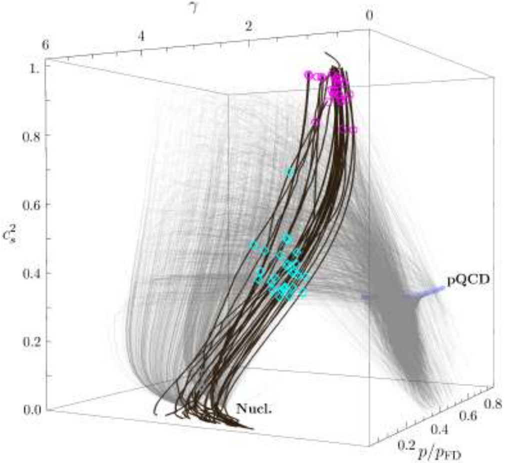

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- Interpolated EoSs consistent with hadronic models at low densities by differ at high

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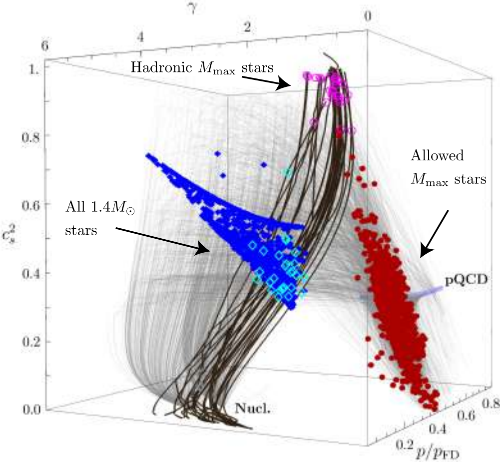
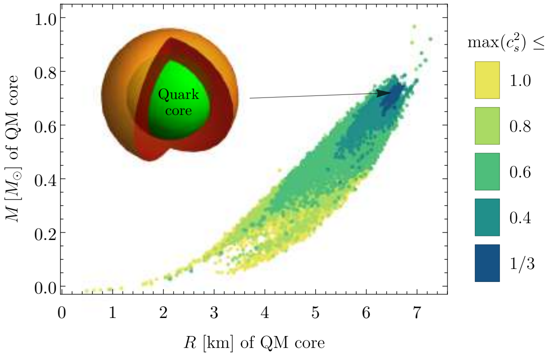


Annala, Gorda, AK, Nättilä, Vuorinen, Nat. Phys. (2020)

- $1.4M_\odot$ stars consistent with hadronic models
- $M_{\rm max}$ stars inconsistent with hadronic models

Link for 3D video: https://www.nature.com/articles/s41567-020-0914-9

Quark core in maximally massive NSs

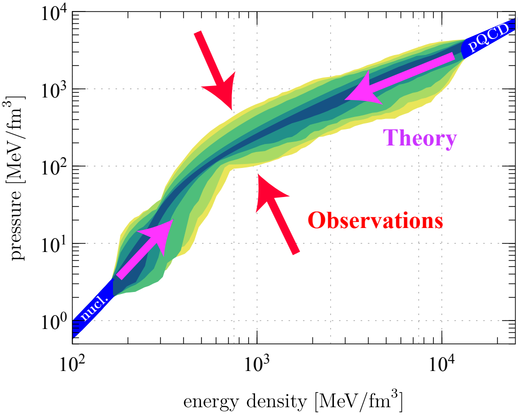


Annala, Gorda, AK, Nättilä, Vuorinen, Nat. Phys. (2020)
Amount of matter with $\gamma = \frac{\log p}{\log \epsilon} < 1.75$

Sizeable fraction of the star (25%) may be in the quark phase.

- If $c_s^2 < 0.4$, at least $0.4M_\odot$ of quark matter.
- If no quark matter, collapse to black hole triggered by the phase transition

Future:



- Combined effort of nuclear physics, QCD, and astrophysical observations will allow to determine the phase of the neutron star cores

Conclusions:

- The competition between gravity and pressure of strong interactions makes neutron stars unique *femtoscopes*

- The astronomical observations are advancing rapidly:
  - The observation of gravitational waves from binary neutron star mergers has started the era of multimessenger astronomy.

  - Current and future missions to measure radii of neutron stars will put stringent conditions on the propreties of neutron star matter.

- Theoretical computations advancing rapidly
  - N^3LO computation underway at high densities, results for $g^6 \log^2 g$
    Gorda, AK, Vuorinen, Romatschke, Säppi, PRL 121 (2018)

- Combining astronomical and theoretical inputs allows to empirically determine properties of strongly interacting matter in extreme conditions where no 1st principles calculations are available

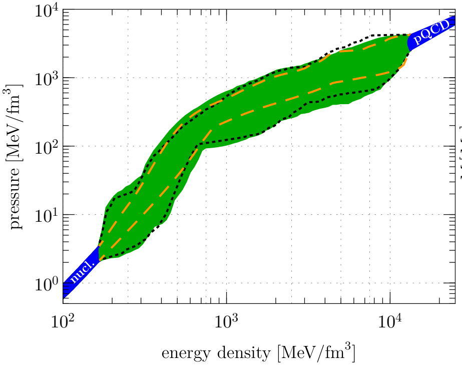
Conclusions:

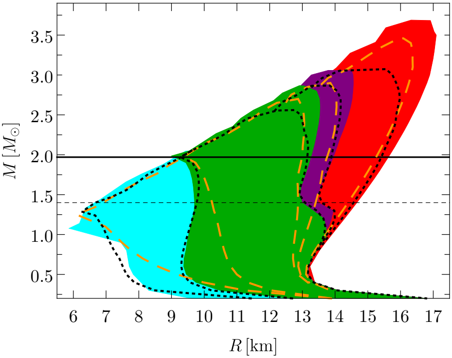
- Hints pointing to quark matter in maximally massive stars. No definite answers yet but quark cores should be treated as a standard scenario

- So far all the different constraints have been in agreement with each other. Possible future inconsistencies will be a sign of physics beyond QCD + GR: dark matter, modified gravity, ...

Extra slides

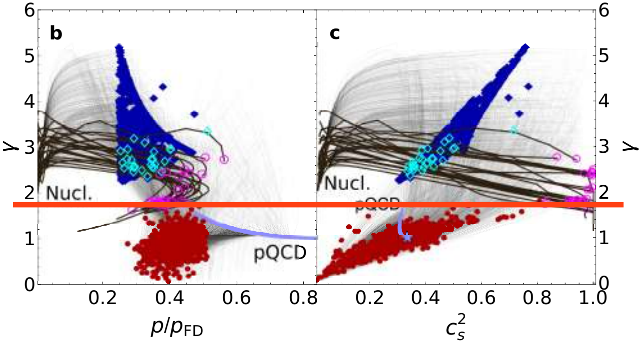
Robustness of the interpolation





- Three different interpolations agree well:
  - piecewise polytropic — up to 4 independent segments
  - Chebyshev polynomial polytropic index, $\gamma(p) = \exp(\sum_k T_k(p)\tilde{\gamma}_k)$ — up to degree 5
  - piecewise linear $c_s^2(p)$ — up to 5 independent segments

Annala, Gorda, AK, Nättilä, Vuorinen, Nat. Phys. (2020)



Approximative criterion for QM used for estimation of core size