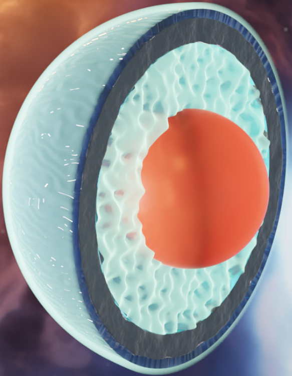
How can one tell if there is quark matter in neutron stars?

Aleksi Kurkela

November 2020

Hot problems in strong interactions

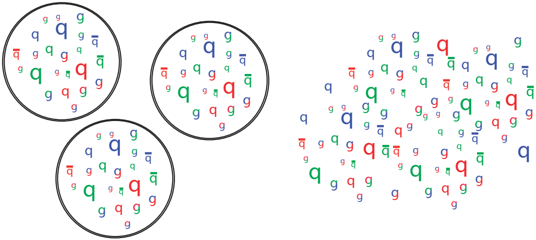
AK, Romatschke, Vuorinen PRD81 (2010)
AK, Fraga, Schaffner-Bielich, Vuorinen, Astrophys.J. 789 (2014)
AK, Fraga, Vuorinen, Astrophys.J.L 781 (2014)
AK, Vuorinen PRL 117 (2016)
Annala, Gorda, AK, Vuorinen PRL 120 (2018)
Gorda, AK, Vuorinen, Romatschke, Säppi, PRL 121 (2018)
Annala, Gorda, AK, Vuorinen,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



Universitetet i Stavanger

Elementary particle matter:

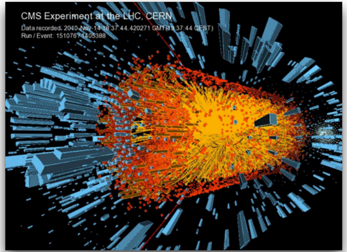
- Matter in extreme conditions reveals its constituents



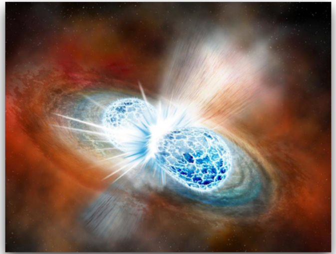
Nuclear matter   Quark matter

Elementary particle matter:

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

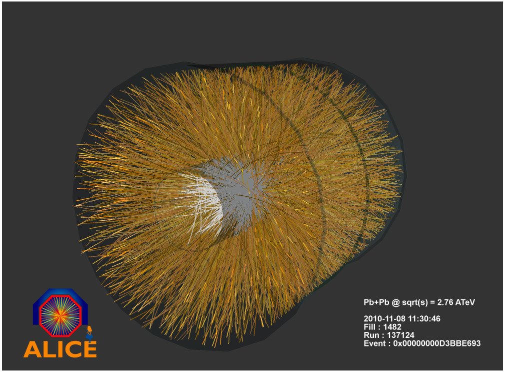


LHC Run 3-4, HL-LHC, FAIR, NICA, ...



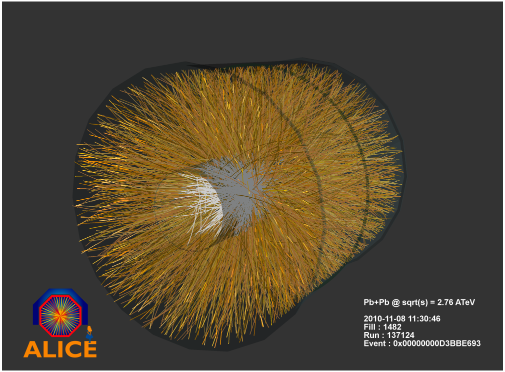
LIGO+Virgo, NICER, eXTP, ...

Hot quark matter in Nuclear Collisions:



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

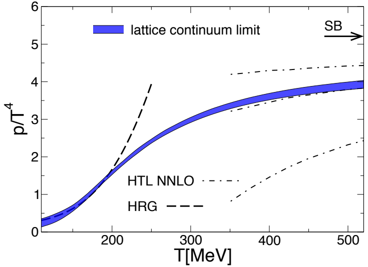
Hot quark matter in Nuclear Collisions:



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

> Is there cold quark matter inside neutron stars?

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

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

Burden of proof: how do we know that the matter is *thermalized*
hydrodynamics, thermal EM radiation, jet quenching,...
AK, Zhu, PRL 115 (2015), ...

How to repeat this logic with neutron stars?

Challenge:

- No lattice simulations available due to the sign problem
  - Reliable information only at low and high density limits

- No direct measurement of energy density inside the star
  - Access only to global properties of stars, masses, radii, deformabilities, etc.

Structure

Competition:

- Gravity tries to pull the star into a black hole

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

- Pressure of strong interactions resists the gravity

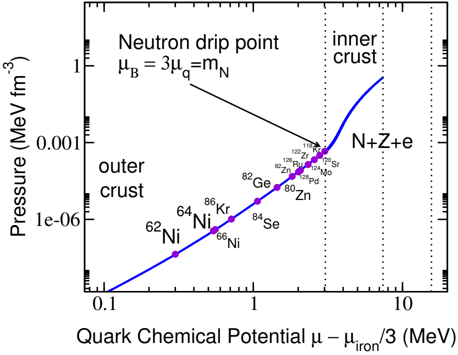
$$\epsilon(P)$$

- Astrophysical observations of macroscopic properties of neutron stars can be used to
  - constrain the EoS where we don't know in from 1st principles
  - indirectly inform about the central densities

Outline

- What we know about the equation of state?
- What can we say about the energy densities of the cores of neutron stars?
- What does that imply about the state of matter inside neutron stars?

Equation of state:



Outer crust:

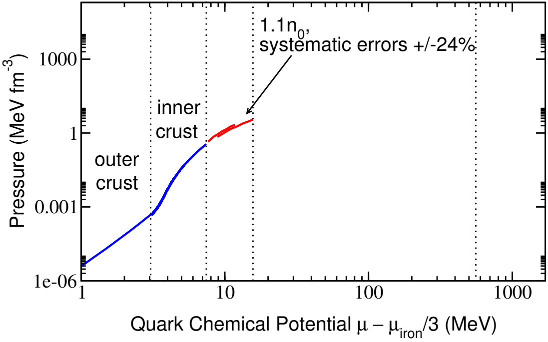
- Lattice of nuclei in electron sea
- As μ increases, more neutron rich elements become favourable

Inner crust:

- Neutron gas + Z + e
- NN interactions become important around $n \sim n_0 \approx 0.16/fm^3$

Negele & Vautherin Nucl.Phys. A207 (1973) 298-320; Baym et al. Nucl.Phys. A207 (1973) 298-320;

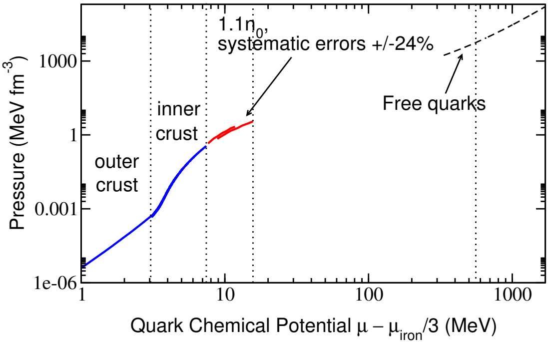
Equation of state:



- 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

Higher order corrections:

$$P(\mu_B) \sim \int \frac{d^3p}{(2\pi)^4} E(p)\theta(\mu_q - E(p))$$

NLO:

- Interactions cause corrections to disp. rel.:

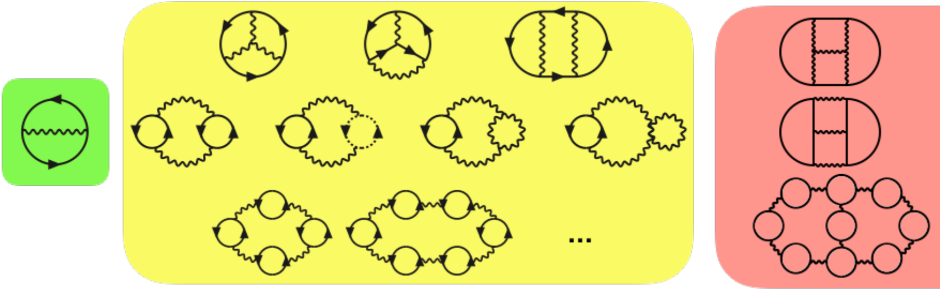
$$E^2(p) \sim p^2 + g^2\mu^2$$
$$P(\mu_B) \sim P_{\text{free}}(1 + c_1 g^2)$$

NNLO:

- Corrections to $E^2(p) \sim p^2 + g^2\mu^2 + g^4\mu^2$.
- $p \sim g\mu$ contribute at $\int d^3p p \sim g^4\mu^4$.
  - Order-1 mod. to disp. rel. $\Rightarrow$ non-perturbative
  - Integral over scales gives a log:

$$P(\mu_B) \sim P_{\text{free}} \left(1 + c_1 g^2 + c_2 g^4 + c_2' g^4 \log\left[\frac{g\mu}{\mu}\right] + \dots\right)$$

High-order QCD



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

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

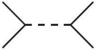
Important technical developments:

- *Cutting-rule* technology to exploit precision-QCD literature developed for Higgs physics AK et al. PRD81 (2010), Ghisoiu et al. NPB915 (2017)

$$\rightarrow$$

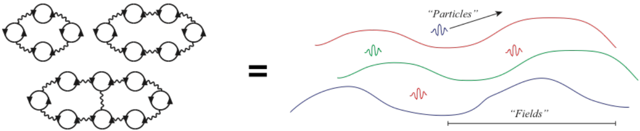
$$- 2 \int \frac{d^3\vec{p}}{(2\pi)^3} \frac{\theta(\mu - E(\vec{p}))}{2E(\vec{p})}$$

$$+ \int \frac{d^3\vec{p}}{(2\pi)^3} \frac{\theta(\mu - E(\vec{p}))}{2E(\vec{p})} \int \frac{d^3\vec{q}}{(2\pi)^3} \frac{\theta(\mu - E(\vec{q}))}{2E(\vec{q})}$$

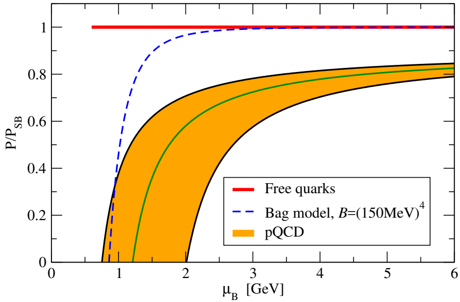


- Effective field theory methods for resummations: classical non-abelian Vlasov equations

Hard-Loop-Theory
AK, Vuorinen PRL 117 (2016)
Gorda, AK, Vuorinen, Romatschke, Säppi, PRL 121 (2018)



Reliability of N^2LO pQCD:

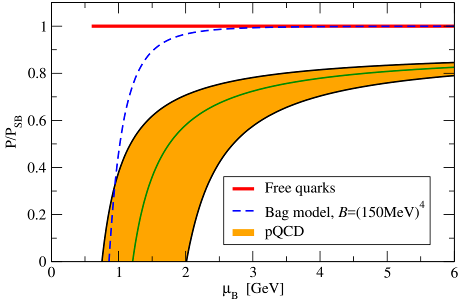


Full NNLO with $m_s \neq 0$: AK et al. Phys.Rev. D81 (2010)
$g^6 \log^2 g$: Gorda, AK, Vuorinen, Romatschke, Säppi, PRL 121 (2018)

$$P(\mu_B)/P_{\text{free}} \sim 1 + c_1 g^2 + c_2 g^4 + c_2' g^4 \log g + c_3' g^6 \log^2 g$$

Interactions are important!

Reliability on N^2LO pQCD:



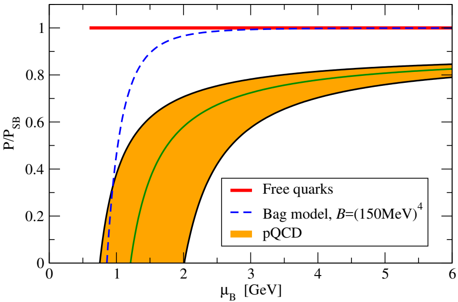
Coefficients depend on renormalization scale $\bar{\Lambda}$

$$P(\mu_B)/P_{\text{free}} \sim 1 + c_1 g^2[\bar{\Lambda}] + c_2[\bar{\Lambda}] g^4[\bar{\Lambda}] + c_2'[\bar{\Lambda}] g^4[\bar{\Lambda}] \log[g] + c_3' g^6 \log^2 g$$

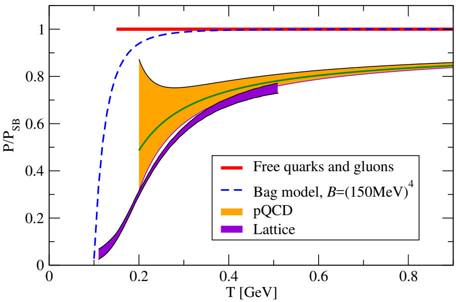
- Uncertainties through scale variation $\bar{\Lambda} = X\mu_q$ with $X = \{1, 2, 4\}$

Reliability of the errorbars

Dense matter:

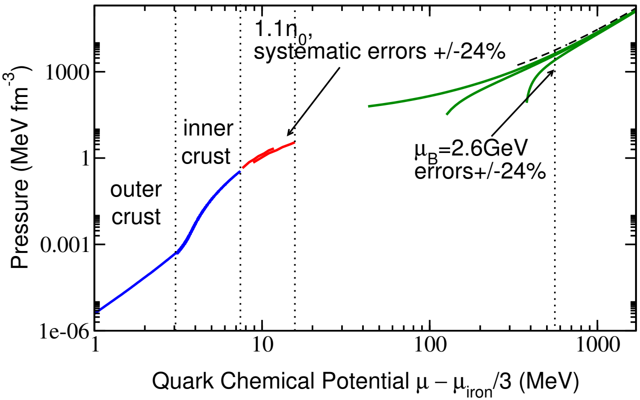


Hot matter:



Finite-T pQCD: Laine & Schröder Phys. Rev. D, 73, 085009
Connection between finite T and μ: AK, Vuorinen PRL 117 (2016)
Lattice: Borsanyi et al. Phys. Lett. B 370 (2014) 99-104

State of the art in pQCD:



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

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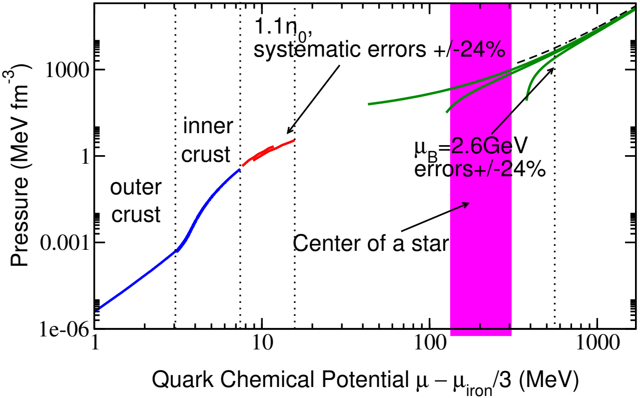

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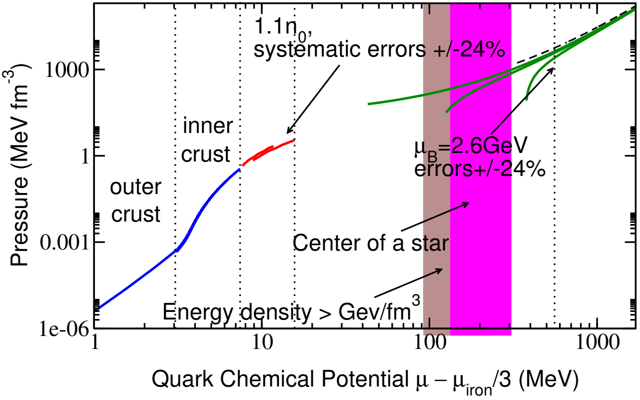
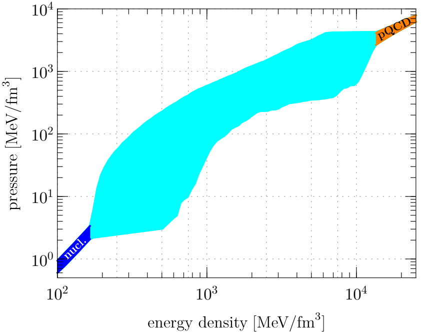


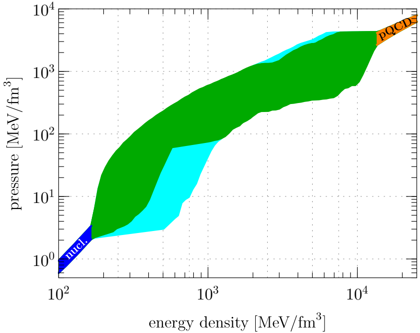
- Relative uncertainty $\pm 24\%$ at $\mu_B = 2.6\text{GeV}$, $n \approx 40 n_0$.
- Cores lie in the poorly known no-man's-land
- Energy densities comparable to QGP

Interpolation in the intermediate densities:



- In order to model the neutron stars, the EoS can be interpolated between the two limits
  See talk of Aleksi Vuorinen tomorrow
    - Interpolations that are inconsistent observations can be excluded

Interpolation in the intermediate densities:



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  - Existence of $2M_\odot$ stars

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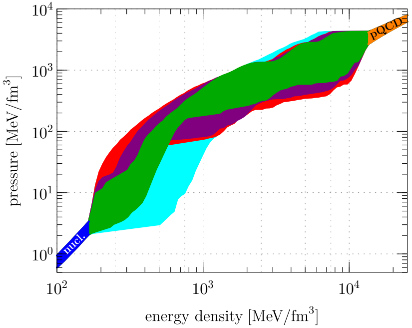

- In order to model the neutron stars, the EoS can be interpolated between the two limits See talk of Aleksi Vuorinen tomorrow
  - Interpolations that are inconsistent observations can be excluded
  - Existence of $2M_{\odot}$ stars
  - Non-detection of tidal deformation by LIGO/Virgo GW170817

Outline

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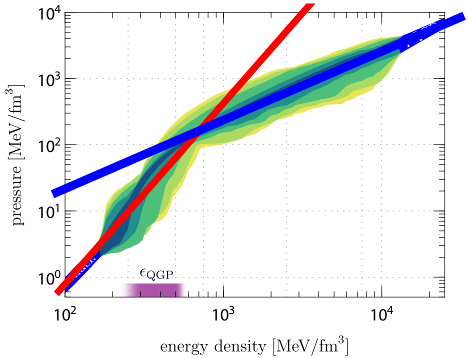
Quark Matter cores in Neutron Stars?



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

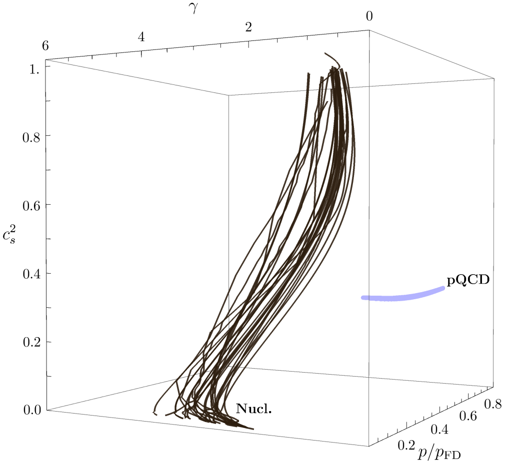
- Rapid softening hints to a phase transition to quark matter

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

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

$\gamma = \frac{d \log p}{d \log \epsilon}$

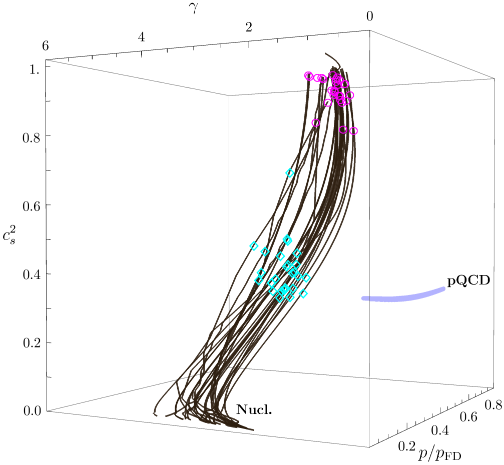
Quark Matter cores in Neutron Stars?



Annala, Gorda, AK, Nättilä, Vuorinen, Nature 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?



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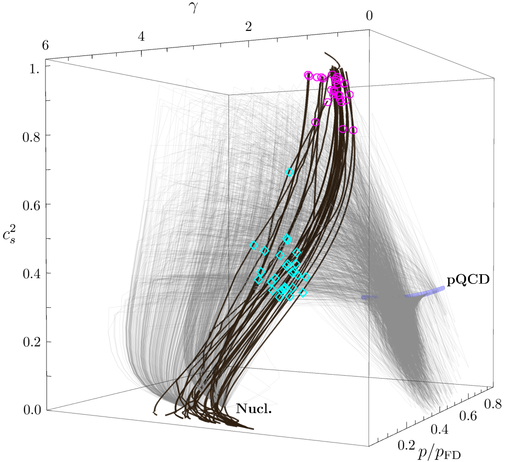
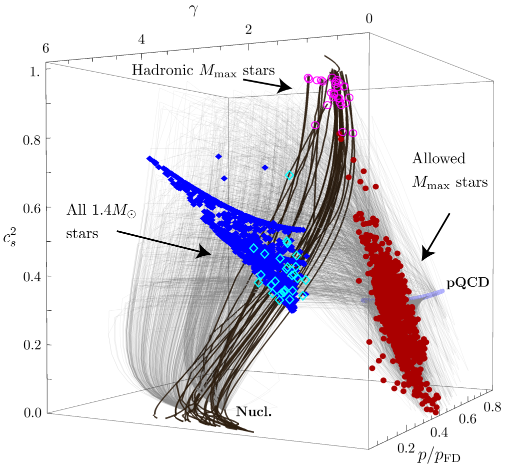


Annala, Gorda, AK, Nättilä, Vuorinen, Nature Phys. (2020)

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

Quark Matter cores in Neutron Stars?

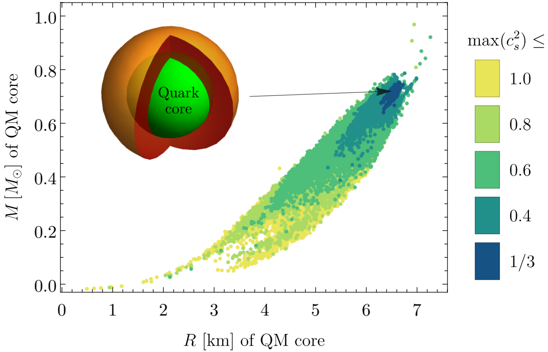


Annala, Gorda, AK, Nättilä, Vuorinen, Nature Phys. (2020)

- $1.4M_\odot$ 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

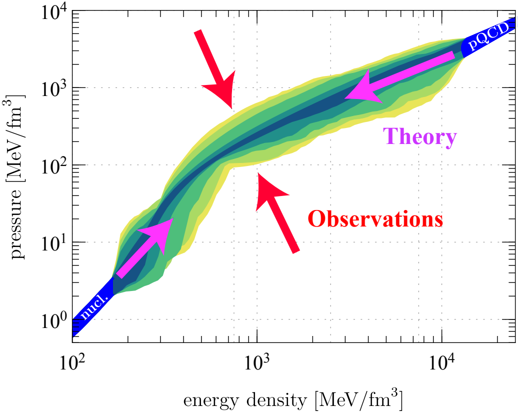


Annala, Gorda, AK, Nättilä, Vuorinen, Nat. Phys. (2020)
Amount of matter with $\gamma = \frac{\log p}{\log \epsilon} < 1.75$

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

- If $c_s^2 < 0.4$, at least $0.4 M_\odot$ 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

Key statements:

- The existence of quark matter in heavy-ion collisions is established not by of a smoking gun signal but by establishing that at energy densities reached, matter is better described by nearly conformal partonic matter than hadronic matter.

- It may be that in the future such a smoking gun may be found for neutron stars (strong 1st order transition?)

- It is also possible that no such smoking gun exists. Then existence/non-existence of quark matter can still be established based on precise information of material properties in the core.
  $\Rightarrow$ QCD theory in key role!

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