# Quark cores in neutron stars

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AK, Fraga, Schaffner-Bielich, Vuorinen, Astrophys.J. 789 (2014)
Gorda, AK, Vuorinen, Romatschke, Säppi, PRL 121 (2018)
Annala, Gorda, AK, Vuorinen, Nättilä, Nature Phys. (2020)

Universitetet
i Stavanger

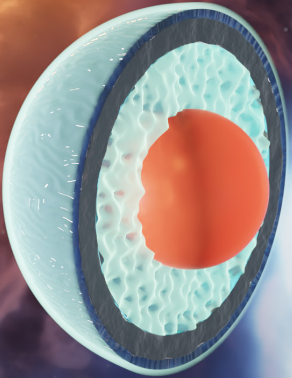
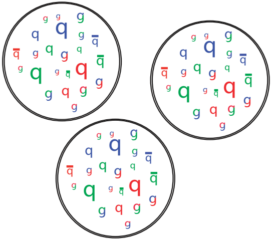


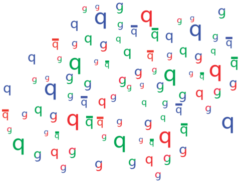
image credit: Jyrki Hokkanen CSC

# Elementary particle matter:

- Matter in extreme conditions reveals its constituents



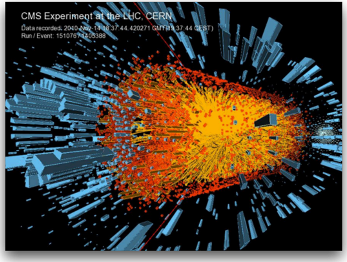
Nuclear matter



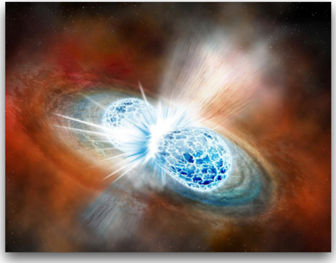
Quark matter

# Elementary particle matter:

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



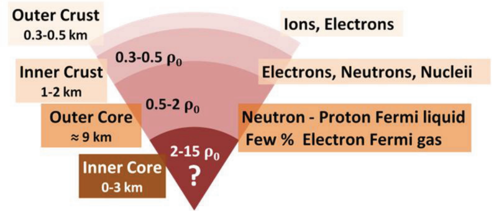
LHC Run 3-4, HL-LHC, FAIR, NICA, . . .



LIGO+Virgo, NICER, eXTP, . . .

# Neutron stars

- Masses $\lesssim 2.0 M_\odot$
- Radii $\sim$ 10km
- $n \lesssim 15\rho_0 \quad (\rho_0 = 0.16\text{fm}^{-3})$
- $\epsilon \lesssim 2\text{GeV}/\text{fm}^3$



- Competition between **gravity** and **pressure of strong interactions** determines the macroscopic features of neutron stars
  mass-radius relationship, maximal stable masses , tidal deformability, etc...
- Neutron stars are nature's own *femtoscopes*

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

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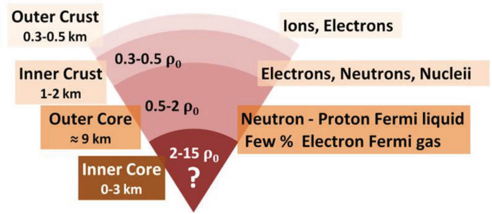
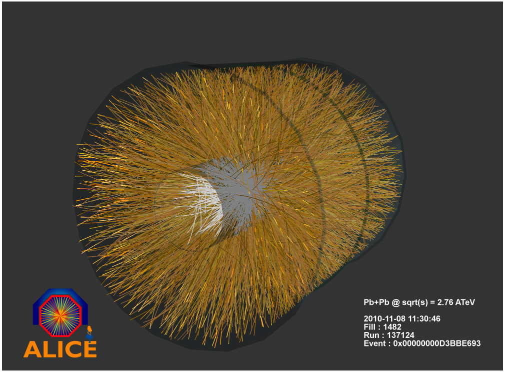


- Competition between **gravity** and **pressure of strong interactions** determines the macroscopic features of neutron stars
  mass-radius relationship, maximal stable masses , tidal deformability, etc...
- Neutron stars are nature's own *femtoscopes*

$$10^{-15}\text{m} \to 10\text{km}$$

$$\text{...but } 10^{19}\text{m away}$$

# The other femtoscope:



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

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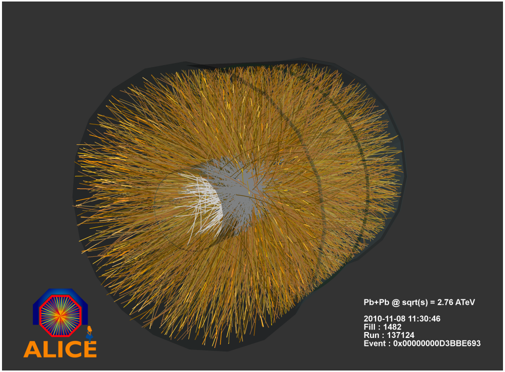
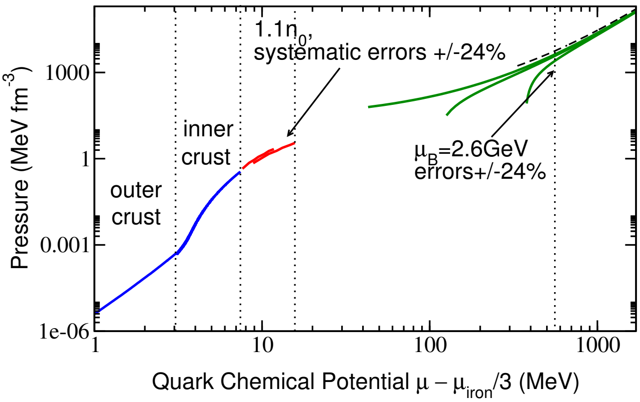


- Transition to hot quark matter around $\epsilon \sim 500 \mathrm{MeV}/\mathrm{fm}^3$.
- The big question:

> Is there cold quark matter inside neutron stars?

# Challenge:



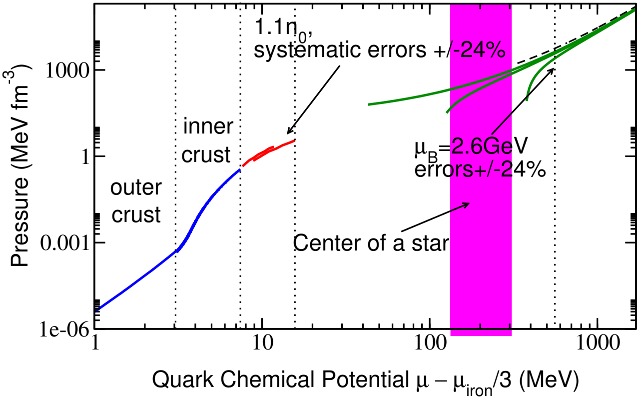
- At low densities nuclear EFTs: Challenges at saturation density

  This takes you about 200m inside the star

- At large densities resummed pQCD

  reliable around $40\rho_0$

# Challenge:



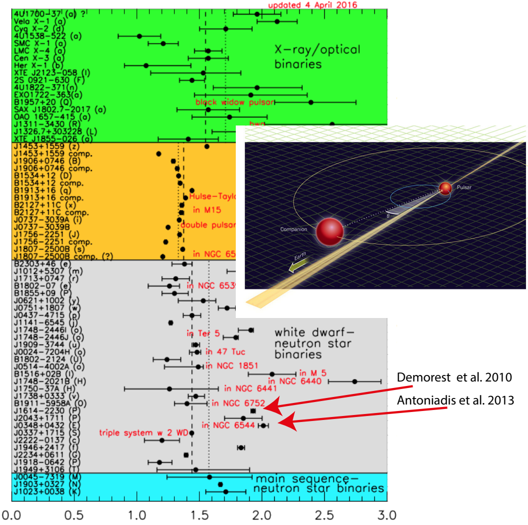
- Cores of neutron stars somewhere in between

Need astrophysical measurements to empirically extract EoS in between

# Neutron star observations:

- Pulsar timing:
  - Shapiro delay
    $M \sim 2M_\odot$

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



Demorest et al. 2010

Antoniadis et al. 2013

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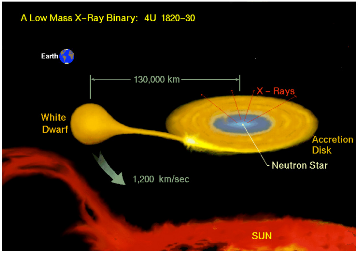

- Pulsar timing:
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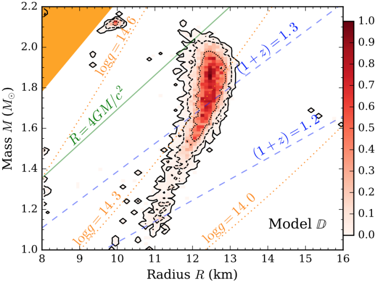
- Time resolved X-ray spectroscopy:
  - Mass and radius measurements

NICER, eXTP,...



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

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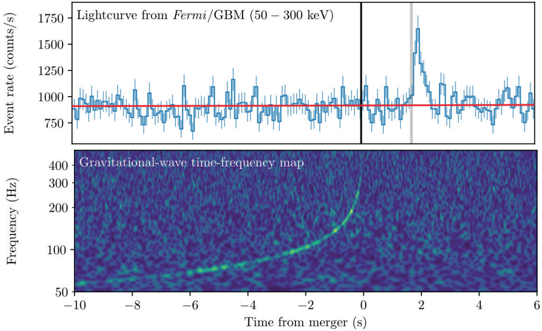

- Pulsar timing:
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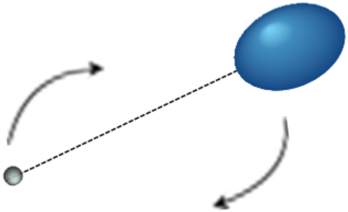
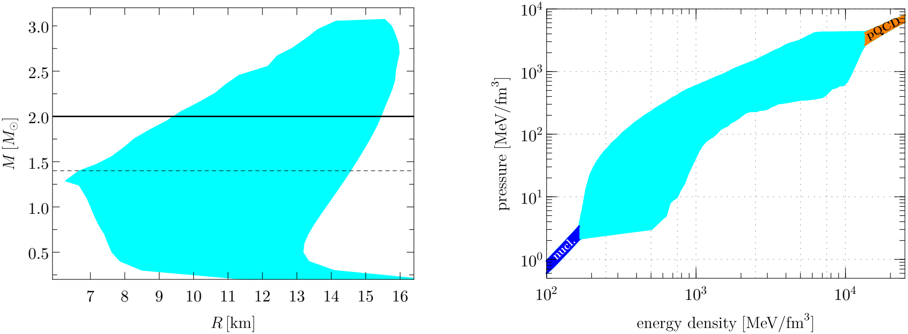
Demorest et al. Nature (2010)
Antoniadis et al., Science (2013)

- Time resolved X-ray spectroscopy:
  - Mass and radius measurements NICER, eXTP,...
- Gravitational waves:
  - Bounds on tidal deformability LIGO+Virgo



# Constraining the Equation of State with neutron stars



Annala et al. PRL 120 (2018)

- Large ensembles of interpolations between known limits

set of 400 000 EoS's

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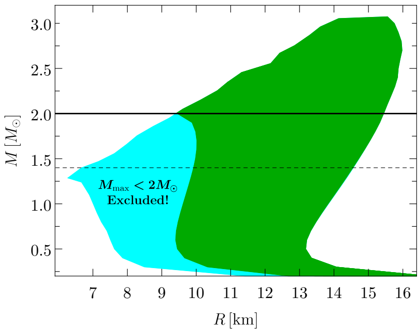

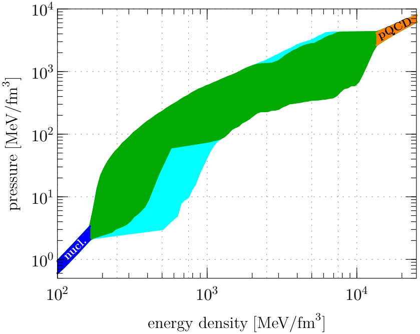

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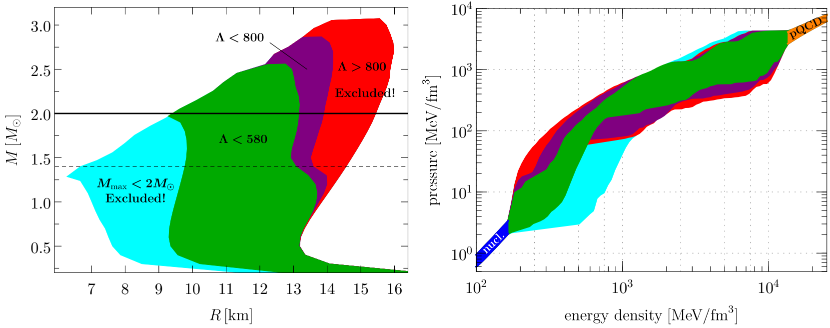


Annala et al. PRL 120 (2018)+LIGO update
Annala et al. PRL 120 (2018)

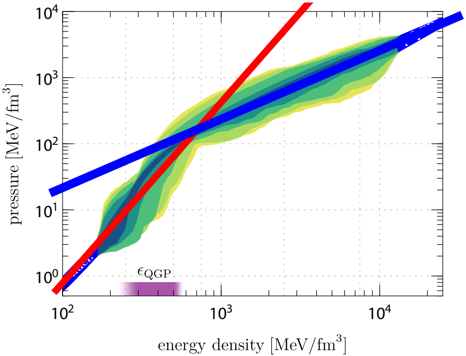
- Large ensembles of interpolations between known limits

  set of 400 000 EoS's

- Existence of a $2M_\odot$ implies that EoS must be stiff enough
- Non-detection of tidal deformation by LIGO/Virgo implies that the EoS must be soft enough

  The first determination of NS radius from GWs

# Quark Matter cores in Neutron Stars?

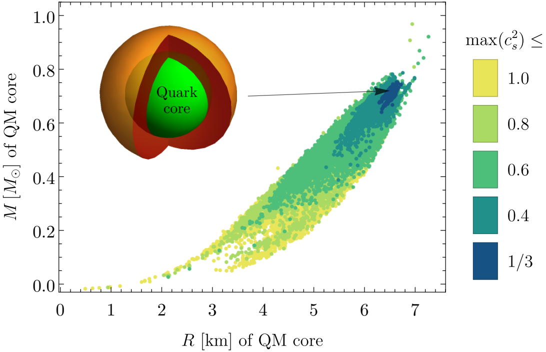


Annala, Gorda, AK, Nättilä, Vuorinen, Nature Phys. (2020)

- Rapid softening hints to a phase transition to quark matter

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

# Quark core in maximally massive NSs

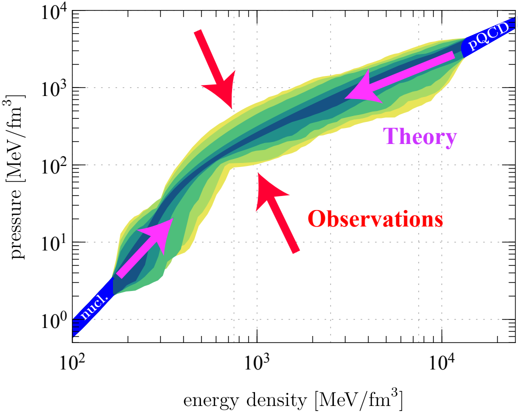


Annala, Gorda, AK, Nättilä, Vuorinen, Nat. Phys. (2020)
Amount of matter with $\gamma = \frac{\log p}{\log \epsilon} < 1.75$

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:



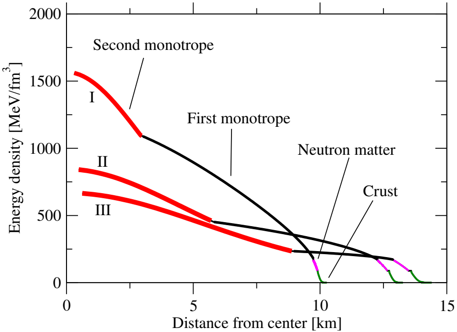
- Combined effort of nuclear physics, QCD, and astrophysical observations will allow to determine the phase of the neutron star cores

# Conclusions:

- Neutron stars have opened up a novel window to extreme QCD matter
- Combining astronomical and theoretical inputs allows to empirically determine properties of strongly interacting matter in extreme conditions where no 1st principles calculations are available
- Hints pointing to quark matter in maximally massive stars. No definite answers yet but quark cores should be treated as a standard scenario

# Extra slides

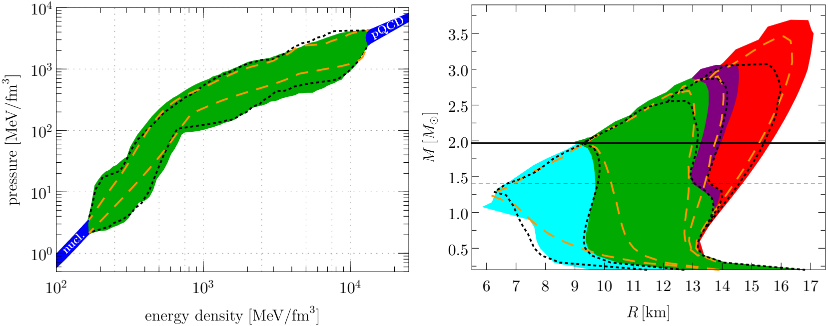
# Building stars



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

- Nuclear EoS present only as thin crust:
  - Important as a boundary condition to interpolation, not the EoS itself!

# 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)