Bounds on the gravitational constant from a two-solar-mass neutron star

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Strong interactions beyond the Standard Model

Physikzentrum Bad Honnef
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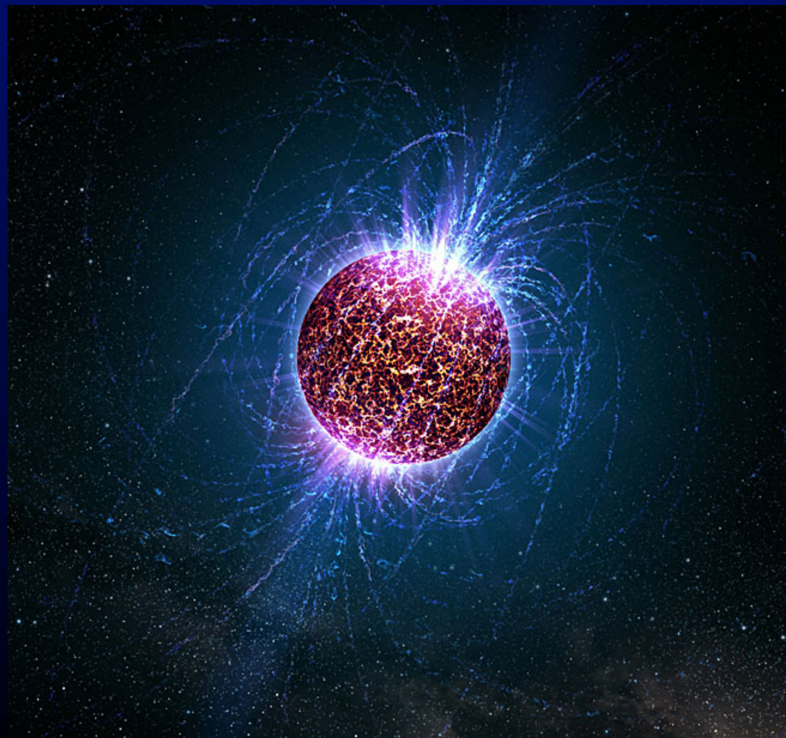
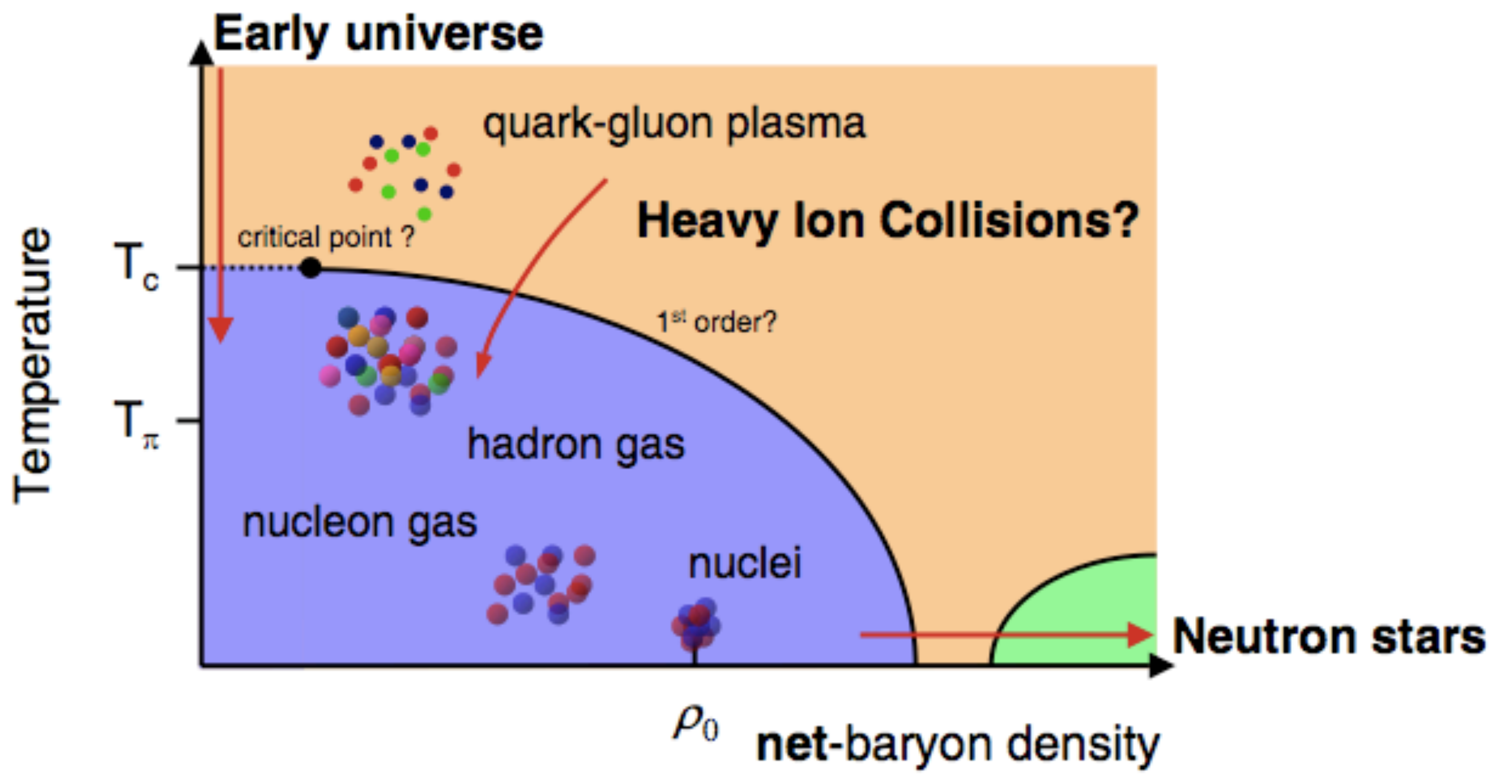
Outline

- Learning nuclear physics from gravity and the other way around by using massive pulsars



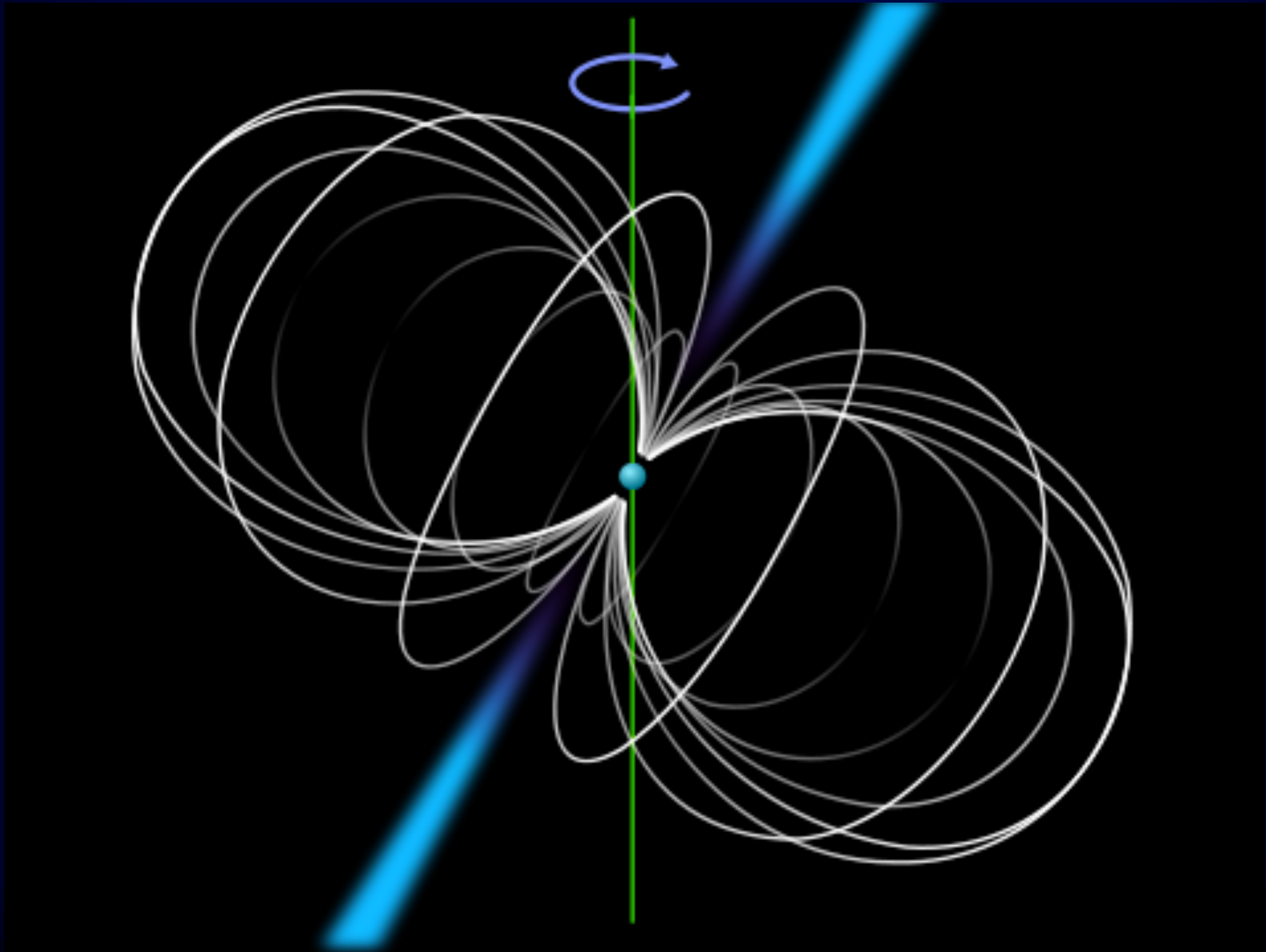
Exploring the nuclear phase diagram

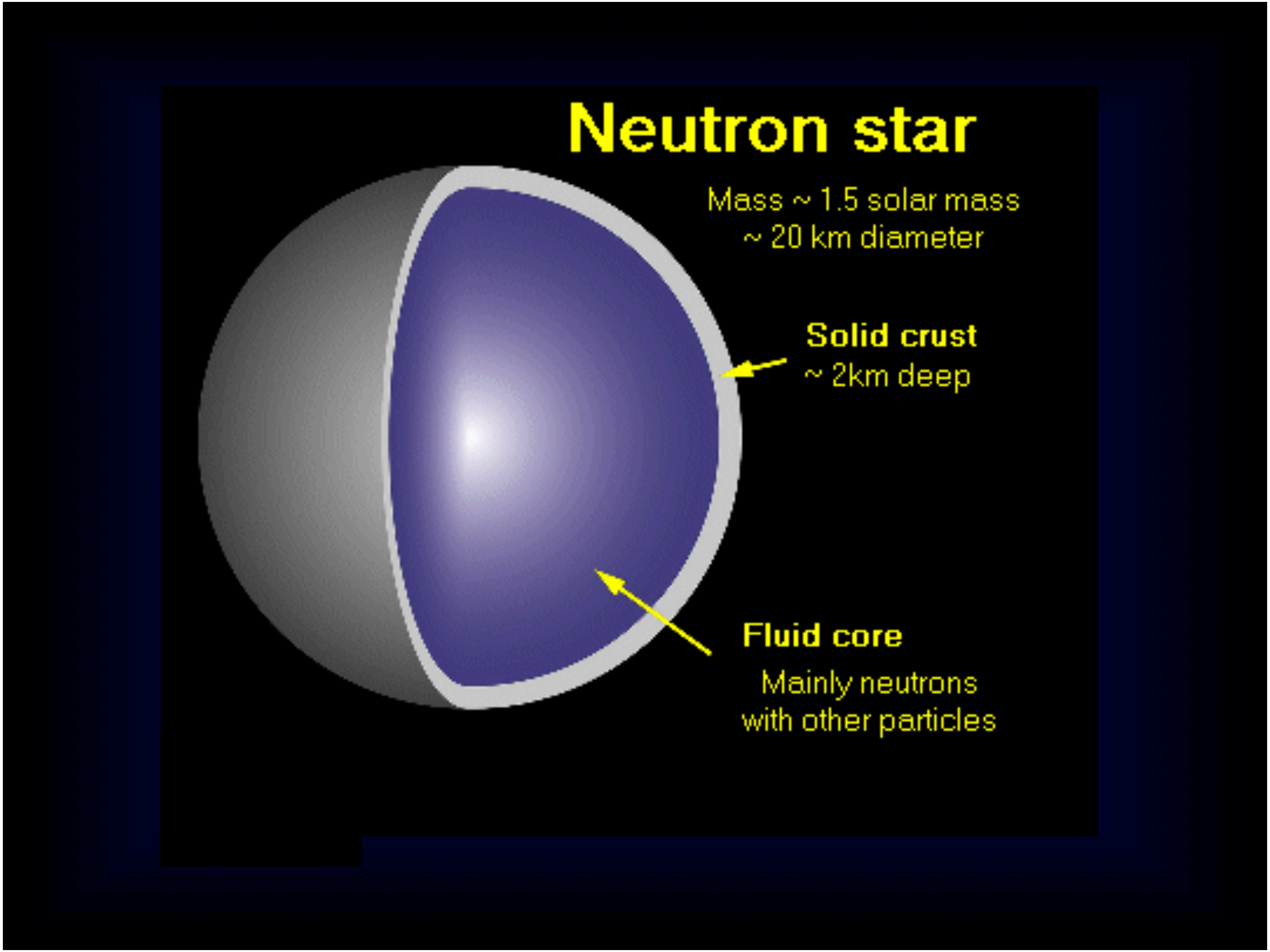


The possible phases of nuclear matter

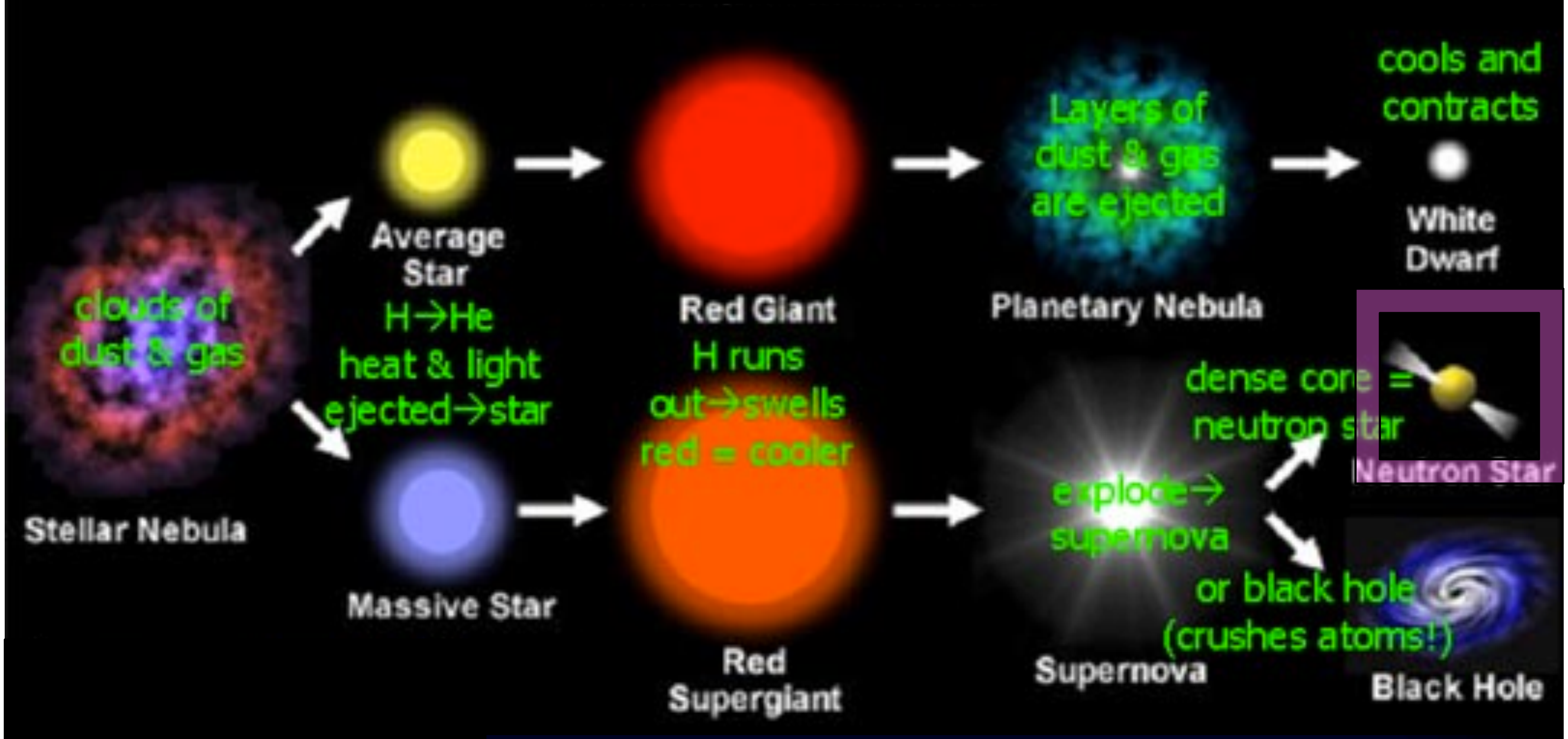
Neutron stars are the only window to part of the QCD phase diagram

The whole idea is based in the interpretation of the pulsars, discovered by Hewish in 1967, as neutron stars (Gold and others)



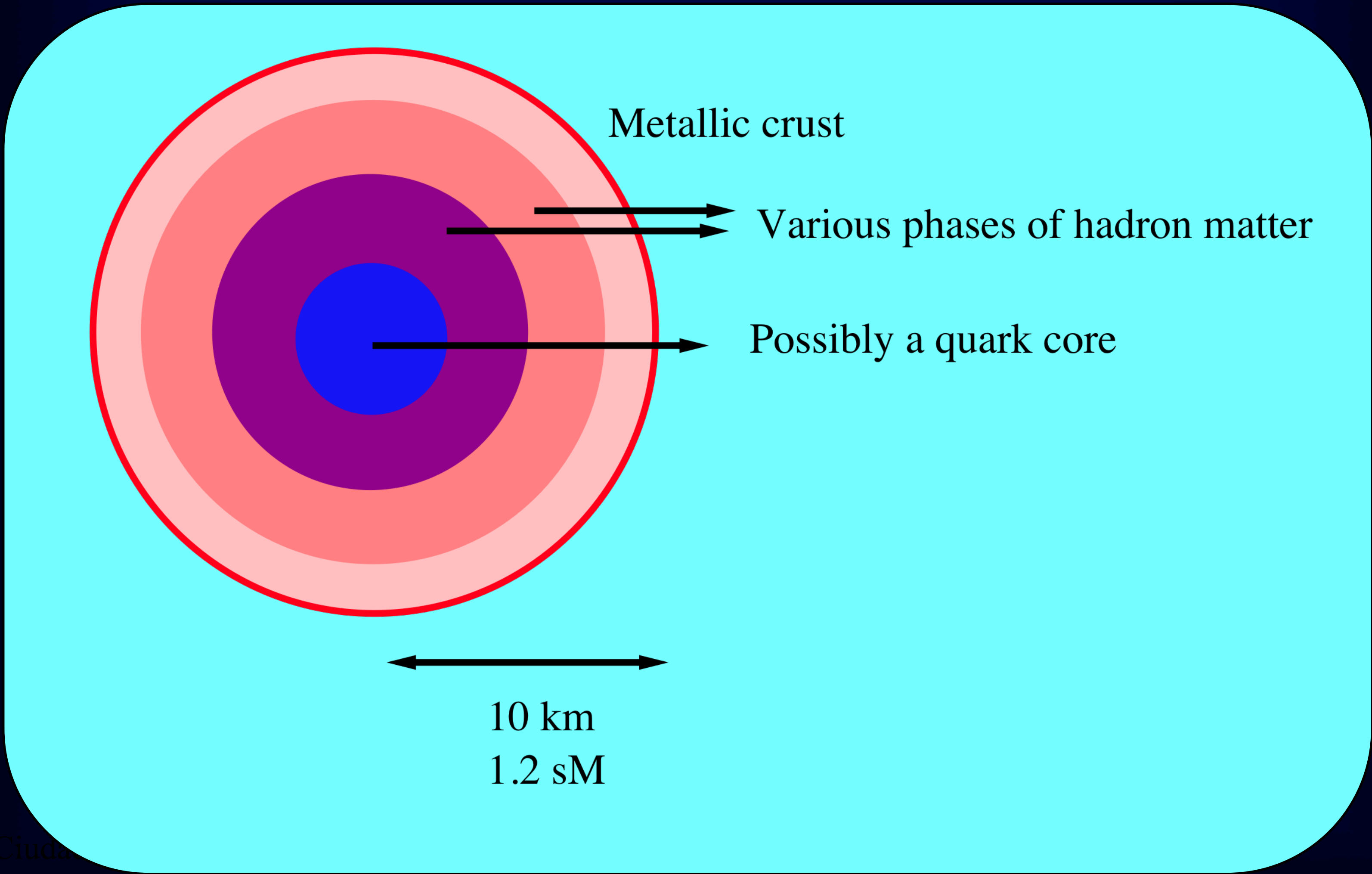

Neutron star
Mass ~ 1.5 solar mass
~ 20 km diameter
Solid crust
~ 2km deep
Fluid core
Mainly neutrons
with other particles

Neutron stars are believed to be the final states of massive stars which are not heavy enough to become black holes.



Neutrons stars are a natural lab for structure of matter

Conjectures on the possibilty of exotic phases in the inner region



doi:10.1038/nature09466

A two-solar-mass neutron star measured using Shapiro delay

P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

The motivation was the recent claim of the discovery of a two-solar-mass neutron star.

(Demorest et al. Nature 2010)

Table 1 | Physical parameters for PSR J1614-2230

Parameter	Value
Ecliptic longitude (λ)	245.78827556(5)°
Ecliptic latitude (β)	−1.256744(2)°
Proper motion in λ	9.79(7) mas yr^{-1}
Proper motion in β	−30(3) mas yr^{-1}
Parallax	0.5(6) mas
Pulsar spin period	3.1508076534271(6) ms
Period derivative	9.6216(9) $\times 10^{-21}$ s s^{-1}
Reference epoch (MJD)	53,600
Dispersion measure*	34.4865 pc cm^{-3}
Orbital period	8.6866194196(2) d
Projected semimajor axis	11.2911975(2) light s
First Laplace parameter (esin ω)	1.1(3) $\times 10^{-7}$
Second Laplace parameter (ecos ω)	−1.29(3) $\times 10^{-6}$
Companion mass	0.500(6) $M_\odot$
Sine of inclination angle	0.999894(5)
Epoch of ascending node (MJD)	52,331.1701098(3)
Span of timing data (MJD)	52,469–55,330
Number of TOAs†	2,206 (454, 1,752)
Root mean squared TOA residual	1.1 μs
Right ascension (J2000)	16 h 14 min 36.5051(5) s
Declination (J2000)	−22° 30′ 31.081(7)″
Orbital eccentricity (e)	1.30(4) $\times 10^{-6}$
Inclination angle	89.17(2)°
Pulsar mass	1.97(4) $M_\odot$
Dispersion-derived distance‡	1.2 kpc
Parallax distance	>0.9 kpc
Surface magnetic field	1.8 $\times 10^{8}$ G
Characteristic age	5.2 Gyr
Spin-down luminosity	1.2 $\times 10^{34}$ erg s^{-1}
Average flux density* at 1.4 GHz	1.2 mJy
Spectral index, 1.1–1.9 GHz	−1.9(1)
Rotation measure	−28.0(3) rad m^{-2}

In contradicion with previous claims from the theoretical side

OBSERVATIONAL CONSTRAINTS ON THE MAXIMUM NEUTRON STAR MASS

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Received 1994 October 3; accepted 1995 March 17

ABSTRACT

We review estimates of the mass of the compact core in SN 1987A and conclude that the most accurate determination can be obtained from the known value of $\sim 0.075\ M_\odot$ of Ni production in the explosion. With binding energy correction, this gives an upper limit of gravitational mass of $\sim 1.56\ M_\odot$, slightly larger than Brown & Bethe's previous estimate of $\sim 1.5\ M_\odot$. Observation by OSSE of the ratio of γ-rays from ^{57}Co and ^{56}Co indicates that neutron-rich material from the inner regions does not reach the mass cut by convection or Rayleigh-Taylor instability.

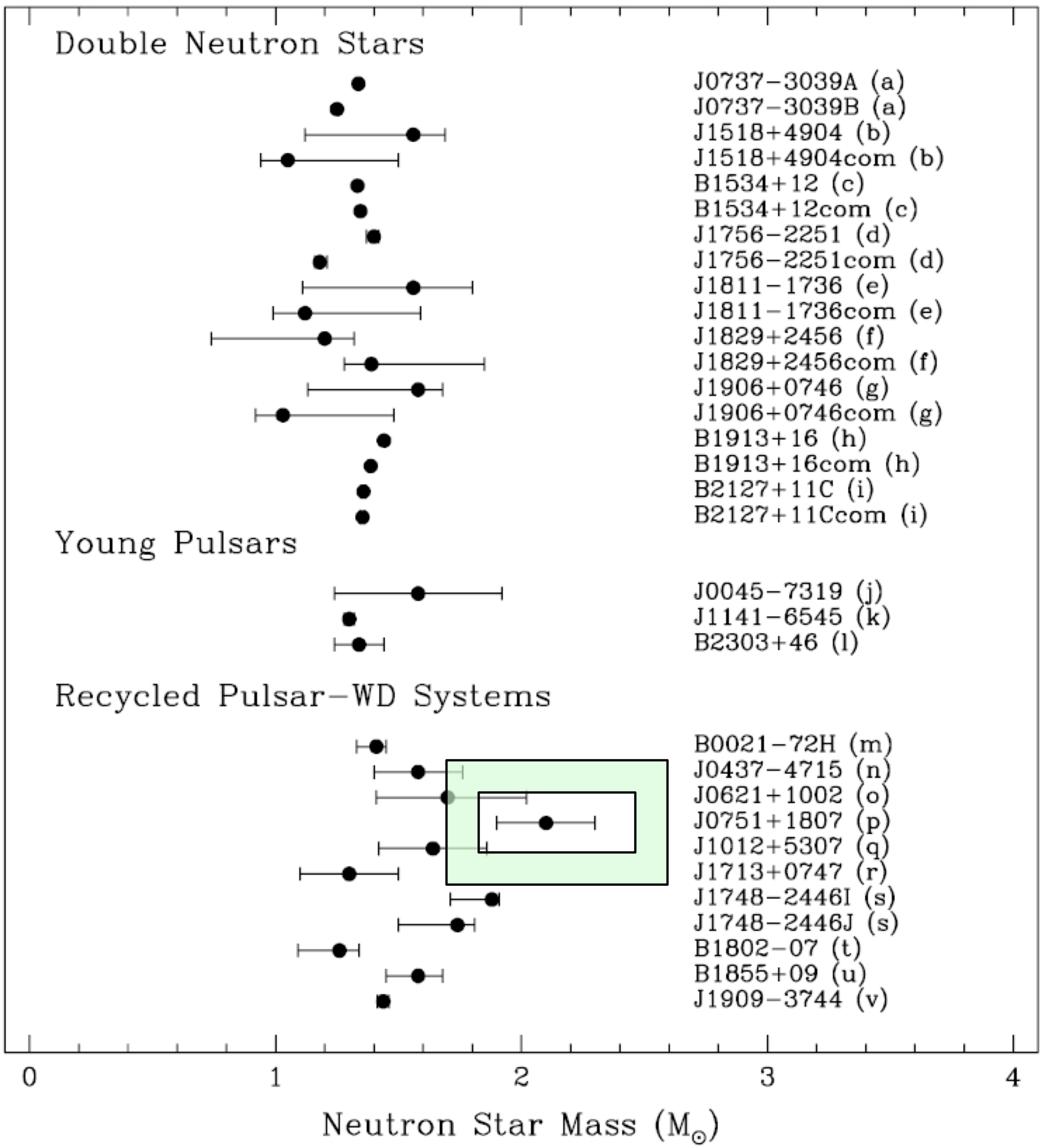
Arguments that the core of SN 1987A went into a black hole are reviewed. If one accepts this to be true, then the maximum compact core mass gives an upper limit on neutron star masses of

$$(M_{NS})_{max} \cong 1.56\ M_\odot$$

(gravitational), in rough agreement with the previous result of Brown & Bethe.

Subject headings: stars: neutron — supernova remnants

And almost all measured pulsar masses



But confirming a previous claim of neutron stars in this mass range

A 2.1 $M_{\odot}$ PULSAR MEASURED BY RELATIVISTIC ORBITAL DECAY

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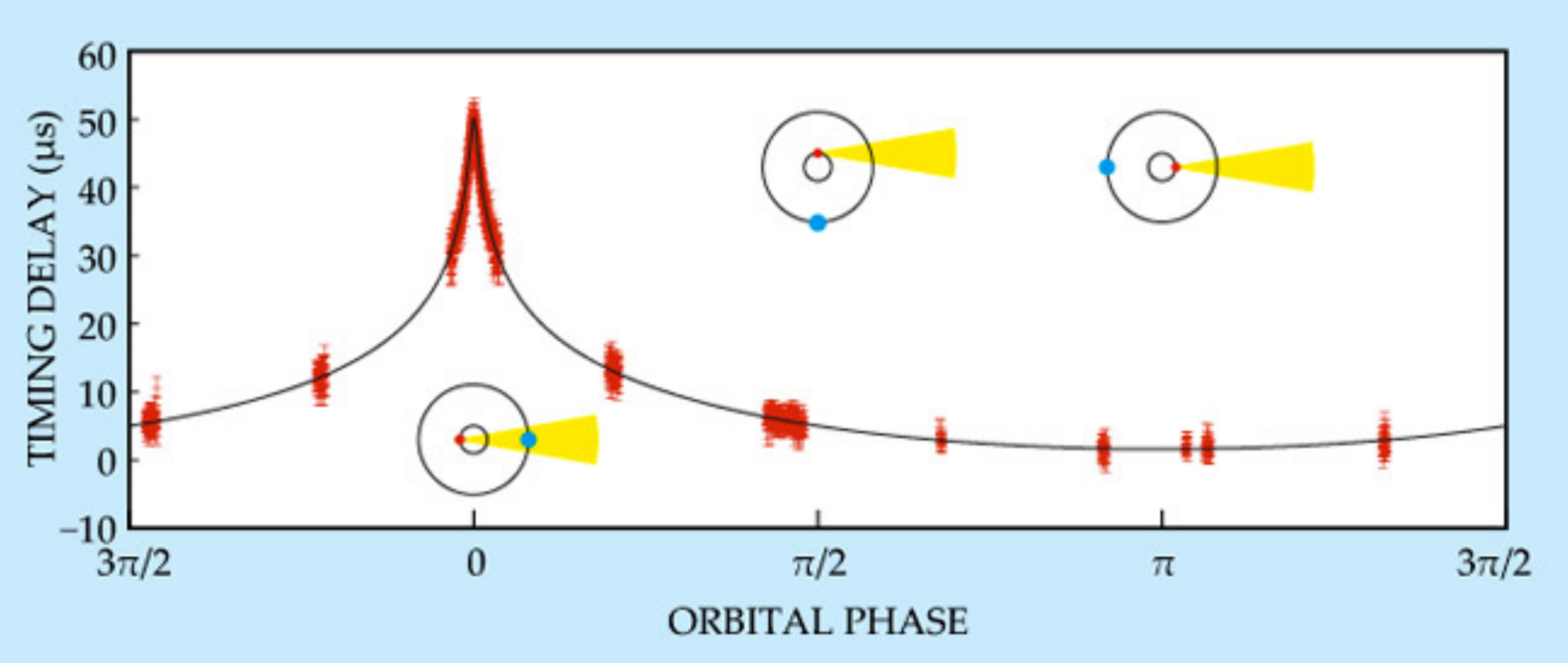
Radio timing observations of the binary millisecond second pulsar J1614-2230 show a strong Shapiro delay signature giving a pulsar mass of about 1.97 +/− 0.04 solar mass.



Demorest et al. 10.1038/nature 09466.

The theory of neutron stars started in 1939 with the seminal work by Oppenheimer-Volkoff and Tolman

FEBRUARY 15, 1939 PHYSICAL REVIEW VOLUME 55

On Massive Neutron Cores

J. R. Oppenheimer and G. M. Volkoff
Department of Physics, University of California, Berkeley, California
(Received January 3, 1939)

It has been suggested that, when the pressure within stellar matter becomes high enough, a new phase consisting of neutrons will be formed. In this paper we study the gravitational equilibrium of masses of neutrons, using the equation of state for a cold Fermi gas, and general relativity. For masses under $\frac{1}{3}\odot$ only one equilibrium solution exists, which is approximately described by the nonrelativistic Fermi equation of state and Newtonian gravitational theory. For masses $\frac{1}{3}\odot < m < \frac{3}{4}\odot$ two solutions exist, one stable and quasi-Newtonian, one more condensed, and unstable. For masses greater than $\frac{3}{4}\odot$ there are no static equilibrium solutions. These results are qualitatively confirmed by comparison with suitably chosen special cases of the analytic solutions recently discovered by Tolman. A discussion of the probable effect of deviations from the Fermi equation of state suggests that actual stellar matter after the exhaustion of thermonuclear sources of energy will, if massive enough, contract indefinitely, although more and more slowly, never reaching true equilibrium.

FEBRUARY 15, 1939 PHYSICAL REVIEW VOLUME 55

Static Solutions of Einstein's Field Equations for Spheres of Fluid

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(Received January 3, 1939)

A method is developed for treating Einstein's field equations, applied to static spheres of fluid, in such a manner as to provide explicit solutions in terms of known analytic functions. A number of new solutions are thus obtained, and the properties of three of the new solutions are examined in detail. It is hoped that the investigation may be of some help in connection with studies of stellar structure. (See the accompanying article by Professor Oppenheimer and Mr. Volkoff.)

Oppenheimer-Volkov-Tolman equation

$$\frac{dP}{dr} = -\frac{G_N}{r^2}\frac{[\varepsilon(r)+P(r)][M(r)+4\pi r^3 P(r)]}{1-\frac{2G_N M(r)}{r}}$$

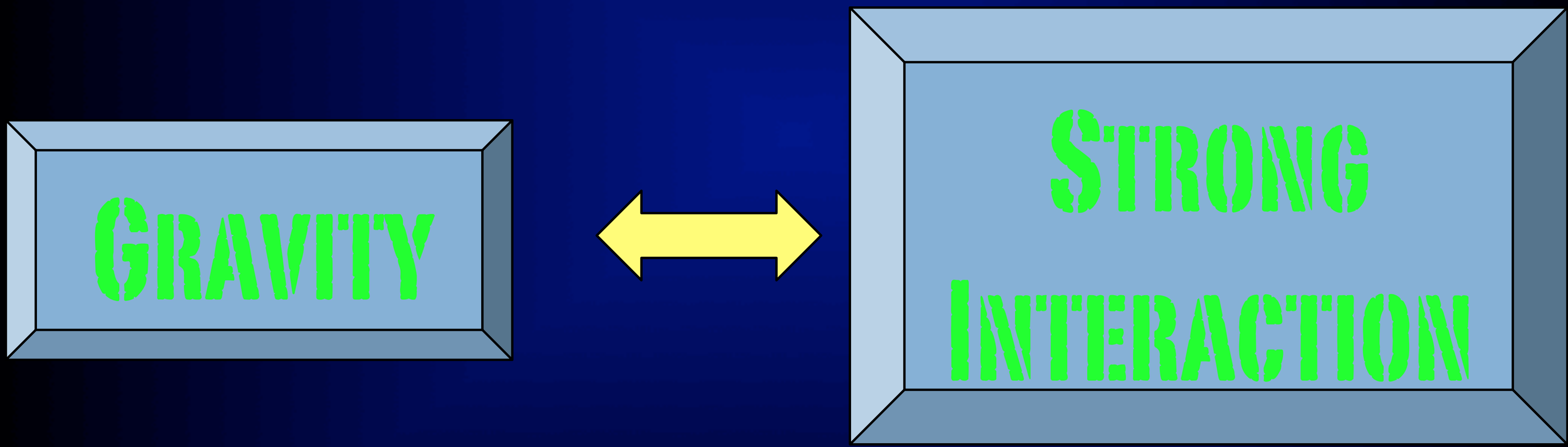
General relativistic hydrostatic equilibrium (spherical bodies)

Important relativistic contributions

Must be supplemented with the matter Equation of State (EoS)

→ $P = P(\varepsilon)$

Oppenheimer–Volkoff and Tolman plus the Equation of State allows the study of the equilibrium conditions for neutron stars

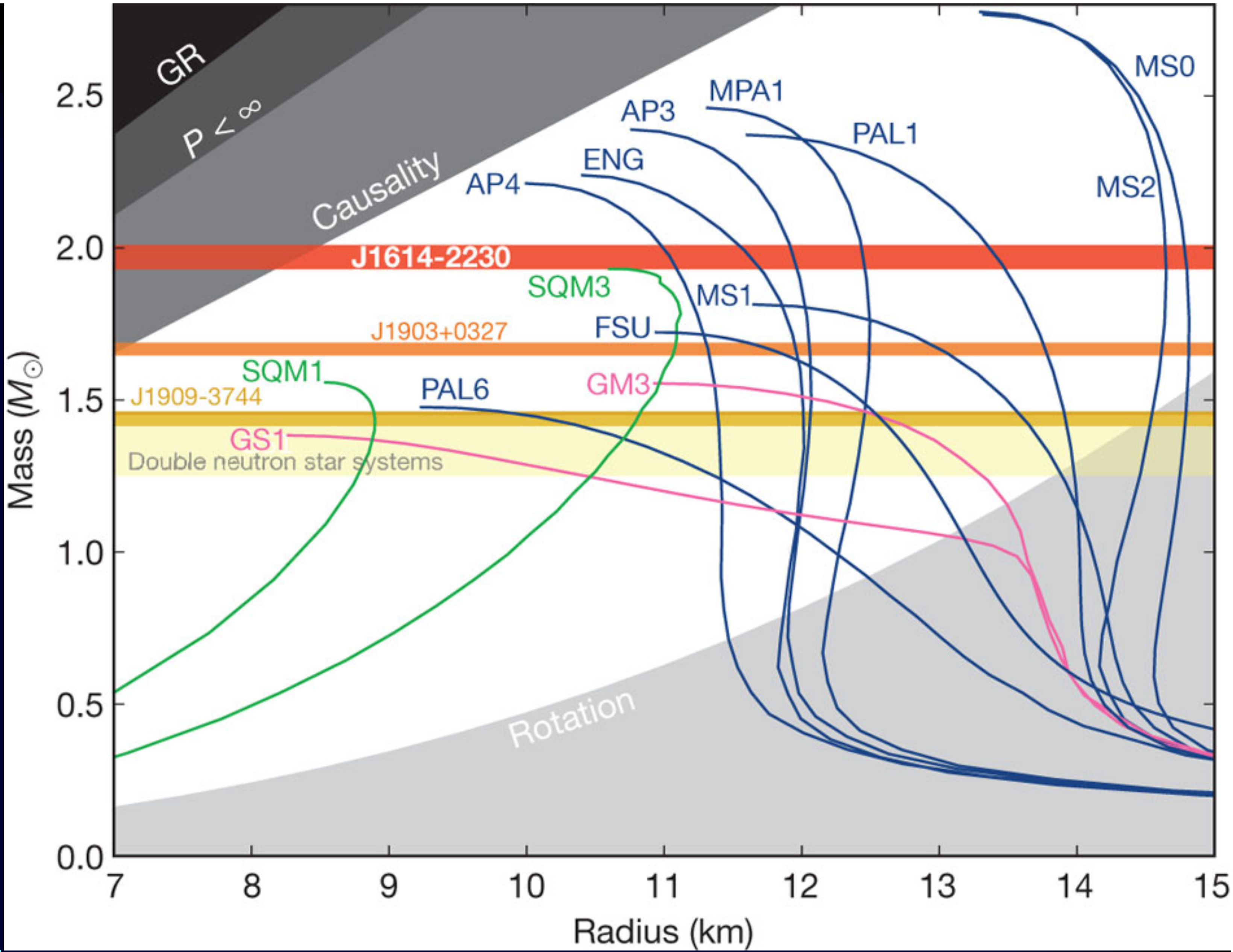


Therefore we have two possibilities:

a) Assuming we know gravity we can learn about strong interactions (EoS).

b) Assuming we know strong interactions we can learn about gravity (G_N).

Case a)

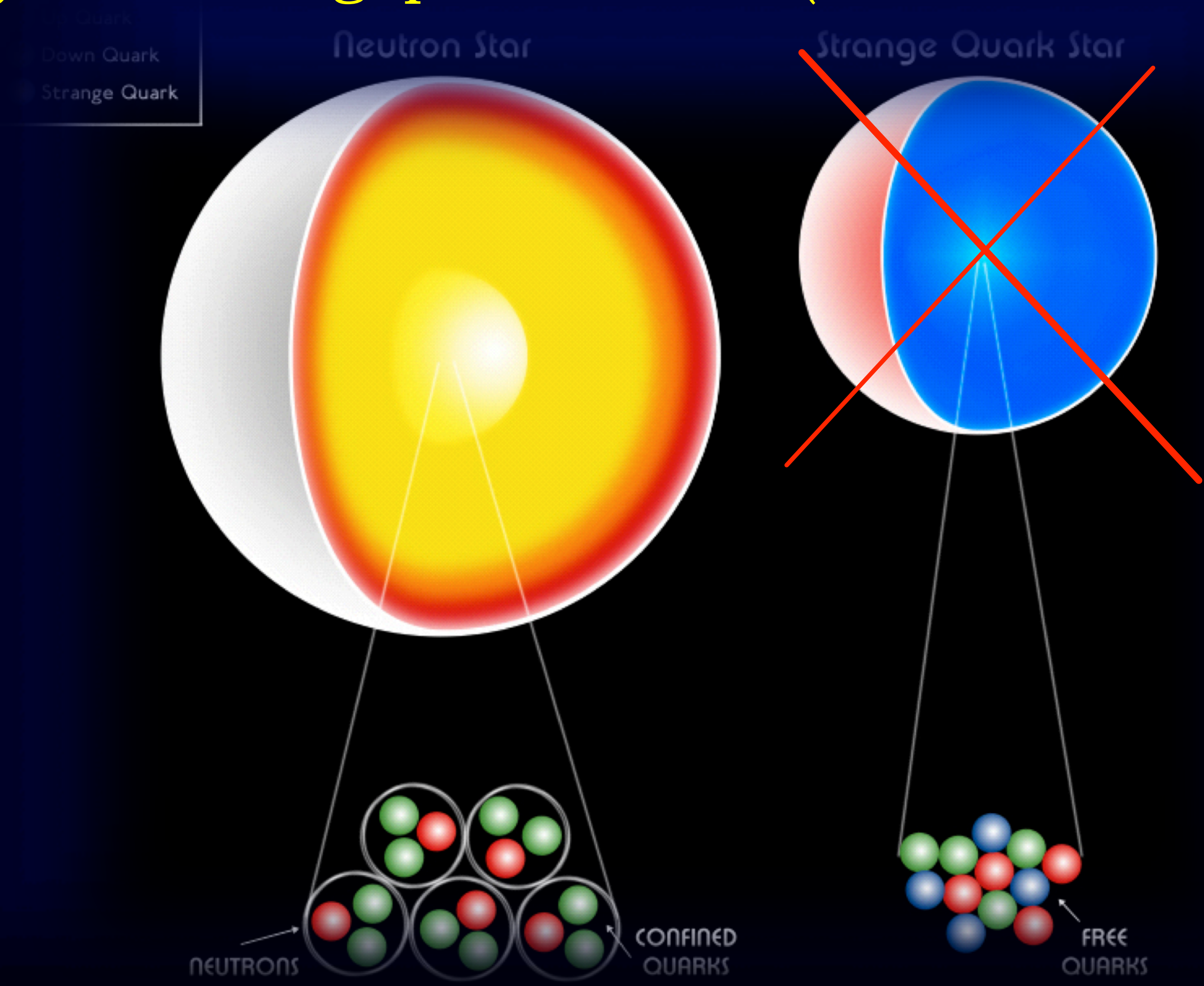


Blue: Nucleons

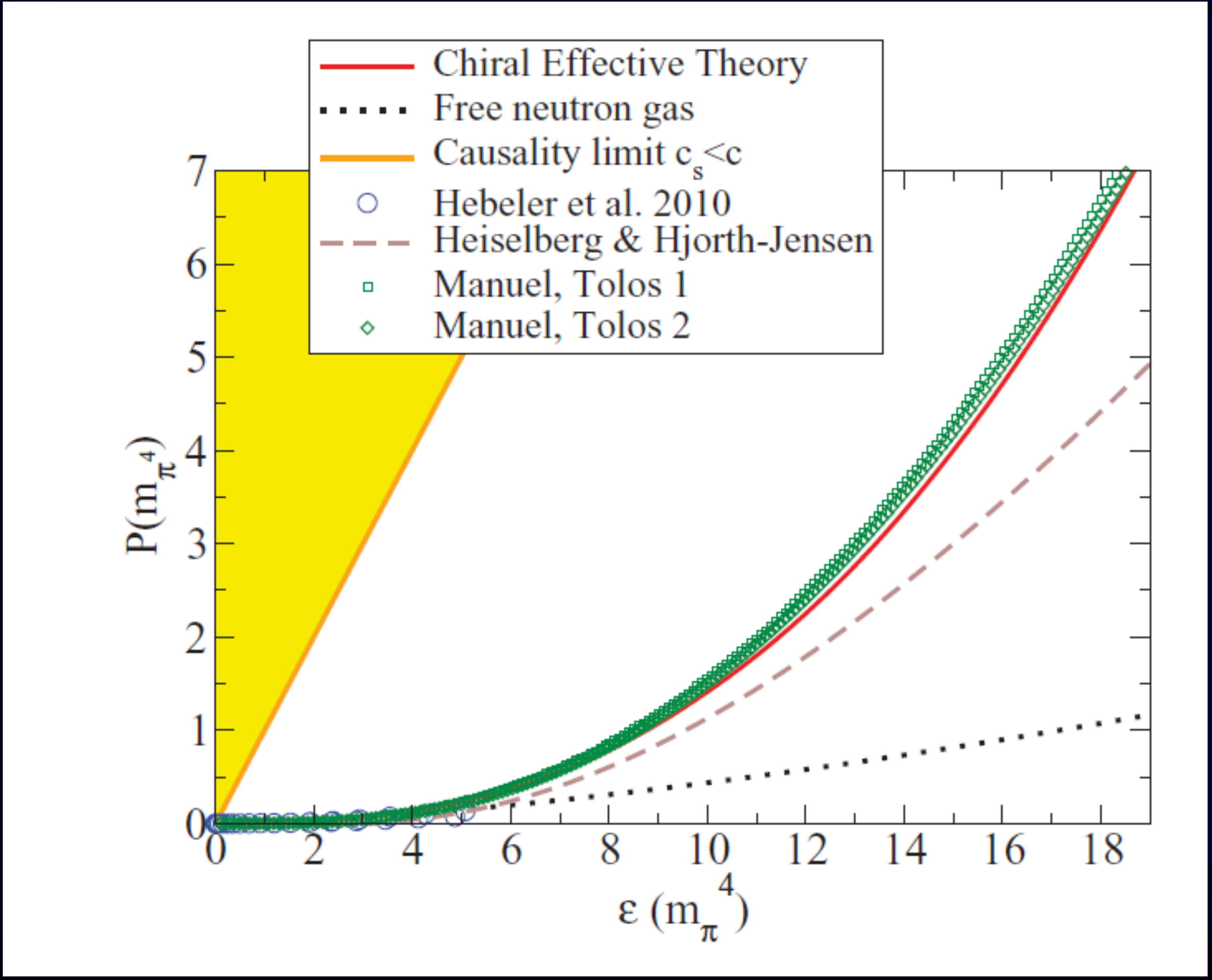
Pink: Nucleons plus exotic matter (kaons, hyperons…)

Green: Strange quark matter

So we can rule out most of the exotic scenarios for the matter of neutron stars (quark matter, hyperons, kaon condensates) from the EoS in the maket, but perhaps strongly interacting quark matter (Demorest et all)



Case b) From a given EoS



We can get information about G_N in an unexplored new regime (relativistic and high g)

$$\mathbf{F} = -G_N \frac{m_1 m_2}{r^2} \hat{\mathbf{r}}.$$

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi \boxed{G_N} T_{\mu\nu},$$

G_N → $6.6738(8)\ 10^{-11}\ \mathrm{N(m/kg)^2}$

$g \simeq 9.8\ \mathrm{m/s^2}$ Earth surface

This value is compatible with the ones found in other scenarios with much larger accelerations

$$6.6738(8)\ 10^{-11}\ \mathrm{N(m/kg)^2}$$

$g \simeq 9.8\ \mathrm{m/s^2}$ Earth surface

$g \simeq 270\ \mathrm{m/s^2}$ J0737-3039

$g \simeq 330\ \mathrm{m/s^2}$ PSR B1913+16 (Hulse-Taylor)

$g \simeq 2 \times 10^6\ \mathrm{m/s^2}$ White darfs

$g \simeq 2 \times 10^{12}\ \mathrm{m/s^2}$ PSR J1614-2230 (Demorest et al)

This result may be relevant since many extensions of GR predict $G_N = G_N(g)$

For example, arXiv:0410117

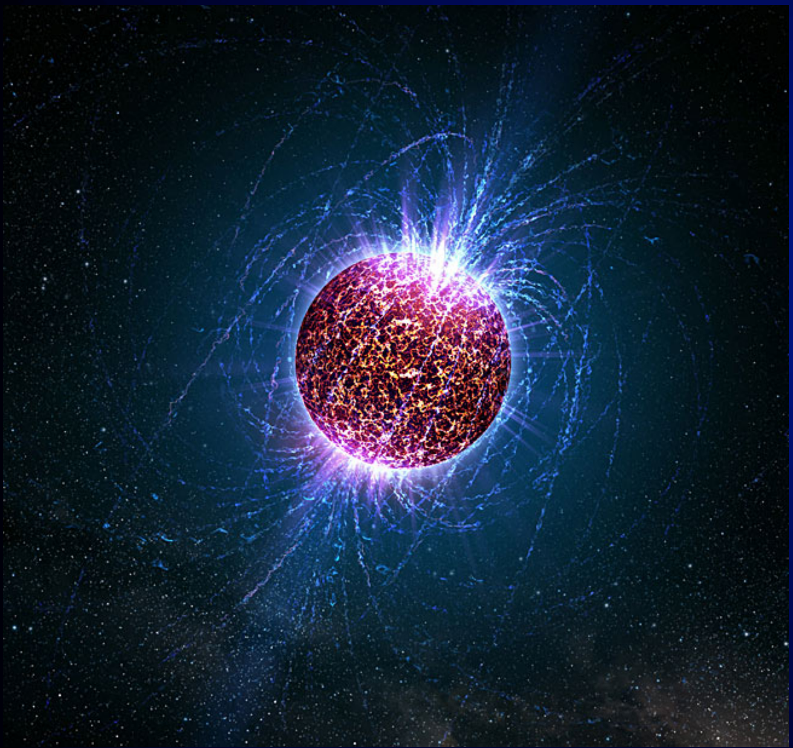
$$G_N \simeq \text{constant} \quad r \to 0$$

$$G_N \propto \frac{1}{k^q} \propto r^q \quad r \to \infty$$

$$q \simeq 10^{-6}$$

Dozens of works 0901.2963, hep-th/9504014, hep-ph/0207282, astro-ph/9501066 ...

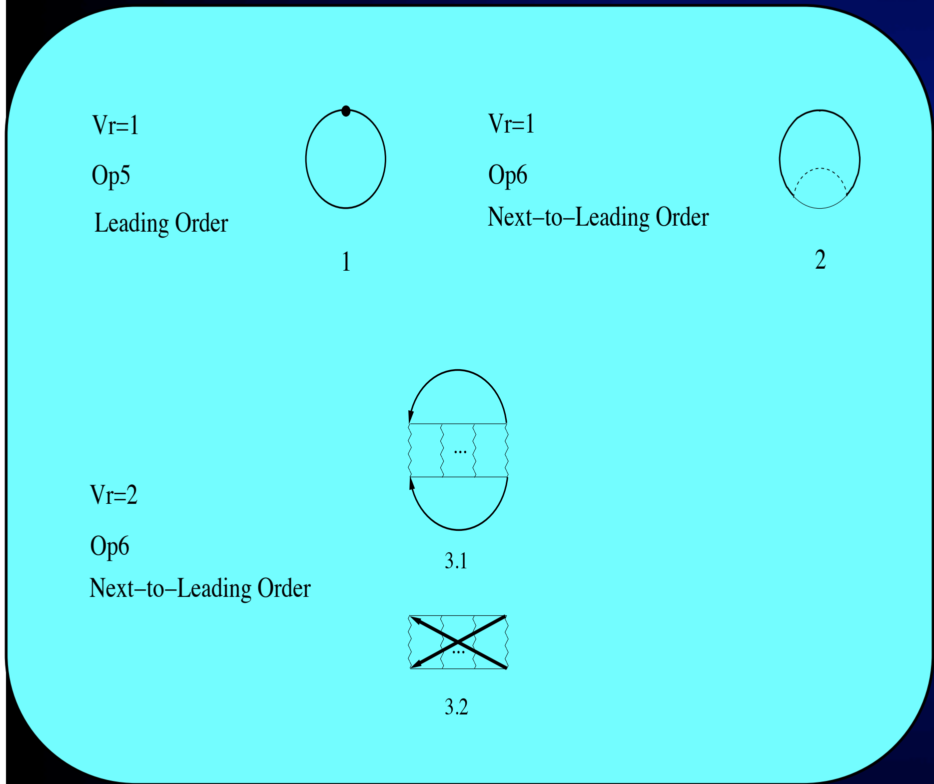
Now we can extrapolate to the 1.97 solar-masses J1614-2230 pulsar assuming a given EoS.

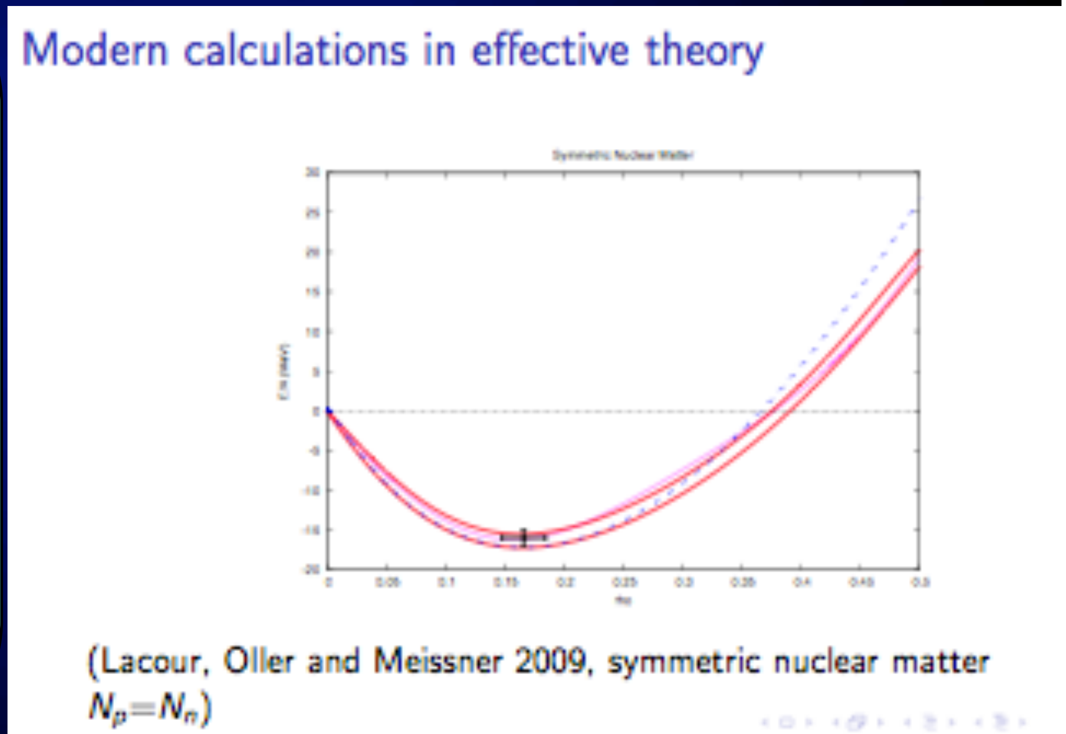


$$g = \frac{d\Phi}{dr} = \frac{M(r) + 4\pi r^3 P(r)}{r[r - 2M(r)]}$$

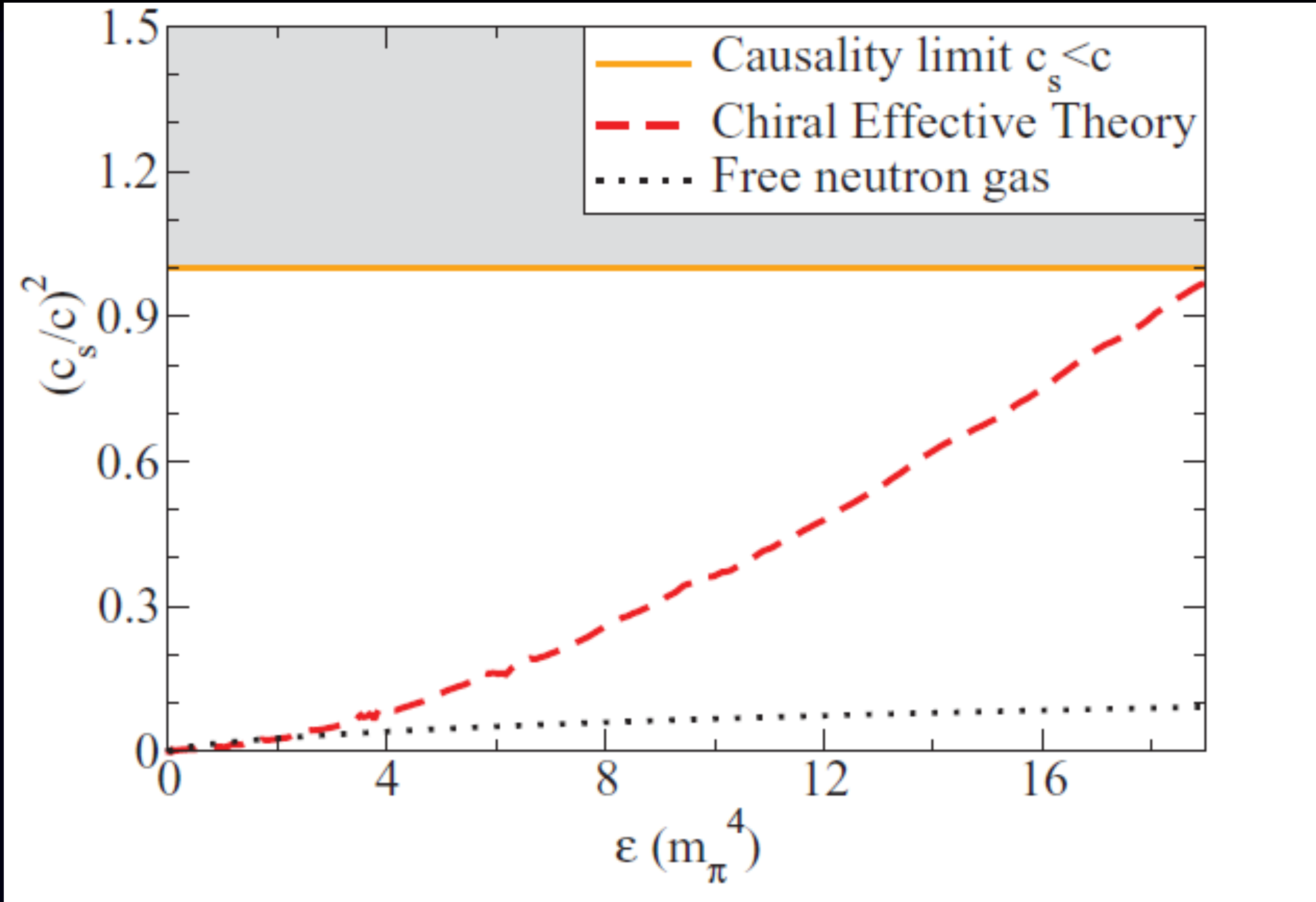
$$c_s^2 = \partial P / \partial \rho < c$$

For example the recently propossed based on Chiral Pertubation Theory which reproduces quite well the nuclear matter density from first principles
(Chiral Symmetry and consistent momentum power counting in nuclear matter)



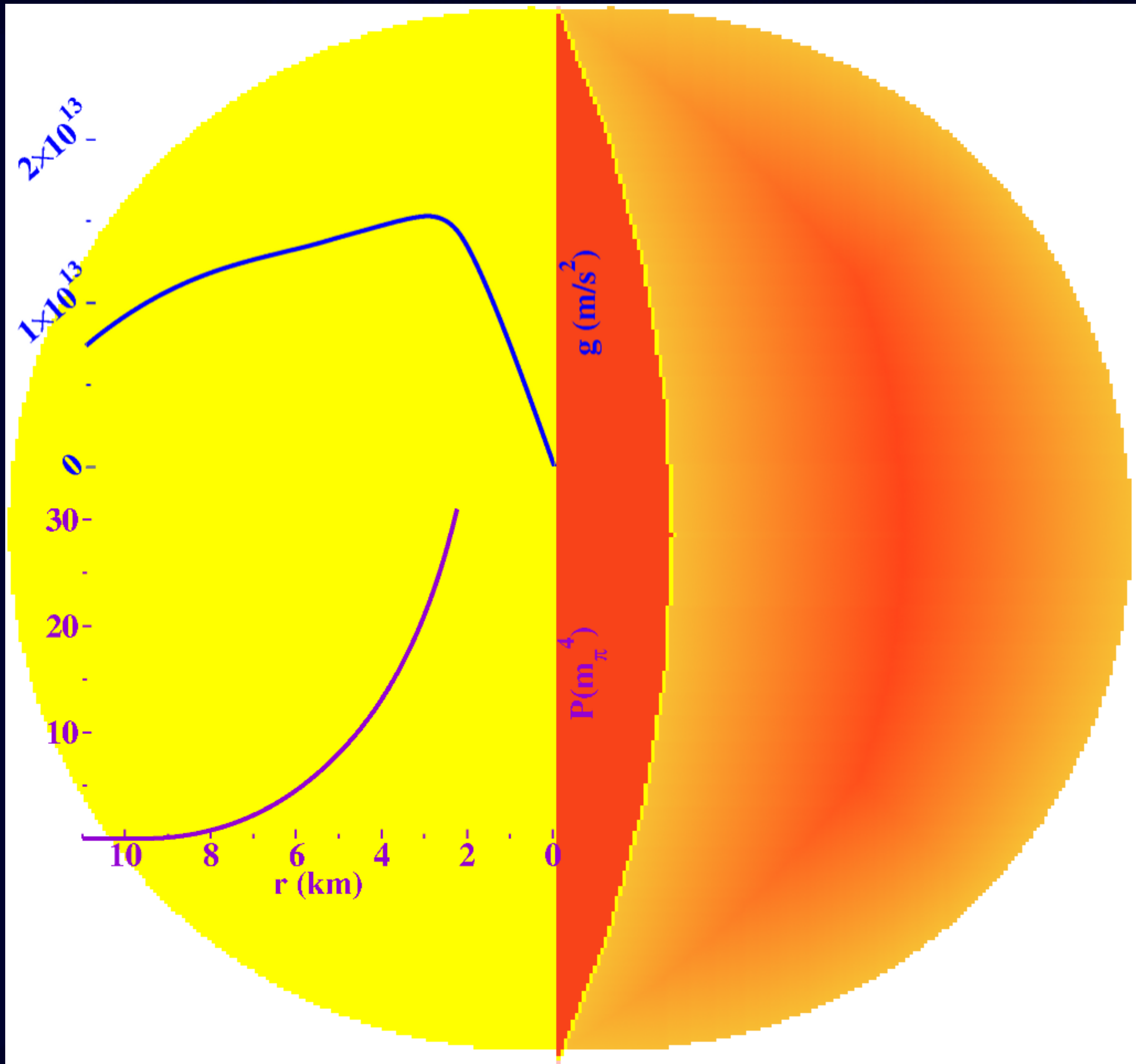


Lacour, Oller and Meissner 2009



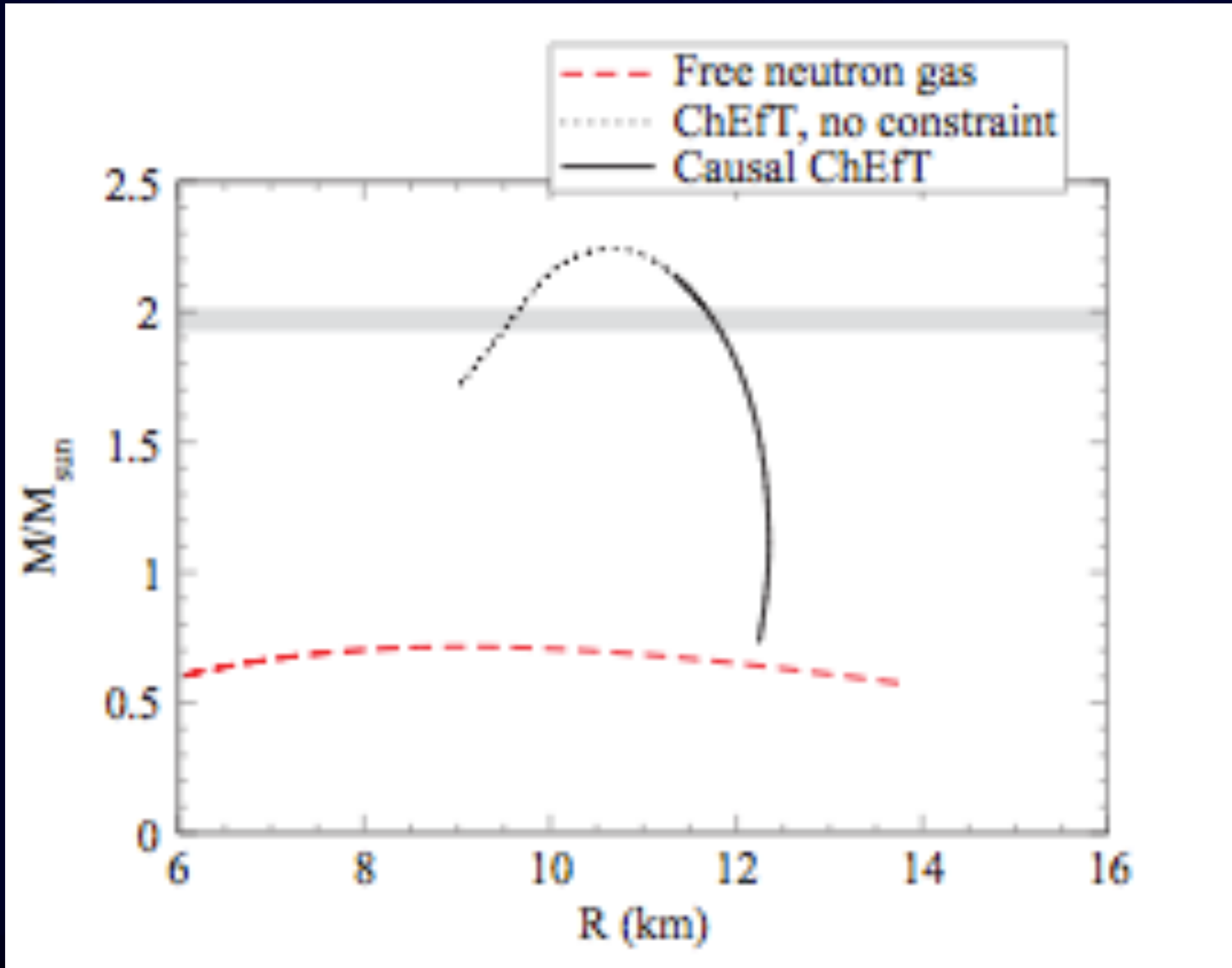
$$c_s^2 = \partial P / \partial \rho < c$$

Solving Oppenheimer-Volkov-Tolman equation it is possible to find the acceleration profile for the two-solar-masses neutron star.



$g \simeq 2 \times 10^{12}$ m/s^2 PSR J1614-2230

Nuclear EoS supports at most 2.2 solar masses



Vary the Newton constant:

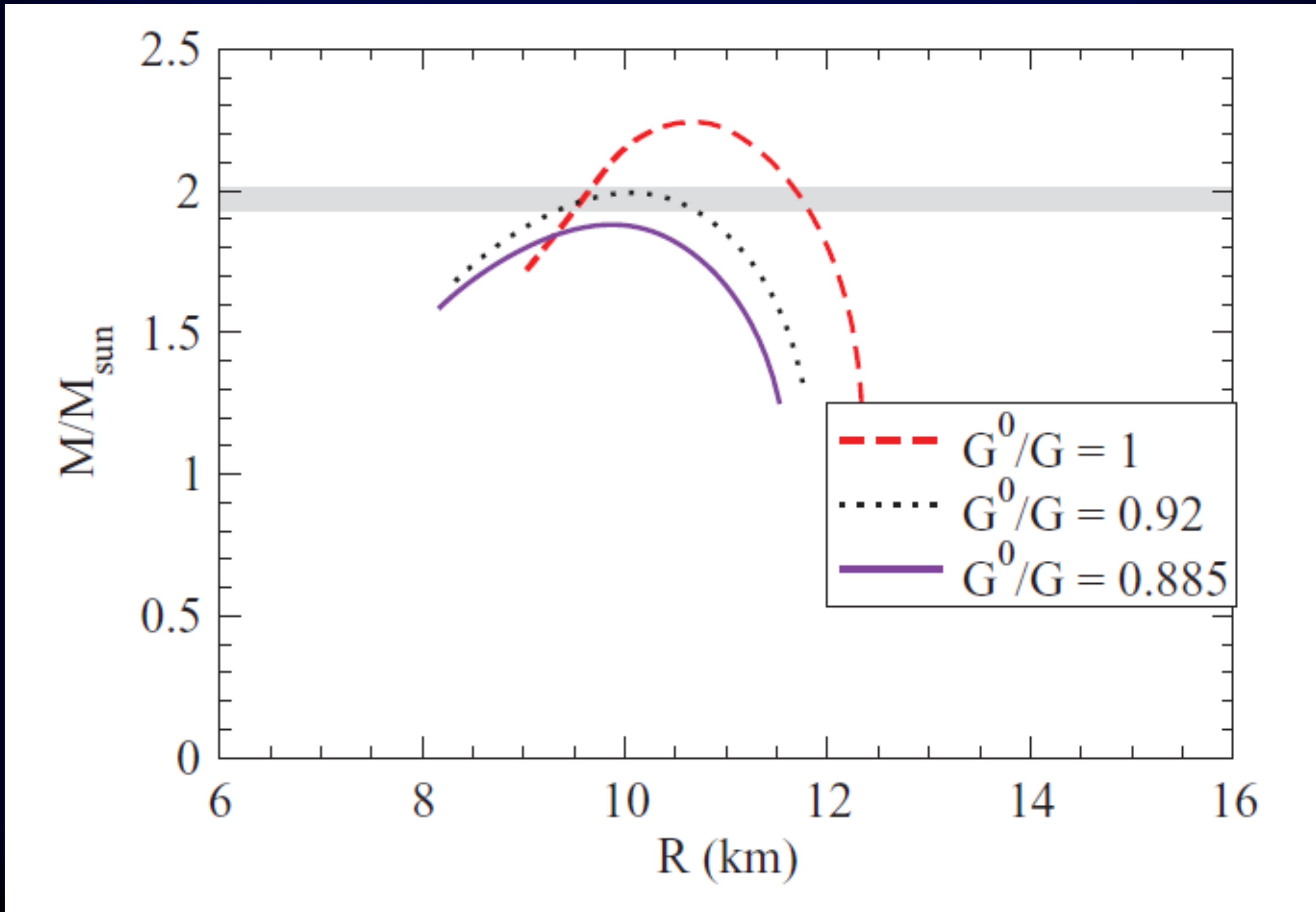
$$\frac{dP}{dr} = -\frac{G_N}{r^2}\frac{(\varepsilon(r) + P(r))(M(r) + 4\pi r^3 P(r))}{1 - \frac{2G_N M(r)}{r}}$$

Where Effective Theory becomes unreliable use the steepmost equation of state

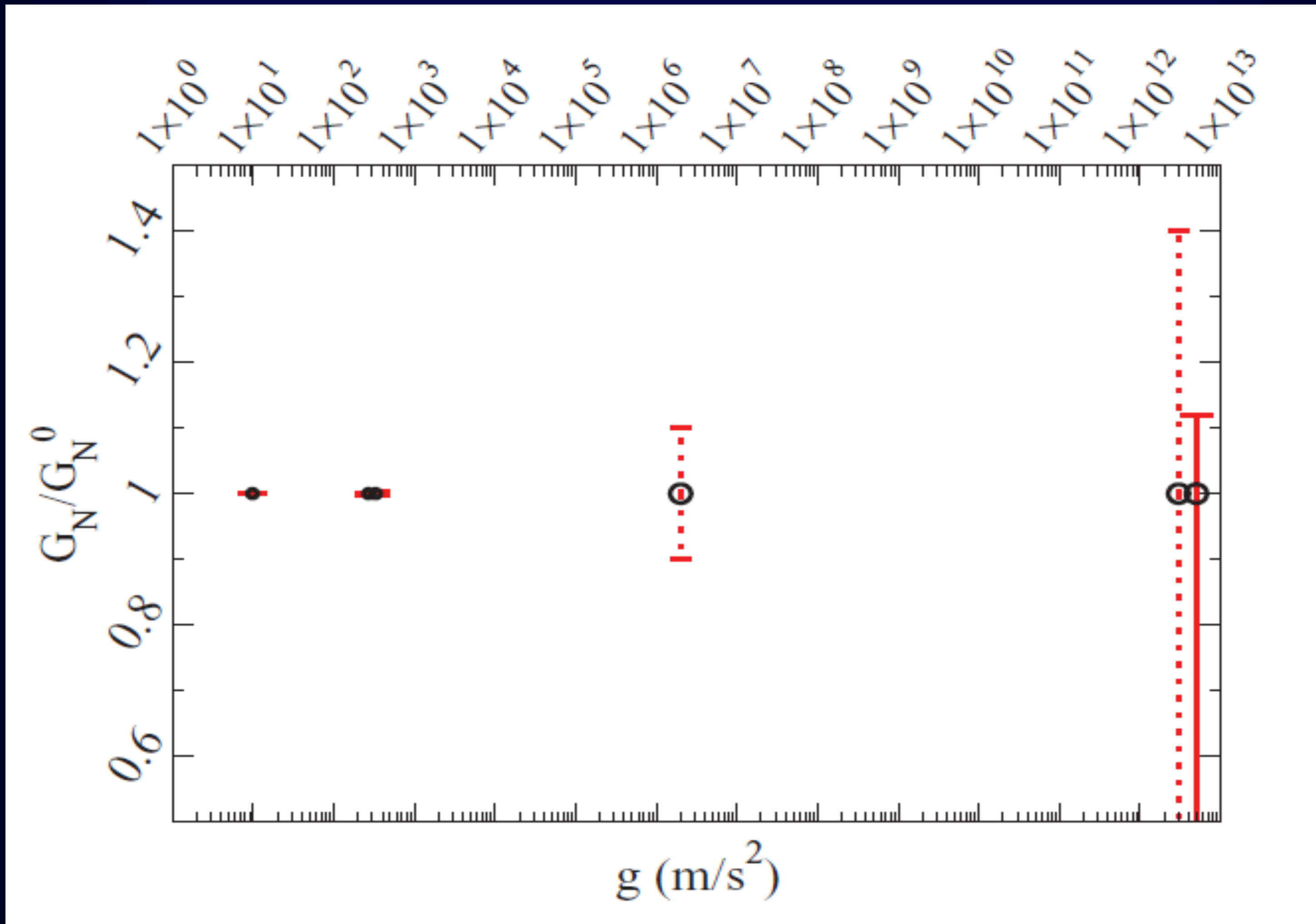
$$P = P_0 + c^2(\rho - \rho_0)$$

(lack of knowledge of dense QCD does not alter conclusions)

Variation of G_N by more than 12% produce gravitational collapse → upper bound on G_N since there is a two-solar-masses neutron star



Setting a new upper bound on G_N at large g.
(12% of the Earth value at he 95% confidence level)



Summary and open questions

- Pulsars are a very interesting laboratory to study the interplay between strong interactions and gravity in the General Relativistic regime.
- The recent finding of a two-solar masses pulsar allows to rule out many models of strange nuclear matter and to set bounds on the variation of G_N in a new regime of extremely high g (12 orders of magnitude the one on Earth).
- This result can be usefull to set new constraints on modifications of GR such as f(R) or Lovelock theories of gravities.
- Work is in progress in that direction.

Thank you very much for your attention