Theory Group at the University of Milano

Astronuclear Physics of Compact Stars

Exploring fundamental physics with Neutron Stars

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EJC 2016

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Plan of the lecture

- **What are neutron stars?** Observed properties and inferred **extreme physical conditions** in their interior.

- **Why stars made of neutrons?** Effects of **strong gravity**: neutronization of matter and instability of relativistic degenerate fermions.

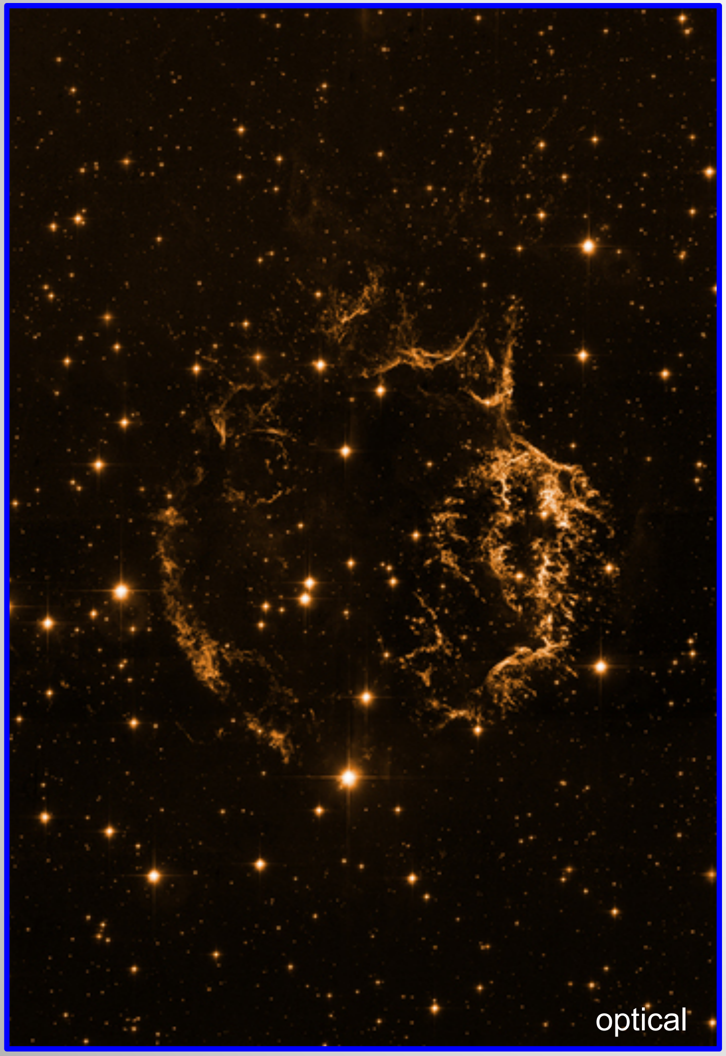
- **How extreme is their nuclear structure?** From the superfluid crust to the ultra-dense exotic core: expected properties of **hadronic matter** with increasing density.

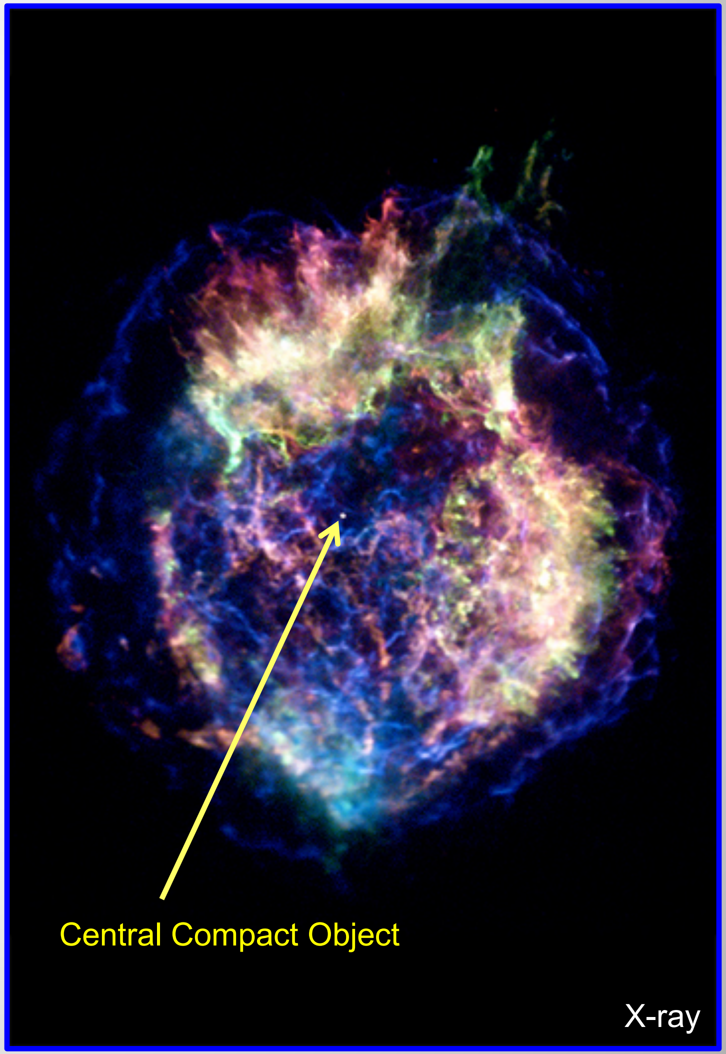
- **Which observations are relevant to fundamental physics?** Some examples: maximum mass, surface temperature, pulsar glitches, gravitational waves, ...

- **What could we learn?** EoS of dense bulk matter and NN interaction, neutrino emissivity and existence of exotic matter, nucleon superfluidity, structure of space-time, ...

Observing neutron stars

Supernova Remnant and CCO in Cassiopeia A

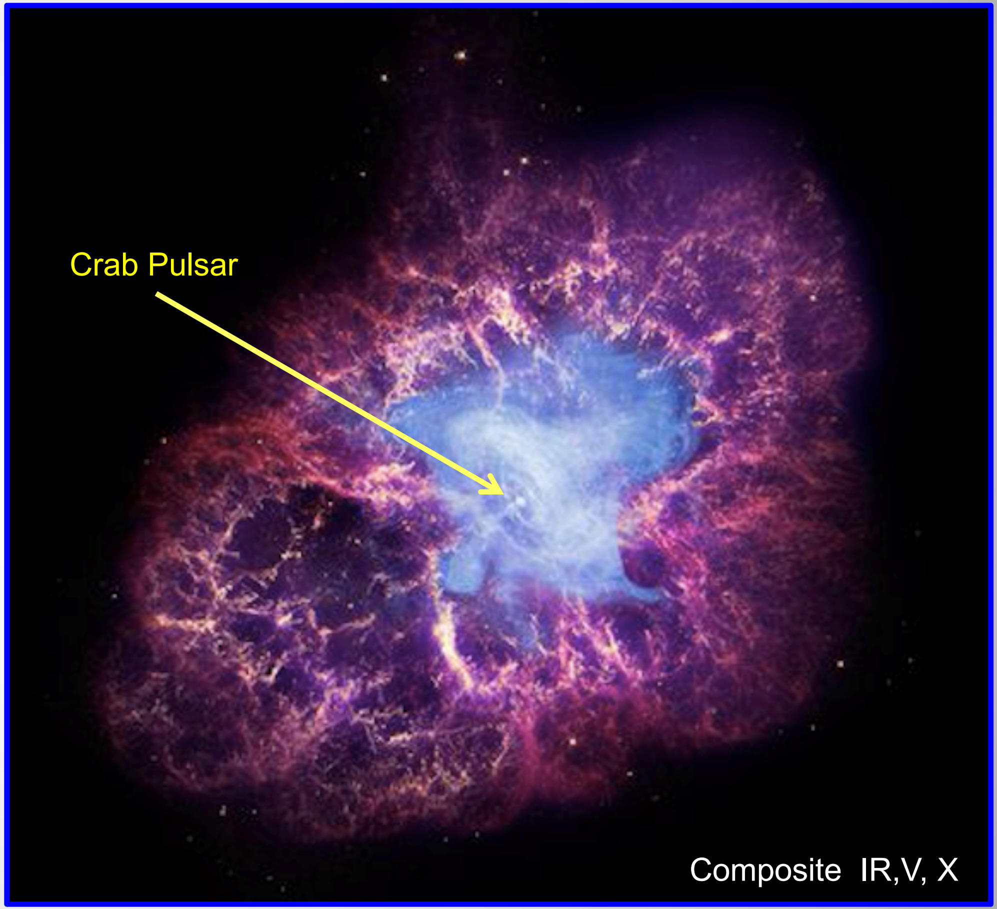




Observing neutron stars

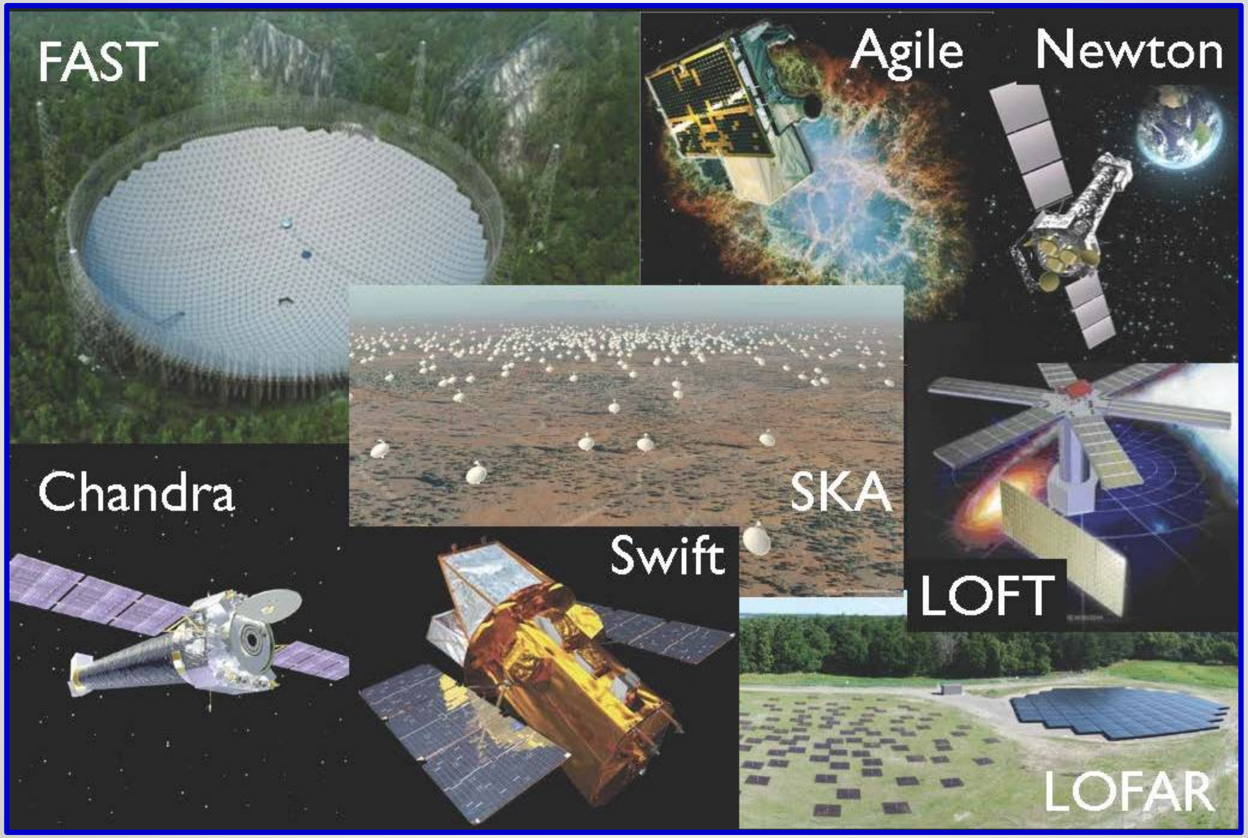
The Crab: SNR, Pulsar and Pulsar Wind Nebula

optical



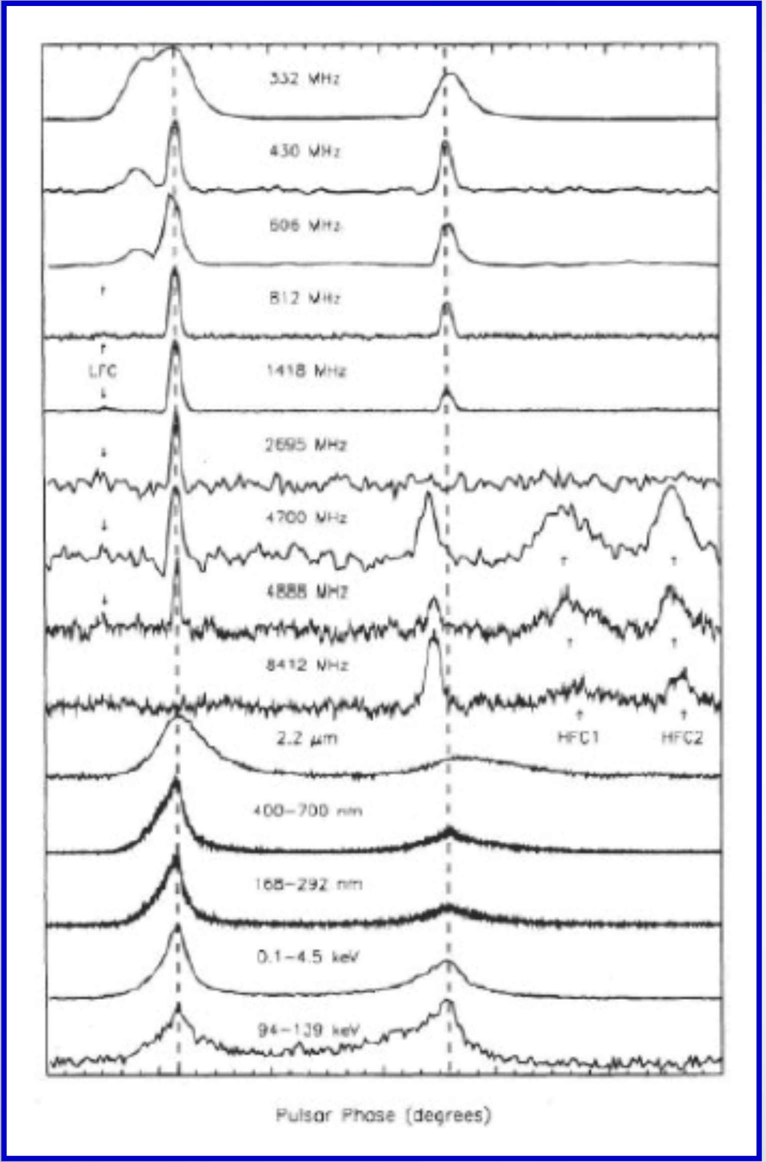
Observing neutron stars

Earth and space-based telescopes for the electromagnetic spectrum (radio to gamma)

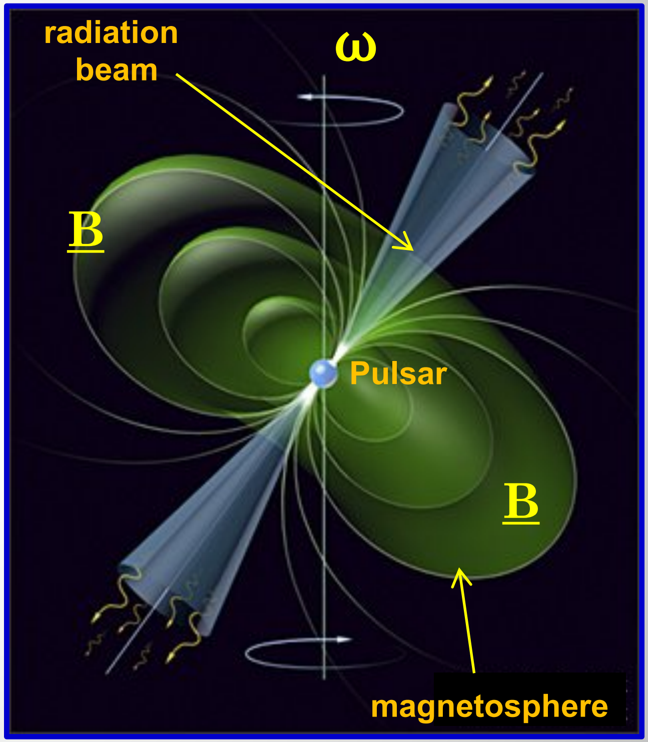


...and the detectors for neutrinos (SN1987A) and gravitational waves (VIRGO, LIGO)

Observing neutron stars



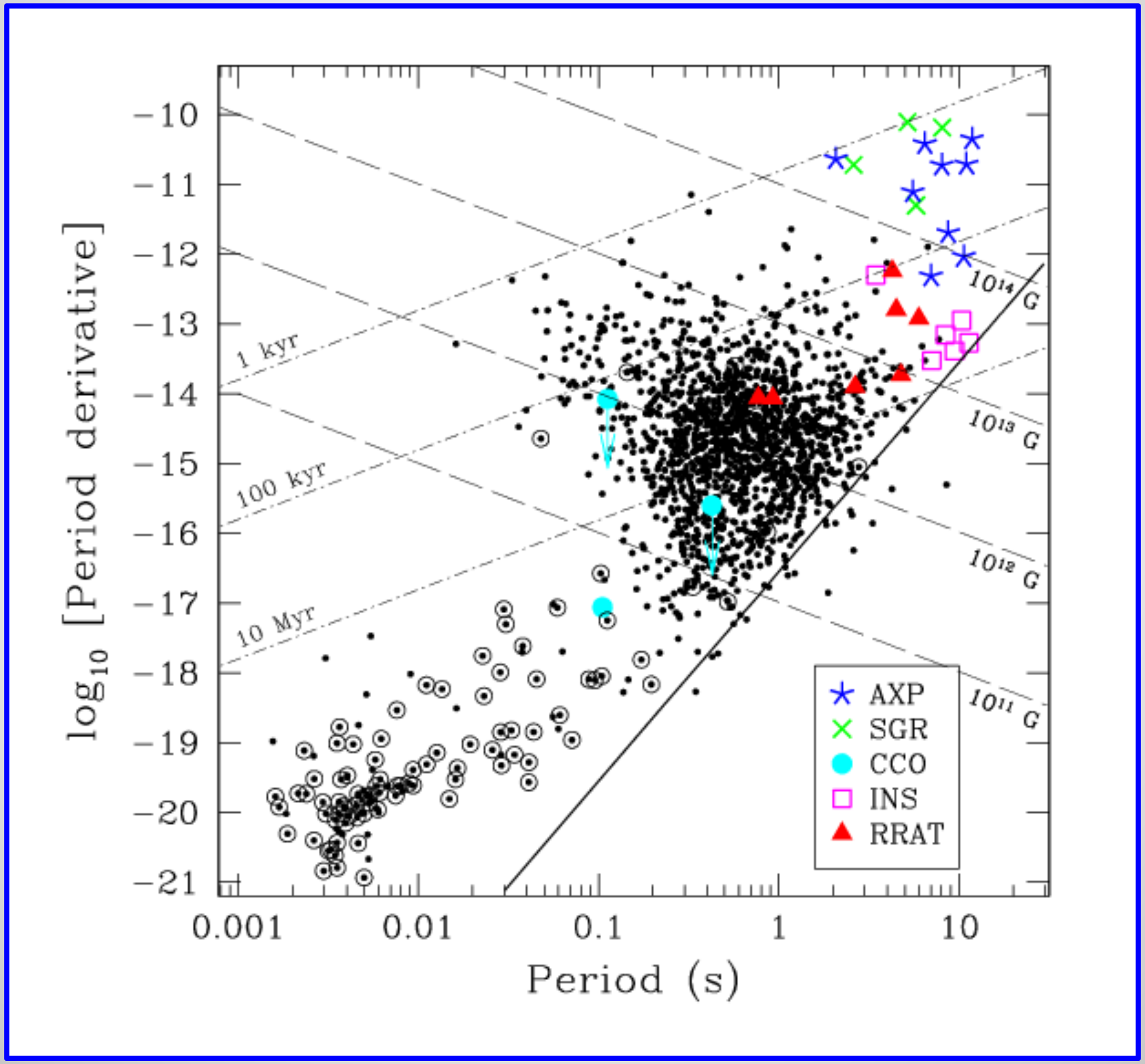
Pulsars: the most accurate clocks in the Universe



The lighthouse model with a rotating magnetic dipole

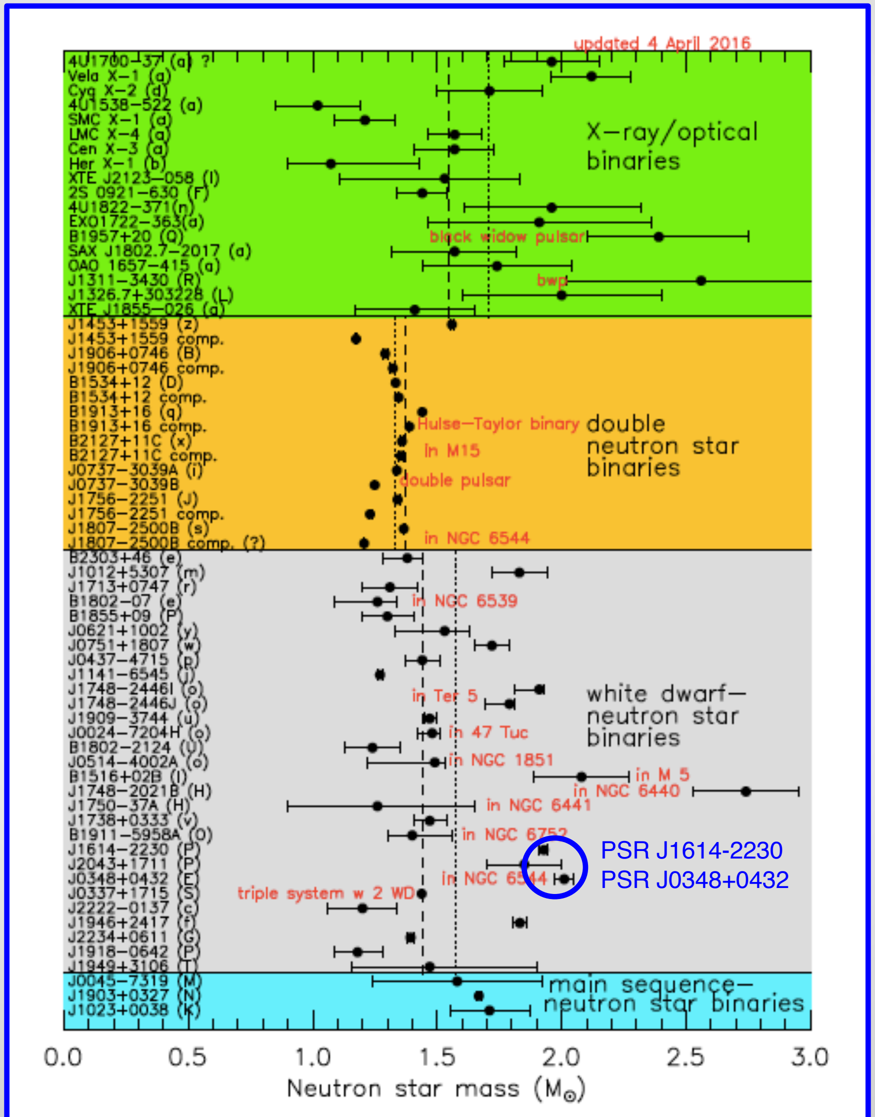
Observing neutron stars

The observed zoo of compact objects



Observing neutron stars

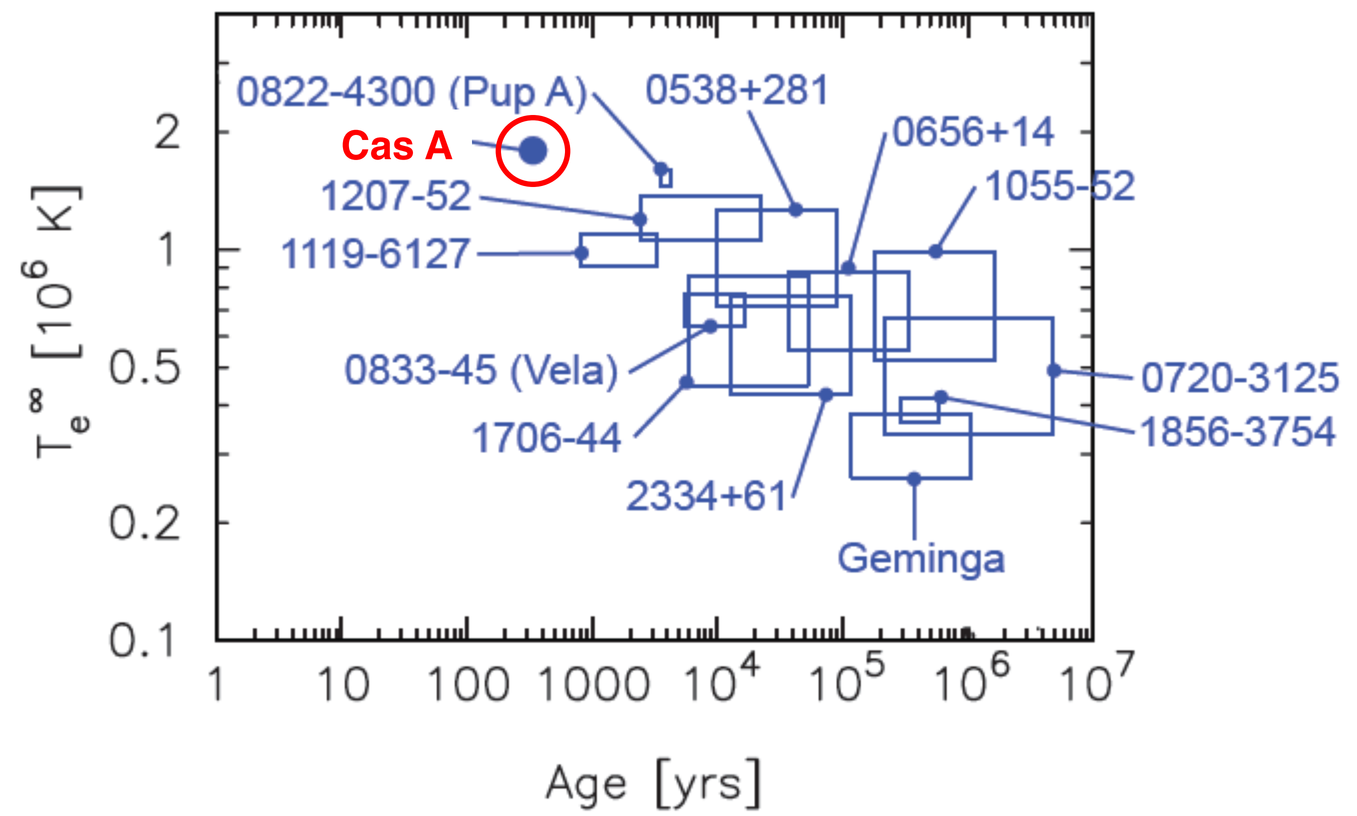
Mass determination in binary systems



Lattimer et al.

Observing neutron stars

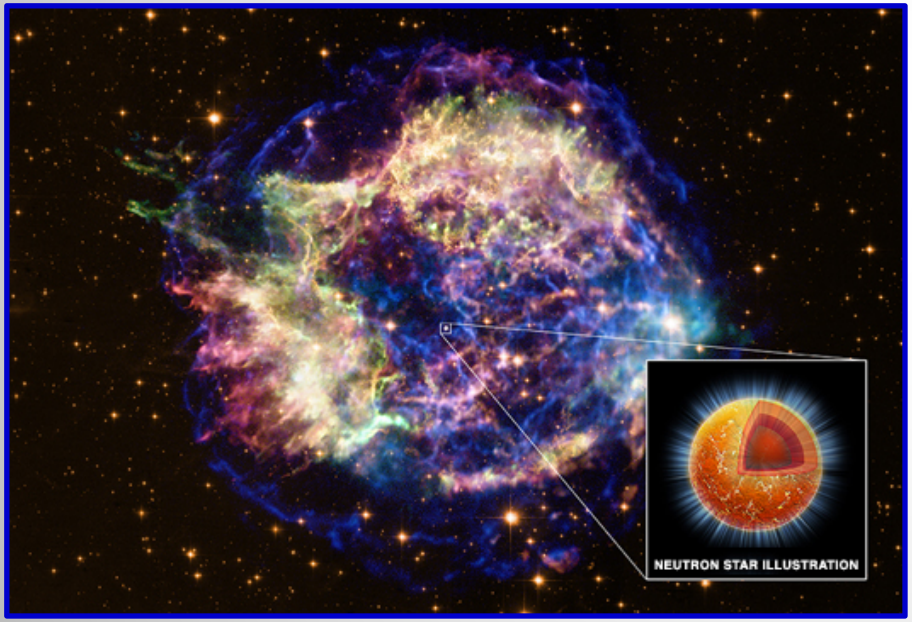
Looking at the x-ray emitting surface of neutron stars



Page et al.

Physical conditions of neutron stars

Extreme physical conditions
of the most exotic objects
in the Universe



$M \sim 1 - 2\ M_\odot$

$R \sim 10 - 15$ km

$\rho_{av} \sim 10^{14} - 10^{15}$ g/cm^3

$T_{obs} \sim 10^5 - 10^6$ K

$T_{int} \sim 10^8 - 10^9$ K

$\omega \sim 0.1 - 1000$ Hz

$V_R/c \sim 0.01 - 0.2$

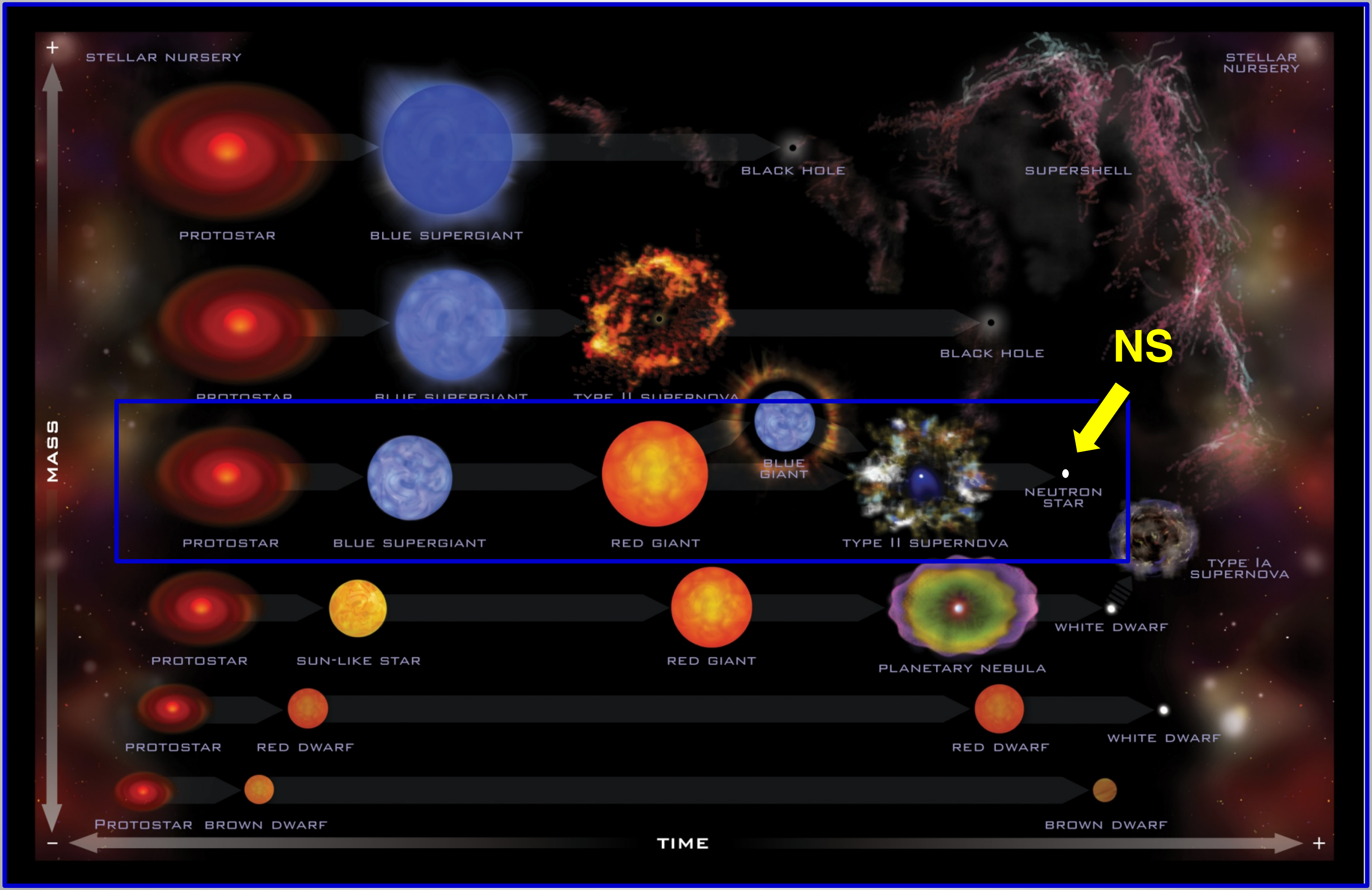
$B \sim 10^8 - 10^{15}$ G

$L_{crab} \sim 10^{38}$ erg/s

$GM/Rc^2 \sim 0.1 - 0.3$

The origin of neutron stars

Gravity-driven evolution: from gaseous nebulae to compact stars



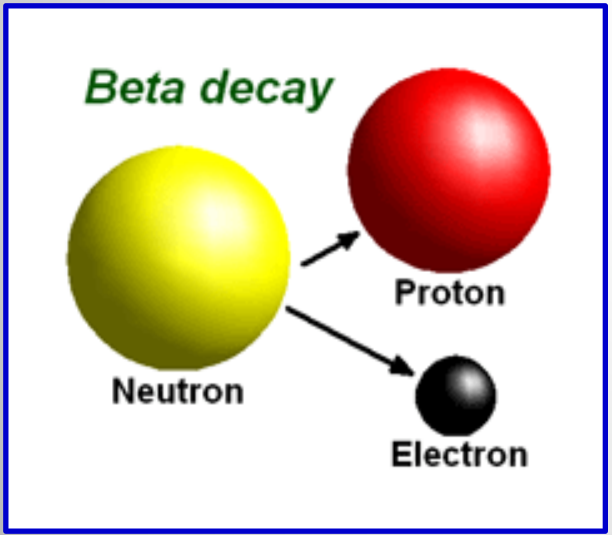
Neutronization in strong gravity

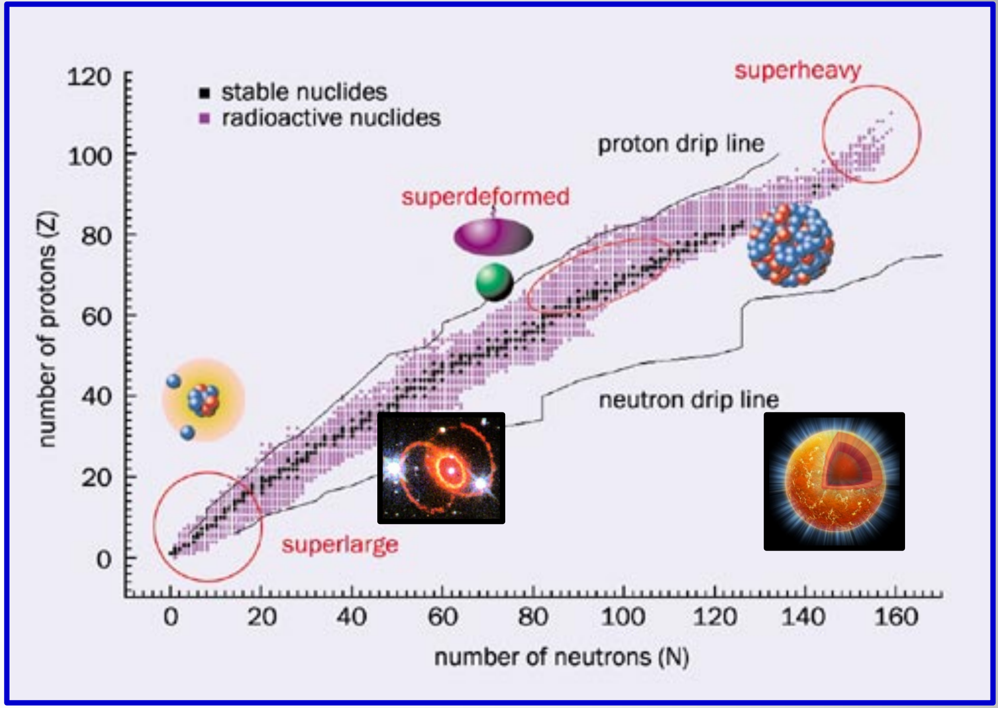
Electron capture

$$p + e \rightleftarrows n$$

$$(m_n - m_p)c^2 = 1.3 \text{ MeV}$$

$$m_e c^2 = 0.5 \text{ MeV}$$





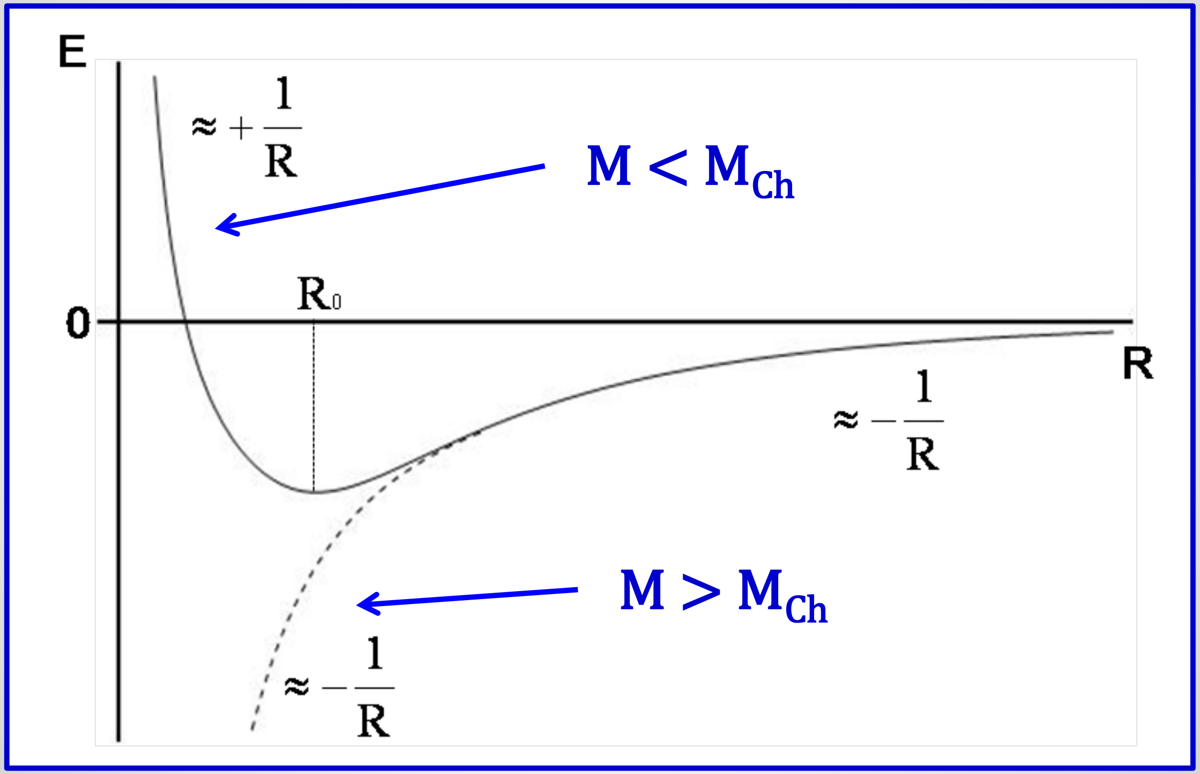
Gravity-induced neutronization by relativistic degenerate electrons

$$\mu_e + \mu_p = \mu_n$$

$$\mu_e = c p_F \propto \rho^{1/3}$$

Chandrasekhar's gravitational instability

Under relativistic degenerate conditions, gravitationally self-bound spheres of fermions become unstable



$\epsilon_{grav} \propto -M/R$

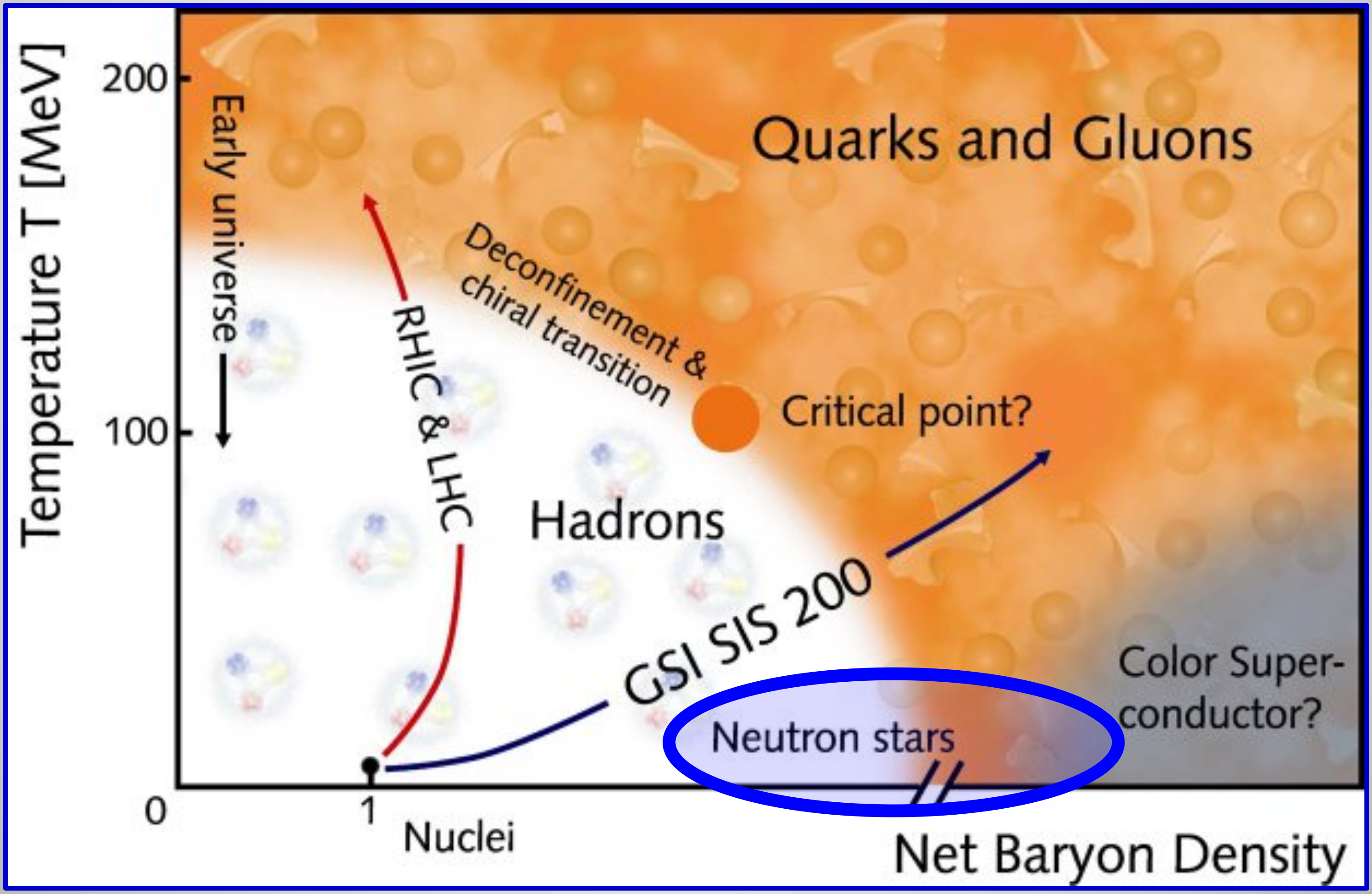
$\epsilon_{int} = cp_F \propto M^{1/3}/R$

$\epsilon_{tot} \propto (M^{1/3} - M)/R$

$M_{Ch} \sim M_{\odot} \sim 10^{57}$ nucleons

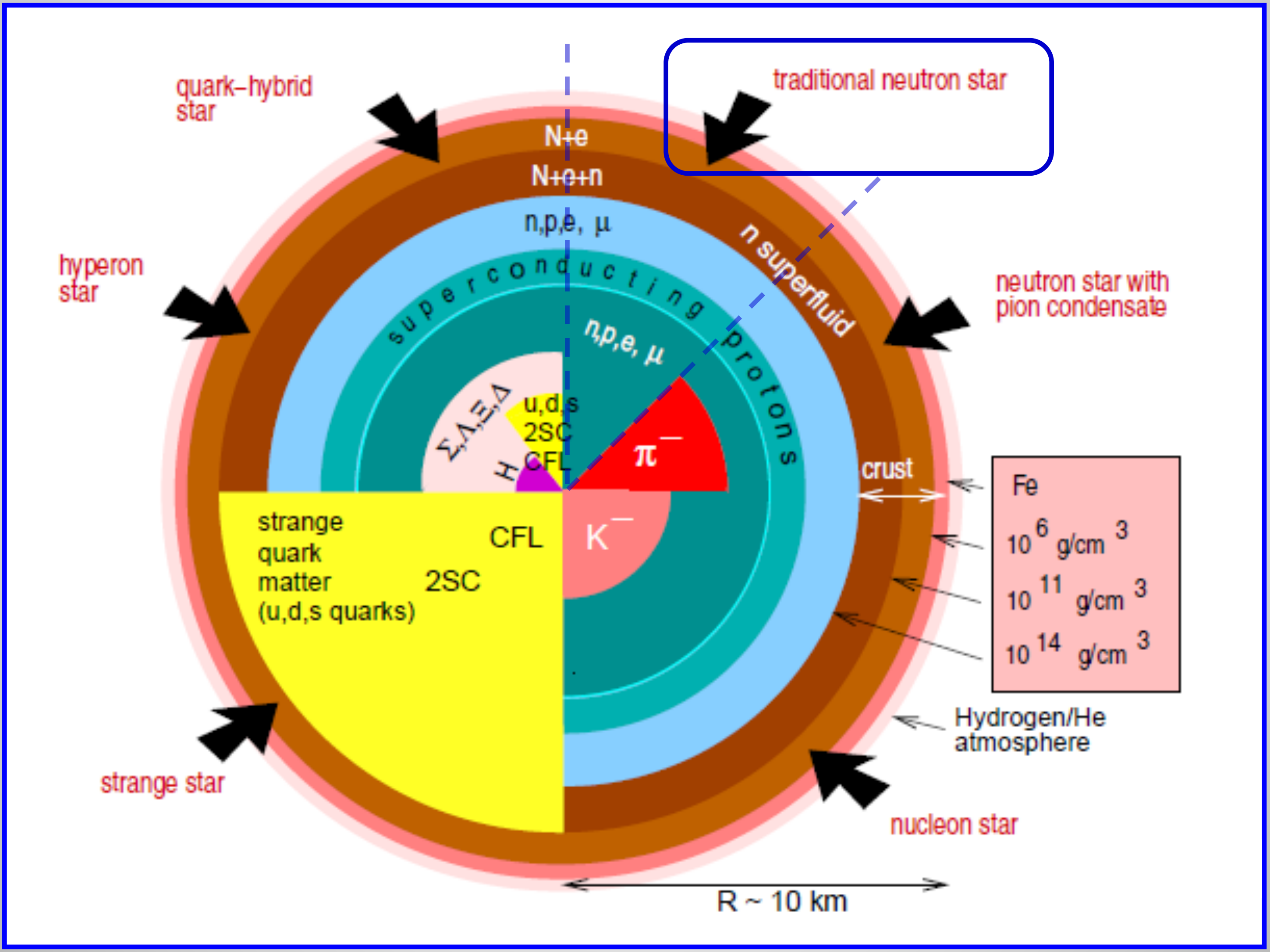
Compact stars and hadronic matter

Probing the phase diagram of cold and dense hadronic matter with compact stars



Compact stars and hadronic matter

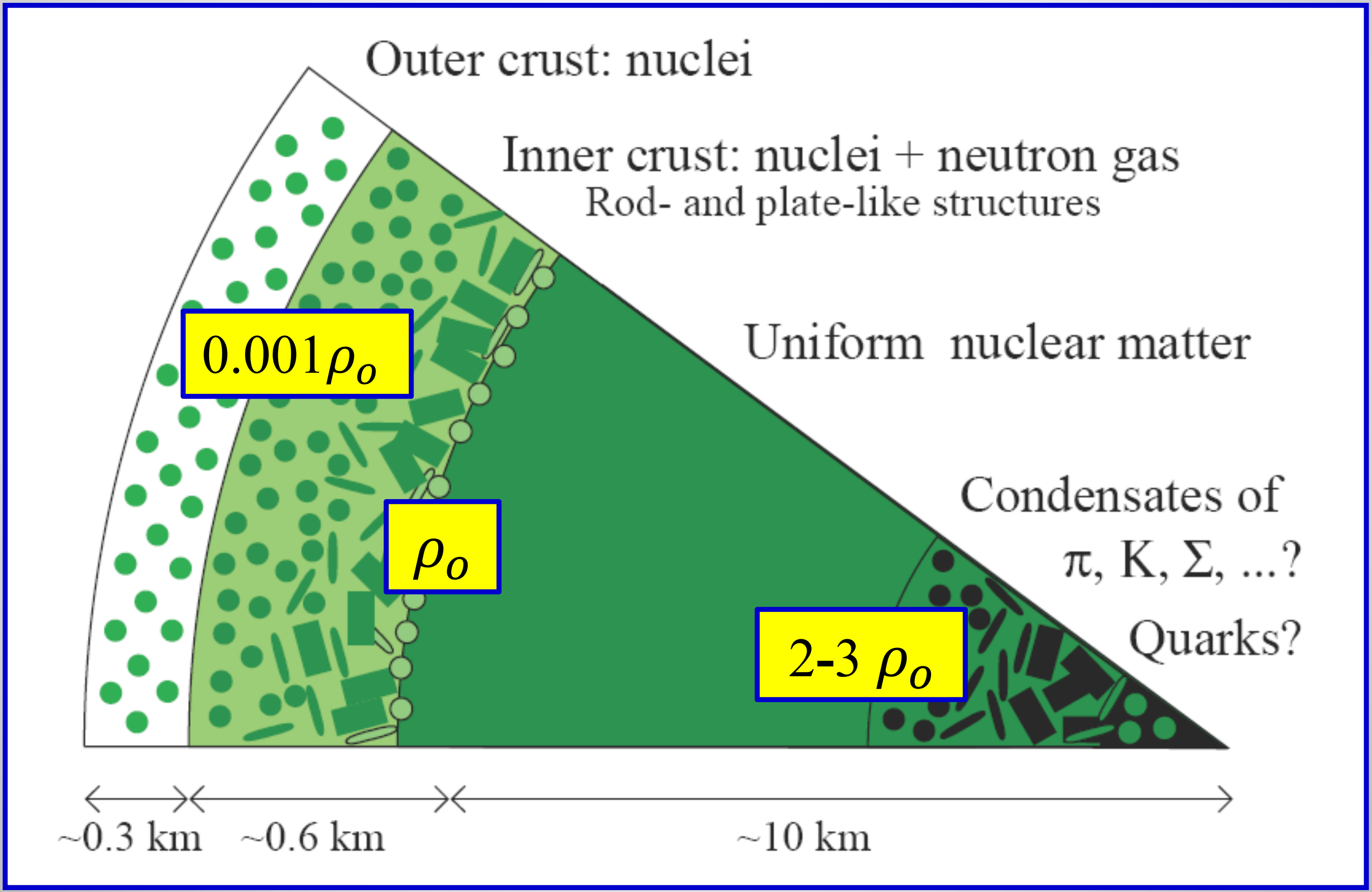
The many theoretical facets of compact stars



F. Weber

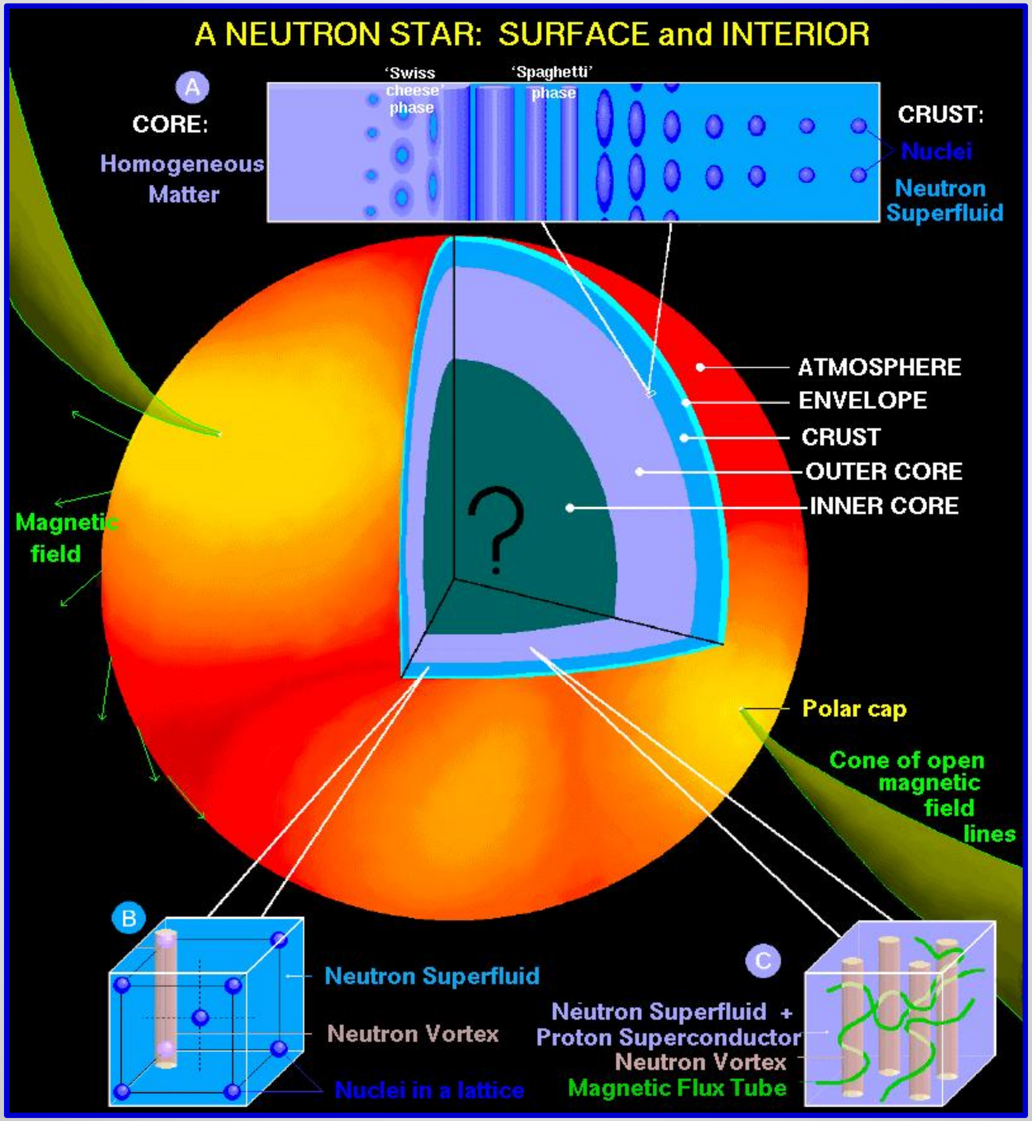
Internal structure of neutron stars

Nuclear structure under strong gravity:
from the superfluid crust to the exotic core



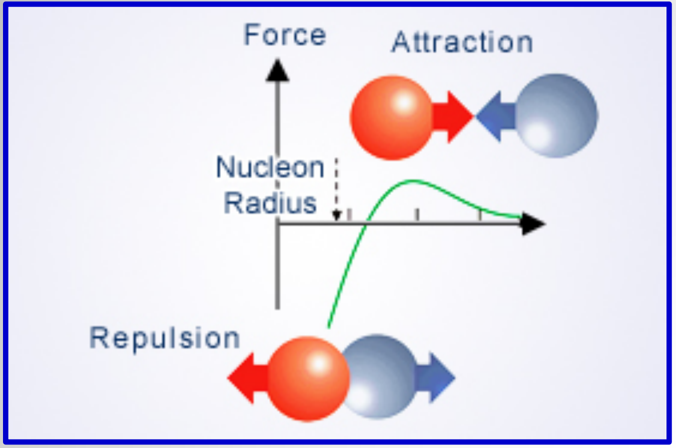
Internal structure of neutron stars

How to probe such an exotic system?



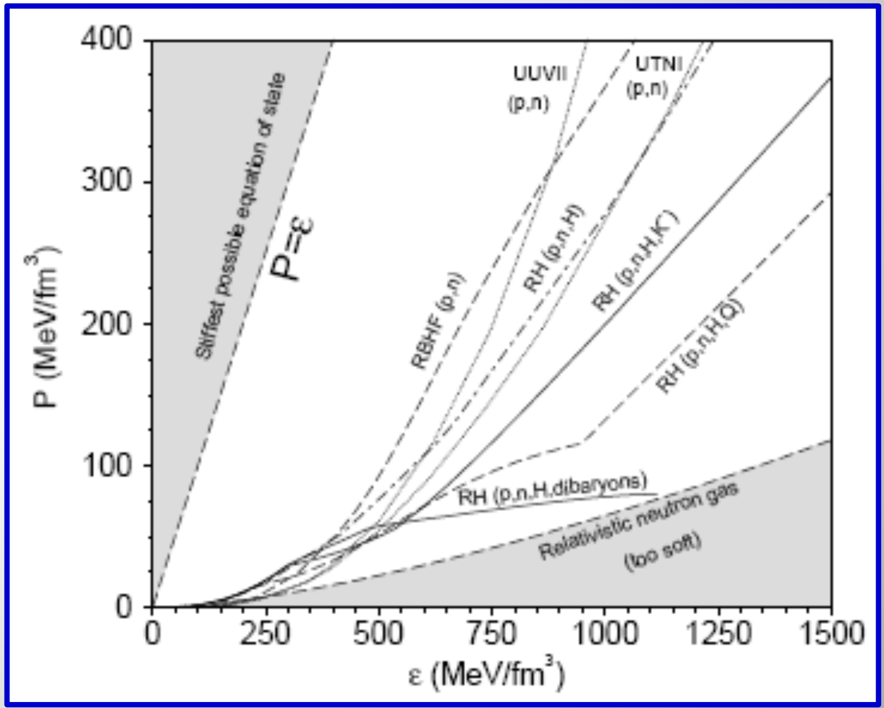
D. Page

Neutron stars and EoS of dense matter



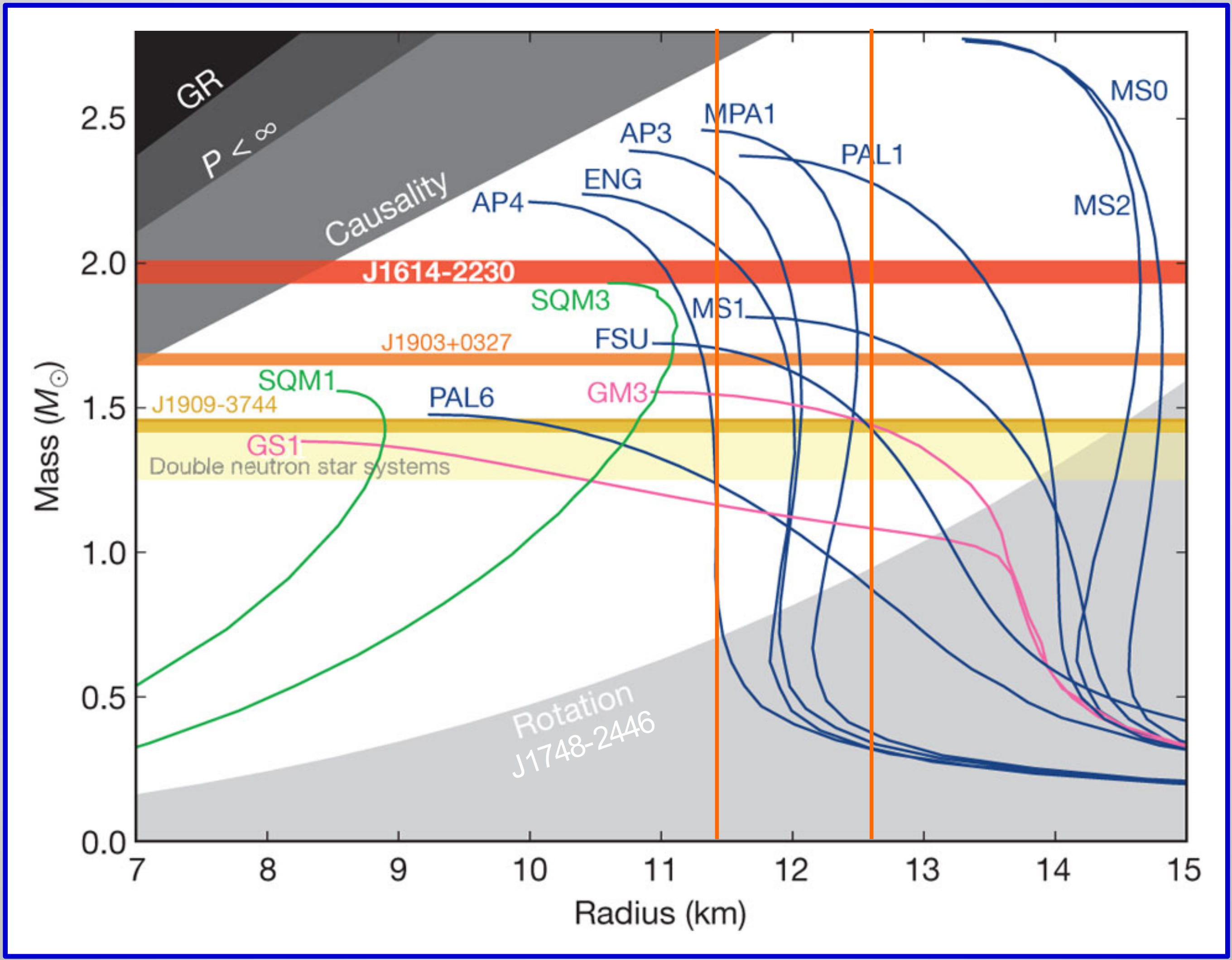
The Nucleon-Nucleon interaction: the Holy Grail of hadronic physics in the confined sector

The bridge to astrophysics: the Equation of State (EoS) of bulk, cold, dense, asymmetric matter



Neutron stars and EoS of dense matter

Constraining the EoS of dense matter: M-R diagram



Lattimer et al.

Cooling of neutron stars

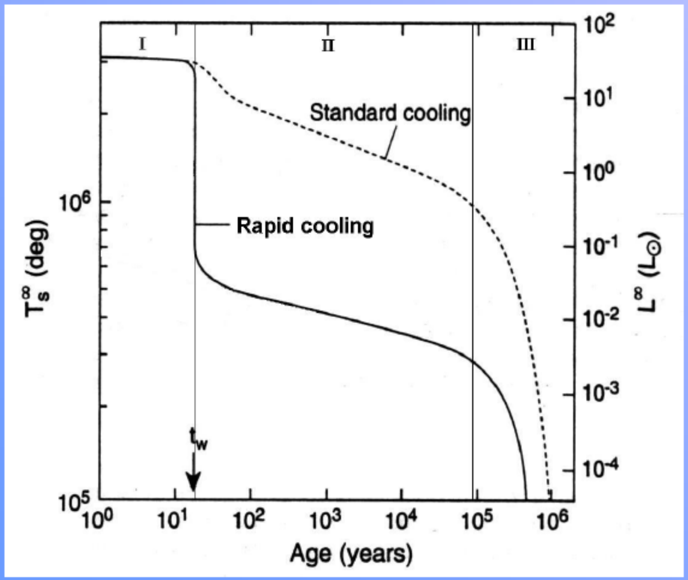
Neutrino cooling: depend on composition and structure of core and crust ⇒ diagnostic tool for NS interior

Standard cooling
(low core density)

low mass NS with stiff EoS

Rapid or exotic cooling
(high core density)

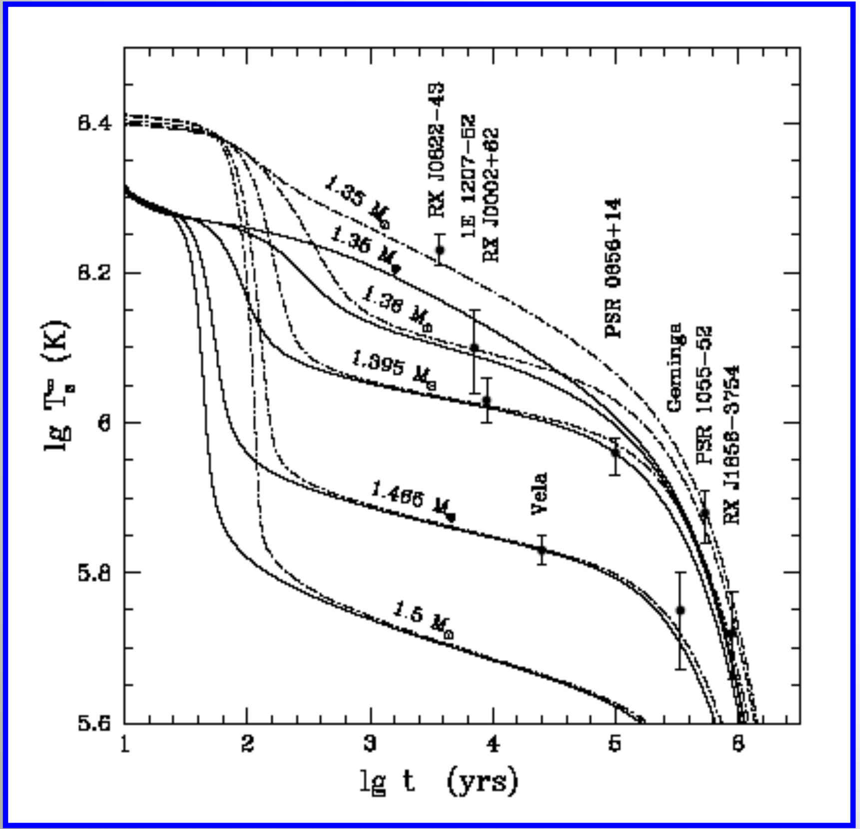
high mass NS or
low mass NS with soft EoS



I. Core relaxation epoch
II. Neutrino cooling epoch
III. Photon cooling epoch

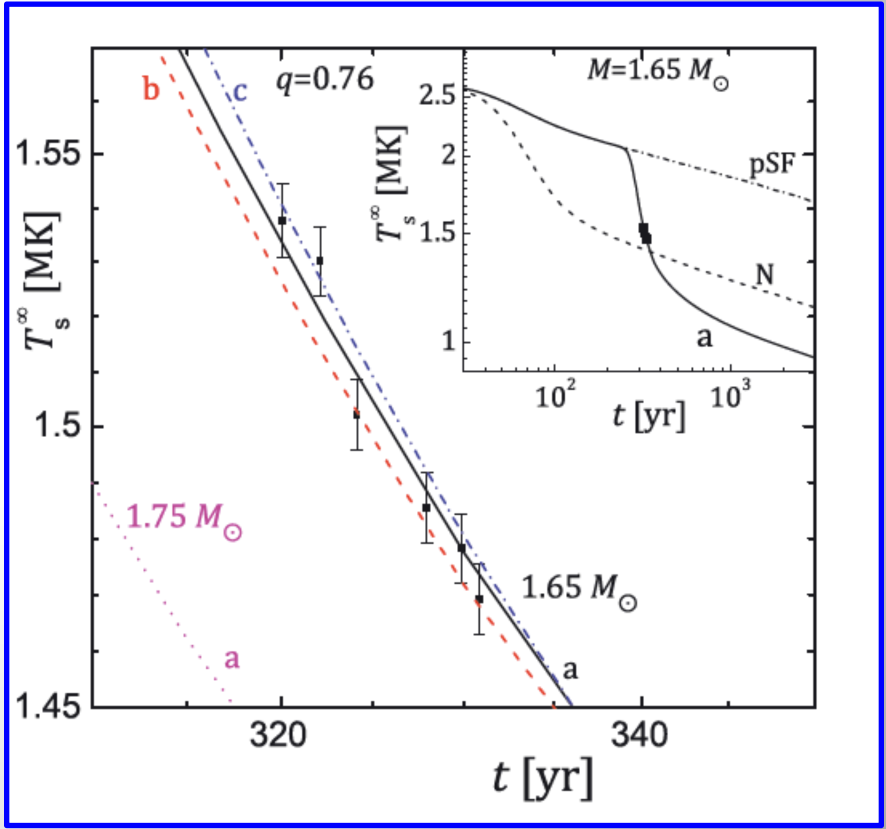
Cooling of neutron stars

The program: cooling as a probe of NS structure



Yakovlev et al.

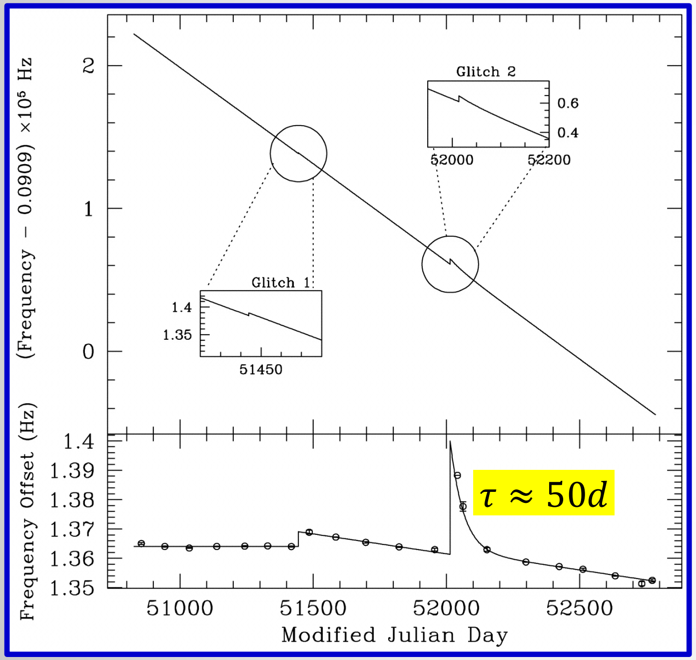
Cas A: seeing neutrino cooling happen in a superfluid star



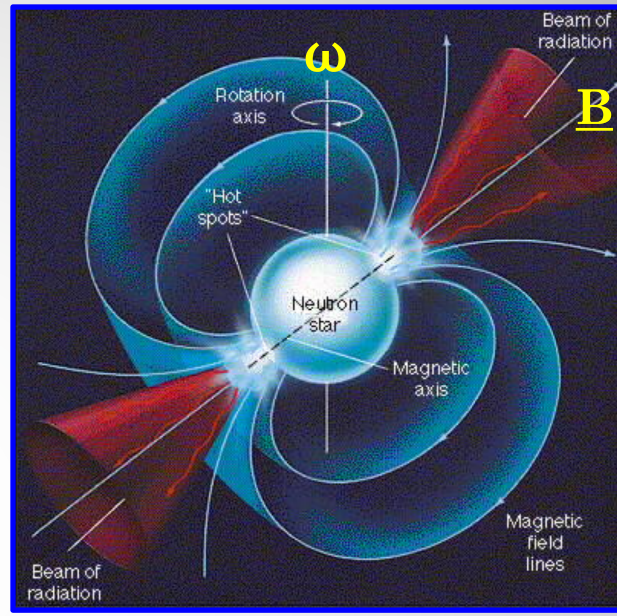
Heinke et al.

Pulsar glitches and superfluidity

Steady rotational slow-down of Pulsar due to emission of e.m. and gravitational waves



Kaspi & Gavrill

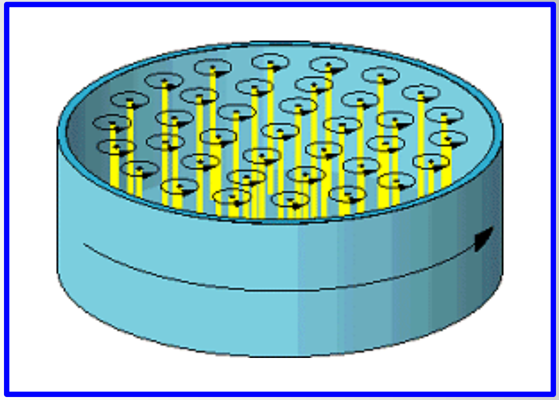


Glitches are recurrent spin-ups of rotational frequency ($\Delta\omega/\omega \sim 10^{-9}$- 10^{-5}) without external causes

Glitches as direct observational evidence of the existence of macroscopic (km-sized) nucleon superfluidity inside NS

Pulsar glitches and superfluidity

Angular momentum of rotating neutron superfluid is quantized in parallel array of vortex lines



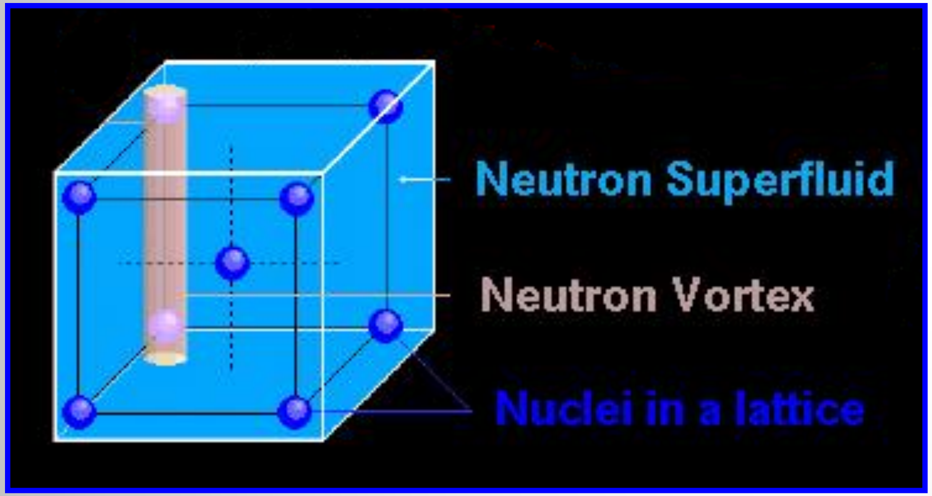
Collective vortex depinning by hydrodynamical forces

⇓

Transfer of vortex angular momentum from superfluid to star crust

⇓

Glitch in rotational frequency

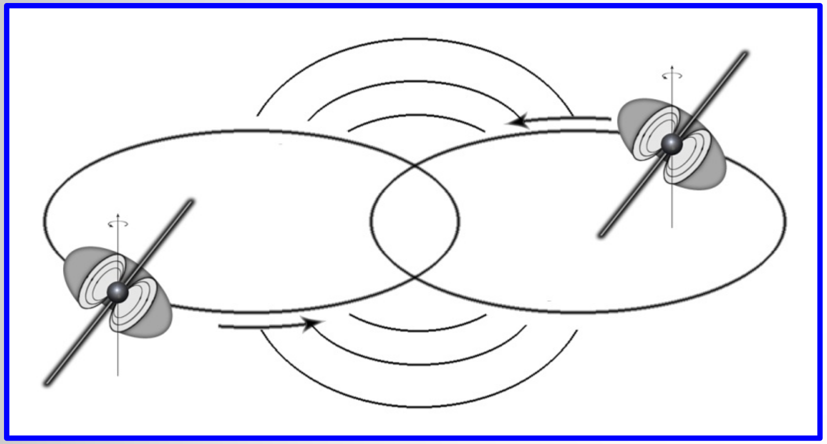


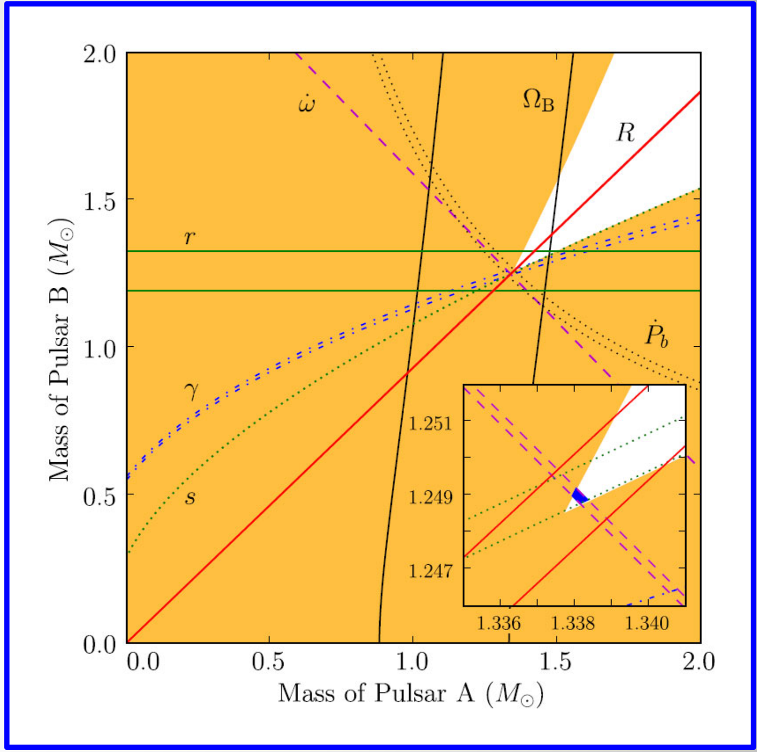
Vortices in the Inner Crust pin to lattice of exotic nuclei ⇒ angular momentum of neutron superfluid is frozen

Microscopic input
⇒ pinning energy

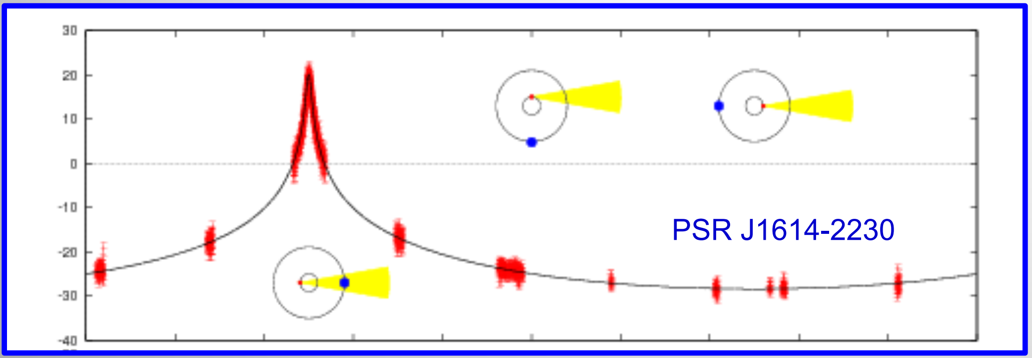
Neutron stars and space-time

Compact stars in binary systems: the ultimate general relativistic flywheel





Kramer et al.

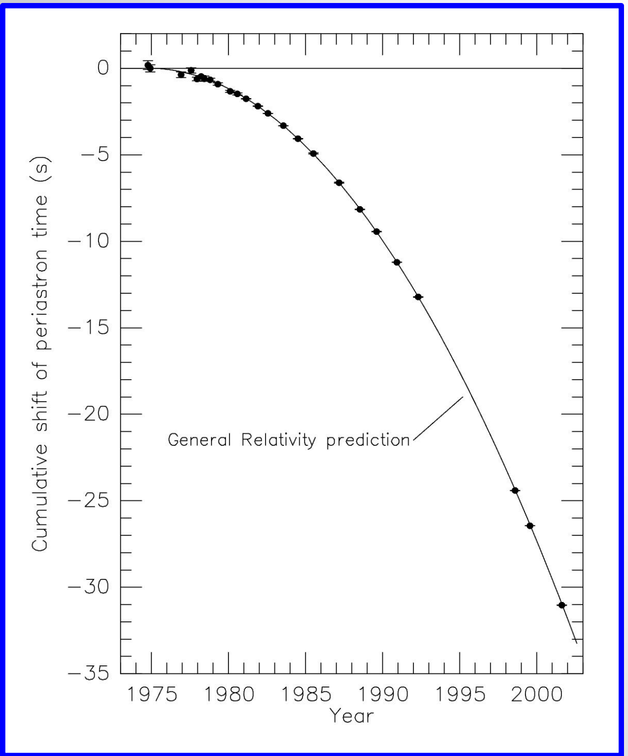


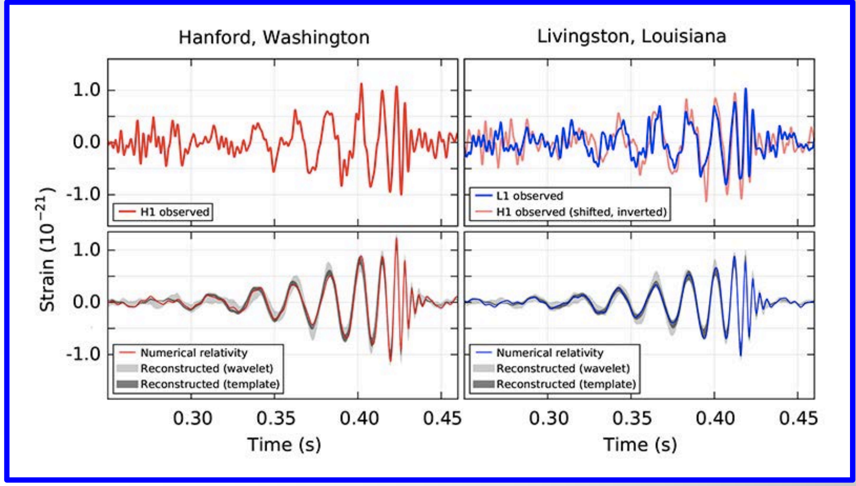
Demorest et al.

Testing General Relativity through high-precision mass measurements

Neutron stars and space-time

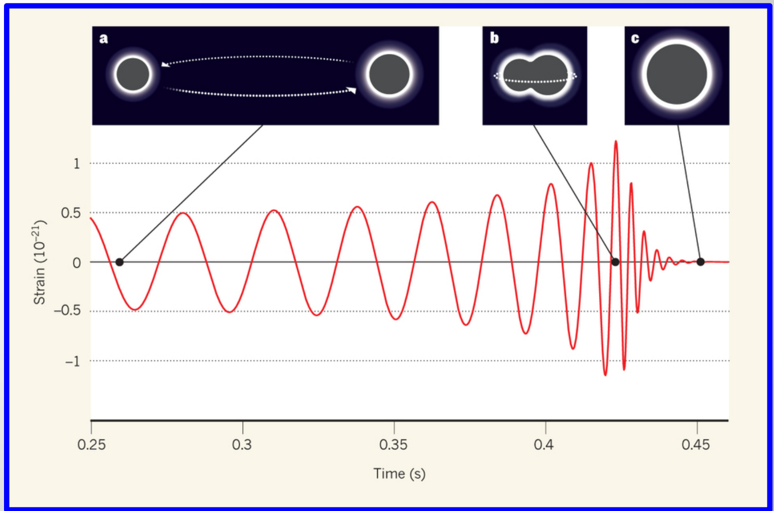
The first evidence for gravitational waves: the Hulse-Taylor binary pulsar





Abbott et al.

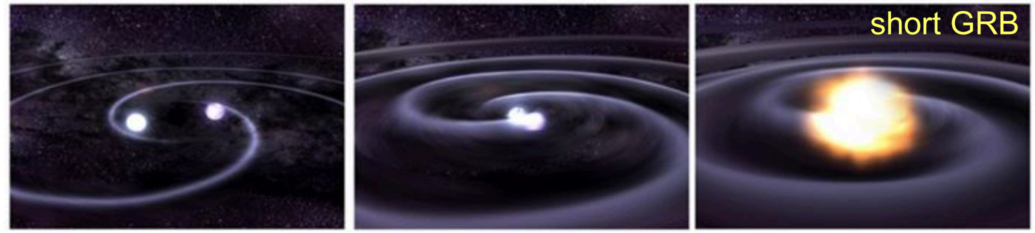
The first detection: GW150914 (@*LIGO*)



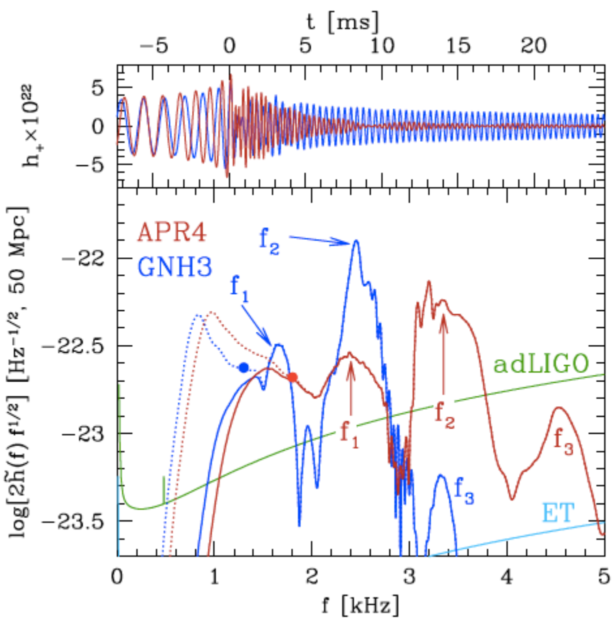
Abbott et al.

Neutron stars and space-time

The utimate probe
for NS interior:
coalescing NS binaries
(expected 2017)



Constraining the EoS of dense matter with GW



Rezzolla et al.

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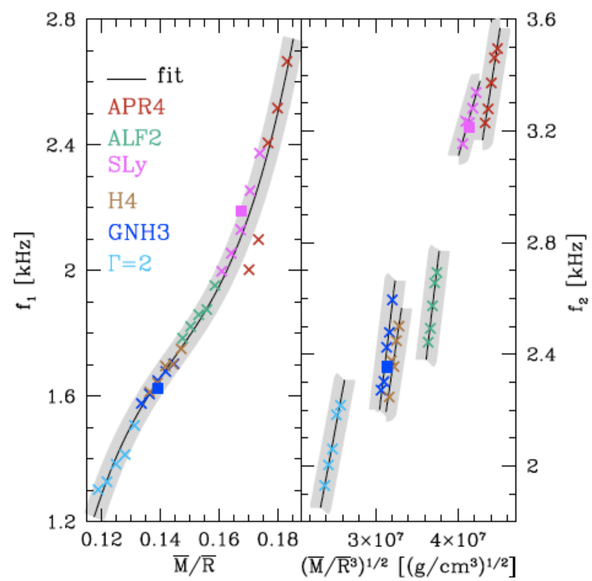

Rezzolla et al.

The CompStar european network

European Science Foundation

comp star

2008-2013

RNP CompStar

http://www.compstar-esf.org

2014-2018

COST Action MP1304

Exploring fundamental physics with compact stars

http://compstar.uni-frankfurt.de