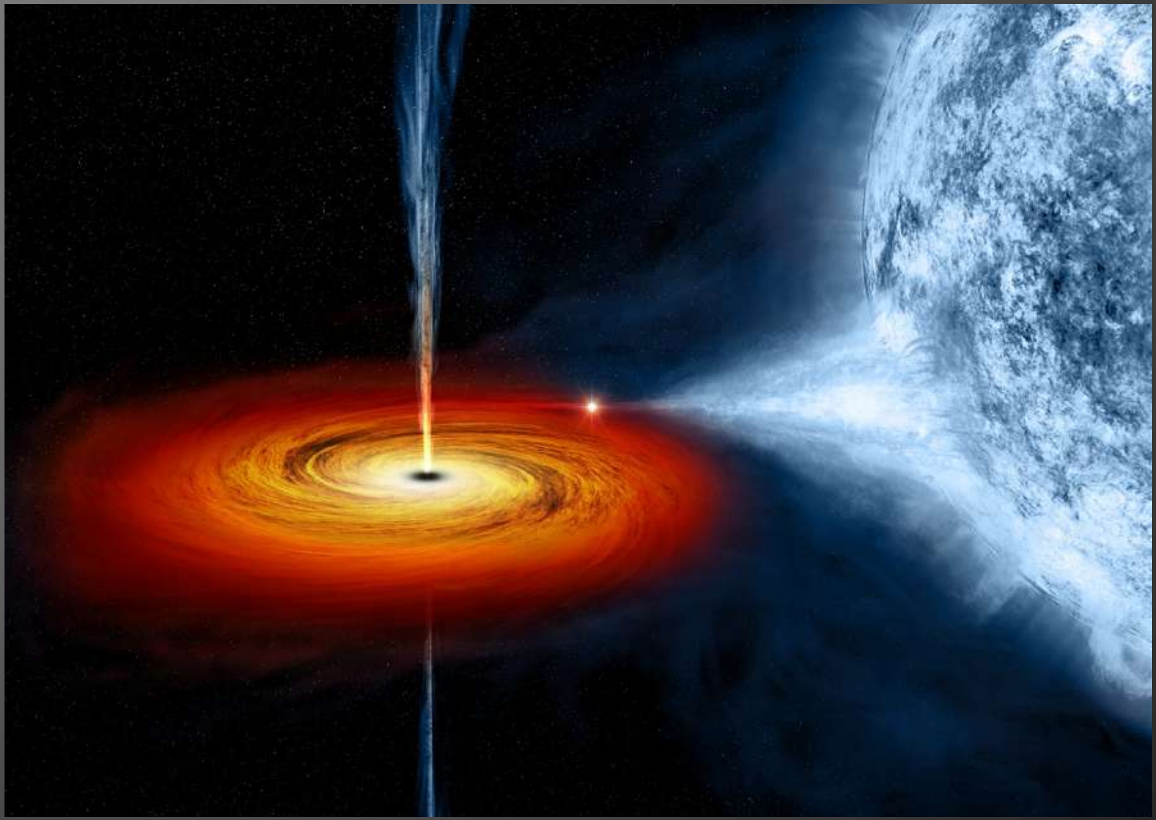
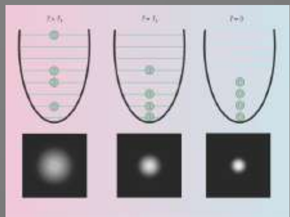
PHYSICS OF COMPACT OBJECTS
AND THEIR BINARY INTERACTIONS

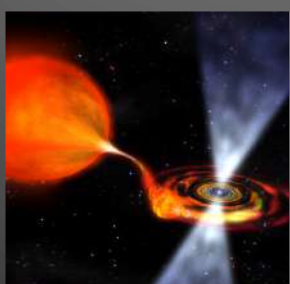


AALBORG UNIVERSITY

Thomas Tauris – Physics, Aalborg University

Programme

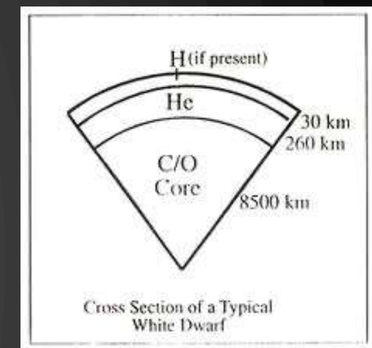



- **Introduction**
- **Degenerate Fermi Gases**
  Non-relativistic and extreme relativistic electron / (n,p,e^-) gases
- **White Dwarfs**
  Structure, cooling models, observations
- **Neutron Stars**
  Structure and equation-of-state
- **Radio Pulsars**
  Characteristics, spin evolution, magnetars, observations, timing
- **Binary Evolution and Interactions**
  X-ray binaries, accretion, formation of millisecond pulsars, recycling
- **Black Holes**
  Observations, characteristics and spins
- **Gravitational Waves**
  Sources and detection, kilonovae
- **Exam**

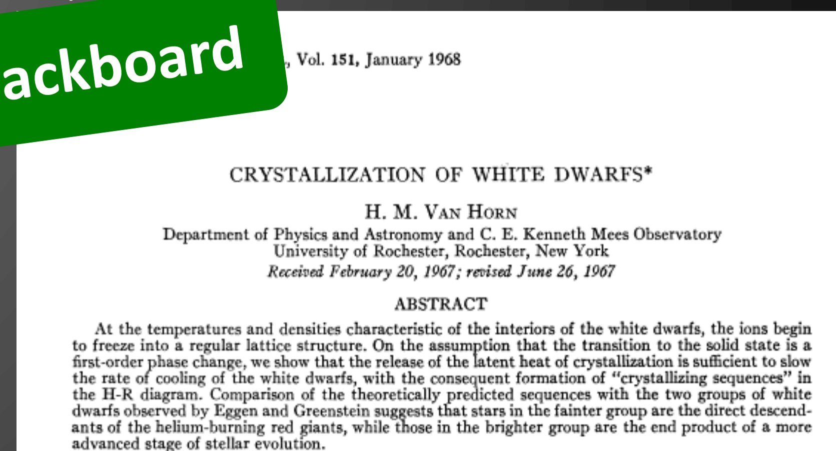
Last week

Cooling of White Dwarfs



- Surface layers and core structure
- Photon diffusion equation $L = -4\pi r^2 \frac{c}{3\kappa\rho} \frac{d}{dr}\left(aT^4\right)$
  - Temperature gradient
  - Pressure gradient (via hydrostatic equilibrium)
  - Core-surface boundary conditions
  - Luminosity as a function of (M, T_*)
- Elementary treatment of WD cooling
  - Residual ion thermal energy
  - Cooling age
- Crystallization
  - Rapid cooling
- Observational support of WD cooling models

Blackboard



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CRYSTALLIZATION OF WHITE DWARFS*

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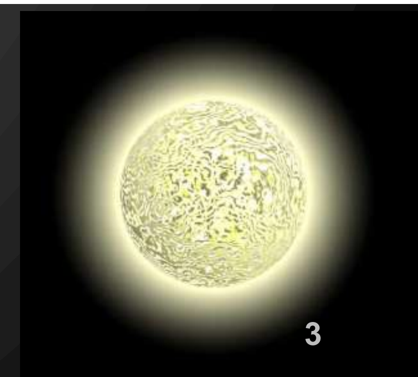
ABSTRACT

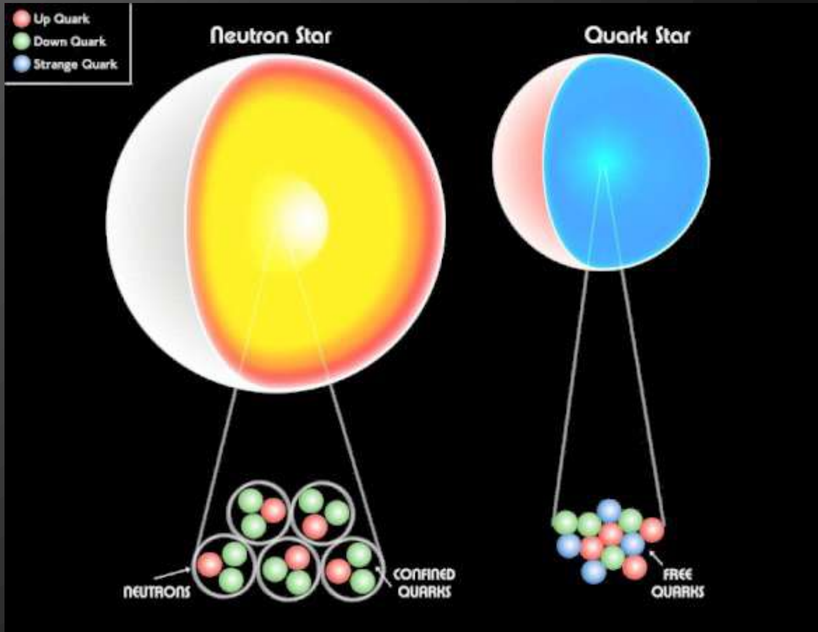
At the temperatures and densities characteristic of the interiors of the white dwarfs, the ions begin to freeze into a regular lattice structure. On the assumption that the transition to the solid state is a first-order phase change, we show that the release of the latent heat of crystallization is sufficient to slow the rate of cooling of the white dwarfs, with the consequent formation of "crystallizing sequences" in the H-R diagram. Comparison of the theoretically predicted sequences with the two groups of white dwarfs observed by Eggen and Greenstein suggests that stars in the fainter group are the direct descendants of the helium-burning red giants, while those in the brighter group are the end product of a more advanced stage of stellar evolution.

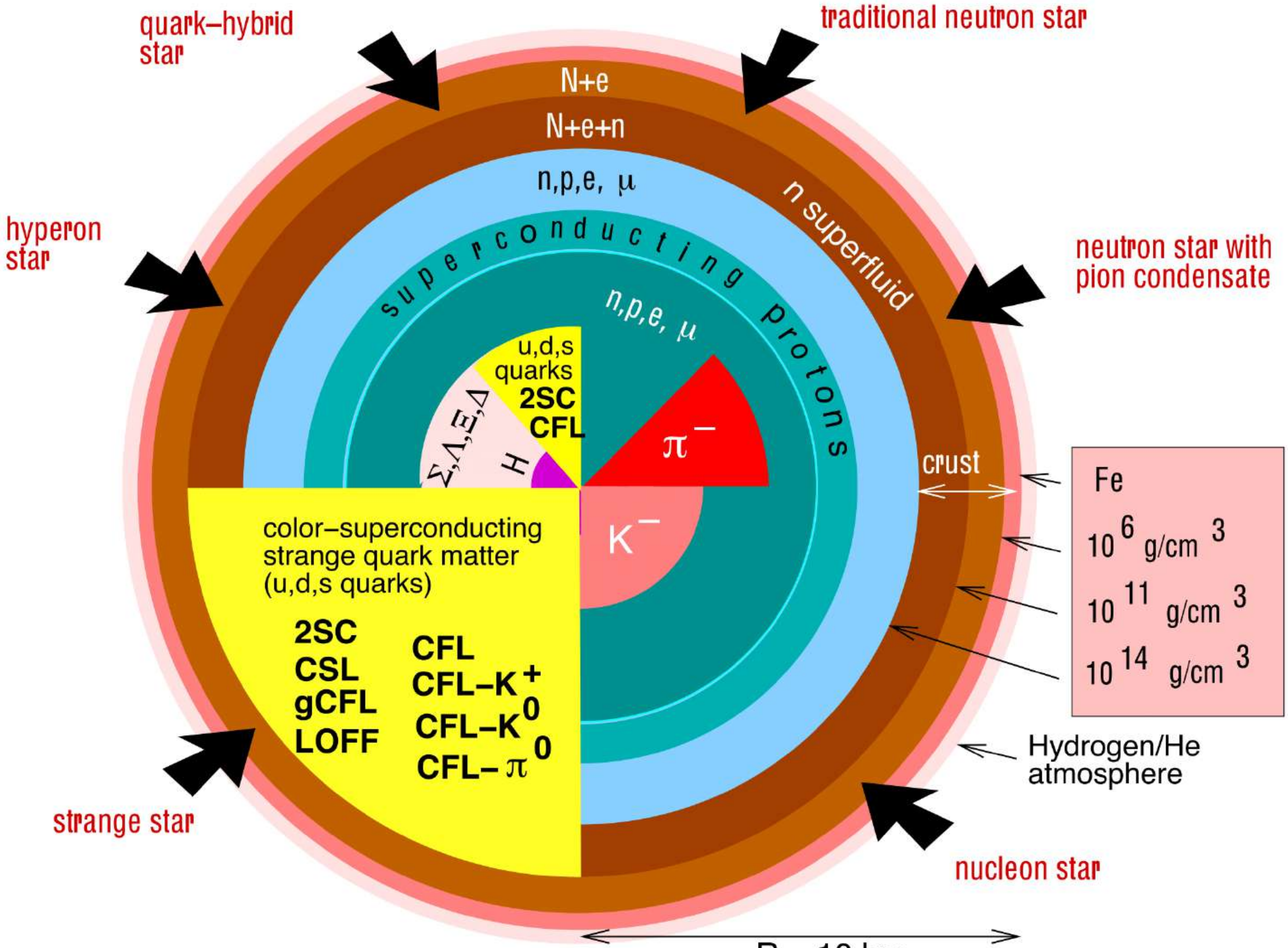


Structure of Neutron Stars

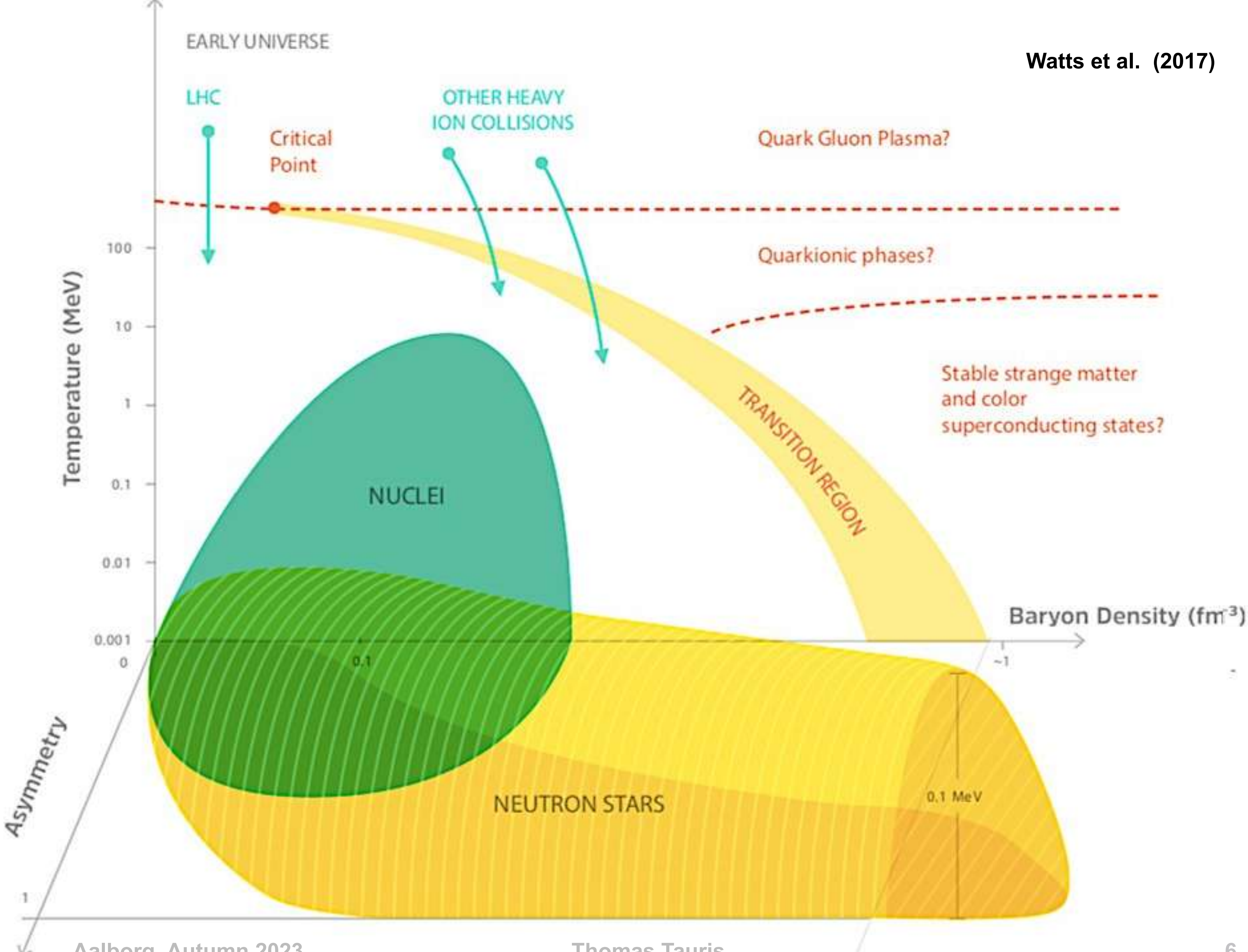
Cold equations-of-state above neutron drip

- EoS for $\rho_{drip} < \rho < \rho_{nuc}$
  - Baym-Bethe-Pethick (BBP) EoS
  - Stability of NSs
- EoS for $\rho > \rho_{nuc}$
  - Nucleon-nucleon interactions
  - Muons, hyperons, Δ-resonances, pion/kaon condensation
  - Superfluidity (glitches/cooling of NSs)
  - Bethe-Johnson (BJ) EoS
  - Quark (strange) stars / quark-novae
- Summary of EoS above neutron drip
- Structure of NSs
  - Cross section
  - Soft vs Stiff EoS
  - Observational constraints on M and R



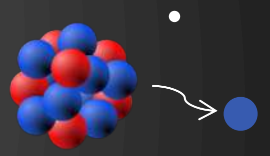

quark–hybrid star
traditional neutron star
hyperon star
neutron star with pion condensate
strange star
nucleon star
N+e
N+e+n
n,p,e, μ
n superfluid
superconducting protons
n,p,e, μ
u,d,s quarks
2SC
CFL
Σ,Λ,Ξ,Δ
H
π⁻
K⁻
color–superconducting strange quark matter (u,d,s quarks)
2SC
CSL
gCFL
LOFF
CFL
CFL–K+
CFL–K0
CFL–π0
crust
Fe
10 6 g/cm 3
10 11 g/cm 3
10 14 g/cm 3
Hydrogen/He atmosphere
R ~ 10 km

Watts et al. (2017)



EoS above neutron drip

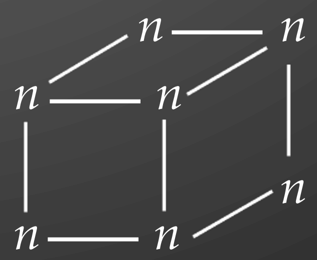
- $\rho_{drip} \approx 4\times10^{11}\ g\,cm^{-3}$ Neutron drip (nuclei, e^-, n) 2 phase system
- $\rho_{drip} < \rho < \rho_{nuc} = 2.8\times10^{14}\ g\,cm^{-3}$ Fairly well-known EoS (e.g. BBP)



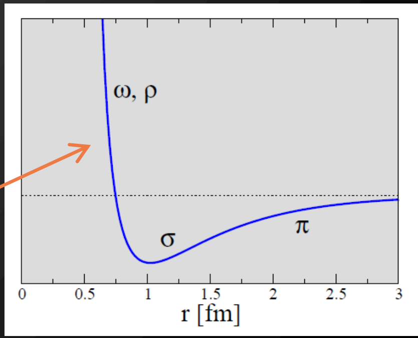
- $\rho > \rho_{nuc}$ not well understood. Problems:
  - nucleon-nucleon interactions
  - many-body problem
  - hyperons (nucleon-like strange baryons)
  - pion/kaon condensation

$\rho > 10\,\rho_{nuc}$ ultra-high densities:

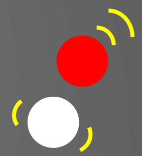
- no relativistic many-body Schrödinger equation is known
- "meson clouds" around nucleons - quark-drip
  (break-down of potential, no longer 2-body interactions)
- neutron lattice?

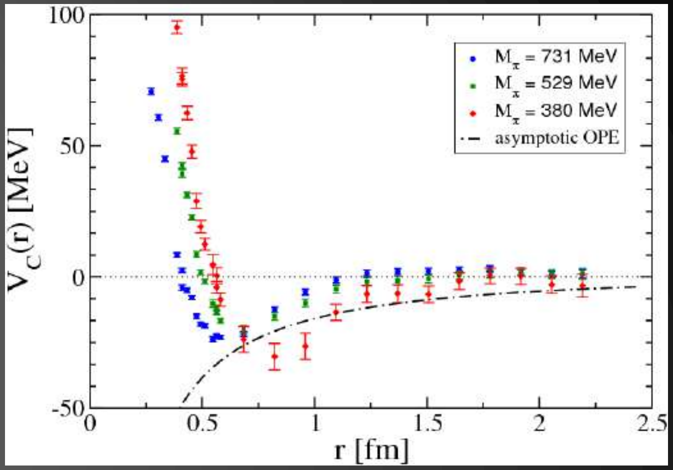


repulsion



Nucleon-nucleon interactions





The exchange of vector mesons (S=1) induces **repulsive** NN forces, while the exchange of scalar mesons (S=0) induces **attractive** forces.

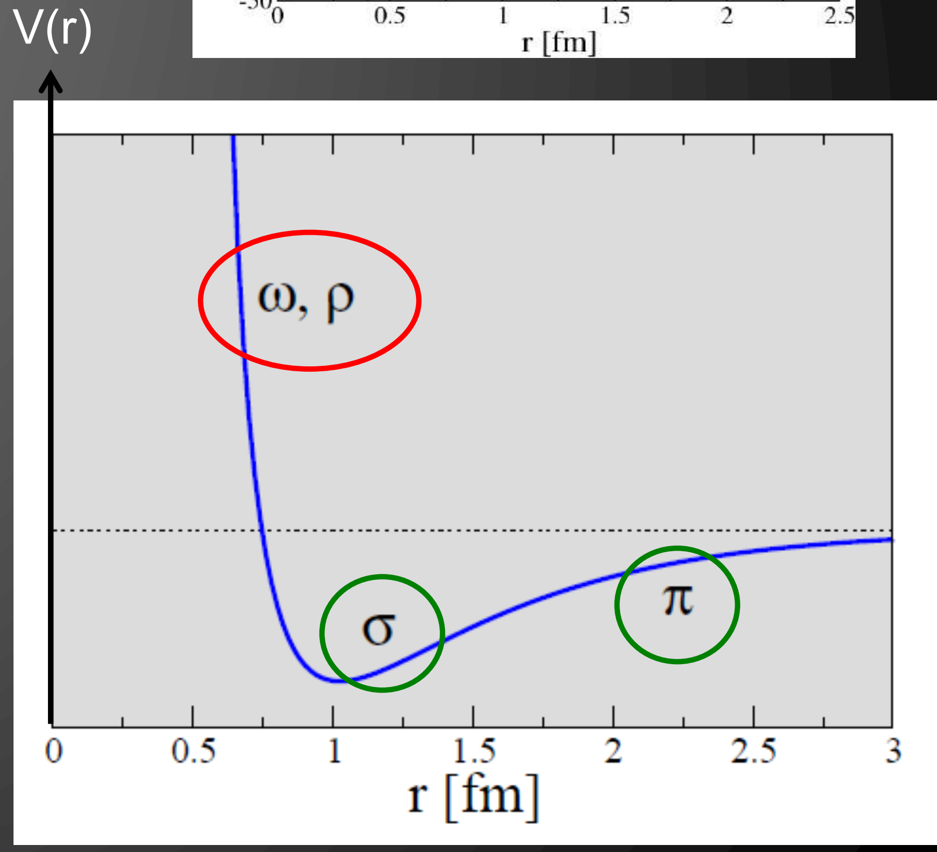
The two lowest mass vector mesons are:
ρ (769 MeV), ω (783 MeV).

The intermediate-range attractive NN force is caused by the σ (f_0) meson (600 MeV), and the long-range NN force by π (140 MeV).

The Yukawa-like potential: $V_{12} = \pm g^2 \frac{e^{-\mu r}}{r}$ *

approximately describes the NN interactions.

$E_V = \frac{1}{2}\sum_{i \neq j} V_{ij}$ (sum all pairs of NN interactions)



* $1/\mu = 1/\alpha m$ = approx. range
$g,\ \alpha$ = scaling constants, m = mass

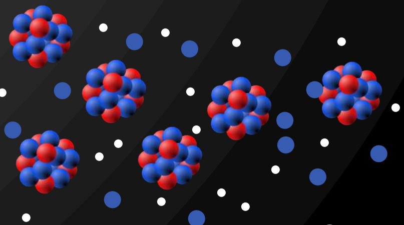
Baym-Bethe-Pethick (BBP) EoS

- "Compressible liquid drop model" 
- Reid soft core: superposition of Yukawa-like potentials $V_{12} = \pm g^2 \frac{e^{-\mu r}}{r}$
- Includes many-body interactions and improved Coulomb lattice effects
- Minimizing the total energy density: $\varepsilon = n_N \cdot (W_N + W_L) + \varepsilon_n (1 - V_N n_N) + \varepsilon'_e(n_e)$ for constant *n* with respect to *A*

  $n = A \cdot n_N + (1 - V_N n_N) \cdot n_n$ (baryon number density)

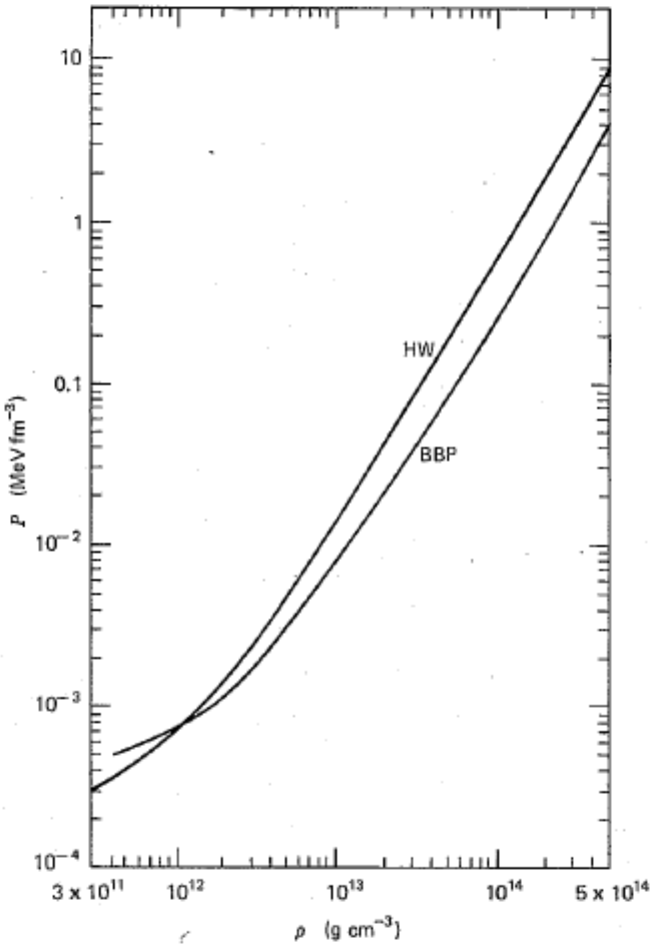
  $(1 - V_N n_N)$: fraction of volume which is gas
- Nuclei must be stable against β-decay (Z ~ const.)

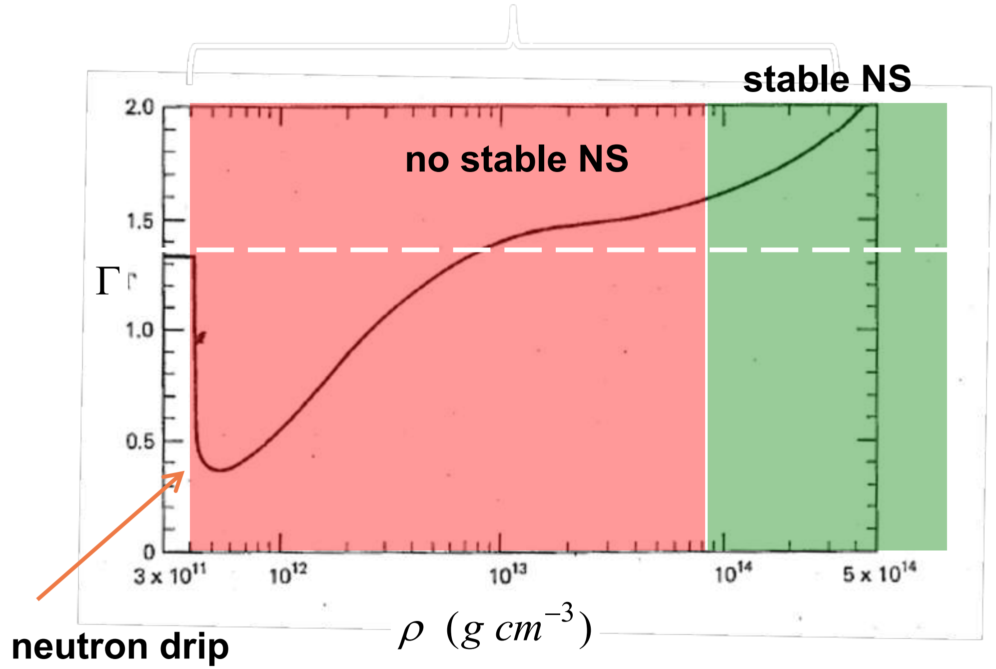
  $n \leftrightarrow p + e^- + \bar{\nu}_e \qquad \mu_n^N = \mu_p^N + \mu_e \quad (\mu_\nu = 0,\ \nu \text{ leaves the star})$
- Free n-gas must be in equilibrium with neutrons inside nuclei: $\mu_n^G = \mu_n^N$
- Pressure balance between n-gas and nuclei: $P_n^G = P_n^N$



Baym-Bethe-Pethick (BBP) EoS

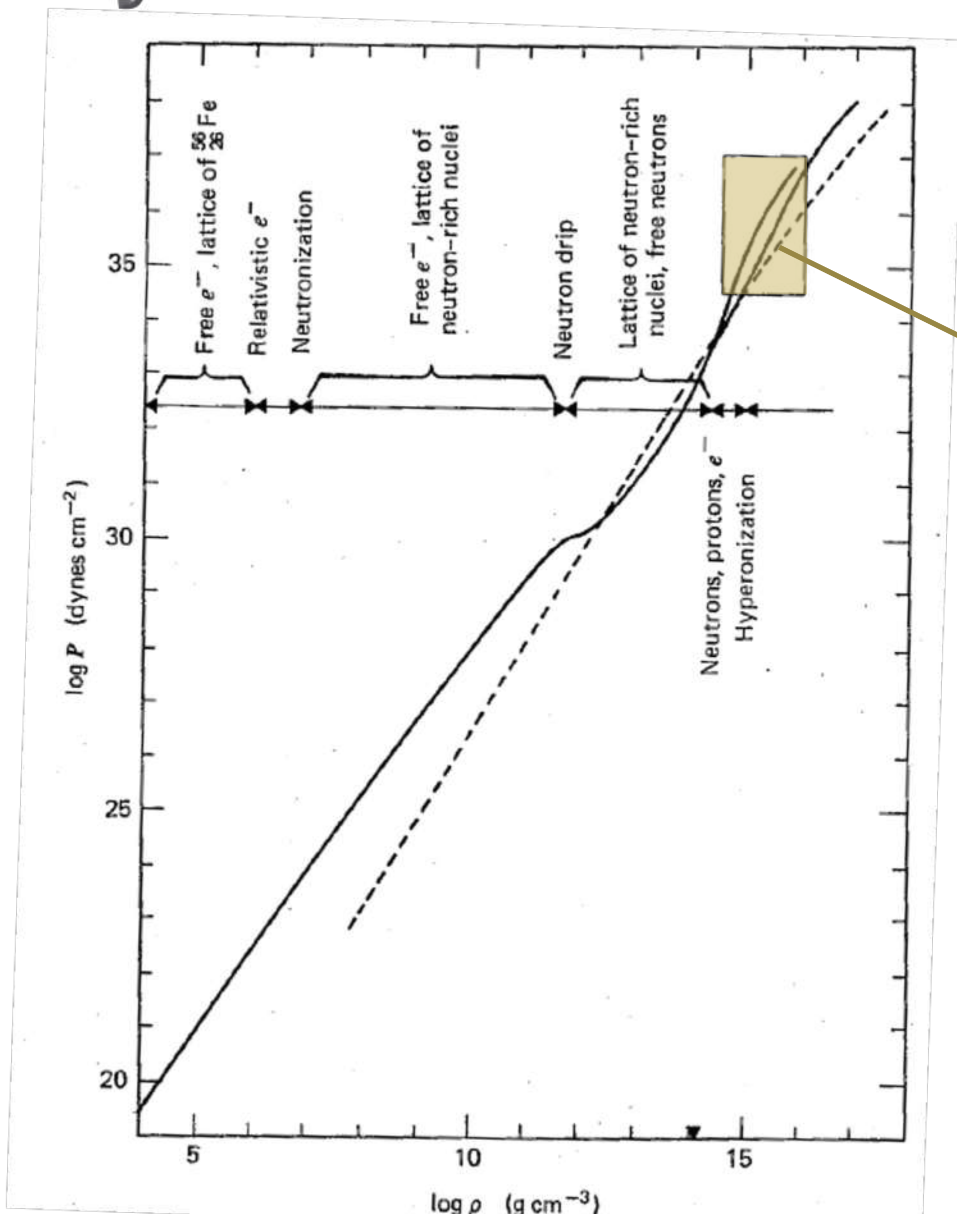
Fig. 8.1 + 8.2 (Bayn, Bethe & Pethick 1971).





For stability: $\bar{\Gamma} > \frac{4}{3} + K_{GTR}$

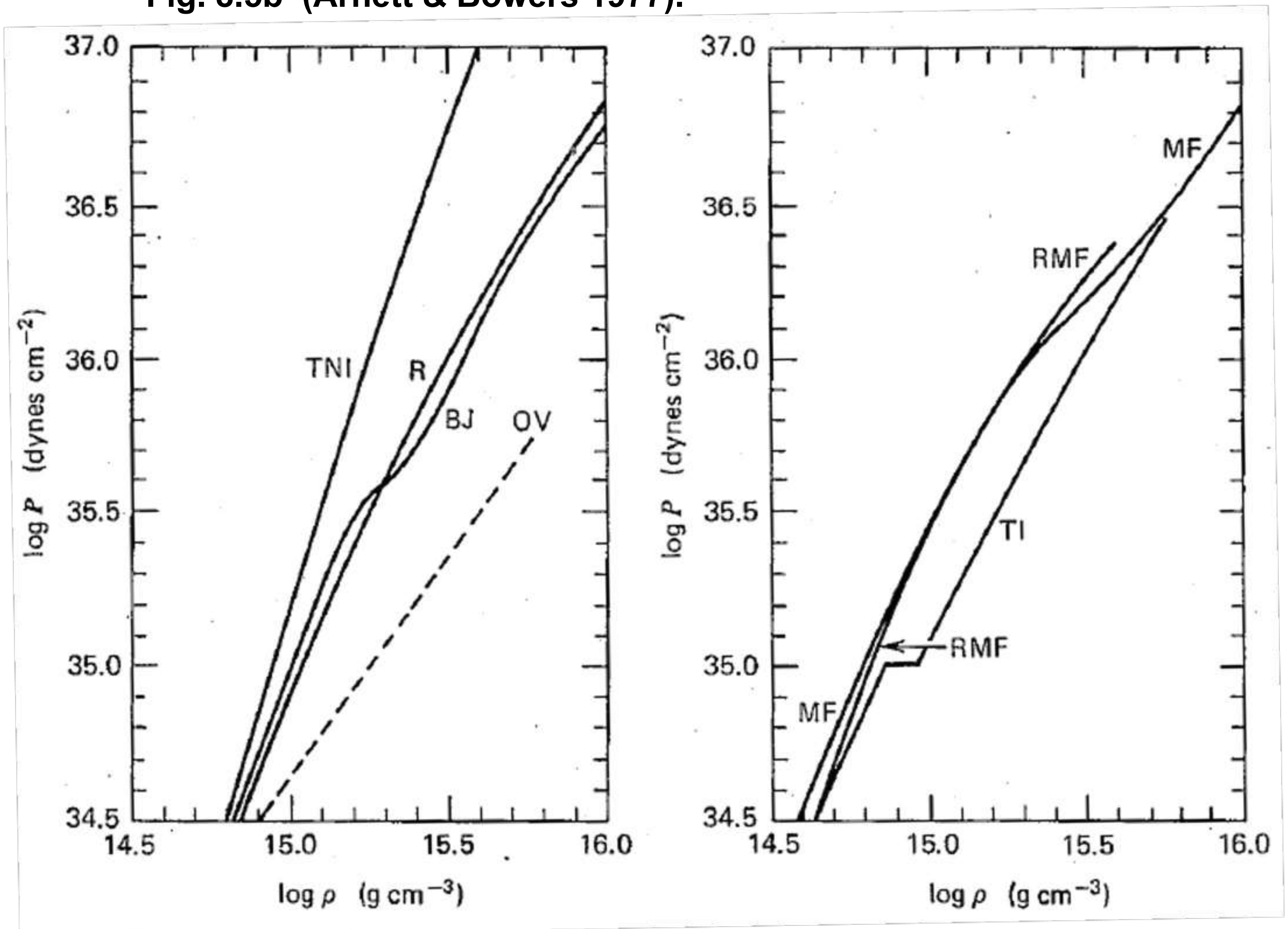
Baym-Bethe-Pethick (BBP) EoS



next slide

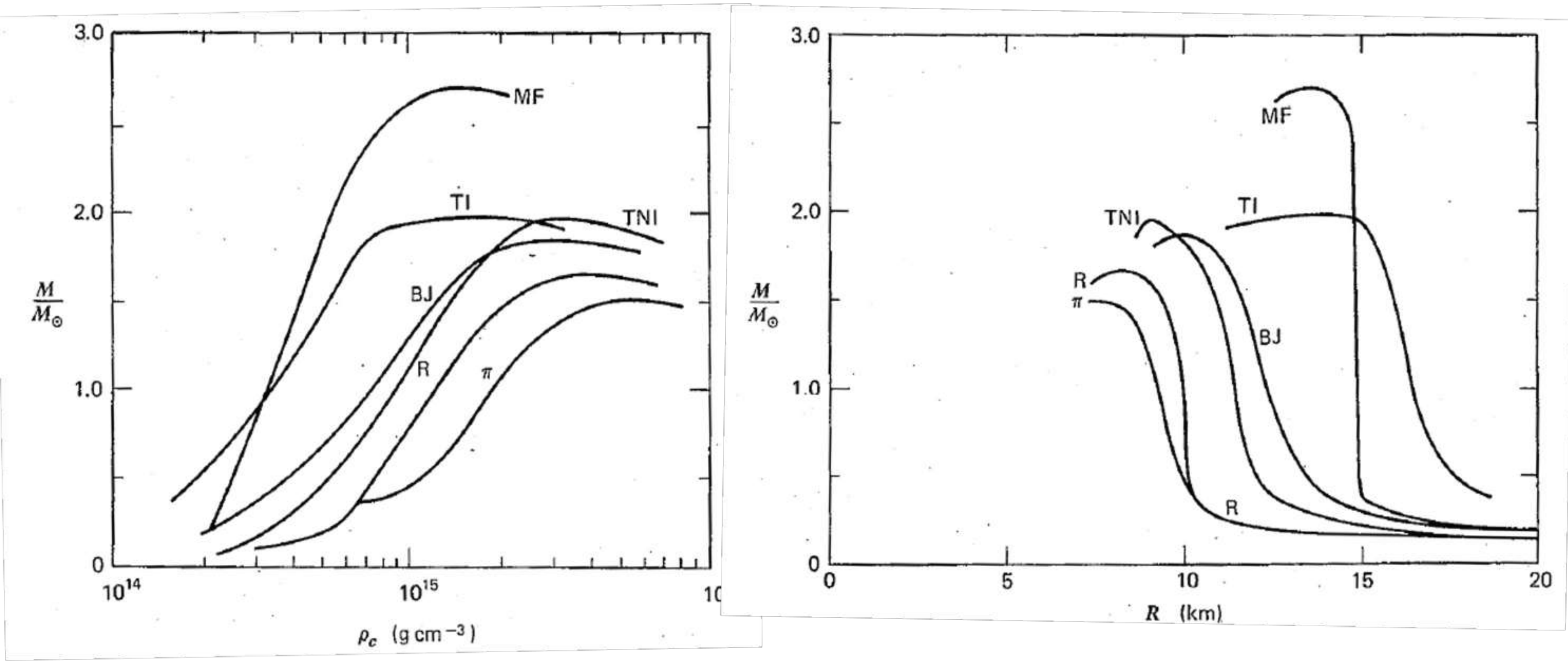
EoS above nuclear density

Fig. 8.5b (Arnett & Bowers 1977).

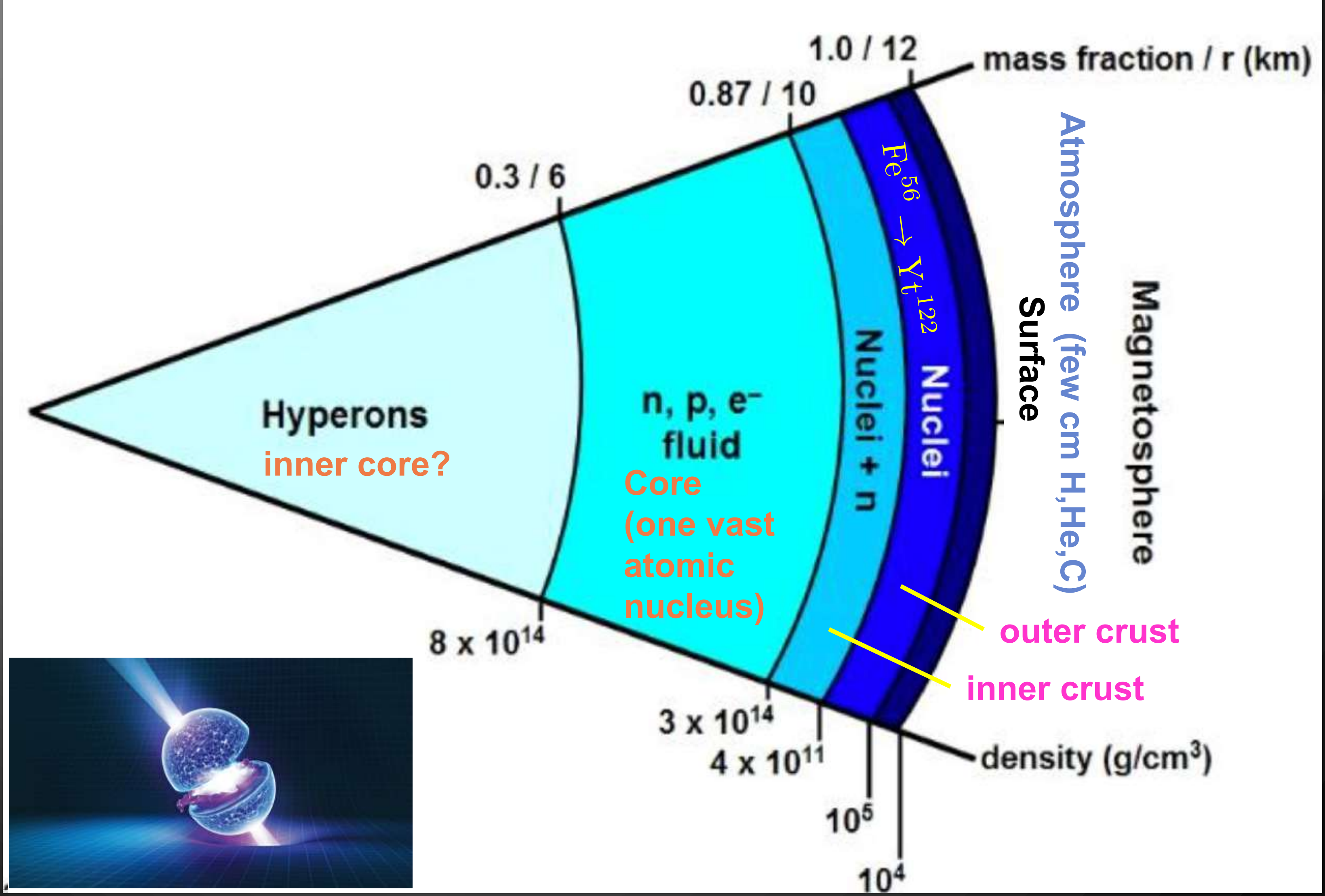


EoS above nuclear density

Fig. 9.2 + 9.3 (Baym & Pethick 1979).

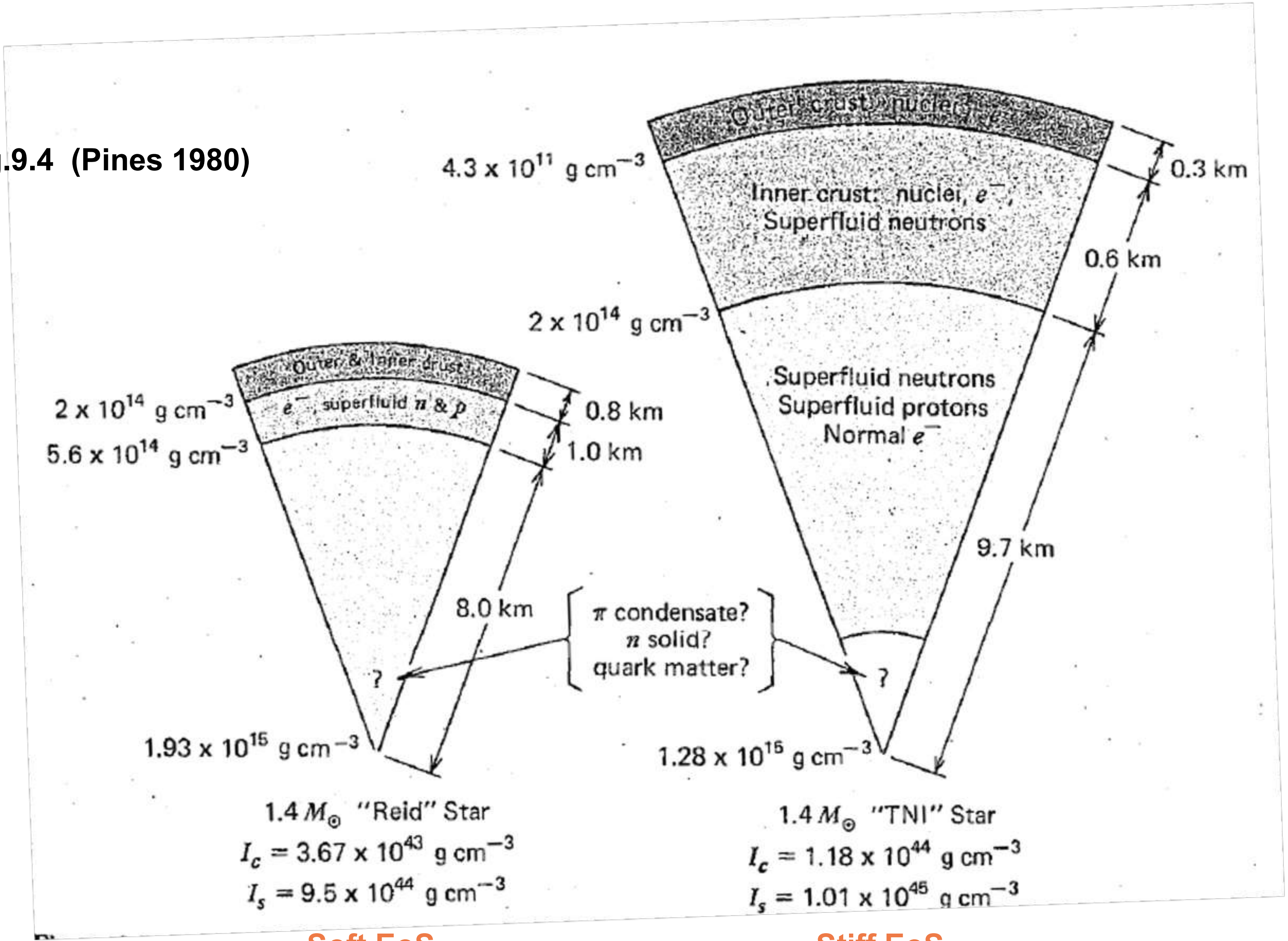


Structure of Neutron Stars



Structure of Neutron Stars

Fig.9.4 (Pines 1980)



Soft EoS

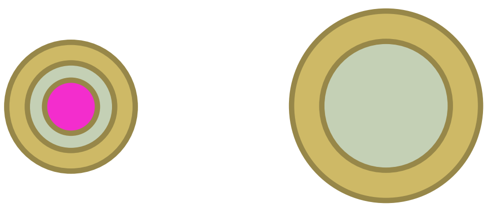
Stiff EoS

Structure of Neutron Stars

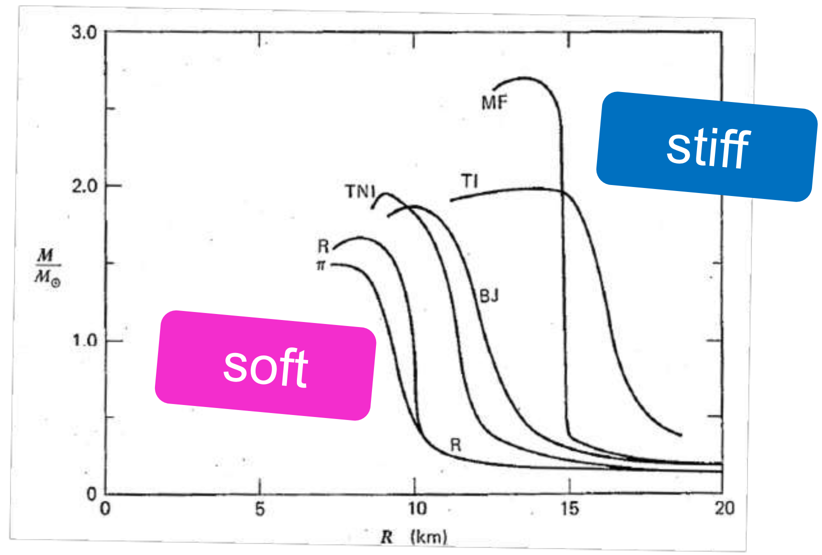
A ”**soft**” equation of state has an average system energy which is attractive at nuclear densities. (e.g. a Reid potential).

A ”**stiff**” equation of state has a repulsive component at higher densities.

For a given mass, M:



soft stiff

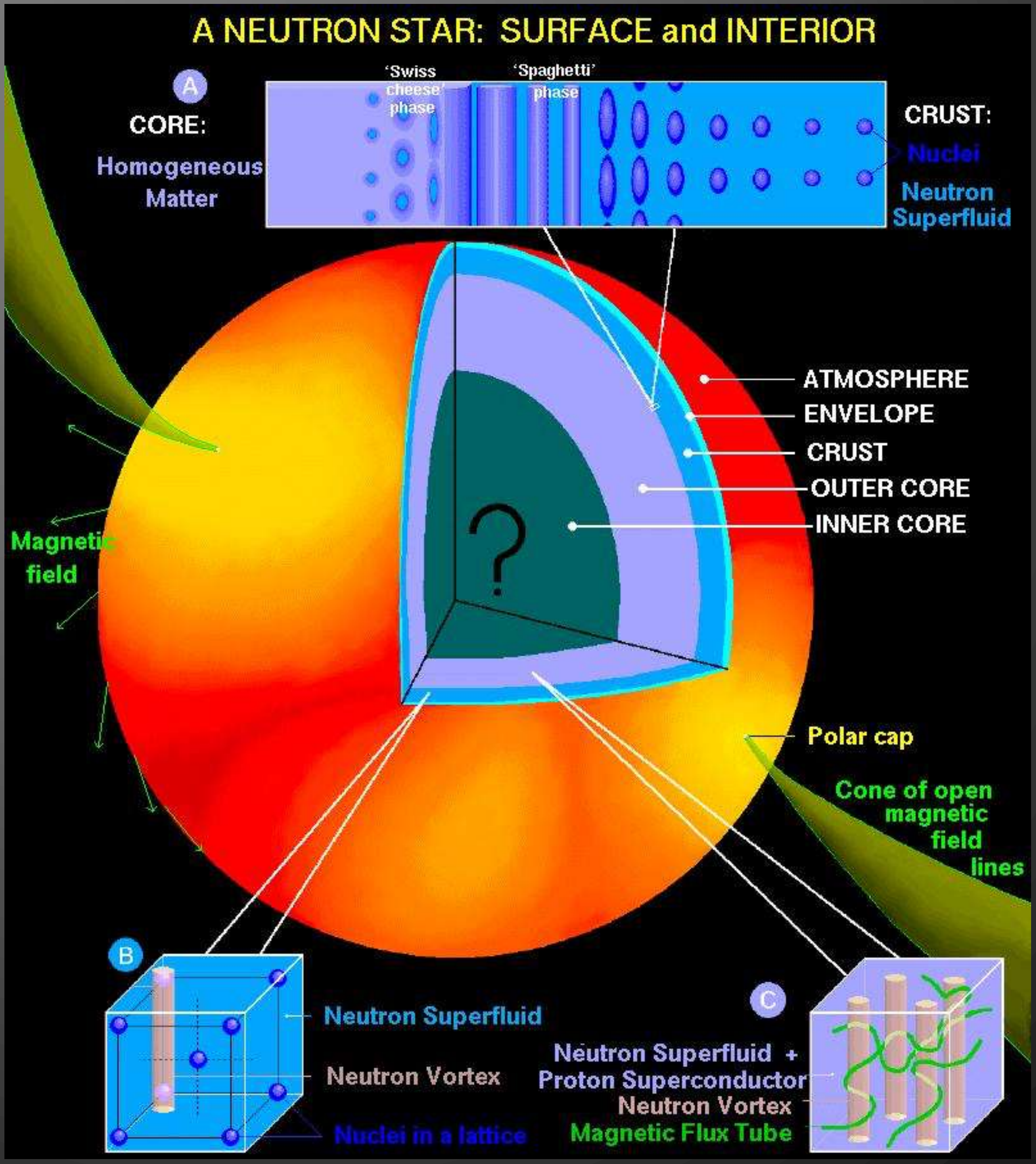


$$\text{soft EoS:} \quad P \text{ is small } (\Gamma \text{ is small}) \rightarrow R \text{ is small, } \rho_c \text{ is large} \quad (M_{\max} \text{ is small})$$

$$\text{stiff EoS:} \quad P \text{ is large } (\Gamma \text{ is large}) \rightarrow R \text{ is large, } \rho_c \text{ is small} \quad (M_{\max} \text{ is large})$$

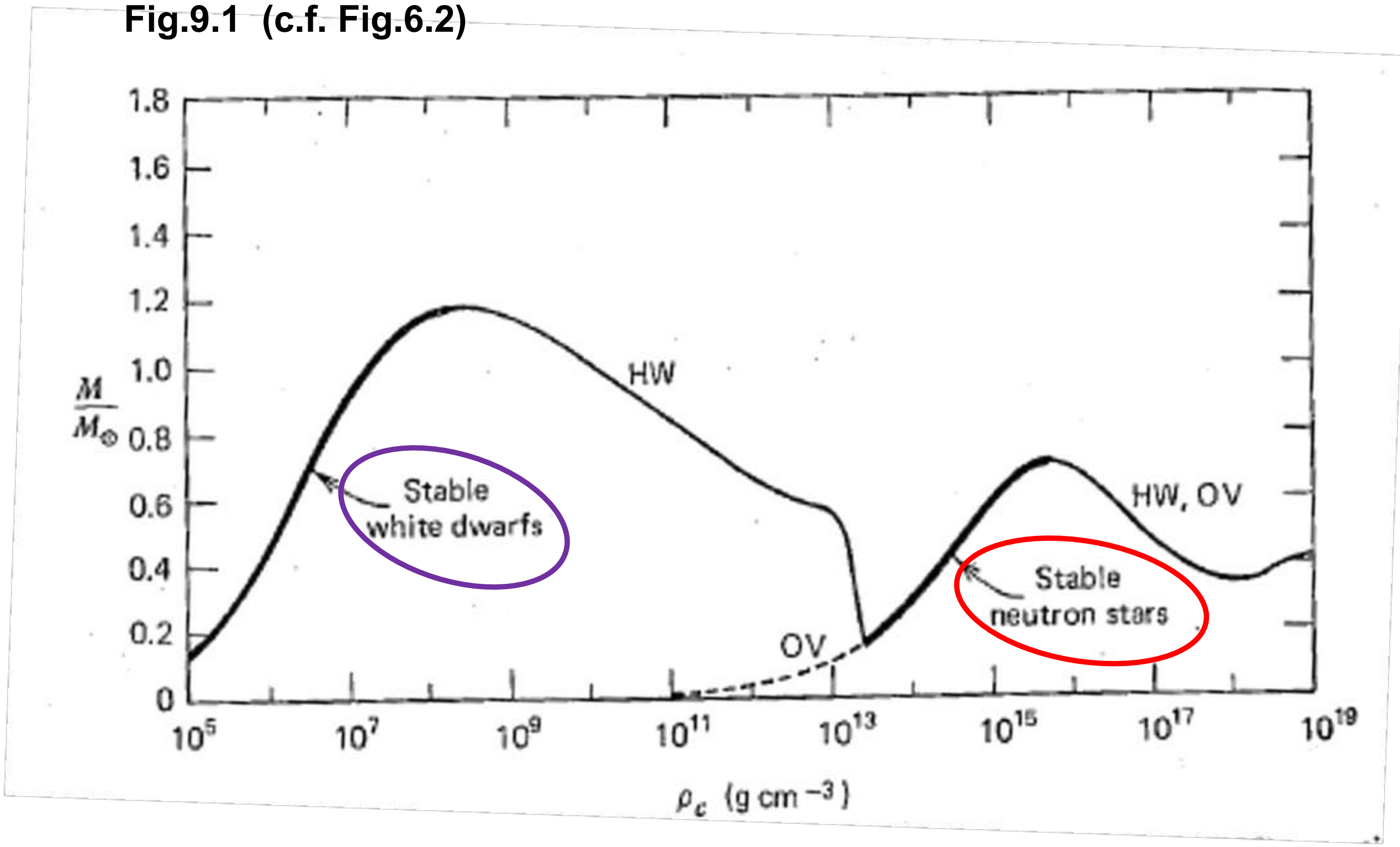
$$P = K\rho^{\Gamma}$$

Structure of Neutron Stars



Stability of Compact Objects

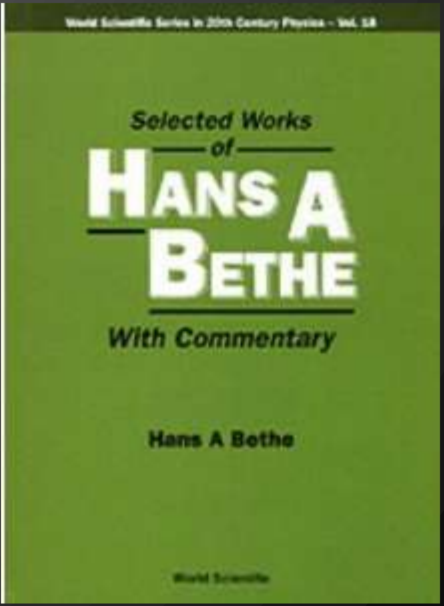
Fig.9.1 (c.f. Fig.6.2)



$$\frac{dM}{d\rho_c} > 0$$

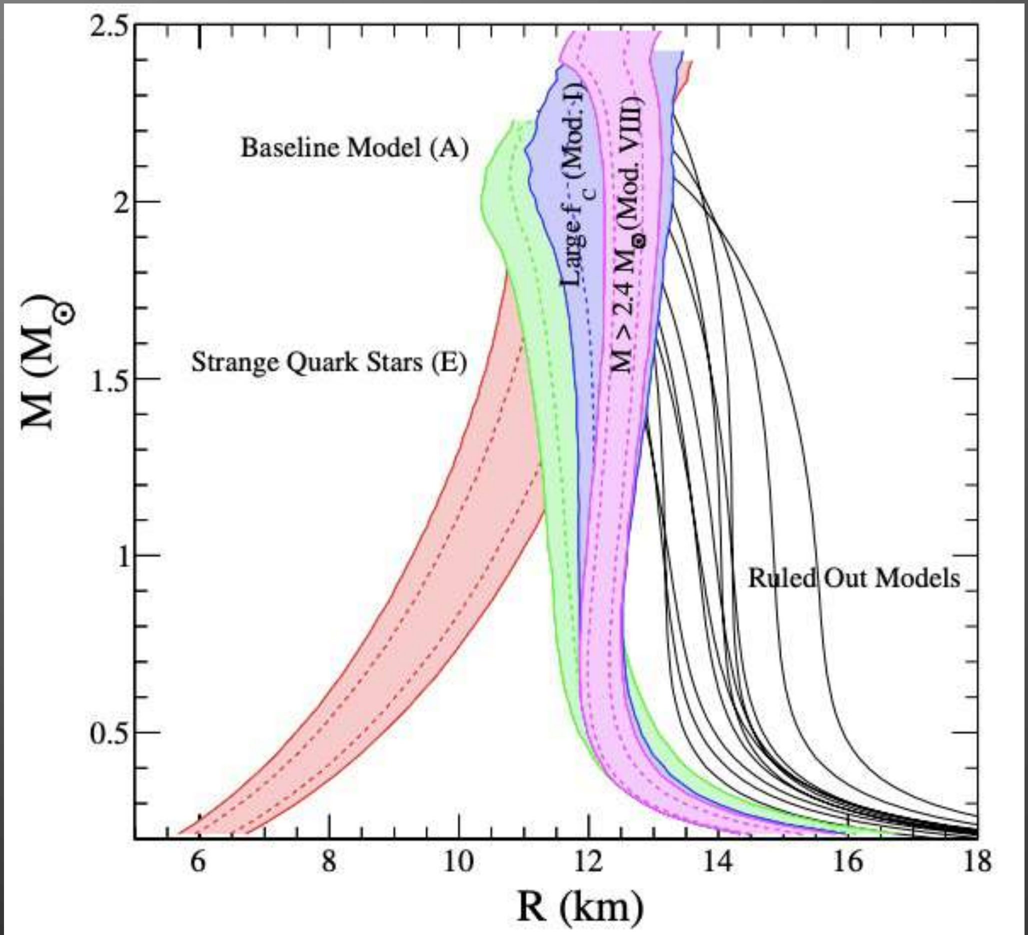
Bethe-Johnson (BJ) EoS

- $\rho_{nuc} < \rho < 3\times10^{16}\ g\,cm^{-3} \qquad (n, p, \Lambda, \Sigma^{\pm,0}, \Delta^{\pm,0,++})$
- Modified Reid soft core (includes the repulsive terms at small distances)
- Variational calculation (mathematical analysis to find minimum ε)
- Hartree-Fock analysis (many-body interactions)
- Stiff EoS: $P \propto \rho^{2.54}$



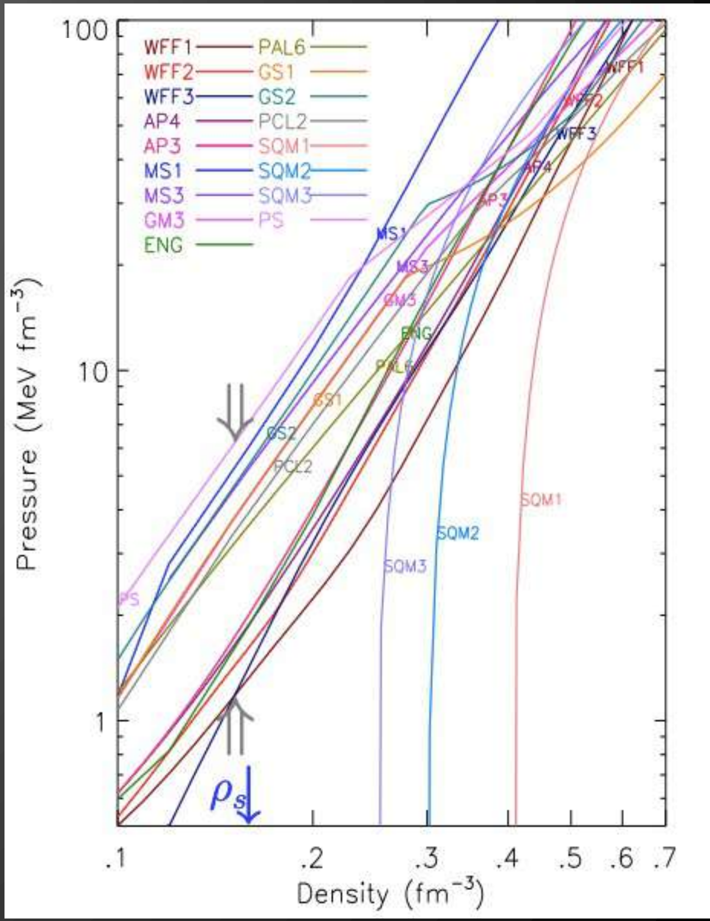
EoS above nuclear density

Steiner, Lattimer & Brown (2012)



Note, deviation from $R \propto M^{-1/3}$

Lattimer (2007)



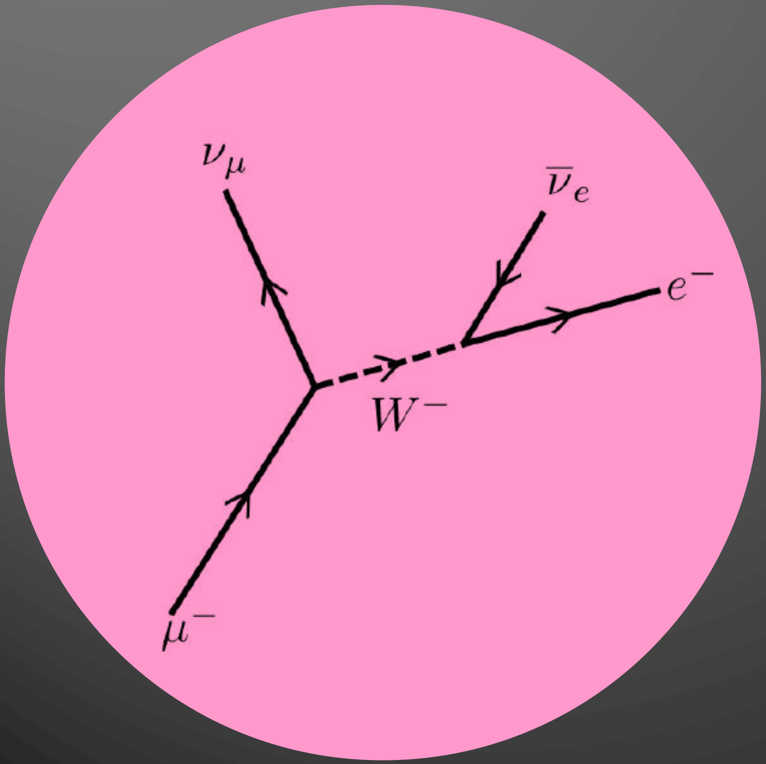
Adding exotic particles to the NS structure

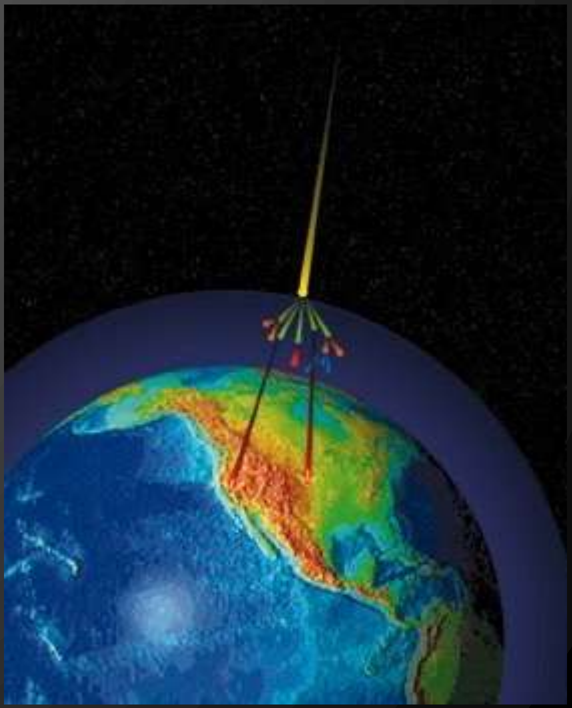
Muons

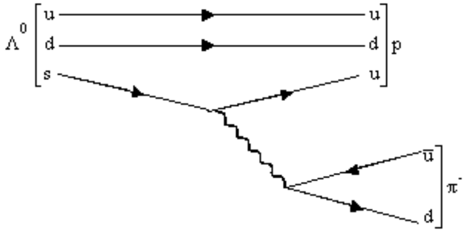
- Muon contribution to EoS: $\mu_e > m_\mu c^2 \quad (106\ \mathrm{MeV}, \quad \rho \approx 2.4 \times 10^{14}\ g\ cm^{-3})$

$e^- \leftrightarrow \mu^- + \bar{\nu}_\mu + \nu_e$ equilibrium: $\mu_\mu = \mu_e \quad \wedge \quad \mu_n = \mu_p + \mu_e$

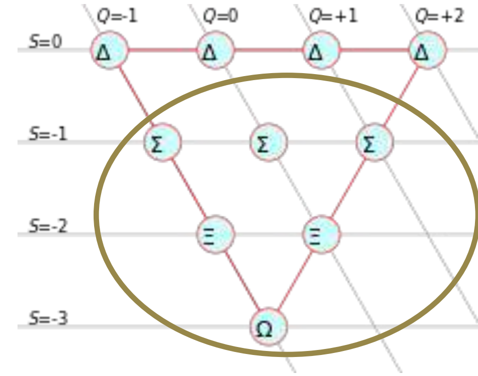
Charge neutrality: $n_p = n_e + n_\mu$







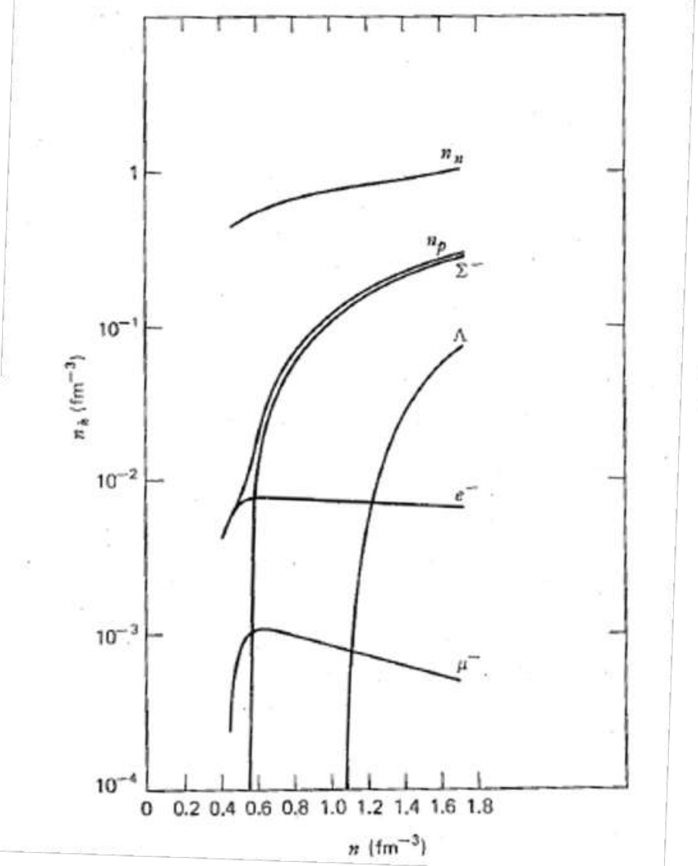
Hyperons



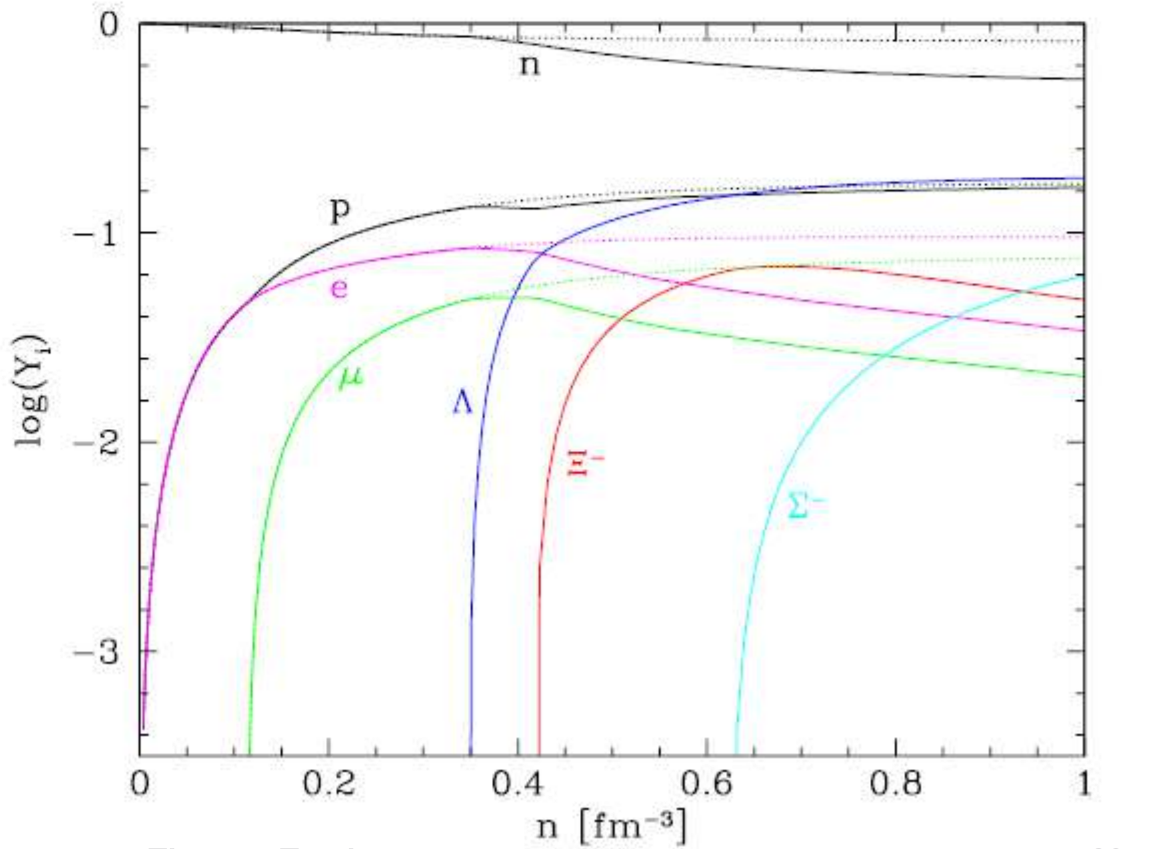
- Hyperons are nucleon-like strange baryons (i.e. at least one s-quark, e.g.: $\Lambda^0 (uds) \quad 1116\, MeV$)

$$\Sigma^+, \Sigma^0, \Sigma^-, \Xi^0, \Xi^-, \Omega^- \quad (uus, uds, dds, uss, dss, sss) \quad \text{when} \quad n \geq 2\ fm^{-3}\ (\rho \geq 10\ \rho_{nuc})$$

Fig. 8.4 (Canuto 1975)



The concentrations in a free hyperonic gas as a function of total baryon density, *n*. Bednarik et al. (2011).



Hyperonic soup

Fig.6.16 (Camenzind 2007)

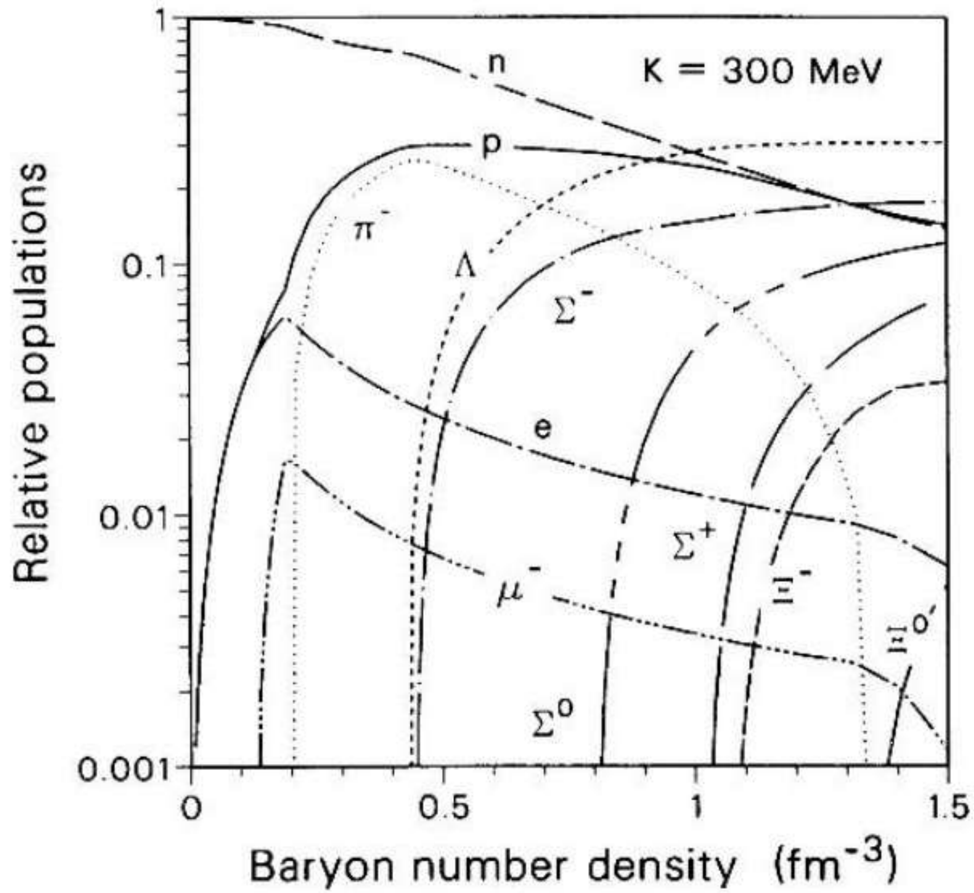


Fig. 6.16. Population of various particles in hadronic stars as a function of baryon density. Nuclear density corresponds to 0.153 fm^{-3}. Figure adapted from Glendenning [5]

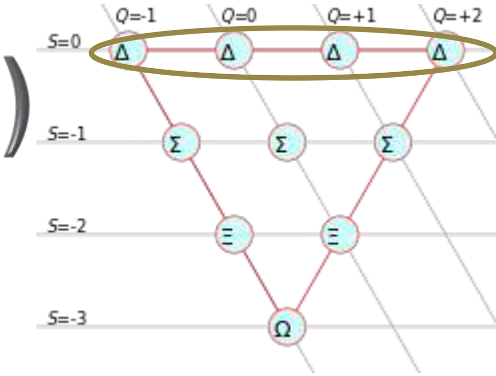
Hyperonic soup

Camenzind (2007)

Table 6.2. Baryon octet and mesonic states relevant for neutron star matter

Particle	m (MeV)	Spin	Isospin	B	Q	S
N	939	1/2	1/2	1	0,1	0
Λ	1115	1/2	0	1	0	–1
Σ	1190	1/2	1	1	–1,0,1	–1
Ξ	1315	1/2	1/2	1	–1,0	–2
σ	800	0	0	0	0	0
ω	782	1	0	0	0	0
ϱ	770	1	1	0	–1,0,1	0
π	139	0	1	0	–1,0,1	0
K^+	494	0	1/2	0	1	1
K^0	494	0	1/2	0	0	1
$\bar{K}^0$	494	0	1/2	0	0	–1
K^-	494	0	1/2	0	–1	–1

Δ-resonances (baryons)

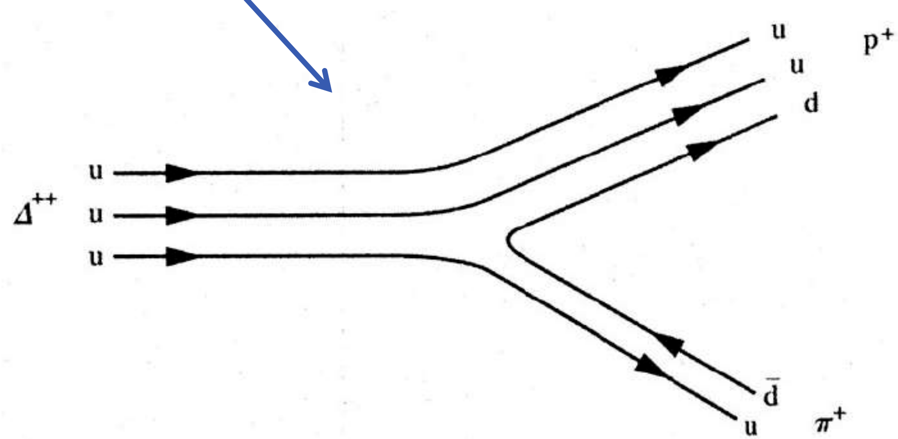


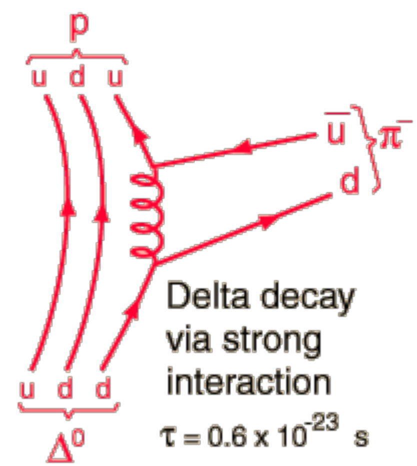
- Baryons with only u- and d-quarks:

$$\mu_n > 1232\,\mathrm{MeV} \qquad \Delta^{++}, \Delta^{+}, \Delta^{0}, \Delta^{-} \qquad (uuu, uud, udd, ddd)$$

$$\Delta^{++} \leftrightarrow p + \pi^{+}, \quad \Delta^{+} \leftrightarrow p + \pi^{0}, \quad \Delta^{0} \leftrightarrow n + \pi^{0}, \quad \Delta^{-} \leftrightarrow n + \pi^{-}$$

$$\Delta^{0} \leftrightarrow p + \pi^{-}$$





Pion condensation

$$n \rightarrow p + \pi^- \qquad (\mu_n - \mu_p = \mu_e > 140\ \text{MeV} \quad \rho > \rho_{nuc})$$

- π have spin S=0 (bosons) and can form a Bose-Einstein condensate.
- Thus in their lowest energy state (z=0) they have no momentum and therefore they do not contribute to the pressure P.
- Pion condensates therefore results in **soft** EoS
- Kaon condensates may form too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Recent developments on kaon condensation and its astrophysical implications

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[a] Department of Physics and Astronomy, State University of New York, Stony Brook, NY 11794, USA

Superfluidity

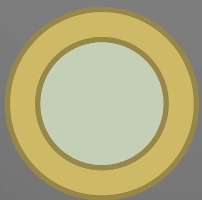
- A fermionic superfluid may form at low temperatures.
- Zero-viscosity due to Cooper pairs (BCS theory).
- Three types:

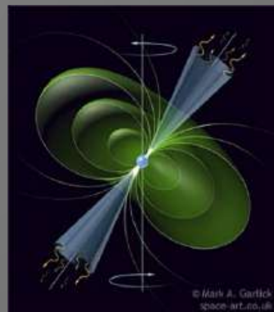
$^1S_0$	neutron superfluid - inner crust
$^3P_2$	neutron superfluid - core
$^1S_0$	proton superfluid - core

- Consequences:
  1) Formation of vortices
  2) Dynamical evolution: pulsar glitches
  3) The cooling of NSs
  4) The Meissner effect (B-flux tubes)

Superfluidity – Pulsar Glitches

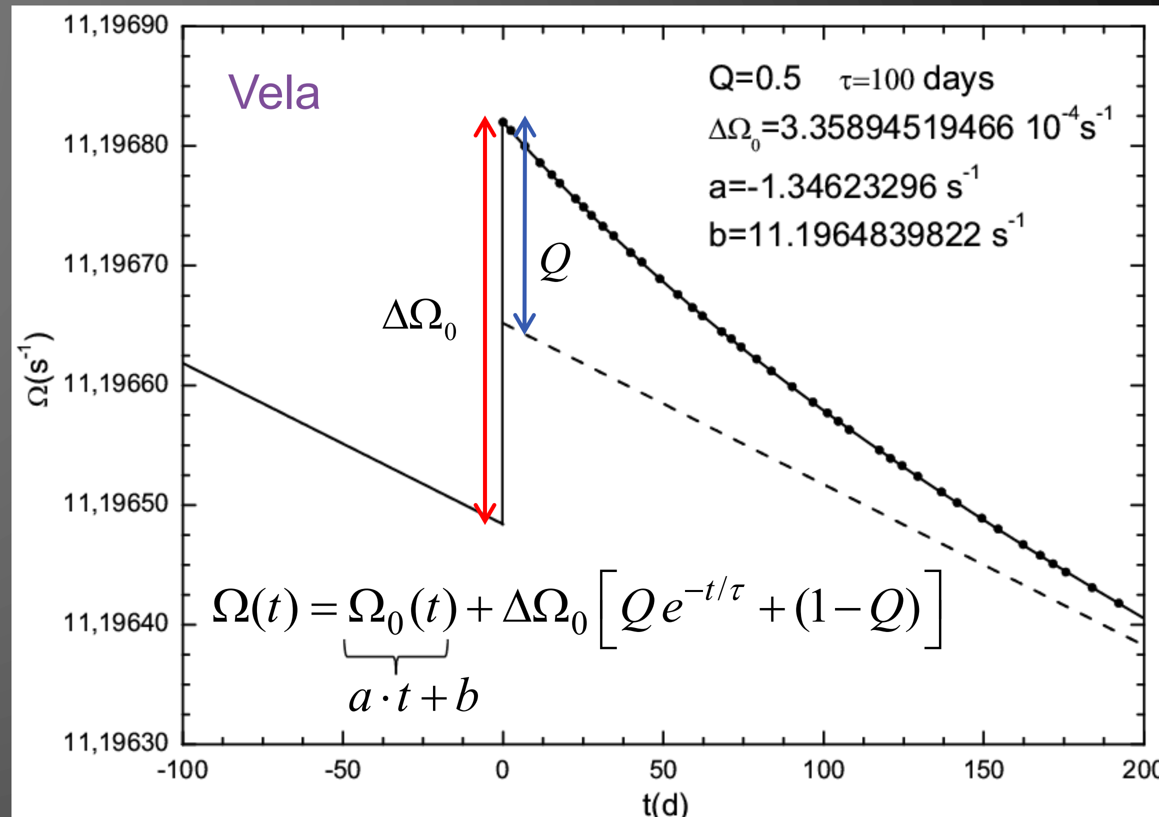
starquake





$$I \equiv I_c + I_n$$ Moment of inertia

Weak coupling between
c: crust + charged particles
n: superfluid neutrons in core
(Two component model).



A glitch is quickly (minutes) communicated to the charged particles via the B-field, but very slowly (months) to the superfluid neutrons.

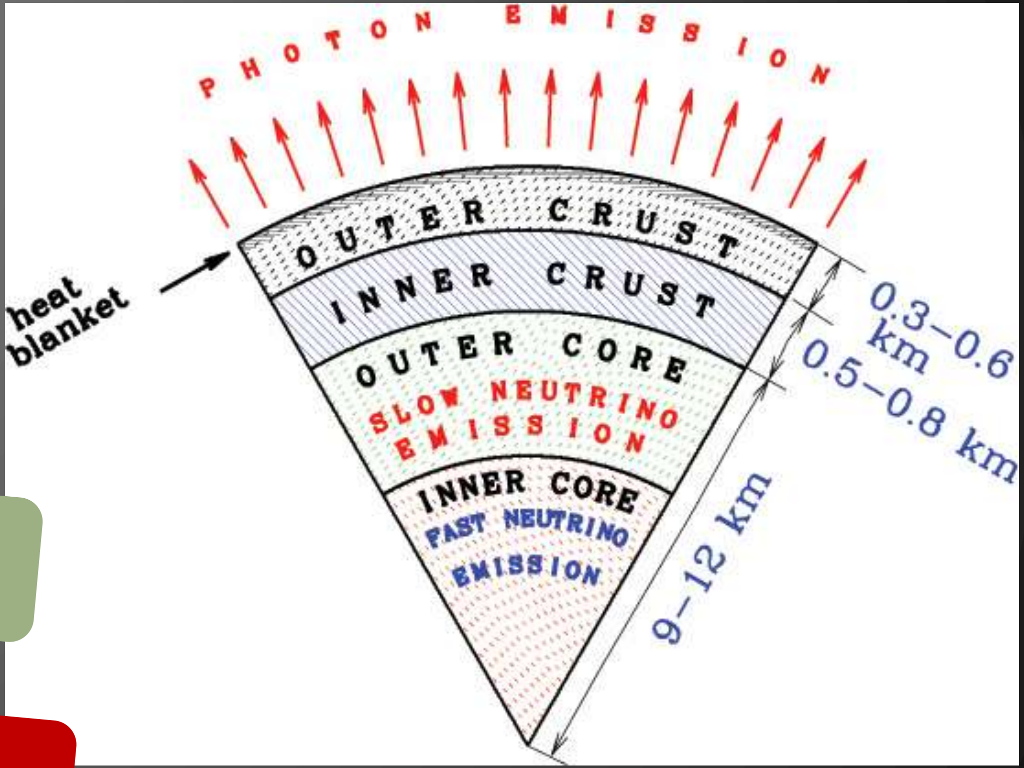
The relaxation depends on the pinning/unpinning between **core superfluid vortices** and the normal component of **nuclei (lattices) in the inner crust**, transferring angular momentum.

Problem: the two-component is too simplified and does not explain data (healing parameter Q and relaxation time τ differ for different glitches from the same pulsar)

Superfluidity – Neutron Star Cooling

NS cooling depends on:

- EoS
- Neutrino emission
- Superfluidity
- Magnetic fields
- Light elements on surface



Direct URCA: $(\rho > 2\rho_{nuc})$

$$n \to p + e^- + \bar{\nu}_e$$

$$p + e^- \to n + \nu_e$$

$$n \to n + \bar{\nu}_e + \nu_e$$

fast cooling

Modified URCA:

$$n + n \to n + p + e^- + \bar{\nu}_e$$

$$p + e^- \to n + \nu_e$$

$$n + n \to n + n + \bar{\nu}_e + \nu_e$$

slow cooling

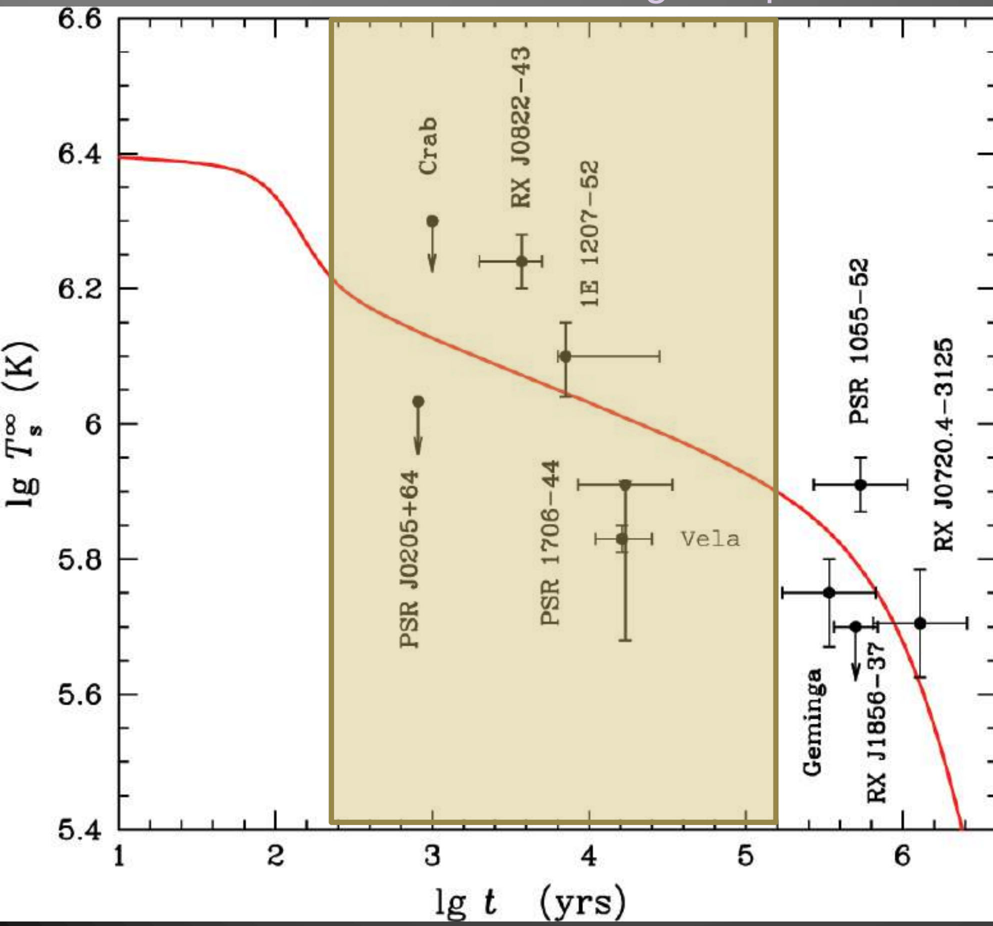
In highly degenerate matter a bystander particle must be present to absorb momentum.

Also neutrino emission due to Cooper pairing and bremsstrahlung.

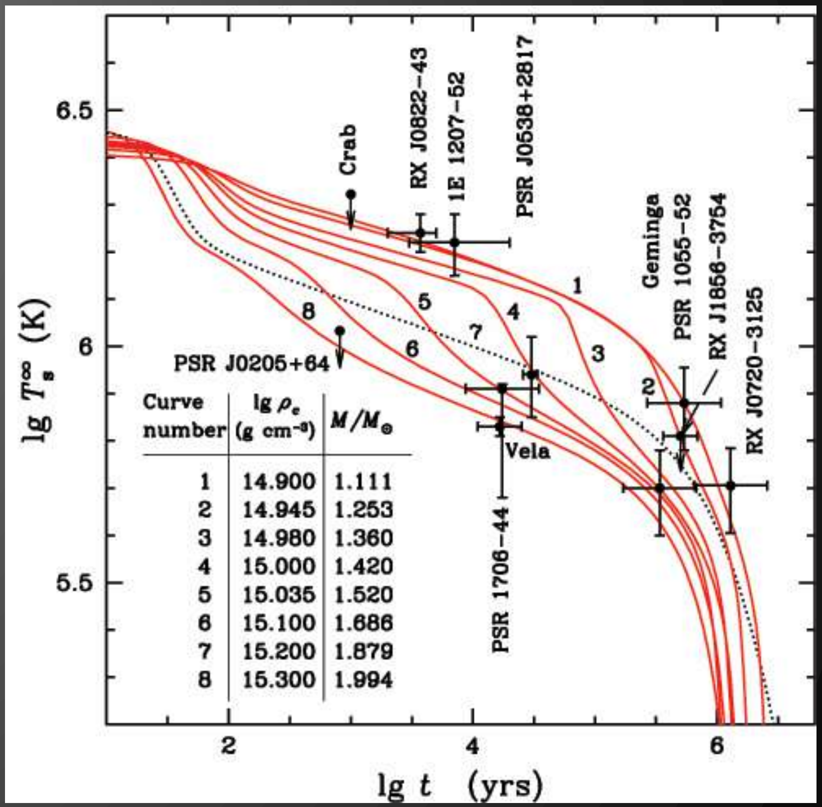
Superfluidity – Neutron Star Cooling

Superfluidity affects the neutrino emission processes and the heat capacity.

neutrino cooling photon cooling



Yakolov & Pethick (2004)



Douchin & Haensel (2001)

Note on WD cooling

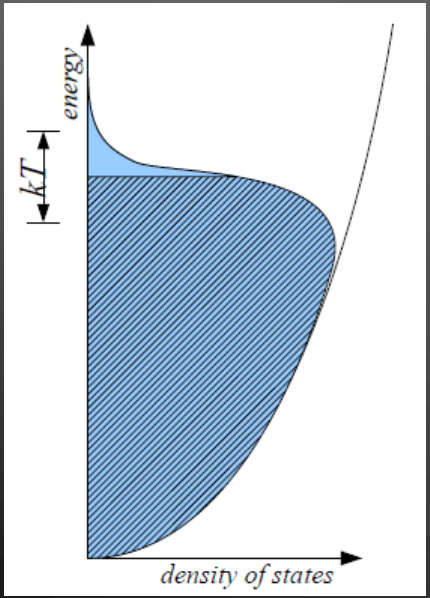
WD neutrino cooling via the so-called **convective URCA process**

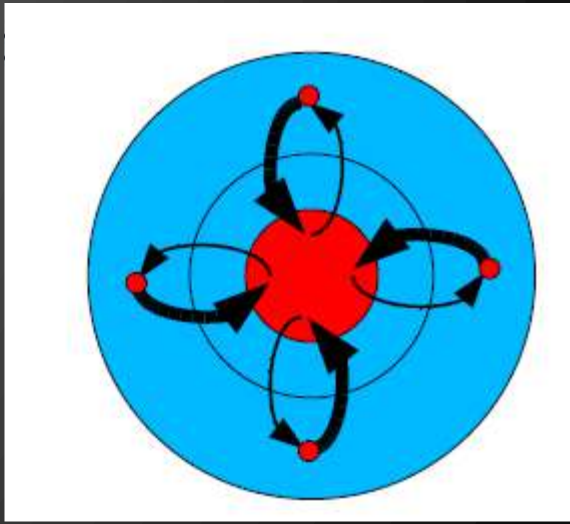
Inside ions:

$$\mu_e(E_F) < Q: \quad n \rightarrow p + e^- + \bar{\nu}_e \qquad \beta\text{-decay}$$

$$\mu_e(E_F) > Q: \quad p + e^- \rightarrow n + \nu_e \qquad \text{electon capture}$$

Idea of **convective URCA process:**
URCA matter is a working fluid for a heat engine driven by convection through the URCA shell





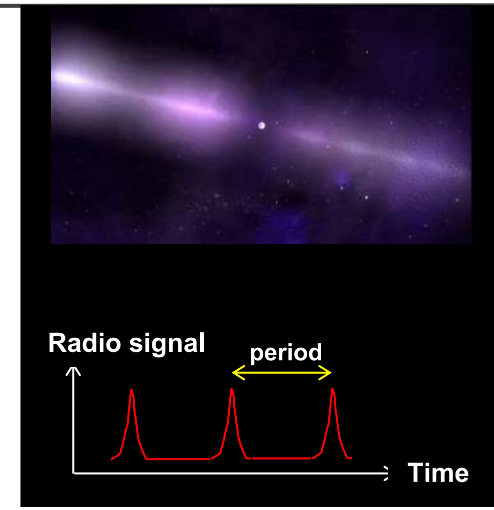
Summary: EoS above nuclear density

Table 8.2
S&T

Table 8.2
Representative Equations of State Above Neutron Drip

Equation of State	Density Range ($g\ cm^{-3}$)	Composition	Interactions	Many-Body Theory
Ideal neutron gas (Oppenheimer and Volkoff, 1939; OV)	$0 \leqslant \rho \leqslant \infty$	n	None	Noninteracting neutrons
Baym–Bethe–Pethick (1971a; BBP)	$4.3 \times 10^{11} < \rho \leqslant 5 \times 10^{14}$	e^-, n, and equilibrium nuclide	Reid soft core	Mass formula for nuclei constructed from compressible liquid-drop model
Reid (Pandharipande, 1971; R)	$\rho > 7 \times 10^{14}$	n	Reid soft core adapted to nuclear matter	Variational principle applied to correlation function
Bethe–Johnson (1974; BJ)	$1.7 \times 10^{14} \leqslant \rho \leqslant 3.2 \times 10^{16}$	n, p, Λ, $\Sigma^{\pm,0}$, $\Delta^{\pm,0}$, and Δ^{++}	Modified Reid soft core	Constrained variational method
Tensor-Interaction (Pandharipande and Smith, 1975a; TI)	$\rho > 8.4 \times 10^{13}$	n	Nuclear attraction due to pion exchange tensor interactions	Constrained variational method
Three-nucleon interaction (Friedman and Pandharipande 1981; TNI)	$\rho > 1.7 \times 10^{14}$	n	Two- and three-nucleon interactions	Constrained variational method
Mean field (Pandharipande and Smith, 1975b; MF)	$\rho > 4.4 \times 10^{11}$	n	Nuclear attraction due to scalar exchange	Mean field approximation for scalar; variational method
Relativistic mean field (Walecka, 1974; RMF)	$\rho > 1.7 \times 10^{14}$	n	Relativistic mean field scalar plus vector exchange fitted to nuclear matter	Relativistic mean field approximation

PULSARS: SPINNING NEUTRON STARS WITH HIGH B-FIELDS



Characteristics:

$\nu = 700\ Hz\ \ (P = 1.4\ \mathrm{ms} - 23\ \mathrm{sec})$

$B = 10^{13}\ G$

$\dot{E}_{rot} = 10^{5}\ L_{\odot}$

$M = 1.4\ M_{\odot}$

$R = 10\ km$

Giant atomic nucleus:

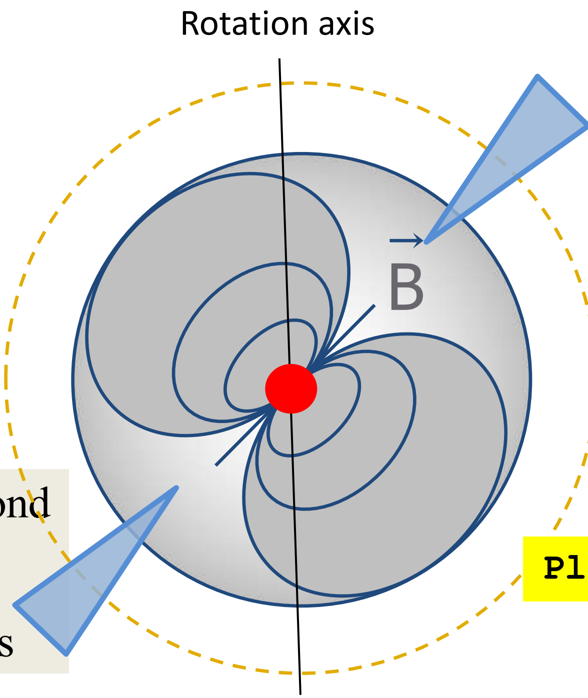
$A = 10^{57}$ baryons, $\quad \rho_{core} = 2 - 10\ \rho_{nuclear}$

Magnetosphere:

production of 10^{38} (e^{-}, e^{+})-pairs per second

TeV γ-rays

e^{-} accleration to $10^{15}\ eV$, $\Delta\phi = 10^{15}$ Volts



Particle physics

Nuclear physics

Solid state physics

Atomic physics

Plasma physics

Relativity

UNIQUE PHYSICS LABORATORY!

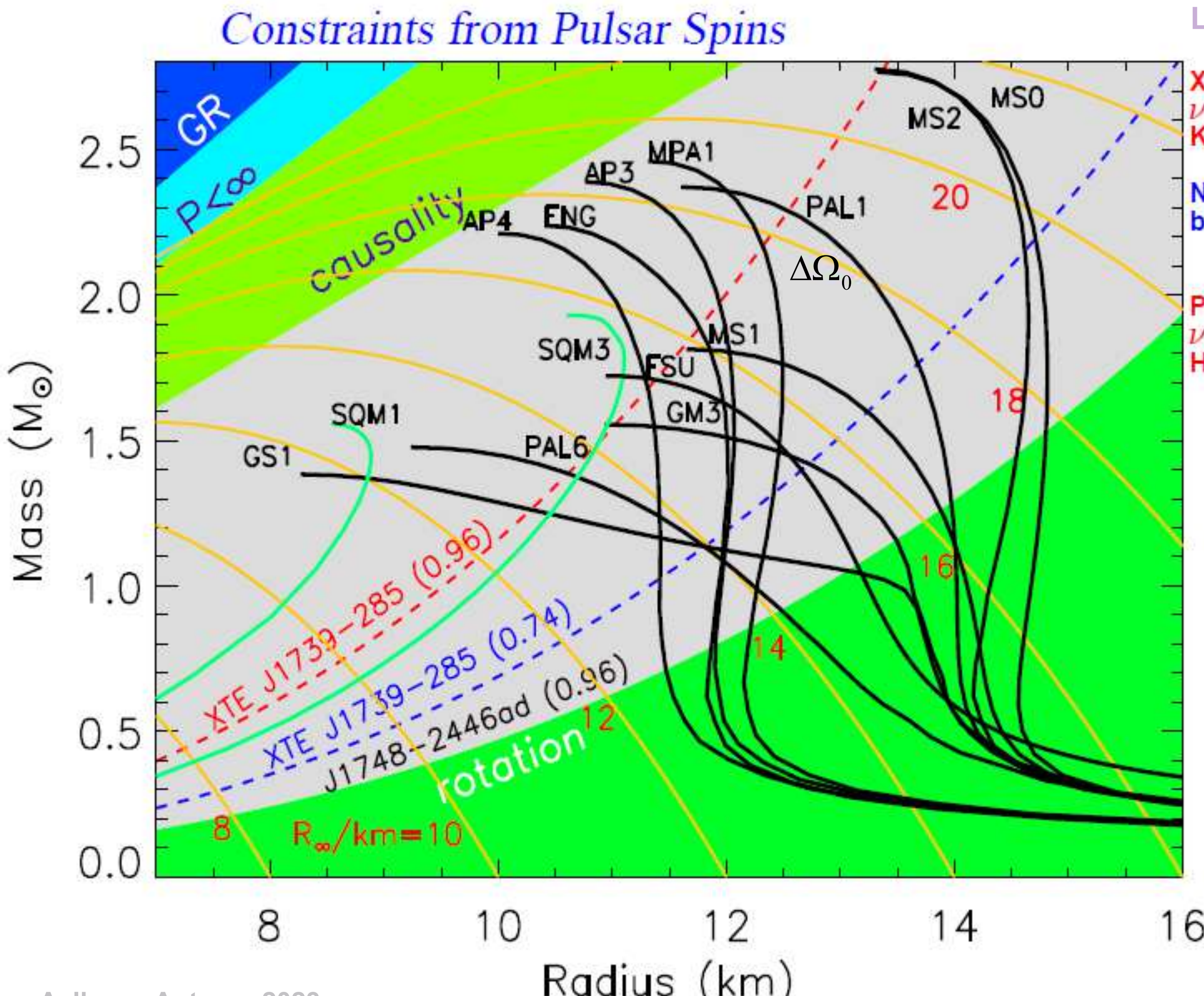
Perfect clock:

$P = 0.001\,557\,806\,448\,872\,75$ seconds (PSR 1937+21)

Challenge atomic clocks

Constraining EoS

Lattimer (2009)



XTE J1739-285
$\nu = 1122$ Hz
Kaaret et al. 2006

Not confirmed to be a rotation rate

PSR J1748-2446ad
$\nu = 716$ Hz
Hessels et al. 2006

Constraining EoS

NS radii can be determined for a few young NSs (the magificent seven) by fitting blackbody spectra:

$$L = 4\pi R^2 \sigma T^4 \quad \wedge \quad F = \frac{L}{4\pi d^2}$$

$$R = d\sqrt{\frac{F}{\sigma T^4}}$$

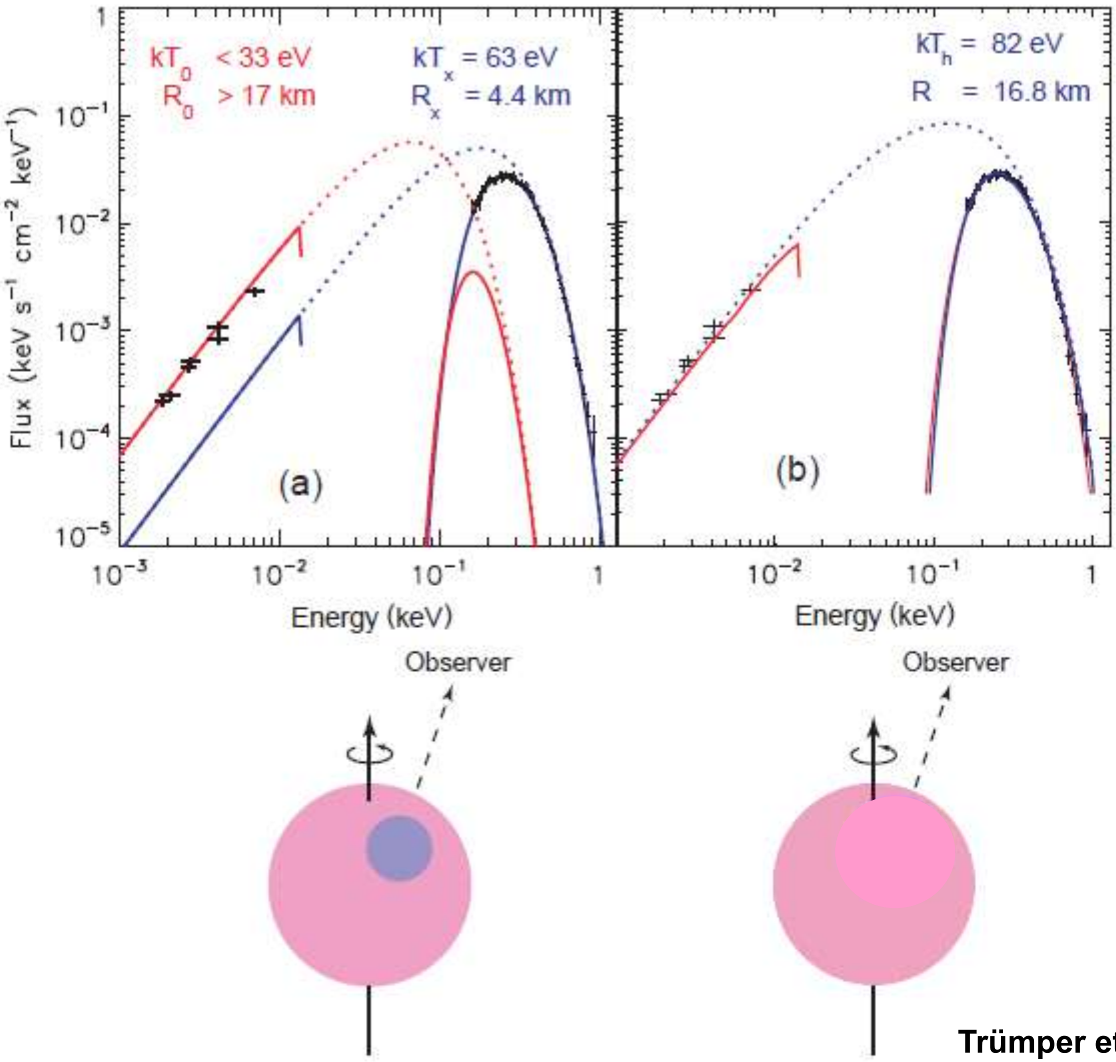
Correction for the gravitational redshift:

$$R_\infty \simeq \frac{R}{\sqrt{1-2\frac{GM}{c^2 R}}} \quad \wedge \quad T_\infty \simeq T\sqrt{1-2\frac{GM}{c^2 R}}$$

> The apparent (observed) radius is larger than the true radius

In practice more difficult because of the unknown spectral hardening (atmospheric corrections), and uncertainties in distance estimates.

Constraining EoS

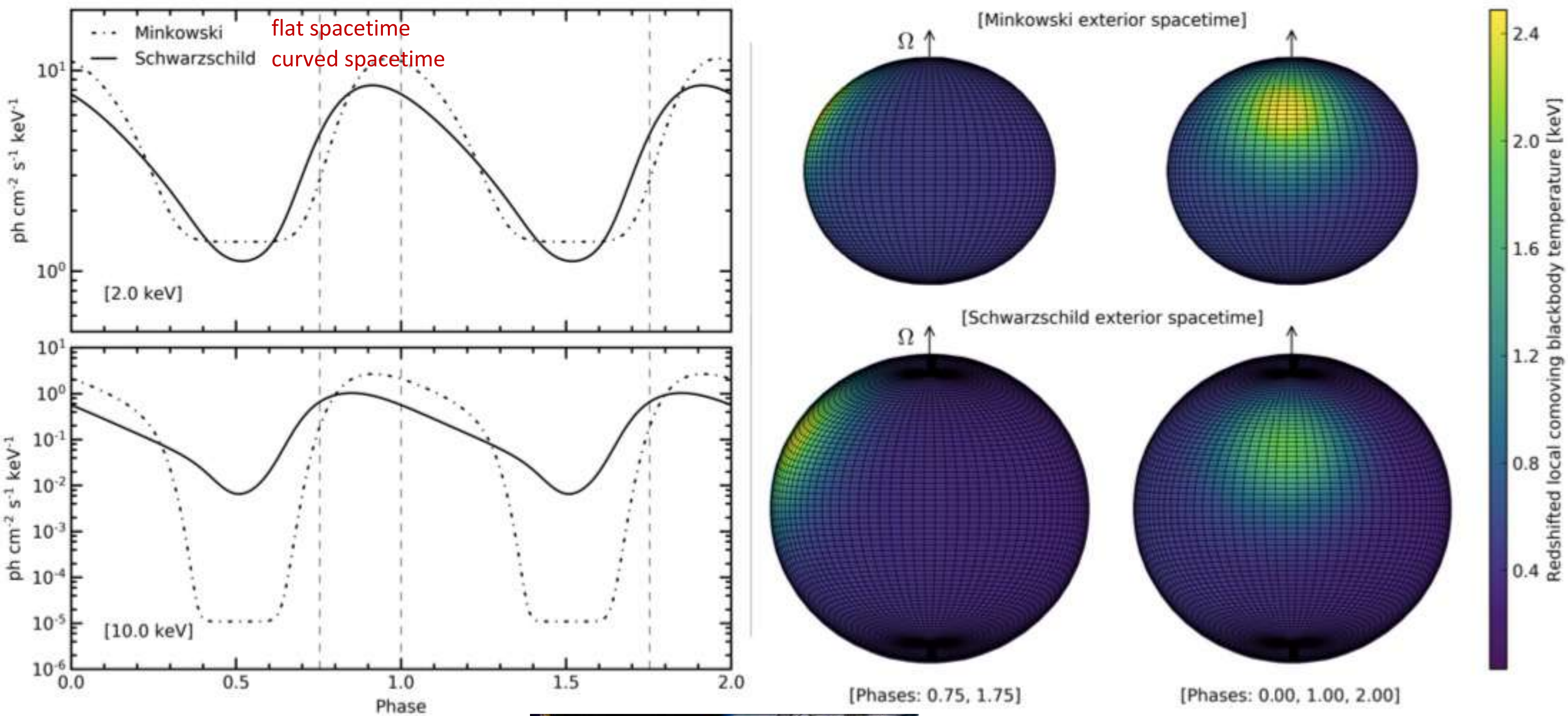


Trümper et al. (2004).

Figure 1. Blackbody fits to the optical and X-ray spectra of RX J1856.5-3754 for a two-component model (a) and a model with a continuous temperature distribution (b).

Constraining EoS

Watts A L, Yu W, Poutanen J, Zhang S, et al Sci. China-Phys. Mech. Astron. January (2017) Vol. 60 No. 1



NICER onboard ISS
NS Interior Composition Explorer

Constraining EoS

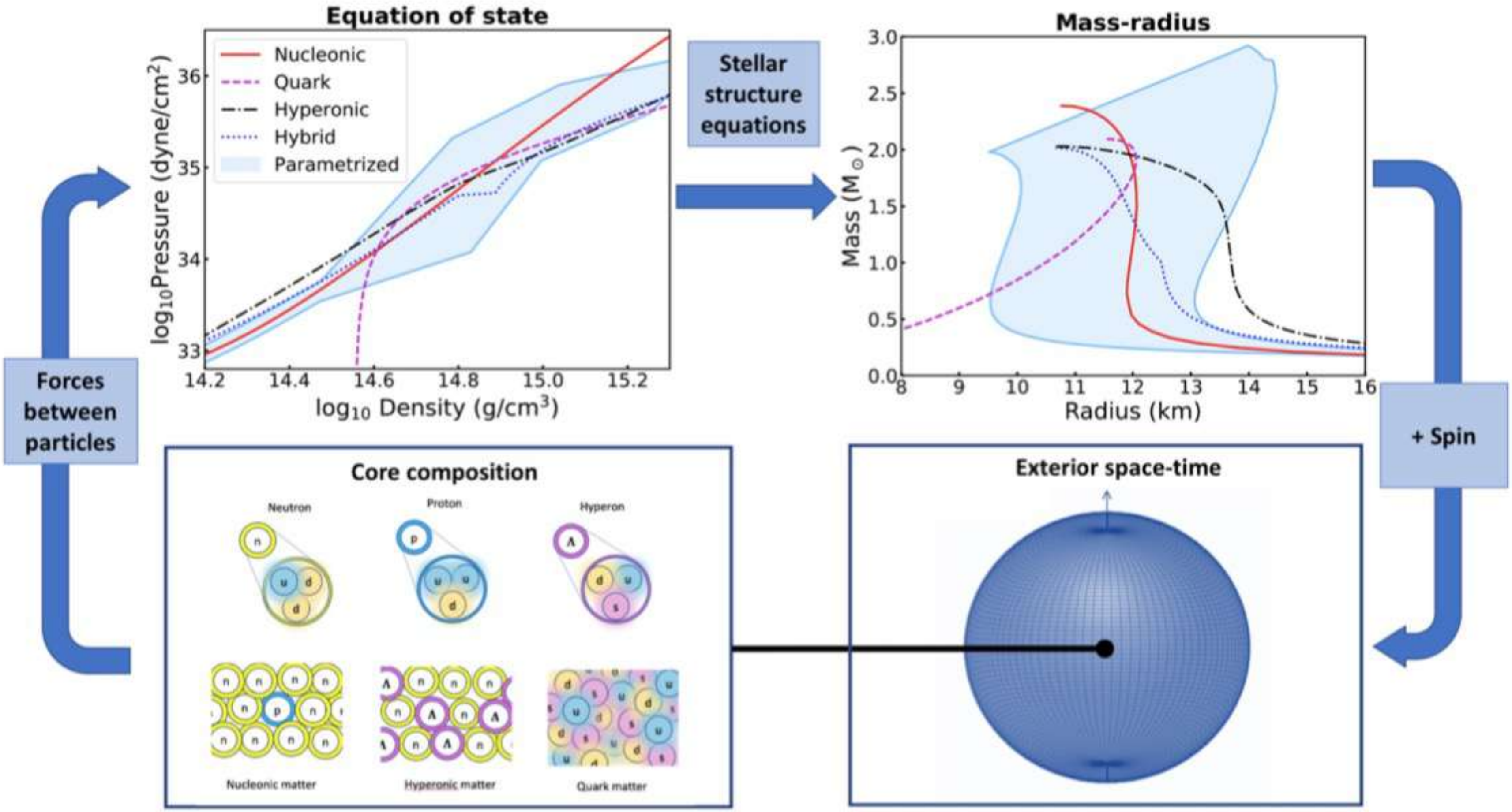
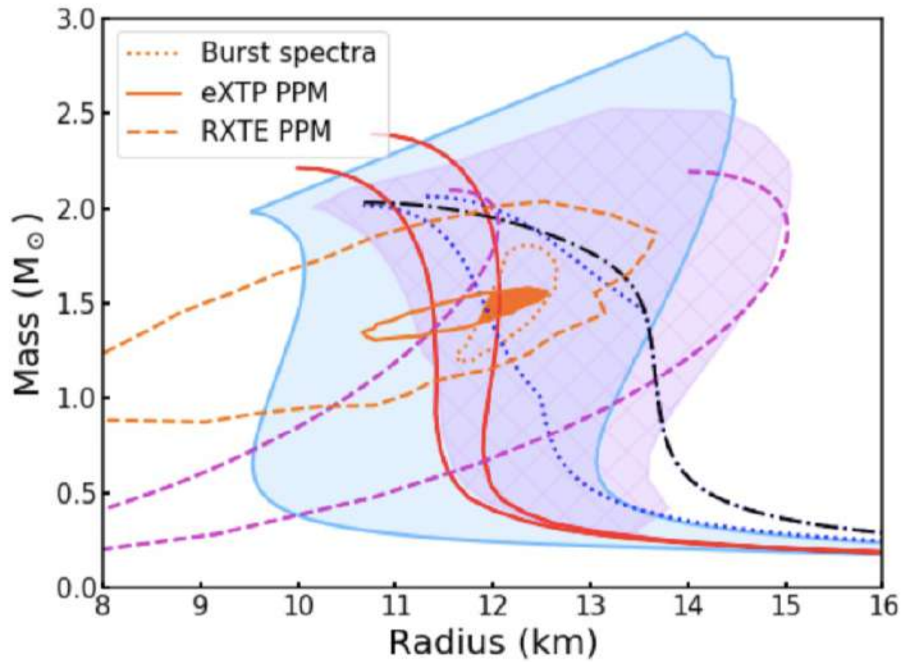


FIGURE 1. The relationship between the composition and inter-particle forces in the neutron star core, the EOS, the mass-radius relation, and the exterior space-time of the star. The space-time of the rotating neutron star imprints its signature on radiation emitted from the stellar surface: we can use this to infer the EOS.

Watts (2019)

Constraining EoS

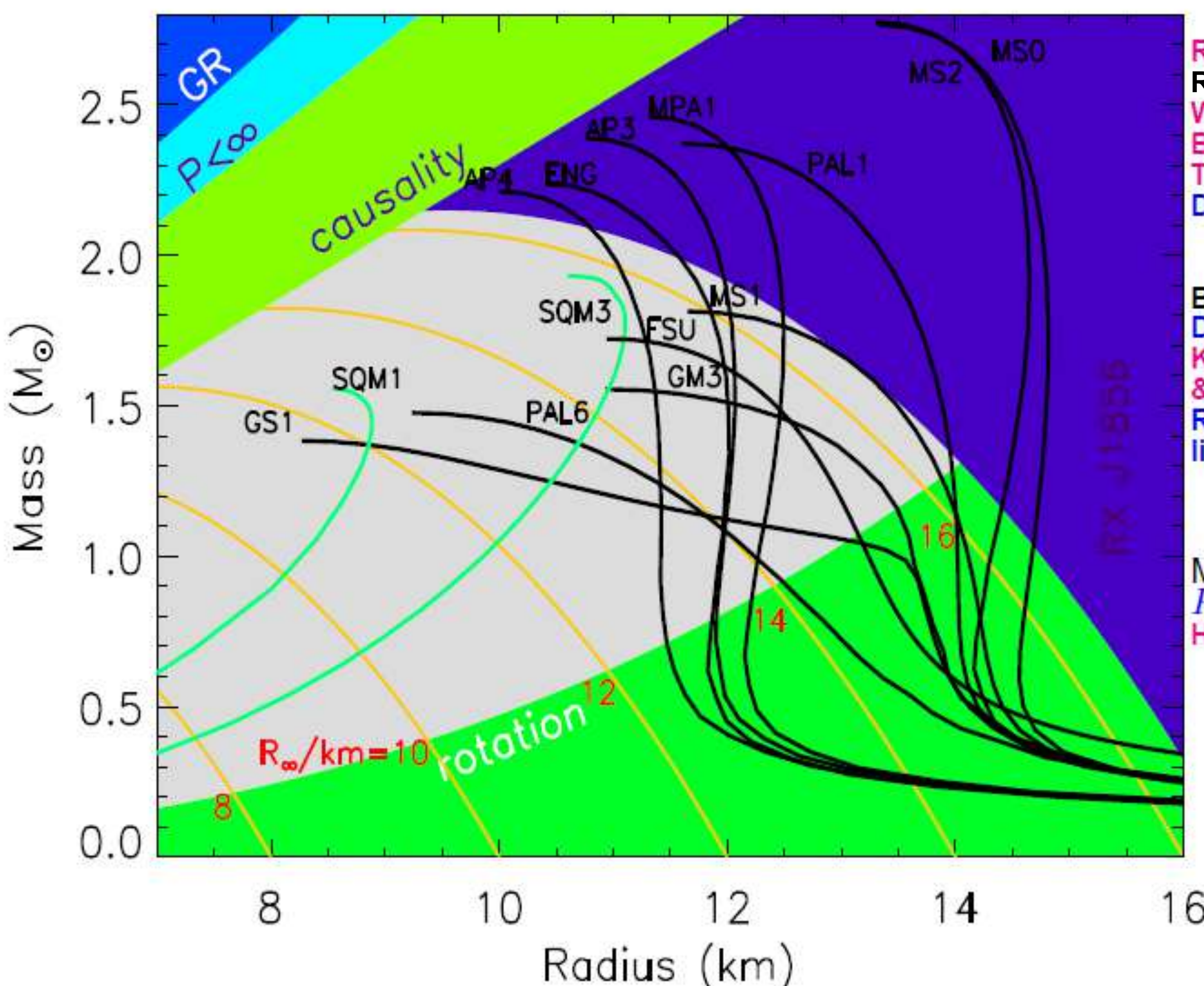


eXTP mission (launch 2025), joint Chinese + EU mission

Constraining EoS

Radiation Radius: Nearby Neutron Star

Lattimer (2009)



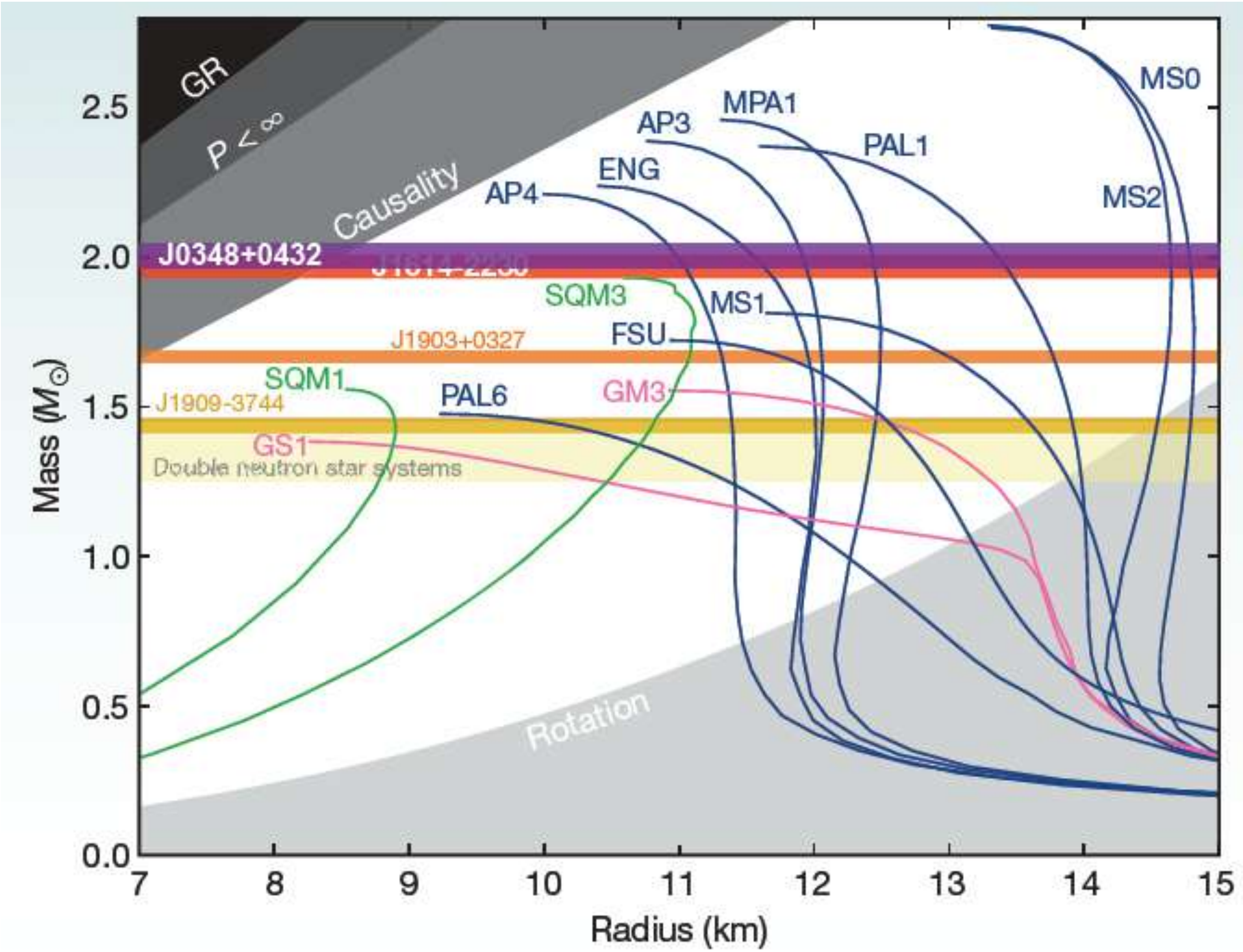
RX J1856-3754:
R= 8 km
Walter & Lattimer 2002
Braje & Romani 2002
Truemper 2005
D=120 pc

BUT
D=140 pc
Kaplan, van Kerkwijk & Anderson 2002
Raises R_∞ limit to 19.5 km

Magnetic H atmosphe
$R_\infty \approx 17$ km
Ho et al. 2007

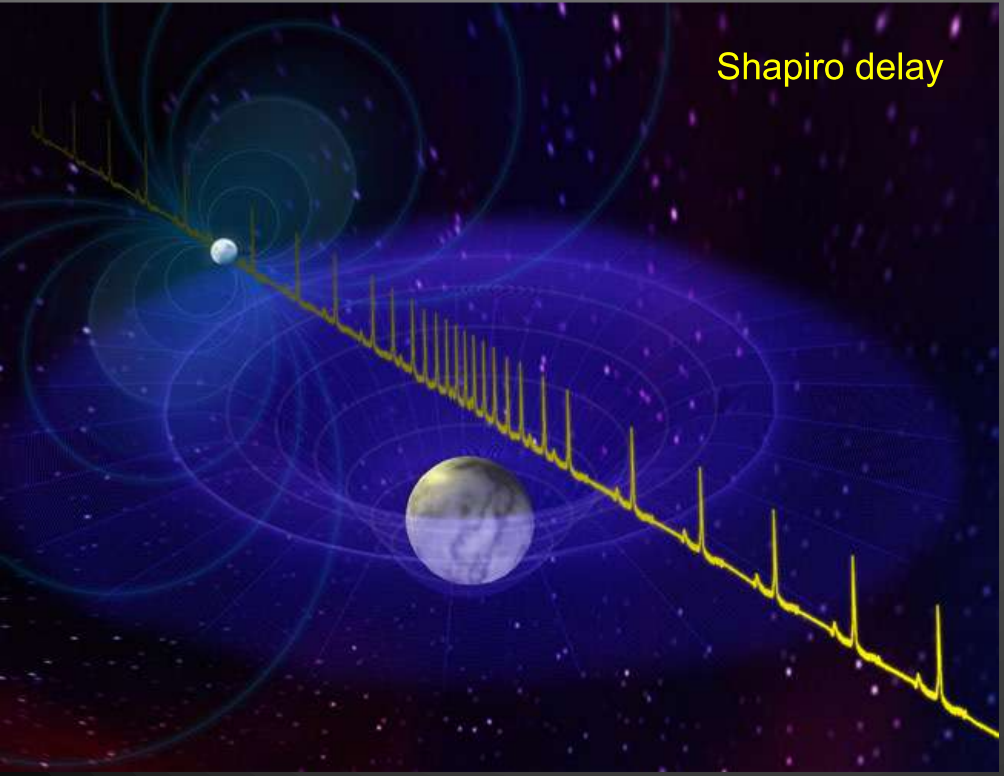
Constraining EoS

Antoniadis et al. (2013)

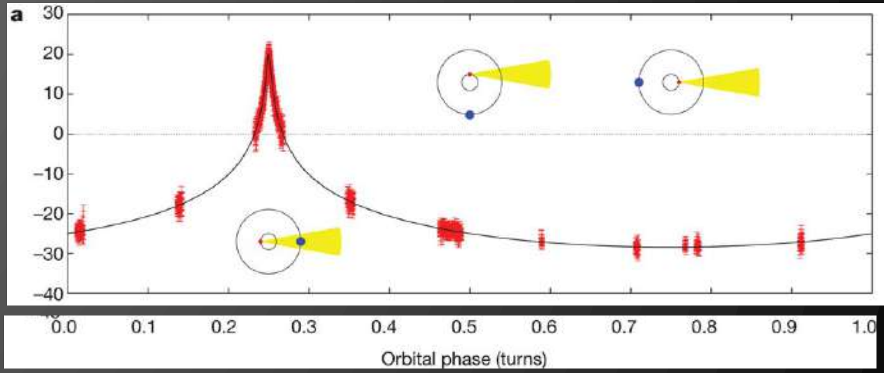


Neutron star masses

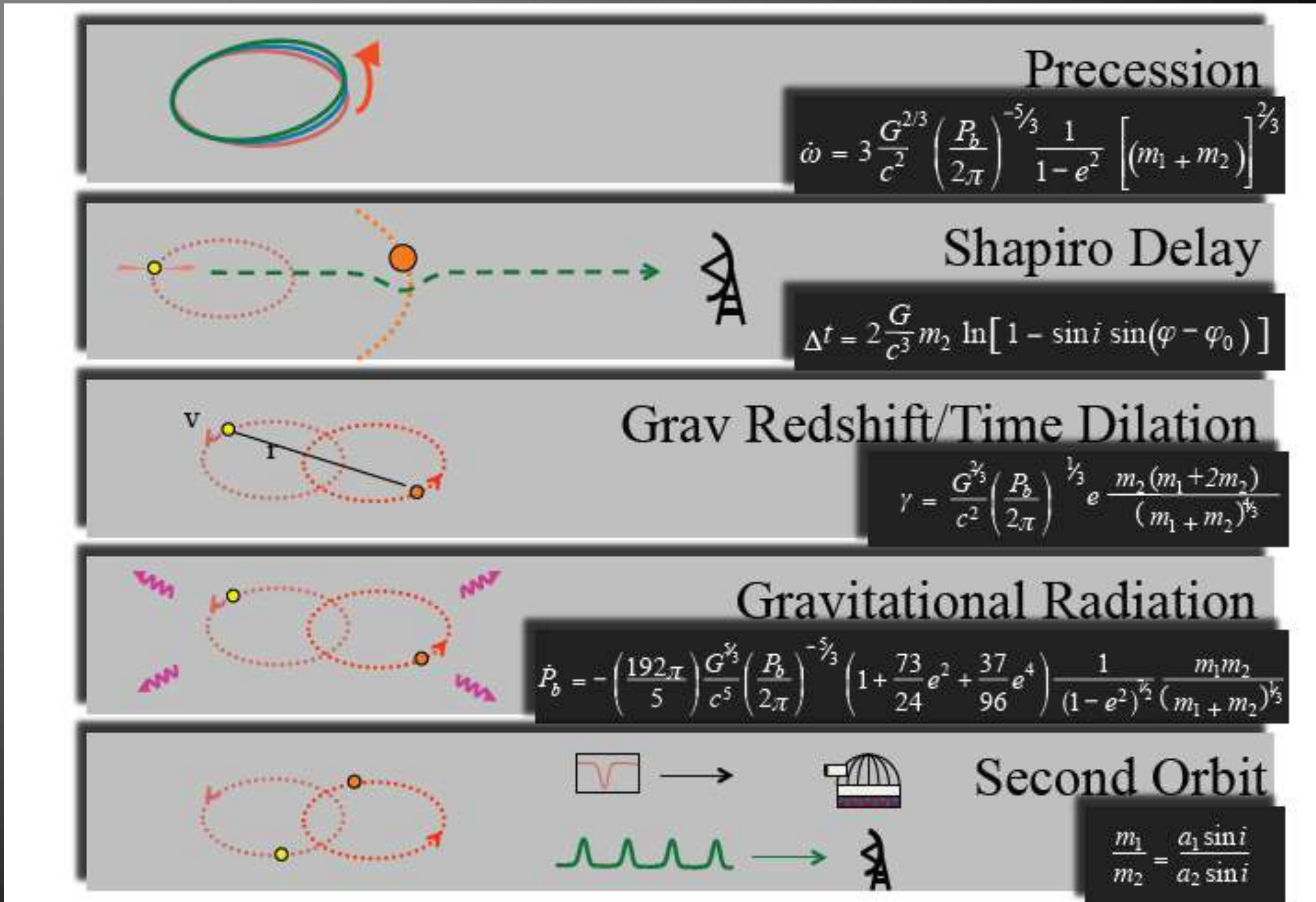
- Shapiro delay (*range* and *shape*) measurements of binary radio pulsars.
- Measurements of other post-Keplerian parameters: $\dot{\omega}, \dot{P}_b, \gamma$
- Dual-line spectroscopy (measurements of WD spectra yields a (dopplershift, besides from radio pulsar timing).



Earth →



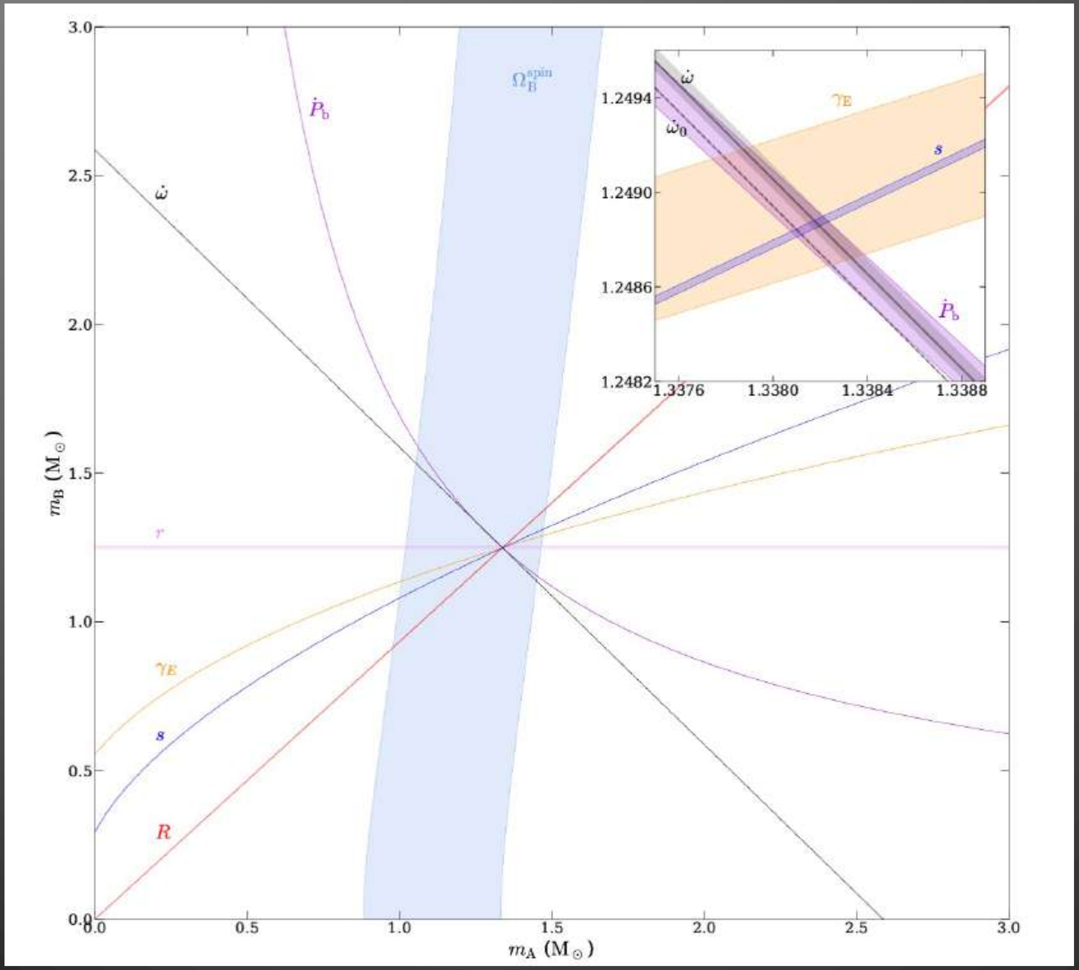
Nice (2013)

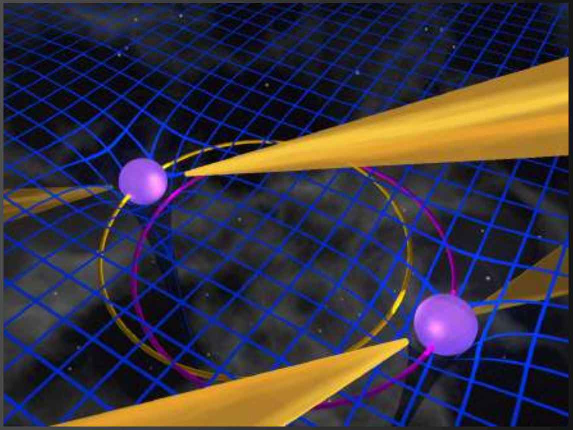


Any PK measurement yields a line in the (m_1,m_2)-plane.
Hence, two PK parametres determines m_1 and m_2 uniquely.

Neutron star masses

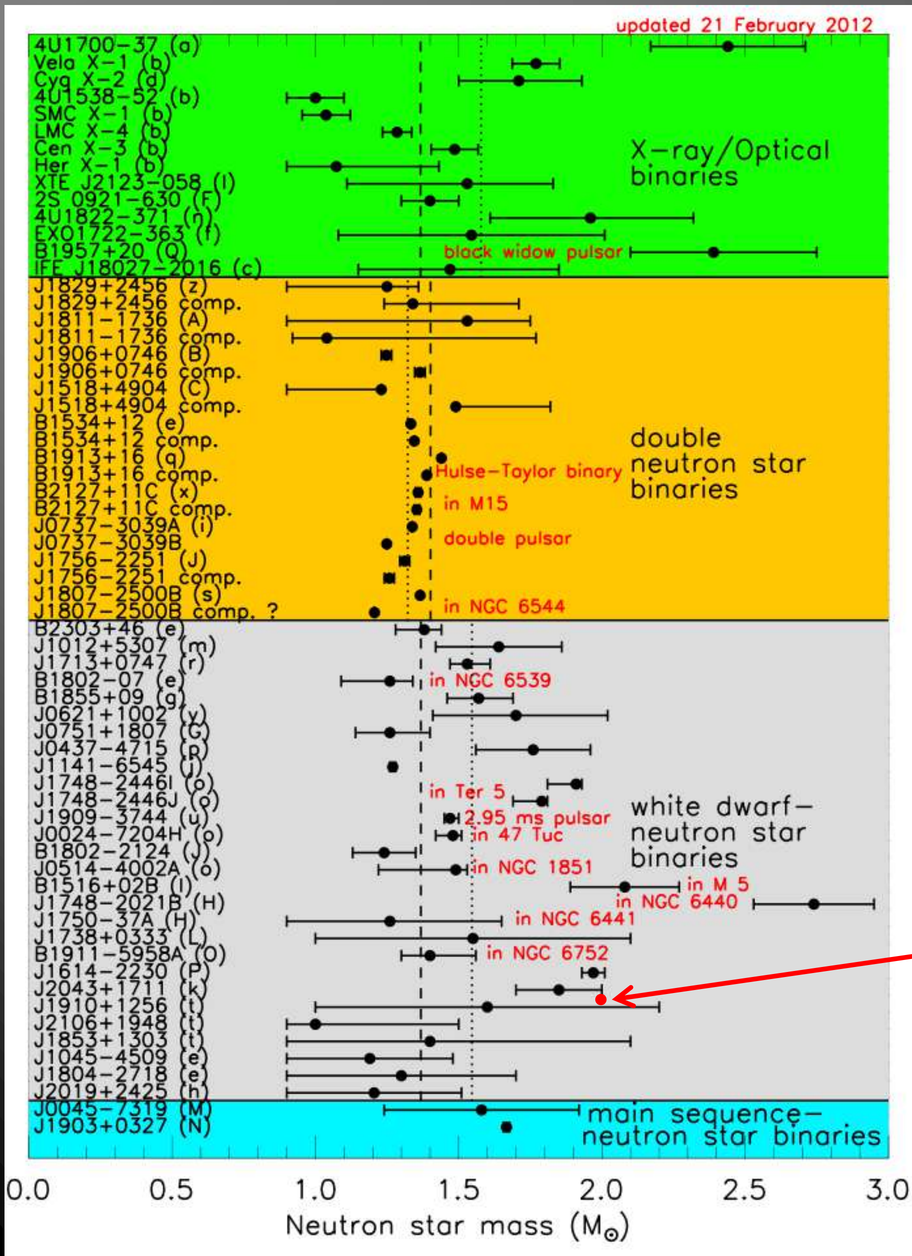
- The double pulsar PSR J0737-3039





Kramer et al. (2021)

Neutron star masses

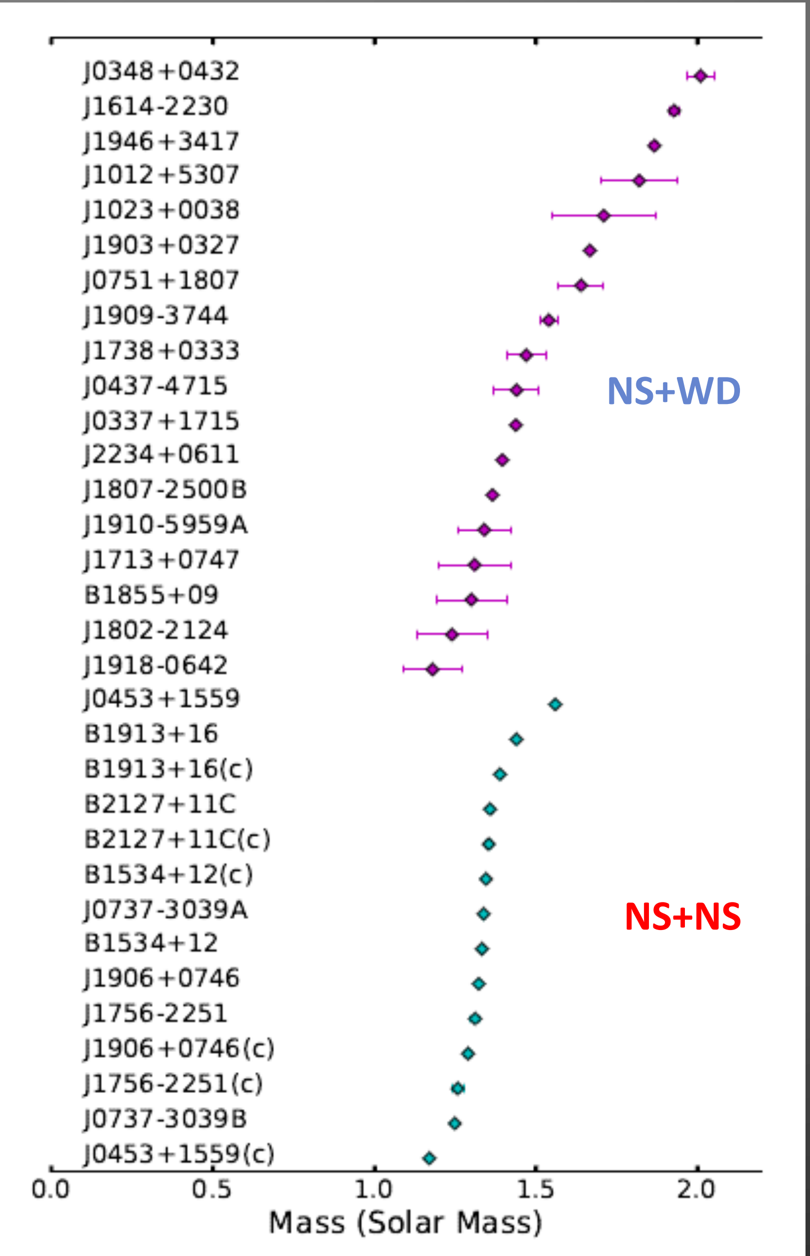


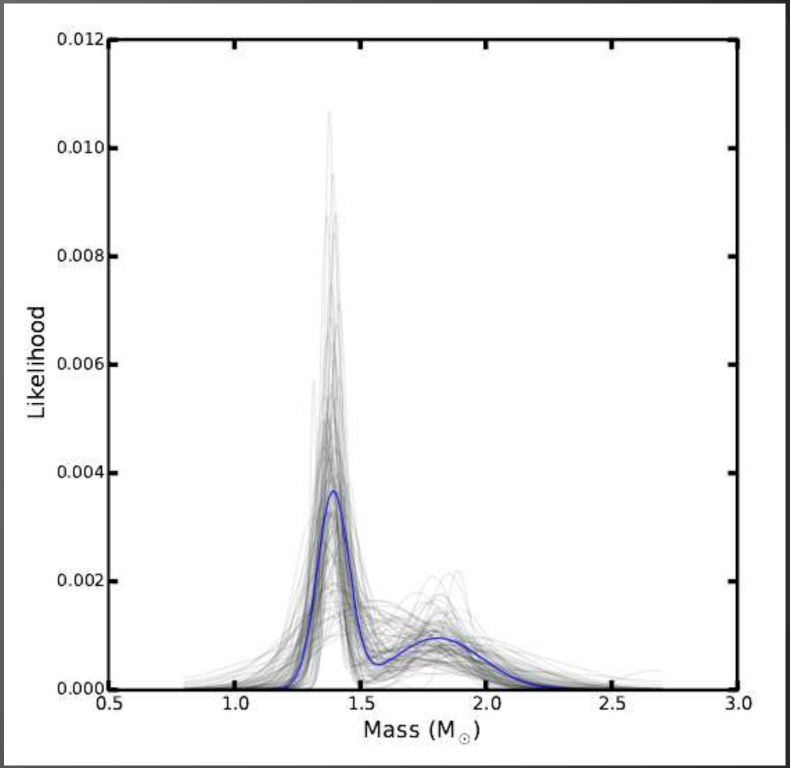
PSR J0348+0432 M=2.01 ± 0.04
Antoniadis et al. (2013)

www.stellarcollapse.org/nsmasses

Lattimer (2013)

Neutron star masses

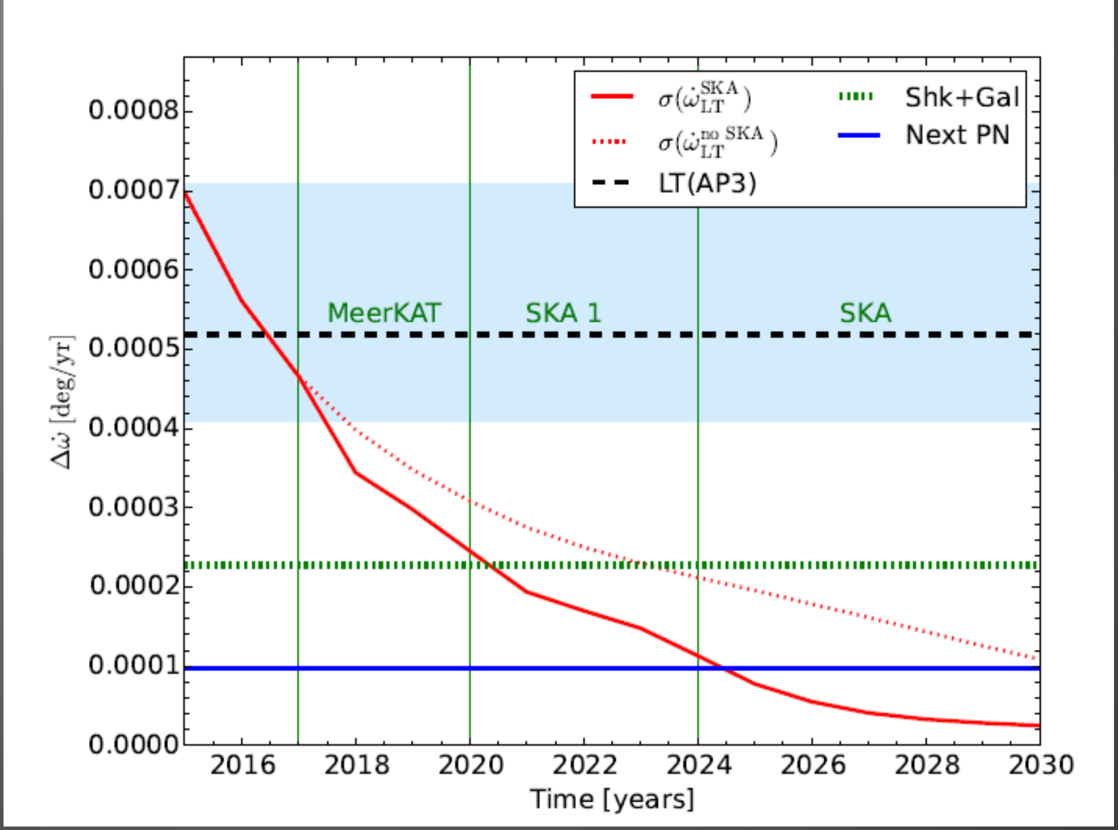




Bimodal NS mass distribution
(reflecting bimodal NS birth mass distribution)

Antoniadis et al. (2016)

Neutron star moment of inertia



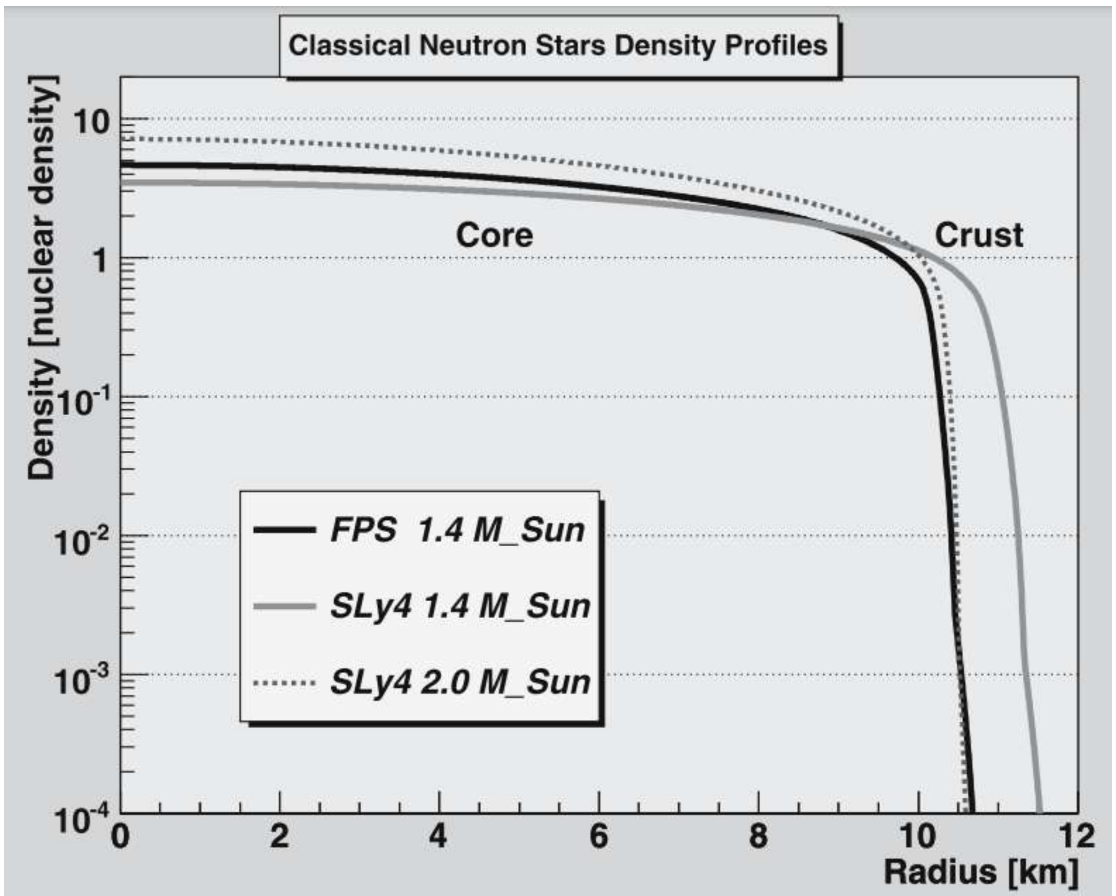
Kehl et al. (2016)

Measurement of the Lense-Thirring effect in the double pulsar system will allow to constrain the NS moment of inertia:

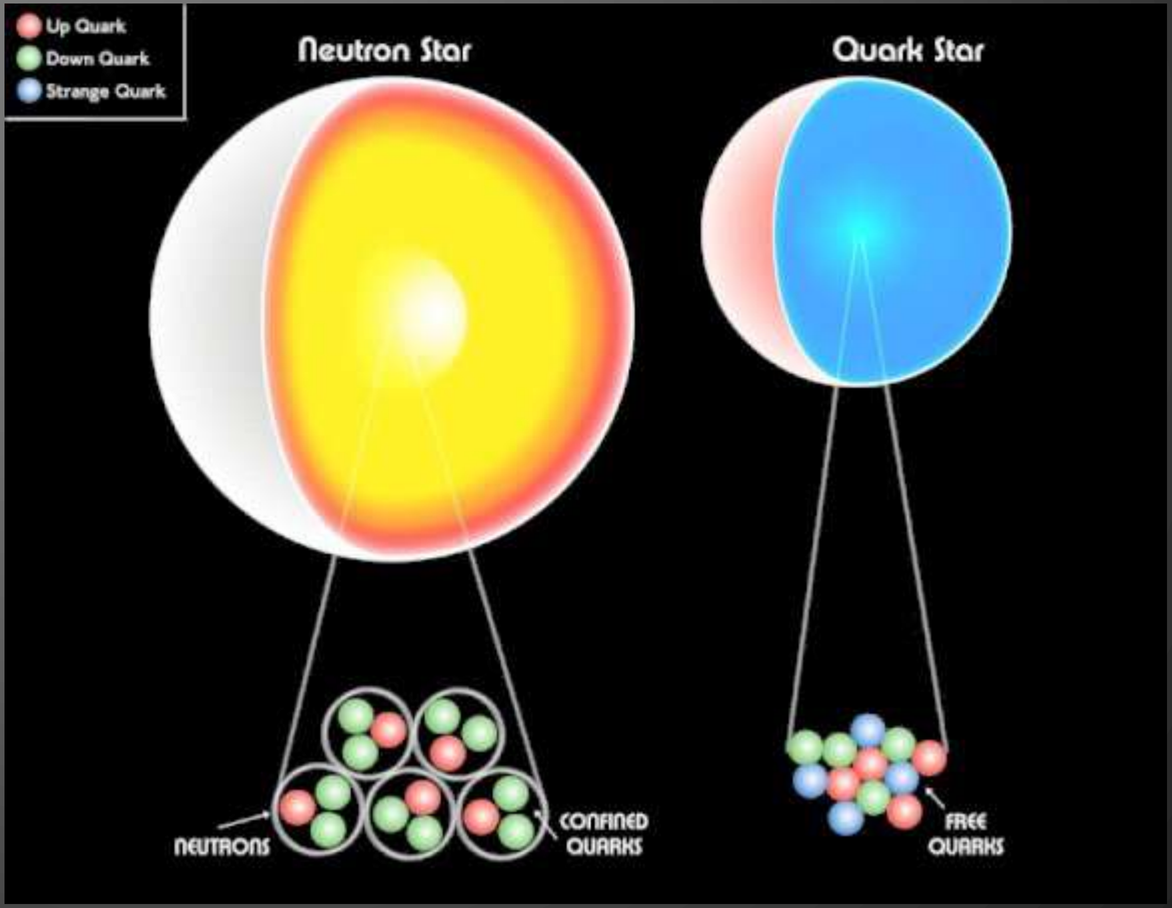
$$I = k^2 M R^2$$

Structure of Neutron Stars

Fig.6.7 (Camenzind 2007)



Strange Star EoS



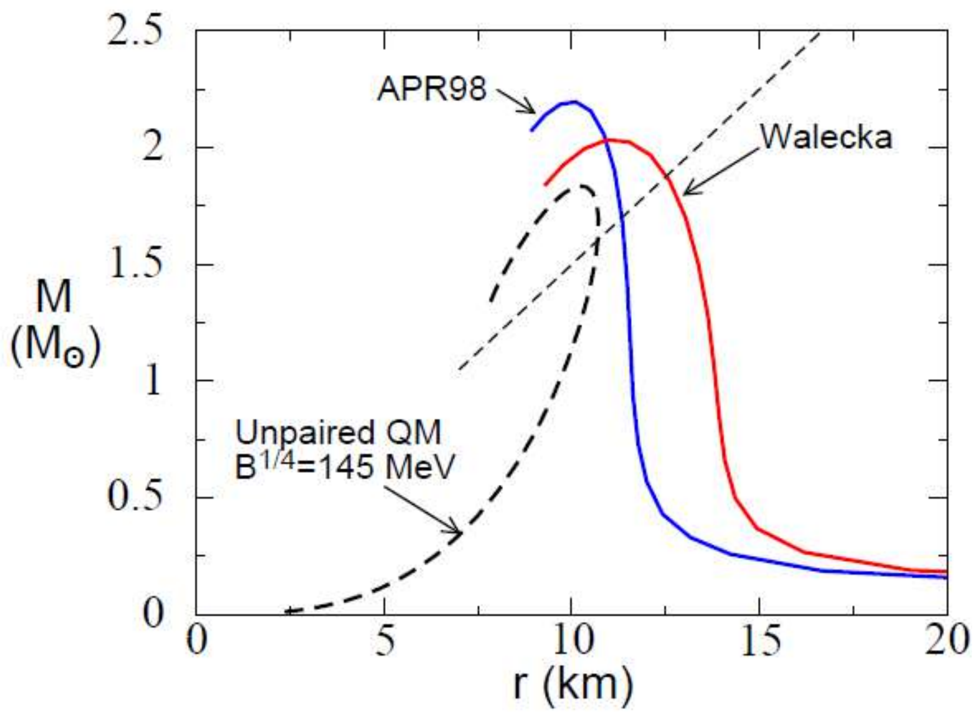
Strange Star EoS

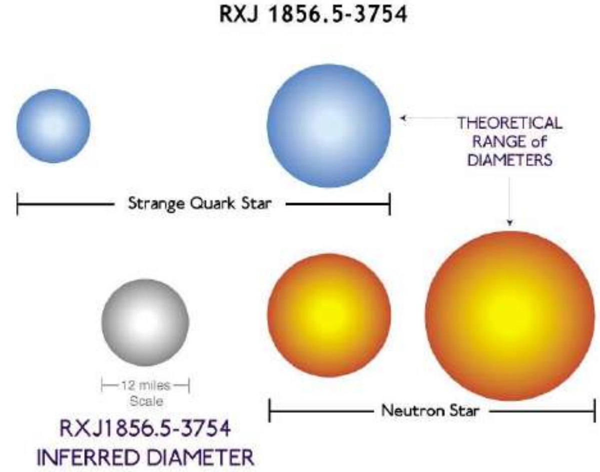
See Weber (2005) Prog.Part.Nucl.Phys.54:193-288, for a review.

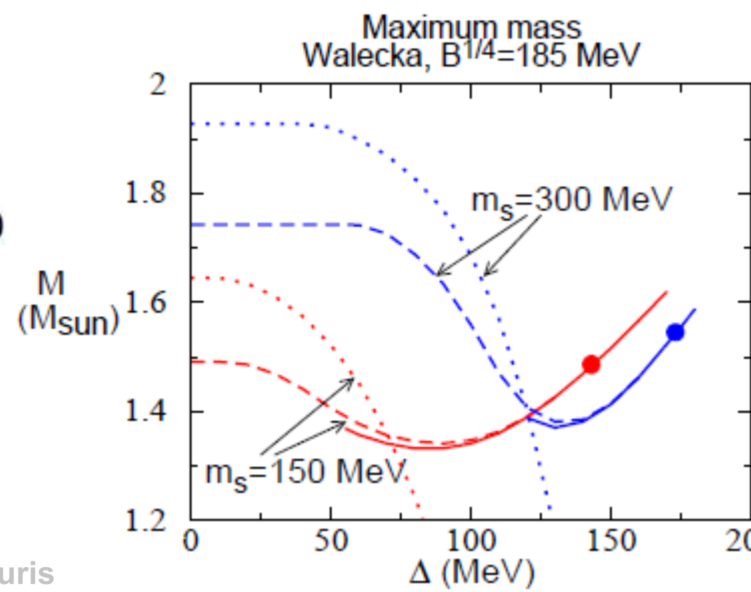
- MIT bagmodel
  - degenerate Fermi sea of massless quarkes
  - energy density B
  - important physics parameters: B, m_s, α_s
    (bag constant, mass of strange quark, strong interaction coupling constant)
  - EoS: $P = \frac{1}{3}(\rho - 4B)$
- M(R) ↑ (quark stars with larger masses have larger radii)
- Difficult to confirm observationally (sub-ms pulsar: $P < 0.6\ ms$)
- Hybrid stars are very popular: quark core + normal matter
- Quark-novae represent the transition from a normal NS to hybrid star

Strange Star EoS

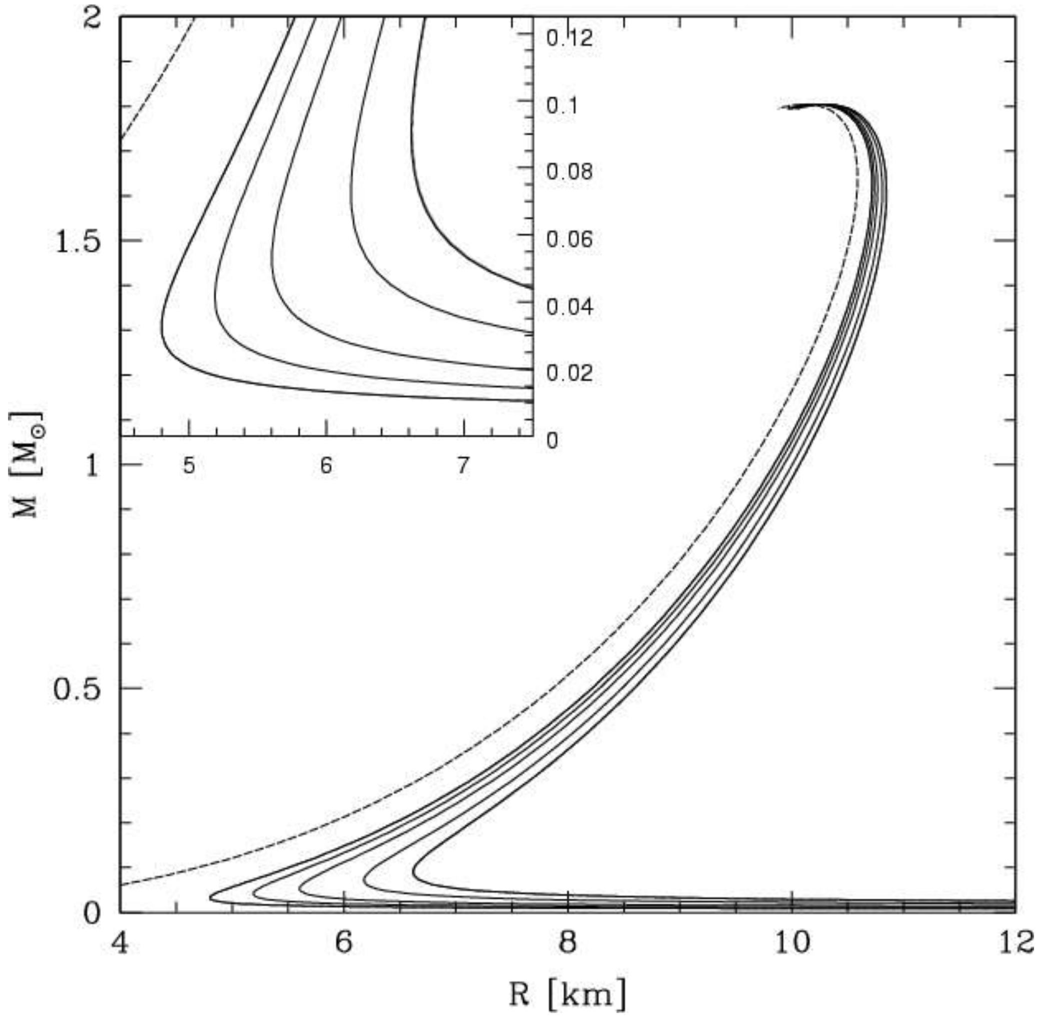
Alford & Reddy (2003)







Strange Star EoS



Hybrid Star

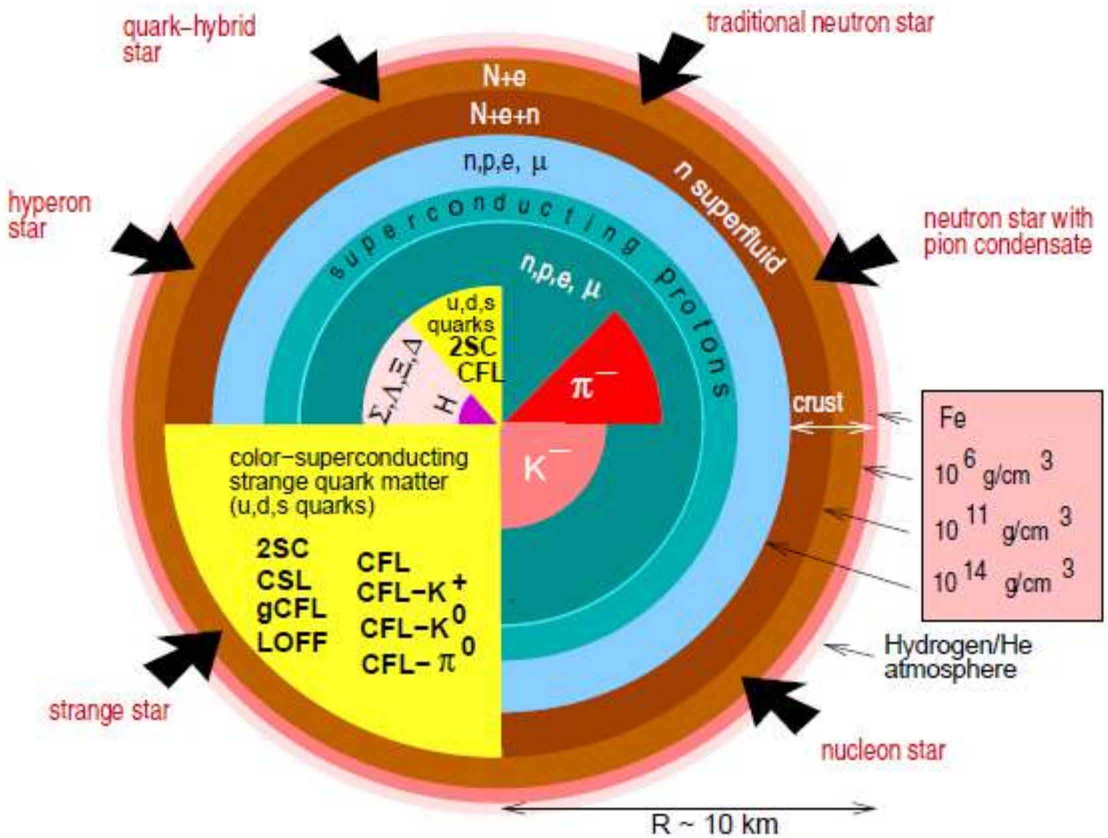


Figure 1: Competing structures and novel phases of subatomic matter predicted by theory to make their appearance in the cores ($R \lesssim 8$ km) of neutron stars [2].

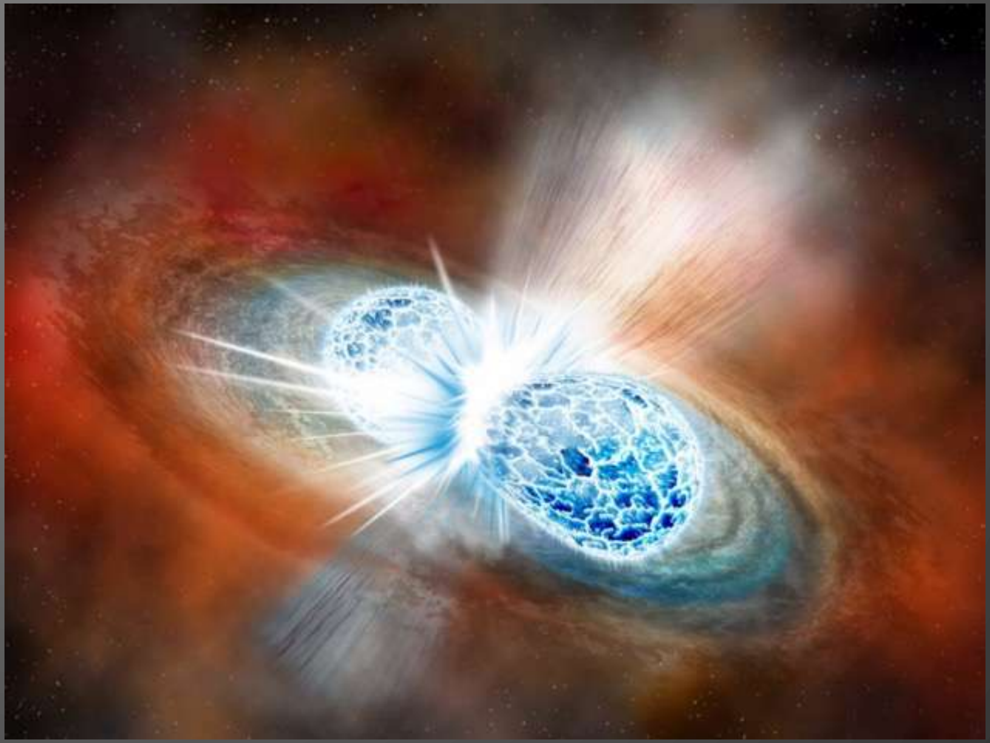
Quark-novae

A quark-nova is the violent explosion resulting from the conversion of a neutron star to a quark star (Oyued, Dey & Dey, A&A 390 L39-42, 2002).

When a neutron star spins down, it may convert to a quark star through a process known as quark deconfinement.

Direct evidence for quark-novae is lacking; however, observations of supernovae SN 2006gy, SN 2005gj and SN 2005ap have been suggested may point to their existence (Leahy & Ouyed, MNRAS 387, 1193, 2008).

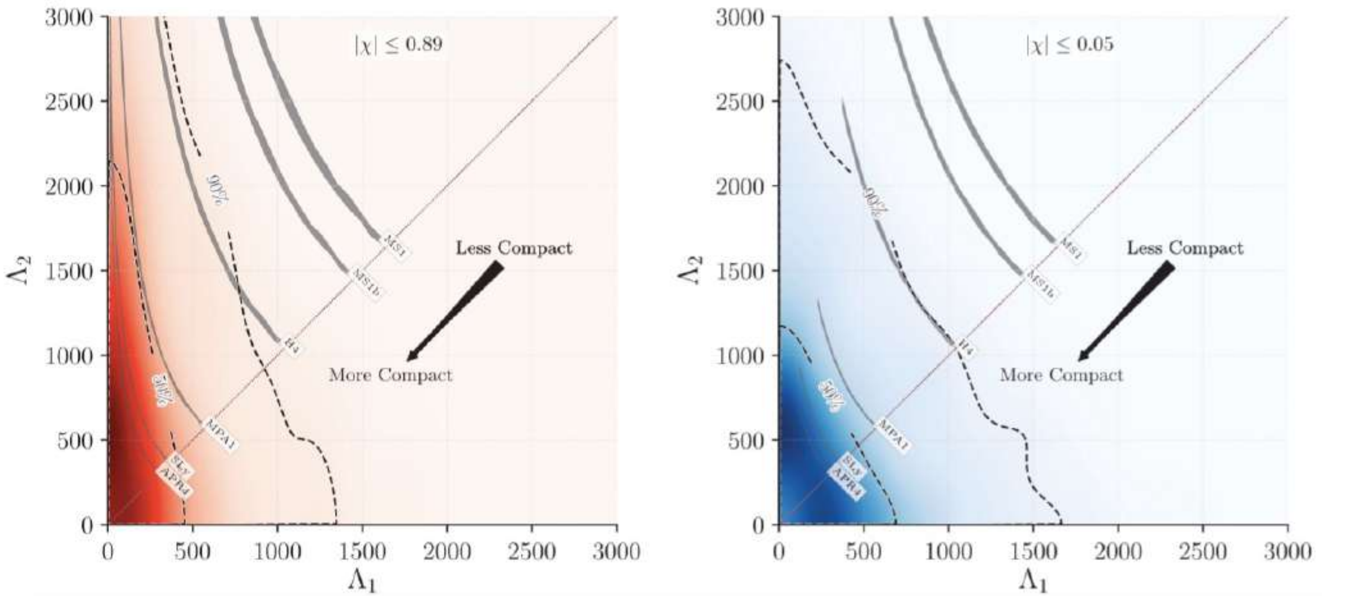
Neutron star / black hole mergers and constraints on the NS EoS

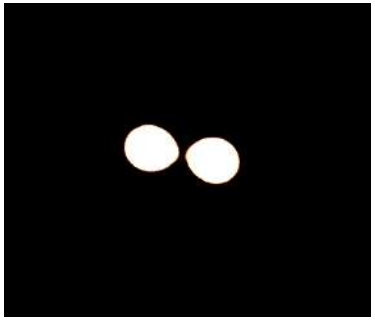


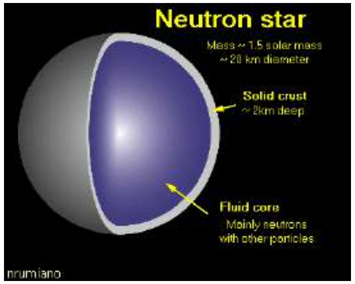
Constraining the NS EoS from tidal interactions in GW170817

- **Tidal deformation and NS EoS**

L 119, 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017




S. Roswogg



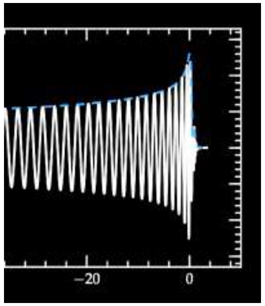
GW phase depends on tidal deformability parameter:

$$\Lambda \propto k\,(R/M)^5$$

$$\lambda \equiv -\frac{Q_{ij}}{\mathcal{E}_{ij}} \qquad \Lambda \equiv \frac{\lambda}{m^5} = \frac{2}{3}k_2\left(\frac{Gm}{Rc^2}\right)^{-5}$$

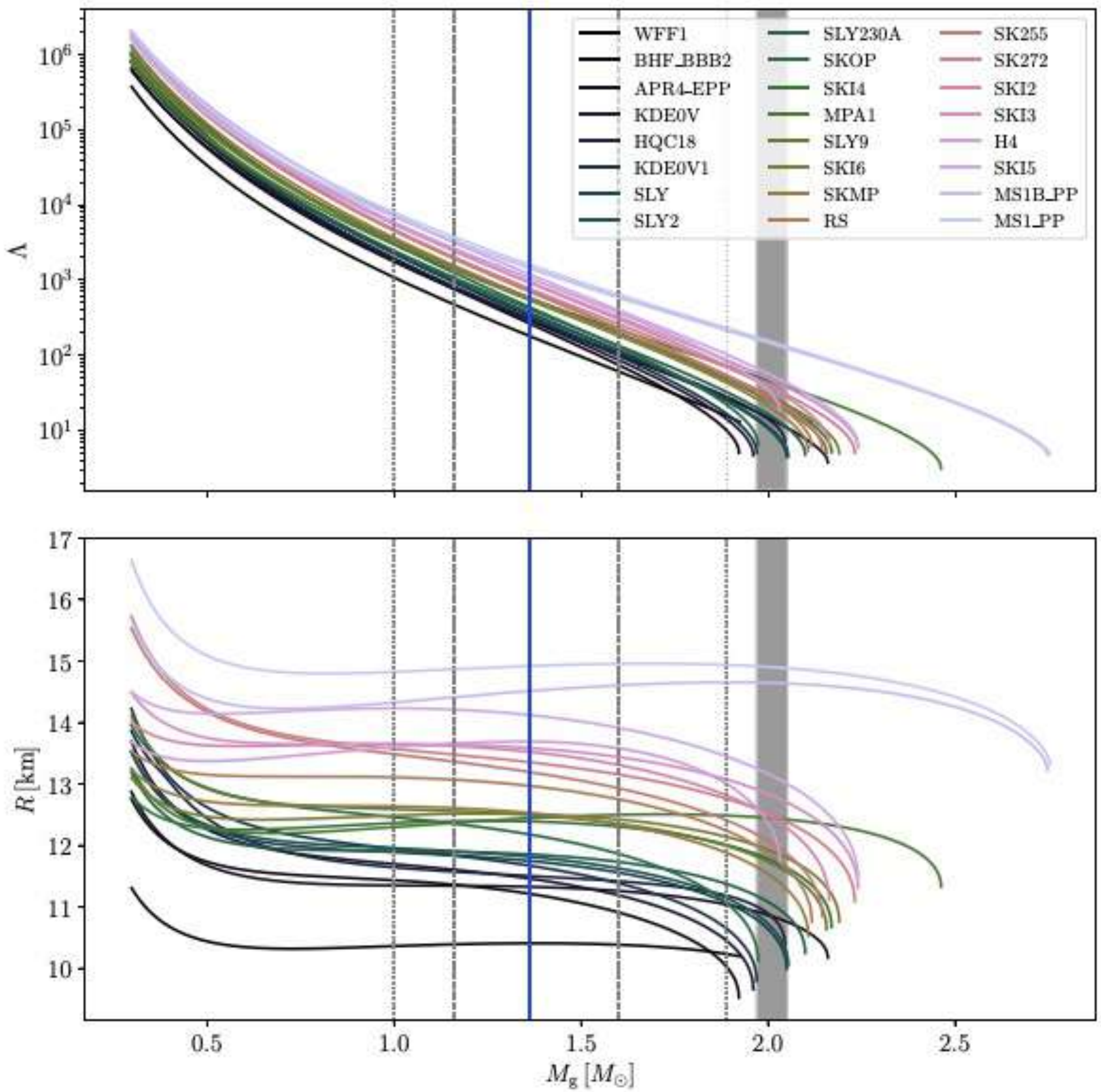
$$\tilde{\Lambda} = \frac{16}{13}\frac{(12q+1)\Lambda_1 + (12+q)q^4\Lambda_2}{(1+q)^5}$$

$$q = m_2/m_1 \le 1$$

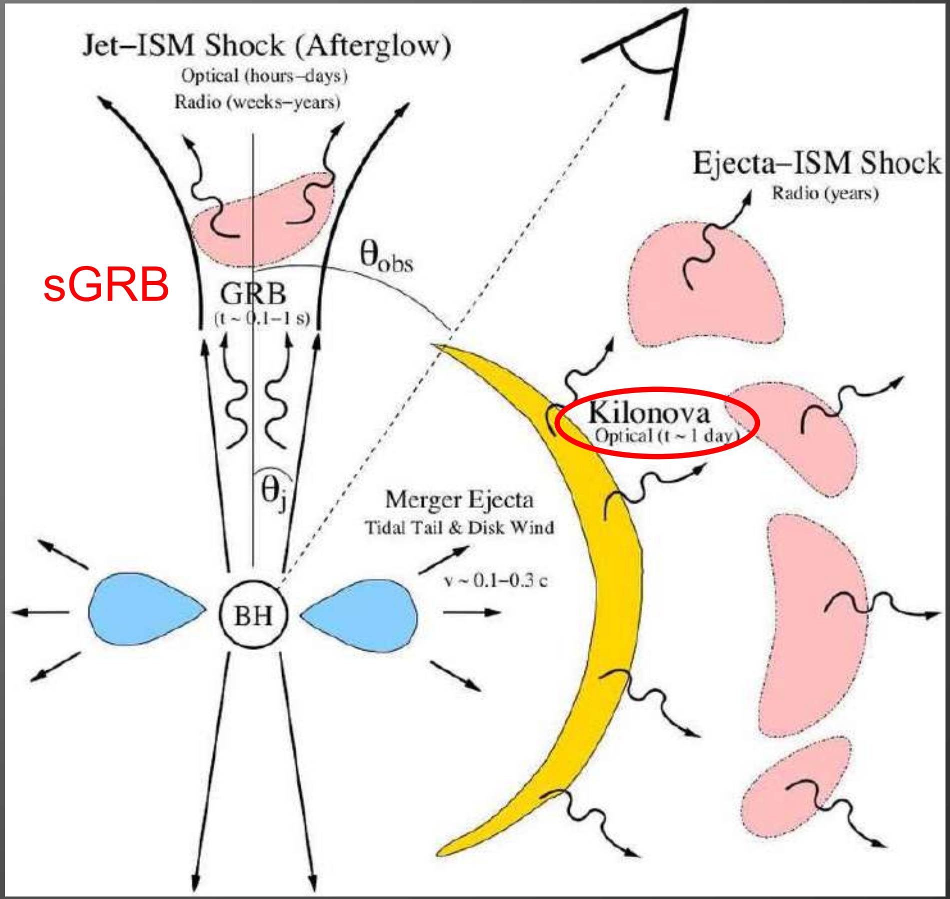


Constraining the NS EoS from tidal interactions in GW170817

Class. Quantum Grav. **37** (2020) 045006 B P Abbott *et al*



Kilonovae



Metzger & Berger(2012)

See also lecture on GWs

Excellent reviews:
Giacomazzo, Eichler & Arcones (2019)
Shibata & Hotokezaka (2019)

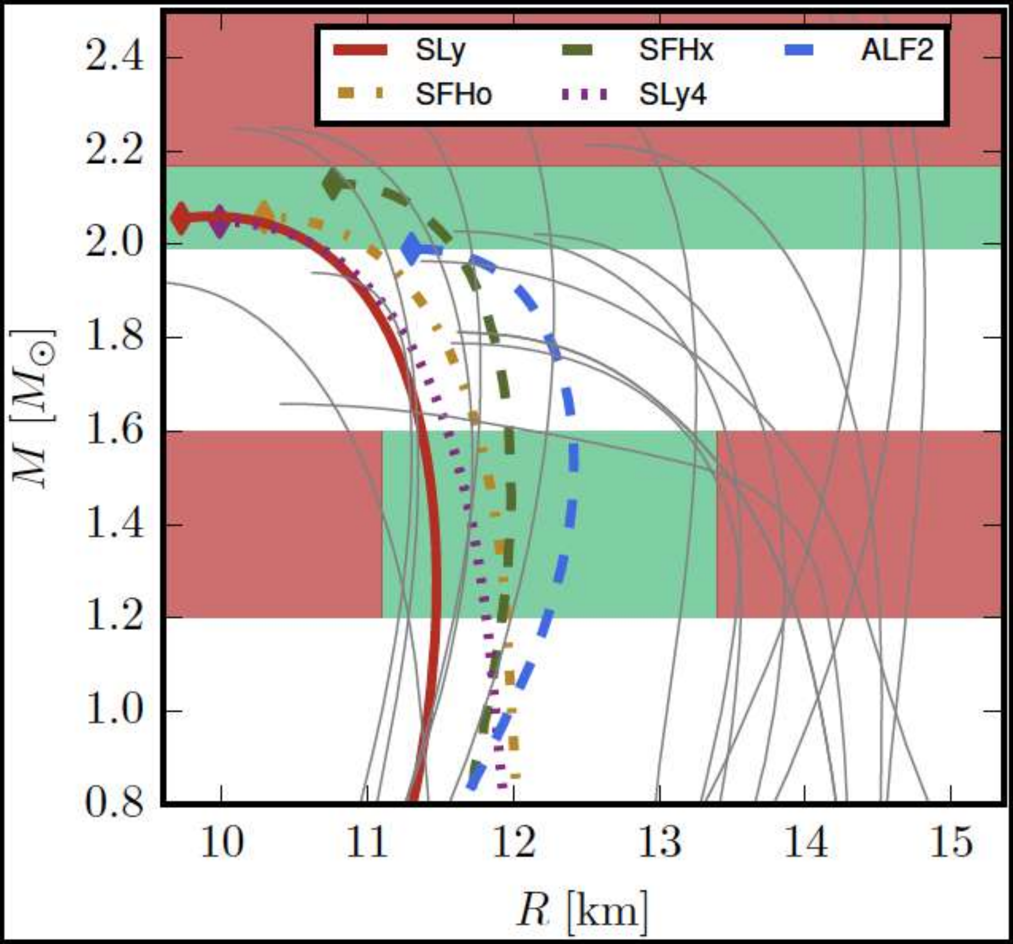
FURTHER LESSONS FROM GW170817 EM FOLLOW-UP

The merger remnant also places a constraint on the maximum neutron star mass

The remnant NS cannot be long lived, or there would be too much energy in the EM observantion

$$M_{\max} \leq 2.17 M_{\odot} \ (90\%)$$

Margalit and Metzger ApJL 850 19 (2018)



Coughlin, Dietrich, Margalit, Metzger arXiv:1812:04803

Slide from Duncan Brown

nature astronomy
LETTERS
https://doi.org/10.1038/s41550-019-0880-2

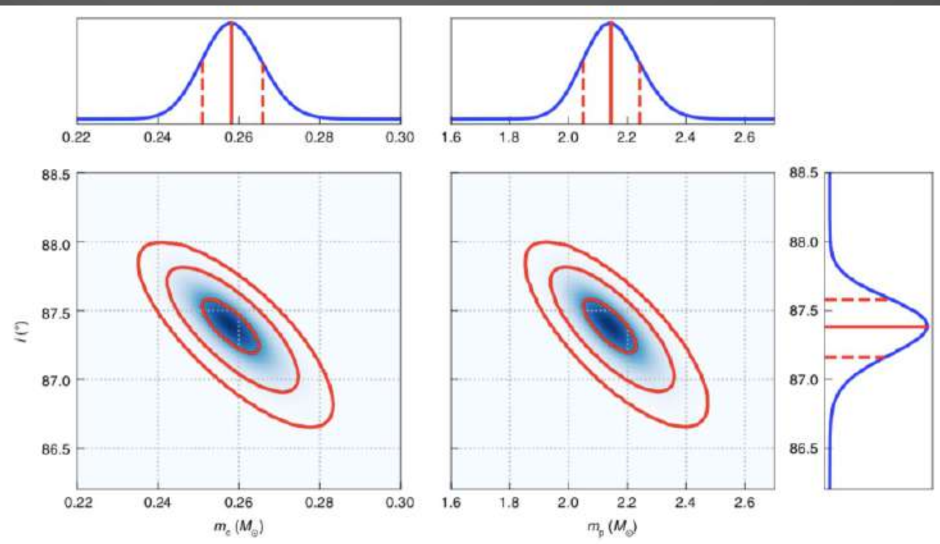
Relativistic Shapiro delay measurements of an extremely massive millisecond pulsar

H. T. Cromartie[1*], E. Fonseca[2], S. M. Ransom[3], P. B. Demorest[4], Z. Arzoumanian[5], H. Blumer[6,7], P. R. Brook[6,7], M. E. DeCesar[8], T. Dolch[9], J. A. Ellis[10], R. D. Ferdman[11], E. C. Ferrara N. Garver-Daniels[6,7], P. A. Gentile[6,7], M. L. Jones[6,7], M. T. Lam[6,7], D. R. Lorimer[6,7], R. S. Lynch[14], M. A. McLaughlin[6,7], C. Ng[15,16], D. J. Nice[8], T. T. Pennucci[17], R. Spiewak[18], I. H. Stairs[15], K. St J. K. Swiggum[19] and W. W. Zhu[20]

Despite its importance to our understanding of physics at supranuclear densities, the equation of state (EoS) of matter deep within neutron stars remains poorly understood. Millisecond pulsars (MSPs) are among the most useful astro-

Precise neutron star mass measurements are an effect constrain the EoS of the ultradense matter in neutron sta Although radio pulsar timing cannot directly determin star radii, the existence of pulsars with masses exceeding

we have measured the mass of the MSP J0740+6620 to be $2.14^{+0.10}_{-0.09}$ $M_{\odot}$ (68.3% credibility interval; the 95.4% credibility interval is $2.14^{+0.20}_{-0.18}$ $M_{\odot}$). It is highly likely to be the most massive neutron star yet observed, and serves as a strong constraint on the neutron star interior EoS.



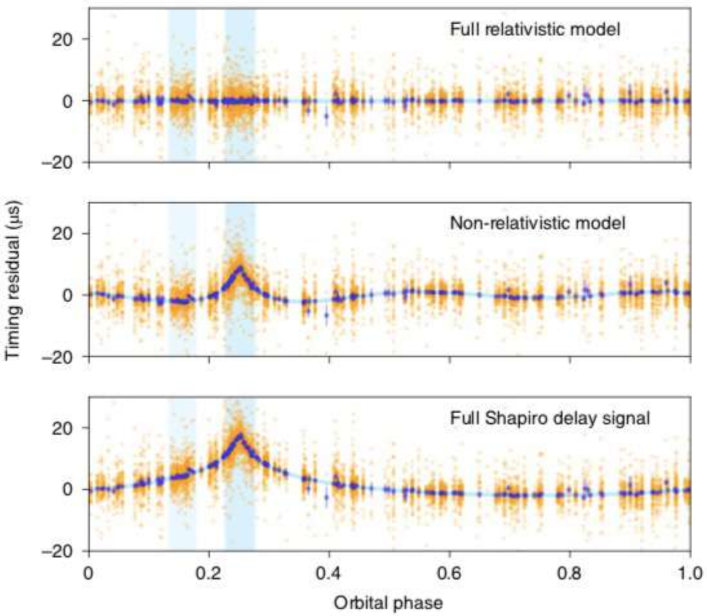
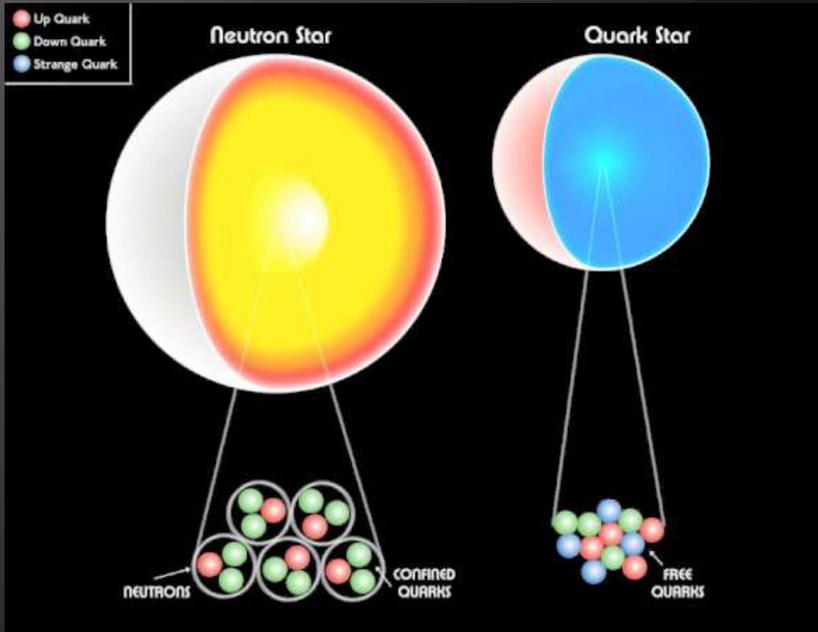


Fig. 1 | Timing residuals from all observations of J0740+6620 as

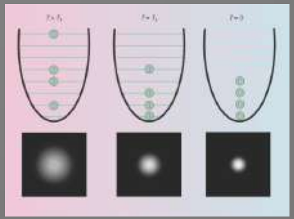
Structure of Neutron Stars

Cold equations-of-state above neutron drip

- EoS for $\rho_{drip} < \rho < \rho_{nuc}$
  - Baym-Bethe-Pethick (BBP) EoS
  - Stability of NSs
- EoS for $\rho > \rho_{nuc}$
  - Nucleon-nucleon interactions
  - Muons, hyperons, Δ-resonances, pion/kaon condensation
  - Superfluidity (glitches/cooling of NSs)
  - Bethe-Johnson (BJ) EoS
  - Quark (strange) stars / quark-novae
- Summary of EoS above neutron drip
- Structure of NSs
  - Cross section
  - Soft vs Stiff EoS
  - Observational constraints on M and R

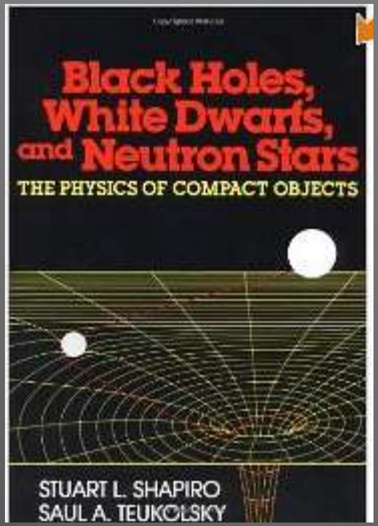


Programme



- ∗ **Introduction**
- ∗ **Degenerate Fermi Gases**
  Non-relativistic and extreme relativistic electron / (n,p,e^-) gases
- ∗ **White Dwarfs**
  Structure, cooling models, observations
- ∗ **Neutron Stars**
  Structure and equation-of-state
- ∗ **Radio Pulsars**
  Characteristics, spin evolution, magnetars, observations, timing
- ∗ **Binary Evolution and Interactions**
  X-ray binaries, accretion, formation of millisecond pulsars, recycling
- ∗ **Black Holes**
  Observations, characteristics and spins
- ∗ **Gravitational Waves**
  Sources and detection, kilonovae
- ∗ **Exam**

Physics of Compact Objects
week 5



Shapiro & Teukolsky (1983), Wiley-Interscience

Curriculum

- Chapter 8: p.(188-197), (220-240)
- Chapter 9: p.241-253, 253-258.

Want to know more? See our course webpage for modern reviews on the NS EoS: e.g. Lattimer & Prakash (2016), Bauswein et al. (2017).

Next lecture: Chapter 10: p.267–290.
+ Tauris & van den Heuvel (2023), Chapter 14.1

Exercises: # 5, 6, 12, 14

- Mon. Oct. 2, 10:15-12:00