Quark Matter in Neutron Stars

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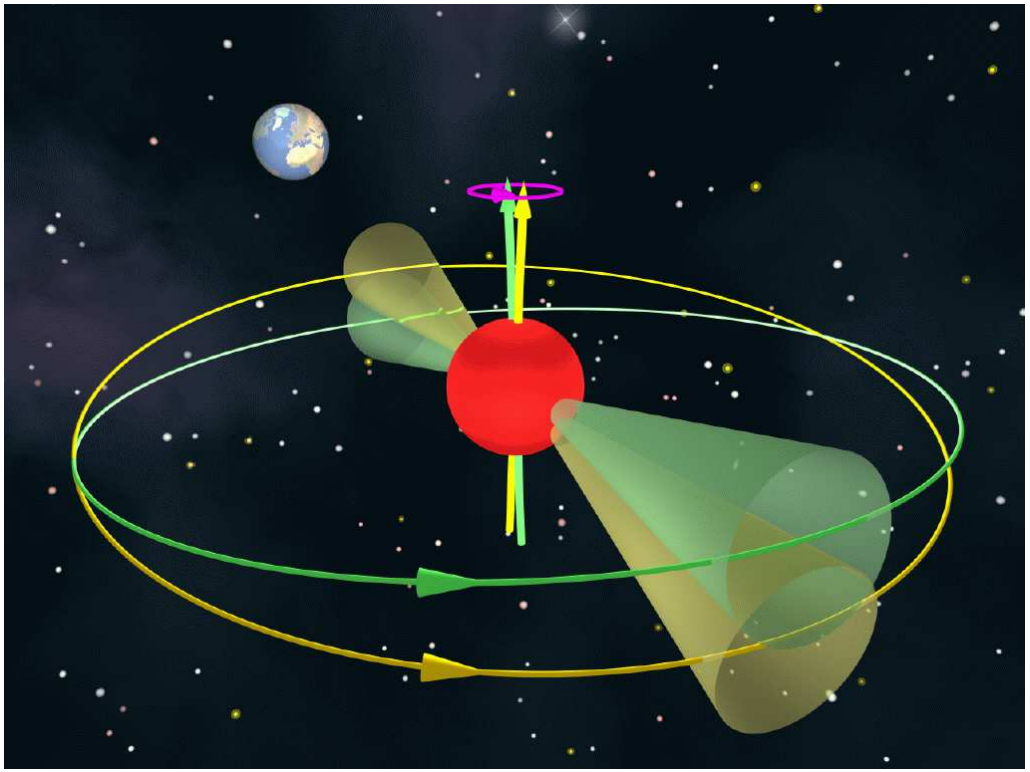
Argonne National Laboratory, (PHY)

September 7th, 2006



Outline

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- Mass-Radius constraints on Equation of State (EoS)

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- Strange Quark stars: Features and "Findings"

- Thermal evolution of Neutron stars
  - Constraints on EoS from cooling
  - Neutrinos from dense quark matter

A history of discovery

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- 1968: Gold [pulsations↔rotating neutron star]

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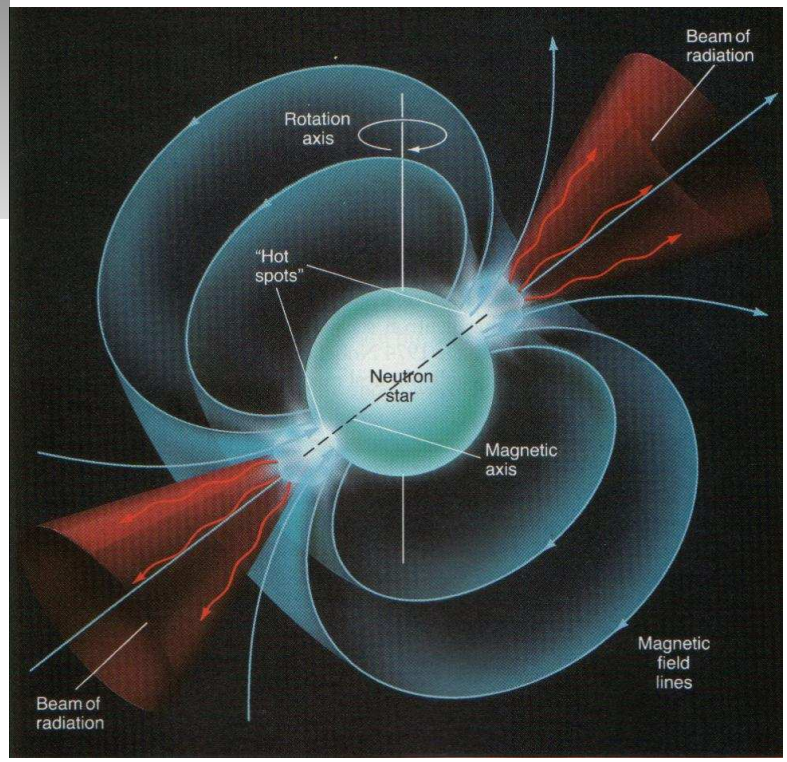
- 2006-: CHANDRA smells a RRAT
  Rotating RAdio Transients

Detection: Pulsed radiation

Rotating dipole model



radio emission is tiny fraction of total radiation

- spin-down

$$\dot{E} = -\frac{B^2 \sin^2 \alpha \Omega^4 R^6}{6c^3} = I\Omega\dot{\Omega}$$

- Braking index

$$\dot{\Omega} = K\Omega^n;\ n = \frac{\Omega\ddot{\Omega}}{\dot{\Omega}^2} = 3$$

- Magnetic field

$$\Omega = \frac{2\pi}{P};\ B = \left(\frac{3Ic^3 P\dot{P}}{2\pi^2 R^6}\right)^{1/2}$$

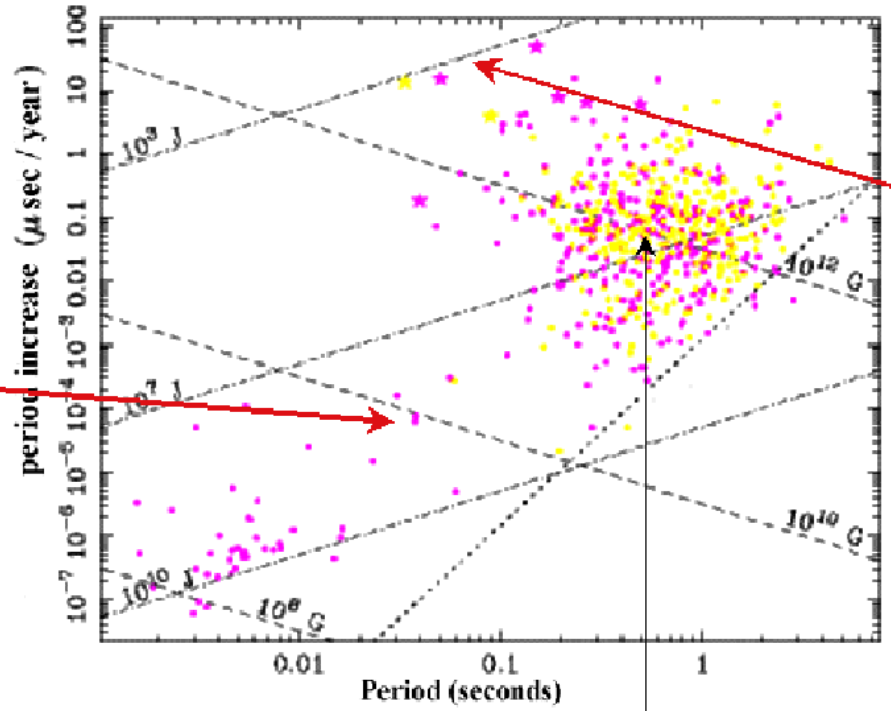
- Characteristic age

$$\tau \approx \frac{-\Omega}{(n-1)\dot{\Omega}} = \frac{P}{2\dot{P}}$$

P-Pdot diagram

Estimated surface field:

$$B_0 \approx 3.2 \times 10^{19} \sqrt{P\dot{P}}\ \mathrm{G}$$



Characteristic ag

$$\tau_c = \frac{P}{2\dot{P}}$$

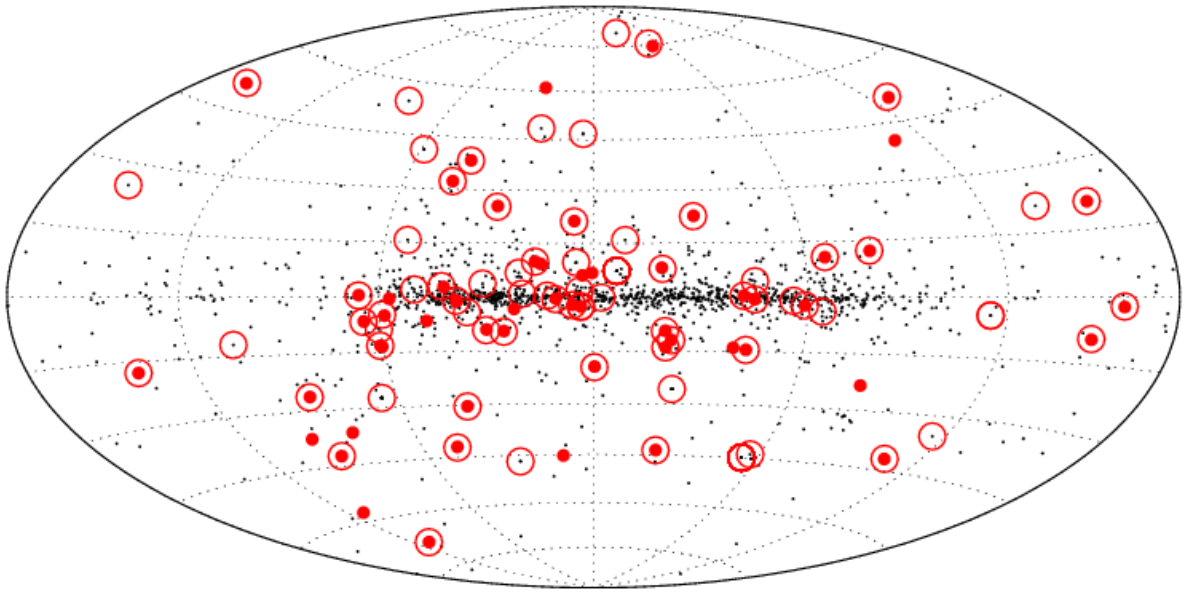
„braking index“

„typical pulsar“ P=0.5s B=10^{12} G

1600 Neutron stars found (out of $\sim 10^8$ in our Galaxy)

1500 radio, 70 X-ray binary, 10 RRATS, 7 AXP, 5 SGR ...

Pulsar distribution



Pulsar type

⊙ - Binary Pulsars

○ - Millisecond Pulsars

● - Radio Pulsars

Selection effects

Luminosity $\propto 1/r^2$

Pulse dispersion (width$\sim$Period)

Beaming angle

Mass-Radius

TOV equations:

Einstein's equations for a spherically symmetric fluid in equilibrium:
(Mass M, Pressure P, red-shift α)

$$\begin{aligned}
\frac{dM(r)}{dr} &= 4\pi r^2 \epsilon(r) \\
\frac{dP(r)}{dr} &= -\frac{(\epsilon(r)+P(r))(M(r)+4\pi r^3 P(r))}{r(r-2M(r))} \\
\frac{d\alpha}{dr} &= \frac{\alpha(M(r)+4\pi r^3 \epsilon(r))}{r(r-2M(r))}
\end{aligned}$$

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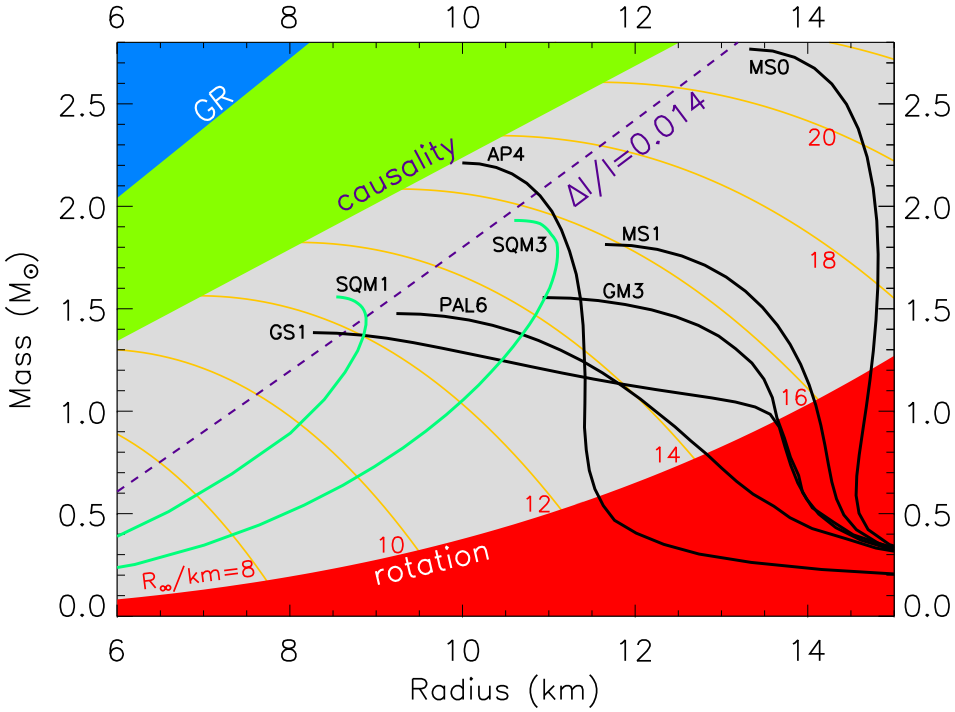
Closed once equation of state (EoS) is given: $P = P(\epsilon)$

with boundary conditions: $M(r=0)=0, \alpha(r=R)=\sqrt{1-2M(R)/R}$

initial choice: $\epsilon(r=0)=\epsilon_0$ generates a 1-parameter (ϵ_0) family

M-R diagram

Lattimer & Prakash, Astrophys.J. 550 (2001) 426



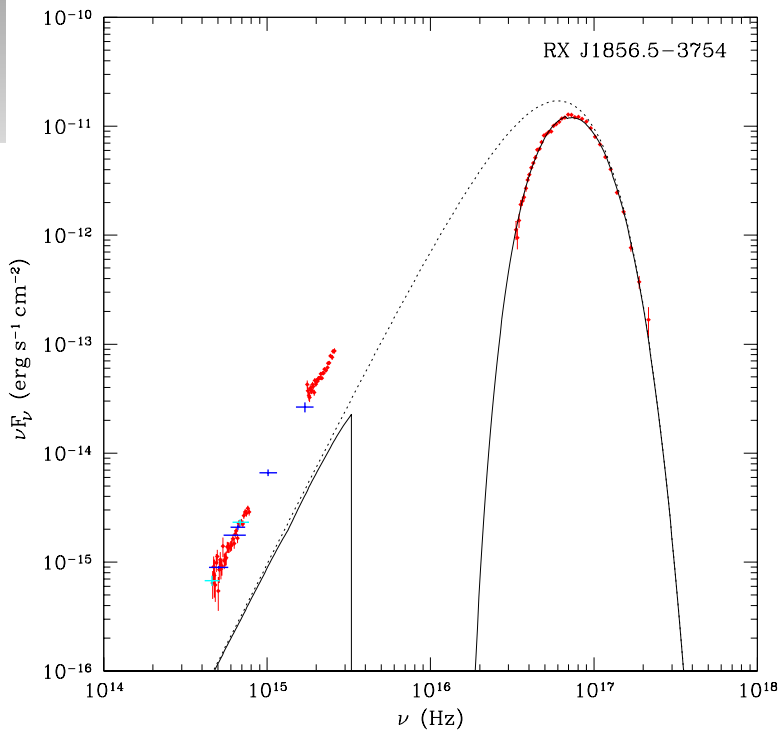
Each curve is a different EoS

(—— Neutron Stars; —- Strange Stars)

Variable along each curve is central density

Mass-radius observations

Isolated neutron stars



Kaplan & van Kerkwijk, astro-ph/0607320

Observed Flux f_∞ and Temp. T_∞ obtained from spectral fit

$$f_\infty = 4\pi R_\infty^2 \sigma_{SB} T_\infty^4 / \mathrm{dist}^2$$

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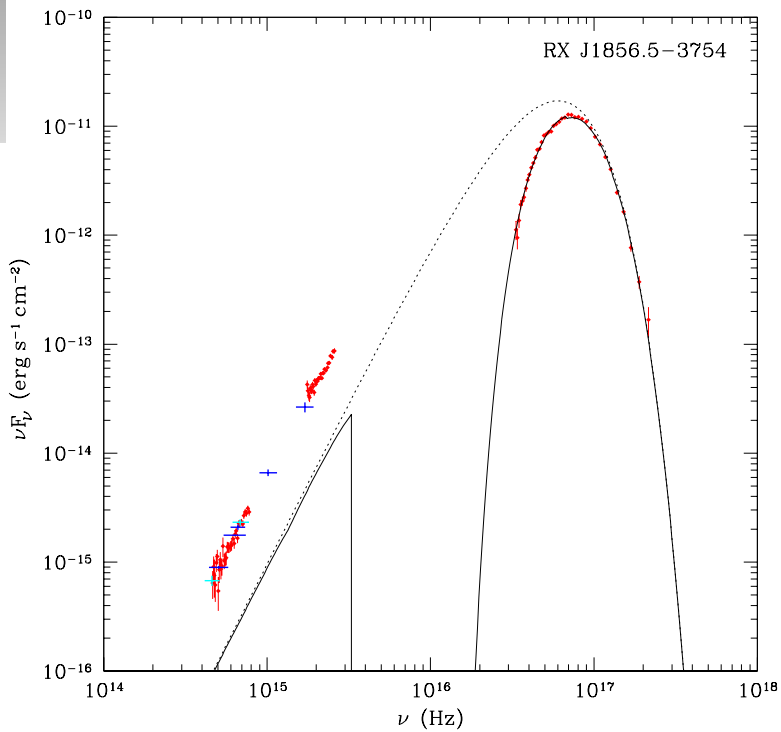

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True radius $R = R_\infty(1+z)$;

$(1+z) = 1/\sqrt{1-2M/R}$

$\therefore$ only a $M-R$ relation can be inferred

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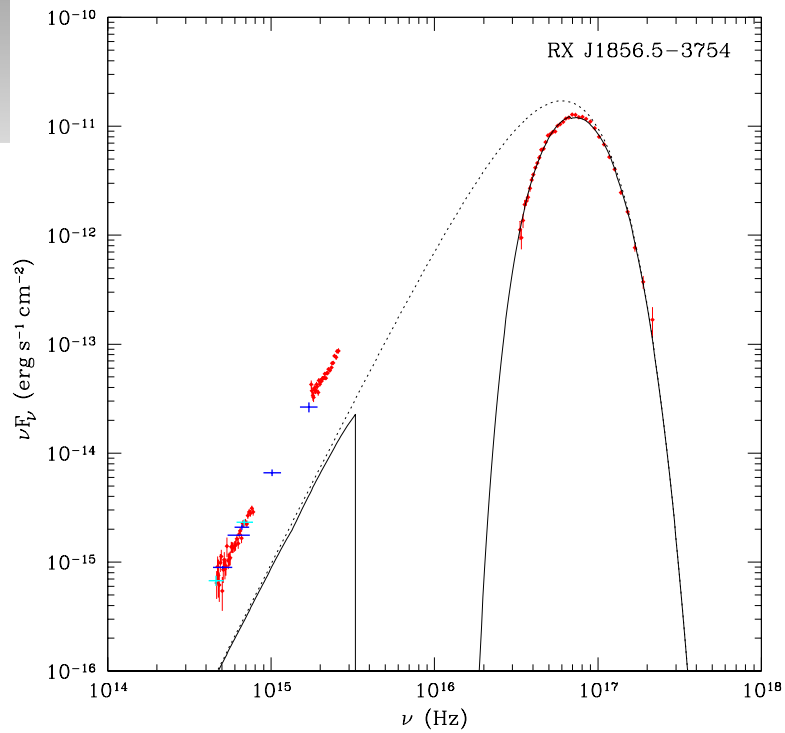

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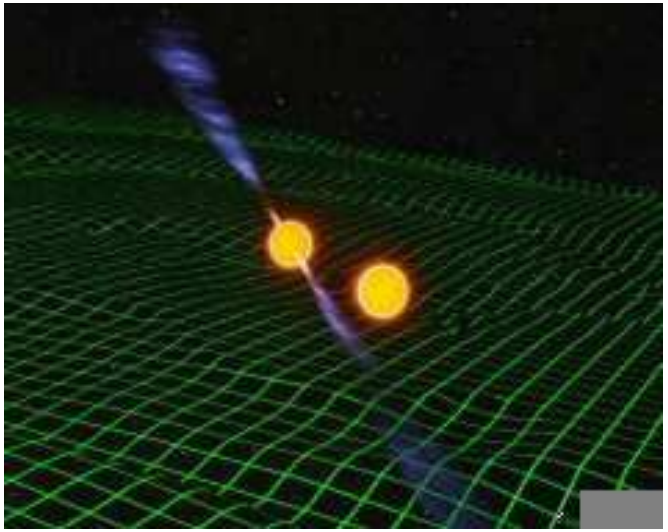
Additional issues:

- Spectrum rarely BB; (atmosphere, B-field)
- red-shift, distance have $>$ 30% uncertainty

Accurate mass determination

Binary systems



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- 2 post-Keplerian ones (periastron advance, Shapiro delay) determine component masses

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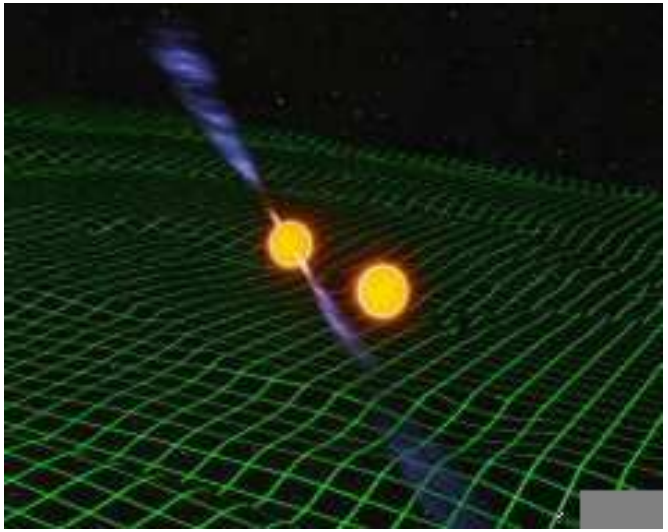

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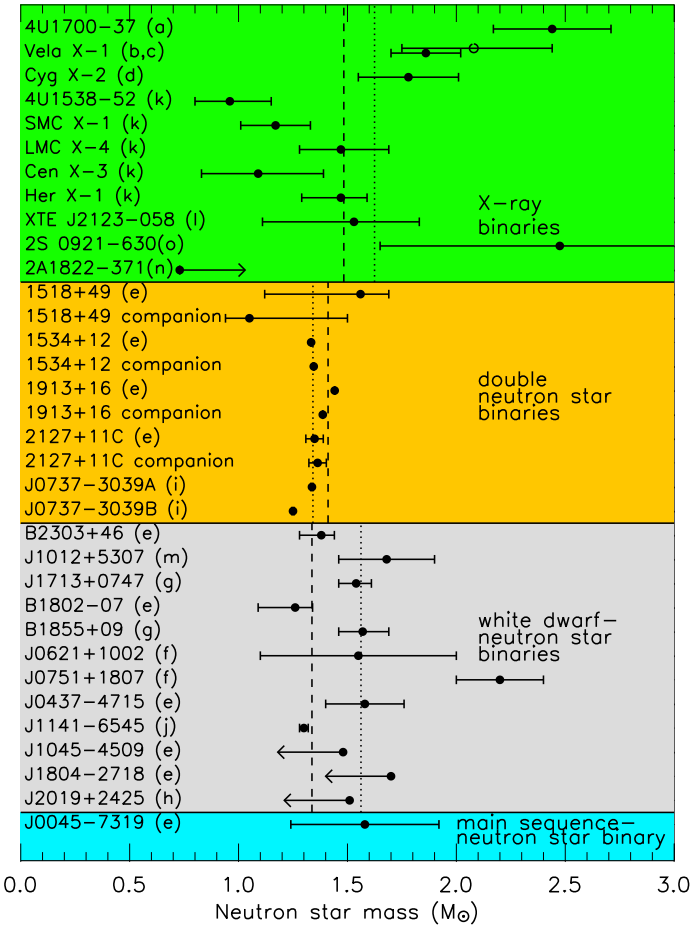
- NS-NS binary: most accurate, centred at $1.4 M_\odot$ (born from HMXBs)
- NS-WD binary: less accurate, $>1.4 M_\odot$ (born from LMXBs)
- X-ray binary: least accurate, $1.2 < M/M_\odot < 3.0$, accretion ongoing

Lattimer & Prakash, Science V 304 2004, 536

Observed Neutron Star Masses



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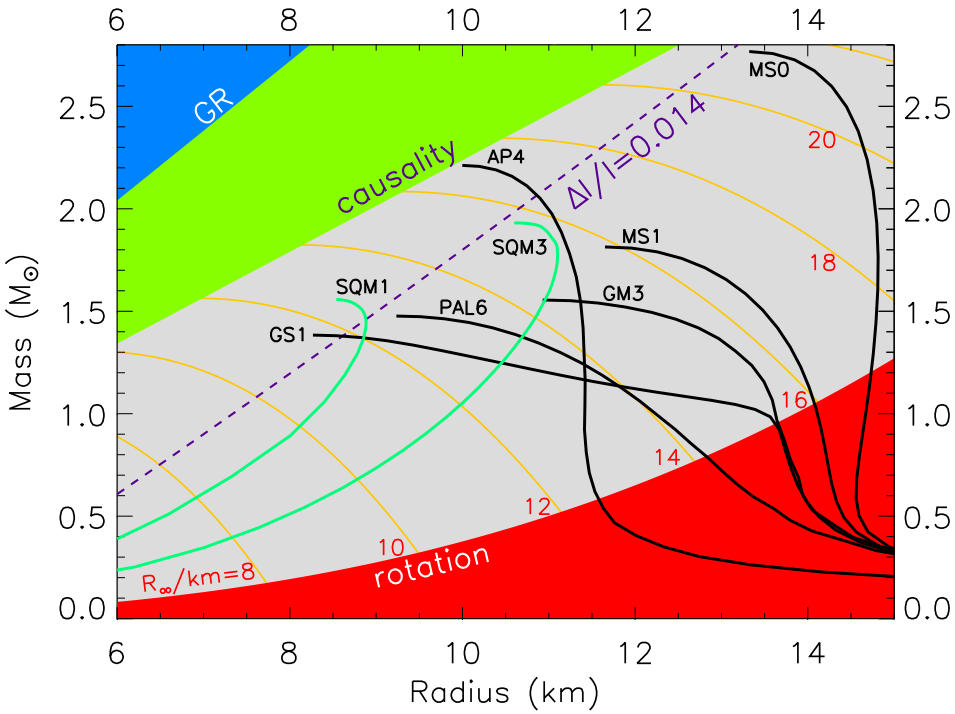
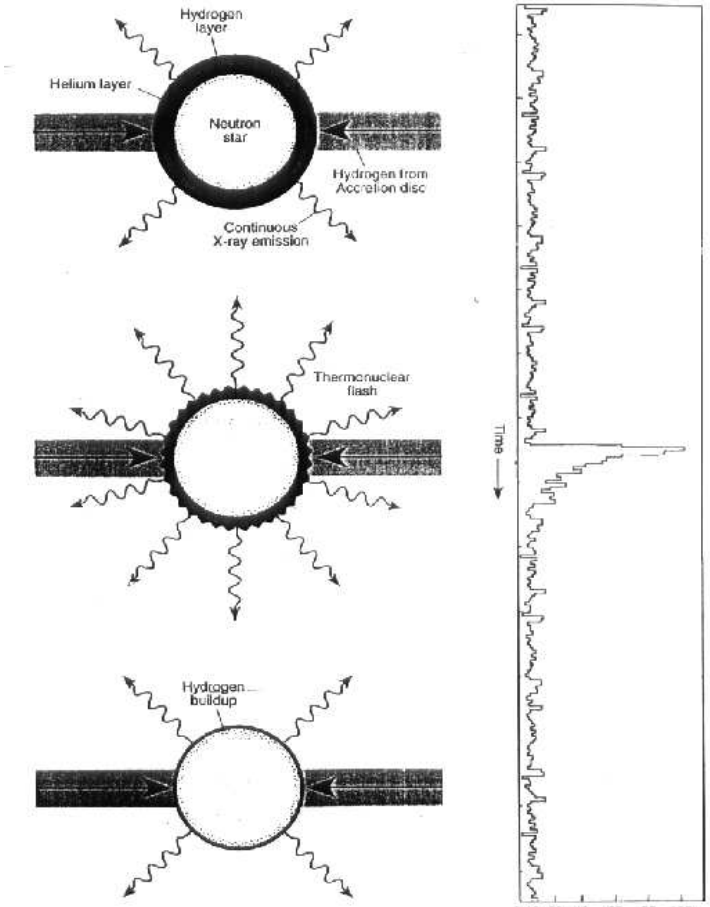


EoS that predict softening at high densities are disfavored

Accurate Radius measurement is required

X-ray bursts (EXO 0748-676)



X-ray bursts (EXO 0748-676)

F. Ozel, *Nature*, to be published:

$$F_{\rm burst} = \frac{M}{D^2\kappa(1+z)}$$

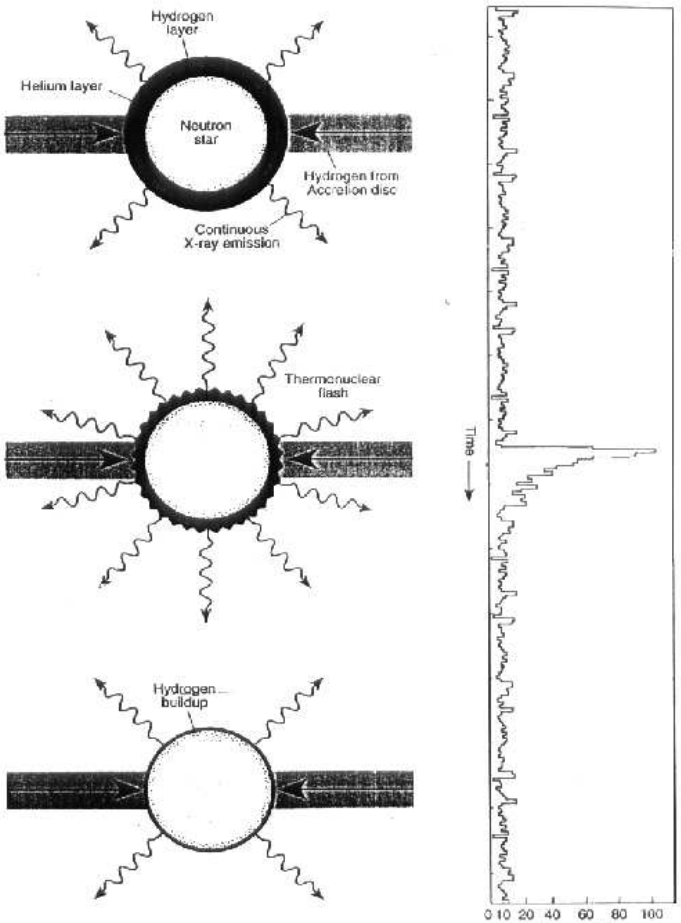
$$z = \frac{1}{\sqrt{1-2M/R}} - 1$$

$$F_{\rm cool}/\sigma_{SB}T_c^4 = f_\infty^2 \frac{R^2(1+z)}{D^2}$$

Mass and Radius

$M \geq 2.10 \pm 0.28 M_\odot$

$R \geq 13.8 \pm 1.8$ km



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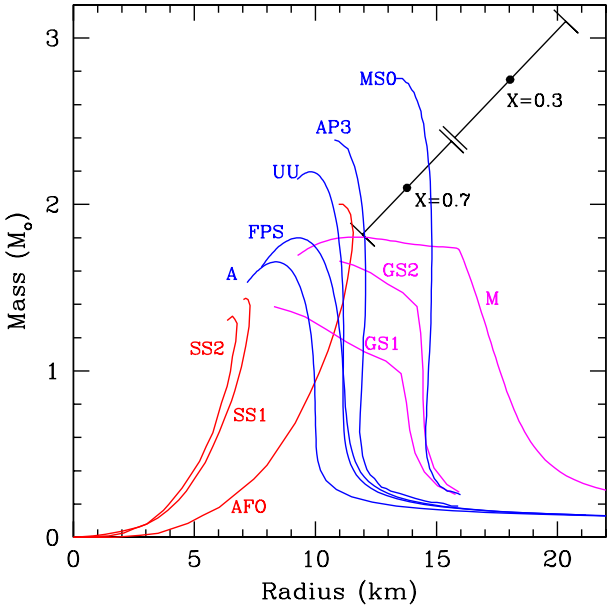
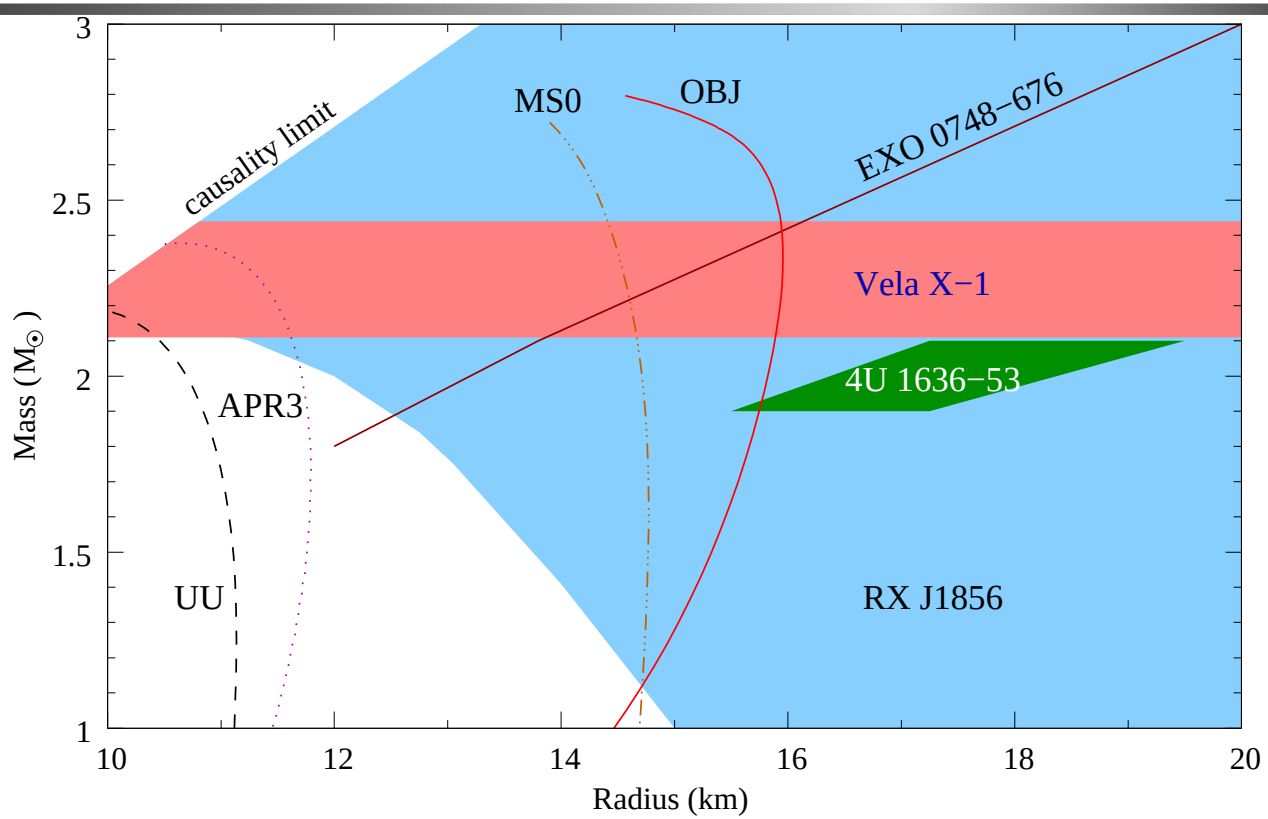


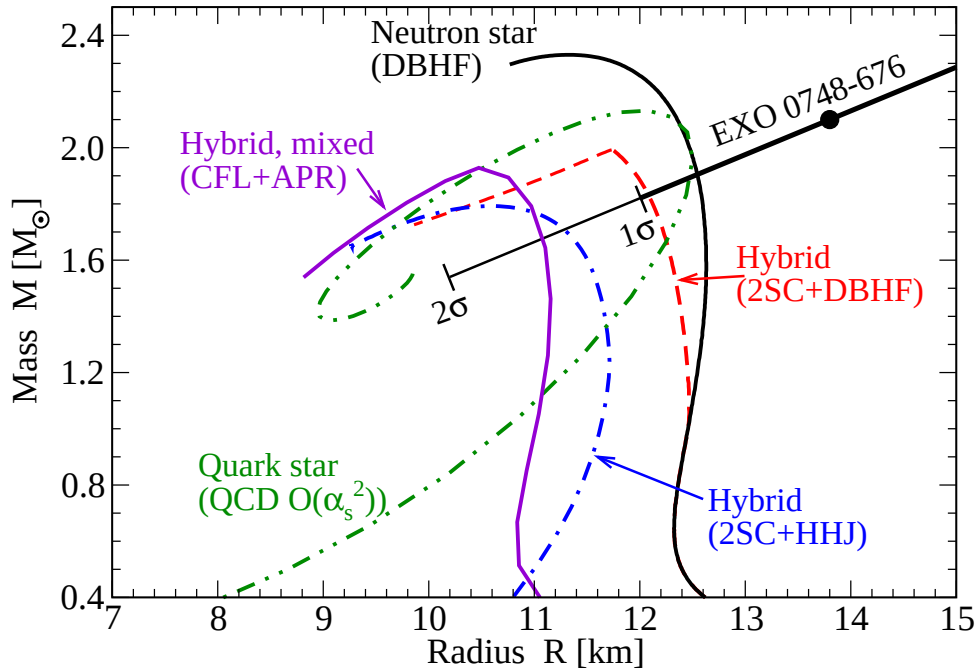
- X = Hydrogen mass fraction in accreting material
- 1-σ errors on $M - R$ are barely consistent with APR
- only stiffest EoS are admissible



- Need to explain high mass, large radius
- The Ouyed-Butler-Jaikumar (OBJ) EoS is promising
- RMF models with increased short distance repulsion?

Is quark matter inside neutron stars ruled out?

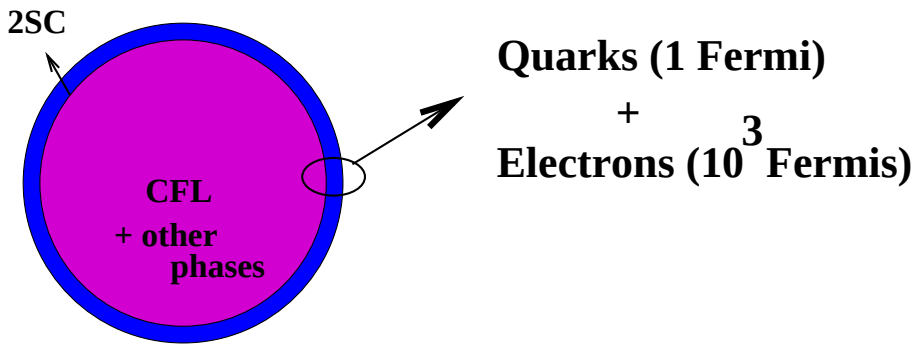
Alford et al., astro-ph/0606524



- Hybrid stars are marginally consistent at 1σ
- Strange quark stars are NOT ruled out
- Hybrid stars are consistent with both high M AND temperature data

Any distinguishing features of strange stars?

Surface structure



a Bare Quark Star has a unique surface

$$\frac{2}{3}n_u - \frac{1}{3}n_d - \frac{1}{3}n_s - n_e = 0$$

$$m_s \neq 0 \Rightarrow n_e \neq 0$$

- For Temperatures of interest ($\leq \mathrm{MeV}$), electrons form a degenerate Fermi gas: Electrosphere

e^+e^- pair emission

- core provides negligible photon luminosity due to high plasma frequency of quark matter

$$\omega_p^2 = \frac{4\alpha_{\rm EM}}{3\pi}\mu_{q,e}^2$$

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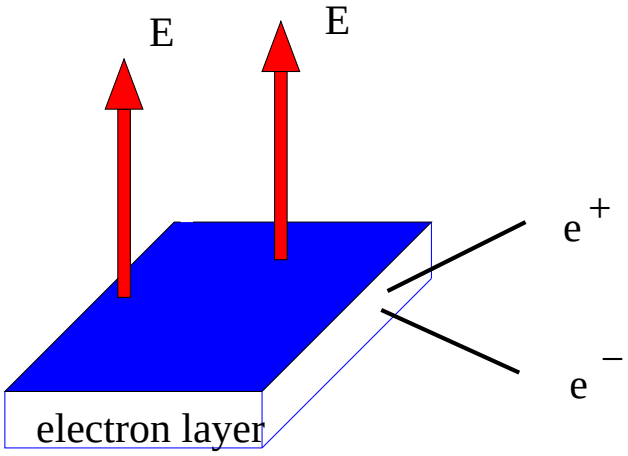


$$l_e \sim 10^3\text{fm},\ E \sim 5\times 10^{16}\ \text{V}$$

$$E_{\rm cr} = \frac{m_e^2c^3}{e\hbar} \simeq 1.3\times 10^{16}\text{V cm}$$

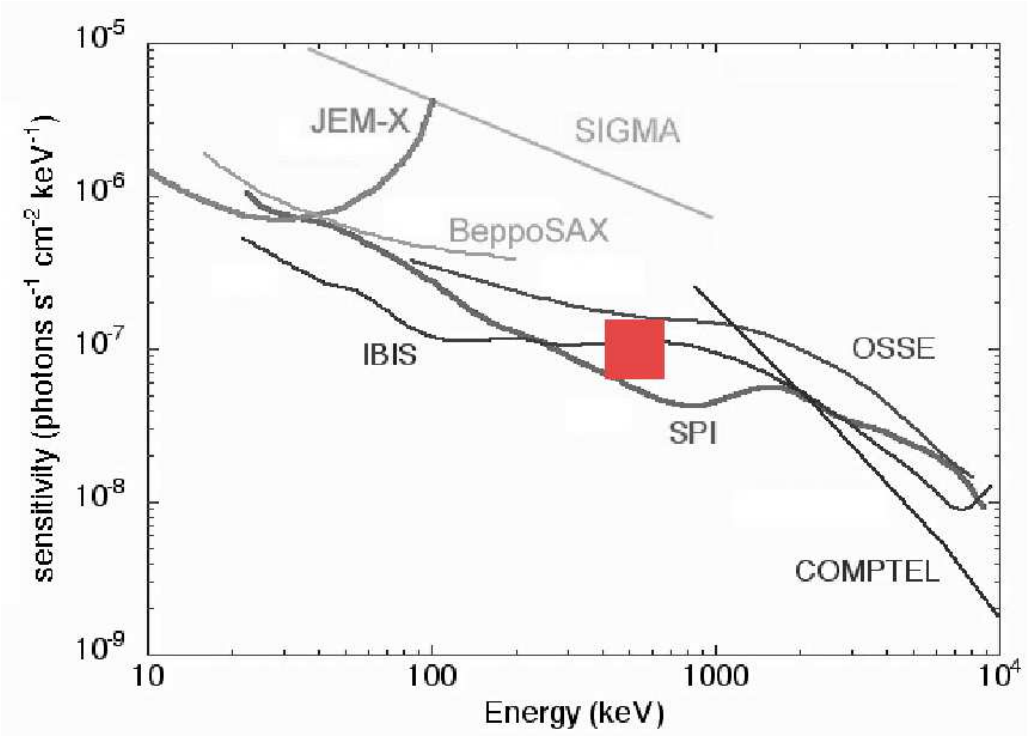
$$R_\pm = \simeq 1.7\times 10^{50}\left(\frac{E}{E_{\rm cr}}\right)^2 \text{cm}$$

$$L_{e^+e^-} \gg L_{\rm Edd}$$

Surface photon emission

J. Knodelseder for the INTEGRAL mission, astro-ph/0207527

- emission is controlled by surface layers



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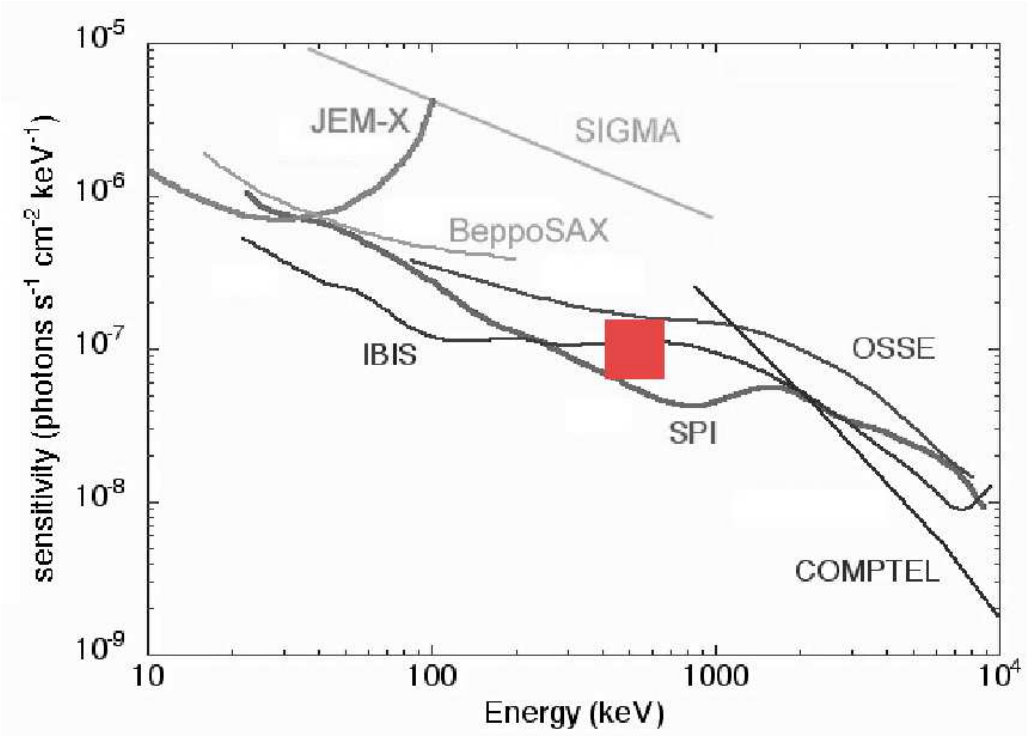

- Mean energy of photons is $\sim \mathrm{MeV}$ (Gamma-rays)
  - Is the surface structure homogeneous?

Mixed phase crust?

If Surface energy is small enough:

$$\epsilon_{s+C} + G_M \leq G_H$$

Surface tension of quark droplet:

$$\sigma \leq 36 \left(\frac{m_s}{150\ \mathrm{MeV}}\right)^3 \frac{m_s}{\mu}\ \mathrm{MeV/fm}^2$$

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Mixed phase $\mu \simeq 300$ MeV, $m_s = 150$ MeV

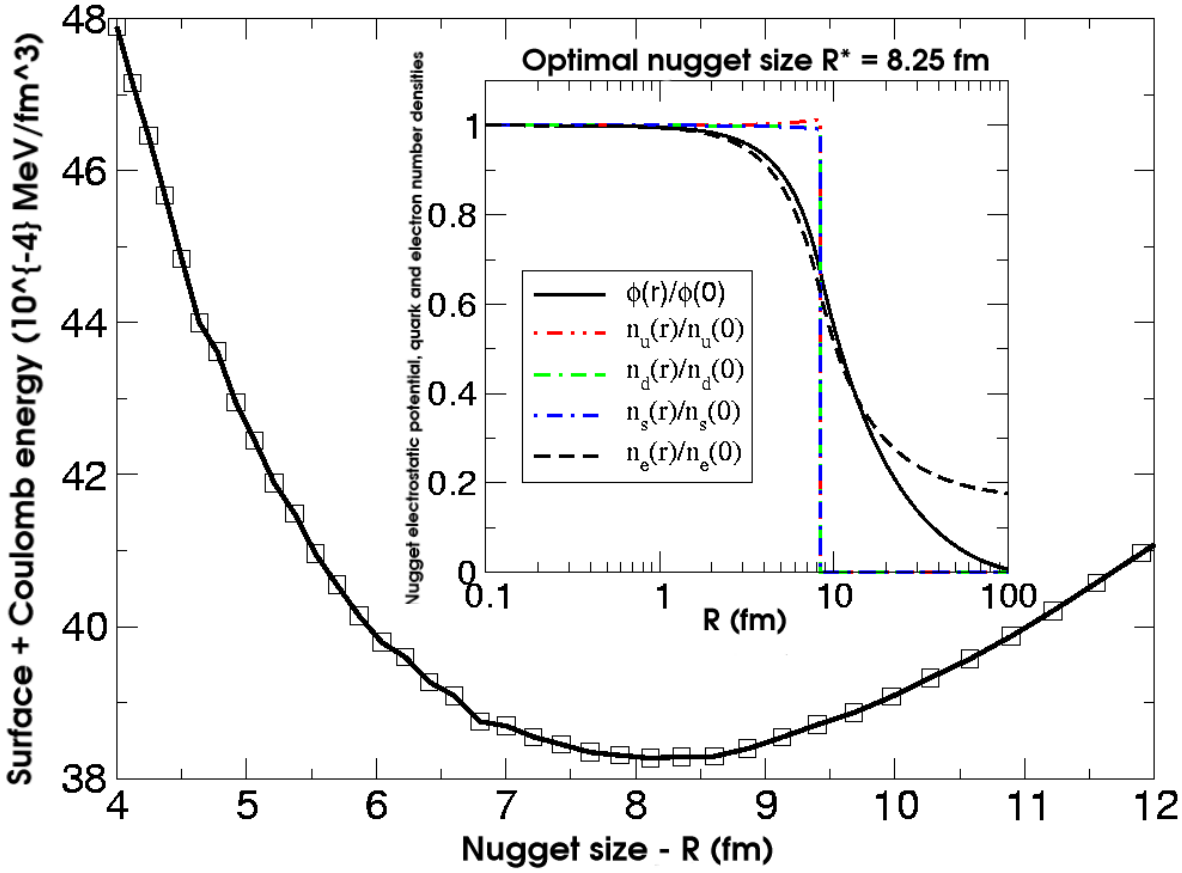
Homogeneous phase

$\mu \simeq 300$ MeV, $m_s = 130$ MeV

A surface of quark nuggets?

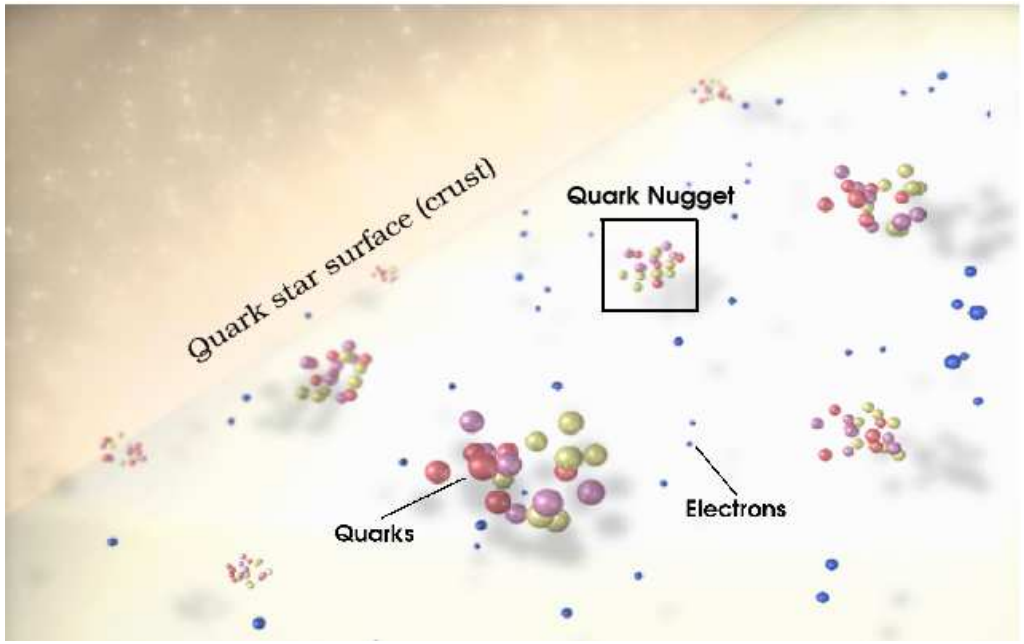
mixed phase: Quark nuggets + Electron sea

Crust size $\Delta R \simeq 0.1$ km



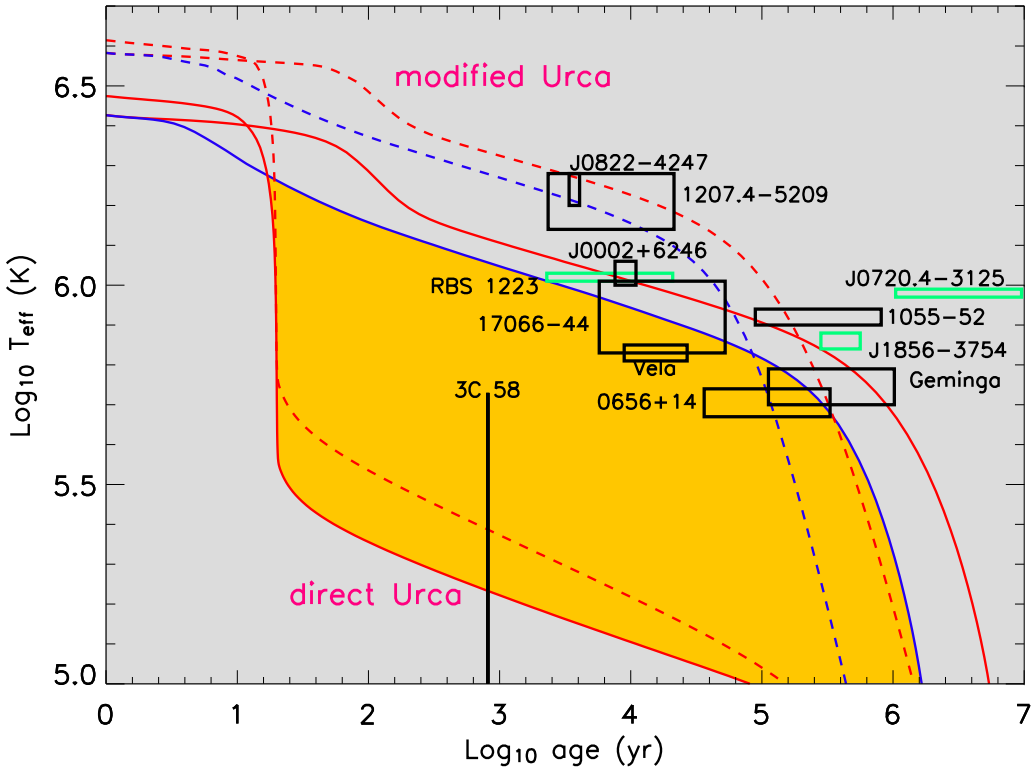
Jaikumar, Reddy & Steiner, Phys. Rev. Lett. 96 (2006), 041101

Quark star surface



- Crust may explain pulsar glitches (except Vela)
- Also connected to superbursts in LMXBs

Neutron star cooling (hadronic matter only)



—— with superfluidity
—— without
—-/- - - (Fe/H envelope)

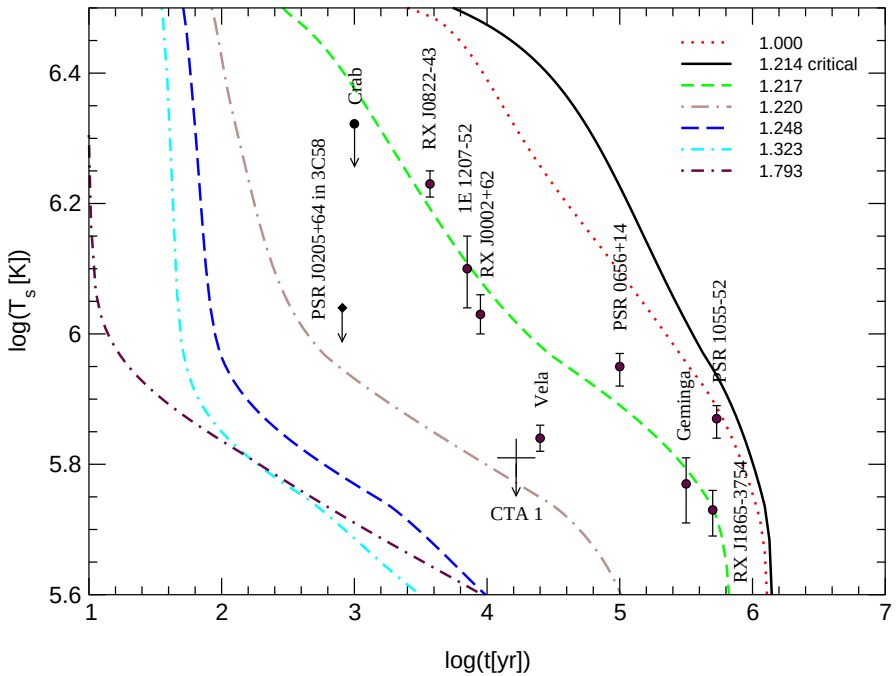
Lattimer & Prakash, Science V304 (2004), 536.

Cooling equation: $c_V \frac{\partial T}{\partial t} = -\epsilon_\nu$

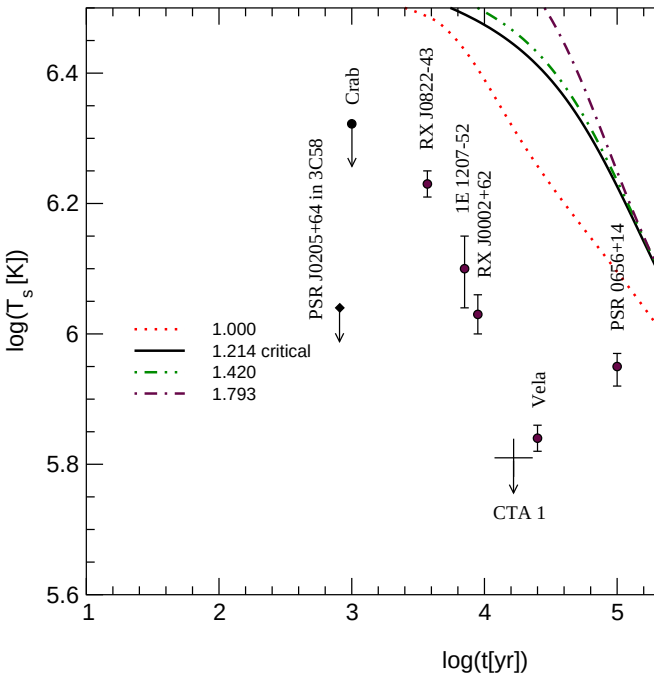
$$\epsilon_\nu = \frac{N_\nu \langle E_\nu \rangle}{\Delta V \Delta t}$$

Neutrino emission and scattering rates depend on the dense phase

Cooling curves



unpaired quark matter in core

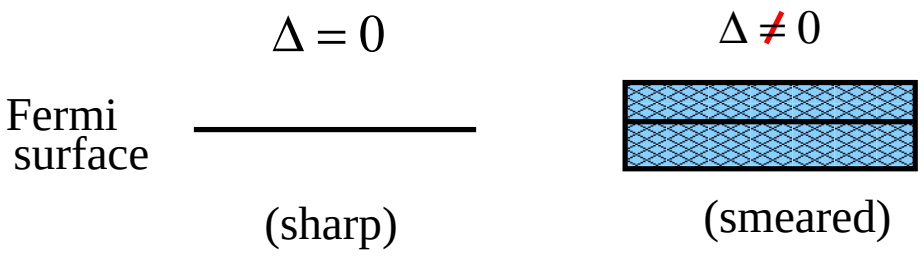


2-flavor + s-s quark gap

Blaschke et al., Phys. Rev. C71 (2005), 045801

Cooling data are consistent with gapped phase of u and d quarks

Neutrino emissivity



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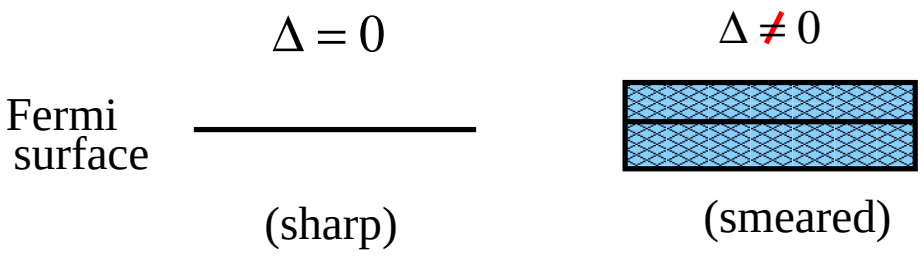

Gap in excitation spectrum of all momentum modes

$$\epsilon_p = \sqrt{\Delta^2 + (p - p_F)^2}$$

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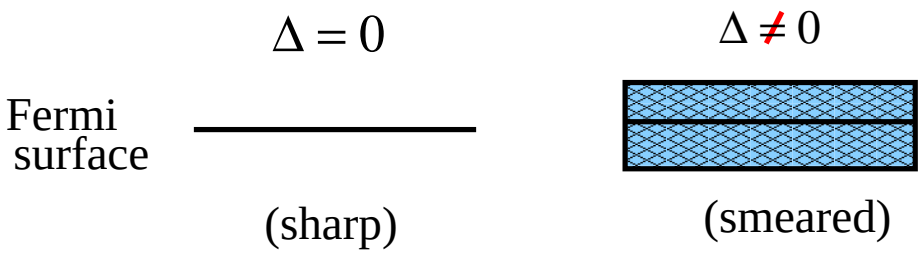

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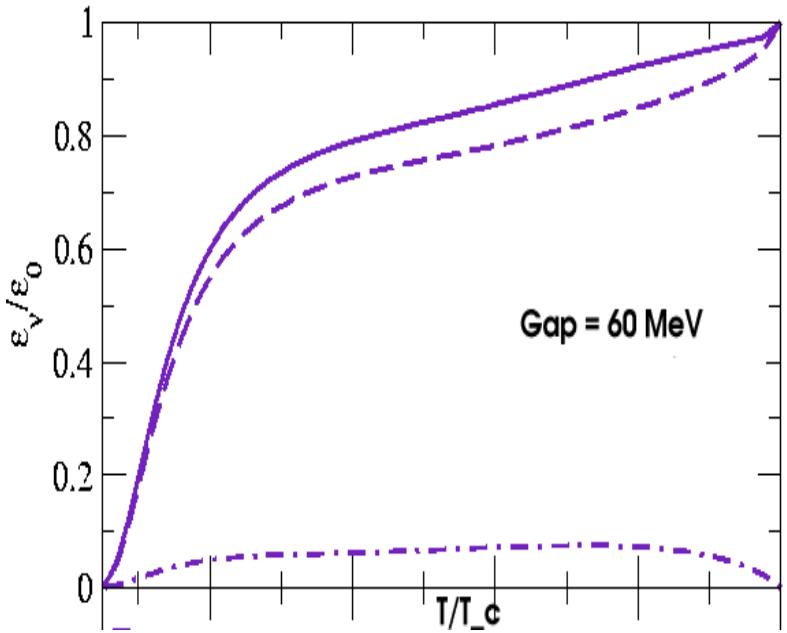

Jaikumar, Roberts & Sedrakian, Phys. Rev. C73 (2006), 042801

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  Thermal evolution can constrain EoS

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- : Re-appraisal of strange star surfaces
  Solid crust a possibility for quark stars
- : Computed neutrino emission in gapped quark matter
  Thermal evolution can constrain EoS
- : Investigated r-process in decompressing neutron stars
  possible site for the r-process?

Future work:

- : Neutrino rates from finite-momentum pairs (ordered phase)

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- : Chemical evolution studies with r-process

Future work:

- : Neutrino rates from finite-momentum pairs (ordered phase)
- : Use neutrino rates to study strange star cooling
- : Chemical evolution studies with r-process
- : Improve OBJ model for neutron stars