

Compact Objects:

Neutron Stars and Black Holes

The Dense Matter Equation of State and Supernovae

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Overview

- Observational Constraints from Neutron Stars
- Recent Developments
- Supernovae and the Equation of State

Observational Constraints from Neutron Stars

- Maximum Mass
- Minimum Mass
- Minimum Rotational Period
- Radius (or Radiation Radius)
- Moment of Inertia
- Binding Energy
- Surface Vibrational Frequencies
- Crustal Cooling Timescale
- Core Cooling Timescale (URCA or not)

Maximum Mass, Minimum Period

- Theoretical limits from causality
 - $M_{max} = 4.2(\rho_s/\rho_f)^{1/2} M_\odot$
 - $R_{min} = 2.9GM/c^2 = 4.3(M/M_\odot) \text{ km}$
 - $\rho_c < 4.5 \times 10^{15} (M_\odot/M_{largest})^2 \text{ g cm}^{-3}$
 - $P_{min} \simeq (0.74 \pm 0.03)(M_\odot/M_{sph})^{1/2} (R_{sph}/10 \text{ km})^{3/2} \text{ ms}$
 - $P_{min} \simeq (0.96 \pm 0.03)(M_\odot/M_{sph})^{1/2} (R_{sph}/10 \text{ km})^{3/2} \text{ ms}$ (empirical)
 - $\rho_c > 0.44 \times 10^{15} (1 \text{ ms}/P_{min})^2 \text{ g cm}^{-3}$ (empirical)
- Experimental/observational probes of maximum mass
 - Possibly accessible from heavy-ion collision flow data, although extrapolation to large neutron excesses is problematic
 - Pulsar timing in binaries ($M > 2M_\odot$?)
 - QPOs of accreting neutron stars
- Implications of the maximum mass
 - Restricts highest density possible in static situations
 - Constrains composition of dense matter (hyperons, Bose condensates, deconfined quarks)
 - Sets stellar black hole minimum mass
 - Implications for stellar evolution in binaries

Mass-Radius Diagram and Theoretical Constraints

GR:

$$R > 2GM/c^2$$

$P < \infty$:

$$R > (9/4)GM/c^2$$

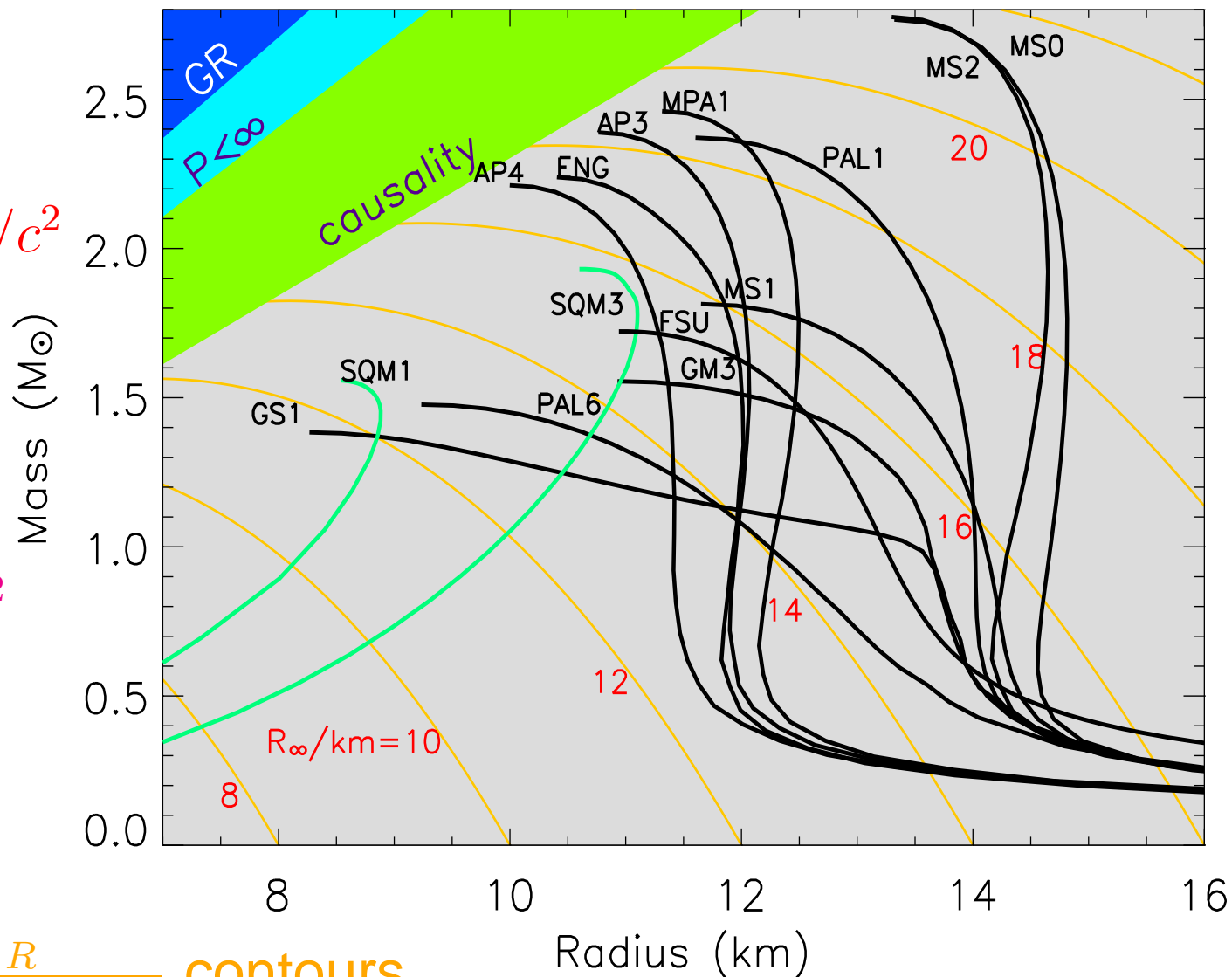
causality:

$$R \gtrsim 2.9GM/c^2$$

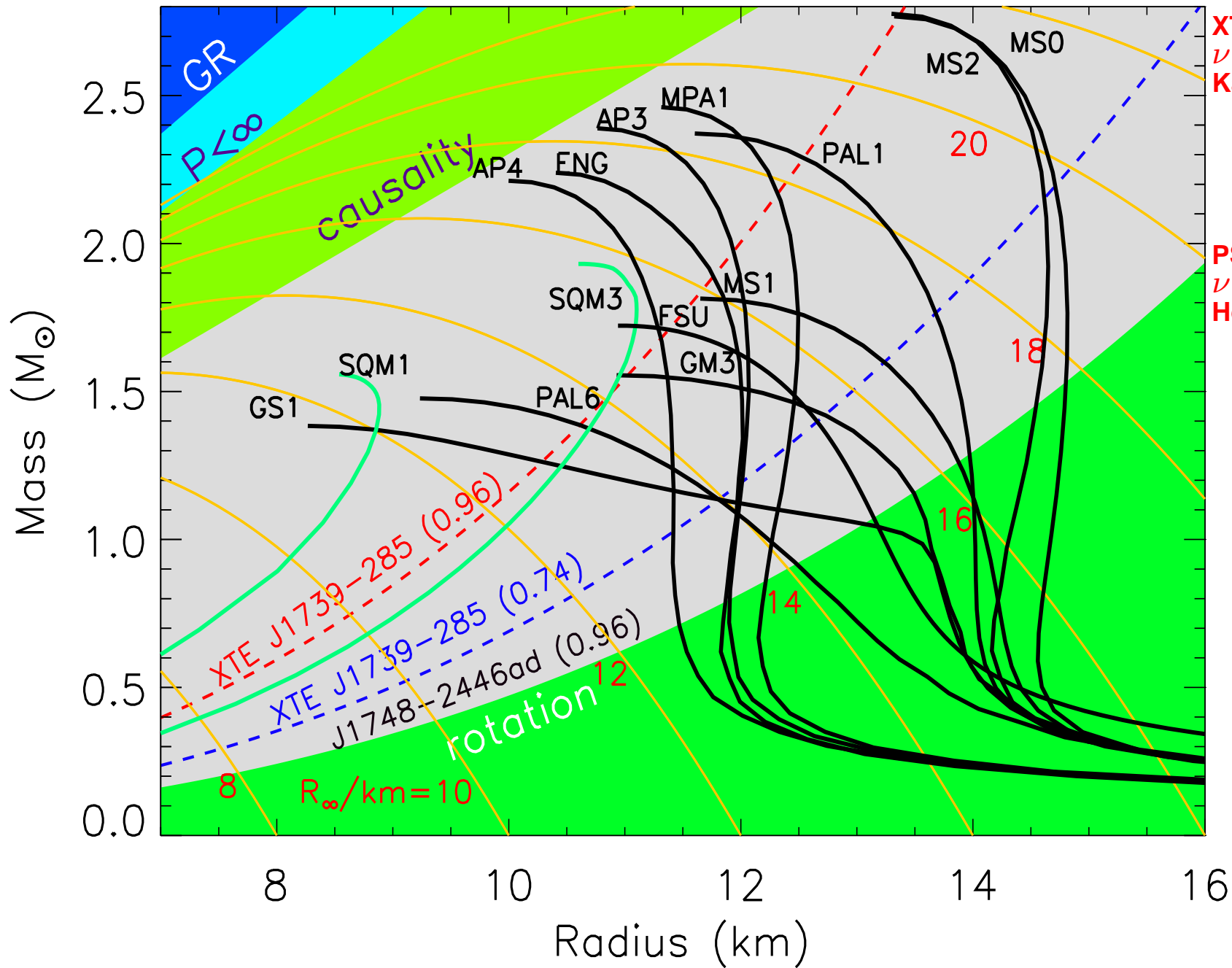
— normal NS

— SQS

— $R_\infty = \frac{R}{\sqrt{1-2GM/Rc^2}}$ contours



Constraints from Pulsar Spins



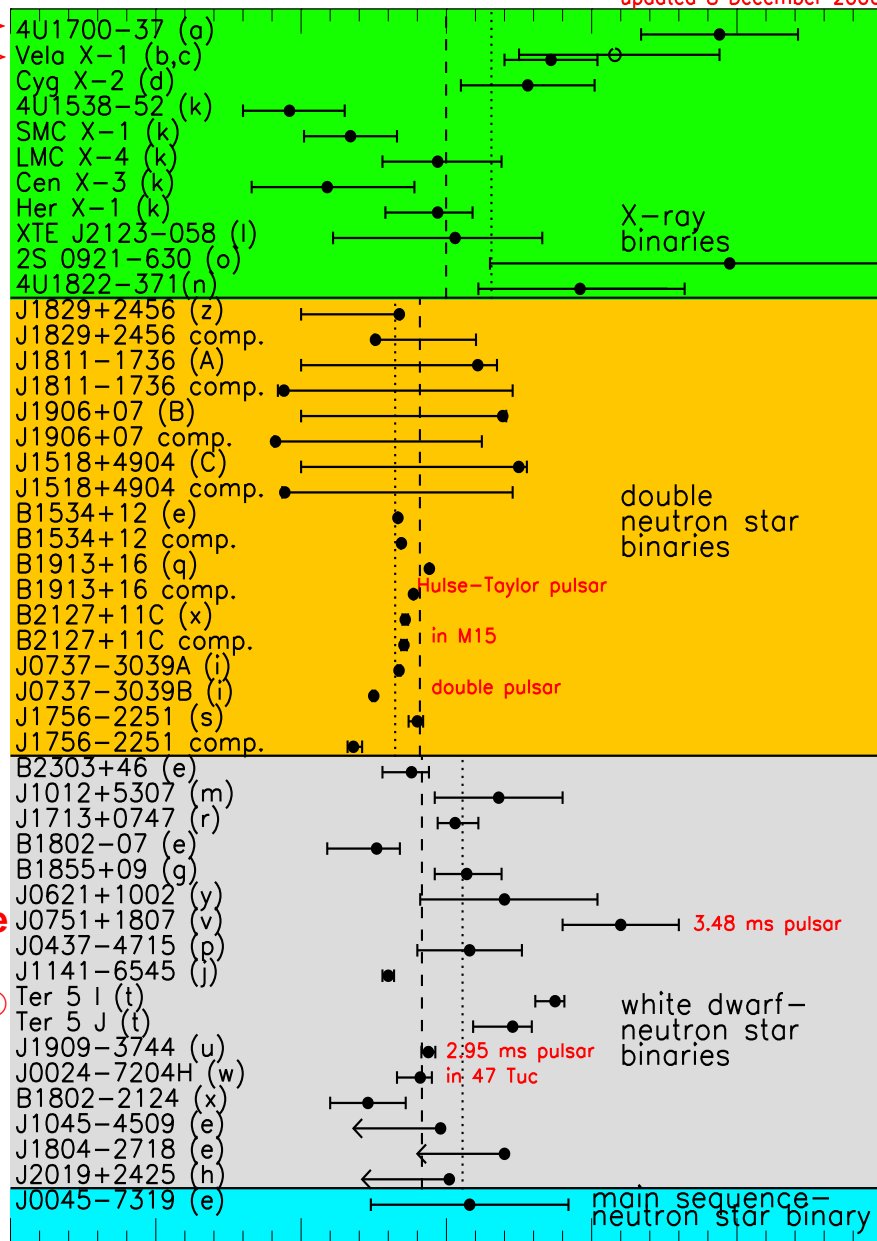
XTE J1739-285
 $\nu = 1122$ Hz
 Kaaret et al. 2006

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

Observed Masses

updated 8 December 2006

Black hole? \Rightarrow
 Firm lower mass limit? \Rightarrow



$M \simeq 1.18 M_{\odot}$

$M > 1.6 M_{\odot}$, 95% confidence

$M > 1.68 M_{\odot}$
 95% confidence

Although simple average mass of w.d. companions is $0.21 M_{\odot}$ larger, weighted averages are the same

0.0 0.5 1.0 1.5 2.0 2.5 3.0
 Neutron star mass (M_{\odot})

Minimum Mass

- Minimum mass of cold, catalyzed star $\simeq 0.09 M_{\odot}$
- Proto-neutron star will be lepton-rich ($Y_L = Y_e + Y_{\nu} \sim 0.35 - 0.4$), with a low-entropy core ($s \sim 1$) and a higher-entropy mantle ($s \sim 8 - 10$)
- Minimum mass of initial proto-neutron star is much larger, about 0.9-1.1 M_{\odot}
(Gondek, Haensel & Zdunik 1998)
- Lowest mass neutron stars from O-Ne-Mg collapse, $\sim 1 M_{\odot}$?
- Smallest well-observed neutron star mass: $M \simeq 1.18 M_{\odot}$, PSR J1756-2251 companion

Neutron Star Matter Pressure

$$P \simeq K \rho^{1+1/n}$$

$$n^{-1} = d \ln P / d \ln \rho - 1 \sim 1$$

$$R \propto K^{n/(3-n)} M^{(1-n)/(3-n)}$$

$$R \propto P_*^{1/2} \rho_*^{-1} M^0$$

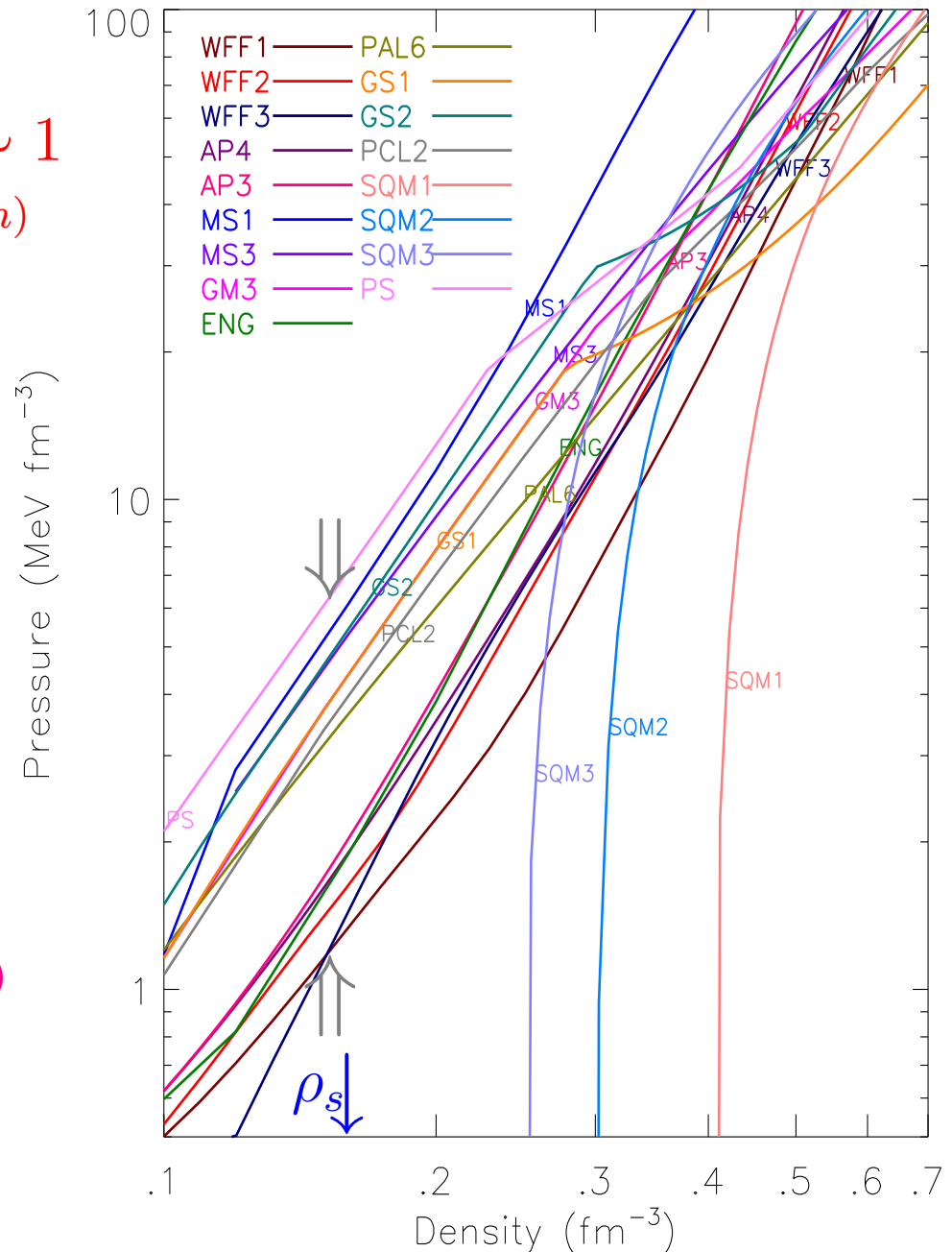
$$(1 < \rho_*/\rho_s < 2)$$

Wide variation:

$$1.2 < \frac{P(\rho_s)}{\text{MeV fm}^{-3}} < 7$$

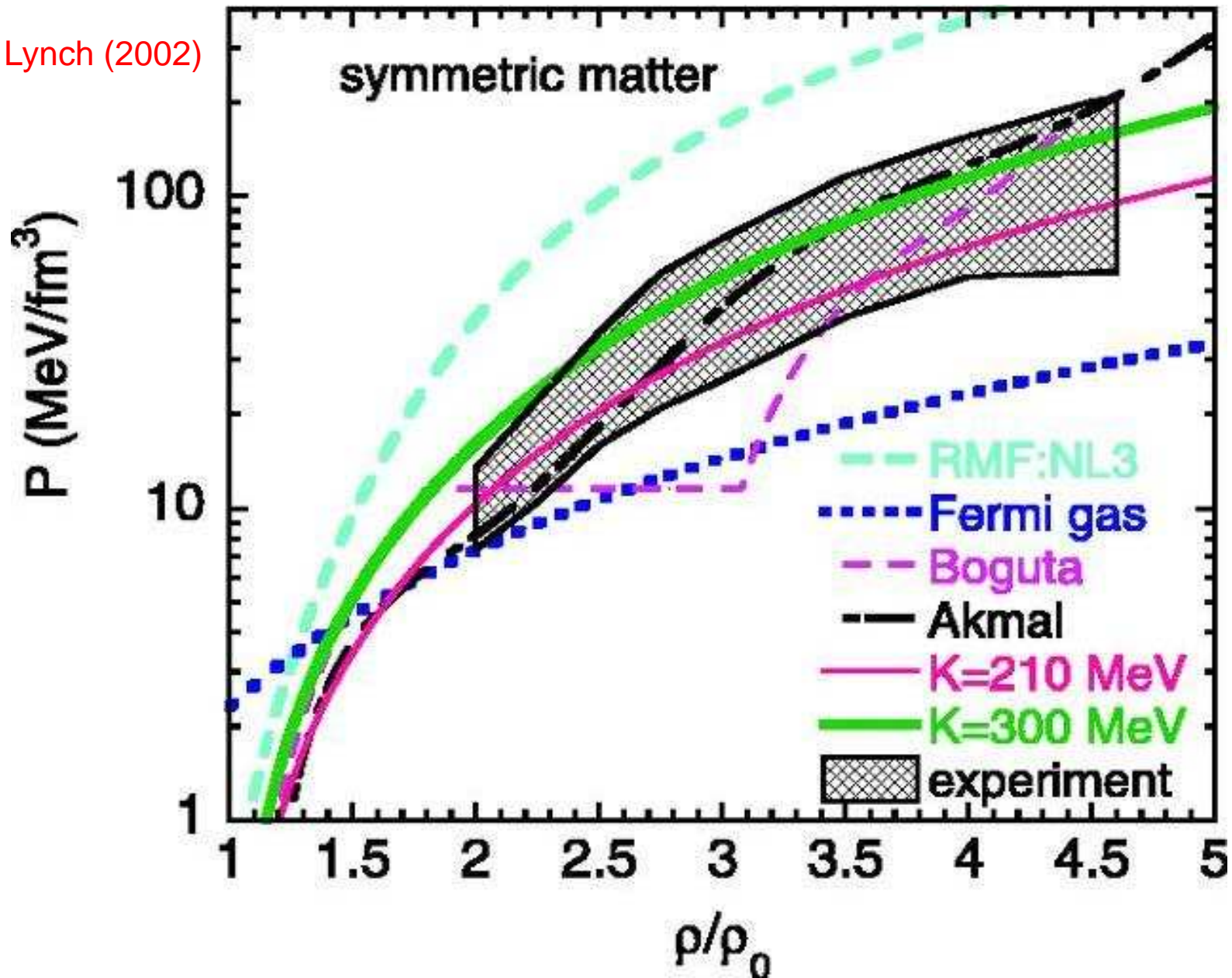
GR phenomenological
result (Lattimer & Prakash 2001)

$$R \propto P_*^{1/4} \rho_*^{-1/2}$$

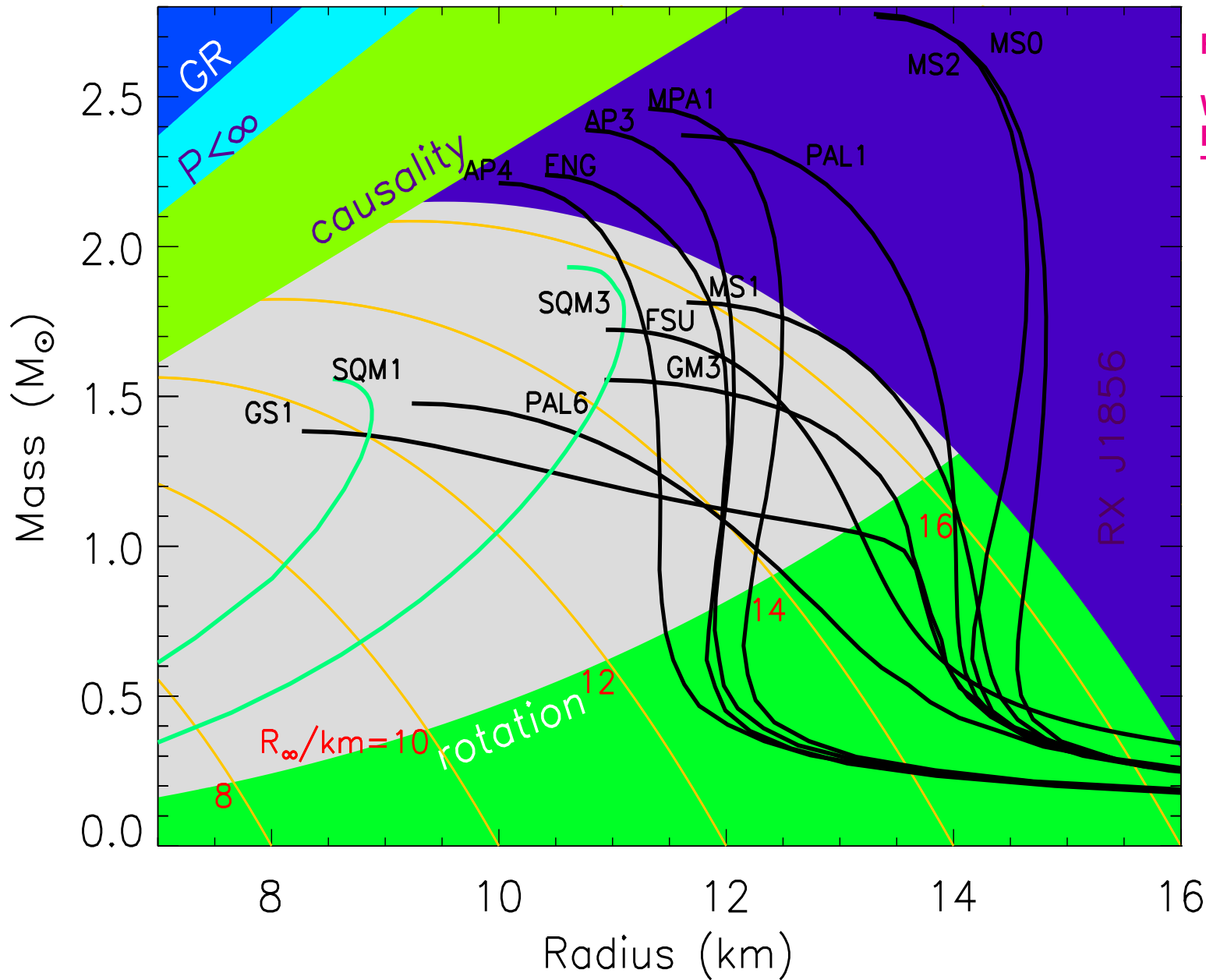


EOS from heavy ion flow data

Danielewicz, Lacey & Lynch (2002)



Radiation Radius: Nearby Neutron Star



RX J1856-3754:

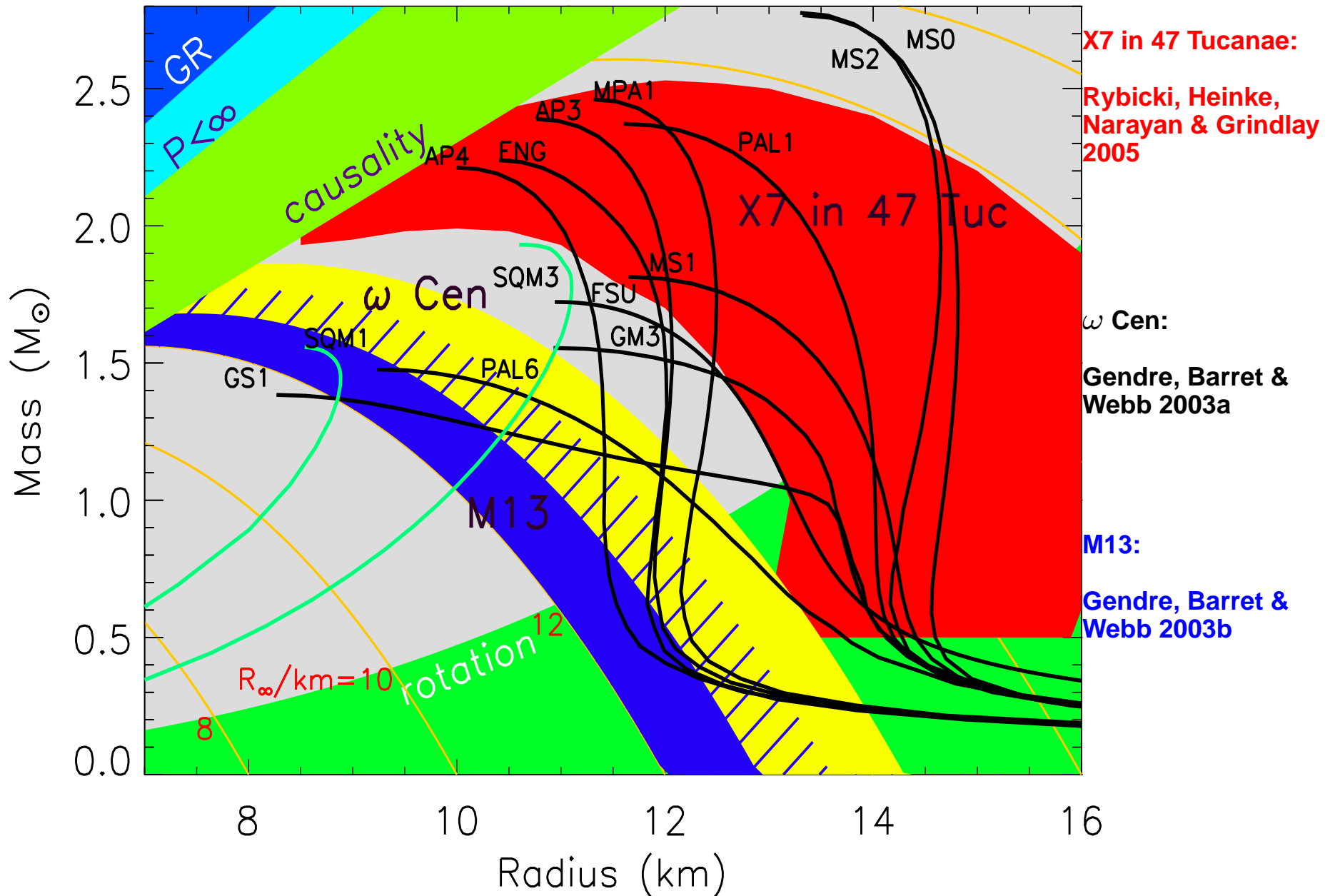
Walter & Lattimer 2002

Braje & Romani 2002

Truemper 2005

D=120 pc

Radiation Radii: Globular Cluster Sources



Symmetry Energy

- Neutron star radius

Directly related to pressure around $1 - 2\rho_s$: $R \sim p_{1-2\rho_s}^{1/4}$

For cold matter in beta equilibrium ($\mu_n - \mu_p = \mu_e$), $p_{1-2\rho_s} \simeq n^2 dE_{sym}/dn$

- Crustal thickness

Depends on M, R and μ_n at core-crust transition density

Extreme sensitivity to $E_{sym}(n)$ and K

Constraints from surface vibrations and post-flare (superburst) cooling

$$\frac{\Delta}{R} = \frac{\mathcal{H} - 1}{\mathcal{H}(1 - 2GM/Rc^2)^{-1} - 1}, \quad \mathcal{H} = e^{2(\mu_n - \mu_0)/m_b c^2}$$

- Neutron star cooling, existence of direct Urca process

Depends on proton fraction, i.e., $E_{sym}(n)$

Absence of X-ray emission from neutron stars in several supernova remnants implies some neutron stars cool rapidly

- Laboratory probes

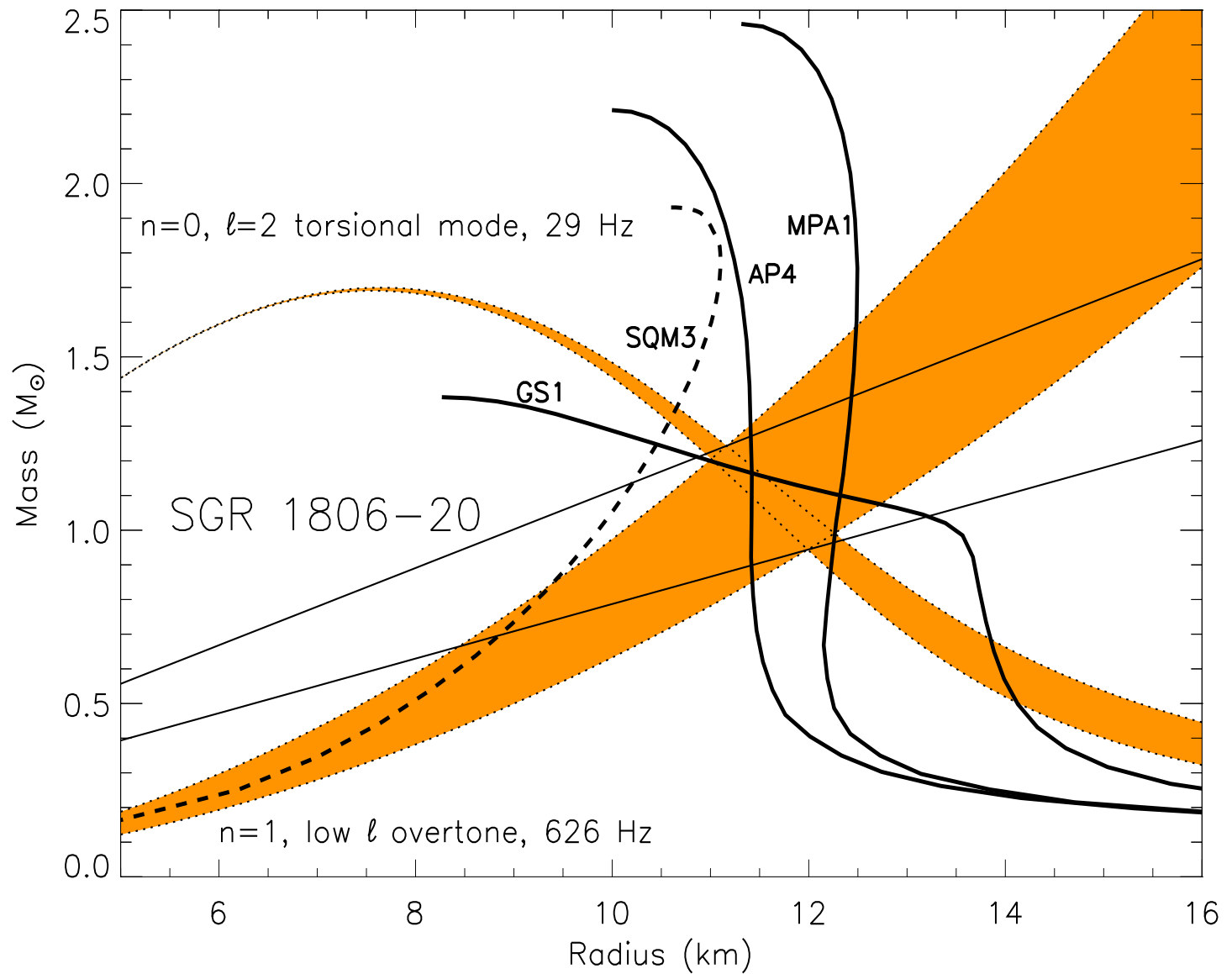
Rare isotope accelerator measurements of ultra neutron-rich nuclei masses (provides an $S_v - S_s$ correlation)

Neutron skin thickness of neutron-rich nuclei (PREX)

Giant dipole resonances provide an independent $S_v - S_s$ correlation

Multifragmentation and isotope diffusion in intermediate energy heavy ion collisions probe the nuclear phase diagram, but finite-size effects large

Neutron Star Seismology



Strohmayer & Watts (2005)
Samuelsson & Andersson (2006)
Lattimer & Prakash (2006)

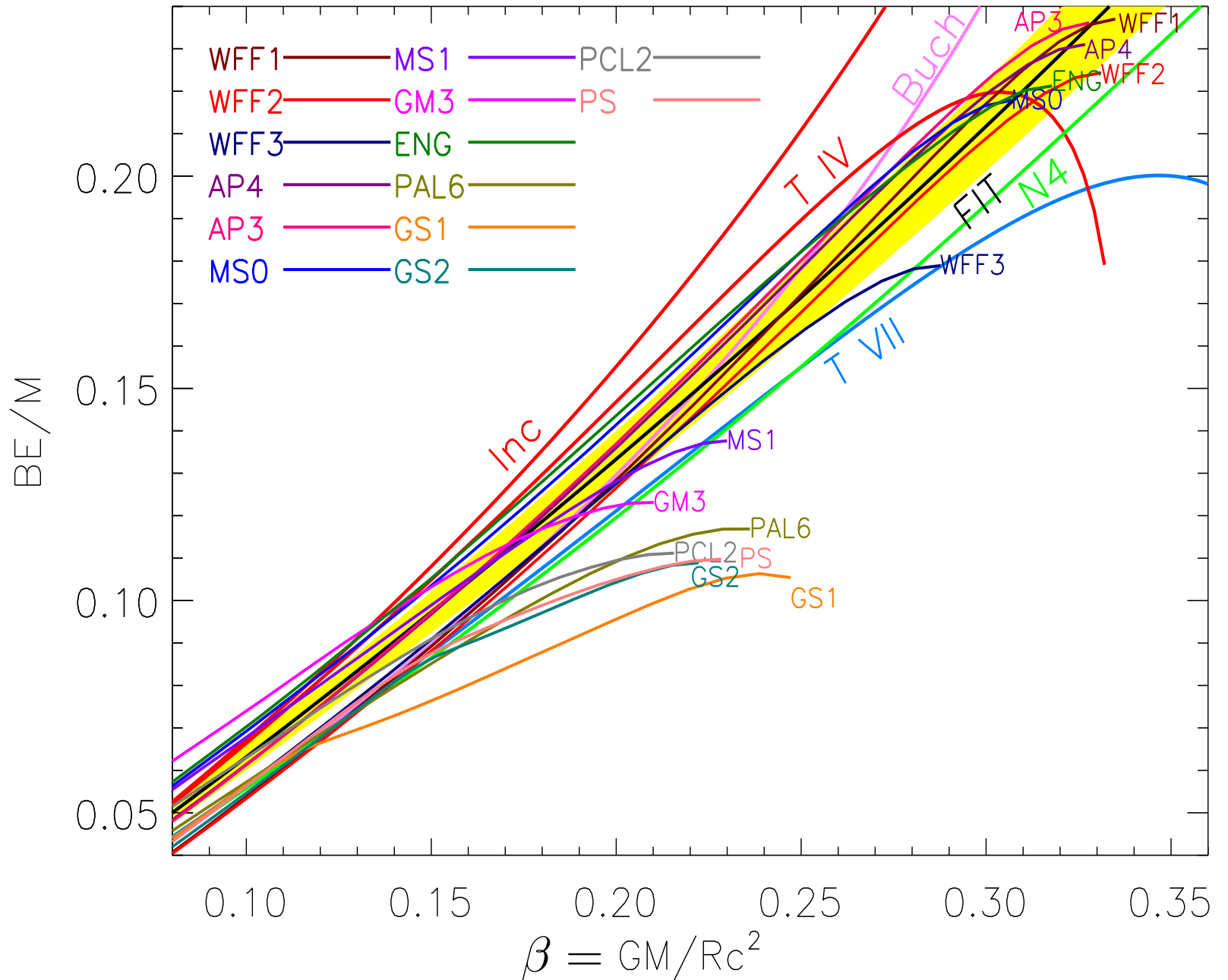
Neutrinos from Galactic Supernovae

- Neutron star binding energies
Nearly model-independent relation between BE and M, R ($M_{max} \geq 1.6 M_{\odot}$)
- Average emitted neutrino energies
Rise with time during deleptonization, first 10-15 s
- Deleptonization and cooling timescales
- Possible metastability of remnants due to strangeness appearance
- Effects of neutrino oscillations
- Pre-bounce ν_e signal is sensitive to $E_{sym}(n)$
(Swesty, Lattimer & Myra 1994)

Binding Energy

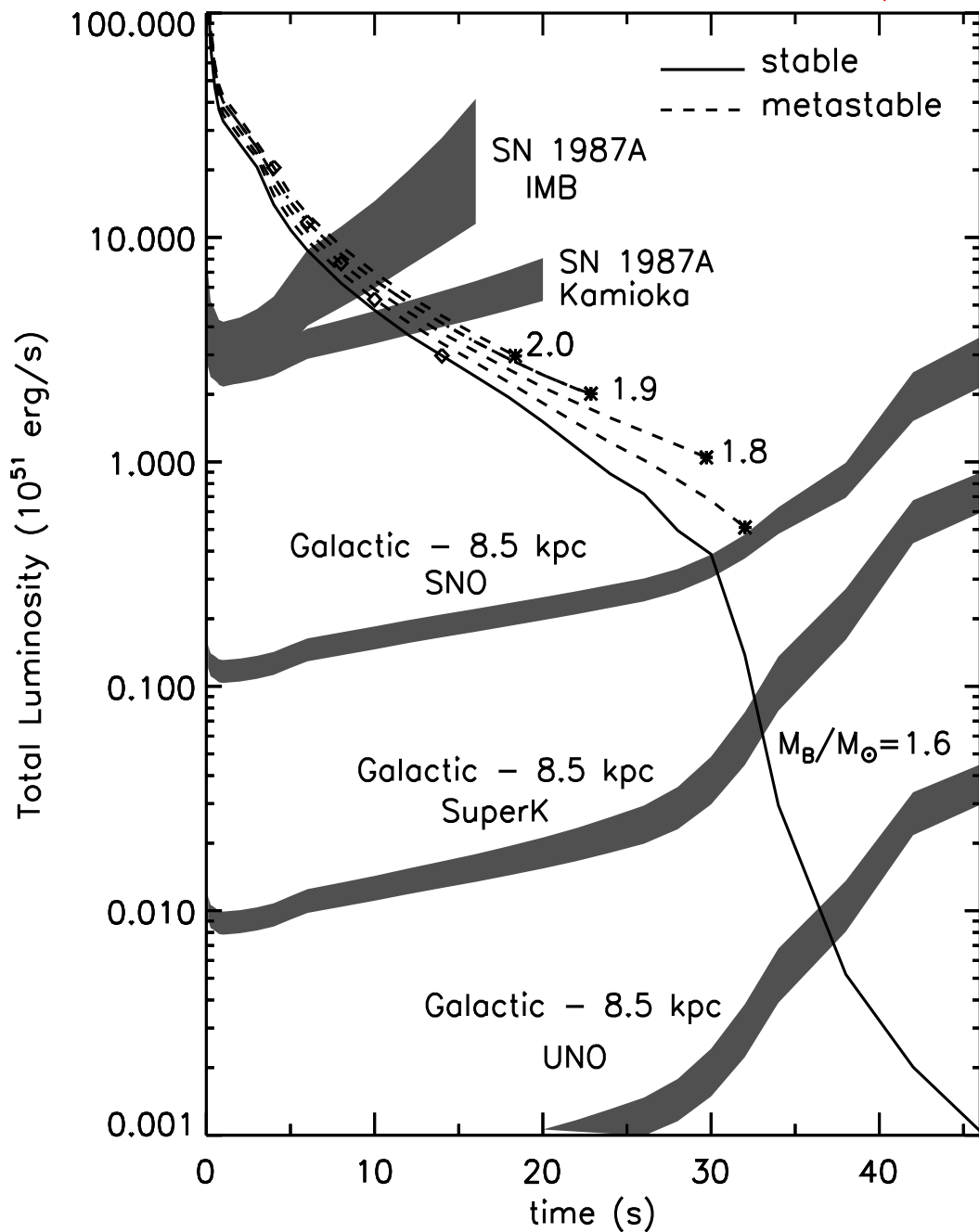
Lattimer & Prakash (2001)

$$BE/M \simeq (0.60 \pm 0.05)\beta(1 - \beta/2)^{-1}$$



Proto-Neutron Star Evolutions

Pons, Steiner, Prakash & Lattimer (2001)



bethe/s