

Quark Matter and Astrophysics of Neutron Stars

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&

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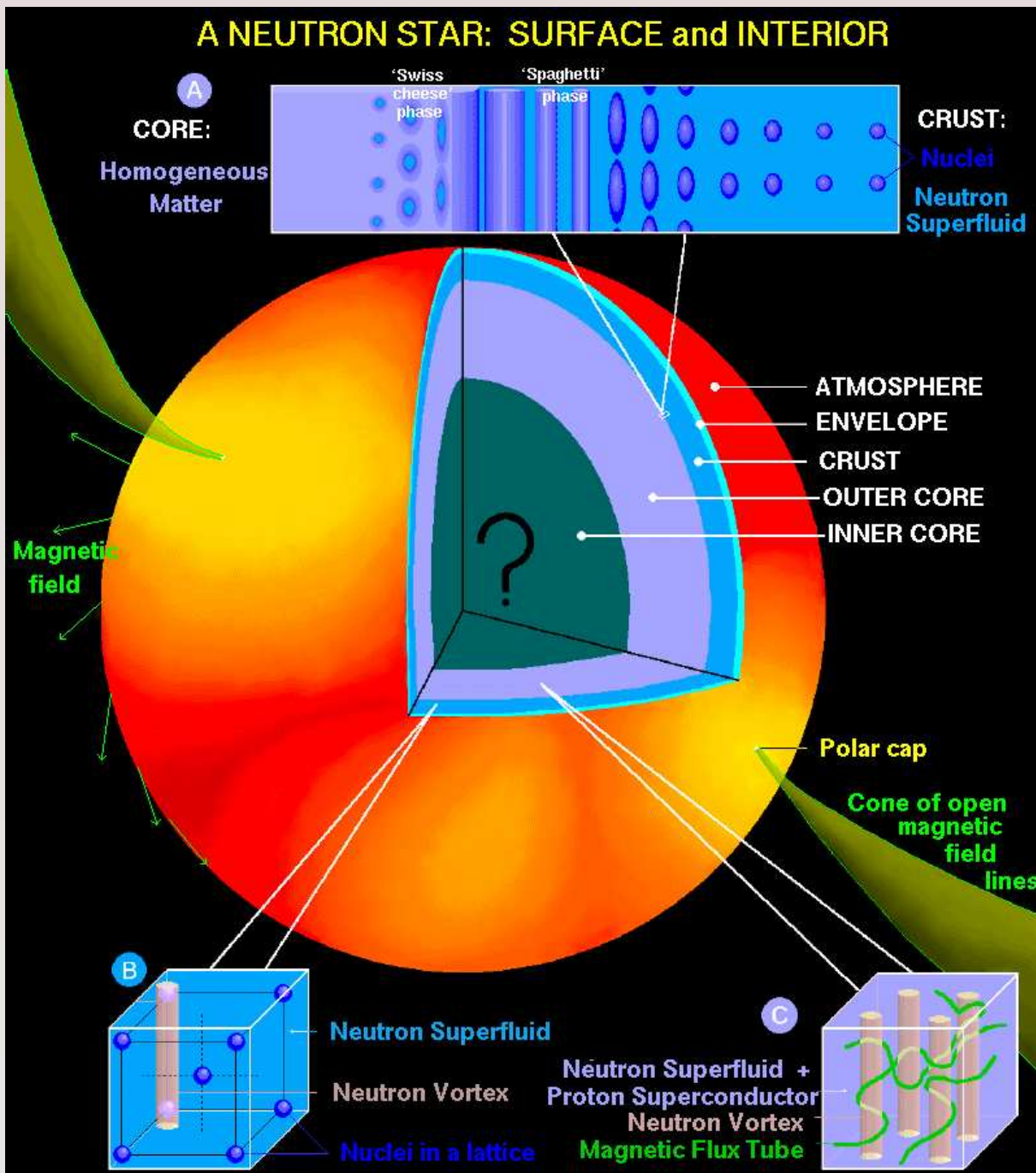
Physics & Astrophysics of Neutron Stars

- ▶ Cores of neutron stars may contain hyperons, Bose condensates, or quarks (*Exotica*)
- ▶ *Can* observations of M , R & B.E (composition & structure) & P , \dot{P} , T_S & B etc., (evolution) reveal *Exotica* ?
- ▶ Neutron stars implicated in x-ray & γ -ray bursters, mergers with other neutron stars & black holes, etc.
- ▶ **Observational Programs :**
 - SK, SNO, LVD's, AMANDA ... (ν 's)
 - HST, CHANDRA, XMM, ASTROE ... (γ 's)
 - LIGO, VIRGO, GEO600, TAMA ... (Gravity Waves)

Connections:

Atomic, Cond. Matter, Nucl. & Part., Grav. Physics

- ▶ Theory : Many-body theory of strongly interacting systems, Dynamical response (ν - & γ - propagation & emissivities)
- ▶ Experiment : h , e^- and ν - scattering experiments on nuclei, masses of neutron-rich nuclei, heavy-ion reactions, etc.

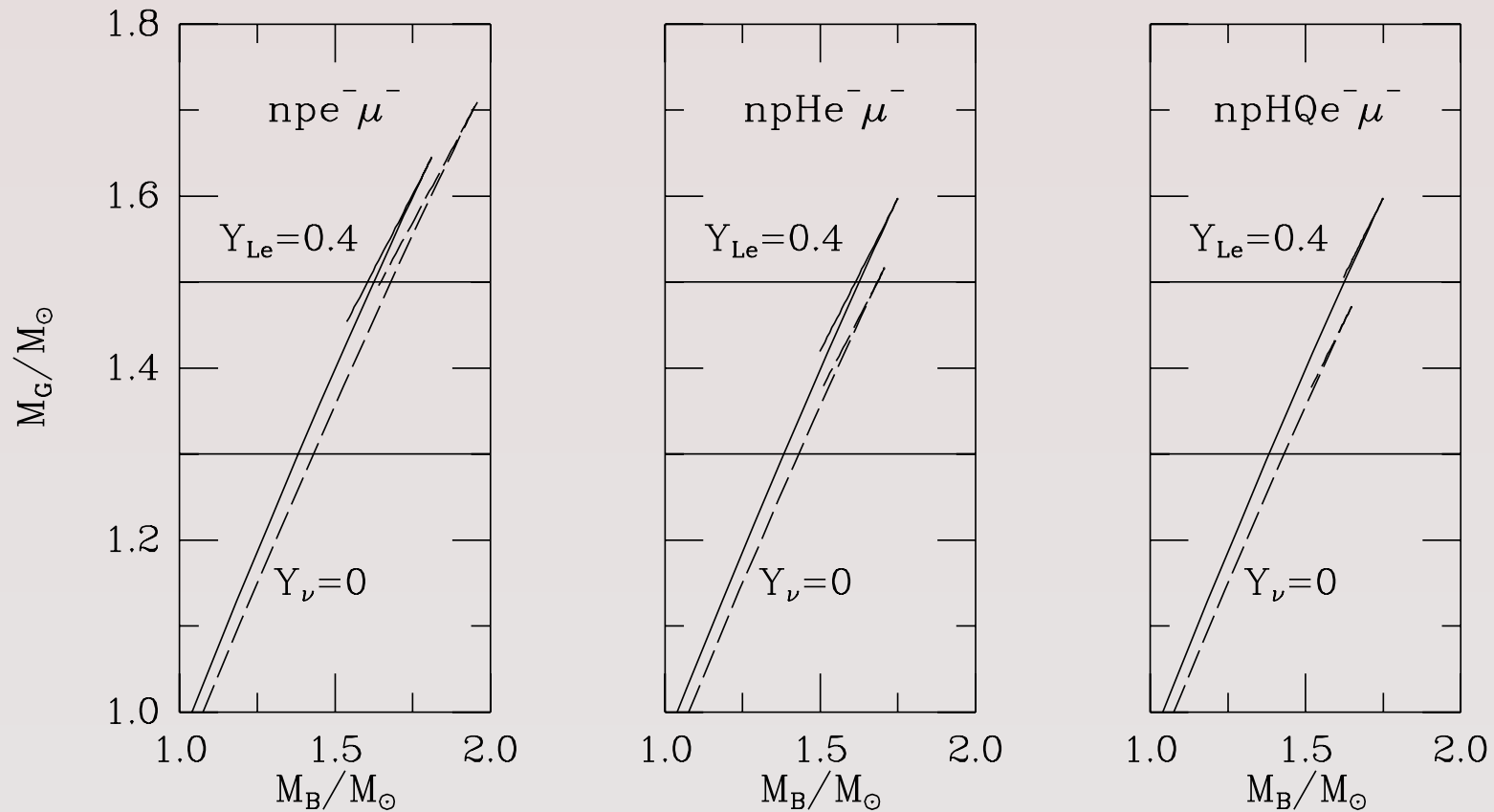


- ▶ Picture, courtesy Dany Page
- ▶ $M \sim (1 - 2)M_{\odot}$
 $M_{\odot} \simeq 2 \times 10^{33} \text{ g.}$
- ▶ $R \sim (8 - 16) \text{ km}$
- ▶ $\rho > 10^{15} \text{ g cm}^{-3}$
- ▶ $B_s = 10^9 - 10^{15} \text{ G.}$
- ▶ Tallest mountain:
 $\sim \frac{E_{liq}}{A m_p g_s} \sim 1 \text{ cm}$
- ▶ Atmospheric height:
 $\sim \frac{RT}{\mu g_s} \sim 1 \text{ cm}$

Lattimer & Prakash , Science 304, 536 (2004).

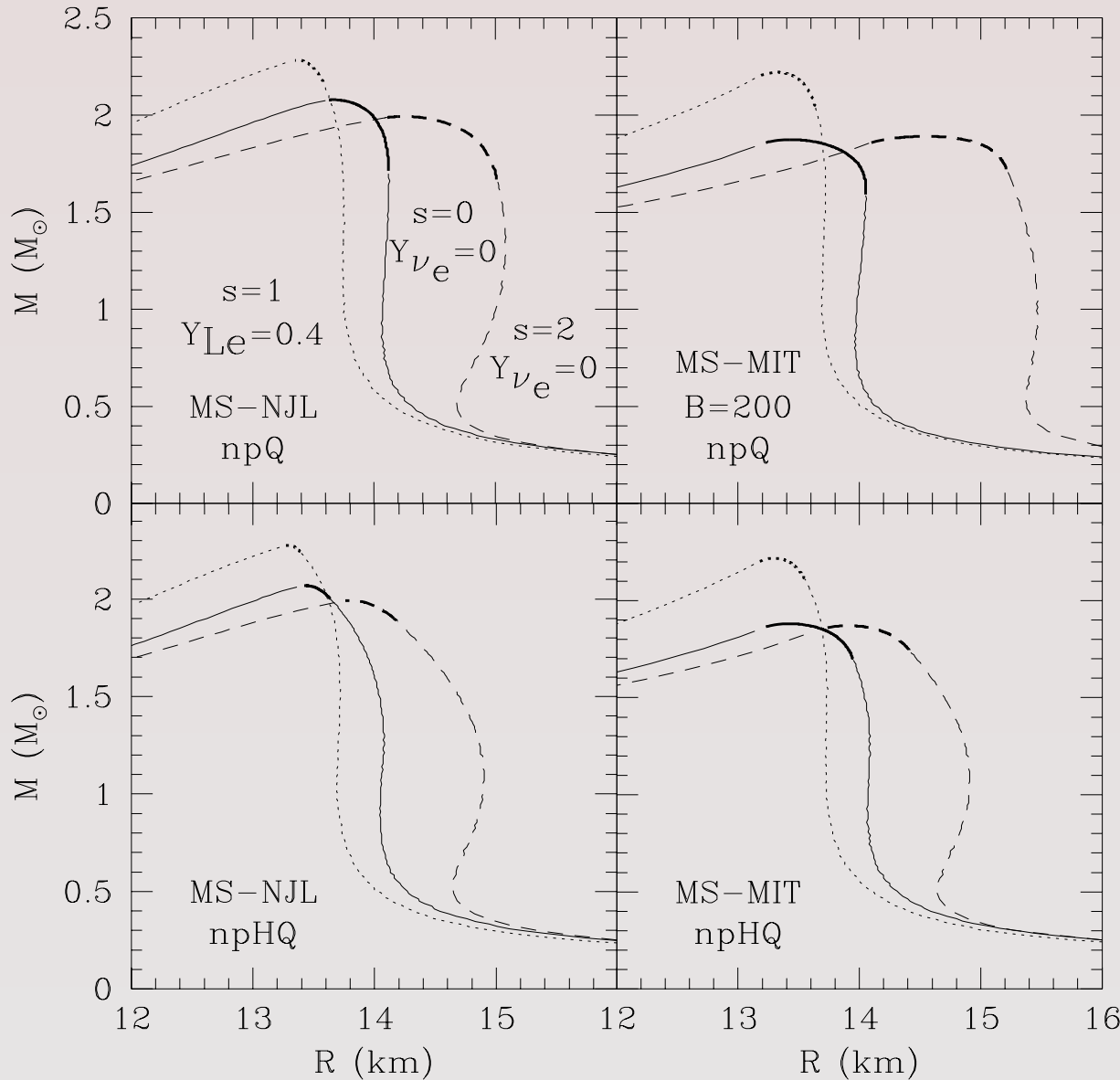
Neutrino Trapping & Metastability

If the initial protoneutron star maximum mass is greater than that of the final configuration, collapse to a black hole is inevitable.



Ellis, Lattimer & Prakash, *Comm. Nucl. & Part. Phys.* **22**, 63 (1996).

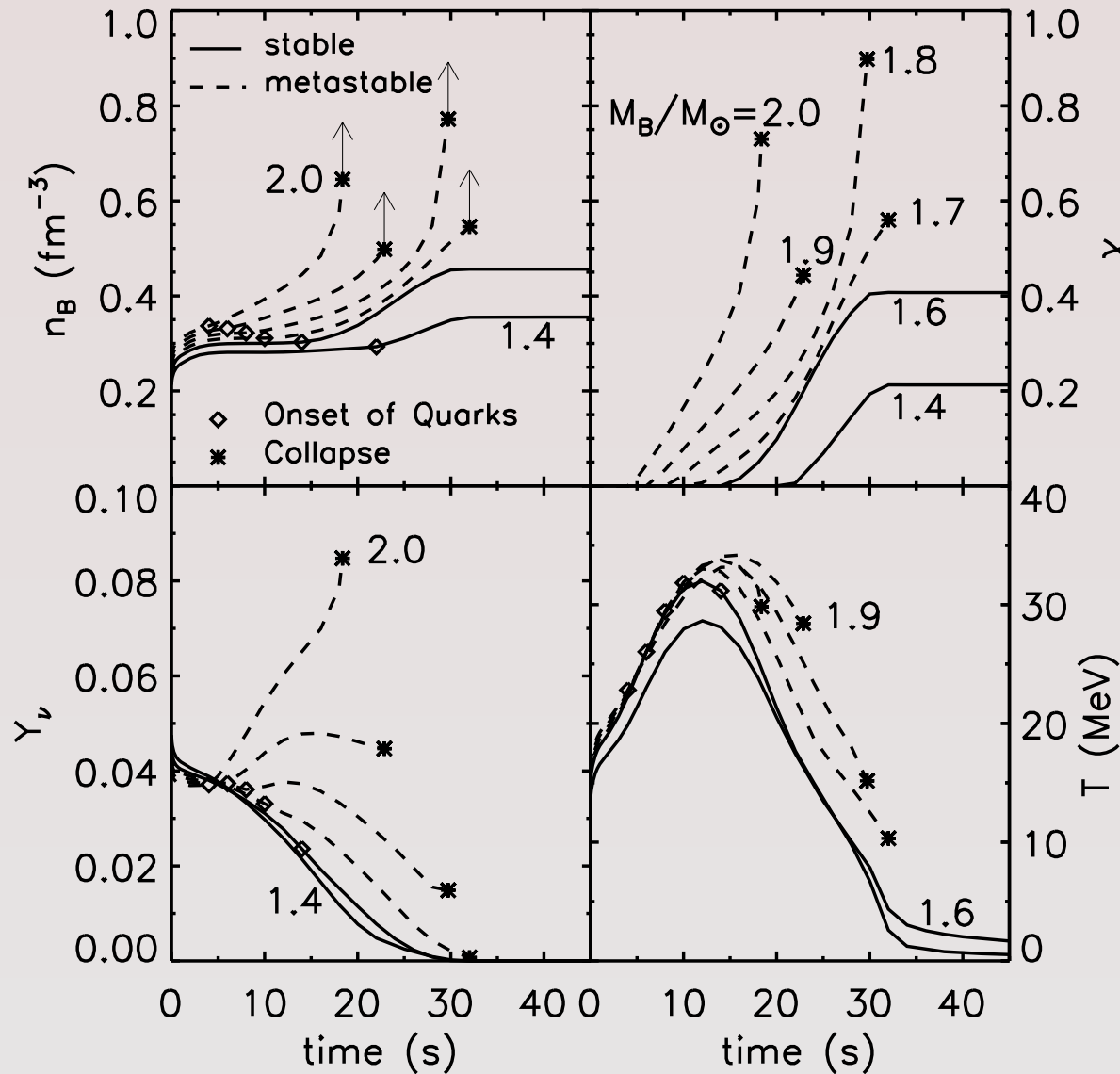
Neutrino Trapping in Quark Matter



- ▶ Dark portions show mixed phase regions
- ▶ ν -free stars with $s = 2$ have smaller maximum masses than those with $s = 0$
- ▶ With ν trapping a range of masses are metastable

Steiner, Prakash & Lattimer, Phys. Lett. B486, 239 (2000).

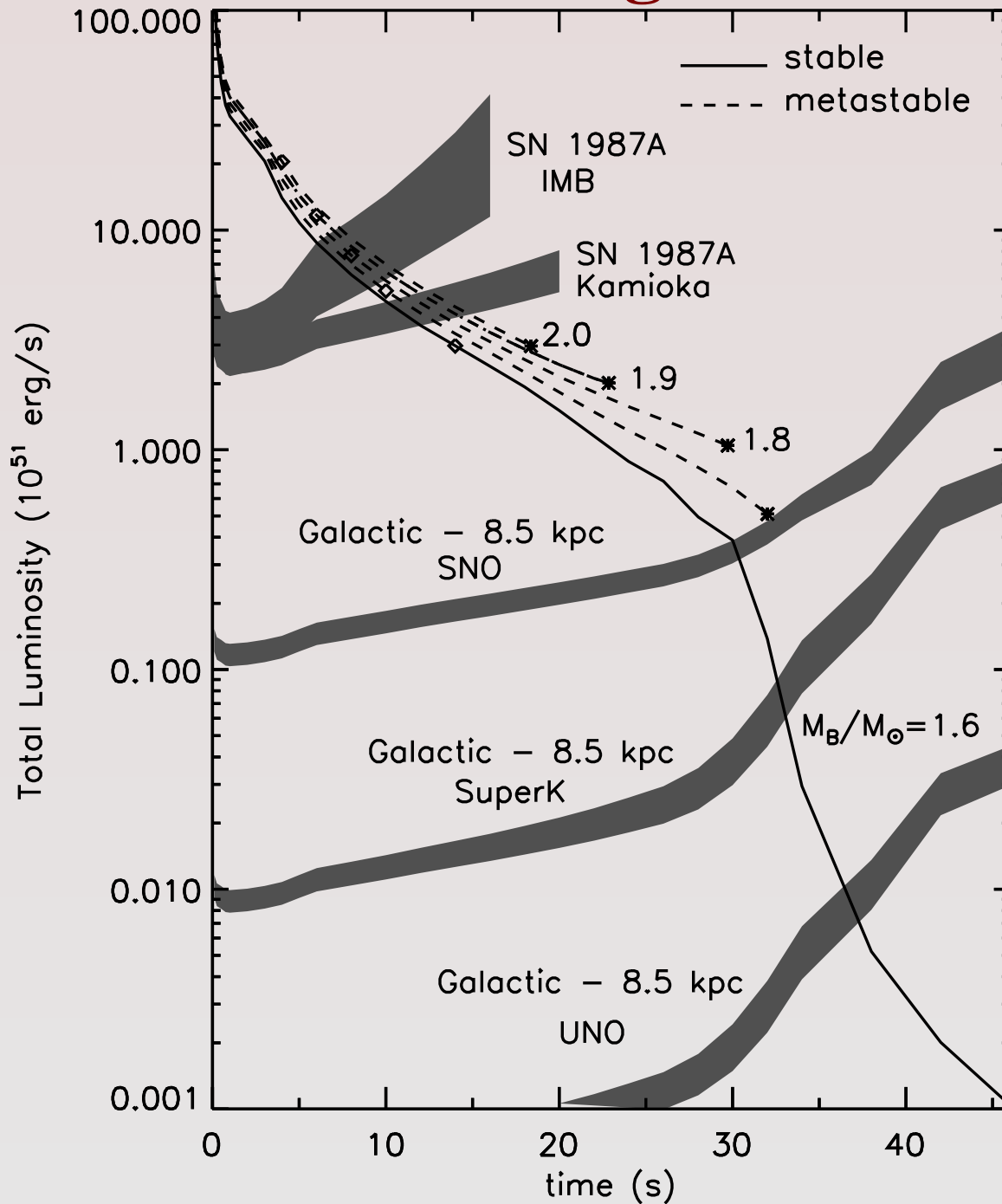
Evolution of Matter with Quarks



- ▶ As ν 's leave, the central density & mass of nucleons-only stars stabilize
- ▶ Massive enough stars with quarks end up as black holes upon deleptonization

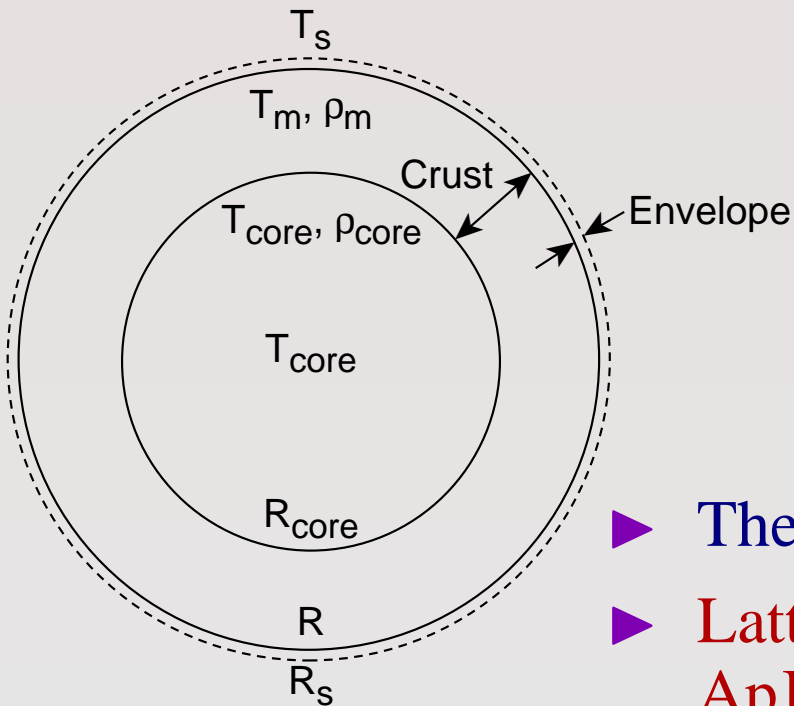
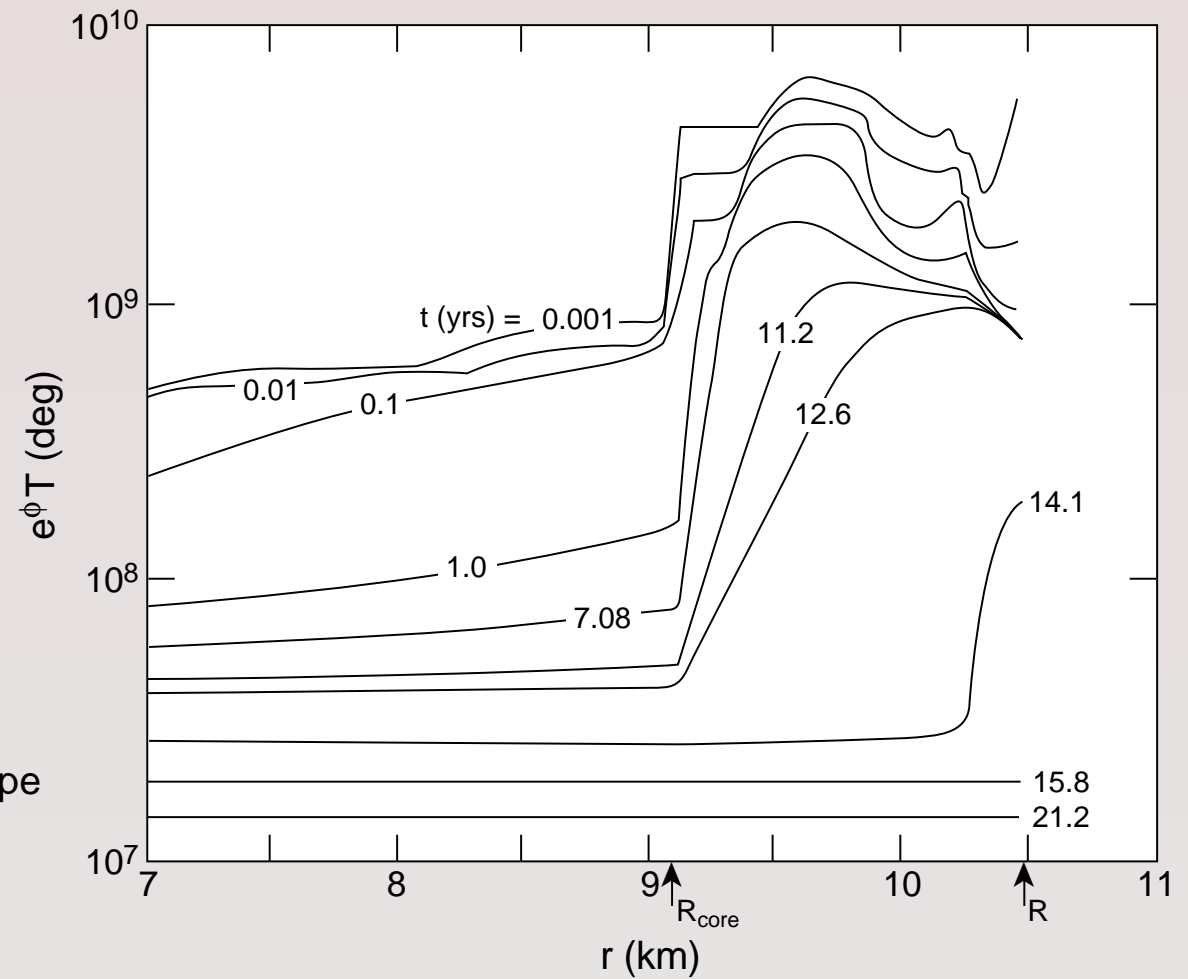
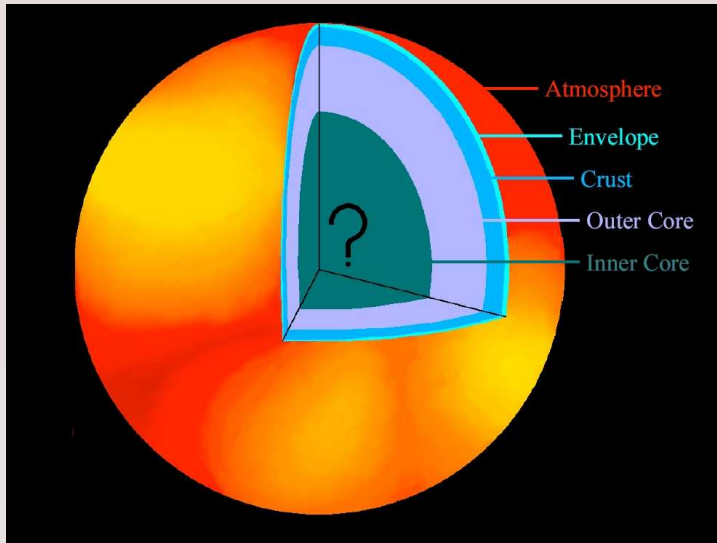
Pons, Steiner, Prakash & Lattimer, Phys. Rev. Lett. 86, 10 (2001).

Neutrino Signals in Current Detectors



- ▶ Early detectors lacked sensitivity to test if SN 1987A ended up as a black hole.
- ▶ Cessation of the ν -signal would signal the presence of exotica
- ▶ Prakash et al., *Ann. Rev. Nucl. & Part. Sci.* **51**, 295 (2001).
- ▶ Figure, courtesy, J. A. Pons

Thermal Evolution



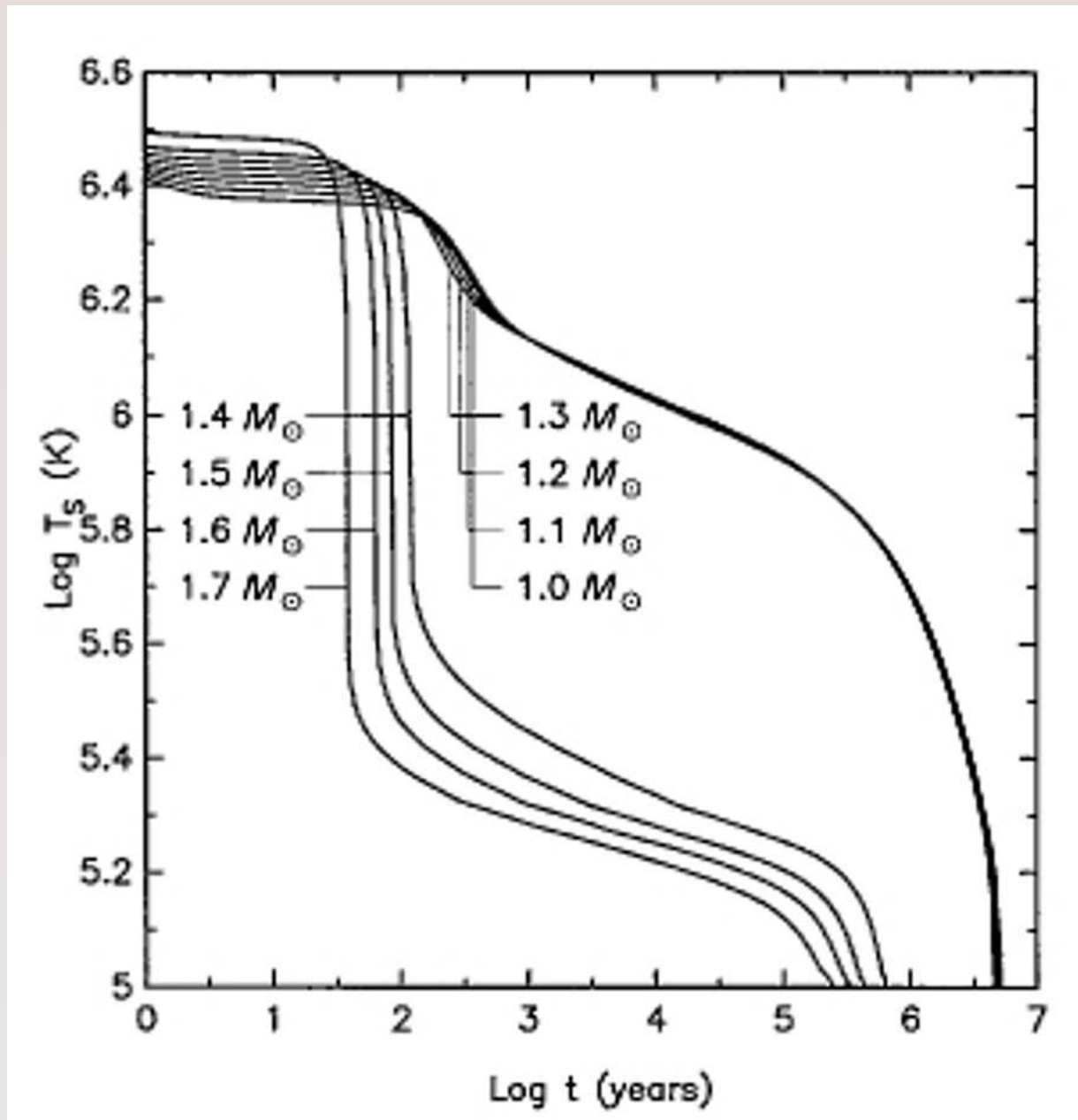
- ▶ The star becomes isothermal in tens of years.
- ▶ Lattimer, Van Riper, Prakash & Prakash, *ApJ* 425, 802 (1993).

Neutrino Emissivities

Name	Process	Emissivity ($\text{erg s}^{-1} \text{cm}^{-3}$)	References
Modified Urca	$n + n' \rightarrow n + p + e^- + \bar{\nu}_e$ $n' + p + e^- \rightarrow n' + n + \nu_e$	$\sim 10^{20} T_9^8$	Friman & Maxwell 1979
Kaon Condensate	$n + K^- \rightarrow n + e^- + \bar{\nu}_e$ $n + e^- \rightarrow n + K^- + \nu_e$	$\sim 10^{24} T_9^6$	Brown et al., 1988
Pion Condensate	$n + \pi^- \rightarrow n + e^- + \bar{\nu}_e$ $n + e^- \rightarrow n + \pi^- + \nu_e$	$\sim 10^{26} T_9^6$	Maxwell et al., 1977
Direct Urca	$n \rightarrow p + e^- + \bar{\nu}_e$ $p + e^- \rightarrow n + \nu_e$	$\sim 10^{27} T_9^6$	Lattimer et al., 1991
Hyperon Urca	$B_1 \rightarrow B_2 + l + \bar{\nu}_l$ $B_2 + l \rightarrow B_1 + \nu_l$	$\sim 10^{26} T_9^6$	Prakash et al., 1992
Quark Urca	$d \rightarrow u + e^- + \bar{\nu}_e$ $u + e^- \rightarrow d + \nu_e$	$\sim 10^{26} \alpha_c T_9^6$	Iwamoto 1980

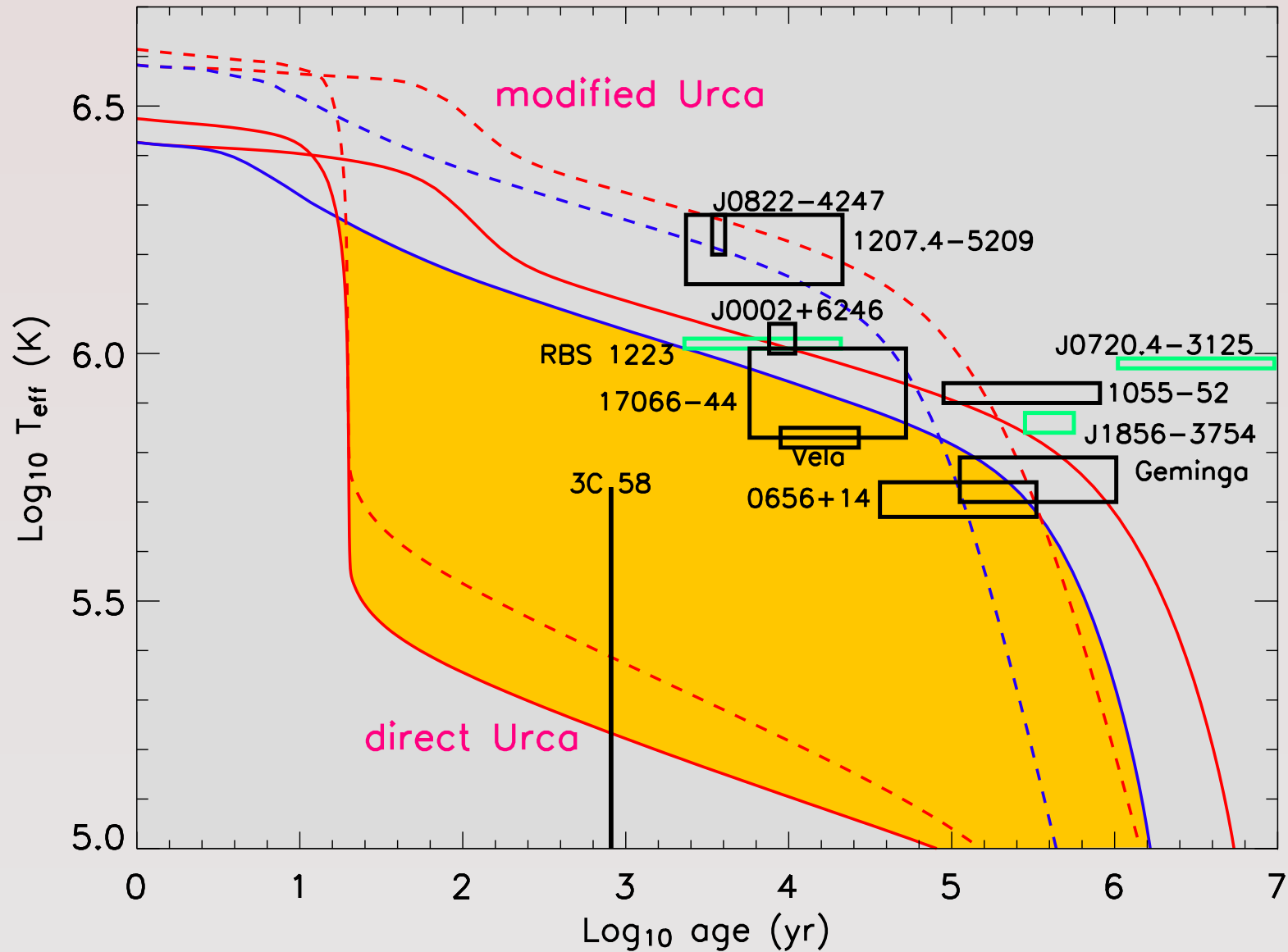
T_9 : Temperature in units of 10^9 K.

Direct versus Modified Urca



- ▶ Unlike MUrca, DUrca exhibits threshold effects.
- ▶ Superfluidity abates DUrca cooling.
- ▶ Page & Applegate, *ApJ* 394, L17 (1992).
- ▶ Cooper pair breaking & reformation affects both DUrca & MUrca.

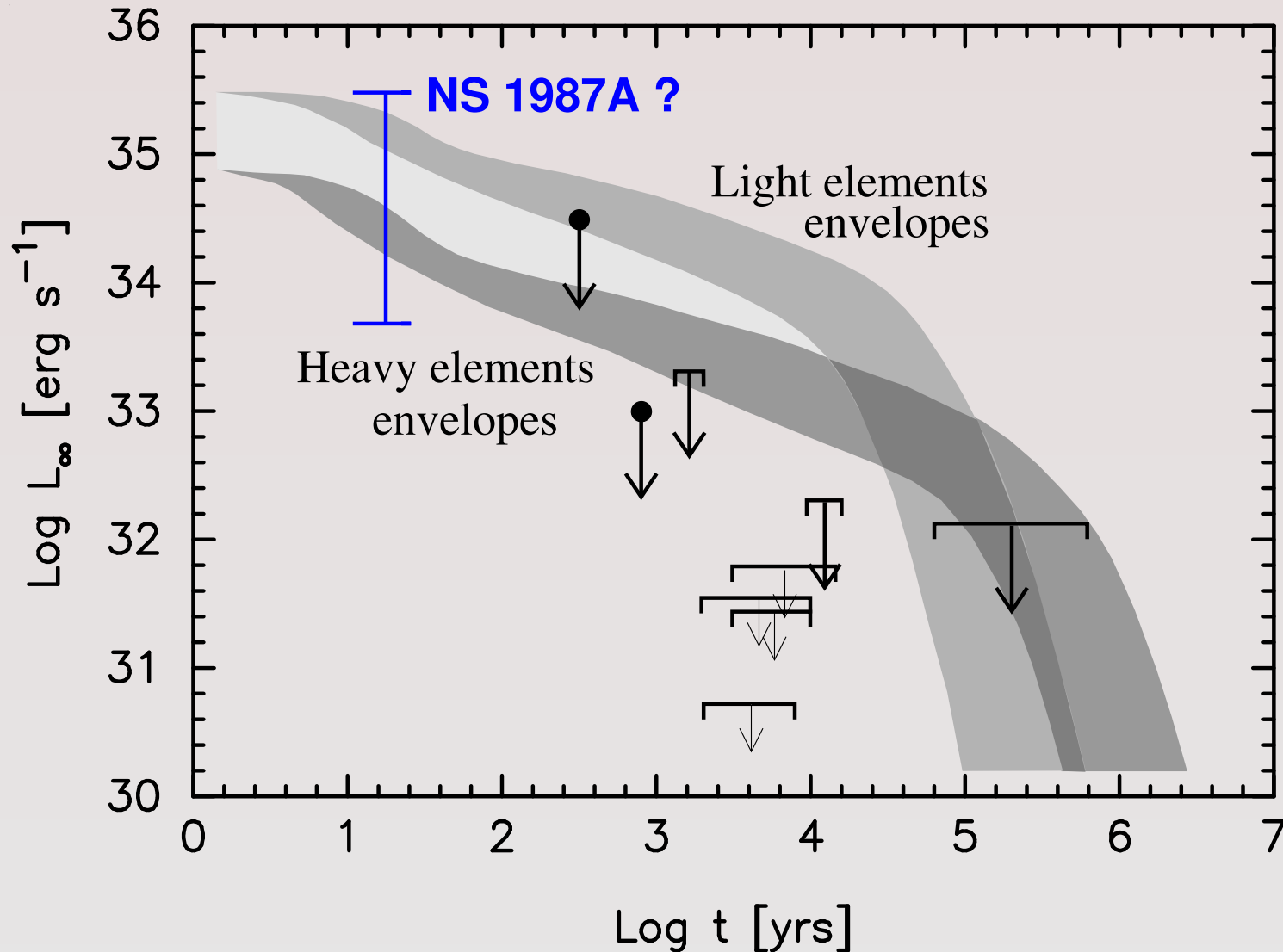
Inferred Surface Temperatures



Lattimer & Prakash, Science 304, 536 (2004).

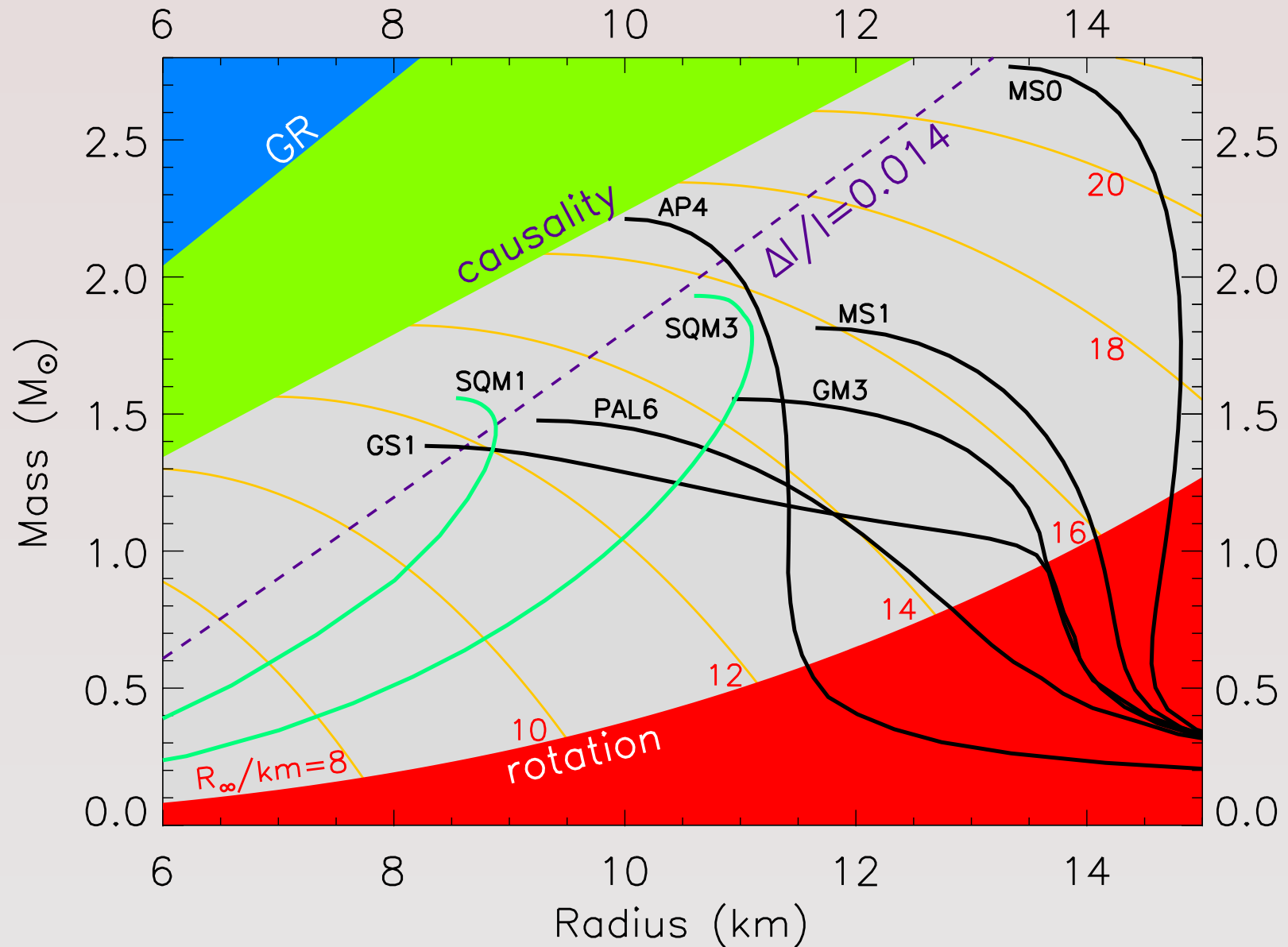
New Cold Objects

Several cases fall below the “Minimal Cooling” paradigm & point to enhanced cooling, if these objects correspond to neutron stars.



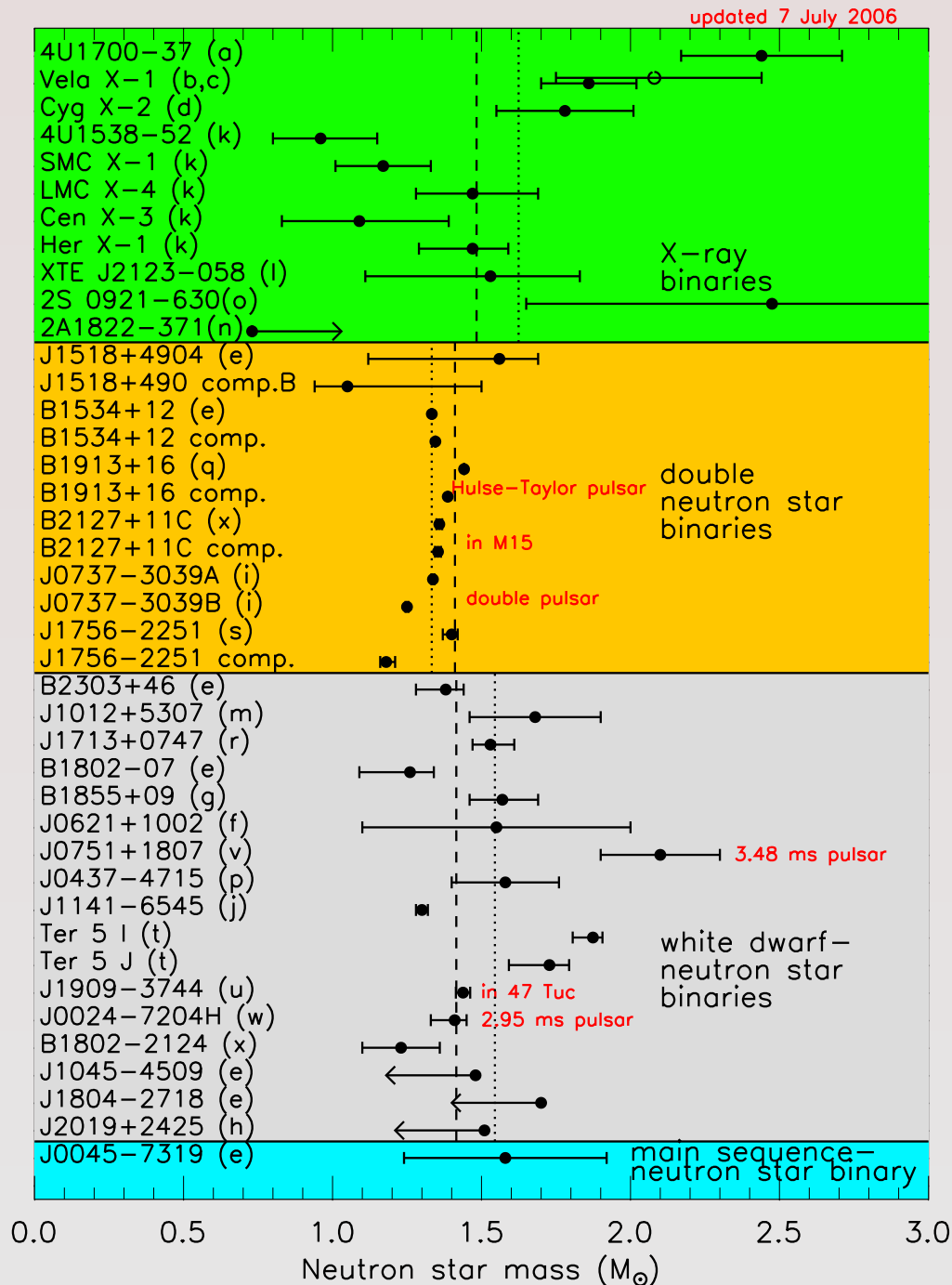
Page, Lattimer, Prakash & Steiner, *ApJS* 155, 623 (2004).

Mass Radius Relationship



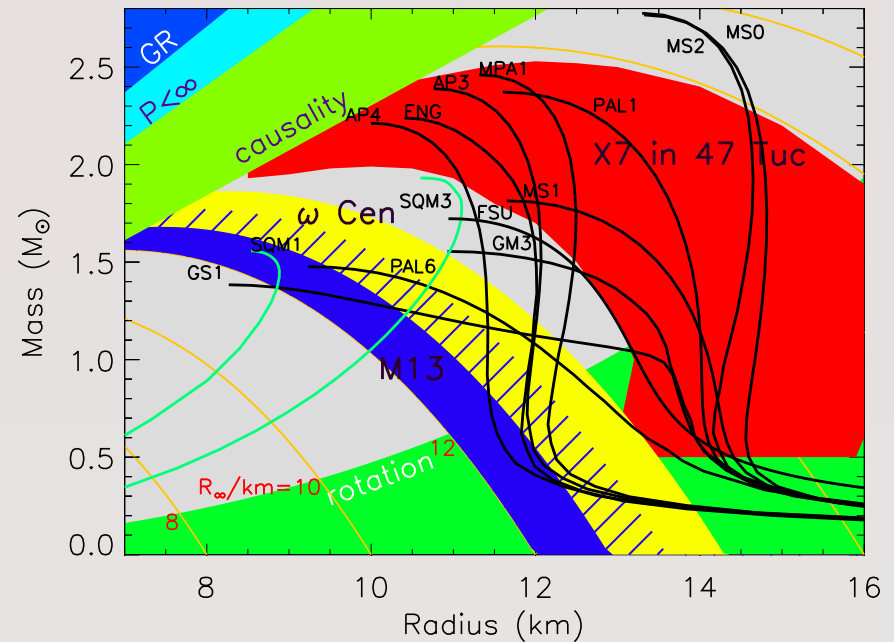
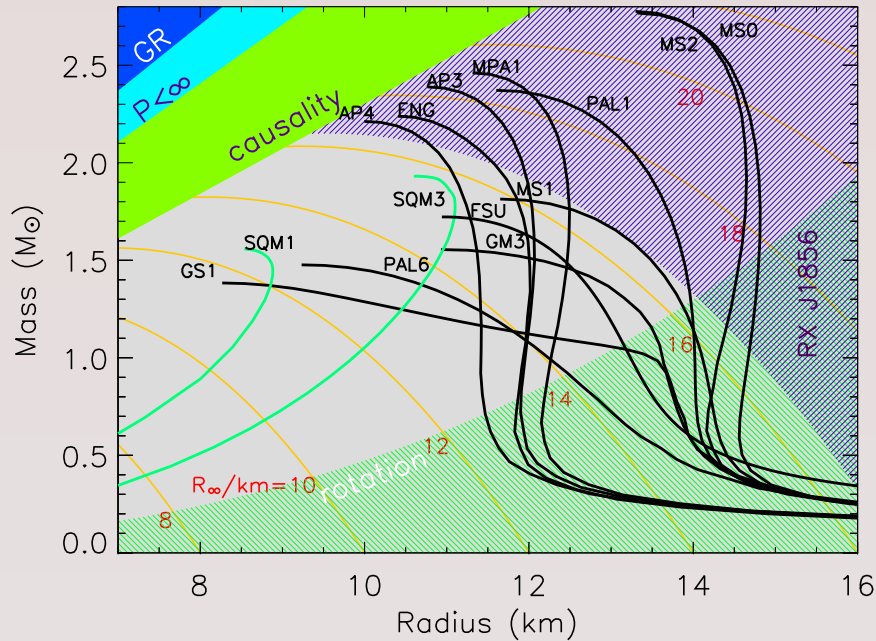
Lattimer & Prakash, Science 304, 536 (2004).

Measured Neutron Star Masses



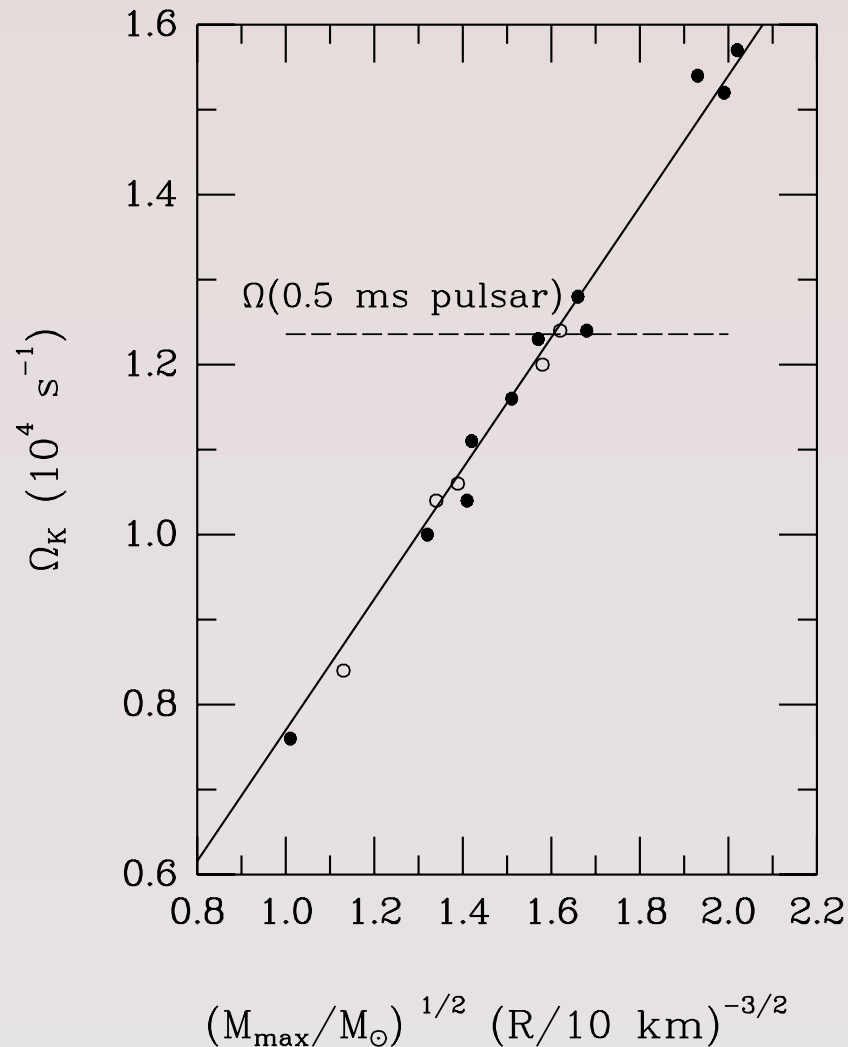
- ▶ Mean & weighted means in M_{\odot}
- ▶ X-ray binaries: 1.63 & 1.48
- ▶ Double NS binaries: 1.33 & 1.41
- ▶ WD & NS binaries: 1.56 & 1.42
- ▶ Lattimer & Prakash, PRL, 94 (2005) 111101

Neutron star radius measurements



- ▶ Despite advances, need more accurate measurements.
- ▶ Özel, Nature, 441, 1115, (2006);
Lattimer & Prakash, Phys. Rep. (2006).

How fast can rotation be?



General Relativity:

$$\Omega_K = 7.7 \times 10^3 \text{ s}^{-1} \times SF .$$

$$SF = \left(\frac{M_{\max}}{M_{\odot}} \right)^{1/2} \left(\frac{R_{\max}}{10 \text{ km}} \right)^{-3/2}$$

Maximum radius:

$$R_{\max} = 10.3 \text{ km} \times \left(\frac{1 \text{ kHz}}{\nu} \right)^{2/3} \left(\frac{M}{M_{\odot}} \right)^{1/3}$$

M: Star of given mass

M_{\max} and R_{\max} refer to the spherical configuration.

Lattimer & Prakash , Science 304, 536 (2004).

Moment of inertia (I) measurements

Spin precession periods:

$$P_{p,i} = \frac{2c^2 a P M (1 - e^2)}{G M_{-i} (4M_i + 3M_{-i})}.$$

Spin-orbit coupling causes a periodic departure from the expected time-of-arrival of pulses from pulsar A of amplitude

$$\delta t_A = \frac{M_B}{M} \frac{a}{c} \delta_i \cos i = \frac{a}{c} \frac{I_A}{M_A a^2} \frac{P}{P_A} \sin \theta_A \cos i$$

P : Orbital period a : Orbital separation e : Eccentricity

$M = M_1 + M_2$: Total mass

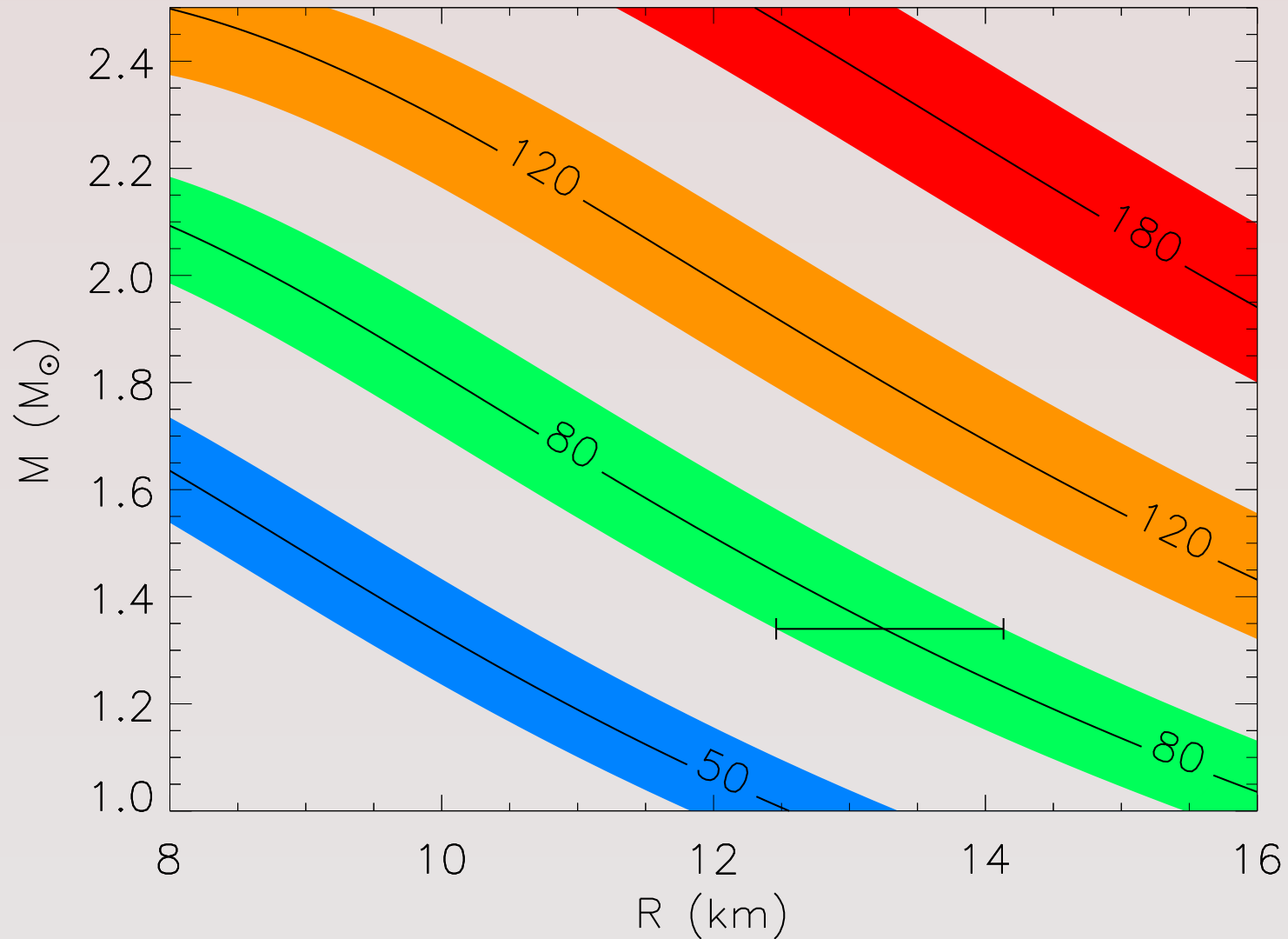
i : Orbital inclination angle θ_A : Angle between S_A and L .

I_A : Moment of Inertia of A

For PSR 0707-3039, $\delta t_A \simeq (0.17 \pm 0.16) I_{A,80} \mu\text{s}$;

Needs improved technology & is being pursued.

Limits on R from M & I measurements

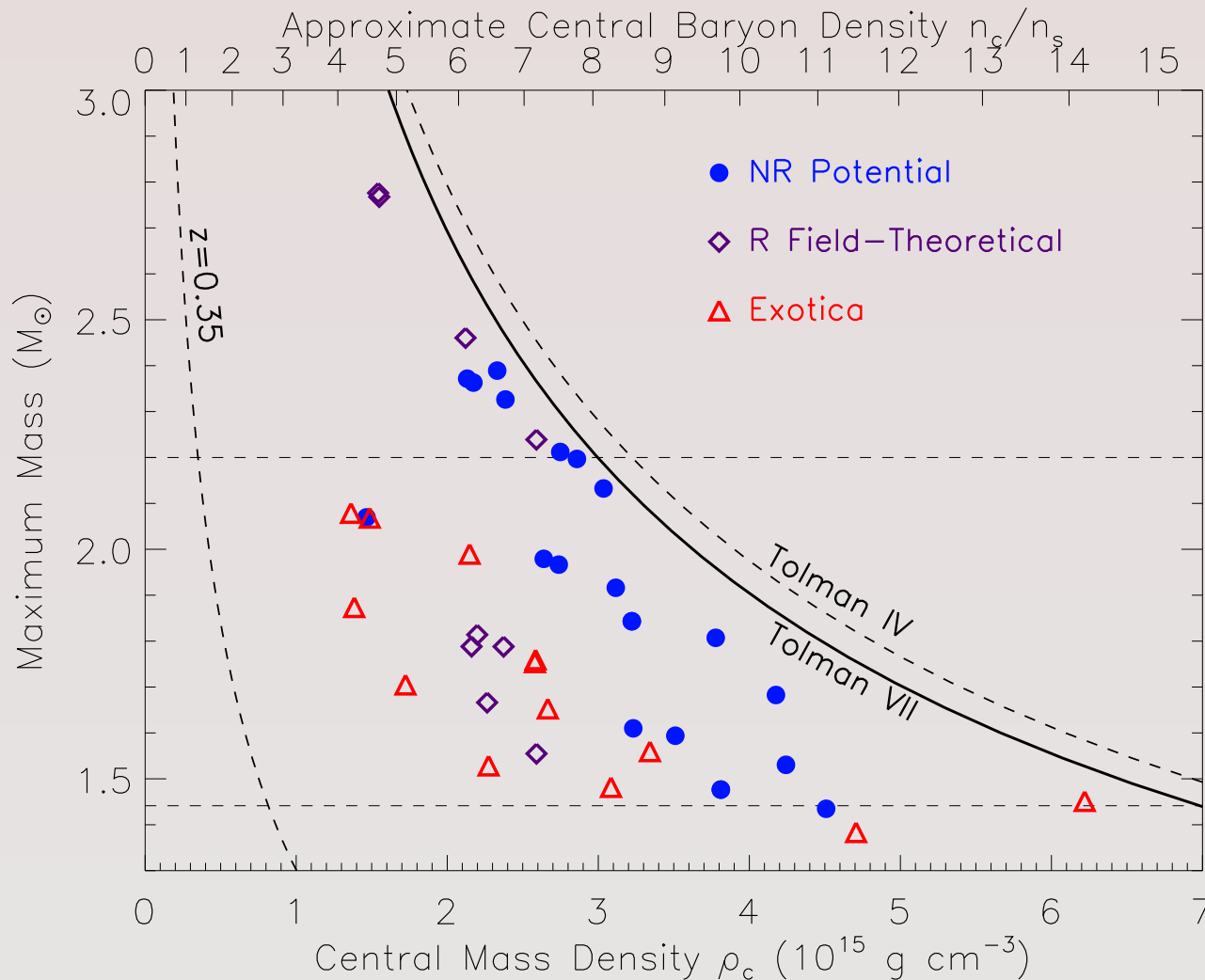


► 10% error bands on I in $M_\odot \text{ km}^2$

► Horizontal error bar for $M = 1.34 M_\odot$ & $I = 80 \pm 8 M_\odot \text{ km}^2$

J. M. Lattimer & B. F. Schutz, *Astrophys. J.* **629** (2005)

Ultimate Energy Density of Cold Matter

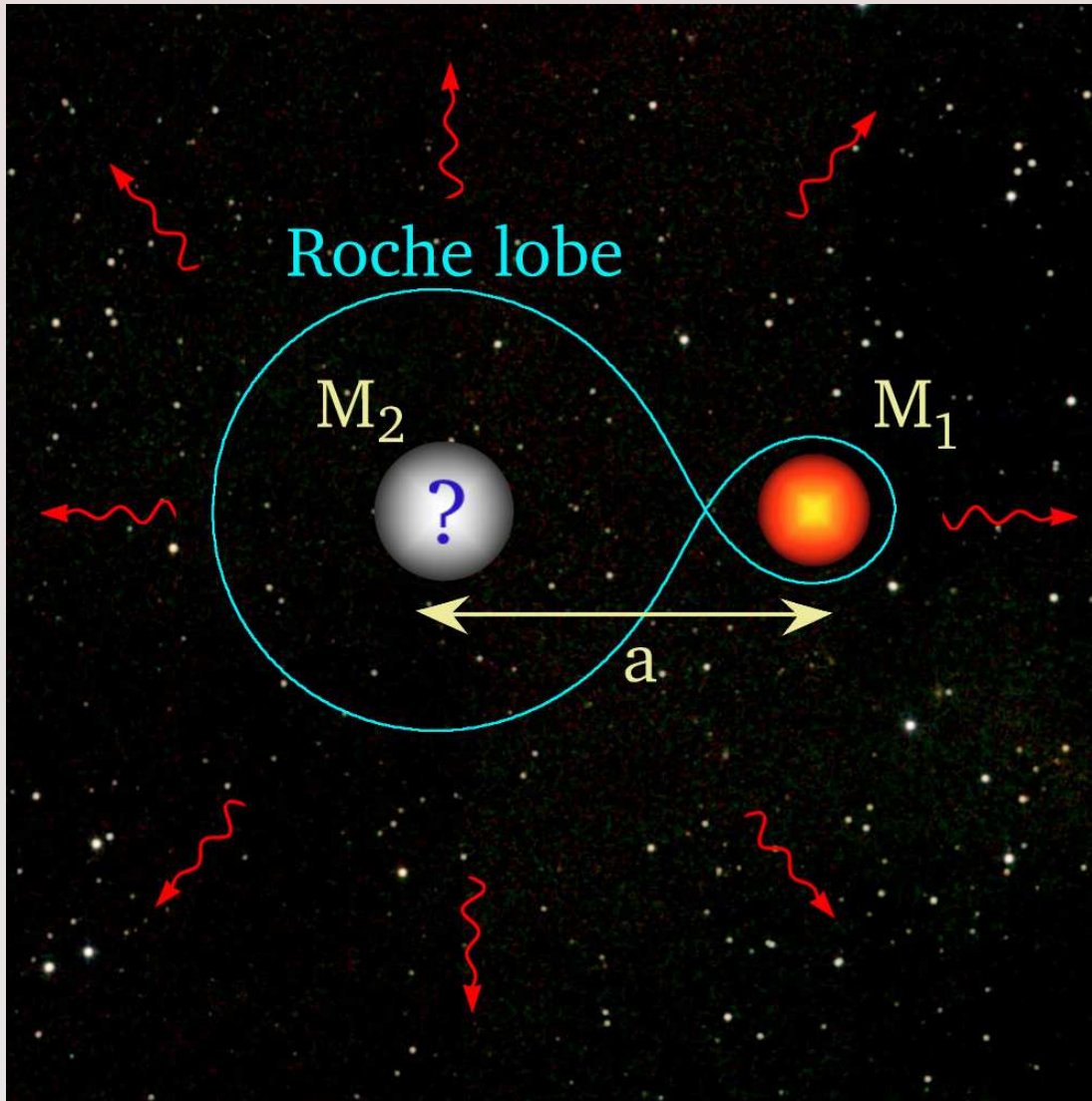


- ▶ Tolman VII:
 $\epsilon = \epsilon_c(1 - (r/R)^2)$
- ▶ $\epsilon_c \propto (M_\odot/M)^2$
- ▶ A measured red-shift provides a lower limit.
- ▶ Crucial to establish an upper limit to M_{max} .

Lattimer & Prakash, PRL, 94 (2005) 111101.

The Binary Merger Experience

The Ultimate Heavy-Ion Collision

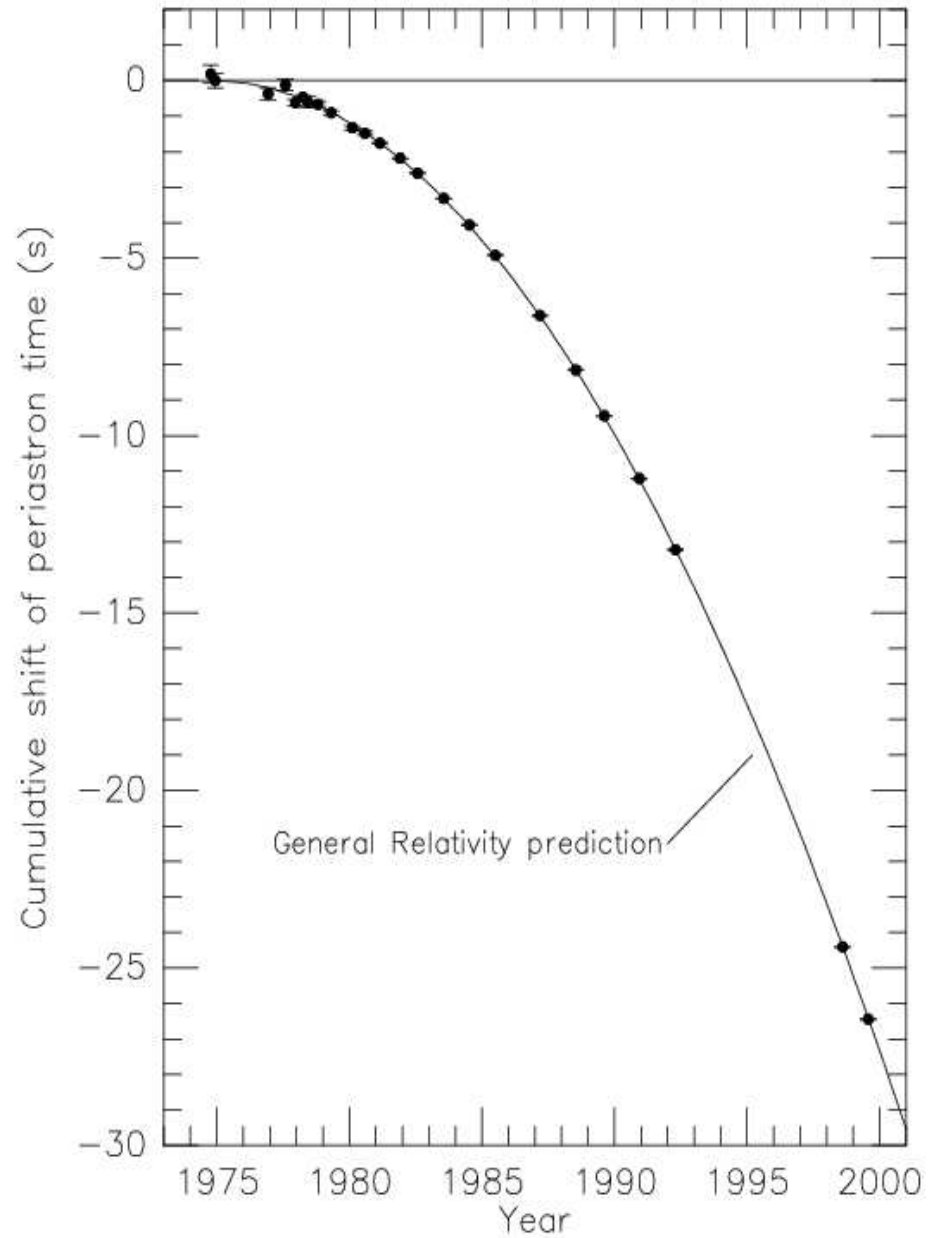


- ▶ $M_1 \leq M_2$
- ▶ radial separation: $a(t)$
- ▶ M_1 - NS or SQM
- ▶ M_2 - BH, NS, ...
- ▶ GW emission \Rightarrow

$$\begin{aligned} L_{GW} &= \frac{1}{5} \frac{G}{c^5} \langle \ddot{I}_{jk} \ddot{I}_{jk} \rangle \\ &= \frac{32}{5} \frac{G^4}{c^5} \frac{M^3 \mu^2}{a^6} \end{aligned}$$

orbit shrinks

- ▶ Mass transfer



Who're they & why so happy?

Gravitational Wave Detection

► GW Strain : $h(t) = F_{\times} h_{\times}(t) + F_{+} h_{+}(t)$

- $F_{\times,+}$: Constants of order unity

- $h_{\times,+} \sim \frac{\delta L}{L_0} \sim \frac{1}{c^2} \frac{4G(E_{kin}^{ns}/c^2)}{r}$: Gravitational waveforms

 - L_0 : Unperturbed length of detector arm

 - δL : Relative change in length

 - E_{kin}^{ns} : Nonspherical part of the internal kinetic energy

- ELF : 10^{-15} - 10^{-18} Hz VLF : 10^{-7} - 10^{-9} Hz*

- LFB : 10^{-4} Hz - 1 Hz, HFB : 1 Hz - 10^4 Hz

► Astrophysical Sources Radiating GW's in the HFB

Supernovae	at 10 Mpc	$h \geq 10^{-25}$
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Supernovae	Milky Way	$h \sim 10^{-18}$
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1.4M _⊙ NS Binaries	at 10 Mpc	$h \sim 10^{-20}$
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10M _⊙ BH Binaries	at 150 Mpc	$h \sim 10^{-20}$
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Discovery of Double-Pulsar System

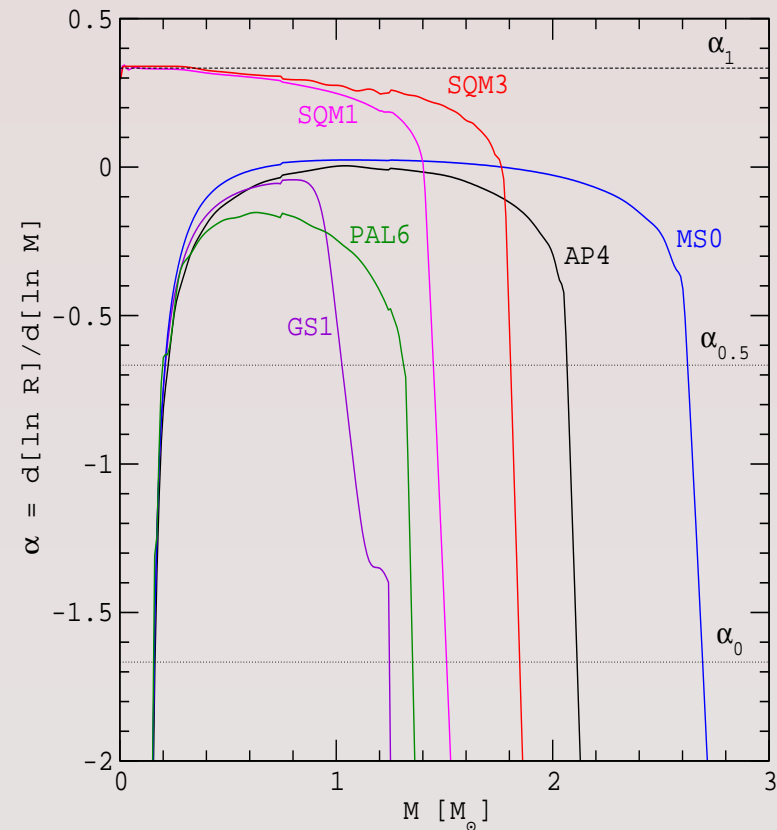
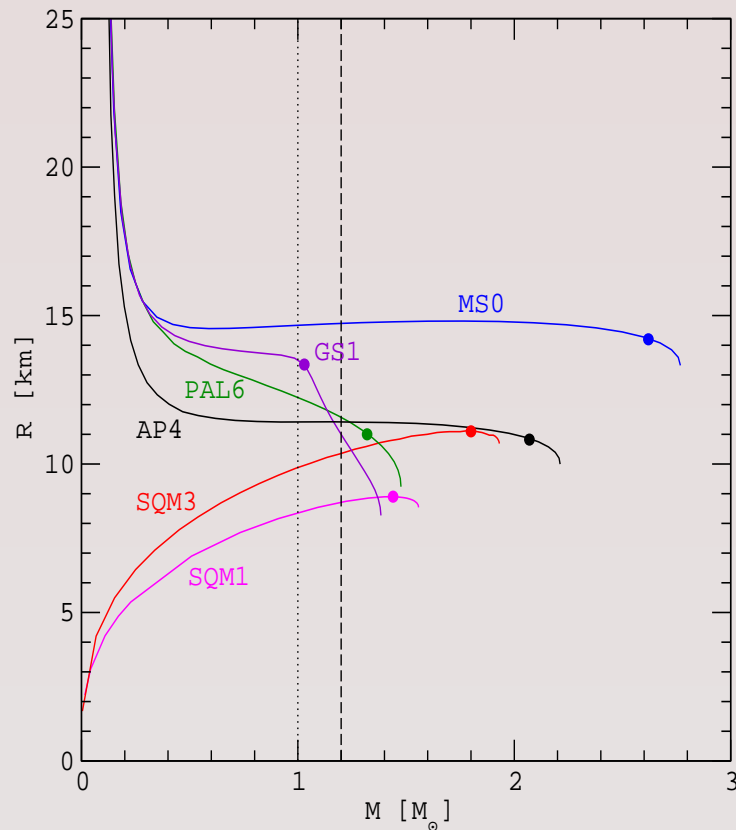
Pulsar	PSR J0737-3039A	PSR J0737-3039B
Pulse Period P (ms)	22.69937855615(6)	2773.4607474(4)
Period derivative \dot{P}	$1.74(5) \times 10^{-18}$	$0.88(13) \times 10^{-15}$
Orbital period P_b (day)	0.102251563(1)	—
Eccentricity e	0.087779(5)	—
Characteristic age (My)	210	50
Magnetic field B_s	6.3×10^9	1.6×10^{12}
Spin-down luminosity \dot{E} (erg/s)	5.8×10^{33}	1.6×10^{30}
Distance (kpc)	~ 0.6	—
Stellar mass	1.337(5)	1.250(5)

Merger expected in 85 Myr, a factor 3.5 shorter than PSR 1913+16

A.G Lyne et al., *Science*, **303**, 1153 (2004)

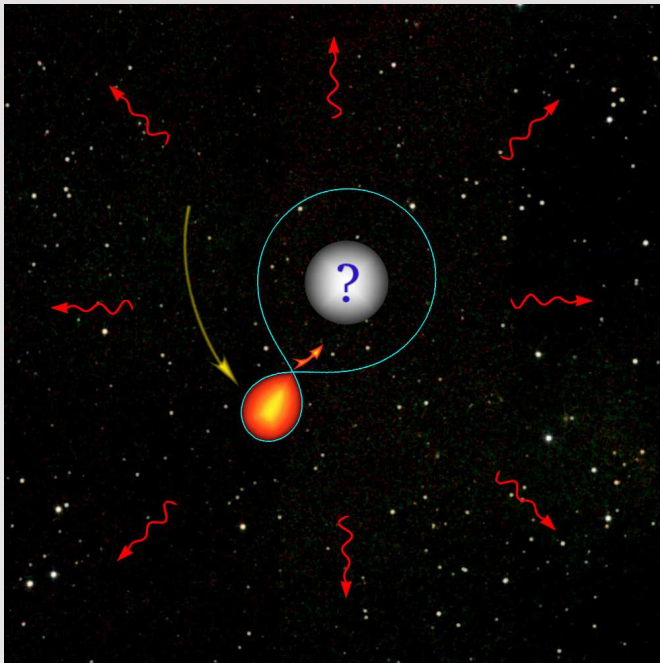
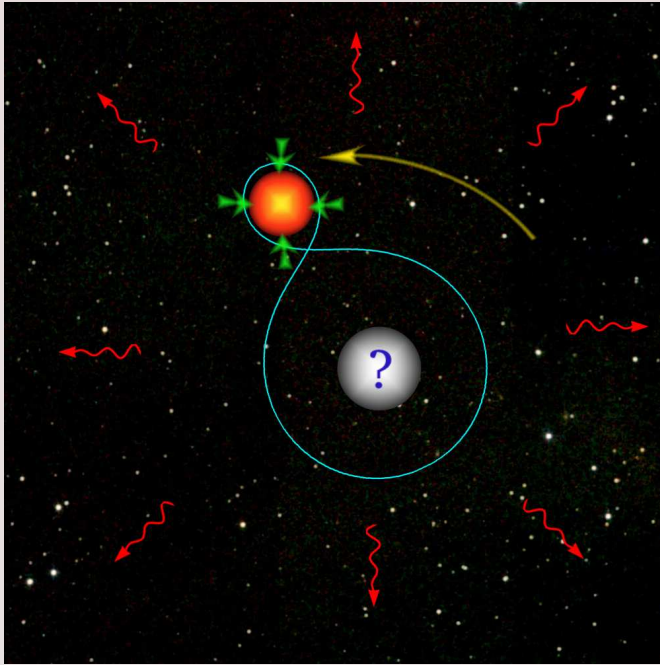
Kalogera et al. (2004): Revisions w/ PSR J037-3039 imply 1 event per 1.5 yr for initial LIGO (for advanced LIGO, 20-1000 events per yr).

Equation of State: $\alpha(M)$



- ▶ EOS parameter : $\alpha = d \ln(R)/d \ln(M)$
- ▶ $\alpha_{NS} \leq 0$ (normal star)
- ▶ $\alpha_{SQM} \geq 0$ ($\approx 1/3$) (self-bound star)

Roche Lobe Overflow



- ▶ Energy Loss

$$L_{GW} = \frac{1}{5} \langle \ddot{I}_{jk} \ddot{I}_{jk} \rangle = \frac{32}{5} a^4 \mu^2 \omega^6$$

- ▶ Angular Momentum Loss

$$\left(\dot{J}_{GW} \right)_i = \frac{2}{5} \epsilon_{ijk} \langle \ddot{I}_{jm} \ddot{I}_{km} \rangle = \frac{32}{5} a^4 \mu^2 \omega^5$$

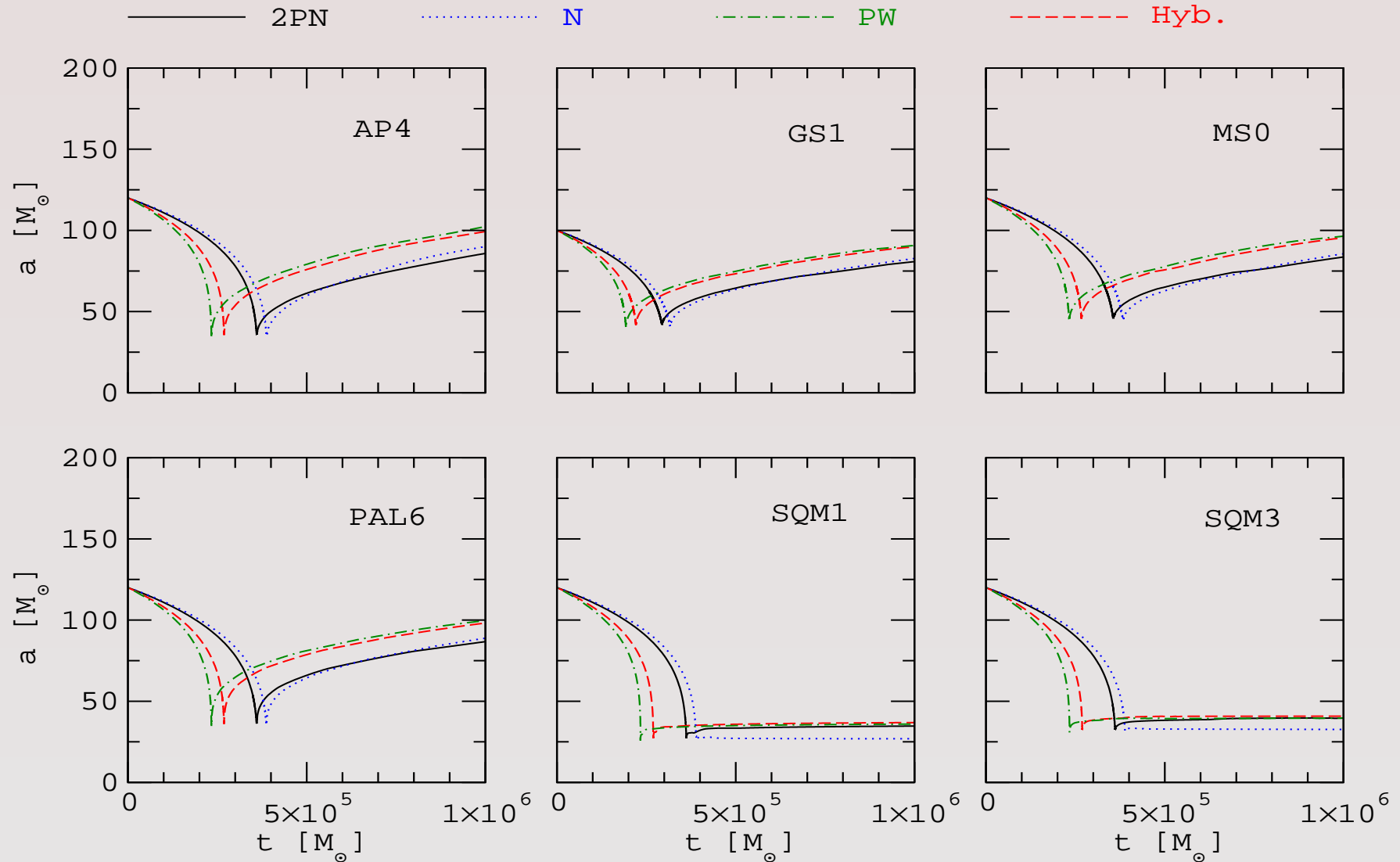
- ▶ $a(t)$ and V_{Roche} shrink!

- ▶ $R_1 = r_{Roche}$

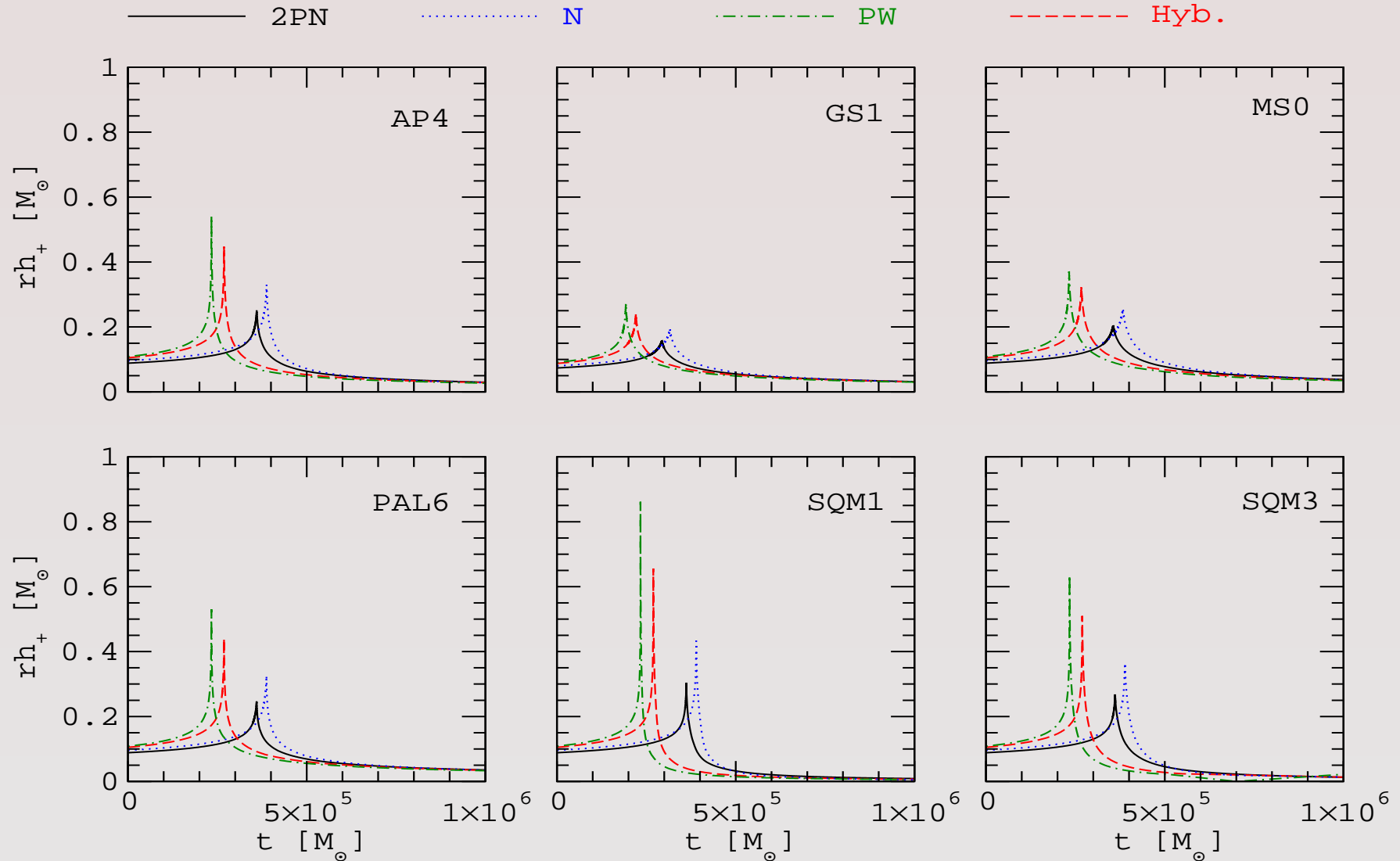
⇒ Mass transfer begins!

- ▶ To merge or not to merge?

Evolution: Orbit Separation a



Evolution: Distance \times Gravitational Amplitude rh_+



Major Results

- ▶ Incorporating GR into orbital dynamics leads to an evolution that is faster than the Newtonian evolution.
- ▶ Large differences exist between mergers of “normal” and “self-bound (SQM)” stars.
 - SQM stars penetrate to smaller orbital radii; stable mass transfer is more difficult than for normal stars.
 - For stable mass transfer, $q = M_1/M_2$ and $M = M_1 + M_2$ limits on SQM stars are more restrictive than for normal stars.
 - The SQM case has exponentially decaying signal and mass, while normal star evolution is slower.

Outlook

- ▶ Growing observations of neutron stars can delineate the equation of state of dense neutron-star matter that likely hosts quark matter.
- ▶ Given the promise of model calculations involving quark matter, lattice results at finite baryon density would be very welcome.
- ▶ A greater number of more accurate measurements, particularly of masses, radii, temperature, etc., are also necessary.



That's All Folks!