Recent Developments in
The Physics of Neutron Stars

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Subal-Fest

Dec 4 , 2004, Montreal

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Physics & Astrophysics of Neutron Stars

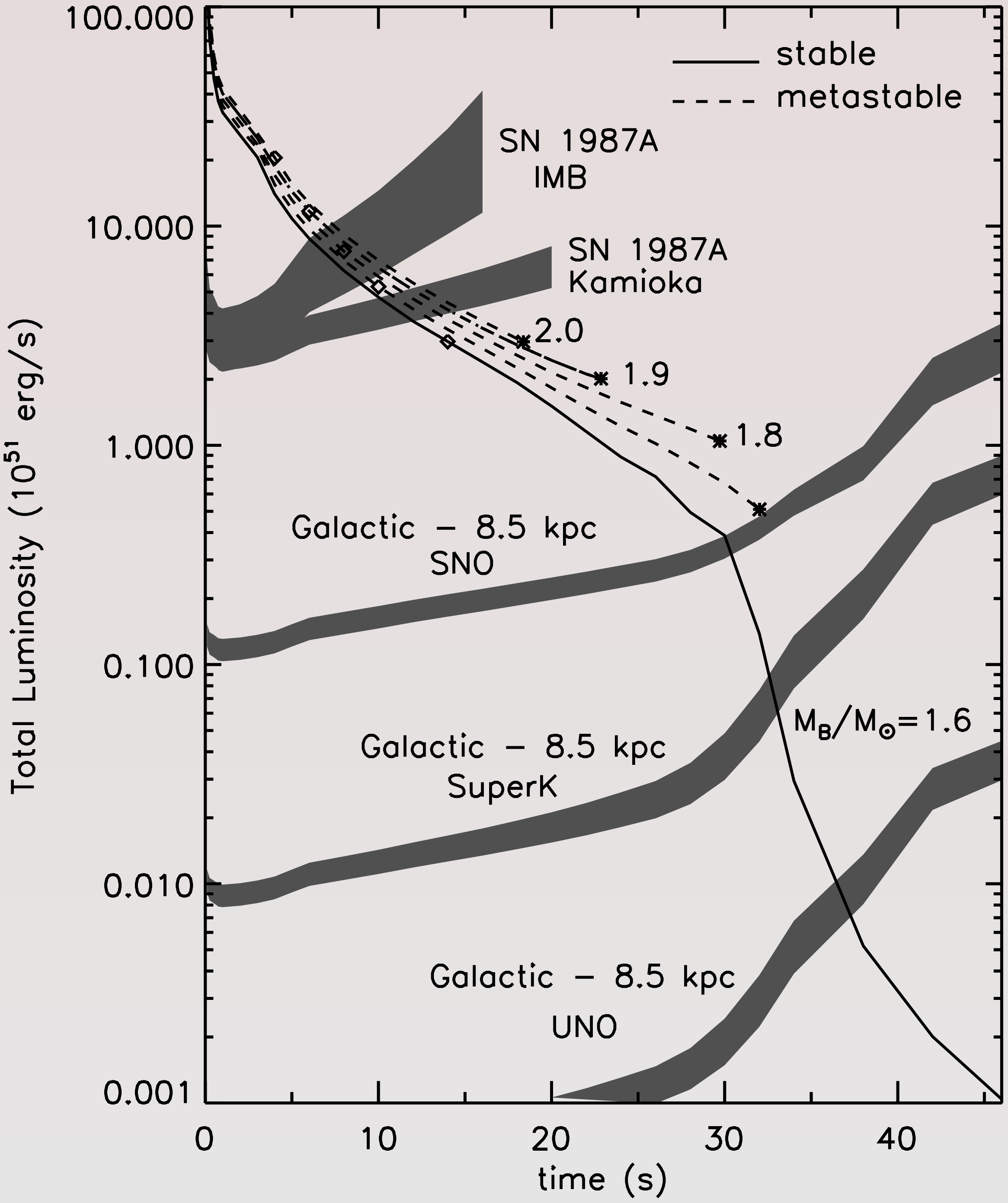
- Cores of neutron stars may contain hyperons, Bose condensates, or quarks (*Exotica*)
- *Can* observations of $M, \ R$ & B.E (composition & structure) & $P, \ \dot{P}, \ T_S$ & B etc., (evolution) reveal *Exotica* ?
- Neutron stars implicated in x-ray & γ-ray bursters, mergers with black holes, etc.
- *Observational Programs* :

  SK, SNO, LVD's, AMANDA ... (ν's)
  HST, CHANDRA, XMM, ASTROE ... (γ's)
  LIGO, VIRGO, GEO600, TAMA ... (Gravity Waves)

Connections to Nuclear Physics

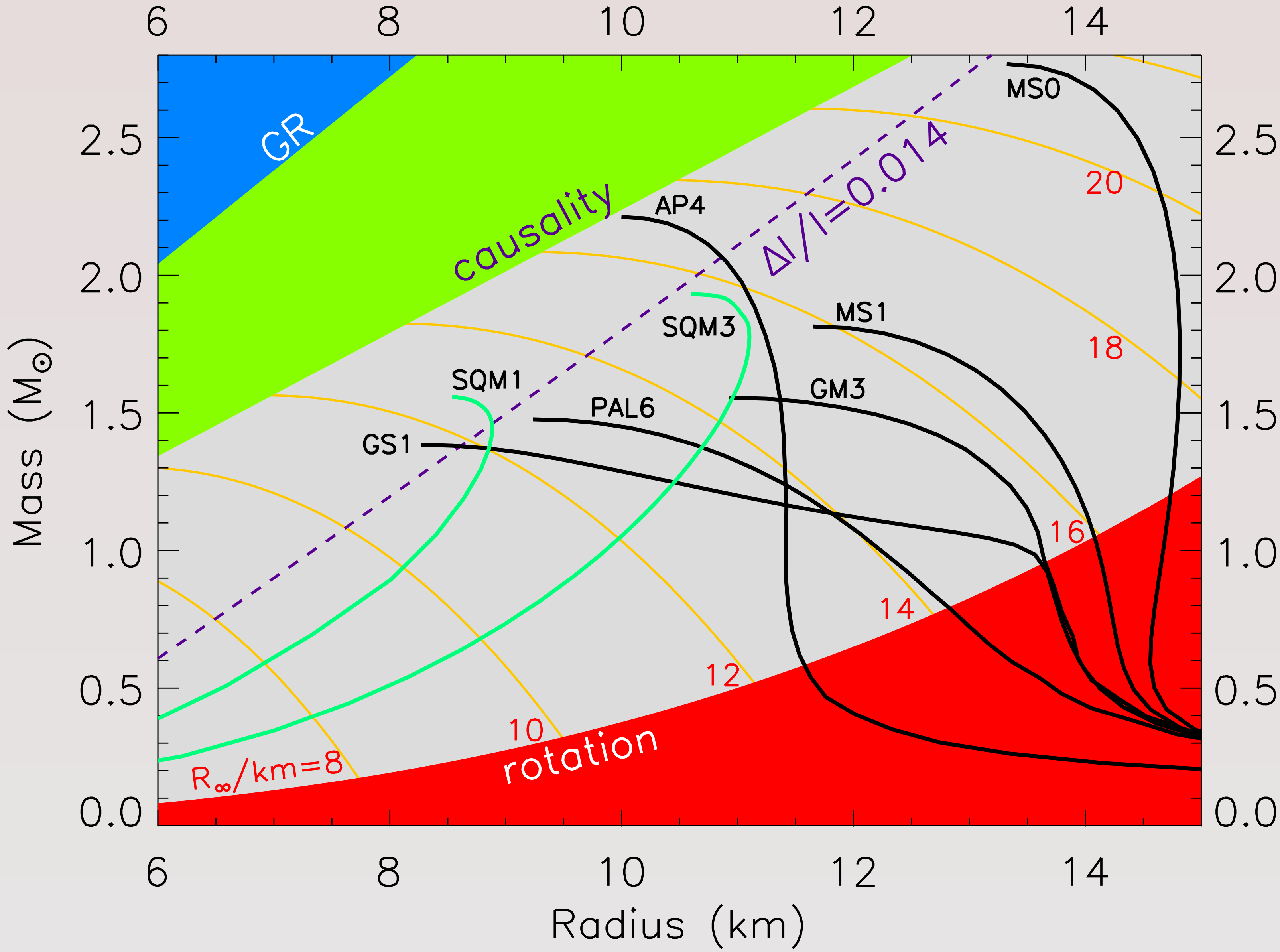
- Theory : Many-body theory of strongly interacting systems, Dynamical response (ν- & γ- propagation & emissivities)
- Experiment : e^- and ν- scattering experiments on nuclei, masses of neutron-rich nuclei, heavy-ion reactions, etc.

Neutrino Luminosities

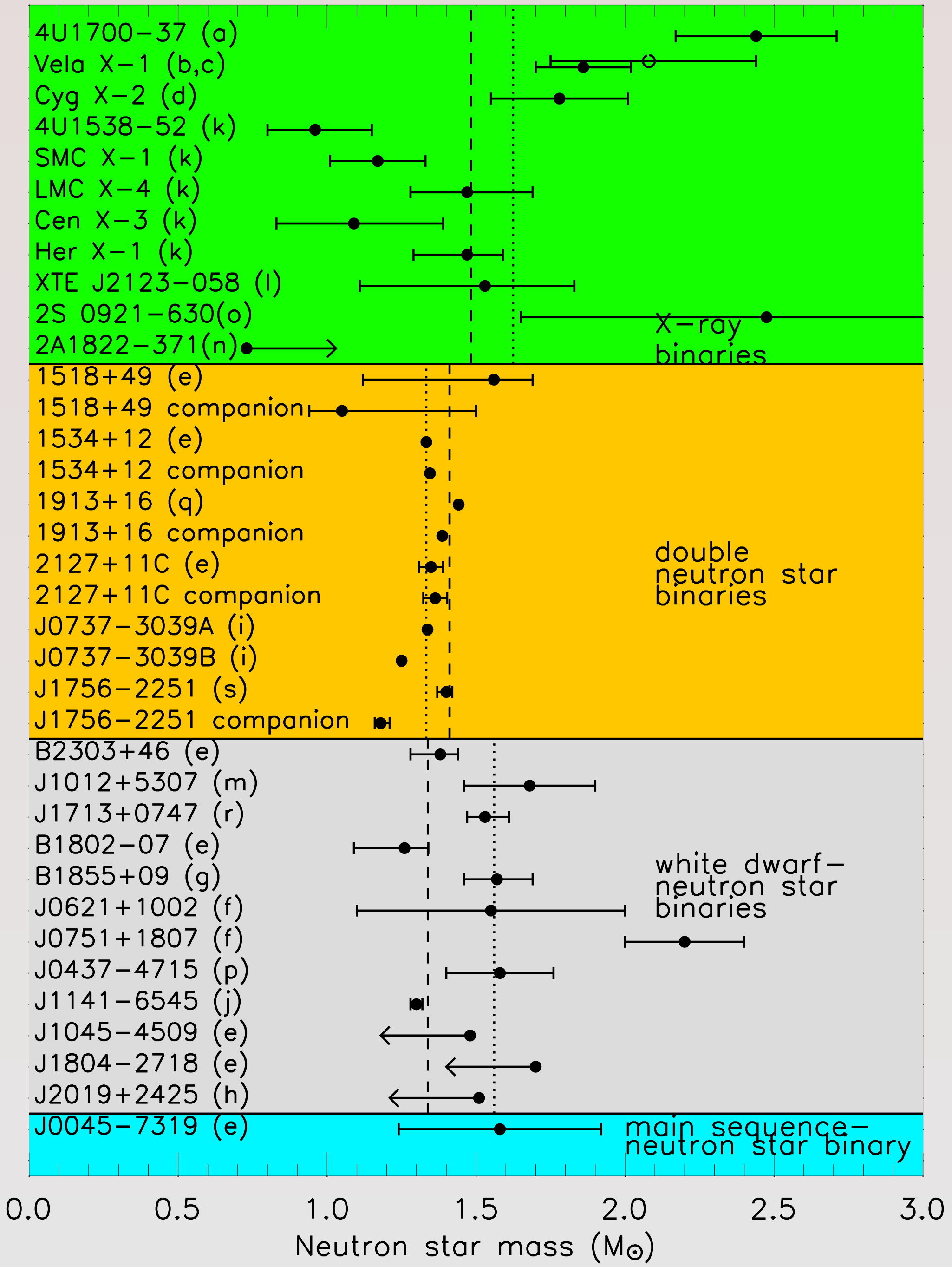


- Early detectors lacked sensitivity to test if SN 1987A ended up as a black hole
- Current & future detectors can do better in the case of a future event

Mass Radius Relationship



Measured Neutron Star Masses



- Mean & weighted means in $M_\odot$
- X-ray binaries: 1.53 & 1.48
- Double NS binaries: 1.34 & 1.41
- WD & NS binaries: 1.58 & 1.34

Moment of inertia (I) measurements

Spin precession periods:

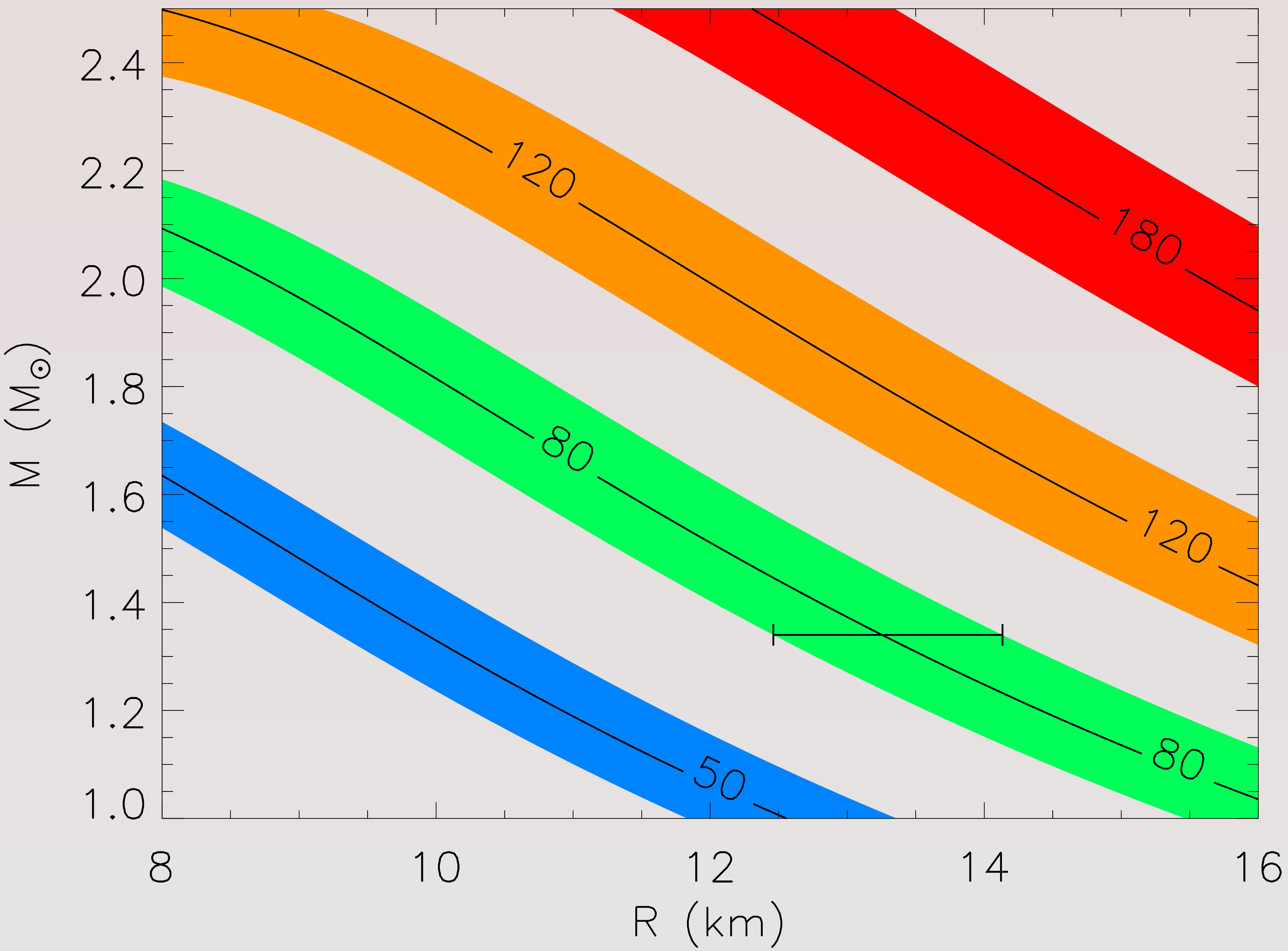
$$P_{p,i} = \frac{2c^2 aPM(1-e^2)}{GM_{-i}(4M_i + 3M_{-i})}$$

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

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

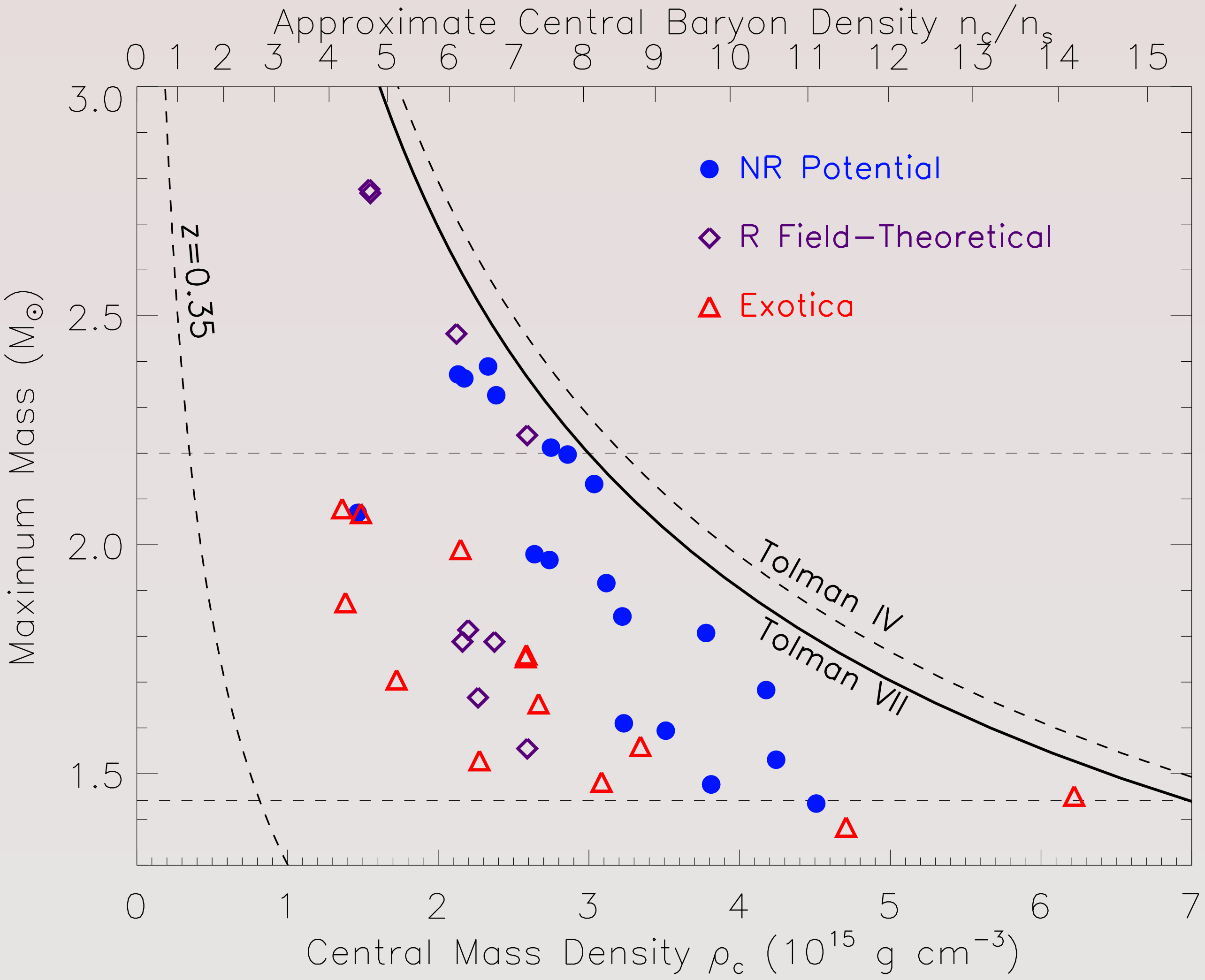
P: Orbital period a: Orbital separation e: Eccentricity
$M = M_1 + M_2$: Total mass
i: Orbital inclination angle θ_A: Angle between $\mathbf{S}_A$ and $\mathbf{L}$.
I_A: Moment of Inertia of A
For PSR 0707-3039, $\delta t_A \simeq (0.17 \pm 0.16) I_{A,80}\ \mu$s ;
Needs improved technology & is being pursued.

Limits on R from M & I measurements



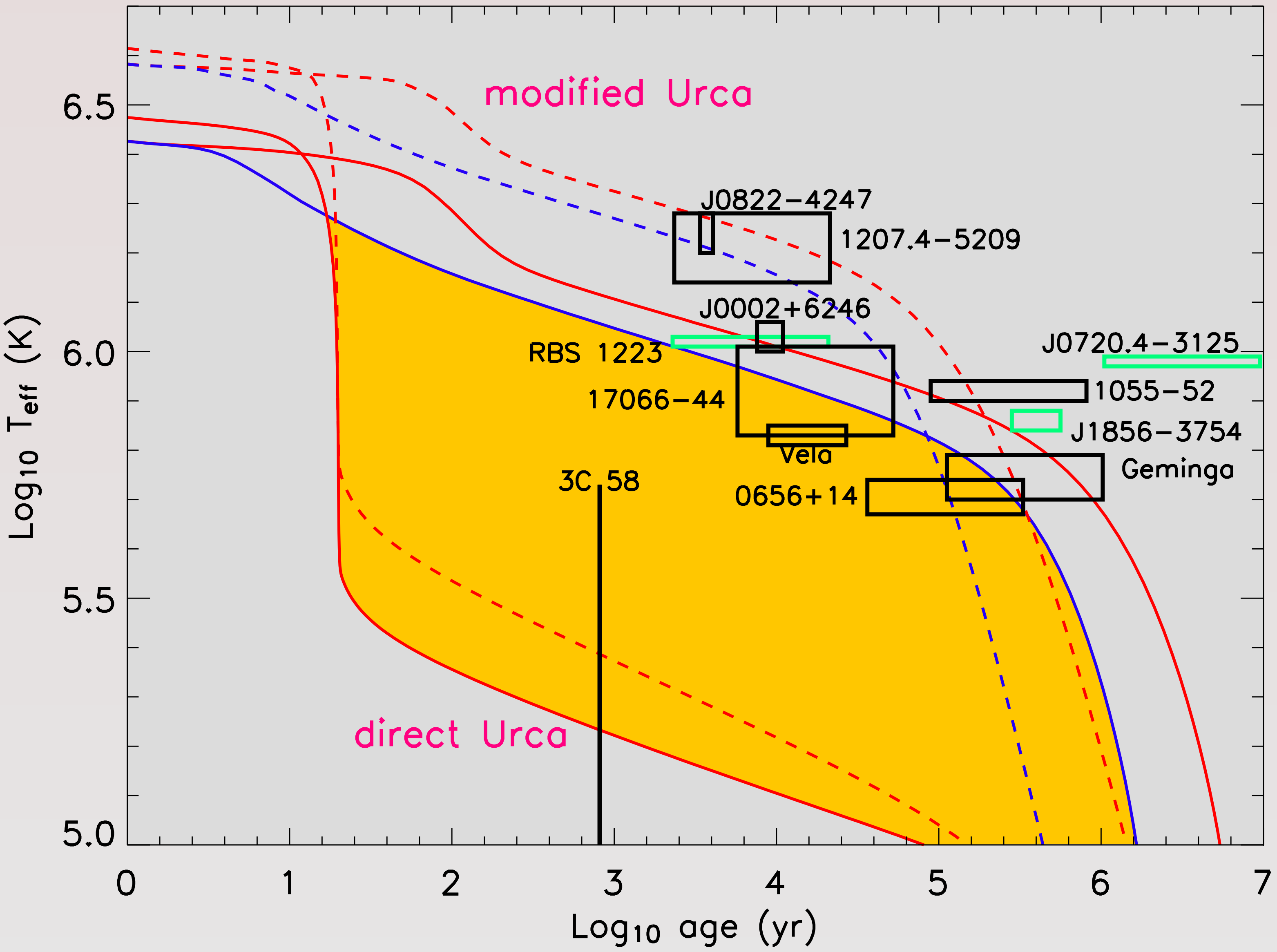
- 10% error bands on I in $\mathrm{M}_\odot$ km^2
- Horizontal error bar for $M = 1.34\ \mathrm{M}_\odot$ & $I = 80 \pm 8\ \mathrm{M}_\odot\ \mathrm{km}^2$

Ultimate Energy Density of Cold Matter



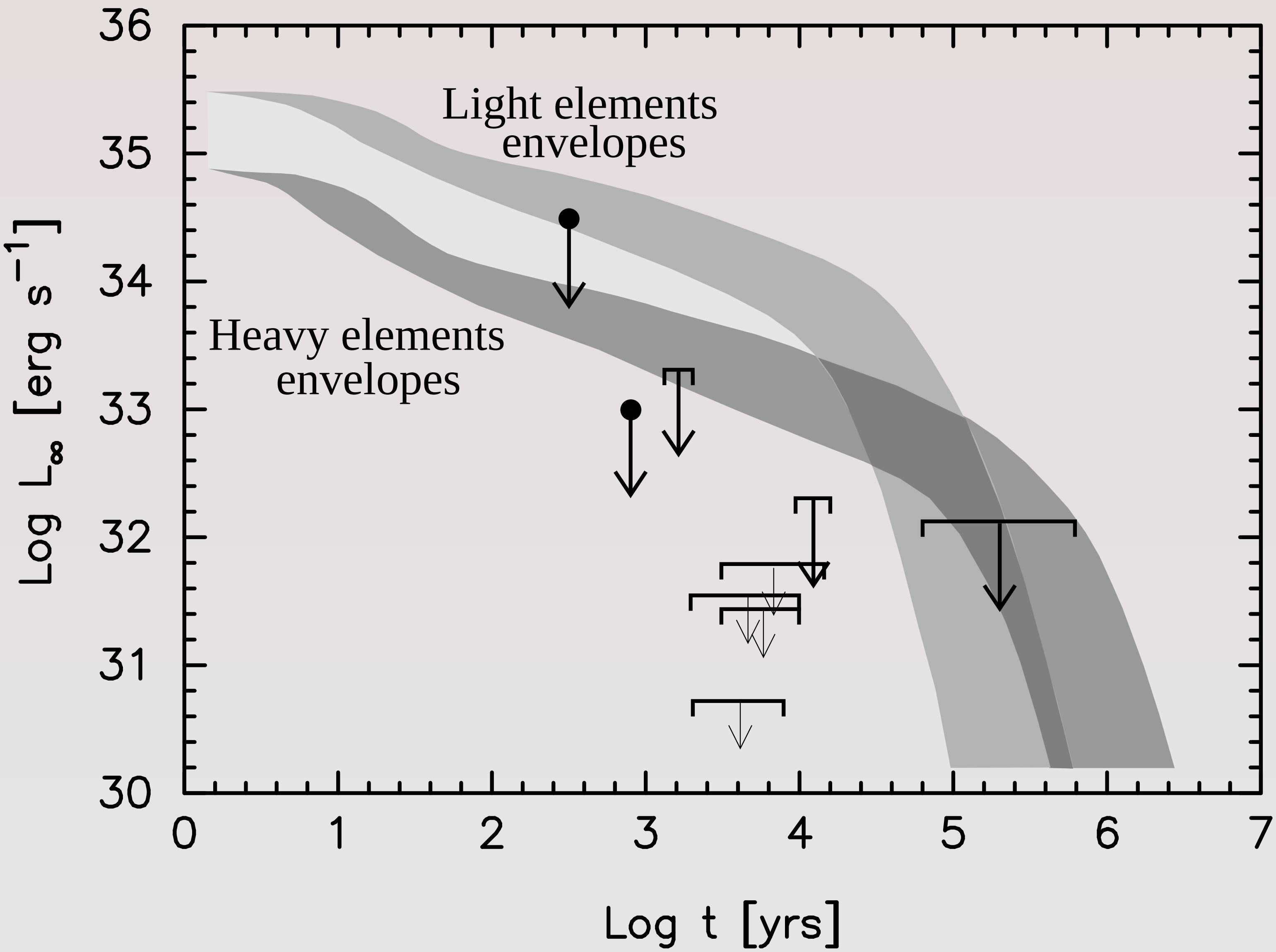
- **Tolman VII:** $\rho = \rho_c(1-(r/R)^2)$ $\rho_c \propto (M_\odot/M)^2$
- **Redshift bound:** $\rho_c > 1.7 \times 10^{15}$ $(M_\odot/M)^2$ g cm^{-3}
- **Crucial to establish an upper limit to** M_{max}

Inferred Surface Temperatures

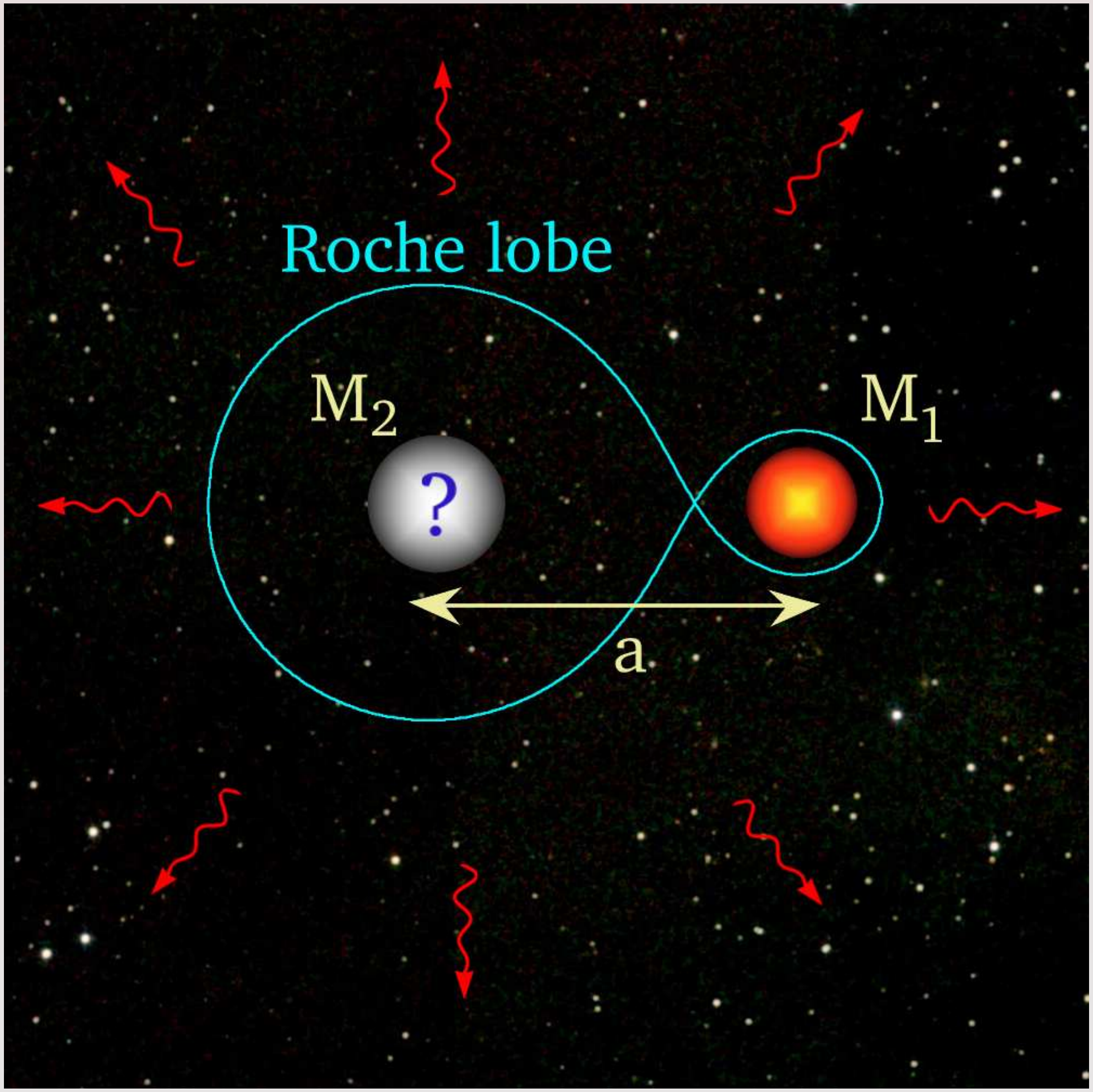


New Cold Objects

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



The Binary Merger Experience



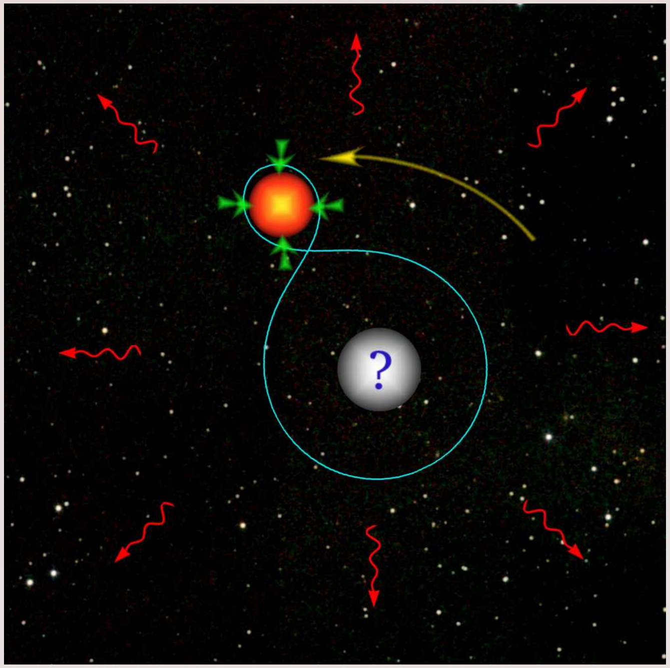
- $M_1 \leq M_2$
- radial separation: $a(t)$
- M_1 - NS or SQM
- M_2 - BH, NS, …
- GW emission ⇒

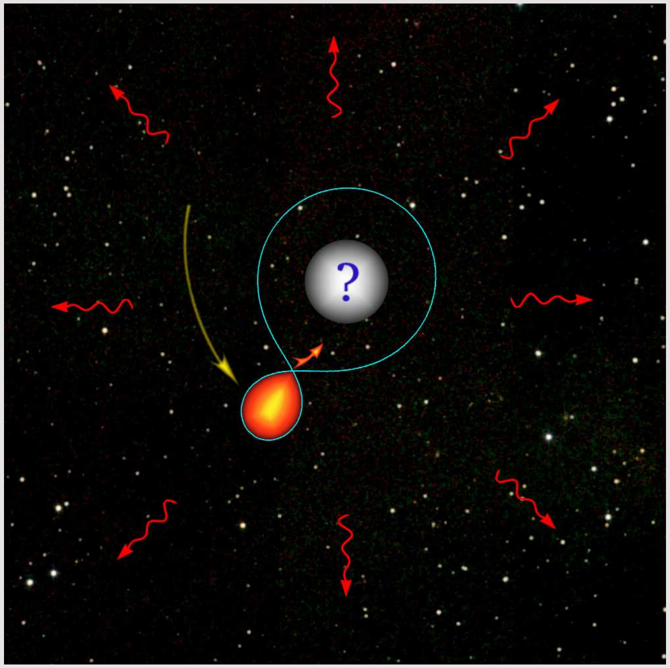
$$L_{GW} = \frac{1}{5}\frac{G}{c^5}\langle \dddot{I\!\!\!-}_{jk}\dddot{I\!\!\!-}_{jk}\rangle = \frac{32}{5}\frac{G^4}{c^5}\frac{M^3\mu^2}{a^6}$$

orbit shrinks

- Mass transfer
- To merge or not to merge?

Roche Lobe Overflow





- Energy Loss

$$L_{GW} = \frac{1}{5}\langle \dddot{\not{I}}_{jk}\dddot{\not{I}}_{jk}\rangle = \frac{32}{5}a^4\mu^2\omega^6$$

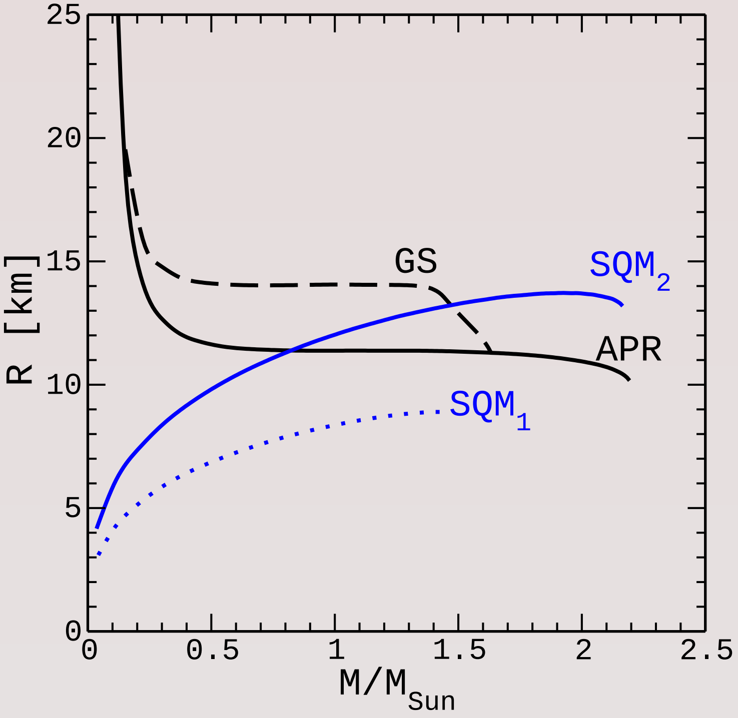
- Angular Momentum Loss

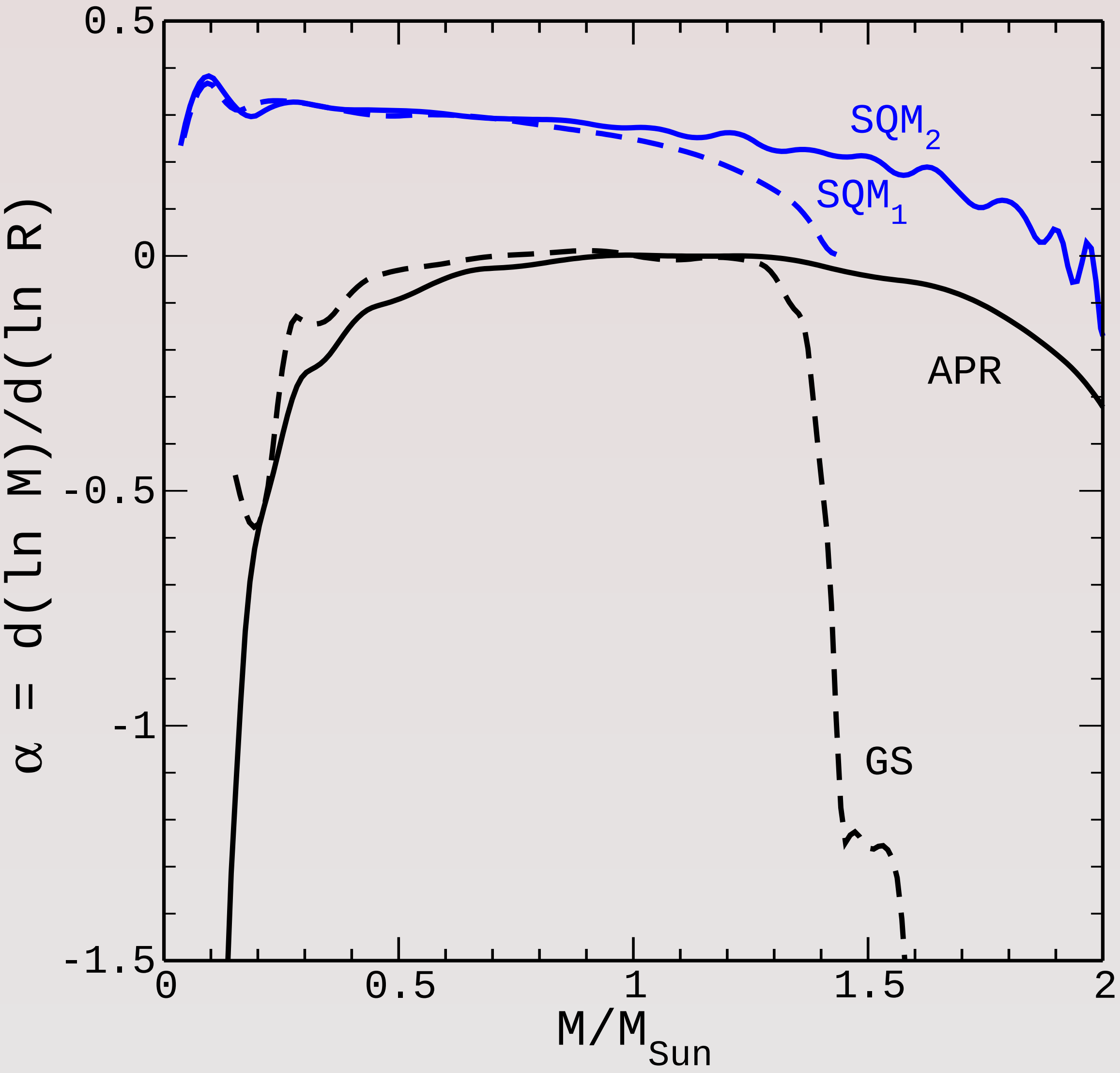
$$\left(\dot{J}_{GW}\right)_i = \frac{2}{5}\epsilon_{ijk}\langle \ddot{\not{I}}_{jm}\dddot{\not{I}}_{km}\rangle = \frac{32}{5}a^4\mu^2\omega^5$$

- $a(t)$ and V_{Roche} shrink!
- $R_1 = r_{Roche}$

  $\Rightarrow$ Mass transfer begins!

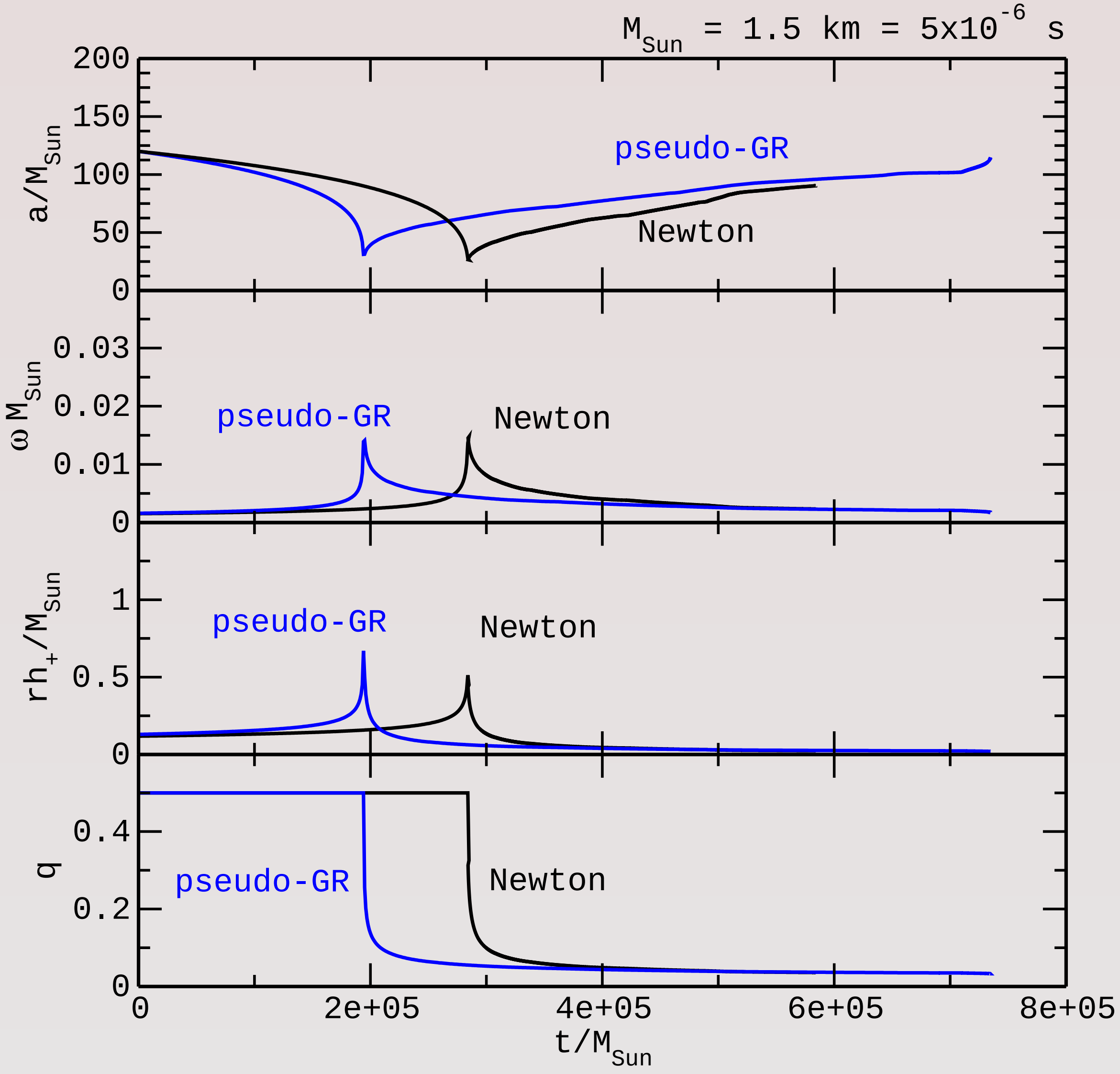
Equation of State: $\alpha(M)$





- $\alpha_{NS} \leq 0$
- $\alpha_{SQM} \geq 0$ $(\approx 1/3)$

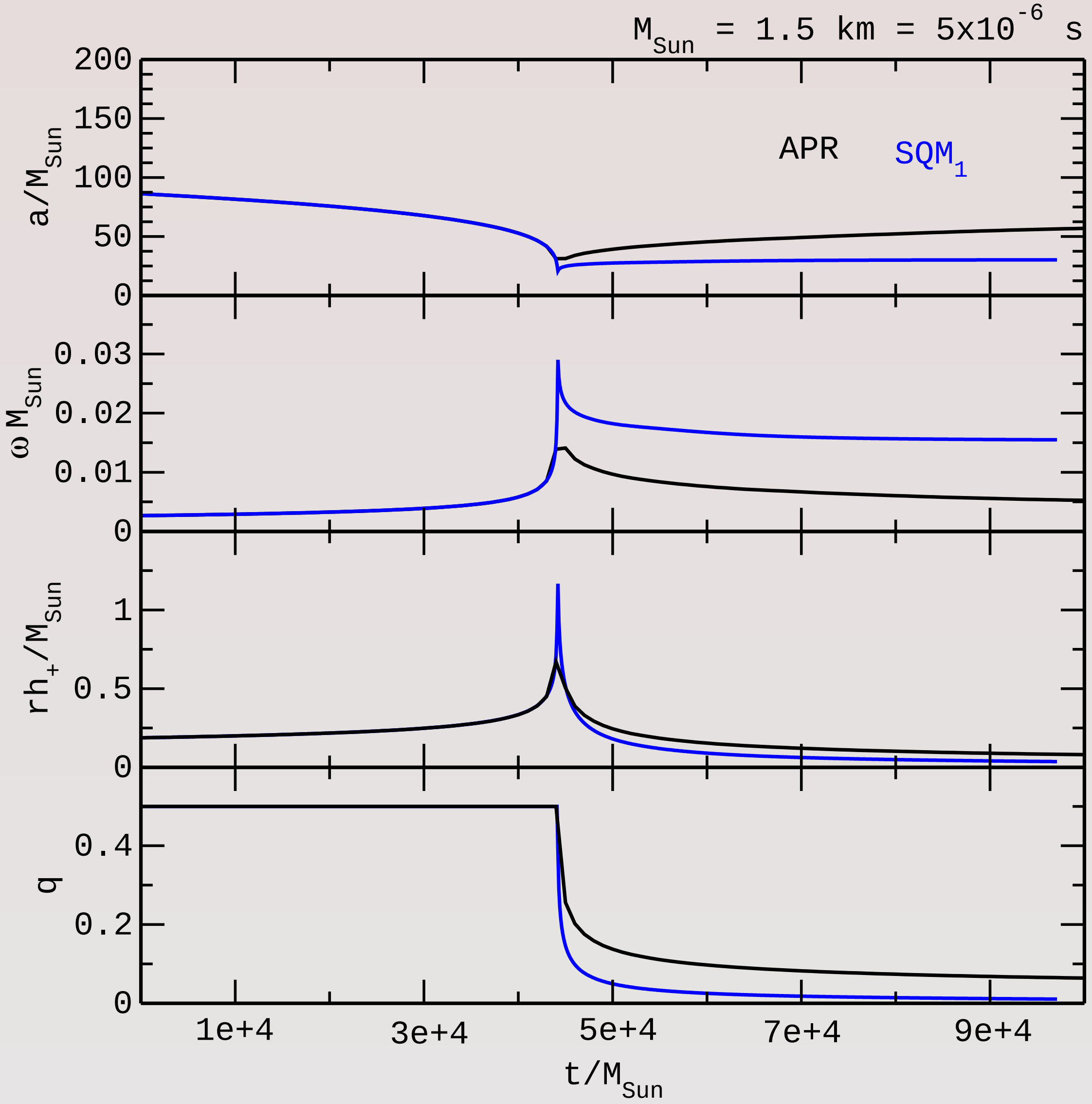
Evolution: Normal Star (APR)



$$h_+ \quad = \quad \frac{4}{r}\,\omega^2\,a^2\,\mu\,\cos(2\omega t)$$

- $M = 4\mathrm{M}_\odot, \quad q_{ini} = 1/3$
- GR speeds up evolution
- $a(t)$ increases after "touchdown"
- $\omega(t)$ stabilizes at long times
- Little variation among EOS's of normal stars.
- M_1 approaches the NS minimum mass; subsequent plunge (timescale $\sim$ a few minutes) yields a second spike in the GW signal!

Evolution: SQM Star



$$h_+ = \frac{4}{r}\,\omega^2\,a^2\,\mu\,\cos(2\omega t)$$

- $M = 4\mathrm{M}_\odot, \quad q_{ini} = 1/3$
- $a(t)$: "hovers" after "touchdown"
- $\omega(t)$: relaxes to $>> \omega_{initial}$
- $h_{+/\times}(t)$ & $q(t)$: exponential decay unlike for a NS
- $M_{1,final} \rightarrow M^{SQM}_{nugget}$ unlike for a normal star; time to tiny $M_{1,final}$ is very long!

Main 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.