Lecture II

Neutron Star Observations

Interpretation and connection to underlying physics

Are neutron stars laboratories for high-density physics ?

- Equation of state $\longrightarrow$ Structure
- Low energy response properties $\longrightarrow$ Thermal Evolution

Building a Neutron Star

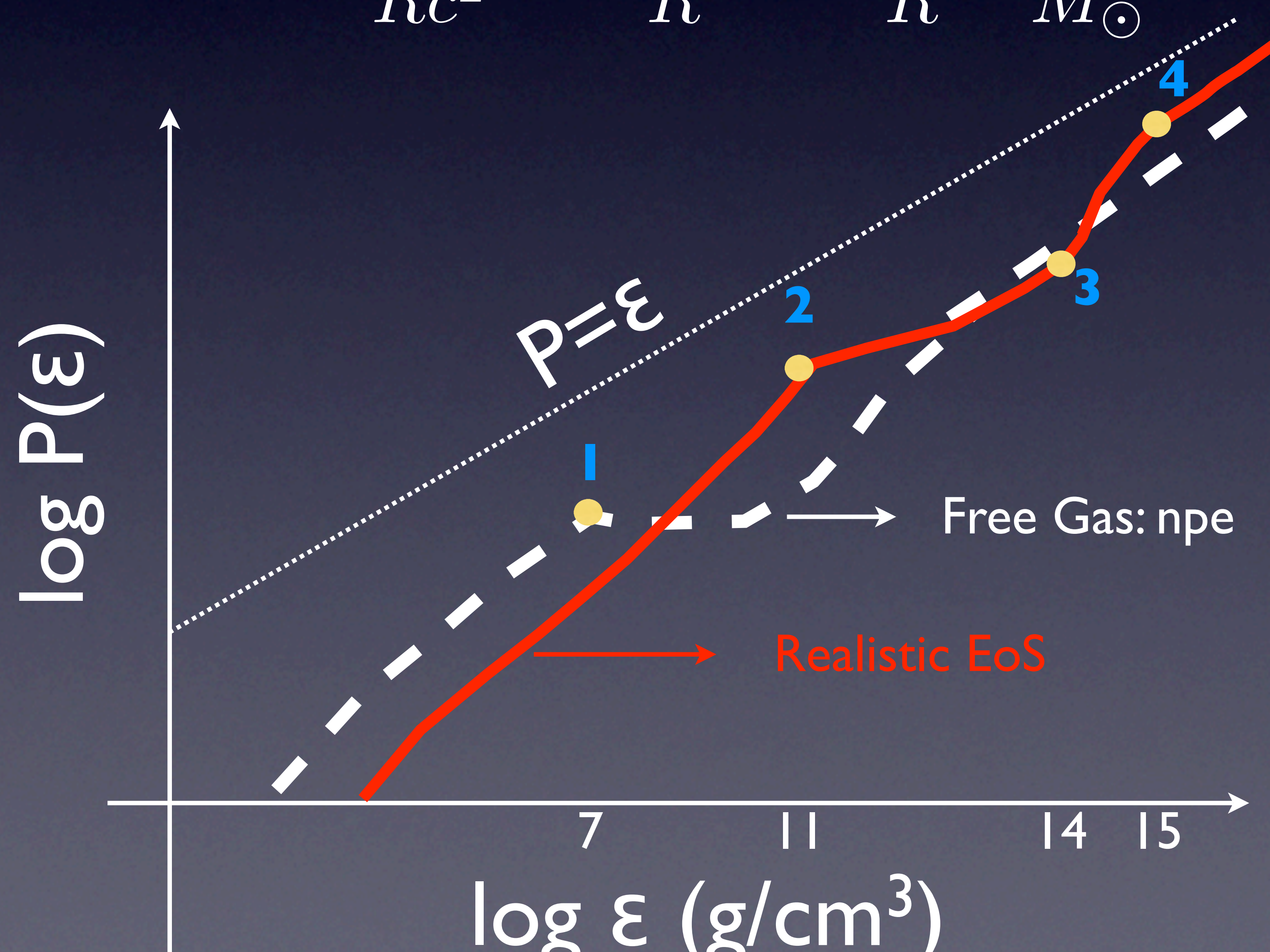
$$\frac{dP}{dr} = -\frac{\tilde{G}\; M(r)(\epsilon(r) + P(r))}{r^2 c^2}\left(1 + \frac{4\pi r^3 P(r)}{M(r)c^2}\right)$$

$$\tilde{G} = \frac{G}{1 - \frac{2GM(r)}{rc^2}}$$

$$P_{\mathrm{central}} \simeq \frac{x}{1 - 3\,x}\,\epsilon_{\mathrm{central}} \qquad x = \frac{2GM}{Rc^2} = \frac{R_S}{R} = \frac{3\ \mathrm{km}}{R}\,\frac{M}{M_\odot}$$

Equation of State:

1. Neutron threshold
2. Neutron drip
3. Nuclear matter
4. Possible phase transition



Pressure of Neutron Matter

(From Lecture 1)

$$E(\rho, x_p) = E_o(\rho, x_p = \frac{1}{2}) + E_{\rm sym}\delta^2 + \cdots$$

$$P(\rho, x_p) \quad = \quad P(\rho, \frac{1}{2}) + \rho\ E_{\rm sym}\ \left[(1 - 2x_p)^2\ \frac{\rho\ E'_{\rm sym}}{E_{\rm sym}} + x_p(1 - 2x_p)\right]$$

$$x_p \quad \simeq \quad 0.04\ \left[\frac{E_{\rm sym}(\rho_o)}{28\ \rm MeV}\right]^3\ \left[1 + \frac{E'_{\rm sym}}{E_{\rm sym}(\rho_o)}\ (\rho - \rho_o)\right]$$

$$E_{\rm sym} = S(\rho) \qquad E'_{\rm sym} = \frac{1}{3}\ \frac{L}{\rho_o}$$

Large pressure implies large proton fraction !

Steiner, Lattimer, Prakash & Ellis (2005)

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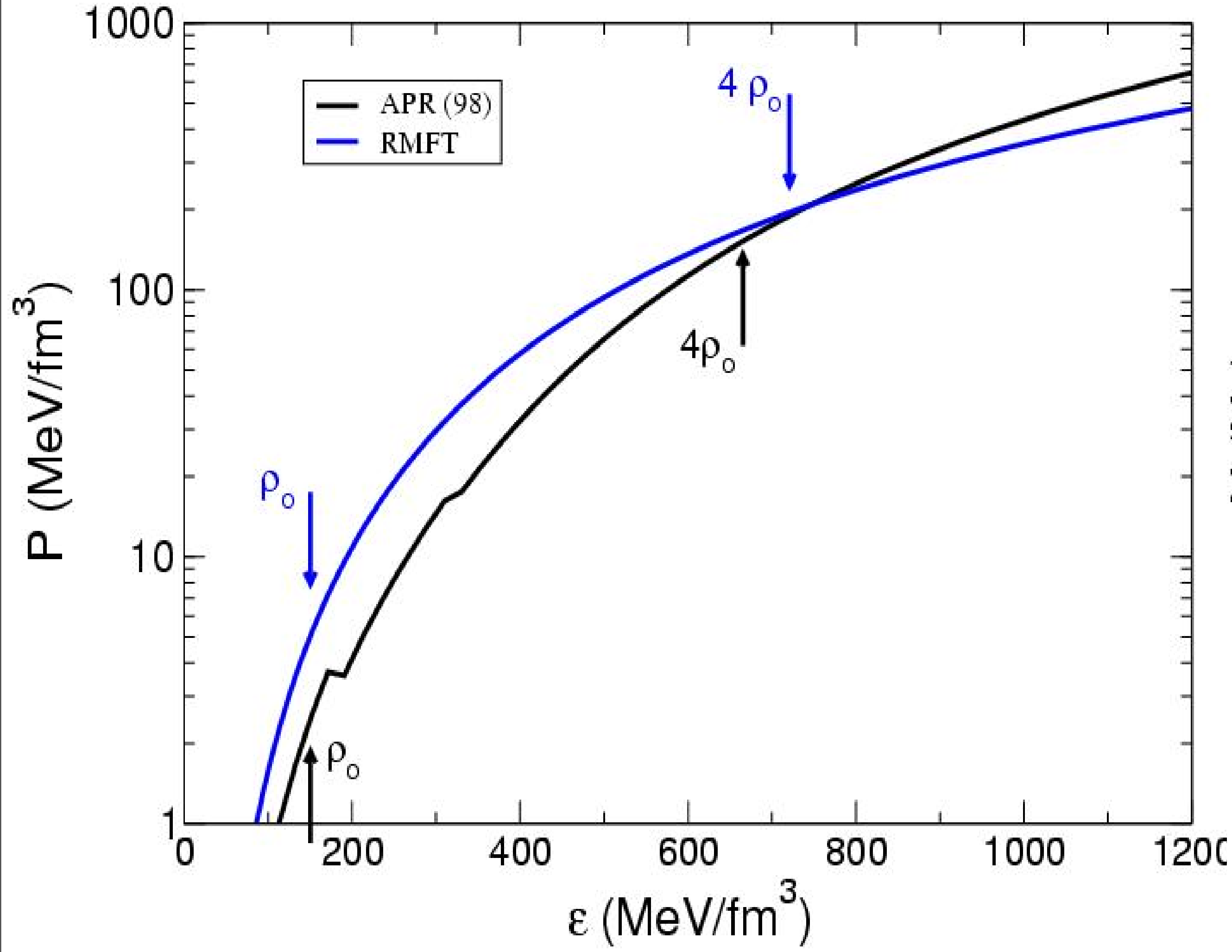
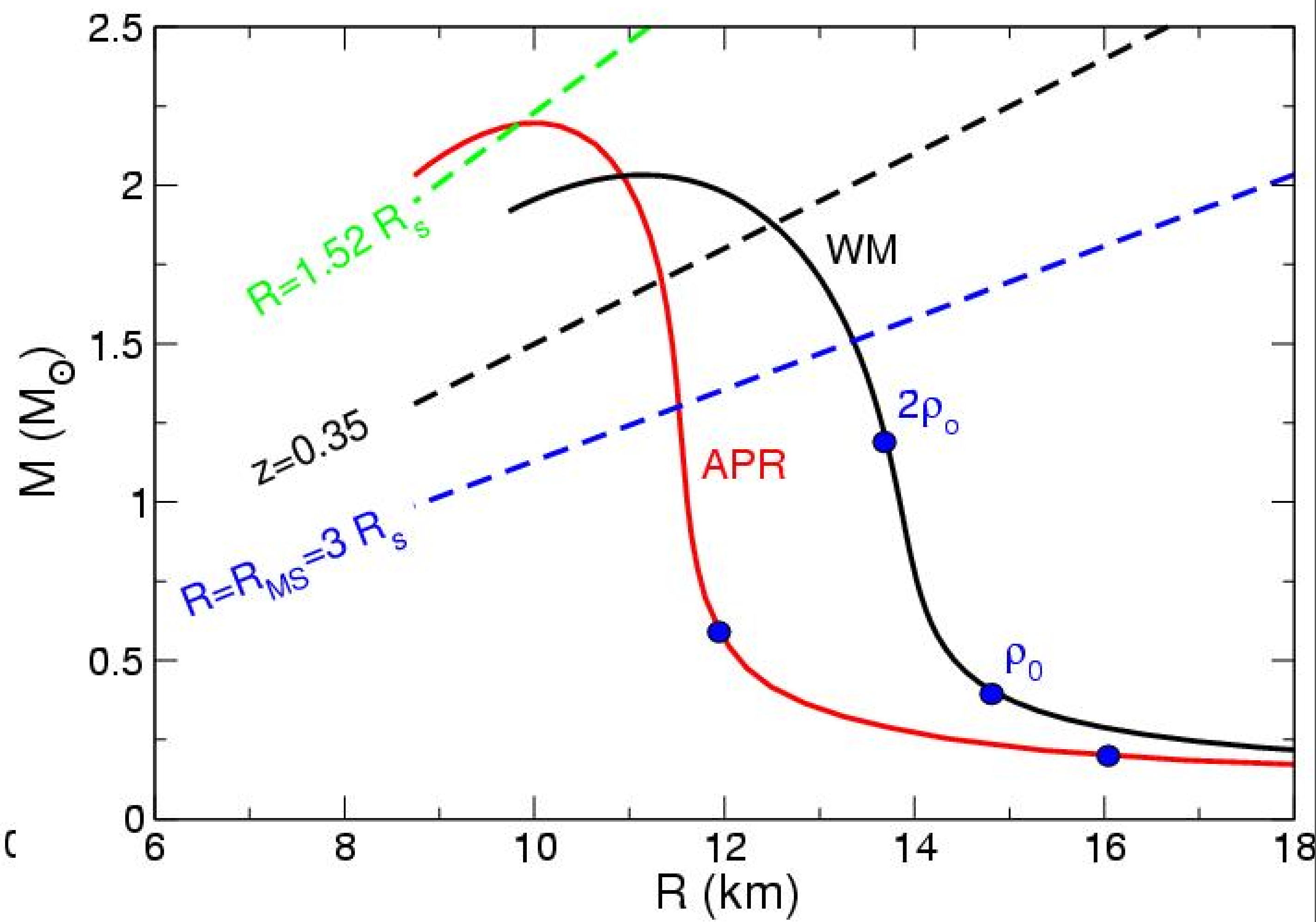
Mass-Radius



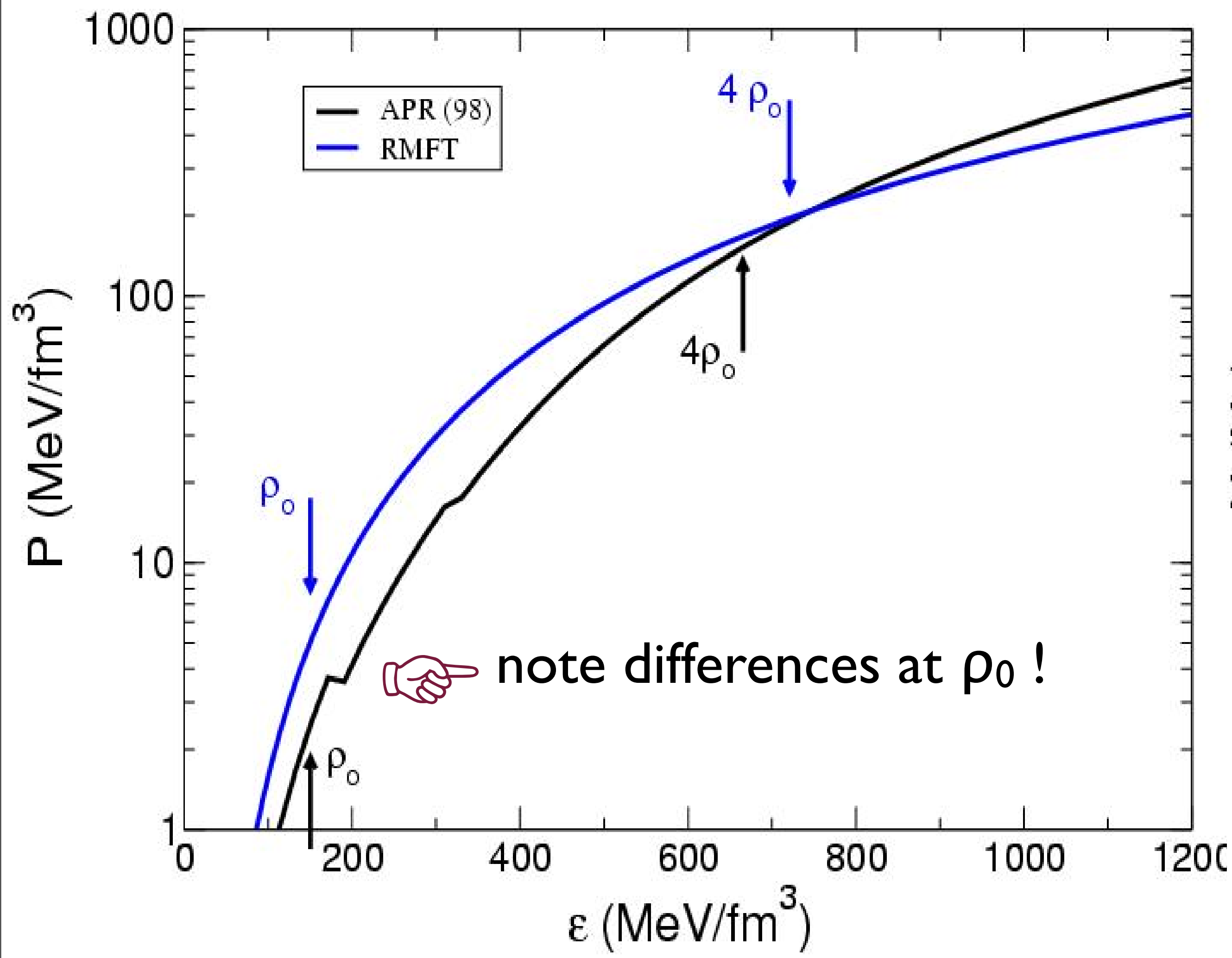


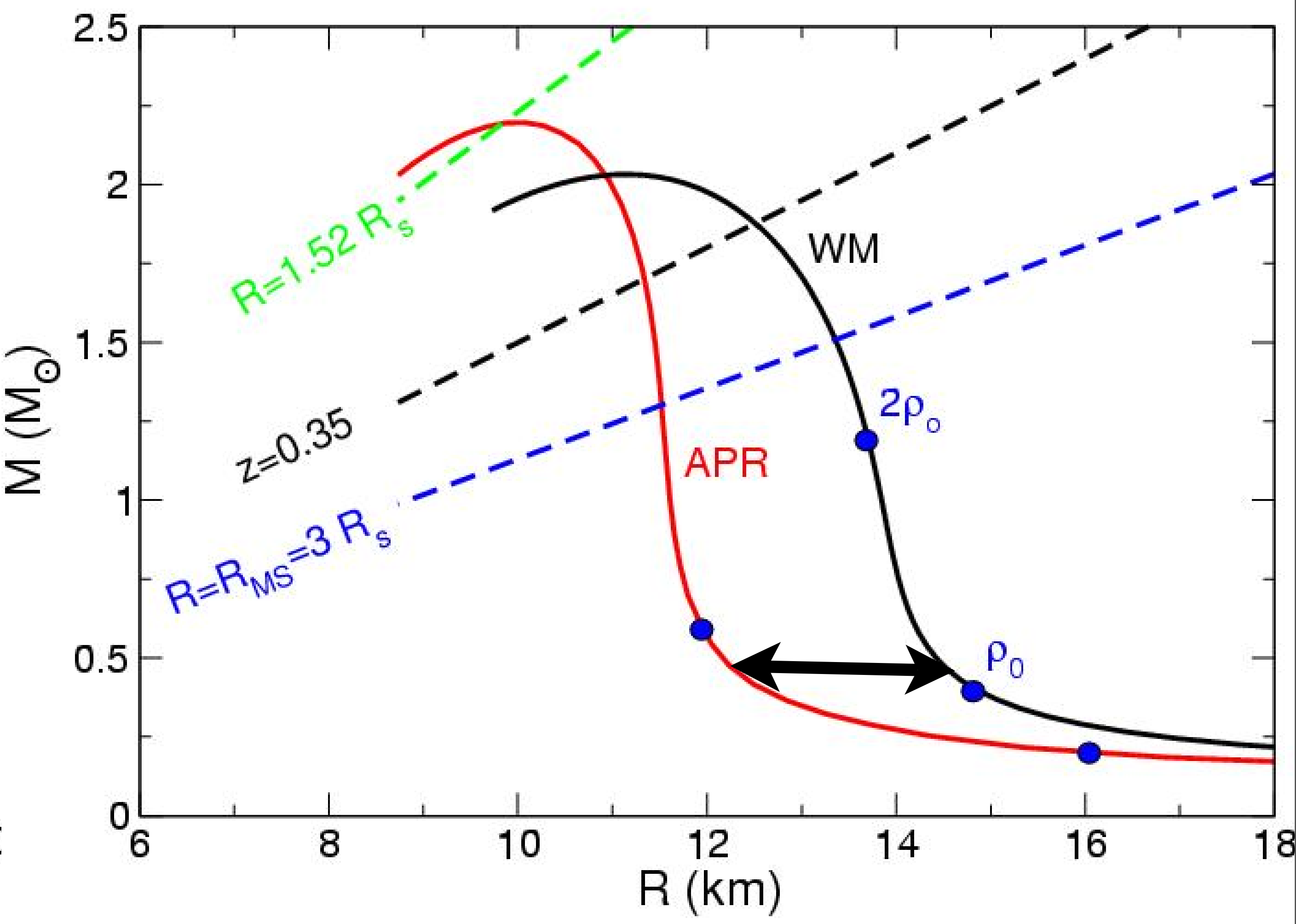
$$\mathrm{M(R)} \leftrightarrow \mathrm{P}(\epsilon)$$

Mass-Radius relation is “unique” to the underlying EoS.

- Soft EoS: low maximum mass and small radii
- Stiff EoS: high maximum mass and large radii

Mass-Radius





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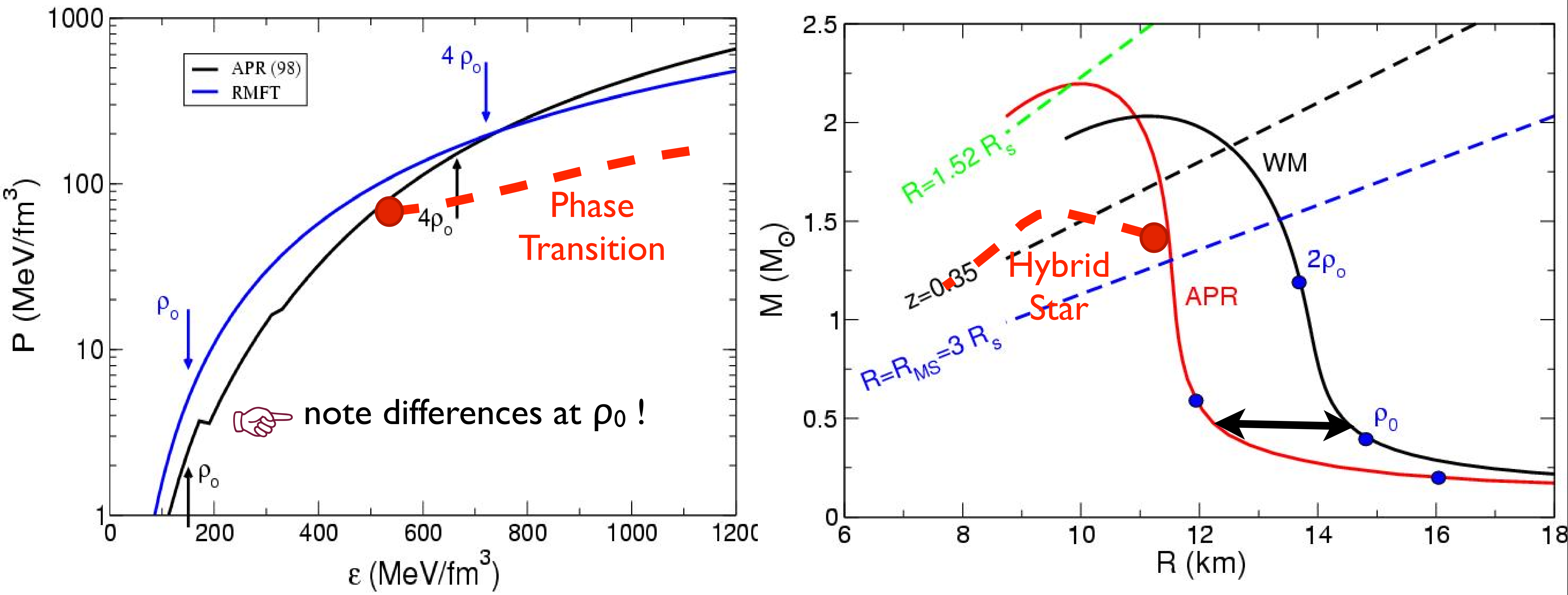

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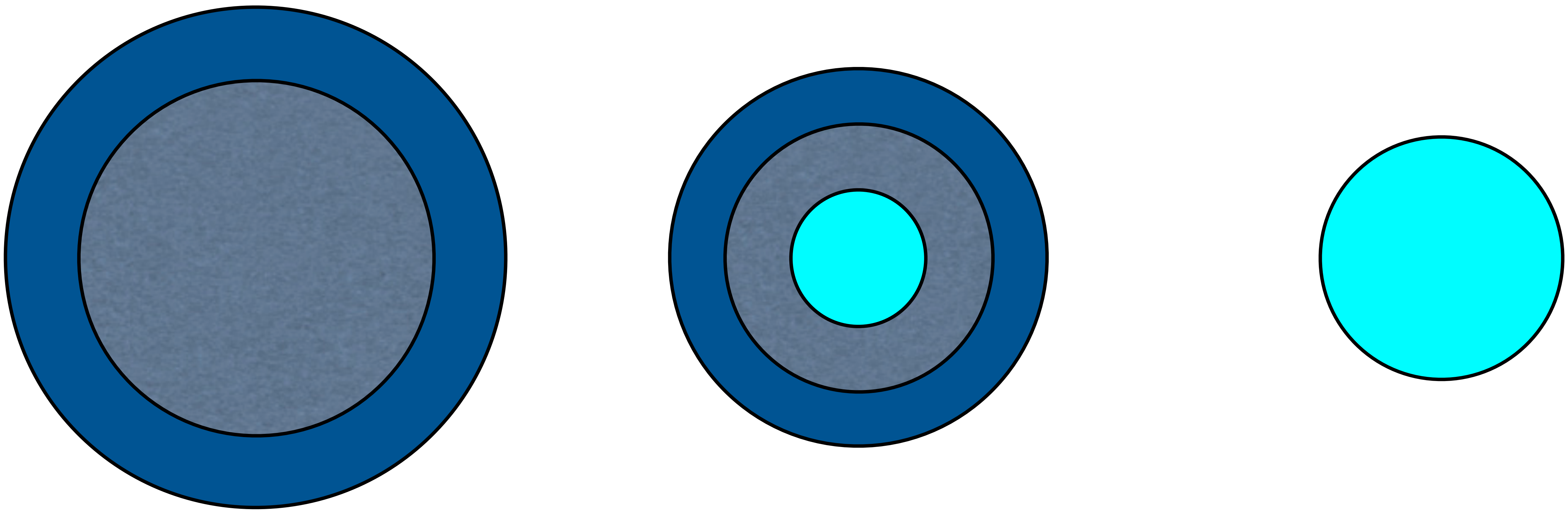
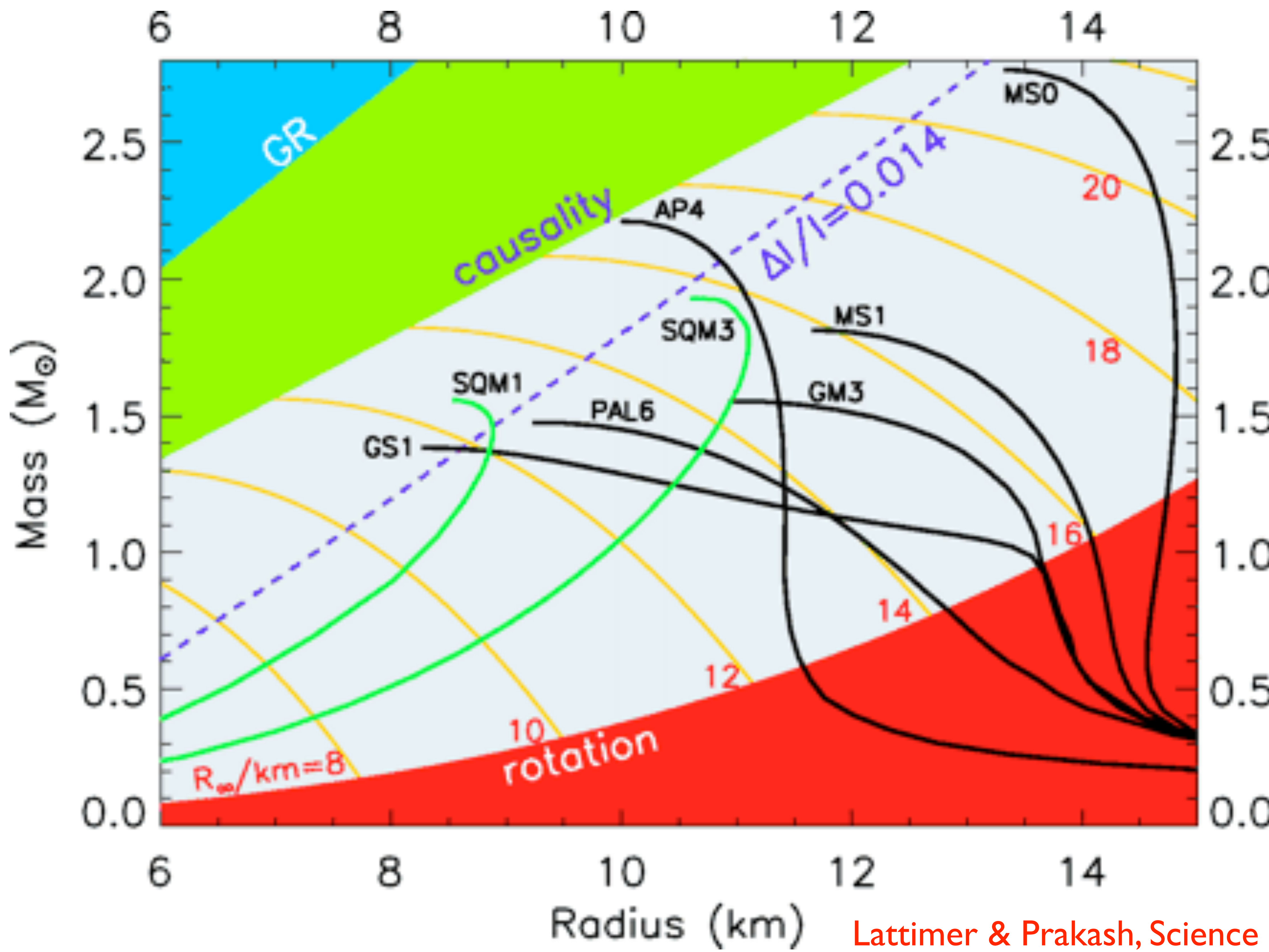
The compact object zoo:

Three Classes:



Nucleon Stars	Hybrid Stars	Strange Stars
$R \cong 11\text{-}15$ km	$R \cong 8\text{-}12$ km	$R \cong$? -12 km
$M \cong 1\text{-}2.5\ M_\odot$	$M \cong 1\text{-}2\ M_\odot$	$M \cong$?-2.5 $M_\odot$

The compact object zoo:



Lattimer & Prakash, Science 2004

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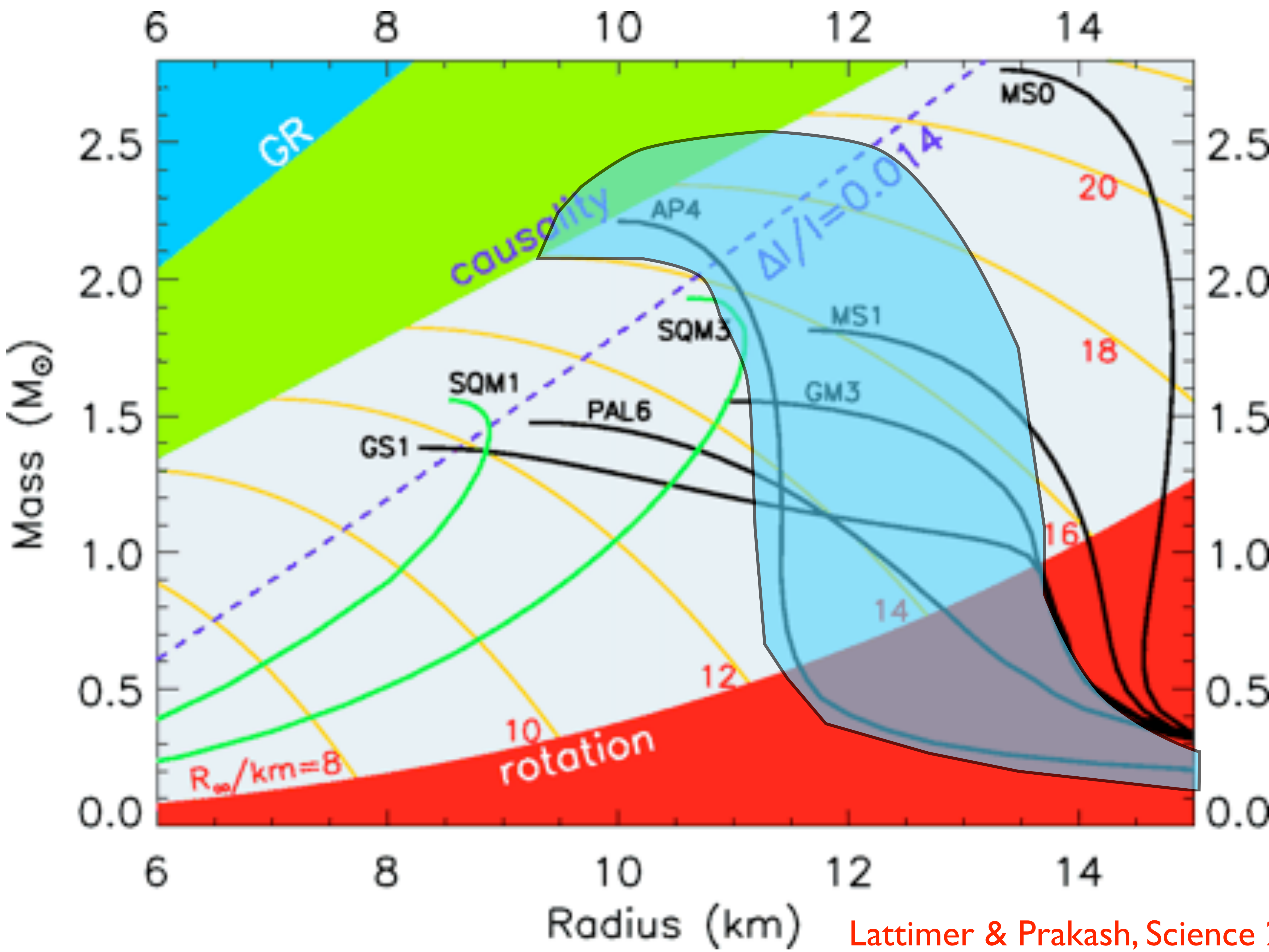

Lattimer & Prakash, Science 2004

Neutron Star Masses

What is the origin of the clustering ?

Massive neutron stars provide a very useful constraint on the high density EoS.

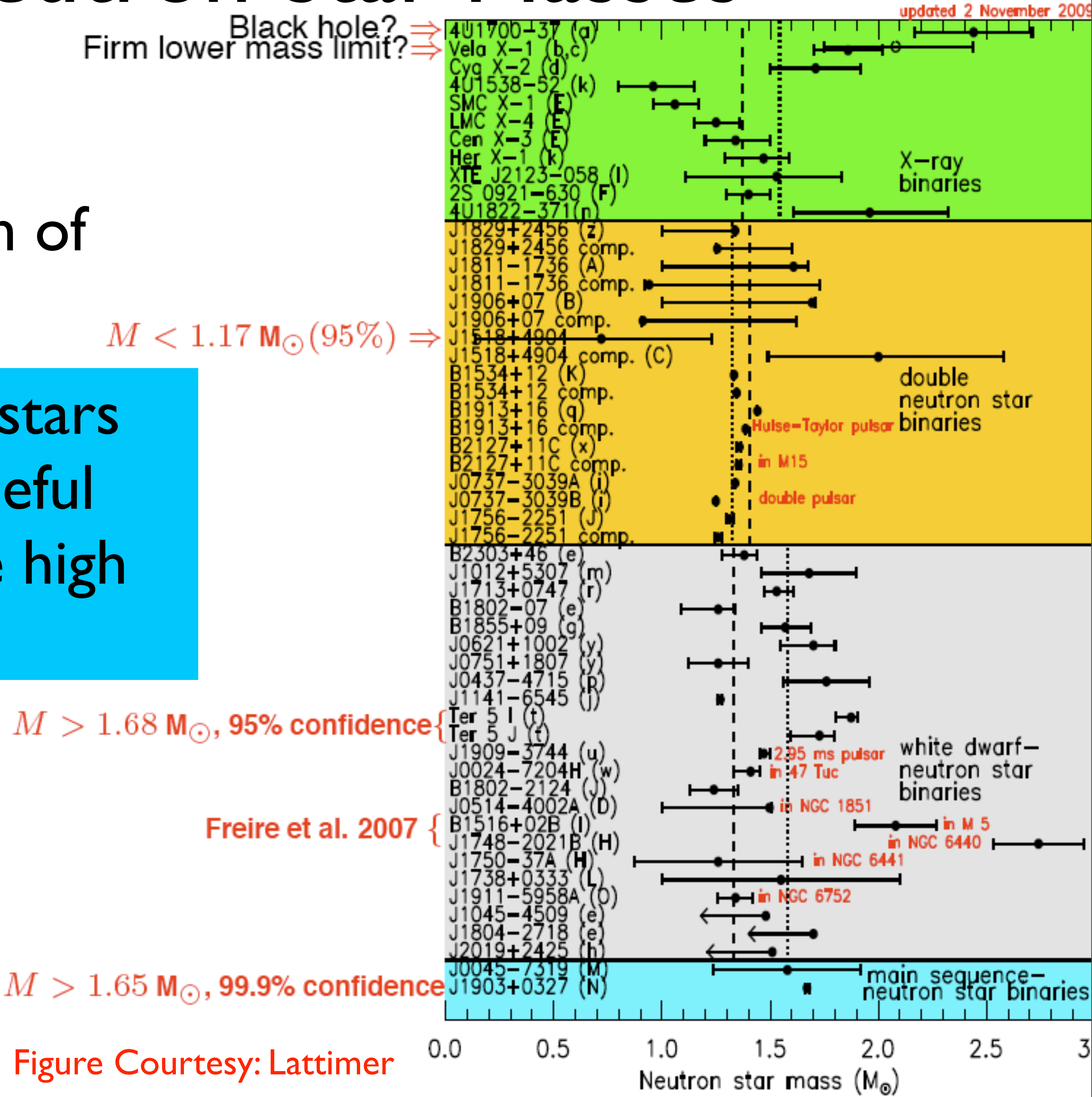

Figure Courtesy: Lattimer

Radius

For a black body the observed flux :

$$F_{\mathrm{BB}} = 4\pi \, \frac{R_\infty^2}{d^2} \, \sigma_{SB} \, T_\infty^4$$

$$R_\infty = \frac{R}{\sqrt{1 - R_S/R}}$$

$$T_\infty = \sqrt{1 - R_S/R} \quad T$$

For NSs: Atmosphere and magnetic fields can affect the spectra

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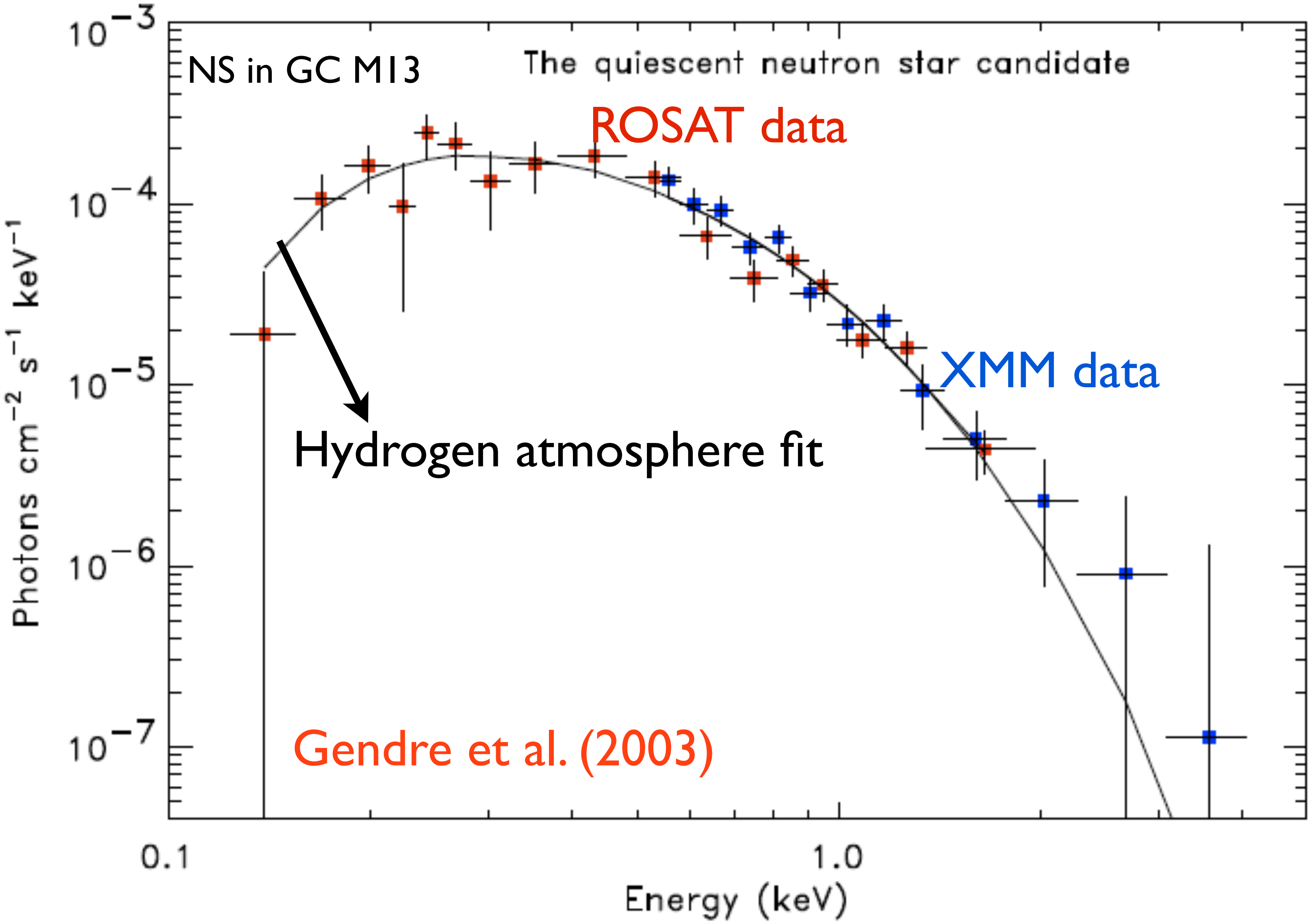
For NSs: Atmosphere and magnetic fields can affect the spectra

For a non-magnetized hydrogen atmosphere:

Spectra is easily modeled - Can extract R_∞



Quiescent NSs in LMXB

Transiently accreting neutron stars in globular clusters:

1. Hydrogen atmosphere
2. Negligible Magnetic Fields
3. Distances are known

Rutledge et al. (2004)

NS	R_∞	Ref.
ω Cen	13.6± 0.3	Gendre et al. (2002)
M13	12.6± 0.4	Gendre et al. (2002)
X7*	14.5+1.6-1.4	Heinke et al. (2005)
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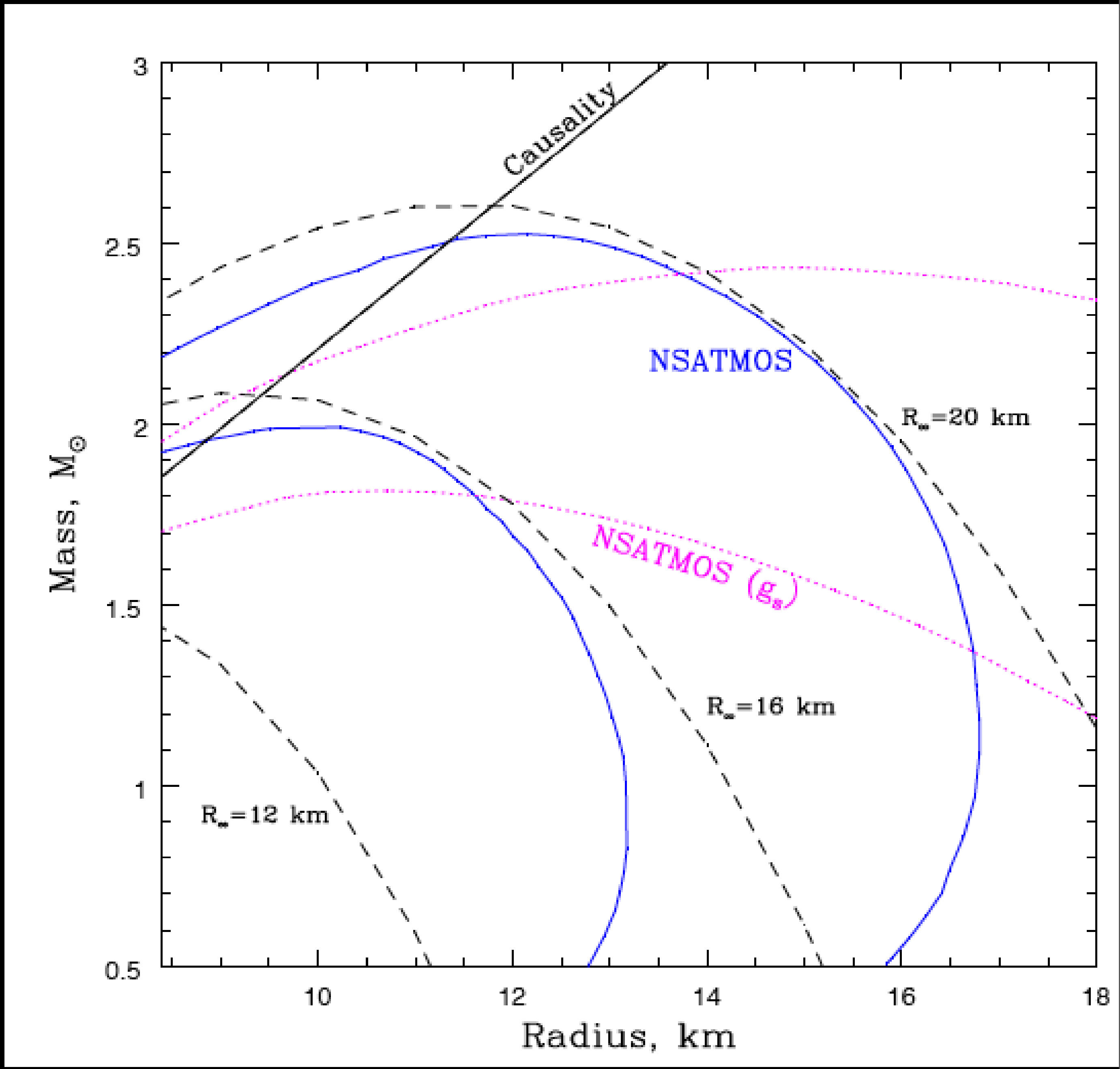

3 more found in GC : NGC 6304

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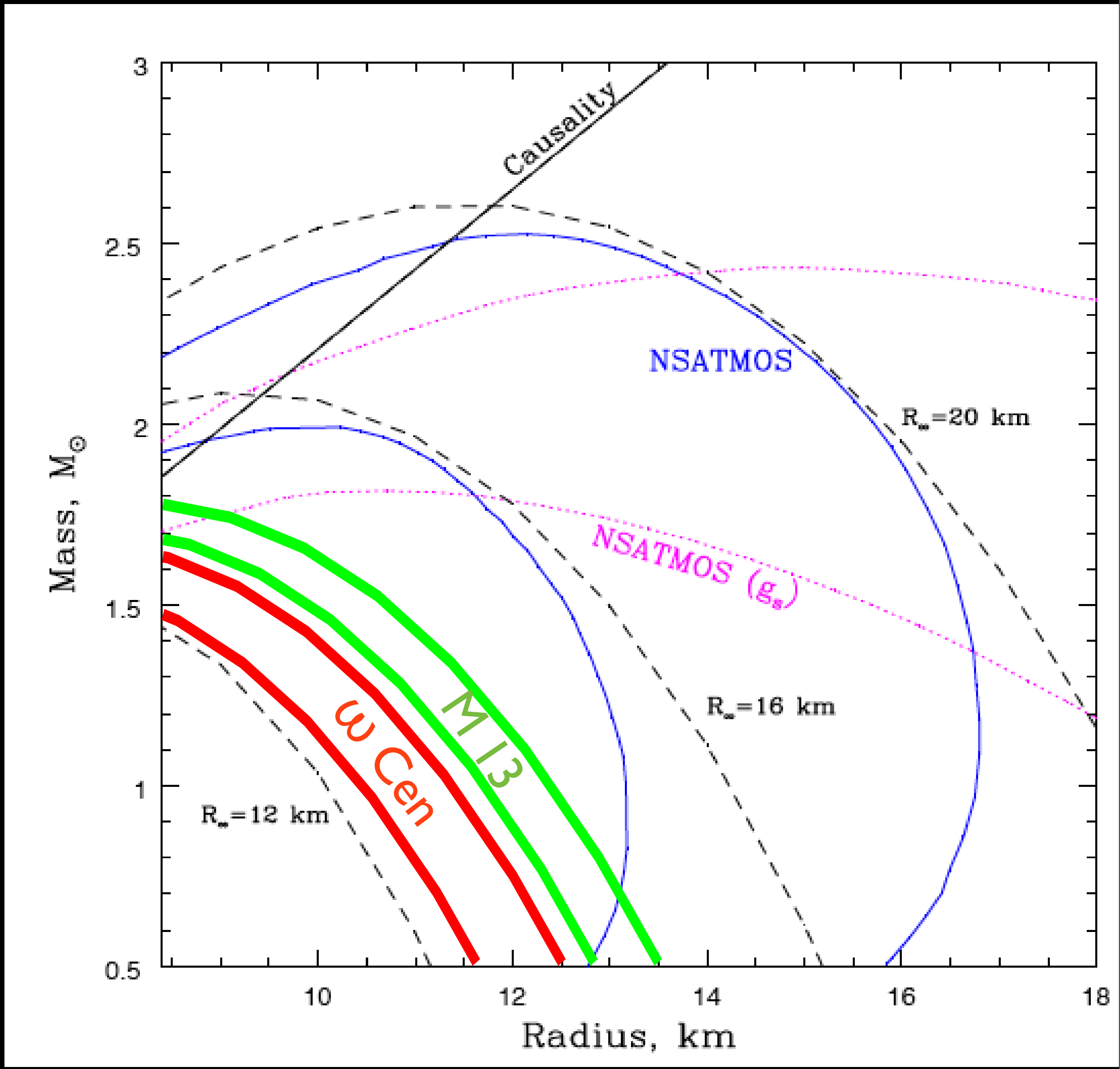

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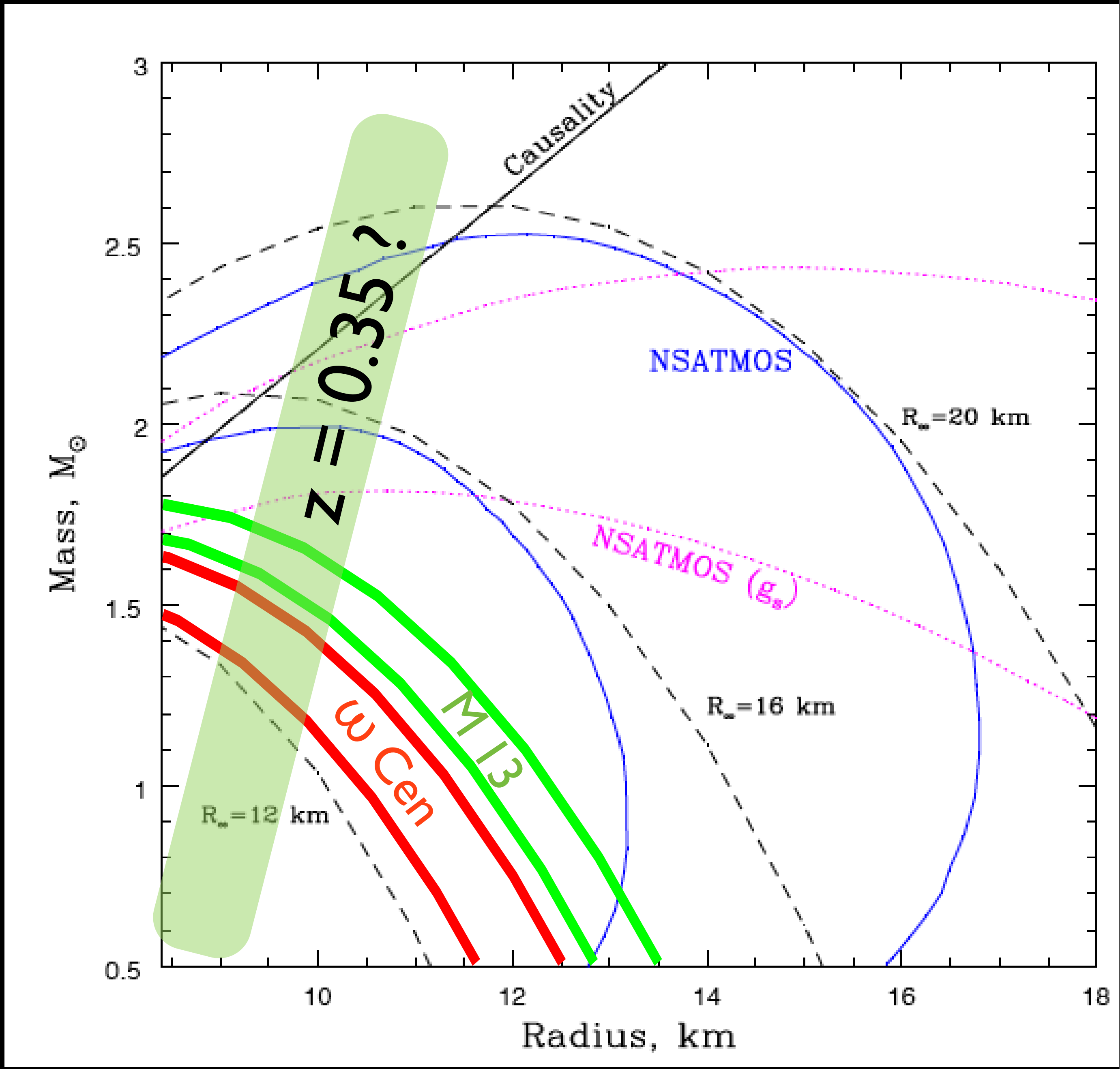

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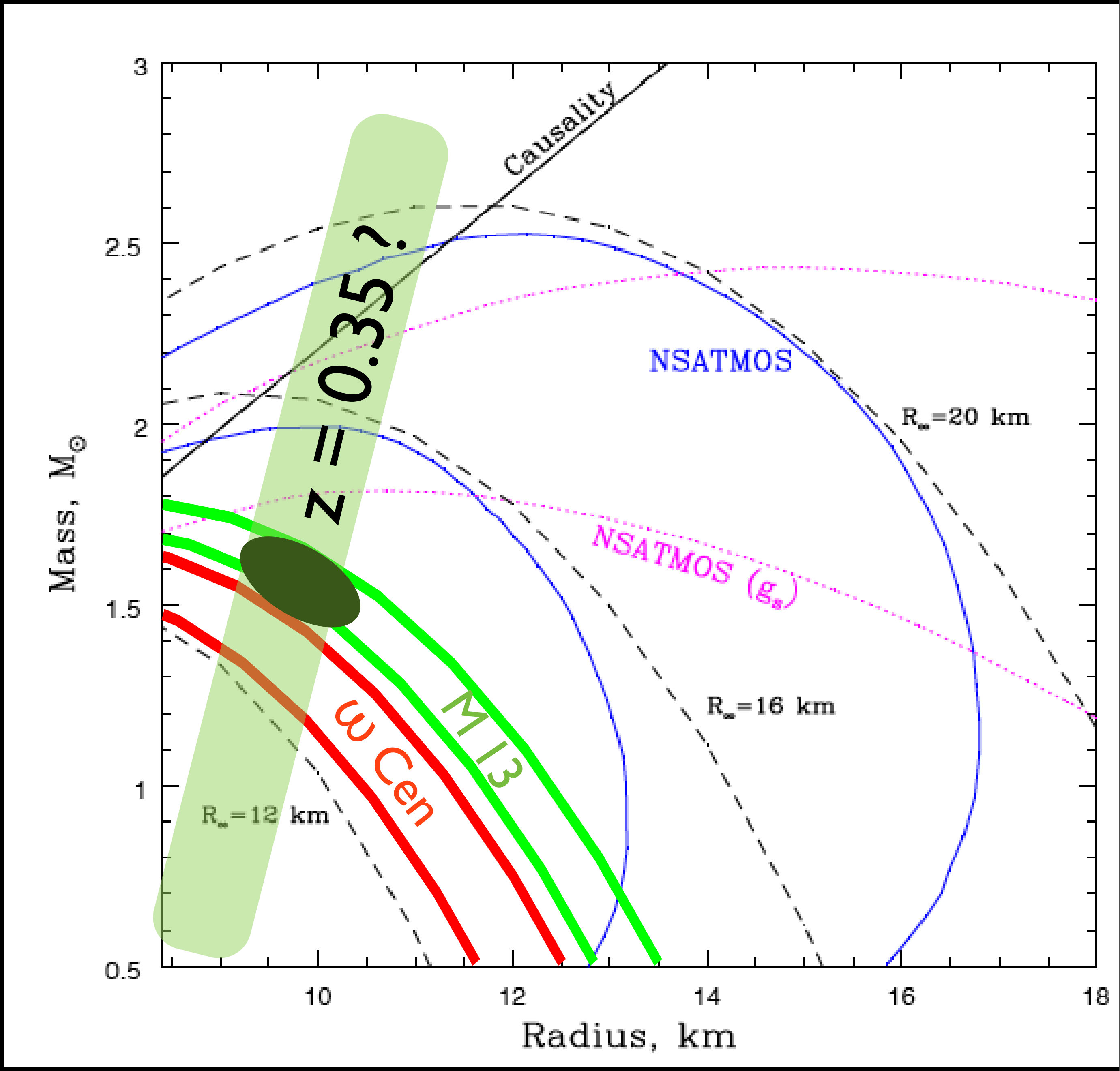

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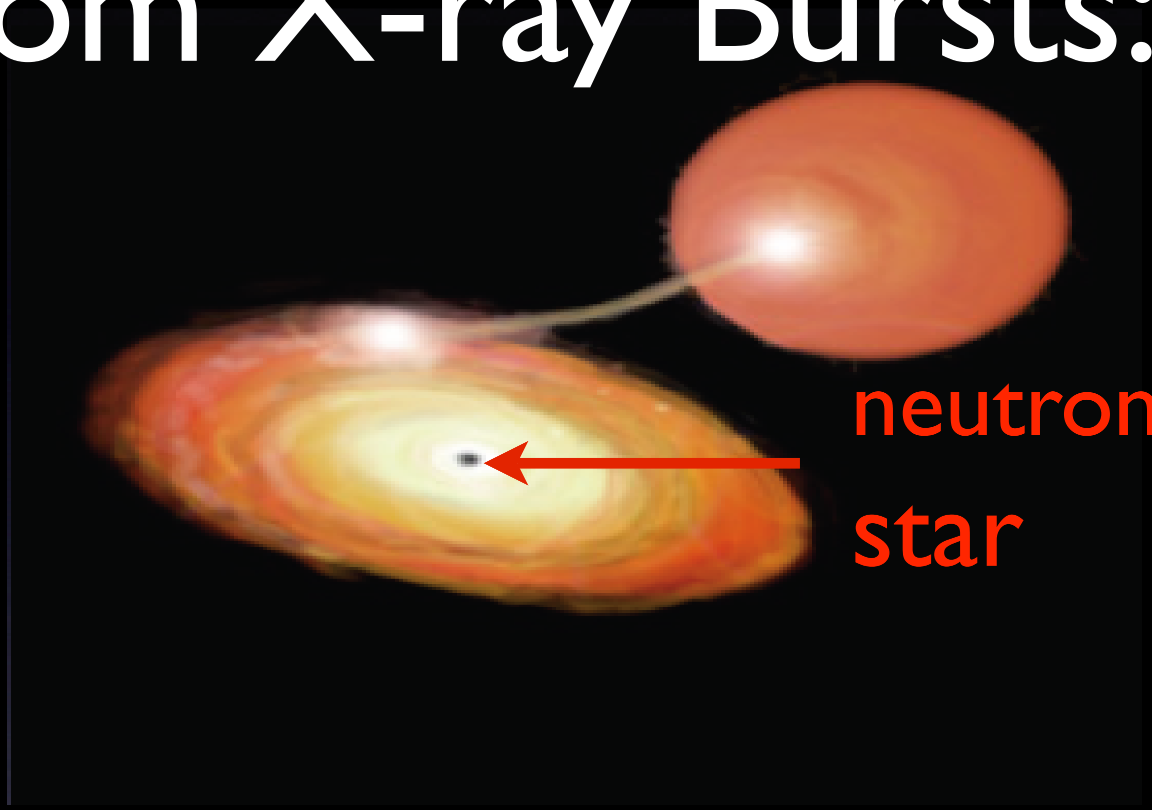
Mass and Radius from X-ray Bursts:

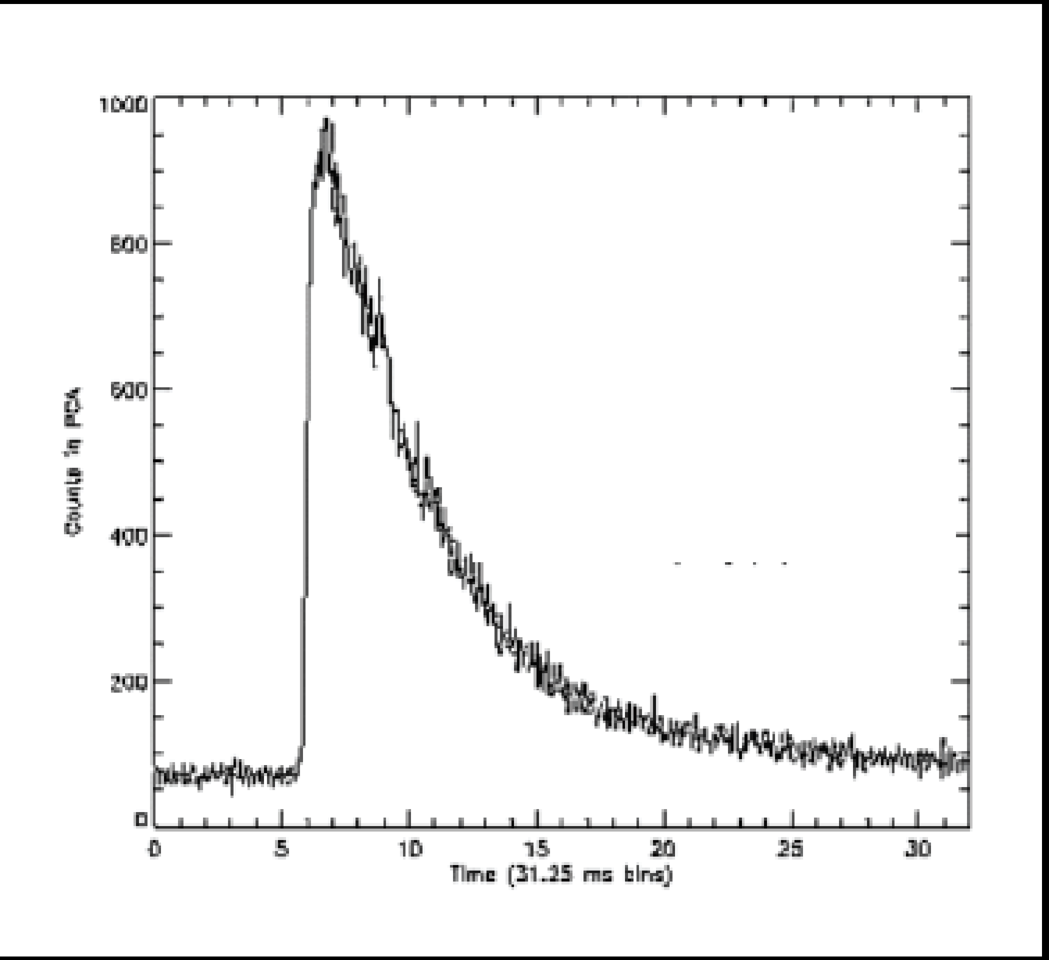
Unstable burning of accreted material produces x-ray bursts



•Most common cosmic explosion in the universe.

•Light curve powered by nuclear reactions (rp -process).

•Features in the light curve are be sensitive to Mass and Radius.



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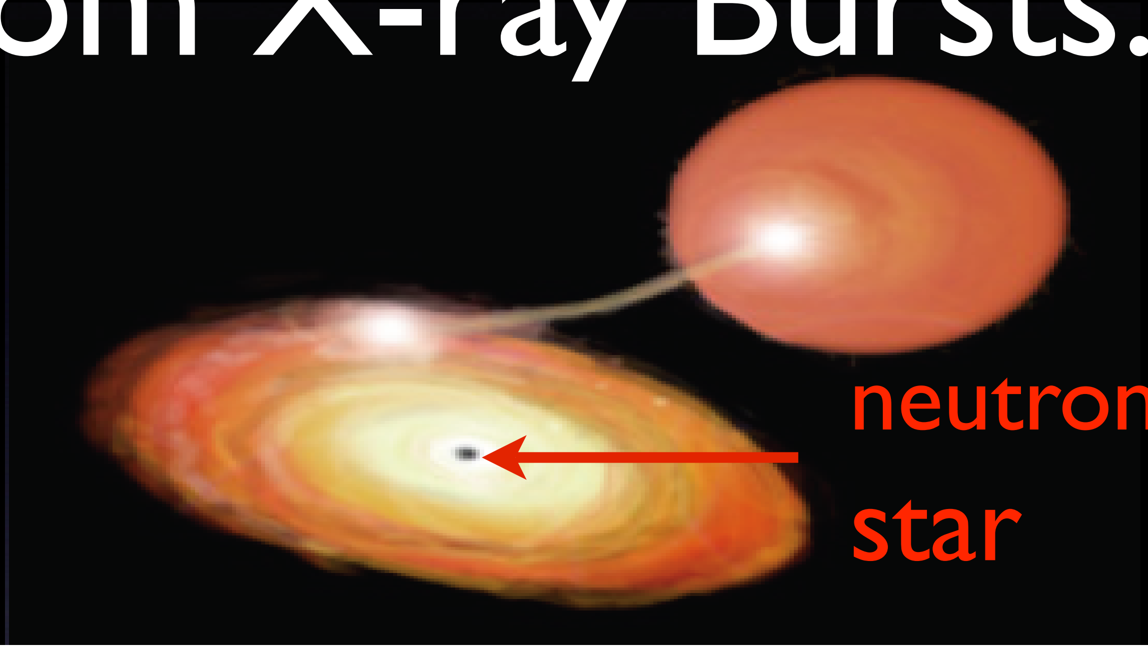

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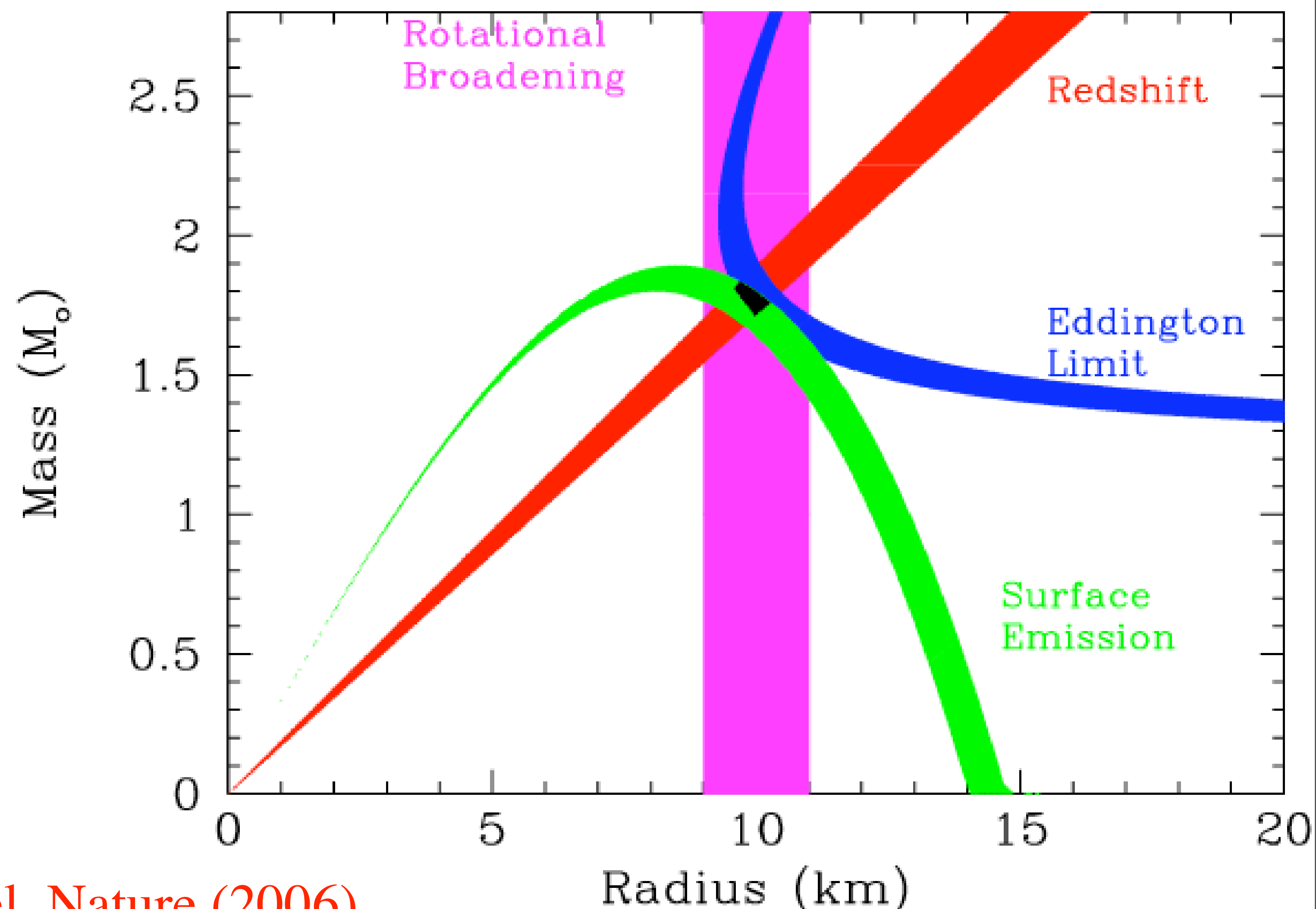

Ozel, Nature (2006)

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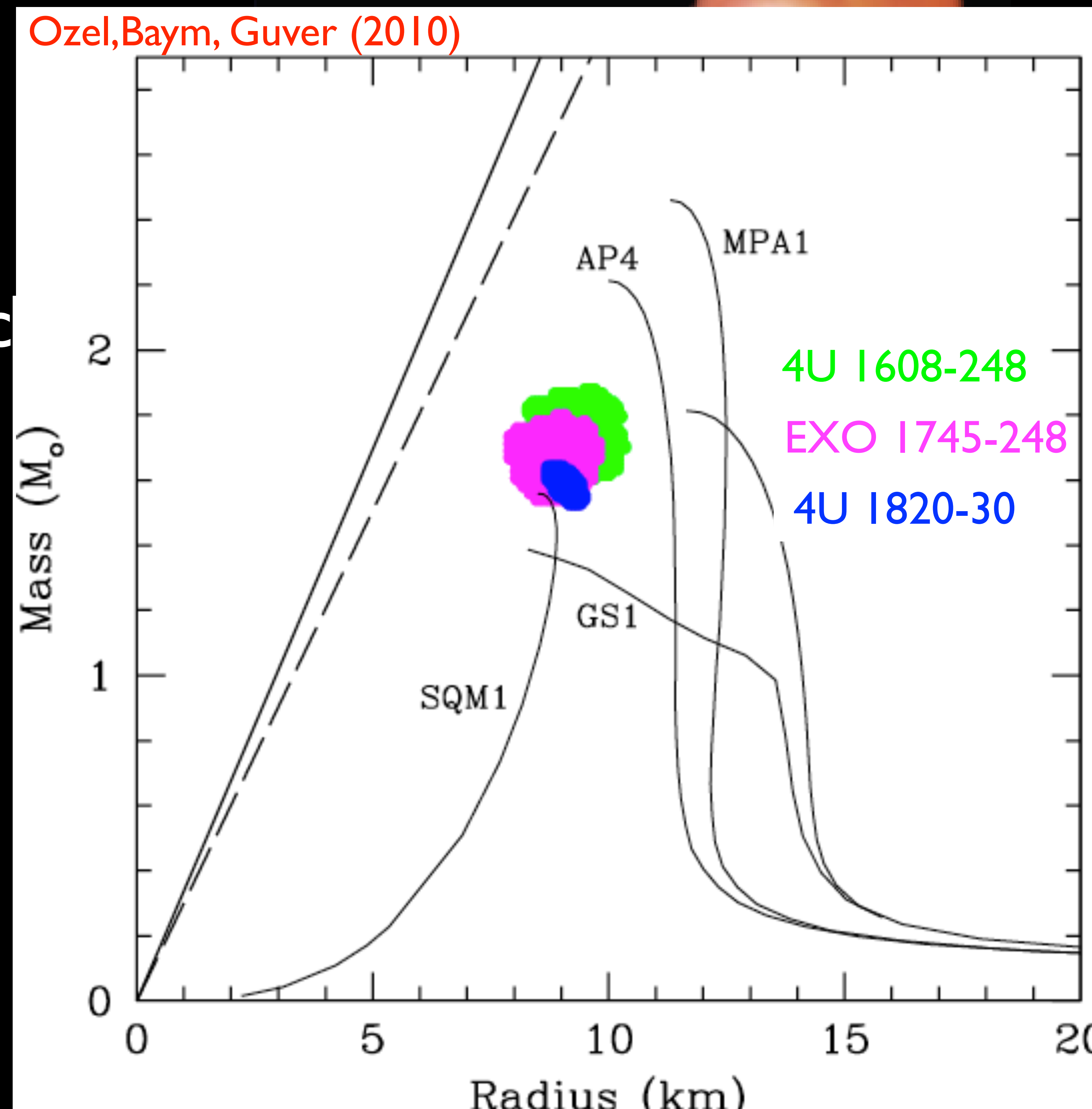
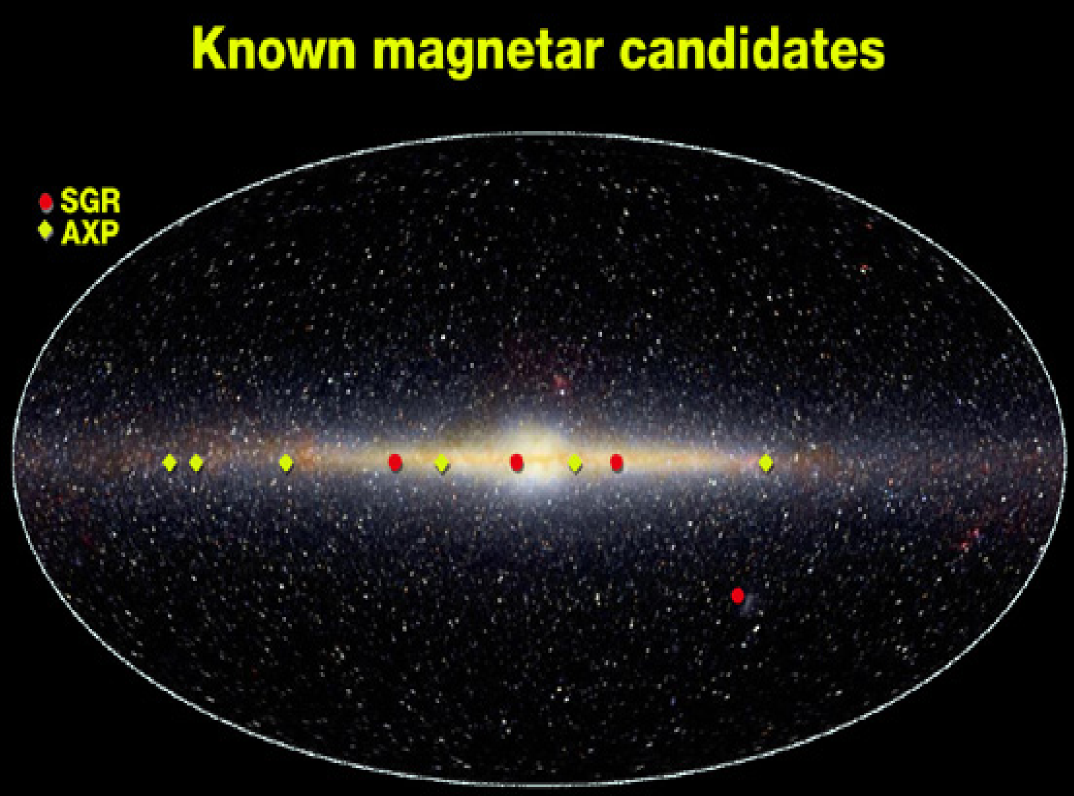


Explosions on Magnetars: Giant Flares



Anomalous X-Ray Pulsars (10)
Soft Gamma Repeaters (8)

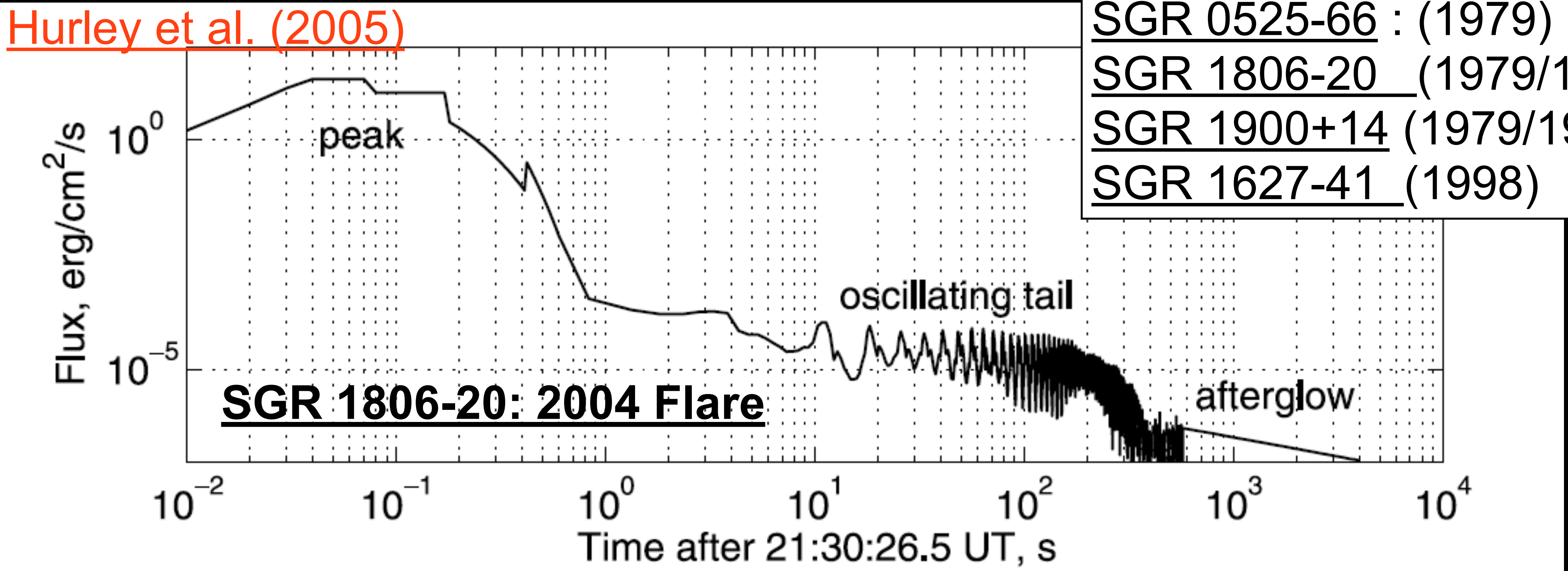
Inferred to have surface fields of the order of 10^{15} Gauss.

http://www.physics.mcgill.ca/~pulsar/magnetar/main.html

SGRs exhibit powerful outburst ~ 10^{46} ergs/s

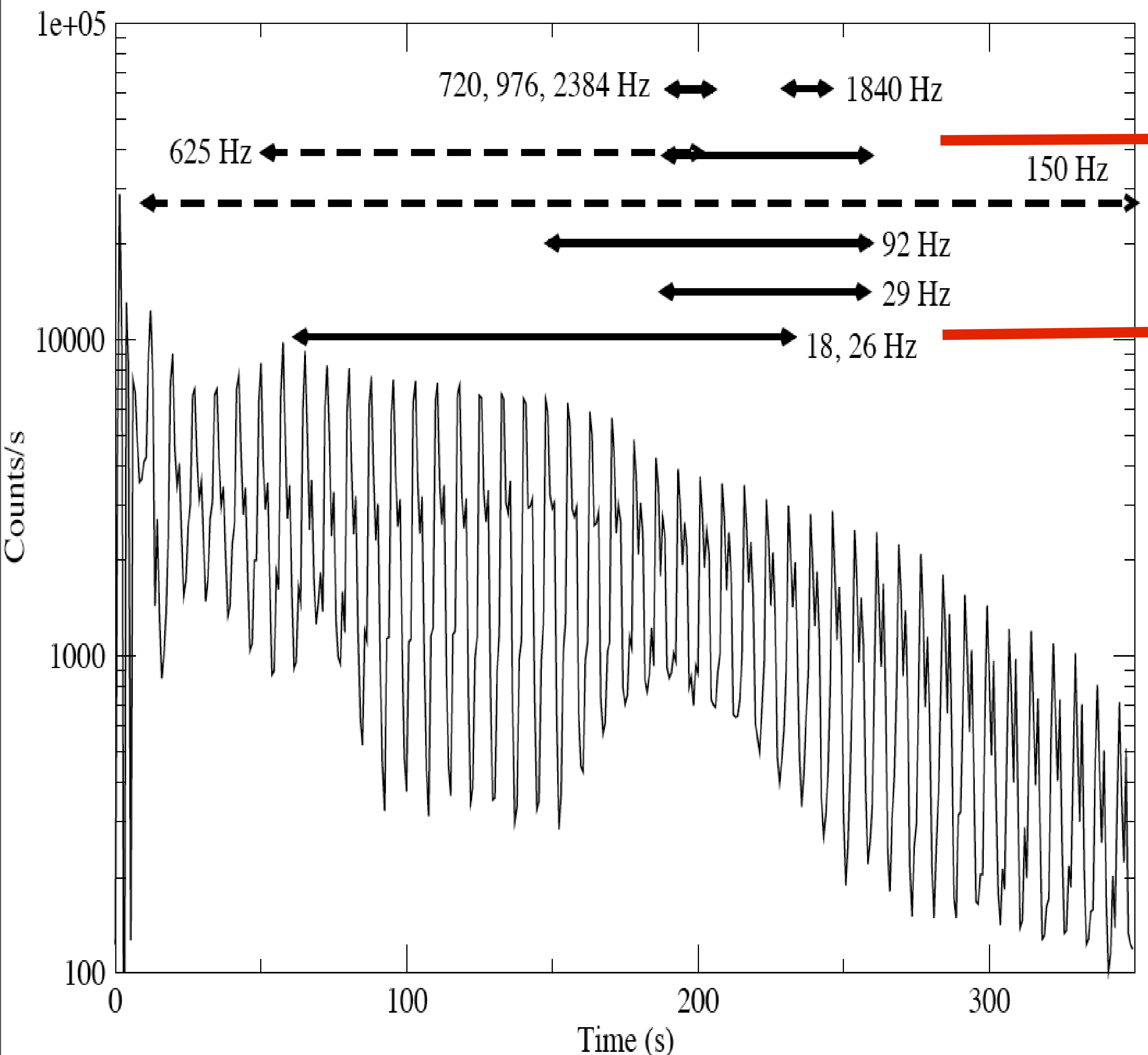
SGR 0525-66 : (1979)
SGR 1806-20 (1979/1986/2004)*
SGR 1900+14 (1979/1986/1998)
SGR 1627-41 (1998)

Hurley et al. (2005)



QPOs are likely to be shear modes in the solid crust

Duncan (1998), Strohmayer, Watts (2006)



$$\omega_{n=1} \simeq \pi \frac{v_S}{R} \frac{R}{\Delta R}$$

$$\omega_{n=0,l=2} \simeq 2 \frac{v_S}{R}$$

$\frac{\Delta R}{R}$ Is sensitive to EoS

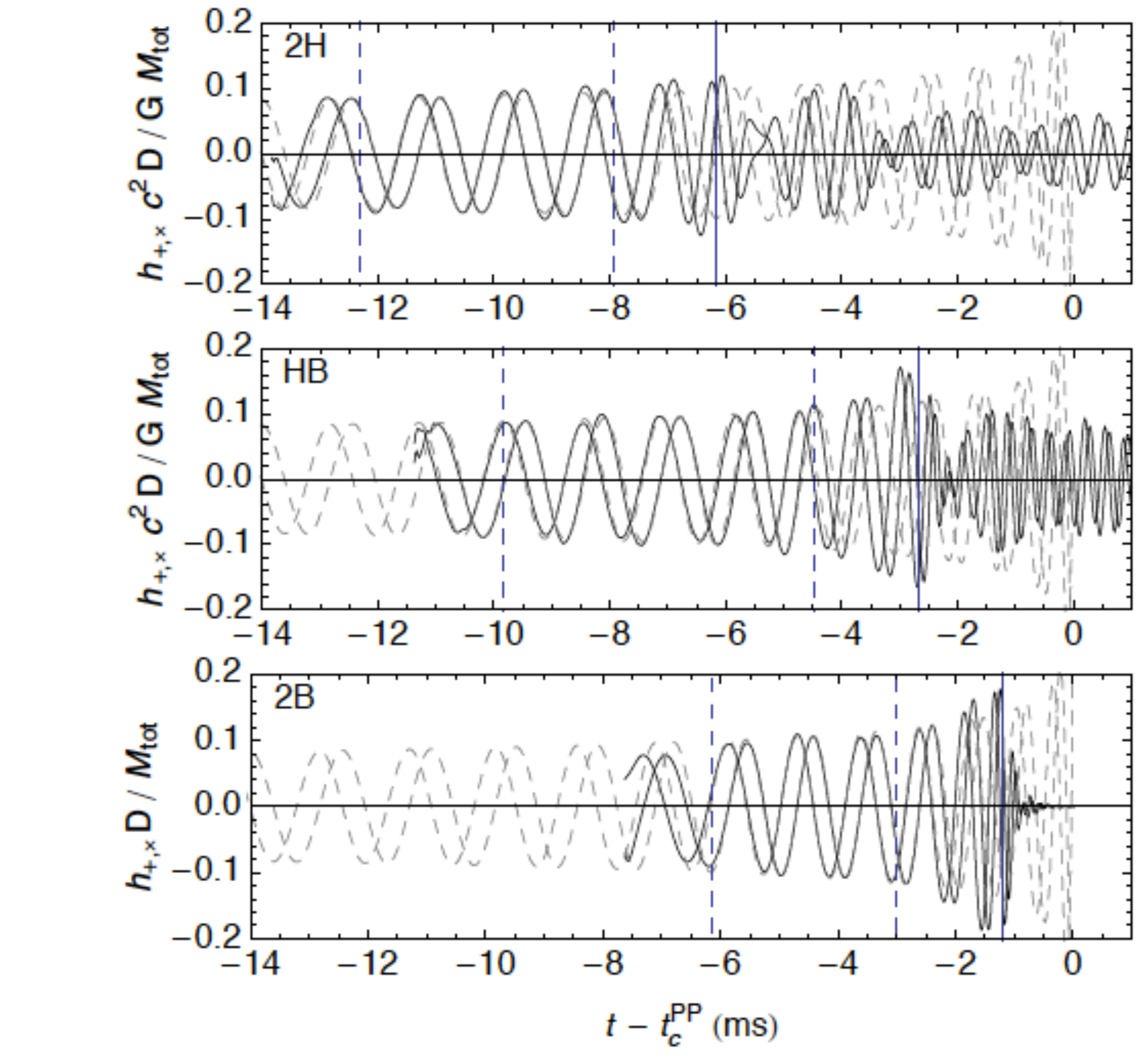
If the n=0 and n=1 mode identifications are secure -
We can constrain the Mass-Radius of neutron stars.

Gravitational Waves From Binary Neutron Star Mergers

Movie Credit: Lucianio Rezzola

Advanced LIGO: Predicted to see between 1-10 mergers a years !

Waveform contains information about masses and radii of the merging stars.



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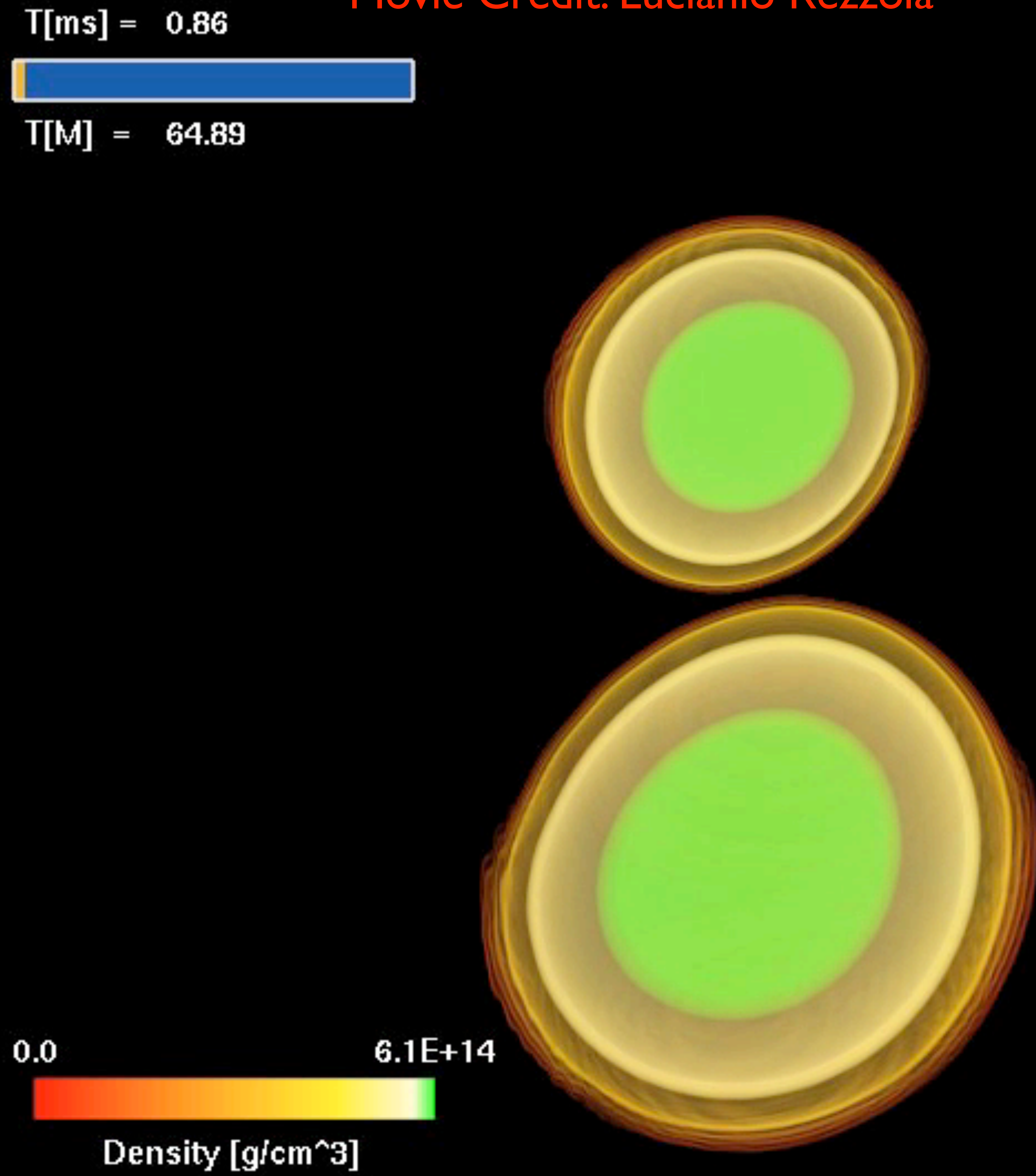

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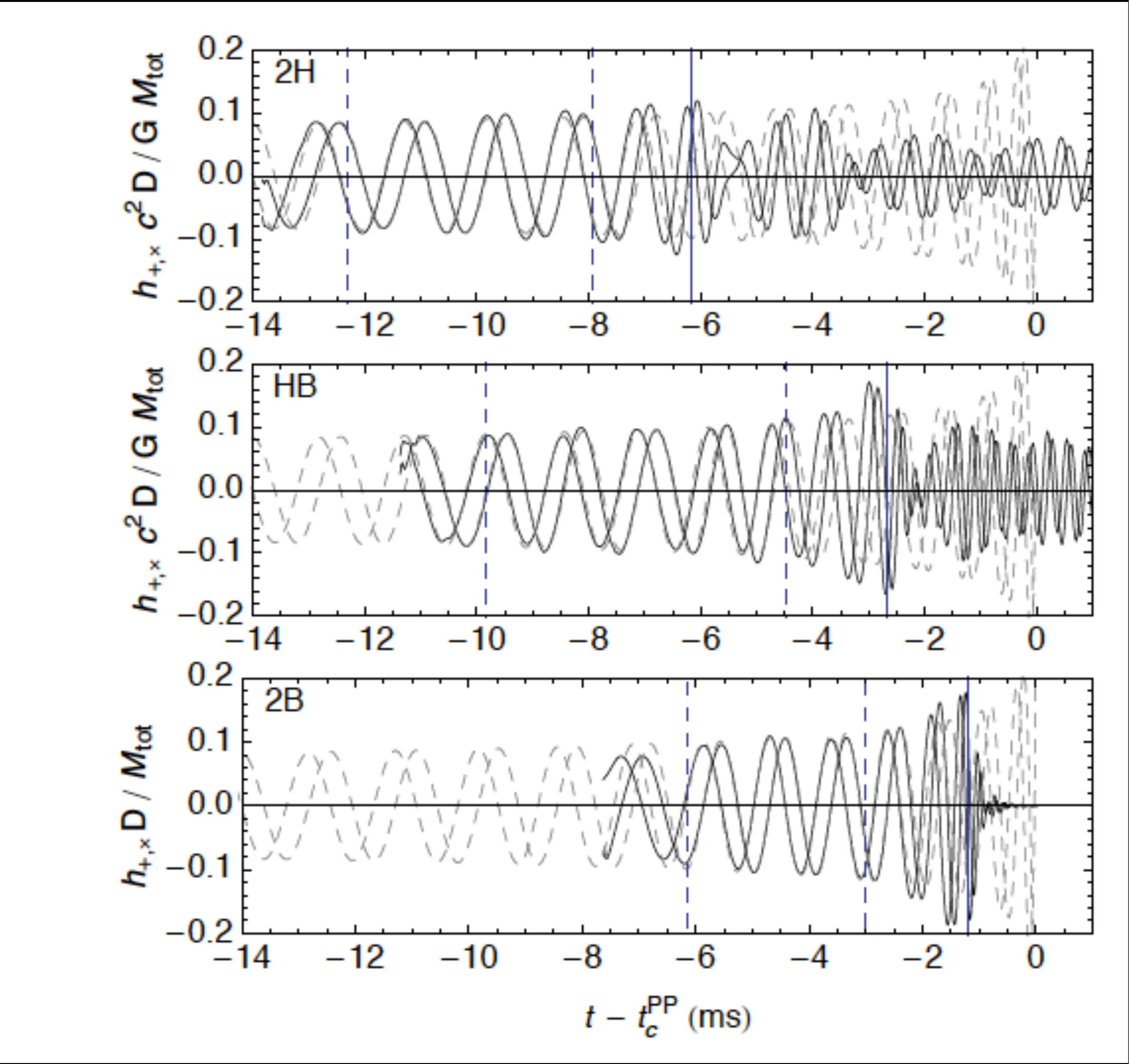
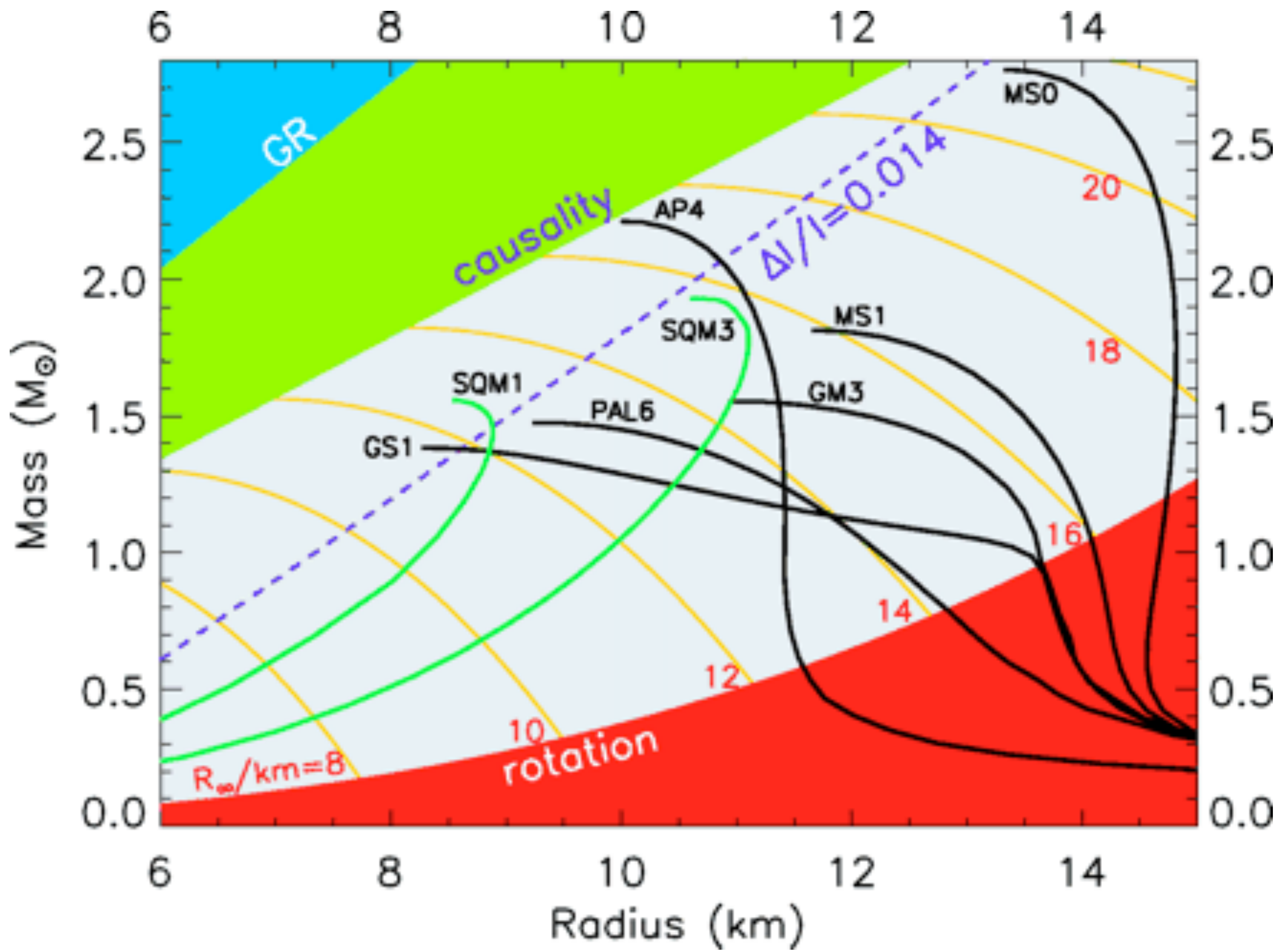


Read, Markakis, Shibata et al. (2009)

Real Constraints Soon



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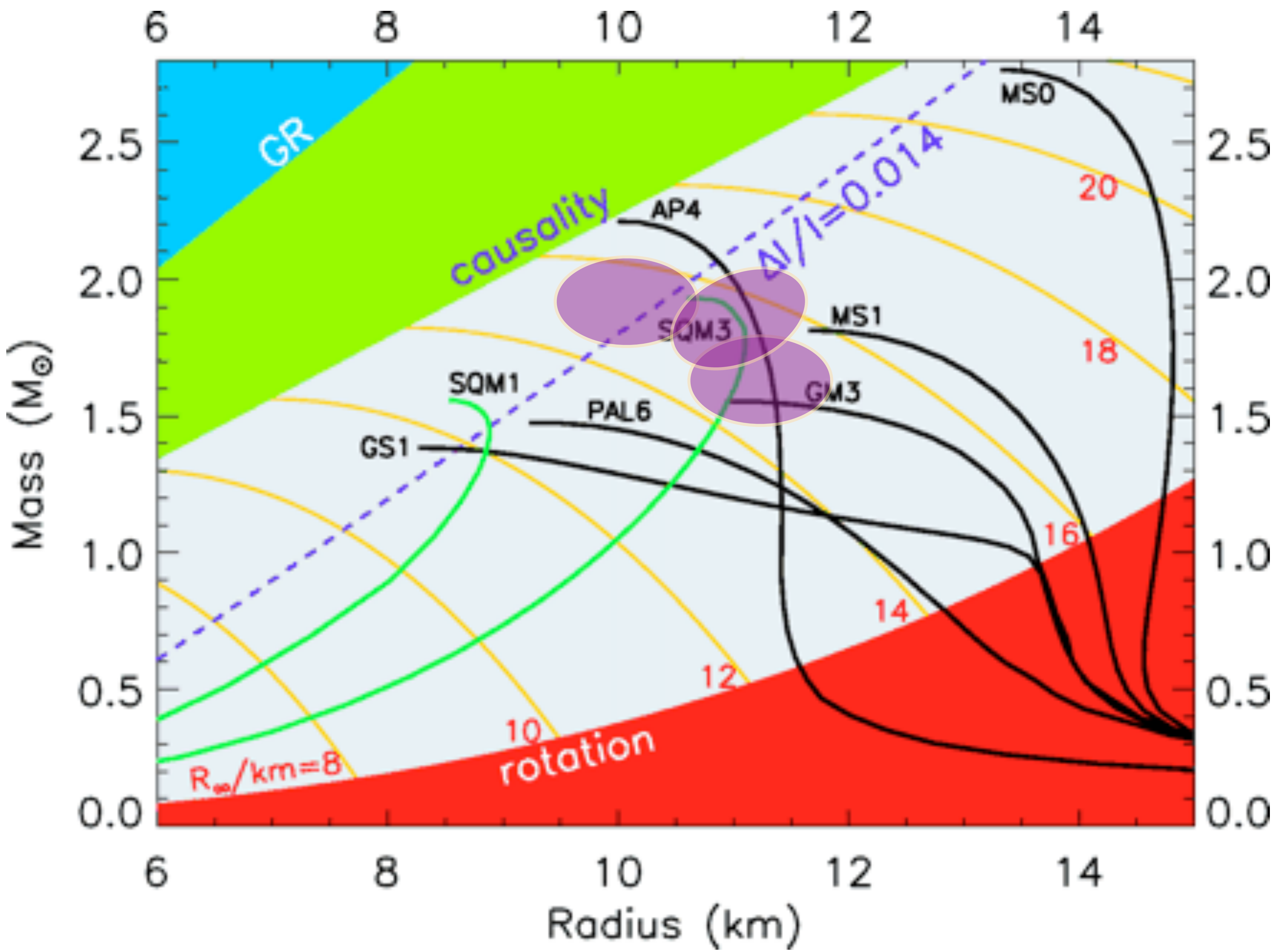
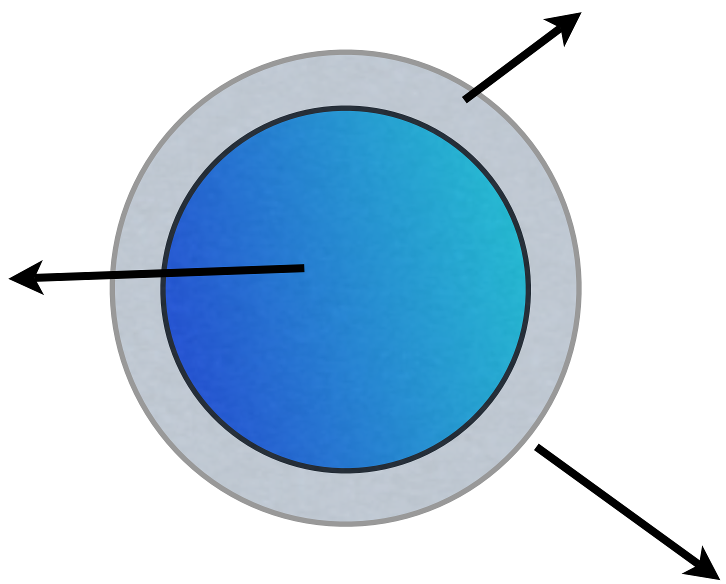


Neutron Star Cooling

Crust cools by conduction

Isothermal core cools by neutrino emission



Surface photon emission dominates at late time t > 10^6 yrs

Basic neutrino reactions:

$$\begin{aligned} n &\rightarrow p + e^- + \bar{\nu}_e \\ e^- + p &\rightarrow n + \nu_e \\ n + n &\rightarrow n + p + e^- + \bar{\nu}_e \\ e^- + p + n &\rightarrow n + n + \nu_e \end{aligned}$$

$$\dot{\epsilon}_\nu|_{\rho=\rho_o} \simeq 10^{25}\ T_9^6\ \frac{\text{ergs}}{\text{cm}^3\ \text{s}}$$

Fast: Direct URCA

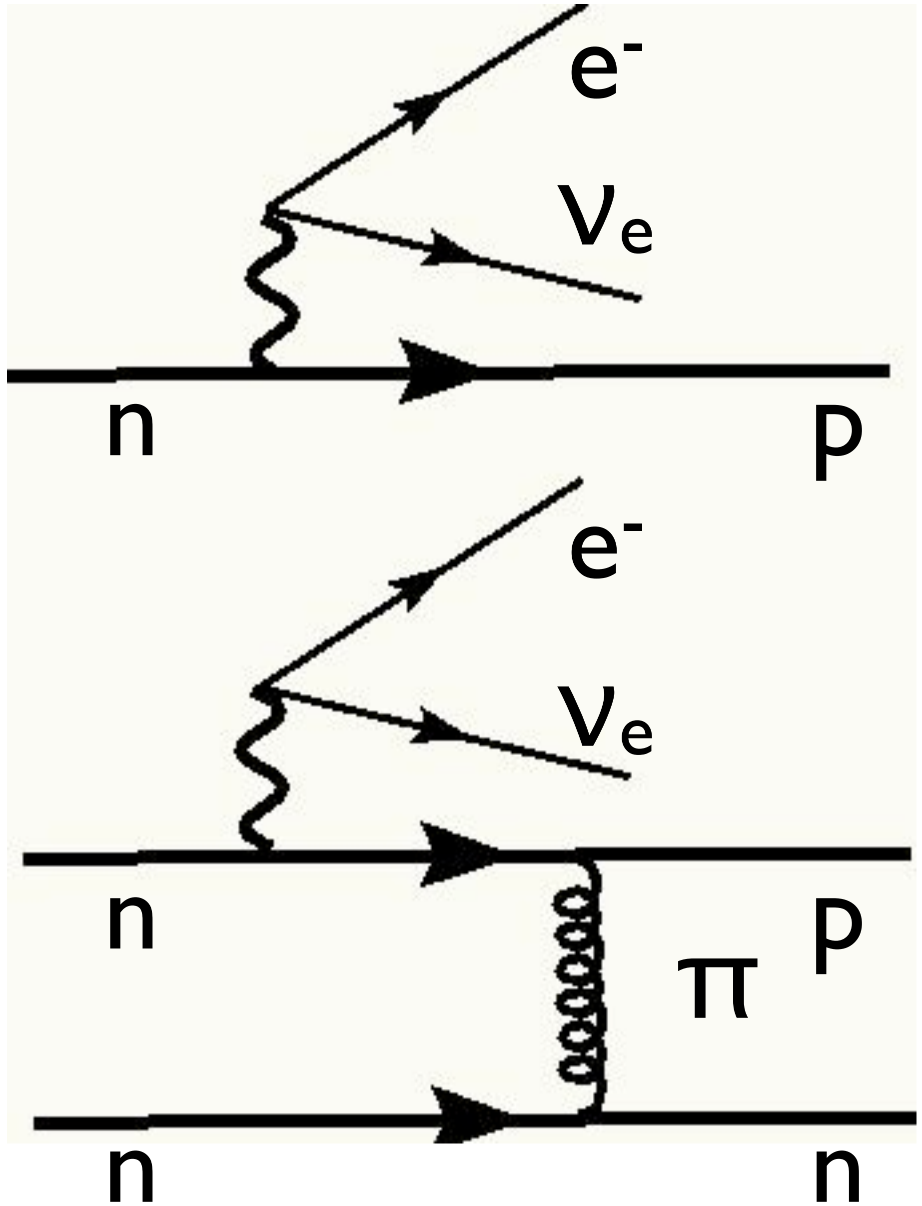
$$\dot{\epsilon}_\nu|_{\rho=\rho_o} \simeq 10^{22}\ T_9^8\ \frac{\text{ergs}}{\text{cm}^3\ \text{s}}$$

Slow: Modified URCA

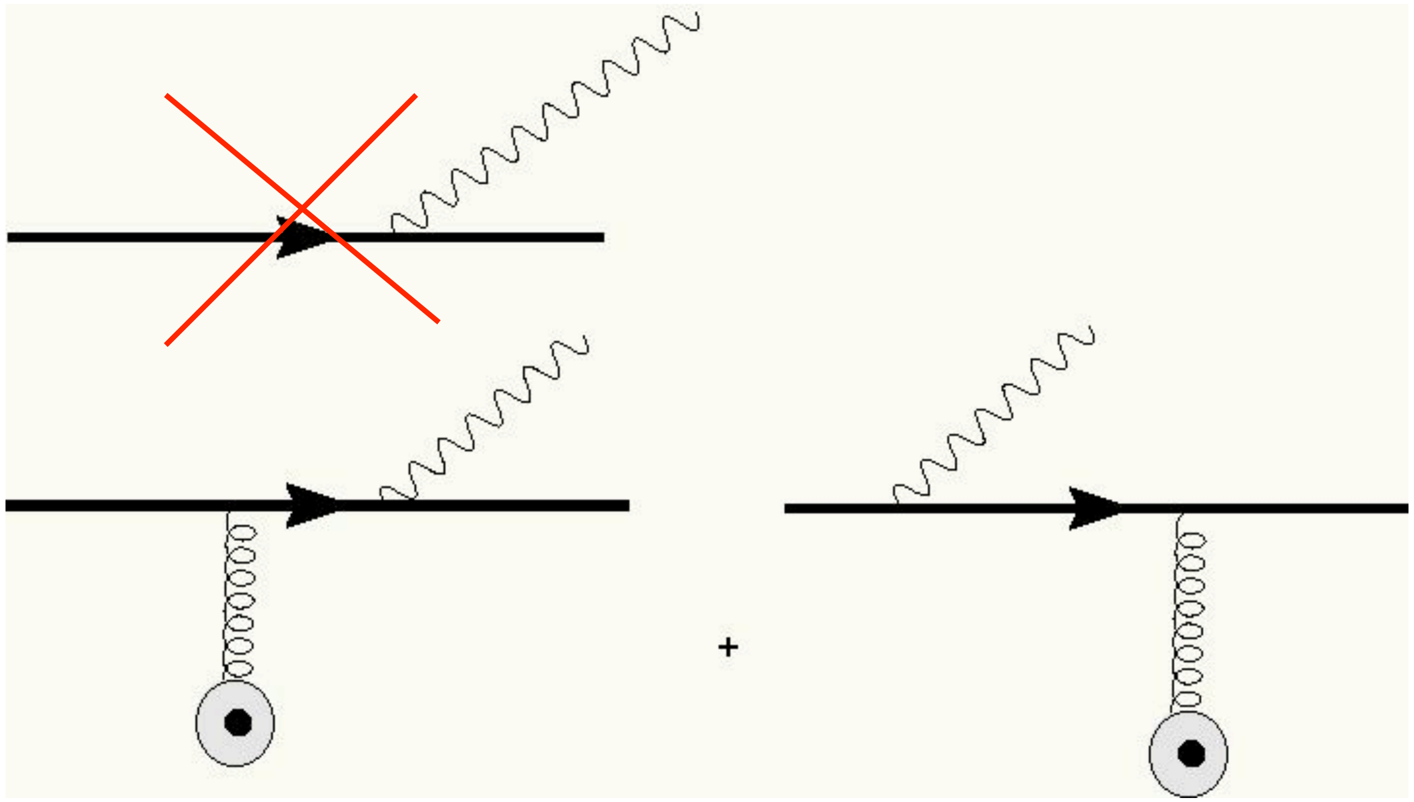
Neutrino Emissivity & Fluctuations

Single -particle reactions are fast. Need unstable particles- beta decay is the only reaction - "Direct Urca"

Multi-particle reactions are slow - typically of the Bremsstrahlung type. "Modified Urca"



Subtle nuclear aspects of neutrino emission:



Kinematically forbidden

Need acceleration for radiation

$$\frac{1}{\frac{p\cdot q}{m}+\frac{q^2}{2m}+\omega}+\frac{1}{\frac{p\cdot q}{m}-\frac{q^2}{2m}-\omega}\approx\frac{1}{\omega}\frac{p}{m}\frac{q}{\omega}$$

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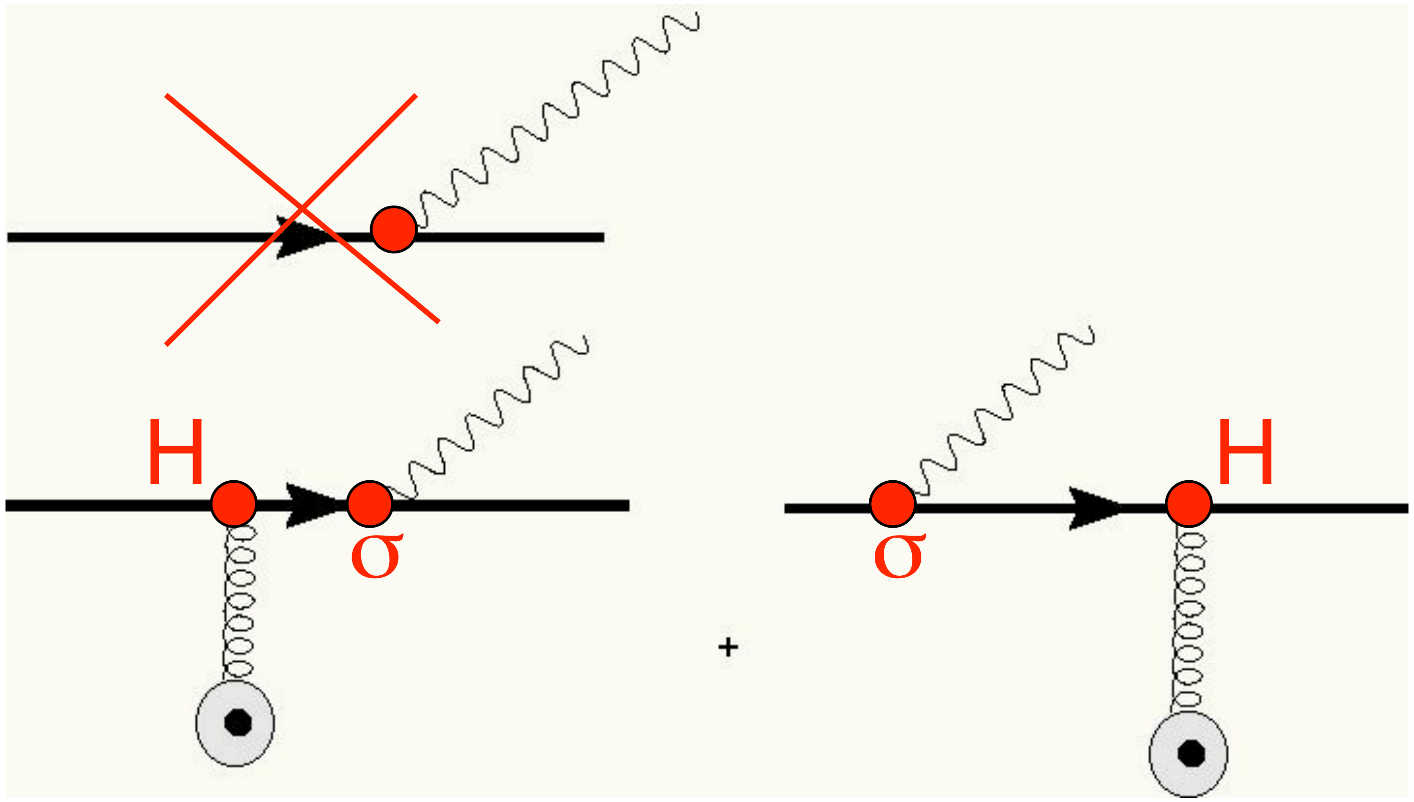

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Radiation without acceleration
set q=0:

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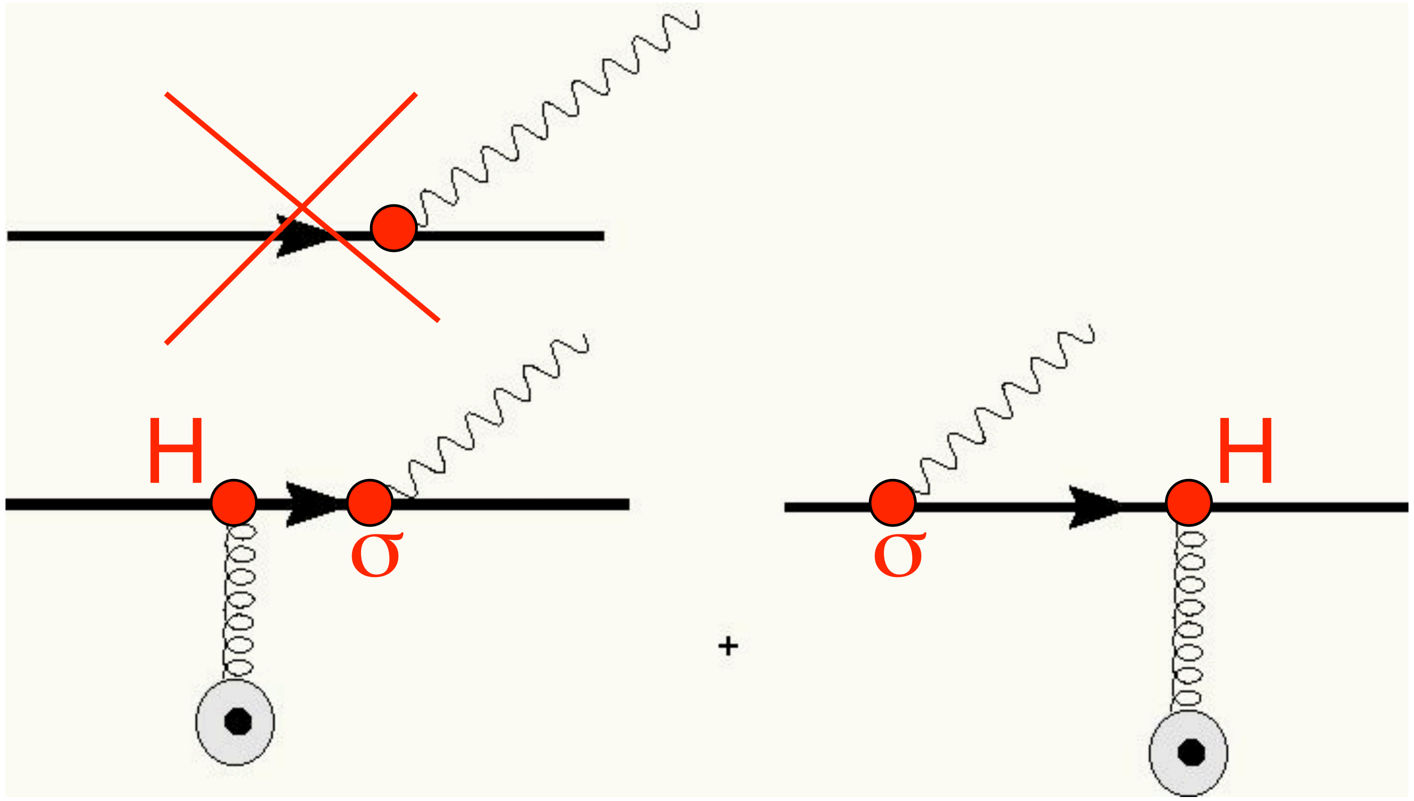

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Radiation without acceleration set q=0:

$$\frac{H\,\sigma}{\omega}-\frac{\sigma\,H}{\omega}\approx\frac{1}{\omega}[H,\sigma]$$

Radiation without acceleration :

$$L = \frac{G_F}{2\sqrt{2}} \; l_\nu(x) \; j^\mu(x)$$

$$j^\mu(x) = \bar{\psi}(x)\, \gamma^\mu (c_V - c_A \gamma_5)\, \psi(x)$$

$$\xrightarrow{NR} c_V \; \psi^+ \psi \, \delta^{\mu 0} - c_A \;\; \psi^+ \, \sigma^i \; \psi \, \delta^{\mu i}$$

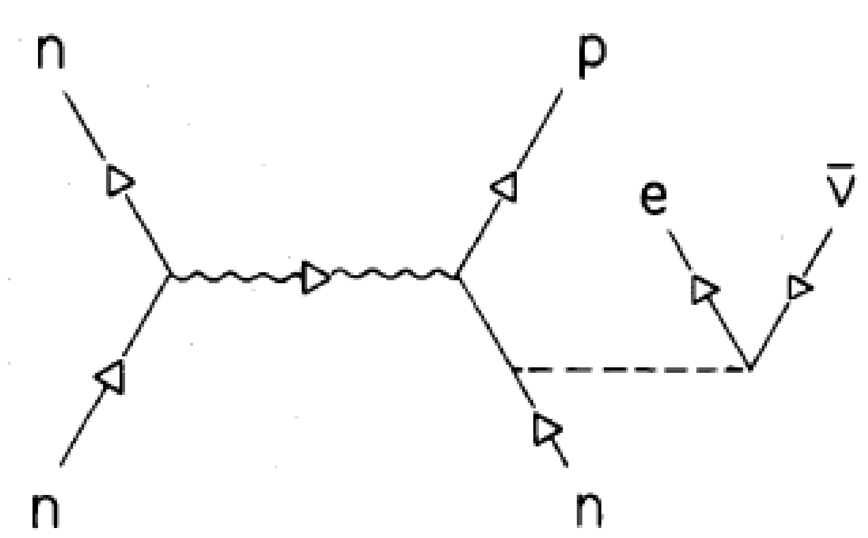
Neutrinos couple to density and spin:

$[H_{\text{nuclear}}, \rho]=0$, but $[H_{\text{nuclear}}, \sigma] \neq 0$

Pion exchange does not conserve spin:

$H_{\text{nuclear}} \sim V_{\text{OPE}}$

$$V_{\text{OPE}} = \left(\frac{f}{m_\pi}\right)^2 \boldsymbol{\sigma}^{(1)} \cdot \boldsymbol{k} \left(\frac{-1}{k^2 + m_\pi{}^2}\right) \boldsymbol{\sigma}^{(2)} \cdot \boldsymbol{k} (\boldsymbol{\tau}^{(1)} \cdot \boldsymbol{\tau}^{(2)})$$

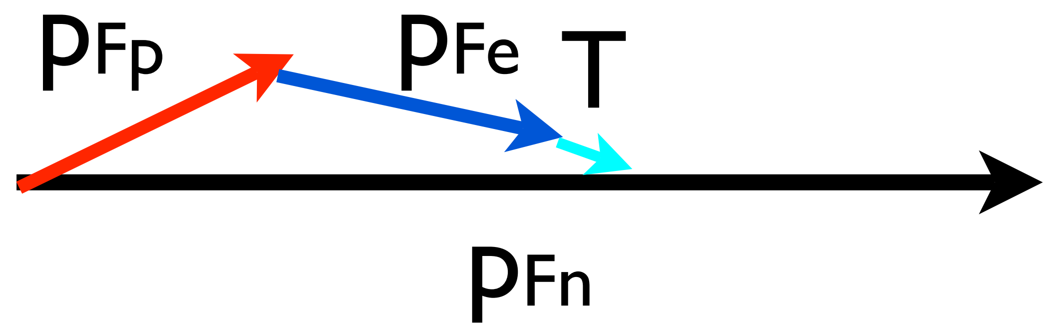


Friman & Maxwell (1979)

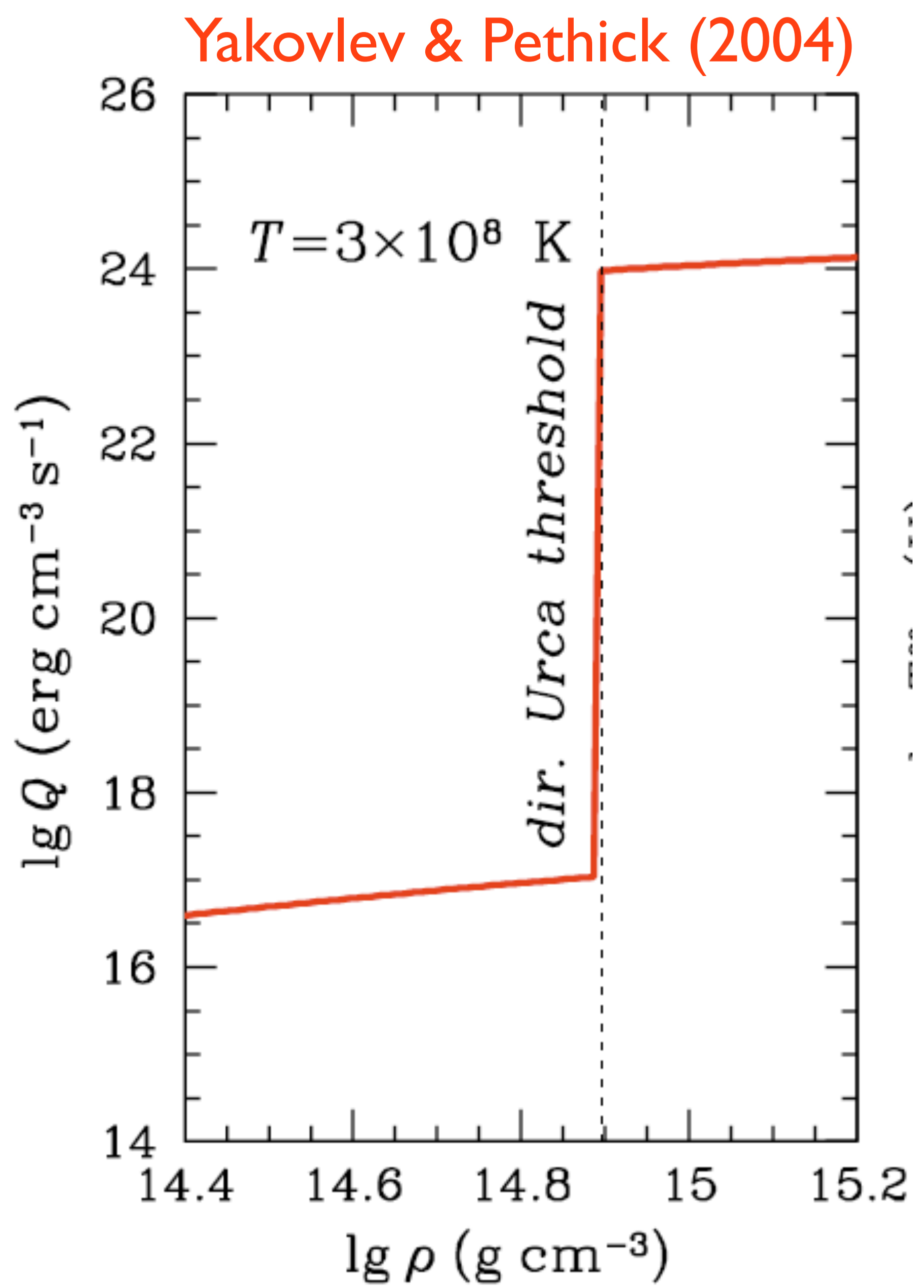
Cooling and EoS

Neutron decay at the Fermi surface cannot conserve momentum if

$x_p \sim (p_{Fp} / p_{Fn})^3 < 0.12\text{-}14$



- In the standard scenario only massive stars (M ~ 2 M☉) cool rapidly.



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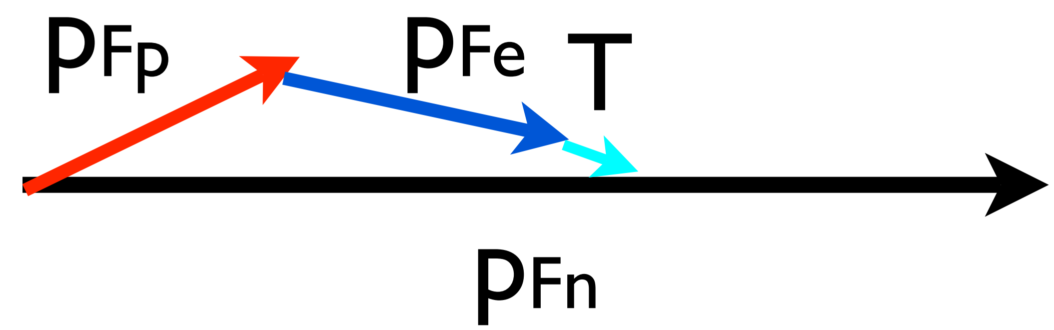
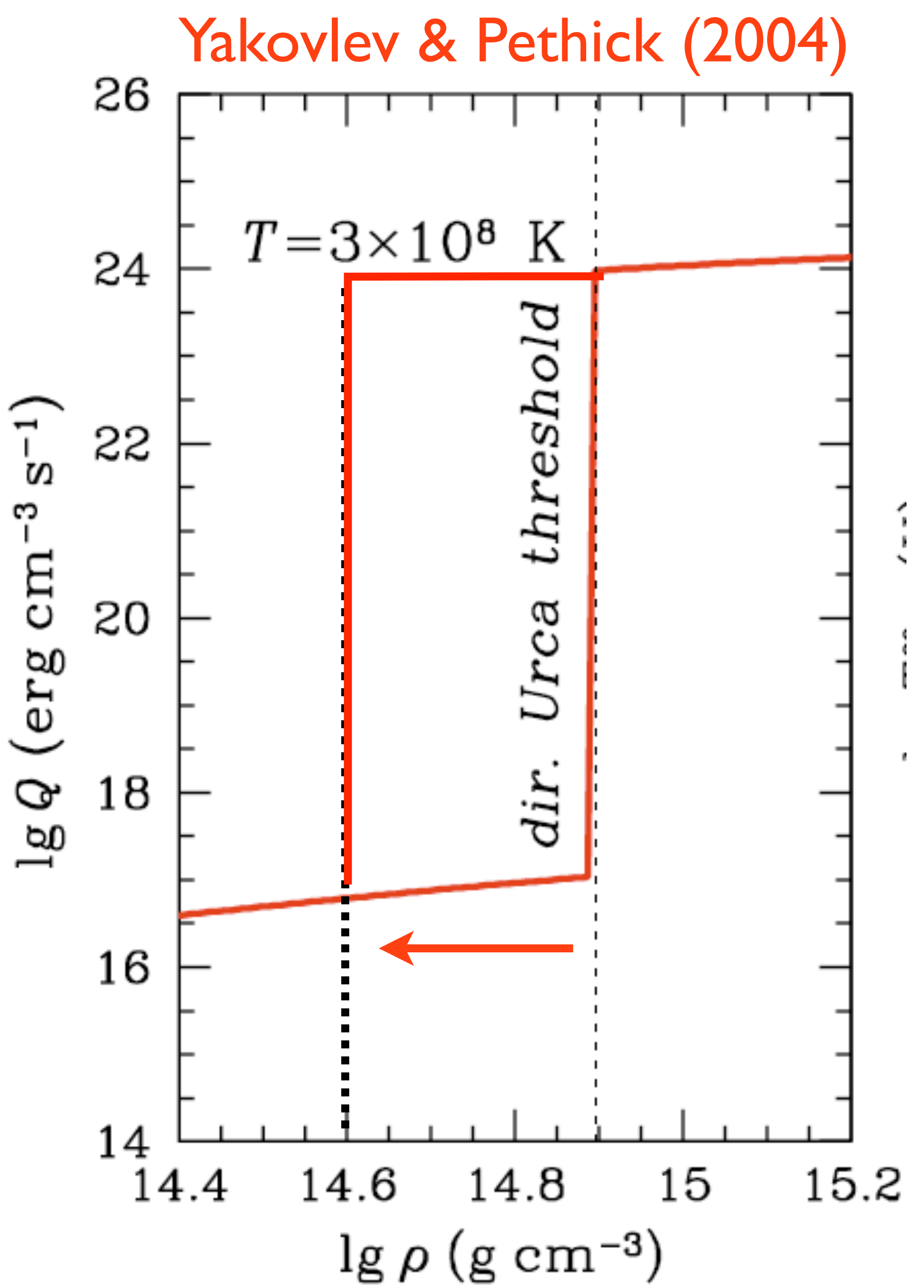
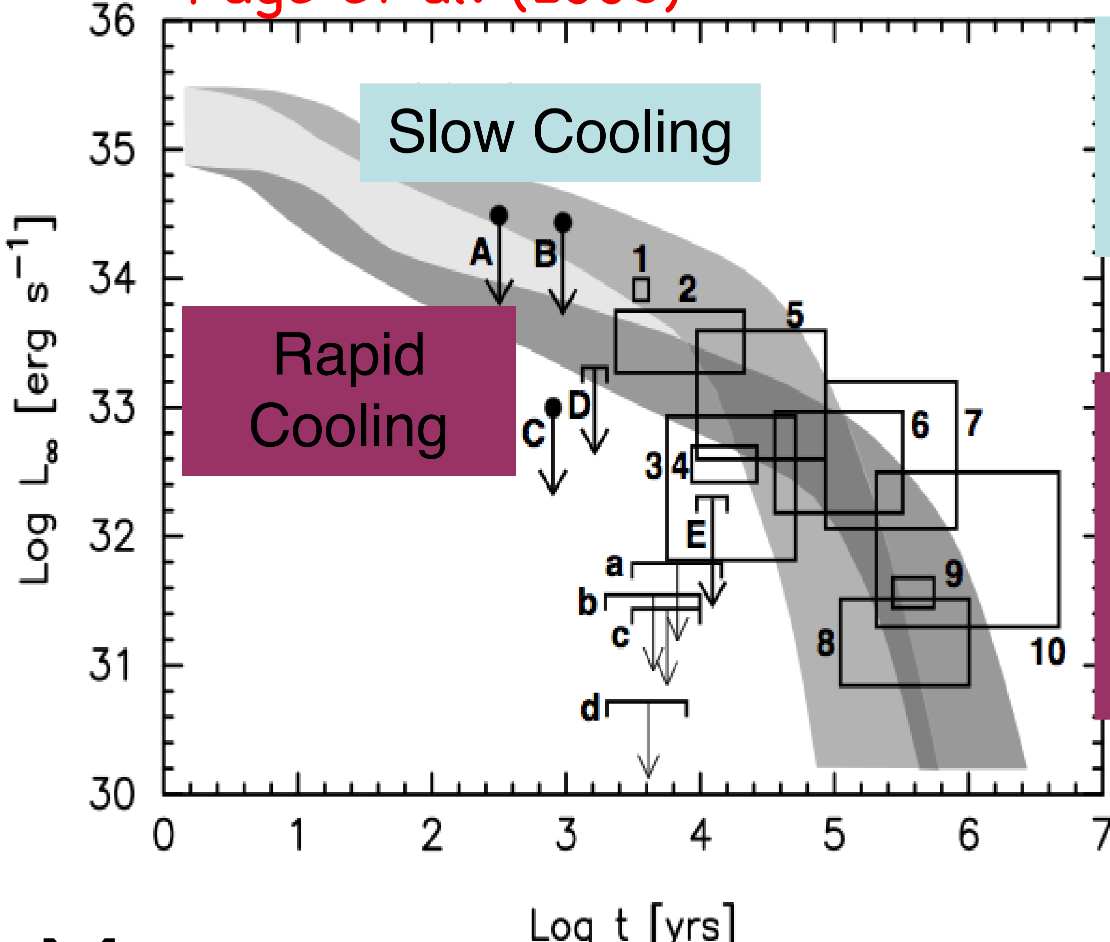


- In the standard scenario only massive stars (M ~ 2 M$_\odot$) cool rapidly.
- A large symmetry energy will allow direct URCA for typical NS (M ~ 1.4 M$_\odot$) .
- Recall a large symmetry energy also favors large radii.



Neutron Star Cooling

Page et al. (2005)



Slow Cooling:

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

Standard Scenario

Rapid Cooling:

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

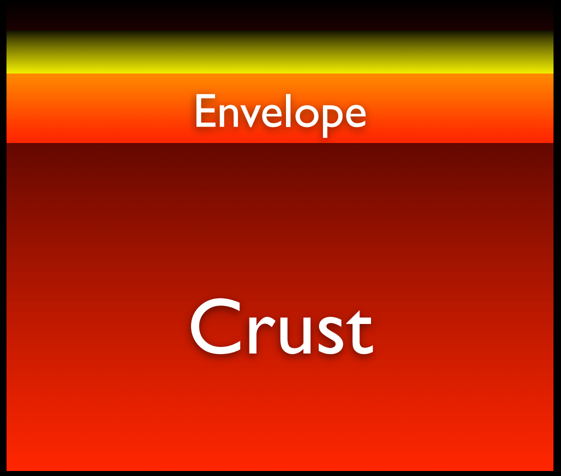
$X \rightarrow Y + e^- + \bar{\nu}_e$

Needs high (>10%) Proton fraction or a phase transition

- Most neutron stars compatible with slow cooling.
- Notable exceptions exist.
- Several young supernova remnants appear "without" neutron stars

Transiently Accreting NSs

SXRTs: High accretion followed by periods of quiescence



Nuclear reactions release: ~ 1.5 MeV / nucleon

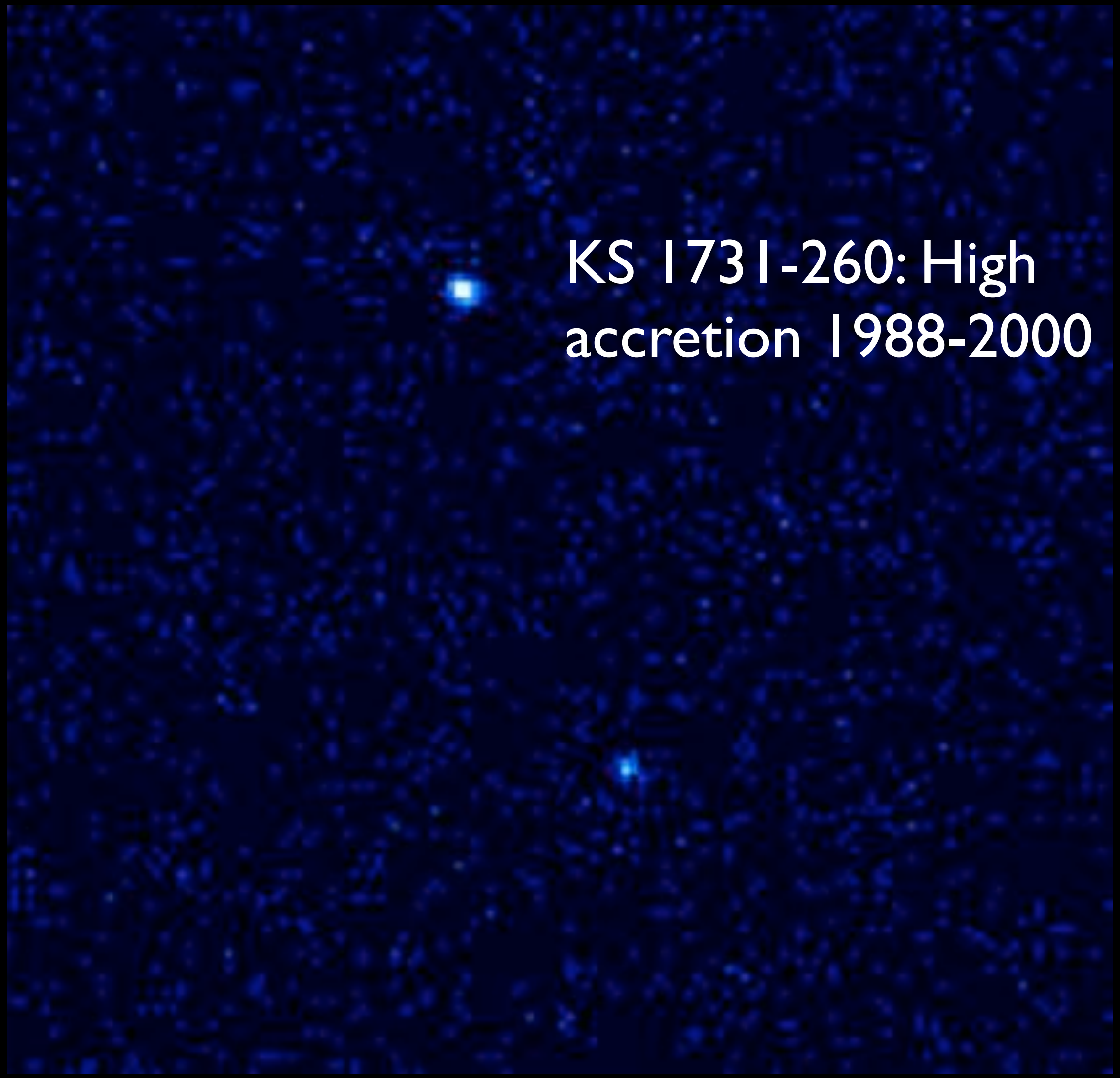


Image credit: NASA/CXC/Wijnands et al.

Deep crustal heating.

Brown, Bildsten Rutledge (1998)
Sato (1974), Haensel & Zdunik (1990)

Warms up old neutron stars

Cooling in Accreting Stars

During accretion heating will heat up the core.
Core temperature set by balance between heating and neutrino cooling.

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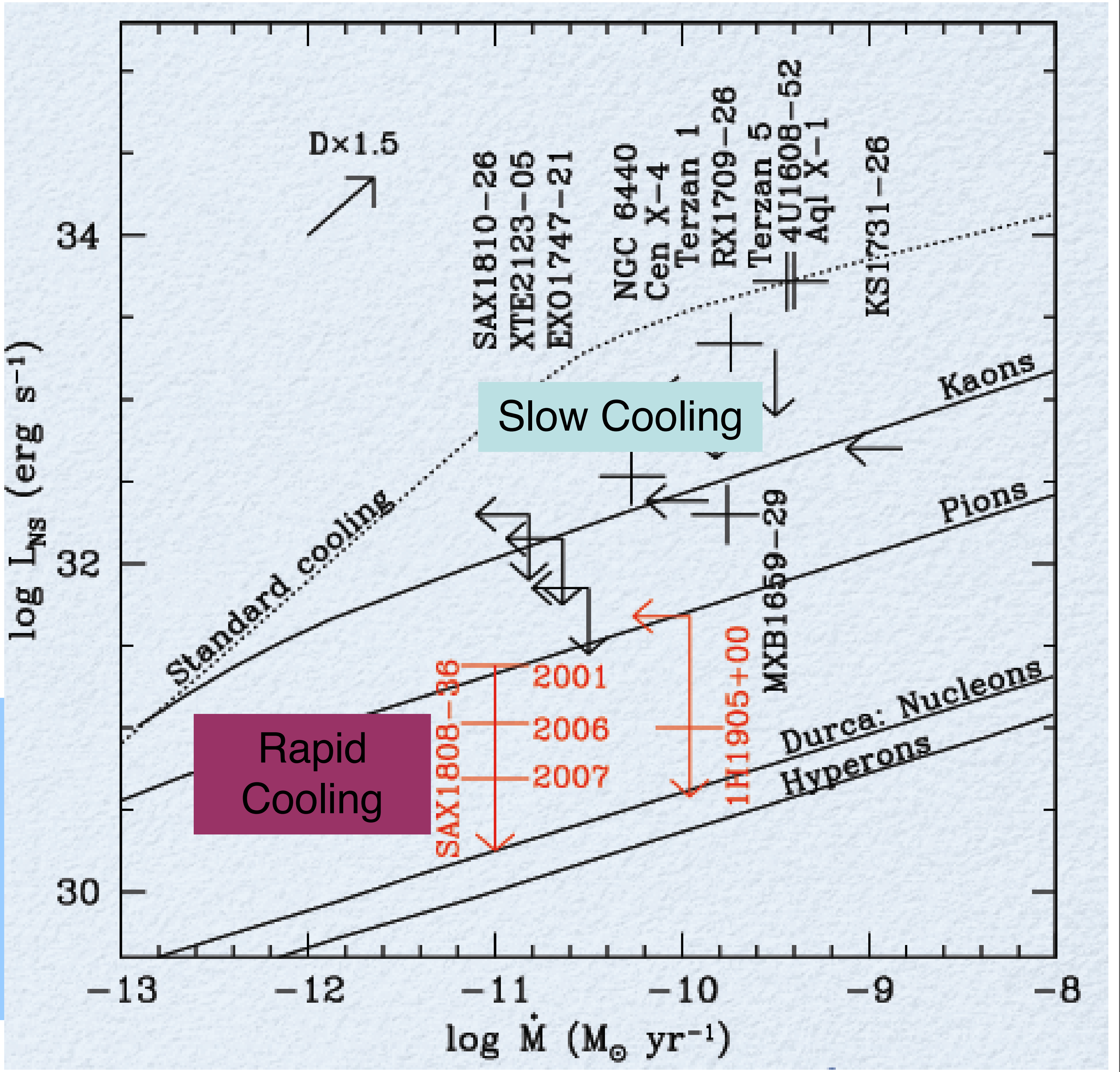
Quiescent emission after periods of bursting in accreting neutron stars (SXRT)



Rutledge (2004) Yakovlev (2006) Heinke (2007)