Title: Neutron Star Mass and Radius Constraints for the Dense Matter Equation of State

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Abstract: Recent discoveries, including a 2 solar mass pulsar, rapid cooling in the Cas A supernova remnant, and estimates of masses and radii from photospheric radius expansion bursts and thermal emissions from neutron stars, are able to constrain significantly the properties of dense matter. Implications for the pressure-density relation and properties of superfluids in neutron star interiors will be discussed.

# Neutron Star Mass and Radius Constraints on the Dense Matter Equation of State

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20 June 2011

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MICRA 2011
Perimeter Institute

# Outline

- Neutron Star Structure
  - Neutron Star Limits from General Relativity and Causality
  - Mass Measurements
    - 2 $M_\odot$ Neutron Stars?
    - Limits to the Extent of Quark Matter
  - Neutron Star Radii
    - Relation to the Nuclear Symmetry Energy
    - Thermal Emission from Cooling Neutron Stars
    - Photospheric Radius Expansion X-Ray Bursters
  - The Universal Mass-Radius Relation and the Neutron Star EOS
    - Consistency with Neutron Matter Expectations
    - Implications for Other Laboratory Constraints
- Time Permitting: The Evolution of Neutron Stars
  - Neutron Star Cooling and the Direct Urca Process
  - Cas A: A Direct Detection of Core Superfluidity?

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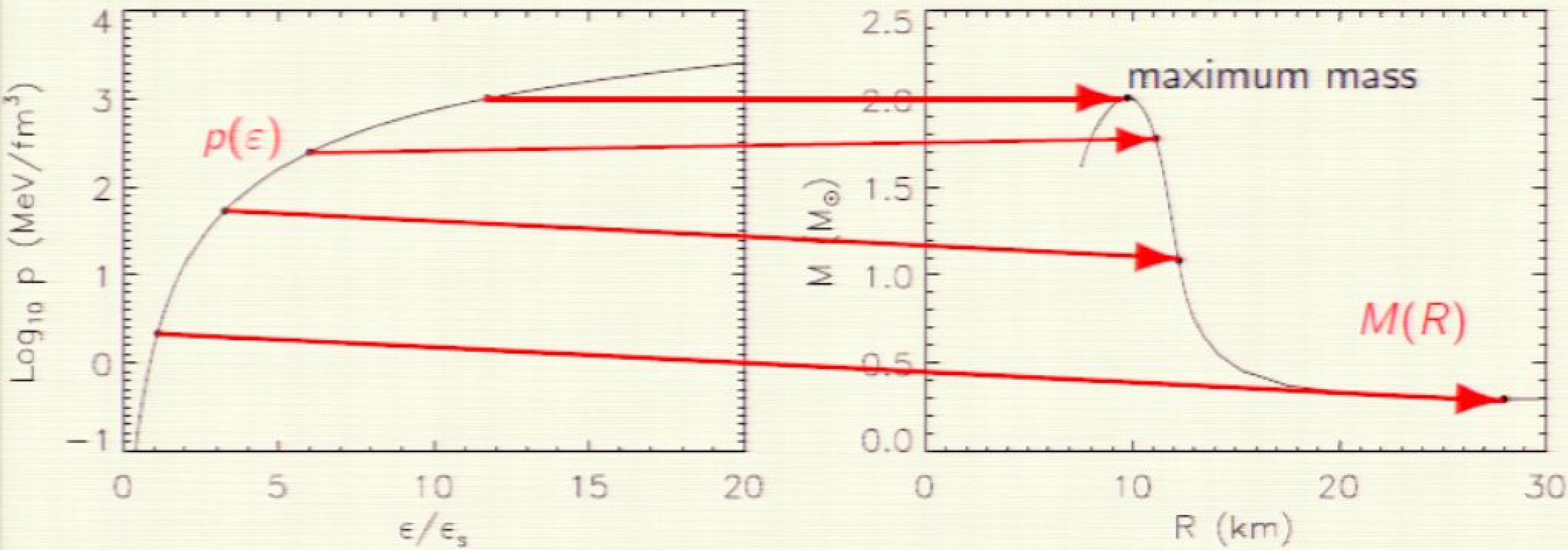
# Neutron Star Structure

Tolman-Oppenheimer-Volkov equations

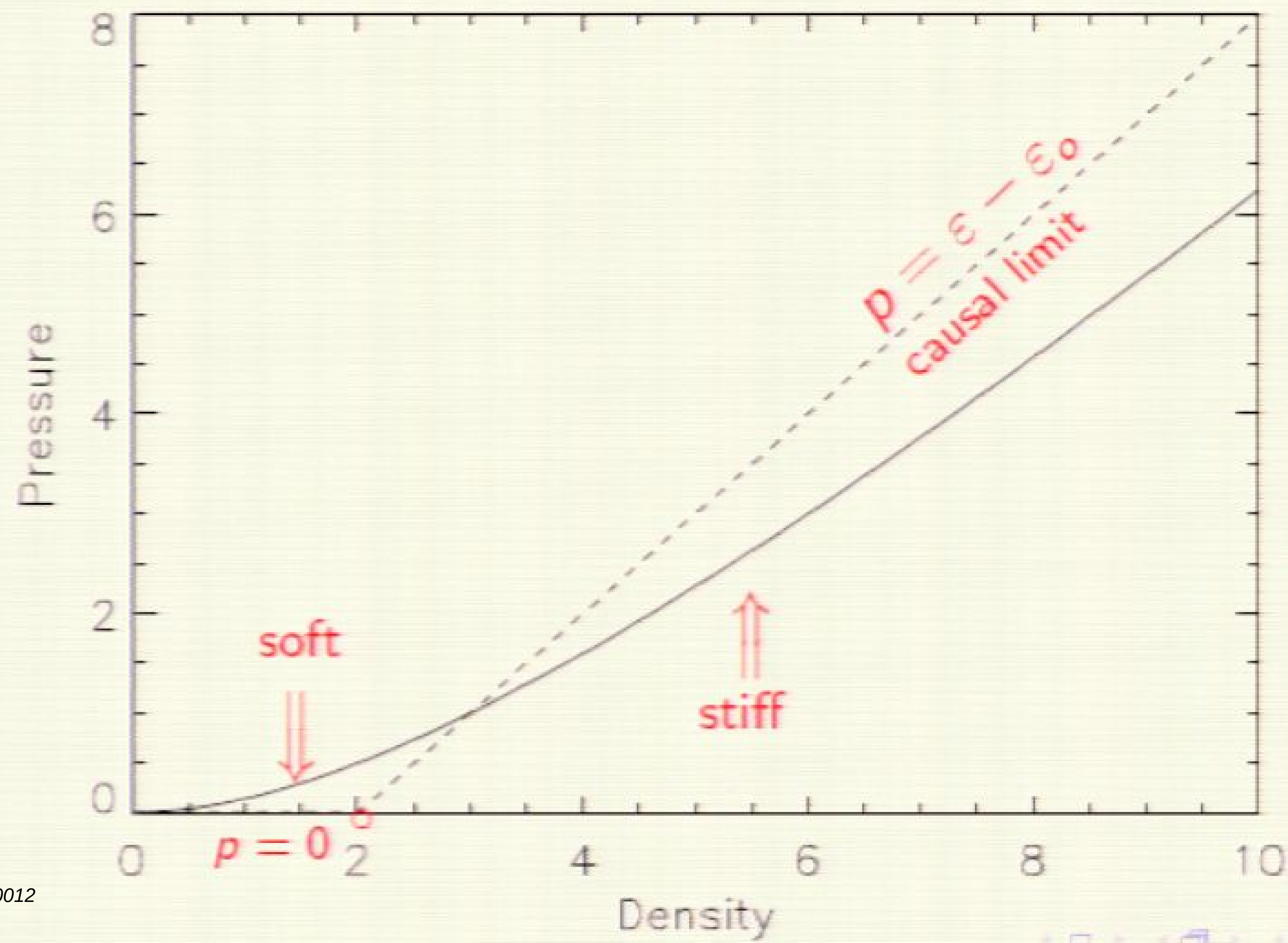
$$\frac{dp}{dr} = -\frac{G}{c^2}\frac{(m+4\pi pr^3)(\varepsilon+p)}{r(r-2Gm/c^2)}$$

$$\frac{dm}{dr} = 4\pi\frac{\varepsilon}{c^2}r^2$$



# Extreme Properties of Neutron Stars

- The most compact and massive configurations occur when the low-density equation of state is "soft" and the high-density equation of state is "stiff" (Koranda, Stergioulas & Friedman 1997).




$\varepsilon_0$ is the only EOS parameter

The TOV solutions scale with $\varepsilon_0$

$w = \varepsilon/\varepsilon_0$
$y = p/\varepsilon_0$
$x = r\sqrt{G\varepsilon_0}/c^2$
$z = m\sqrt{G^3\varepsilon_0}/c^2$

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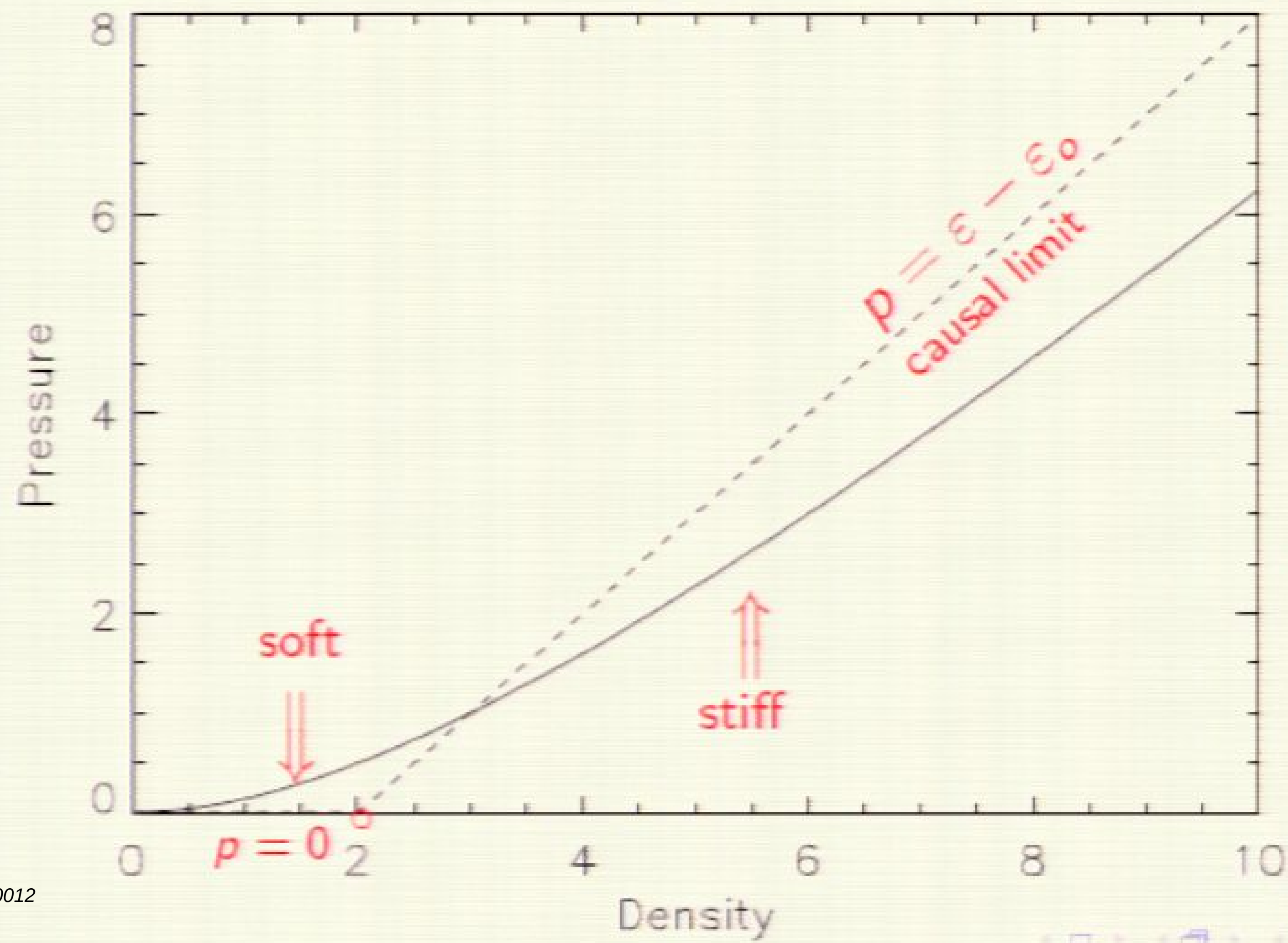


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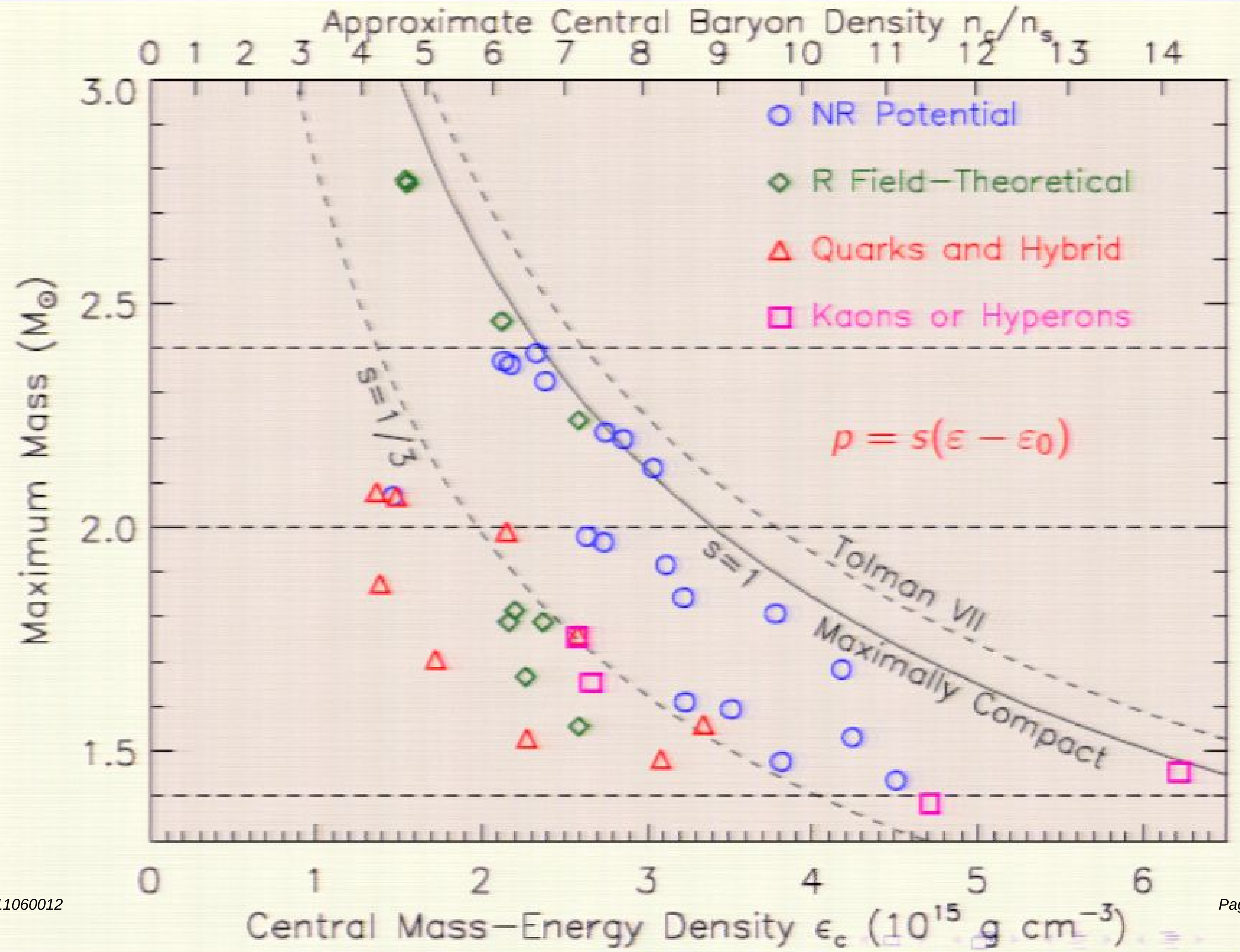
# Extreme Properties of Neutron Stars

- $M_{max} = 4.1\ (\varepsilon_s/\varepsilon_0)^{1/2}\ \mathrm{M}_\odot$ (Rhoades & Ruffini 1974)
- $M_{B,max} = 5.41\ (m_B c^2/\mu_o)(\varepsilon_s/\varepsilon_0)^{1/2}\ \mathrm{M}_\odot$
- $R_{min} = 2.82\ GM/c^2 = 4.3\ (M/\mathrm{M}_\odot)$ km
- $\mu_{B,max} = 2.09$ GeV
- $\varepsilon_{c,max} = 3.034\ \varepsilon_0 \simeq 51\ (\mathrm{M}_\odot/M_{largest})^2\ \varepsilon_s$
- $p_{c,max} = 2.034\ \varepsilon_0 \simeq 34\ (\mathrm{M}_\odot/M_{largest})^2\ \varepsilon_s$
- $n_{B,max} \simeq 38\ (\mathrm{M}_\odot/M_{largest})^2\ n_s$
- $\mathrm{BE}_{max} = 0.34\ M$
- $P_{min} = 0.74\ (\mathrm{M}_\odot/M_{sph})^{1/2}(R_{sph}/10\ \mathrm{km})^{3/2}\ \mathrm{ms} = 0.20\ (M_{sph,max}/\mathrm{M}_\odot)\ \mathrm{ms}$

# Maximum Energy Density in Neutron Stars



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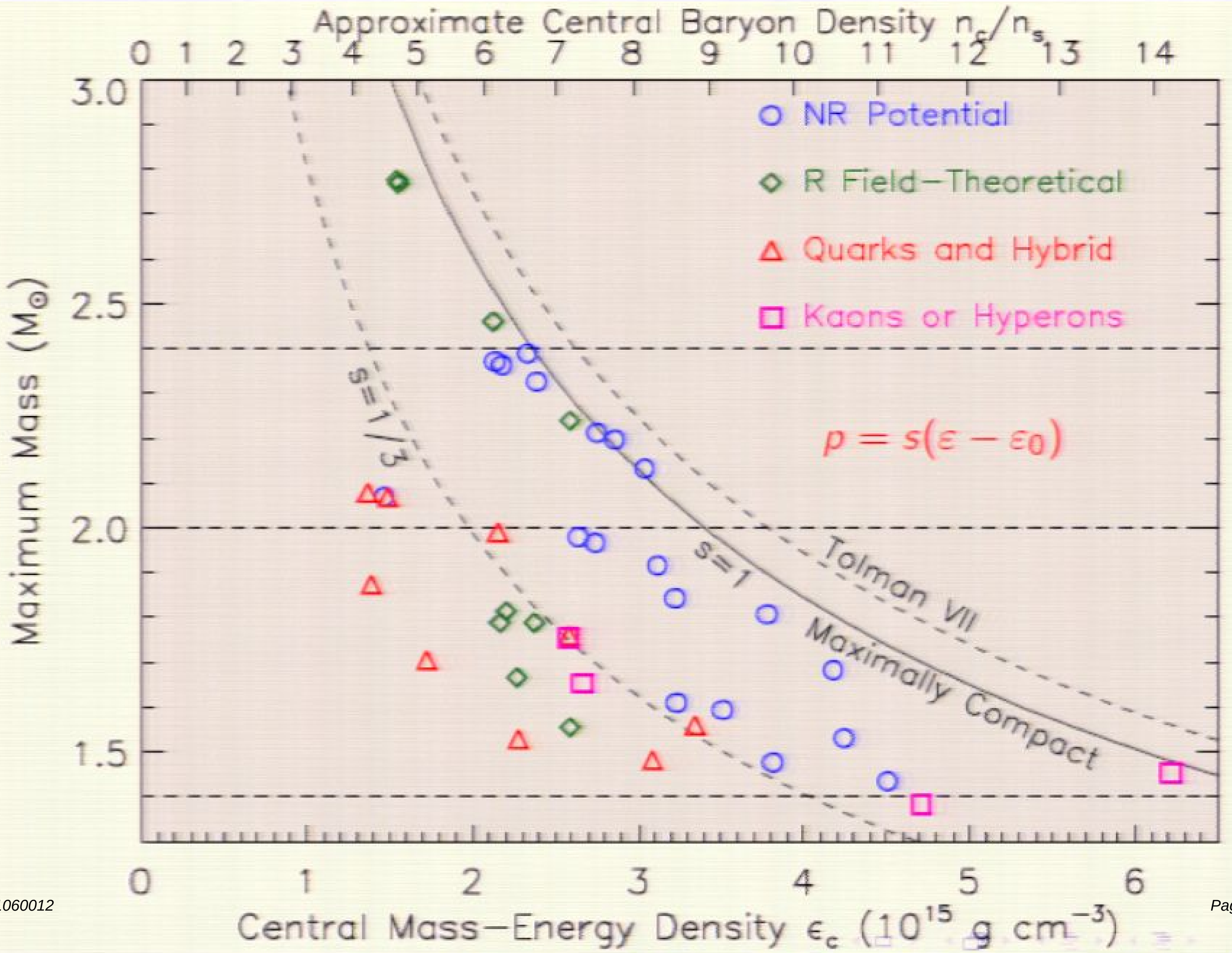


# Mass-Radius Diagram and Theoretical Constraints

GR:

$R > 2GM/c^2$

$P < \infty$ :

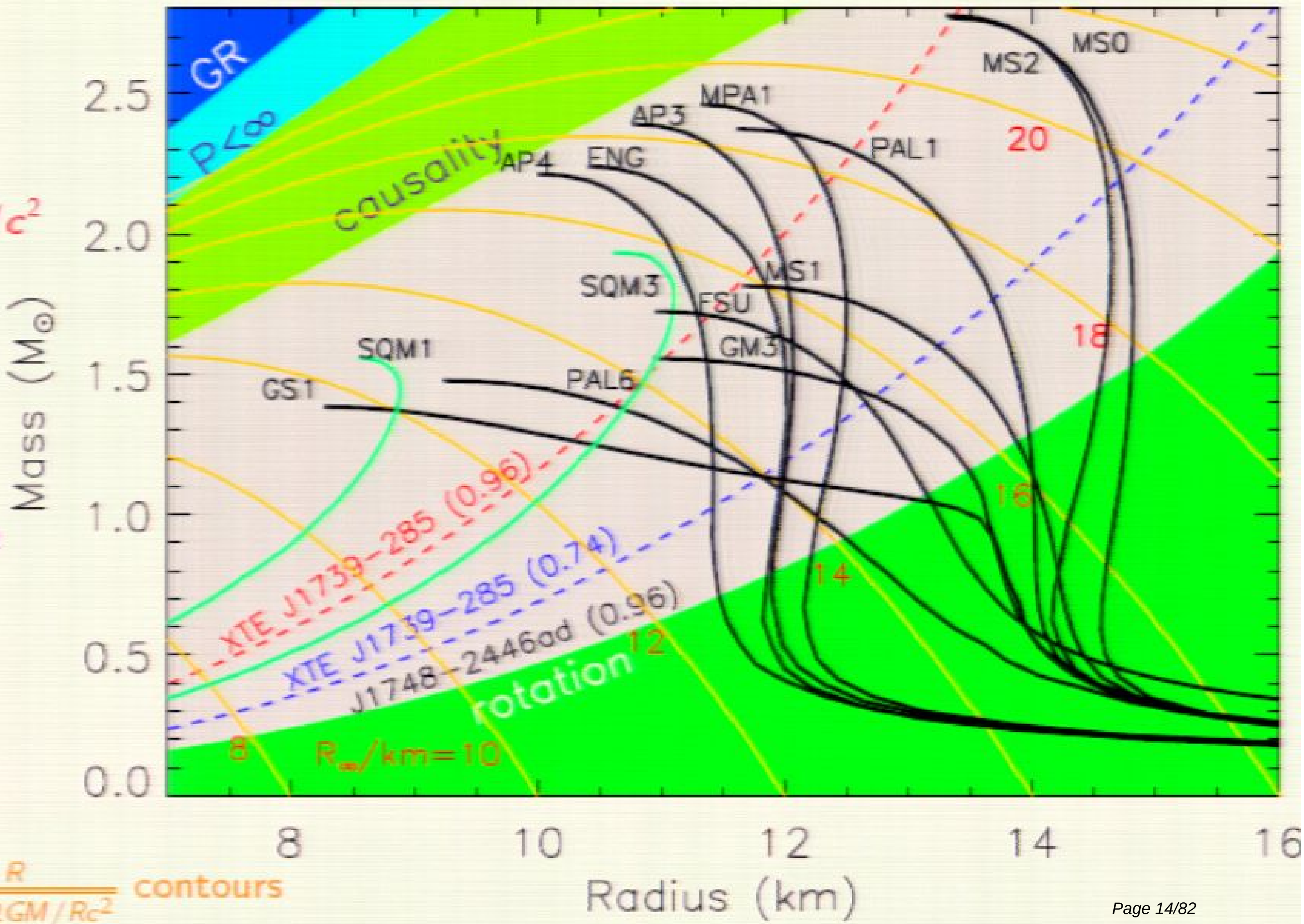
$R > (9/4)GM/c^2$

causality:

$R \gtrsim 2.9GM/c^2$

— normal NS

— SQS




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

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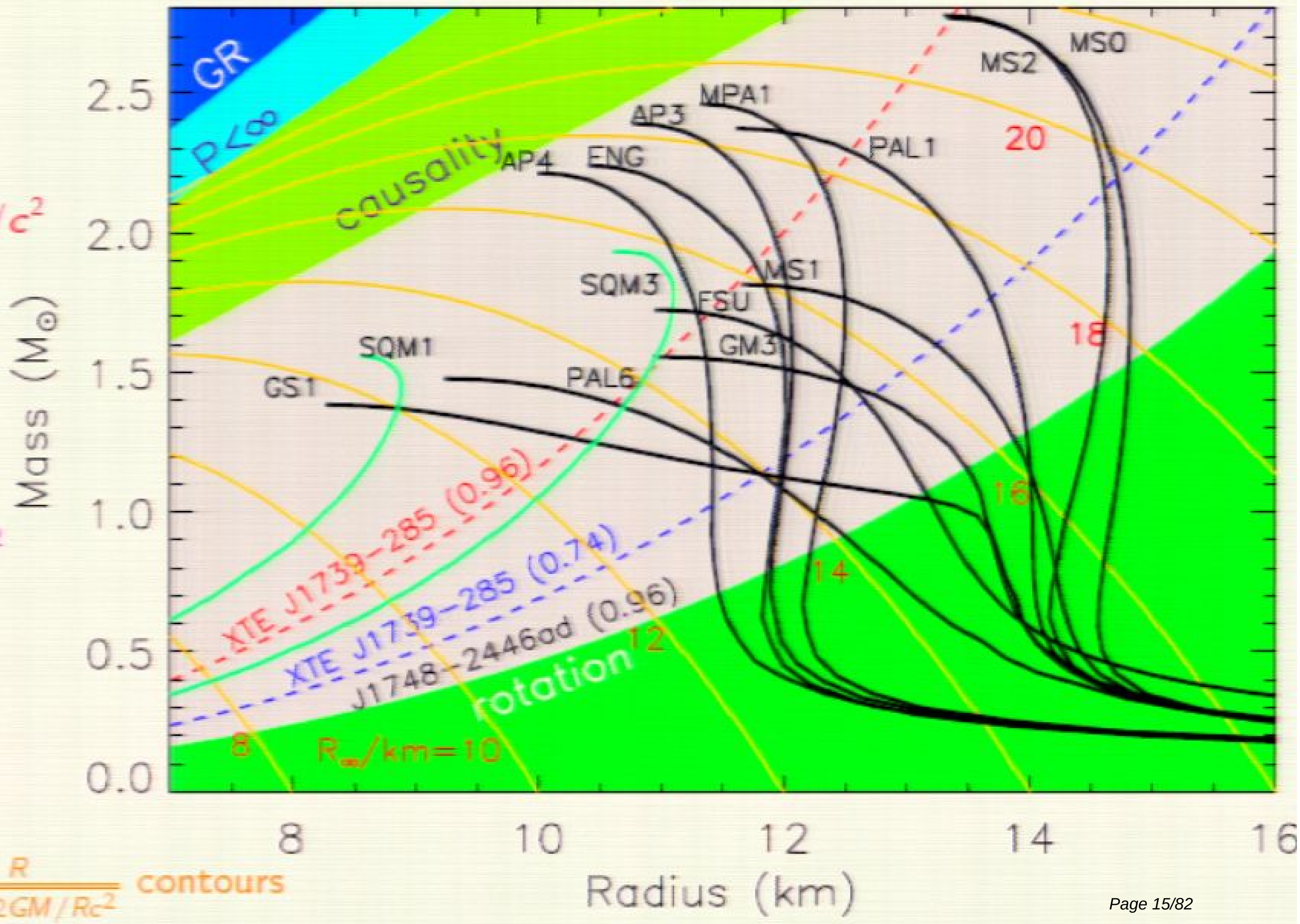


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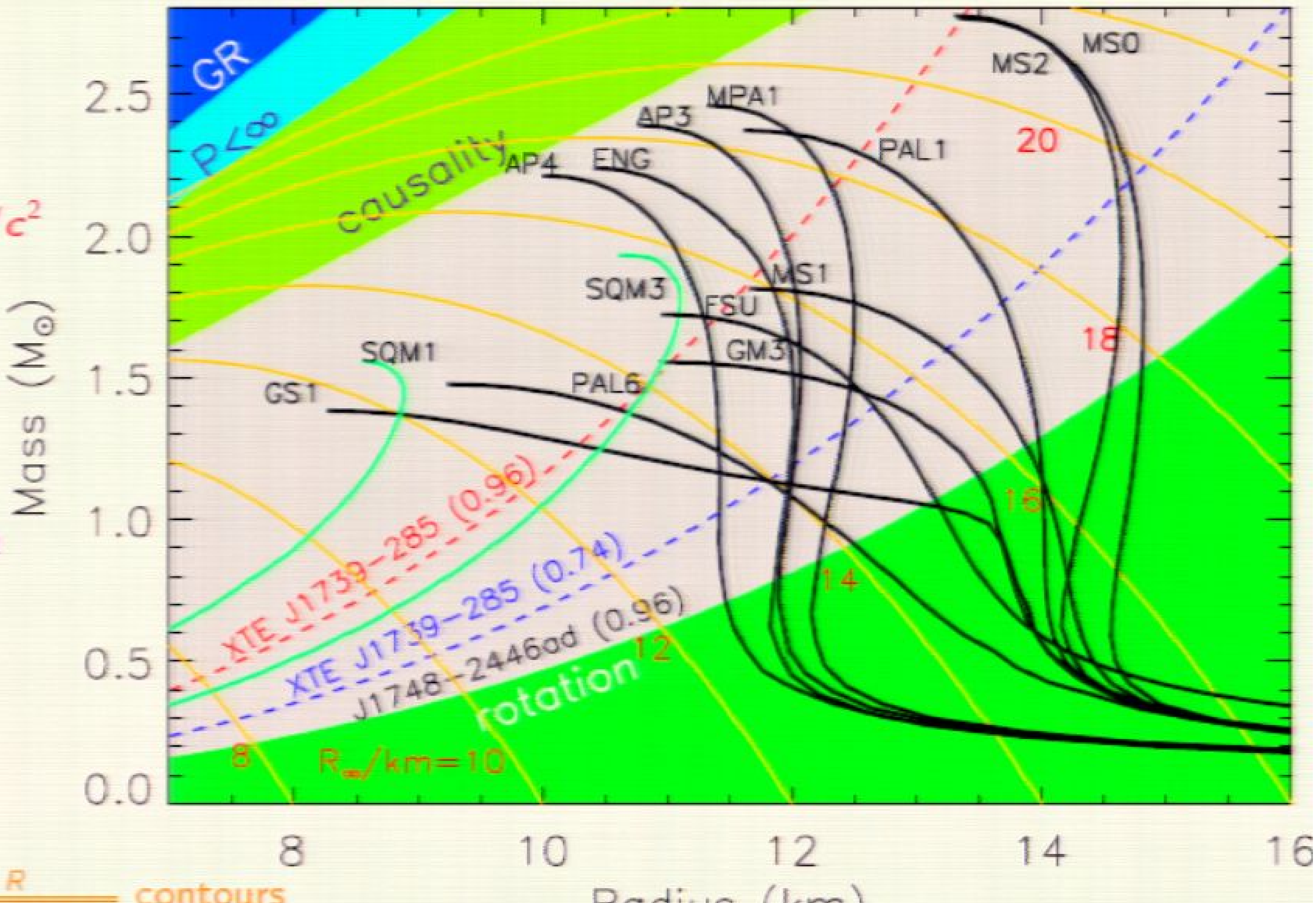


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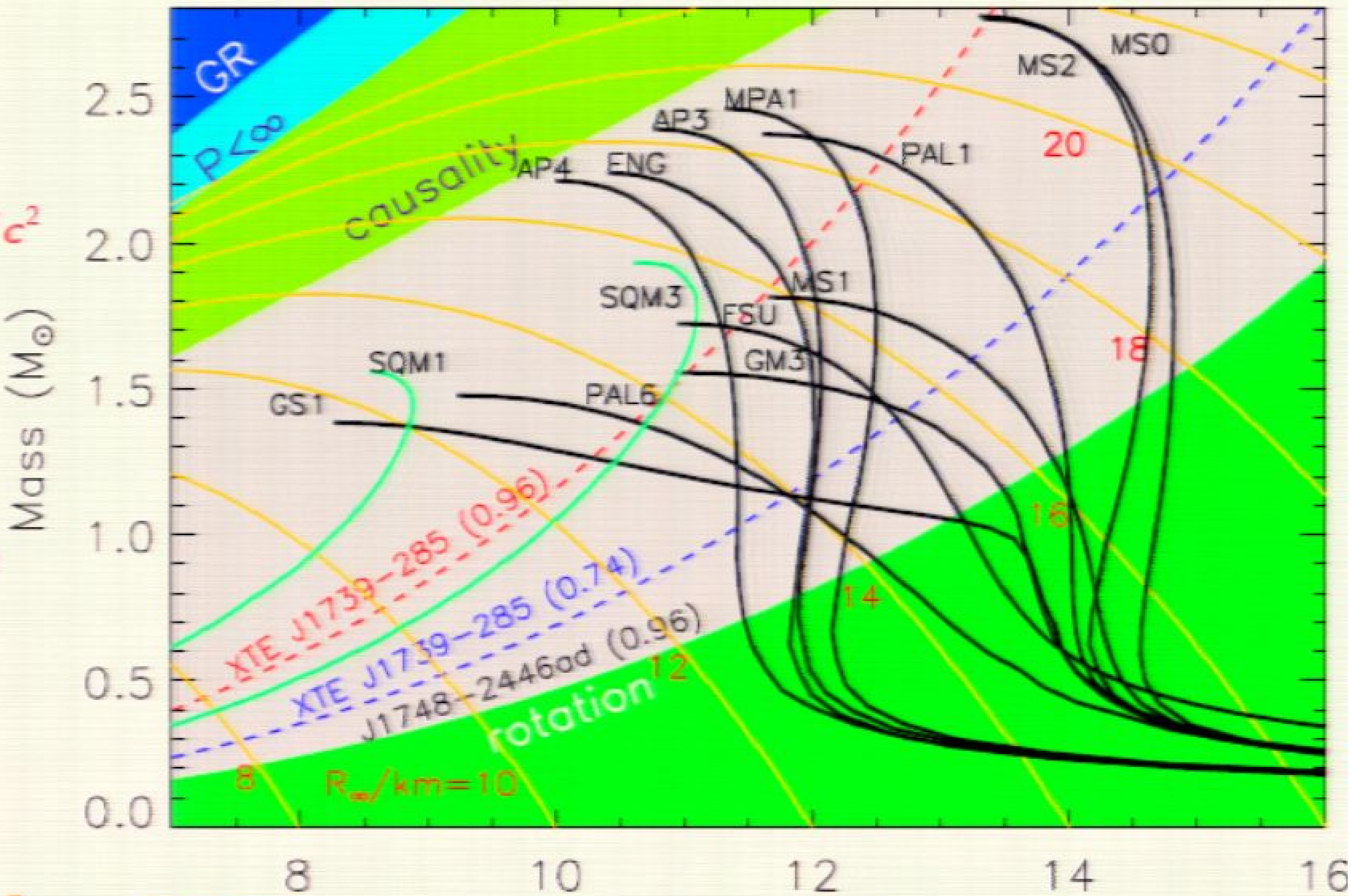

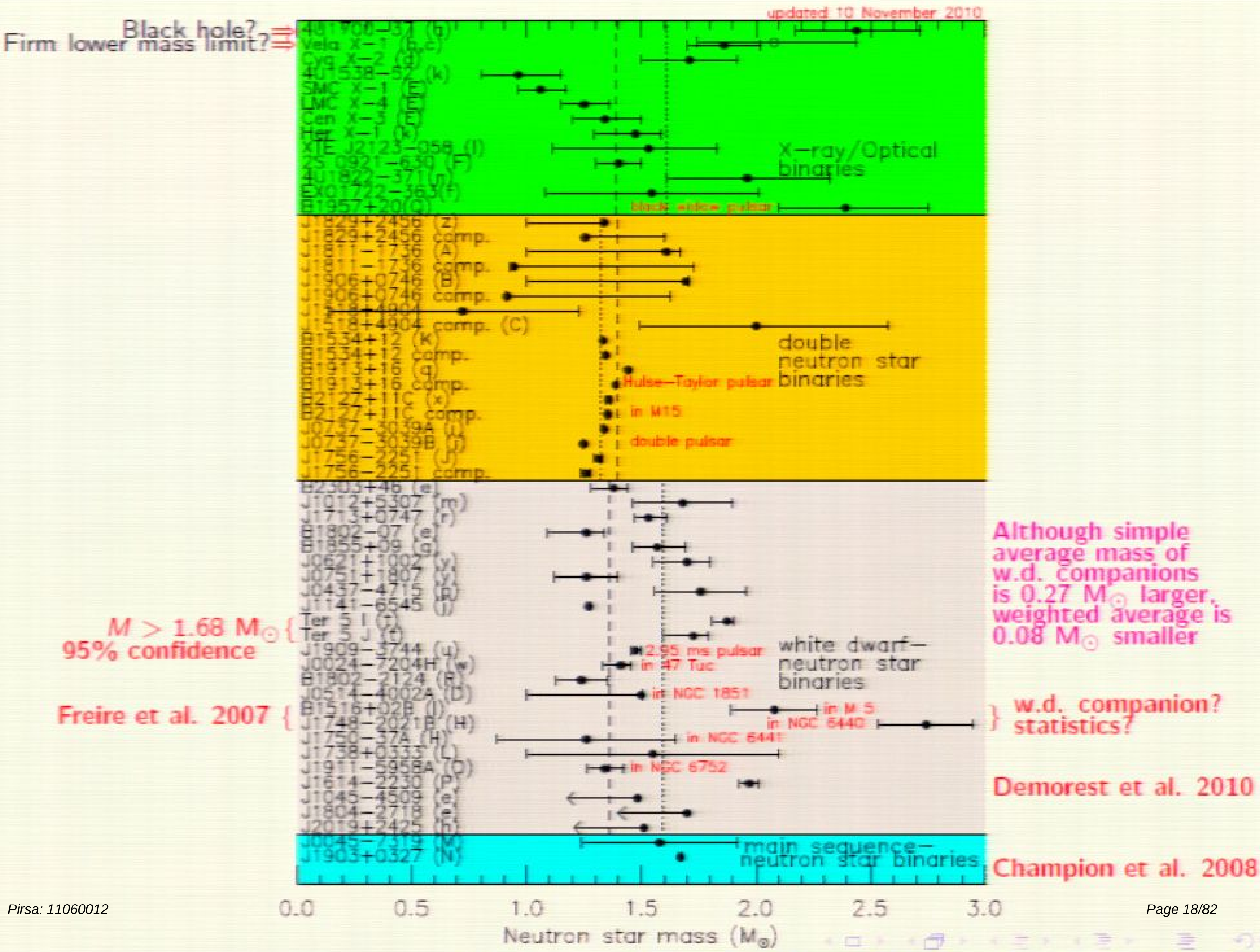
updated 10 November 2010
Black hole?
Firm lower mass limit?
4U1700−37 (b)
Vela X−1 (b,c)
Cyg X−2 (d)
4U1538−52 (k)
SMC X−1 (E)
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X−ray/Optical binaries
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J1903+0327 (N)
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Neutron star mass (M⊙)
M > 1.68 M⊙ 95% confidence
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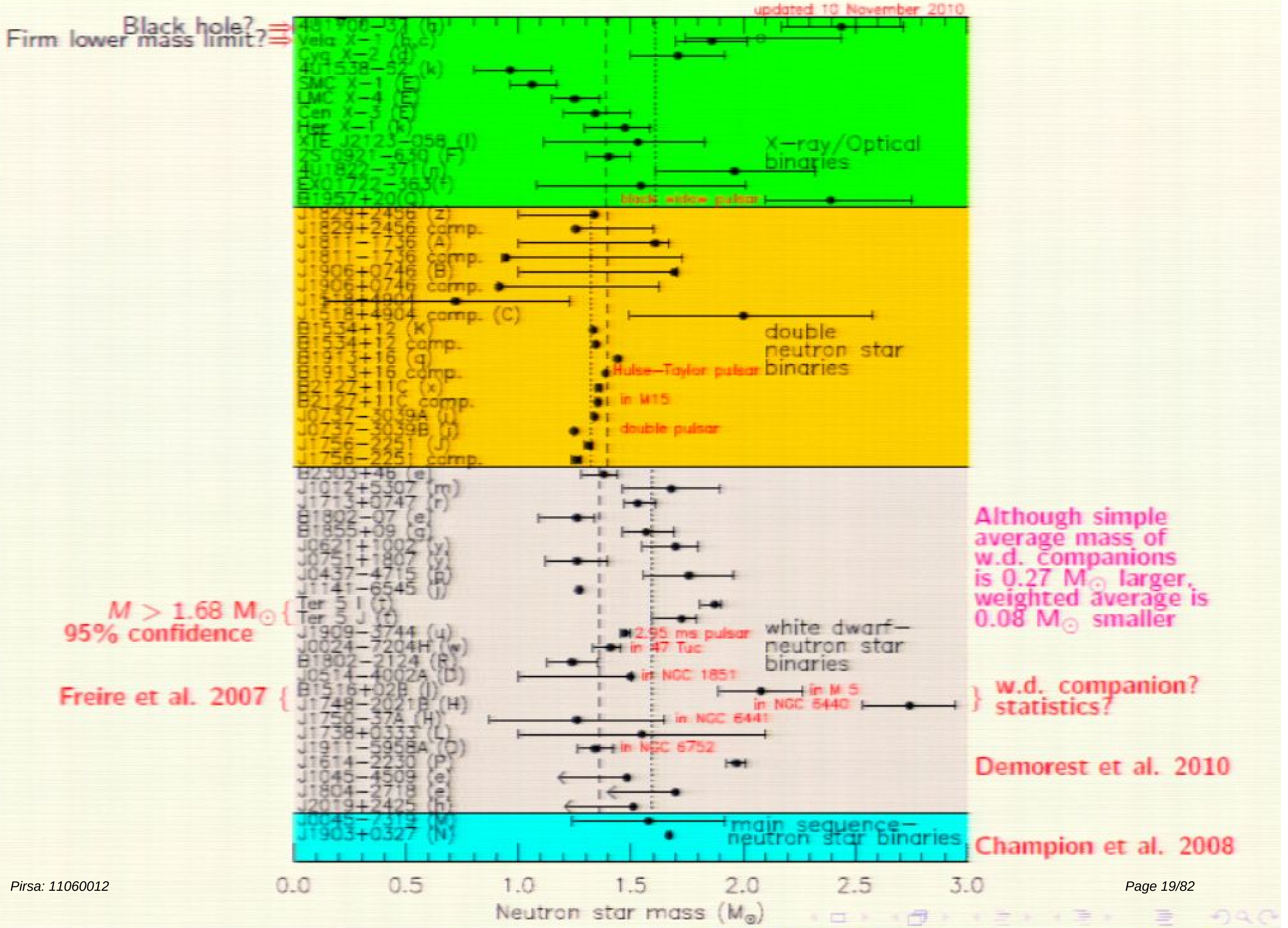
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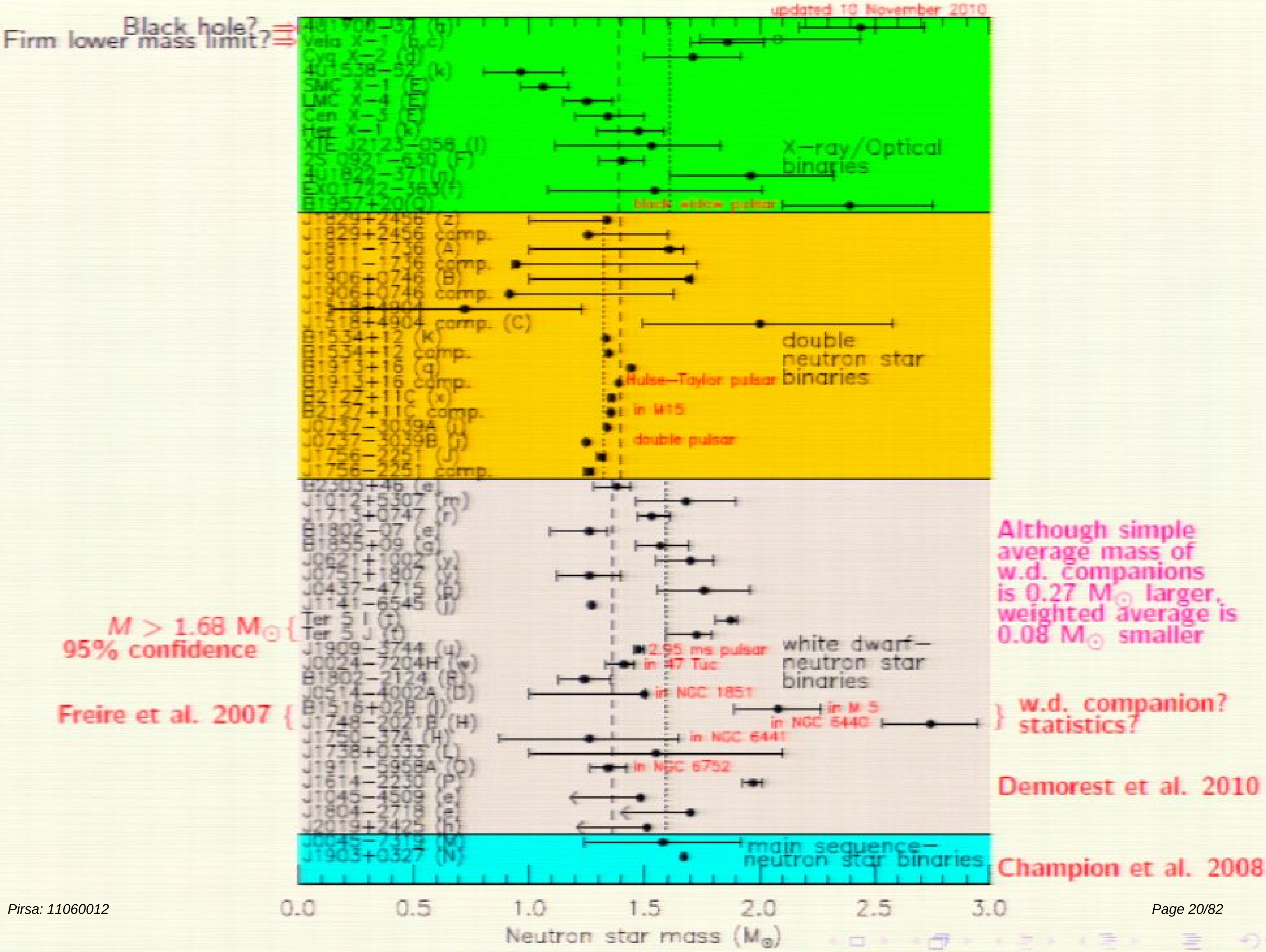

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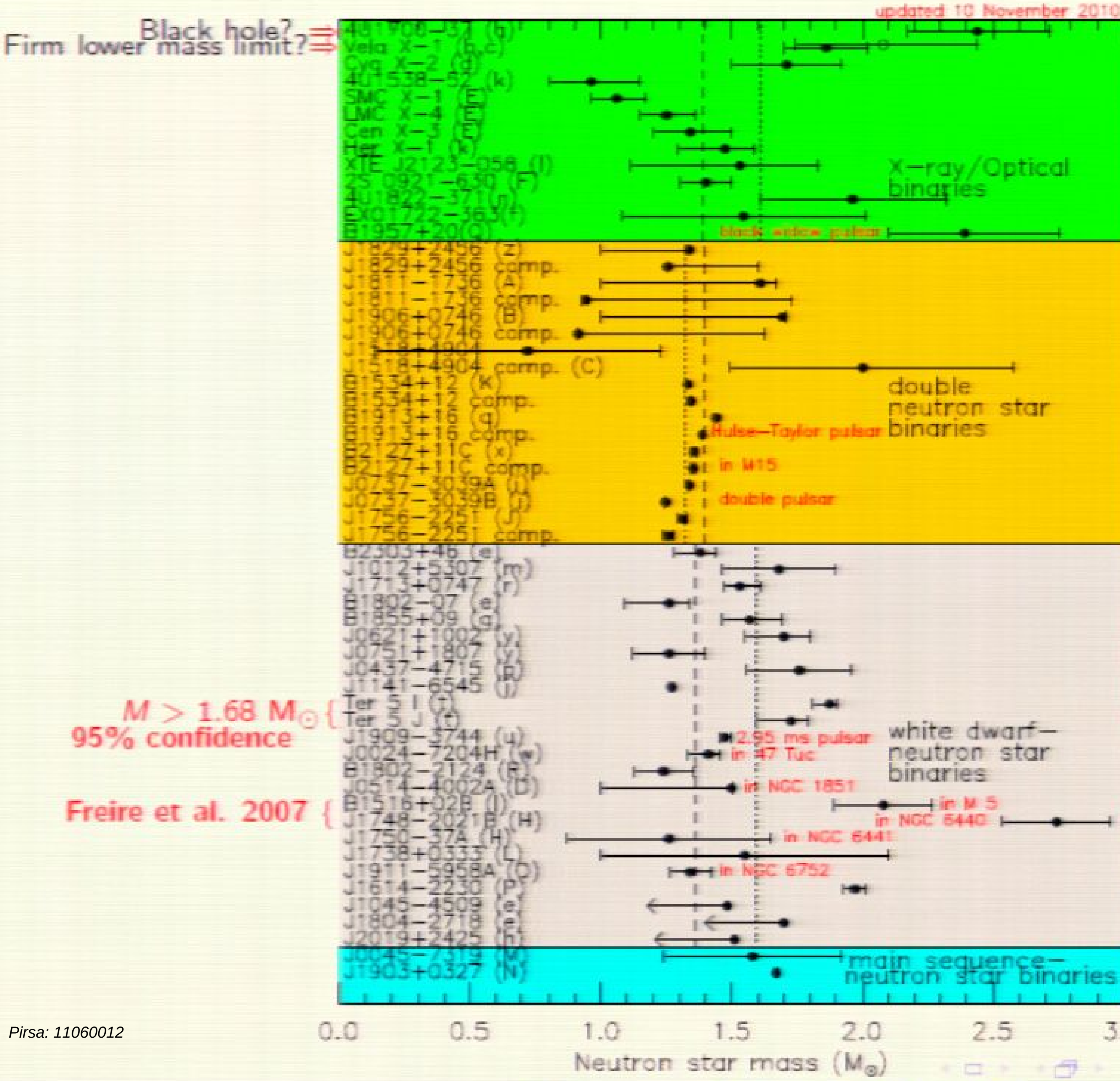


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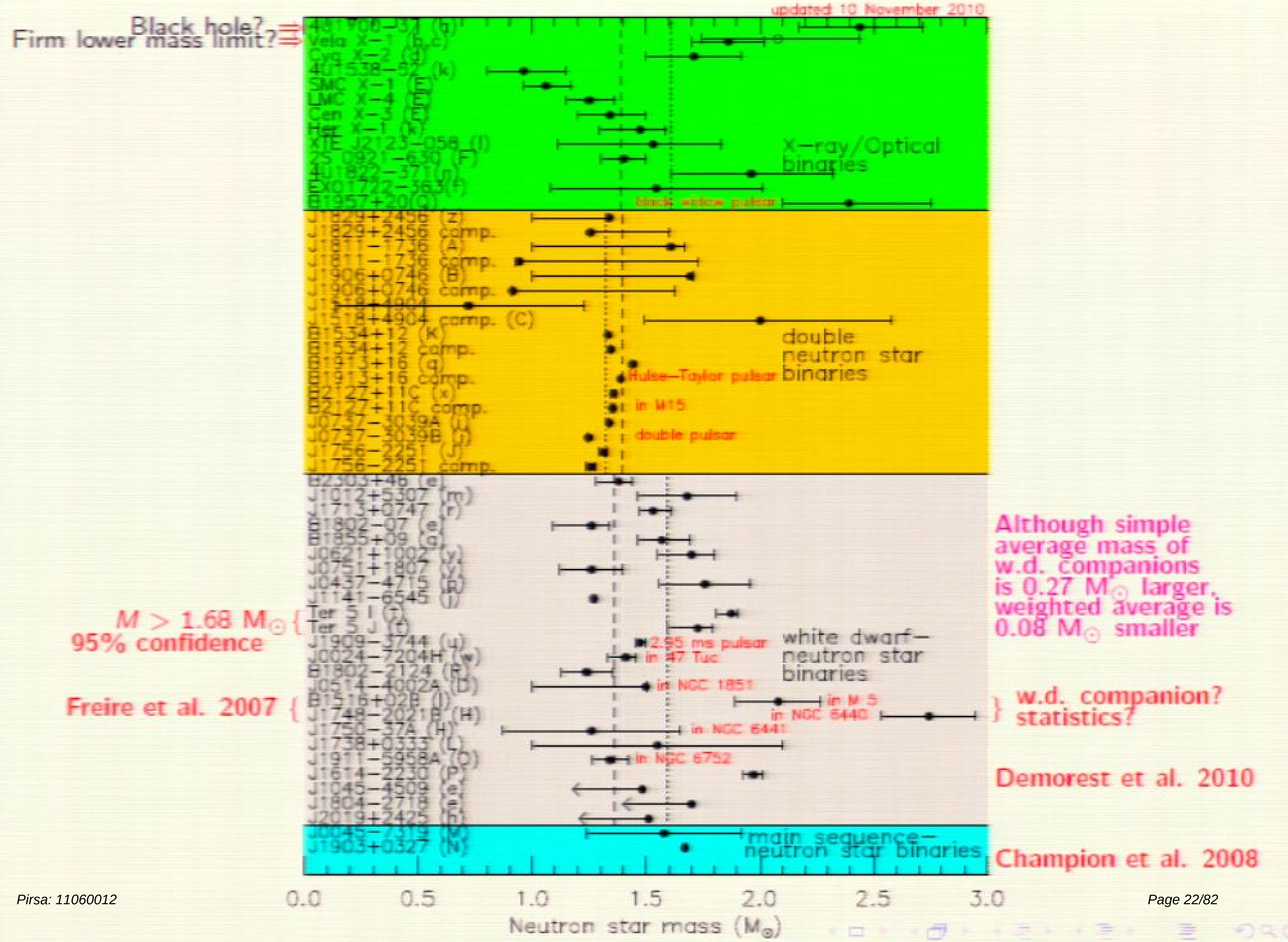
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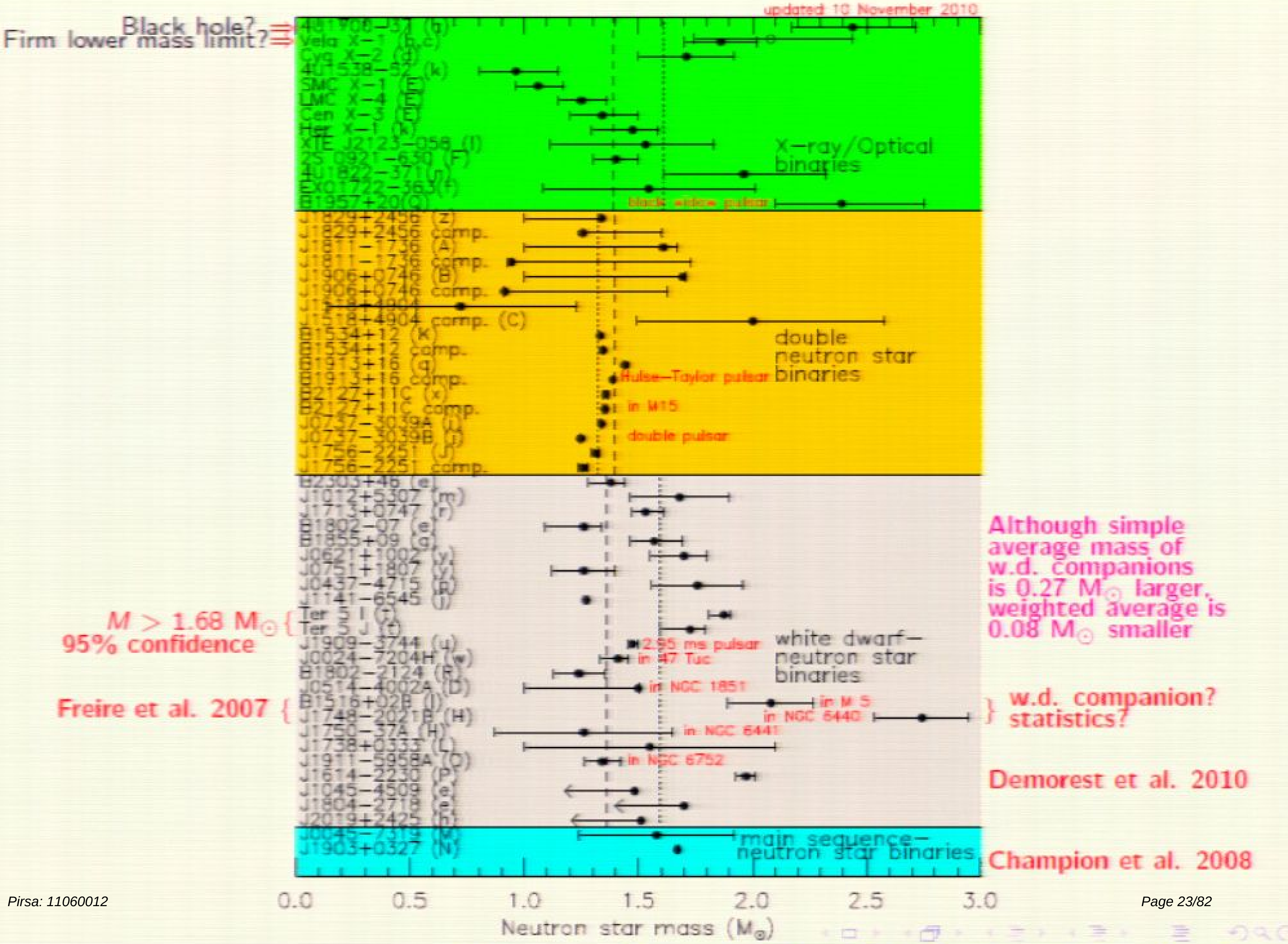

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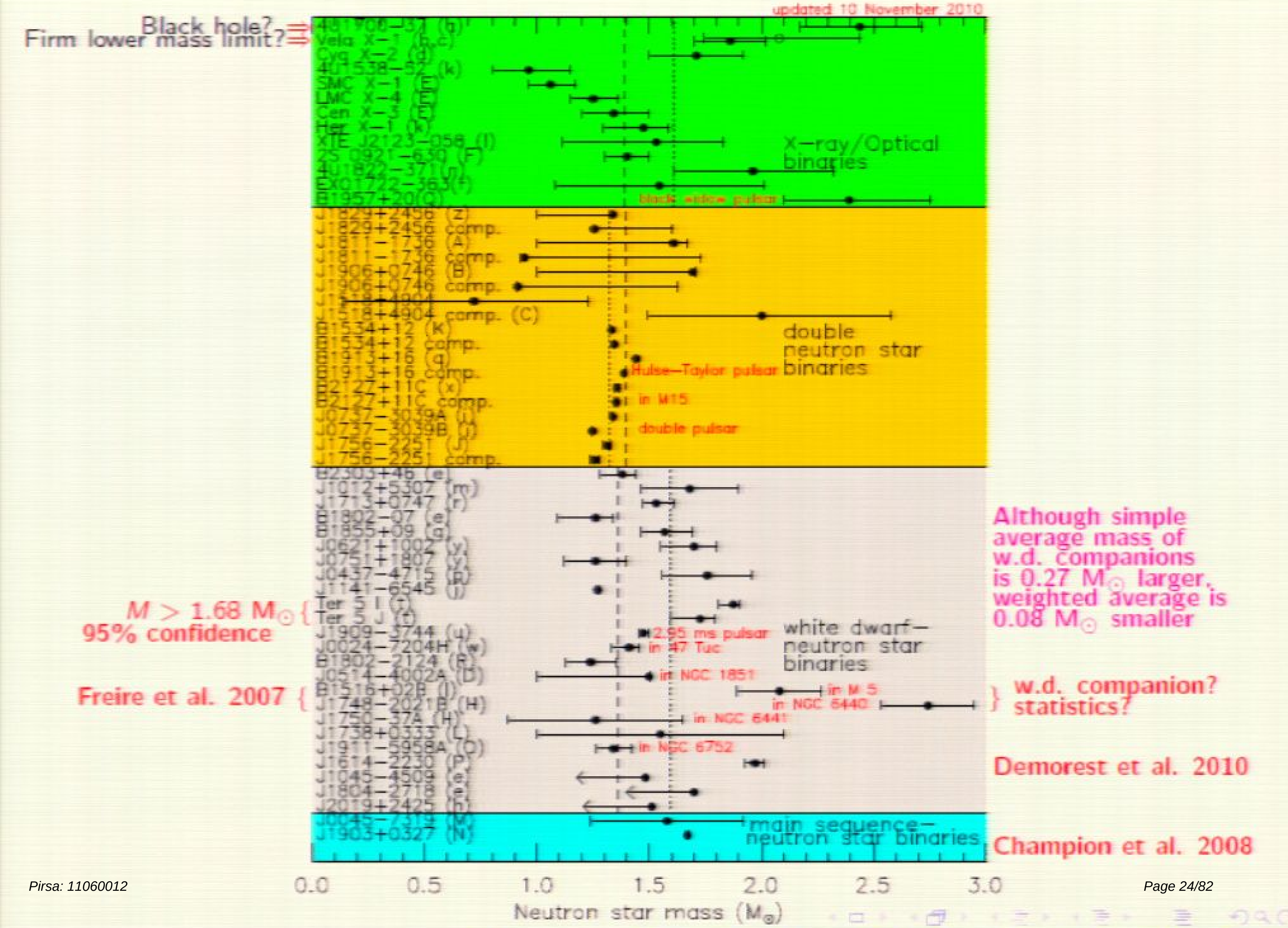

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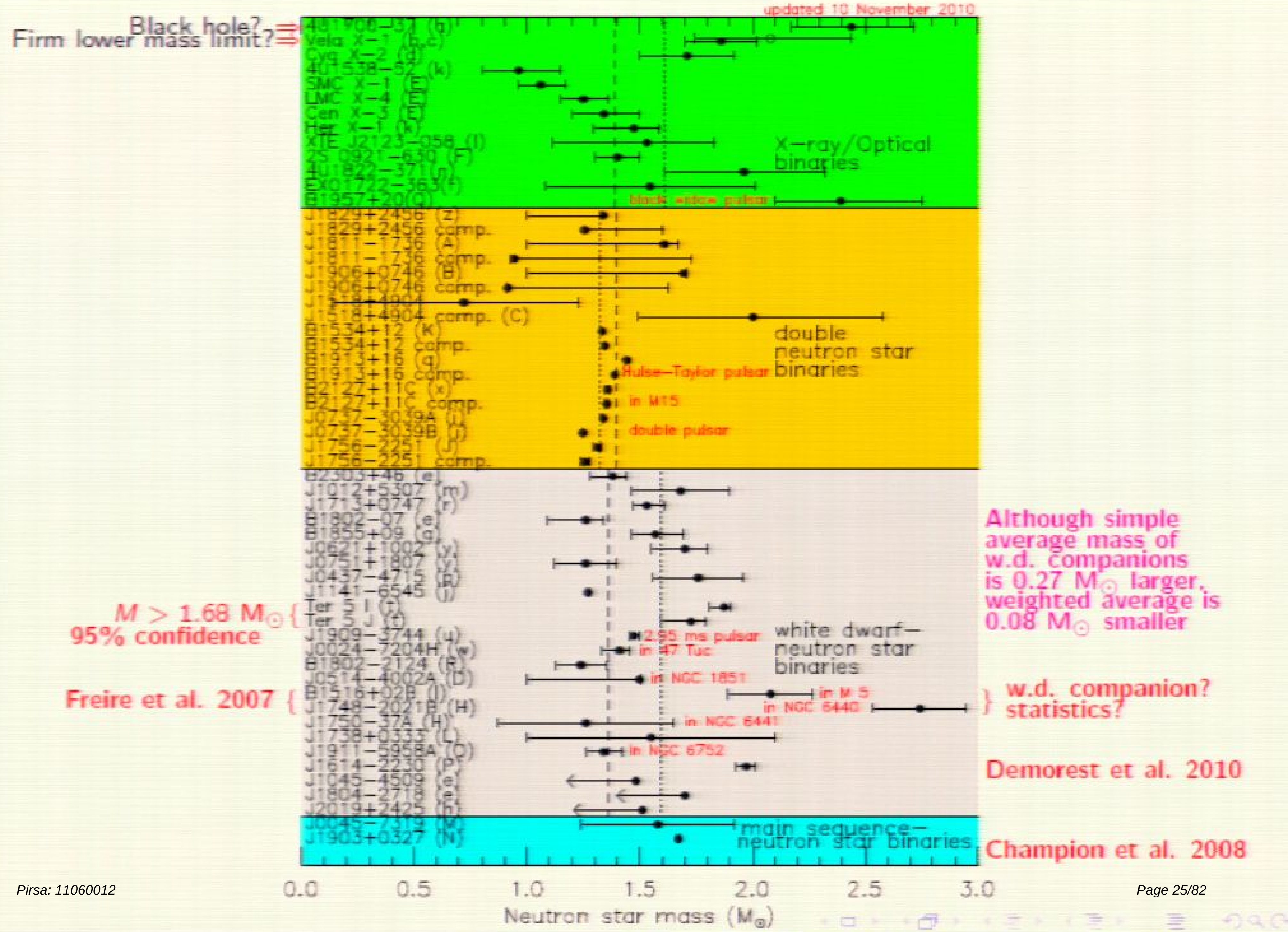
updated 10 November 2010
Black hole?
Firm lower mass limit?
X-ray/Optical binaries
double neutron star binaries
white dwarf-neutron star binaries
main sequence-neutron star binaries
Although simple average mass of w.d. companions is 0.27 M⊙ larger, weighted average is 0.08 M⊙ smaller
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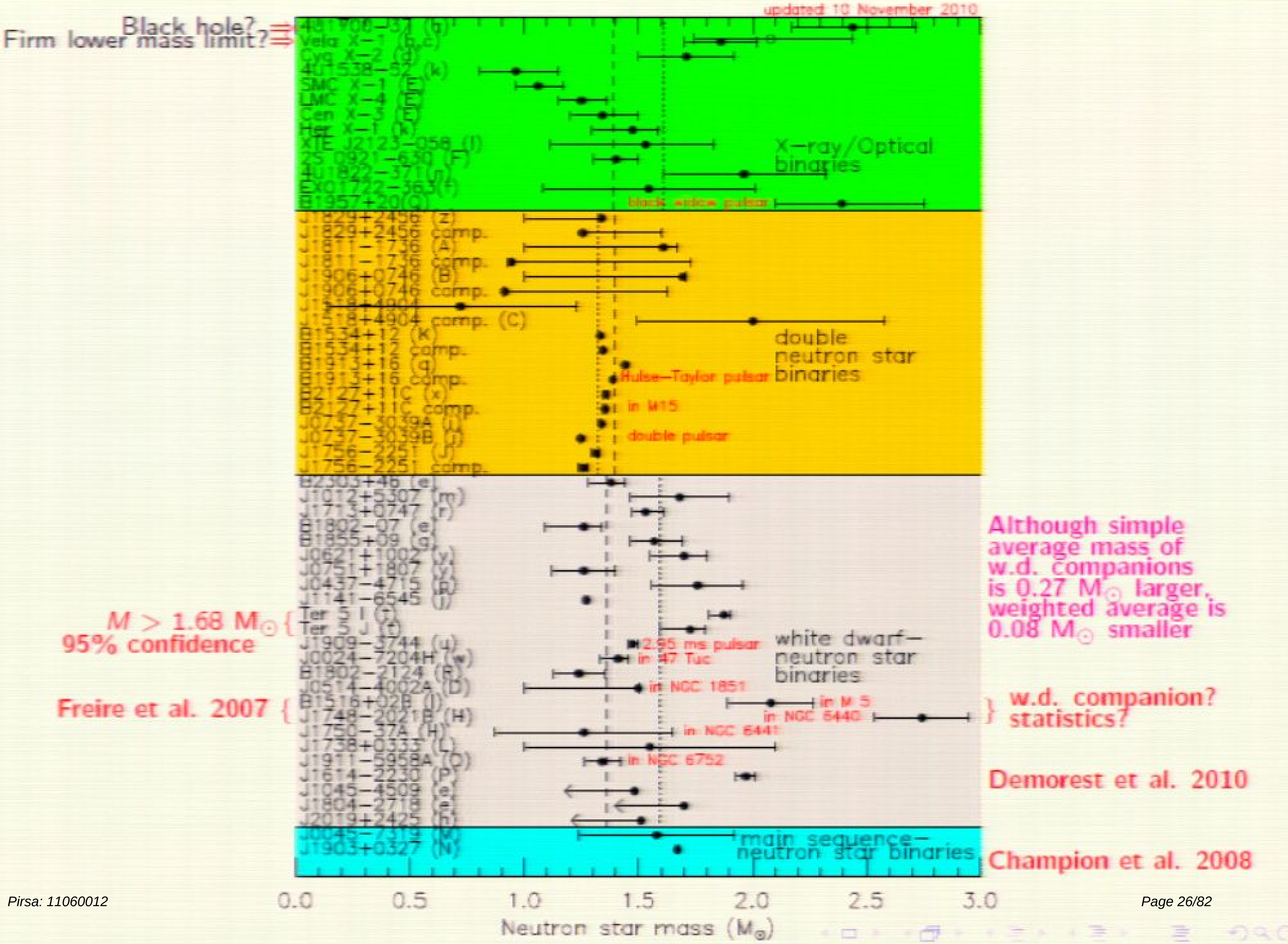
Freire et al. 2007
w.d. companion? statistics?
Demorest et al. 2010
Champion et al. 2008
Neutron star mass (M⊙)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Black hole?
Firm lower mass limit?
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in M15
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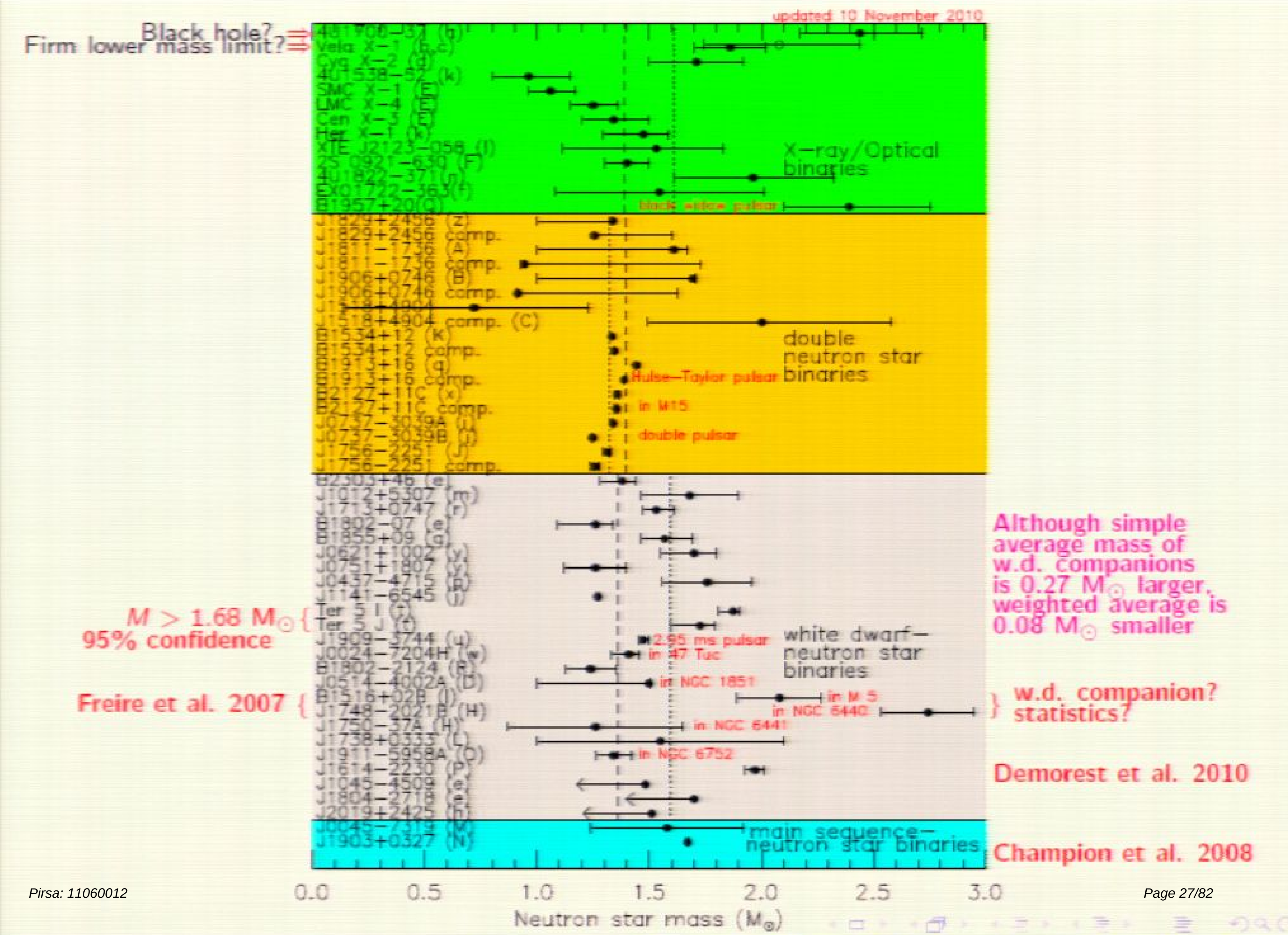
Champion et al. 2008
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Neutron star mass (M☉)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Black hole?
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0.0
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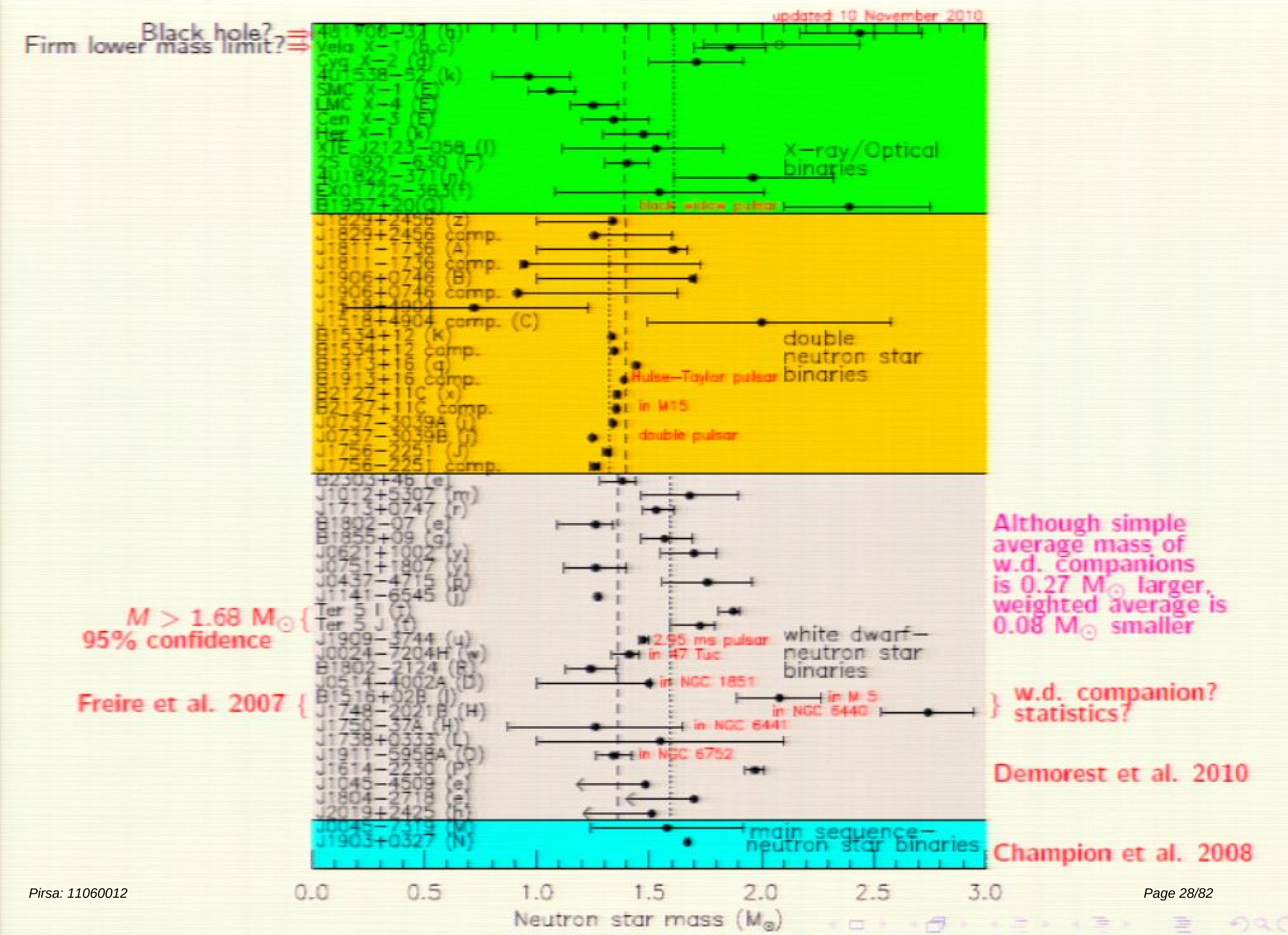
1.0
1.5
2.0
2.5
3.0
Neutron star mass (M☉)



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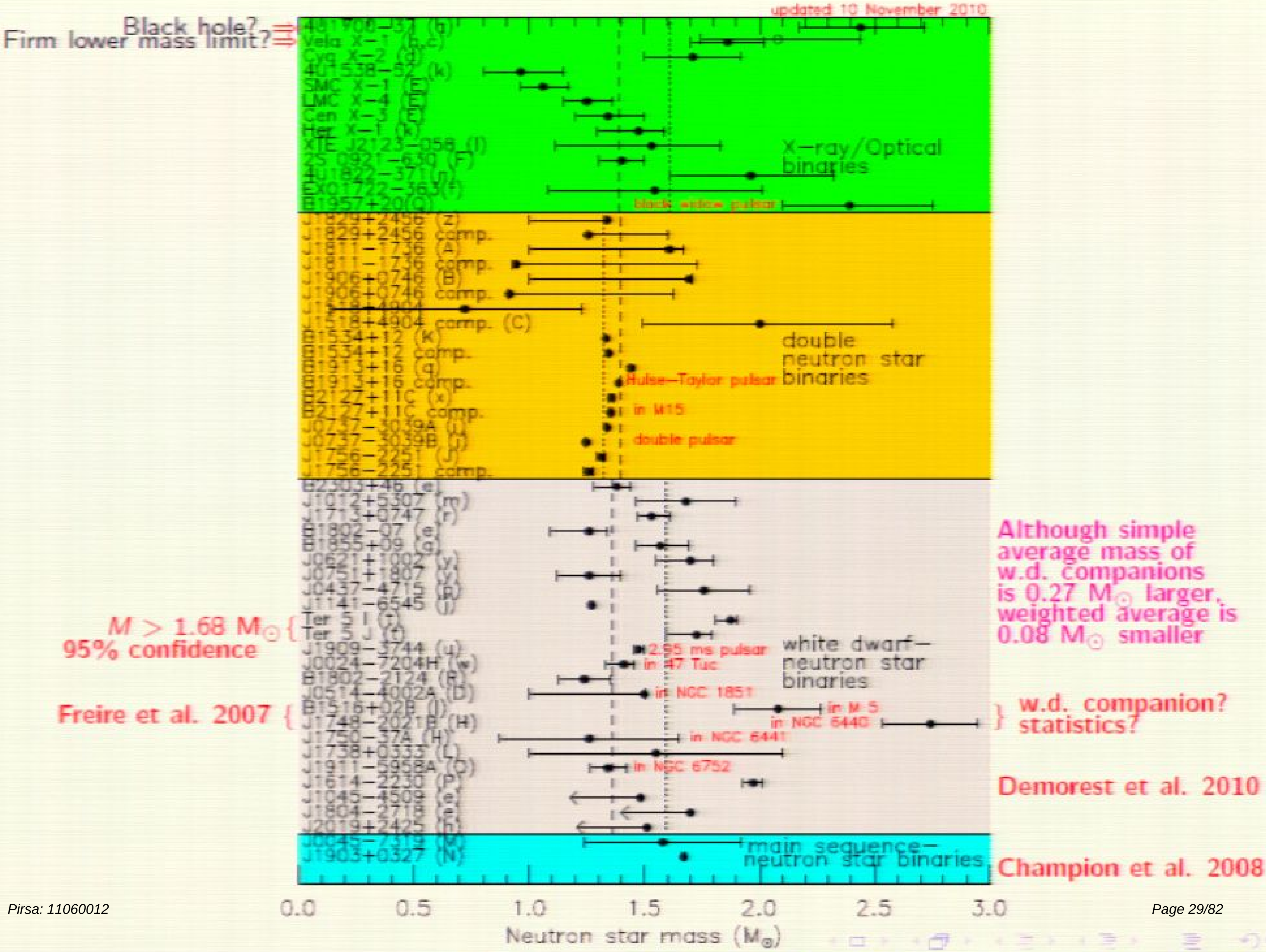
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Neutron star mass ($M_\odot$)



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Black hole?
Firm lower mass limit?
4U1700−37
Vela X−1
Cyg X−2
4U1538−52
SMC X−1
LMC X−4
Cen X−3
Her X−1
XTE J2123−058
2S 0921−630
4U1822−371
EXO1722−363
B1957+20
black widow pulsar
X−ray/Optical binaries
J1829+2456
J1829+2456 comp.
J1811−1736
J1811−1736 comp.
J1906+0746
J1906+0746 comp.
J1518+4904
J1518+4904 comp.
B1534+12
B1534+12 comp.
B1913+16
B1913+16 comp.
Hulse−Taylor pulsar
B2127+11C
B2127+11C comp.
in M15
J0737−3039A
J0737−3039B
double pulsar
J1756−2251
J1756−2251 comp.
double neutron star binaries
B2303+46
J1012+5307
J1713+0747
B1802−07
B1855+09
J0621+1002
J0751+1807
J0437−4715
J1141−6545
Ter 5 I
Ter 5 J
J1909−3744
2.95 ms pulsar
J0024−7204H
in 47 Tuc
B1802−2124
J0514−4002A
in NGC 1851
B1516+02B
in M 5
J1748−2021B
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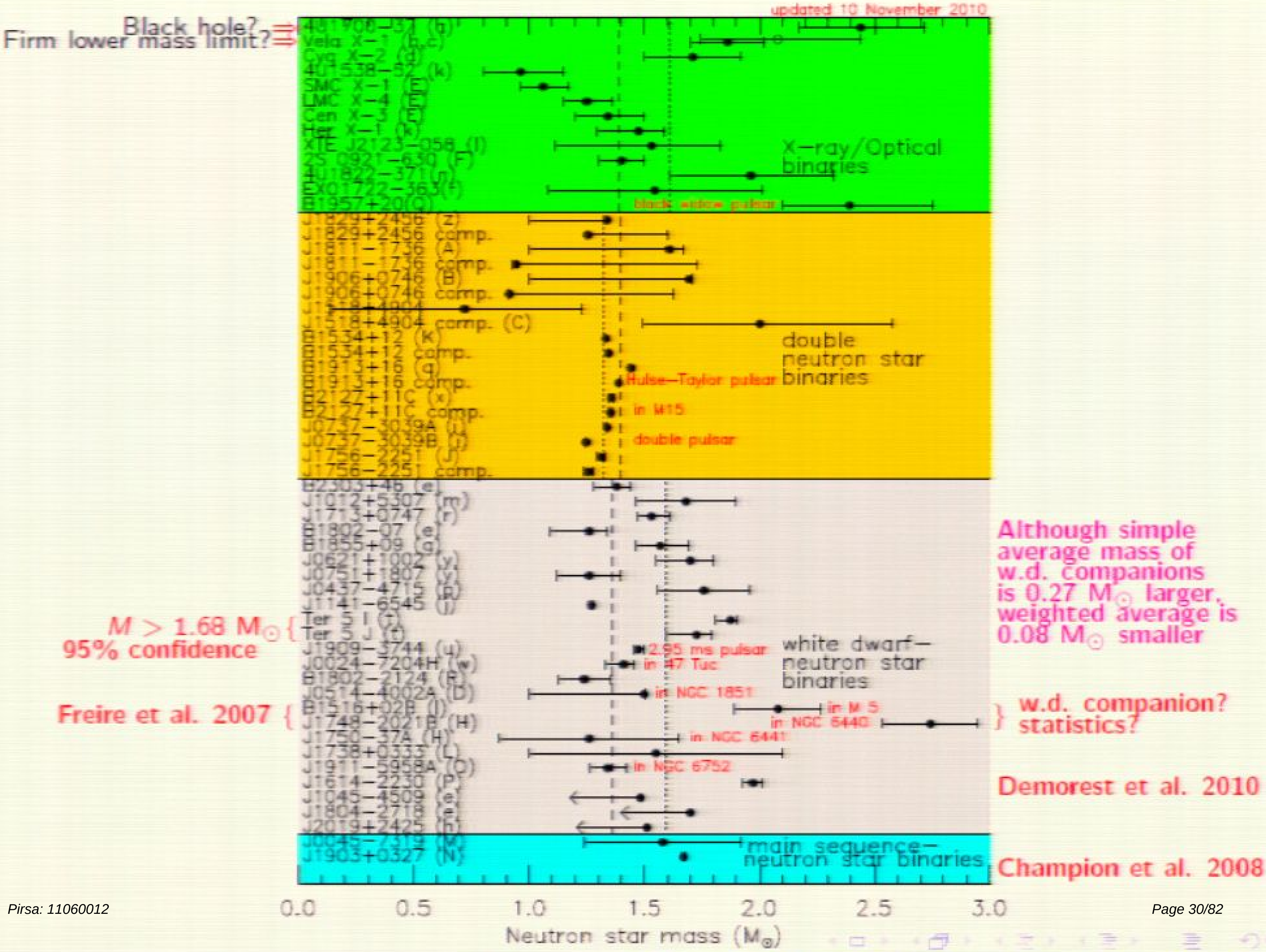
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4U1700−377 (g)
Vela X−1 (b,c)
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4U1538−52 (k)
SMC X−1 (E)
LMC X−4 (E)
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J1518+4904 comp. (C)
B1534+12 (k)
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J0737−3039A (J)
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0.0
0.5
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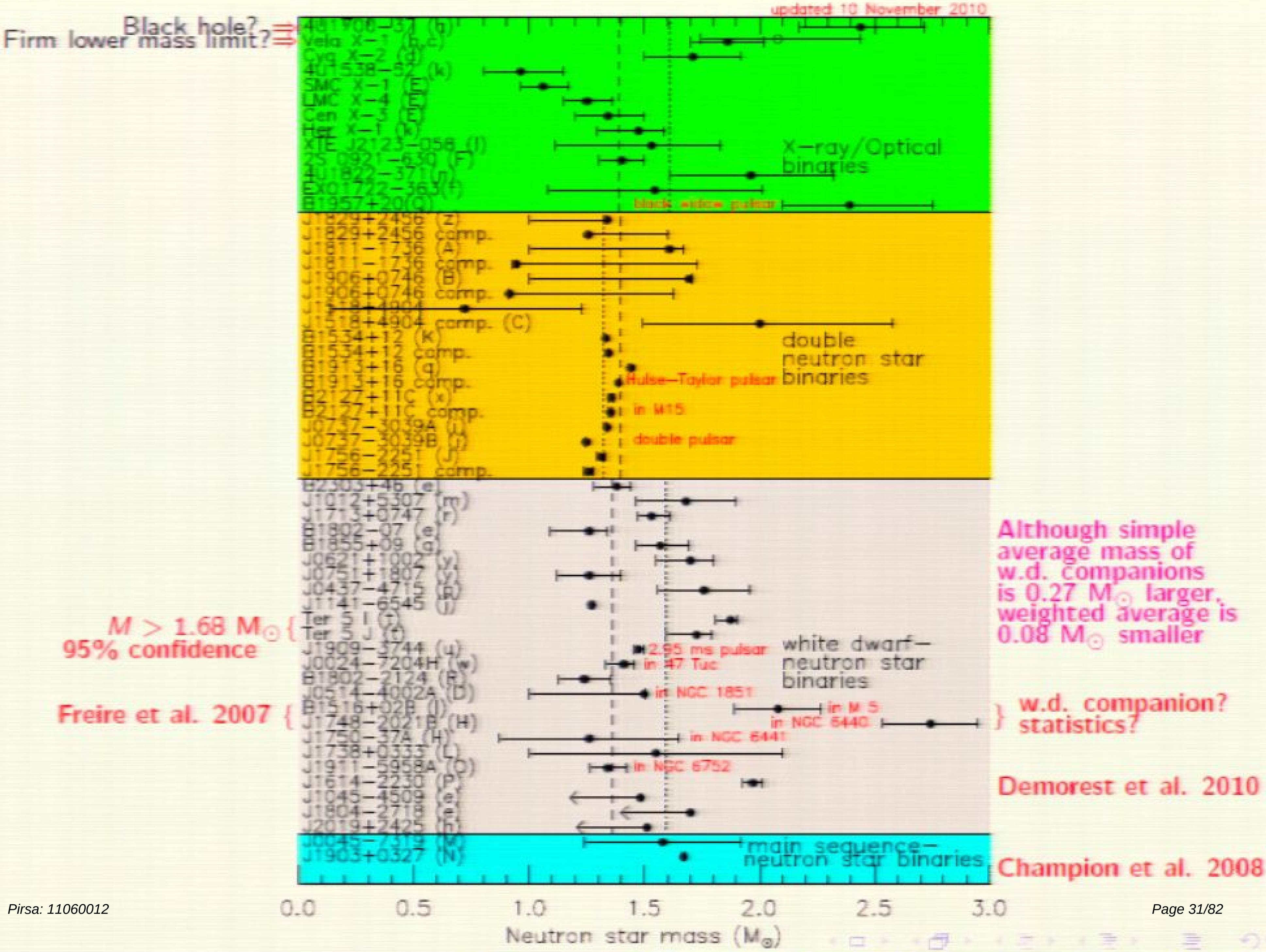
Neutron star mass ($M_\odot$)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0.0
0.5
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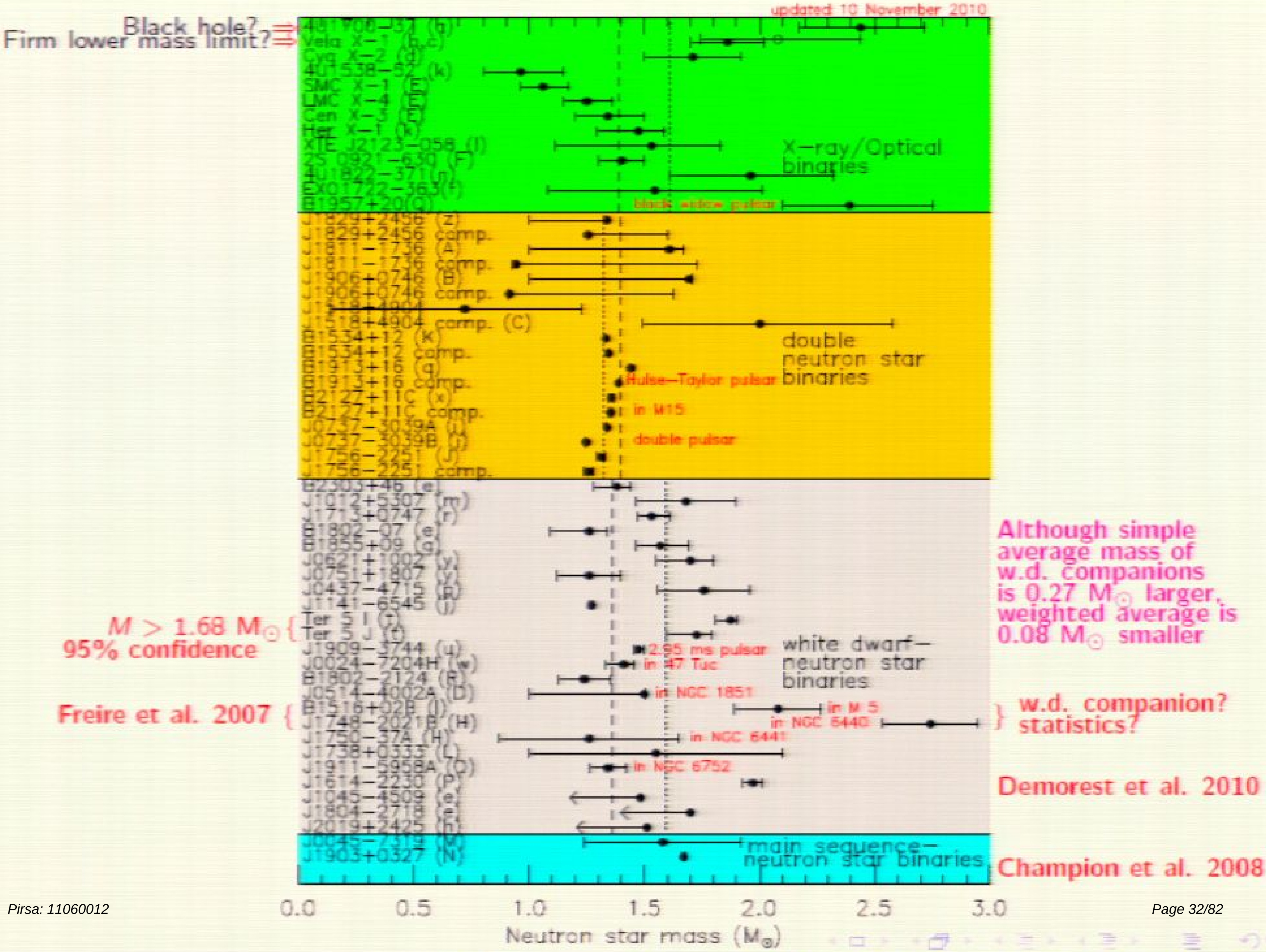
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0.0
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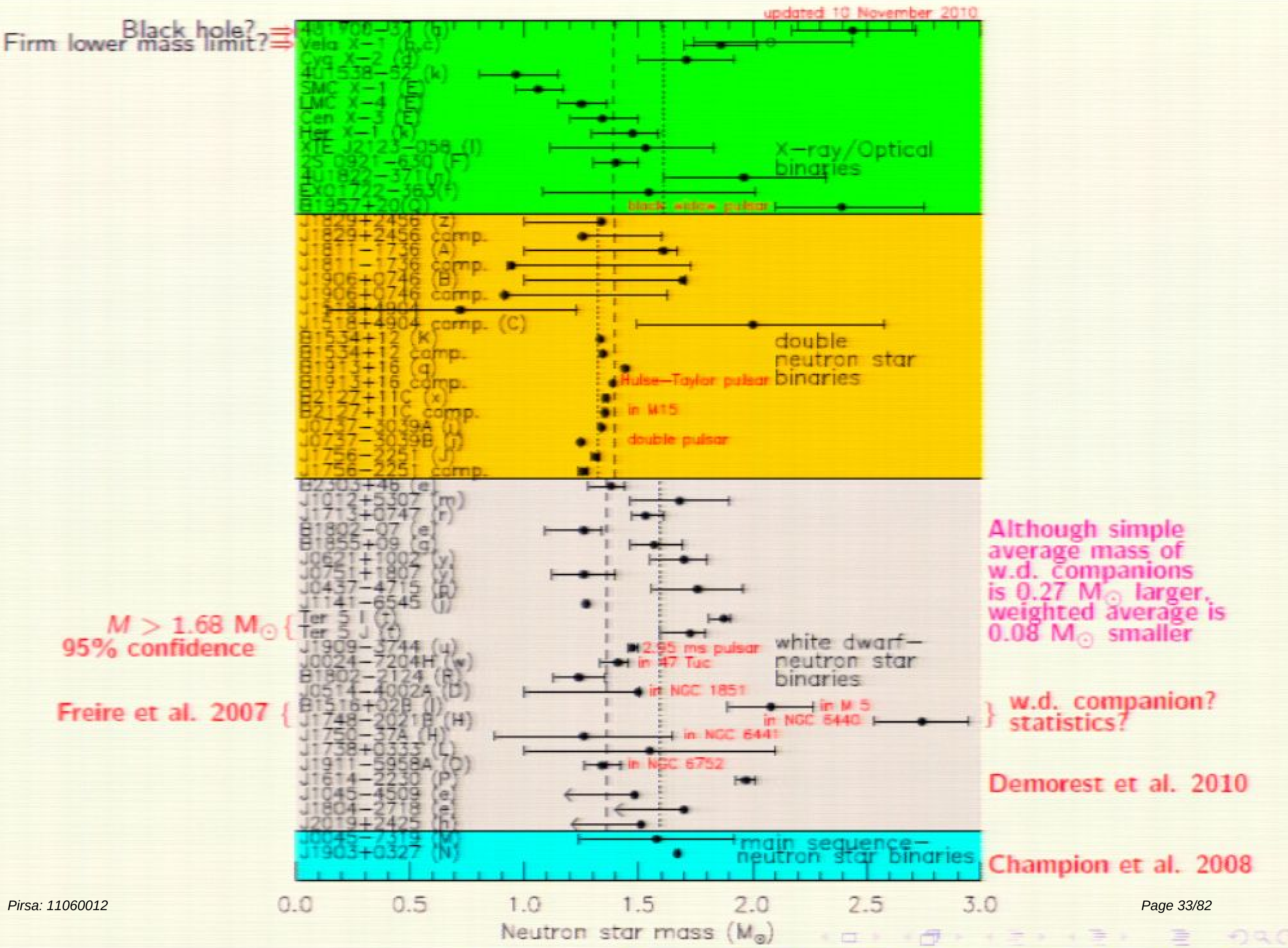

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Black hole?
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0.0
0.5
1.0
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2.5
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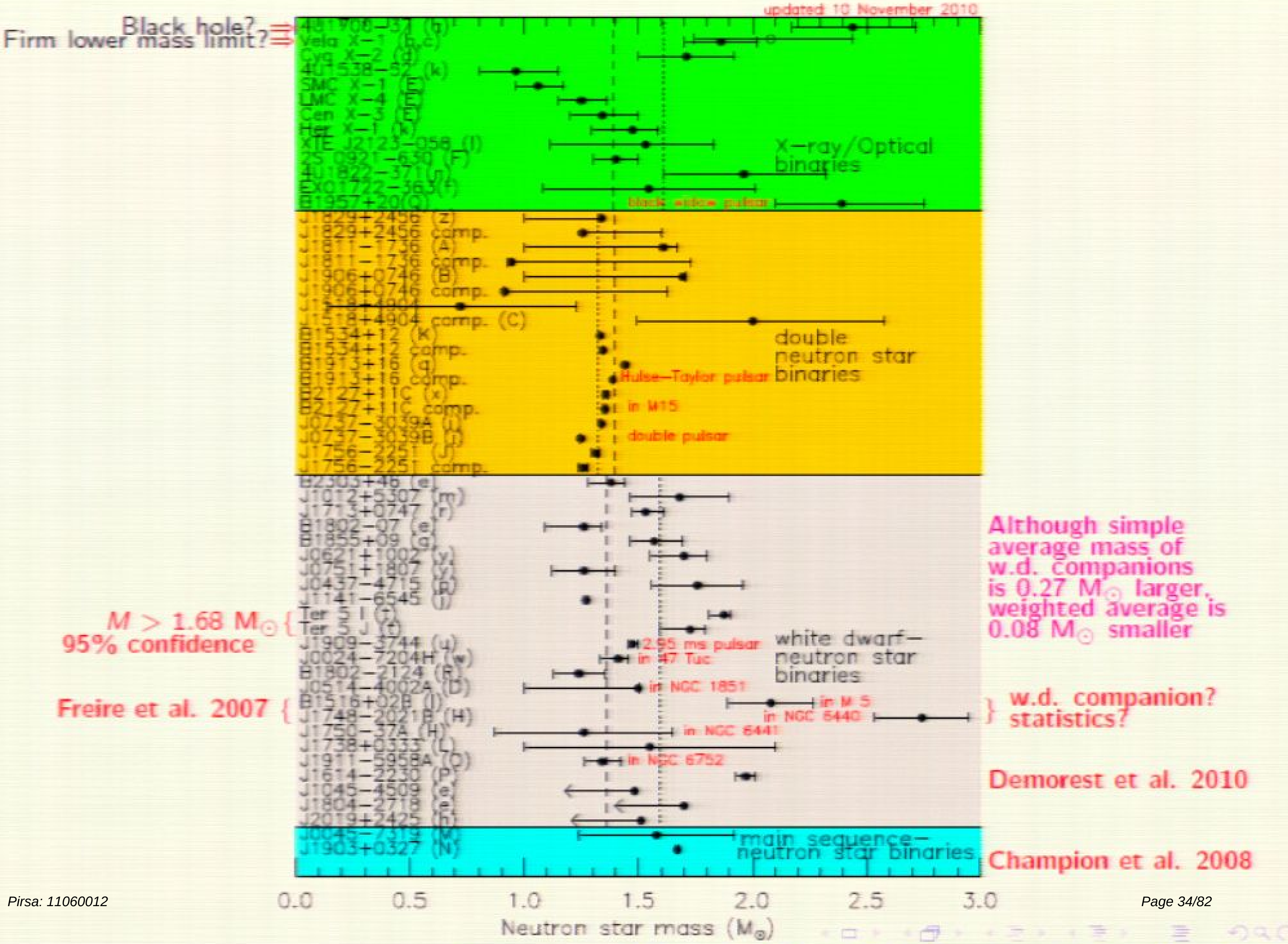
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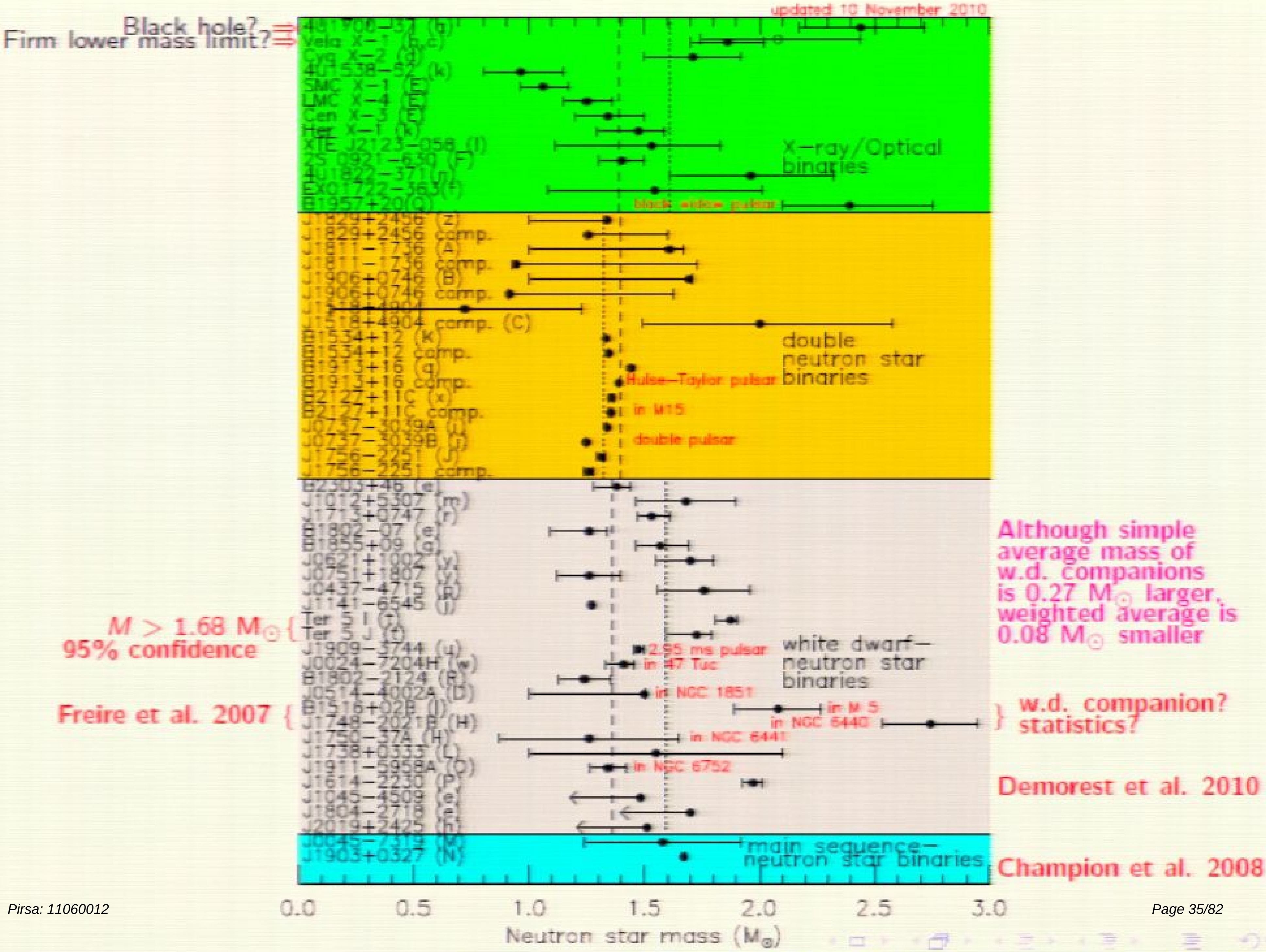
Neutron star mass ($M_\odot$)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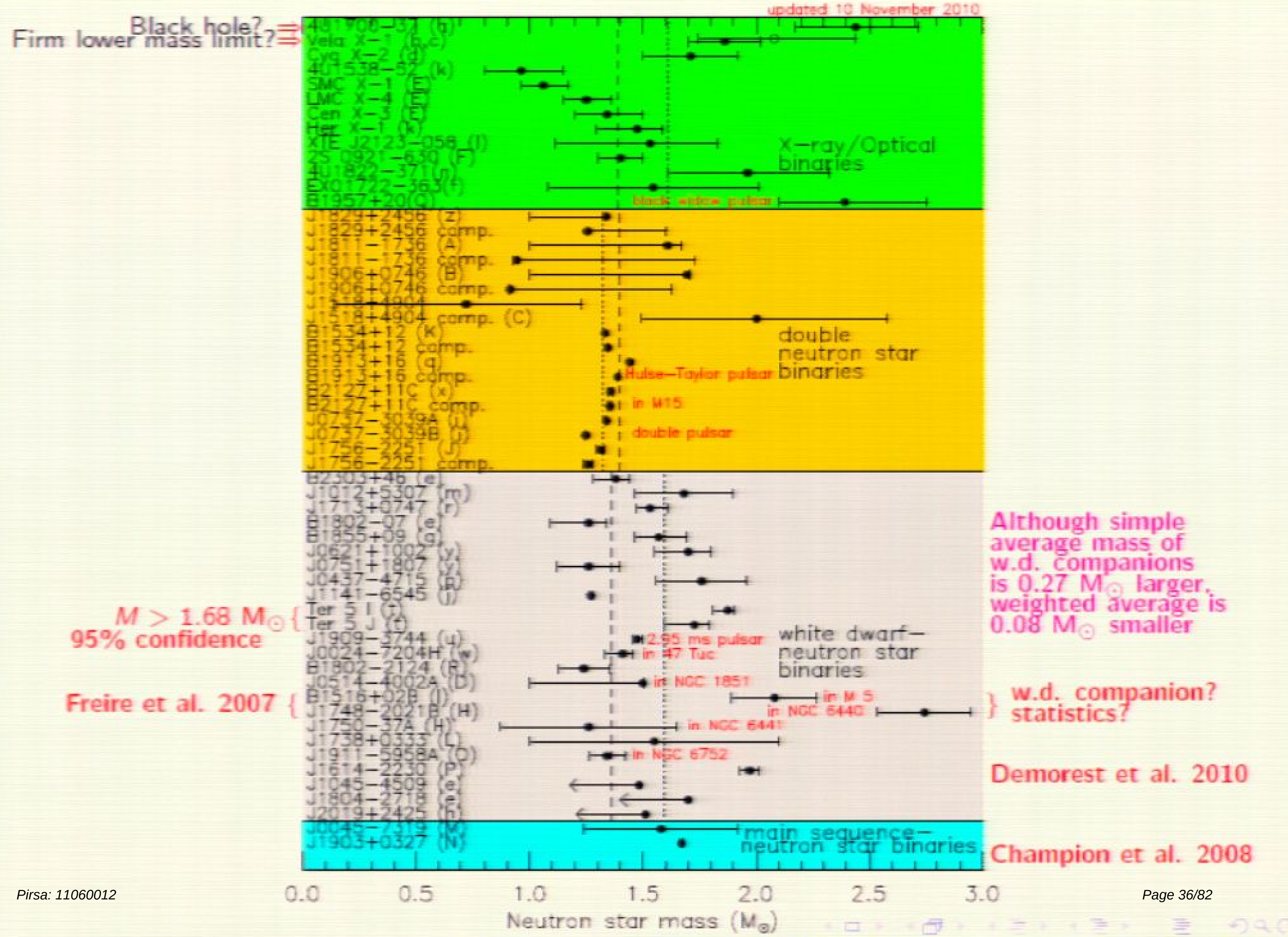
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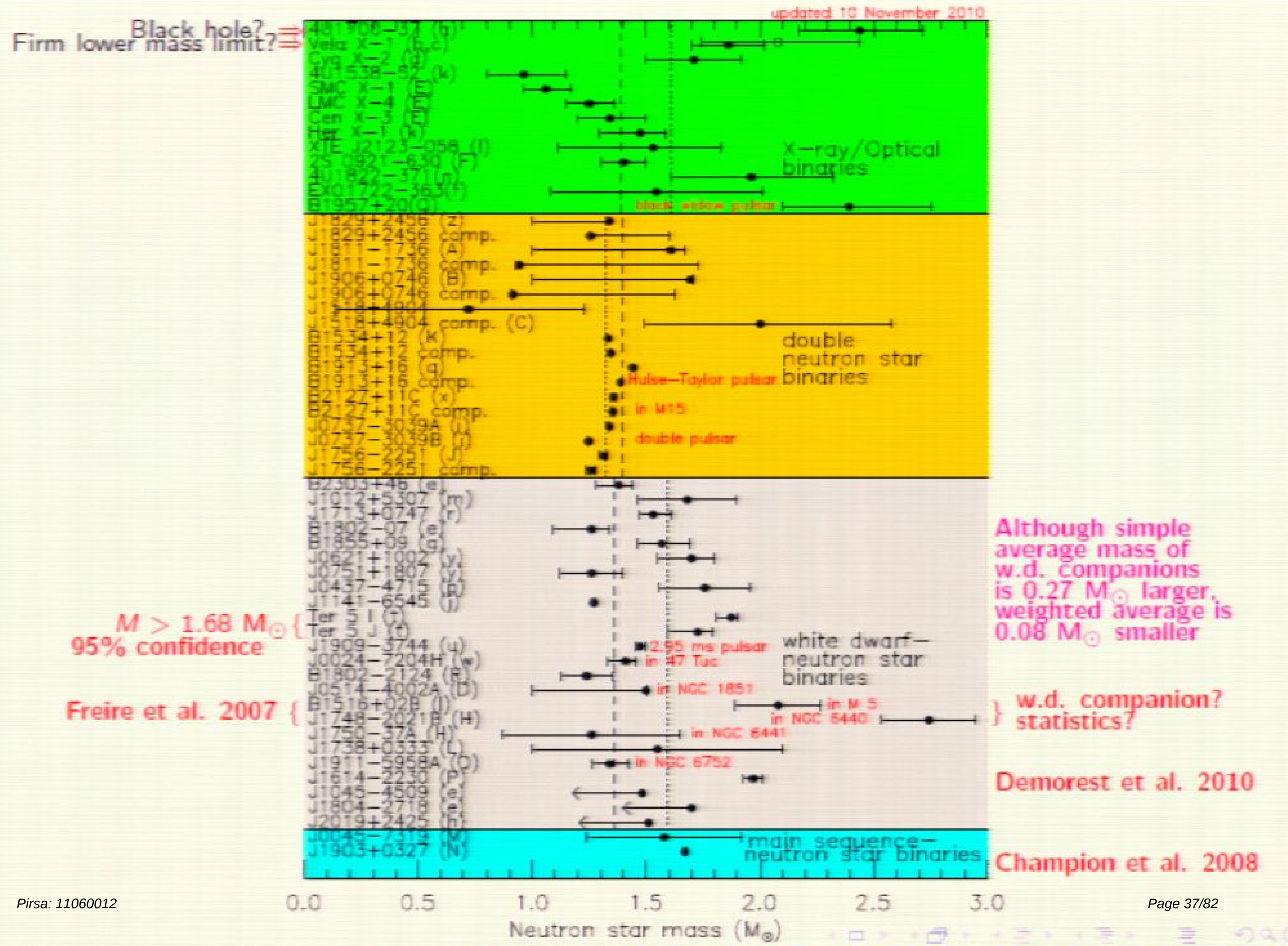
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Neutron star mass (M⊙)


updated 10 November 2010
Black hole?
Firm lower mass limit?
4U1700−377 (g)
Vela X−1 (b,c)
Cyg X−2 (d)
4U1538−52 (k)
SMC X−1 (E)
LMC X−4 (E)
Cen X−3 (E)
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EXO1722−363 (f)
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black widow pulsar
X−ray/Optical binaries
J1829+2456 (z)
J1829+2456 comp.
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J1811−1736 comp.
J1906+0746 (B)
J1906+0746 comp.
J1518+4904
J1518+4904 comp. (C)
B1534+12 (k)
B1534+12 comp.
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in M15
J0737−3039A (J)
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J1141−6545 (J)
Ter 5 I (T)
Ter 5 J (T)
J1909−3744 (u)
2.95 ms pulsar
J0024−7204H (w)
in 47 Tuc
B1802−2124 (R)
J0514−4002A (D)
in NGC 1851
B1516+02B (I)
in M 5
J1748−2021B (H)
in NGC 6440
J1750−37A (H)
in NGC 6441
J1738+0333 (L)
J1911−5958A (O)
in NGC 6752
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J1804−2718 (e)
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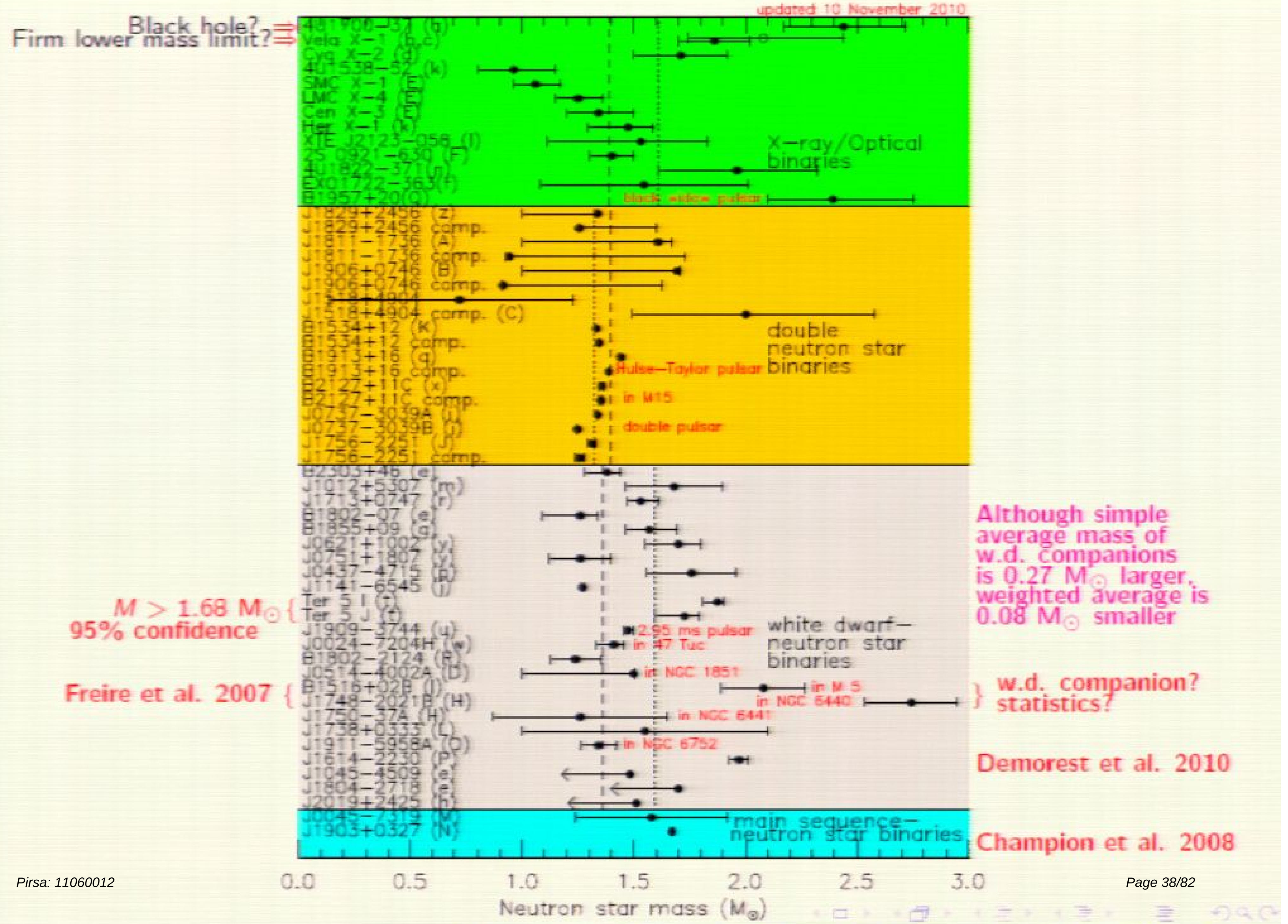
white dwarf−neutron star binaries
J0045−7319 (M)
J1903+0327 (N)
main sequence−neutron star binaries
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Neutron star mass ($M_\odot$)
$M > 1.68\ M_\odot$
95% confidence
Freire et al. 2007
Although simple average mass of w.d. companions is 0.27 $M_\odot$ larger, weighted average is 0.08 $M_\odot$ smaller
w.d. companion? statistics?
Demorest et al. 2010
Champion et al. 2008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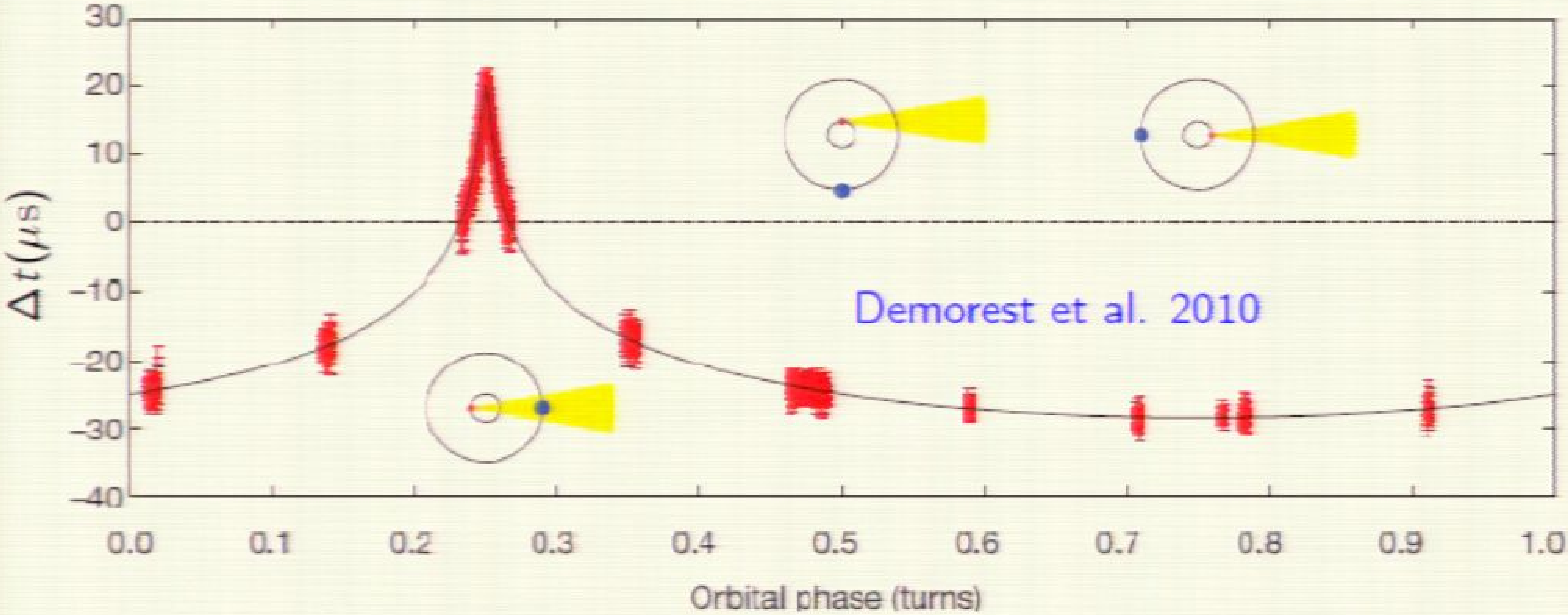
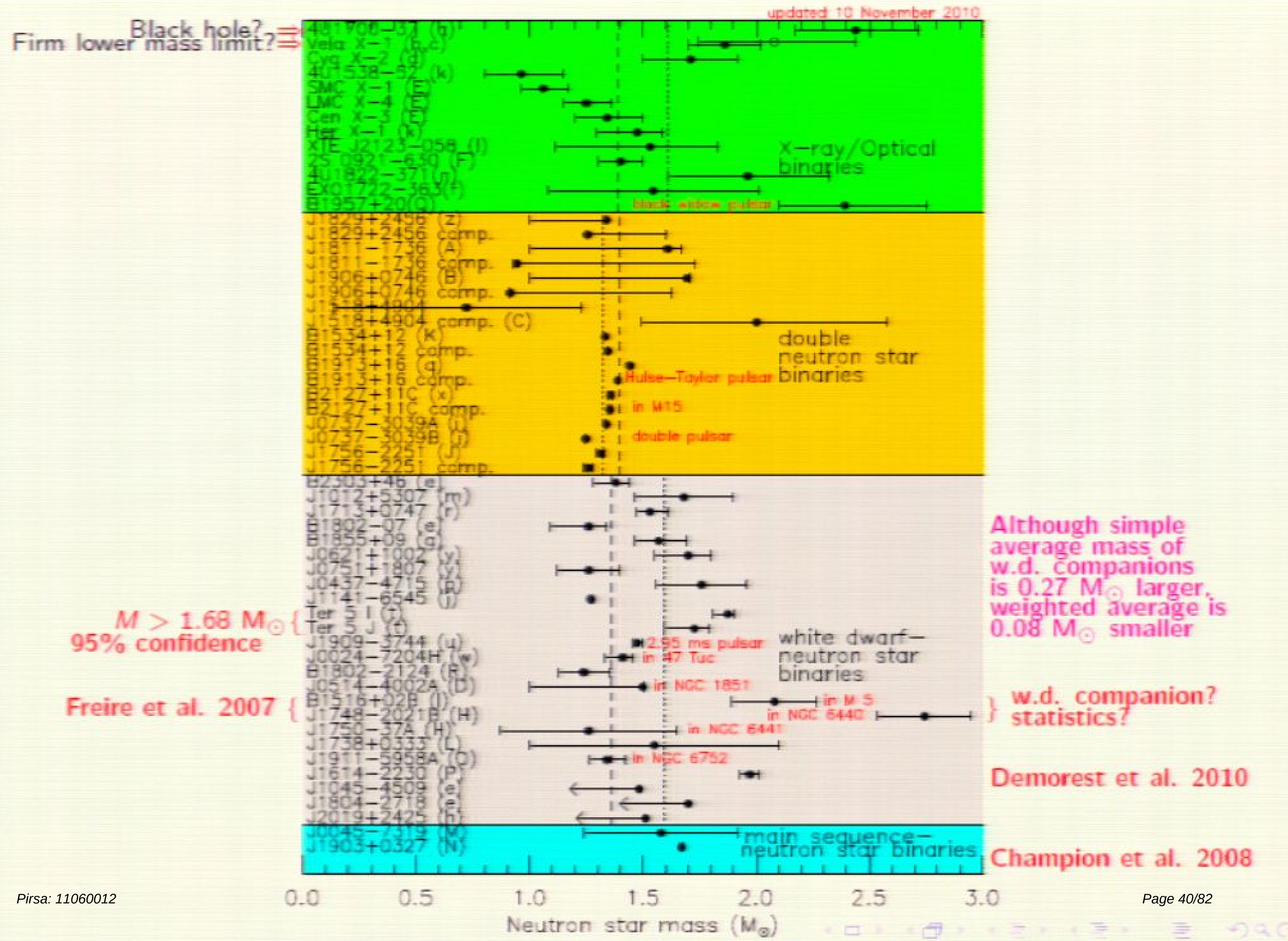
Neutron star mass (M⊙)
0.0
0.5
1.0
1.5
2.0
2.5
3.0

# PSR J1614-2230

3.15 ms pulsar in 8.69d orbit with 0.5 $M_\odot$ white dwarf companion.
Shapiro delay tightly confines the edge-on inclination: $\sin i = 0.99984$
Pulsar mass is $1.97 \pm 0.04$ $M_\odot$
Distance > 1 kpc, $B \simeq 1.8 \times 10^8$ G

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4U1700−37 (g)
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black widow pulsar
X−ray/Optical binaries
J1829+2456 (z)
J1829+2456 comp.
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J1906+0746 comp.
J1518+4904
J1518+4904 comp. (C)
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white dwarf−neutron star binaries
J0045−7319 (M)
J1903+0327 (N)
main sequence−neutron star binaries
0.0
0.5
1.0
1.5
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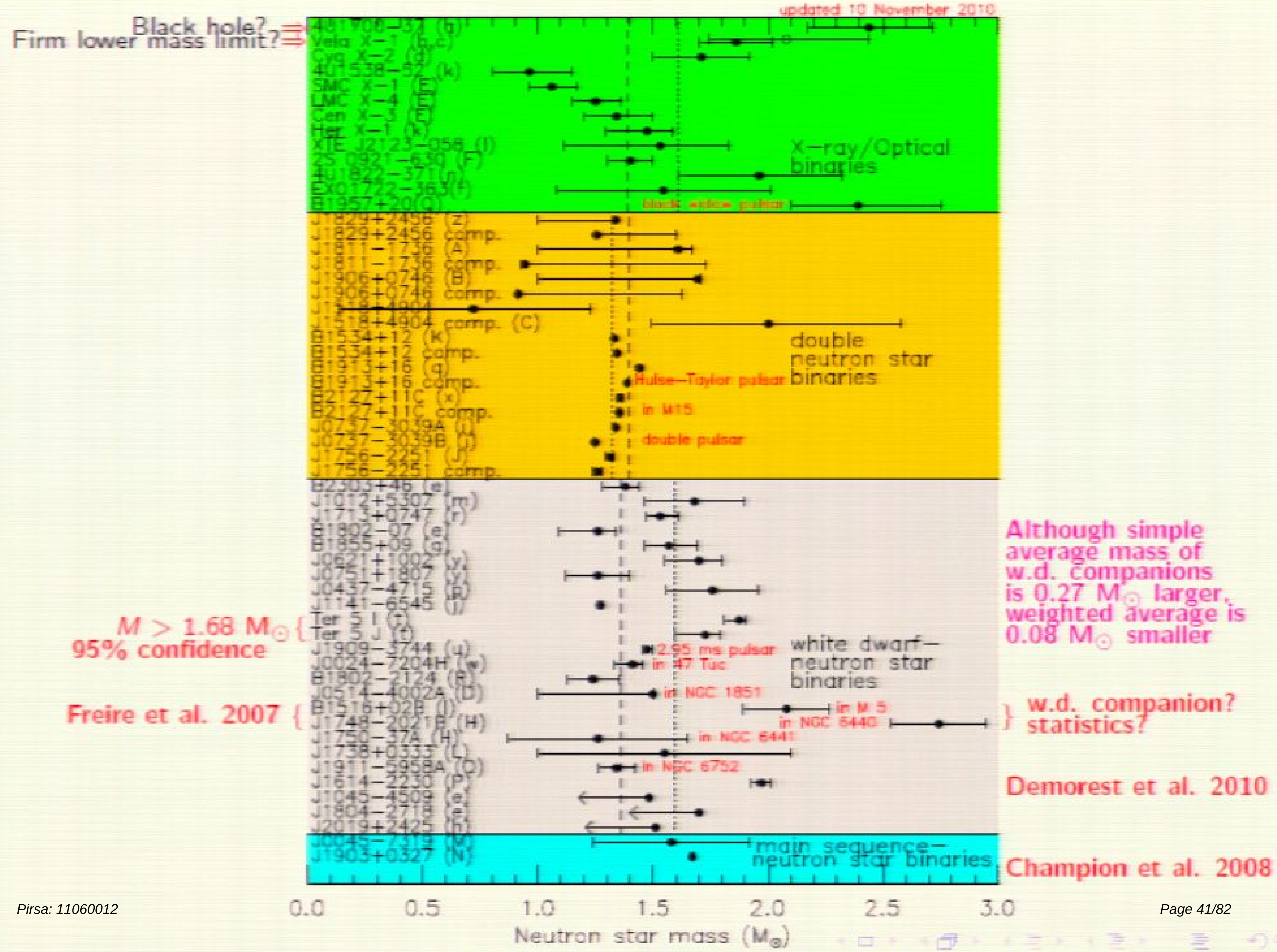
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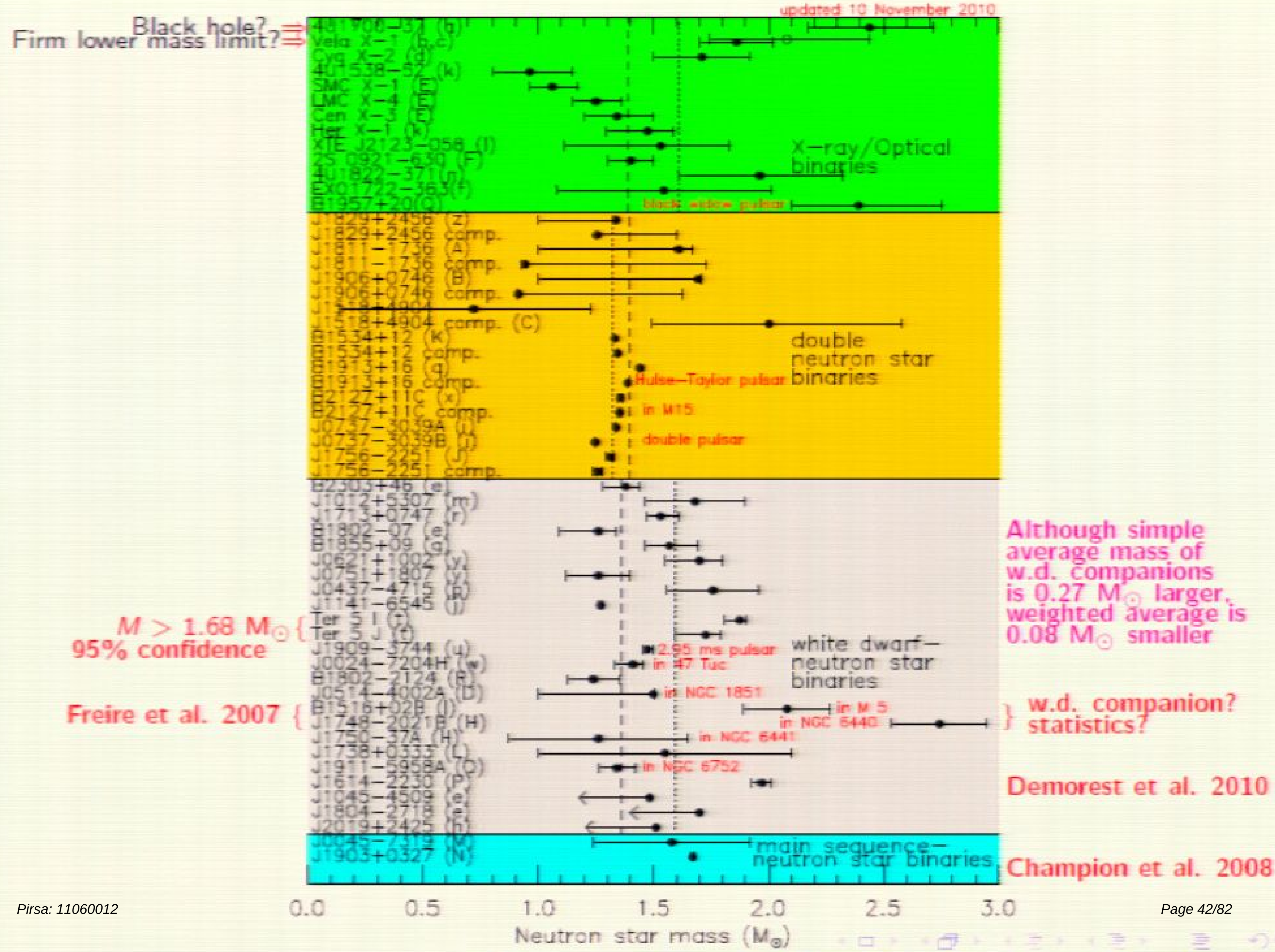

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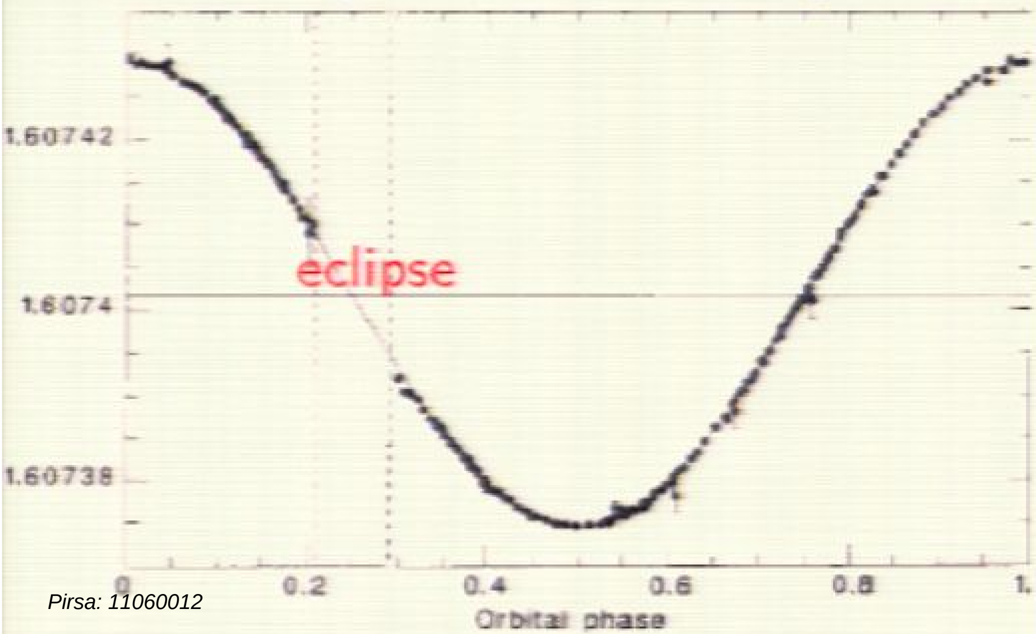
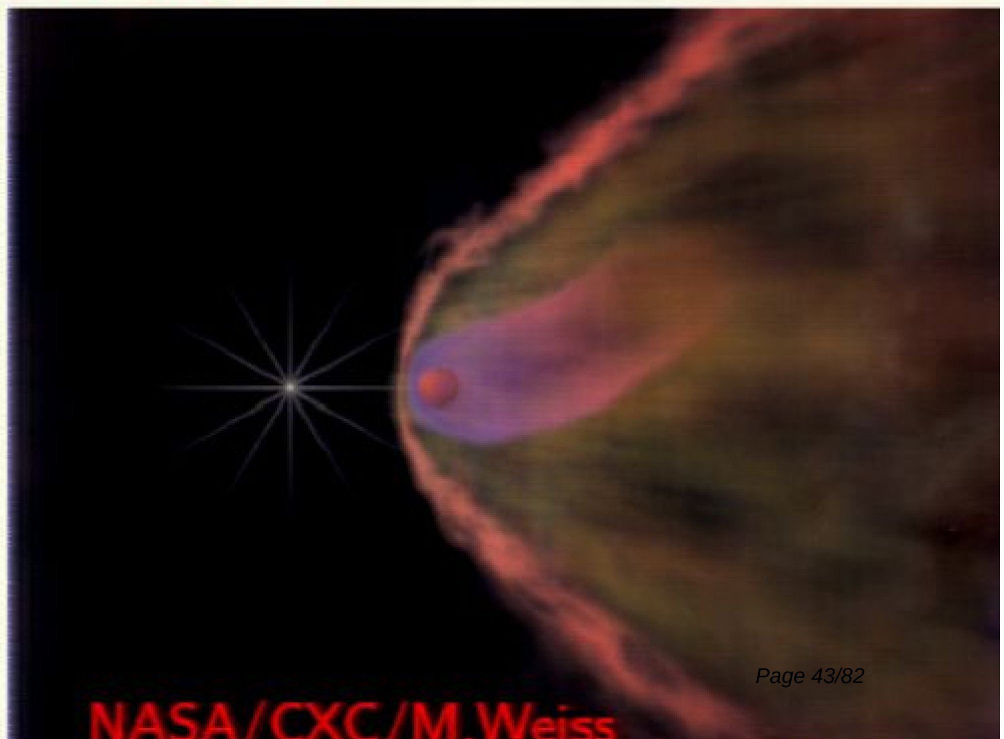
# Black Widow Pulsar PSR B1957+20

1.6ms pulsar in circular 9.17h orbit with a $M_c \sim 0.03\ M_\odot$ companion.
Pulsar is eclipsed for 50-60 minutes each orbit; eclipsing object has a volume much larger than the companion or its Roche lobe.
It is believed the companion is ablated by the pulsar leading to mass loss and an eclipsing plasma cloud. Companion nearly fills its Roche lobe.
Ablation by pulsar leads to eventual disappearance of companion.
The optical light curve does not represent the center of mass of the companion, but the motion of its irradiated hot spot.

pulsar radial velocity



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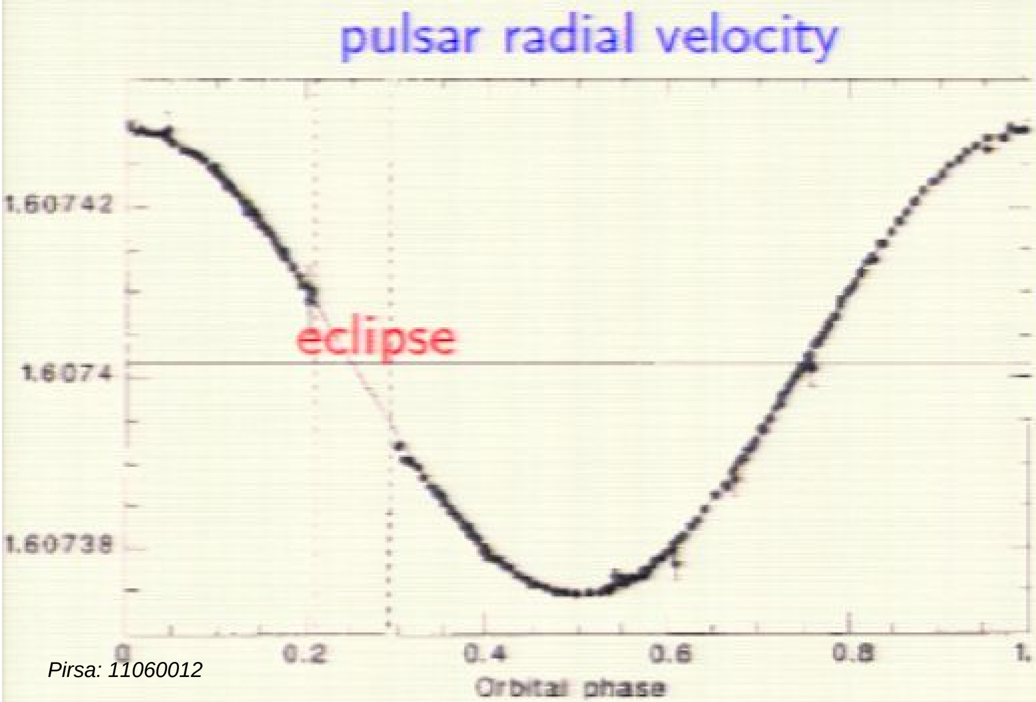


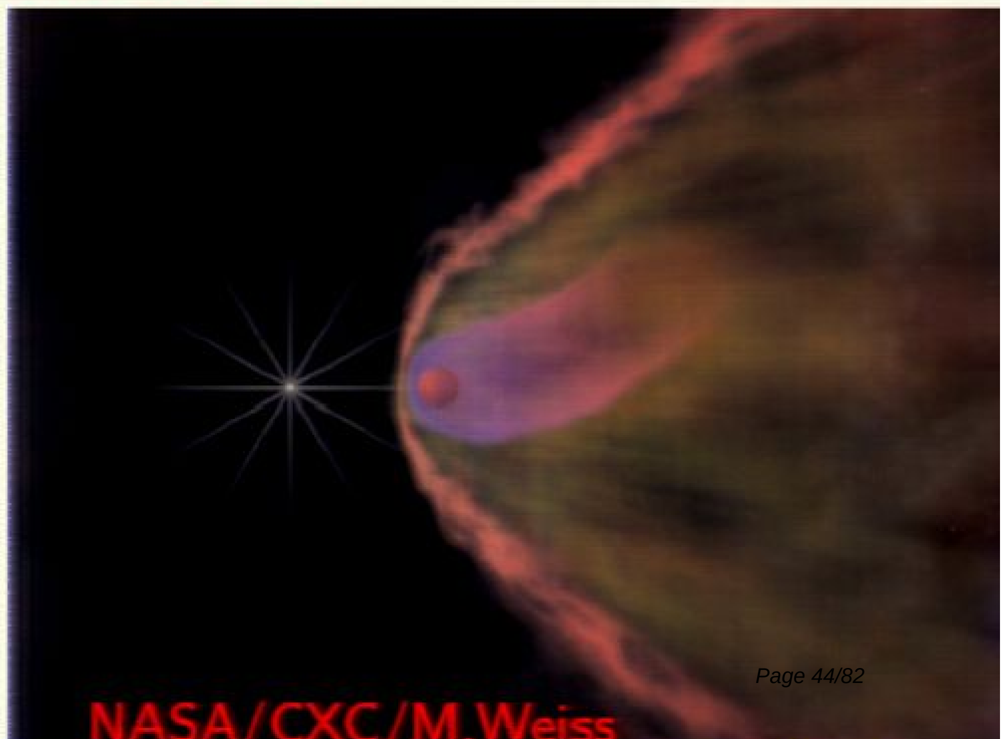

# mplications of Maximum Masses

$M_{max} > 2\ \mathrm{M}_\odot$

- Upper limits to energy density, pressure and baryon density:
  - $\varepsilon < 13.1\varepsilon_s$
  - $p < 8.8\varepsilon_s$
  - $n_B < 9.8n_s$
- Lower limit to spin period: $P > 0.56$ ms
- Lower limit to neutron star radius: $R > 8.5$ km
- Upper limits to energy density, pressure and baryon density in the case of a quark matter core $(s = 1/3)$:
  - $\varepsilon < 7.7\varepsilon_s$
  - $p < 2.0\varepsilon_s$
  - $n_B < 6.9n_s$

$M_{max} > 2.4\ \mathrm{M}_\odot$

- Upper limits to energy density, pressure and baryon density:
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  - $p < 5.9\varepsilon_s$
  - $n_B < 6.6n_s$
- Lower limit to spin period: $P > 0.68$ ms
- Lower limit to neutron star radius: $R > 10.4$ km
- Upper limits to energy density, pressure and baryon density in the case of a quark matter core $(s = 1/3)$:
  - $\varepsilon < 5.2\varepsilon_s$
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# Low-Mass Neutron Stars

Theoretial limit for minimum mass of neutron stars is about 0.09 $M_\odot$.

Practical limit, on the basis that neutron stars form from lepton-rich proto-neutron stars, can't exceed of 1 $M_\odot$ and could be close to 1.2 $M_\odot$.

Recent refined mass determinations of X-ray pulsar binaries (Rawls, Orosz, McClintock and Torres (2011):

- Vela X-1: $1.77 \pm 0.08\ M_\odot$
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  $0.87 \pm 0.07\ M_\odot$ (eccentric orbit),
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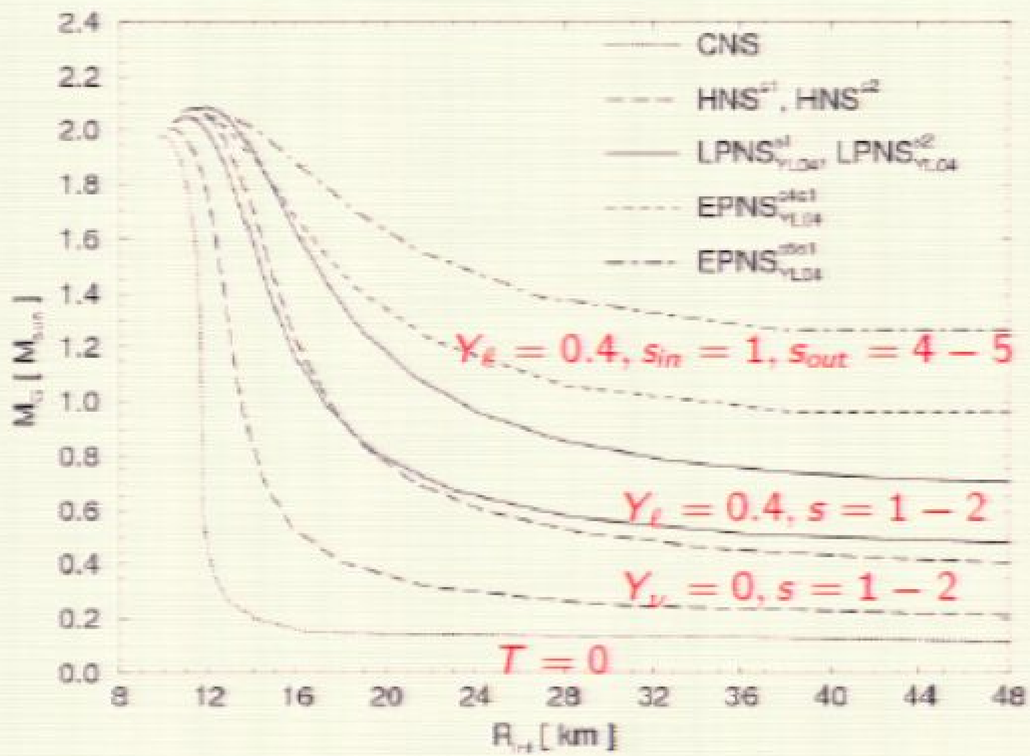


Strobel, Schaab & Weigel (1999)

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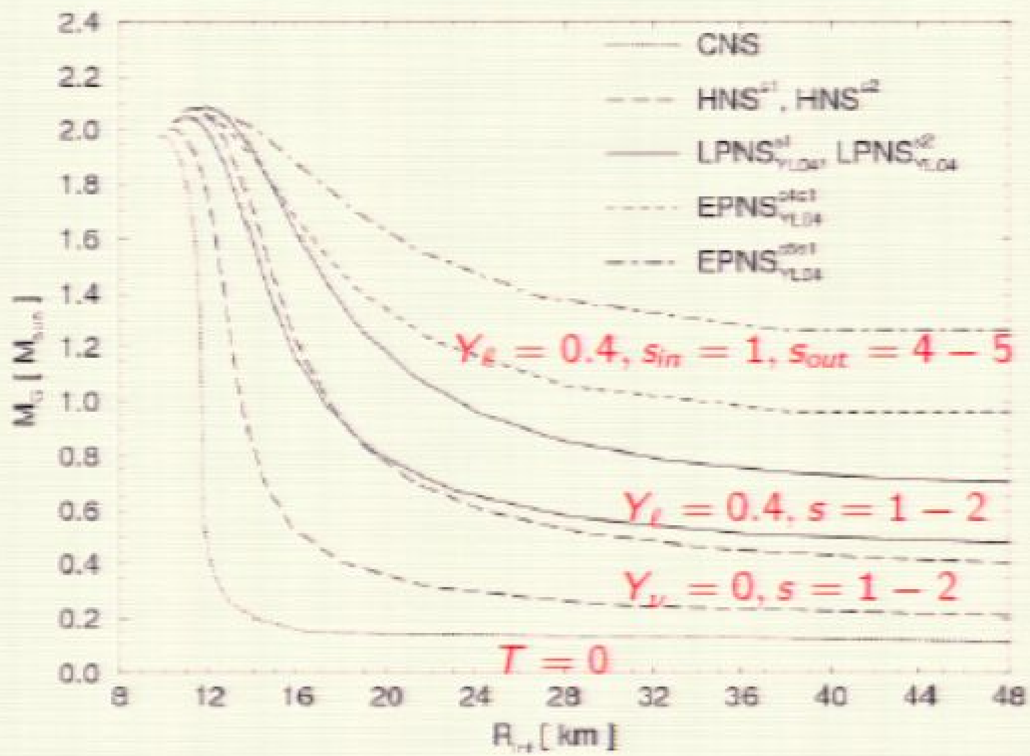



Strobel, Schaab & Weigel (1999)

# Neutron Star Matter Pressure and the Radius

$p \simeq K n^{\gamma}$

$\gamma = d \ln p / d \ln \; n \sim 2$

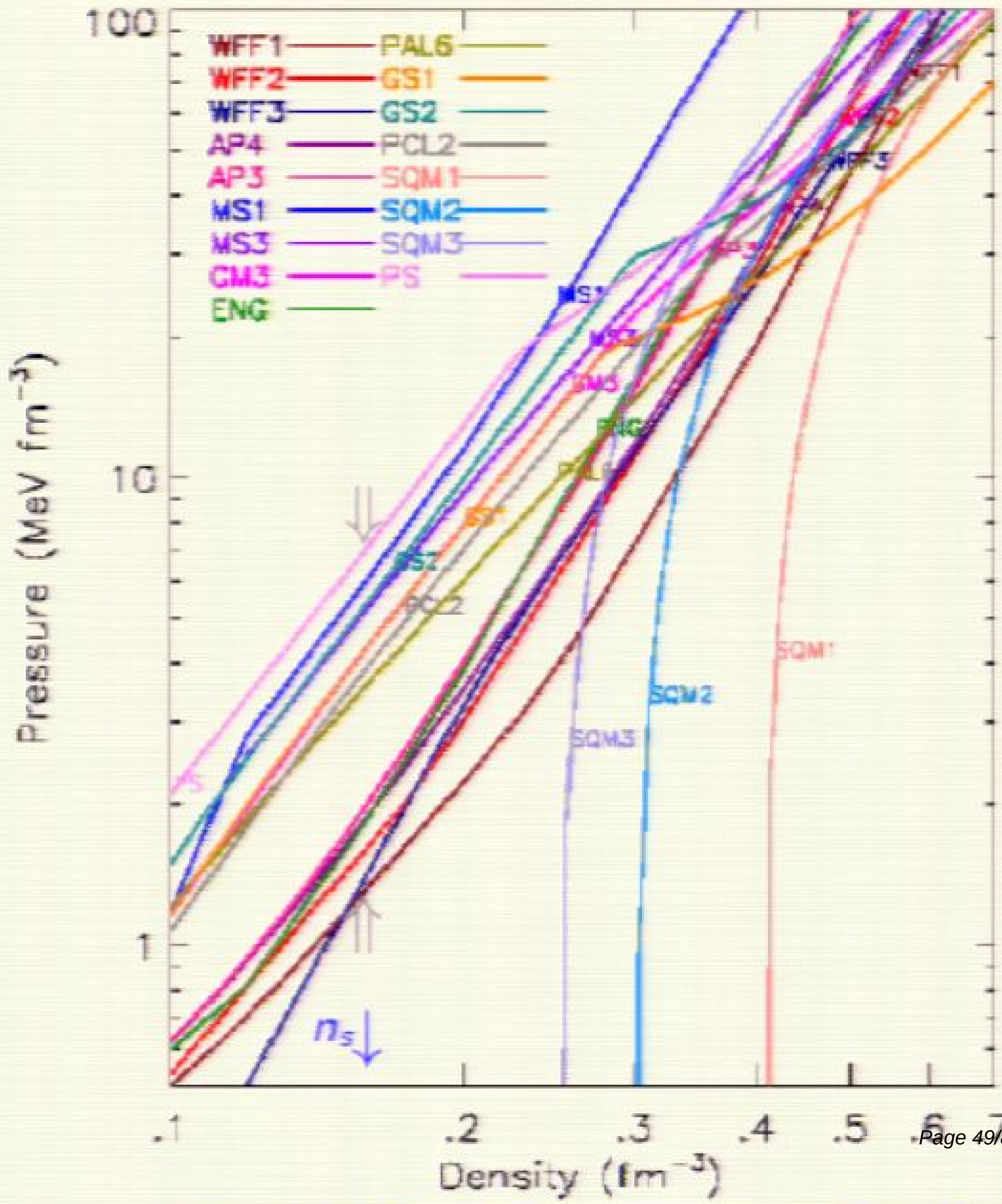
$R \propto K^{1/(3\gamma-4)} M^{(\gamma-2)/(3\gamma-4)}$

$R \propto p_f^{1/2} n_f^{-1} M^0$

$(1 < n_f/n_s < 2)$

Wide variation:

$1.2 < \frac{p(n_s)}{\mathrm{MeV\ fm^{-3}}} < 7$



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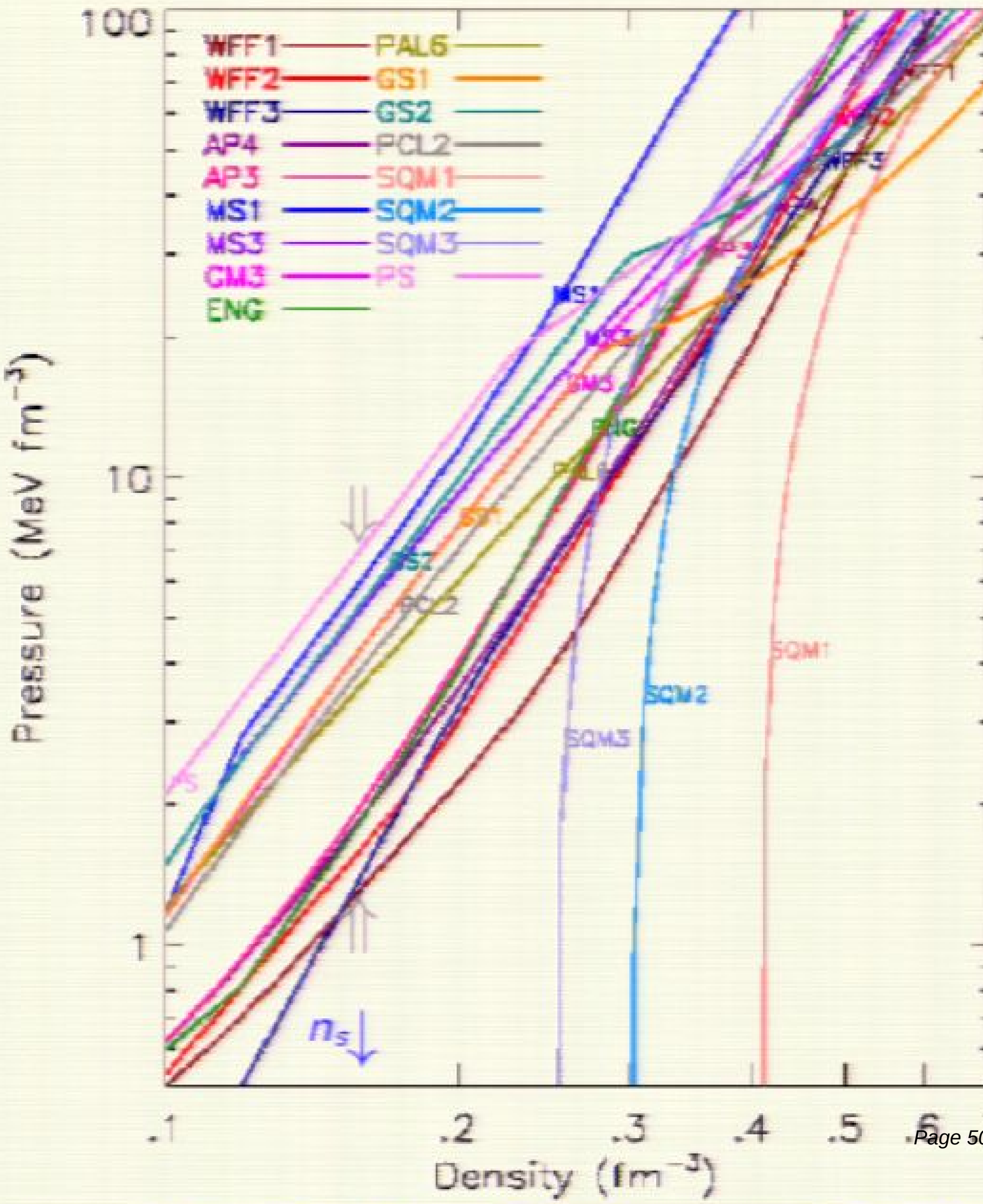
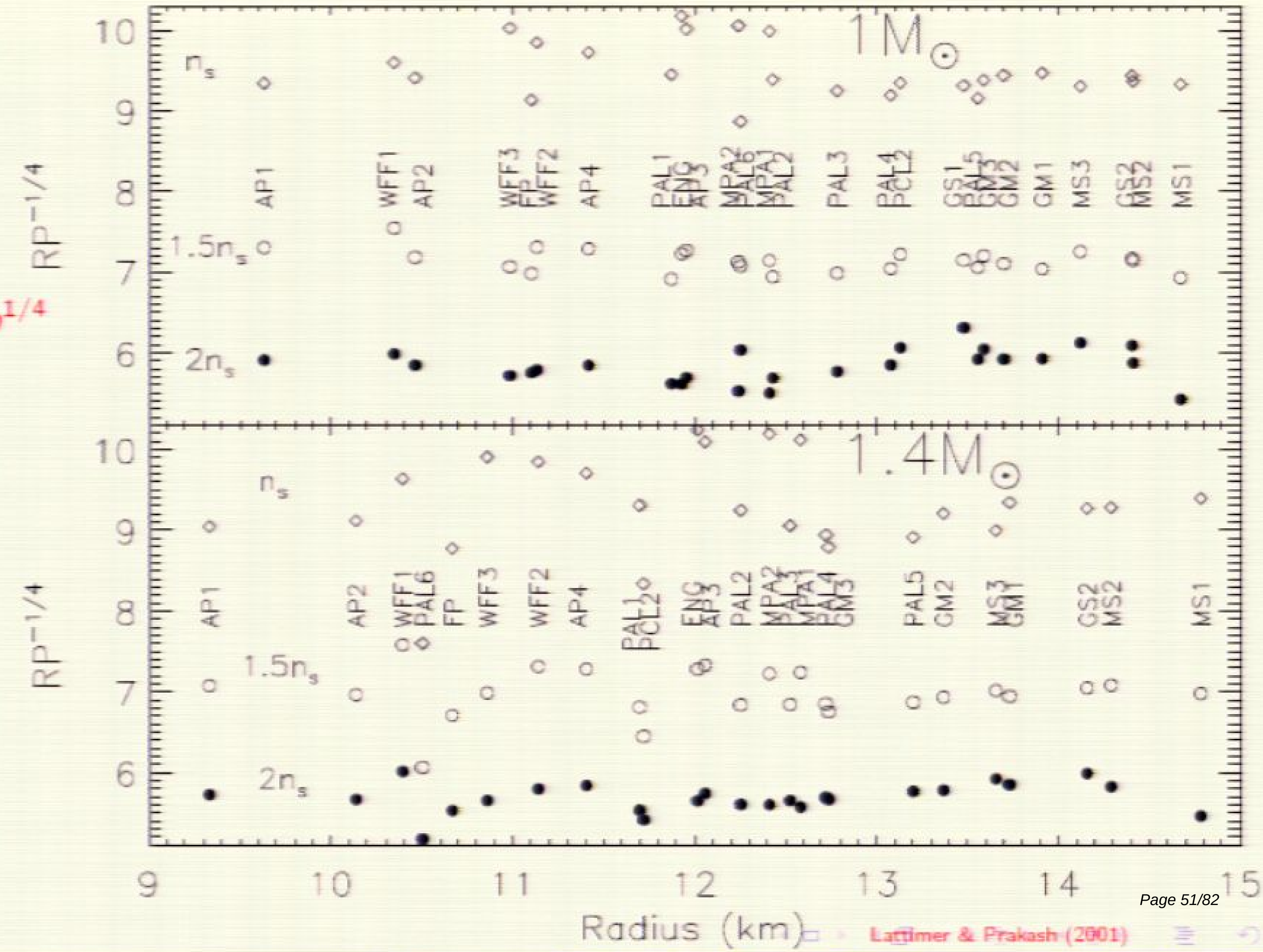


# The Radius – Pressure Correlation

$R \propto p^{1/4}$



# The Pressure of Neutron Star Matter

Expansion of cold nucleonic matter energy near $n_s$ and isospin symmetry $x = 1/2$:

$$E(n,x) \simeq E(n,1/2) + E_{sym}(n)(1-2x)^2 + \frac{3\hbar c}{4}x(3\pi^2 nx)^{1/3},$$

$$P(n,x) \simeq n^2\left[\frac{dE(n,1/2)}{dn} + \frac{dE_{sym}}{dn}(1-2x)^2\right] + \frac{\hbar c}{4}nx(3\pi^2 nx)^{1/3},$$

$$\mu_e = \hbar c(3\pi^2 nx)^{1/3}, \qquad E(n,1/2) \simeq -B + \frac{K}{18}\left(1-\frac{n}{n_s}\right)^2.$$

Beta Equilibrium: $\left(\frac{\partial E}{\partial x}\right)_n = \mu_p - \mu_n + \mu_e = 0.$

$$x_\beta \simeq (3\pi^2 n)^{-1}\left(\frac{4E_{sym}}{\hbar c}\right)^3,$$

$$P_\beta \simeq \frac{Kn^2}{9n_0}\left(\frac{n}{n_s}-1\right) + n^2(1-2x_\beta)^2\frac{dE_{sym}}{dn} + E_{sym}nx_\beta(1-2x_\beta)$$

$E_{sym}(n_s) \sim S_v \simeq 30$ MeV, $\hbar c \simeq 200$ MeV/fm,

$$n \rightarrow n_s \Longrightarrow \qquad x_\beta \rightarrow 0.04, \qquad P_\beta \rightarrow n_s^2(dE_{sym}/dn)_{n_s}.$$

# The Pressure of Neutron Star Matter

Expansion of cold nucleonic matter energy near $n_s$ and isospin symmetry $x = 1/2$:

$$E(n,x) \simeq E(n,1/2) + E_{sym}(n)(1-2x)^2 + \frac{3\hbar c}{4} x (3\pi^2 n x)^{1/3},$$

$$P(n,x) \simeq n^2 \left[\frac{dE(n,1/2)}{dn} + \frac{dE_{sym}}{dn}(1-2x)^2\right] + \frac{\hbar c}{4} n x (3\pi^2 n x)^{1/3},$$

$$\mu_e = \hbar c (3\pi^2 n x)^{1/3}, \qquad E(n,1/2) \simeq -B + \frac{K}{18}\left(1 - \frac{n}{n_s}\right)^2.$$

Beta Equilibrium: $\left(\frac{\partial E}{\partial x}\right)_n = \mu_p - \mu_n + \mu_e = 0\,.$

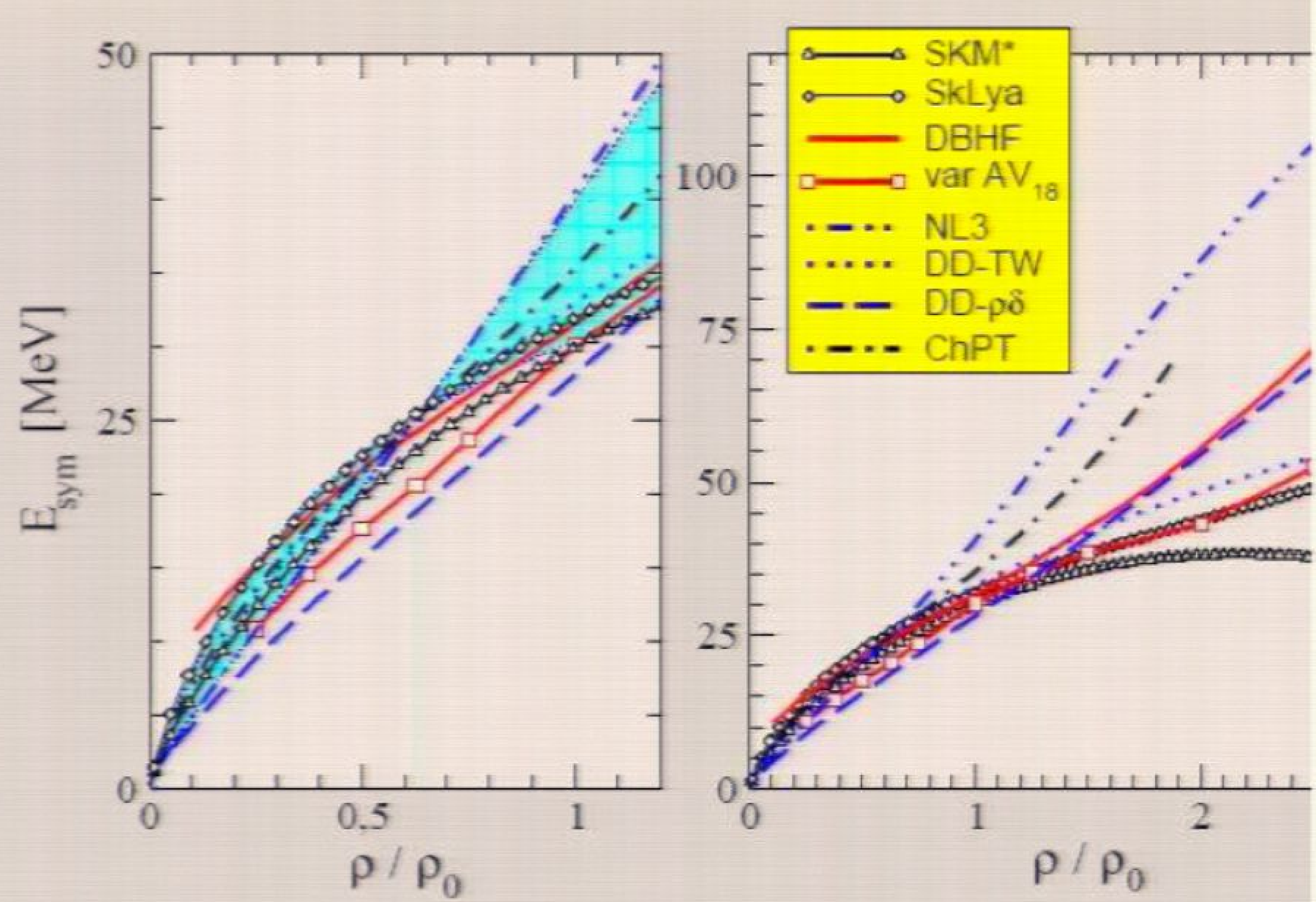
$$x_\beta \simeq (3\pi^2 n)^{-1}\left(\frac{4E_{sym}}{\hbar c}\right)^3,$$

$$P_\beta \simeq \frac{Kn^2}{9n_0}\left(\frac{n}{n_s} - 1\right) + n^2(1-2x_\beta)^2 \frac{dE_{sym}}{dn} + E_{sym} n x_\beta (1-2x_\beta)$$

$E_{sym}(n_s) \sim S_v \simeq 30$ MeV, $\hbar c \simeq 200$ MeV/fm,

$$n \to n_s \Longrightarrow \qquad x_\beta \to 0.04\,, \qquad P_\beta \to n_s^2 \left(dE_{sym}/dn\right)_{n_s}.$$

# The Uncertain $E_{sym}(n)$






C. Fuchs, H.H. Wolter, EPJA 30(2006) 5

# Nuclear Structure Considerations

Information about $E_{sym}(n)$ can be extracted from nuclear binding energies and models for nuclei. For example, consider the schematic liquid droplet model (Myers & Swiatecki):

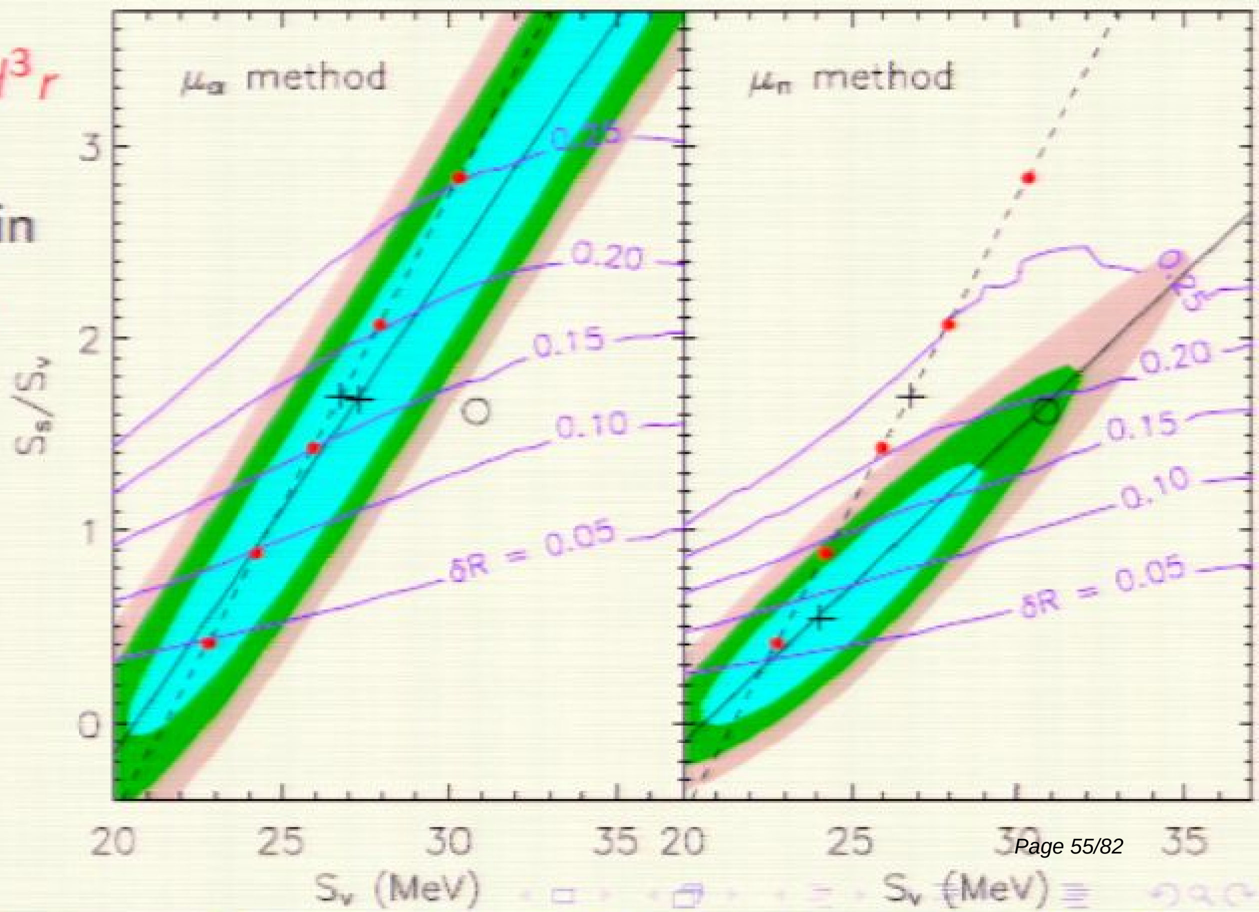
$$E(A,Z) \simeq -a_v A + a_s A^{2/3} + \frac{S_v}{1+(S_s/S_v)A^{-1/3}}A + a_C Z^2 A^{-1/3}$$

$$S_s \propto S_v \int_0^R n\left(\frac{S_v}{E_{sym}(n)} - 1\right) d^3r$$

Fitting binding energies results in a strong correlation between $S_v$ and $S_s$, but not definite values.

Another observable: neutron skin thickness $\delta R \propto S_s/S_v$.

Blue: $\Delta E < 0.01$ MeV/b
Green: $\Delta E < 0.02$ MeV/b
Gray: $\Delta E < 0.03$ MeV/b
Circle: Moeller et al. (1995)
Crosses: Best fits
Dashed: Danielewicz (2004)
Solid: Steiner et al. (2005)



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Information about $E_{sym}(n)$ can be extracted from nuclear binding energies and models for nuclei. For example, consider the schematic liquid droplet model (Myers & Swiatecki):

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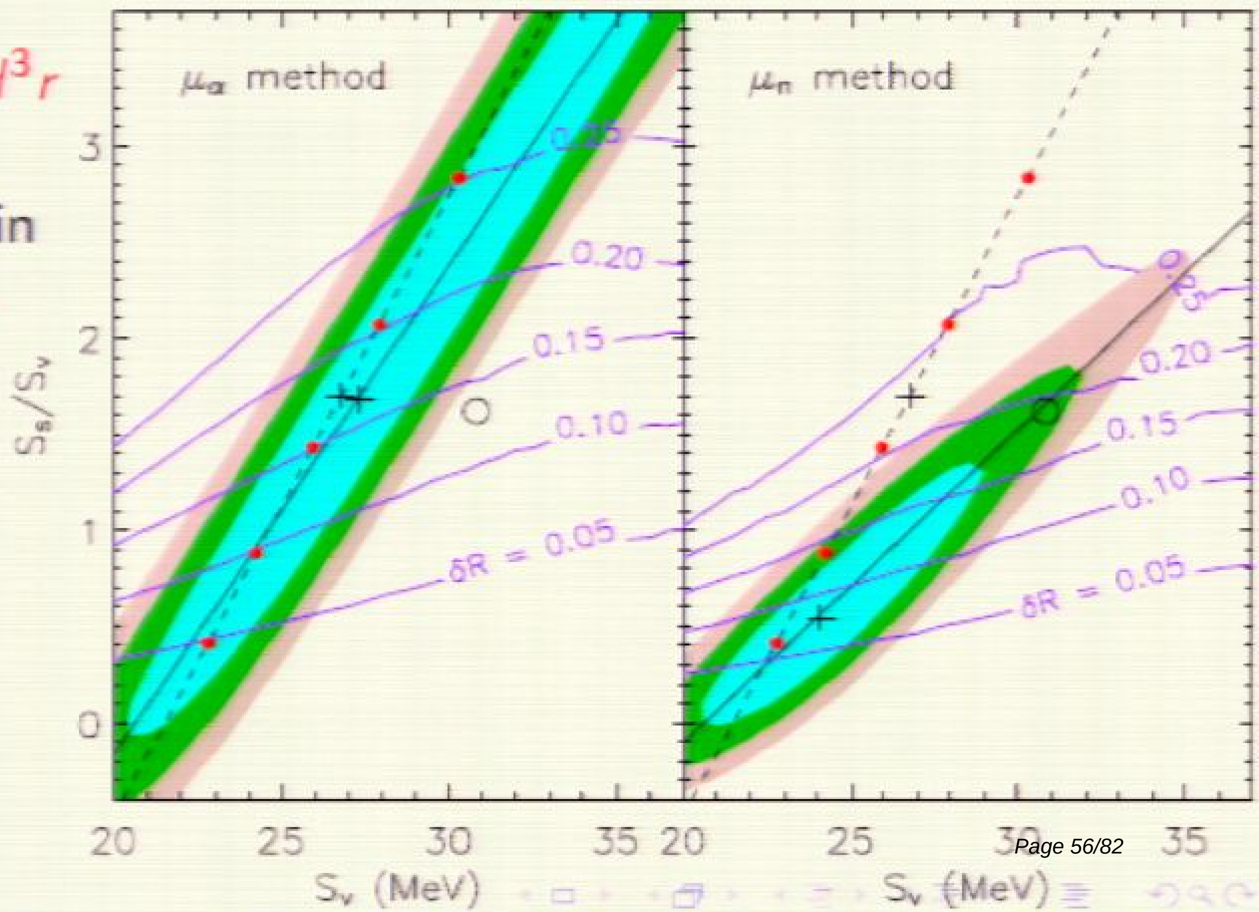

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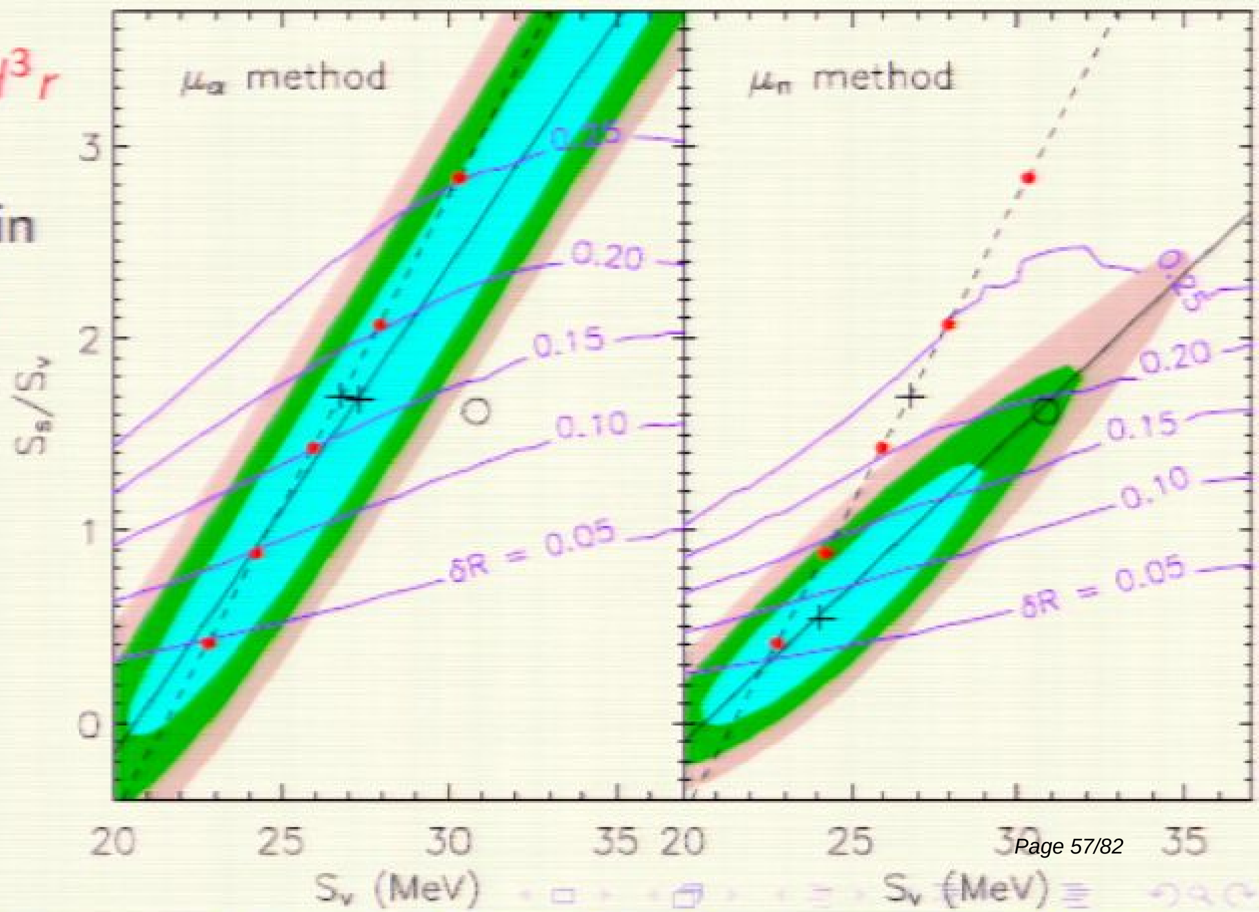


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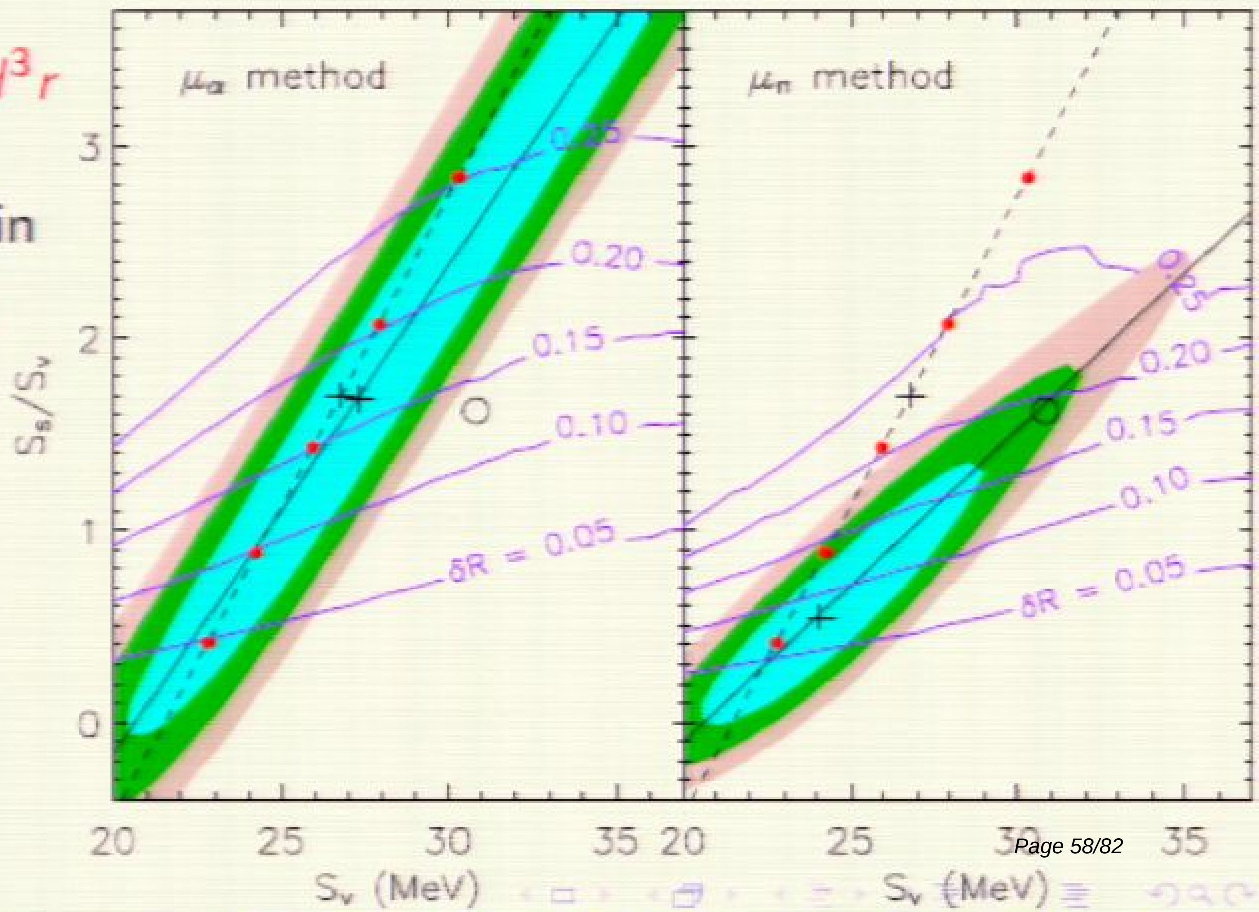

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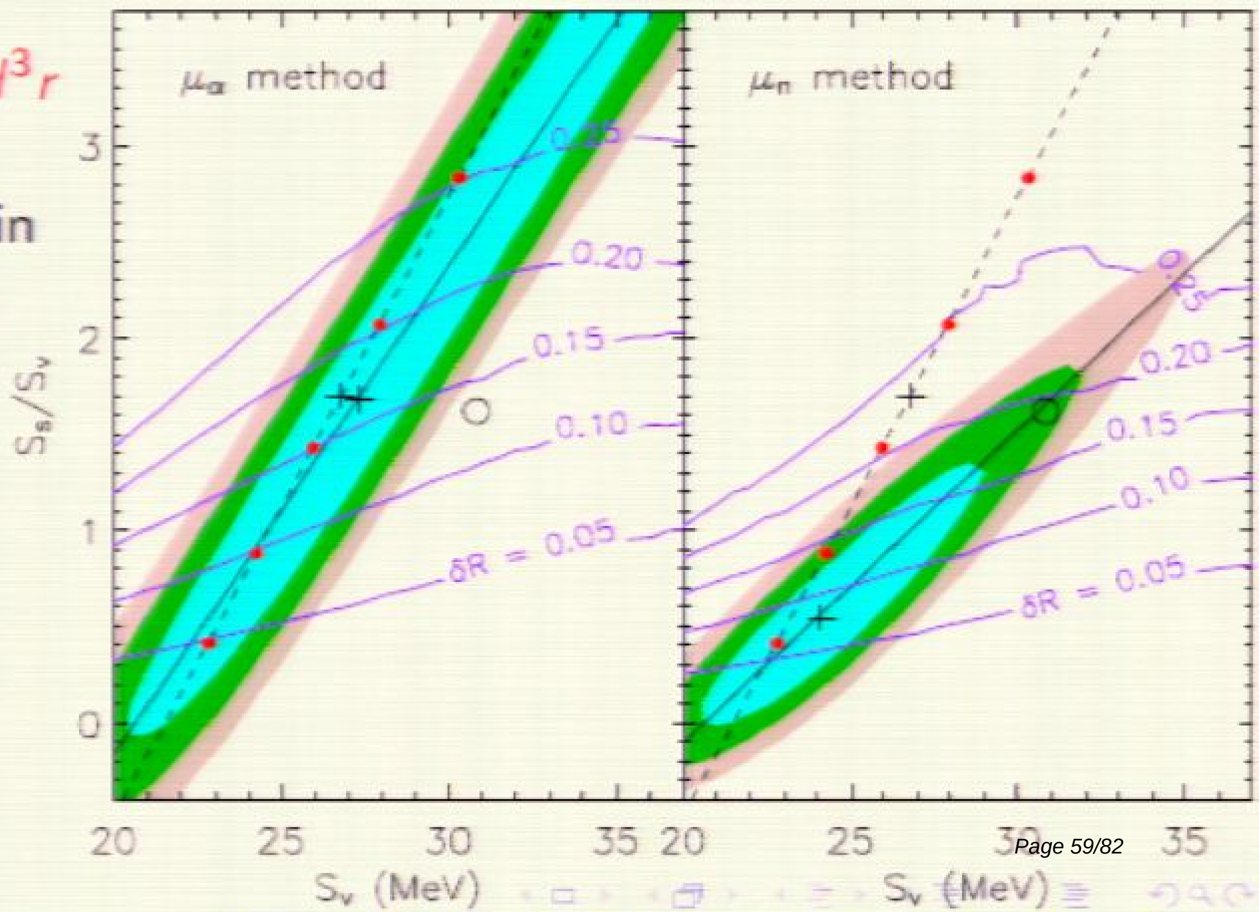


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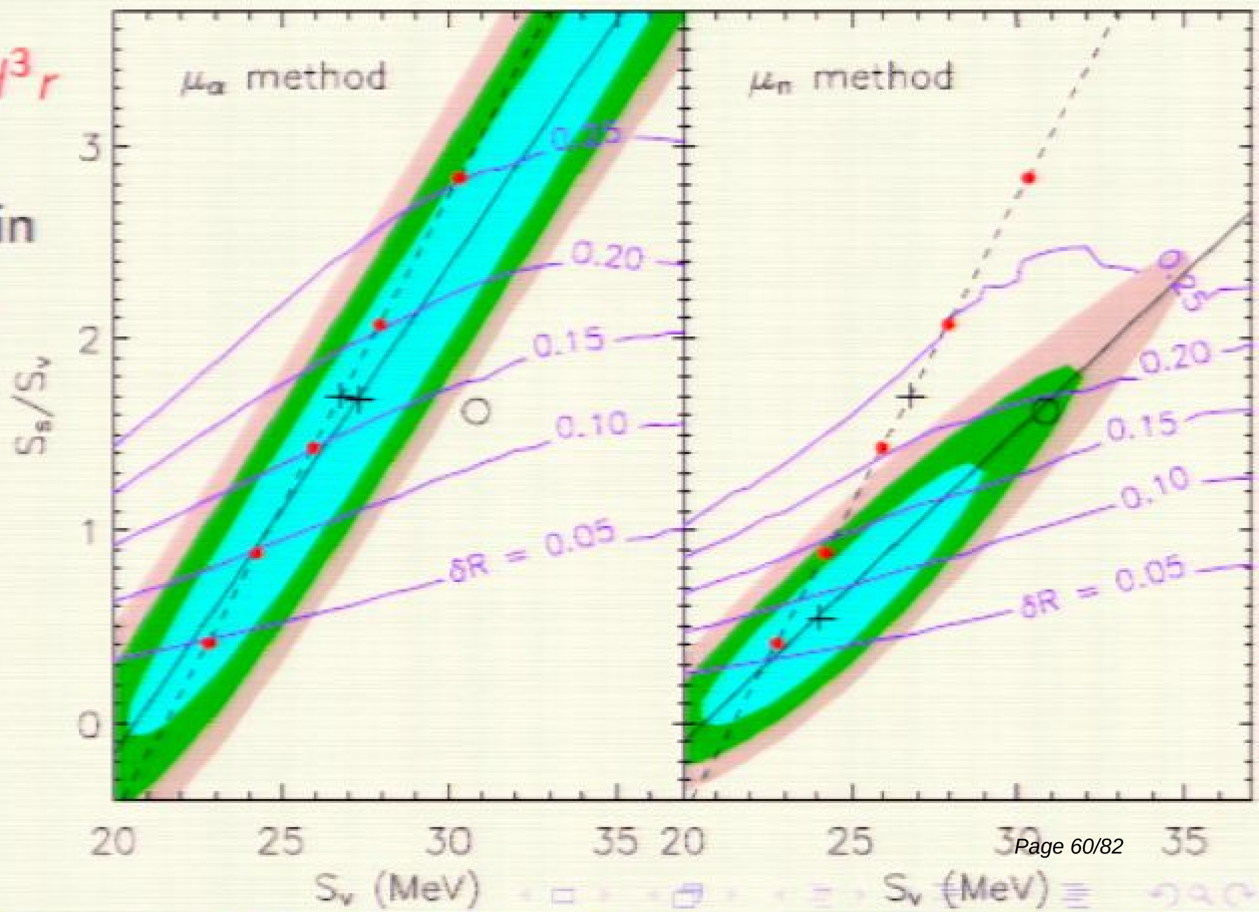

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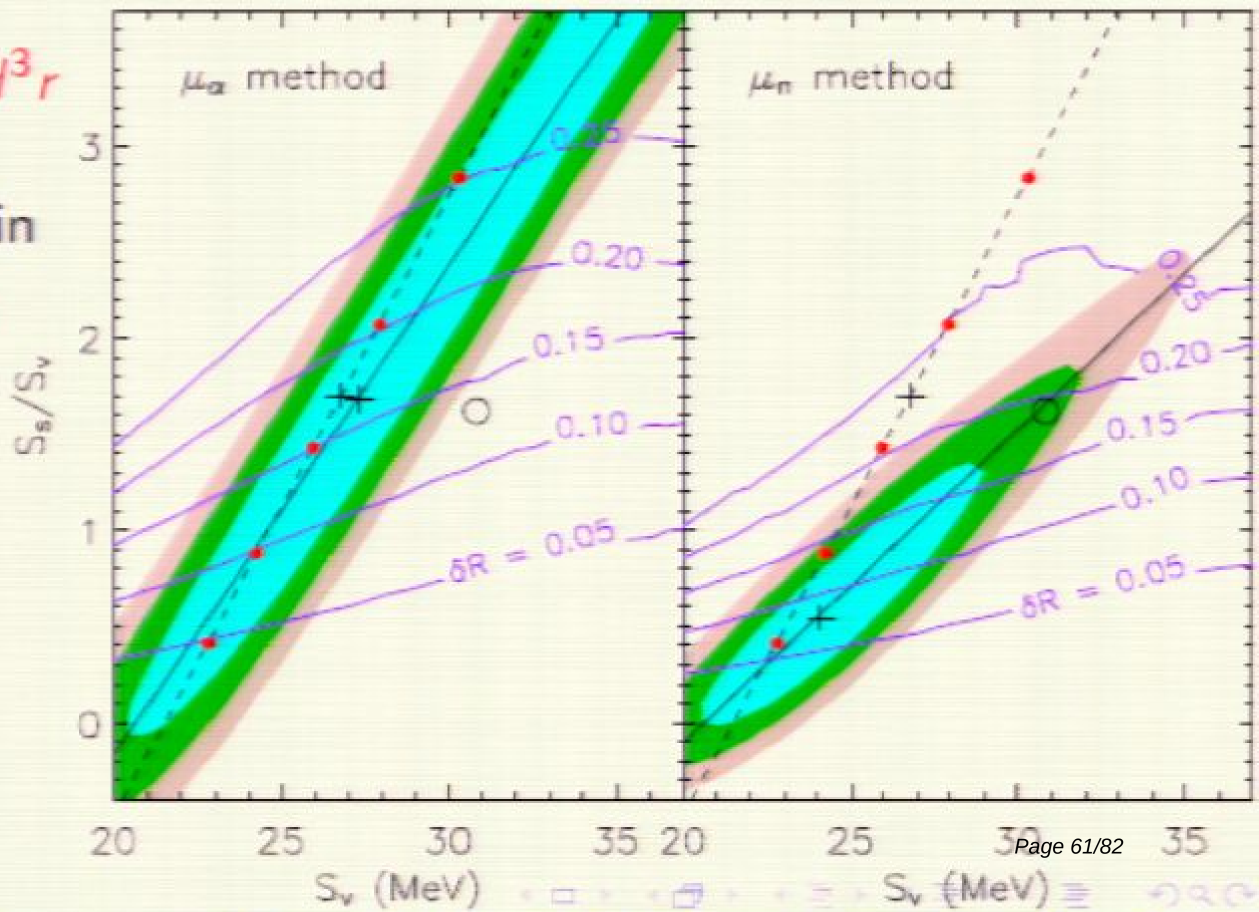


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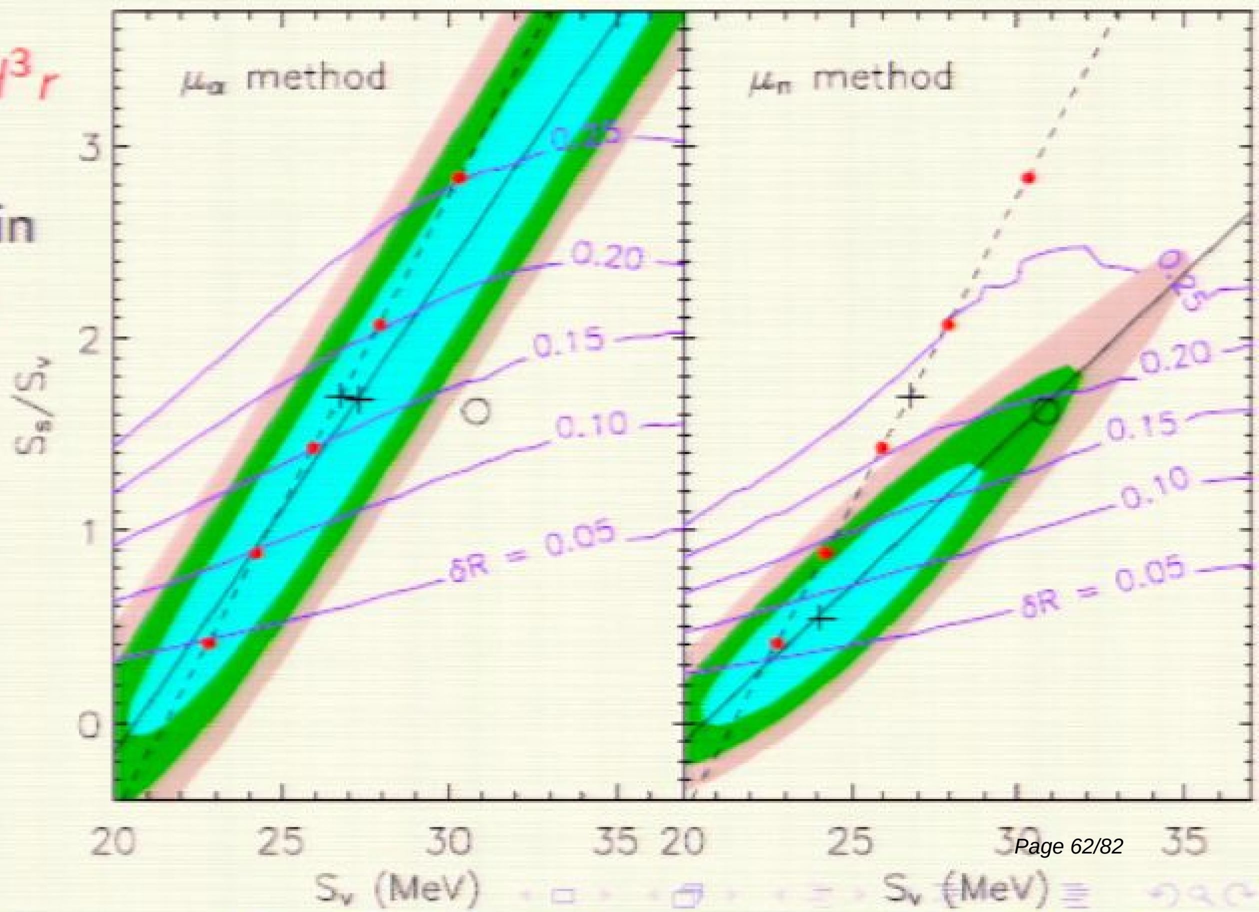


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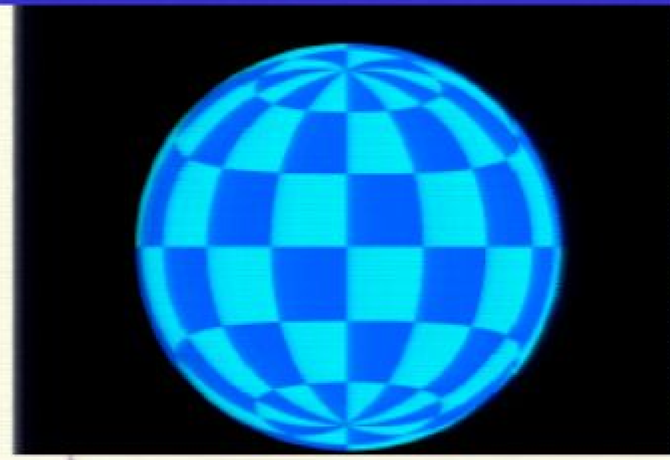
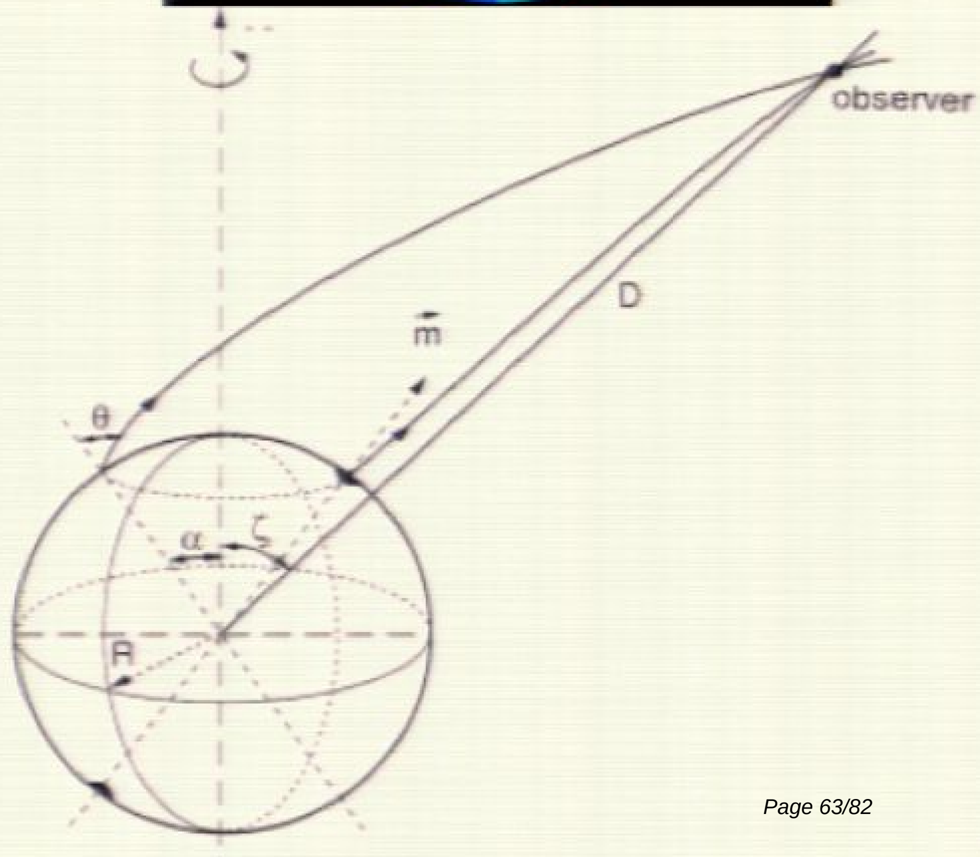
# Radiation Radius

- The measurement of flux and temperature yields an apparent angular size (pseudo-BB):

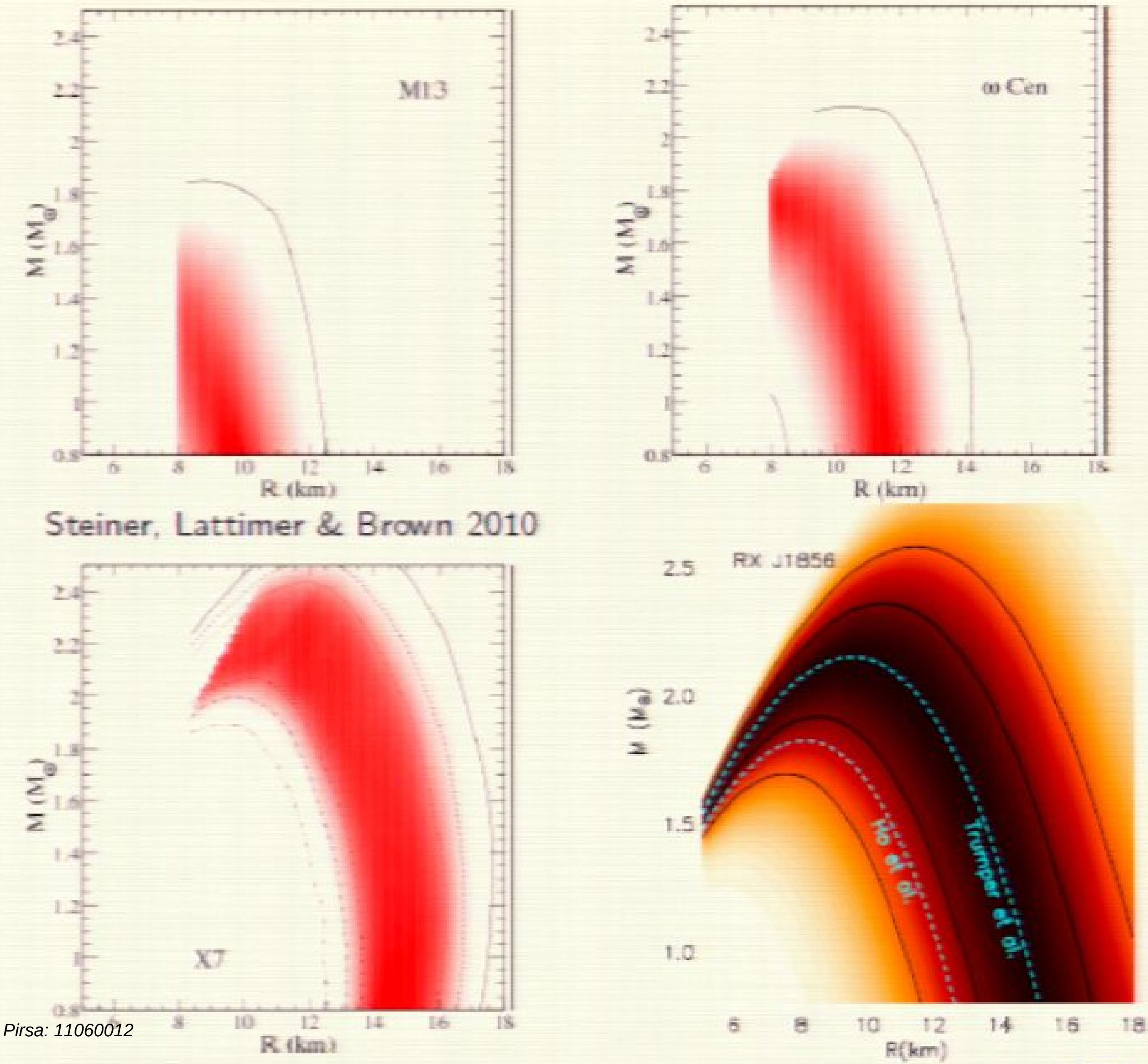
$$\frac{R_\infty}{d} = \frac{R}{d}\frac{1}{\sqrt{1-2GM/Rc^2}}$$

- Observational uncertainties include distance, interstellar H absorption (hard UV and X-rays), atmospheric composition
- Best chances for accurate radii:
  - Nearby isolated neutron stars (parallax measurable)
  - Quiescent X-ray binaries in globular clusters (reliable distances, low $B$ H-atmosperes)

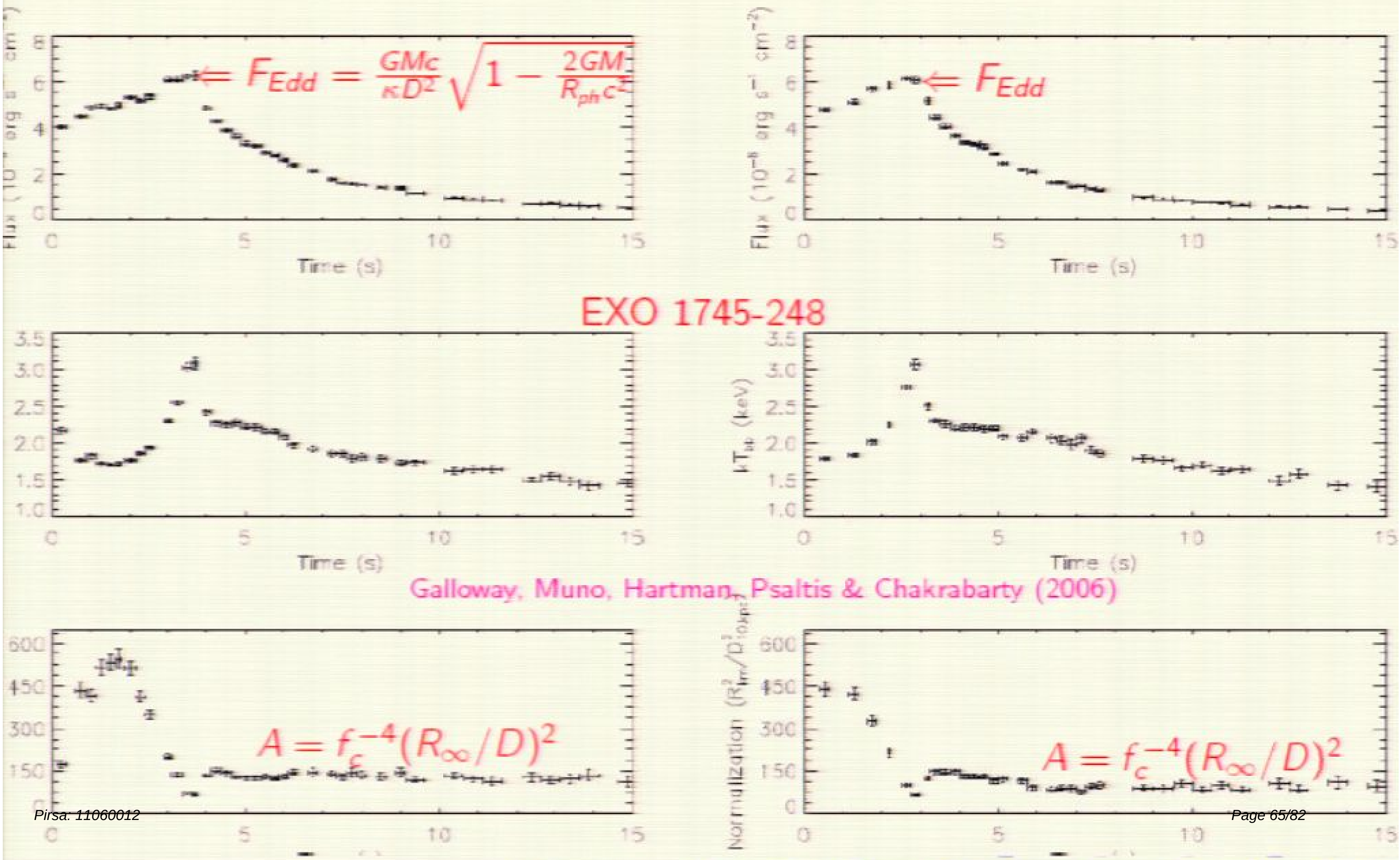




# nferred M-R Probability Estimates from Thermal Sources



# Photospheric Radius Expansion X-Ray Bursts



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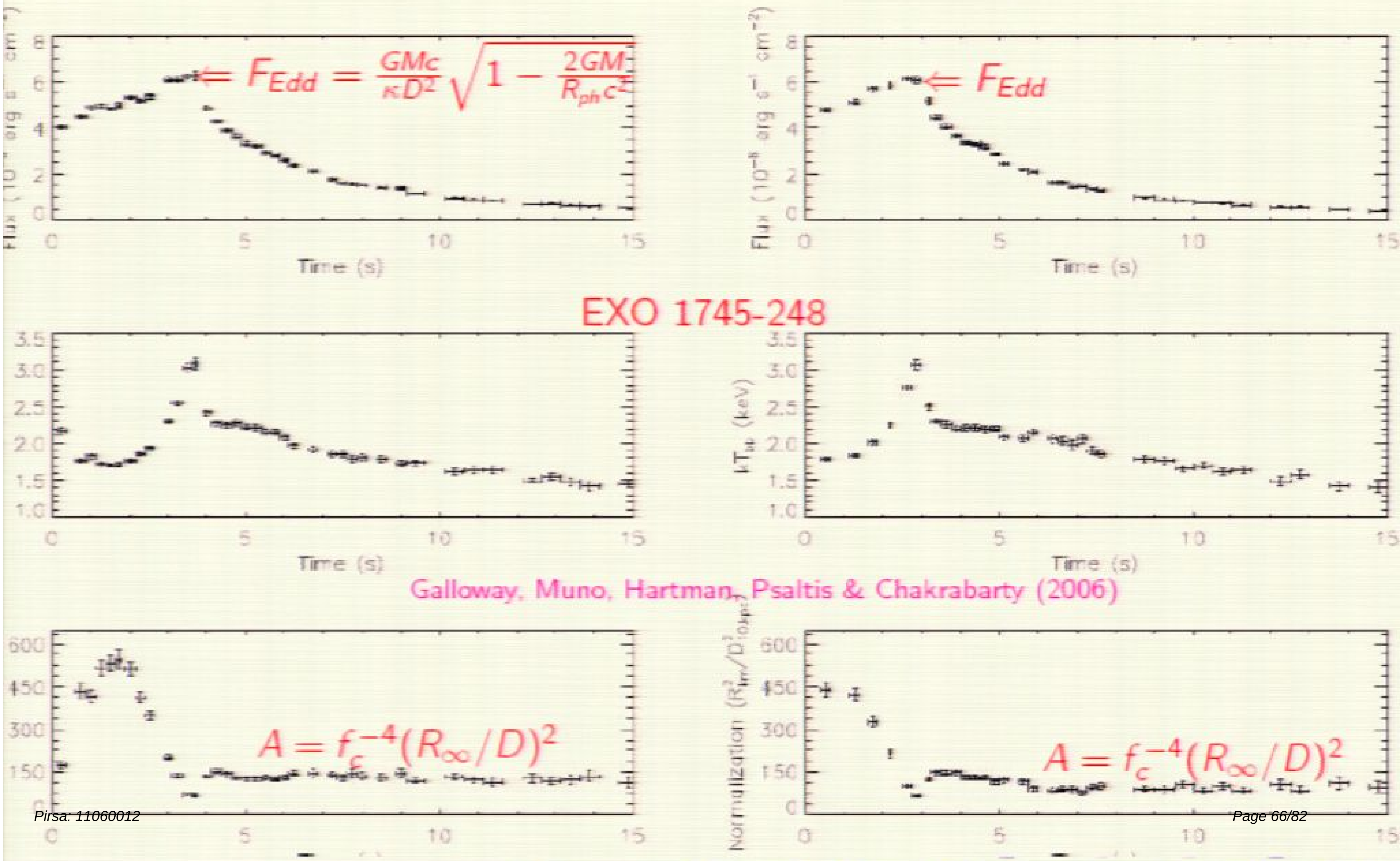


# Systematics with $R_{ph} = R$

$$F_{Edd} = \frac{GMc}{\kappa D^2}\sqrt{1 - 2\frac{GM}{R_{ph}c^2}} = \frac{GMc}{\kappa D^2}\sqrt{1-2\beta}$$

$$\kappa \simeq 0.2(1+X)\ \mathrm{cm^2 g^{-1}}$$

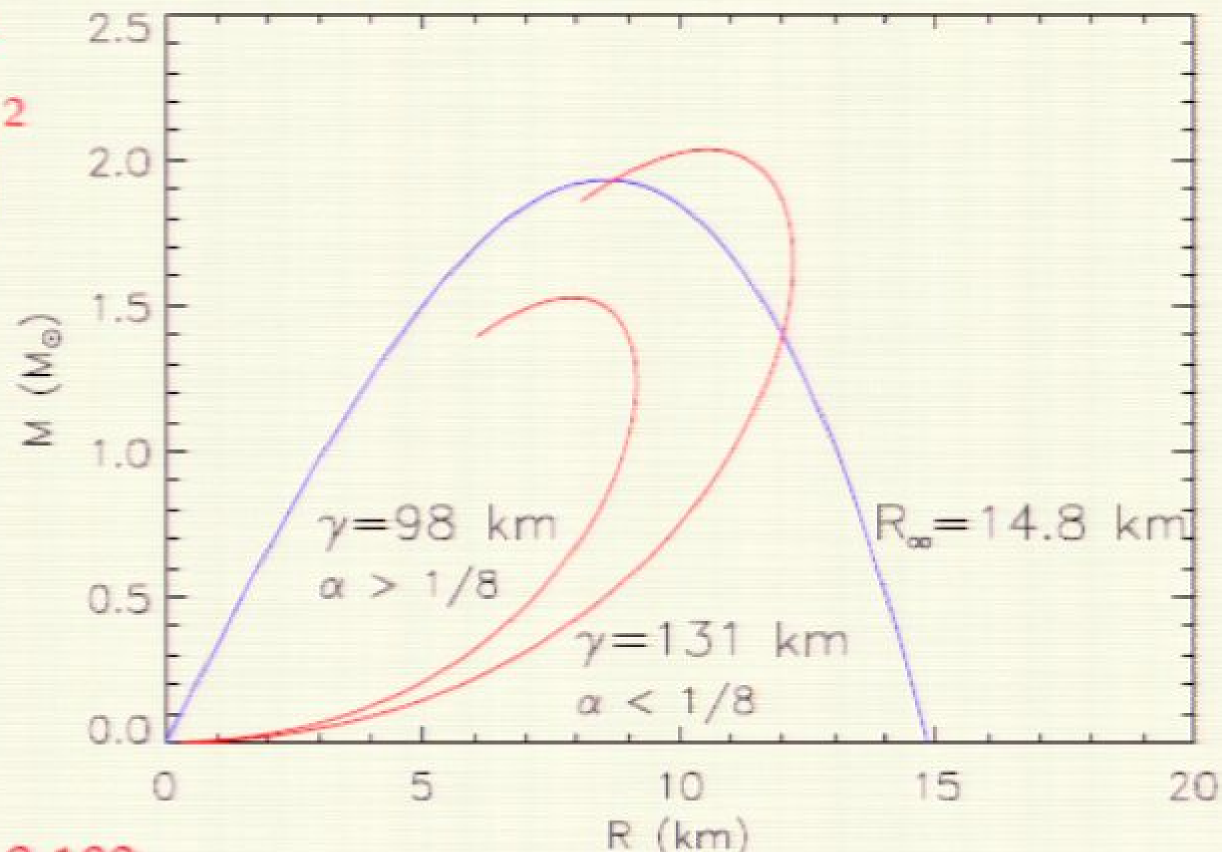
$$A = \frac{F_\infty}{\sigma T_\infty^4} = f_c^{-4}\left(\frac{R_\infty}{D}\right)^2$$

$$\alpha = \frac{F_{Edd}}{\sqrt{A}}\frac{\kappa D}{c^3 f_c^2} = \beta(1-2\beta)$$

$$\gamma = \frac{Ac^3 f_c^4}{F_{Edd}\kappa} = \frac{R}{\beta(1-2\beta)^{3/2}}$$

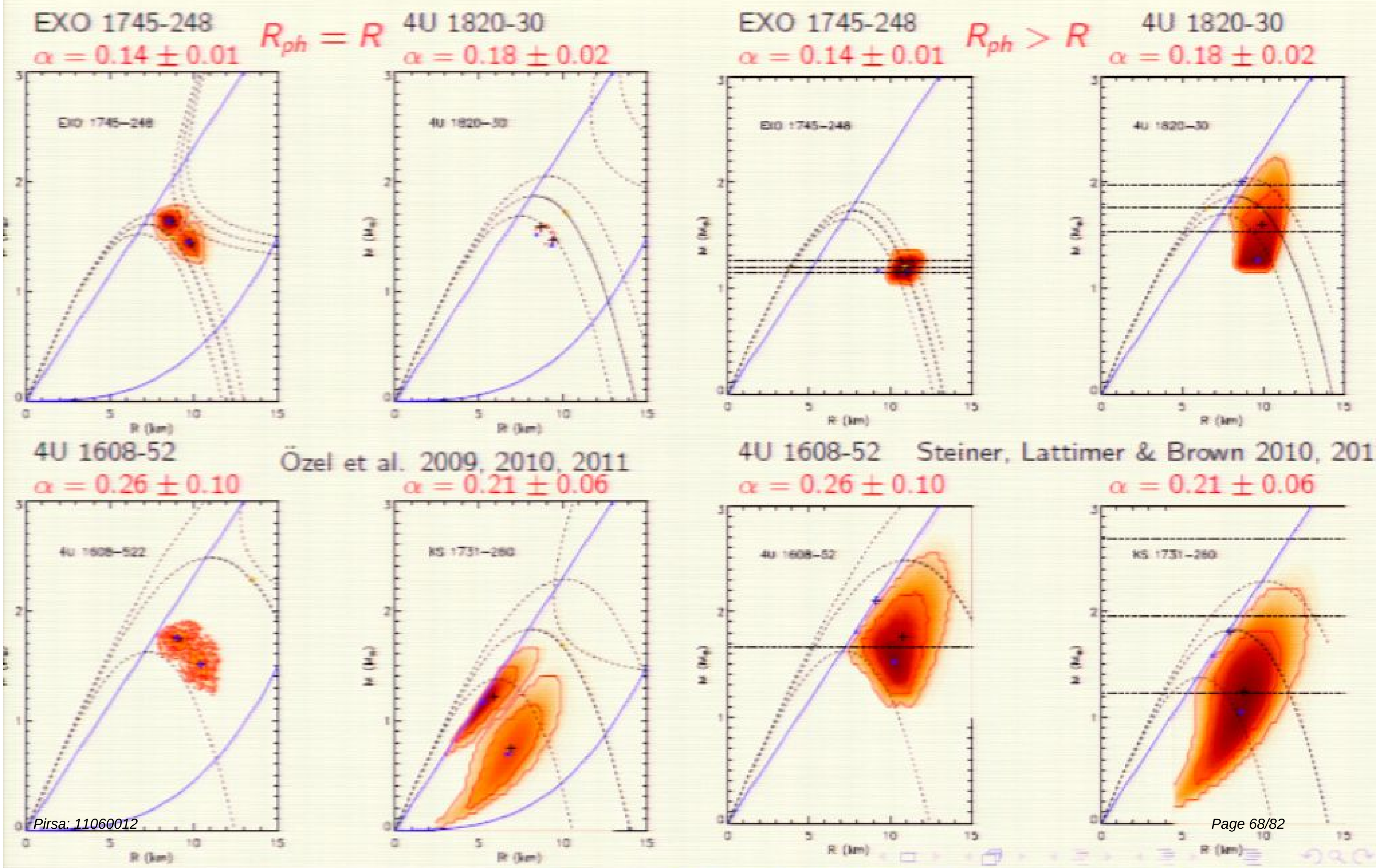
$$\beta = \frac{1}{4} \pm \frac{1}{4}\sqrt{1-8\alpha}$$

$$R_\infty = \alpha\gamma$$




If $R_{ph} >> R$, $\alpha < 1/\sqrt{27} \simeq 0.192$

# $M - R$ Probability Estimates from PRE Bursts



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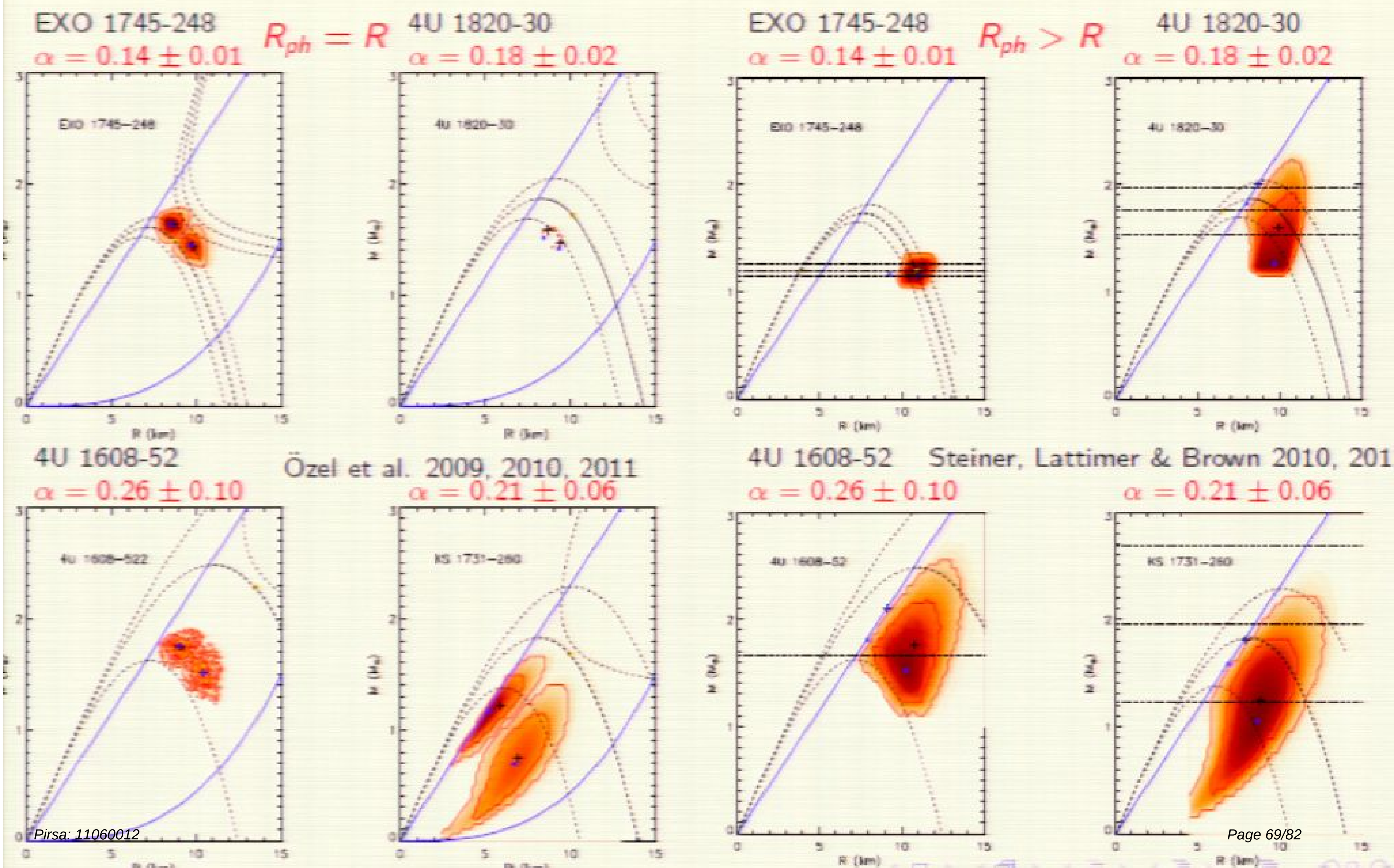
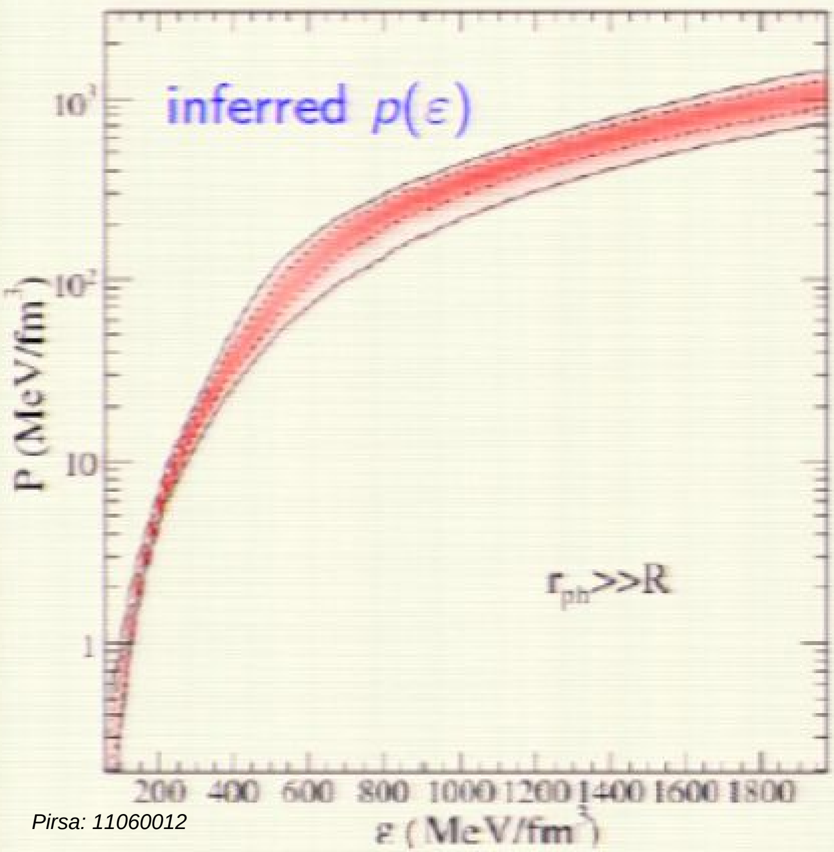
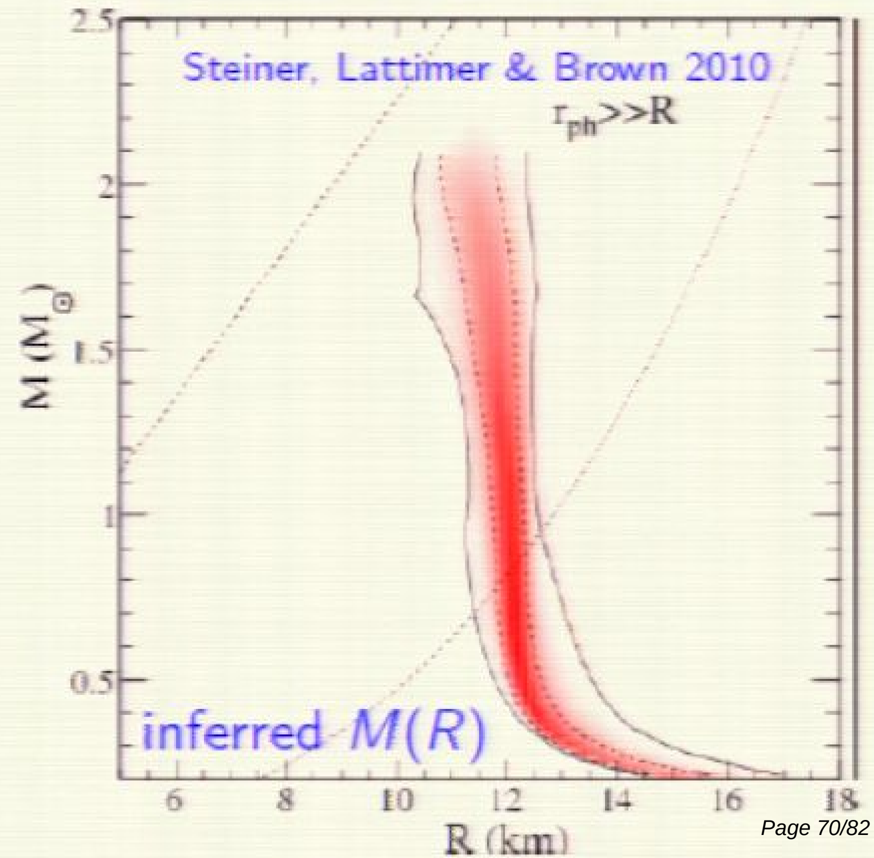


# Bayesian TOV Inversion

- $\varepsilon < 0.5\varepsilon_0$: Known crustal EOS
- $0.5\varepsilon_0 < \varepsilon < \varepsilon_1$: EOS parametrized by $K, K', S_v, \gamma$
- $\varepsilon_1 < \varepsilon < \varepsilon_2$: $n_1$; $\varepsilon > \varepsilon_2$: Polytropic EOS with $n_2$
- EOS parameters $(K, K', S_v, \gamma, \varepsilon_1, n_1, \varepsilon_2, n_2)$ uniformly distributed
- $M$ and $R$ probability distributions for 7 neutron stars treated equally.



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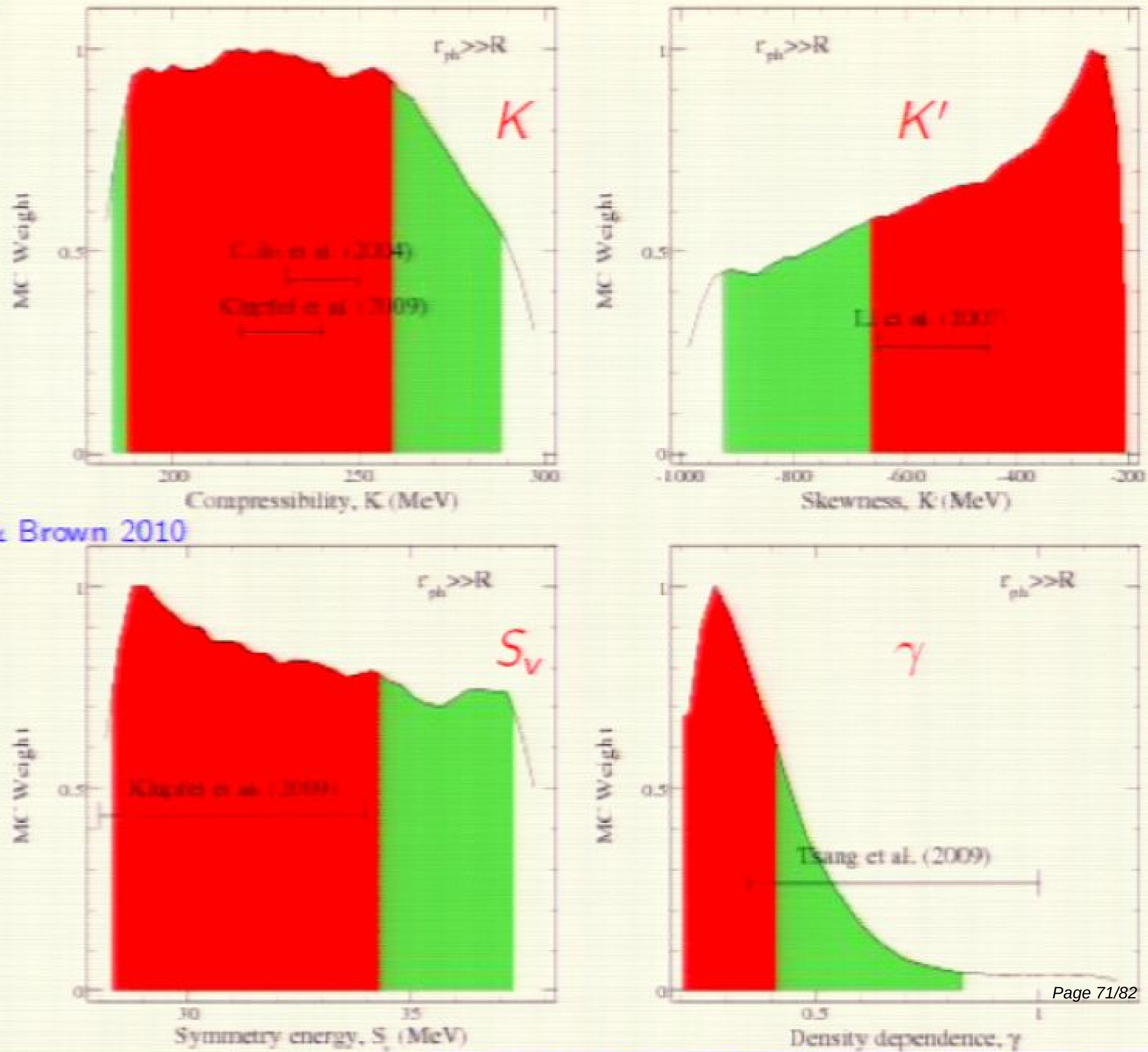
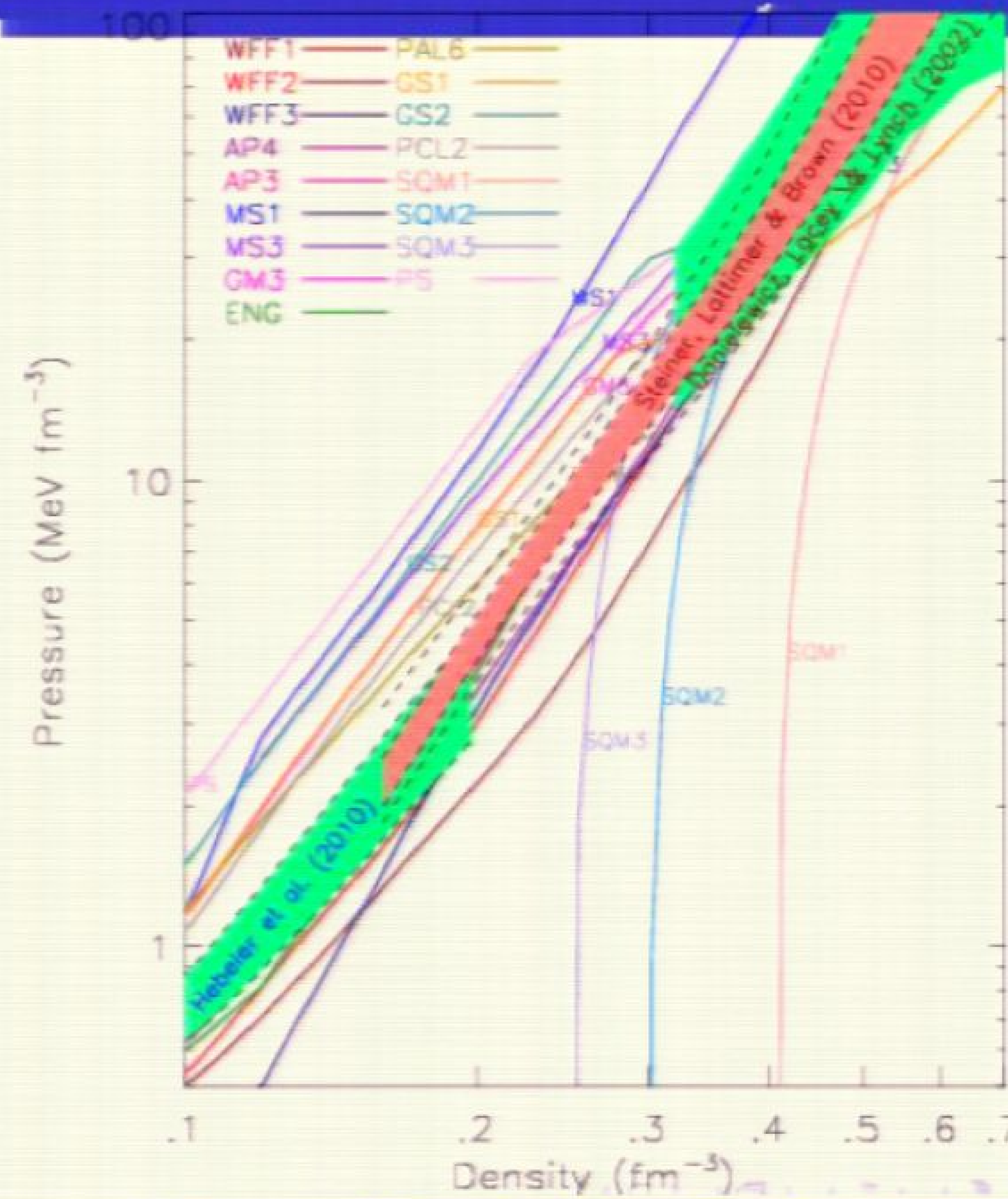
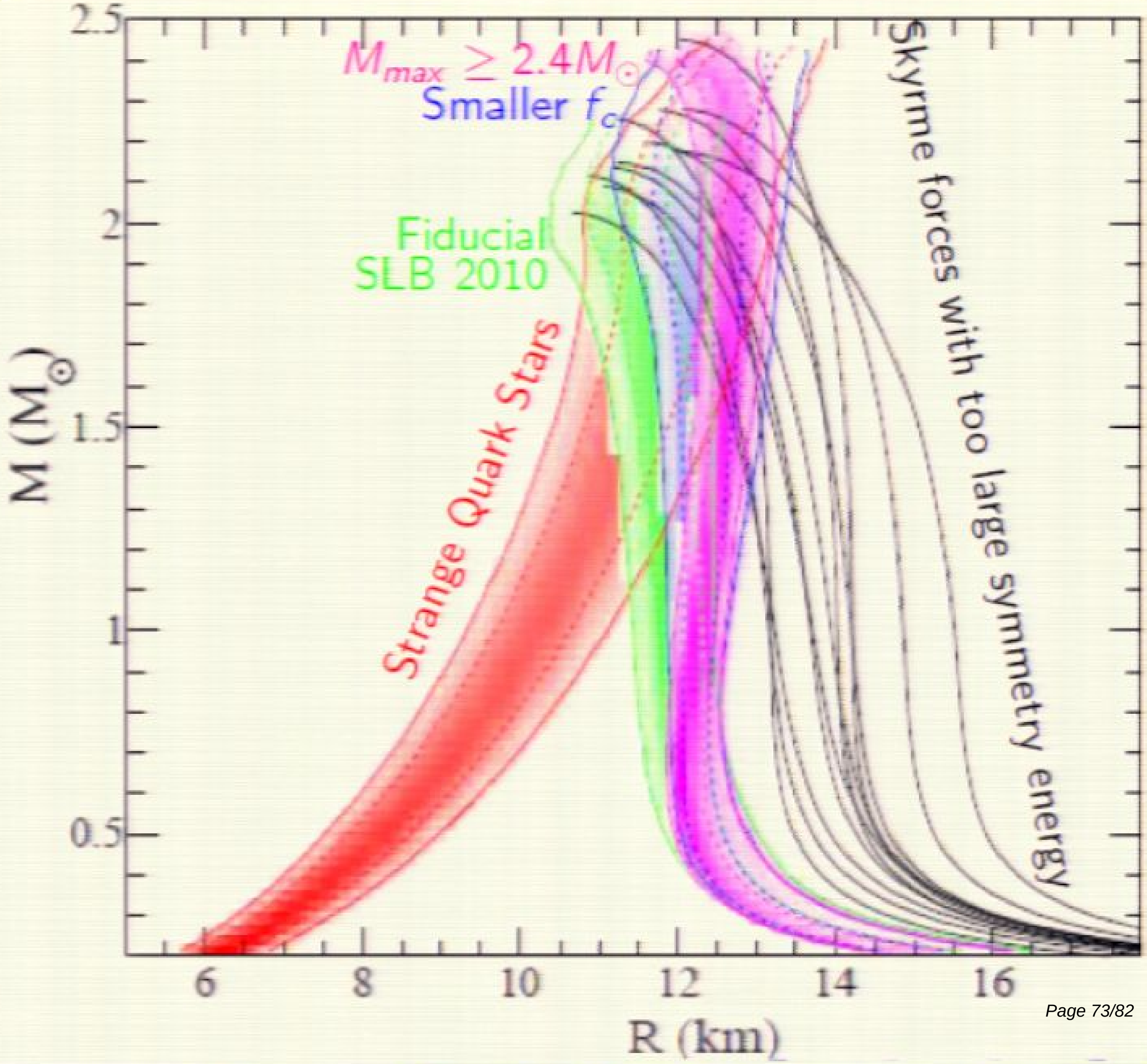



Steiner, Lattimer & Brown 2010

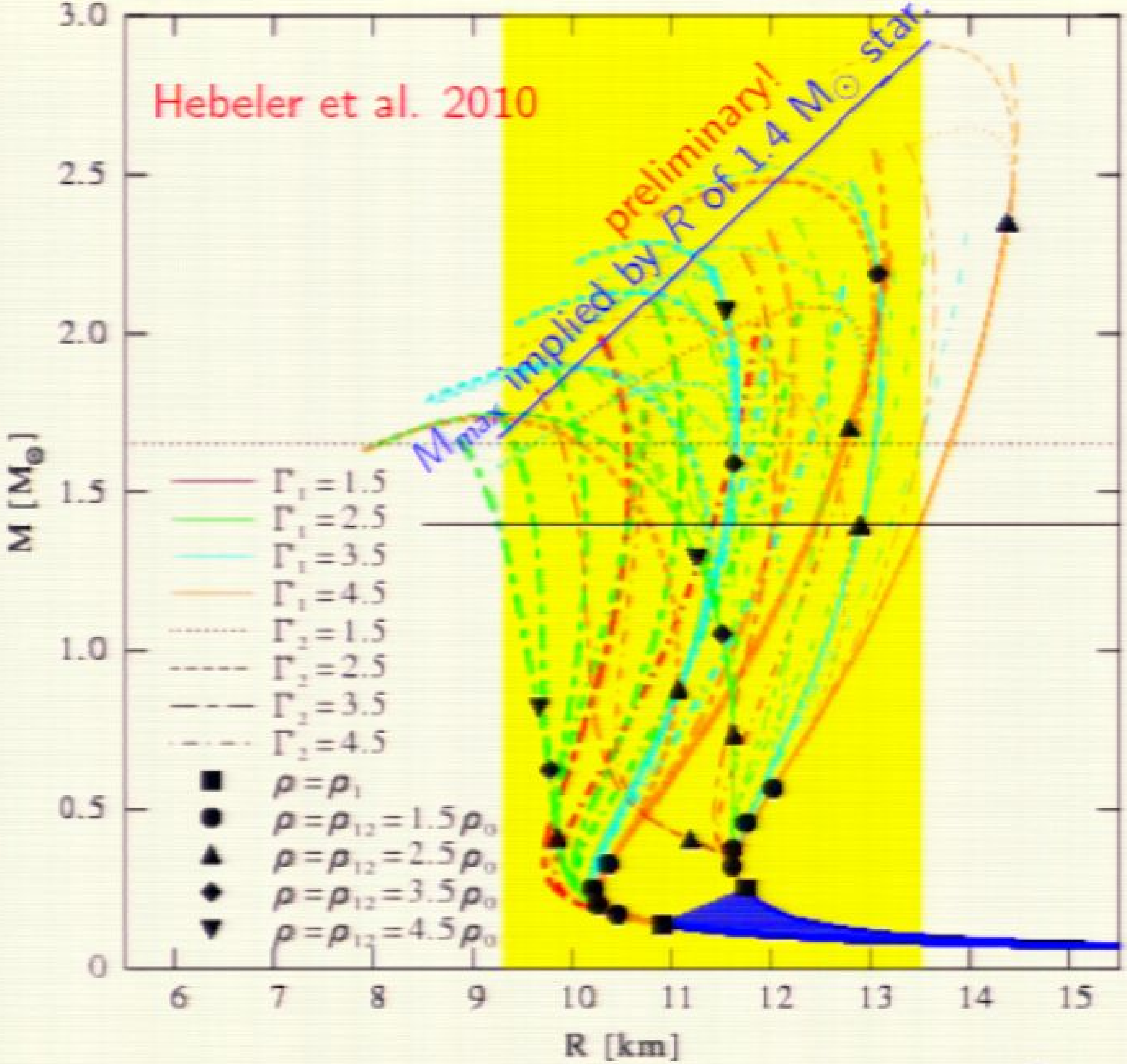
# Consistency with Neutron Matter and Heavy-Ion Collisions



# With More Extreme Assumptions



# Radius and Maximum Mass Limits



# Neutron Matter and the Symmetry Energy

- Fits to nuclear binding energies result in a strong, nearly linear, correlation between volume and surface symmetry energy coefficients of the liquid droplet model.
- This correlation is dependent on the nature of the liquid droplet model and how it treats the interaction between the Coulomb effects on the nuclear surface, and does not translate directly into a correlation between $S_v$ and $L = 3(dS_v/d\ln n)_{n_s}$.
- Finite nucleus models, such as Thomas-Fermi and Hartree or Hartree-Fock, for a particular nuclear interaction, can be fit to binding energies to obtain the correlation between $S_v$ and $L$.
- Neutron matter studies (Hebeler & Schwenk; Carlson et al.) indicate that $E_{sym}$ and $dE_{sym}/d\ln n)_{n_s}$ are also correlated.
- Comparing these correlations could constrain the properties of the symmetry energy. It could be dependent on the nature of the nuclear interaction model, but this has not been thoroughly explored.

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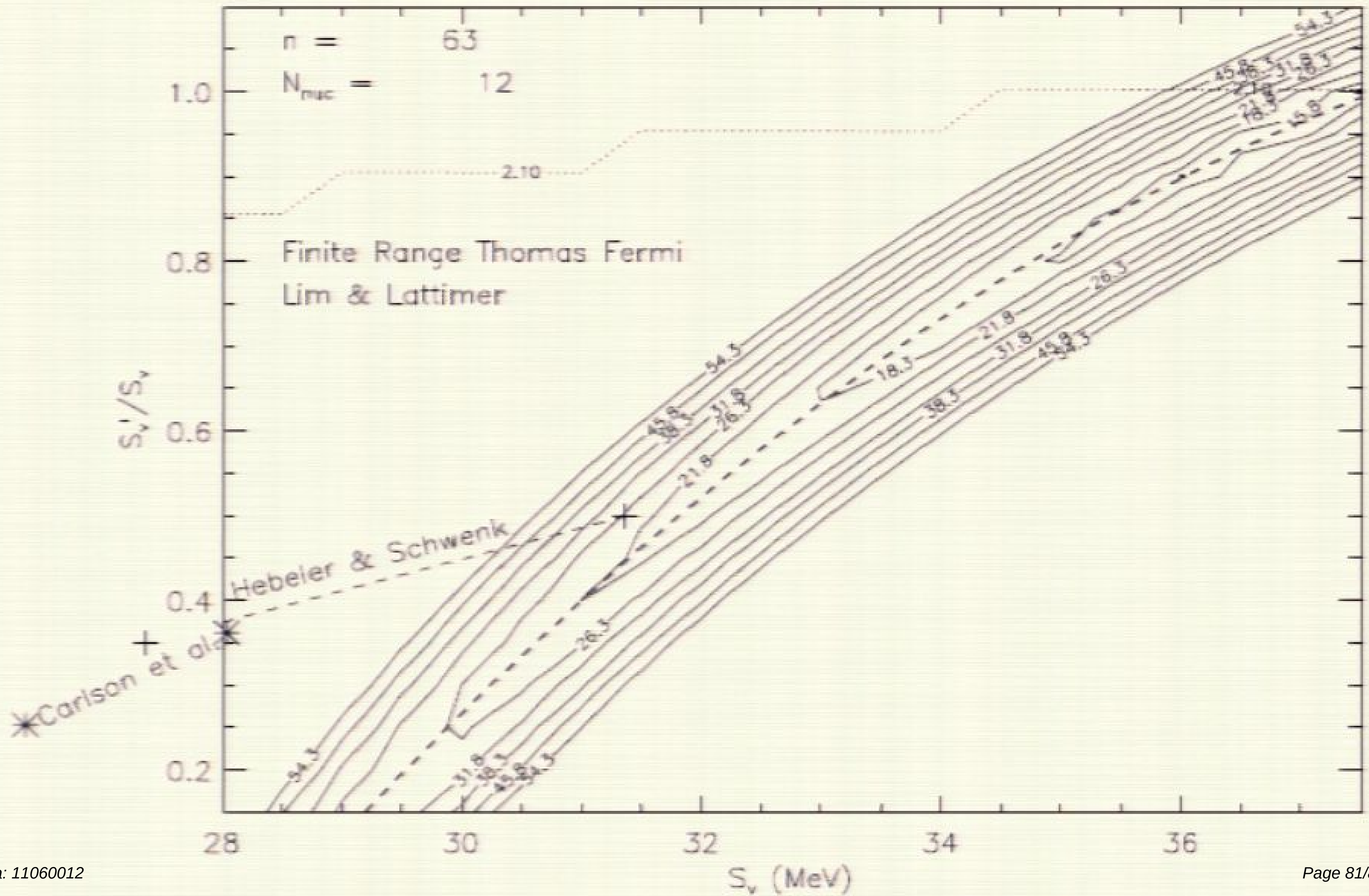

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