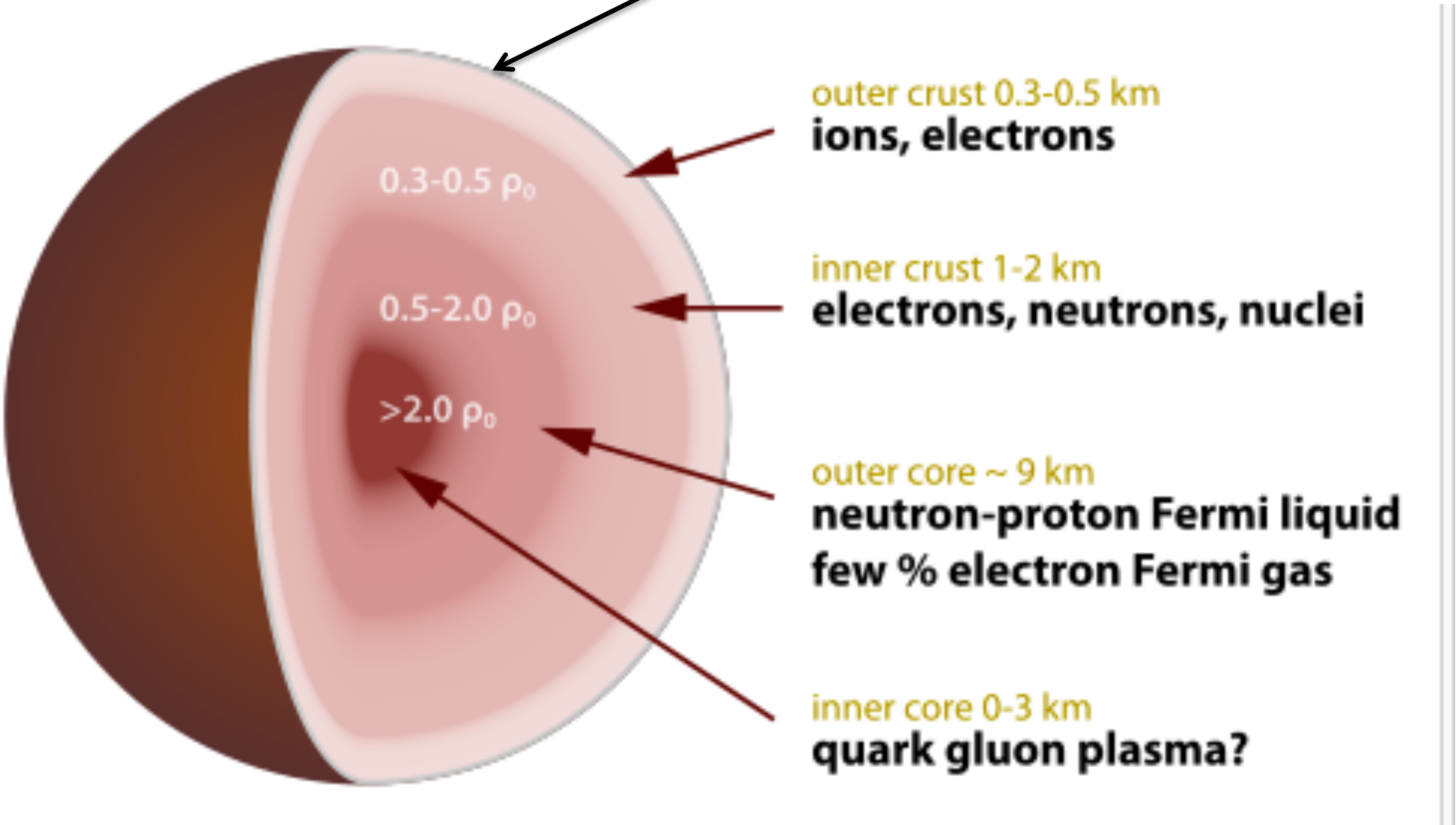
Neutron Star

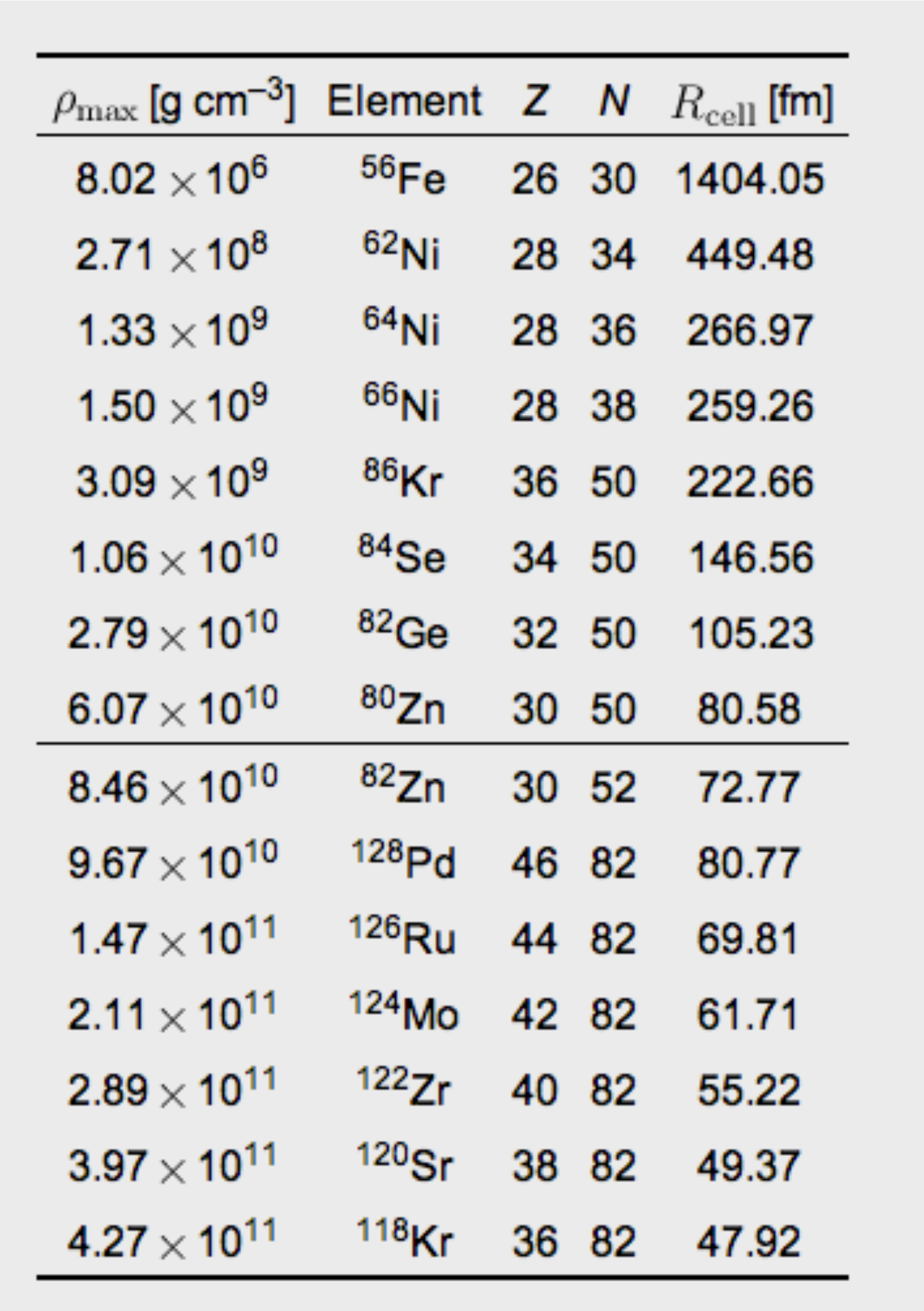
Typical mass: 1.4 solar masses
Typical total radius: 10 km

Gaseous atmosphere ~1 m

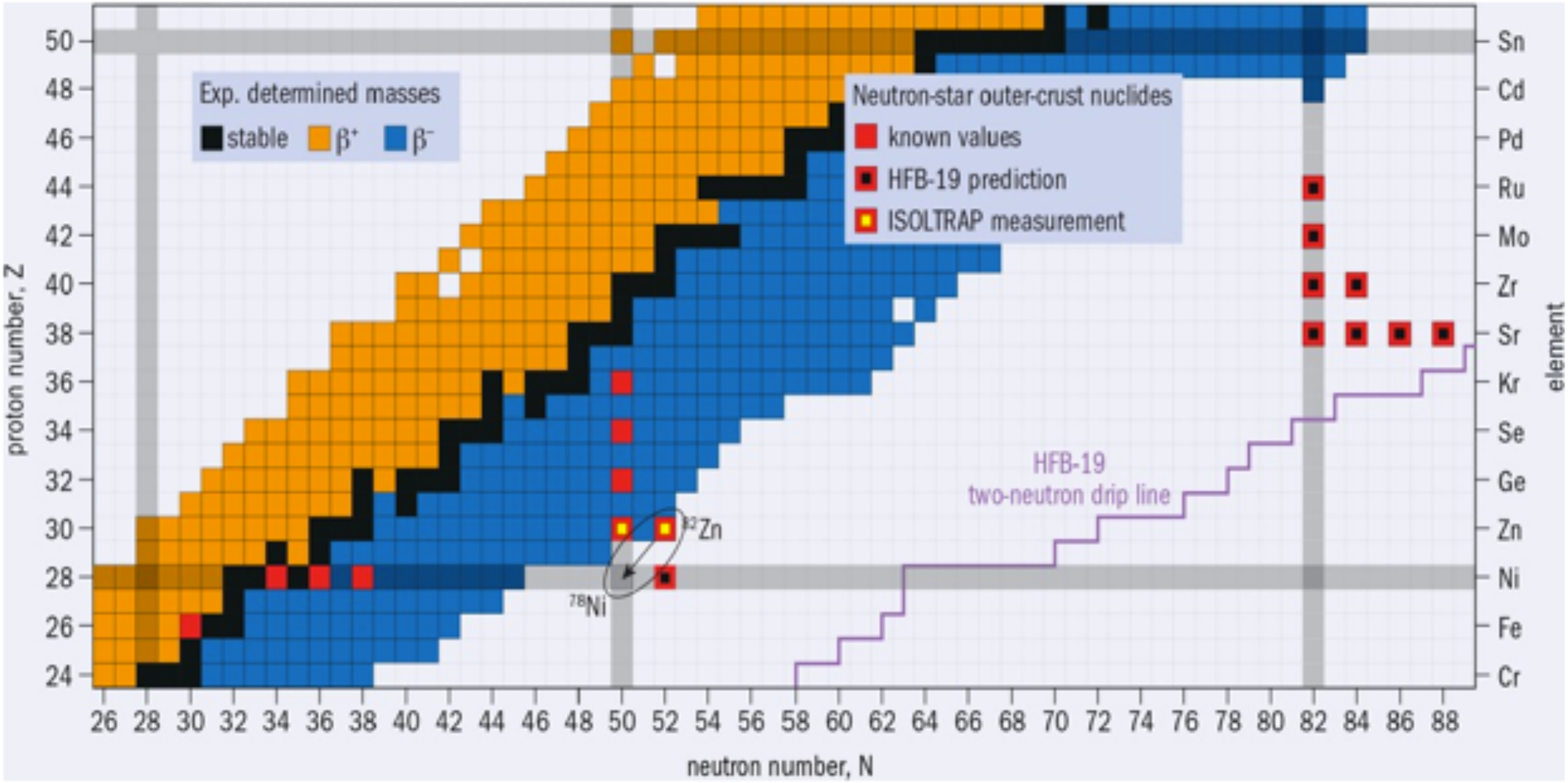
Liquid ocean ~10 m



Saturation density $\rho_0 \sim 3\text{x}10^{14}$ g/cm^3

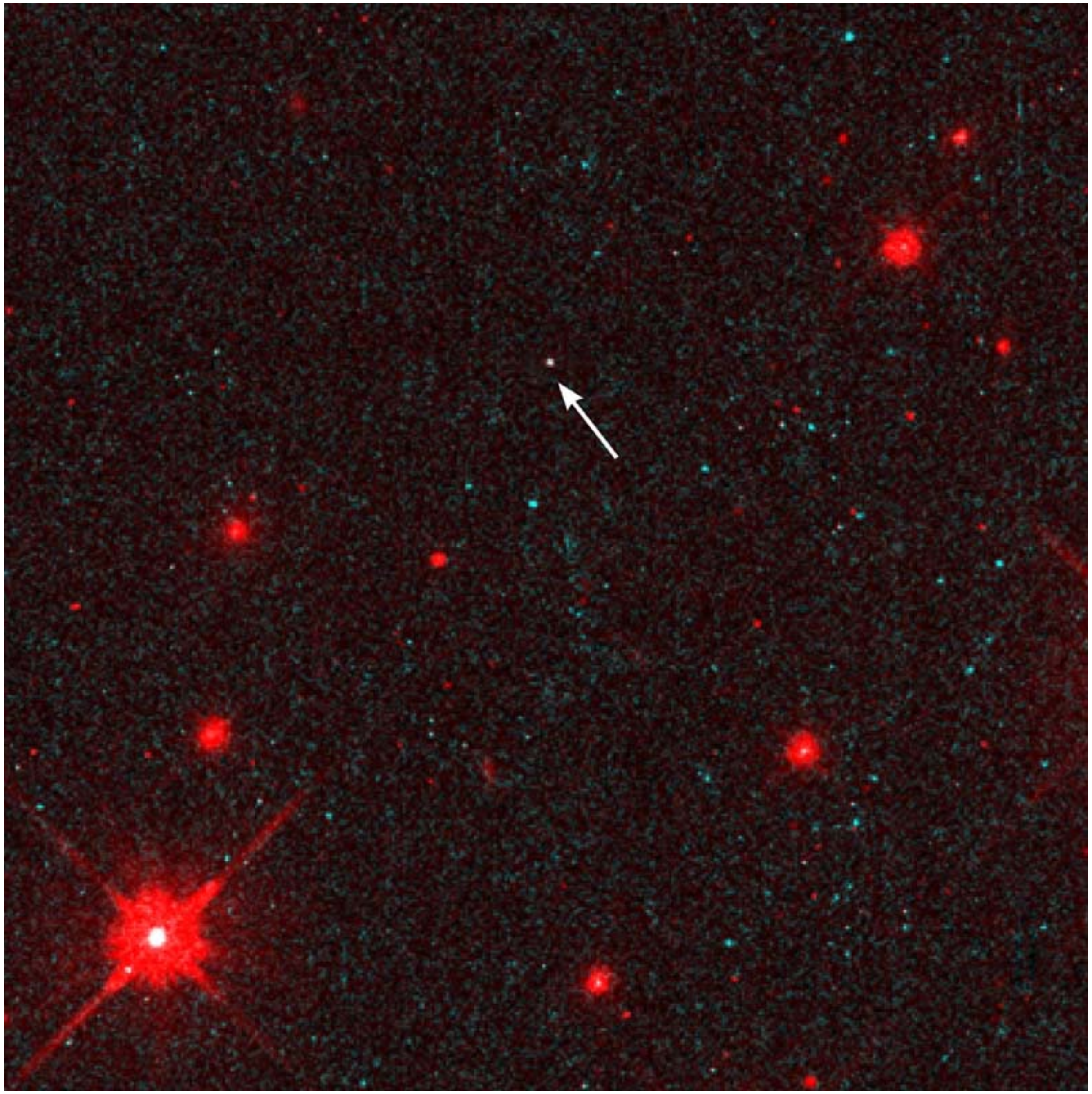


$\rho_{\rm max}$ [g cm^{-3}]	Element	Z	N	$R_{\rm cell}$ [fm]
8.02×10^6	^{56}Fe	26	30	1404.05
2.71×10^8	^{62}Ni	28	34	449.48
1.33×10^9	^{64}Ni	28	36	266.97
1.50×10^9	^{66}Ni	28	38	259.26
3.09×10^9	^{86}Kr	36	50	222.66
1.06×10^{10}	^{84}Se	34	50	146.56
2.79×10^{10}	^{82}Ge	32	50	105.23
6.07×10^{10}	^{80}Zn	30	50	80.58
8.46×10^{10}	^{82}Zn	30	52	72.77
9.67×10^{10}	^{128}Pd	46	82	80.77
1.47×10^{11}	^{126}Ru	44	82	69.81
2.11×10^{11}	^{124}Mo	42	82	61.71
2.89×10^{11}	^{122}Zr	40	82	55.22
3.97×10^{11}	^{120}Sr	38	82	49.37
4.27×10^{11}	^{118}Kr	36	82	47.92



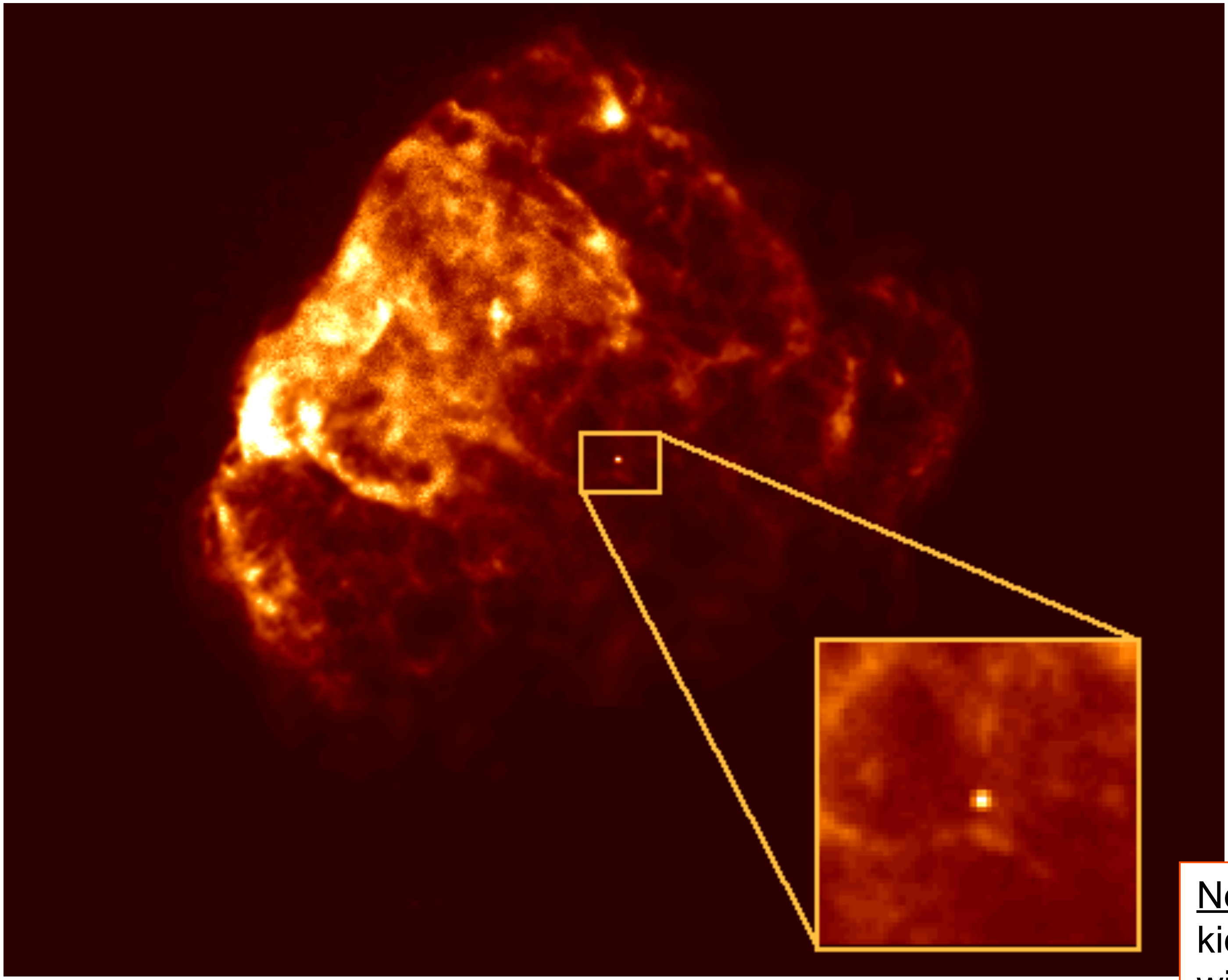
For inner crust: composition “beyond neutron drip” → mix of neutrons and nuclei
Drip density: ~4 x 10^{11} g/cm^3

An isolated neutron star seen with HST:



Its estimated that there are ~100’s of millions of neutron stars in our Galaxy

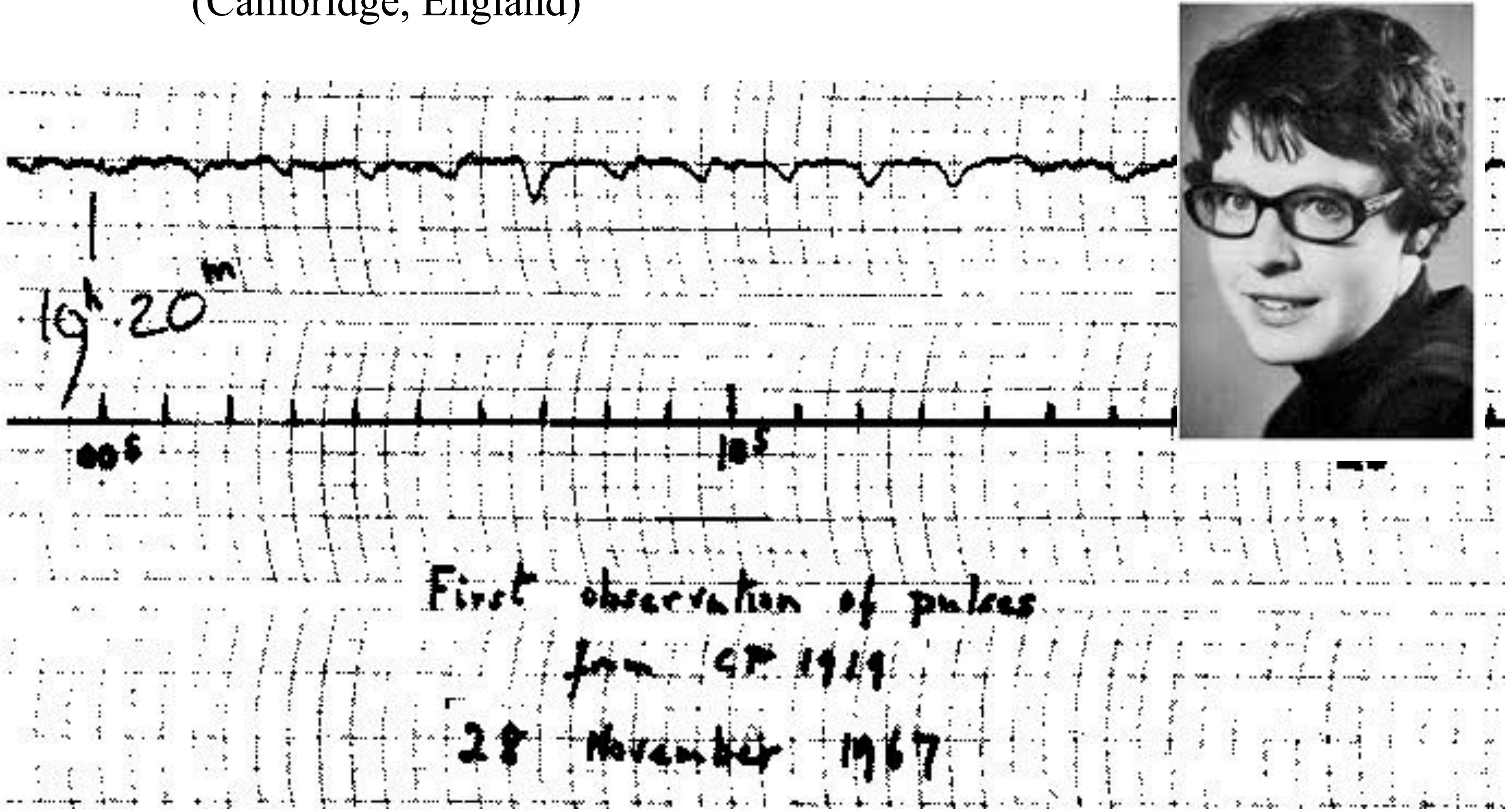
Supernova remants – neutron stars



Neutron star kicked out with ~600 mi/s

SN remnant Puppis A (Rosat)

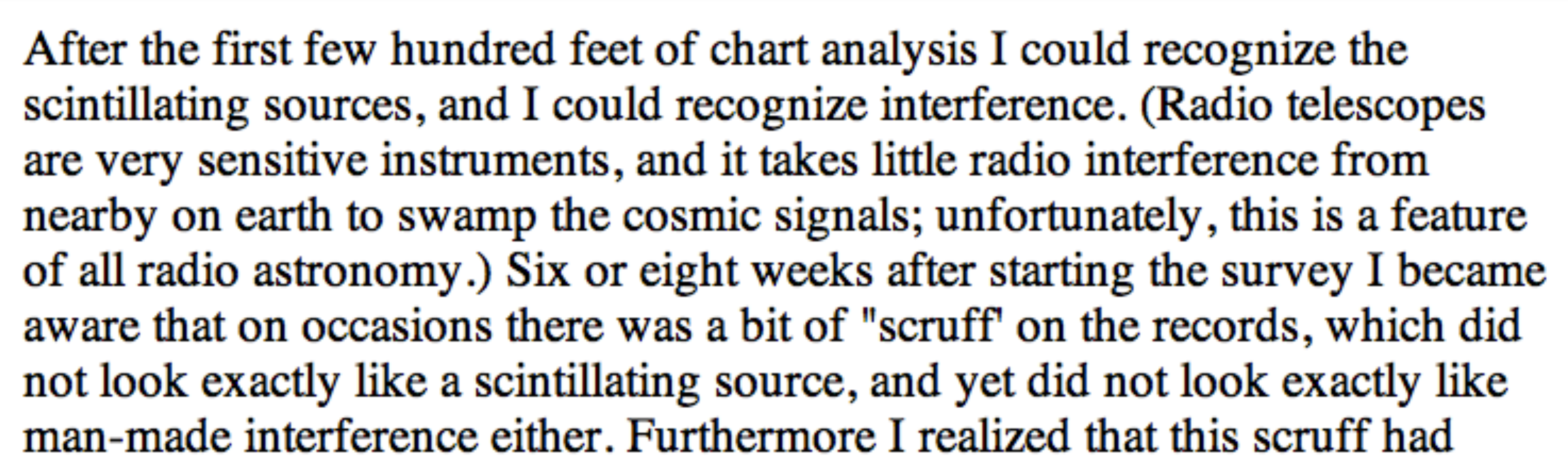
Grad student Jocelyn Bell: Discovery of Pulsars
(Cambridge, England)



Anthony Hewish won the Nobel Prize in 1974

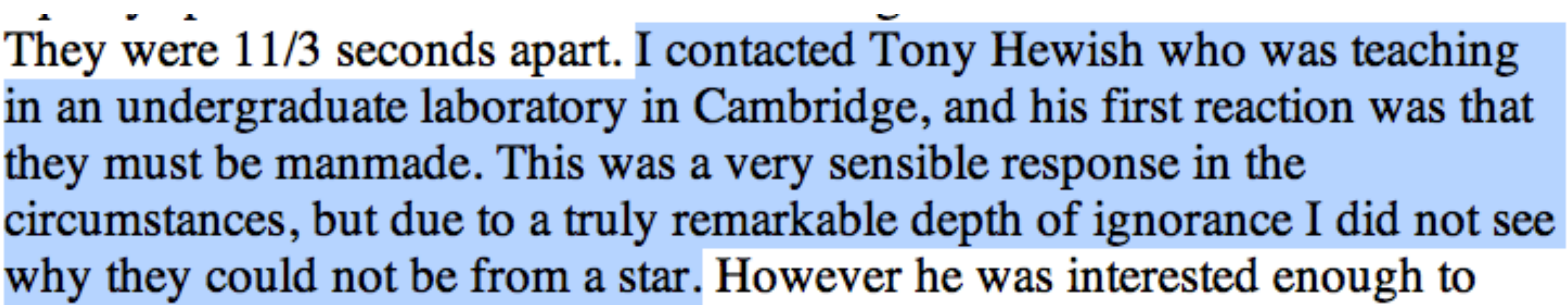
http://www.bigear.org/vol1no1/burnell.htm
http://www.aip.org/history/mod/pulsar/pulsar1/01.html

Some interesting lessons learned



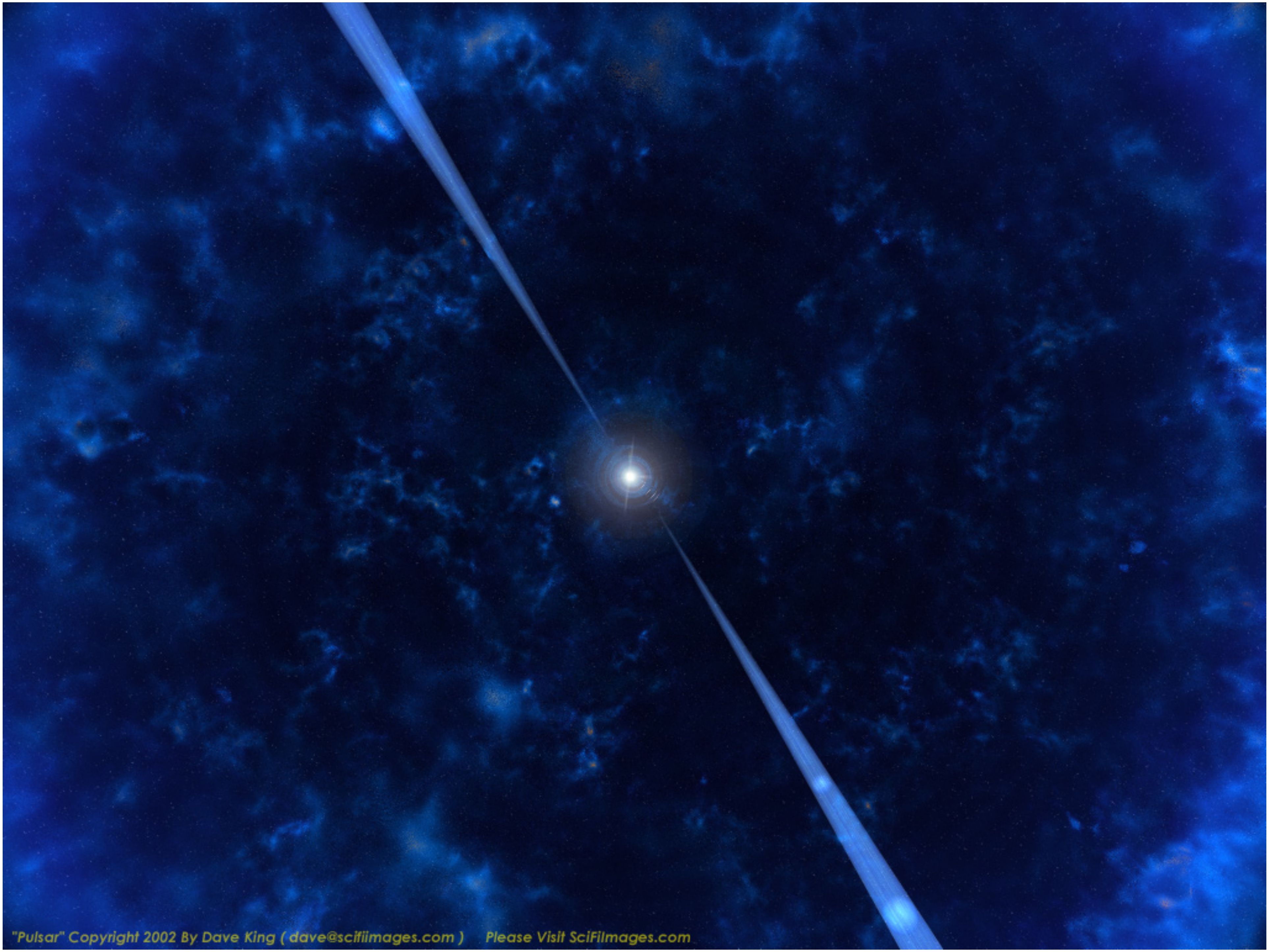
After the first few hundred feet of chart analysis I could recognize the scintillating sources, and I could recognize interference. (Radio telescopes are very sensitive instruments, and it takes little radio interference from nearby on earth to swamp the cosmic signals; unfortunately, this is a feature of all radio astronomy.) Six or eight weeks after starting the survey I became aware that on occasions there was a bit of "scruff' on the records, which did not look exactly like a scintillating source, and yet did not look exactly like man-made interference either. Furthermore I realized that this scruff had

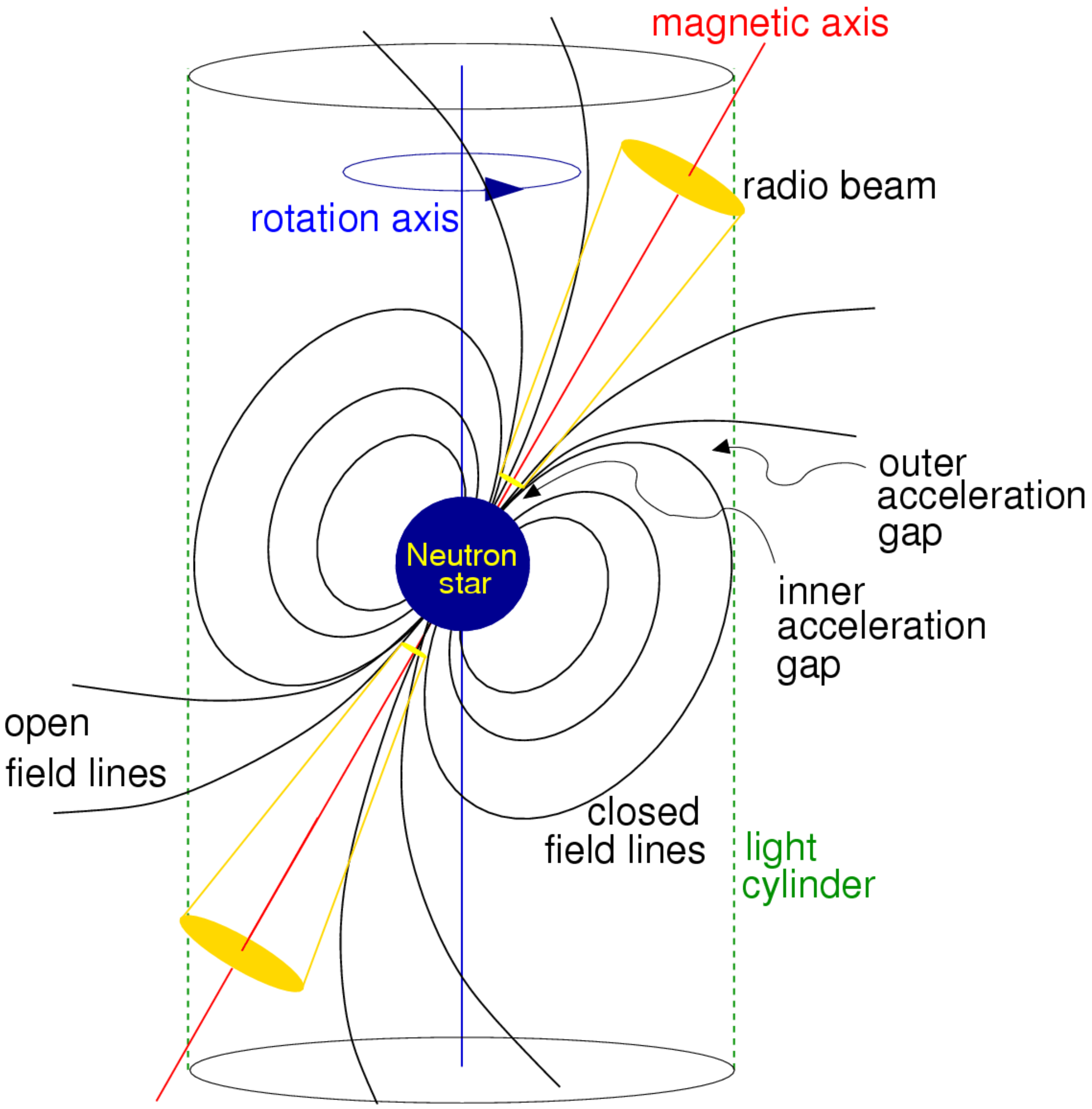
- Always look at the raw data
- Followup on everything you don’t understand

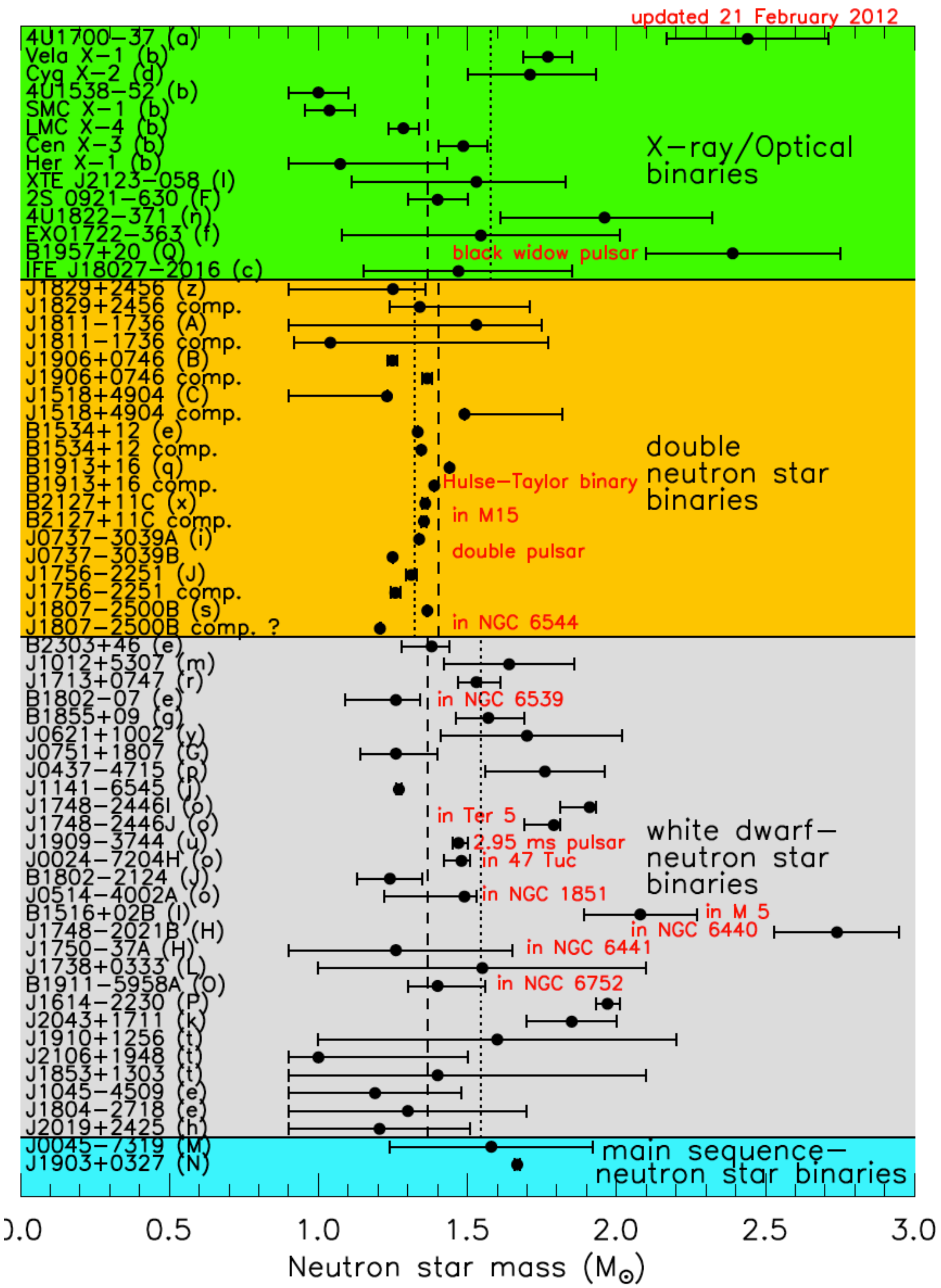


They were 11/3 seconds apart. I contacted Tony Hewish who was teaching in an undergraduate laboratory in Cambridge, and his first reaction was that they must be manmade. This was a very sensible response in the circumstances, but due to a truly remarkable depth of ignorance I did not see why they could not be from a star. However he was interested enough to

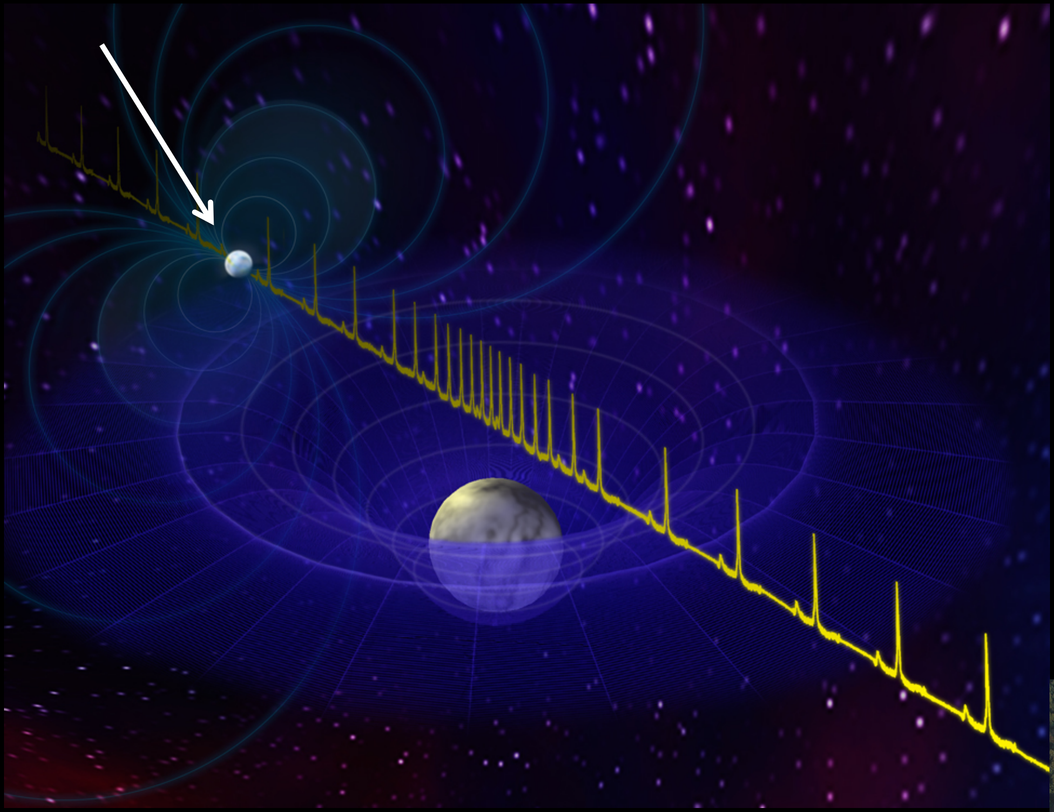
- Never (blindly) believe your advisor

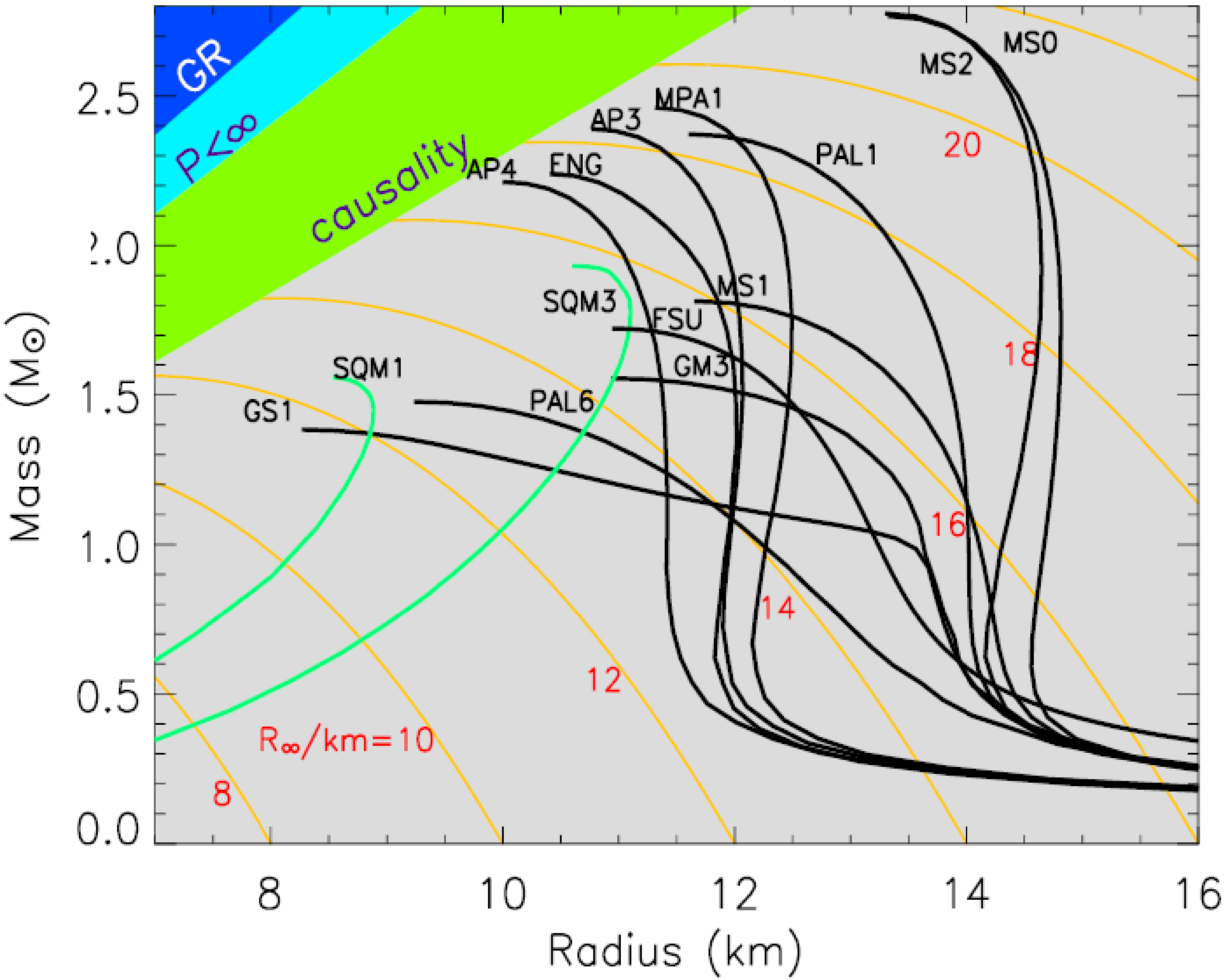

"Pulsar" Copyright 2002 By Dave King (dave@scifiimages.com)
Please Visit SciFiImages.com


magnetic axis
radio beam
rotation axis
outer acceleration gap
Neutron star
inner acceleration gap
open field lines
closed field lines
light cylinder


updated 21 February 2012
4U1700−37 (a)
Vela X−1 (b)
Cyg X−2 (d)
4U1538−52 (b)
SMC X−1 (b)
LMC X−4 (b)
Cen X−3 (b)
Her X−1 (b)
XTE J2123−058 (l)
2S 0921−630 (F)
4U1822−371 (n)
EXO1722−363 (f)
B1957+20 (Q)
IFE J18027−2016 (c)
black widow pulsar
X−ray/Optical binaries
J1829+2456 (z)
J1829+2456 comp.
J1811−1736 (A)
J1811−1736 comp.
J1906+0746 (B)
J1906+0746 comp.
J1518+4904 (C)
J1518+4904 comp.
B1534+12 (e)
B1534+12 comp.
B1913+16 (q)
B1913+16 comp.
B2127+11C (x)
B2127+11C comp.
J0737−3039A (i)
J0737−3039B
J1756−2251 (J)
J1756−2251 comp.
J1807−2500B (s)
J1807−2500B comp. ?
Hulse−Taylor binary
in M15
double pulsar
in NGC 6544
double neutron star binaries
B2303+46 (e)
J1012+5307 (m)
J1713+0747 (r)
B1802−07 (e)
B1855+09 (g)
J0621+1002 (y)
J0751+1807 (G)
J0437−4715 (p)
J1141−6545 (j)
J1748−2446I (o)
J1748−2446J (o)
J1909−3744 (u)
J0024−7204H (o)
B1802−2124 (J)
J0514−4002A (o)
B1516+02B (I)
J1748−2021B (H)
J1750−37A (H)
J1738+0333 (L)
B1911−5958A (O)
J1614−2230 (P)
J2043+1711 (k)
J1910+1256 (t)
J2106+1948 (t)
J1853+1303 (t)
J1045−4509 (e)
J1804−2718 (e)
J2019+2425 (h)
in NGC 6539
in Ter 5
2.95 ms pulsar
in 47 Tuc
in NGC 1851
in M 5
in NGC 6440
in NGC 6441
in NGC 6752
white dwarf−neutron star binaries
J0045−7319 (M)
J1903+0327 (N)
main sequence−neutron star binaries
.0
0.5
1.0
1.5
2.0
2.5
3.0
Neutron star mass ($M_\odot$)

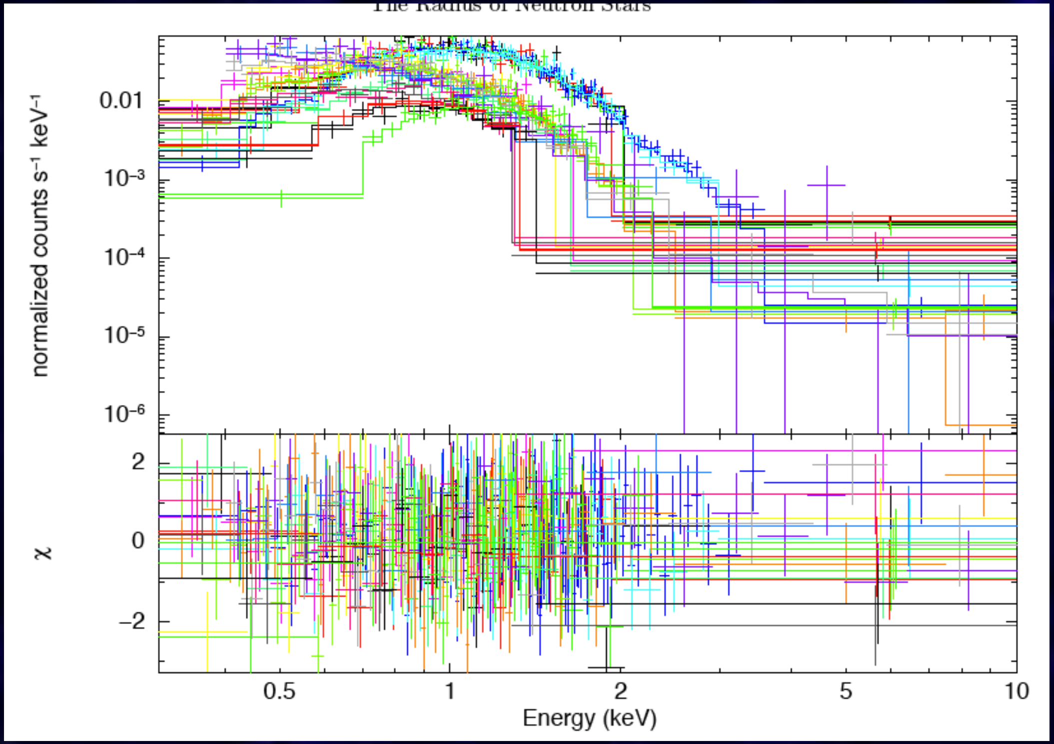
Neutron star:
Typical mass: 1.4 solar masses
Demorest et al. 2012: 1.97 +- 0.04 solar masses
What is maximum ???




GR
P<∞
causality
MS0
MS2
MPA1
AP3
PAL1
AP4
ENG
20
MS1
SQM3
FSU
18
GM3
SQM1
PAL6
GS1
16
14
12
R∞/km=10
8
Mass (M⊙)
Radius (km)
0.0
0.5
1.0
1.5
2.0
2.5
8
10
12
14
16

Quiescent Low Mass X-ray Binary (here KS1731-260)

“Black body like” spectra



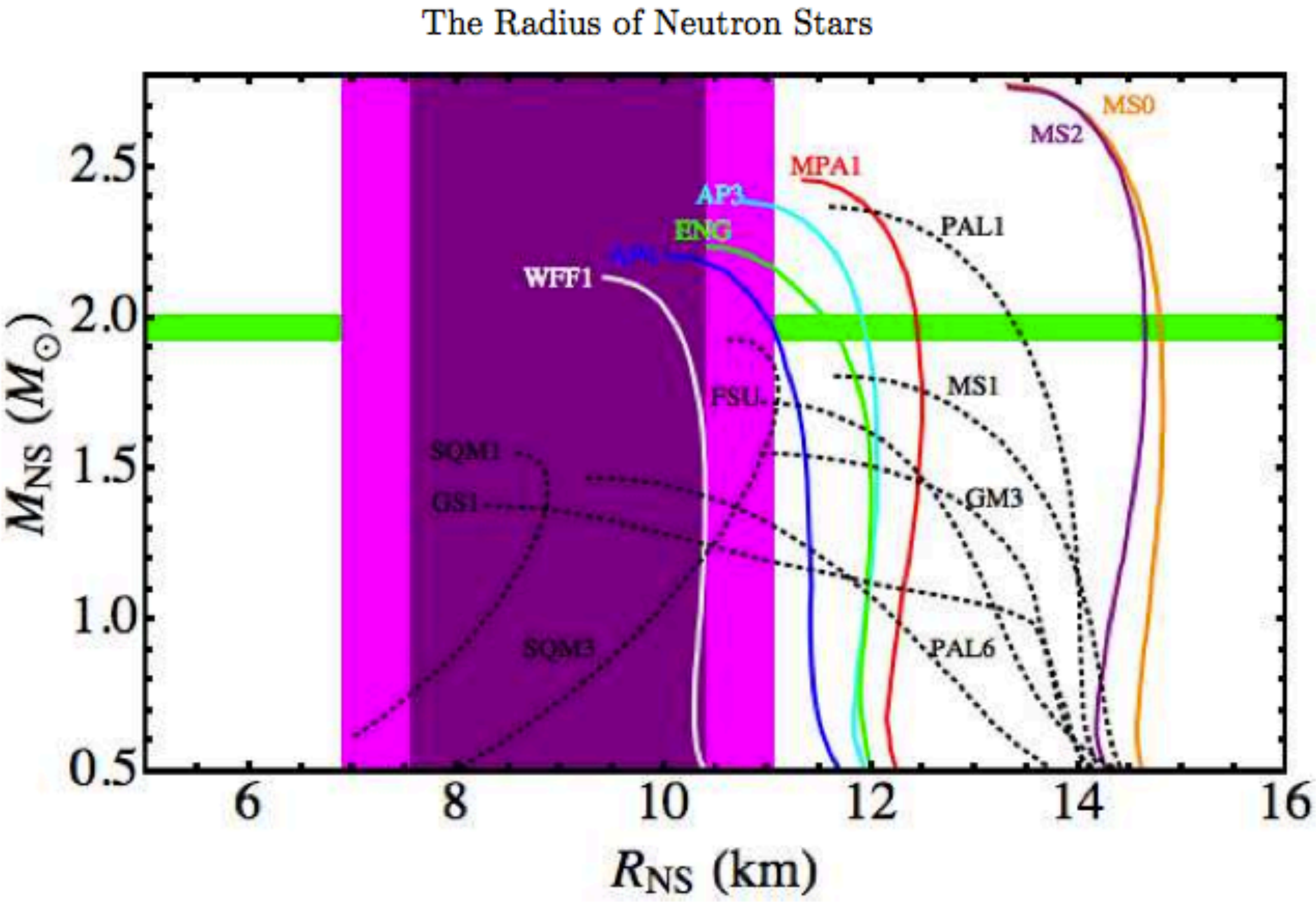
Stefan;s Law:

$$L = 4\pi R^2 \sigma T_{\mathrm{eff}}^4,$$

Measure L (distance)

T_{eff} from spectrum

→ Get R



http://arxiv.org/pdf/1302.0023v1.pdf - Guillot et al. 2013

Neutron star cooling

Chamel & Haensel

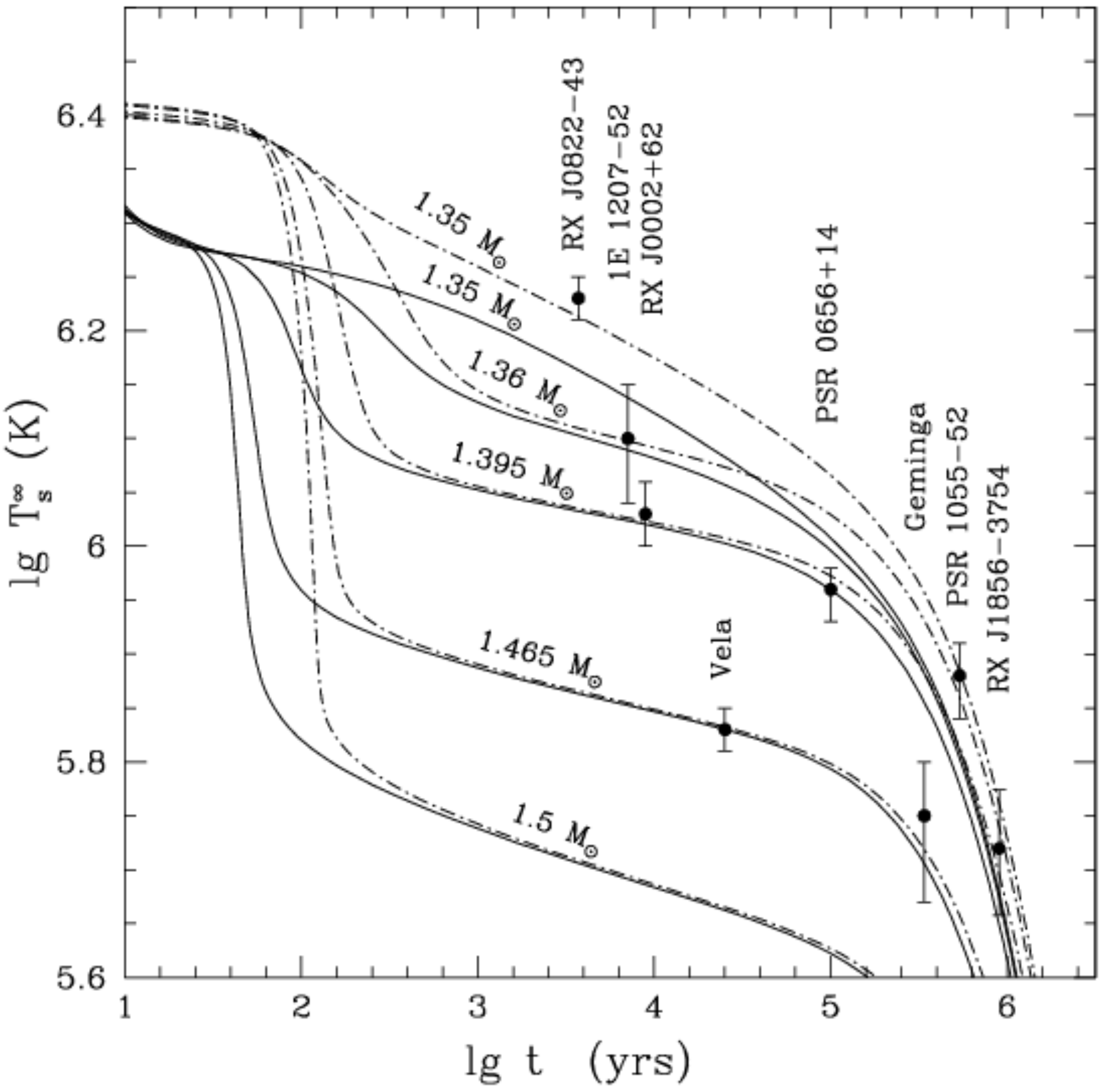
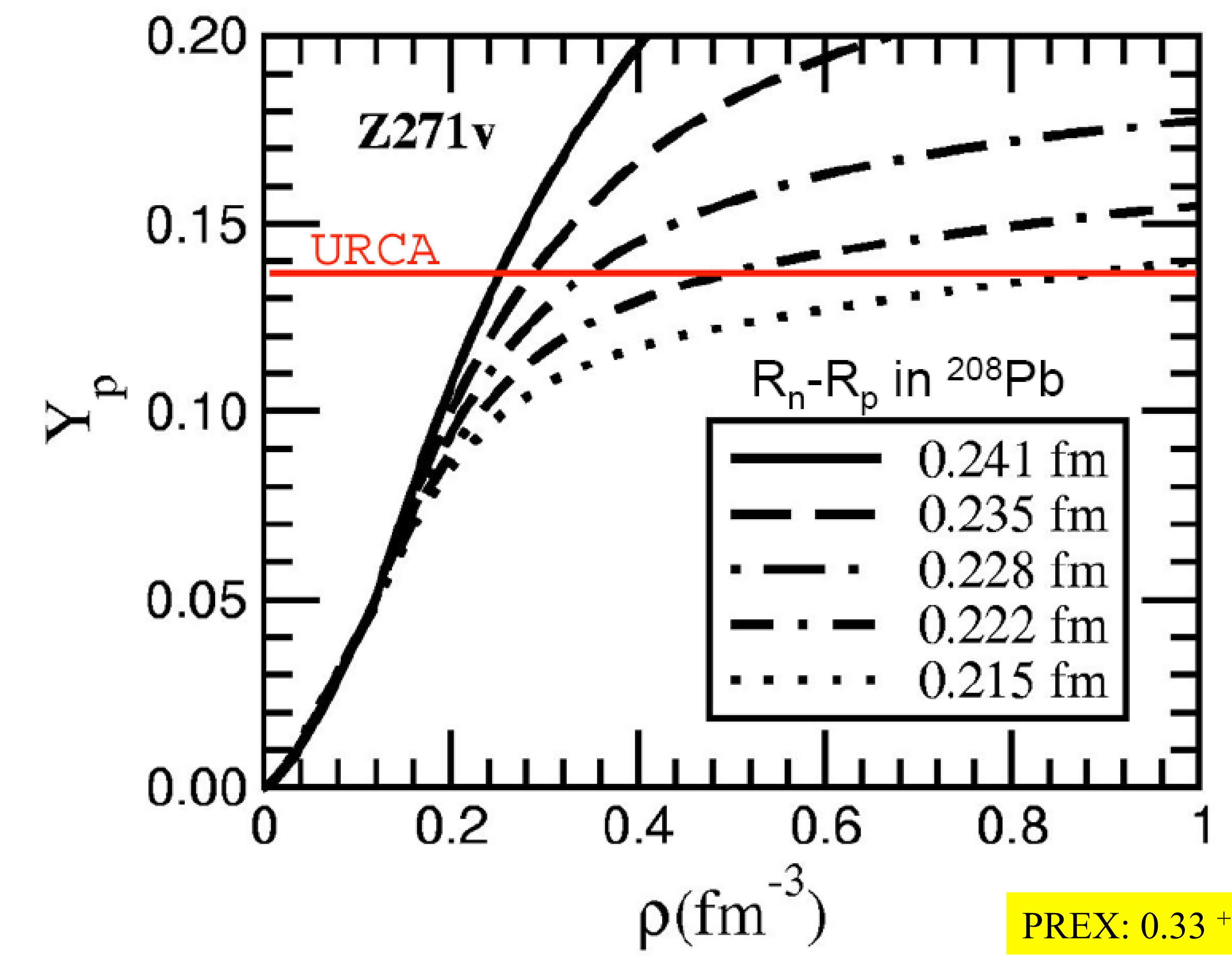


Figure 68: Redshifted surface temperatures (as seen by an observer at infinity) vs. age of neutron stars with different masses as compared with observation. Dot-dashed curves are calculated with only proton superfluidity in the core. Solid curves also include neutron superfluidity in the crust and outer core [428].

1. Neutrons stream freely
2. Direct Urca cooling



PREX: 0.33 $^{+0.16\ -0.18}$

Proton fraction for EOS with different neutron skin thicknesses in 208Pb