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The supernova-neutron star connection

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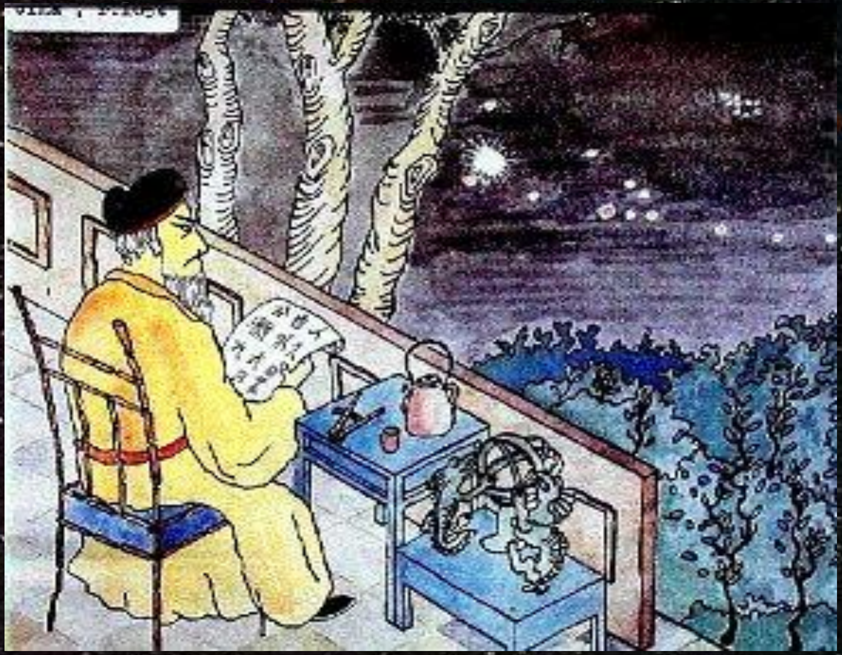
Supernova 1054 a.D. and the Crab pulsar

The Emperor Henry III in Tivoli, Italy



Astronomers of the Sung Dinasty

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However, when the Crab was observed since 1821, many obscure points appeared;;;

Cas A

≠

Crab

A SNR contains many solar masses, the Crab estimate is somewhere between 1 and 7 Msun at most. What we see is a *Pulsar Wind Nebula*, ionized by the injection of particles from the central object, not a SNR

The paradigmatic SN explosion in which a pulsar was born is just anything but “paradigmatic” or “standard”

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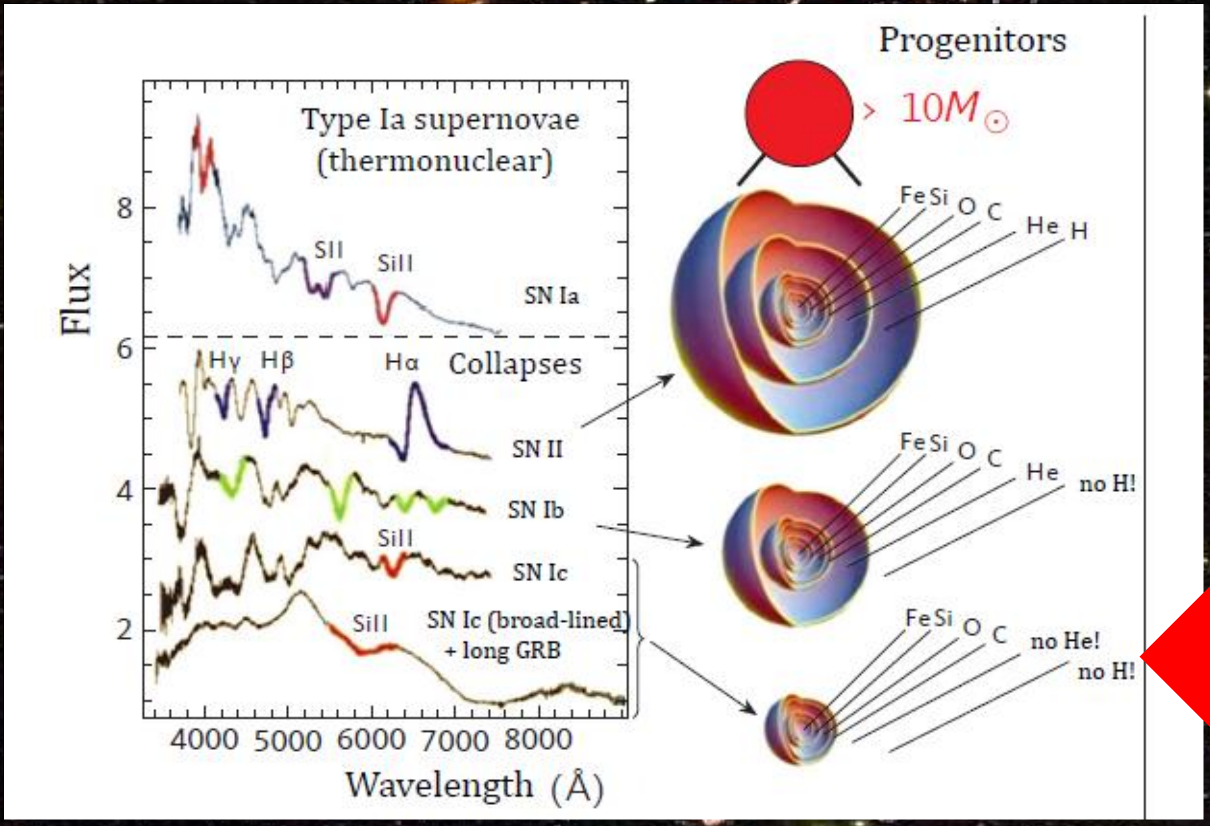

"Hypernovae"
Stripped He envelope,
large mass, GRBs
BHs?

("Superluminous" SN are not shown)

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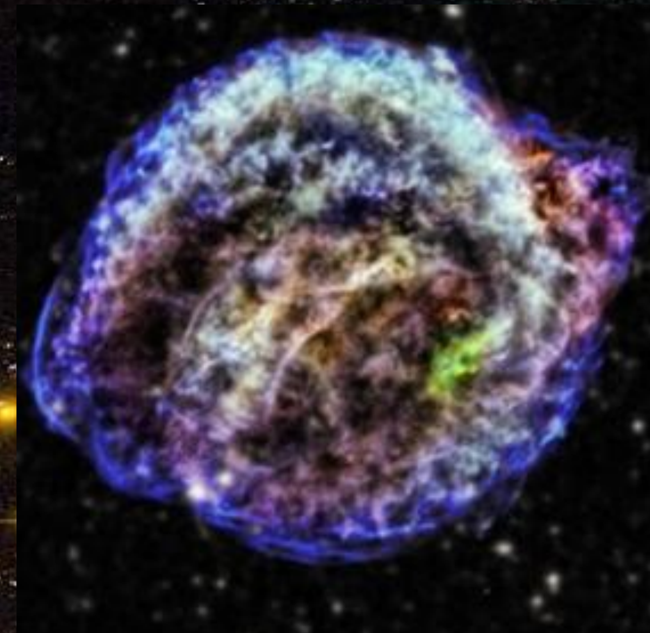
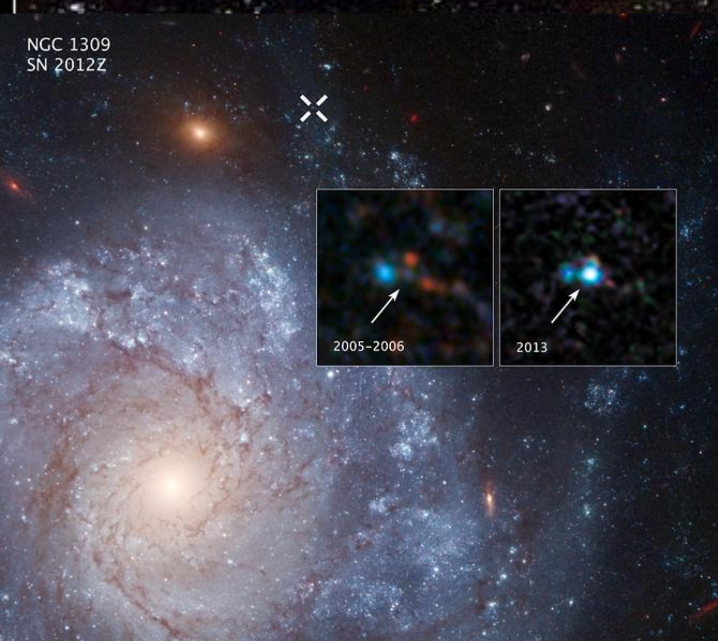
Type Ia (thermonuclear, single or double degenerate)

Never associated with a pulsar

Kepler SNR 1604





A class of thermonuclear explosions may not disrupt totally the star, but do not form NSs either. A zombie WD is left behind

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Accretion Induced Collapse vs. Type Ia

Electron capture must be quicker than thermonuclear ignition. This may happen if the accretion rate and the mass of the WDs are in a restricted range

Thought to be rare because of the ejection of exotic isotopes (Fryer et al. 1999). Recurrent idea in Astrophysics, related to many situations

Single-degenerate channel produces NS with ~ 1.25 $M_{\odot}$
Double-degenerate channel may allow NS masses 1.4-2.8 $M_{\odot}$
(Wang and Liu 2020)

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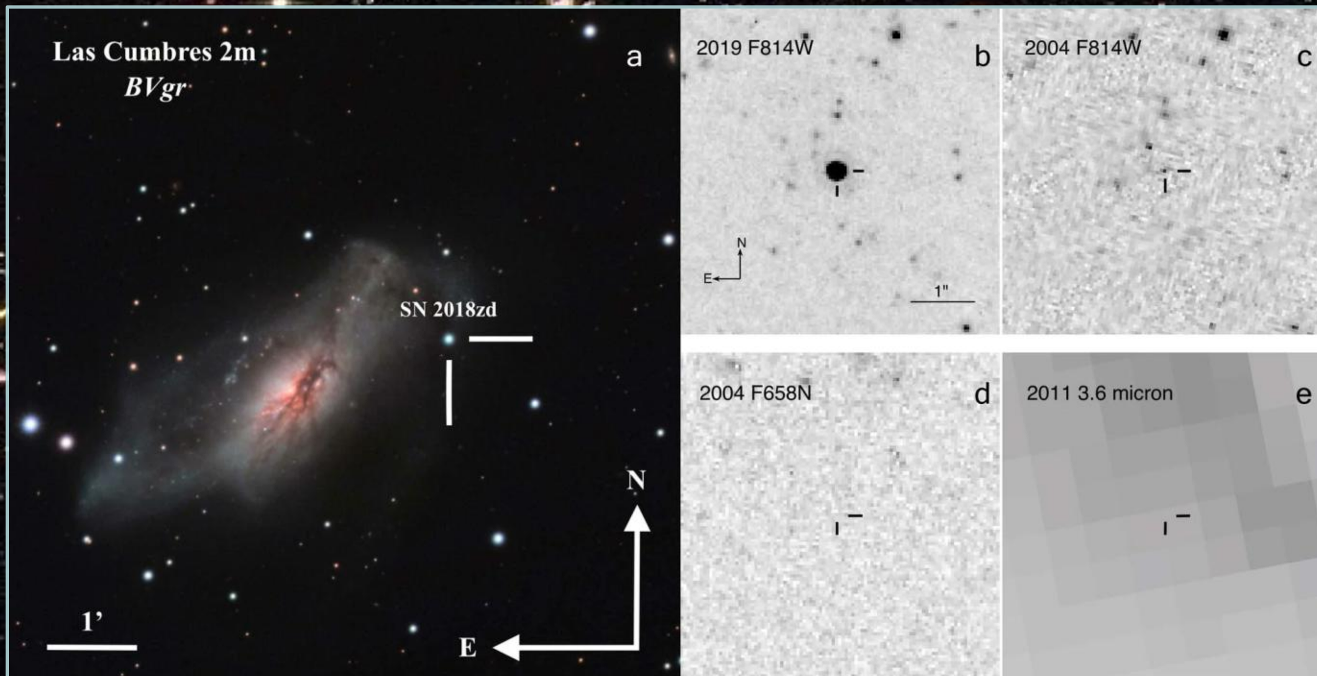
Supernova 2018zd: an electron-capture event ?
Collapse + oxygen fusion energy release,



Progenitor identified
Circumstellar material
Chemical composition
Explosion energy
Lightcurve
Nucleosynthesis

Super-AGB progenitor

electron-capture onto a O-Ne-Mg degenerate core

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What about NSs? (Baade & Zwicky, 1934)

In the last century, after > 40 years of neutron star studies, the idea of a single mass scale was firmly rooted in the community

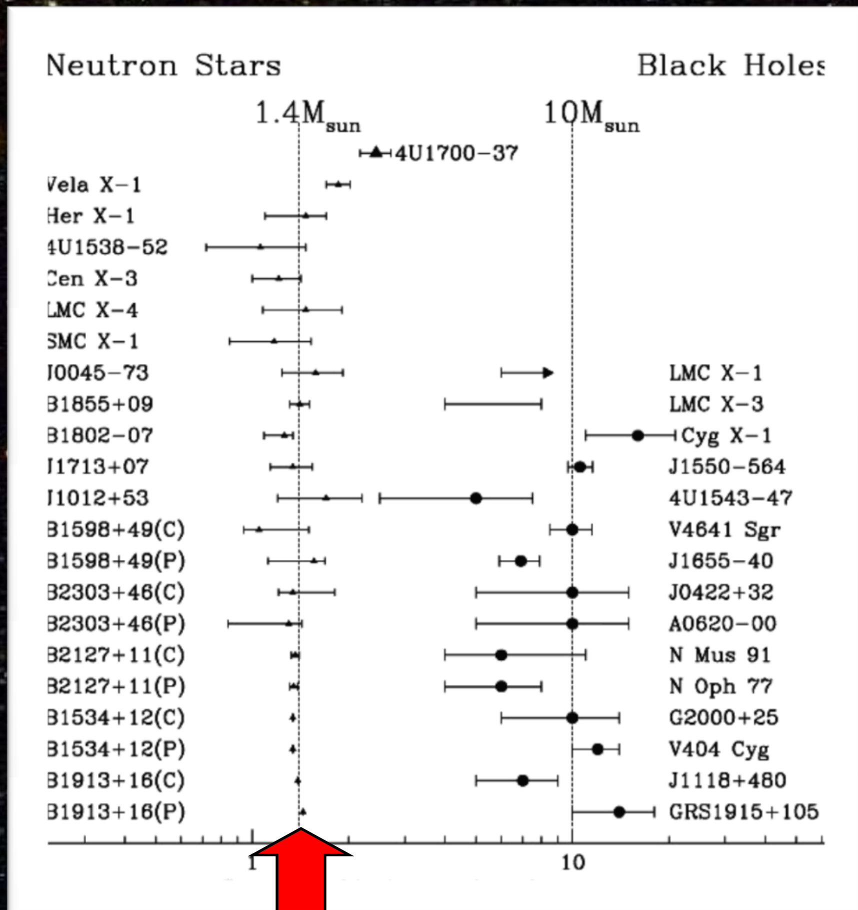

Figure from Clark et al. A&A 392, 909 (2002)

Consistent with 1.4 $M_{\odot}$

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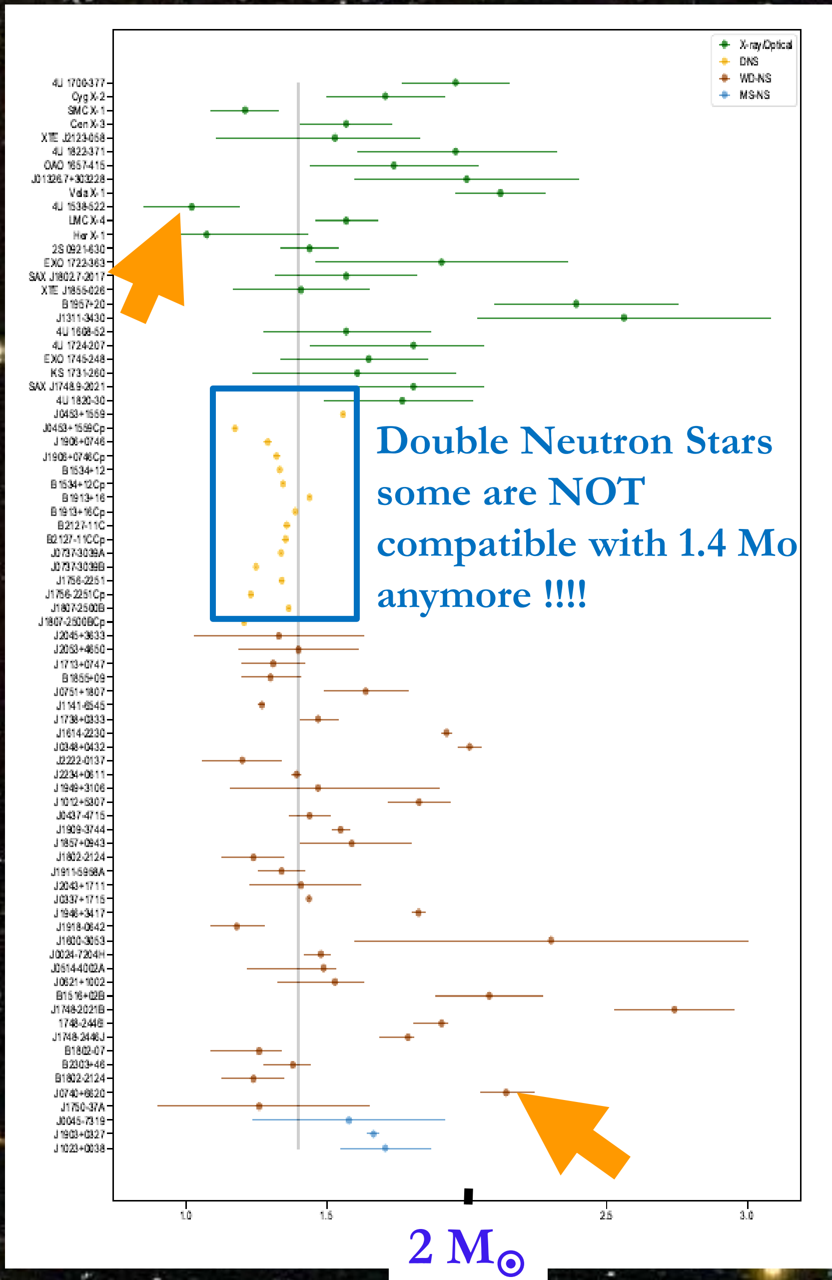

However, in the last 15 years or so, evidence points towards a *much wider* range of masses

http://www.stellarcollapse.org/nsmasses

Updated sample by L.S. Rocha

Which are the lessons for us?
Where do these objects form?
Do they gain mass (binaries?) How much?
Which are the lowest and highest values? What does it mean for the constitution of dense matter?

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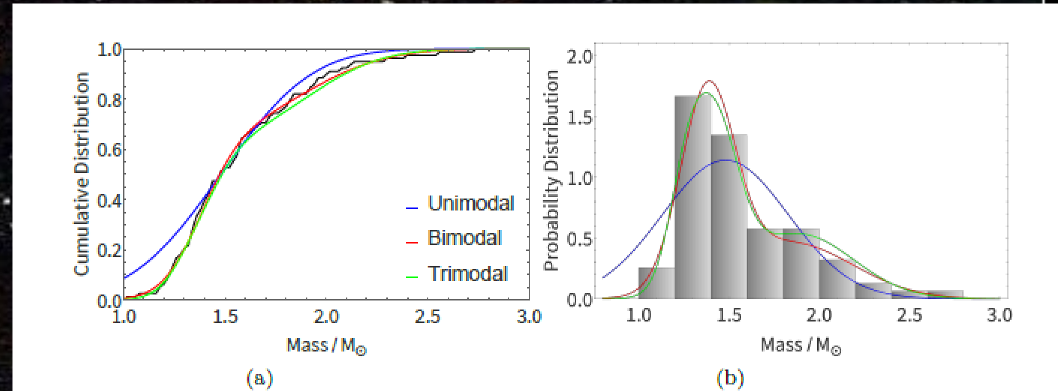
Frequentist analysis of the NS mass distribution: more than one maximum granted



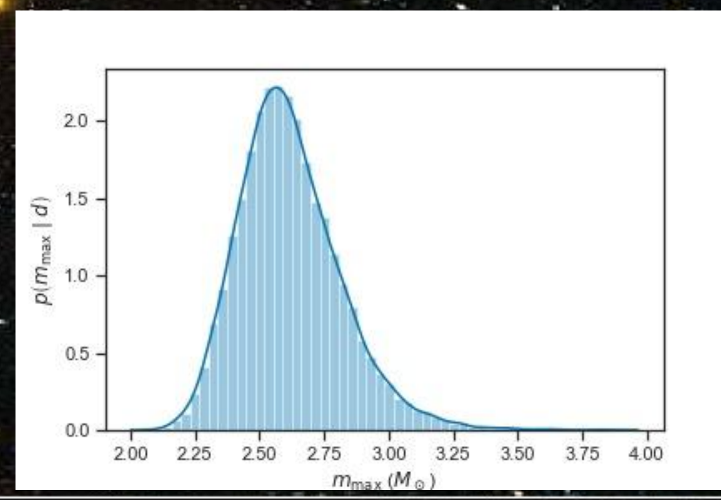
Bayesian analysis

Location of the peak

$$\propto \ \exp\left(-\frac{m-\mu_i}{2\sigma_i}\right)$$

Width of the peak

If assumed to be the 3σ value of the μ_2 peak, the M_{max} is quite robust and looks like this



The MCC algorithm finds the optimal values, which happen to be compatible with the ones find within the frequentist ones μ_1 ~1.35 Mo ; μ_2 ~1.76 Mo

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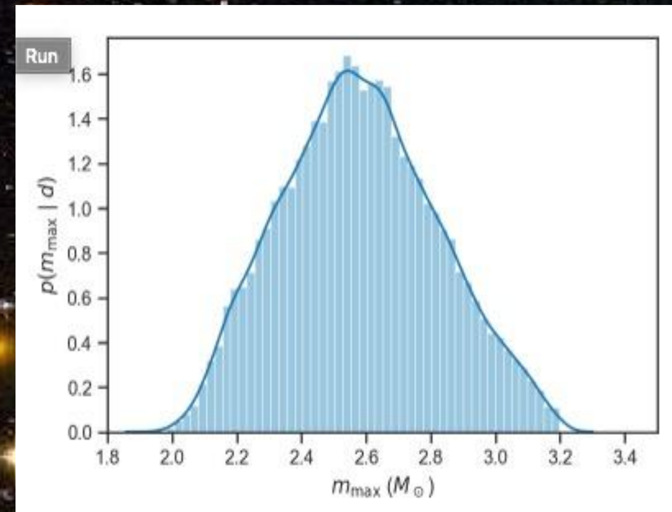
One step ahead within the Bayesian analysis: introducing M_{max} as an additional parameter

Truncated Gaussian beyond $m=m_{max}$



$m=m_{max}$ is determined to be ~2.5 Mo, although its probability distribution depends somewhat on the *prior* . This coincides with the naive "3 sigma" frequentist value

Empirically the observed distribution allows a large value of m_{max} , if these are confirmed for individual objects, theory must accommodate they (even if close to the Rhoades-Ruffini limit) It also "makes room" for a 2.5 Mo neutron star in GW190814

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In brief, Bayesian analysis (Valentim, Rangel &Horvath, *MNRAS* 414, 1427, 2011) pointed out that one mass scale is strongly disfavored, two masses are present : ~1.37 and ~1.75 $M_{\odot}$

Other works finding the same pattern (somewhat different values):
Zhang et al. A&A 527, A83, 2011
Özel et al., ApJ 757, 55, 2012
Kiziltan, Kottas & Thorsett, 2013

This results is stronger with the new data
Is this related to the size of the Fe core? ("jump" @ 19 $M_{\odot}$) or
Are some of them born as such, massive ?

Probably not, but there is a problem here…
While Deng, Gao, Li & Shao (2020) argue that the 2.14 $M_{\odot}$ pulsar was born massive (see also Sfarzadeh, Ramirez-Ruiz & Berger 2020), do simulations of SN explosions produce "heavy" NSs ?

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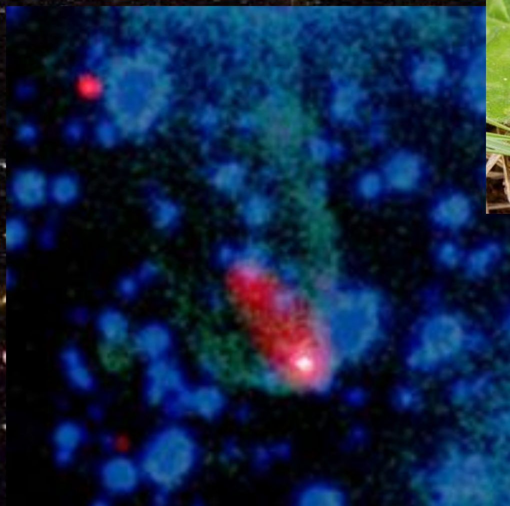
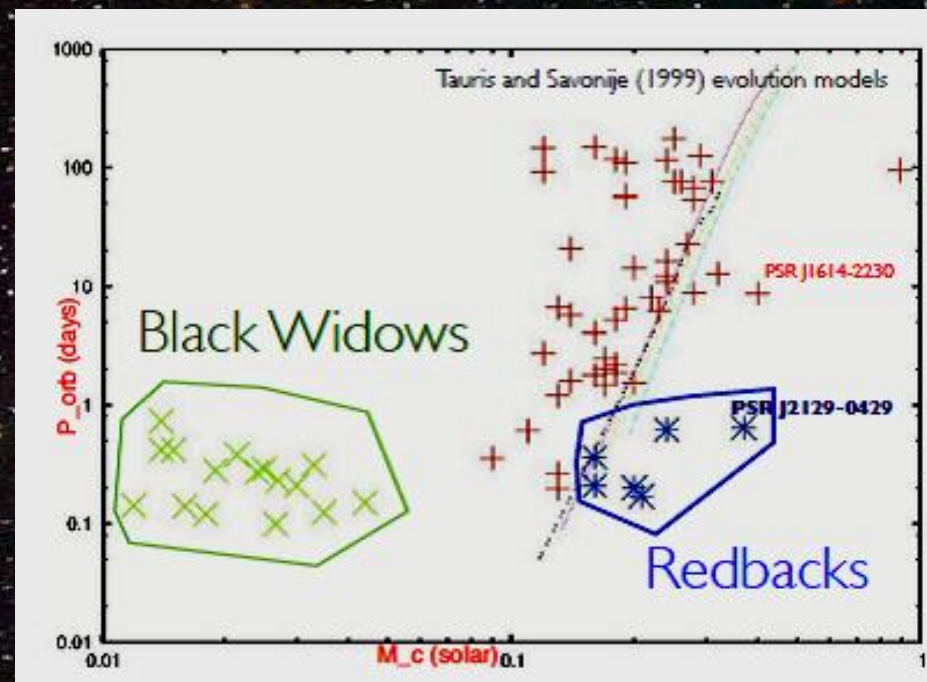
A class of NS systems which may be crucial for the high-mass bin and the M_{max} as an additional parameter issue: the “spider” systems



PSR 1957+20 original “black widow”: the previously accelerated pulsar is now ablating its companion



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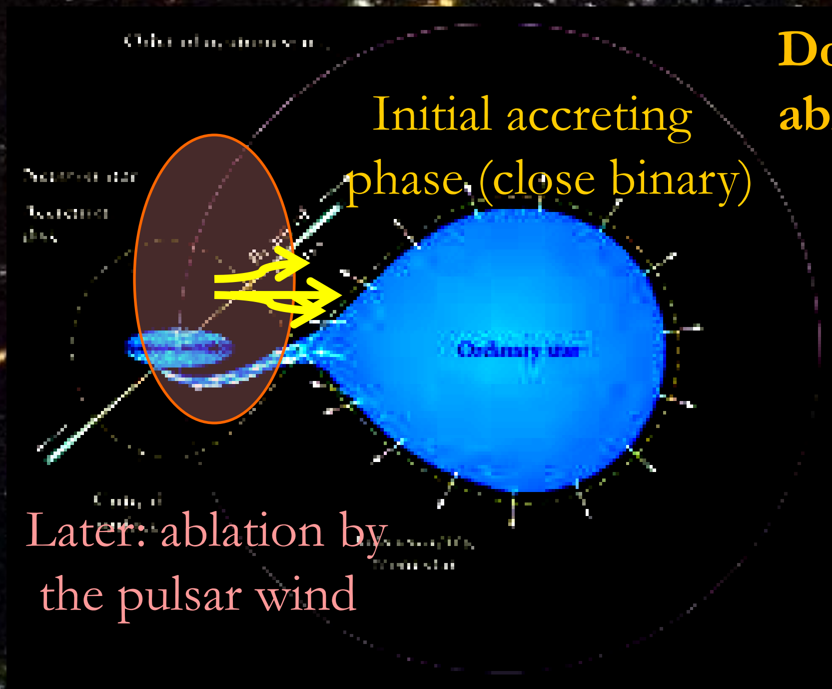
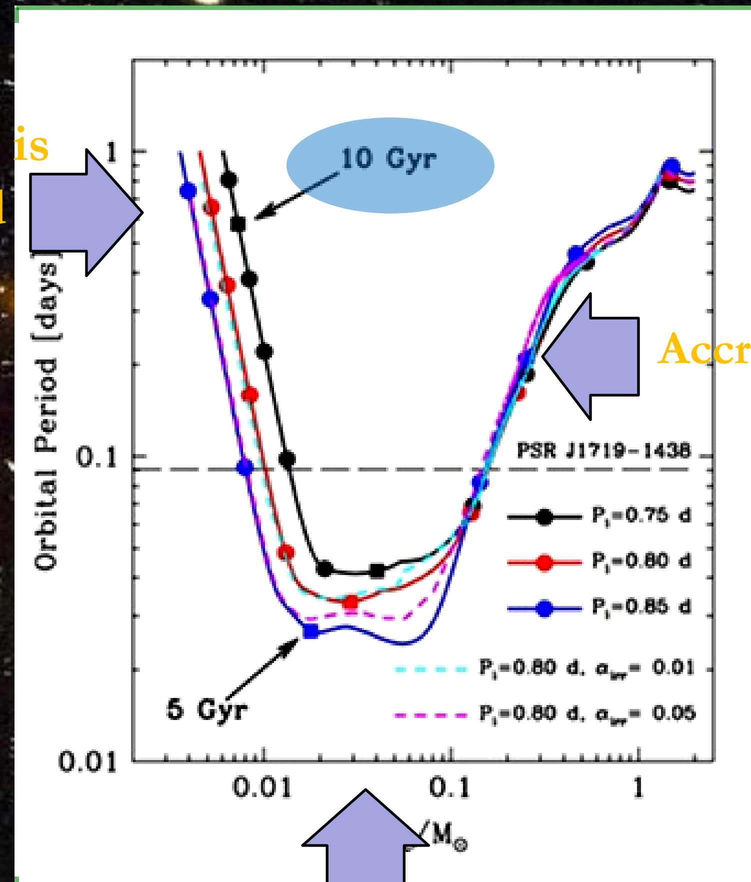
Two important ingredients for their evolution: back illumination and ablation by the pulsar wind

(Benvenuto, De Vito & Horvath ApJL 753, L33, 2012)





The history of accretion phase alone lasts ~Gyr , therefore the mass transfer onto the pulsar has to be substantial (theory)

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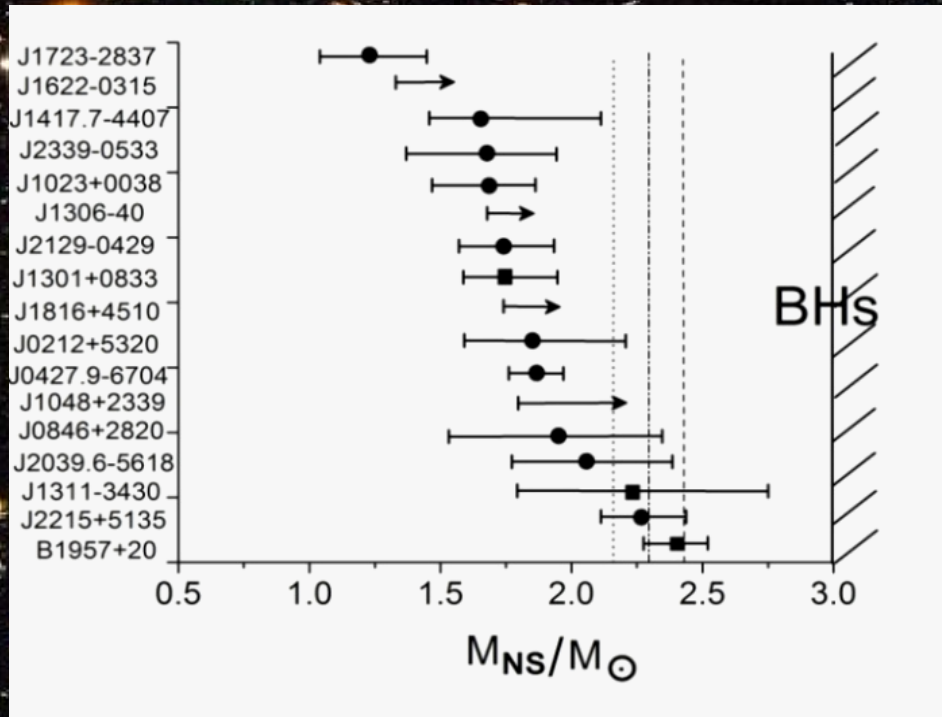
Measurements of 17 known observed Redback/Black Widow systems



Error bars are still substantial, but these systems should in some cases produce the heaviest neutron stars in Nature by accretion, and possibly the lightest Black Holes immediately above the maximum mass value with ~3Mo

(Horvath et al. Science China 63, 129531, 2020)

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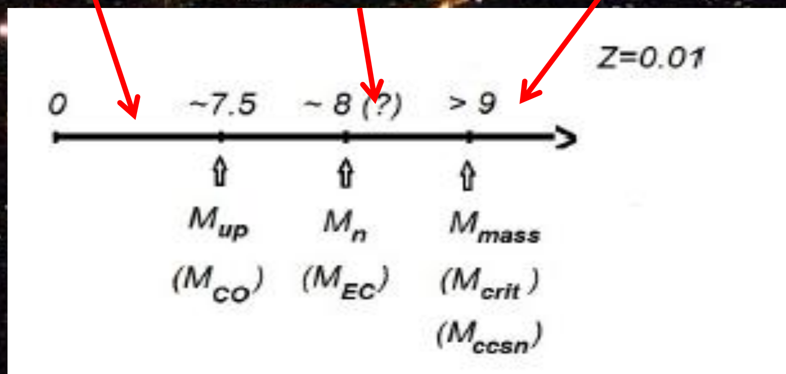
Origin of NS masses: single-star evolution

WD

Electron Capture SN

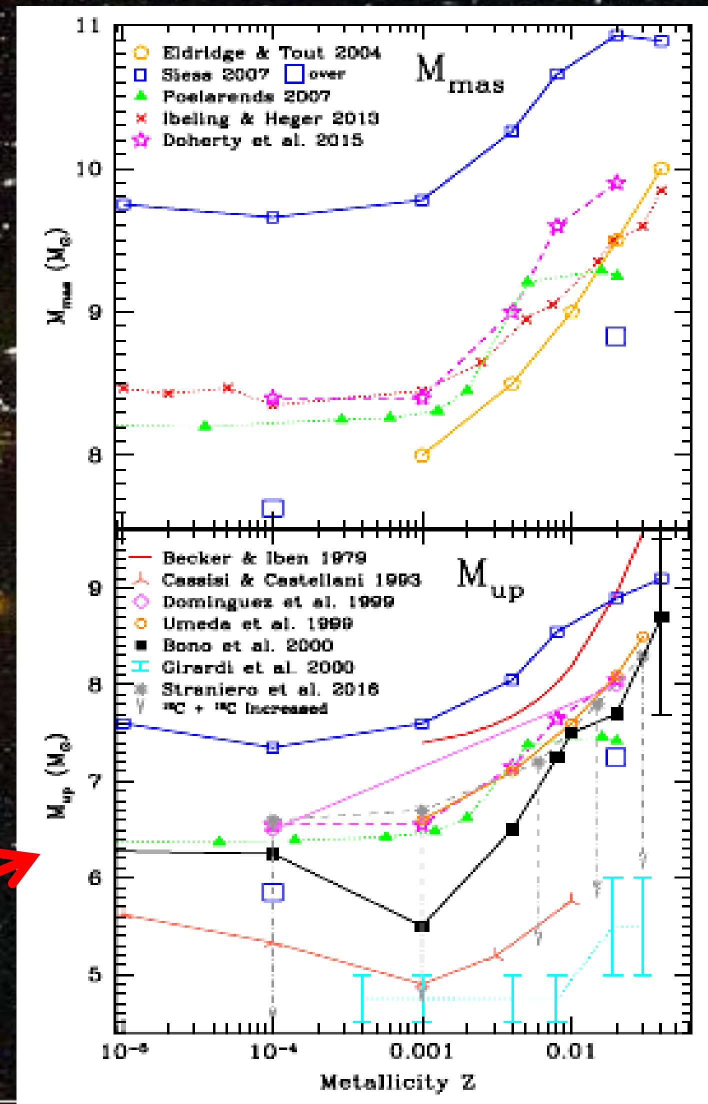
Iron core SN



Super-AGB ?

These boundaries are:
metallicity -dependent,
mass-loss dependent
and convection-dependent

Doherty et al. (2017)



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O-Mg-Ne cores of electron capture SN are degenerate and of "fixed" mass ~ 1.37 $M_\odot$ → after emission of the binding energy

$$\frac{M_B - M_G}{M_G} = 0.6\frac{\beta}{1-0.5\beta}$$ with $\beta = GM_G/c^2R_0$ Lattimer & Prakash (2001)

the formed NS have essentially a fixed mass ~1.25 $M_\odot$

The lightest NS ever observed is PSR J1453+1559 companion with

$$1.174 \pm 0.004 M_\odot$$

therefore, small iron cores from progenitors having M >9 $M_\odot$ must be produced to obtain NSs lighter than electron-capture SN

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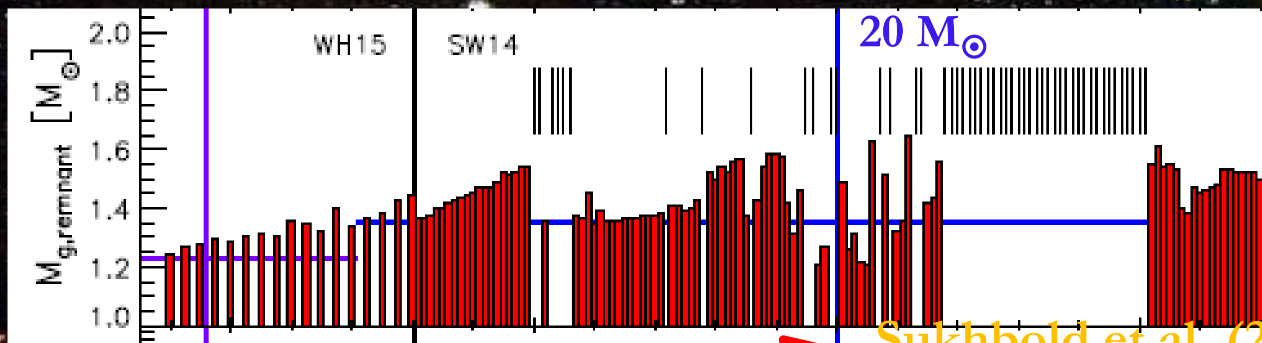
Origin of NS masses: single-star explosions

On the high-mass end, we know that NS with $M > 2\ M_\odot$ must be produced promptly, but this is difficult theoretically

$$M_{\mathrm{Ch,eff}} \simeq M_{Ch,0}\left(1 + \left(\frac{s_e}{\pi Y_e}\right)^2\right)$$

Iron cores grow well beyond $1.4\ M_\odot$ because of finite entropy



Sukhbold et al. (2016)

The highest NS masses can not be formed directly in single-progenitor explosions (unless there is something very wrong)
However, Burrows and co. found massive NSs from single explosions

The "intermittency" of NS-BH formation is under discussion by several groups. Low NS masses may be produced, but do not necessarily come from light progenitors

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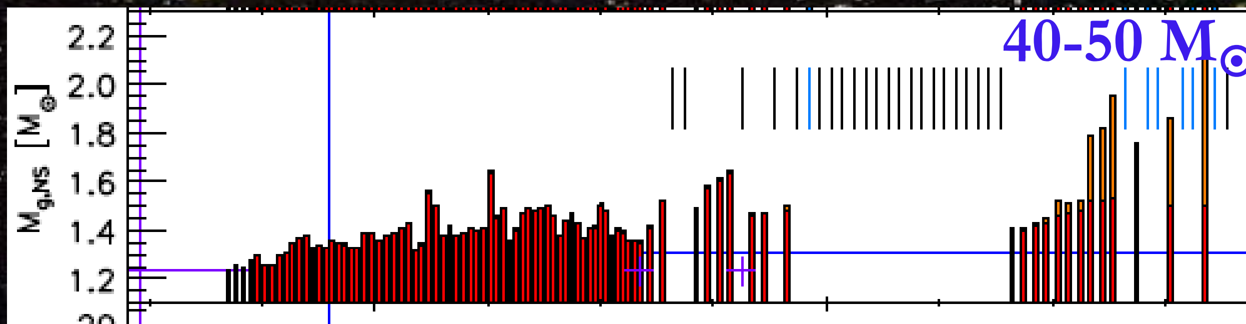
Origin of NS masses: binary star evolution and explosions

Common evolution prescription : removal of the hydrogen envelope
Pre-SN structure not really known



Ertl et al. (2020)

Substantial fallback now produces heavy NS, but for very heavy progenitors only

This could allow a “born massive” NS such as PSR J1640+2224
(Deng, Gao, Li & Shao 2020)

In both single and double star explosions the formation of BH does not start at a big progenitor mass, NSs and BHs form back and forth

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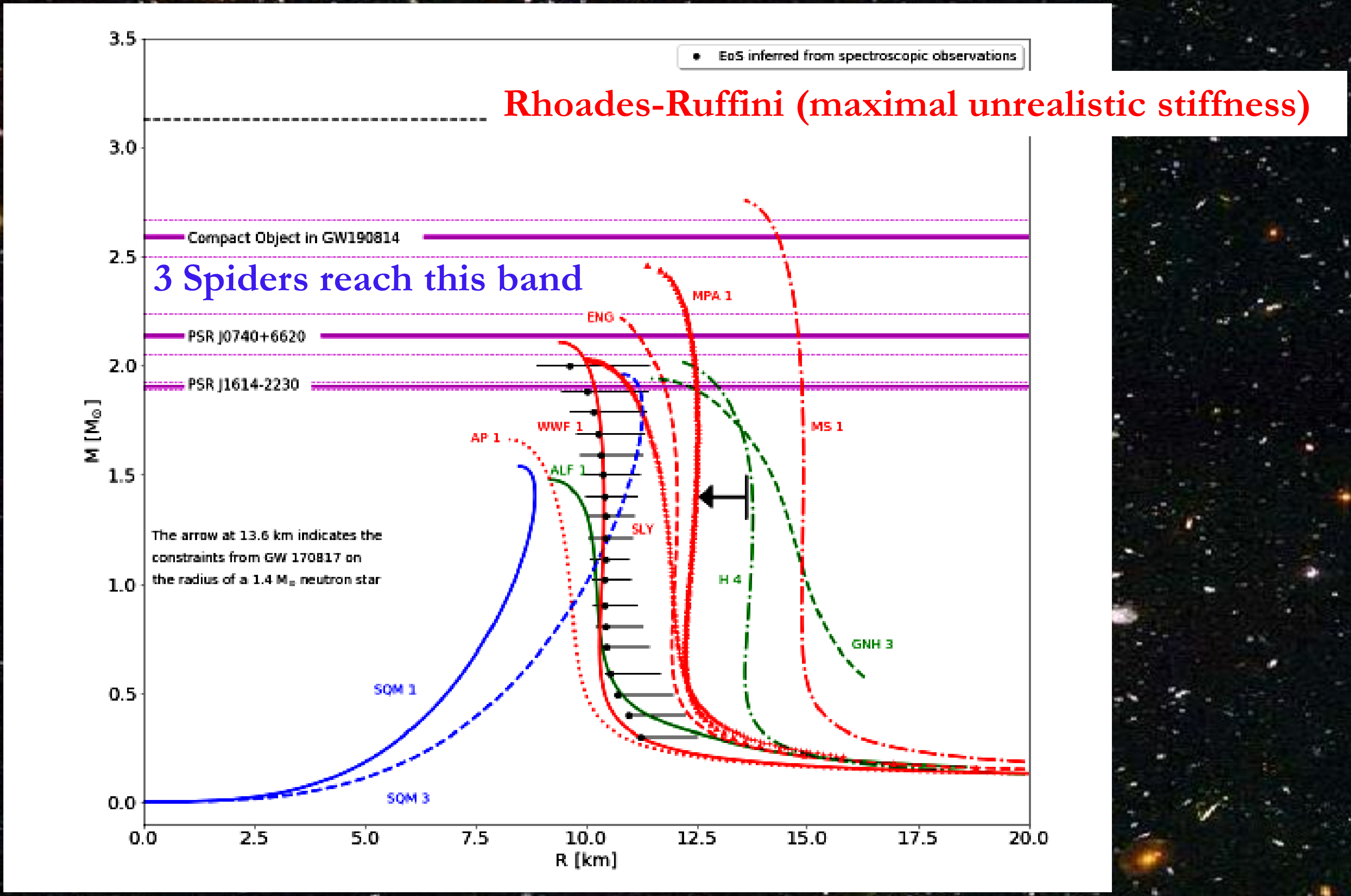
Where do we stand ? Is the "gap" being filled?



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Conclusions


Shalom Opher!

- Never talk or write of a "canonical" mass again. There is no such a thing. The mass distribution is wide

- Double Neutron Stars are not symmetrical in mass, although the standard formation channel may be incomplete, and it is not clear how

- The "mass gap" may be being filled, or at least NS with >2.2-2.4 $M_\odot$ must be considered, as indicated by observations (*spiders* first). Low-mass BHs may be "hidden", some could be a product of "spiders" being pushed over the Rhoades-Ruffini value

- The plot thickens for the description of dense matter, particularly if the Mmax continues to be "pushed up" by measurements