Hubble Ultra Deep Field HST ■ ACS

FiTópicos em Astrofísica Estelar
III. Remanescentes compactos

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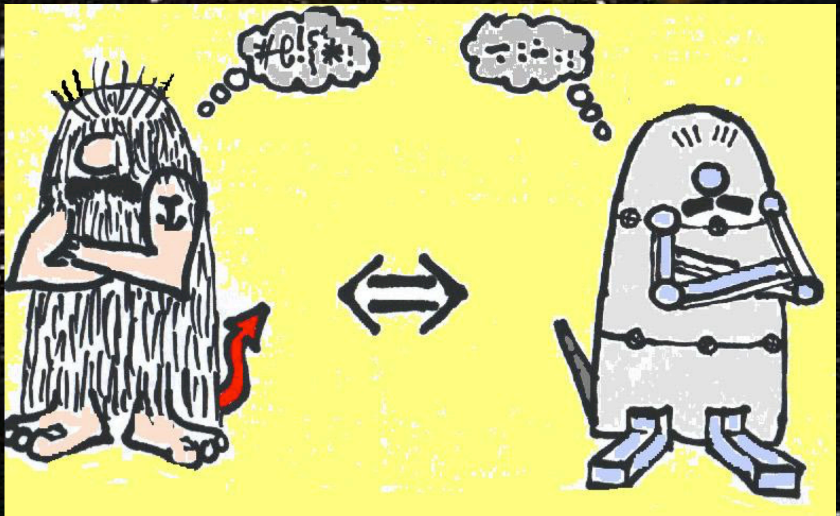
OBSERVATÓRIO DE SÃO PAULO
SANCTI PAVLI CÆLVM AGER MEVS

Perdón, Urania !



Science is all about Reality and Model shaking hands...

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A massa máxima das estrelas: em equilíbrio hidrostâtico, pressão e gravitação se igualam

$$P_{total} = P_{gas} + P_{rad}$$

$$P_{grav} = -\frac{\partial E_{grav}}{\partial V}$$

$$P_{gas} = \frac{\rho}{\mu m} k_B T$$

$$P_{rad} = \frac{1}{3} a T^4$$

$$E_{grav} = -\frac{3}{5}\left(\frac{4\pi}{3}\right)^{1/3} \frac{GM^2}{V^{1/3}}$$

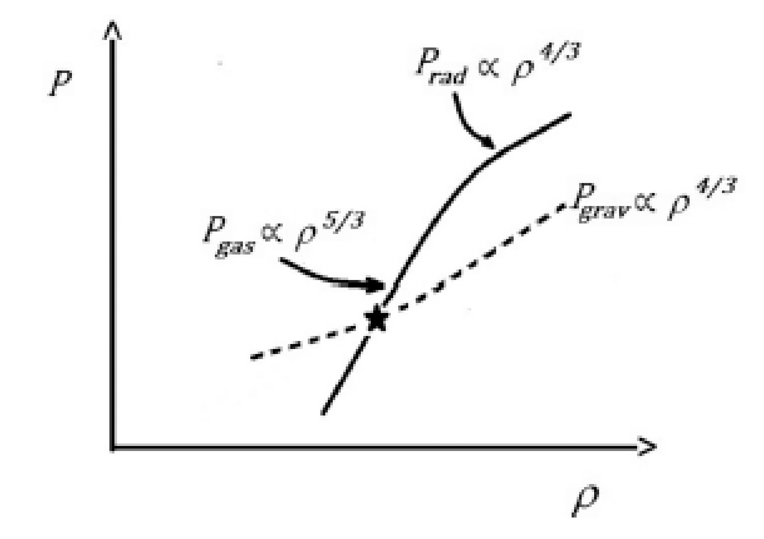
Assim, temos que “ $P_{grav} = C M^{2/3} \rho^{4/3}$

Quando a massa estelar cresce, a convecção domina cada vez mais e também a componente da radiação ganha importância

Lord Kelvin: uma estrela totalmente convectiva (gás+radiação)

$$P^{1-1/\nabla_{ad}} \propto \rho^{-1/\nabla_{ad}} \Rightarrow P = K \rho^{\frac{1}{1-\nabla_{ad}}} \Rightarrow P = K\rho^{5/3},$$

$$P_{tot} \rightarrow P_{rad} = \frac{1}{3} a T^4 \propto \rho^{4/3}$$



Se a massa cresce muito, não há solução

→ As estrelas têm uma **massa máxima** ~100 Mo

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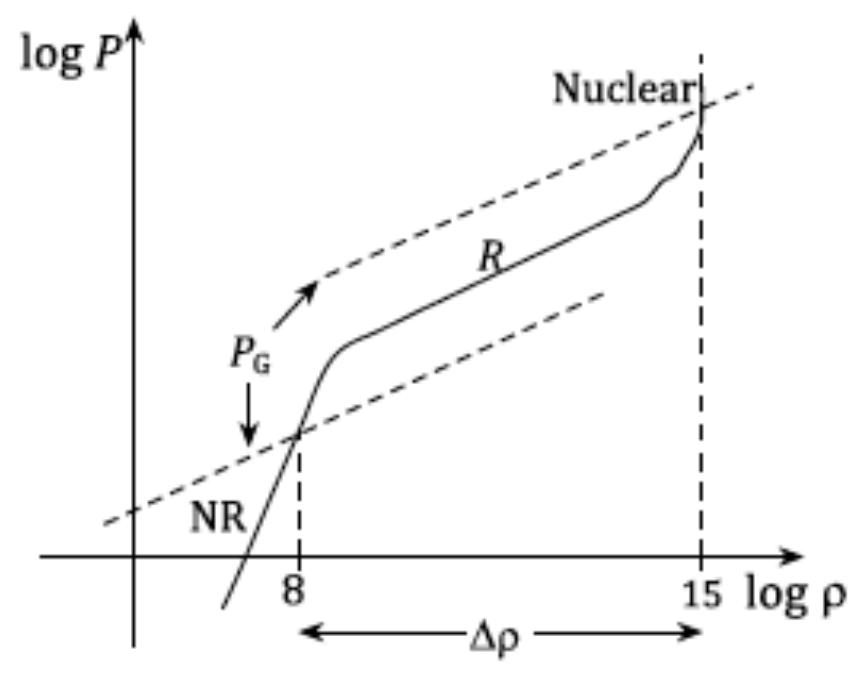
Refujos das duas primeiras...

Equilibrium solutions: there is nothing between WDs and NSs

$P_G = -\partial E_G/\partial V = C \times M^{2/3}\rho^{4/3}$ with $P_G = P_M$ we see that



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Supernovas superluminosas > 10^{52} erg

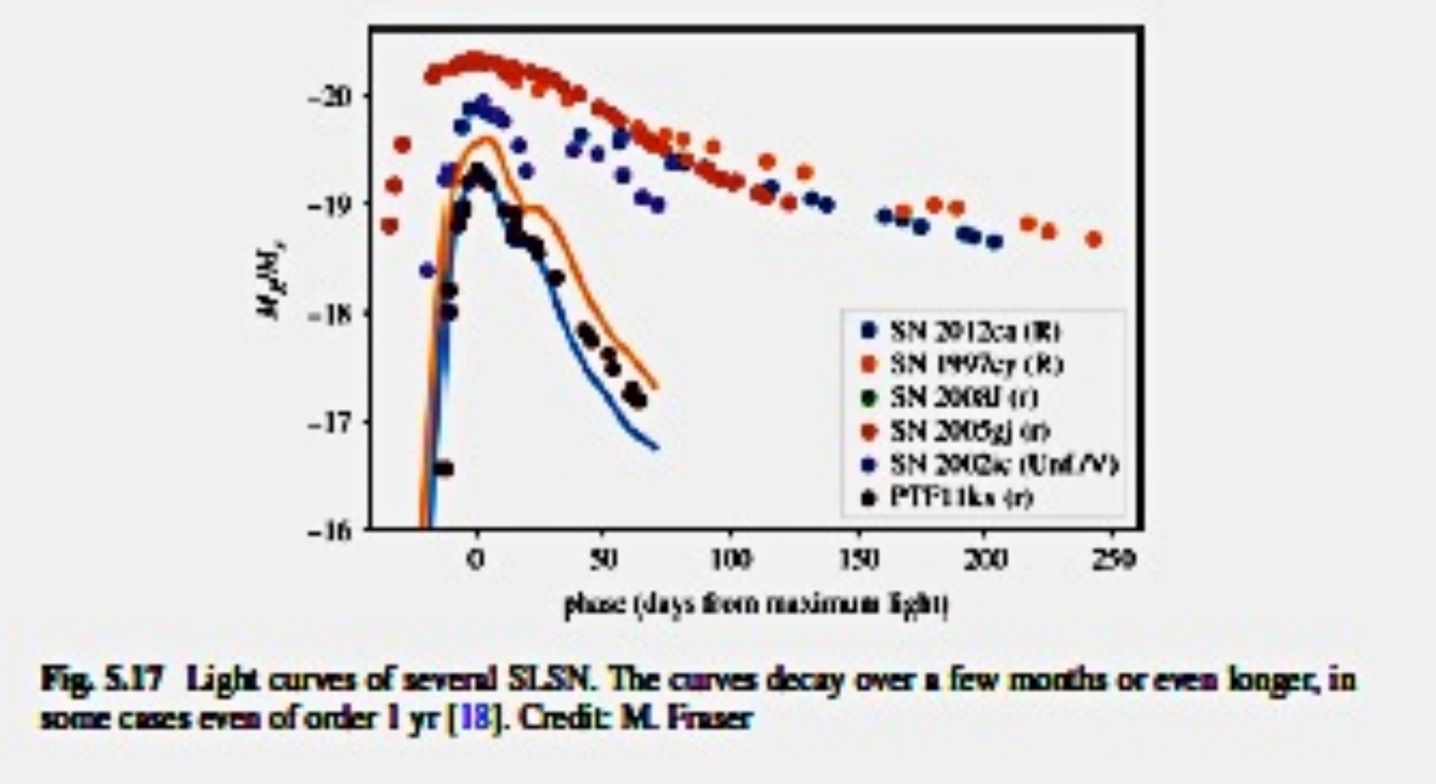

Fig. 5.17 Light curves of several SLSN. The curves decay over a few months or even longer, in some cases even of order 1 yr [18]. Credit: M. Fraser

É um grupo que inclui a) colisão do choque com o ISM b) injeção de energia por um magnetar c) instabilidade de pares (próximas do limite superior de massa)

Supernova 1054 a.D. and the Crab pulsar

The Emperor Henry III in Tivoli, Italy

Astronomers of the Sung Dinasty

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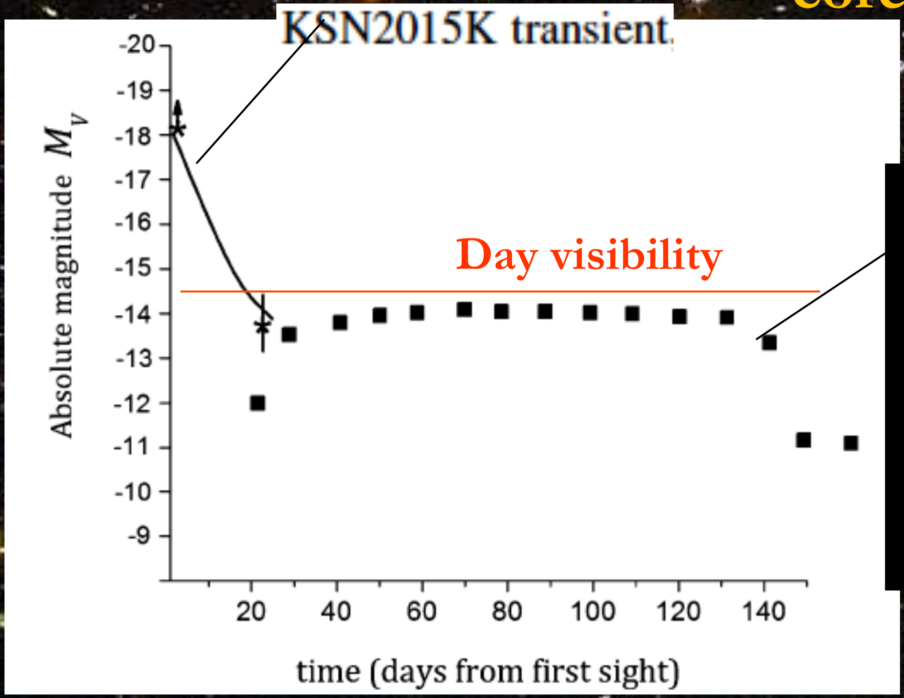
1054 was the year of the Great Schism. Pope Leo XI died July 4th , and some ambigous writingswere interpreted as describing the SN 1054…but there is a 3 month interval. And worse, they are at odds with the Chinese records.The supernova decayed ~ 4 manitudes in 3 weeks (!)

Perhaps the Crab SN was a precursor followed by a core-collapse explosion



Core-collapse lightcurve
Electron-capture does not explain the Chinese records, it would be too bright (Nomoto et al. insisted on the electron-capture for decades)

J.E. Horvath A&SS 367, 81, 2022

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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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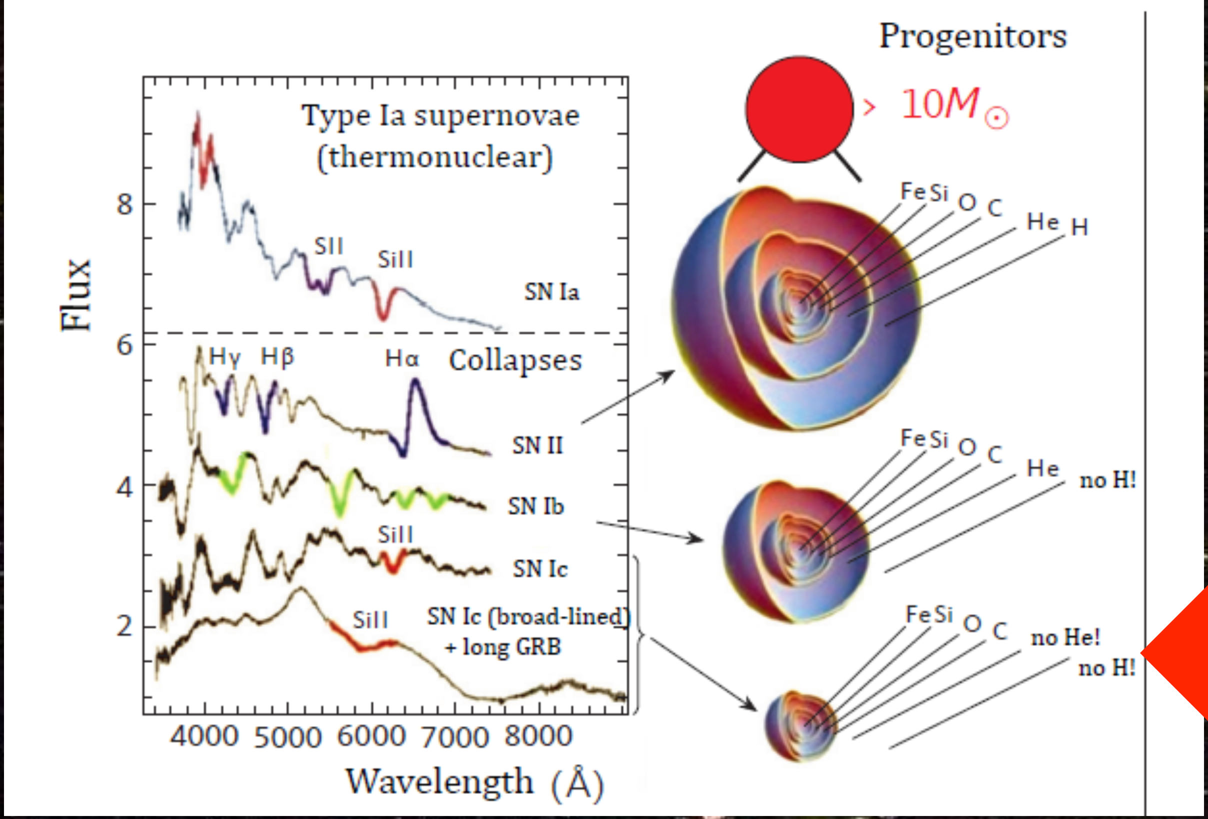

“Hypernovae”
Stripped He envelope,
large mass, GRBs
BHs?

(“Superluminous” SN are not shown see previous talk)

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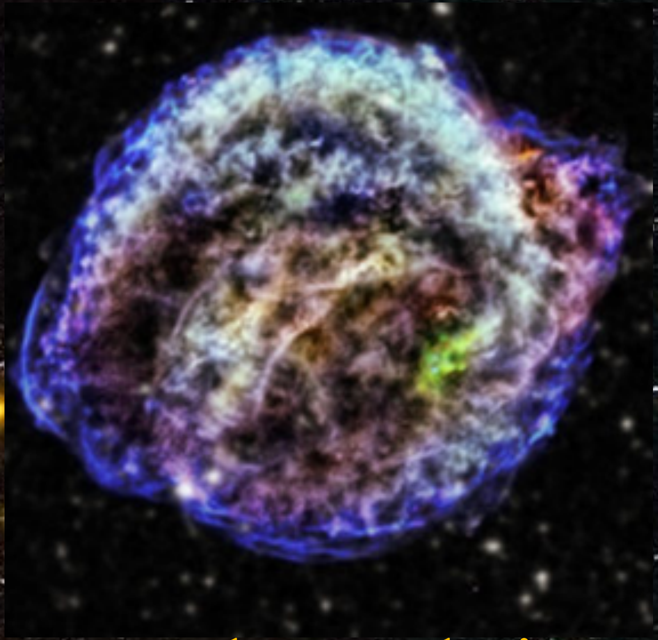
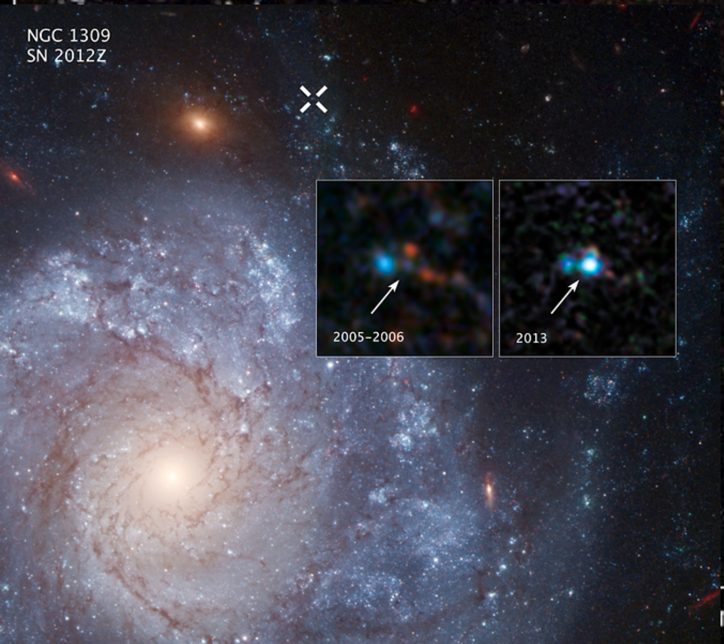
Type Ia (thermonuclear, single or double degenerate)
Never associated with a pulsar



Kepler SNR 1604



But…

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

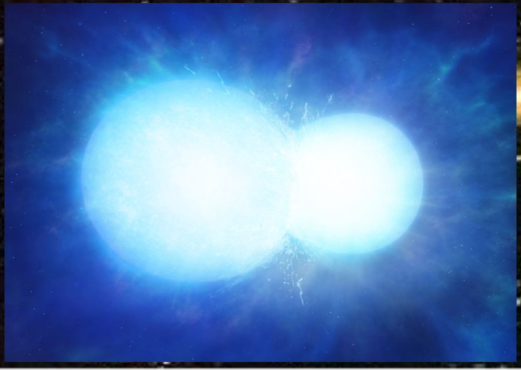
nd The HUDF Team STScI-PRC04-07a

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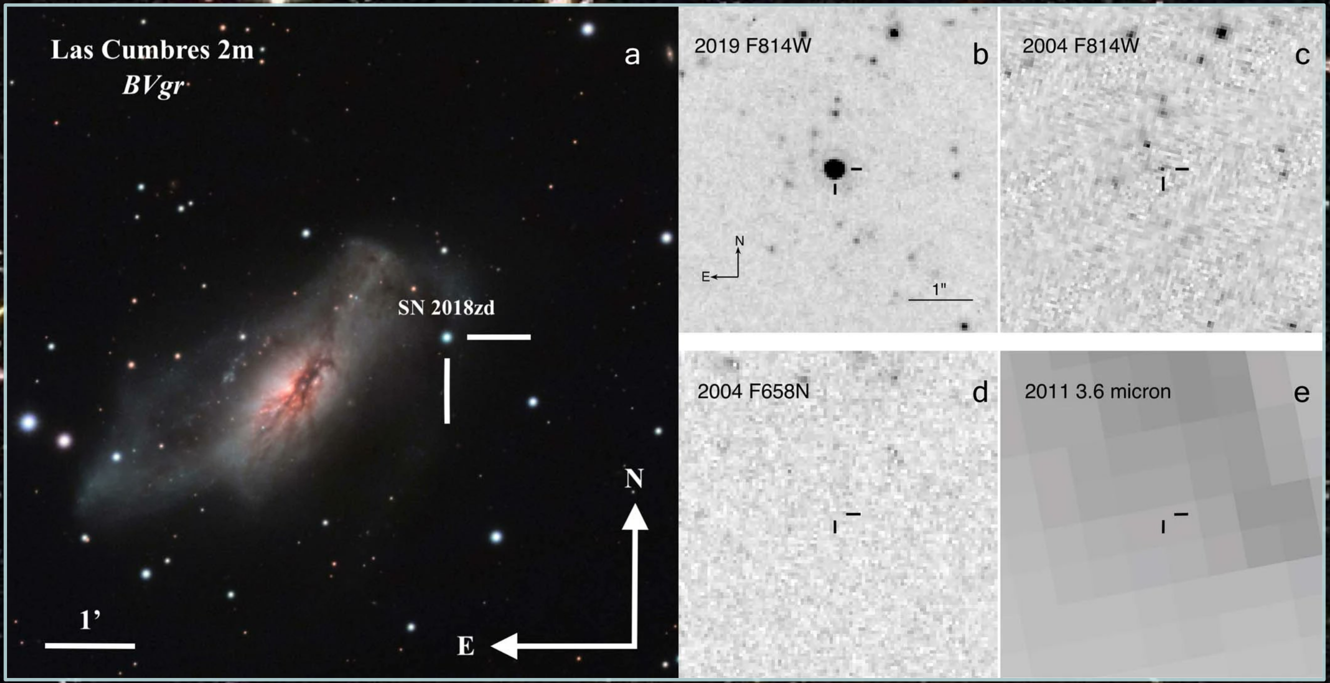
Supernova 2018zd: an electron-capture event ?
Collapse + oxygen fusion energy release,



- 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

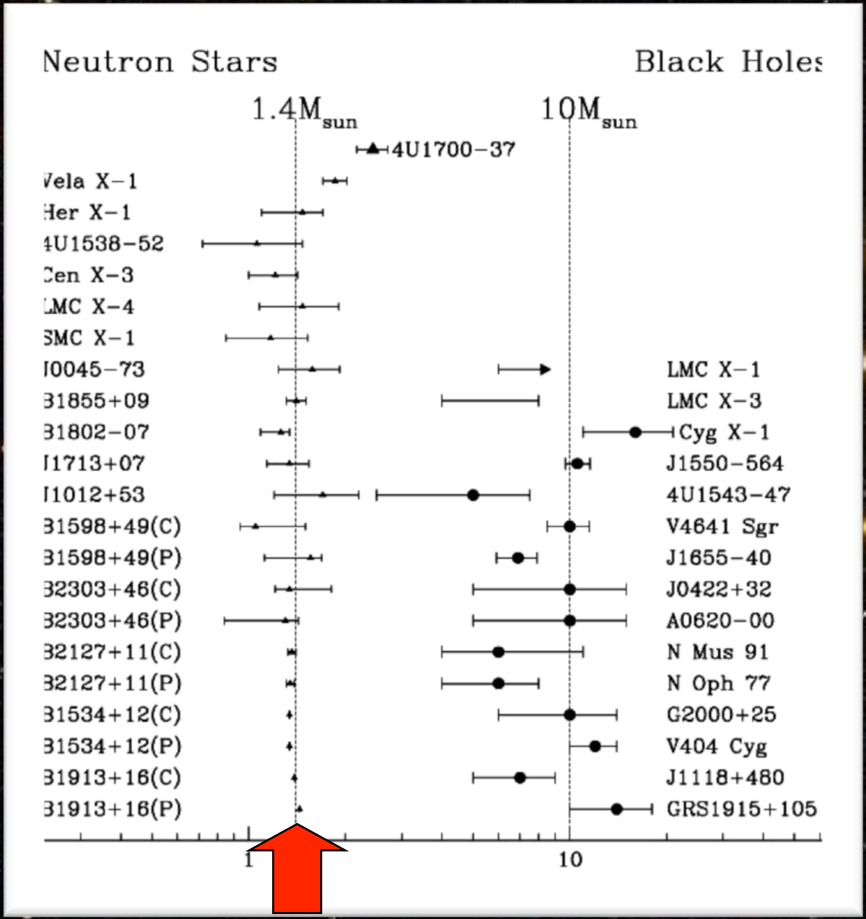

Figure from Clark et al. A&A 392, 909 (2002)

Consistent with 1.4 $M_\odot$

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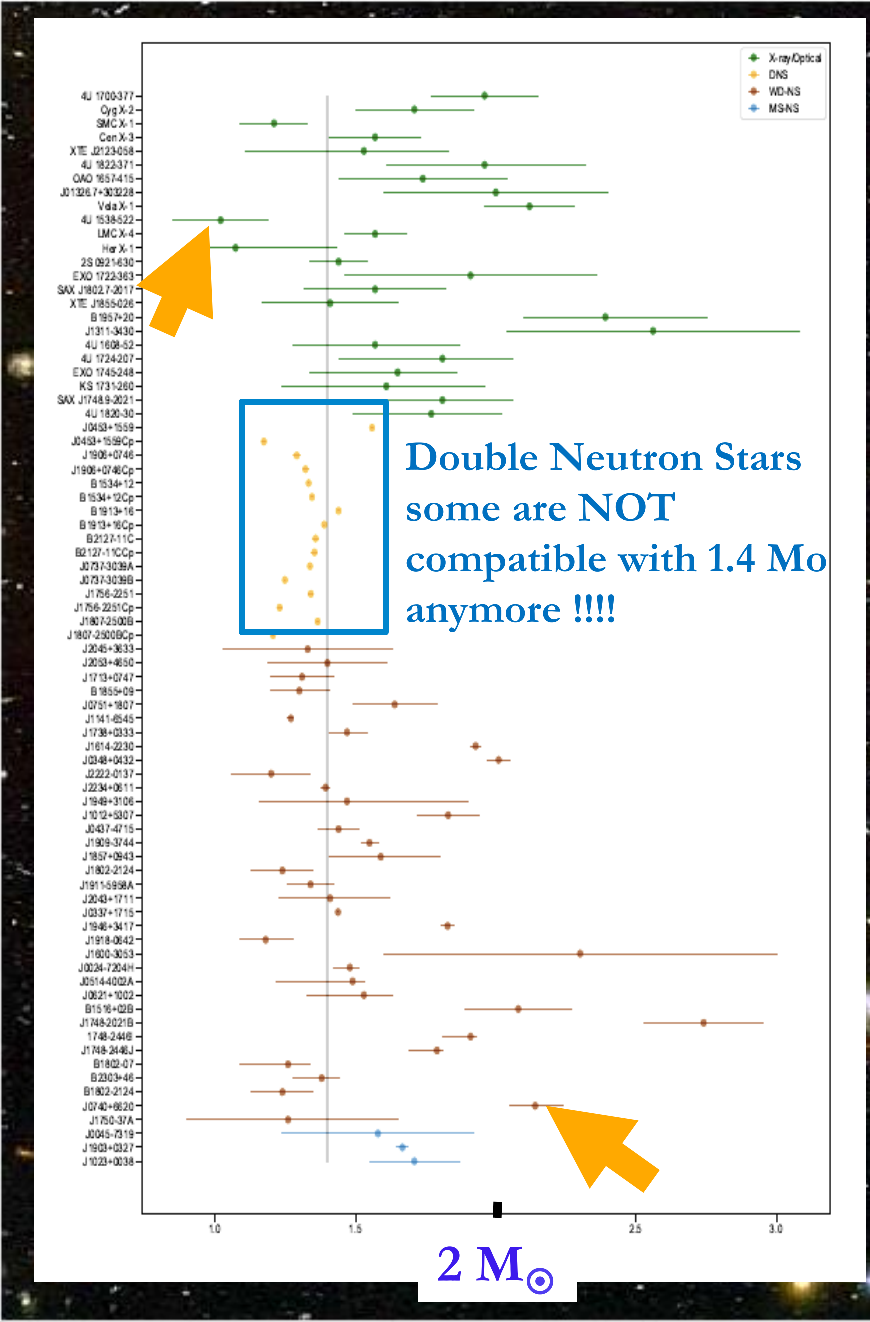

Double Neutron Stars some are NOT compatible with 1.4 Mo anymore !!!!

2 M$_\odot$

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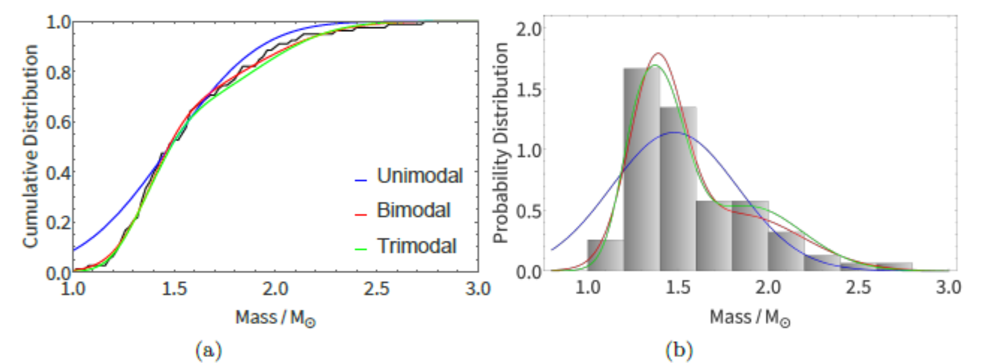
Frequentist analysis of the NS mass distribution: more than one maximum granted



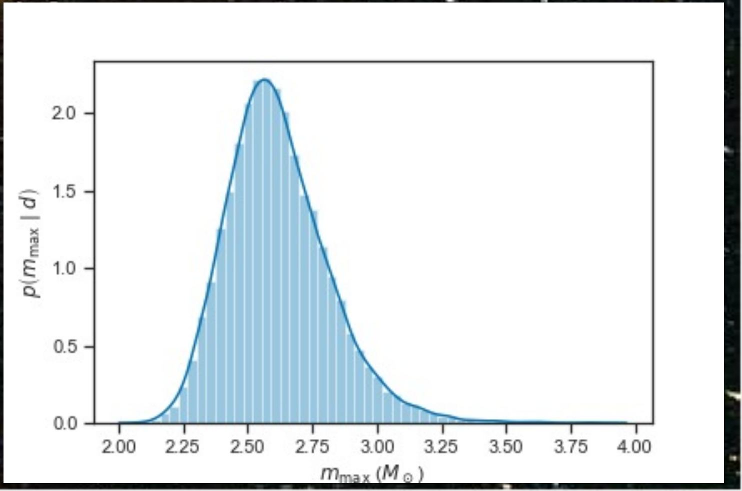
Bayesian analysis

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 ~1.36 Mo ; μ_2 ~1.8 Mo

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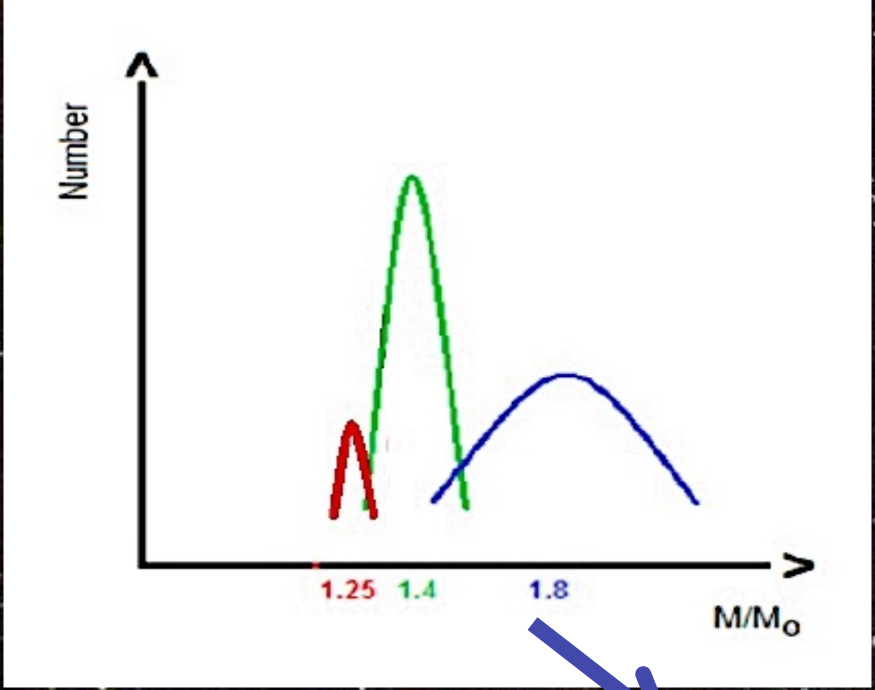
The observed NS distribution is a Gaussian bimodal



(Valentim, Rangel & Horvath 2011
C.M. Zhang et al. 2011
Ozel et al. 2012
Kiziltan, Kottas, Yoreo & Thorsett 2013)

Reconstructed mass distribution from the observed data

Bayesian analysis gives the position of the peaks, the amplitudes and the widths within a Gaussian parametrization (R. Valentim)

$$P(m) = \frac{0.14}{\sqrt{2\pi}\,\sigma_0}\, e^{-\frac{(m-1.25\,M_\odot)^2}{2\sigma_0^2}} + \frac{0.5}{\sqrt{2\pi}\,\sigma_1}\, e^{-\frac{(m-1.4\,M_\odot)^2}{2\sigma_1^2}} + \frac{0.36}{\sqrt{2\pi}\,\sigma_2}\, e^{-\frac{(m-1.8\,M_\odot)^2}{2\sigma_2^2}}$$

NOT FOUND
Mainly from electron capture SN

$$\sigma_0 = 0.07\, M_\odot$$
$$\sigma_1 = 0.08\, M_\odot$$
$$\sigma_2 = 0.28\, M_\odot$$

If assumed to be the 3σ value of the μ_2 peak, the M_{max} is around 2.5 Mo quite robust

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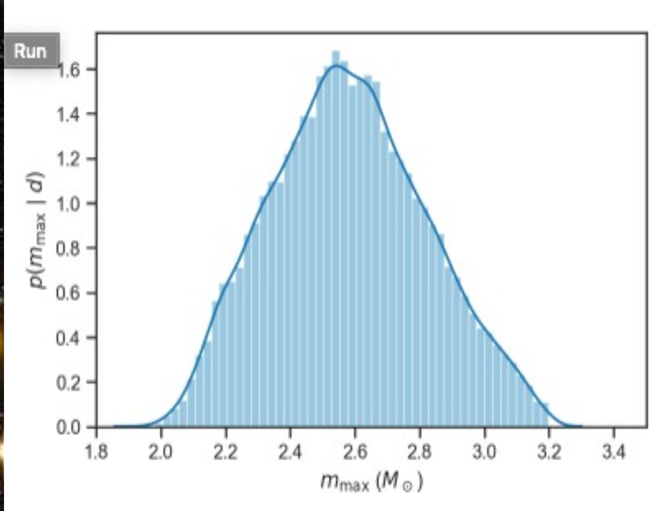
One step ahead within the Bayesian analysis: Introducing m_{max} as an additional parameter

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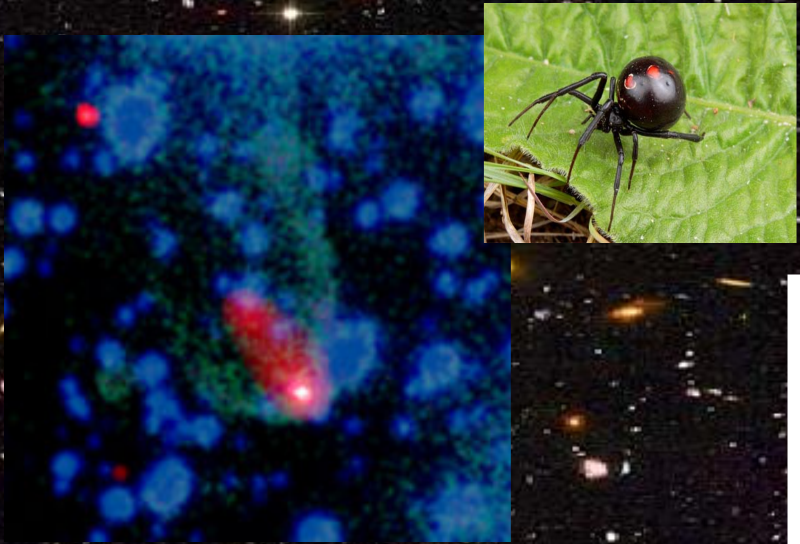
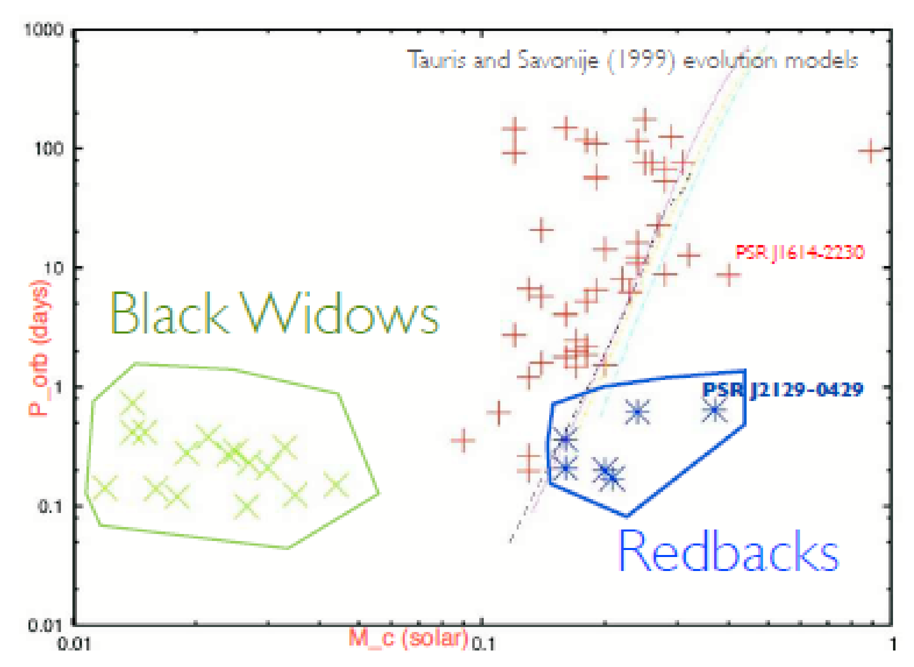
A class of NS systems which may be crucial for the high-mass bin and the M_{max} as an additional parameter issue: the "spider" systems



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



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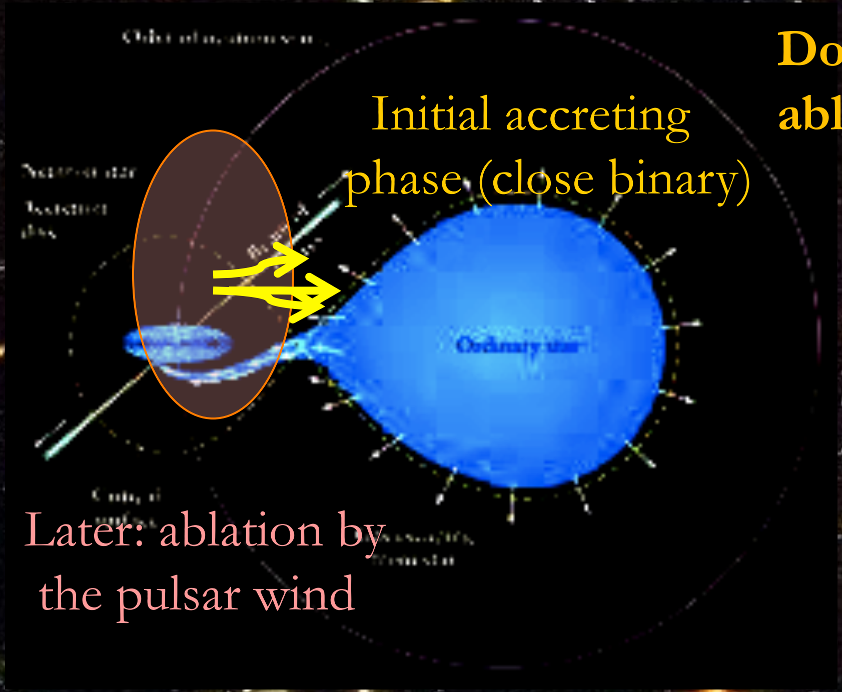
Two important ingredients for their evolution: back illumination and ablation by the pulsar wind

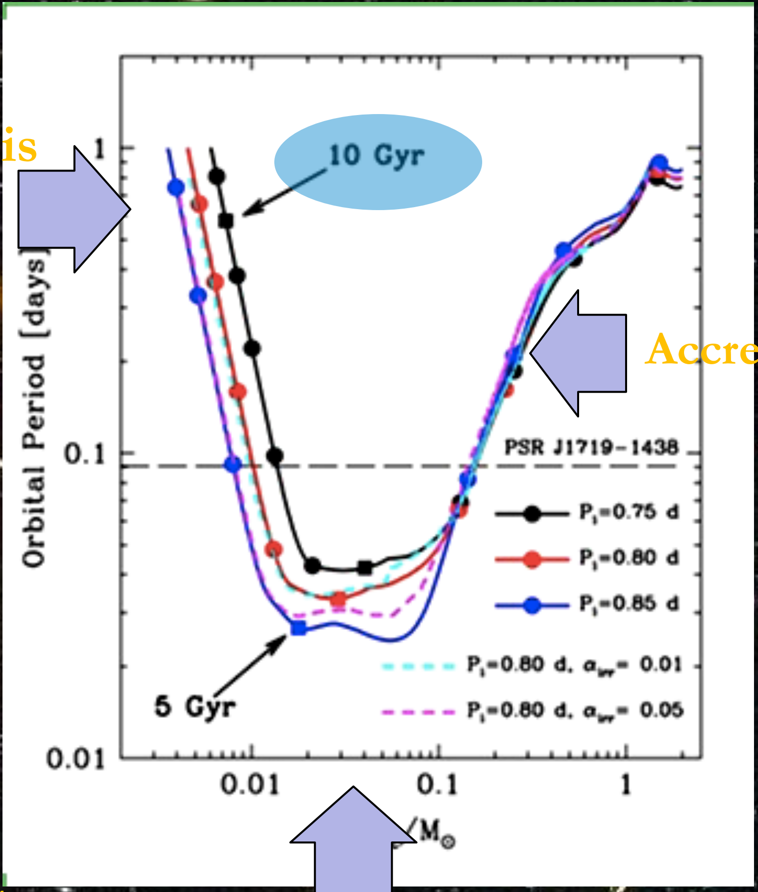
(Benvenuto, De Vito & Horvath ApJL 753, L33, 2012)



Initial accreting phase (close binary)

Later: ablation by the pulsar wind

Donor is ablated



Accretion

Donor becomes degenerate

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

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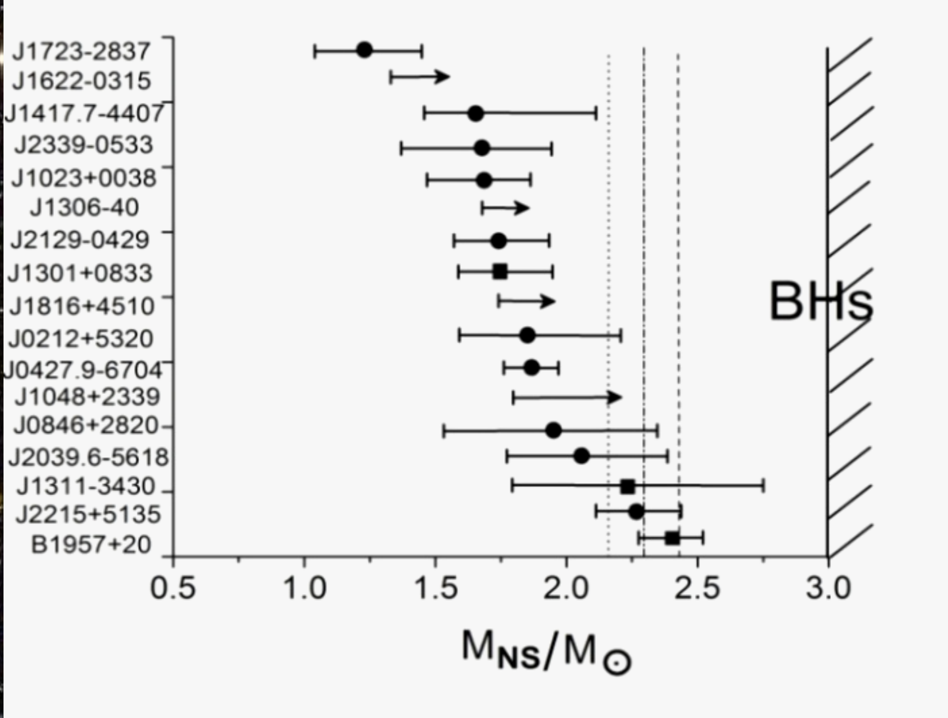
Measurements of 17 known observed Redback/Black Widow systems



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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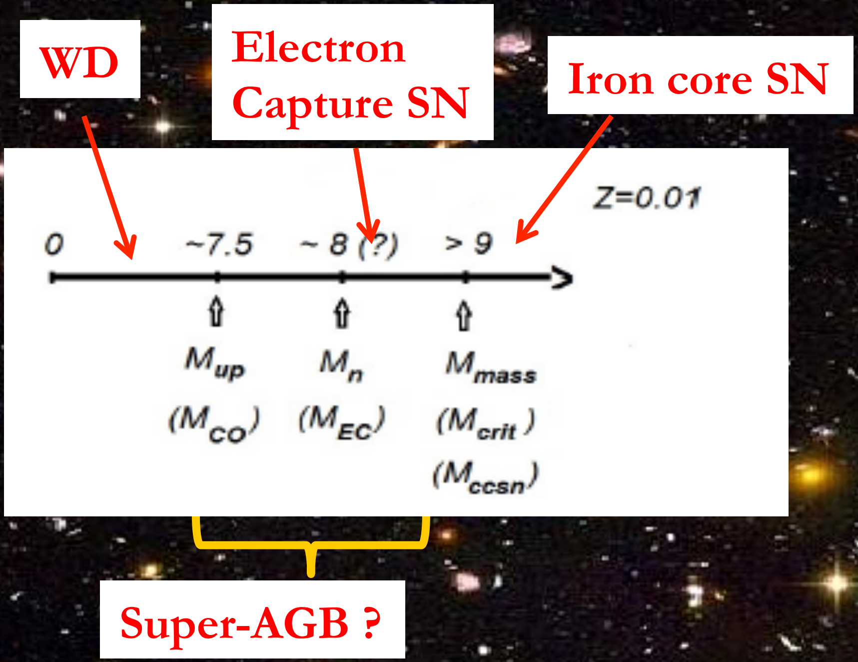
Origin of NS masses: single-star evolution


WD

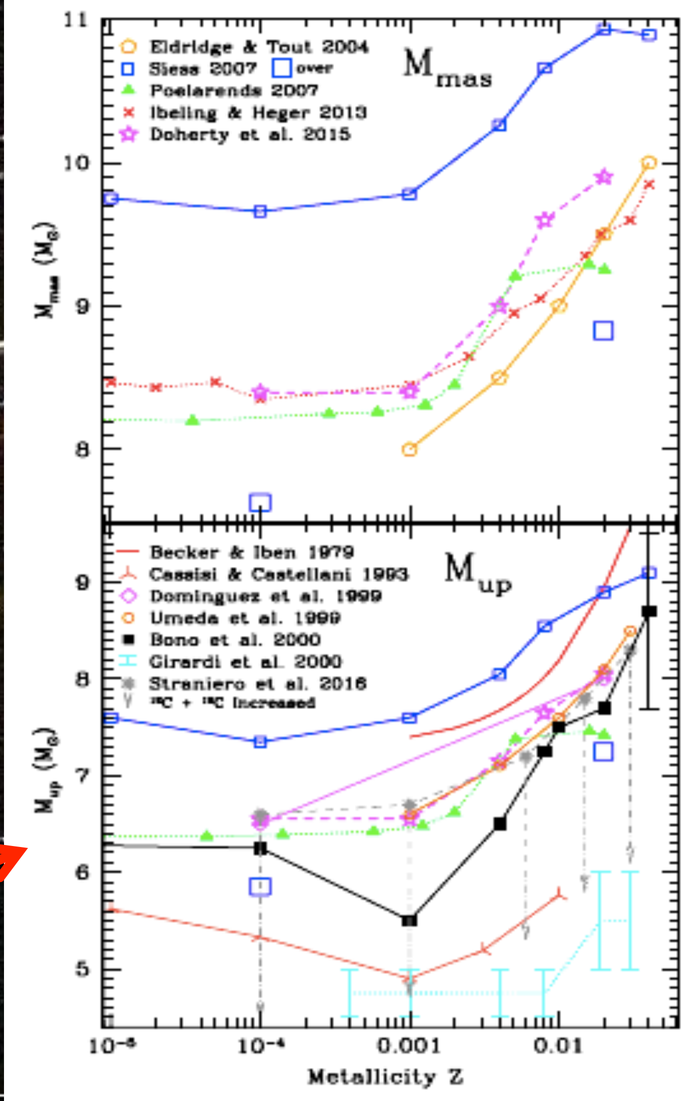
Electron Capture SN

Iron core SN

Super-AGB ?

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

Doherty et al. (2017)



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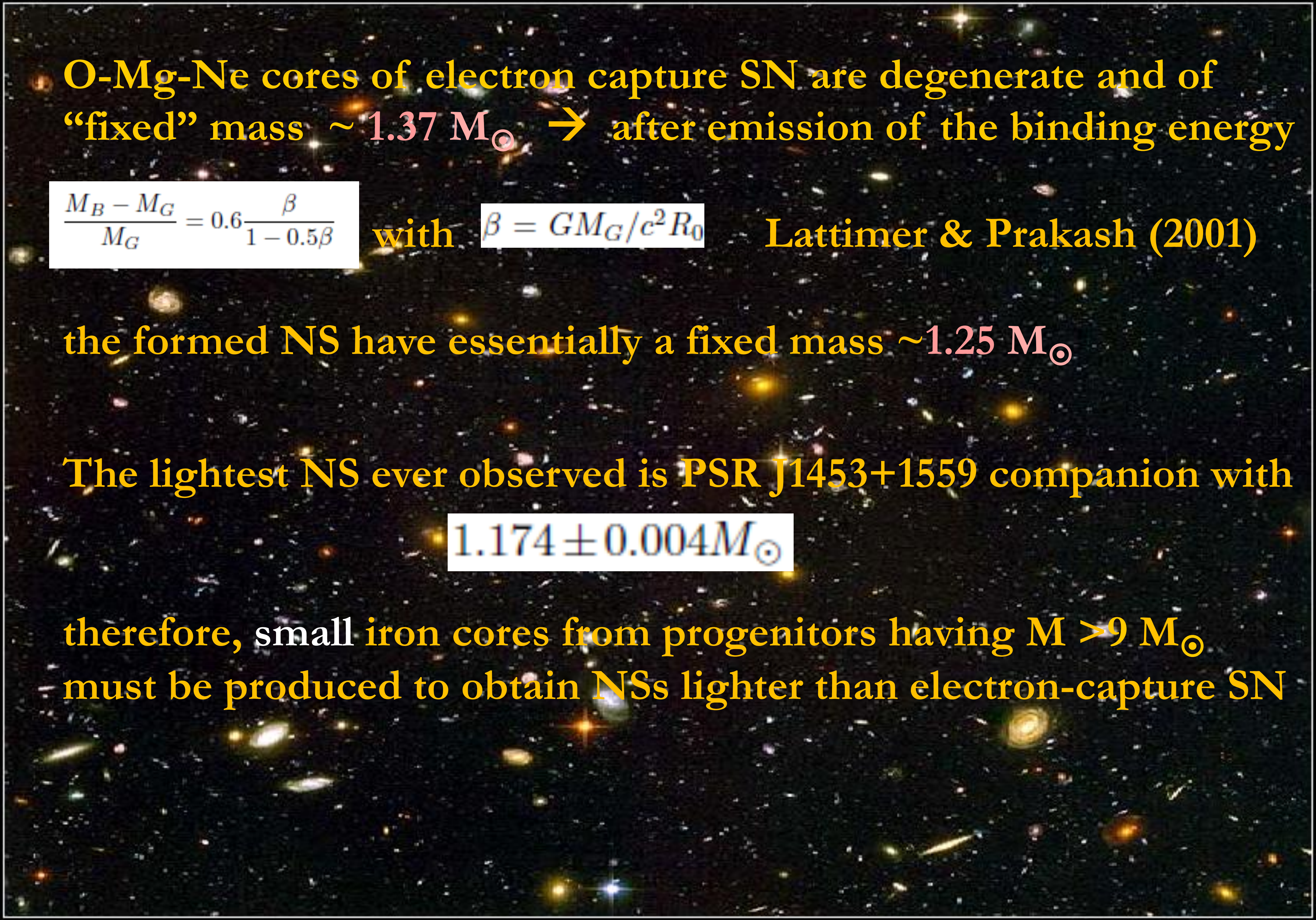

O-Mg-Ne cores of electron capture SN are degenerate and of "fixed" mass ~ 1.37 $M_\odot$ → after emission of the binding energy

$\frac{M_B - M_G}{M_G} = 0.6\frac{\beta}{1-0.5\beta}$ 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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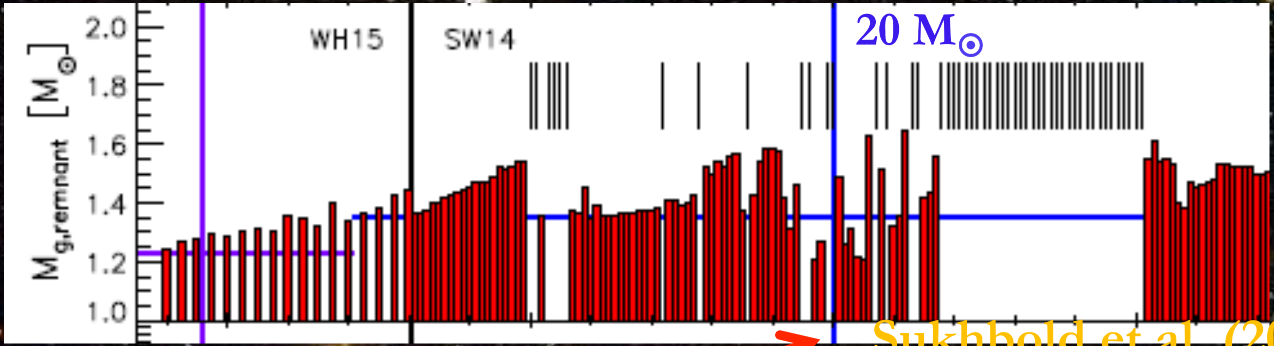
Origin of NS masses: single-star explosions

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

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

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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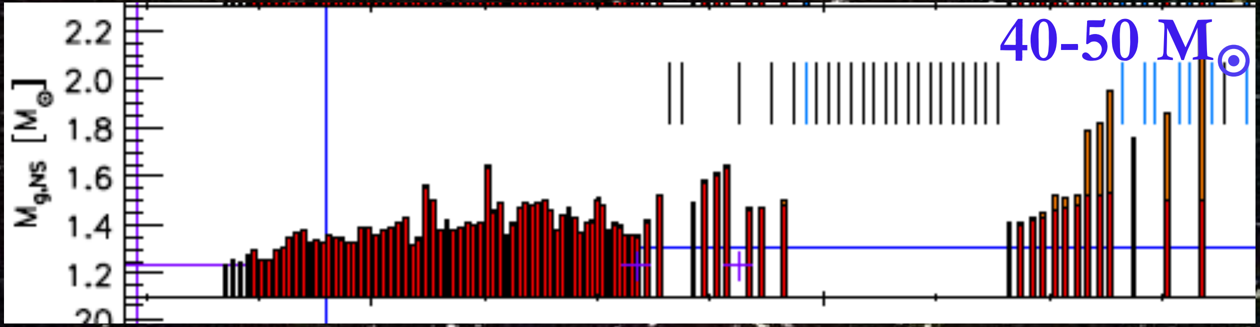
Origin of NS masses: binary star evolution and explosions

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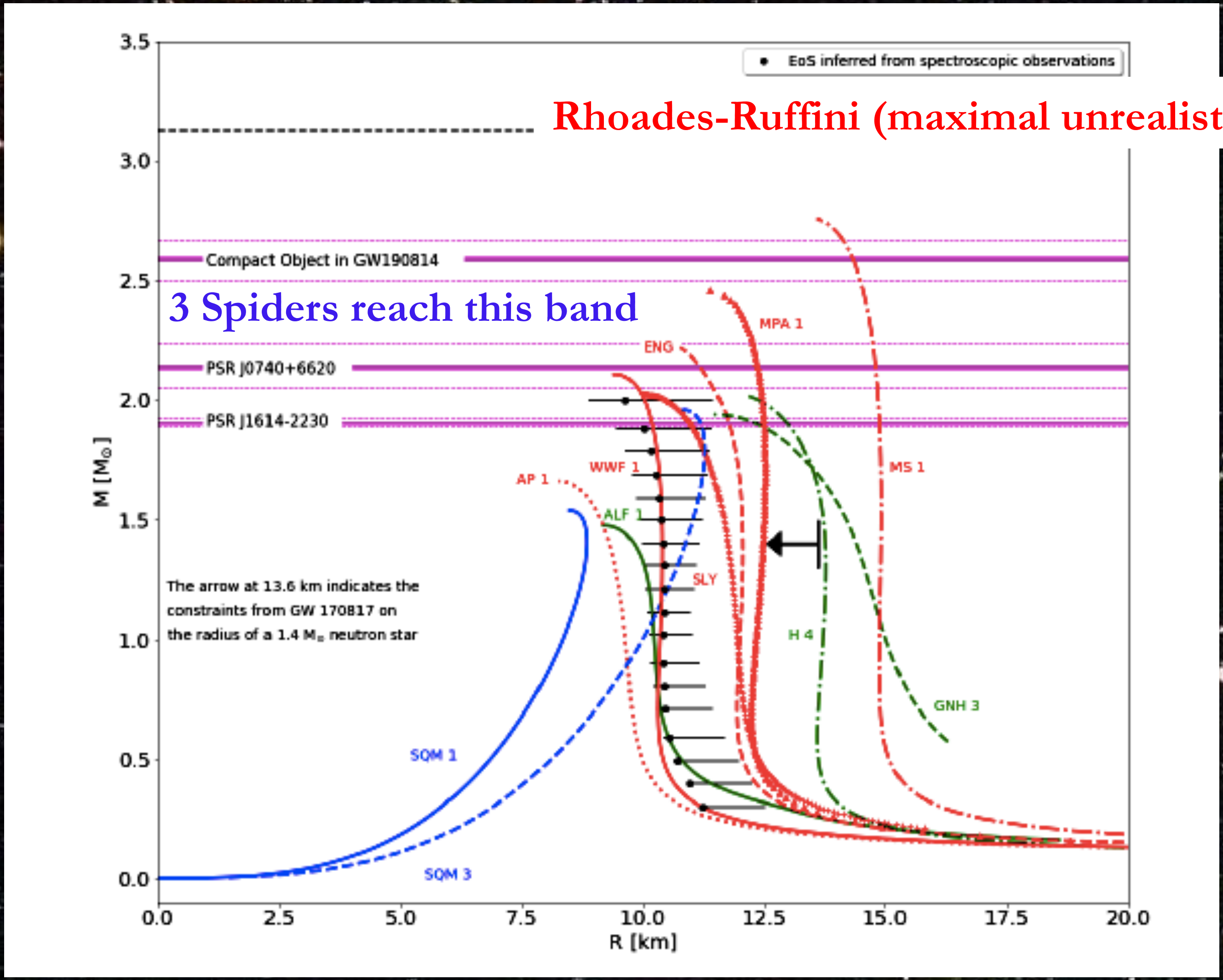
Where do we stand ? Is the "gap" being filled?



The arrow at 13.6 km indicates the constraints from GW 170817 on the radius of a 1.4 $M_\odot$ neutron star

Rhoades-Ruffini (maximal unrealistic stiffness)

3 Spiders reach this band

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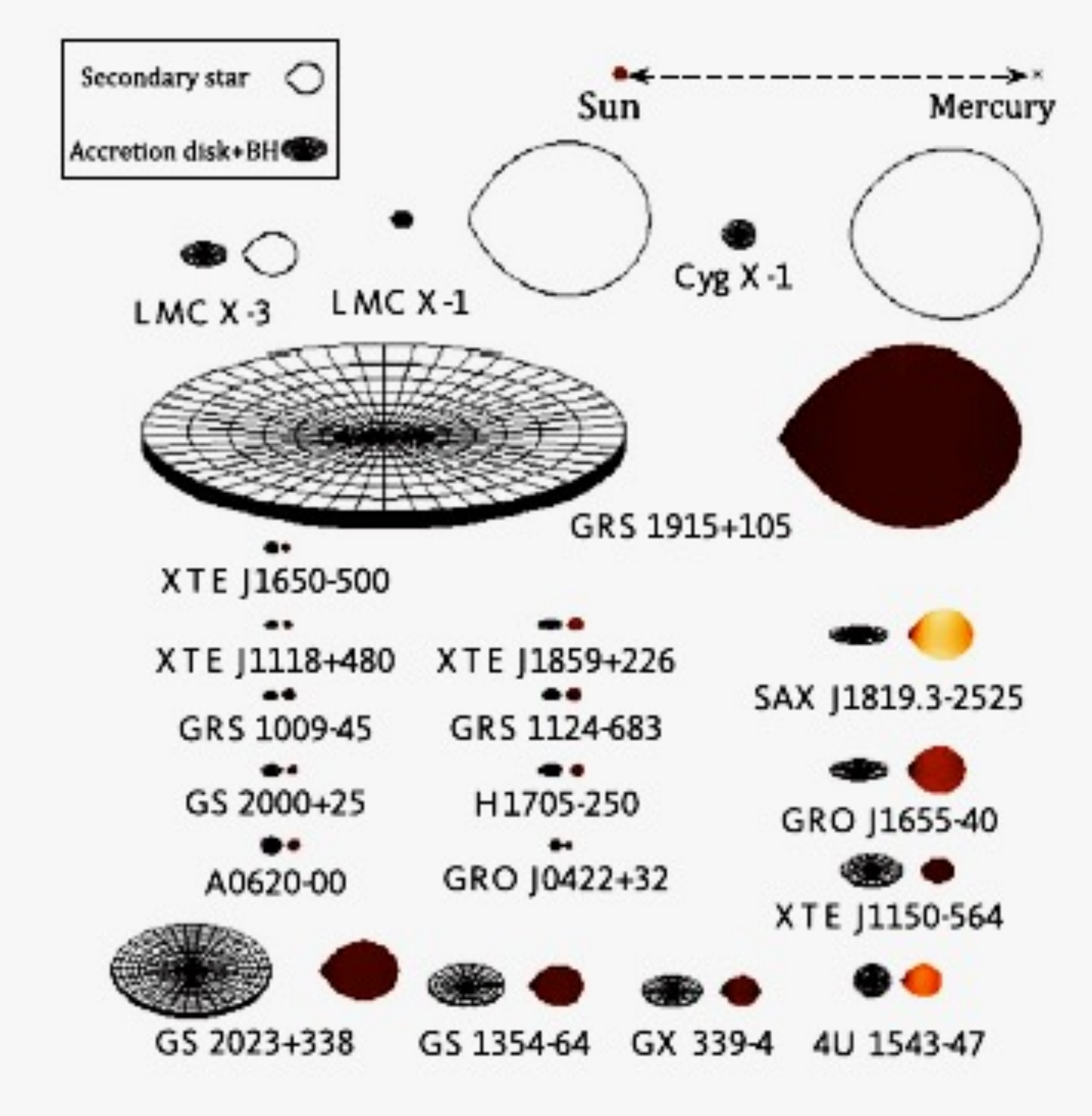
Astrophysical (stellar) black holes



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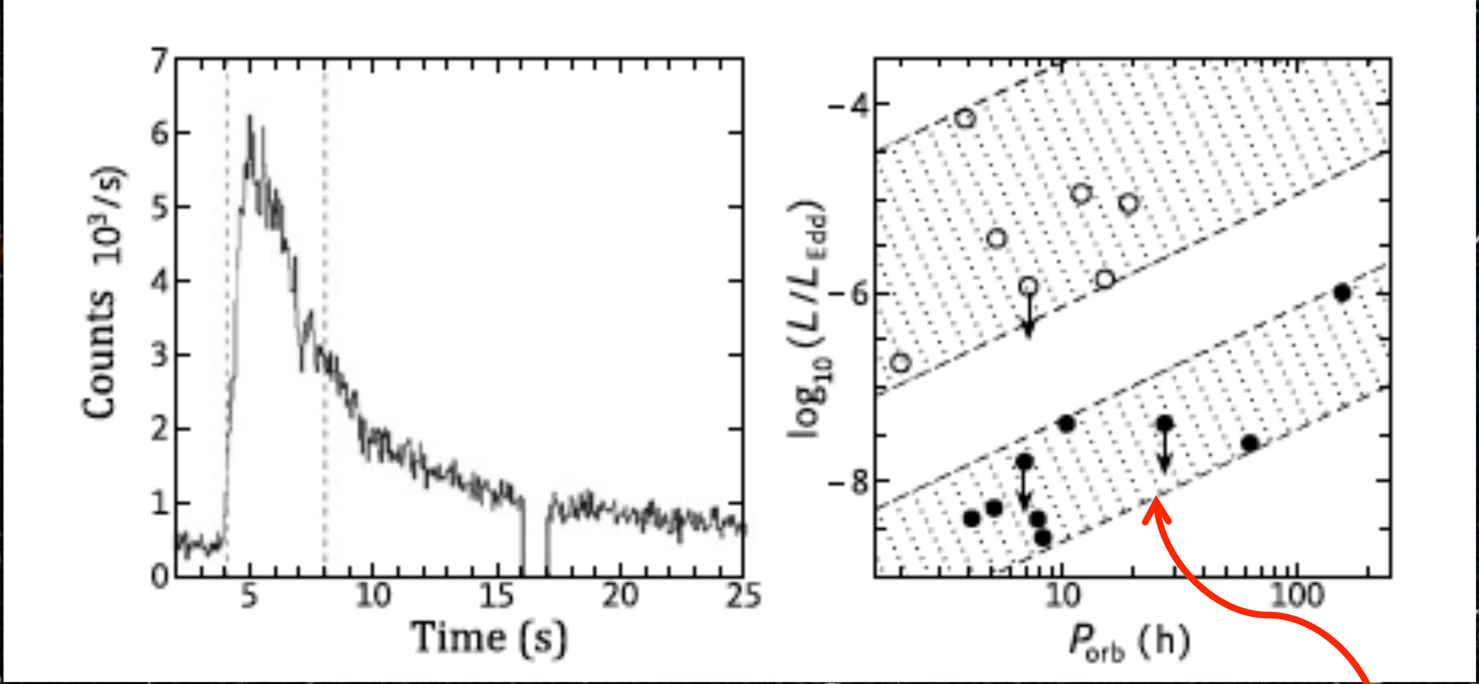
X-ray bursts and NS-BHs



These must be BHs, matter falls beyond the horizon and L is reduced.

Never observed to burst

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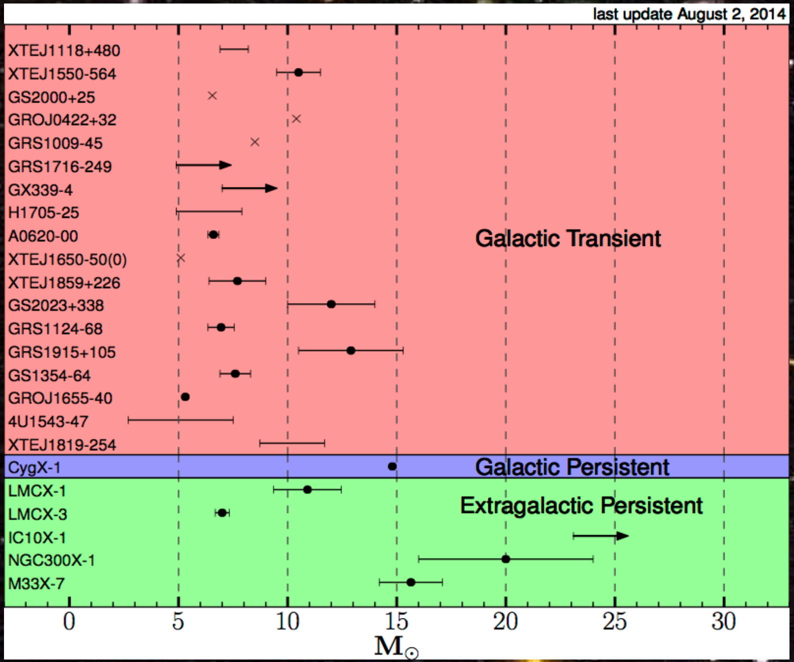
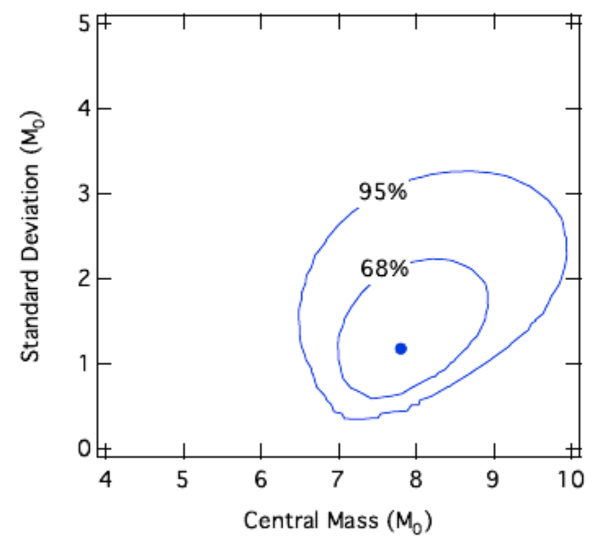
What about black holes?



Many years ago (2014):
nothing below 5 $M_\odot$
for the known 24 objects



Best Gaussian fit by Ozel et al (2010)
with peak at 7.8 +-1.2 $M_\odot$ and
a 3σ lower cutoff around 5 $M_\odot$
16 systems

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The *mass gap* hypothesis:

There are no objects between 2 and 5 M$_\odot$ (Baylin et al. 1998, Fryer et al. 2012), we call it a *desert gap*. Alternatively there can be a deficit –*depleted gap*-)

But in fact…

recently many candidates appeared

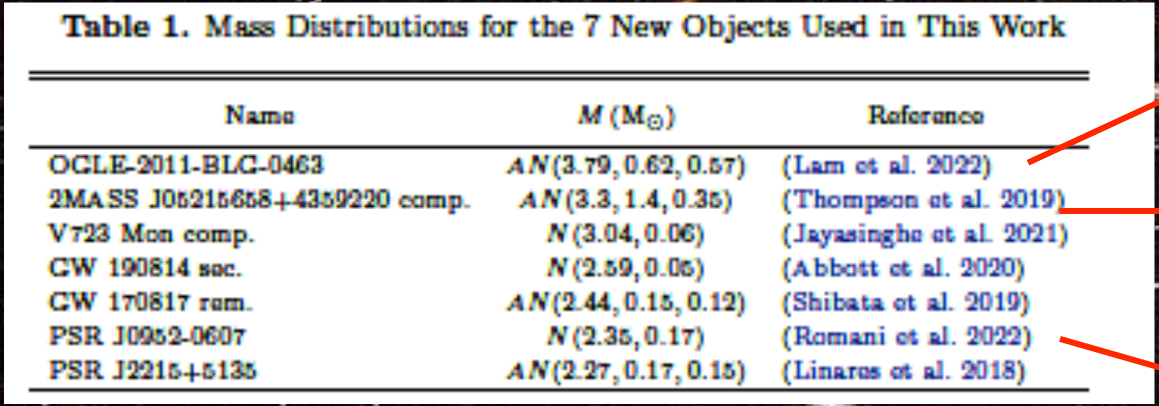

Table 1. Mass Distributions for the 7 New Objects Used in This Work

Name	M (M$_\odot$)	Reference
OGLE-2011-BLG-0463	$AN(3.79, 0.62, 0.57)$	(Lam et al. 2022)
2MASS J05215658+4359220 comp.	$AN(3.3, 1.4, 0.35)$	(Thompson et al. 2019)
V723 Mon comp.	$N(3.04, 0.06)$	(Jayasinghe et al. 2021)
GW 190814 sec.	$N(2.59, 0.05)$	(Abbott et al. 2020)
GW 170817 rem.	$AN(2.44, 0.15, 0.12)$	(Shibata et al. 2019)
PSR J0952-0607	$N(2.35, 0.17)$	(Romani et al. 2022)
PSR J2215+5135	$AN(2.27, 0.17, 0.15)$	(Linares et al. 2018)

Microlensing source in the halo

"Unicorn" in Monoceros: A quiet BH with M = 3.04 +- 0.06 M$_\odot$

PSR J0952-0607 Heaviest NS measured M = 2.35 +- 0.17 M$_\odot$

There are others, with less certain values and uncertainties, not included

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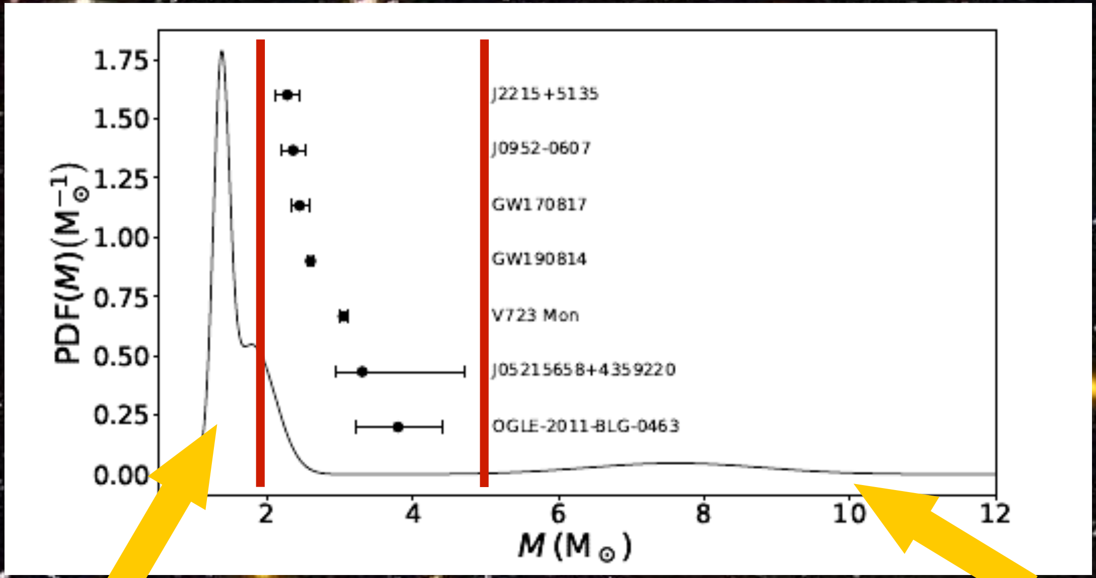
The candidates in the joint distribution NS-BH vs. the Gap hypothesis



Rocha et al. (2021)

Özel et al. (2011)

Is the desert gap real?
Is there a depleted gap?

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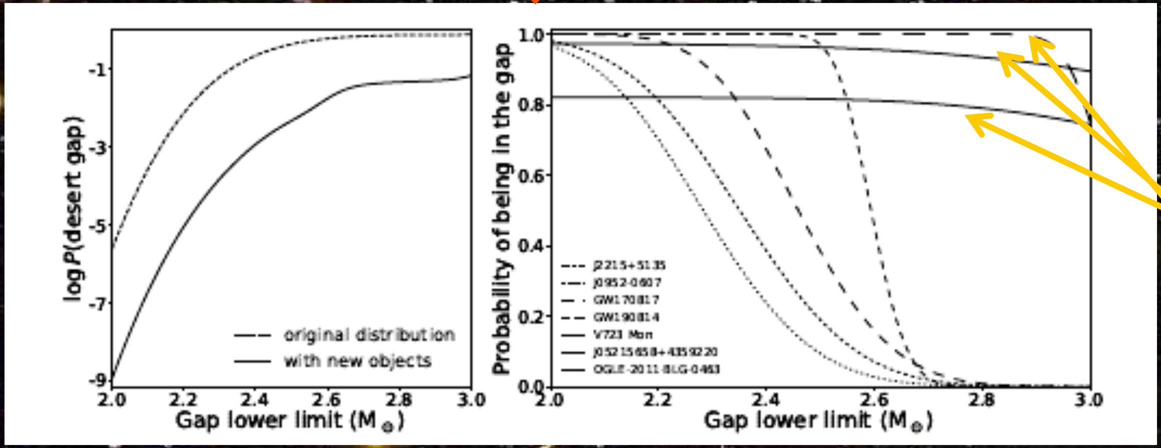
Joint probability of a desert gap

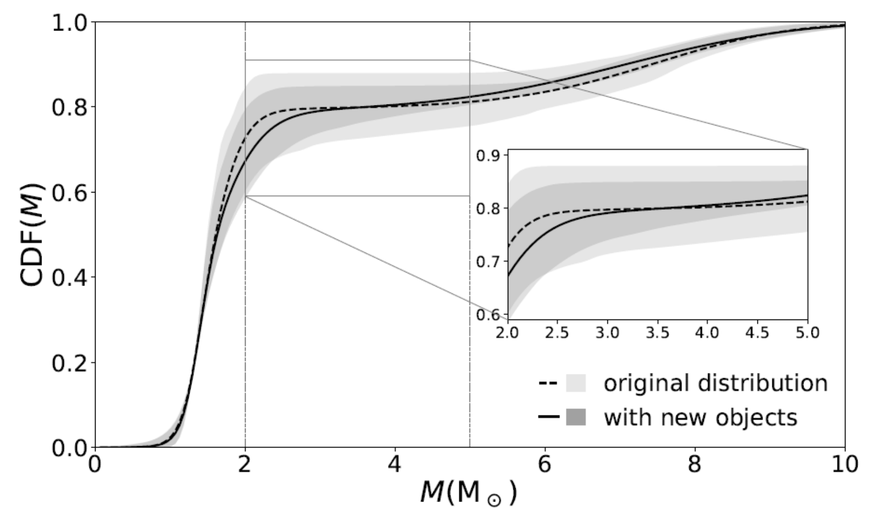
$$P(\text{desert gap}) = \left[1 - \left(C_0 \int_{\text{gap}} \text{PDF}_0\, \mathrm{d}M + \sum_{i=1}^{7} C_i \int_{\text{gap}} \text{PDF}_i\, \mathrm{d}M\right)\right]^N ,$$

Obviously more objects decrease the probability of the desert gap



These three are inside the gap for any value of the lower limit

Synthetic Cumulative distribution (CDF)



The probability that CDF with new objects is still compatible with the original CDF results in a p-value of 0.14 %

Hubble Ultra Deep Field HST ▪ ACS

Likelihood test: consider the number of objects *n* falling in the gap, assumed a *plateau* of unknown amplitude h between $M_{\rm upper}^{\rm plat}$ and $M_{\rm lower}^{\rm plat}$

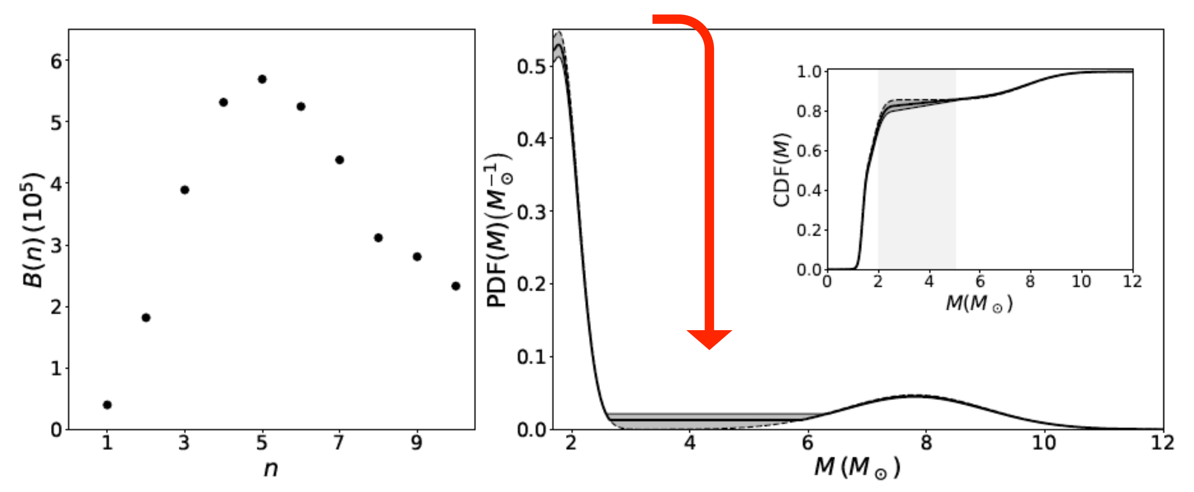
$$n = h\left(M_{\rm upper}^{\rm plat} - M_{\rm lower}^{\rm plat}\right) N$$

Number of objects in the Present sample N=119

We compute the Bayes factor between a depleted and desert gaps (for *n* = 0 they coincide)

$$B(n) = \frac{\mathcal{L}\left(M|D_{\rm depleted,n}\right)}{\mathcal{L}\left(M|D_{\rm desert}\right)} = \frac{\prod_{i=1}^{N} P_{\rm depleted,n}(M_i)}{\prod_{i=1}^{N} P_{\rm desert}(M_i)}$$

The results show a very high peak at n = 5 (it goes down because adding more points increases the sample and hence the denominator). This is a 1-parameter approach (the amplitude h)



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Conclusions

- 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" is 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

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Obrigado !

Perguntas?