Hubble Ultra Deep Field HST ▪ ACS

Why "black widow" pulsar systems are important for the quest of neutron star maximum mass

J.E. Horvath,
IAG – USP
São Paulo, Brazil

with O. Benvenuto & M.A. De Vito (La Plata)

Hubble Ultra Deep Field HST ▪ ACS

Once upon a time the idea of a single mass scale was firmly rooted in the community

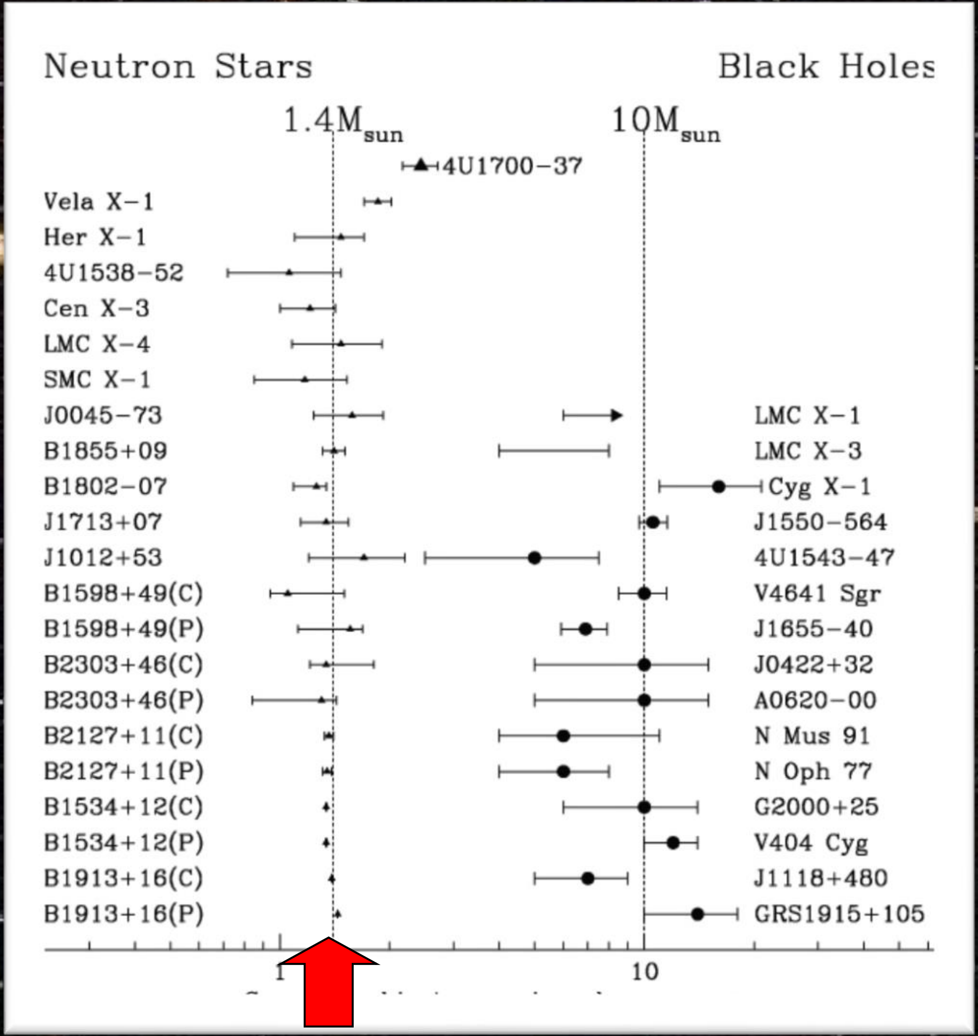
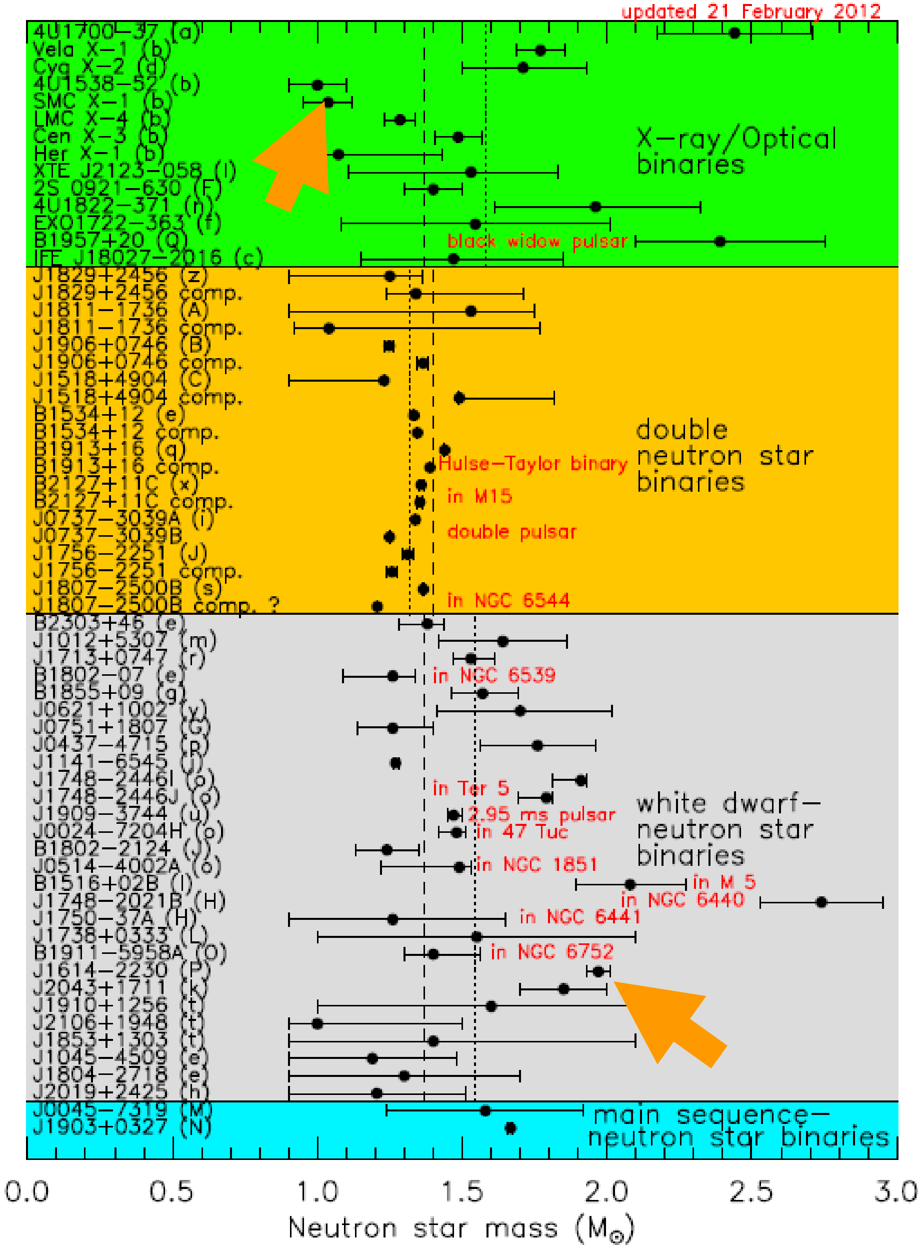


Figure from Clark et al. A&A 392, 909 (2002)

Consistent with 1.4 $M_\odot$

NASA, ESA, S. Beckwith (STScI) and The HUDF Team STScI-PRC04-07a

Hubble Ultra Deep Field HST ▪ ACS

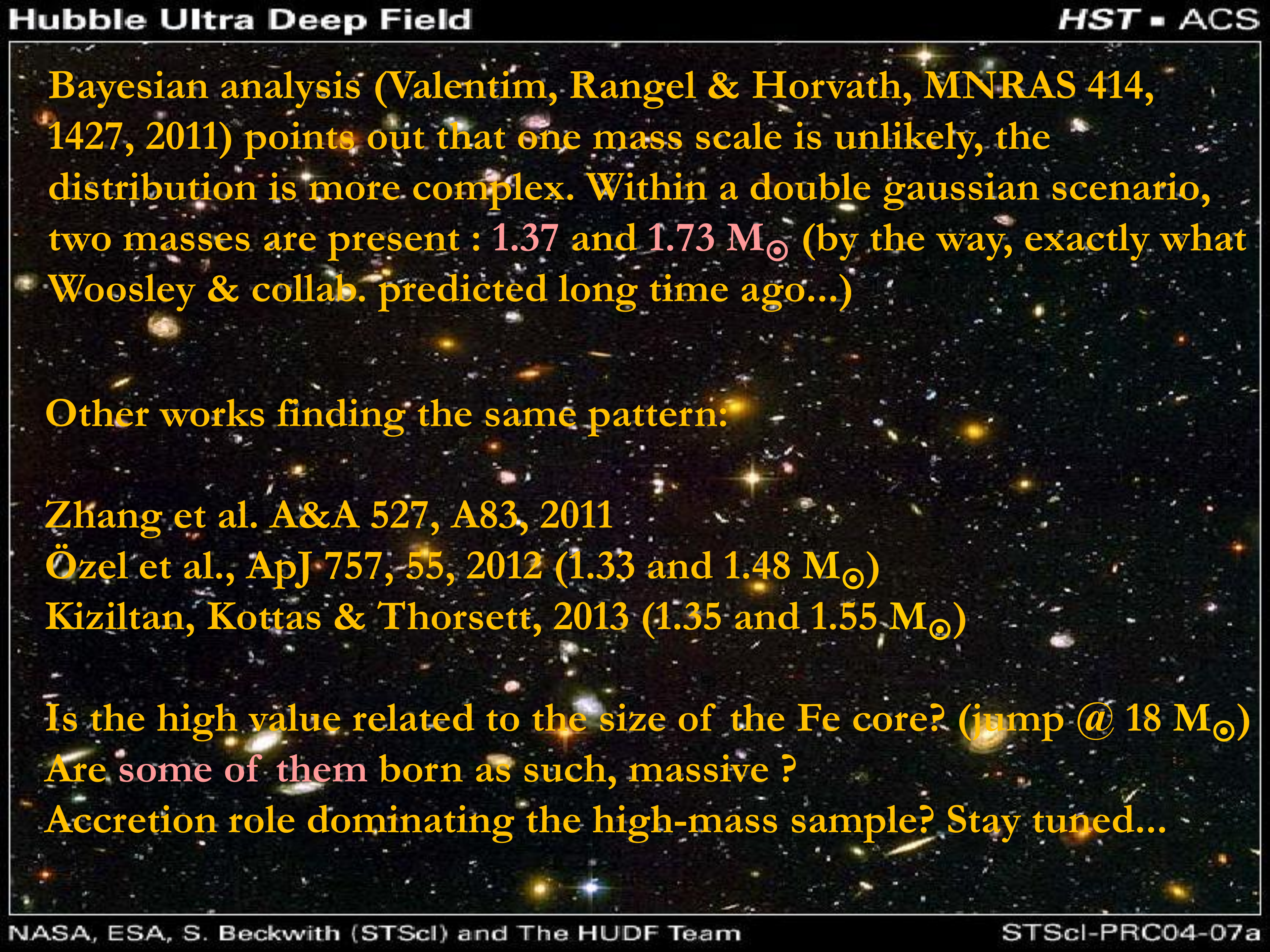


However, the newest evidence points towards a *much wider* range of masses

Sample compiled by Lattimer et al 2012, available at

http://www.stellarcollapse.org/asses

NASA, ESA, S. Beckwith (STScI) and The HUDF Team STScI-PRC04-07a



Bayesian analysis (Valentim, Rangel & Horvath, MNRAS 414, 1427, 2011) points out that one mass scale is unlikely, the distribution is more complex. Within a double gaussian scenario, two masses are present : 1.37 and 1.73 $M_{\odot}$ (by the way, exactly what Woosley & collab. predicted long time ago...)

Other works finding the same pattern:

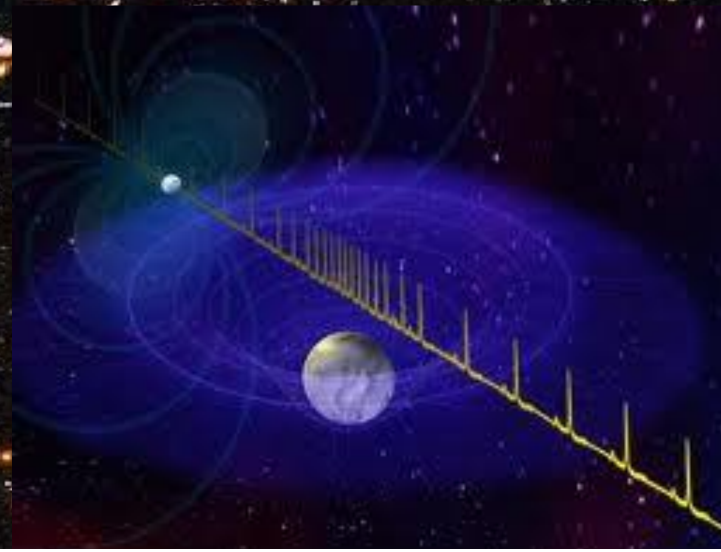
Zhang et al. A&A 527, A83, 2011
Özel et al., ApJ 757, 55, 2012 (1.33 and 1.48 $M_{\odot}$)
Kiziltan, Kottas & Thorsett, 2013 (1.35 and 1.55 $M_{\odot}$)

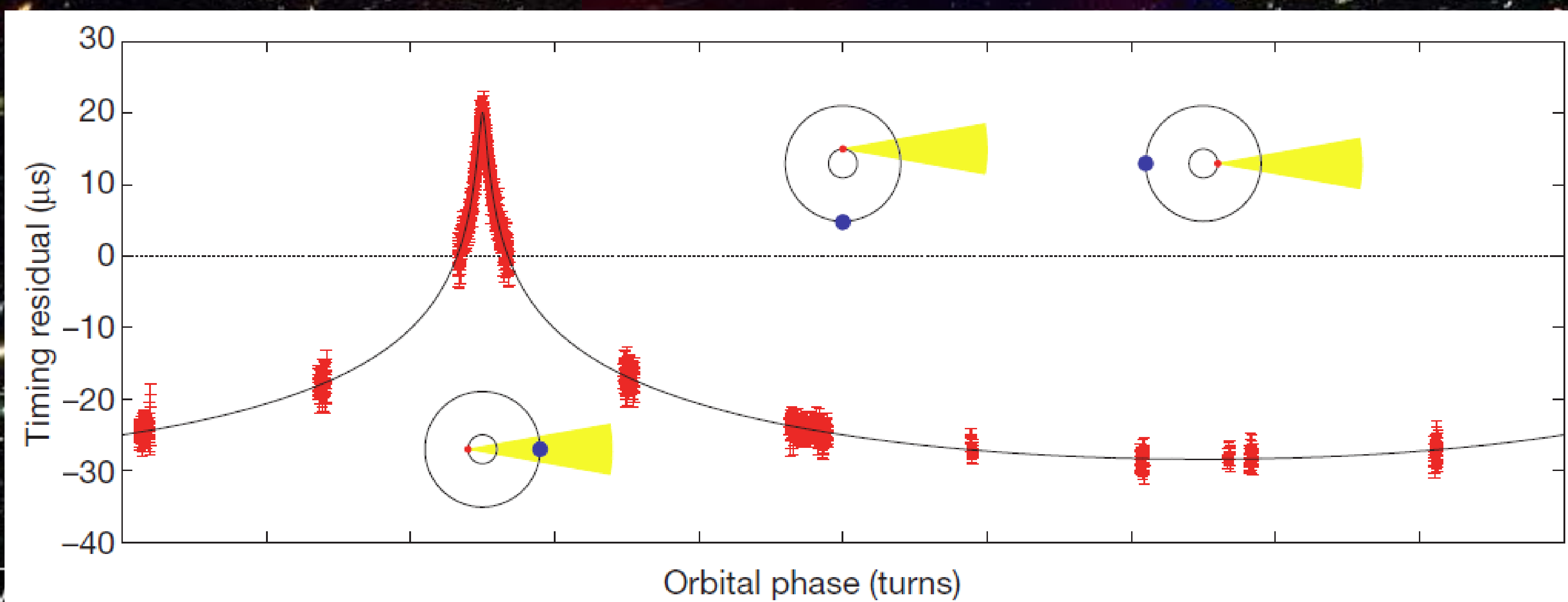
Is the high value related to the size of the Fe core? (jump @ 18 $M_{\odot}$)
Are some of them born as such, massive ?
Accretion role dominating the high-mass sample? Stay tuned...

Hubble Ultra Deep Field HST ▪ ACS

Demorest et al 2010: a NS with M~ 2 $M_\odot$ measuring the Shapiro delay

"clean" measurement
widely accepted



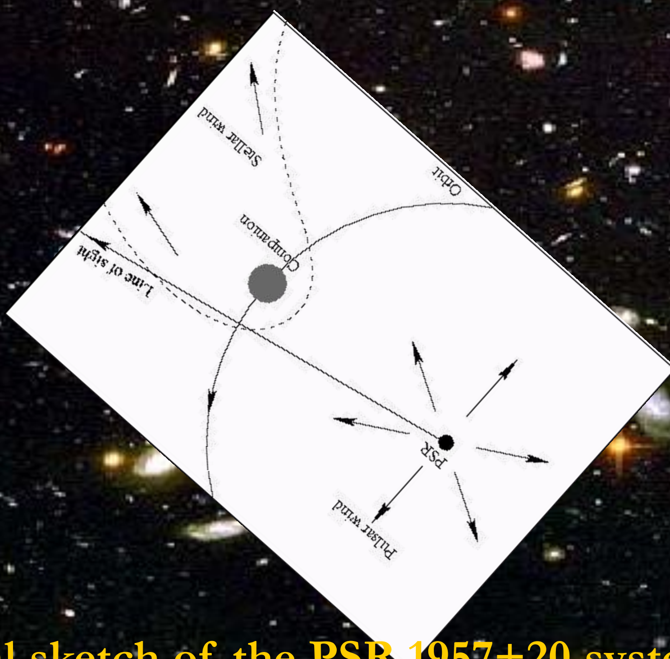


Hubble Ultra Deep Field HST ▪ ACS

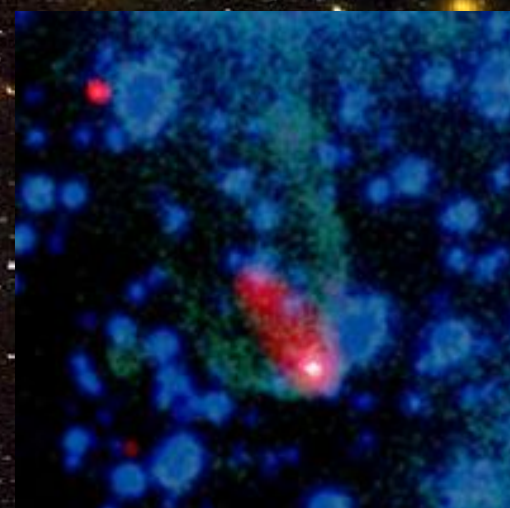
A class of NS systems which may be crucial for the mass iss

1982: Backer et al. discovered the first member of the *ms* pulsar class RECYCLED BY ACCRETION?

1988: Fruchter, Stinebring & Taylor (Nature 333, 237, 1988) found an eclipsing pulsar with a very low mass companion, the hypothesis of ablation wind quickly follows



Original sketch of the PSR 1957+20 system



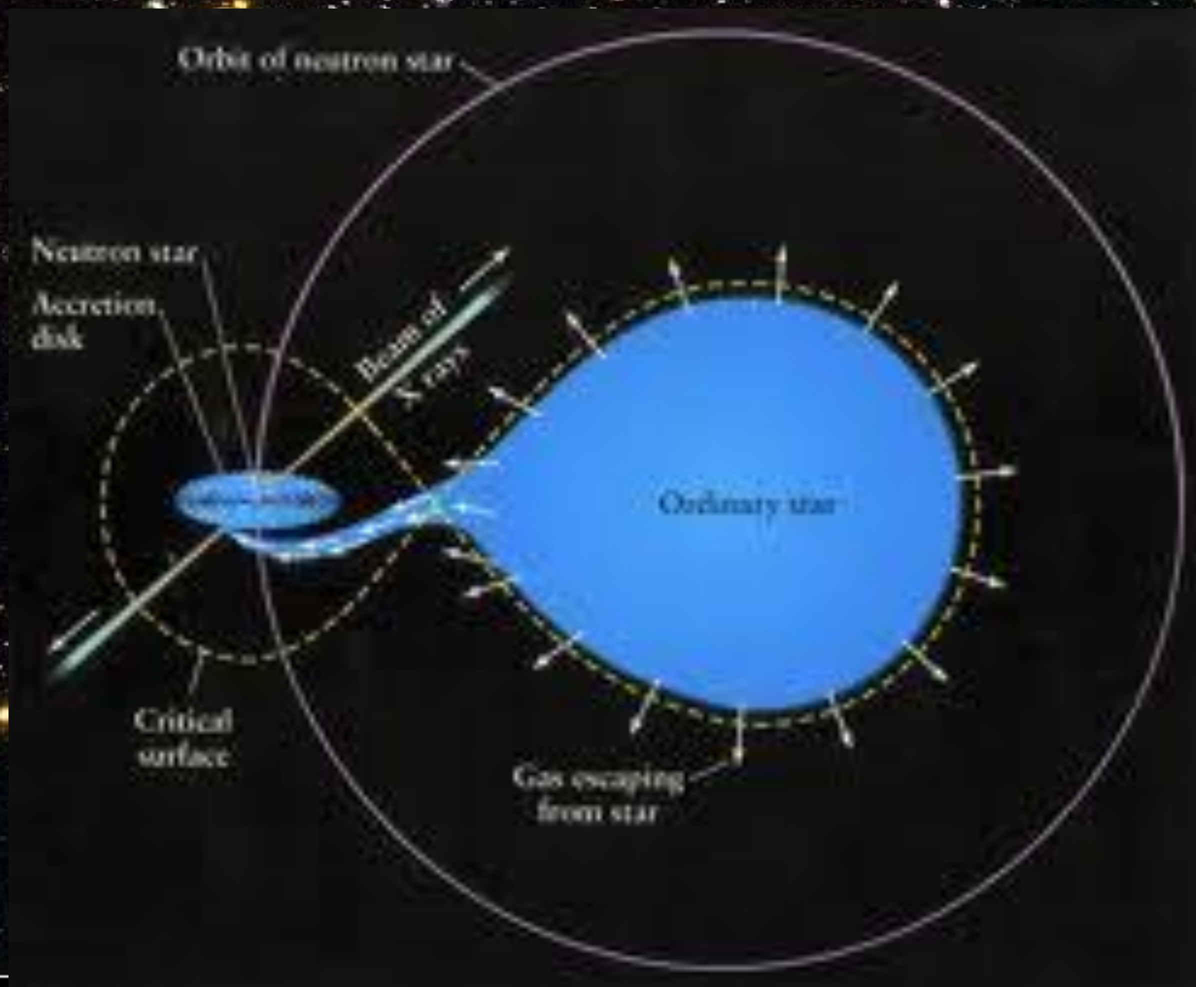
Composite Image from *Chandra* (2012)

NASA, ESA, S. Beckwith (STScI) and The HUDF Team STScI-PRC04-07a

Hubble Ultra Deep Field HST ▪ ACS

"Black widow" pulsars

Relatives of the accreting X-ray binaries…

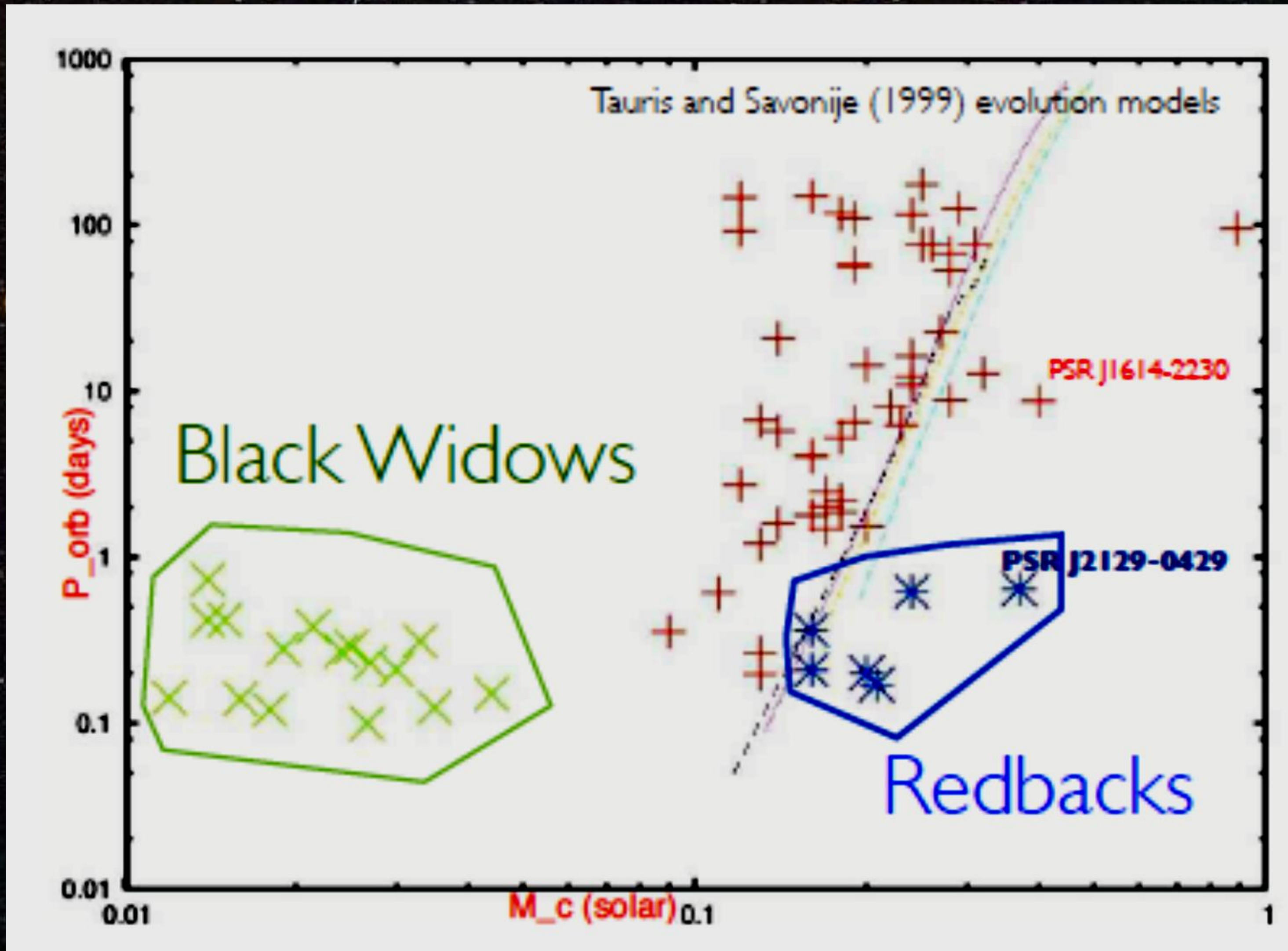


LMXRB and others

Many ms pulsars in binaries

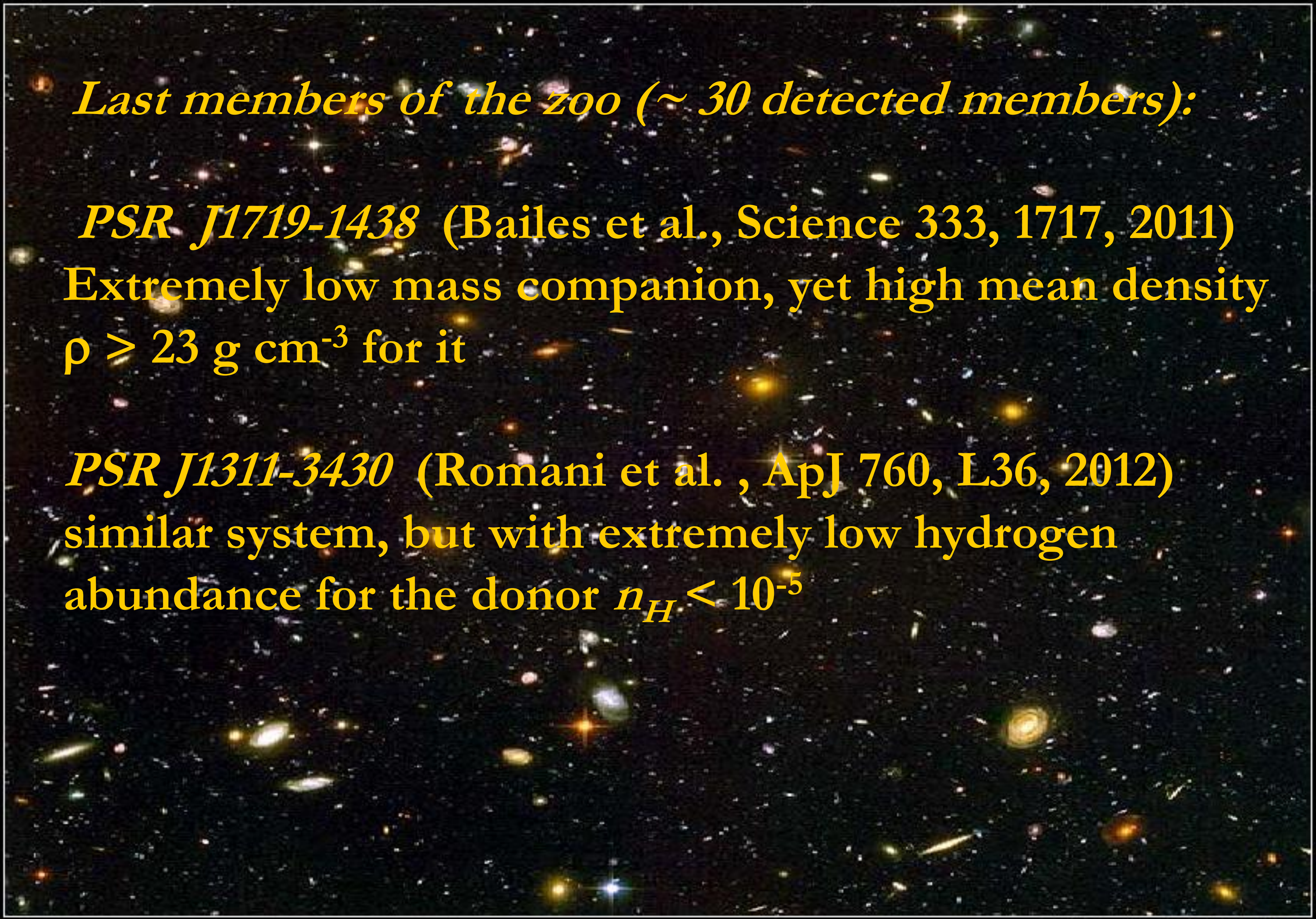
NASA, ESA, S. Beckwith (STScI) and The HUDF Team STScI-PRC04-07a

Hubble Ultra Deep Field HST ▪ ACS



M. Roberts, arXiv:1210.6903

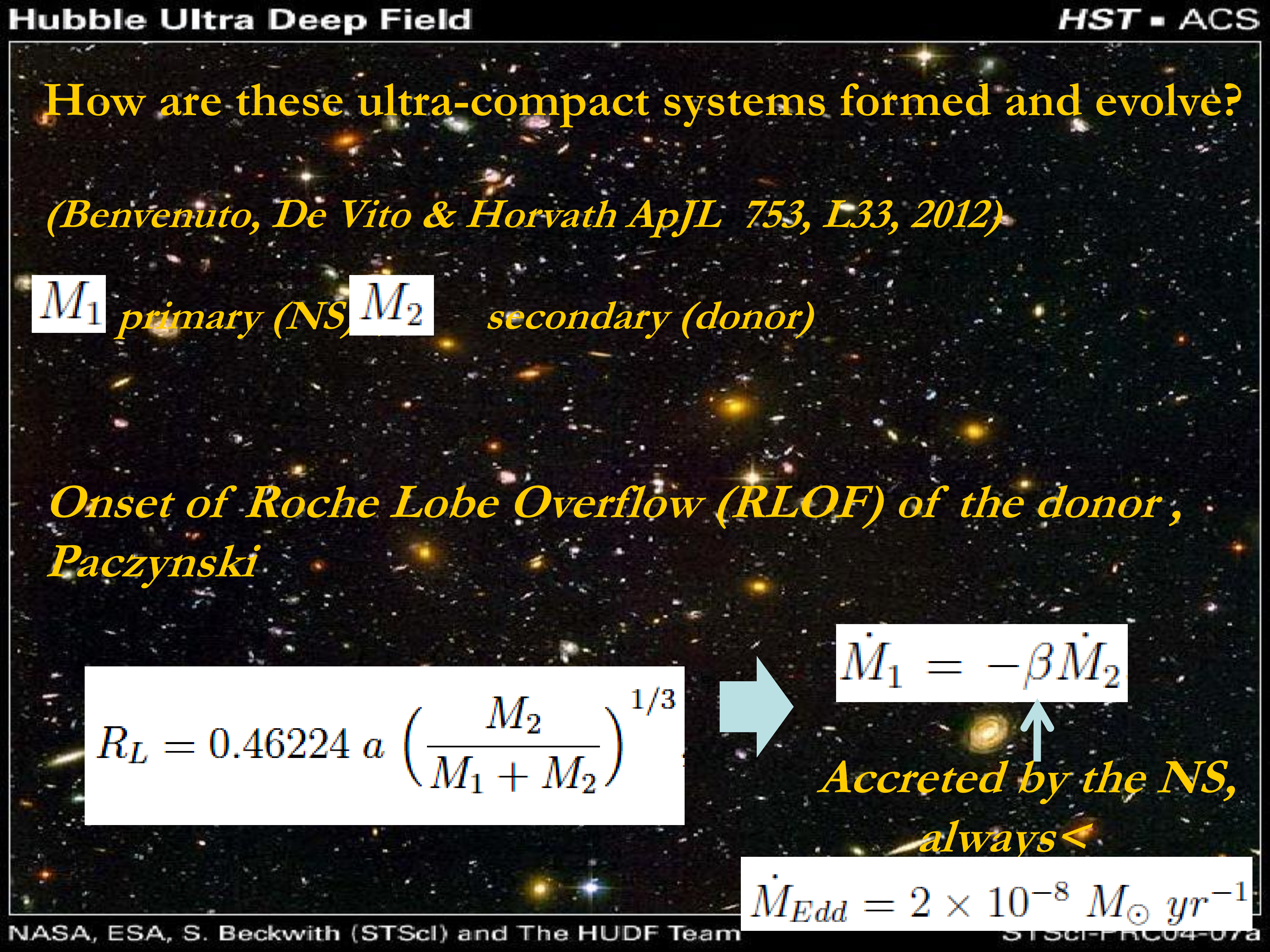
NASA, ESA, S. Beckwith (STScI) and The HUDF Team STScI-PRC04-07a



Last members of the zoo (~ 30 detected members):

PSR J1719-1438 **(Bailes et al., Science 333, 1717, 2011)**
Extremely low mass companion, yet high mean density $\rho > 23$ g cm^{-3} for it

PSR J1311-3430 **(Romani et al. , ApJ 760, L36, 2012)**
similar system, but with extremely low hydrogen abundance for the donor $n_H < 10^{-5}$



How are these ultra-compact systems formed and evolve?

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

M_1 *primary (NS)* M_2 *secondary (donor)*

Onset of Roche Lobe Overflow (RLOF) of the donor , Paczynski

$$R_L = 0.46224\, a \left(\frac{M_2}{M_1 + M_2}\right)^{1/3}$$

$$\dot{M}_1 = -\beta \dot{M}_2$$

Accreted by the NS, always<

$$\dot{M}_{Edd} = 2 \times 10^{-8}\ M_{\odot}\ yr^{-1}$$

Hubble Ultra Deep Field HST ▪ ACS

In general, $\beta < 1$ and angular momentum is lost from the system. The exact value of β is not critical for evolution (but keep an eye on it !!!)

$$\dot{M}_{2,RLOF} = -\dot{M}_0 \exp\left(\frac{R_2 - R_L}{H_P}\right)$$

1st ingredient
(Ritter, A&A 202, 93, 1988)

Evaporating wind

$$\dot{M}_{2,evap} = -\frac{f}{2v_{2,esc}^2} L_P \left(\frac{R_2}{a}\right)^2$$

2nd ingredient
(Stevens et al., MNRAS 254, 19, 1992)

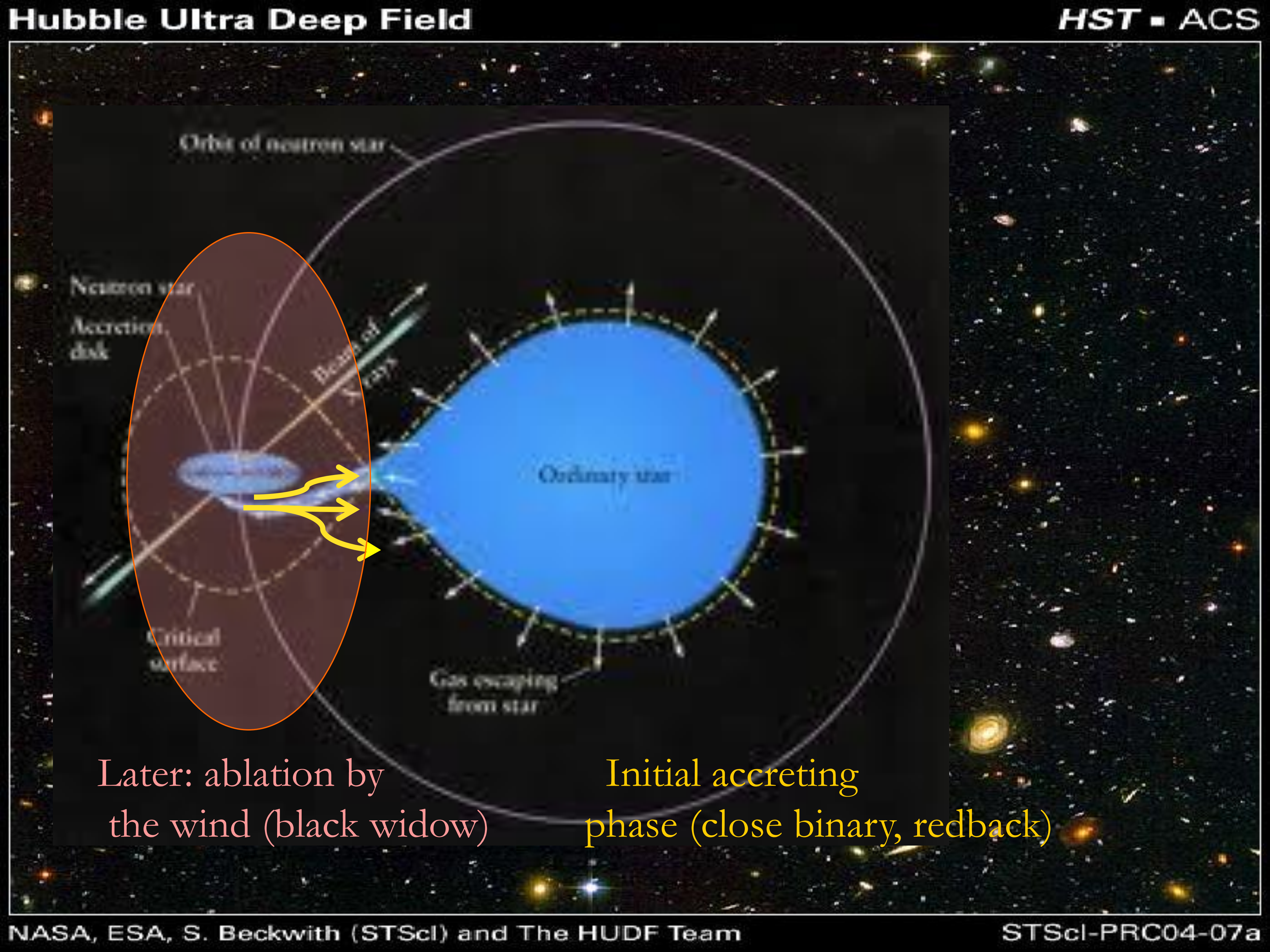
with

$$L_P = 4\pi^2 I_1 P_1 \dot{P}_1$$

Irradiation feedback

$$F_{irr} = \frac{\alpha_{irr}}{4\pi a^2} \frac{GM_1}{R_1} \dot{M}_1$$

3rd ingredient
(Bunning & Ritter, A&A 423, 281, 2004
Hameury)


Hubble Ultra Deep Field
HST ▪ ACS
Orbit of neutron star
Neutron star
Accretion disk
Beam of X rays
Ordinary star
Critical surface
Gas escaping from star
Later: ablation by the wind (black widow)
Initial accreting phase (close binary, redback)
NASA, ESA, S. Beckwith (STScI) and The HUDF Team
STScI-PRC04-07a

All three effects incorporated into an adaptative Henyey code, solving simultaneously structure and orbital evolution (Benvenuto & De Vito, 2003 ; De Vito & Benvenuto, 2012)

(M_1, M_2, P_i) *must be in the "right" range to explain th observed systems*

If P_i is too short (< 0.5 d), the mass transfer would start at ZAMS

If P_i is too long (> 0.9 d), the orbit widens when donor is ~0.3 $M_\odot$ not the observed "black widow" state !

If M_2 is too small, mass transfer would be > age universe

If M_2 is too high, mass transfer is unstable (Podsiadlowski et al)

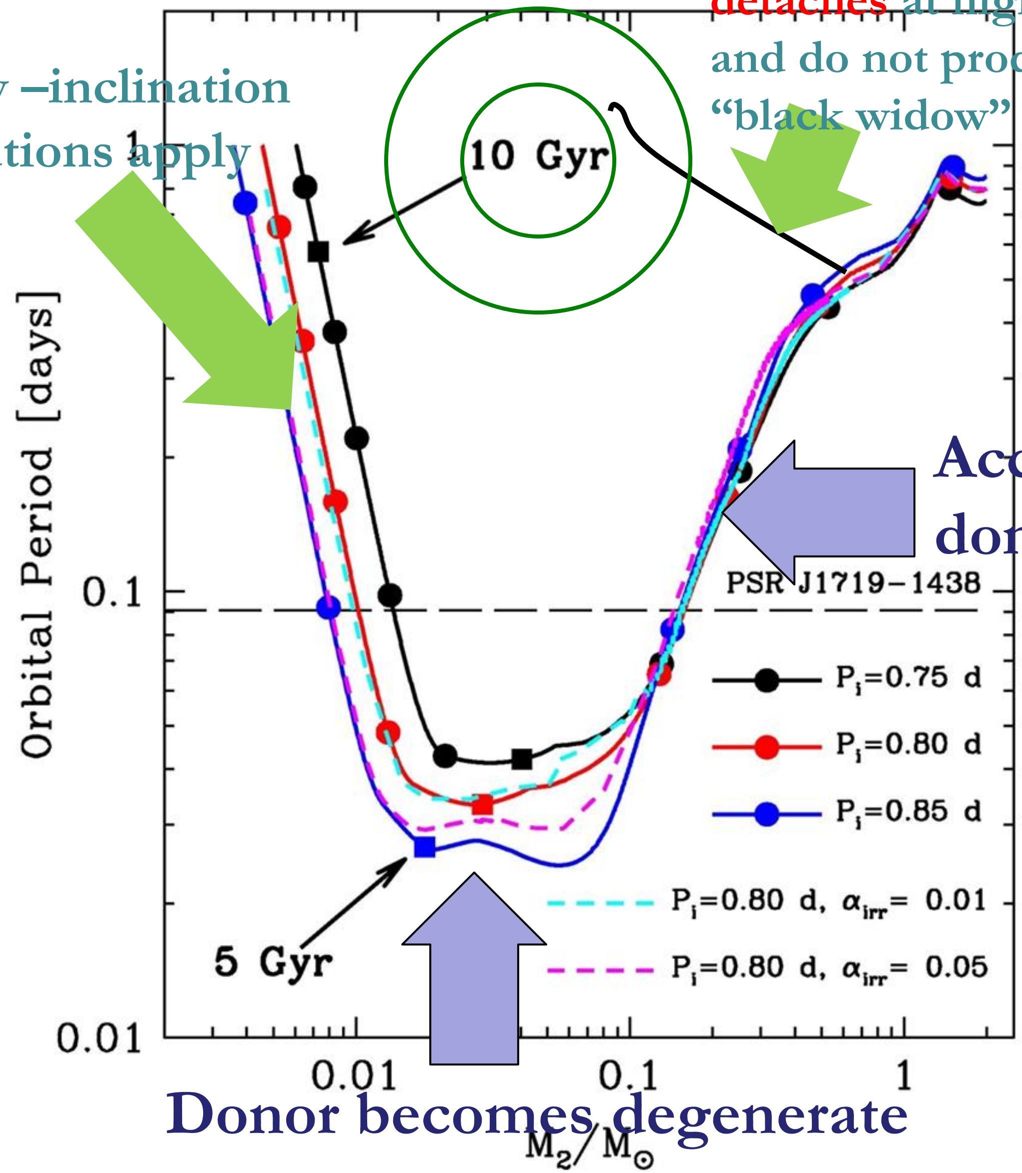
Started calculations right after the NS formation $M_2 = 2M_\odot$

CAVEAT !!!, just an hypothesis ➡ $M_1 = 1.4M_\odot$

PSR J1719-1438

At slightly larger initial periods, the secondary detaches at high mass and do not produce “black widow” systems

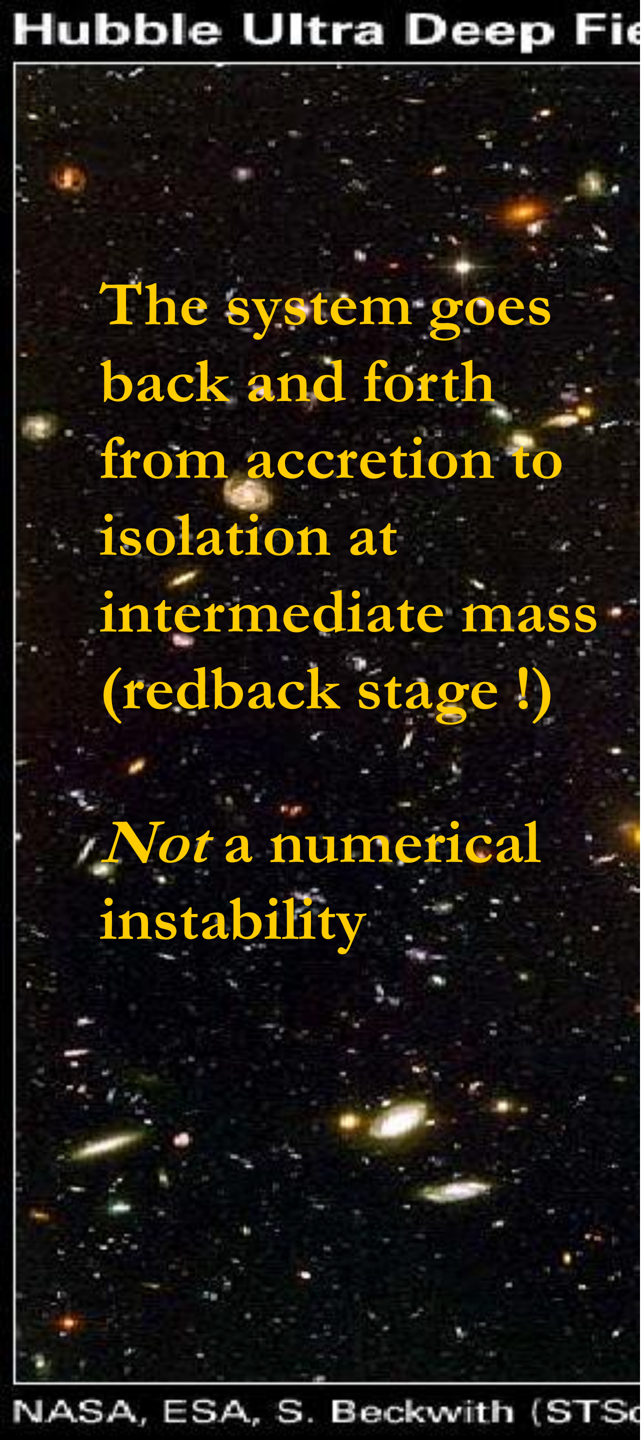
Low –inclination solutions apply



Accretion dominant

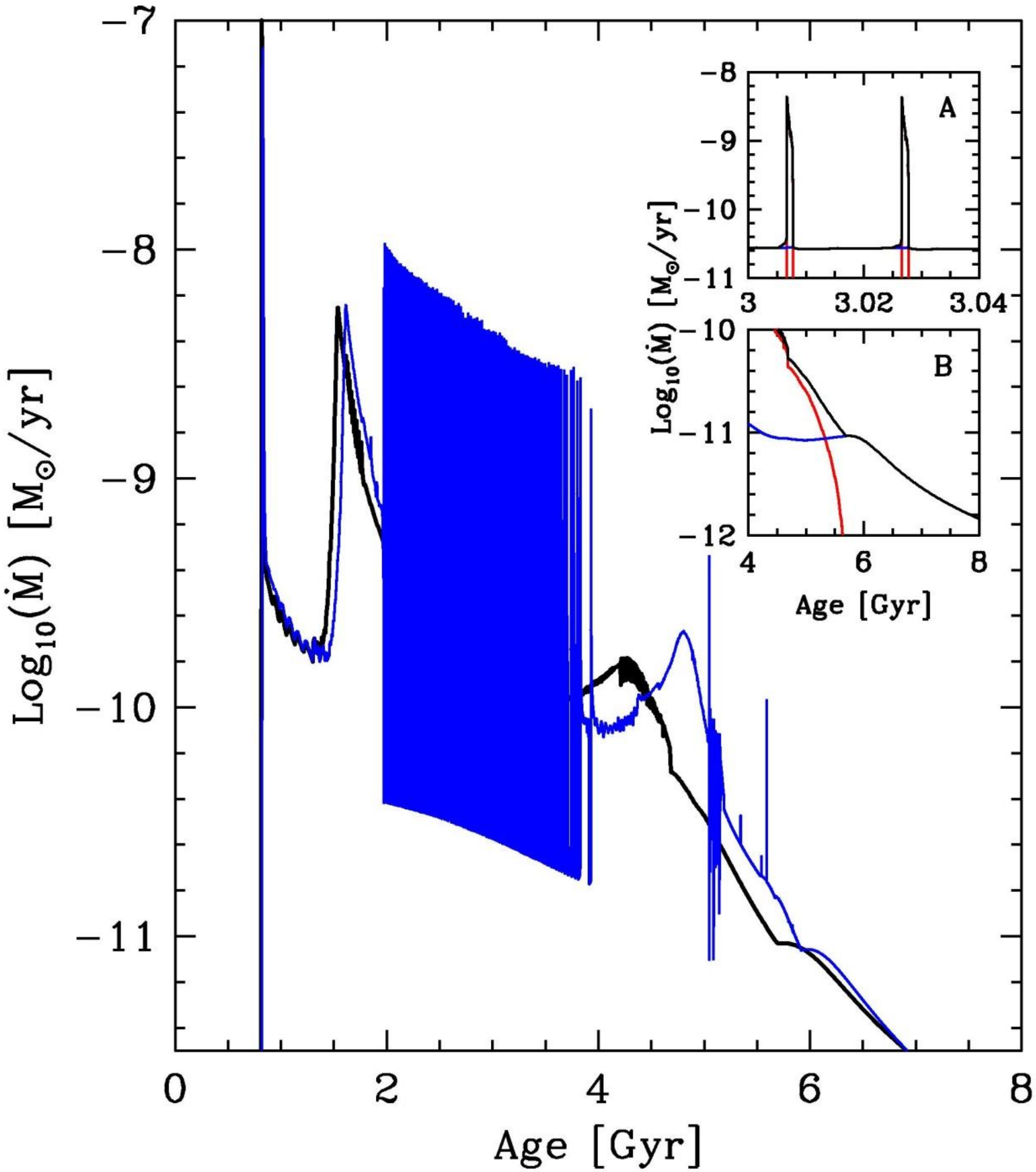
Donor becomes degenerate

PSR J1719-1438



The system goes back and forth from accretion to isolation at intermediate mass (redback stage !)

Not a numerical instability



Hubble Ultra Deep Field HST ▪ ACS

The original "black widow" PSR 1957+20: new results (van Kerkwijk, Breton & Kulkarni, ApJ 728, 95, 2011)

Mpsr/M_2 ~ 70 (through spectral lines, radial velocity)

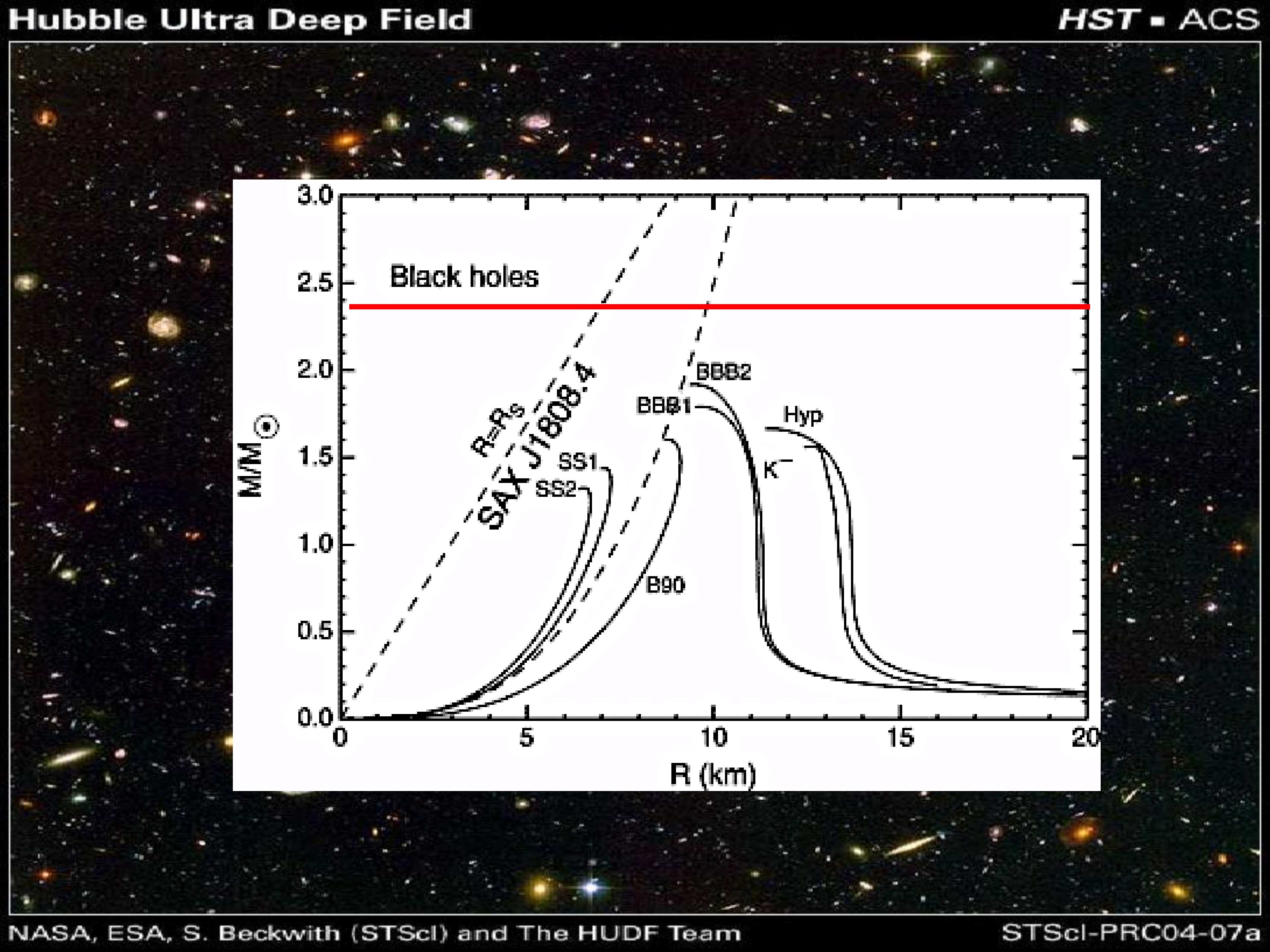
$$M_{psr} = 2.4 \pm 0.12\ M_{\odot}$$

(M_{psr} > 1.66 $M_{\odot}$ very firm)

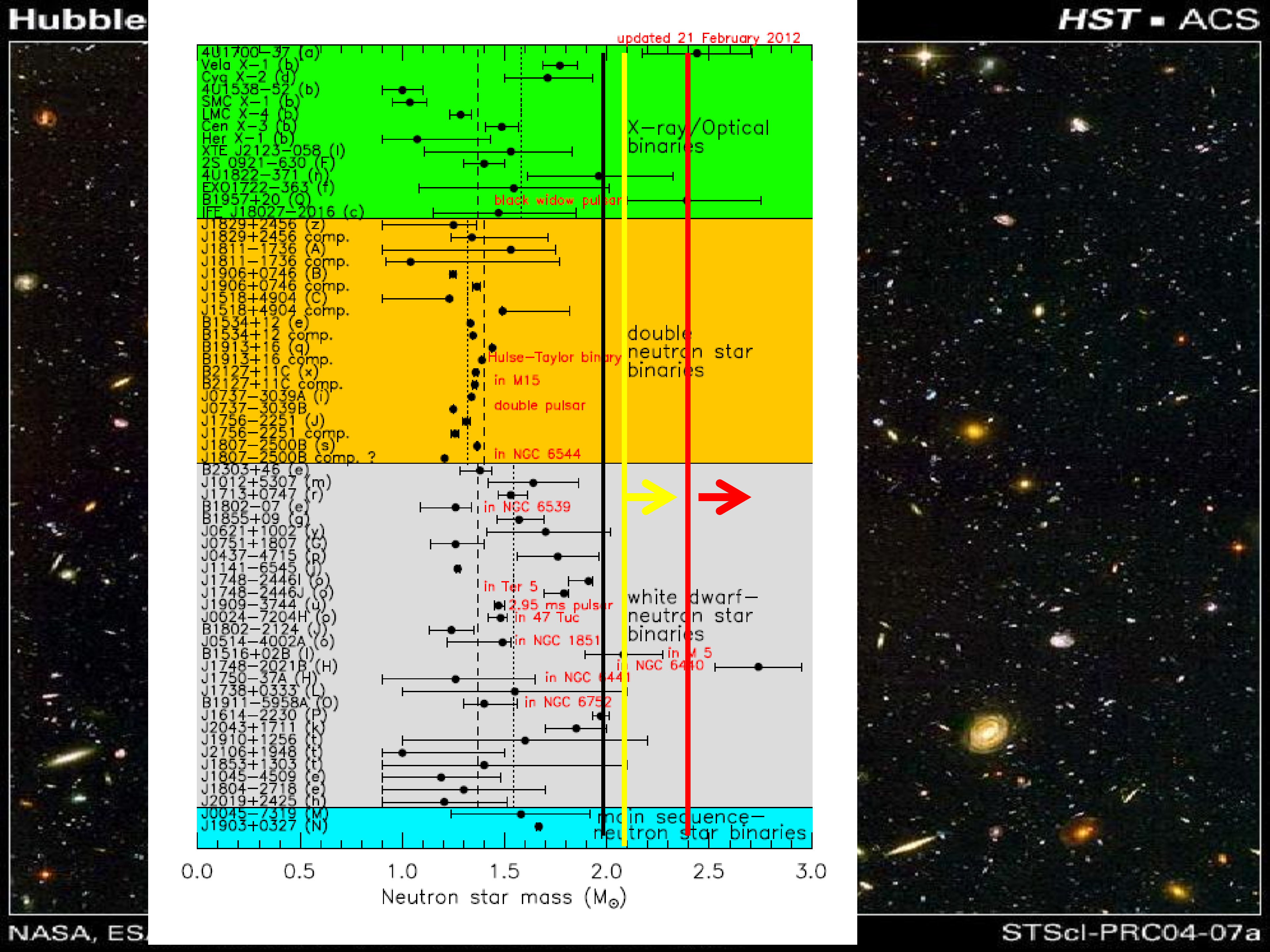
Romani et al. (ApJ 760, L36, 2012) found three high values for the neutron star in PSR J1311-3430, depending on the interpretation M_{psr}> 2.1 $M_{\odot}$ up to ~ 3 $M_{\odot}$ but…

Latest news: systematic errors dominate and no value of the NS can be reliably confirmed (Romani, Filippenko & Cenko arXiv:1503.05247 2015)

NASA, ESA, S. Beckwith (STScI) and The HUDF Team STScI-PRC04-07a



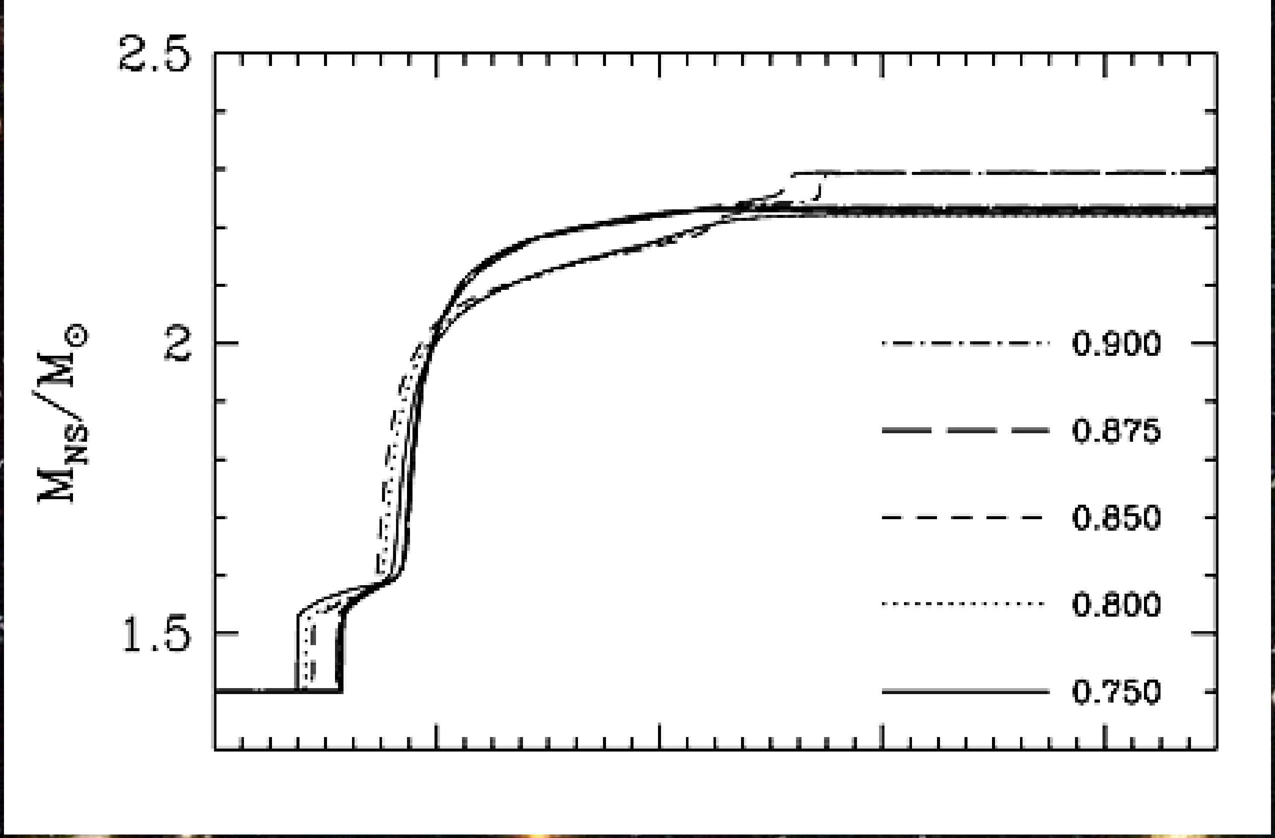
Hubble Ultra Deep Field
HST ▪ ACS
Black holes
R=Rs
SAX J1808.4
SS1
SS2
BBB2
BBB1
Hyp
K⁻
B90
M/M⊙
R (km)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
NASA, ESA, S. Beckwith (STScI) and The HUDF Team
STScI-PRC04-07a



Hubble
HST ■ ACS
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 (R)
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
0.5
1.0
1.5
2.0
2.5
3.0
Neutron star mass ($M_\odot$)
NASA, ES
STScI-PRC04-07a

Hubble Ultra Deep Field HST ▪ ACS

Self-consistent calculations of the PSR J1311-3430 system require such high values to reach the observed state



Calculations for several values of the initial period, and fixed accretion efficiency β of 50%

Hubble Ultra Deep Field — HST ▪ ACS

What do high masses mean: the "hyperon puzzle"

Hyperons soften the equation of state, do they?

Hyperon Puzzle: Hints from Quantum Monte Carlo Calculations

Diego Lonardoni,[1] Alessandro Lovato,[1] Stefano Gandolfi,[2] and Francesco Pederiva[3,4]

[1]*Physics Division, Argonne National Laboratory, Lemont, Illinois 60439, USA*
[2]*Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[3]*Physics Department, University of Trento, via Sommarive 14, I-38123 Trento, Italy*
[4]*INFN-TIFPA, Trento Institute for Fundamental Physics and Applications, I-38123 Trento, Italy*

The onset of hyperons in the core of neutron stars and the consequent softening of the equation of state have been questioned for a long time. Controversial theoretical predictions and recent astrophysical observations of neutron stars are the grounds for the so-called *hyperon puzzle*. We calculate the equation of state and the neutron star mass-radius relation of an infinite systems of neutrons and Λ particles by using the auxiliary field diffusion Monte Carlo algorithm. We find that the three-body hyperon-nucleon interaction plays a fundamental role in the softening of the equation of state and for the consequent reduction of the predicted maximum mass. We have considered two different models of three-body force that successfully describe the binding energy of medium mass hypernuclei. Our results indicate that they give dramatically different results on the maximum mass of neutron stars, not necessarily incompatible with the recent observation of very massive neutron stars. We conclude that stronger constraints on the hyperon-neutron force are necessary in order to properly assess the role of hyperons in neutron stars.

Can NS *avoid* the presence of hyperons?
(the return of "pure neutrons")

NASA, ESA, S. Beckwith (STScI) and The HUDF Team — STScI-PRC04-07a

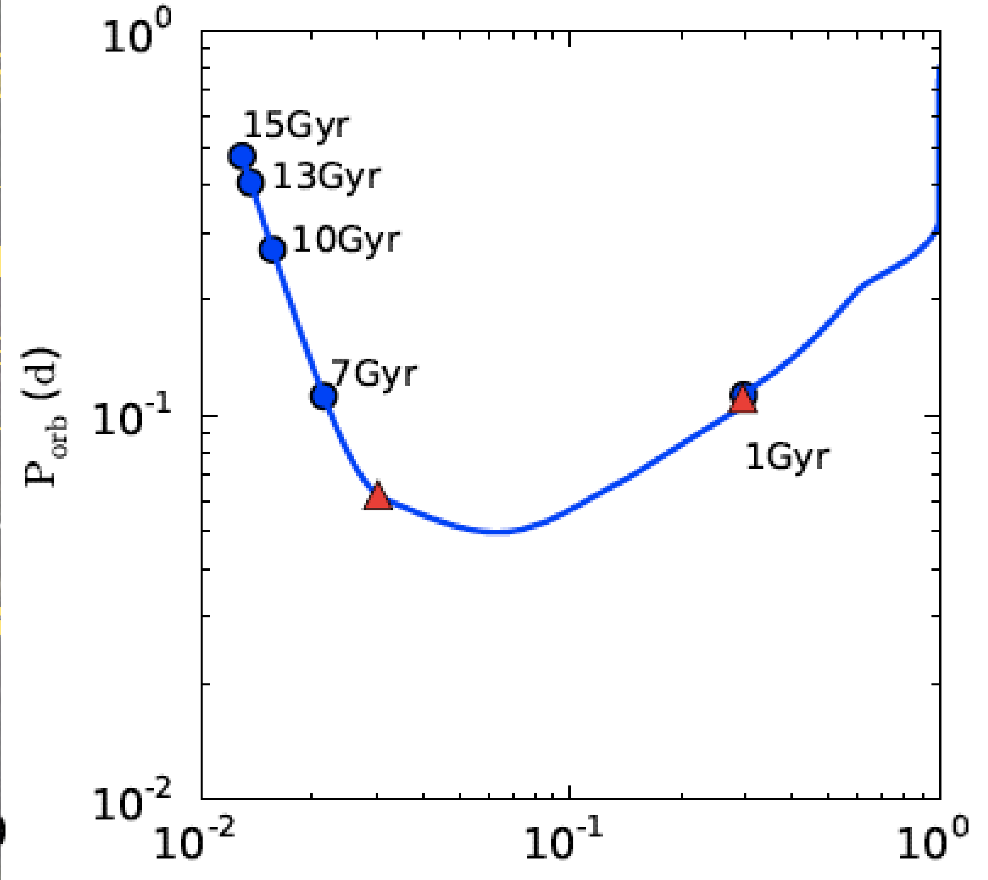
Hubble Ultra Deep Field HST ▪ ACS

Conclusions

* Ultra-compact "black widow" pulsar systems result from a bifurcation in parameter space, in this sense they follow a new evolutionary path.

* The role of winds+irradiati
would not produce anything
PSR J1311-3430 The full para
but we can state that PSR ma
very large because this is req
they are currently observed
Evolution supports high mas

β Important for the final
pulsar mass, but surely high



Chen, Chen, Tauris & Han 2013

NASA, ESA, S. Beckwith (STScI) and The HU