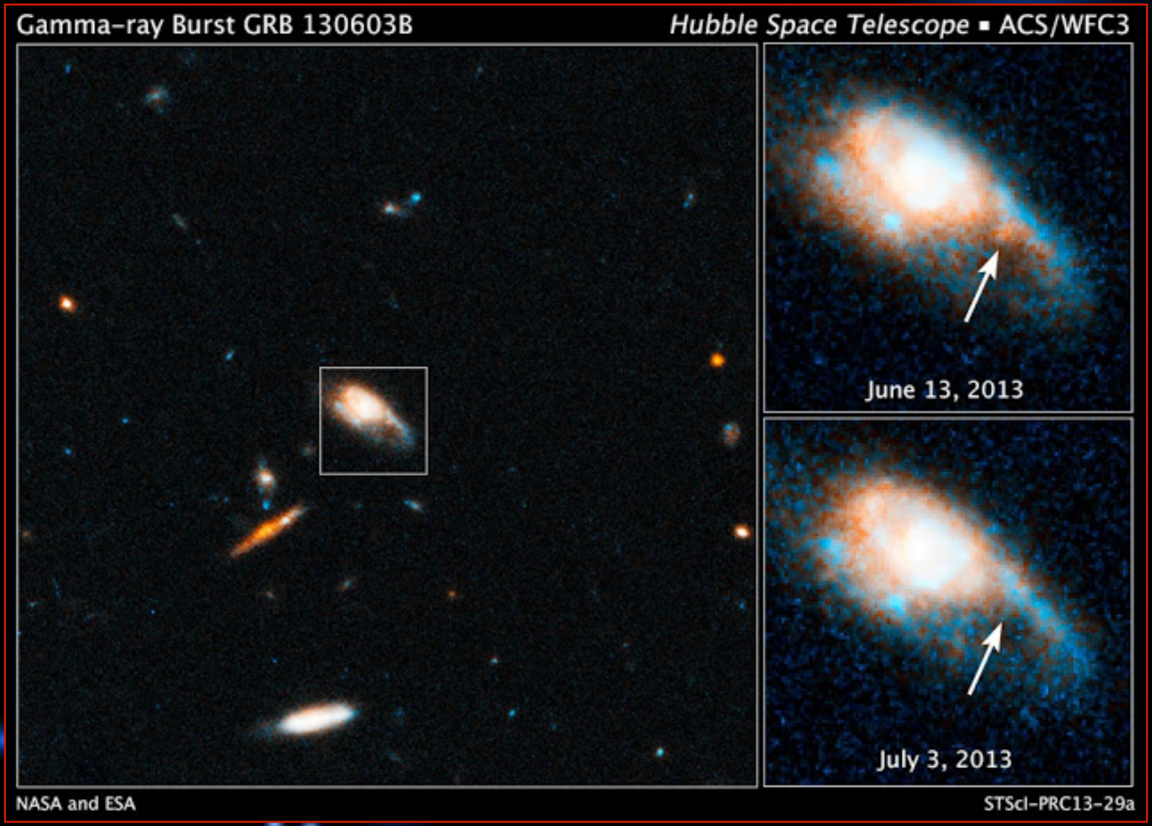
Nucleosynthesis and kilonovae from starnge star mergers

J.E. Horvath
Astronomy IAG-USP, Sao Paulo, Brazil

with L. Paulucci, O.G. Benvenuto , E. Bauer, A. Bernardo and T. Viturro

Perdón, Urânia !



Kilonovae

NIR excess after a Gamma-ray burst

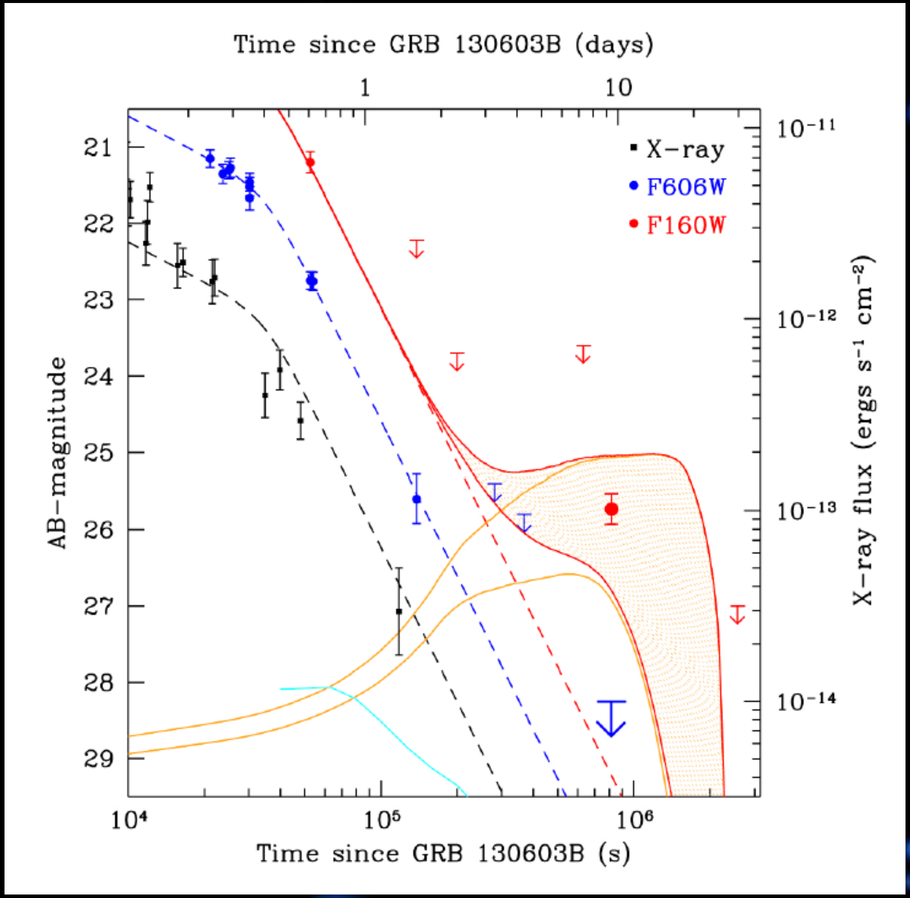
NASA Evidence Suggests Gold On Earth Caused by Colliding Neutron .Stars

NASA's Swift X-ray telescope satellite detected a high-energy flash of gamma rays, a "gamma ray burst" called GRB 130603B.

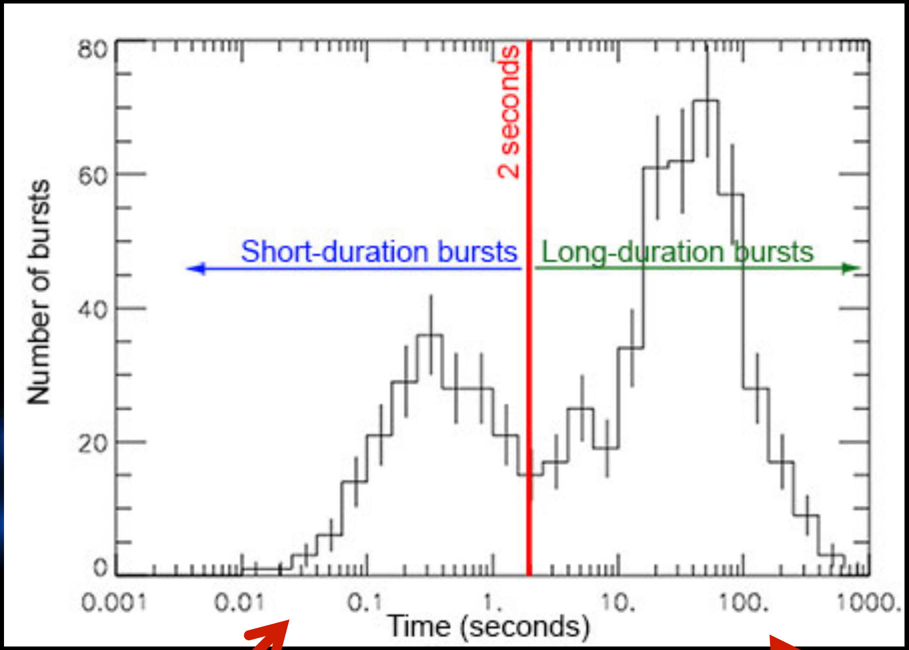
20 $M_{\oplus}$ of gold and 140 $M_{\oplus}$ platinum !!!

The case of GRB 130603B (Tanvir et al. 2013)

A NIR excess was observed with the HST ~9 days after the GRB
The interpretation is that nucleosynthsis produced lanthanides (high-opacity) and r-process elements injecting energy into the ejecta



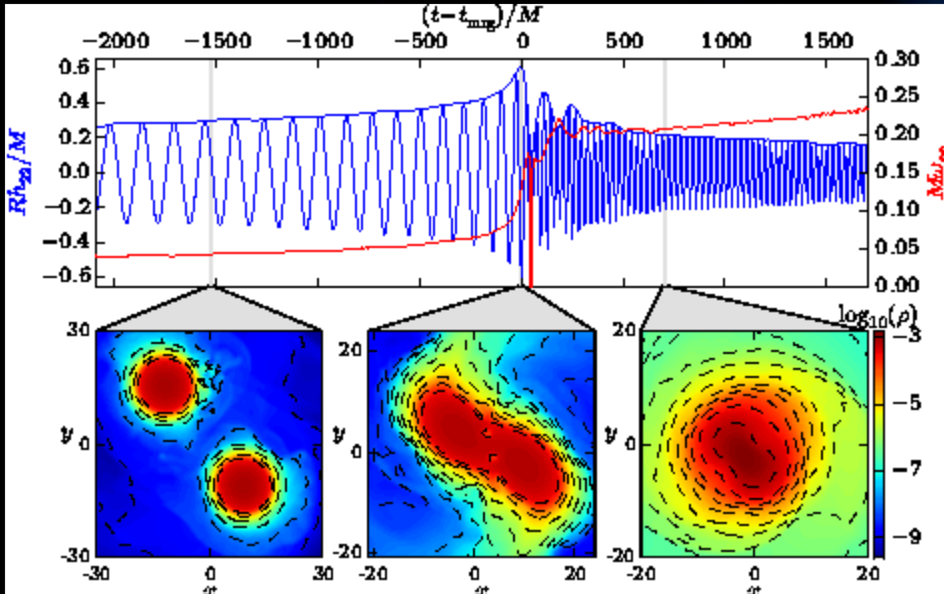
“short” and “long” GRBs

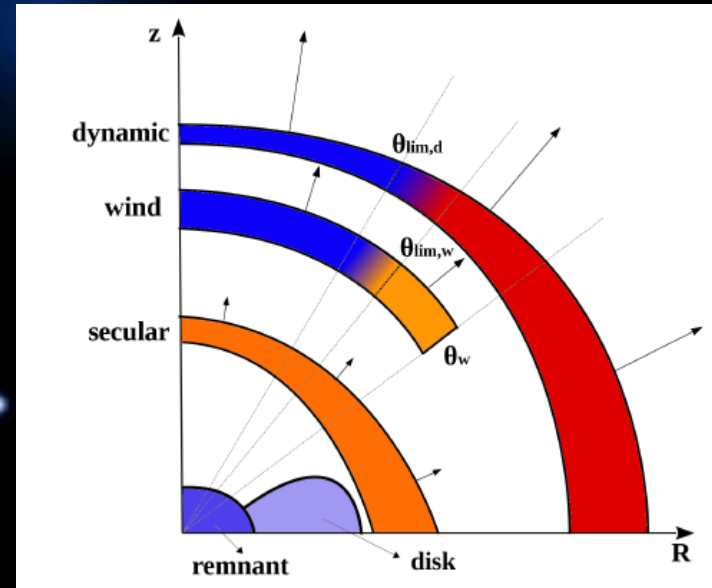


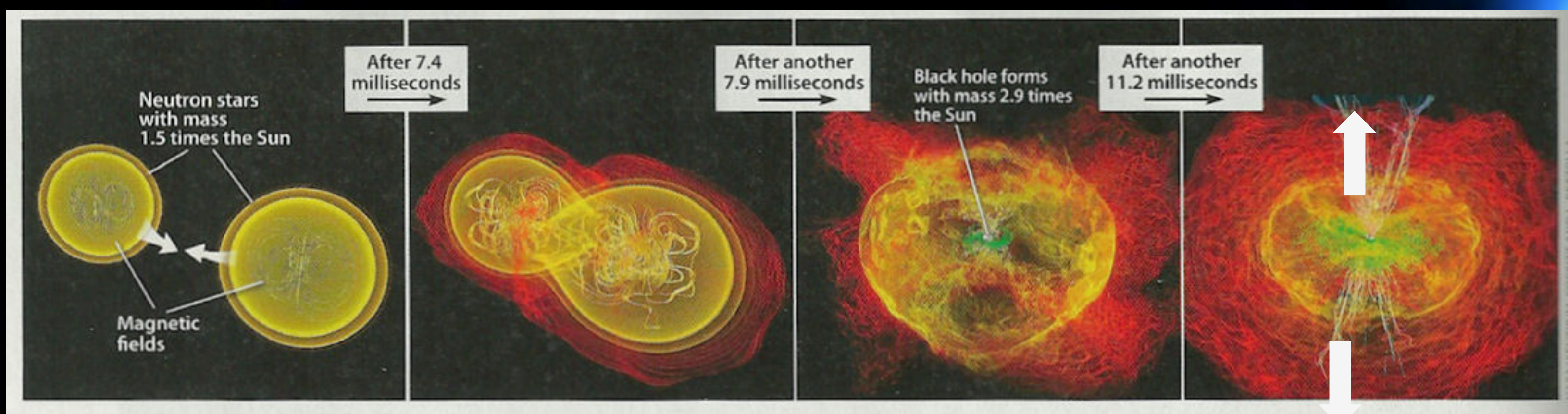
“NS” fusion(?)

Hipernovae (?)

Candidates to GW emission



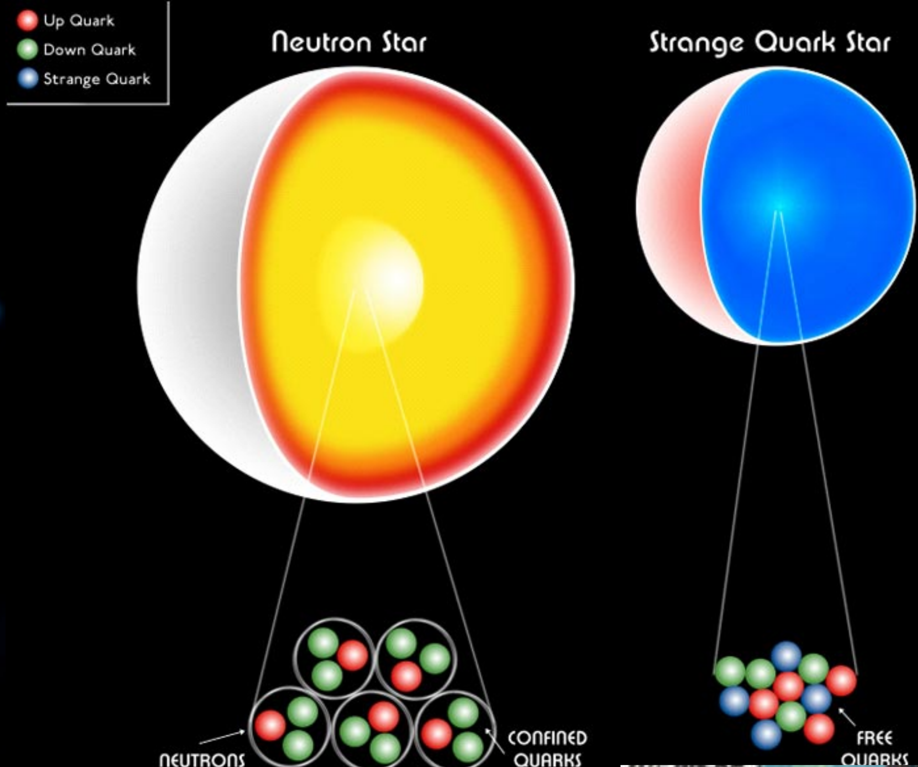




Scientists think that short-duration gamma-ray bursts (GRBs) result from two neutron stars (or a neutron star and a black hole) colliding and merging. Recent computer simulations of the former scenario show that the neutron stars' combined magnetic field can produce jetlike structures capable of powering a GRB.

Ejection in cones (high velocity) and transient accretion disc (lower velocity)

"dynamical" "delayed"



SQM stars have been studied for > 30 yr (Bodmer 1971, Terasawa 1979, Witten 1984…)

free vs. CFL SQM

pairing energy

$$\Omega_{CFL} = \Omega_{free} - \frac{3}{\pi^2}\Delta^2\mu^2 + B =$$

$$= \frac{6}{\pi^2}\int_0^{\nu}[p-\mu]p^2 dp + \frac{3}{\pi^2}\int_0^{\nu}[(p^2+m_s^2)^{1/2}-\mu]p^2 dp - \frac{3}{\pi^2}\Delta^2\mu^2 + B.$$

$$= \frac{-3\mu^4 + 3m_s^2\mu^2}{4\pi^2} - \frac{1-12log(m_s/2\mu)}{32\pi^2}m_s^4 - \frac{3}{\pi^2}\Delta^2\mu^2 + B.$$

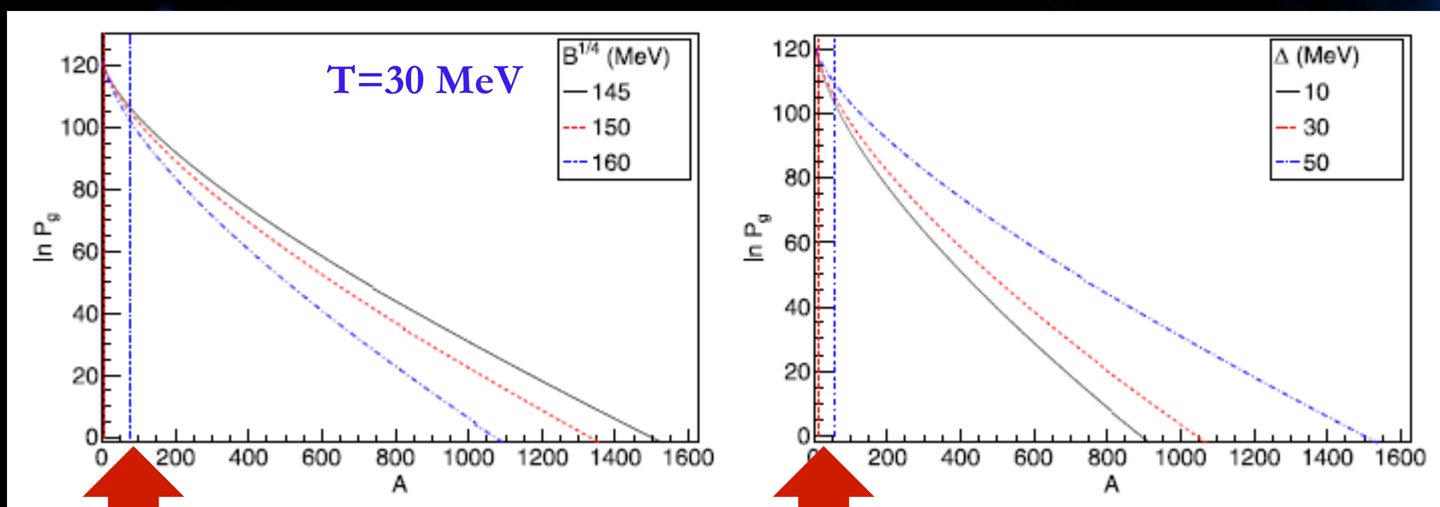
Statistical fragmentation of ejected SQM in "NS-NS" mergers

Why should *strange matter* fragment? Because it is a minimum of the E/A but not a minimum of free energy !

SQM evaporates into ordinary hadrons if temperature is high

The masss distribution of fragments is

$$\mathcal{P}_g(A) = \frac{\partial}{\partial \mu_A} p_g = \left(\frac{m_0 T}{2\pi}\right)^{3/2} A^{3/2} e^{[(\mu+W-bp_g)A-\sigma A^{2/3}-CA^{1/3}]/T}$$



A_{min} for stability for a given T

Almost all the ejected matter fragments into Λs, later decaying into n and p

(by the way, this explains why there are no strangelet events in the AMS-02 experiment…)

Ejecta consists ultimately in p and n, but their relative abundance n/p is strongly dependent of what happens before weak interactions freezout because of degeneracy vs. expansion…

Fragmentation of bulk SQM happens at T ~ 5-10 MeV and high density

Adiabatic expansion $TV^{\gamma-1} = constant$ hypothesis yields $T = T_0\left(\frac{1}{1+v/R_0 t}\right)$

$\gamma = 4/3$ monoatomic relativistic gas

If degeneracy is ignored, before the freezout temperature, the ratio n/p evolves as

$$n_n/n_p \sim \exp\left[-\frac{(m_n - m_p)c^2}{kT}\right]$$

where the n p mass difference is = 1.29 MeV

The freezout condition (fixing the relative abundances) is $\eta < \frac{\dot{R}}{R} = \frac{v}{R_0+vt}$

or, using the standard expressions $\eta \sim \left(\frac{kT}{1MeV}\right)^5 s^{-1}$

written as $kT_{freezeout} = \left(\frac{v}{R_0 kT_0}\right)^{1/4}$

After freezout, and up to T ~ 1MeV some neutrons decay

$$\frac{n_n}{n_p}|_{T=1MeV} \sim \frac{n_n}{n_p}|_{T_{freezeout}} \exp\left(-\frac{\Delta t}{\tau_n}\right)$$

But n/p does not change much because τ_n >> Δt

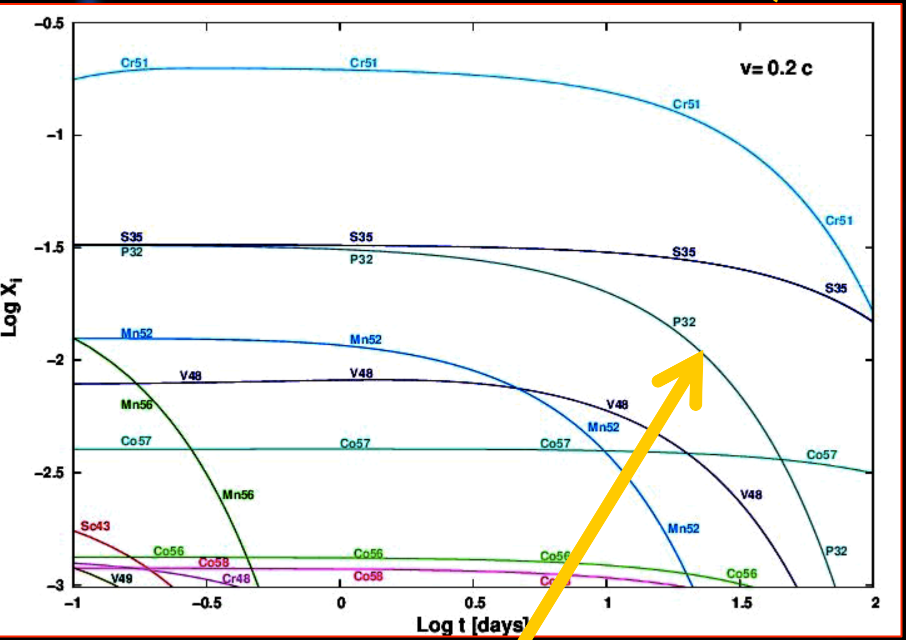
For different initial temperatures and expansion radii we found

v/c	T_i (MeV)	T_{fout} (MeV)	R_{fout} (km)	Δt (ms)	$(n_n/n_p)_{fout}$	$(n_n/n_p)_f$
0.1	5	4.2	24.0	2.53	0.73	0.73
0.1	10	3.5	57.1	4.76	0.69	0.69
0.3	5	*	20.0	0.89	0.77	0.77
0.3	10	4.6	43.4	1.74	0.76	0.76

Huge fractions (Big Bang values are n/p ~ 0.15). Matter keeps memory of its SQM origin…

The nucleosynthesis yield

Calculated with TORCH (3000 isotopes) by F. Timmes



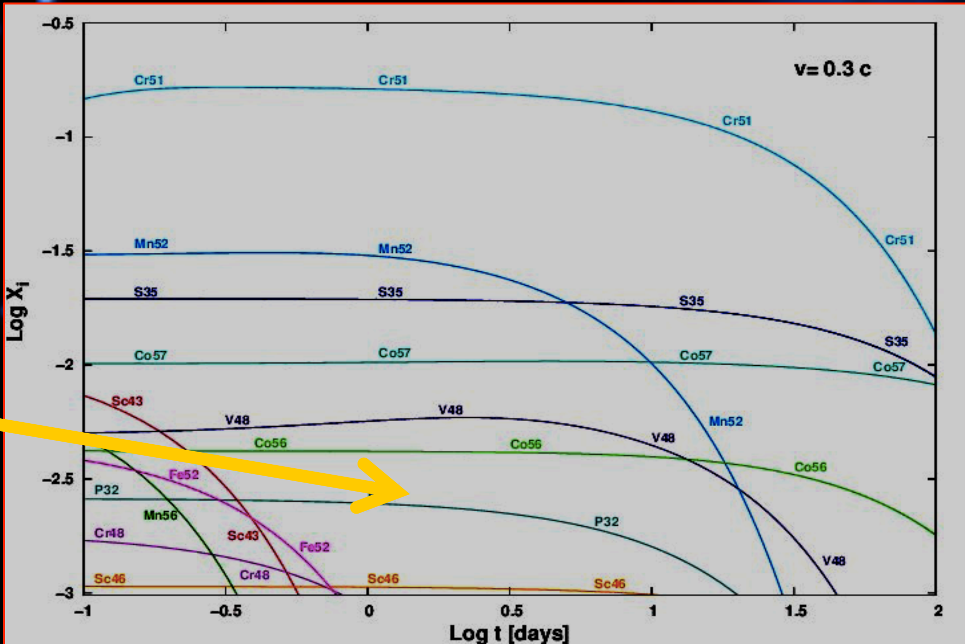
As expected, it is dominated by Fe peak elements (Fowler 1957)

No lanthanides formed !!!!

However…

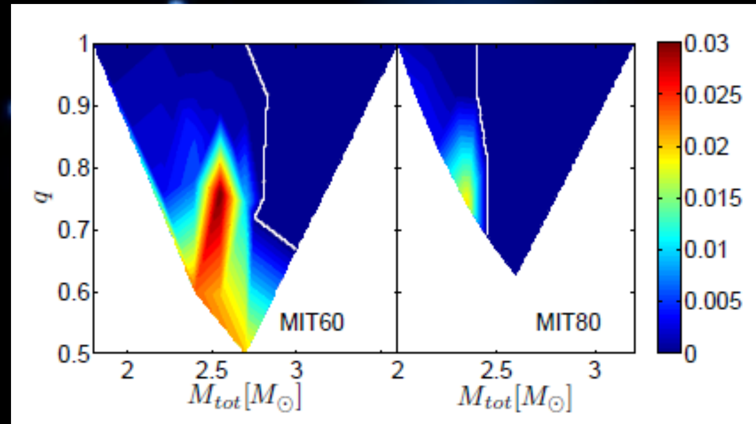
^{32}P

Decays in 14.3 days injecting 1.7 MeV positrons into the opaque ejecta (similar to SNIa with Ni->Co -> Fe)



Light curves

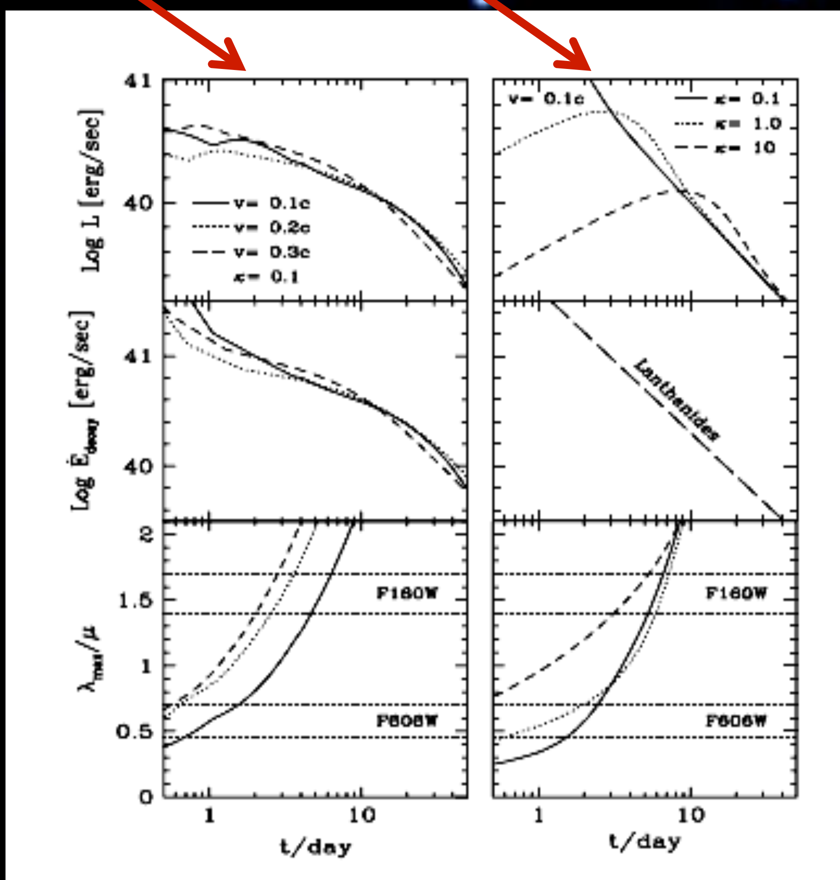
10^{-2} $M_\odot$ ejected

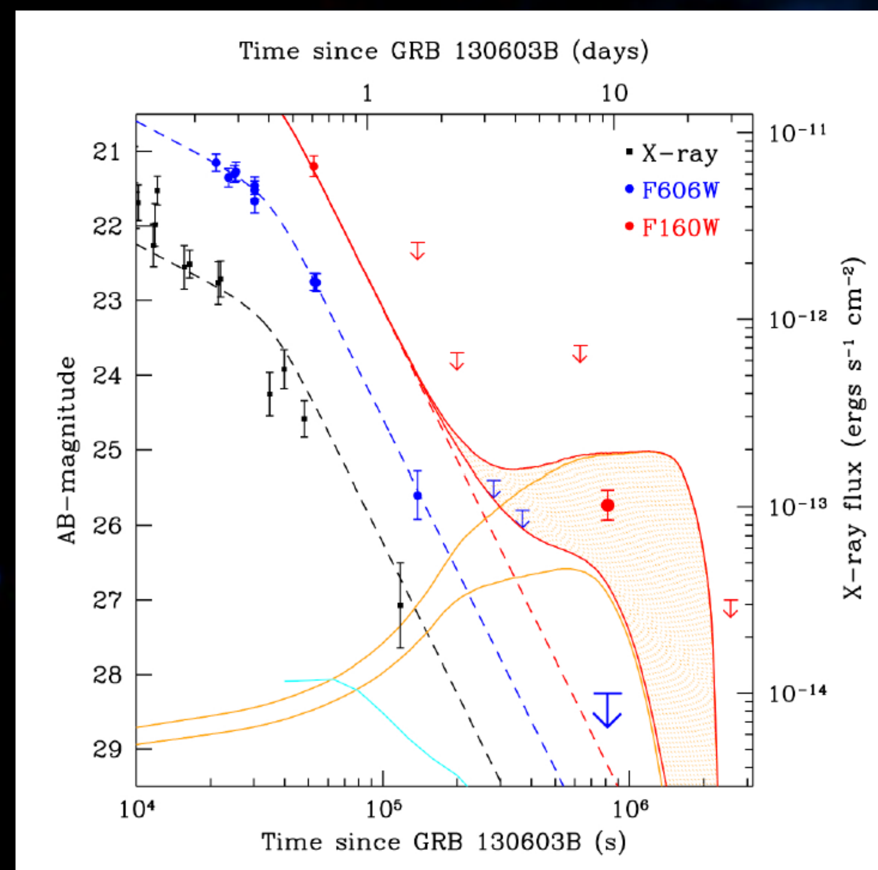


Mergers of SS, Bauswein et al. 2009)

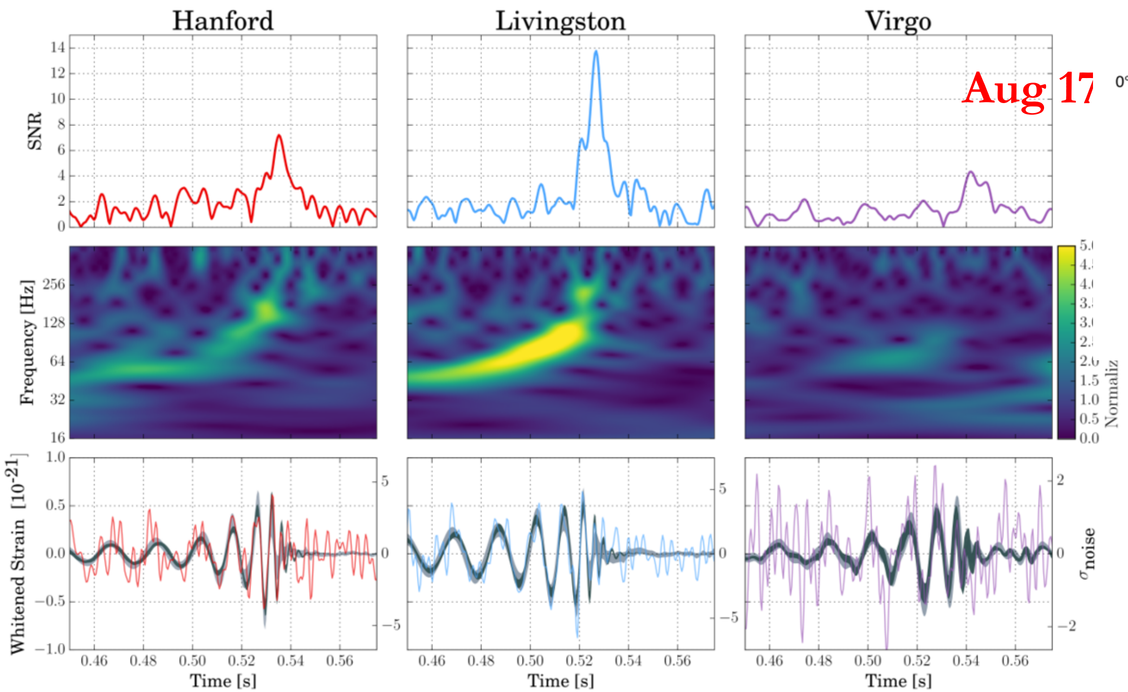
Our calculations

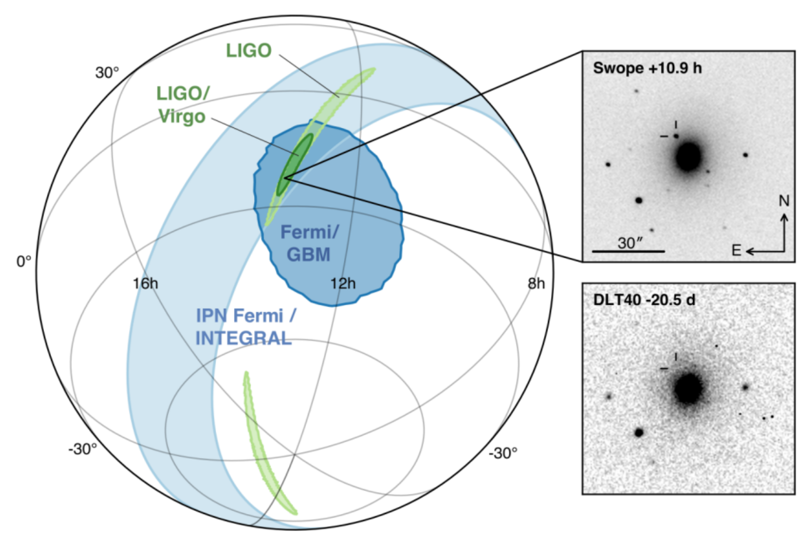
“standard NS”

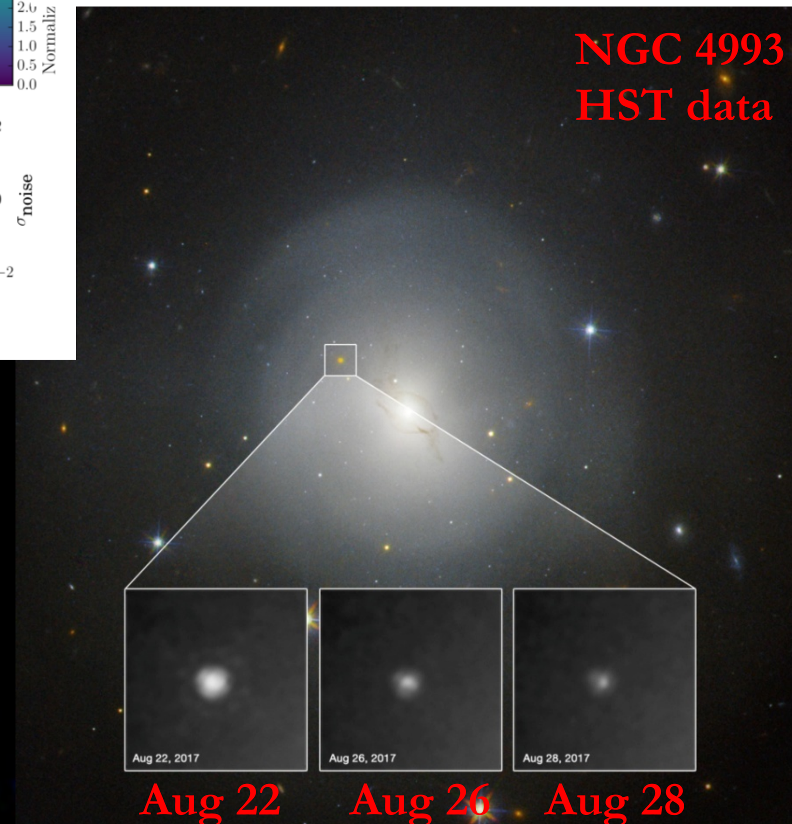




GW 170817 @ 12:41:04.4 UTC





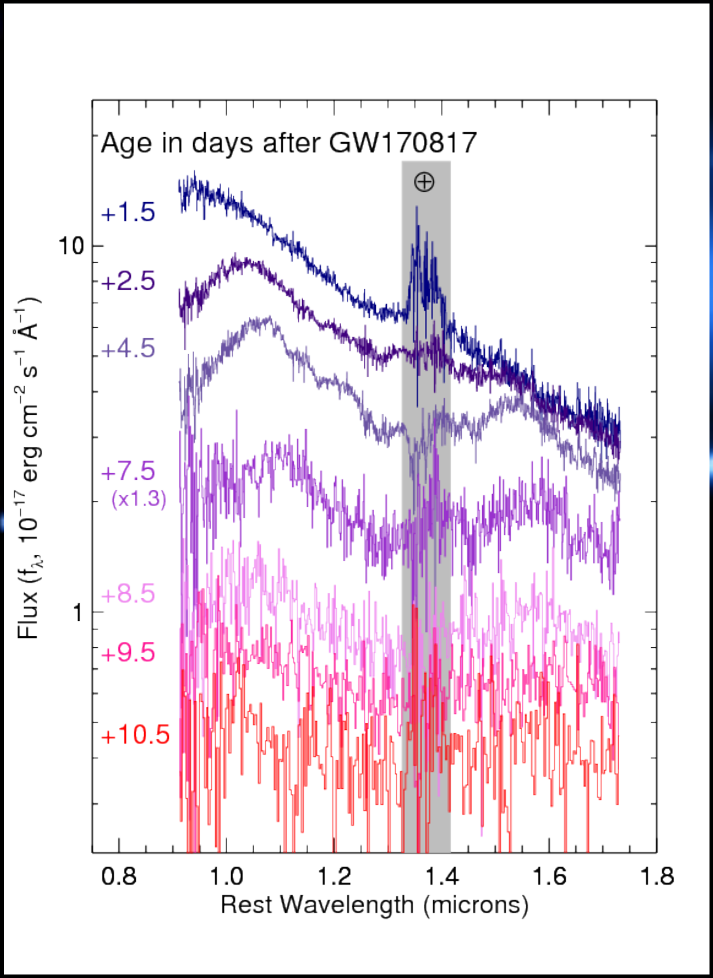


V_{dyn} ~ 0.3 c inferred

10^{-3} Mo ejected

The spectral and lightcurve evidences

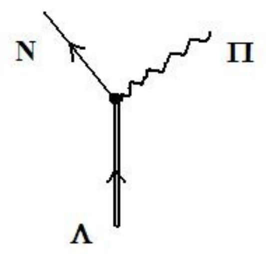
Peaks in the IR spectra associated to lanthanides



Two groups of r-process elements A< 140 and A> 140 give a "best fit" for the lightcurve, tentatively associated with the "dynamical" and "delayed" ejecta

Is all this compatible with a SS-SS merger?

Sources of p,n in the ejecta

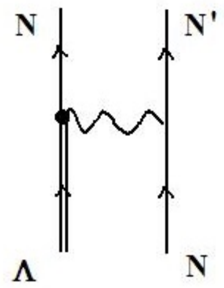


$\Lambda \longrightarrow p\,\pi^-$ 2/3

$\Lambda \longrightarrow n\,\pi^0$ 1/3

Measured vacuum values

In medium



$\Lambda \longrightarrow$ "N N"

Also the weak reactions

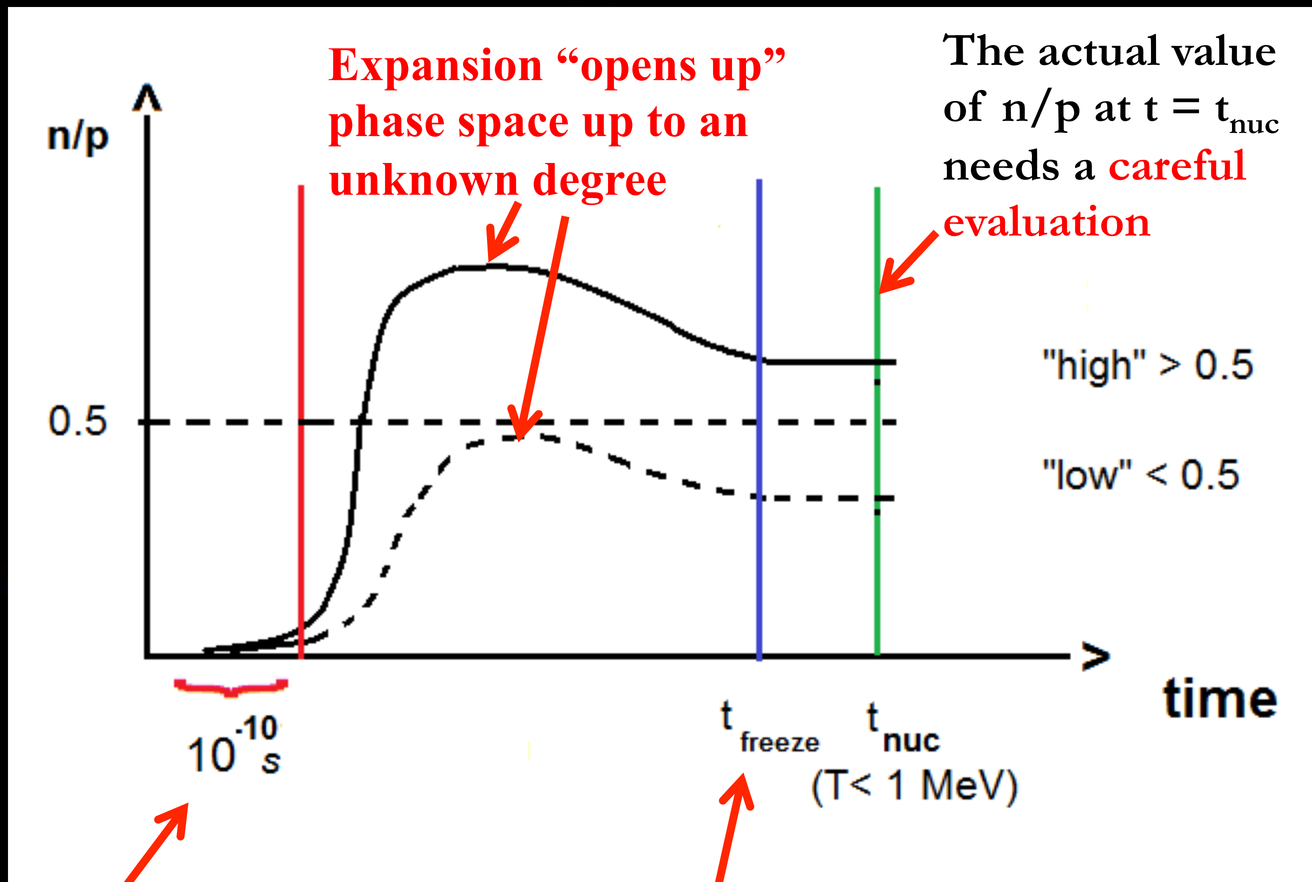
$$n + e^+ \Leftrightarrow \bar{\nu}_e + p$$

$$p + e^- \Leftrightarrow n + \nu_e$$

Beware: because of the high density blocking factors may preclude an equilibrium rate

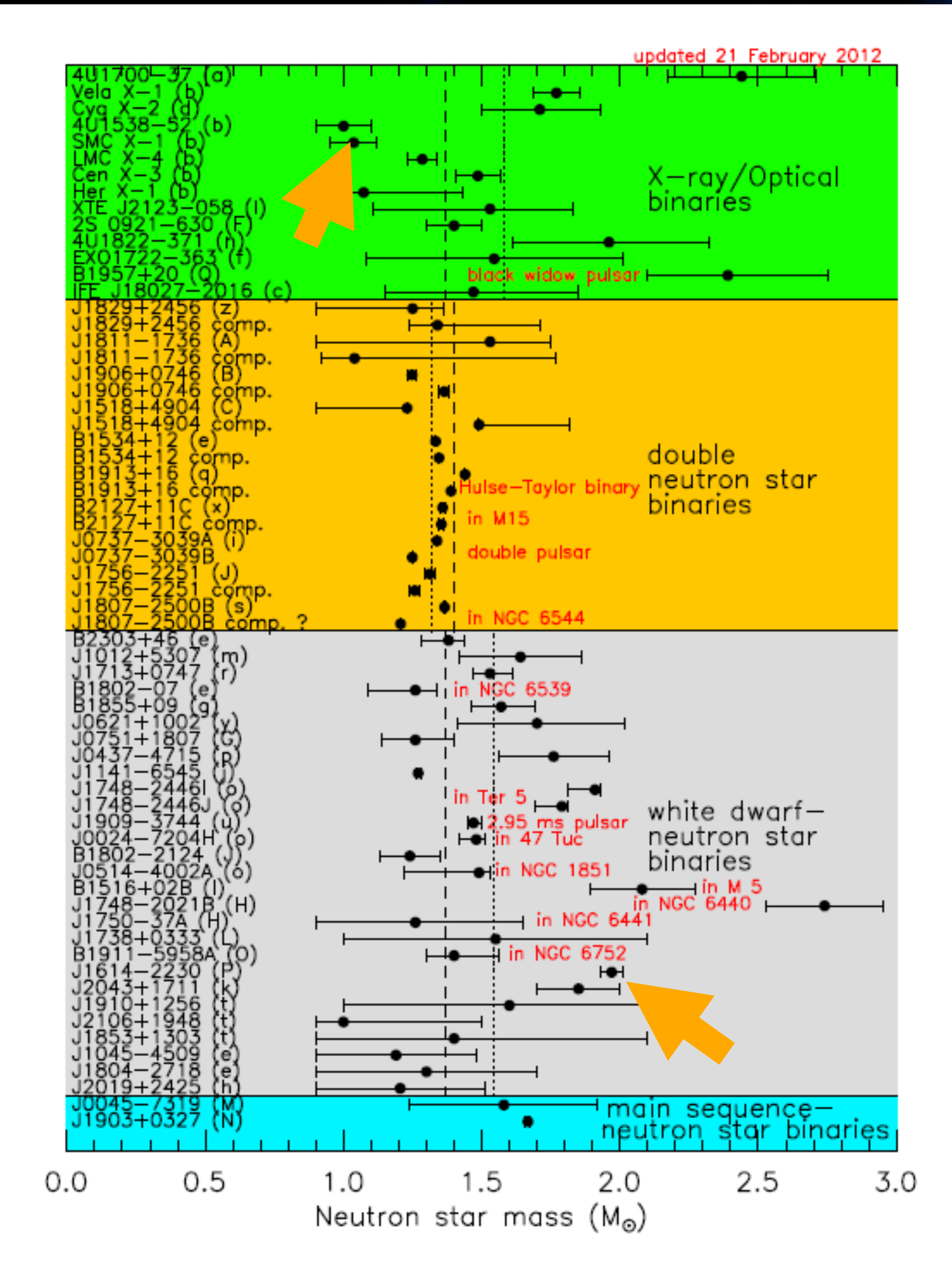
Modify the n/p ratio

Detailed evolution of the n/p ratio (in progress)



Initially there are no p or n. Lambdas decay quickly , but $\rho \sim 3\rho_0$ $T \sim few\ MeV$

Freezeout happens when weak decays = expansion



Which kind of binary M_1, M_2?

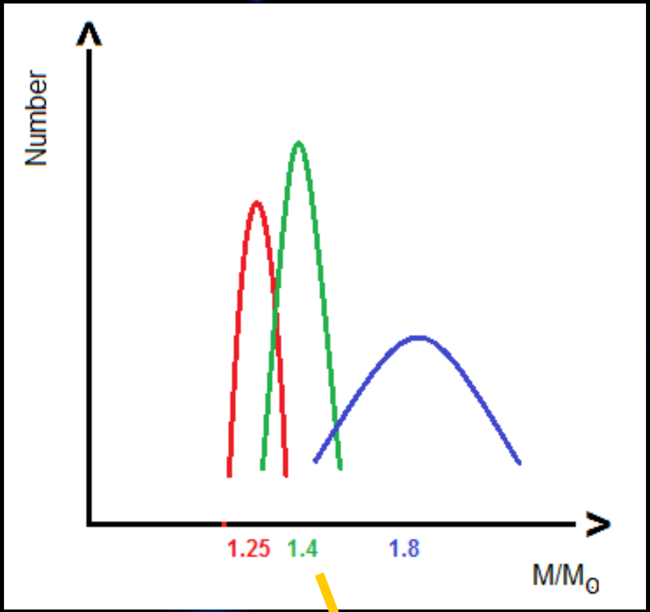
NS mass range is much wider than it used to be

Lattimer et al 2015, available at

http://www.stellarcollapse.org/nsmasses

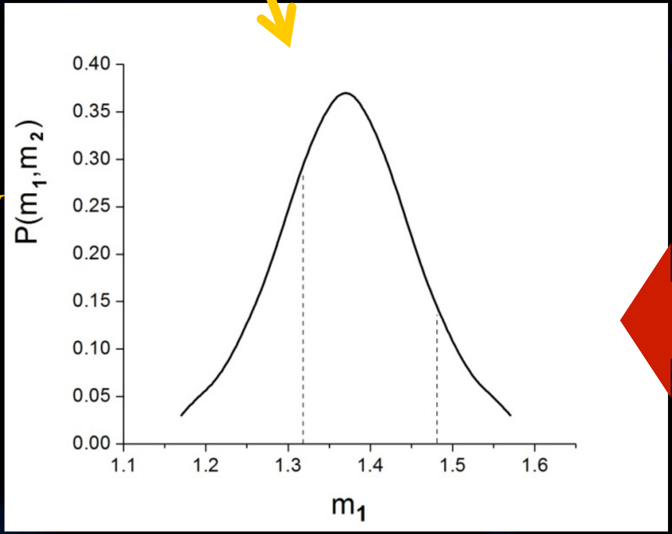
(see also Valentim & Horvath, Handbook of Supernovae (in the press) astro-ph/1607.06981)

Calculations of the asymmetry of the binary in GW170817



The observed mass distribution shows three peaks with different widths

P(m_1 , m_2) subject to the observed constraints $m_1 + m_2 = 2.74 \pm^{0.04}_{0.01} M_\odot$ and $[1.17, 1.60]\, M_\odot$ is constructed using Bayesian methods



The asymmetry probability is > 35%

PSR J0453+1559 : an asymmetric double neutron star (Martinez et al. 2016) measured with the Shapiro delay

$M_p = 1.559 \pm 0.005\, M_\odot$

$M_c = 1.174 \pm 0.004\, M_\odot$

Conclusions

- "Kilonovae" follow a (short) GRB, now proved to be associated to mergers of "neutron" stars
- In "normal" (NS) models, there is a synthesis of lanthanides which yield enough opacity (~100 g^{-1} cm^2) to make the light curve bump ~days after the GRB
- In SS models, the ejected matter decays into Λ → neutrons and protons com n/p ~0.7, producing a "Dense Big Bang" in which nucleosynthesis reaches iron peak elements if equilibrium sets in. There are no lanthanides nor ("gold") (r-process third peak),, but the light curves are powered by ^{32}P

This is why direct evidence of lanthanides and/or r-process elements is crucial !!!