

There may be no “gold” coming out from compact star mergers

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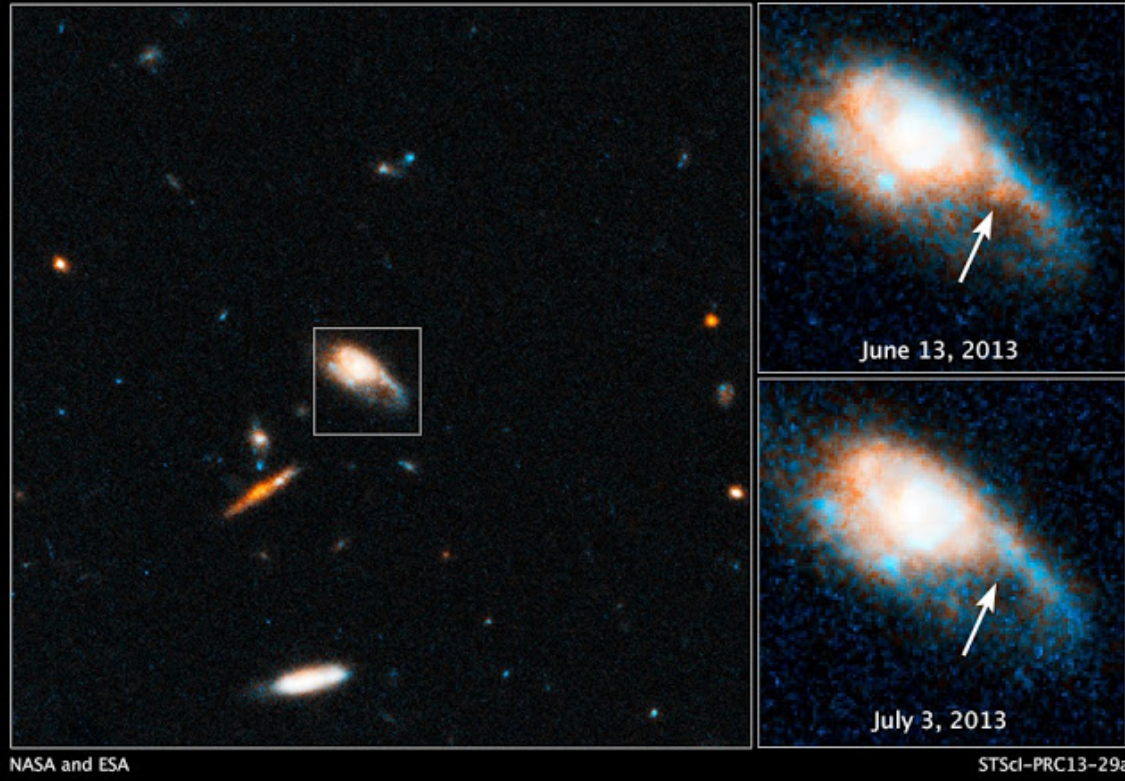
with L. Paulucci, O.G. Benvenuto and T. Viturro



Perdão, Urânia !

Gamma-ray Burst GRB 130603B

Hubble Space Telescope ■ ACS/WFC3



NASA and ESA

STScI-PRC13-29a

Kilonovae

Excess in the NIR after a gamma-ray burst

NASA Evidence Suggests Gold On Earth Caused by Colliding Neutron Stars

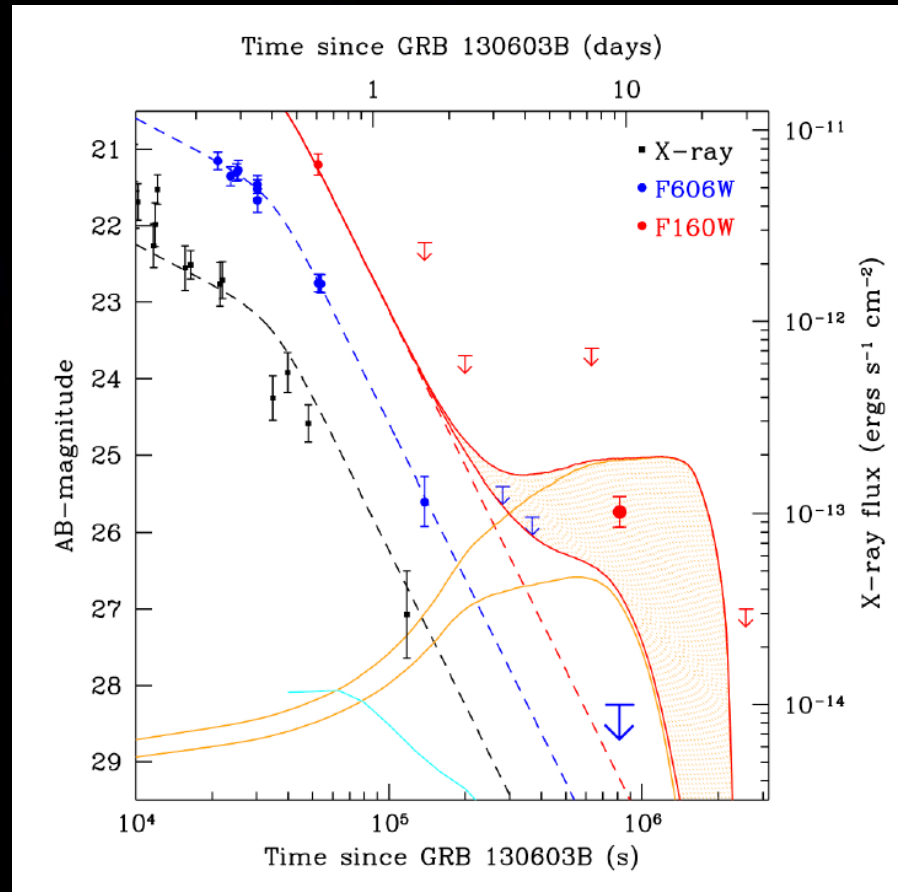
NASA's Swift X-ray telescope satellite detected a high-energy flash of gamma rays, a “gamma ray burst” called GRB 130603B.



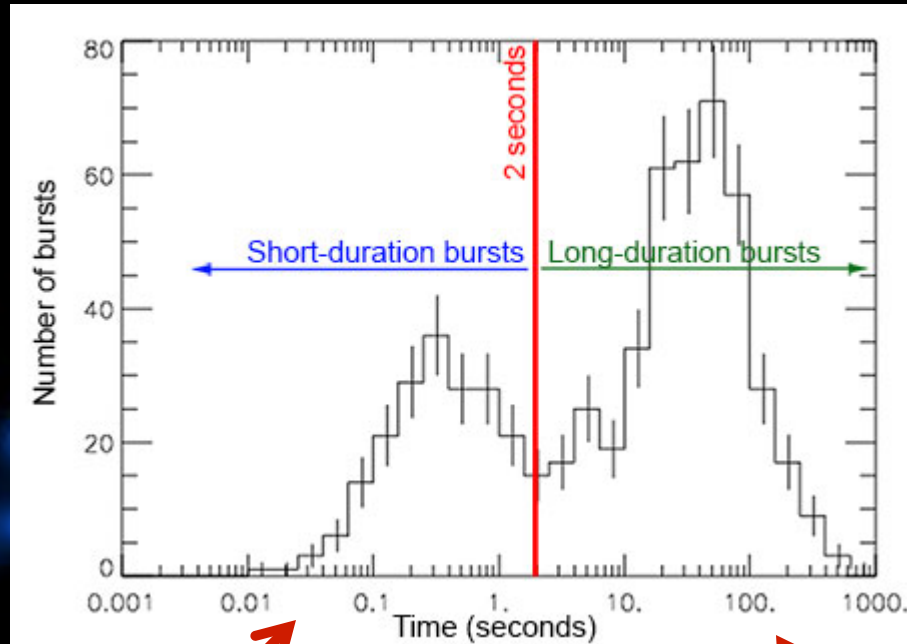
$20 M_{\oplus}$ of gold and $140 M_{\oplus}$ de platinum formed !!!

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

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



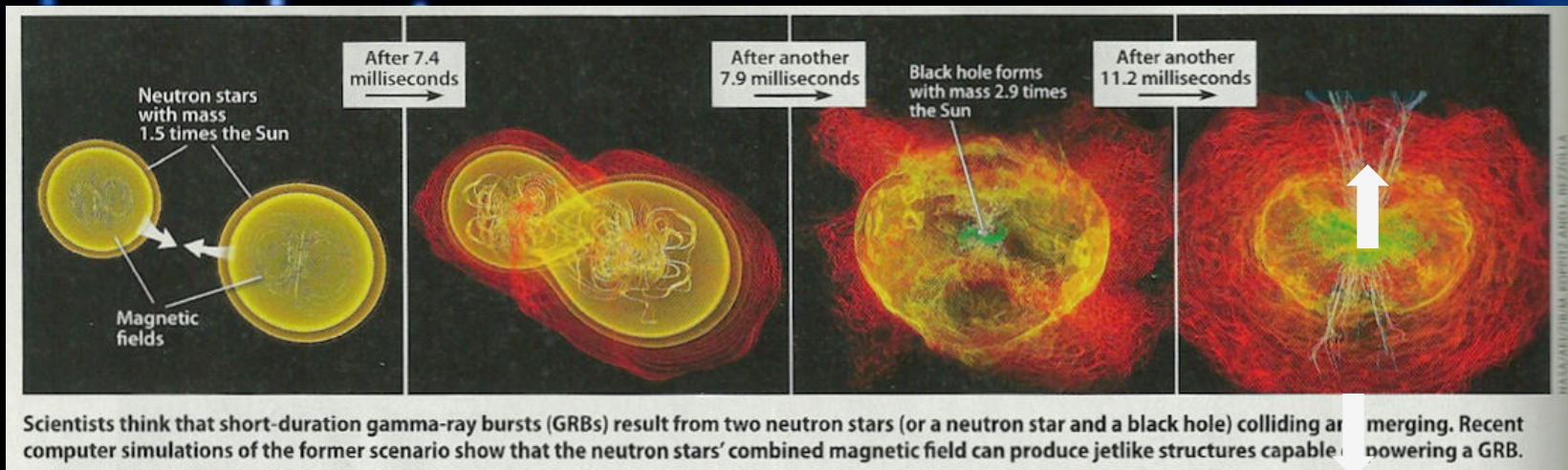
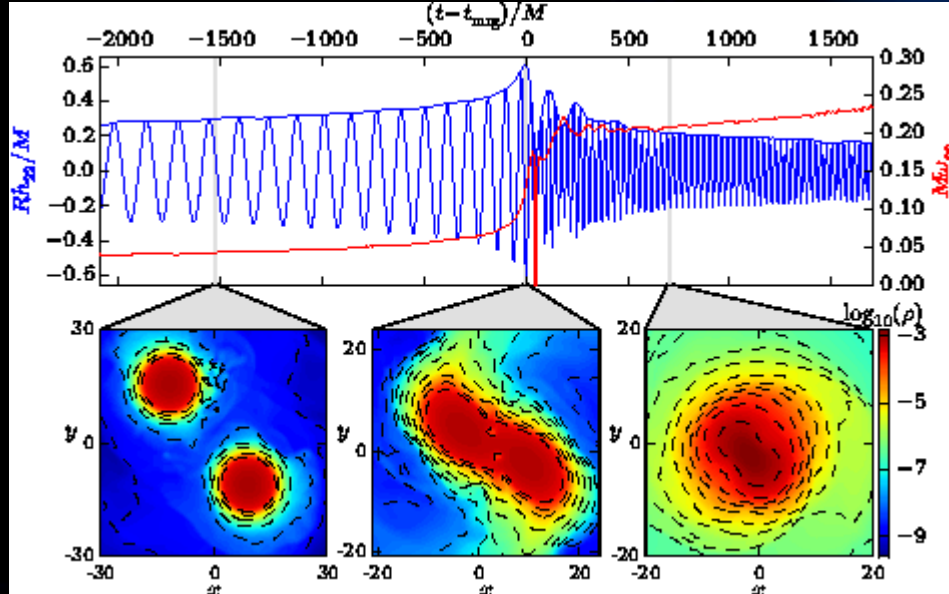
“Short” and “long” GRB



Merging of “NS” (?)

Hypernovae (?)

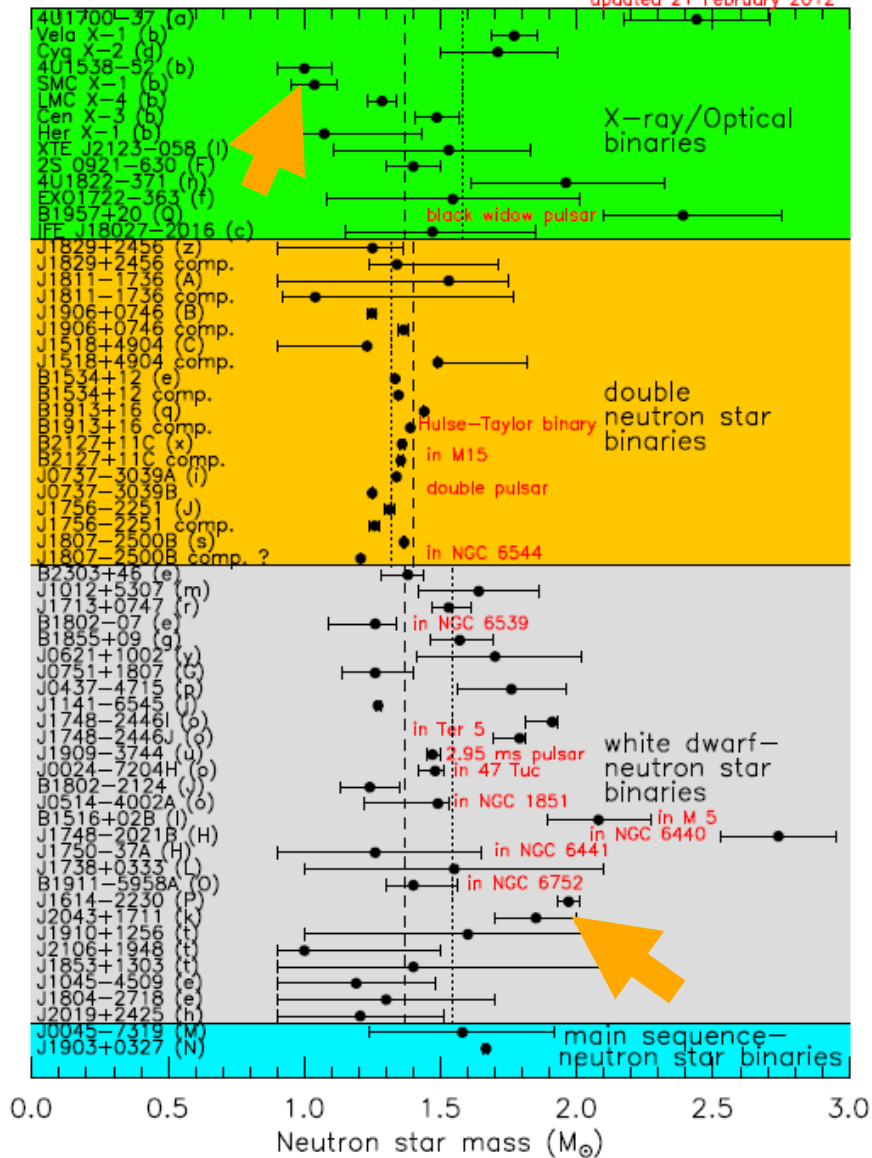
Candidates to GW
emission



Ejection in jet-like (high velocity) and transient accretion disc (low velocity). We shall refer to the first (prompt ejecta) only in the rest of the talk

(Ke Fang, yesterday's talk)

updated 21 February 2012



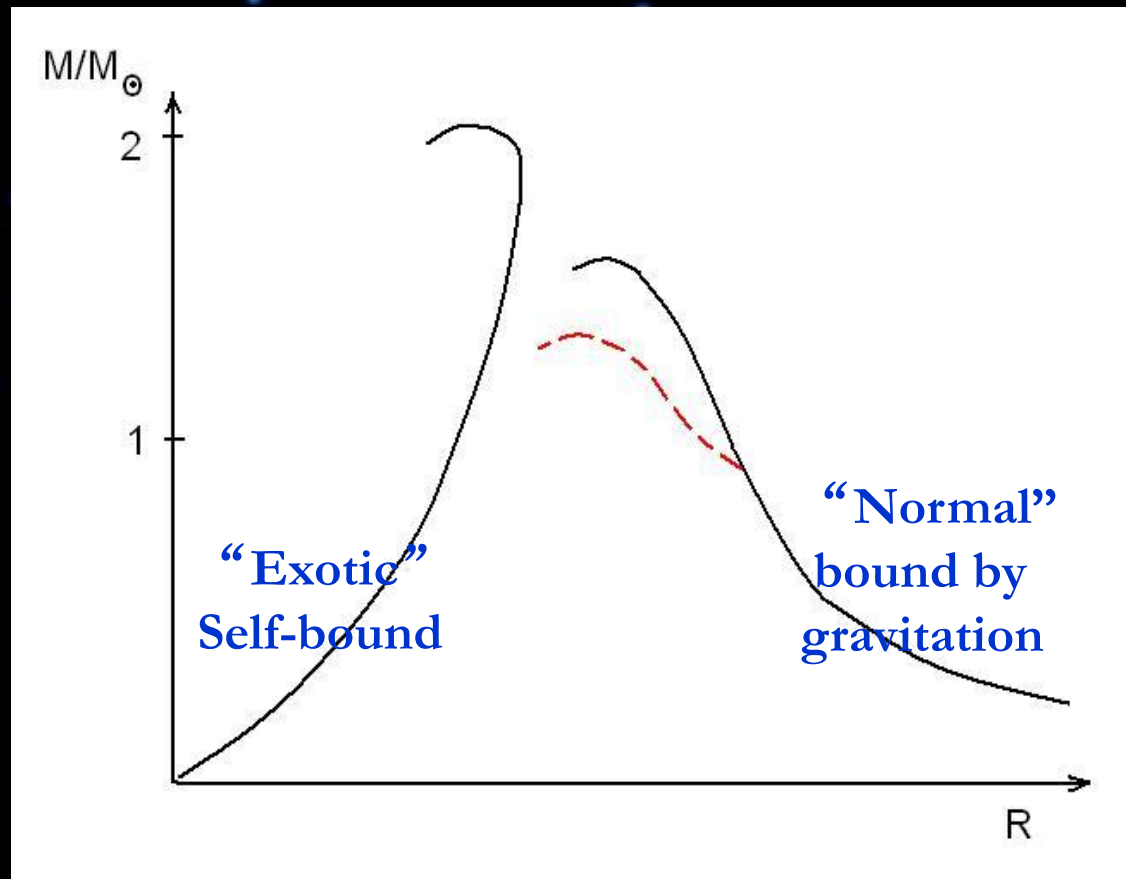
A single $1.4 M_{\odot}$ mass scale was discussed over the years. However a much wider range of masses is now known to be present

Lattimer et al 2015, available at

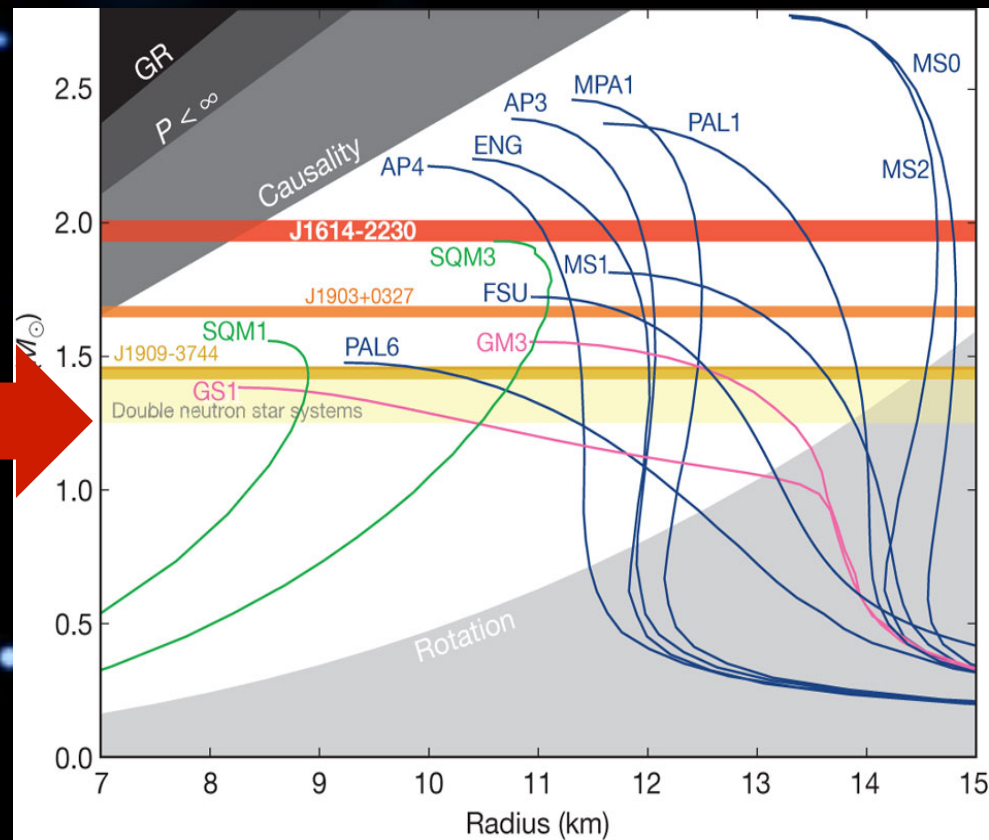
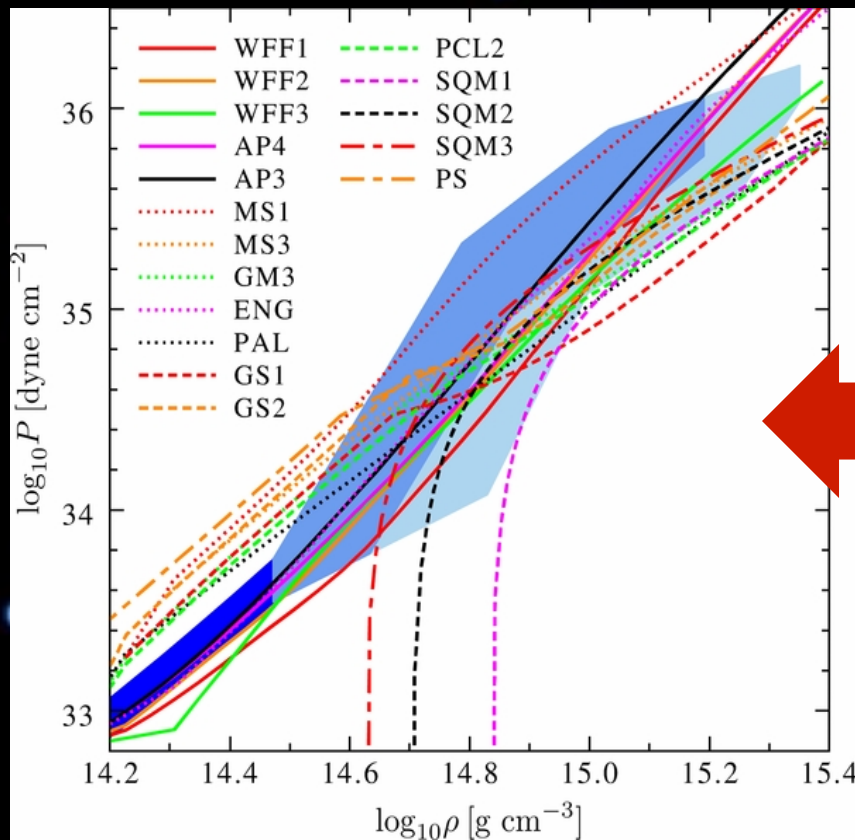
<http://www.stellarcollapse.org/nsmasses>

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

What are compact stars made of?



The EoS of dense matter can be considered as known up to $\sim 2\rho_0$, but...



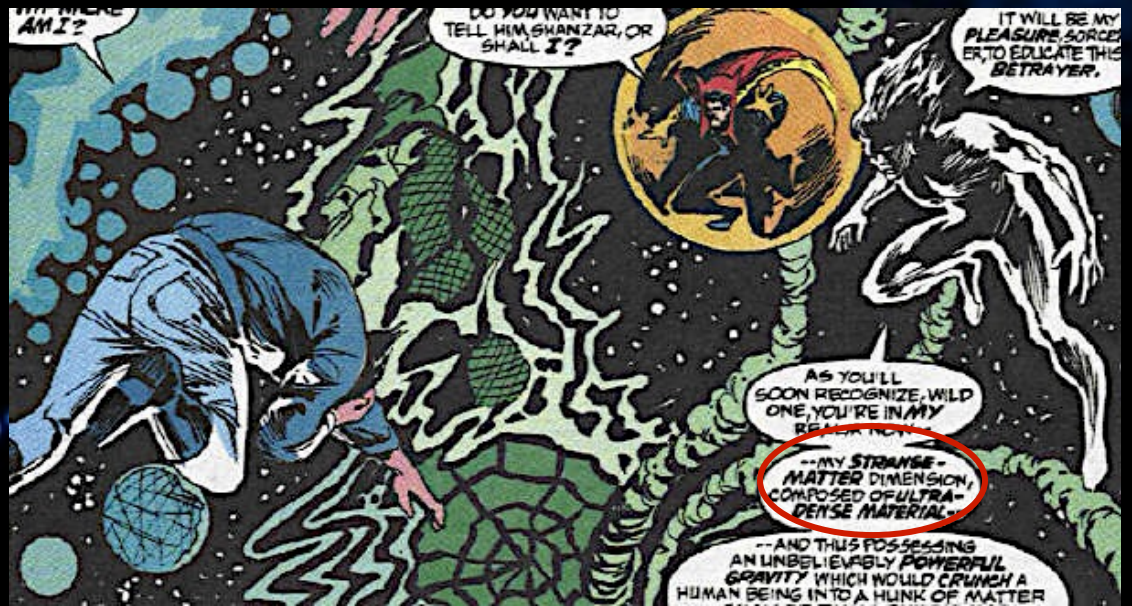
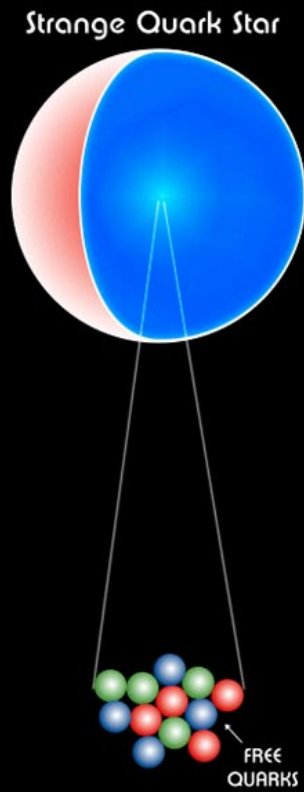
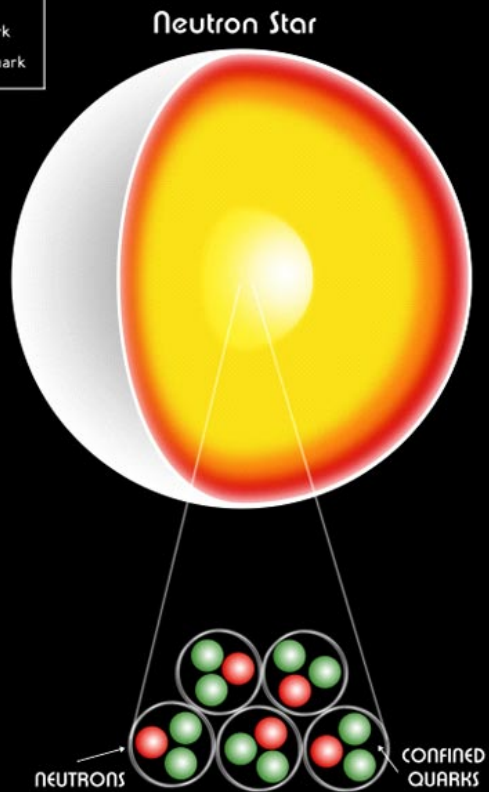
Interactions (including 3-body forces)

Medium effects (more interactions, effective masses...)

Degrees of freedom (i.e. hyperons, quarks, etc)

...

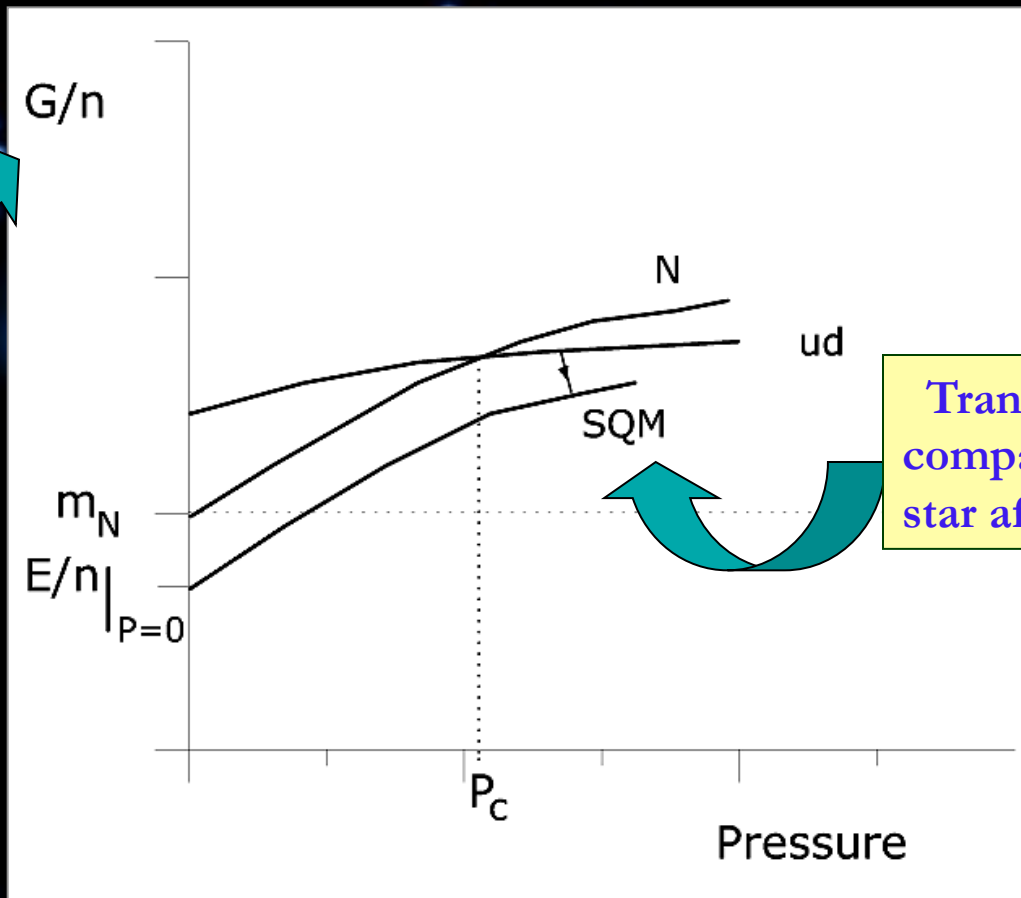
- Up Quark
- Down Quark
- Strange Quark



Strange matter: hypothetical QCD ground state
(Bodmer 1971, Terazawa 1979, Witten 1984) :

$E/A < 939 \text{ MeV}$ even at $P=0$!!!

Gibbs free
energy
per particle



Transition during the
compactification of the
star after $\sim$ seconds

Strange matter at high densities: free gas vs. CFL

Pairing energy (negative)



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

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

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

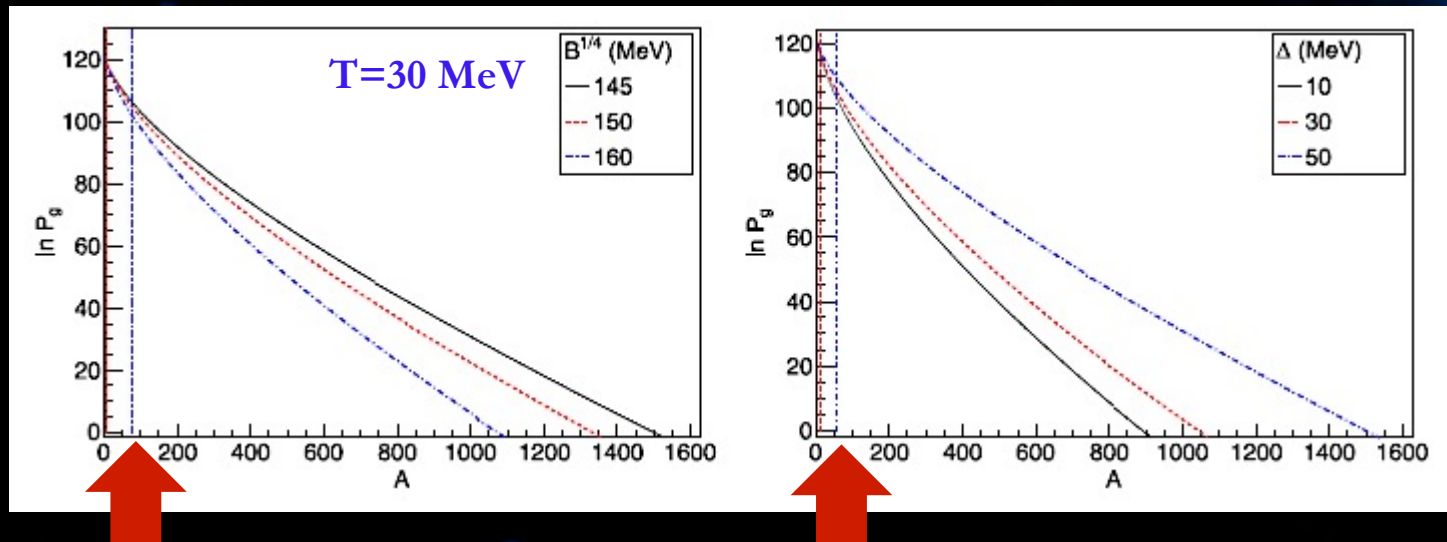
Statistical fragmentation of SQM in SS-SS collisions

Why *strange matter* should fragment? Because it is a minimum of the energy per baryon, but not a minimum of the free energy ! (the $-TS$ term..)

Strange matter evaporates and eventually fragments into em hadrons if the temperature is high

The mass distribution of fragments is

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



There is a minimum baryon number $A_{\min}$ to achieve stability for each given T (Paulucci & Horvath, PLB 733, 164 (2014))

Since the peak of the fragmentation is always below $A_{\min}$, almost all the ejected matter fragments into n and p (and some clusters)

(by the way, this explains why there are no strangelet candidate events in AMS-02 and other experiments...)

Thus, the ejection consists of protons and neutrons, but their abundances are determined by the freezout of weak interactions (that is, freezes when the weak decay rate falls below the expansion rate...)

SQM fragmentation into n,p happens at a temperature of 5-10 MeV

Adiabatic expansion $TV^{\gamma-1} = \text{constant}$ yields

$$T = T_0 \left(\frac{1}{1 + v/R_0 t} \right)$$

$\gamma = 4/3$ for a monoatomic relativistic gas

Above the *freezeout* temperature the n,p abundances are just

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

with the mass difference = 1.29 MeV

The *freezeout* condition (fixing the relative abundances) is

$$\eta < \frac{\dot{R}}{R} = \frac{v}{R_0 + vt}$$

which using the adiabatic temperature evolution and imposing that weak

interactions satisfy $\eta \sim \left(\frac{kT}{1\text{MeV}} \right)^5 s^{-1}$ can be cast as

$$kT_{\text{freezeout}} = \left(\frac{v}{R_0 k T_0} \right)^{1/4}$$

After freezout, and up to $T \sim 1\text{MeV}$ some neutrons decay

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

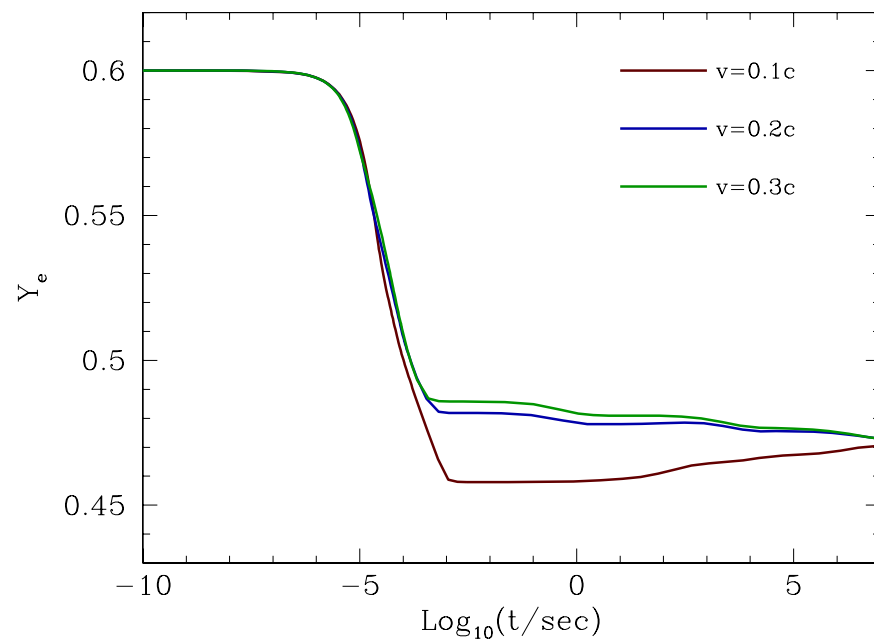
but this does not modify the n/p too much because $\tau_n \gg \Delta t$

For different initial temperatures and initial expansion radii we obtain

v/c	T_i (MeV)	$T_{f\text{out}}$ (MeV)	$R_{f\text{out}}$ (km)	Δt (ms)	$(n_n/n_p)_{f\text{out}}$	$(n_n/n_p)_f$
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

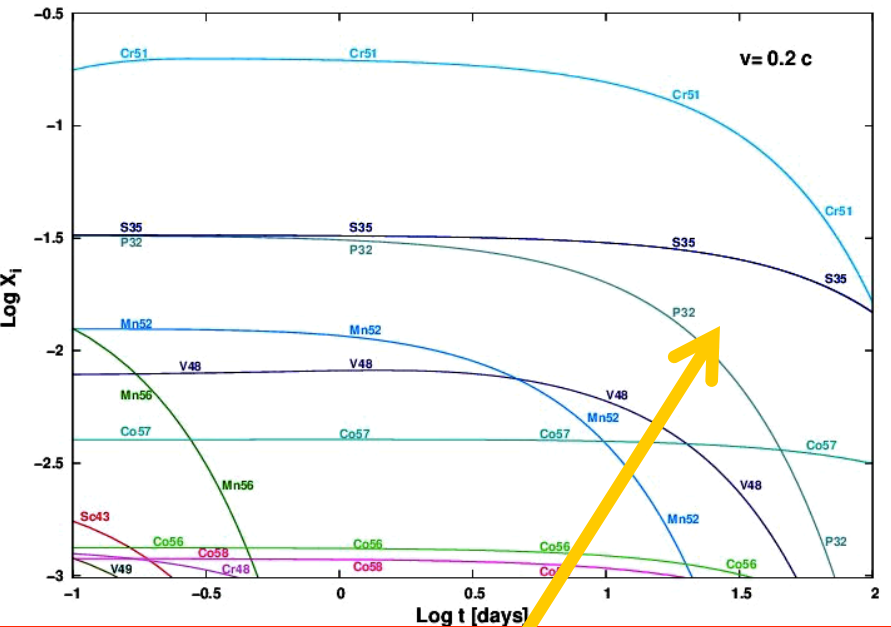


Huge fractions, in the Big Bang $n/p \sim 0.15$. Expanding matter keeps track of the SQM composition through them



The nucleosynthesis

Calculated with the TORCH code(3000 isotopes) by F. Tim

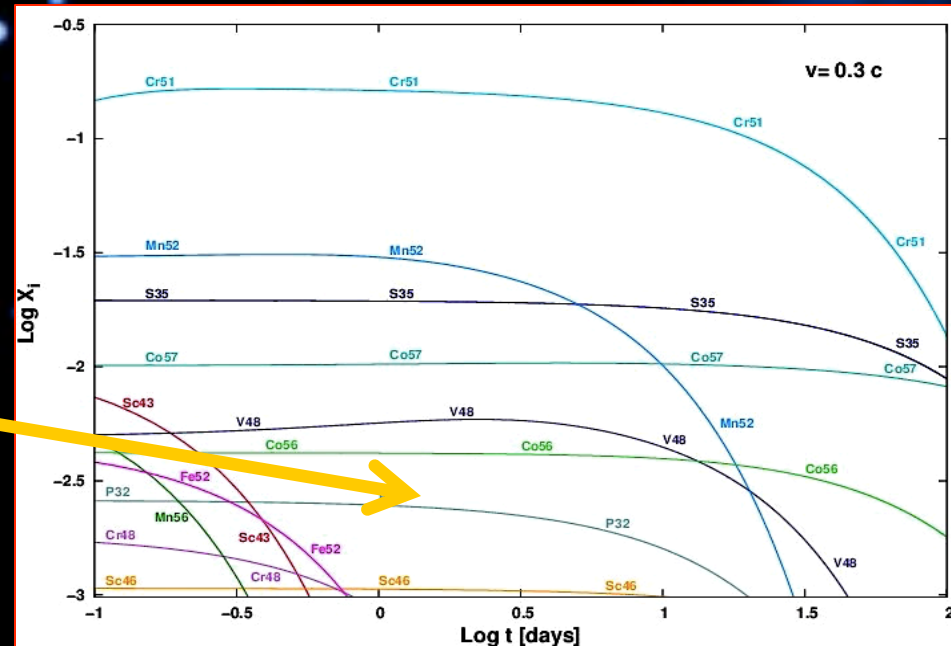


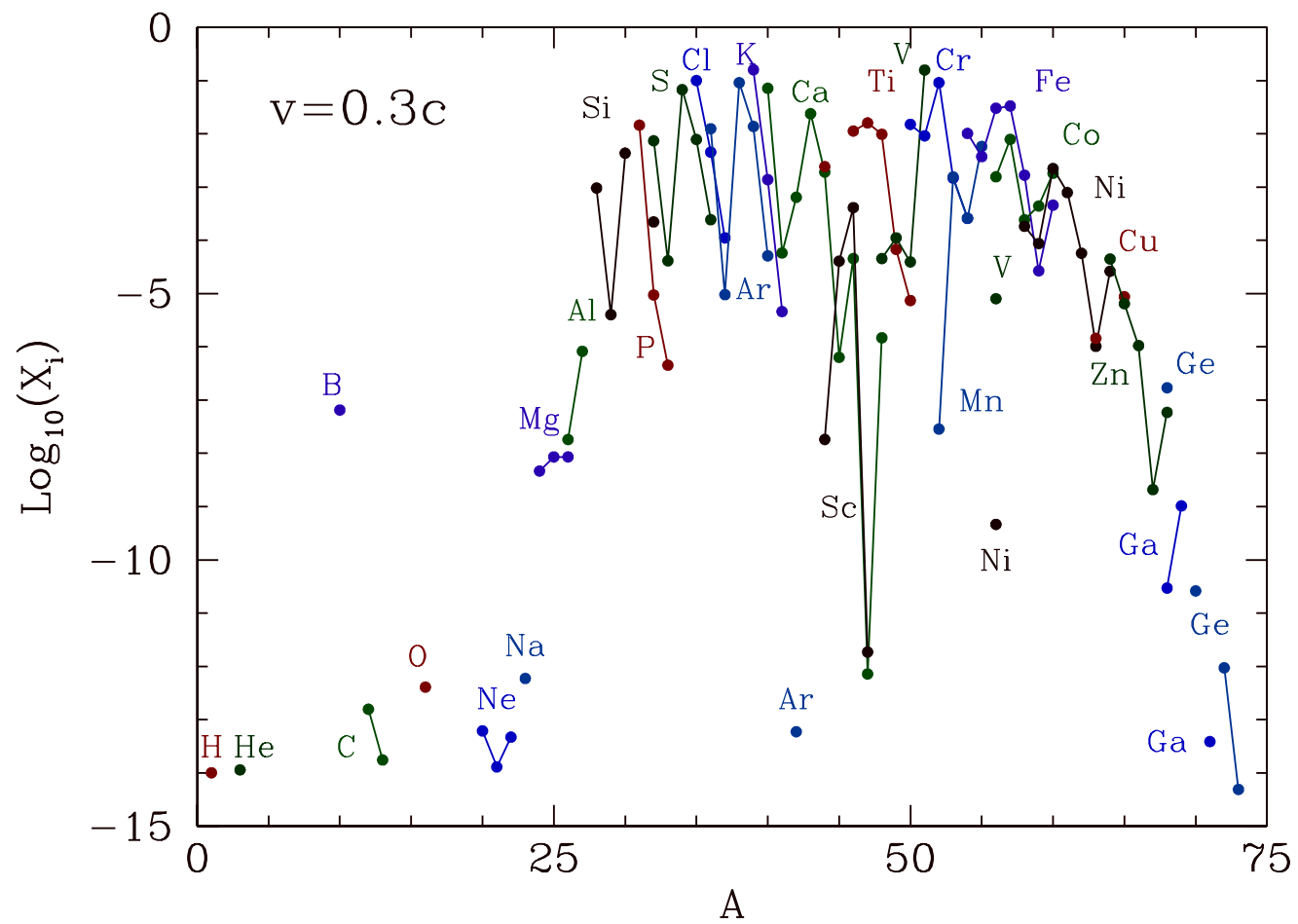
^{32}P

Decays in 14.3 days injecting 1.7 MeV positrons into the opaque expanding ejecta (similar to SNIa with Ni $\rightarrow$ Co $\rightarrow$ Fe)

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

No lanthanides or r-process elements are formed !!!!

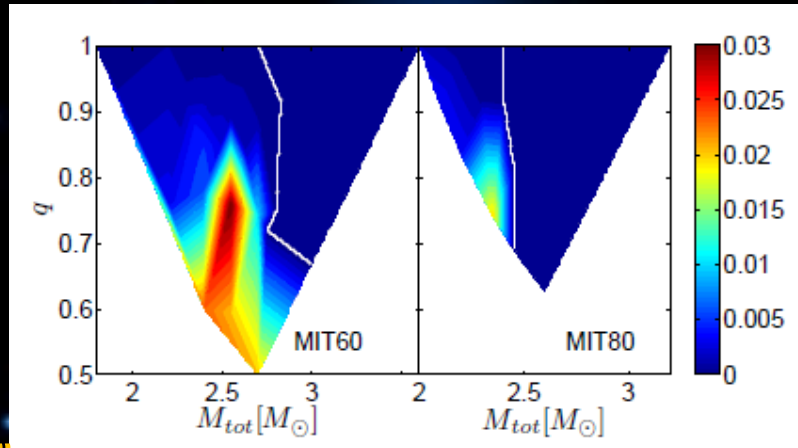




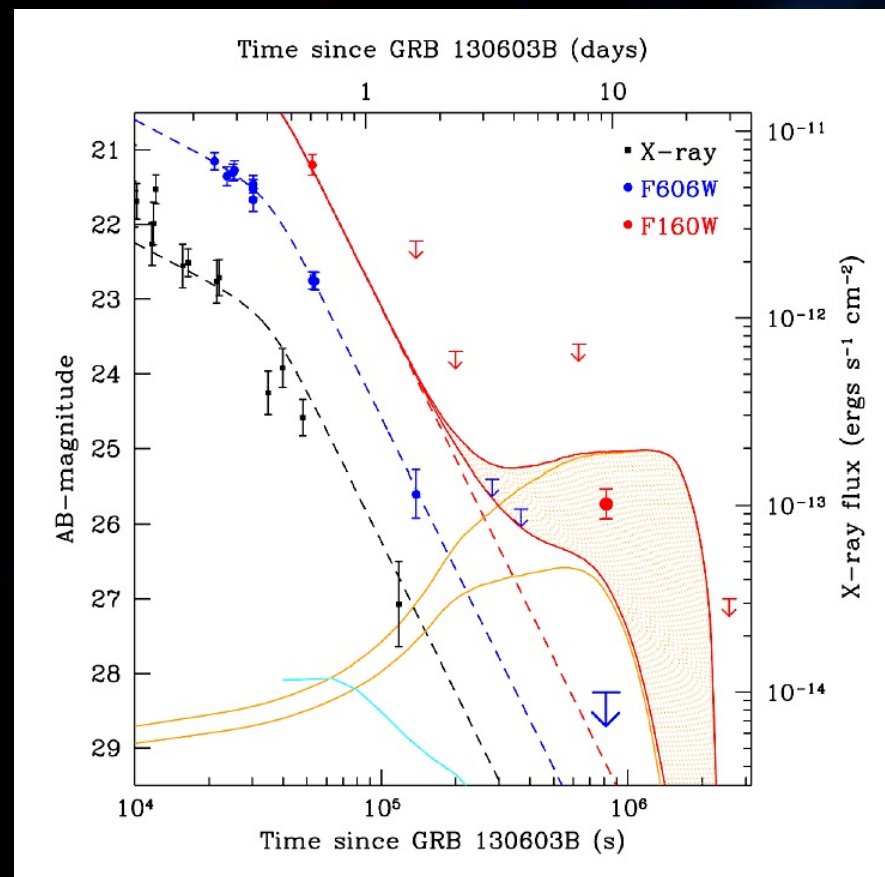
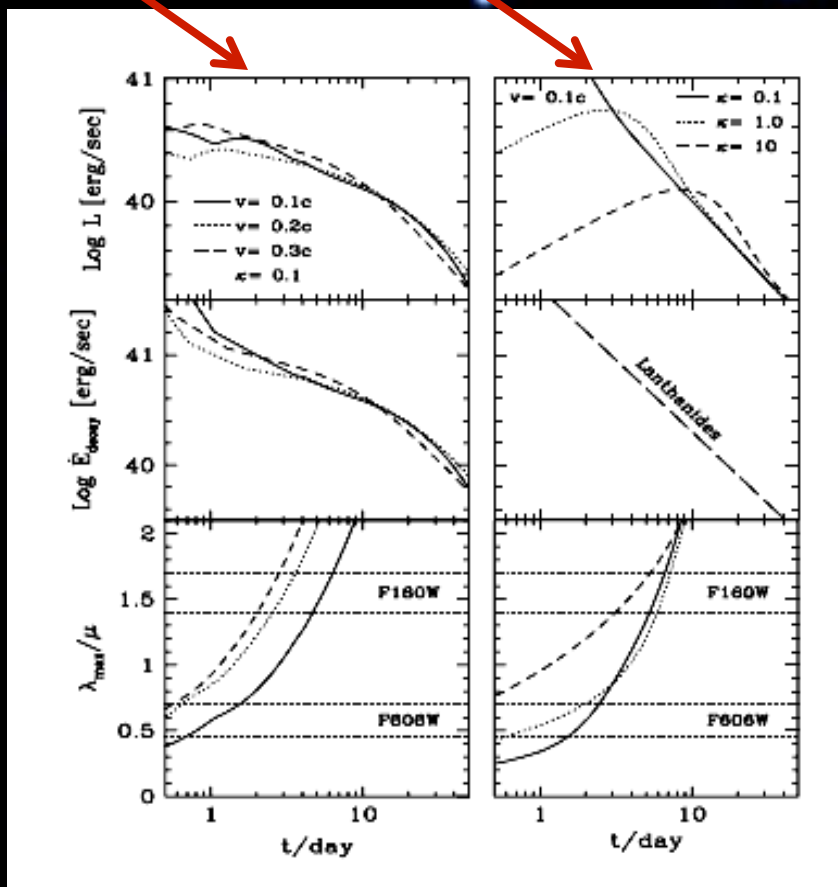
Light curves

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

Our calculations “standard”



(Mergers of SS,
Bauswein et al. 2009)



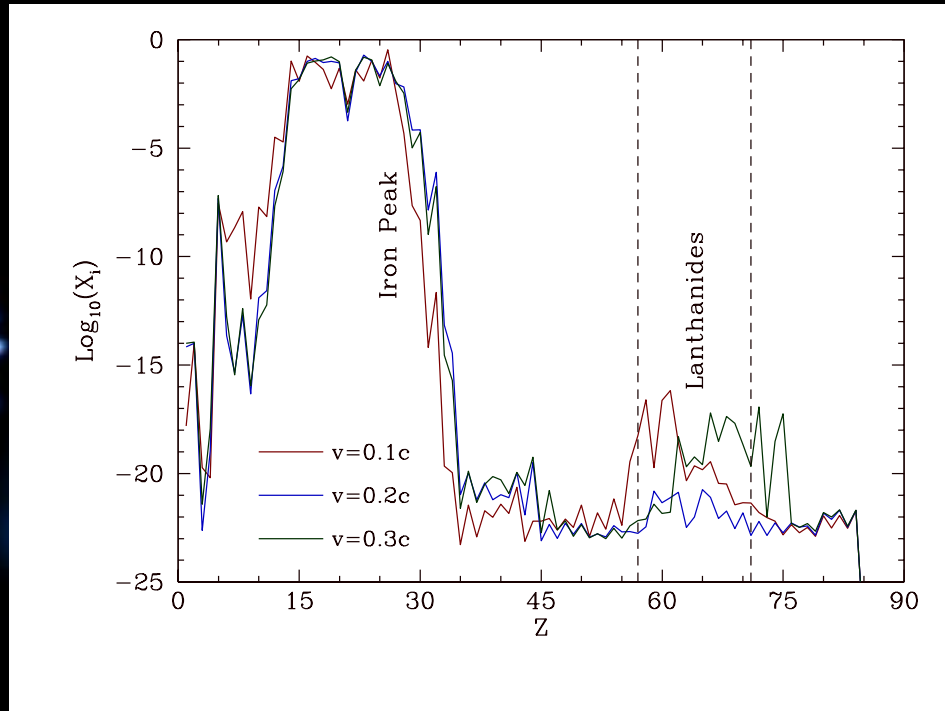
Conclusions

- “Kilonovae” follow a (short) GRB and are associated to the merging of “neutron” stars
- In current models (i.e. NS-NS), there is lanthanide production which provide enough opacity ($\sim 100 \text{ g}^{-1} \text{ cm}^2$) for a secondary bump in the lightcurve $\sim$ days after the GRB
- In SS-SS models, the exotic ejected matter fragments into n and p with $n/p \sim 0.7$, producing a “Dense Big Bang” in which nucleosynthesis reaches the Fe peak only.
- Other events (GRB 050709 and GRB 060614) show NIR excess, to be studied in detail.

There are **no** lanthanides, nor “gold” (r-process actinides), and the lightcurve peaks when ^{32}P does



Crucial observation: detection of r-elements and/or lanthanides !!!



The absence of lanthanides and actinides may tell us that compact stars are a different kind of beast...

Xie Xie !!

