New insights on Nuclear Physics from neutron star mergers

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Outline

- What did we learn from GW170817, GRB170817A, etc?
  - Tidal deformability (upper limit on radii of mergers)
  - Maximum mass of non-rotating compact star (no supramassive)
  - Minimum radius of compact stars (no direct collapse to a BH)
  - Kilonova → possible indications of very small radii of the mergers
- How these observations compare with previous ones?
  - Indications of very small radii of compact stars
  - «tension» between large masses and small radii
- What these constraints imply for the composition of compact stars?
  - Very large radii (R_{14}> 13 km)→ only neutrons and protons
  - Intermediate radii (11.5 km < R_{14} <13 km) →hyperonic stars or hybrid stars
  - Very small radii (R_{14} < 11.5 km) two families of compact stars: hadronic and quark stars co-exist
    - Two-families interpretation of GW170817&GRB179817A
- What can we learn from future observations?

What do we learn from the measured GW signal:

The power and frequency of the GW signal during the inspiral phase depend on the chirp mass which in turn is related to the total mass.

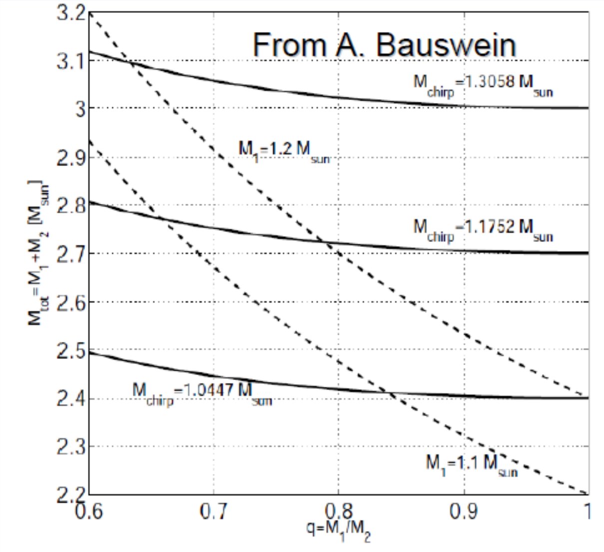
$$M_{\rm chirp} = (M_1 M_2)^{3/5}(M_1 + M_2)^{-1/5}$$

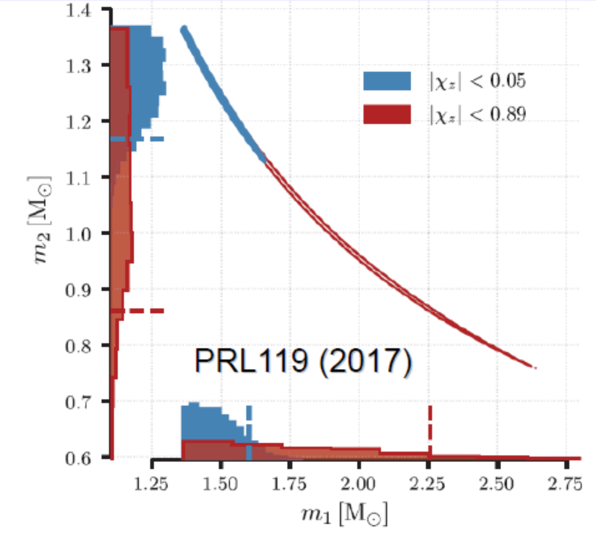
Mesurement: M_{chirp} =1.188 M_{sun} which leads to a total mass

$$M_{tot} = M_1 + M_2 = 2.74^{+0.04}_{-0.02}\, M_\odot$$

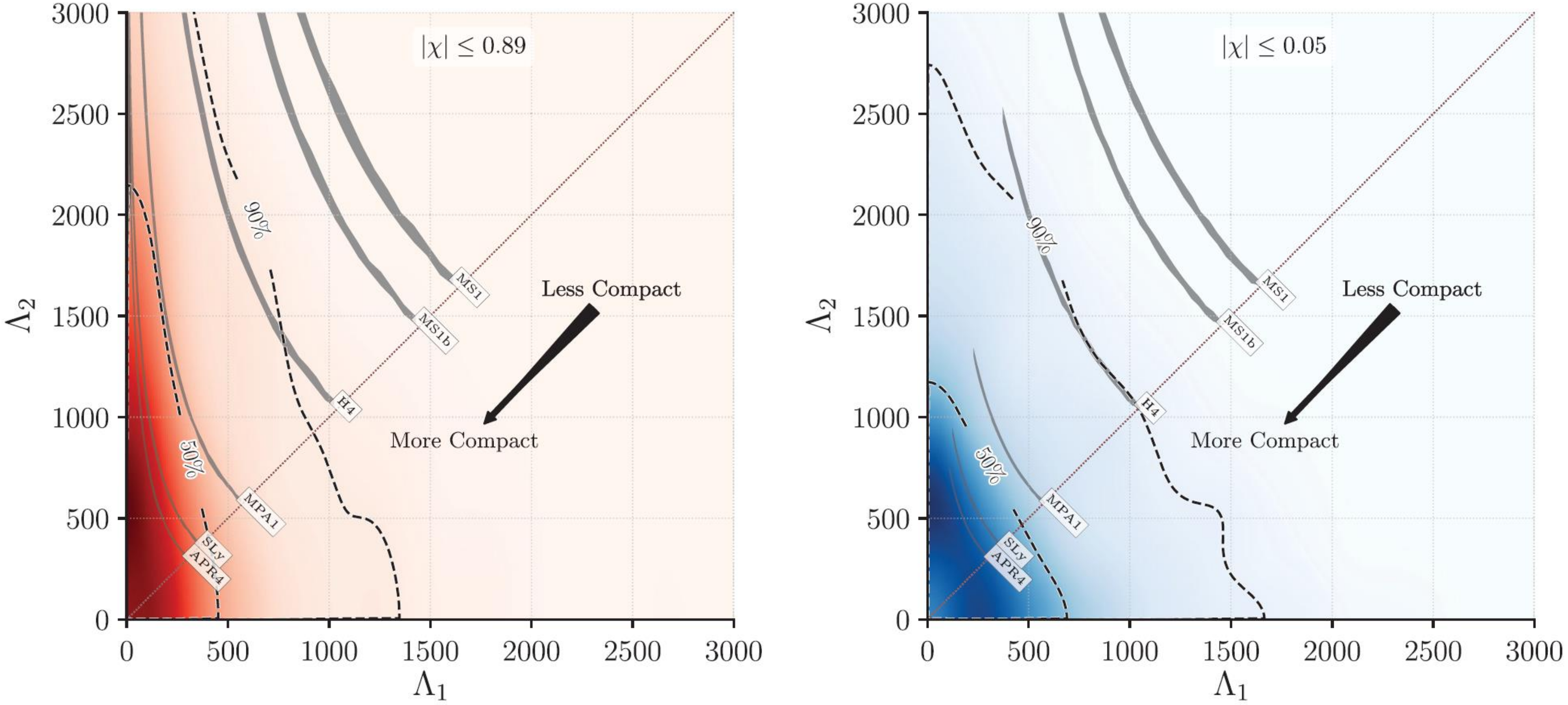
Indications of an asymmetric system: M_1 ~1.36-1.6 M_{sun}
M_2 ~ 1.17 -1.36 M_{sun}

Values consistent with the distribution of masses in binary systems. Consistent with the hyp. that the two compact stars are both neutron stars (BH -NS system very unlikely)





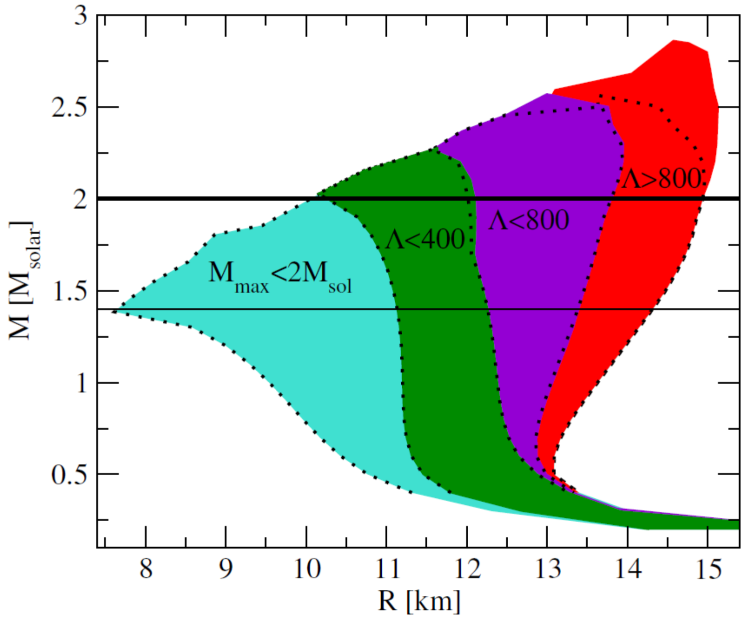
Tidal deformability PRL 119(2017)161101



Annala et al. 1711.02644

Same scheme of Kurkela et al. 2014: many politropes with constrains at low and at high density.

«one family»:
R> 11Km for M=1.4 M_s



$\Lambda < 800 \rightarrow R < 13.4$ km
$\Lambda < 400 \rightarrow R < 12.3$ km

Maximum mass of a non-rotating star

- No long-living supramassive produced
- $M_{tot} - B.E. > M_{supra} = \alpha\, M_{TOV}$
- $M_{tot} = 2.74\ M_s$
- $B.E. = 0.95\ M_{tot}$
- $\alpha = 1.2$
- $M_{TOV} < 2.17\ M_s$

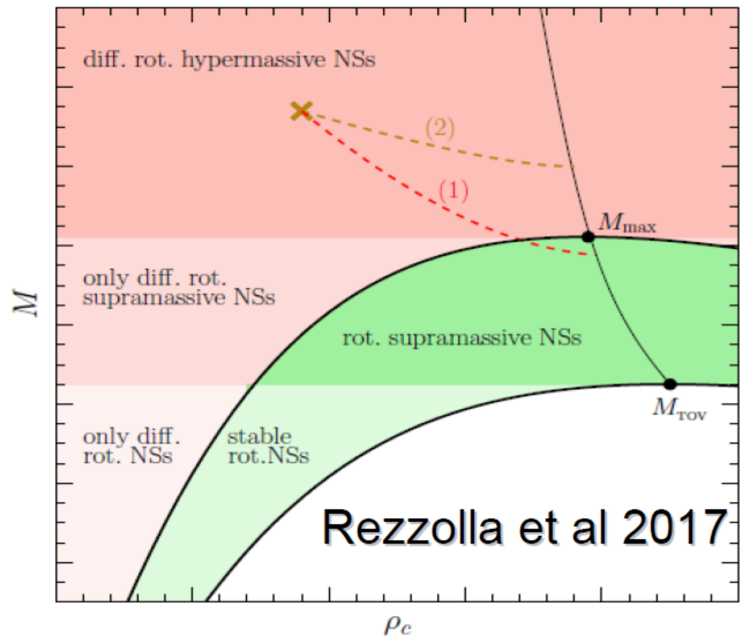


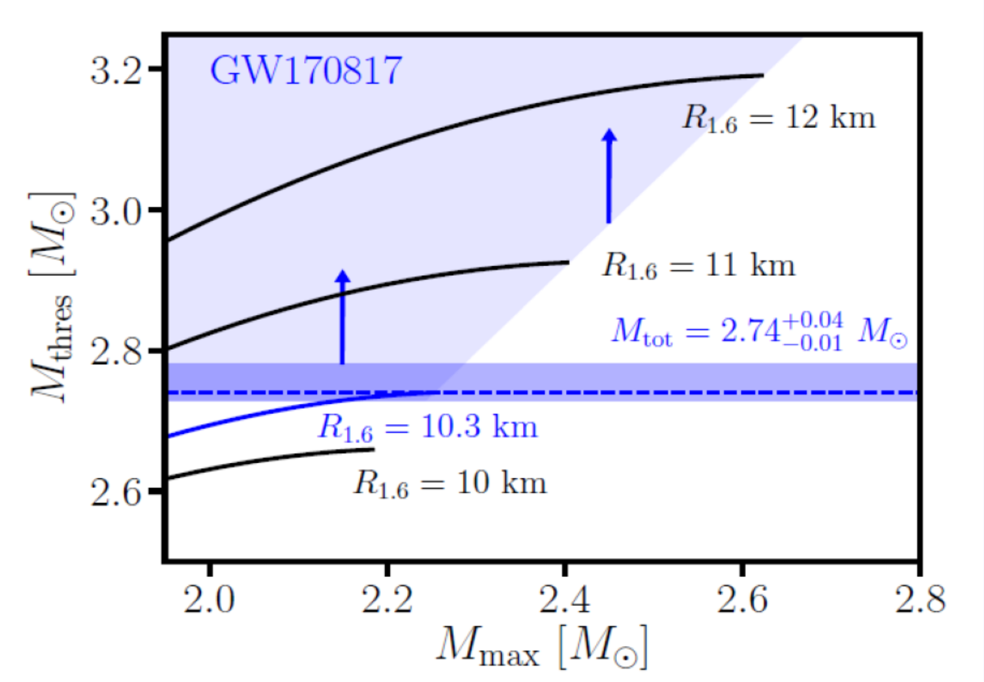
FIG. 1.— Schematic diagram of the different types of equilibrium models for neutron stars. The golden cross marks the initial position of the merger product and the dashed lines its possible trajectories in the (M, ρ_c) plane before it collapses to a black hole.

Constraining the equation of state: radii

Hyp: no prompt collapse in GW170817.
Use of empirical relations between the maximum mass and the radius $R_{1.6}$ of the $1.6M_{sun}$ configuration found in numerical simulations of the merger.
(Bauswein et al 2017)

$$M_{\rm thres} = \left(-3.606\frac{GM_{\rm max}}{c^2 R_{1.6}} + 2.38\right) \cdot M_{\rm max}$$

$$M_{\rm thres} > M_{\rm tot}^{\rm GW170817} = 2.74^{+0.04}_{-0.01}\ M_\odot$$



$R_{1.6}$ larger than about 10.3km

Also from the kilonova indications of small radii

Comparison between a soft and stiff equation of state (Shibata et al 2017)

TABLE I. Equations of state employed, the maximum mass for cold spherical neutron stars, $M_{\max}$, in units of the solar mass, the radius, R_M, and the dimensionless tidal deformability Λ_M of spherical neutron stars of gravitational mass $M = 1.20$, 1.30, 1.40, and $1.50 M_\odot$. R_M is listed in units of km. The last five data show the binary tidal deformability for $\eta = 0.250$, 0.248, 0.246, 0.244, and 0.242 with $\mathcal{M} = 1.19 M_\odot$.

EOS	$M_{\max}$	$R_{1.20}$	$R_{1.30}$	$R_{1.40}$	$R_{1.50}$	$\Lambda_{1.20}$	$\Lambda_{1.30}$	$\Lambda_{1.40}$	$\Lambda_{1.50}$	Λ
SFHo	2.06	11.96	11.93	11.88	11.83	864	533	332	208	388, 387, 387, 386, 385
DD2	2.42	13.14	13.18	13.21	13.24	1622	1053	696	467	797, 788, 780, 772, 764

TABLE II. Merger remnants and properties of dynamical ejecta for two finite-temperature neutron-star EOS, SFHo and DD2 and for the cases with different mass. The quantities for the remnants are determined at ≈ 30 ms after the onset of merger. HMNS, BH, and MNS denote hypermassive neutron star, black hole, and massive neutron star, respectively. The torus mass for the DD2 EOS is determined from the mass located outside the central region of MNS with density $\rho \le 10^{13}\,\mathrm{g/cm^3}$. The values of mass are shown in units of $M_\odot$. The BH spin means the dimensionless spin of the remnant black hole. $\bar{Y}_e$ and $\bar{v}_{\rm ej}$ are the average value of the electron fraction, Y_e, and average velocity of the dynamical ejecta, respectively. We note that Y_e is broadly distributed between ~ 0.05 and ~ 0.5, irrespective of the models (see Refs. [34, 35]).

EOS	m_1 & m_2	m_2/m_1	Remnant	BH mass	BH spin	Torus mass	$M_{\rm ej}$	$\bar{Y}_e$	$\bar{v}_{\rm ej}/c$
SFHo	1.35, 1.35	1.00	HMNS → BH	2.59	0.69	0.05	0.011	0.31	0.22
SFHo	1.37, 1.33	0.97	HMNS → BH	2.59	0.70	0.06	0.008	0.30	0.21
SFHo	1.40, 1.30	0.93	HMNS → BH	2.58	0.67	0.09	0.006	0.27	0.20
SFHo	1.45, 1.25	0.86	HMNS → BH	2.58	0.69	0.12	0.011	0.18	0.24
SFHo	1.55, 1.25	0.81	HMNS → BH	2.69	0.76	0.07	0.016	0.13	0.25
SFHo	1.65, 1.25	0.76	BH	2.76	0.77	0.09	0.007	0.16	0.23
DD2	1.35, 1.35	1.00	MNS	—	—	0.23	0.002	0.30	0.16
DD2	1.40, 1.30	0.93	MNS	—	—	0.23	0.003	0.26	0.18
DD2	1.45, 1.25	0.86	MNS	—	—	0.30	0.005	0.20	0.19
DD2	1.40, 1.40	1.00	MNS	—	—	0.17	0.002	0.31	0.16

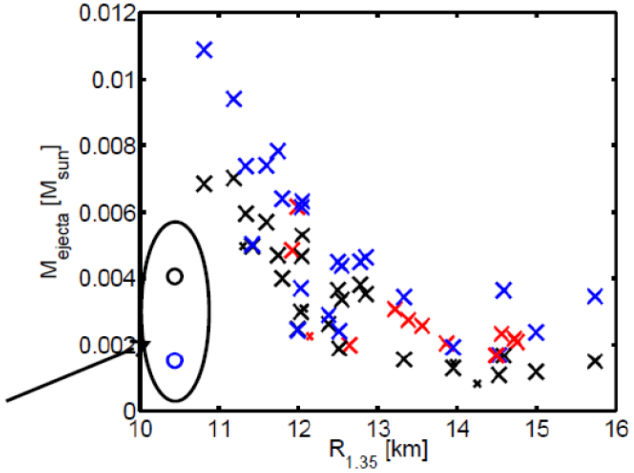
THE ELECTROMAGNETIC COUNTERPART OF THE BINARY NEUTRON STAR MERGER LIGO/VIRGO GW170817.
III. OPTICAL AND UV SPECTRA OF A BLUE KILONOVA FROM FAST POLAR EJECTA

M. NICHOLL[1], E. BERGER[1], D. KASEN[2,3], B. D. METZGER[4], J. ELIAS[5], C. BRICEÑO[6], K. D. ALEXANDER[1], P. K. BLANCHARD[1], R. CHORNOCK[7], P. S. COWPERTHWAITE[1], T. EFTEKHARI[1], W. FONG[8], R. MARGUTTI[8], V. A. VILLAR[1], P. K. G. WILLIAMS[1], W. BROWN[1], J. ANNIS[9], A. BAHRAMIAN[10], D. BROUT[11], D. A. BROWN[12], H.-Y. CHEN[13], J. C. CLEMENS[14], E. DENNIHY[14], B. DUNLAP[14], D. E. HOLZ[15,13,16,17], E. MARCHESINI[18,19,20,21,22], F. MASSARO[20,21,23], N. MOSKOVITZ[24], I. PELISOLI[25,26], A. REST[27,28], F. RICCI[29,1], M. SAKO[11], M. SOARES-SANTOS[9,30], J. STRADER[10]

ABSTRACT

We present optical and ultraviolet spectra of the first electromagnetic counterpart to a gravitational wave (GW) source, the binary neutron star merger GW170817. Spectra were obtained nightly between 1.5 and 9.5 days post-merger, using the SOAR and Magellan telescopes; the UV spectrum was obtained with the *Hubble Space Telescope* at 5.5 days. Our data reveal a rapidly-fading blue component ($T \approx 5500$ K at 1.5 days) that quickly reddens; spectra later than $\gtrsim 4.5$ days peak beyond the optical regime. The spectra are mostly featureless, although we identify a possible weak emission line at ~ 7900 Å at $t \lesssim 4.5$ days. The colours, rapid evolution and featureless spectrum are consistent with a "blue" kilonova from polar ejecta comprised mainly of light r-process nuclei with atomic mass number $A \lesssim 140$. This indicates a sight-line within $\theta_{\rm obs} \lesssim 45°$ of the orbital axis. Comparison to models suggests ~ 0.03 $M_\odot$ of blue ejecta, with a velocity of ~ 0.3c. The required lanthanide fraction is ~ 10^{-4}, but this drops to $< 10^{-5}$ in the outermost ejecta. The large velocities point to a dynamical origin, rather than a disk wind, for this blue component, suggesting that both binary constituents are neutron stars (as opposed to a binary consisting of a neutron star and a black hole). For dynamical ejecta, the high mass favors a small neutron star radius of $\lesssim 12$ km. This mass also supports the idea that neutron star mergers are a major contributor to r-process nucleosynthesis.

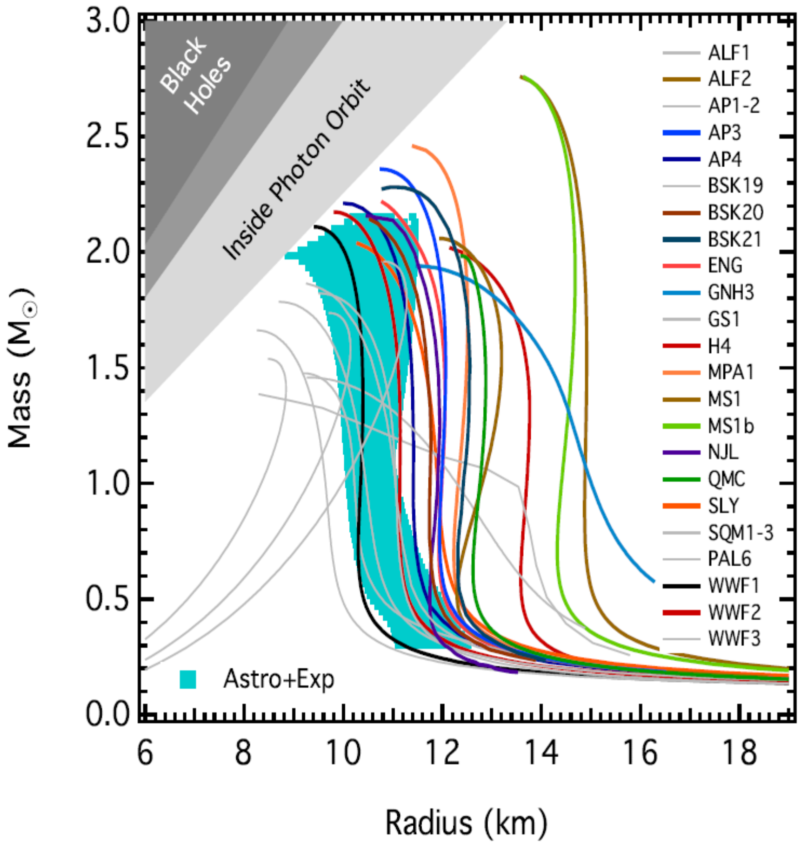
Computations of mass ejected not yet completely under control: for instance the neutrino transport is modeled by simple leakage schemes.



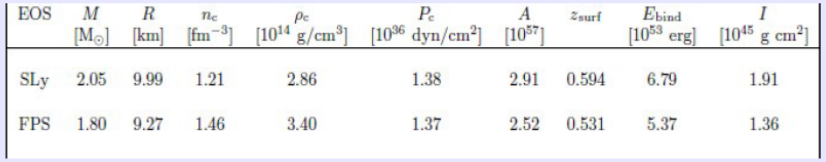
Prompt collapse

Bauswein et al 2013

Small radii? Not so surprising!
Oezel and Freire, Ann.Rev.Astron.Astrophys. 54 (2016) 401



What if the radii are small?
What does this imply on nuclear physics?



EOS	M $[\mathrm{M}_\odot]$	R [km]	n_c $[\mathrm{fm}^{-3}]$	ρ_c $[10^{14}\ \mathrm{g/cm}^3]$	P_c $[10^{36}\ \mathrm{dyn/cm}^2]$	A $[10^{57}]$	$z_{\rm surf}$	$E_{\rm bind}$ $[10^{53}\ \mathrm{erg}]$	I $[10^{45}\ \mathrm{g\ cm}^2]$
SLy	2.05	9.99	1.21	2.86	1.38	2.91	0.594	6.79	1.91
FPS	1.80	9.27	1.46	3.40	1.37	2.52	0.531	5.37	1.36

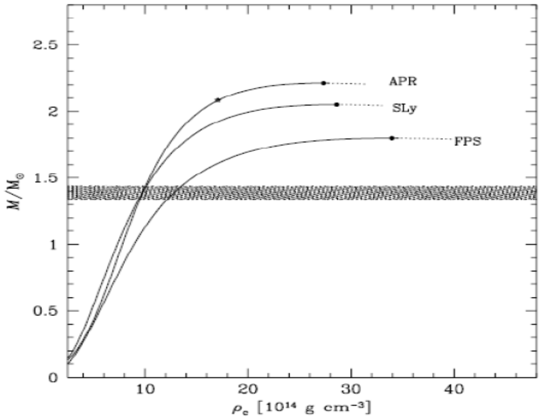


Fig. 4. Gravitational mass M versus central density ρ_c, for the SLy, FPS, and APR EOS of dense matter. Maximum on the mass-central density curves is indicated by a filled circle. On the APR curve, configurations to the right of the asterisk contain a central core with $v_{\rm sound} > c$. Configurations to the right of the maxima are unstable with respect to small radial perturbations, and are denoted by a dotted line. The shaded band corresponds to the range of precisely measured masses of binary radio pulsars.

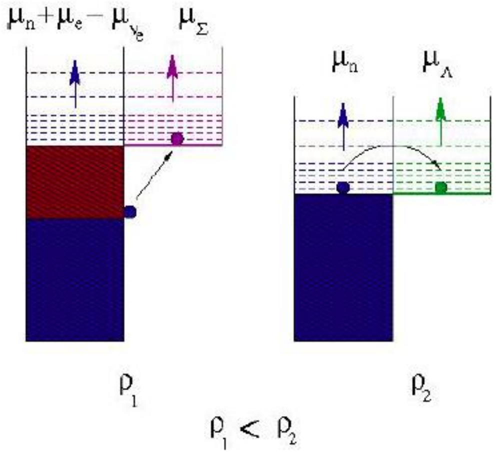
Calculations performed much before the discovery of the $2M_{\rm sun}$ stars. At the maximum mass densities close to 10 times saturation density.

In general : soft nucleonic equations of state predict large densities.

Heavy baryons must be taken into account at such high densities!

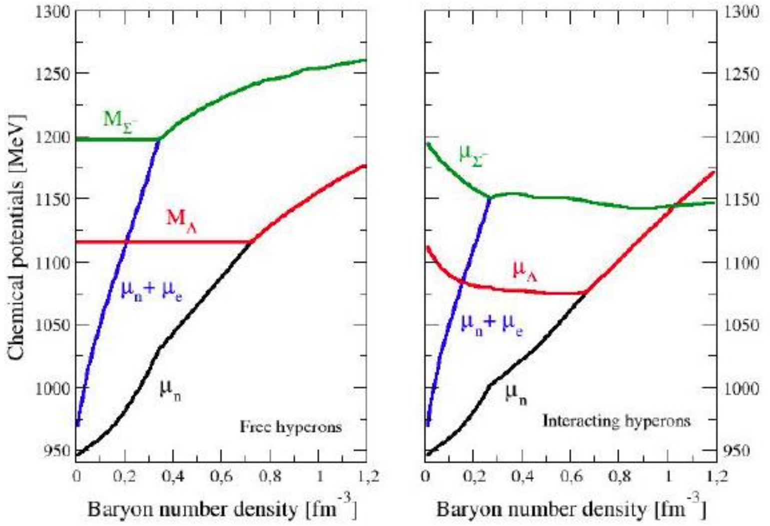
Borrowed from I. Vidana

Hyperons are expected to appear in the core of neutron stars at $\rho \sim (2\text{-}3)\rho_0$ when μ_N is large enough to make the conversion of N into Y energetically favorable.



$$\mu_{\Sigma^-} = \mu_n + \mu_{e^-} - \mu_{\nu_{e^-}}$$

$$\mu_\Lambda = \mu_n$$



$$n + n \rightarrow n + \Lambda$$

$$p + e^- \rightarrow \Lambda + \nu_{e^-}$$

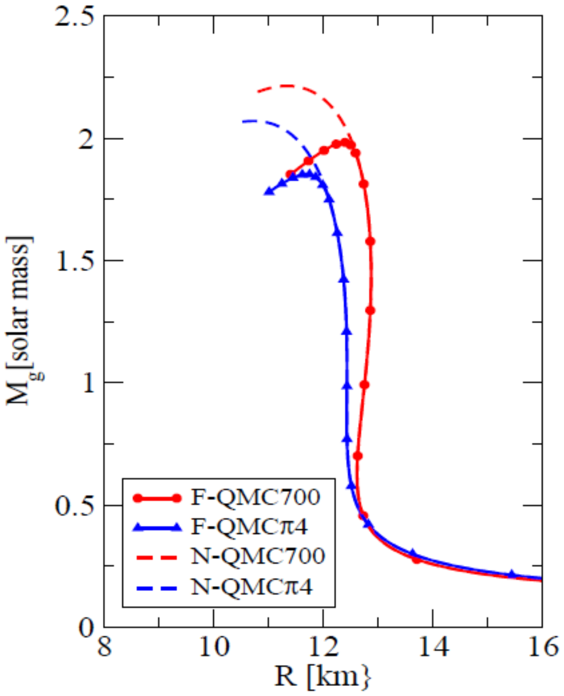
$$n + n \rightarrow p + \Sigma^-$$

$$n + e^- \rightarrow \Sigma^- + \nu_{e^-}$$

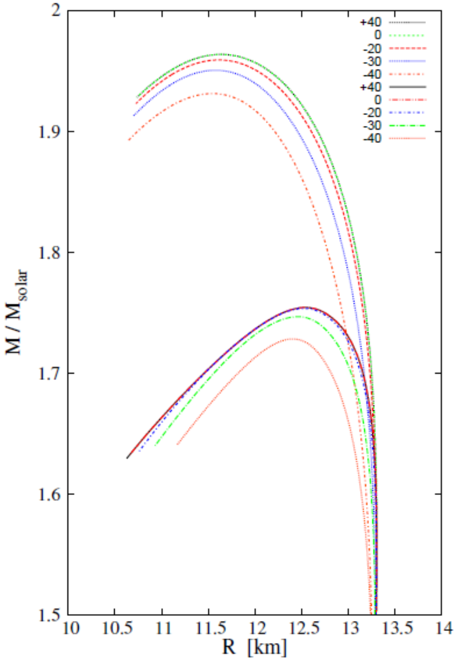
Hyperons in compact stars

Few experimental data allow to fix some of the interactions parameters.

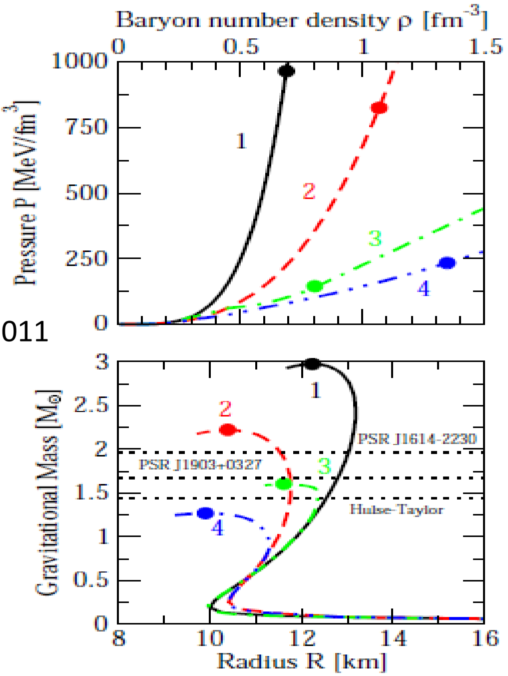
Stone et al. NPA 792(2007)341



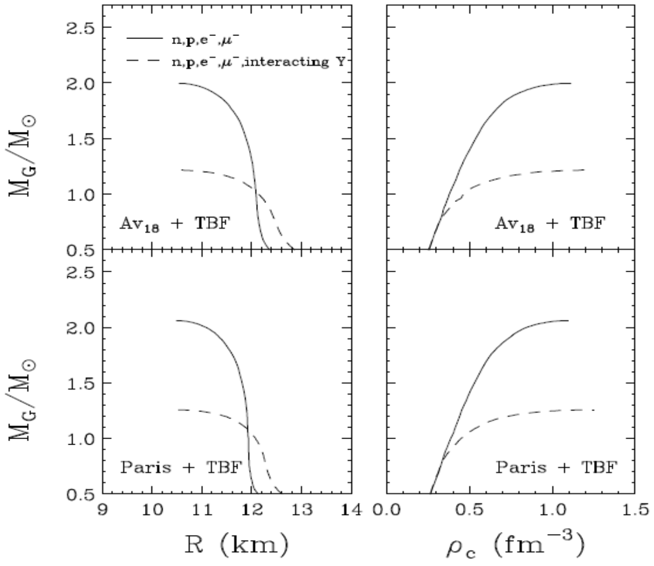
Weissenborn et al.
NPA 881(2011)62



Vidana et al 2011

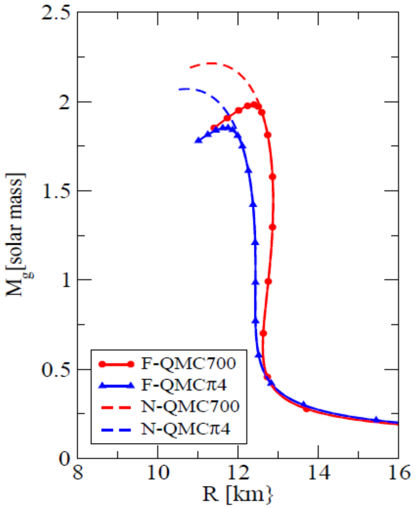


Baldo et al 2000

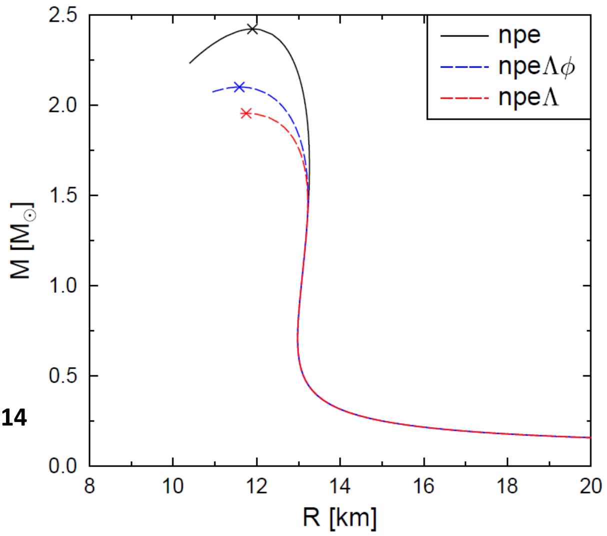


The 2Msun limit can be fulfilled within RMF models.
In microscopic non-relativisitc calculations it is fulfilled only if very strong and repulsive 3-body forces YNN are present (Pederiva et al. 2014).

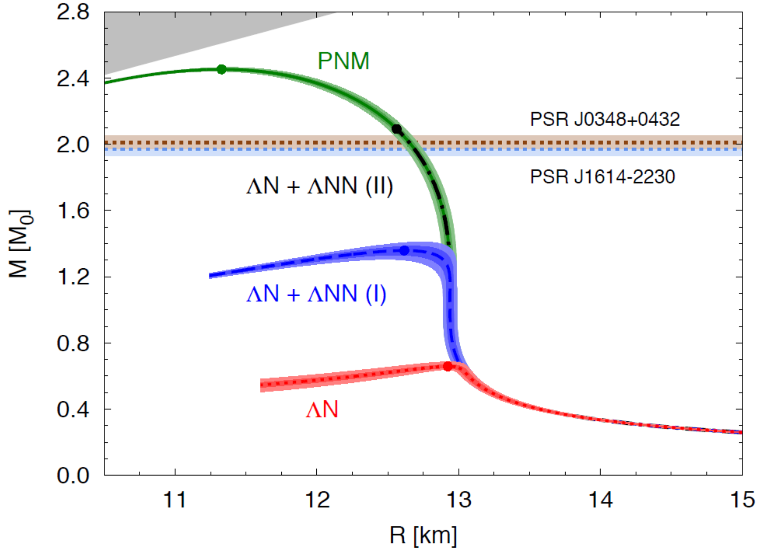
Minimum radius for a 1.4 M_s star: hadronic stars



Stone et al 2006



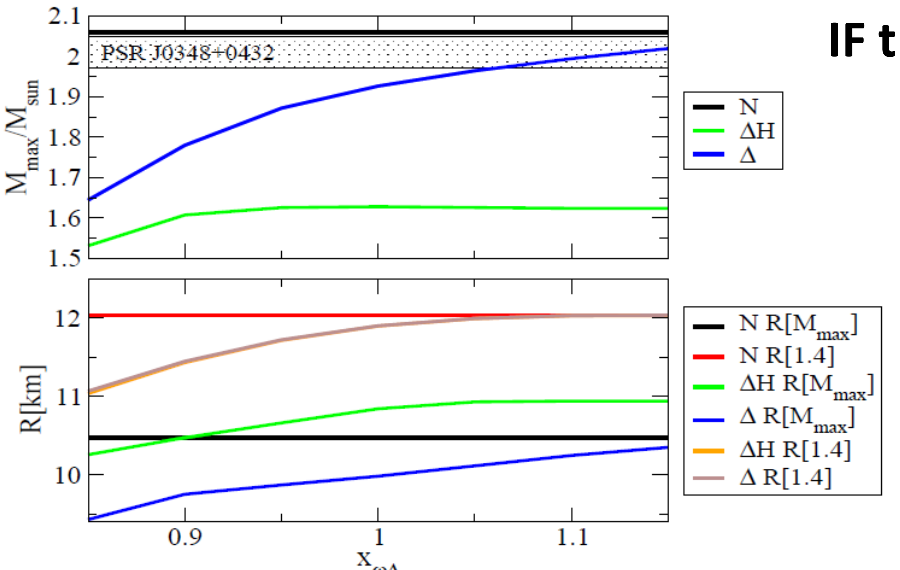
Banik et al. 2014



Lonardoni et al 2015

Hyperonic stars: $R_{1.4}$ > 12 km

IF the 2 M s constraint needs to be imposed



Delta – resonance stars
$R_{1.4}$ order of (10-11) km,
BUT the maximum mass
is smaller than 2 M_s

What about hybrid quark-hadron stars?
From Alford, Burgio, Han, Taranto, Zappalà, **Phys.Rev. D92 (2015) 083002**

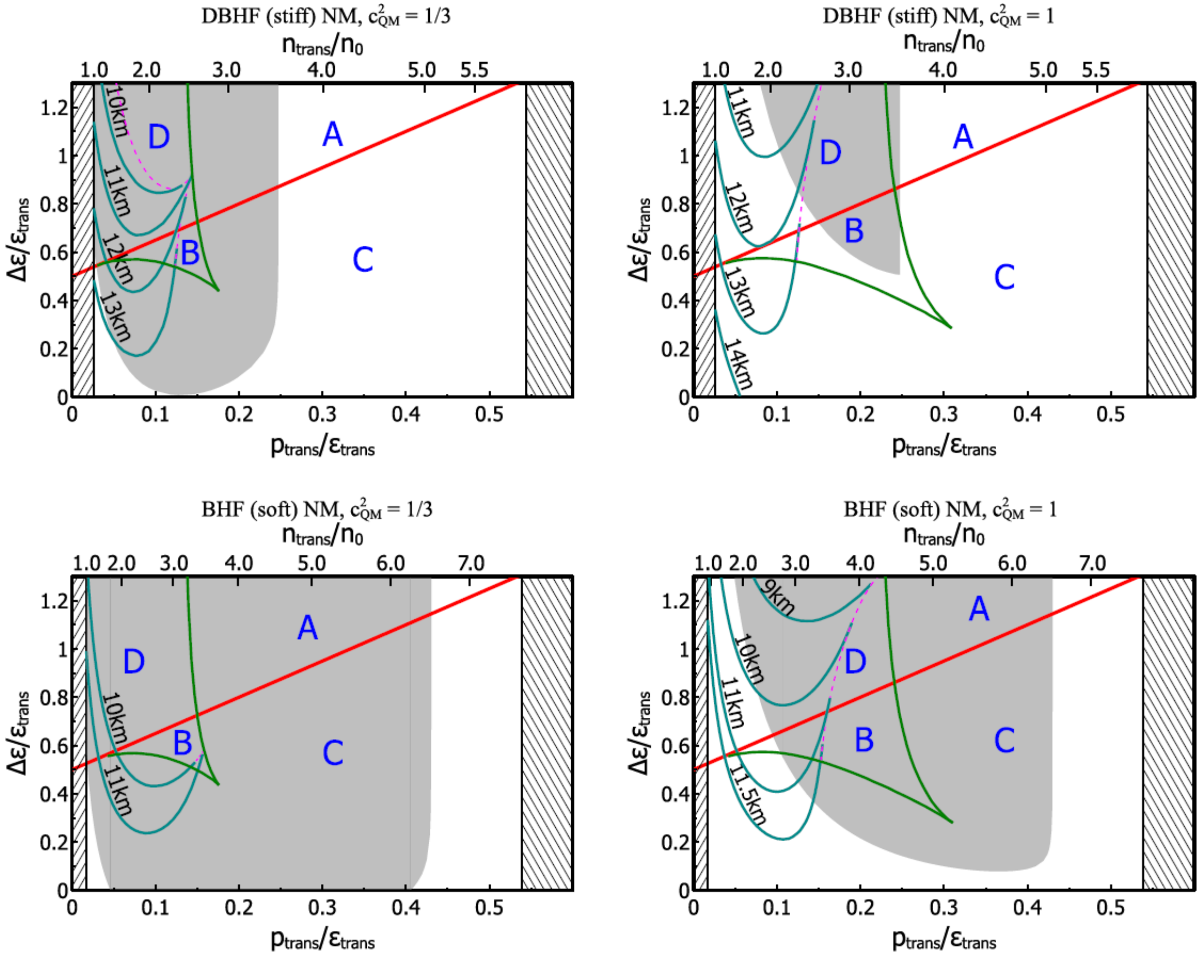
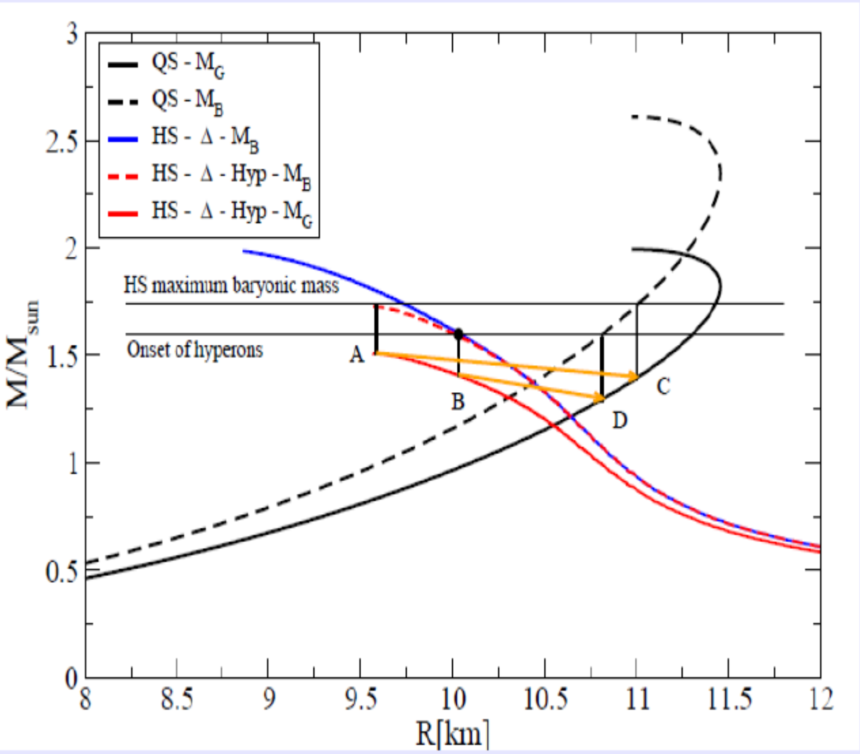


FIG. 4: (Color online). Contour plots similar to Fig. 3 showing the radius of a hybrid star of mass $M = 1.4\,M_\odot$ as a function of the CSS parameters. Such stars only exist in a limited region of the space of EoSs [delimited by dashed (magenta) lines]. The grey shaded region is excluded by the observational constraint $M_{max} > 2M_\odot$. For a magnified version of the low-transition-pressure region for $c^2_{QM} = 1/3$, see Fig. 5.

Radii smaller than about 11 km for stars of $M = 1.4\ M_s$ are possible ONLY if c^2 is close to 1. Not very realistic.

Very small radii, $R_{1.4} < 11.5$ km: two-families of compact stars?

Main hypothesis: the ground state of nuclear matter is strange quark matter.
Hadronic stars are metastable and, under some specific conditions, convert into strange quark stars (at fixed baryonic mass the gravitational mass of strange quark stars is smaller).
Hadronic stars and strange quark stars would populate two separated branches.
Heavy stars ($2M_{sun}$) are strange quark stars.



Observations will tell the maximum mass of the strange quark star family.
Probably it is of about 2 M_s or slightly larger.

The merger of two NSs produces a strange quark star

Rayleigh-Taylor instabilities develop and **the conversion of the core occurs on the time scale of ms.**

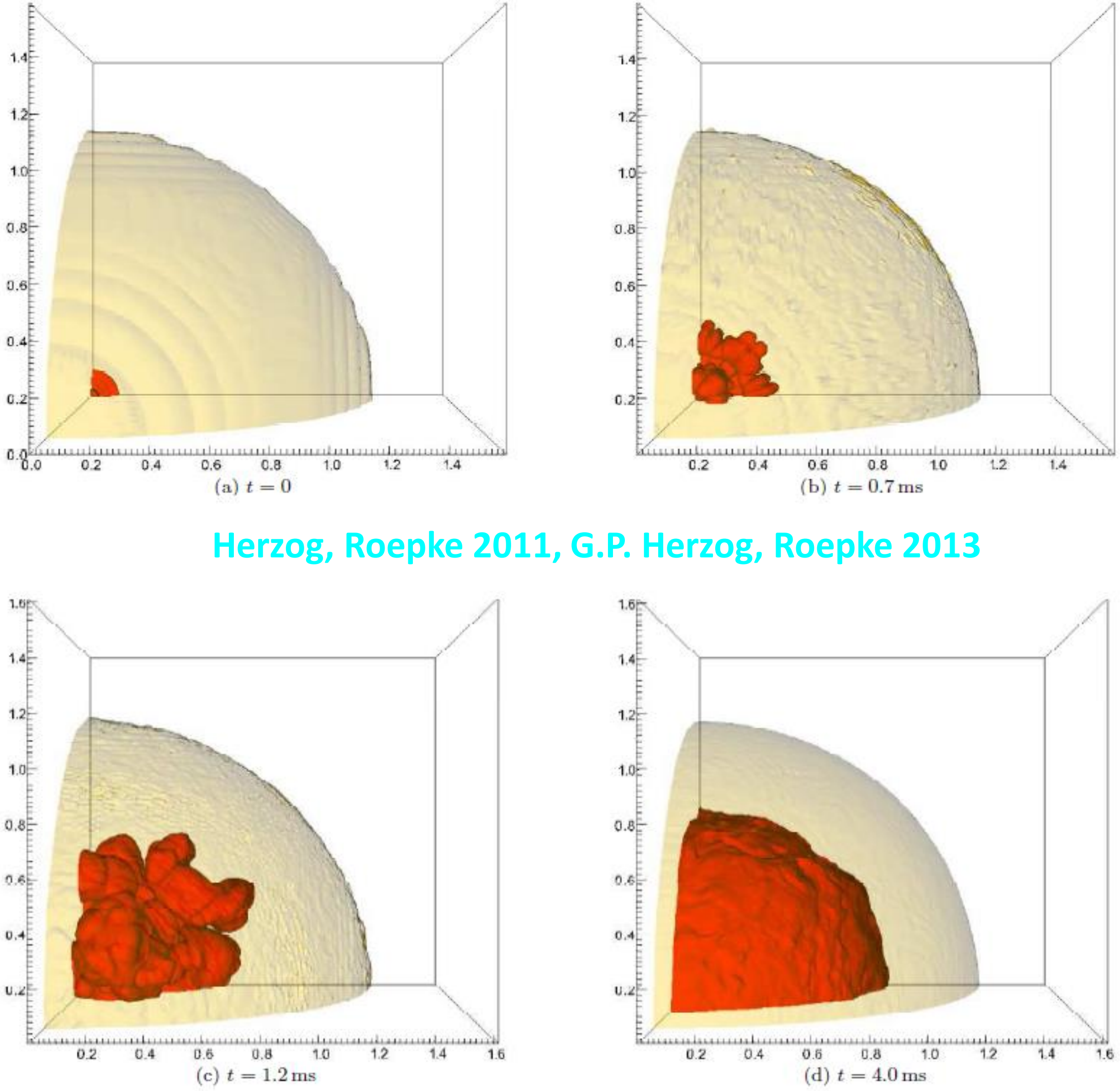
The rapid burning stops before the whole hadronic matter has converted
(the process is no more exothermic
as a hydrodynamical process,
about 0.5 Msun of unburned material)

The configuration obtained after the rapid burning is mechanically stable

although not yet in chemical equilibrium

After the rapid burning the conversion proceeds via strangeness production and diffusion.

The burning reaches the surface of the star after about 10s.



(a) $t = 0$ (b) $t = 0.7\,\mathrm{ms}$

Herzog, Roepke 2011, G.P. Herzog, Roepke 2013

(c) $t = 1.2\,\mathrm{ms}$ (d) $t = 4.0\,\mathrm{ms}$

FIG. 1: (color online) Model: Set 1, $M = 1.4 M_{\odot}$. Conversion front (red) and surface of the neutron star (yellow) at different times t. Spatial units 10^6 cm.

How to describe within the protomagnetar model the prompt emission of short GRBs?

Long GRBs quasi-plateau **and short** GRBs extended emission are described very well by the spin-down of a rapidly rotating magnetar **with similar values of B and P**.

The promt emission of long GRBs is well described by the wind of a newly formed magnetar having values of B and P compatible with the description of the quasi-plateau. The duration of the prompt emission is of the order of the cooling time of the proto-magnetar, i.e. a few tens seconds.
During that time baryonic matter is ablated from the surface of the star by the neutrinos and accelerated by the radiation pressure.

Question: why the prompt emission of short GRBs lasts only a fraction of a second? What regulates the duration of ablation in that case?
Notice that the temperature in the short GRBs is even larger than in the long GRBs.

Prompt emission of long and short GRBs

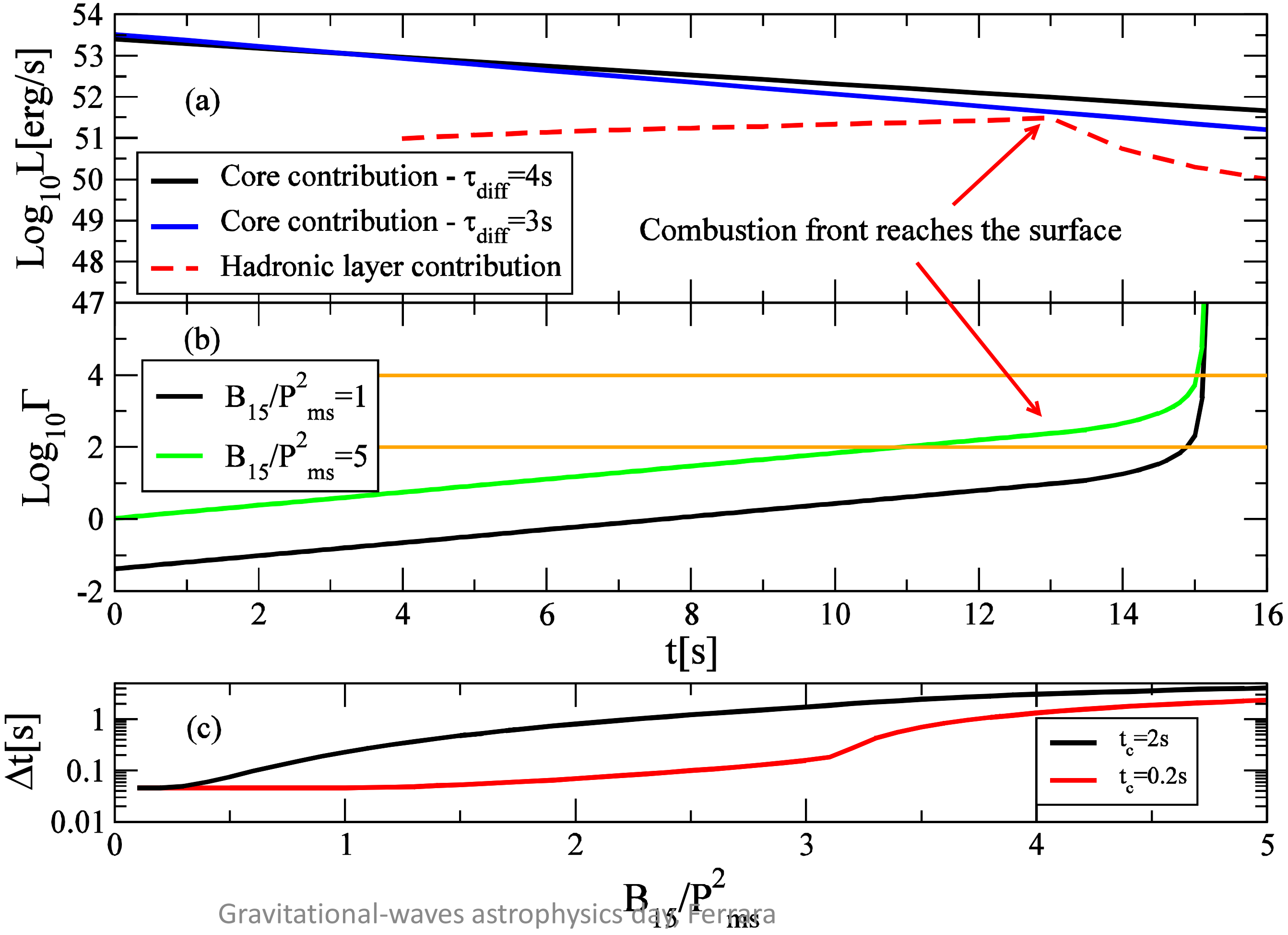
It was generally assumed that the prompt emission of short GRBs is spectrally harder than
the one of long GRBs, but the differences are less evident when the sample is restricted
to short GRBs with the highest peak fluxes (Kaneko et al. (2006))
or when considering only the first ~ 2 s of long GRBs light curves.

When comparing the prompt emission of short GRBs and the first seconds of long's one finds:
(i) the same variability, (ii) the same spectrum, (iii) the same luminosity and (iv) the
same $E_{peak} – L_{iso}$ correlation (Ghirlanda et al. 2009).

In other words, **if the central engine of a long GRB would stop after ~ 0.3 (1+z) seconds the resulting event would be indistinguishable from a short GRB** (Calderone et al. 2014).

Duration of the sGRB in the two-families scenario

A.D., A.Lavagno, B.Metzger, G.Pagliara PRD93 (2016) 103001



Neutrino luminosity

Magnetization or maximum Lorentz factor

Duration of the burst

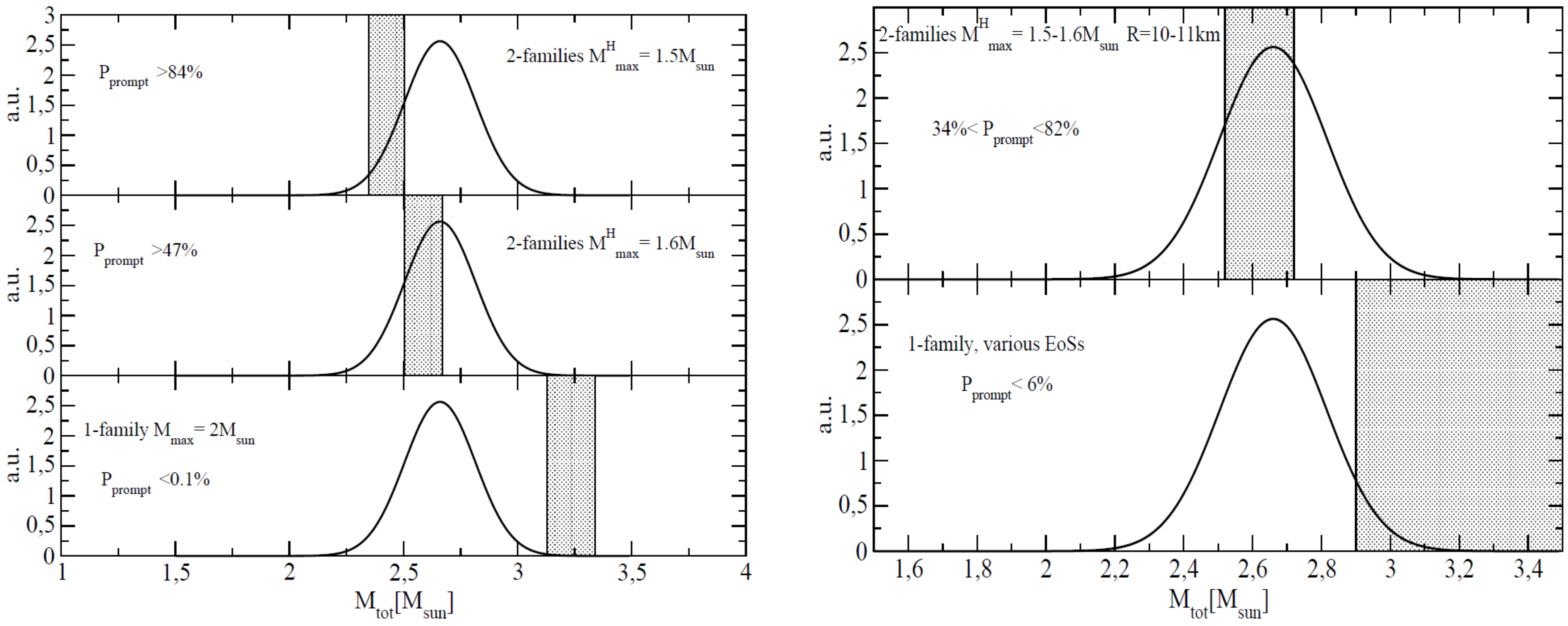
Strong correlation between duration and luminosity

as seen in the data Shahmoradi, Nemiroff MNRAS 451 (2015) 1

Strange quark star formation vs BH formation

- BH formation and Strange Quark Star formation BOTH help in reducing the baryon load thus allowing the formation of the jet associated with the prompt emission. There are differences in the time order of the events:
  - If a BH forms the activity of the protomagnetar needs to take place BEFORE that moment, so the «time-reversal» scenario of Ciolfi et al. and Rezzolla et al. is needed.
  - If a SQS forms the protomagnetar is active also after the formation of the SQS, so there is no need of a «time-reversal» scenario.
- Also the time delay between merger and prompt emission is different:
  - In the «time-reversal» scenario the prompt emission takes place after a supramassive star collapses to a BH and the time delay between merger and prompt can easily exceed 10^3 s.
  - In the SQS formation scenario the prompt emission takes place when quark deconfinement reaches the surface of the star, implying a delay between merger and prompt emission of the order of about 10 s.
- The combined analysis of GW and of EM signals will allow to discriminate betwen these two scenarios.

Prompt collapse to a BH of a **NS-NS**: 2-families vs 1-family scenario



Distribution of M_{tot} = m1 + m2 (solid line). Range of values of $M_{threshold}$ is indicated by the shaded area.

The fraction of prompt collapses within the two-families scenario is MUCH larger than in the one-family case.

Mass of the **NS-NS** merger and short GRBs

An example:

$M^{H}_{TOV} = 1.6\,M_{\odot}$, $M^{Q}_{TOV} = 2\,M_{\odot}$

$M_{max,dr} = 1.6 \times M^{H}_{max} = 2.56\,M_{\odot}$

$M^{q}_{supra} = 1.2 \times M^{Q}_{TOV} = 2.4\,M_{\odot}$

a) if $M_g > M_{max,dr} = 2.56 M_{\odot}$ (approx. above $1.35\,M_{\odot} + 1.35\,M_{\odot}$)

direct collapse to a BH without any significant electromagnetic emission;

b) if $M^{q}_{supra} = 2.4\,M_{\odot} < Mg < M_{max,dr} = 2.56\,M_{\odot}$ (approx. from $1.25\,M_{\odot} + 1.25\,M_{\odot}$ to $1.35\,M_{\odot} + 1.35\,M_{\odot}$)

formation of a hypermassive SQS (sGRBs without extended emission);

c) if $Mg < M^{q}_{supra} = 2.4\,M_{\odot}$ (approx. below $1.25\,M_{\odot} + 1.25\,M_{\odot}$)

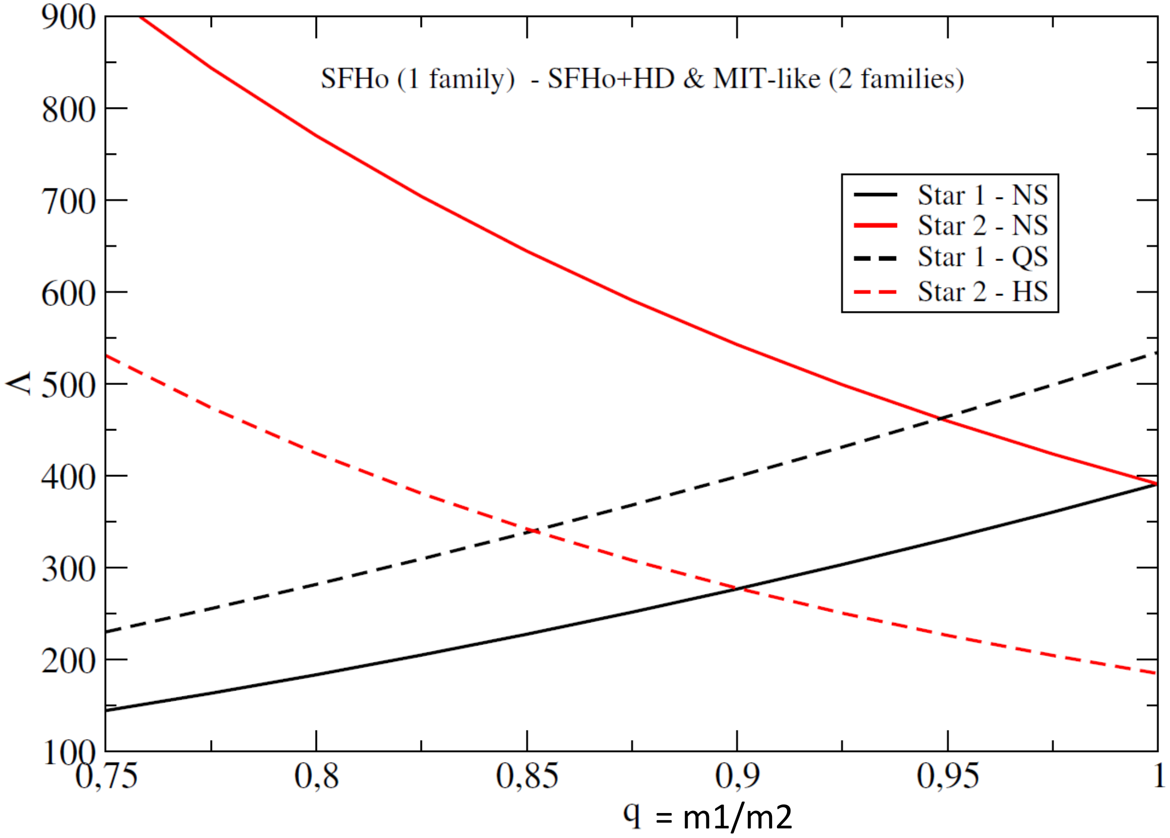
formation of supramassive SQSs → sGRBs with an extended emission.

NS-QS mergers: possible ONLY within the two-families scenario

- The maximum mass of the hypermassive star is much larger, because the quark core stabilizies mechanically the not yet chemically equilibrated system
- Both symmetric AND asymmetric masses are possible, e.g.

  NS of about 1.2 M_s and QS of about 1.6 M_s
- The number of NS-QS is comparable to the number of NS-NS mergers for «large» values of total mass (preliminary result by G.Wiktorowicz)
- The process of combustion into quarks of the external layers of the NS is very slow, order of seconds, therefore mass ejection is possible. Both objects are very compact so the shock ejection should be large (although it comes only from the NS component)
- Within a same range of total masses both NS-NS and NS-QS mergers are possible,
  - but the firsts often directly produce a BH, therefore we can have events with the same total mass with large mass ejected and events with very small mass ejected (and different type of EM signal)
  - tidal deformability also can distinguish between various possibilities:

Tidal deformability:
NS-NS (one family) vs NS-QS (two families)



Future observations

- New missions (NICER, LOFT), reaching a precision of ~ 1km in the measure of radii , can clarify the composition of compact stars, similarly a measure of the moment of inertia with a precision of about 20-30 percent (SKA):

- $R_{1.4}$ >= 13 km or I_{45} >= 1.6 purely nucleonic stars ($\rho_{max} \leq 3\ \rho_0$)

- 11.5 km < $R_{1.4}$ < 13 km or 1.3 <= I_{45} <= 1.6 hyperonic or hybrid stars (ρ_{max} as large as 5 ρ_0)

- $R_{1.4}$ << 11.5 km or I_{45} << 1.3 two families of compact stars

Conclusions

- Mergers offer a unique possibility to study matter at extreme conditions
- It will be possible to discriminate among the various models (already now a few EoSs have been ruled out, after only one event!)
- The two-families scenario has specific and testable features:
  - Very small radii and moments of inertia for low masses, larger for high masses
  - Co-existence of «soft» hadronic configurations and of «stiff» quark ones
  - Possibility of explaining the prompt emission of a short GRB within the protomagnetar model

- A.D., A.Lavagno, G.Pagliara, Phys.Rev. D89 (2014) 043014

  Two-families scenario

- A.D., A.Lavagno, G.Pagliara, D.Pigato, Phys.Rev. C90 (2014) 065809

  Delta resonances and «delta-puzzle»

- A.D., G.Pagliara, Phys. Rev. C 92 (2015) 045801

  Combustion of hadronic stars into quark stars: the turbulent and the diffusive regime

- A.D., A.Lavagno, G.Pagliara, D.Pigato, Eur.Phys.J. A52 (2016) 40

  A.D., G.Pagliara, Eur.Phys.J. A52 (2016) 41

  Review papers on the two-families scenario

- A.D., A.Lavagno, B.Metzger, G.Pagliara, Phys. Rev. D93 (2016) 103001

  Quark deconfinement and duration of short GRBs

- A.G.Pili, N.Bucciantini, A.D., G.Pagliara, L. del Zanna, MNRAS 462 (2016) L26

  Quark deconfinement and late-time activity in long GRBs

- G.Wiktorowicz, A.D., G.Pagliara, S.Popov, Astrophys.J. 846 (2017) 163

  Strange quark stars in binaries: formation rates, mergers and explosive phenomena

- A.D., G.Pagliara, 1710.02003

  Merger of two neutron stars: predictions from the two-families scenario

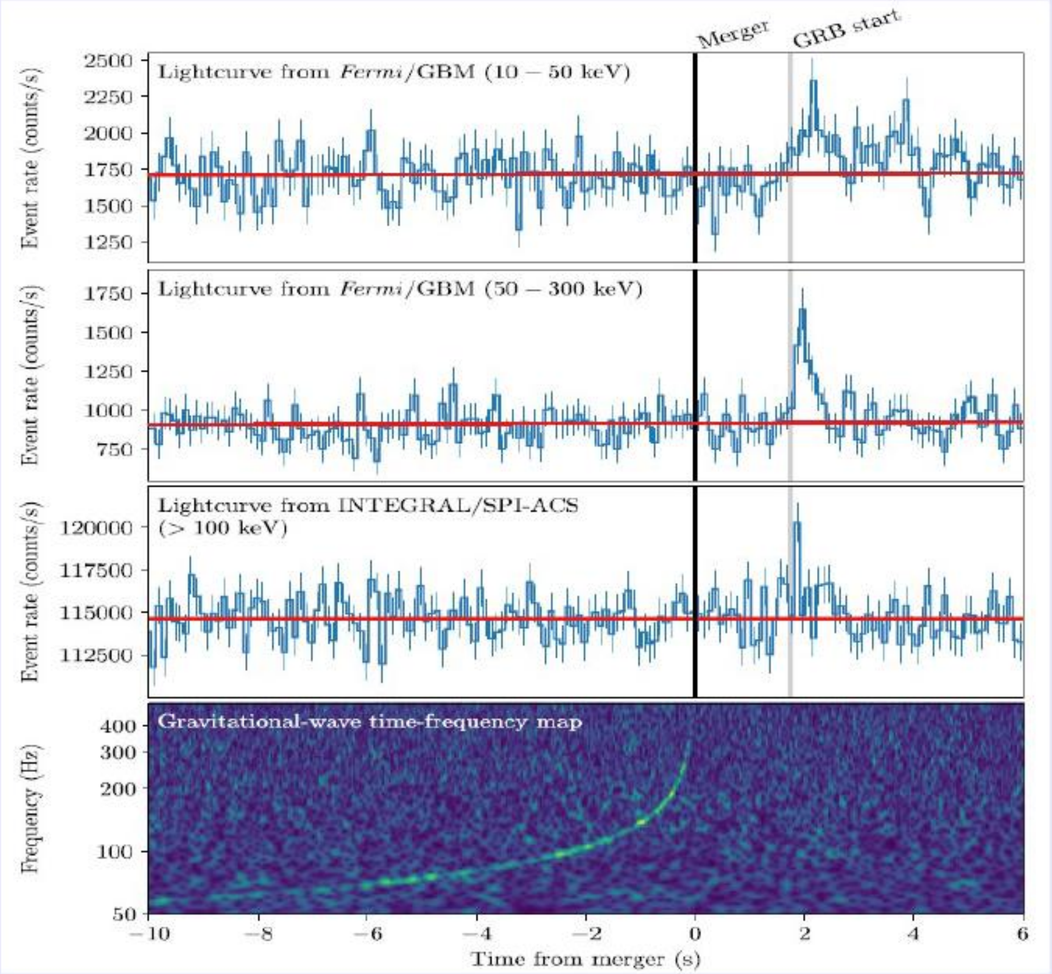
First GW detection of a NS-NS merger

1) Gravitational waves from the inspiral phase seen by LIGO&VIRGO

2) Prompt short gamma-ray-bursts seen by FERMI&INTEGRAL delayed by about 2 sec and lasting about 2sec. Very low luminosity as compared to standard sGRBs: 10^{47} erg/sec

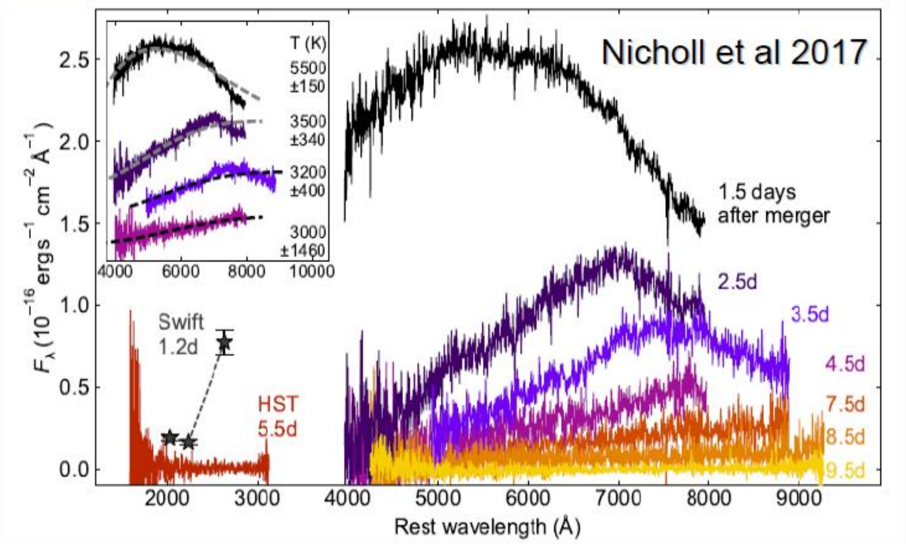
3) Localization of the source (the host galaxy) and estimate of the distance: 40Mpc

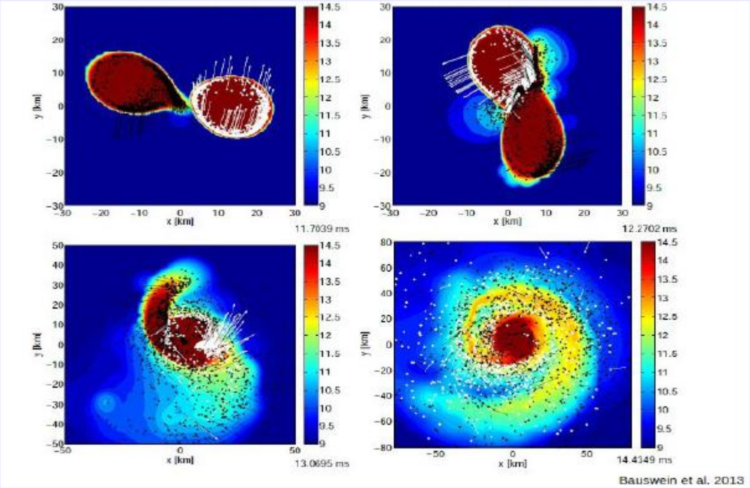
The prompt of the short GRB has not been observed, but there are indirect indications that a jet was launched.
First example of off-axis short GRB?
«Delay» due to being off-axis?



The subsequent kilonova

The merger of two neutron stars causes the ejection of neutron rich material.
Fitting the spectra:
1) amount of material: few 10^{-2} M_{sun}
2) speed of the expanding material: few 0.1c
3) different components (red & blue kilonova):
material ejected from tidal disruption
shock heated material
accretion disk wind


Nicholl et al 2017



Bauswein et al. 2013

The kilonova signal is due to the radioactive decays of the heavy elements synthesized in the ejecta.

Another example: Kolomeitsev et al. 1710.06749 effect of ρ–meson condensation