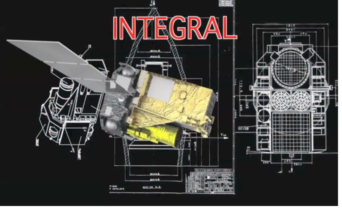


INTEGRAL rivela raggi Gamma da due stelle di neutroni collassate

Integral results from GW170817 and future perspectives

Pietro Ubertini, IAPS-INAF
on behalf of the INTEGRAL Gravitational Team

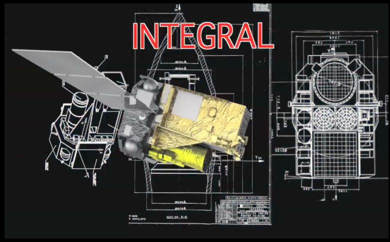
INTEGRAL GW Team members:

A. Bazzano, E. Bozzo, S. Brandt, J. Chenevez, T. J.-L. Courvoisier, R. Diehl, A. Domingo, **C. Ferrigno**, L. Hanlon, E. Kuulkers, E. Jourdain, A. von Kienlin, P. Laurent, F. Lebrun, A. Lutovinov, A. Martin-Carrillo, **S. Mereghetti, L. Natalucci, J. Rodi,** J.-P. Roques, V. Savchenko, R. Sunyaev, **and P. Ubertini**, et al.…

New physics with gravitational waves, December 18, 2017, E. Fermi building, Aula 7 – Dip. di Fisica

Institute for Space Astrophysics and Planetology
Istituto di Astrofisica e Planetologia Spaziali

INTEGRAL ESA M2 mission of the Horizon 2000 program, launched 2002



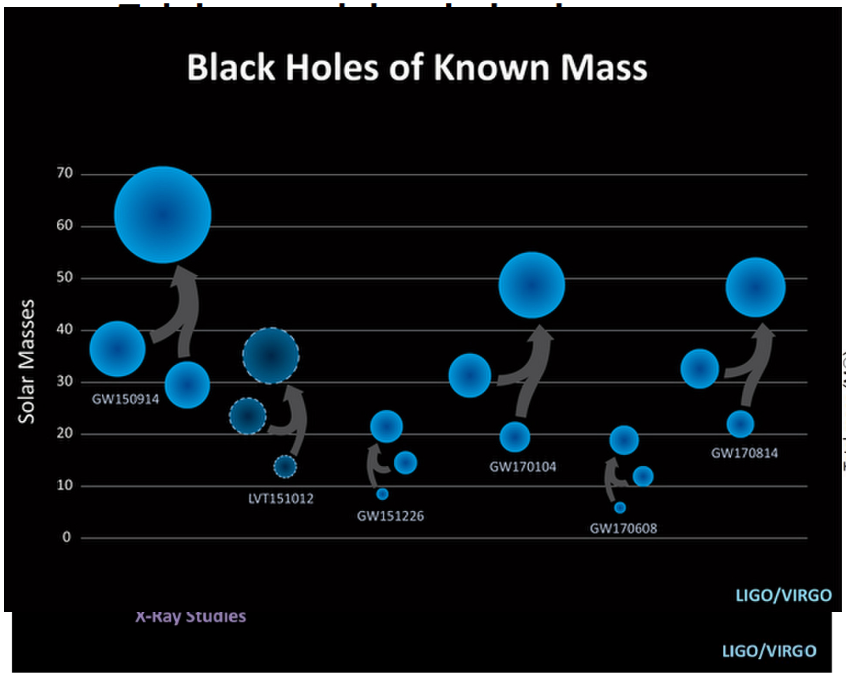
INTEGRAL main features: (Key for GW prompt and afterglow science)

- ✓ 3 keV-10 MeV energy range with unprecedented sensitivity
- ✓ All-sky monitor capability in the range 80 keV - 2.5 MeV
- ✓ Very elliptical orbit with duty cycle >85% and all-sky coverage
- ✓ Long uninterrupted observations 2.7days 6 h perigee passage
- ✓ Wide FoV: ≈ 100-1000 deg^2 plus..
- ✓ High time resolution: <120 µs absolute
- ✓ Arc min angular and keV energy resolution and
- ✓ Unique polarimetry capabity

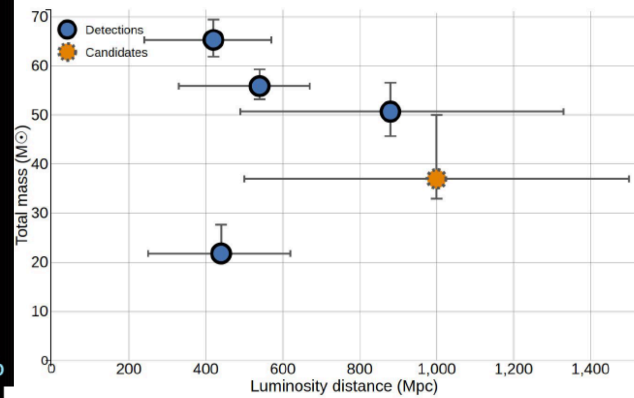
INTEGRAL is the link between the soft X-ray and high energy γ-ray

LIGO/Virgo 2015- August 2017:

In fact, INTEGRAL has observed 5 out of 6 BH-BH mergers



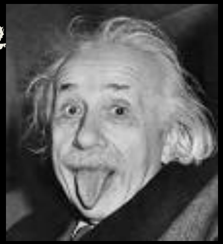
LIGO/Virgo network discovered an unexpectedly larger population of heavy BBH, observable up to **1500 Mpc**

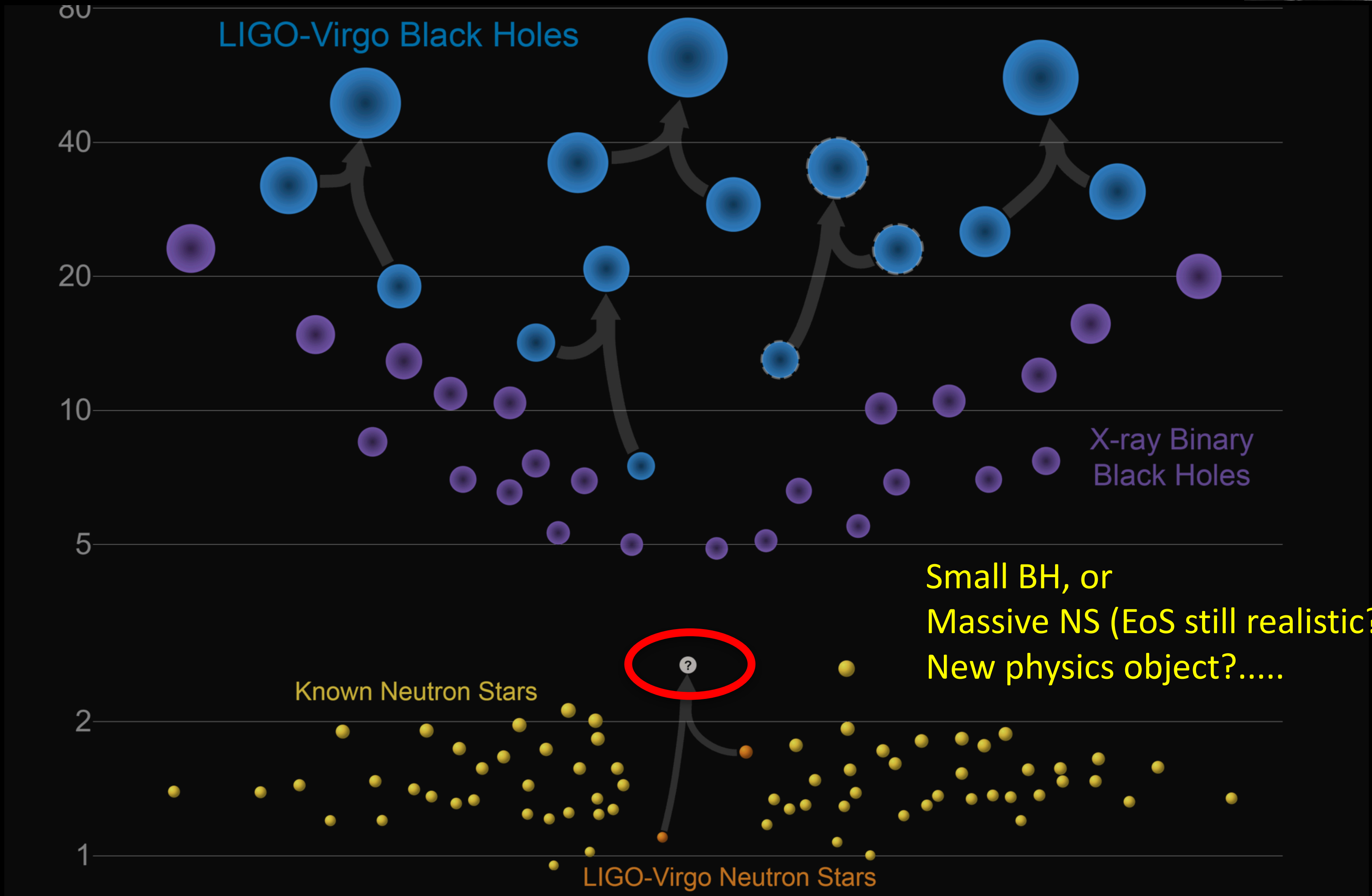


http://chrisnorth.github.io/plotgw/

LIGO-VIRGO detection	**INTEGRAL Observation**
GW150914	Savchenko et al., ApJL, 820, 2, L36, 2016, Abbot et al., ApJL, 826, L13, 2016 Abbot et al., ApJS., 225, 8A, 2016
LVT151012	Savchenko et al., A&A, 603, A46, 2017
GW151226	Missed, pergee passage
GW170104	Savchenko et al., ApJL, 2017
GW170814	Savchenko et al., GCN
GW170817 NS-NS Inspiral	**Savchenko et al., ApJL 848, L15, 2017, Abbott et al., ApJL 848, L12, 2017** **Abbott et al., ApJL 848, L13, 2017**

However , one of the main expected sou
of GW is the inspiral of binary NS:
GW170817 = GRB170817A
is the text book case!!





Small BH, or
Massive NS (EoS still realistic?),
New physics object?.....

Credits: LIGO-VIRGO Collaboration

P. Ubertini, IAPS-INAF

L'Universo

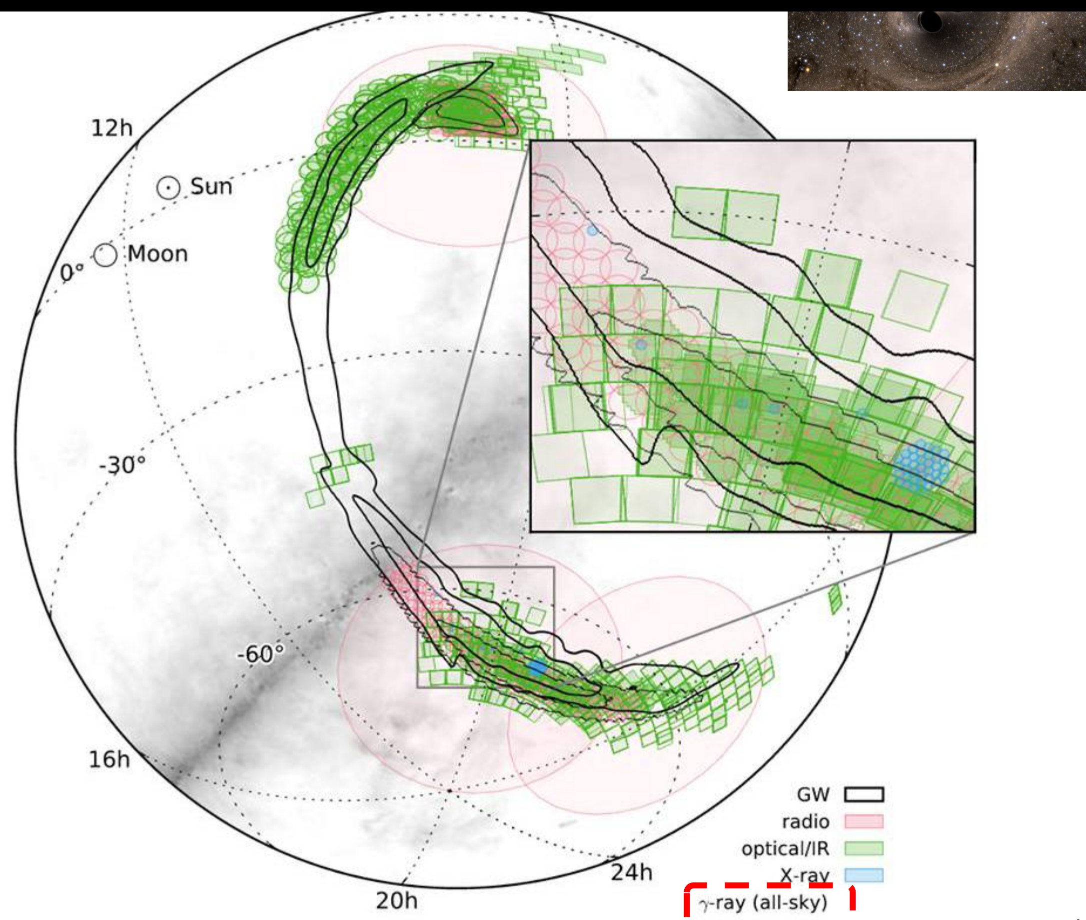
Before GW 170817 there were 2 missing informations: a signal in gamma-ray contemporary to the LVC trigger and an accurate error box: INTEGRAL and FERMI have detected for the first time a quasi-simultaneous GRB, and refined in real time the error box that VIRGO improved drammatically

follow-up challenges: localization

The alerts are promptly distributed to observers from radio to gamma-ray, who made the agreements with LIGO/Virgo collaboration

LIGO/Virgo - INTEGRAL MoU was lead by the project scientist, ISDC, and institutes from the entire INTEGRAL collaboration

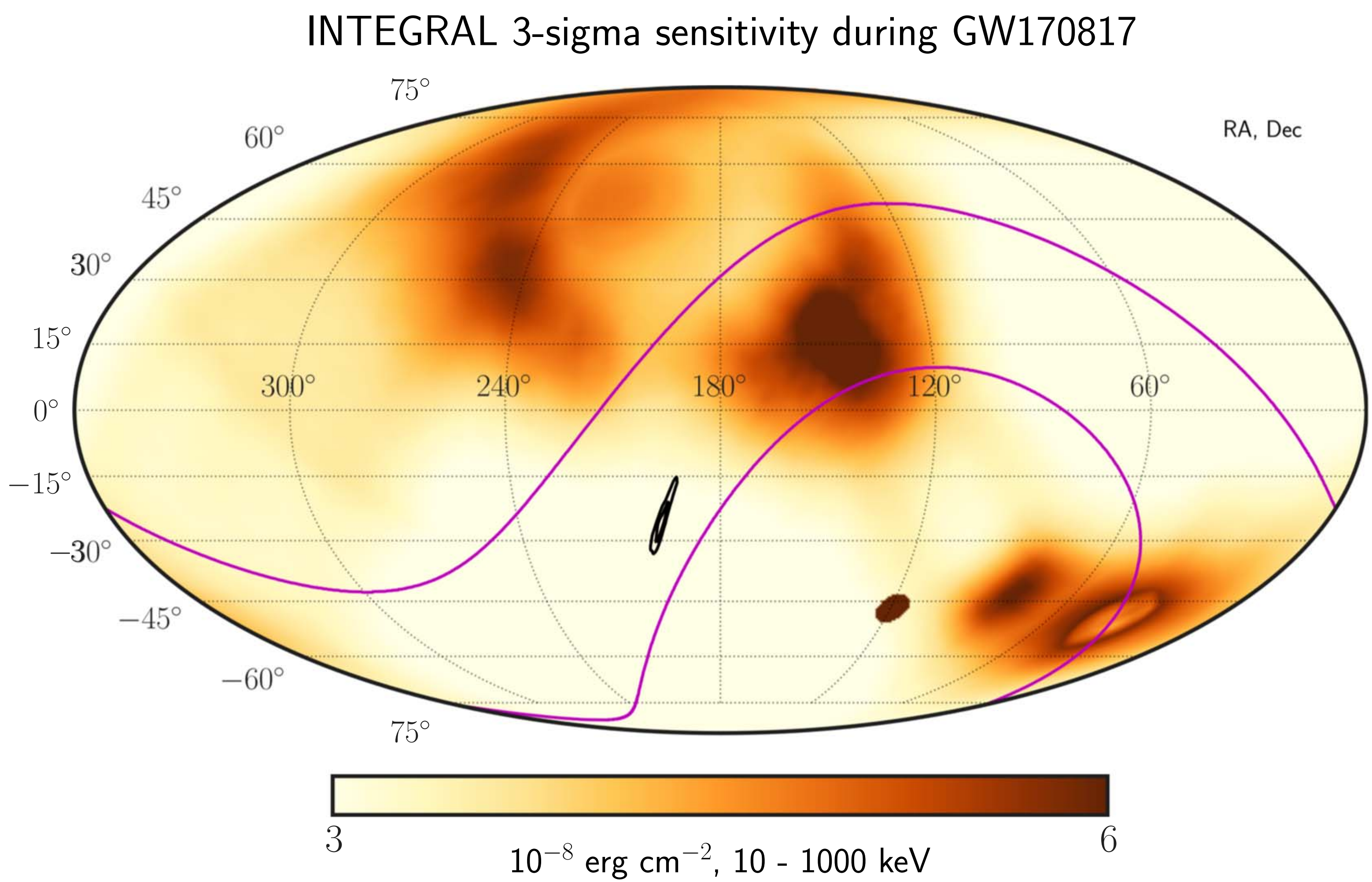
Very extended localization creates special challenges



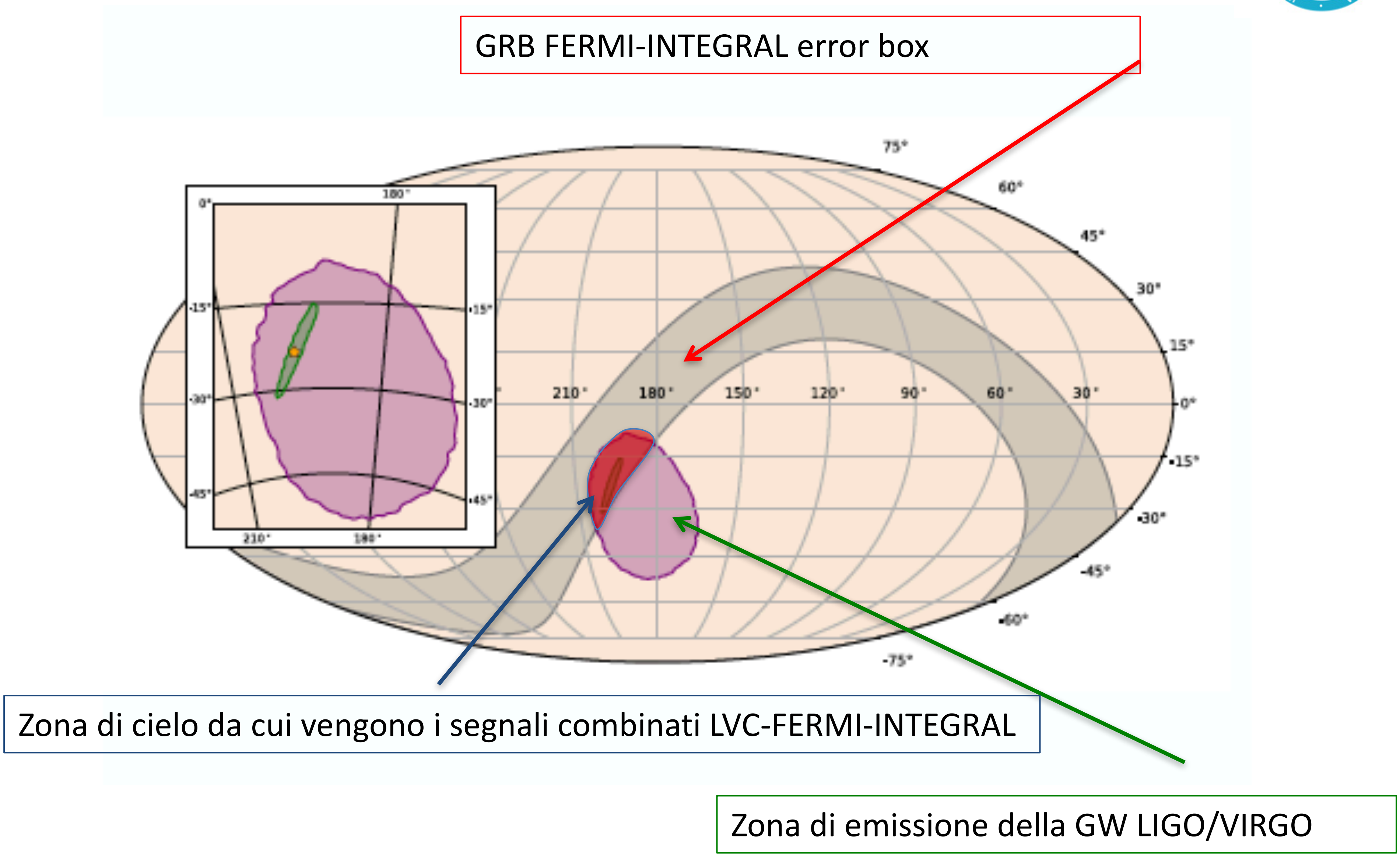
Follow-up of GW150914

Only INTEGRAL, Konus

INTEGRAL Sensitivity to GW170817 direction

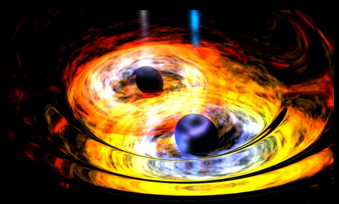


INTEGRAL detects prompt gamma ray emission quasi-contemporary to GWs

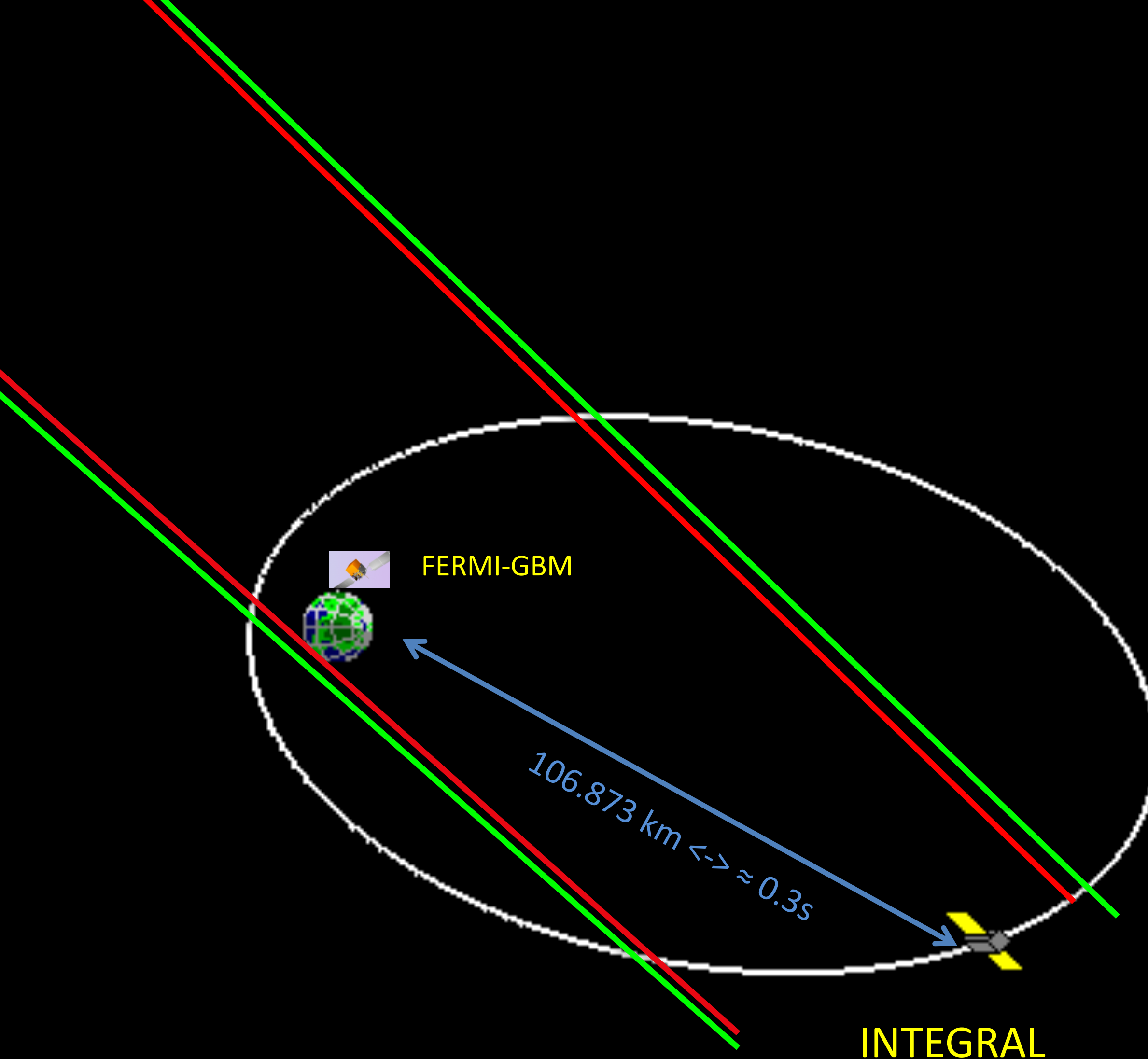


Credits: B.P. Abbot et al., ApJL, 2017, in press; Savchenko et al., ApJL, 2017, in press

P. Ubertini, IAPS-INAF



Direzione di arrivo del segnale Gravitazionale (GW) dalle due stelle di neutroni che si fondono (NS-NS)



Arrival sequence of the Signals:

- Virgo (Pisa)
- FERMI LEO
- Geo Centre
- LIGO Livingston
- LIGO Hartford
- INTEGRAL HEO

P. Ubertini, IAPS-INAF

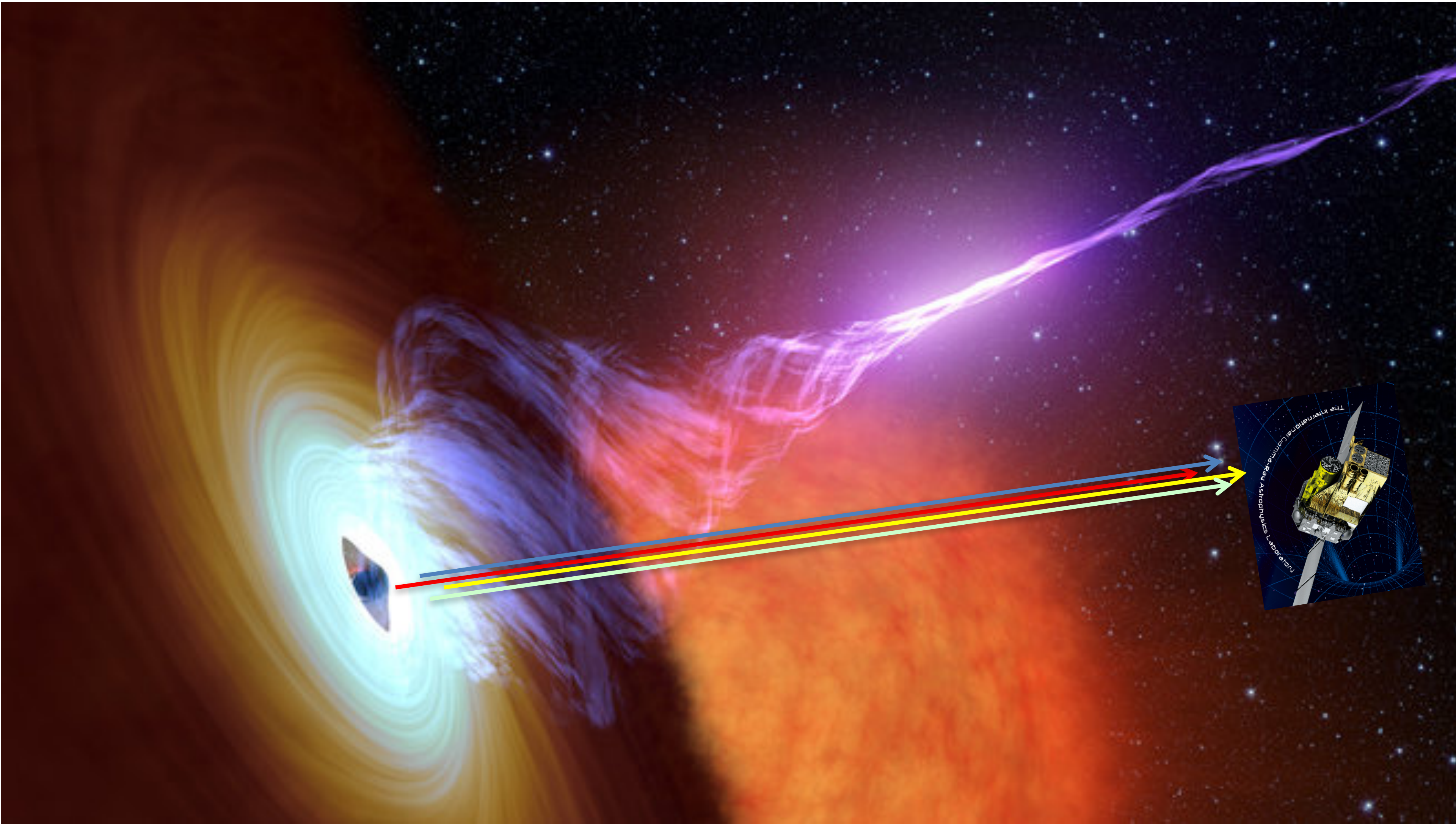
NOTICE and GCN sequences

- On 2017-08-17 at 12:41:20 FERMI/GBM NOTICE in response to a real-time Fermi/GBM trigger on a sGRB at 12:41:06.48 UTC
- LVC GCN 21505, issued 2017-08-17 at 13:21:42 GMT LIGO/Virgo G298048: Fermi GBM trigger 524666471/17081752:, LIGO/Virgo Identification of a possible gravitational-wave
- LVC GCN 21506, issued 2017-08-17 at 13:47:37 LIGO/Virgo G298048: Fermi GBM trigger 170817.529 and LIGO single IFO
- INTEGRAL detection, GCN 21507, of prompt γ-ray counterpart to LIGO VIRGO G298048, coincident with GBM trigger, issued at 2017-08-17 at 13:57:47 GMT

P. Ubertini

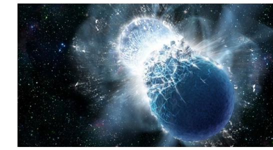
INTEGRAL has detected a short GRB 1.7s after the NS-NS coalescence: this has been the first detection of the Kilonova resulted from the debris of the NS-NS fusion….

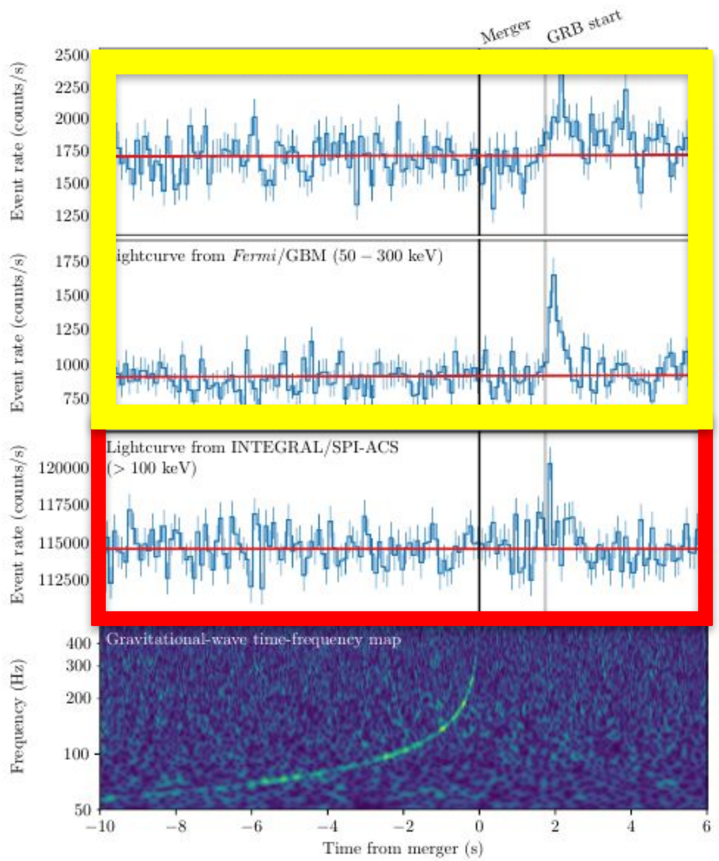
Just after the SGRB detection we have **failed to detect any gamma ray afterglow**, with the best sensitivity to the continuum and gamma-ray lines so far achieved.



The observational data

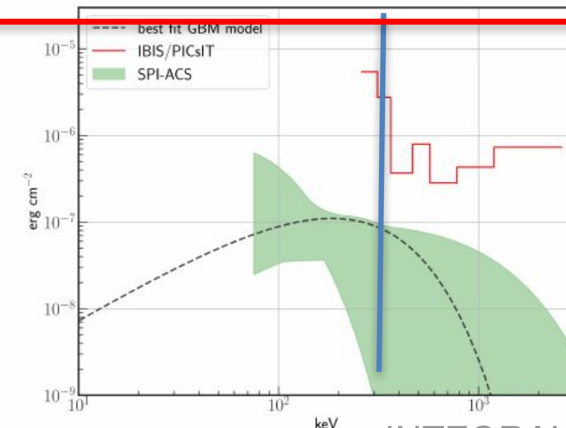
GW170817+GRB170817A





LVC+Fermi+INTEGRAL 2017

Binary Neutron Star merger, discovered by Fermi/GBM and LIGO, independently observed by INTEGRAL/SPI-ACS, in good agreement with Fermi/GBM



INTEGRAL 2017

Despite **soft GRB spectrum** and moderately favorable orientation, INTEGRAL achieved confident detection

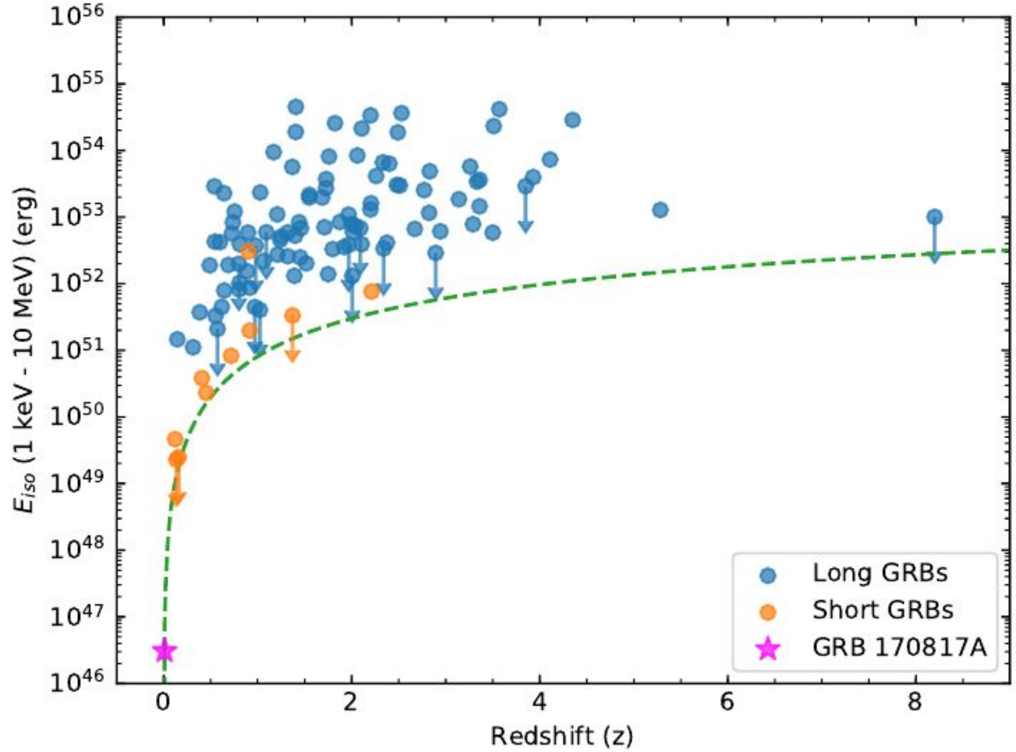
B. P. Abbott et al. 2017 ApJL 848 L13

V. Savchenko et al. 2017 ApJL 848 L15

Extremely low luminosity of GRB170817A

Distance of **40 Mpc** is much less than ever measured for any GRB (short or long)

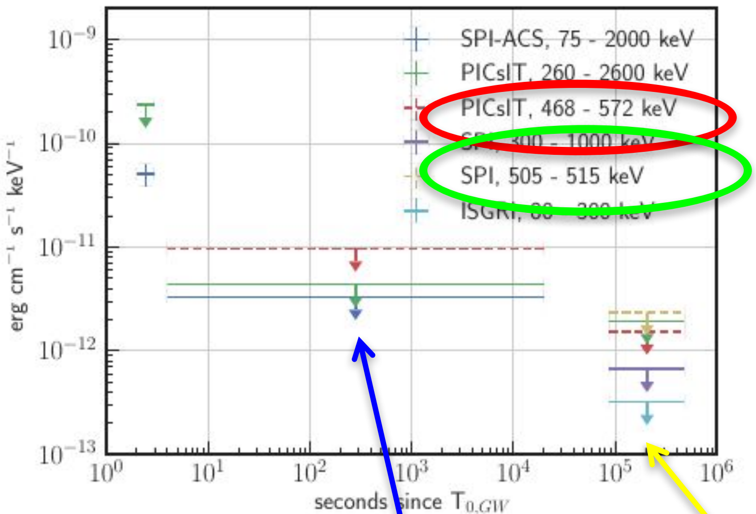
This implies low luminosity, and Gamma-to-GW ratio of **$<10^{-6}$** is much less than that measured for other sGRB with known distances

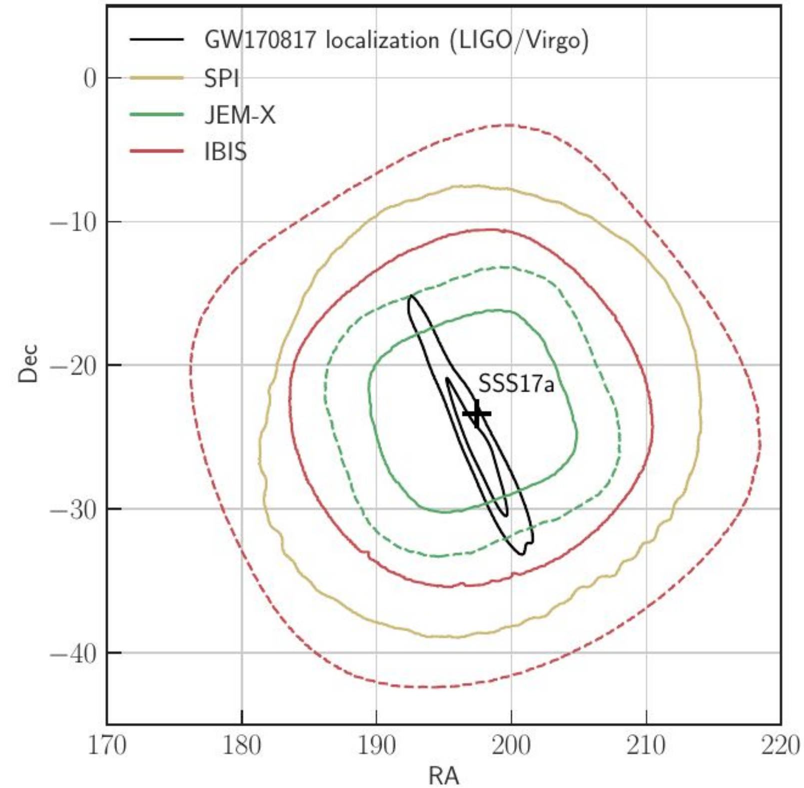


LVC+Fermi+INTEGRAL 2017

INTEGRAL pointed follow-up

A GRB at 40 Mpc could have produced bright hard X-ray afterglow. INTEGRAL can constrain new flux at least from T_0 to T_0+20ks.





VS 2017

Allsky momitoring
SPI-ACS + IBIS-PICsIT + IBIS-VETO

Pointed observations
SPI + IBIS + JemX +OMC

INTEGRAL spent about 20ks in with the same aspect after the prompt detection, then was Repointed toward the most probable error-box (known at that time) and then toward the refined error box position for about 5 days

Kilonova models published on 16 October, obtained from the prompt Short GRB seen by INTEGRAL and FERMI/GBM

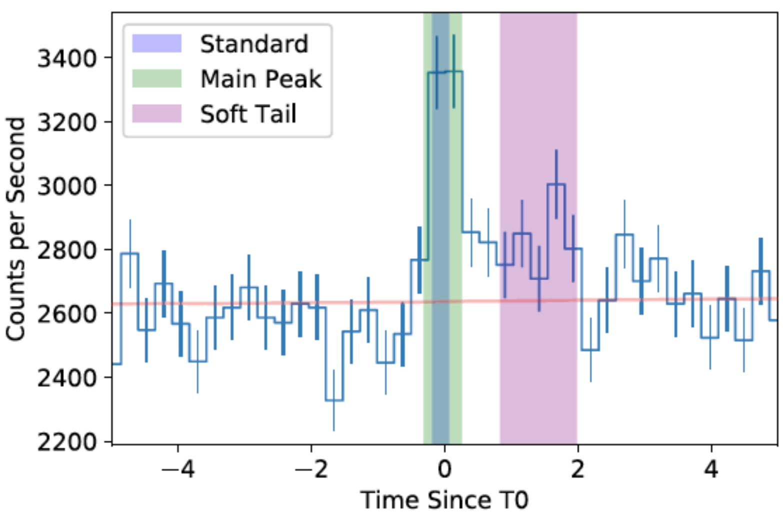
Short burst, 1.7s latency → emitted by internal shocks, from 100-200.000 km region

B. P. Abbott et al. 2017 ApJL 848 L13 (LIGO-VIRGO + FERMI/GBM + INTEGRAL

Goldstein et al., ApJL, 848, L14 , 2017

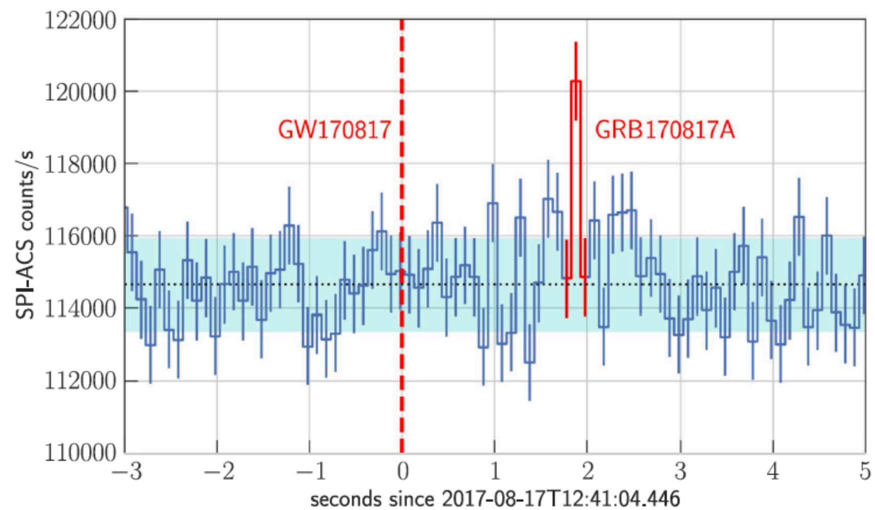
Savchenko et al., ApJL 848, L15, 2017

FERMI-GBM data



The 256 ms binned light curve of GRB 170817A in the 10–300 keV band for NaI 1, 2, and 5. The shaded regions are the different time intervals selected for spectral analysis. The inclusion of the lower energies shows the soft tail out to T0+2 s.

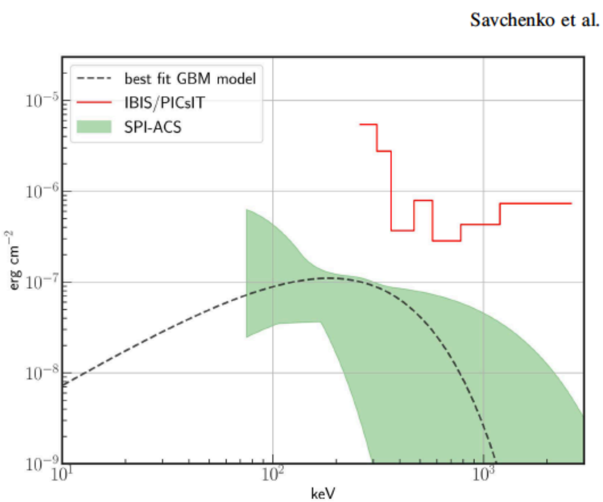
INTEGRAL SPI-ACS data

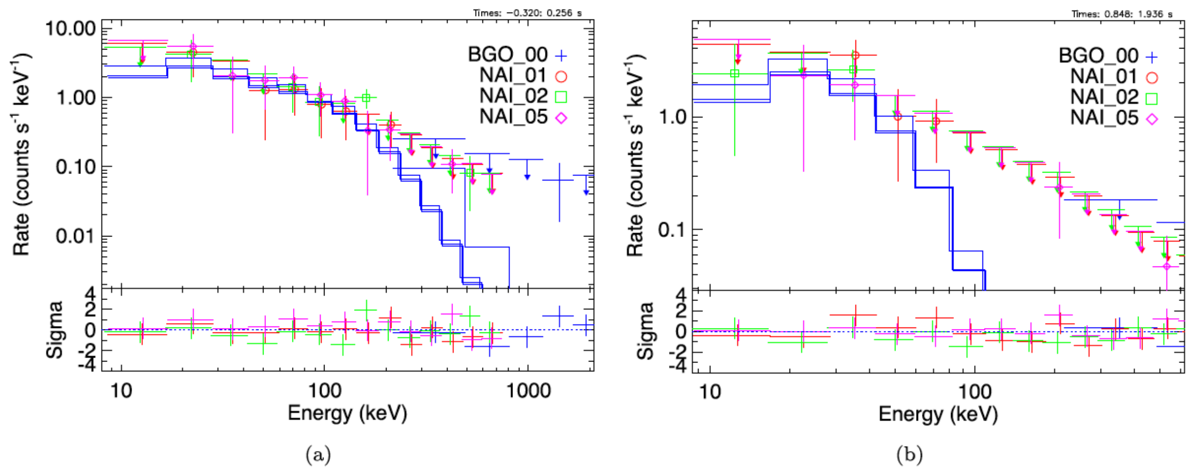


SPI-ACS light curve of GRB 170817A (100 ms time resolution), detected 1.7s after GW170817. The red line highlights the 100 ms pulse, which has an S/N of 4.6 in SPI-ACS. The blue shaded region corresponds to a range of one standard deviation of the background.

Kilonova models published on 16 October, obtained from the prompt Short GRB seen by INTEGRAL and FERMI/GBM

No lines, no spectral features, soft Gamma-ray spectrum





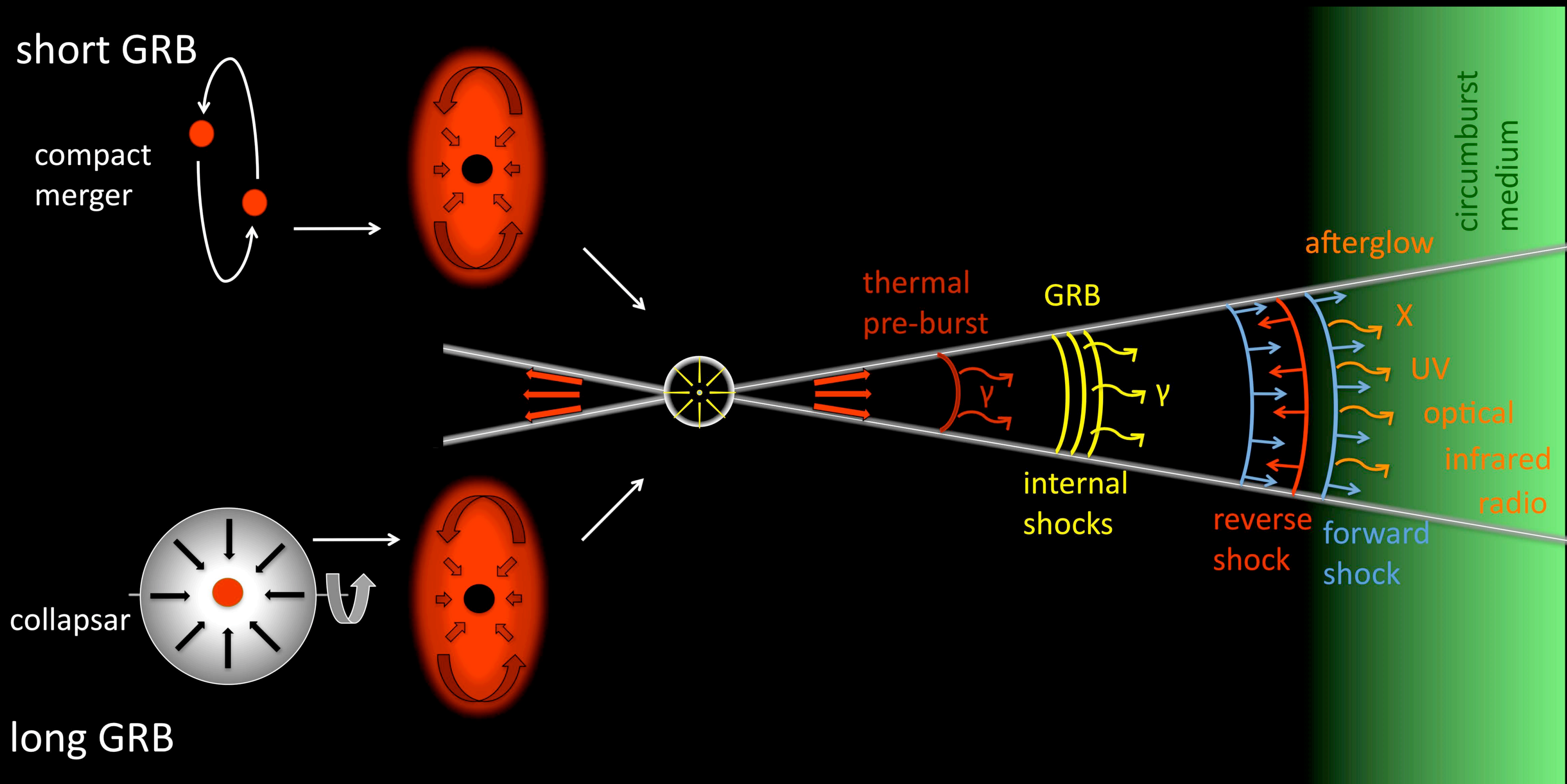
Average hard X-ray/gamma-ray spectrum of the initial pulse of GRB170817A. The shaded green region corresponds to the range of spectra compatible with the INTEGRAL/SPI-ACS. IBIS/PICsIT provides a complementary independent upper limit at high Energies

Spectral fits of the count rate spectrum for the [Left] main pulse (Comptonized) and [Right] softer emission (blackbody). The blue bins are the forward-folded model t to the count rate spectrum, the data points are colored based on the detector, and 2 upper limits estimated from the model variance are shown as downward-pointing arrows. The residuals are shown in the lower subpanels.

We assumed a very simple and standard model to be compared with observed data:

- ✓ No pre-burs,
- ✓ Short gamma-ray burst
- ✓ No gamma-ray afterglow

Model for short GRBs

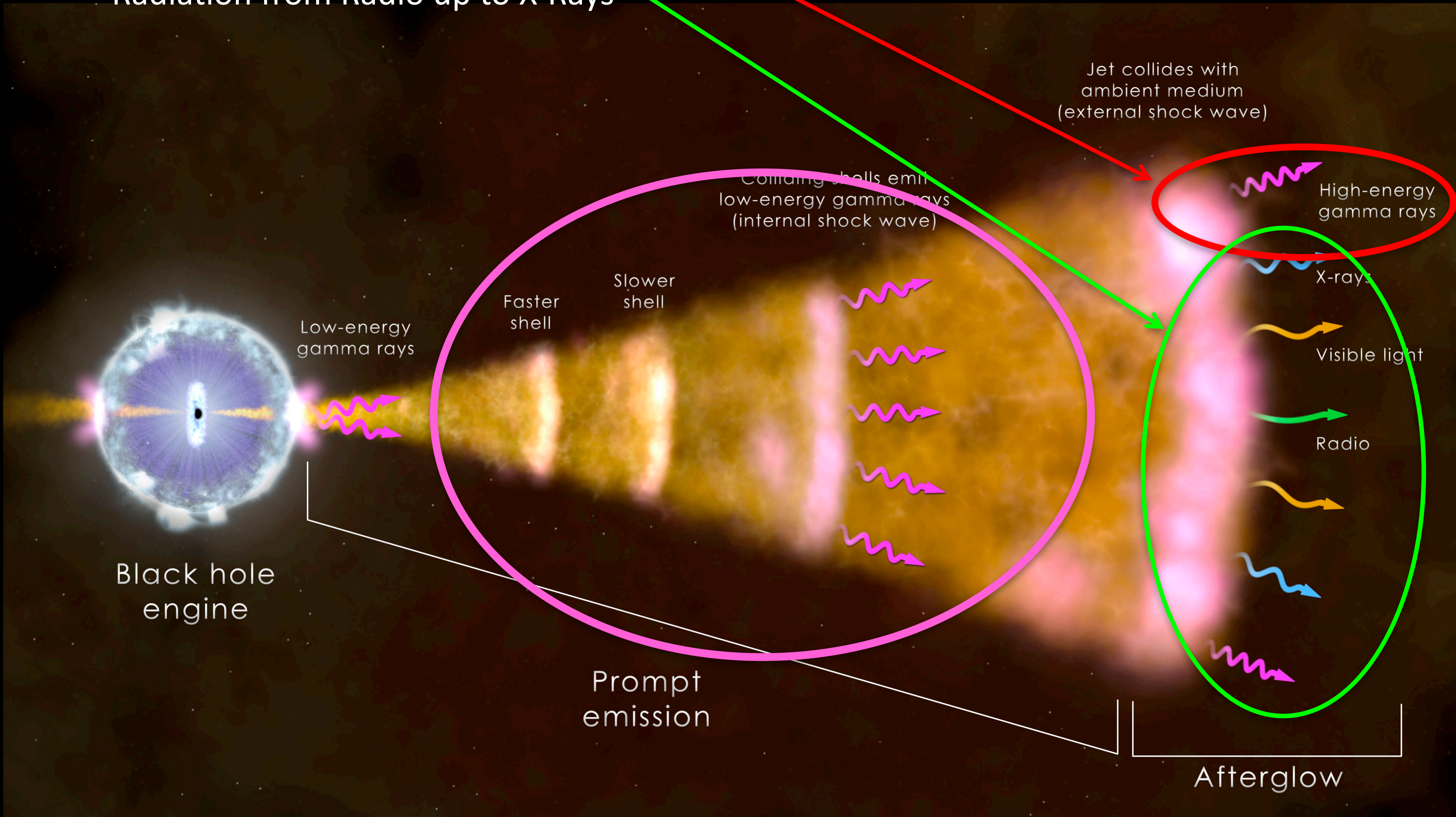


What we learned immediately:

- ✓ Short weak burst 1.7s (?) after the Inspiral
- ◆ No high energy gamma-rays

and after a few days:

- ✓ Radiation from Radio up to X-Rays



The same model a bit more "physical" and quantitative:
In this pure hat-top jet model we should not have seen the SGRB….

Gamma Ray Bursts - emission mechanism

the standard ("Fireball") model (Piran 1999) :

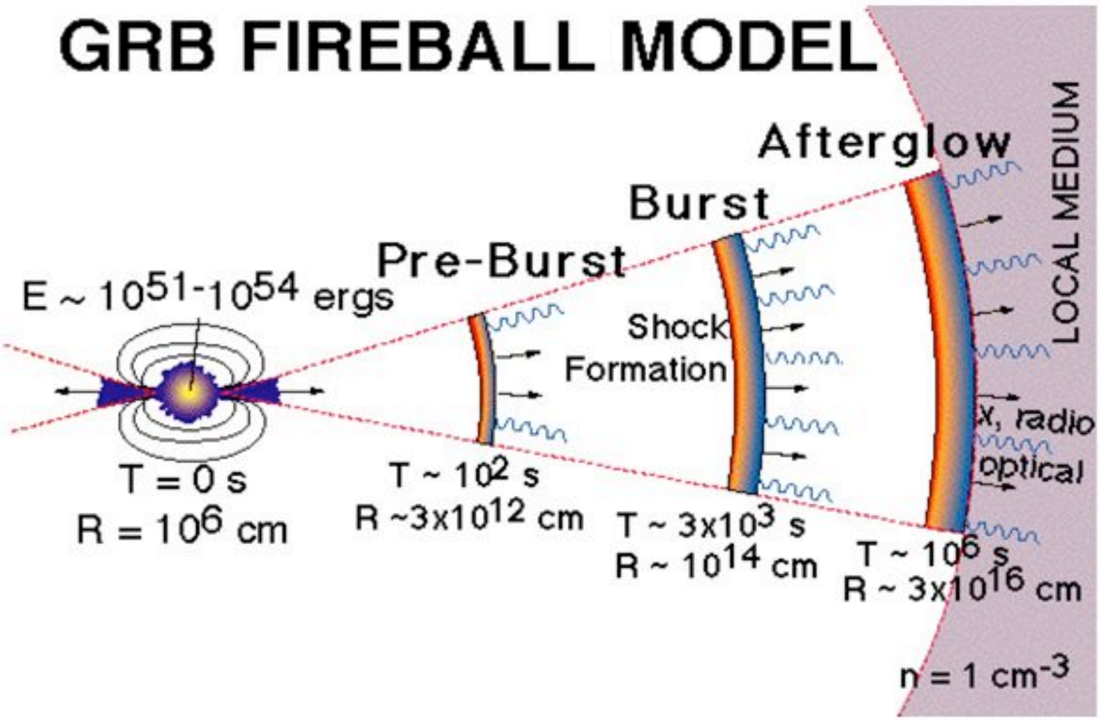


figure from A. Dar, Chin. J. A. A. Vol 6 (2006)

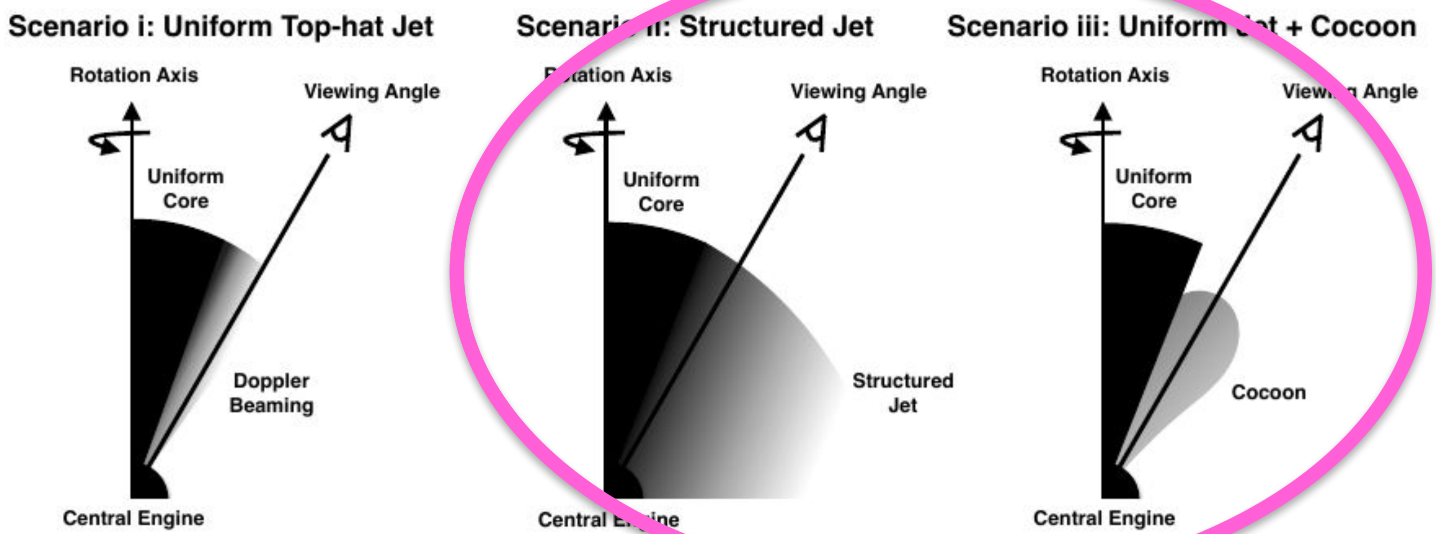
- hypernova explosion or similar
- emission of an optically thick "fireball"
- expansion of fireball into highly relat., optically thin, conical shells of electrons and positrons
- GRB: synchrotron emission in collision between shells, Inverse Compton emission (SSC)
- afterglow: synchrotron emission from collision of shells into ISM (blast wave)
- reverse shocks can form and lead to delayed flares

Possible models published on 16 October, obtained from the prompt Short GRB seen by INTEGRAL and FERMI/GBM
No lines, no spectral features....

Possible models

This were the best models available
At the 30 November GSSI meeting

As revealed by LIGO/Virgo data, the merger was observed at **20-60 deg off-axis,** proving that a considerable amount of gamma-ray energy is emitted far from the symmetry axis of the system



To establishing the true luminosity function we need more off-axis GRBs

LVC+Fermi+INTEGRAL 2017

The X-ray counterpart to the gravitational-wave event GW170817

E. Troja[1,2], L. Piro[3], H. van Eerten[4], R. T. Wollaeger[5], M. Im[6], O. D. Fox[7], N. R. Butler[8], S. B. Cenko[2,9], T. Sakamoto[10], C. L. Fryer[5], R. Ricci[11], A. Lien[2,12], R. E. Ryan Jr[7], O. Korobkin[5], S.-K. Lee[6], J. M. Burgess[13], W. H. Lee[14], A. M. Watson[14], C. Choi[6], S. Covino[15], P. D'Avanzo[15], C. J. Fontes[5], J. Becerra González[16,17], H. G. Khandrika[7], J. Kim[6], S.-L. Kim[18], C.-U. Lee[18], H. M. Lee[19], A. Kutyrev[1,2], G. Lim[6], R. Sánchez-Ramírez[3], S. Veilleux[1,9], M. H. Wieringa[20] & Y. Yoon[6]

X-Ray and optical Imaging … and spectroscopy…

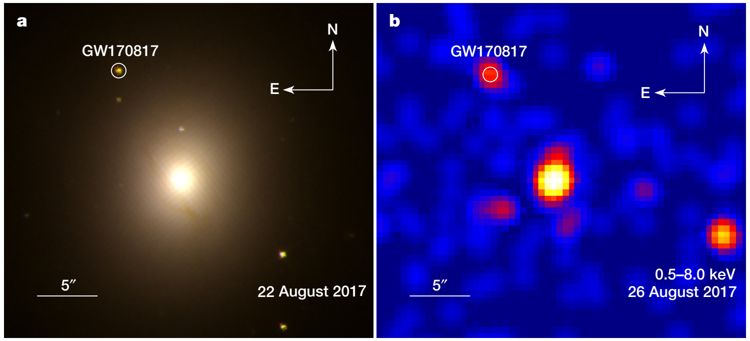
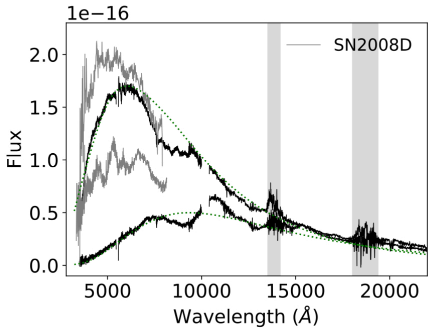


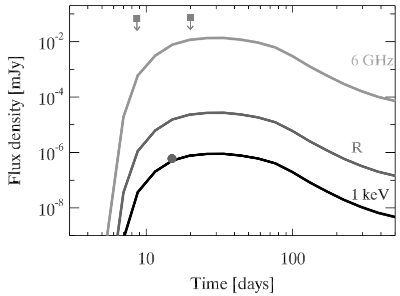
Figure 1 | Optical/infrared and X-ray images of the counterpart of GW170817. a, Hubble Space Telescope observations show a bright and red transient in the early-type galaxy NGC 4993, at a projected physical offset of about 2 kpc from its nucleus. A similar small offset is observed in less than a quarter of short GRBs[5]. Dust lanes are visible in the inne regions, suggestive of a past merger activity (see Methods). **b**, Chandra observations revealed a faint X-ray source at the position of the optica infrared transient. X-ray emission from the galaxy nucleus is also visib

Spectroscopic identification of r-process nucleosynthesis in a double neutron star merger

E. Pian[1], P. D'Avanzo[2], S. Benetti[3], M. Branchesi[4,5], E. Brocato[6], S. Campana[2], E. Capp



Extended Data Figure 2: Black-body fit to the SSS17a/DLT17ck spectra. The two early X-shooter spectra of GW170817, obtained 1.5 and 3.5 d after discovery are compared with the spectra of the type Ib SN 2008D[59] obtained at 2-5 days after explosion respectively (blue, arbitrarily scaled in flux). The dotted line show the black-body fit of the optical continuum of GW170817 with temperature 5000 and 3200 K respectively.

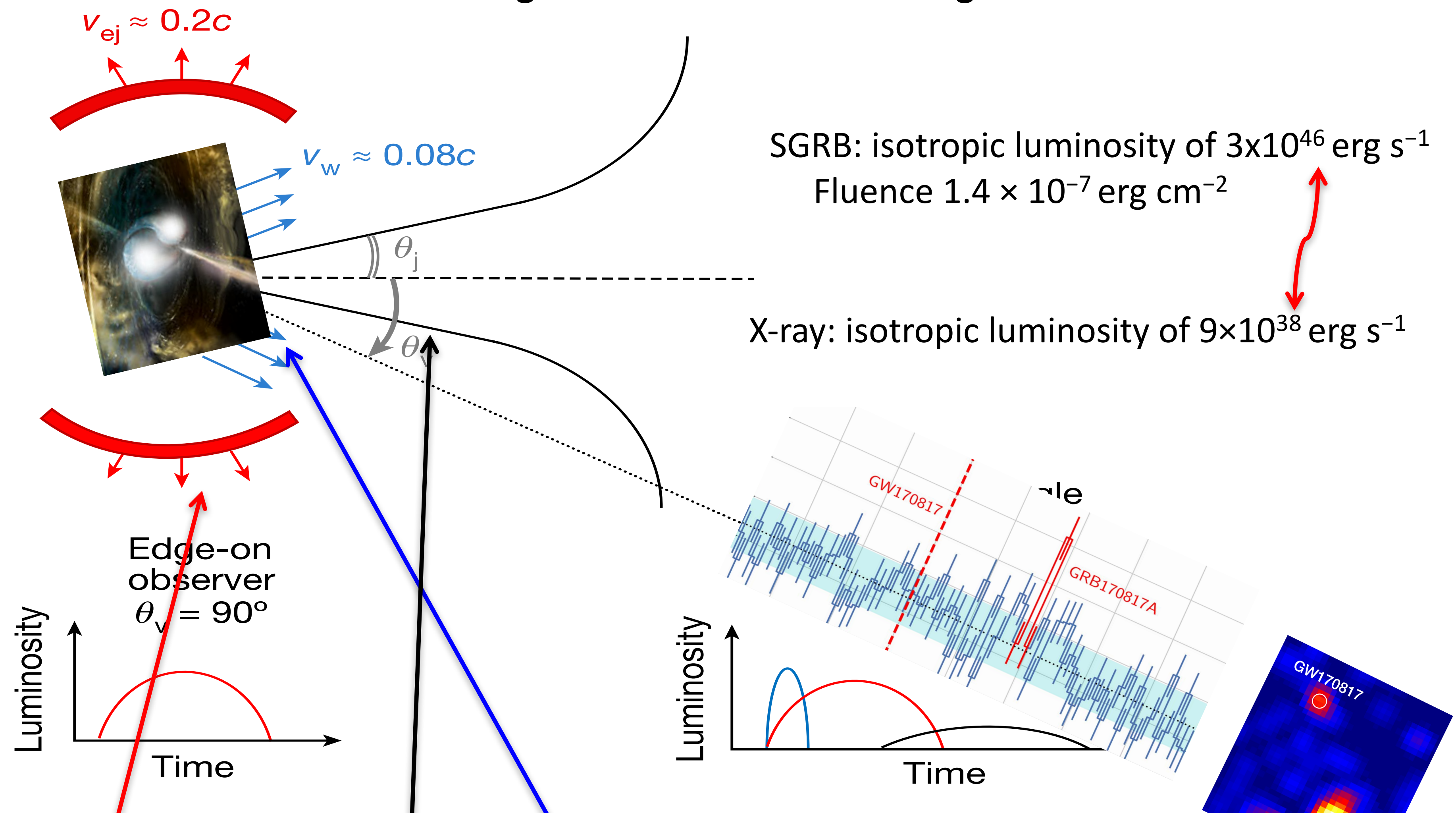


Extended Data Figure 4: Off-axis GRB afterglow modeling. Synthetic X-ray, optical and radio light curve of the GRB afterglow as predicted in an off-axis jet model. The filled dot symbol shows the X-ray detection[23] and the arrows two representative radio upper limits [77,78].

The merger of two neutron stars is predicted to give rise to three major detectable phenomena: **a short burst of γ-rays, a gravitational wave signal, and a transient optical/near-infrared source powered by the synthesis of large amounts of very heavy elements via rapid neutron capture (the r-process)**.

Such transients, named "kilonovae", are believed to be centres of production of rare elements such as gold and platinum.

Schematic diagram for the model working for GW170817



Following the neutron-star merger, a small amount of fast-moving neutron-rich ejecta (red shells) emits an isotropic kilonova p e infrared.

A larger mass neutron-free wind along the polar axis (blue arrows) produces kilonova emission peaking at optical wavelengths. This emission, although isotropic, is not visible to edge-on observers because it is only visible within a range of angles and otherwise shielded by the high-opacity ejecta. → light material

A collimated jet (black solid cone) emits synchrotron radiation visible at radio, X-ray and optical wavelengths. This afterglow emission outshines all other components if the jet is seen on-axis. However, to an off-axis observer, it appears as a low-luminosity component delayed by several days or weeks

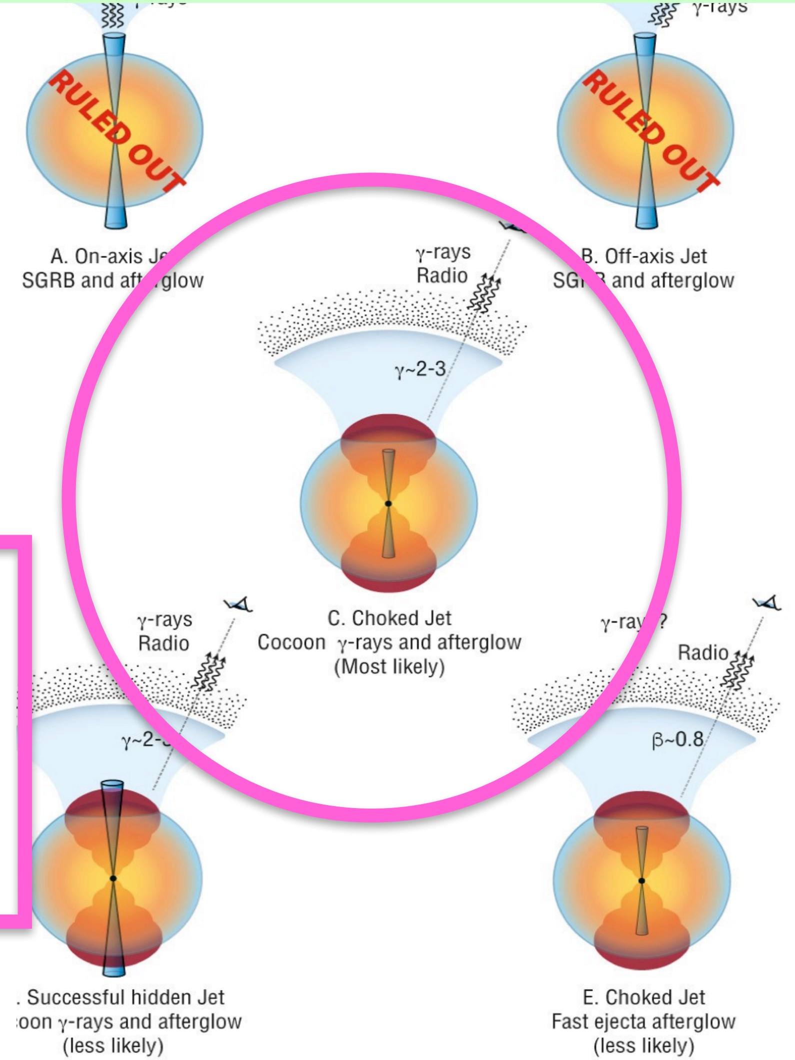
A mildly relativistic wide-angle outflow in the neutron star merger GW170817

K. P. Mooley (1,2,3), E. Nakar (4), K. Hotokezaka (5), G. Hallinan (3), A. Corsi (6), D.A et al.

arXiv:1711.11573, 30 November 2017

Figure 2. Schematic illustration of the various possible jet and dynamical ejecta scenarios. A) A jet seen on-axis, generating both the low-luminosity gamma-rays and the observed radio afterglow. This scenario cannot explain the late rise of the radio emission. It is also unable to explain11 how a low-luminosity jet penetrates the ejecta. It is therefore ruled out. B) A regular (luminous) SGRB jet seen off-axis, producing the gamma-rays and the radio. The continuous moderate rise in the radio light curve rules out this scenario.

C) A choked jet giving rise to a mildly relativistic (ɣ~2-3) cocoon which generates the gamma-rays and the radio waves via an on-axis emission. This is the model that is most consistent with the data. It accounts for the observed gamma-rays, X-rays (possibly also ultraviolet and optical) and radio emission, and provides a natural explanation to the lack of an off-axis jet signature in the radio.



→ Note that this model require an energy injection in the cocoon after the GW collapse…is resembling the AGN case…

THE ASTROPHYSICAL JOURNAL LETTERS, 732:L6 (6pp), 2011 May 1 doi:10.1088/2041-8205/732/1/L6

THE MISSING LINK: MERGING NEUTRON STARS NATURALLY PRODUCE JET-LIKE STRUCTURES AND CAN POWER SHORT GAMMA-RAY BURSTS

LUCIANO REZZOLLA[1], BRUNO GIACOMAZZO[2,3], LUCA BAIOTTI[4], JONATHAN GRANOT[5], CHRYSSA KOUVELIOTOU[6], AND MIGUEL A. ALOY[7]

More specifically, we simulate two equal-mass NSs, each with a gravitational mass of $1.5M_{\odot}$, an equatorial radius of 13.6 km, and on a circular orbit with initial separation of ≃45 km between the centers.
Confined in each star is a poloidal magnetic field with a maximum strength of 10^{12} G. At this separation, the binary loses energy and angular momentum **via emission of gravitational waves** , thus rapidly proceeding on tighter orbits as it evolves.
After about 8 ms (~3 orbits), the two NSs merge forming a **hypermassive NS (HMNS),** namely, a rapidly and differentially rotating NS, whose mass, 3.0 $M_{\odot}$, is above the maximum mass, 2.1 $M_{\odot}$, allowed with uniform rotation by our ideal-gas EOS8 with an adiabatic index of 2.
Being metastable, an HMNS can exist as long as it is able to resist against collapse via a suitable redistribution of angular momentum, or through the pressure support coming from the large temperature increase produced by the merger.

However, **because the HMNS is also losing a gular momentum through GWs**, its lifetime is limited to a few ms, after which it collapses to a BH with mass M = 2.91 M☉ and spin J/M2 = 0.81, surrounded by a hot and dense torus with mass Mtor = 0.063 $M_{\odot}$ (Giacomazzo et al. 2011).

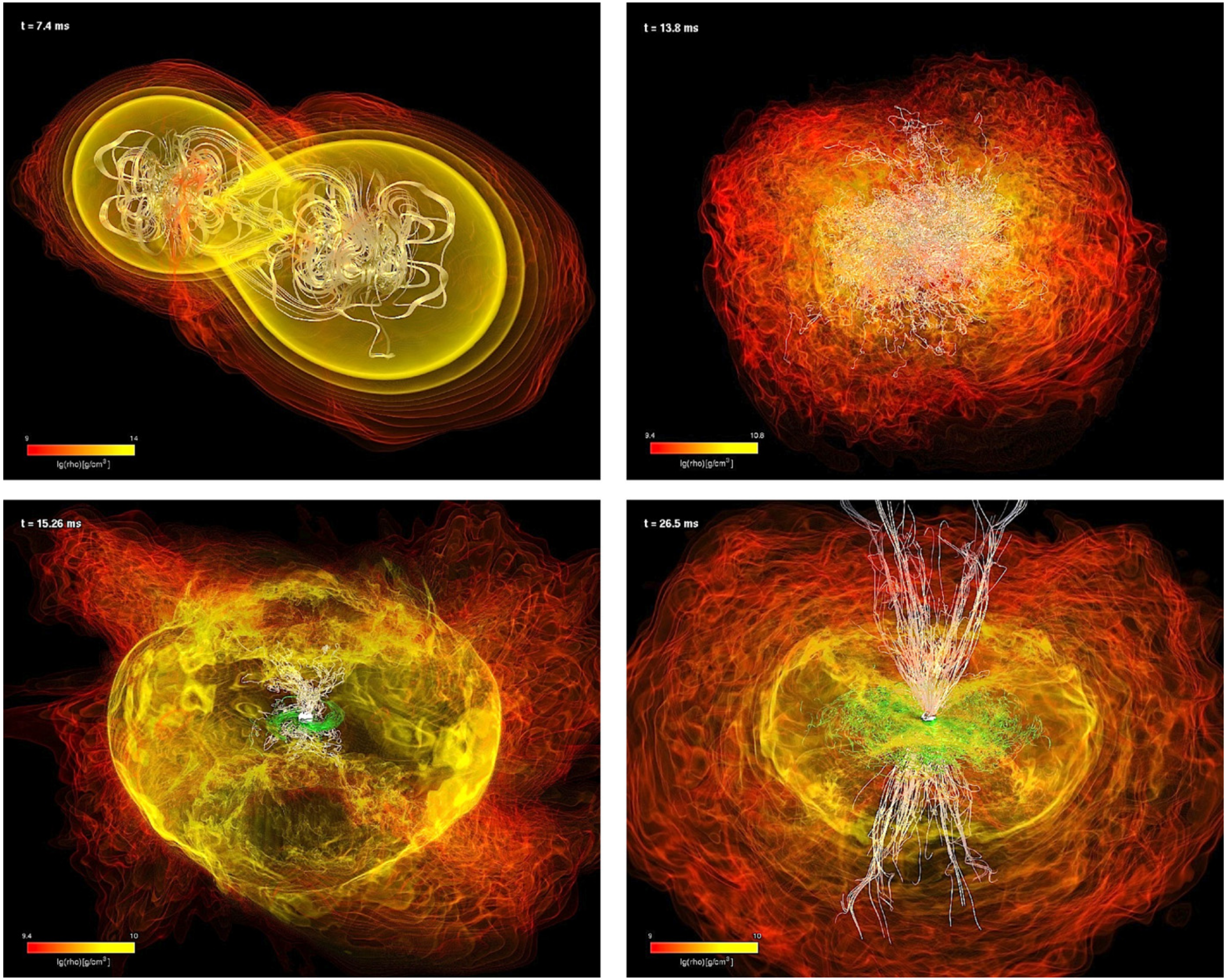


Figure 1. Snapshots at representative times of the evolution of the binary and of the formation of a large-scale ordered magnetic field. Shown with a color-code map is the density, over which the magnetic-field lines are superposed. The panels in the upper row refer to the binary during the merger ($t = 7.4$ ms) and before the collapse to BH ($t = 13.8$ ms), while those in the lower row to the evolution after the formation of the BH ($t = 15.26$ ms, $t = 26.5$ ms). Green lines sample the magnetic field in the torus and on the equatorial plane, while white lines show the magnetic field outside the torus and near the BH spin axis. The inner/outer part of the torus has a size of $\sim 90/170$ km, while the horizon has a diameter of $\simeq 9$ km.

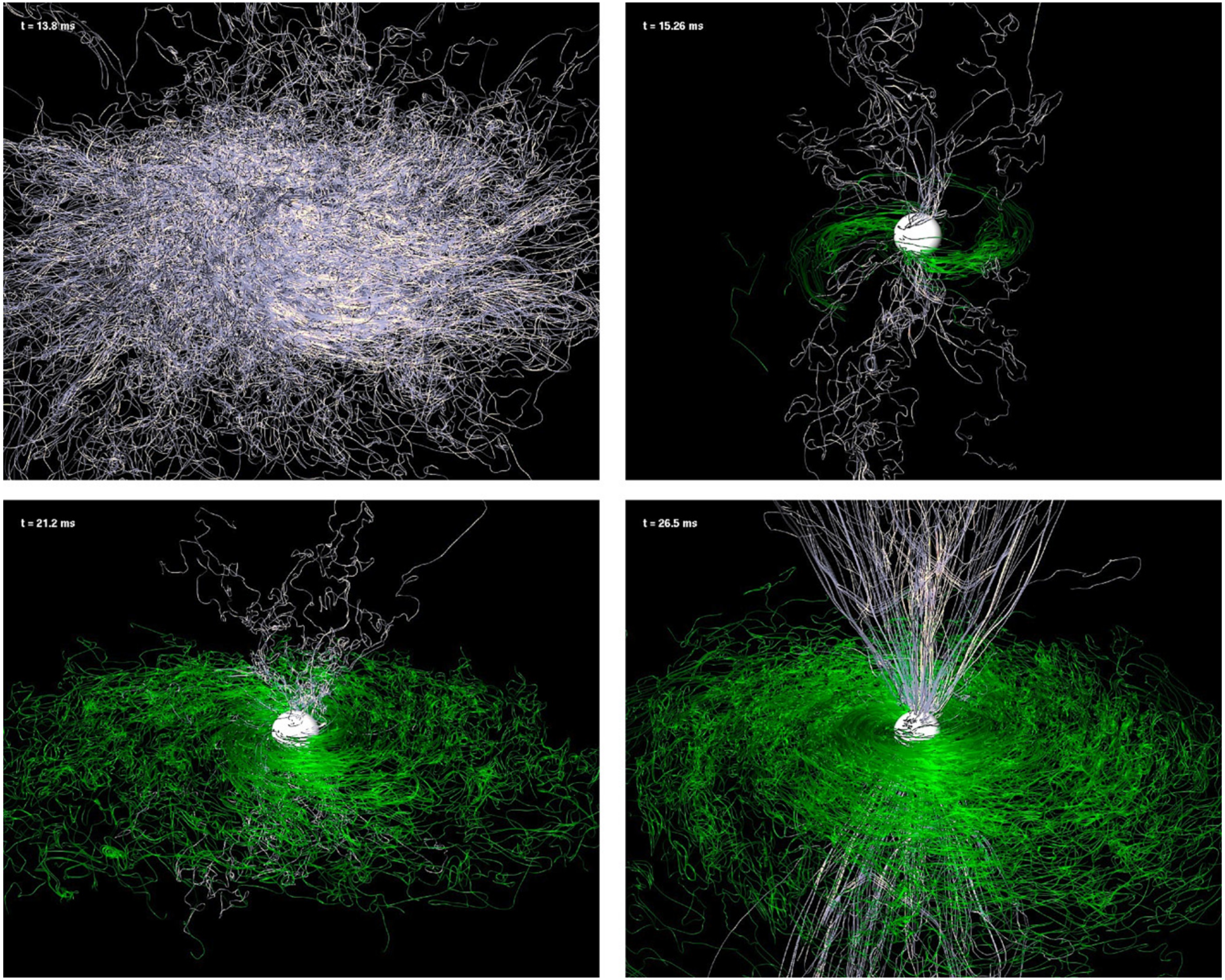


Figure 3. Magnetic-field structure in the HMNS (first panel) and after the collapse to BH (last three panels). Green refers to magnetic-field lines inside the torus and on the equatorial plane, while white refers to magnetic-field lines outside the torus and near the axis. The highly turbulent, predominantly poloidal magnetic-field structure in the HMNS ($t = 13.8$ ms) changes systematically as the BH is produced ($t = 15.26$ ms), leading to the formation of a predominantly toroidal magnetic field in the torus ($t = 21.2$ ms). All panels have the same linear scale, with the horizon diameter being of $\simeq$9 km.

Fundamental consequences

This is the **first multimessenger detection, with total of 5.3 sigma GW-GRB association significance**

At least some **short GRBs are associated to BNS mergers**

The 2 s delay comparing to 130 Mly distance implies that **speed of gravity** can be constrained to unprecedented precision:

$$-3 \times 10^{-15} \leq \frac{\Delta v}{v_{\mathrm{EM}}} \leq +7 \times 10^{-16}$$

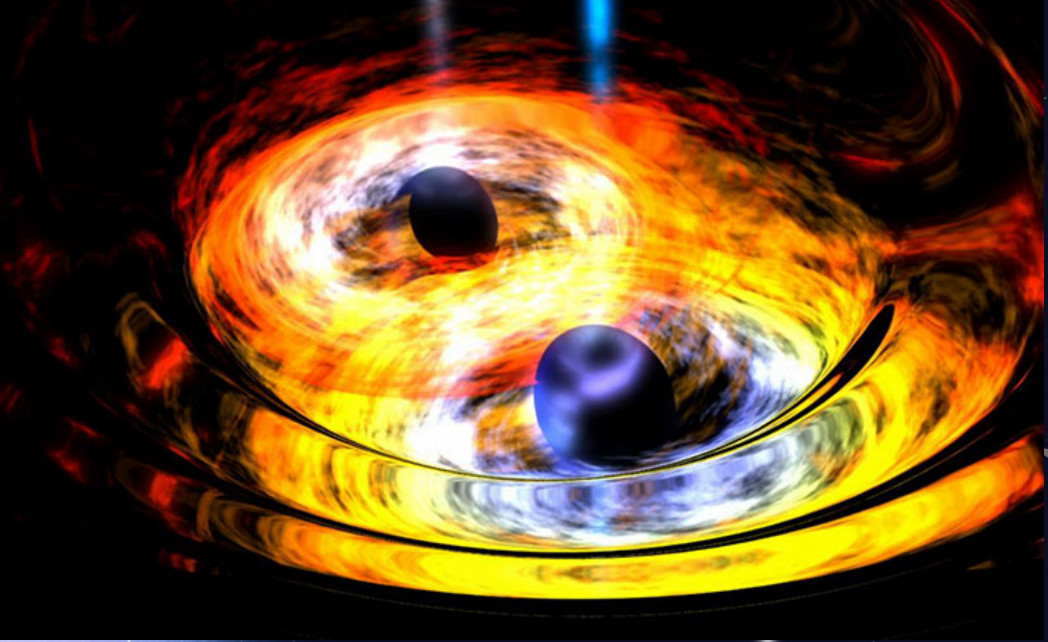
Such a consistency between GW speed and speed of light, implies stringent **limits on Lorentz Invariance Violation**

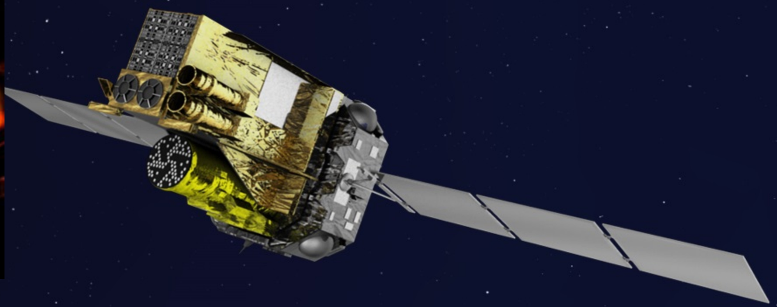
This observation provides the **new insights into the EoS of the neutron matter**

LVC+Fermi+INTEGRAL 2017

Conclusions

- ✓ **Detection of a GRB from an off-axis merger implies much more frequent GRB-BNS associations, which might happen regularly in O3, the bright triggers will be most probably immediately public →**
- ✓ **be prepared for unexpected optimistic scenario!..i.e. several NS-NS inspiral/year**
- ✓ **VIRGO and INTEGRAL and the GRAVITA have played a key role in the successful investigation of the GW170817 event(s). This will be remembered as a key step in the understanding of the astrophysical scenario of the closeby Universe → we are proud to be the follower the Fermi-Amaldi road in the area of great discoveries…..**
- ✓ **Be proud to be part of the La Sapienza University!**





THANKS FOR YOUR ATTENTION.. &..

STAY TUNED!!...NEW DATA AND MODELS ARRIVING!