Istituto Nazionale di Astrofisica

Osservatorio Astronomico di Brera

ACME

Astrophysics Centre for Multimessenger studies in Europe

GRB & GW electromagnetic counterparts: an observational review

Paolo D’Avanzo

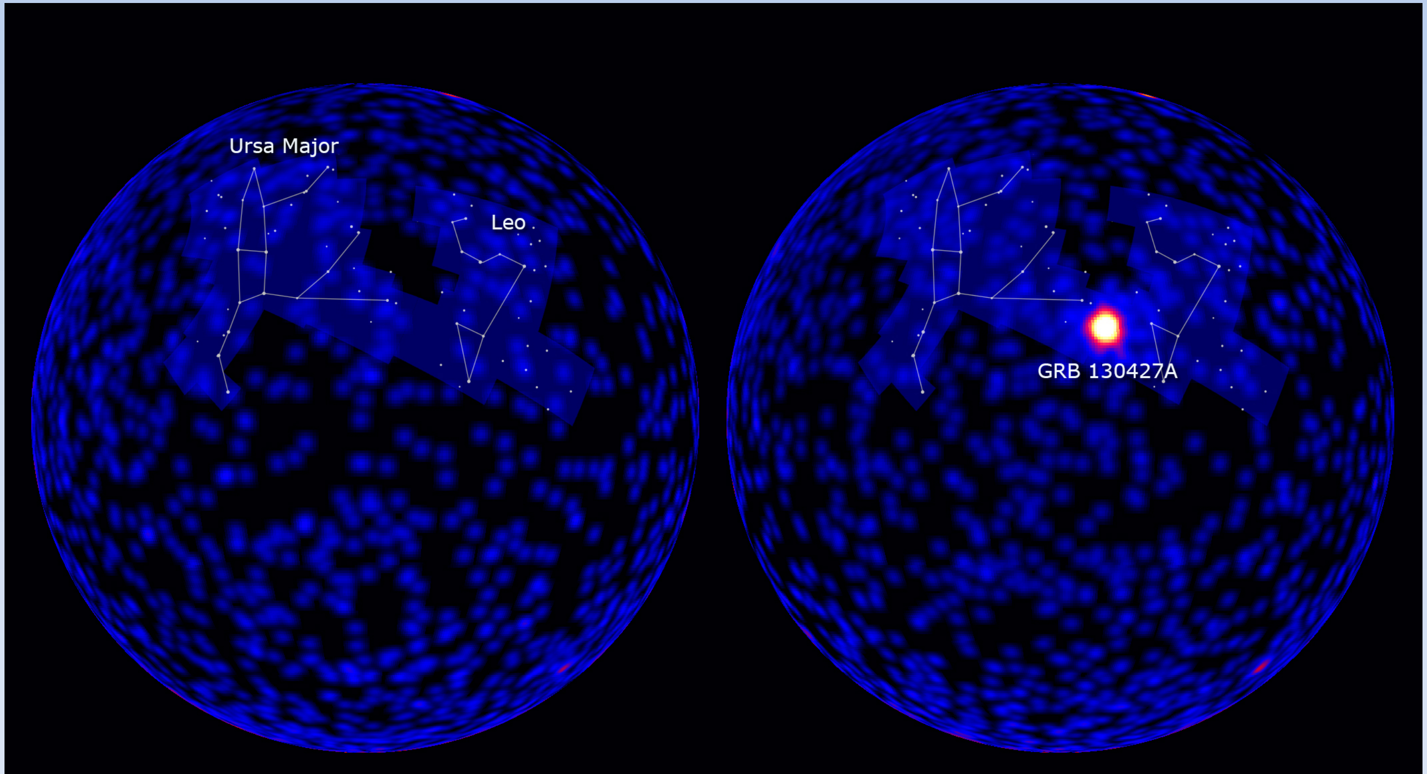
INAF – Osservatorio Astronomico di Brera

Funded by the European Union

ACME project has received funding from the European Union's Horizon Europe Research and Innovation programme under Grant Agreement No 101131928.

What is a Gamma-Ray Burst?

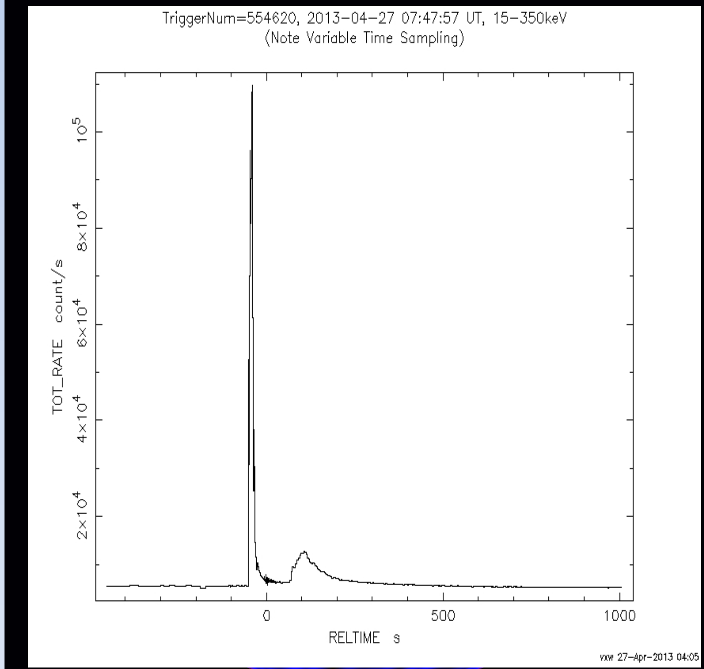
Brief, sudden, intense flash of gamma-ray radiation

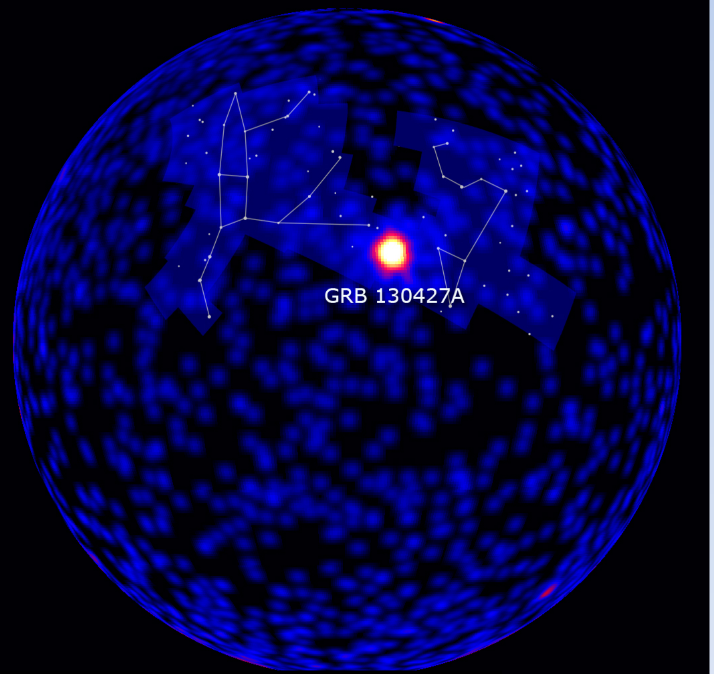


Before and after Fermi LAT views of GRB 130427A, centered on the north galactic pole

What is a Gamma-Ray Burst?

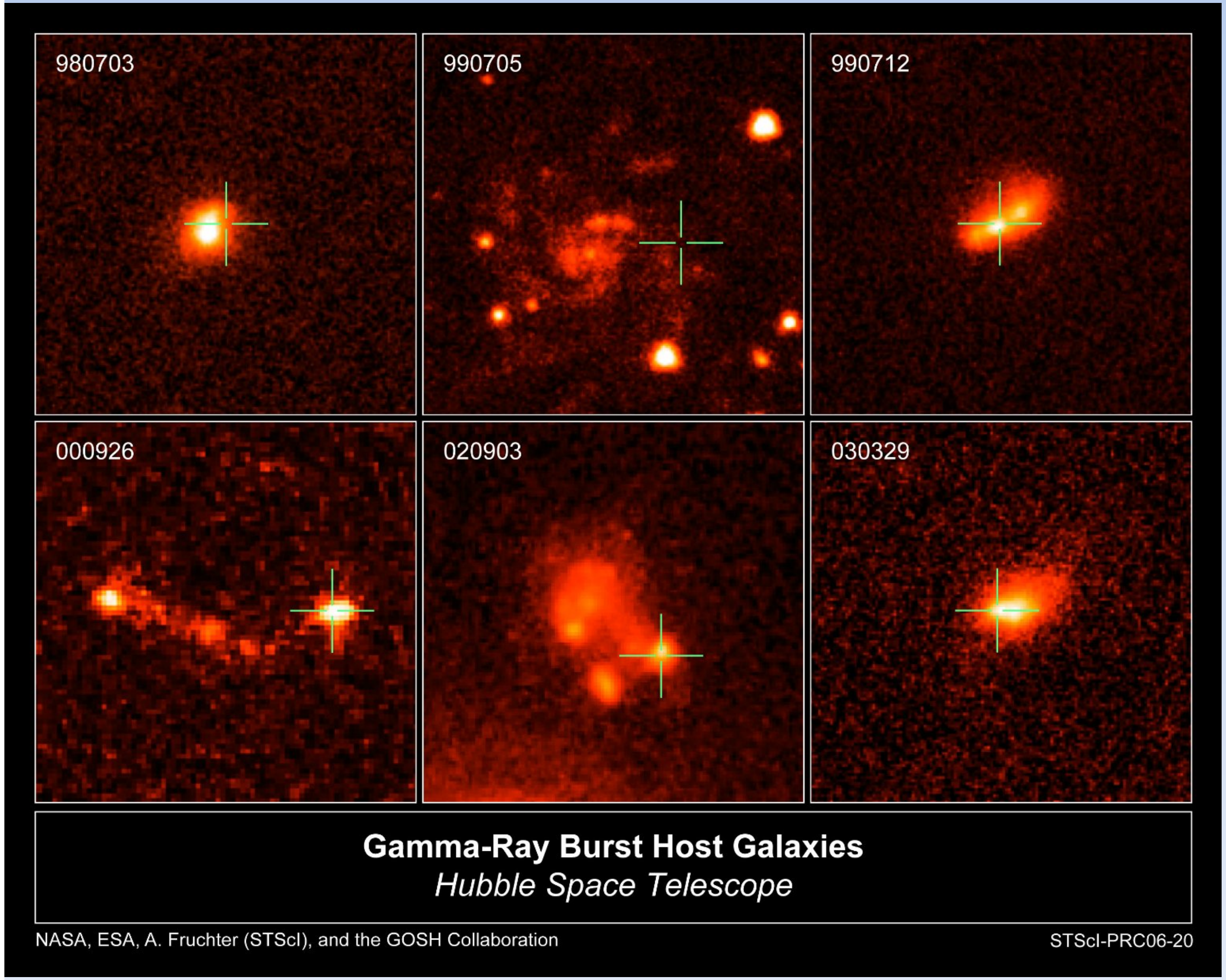
Brief, sudden, intense flash of gamma-ray radiation

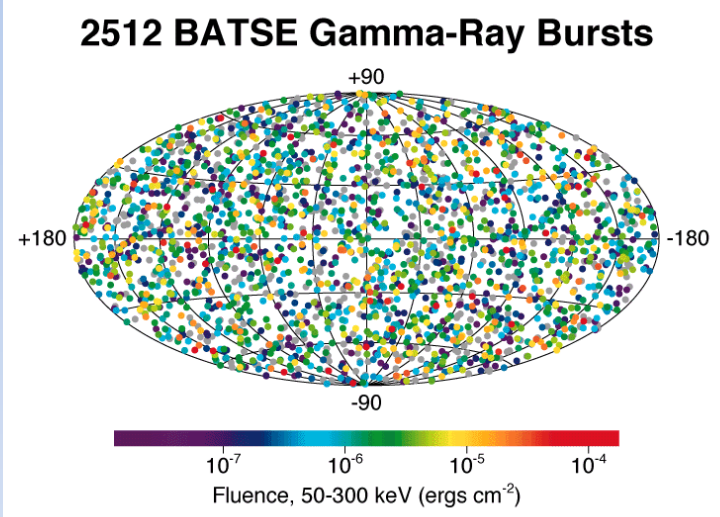




Duration: **from few ms to hundreds of s**
Frequency: **10 keV – 1 MeV**
Fluence: **10^{-7} - 10^{-3} erg cm^{-2}**
Flux: **10^{-8} - 10^{-4} erg cm^{-2} s^{-1}**

GRBs are cosmological and occur in galaxies





Fluence: **10^{-5} erg cm^{-2}**

Distance: **<z>=2.1 ~ 10^{28} cm**

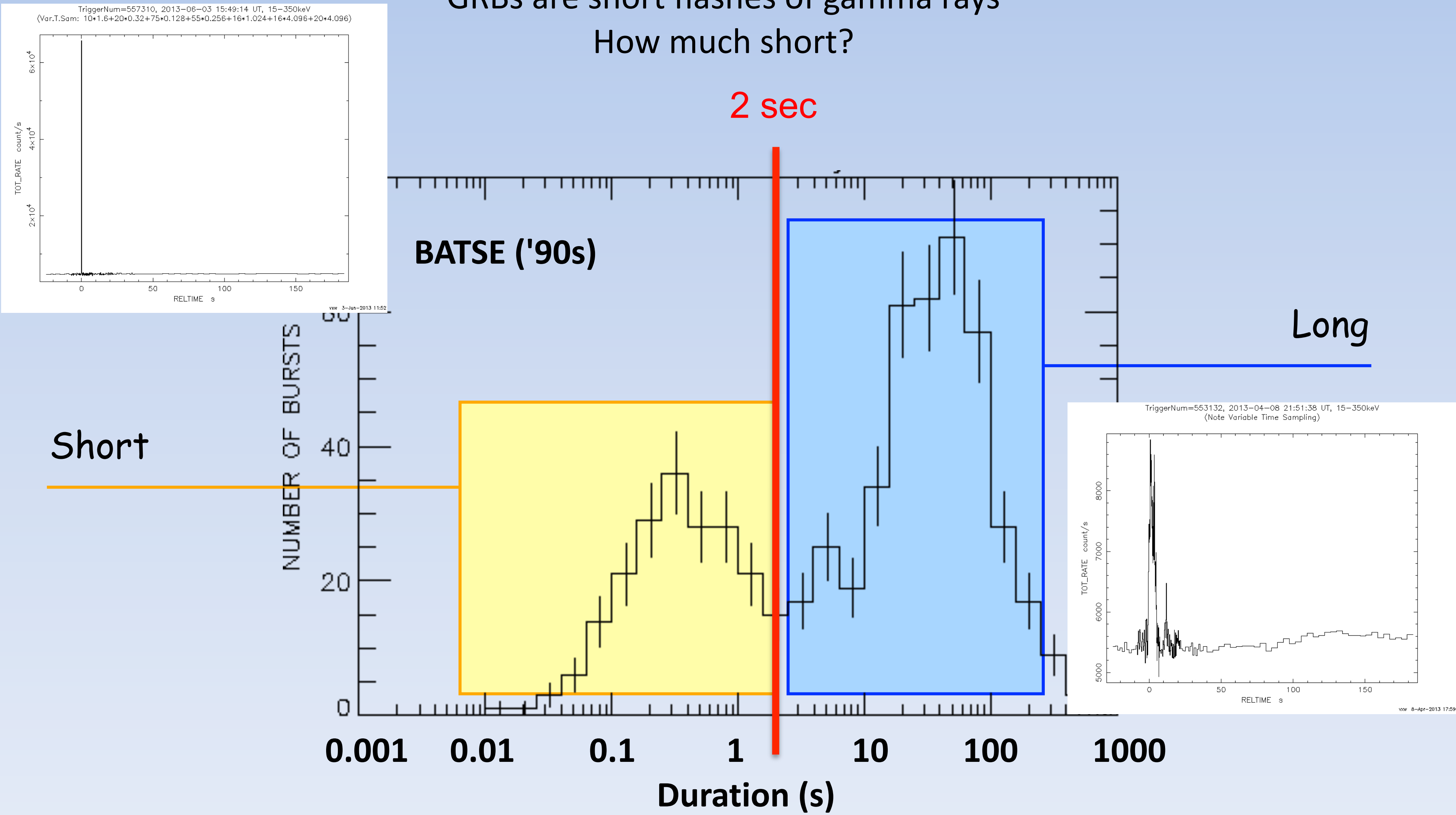
↓

Energy: ~ 10^{53} erg

Like the energy emitted by our Galaxy in 10 years

Two flavors of GRBs

GRBs are short flashes of gamma rays
How much short?



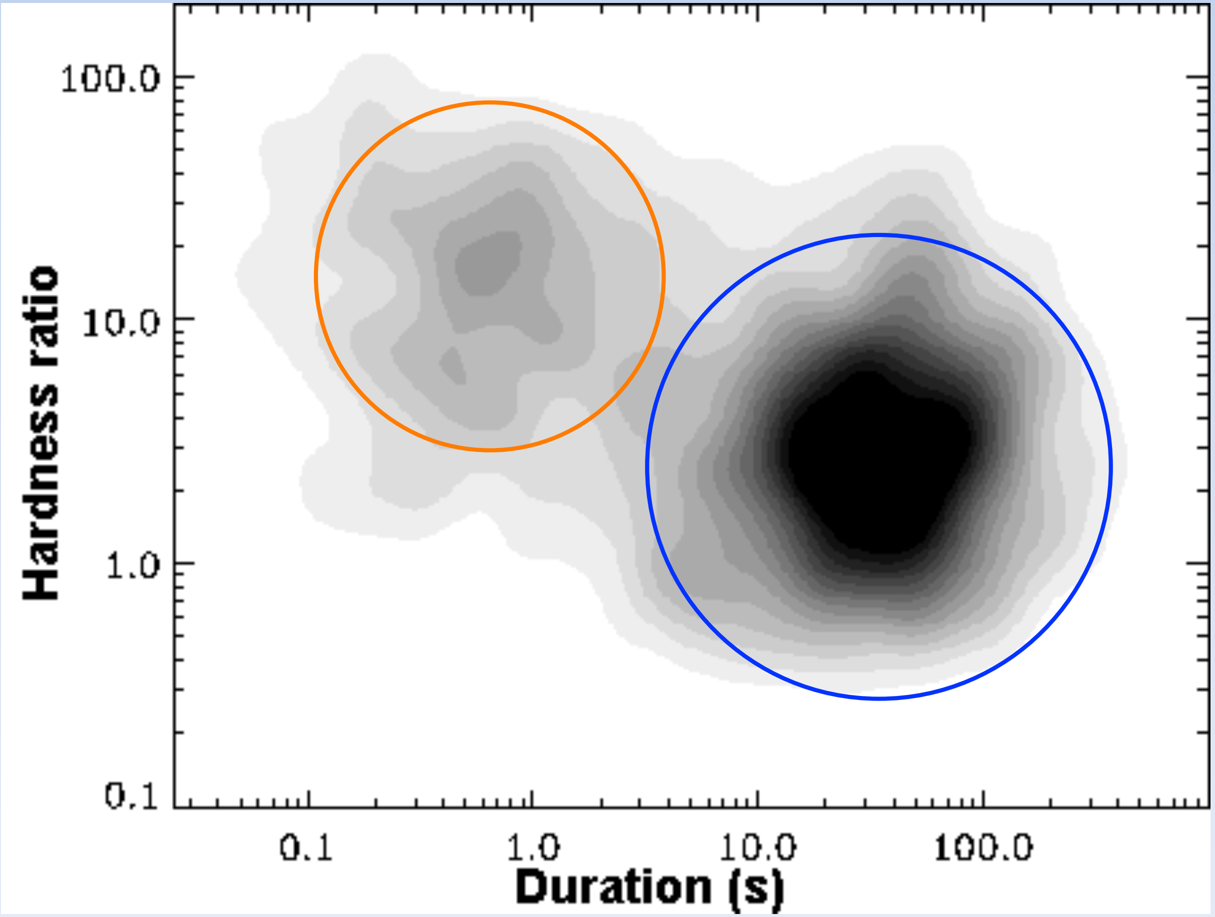
Kouveliotou et al. 1993

Another angle

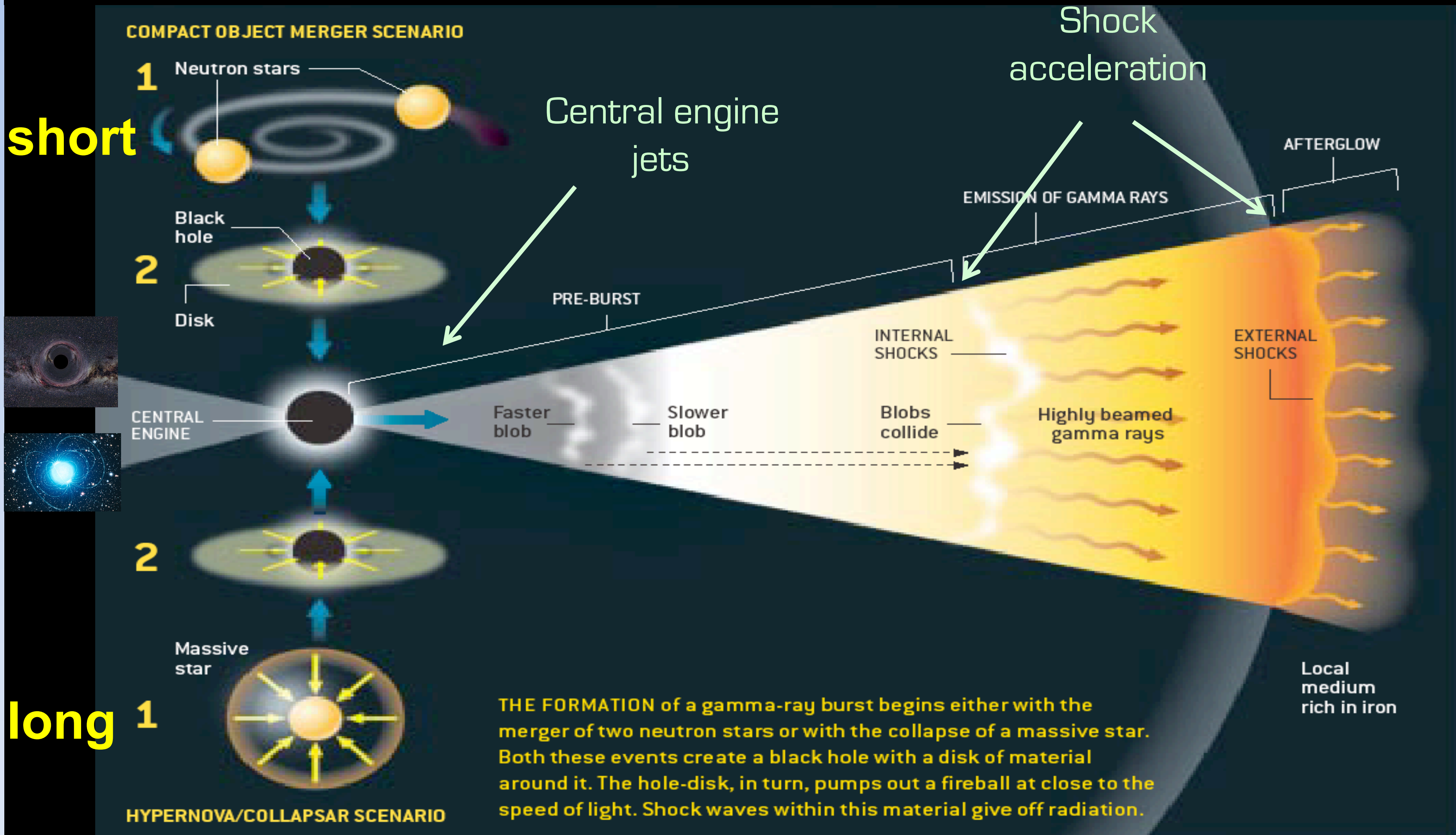
Hardness ratio: $HR = \dfrac{\text{countrate(hard)}}{\text{countrate(soft)}}$

Paradigm:

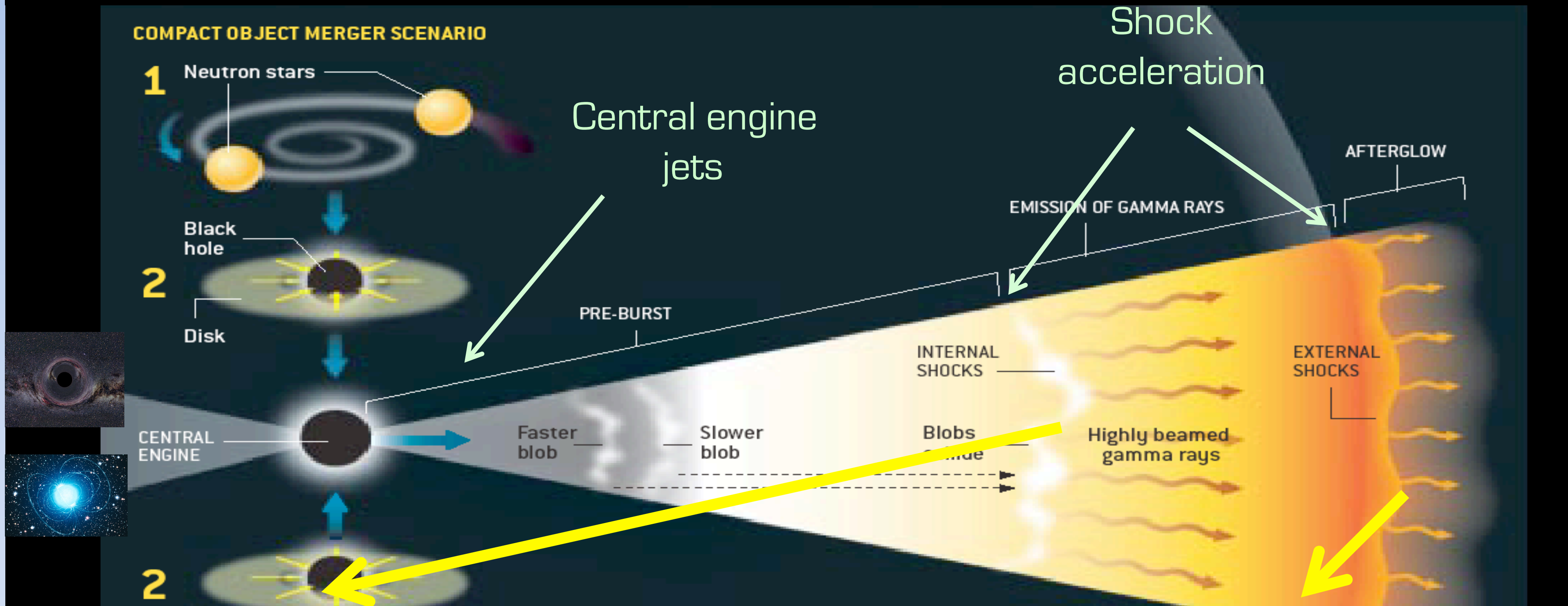
Long/soft
Short/hard

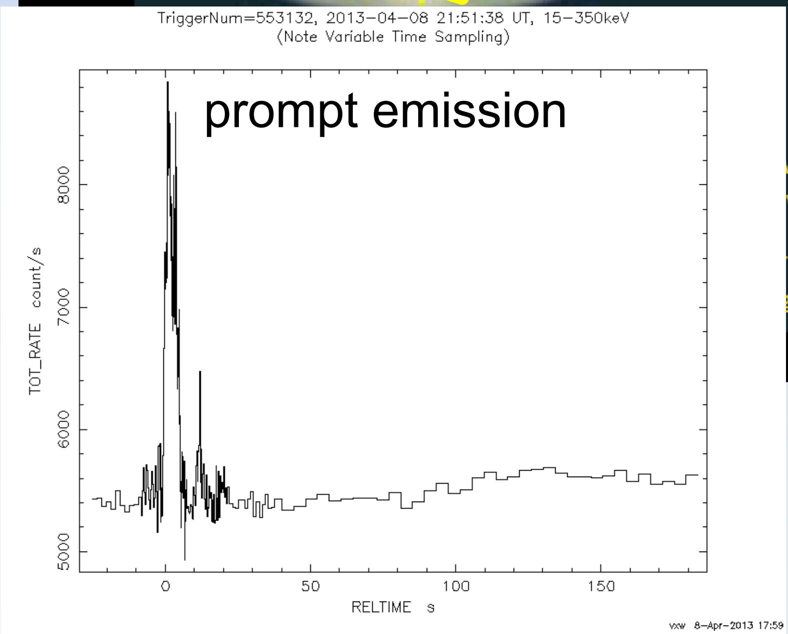


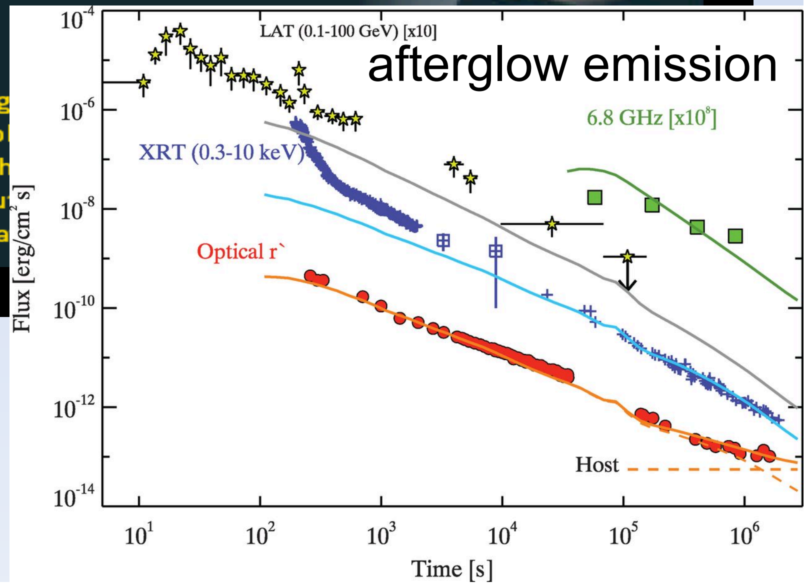
The standard model



The standard model



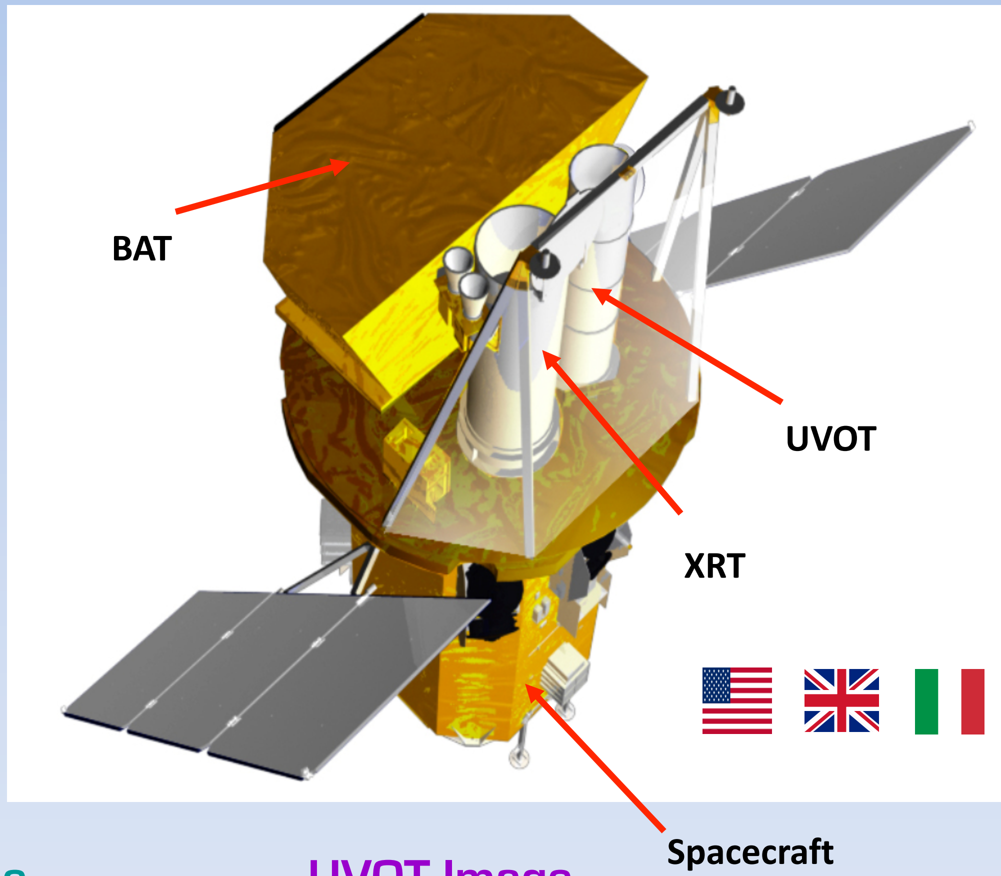




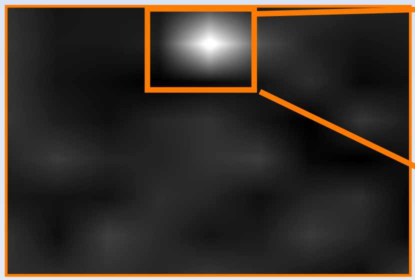
Swift Mission (2004)

Gehrels et al. 2004

- **Burst Alert Telescope (BAT)**
  - 15-150 keV
  - FOV: 2 steradiants
  - Centroid accuracy: 1' - 4'
- **X-Ray Telescope (XRT)**
  - 0.2-10.0 keV
  - FOV: 23.6' x 23.6'
  - Centroid accuracy: 5"
- **UV/Optical Telescope (UVOT)**
  - 30 cm telescope
  - 6 filters (170 nm – 600 nm)
  - FOV: 17' x 17'
  - Centroid accuracy: 0.5"

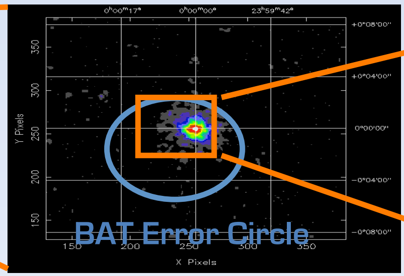


BAT Burst Image



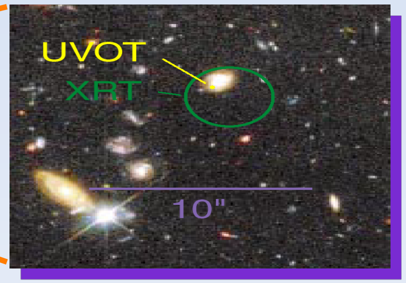
$\theta < 4'$

XRT Image



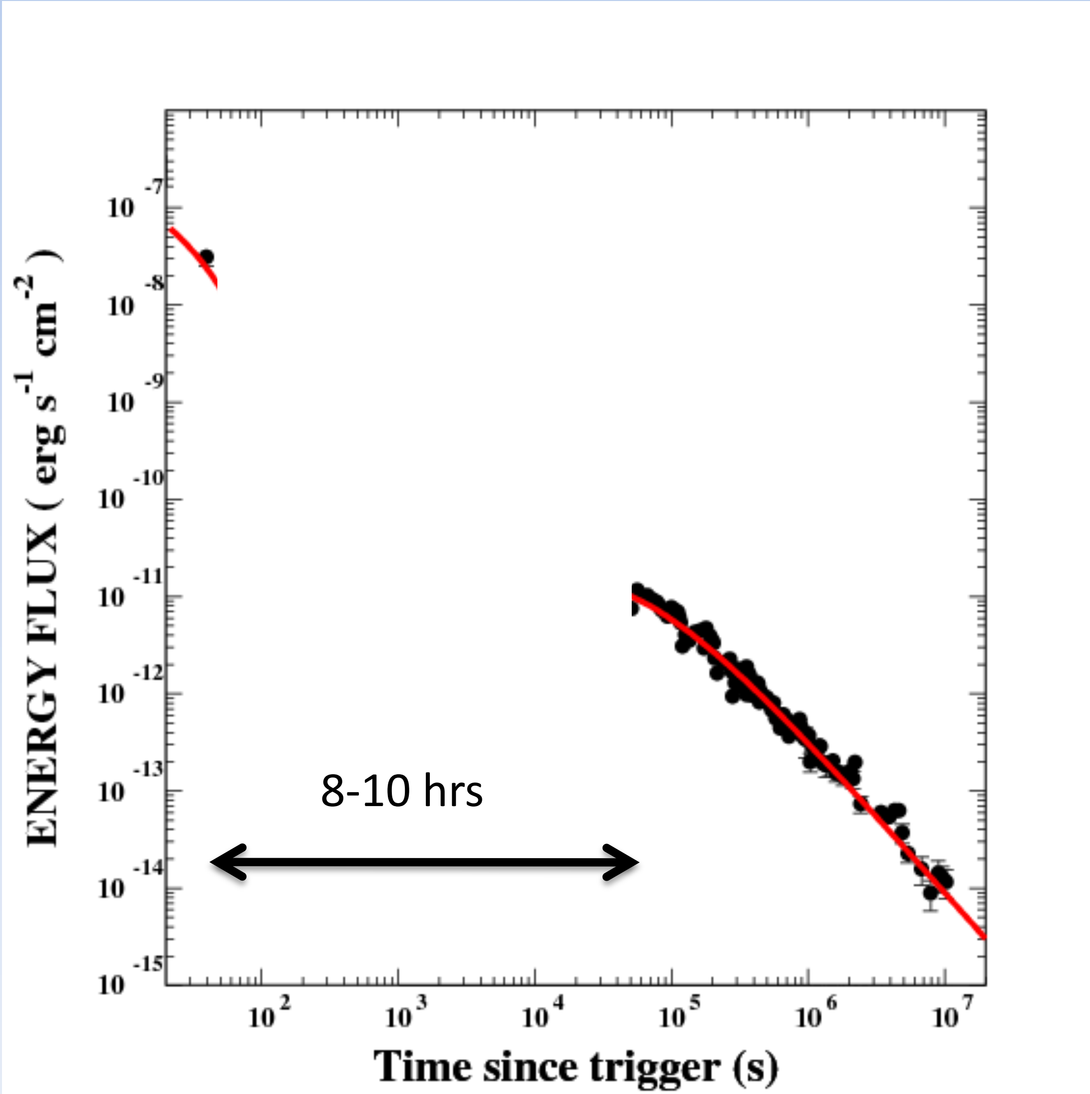
$T<100$ s; $\theta < 5''$

UVOT Image

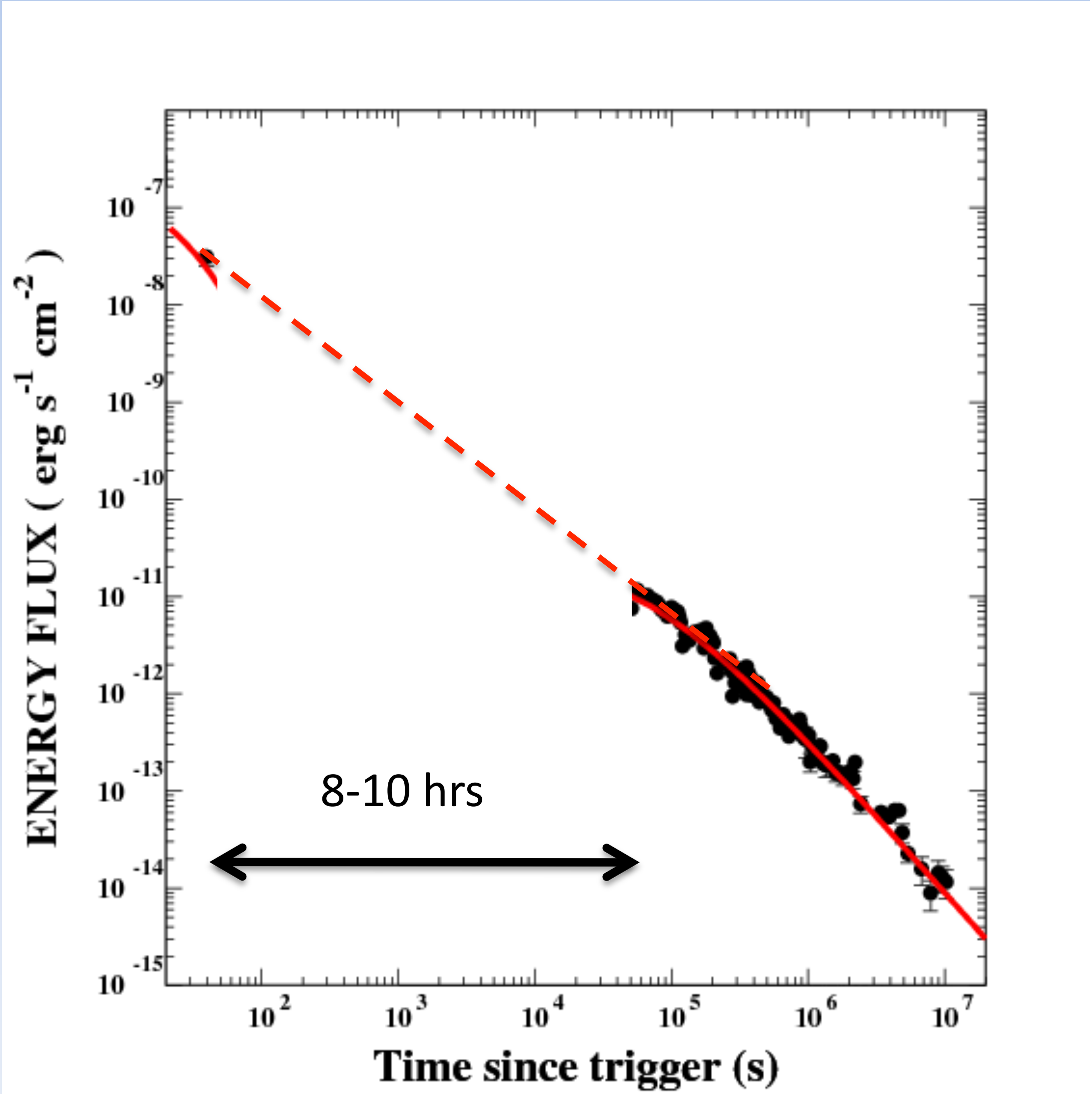


$\theta < 0.5''$

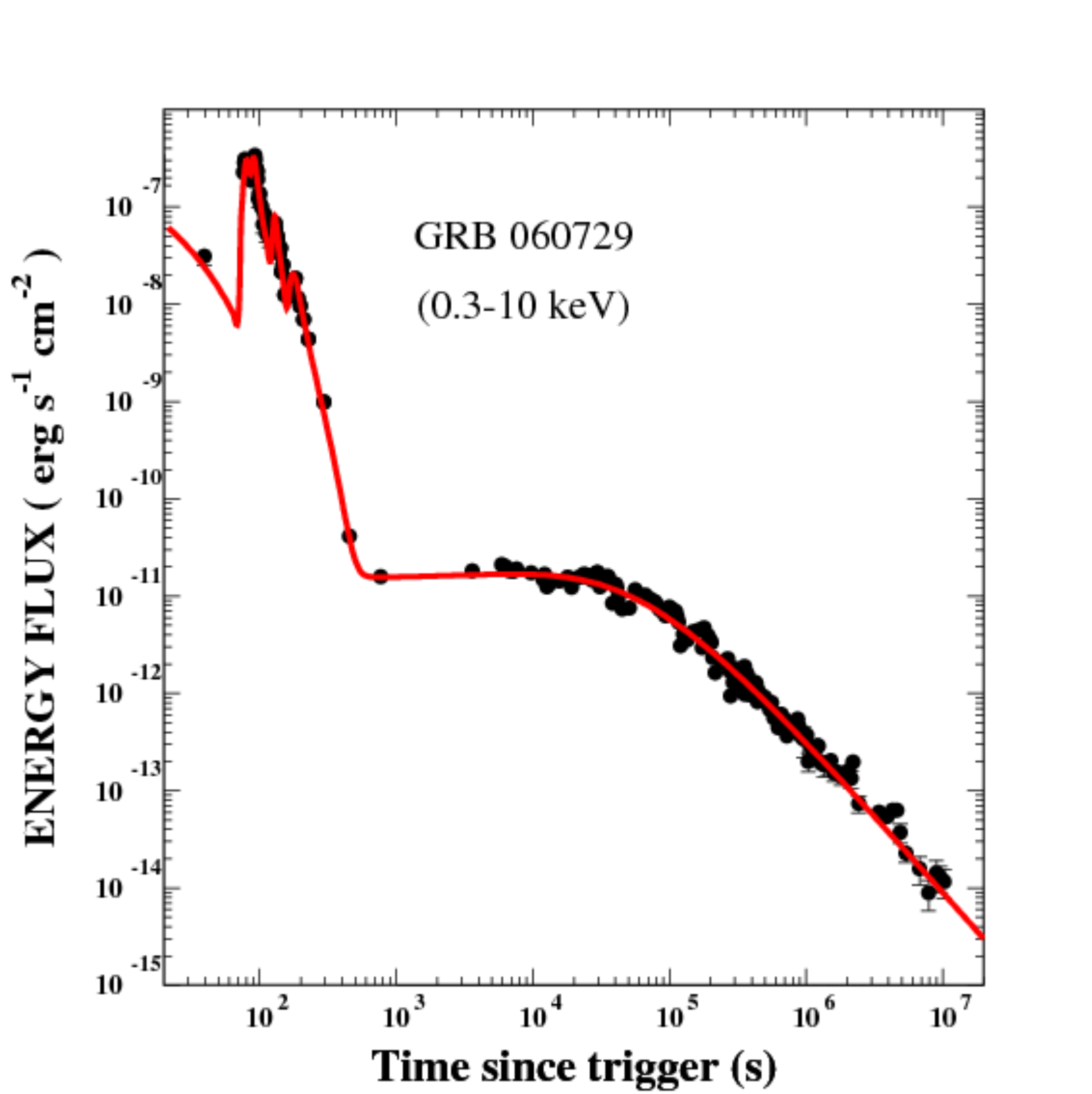
pre-Swift afterglow light curves



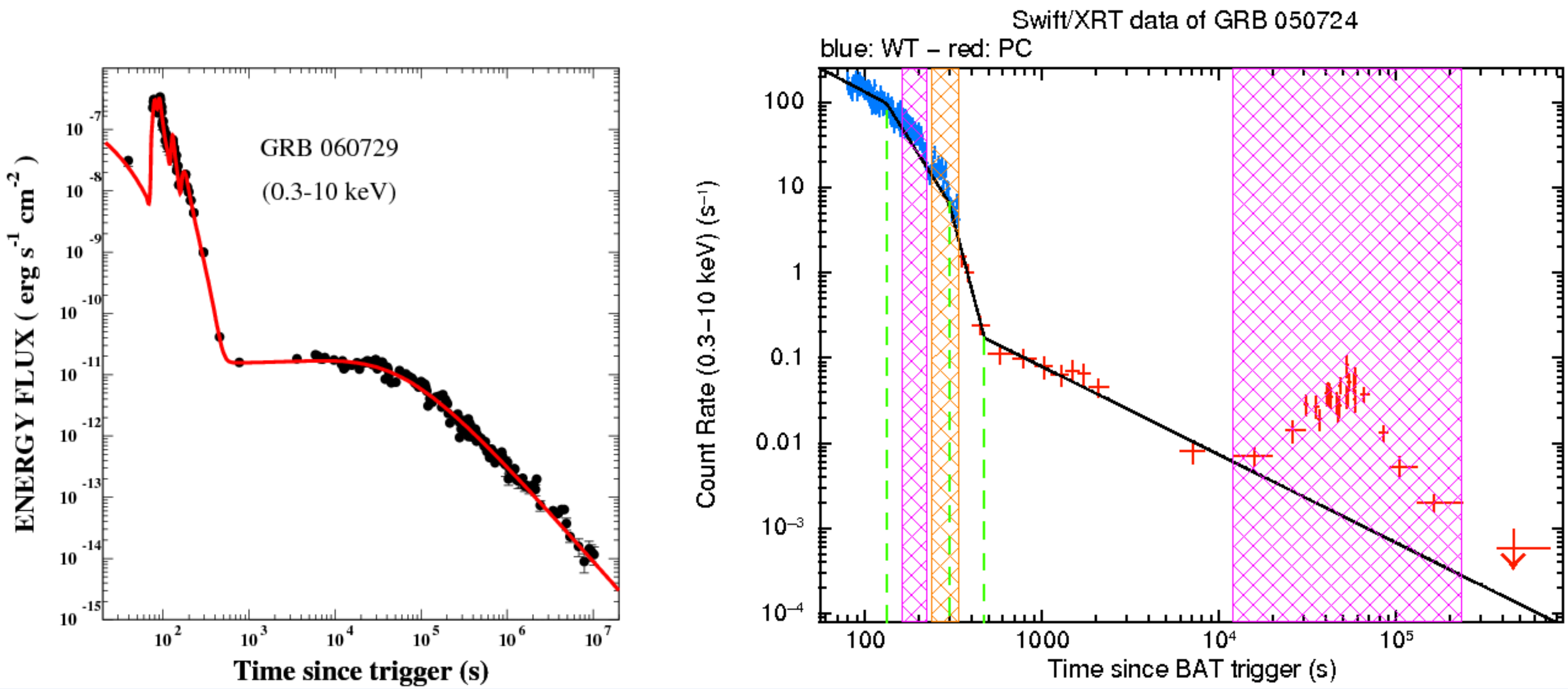
pre-Swift afterglow light curves



Swift afterglow light curves



Swift afterglow light curves



Steep decay, plateaus, flares:
common to long and short GRB afterglow light curves

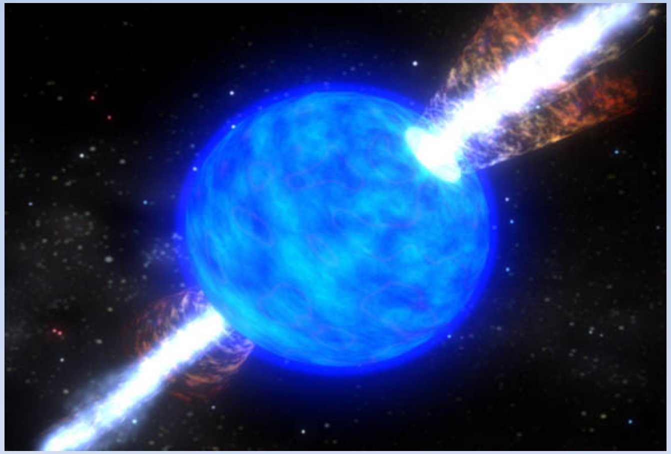
GRB progenitors

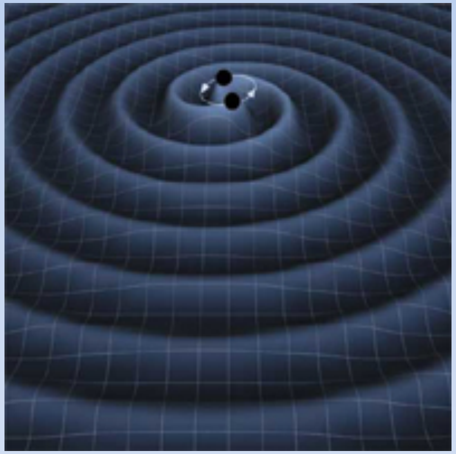
Long/soft GRBs

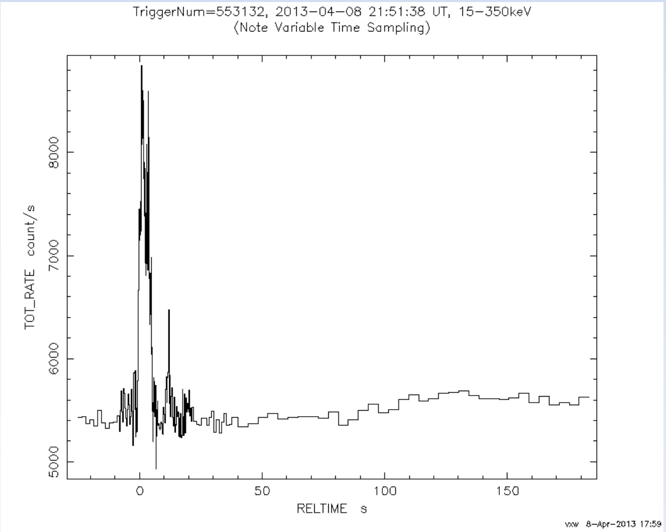
collapsar progenitor model

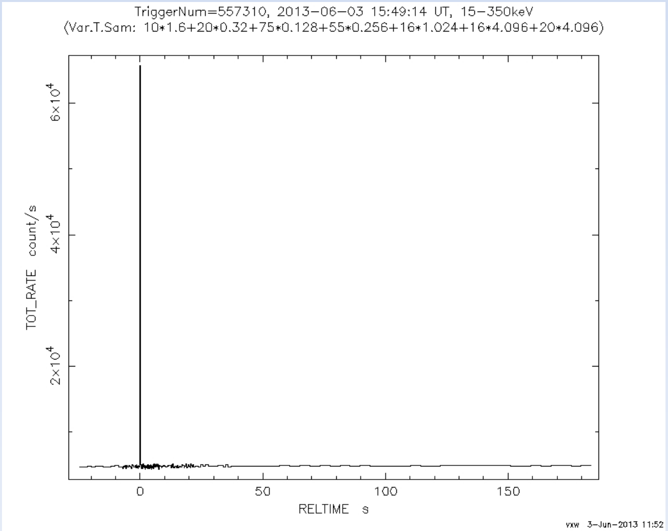
Short/hard GRBs

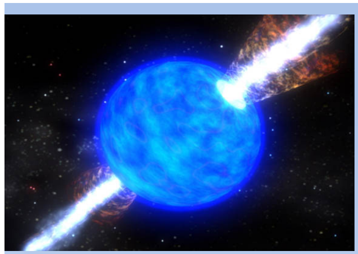
merger progenitor model



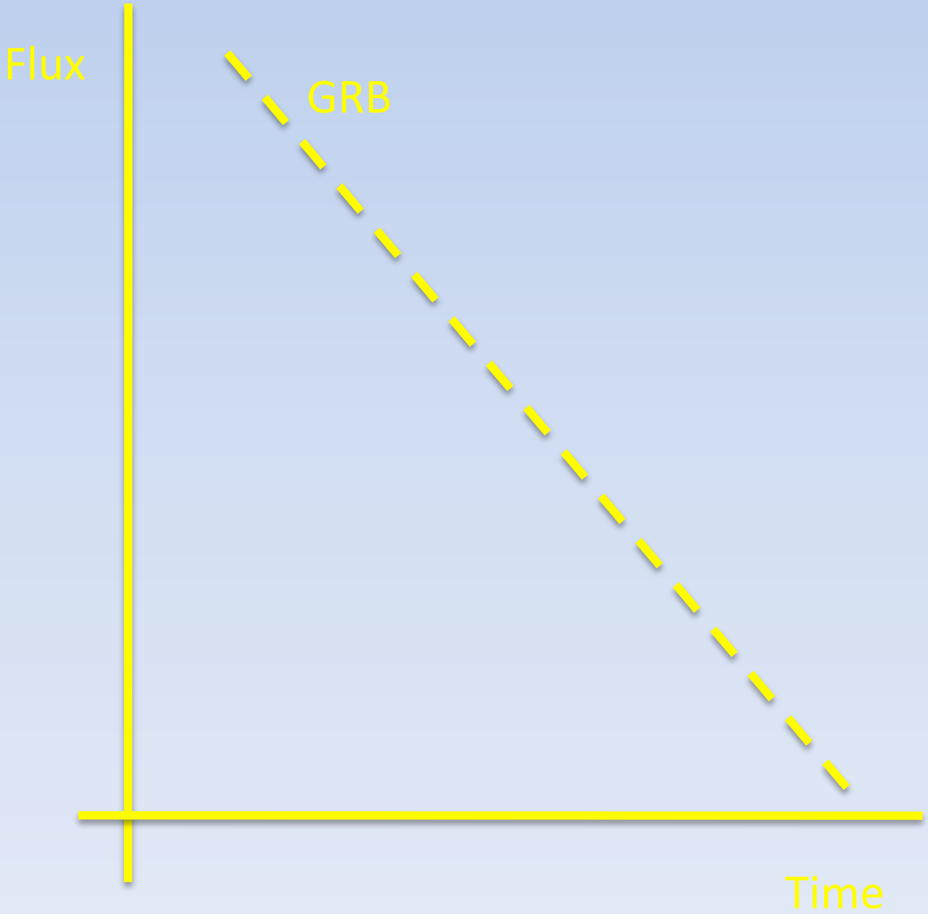


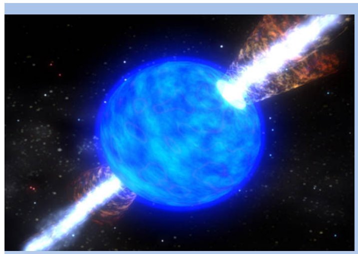




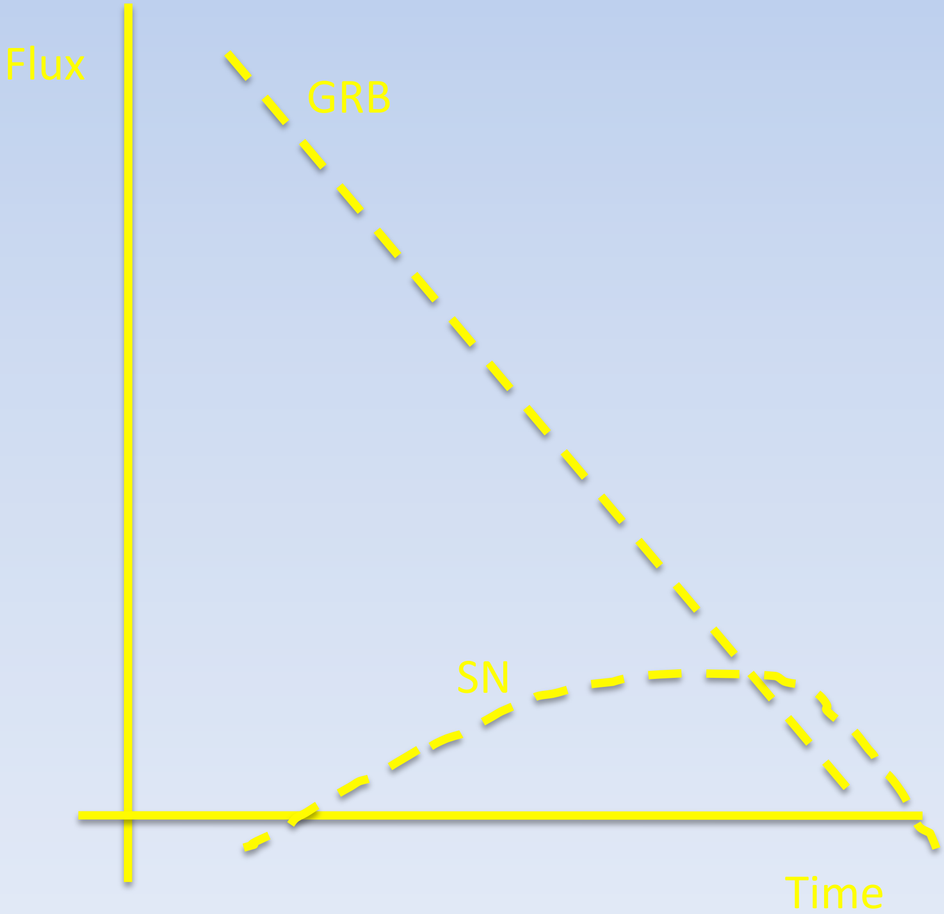


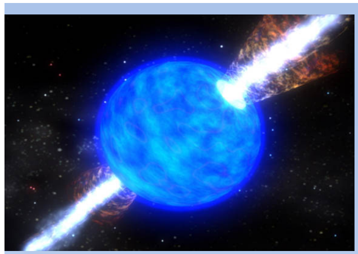
Long GRB & Supernovae



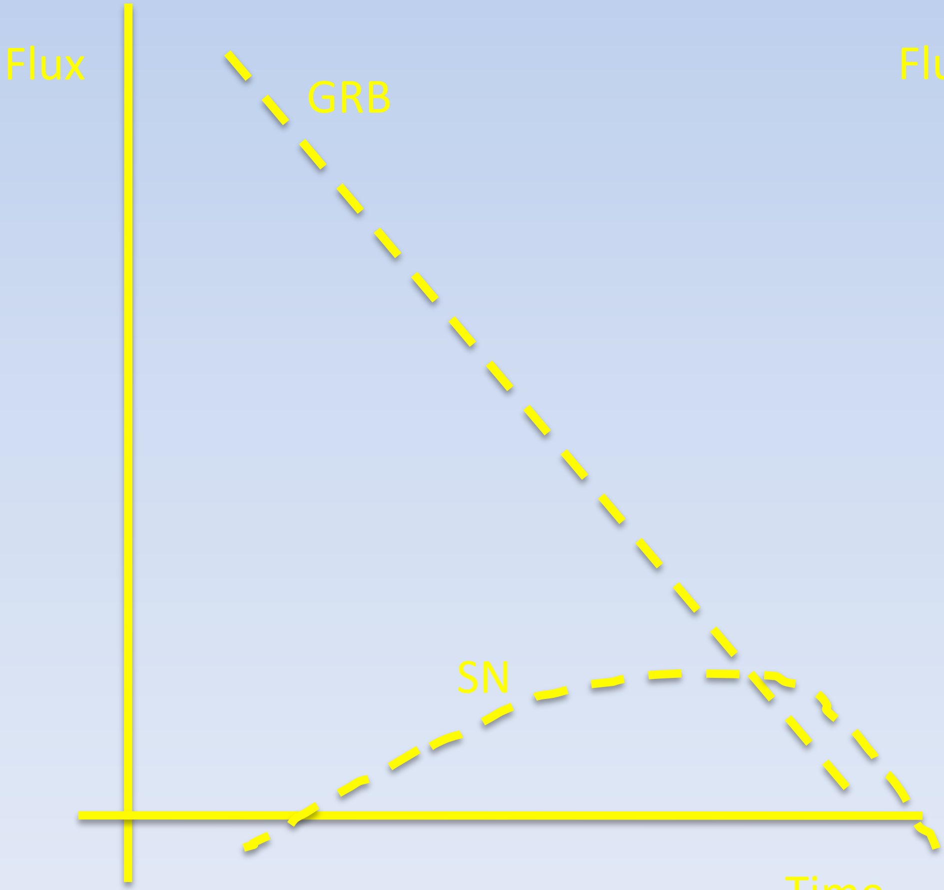


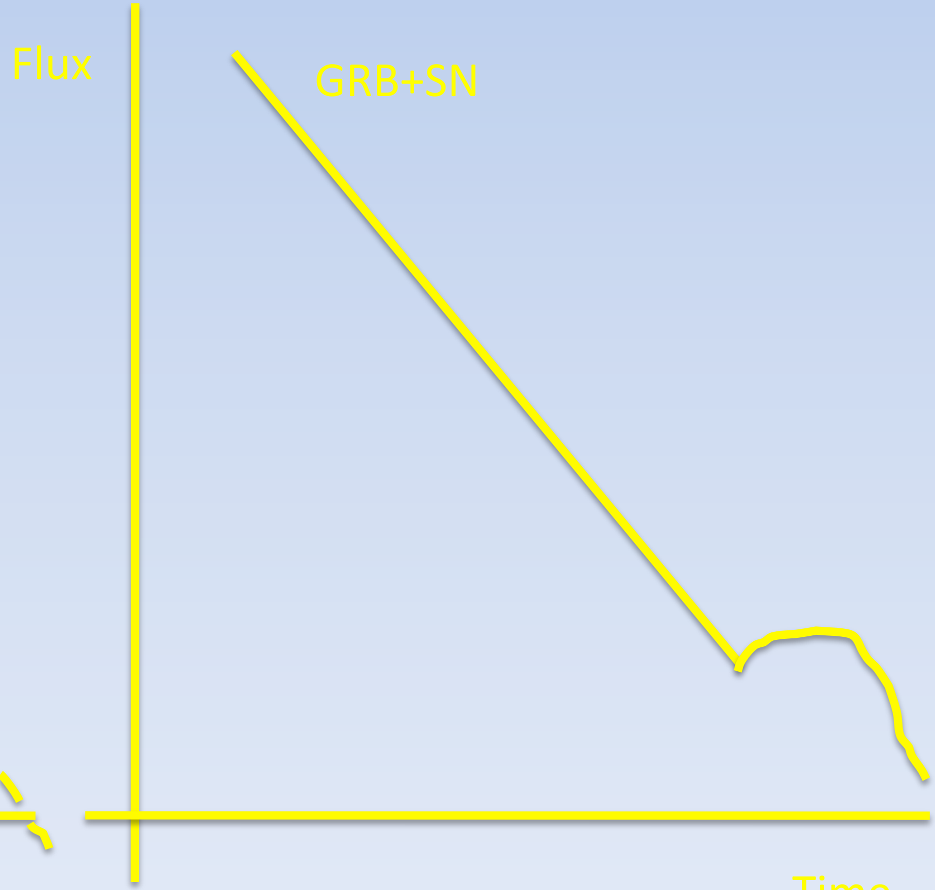
Long GRB & Supernovae

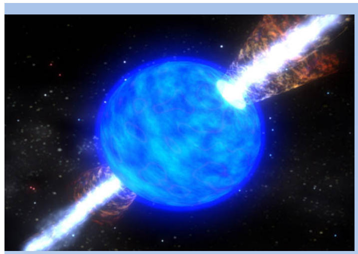




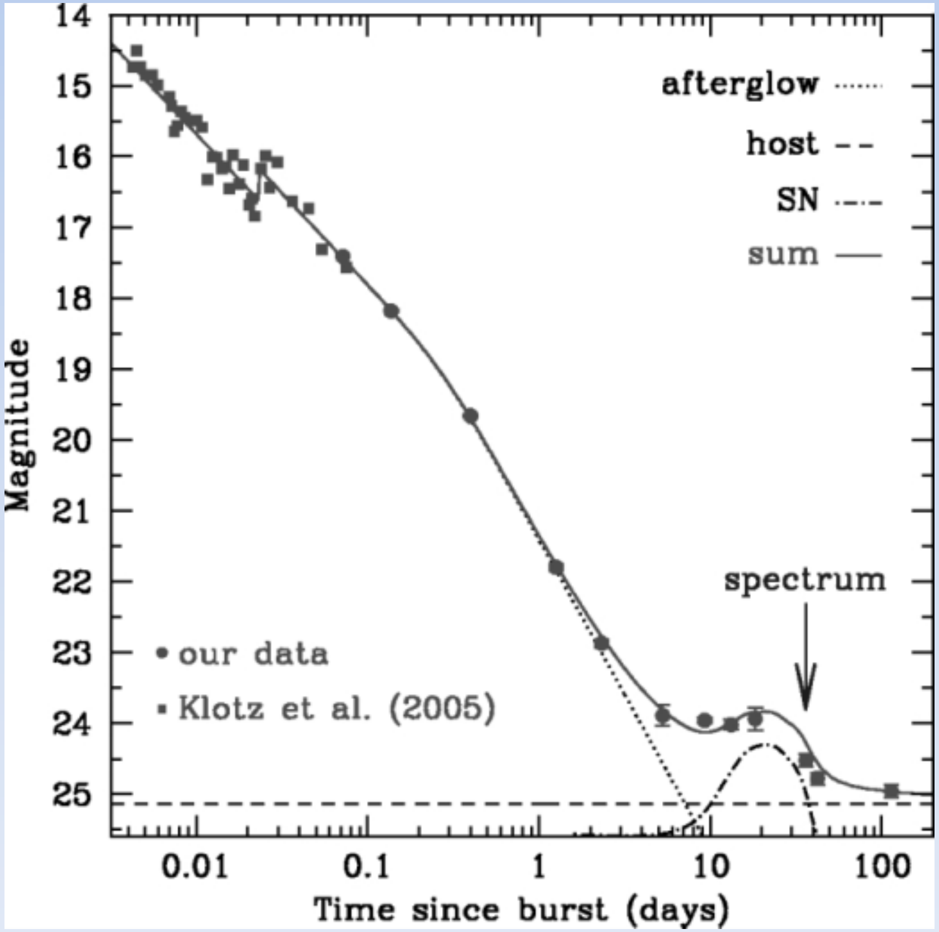
Long GRB & Supernovae

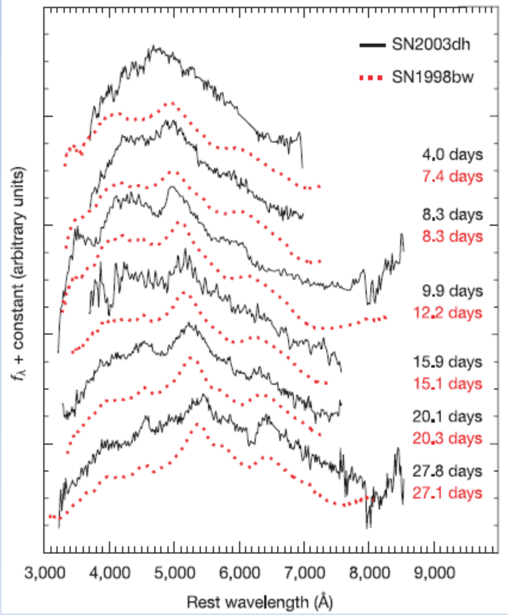


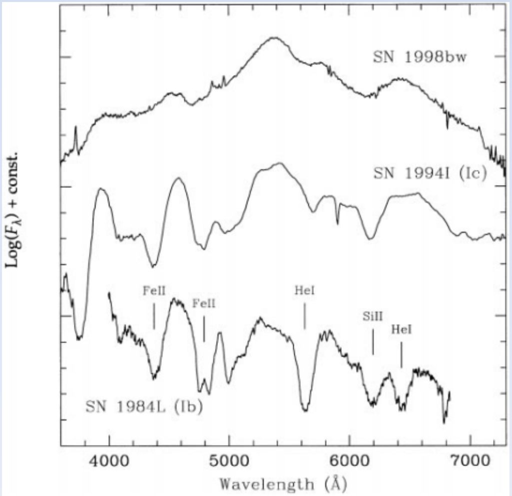




Long GRB & Supernovae







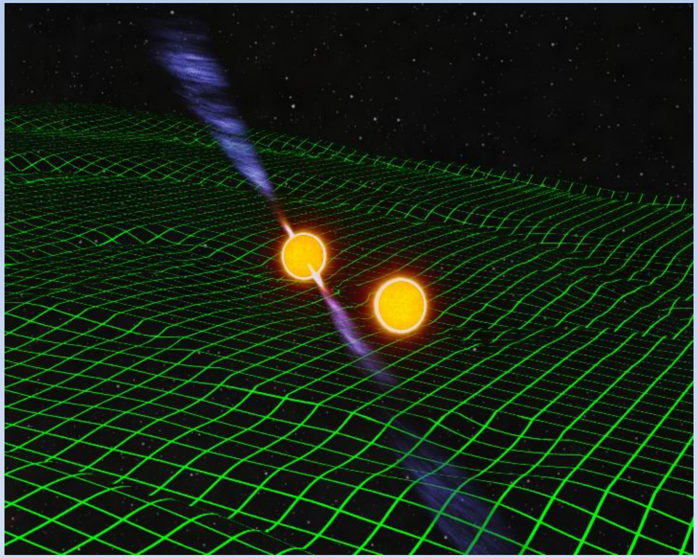
Galama et al. 1998; Stanek et al. 2003; Hjorth et al. 2003; Della Valle et al. 2003; Malesani et al. 2004; Soderberg et al. 2005; Pian et al. 2006; Campana et al. 2006; Della Valle et al. 2006, Bufano et al. 2012, Melandri et al. 2012, Schulze et al. 2014, Melandri et al. 2014, D'Elia et al. 2015 and others…

The progenitors of short GRBs

Most popular model:

Coalescence (merging) of a compact object binary system
(NS-NS ; NS-BH)

While orbiting, the two objects emit gravitational waves losing energy: MERGING



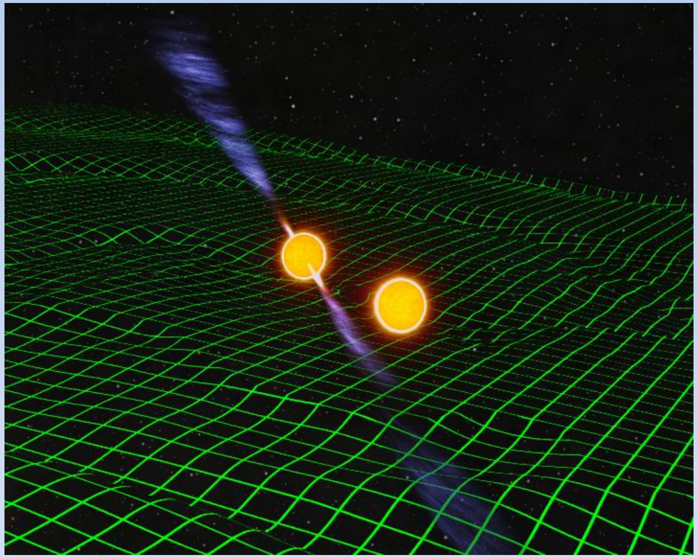
NS-NS systems are observed in our Galaxy:

The progenitors of short GRBs

Most popular model:

Coalescence (merging) of a compact object binary system
(NS-NS ; NS-BH)

While orbiting, the two objects emit gravitational waves losing energy: MERGING



- critical parameter: **merging time t_m**

Time between the formation of the system and its coalescence

$t_m \propto a^4$ (*a:* system separation) **->** **~10 Myr < t_m < ~10 Gyr**

- merging can occur in old and young stellar populations

"primordial binaries"

- **kick velocities**:

Compact objects are the remnants of core-collapse SNe, that can give a "kick"

The system can escape from the HG-> OFFSET! (**1÷100 kpc**)/low density CBM

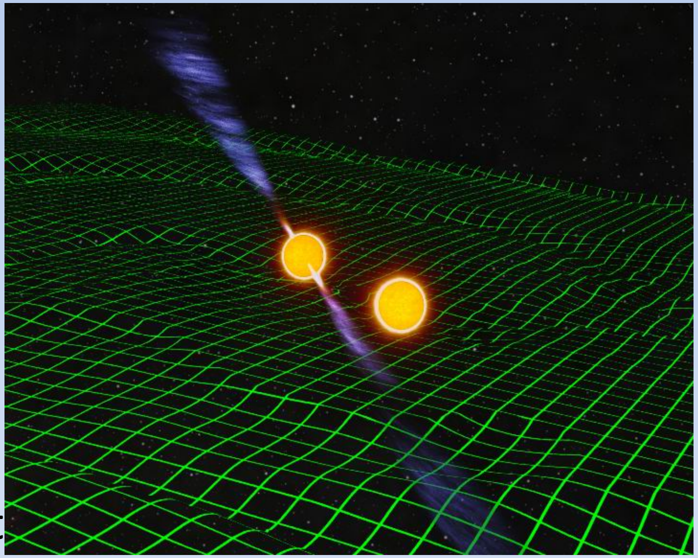
(Belczynski & Kalogera 2001; Perna & Belczynski 2002; Belczynski et al. 2006)

The progenitors of short GRBs

Most popular model:

Coalescence (merging) of a compact object binary system (NS-NS ; NS-BH)

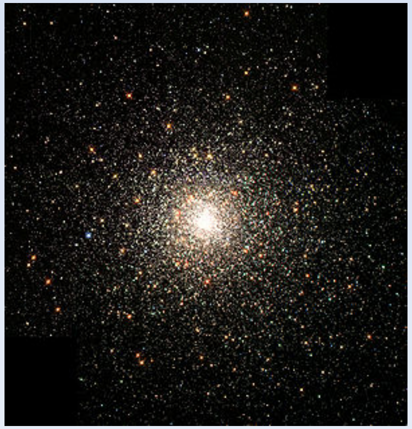
While orbiting, the two objects emit gravitational waves losing energy: MERGING

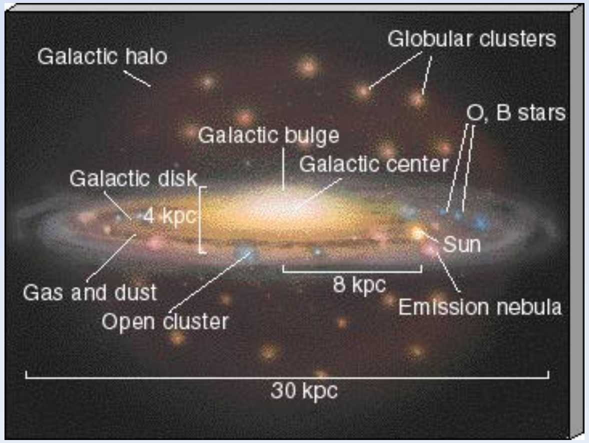


Another possibility: dynamical formation of a double compact object system (e.g. in globular clusters)

(Grindlay et al. 2006; Salvaterra et al. 2008)

“dynamically formed binaries”





OFFSET/low density CBM

Compact object mergers: what we do expect

Diverse delay times:
- A mix of early and late type host galaxies

Kicks/migration from birth site:
- Offsets
- No correlation with UV/optical HG light
- Diversity in the environment (ev. channel)

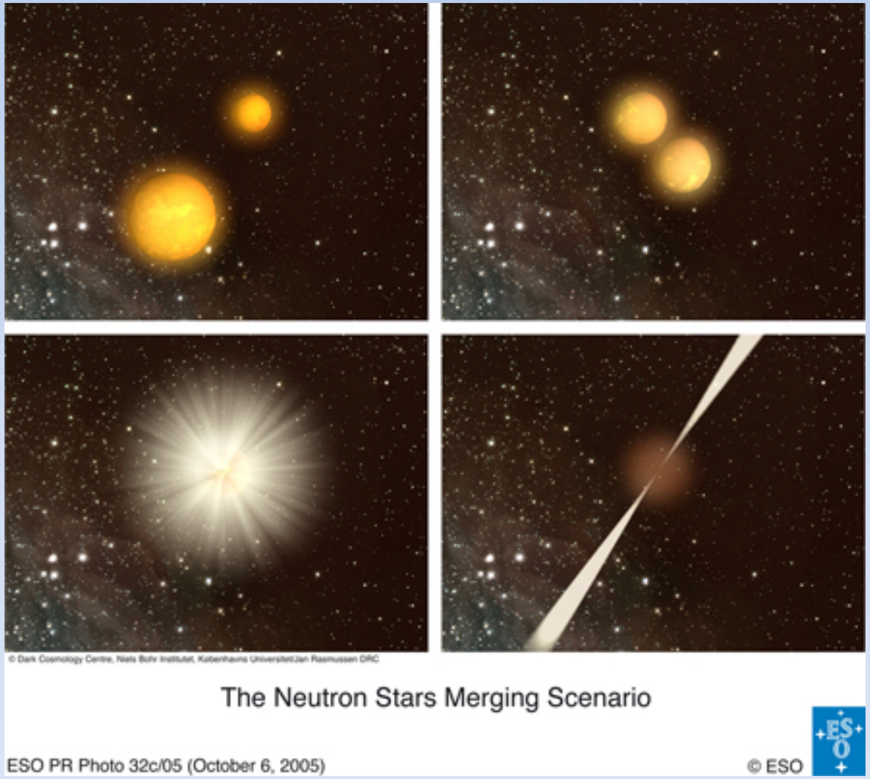
No associated supernova

Remnant (magnetar/BH?)

Emission geometry (jet?)

Kilonova association

Gravitational waves



Compact object mergers: what we do expect

Diverse delay times:
- A mix of early and late type host galaxies

Kicks/migration from birth site:
- Offsets
- No correlation with UV/optical HG light
- Diversity in the environment (ev. channel)

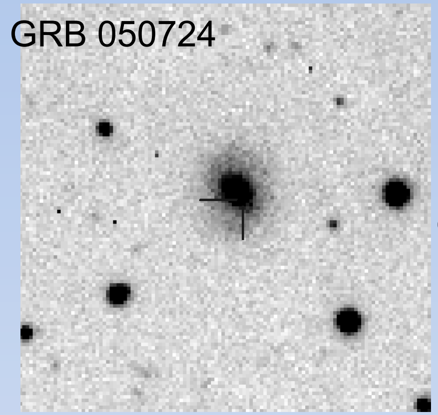
No associated supernova

Remnant (magnetar/BH?)

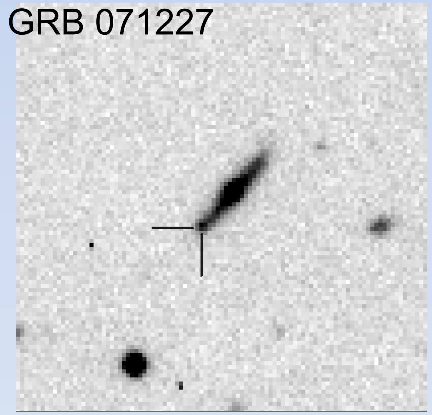
Emission geometry (jet?)

Kilonova association

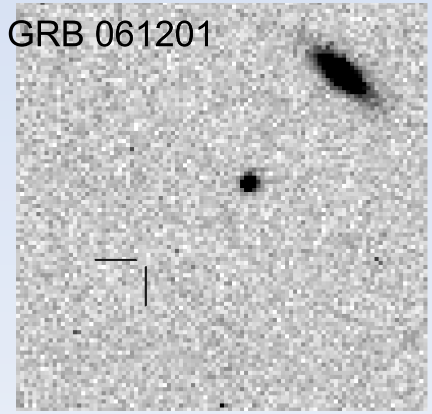
Gravitational waves



early type



late **type**



hostless

Barthelmy+05
Malesani+07
Stratta+07
PDA+09
Fong+13
Berger14

Compact object mergers: what we do expect

Diverse delay times:
- A mix of early and late type host galaxies

Kicks/migration from birth site:
- Offsets
- No correlation with UV/optical HG light
- Diversity in the environment (ev. channel)

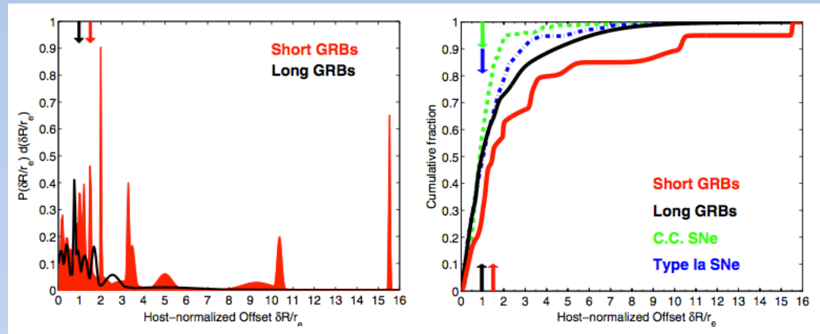
No associated supernova

Remnant (magnetar/BH?)

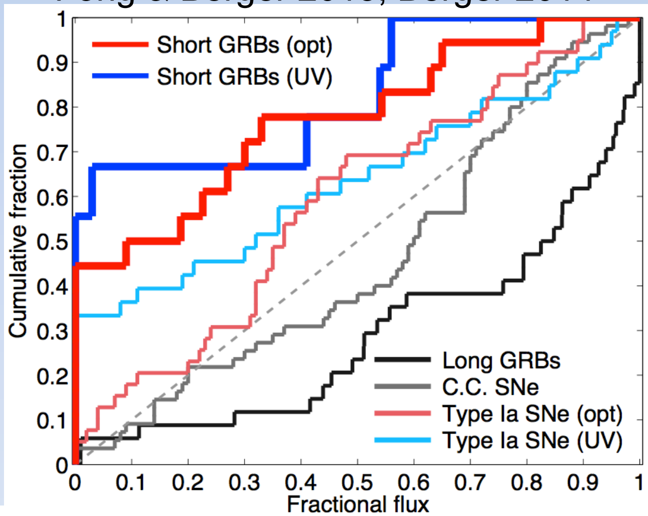
Emission geometry (jet?)

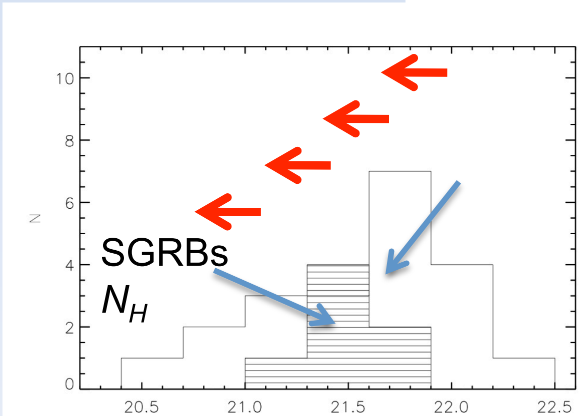
Kilonova association

Gravitational waves

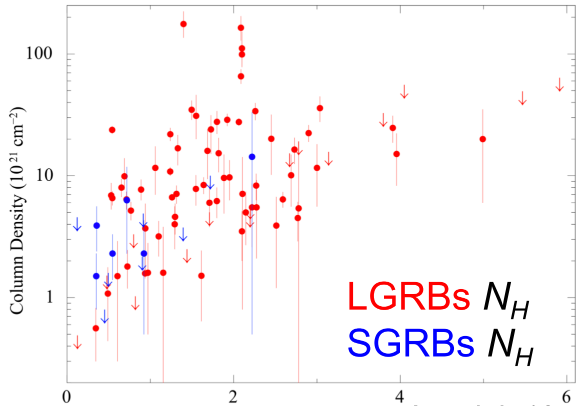


Fong & Berger 2013; Berger 2014





PDA+14



Asquini+19

Compact object mergers: what we do expect

<u>Diverse delay times:</u>
- A mix of early and late type host galaxies

<u>Kicks/migration from birth site:</u>
- Offsets
- No correlation with UV/optical HG light
- Diversity in the environment (ev. channel)

<u>No associated supernova</u>

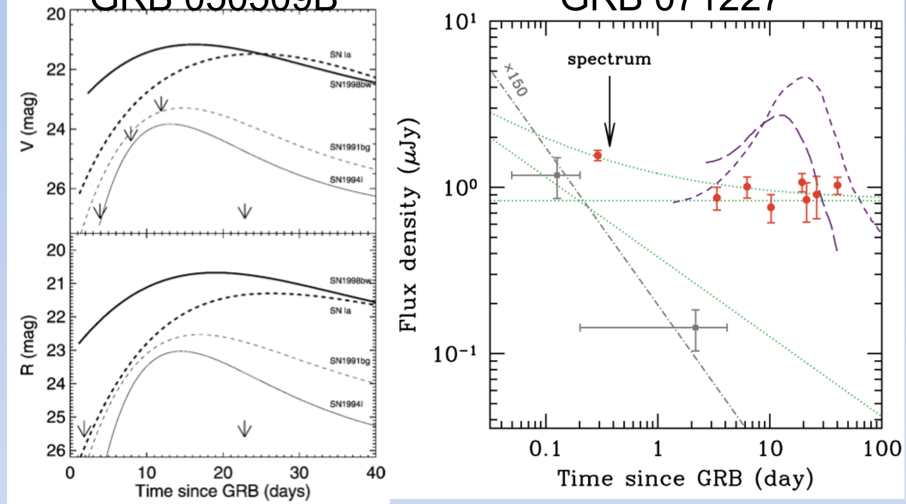
<u>Remnant (magnetar/BH?)</u>

<u>Emission geometry (jet?)</u>

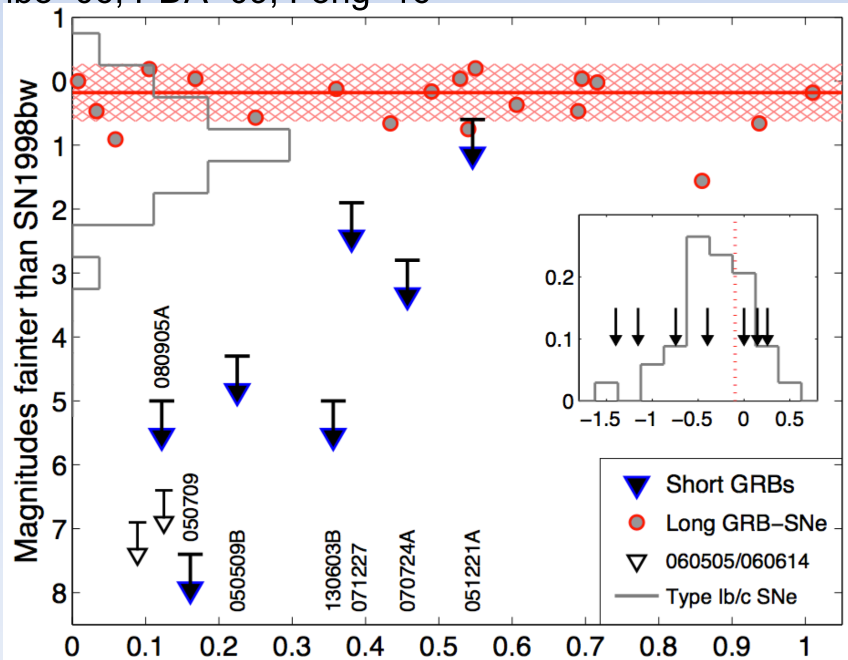
<u>Kilonova association</u>

<u>Gravitational waves</u>

GRB 050509B GRB 071227



Hjorth+05; Covino+06; Della Valle+06;
Fynbo+06; PDA+09; Fong+16



Berger14

Compact object mergers: what we do expect

<u>Diverse delay times:</u>
- A mix of early and late type host galaxies

<u>Kicks/migration from birth site:</u>
- Offsets
- No correlation with UV/optical HG light
- Diversity in the environment (ev. channel)

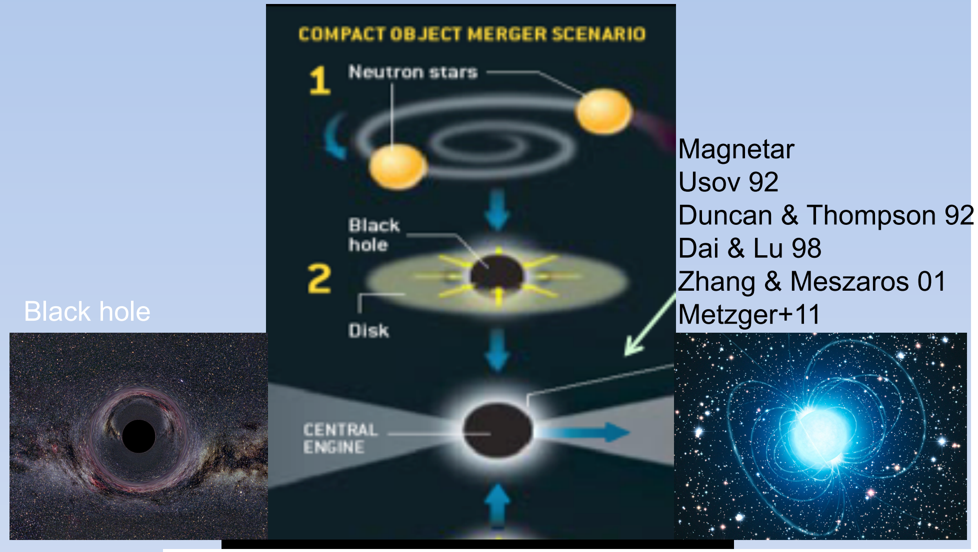
<u>No associated supernova</u>

<u>Remnant (magnetar/BH?)</u>

<u>Emission geometry (jet?)</u>

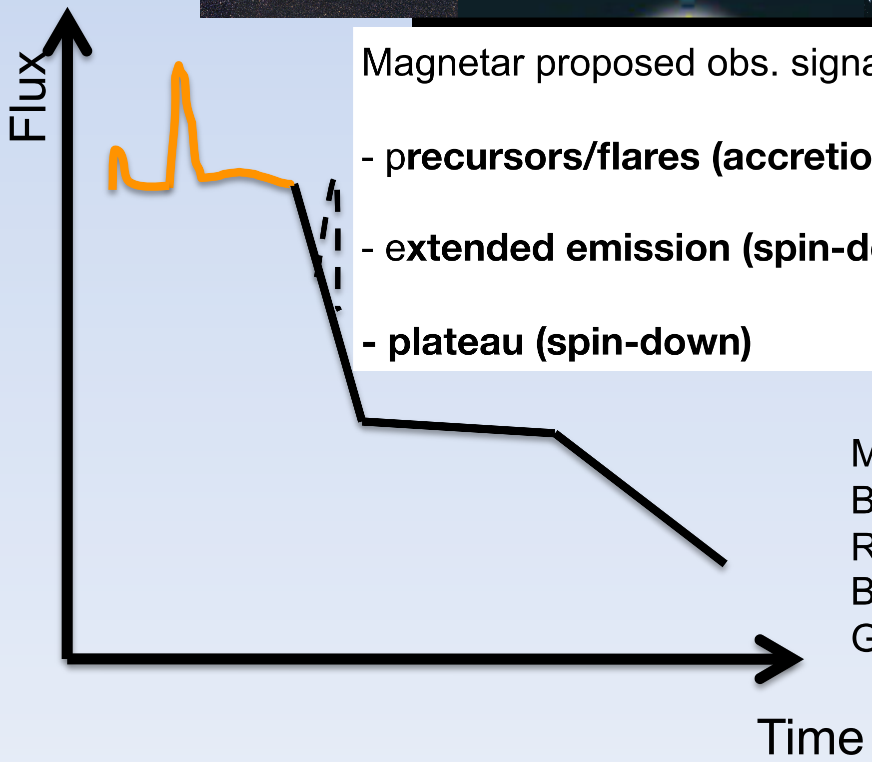
<u>Kilonova association</u>

<u>Gravitational waves</u>



Magnetar proposed obs. signatures:

- **precursors/flares (accretion)**
- **extended emission (spin-down/accretion)**
- **plateau (spin-down)**



Metzger+08
Bucciantini+12
Rowlinson+13
Bernardini+13
Gompertz+14

Compact object mergers: what we do expect

<u>Diverse delay times:</u>
- A mix of early and late type host galaxies

<u>Kicks/migration from birth site:</u>
- Offsets
- No correlation with UV/optical HG light
- Diversity in the environment (ev. channel)

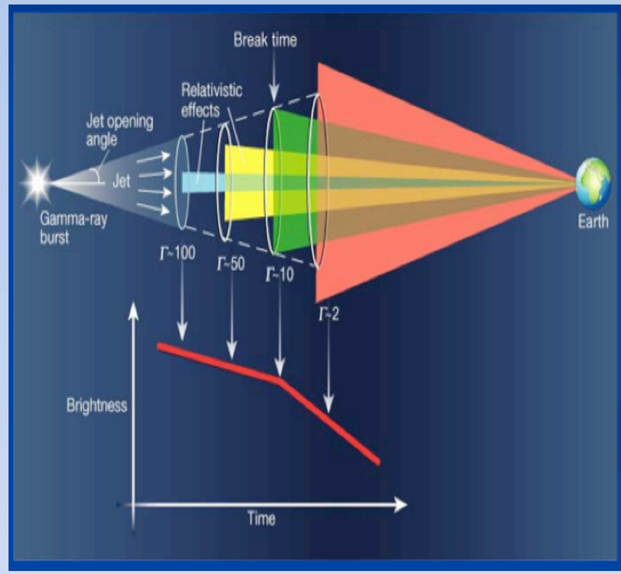
<u>No associated supernova</u>

<u>Remnant (magnetar/BH?)</u>

<u>Emission geometry (jet?)</u>

<u>Kilonova association</u>

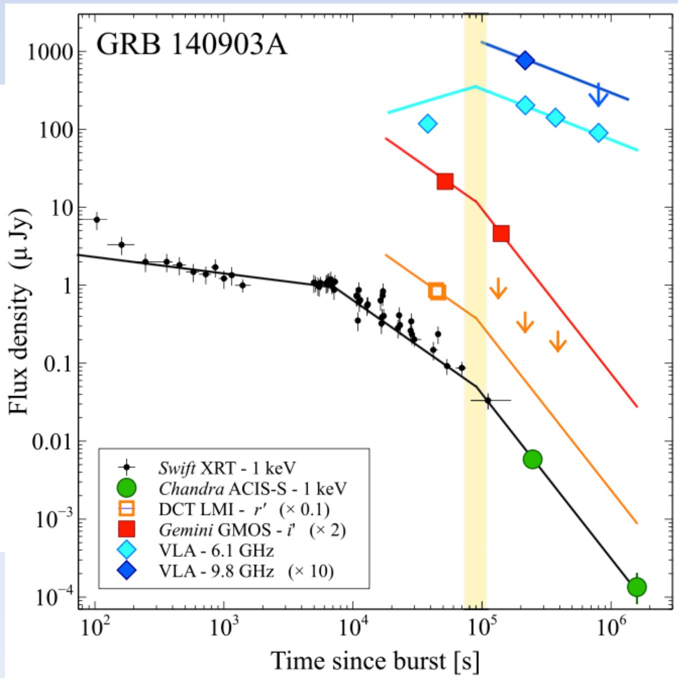
<u>Gravitational waves</u>



Short GRB Opening Angles

GRB	Band[a]	θ_j (deg)	$\delta t^{b}_{\rm last}$ (days)	Reference
050709	O	$\gtrsim 15^\circ$	16.2	1
050724A	X	$\gtrsim 25^\circ$	22.0	2
051221A	X	$6-7^\circ$	26.6	3
090426A	O	$5-7^\circ$	2.7	4
101219A	X	$\gtrsim 4^\circ$	3.9	5, This work
111020A	X	$3-8^\circ$	10.2	6
111117A	X	$\gtrsim 3-10^\circ$	3.0	7, 8
120804A	X	$\gtrsim 13^\circ$	45.9	9, This work
130603B	OR	$4-8^\circ$	6.5	10
140903A	X	$\gtrsim 6^\circ$	3.0	11, This work
140930B	X	$\gtrsim 9^\circ$	23.1	This work

$\langle\theta_{jet}\rangle \sim 10^o$ Fong et al. 2015



Compact object mergers: what we do expect

Diverse delay times:
- A mix of early and late type host galaxies

Kicks/migration from birth site:
- Offsets
- No correlation with UV/optical HG light
- Diversity in the environment (ev. channel)

No associated supernova

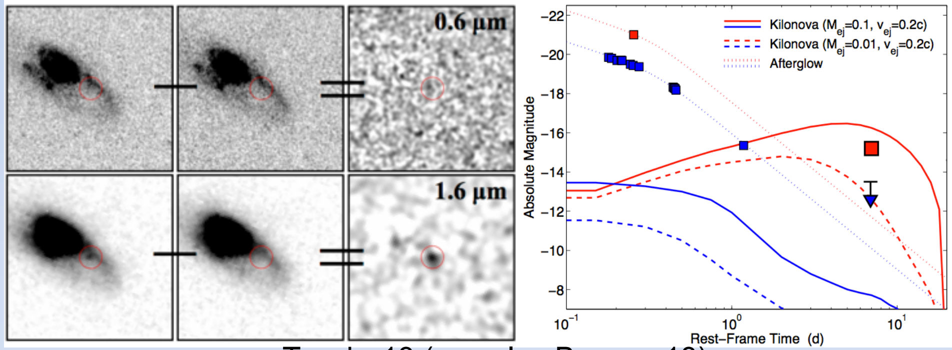
Remnant (magnetar/BH?)

Emission geometry (jet?)

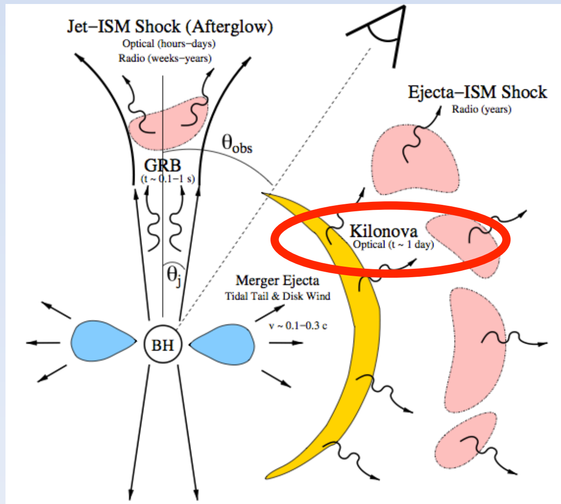
Kilonova association

Gravitational waves

GRB 130613B (z=0.356)



Tanvir+13 (see also Berger+13)



Metzger & Berger 2012

Compact object mergers: what we do expect

<u>Diverse delay times:</u>
- A mix of early and late type host galaxies

<u>Kicks/migration from birth site:</u>
- Offsets
- No correlation with UV/optical HG light
- Diversity in the environment (ev. channel)

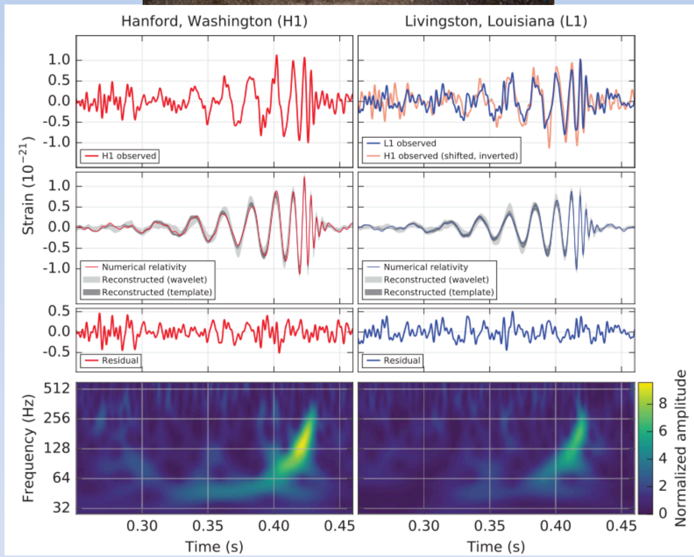
<u>No associated supernova</u>

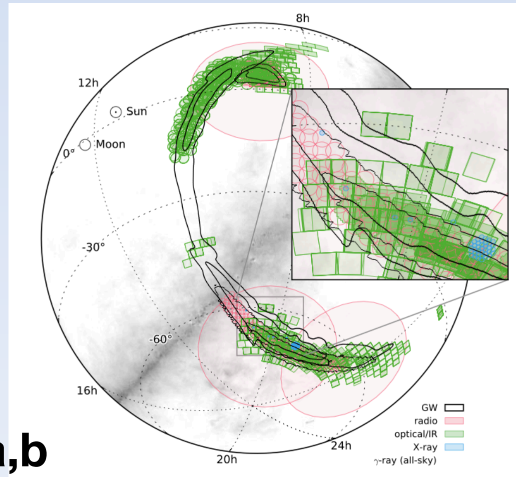
<u>Remnant (magnetar/BH?)</u>

<u>Emission geometry (jet?)</u>

<u>Kilonova association</u>

<u>Gravitational waves</u>





Abbott+16a,b

Compact object mergers: what we do expect

Diverse delay times:
- A mix of early and late type host galaxies

Kicks/migration from birth site:
- Offsets
- No correlation with UV/optical HG light
- Diversity in the environment (ev. channel)

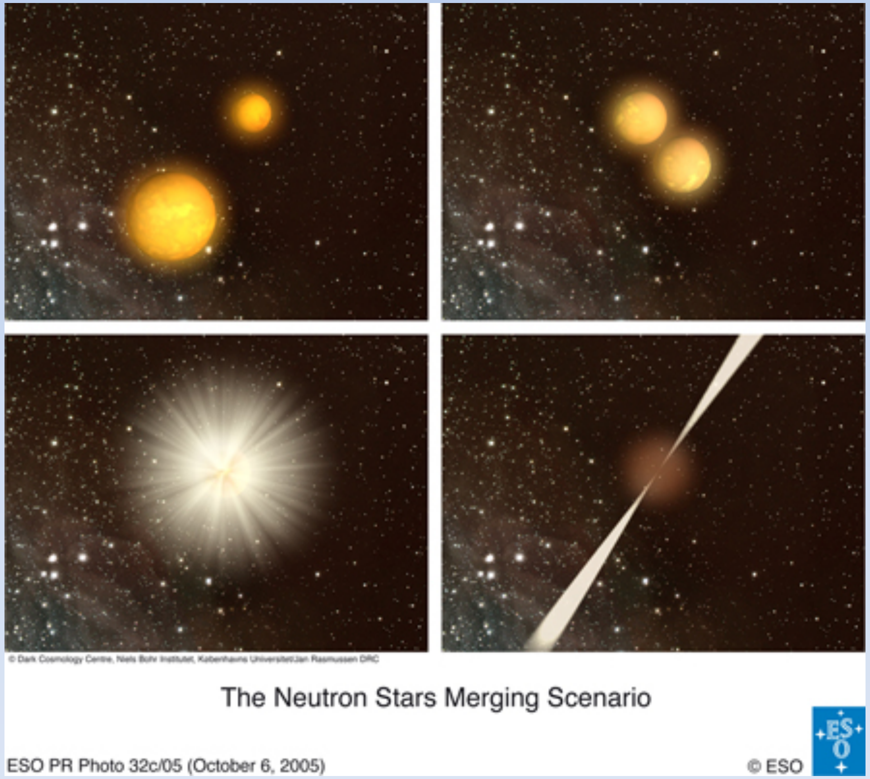
No associated supernova

Remnant (magnetar/BH?)

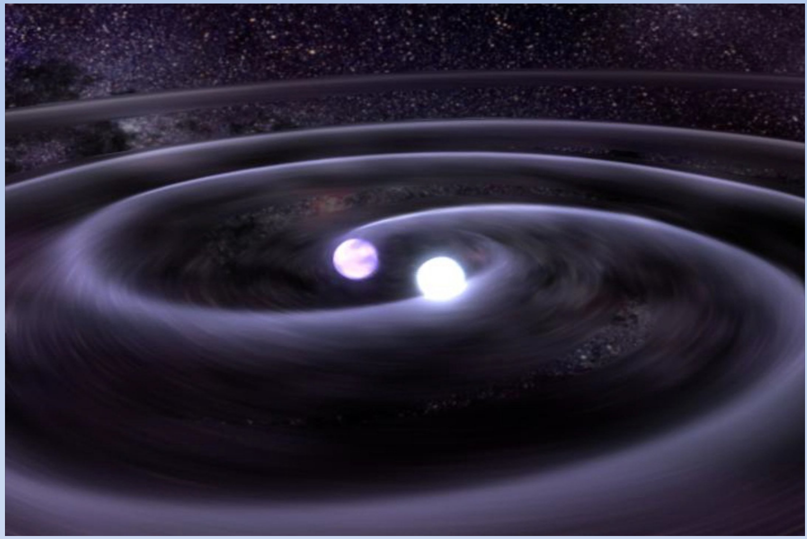
Emission geometry (jet?)

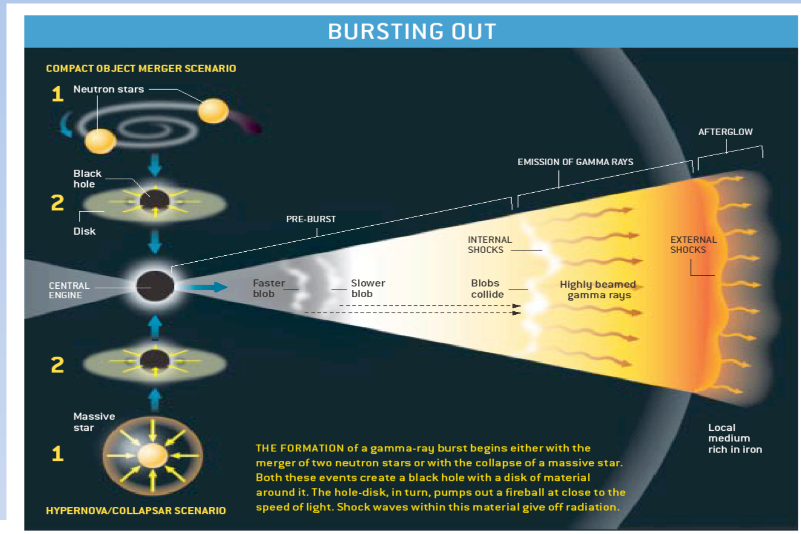
Kilonova association

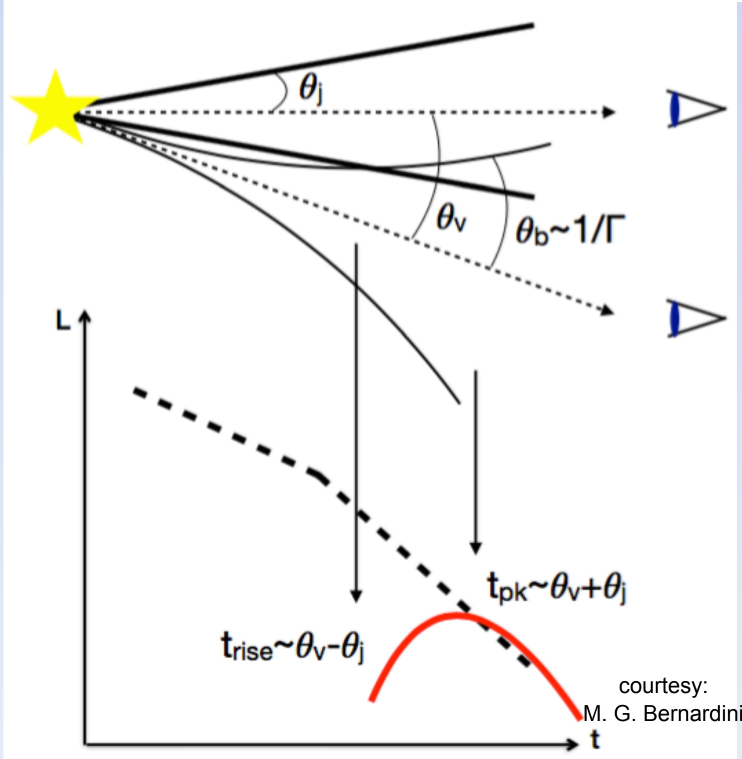
Gravitational waves



NS-NS / NS-BH electromagnetic counterparts





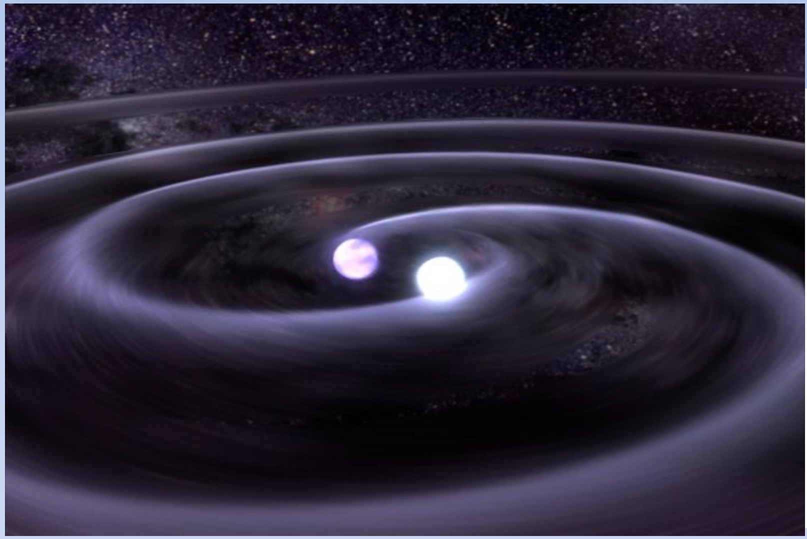


on-axis

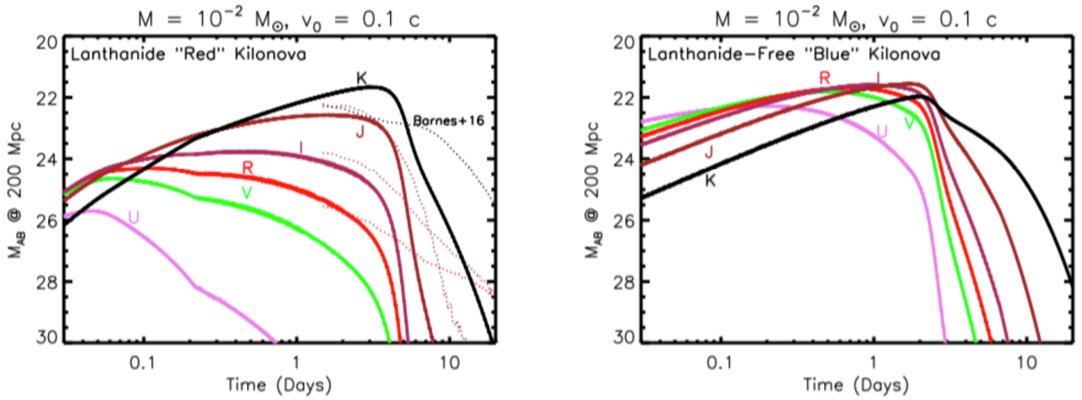
off-axis

Short GRB

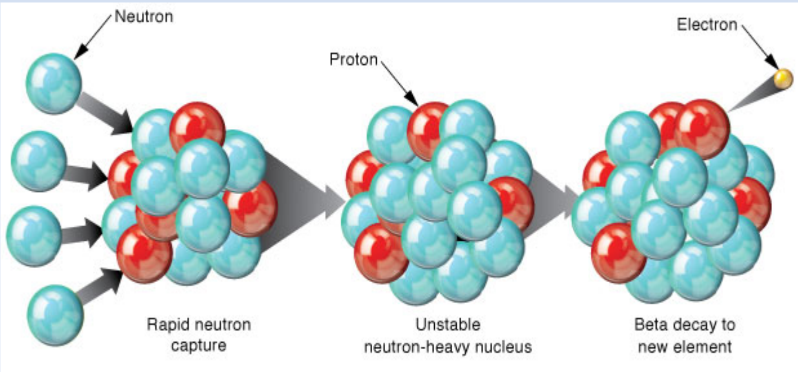
NS-NS / NS-BH electromagnetic counterparts

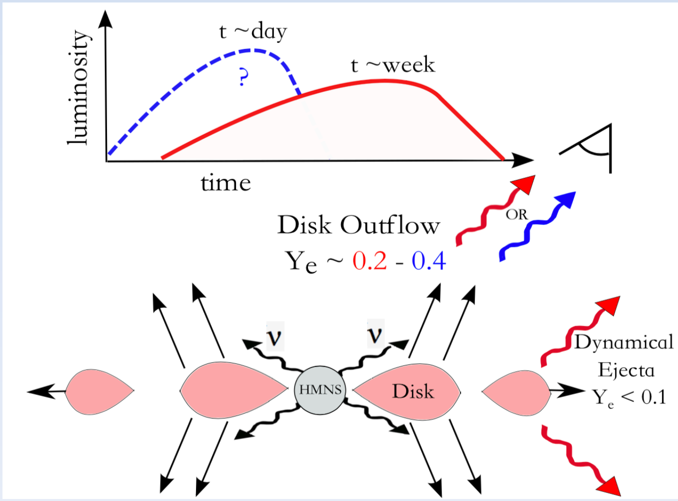


Kilonova



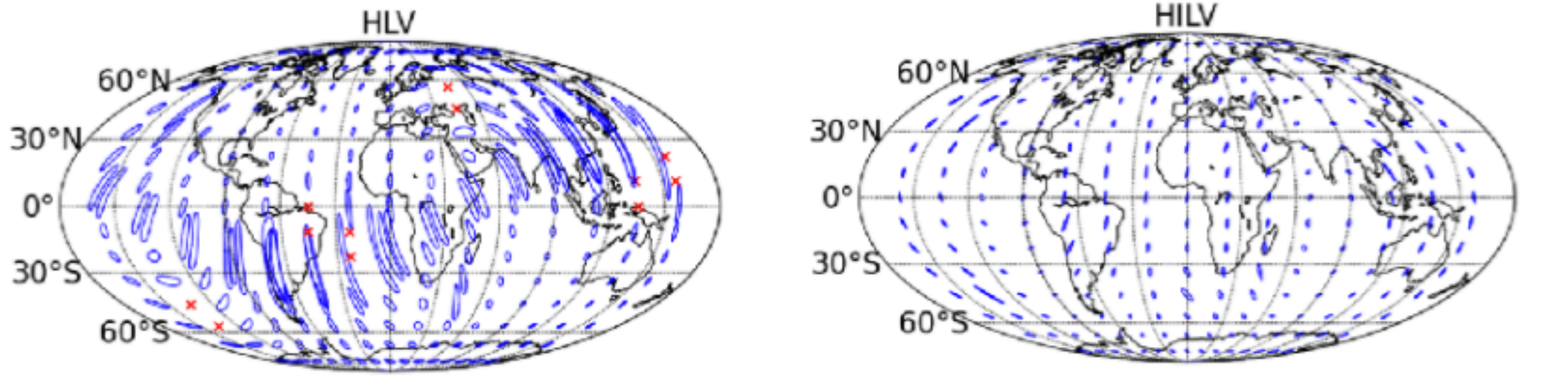
A key signature of a NS–NS/NS–BH binary merger is the production of a so-called "kilonova" (aka "macronova") due to the decay of heavy radioactive species produced by the *r*-process and ejected during the merger that is expected to provide a source of heating and radiation (Li and Paczynski 1998; Rosswog, 2005; Metzger et al., 2010).





Metzger & Fernandez 2014

The era of advanced GW detectors

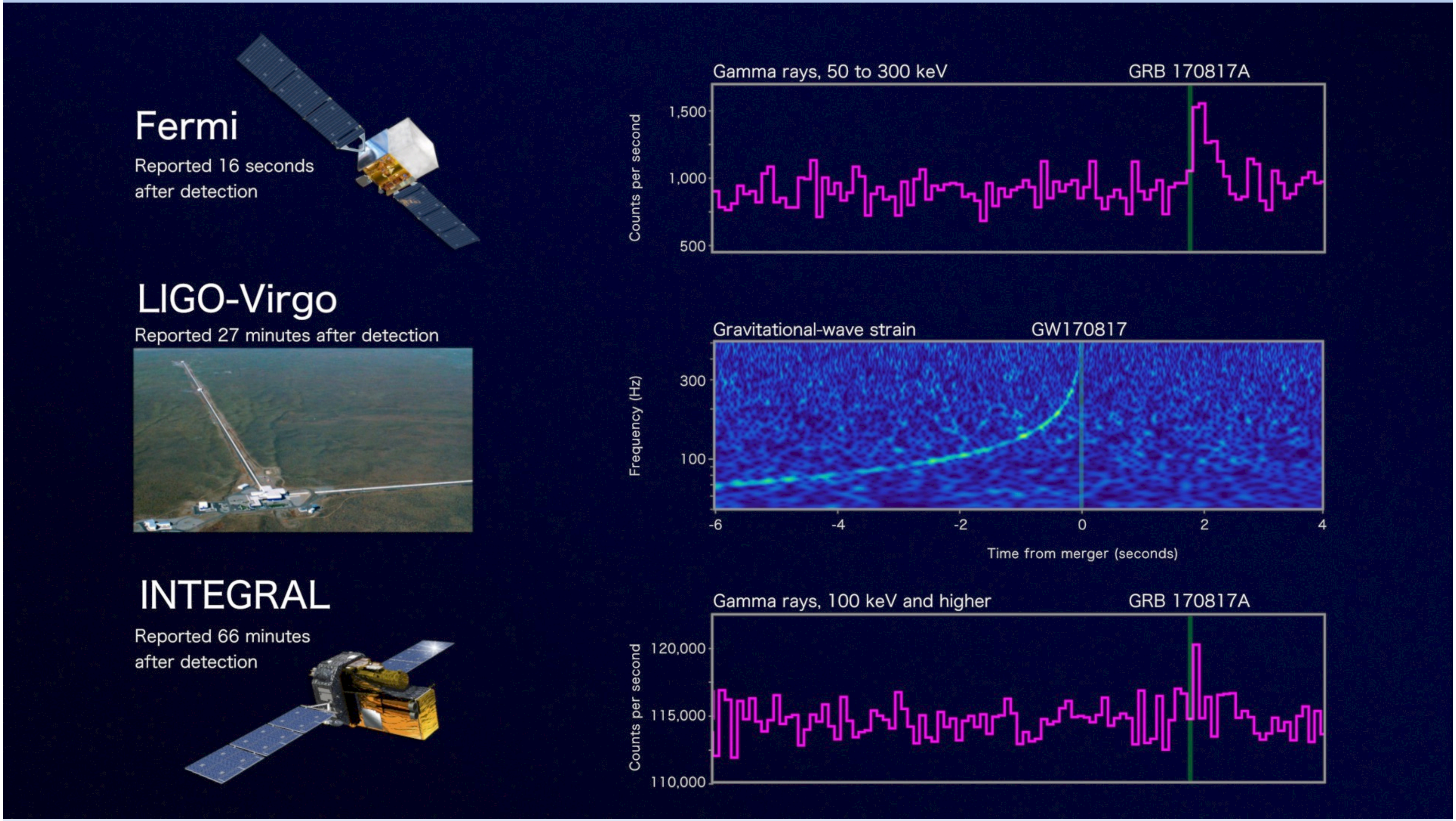


3 detectors

4 detectors

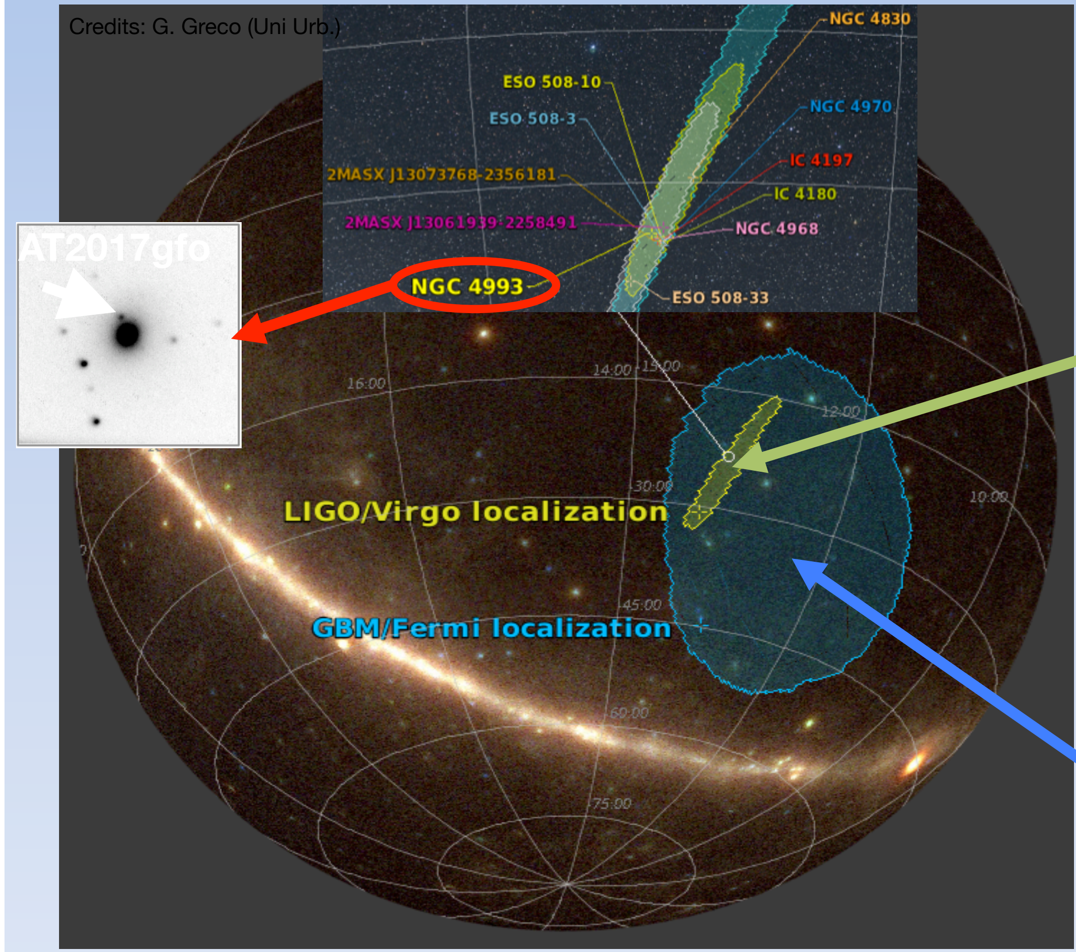
sky localization (90% confidence level)

GW 170817 & GRB 170817A



Abbott+17; Goldstein+17; Savchenko+17

GW 170817 / GRB 170817A / AT2017gfo



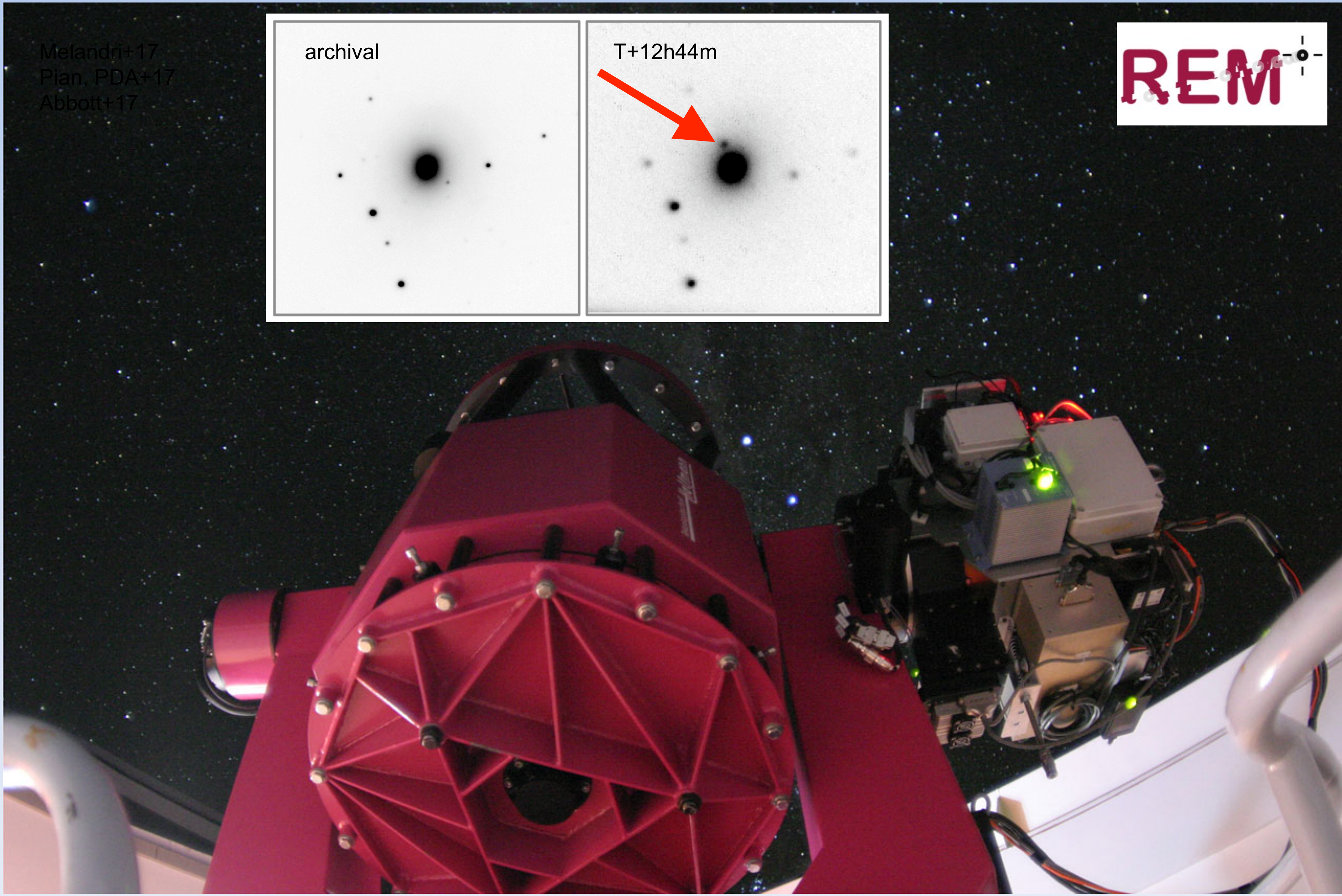
PRL 119, 161101 (2017) Selected for a Viewpoint in Physics
PHYSICAL REVIEW LETTERS
week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

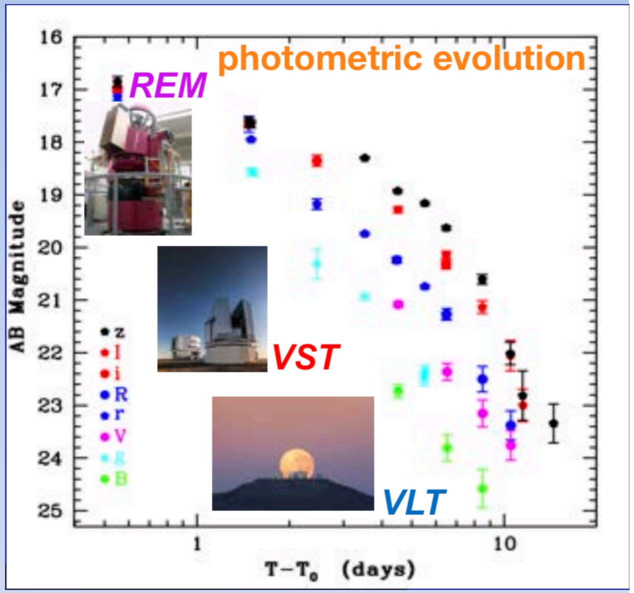
B. P. Abbott et al.*
(LIGO Scientific Collaboration and Virgo Collaboration)

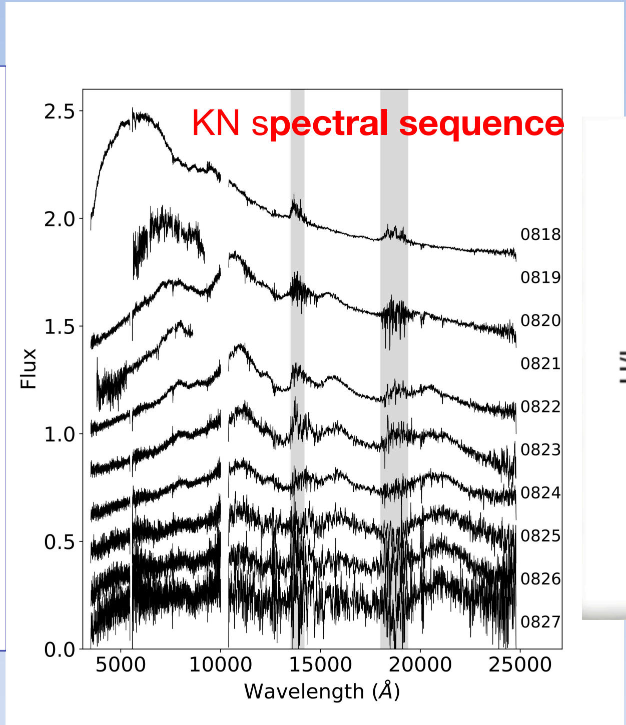
(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

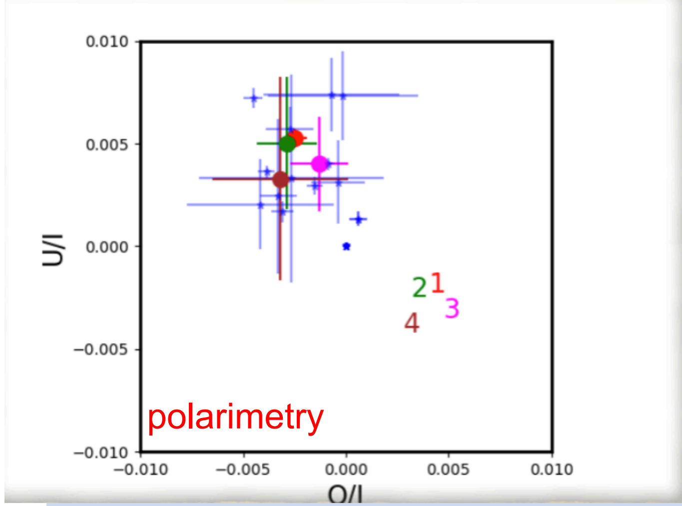
GW 170817 / AT2017gfo



GW 170817 / AT2017gfo





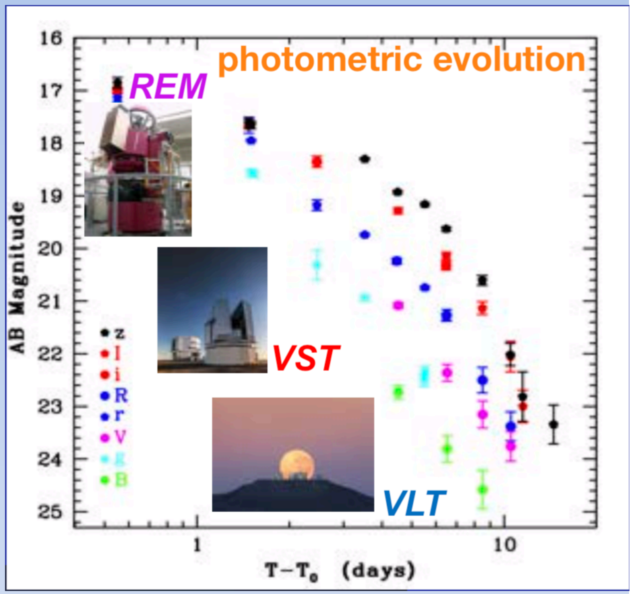


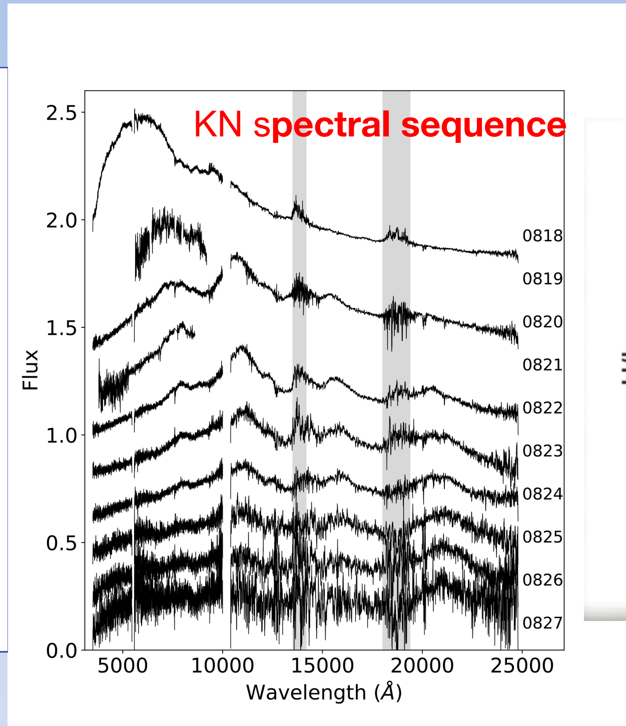
Pian, PDA et al., 2017

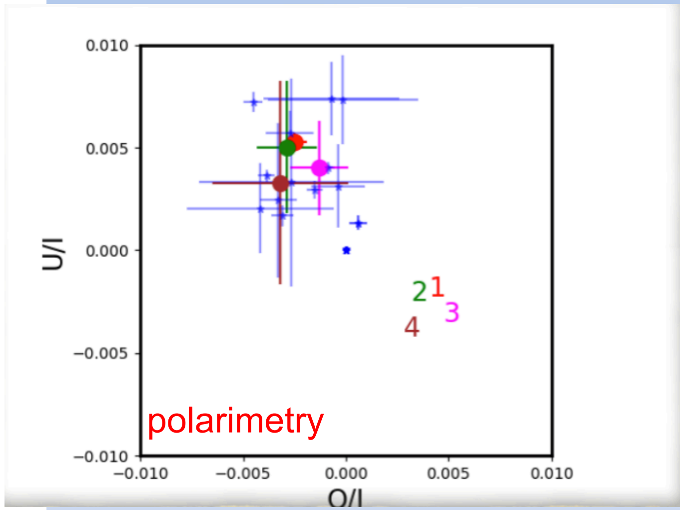
(see also Arcavi+17; Coulter+17; Evans+17; Lipunov+17; Smartt+17; Soares-Santos+17; Tanvir+17; Valenti+17 and many others)

Covino et al., 2017

GW 170817 / AT2017gfo





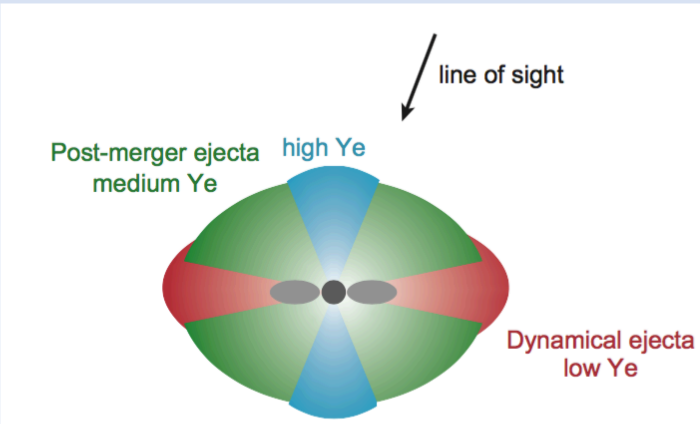


Pian, PDA et al., 2017

Covino et al., 2017

(see also Arcavi+17; Coulter+17; Evans+17; Lipunov+17; Smartt+17; Soares-Santos+17; Tanvir+17; Valenti+17 and many others)

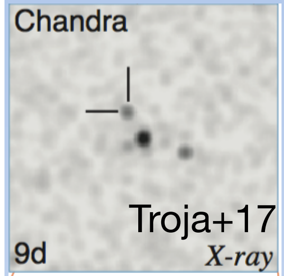
Full characterization of the KN properties

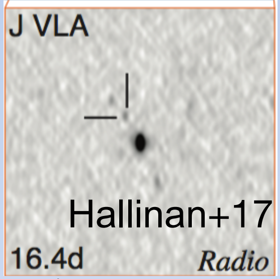


Three components kilonova model with different velocity, composition and electron (proton) fraction (low Ye: lanthanide-rich; high Ye: lanthanide-poor)

0.03-0.05 M_{Sun} ejected mass
Fast moving dynamical ejecta (0.2c) + slower wind (0.05c)

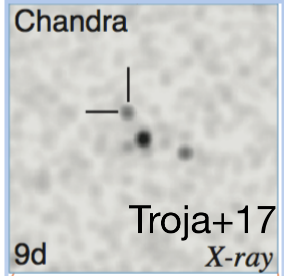
GW 170817 / GRB 170817A

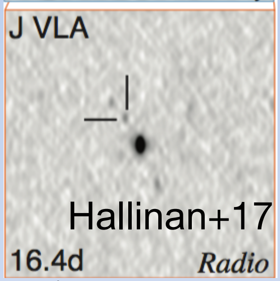




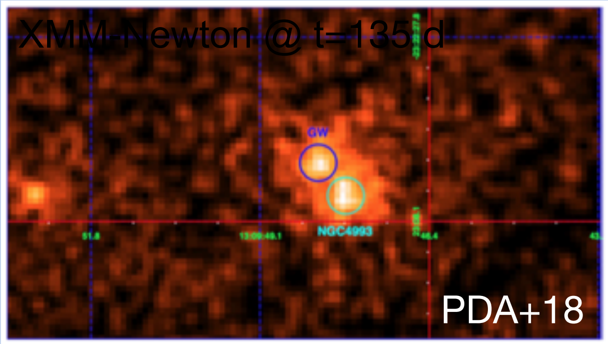
1st detection of the afterglow

GW 170817 / GRB 170817A



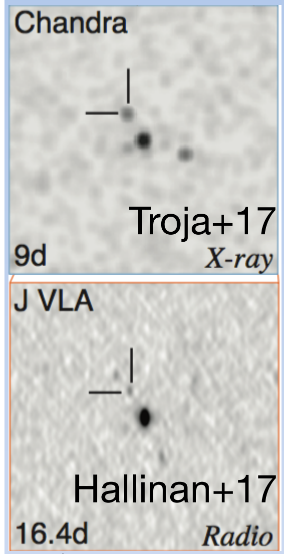


1st detection of the afterglow

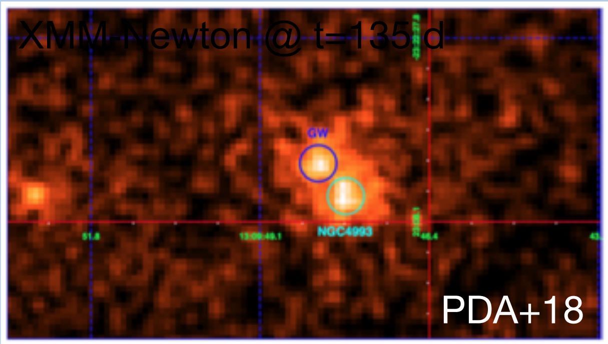


detection of the afterglow at the **peak**

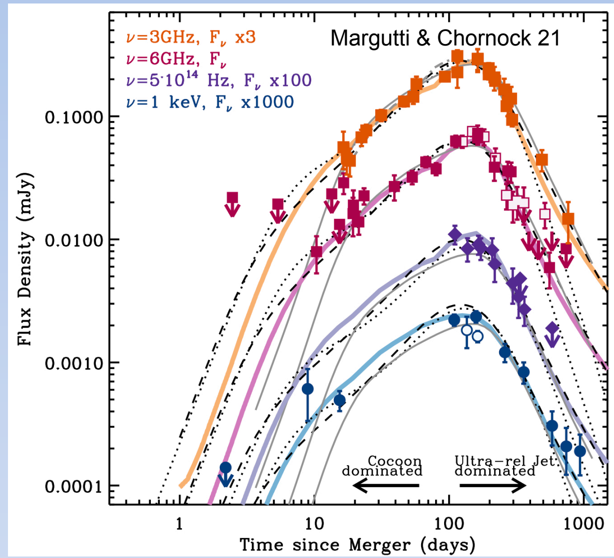
GW 170817 / GRB 170817A



1st detection of the afterglow

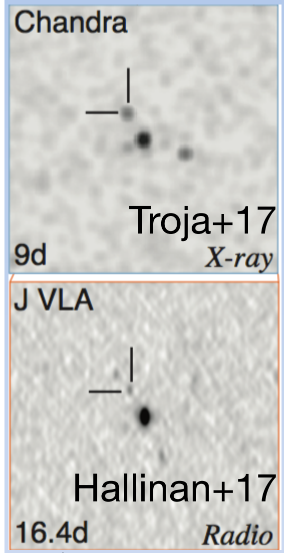


detection of the afterglow at the **peak**

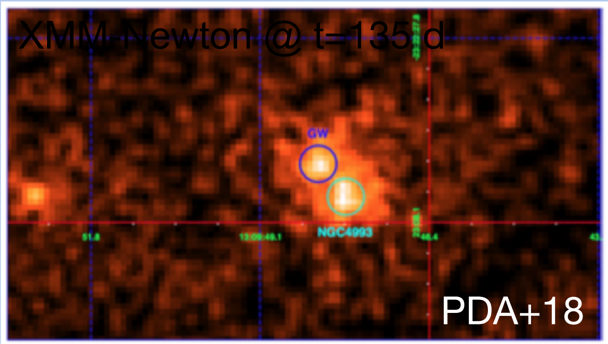


overall afterglow light curve

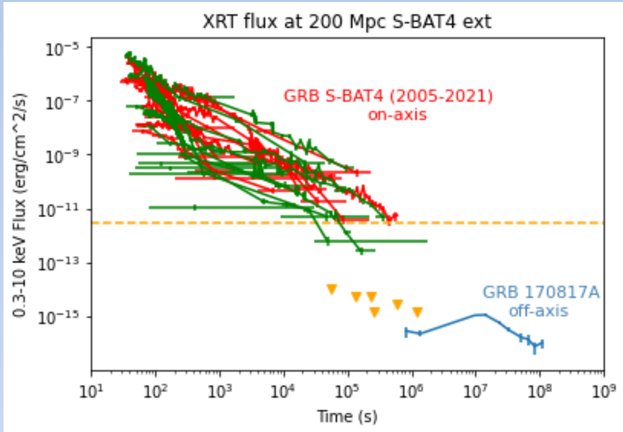
GW 170817 / GRB 170817A



1st detection of the afterglow

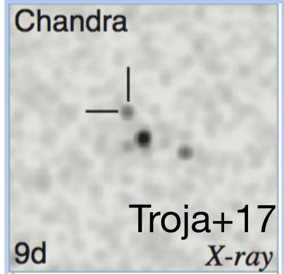


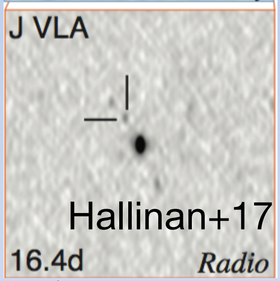
detection of the afterglow at the **peak**



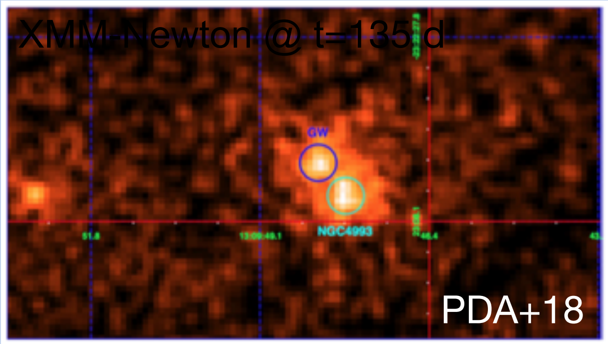
GRB 170817A w.r.t. SGRBs
Michela Dinatolo (Bachelor student)
see also Duan+19; Salafia+19

GW 170817 / GRB 170817A

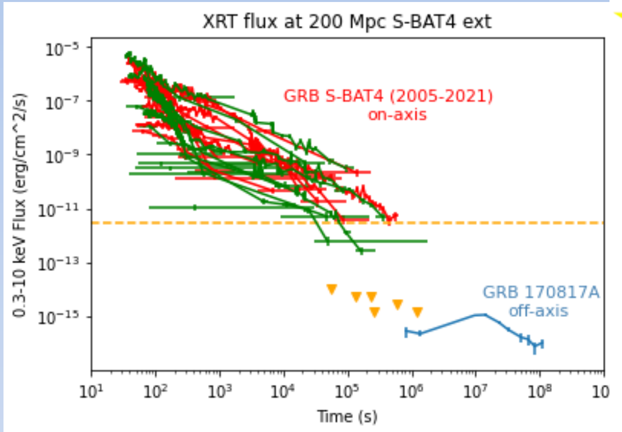




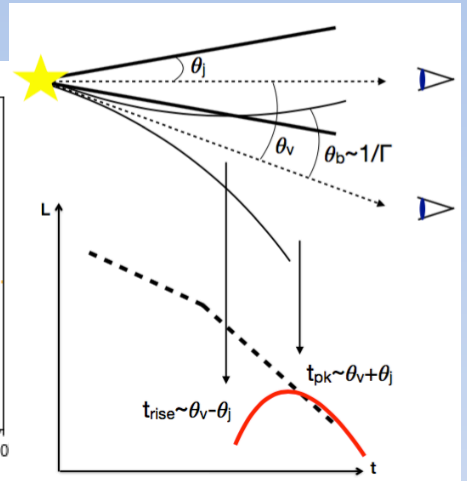
1st detection of the afterglow



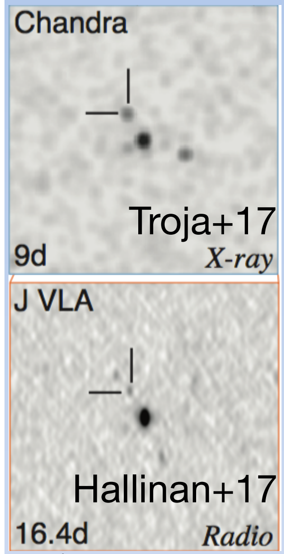
detection of the afterglow at the **peak**



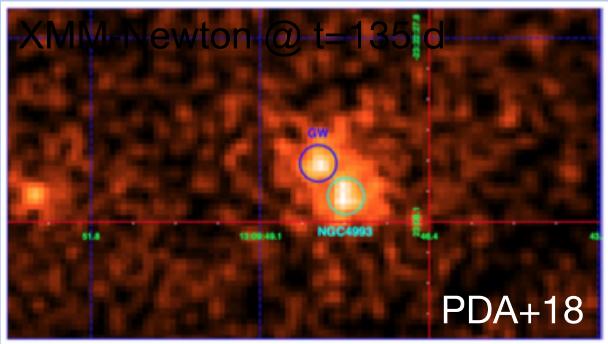
GRB 170817A w.r.t. SGRBs
Michela Dinatolo (Bachelor student)
see also Duan+19; Salafia+19



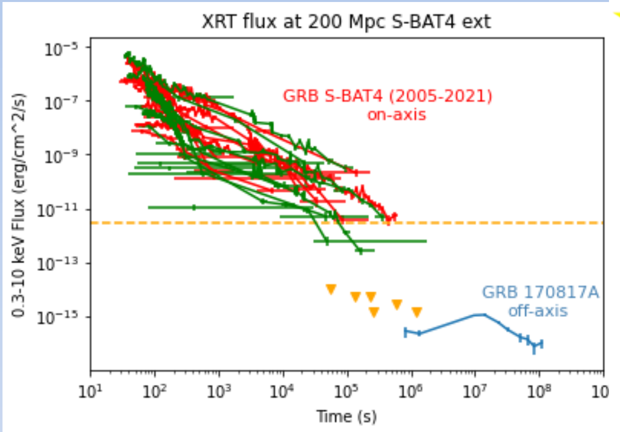
GW 170817 / GRB 170817A

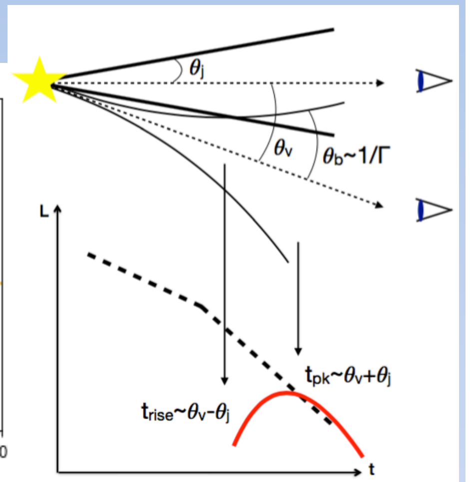


1st detection of the afterglow

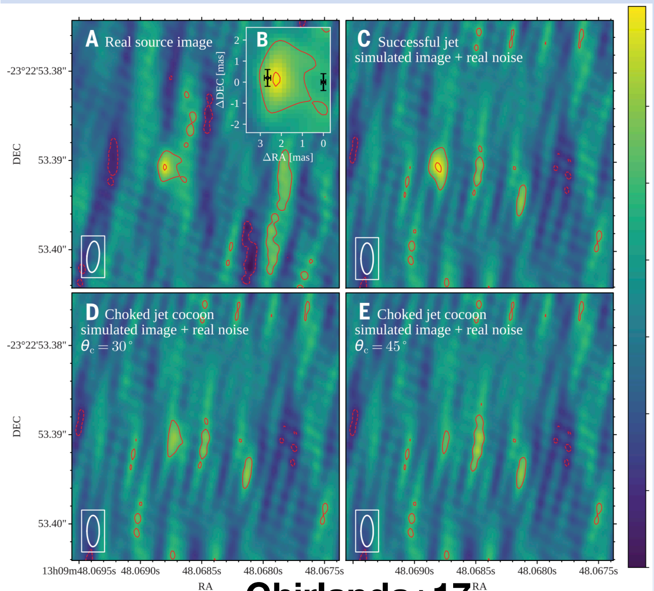


detection of the afterglow at the **peak**





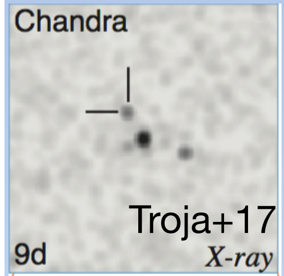
GRB 170817A w.r.t. SGRBs
Michela Dinatolo (Bachelor student)
see also Duan+19; Salafia+19

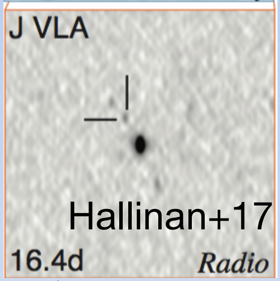


Ghirlanda+17

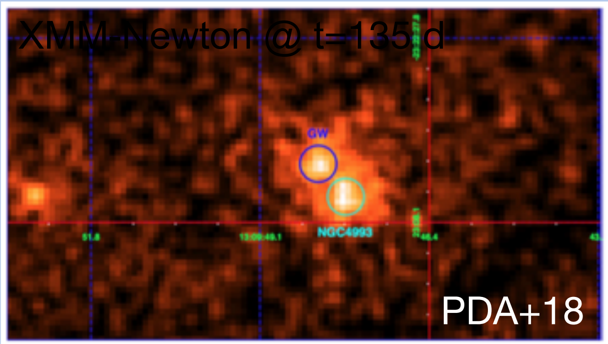
The radio afterglow is detected with an angular size < 2 mas in VLBI data obtained ~ 207 d after the merger. Evidence for superluminal motion is also found measuring an angular offset between T+75 d and T+235 d.

GW 170817 / GRB 170817A

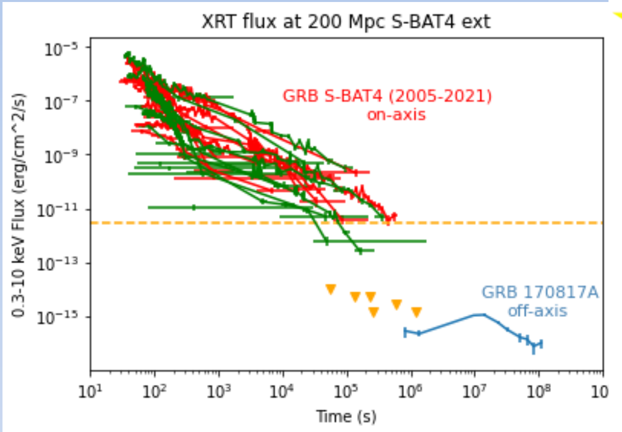


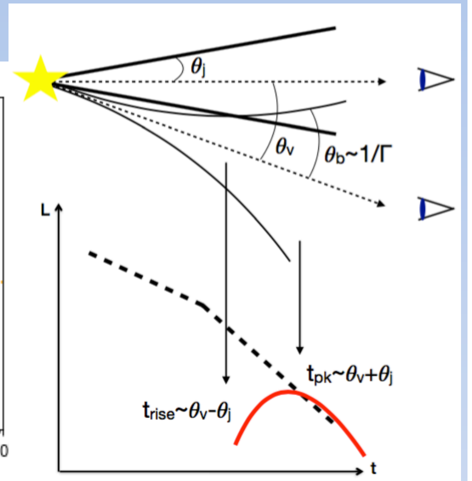


1st detection of the afterglow



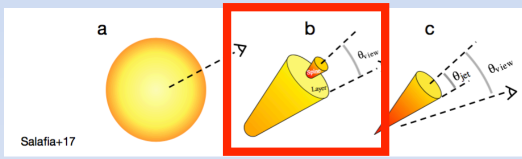
detection of the afterglow at the **peak**

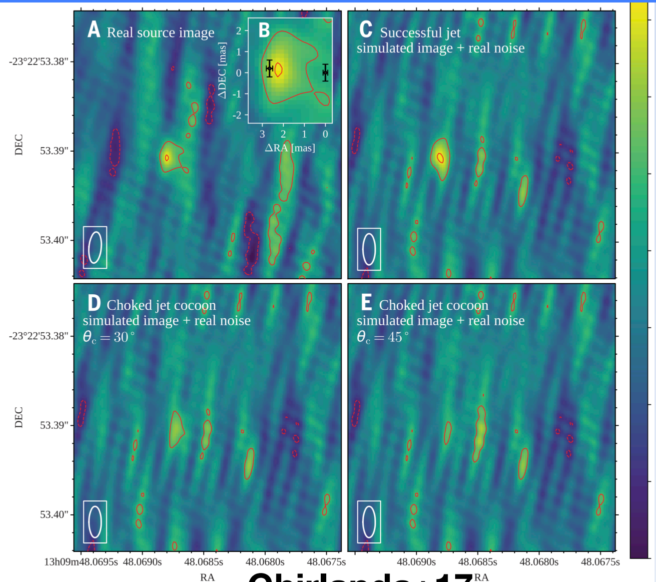




GRB 170817A w.r.t. SGRBs
Michela Dinatolo (Bachelor student)
see also Duan+19; Salafia+19

Full characterization of the GRB properties: evidence for a structured jet





Ghirlanda+17

The radio afterglow is detected with an angular size < 2 mas in VLBI data obtained ~ 207 d after the merger. Evidence for superluminal motion is also found measuring an angular offset between T+75 d and T+235 d.

These findings, together with the afterglow light curve modelling, support the structured jet model. Fit to the data and numerical simulations are in agreement with the scenario of a structured jet with a relativistic core with θ_{jet} < 5 deg and θ_{view} ~ 20 deg.

Alexander+17,18; PDA+18; Dobie+18; Fong+19; Haggard+17; Hallinan+17; Hajela+19; Margutti+17,18; Mooley+18a,b; Reasmi+18; Ruan+18; Troja+18a,b,19,20; Ghirlanda+19; Piro+19; Margutti & Chornock 21 and many others