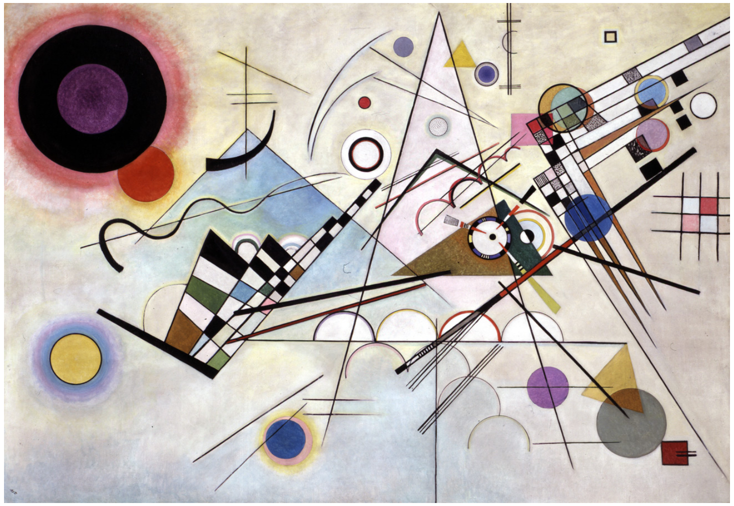
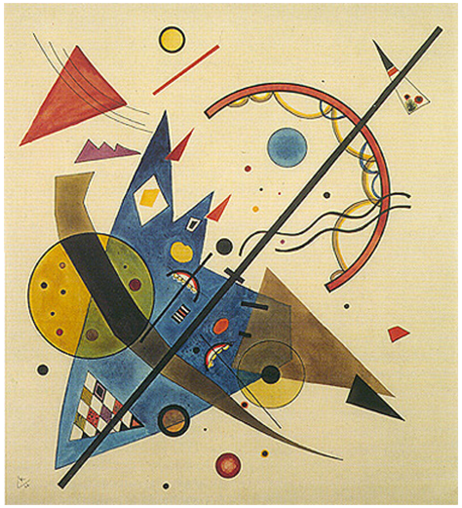
Compact binaries and gamma-ray bursts

Frédéric Daigne (Institut d'Astrophysique de Paris – Sorbonne Université)



Kandinksy – Ccomposition 8- 1923



Kandinksy – Curves and sharp angles - 1923

Third SVOM Scientific Workshop – Les Houches – May 15, 2018

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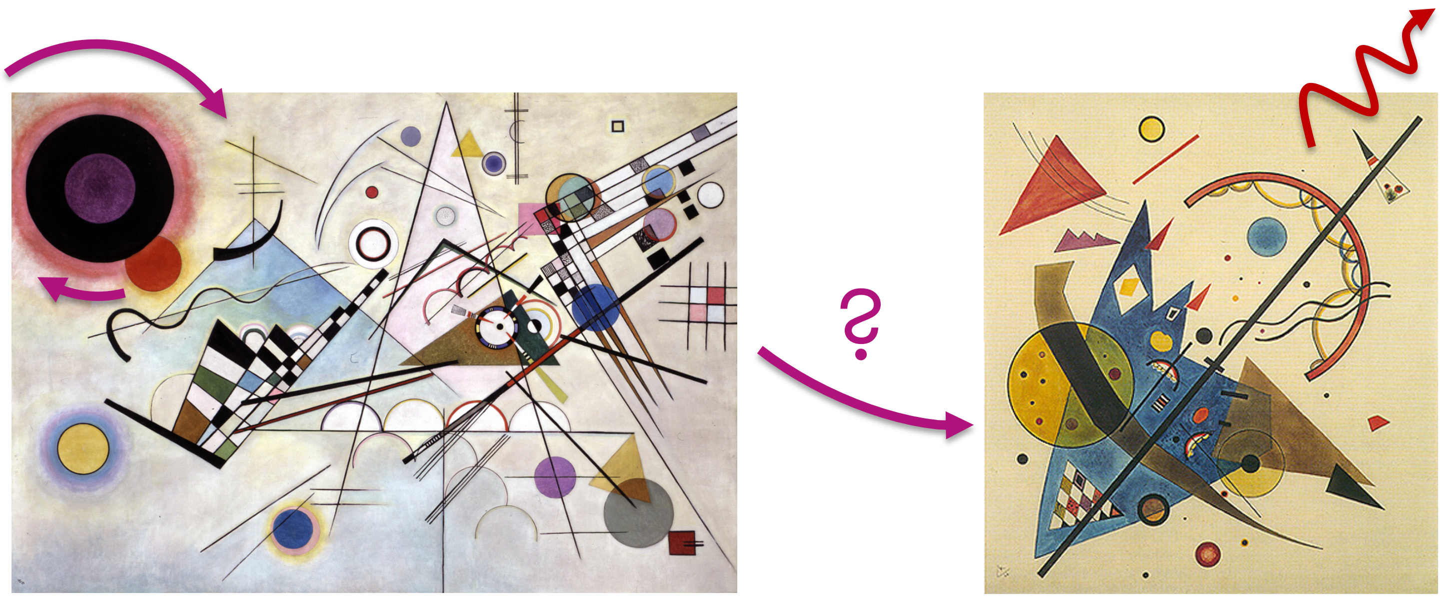


Kandinksy – Ccomposition 8- 1923

Kandinksy – Curves and sharp angles - 1923

Binary systems of compact objects

Observed systems

Formation scenario

Binary systems of compact objects: known systems

Known systems in our Galaxy:

- WD+WD: ~10 systems are known: T = 10 min à 1 h
- WD+NS: a few cases among LMXB

Detection: accretion 2→1 V, X

- **NS+NS: ~10 systems are known – detection : at least one NS is a pulsar**

Name	Pulsar period P (ms)	Orbital period T (jour)	Orbit excentricity e	Pulsar age t (Myr)	Merger time τ_c (Myr)	Masses M_1, M_2 ($M_\odot$)
J0737-3039	22.7/2770	0.102	0.088	200/50	79	1.35/1.24
J1906+0746	144.1	0.17	0.085	0.13	320	1.29/1.32
B1913+16	59.0	0.3	0.62	100	320	1.441/1.387
B2127+11C	30.5	0.3	0.68	100	200	1.36/1.35
J1756-2251	28.5	0.32	0.18	400	$1.6\,10^4$	1.34 / 1.23
B1534+12	37.9	0.4	0.27	250	$2.5\,10^3$	1.333 / 1.345
B1829-2456	41.0	1.18	0.14	$1.3\,10^4$	$6.3\,10^4$	?/ ?
J1518-4904	40.9	8.6	0.25	$2.0\,10^4$	$2.5\,10^6$	< 1.17 / > 1.55
J1811-1736	104.2	18.8	0.83	$1.0\,10^3$	$1.0\,10^7$	$M_1 + M_2 = 2.57$, $M_2 > 0.93$
B1820-11	279.8	357.8	0.79	3.2	$6.3\,10^9$	?/ ?

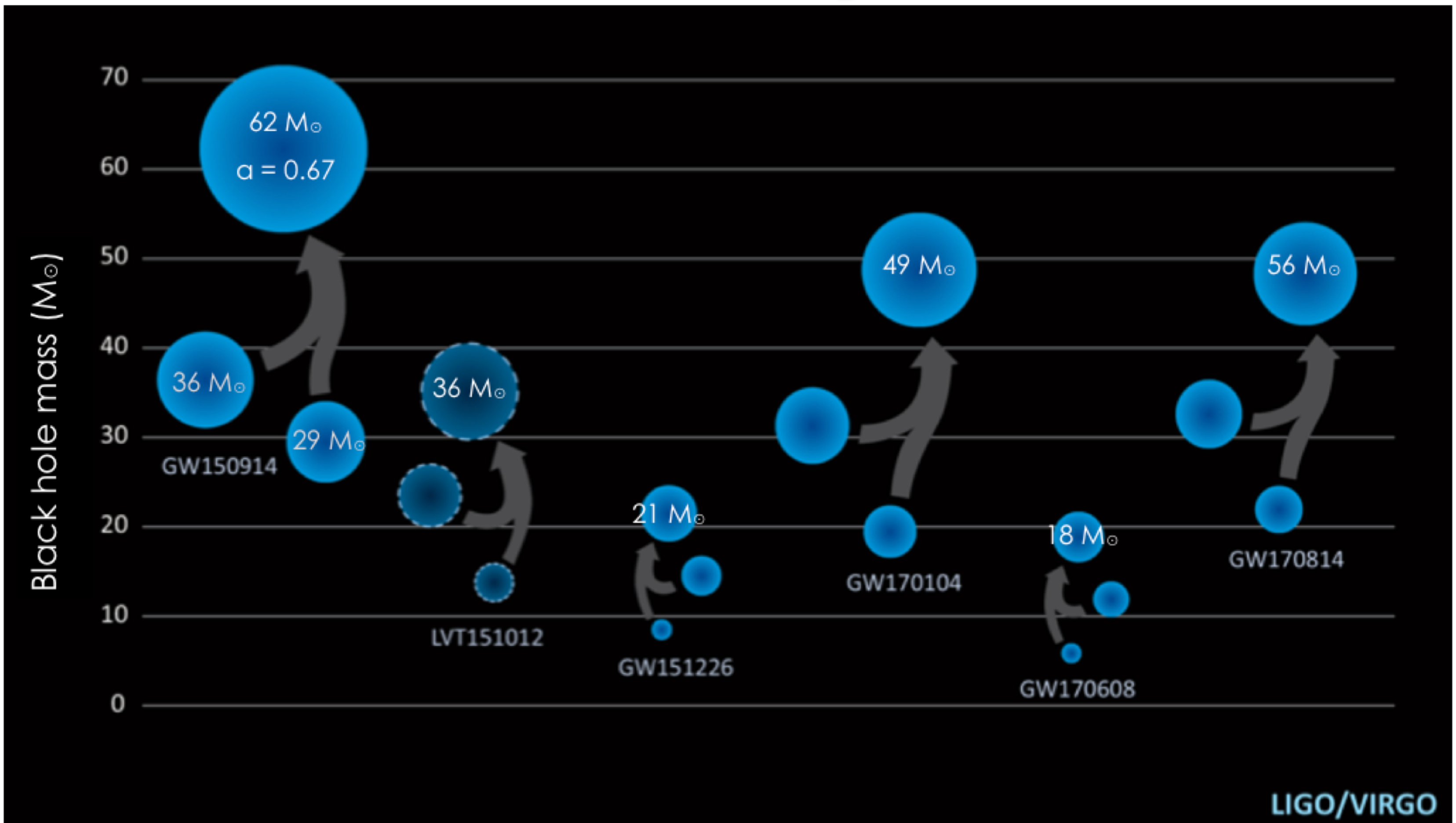
- **NS+BH: no system known, should exist**
- **BH+BH: no system known, do exist**

Binary systems of compact objects: known systems

Known systems from GW: **(detection: last orbits and merger)**

- **NS+NS: 1 system (GW 170817) at 40 Mpc**
- **NS+BH: 0**
- **BH+BH: a few systems**

The BNS is the only system that can be compared to the Galactic population



Formation is difficult!

1. **Two OB main sequence stars**
   8+20 $M_\odot$ / a=35 $R_\odot$ / T=4.6 d

1.

T~3 Myr, N~10^4

~10^4 systems in the MW ?

(MW: ~2 10^{11} stars)

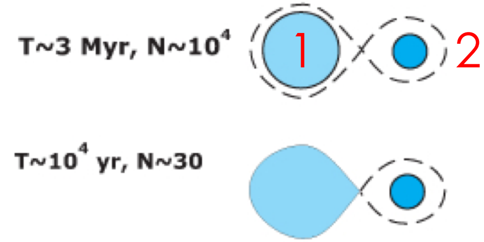
« Standard » formation of a NS+NS system

Fig. from Tutukov & Yungelson Living Review in Relativity

Formation is difficult!

1. **Two OB main sequence stars**
   8+20 $M_\odot$ / a=35 $R_\odot$ / T=4.6 d
2. **1 evolves**: fills its Roche lobe
   Transfer 1→2: conservative?

1.
2.



~30 systems in the MW ?

Fig. from Tutukov & Yungelson Living Review in Relativity

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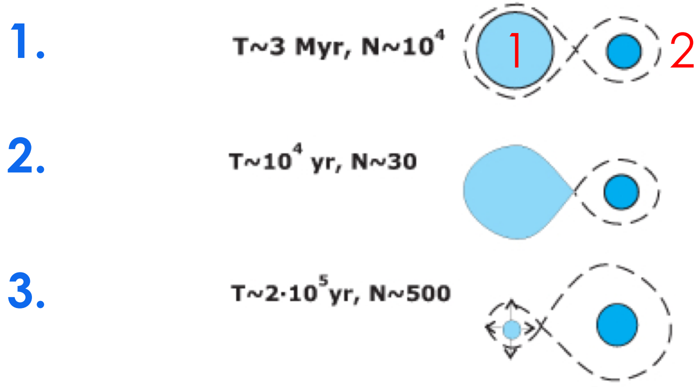
   (naked He core+strong wind)
   2 becomes a Be star ($\Omega \sim \Omega_K$)
   22.6+5.4 $M_\odot$ / a=62 $R_\odot$ / T=11 d



~500 systems in the MW ?

Fig. from Tutukov & Yungelson Living Review in Relativity

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4. **1 explodes**: supernova → NS
   High probability to eject 1
   4-10% of systems survive?

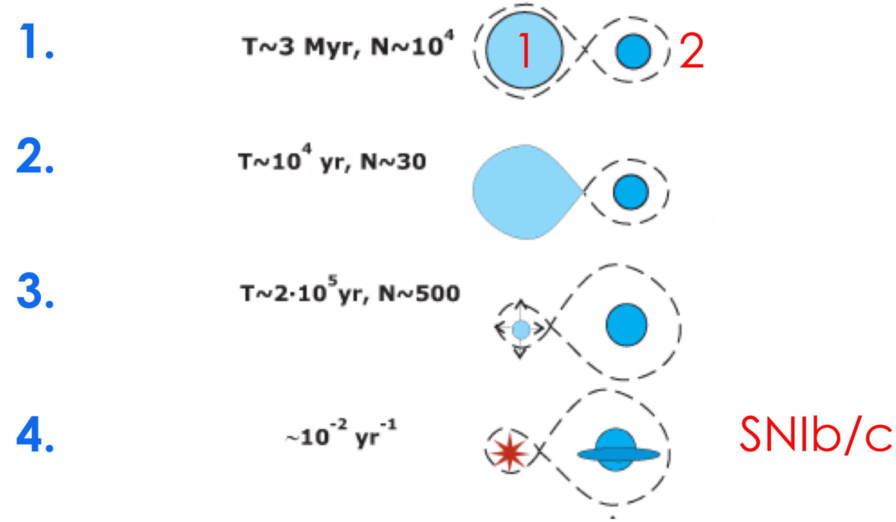

Fig. from Tutukov & Yungelson Living Review in Relativity

~half of SN Ib/c in the milky way ?
(~1 per century)

Link with long GRBs?

« Standard » formation of a NS+NS system

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5. **2 still on main sequence**
   close to Roche lobe
   wind: transfert 2→1

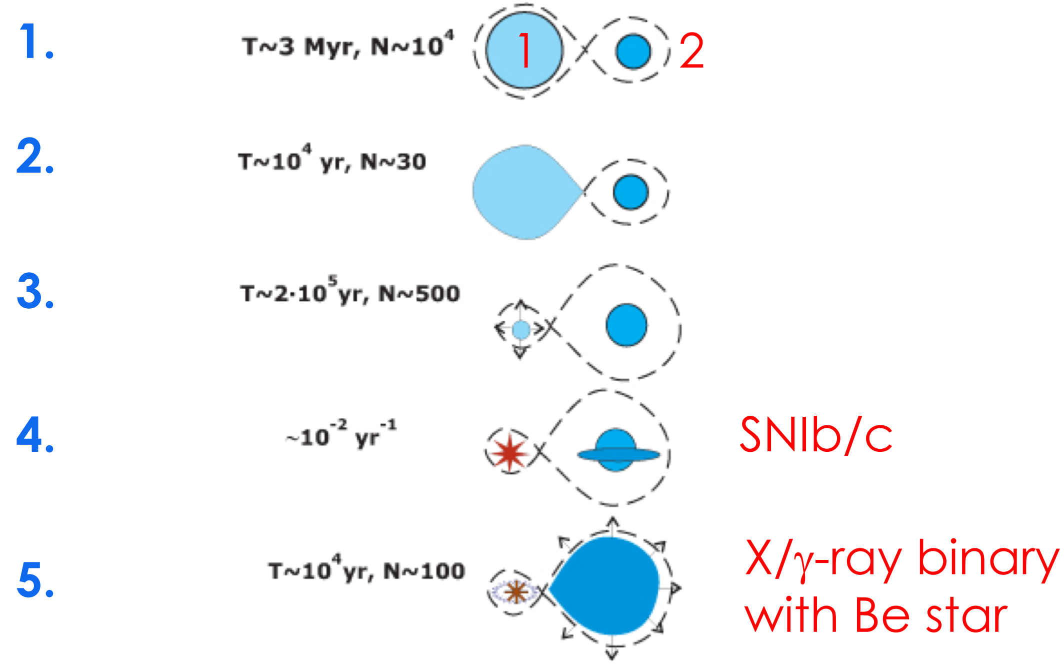

Fig. from Tutukov & Yungelson Living Review in Relativity

~100 systems in the MW ?

« Standard » formation of a NS+NS system

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   wind: transfert 2→1
6. **2 evolves: common envelope merger ?**

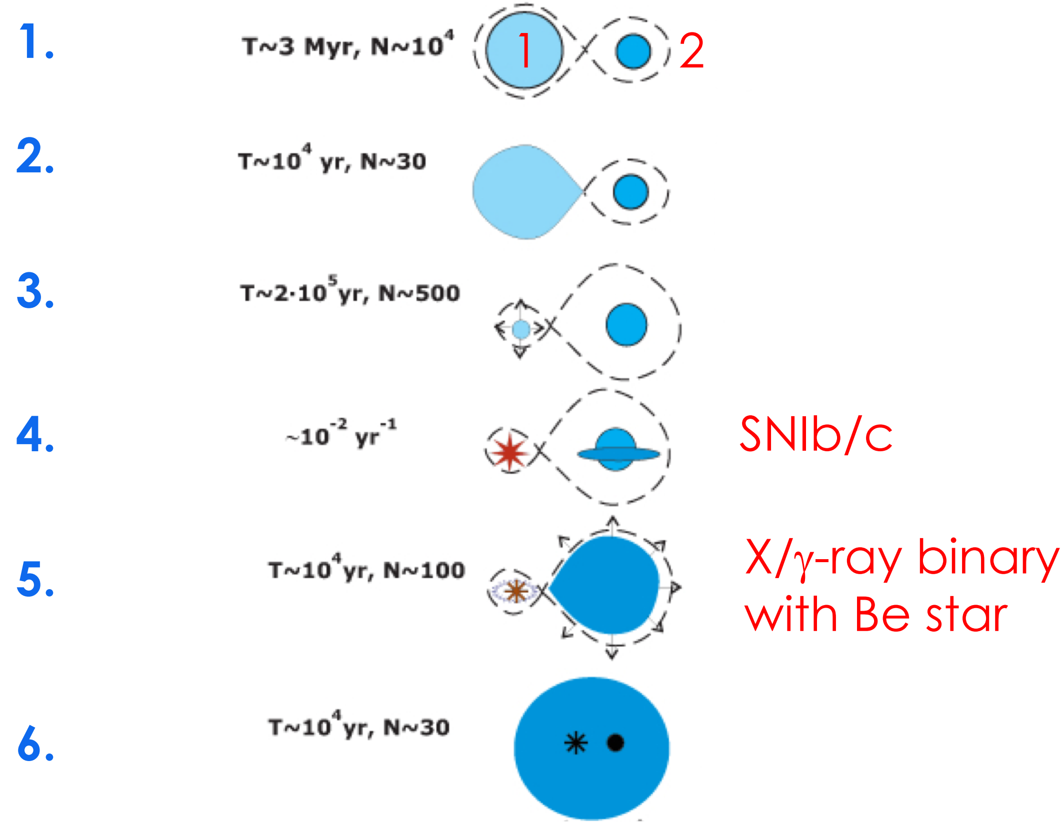

Fig. from Tutukov & Yungelson Living Review in Relativity

~30 systems in the MW ?

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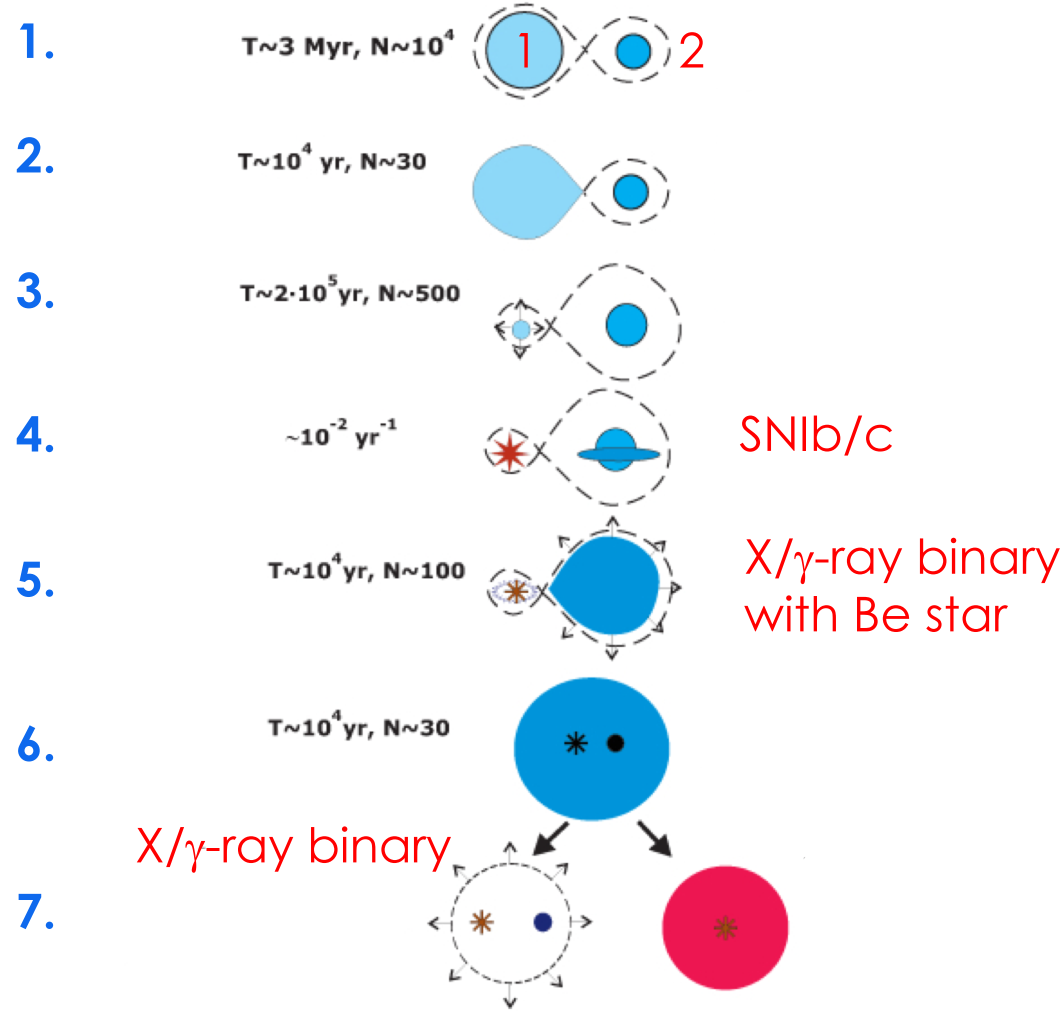
   merger ?
7. **NS+WR star**
   $6.3+1\text{-}2\ M_\odot$ / $a=1.4\ R_\odot$
   (variant: Thorne-Zytkow ?)



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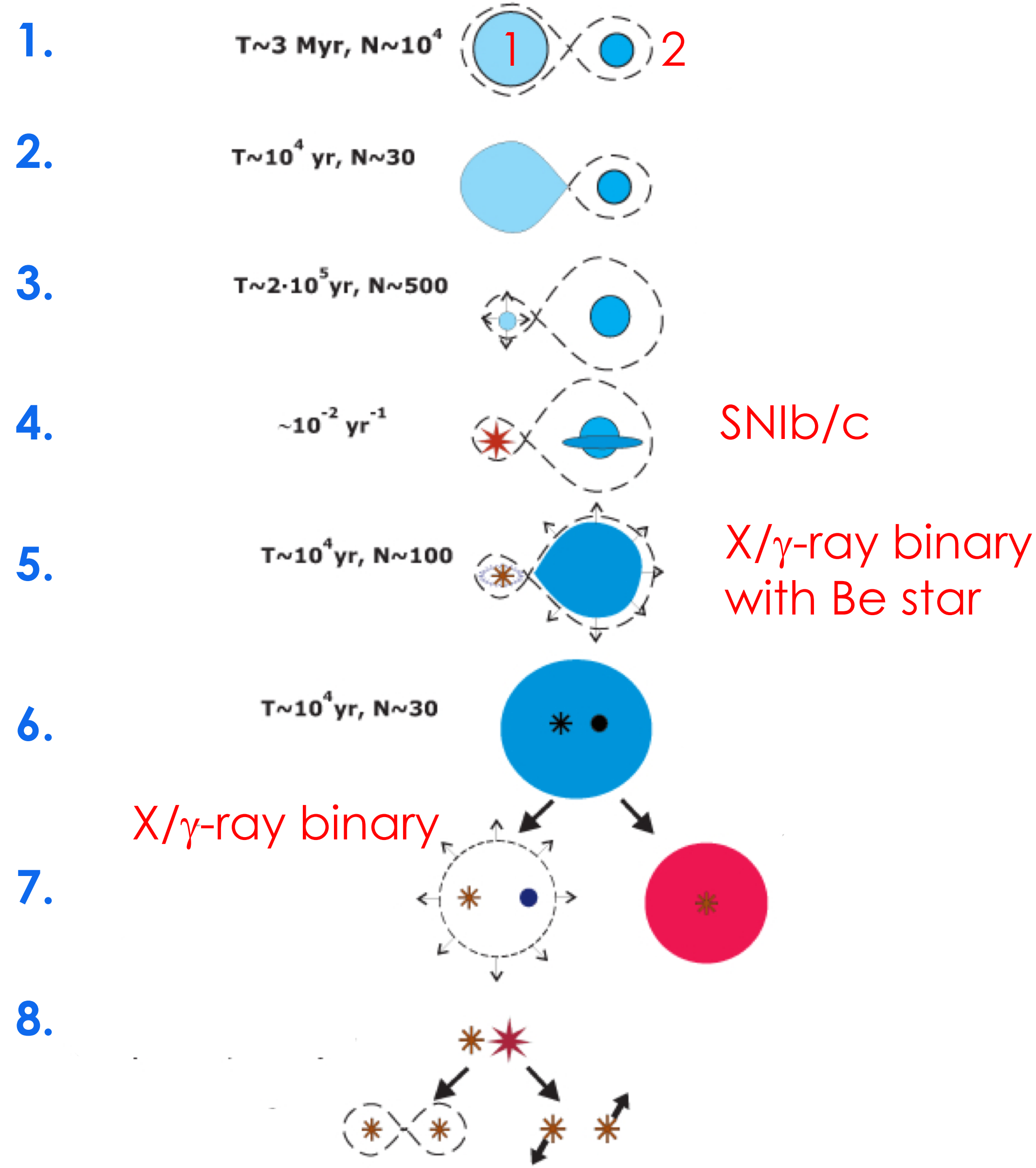
   merger ?
7. **NS+WR star**
   6.3+1-2 $M_\odot$ / a=1.4 $R_\odot$
   (variant: Thorne-Zytkow ?)
8. **2 explodes**: supernova → NS
   Probability to survive ?



« Standard » formation of a NS+NS system

Fig. from Tutukov & Yungelson Living Review in Relativity

Formation is difficult!

10^6 BNS in the Milky way?
(lifetime Gyr)

9. Inspiral GW 

10. 

Merger GW+em

« Standard » formation of a NS+NS system

Fig. from Tutukov & Yungelson Living Review in Relativity

Formation is difficult!

BNS: many uncertainties

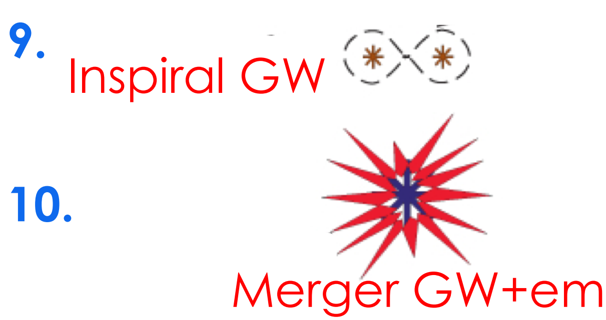
Population models difficult to calibrate (only 10 known BNS in the MW)

Even worse for NS+BH and BBH

Additional (big) problem: BBH GW-detections show very massive objects

- Very massive progenitors?
- Formation in a dense stellar environment

10^6 BNS in the Milky way? (lifetime Gyr)



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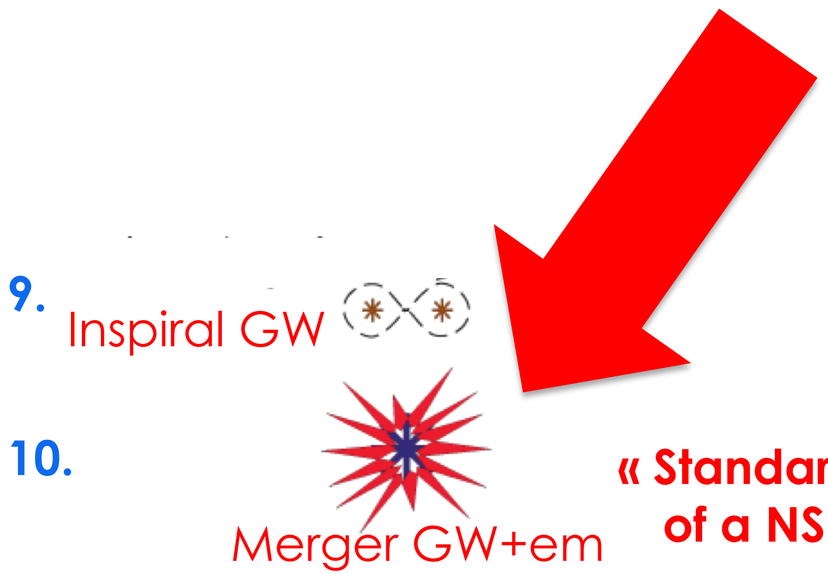


« Standard » formation of a NS+NS system

Fig. from Tutukov & Yungelson Living Review in Relativity

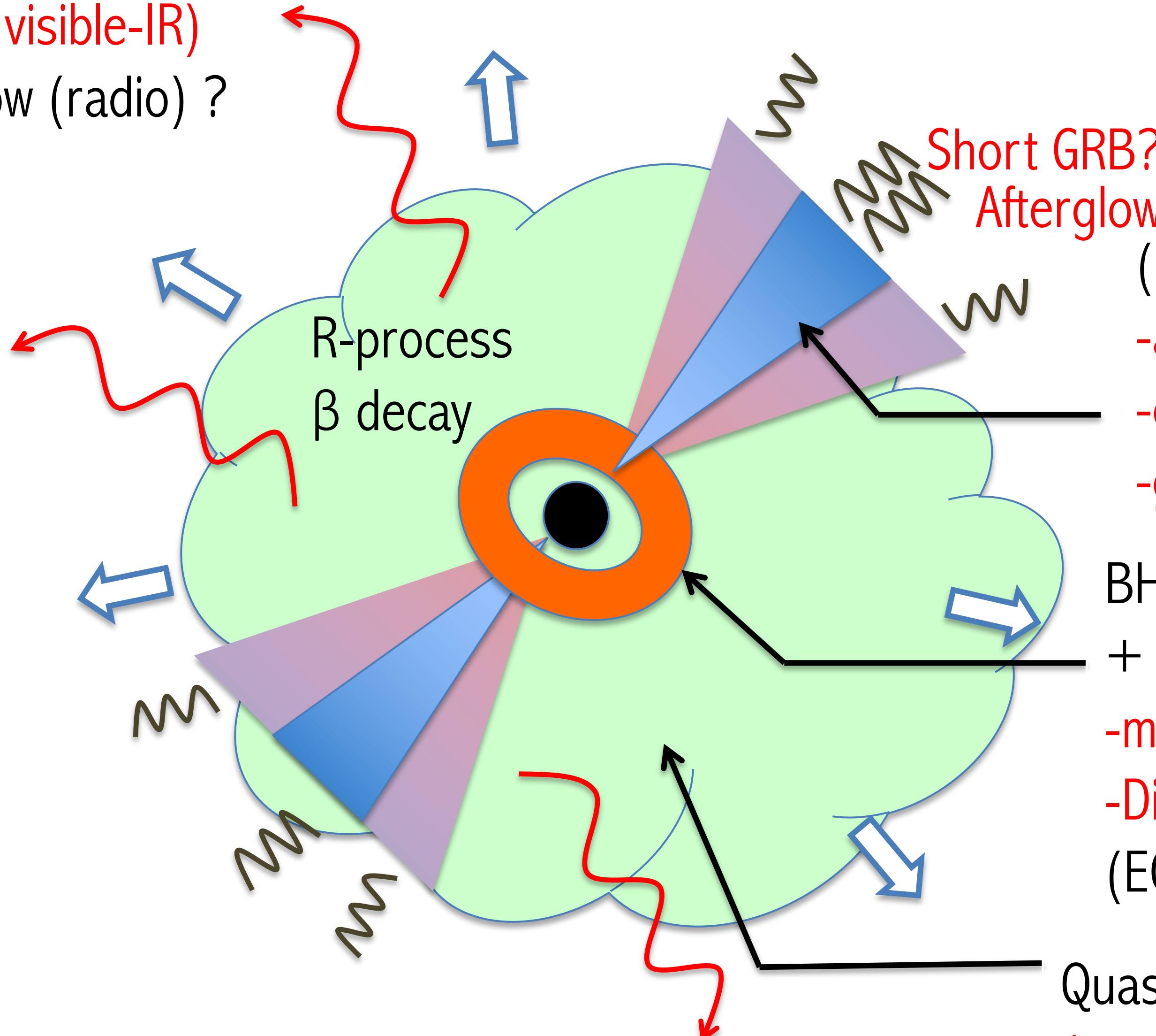
NS+NS/BH? mergers

Remnant

Electromagnetic emission

Remnant of a NS+NS merger

Radioactively powered emission
(kilonova: visible-IR)
+ afterglow (radio) ?



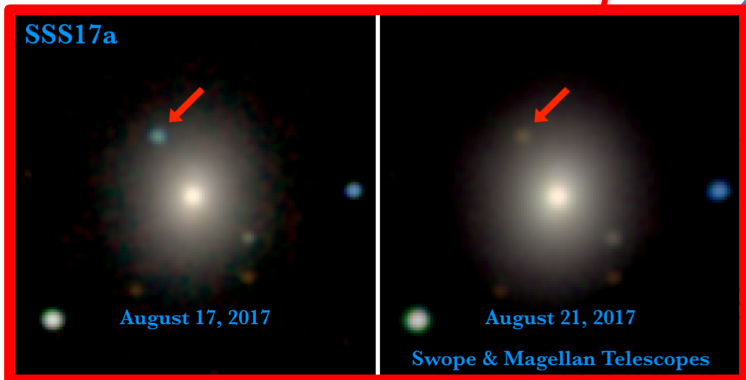
(Relativistic?) ejecta
-acceleration?
-composition?
-geometry?

BH/magnetar
+ accretion torus
-mass, spin?
-Disk mass?
(EOS…)

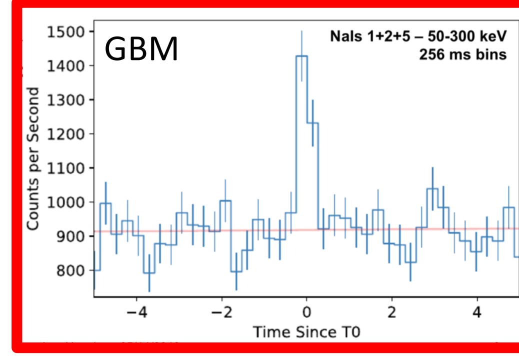
Quasi-spherical ejecta
(several components?)

Remnant of a NS+NS merger

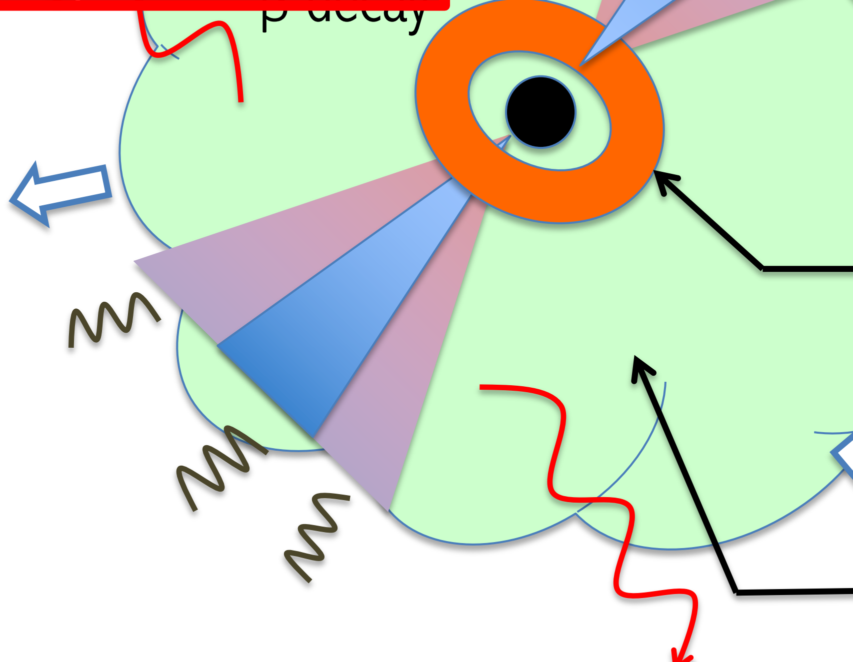
Radioactively powered emission
(kilonova: visible-IR)



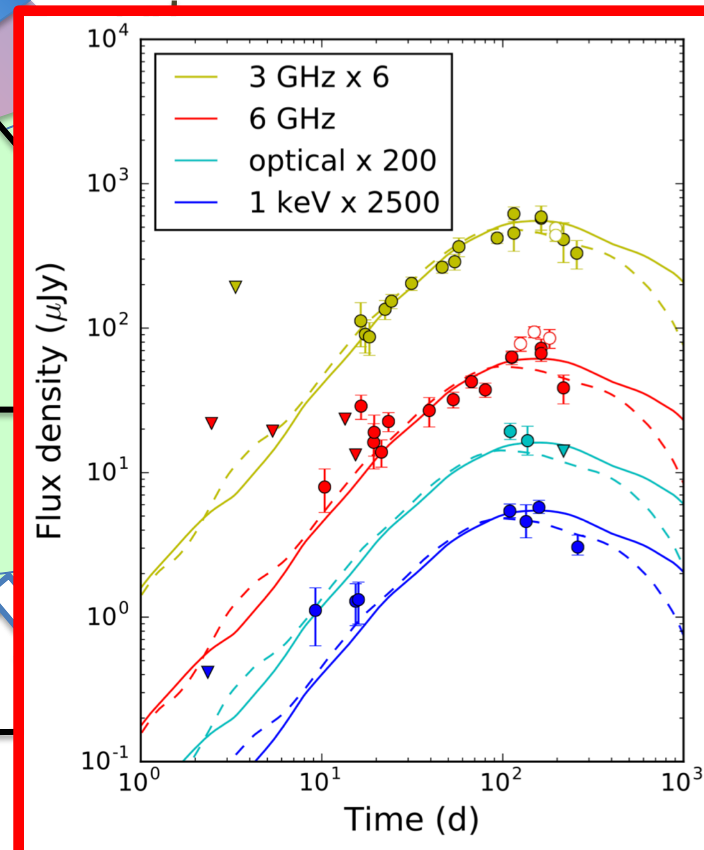
Obs.



?



Short GRB?
Afterglow

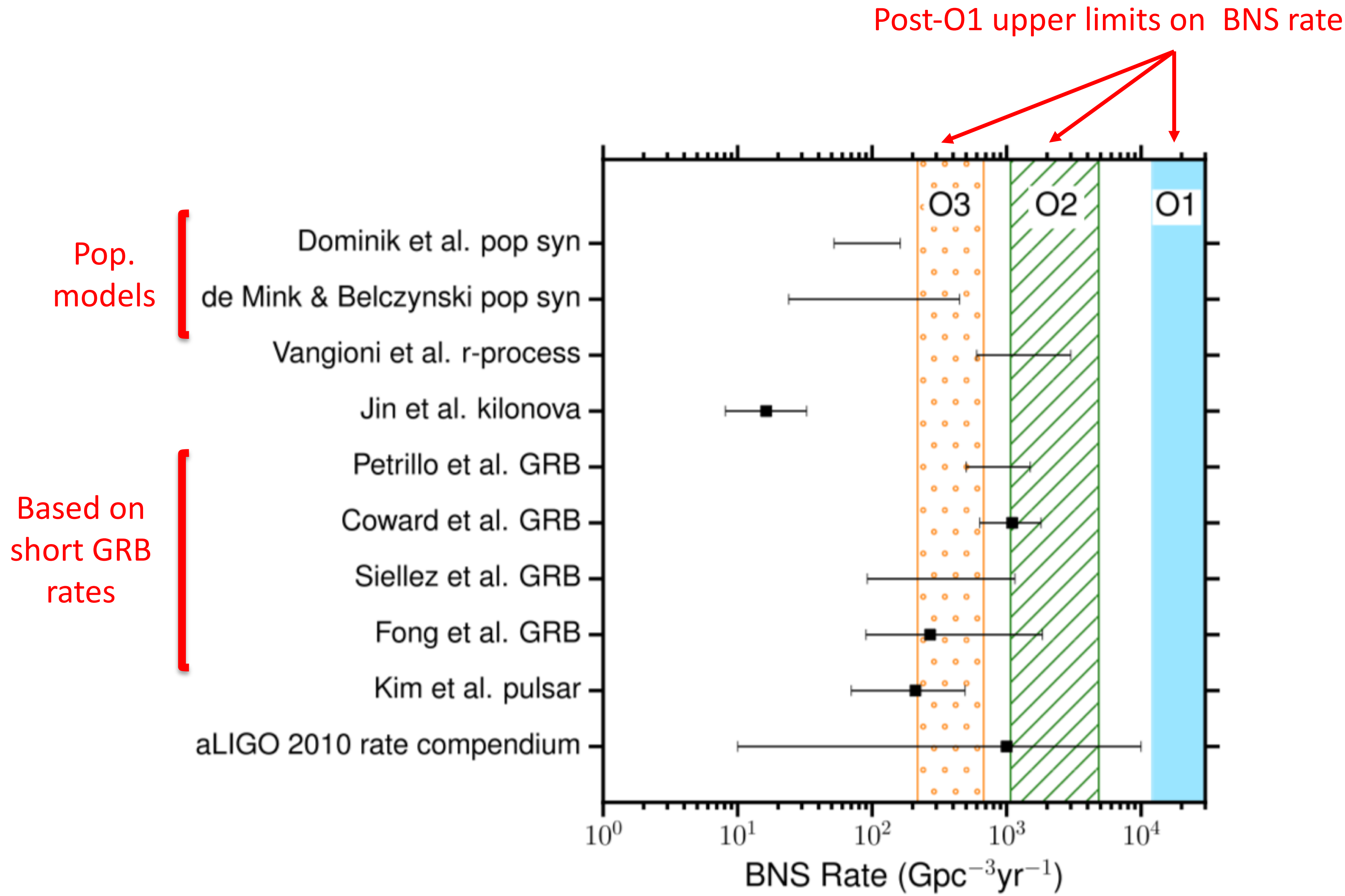


Alexander et al. 2018

The case of 170817

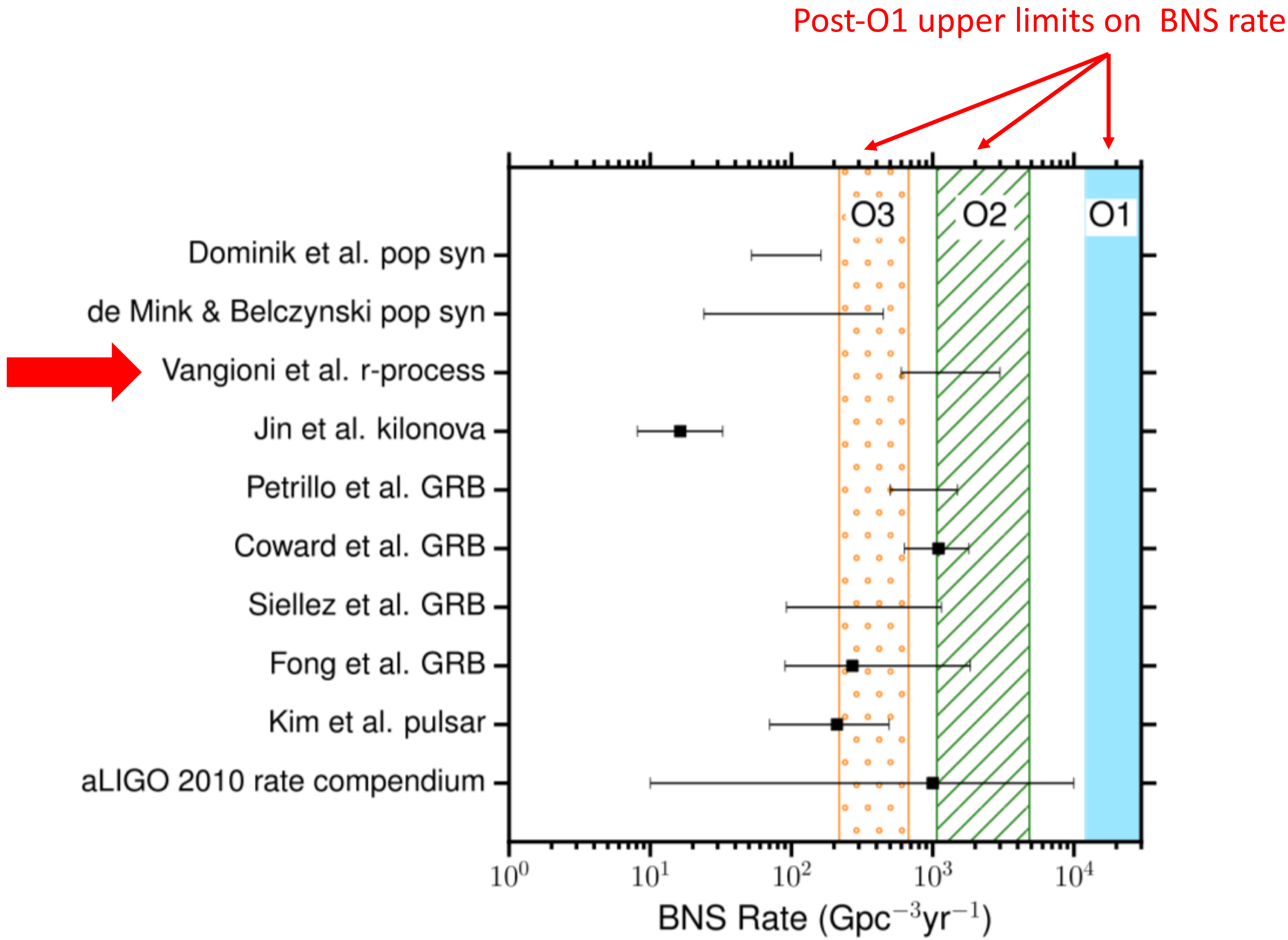
Merger rates: BNS (or NS+BH)

Merger rate: BNS



Abbott et al. 2016, post-O1

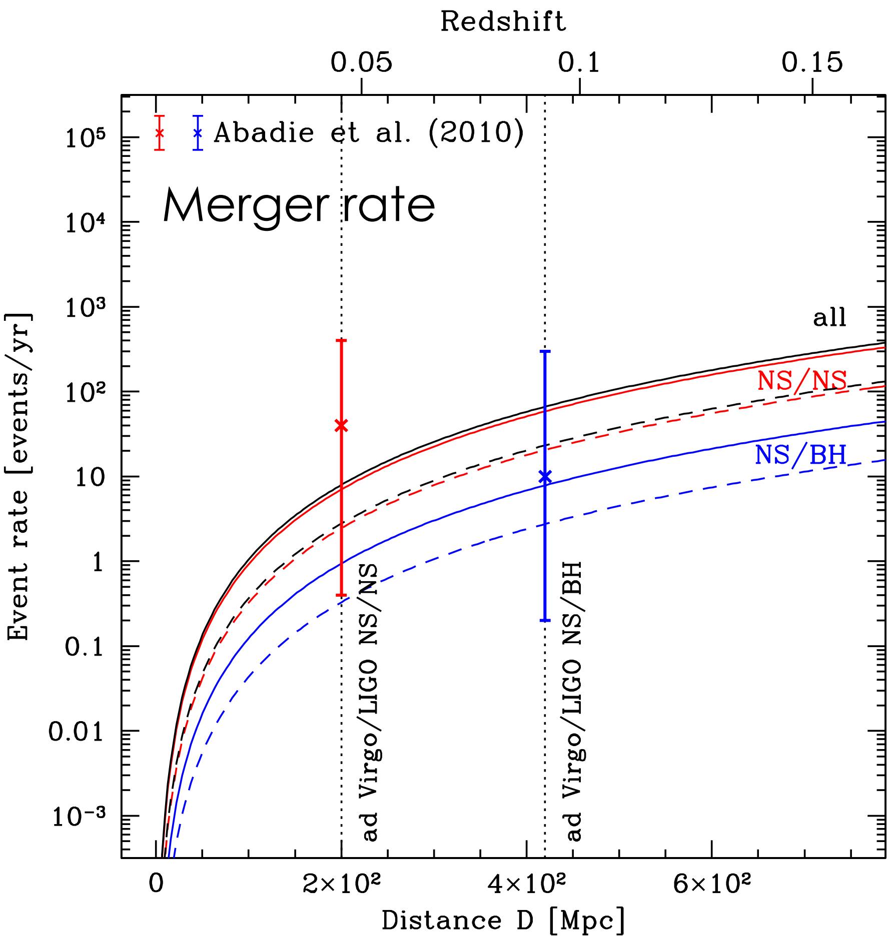
Merger rate: BNS

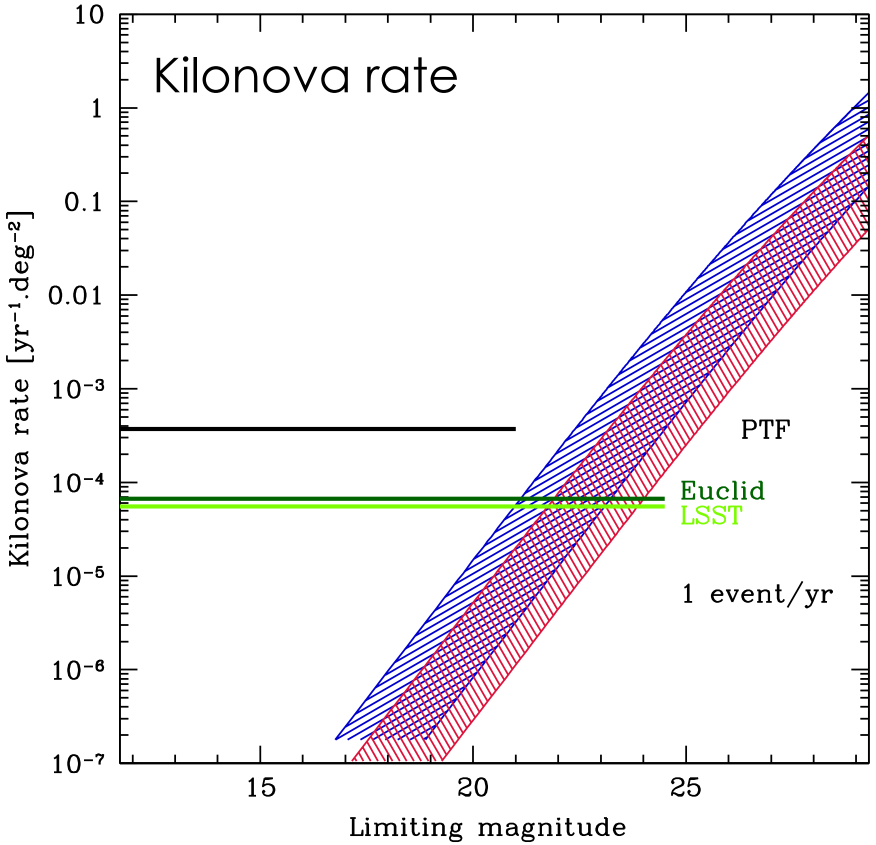


Abbott et al. 2016, post-O1

Merger rate: BNS

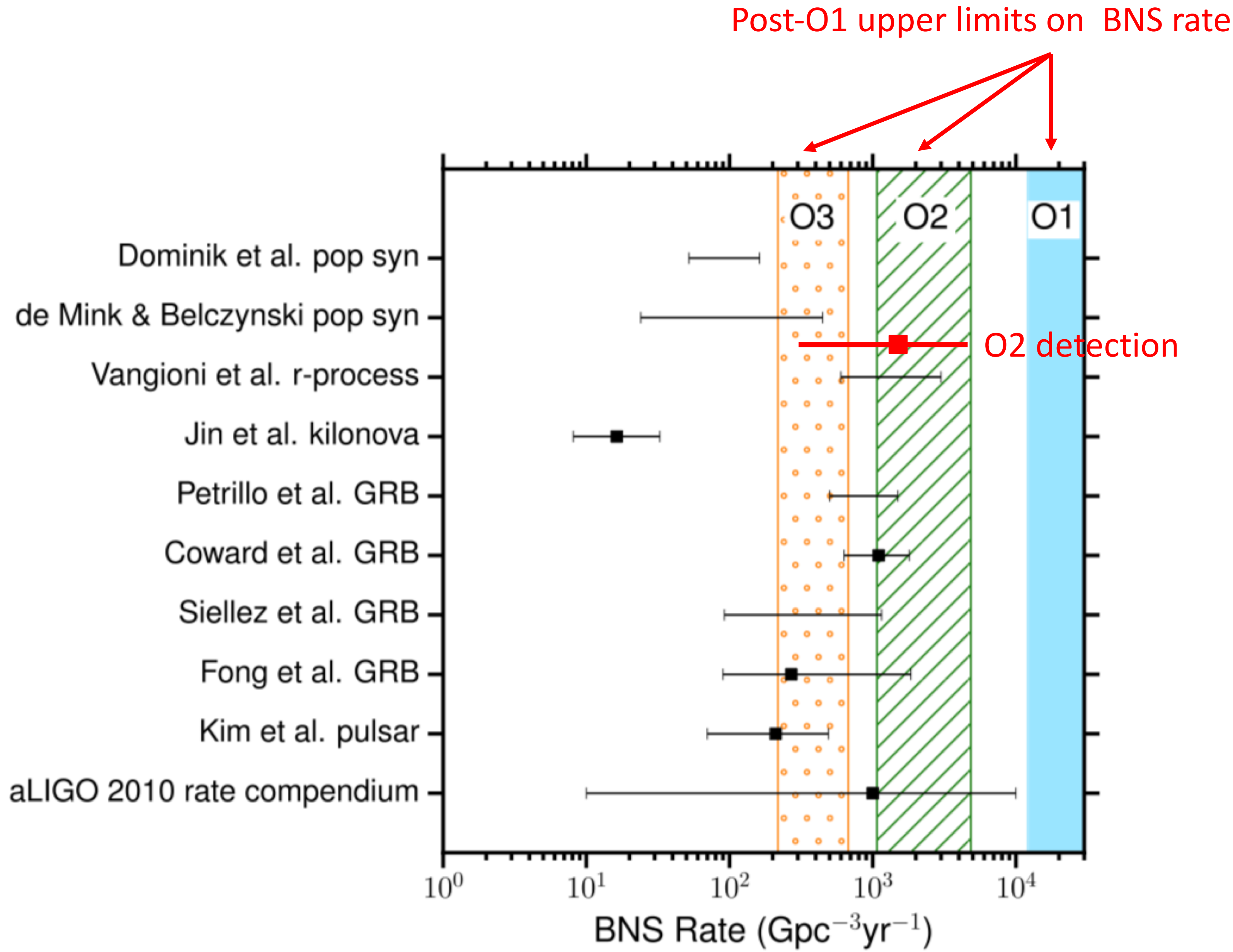
- **Model:** estimate the BNS rate assuming that most of the r-process elements are produced by NS+NS mergers
- **Observations:** Eu measured in metal-poor halo stars in the Milky Way = tracer of the time evolution of the r-process





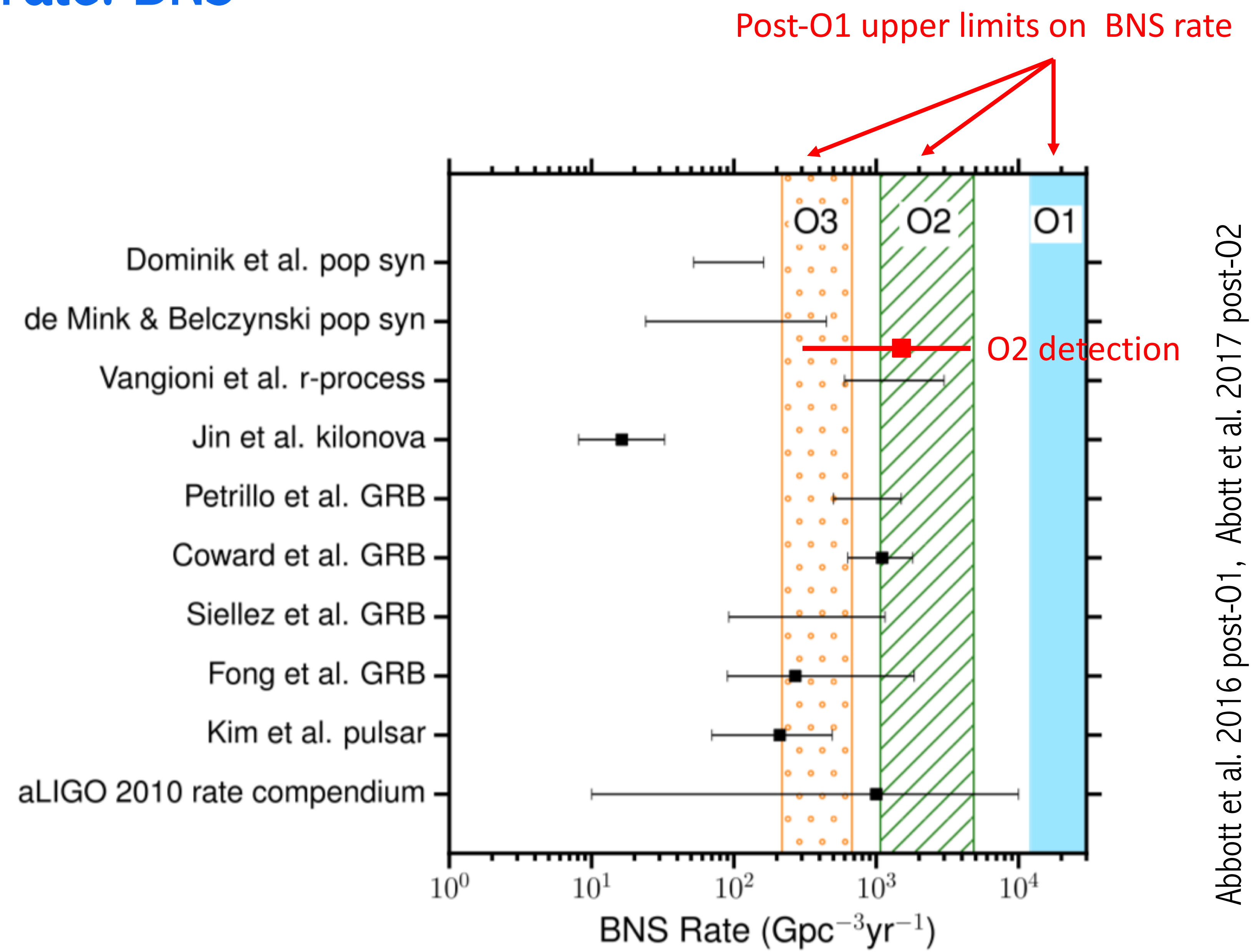
Vangioni, Goriely, Daigne, François & Belczynski (2016)

Merger rate: BNS



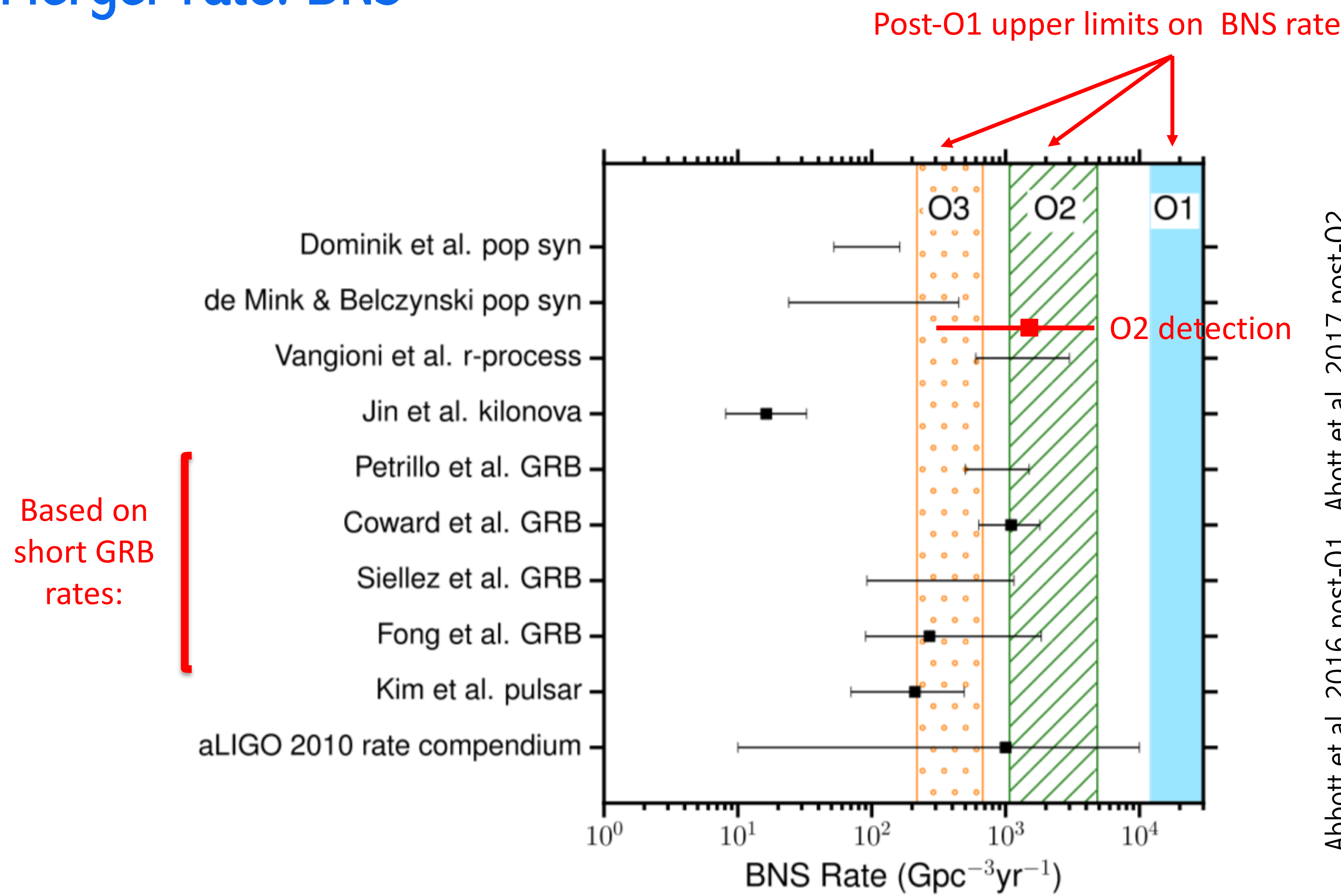
Abbott et al. 2016, post-O1

Merger rate: BNS



To confirme that mergers are the main contributers of r-process elements: more evidence for heavy elements formation, estimate of the ejected mass, …

Merger rate: BNS



Abbott et al. 2016 post-O1, Abott et al. 2017 post-O2

Short GRBs from NS+NS(/BH?) mergers?

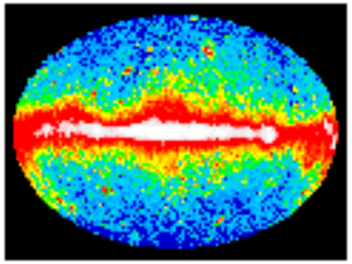
Observations: short vs long GRBS

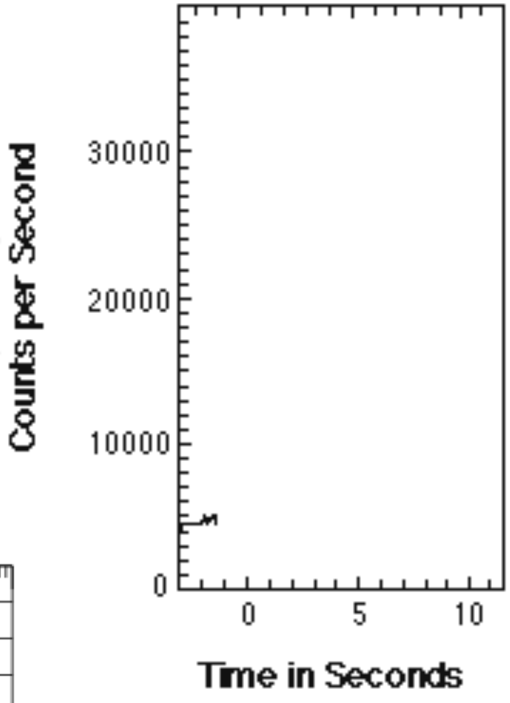
Evidence for a different progenitor

Models?

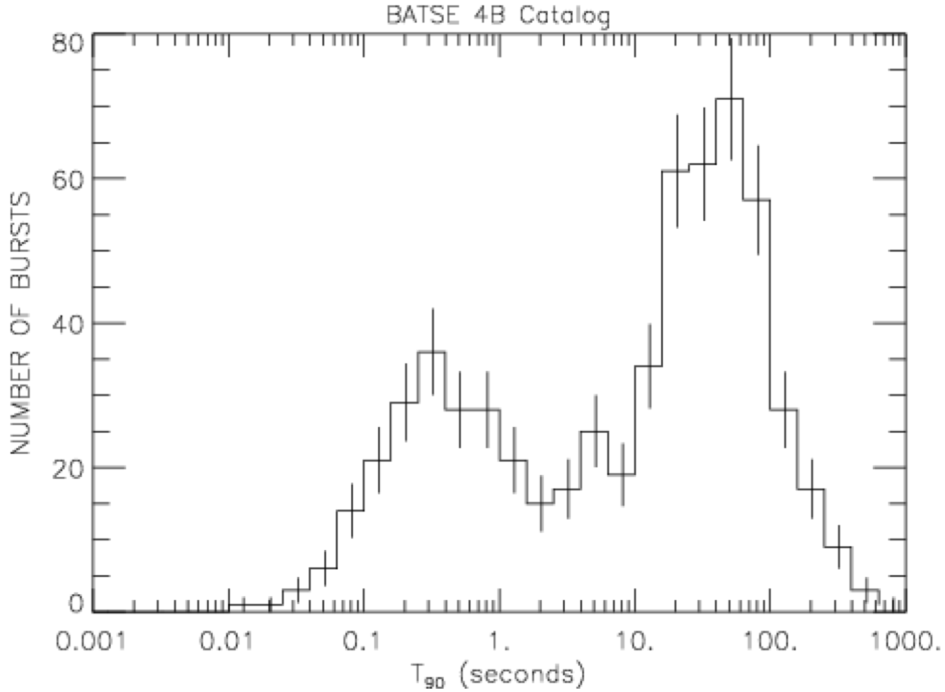
Gamma-ray bursts :

- Short duration:
  a few ms to a few min





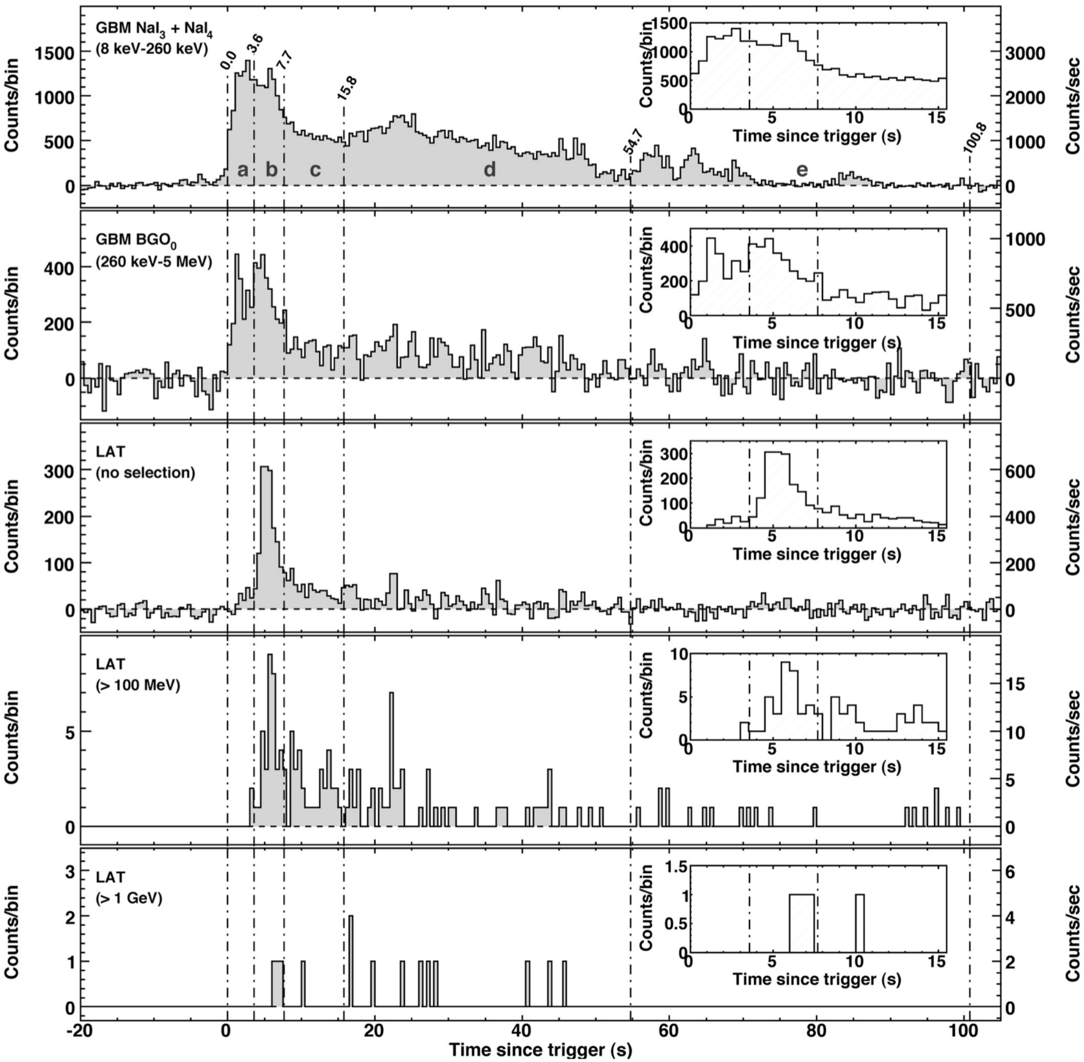
- Two groups



- Cosmological distance

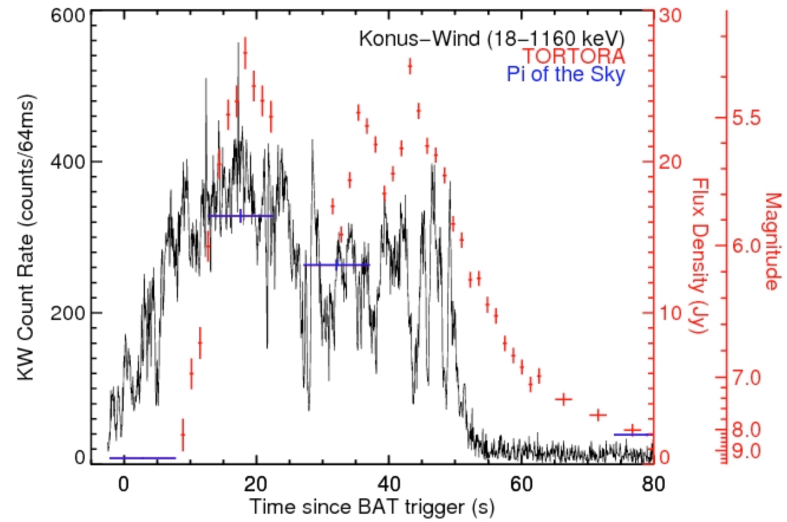
Gamma-ray bursts: prompt emission (opt. → GeV)

Fermi GBM+LAT



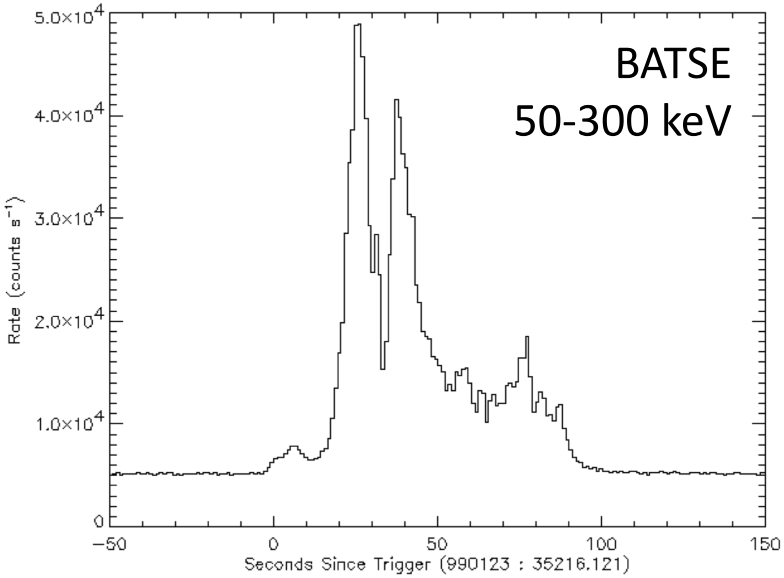
Abdo et al. 2009

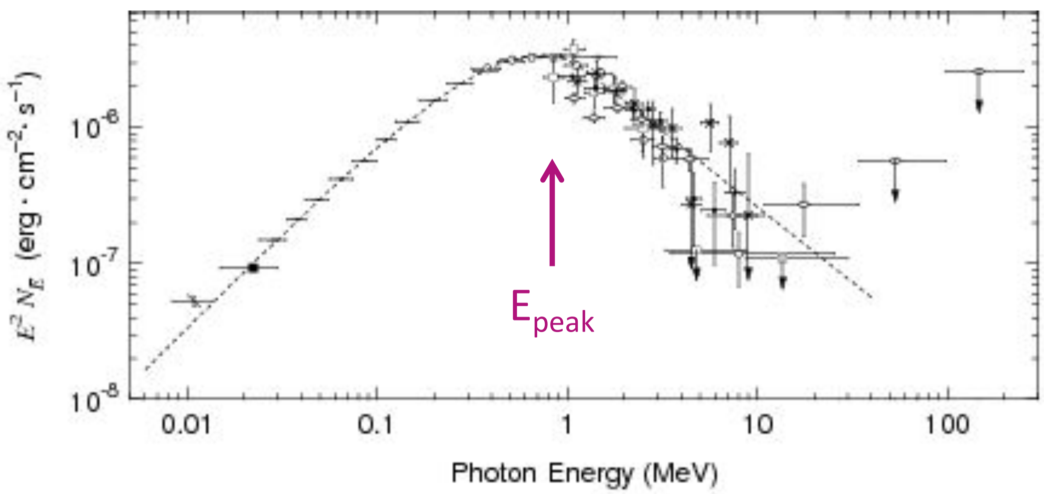
Swift+robotic



Racusin et al. 2008

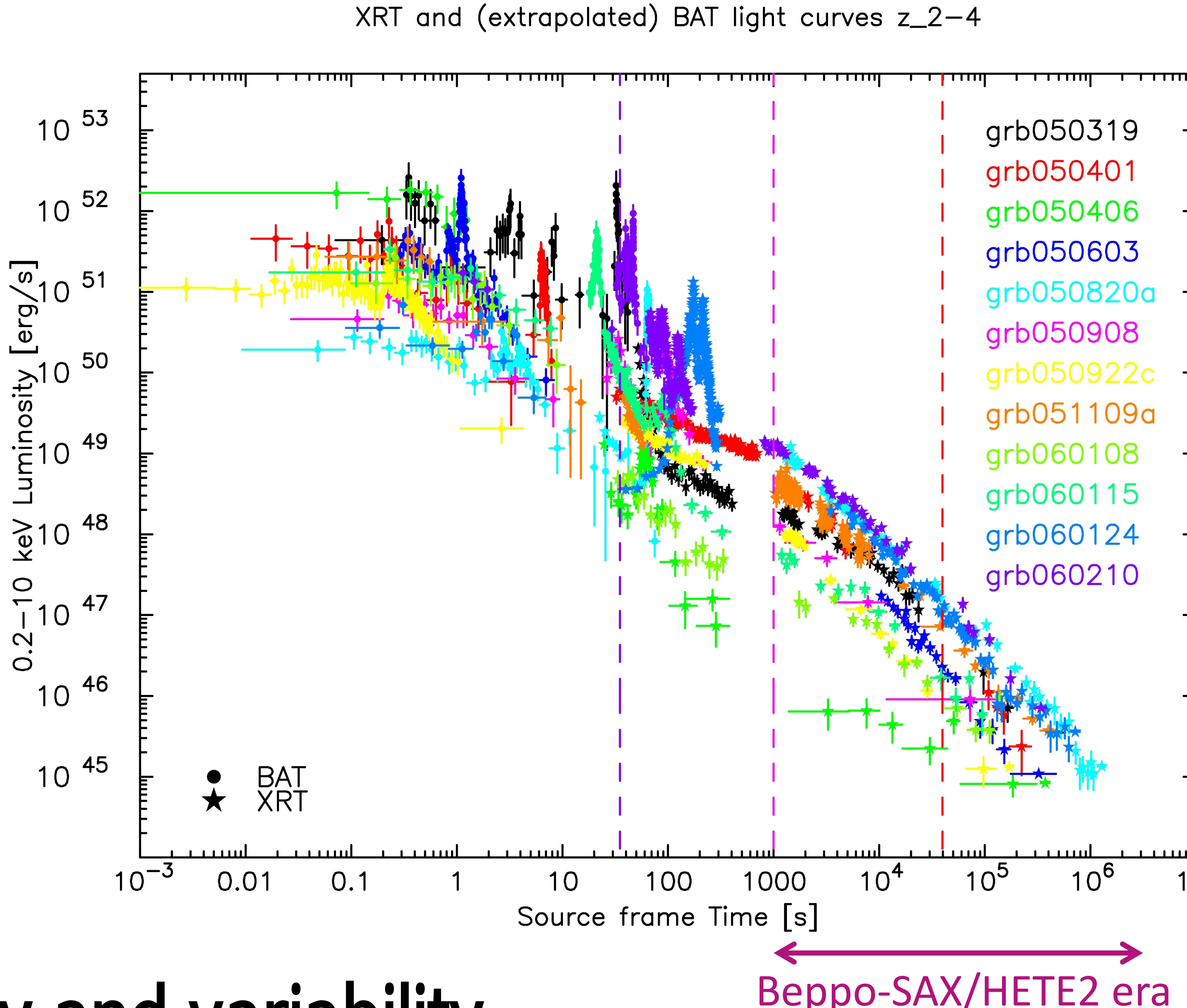
Gamma-ray bursts: prompt emission





- Peak energy : 100 keV – 1 MeV
- Short timescale variability : ms → 100 ms
- Pulses : 100 ms → 10 ms

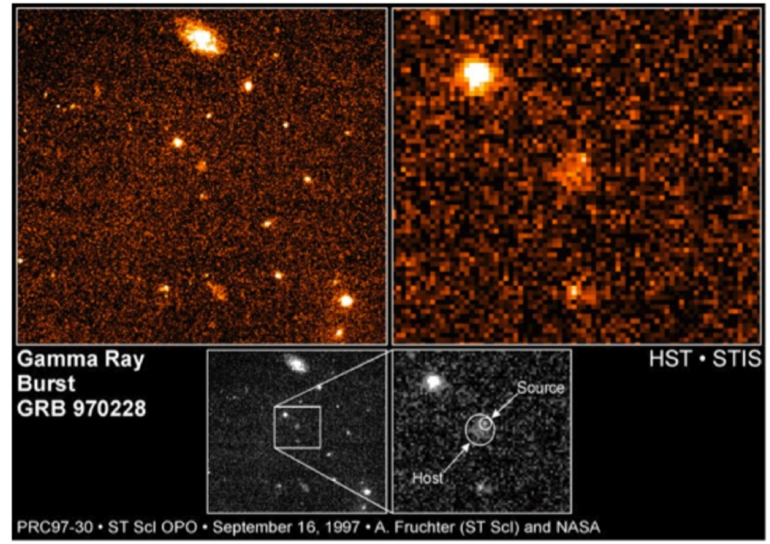
Gamma-ray bursts: afterglow (X, opt, radio)



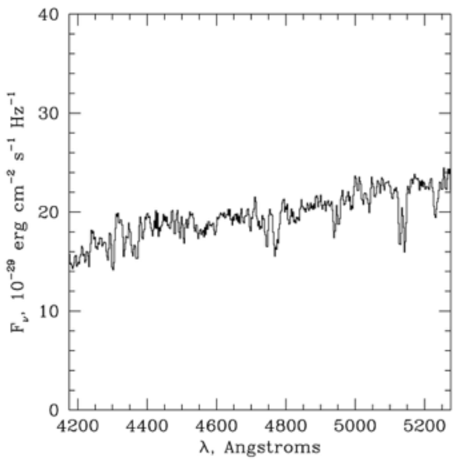
- Diversity and variability
- Plateaus, flares, …

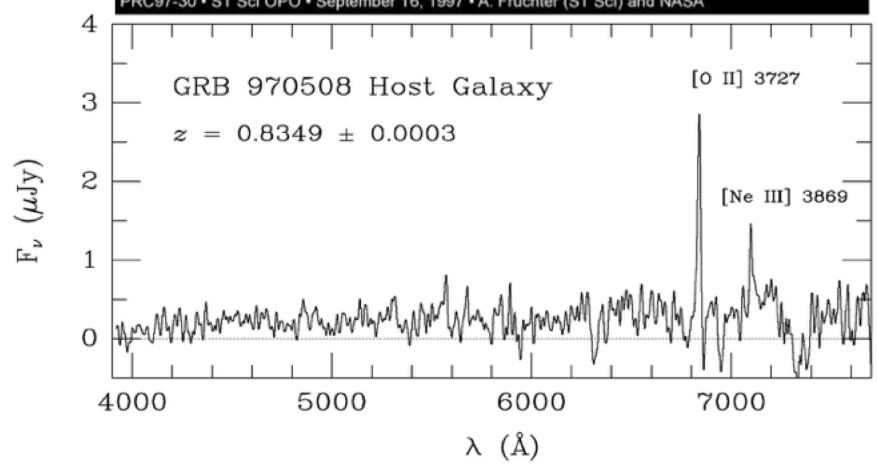
Gamma-ray bursts : redshift & host galaxy

- GRB 970228



- GRB 970508





- Present: ~400 GRBs with redshift

Maximum : GRB 090423 at z = 8.2
GRB 090429B at z = 9.3
(t~500-600 Myr)

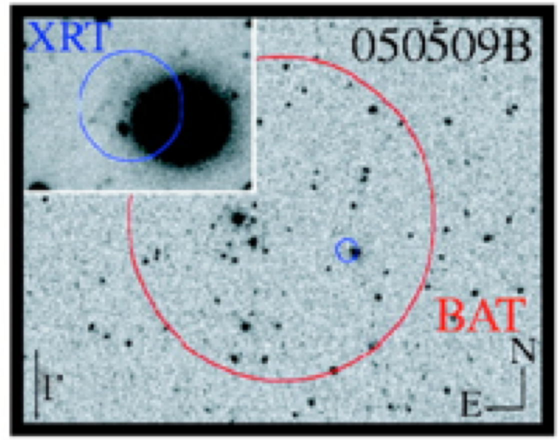
E_{iso} ~ 10^{51} to 10^{54} erg (some under-luminous ; some monsters…)

Short vs Long GRBs: Host galaxies

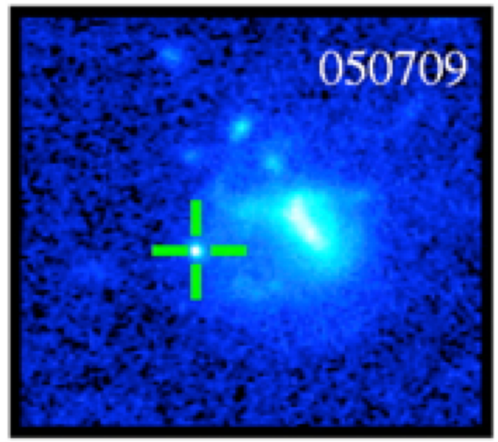
- Short GRBs:
  - -all morphologies
  - -no correlation with star formation
  - -offsets

See review by Berger 2014

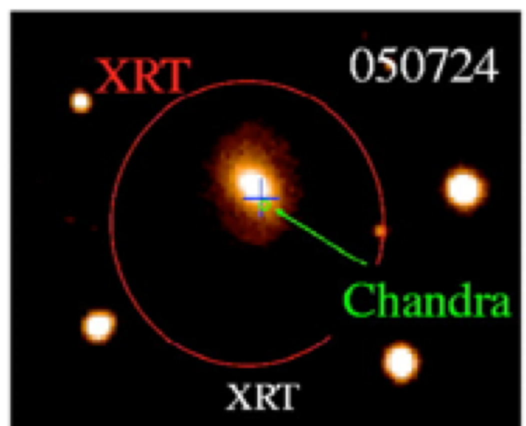
- Long GRBs:
  - -star forming hosts
  - -associations with SNae



cD elliptical
SFR < $0.2\ M_\odot\ yr^{-1}$
Swift



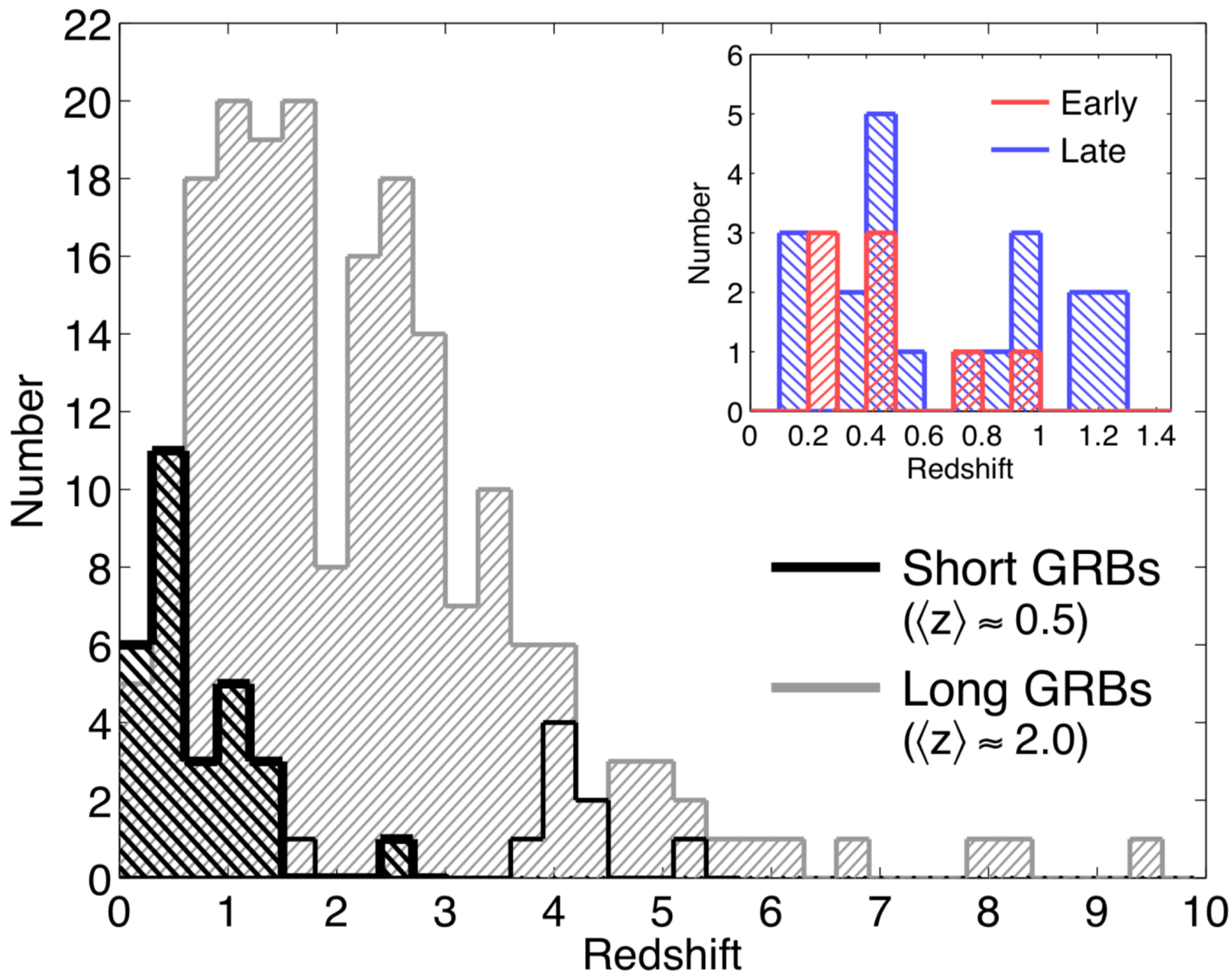
SF galaxy
with offset
HETE-2



elliptical
SFR < $0.02\ M_\odot\ yr^{-1}$
Swift

Figure prepared by Suzanna Vergani

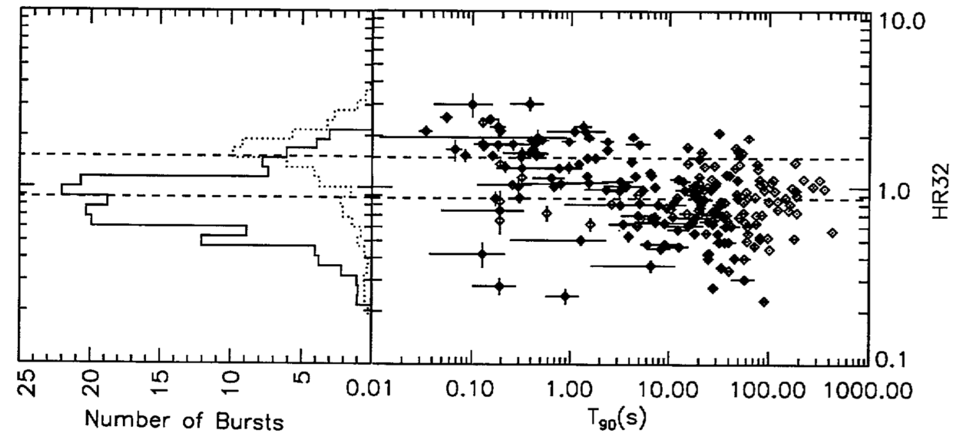
Short vs Long GRBs: Redshift distribution



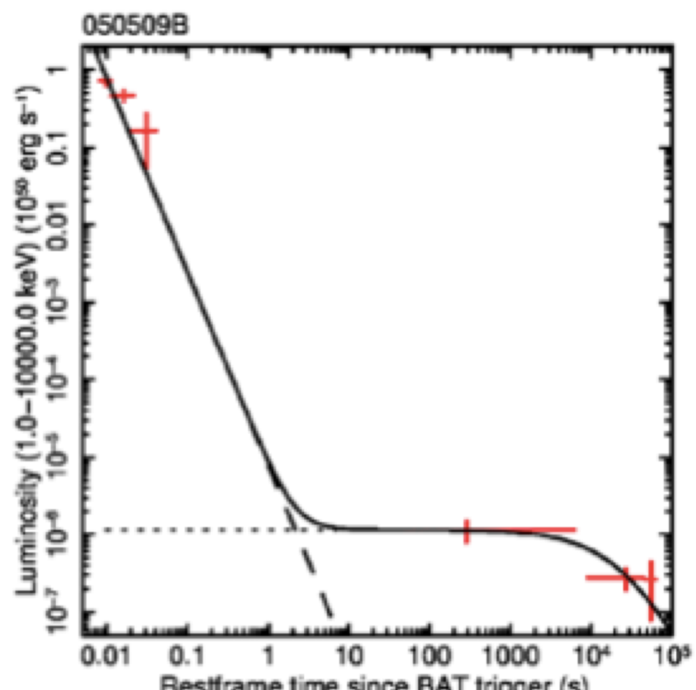
(Berger 2014)

Short vs Long GRBs: Prompt & afterglow emission

- Prompt :
  - short GRBs are harder
  - all timescales are contracted



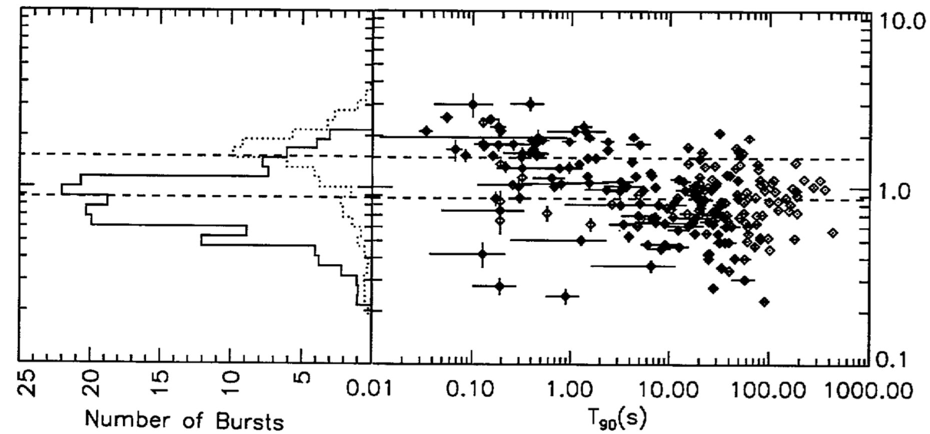
- Afterglows :
  - small sample for short bursts
  - weaker; faster decay in many cases



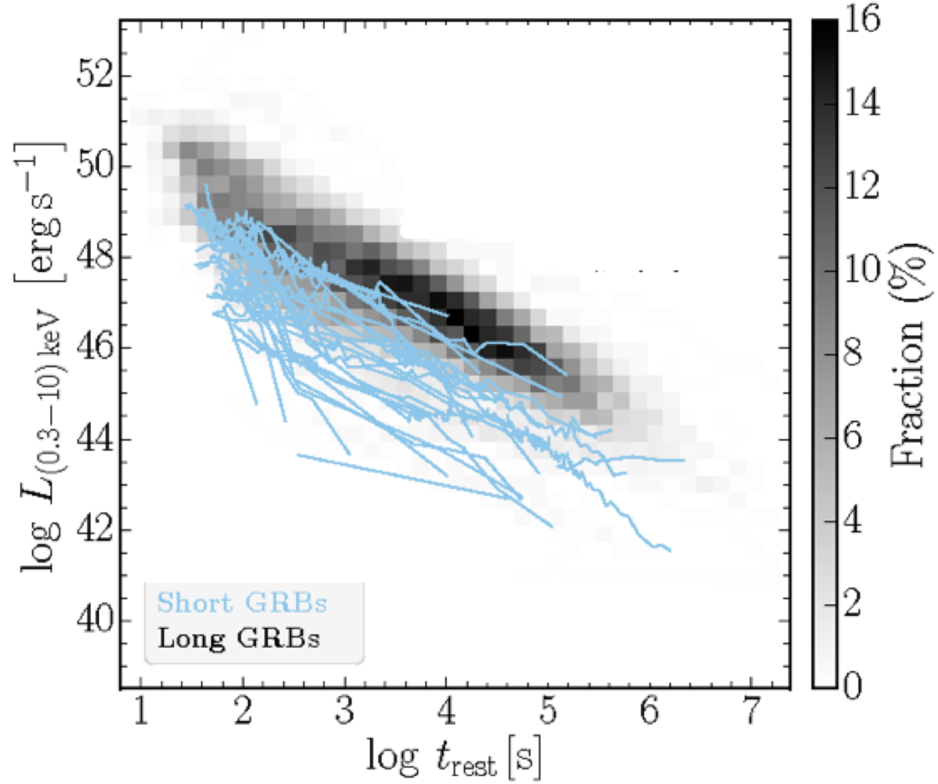
Swift short GRB sample

Short vs Long GRBs: Prompt & afterglow emission

- Prompt :
  - short GRBs are harder
  - all timescales are contracted



- Afterglows :
  - small sample for short bursts
  - weaker; faster decay in many cases



Swift XRT short GRB sample

A short GRB seen by Fermi/GBM :

Short GRBs emit
at higher energies
→ MeV domain

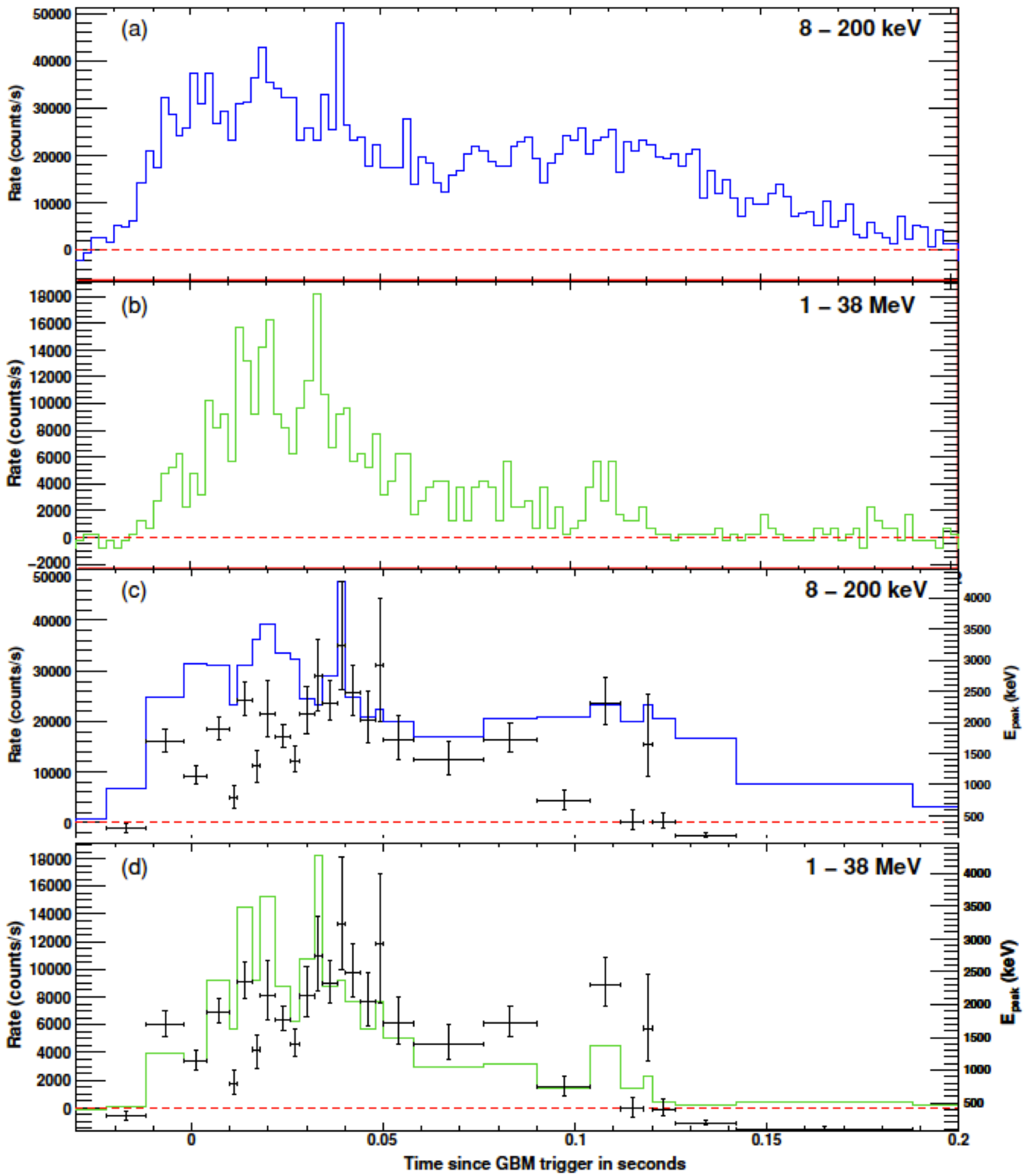
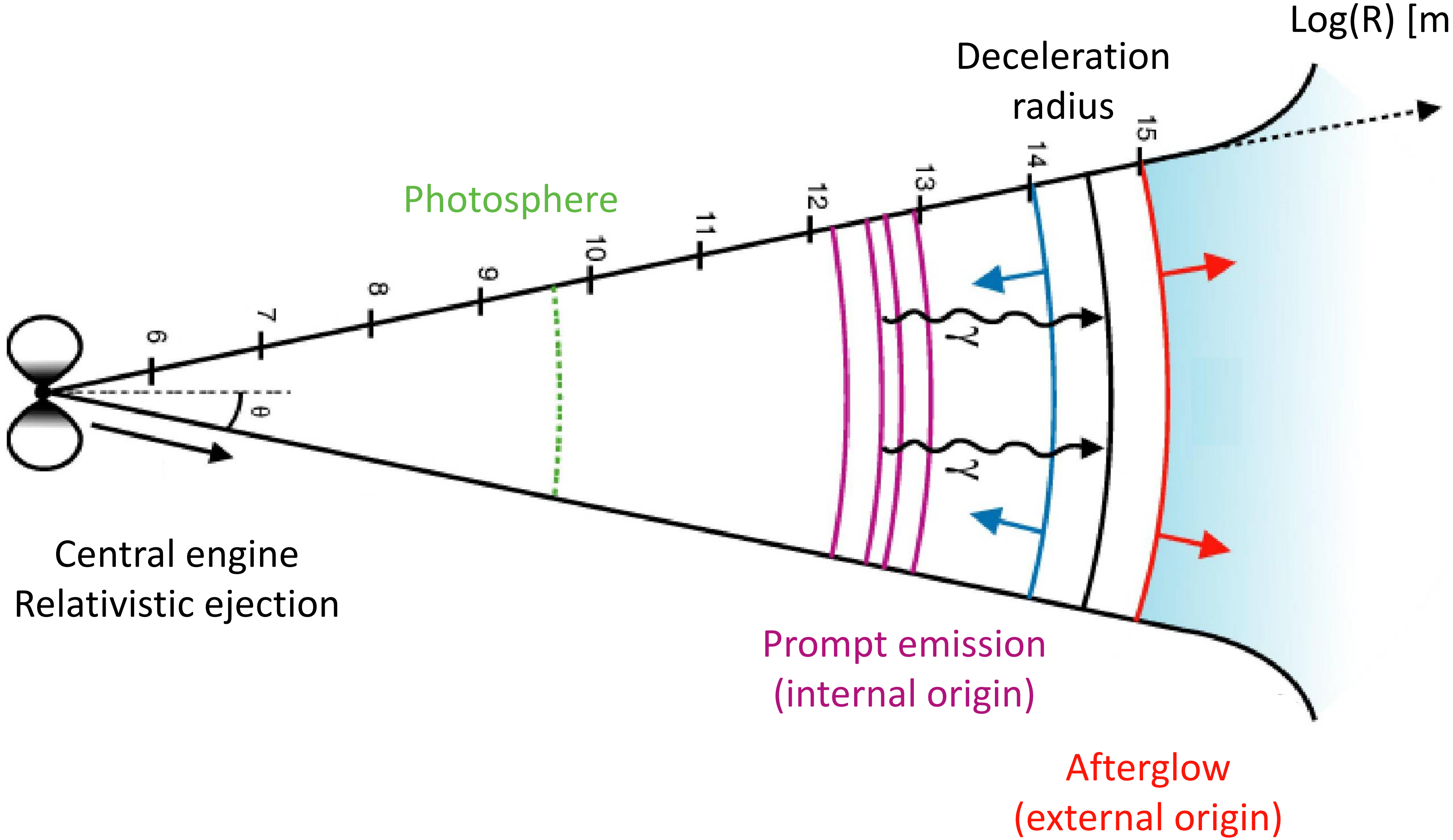


Figure 1. Light curves of GRB 090227B in two energy bands (panel (a): 8 keV to 200 keV, NaI detectors) and (panel (b): 1 MeV to 38 MeV, BGO detectors) with 2 ms time resolution. The count rates are background subtracted. Two bottom panels: the same light curves with variable time bins (histograms), optimized for time-resolved spectroscopy. The Band function peak energy, E_{peak}, is plotted over the light curve for each time interval.

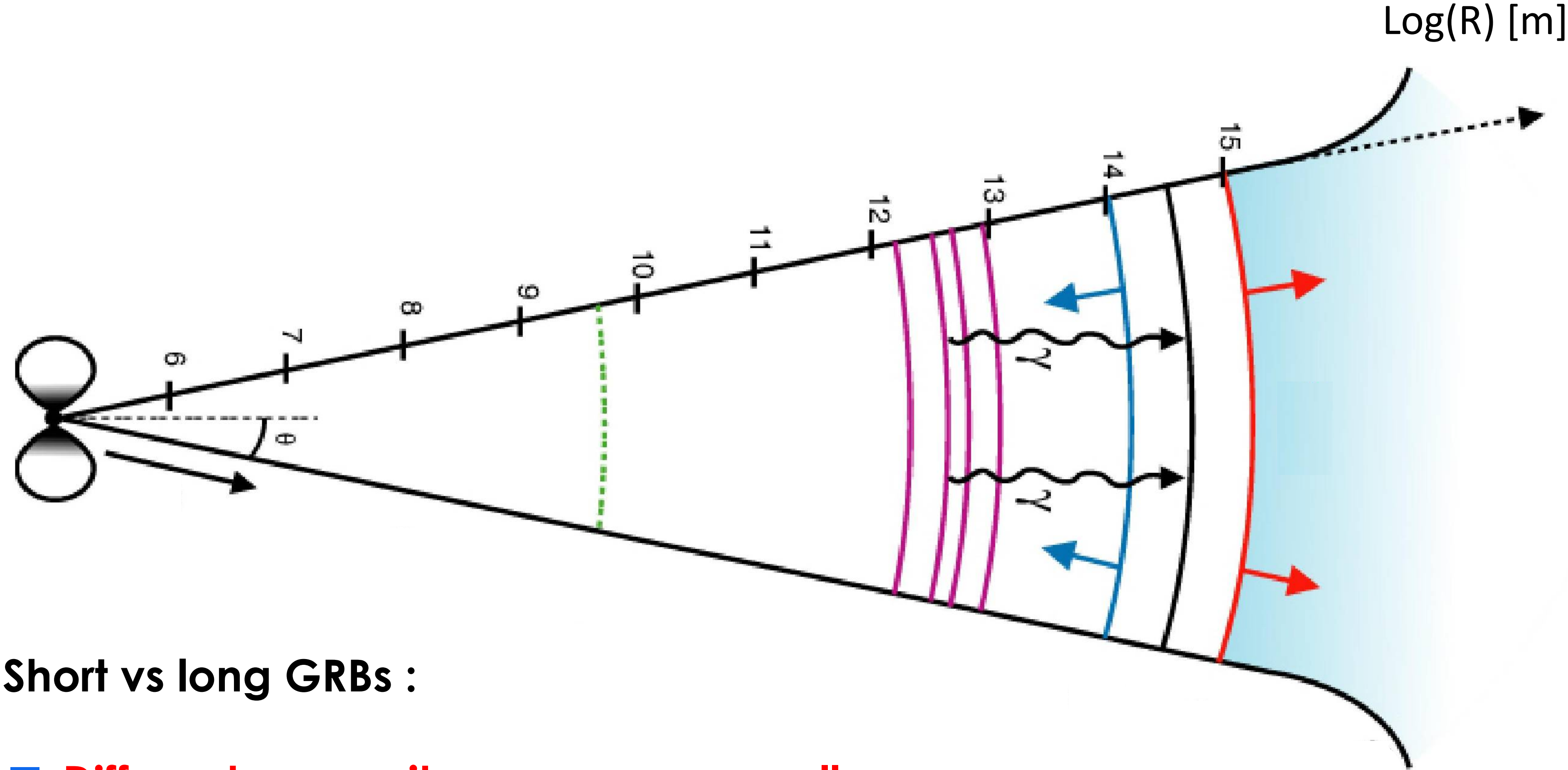
GRB 090227B
(*Fermi*/GBM)
duration ~ 0.15 s

Guiriec et al. 2010

Gamma-ray bursts: model(s ?)



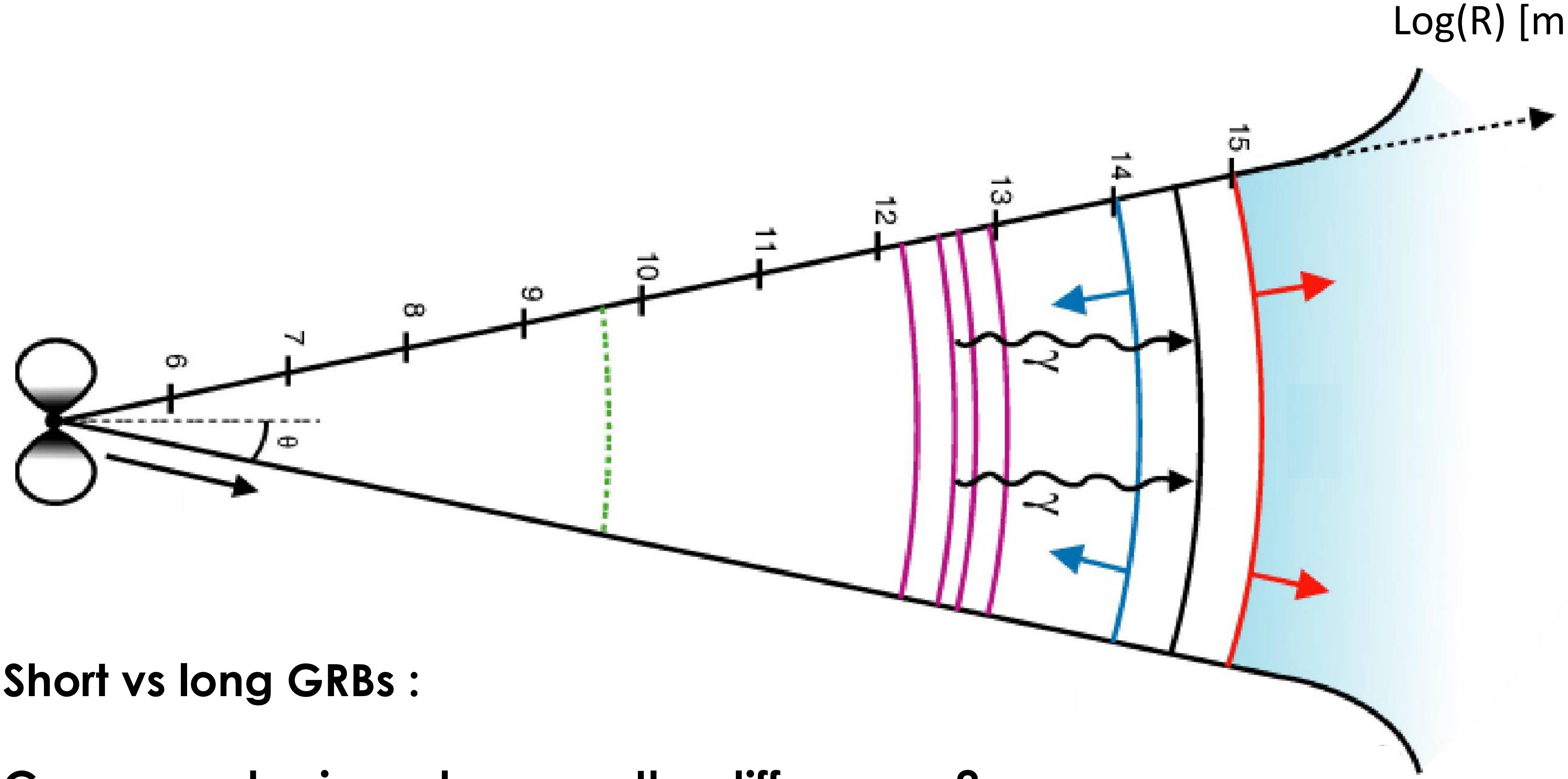
Gamma-ray bursts: model(s ?)



Short vs long GRBs :

- **Different progenitors: mergers vs collapsars**
- Similar central engines? hyper-accreting BH (or magnetar?)
- Prompt emission: same physics, but shorter timescales for short GRBs (due to a smaller energy reservoir in central engine)
- Afterglow: same physics but lower density for short GRBs (due to merger time)

Gamma-ray bursts: model(s ?)



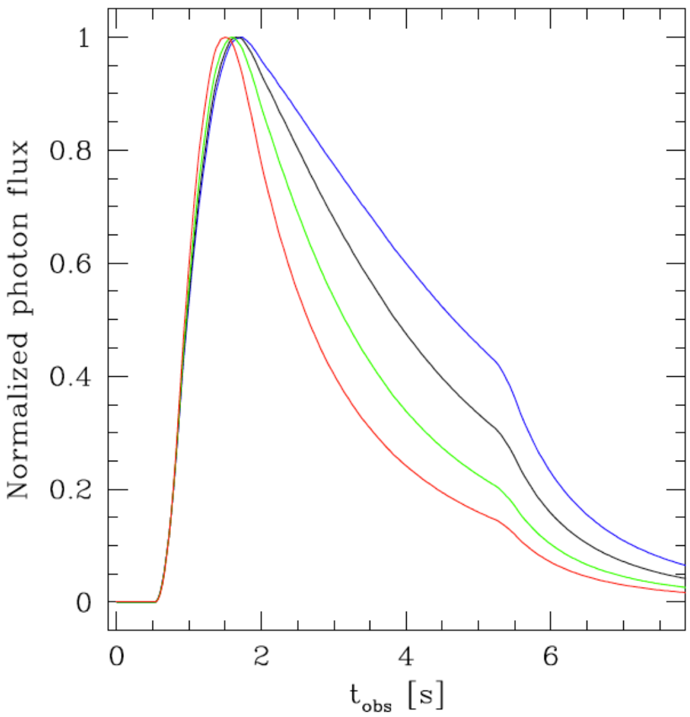
Short vs long GRBs :

Common physics: where are the differences?

- **Progenitor**
- Central engine
- Relativistic outflow
- Internal dissipation
- Deceleration

Prompt emission: the case of internal shocks

Example of a simulated GRB pulse produced by internal shocks
(full simulation: dynamics+radiation)

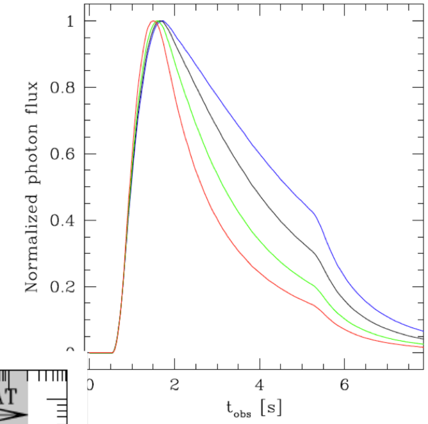


Light curve in BATSE range :
channels 1 (blue) to 4 (red)

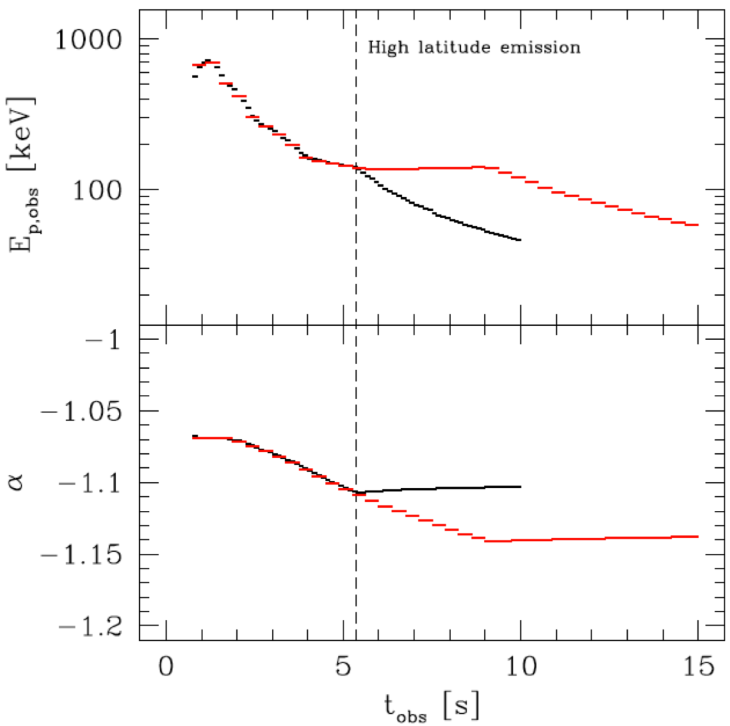
Bosnjak & Daigne 2014

Prompt emission: the case of internal shocks

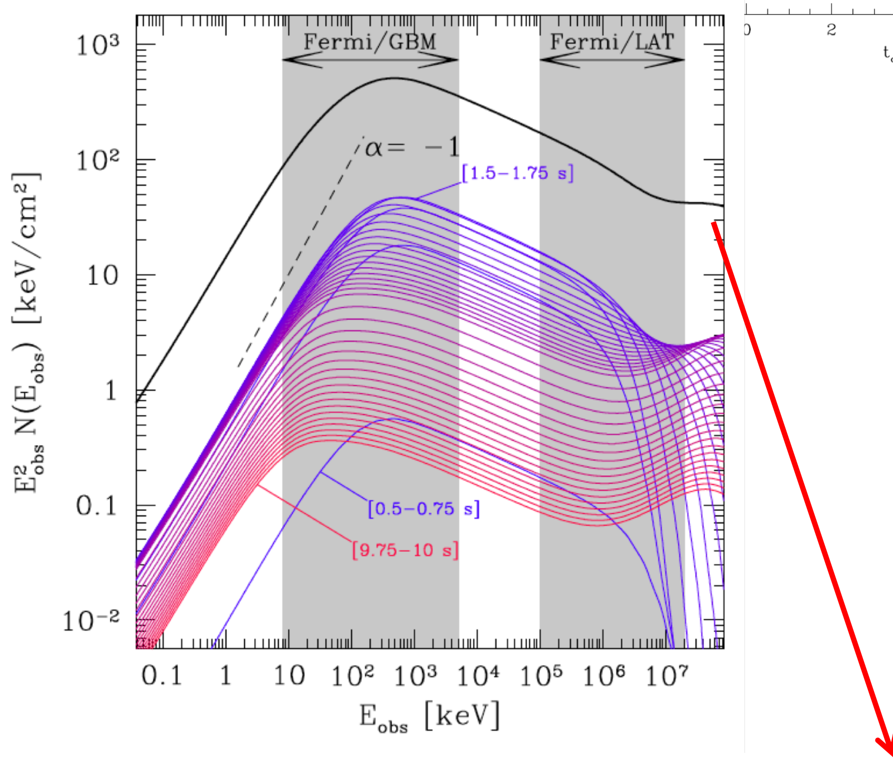
Example of a simulated GRB pulse produced by internal shocks
(full simulation: dynamics+radiation)



Evolution of E_{peak} and α



Time-evolving spectrum

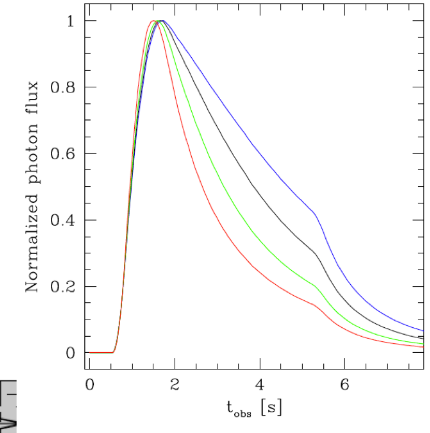


Extra component

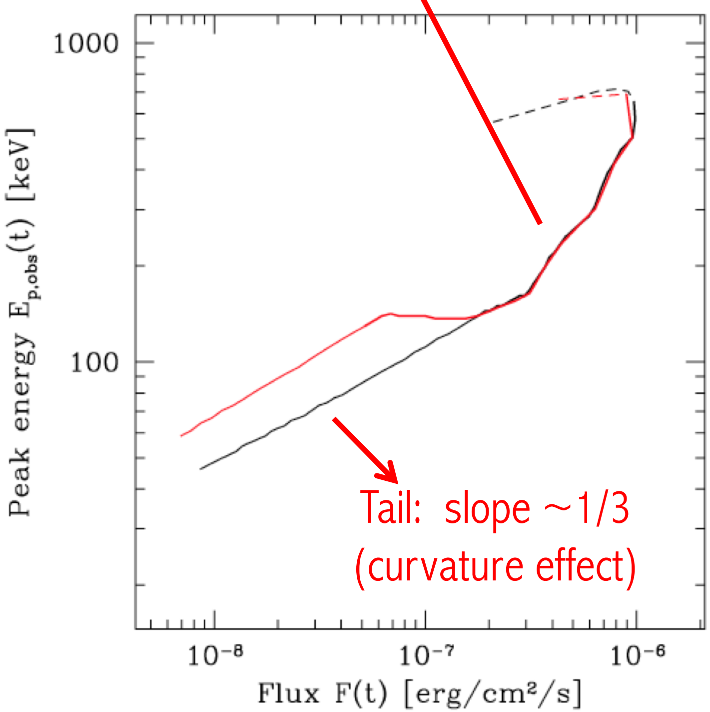
Bosnjak & Daigne 2014

Prompt emission: the case of internal shocks

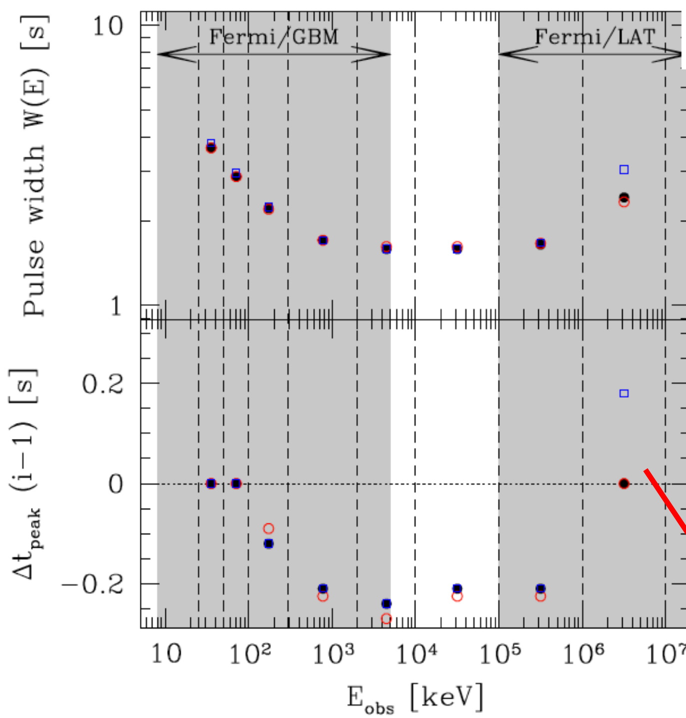
Example of a simulated GRB pulse produced by internal shocks
(full simulation: dynamics+radiation)



Slope ~1-1.5 fixed by shock propagation



Tail: slope ~1/3
(curvature effect)



$$W(E) \propto E^{-a}$$

$$a \simeq 0.2 - 0.3$$

Hardness-Intensity Correlation

Pulse width and time lags

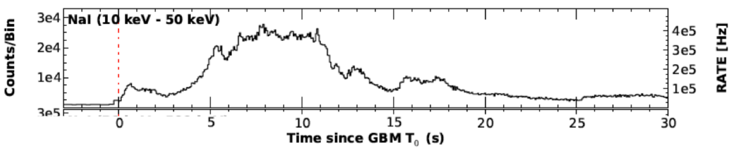
Delayed onset ? $\gamma\gamma$?

Bosnjak & Daigne 2014

(Hascoet [Daigne] et al. 2012)

Prompt emission: the case o

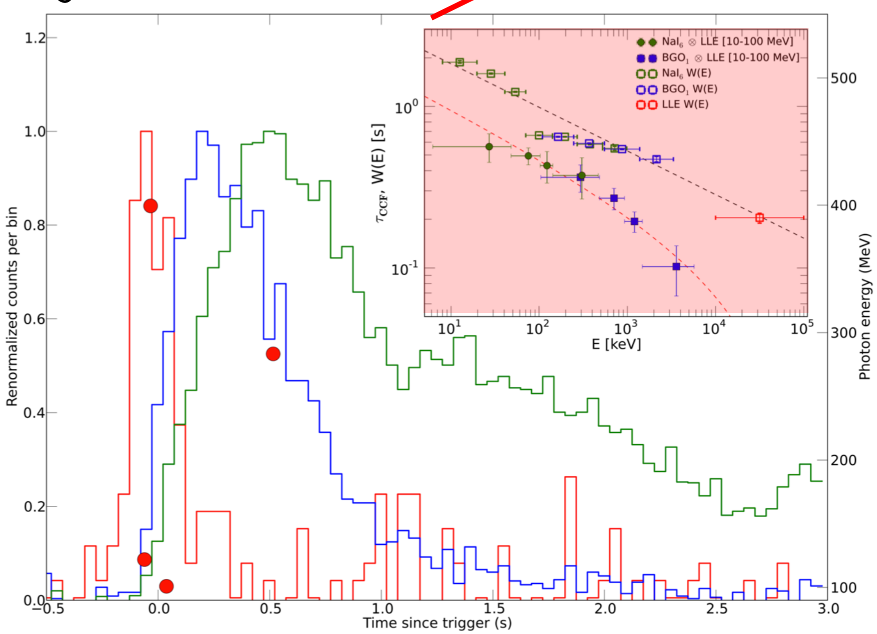
GRB 130427A

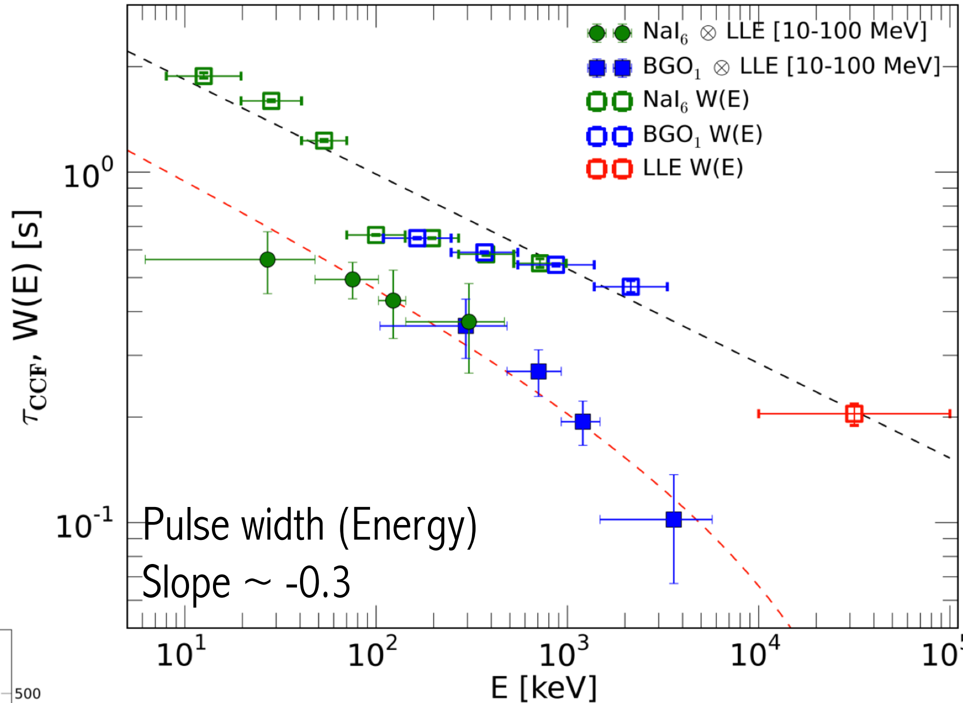


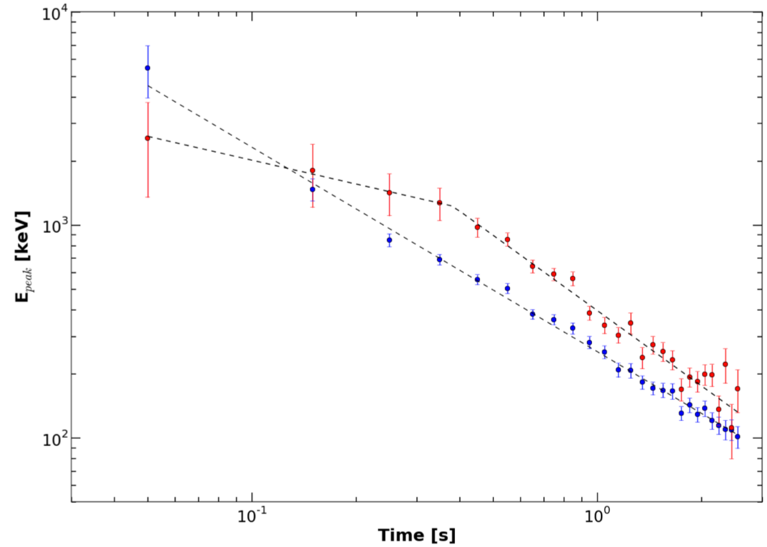
The first 3 s

zoom

Time lags





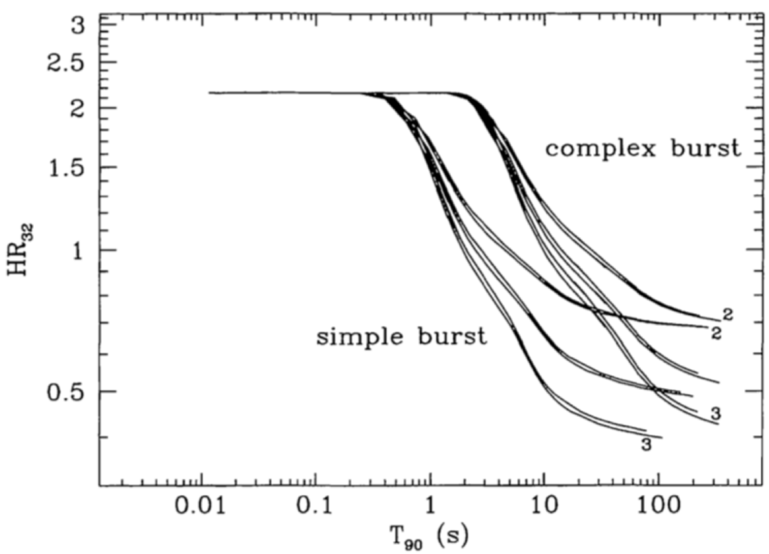


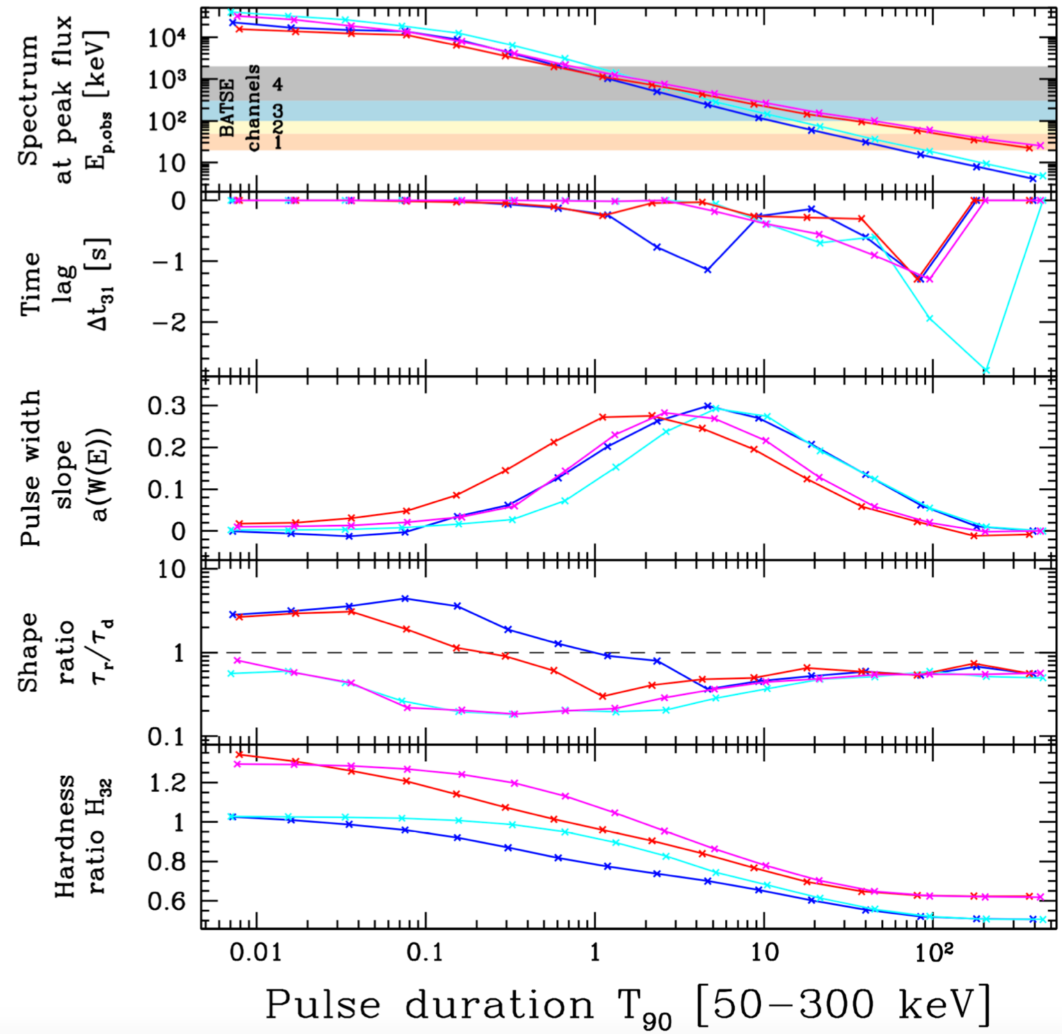
Preece et a.l. 2014

Not shown: hardness-intensity correlation slope 1.4

Prompt emission: the case of internal shocks

- Model a pulse with internal shocks
- Vary only the duration of the relativistic ejection (L=cst)
- Main properties of the short GRB population emerge (harder, no lags, …)

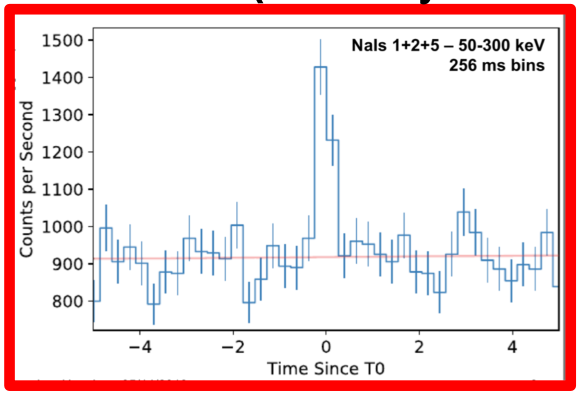




Daigne & Mochkovitch 1998
Bosnjak & Daigne 2014

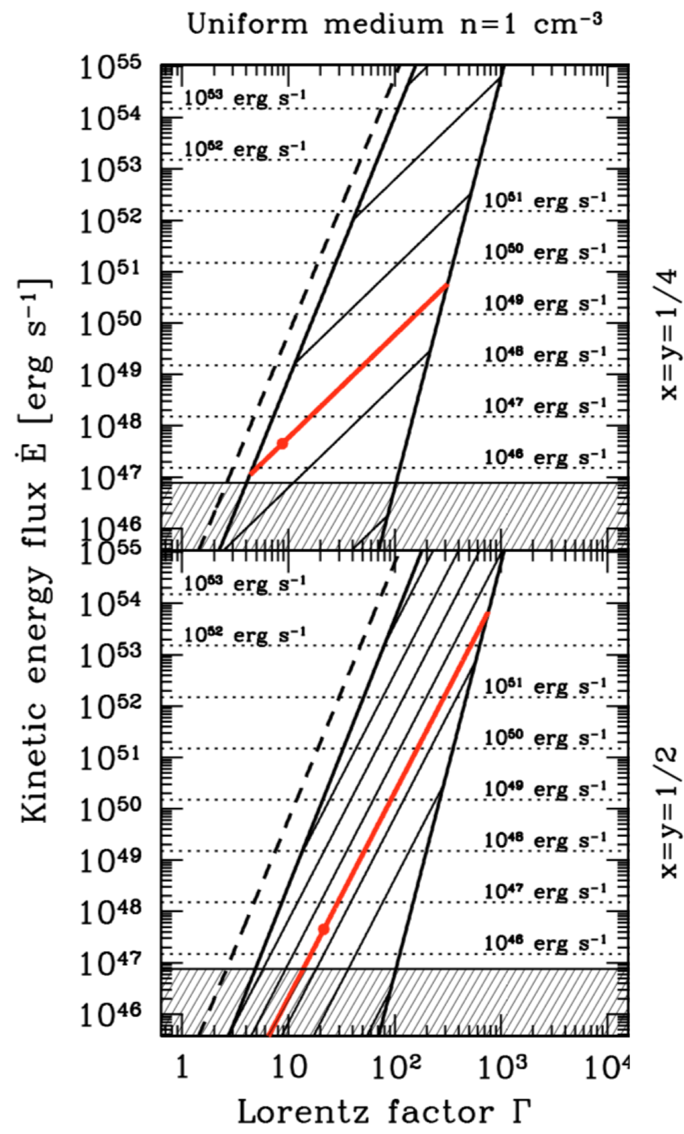
Prompt emission: the case of internal shocks

GRB170817A (not very hard, very under-luminous) ?



- Standard GRB seen off-axis unlikely
  (Ep would be very high if seen on-axis)
- Dissipation in a mildly relativistic outflow pointing towards us?
  (jet with lateral structure, cocoon, …)
- Internal shocks can explain the peculiar properties of GRB170817A
  for a low Lorentz factor/moderate kinetic energy flux
- GW-GRB delay: ~burst duration
  if the relativistic ejection occurs rapidly after the merger (i.e. << s)

GRB980425 at 40 Mpc
(Daigne & Mochkovitch 2007)



Conclusion

Conclusions

- Solid pre-170817 indirect arguments in favor of the sGRB/merger association

- Details of the short vs long GRB differences remain to be understood:
  -minimum: progenitor+external density
  -other ingredients often discussed:
  central engine, geometry/magnetization of the jet, ...
- Prompt emission: in the internal shock model, properties of short GRBs derive naturally from the shorter timescales

- GRB170817A is not standard
- Dissipation in a mildy relativistic ejecta pointings towards us?
- Connection with the classical short GRB population remains unclear:
  is there a hidden highly relativistic jet?

- More observations of NS+NS mergers needed, with different angles
- Better description of the classical short GRB population needed
  (more redshift & afterglow?)