Istituto Nazionale di Astrofisica

Osservatorio Astronomico di Brera

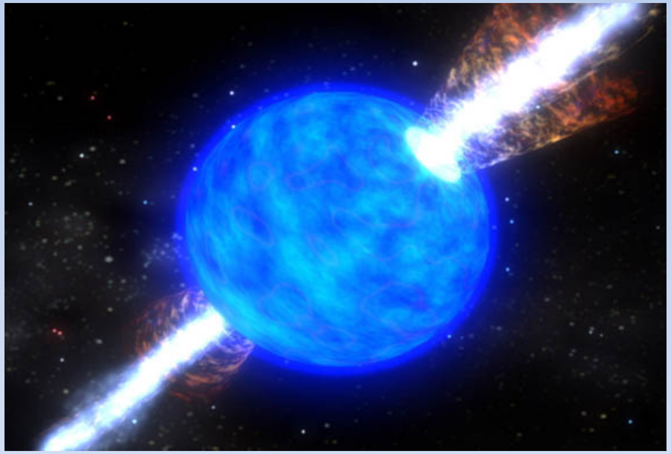
The short GRBs – GW connection

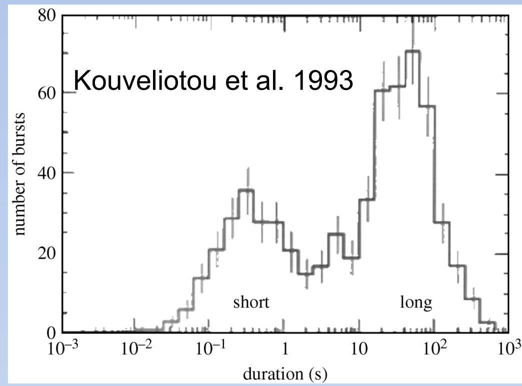
Paolo D'Avanzo

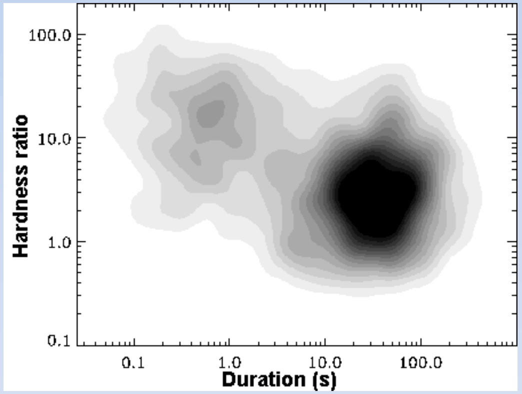
INAF – Osservatorio Astronomico di Brera

GRB progenitors

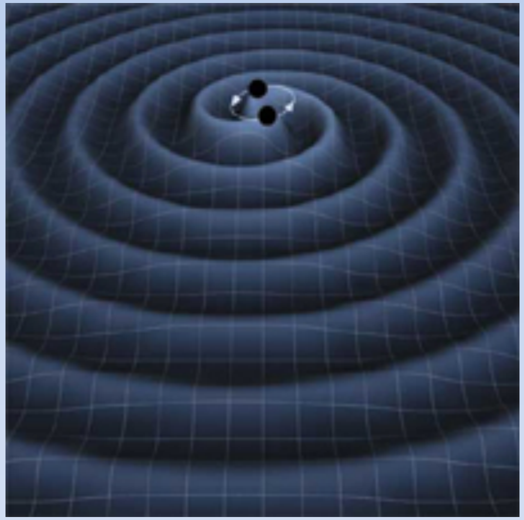
Long/soft GRBs
collapsar progenitor model

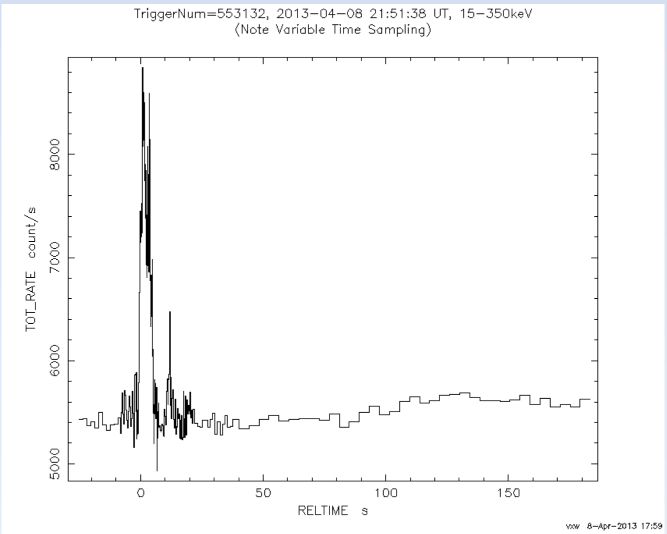


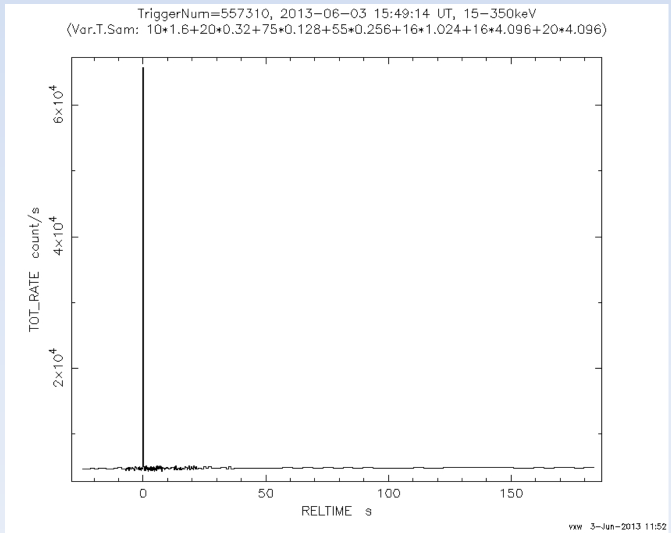




Short/hard GRBs
merger progenitor model







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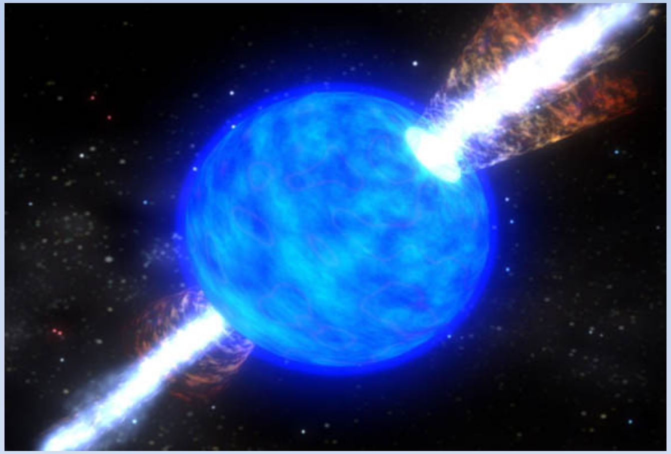

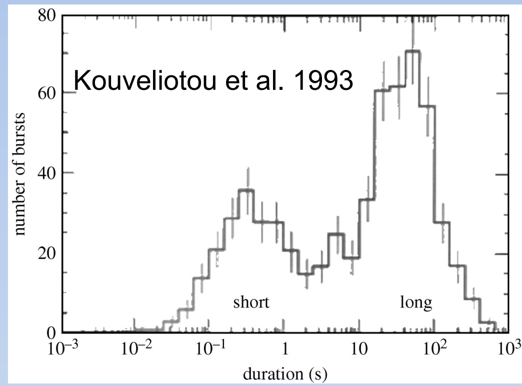

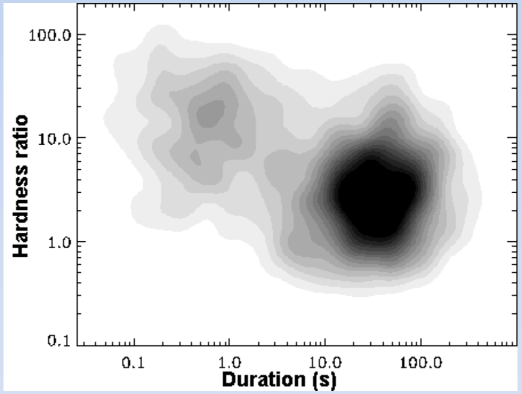

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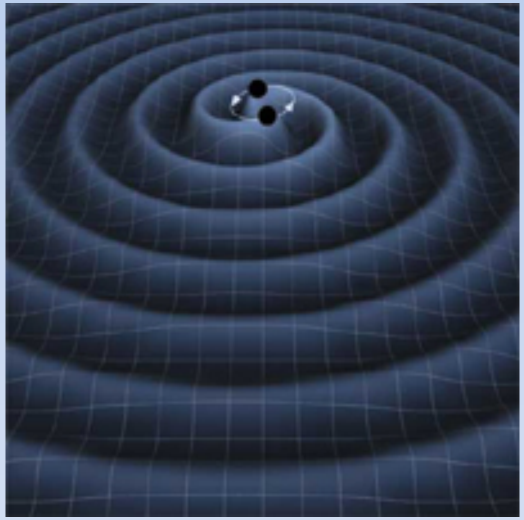
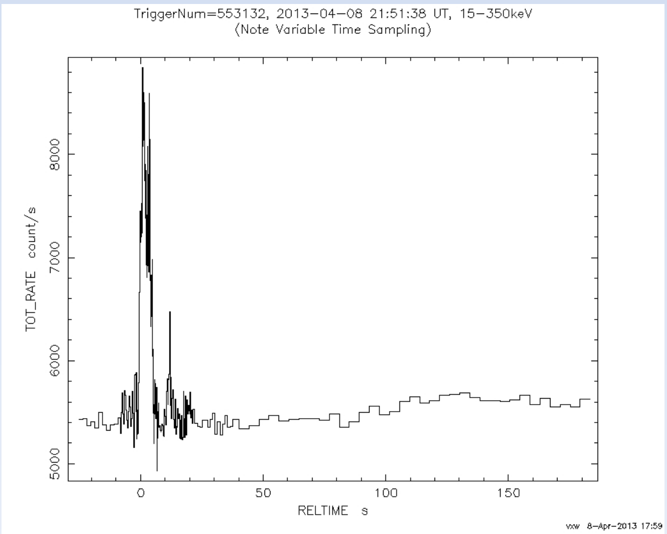
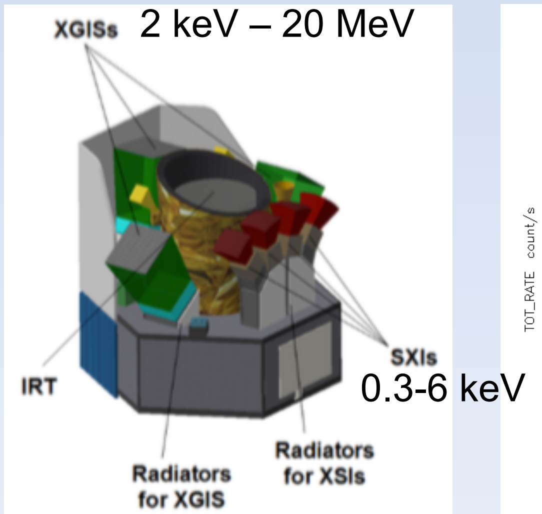
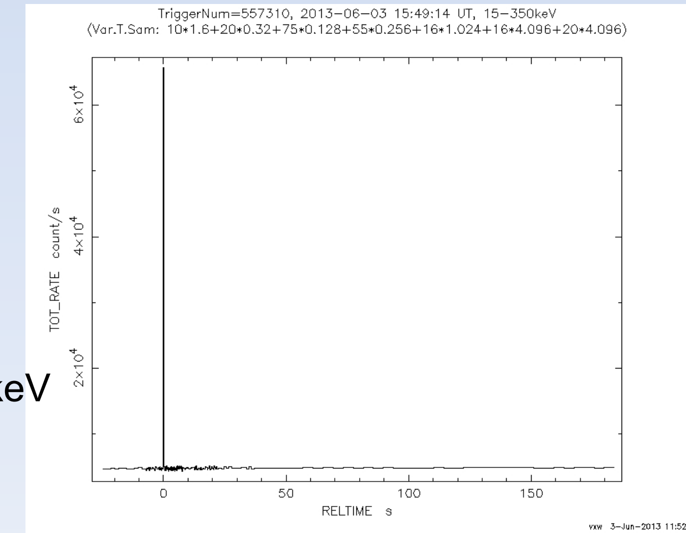






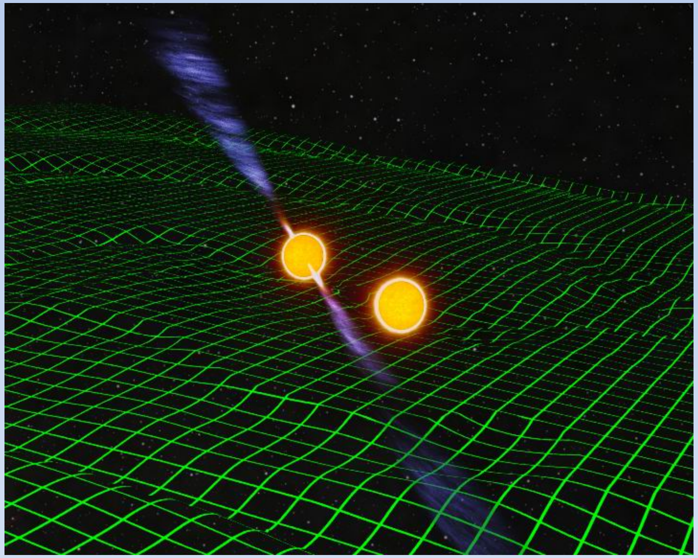


The progenitors of short GRBs

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

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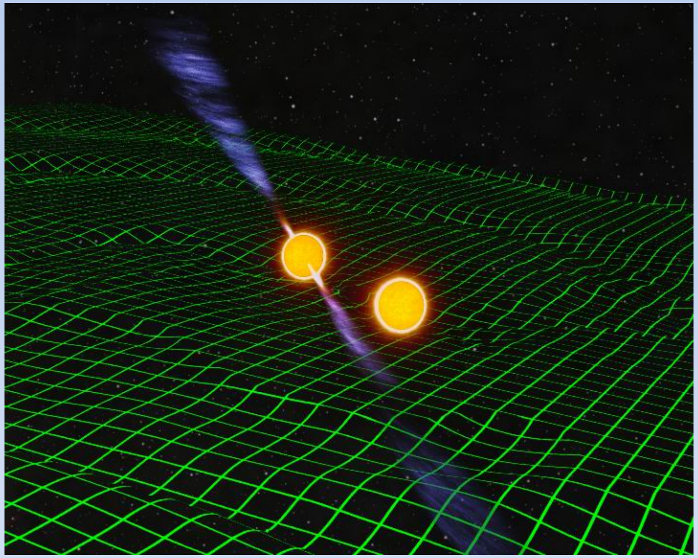

- critical parameter: **merging time t_m**
Time between the formation of the system and its coalescence
$t_m \propto a^4$ (*a:* system separation) **->** **~10 Myr < t_m < ~10 Gyr**

- 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

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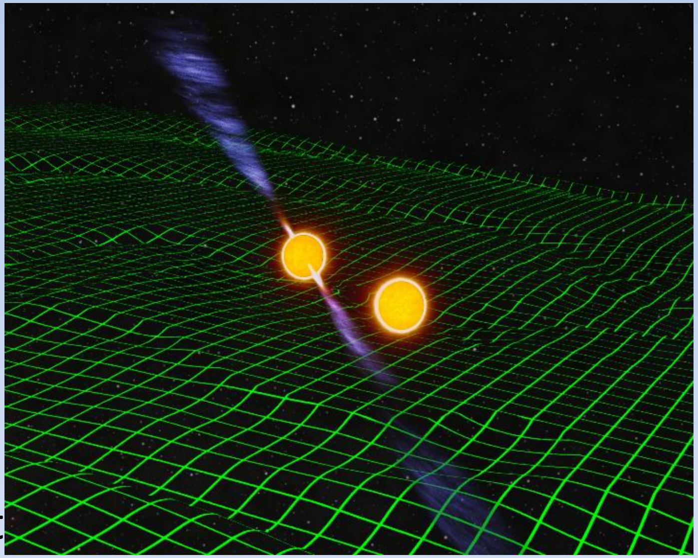
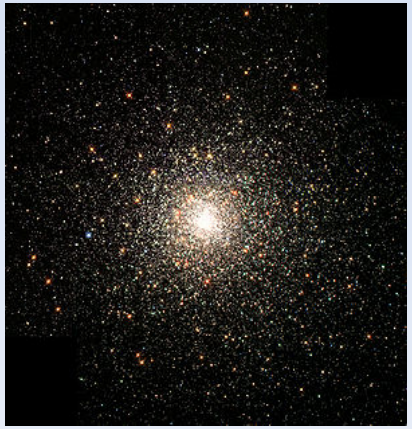
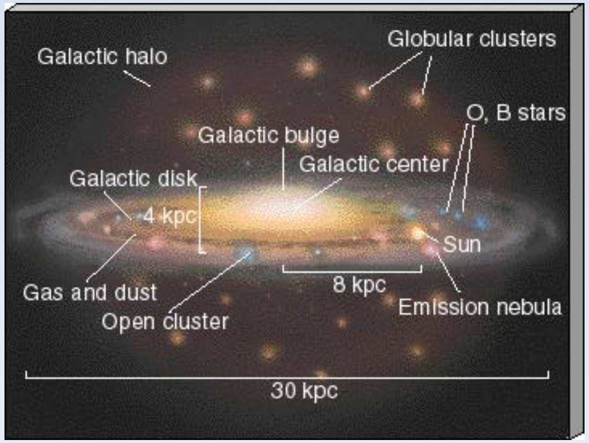


Another possibility: dynamical formation of a double compact object system (e.g. in globular clusters)

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

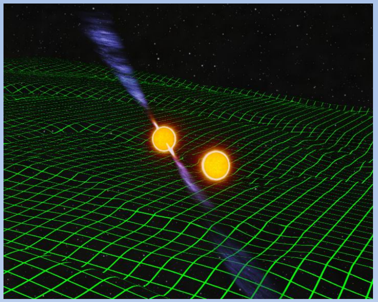




"dynamically formed binaries"

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:

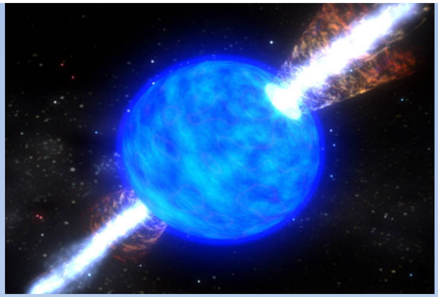
- Offsets
- No correlation with UV/optical HG light
- Diversity in the environment (ev. channel)

No associated supernova

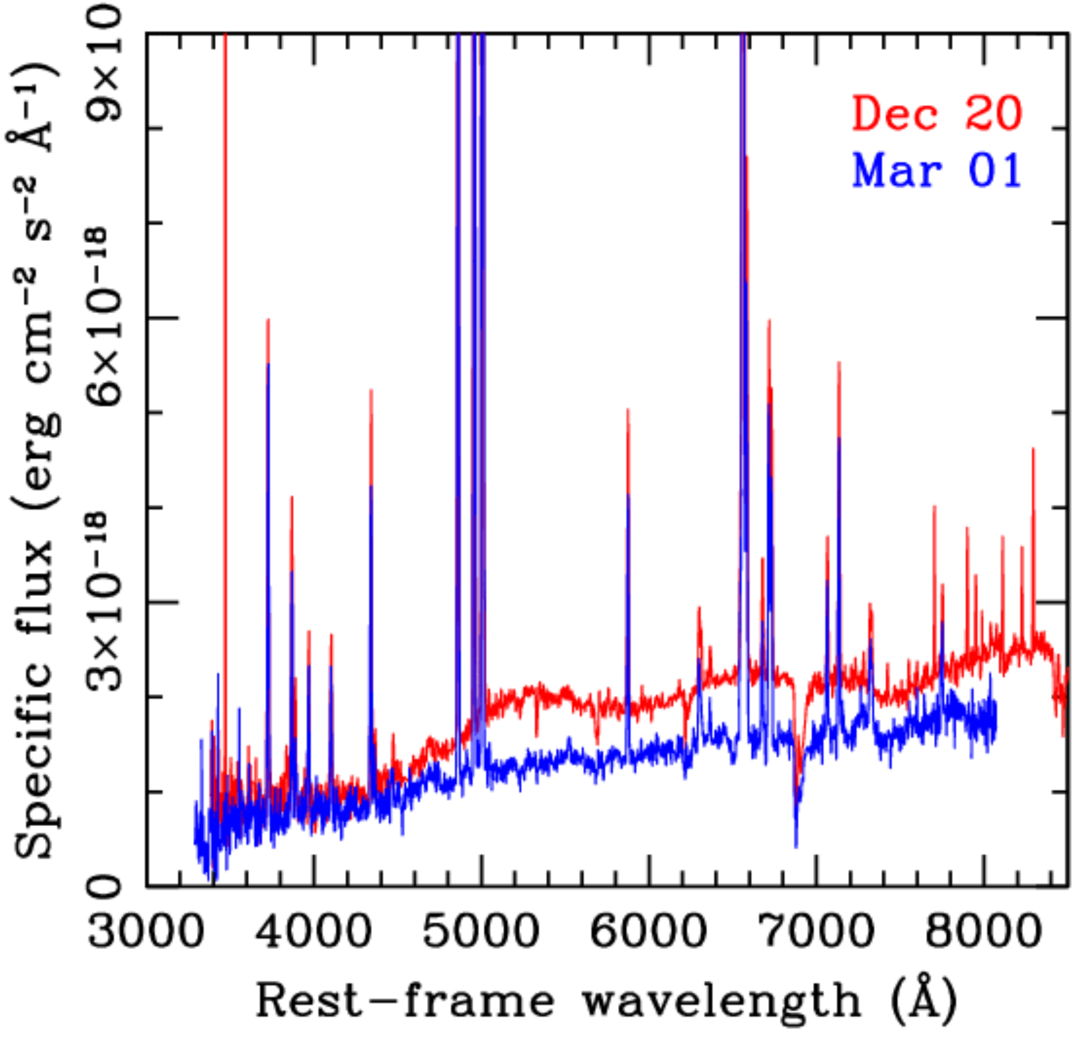
Kilonova/macronova association

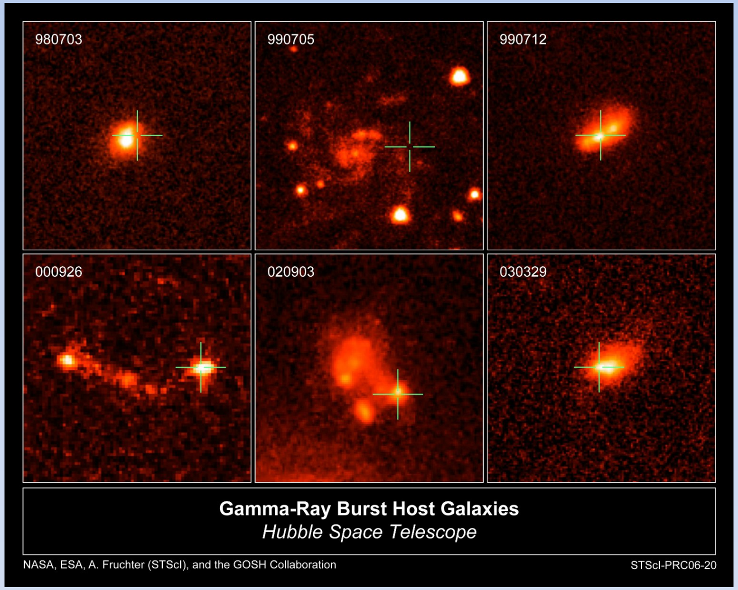
Gravitational waves

Long GRB hosts



Emission line spectra





Nebular emission lines excited by hot, young stars

Blue

⇔

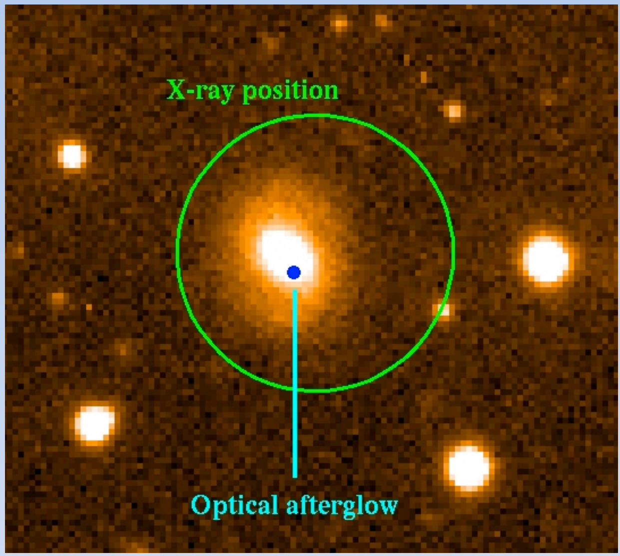
Hot

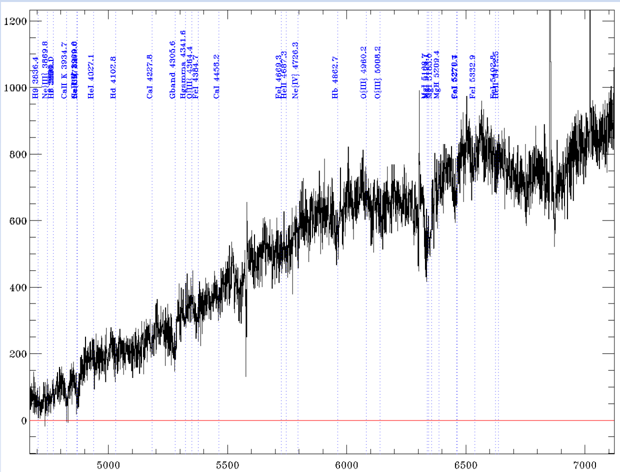
⇔

Young stars

Short GRB hosts

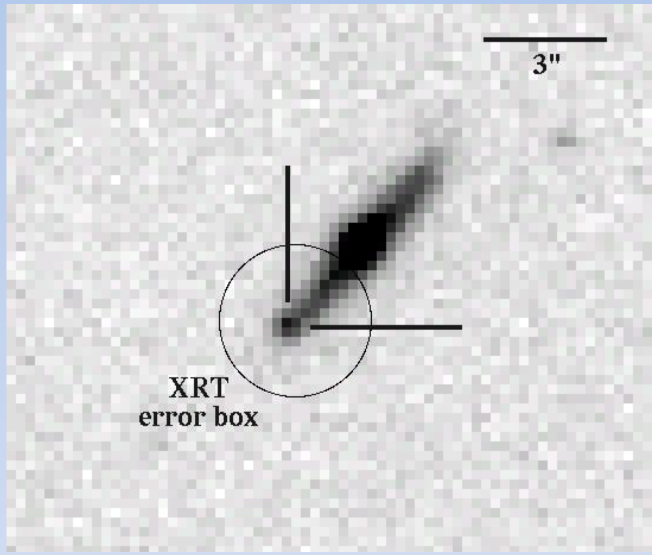
Early-type

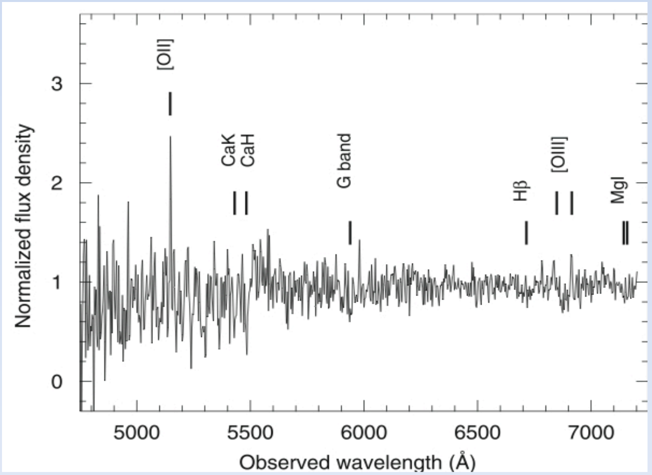




GRB 050724
Barthelmy et al. 2005;
Malesani et al. 2007

Late-type





GRB 071227
D'Avanzo et al. 2009

Host-less

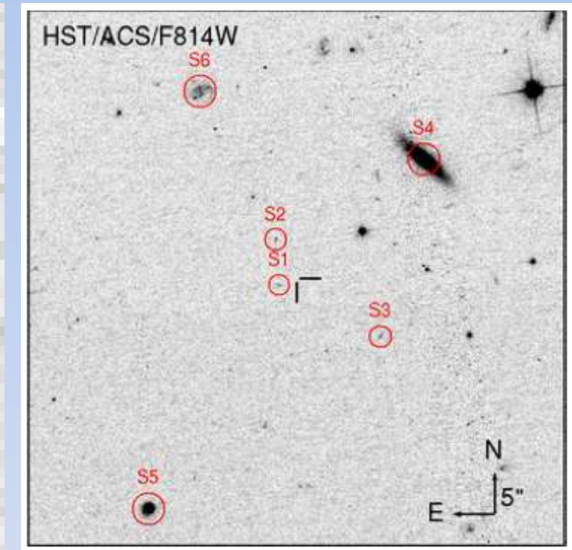


TABLE 2
OBSERVATIONS OF SHORT GRBS WITH OPTICAL AFTERGLOWS AND NO COINCIDENT HOST GALAXIES
(*Sample 2*)

GRB	Instrument	Filter	t_{exp} (s)	m_{lim} [a] (AB mag)
061201	HST/ACS	F814W	2224	26.0
070809	Magellan/LDSS3	*r*	1500	25.4
080503	HST/WFPC2	F606W	4000	25.7
090305	Magellan/LDSS3	*r*	2400	25.6
090515	Gemini-N/GMOS	*r*	1800	26.5

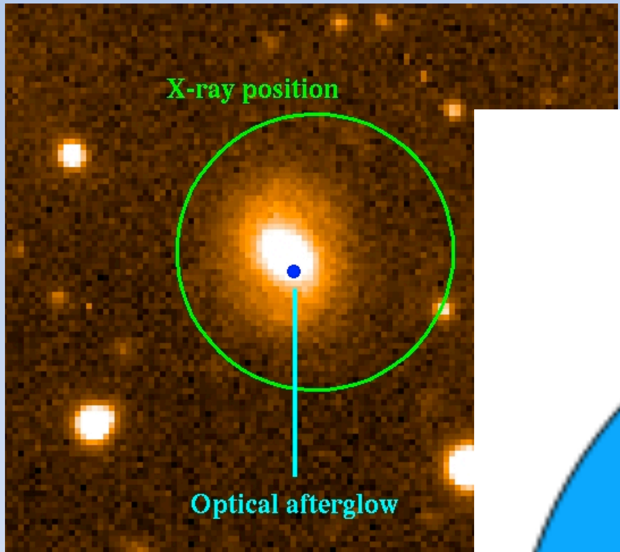
NOTE. — [a] Limits are 3σ.

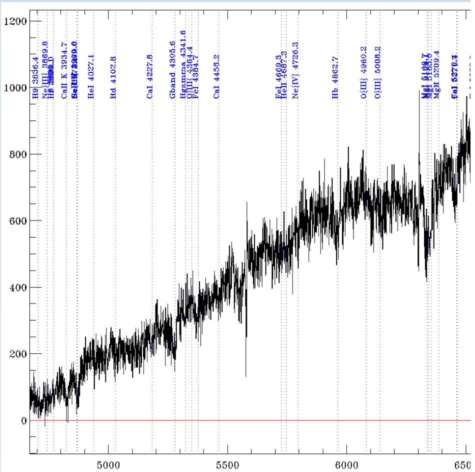
Berger 2010

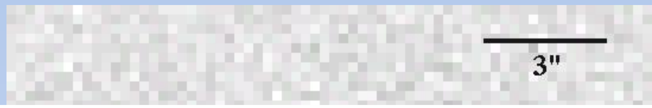
- High-z?
- (very-)low lum HG?
- kicked progenitor?

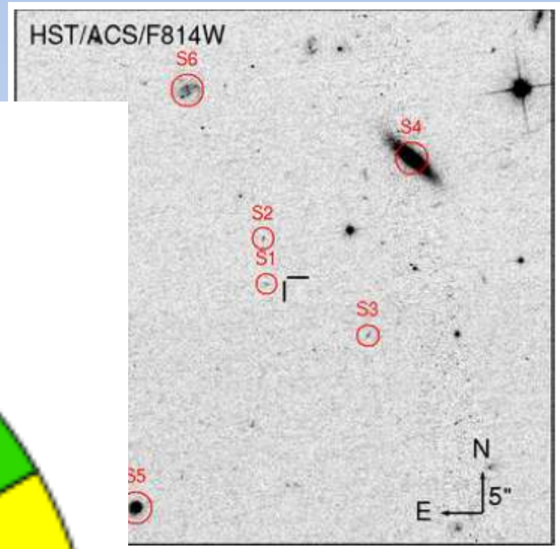
Short GRB hosts

Early-type	Late-type	Host-less









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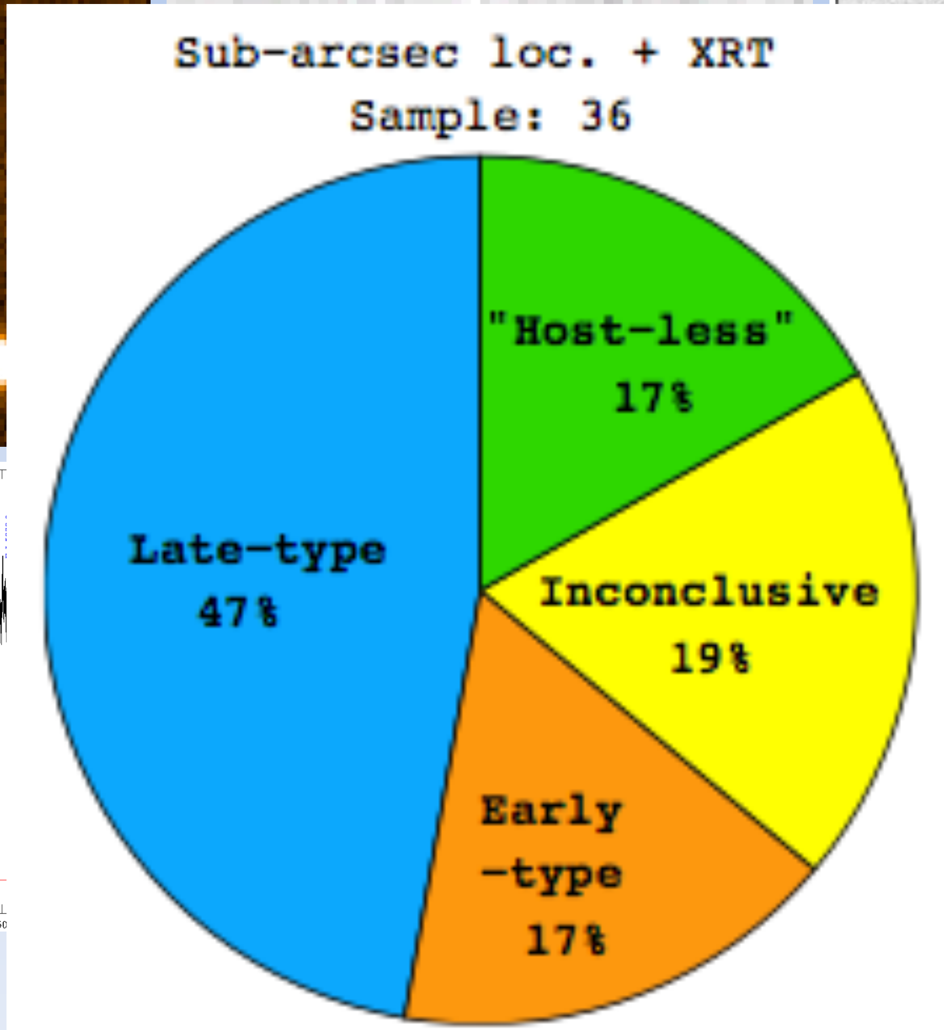

Fong et al. 2013; Berger 2014

GRB 050724
Barthelmy et al. 2005
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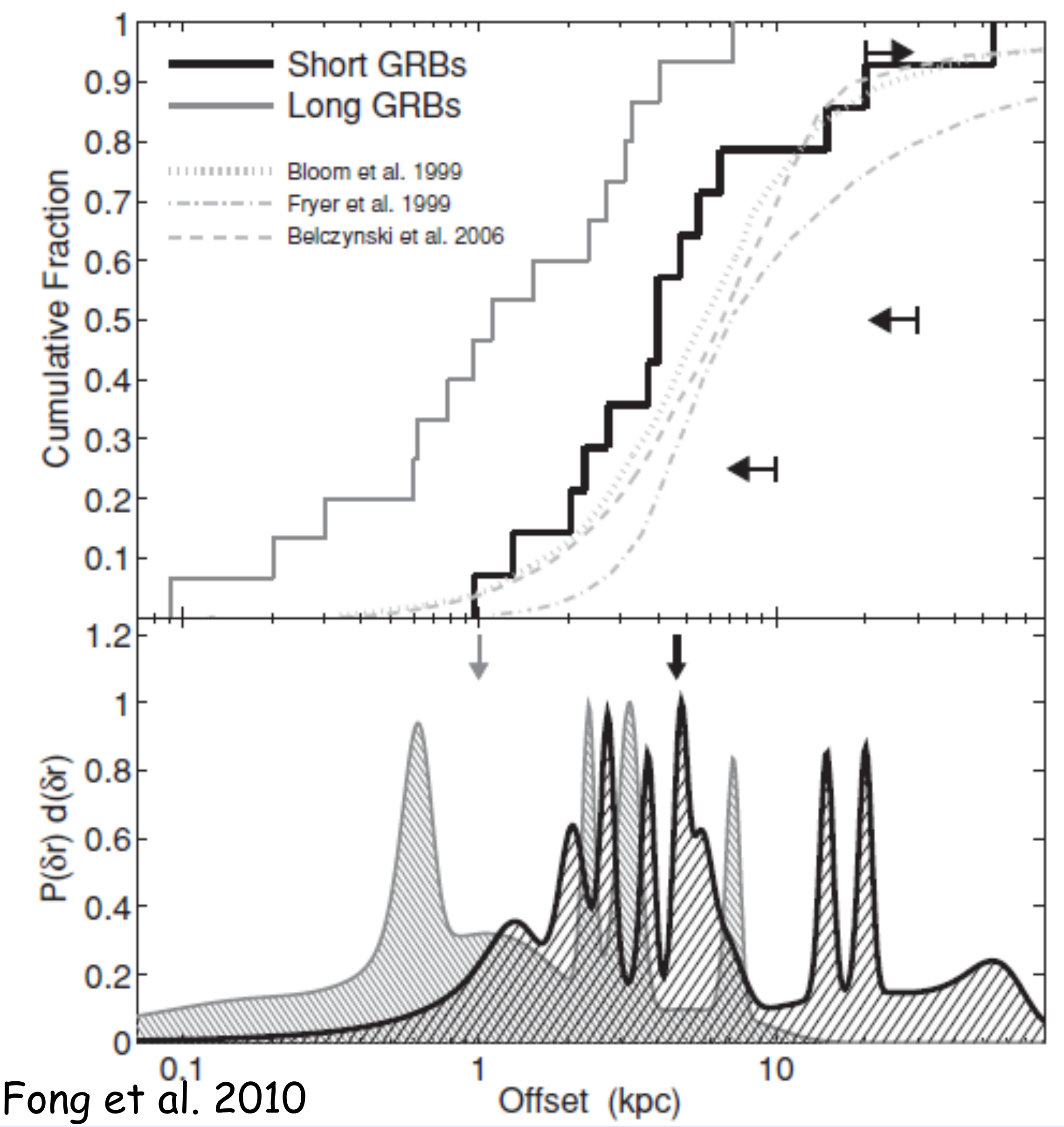
igh-z?
very-)low lum HG?
kicked progenitor?

Short GRBs: Offsets

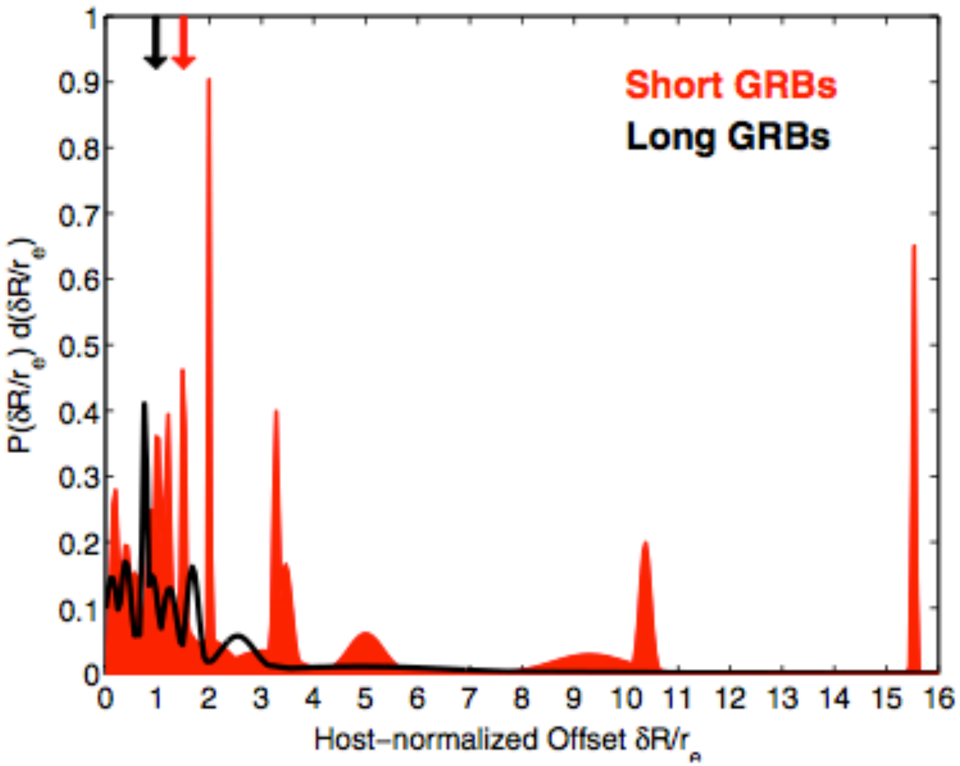
Offset from HG centre

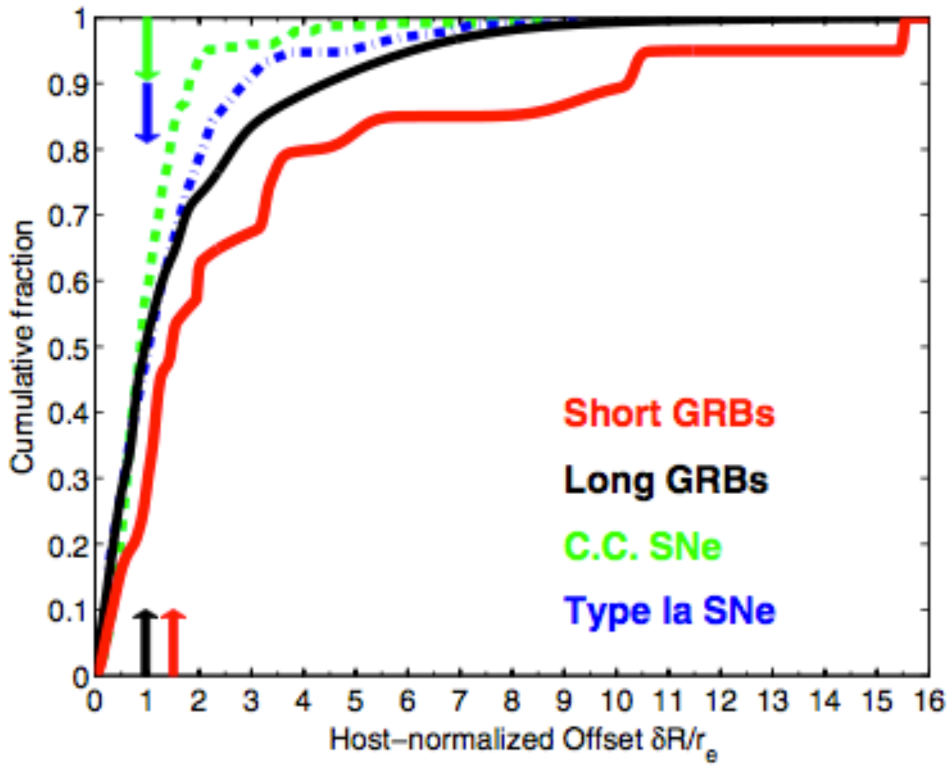


Fong et al. 2010

Short GRBs: Offsets

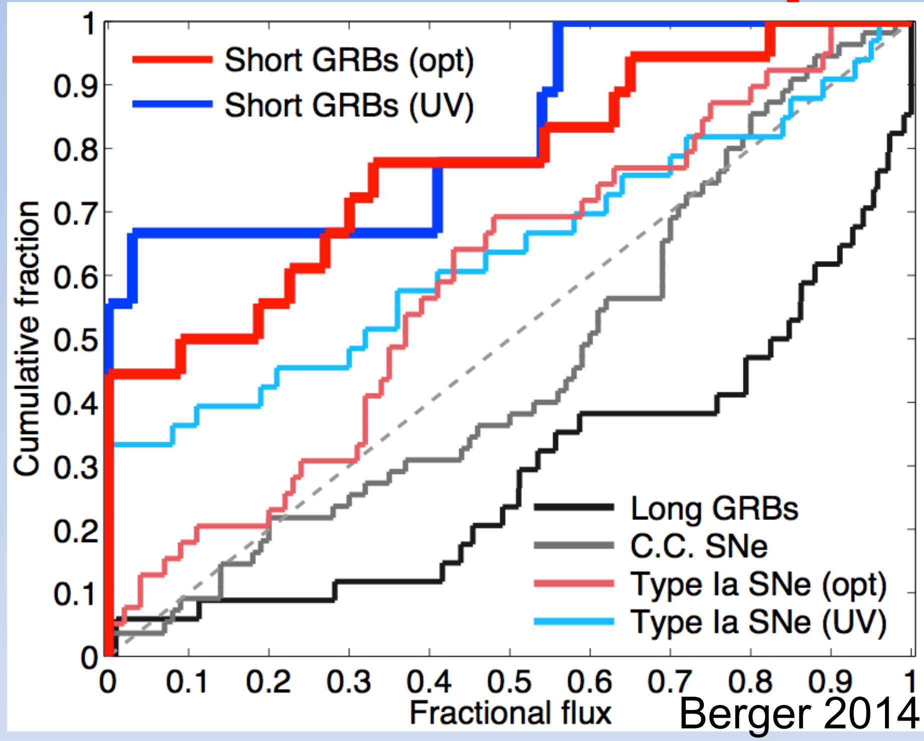
Offset normalized to HG eff. radius





Fong & Berger 2013

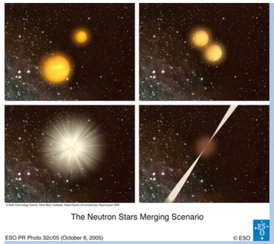
(no) correlation with UV/optical light



- LGRBs (and CC Sne) show direct spatial correlation with the underlying rest-frame UV light (Fruchter et al.); this is what expected for transients whose progenitors track star formation activity with a short delay

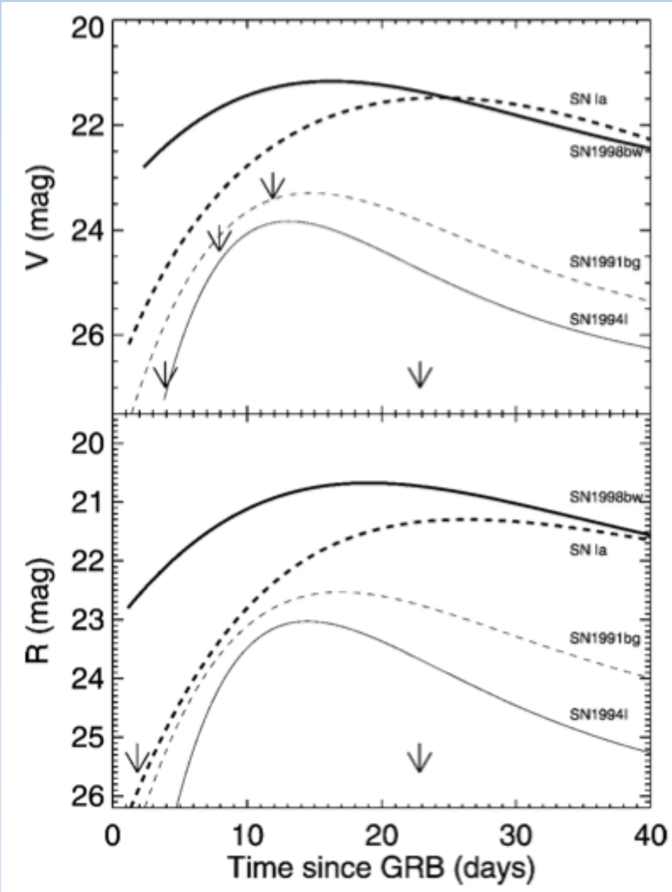
- about half of the SGRBs are located in regions of their hosts that are faint in both the UV and optical

→ at least a significant fraction of SGRBs occur in distinct environments w.r.t. LGRBs (or other explosive transients not experiencing natal kicks). For those SGRBs the explosion sites are not representative of the progenitor birth-sites, requiring significant migration (kicks).



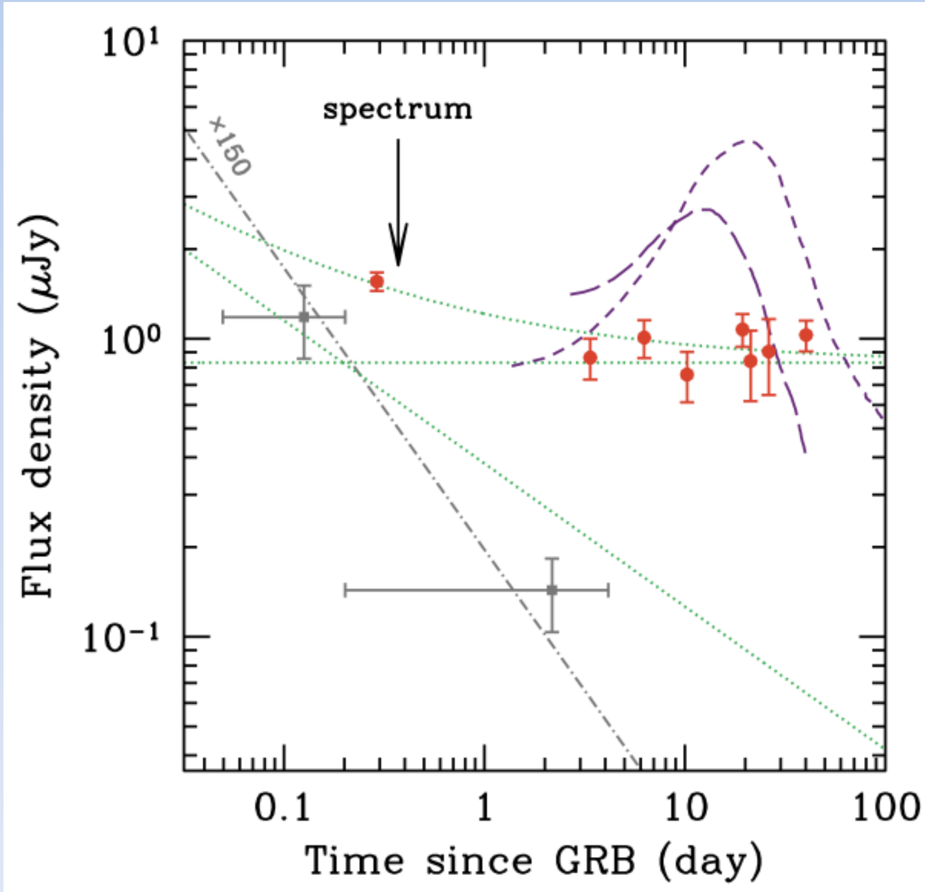
Short GRB & NO Supernovae

GRB 050509B



Hjorth et al. 2005

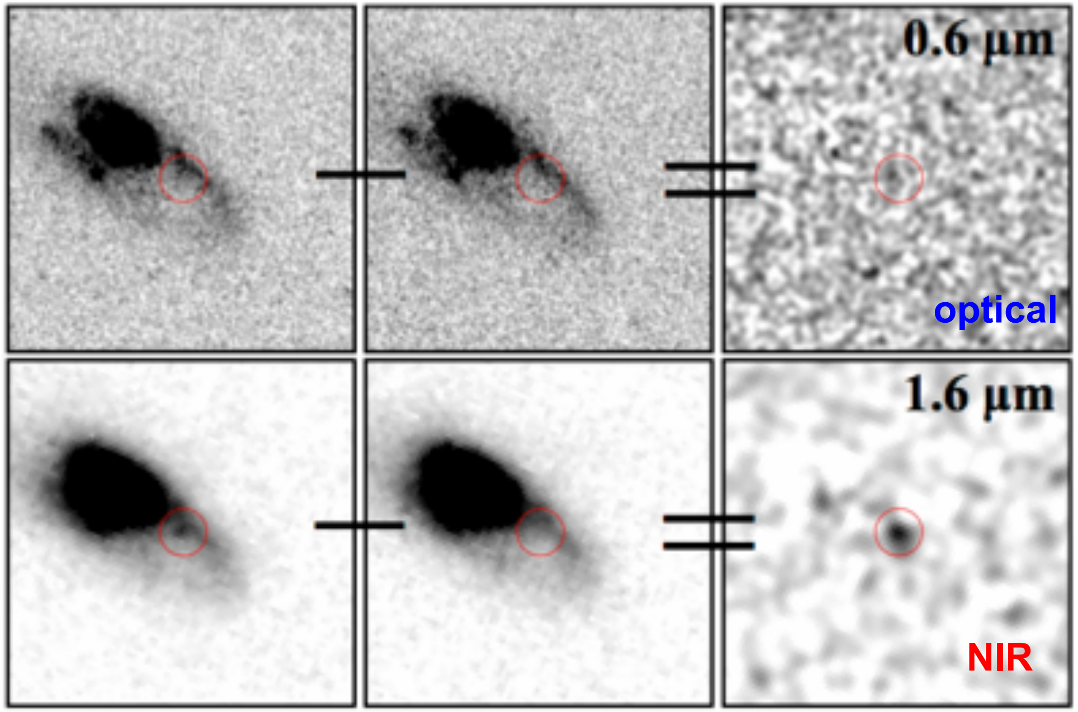
GRB 071227

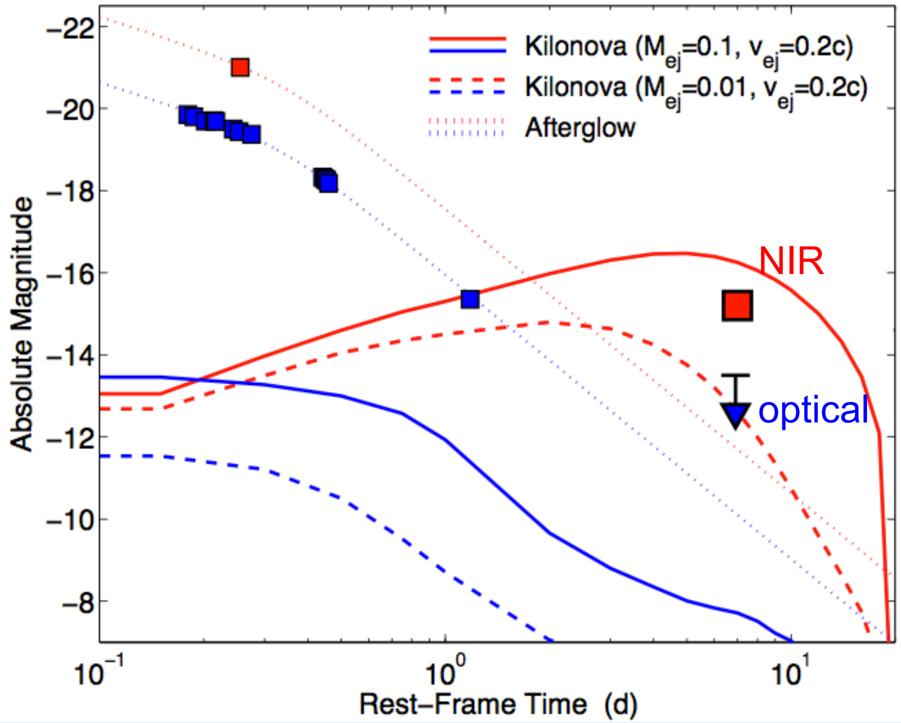


D'Avanzo et al. 2009

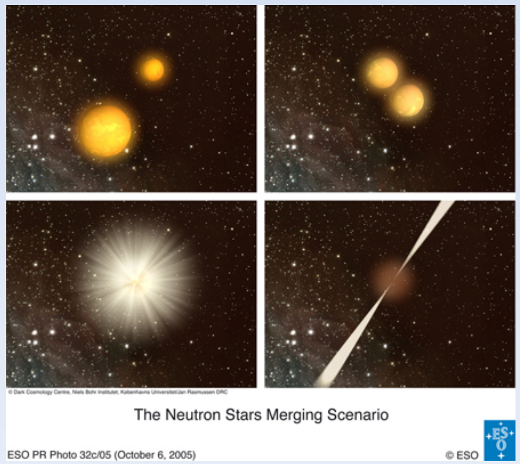
See also: Covino et al. 2006; Della Valle et al. 2006; Fynbo et al. 2006

A kilonova/macronova associated to GRB 130603B?



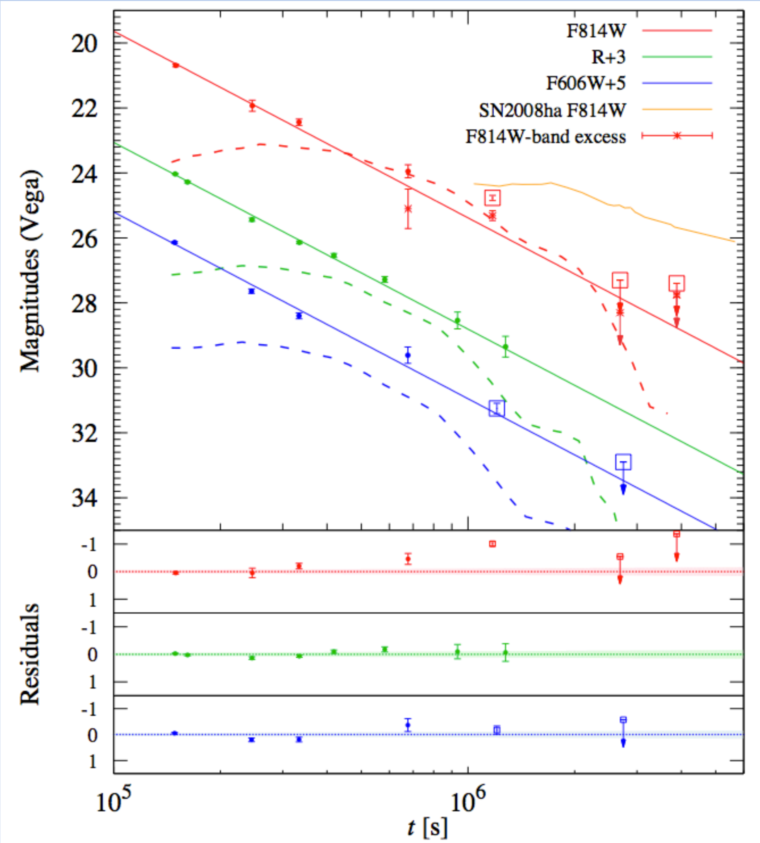


Tanvir et al. 2013; Berger et al. 2013



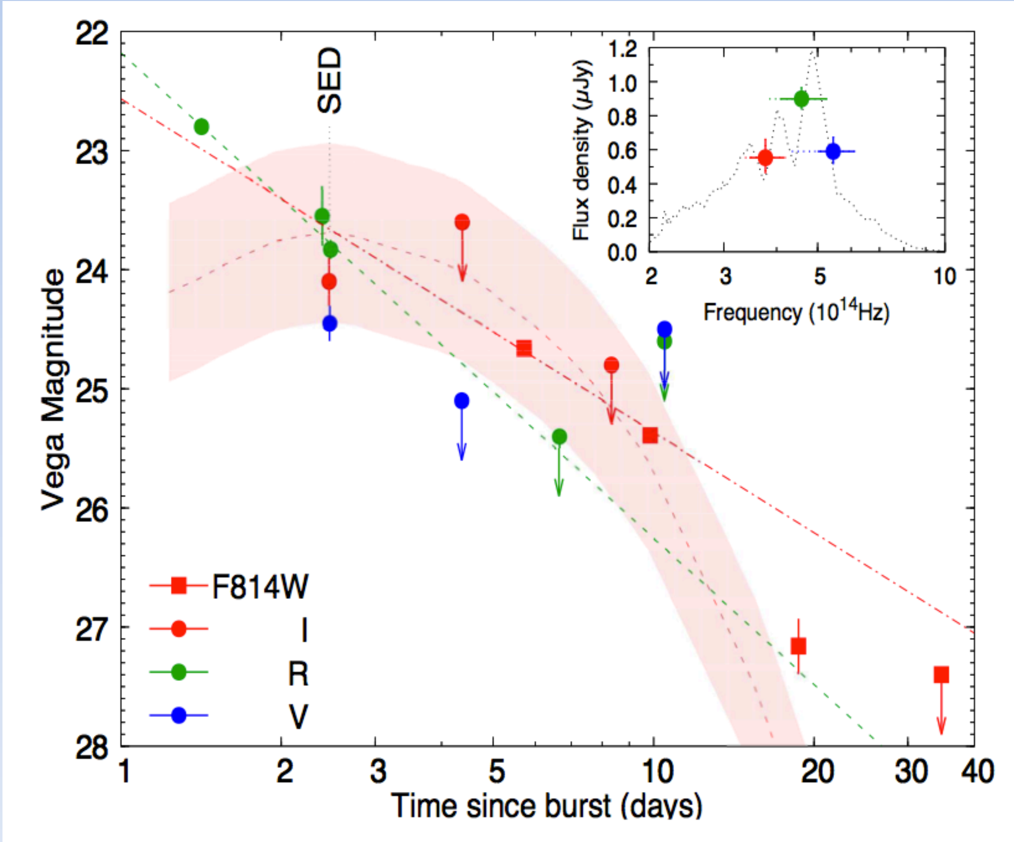
A kilonova/macronova associated to GRB 060614 & GRB 050709?

GRB 060614



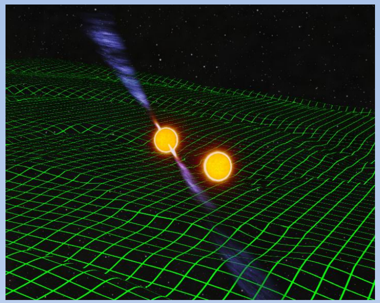
Yang et al. 2015

GRB 050709



Jin et al. 2016

Compact object mergers: what we do expect



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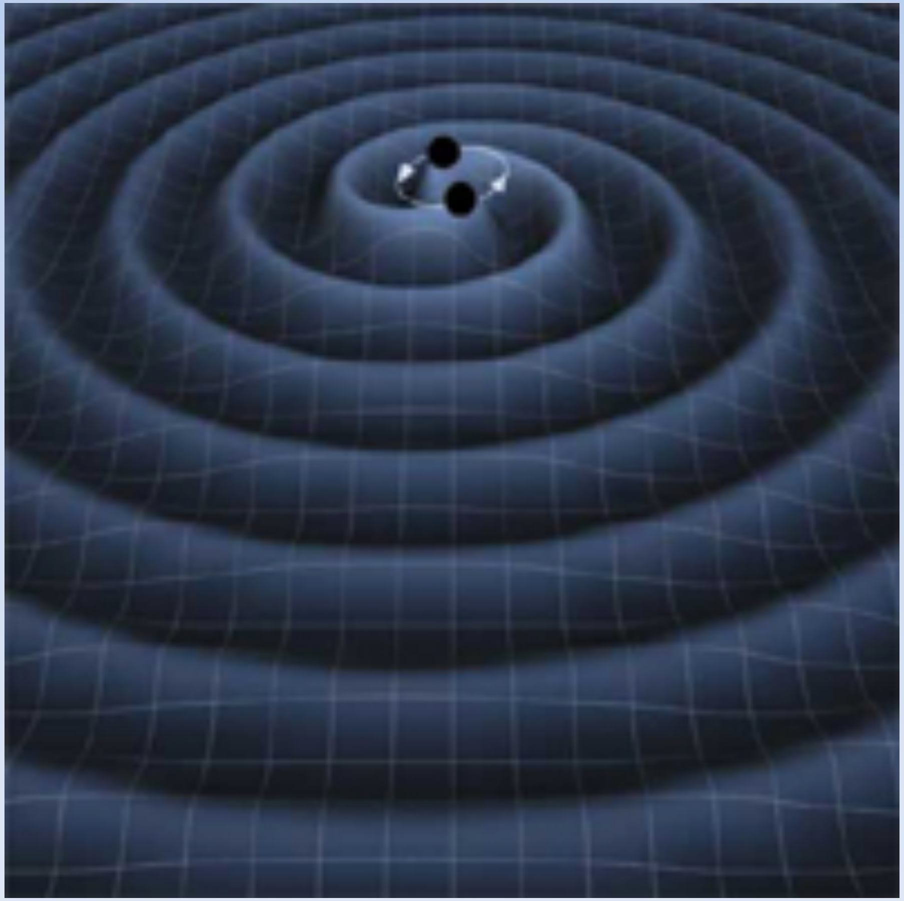
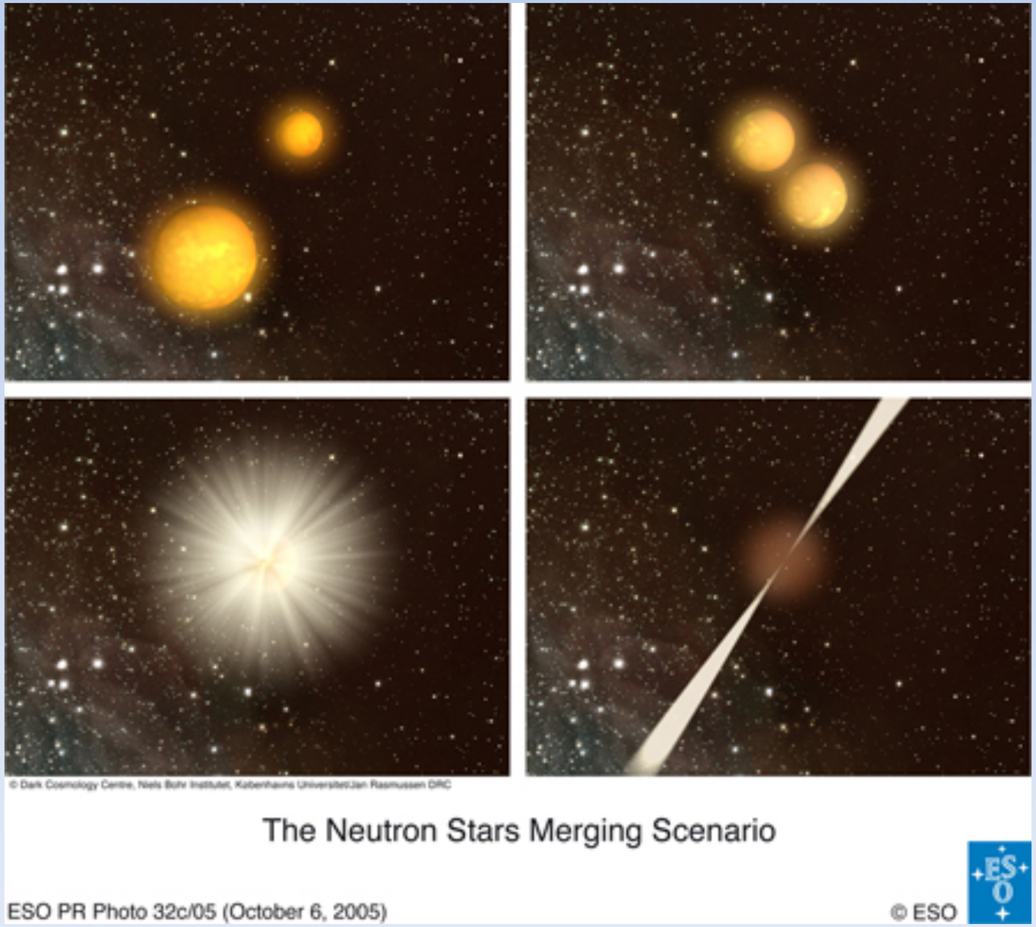
Gravitational waves

Short GRBs as GW sources





The GW era – O1 & O2

Sept 2015 – Jan 2016: LVC O1 science run

2 high-significance (FAR < 1/century) GW events during O1 (GW 150914, GW 151226) + 1 possible, low-significance event (LVT 151210). All BBH. (Abbott et al. 2016a,b)

LVC O2 run is ongoing (until August 2017)

Other BBH detected (GW 170104, Abbott et al. 2017; GW 170814, LVC 2017). Improved strategies for EM follow-up at all wavelengths.

Sky localizations (90% credible area)
600 deg^2 GW 150914
1600 deg^2 LVT 151012
1000 deg^2 GW 151226

No EM counterpart found
(despite huge observational effort)

No significant EM emission expected from BBH
EM emission expected for NSNS and/or NSBH

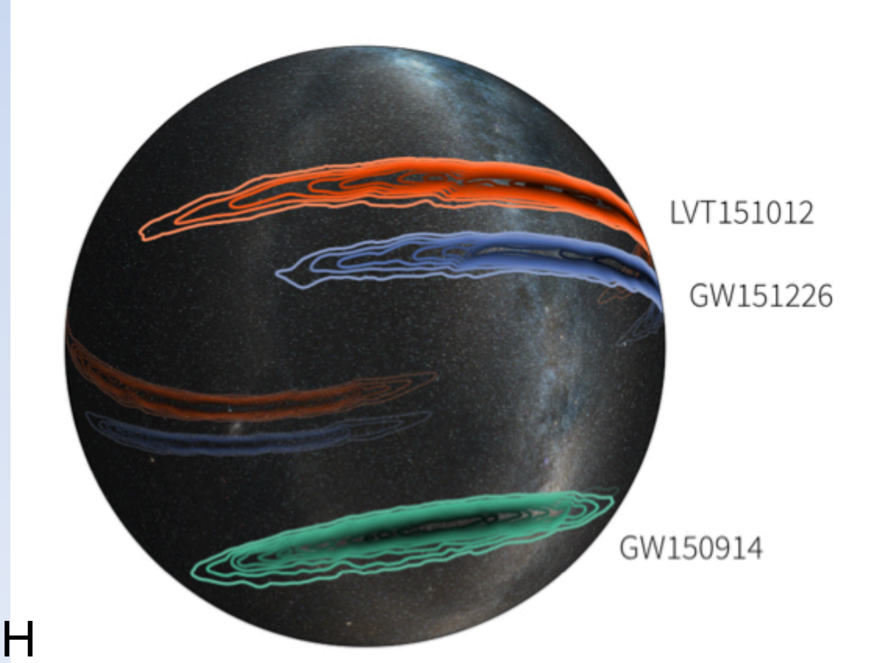


Image credit: LIGO/L. Singer/A. Mellinger

The GW era – O1 & O2

Sept 2015 – Jan 2

2 high-significance
+ 1 possible, low-s

LVC O2 run is on

Other BBH detect

1000 d

No EM
(despite hu

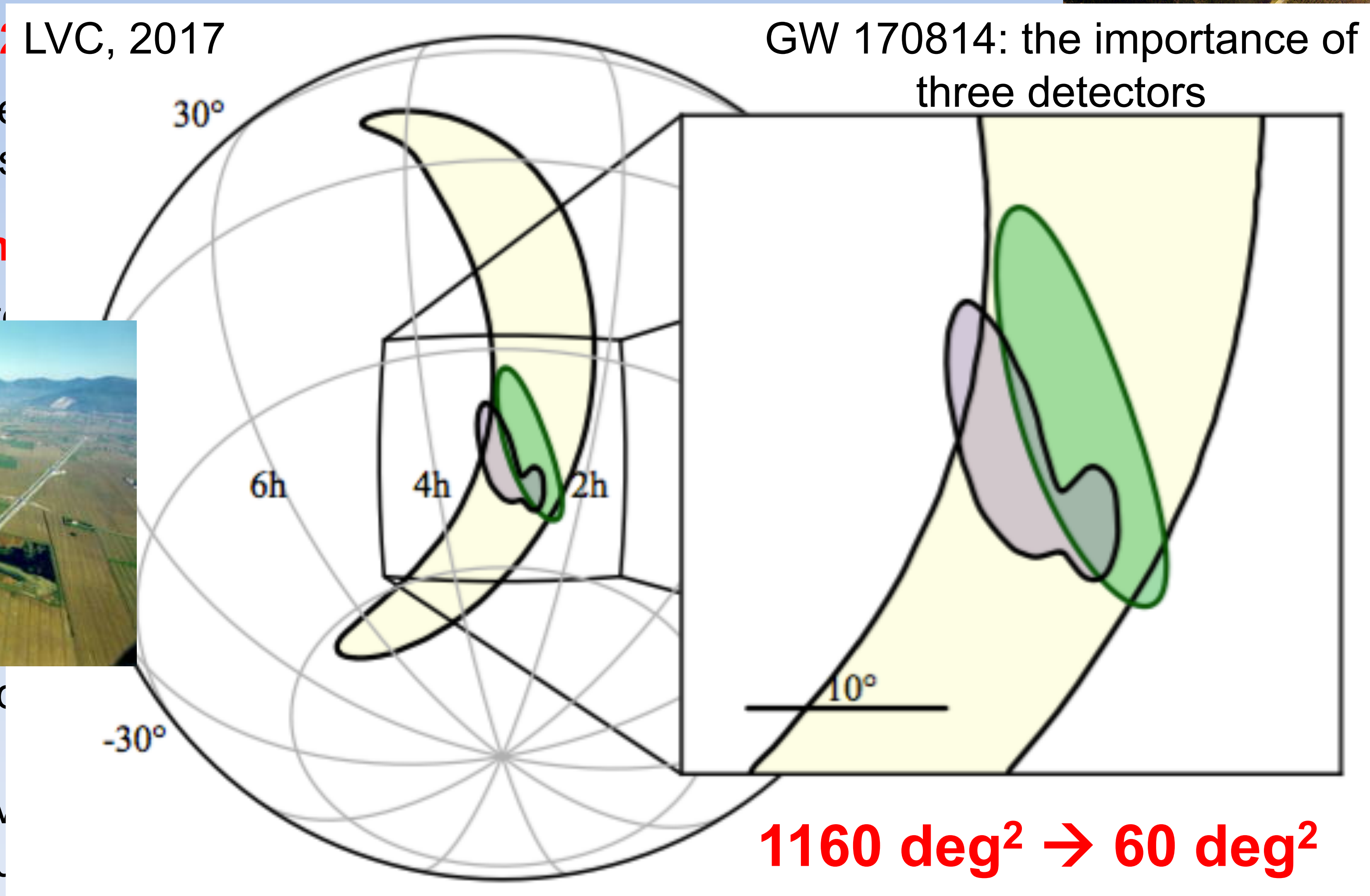


Image credit: LIGO/L. Singer/A. Mellinger

No significant EM emission expected from BBH
EM emission expected for NSNS and/or NSBH

The GW era: importance of EM detections

Precise sky localization

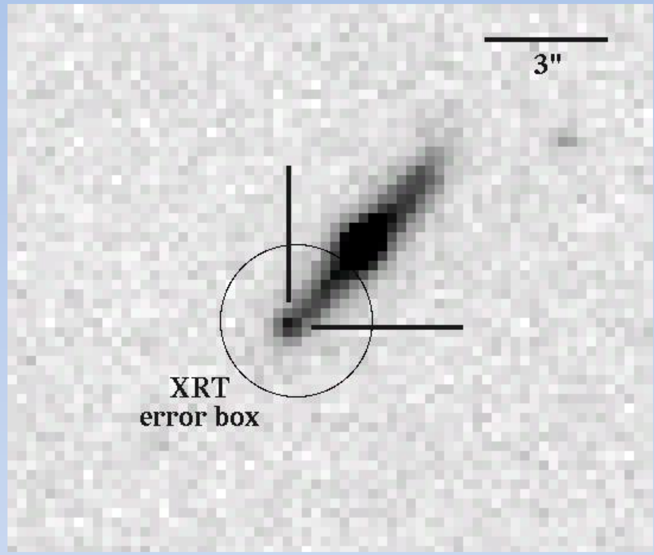
Independent measure of distance (redshift)

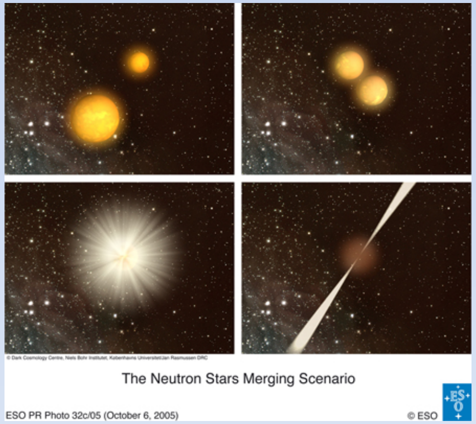
Luminosity & Energy

Possibility to study the environment

Contraints to the progenitor evolutionary channels

Progenitors ‘smoking gun’ for short GRBs





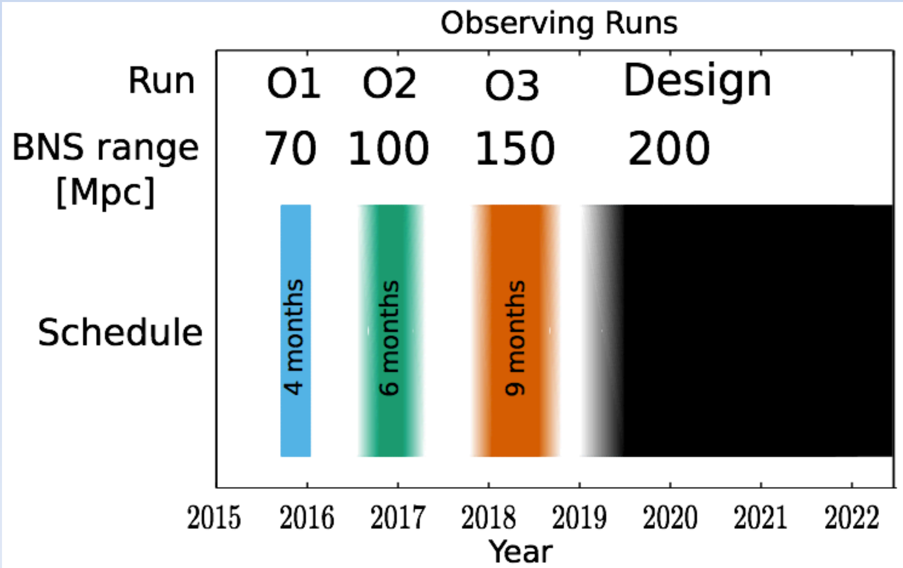
Expected NSNS – NSBH EM counterparts

Short GRBs (γ-ray, X-ray, opt, NIR, radio)

Orphan afterglow (X-ray, opt, NIR, radio)

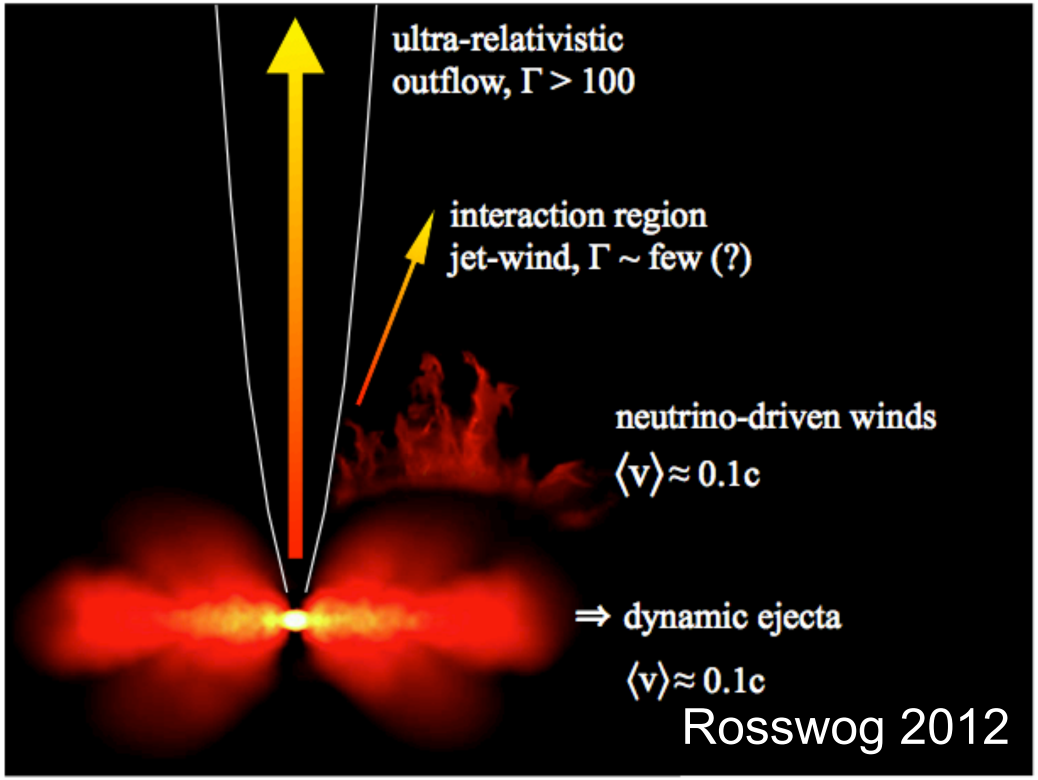
Macronova/Kilonova (optical, NIR)

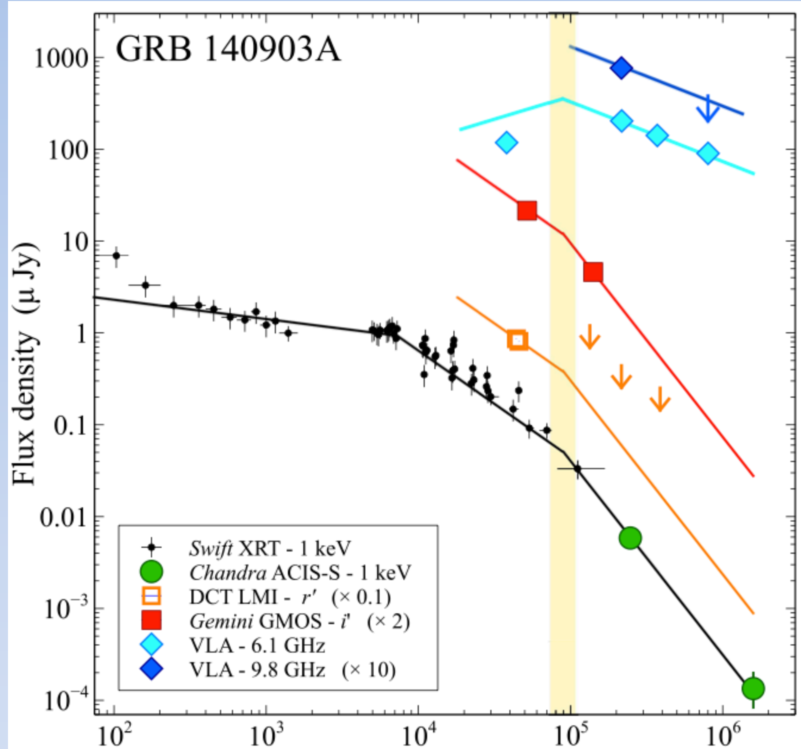
Late-time radio remnant (radio)



How many within the LIGO-Virgo horizon?

Jets in SGRBs





Troja et al. 2016

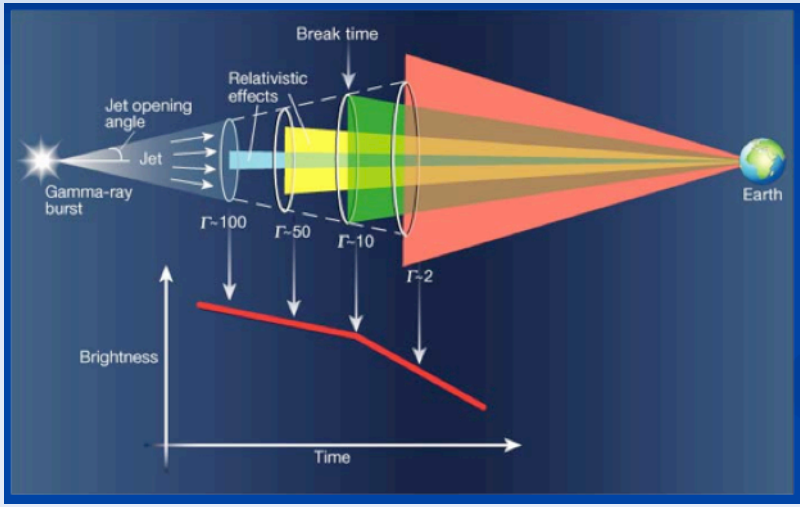
Short GRB Opening Angles

Fong et al. 2015

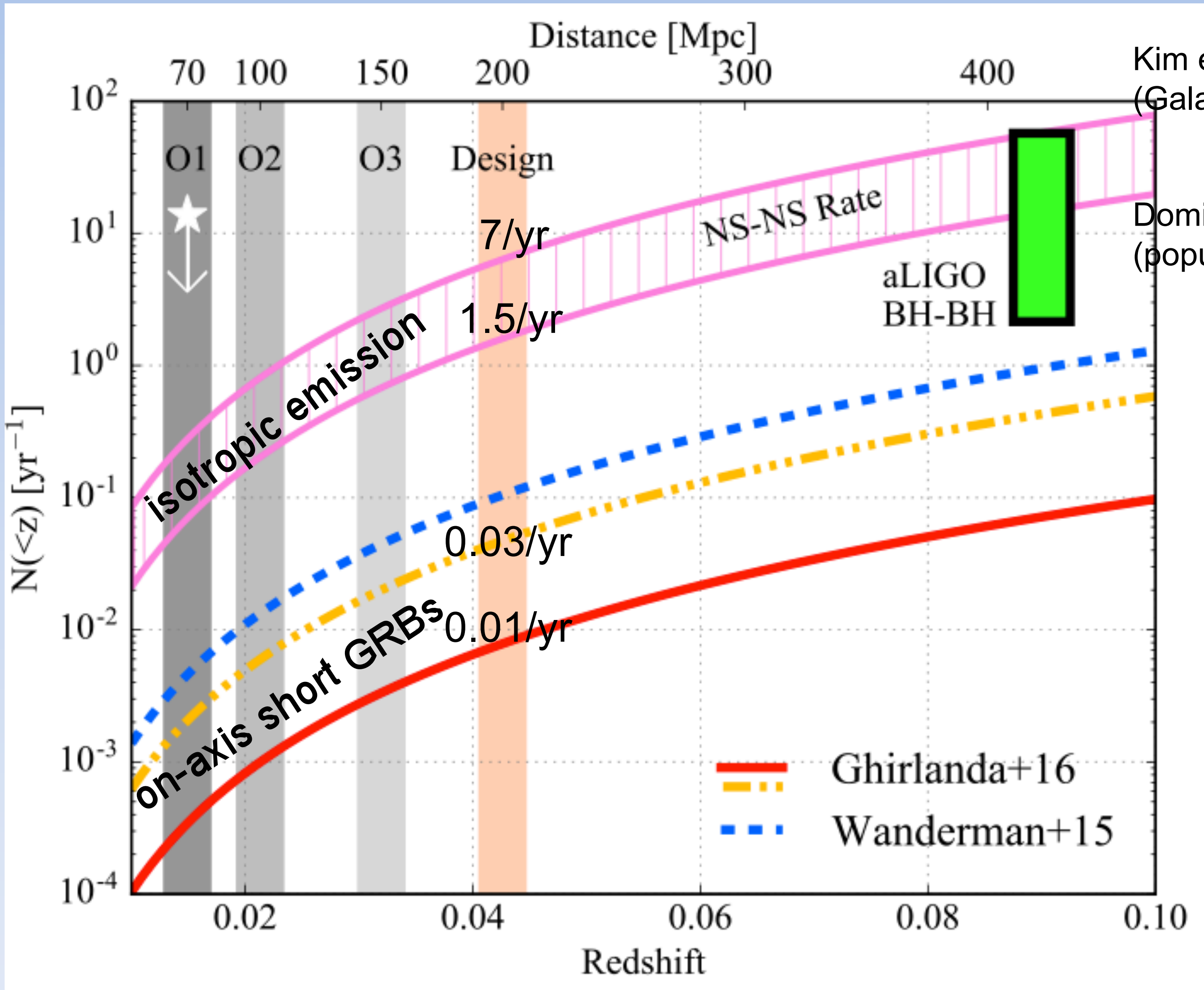
GRB	Band[a]	θ_j (deg)	$\delta t^b_{\mathrm{last}}$ (days)	Reference
050709	O	$\gtrsim 15^\circ$	16.2	1
050724A	X	$\gtrsim 25^\circ$	22.0	2
051221A	X	$6-7^\circ$	26.6	3
090426A	O	$5-7^\circ$	2.7	4
101219A	X	$\gtrsim 4^\circ$	3.9	5, This work
111020A	X	$3-8^\circ$	10.2	6
111117A	X	$\gtrsim 3-10^\circ$	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

The true SGRB event rate is increased by a factor:

$$f_b^{-1} = (1-\cos\Theta_j)^{-1}$$



Short GRB rate: forthcoming LIGO-Virgo runs

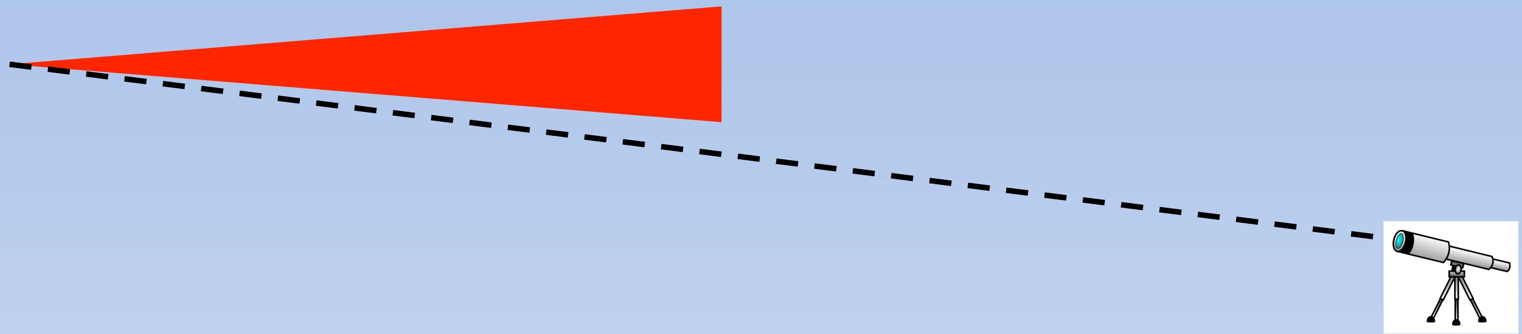


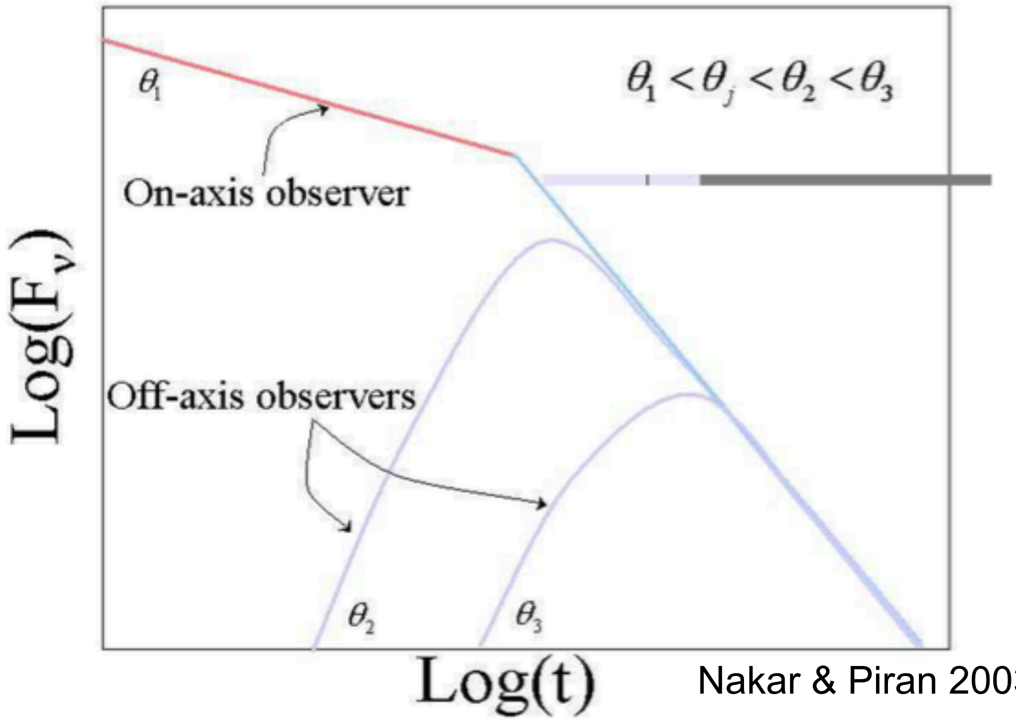
Kim et al. 2015
(Galactic binaries)

Dominik et al. 2015
(population synthesis)

Kilonova/macronova, off-axis SGRBs/“orphan” afterglows more promising EM counterparts of NS-NS / NS-BH GW events

Off-axis SGRBs

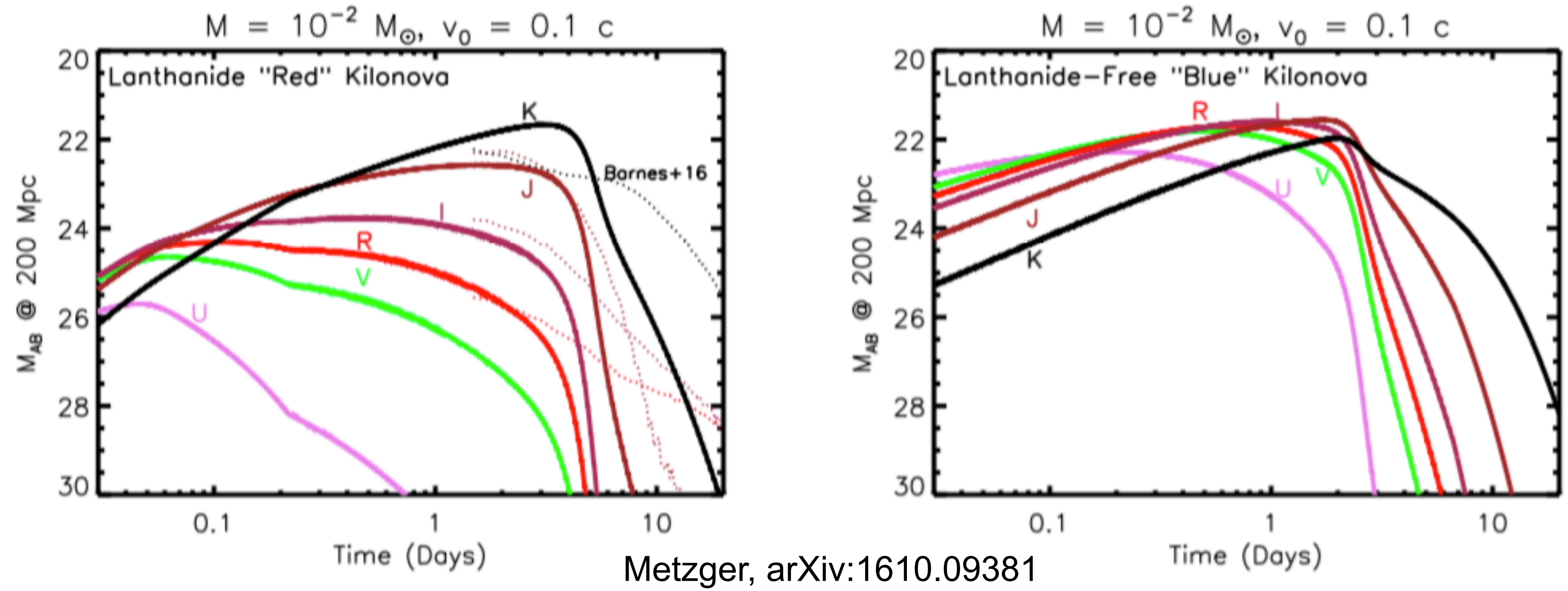




Nakar & Piran 2003

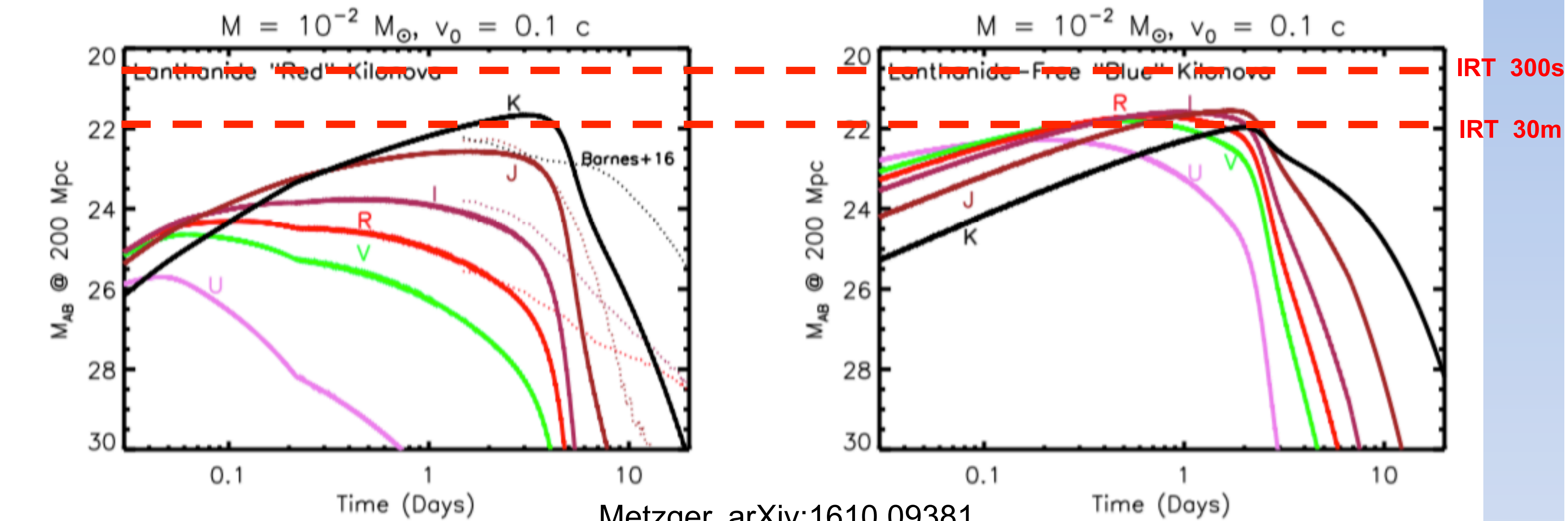
Fig. 3. Schematic light curves of on-axis and off-axis orphan afterglows. Naturally, early, when the observers is outside the initial beam, off-axis afterglows are much weaker. Later, after the jet break both light curves are similar.

Kilonova/macronova opt/NIR emission



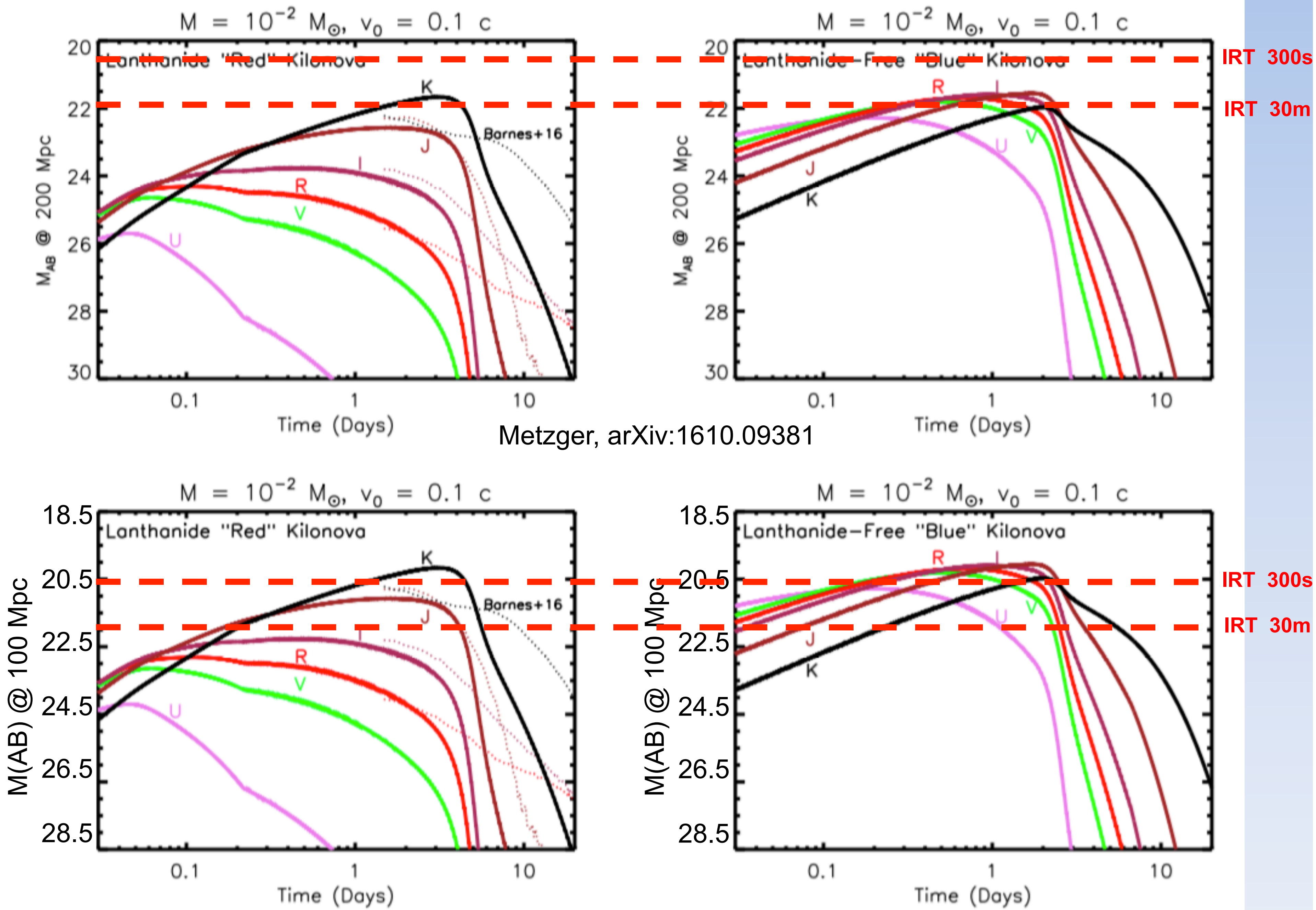
Metzger, arXiv:1610.09381

Kilonova/macronova opt/NIR emission

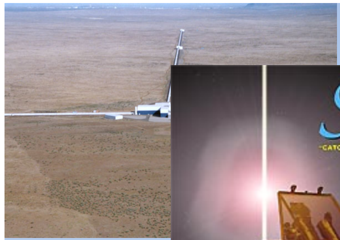


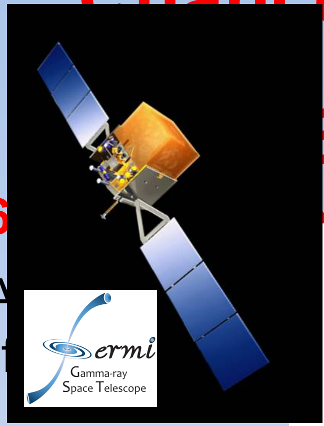
Metzger, arXiv:1610.09381

Kilonova/macronova opt/NIR emission



Metzger, arXiv:1610.09381



Chances for coincident ... B-GW detection

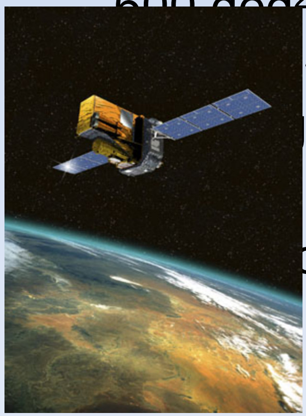
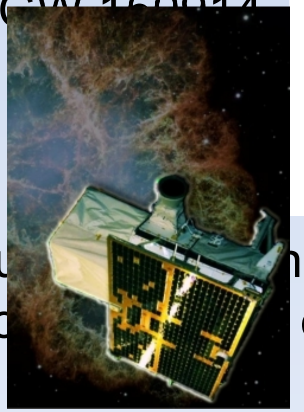
Sept 2 ... 6 ... nce run

2 high- ... A ... 226)
+ 1 pos ... i

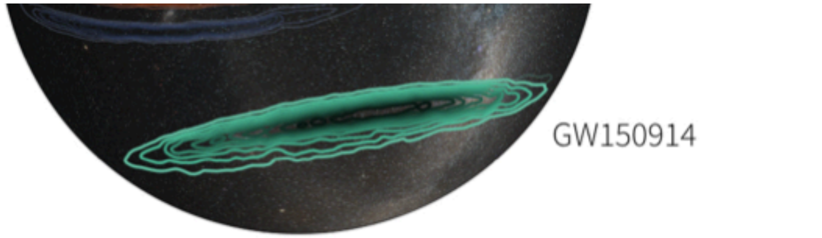
LVC O2 r ... g

Another I ... 4 ... M
follow-up

Sky ... e
600 deg2 (GW150914
2
2

... ou ... nd
c ... effort)



No significant EM emission expected from BBH
EM emission expected for NSNS and/or NSBH

Image credit: LIGO/L. Singer/A. Mellinger

Short GRBs: some conclusions

- Evidences for compact binary merger progenitors:
    - No SNe
    - Different host galaxies (also early-type)
    - No-host SGRBs (large offset? Dynamical channel?)
    - Diversity in the environment w.r.t. long GRBs
    - Possible macronova/kilonova in some short GRB (smoking gun?)
    - Waiting for (more) GWs

- Perspectives:
    - systematic search for jet-breaks (true energetics and rate)
    - systematic search for associated kilonovae/macronovae
    - GW EM counterparts: good perspectives for associated detections of off-axis SGRBs/orphan afterglows/macronovae/kilonovae

Observational reviews: Berger 2014, ARA&A, 52, 43; D'Avanzo, 2015, JHEAp, 7, 73

Short GRB rate: forthcoming LIGO-Virgo runs

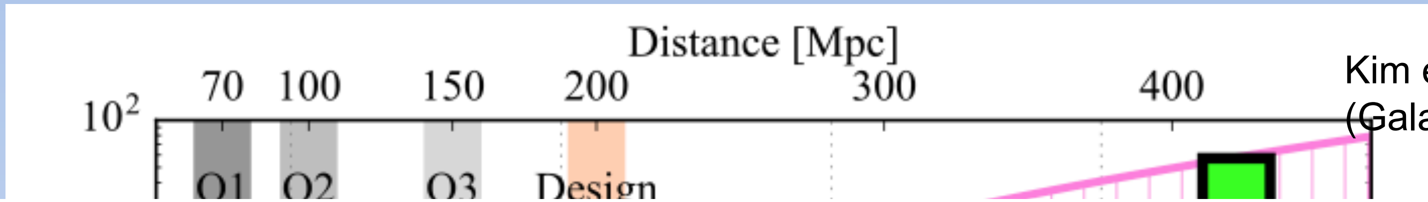


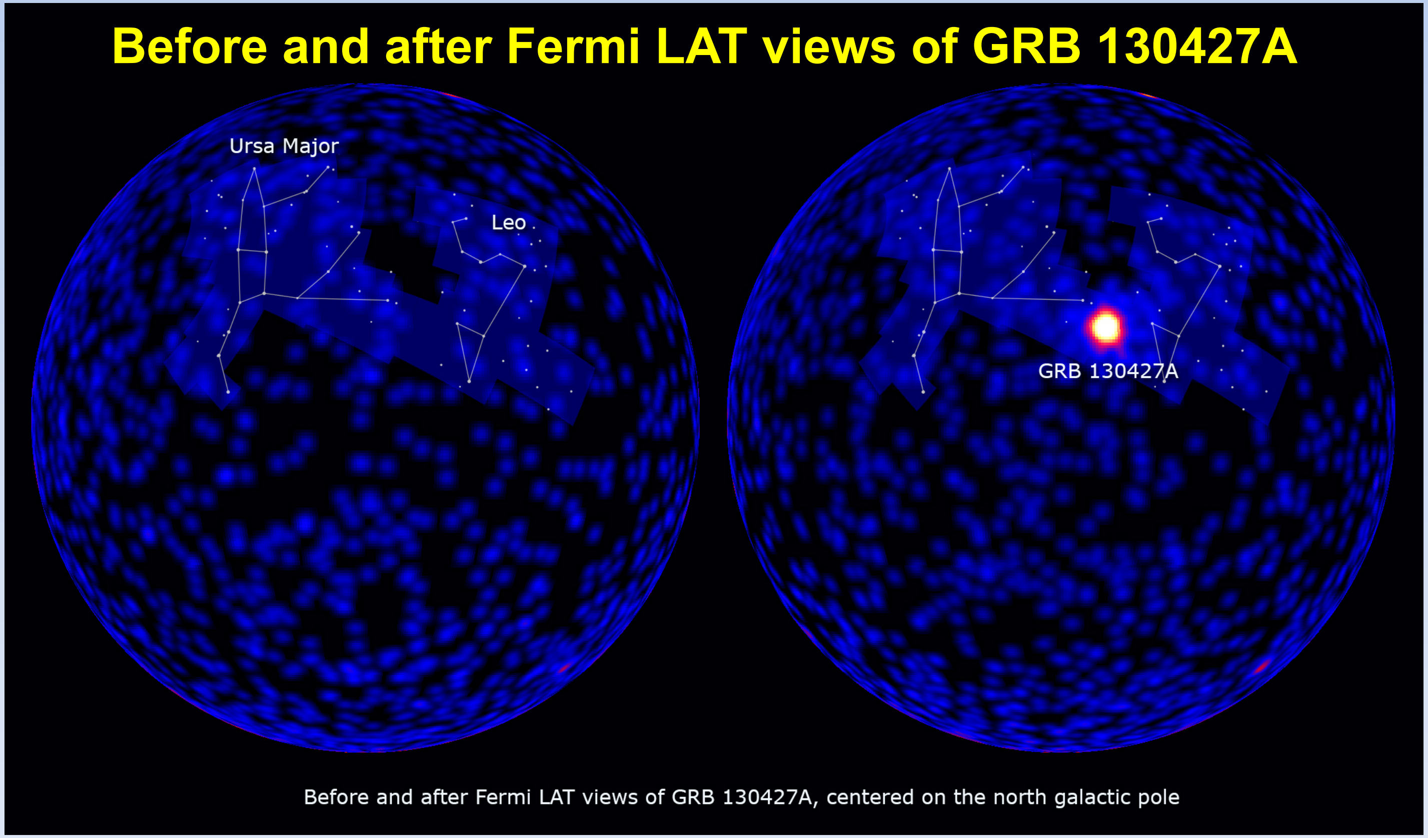
Table 1 Realistic number of NS-NS (BNS) mergers expected to be detected in the next years by second- (2020+) and third- (2030+) generation GW detectors and the expected number of electromagnetic counterparts as short GRBs (collimated) and X-ray isotropic emitting counterparts (see, e.g., Ciolfi and Siegel 2015b; Rezzolla and Kumar 2015) with THESEUS SXI and XGIS. BNS horizon indicates the GW detector sensitivity distance for face-on BNS systems (see, e.g., Abadie et al. 2010a). The rate of GW+GRB takes into account a combination of collimation angle range, XGIS FoV as a function of energy, and possible prompt off-axis detection. X-ray counterpart rate estimates assume that at least 1/3 of BNSs produce a long-lived NS remnant (but see Gao et al. 2016; Piro et al. 2017).

GW observations			THESEUS XGIS/SXI joint GW+EM observations		
Epoch	GW detector	BNS horizon	BNS rate (yr^{-1})	XGIS/sGRB rate (yr^{-1})	SXI/X-ray isotropic counterpart rate (yr^{-1})
2020+	Second-generation (advanced LIGO, Advanced Virgo, India-LIGO, KAGRA)	~400 Mpc	~40	~0.5-5	~1-3 (simultaneous) ~6-18 (+follow-up)
2030+	Second + Third-generation (e.g. ET, Cosmic Explorer)	~15-20 Gpc	>10000	~15-25	≳100

Kilonova/macronova, off-axis SGRBs/“orphan” afterglows more promising EM counterparts of NS-NS / NS-BH GW events

What is a Gamma-Ray Burst?

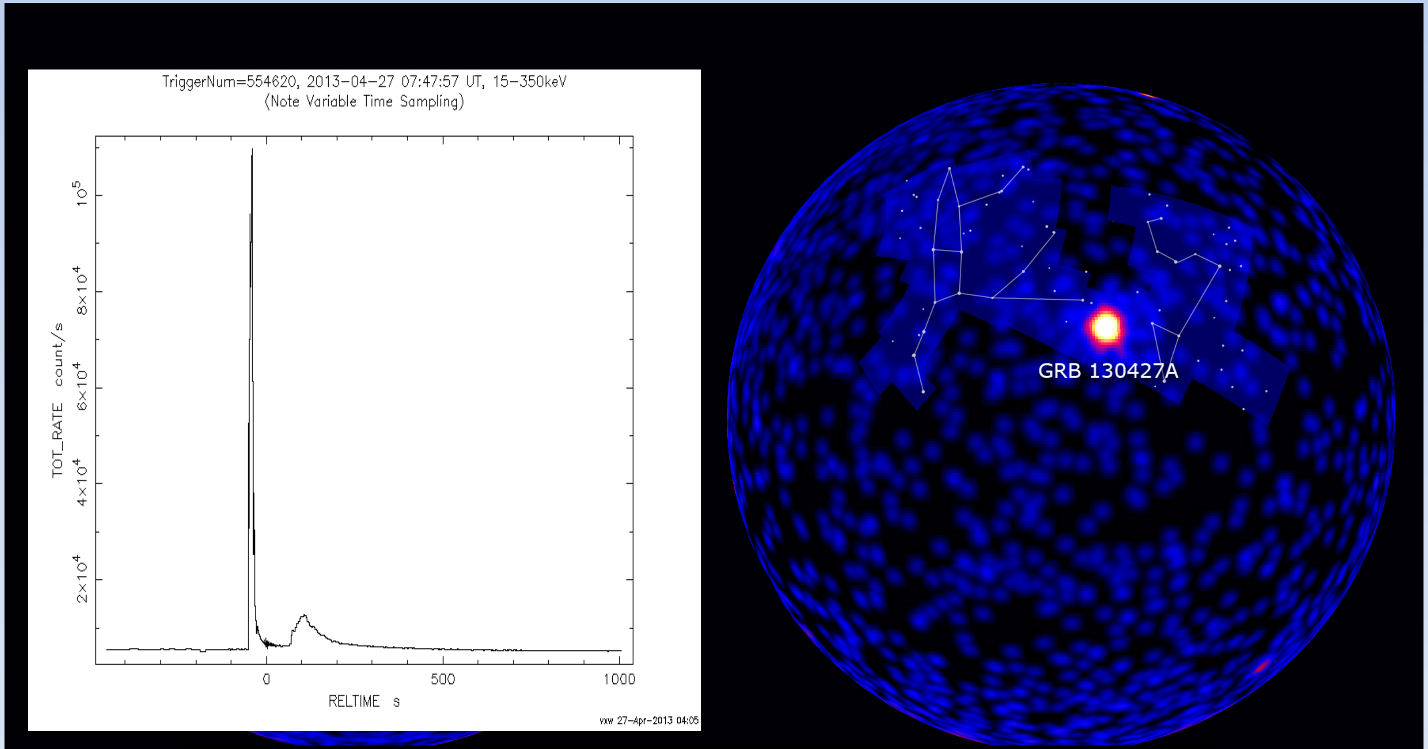
Brief, sudden, intense flash of gamma-ray radiation



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

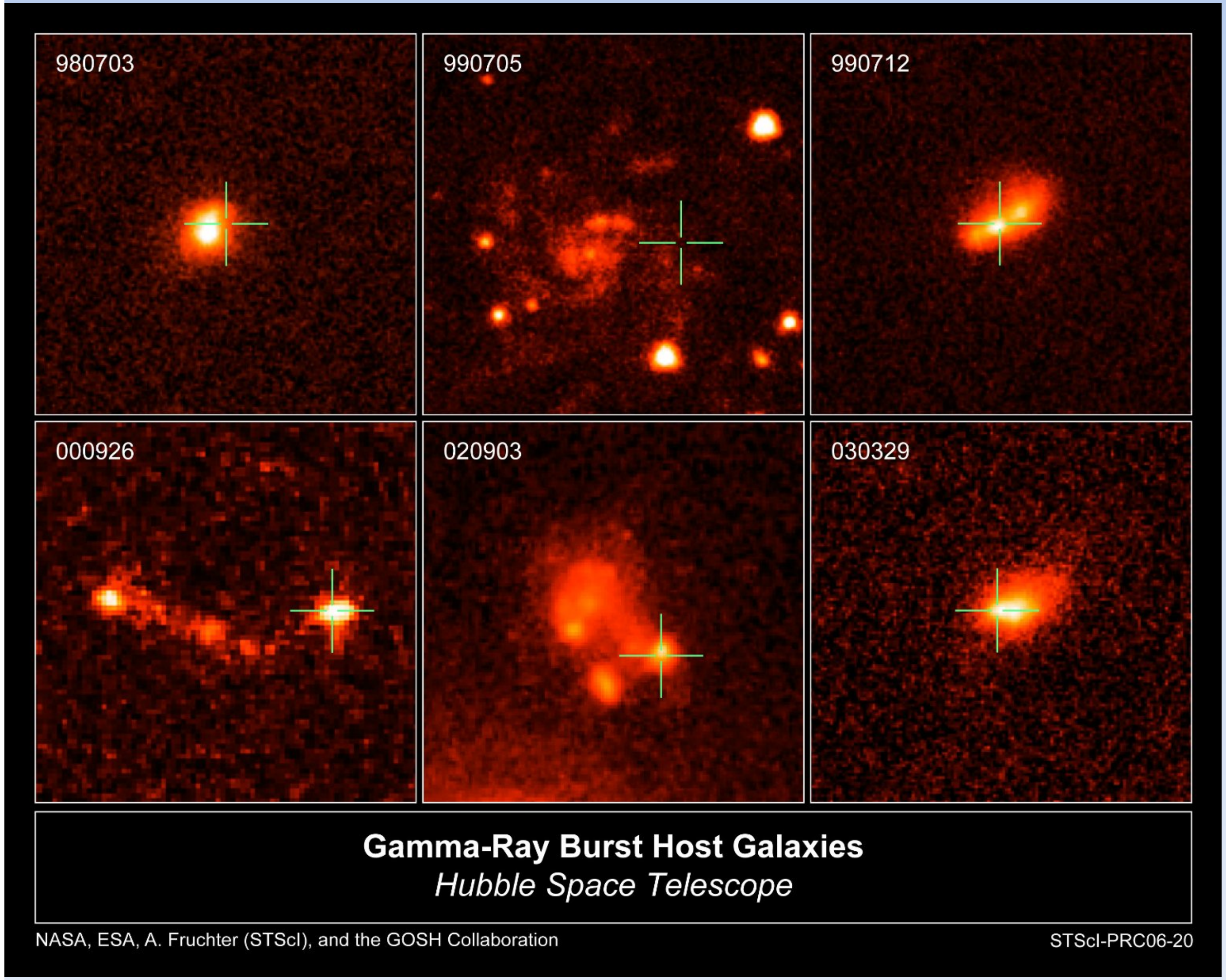
What is a Gamma-Ray Burst?

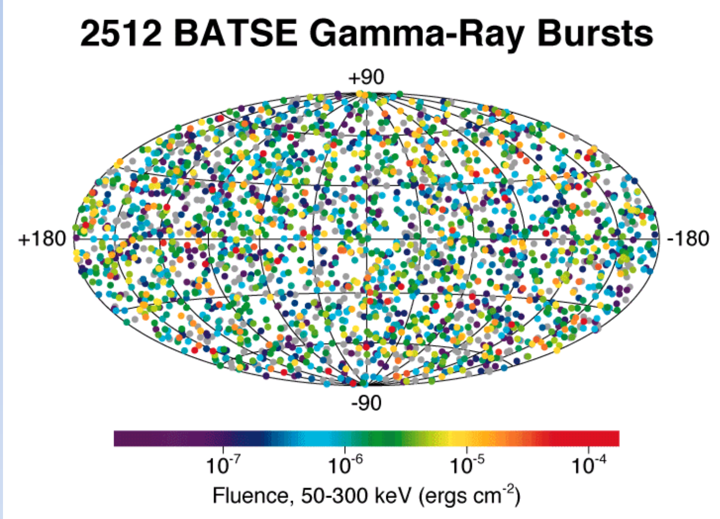
Brief, sudden, intense flash of gamma-ray radiation



Duration: **from few ms to hundreds of s**
Frequency: **10 keV – 1 MeV (and more)**
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**

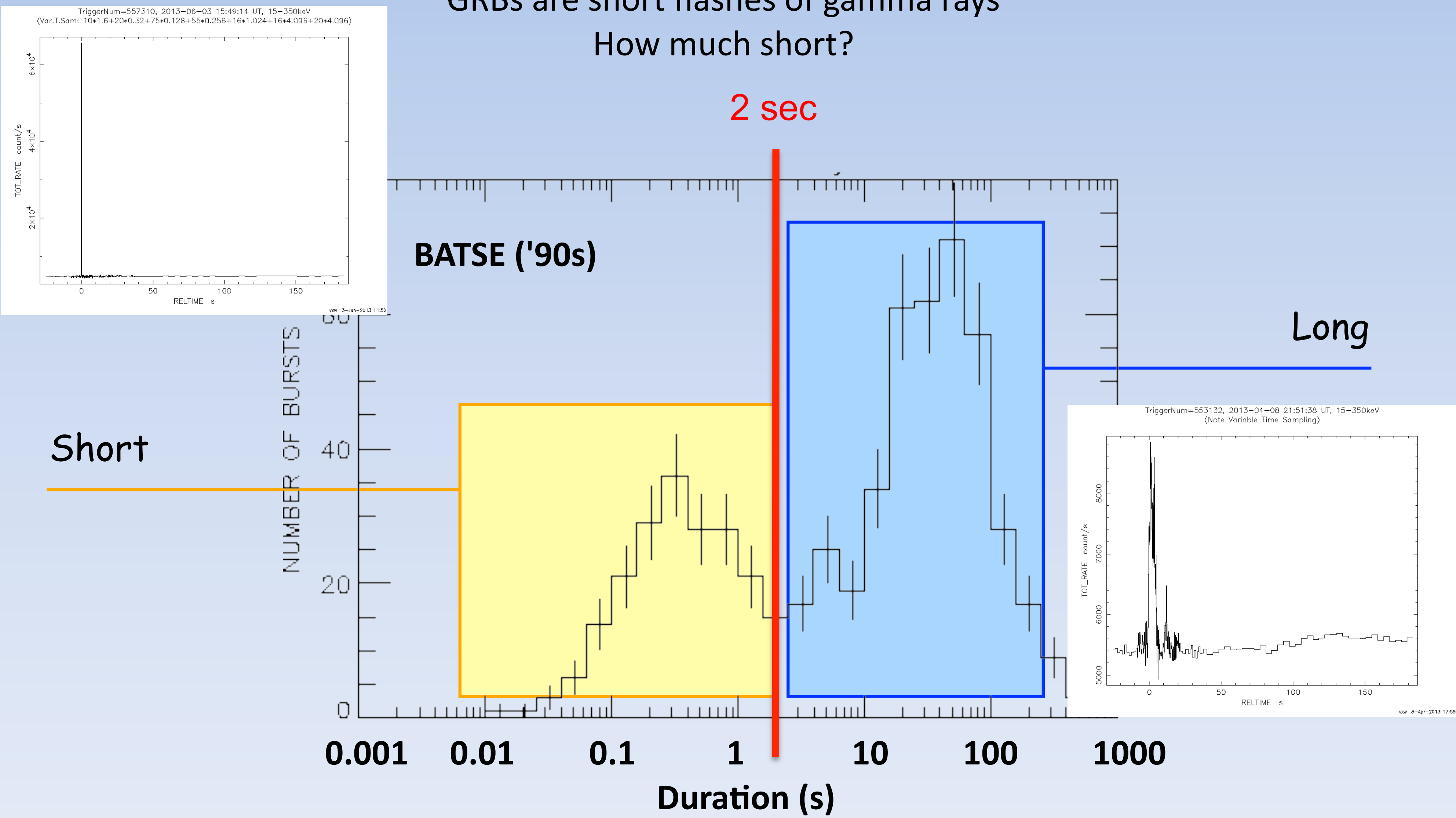
↓

Energy: ~ 10^{53} erg

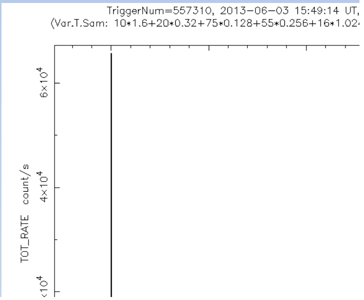
Like the energy emitted by our Galaxy in 10 years

Two flavors of GRBs

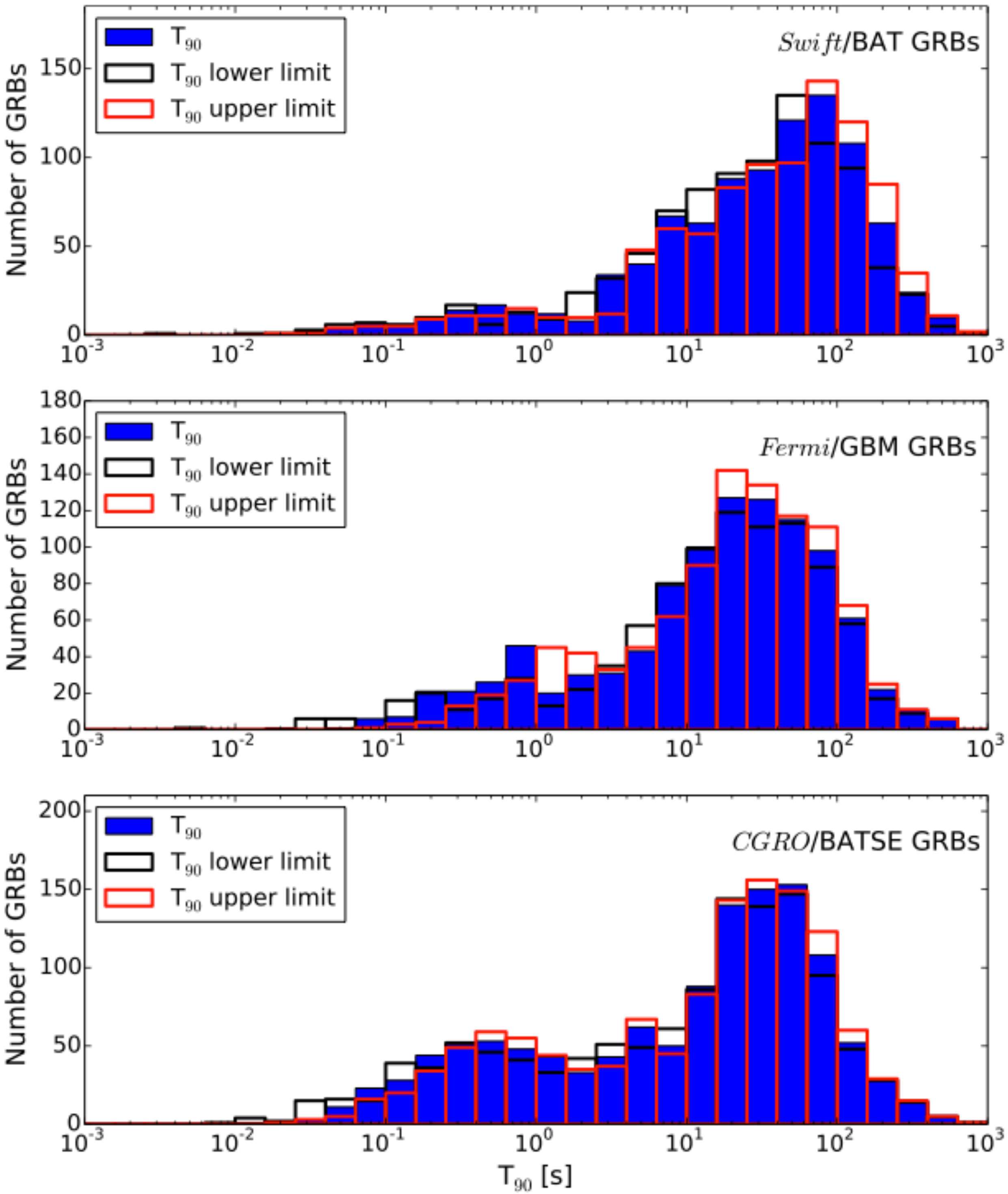
GRBs are short flashes of gamma rays
How much short?

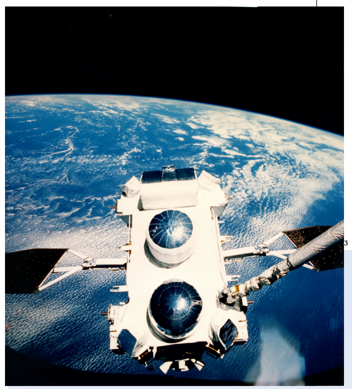


Kouveliotou et al. 1993



Paciesas+99
Gruber+14
Von Kienlin+14
Bhat+16
Lien+16





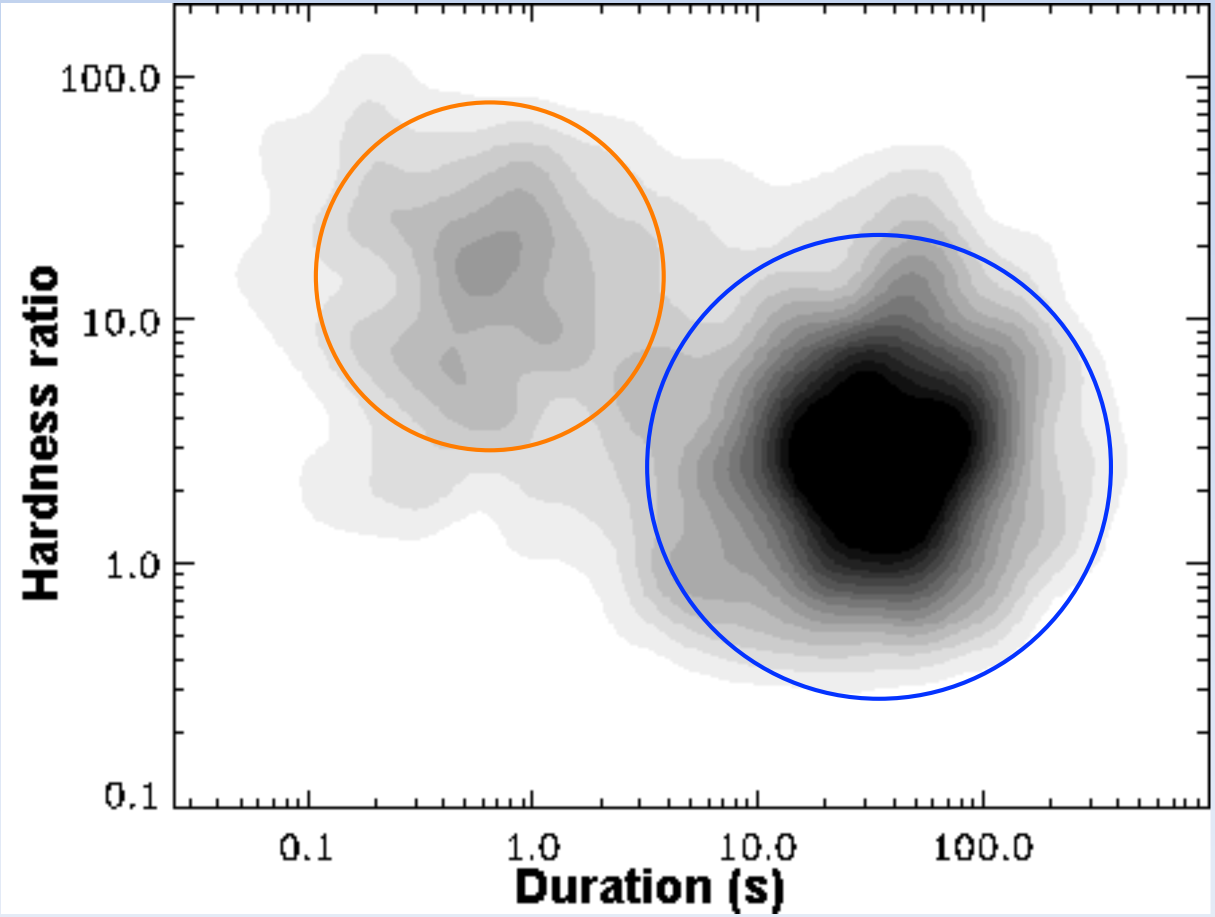
tou et al. 1993

Another angle

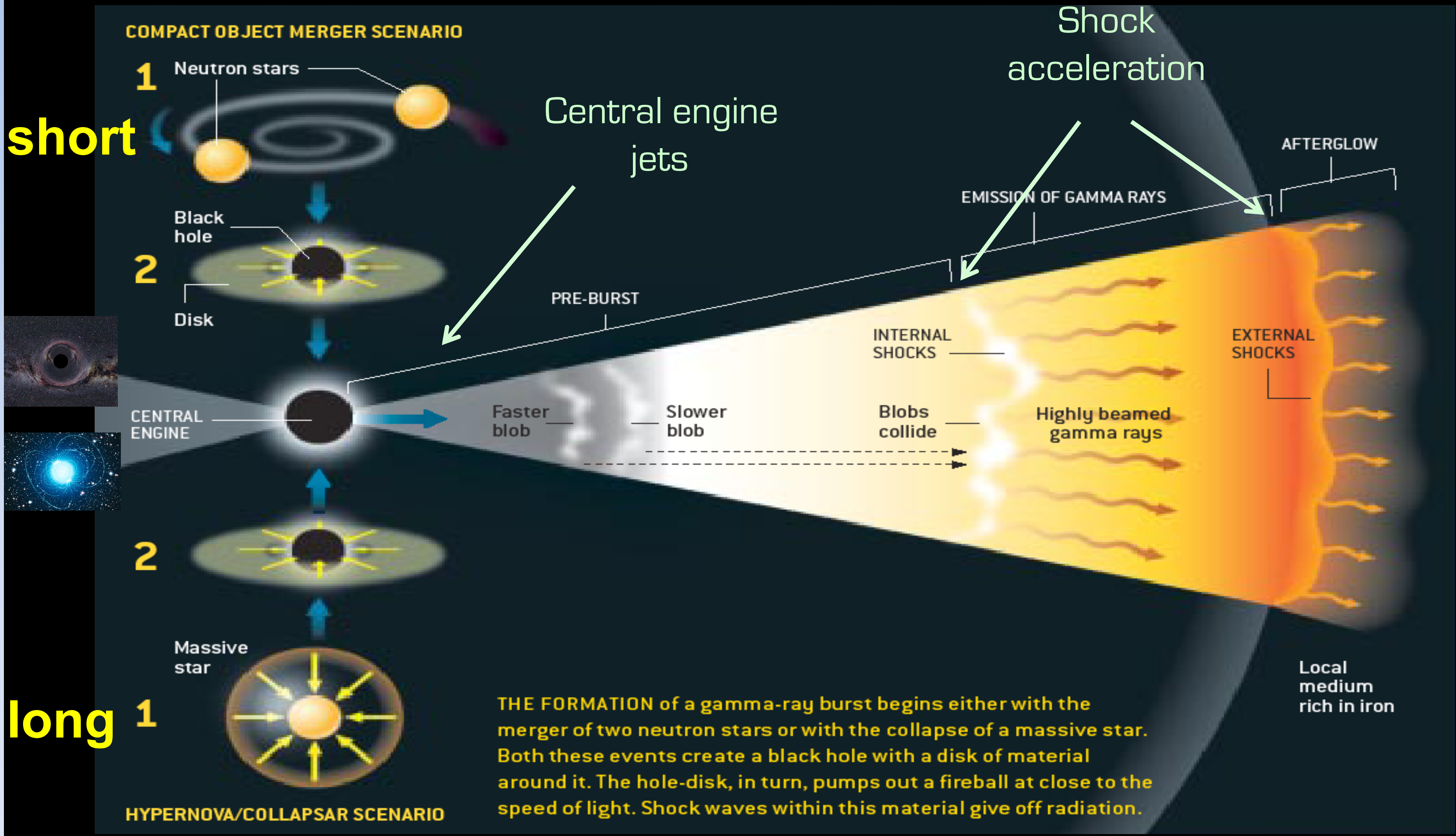
Hardness ratio: $HR = \frac{\text{countrate(hard)}}{\text{countrate(soft)}}$

Paradigm:

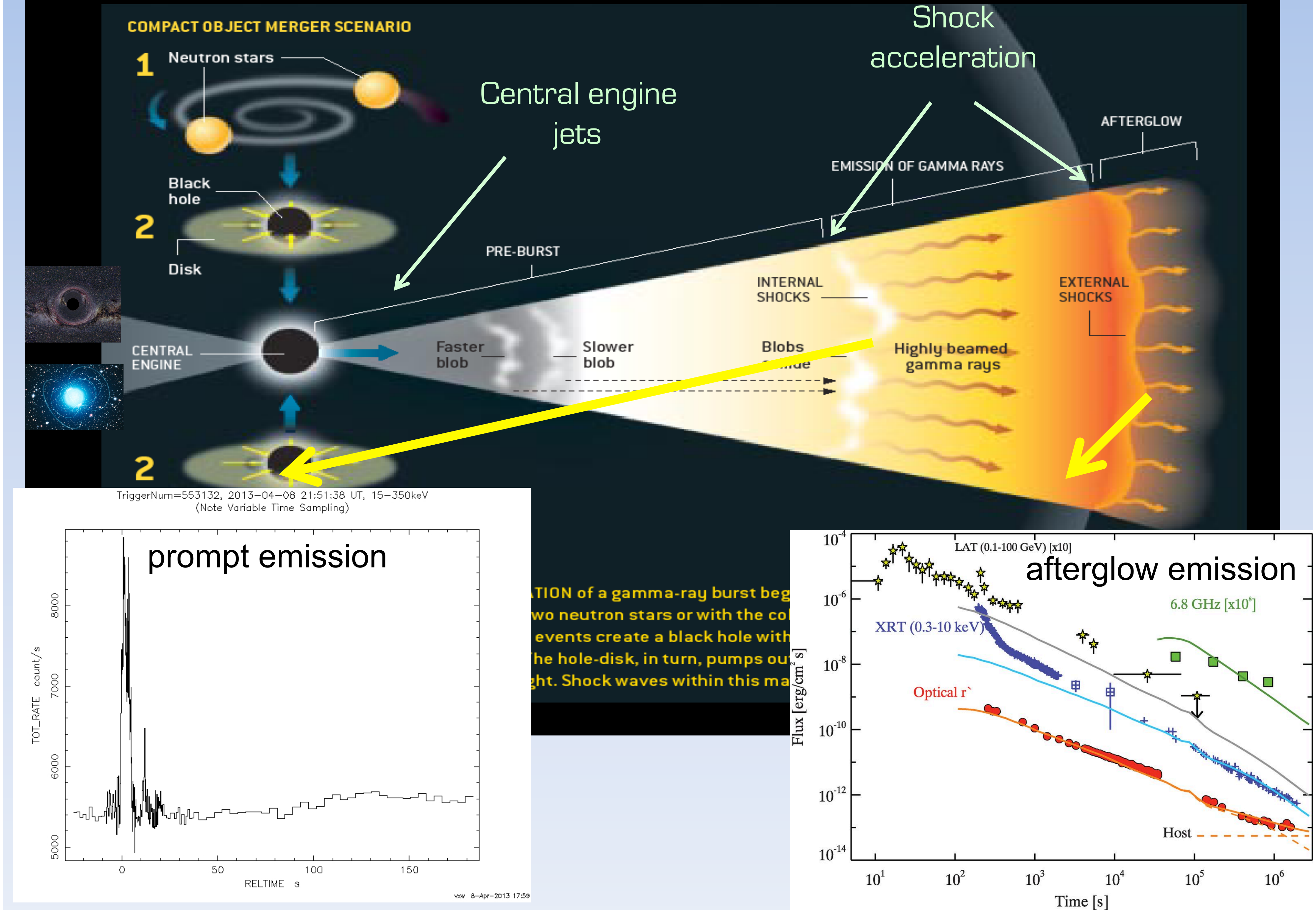
Long/soft
Short/hard

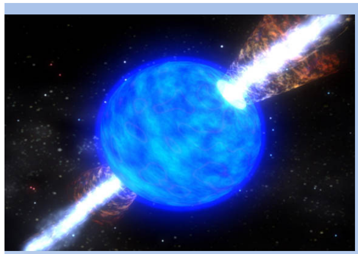


The standard model

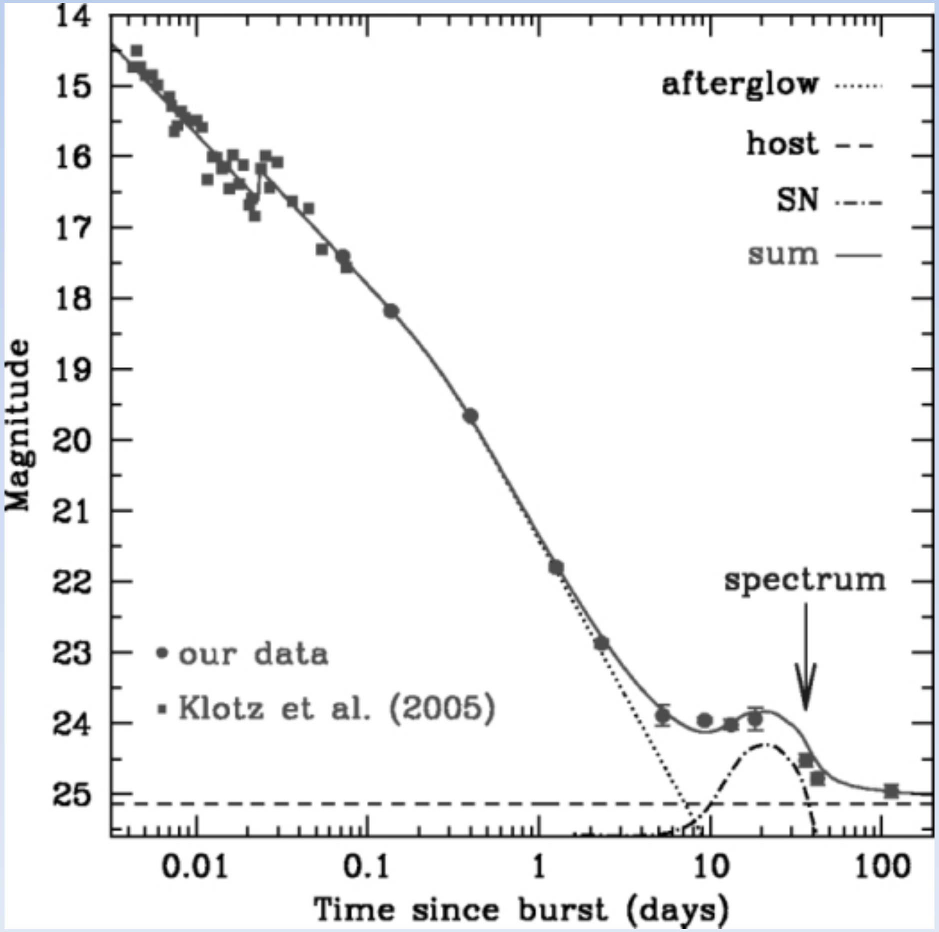


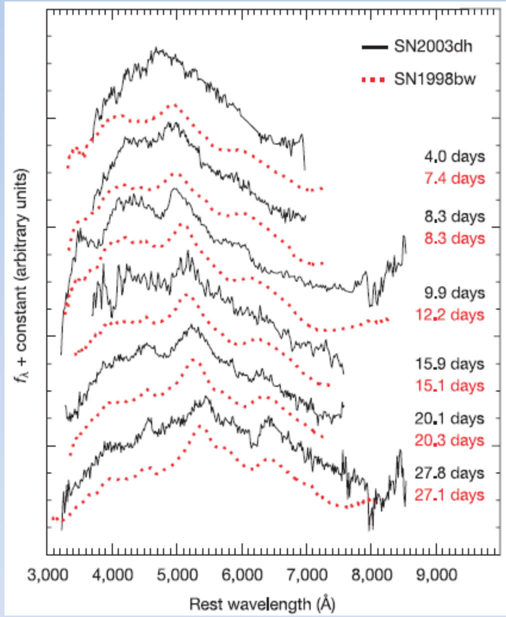
The standard model

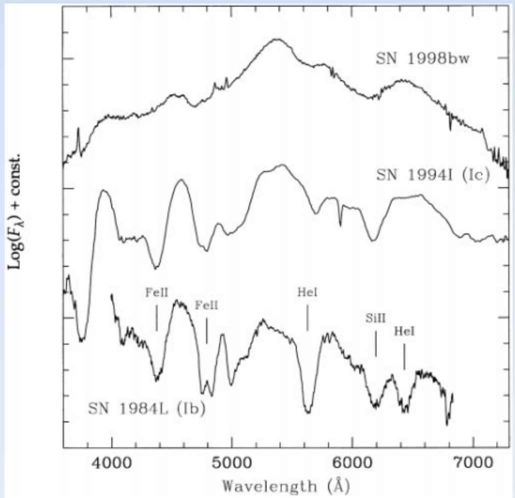




Long GRB & Supernovae

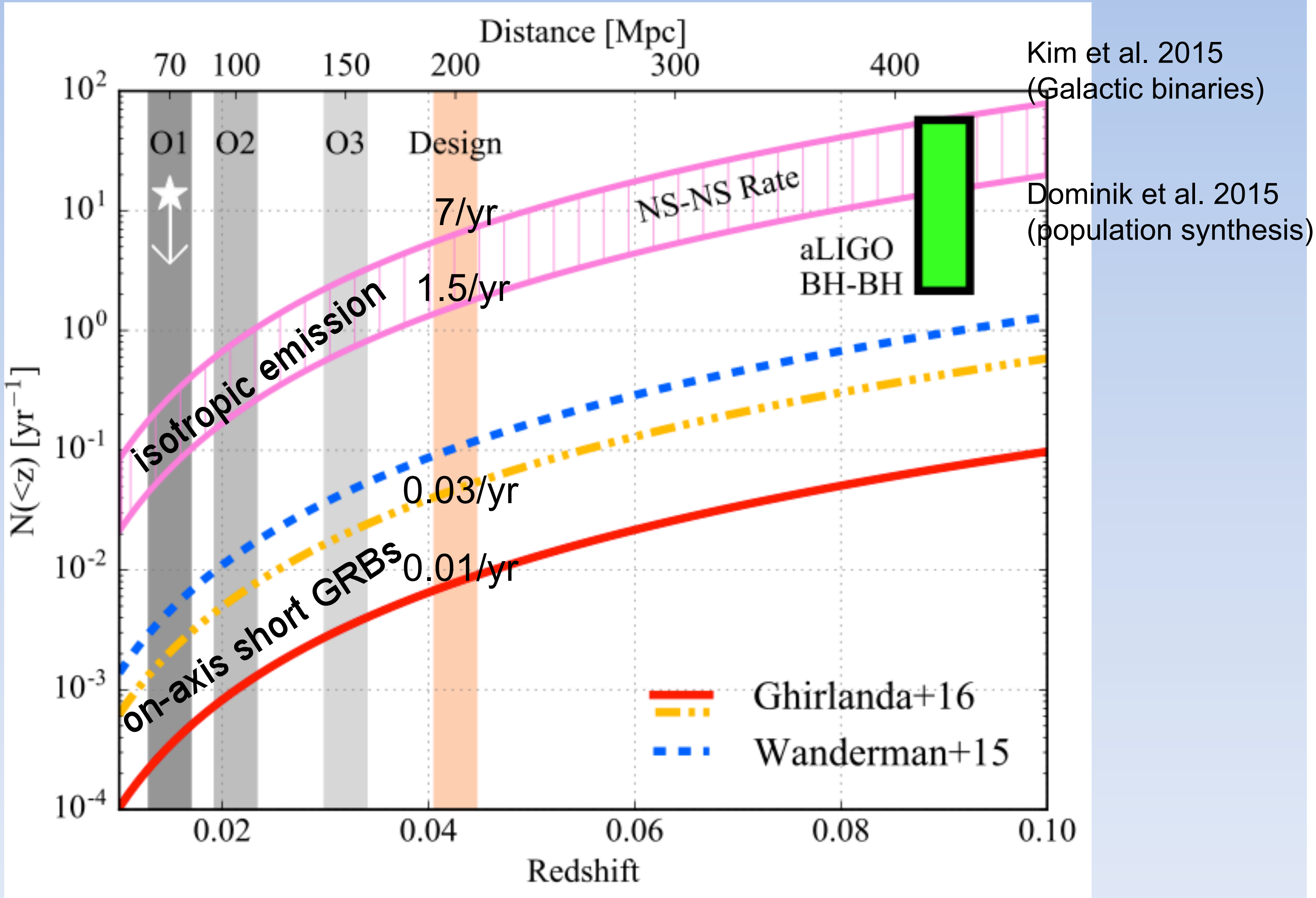






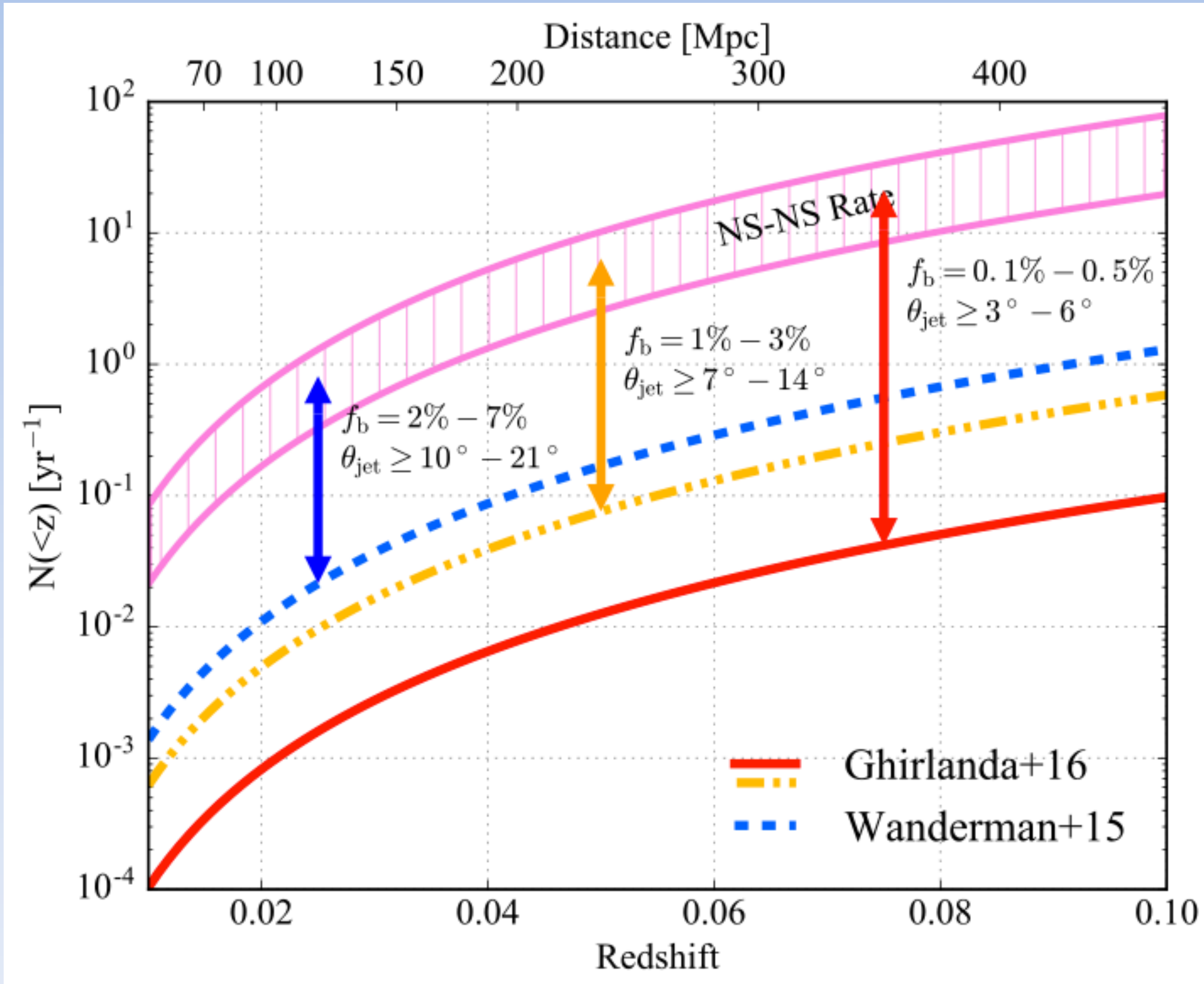
Galama et al. 1998; Stanek et al. 2003; Hjorth et al. 2003; Della Valle et al. 2003; Malesani et al. 2004; Soderberg et al. 2005; Pian et al. 2006; Campana et al. 2006; Della Valle et al. 2006, Bufano et al. 2012, Melandri et al. 2012, Schulze et al. 2014, Melnadri et al. 2014 and others…

Short GRB rate: forthcoming LIGO-Virgo runs

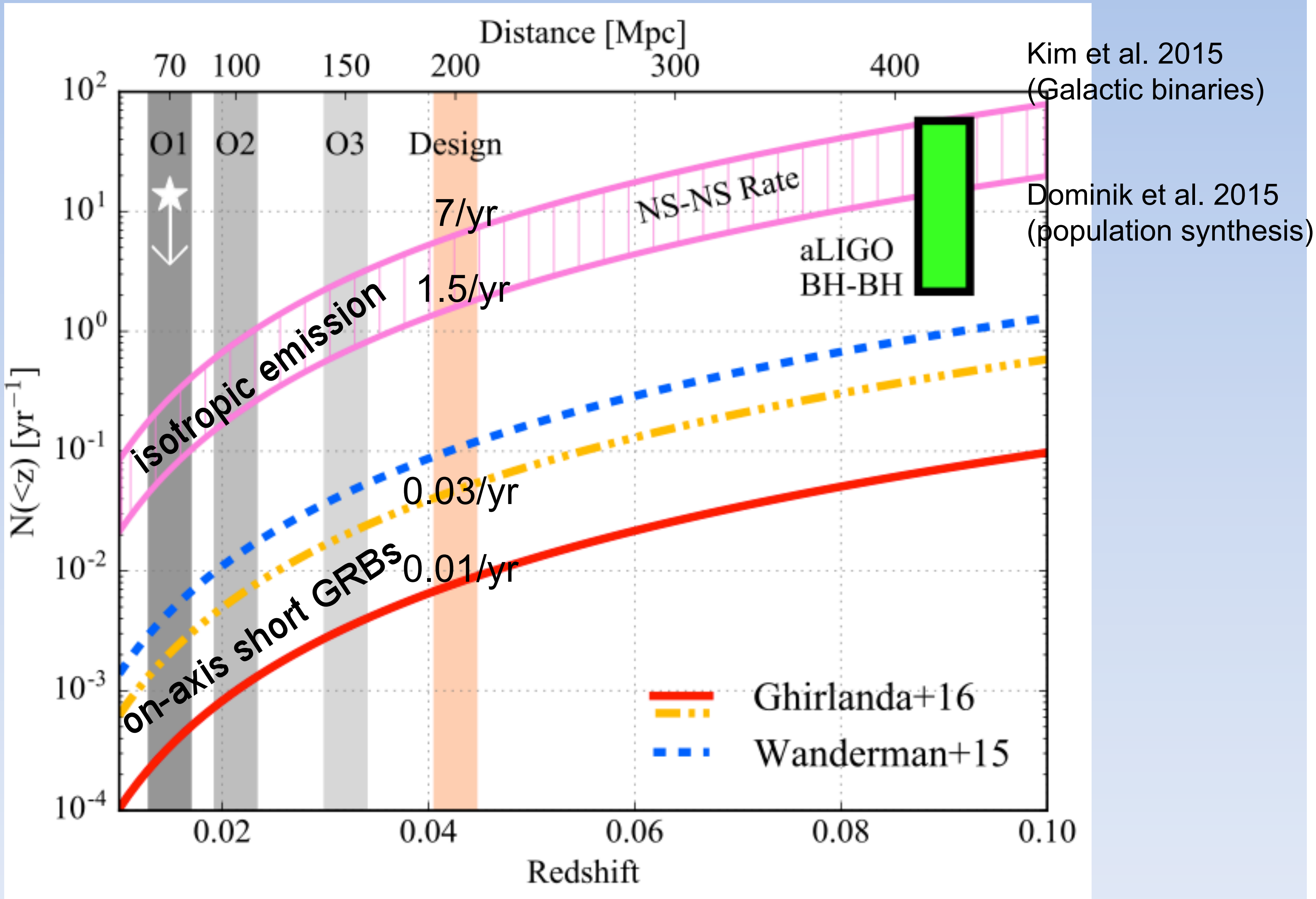


On-axis SGRB rate in the local Universe inferred from the SGRB luminosity function and redshift distribution (Ghirlanda et al. 2016)

Short GRB rate: forthcoming LIGO-Virgo runs



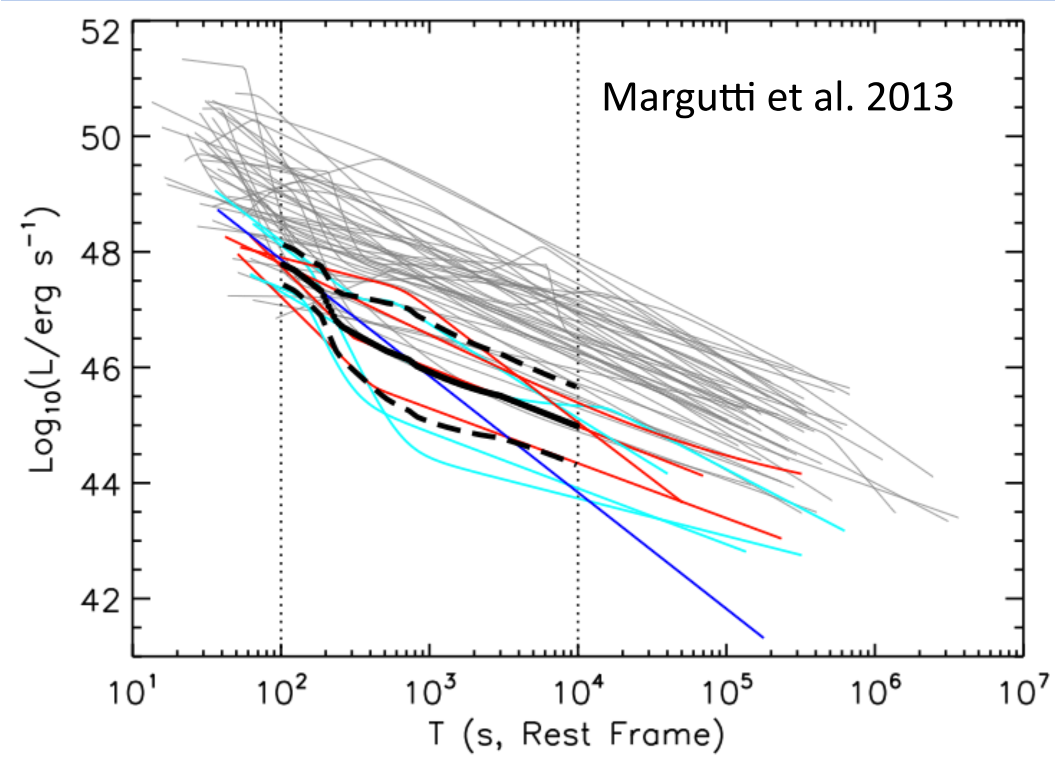
Short GRB rate: forthcoming LIGO-Virgo runs



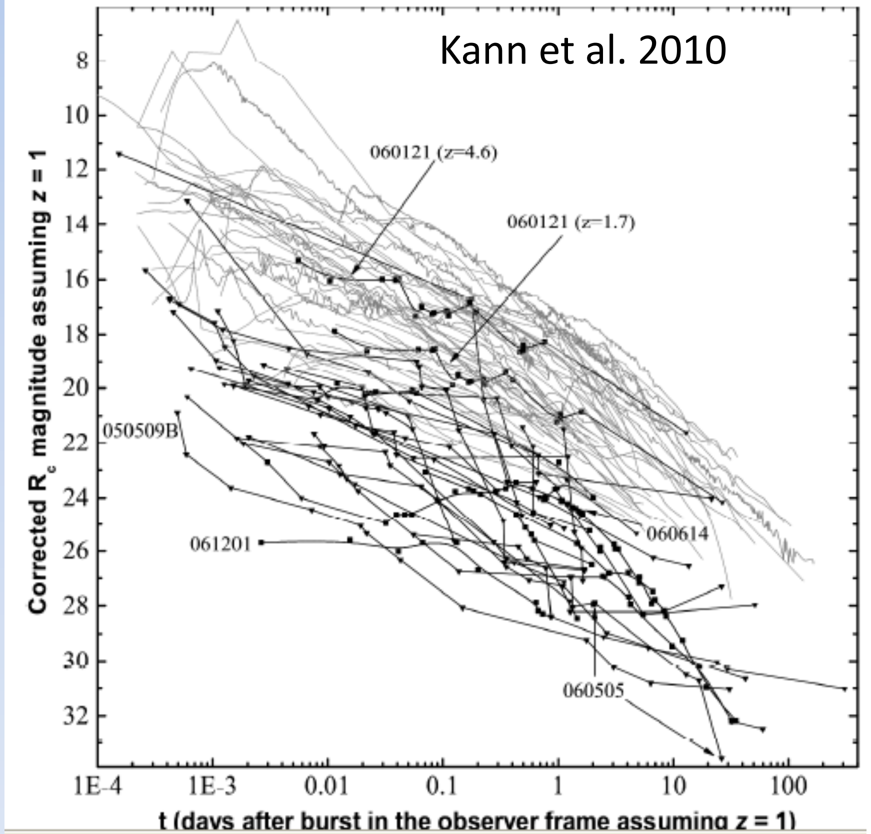
Kilonova/macronova, off-axis SGRBs/“orphan” afterglows more promising EM counterparts of NS-NS / NS-BH GW events

Short *vs.* long GRBs: the afterglow emission

Rest frame X-ray luminosity



optical



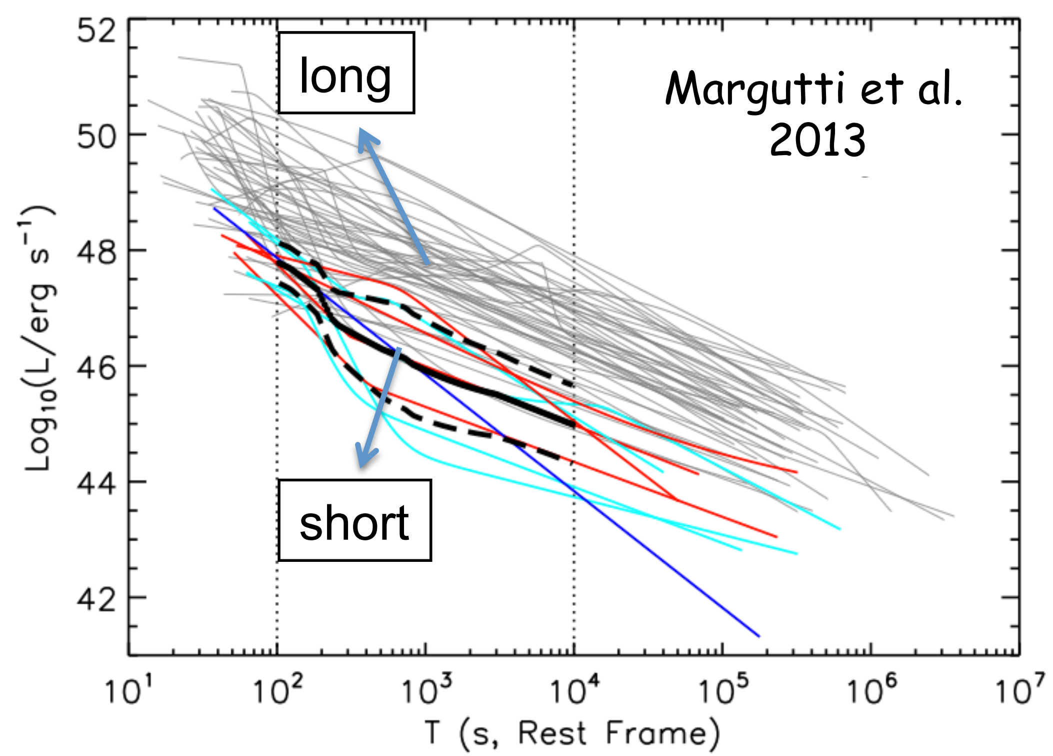
Short GRBs afterglows are fainter:

- less dense environment?

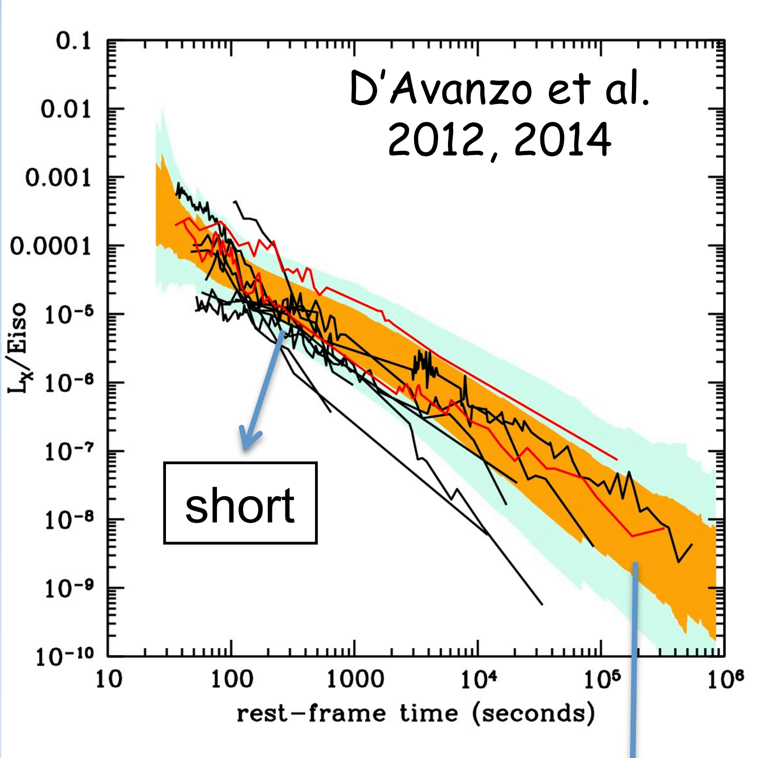
- less energetic?

Short *vs.* long GRBs: the afterglow emission

Rest frame X-ray luminosity



Rest frame X-ray luminosity normalized to Eiso



The afterglow X-ray luminosity is a good proxy of Eiso for both long and short GRBs

1sigma scatter for long GRBs

The GW era – O1 & O2

Sept 2015 – Jan 2016: LVC O1 science run

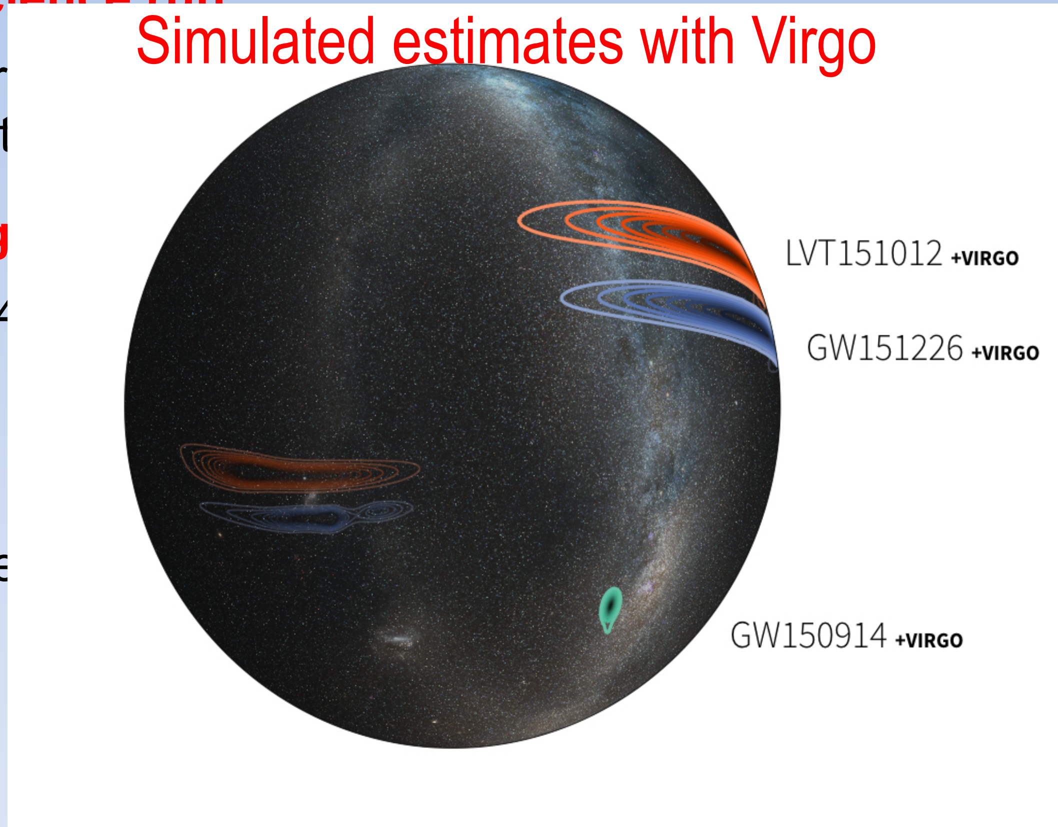
2 high-significance (FAR < 1/centur ... 226)
+ 1 possible, low-significance event

LVC O2

Another ...
follow-up

Sky ...

600 deg^2 GW 150914
1600 deg^2 LVT 151012
1000 deg^2 GW 151226



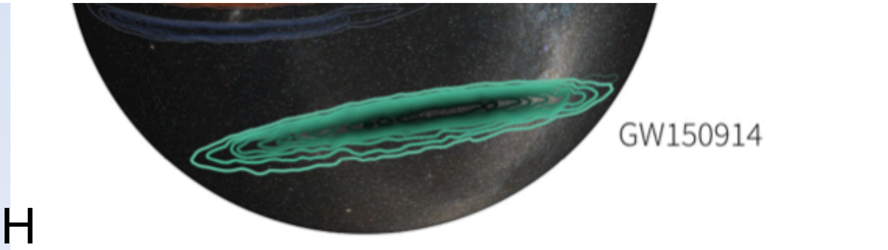


Image credit: LIGO/L. Singer/A. Mellinger

No EM counterpart found
(despite huge observational effort)

No significant EM emission expected from BBH
EM emission expected for NSNS and/or NSBH