Electromagnetic follow-ups of GW events

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On behalf of the
LIGO scientific collaboration, Virgo collaboration & partner telescopes

Ground-based GW detectors

LIGO Hanford
(4km - USA)

LIGO Livingston
(4km -USA)

Virgo (3km - Italy)

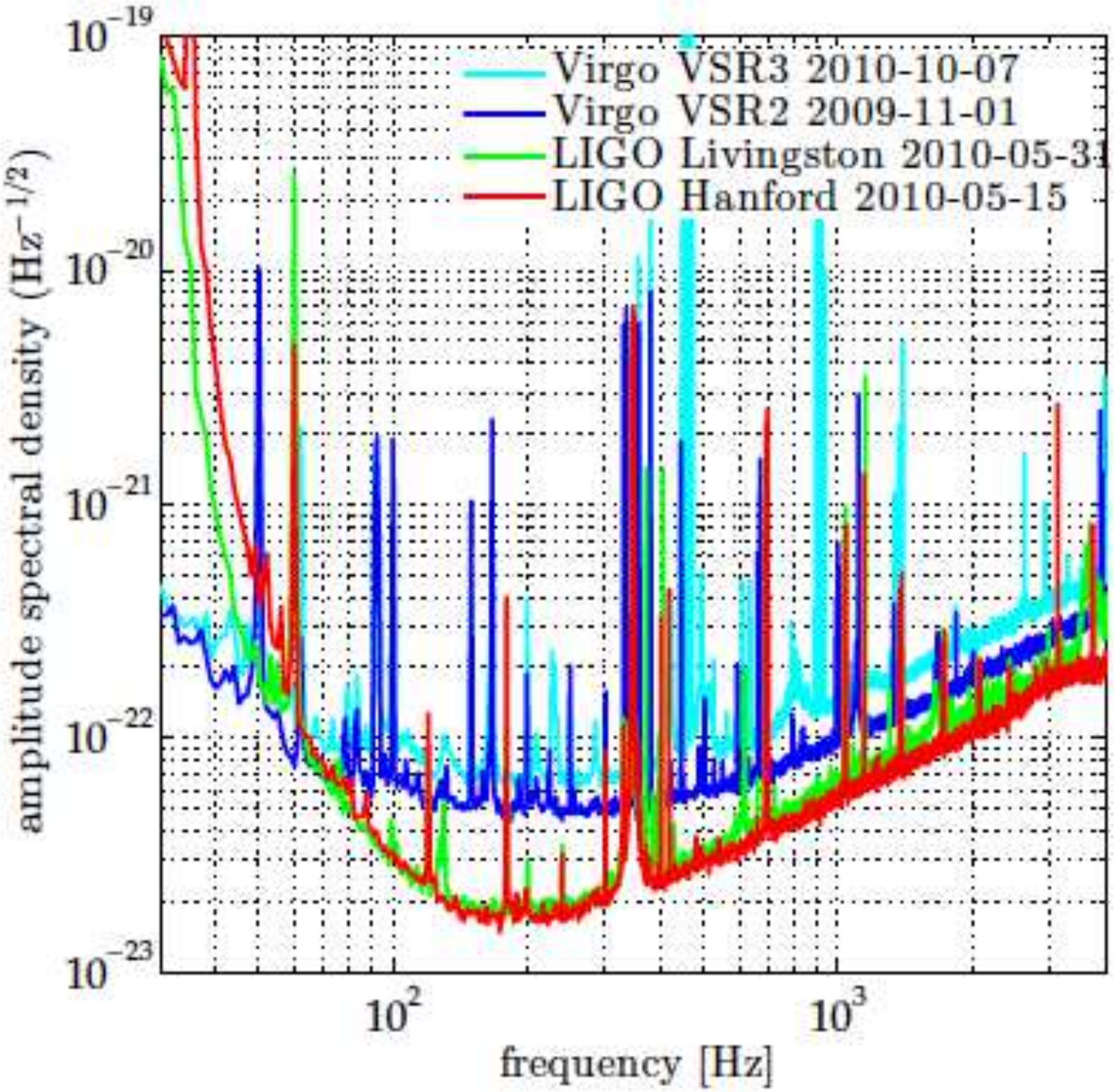
GEO (600m - Germany)

But also:

- Kamioka cryogenic GW detector (KAGRA **Kawai's talk**)

- Possibly LIGO India

LIGO – Virgo sensitivity (latest runs)



LIGO and Virgo detectors reached comparable sensitivities during the latest runs.

Joint EM-GW studies

EM → GW

e.g. GRBs, SGR flares, core collapse supernovae, pulsar glitches, …

- ☐ Known event time and sky position: deeper GW search.
- ☐ Event type suggests what kind of GW signal to look for: e.g. burst, chirp, longer duration GW, …
- ☐ EM data may suggest signal parameters (e.g. GRB opening angle).

GW → EM

EM follow-up observations (prompt and/or delayed) of (at least) triple coincident LIGO-Virgo triggers

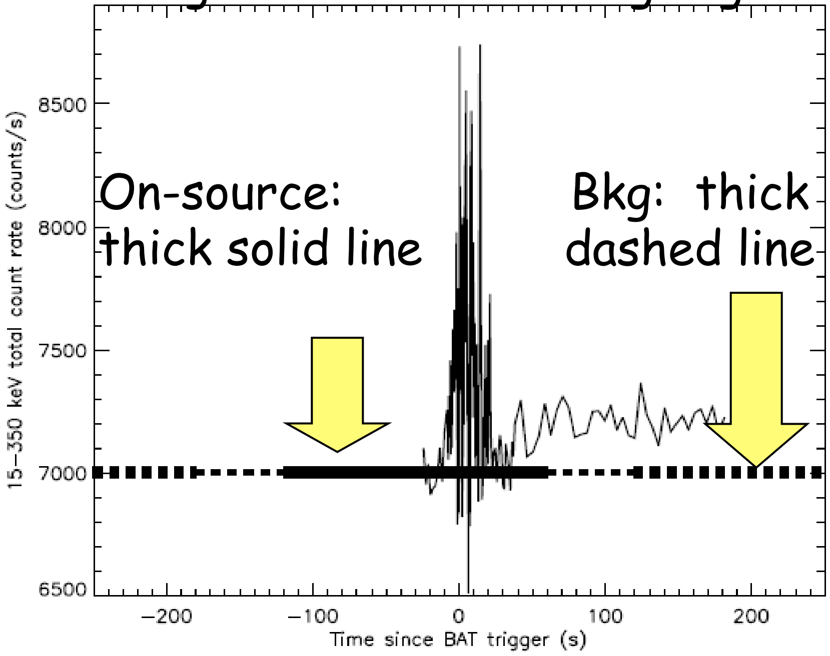
- ☐ May catch counterpart that would have been missed (e.g., off-axis GRBs), or detected only on longer timescales.
- ☐ Allows lowering threshold/enhancing confidence in GW detection.

LIGO-Virgo EM triggered searches: e.g. GRBs

Triggered searches: ~2x improvement in sensitivity with respect to un-triggered (e.g., Kochanek & Piran 1993; Abadie et al. 2010, Phys. Rev. D, 81, 102001,Abadie et al. 1205.2216v1)

See Was' talk.

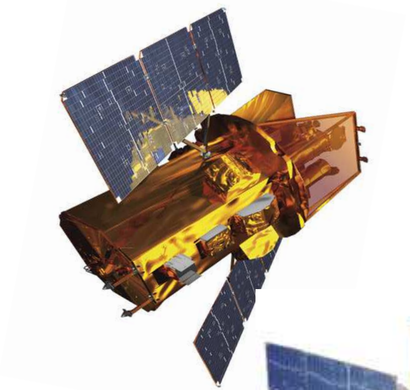
Long GRB on-source/bkg region



On-source: thick solid line

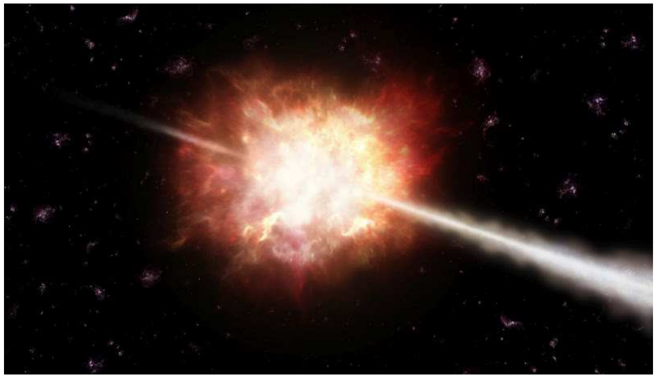
Bkg: thick dashed line

Acernese et al. 2008, CQG, 25, 225001

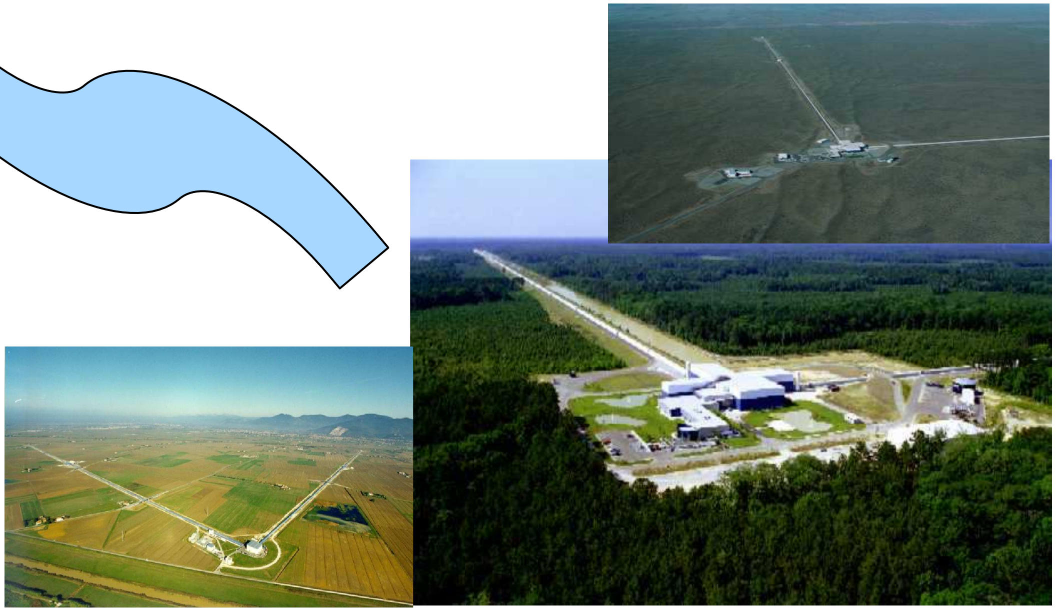


On source time window:

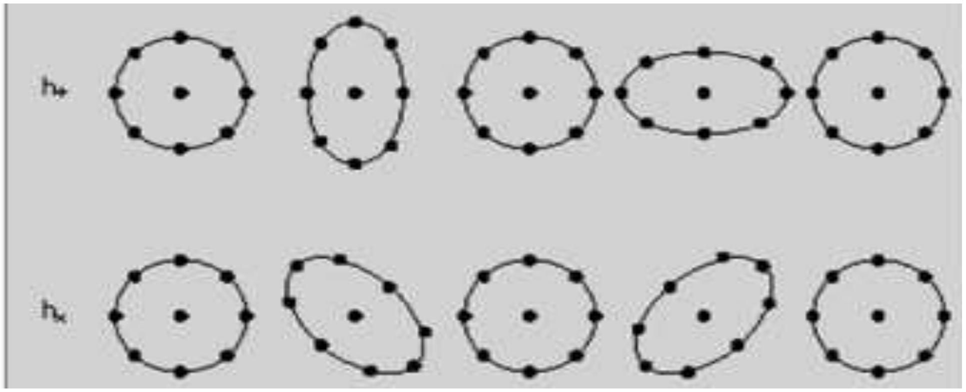
- Typically 2min before, 1 min after GRB
- Extended to -600s to cover precursors
- -5s to +1s for short GRBs



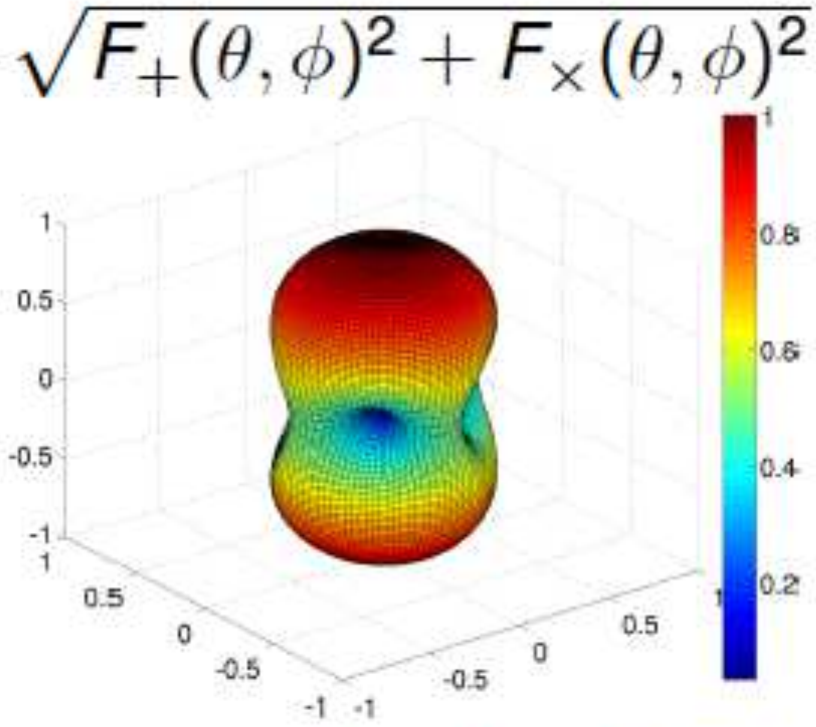
Reversing the chain:
EM follow-up of GW triggers



Single IFO directional sensitivity

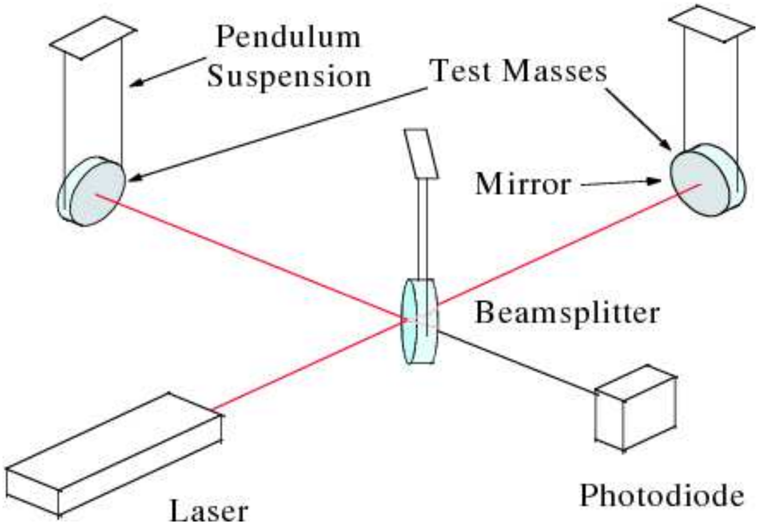


- GWs change the distance between free falling masses as measured by a light beam, thus changing the amount of light collected on the output photodetector.
- IFO response greater than half-maximum over 65% of sky.

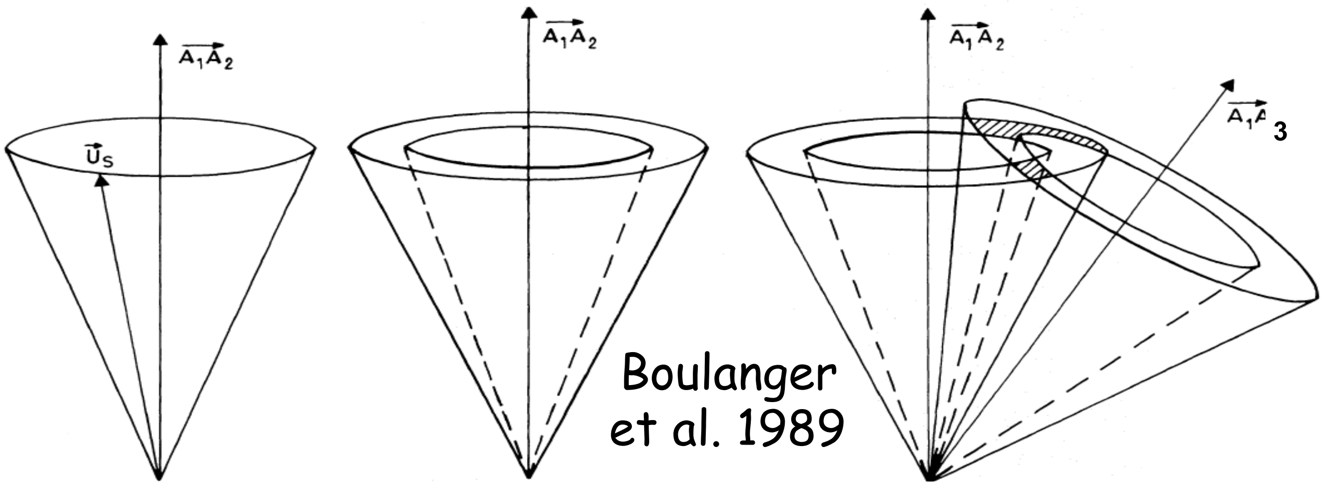


$$\sqrt{F_+(\theta,\phi)^2 + F_\times(\theta,\phi)^2}$$

$$\delta l / l = h(t) = F_+ h_+(t) + F_\times h_\times(t)$$



Position reconstruction needs 3 IFOs



Boulanger et al. 1989

2 IFOs (ideal) 2 IFOs, finite timing accuracy 3 IFOs, finite timing accuracy

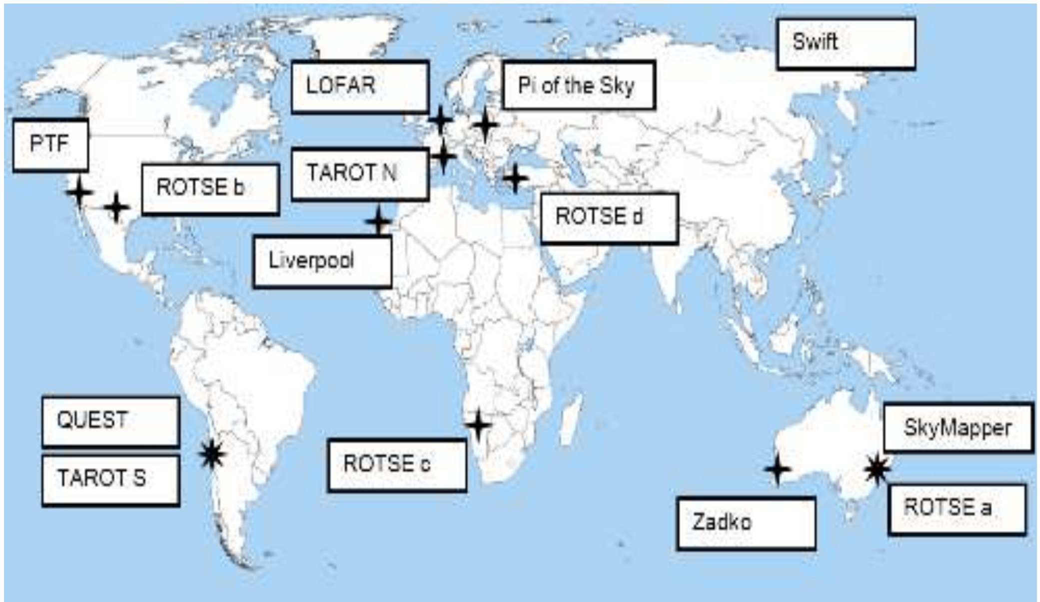
Source localization needs multiple IFOs, and uses time delays (and amplitude information).

Also: **Klimenko's talk**

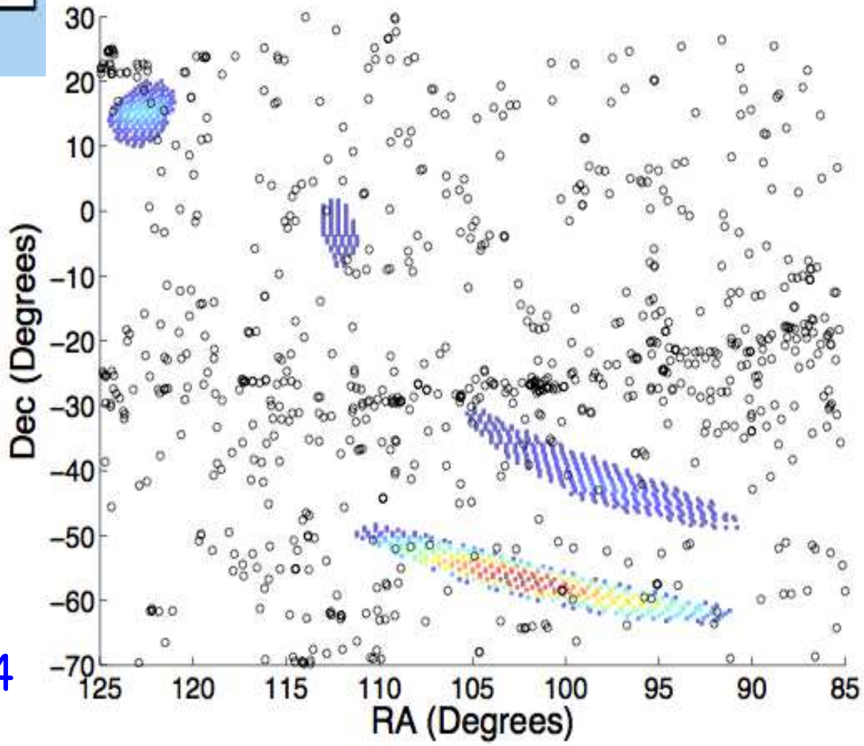
- Light travel time between IFOs in LVC network: 10-30 ms. Timing accuracy: $\sigma_t \sim (2\pi\sigma_f \mathrm{SNR})^{-1}$ where σ_f=signal effective bandwidth (Fairhurst 2009).

-E.g. BNS with SNR=7 in each of the LIGO-Virgo IFOs: $\sigma_t \sim 0.27$ ms for LIGO, $\sigma_t \sim 0.19$ ms for Virgo. Best case (signal is directly over the plane of IFOs) localization of 20 deg^2, median of 40 deg^2 (Fairhurst 2009).

"LOOC-UP" project



LOOC-UP
"Locating and Observing Optical Counterparts to Unmodeled Pulses" of GWs. Use of optical (but also X-ray/radio telescopes) for follow-ups of LIGO-Virgo triple coincidences.

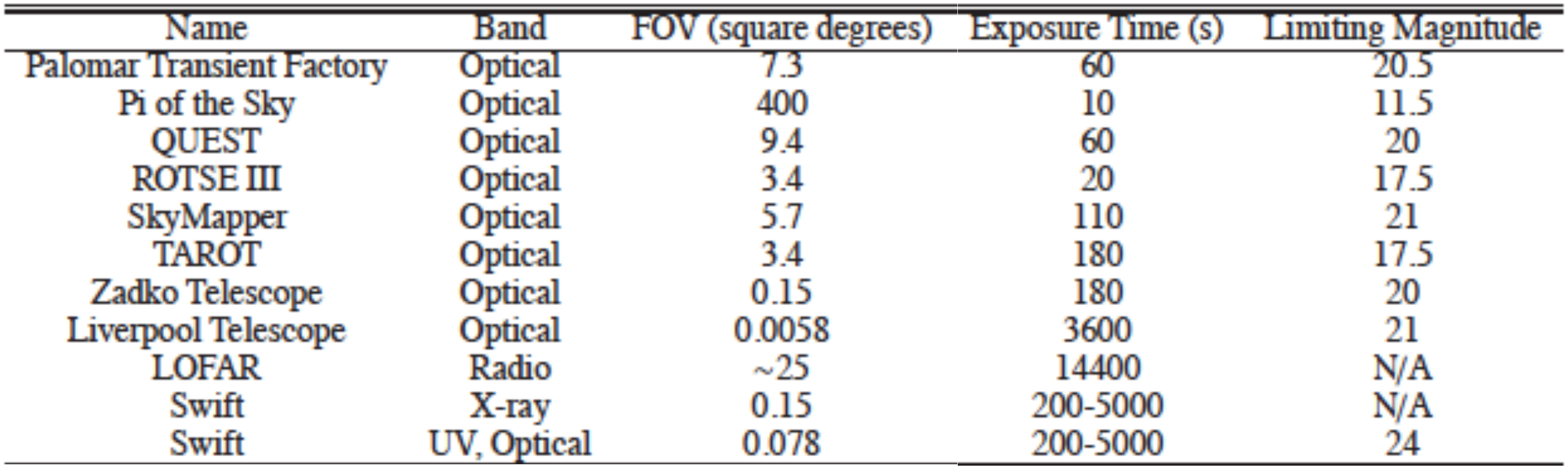


Main challenge: tens of sqr degs for GWs localization error, and error-area may spread on disjoint patches of the sky. Galaxies in the nearby Universe (<50 Mpc) used to prioritize tiles. **Kanner's talk.**

Abadie et al. 2012, A&A 539, A124

2009-2010 "LOOC-UP" runs

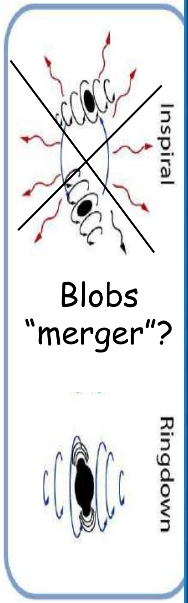
- Two looc-up runs: S6/VSR2 (17 Dec 2009 to 8 Jan 2010), S6/VSR3 (2 Sept to 20 Oct 2010)
- Alert rates:
  - S6/VSR2: 1 per day of 3-site science mode
  - S6/VSR3: 1 per 4 days of 3-site science mode (lower for Swift, PTF)
- Latency:
  - Alerts sent within ~30 min, telescopes imaged when possible
  - 9 GW candidates followed by at least one telescope
  - Follow-up typically asap (apart from daylight, weather, moon... constraints) and on one or more of later nights.



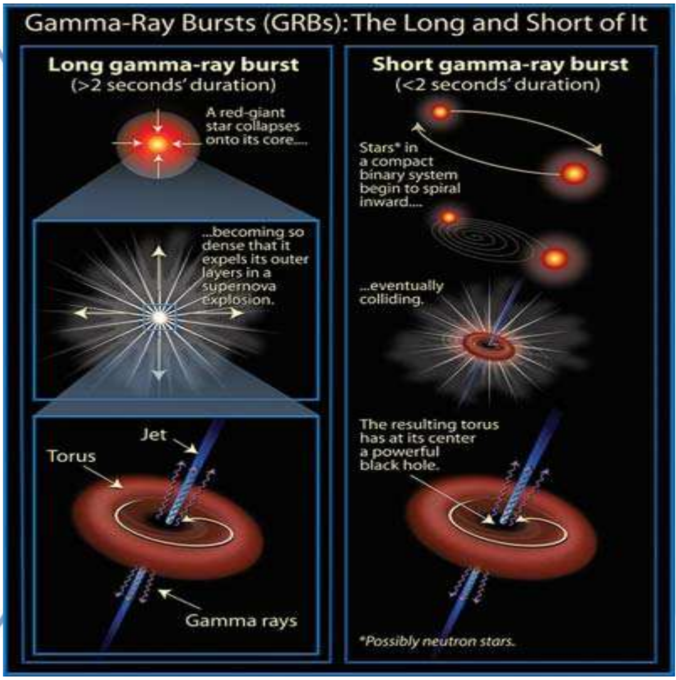
Name	Band	FOV (square degrees)	Exposure Time (s)	Limiting Magnitude
Palomar Transient Factory	Optical	7.3	60	20.5
Pi of the Sky	Optical	400	10	11.5
QUEST	Optical	9.4	60	20
ROTSE III	Optical	3.4	20	17.5
SkyMapper	Optical	5.7	110	21
TAROT	Optical	3.4	180	17.5
Zadko Telescope	Optical	0.15	180	20
Liverpool Telescope	Optical	0.0058	3600	21
LOFAR	Radio	~25	14400	N/A
Swift	X-ray	0.15	200-5000	N/A
Swift	UV, Optical	0.078	200-5000	24

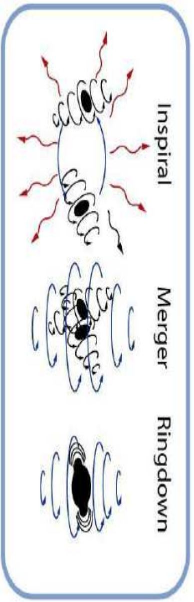
X-ray follow-ups

Multi-messenger study of GRBs

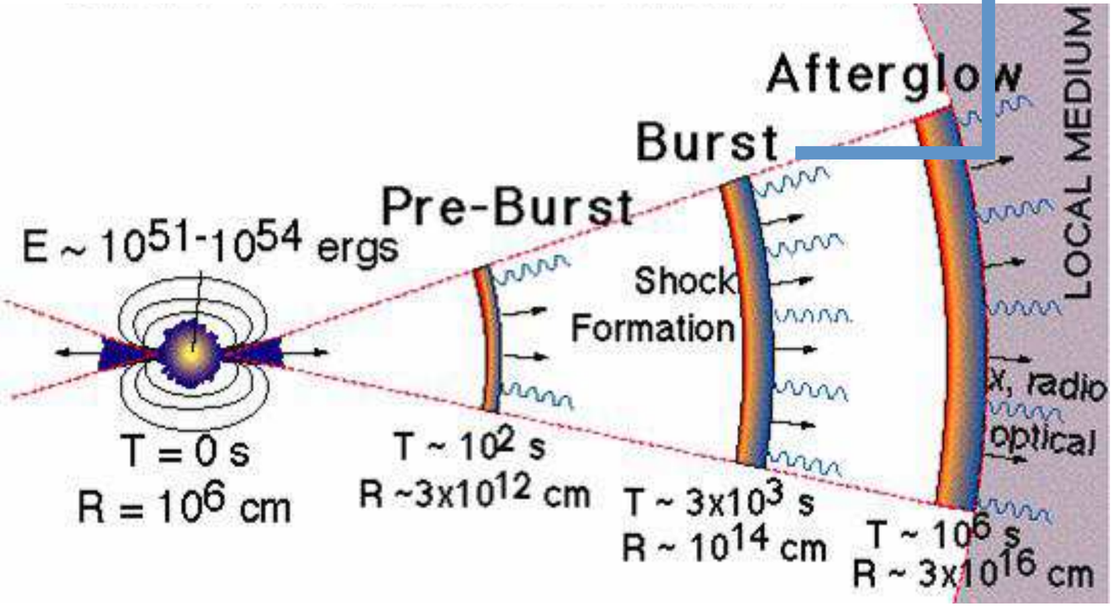


Blobs "merger"?

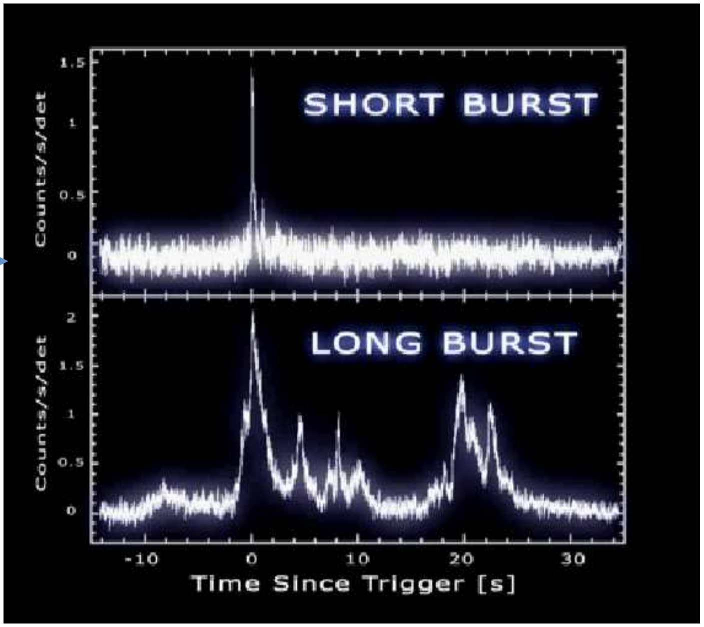




GWs emitted directly from the progenitor



Nasa image



EM signal emitted at large distances: indirect info on the progenitor

(Some) possible scenarios for GW production in GRBs

- Chirp signal (NS-NS/BH-NS binaries) in short GRBs: most promising for detection in adv LIGO/Virgo Era (e.g. Flanagan & Hughes 1998 for SNR estimates; Kochanek & Piran 1993, Abadie et al. 2010 and ref therein for GW detection rates).

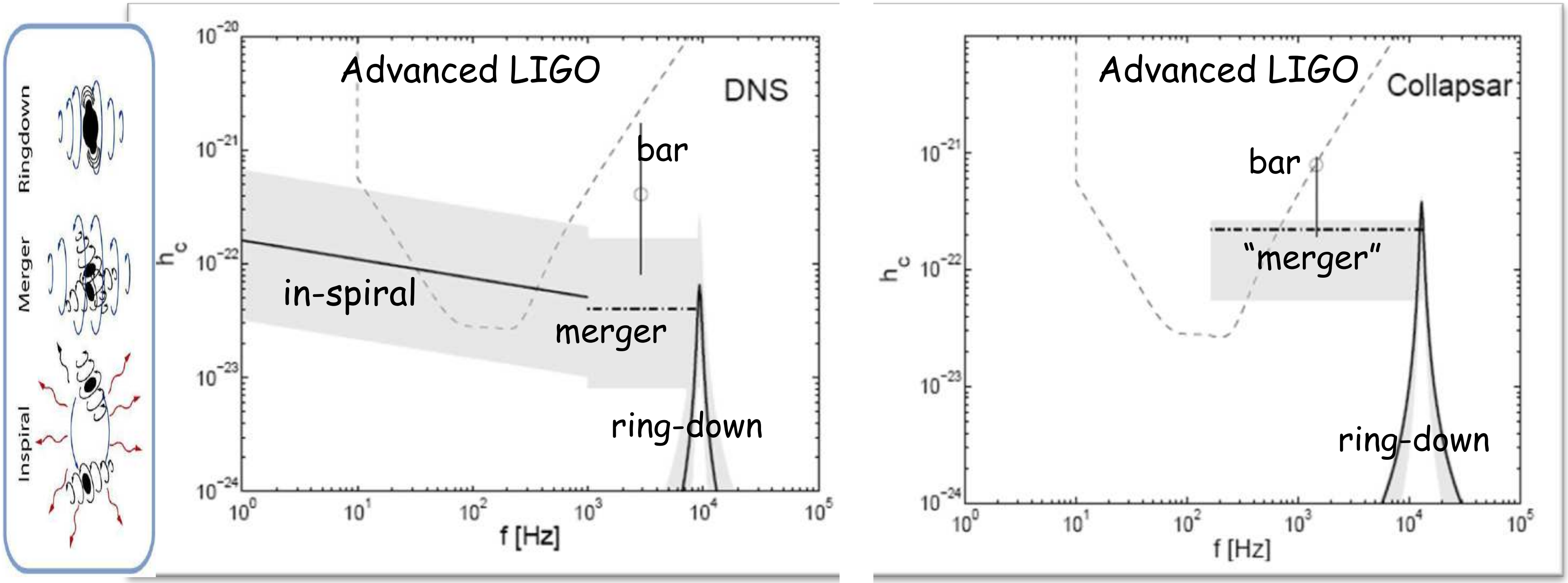
- Collapsing core or disk may fragment to produce two or more compact objects (e.g. Fryer et al. 2002). May be significant source of GWs; possible chirp signature similar to a coalescing NS binary (e.g. Davies et al. 2002, Piro & Pfahl 2007) or burst of GWs in a "merger"-type signal (e.g. Kobayashi & Meszaros 2003).

- Core or disk may undergo non-axisymmetric instabilities (e.g. dynamical bar-mode instability; Fryer et al. 2002, Shibata 2003, Kobayashi and Meszaros 2003, Baiotti et al. 2007, Dimmelmeier et al. 2008, … etc. for recent reviews: e.g. Andersson 2003, Ott 2009).

- Nascent BH quite distorted from quiescent Kerr form (e.g. Fryer at el. 2002). Distortion drives GW radiation as BH settles down to Kerr state (ringing waves; e.g. Echeverria 1993, Shibata & Taniguchi 2006, ...).

- If magnetar formed and survives on longer timescales, secular bar-mode instability (e.g. Lai & Shapiro 1995, Shibata et al. 2004, Ou et al. 2004), may be coupled to obs. signatures of energy injection in fireball (Corsi & Meszaros 2009).

GW from GRBs: upper-limit estimates



Most optimistic estimates:

Kobayashi & Meszaros 2003 (and Fryer et al. 2002)

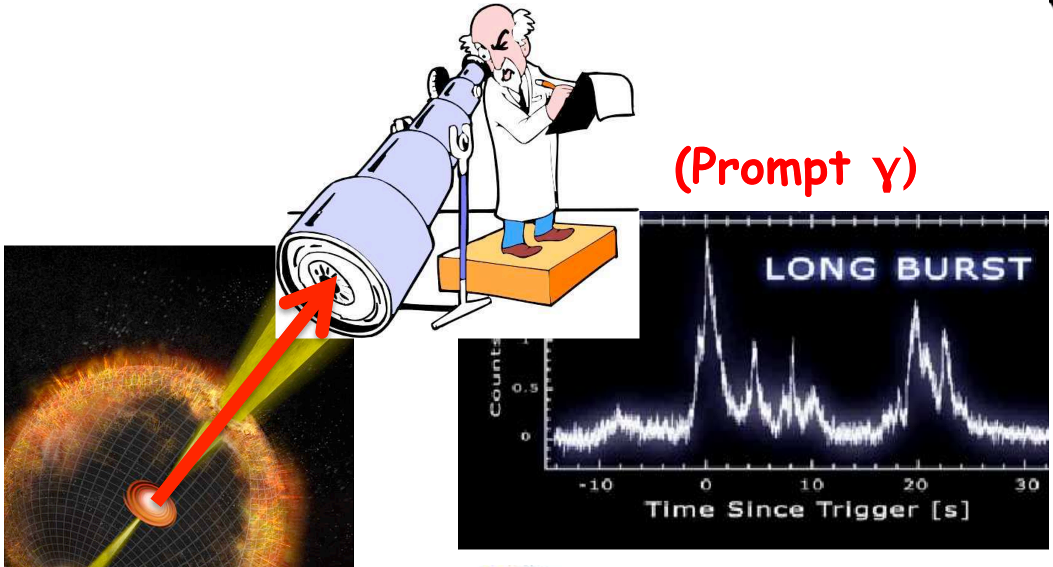
ULs assume 1% of tot mass in GW during merger, 5% in BH ring-down

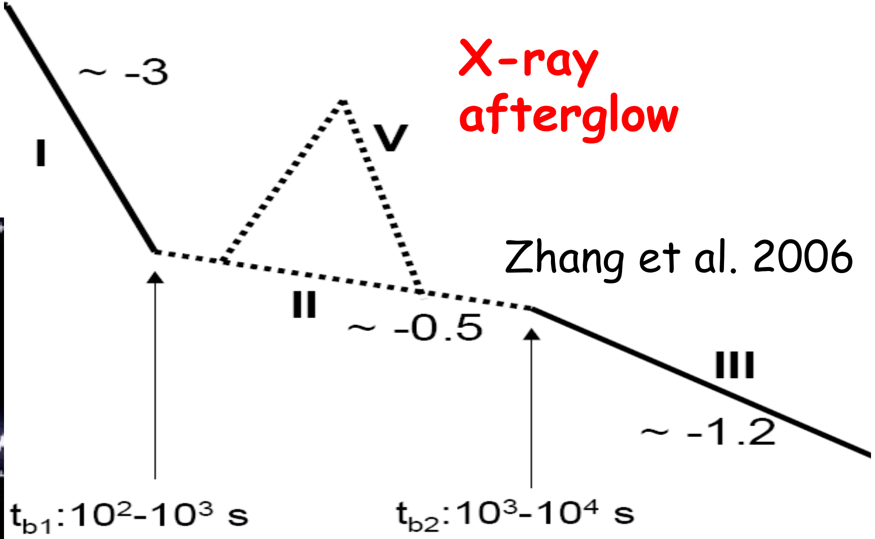
Distance range used for shadowed regions in plot:

- 50 Mpc - 1 Gpc for NS-NS;
- 20-100 Mpc for collapsar.

LGRB on-axis: HE emission

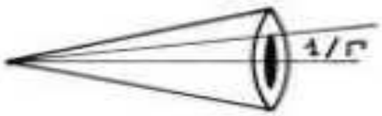
(Prompt γ)

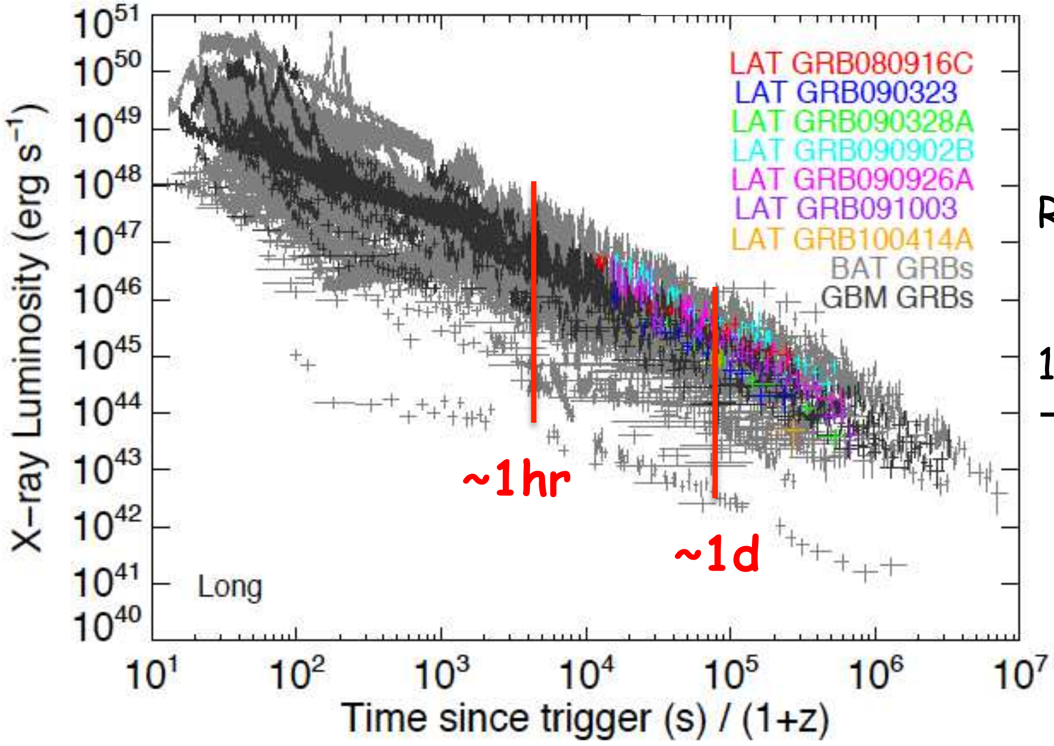




X-ray afterglow

Zhang et al. 2006



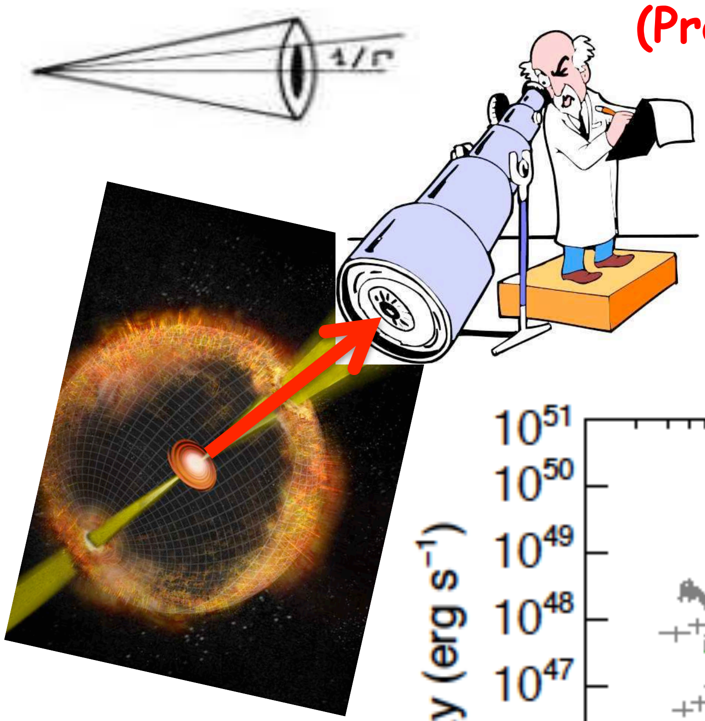


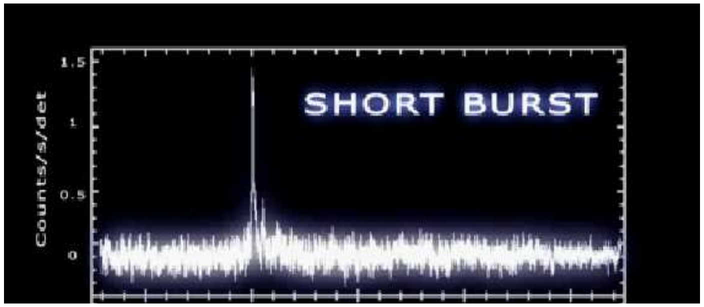
Racusin et al. 2011

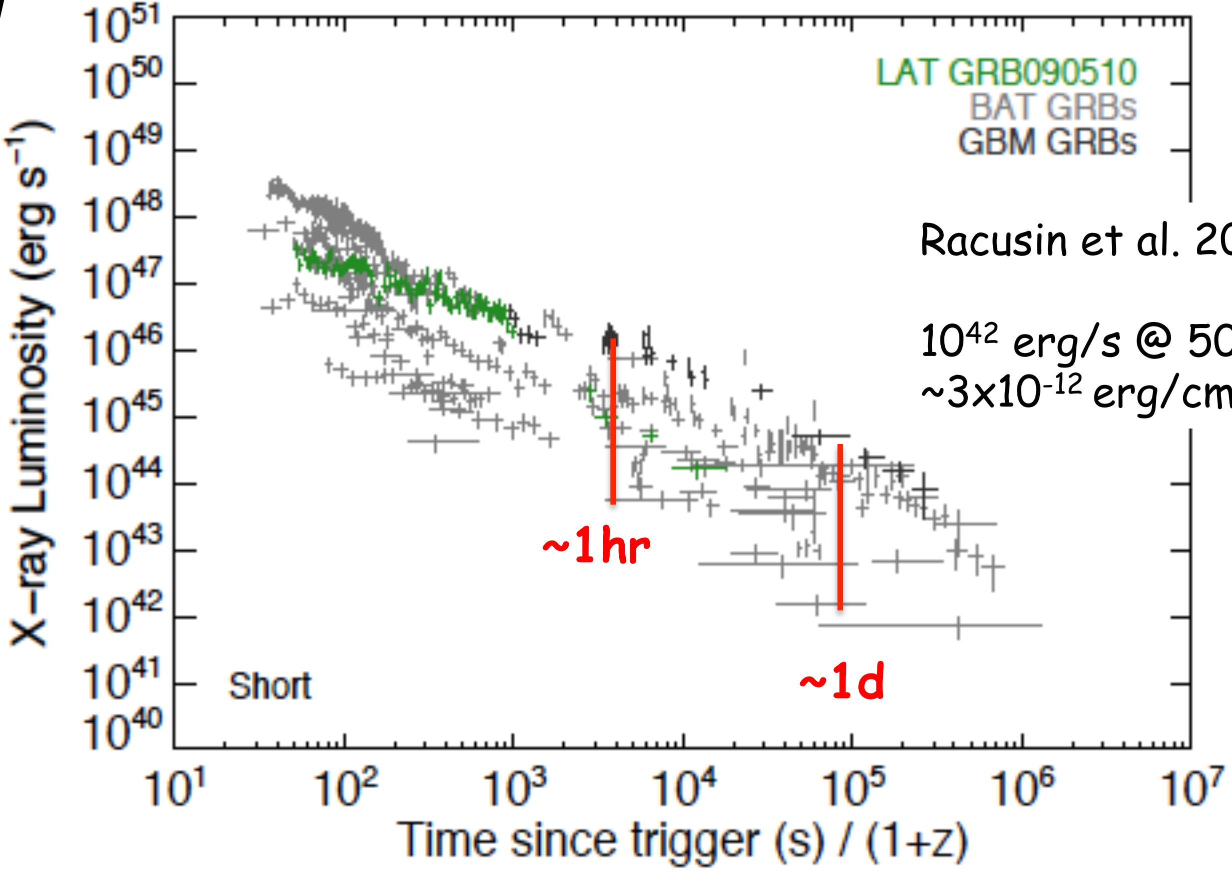
10^{43} erg/s @ 50 Mpc
→ ~3×10^{-11} erg/cm^2/s

SGRB on-axis: HE emission

(Prompt γ)







Racusin et al. 2011

10^{42} erg/s @ 50 Mpc → ~3×10^{-12} erg/cm^2/s

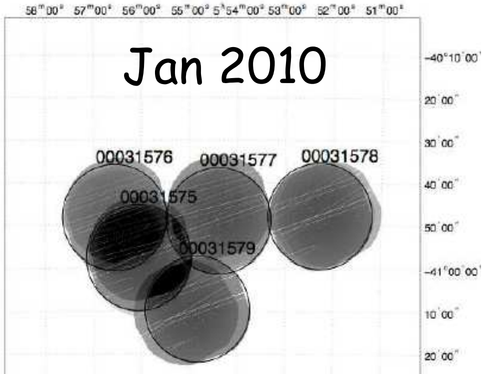
Follow-up of GW triggers with Swift

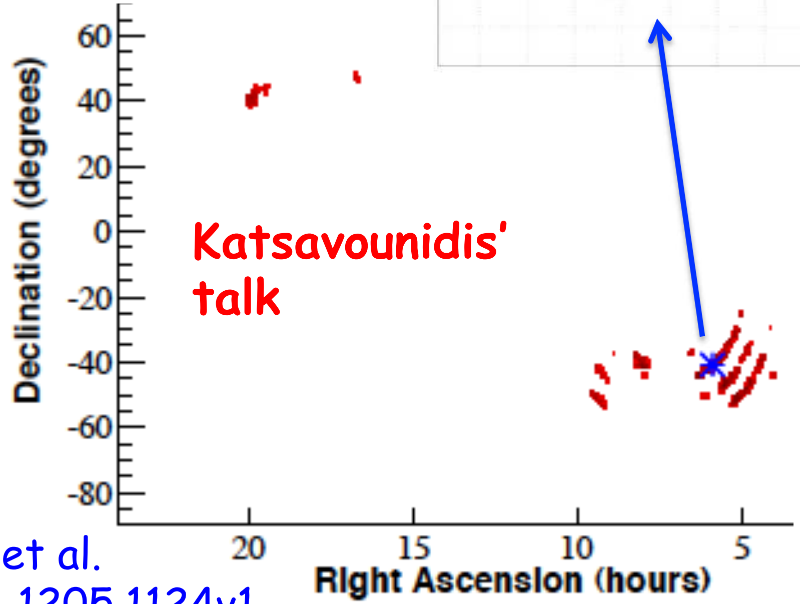
- 2 LOOC-UP events observed by Swift within ~12 hrs after GW alert (Jan '10: blind inj.; Sep '10: low threshold test).

- XRT data from 7 observed fields: consistent with serendipitous sources.

FAR <1/35 d (of triple coinc.).

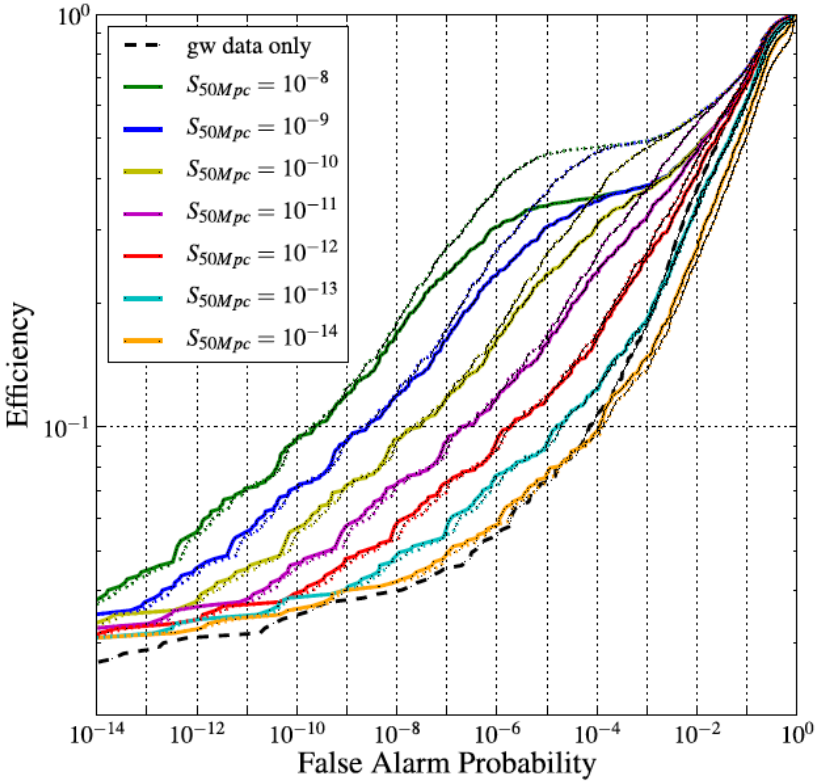
>=20% of prob. covered by max 5 (0.4x0.4 deg^2) tiles.





Katsavounidis' talk

Evans et al.
ArXiv: 1205.1124v1

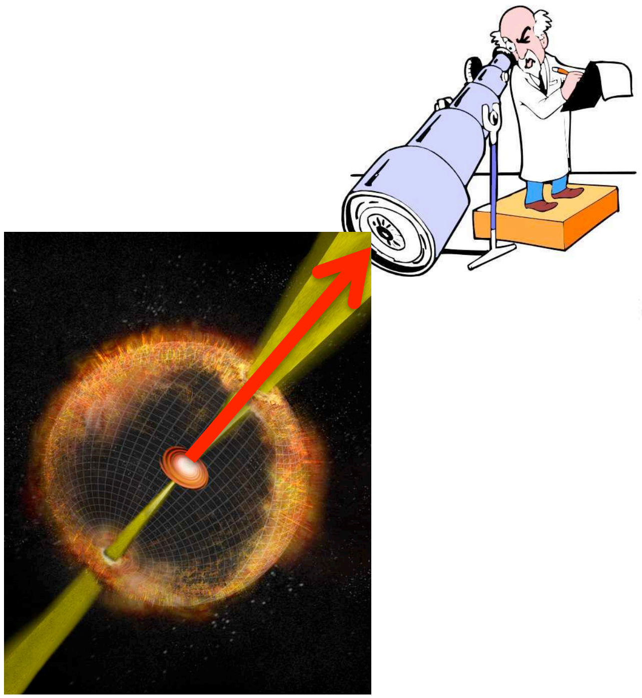


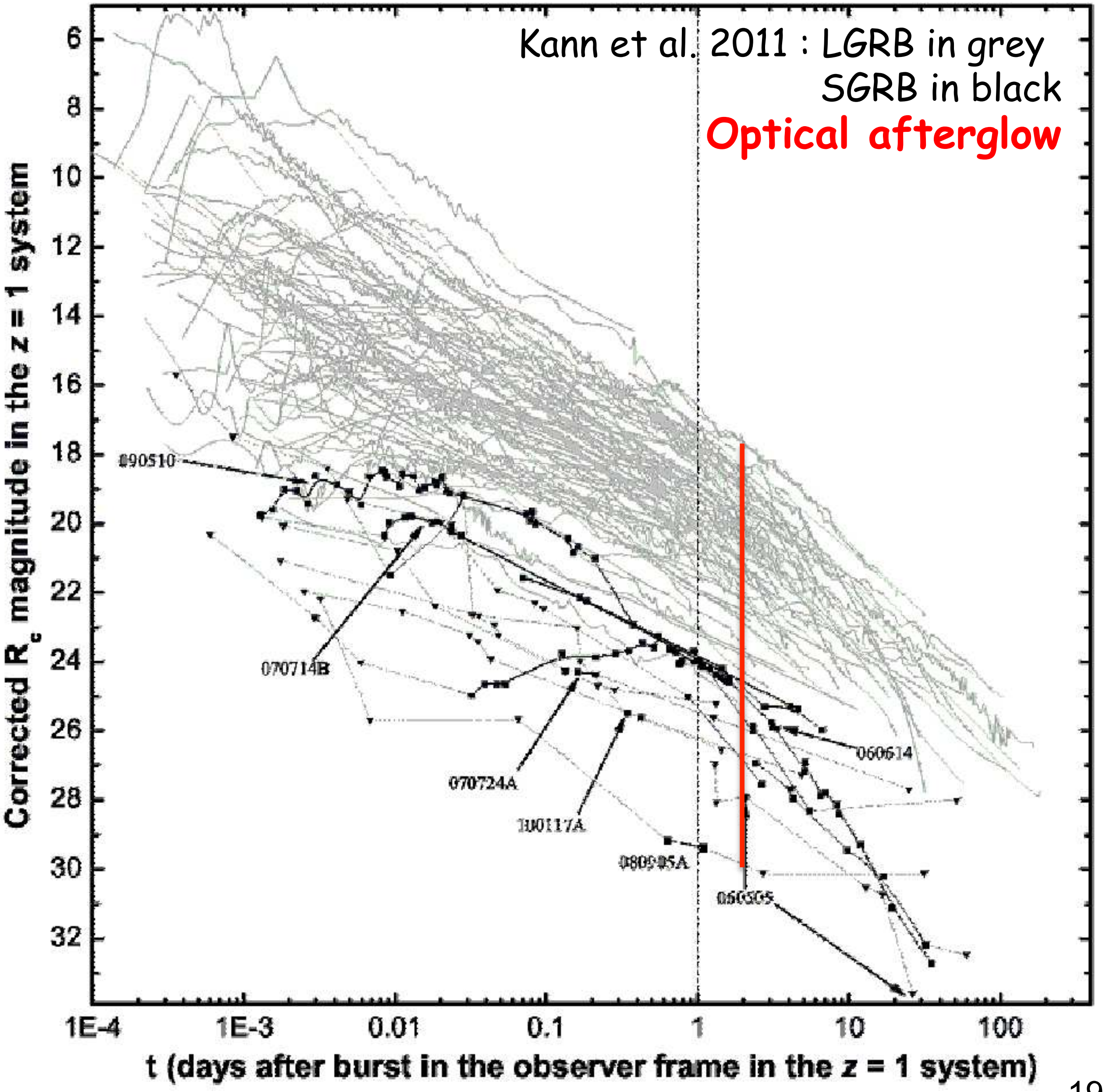
Efficiency vs FAP for LIGO-Virgo+Swift. Solid (dotted): five (ten) Swift fields for various X-ray counterpart fluxes at 50Mpc (erg s^{-1} cm^{-2}). Dashed line: GW only search.

Optical follow-ups

LGRB/SGRs on-axis: optical

@30 Mpc: brightest long ~5 mag at 1 day; UL on dim short GRB ~ 18 mag



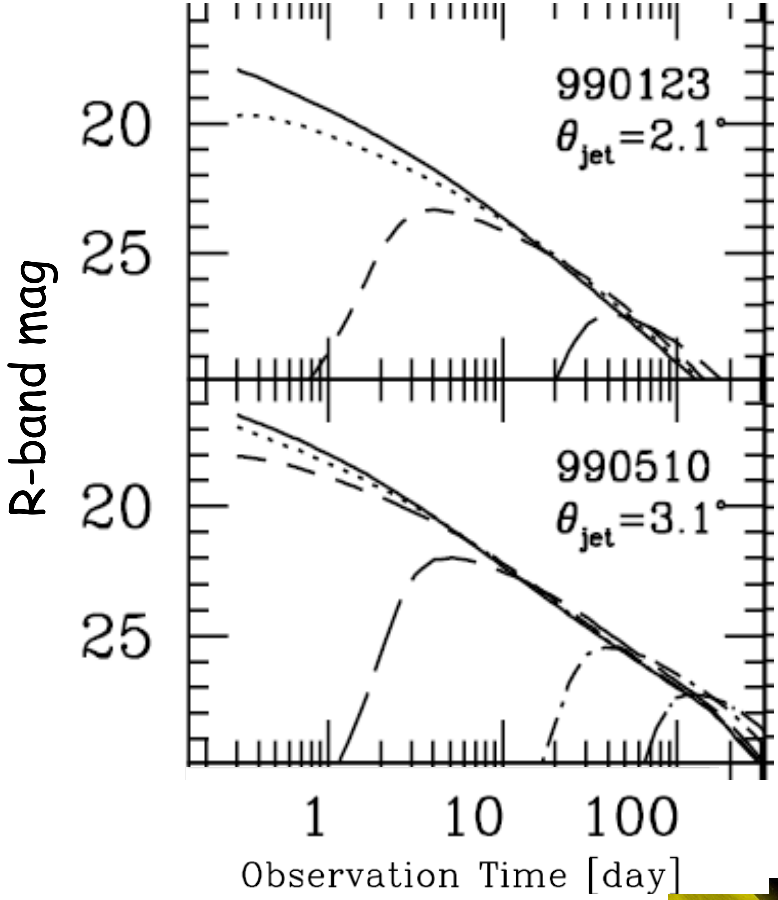


Kann et al. 2011 : LGRB in grey
SGRB in black

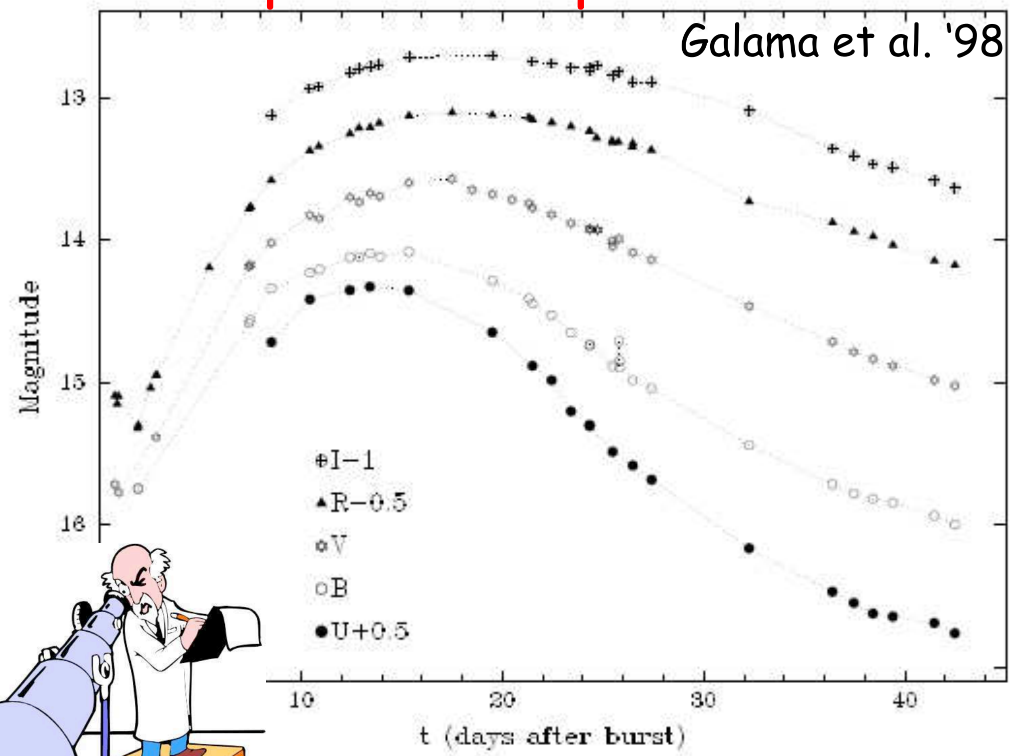
Optical afterglow

LGRB off-axis: optical

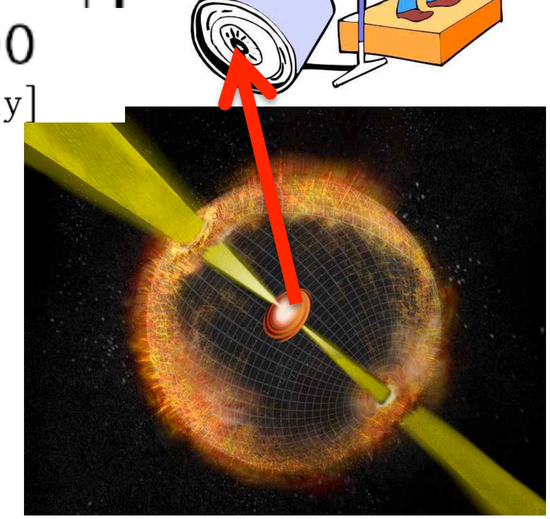
Optical afterglow

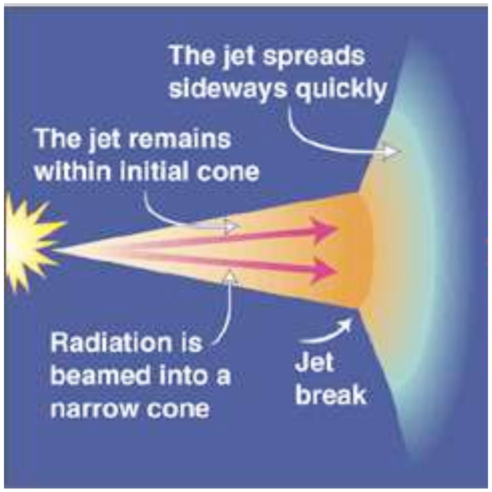


SN1998bw optical – 38 Mpc


Galama et al. '98

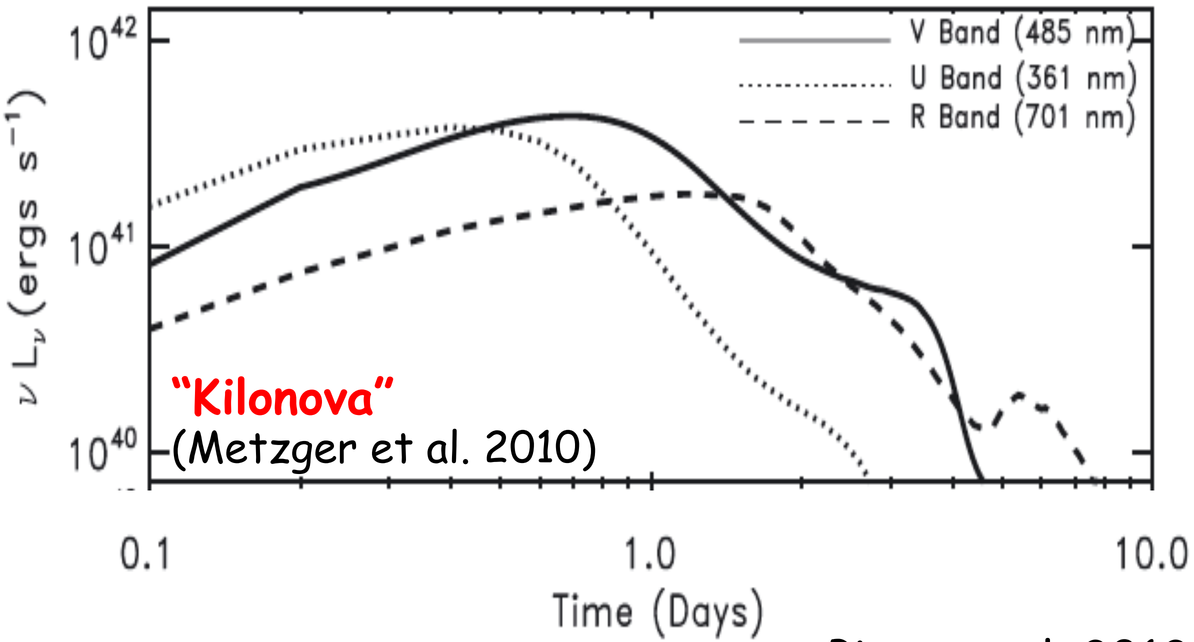
Totani & Panaitescu '02:
z=1, view. angl. 1-30 deg:
~[23, 18] mag (t<~7d).
@30 Mpc ~11.3-6.3 mag
@300Mpc ~16.3-11.3 mag





NS (BH) - NS mergers: optical

- NS-NS and BH-NS: primary GW sources.
- Abadie et al. 2010, CQG, 27, 173001: GW horizon is ~440 Mpc for NS-NS (expected ~0.4-400/yr and ~930 Mpc for BH-NS).



"Kilonova"

(Metzger et al. 2010)

Piran et al. 2012

- Sub-relativistic material ejected during merger should produce kilonova (optical/UV – days).

Run	Masses $m_\odot$	m_{ej} $10^{-2} m_\odot$	L† 10^{42} erg/s	t(peak) day	mag at 300 Mpc
8	1.4 -1.2	2.1	1.8	0.5	20.5
12^a	1.4 -1.4	1.3	1.3	0.4	21
15^b	1.4 - 2.0	3.9	2.5	0.6	20.2
23^c	1.4 - 10	4.9	3.2	0.6	20

[†] Bolometric luminosity. Most of this luminosity is emitted in Optical/UV.

[a] The canonical ns^2 case.

[b] This is the maximal signal among the ns^2 mergers runs.

[c] nsbh merger.

NS (BH)-NS mergers and short GRBs

- Estimated rate of short Gamma-Ray Bursts (GRBs) comparable to binary pulsars estimates (e.g., Guetta & Stella 2009).

- If short GRBs are binary mergers, their rate of ~10 $\mathrm{Gpc^{-3}yr^{-1}}$ provides lower limit to merger rate. The true rate depends on the unknown beaming angle (two orders of magnitude uncertainty).

- GRB signal only present if observer is on-axis, so optical and radio follow-ups of GW events are important.

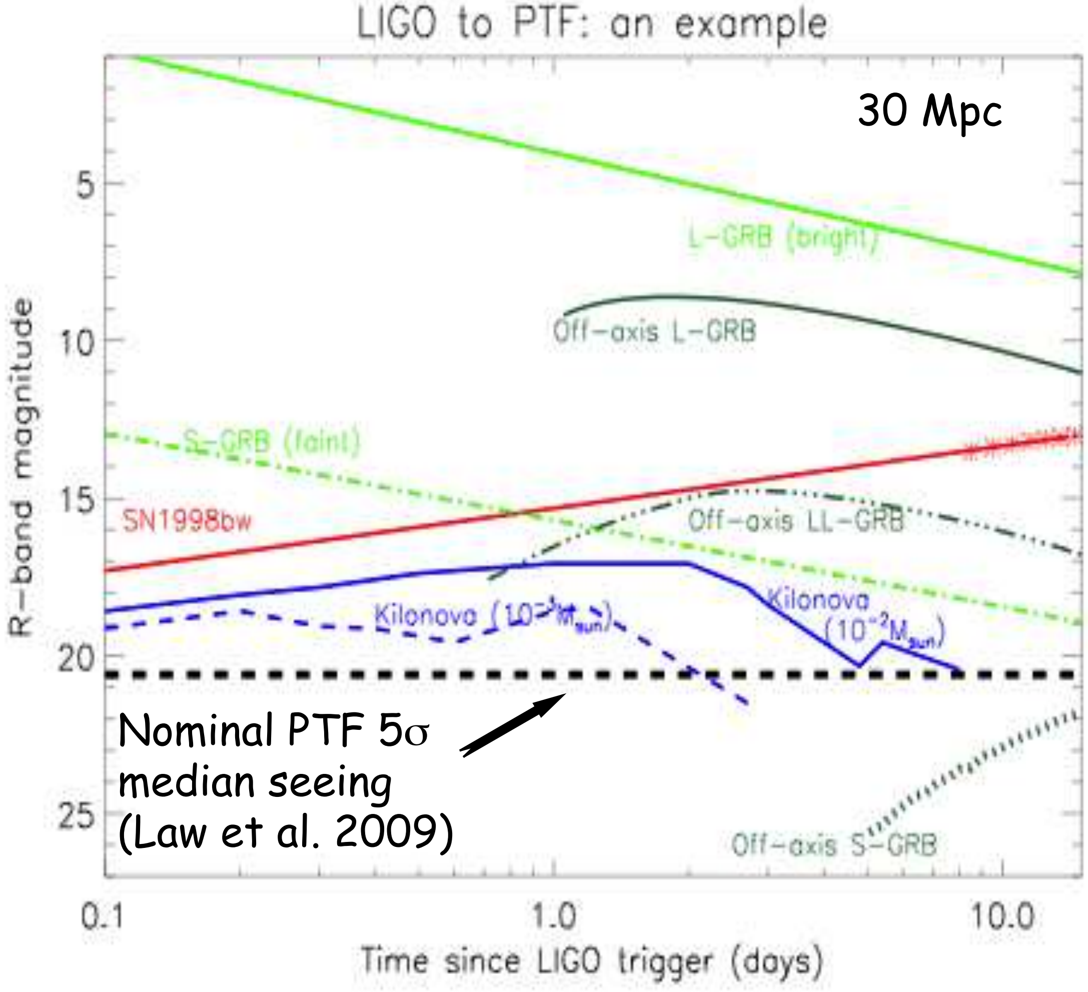
- Levinson et al 2002: the narrower the beaming, the higher the true rate, BUT the smaller the energy → this overall reduces the detectability of orphan radio/optical afterglows from off-axis short GRBs.

- Kilonova: isotropic optical emission for NS-NS merger, DOES NOT require GRB.

LOOC-UP searches: optical

E.g., Palomar Transient Factory: ~30-150 per 100-200 sqr deg after selective cuts (Bloom et a.l 2011). But, transients NOT belonging to the "typical" categories (varstars, AGNs, novae, "typical" SN), are the most interesting as GW sources (given LIGO/Virgo sensitivity).

7.8 sq deg CCD array camera mounted on the 48 inch telescope at Palomar Observatory (P48).



30 Mpc

Nominal PTF 5σ median seeing (Law et al. 2009)

Scanning the optical transient sky

(before spectroscopic classification)

- **Variable stars:** point source, already present in the reference image.

- **AGNs** (in the broad sense): typically look like a transient source right in the center of a galaxy.

- **SN**: point-like, inside a host but offset from the center. Sometimes the host is too faint to be seen.

- **Dwarf Novae** outbursts: can be confused with SN, but temporal properties help: e.g. an outburst takes 1-3 days to rise, a SN 10-20 days.

- **Asteroids:** eliminated by requiring at least one match between 2 images.

- **Subtraction artifacts:** common but also eliminated by the "human" scanner comparing with other subtractions in the field.

LOOC-UP optical image analysis: summary

Two basic approaches explored with current data:

- ☐ Object identification followed by comparison of object lists.
- ☐ Image subtraction followed by object identification.

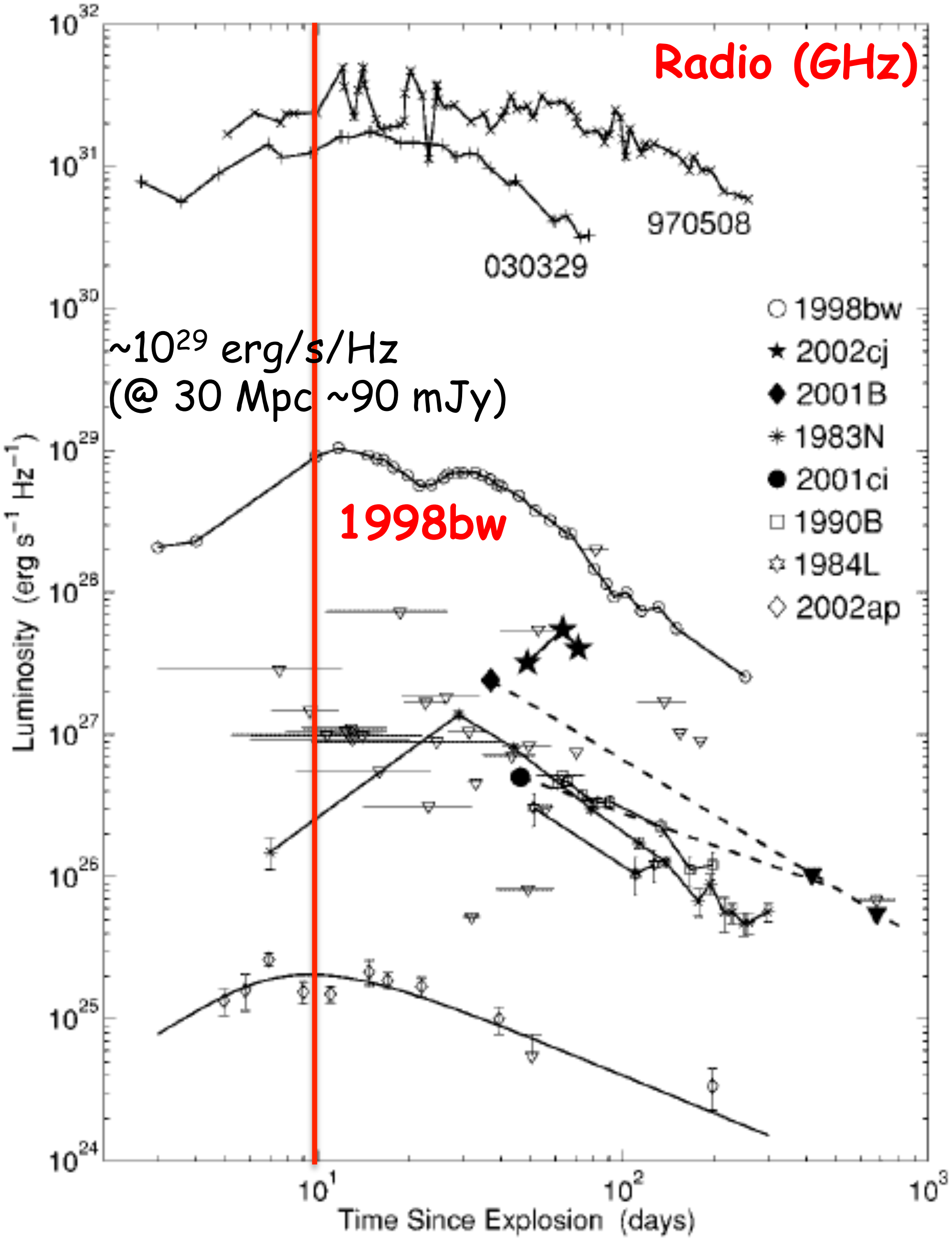
(Some of the) challenges

- ☐ Very large search area : artifacts and unrelated transients.
- ☐ Optical transients may be on top of galaxy images—harder to identify.
- ☐ Need good reference images.
- ☐ Interpretation of candidate counterpart in the absence of spectral classification: LIGO interesting or not?

Image analysis in progress

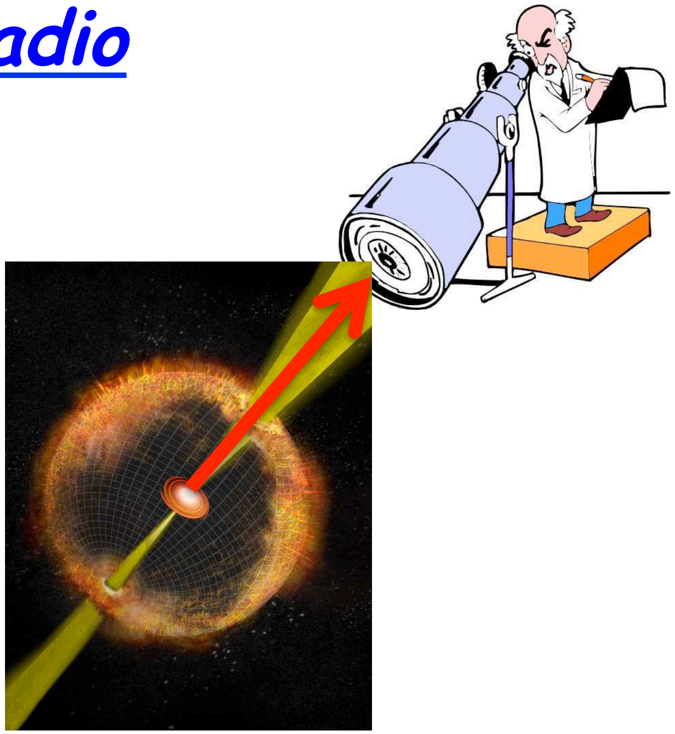
Radio follow-ups

LGRB on-axis: radio


Radio (GHz)

~10^{29} erg/s/Hz
(@ 30 Mpc ~90 mJy)

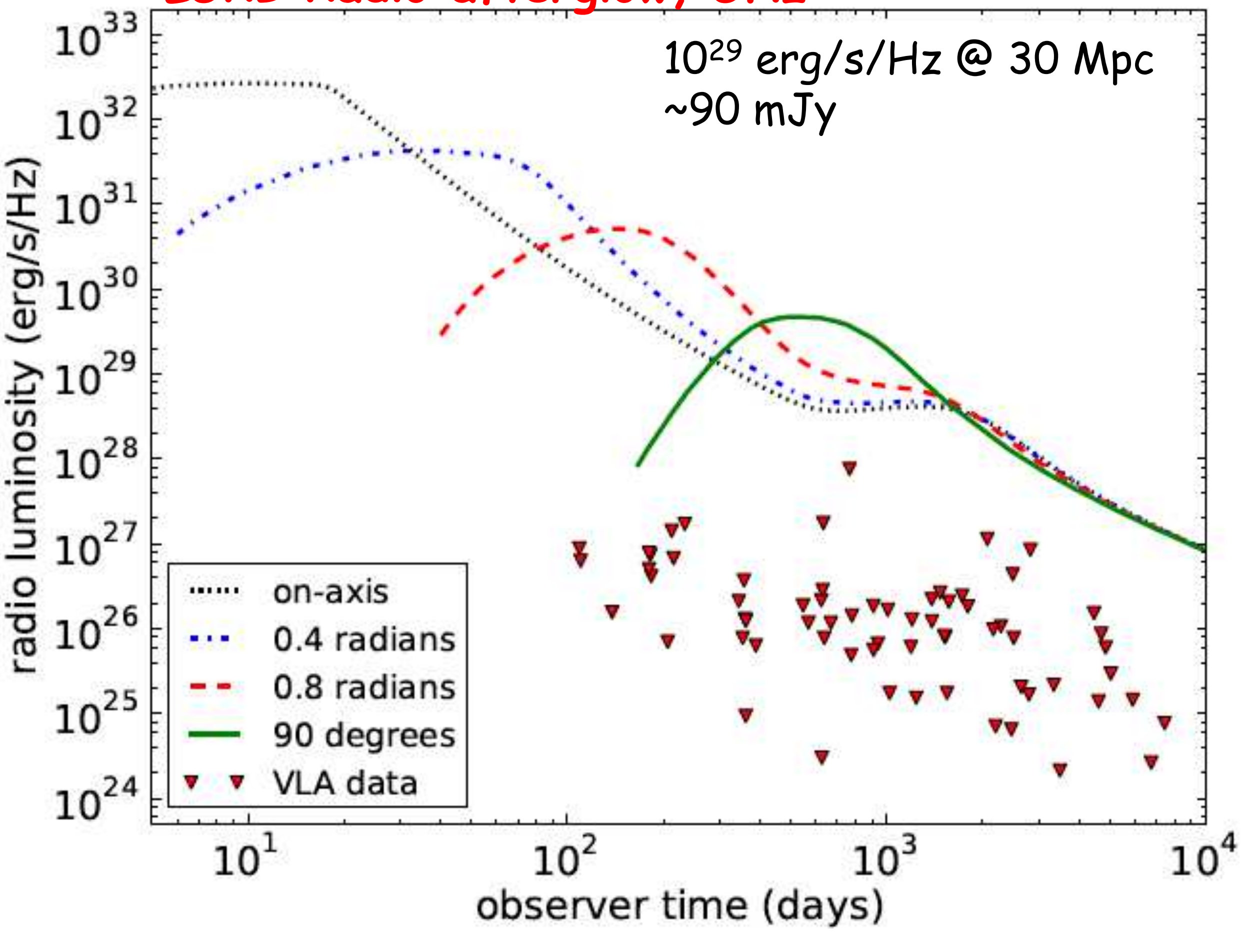
1998bw



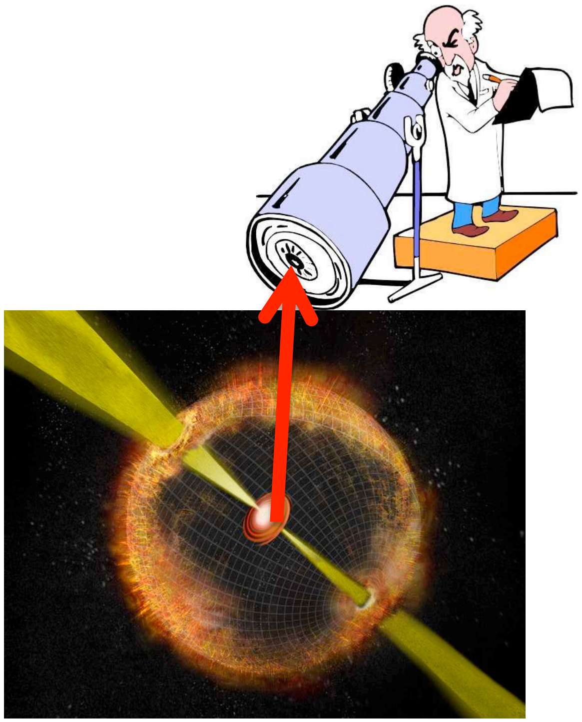
Berger et al. '03

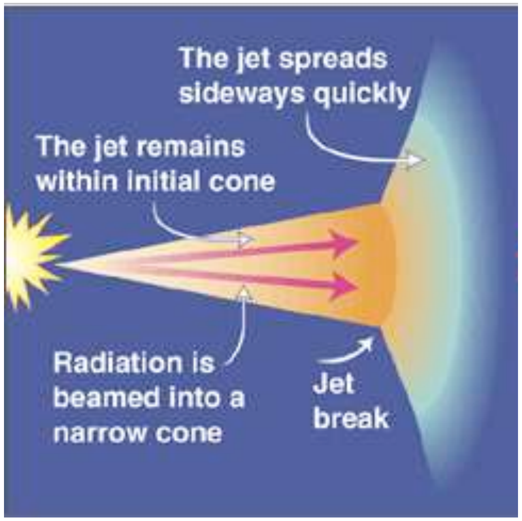
LGRB off-axis: radio

LGRB Radio afterglow, GHz



10^{29} erg/s/Hz @ 30 Mpc
~90 mJy



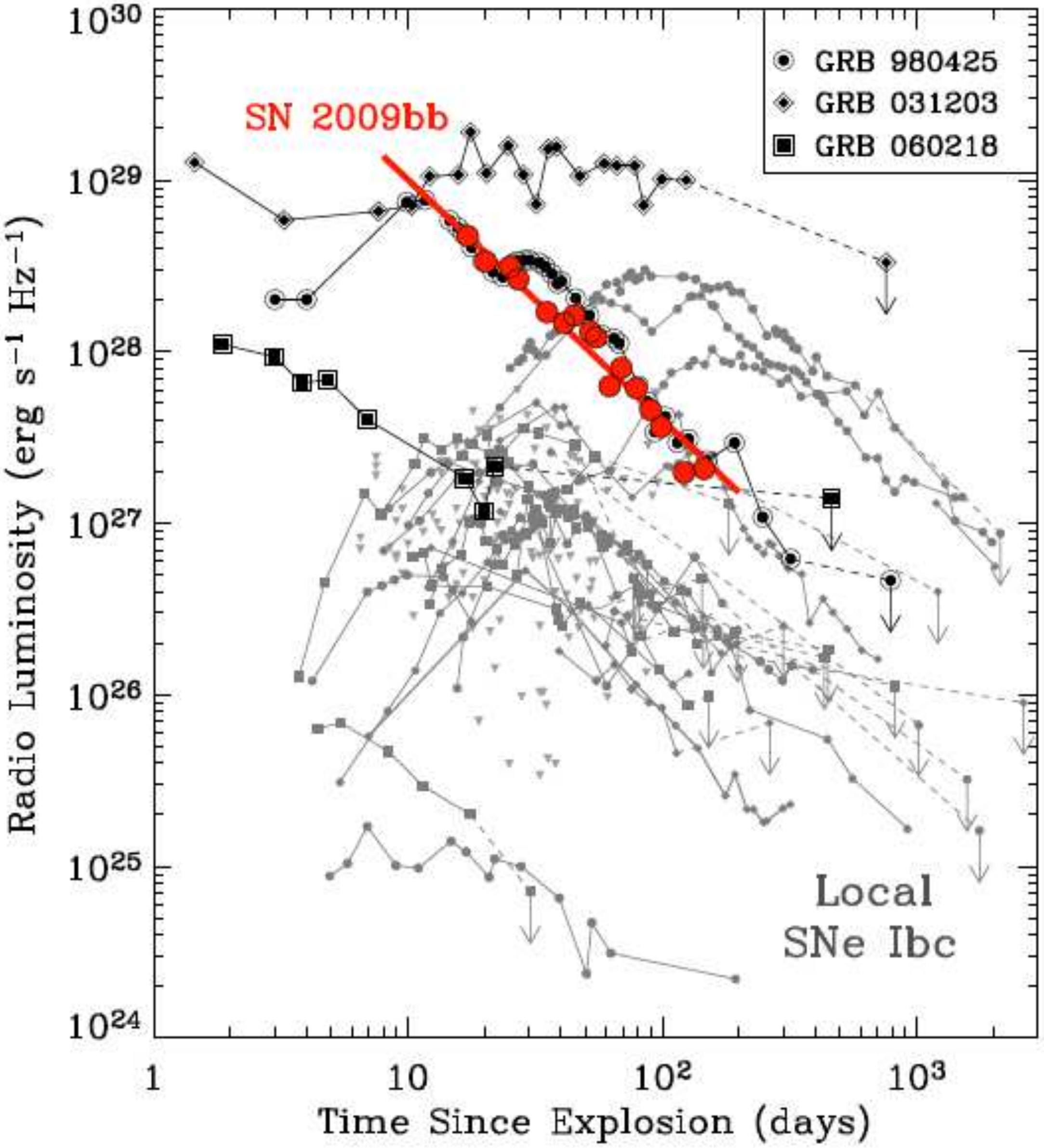


van Eerten et al. '10:
off-axis models (for a 0.2 rad GRB jet) and Ib/c SNe ULs.

Off-axis GRB radio searches: GW independent studies

Soderberg et al. 2010, Nature: relativistic SN2009bb without a detected GRB.

Radio follow-ups of Ib/c SNe: GRB-associated SNe ~1% of Ib/c.



NS (BH) – NS mergers (and off-axis SGRBs): radio

Run	Masses		$n=1$		$n=0.1$
		1.4 GHz		1.4 GHz	
		F_ν(peak^a)	t(peak^a)	F_ν(peak^a)	t(peak^a)
	$m_\odot$	mJy	yr	μJy	yr
8	1.4 -1.2	0.09	4	10	9
12^b	1.4 -1.4	0.04	1.5	5	3
15^c	1.4 - 2.0	0.3	5	50	10
23^d	1.4 - 10	1.5	4	200	10

[a] This is the peak of the sub-relativistic our outflow, not calculated
produce a stronger and earlier peak.

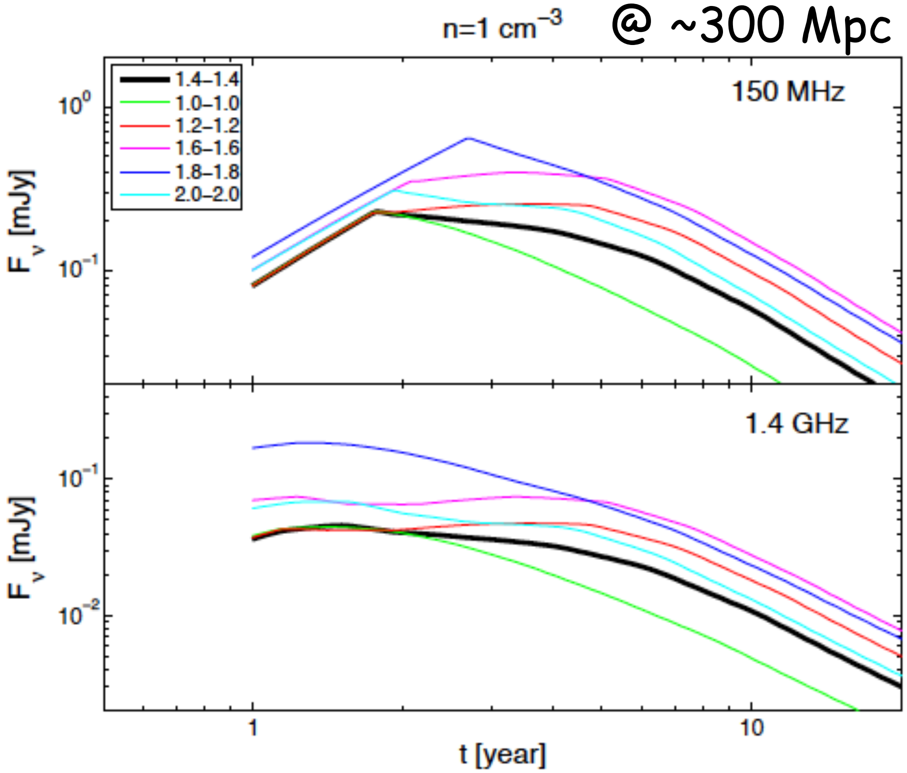
[b] The canonical ns^2 case.

[c] This is the maximal signal from our runs o

[d] nsbh merger.

Piran, Nakar, Rosswog 2012

@ ~300 Mpc



"Radio flare"
(Piran et al. 2012; Nakar & Piran 2011)

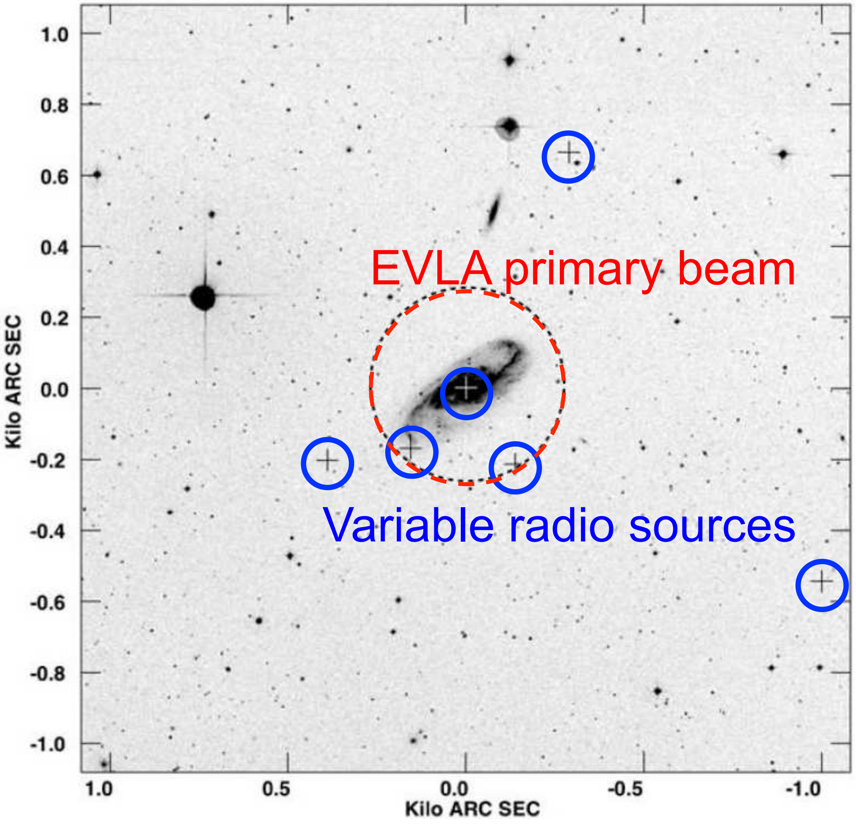
Material ejected at sub-relativistic velocities during merger expected to produce radio flares (years timescale).

EVLA follow-up of LOOC-UP triggers

- Three (20d, 40d, 230d) obs. for each of two LOOC-UP events, 3 most probable hosts within the uncertainty region observed for each event.
- Detected ~6 sources in the field of each galaxy.
- Consistent with the number of expected extragalactic sources (Windhorst 2003).

Radio counterparts to GW events:
Fender's talk
Kaplan's talk

Lazio et al.,arXiv:1203.0093



Conclusion and future prospects

- Joint EM-GW studies: LIGO-Virgo detectors have been actively following EM triggers (e.g., GRBs, SGR flares, etc.) during these years.

- First LOOC-UP experiment performed, optical image analysis in progress, Swift/LOOC-UP results on arXiv, EVLA results in preparation.

- Starting from 2015, advanced LIGO/Virgo detectors (10 times better sensitivity), plus (eventually) KAGRA and potentially LIGO India, will provide a totally new view of the Universe.

- Better engagement with astronomers is needed to: ensure sufficient sky coverage, ensure prompt image analysis and interpretation, plan follow-up strategies (including spectroscopy).

- Necessary to be prepared to quantify the significance of an apparent counterpart.

- Issue public alerts after the first few detections.