# Gravitational Waves and GRBs

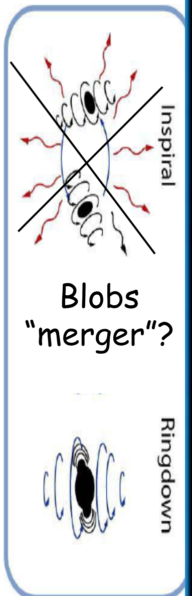
**Alessandra Corsi**

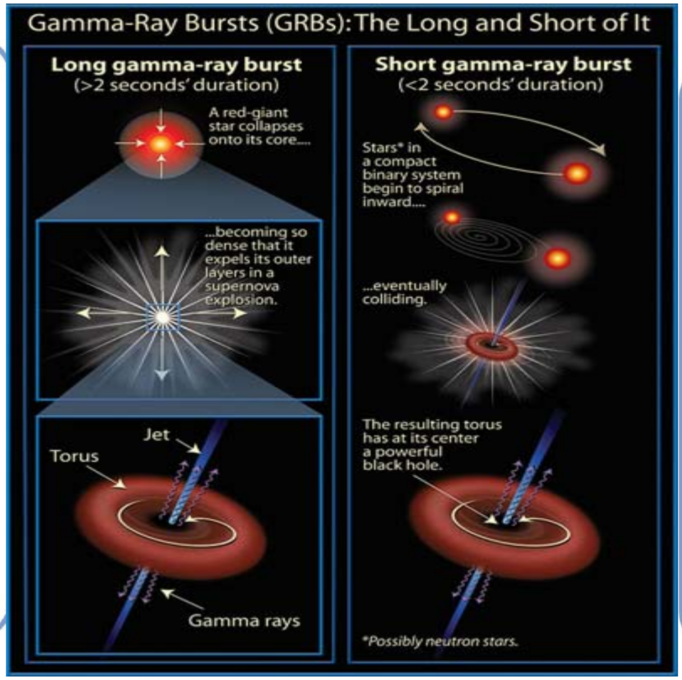
California Institute of Technology

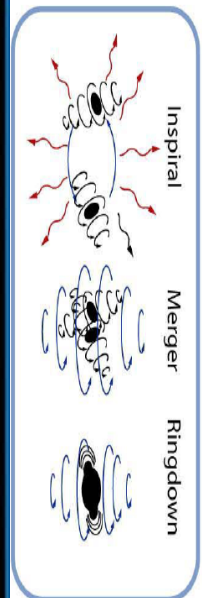
On behalf of the

LIGO scientific collaboration, Virgo collaboration & partner telescopes

# Unraveling the nature of GRBs: joint EM-GW studies

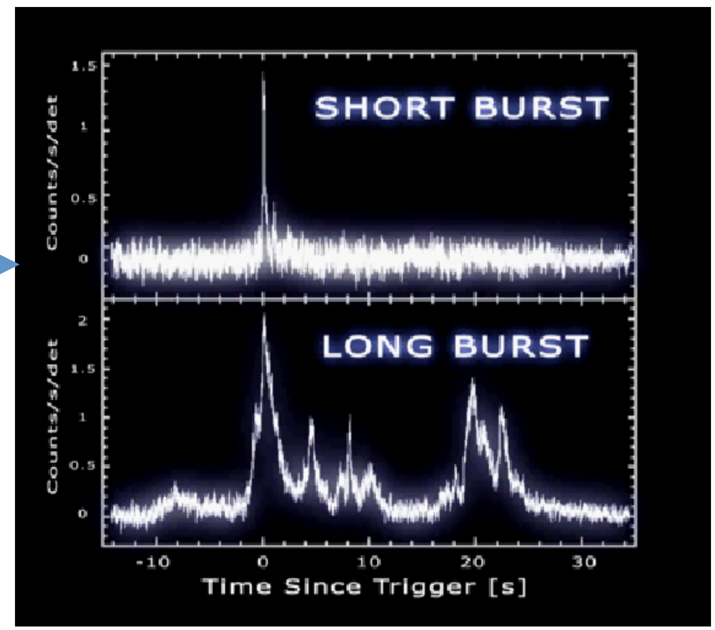


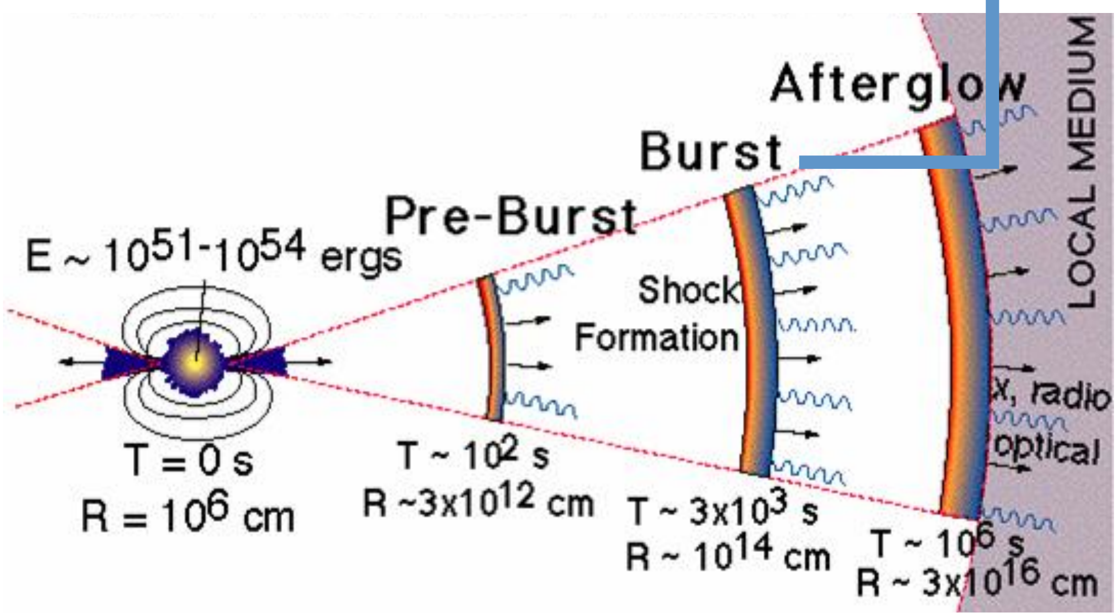




**GWs** emitted directly from the progenitor

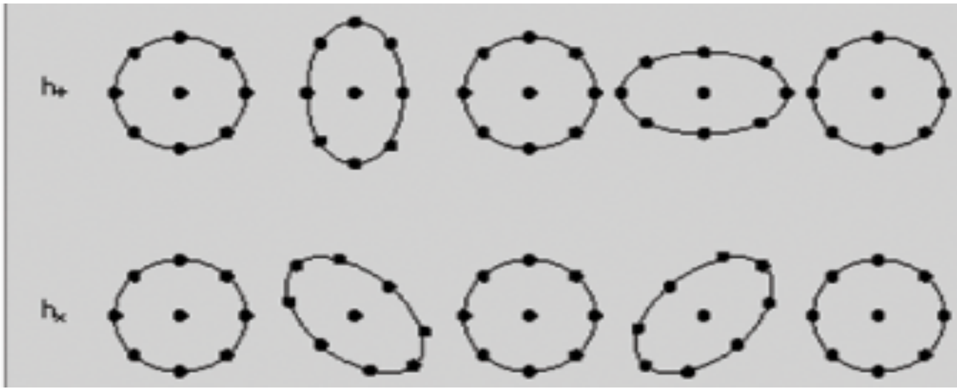
Nasa image

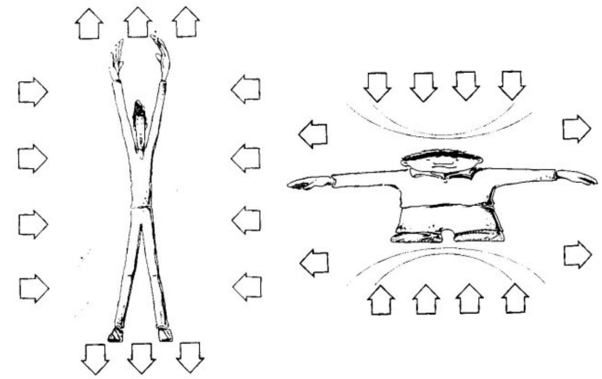


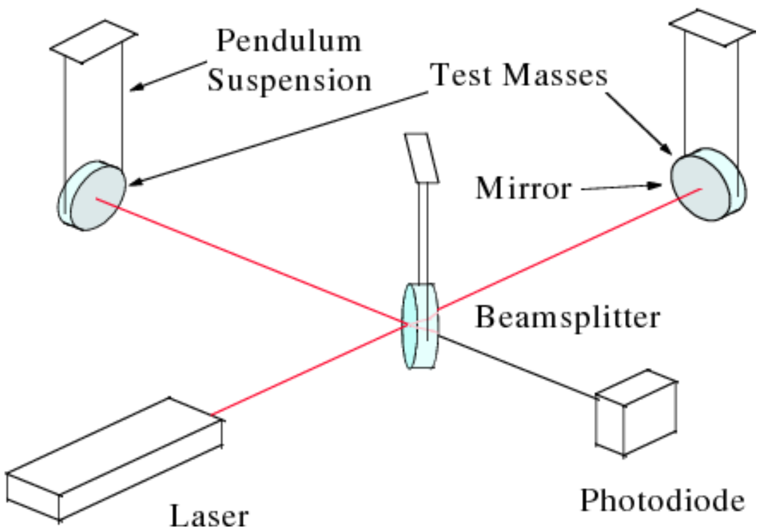

**EM** signal emitted at large distances: indirect info on the progenitor

# How to detect GWs?



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




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

$$h_{rss} = \sqrt{\int_{-\infty}^{+\infty} \left(h_+^2(t) + h_\times^2(t)\right) dt}.$$

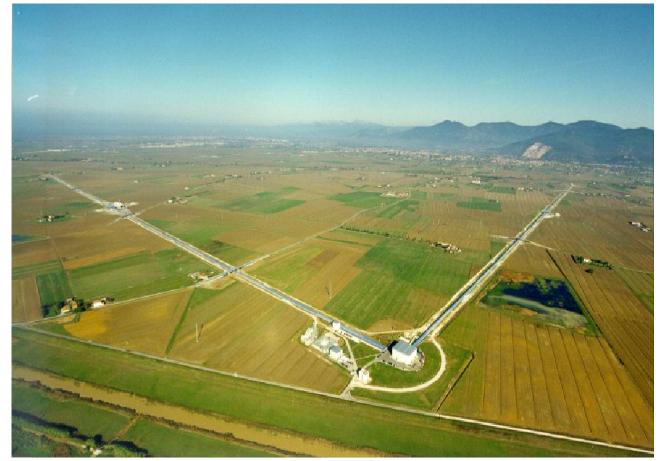
rss amplitude of the incoh. sum of the contributions from the + and x pol.

$h_c = |h(f)|\, f \sim \sqrt{N}\, h$ "characteristic amplitude"

# LIGO – Virgo – GEO detectors

LIGO Hanford
(4km - USA)

LIGO Livingston
(4km -USA)



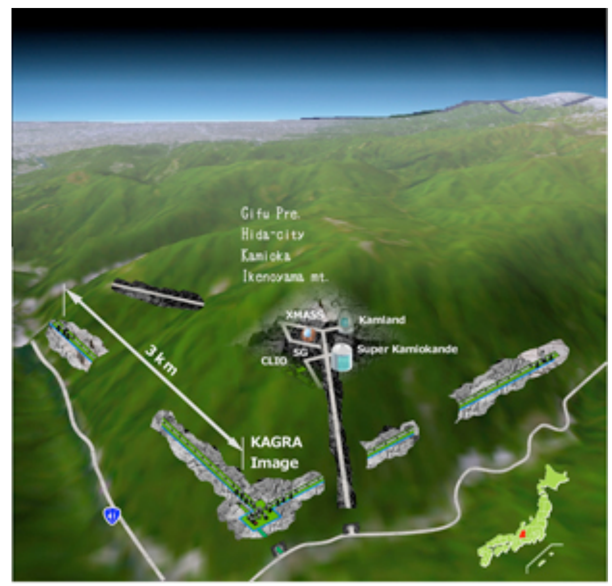
Virgo (3km - Italy)

GEO (600m - Germany)

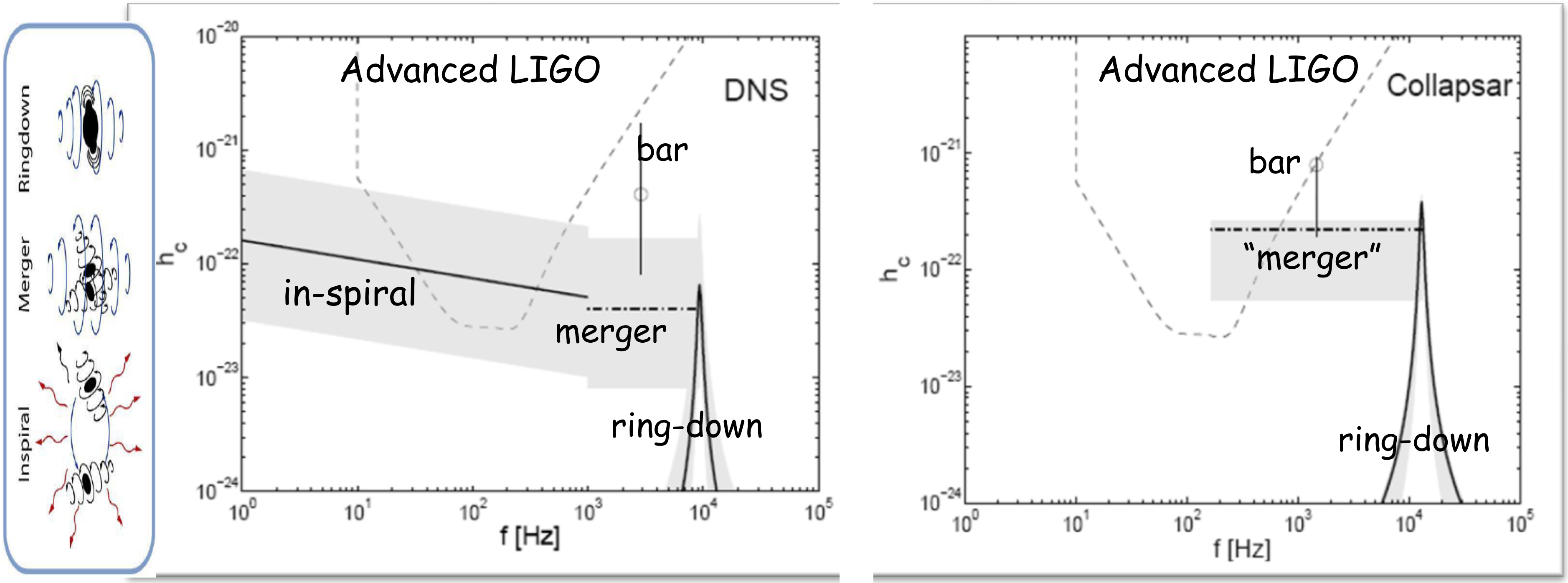
But also:

- Kamioka cryogenic GW detector (KAGRA)

- Possibly LIGO India



# GW from GRBs: order of magnitude estimates



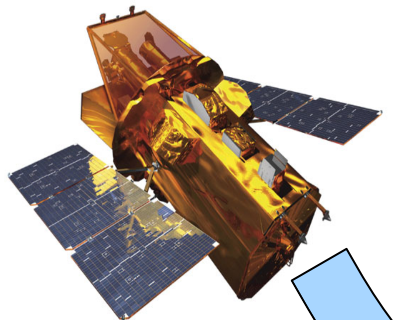

Kobayashi & Meszaros 2003 (and Fryer et al. 2002)

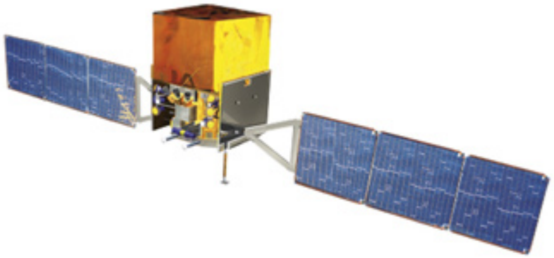
ULs assume 1% of tot mass in GW during merger, 5% in BH ring-down

Distance range used for shadowed regions in plot:

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

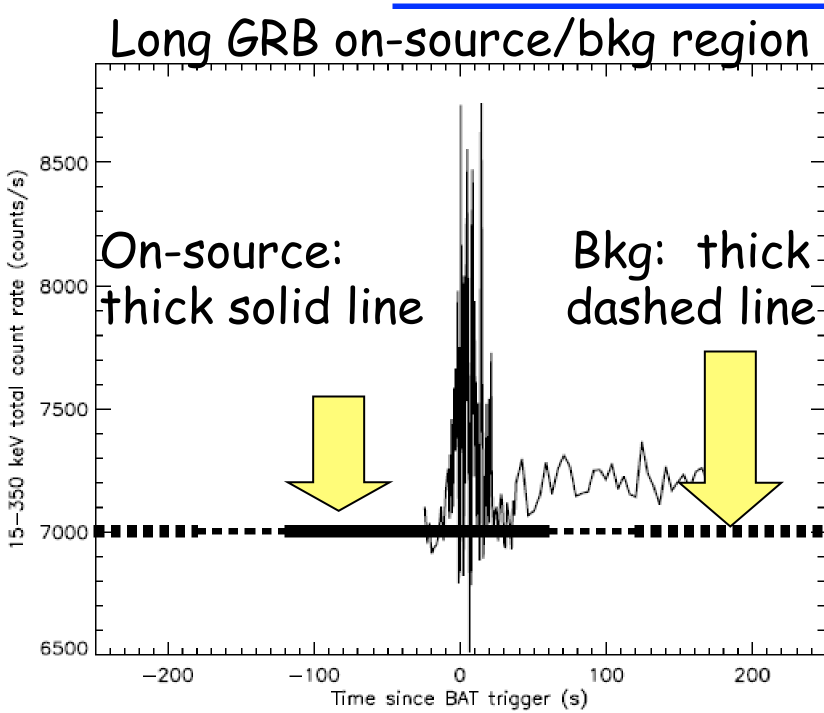
445 Mpc: optimal horizon for NS-NS in adv Era, expected ~40/year (but large scatter in predictions: 0.4-400 /yr – see Abadie et al. 2010  CQG, 27, 173001, and ref therein).



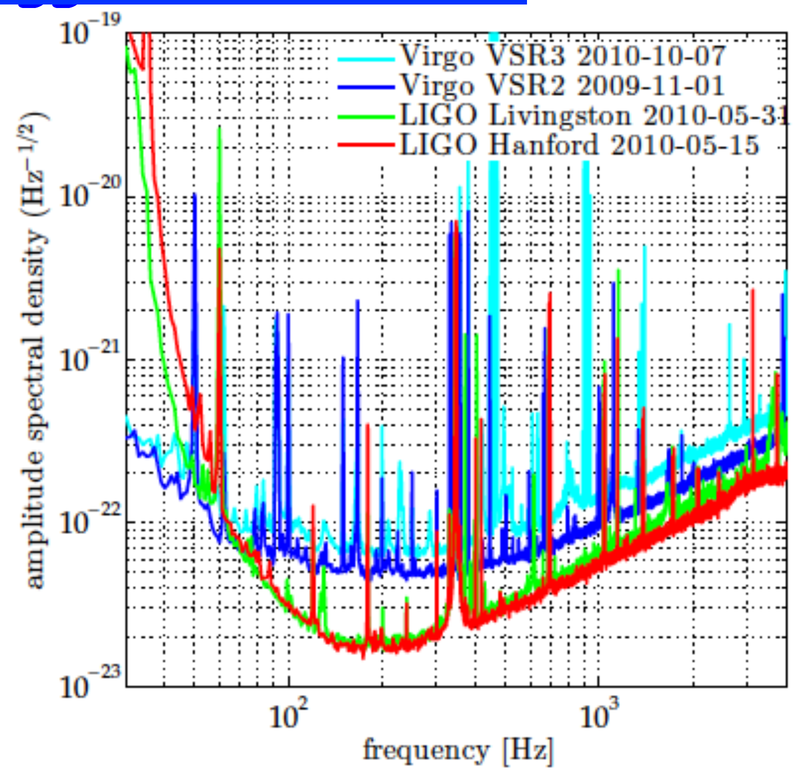


**Triggered searches:**
**EM ---> GW**

# GWs and GRBs: triggered searches




Acernese et al. 2008, CQG, 25, 225001, 2008




- 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 for all-sky; Abadie et al. 2010, ApJ, 715, 1438 for GRB-triggered).

- Latest ULs (S6/VSR2-3: ~155 GRB during '09/'10 mostly BAT/GBM): for $10^{-2} M_{\odot} c^2$ @150 Hz in short burst of GWs : D>17 Mpc (median limit for all GRBs). For short GRBs, assuming BH-NS progenitor: D>28Mpc (Abadie et al. 2012, soon on ArXiv).

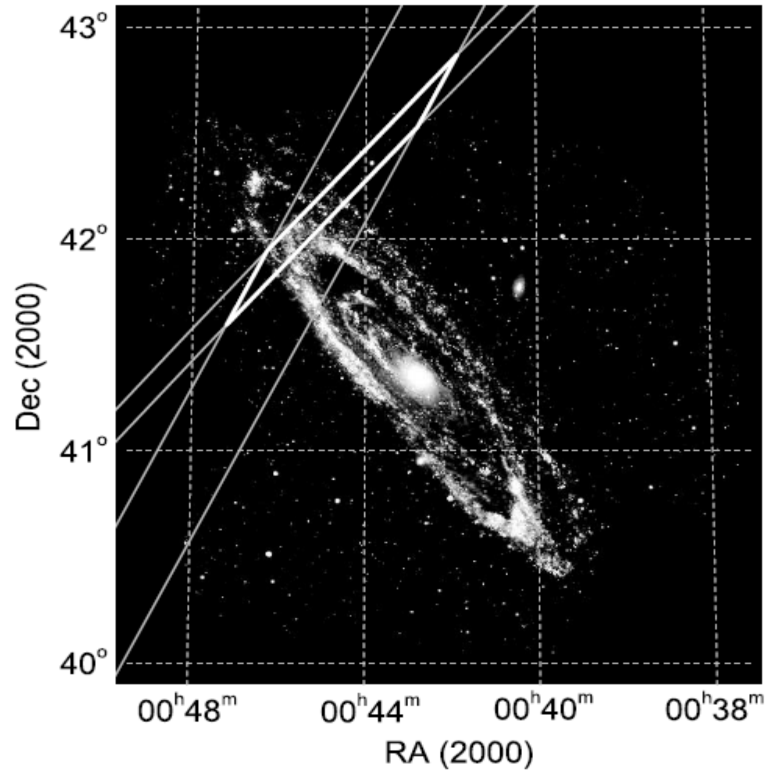
# Implications for the origin of GRB 070201 and GRB 051103

- GRB 070201 in M31 (770 kpc)? GRB 051103 in M81 (3.6 Mpc)? (e.g. Ofek et al. 2006, Ofek et al. 2008, Hurley et al. 2010)

- No GW candidates in on-source window

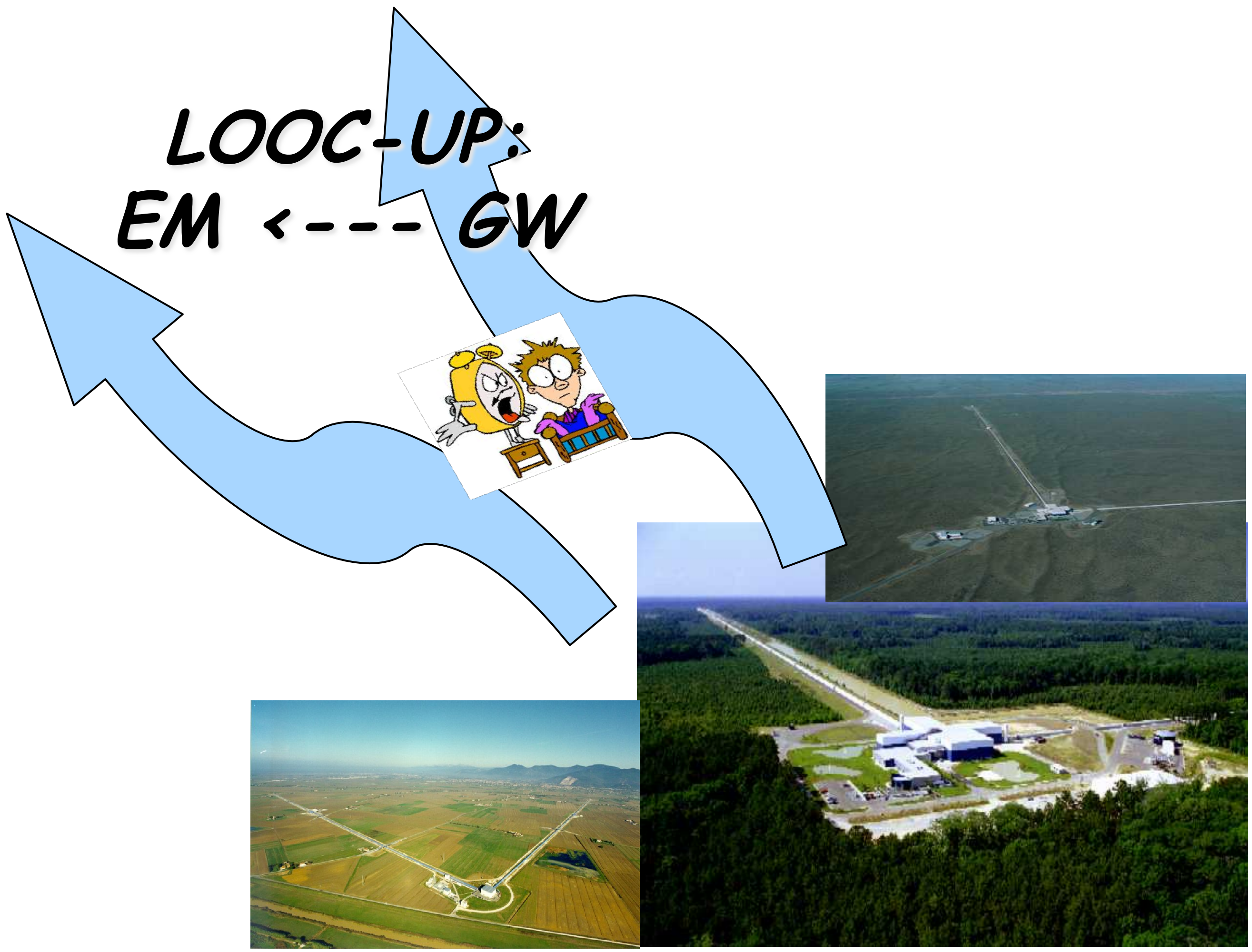
- NS-NS merger: M31 excluded 99% conf. for 070201 (D<3.5 Mpc at 90%); M81 excluded at 71% for 051103 (or 98% with 30deg max inclination).

- UL do not exclude an SGR in M31/M81 (Energy UL for un-modeled GW bursts $\geq 10^{51}$ erg, above e.g. Ioka 2001, and max GW energy by Corsi & Owen 2011, $\sim 10^{48}$ erg).

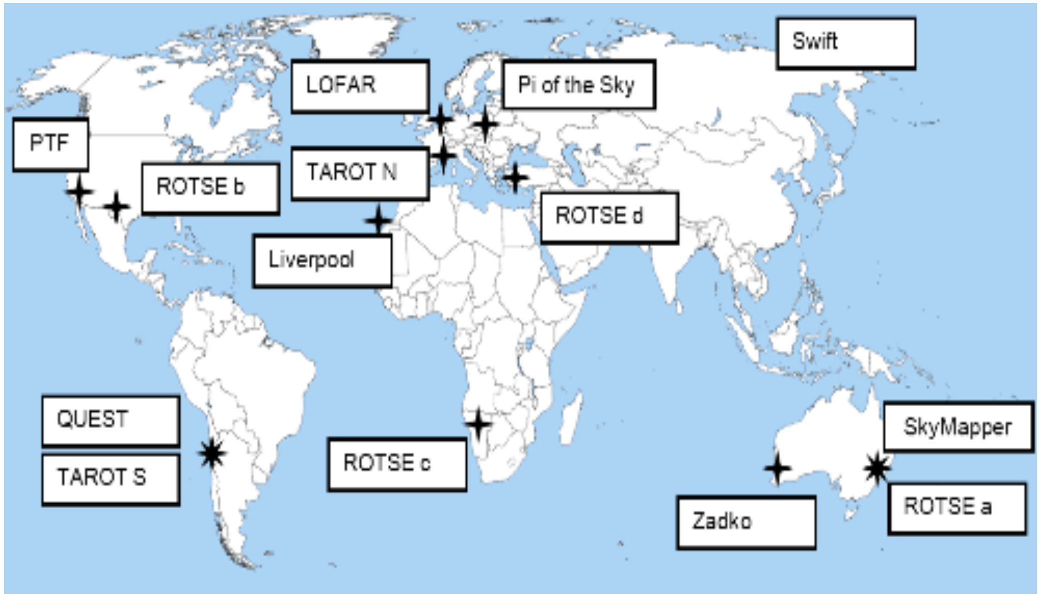



Mazets et al 2008: UV image of the M31 galaxy (Thilker et al. 2005) and the 3 **IPN** error box of GRB 070201 (**Hurley's talk**).

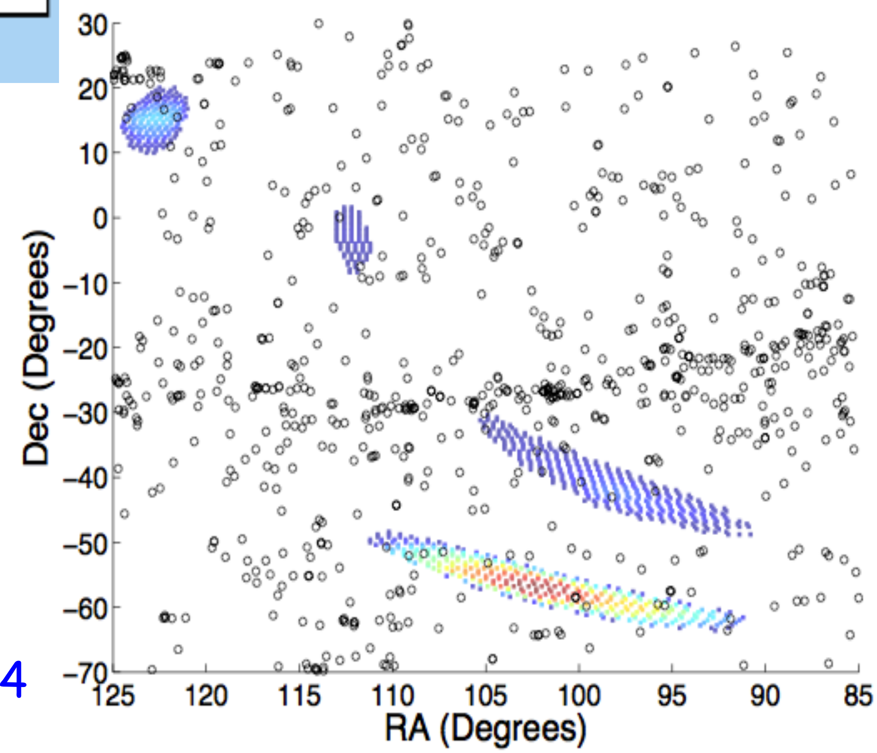
Abbott et al. 2008, ApJ, 681, 1419; Abadie et al. 2012, arXiv1201.4413


LOOC-UP:
EM <---- GW

# "LOOC-UP" project



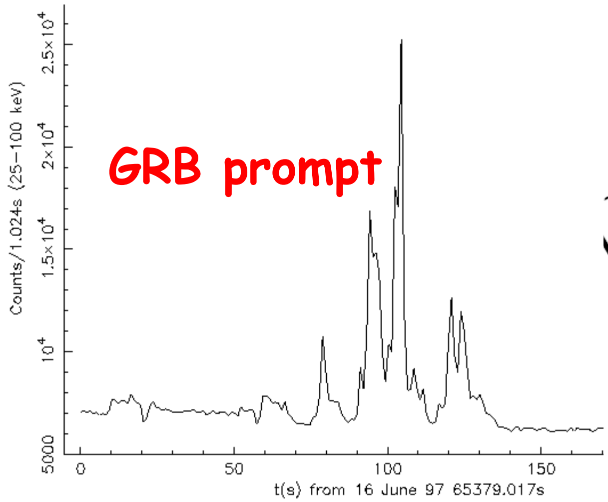

LOOC-UP
"Locating and Observing Optical Counterparts to Unmodeled Pulses" of GWs.
Use of robotic, wide field optical telescopes for follow-up observations of LIGO-Virgo triple coincidences.

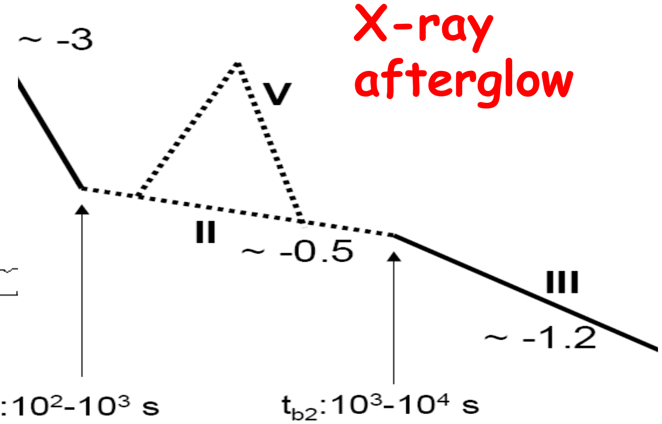



Main challenge: tens of sqr degs for GWs localization error, and error-area may spread on disjoint patches of the sky. Galaxies in the nearby Universe (<50 Mpc) used to prioritize tiles.

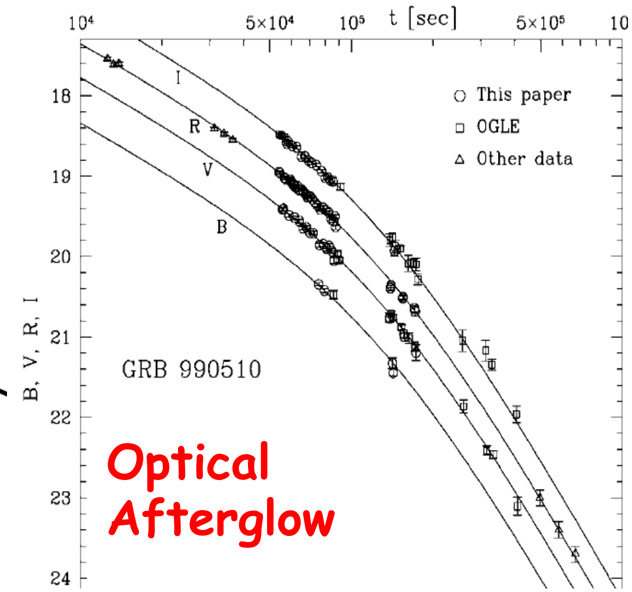
Abadie et al. 2012, A&A 539, A124

# On-axis observer

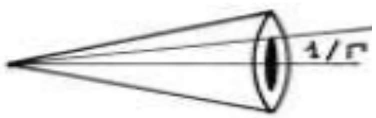


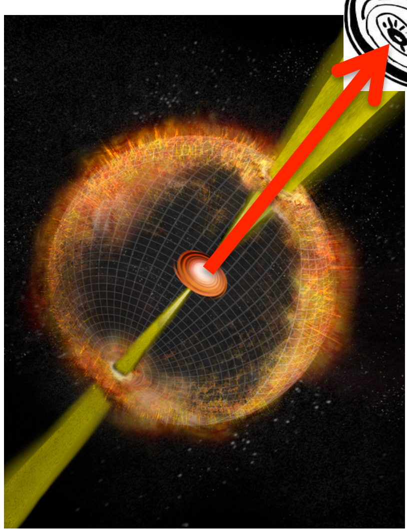



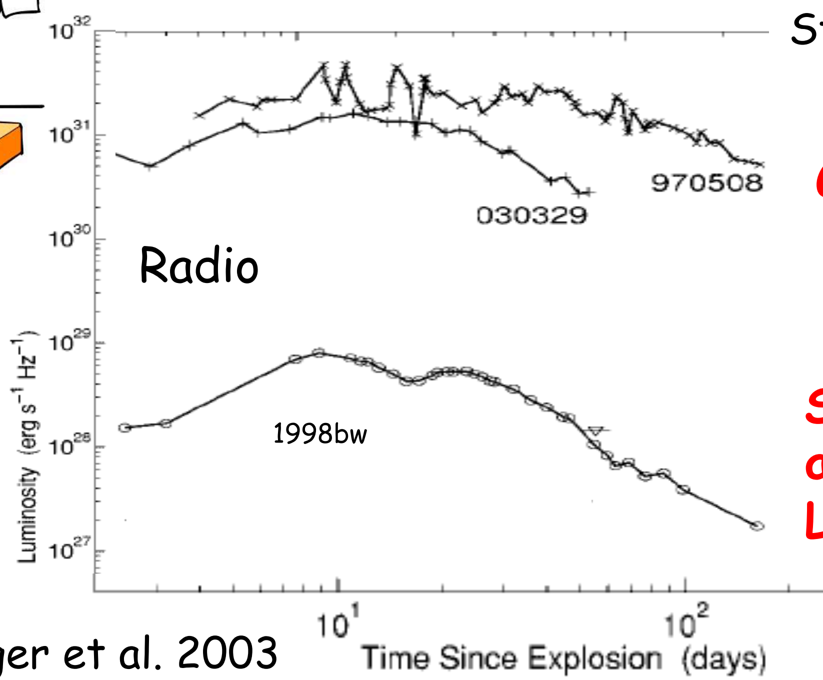

Zhang et al. 2006




Stanek et al. 1999



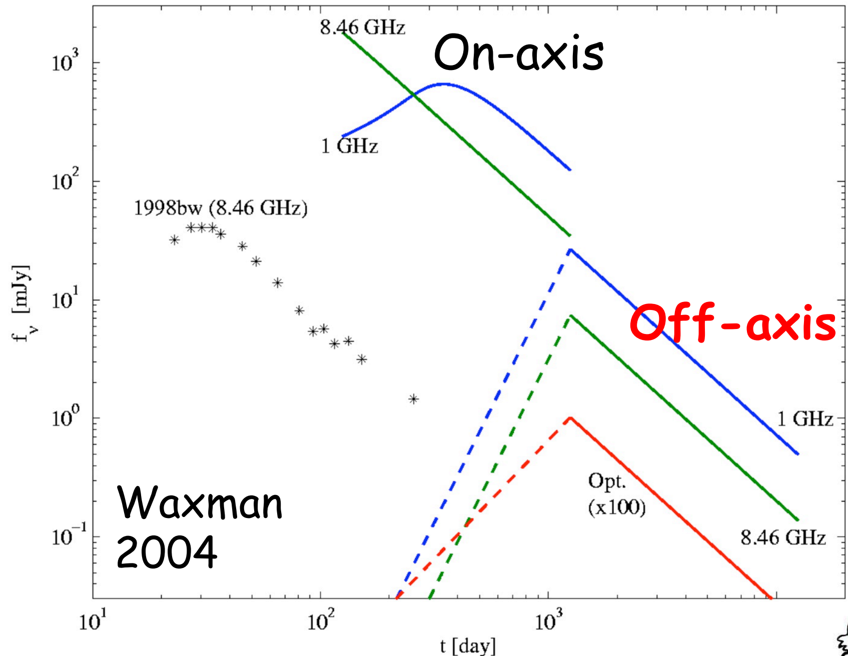



GRB

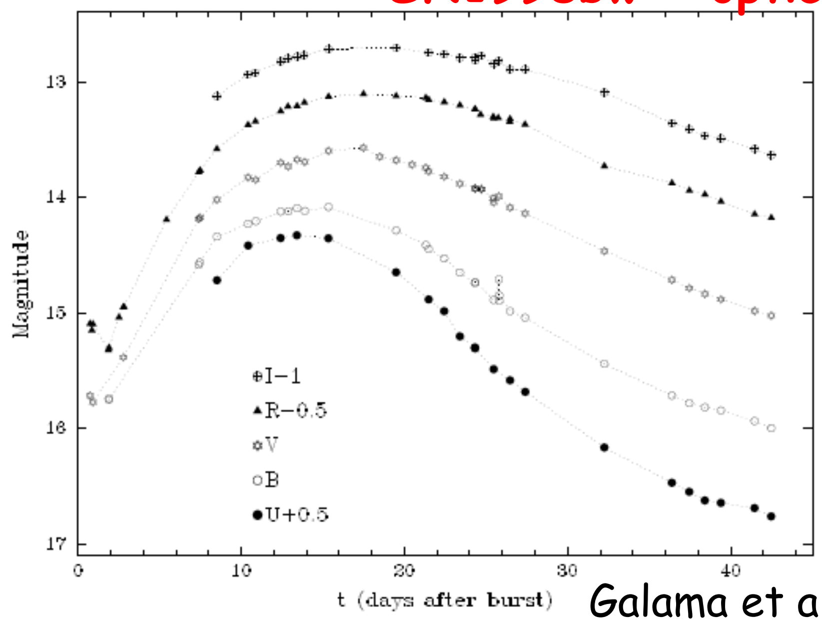
SN associated to LLGRB

Berger et al. 2003

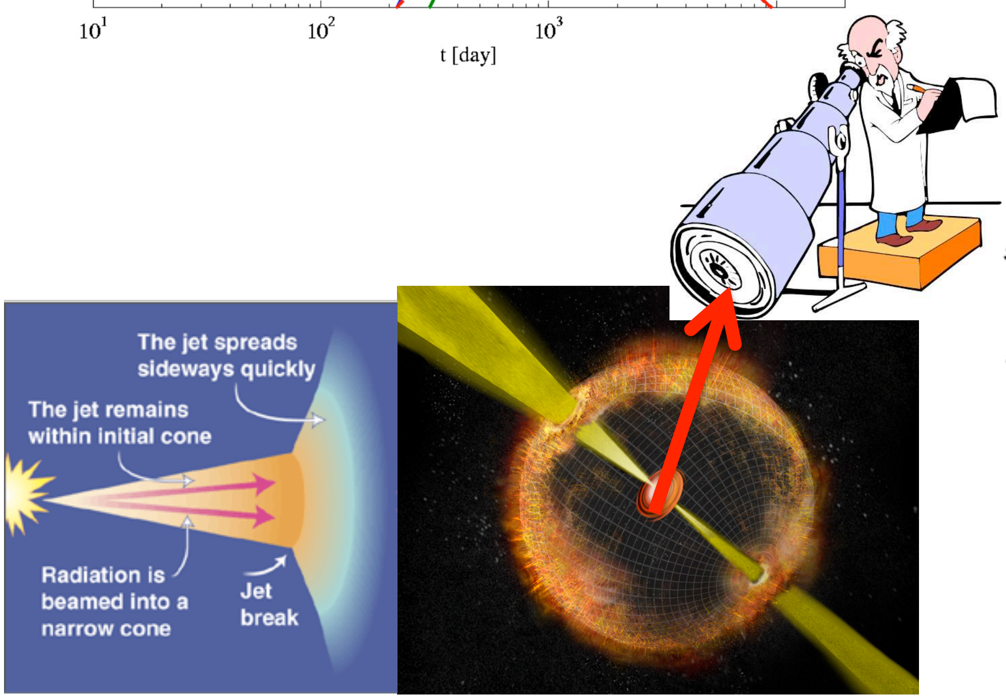
# Off-axis observer

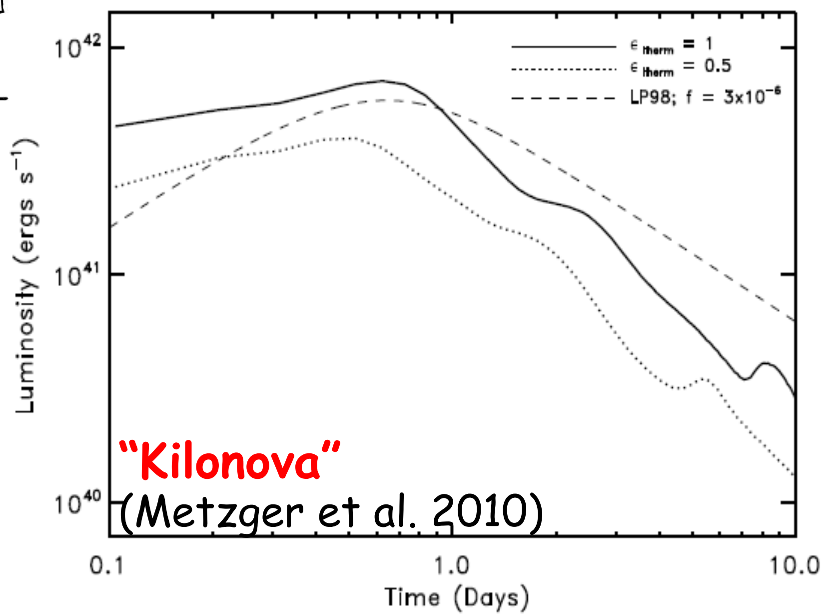



SN1998bw - optical




Galama et al. '98



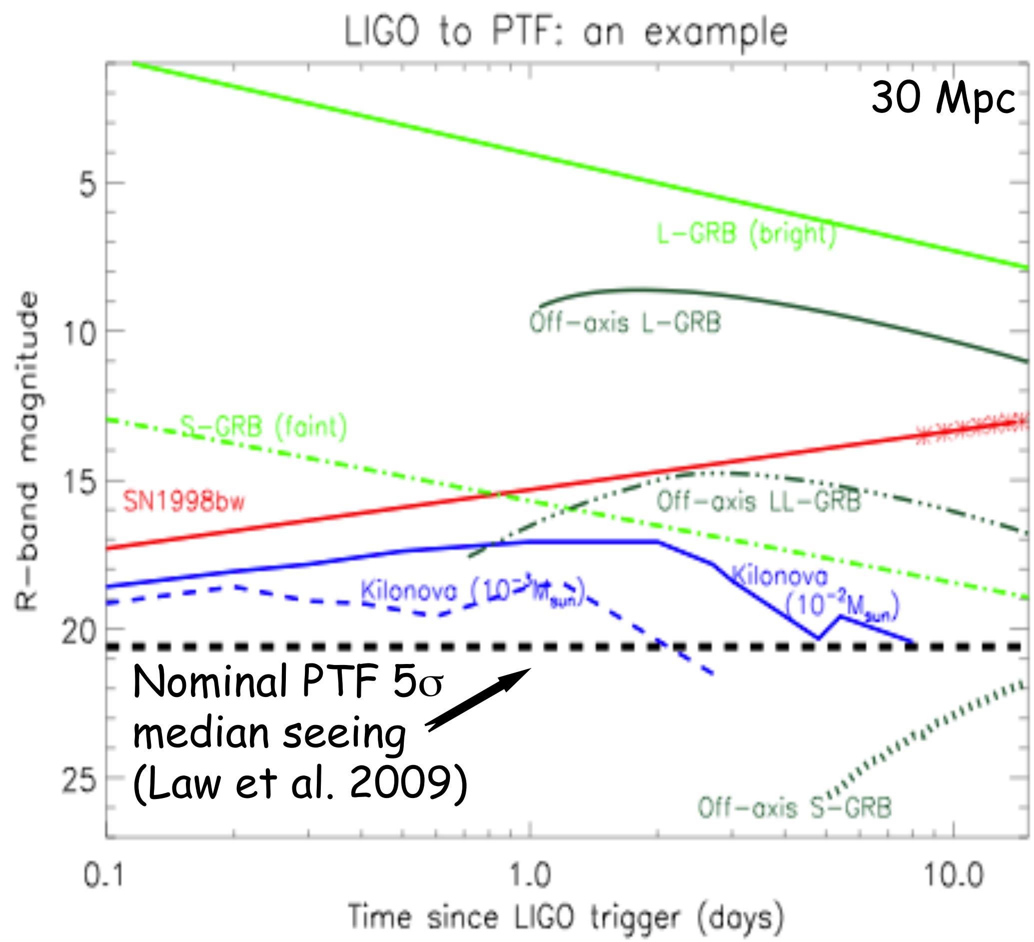
# On/off-axis GRBs as LOOC-UP targets

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):

- **On-axis GRB optical afterglows** (e.g. Kann et al. 2011).

- **Off-axis GRB afterglow** (e.g. van Eerten 2010/11 for R-band LC predictions; **MacFadyen's talk**): would yield a dramatic confirmation of the "jet model" for GRBs.

- **NS-NS** coalescences observed via their optical SN-like emission (e.g. Kulkarni 2005, Metzger et al. 2010).



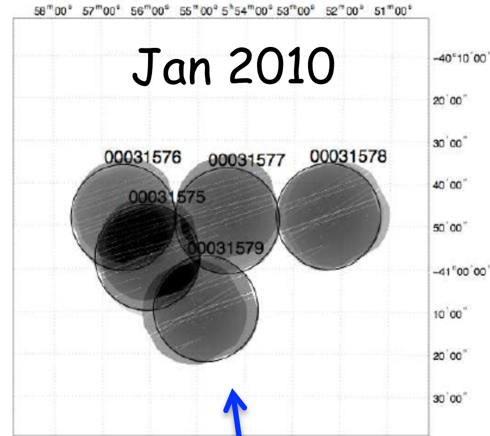
# Follow-up of GW triggers with Swift

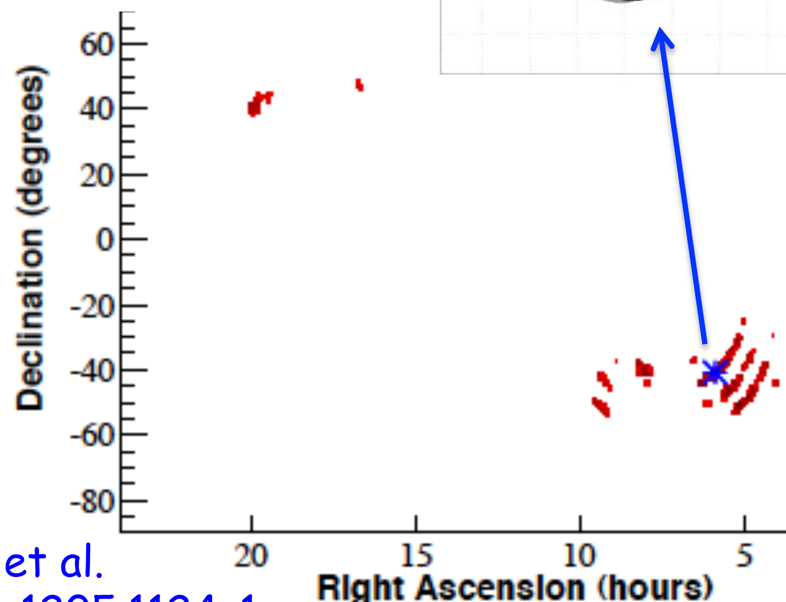
- 2 LOOC-UP events followed by Swift (Jan '10: blind injection; Sep '10: low threshold test).

- XRT/UVOT data from (7 total) observed fields: consistent with expectations for serendipitous sources.

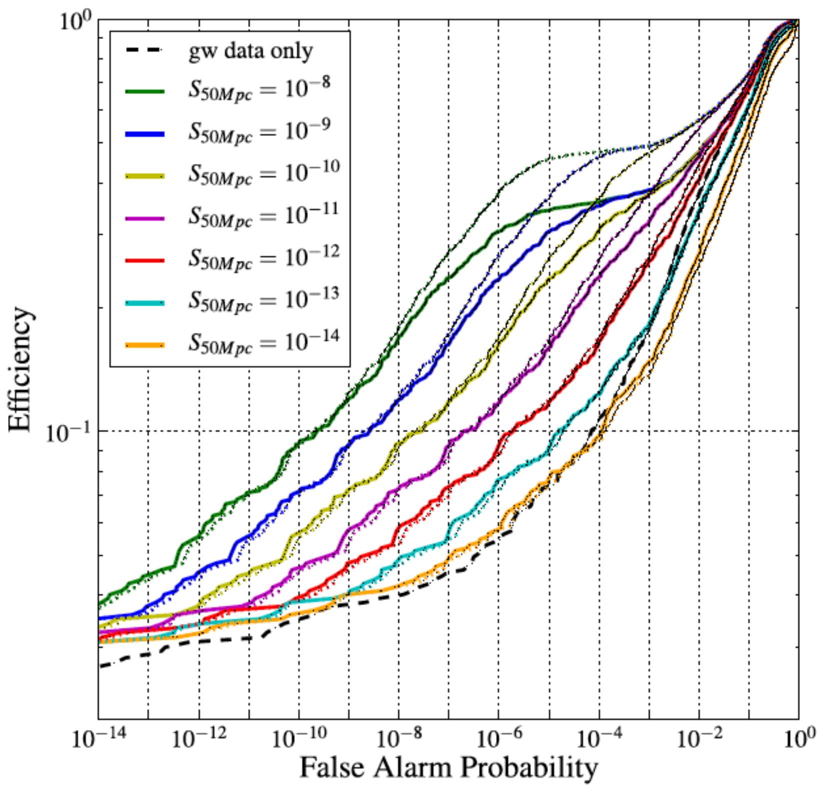
FAR <1/35 d (of triple coinc.).

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



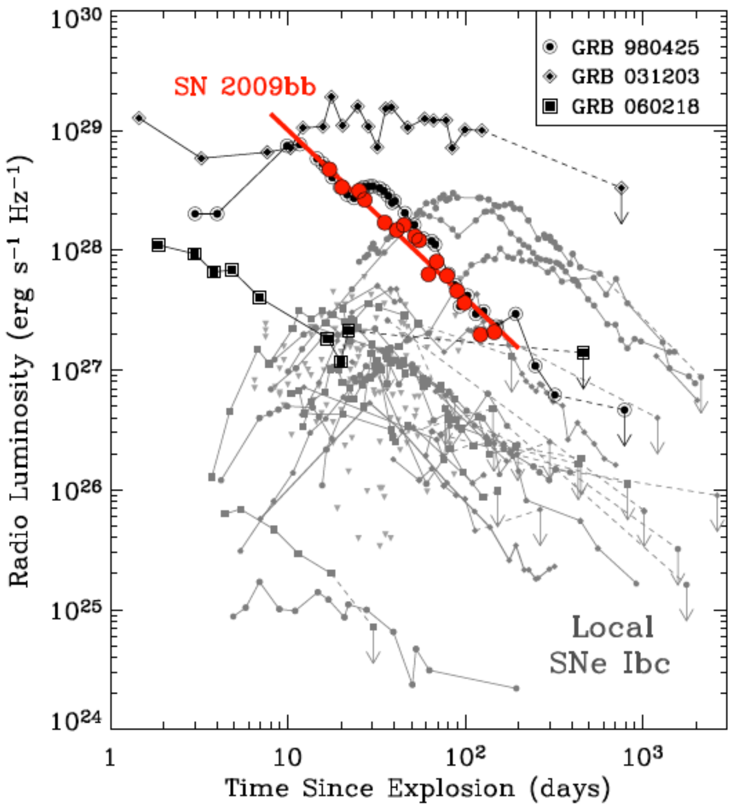




Evans et al.
ArXiv: 1205.1124v1




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.

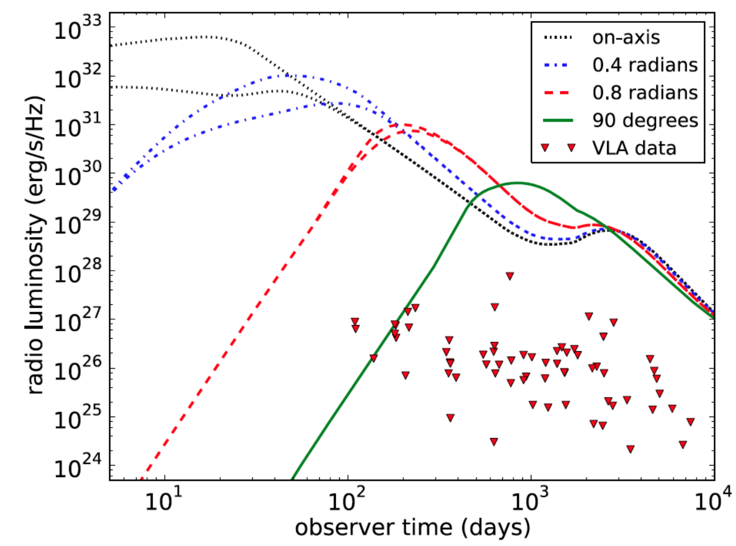
# Radio searches: current studies and future prospects

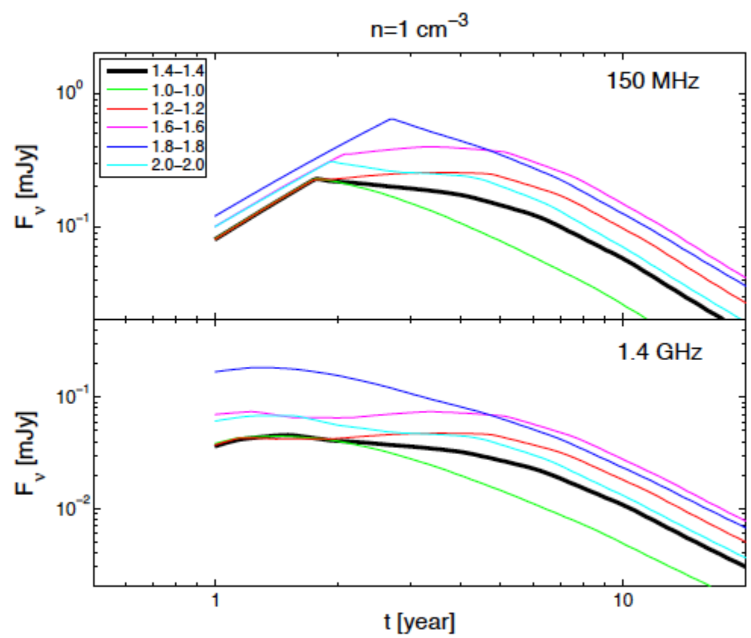



Soderberg et al. 2010, Nature: relativistic SN2009bb without a detected GRB.

ALSO: LOFAR – **Rowlinson's talk**

Right: van Eerten et al. 2010: off-axis GRB models and Ib/c SNe ULs (Soderberg et al. '06).



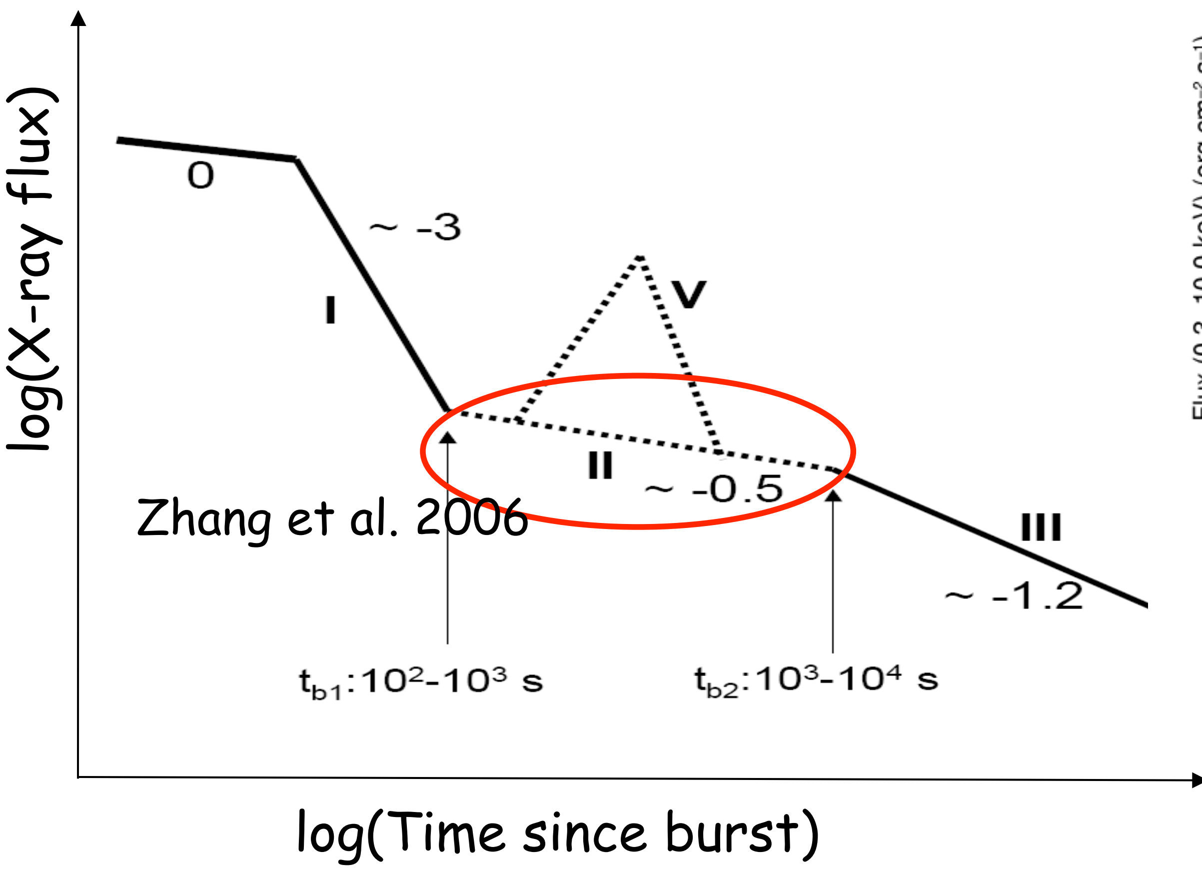



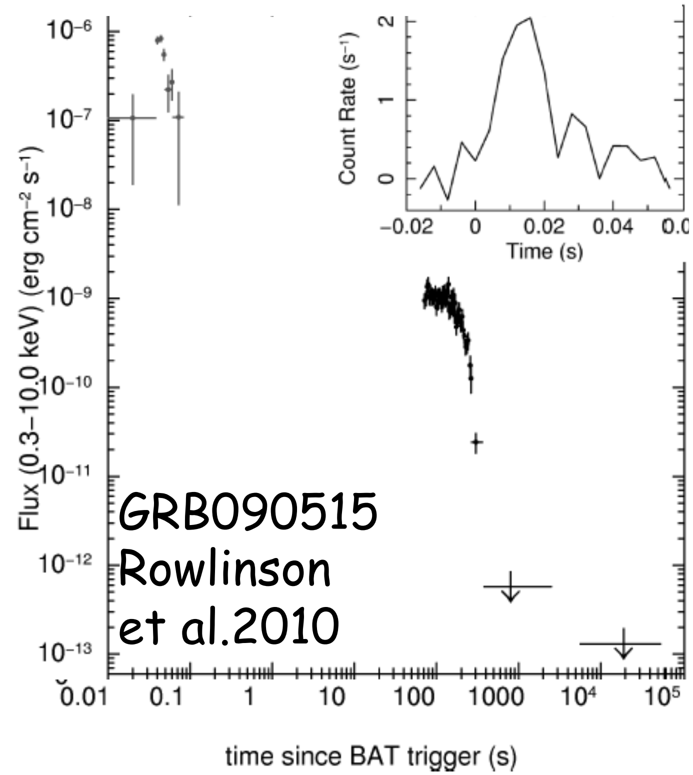

Radio from sub-rel. ejecta in binary mergers (Nakar & Piran 2011, Nature; **Rosswog's talk**)

# Swift results: impact on GW searches

- Magnetar rather than BH may form in explosion (e.g. GRB060218/SN2006aj, Mazzali et al. 2006; **Nagataki's talk**).

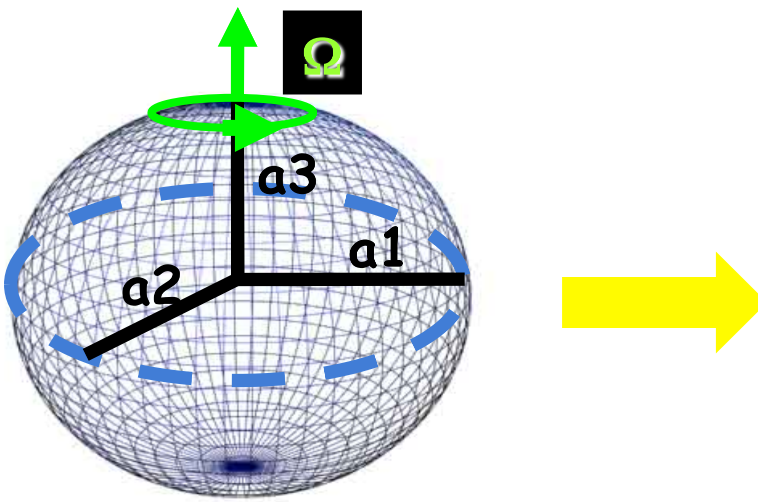
- Magnetar pumping energy into the fireball (e.g. Dai & Lu 1998, Zhang & Meszaros, 2001; … Bernardini et al. 2012)? An associated bar-like GW signal (e.g. Lai & Shapiro 1995, Corsi & Meszaros 2009)?

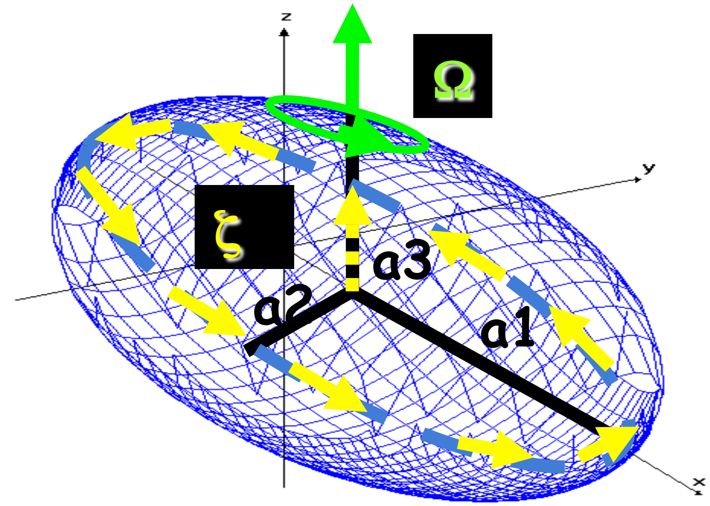



Plateaus in short GRBs?
**O'Brien's talk**

# Secular bar-mode instability in newly born magnetar?




**Initial configuration: Maclaurin spheroid**
**a1=a2≠a3**

**Riemann-S ellipsoid a1≠a2≠a3**

Non-axisymmetric instabilities in rapidly rotating fluid bodies

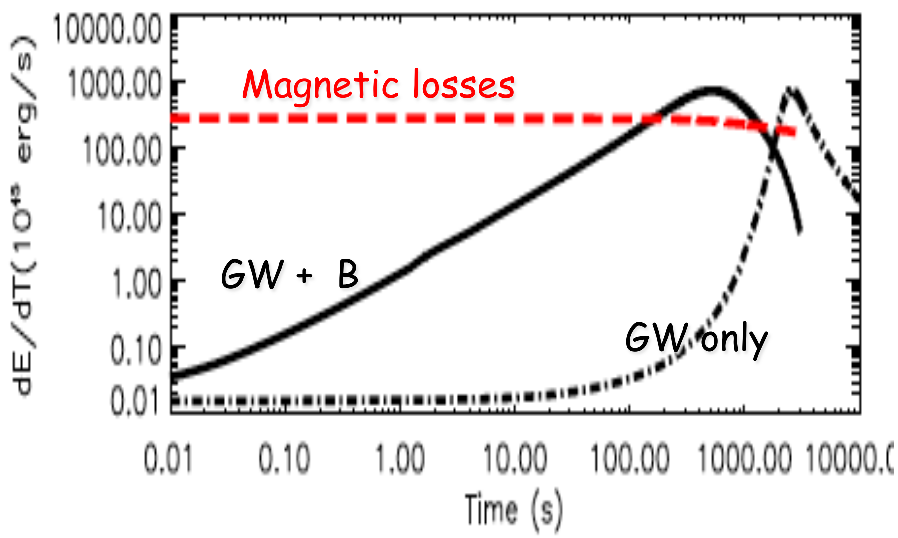
- kinetic-to-gravitational potential energy ratio, $\beta = T/|W|$

- $\beta > 0.27$ : dynamical instability (possibly a burst-type signal)

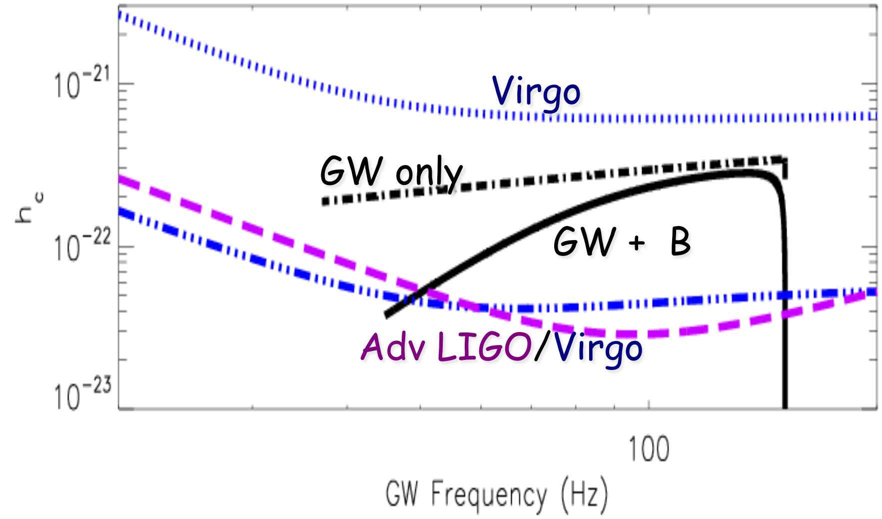
– $\beta > 0.14$ : l=m=2 “bar”-mode oscillations secularly unstable due to e.g. gravitational radiation (e.g. Lai & Shapiro 1995) →sequence of compressible Riemann-S ellipsoids

# GW signal associated to EM plateau

$\beta$=0.20 n=1 M=1.4 $M_\odot$ R=20 km B=$10^{14}$ G

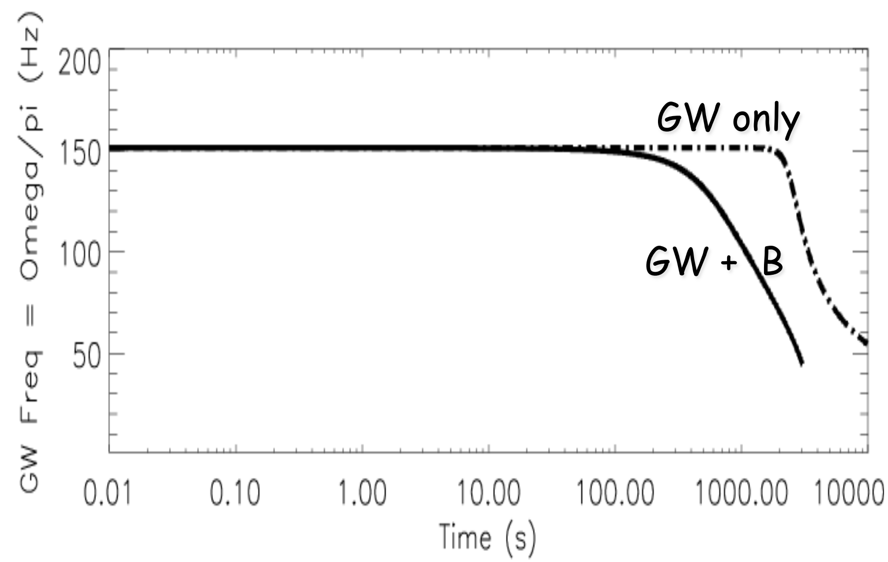



$SNR_{match}$=5 @ d=100-150 Mpc




$$h(t) = \sqrt{\left(\frac{2c^3 d^2 \Omega^2}{5G}\right)^{-1} |L_{GW}|} = \frac{4G\Omega^2}{c^4 d} I\epsilon$$

$$h_+ = -\frac{h(t)}{2}\cos\Phi(1+\cos^2\theta) \quad h_\times = -h(t)\sin\Phi\cos\theta$$




Corsi & Meszaros, 2009

# Conclusion

- GRBs are promising GW sources, EM studies can provide very helpful but indirect constraints on the nature of the progenitor.

- Joint GW studies in coincidence with GRBs are already happening: LIGO-Virgo detectors have been actively following GRB triggers during these years, first LOOC-UP experiment performed, S6/VSR2-3 triggered searches soon on ArXiv; GW searches on IPN GRBs in progress (e.g., Predoi et al. arXiv1112.1637).

- Prospects for the future: more searches possible in the future (e.g. plateau); starting from 2015, advanced LIGO/Virgo detectors (10 times better sensitivity), plus KAGRA, and potentially LIGO India, will provide a totally new view of the Universe.

# The End

## (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).