Gravitational Waves associated with Gamma-Ray Bursts

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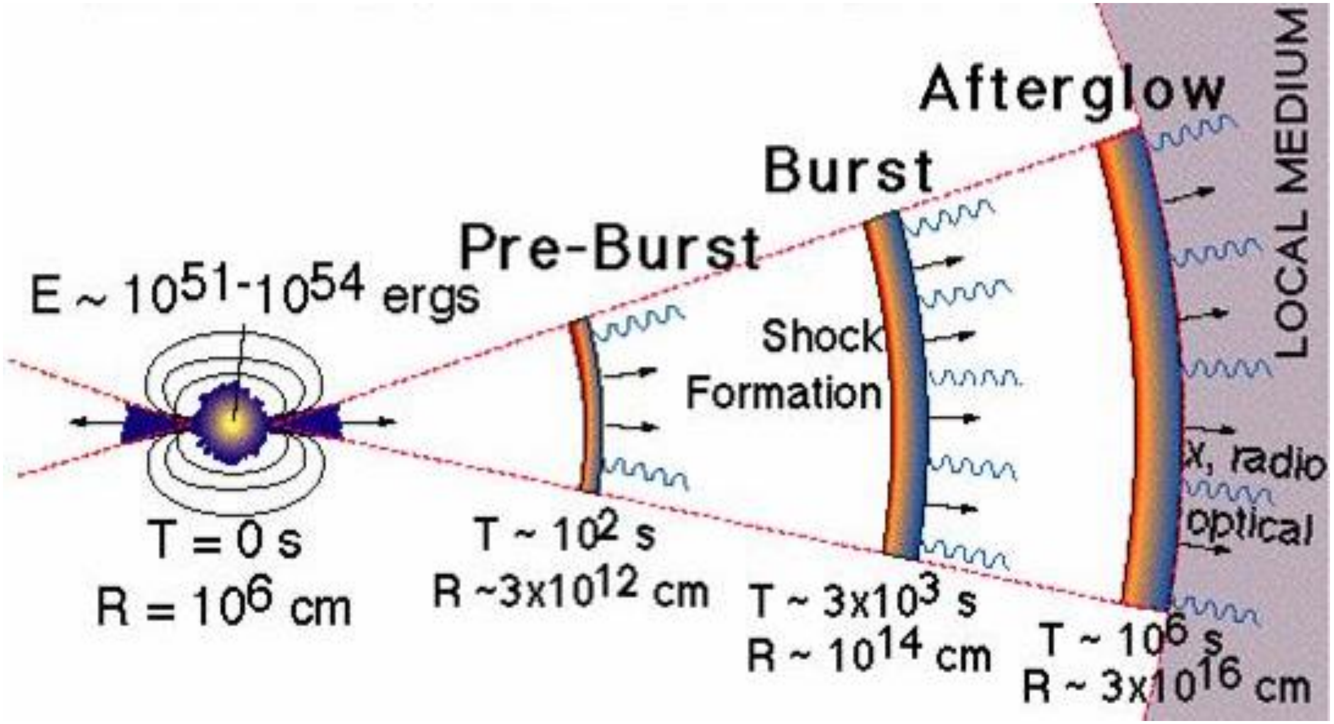
Ioffe Workshop on GRBs: 20 Years of Konus-Wind Experiment

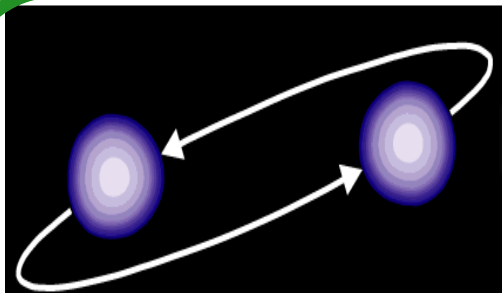
GRBs: EM signal and GW emission

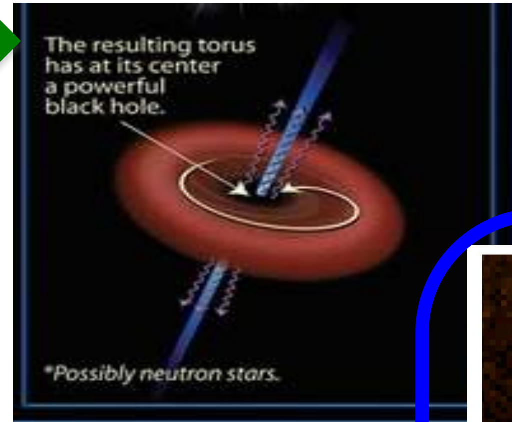


EM signal emitted at large distances: only indirect info on the progenitor.

GWs can probe **for the first time directly** the nature of the progenitor.

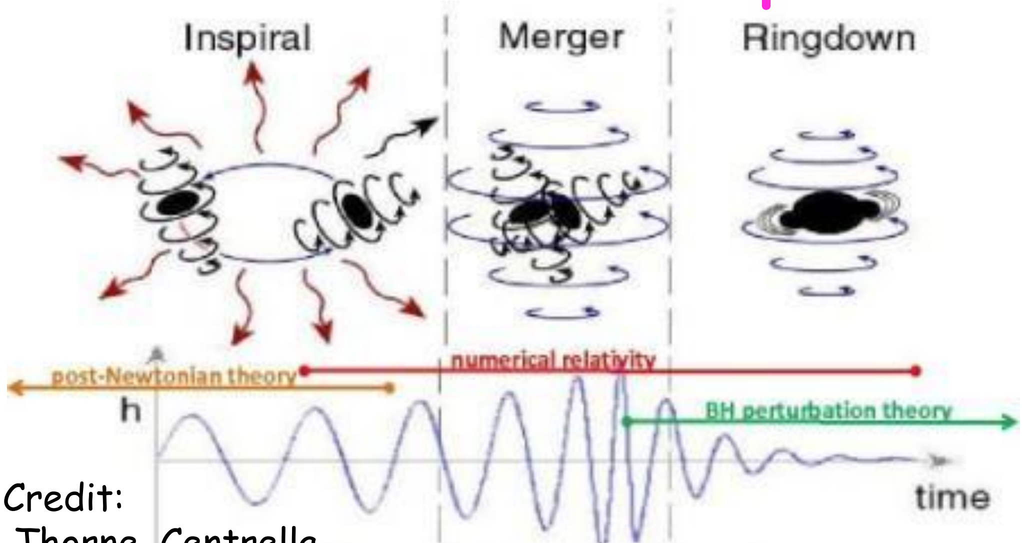
Short GRB progenitors





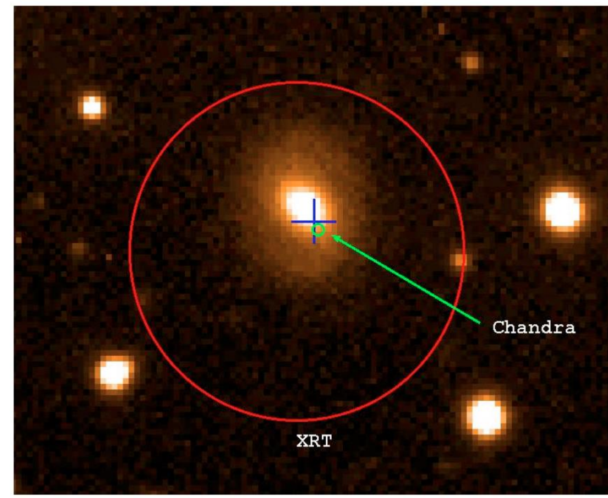
Less massive debris (lower energy), shorter duration (accretion timescale) due to smaller scale of system.

GWs: model's direct probe!



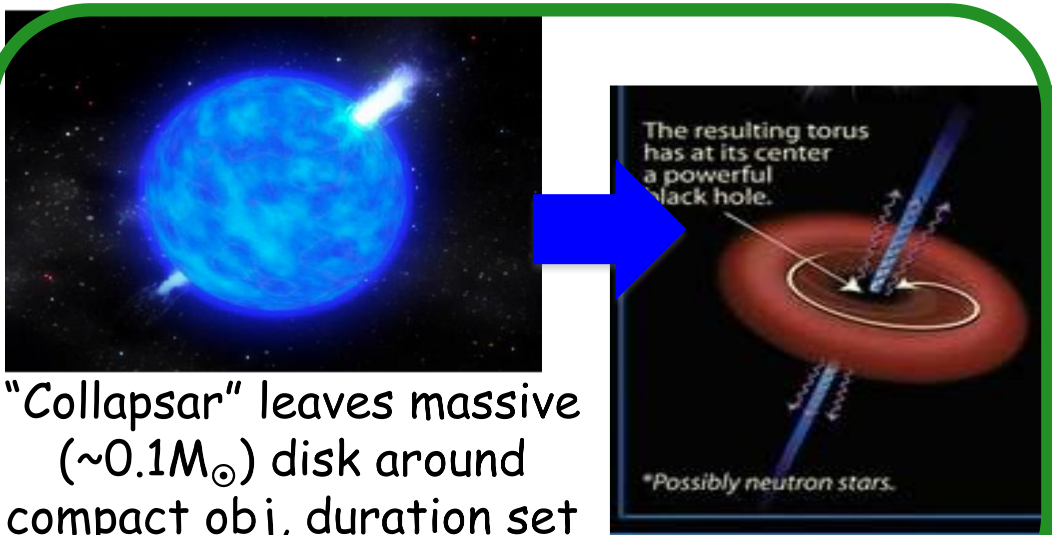
Credit:
Thorne, Centrella

EM obs

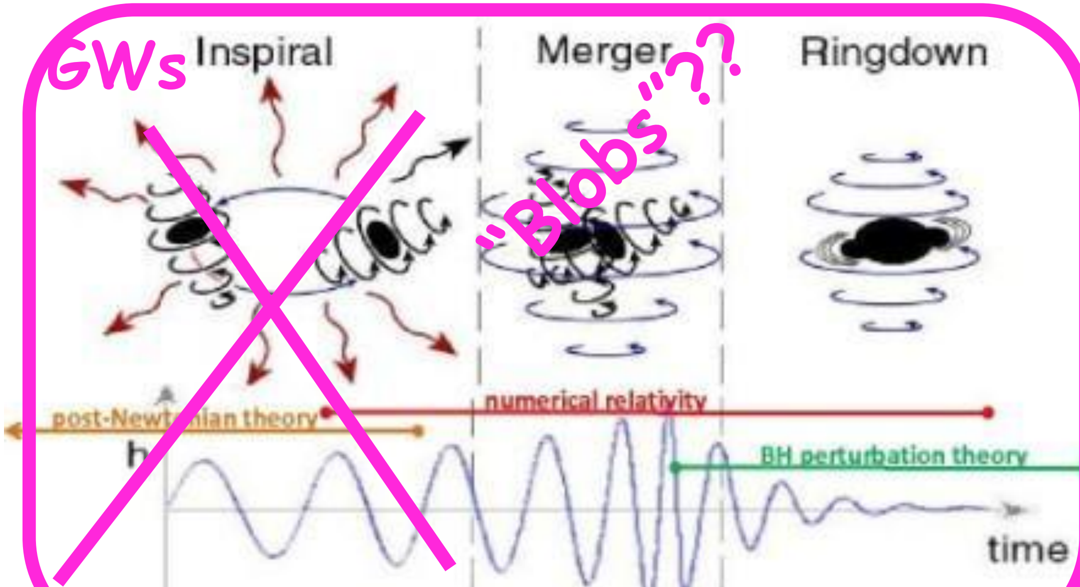


E.g. GRB 050724, Barthelmy et al. 2005 (VLT image): in elliptical galaxy (z~0.26). Low SFR makes SN origin unlikely. E_{iso}~3x10^{50} erg (vs 10^{52}-10^{54} erg of long GRBs).

Long GRB progenitors

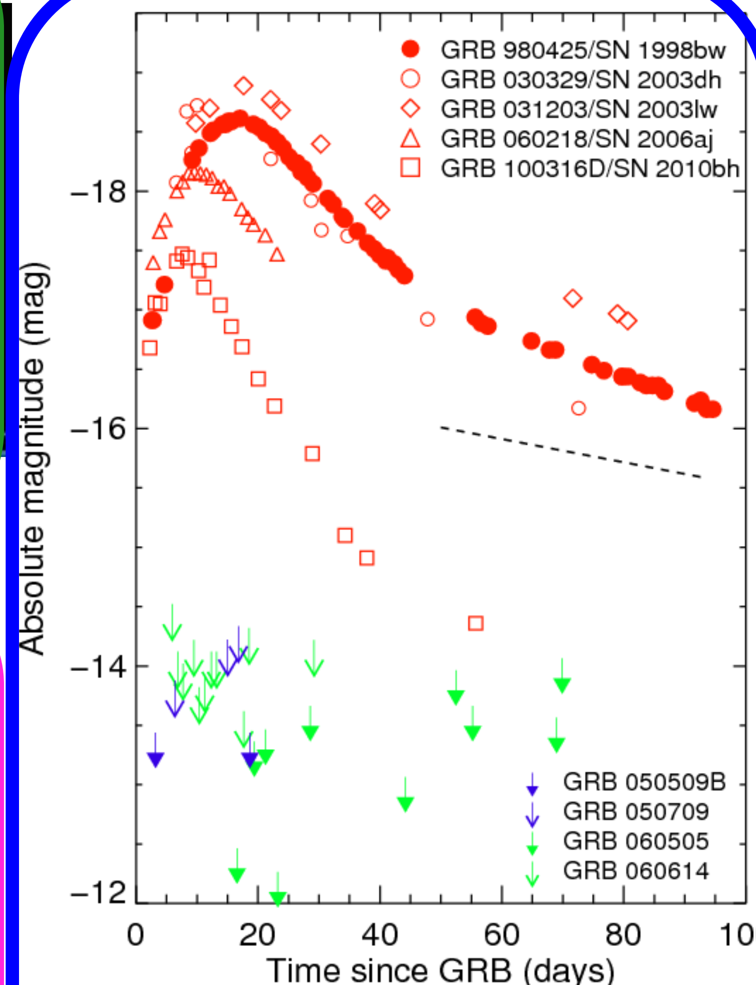


"Collapsar" leaves massive ($\sim 0.1 M_\odot$) disk around compact obj, duration set by fallback timescale.



Credit: Thorne, Centrella

EM obs



Long GRB-SN connection (Hjorth & Bloom 2012)

GRBs as GWs sources

- **CHIRP SIGNAL** (NS-NS/BH-NS) in short GRBs: "golden" target for aLIGO detection (e.g. Flanagan & Hughes 1998; Kochanek & Piran 1993, Abadie et al. 2010, …).

NON-CHIRPS: What can we hope to detect (or at least rule out…)?

- Collapsing core or disk may fragment to produce two or more compact objects (e.g. Fryer et al. 2002). Possible chirp similar to NS-NS (e.g. Davies et al. 2002, Piro & Pfahl 2007) or "merger"-like GW burst (e.g. Kobayashi & Meszaros 2003).

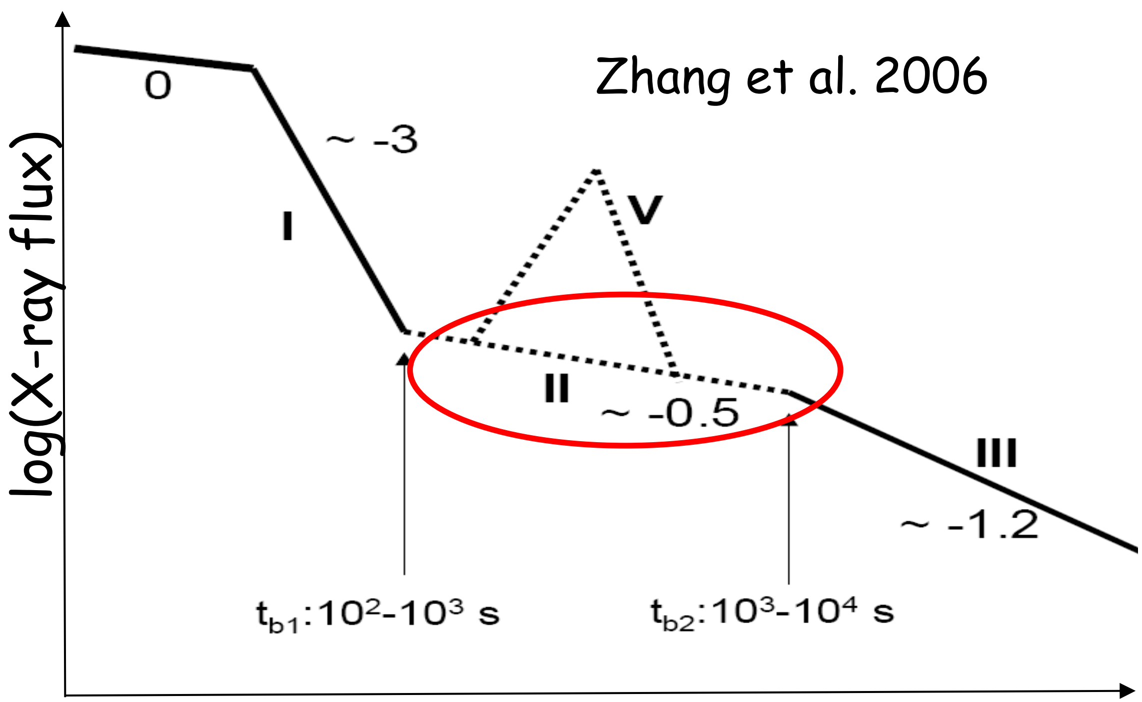
- Core or disk may undergo non-axisymmetric instabilities (e.g. dynamical bar-mode instability; Fryer et al. 2002, Shibata 2003, Kobayashi & Meszaros 2003, Baiotti et al. 2007, Dimmelmeier et al. 2008, … etc. for recent reviews: e.g. Andersson 2003, Ott 2009, Fryer & New 2011).

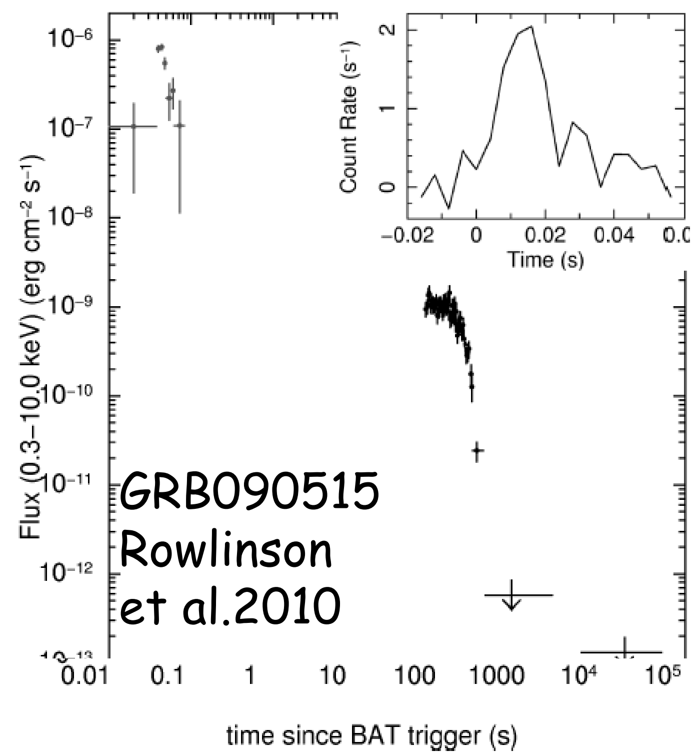
- Nascent BH distorted from quiescent Kerr (e.g. Fryer et al. 2002). Distortion drives GWs as BH settles down to Kerr state (ringing waves; e.g. Echeverria 1993, Shibata & Taniguchi 2006, …).

- If magnetar formed and survives, secular bar-mode instability (e.g. Lai & Shapiro 1995, Shibata et al. 2004, Ou et al. 2004), may be coupled to EM signatures (Corsi & Meszaros 2009).

Magnetar scenario

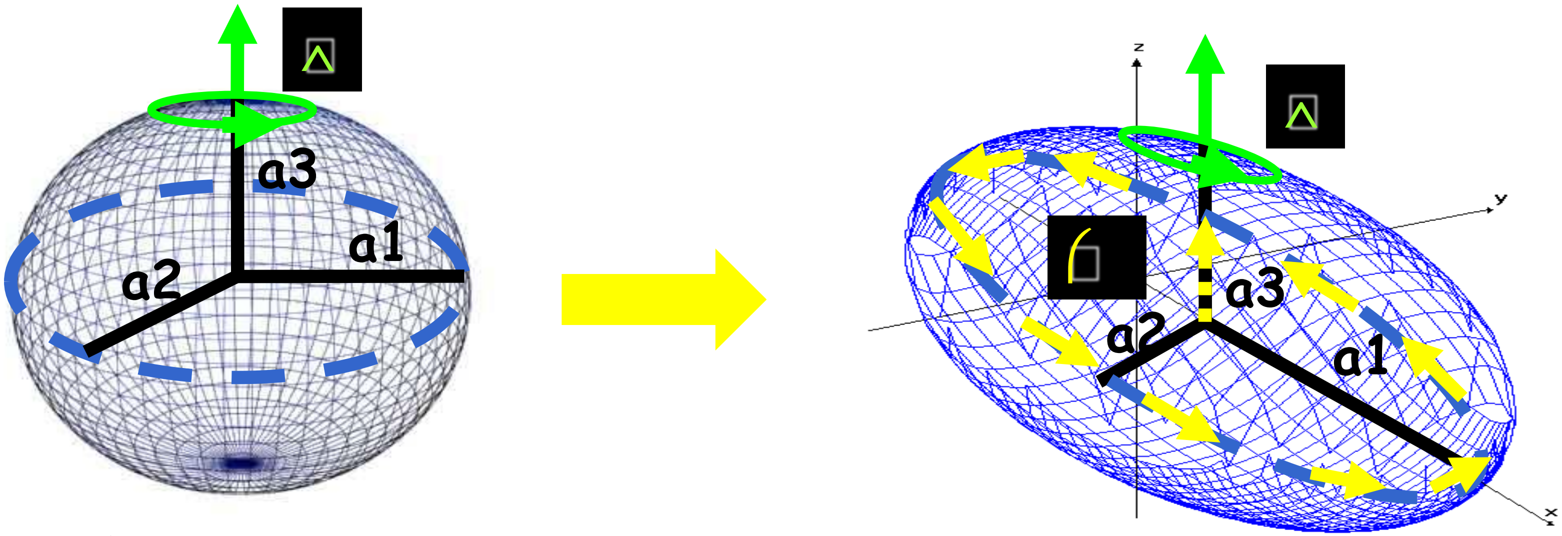
- Magnetar rather than BH may form in explosion (e.g. GRB060218/SN2006aj, Mazzali et al. 2006).
- Magnetar pumping energy into the fireball (e.g. Dai & Lu 1998; Zhang & Meszaros, 2001; … Bernardini et al. 2012, Rowlinson et al. 2013, …)?
- Possible FRB-magnetar connection (e.g., Zhang 2014)?





Plateaus in short GRBs?

Secular bar-mode instability?



Initial configuration:
Maclaurin spheroid a1=a2□a3

Riemann-S ellipsoid a1□a2□a3

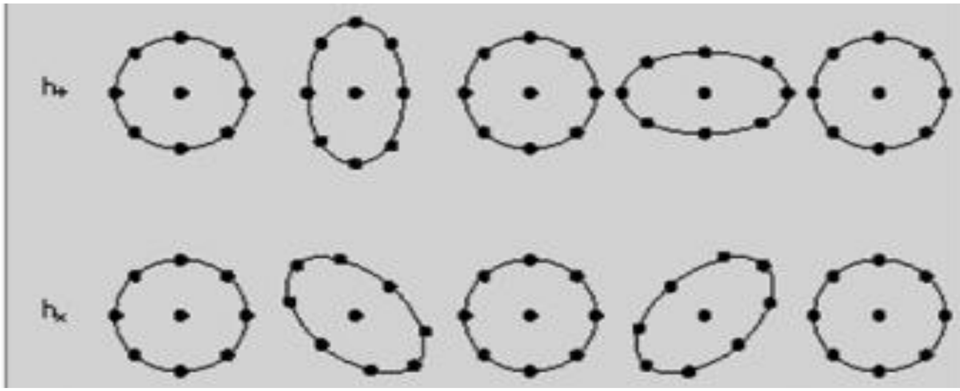
Non-axisymmetric instabilities in rapidly rotating fluid bodies

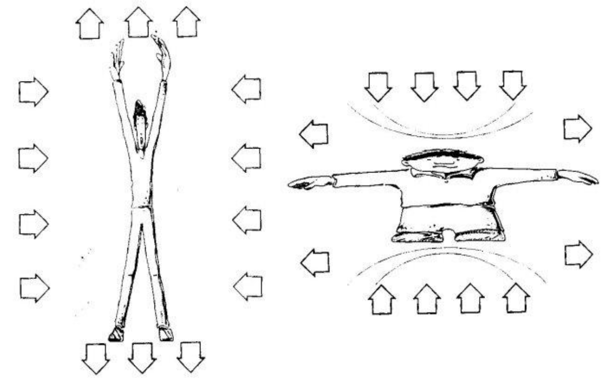
- kinetic-to-gravitational potential energy ratio, ®=T/|W|

- β > 0.27 (classical): dynamical instability (possibly a burst-type signal). Also lower-β instability possible (e.g., Watts et al. 2005).

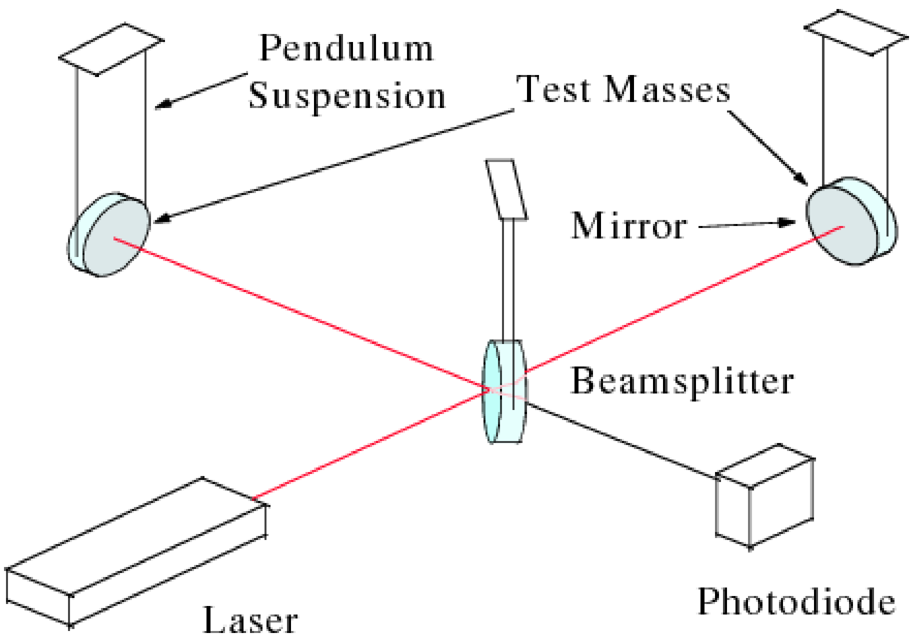
– ® > 0.14 : l=m=2 "bar"-mode oscillations secularly unstable due to e.g. gravitational radiation (e.g. Lai & Shapiro 1995) →sequence of compressible Riemann-S ellipsoids

Detecting gravitational waves





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.

$h_c=|h(f)|\ f\sim$ □N h "characteristic amplitude"

The network of ground-based GW detectors

LIGO Hanford
(4km - USA)

LIGO Livingston
(4km -USA)

Virgo (3km - Italy)

GEO (600m - Germany)

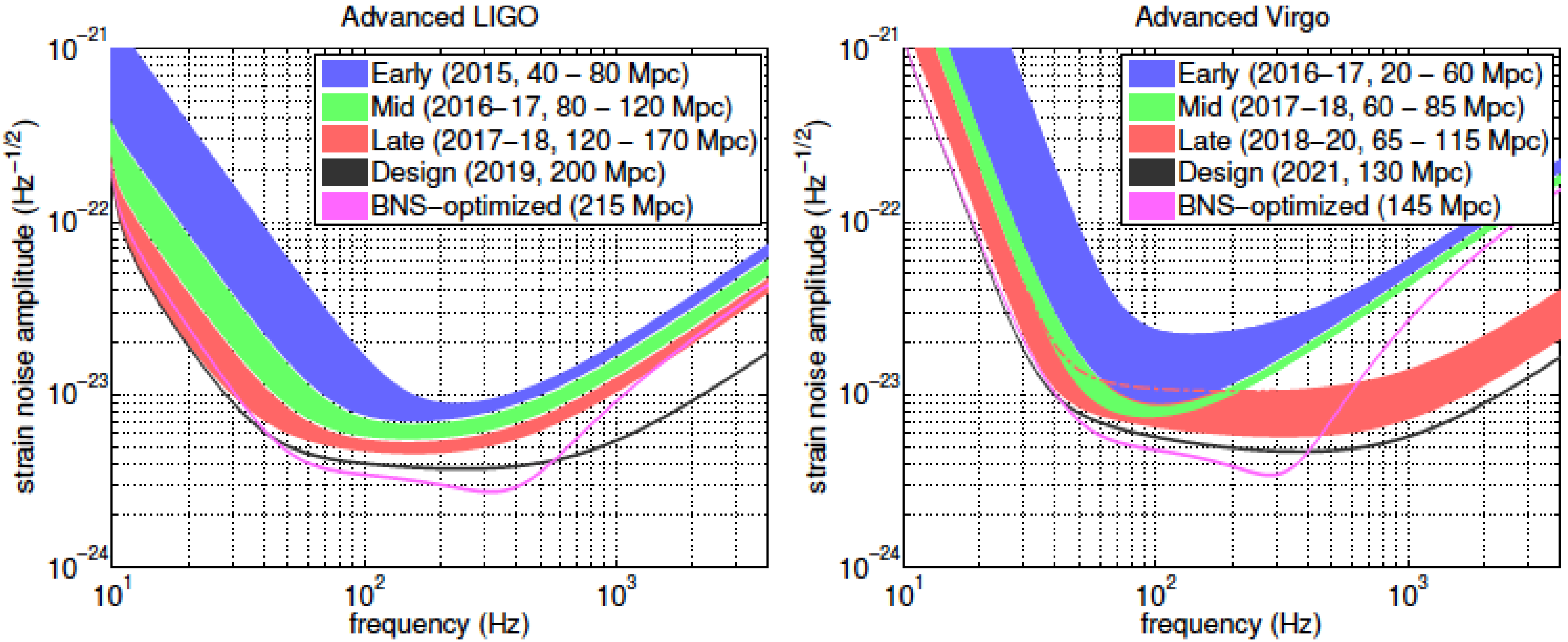
But also:

- Kamioka cryogenic GW detector (KAGRA)

- LIGO India

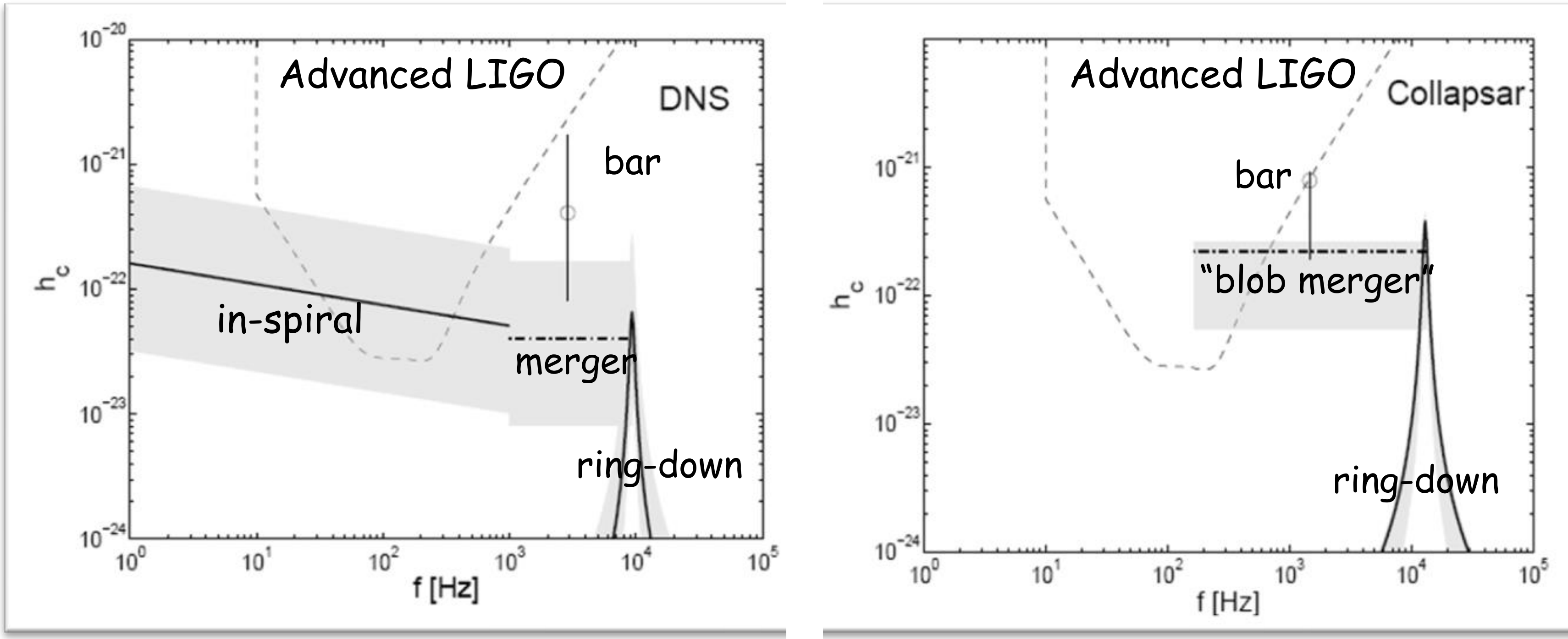
Toward the advanced detectors era

Aasi et al. 2013 (arXiv:1304.0670)



- Target strain sensitivity as a function of frequency for early, middle, and late commissioning phases.
- Average detection distance for NS-NS binaries (BNS) given in Mpc.
- Dates / sensitivities are current best estimates (subject to changes).

GWs and GRBs: "standard" scenario ULs

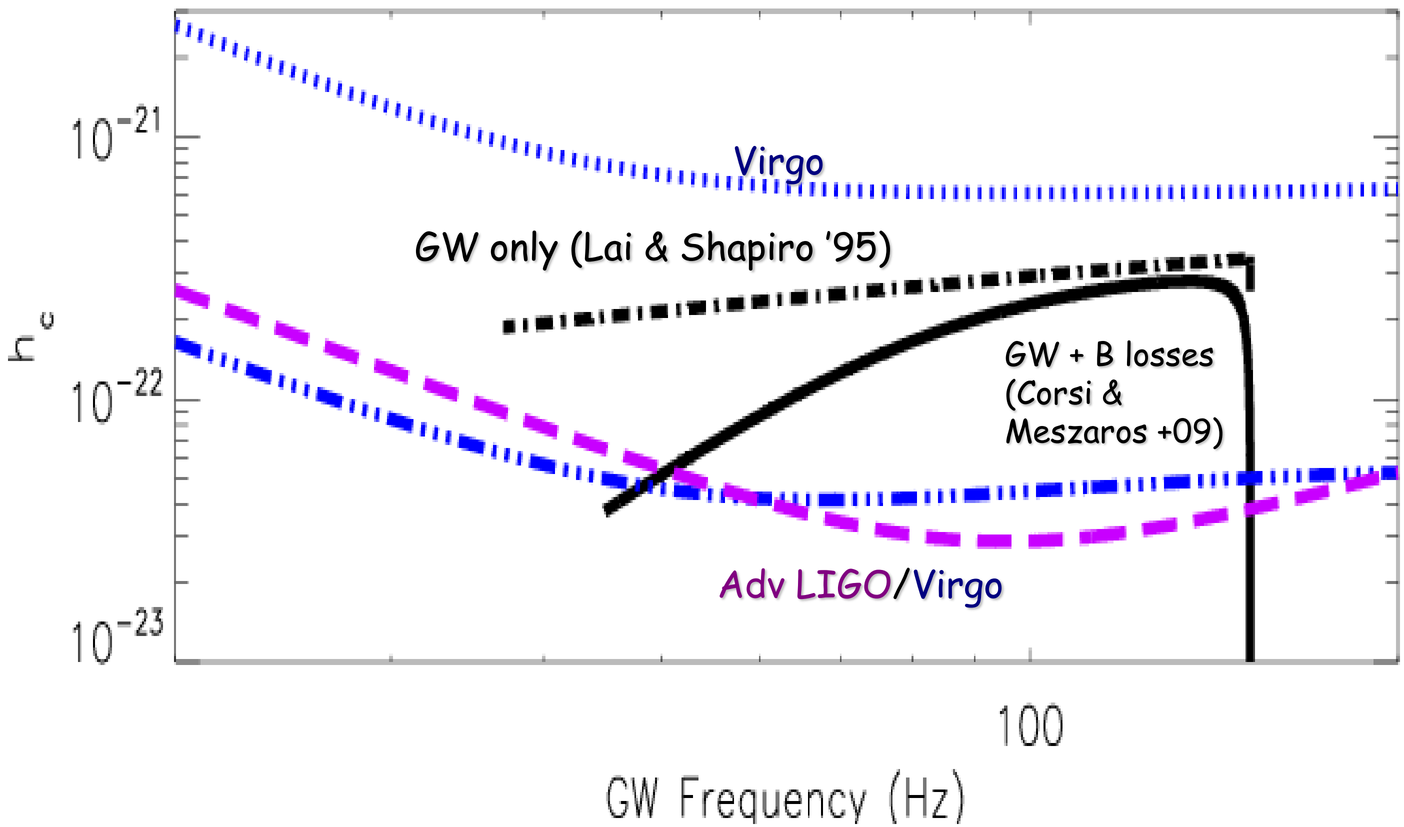


Kobayashi & Meszaros 2003 (and Fryer et al. 2002)
ULs assume 1% of tot mass in GW during merger, 5% in BH ring-down

Distance range used for shadowed regions in plot:
- 50 Mpc - 1 Gpc for NS-NS;
- 20-100 Mpc for collapsar.

GWs and GRBs: magnetar / plateau scenario

®=0.20 n=1 M=1.4 $M_\odot$ R=20 km B=10^{14} G SNR$_{match}$=5 @ d=100-150 Mpc



$$\frac{dE}{dT} = -\frac{B_p^2 R^6 \Omega_{eff}^4}{6c^3} - \frac{32 G I^2 \epsilon^2 \Omega^6}{5c^5} = L_{dip} + L_{GW}$$

$$h_+ = -\frac{h(t)}{2}\cos\Phi(1+\cos^2\theta) \quad h_\times = -h(t)\sin\Phi\cos\theta \qquad h(t) = \sqrt{\left(\frac{2c^3 d^2 \Omega^2}{5G}\right)^{-1} |L_{GW}|} = \frac{4G\Omega^2}{c^4 d} I\epsilon$$

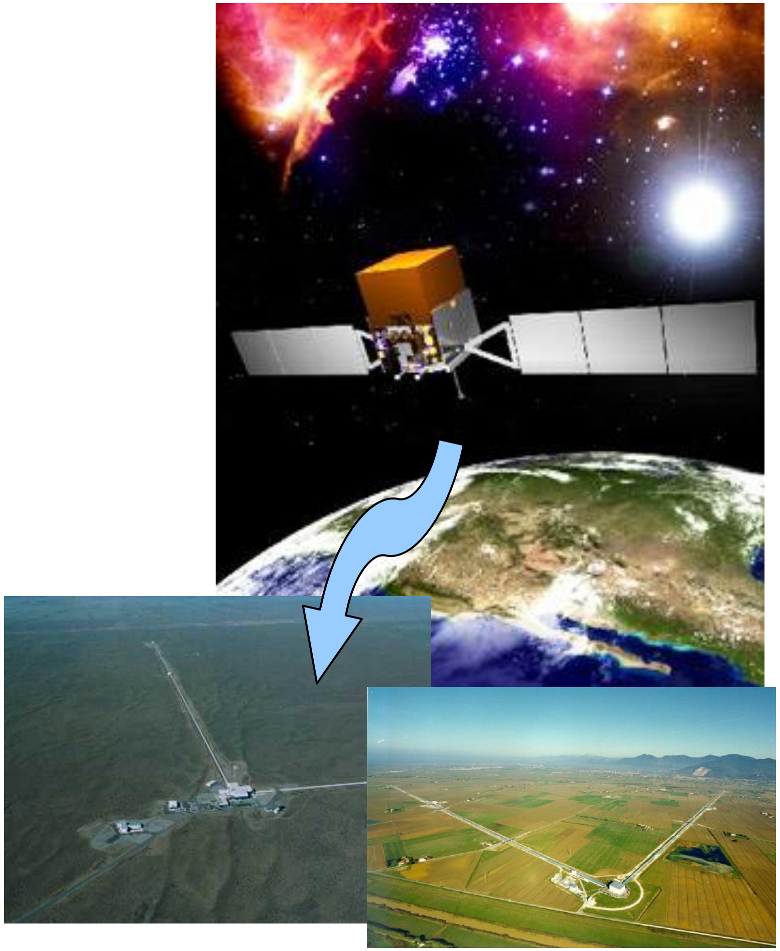
BNS detection rates in the GW window

Epoch	Estimated Run Duration	BNS Range (Mpc) LIGO	BNS Range (Mpc) Virgo	Number of BNS Detections
2015	3 months	40 – 80	–	0.0004 – 3
2016–17	6 months	80 – 120	20 – 60	0.006 – 20
2017–18	9 months	120 – 170	60 – 85	0.04 – 100
2019+	(per year)	200	65 – 130	0.2 – 200
2022+ (India)	(per year)	200	130	0.4 – 400

Aasi et al. +13, arxiv:1304.0670

- The BNS range reflects the uncertainty in the detector noise spectra.
- The BNS detection numbers also account for the uncertainty in the BNS source rate density (10^{-8}-10^{-5} Mpc^{-3}yr^{-1}; also M. Pruzhinskaya's talk).

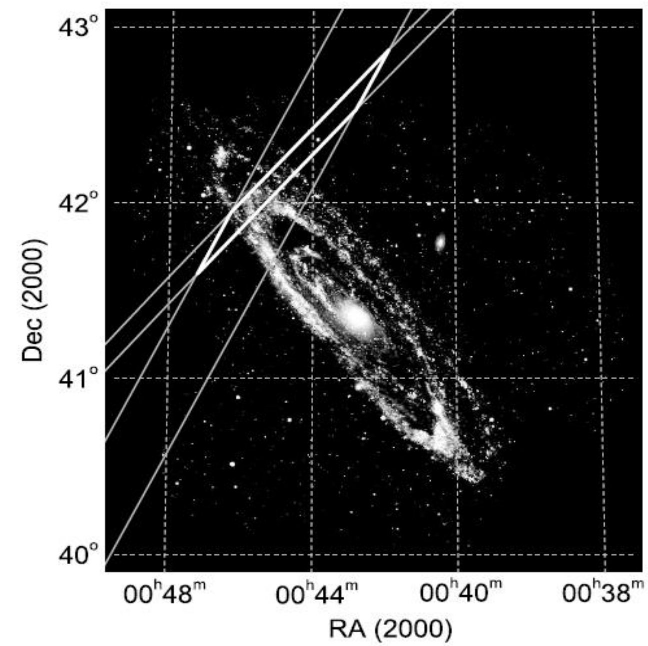
Short-GRB triggered detections of BNS



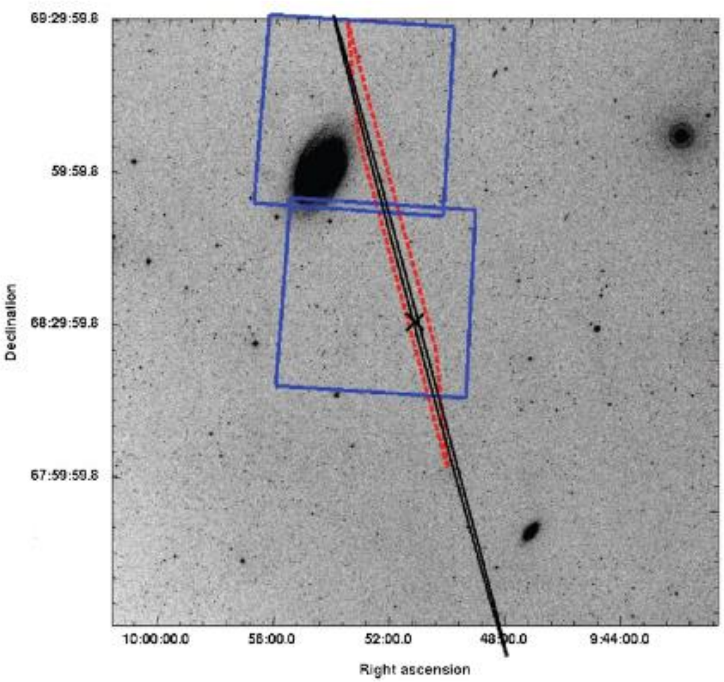
- Known trigger time (and position).
- ~2x improvement in horizon distance with respect to un-triggered (e.g., Kochanek & Piran 1993; Acernese et al. 2008; Abadie et al. 2010, Phys. Rev.; Abadie et al. 2010, ApJ).
- Short GRBs within 200 Mpc are ~0.3/yr (Nakar 2006, Metzger & Berger 2012), at the lowest end of the BNS source rate estimates, can be explained by beaming if θ_j~0.12 (as for GRB051221A; Soderberg et al. 2006).
- Still in a few years aLIGO could probe the BNS progenitor scenario for short GRBs!

Short GRB triggered searches with LIGO

- GRB 070201 in M31 (770 kpc)? (e.g. Ofek et al. 2008; Abbott et al. 2008). GRB 051103 in M81?
- No GW in-spiral signal in on-source window. NS-NS merger: M31 excluded 99% confidence.
- SGR scenario NOT excluded by LIGO upper-limits.



Mazets et al 2008: UV image of the M31 galaxy (Thilker et al. 2005) and the 3σ IPN error box of GRB 070201.

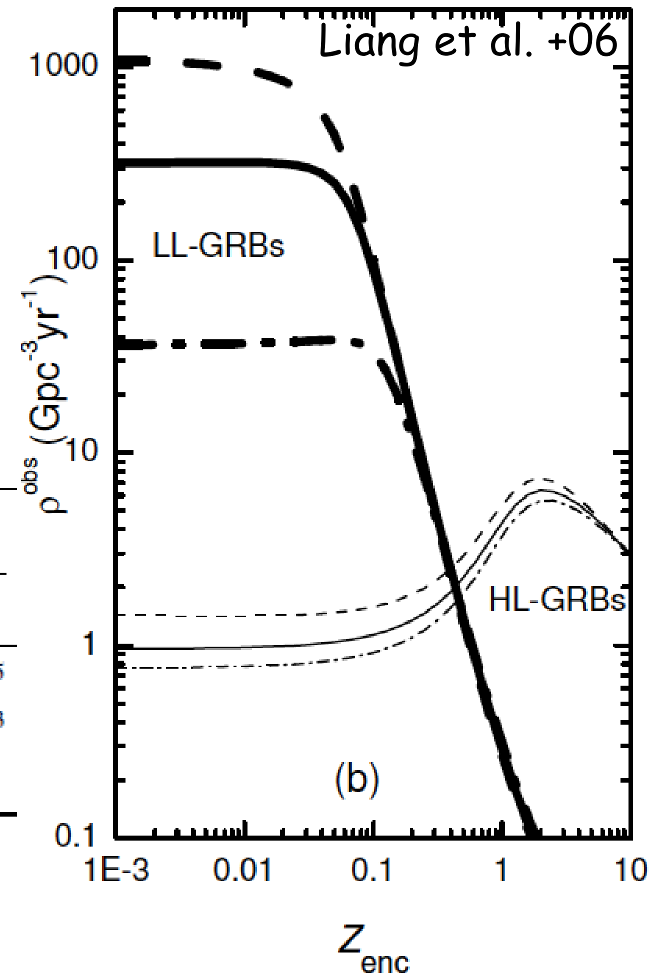


Central region of the M81 group, with original IPN error trapezium (red) and refined 3σ error ellipse (black) of GRB 051103. Blue are regions studied in optical (Hurley et al. 2010).

Prospects for GW bursts (and long GRBs)…

Epoch	Estimated Run Duration	$E_{\rm GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc) LIGO	Virgo
2015	3 months	40 – 60	–
2016–17	6 months	60 – 75	20 – 40
2017–18	9 months	75 – 90	40 – 50
2019+	(per year)	105	40 – 80
2022+ (India)	(per year)	105	80

Non EM-triggered distance reach (Aasi et al. 2013)



GRB-triggered

Detector	Estimated average distance reach (Mpc)	Estimated detection rate (yr^{-1}) Long GRBs	Short GRBs
Initial LIGO–Virgo[a]	~15	$\sim 1 \times 10^{-6}$	$\sim(1.6\text{–}6.1) \times 10^{-5}$
Enhanced LIGO–Virgo[b]	~30	$\sim 5.7 \times 10^{-5}$	$\sim(0.9\text{–}3.4) \times 10^{-3}$
Advanced LIGO–Virgo	~150	$\sim 7.1 \times 10^{-3}$	~0.11–0.42

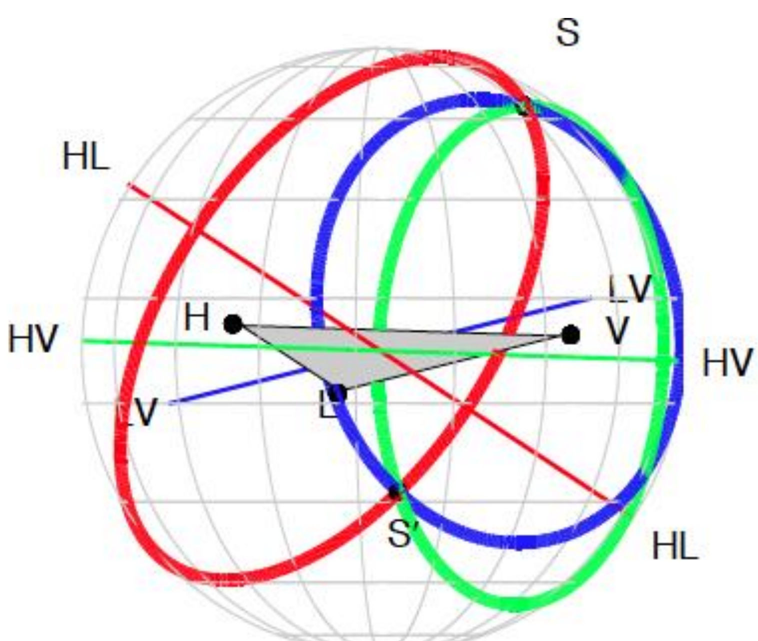
Leonor et al. 2009: assumes BATSE-like sample of ~100 short GRB/yr (or Fermi+Swift sample including GRBs found off-line).

$$R_{\rm GWB} = R_{\rm GWB,ref} \left(\frac{E_{\rm GW}}{0.01 M_\odot} \right)^{3/2}$$

Localizing BNS with ground-based interferometers

Epoch	Estimated Run Duration	Number of BNS Detections	% BNS Localized within 5 deg^2	% BNS Localized within 20 deg^2
2015	3 months	0.0004 – 3	–	–
2016–17	6 months	0.006 – 20	2	5 – 12
2017–18	9 months	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	0.4 – 400	17	48

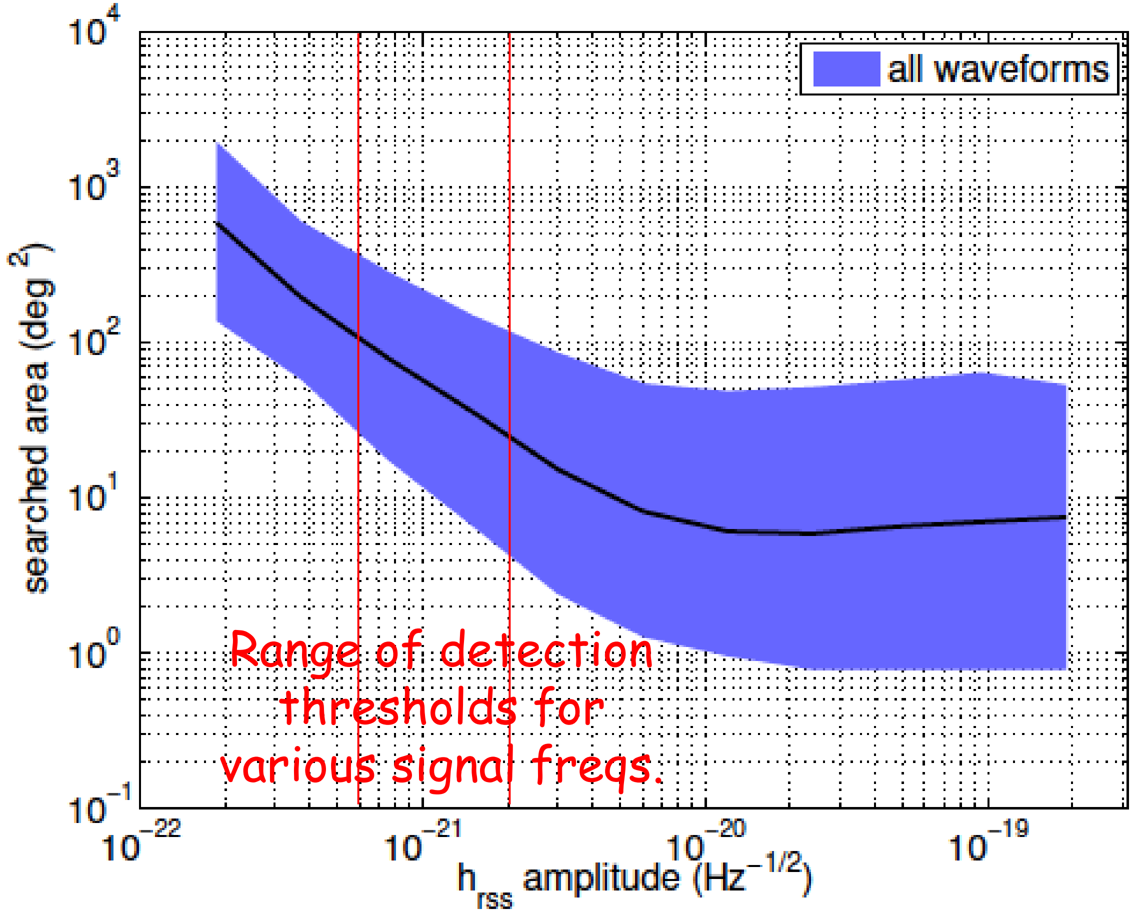
Aasi et al. 2013, arxiv:1304.0670



- Time delay (and associated uncertainty) between 2 detectors → annulus on the sky concentric about the baseline between the two sites.

- 3 detectors → annuli may intersect in (S,S'). S is centered on the true source direction, S' is its mirror image with respect to the plane passing through the 3 sites.

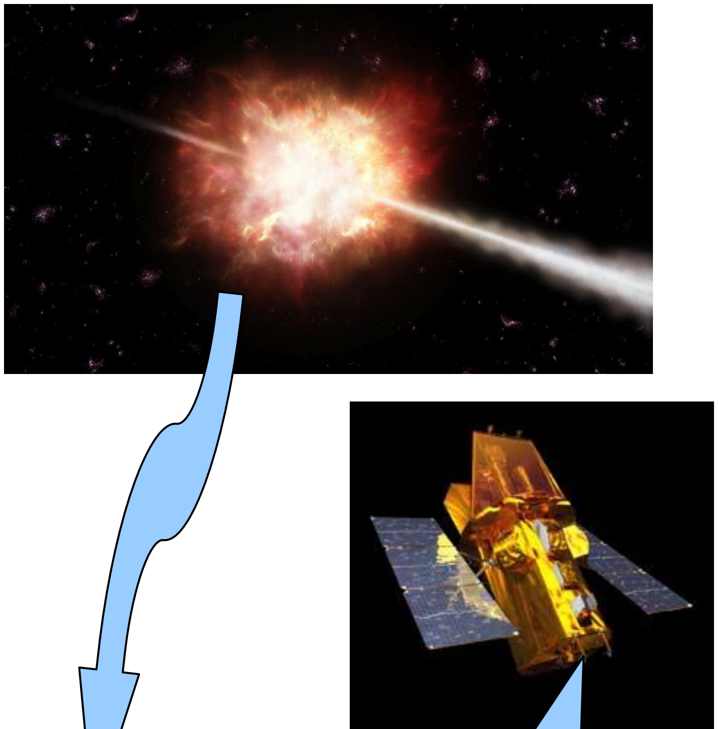
Localizing GW bursts



Aasi et al. 2013, arxiv:1304.0670

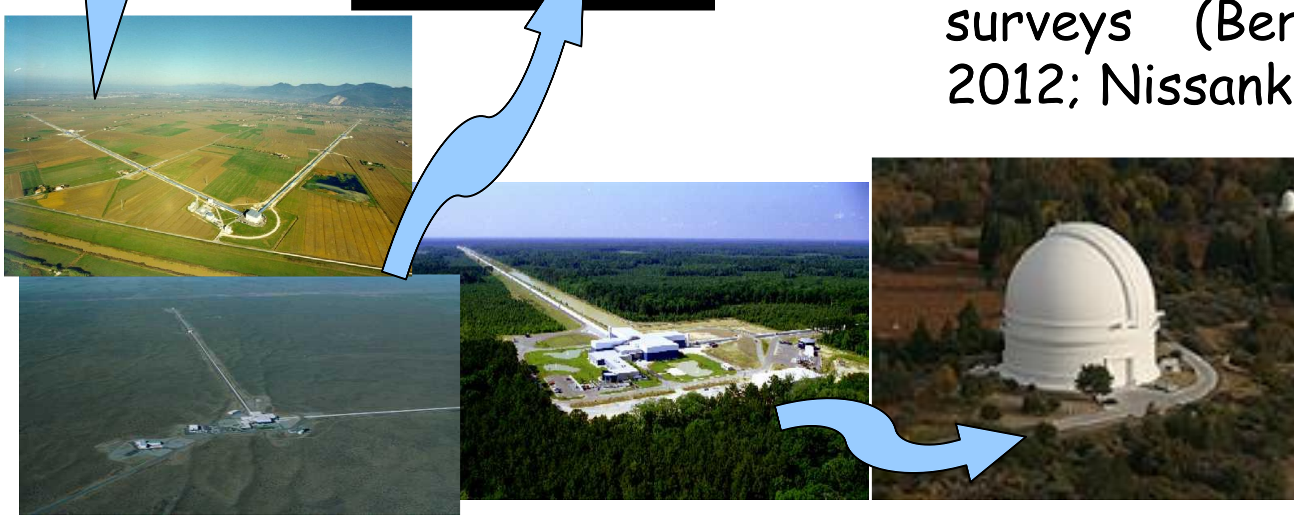
Typical uncertainty regions for burst searches, as a function of GW strain amplitude at Earth, for a mix of ad hoc Gaussian, sine-Gaussian, and broadband white noise burst waveforms.

GW-triggered detections of GRB afterglows



- On-axis optical afterglow emission easily detectable with existing and planned wide-field telescopes at 200Mpc (Berger & Metzger 2012; Nissanke et al. 2103).

- Off-axis optical afterglows of short GRBs can be detected only for θ_{obs}<=2θj (~10% of the total) with deep / fast cadence surveys (Berger & Metzger 2012; Nissanke et al. 2003).



EM follow-up of GW events

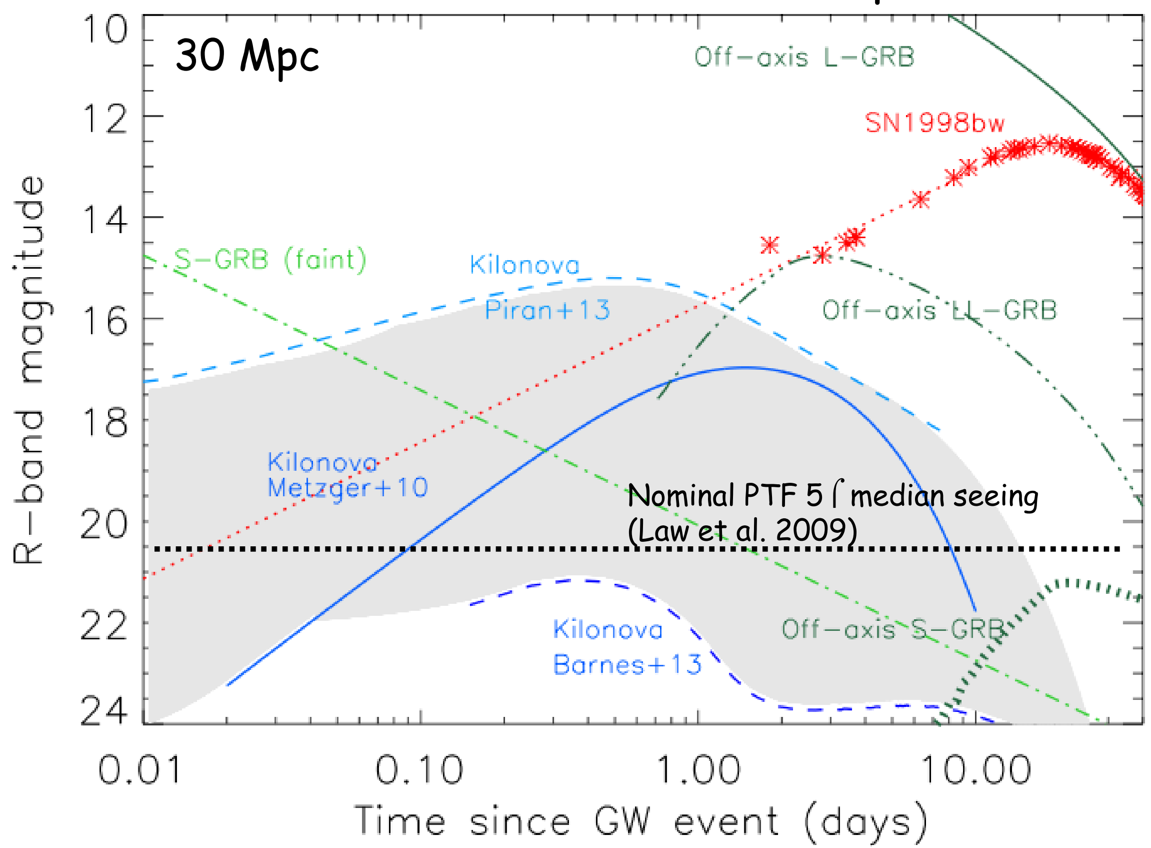
E.g., Palomar Transient Factory: ~30-150 per 100-200 deg^2 after selective cuts (Bloom et a.l 2011). But, transients NOT belonging to the "typical" categories (varstars, AGNs, novae, "typical" SN), are the most interesting as GW sources (given LIGO/Virgo sensitivity). See also results from PAN-STARRS1 medium-deep survey (Berger et al. 2013).

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

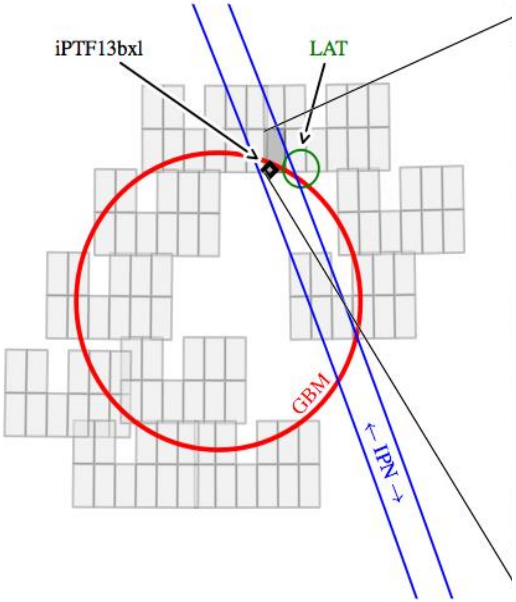
- **Off-axis GRB afterglow** (e.g. van Eerten 2010/2011): would yield a dramatic confirmation of the "jet model" for GRBs.

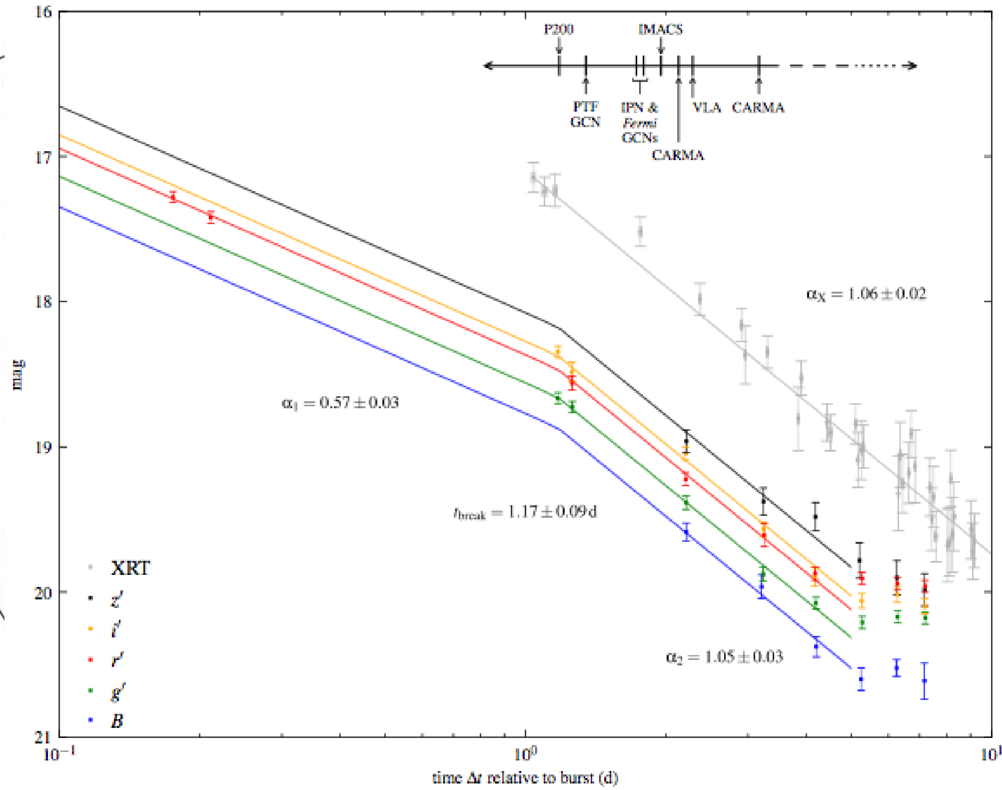
- **BNS** observed via their optical SN-like (Kilonova)emission (N. Tanvir's talk; e.g. Kulkarni 2005, Metzger et al. 2010).

Aasi et al. 2014, ApJS, 211, 7



iPTF identifies afterglow of GRB130702a in 71srq deg



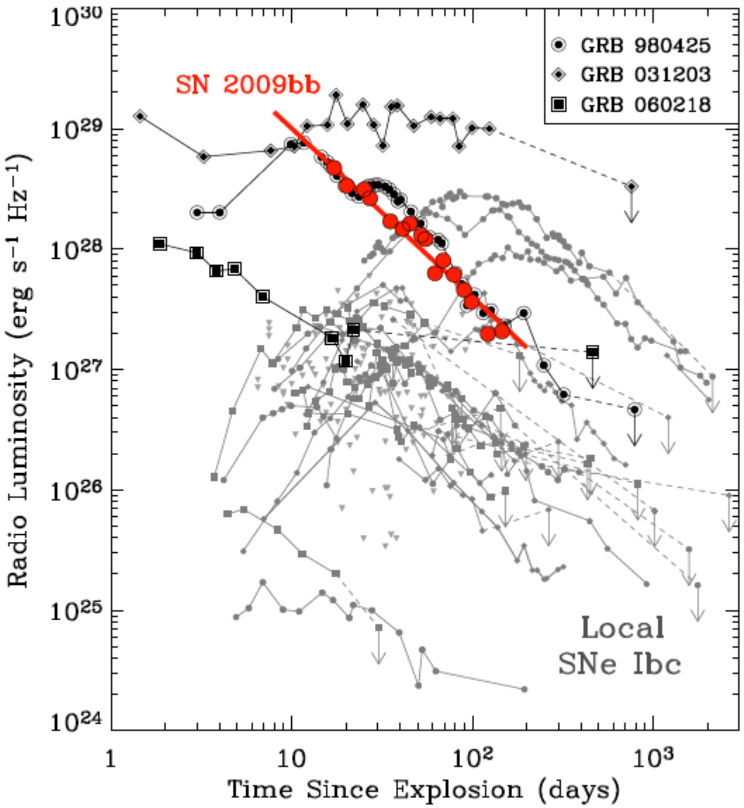


Singer et al. 2013

- iPTF real-time analysis: 27004 sources of which 44 known asteroids
- Real/bogus (Bloom 2012) > 0.1 → 4214 sources left
- No coincidences with SDSS point sources → 2470 sources left
- Detection in both P48 visits, CCD-wide data quality cuts → 43 left
- Human scanning → 7 sources left

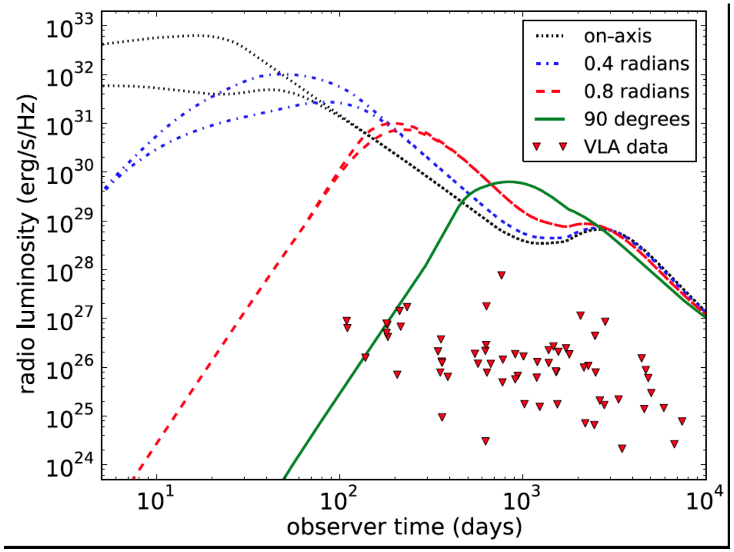
iPTF13bxl most likely given significant intra-night decline

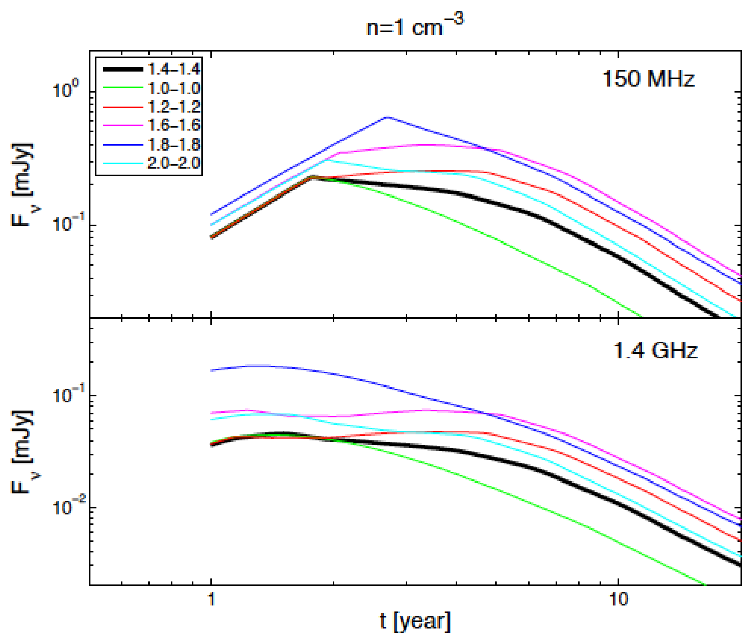
Radio searches



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

Right: van Eerten et al. 2010: off-axis GRB models and Ib/c SNe ULs (Soderberg et al. 2006).





Radio from sub-rel. ejecta in binary mergers (Nakar & Piran 2011)

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 EM follow-up experiment performed, call for EM partners issued (info available at: http://www.ligo.org/scientists/GWEMalerts.php).

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