LIGO

CALTECH

Gravitational Waves from GRBs

Alessandra Corsi

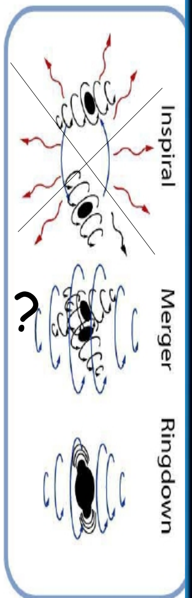
LIGO lab, California Institute of Technology

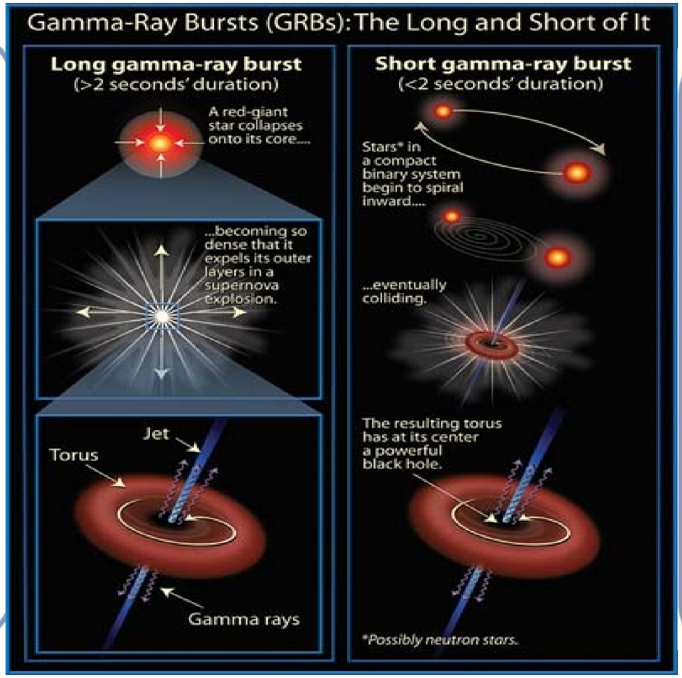
On behalf of the LSC/Virgo collab. & partner telescopes

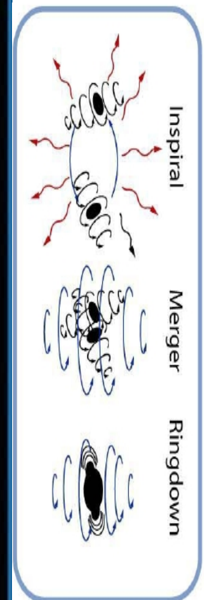
(PTF, PI of the Sky, QUEST, ROTSE III, Sky mapper, TAROT, ZADKO, Liverpool)

IAU 279- Nikko- March 2012

Unraveling the nature of GRBs: joint EM-GW studies

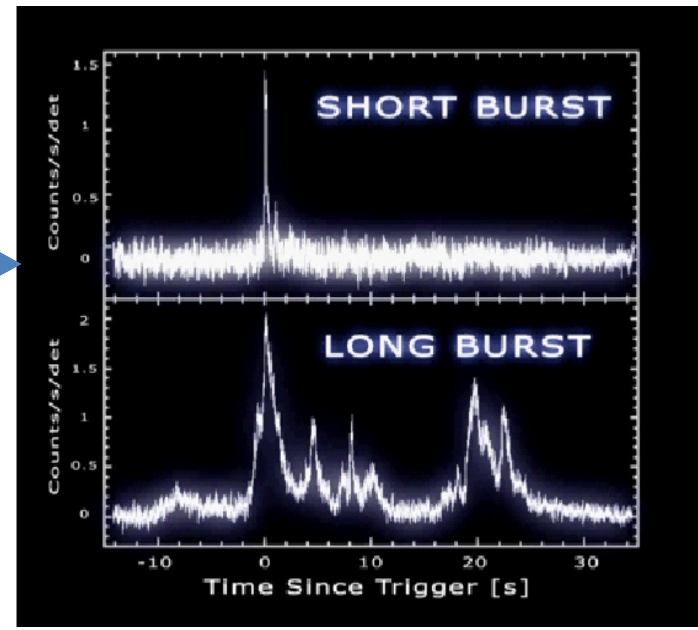


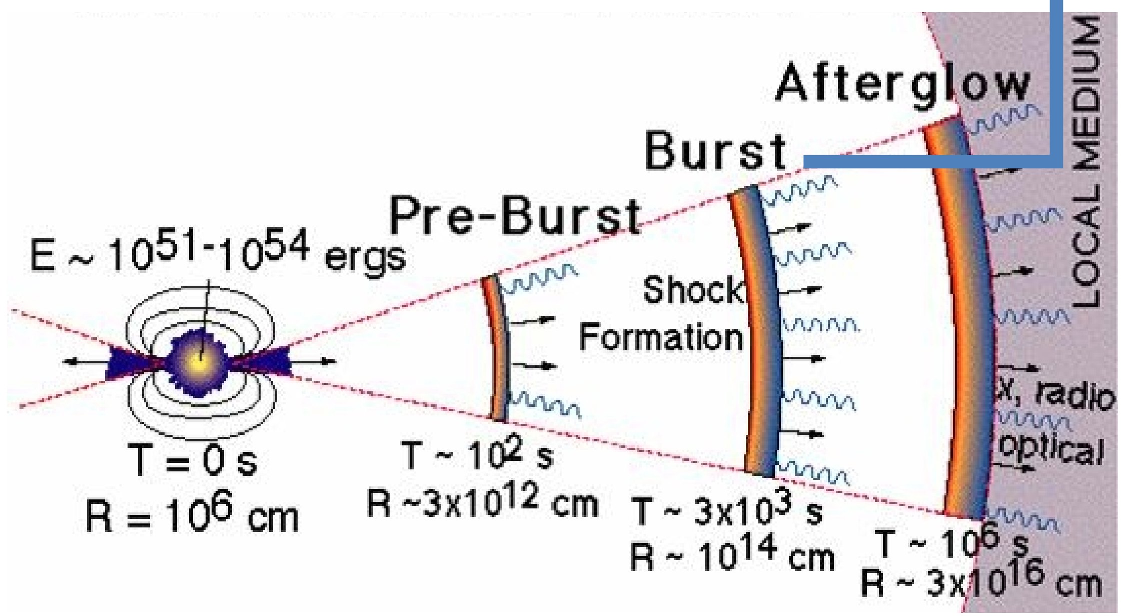




GWs emitted directly form the progenitor

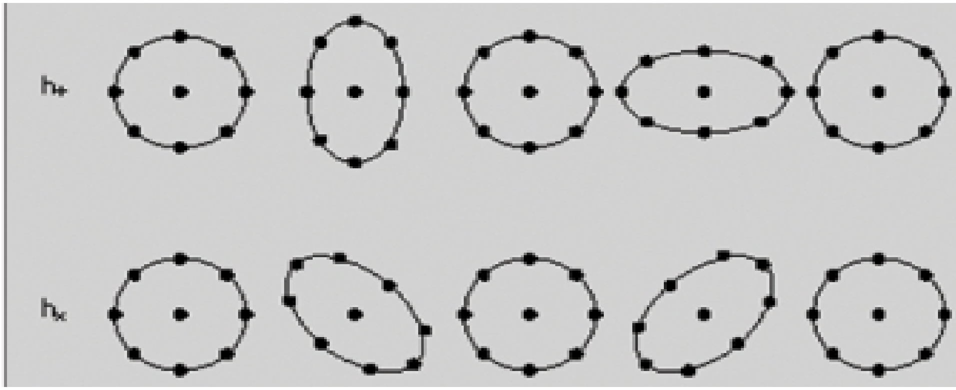
Nasa image

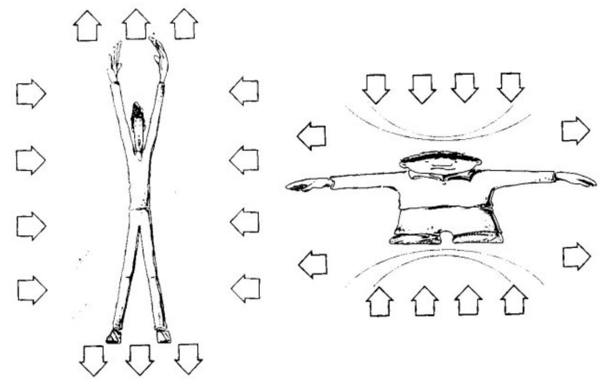




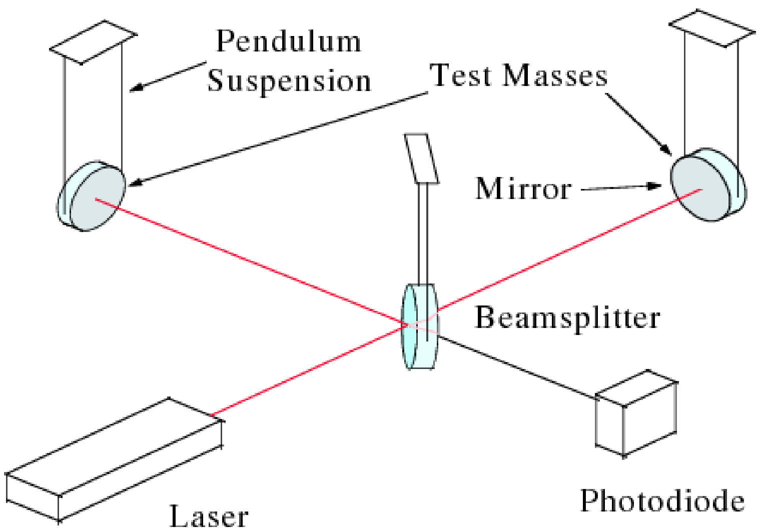
EM signal emitted at large distances: indirect info on the progenitor

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.

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

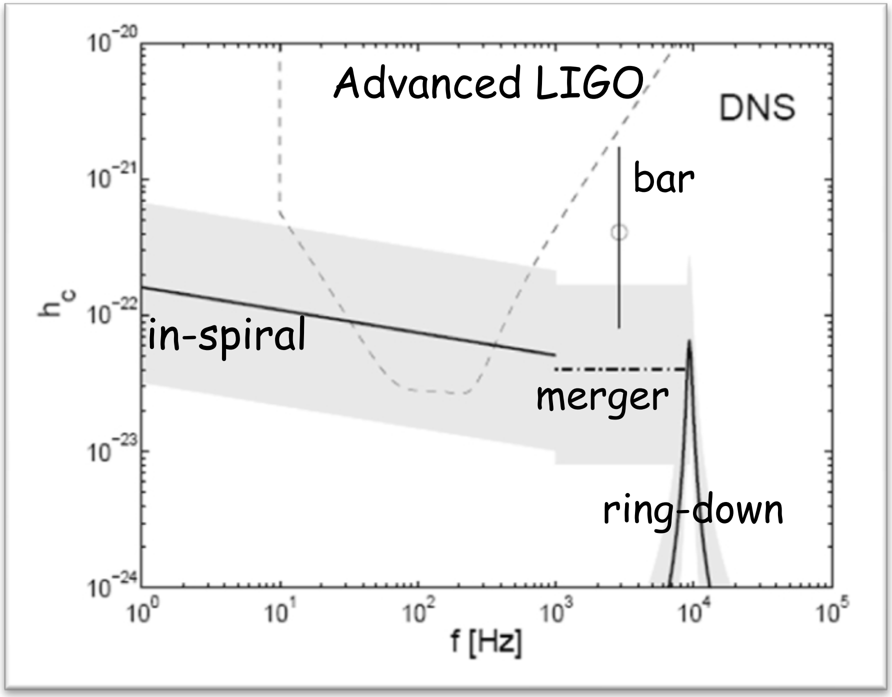
LIGO and Virgo GW detectors

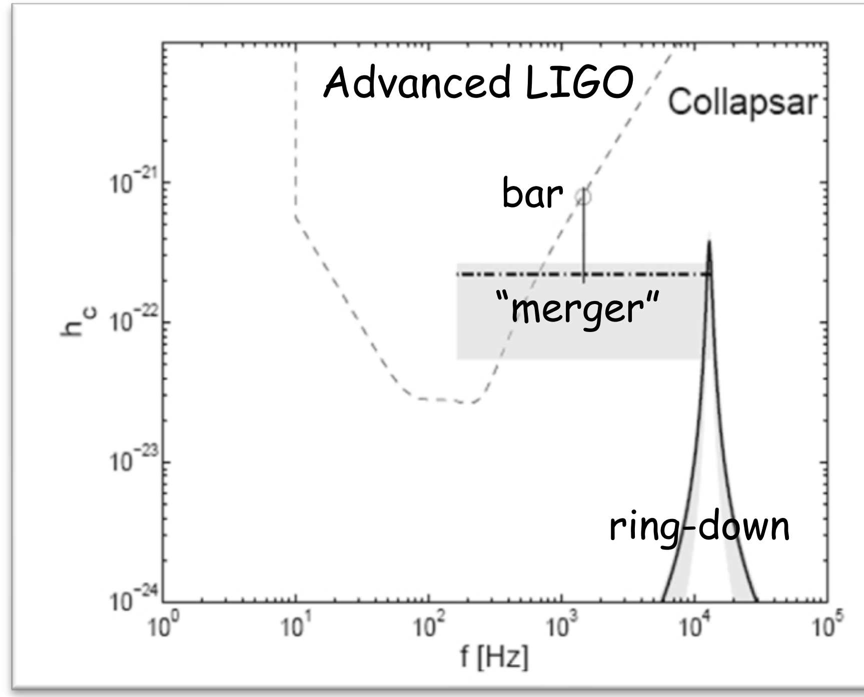
LIGO Hanford (US)

LIGO Livingston (US)

Virgo (Pisa, Italy)

GW from GRBs: order of magnitude estimates



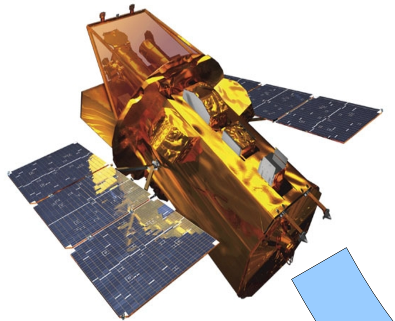


Kobayashi & Meszaros 2003 (and Fryer et al. 2002)

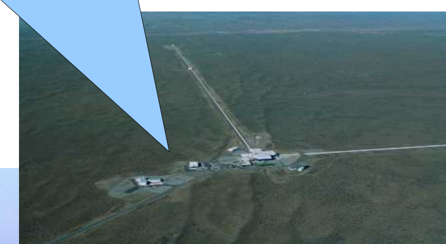
UL estimate assumes 1% of tot mass in GW during merger, 5% in BH ring-down

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

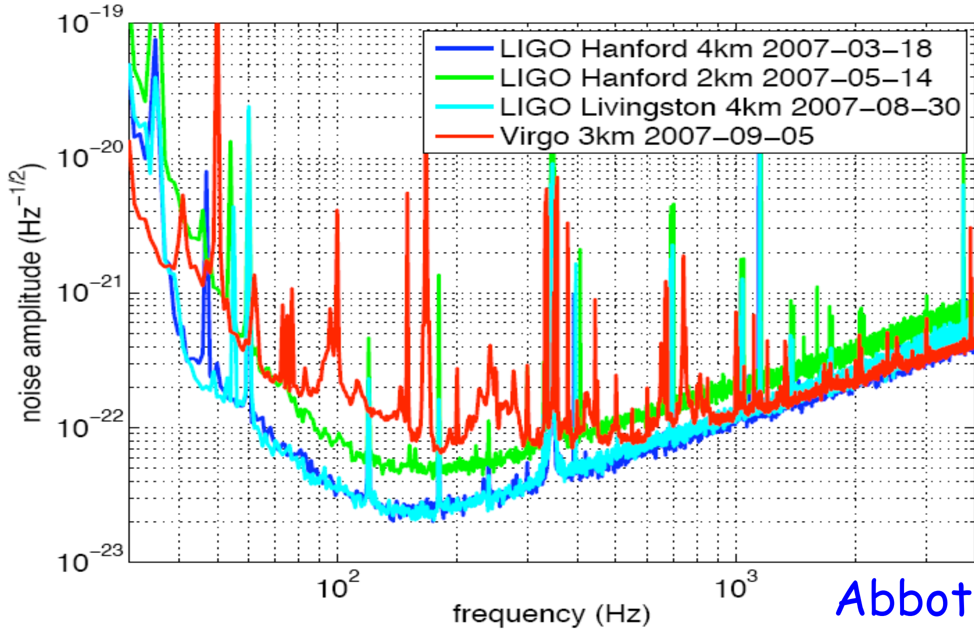
445 Mpc: optimal horizon for NS-NS in adv Era, expected ~40/year (but large scatter in predictions: 0.4-1000 /yr – see Abadie et al. 2010 and ref therein).

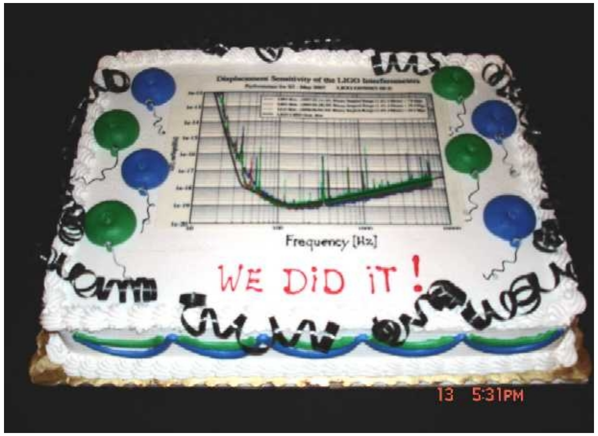


Triggered searches:
EM ---> GW



GW bursts from GRBs in LIGO S5 and VSR1





Abbott et al. ApJ, 715, 1438 (2010)

• 137 GRBs during S5/VSR1 (2005 Nov. 4 to 2007 Oct. 1). On source windows of [-2; +1] min around trigger (yields ~2x improvement in sensitivity with respect to un-triggered searches).

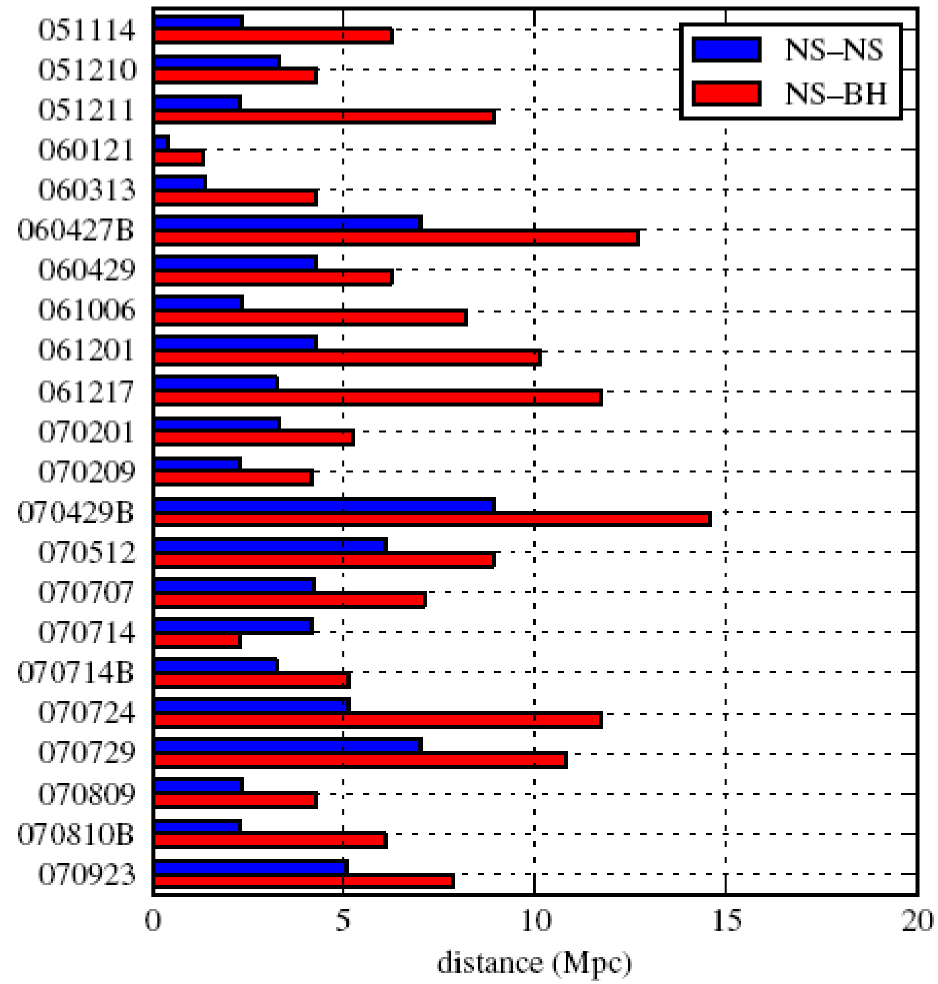
• No GW candidate. Simulated short (<1 s) GW signals to set ULs. Best value: h_{rss}=1.75x10^{-22} Hz$^{-1/2}$ (@150 Hz) → Lower bound on distance assuming an energy of 0.01 $M_{\odot}c^2$ in GWs: D>26 Mpc.

GW in-spirals from GRBs in LIGO S5 and Virgo VSR1

- Search for GW in-spiral signals from short GRBs during S5/VSR1.

- No statistically significant GW candidates in on-source window of [-5; +1) s around GRB trigger time.

Exclusion distance to each GRB for compact binary progenitors with masses: m_1=[1; 3) $M_\odot$ and m_2=[1; 4) $M_\odot$ (NS-NS system) or m_2=[7; 10) $M_\odot$ (NS-BH system).



Abadie et al. ApJ, 715, 1453 (2010)

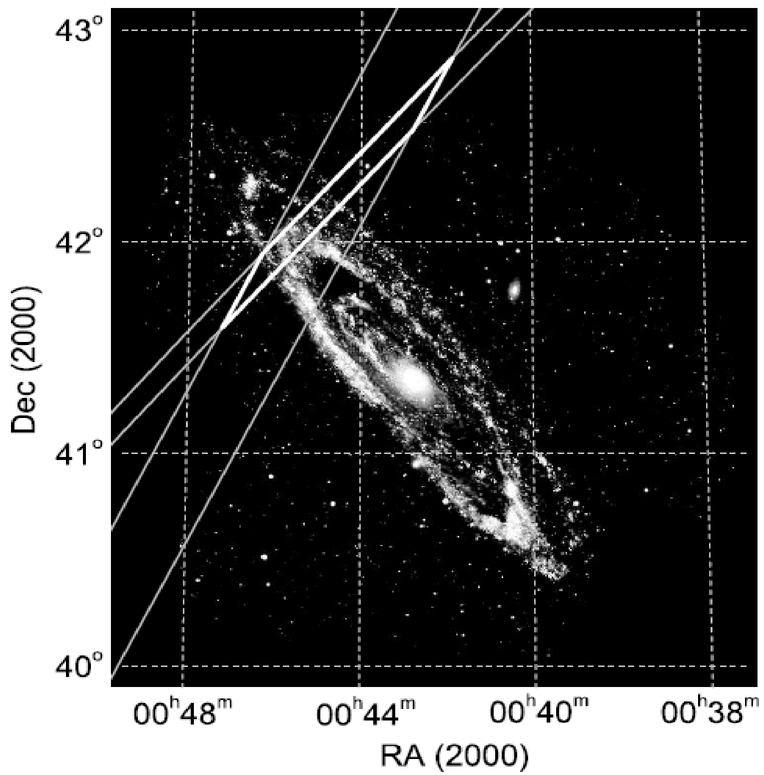
Implications for the origin of GRB 070201 and GRB 051103

- 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).

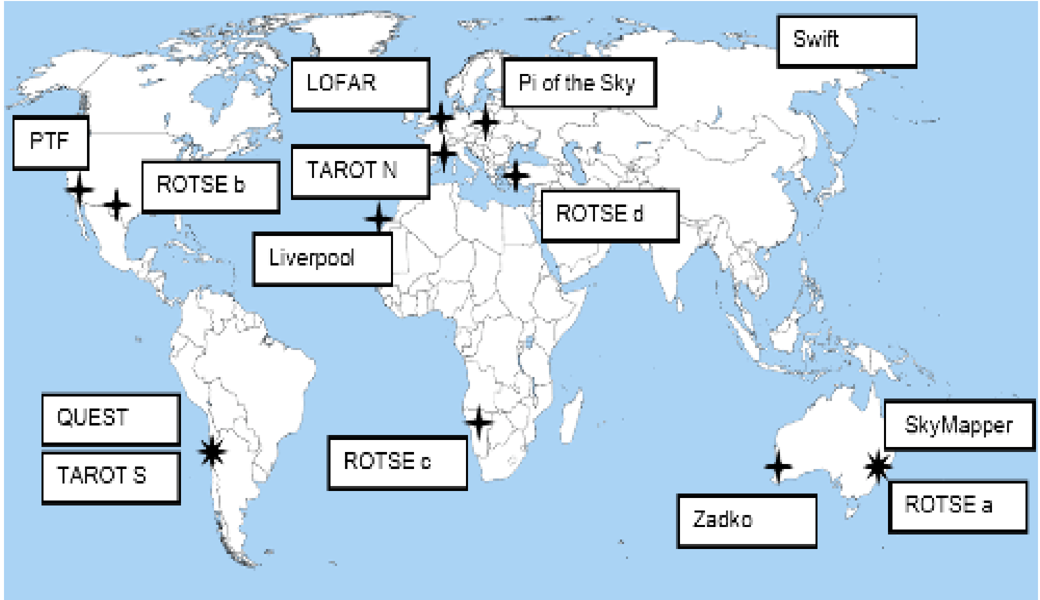


Mazets et al 2008: UV image of the M31 galaxy (Thilker et al. 2005) and the 3 IPN error box of GRB 070201.

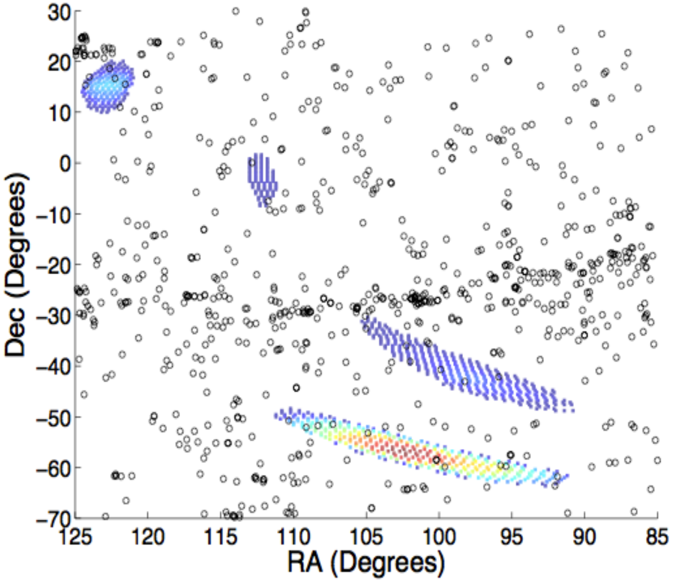
Abbott et al. ApJ, 681, 1419 (2008); Abadie et al. 2012, arXiv1201.4413


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: several 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, to appear in A&A, arXiv:1109.3498

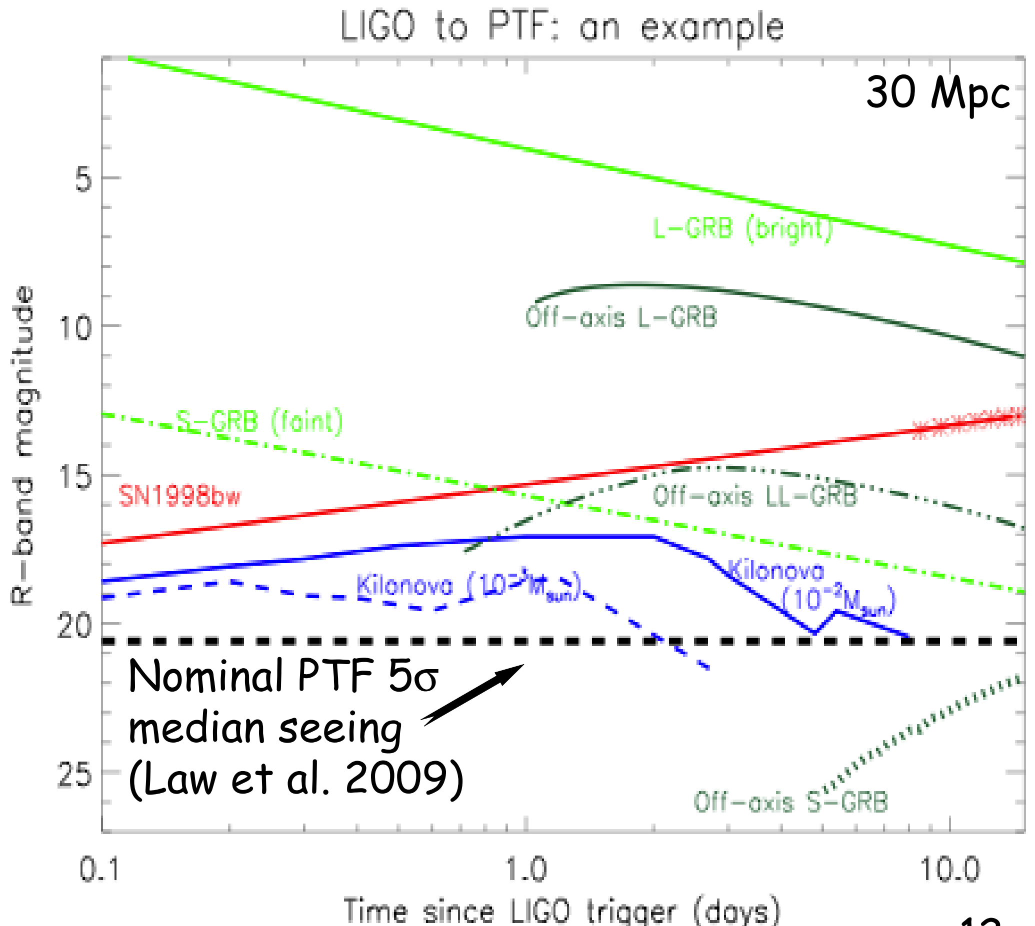
On/off-axis GRBs as LOOC-UP targets

N. of transients and sub. artifacts in tens of sqr deg is high (e.g., PTF: ~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): Discovery would yield a dramatic confirmation of the "jet model" for GRBs, could map out the beaming distribution, provide inputs to models of relativistic outflows.

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

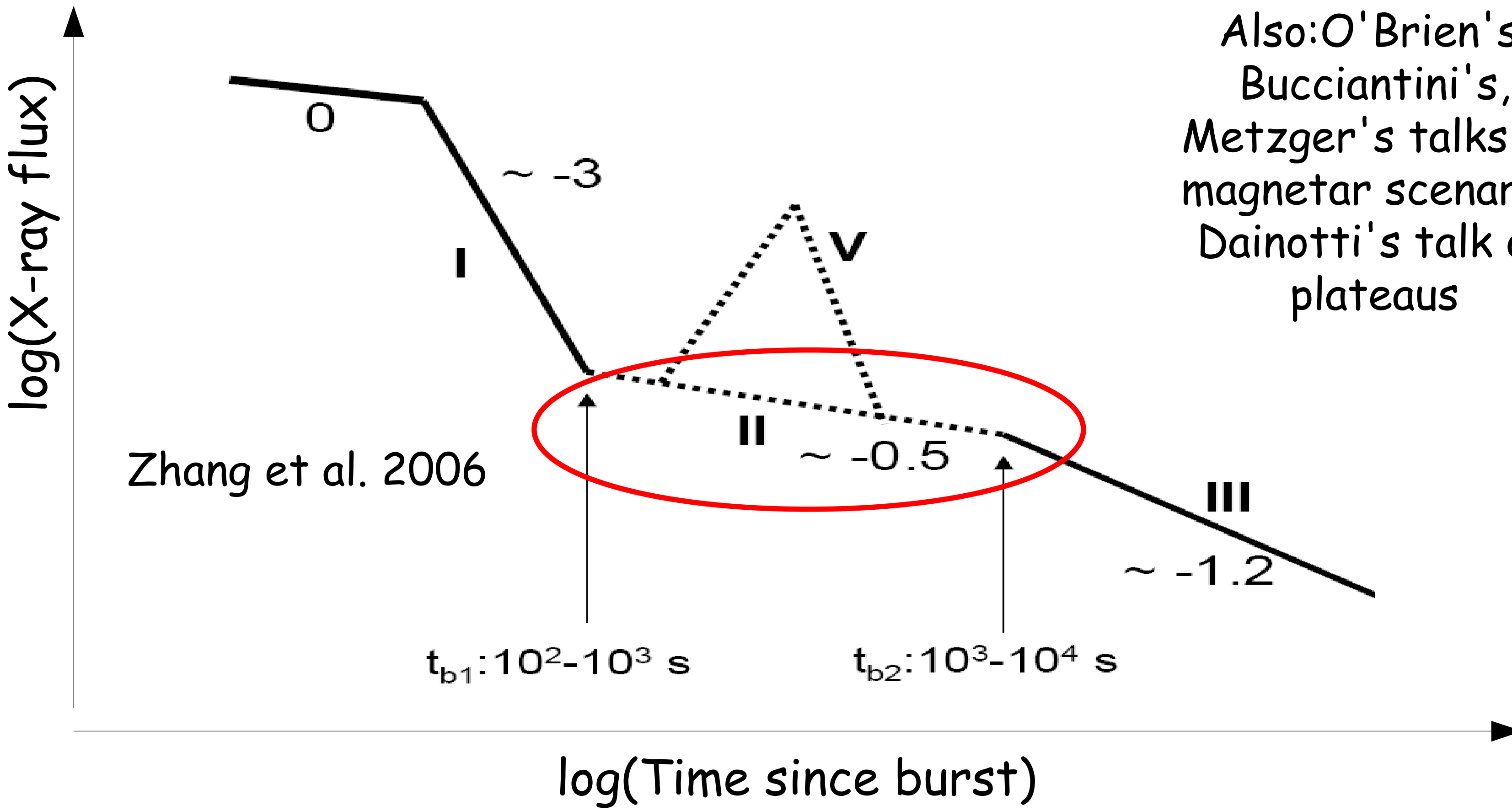



(Some) prospects
for the adv detectors Era

Swift results: impact on GW searches

- Magnetar rather than BH may form in explosion (e.g. GRB060218/SN2006aj, Mazzali et al. 2006).

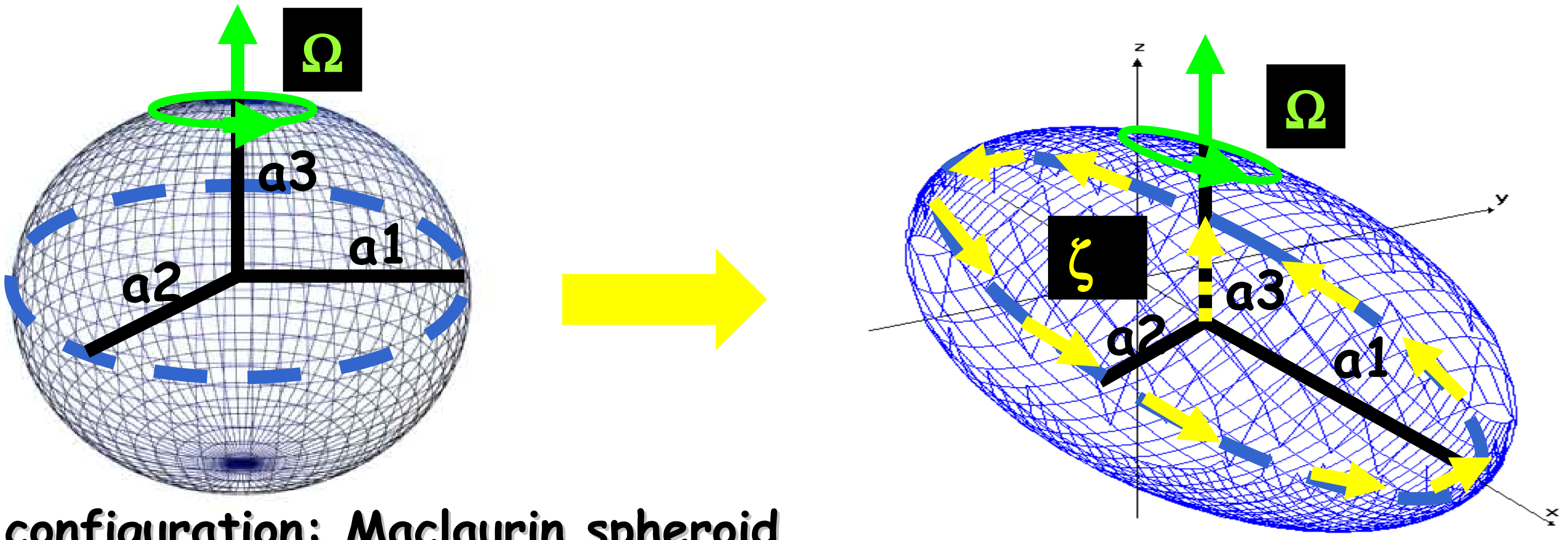
- Magnetar pumping energy into the fireball (e.g. Dai & Lu 1998, Zhang & Meszaros, 2006)? An associated bar-like GW signal (e.g. Lai & Shapiro 1995, Corsi & Meszaros 2009)?



Zhang et al. 2006

Also: O'Brien's, Bucciantini's, Metzger's talks on magnetar scenario; Dainotti's talk on plateaus

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

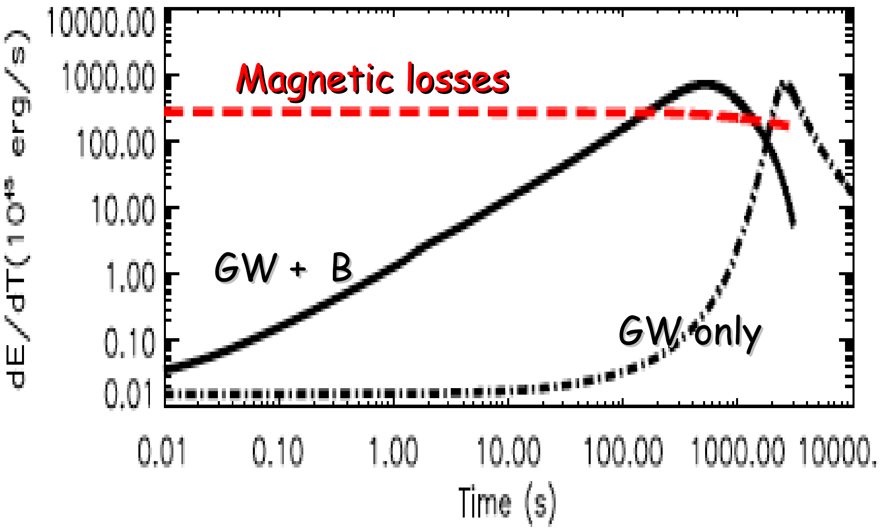
- kinetic-to-gravitational potential energy ratio, $\beta = T/|W|$

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

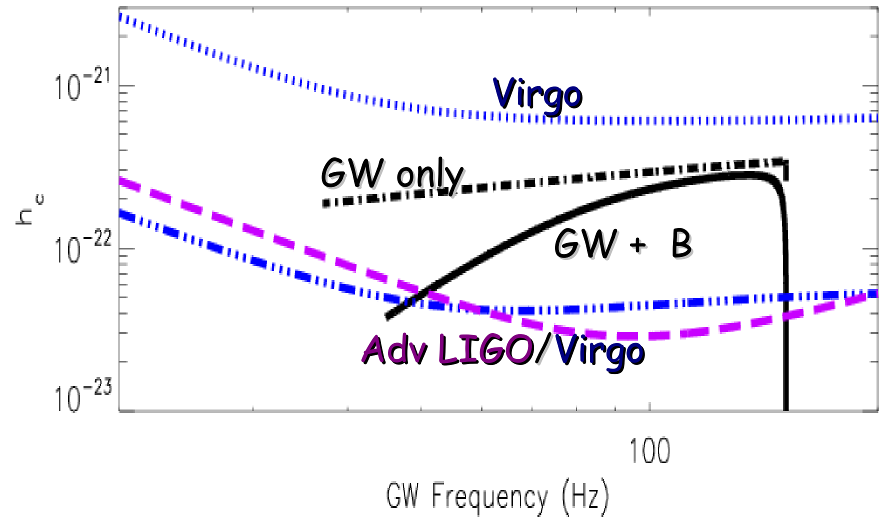
–$\beta > 0.14$: l=m=2 “bar”-mode oscillations secularly unstable due to e.g. gravitational radiation (e.g. Lai & Shapiro 1995) →sequence of compressible Riemann-S ellipsoids

GW signal associated to EM plateau

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

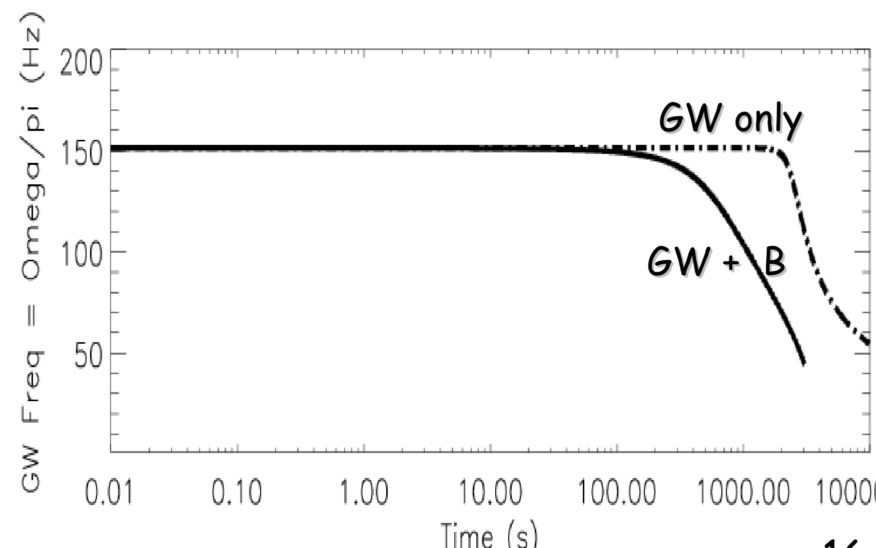


SNR_{match}=5 @ d=100-150 Mpc



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

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



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 GWs studies in coincidence with GRBs are already happening: LIGO-Virgo detectors have been actively following GRB triggers during these years, and first LOOC-UP experiment performed.

- Prospects for the future: more results coming soon from S6/VSR2-3 data; more searches possible in the future (e.g. plateau); starting from 2014/2015, advanced LIGO/Virgo (10 times better sensitivity) GW detectors 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).

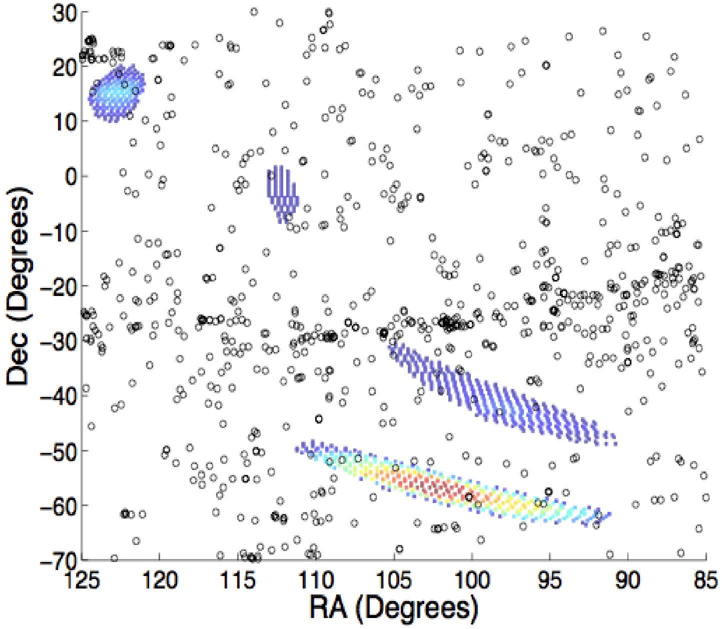
- Collapsing core or disk may fragment to produce two or more compact objects (e.g. Fryer et al. 2002). May be significant source of GWs; possible chirp signature similar to a coalescing NS binary (e.g. Davies et al. 2002, Piro & Pfahl 2002) or burst of GWs in a "merger"-type signal (e.g. Kobayashi &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

Autumn-winter 2010 LOOC-UP runs



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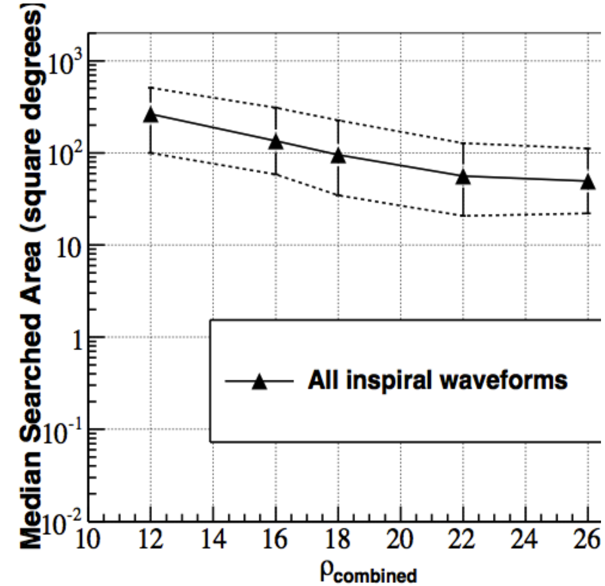

Name	Run	Tiles per Trigger	Target Alerts Per Week	Triggers Imaged
Palomar Transient Factory	Autumn	10	1/3	1
Pi of the Sky	Autumn	1	1	1
QUEST	Both	3	1	5
ROTSE III	Autumn	1	1	5
SkyMapper	Autumn	~9	1	3
TAROT	Both	1	1	3
Zadko Telescope	Autumn	5	1	2
Liverpool Telescope	Autumn	1	1	1
LOFAR	Autumn	1	1	2
Swift	Both	5	1/4	2

Abadie et al. 2012, to appear in A&A, arXiv:1109.3498

Summary of my talk

- GWs by GRBs: predictions/expectations for ground-based interferometers (LIGO/Virgo)

- GRB "triggered" searches: GW data analyzed in coincidence with GRB triggers

- "LOOC-UP": search for optical counterparts of GW triggers

- Prospects: future analyses for the advanced detectors Era