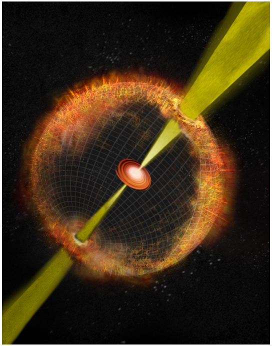
Astrophysically triggered Gravitational Wave searches

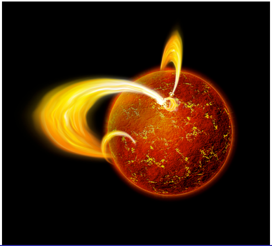
Michał Wąs

Albert Einstein Institute - Hannover
michal.was@aei.mpg.de

Outline



Credit: Bill Saxton, NRAO/AUI/NSF



Motivations for triggered GW searches

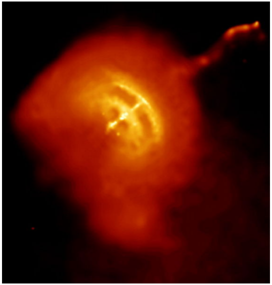
- Astrophysics
  - We know about:
    - Gamma-ray bursts
    - Soft gamma repeaters
    - Supernovae
    - Pulsars
  - GWs give information on core mass dynamics
- Detector noise
  - Instrumental/environmental noise is limiting
  - Any information helps removing some noise

Example of sensitivity improvement unrelated to GRBs

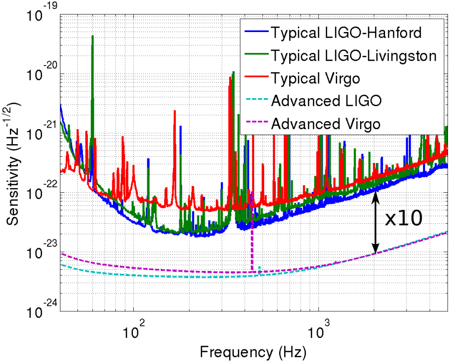
- Young pulsars (neutron stars)
  - Crab (SN 1054)
  - Vela (SN $\sim 10^4$ yr ago)

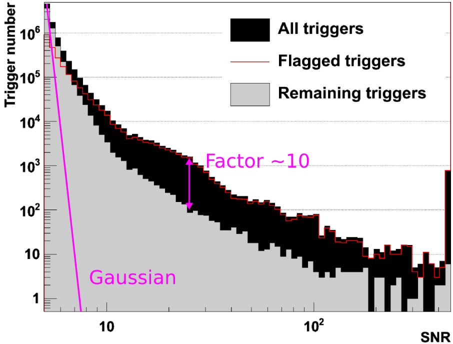
  spin frequency is precisely observed in radio
- The rotation period is decreasing
  $\longrightarrow$ loss of rotational energy
- LIGO 2005-2007: less than 2% of Crab energy loss is due to GW emission (Abbott et al., 2010)
- Virgo 2009-2010: less than 40% of Vela energy loss is due to GW emission (Abadie et al., 2011b)
- Without any radio observation the limits on energy loss higher by $\sim 10^2 - 10^3$ (Abadie et al., 2011a)

$\Rightarrow$ EM observation enhance GW searches sensitivity



Improving GW sensitivity



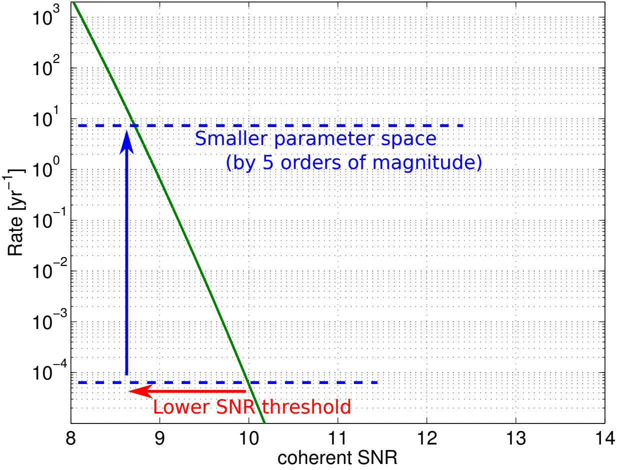


smallest observable GW amplitude $\propto \sqrt{S(f)} \times \mathrm{SNR}_{\mathrm{threshold}}$

- Astrophysical triggers, GW models, etc ... changes search parameter space

$\Rightarrow$ $\mathrm{SNR}_{\mathrm{threshold}}$ depends on the search hypothesis

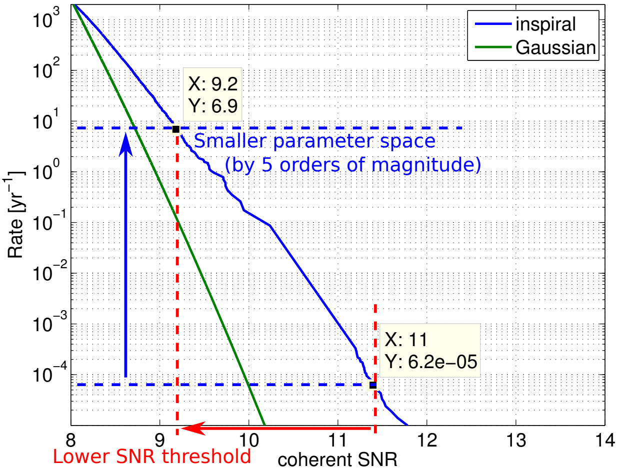
Triggered search in Gaussian noise



Localization in time: $\frac{\text{few minutes}}{\text{few months}} \sim 10^{-5}$

$\Rightarrow$ Improves sensitivity by 15%, 50% in volume

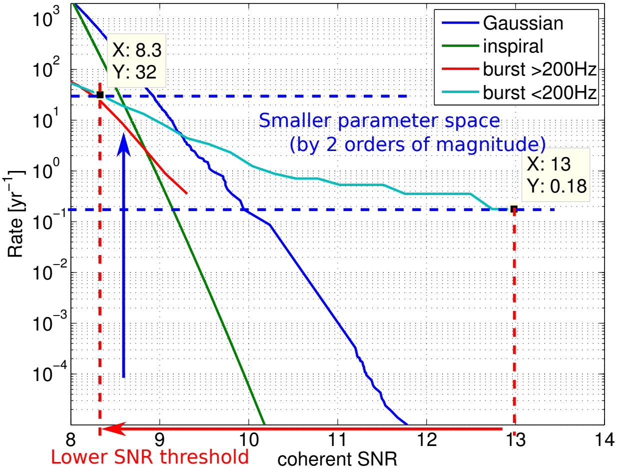
Well cleaned real noise (inspiral + χ^2 test)



Localization in time: $\frac{\text{few minutes}}{\text{few months}} \sim 10^{-5}$

$\Rightarrow$ Improves sensitivity by 20%, 70% in volume

Real data, no GW model



Localization in time: $\frac{1\ \text{day}}{\text{few months}} \sim 10^{-2}$

$\Rightarrow$ Improves sensitivity by 60%, factor 4 in volume

Astrophysical trigger

$\Rightarrow$ reduction in search parameter space

$\Rightarrow$ gain in sensitivity

- especially for non-Gaussian data

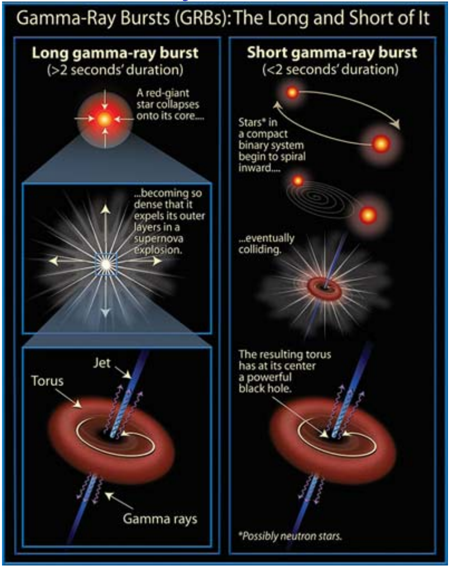
Practical example on GRB case

Astrophysical inputs & analysis strategy

Goal: Find GW associated with GRBs

- What to look for?
  - GW signal waveform
  - GW signal amplitude
  - GW signal polarization
- Where to look for?
  - GRB sky localization
  - Timing between GRB trigger and GW trigger
    $\Rightarrow$ Understand both EM and GW emission
- Is it worthwhile to search?
  - GRB progenitors distance distribution
  - Is it better than blind (all-sky, all-time) search?

Gamma-ray burst models



credit: Ute Kraus

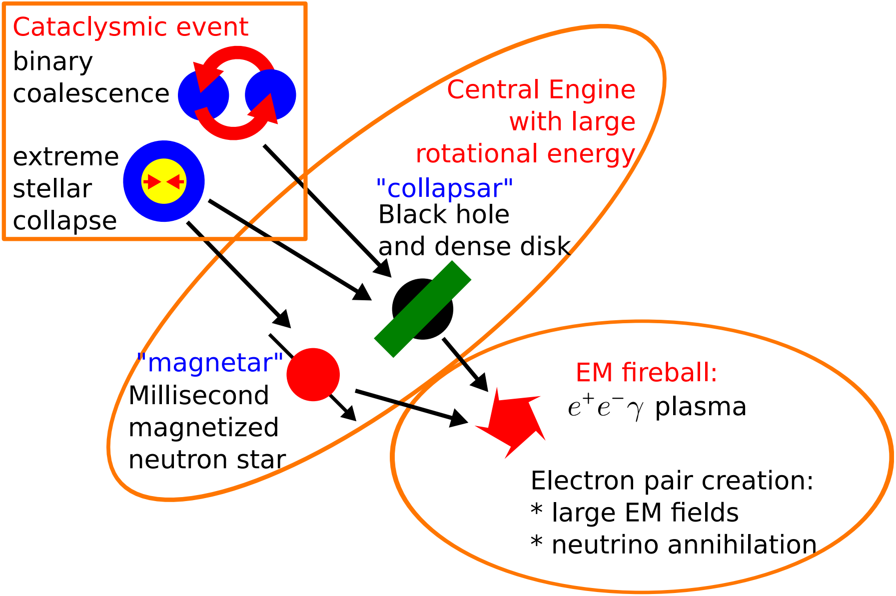
- Long GRBs

⇒ Massive rapidly spinning star collapse and explosion

- Short GRBs

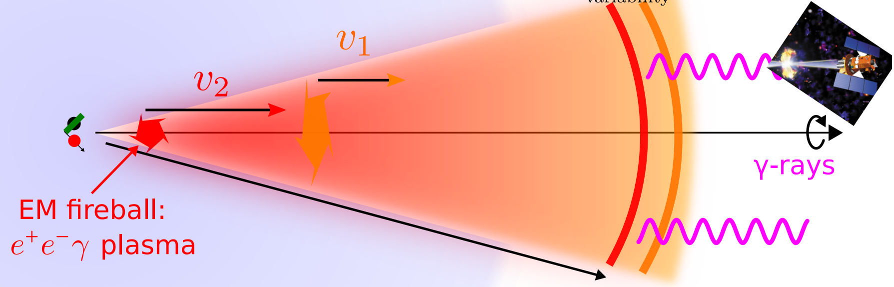
⇒ Coalescence of a neutron star and a compact object
  - small fraction is actually neutron star quakes ($\lesssim$ 15%)
- GWs see the core of the mass distribution dynamics
- Measured gamma emission: $\sim 10^{51}$ erg $= 10^{-3}\,M_\odot c^2$

EM emission - standard fireball model



γ-rays produced at large distances

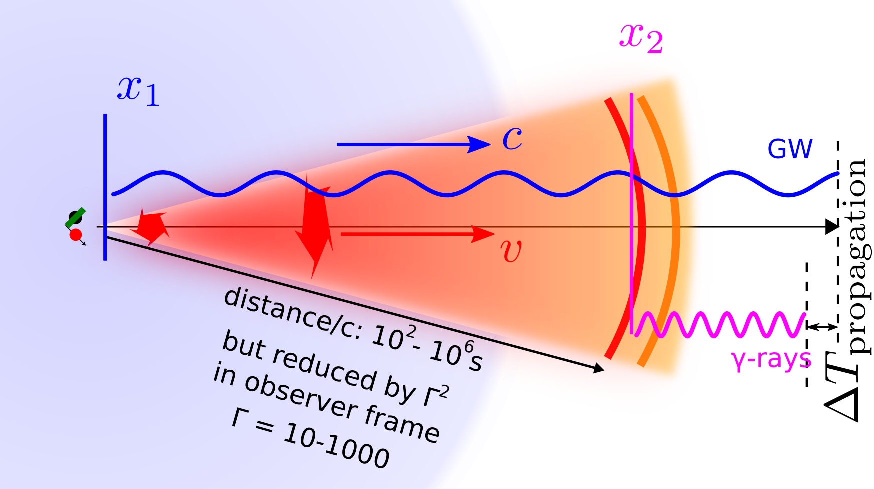
$$v_1 t = v_2 (t - t_{\text{variability}})$$
$$\frac{t_{\text{variability}}}{t} = \frac{v_2 - v_1}{v_2} \sim \frac{1}{\Gamma^2}$$
$$t = \Gamma^2 t_{\text{variability}}$$



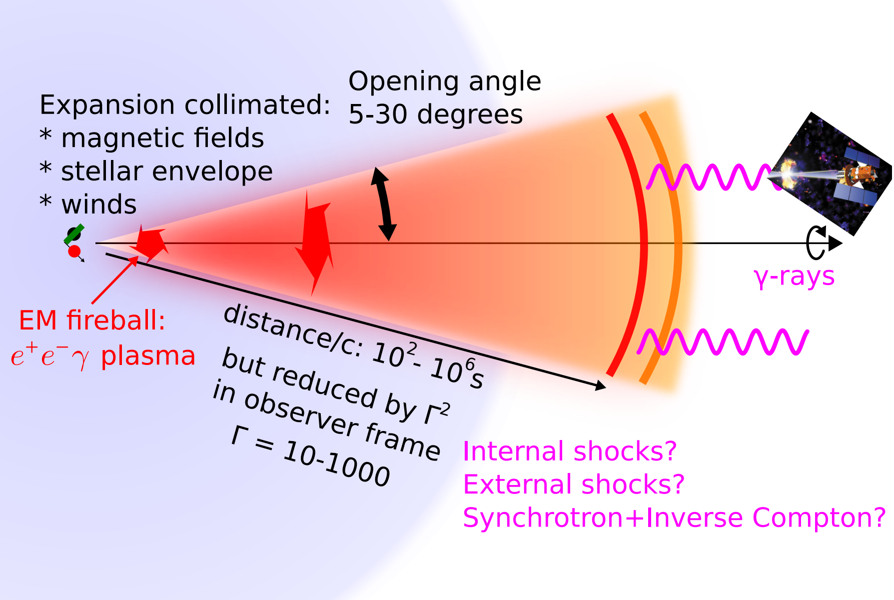
$$\text{distance}/c = \Gamma^2 t_{\text{variability}}$$
$$\sim 10^2 - 10^6 \text{sec}$$

Relativistic contraction

$$\Delta T_{\text{propagation}} = \frac{x_2 - x_1}{v} - \frac{x_2 - x_1}{c} \underset{\Gamma \gg 1}{\simeq} \frac{x_2 - x_1}{2c\Gamma^2} \sim t_{\text{variability}} \lesssim \text{GRB duration}$$



EM emission - standard fireball model



Gravitational source quadrupolar approximation

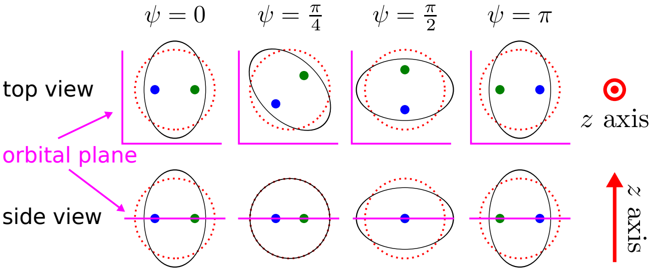
Approximation: far field + slow moving source

- Mass distribution quadrupolar moment

$$I_{ij} = \int (x_i x_j - \tfrac{1}{3}\delta_{ij}\delta_{km}x^k x^m)\rho(x)\mathrm{d}^3x.$$

- Source of gravitational waves

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \quad \longrightarrow \quad h_{jk}^{TT} = \frac{2G}{c^4}\frac{1}{r} \underbrace{P_{jkmn}}_{\text{projection}} \ddot{I}^{mn}(t - \tfrac{r}{c}),$$

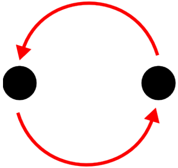


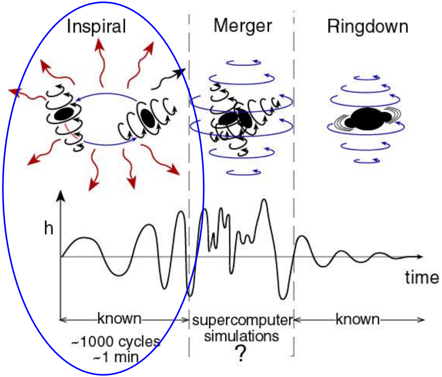
circular polarization
$h_+ = \pm i h_\times$

linear polarization
$h_+ \neq 0, \quad h_\times = 0$

GW emission - coalescence scenario

- Binary system of two compact objects (NSNS or NSBH)





- Lose energy by GW radiation
- GW emission enters sensitive band ($\gtrsim 50\,\mathrm{Hz}$) $< 50\,\mathrm{s}$ before coalescence
- GW at merger, ringdown $\rightarrow$ high frequency ($M_{\mathrm{BH}} \lesssim 20\,\mathrm{M}_\odot$) $\rightarrow$ low SNR

GW emission - coalescence scenario

- GRB central engine formed in $\lesssim 1$ s

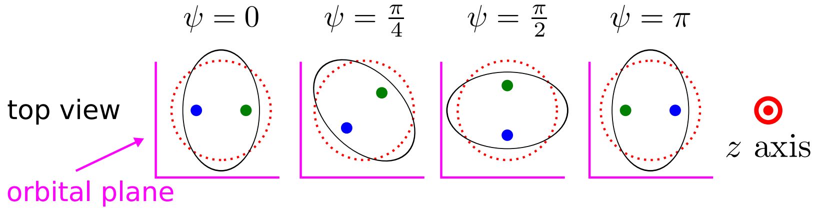
⇒ merger $[-1, 0]$ s prior to jet launch

- 1-2 second to produce γ-rays

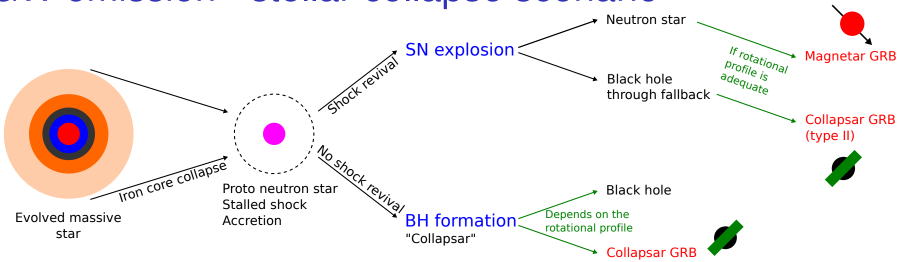
⇒ Inspiral ends $\simeq [-3, 0]$ s prior to GRB

- GRB observed → rotation axis points at observer

⇒ GW well known and circularly polarized
up to inclination of 60°→ loose constraint
(jet opening angle $\lesssim 30°$)



GW emission - stellar collapse scenario



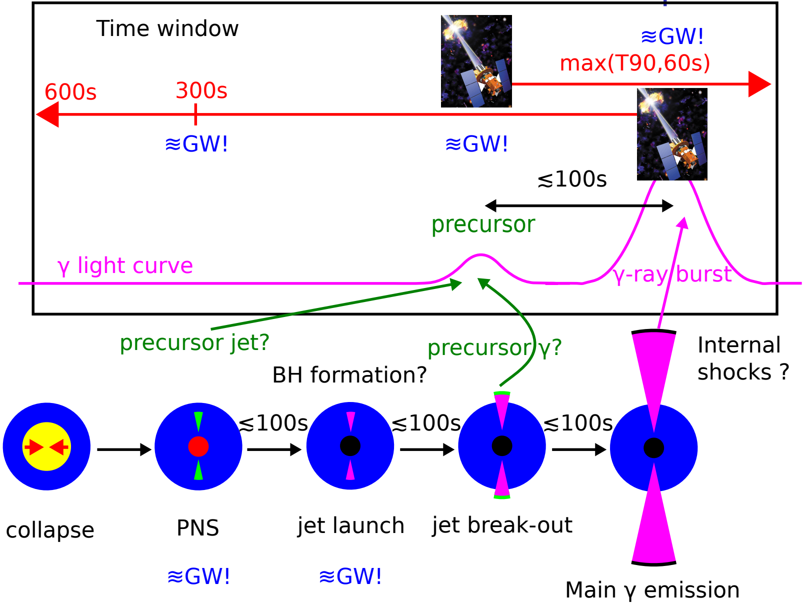
- Magnetar central engine / Proto neutron star
  - bar mode instability in the star
  - neutron star core fragmentation
- Black hole and accretion disk
  - Disk fragmentation
  - Disk precession

$\Rightarrow$ circular polarization along rotation axis

$\Rightarrow$ Emitted GW energy $\lesssim 10^{-2}\, M_\odot c^2$

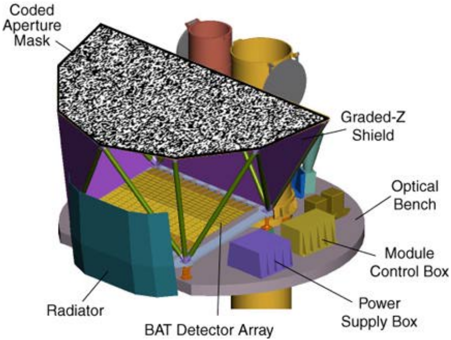
- Other emission mechanism but no prospects for extra-galactic reach
  - Out of frequency band (Neutrino, normal modes, ...)
  - Too small amplitude (Core bounce, SASI, ...)

GW vs GRB time of arrival - stellar collapse



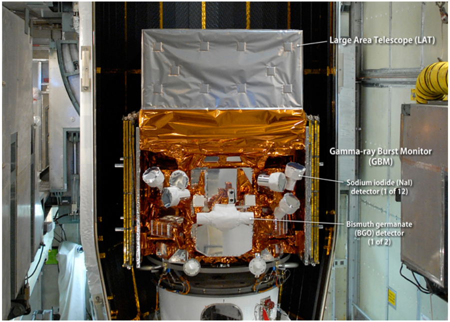
GRB sky localization - two technologies

Swift/BAT



FoV $\sim$ 10% of the sky
errors $\lesssim 0.3^\circ$

Fermi/GBM

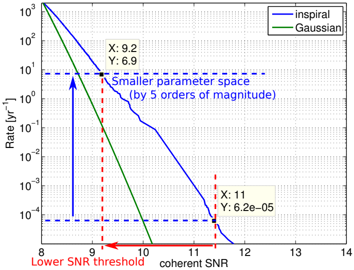


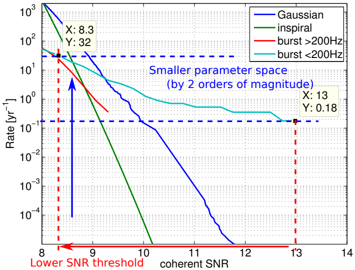
Fo

$\sim$ 70% of the sky
errors $\lesssim 5^\circ$

Astrophysical inputs summary

- Short GRBs
  - GWs: inspiral waveform
  - Inspiral ends a few seconds before start of GRB
  - ⇒ parameter space reduced by $\sim 30 \times 6\,\mathrm{s}/1\,\mathrm{year} \simeq 10^{-5}$
    - ⇒ at least factor 1.2 sensitivity gain
- Long GRBs
  - GWs: circularly polarized
  - Up to a few minutes before GRB trigger
  - ⇒ parameter space reduced by $\sim 400 \times 660\,\mathrm{s}/1\,\mathrm{year} \simeq 10^{-2}$
    - ⇒ at least factor 1.6 sensitivity gain
  - GW amplitude highly uncertain
- All GRBs
  - Located on the sky with
    - $\sim 0.3°$ precision ($\sim 25\%$)
    - $\sim 5°$ precision ($\sim 75\%$)



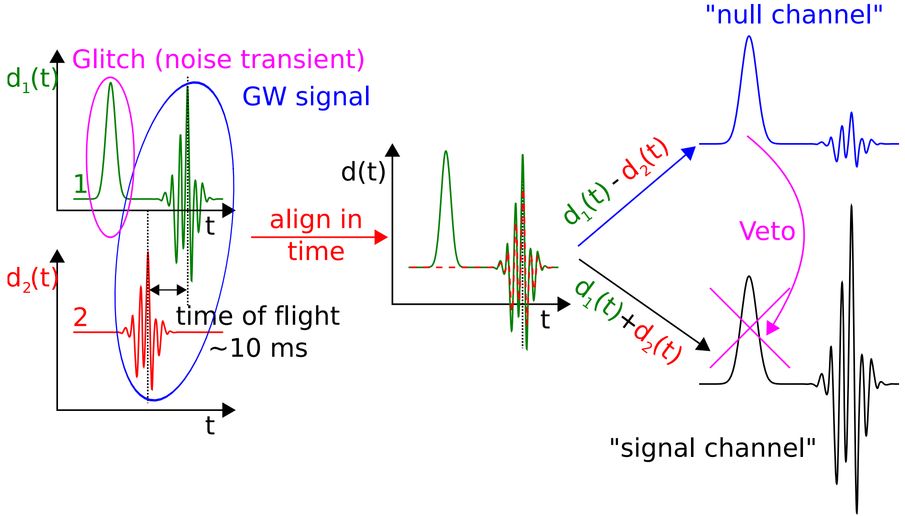


Two complementary searches

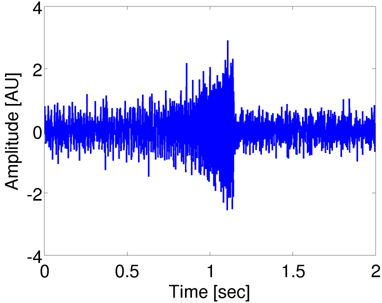
- Broad in scope – covers most possibilities
  - "burst" searching method – any signal shapes
  - Limited to $60 - 500\,\mathrm{Hz}$ band, $\lesssim 1\,\mathrm{s}$ duration
  - Assumes circular polarization
  - Loose time coincidence between γ-rays and GW
    $T_\gamma - T_{\mathrm{GW}} \in [-600, \max(T_{90}, 60)]\,\mathrm{s}$
- Focused on short GRBs – binary coalesence
  - Inspiral waveform templates, NS-NS and NS-BH
  - Tight time coincidence between γ-rays and GW
    $T_\gamma - T_{\mathrm{GW}} \in [-5, 1]\,\mathrm{s}$
  - More sensitive to inspiral signals by factor ~ 2
- GW data combined coherently in both searches

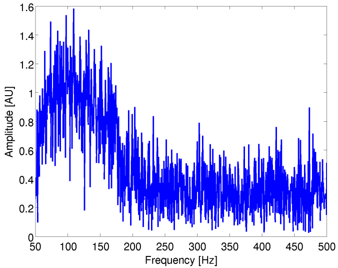
- (Abadie et al., 2012b)

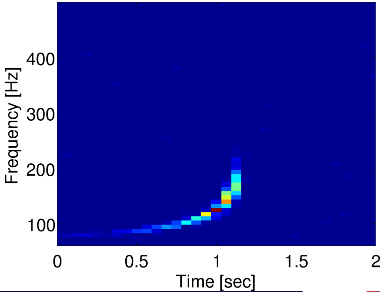
Coherent GW analysis



Excess wrt Gaussian noise → Time frequency maps



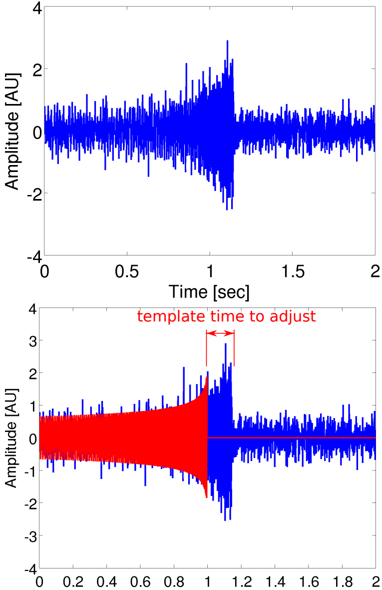




- Burst search
  - Concentrate signal energy in a small number of pixels
  - Sum energy over clusters of "loud" pixels

⇒ Ranking statistic

Excess wrt Gaussian noise $\rightarrow$ match with templates

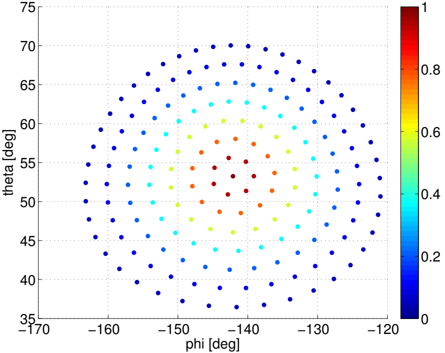


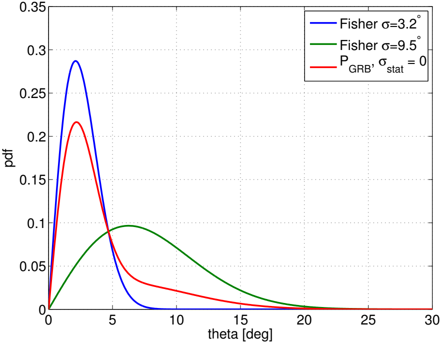
- Coalescence search
  - Adjust template time, parameters (masses, ...)
  - Sum coherently energy using waveform template
  - Check that residual is consistent with Gaussian noise (χ^2)

$\Rightarrow$ Ranking statistic

GRB sky localization

- Swift: errors $\sim 0.3^\circ \Rightarrow$ negligible for GW searches
- Fermi/GBM: large errors $\Rightarrow$ apply coherent analysis to grid covering error box

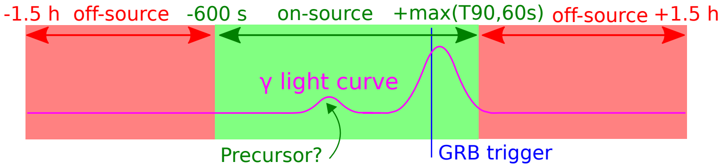




$$P_F(\theta;\kappa) = \frac{\kappa \sin\theta}{e^{\kappa} - e^{-\kappa}} e^{\kappa\cos\theta}, \quad \kappa \simeq \frac{1}{(0.66\sigma)^2}$$

- systematic $\sigma_{\text{core}} = 3.2^\circ$, $f_{\text{core}} = 0.7$, $\sigma_{\text{tail}} = 9.5^\circ$

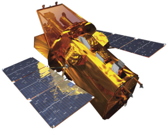
GRB triggered GW burst search

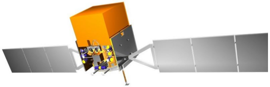


- Known position and time
  - Reduced time → reduced background
  - Position → simplify coherent analysis
    - time delays between detectors constrained by sky location box
    - ∼ 20% sensitivity improvement (Wąs et al., 2012)
  - ⇒ Burst search sensitivity improved by a factor ∼ 2 (instead of 1.6)
  - ⇒ Inspiral search sensitivity improved by a factor ∼ 1.4 (instead of 1.2)
- On-source data
  - Search for potential GW events
- Off-source data, time slides
  - Measurement of event background distribution
- Repeated independently for each GRB

Data sample

- July 2009 – October 2010
- Network of three GW detectors
  - LIGO Hanford
  - LIGO Livingston
  - Virgo, Italy
- 404 GRBs observed by γ-ray satellites
  Gamma-ray burst Coordinates Network
  - Swift
  - Fermi
  - ...

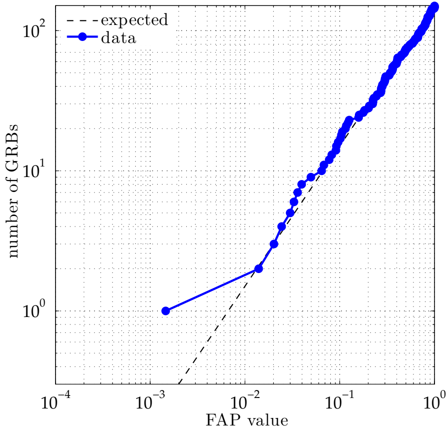




- 154 GRBs with good data from at least two GW detectors
- includes 26 short GRBs

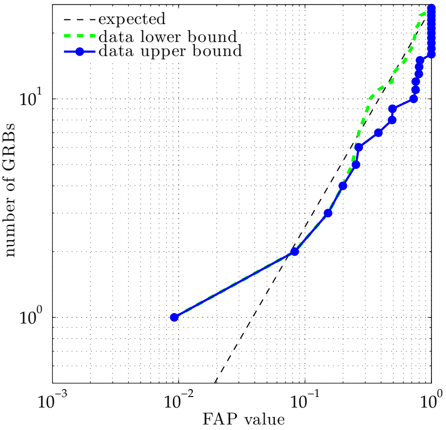
Event distribution consistent with background

GW bursts search



25% background probability

Binary coalescence search

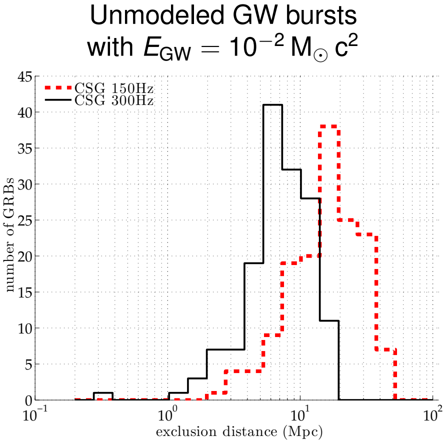


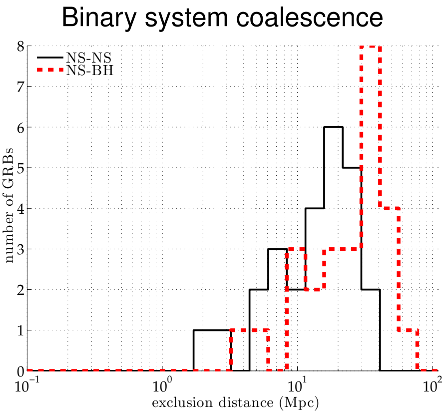
8% background probability

(Abadie et al., 2012b)

GW burst non detection consequences

GRB progenitor distance exclusion





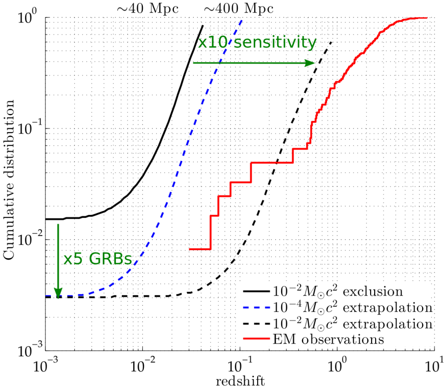
	burst 150Hz	burst 300Hz	NS-NS	NS-BH
median (Mpc)	17	7	7	28

(Abadie et al., 2012b)

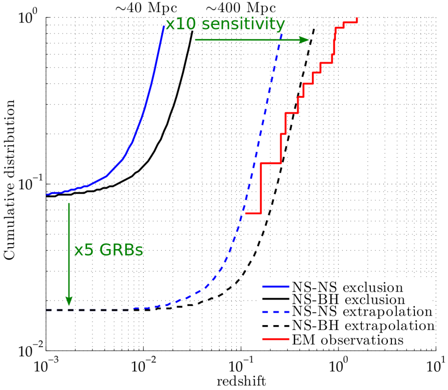
Expectations & Prospects

- 2009-2010 results

Unmodeled GW bursts



Binary coalescence



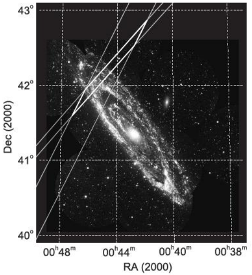
- Prospects for advanced detectors (Abadie et al., 2012b)
  - $\times$10 sensitivity, $\times$5 number of GRBs
  - long GRBs, possible if optimistic GW emission
  - short GRBs, quite possible, especially if significant NS-BH fraction

GRB070201 / GRB051103

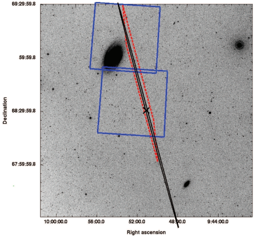
Significant previous non detections

- Short GRBs,
  - GRB070201 sky location overlap with M31, (Andromeda 770 kpc)
  - GRB051103 sky location overlap with M81 ($\sim$ 3.6 Mpc)
- no GW found
  - ⇒ Binary coalescence in M31 excluded at >99% confidence level (Abbott et al., 2008)
  - ⇒ Binary coalescence in M81 excluded at 98% confidence level (Abadie et al., 2012a)
- Compatible with
  - Neutron star quake in M31/M81 (Soft gamma-repeater giant flare)
  - Coalescence in galaxy behind M31/M81

GRB070201 error box (Mazets et al., 2008)



GRB051103 error box (Hurley et al., 2010)



What might we learn from GW-GRB observation?

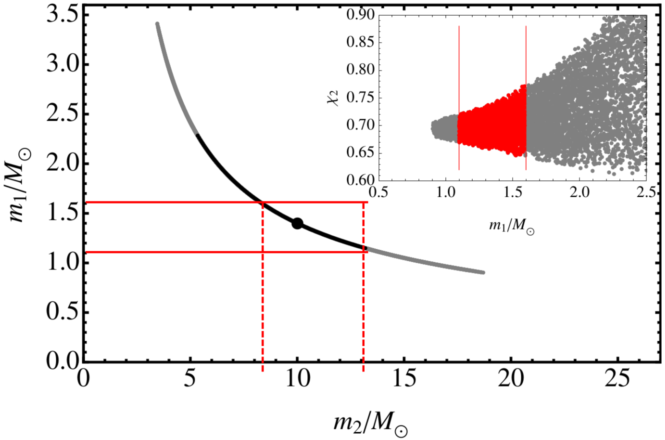
Models for short/long GRBs remain uncertain

- long GRBs
  - localization in star forming regions
  - associations with supernova
  - but also some long GRBs with strong limits on supernova ($< 10^{-3}$ typical luminosity)
- short GRBs
  - localization in galaxies with old stellar population
  - lack of supernova
  - observational confirmation weaker than for long GRBs

Potential lessons from GW-GRB detection

- Confirm the binary coalescence model for short GRBs
- Measure typical GRB jet opening angle
- Measure BH spin
- Precise measurement of GW speed, $\Delta v/c \sim 10^{-16}$
- Measure of Hubble's constant, distance $\leftrightarrow$ redshift relation

Measuring BH spin



(Hannam et al., 2013)

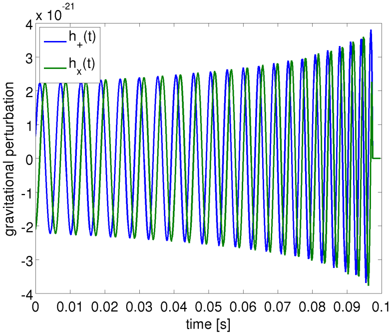
- Binary coalescence: large degeneracies between parameters
- GRB: one of the bodies is a NS, $m \sim 1.4\,\mathrm{M}_\odot$
- more precise measurement of other parameters

Measuring Hubble's constant with GWs

All potential GWs sources $z \lesssim 0.1$: $H_0 = c\frac{z}{D_L}$

$$\begin{bmatrix} h_+(t) \\ h_\times(t) \end{bmatrix} = \underbrace{\frac{A(t;\,(1+z)\mathcal{M})}{D_L}}_{\text{enveloppe}} \underbrace{\begin{bmatrix} (1+\cos^2\iota)\cos(\Psi(t)) \\ 2\cos\iota\sin(\Psi(t)) \end{bmatrix}}_{\text{polarized oscillations}}$$

- $A(t;\,(1+z)\mathcal{M})$ - GW shape sets absolute amplitude of the waveform
- D_L - luminosity distance
- ι - binary inclination angle - degenerate with luminosity distance (polarization is hard to measure)
- z - redshift - degenerate with the mass of the binary



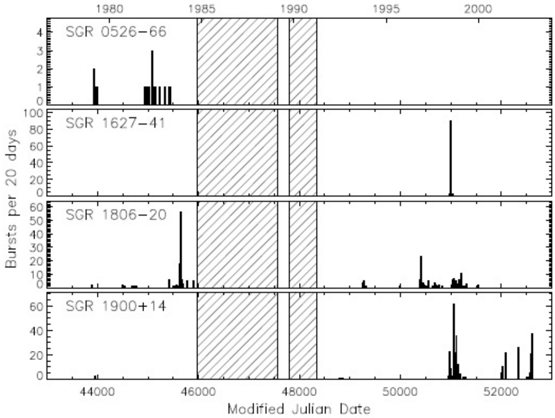
Measuring Hubble's constant with GWs

$$\begin{bmatrix} h_+(t) \\ h_\times(t) \end{bmatrix} = \frac{A(t; (1+z)\mathcal{M})}{D_L} \begin{bmatrix} (1+\cos^2\iota)\cos(\Psi(t)) \\ 2\cos\iota\sin(\Psi(t)) \end{bmatrix}$$

Several approaches

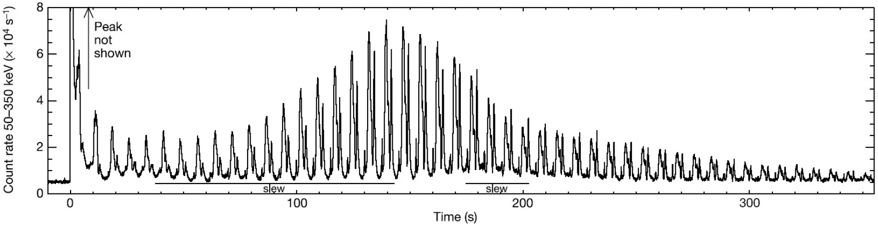
- Combine GW and GRB observation (Nissanke et al., 2010)
  - redshift given by EM observations
  - GW shape yields absolute amplitude
    $\rightarrow$ Measure D_L from GW amplitude
  - γ-ray observation means binary close to face-on
    $\rightarrow$ helps breaking the D_L vs inclination degeneracy
- Use GW information alone (Taylor et al., 2012)
  - Assume $\mathcal{M}$ known - binary neutron star system
    $\rightarrow$ Measure redshift from GW shape
  - GW shape yields absolute amplitude
    $\rightarrow$ Measure D_L from GW amplitude
  - Dozens of events per year
    $\rightarrow$ helps breaking the D_L vs inclination degeneracy
- In both cases $\sim$ 10% precision on H_0
- Measurement independent of cosmic ladder

Soft Gamma Repeater → recurring galactic "GRB"



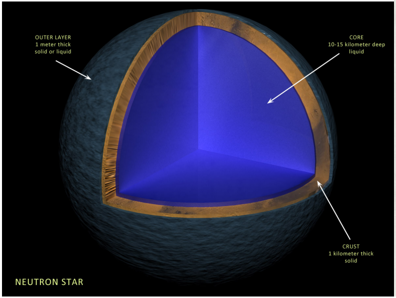
- Common bursts: $10^{35} - 10^{42}$ erg
- $\sim$ 100 ms duration, soft-gamma / hard X-ray (soft gamma repeaters and anomalous X-ray pulsars, same objects?)
- $\frac{dN}{dE} \propto E^{-5/3}$ – similar to earthquakes

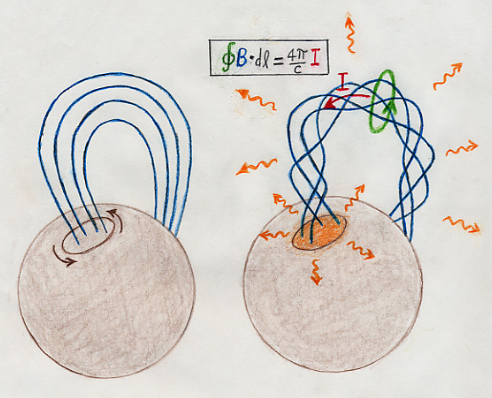
Some dramatic events – giant flare



- Giant flare: $\sim 3 \times 10^{46}$ erg $\simeq 10^{-8}\,M_{\odot}c^2$
- Saturated γ-ray satellites, perturbed radio communications
- $\sim$ 100 ms long initial peak
- Slow (5-10 sec) pulsation in the tail
- Source $\sim$10 kpc away (SGR 1806-20)
- Every $\sim$ 50 years per object?

Magnetar model

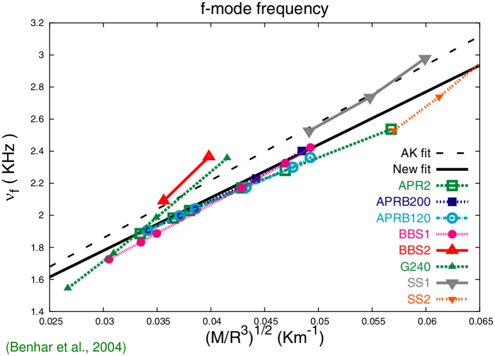




(Thompson and Duncan, 1995)

- Energy reservoir: magnetic field not rotation (unlike pulsars)
- $B_{\text{surface}} \sim 10^{15} - 10^{16}$ G
- Exterior magnetic field reconnections
  $\rightarrow$ common bursts ($10^{35} - 10^{42}$ erg)
- Large scale reconfigurations, up to $E_{\text{jump}} \sim 10^{48}$ erg (Corsi and Owen, 2011; Ioka, 2001)

Neutron star seismology



(Benhar et al., 2004)

"Standard" oscillation modes

(present in the sun)

- p/g/f-modes
- f-modes
  - buoyancy as restoring force
  - ripples on star surface
  - mainly damped through GWs
  - 1-3 kHz

Oscillation coming from extreme properties

- crust/fluid structure, fast rotation, space-time deformation, ...
- s/i/t/r/w-modes

⇒ How the large scale reconfiguration excite these modes?

Gravitational wave emission

⇒ How does the large scale reconfiguration unfold?

Main question

- $E_{\mathrm{GW}}/E_{\mathrm{jump}} = ?$
  - What fraction of the released energy get converted into GWs?
  - ⇒ How much into f-modes
  - ⇒ How much non-linear / out of modal decomposition scope?
- $E_{\mathrm{GW}}/E_{\gamma\text{-ray}} = ?$
  How the EM and GW luminosities are related

Some answer (Zink et al., 2012)

- General relativity, magnetohydrodynamic simulations
  initial state: unstable poloidal magnetic field

$$E_{\mathrm{GW}} = 10^{43} \times \left(\frac{B_{\mathrm{surface}}}{10^{16}\ \mathrm{G}}\right)^{6.5} \mathrm{erg}$$

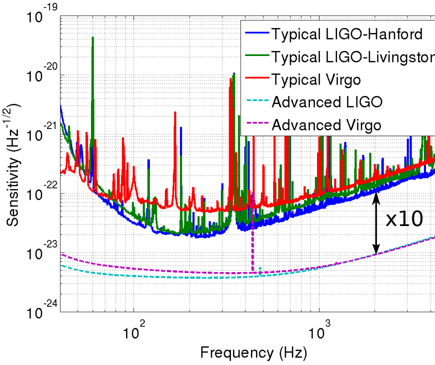
- Very strong dependence on magnetic field
- Overall scale might depend strongly on the initial state

A priori sensitivity

$$E_{\mathrm{GW}} = \frac{\pi^2 c^3}{G} r^2 f^2 h_{\mathrm{rss}}^2$$

$$h_{\mathrm{rss}} \propto \sqrt{S(f)}\mathrm{SNR}_{\mathrm{threshold}}$$

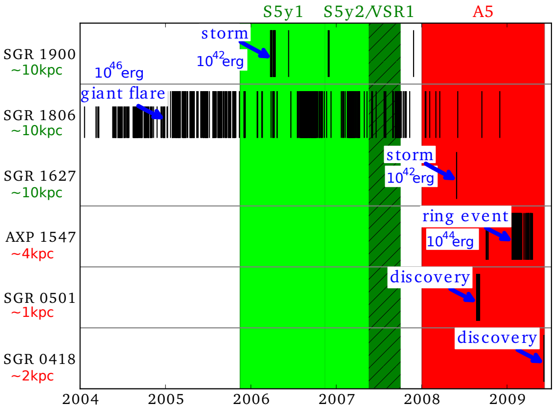
at 1 kpc	LIGO	advanced LIGO
150 Hz	5×10^{43} erg	10^{42} erg
2 kHz	5×10^{47} erg	10^{45} erg
at 10 kpc		
150 Hz	5×10^{45} erg	10^{44} erg
2 kHz	5×10^{49} erg	10^{47} erg

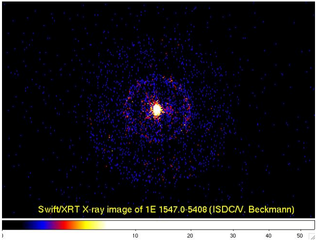


simulation: $E_{\mathrm{GW}} = 10^{43} \times \left(\frac{B_{\mathrm{surface}}}{10^{16}\,\mathrm{G}}\right)^{6.5}$ erg

⇒ nearby giant flare ... SGR 0501, SGR 0418, ... only?

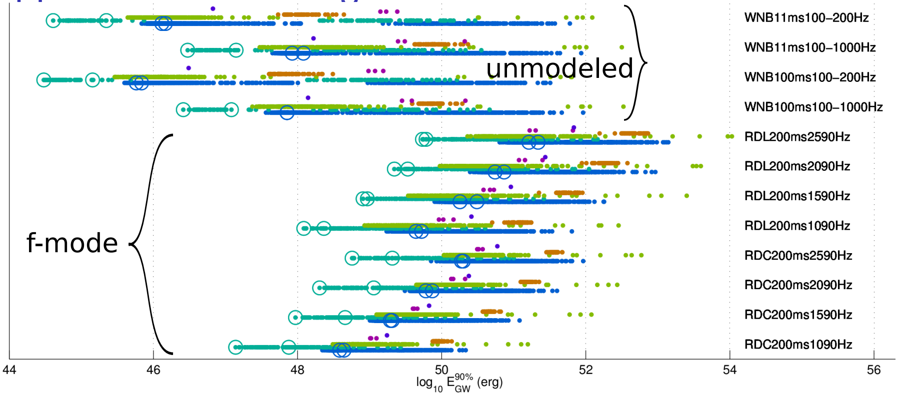
Recent SGR activity





- No exceptional events since
- Astrowatch data less sensitive

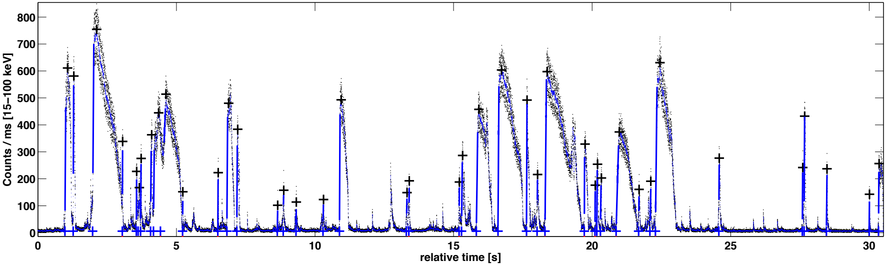
Upper limits for 6 magnetars with 2007–2009 data



(Abadie et al., 2011c)

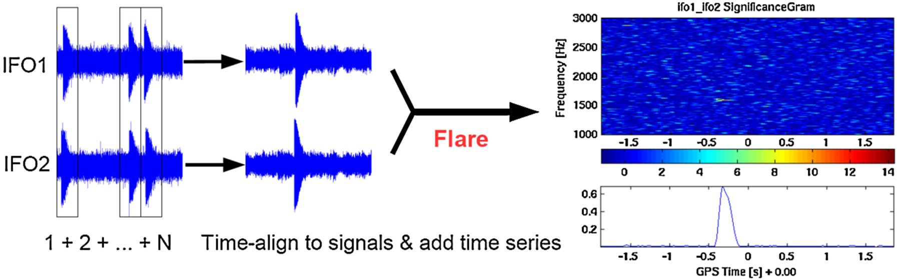
- cyan – SGR 0501 (1 kpc), blue – AXP 1547 (4 kpc)
- but both in Astrowatch data
- blue circles, AXP 1547 ring events (10^{44} erg)

SGR 1900+14 storm in 2006



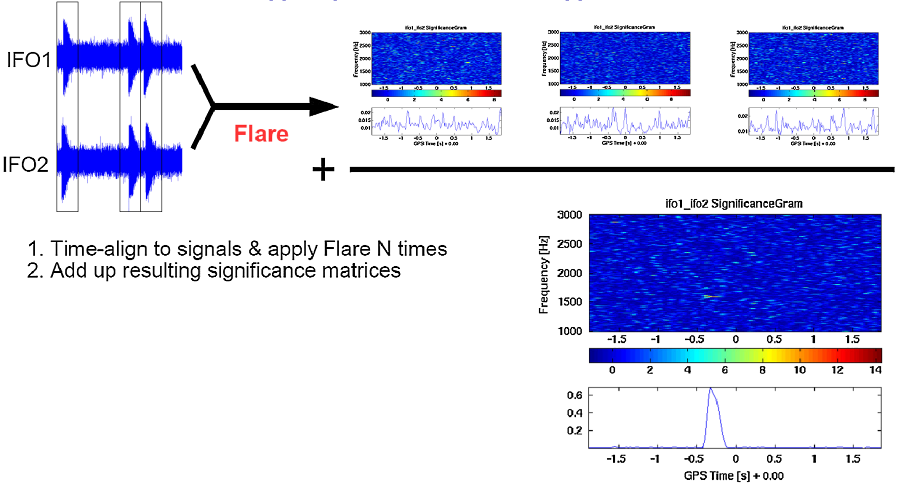
- Energy $\sim 10^{42}$ erg
- spread over many bursts, can they be combined?

GW data stacking – time stacking



- sensitivity $\propto \sqrt{N_{\text{bursts}}}$
- requires $\lesssim 100\ \mu$s accuracy
- observation and emission uncertainties $\rightarrow$ not usable in practice

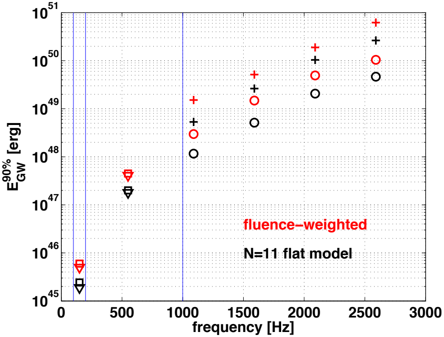
GW data stacking – power stacking



1. Time-align to signals & apply Flare N times
2. Add up resulting significance matrices

- sensitivity $\propto (N_{\text{bursts}})^{1/4}$
- requires $\lesssim 30\,\text{ms}$ accuracy

GW search energy upper limits



(Abbott et al., 2009)

Follows a priori sensitivity:

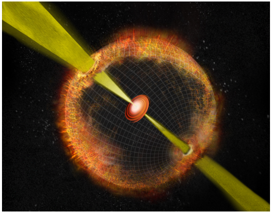
at 10 kpc	LIGO	advanced LIGO
150 Hz	5×10^{45} erg	10^{44} erg
2 kHz	5×10^{49} erg	10^{47} erg

Summary

- Astrophysical triggers:
  - more sensitive GW search
  - more interesting interpretations

⇒ Require study EM & GW phenomenology

- Both short and long GRB may produce GWs
- Non detections already interesting (GRB070201, GRB051103)
- Good prospects for advanced LIGO/Virgo
- With more detections come interesting measures:
  BH spin, jets, Hubble's constant
- SGR interesting source if nearby ($\sim 1\,$kpc) giant flare ($\sim 10^{45}\,$erg)



References

Abadie, J. et al. (2011a). All-sky search for periodic gravitational waves in the full S5 LIGO data. *Astrophys. J.*, 737:93.

Abadie, J. et al. (2011b). Beating the spin-down limit on gravitational wave emission from the vela pulsar. *Astrophys. J.*, 737:93.

Abadie, J. et al. (2011c). Search for gravitational wave bursts from six magnetars. *Astrophys. J. Lett.*, 734:L35.

Abadie, J. et al. (2012a). Implications for the Origin Of GRB 051103 From LIGO Observations. *Astrophys. J.*, 755:2.

Abadie, J. et al. (2012b). Search for gravitational waves associated with gamma-ray bursts during LIGO science run 6 and Virgo science run 2 and 3. *Astrophys. J.*, 760:12.

Abbott, B. P. et al. (2008). Implications for the origin of GRB 070201 from LIGO observations. *Astrophys. J*, 681:1419.

Abbott, B. P. et al. (2009). Stacked search for gravitational waves from the 2006 SGR 1900+14 storm. *Astrophys. J. Lett.*, 701:68.

Abbott, B. P. et al. (2010). Searches for gravitational waves from known pulsars with science run 5 LIGO data. *Astrophys. J.*, 713:671.

Benhar, O., Ferrari, V., and Gualtieri, L. (2004). Gravitational wave asteroseismology reexamined. *Physical Review D*, 70(12):124015.

Corsi, A. and Owen, B. J. (2011). Maximum gravitational-wave energy emissible in magnetar flares. *Phys. Rev. D*, 83:104014.

Hannam, M., Brown, D. A., Fairhurst, S., Fryer, C. L., and Harry, I. W. (2013). When can gravitational-wave observations distinguish between black holes and neutron stars? *Astrophys. J. Lett.*, 766:L14.

Hurley, H. et al. (2010). A new analysis of the short-duration, hard-spectrum GRB 051103, a possible extragalactic soft gamma repeater giant flare. *Mon. Not. R. Astron. Soc.*, 403:342.

Ioka, K. (2001). Magnetic deformation of magnetars for the giant flares of the soft gamma-ray repeaters. *Mon. Not. R. Astron. Soc.*, 327:639.

Mazets, E. P. et al. (2008). A giant flare from a soft gamma repeater in the andromeda galaxy (m31). *Astrophys. J.*, 680:545.

Nissanke, S. et al. (2010). Exploring short gamma-ray bursts as gravitational-wave standard sirens. *Astrophys. J.*, 725:496.

Taylor, S. R., Gair, J. R., and Mandel, I. (2012). Cosmology using advanced gravitational-wave detectors alone. *Phys. Rev. D*, 85:023535.

Thompson, C. and Duncan, R. C. (1995). The soft gamma repeaters as very strongly magnetized neutron stars - I. Radiative mechanism for outbursts. *Mon. Not. R. Astron. Soc.*, 275:255.

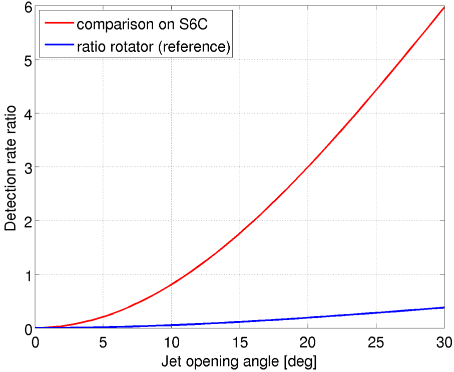
Wąs, M., Sutton, P. J., Jones, G., and Leonor, I. (2012). Performance of externally triggered gravitational-wave burst search with X-Pipeline. *Phys. Rev. D*, 86:022003.

Zink, B., Lasky, P. D., and Kokkotas, K. D. (2012). Are gravitational waves from giant magnetar flares observable? *Phys. Rev. D*, 85:024030.

Relevance of triggered search vs all-sky search

Is a GRB triggered search a good of detecting GWs from binary coalescences / star collapse?

- Triggered search misses progenitors beaming away from Earth
- Triggered search is more sensitive

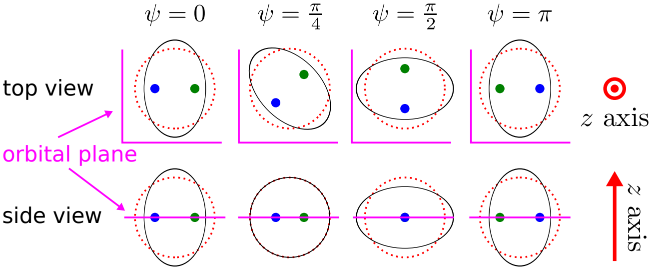


Astrophysical framework

- GRB progenitors (CBC, hypernova,...) are standard GW sirens $\Rightarrow$ fixed E_{GW}
- Uniform distribution in space
- Rotator GW emission pattern (binary, bar mode, ...)

$$\begin{pmatrix} h_+ \\ h_\times \end{pmatrix} \propto \begin{pmatrix} 1 + \cos^2 \iota \\ 2 \cos \iota \end{pmatrix}$$

  - face on $\longrightarrow$ circular polarization
  - edge on $\longrightarrow$ linear polarization
  - inclination ι $\longrightarrow$ elliptical



circular polarization
$h_+ = \pm i h_\times$

linear polarization
$h_+ \neq 0, \quad h_\times = 0$

EM & GW beaming

$$\begin{pmatrix} h_+ \\ h_\times \end{pmatrix} \propto \begin{pmatrix} 1 + \cos^2 \iota \\ 2 \cos \iota \end{pmatrix}$$

- GW power flux dependence on ι, slight GW beaming

$$F(\iota) = \frac{(2\cos\iota)^2 + (1+\cos^2\iota)^2}{8}, \quad F(0) = 1, \quad F(\pi/2) = 1/8$$

- γ-ray emission in a cone around rotation axis, top hat emission
  - two sided jet $\longrightarrow$ $\iota \in [0, \pi/2]$
  - jet of opening angle θ_j (thought to be in $5 - 30°$ range)
  - $\iota < \theta_j \longrightarrow$ GRB detected on Earth
  - $\iota > \theta_j \longrightarrow$ progenitor dark in γ-rays (missed by exttrig search)

Theoretical comparison

Issue

- All-sky searches for GW from all progenitors
- Exttrig searches only for progenitors with $\iota < \theta_j$

$\Rightarrow$ Gain in sensitivity $\leftrightarrow$ loss in GW source density rate

Analysis toy model

- Forget about ITF antenna patterns
- Analysis detection based on a sharp threshold on h_{rss}
  - At given inclination ι analysis efficiency drops from 1 to 0 at horizon distance $r(\iota)$
  - Simple dependence on inclination: $r(\iota) = \sqrt{F(\iota)}r(0)$
- Hopefully $r_{\text{exttrig}}(\iota) > r_{\text{all-sky}}(\iota)$ for $\iota < \theta_j$
- Effective search volume, marginalize over inclination
  - For all-sky

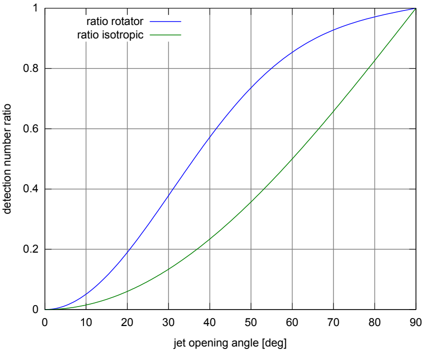
$$V_{\text{all-sky}} = \int_{\iota=0}^{\pi/2} \frac{4\pi}{3} r^3_{\text{all-sky}}(\iota)\sin(\iota)\mathrm{d}\iota$$

  - For exttrig

$$V_{\text{exttrig}} = \int_{\iota=0}^{\theta_j} \frac{4\pi}{3} r^3_{\text{exttrig}}(\iota)\sin(\iota)\mathrm{d}\iota$$

Detection rate ratio

- Detection rate ratio $R(\theta_j)$ for equal horizons: $r_{\text{all-sky}} = r_{\text{exttrig}}$



$$R(\theta_j) = \frac{V_{\text{exttrig}}(\theta_j)}{V_{\text{all-sky}}}$$

$$r(\iota) = \sqrt{F(\iota)}\, r(0)$$

$$F_{\text{rotator}}(\iota) = \frac{(2\cos\iota)^2 + (1+\cos^2\iota)^2}{8}$$

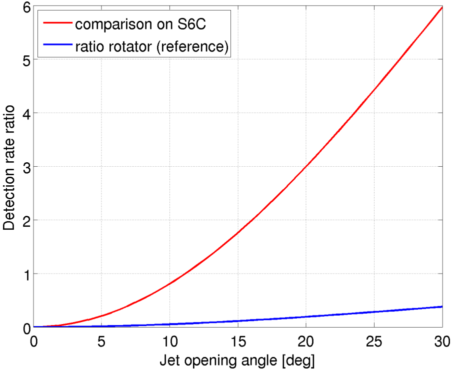
$$F_{\text{isotropic}} = 1$$

- For other sensitivity ratio, multiply curve by $(r_{\text{exttrig}}/r_{\text{all-sky}})^3$

$\Rightarrow$ GW beaming helps the exttrig approach by a factor ~ 3
(in the small opening angle limit)

Relevance of triggered search vs all-sky search

- Triggered search misses progenitors beaming away from Earth
- Triggered search is more sensitive



⇒ interesting even for small jet opening angles

- Reference: fraction found by all-sky search with γ-ray counterpart

⇒ Two approaches see (mostly) independent events

Signal to noise ratio – SNR

- Perfectly known signal $s(t) \leftrightarrow \tilde{s}(f)$

$$\mathrm{SNR}^2_{\mathrm{optimal}} = 2 \int_{-\infty}^{\infty} \frac{|\tilde{s}(f)|^2}{A(|f|)^2} \mathrm{d}f$$

- Whitened signal/data

$$\tilde{d}^w(f) = \tilde{d}(f) \times \frac{\sqrt{2}}{A(|f|)}$$

- Matched filtering: scalar product between template and data

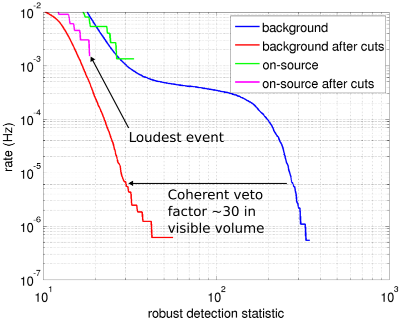
$$\mathrm{SNR} = \int_{-\infty}^{\infty} \tilde{s}^w(f)^* \tilde{d}^w(f) \mathrm{d}f \Big/ \sqrt{\int_{-\infty}^{\infty} |\tilde{s}^w(f)|^2 \mathrm{d}f}$$

- $d(f) = n(f)$ – SNR normally distributed
- $d(f) = s(f) + n(f)$ – distribution mean is shifted by $\mathrm{SNR}_{\mathrm{optimal}}$

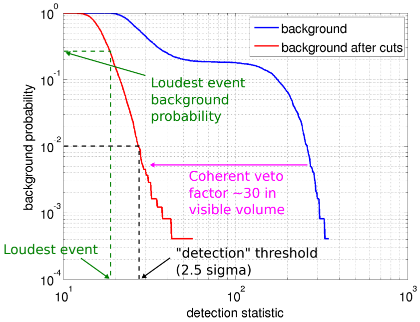
$\Rightarrow$ $\mathrm{SNR}_{\mathrm{optimal}}$ – detectability in perfect conditions

Background estimation

Event rate above threshold



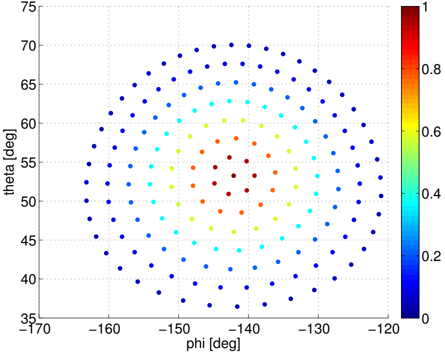
background probability in window



Background probability $\simeq$ background event rate $\times$ time window length

Loudest event in on-source window $\Rightarrow$ Effective clustering over the window

Sky position error box

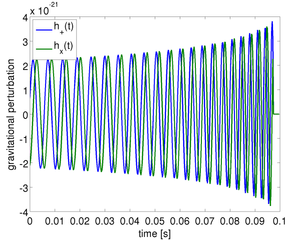


$$L(\mathbf{d}|\circlearrowright,\sigma_h) = \frac{|\mathbf{e}^{\circlearrowright}\cdot\mathbf{d}|^2}{1+1/(\sigma_h|\mathbf{f}^{\circlearrowright}|)^2} - \log(1+\sigma_h^2|\mathbf{f}^{\circlearrowright}|^2),$$

$$L(\mathbf{d}|\text{circular}) = 2\log\sum_{\sigma_h\in\mathcal{A}} \frac{\max\left\{\exp\left[\frac{1}{2}L(\mathbf{d}|\circlearrowright,\sigma_h)\right],\exp\left[\frac{1}{2}L(\mathbf{d}|\circlearrowleft,\sigma_h)\right]\right\}}{|\mathcal{A}|}.$$

Sensitivity estimation - signal models

- Compact object coalescence (inspiral)
  - BH-NS: $m_{\mathrm{BH}} = 10 \pm 6\,\mathrm{M}_\odot$
    $m_{\mathrm{NS}} = 1.4 \pm 0.4\,\mathrm{M}_\odot$
  - NS-NS: $m_{\mathrm{NS}} = 1.4 \pm 0.2\,\mathrm{M}_\odot$
- Extreme stellar collapse
  - Ad-hoc model to sample parameter space – sine-Gaussian



$$\begin{bmatrix} h_+(t+t_0) \\ h_\times(t+t_0) \end{bmatrix} = A_0 \begin{bmatrix} \cos(2\pi f_0 t)(1+\cos^2\iota) \\ \underbrace{\sin(2\pi f_0 t)}_{\text{rotation}}\ \underbrace{2\cos\iota}_{\text{inclination}} \end{bmatrix} \underbrace{\exp\left[-\frac{(2\pi f_0 t)^2}{2Q^2}\right]}_{\text{envelope}}$$

  - $f_0 = 2f_{\mathrm{rot}} = 100, 150, 300\,\mathrm{Hz},\ Q = 9$
  - $E_{\mathrm{GW}} = 10^{-2}\,\mathrm{M}_\odot c^2$, distance $\rightarrow A_0$
- Nuisance parameters $\rightarrow$ jitter injections
  - Sky localization error
  - Calibration errors
  - System inclination ι