Connection between Gravitational Waves and Gamma-ray Bursts

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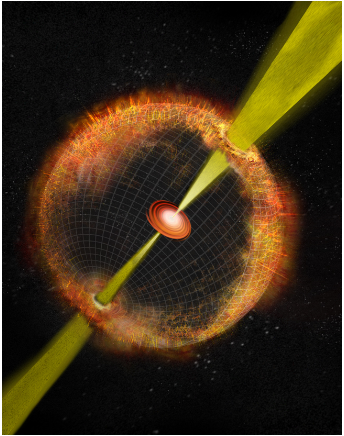
Outline



Credit: Bill Saxton, NRAO/AUI/NSF

Motivations for triggered GW searches

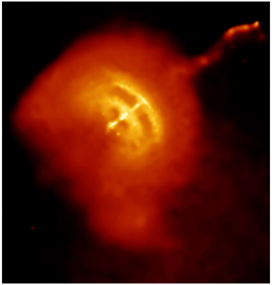
- Astrophysics
  - We know about:
    - Gamma-ray bursts
    - Soft gamma repeaters
    - Supernovae
    - Pulsars
  - GWs give information on core mass dynamics
- Detector noise
  - Instrumental/environmental noise is limiting
  - Any information helps removing some noise

Example of sensitivity improvement unrelated to GRBs

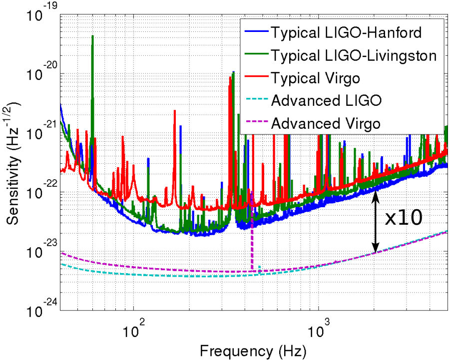
- Young pulsars (neutron stars)
  - Crab (SN 1054)
  - Vela (SN $\sim 10^4$ yr ago)

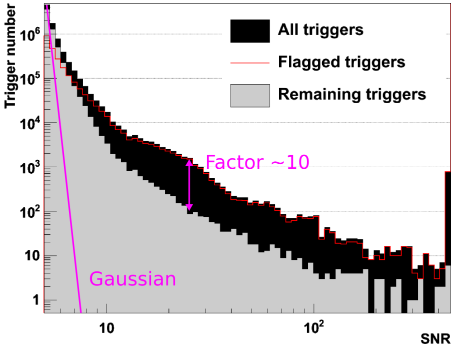
  spin frequency is precisely observed in radio
- The rotation period is decreasing
  $\rightarrow$ loss of rotational energy
- LIGO 2005-2007: less than 2% of Crab energy loss is due to GW emission (Abbott et al., 2010)
- Virgo 2009-2010: less than 40% of Vela energy loss is due to GW emission (Abadie 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



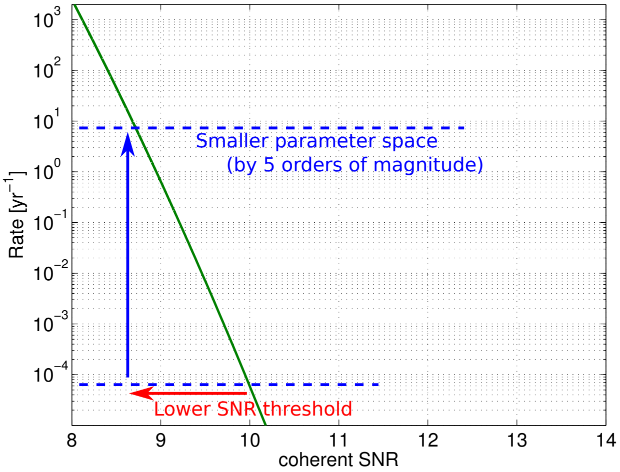


smallest observable GW amplitude $\propto \sqrt{S(f)} \times \mathrm{SNR}_{\mathrm{threshold}}$

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

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

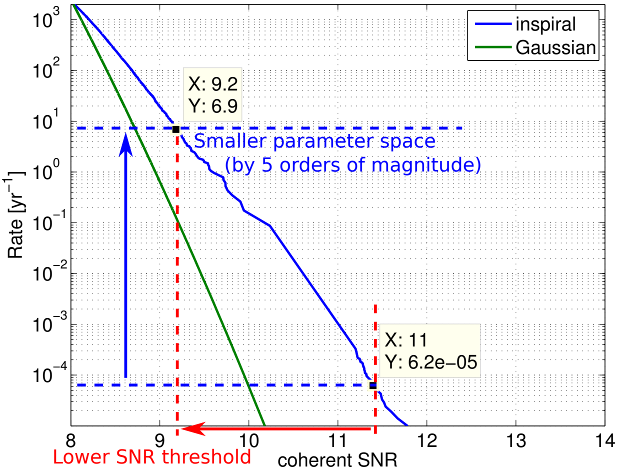
Triggered search in Gaussian noise



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

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

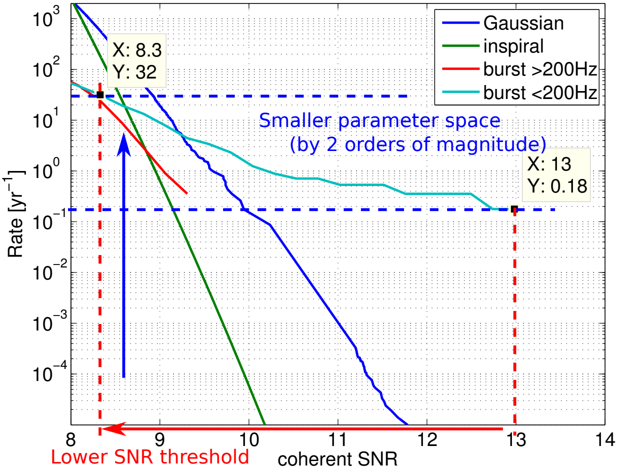
Well cleaned real noise (inspiral + χ^2 test)



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

$\Rightarrow$ 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

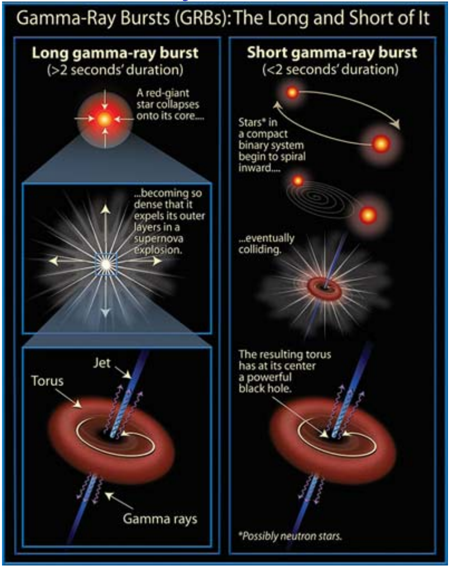
Practical example on GRB case

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

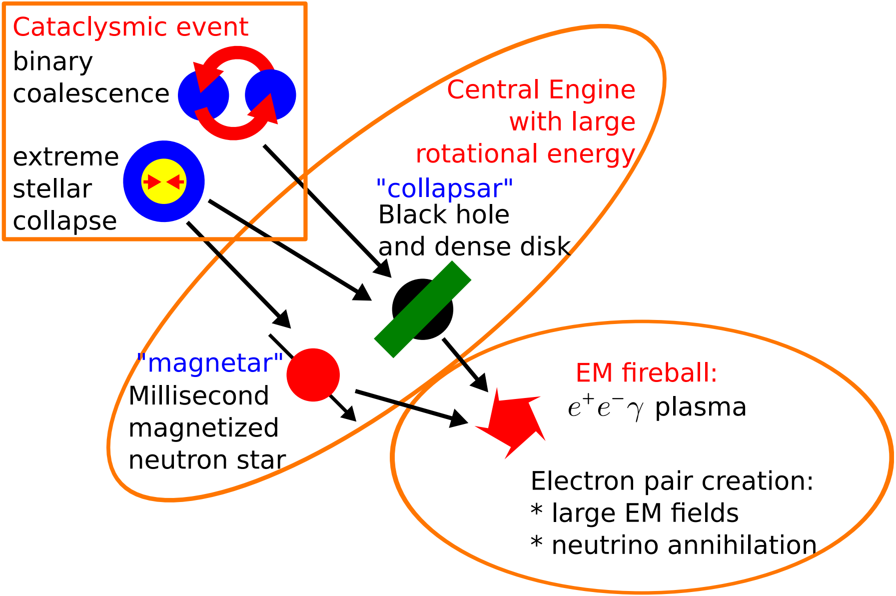
- Long GRBs

⇒ Massive rapidly spinning star collapse and explosion

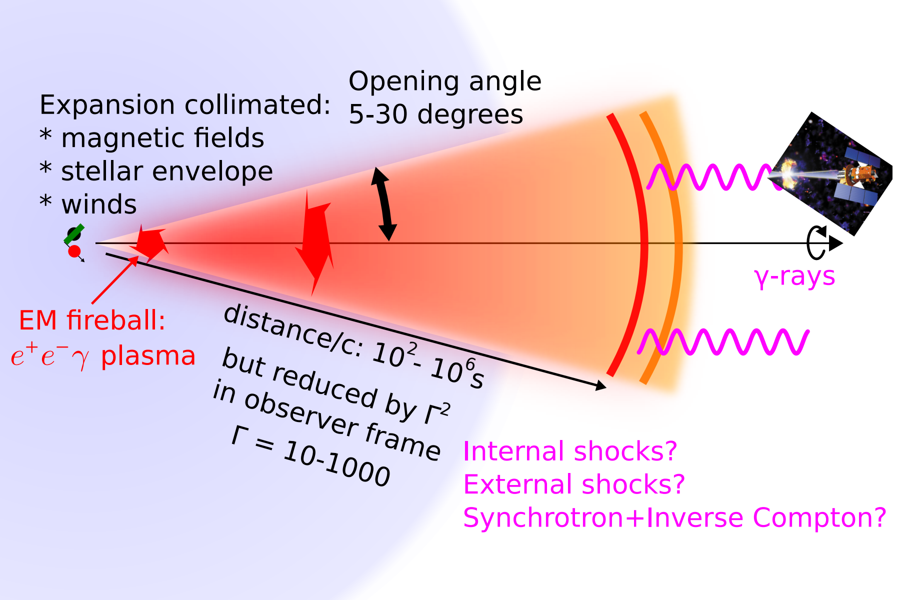
- Short GRBs

⇒ 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: $\sim 10^{51}\,\mathrm{erg} = 10^{-3}\,M_\odot c^2$

EM emission - standard fireball model

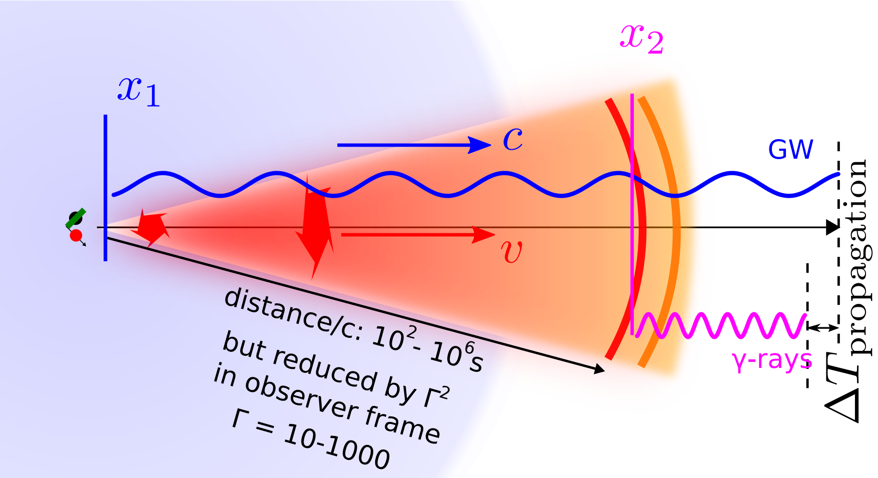


EM emission - standard fireball model



Relativistic contraction

$$\Gamma = \frac{1}{\sqrt{1-(v/c)^2}}, \qquad \Delta T_{\text{propagation}} = \frac{x_2 - x_1}{v} - \frac{x_2 - x_1}{c} \underset{\Gamma \gg 1}{\simeq} \frac{x_2 - x_1}{2c\Gamma^2}$$



Gravitational source quadrupolar approximation

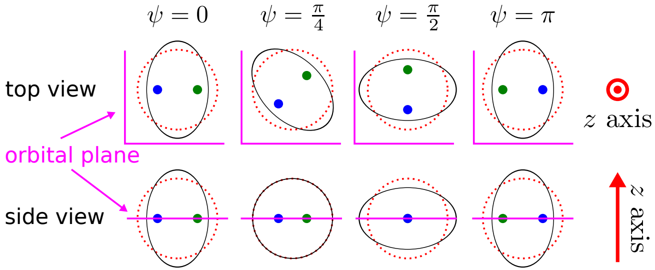
Approximation: far field + slow moving source

- 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

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

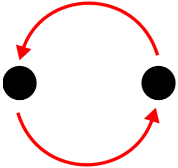


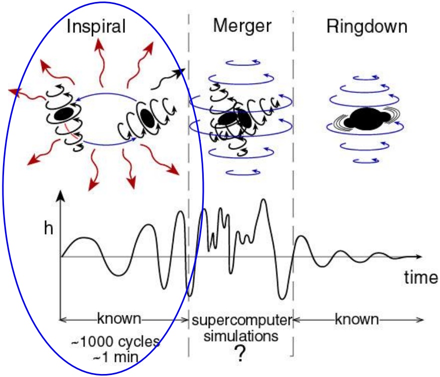
circular polarization
$h_+ = \pm i h_\times$

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 Hz) $<$ 50 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

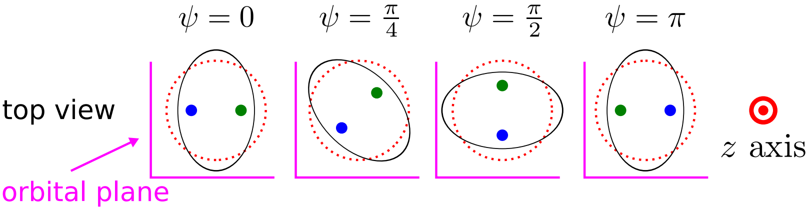
$\Rightarrow$ merger $[-1, 0]$ s prior to jet launch

- 1-2 second to produce γ-rays

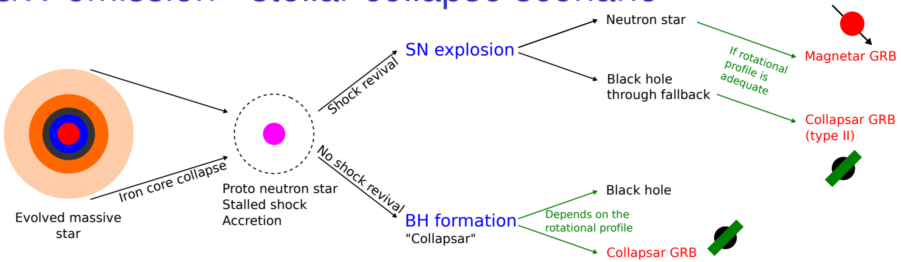
$\Rightarrow$ Inspiral ends $\simeq [-3, 0]$ s prior to GRB

- GRB observed $\rightarrow$ rotation axis points at observer

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



GW emission - stellar collapse scenario



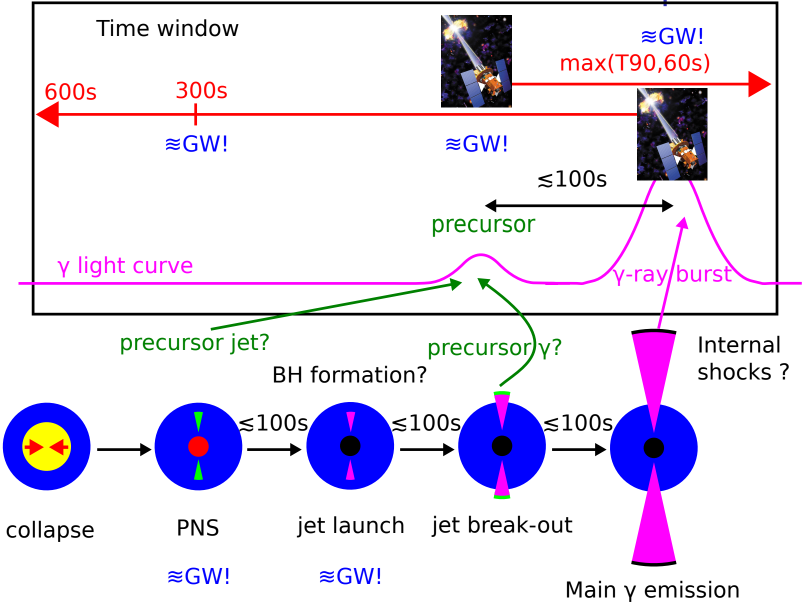
- Magnetar central engine / Proto neutron star
  - bar mode instability in the star
  - neutron star core fragmentation
- Black hole and accretion disk
  - Disk fragmentation
  - Disk precession

$\Rightarrow$ circular polarization along rotation axis

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

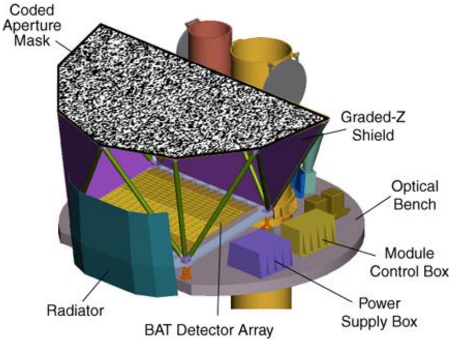
- Other emission mechanism but no prospects for extra-galactic reach
  - Out of frequency band (Neutrino, normal modes, ...)
  - Too small amplitude (Core bounce, SASI, ...)

GW vs GRB time of arrival - stellar collapse



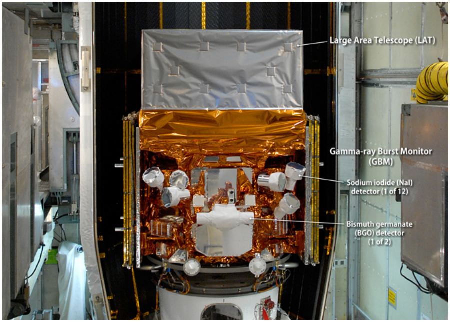
GRB sky localization - two technologies

Swift/BAT



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

Fermi/GBM

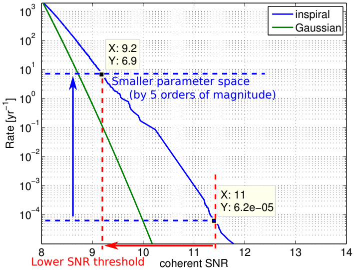


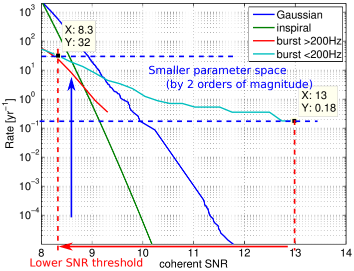
Fo

$\sim$ 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 ($\sim 75\%$)

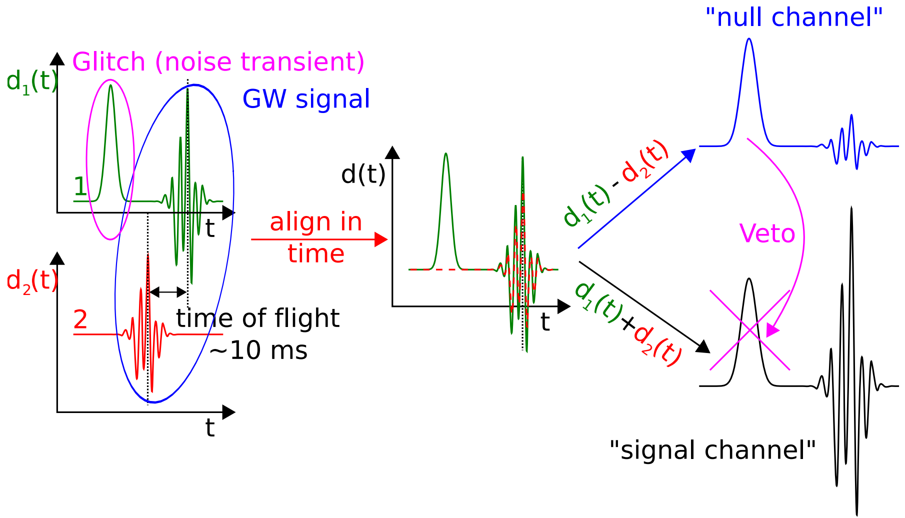




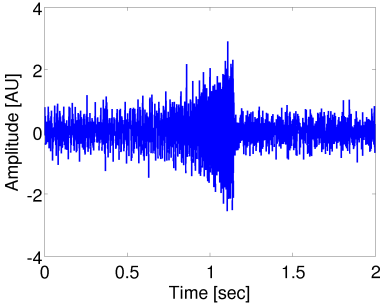
Two complementary searches

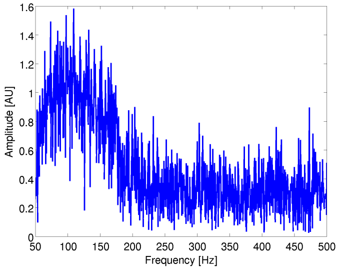
- Broad in scope – covers most possibilities
  - "burst" searching method – any signal shapes
  - Limited to $60 - 500\,\text{Hz}$ band, $\lesssim 1\,\text{s}$ duration
  - Assumes circular polarization
  - Loose time coincidence between γ-rays and GW $T_\gamma - T_{\text{GW}} \in [-600, \max(T_{90}, 60)]\,\text{s}$
- Focused on short GRBs – binary coalesence
  - Inspiral waveform templates, NS-NS and NS-BH
  - Tight time coincidence between γ-rays and GW $T_\gamma - T_{\text{GW}} \in [-5, 1]\,\text{s}$
  - More sensitive to inspiral signals by factor ~ 2
- GW data combined coherently in both searches
- (Abadie et al., 2012b)

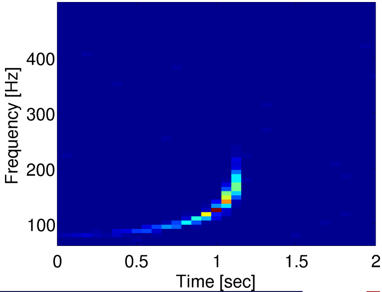
Coherent GW analysis



Excess wrt Gaussian noise $\rightarrow$ Time frequency maps



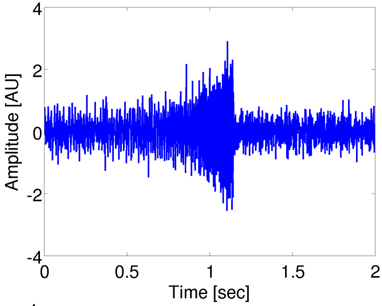


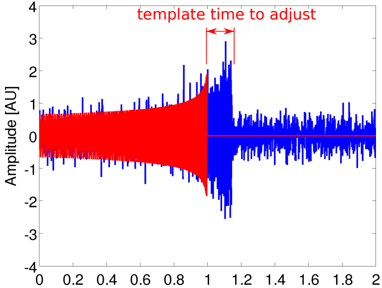


- Burst search
  - Concentrate signal energy in a small number of pixels
  - Sum energy over clusters of “loud” pixels

$\Rightarrow$ Ranking statistic

Excess wrt Gaussian noise → match with templates



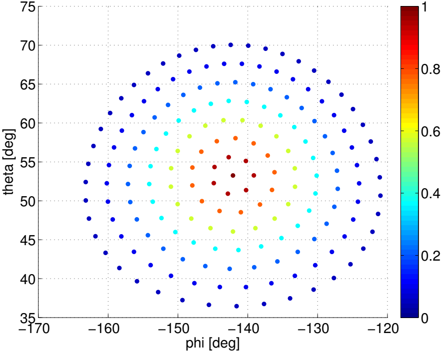


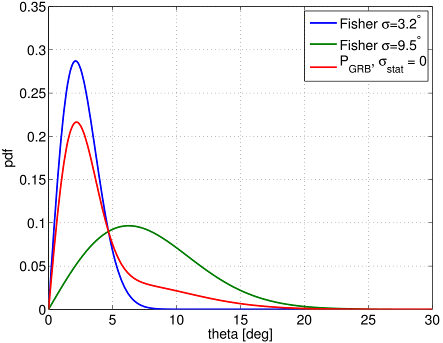
- Coalescence search
  - Adjust template time, parameters (masses, ...)
  - Sum coherently energy using waveform template
  - Check that residual is consistent with Gaussian noise (χ^2)

⇒ 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

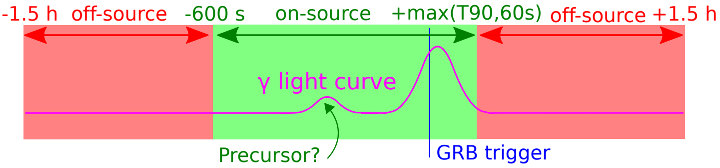




$$P_F(\theta;\kappa) = \frac{\kappa \sin\theta}{e^{\kappa} - e^{-\kappa}} e^{\kappa \cos\theta}, \quad \kappa \simeq \frac{1}{(0.66\sigma)^2}$$

- 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
    - $\sim$ 20% sensitivity improvement (Wąs et al., 2012)

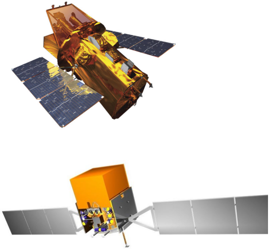
⇒ Burst search sensitivity improved by a factor $\sim$ 2 (instead of 1.6)

⇒ Inspiral search sensitivity improved by a factor $\sim$ 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

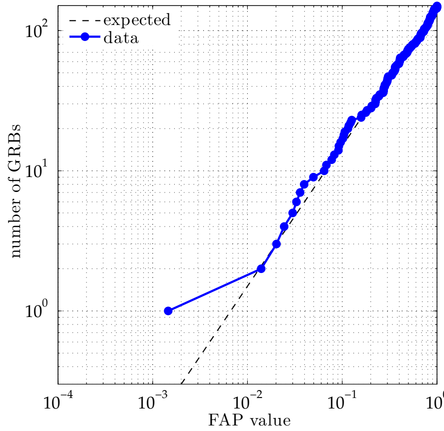
- July 2009 – October 2010
- Network of three GW detectors
  - LIGO Hanford
  - LIGO Livingston
  - Virgo, Italy
- 404 GRBs observed by γ-ray satellites
  Gamma-ray burst Coordinates Network
  - Swift
  - Fermi
  - ...



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

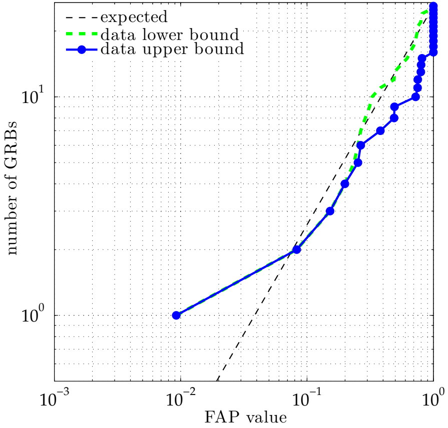
Event distribution consistent with background

GW bursts search



25% background probability

Binary coalescence search



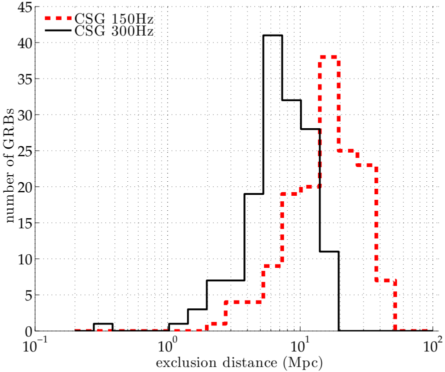
8% background probability

(Abadie et al., 2012b)

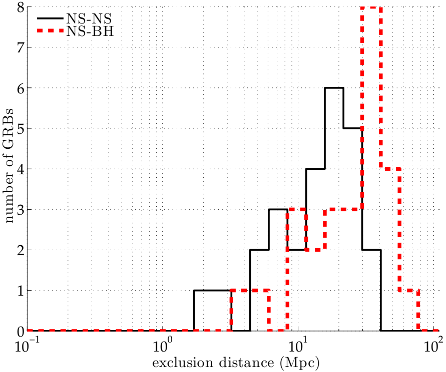
GW burst non detection consequences

GRB progenitor distance exclusion

Unmoded GW bursts with $E_{GW} = 10^{-2}\,M_\odot\,c^2$



Binary system coalescence



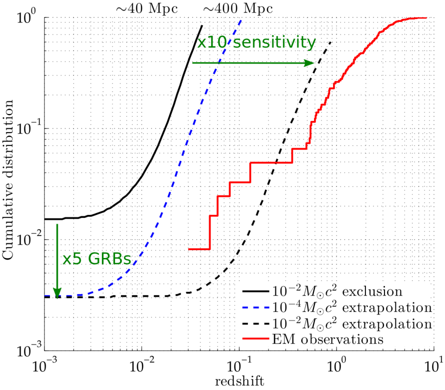
	burst 150Hz	burst 300Hz	NS-NS	NS-BH
median (Mpc)	17	7	7	28

(Abadie et al., 2012b)

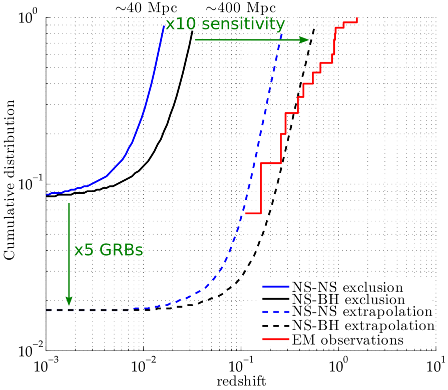
Expectations & Prospects

- 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

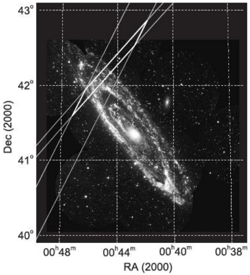
Significant previous non detections

- Short GRBs,
  - GRB070201 sky location overlap with M31, (Andromeda 770 kpc)
  - GRB051103 sky location overlap with M81 ($\sim$ 3.6 Mpc)
- no GW found

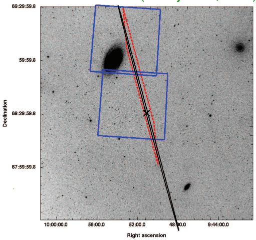
  ⇒ Binary coalescence in M31 excluded at >99% confidence level (Abbott et al., 2008)

  ⇒ Binary coalescence in M81 excluded at 98% confidence level (Abadie et al., 2012a)
- Compatible with
  - Neutron star quake in M31/M81 (Soft gamma-repeater)
  - 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?

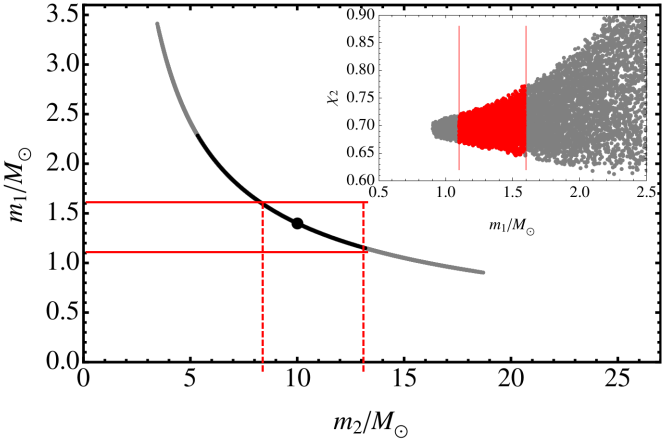
Models for short/long GRBs remain uncertain

- 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)

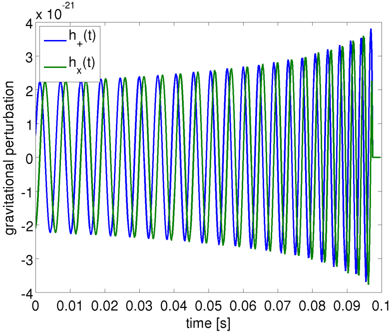
- Binary coalescence: large degeneracies between parameters
- GRB: one of the bodies is a NS, $m \sim 1.4\,M_\odot$
- more precise measurement of other parameters

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

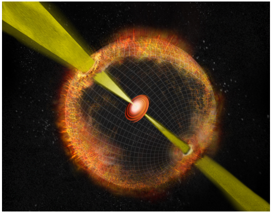
- Combine GW and GRB observation (Nissanke et al., 2010)
  - redshift given by EM observations
  - GW shape yields absolute amplitude
    $\rightarrow$ Measure D_L from GW amplitude
  - γ-ray observation means binary close to face-on
    $\rightarrow$ helps breaking the D_L vs inclination degeneracy
- 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

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 provide information (GRB070201, GRB051103)
- Good prospects for advanced LIGO/Virgo
- With more detections come interesting measures:
  BH spin, jets, Hubble's constant



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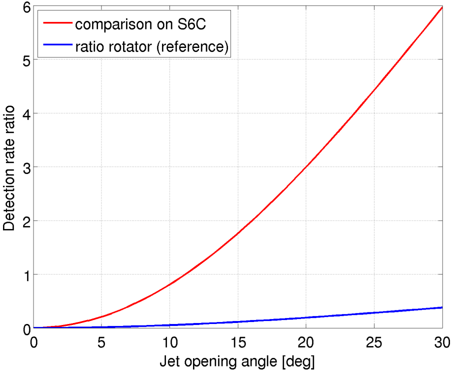
Relevance of triggered search vs all-sky search

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

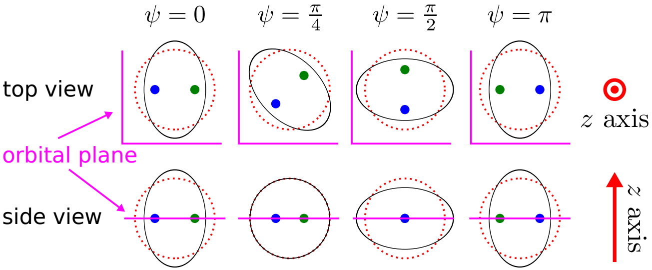


Astrophysical framework

- 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 $r_{\mathrm{exttrig}}(\iota) > r_{\mathrm{all\text{-}sky}}(\iota)$ for $\iota < \theta_j$
- Effective search volume, marginalize over inclination
  - For all-sky

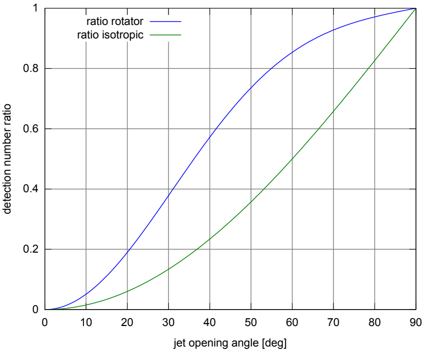
$$V_{\mathrm{all\text{-}sky}} = \int_{\iota=0}^{\pi/2} \frac{4\pi}{3} r^3_{\mathrm{all\text{-}sky}}(\iota)\sin(\iota)\mathrm{d}\iota$$

  - For exttrig

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

Detection rate ratio

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



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

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

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

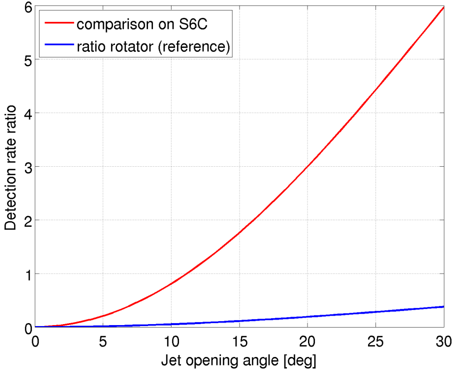
$$F_{\text{isotropic}} = 1$$

- 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

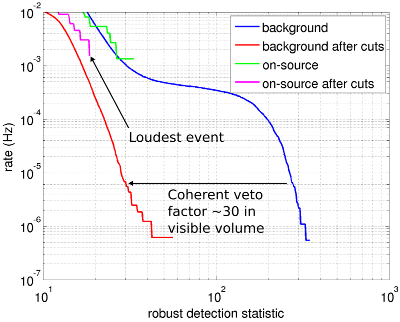
$$\mathrm{SNR} = \int_{-\infty}^{\infty} \tilde{s}^w(f)^* \tilde{d}^w(f) \mathrm{d}f \Bigg/ \sqrt{\int_{-\infty}^{\infty} |\tilde{s}^w(f)|^2 \mathrm{d}f}$$

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

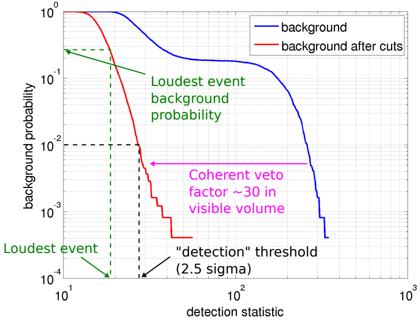
⇒ $\mathrm{SNR}_{\mathrm{optimal}}$ – detectability in perfect conditions

Background estimation

Event rate above threshold



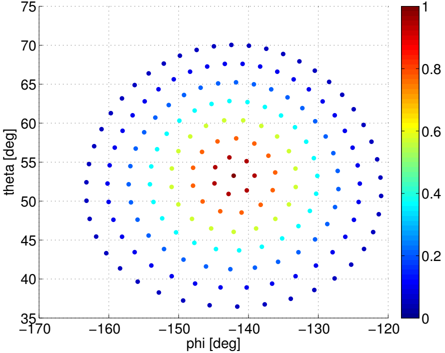
background probability in window



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

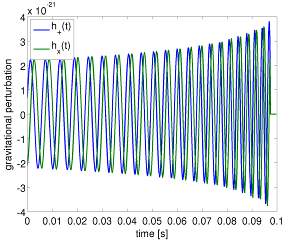


$$L(\mathbf{d}|\circlearrowright, \sigma_h) = \frac{|\mathbf{e}^{\circlearrowright} \cdot \mathbf{d}|^2}{1 + 1/(\sigma_h |\mathbf{f}^{\circlearrowright}|)^2} - \log(1 + \sigma_h^2 |\mathbf{f}^{\circlearrowright}|^2),$$

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

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



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

- $f_0 = 2 f_{\mathrm{rot}} = 100, 150, 300\,\mathrm{Hz}$, $Q = 9$
- $E_{\mathrm{GW}} = 10^{-2}\,\mathrm{M}_{\odot}\mathrm{c}^2$, distance $\rightarrow A_0$

- Nuisance parameters $\rightarrow$ jitter injections
  - Sky localization error
  - Calibration errors
  - System inclination ι