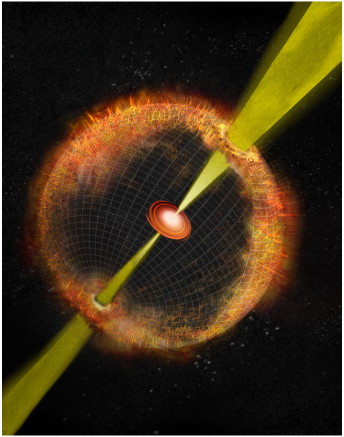
Searches for gravitational waves associated with gamma-ray bursts

Michał Wąs
for the LIGO Scientific Collaboration and the Virgo Collaboration

Albert Einstein Institute - Hannover

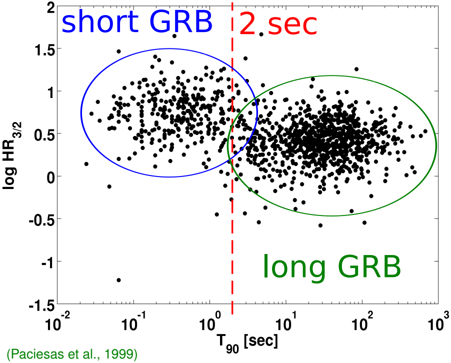
GWPAW 2012



Credit: Bill Saxton, NRAO/AUI/NSF

Gamma-ray bursts

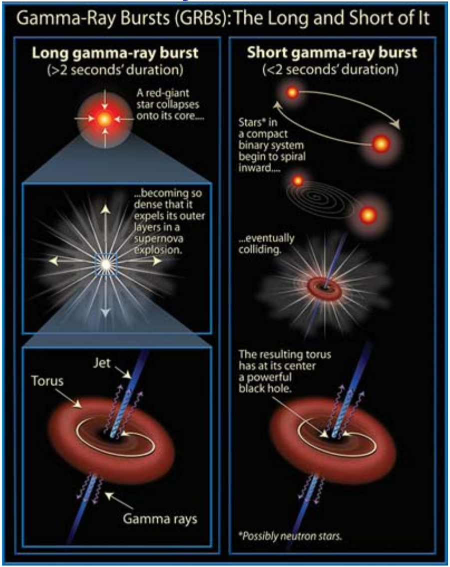
- Observational definition $\rightarrow$ a burst of γ-rays (10 keV – 1 MeV)
- Discovered in the 70's by nuclear bomb test surveillance satellites



(Paciesas et al., 1999)

- T_{90} - duration of 90% of photon counts ($\sim$ 15 – 300 keV)
- Two observational populations:
  - short-hard GRBs $T_{90} \lesssim 2$ s spectrum peaks at higher energy
  - long-soft GRBs $T_{90} \gtrsim 2$ s spectrum peaks at lower energy

Gamma-ray burst models



credit: Ute Kraus

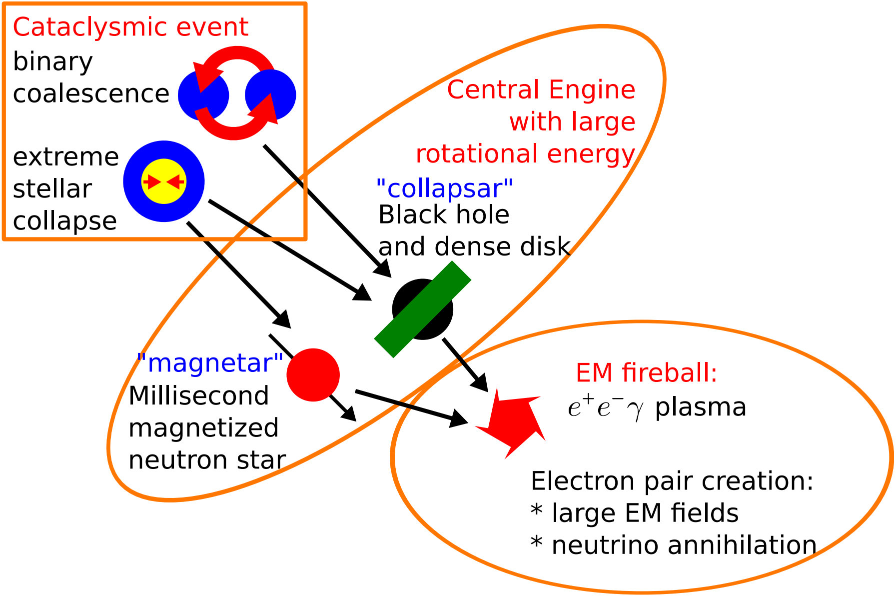
- Long GRBs

$\Rightarrow$ Massive rapidly spinning star collapse and explosion

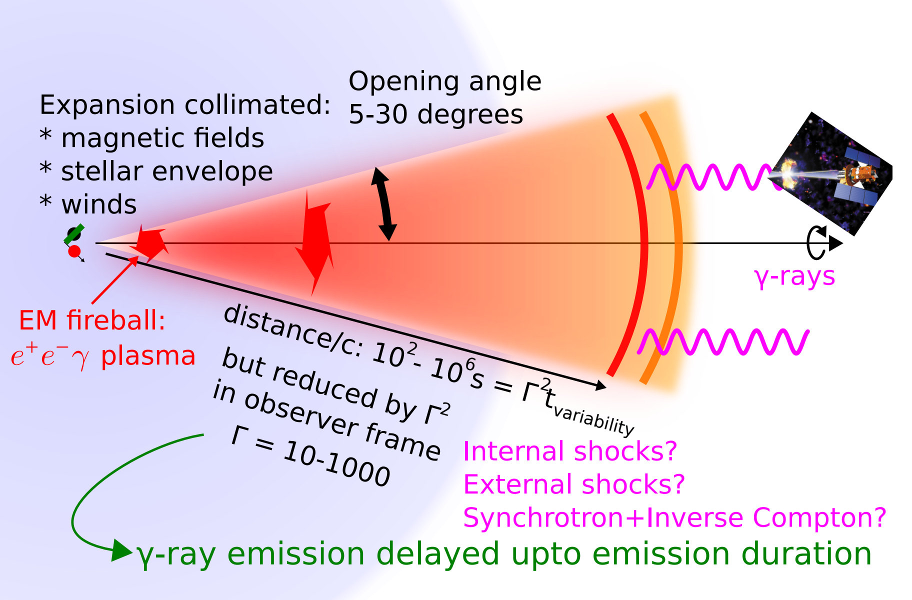
- Short GRBs

$\Rightarrow$ Coalescence of a neutron star and a compact object
  - small fraction is actually neutron star quakes ($\lesssim 15\%$)
- Both cases: asymmetric, compact, relativistic
  $\Rightarrow$ good GW source
- Measured gamma emission:
  $\sim 10^{51}\,\mathrm{erg} = 10^{-3}\,M_\odot c^2$
- Problem:
  typical distance $\sim 10\,\mathrm{Gpc}$
  but some closer

EM emission - standard fireball model



EM emission - standard fireball model



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
- Learn more about progenitor of long GRBs
  - black hole or magnetar?
- Precise measurement of GW speed, $\Delta v/c \sim 10^{-16}$
- Measure of Hubble's constant, distance $\leftrightarrow$ redshift relation

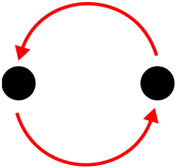
Astrophysical inputs & analysis strategy

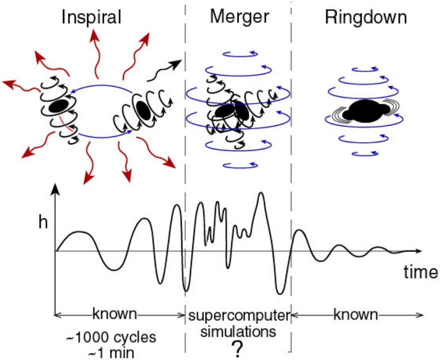
Goal: Find GW associated with GRBs

- 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?

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
- NS needs to be disrupted $\longrightarrow M_{\mathrm{BH}} < 20\,\mathrm{M}_{\odot}$
  $\longrightarrow$ negligible GW SNR at merger, ringdown

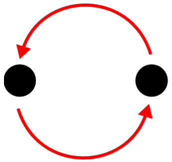
GW emission - coalescence scenario

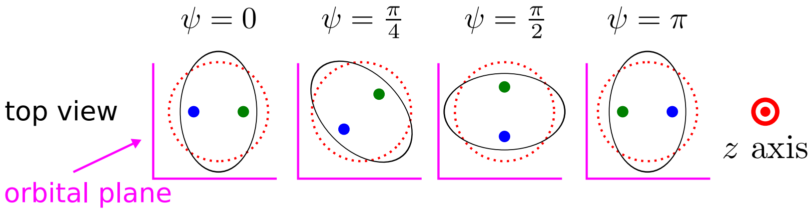
- GRB central engine formed in $\lesssim 1\,\mathrm{s}$
- γ-ray emission delayed by $\lesssim T_{90} \sim 2\,\mathrm{s}$

$\Rightarrow$ coalescence time $[-5, 1]\,\mathrm{s}$ prior to GRB observation

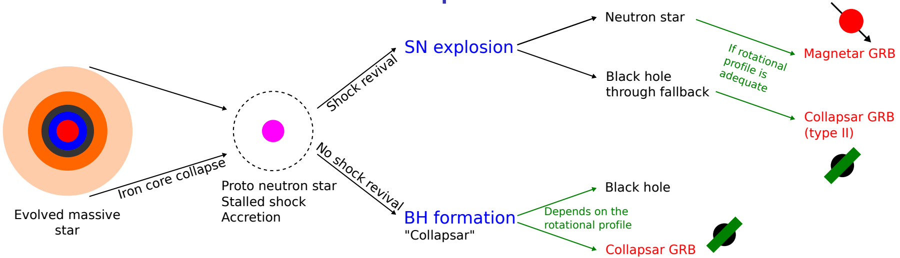
- GRB observed $\rightarrow$ rotation axis points at observer

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





GW emission - stellar collapse scenario

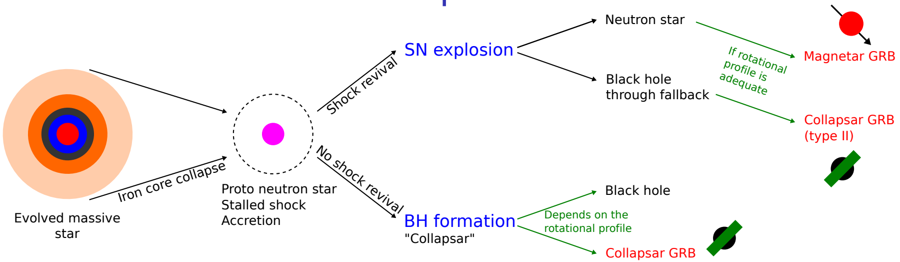


- Magnetar central engine / Proto neutron star
  - bar mode instability in the star (Shibata et al., 2003)
  - neutron star core fragmentation (Davies et al., 2002; Kobayashi and Mészáros, 2003)
- Black hole and accretion disk
  - Disk fragmentation (Piro and Pfahl, 2007)
  - Disk precession (Romero et al., 2010)

$\Rightarrow$ circular polarization along rotation axis

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

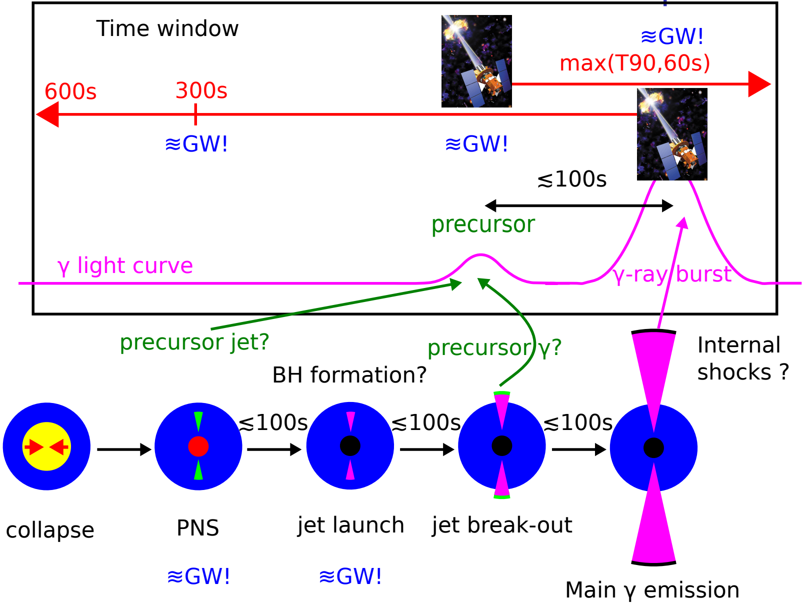
GW emission - stellar collapse scenario



Emission paths we do not look for yet

- long GW bursts ($10 - 1000\,\mathrm{s}$)
  - secular instability in proto neutron star
  - R-modes
  - accretion disk instability
  - ⇒ search under-development (Thrane et al., 2011)
- 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

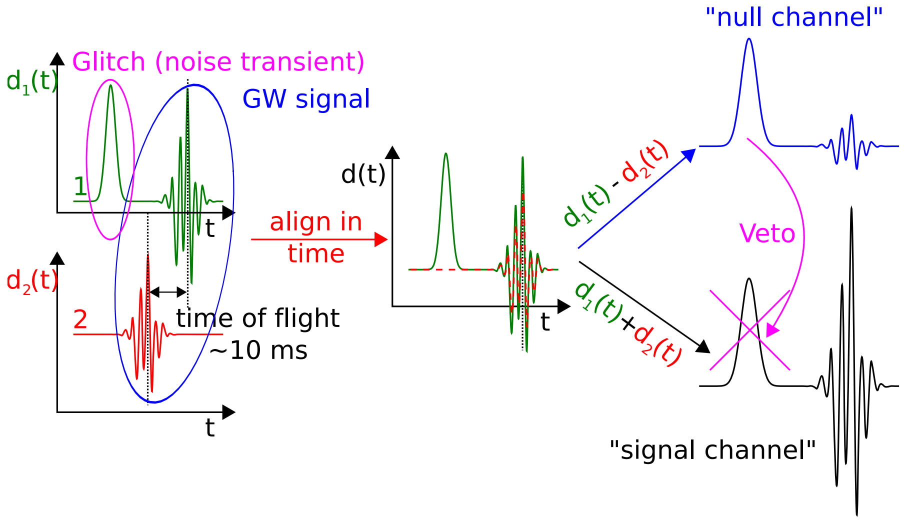


Two complementary searches

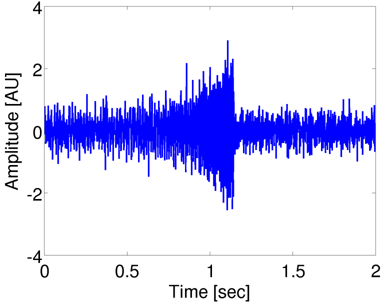
- Broad in scope – covers most possibilities
  - "burst" searching method – any signal shapes
  - Limited to $60-500\,\mathrm{Hz}$ band, $\lesssim 1\,\mathrm{s}$ duration
  - Assumes circular polarization
  - Loose time coincidence between γ-rays and GW $T_{\mathrm{GW}} - T_{\gamma} \in [-600, \max(T_{90}, 60)]\,\mathrm{s}$
- Focused on short GRBs – binary coalesence
  - Inspiral waveform templates, NS-NS and NS-BH
  - Tight time coincidence between γ-rays and GW inspiral end time $T_{\mathrm{GW,\,coalescene}} - T_{\gamma} \in [-5, 1]\,\mathrm{s}$
  - More sensitive to inspiral signals by factor ~ 2
- GW data combined coherently in both searches
  - Novel for compact binary coalescence searches (Harry and Fairhurst, 2011)
- (Abadie et al., 2012b)

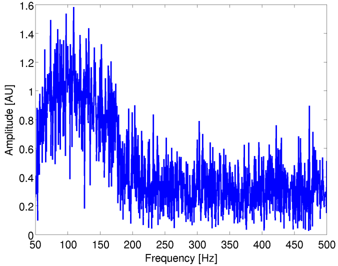
- A search for longer ($\sim 10-100\,\mathrm{s}$) GW transients under-construction (secular instability, R-modes, ...)

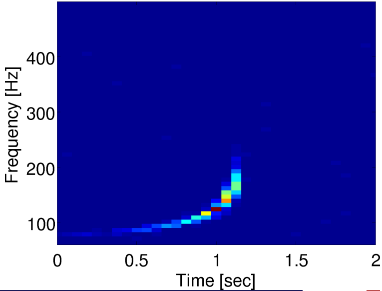
Combine data (add/substract) from several detectors



Excess wrt Gaussian noise → Time frequency maps



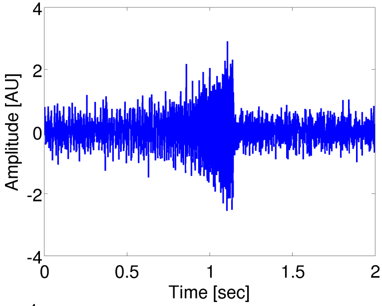


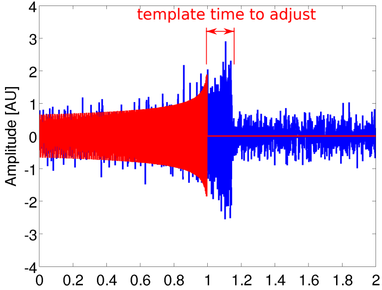


- Burst search
  - Concentrate signal energy in a small number of pixels
  - Sum energy over clusters of “loud” pixels

⇒ Ranking statistic

Excess wrt Gaussian noise → match with templates

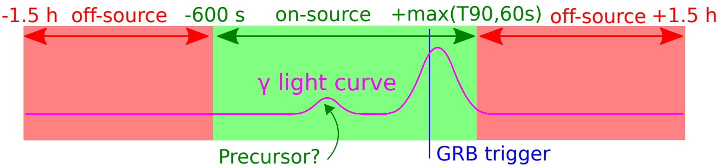




- Coalescence search
  - Adjust template time, parameters (masses, ...)
  - Sum coherently energy using waveform template
  - Check that residual is consistent with Gaussian noise (χ^2)

⇒ Ranking statistic

GRB triggered GW burst search

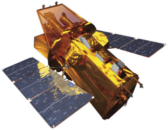


- Known position and time
  - Reduced time ⟶ reduced background
  - Position ⟶ simplify coherent analysis
    - time delays between detectors constrained by sky location box
    - $\sim$ 20% sensitivity improvement (Wąs et al., 2012)

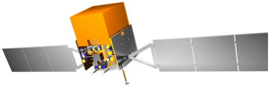
  ⇒ Better sensitivity by a factor $\sim$ 2 wrt to all-sky/all-time search
- On-source data
  - Search for potential GW events
- Off-source data, time slides
  - Measurement of event background distribution
- Result of search
  - Background probability of most interesting on-source event
- Repeated independently for each GRB

Major gamma-ray burst detectors

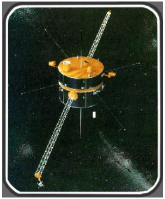
- Swift (launched 2004)
  - BAT - coded aperture telescope
  - 15-150 keV
  - $\ll$ 1 degree accuracy
  - Field of view $\sim$ 10% of sky
- Fermi (launched 2008)
  - GBM - multiple thin disk scintillators
  - localization by comparing fluxes on scintillators
  - $\sim$ 5 degree error (statistic+systematic)
  - Field of view $\sim$ 70% of sky
- IPN - Third Interplanetary network (since 1990)
  - Field of view $\sim$ 100% of sky
  - Localization by time of arrival triangulation
    - MESSENGER (Mercury)
    - Mars Odyssey
    - Konus-Wind (up to 6 light seconds)
  - error from $\ll$ 1 degree to fraction of sky
  - Effective full sky coverage



(Barthelmy et al., 2005)



(Meegan et al., 2009)

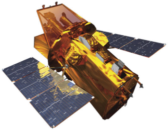
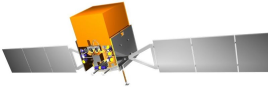


(Hurley et al., 2009)

Data sample



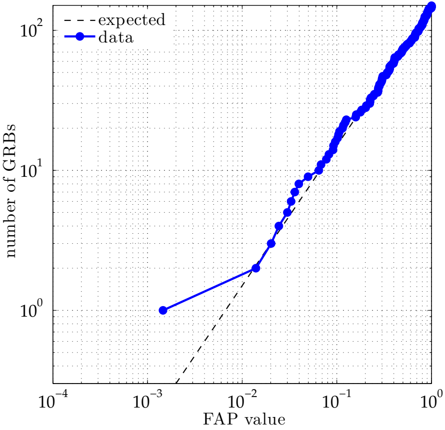
- July 2009 – October 2010
- Network of three GW detectors
  - LIGO Hanford
  - LIGO Livingston
  - Virgo, Italy
- 404 GRBs observed by γ-ray satellites
  Gamma-ray burst Coordinates Network
  - Swift
  - Fermi
  - IPN in most cases not distributed

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

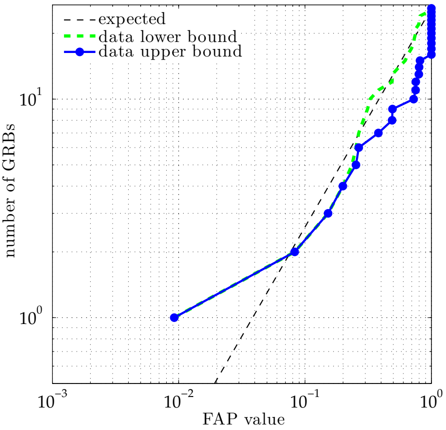
Event distribution consistent with background

GW bursts search



25% background probability

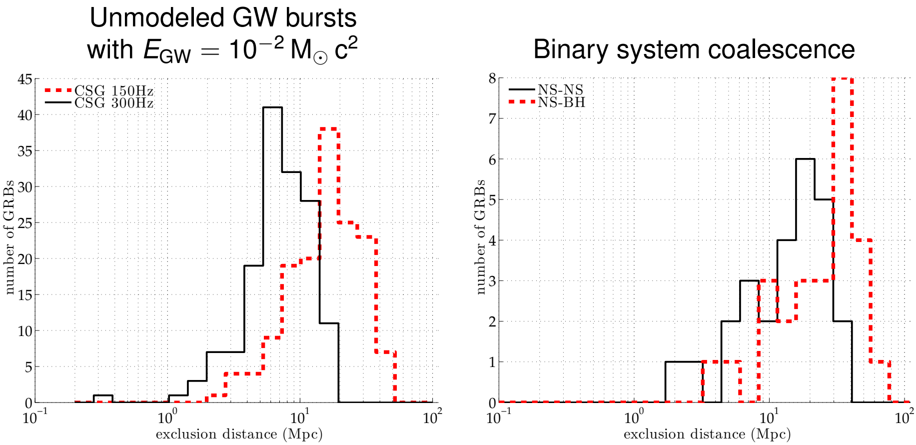
Binary coalescence search



8% background probability

GW burst non detection consequences

GRB progenitor distance exclusion

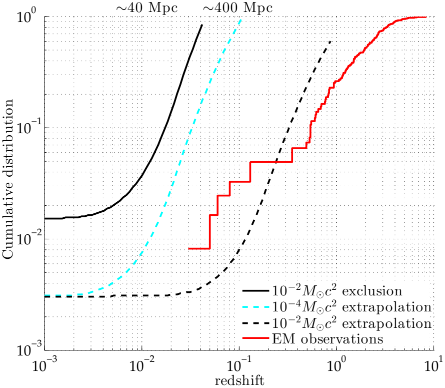


	burst 150Hz	burst 300Hz	NS-NS	NS-BH
median (Mpc)	17	7	16	28

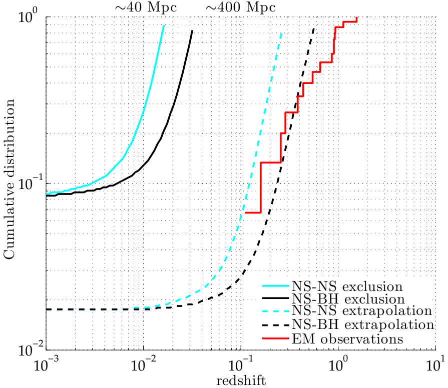
(Abadie et al., 2012b)

Global interpretation & Prospects

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

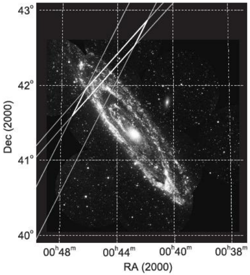
- Short GRBs,
  - GRB070201 sky location overlap with M31, (Andromeda 770 kpc)
  - GRB051103 sky location overlap with M81 ($\sim$ 3.6 Mpc)
- no GW found

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

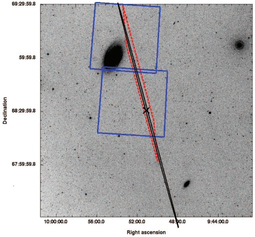
$\Rightarrow$ Binary coalescence in M81 excluded at 98% confidence level (Abadie et al., 2012a)

- Compatible with
  - Neutron star quake in M31/M81 (Soft gamma-repeater)
  - Coalescence in galaxy behind M31/M81

GRB070201 error box (Mazets et al., 2008)



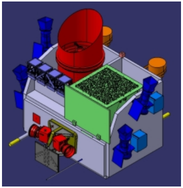
GRB051103 error box (Hurley et al., 2010)



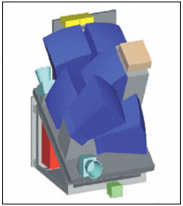
Will there be GRB triggers in 2015-2020?

- Typical mission operation time 10-15 years
  - Swift 2004
    - 3 year mission
    - likely to have a major failure
  - Fermi 2008
    - should still be flying
    - Poor localization $\longrightarrow$ no multi-wavelength followup
  - InterPlanetary Network – bad prospects
    - Single person collecting the data – about to retire
    - No plans for γ-ray detector on new interplanetary satellites
- Possible future – no approved missions, > 2017
  - SVOM
    - Larger Swift focused on high redshift GRBs
    - FOV 15% of the sky
  - Lobster
    - X-ray focusing telescope $0.1 - 3\,\mathrm{keV}$
    - modules with 30×30 degrees FOV
    - mission with 1, 3 or a dozen such modules
- Full sky GRB coverage is not granted!

SVOM

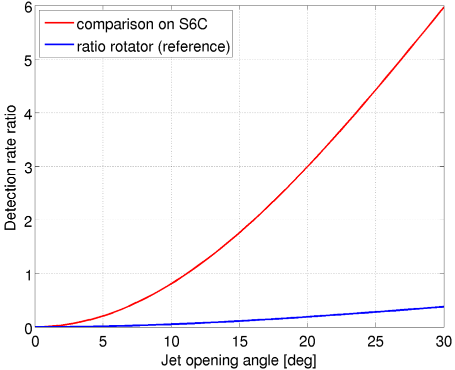


Lobster



Relevance of triggered search vs all-sky search

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



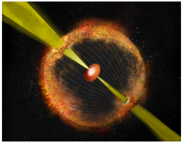
⇒ interesting even for small jet opening angles

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

⇒ Two approaches see (mostly) independent events

Summary

- Long and short GRBs progenitors may produce large amounts of GWs
- No associated GW detection to date
- Some relevant exclusions: GRB070201, GRB051103
- Good prospects for first detection with advanced detectors $\gtrsim$ 2015
- Joint GW-γ observation should determine the nature of GRB central engine
- Full sky γ-ray coverage essential
- Extending the scope in the meantime
  - IPN network – full sky coverage, non automated sky localization
  - longer GW bursts
  - sub-threshold GRB triggers



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