LIGO DCC G1500187

Overview of GW searches associated with GRBs

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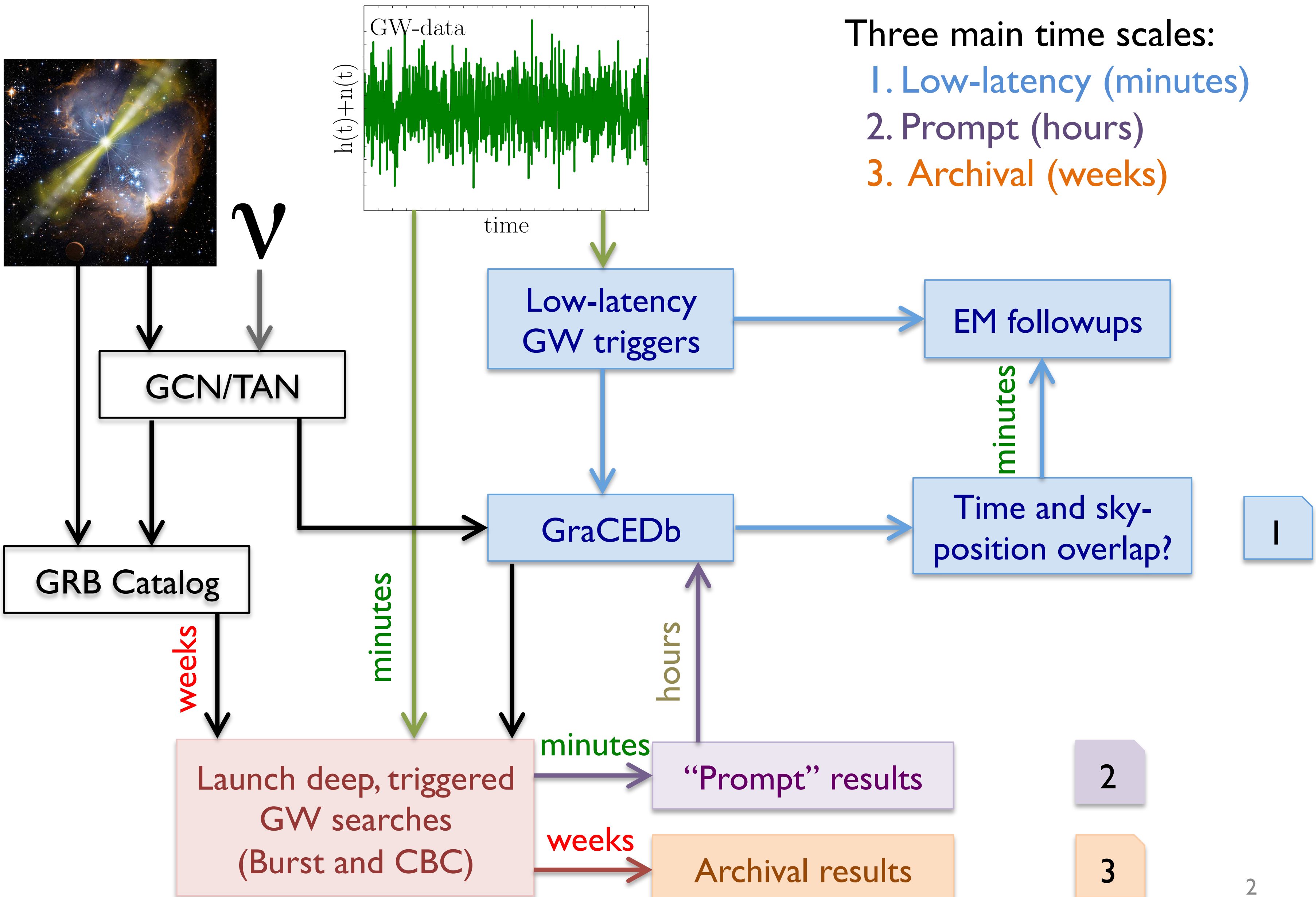
for the LSC/VSC GW-GRB group

GRB analysis strategy with advanced detectors

Three main time scales:

1. Low-latency (minutes)
2. Prompt (hours)
3. Archival (weeks)

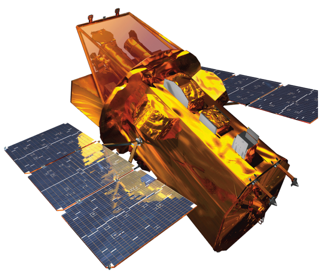


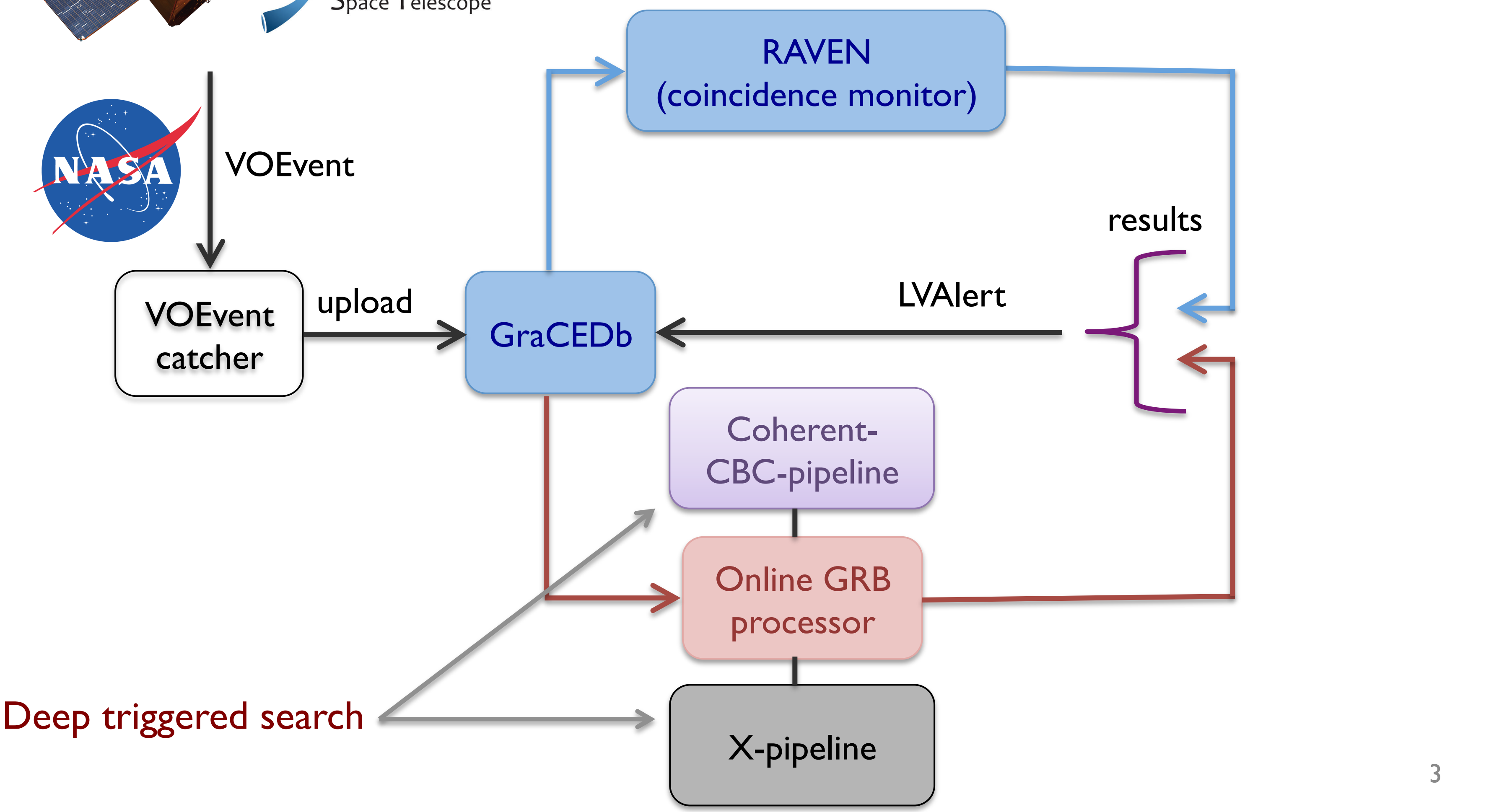
Automated analysis

Two main processes:

Low-latency coincidence analysis (RAVEN)

Triggered deep searches (through GRB processor) using our two most sensitive pipelines.





RAVEN: Rapid on-source VOEvent coincidence monitor

GW triggers from rapid all-sky searches,

CBC: GstLAL, MBTA

Burst: cWB

and sky localization from BAYESTAR within minutes.

RAVEN

Urban *et al.*, in preparation

1. Search for **coincidence** of **GW triggers** within some time window of a **GRB** in nearly real time.

   Short GRBs: [-5, +1] seconds around GW geocentric end time **

   Long GRBs: [-600, +max(T90,60)] seconds

2. Identify all time-coincident triggers, and compare location on-sky if possible.
3. Once coincident triggers have been found (with some significance threshold?), report back over GCN.

   Typical LIGO-Virgo sky map resolution > 1 deg^2.

Opportunity of rapid parameter estimation: e.g., a joint sky map, or distance and beaming angle estimates.

Need for deep triggered searches

Known "position": simplify coherent analysis
Known time: reduce background
Targeted search more sensitive than all-sky search.

Two classes of GRBs
Short GRBs: likely result from mergers of binary systems consisting of neutron stars (BNS) or a neutron star and a stellar mass (<10 $M_{\odot}$) black hole (NSBH).
GW waveforms for BNS and NSBH inspiral phase well modeled.

Long GRBs: Collapsar model, potential GW emission mechanisms include proto-NS oscillations; bar mode and accretion disk instabilities, etc.
GW emission poorly characterized (unmodeled or unknown).

Deep triggered searches

Two complementary analyses

Binary coalescence - focused on short GRBs

Coherent-CBC-pipeline

Template-based matched filter coherent search (matched-filtering against a bank of binary merger GW waveforms containing BNS and NSBH systems).

Suite of statistics to discriminate signal from noise, signal based veto.

Computationally expensive, but more sensitive to inspiral signal (factor ~2)

Burst – broader coverage, all GRBs

X-pipeline

Unmodeled short-duration coherent burst search.

Suite of statistics to discriminate signal from noise.

Coherent-CBC-pipeline

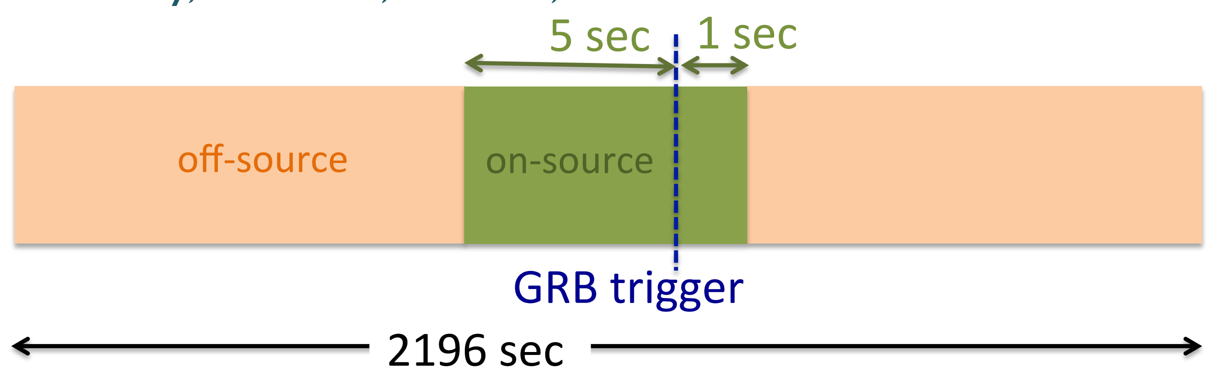
About 25% increase in distance sensitivity (doubling of the event rate) for single sky point and 15% for extended region over the all-sky search.

Methods: Harry, Fairhurst, PRD 83, 084002

S6/IPN:

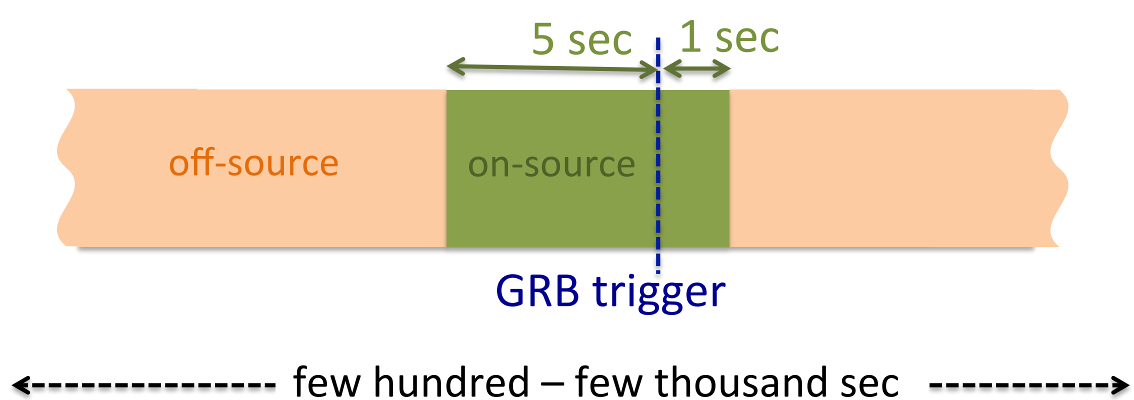
Abadie *et al.*, ApJ 760 12

Aasi *et al.*, PRL. 113, 011102



Advanced detector era **prompt** search

Dynamical selection



On-source data: Search for potential GW events

Off-source data: Background (time-slide) measurements to estimate the significance of the on-source GW candidate

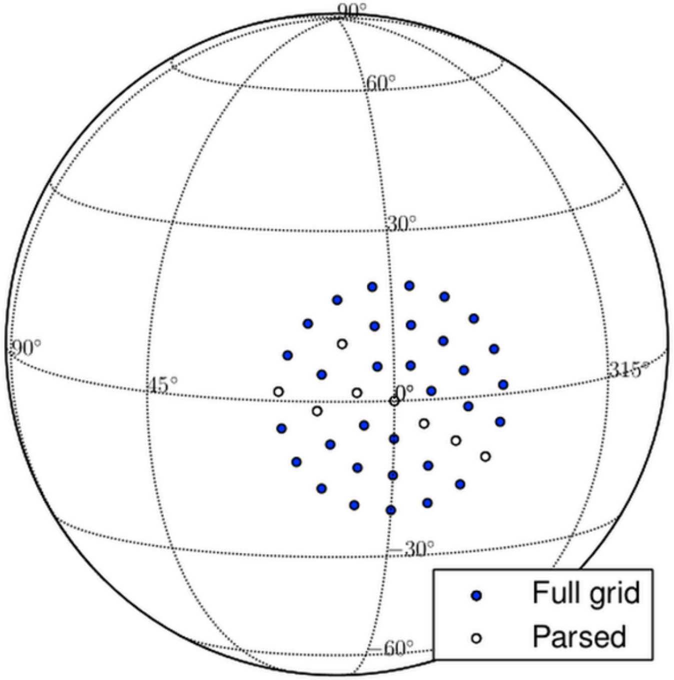
Coherent-CBC-pipeline

Typical GW localization several square degrees

GW search for Swift GRBs: At a single point on the sky
(BAT localization 1-4 arcminutes)

GW search for Fermi or IPN GRBs: Sky patches covering 3σ confidence region

Williamson *et al.*, PRD 90, 122004



Angular spacing determined by maximum time offset tolerated.

Angular scale for time offset = 0.5 ms (~5% SNR loss in a single detector):
2° for LIGO
1° for LIGO and Virgo

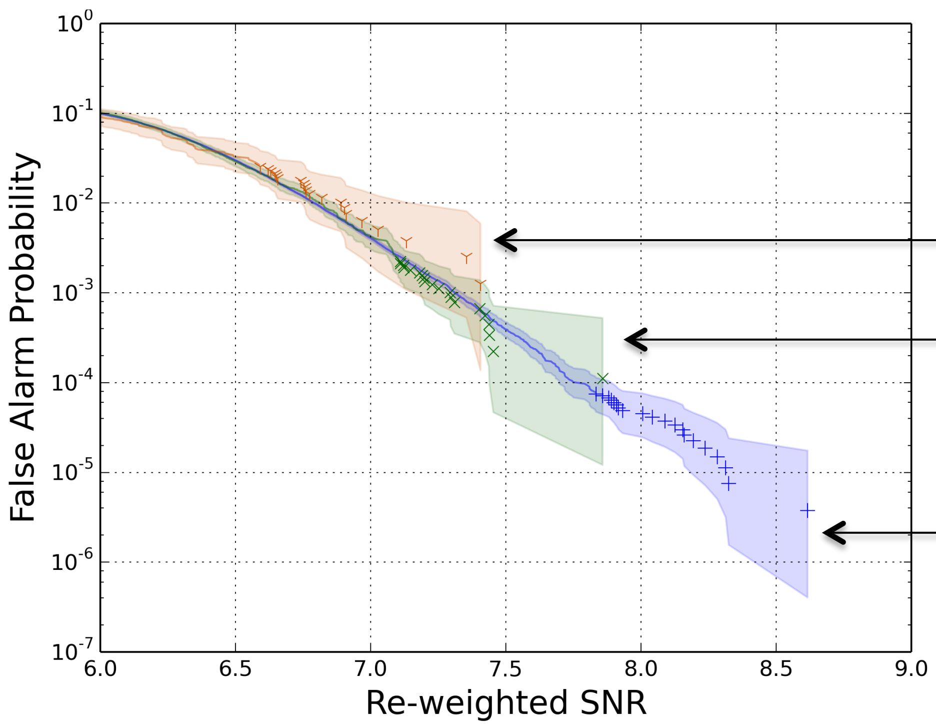
Note: Light travel time 10 ms between LIGO detectors, 25 ms for LIGO and Virgo.

Parsed: map unique differences in signal arrival time between LIGO sites.

Coherent-CBC-pipeline improvements

- Improved estimation of background to obtain event significance required to make "detections"

Williamson *et al.*, PRD 90, 122004



off-source, no slide (787 trials)

off-source, slides (8917 trials)

can be achieved in prompt search

off-source, slides (267185 trials)

target for archival search or followup
to an interesting event in prompt search

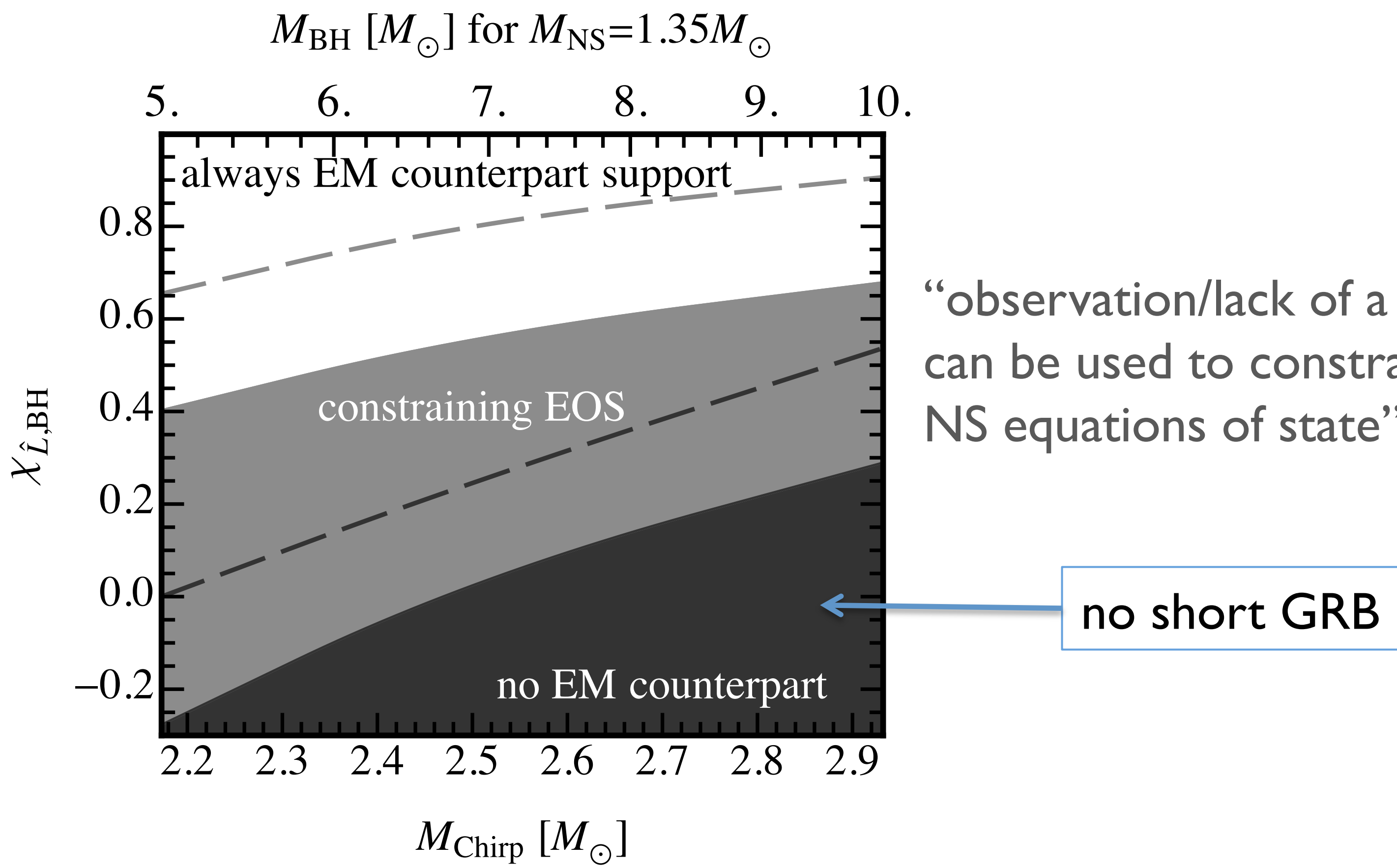
- Incorporated astrophysically motivated restriction on source inclination angles

Source GW signals roughly circularly polarized for system inclinations < 30°

⇨ 3% improvement in distance reach with face-on/face-away signals.

Speed-up search for NSBH progenitor

Pannarale, Ohme, ApJ **791** L7



"observation/lack of a short GRB can be used to constrain possible NS equations of state"

dimensionless spin projection $\chi_{\hat{L},\rm BH} \in [-1, 1]$; chirp mas $M_{\rm Chirp} = \frac{(M_{\rm NS}\, M_{\rm BH})^{3/5}}{(M_{\rm NS} + M_{\rm BH})^{1/5}}$

About half of the templates can be disregarded in a search for NSBH progenitor.

X-pipeline

About 20% increase in distance sensitivity for single sky point and 10% for extended region (few hundred square degrees) over the all-sky search.

Methods: Sutton *et al.*, New J. Phys. 12 053034

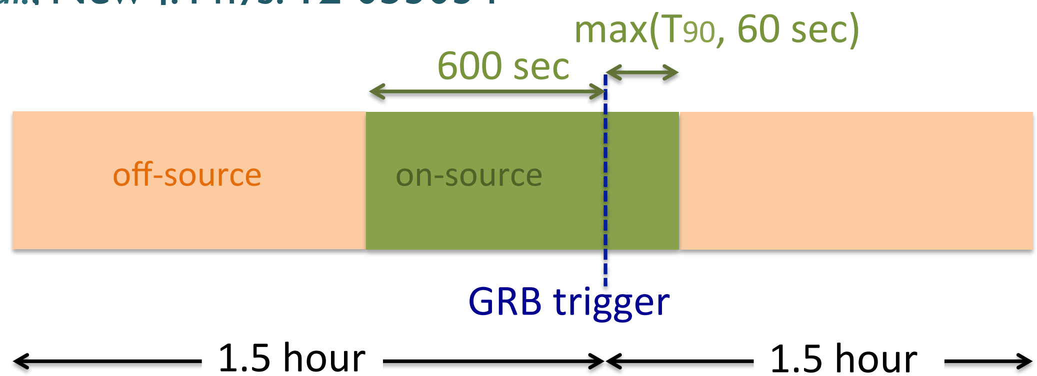
S5/S6/IPN/GEO:

Abadie *et al.*, ApJ 715 1453

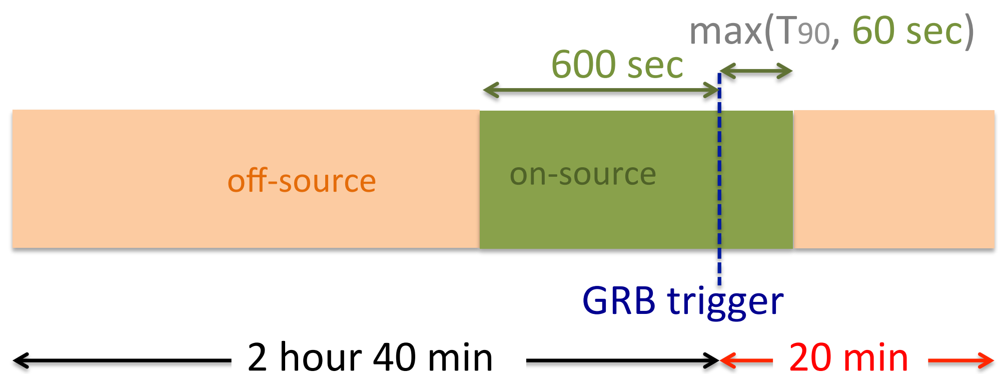
Abadie *et al.*, ApJ 760 12

Aasi *et al.*, PRL. 113, 011102

Aasi *et al.*, PRD 89, 122004



Advanced detector era **prompt** search

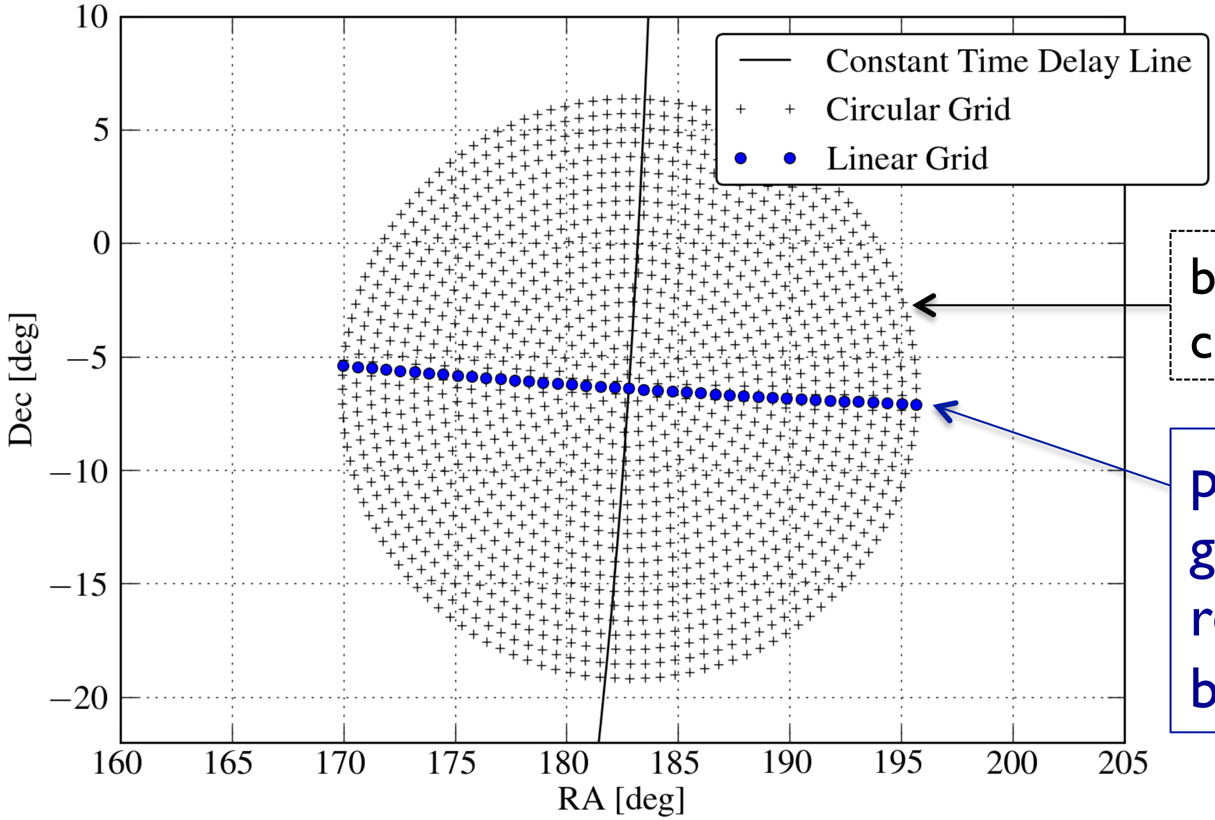


On-source events with detection statistic > 99% of the off-sources events are considered detection candidates.

X-pipeline

Localizations from **Fermi** GBM require a sky tiling procedure to account for the phase delay across the error region.

Aasi *et al*., PRD 89, 122004



background estimation computationally expensive

parallel to maximum gradient of change in relative time-of-arrival between two detectors

Prospect for joint GW and short GRB observations

Expected rate of joint GW-GRB observations

Clark *et al.*, arXiv:1409.8149

If progenitor of every short GRB is a BNS merger

Epoch	Run Duration	BNS Range (Mpc)		Number of BNS detections	Number of GW–GRB detections		
		LIGO	Virgo		All Sky	Fermi GBM	Swift BAT
2015	3 months	40 - 80	-	0.0004 - 3	3×10^{-4} - 0.02	2×10^{-4} - 0.02	4×10^{-5} - 0.004
2016–17	6 months	80 - 120	20 - 60	0.006 - 20	0.004 - 0.2	0.003 - 0.1	7×10^{-4} - 0.03
2017–18	9 months	120-170	60 - 85	0.04 - 100	0.03 - 0.9	0.02 - 0.6	0.004 - 0.1
2019+	(per year)	200	65 - 130	0.2 - 200	0.1 - 2	0.1 - 1	0.01 - 0.3
2022+	(per year)	200	130	0.4 - 400	0.3 - 5	0.2 - 2	0.04 - 0.5

If progenitor of every short GRB is a NSBH merger

Epoch	Run Duration	NSBH Range (Mpc)		Number of NSBH detections	Number of GW–GRB detections		
		LIGO	Virgo		All Sky	Fermi GBM	Swift BAT
2015	3 months	100 - 200	-	0.0002 - 2	6×10^{-4} - 0.2	4×10^{-4} - 0.1	1×10^{-4} - 0.03
2016–17	6 months	200 - 300	50 - 150	0.003 - 20	0.01 - 1	0.007 - 1	0.002 - 0.2
2017–18	9 months	300- 425	150 - 215	0.02 - 80	0.07 - 6	0.04 - 4	0.01 - 1
2019+	(per year)	500	175 - 325	0.1 - 200	0.4 - 15	0.2 - 10	0.06 - 2
2022+	(per year)	500	325	0.2 - 300	0.7 - 20	0.4 - 15	0.06 - 4

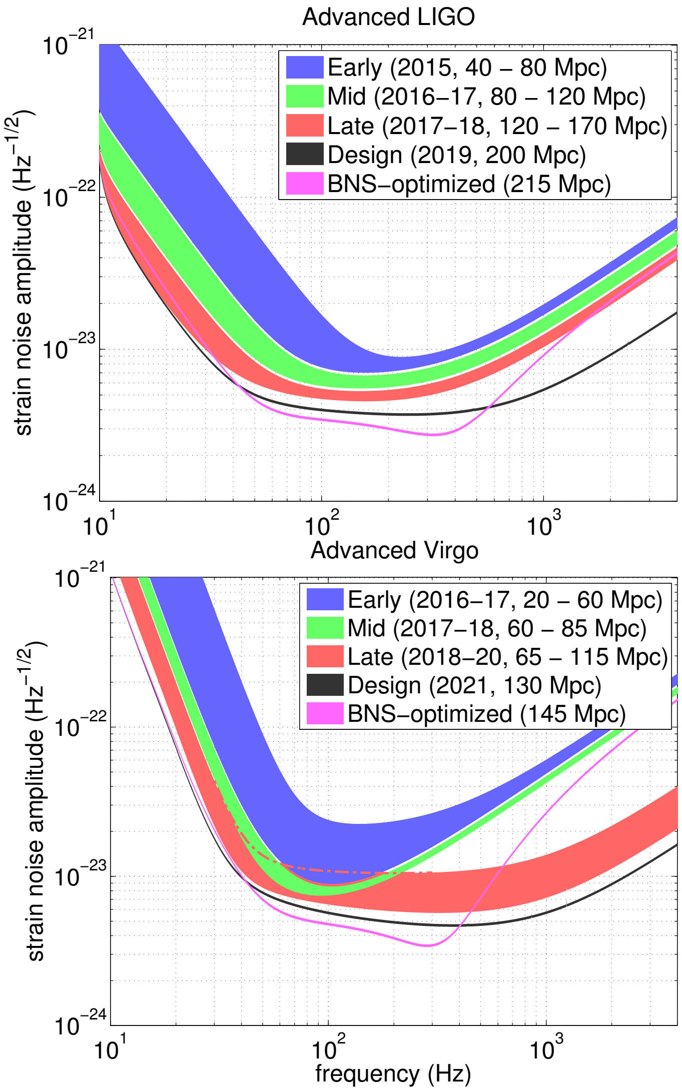
Neutron star mass $1.4 M_\odot$, black hole mass $5.0 M_\odot$ (non-spinning)

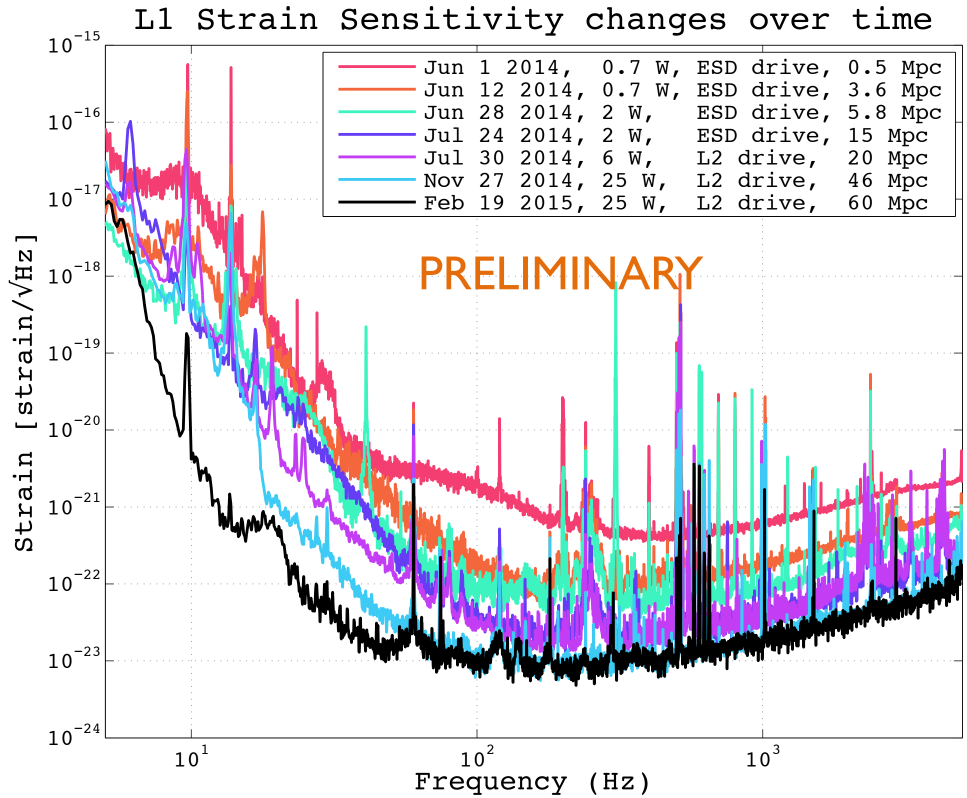
No detection: Expected bounds on GRB opening angle

Epoch	Run Duration	BNS Range (Mpc)		limit on GRB opening angle (°)	
		LIGO	Virgo	BNS	NSBH
2015	3 months	40 - 80	-	0 - 3	1 - 8
2016–17	6 months	80 - 120	20 - 60	1 - 8	3 - 20
2017–18	9 months	120-170	60 - 85	3 - 18	10 - 50

LIGO's progress

Aasi *et al.*, arXiv:1304.0670





Livingston (L1) achieved ~60 Mpc inspiral range on Feb 19, 2015!

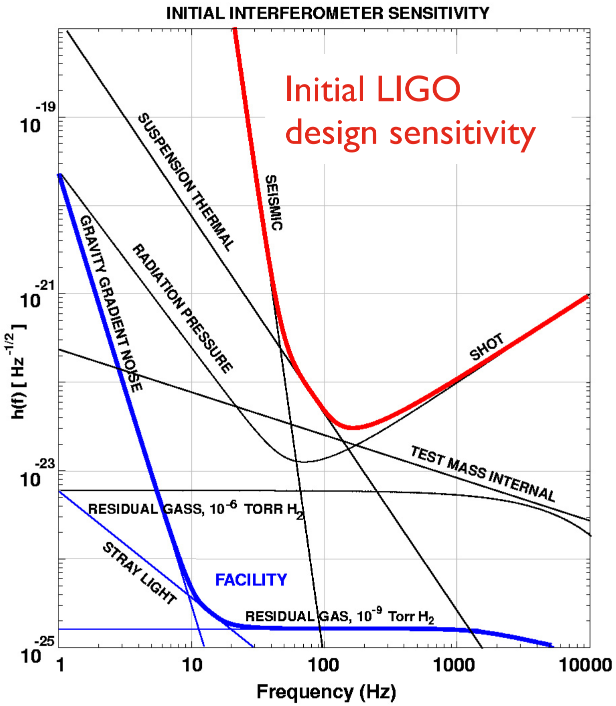
Hanford (H1) achieved ~10 Mpc, sensitivity ramping up.

THANKS

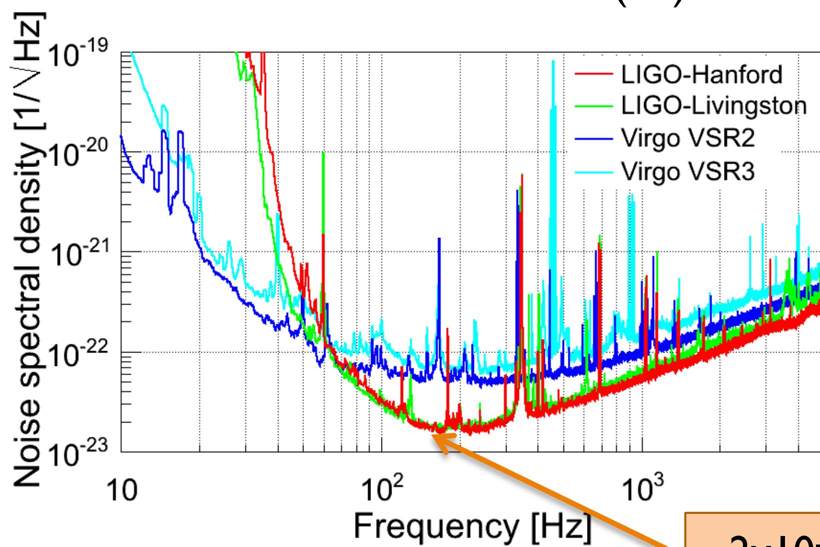
EXTRA SLIDES

What limits the sensitivity of the detectors

LIGO-P980007-00-D



Achieved enhanced LIGO (S6) sensitivity:



Phys. Rev. D 85, 122007

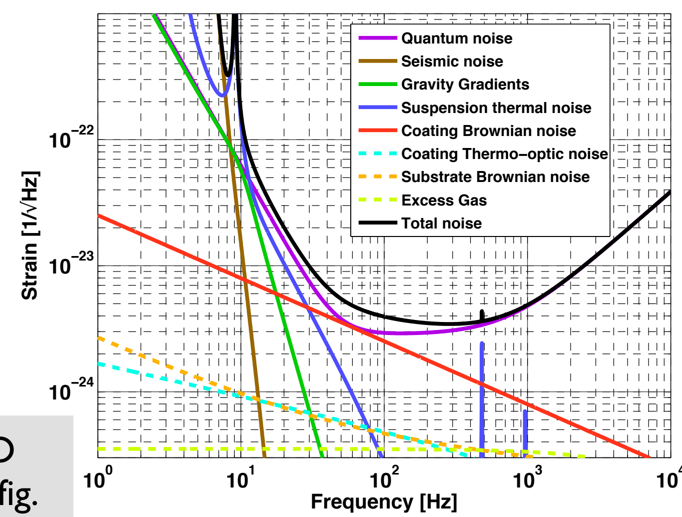
~2x10^{-23} at 150 Hz

Low frequencies: Seismic noise and vibration

Mid frequencies: Atomic vibrations (thermal noise) inside components

High frequencies: Quantum nature of light (photon shot noise)

How?

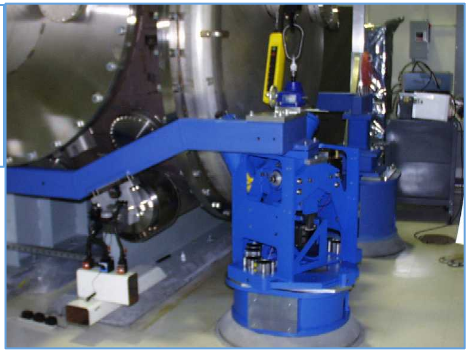


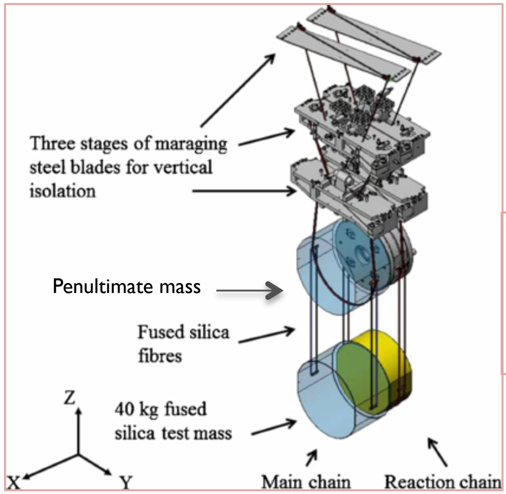
Advanced LIGO broadband config.

Class. Quan. Grav. 29 124006

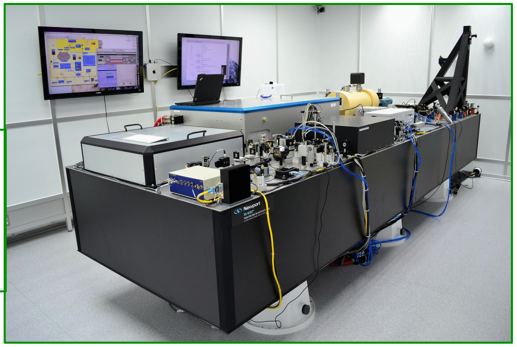
Advanced LIGO: Improvement in sensitivity

Improved seismic isolation (passive ⇨ active), lowers seismic "wall" to ~10 Hz.

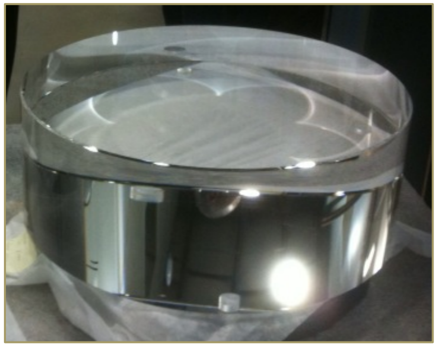




New suspensions (single ⇨ quadruple pendulum), lower suspension thermal noise.



Increased laser power (10 W ⇨ 180 W), improved shot noise.

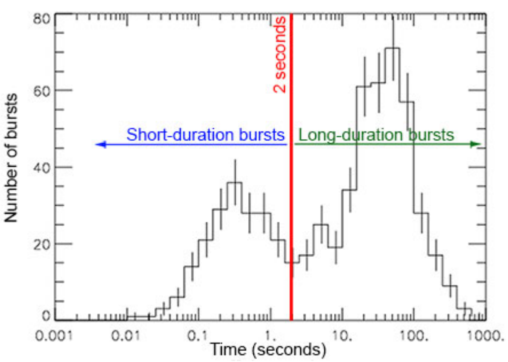


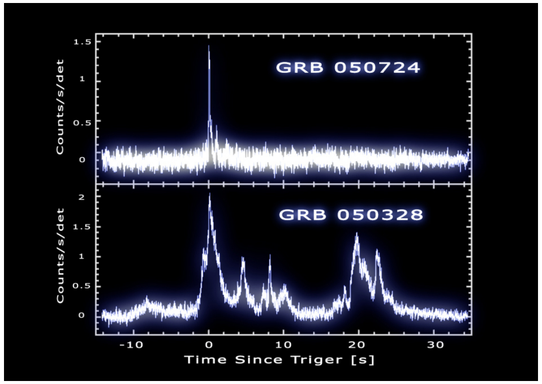
Increased test mass (10 kg ⇨ 40 kg), compensates increased radiation pressure noise.

Higher-Q test mass & fused silica with better optical coatings, lower internal thermal noise.

GRB progenitor models and GW emission

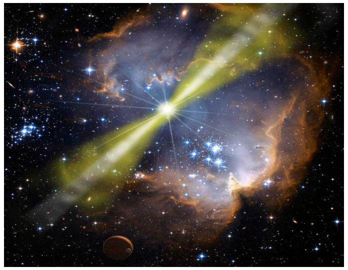
BATSE, NASA





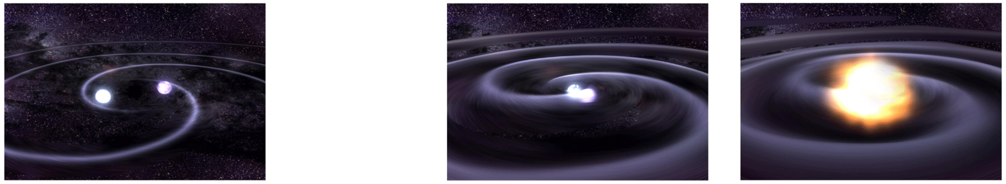
Progenitors of long GRBs:

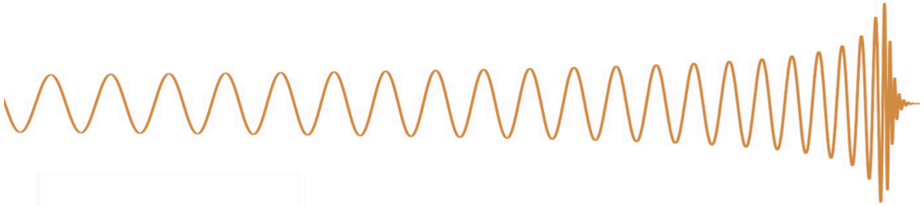
Massive stars exploding due to collapse of their cores.



Progenitor of short GRBs:

systems composed of neutron stars or a neutron star and a stellar-mass black hole (NSBH).





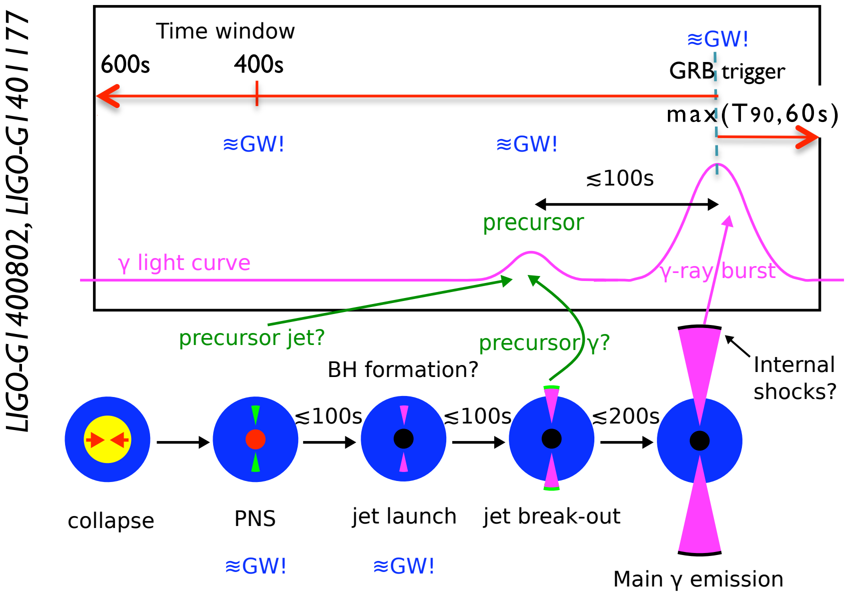
GW emission is expected to accompany these events.

Time of arrival of GRB and GW window

Long GRBs

- Collapsar model, potential GW emission mechanisms: proto-NS oscillations; bar mode, accretion disk instabilities, etc.
- GW emission poorly characterized (unmodeled or unknown)
- Emitted GW energy $\lesssim 10^{-2}\, M_{\odot}c^2$
- Loose time coincidence between γ-rays and GW

$$T_{GW} - T\gamma \in [-600, +\max(T90,60)]\ \mathrm{s}$$



Short GRBs

- GRB central engine formation $\lesssim 1$ s, γ-ray emission delayed by $\lesssim 2$ s
- GW waveforms for BNS and NSBH inspiral phase well modeled
- Efficient GW radiator
- Distance sensitivity ~40 Mpc with initial LIGO and ~400 Mpc with advanced LIGO for BNS (larger for NSBH)
- Tight time coincidence between γ-rays and GW inspiral end-time

$$T_{GW,\ coalescene} - T\gamma \in [-5, +1]\ \mathrm{s}$$

Results from the initial detectors

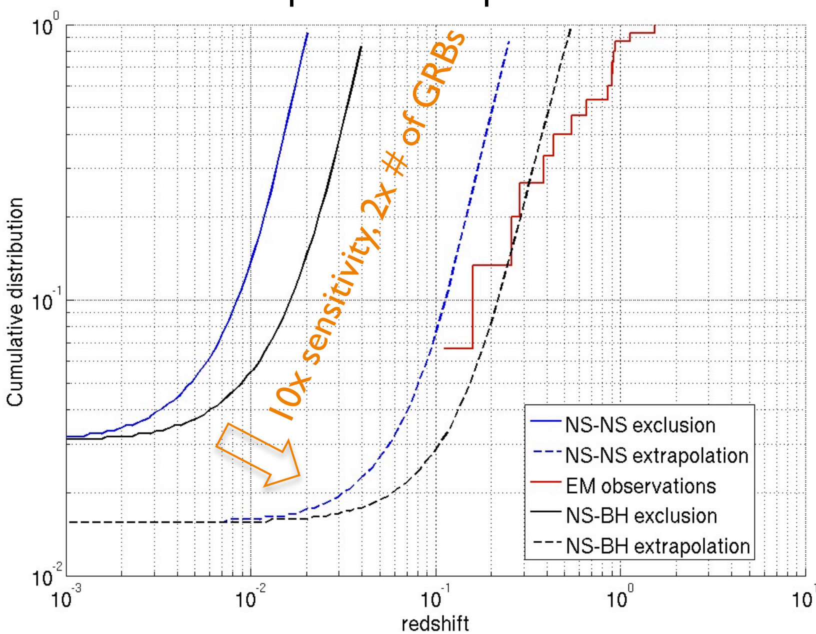
LIGO/Virgo analysis of GRBs detected by Gamma-ray Coordinates Network (GCN) and InterPlanetary Network (IPN) in 2005-2010.

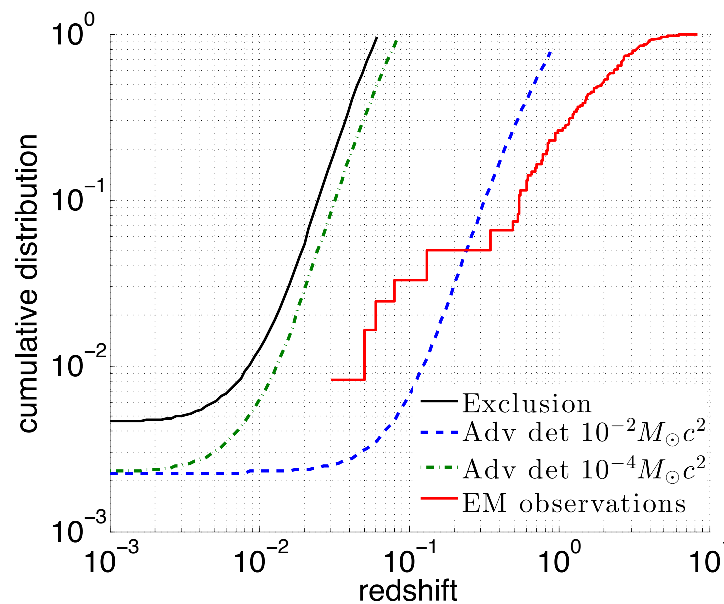
No evidence of a gravitational wave signal associated with the GRBs in the sample.

Exclusions (90% confidence level)

Phys. Rev. Lett. 113, 011102

~40 Mpc ~400 Mpc



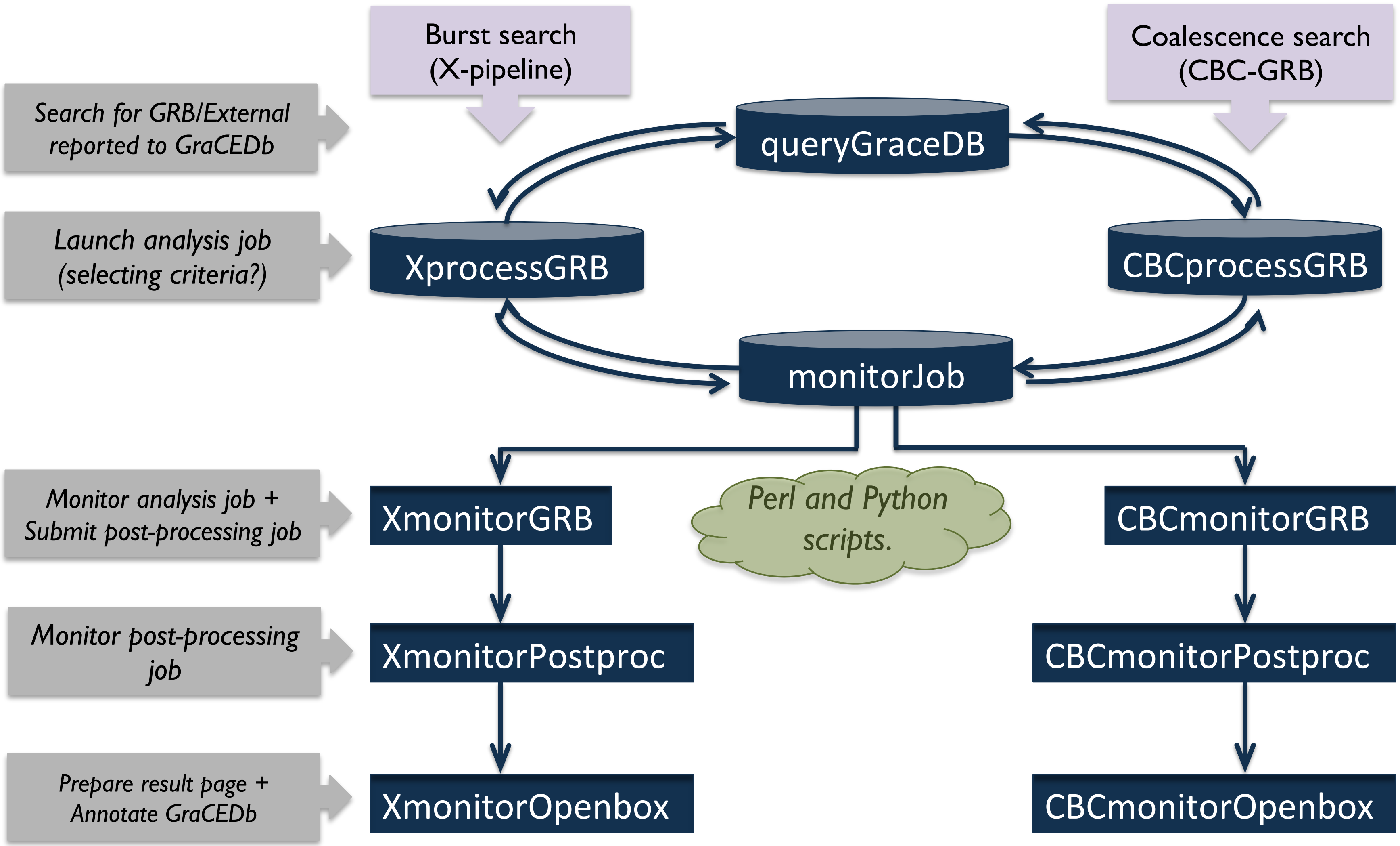


Typical GRB distance ~ 10 Gpc!

EM observations: cumulative distribution of measured redshifts for Swift GRBs

Prospects: Reasonable if significant NSBH systems, optimistic for others.

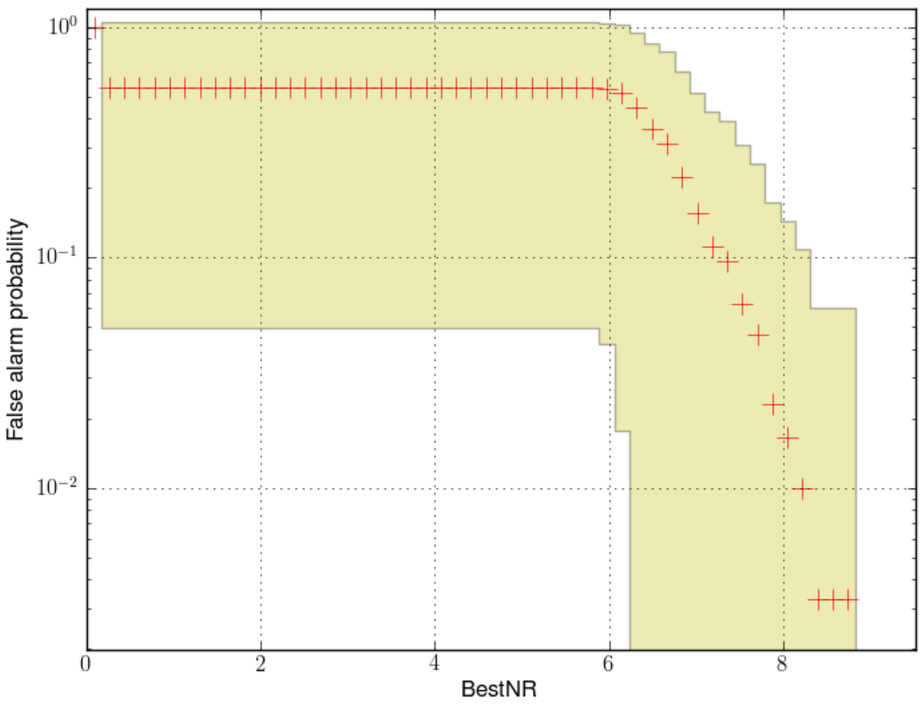
Online GRB processor

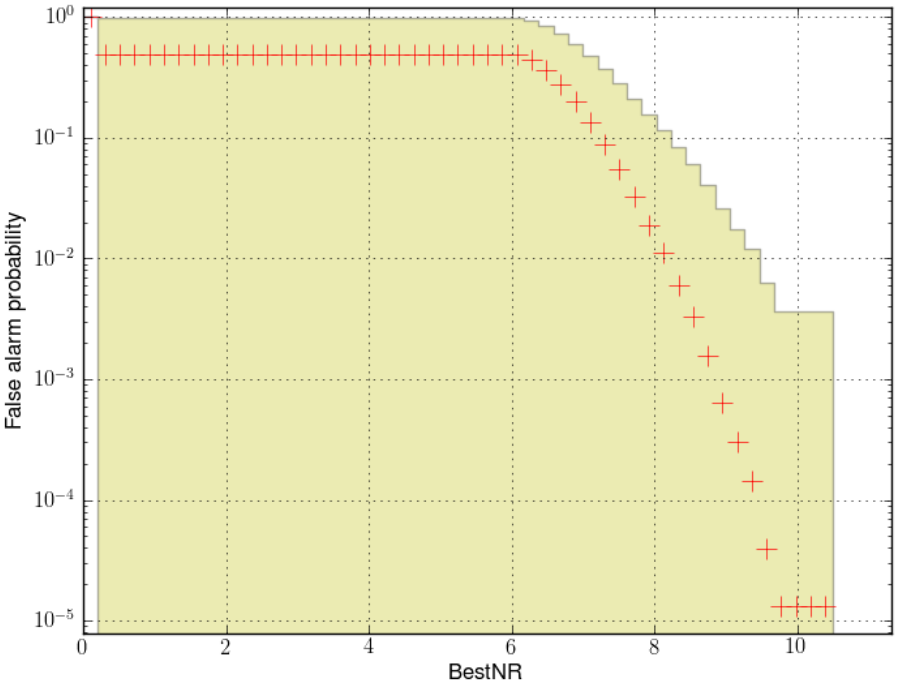


Make the entire process fully automated.

Improved event significance

Coherent-CBC-pipeline





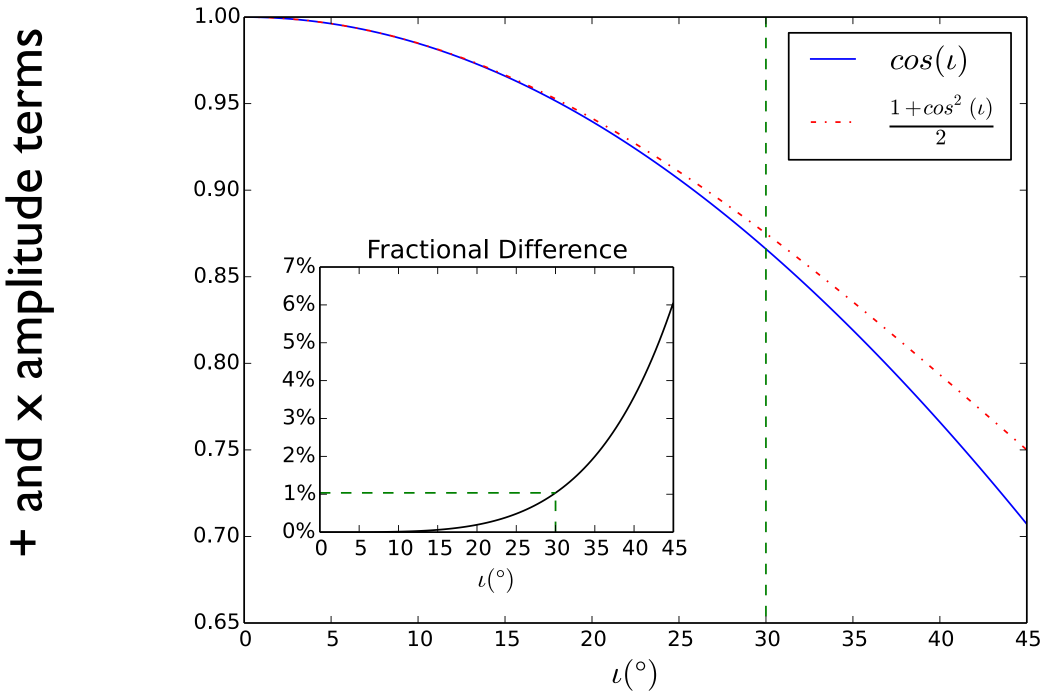
Before

After

Face-on

Coherent-CBC-pipeline

Williamson et al., PRD 90, 122004



$$h_+(t) = \mathcal{A}^1 h_0(t) + \mathcal{A}^3 h_{\pi/2}(t)$$

$$h_\times(t) = \mathcal{A}^2 h_0(t) + \mathcal{A}^4 h_{\pi/2}(t)$$

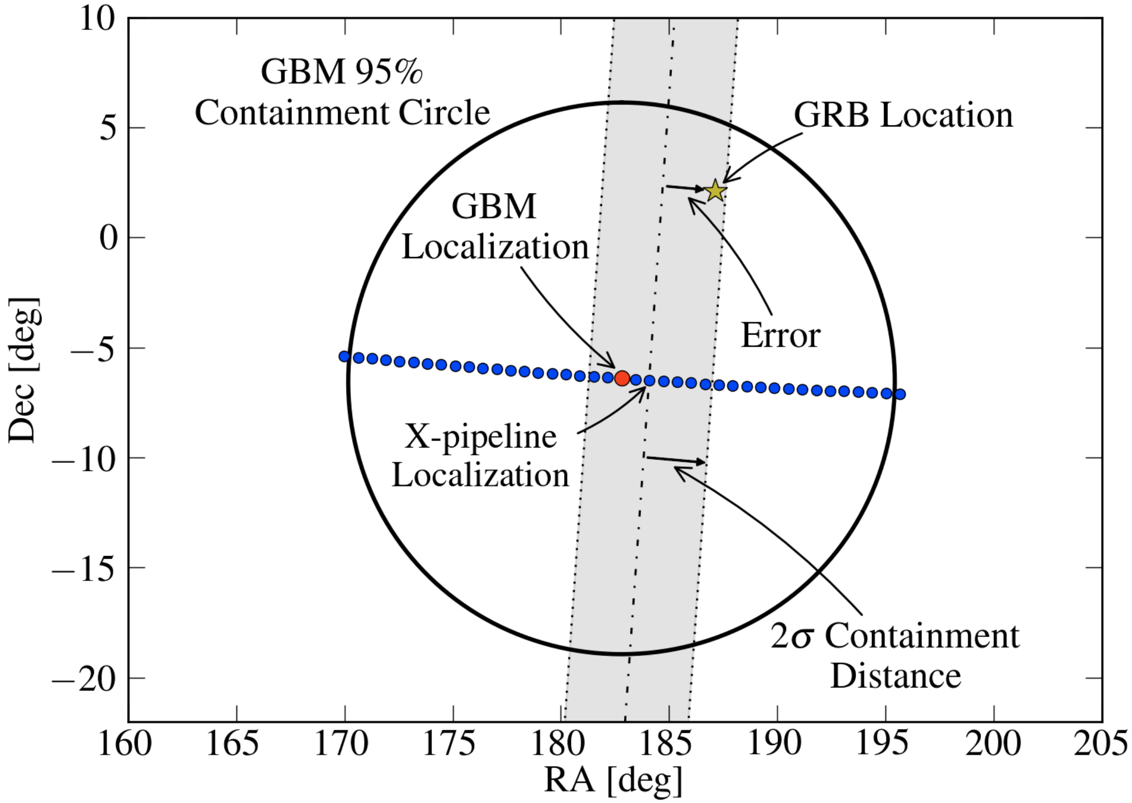
$$\begin{aligned}
\mathcal{A}^1 &= \frac{D_0}{D}\frac{(1+\cos^2\iota)}{2}\cos 2\phi_0 \cos 2\psi \\
&\quad - \frac{D_0}{D}\cos\iota \sin 2\phi_0 \sin 2\psi, \\
\mathcal{A}^2 &= \frac{D_0}{D}\frac{(1+\cos^2\iota)}{2}\cos 2\phi_0 \sin 2\psi \\
&\quad + \frac{D_0}{D}\cos\iota \sin 2\phi_0 \cos 2\psi, \\
\mathcal{A}^3 &= -\frac{D_0}{D}\frac{(1+\cos^2\iota)}{2}\sin 2\phi_0 \cos 2\psi \\
&\quad - \frac{D_0}{D}\cos\iota \cos 2\phi_0 \sin 2\psi, \\
\mathcal{A}^4 &= -\frac{D_0}{D}\frac{(1+\cos^2\iota)}{2}\sin 2\phi_0 \sin 2\psi \\
&\quad + \frac{D_0}{D}\cos\iota \cos 2\phi_0 \cos 2\psi.
\end{aligned}$$

At 30° the difference is ~ 1%

Sky localization

X-pipeline

Aasi *et al.*, PRD 89, 122004



An example of two detector case.

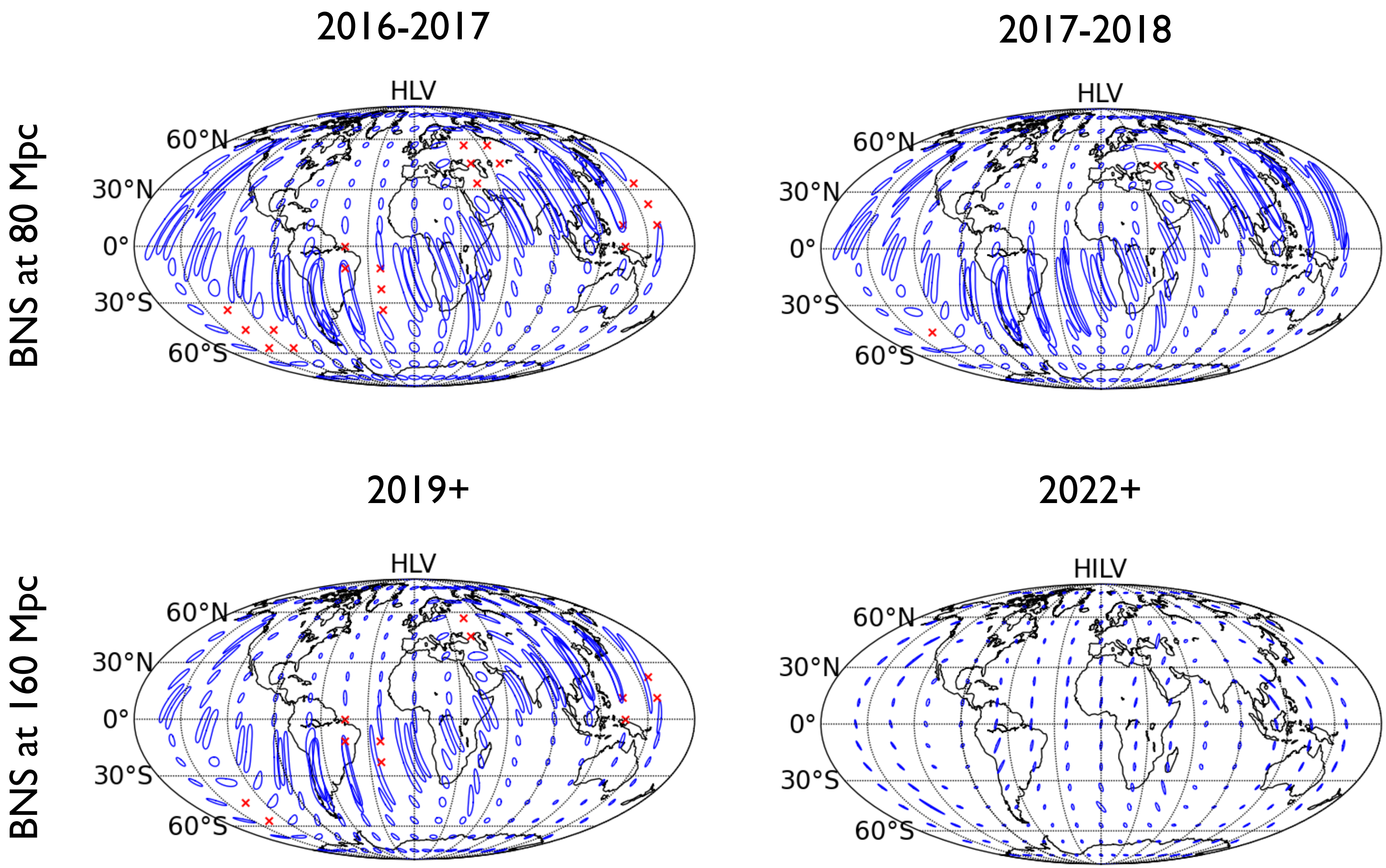
Hard to improve upon gamma-ray satellite localizations.

Other archival searches

GRB plateaus: A data analysis technique is currently under development to target secular bar-mode signals of duration of order 1000 s, triggered by GRBs showing evidence for longer-lived energy injection (plateaus).

Long duration GW bursts: The STAMP pipeline targets GW signals lasting 10–1000 s. It has been applied to initial LIGO data to constrain extreme models of stellar collapse.

Localization accuracy for face-on BNS



Ellipse: 90% confidence localization areas