

GW background and foregrounds

Prospects for detection

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LSC-Virgo Data Analysis Council Chairs
Amsterdam, August 29 2013
Chicago, September 10 2013



LIGO-G1300884



Foreground rate

- Given the sensitivity (reach), the number of detectors, the run duration and astrophysical predictions on the rate (per time and volume) of certain events, we can compute the expected foreground rate
- We will mostly refer to compact binary coalescences (CBC), and in particular binary neutron star (BNS) coalescences for illustration purposes

- Low mass systems, binary systems with a maximum total mass of $25 M_{\odot}$ and a minimum component mass of $1 M_{\odot}$: prime target, we will concentrate on these.
- Astrophysical event rates are uncertain ranging between 10^{-8} - 10^{-5} $\text{Mpc}^{-3} \text{ yr}^{-1}$.
- A standard figure of merit for the sensitivity of an interferometer is the binary neutron star (BNS) **reach**: the volume- and orientation-averaged distance at which a compact binary coalescence consisting of two $1.4 M_{\odot}$ neutron stars gives a matched filter signal-to-noise ratio of 8 in a single detector.
- For a single detector with reach of 215 Mpc this yields 0.4-400 events/yr.
- Reach is defined on one detector (@SNR = 8).
- With more detectors expected # events increases $\approx N_{\text{det}}^{1/2}$.
- The number of expected events increases $\approx (\text{reach})^3$

- The accessible volume of a search with effective duration T and reach R is

$$V = \frac{4}{3} \pi R^3 \times T \text{ Mpc}^3 \text{ yr}$$

- V times astrophysical rate per Mpc^3 and per yr yields the expected foreground

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- \mathcal{V} times astrophysical rate per Mpc^3 and per yr yields expected foreground

For example:

- consider 2 detectors with 40-80 Mpc reach observing for 3 months
- for confident detection with 2 detectors we need $\text{SNR} = 8.5$ so reach R decreases to 37.6-75 Mpc
- with 80% duty factor T decreases to $8.3 \times 10^6 \text{ s}$: $(0.4-3) \times 10^5 \text{ Mpc}^3 \text{ yr}$
- BNS coalescence astrophysical rates: $(0.01-10) \times 10^{-6} \text{ Mpc}^{-3} \text{ yr}^{-1}$

 **Foreground : 0.0004-3 events**

Foreground rate

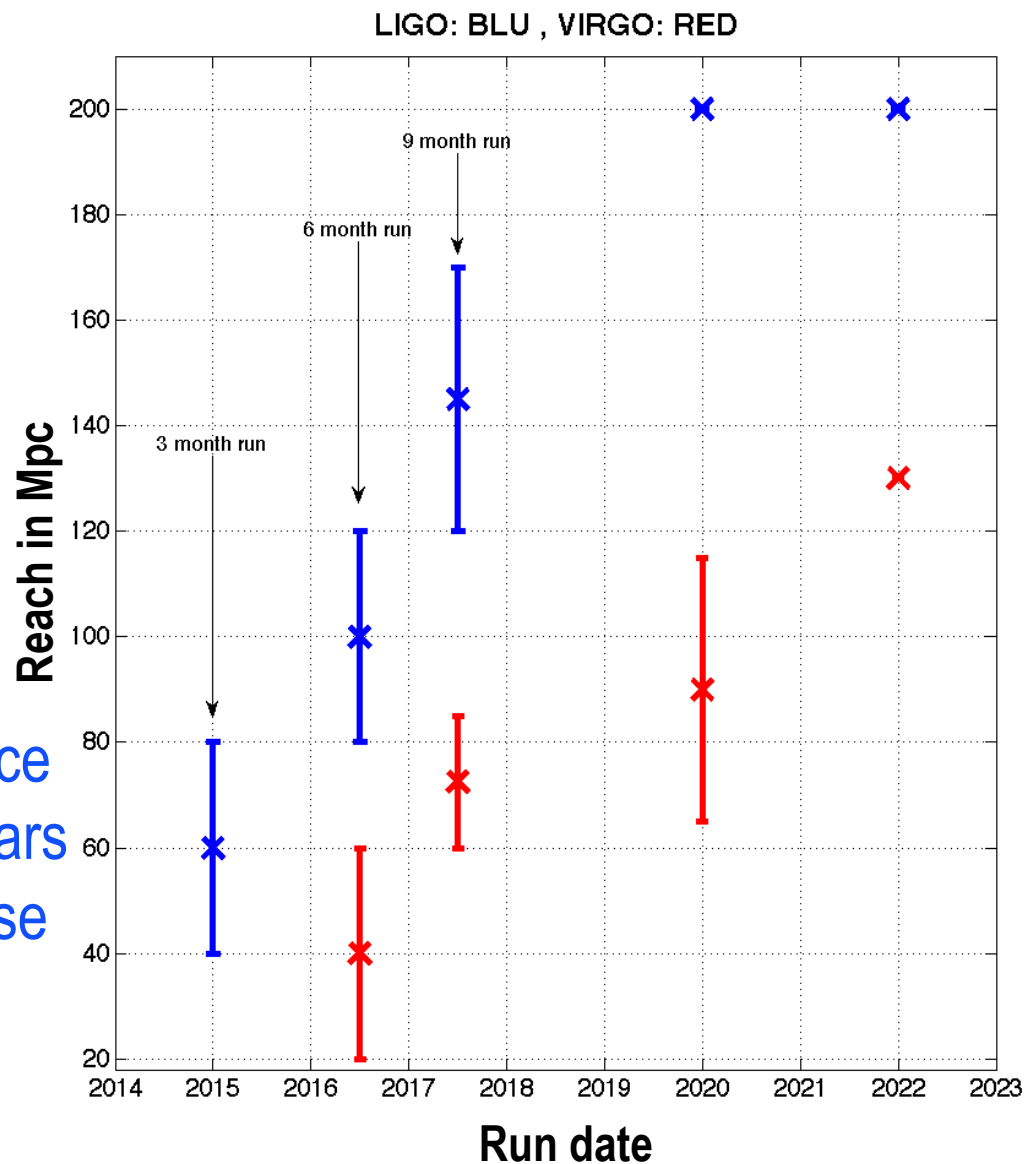
- Given the sensitivity (reach), the number of detectors, the run duration (t_0) and astrophysical predictions on the rate (per time and volume) of certain events, we can compute the expected foreground, f_0
- We can use this foreground to evaluate the probability p of making a detection with any run duration, t :
 - $\lambda_0 = f_0/t_0$ $f = \lambda_0 t$ $p = 1.0 - \text{PoissonCDF}(0, f)$
- Conversely we can set p to some confidence, say 90%, and find how long a run has to be before you can be p confident that we will have at least a detection

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- **Let take a step back and look at detector sensitivity**

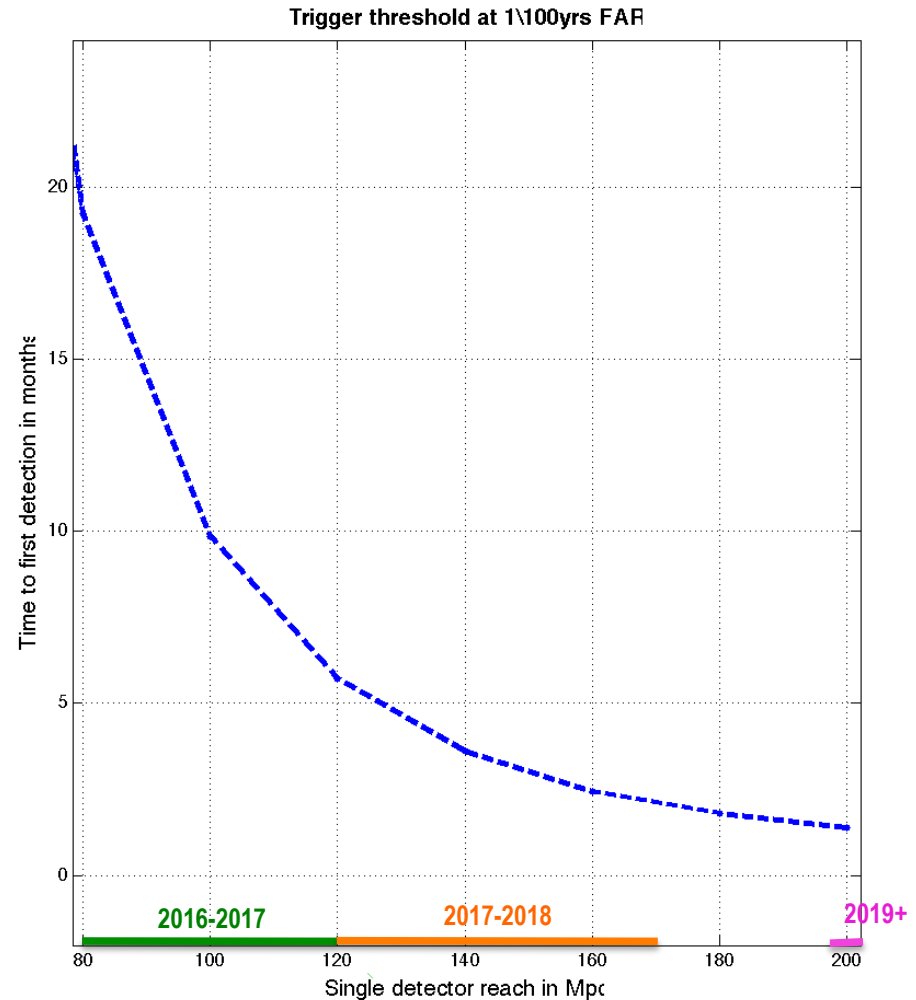
- It is difficult to make predictions of sensitivity improvements
- Now we can present *plausible* scenarios
- Unexpected problems might slow down progress
- Progress might also happen faster
- More information on event rates, including first detections, might change run schedule
- Before first detection we will strive to minimize time to first GW detection

Reach: the volume- and orientation-averaged distance at which a compact binary coalescence consisting of two $1.4M_{\odot}$ neutron stars gives a matched filter signal-to-noise ratio of 8 in a single detector



Expected time to first confident GW detection

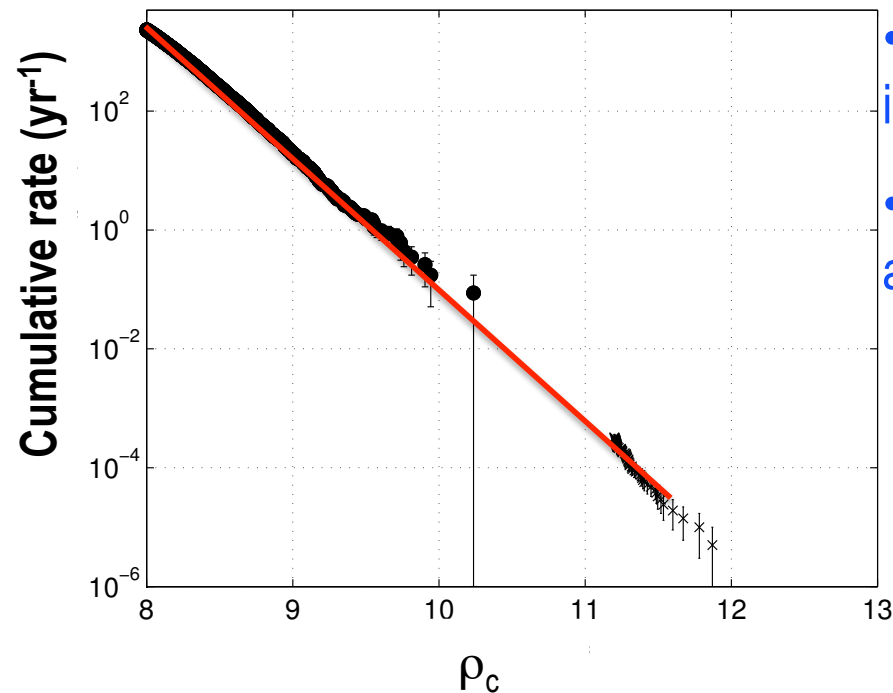
- By 2017-2018 we should have the first confident detection within a year of observation
- Could we make that first detection earlier ?
- How does foreground improve if we lower the threshold (give up detection confidence) ?



**BNS “realistic” astrophysical rate (LVC,CQG 27,2010)
2 equally sensitive detectors**

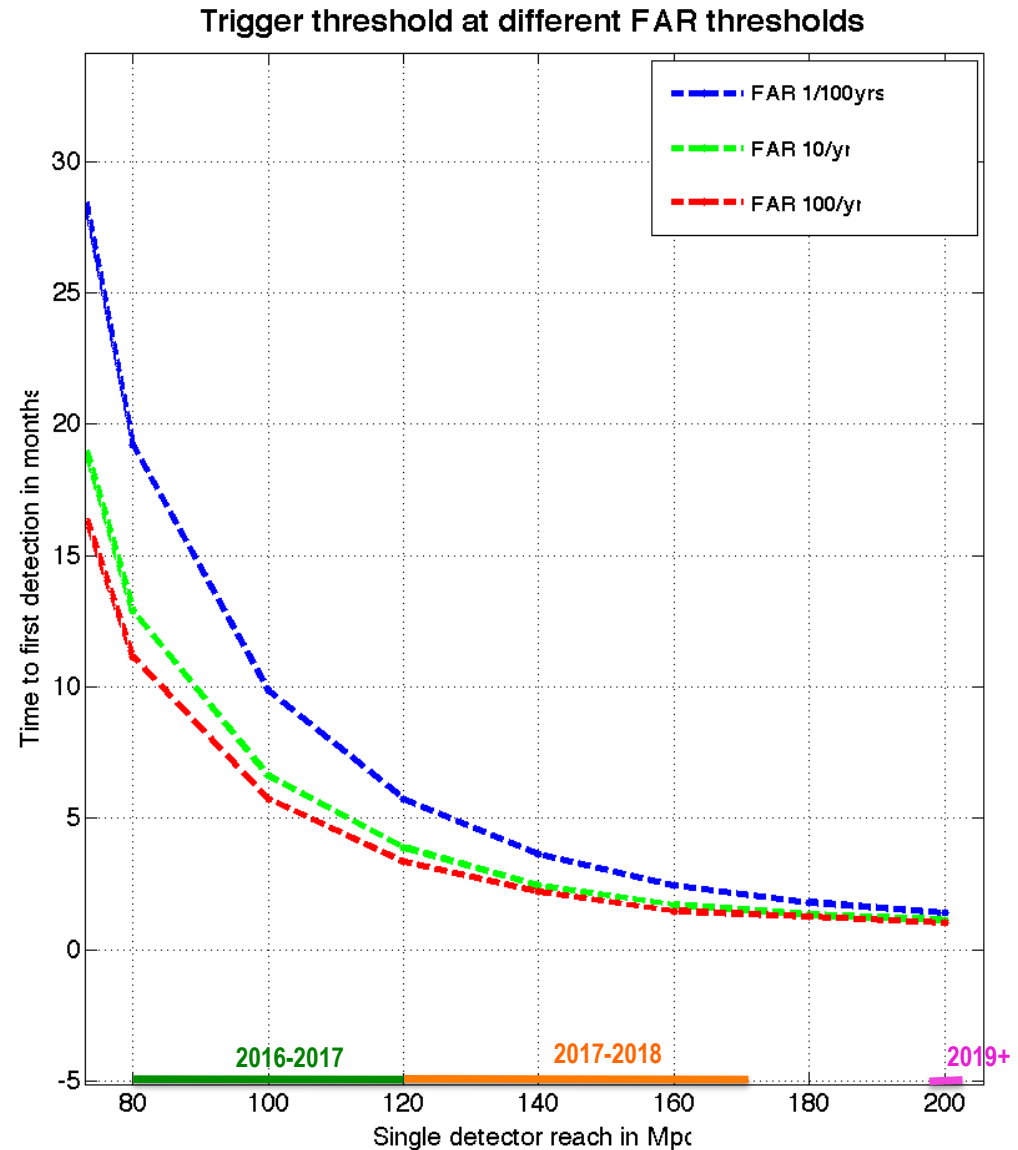
give up confidence to increase foreground

Background from the last LIGO run.



- Combined SNR ρ_c for signals $\approx \sqrt{\sum_{i=1}^{N_{\text{det}}} \rho_i^2}$
- Background rate decreases by ~ 100 for every unit increase in ρ_c
- Foreground rate increases like ρ_c^{-3} (ρ_c propto GW amplitude propto distance $^{-1}$)
 - for example if we accept 10 times more false alarms we only increase the foreground by $\sim 10\%$
- Confident detection requires $\rho_c = 12$, corresponding to a false alarm rate of 10^{-2} yr^{-1} (conservative estimate folding in effect of trial factors)

- real GW candidates among top 10 or 100 most significant ones already with a 80 Mpc reach with less than 15 months of observation
- Could EM follow-ups provide additional confidence ? Sky localization uncertainty* : significant fraction of sky to few tens deg²



*(S. Fairhurst : Class.Quant.Grav. 28 (2011) 105021 and arxiv:1010.6192)

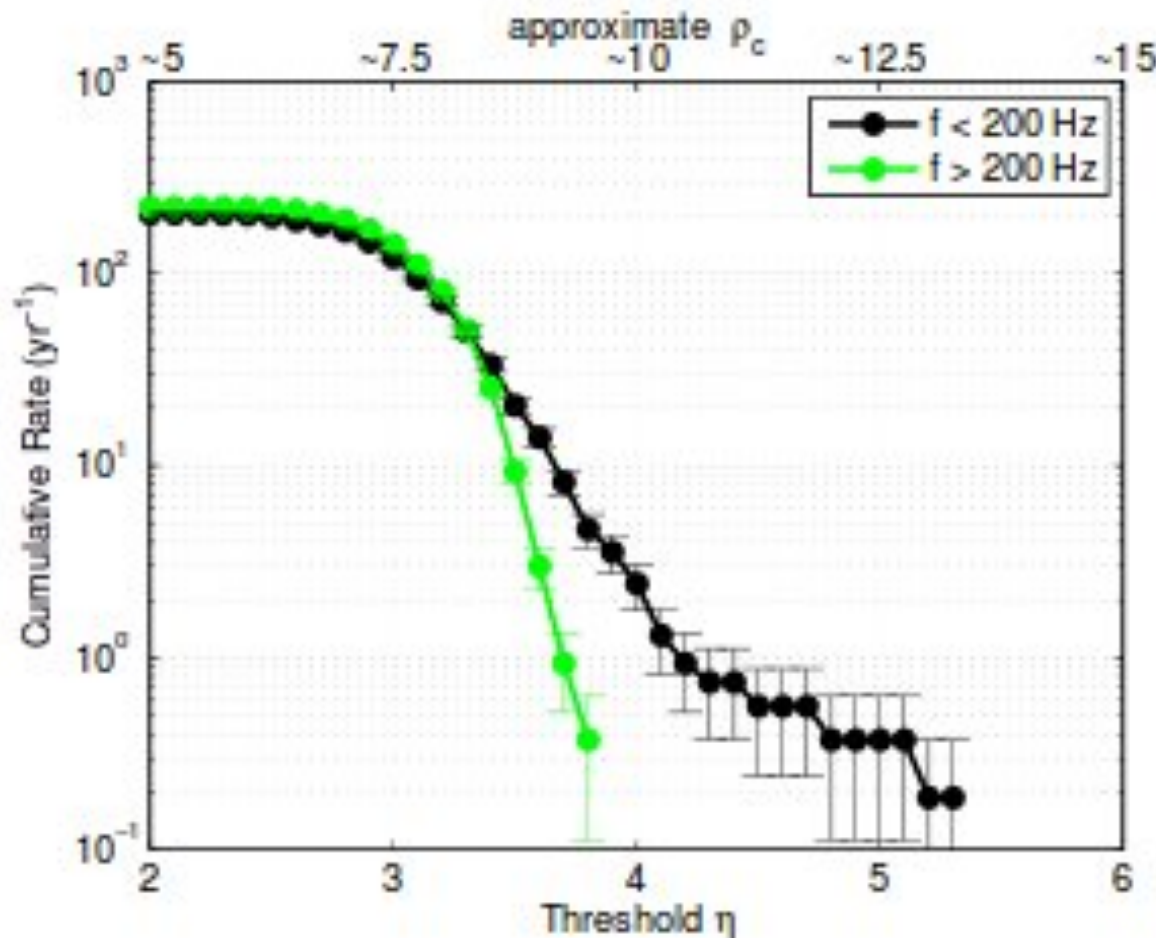
BURST searches :

- In addition to matched filtering searches for CBC events, we pursue generic short-duration signals ($< 1\text{s}$): bursts.
- Targets: core-collapse SN, BBH coalescence, cosmic strings cusps, magnetar flares and unknown systems.
- These searches don't assume a model/waveform and are based on coherent excess power in multiple interferometers.

Thus: artifacts in the data might have a greater effect here.

BURST searches background :

Background from the last run



η is the coherent network amplitude
 $\rho_c \sim \sqrt{2N} \eta$ with N = number of detectors

Advanced detectors are designed with many technical improvements, but we expect tails in the distribution, in particular from the low frequencies.

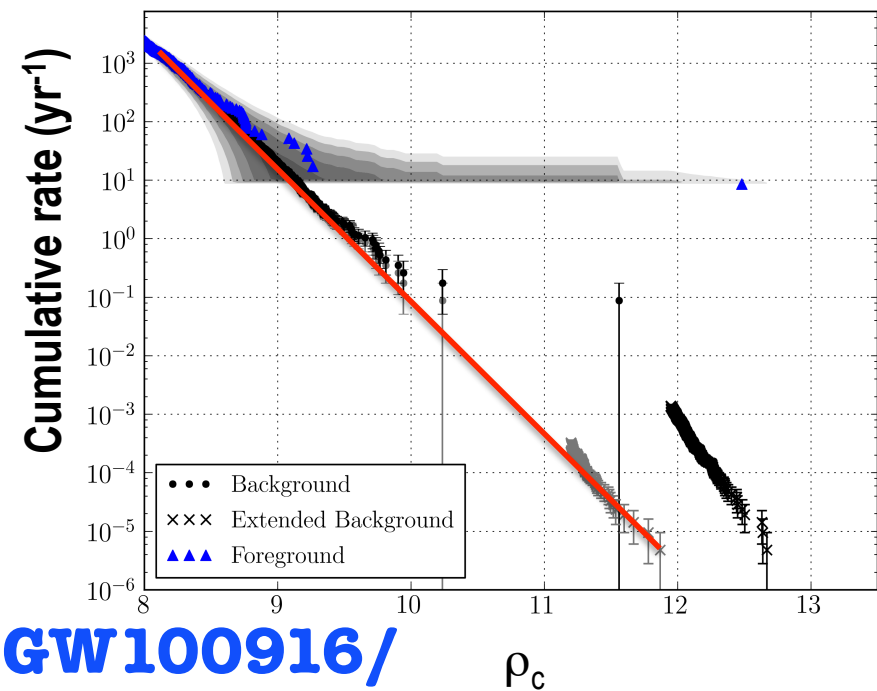
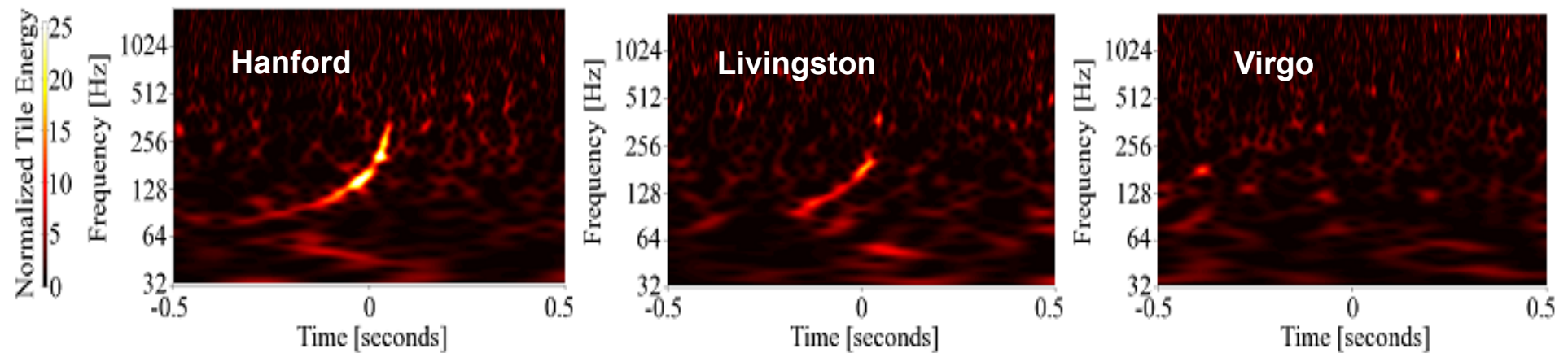
Another problem for short signals is that the sky localisation region could comprise multiple disjoint spots (see LIGO-G1300742)

Additional caveat

- We do blind injections

Blind Injections

- End-to-end test of our ability to detect GWs
- Simulated GW signals are coherently injected into the LV interferometers
 - End test masses are 'wiggled' with the characteristic gravitational waveform corresponding to specific source type, event time, sky location, and distance
- Secretly injected by a very small select group within LIGO-Virgo; information kept confidentially from the LIGO-Virgo Collaboration
- Blind injections were performed in S5/VSR1 and S6/VSR2,3 science runs.
 - Injection rate during a science run was Poissonian with an expected value of 1



Blind Injections in Advanced Detector Era

- Blind injections are not revealed as such until LIGO-Virgo has fully vetted potential candidates and declared them as detection (or not)
- Although we will strive to assess detection candidates quickly, in the past it has taken a while (eg, GW100916 took 6 months)
- Blind injections have proven to be very valuable to LIGO-Virgo in the past, so the LVC has made the decision to continue them into the next science runs (at least through the first detection)
 - valuable lessons on detection confidence, importance of parameter estimation
- Although the BI rate hasn't been formally decided, it will very likely be quite low
 - 0, 1, or possibly 2 during a science run in the early going, commensurate with expected rates for binary coalescences
- It will be very difficult to selectively unblind the injections before passing them to EM follow up partners

Blind Injections in Advanced Detector Era

- It is possible that during a science run, you will receive an alert that isn't real.
- Are you willing to 'chase a ghost'?
- What rate would be considered tolerable?

Conclusions

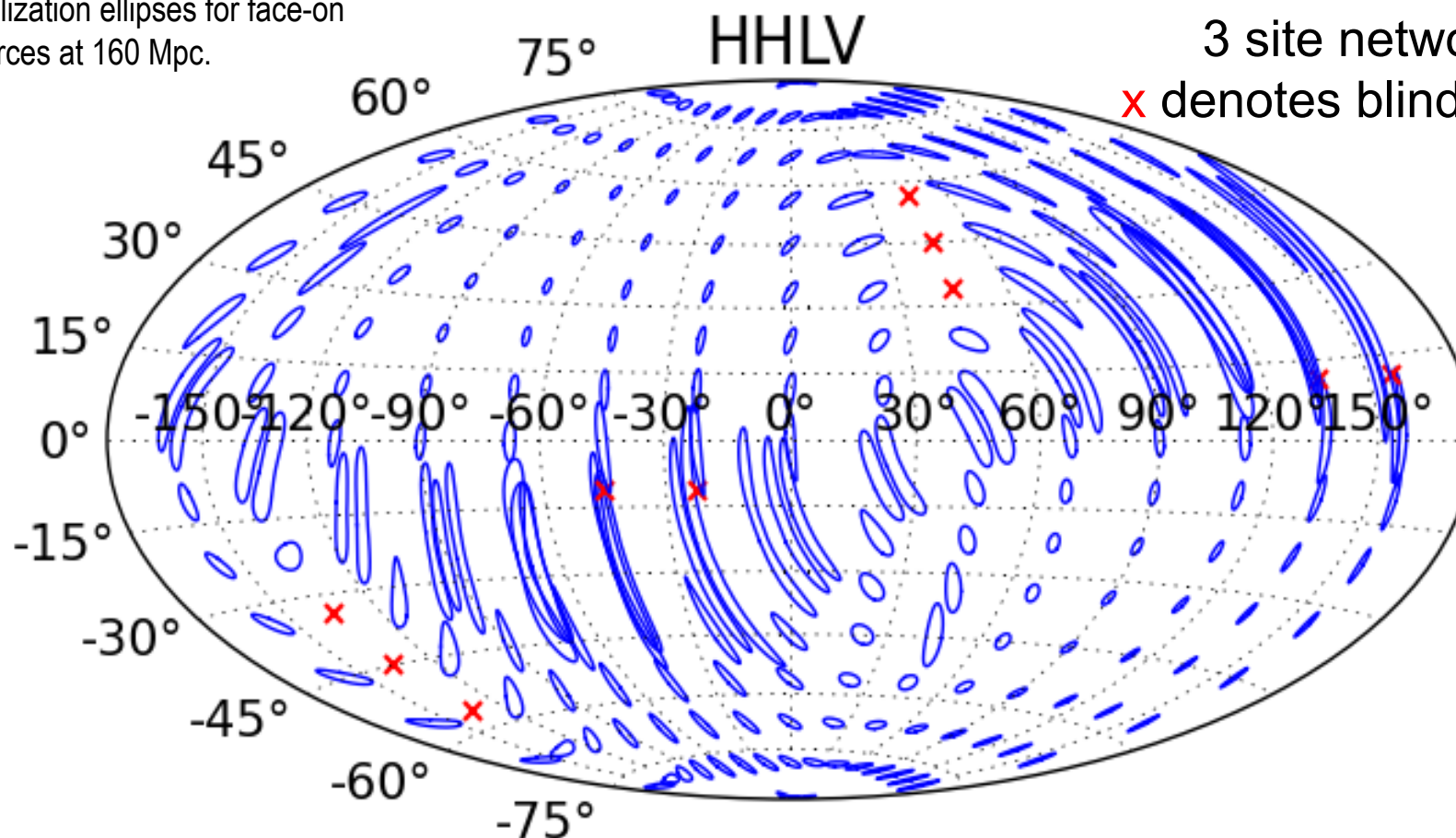
- In the early advanced detector era:
 - In the case of a confident GW detection it would make a much more interesting case if EM observations had identified a counterpart
 - Could EM follow-ups help promote a marginal GW candidate (with associated poor sky localization) to a confirmed detection ?
 - How are we going to do this ?
 - Much to think about in terms of organization
 - Blind injections

Thank you

Spare slides

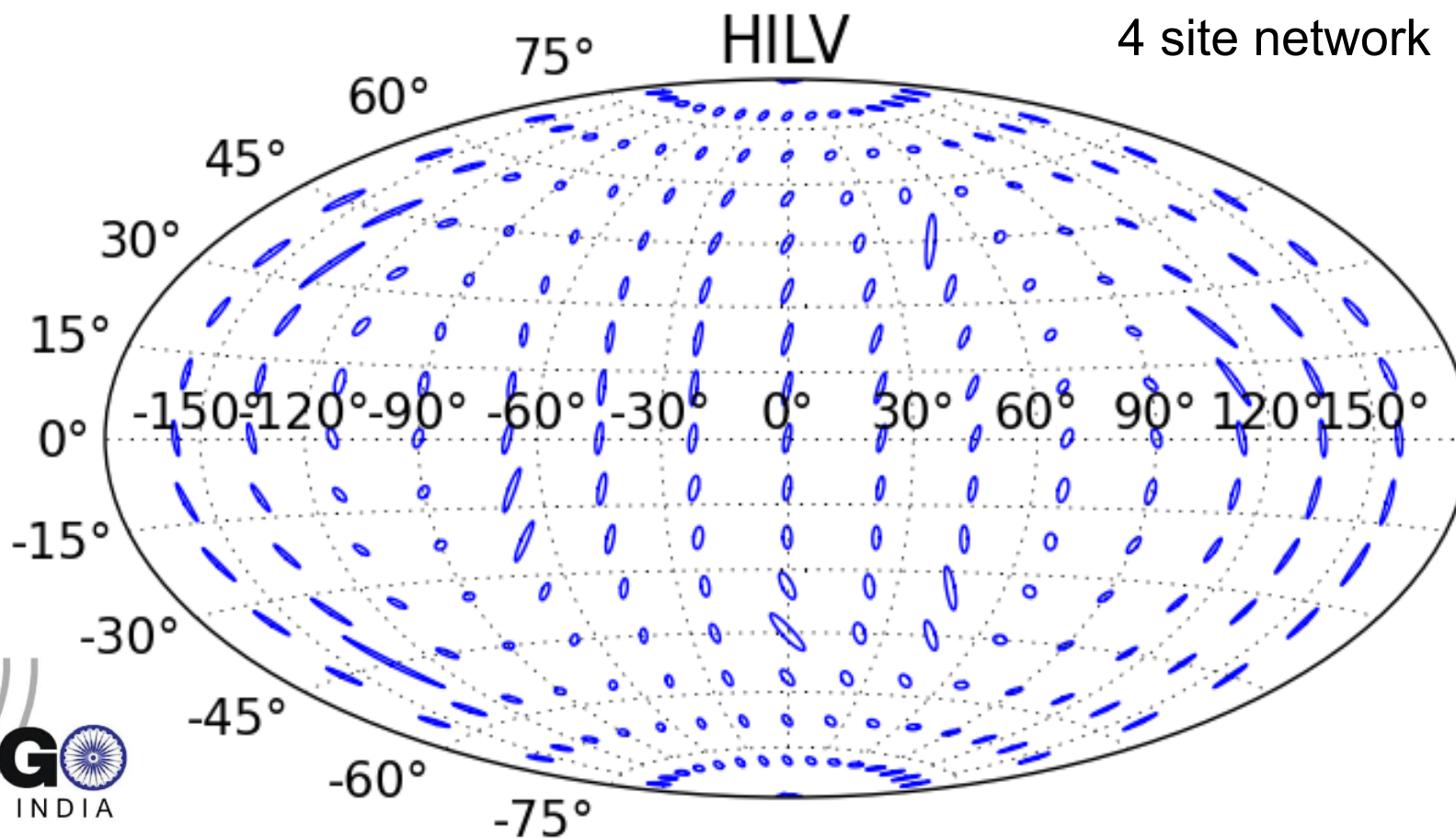
- 2016-2017, 6 months : expect 0.09-30 BNS signals from marginal GW candidates with only 5-12% of the signals localized to better than 20 deg²
- 2017-2018 , 9 months: expect 0.06-150 BNS detections, with 10-12% localized to better than 20 deg²
- 2019+ : expect 0.3-300 BNS detections per year, with 8-28% localized to better than 20 deg²
- 2022 + (India) : expect 0.6-600 BNS detections per year 48% localized to better than 20 deg² and 17% to better than 5 deg²

90% localization ellipses for face-on
BNS sources at 160 Mpc.



3 site network
x denotes blind spots

S. Fairhurst, "Improved source localization with
LIGO India", [arXiv:1205.6611](https://arxiv.org/abs/1205.6611)



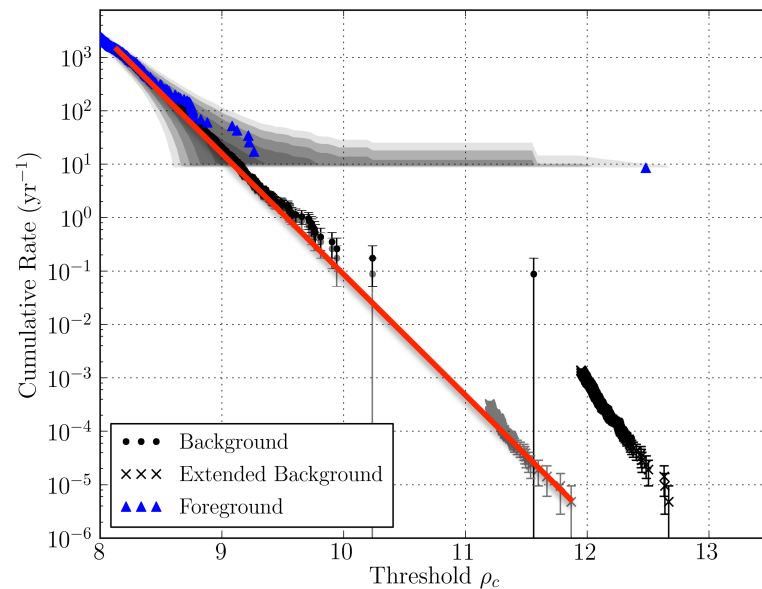
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Localization accuracies

- 2016-2017, 6 months : expect 0.06-20 confident BNS detections with only 5-12% of the signals localized to better than 20 deg^2
- 2017-2018 , 9 months: expect 0.04-100 BNS detections, with 10-12% localized to better than 20 deg^2
- 2019+ : expect 0.2-200 BNS detections per year, with 8-28% localized to better than 20 deg^2
- 2022 + (India) : expect 0.4-400 BNS detections per year 48% localized to better than 20 deg^2 and 17% to better than 5 deg^2
- For lower threshold candidates results only marginally worse.

CBC searches : background

Background from the last LIGO



- Background rate decreases by ~ 100 for every unit increase in ρ_c

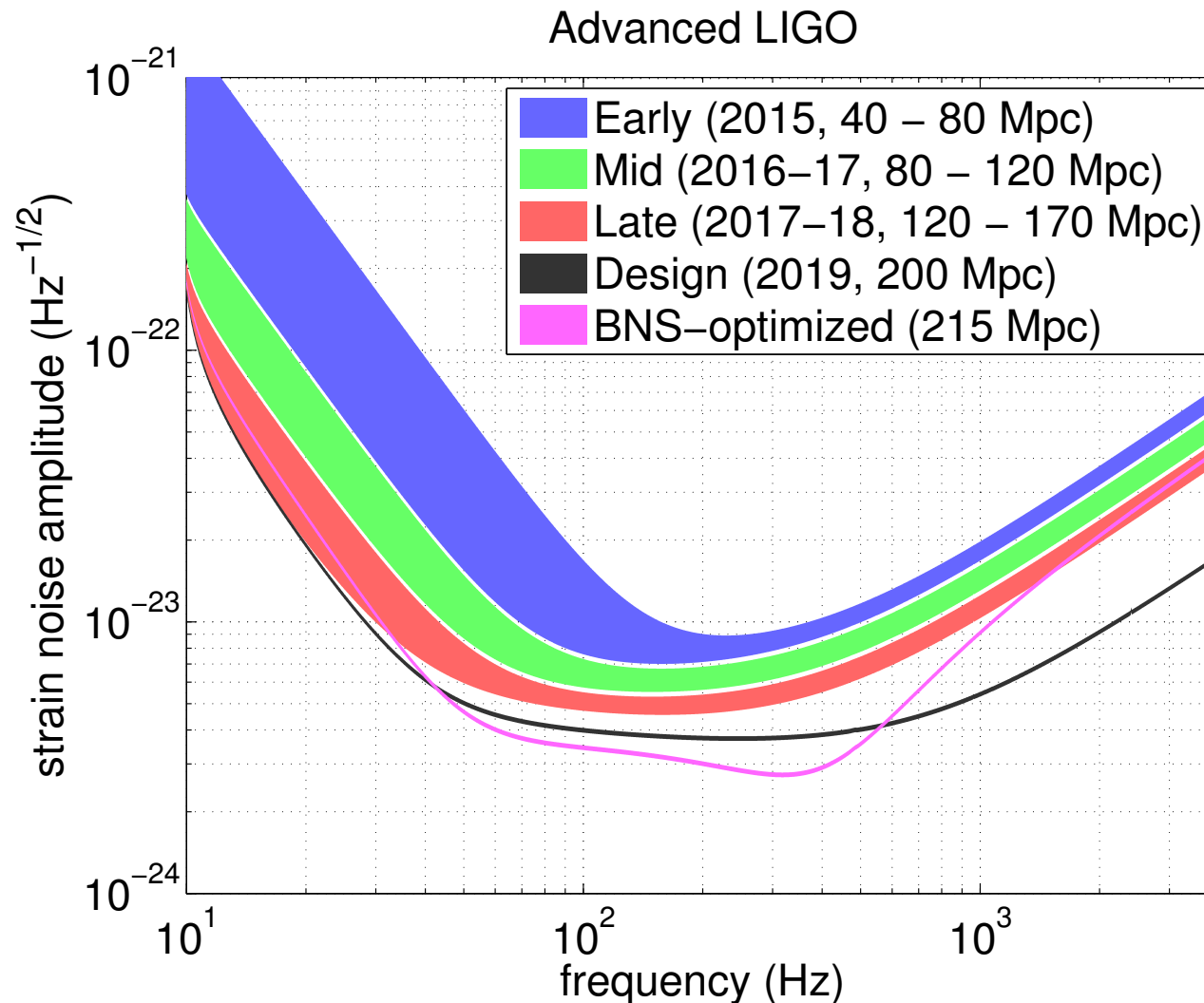
$$\sqrt{\sum_{i=1}^{N_{\text{det}}} \rho_i^2}$$

- Combined SNR ρ_c for signals \approx

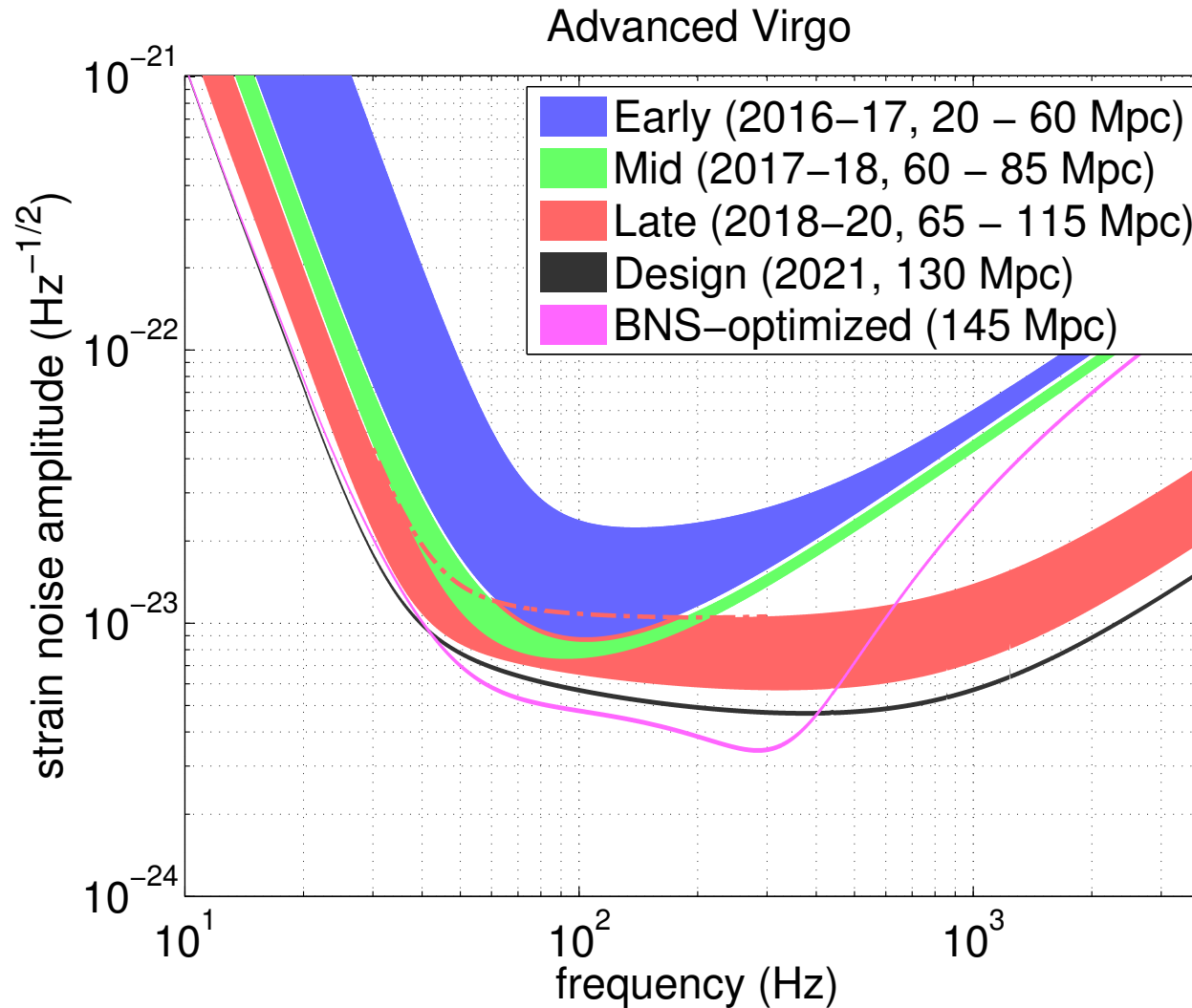
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Possible progression in sensitivity of the LIGO detectors



Possible progression in sensitivity of the Virgo detector



- LIGO-India :
 - Configured to be identical to H1 and L1
 - Once funding is secured, schedule finalized.
 - Expect begin site development is 2014, installation in 2018, first runs in 2020 and design sensitivity in 2022
- Kagra :
 - Located in Japan
 - Construction has begun
 - Sensivity comparable to aLIGO
- GEO :
 - Likely operating 2016-2017
 - Similar sensitivities as contemporary aLIGO above kHz, at 100 Hz ~ 10 times less sensitive



Searches for GW signals from inspirals of compact binary systems

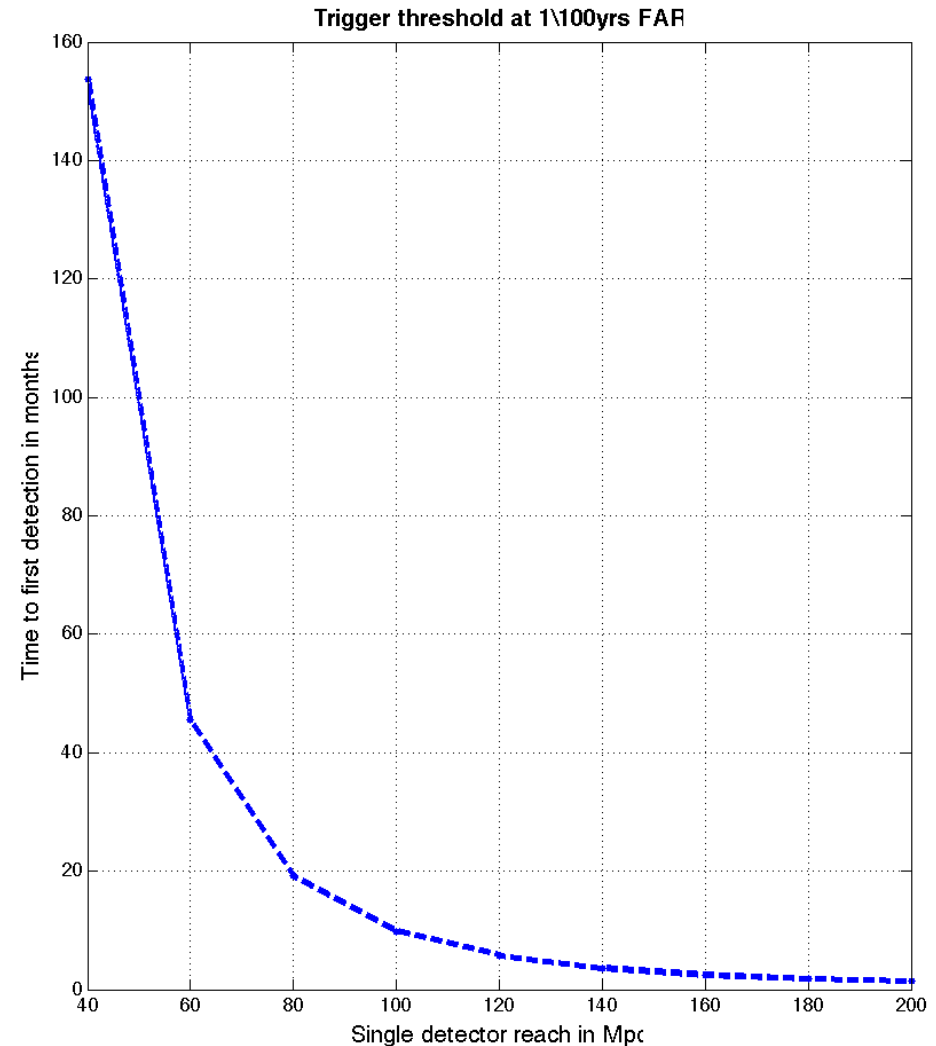


(CBC)

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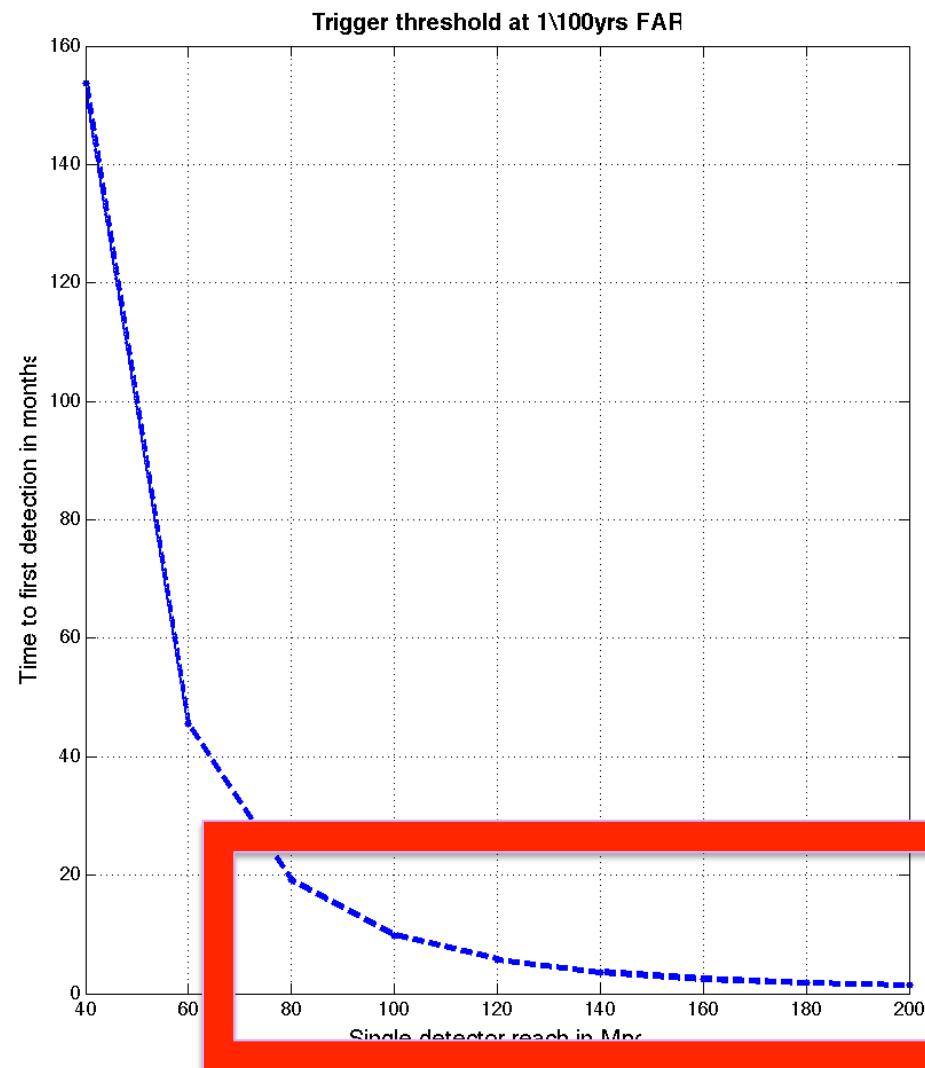
Expected time to first confident GW detection

- 90% Poisson probability of a detection with “realistic astrophysical rate”
- assumed 2 detectors
- Before having reached ~ 100Mpc a detection is unlikely, unless optimistic rates hold

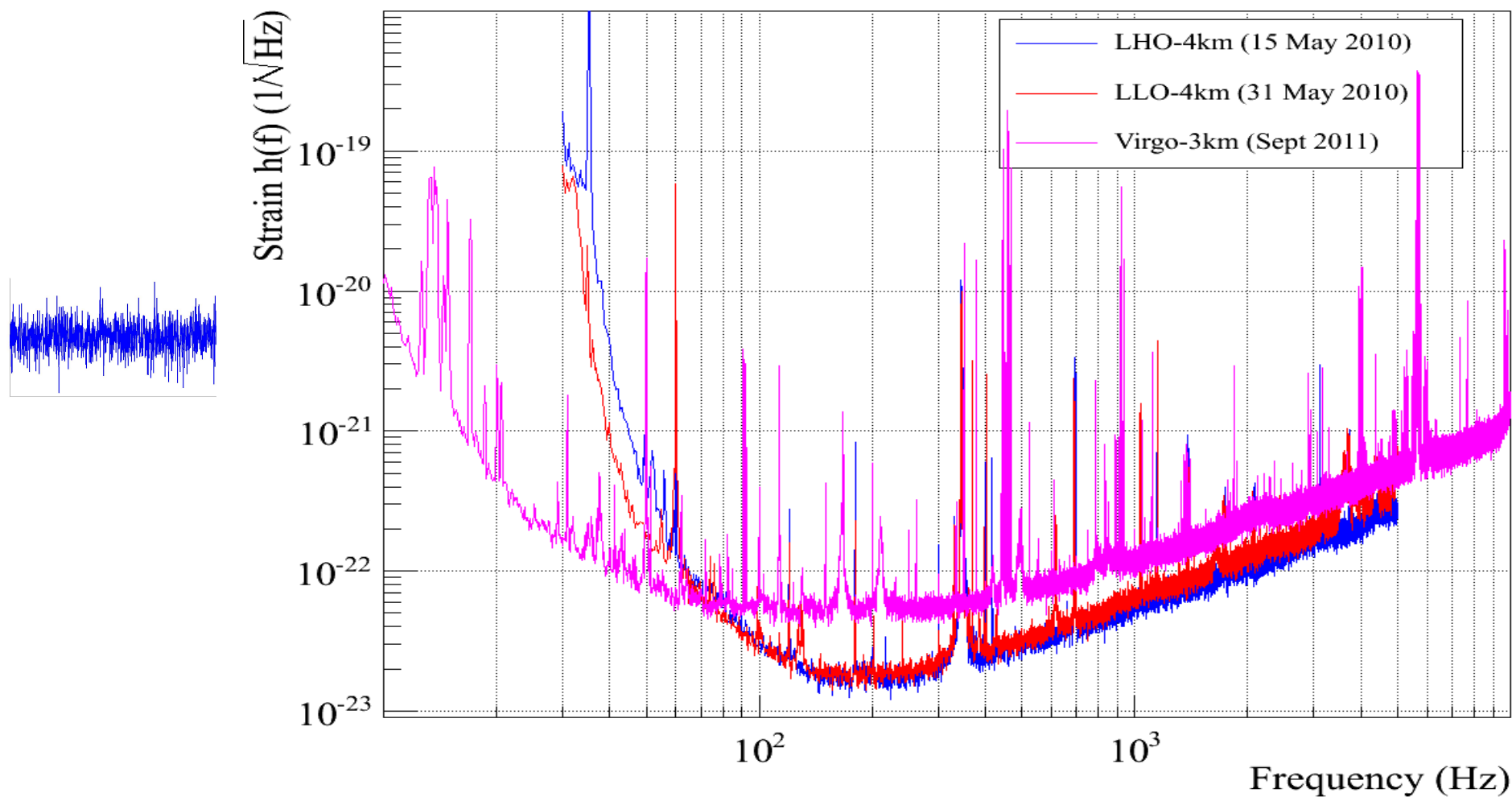


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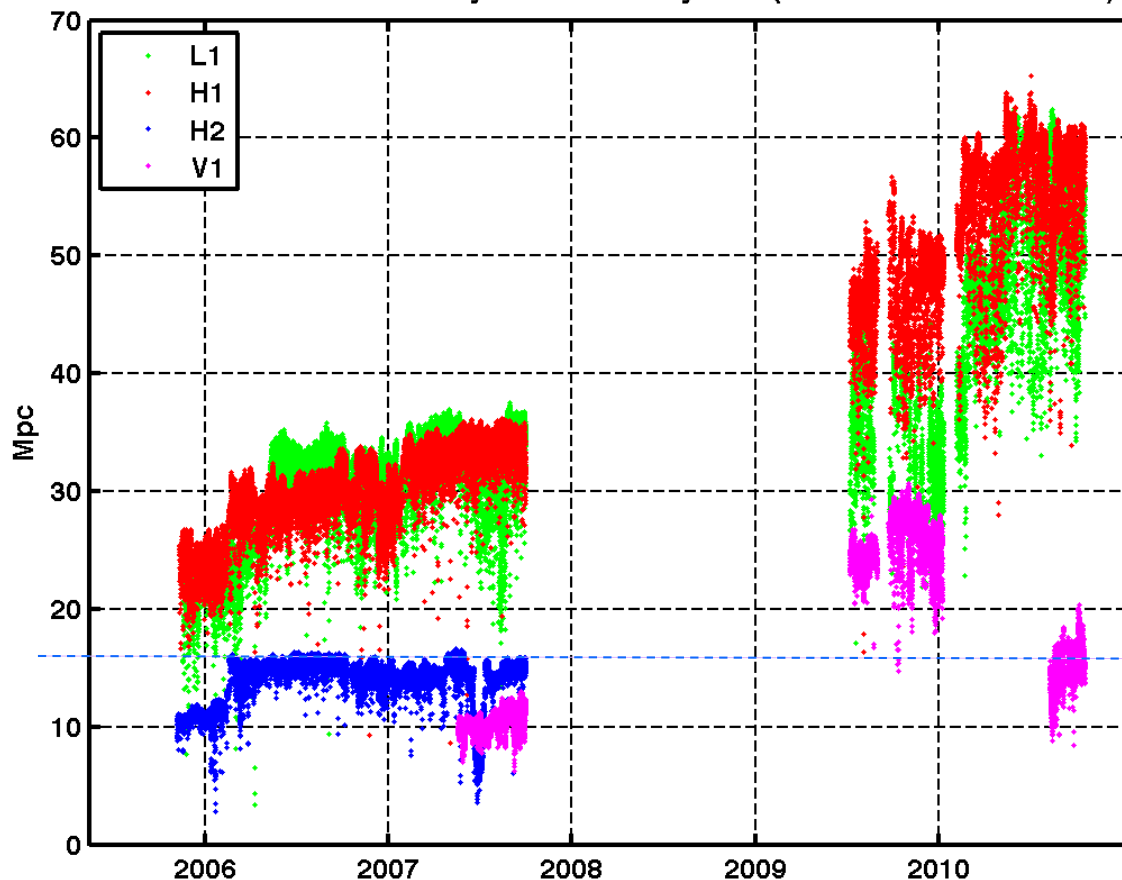


1st generation Detectors' noise (spectral density)

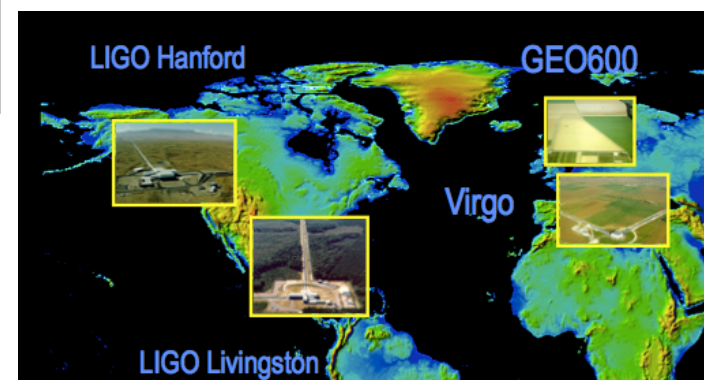
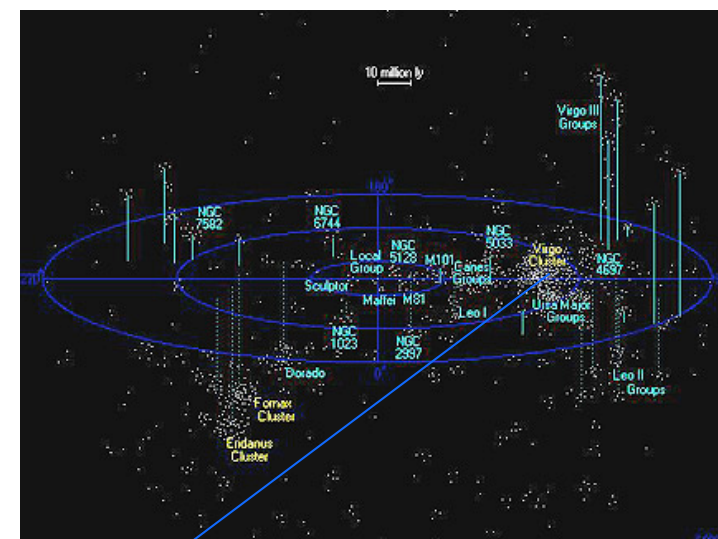


Distance reach to coalescing binary neutron star systems

Horizon distance for a binary neutron star system (with $m=1.4$ solar masses)



atlasofthe universe.com



GW-EM follow up: two eras

- After the published discovery of four gravitational events with data from LSC and/or Virgo detectors, both the LSC and Virgo will begin releasing especially significant triggers (with FAR < 1/100 yrs) promptly to the entire scientific community to enable a wider range of follow-up observations. This may happen after 2018 (?).
- Before that (starting in 2015); LVC will partner with astronomers to carry out an inclusive observing campaign for potentially interesting GW triggers, with MoUs to ensure coordination and confidentiality of the information. They are open to all requests from interested astronomers or astronomy projects which want to become partners through signing an MoU. Partners who have signed an MoU with the LSC and Virgo will have access to GW triggers with a lower significance threshold and/or lower latency, according to the terms of the MoU, in order to carry out a more systematic joint observing campaign and combined interpretation of the results.

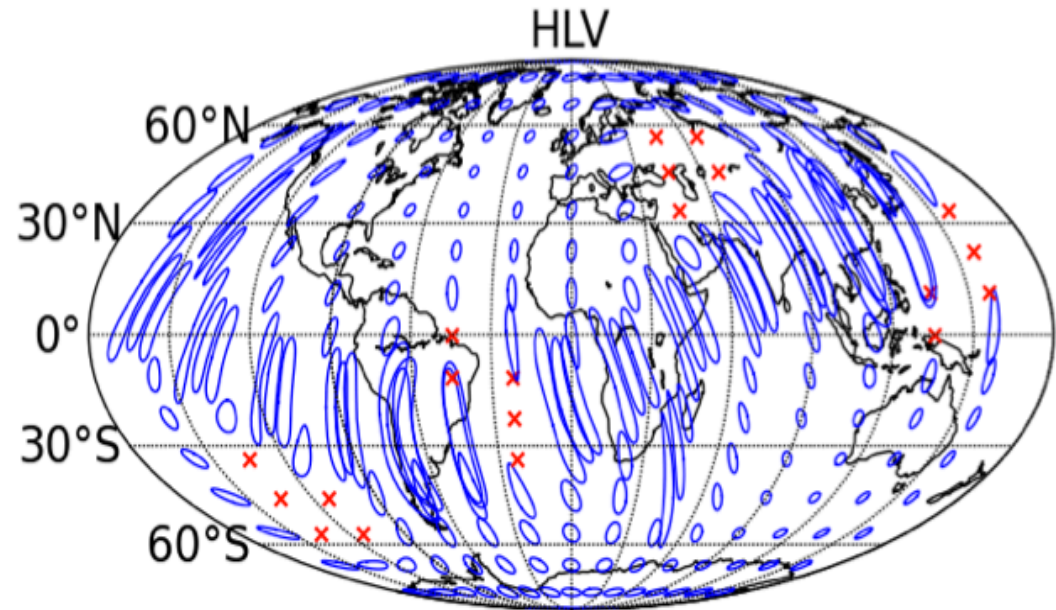


When ?

Prospects for Localization of Gravitational Wave Transients by the Advanced LIGO and Advanced Virgo Observatories

Aiming to source localization in the sky

J. Aasi¹, J. Abadie¹, B. P. Abbott¹, R. Abbott¹, T. D. Abbott², M. Abe³, F. Acernese^{5ac}, C. Adams⁶, T. Adams⁷, P. Addesso⁸, R. X. Adhikari¹, C. A. O. D. Aguiar¹², P. Ajith¹, B. Allen^{9,13,10}, A. Allocca^{14ac}, E. Amador Cea¹⁵, S. B. Anderson¹, W. G. Anderson¹³, K. Arai¹, M. C. Araya¹, C. Arceneaux¹⁶, P. Astone^{17a}, D. Atkinson¹⁸, P. Aufmuth^{10,9}, C. Aulbert^{9,10}, L. Austin¹, B. P. Baker²¹, G. Ballardín²², S. Ballmer²³, Y. Bao¹⁵, J. C. Barayoga¹, D. Barke²⁴, L. Barsotti²⁴, M. Barsuglia²⁵, M. A. Barton¹⁸, I. Bartos²⁶, R. Bassiri^{9,27}, M. J. Batch¹⁸, J. Bauchrowitz^{9,10}, Th. S. Bauer^{11a}, M. Bebronne⁴, B. Behnke²⁰, M. A. S. Bell³, C. Bell³, G. Bergmann^{9,10}, J. M. Berliner¹⁸, A. Bertolini^{9,10}, J. F. P. T. Beyersdorff²⁹, T. Bhadrade²⁷, I. A. Bilenko³⁰, G. Billingsley¹, J. Birch⁶, M. A. Bizouard^{31a}, E. Black¹, J. K. Blackburn¹, L. Blackburn³², D. Blair³³, O. Bock^{9,10}, T. P. Bodiya²⁴, C. Bogan^{9,10}, C. Bond¹⁹, F. Bondu^{34b}, L. Borra¹, R. Bork¹, M. Born^{9,10}, V. Boschi^{14a}, S. Bose³⁶, L. Bosi^{37a}, B. Bouhou²⁵, J. L. Bracciatelli¹, P. R. Brady¹³, V. B. Braginsky³⁰, M. Branchesi^{38ab}, J. E. Brau³⁹, J. Bracciatelli¹, D. O. Bridges⁶, A. Brillet^{34a}, M. Brinkmann^{9,10}, V. Brisson^{31a}, M. Britz⁴⁰, D. A. Brown²³, D. D. Brown¹⁹, F. Brueckner¹⁹, K. Buckland¹, T. Bulik⁴¹, A. Buonanno⁴¹, J. Burguet-Castell⁴², D. Buskulic⁴, C. Buy²⁵, R. L. Burdick⁴³, G. Cagnoli^{35,44}, E. Calloni^{5ab}, J. B. Camp³², P. Campsie³, K. Cannon⁴⁵, C. D. Capapo⁴¹, F. Carbognani²², L. Carbone¹⁹, S. Caride⁴⁷, A. D. Casaferr⁴⁸, M. Cavaglià¹⁶, F. Cavalieri^{31a}, R. Cavalieri²², G. Cella^{14a}, C. Cepeda¹, E. Cesarini⁴⁹, S. Chao¹⁰¹, P. Charlton⁵⁰, E. Chassande-Mottin²⁵, X. Chen³³, Y. Chen⁵¹, A. C. Chua⁵², H. S. Cho⁵³, J. Chow⁵⁴, N. Christensen⁵⁵, Q. Chu³³, S. S. Y. Chua⁵⁴, C. T. Cui⁵⁶, F. Clara¹⁸, D. E. Clark²⁷, J. A. Clark⁴³, F. Cleva^{34a}, E. Coccia^{49ab}, P.-F. Cohadon⁵⁷, A. Colla^{17ab}, M. Colombini^{17b}, M. Constancio Jr.¹², A. Conte^{17ab}, D. Cook¹⁸, T. Corbitt⁵⁸, N. Cornish²¹, A. Corsi¹⁰³, C. A. Costa^{2,12}, M. Coughlin⁵⁷, J.-P. Coulon⁵⁹, P. Couvares²³, D. M. Coward³³, M. Cowart⁶, D. C. Coyne¹, K. Craig³, C. Creighton⁶⁰, T. D. Creighton⁴⁴, A. Cumming³, L. Cunningham³, E. Cuoco²², K. Dahl⁶¹, S. Danilov⁶², C. D'Amico⁶³, P. D'Antonio⁶⁴, R. D'Emilio⁶⁵, F. D'Amico⁶⁶, M. D'Antonio⁶⁷, L. D'Emilio⁶⁸, S. D'Antonio⁶⁹, P. D'Antonio⁷⁰, M. D'Antonio⁷¹, L. D'Emilio⁷², S. D'Antonio⁷³, P. D'Antonio⁷⁴, M. D'Antonio⁷⁵, L. D'Emilio⁷⁶, S. D'Antonio⁷⁷, P. D'Antonio⁷⁸, M. D'Antonio⁷⁹, L. D'Emilio⁸⁰, S. D'Antonio⁸¹, P. D'Antonio⁸², M. D'Antonio⁸³, L. D'Emilio⁸⁴, S. D'Antonio⁸⁵, P. D'Antonio⁸⁶, M. D'Antonio⁸⁷, L. D'Emilio⁸⁸, S. D'Antonio⁸⁹, P. D'Antonio⁹⁰, M. D'Antonio⁹¹, L. D'Emilio⁹², S. D'Antonio⁹³, P. D'Antonio⁹⁴, M. D'Antonio⁹⁵, L. D'Emilio⁹⁶, S. D'Antonio⁹⁷, P. D'Antonio⁹⁸, M. D'Antonio⁹⁹, L. D'Emilio¹⁰⁰



304.0670v1 [gr-qc] 2 Apr 2013

Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc)		BNS Range (Mpc)		Number of BNS Detections	% BNS Localized within	
		LIGO	Virgo	LIGO	Virgo		5 deg ²	20 deg ²
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

“Observing Scenario”

- Prospects for Localization of Gravitational Wave Transients by the Advanced LIGO and Advanced Virgo Observatories, The LIGO Scientific Collaboration and The Virgo Collaboration, [arXiv:1304.0670](https://arxiv.org/abs/1304.0670)
- In review by Living Reviews in Relativity

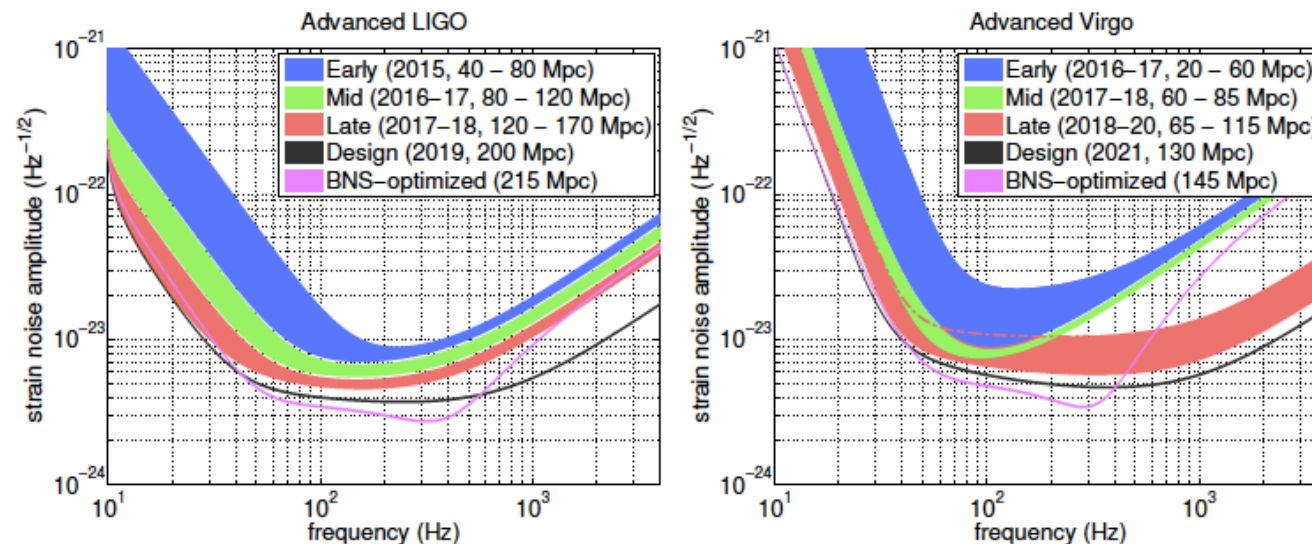


Figure 1: aLIGO (left) and AdV (right) target strain sensitivity as a function of frequency. The average distance to which binary neutron star (BNS) signals could be seen is given in Mpc. Current notions of the progression of sensitivity are given for early, middle, and late commissioning phases, as well as the final design sensitivity target and the BNS-optimized sensitivity. While both dates and sensitivity curves are subject to change, the overall progression represents our best current estimates.

Observing Scenario

Epoch	Estimated Run Duration	$E_{\text{GW}} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc)		BNS Range (Mpc)		Number of BNS Detections	% BNS Localized within	
		LIGO	Virgo	LIGO	Virgo		5 deg ²	20 deg ²
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

Table 1: Summary of a plausible observing schedule, expected sensitivities, and source localization with the advanced LIGO and Virgo detectors, which will be strongly dependent on the detectors' commissioning progress. The burst ranges assume standard-candle emission of $10^{-2} M_{\odot} c^2$ in GWs at 150 Hz and scale as $E_{\text{GW}}^{1/2}$. The burst and binary neutron star (BNS) ranges and the BNS localizations reflect the uncertainty in the detector noise spectra shown in Fig. 1. The BNS detection numbers also account for the uncertainty in the BNS source rate density [28], and are computed assuming a false alarm rate of 10^{-2} yr^{-1} . Burst localizations are expected to be broadly similar to those for BNS systems, but will vary depending on the signal bandwidth. Localization and detection numbers assume an 80% duty cycle for each instrument.

How?

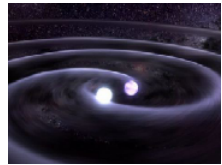
- Current plan (<http://www.ligo.org/science/GWEMAlerts.php>), on advice of internal and external experts:
 - Before defining MOU templates, open call for “Letters of Interest” from any astronomer or group of astronomers or collaboration who wants to follow up GW triggers. Received >60 responses!
 - Meet with LOI submitters for input on MOUs, modes of partnership (“independent” and “coordinated”), and publication models. (*This meeting!*)
 - LVC defines the MOUs, and makes a call for signing MOUs (Oct?), publishing criteria for evaluation.
 - LVC evaluates proposals, and decides on signing MOUs (~March).

Goals for this meeting

- Meet all who expressed interest in GW-EM astronomy!
- Explain status of GW detectors and prospects for GW events in the next several years.
- Hear and understand opinions and constraints on partnerships, agreements, publications,...

Expected result after discussions in Amsterdam, Chicago and within LVC: signed MOUs for partnerships leading to new astrophysics.

(false alarms background)



1-30 Ms binary systems

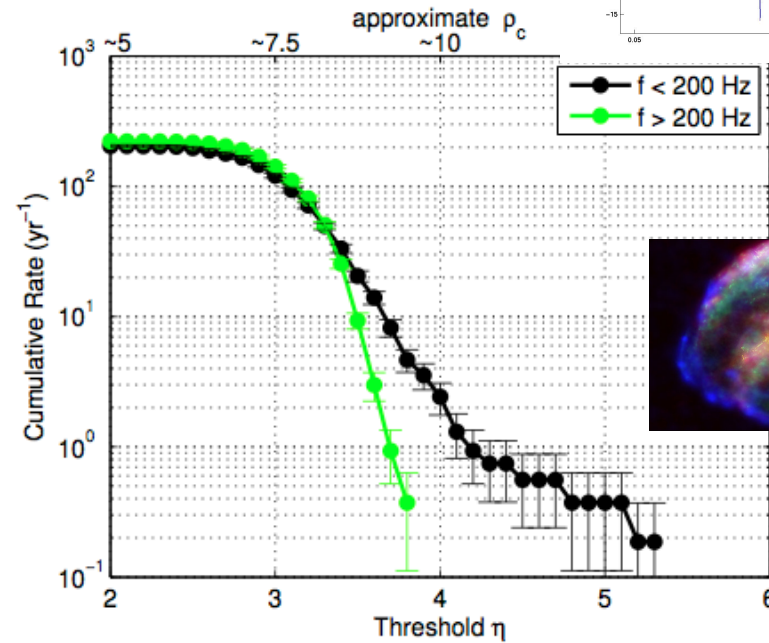
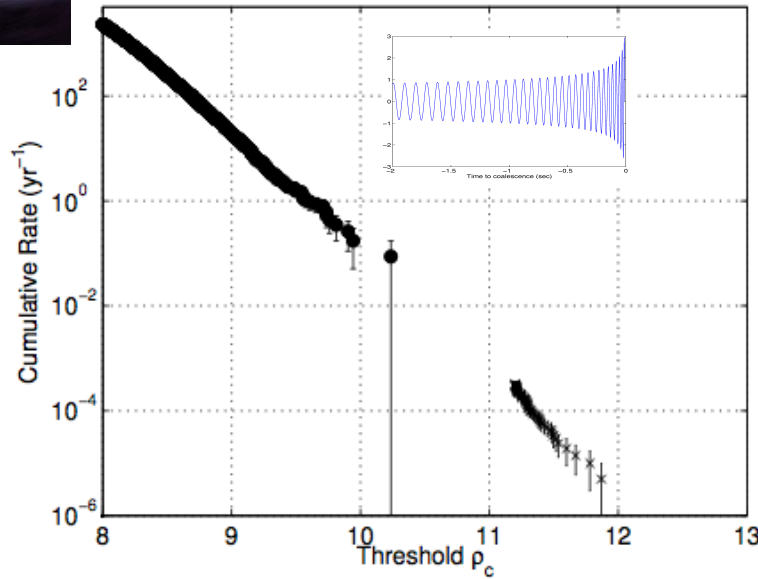


Figure 3: False alarm rate versus detection statistic for CBC and burst searches on 2009-2010 LIGO-Virgo data. Left: Cumulative rate of background events for the CBC search, as a function of the threshold ranking statistic ρ_c [9]. Right: Cumulative rate of background events for the burst search, as a function of the coherent network amplitude η [11]. In the large-amplitude limit η is related to the combined SNR by $\rho_c \sim \sqrt{2K}\eta$, where K is the number of detectors. The burst events are divided into two sets based on their central frequency.

Signals (vs noise)

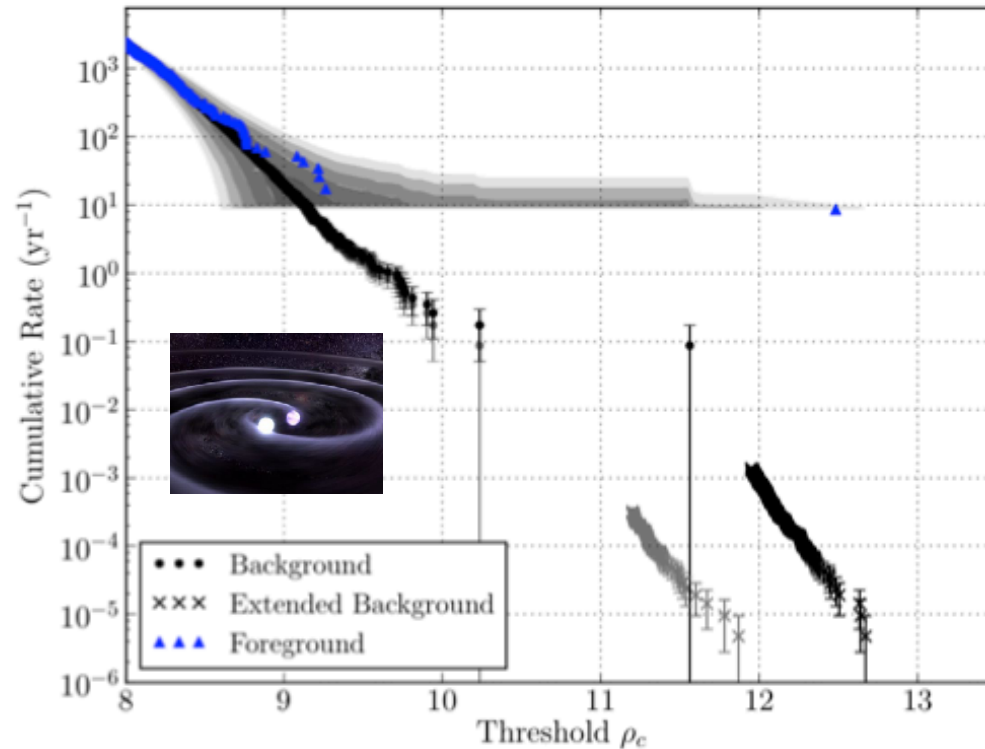
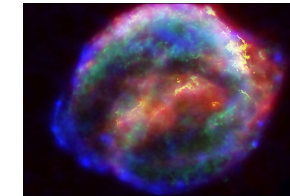


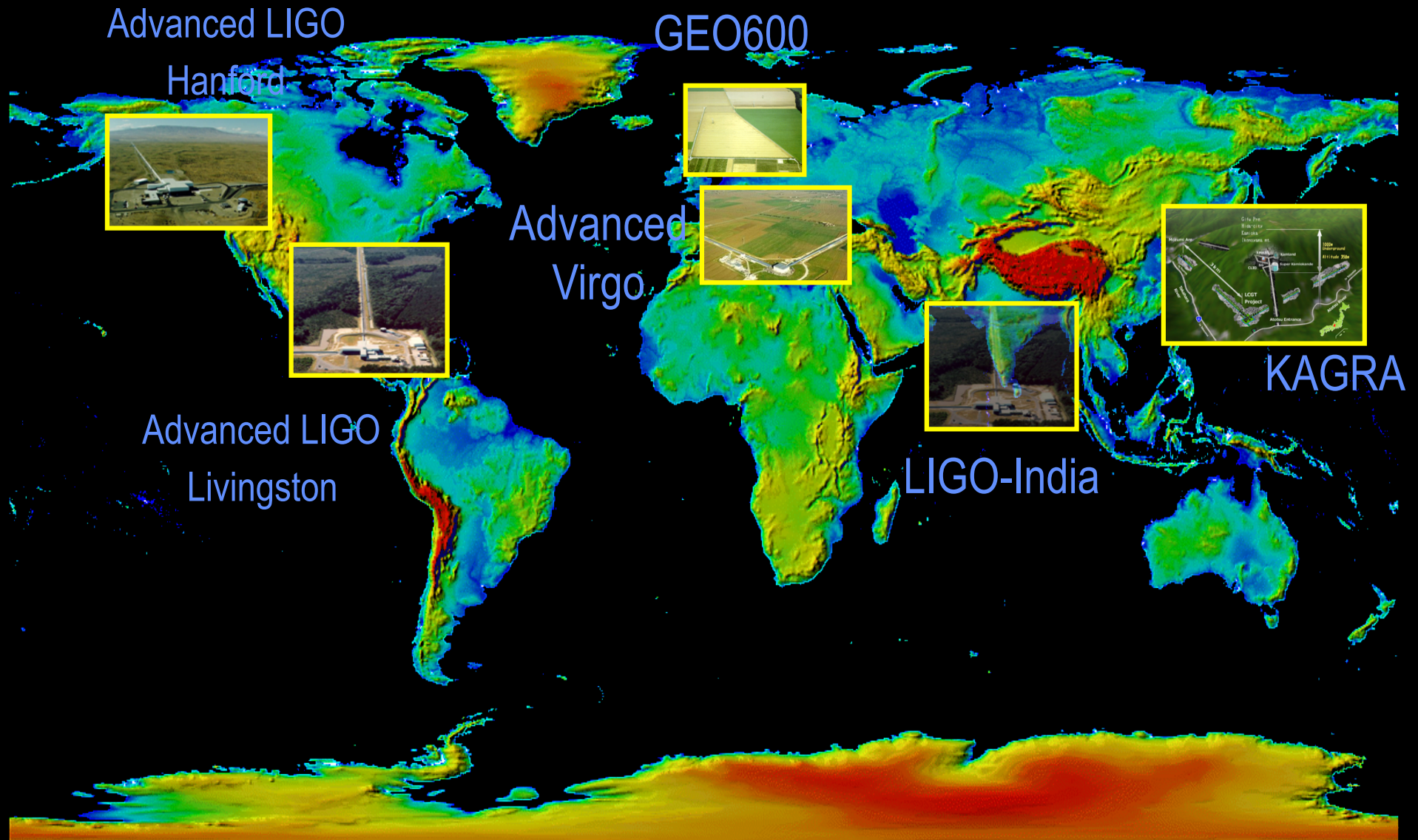
FIG. 3: The cumulative rate of events with chirp mass $3.48 \leq M/M_{\odot} < 7.40$ coincident in the H1 and L1 detectors, seen in four months of data around the 16 September candidate, as a function of the threshold ranking statistic ρ_c . The blue triangles show coincident events. Black dots show the background estimated from 100 time-shifts. Black crosses show the extended background estimation from all possible 5-second shifts on this data restricted, for computational reasons, to only the tail of loudest events. The gray dots and crosses show the corresponding background estimates when 8 seconds of data around the time of the candidate are excluded. Gray shaded contours show the $1 - 5\sigma$ (dark to light) consistency of coincident events with the estimated background including the extended background estimate, for the events and analysis time shown, including the candidate time. This event was later revealed to have been a blind injection.



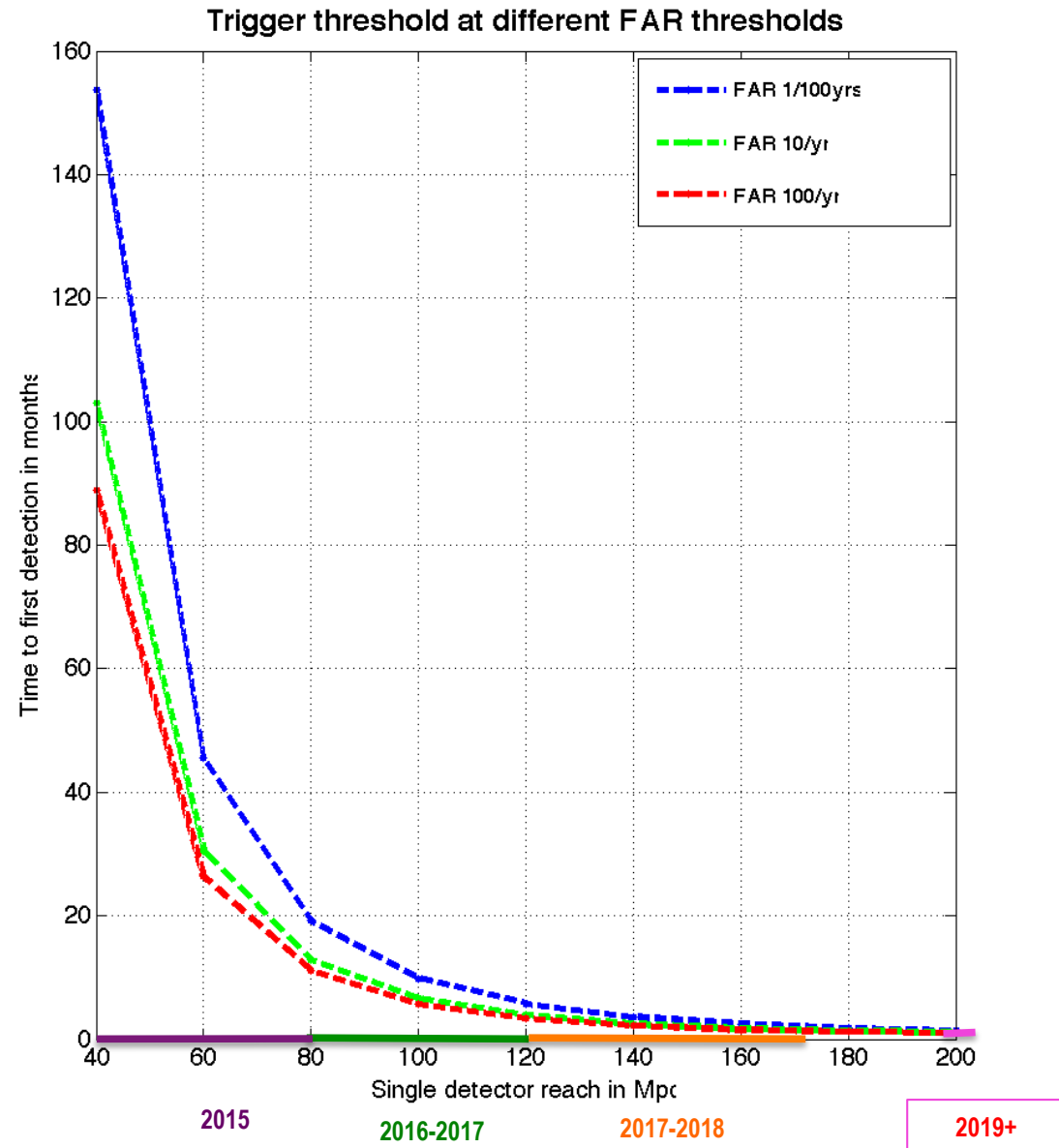
IFAR [yr]	freq. band	network	SNR	FAP
0.64	0.2-1.6 kHz	H1L1	11	0.59
0.36	64-200 Hz	H1L1V1	19	0.47
0.28	0.2-1.6 kHz	H1L1	12	0.33
0.19	0.2-1.6 kHz	H1L1	10	0.35
0.17	1.6-5 kHz	H1V1	9	0.24

TABLE V: The five most significant events present in the on-source data. IFAR is the Inverse False Alarm Rate [yr] of the event in the entire search, SNR is the signal-to-noise ratio in the whole network, and FAP is the false alarm probability (probability of getting at least as many accidental events as those observed with $\text{IFAR} \geq$ the value reported in the first column).

The GW Detector Network ~2020



- 90% Poisson probability of a detection with “realistic astrophysical rate” for different FAR thresholds
- real GW candidates among top 10 or 100 most significant GW candidates already with a 80 Mpc reach, hence one year earlier than if we require a confident detection



Doing EM follow-ups

- Different scenarios can be imagined:
 - try and confirm a GW candidate by identifying an EM counterpart
 - want to identify EM counterpart of a GW source
 - both might need a hierarchy of EM observations
- EM observing features/constraints will be different and requirements will vary depending on nature of the follow-up :
FOV, FAR, sensitivity, freq range, acceptable GW FAR, response time, up time and sky coverage, lifetime
- How to make sure that in the end we extract the best science ? Have to strike the right balance between organization and not being too prescriptive.
 - Science deliverables, of course
 - Trivial practicalities : how to bring together different (competing ?) groups of astronomers ? publication rules,

GW-EM observations

- LIGO and Virgo will not publicly release information pertaining GW events in the detection/discovery phase, i.e. before the first few GW detections have happened
 - Will release data after publication of detection or around important non detections (<http://www.ligo.org/science/data-releases.php>)
 - Policy: <https://dcc.ligo.org/cgi-bin/LIGO-M1200055>
- Before the first few detections integration of GW-EM observations can happen within the framework of a GW-EM joint program
 - GW community hopes to develop a light-weight standard MOU template for collaborative work
 - Perhaps 2-tier system of collaborators
 - Will seek input from the astronomical community
 - Current plan is to issue an open call for LOIs in 2013
- After first few detections, policy on release of triggers and data is detailed in <https://dcc.ligo.org/LIGO-M1000066>
 - Observational phase (public real time release of interesting triggers)
 - Open data