Introduction: LIGO-Virgo Event Follow-up Program

Gabriela González (LSC spokesperson)
Jean-Yves Vinet (Virgo spokesperson)
Amsterdam, August 29 2013
Chicago, September 10 2013

Virgo detector, Cascina, Italy

LIGO Livingston Observatory,
Louisiana, USA

LIGO Hanford Observatory
Washington, USA

Why ?

- Almost exactly a century after GR, gravitational wave detectors will reach sensitivities allowing expected first detections

- Science return will be strongly enhanced if there are simultaneous EM observations.

- Since there have been no gravitational wave detections yet, everything is unexplored (and exciting) territory – we need to be both proactive and cautious.

Who (people) ?

- The gravitational waves « triggers » to be `followed up' in the EM spectrum are detected by the LIGO-Virgo Collaboration with LIGO and Virgo detectors.
- LIGO denotes the LIGO Laboratory and the LIGO Scientific Collaboration (LSC) : about 900 scientists+engineers
- Virgo denotes the Virgo Collaboration and the European Gravitational Observatory (EGO) : about 200 scientists +engineers

LIGO and Virgo scientists work together on the joint analysis of LIGO and Virgo data (online and offline, searching for many different sources). People leading the collaboration and the data analysis working groups are represented here [Introductions].

Who (detectors)?

- LIGO : 2 interferometers (4km arm lengths) built in Livingston (Louisiana) and Hanford (Washington) by Caltech and MIT. Funding agency : NSF with contributions of SFTC, MPG, ARC…
- Virgo : 1 interferometer (3km arm lengths) built in Cascina (near Pisa) by Italy, France, The Netherlands, Hungary, Poland. Funding Agencies : CNRS, INFN, NIKHEF
- Also (current): GEO600, 1 interferometer (600m arm lengths) built in Hannover. Funding by British and German institutions. LIGO and GEO are linked by an agreement such that GEO is included in « LIGO » in a wide sense.
- Also (future): 4km LIGO detector in India.
- Also (future): 3km Japanese detector (KAGRA) – will have collaboration agreements with LSC and Virgo when operational.

The Virgo Collaboration :
19 European teams

EGO Council (CNRS, INFN, NIKHEF)

RMKI,
Academy of sciences
Budapest
HUNGARY

NIKHEF, Amsterdam
Radboud University , Nijmegen
The NETHERLANDS

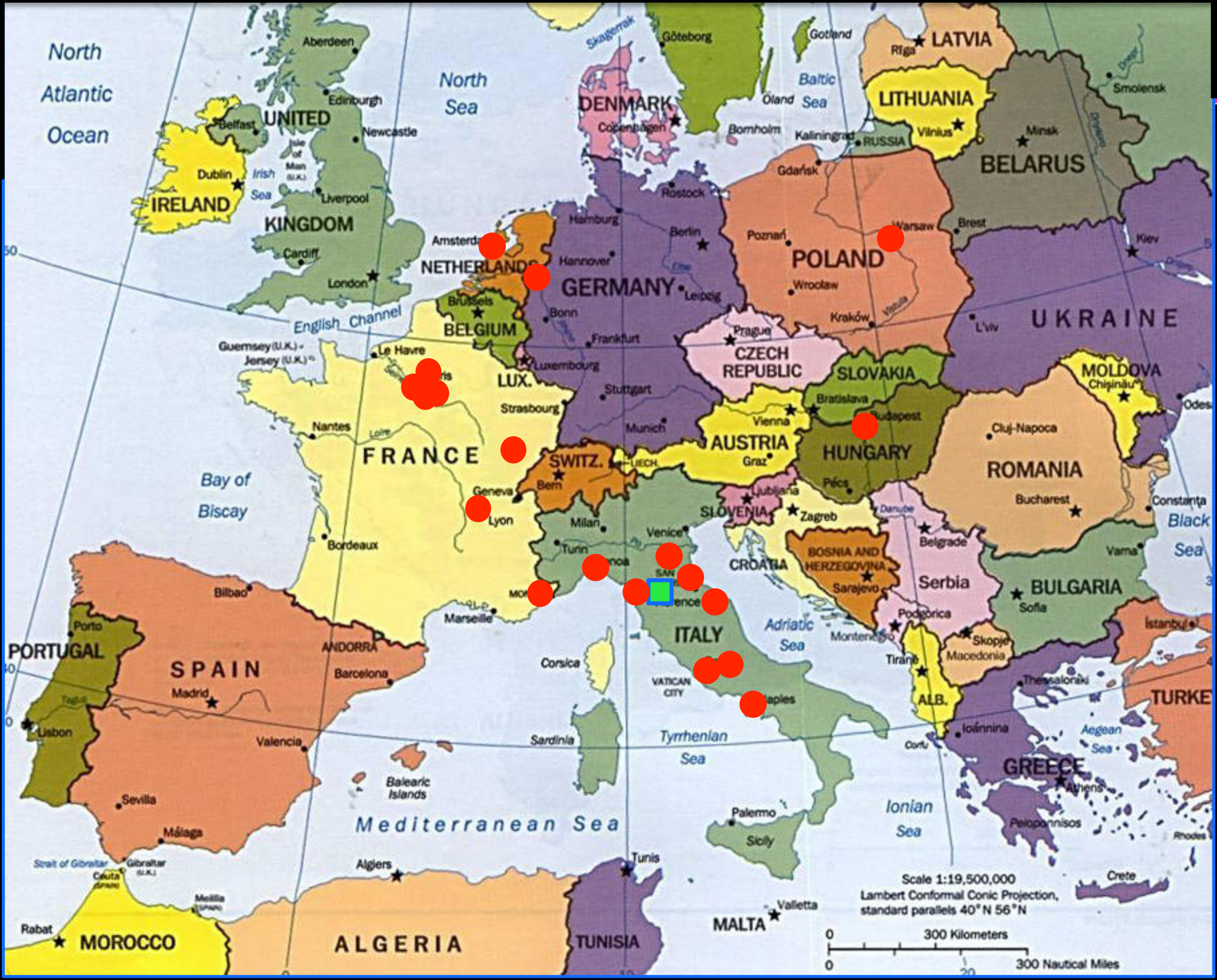
**EGO Site
Cascina**

Institute of Mathematics
Polish Academy of Sciences
Varsaw
POLAND

ITALY:

INFN + Universities of
Firenze-Urbino
Genova
Napoli
Perugia
Roma La Sapienza
Roma Tor Vergata
Pisa
Padova-Trento

FRANCE :
Laboratoire de l'Accélérateur Linéaire (U. Paris-Sud+CNRS)
Laboratoire d'Annecy de Physique des Particules (CNRS)
Astroparticules et Cosmologie (U. Paris 7+CNRS)
Laboratoire des Matériaux Avancés (Lyon-CNRS)
Laboratoire Kastler-Brossel (ENS – U. Paris 6 - CNRS)
Observatoire de la Côte d'Azur (CNRS, Nice)
ESPCI (Paris)


North Atlantic Ocean
North Sea
IRELAND
Dublin
Irish Sea
UNITED KINGDOM
Aberdeen
Edinburgh
Belfast
Newcastle
Isle of Man (U.K.)
Liverpool
Cardiff
London
English Channel
Guernsey (U.K.)
Jersey (U.K.)
Le Havre
Skagerrak
DENMARK
Copenhagen
Göteborg
Gotland
Baltic Sea
Öland
Bornholm
Kaliningrad
RUSSIA
LATVIA
Riga
LITHUANIA
Vilnius
BELARUS
Minsk
Smolensk
Brest
Amsterdam
NETHERLANDS
Brussels
BELGIUM
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Luxembourg
GERMANY
Hamburg
Rostock
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Hannover
Leipzig
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GREECE
Athens
Peloponnisos
Aegean Sea
Crete
Rhodes
Istanbul
TURKEY
Milan
Turin
Genoa
Venice
SAN MARINO
Florence
MONACO
ITALY
VATICAN CITY
Naples
Adriatic Sea
Tyrrhenian Sea
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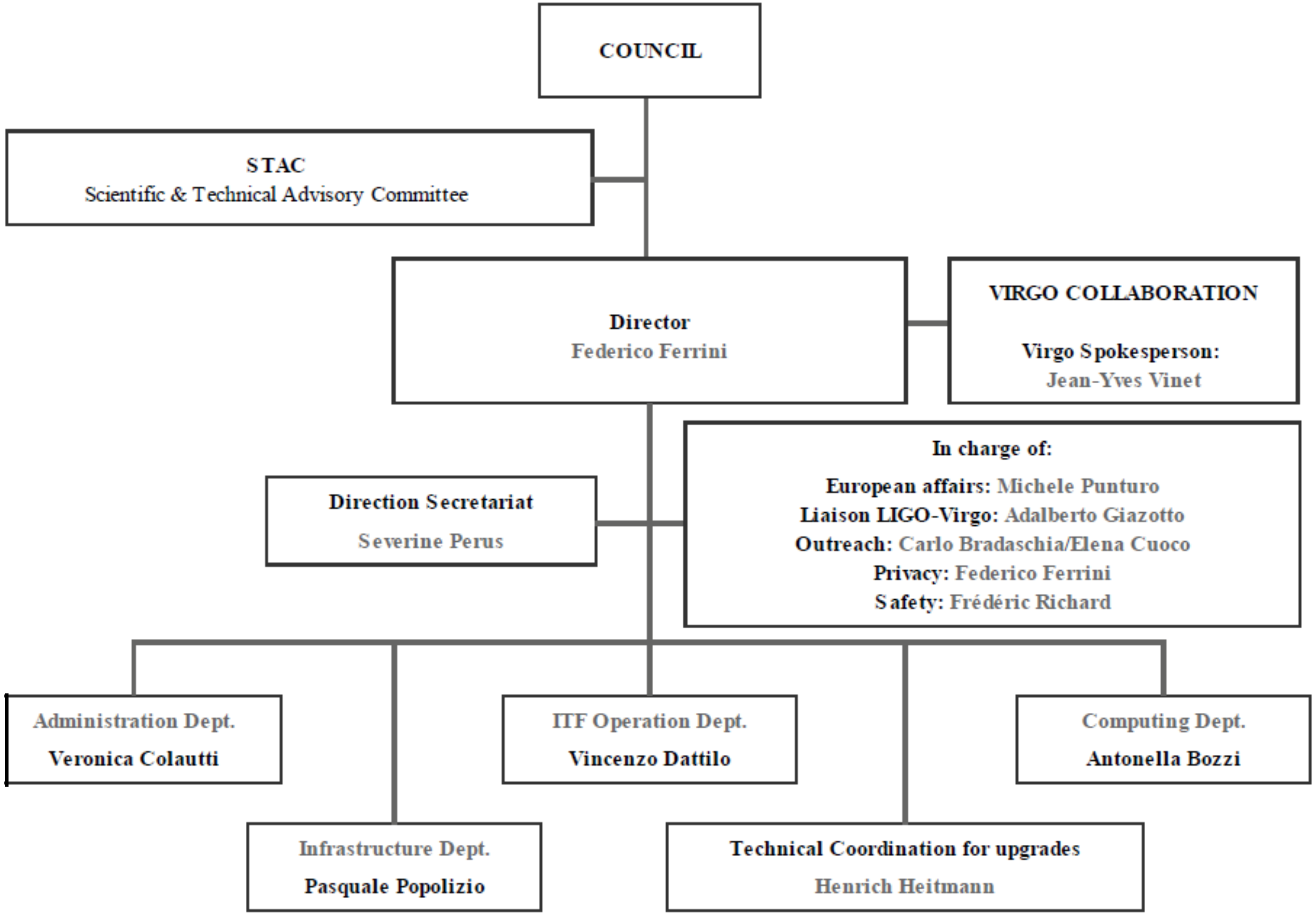
PORTUGAL
Porto
Lisbon
SPAIN
Madrid
Bilbao
ANDORRA
Barcelona
Valencia
Sevilla
Málaga
Balearic Islands
Gibraltar (U.K.)
Strait of Gibraltar
Ceuta (SPAIN)
Melilla (SPAIN)
Mediterranean Sea
Rabat
MOROCCO
Algiers
ALGERIA
Tunis
TUNISIA
Scale 1:19,500,000
Lambert Conformal Conic Projection, standard parallels 40° N 56° N
300 Kilometers
300 Nautical Miles

EGO



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Henrich Heitmann

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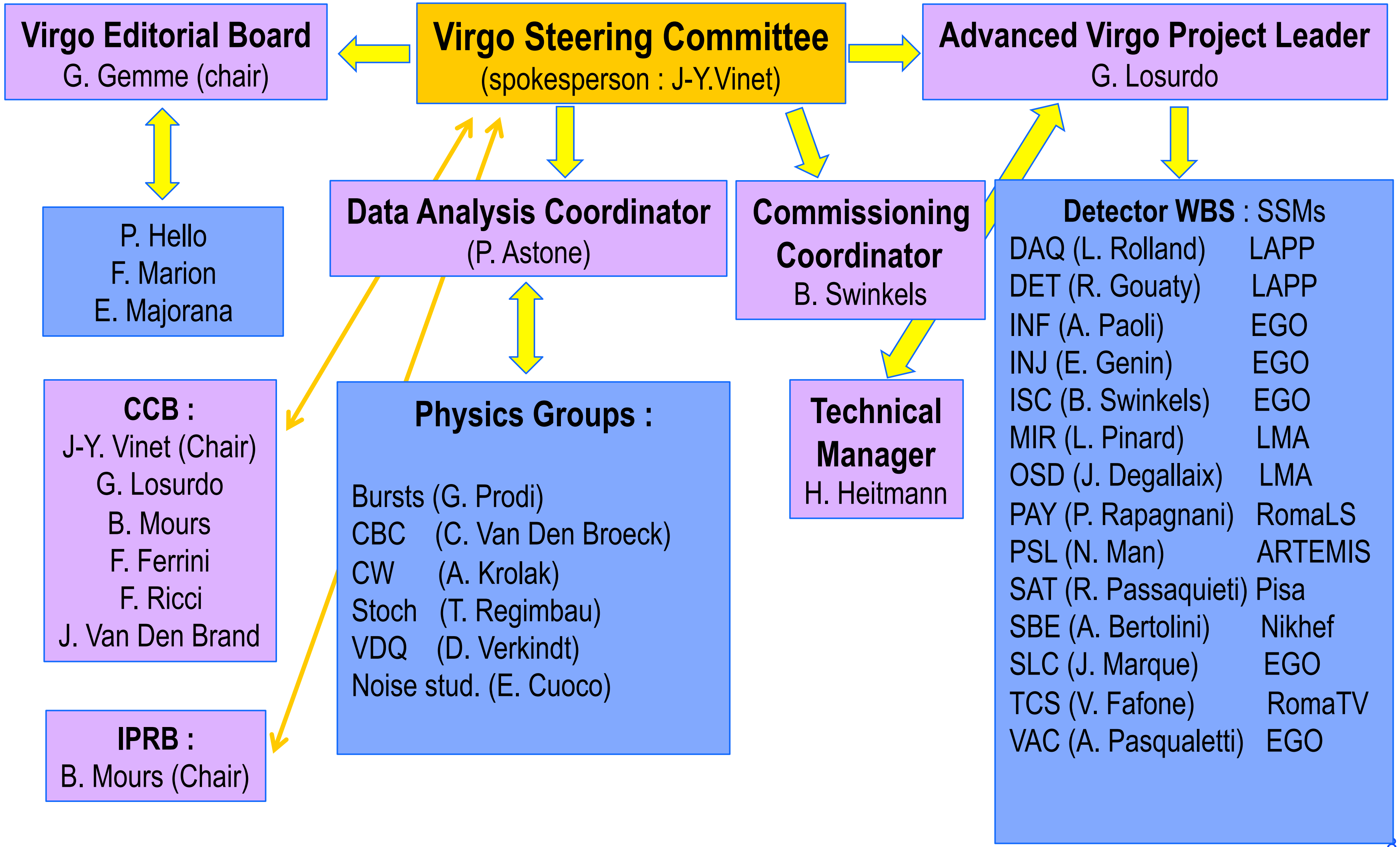

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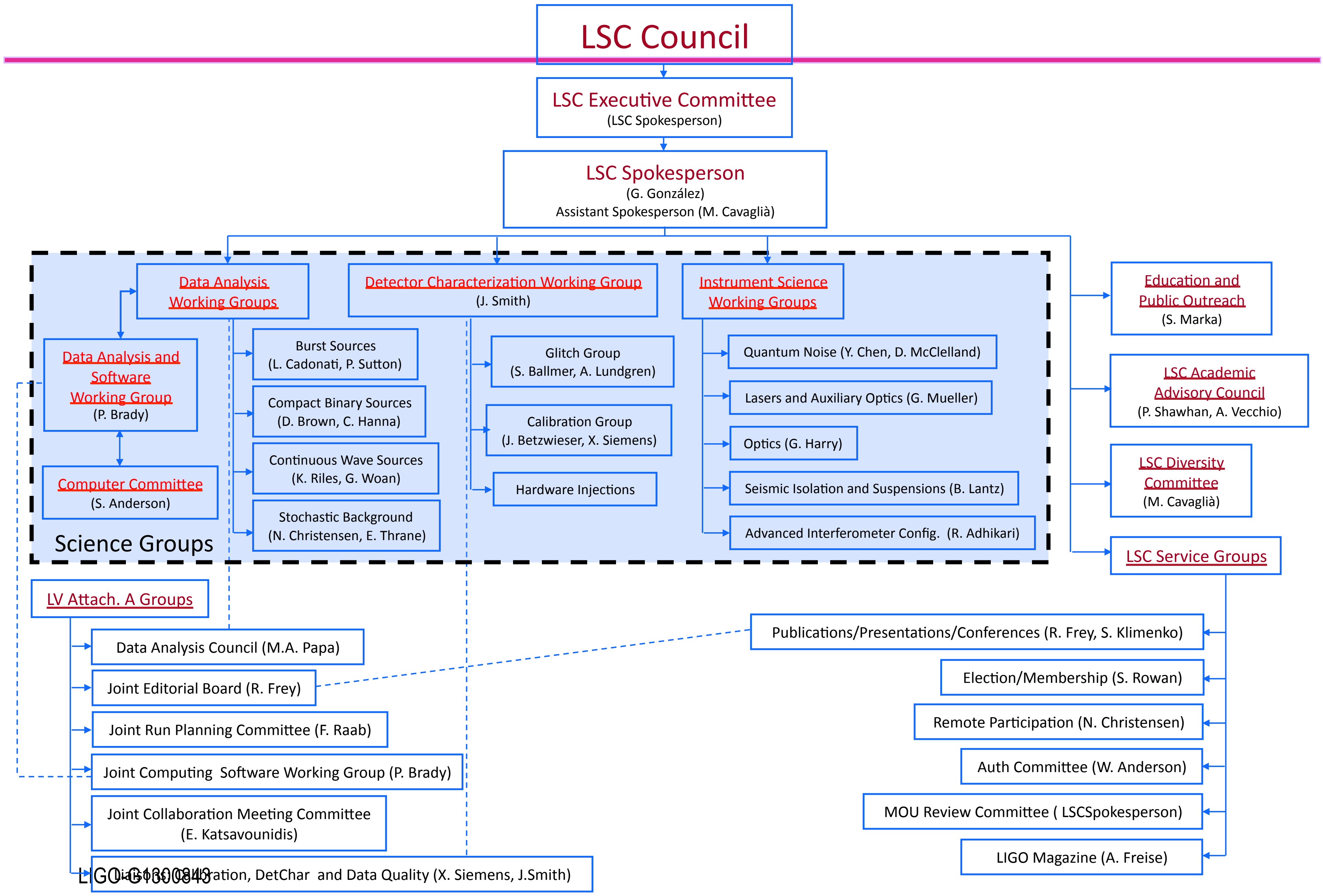
SBE (A. Bertolini)	Nikhef
SLC (J. Marque)	EGO
TCS (V. Fafone)	RomaTV
VAC (A. Pasqualetti)	EGO

LIGO Scientific Collaboration

>900 members, >80 institutions, 17 countries

https://www.zeemaps.com/map?group=245330

LIGO Scientific Collaboration



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LSC Spokesperson
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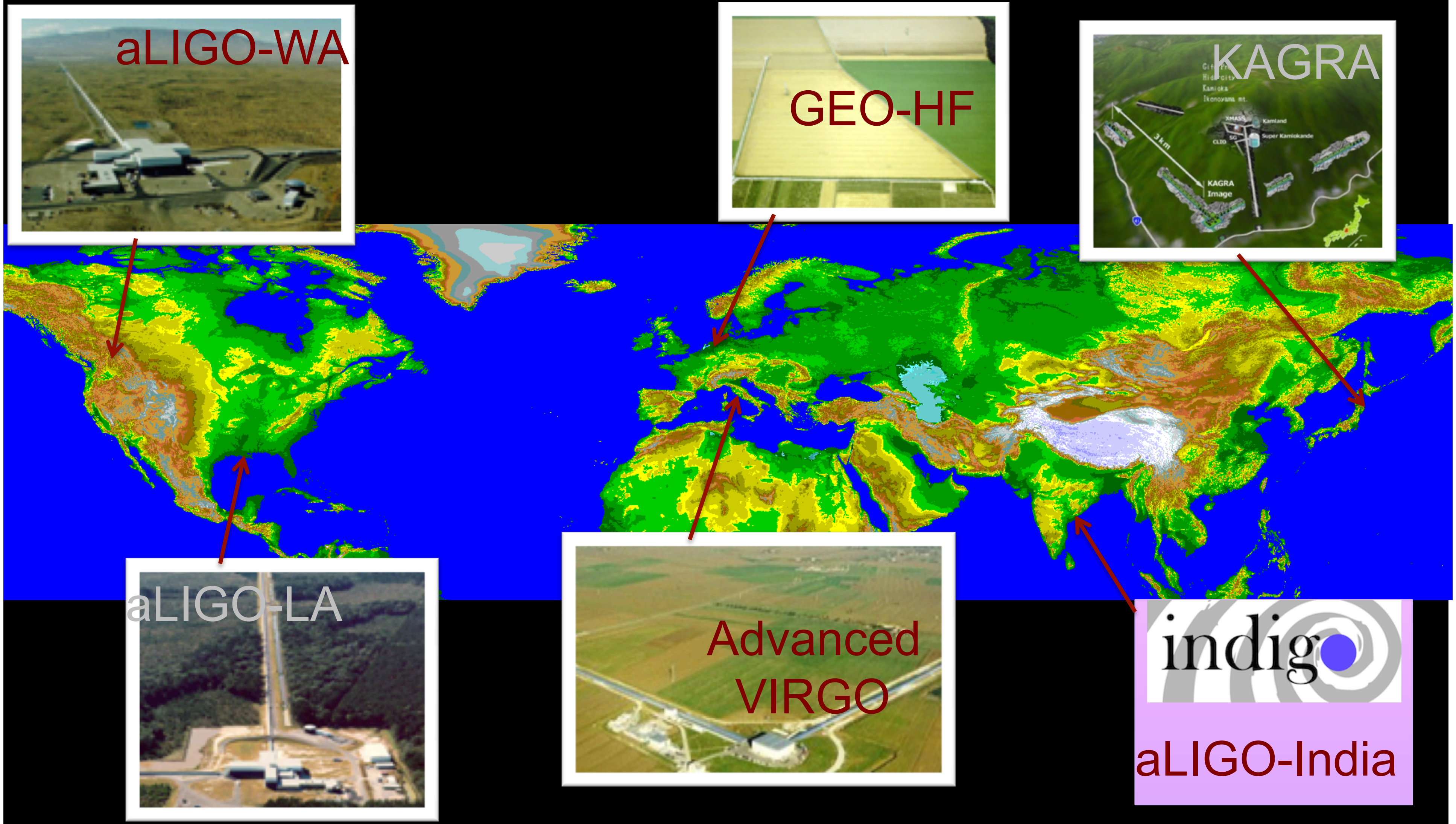
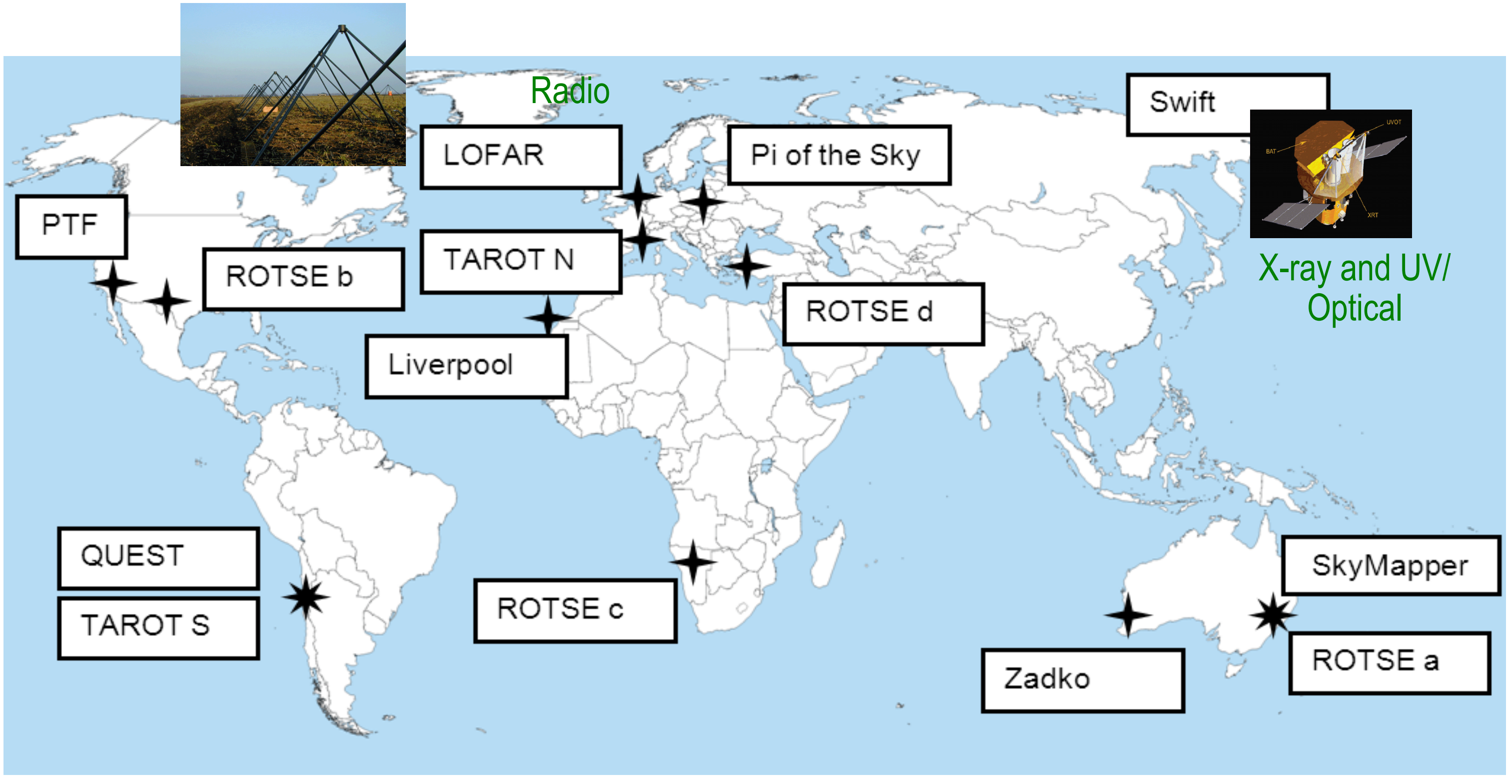
LIGO Magazine (A. Freise)

Where ?


aLIGO-WA
GEO-HF
KAGRA
3km
Kamland
Super Kamiokande
KAGRA Image
aLIGO-LA
Advanced VIRGO
indigo
aLIGO-India

LSC, Virgo past collaborations

- Observing partners in S6/VSR3:



Radio

LOFAR

Pi of the Sky

Swift

X-ray and UV/
Optical

PTF

ROTSE b

TAROT N

Liverpool

ROTSE d

QUEST

TAROT S

ROTSE c

SkyMapper

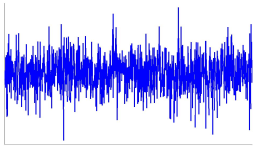
ROTSE a

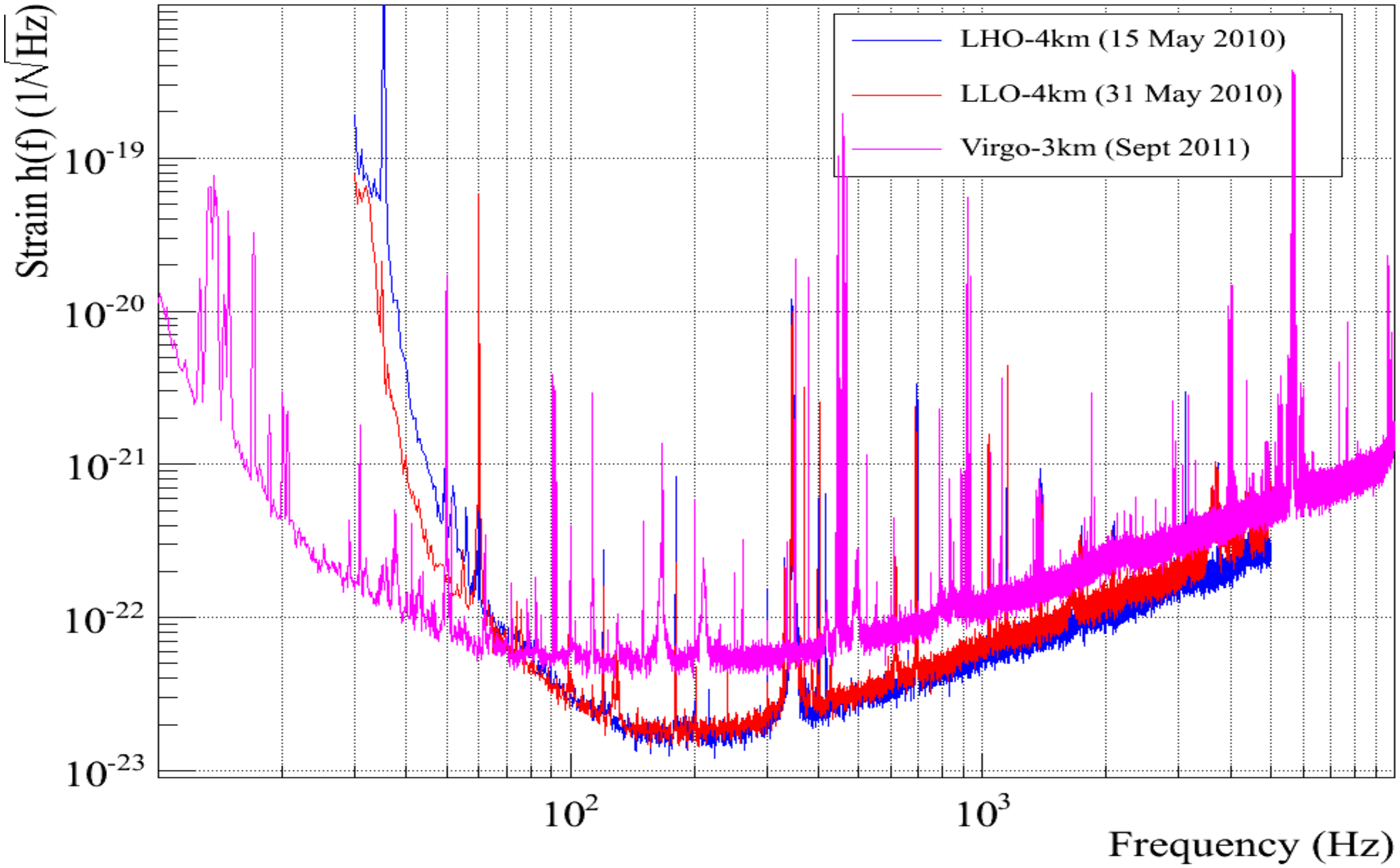
Zadko

Astron Astrophys **541** (2012) A155

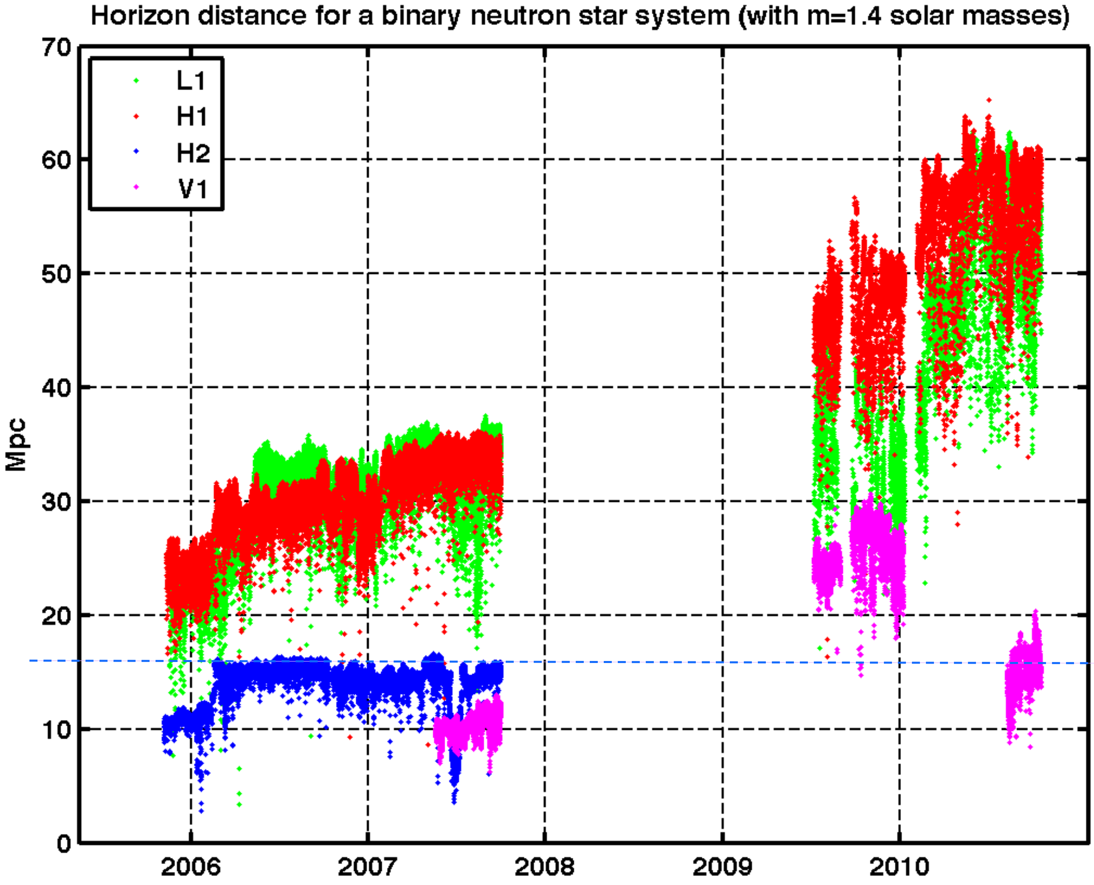
Astron Astrophys **539** (2012) A124

1^{st} generation Detectors' noise (spectral density)

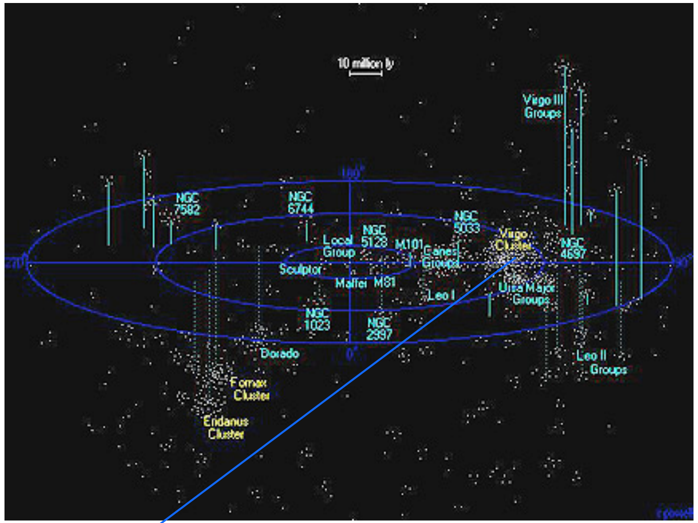


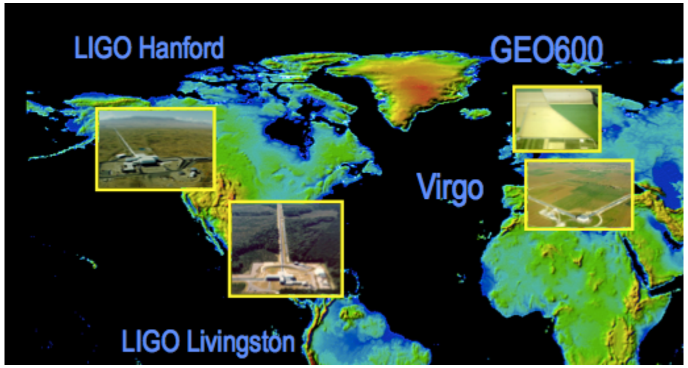


Distance reach to coalescing binary neutron star systems



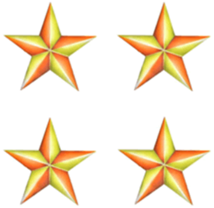
atlasofthe universe.com





GW-EM follow up: two eras

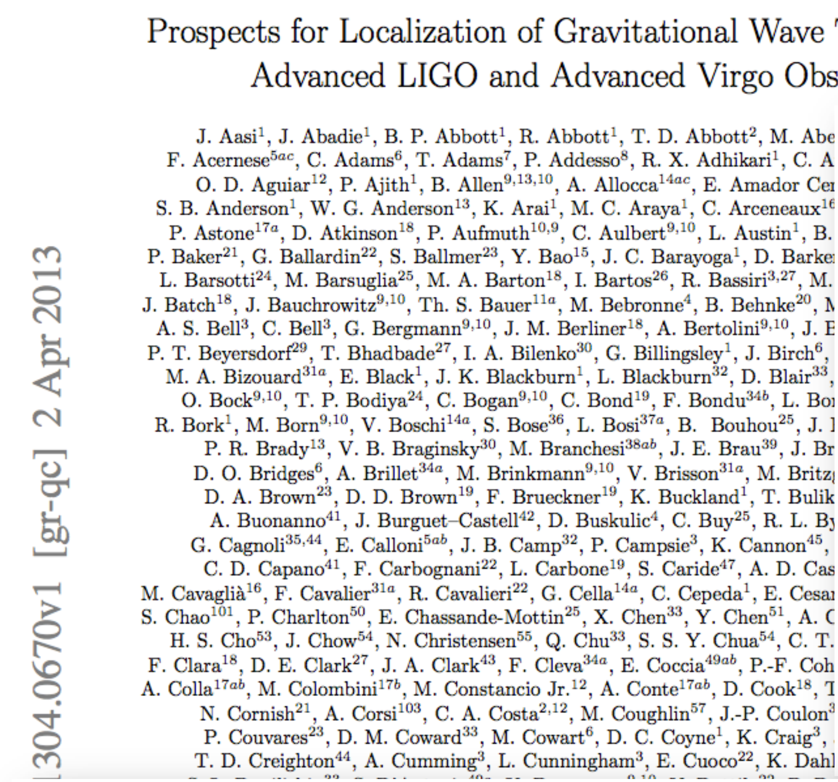
- After the published discovery of four gravitational events with data from LSC and/or Virgo detectors, both the LSC and Virgo will begin releasing especially significant triggers (with FAR< 1/100 yrs) promptly to the entire scientific community to enable a wider range of follow-up observations. This may happen after 2018 (?).



- Before that (staring 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.

dcc.ligo.org, LIGO-M1200055

When ?



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

J. Aasi[1], J. Abadie[1], B. P. Abbott[1], R. Abbott[1], T. D. Abbott[2], M. Abe
F. Acernese[5ac], C. Adams[6], T. Adams[7], P. Addesso[8], R. X. Adhikari[1], C. A
O. D. Aguiar[12], P. Ajith[1], B. Allen[9,13,10], A. Allocca[14ac], E. Amador Cer
S. B. Anderson[1], W. G. Anderson[13], K. Arai[1], M. C. Araya[1], C. Arceneaux[16
P. Astone[17a], D. Atkinson[18], P. Aufmuth[10,9], C. Aulbert[9,10], L. Austin[1], B.
P. Baker[21], G. Ballardin[22], S. Ballmer[23], Y. Bao[15], J. C. Barayoga[1], D. Barke
L. Barsotti[24], M. Barsuglia[25], M. A. Barton[18], I. Bartos[26], R. Bassiri[3,27], M.
J. Batch[18], J. Bauchrowitz[9,10], Th. S. Bauer[11a], M. Bebronne[4], B. Behnke[20],
A. S. Bell[3], C. Bell[3], G. Bergmann[9,10], J. M. Berliner[18], A. Bertolini[9,10], J.
P. T. Beyersdorf[29], T. Bhadbade[27], I. A. Bilenko[30], G. Billingsley[1], J. Birch[6],
M. A. Bizouard[31a], E. Black[1], J. K. Blackburn[1], L. Blackburn[32], D. Blair[33],
O. Bock[9,10], T. P. Bodiya[24], C. Bogan[9,10], C. Bond[19], F. Bondu[34b], L. Bo
R. Bork[1], M. Born[9,10], V. Boschi[14a], S. Bose[36], L. Bosi[37a], B. Bouhou[25], J.
P. R. Brady[13], V. B. Braginsky[30], M. Branchesi[38ab], J. E. Brau[39], J. Br
D. O. Bridges[6], A. Brillet[34a], M. Brinkmann[9,10], V. Brisson[31a], M. Britz
D. A. Brown[23], D. D. Brown[19], F. Brueckner[19], K. Buckland[1], T. Bulik
A. Buonanno[41], J. Burguet–Castell[42], D. Buskulic[4], C. Buy[25], R. L. B
G. Cagnoli[35,44], E. Calloni[5ab], J. B. Camp[32], P. Campsie[3], K. Cannon[45],
C. D. Capano[41], F. Carbognani[22], L. Carbone[19], S. Caride[47], A. D. Cas
M. Cavaglià[16], F. Cavalier[31a], R. Cavalieri[22], G. Cella[14a], C. Cepeda[1], E. Cesa
S. Chao[101], P. Charlton[50], E. Chassande-Mottin[25], X. Chen[33], Y. Chen[51], A.
H. S. Cho[53], J. Chow[54], N. Christensen[55], Q. Chu[33], S. S. Y. Chua[54], C. T.
F. Clara[18], D. E. Clark[27], J. A. Clark[43], F. Cleva[34a], E. Coccia[49ab], P.-F. Coh
A. Colla[17ab], M. Colombini[17b], M. Constancio Jr.[12], A. Conte[17ab], D. Cook[18],
N. Cornish[21], A. Corsi[103], C. A. Costa[2,12], M. Coughlin[57], J.-P. Coulon
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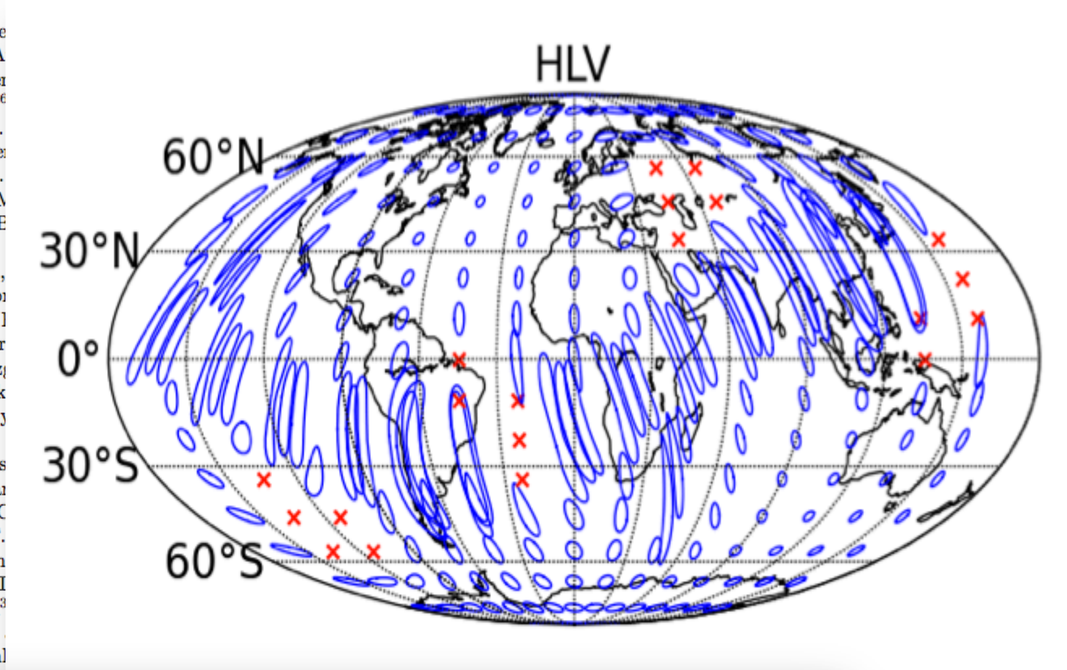
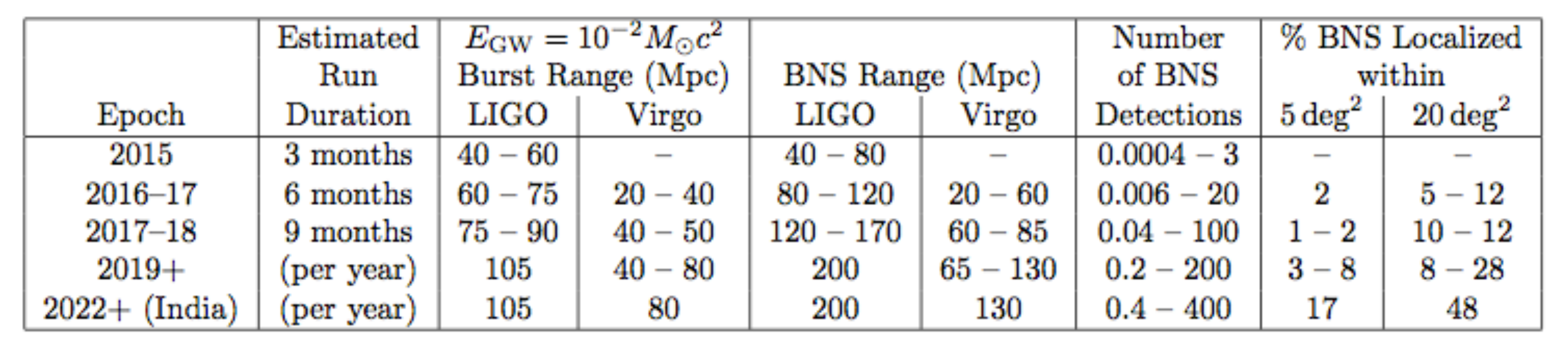
T. D. Creighton[44], A. Cumming[3], L. Cunningham[3], E. Cuoco[22], K. Dahl

1304.0670v1 [gr-qc] 2 Apr 2013

Aiming to source localization in the sky





Epoch	Estimated Run Duration	$E_{\rm GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 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

LIGO-G1300843

“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
- In review by Living Reviews in Relativity

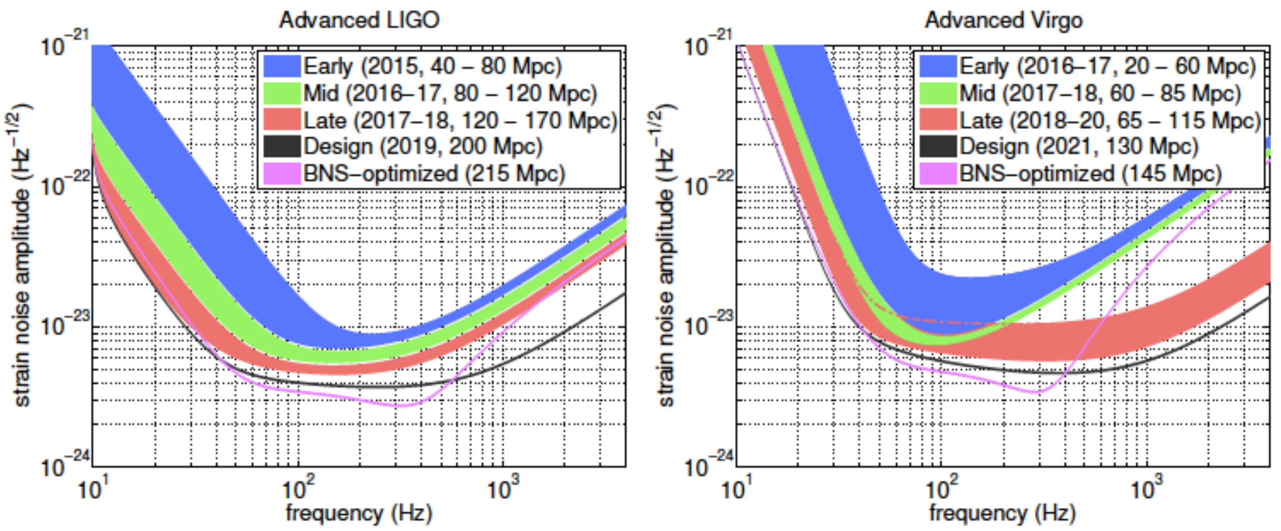
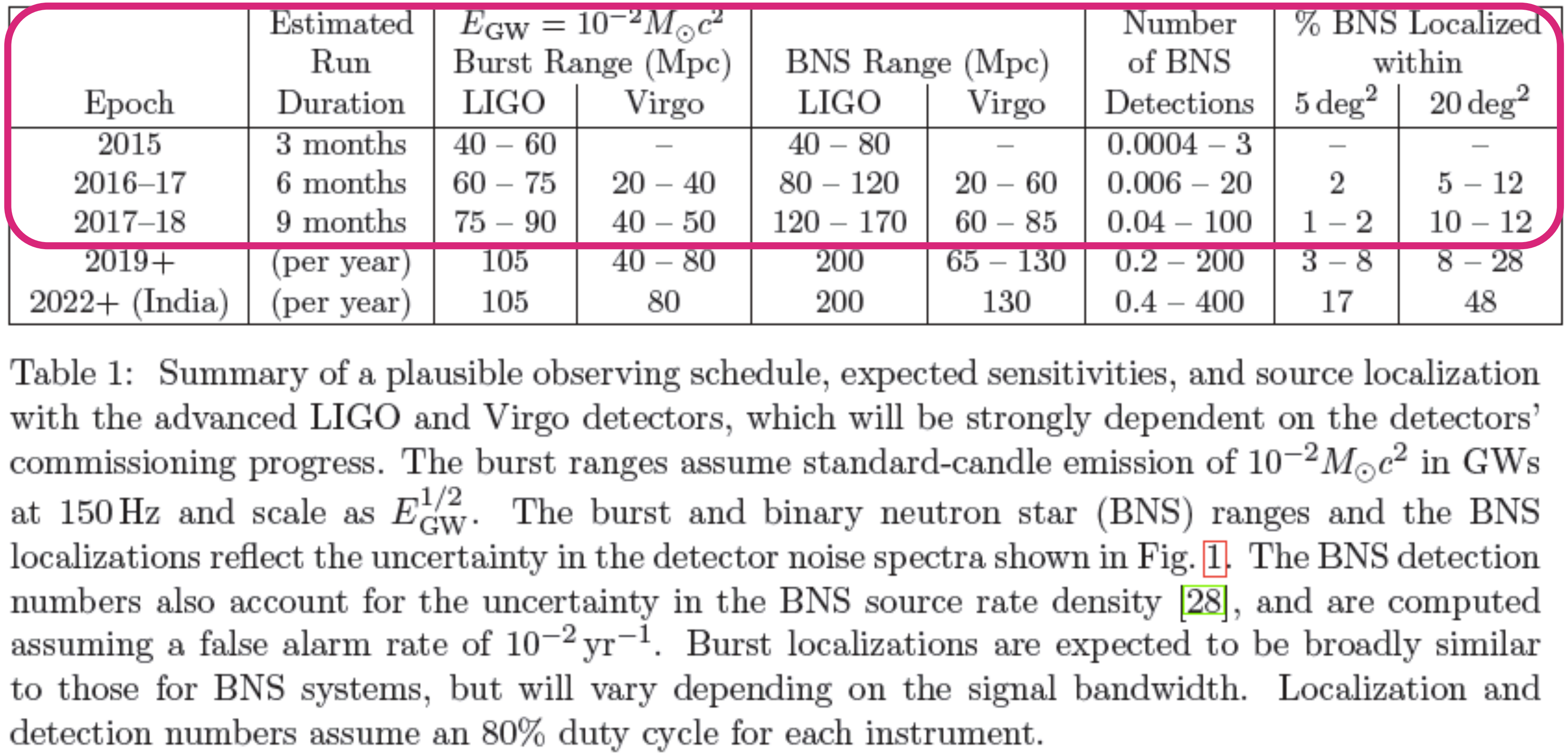


Figure 1: aLIGO (left) and AdV (right) target strain sensitivity as a function of frequency. The average distance to which binary neutron star (BNS) signals could be seen is given in Mpc. Current notions of the progression of sensitivity are given for early, middle, and late commissioning phases, as 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	$E_{\rm GW} = 10^{-2} M_\odot c^2$ 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	–	–
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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 $E_{\rm GW}^{1/2}$. 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 $10^{-2}\,\mathrm{yr}^{-1}$. 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).

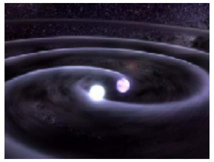
Goals for this meeting

- Meet all who expressed 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,…

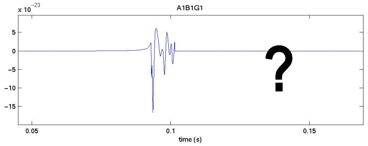
Expected result after discussions in Amsterdam, Chicago and within LVC: signed MOUs for partnerships leading to new astrophysics.

Spare slides

Noise (false alarms background)



1-30 Ms binary systems



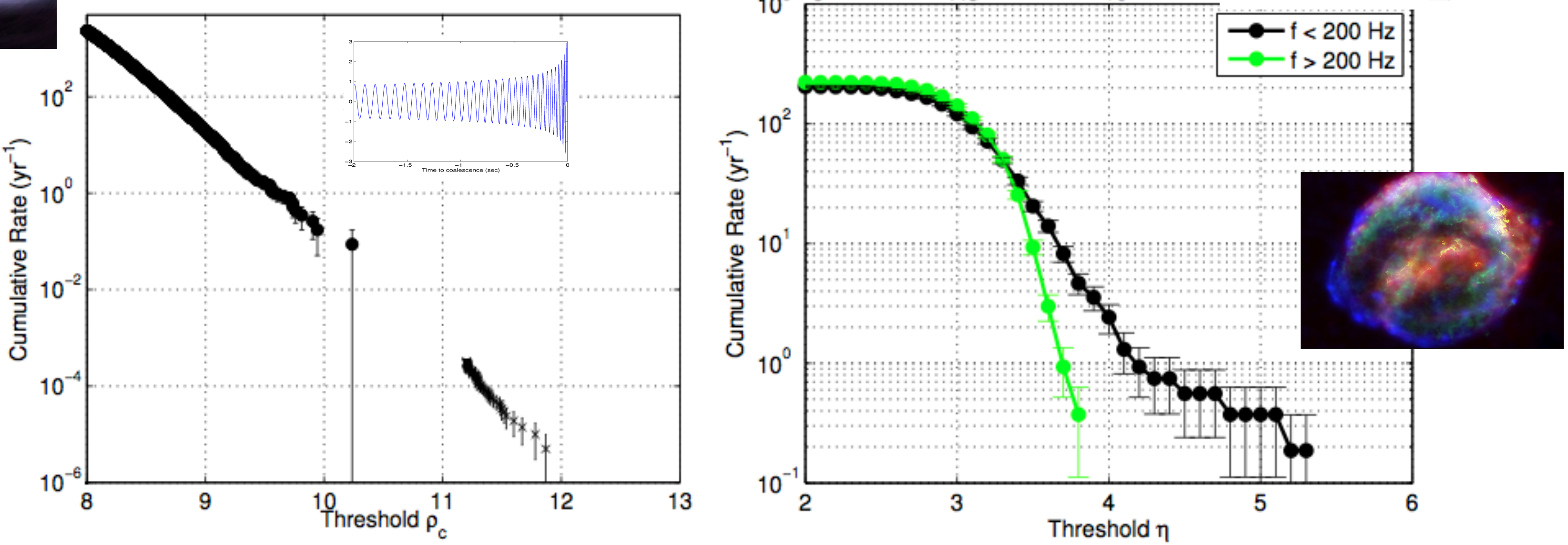


Figure 3: False alarm rate versus detection statistic for CBC and burst searches on 2009-2010 LIGO-Virgo data. Left: Cumulative rate of background events for the CBC search, as a function of the threshold ranking statistic ρ_c [9]. Right: Cumulative rate of background events for the burst search, as 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)

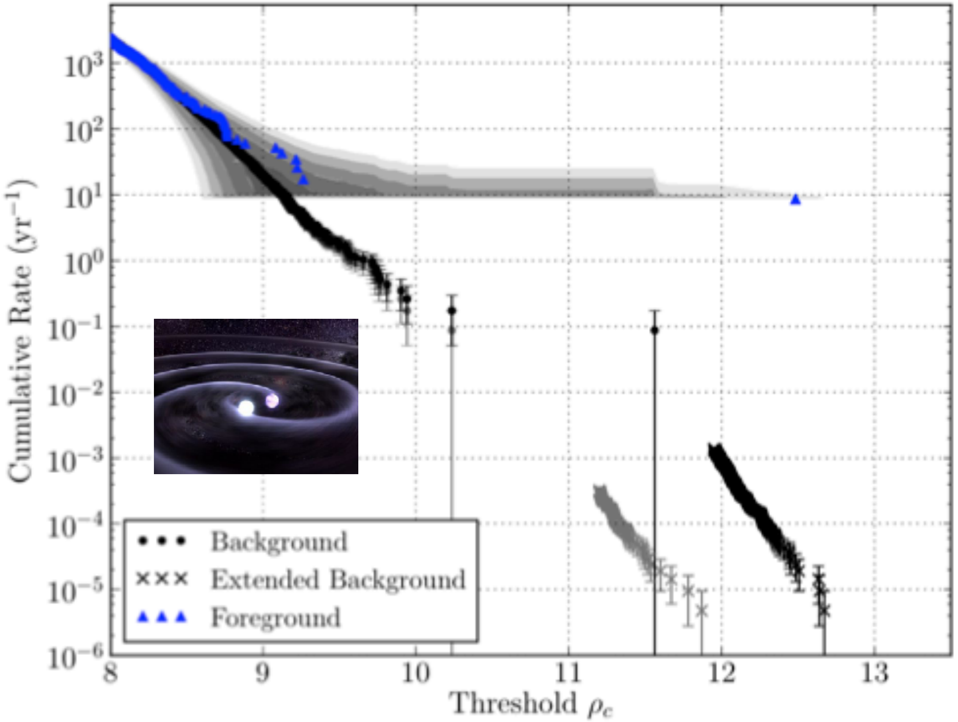
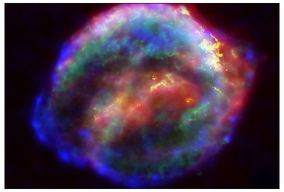


FIG. 3: The cumulative rate of events with chirp mass $3.48 \le \mathcal{M}/\mathrm{M}_\odot < 7.40$ coincident in the H1 and L1 detectors, seen in four months of data around the 16 September candidate, as a function of the threshold ranking statistic ρ_c. The blue triangles show coincident events. Black 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 IFAR $\geq$ the value reported in the first column).