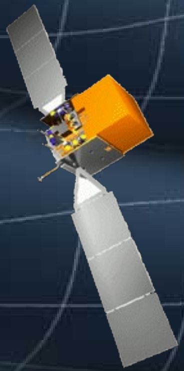
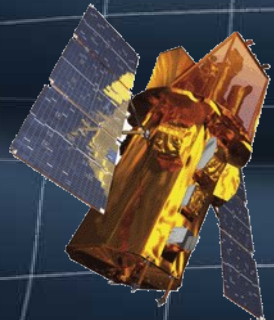
Gravitational Waves and VO: perspectives and opportunities

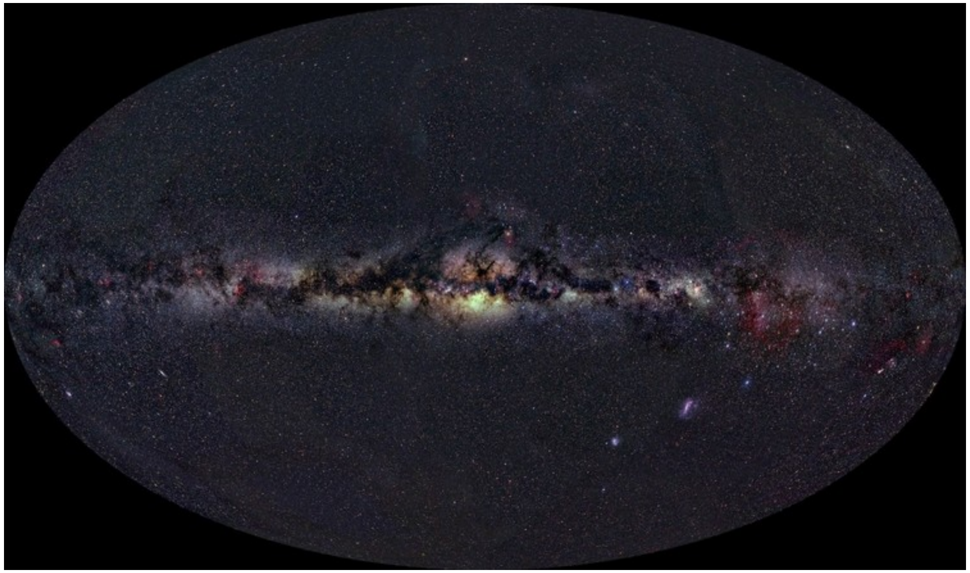
(M. Razzano – University of Pisa & INFN-Pisa)
G. Greco, E. Chassande-Mottin, M. Branchesi



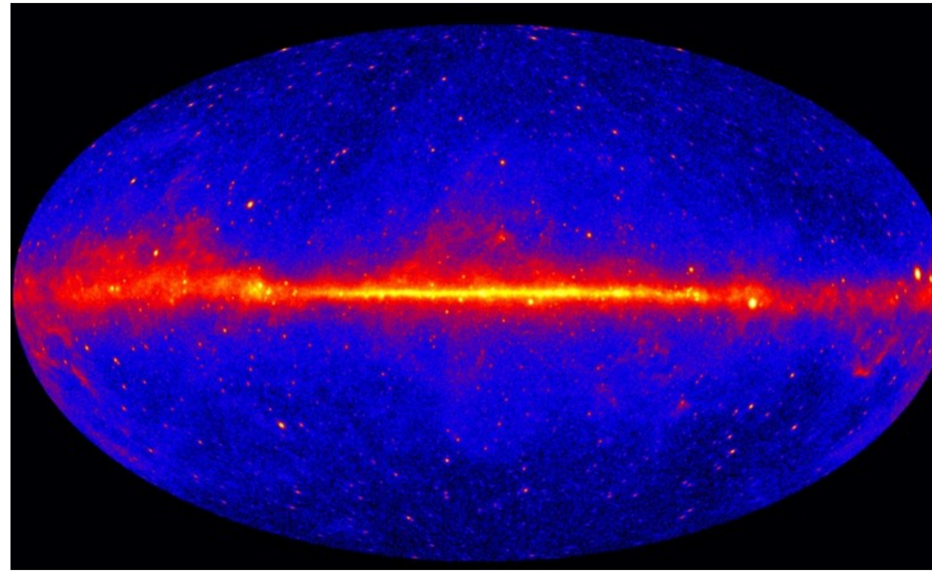


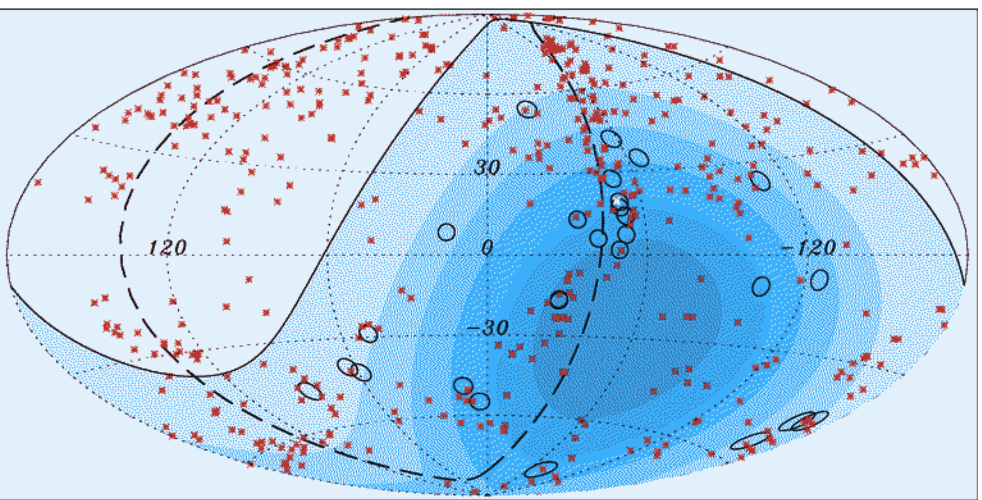
A multi-messenger sky

Optical (APOD)

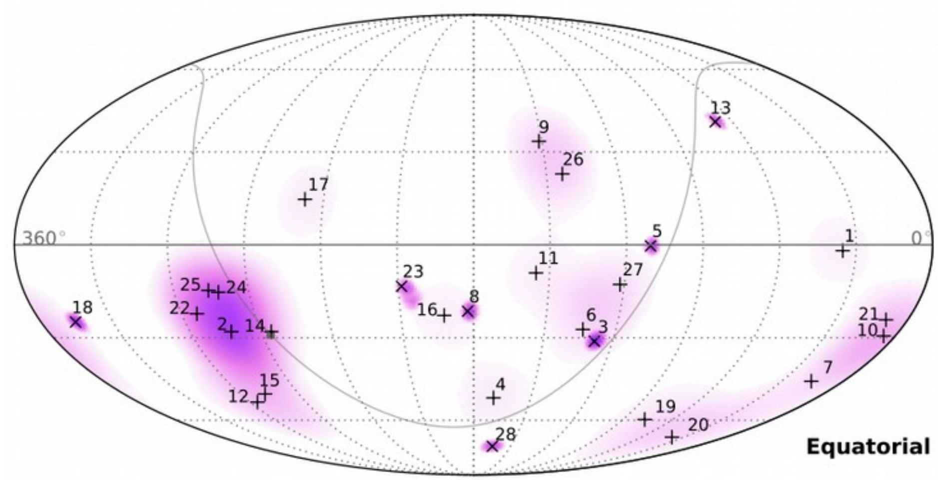


Gamma rays > 0.1 GeV (Fermi-LAT, 2013)





Cosmic rays > 57 Eev (Auger, 2007)



Neutrinos > 30 Tev (Icecube, 2013)

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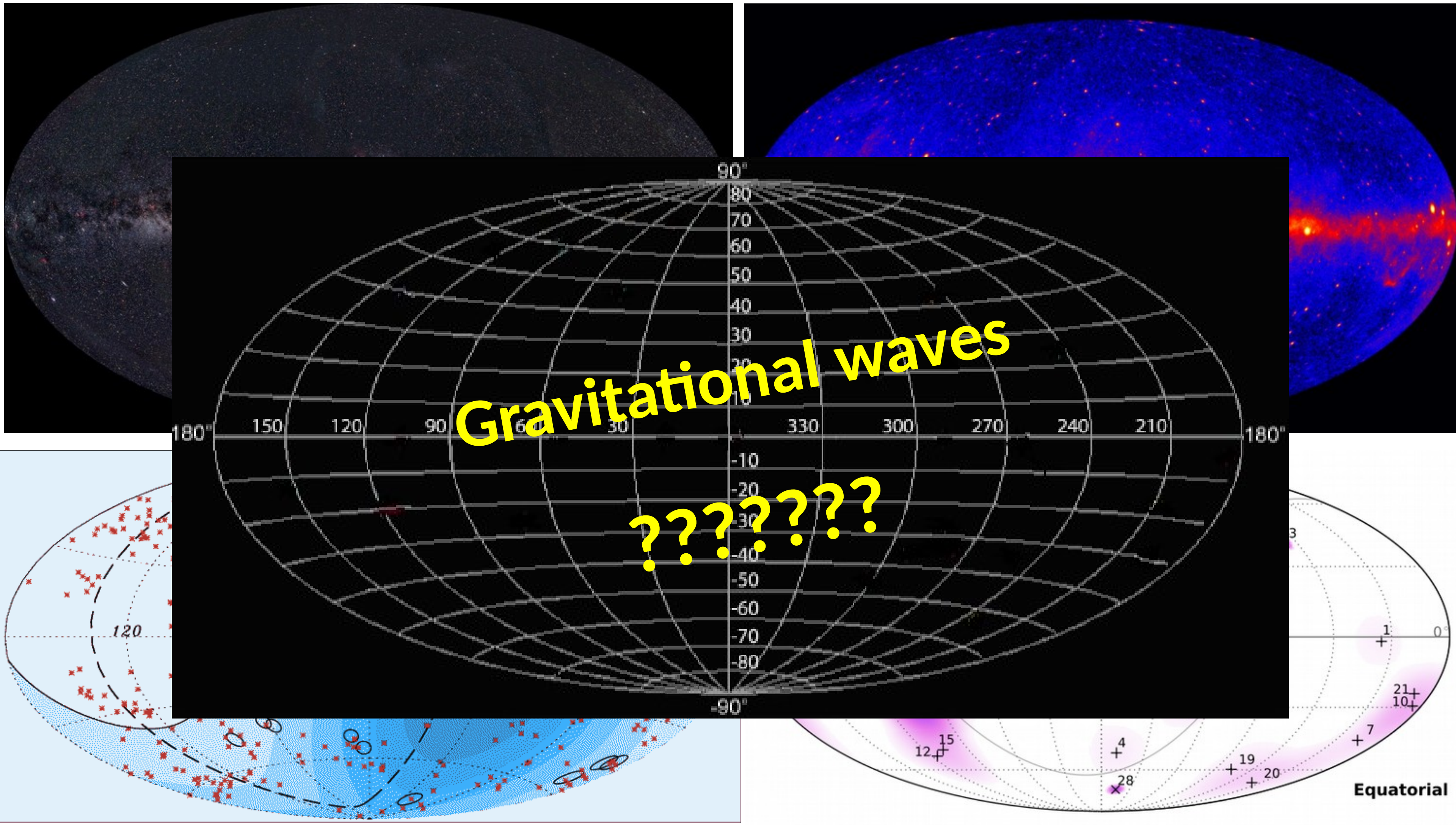
M. Razzano

A multi-messenger sky

Optical (APOD)

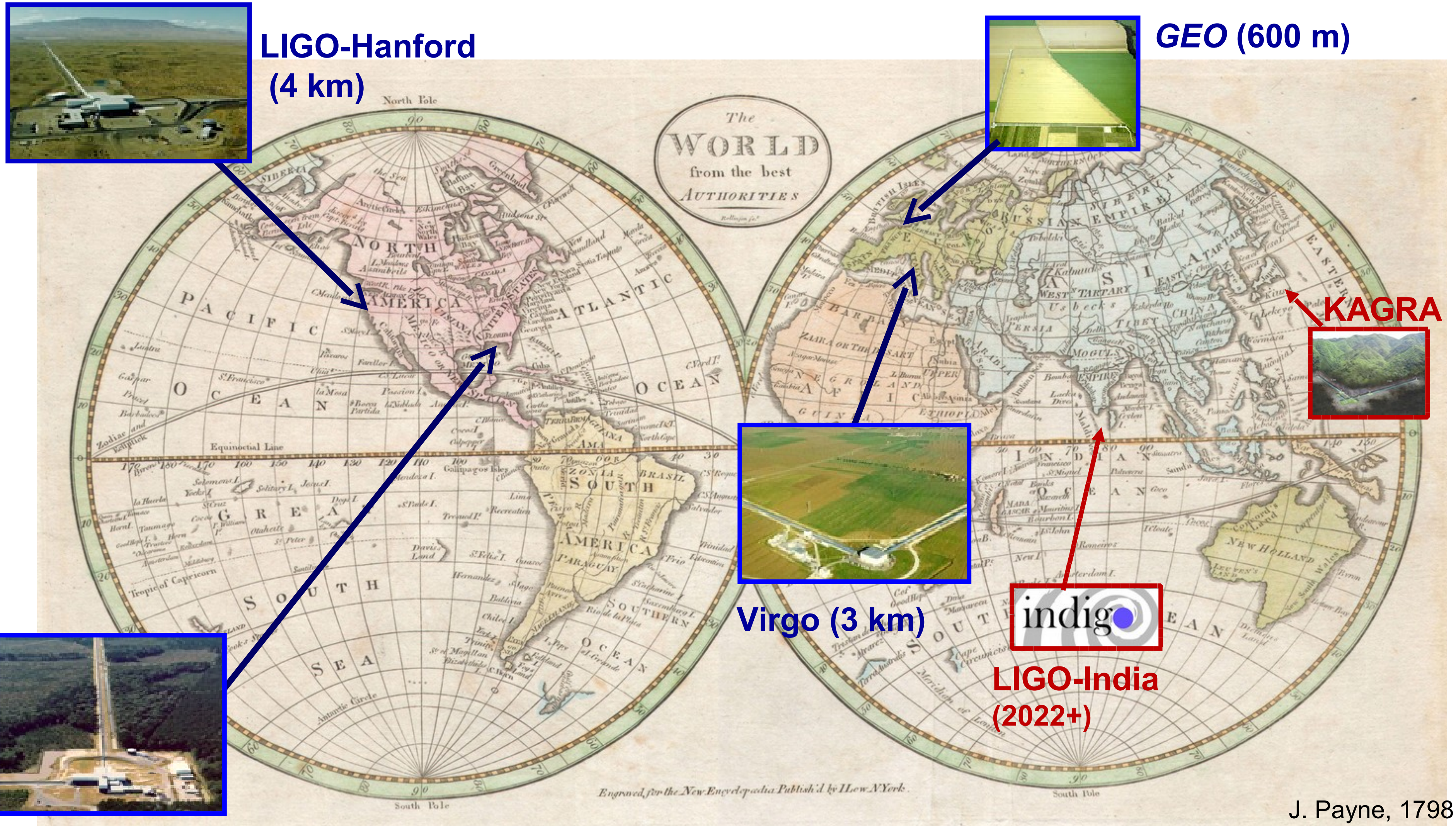
Gamma rays > 0.1 GeV (Fermi-LAT, 2013)



Cosmic rays > 57 Eev (Auger, 2007)

Neutrinos > 30 Tev (Icecube, 2013)

The new era of Advanced GW detectors



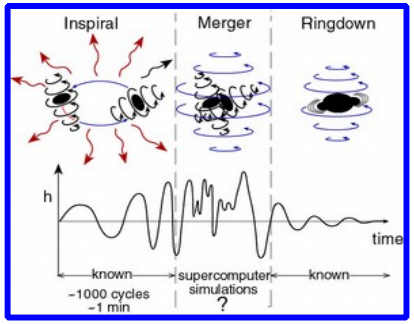
LIGO-Livingston
(4 km)

Advanced LIGO + Advanced Virgo
First joint runs in 2016

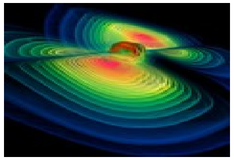
Expected GW sources detectable by LIGO/Virgo

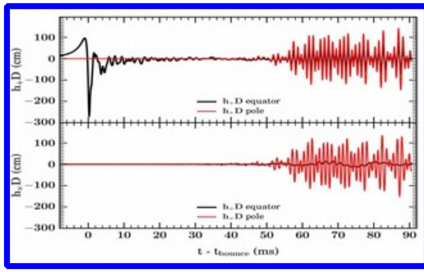
Transients

- **Coalescence of compact binary systems (NSs and/or BHs)**
  - Known waveforms (template banks)
  - $E_{gw} \sim 10^{-2}\ Mc^2$



- **Core-collapse of massive stars**
  - Uncertain waveform
  - $E_{gw} \sim 10^{-8} – 10^{-4}\ Mc^2$



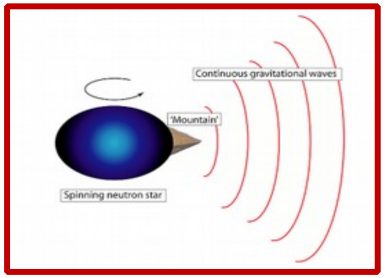


Ott, C. 2009

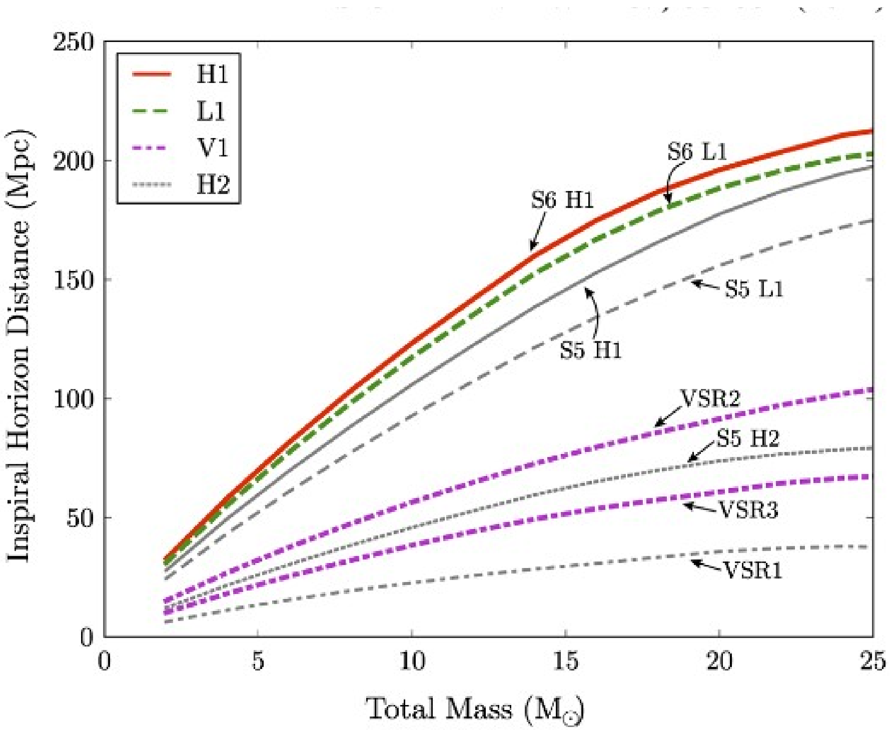
Non transients

- **Rotating neutron stars**
  - Quadrupole emission from star's asymmetry
  - Continuous and Periodic

- **Stochastic background**
  - Superposition of many signals (mergers, cosmological, etc)
  - Low frequency

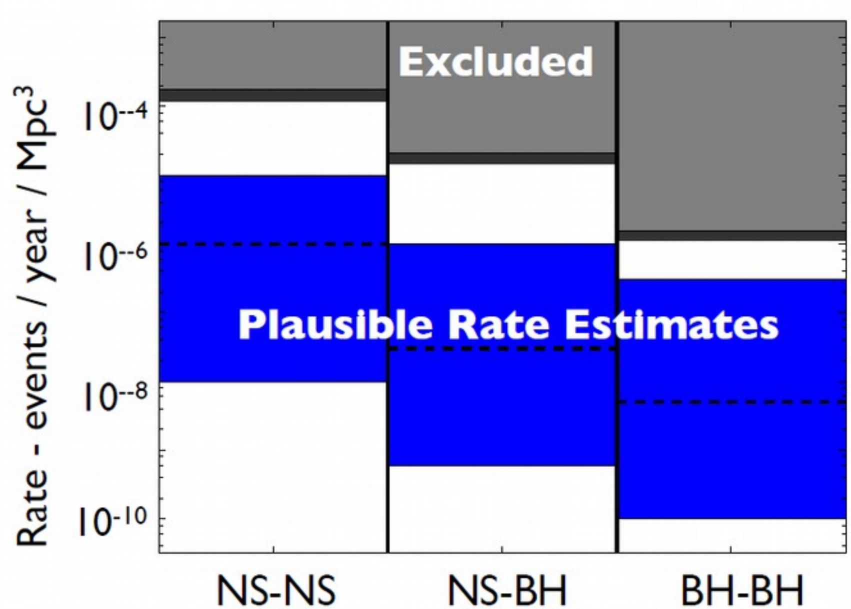


GW science so far
Example from LIGO/Virgo runs (2005-2010)



- •LIGO S6, VSR2 & 3
Matched filtering

- •No detections, but useful exclusion ranges
- •Upper limits on the rate of low mass compact binary coalescence
- •Total mass 2-25 M_{sun}



Abadie et al. 2012, *Phys. Rev. D*, 85

Why joint GW/electromagnetic observations?

LIGO

- Complementary information:
  - GW → mass distribution
  - EM → emission processes, environment
- Give a precise (arcmin/arcsecond) localization
  - Localize host galaxy of a merger
  - Identify an EM counterpart with timing signature (e.g. pulsars)
- Provide a more complete insight into the most energetic events in the Universe
- Explore the physics of the progenitors (mass, spin, distance..) and their environment (temperature, density, redshift..)
- Open a new era of multi-messenger (GW and photon) astronomy

Entering the Advanced Era

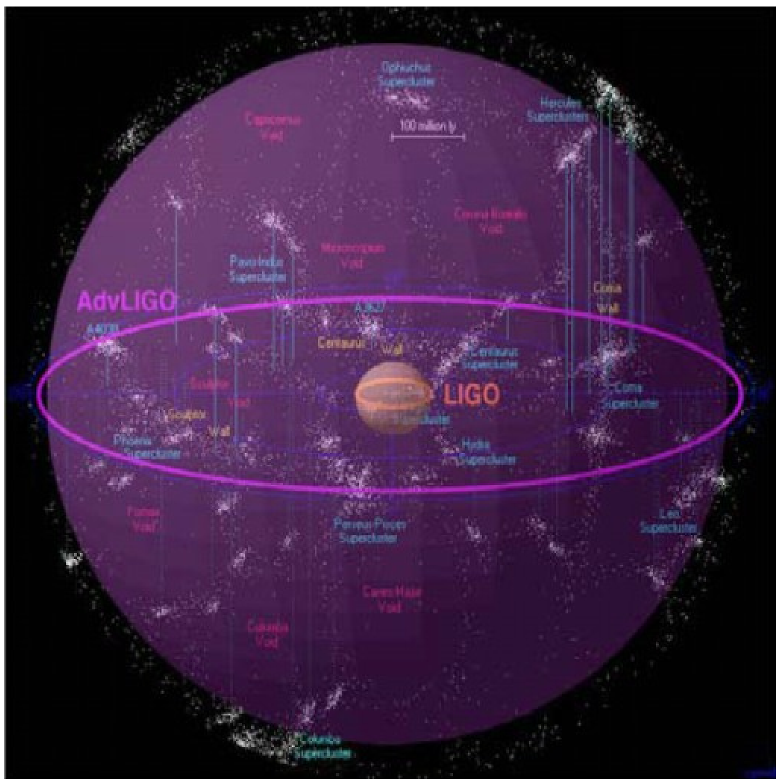
LIGO-H

LIGO-L

Virgo

Advanced LIGO started Observation Run (O1) in September
Advanced Virgo to be completed soon

10x sensitivity
→x1000 larger Volume



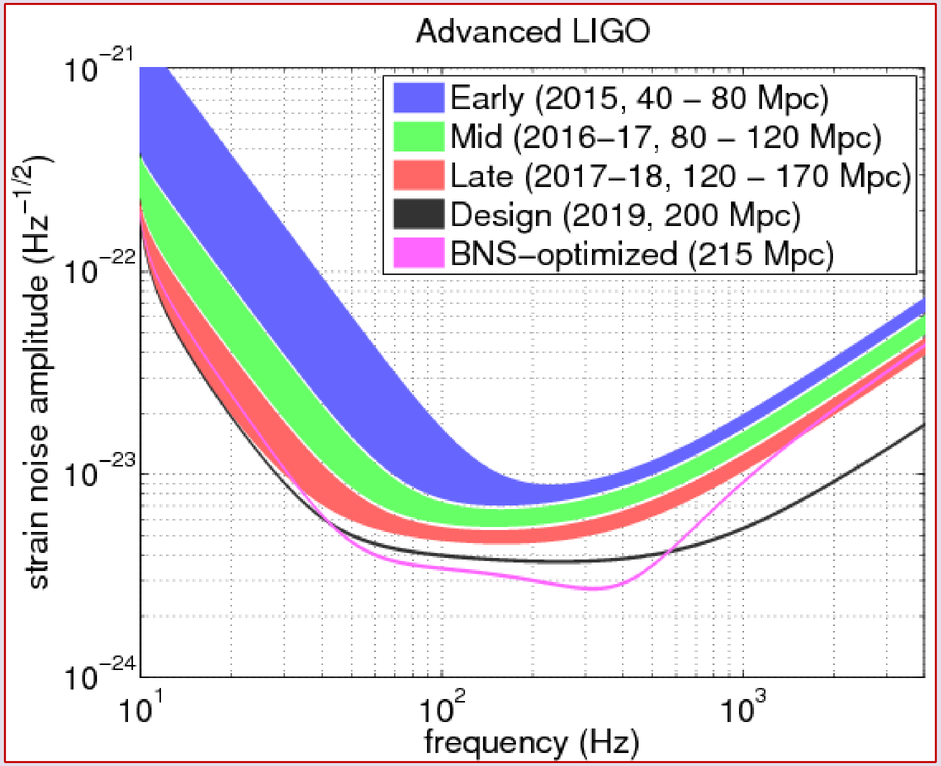
Advanced ERA Horizon :
Mass: NS = 1.4 Mo
BH = 10 Mo
Sky location and orientation averaged range
197 Mpc for NS-NS
410 Mpc for NS-BH
968 Mpc for BH-BH

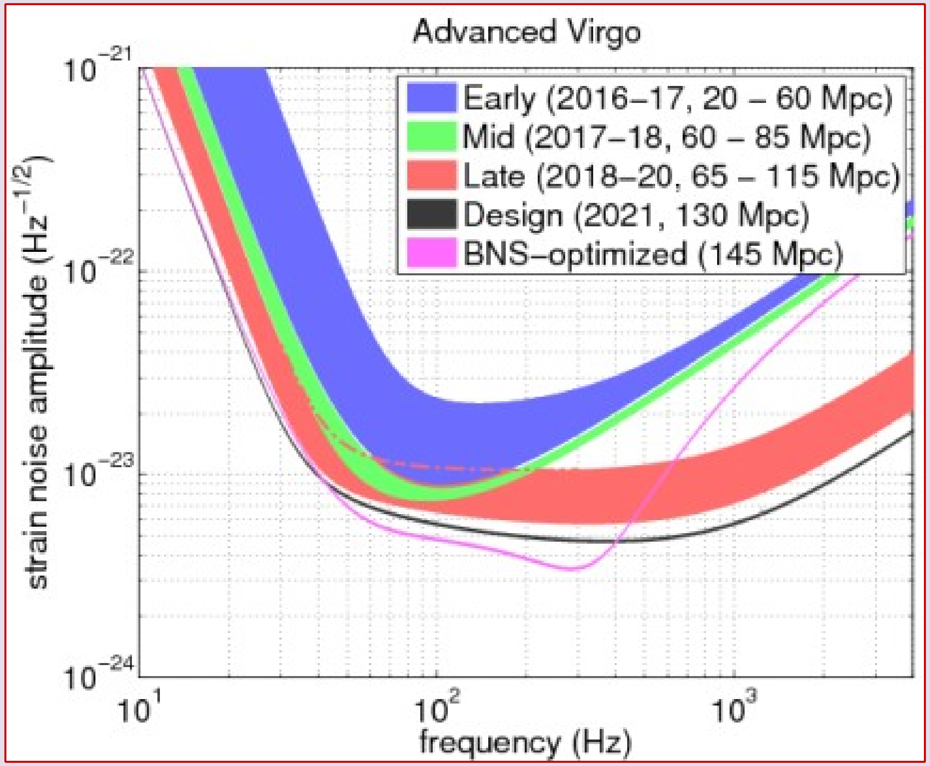
(Abadie et al. 2010, CQG 27)

Advanced GW Detectors: Sensitivities

LSC & Virgo Collaborations, arXiv:1304.0670

Progression of sensitivity and range for Binary Neutron Stars





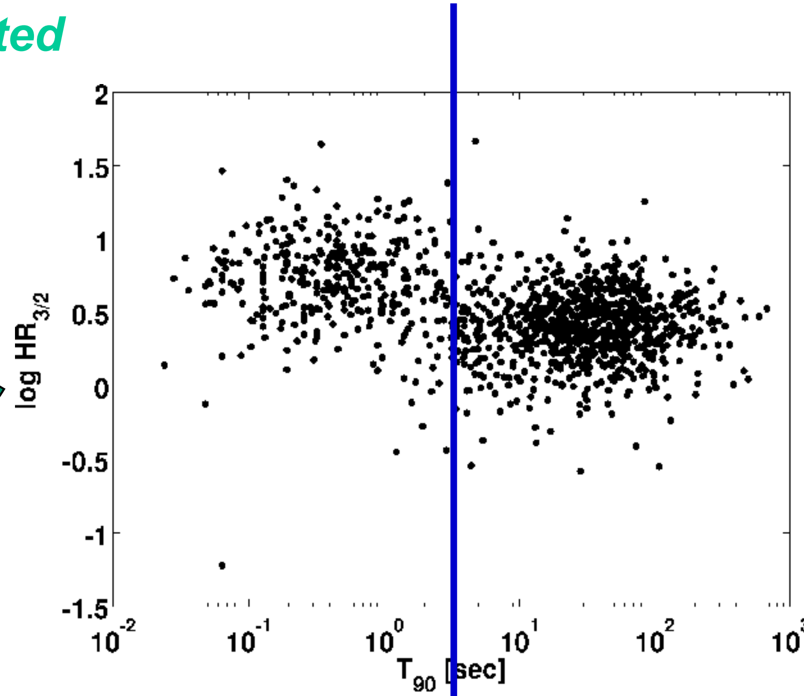
Larger GW-detectable Universe

Photons and GW: the GRB connection

Gamma Ray Bursts are intense flashes of gamma rays
Very Energetic (up to E_{iso} 10^{53} erg)

- **Short GRBs (<2 s)**

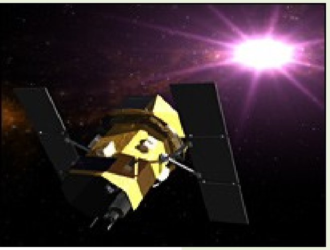
believed to be associated with mergers



- **Long GRBs (>2 s)**
- **Believed to be associated with core-collapse of massive stars**

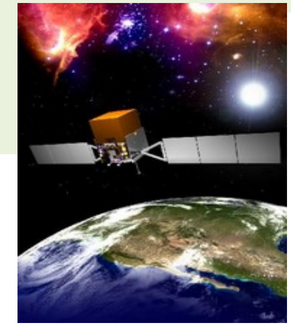
Multimessenger observations
Key to test associations!

GRB prompt emission ➜ TRIGGERED GW SEARCH

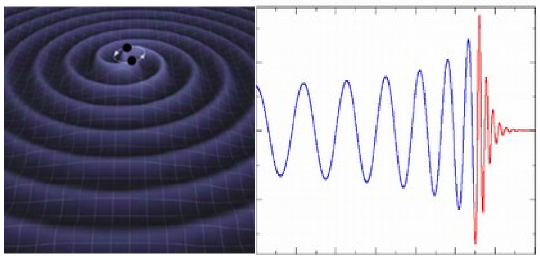


Known **GRB event time** and **sky position:**

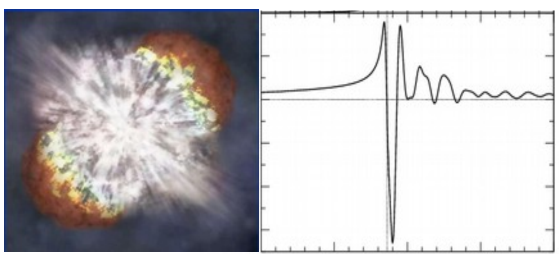
- reduction in search parameter space
- gain in search sensitivity



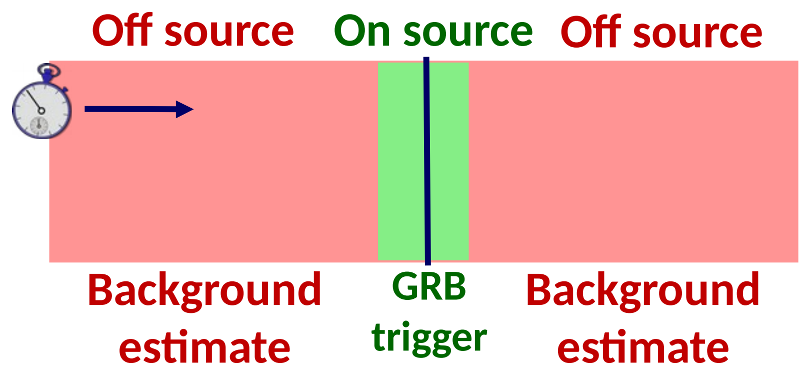
GW transient searches



Unmodeled GW burst
(< 1 sec duration)
Arbitrary waveform
- **Excess power**



Compact Binary Coalescence
Known waveform
- **Matched filter**



Analyzed 154 GRBs detected by gamma-ray satellites during **2009-2010**
while 2 or 3 LIGO/Virgo detectors were taken good data

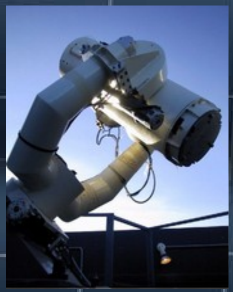
No evidence for gravitational-wave counterparts Abadie et al. 2012, ApJ, 760

Courtesy M. Branchesi

Electromagnetic follow-up

(GW → prompt EM observations)

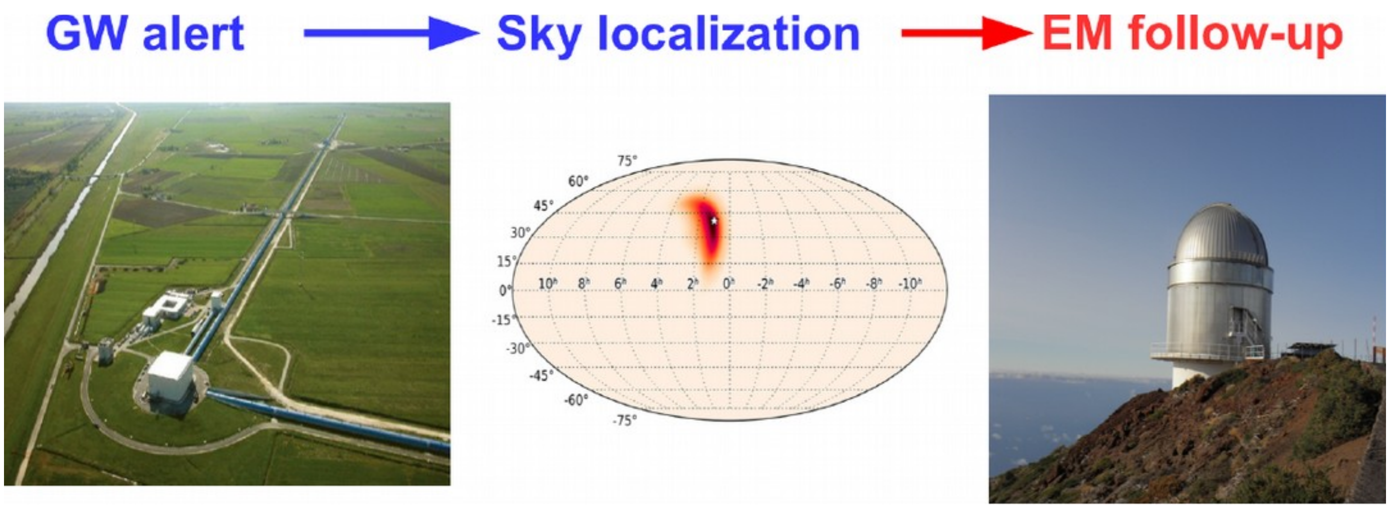



The role of EM follow-up

Key tool to

- **better understand the physics of compact objects**
- **unveil the nature of short GRB progenitors**



Latency to generate GW alerts with sky localization: few – tens minutes

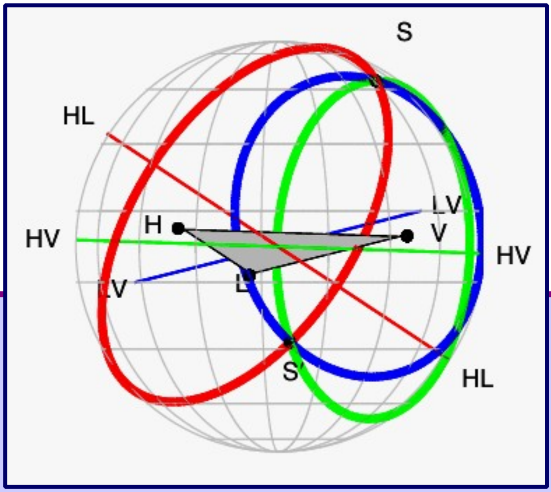
→ EM observations mainly of the afterglow emission

GW Localization uncertainties within 10-100 sq deg

→ Wide field of view (FOV) EM detectors are needed

→ High-Energy (X, gamma) very well suited (large FOVs + spectral coverage)

Sky Localization of GW transients



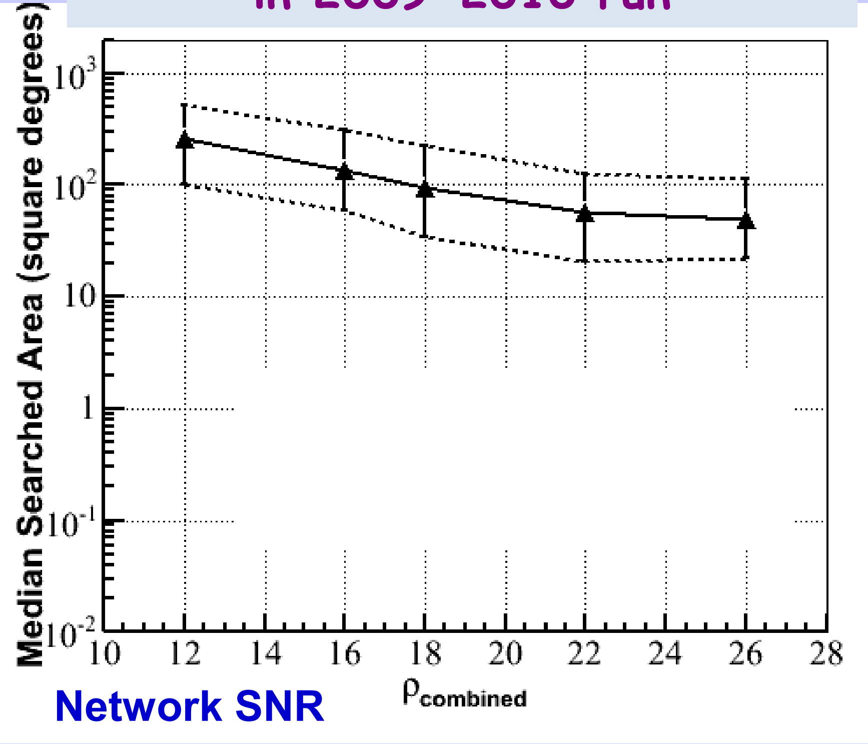
The **sky position of a GW source** is mainly evaluated by **"triangulation"** based on **arrival time delay between detector sites**

low SNR signals were localized into regions of **tens to hundreds of sq. degrees** possibly in several disconnected patches

⬇

Necessity of large wide field of view EM telescopes

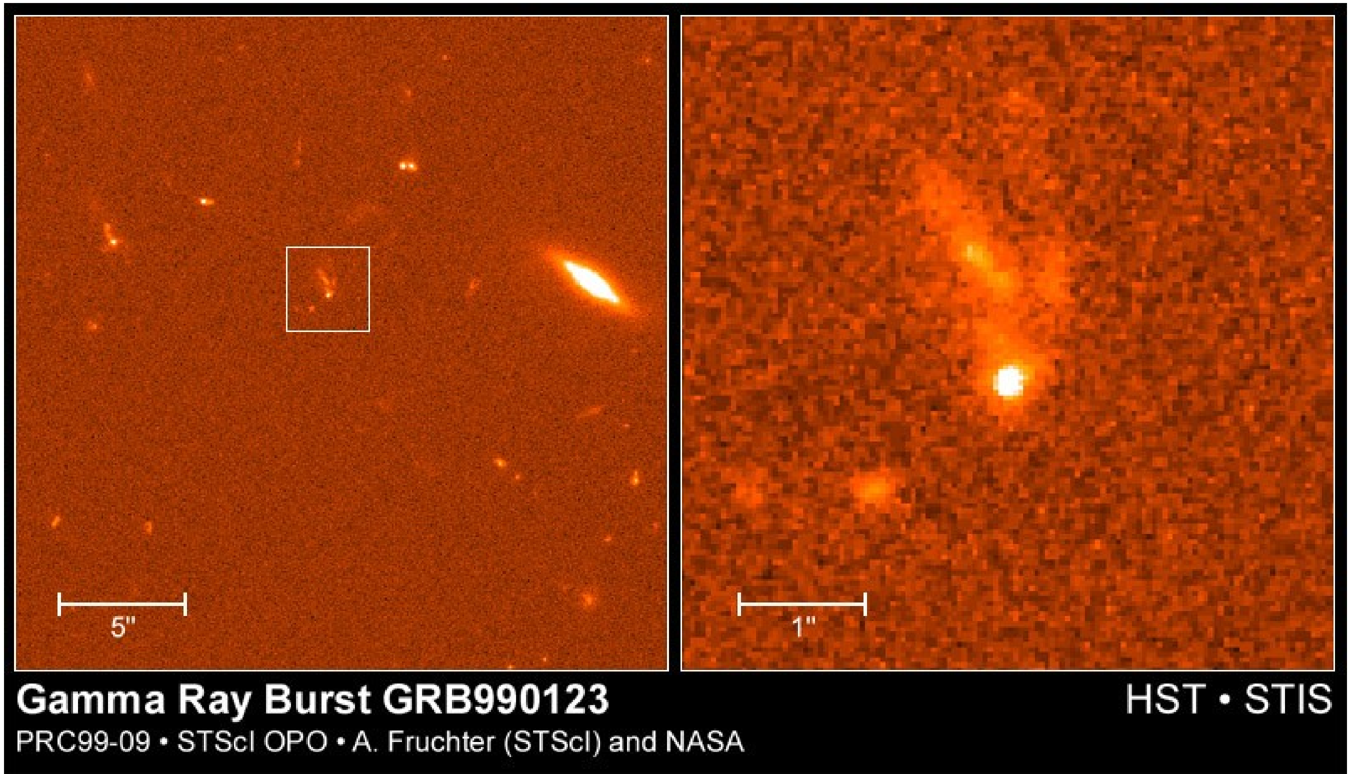
Binary coalescence localization in 2009-2010 run



Abadie et al. 2012, A&A 539

EM follow-up : key questions

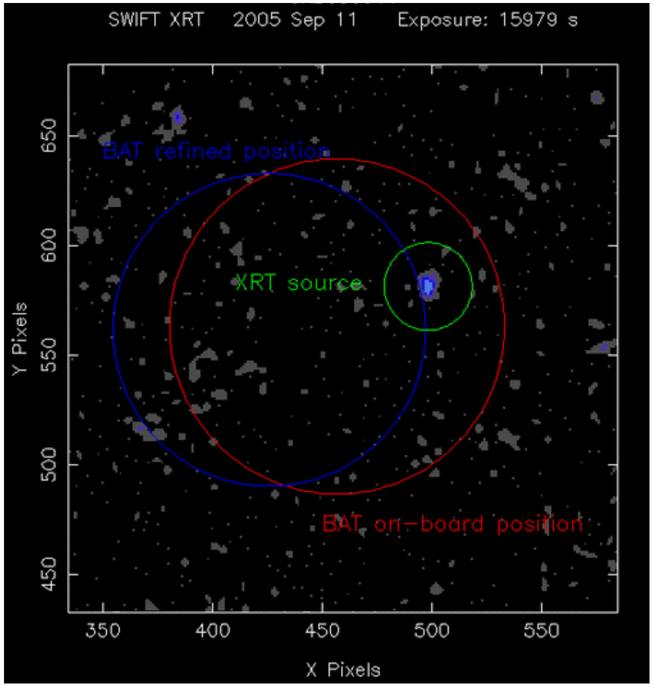
- What is the best observing strategy?
  - Scan the full error box?
  - Look only to specific regions (e.g. potential galaxy hosts?
  - How to identify the potential host?
- If there is more than one candidate…
  - How can we uniquely identify it?
  - How can models help us?
  - How can VO infrastructure help?



The VO & EM follow-up

- Find a counterpart is not easy!
- EM Transients might be
  - Fast
  - Faint
  - Too many

- Think about the case of GRBs!



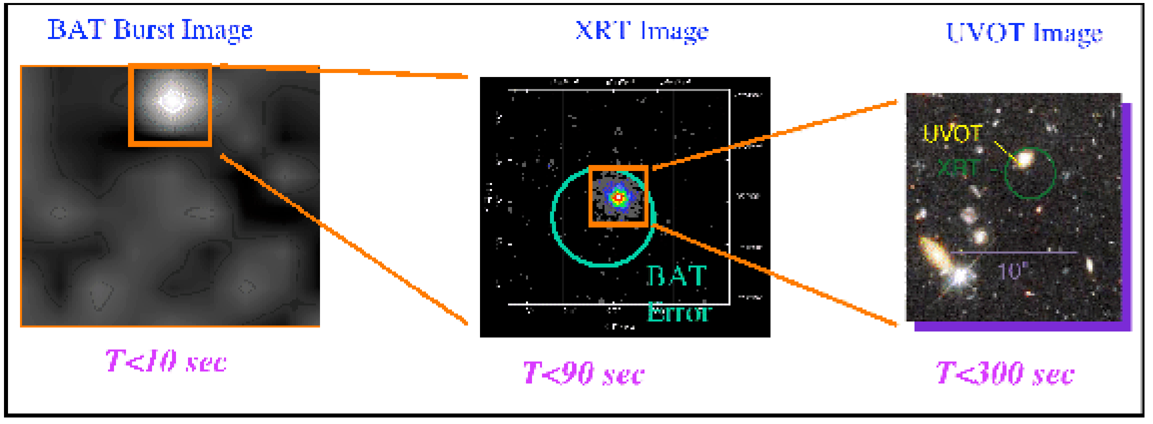
Swift

For GW, the situation is worse!

Larger error boxes
→Many candidates
→Lots of contamination

VO input
- Provide catalogs of potential counterparts
- Tool to search/correlate

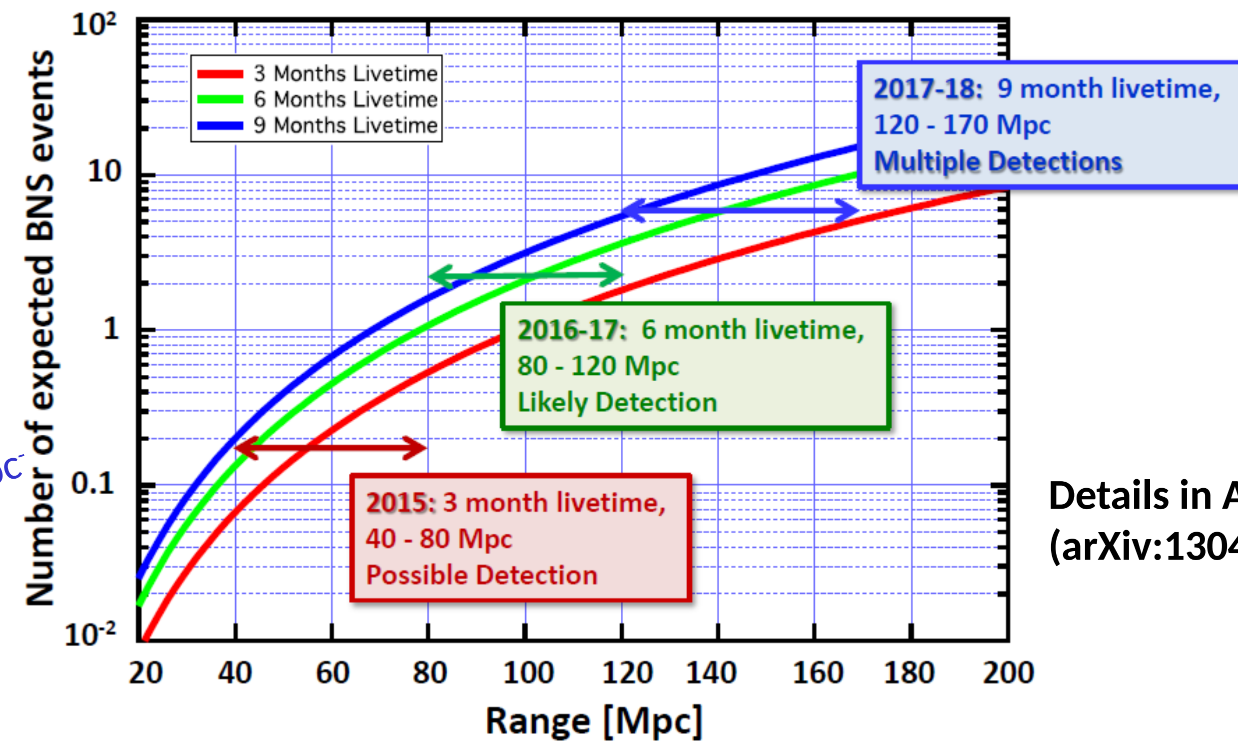
See Giuseppe's talk later



The plausible scenario

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

Estimate BNS Detection Rate, assuming a merger rate 1×10^{-6} Mpc^{-3} year^{-1}

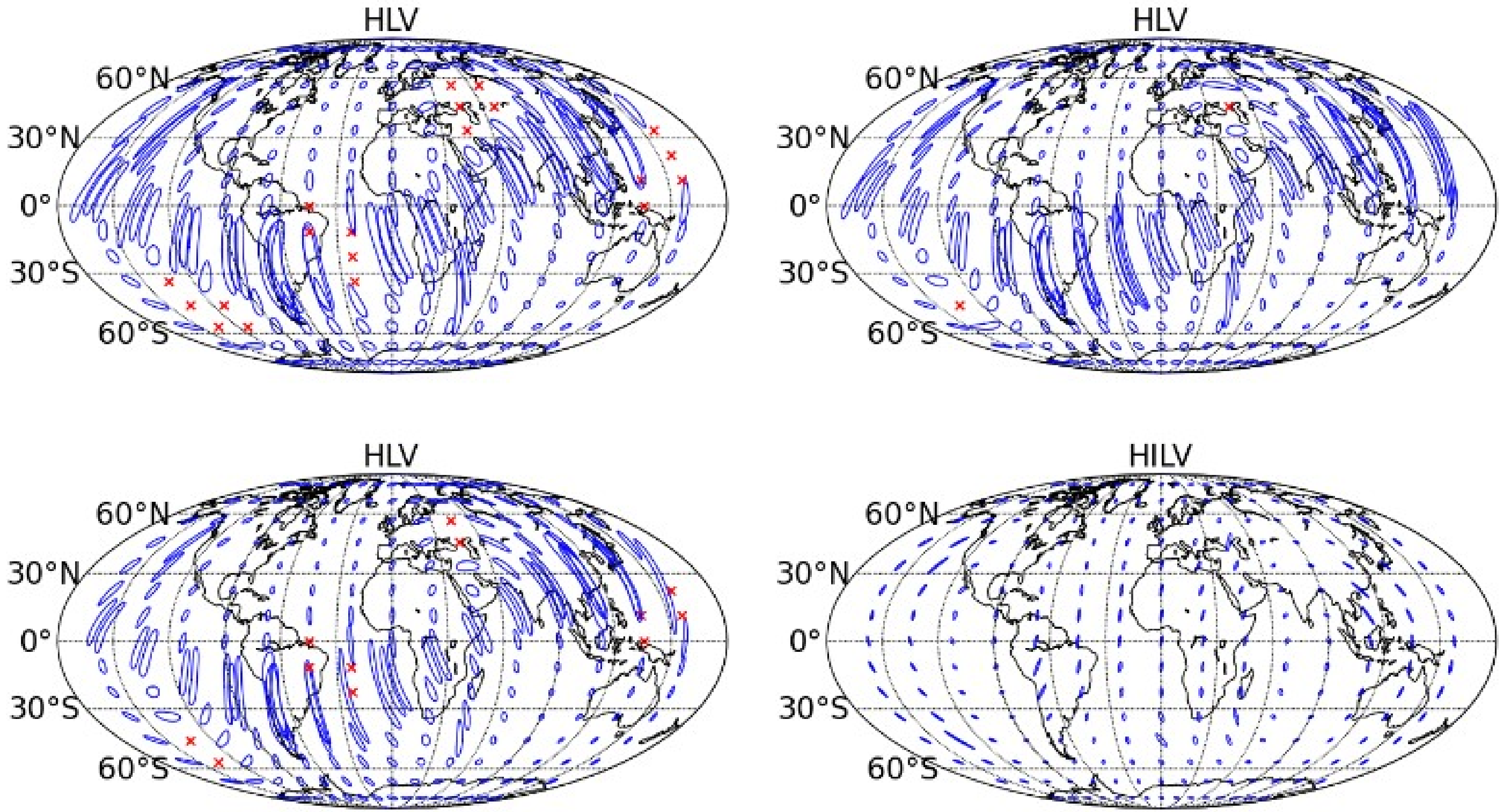


Details in Abadie et al. (arXiv:1304.0670)

Sky Localization

BNS, 80 Mpc

2016-17 | 2017-18



2019+ | 2022+

BNS, 160 Mpc

→ **90% CL**

X → **No detection**

Details in Abadie et al. (arXiv:1304.0670)

What is an EM follow-up program?

- EM follow-up is key to find counterparts and do great science
  - GW analysis and checks will require time
  - Need to avoid misinformation/rumors
  - Encourage multiwavelength coverage

- EM follow-up program
  - Standard MoU to share information promptly while mantaining confidentiality for event candidates
  - Once first few (>=4) detections, prompt alerts will be made public for high-confidence detections

- Status
  - More than 70 groups have signed MoU with LIGO & Virgo
  - From radio to gamma rays
  - Special LVC GCN Notices and Circulars with distribution limited to partners

In 2012, **LVC agreed policy on releasing GW alerts**

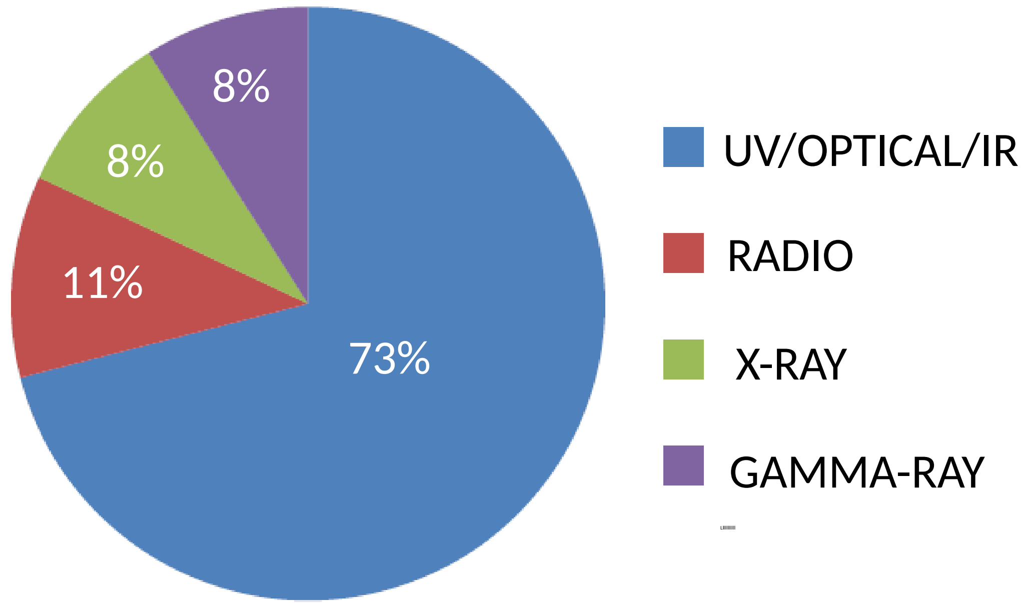
*"Initially, **triggers** (partially-validated event candidates) will be **shared promptly only with astronomy partners who have signed a Memorandum of Understanding** (MoU) with LVC involving an agreement on deliverables, publication policies, confidentiality, and reporting.*

***After four GW events have been published**, further event candidates with high confidence will be **shared immediately with the entire astronomy community**, while lower-significance candidates will continue to be shared promptly only with partners who have signed an MoU."*

- The first (2014) and second (2015) open call for participation in GW-EM follow-up program (last year) ✉ **72 MoUs signed**

Courtesy M. Branchesi

LVC GW-EM follow-up program



Seventy MoUs involving

- **160 instruments**
(space and ground-based facilities)
Full coverage, radio - VHE

- **Astronomical institutions, agencies and large/small groups of astronomers** (20 countries)

The present: what is happening now?

- Advanced LIGO is observing now !

- Pre-observations
  - Commissioning till end August
  - Early September: calibration studies

- The first Observing Run (O1) has begun
  - From 18 September to January 12
  - Both Hanford and Livingstone are working

- Advanced Virgo is close to completion
  - Construction and commissioning

- Get the status of the interferometers

  https://ldas-jobs.ligo.caltech.edu/~gwistat/gwsnap.html

The future: possible contributions from the VO

- **Now, the data flow is:**
  - **GW data are analyzed by online, low-latency, pipelines**
  - **GW triggers (times, probability maps) sent to the MoU partners**
  - **Observations/archival searches**
  - **Sharing of results among partners within 24 hrs**
- **Now, GW data are**
  - **Private (internal GCN notices/circulars)**
  - **Some key info shared with MoU partners**

First join LIGO-Virgo run in fall 2016 (O2)

- **According to MoU, after 4 candidates published, GW trigger will be**
  - **Made public (not just to the partners)**
  - **Everyone could access it and do follow-up observations**

- **How can VO be involved?**
  - **Support counterpart searches**
  - **Help hosting GW triggers?**
  - **Any other ideas?**

Conclusions

- GW and photons provide complementary information
  - Multimessenger observations extremely promising
- Multimessenger approach is key to study the most extreme objects in the Universe
  - Natural laboratories to probe fundamental physics
  - Transients (e.g. GRBs)
  - Also, other sources (e.g. neutron stars)
- Virgo and LIGO are undergoing major upgrades
  - Increased sensitivity → Larger volumes to probe
  - Joint observations planned for 2016
- Good availability of other facilities
  - Ground: many optical/radio telescopes in EM-followup program
  - Space, Swift & Fermi mission extended (Senior Review 2014)
- VO & GW
  - GRBs are a great science case (searching for host)
  - Other inputs/ideas?

A new, growing community,
preparing for the challenges of the multimessenger era !