# Searches for high energy neutrinos and gravitational waves

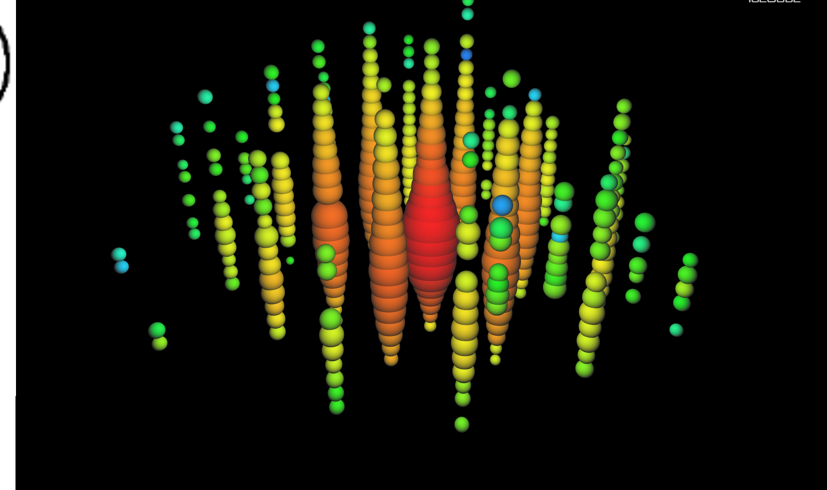
- Gravitational waves
- Multimessenger results for GW+HEN analyses
- Advanced Detector Era for LIGO and Virgo


**Irene Di Palma**

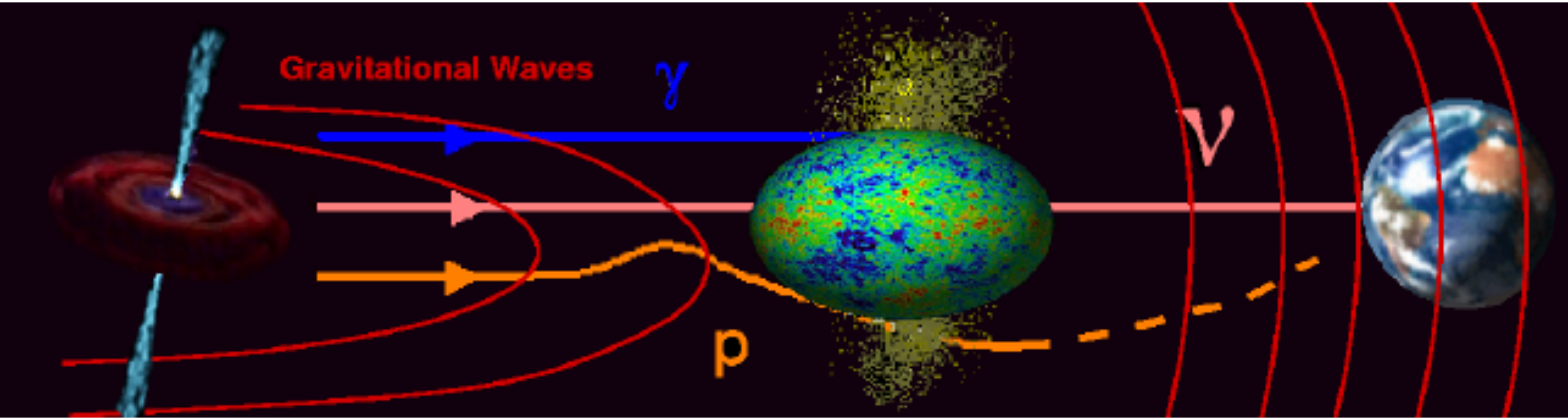
**on behalf of the LVC**



**LIGO-G1501332**

# Multi-messenger strategy




- Gravitational Waves and High Energy Neutrino can escape very dense media and travel unaffected over cosmological distances, carrying information from the innermost regions of the astrophysical engines. Such messengers could also reveal new, hidden sources that are not observed by conventional photon astronomy.

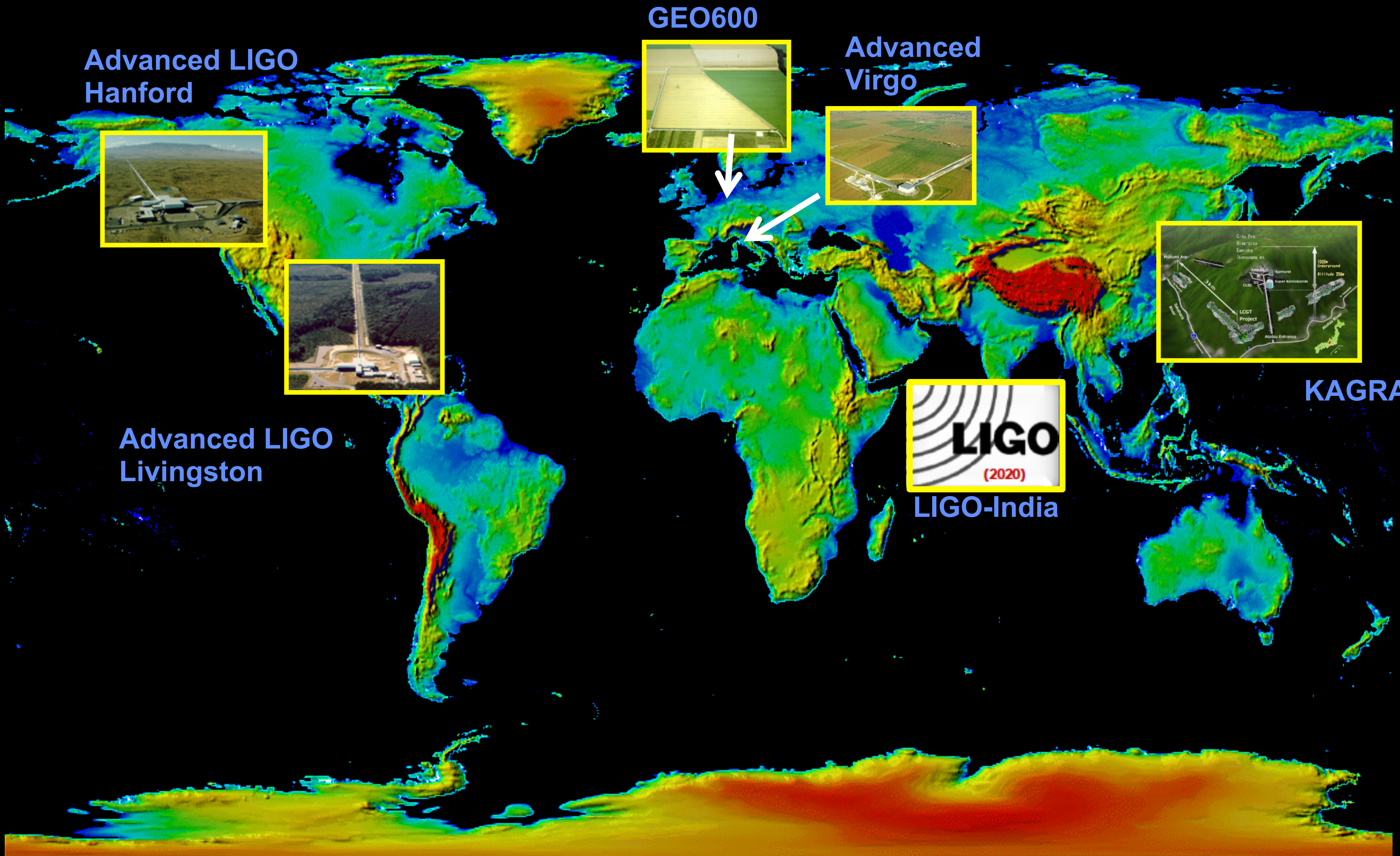
- The basic idea is that the accidental occurrence of the coincidence (in time and sky location) of GW and HEN triggers is very unlikely. If such coincidence is observed, this would provide strong evidence that GWs and HENs have been observed and that they originate from a common astrophysical source.

*JCAP* 1306 (2013) 008

# Potential sources

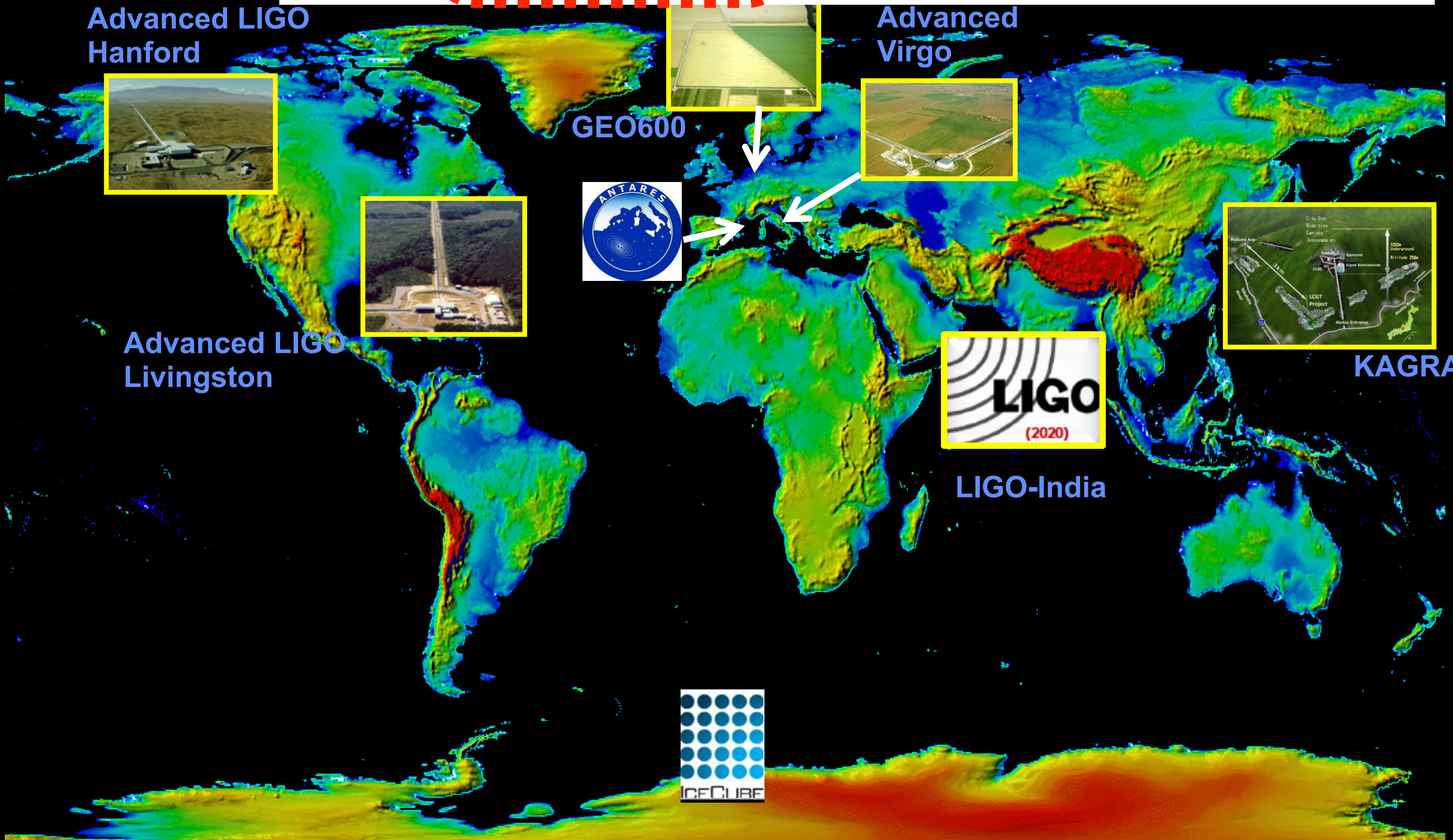
- Potential astrophysical sources of GW+HEN:
  - Galactic sources: Soft Gamma Repeaters *(Duncan & Thompson 1992; Aso et al. 2008, etc.)*
  - Extragalactic sources: Gamma Ray Burst (short and long) *(Narayan & Piran 1992; Eichler et al. 1989; Galama et al. 1998; Fryer et al. 2002; Bahcall & Waxman 1997; Kobayashi & Meszaros 2003, etc.)*
  - Choked GRBs *(Meszaros & Waxman 2001; Bromberg et al. 2012)*
  - Exotic class: Cosmic Strings *(Damour & Vilenkin 2000; Mosquera Cuesta & Gonzalez 2001; Siemens et al. 2006; Berezinsky et al. 2011)*
  - ....

# The Advanced GW Detector Network

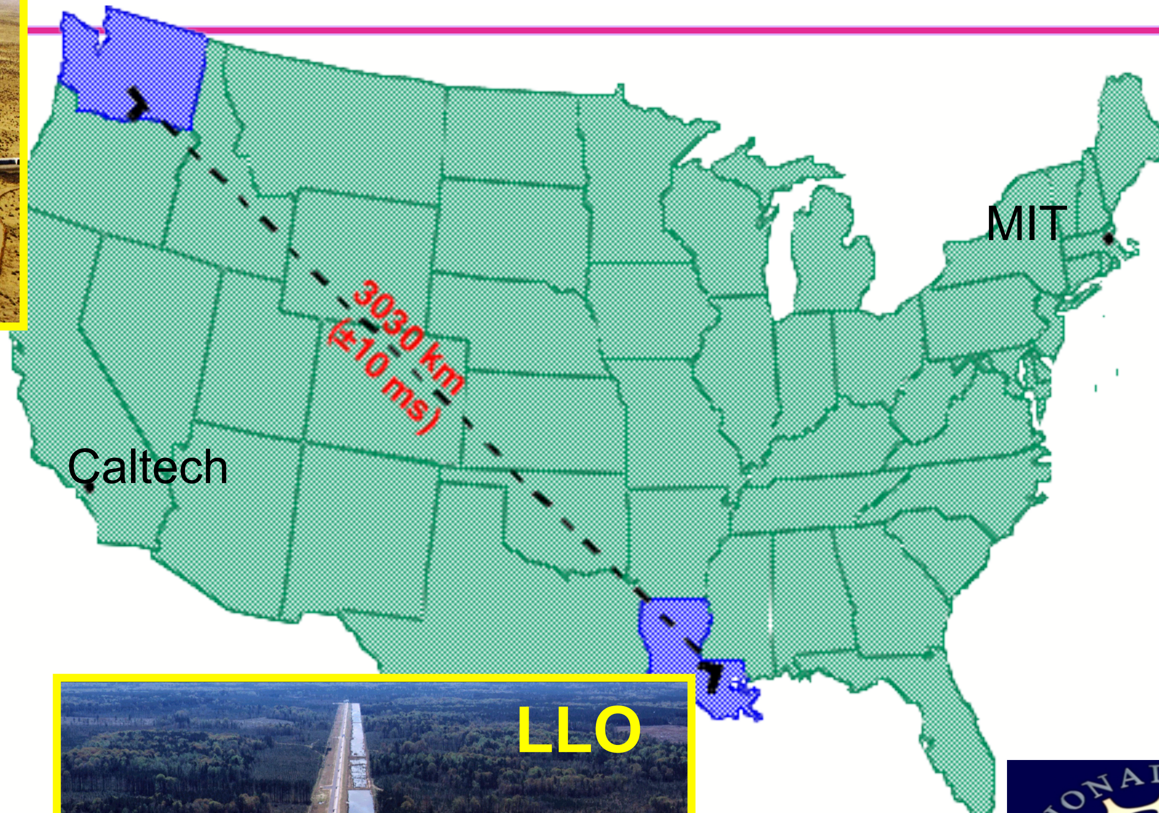


LIGO

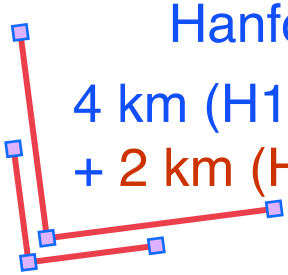
| | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ANTARES | 5L | 10L | 12L | | | | | | | KM3NeT | |
| IceCube | 9s 22s | 40s | 59s | 79s | | Ice Cube 86 strings | | | | | |
| LIGO | S5 | | S6 | | | | | | | advanced LIGO | |
| VIRGO | VSR1 | | VSR2 | VS R3 | VS R4 | | | | | Adv. VIRGO | |

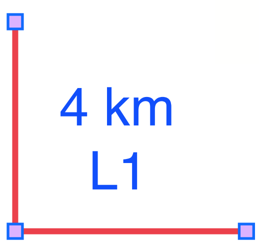


# LIGO: Laser Interferometer Gravitational-wave Observatory




Hanford, WA

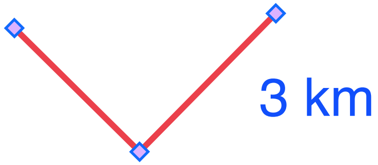



Livingston, LA

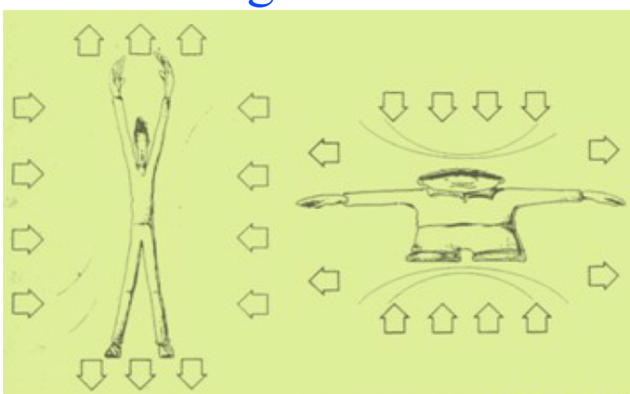
# Virgo Interferometer

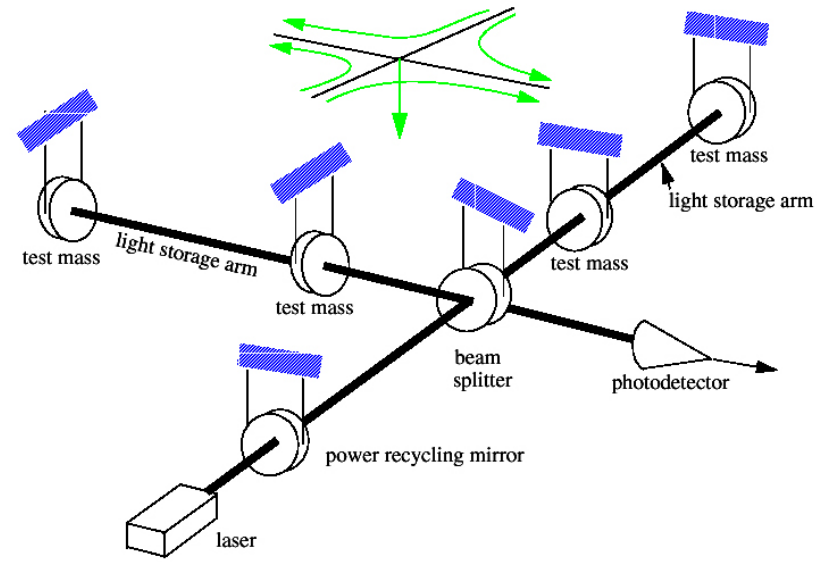
Cascina, Pisa



# How does an interferometer work?

- Gravitational waves twist the space-time and during their crossing they produce a positive or negative separation among the two free masses.

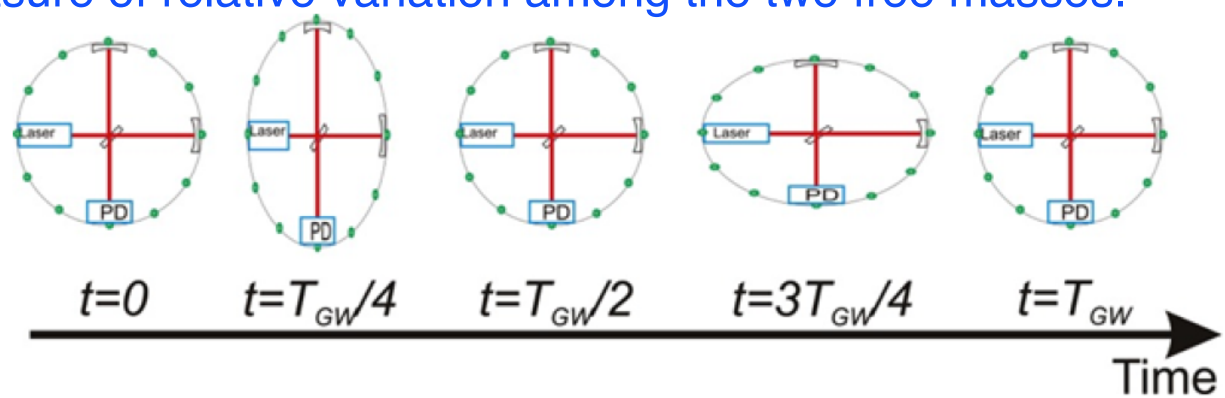




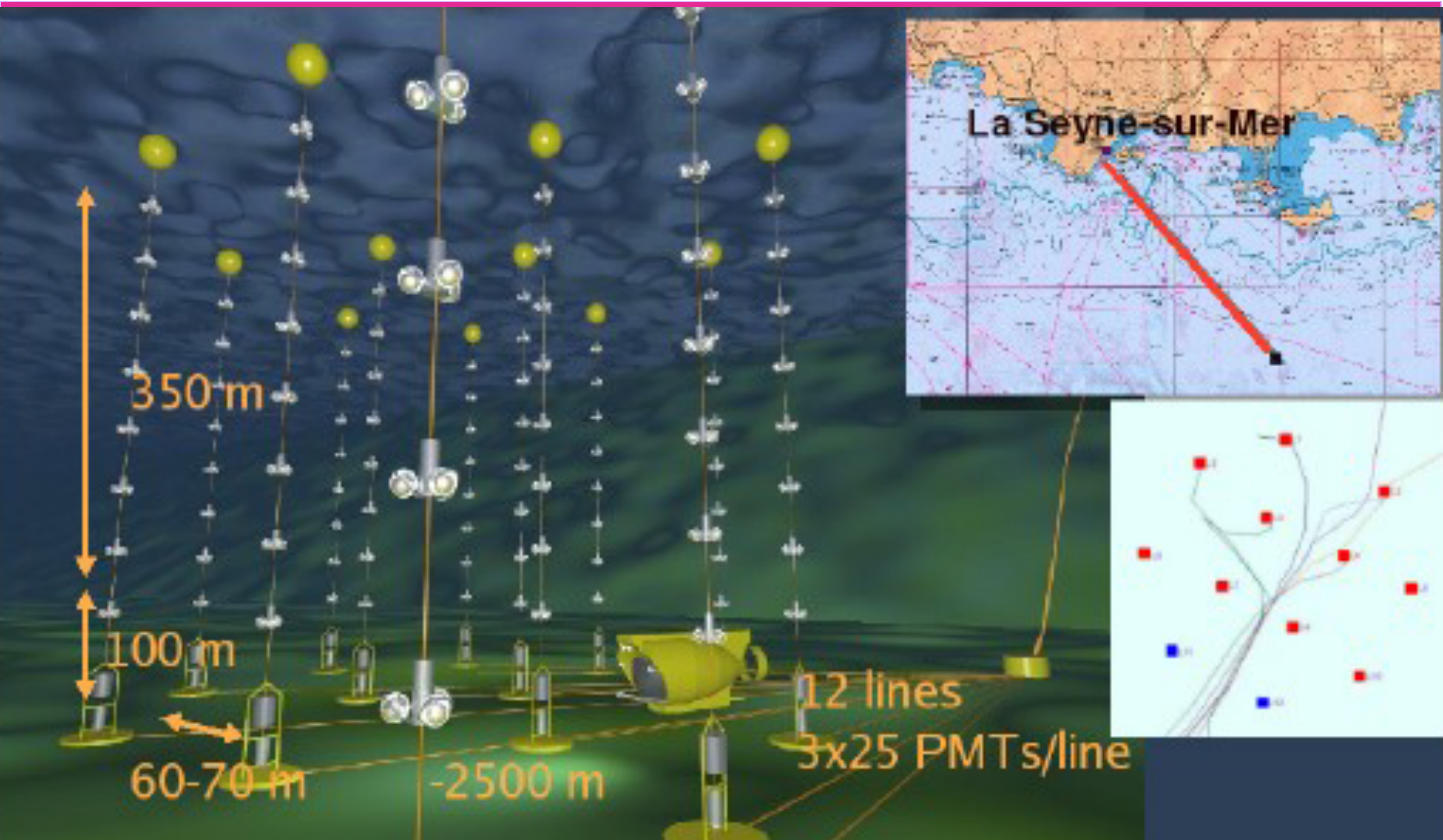

- The $h$ parameter is the measure of relative variation among the two free masses.

- $h = \Delta L / L$

  **Goal: get $h \leq 10^{-22}$;**
  **can build $L =$ 4 km;**
  **must measure**
  **$\Delta L = h\,L \leq 4\times10^{-19}$ m**



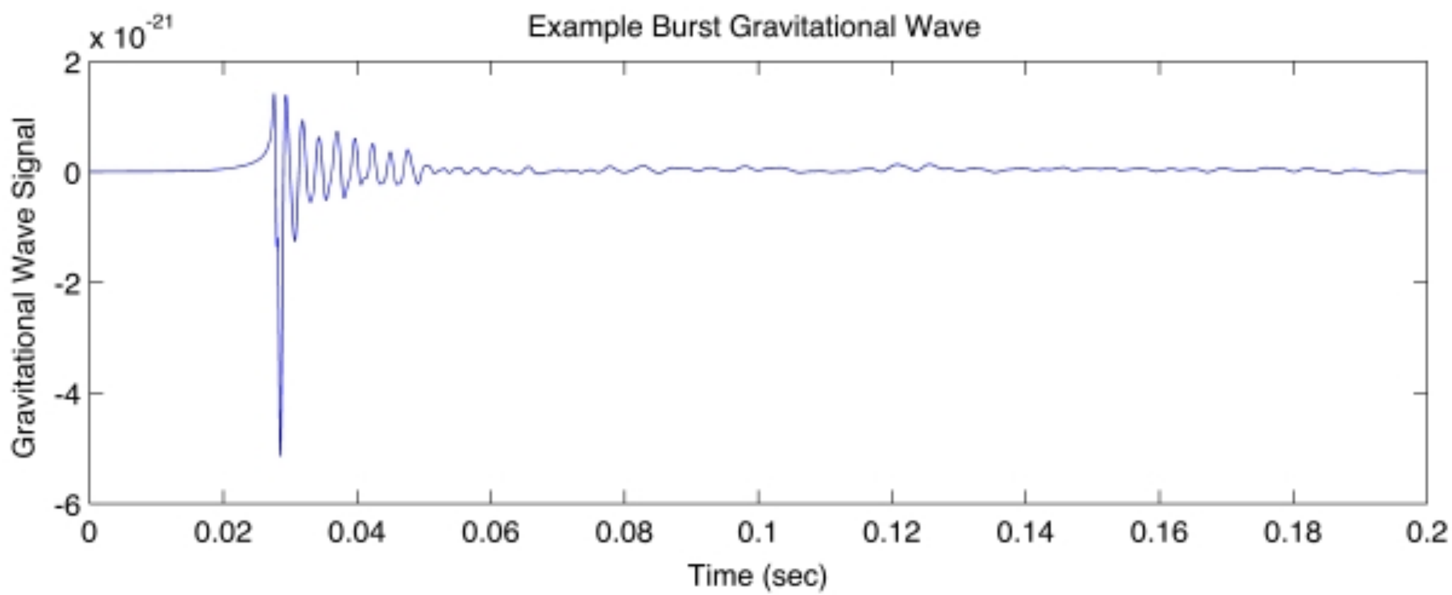
# ANTARES Neutrino telescope



# The GW signal: a generic burst

GW bursts are defined loosely as any transient signal for which there is no good theoretical model. Search for GW bursts typically focus on detecting generic waveform with duration range 1-100 ms.

There are hypotheses that some systems such as supernovae or gamma ray bursts may produce burst gravitational waves, but too little is known about the details of these systems to anticipate the exact form these waves will have.



# Gravitational Wave Bursts

GW bursts are defined loosely as any transient signal for which we do not rely on a specific theoretical model for the GW waveform. Search for GW bursts typically focusses on detecting generic waveform with duration range 1-100 ms.

- **"Untriggered"** searches scan all available data, they look for simultaneous jumps of energy in all detectors in some time-frequency region, with consistent measurement of amplitude or correlation between the detectors.

- **"Triggered"** searches scan a small amount of data around the time of an astronomical event (GRB, neutrinos). These searches exploit knowledge of the time and direction to the astronomical event to improve the sensitivity of the search.

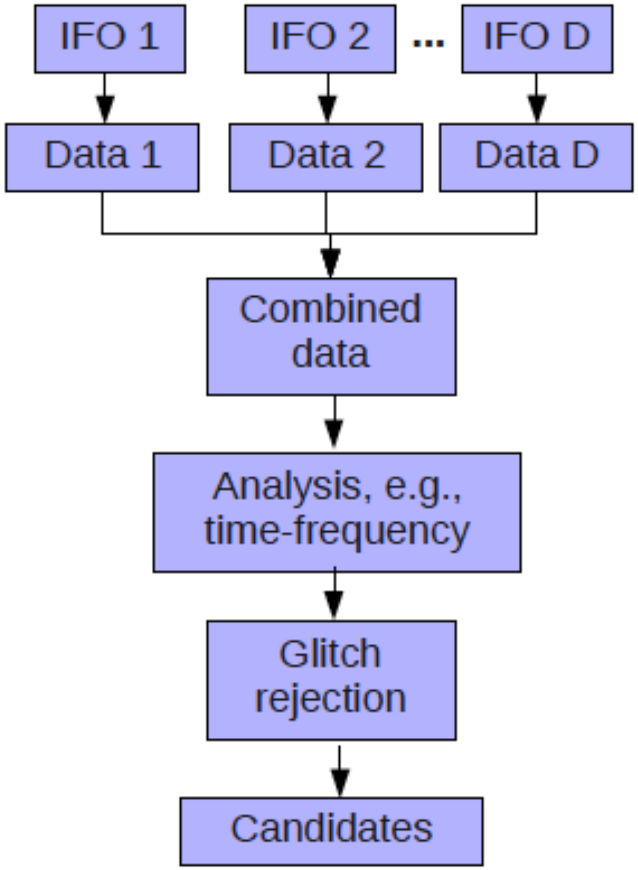
# GW search method

X Pipeline is a matlab-based software package for performing coherent searches for gravitational-wave bursts in data multiple detectors, weighted by relative sensitivity to the sky location of the neutrino.

Coherent analysis combines data before generating triggers meaning more info can be extracted. Automatically takes into account varying ifo sensitivity and measures similarity in data.

Blind non-biased analysis:

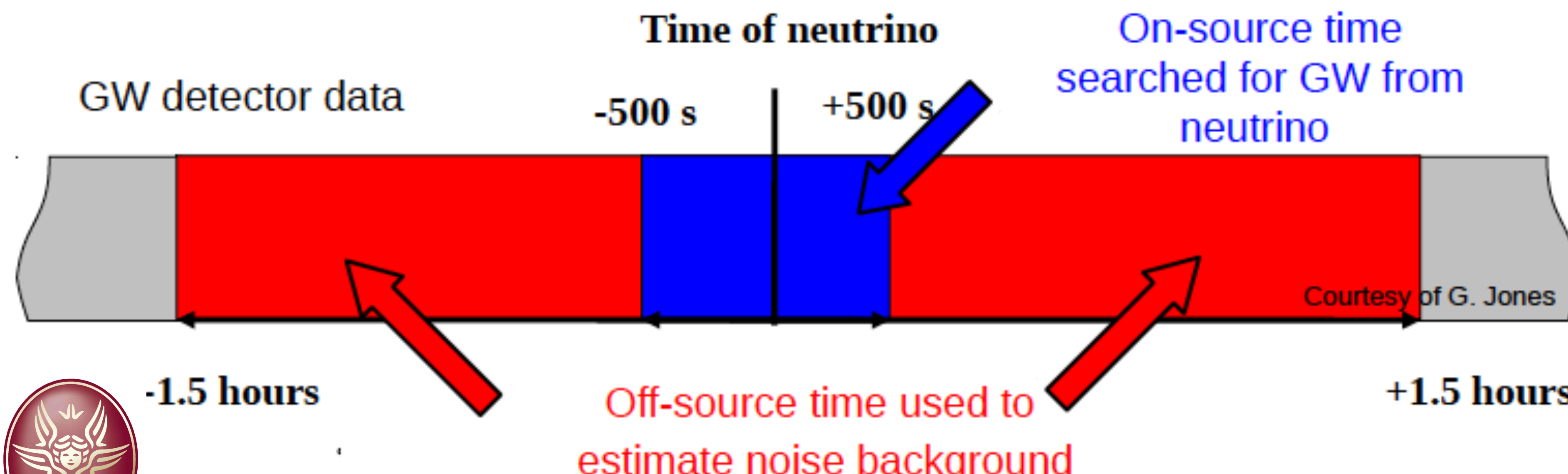
- Closed-box analysis: Tune our search parameters on off-source.
- Open-box analysis: Search for GW in on-source with optimal parameters.




*References: astro-ph.0908.3824v1*
*https://trac.ligo.caltech.edu/xpipeline/*

# X-Pipeline search

- The data is divided into two sets:
  - On-source: [-500, +500] s around each neutrino trigger *(Astropart.Phys.35:1-7,2011)*.
  - Off-source: all other data within +/- 1.5 hr of the neutrino, divided into blocks of the same length as the on-source period + time slides.
- The on-source data is searched for large excess energy events.
  - The significance of each event is estimated by comparing to typical values in the off-source data.

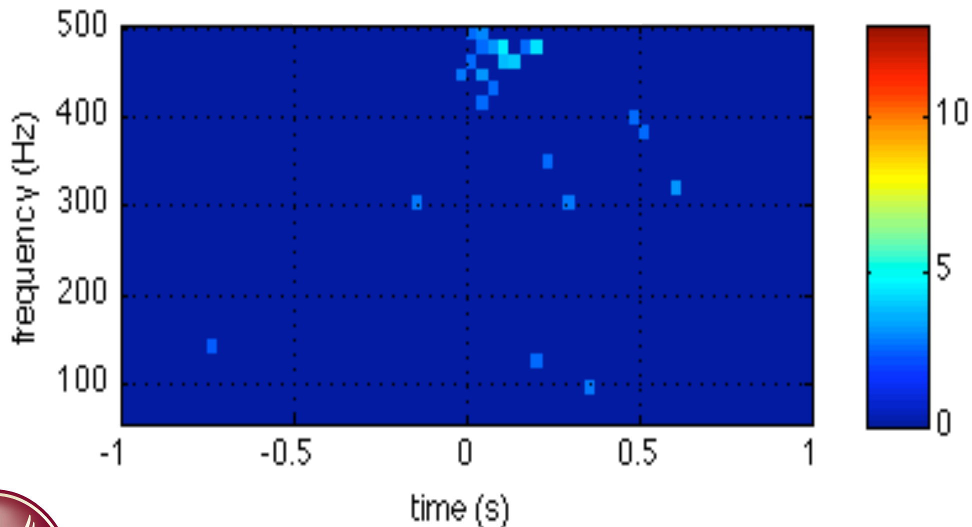



***JCAP*** *1306 (2013) 008*

# Most significant outlier

Having one event like this, with FAP=0.004, given O(200) neutrinos triggers is entirely consistent with background.

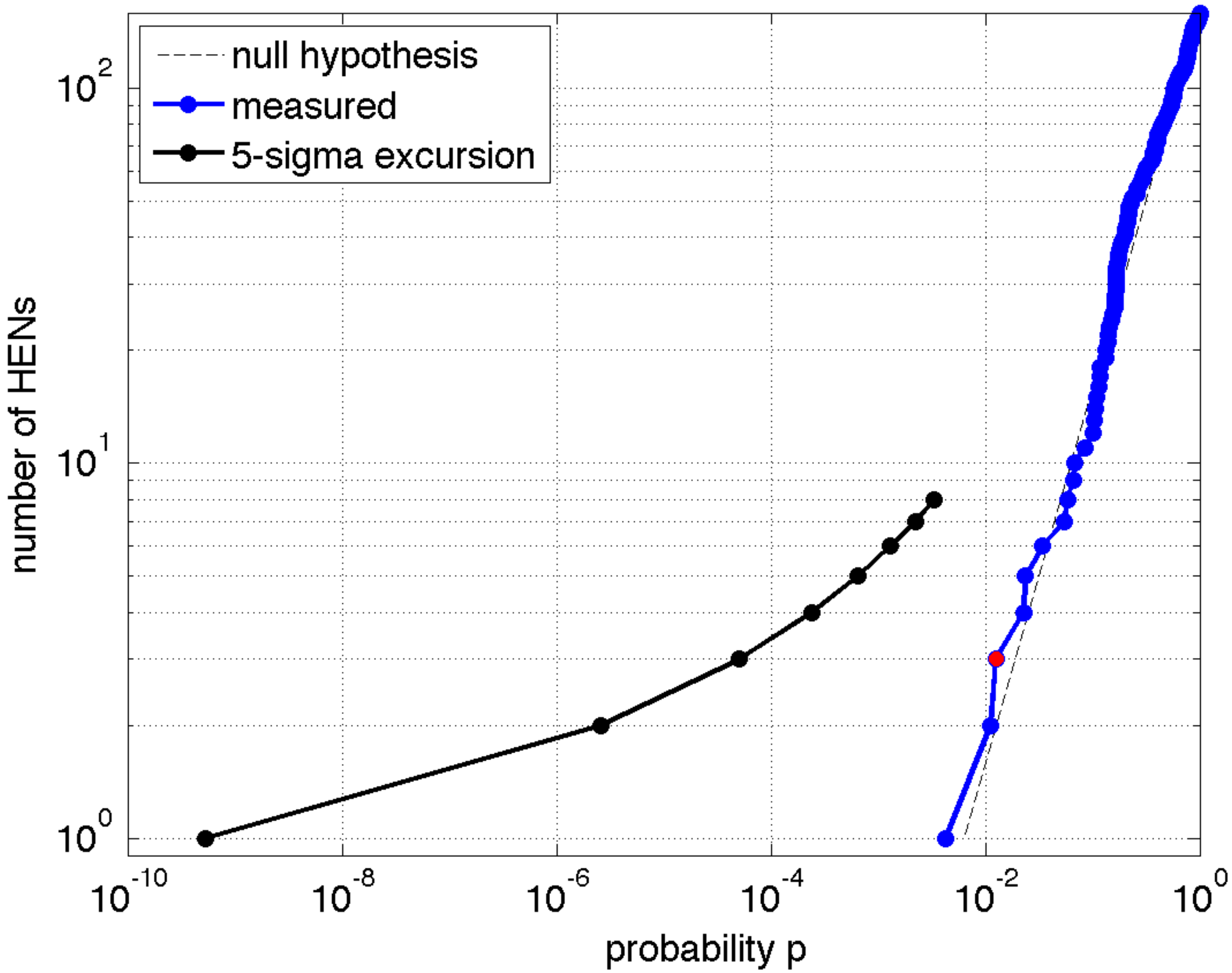
| | |
|---|---|
| name | Nu385_386 |
| Right ascension | 204.404 deg |
| Declination | -13.027 deg |
| GPS | 873597124.85938 |
| network | H1H2V1 |
| FAP (p-value) | 0.004 |




We have a single outlier that passed a first-stage threshold but has not reached the level of a candidate.

# Coincident search results

## Binomial Test




Test for a cumulative signature associated with our neutrino sample.

The distribution of p-values is consistent with the null hypothesis (dashed line).

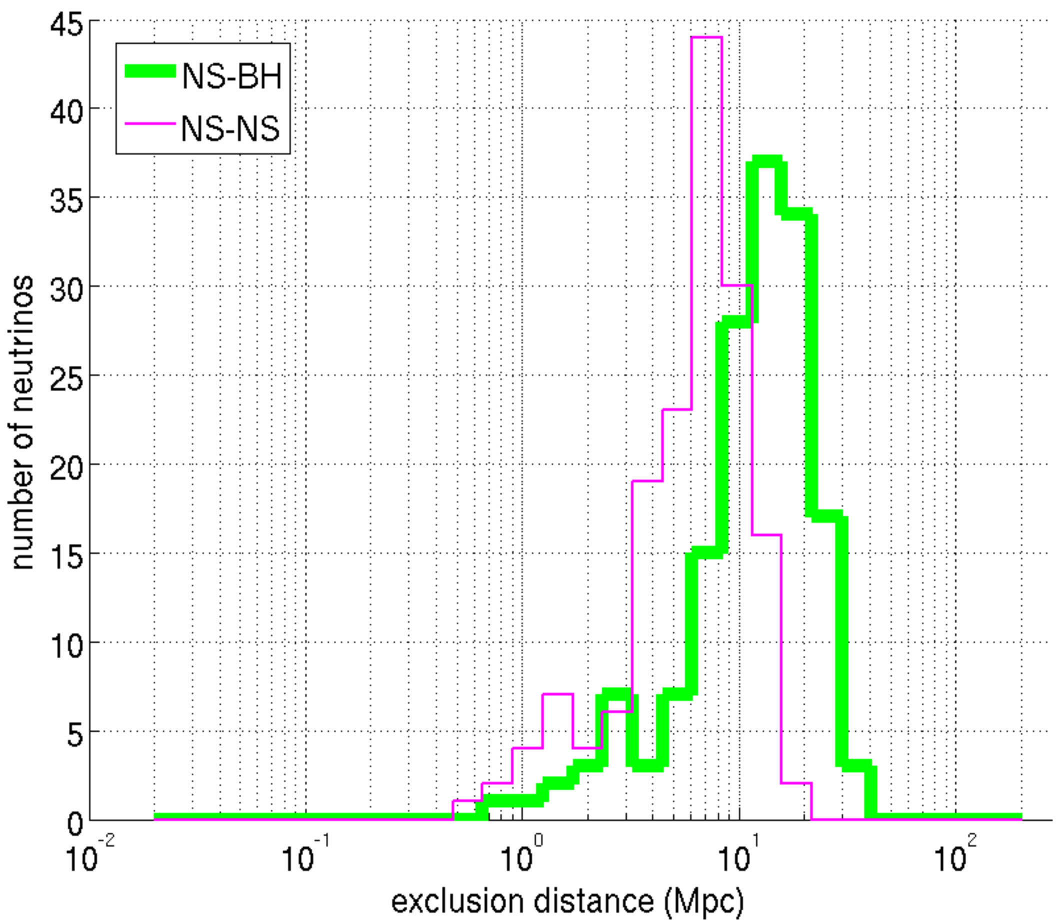
The **red dot** indicates the largest deviation of the low p tail from the uniform distribution null hypothesis.
The **black line** shows the threshold for a 5-sigma deviation from the null hypothesis.

*JCAP* 1306 (2013) 008

# Coincident search results

To convert injected signal amplitude into distance we assume that an energy
$E_{GW} = 10^{-2} M_{\odot} c^2$
is emitted.

We are able to rule out the existence of coalescing binary neutron star systems and black hole-neutron star systems up to distances that are typically of 5 Mpc and 10 Mpc respectively.

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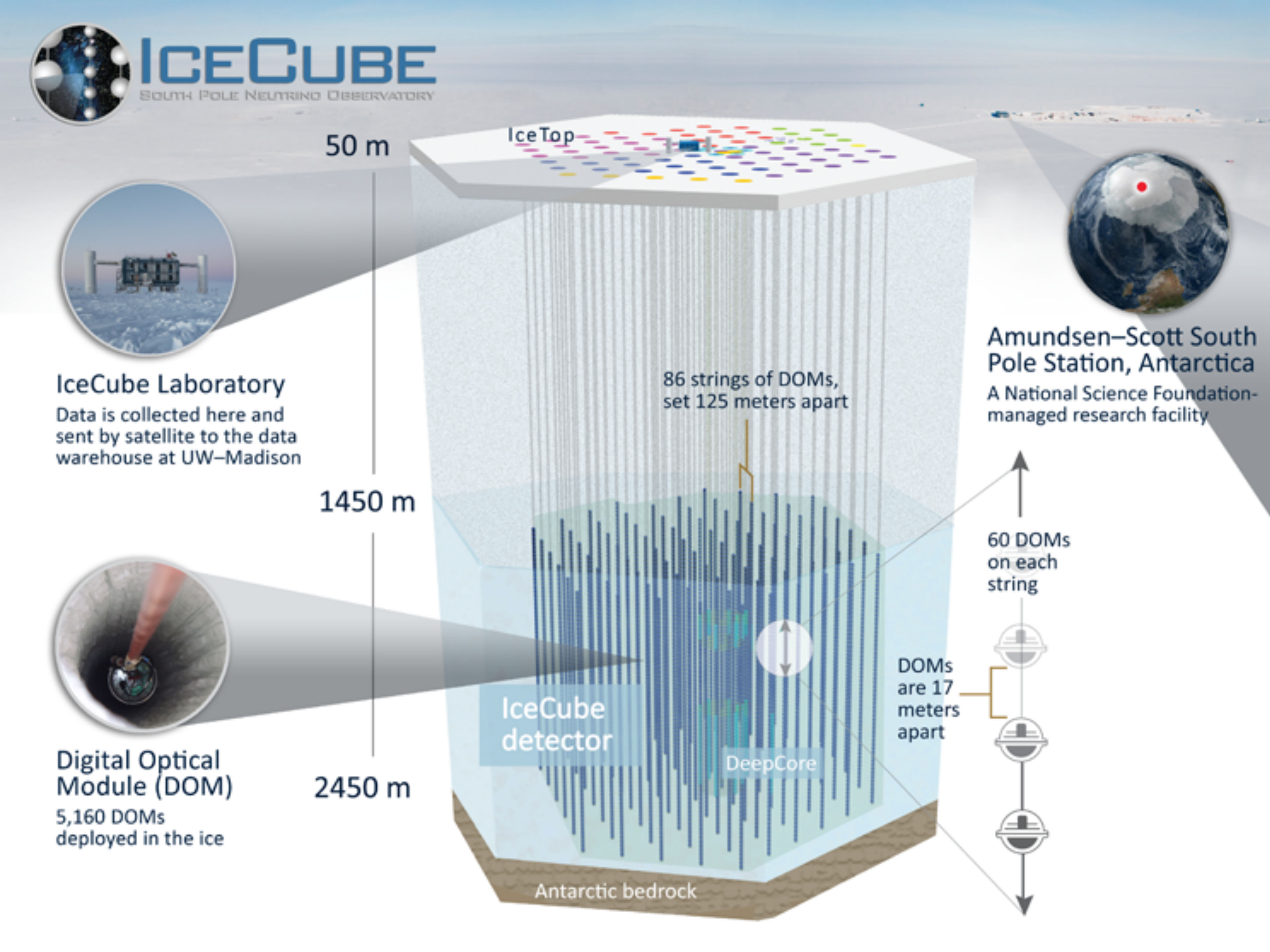
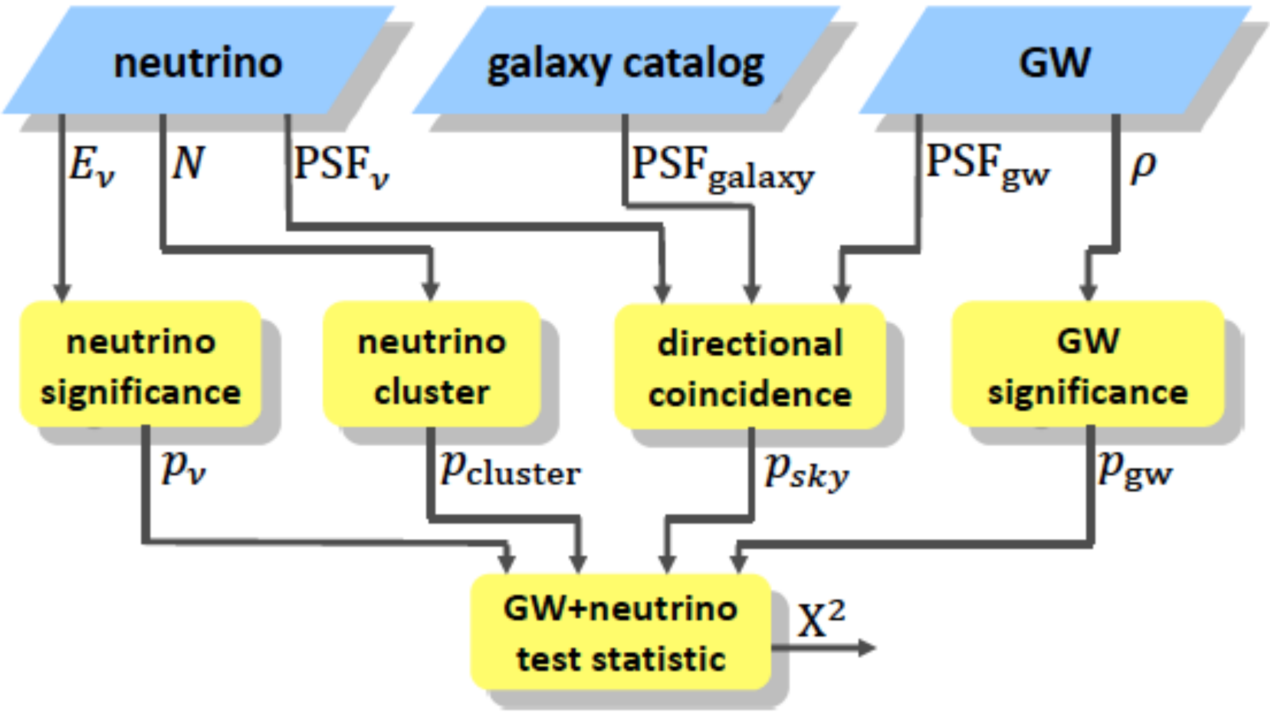

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Antarctic bedrock

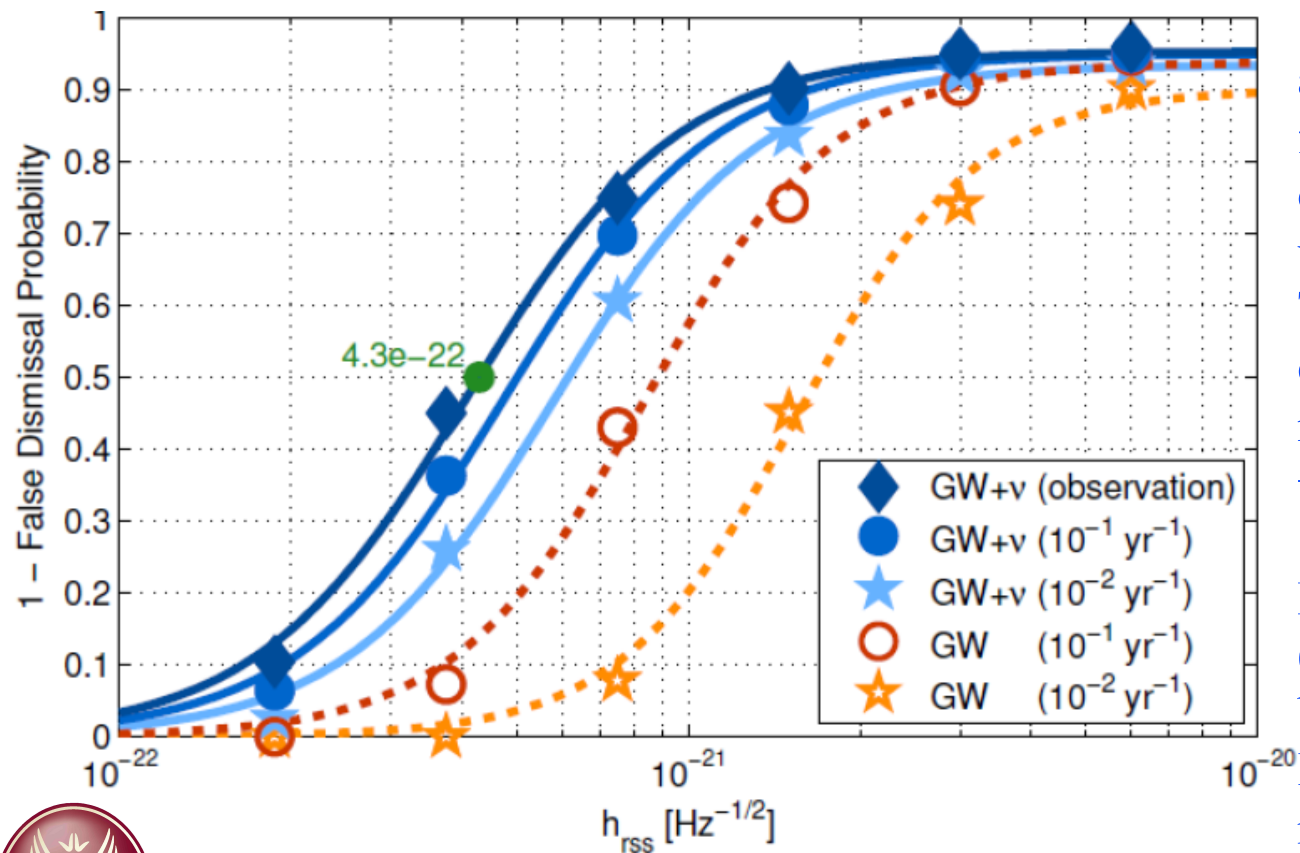
# Joint Analysis




Flow diagram of the joint GW+neutrino analysis algorithm, showing how information on neutrinos, galaxies and GWs are combined into one test statistic. PSFs denote the point spread functions of GWs and neutrinos, and the weighted directional distribution of galaxies.

Phys. Rev. D 85, 103004

# Detection prospects




Sensitivity of the joint analysis and the GW search as a function of GW $h_{rss}$, for different FARs. The FAR values are shown in the legend. The threshold "Observation" corresponds to the FAR of the most significant observed GW +neutrino event.

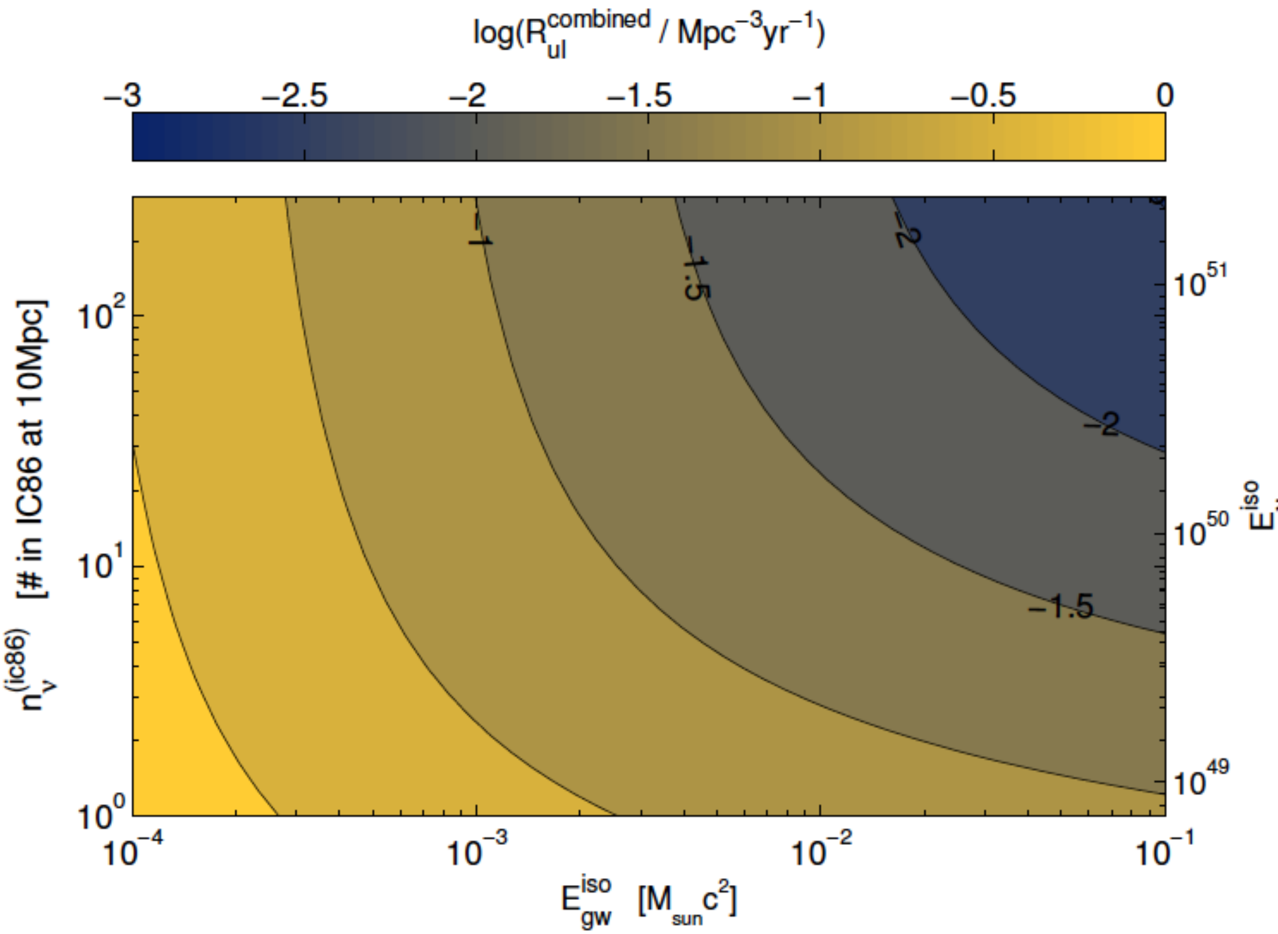
Results with initial detectors (aLIGO-Virgo will be 10x better)

Increased sensitivity with neutrinos

Phys. Rev. D 85, 103004

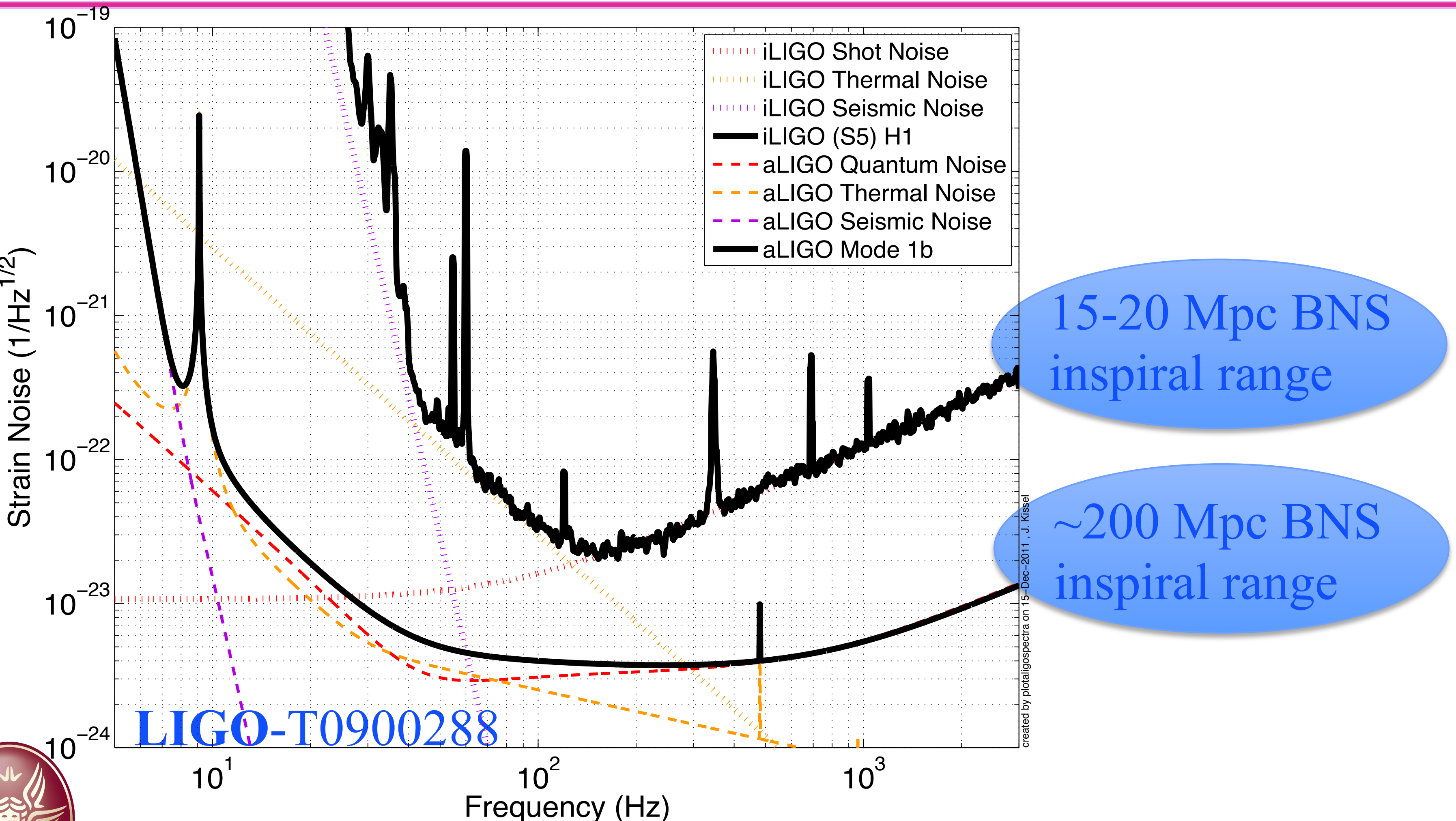
# Joint population upper limit

Joint GW+neutrino source rate upper limit of the present search as a function of isotropic-equivalent GW emission $E_{iso}^{gw}$ and neutrino emission. Neutrino emission is given both in terms of average number of neutrinos detected by IceCube with 86 strings from 10Mpc (n(ic86)), and in terms of emitted isotropic-equivalent neutrino energy ($E_{iso}$; in all flavors). The results here assume an $E^{-2}$ neutrino energy spectrum.

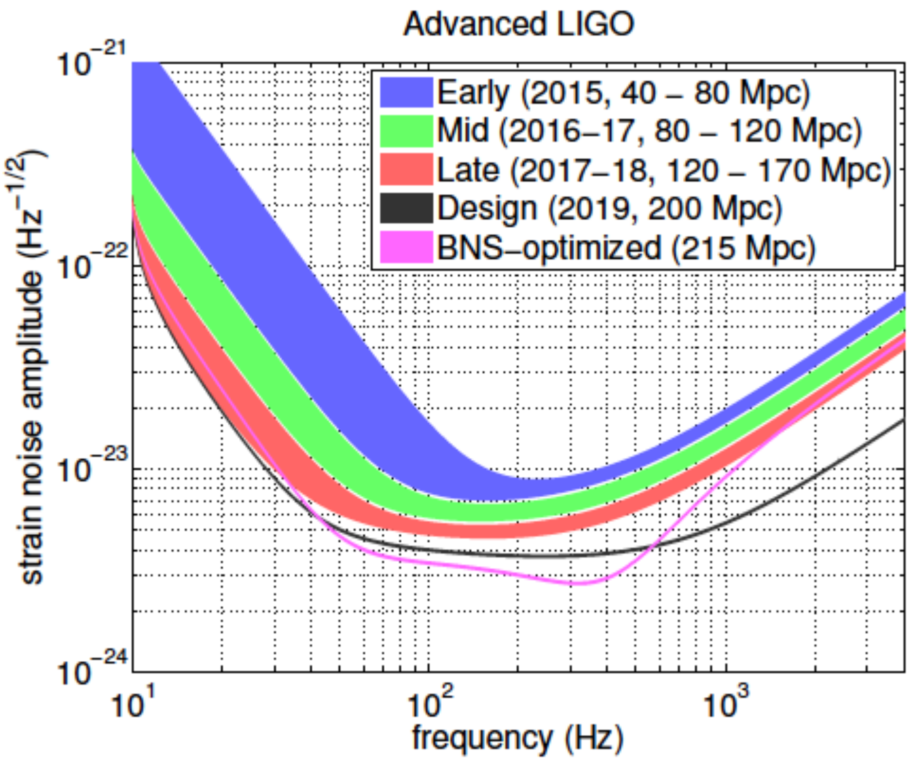


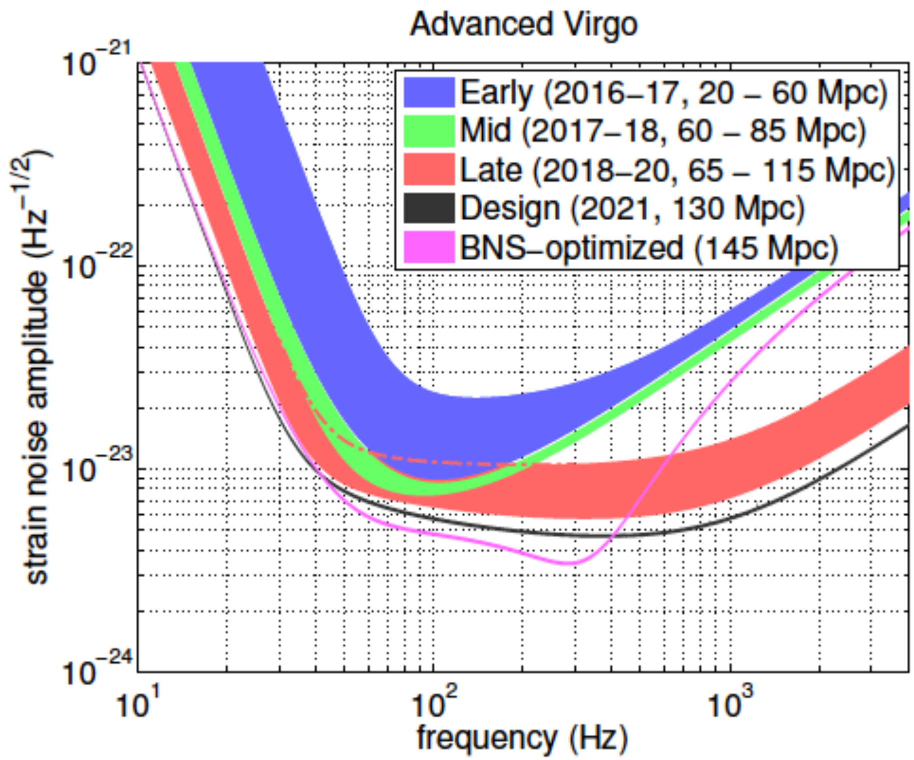

Phys. Rev. D 85, 103004

# Advanced LIGO vs. Initial LIGO

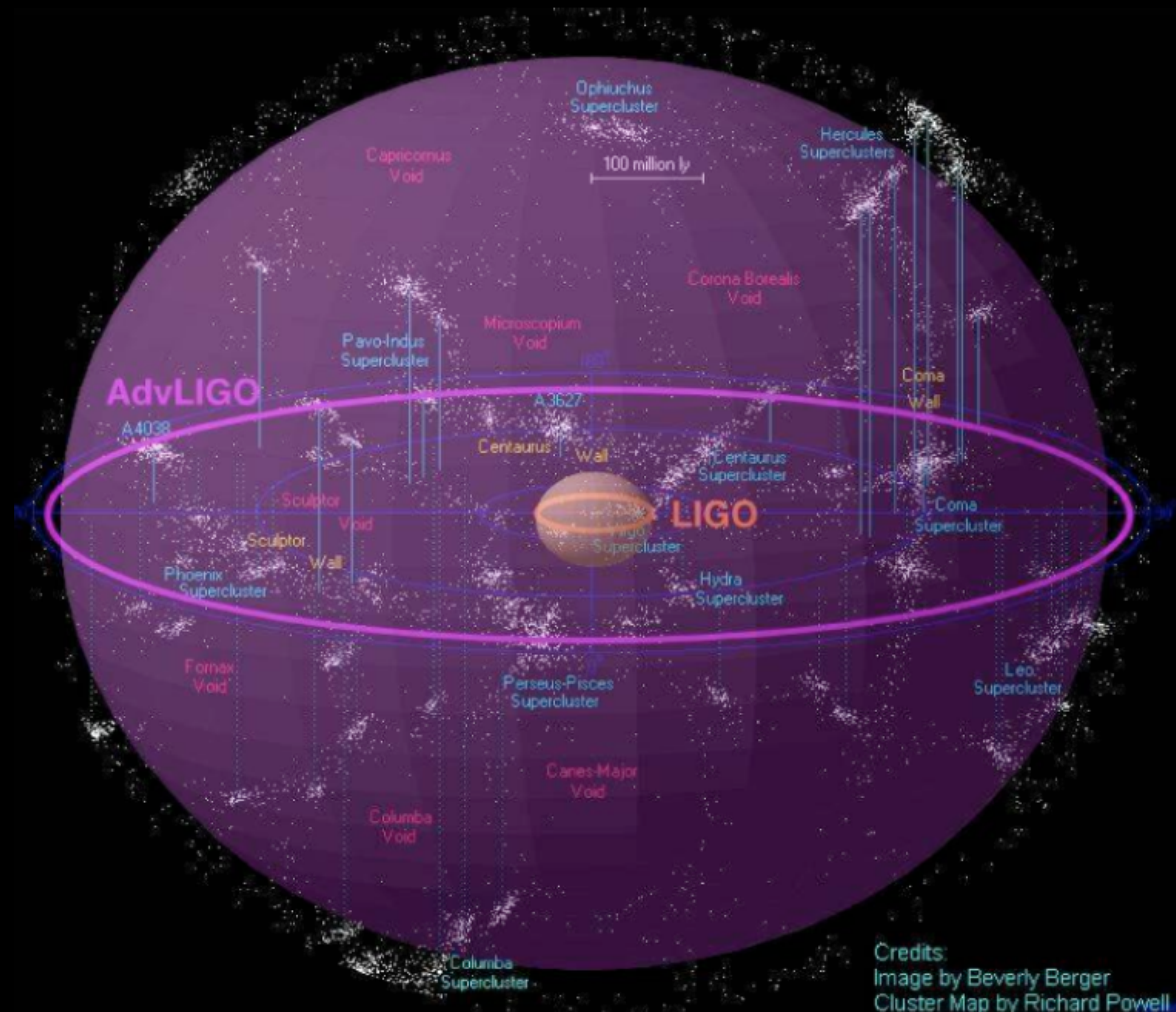


# Advanced Detector Era for LIGO and Virgo



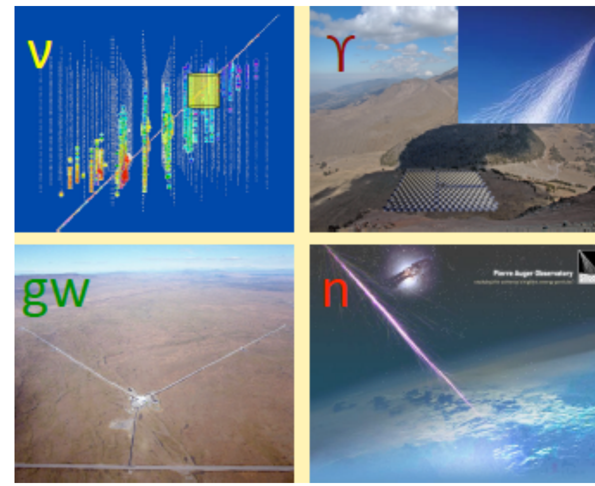

| Epoch | Estimated Run Duration | $E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) | | BNS Range (Mpc) | | Number of BNS Detections | % BNS Localized within | |
|---|---|---|---|---|---|---|---|---|
| | | LIGO | Virgo | LIGO | Virgo | | 5 deg$^2$ | 20 deg$^2$ |
| 2015 | 3 months | 40 – 60 | – | 40 – 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 |


Ophiuchus Supercluster
Hercules Superclusters
Capricornus Void
100 million ly
Corona Borealis Void
Microscopium Void
Pavo-Indus Supercluster
AdvLIGO
A4038
A3627
Coma Wall
Centaurus Wall
Centaurus Supercluster
Sculptor Void
Sculptor Wall
LIGO
Supercluster
Coma Supercluster
Phoenix Supercluster
Hydra Supercluster
Fornax Void
Perseus-Pisces Supercluster
Leo Supercluster
Canes-Major Void
Columba Void
Columba Supercluster
Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

# AMON

Astrophysical Multimessenger Observatory Network

AMON is a consortium of observatories and shared cyber infrastructure

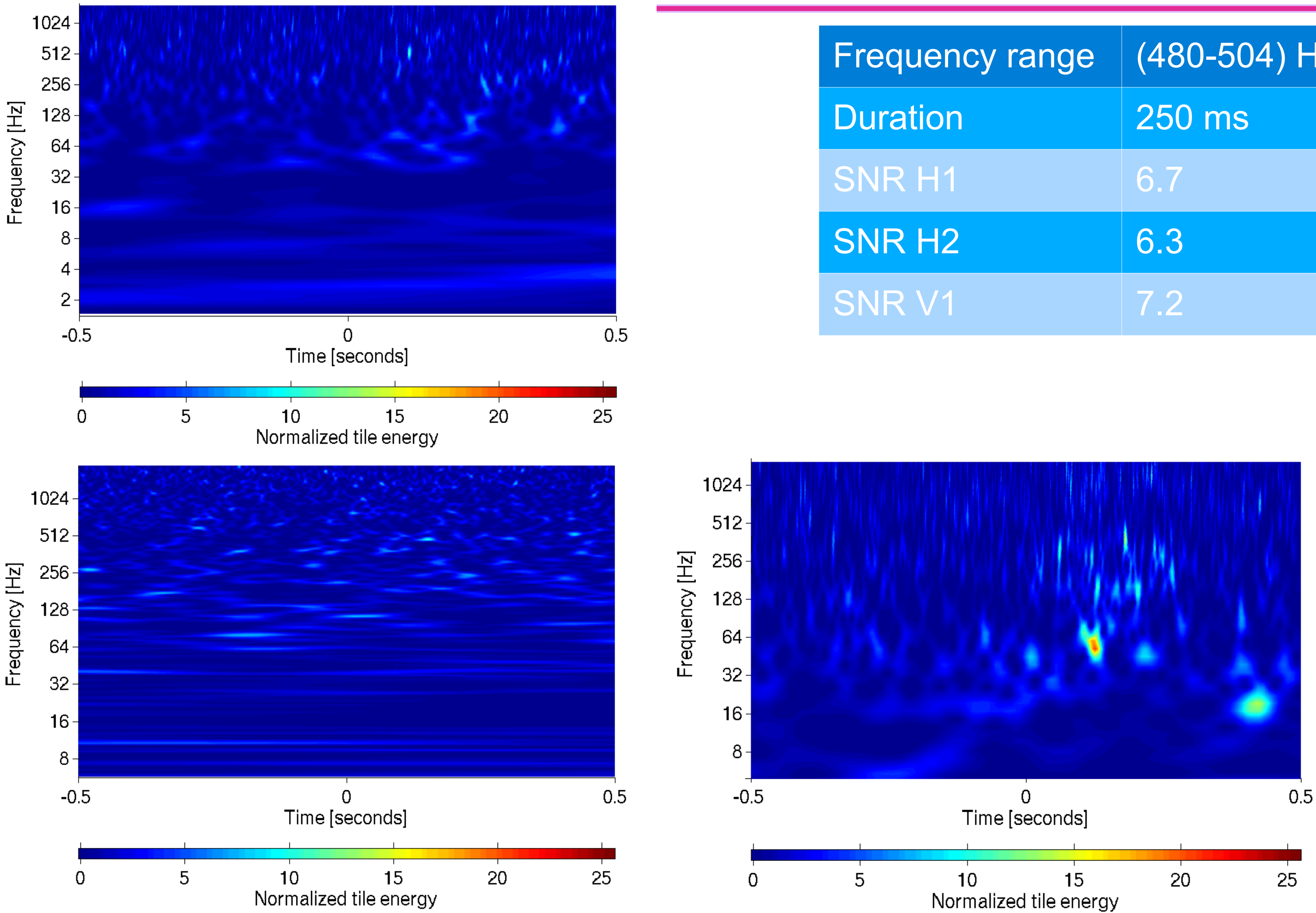



- Will enable searches for multimessenger coincidences using particles representing the four fundamental forces.
- Provides framework for real-time coincidence searches of data in direction and time.
- Broadcasts real time alerts (via VOEvent & GCN).

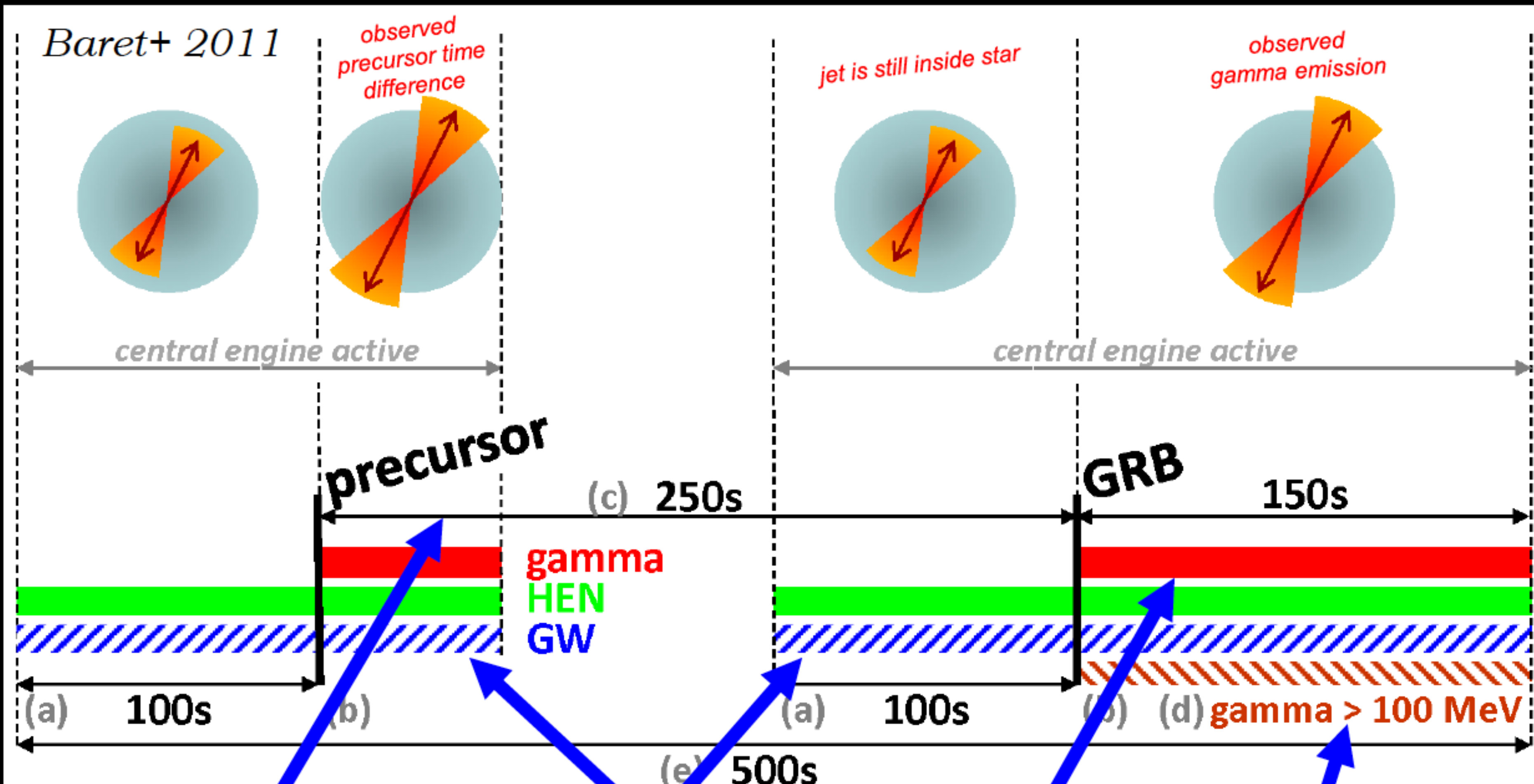

THANK YOU

# Original data: no evident signal signature

| Frequency range | (480-504) Hz |
| --- | --- |
| Duration | 250 ms |
| SNR H1 | 6.7 |
| SNR H2 | 6.3 |
| SNR V1 | 7.2 |



# Coincident time window



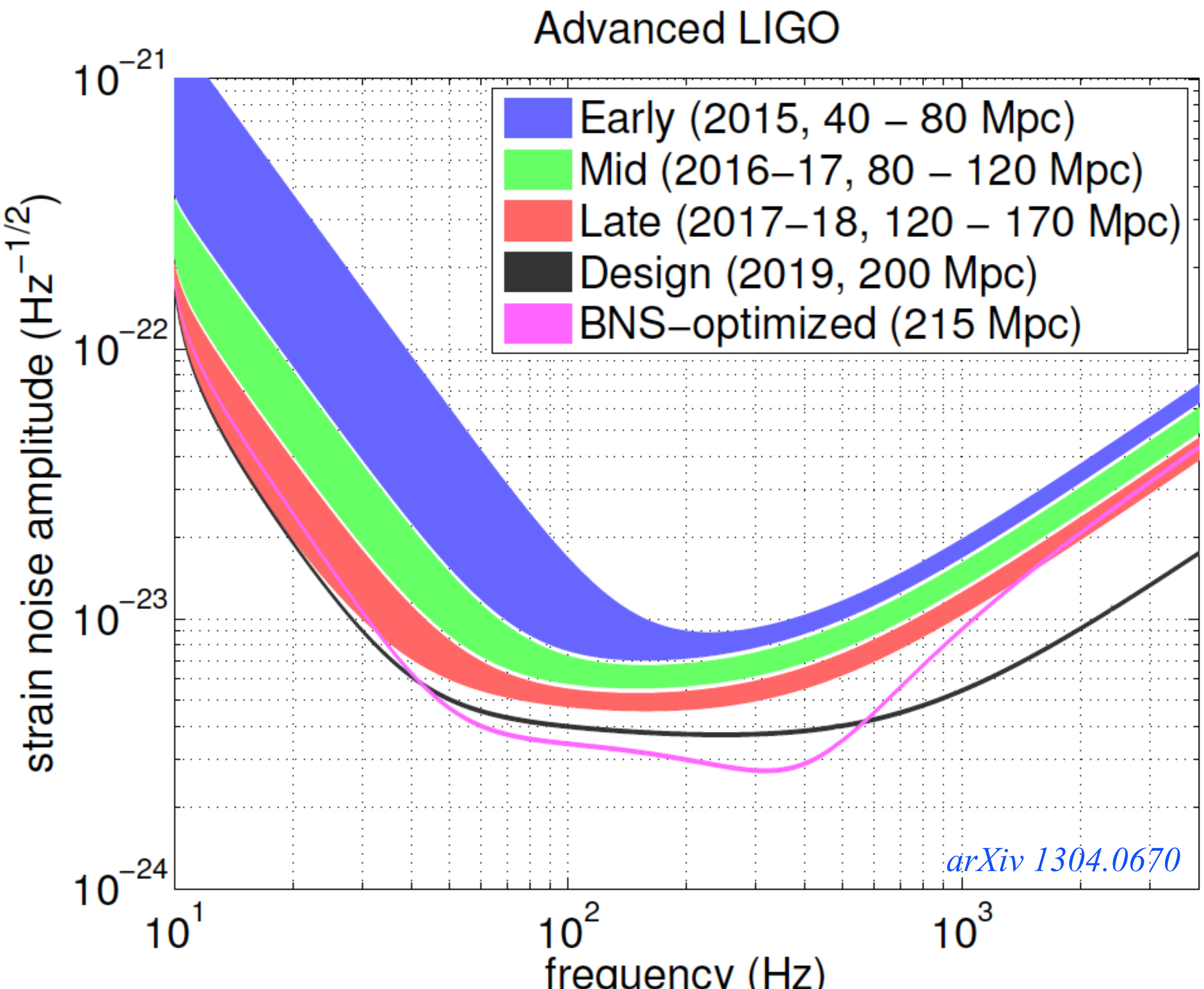

**BATSE precursors (374)**
Burlon et al., 2008

**Ott, 2009 ++**

**BATSE GRBs (~1200)**
**> 100 MeV photons from Fermi**

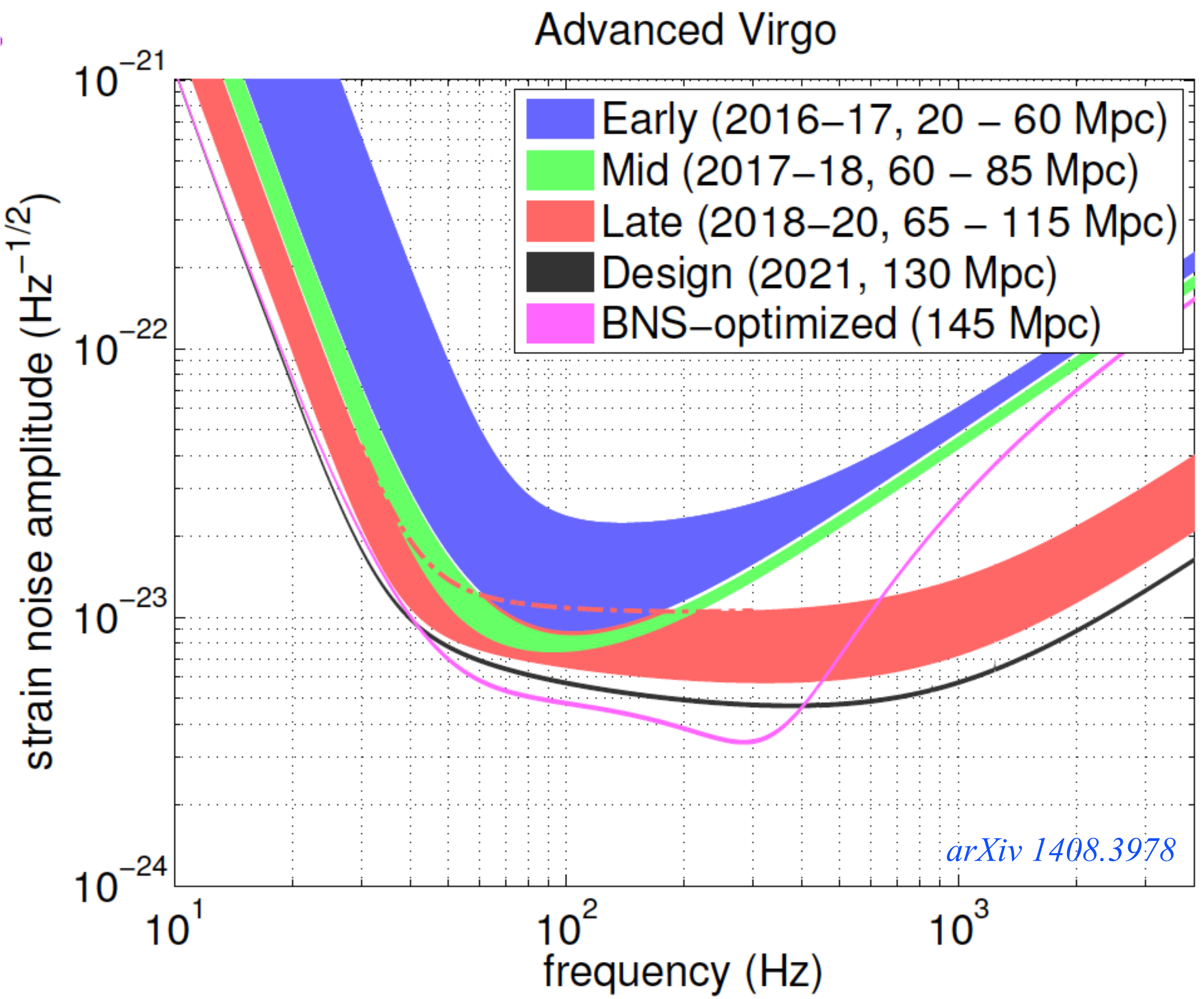
**Coincidence time window: 500s**

# Advanced LIGO Evolution




- A standard figure of merit for the sensitivity of an interferometer is the binary neutron star range: the volume and the orientation average distance at which a compact binary coalescence, consisting of two 1.4 $M_{sun}$ neutron stars, gives a matched filter signal-to-noise-ratio of 8 in a single detector.
- 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.

# Advanced Virgo Evolution




- 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.

# Estimated observing scenario

| 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 |

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 $10^{-2}\,{\rm yr}^{-1}$. 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.

*arXiv 1304.0670*