Searches for Gamma Ray coincidences with GW detectors

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for the LIGO Scientific Collaboration and the Virgo Collaboration

GW: ripples in the Cosmic Sea

- Linearized Einstein equations admit wave solutions

$$\boxed{\mathbf{G} = \frac{8\pi G}{c^4}\mathbf{T}}$$

$$\mathbf{g} = \eta + \mathbf{h} \quad \text{with} \left|h_{\mu\nu}\right| << 1 \;\Rightarrow\; \left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)h_{\mu\nu} = 0$$

- **GW**: transverse space-time distortions propagating at the speed of light, 2 independent polarization

$$\mathbf{h}(z,t) = e^{i(\omega t - kz)}\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

- In SN collapse ν withstand 10^3 interactions before leaving the star, the GW leave the core *undisturbed.* **Ideal information carrier**

strong	*e.m.*	*Weak*	*gravity*
0.1	1/137	10^{-5}	10^{-39}

Plausible target GW amplitude

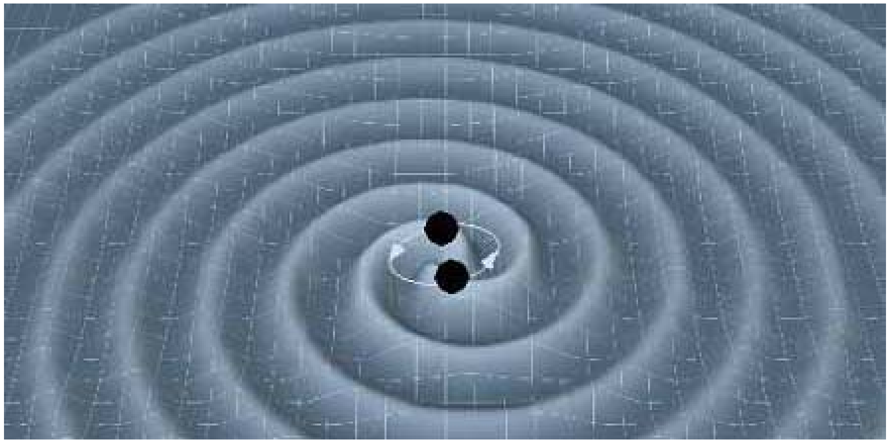
- Luminosity: $$P = \frac{G}{5c^5} < \dddot{Q}^{ij} \dddot{Q}_{ij} > \approx \varepsilon \cdot \frac{c^5}{G} \left(\frac{R_S}{R} \right)^2 \left(\frac{v}{c} \right)^6$$

- Amplitude: $$h_{\mu\nu} = \frac{2G}{c^4} \cdot \frac{1}{r} \ddot{Q}_{\mu\nu}$$

<u>Compactness C</u>
1 for BH
0.3 for NS
10^{-4} for WD

Efficient sources of GW must be **asymmetric**, **compact** and **fast**

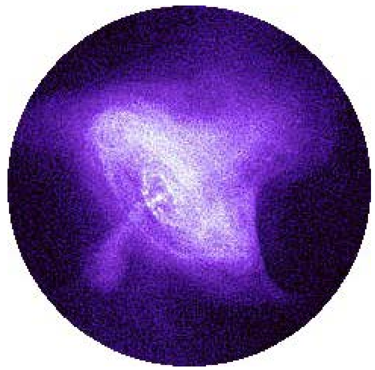
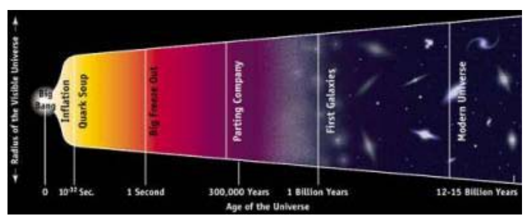
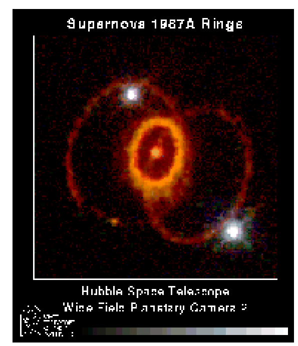
GW detectors sensitivity expressed in amplitude h : $1/r$ attenuation



Example target amplitude:
coalescing NS/NS in the Virgo cluster
(r ~10 Mpc)

$h \sim 10^{-21}$

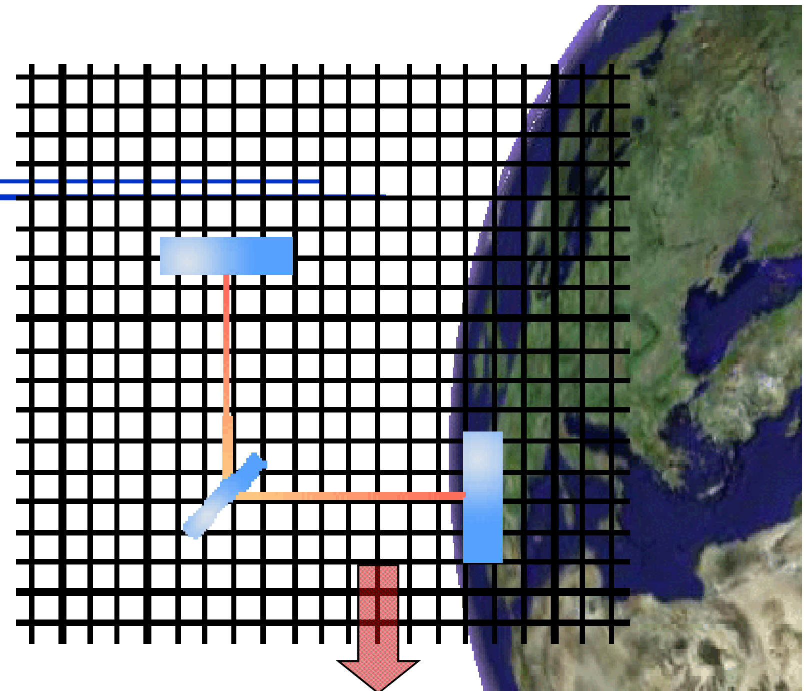
Synopsis of sources

	LONG DURATION	SHORT DURATION
MATCHED FILTERING	 Rotating NS	 Coalescing compact binaries
TEMPLATE-LESS METHODS	 Stochastic GW	 Supernovae

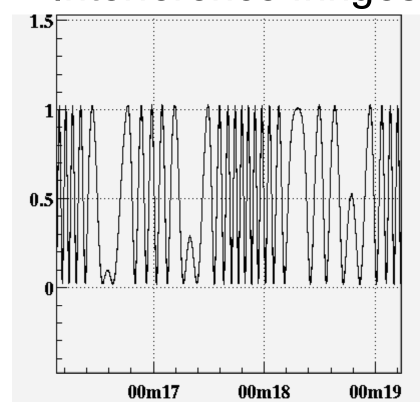
Principle of Detection

GW induce space-time deformation

Measure space-time strain using light



Interference fringes



$$\boxed{\Delta L \approx \frac{1}{2} h L}$$

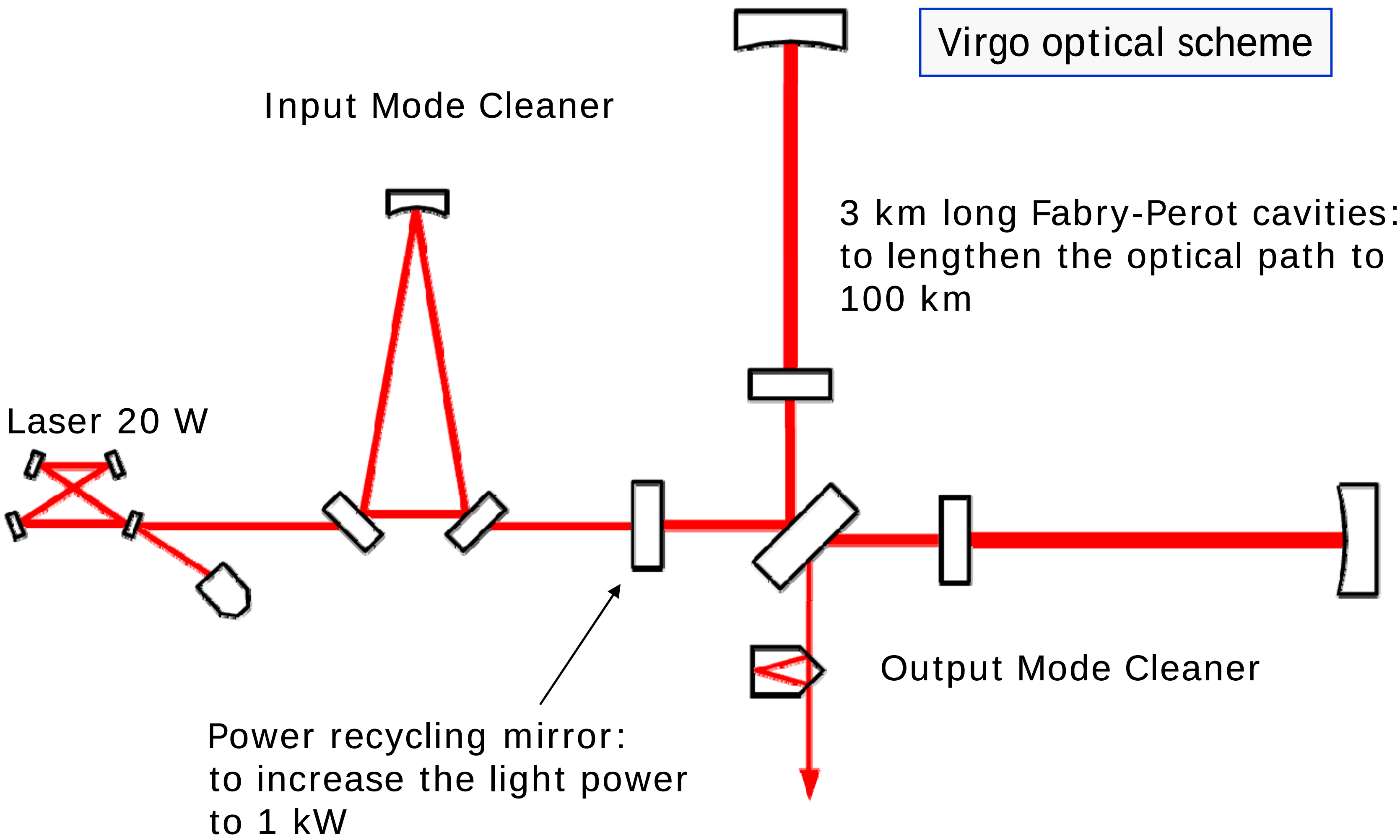
Target h ~ 10^{-21}
(NS/NS @Virgo Cluster)

Feasible L ~ 10^{3} m

Need to measure: $\Delta L \sim 10^{-18}$ m

Big challenge for experimentalists!

A real detector scheme



Super mirrors

Fused silica mirrors

35 cm diam, 10 cm thick, 21 kg

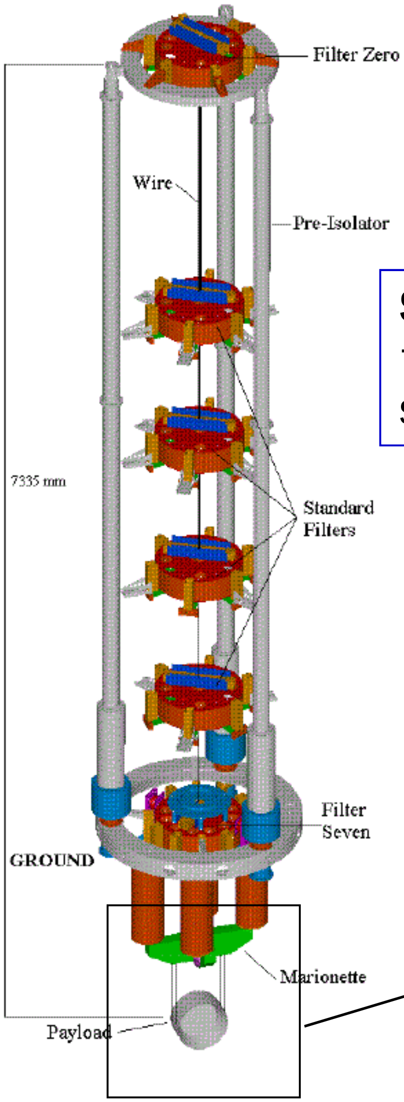
Scattering losses: a few ppm

Substrate losses: 1 ppm

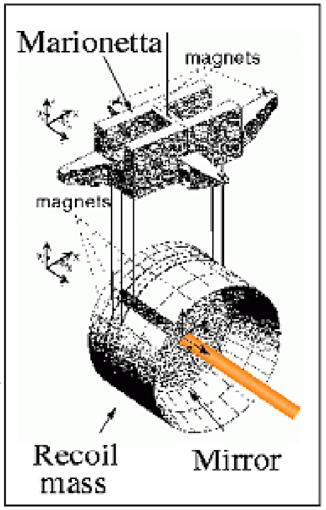
Coating losses: <5 ppm

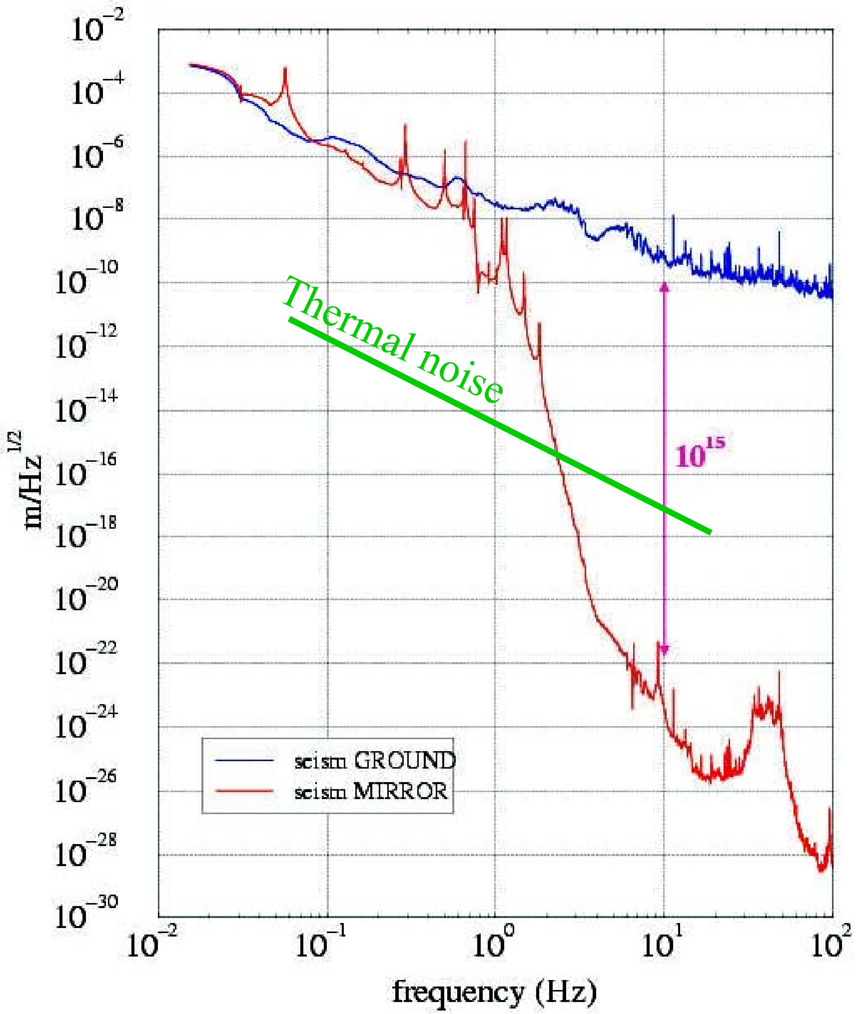
Surface deformation: $\lambda/100$

VIBRATION ISOLATION

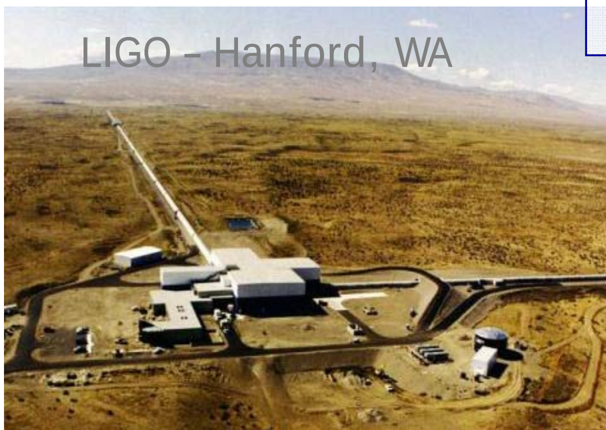


Superattenuator: filters off the seismic vibrations.





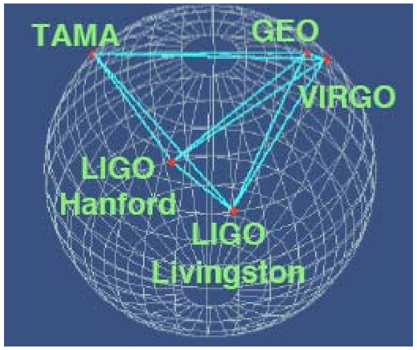
The GW detectors network



A network of 4 (5) GW detectors

Virgo and the LIGO Scientific Collaboration have signed a MoA for full data exchange and joint data analysis and publication policy

Benefits by the LIGO-Virgo network

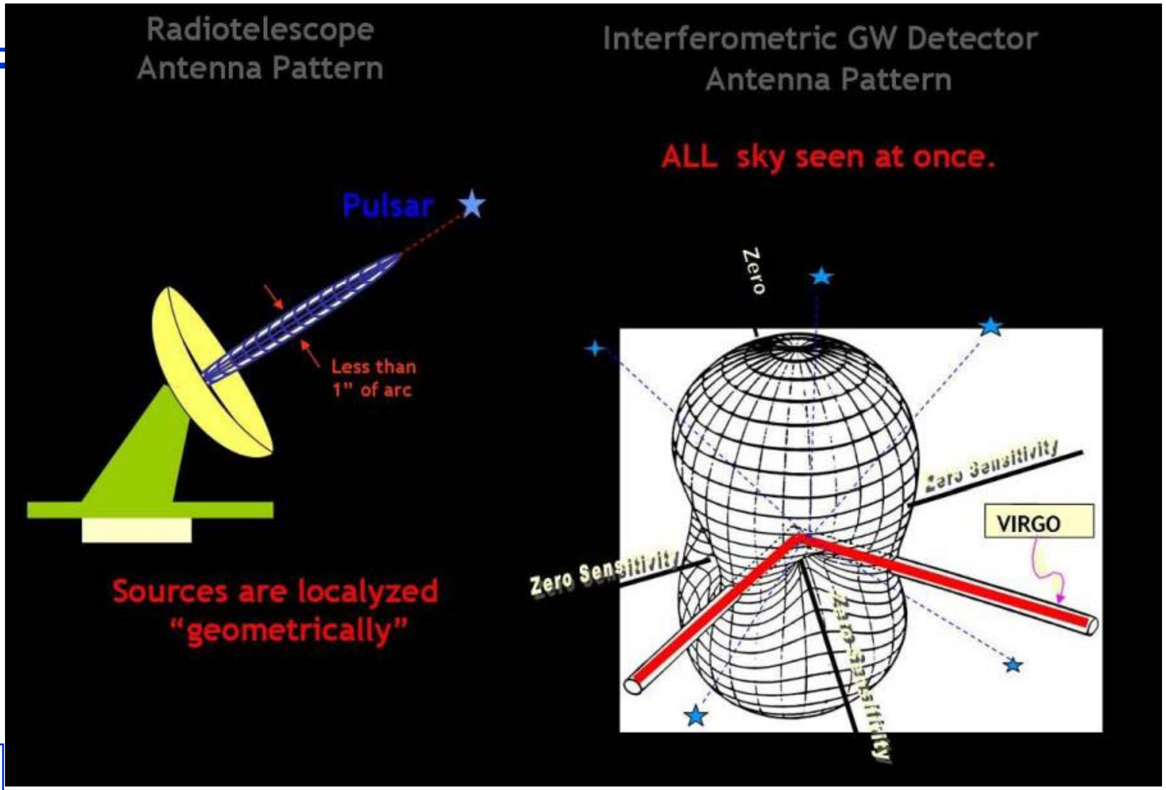


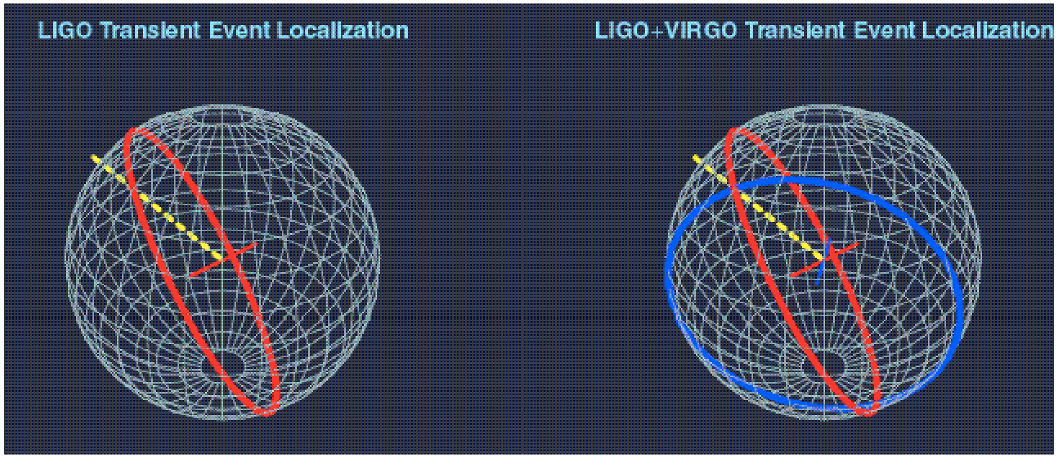
False alarm rejection thanks to coincidence

Triangulation allowing to **pinpoint the source**

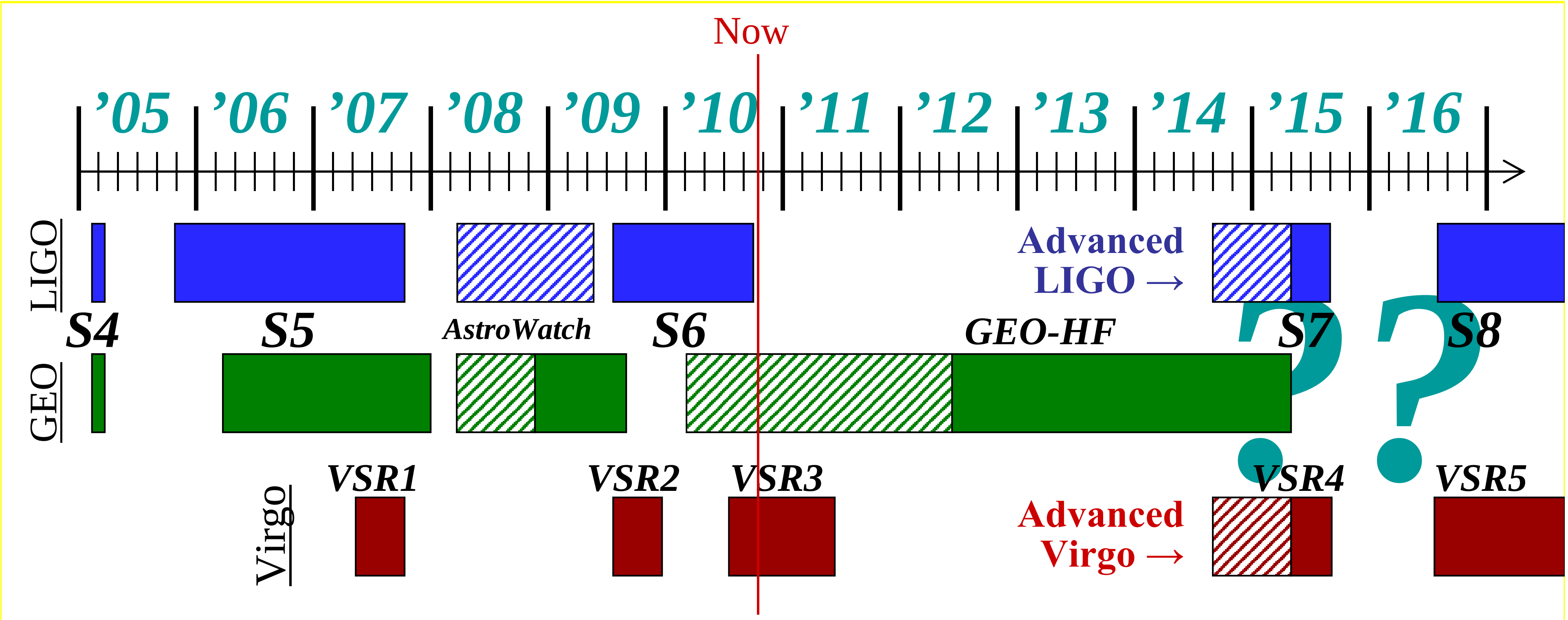
A network allows to deconvolve detector response and regress signal waveform --> **measure signal parameters, including source distance for BNS signals**

Joint operation yields a longer **observation time**, and a better **sky coverage**





Science runs

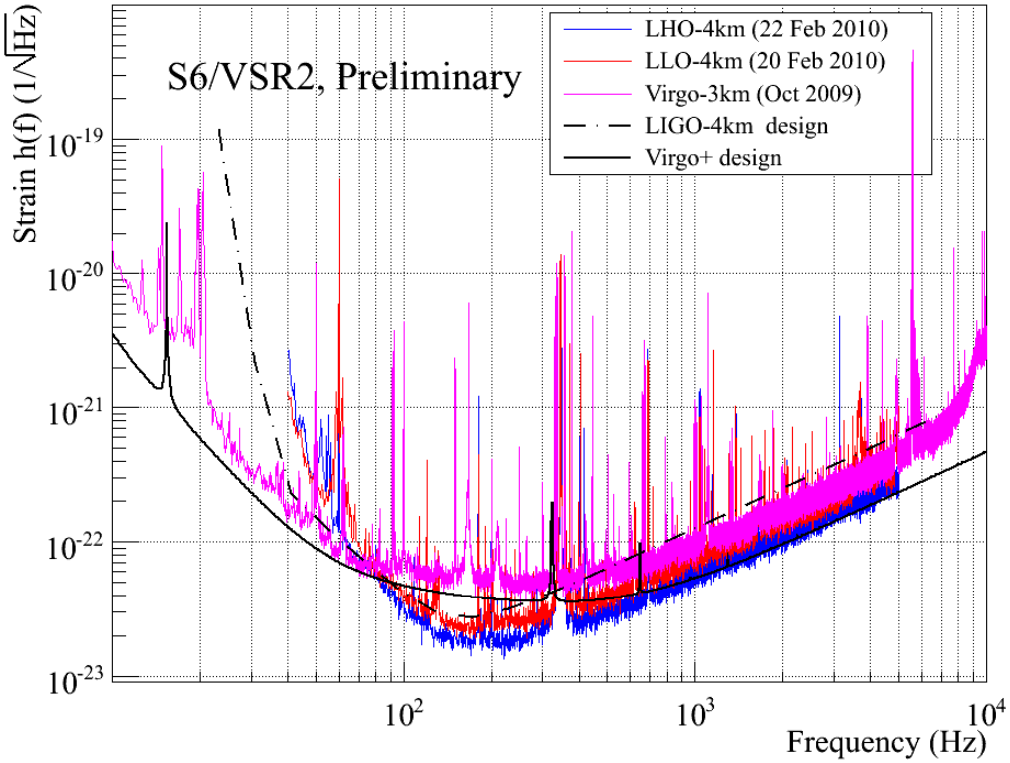


Advanced detectors should be 10 times more

Probe 1000 larger universe volume !

LSC - Virgo sensitivities

- Same HF sensitivity
- LIGO at design sensitivity since S5, already in 2007 !
- Virgo reached design during VSR2, in 2009
- By design, LIGO better in the intermediate range, Virgo better at low frequencies



The last decade has seen the demonstration of GW interferometers technology.

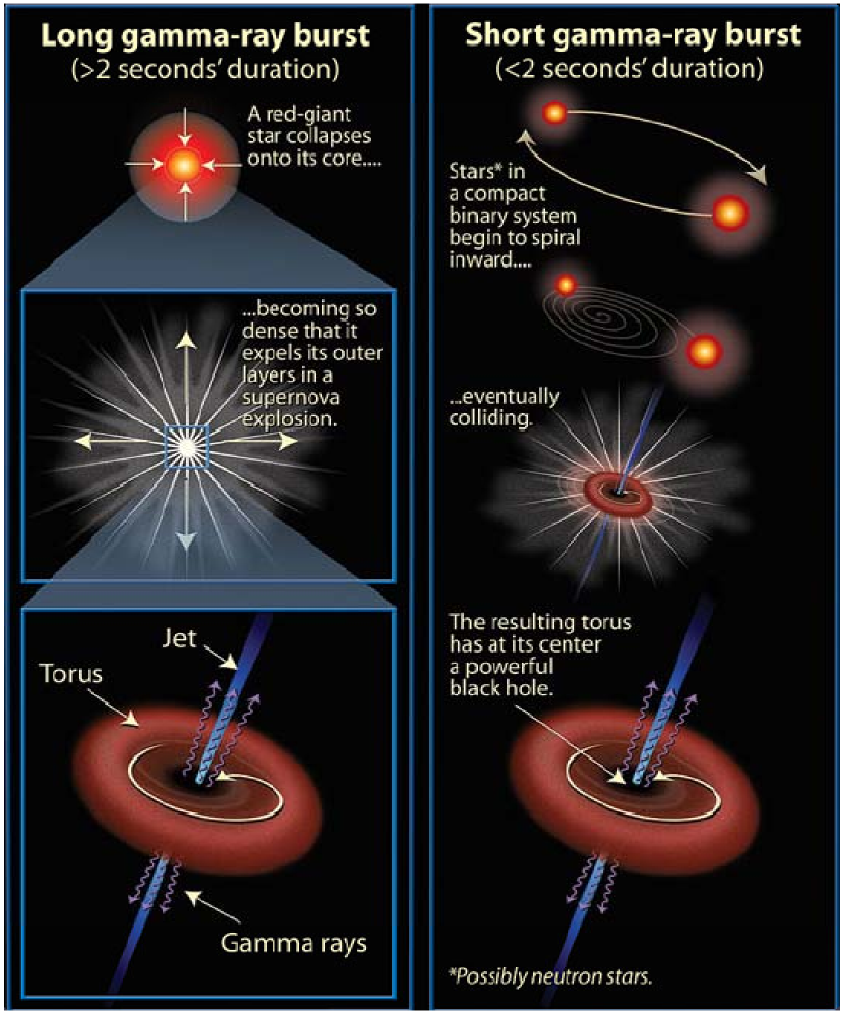
Design sensitivity reached, high duty cycle is O(90%)

NO DETECTION, YET

GRB - triggered searches of GW events

Long GRBs:

- Core-collapse "hypernovae"
- Modelling is complicated; GW emission not well understood.
- Use "burst" detection methods (less sensitive, more robust)
- **Burst search**

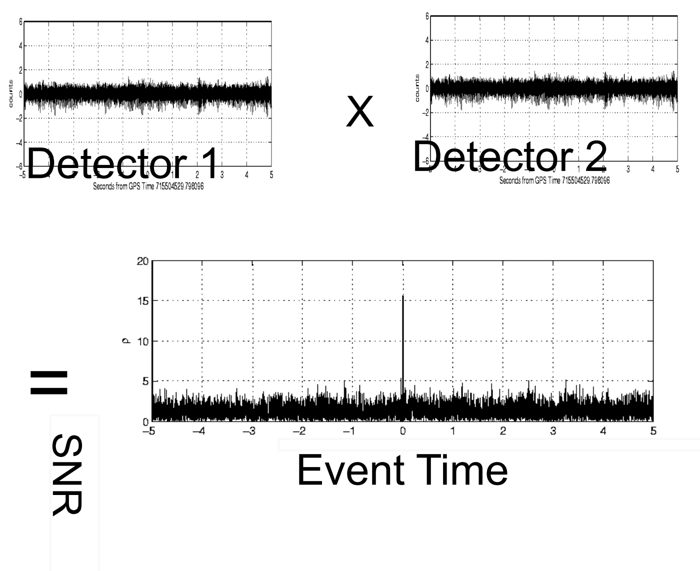


Short GRBs:

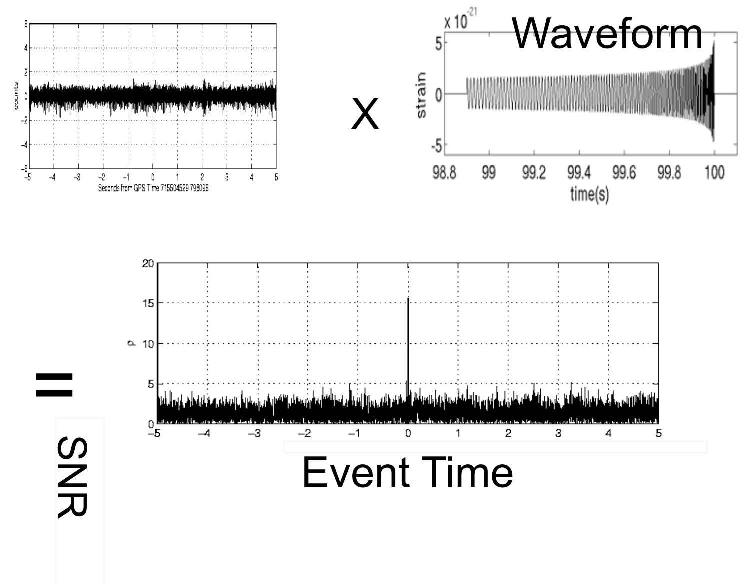
- Coalescence of NS-NS or NS-BH binaries.
- Inspiral due to GW emission, clean signal; well understood waveform.
- Use "matched filtering" (more sensitive, but only for precise waveform)
- **Inspiral search**

Oversimplified analysis strategy

- ## Burst search:
  - Looking for excess power coherently from different detectors
  - Cross-correlation between data of different sites
  - Sensitive to unknown waveform with duration between 1ms to 1s
  - Analyzing data around each GRB

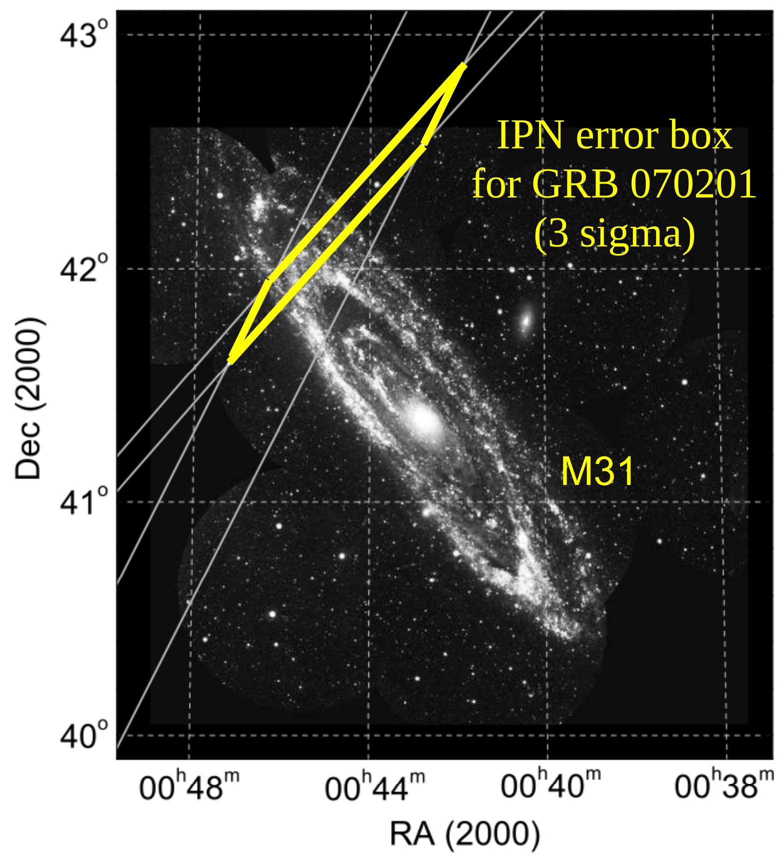


- ## Inspiral search:
  - Matched filtering
  - Coincidence between different sites required
  - Template-based (known waveform)
  - Favored signal for 'short' GRBs, but applied to all GRBs.



Example: GRB 070201

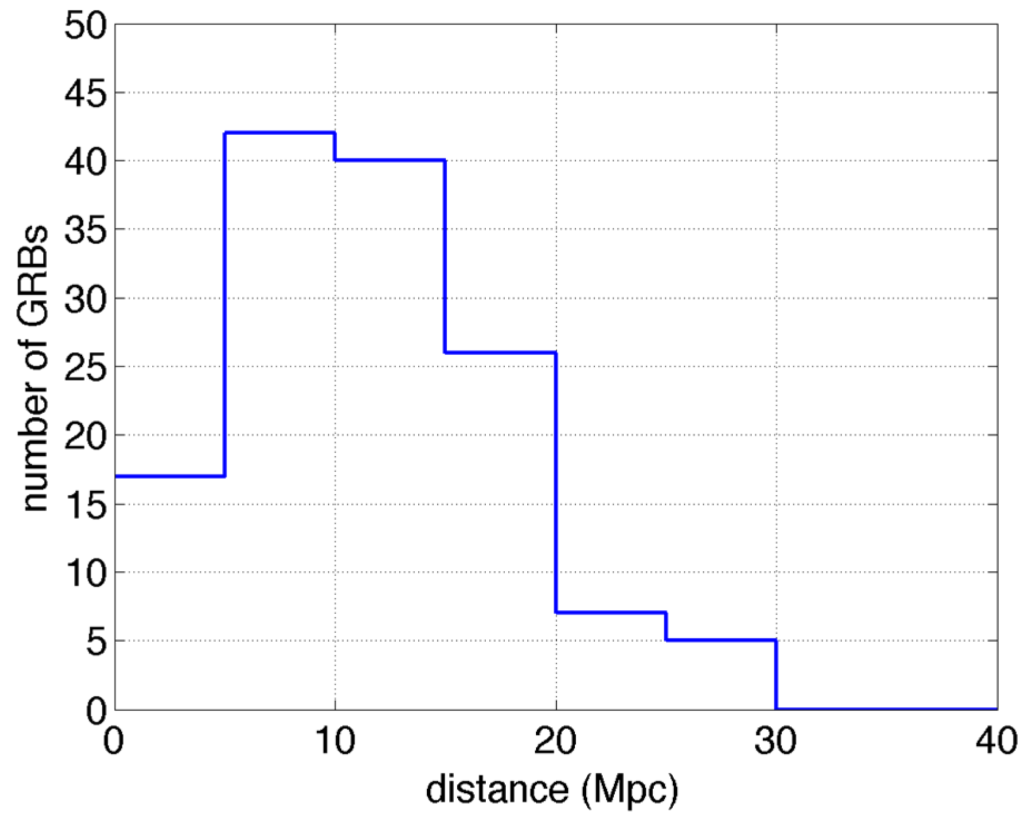
- A short GRB observed in direction of M31.
- Inspiral Merger in M31 excluded at >99% C.L. [1]
- GRB *probably* merger farther away or a SGR in M31 [2,3]
- Burst search: energy emitted at 150Hz at M31 distance less than 7.9×10^{50} ergs ($\sim 4.4 \times 10^{-4}\ M_{\odot}$) within 100 ms.



[1] Abbott et.al., ApJ 681, 1419 (2008)
[2] Mazets et.al., ApJ 680, 545 (2008)
[3] Ofek et.al., ApJ, 681, 1464 (2008)

S5/VSR1 GRB burst searches

- Data spanning 2005-2007
- Analysed 137 GRBs (long *and* short) with coincident LIGO-Virgo data, looking for generic GW bursts.
- 90% CL distance limits assuming $E_{GW} = 0.01\ M_o\ c^2 \sim 10^{52}$ ergs at 150 Hz.



Abbott et al. (LSC & Virgo), arXiv:0908.3824;
ApJ 715, 1438 (2010)

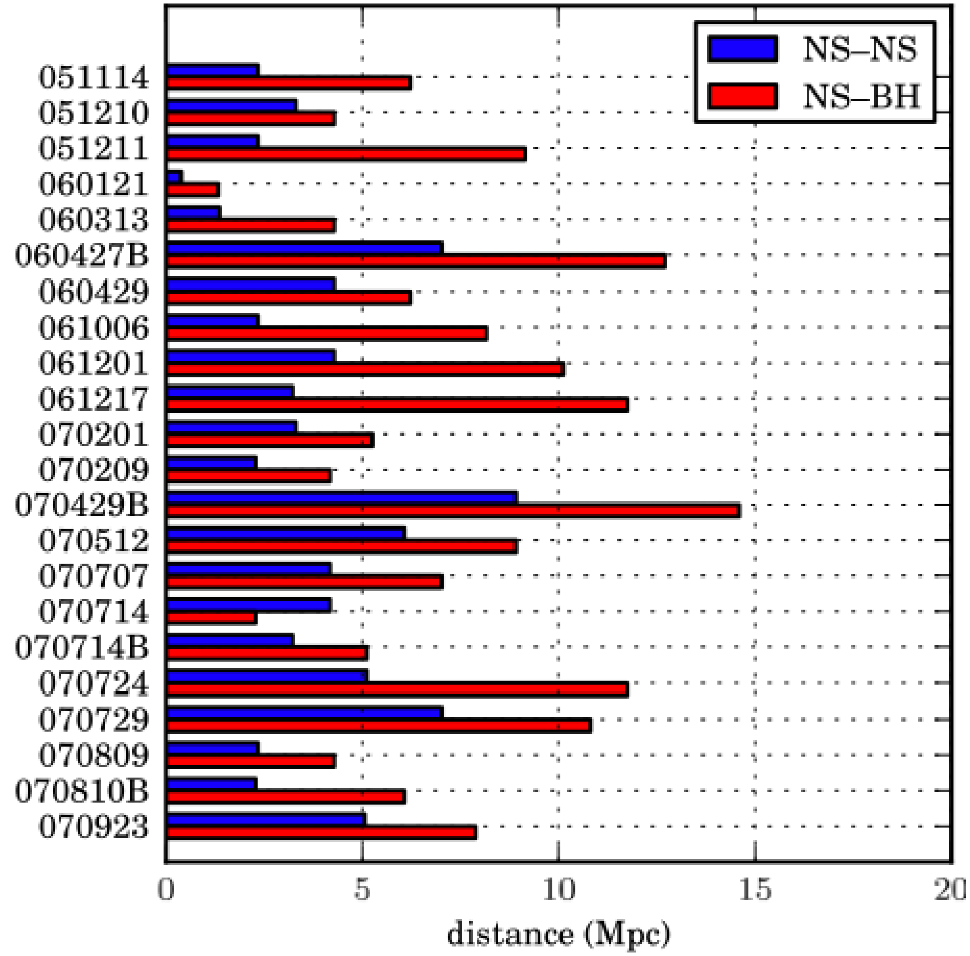
E_{GW} references:

- Short GRBs: Merger of NS-BH: 0.01-0.1 Msol c^2 in 100-200Hz
- Long GRBs: Davies et al., 2002, ApJ, 579, L63, King et al., 2005, ApJ, 630, L113

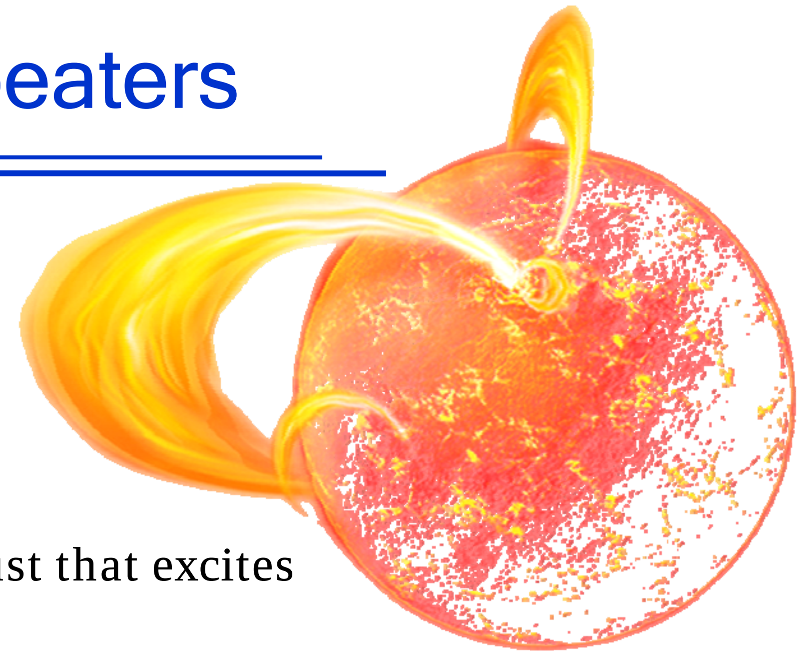
S5/VSR1 GRB inspiral searches

- Analysed 22 *short* GRBs with coincident LIGO-Virgo data, looking for inspiral signal.
- Median 90% CL distance limits
  - NS-NS: (1.4/1.4) $M_\odot$: 3.3 Mpc
  - BH-NS: (1.4/10) $M_\odot$: 6.7 Mpc

Abbott et al. (LSC & Virgo), arXiv:1001.0165. ApJ 715, 1454 (2010)



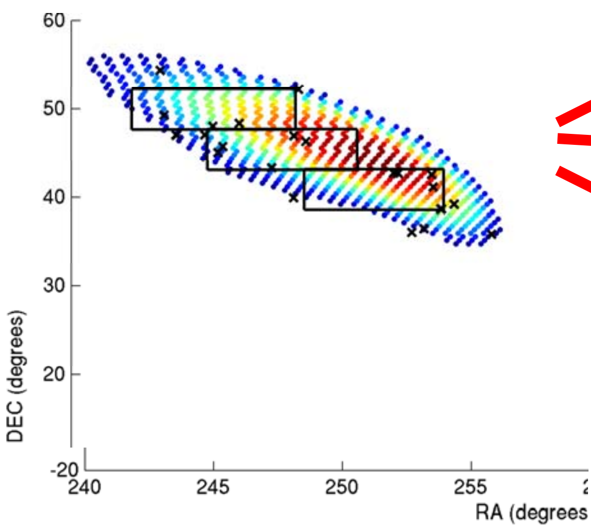
GW from Soft Gamma Repeaters

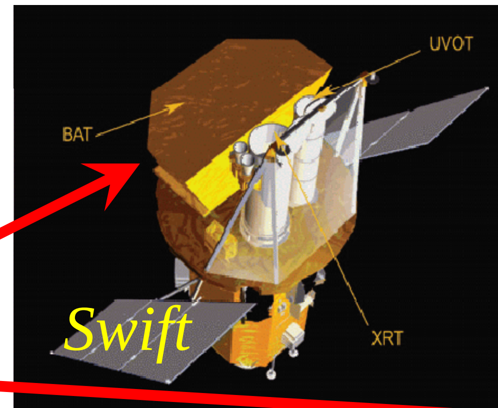


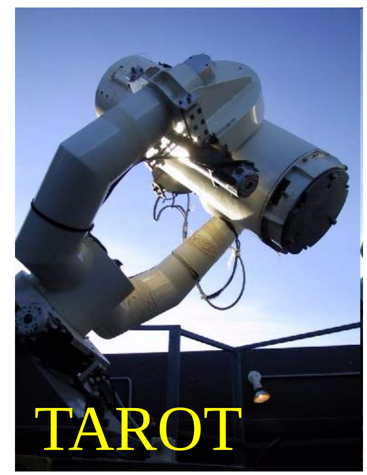
- **SGRs are believed to be magnetars**
  - Occasional flares of soft gamma rays
  - May be associated with cracking of the crust that excites vibrational f-modes of the neutron star
- **LIGO searched for GW signals associated with SGR flares**
  - Dec. 2004 “giant” flare of SGR 1806–20
  - 190 flares from SGR 1806–20 and SGR 1900+14 during first year of S5
  - Placed upper limits on GW signal energy for each flare
  - *[PRL **101**, 211102 (2008)]*
  - Within the energy range predicted by some models
- LIGO also searched for GW signals matching the quasiperiodic oscillations seen in X-rays in the tail of the Dec. 2004 giant flare
  - Placed upper limits *[PRD **76**, 062003 (2007)]*

Electromagnetic Follow-Ups to GW Triggers

- Analyze GW data *promptly* to identify event candidates and reconstruct their apparent sky positions; alert telescopes
  - Try to capture an EM transient that would otherwise have been missed !
  - **First attempts underway**

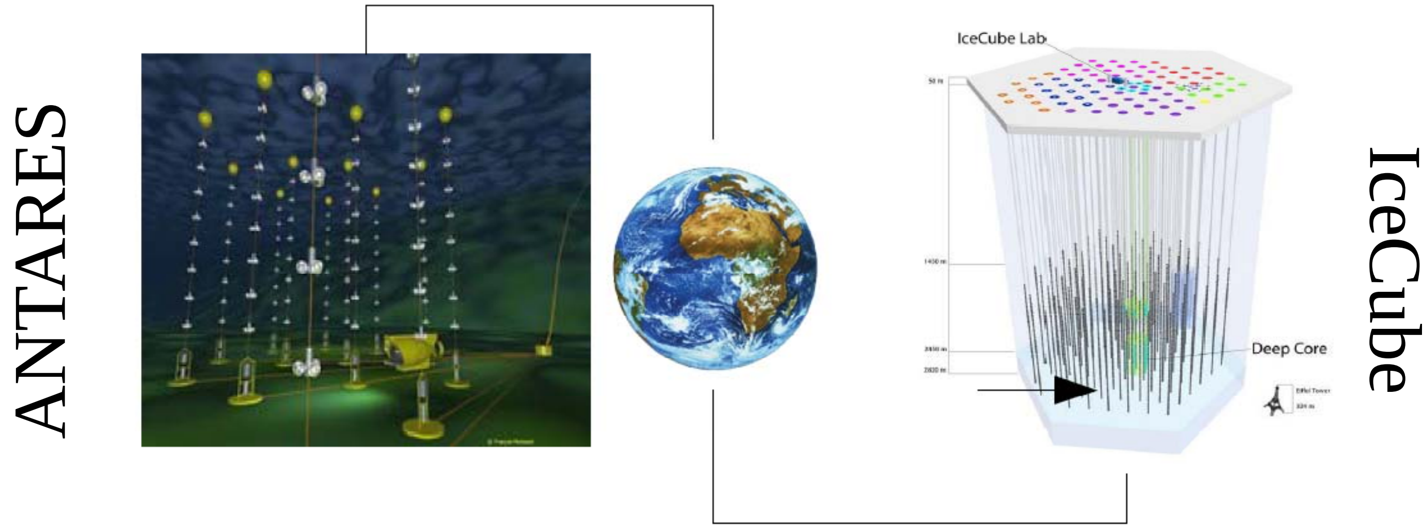






Additional Messengers

- **High-energy neutrinos**
  - Models for emission from GRBs – even “failed GRBs”
  - Joint searches <u>planned</u> with neutrino telescopes



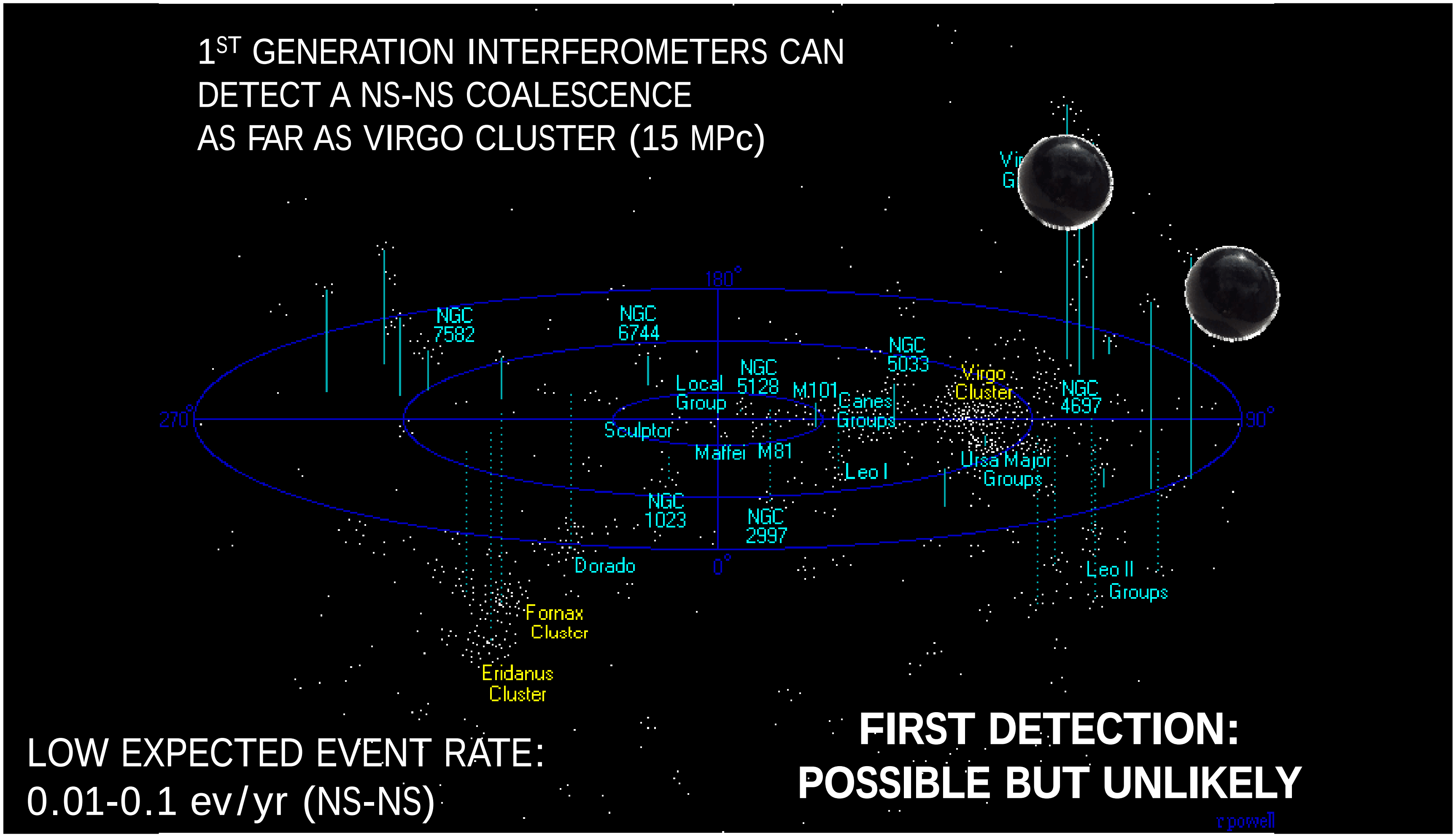
- **Radio transients**


Arecibo

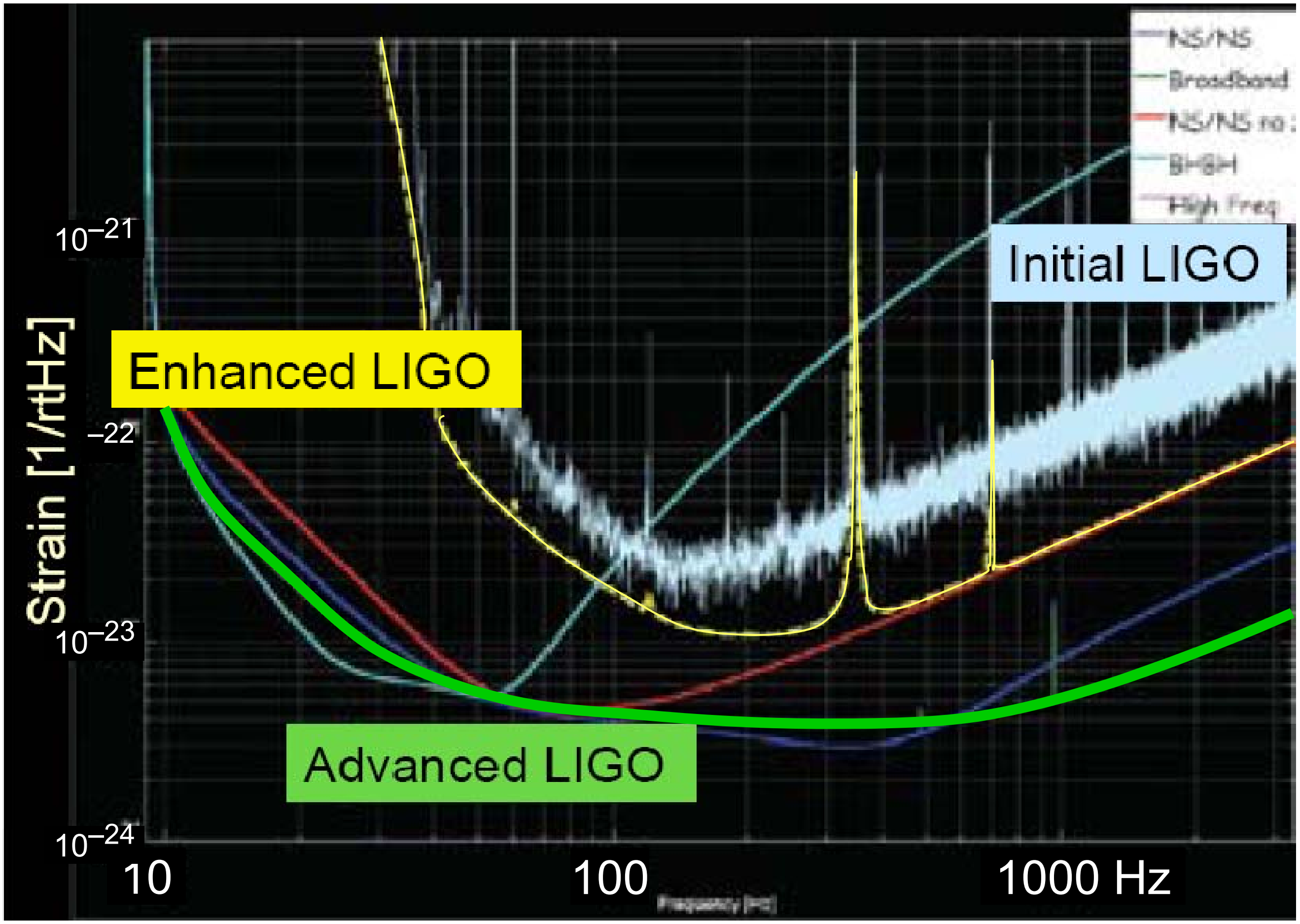

Green Bank


LOFAR

1st generation detection chances



Advanced LIGO Projected Sensitivity



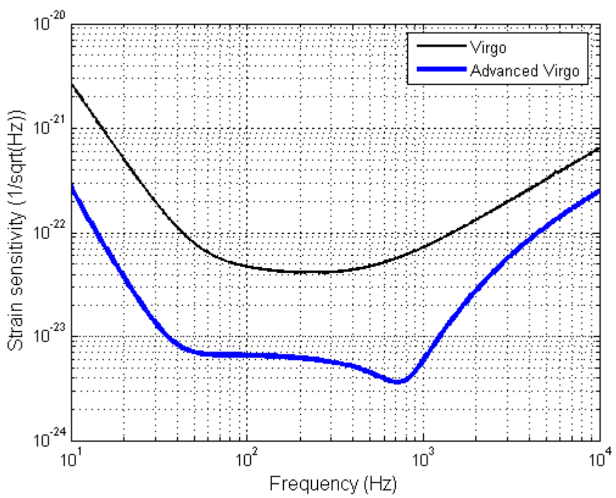
Factor of ~10 in amplitude sensitivity

Factor of ~1000 in volume

Advanced LIGO is approved and funded; construction has begun

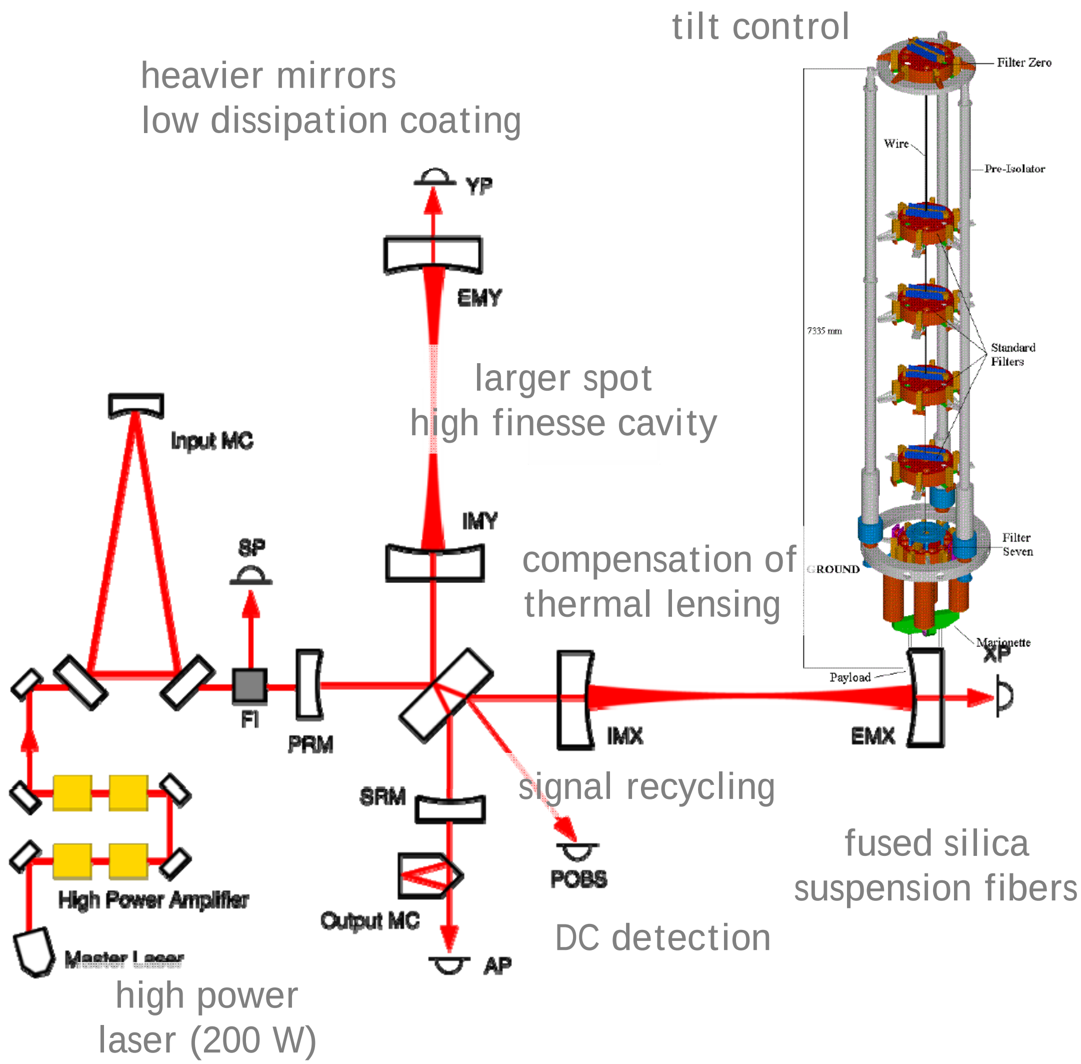
Expect to be operational starting in 2014 or 2015

Adv design features



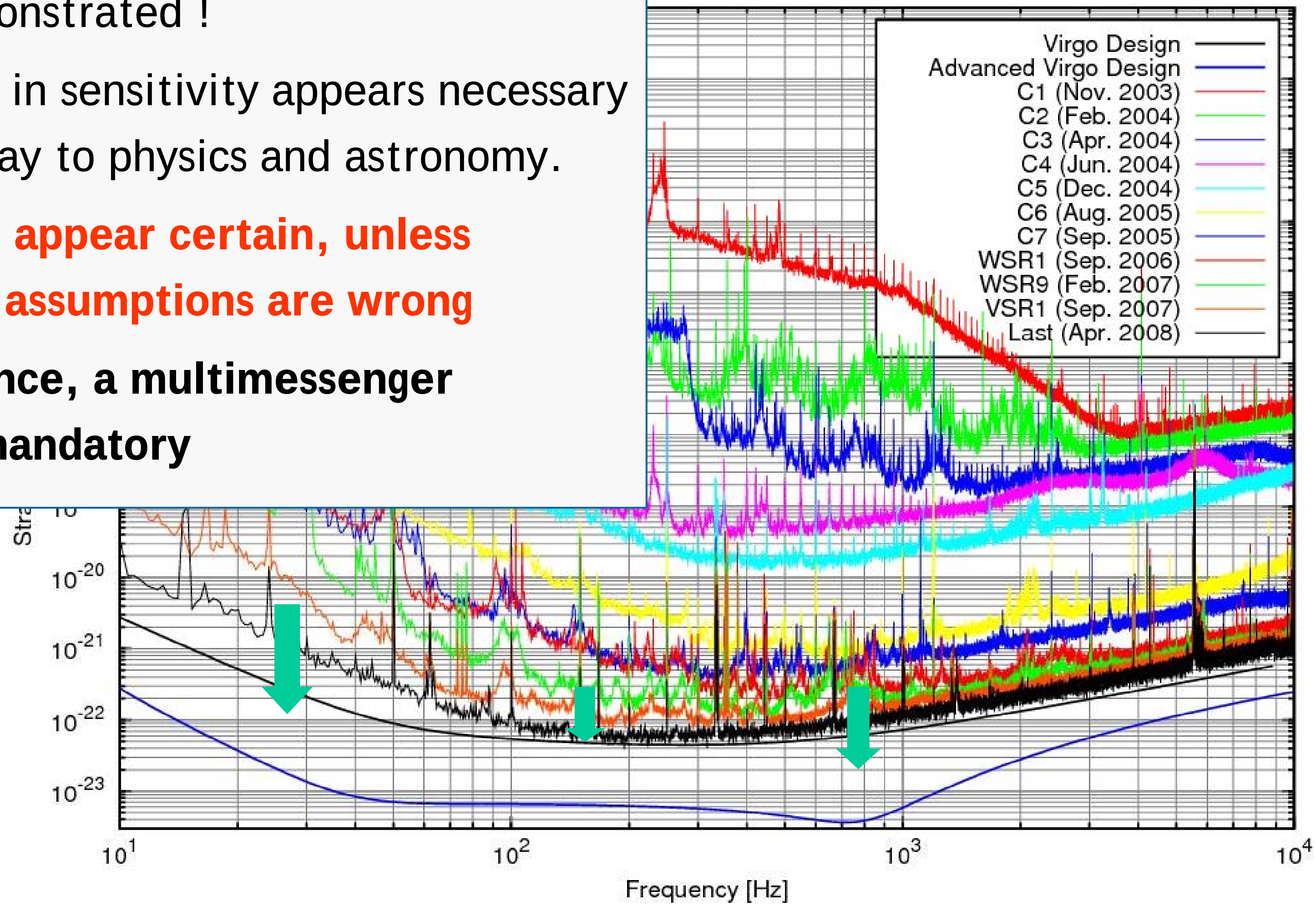
moreover…

- better vacuum
- environmental noise reduction
- low noise electronics
- …



Advanced Detectors will see GWs ?

- The technology of interferometric detectors has been demonstrated !
- A further step in sensitivity appears necessary to open the way to physics and astronomy.
- **Some sources appear certain, unless astrophysical assumptions are wrong**
- **To make science, a multimessenger approach is mandatory**



A look further, beyond 2° generation?

Where and how can we *further* reduce the detector noise?

Seismic

Underground detectors

Thermal

New materials

Cryogenic interferometers

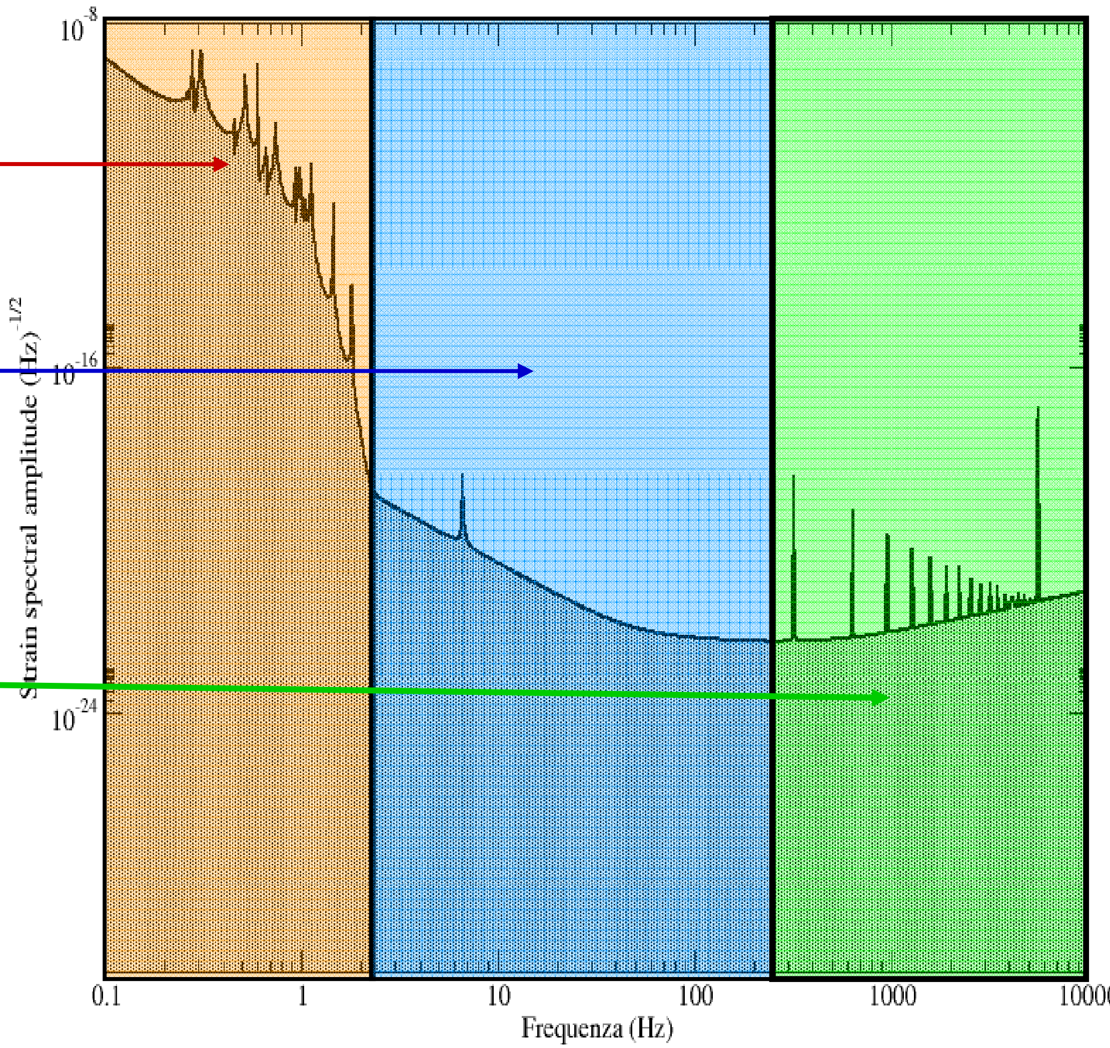
Shot

High power laser

Better optics

New optical configuration

QND techniques

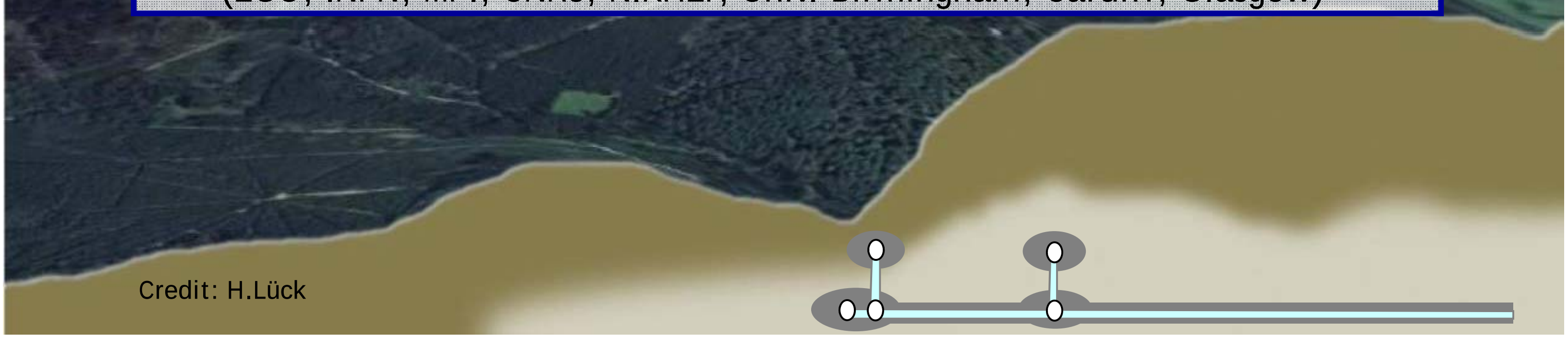


ET, THE "ULTIMATE" DETECTOR

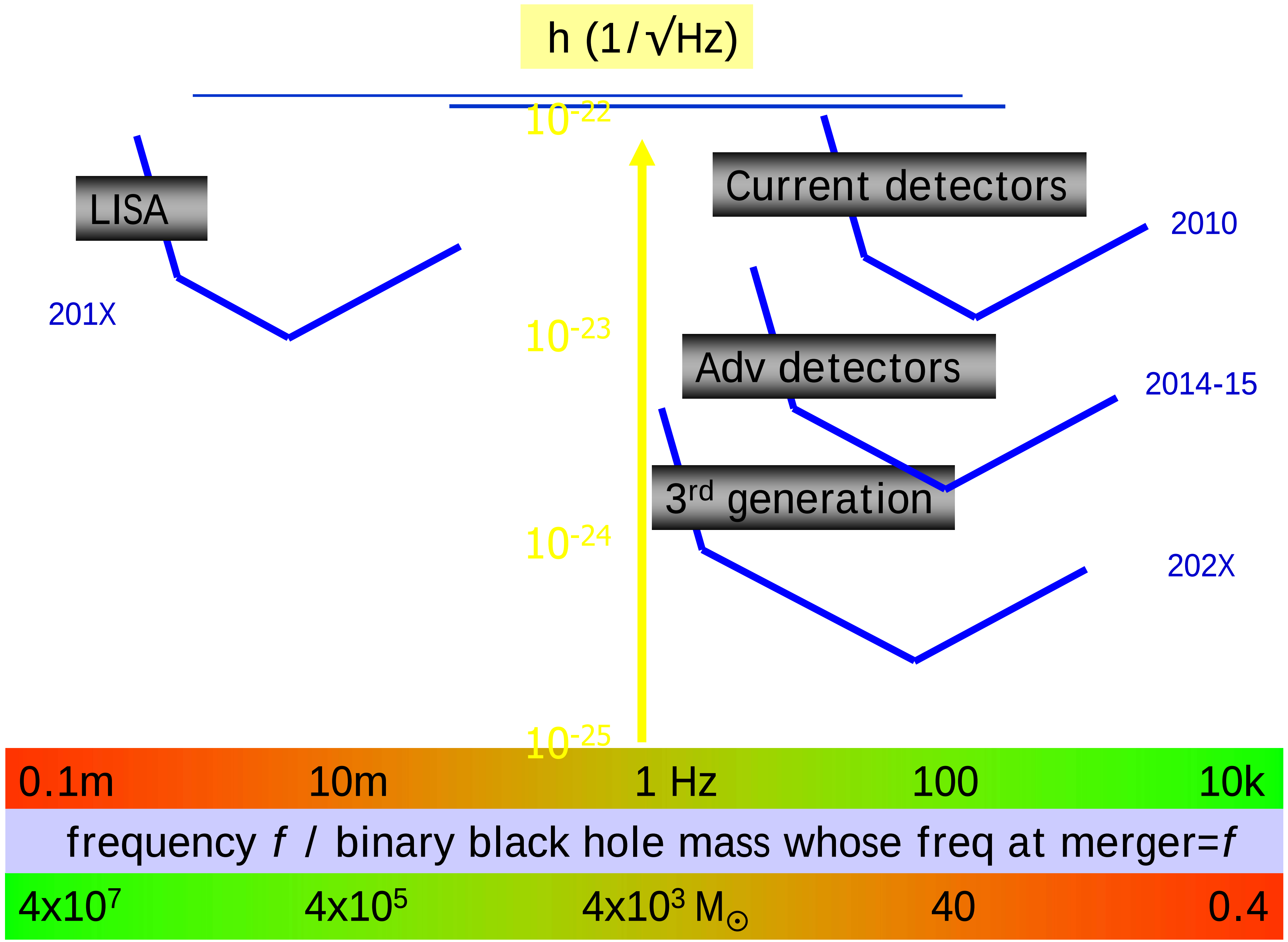
- Underground facility to minimize seismic noise
- Mirrors held at cryogenic temperature
- 10 km arms, new geometries

E.T. - Einstein gravitational-wave Telescope

- Design Study Proposal funded by EU within FP7
- Large part of the European GW community involved (EGO, INFN, MPI, CNRS, NIKHEF, Univ. Birmingham, Cardiff, Glasgow)



Credit: H.Lück


h (1/√Hz)
10^{-22}
10^{-23}
10^{-24}
10^{-25}
LISA
201X
Current detectors
2010
Adv detectors
2014-15
3rd generation
202X
0.1m
10m
1 Hz
100
10k
frequency f / binary black hole mass whose freq at merger=f
$4x10^7$
$4x10^5$
$4x10^3$ $M_\odot$
40
0.4

Conclusions?

First generation GW detectors demonstrated!

LIGO and Virgo upgrading towards 2° generation!!

Science results start to flow in, good hope that 2° generation will **start GW ASTRONOMY!**

Closer cooperation with the astrophysical community is a must.

Gamma, neutrino, radio, optical, GW information are complementary to understand emission mechanisms and ultimately the physics of the sources.