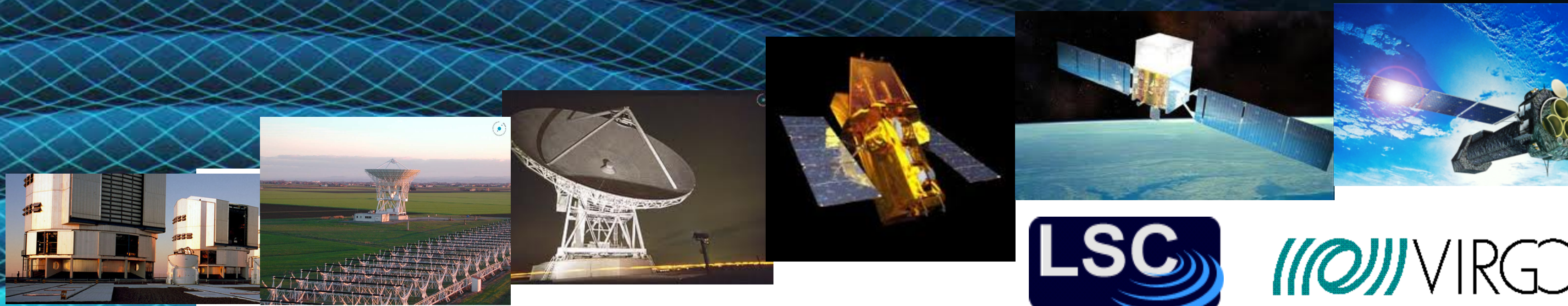
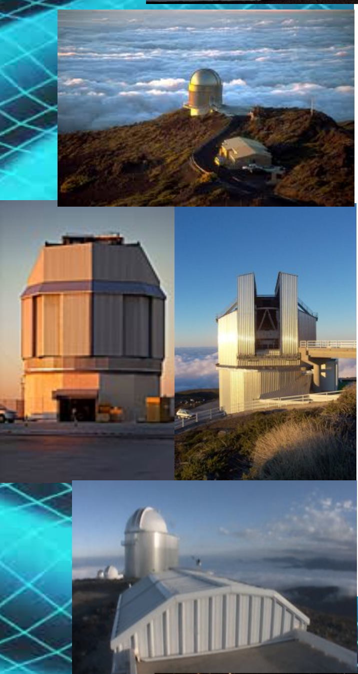
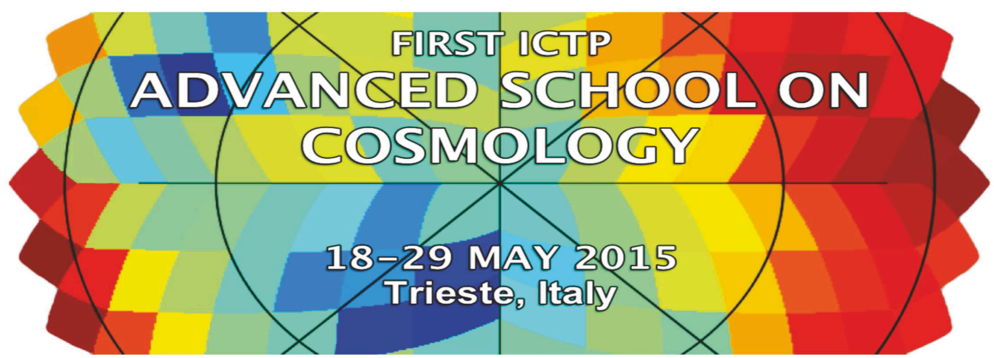


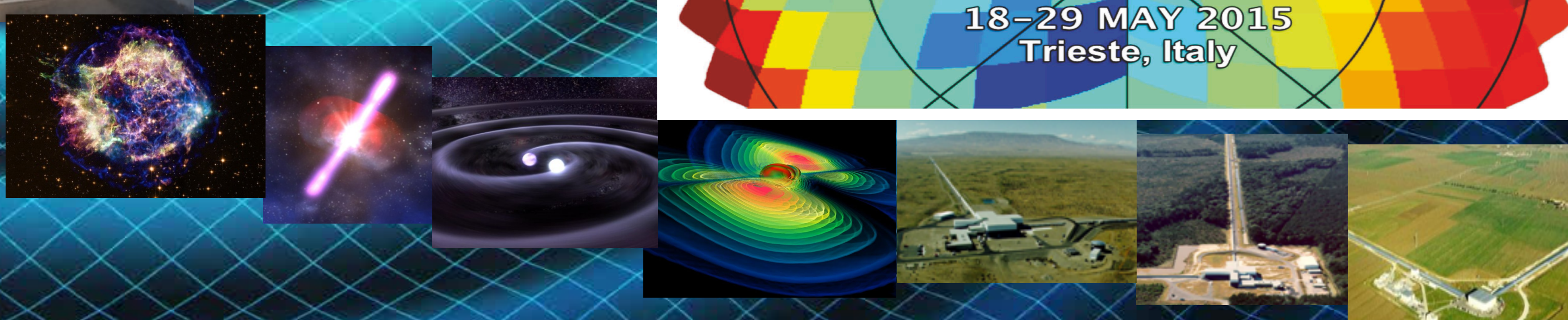


Gravitational waves – Experiments and sources
I PART

M.Branchesi

(Università di Urbino/INFN Sezione di Firenze)

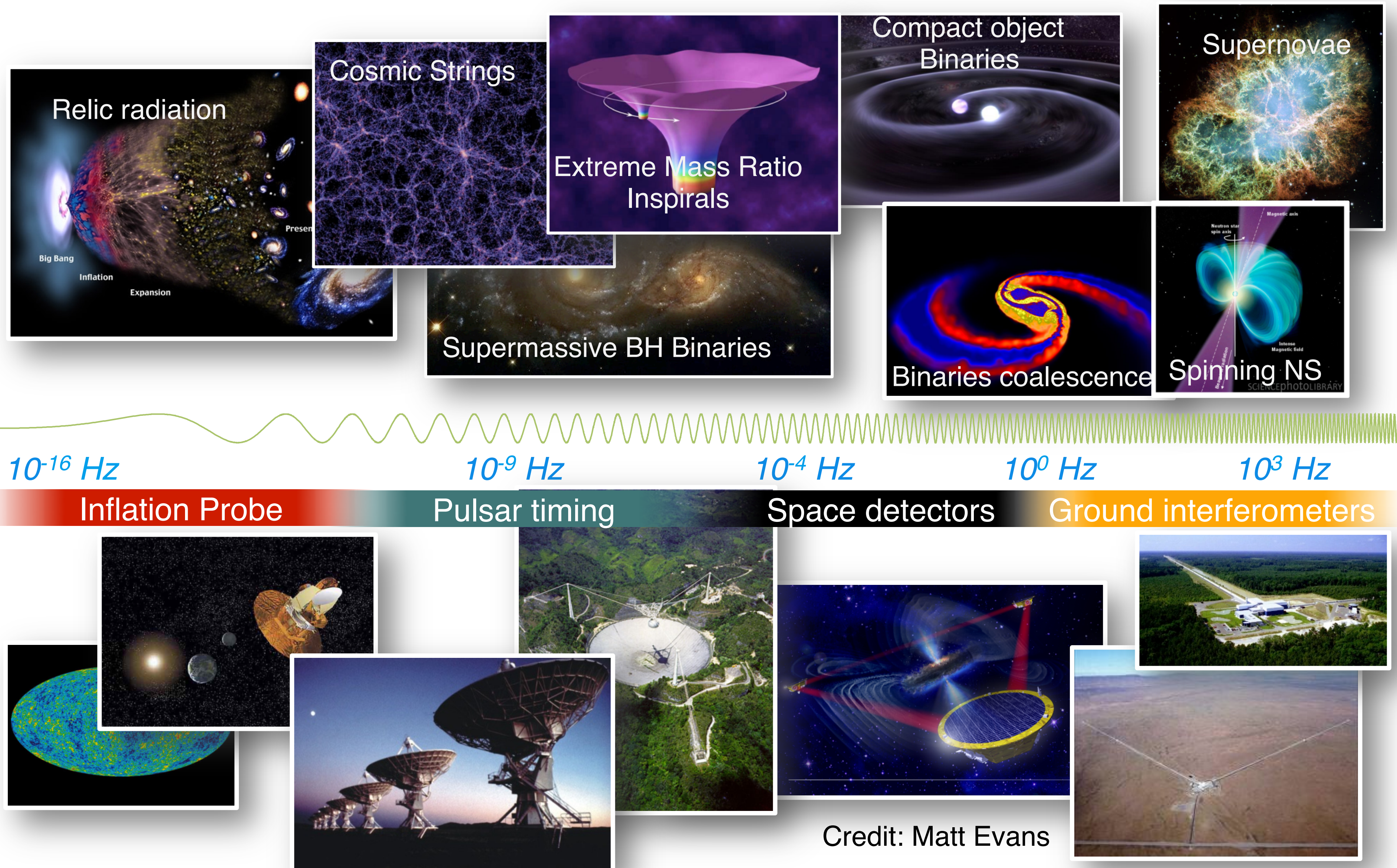




Outline

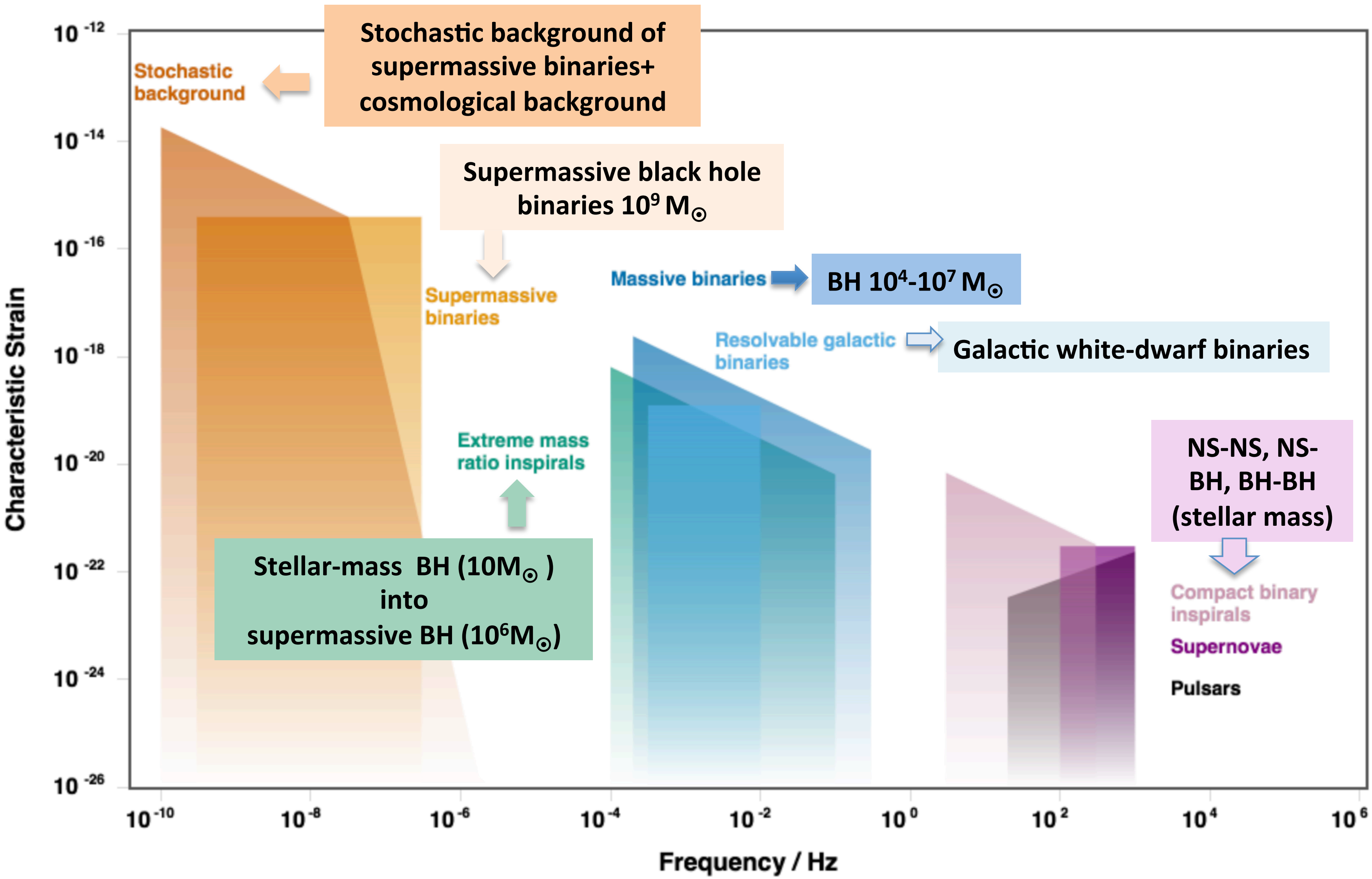
- Gravitational waves and their detection
  - GW spectrum, astrophysical sources and GW detectors
  - First generation of ground based detectors
  - Second generation of ground based detectors
  - Network of GW detectors
- Scientific results for different astrophysical sources
  - Initial LIGO and Virgo
  - Prospects for the advanced LIGO and Virgo

The GW Spectrum



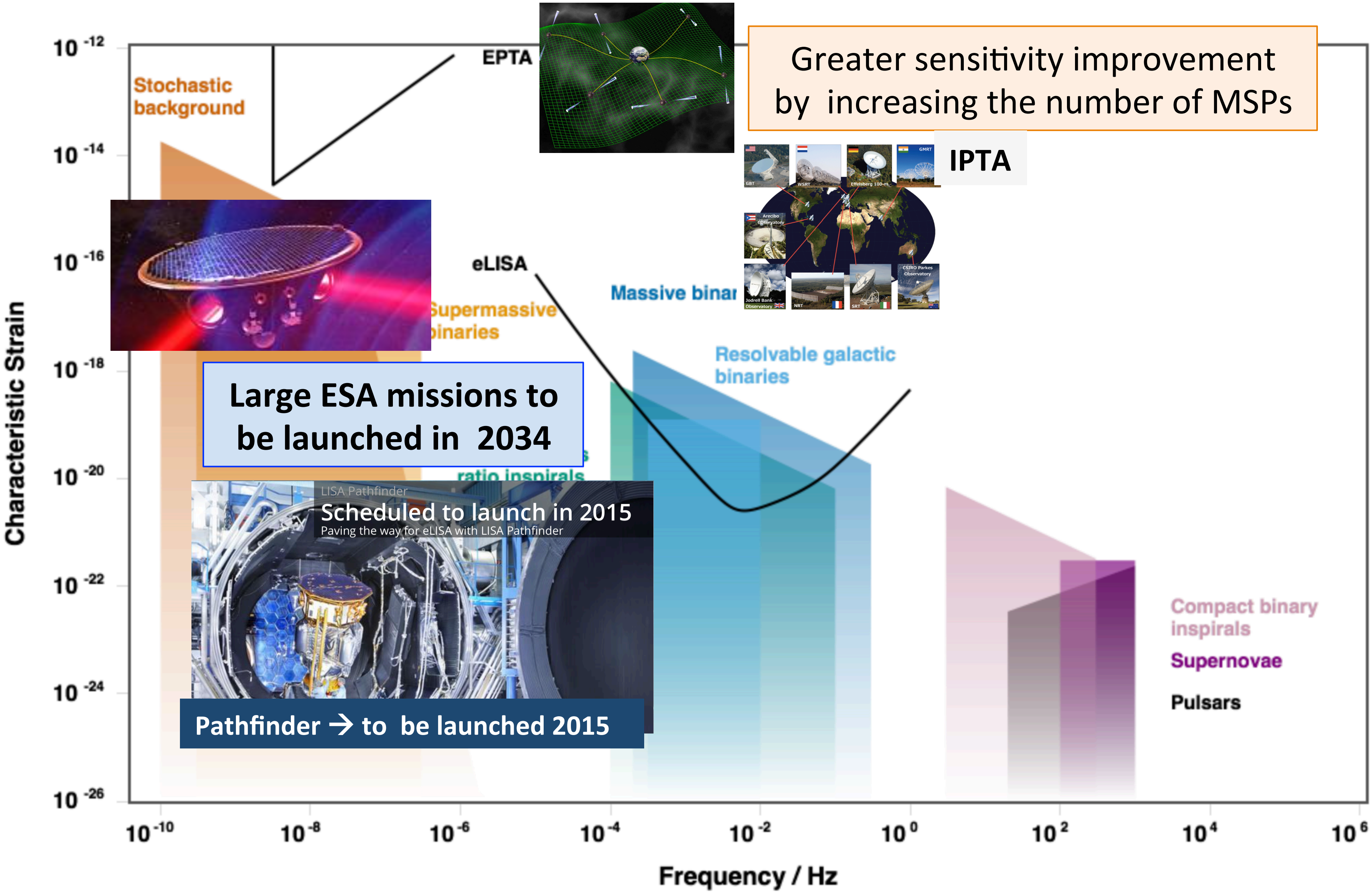
Credit: Matt Evans

Astrophysical Sources



http://rhcole.com/apps/GWplotter/

Astrophysical Sources



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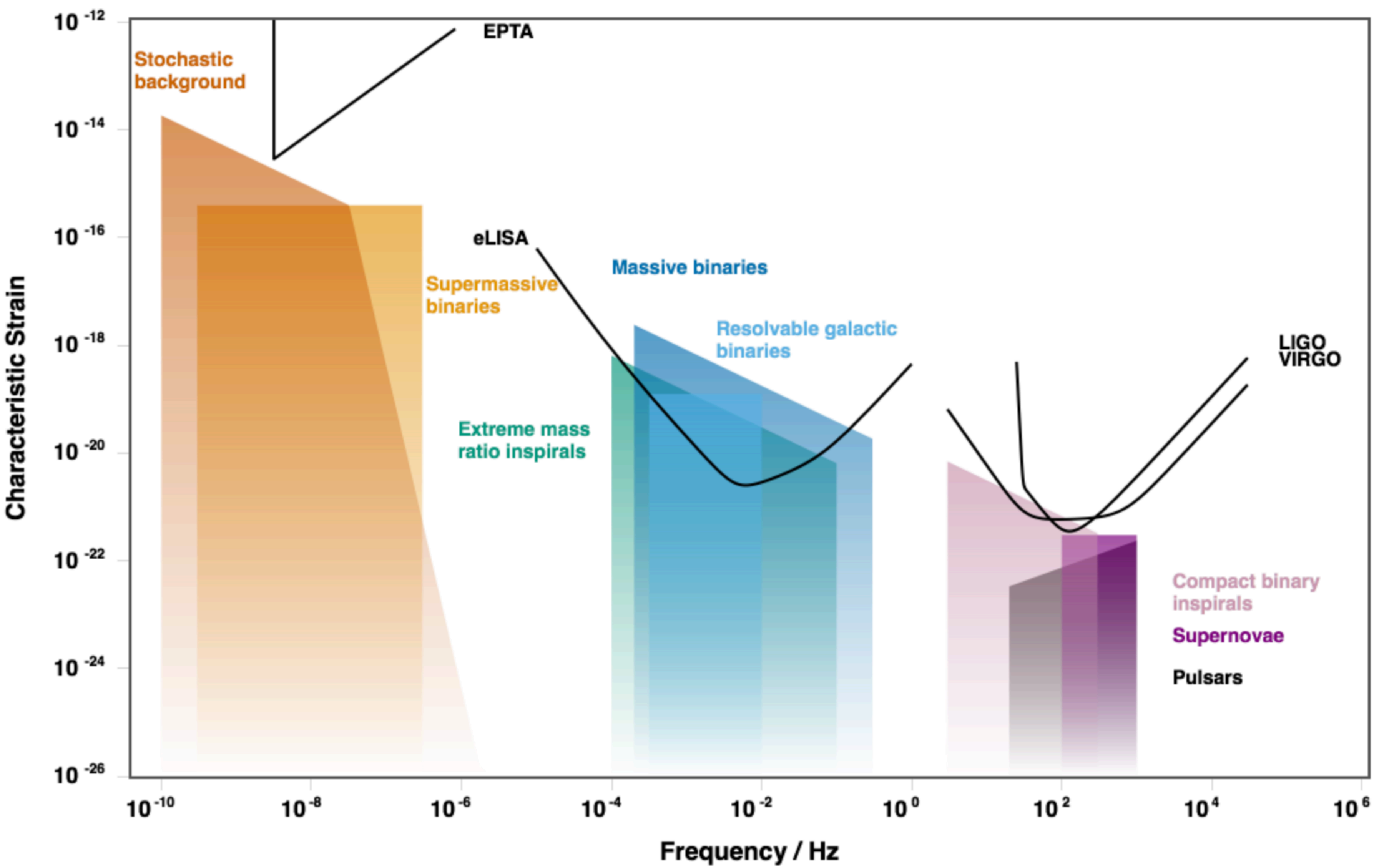
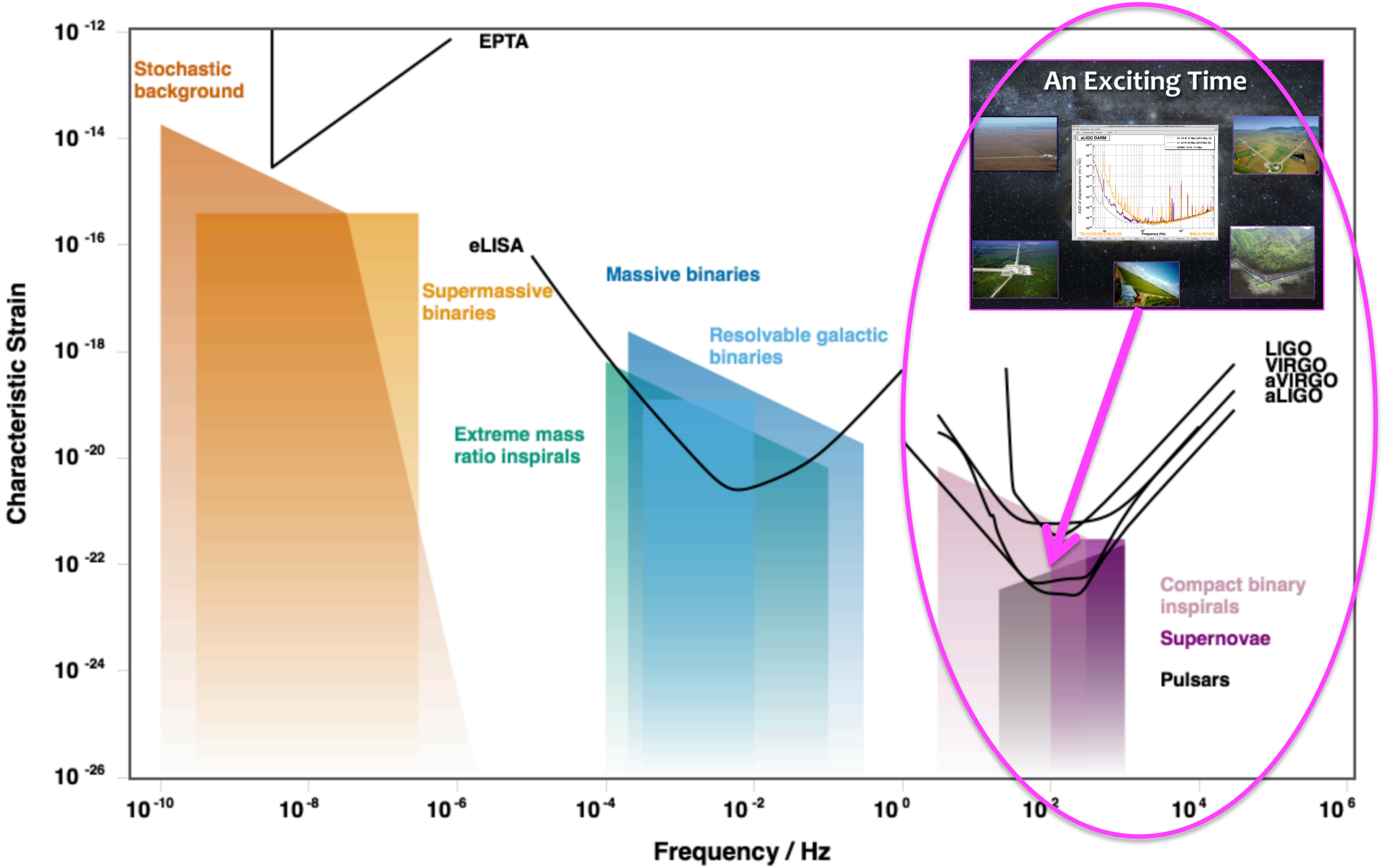
Astrophysical Sources



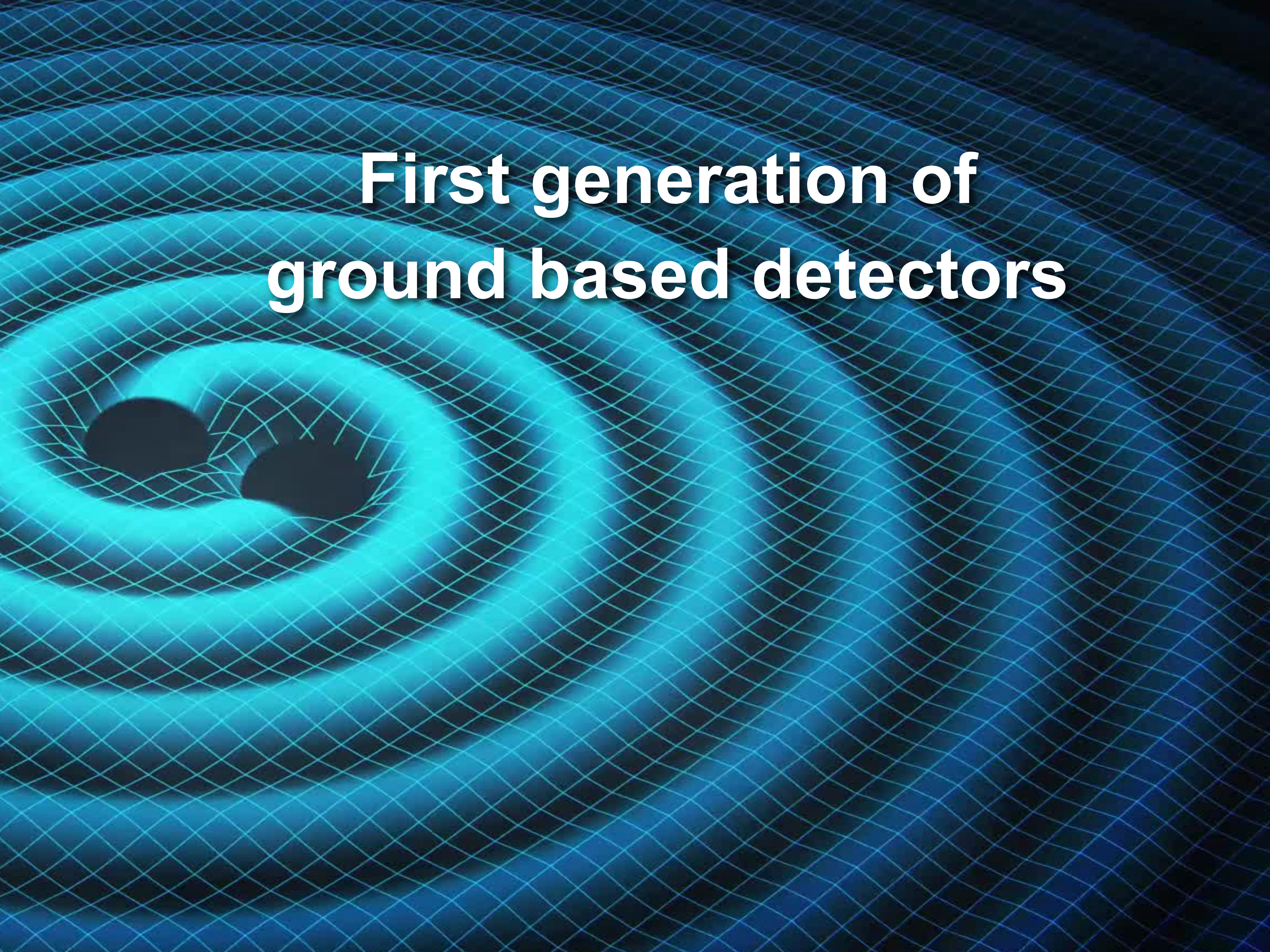
http://rhcole.com/apps/GWplotter/

Astrophysical Sources

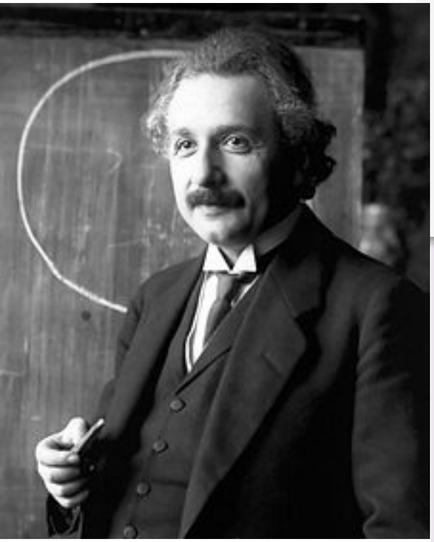


http://rhcole.com/apps/GWplotter/

First generation of ground based detectors

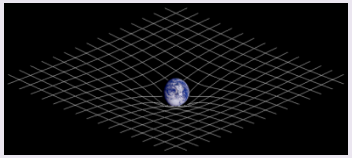


To reiterate:

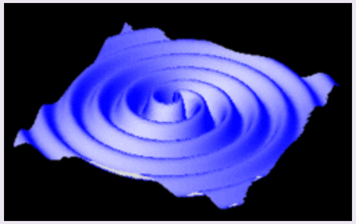


1916 → Einstein's theory of relativity predicts the existence of a new type of wave: the gravitational waves

GWs are perturbations of the space-time metric:



- Generated by mass distributions with time-varying quadrupole moments
- Propagating at the speed of light

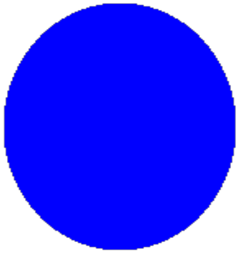


- Change in the distance between stationary (inertial) masses

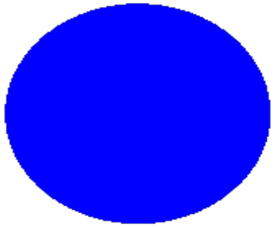
According to GR, GWs have two independent polarization states

Each GW signal can be described as a linear combination of them:

$$h = A_+ h_+(t) + A_x h_x(t)$$



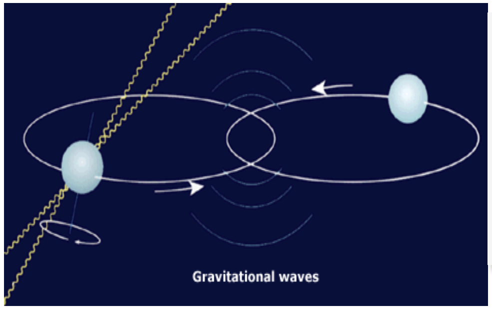
Polarization “Plus” h_+



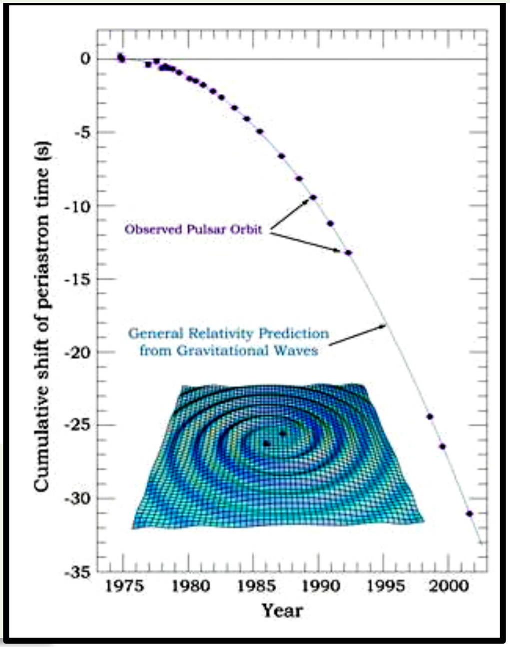
“Cross” h_x

Do GWs exist?

PSR 1913+16 was the first Binary Pulsar discovered
(Hulse & Taylor 1973)
It was the laboratory for the **indirect evidence of GW existence**



Orbiting stars stir space time around them, lose energy by emitting GW and spiral closer together



In 1993 Taylor & Hulse received Nobel prize for the discovery. The orbital period of PSR 1913+16 is decreasing at exactly the rate predicted by Einstein's general relativity.

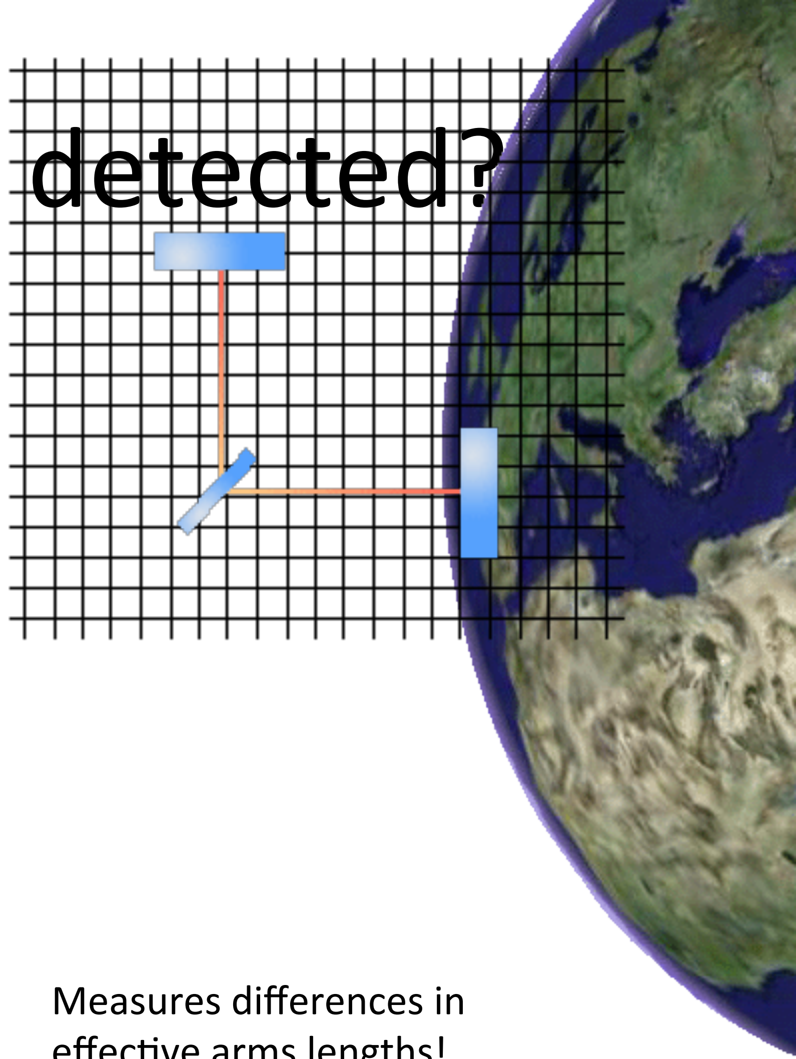
No direct GW observation has been claimed yet!

GWs have a very weak interaction with matter

→ **Powerful probes** of faraway regions of the Universe and dense inner regions of astrophysical systems opaque to photons

→ **Very hard to detect**

How can GWs be detected?



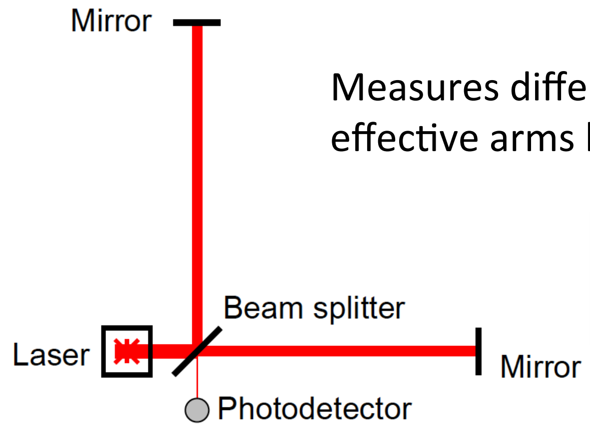
A GW deforms space

$$\Delta L = \frac{1}{2} L h(t)$$

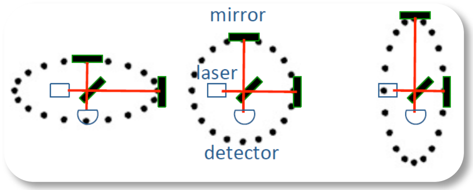
*The displacement is proportional to length: it is a **strain**!*

Do we know how to detect displacement?

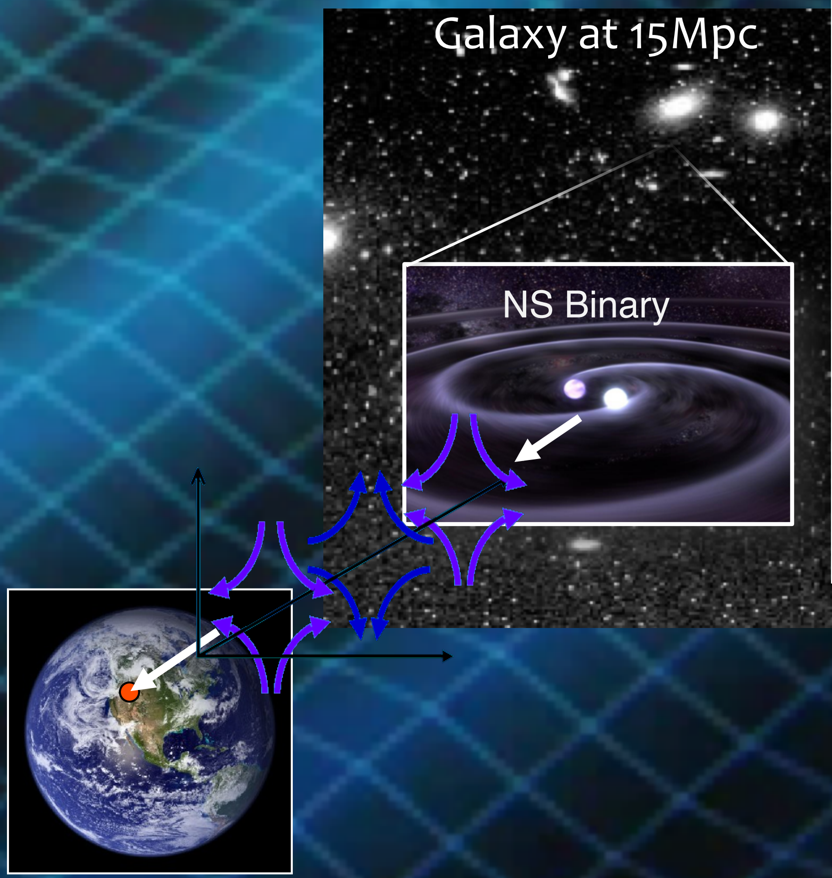
*The length change is measured interferometrically by using a **laser light beam***

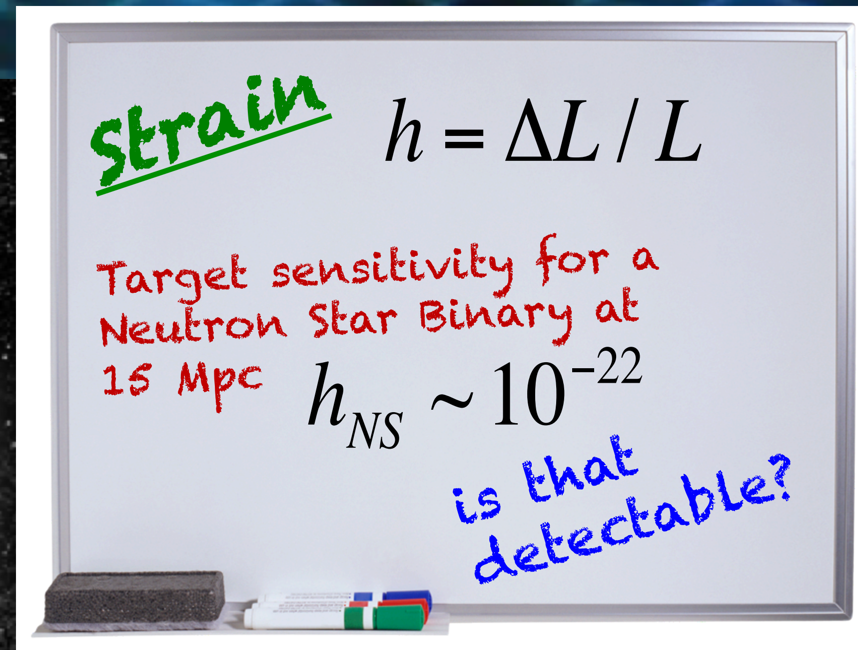


Measures differences in effective arms lengths!



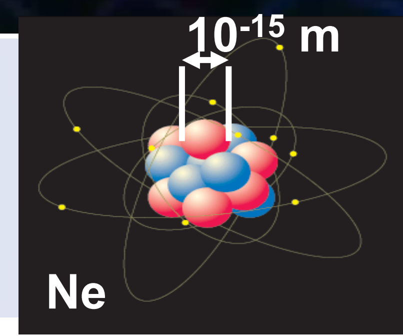
Some numbers…



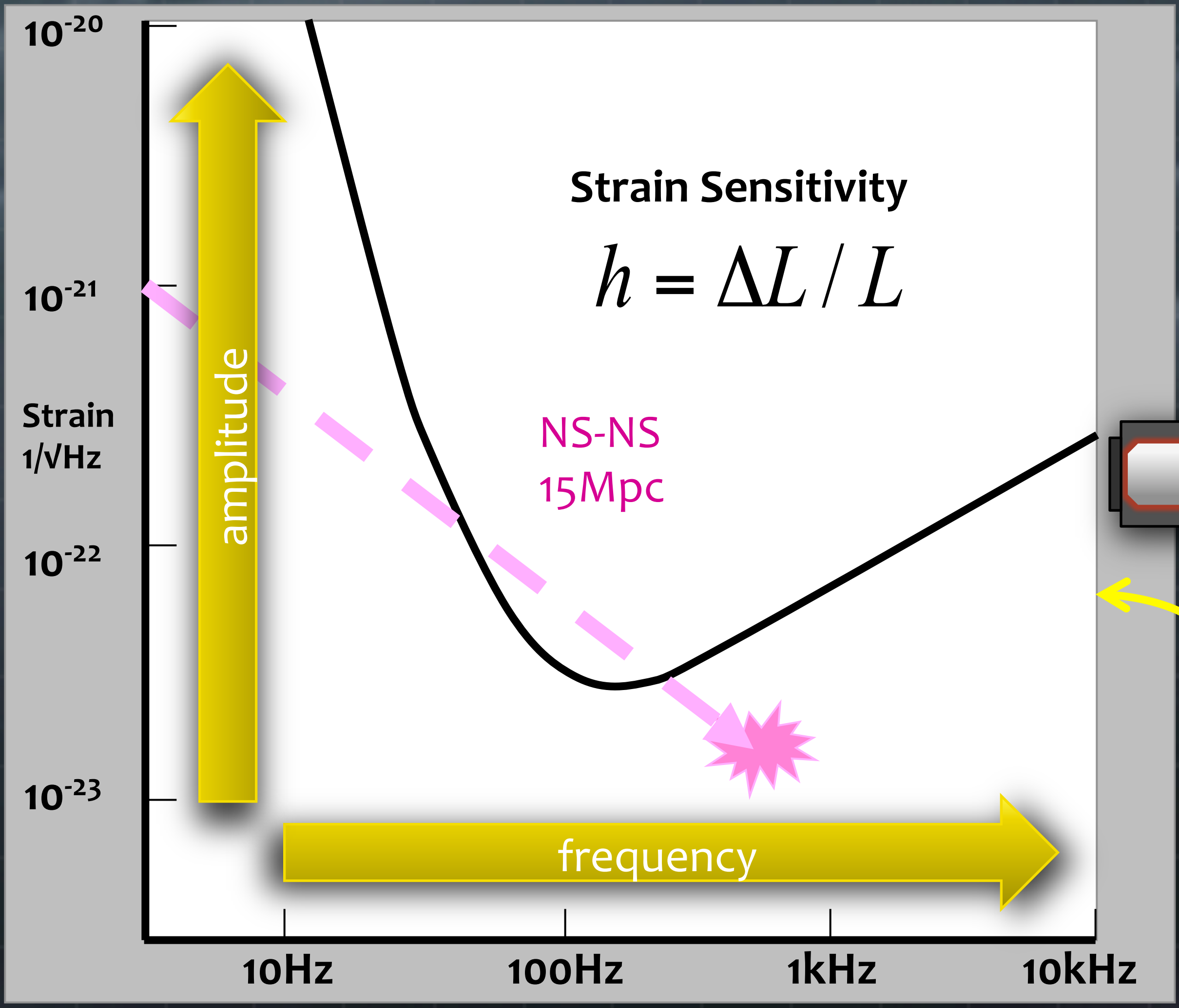


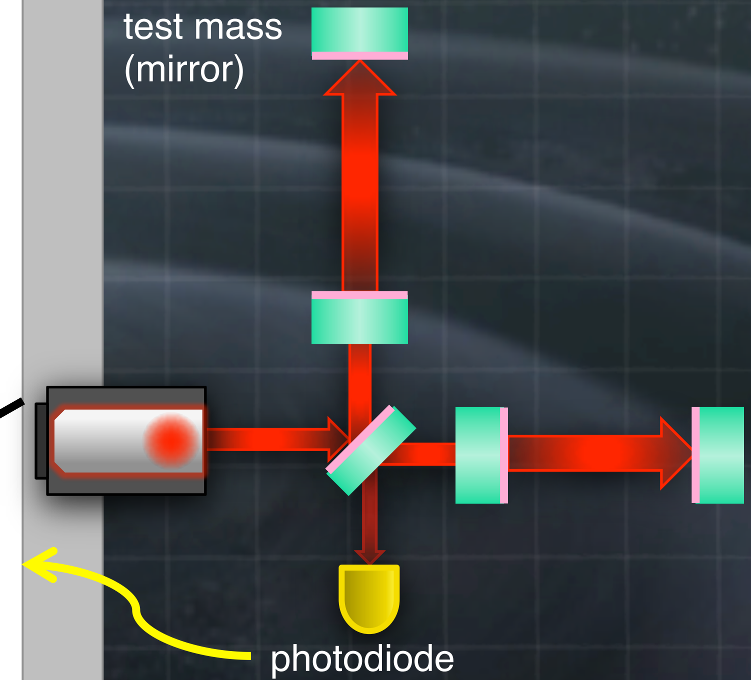
Ground-based GW detectors:

- ➢ km arms interferometers
- ➢ measure **length changes 10^{-19} m**, a few orders of magnitude smaller than the size of an atomic nucleus!



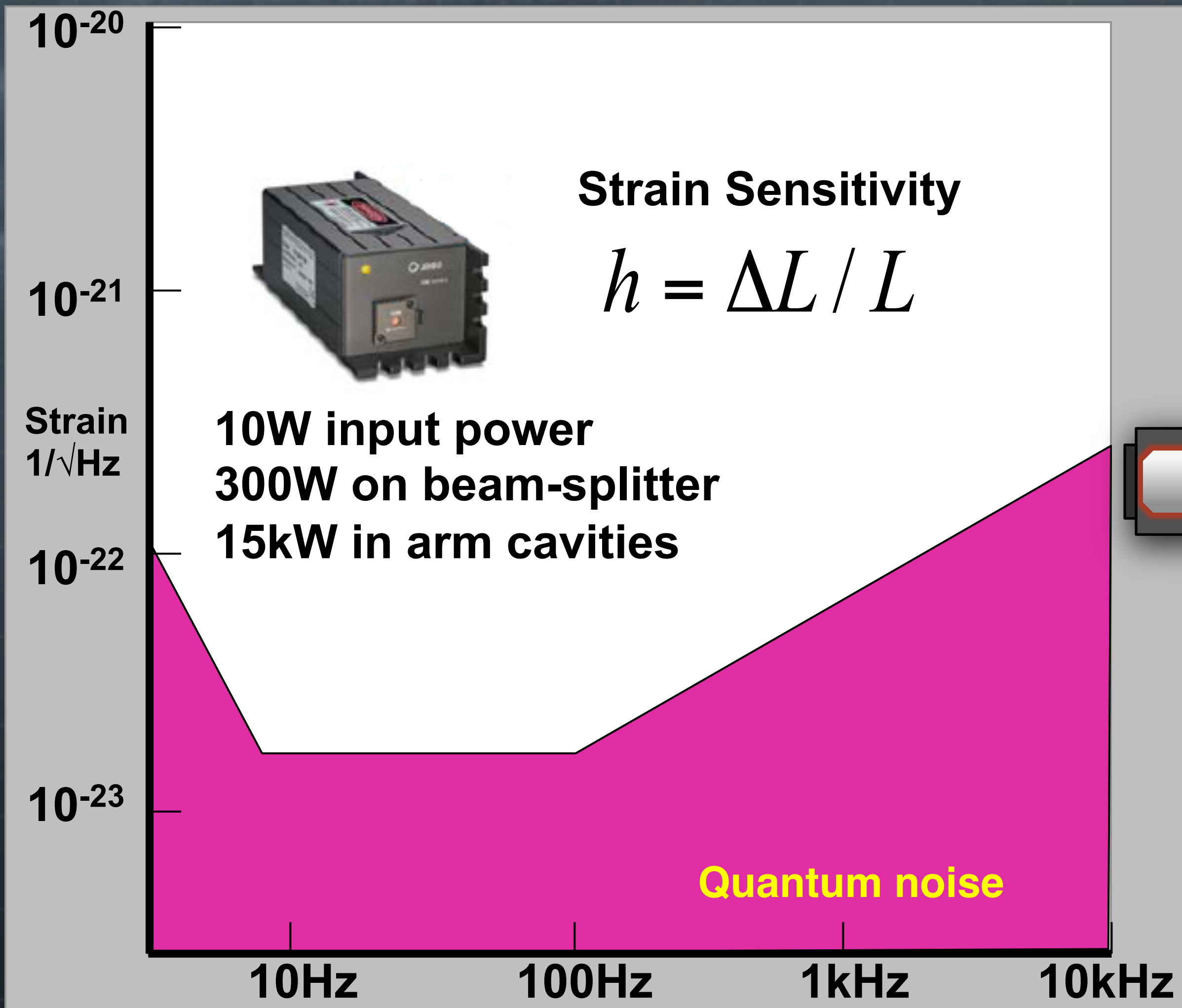
First Generation Sensitivity

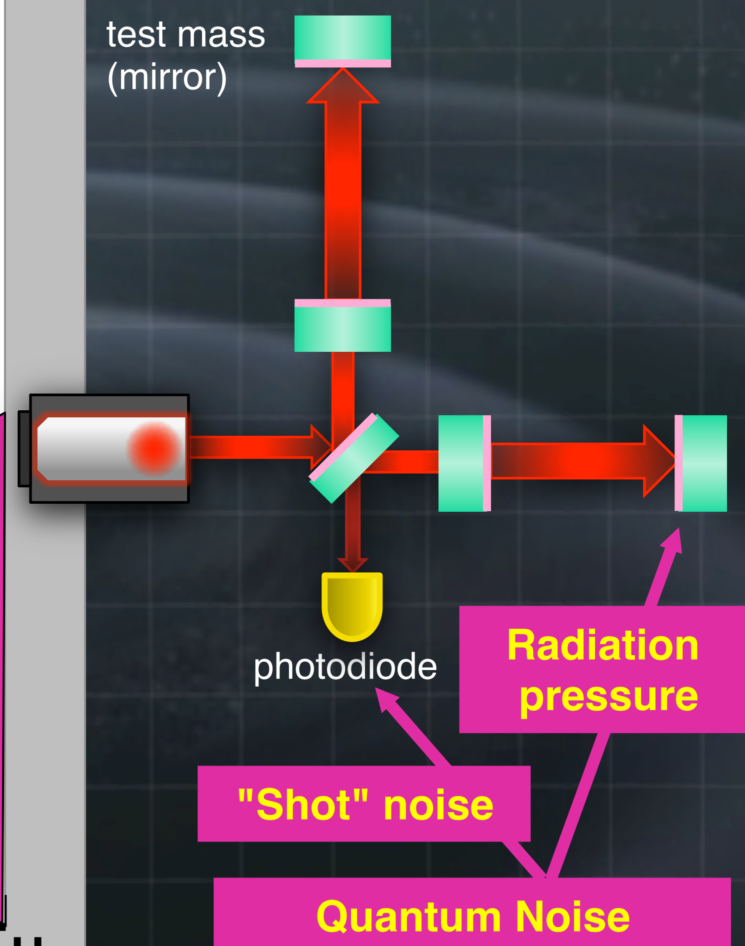




Slide Credit M. Evans, Amaldi 10

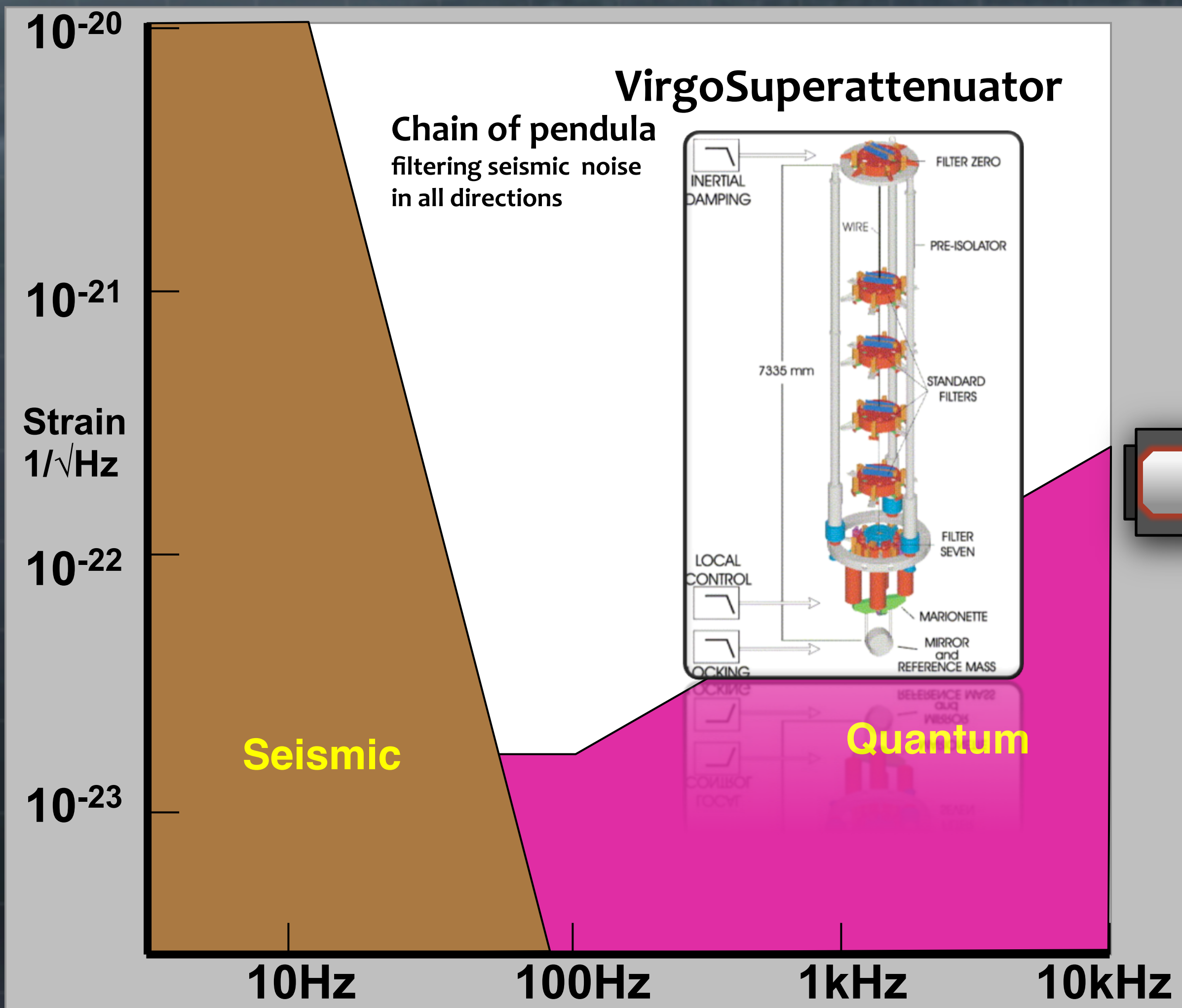
First Generation Sensitivity

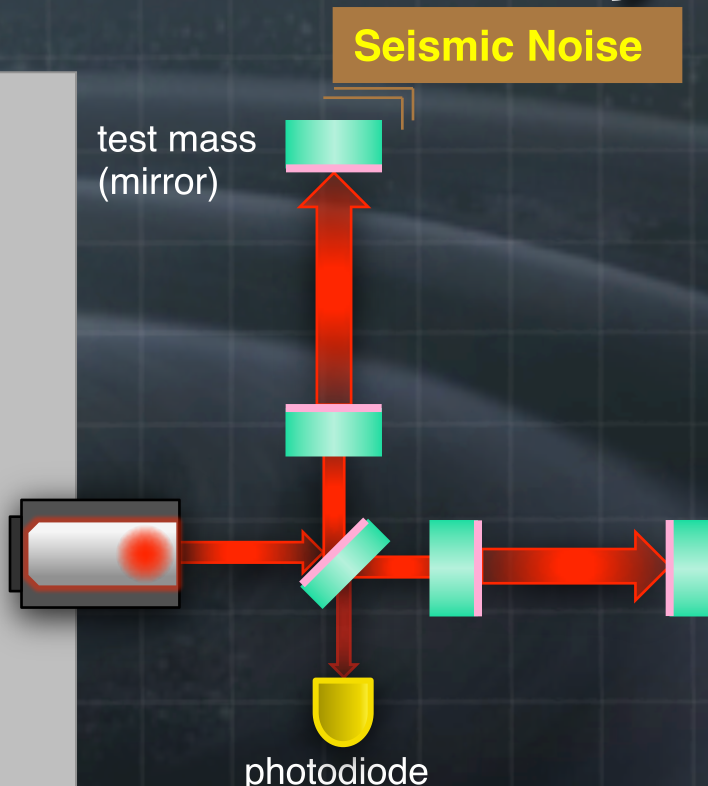




Slide Credit M. Evans, Amaldi 10

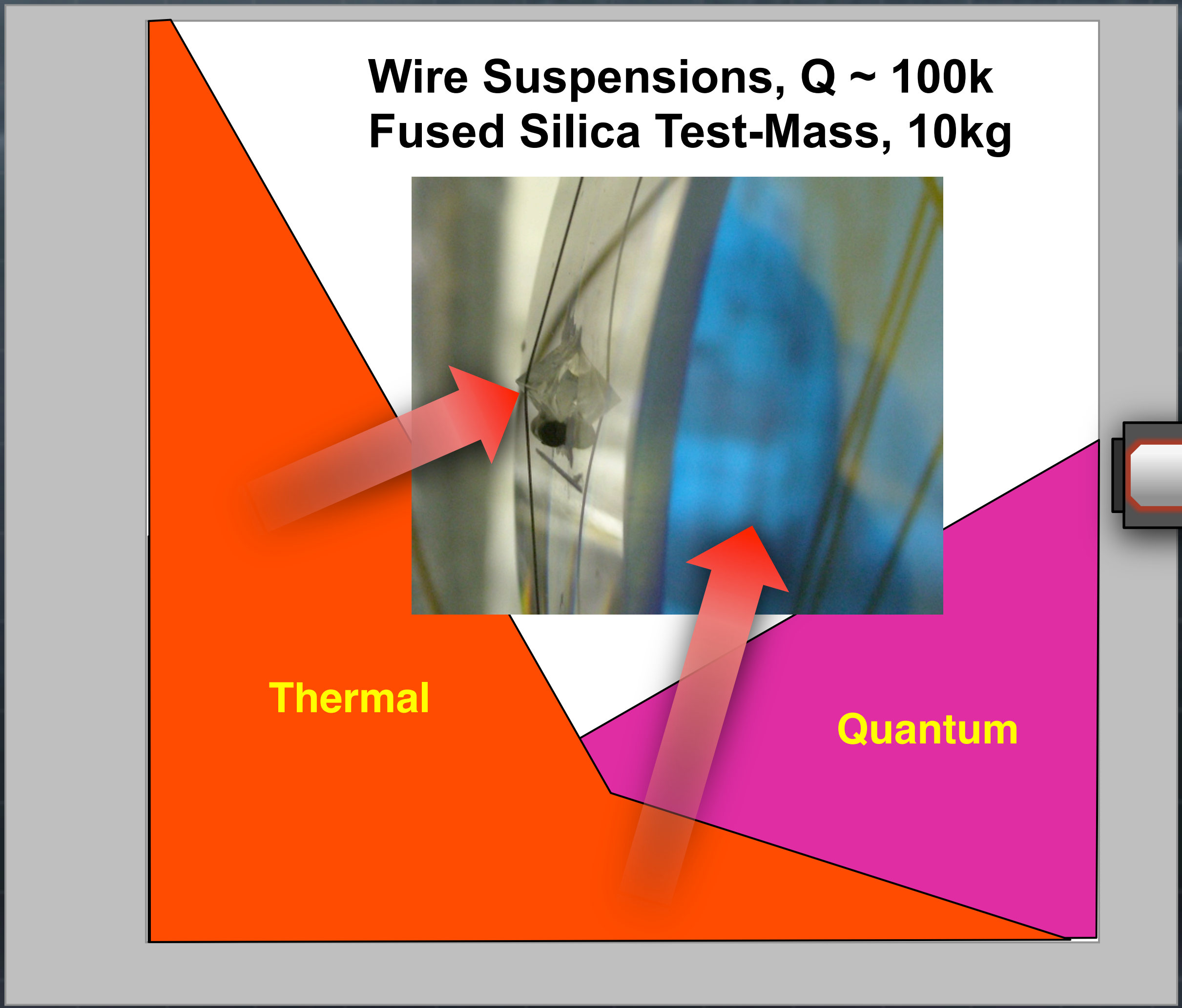
First Generation Sensitivity

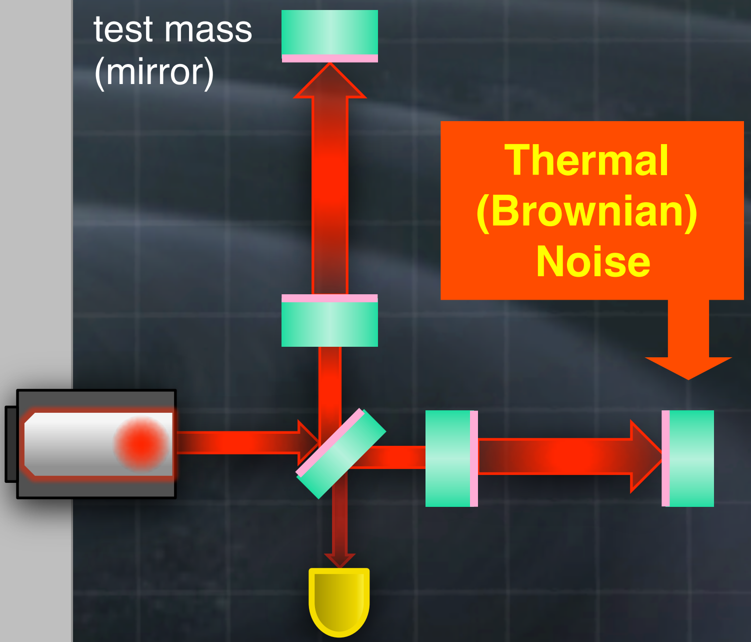




Slide Credit M. Evans, Amaldi 10

First Generation Sensitivity





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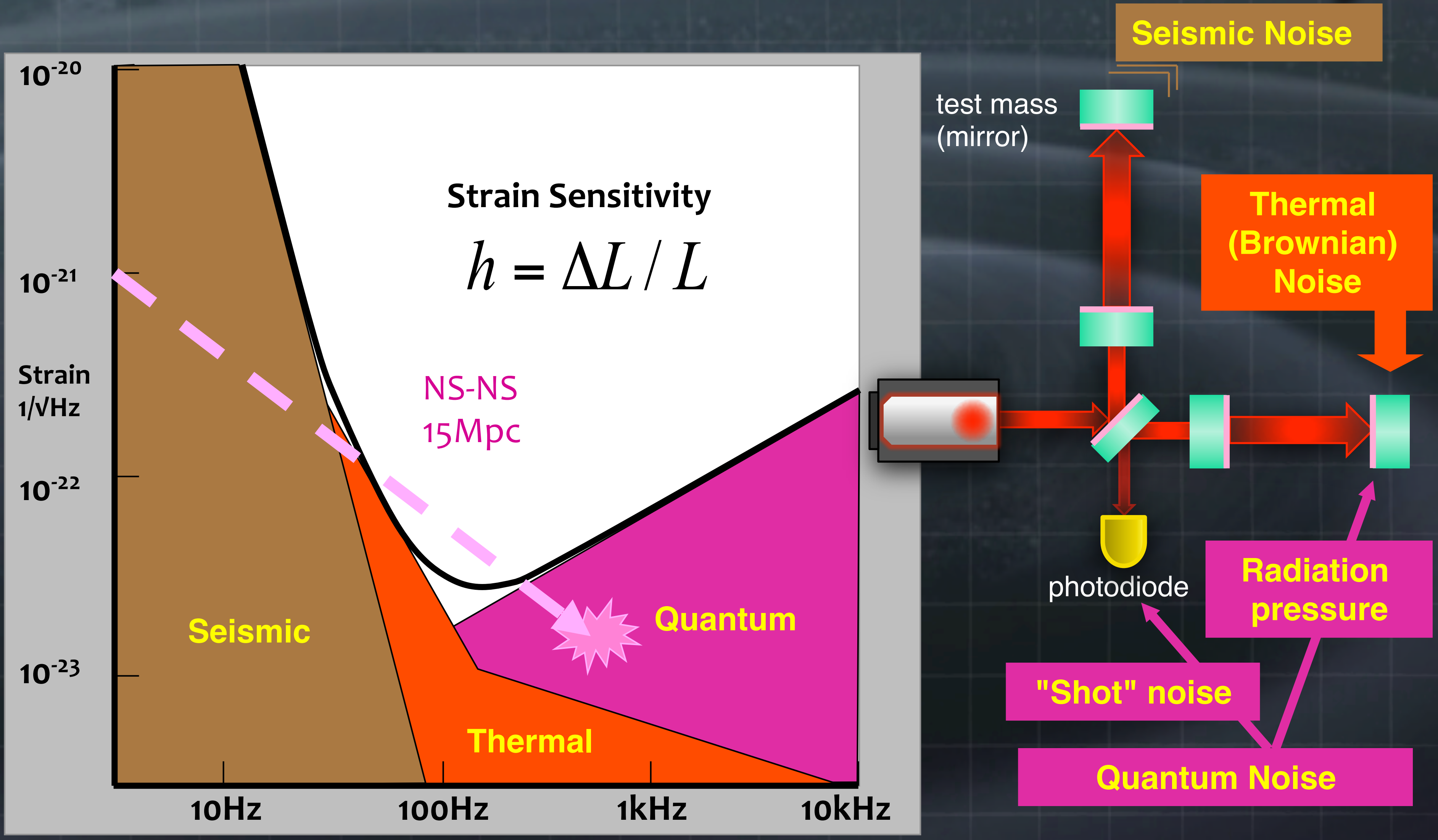
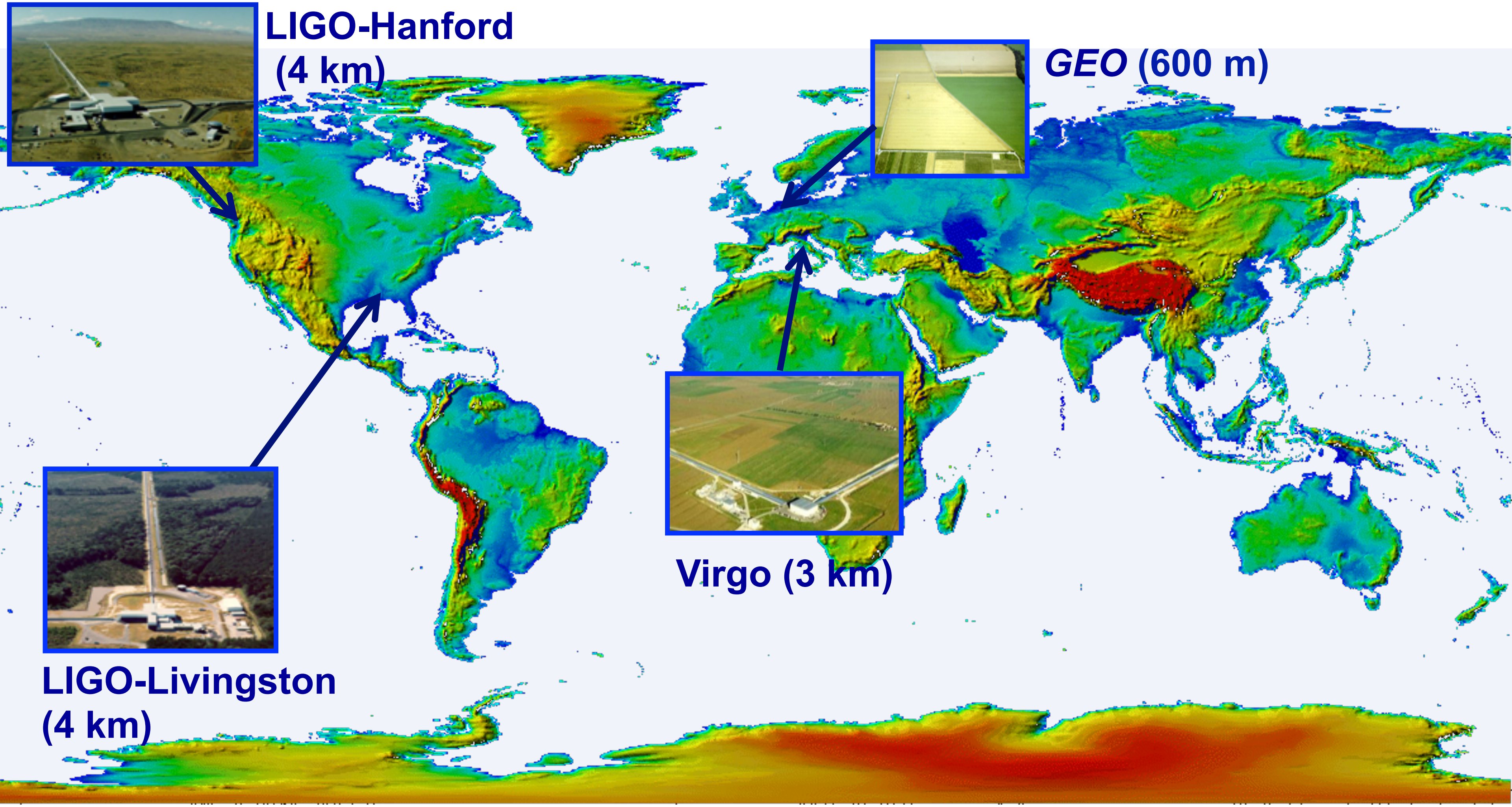
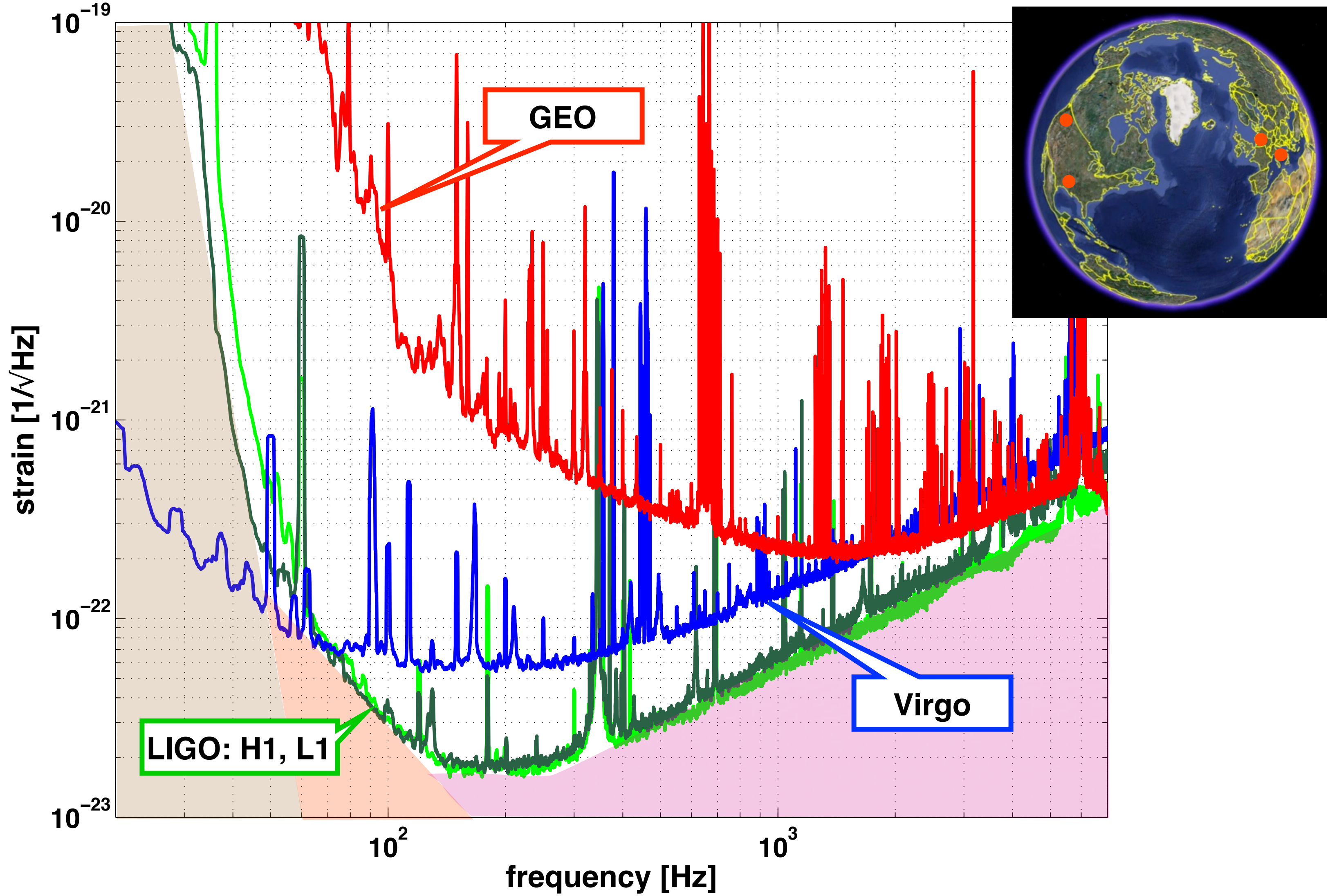
First Generation Sensitivity



Ground-based Gravitational Wave Detectors



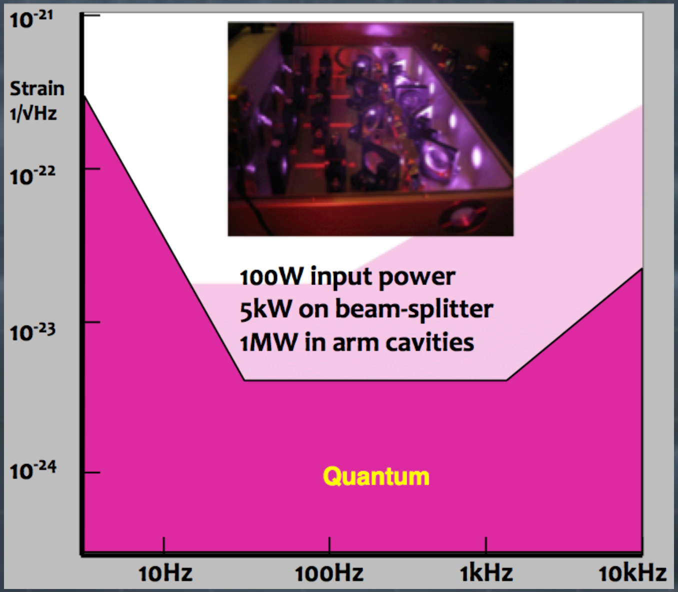
Ground-based Gravitational Wave Detectors



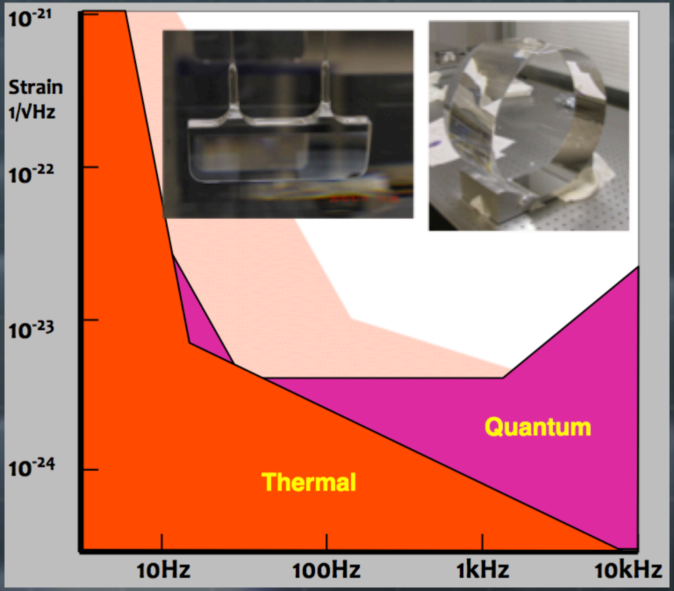
The LIGO and Virgo detectors are currently being upgraded to the 2nd interferometer generation: the Avanced LIGO and Virgo

Advanced GW detectors

More Laser Power…

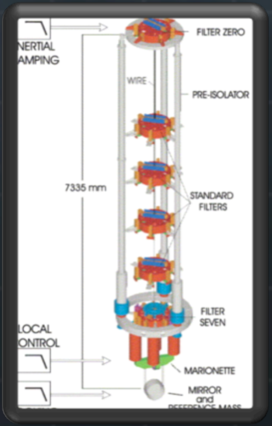


Better mechanical quality…

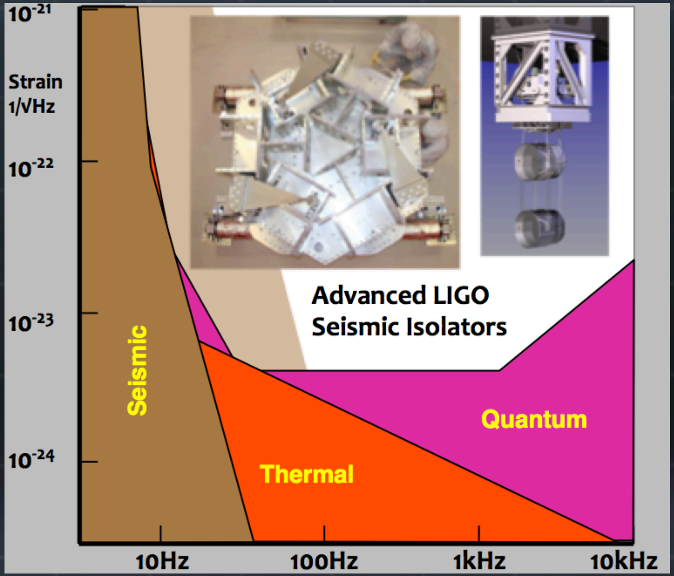


Test mass of 40kg suspended by 400 micron glass fibers…

… and better isolation

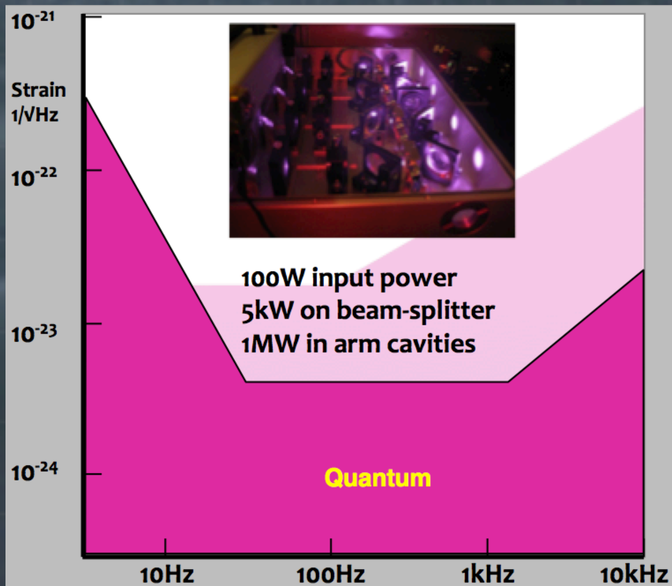


Virgo Super Attenuator

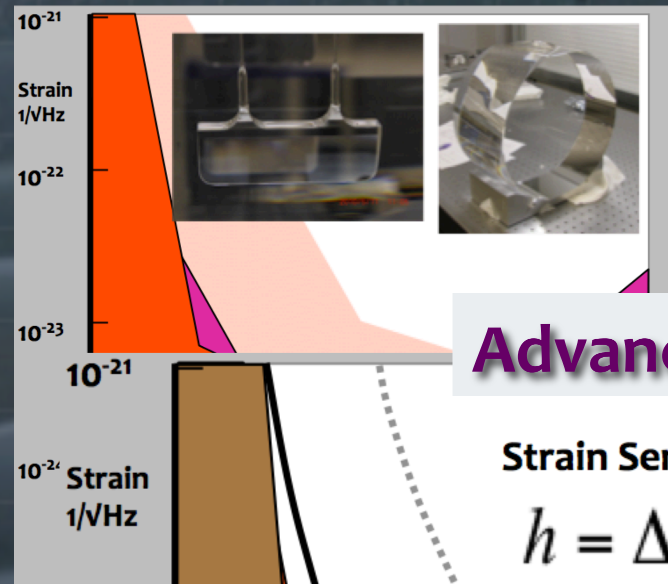


Advanced GW detectors

More Laser Power…

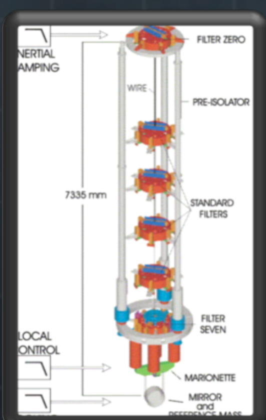


Better mechanical quality…

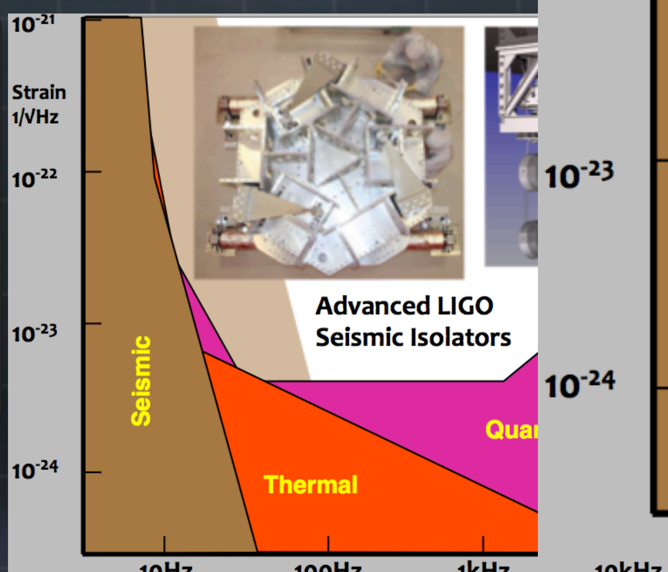


Test mass of 40kg suspended by 400 micron glass fibers

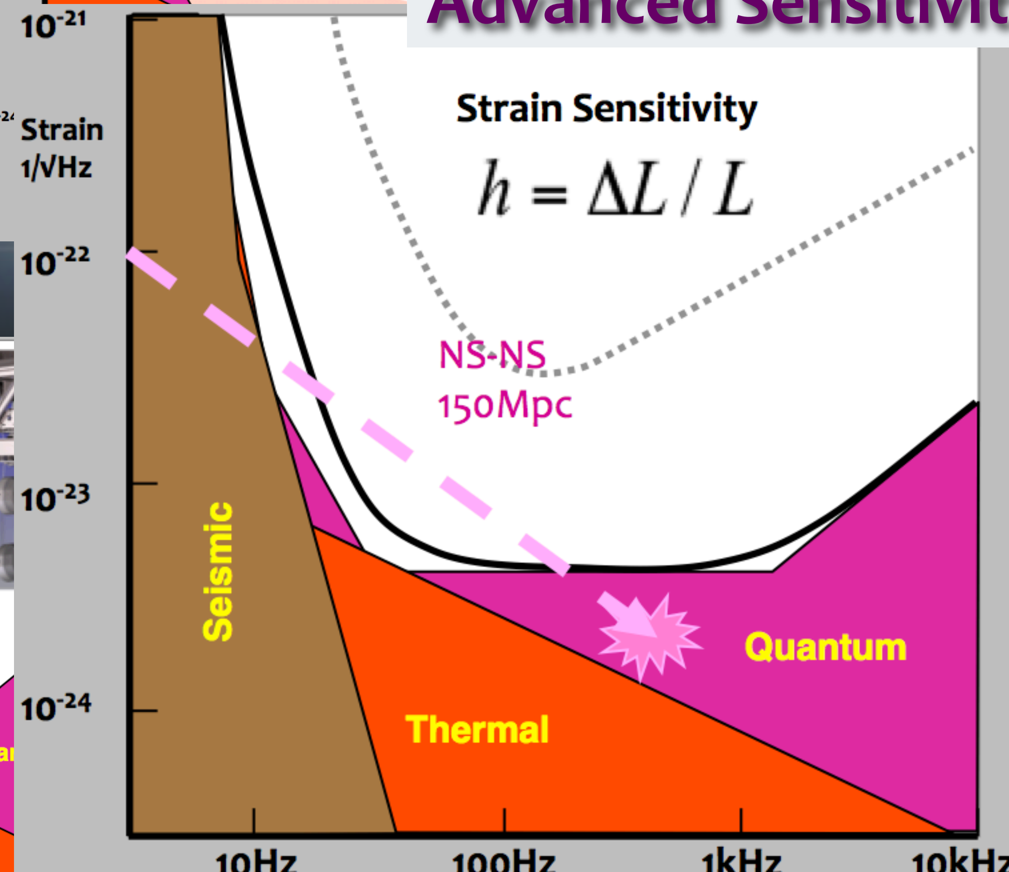
… and better isolation



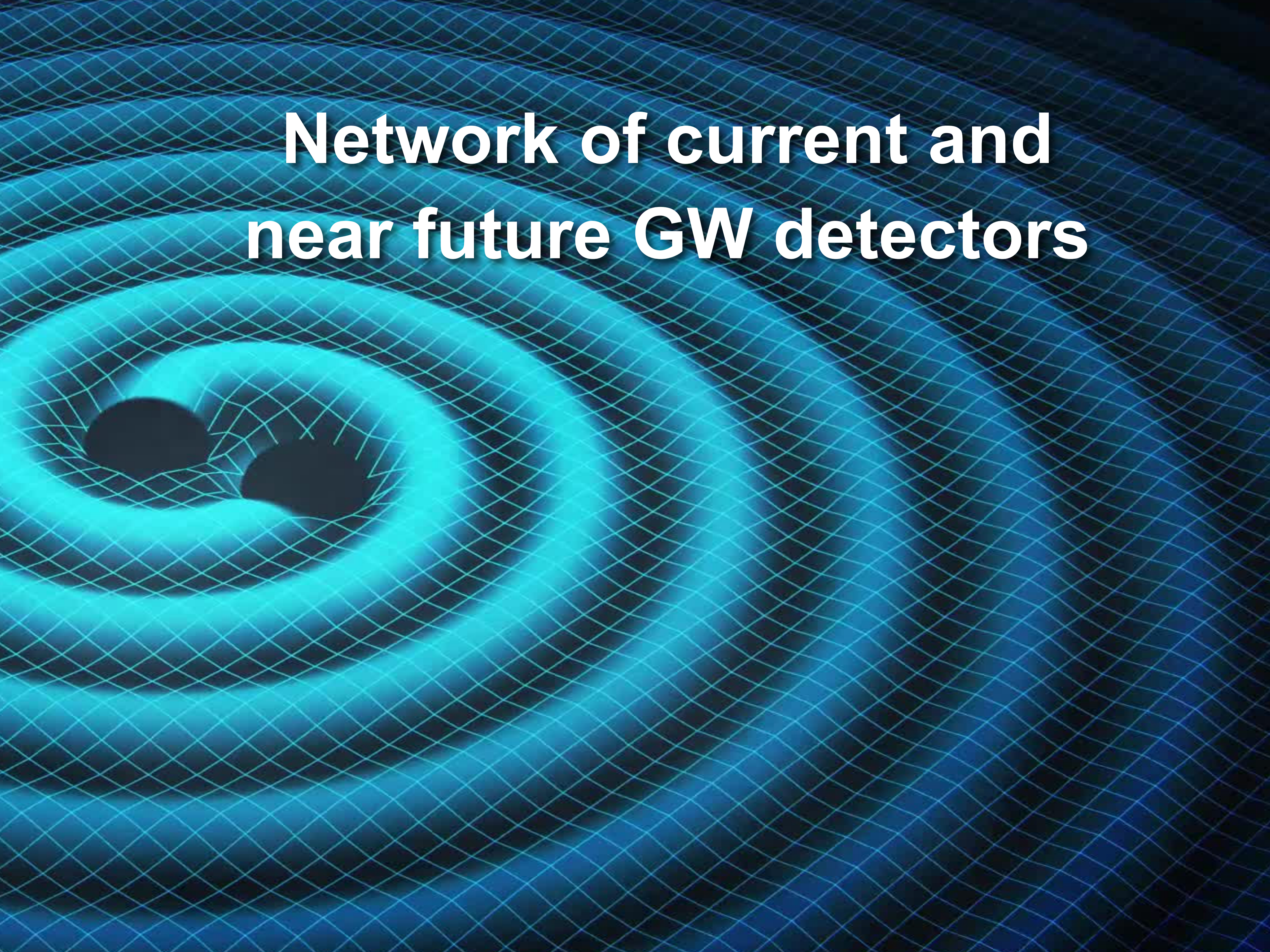
Virgo Super Attenuator



Advanced Sensitivity



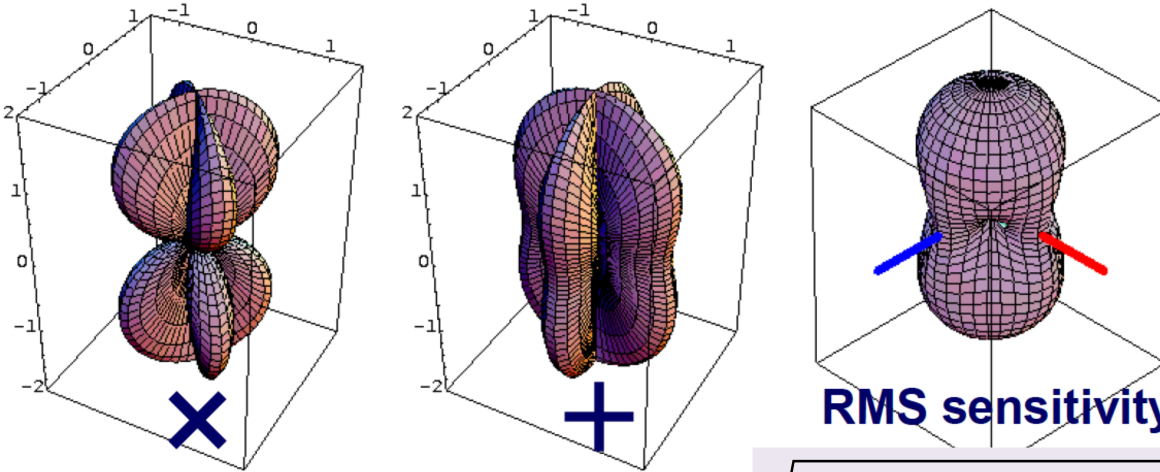
Network of current and near future GW detectors



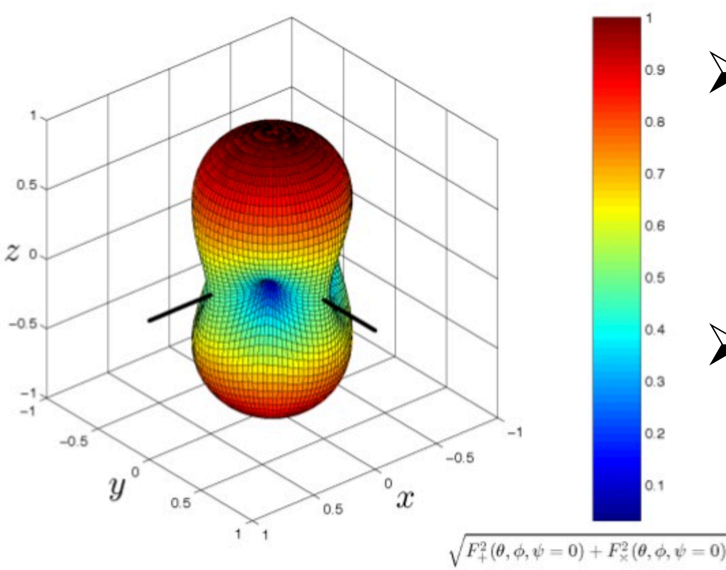
Single GW detector directional sensitivity

$$\frac{\Delta L}{L} = h_{\text{det}}(t) = F_+ h_+(t) + F_x h_x(t)$$

The **antenna pattern** depends on the polarization in a certain (x,+) basis.



$$\sqrt{F_+(\theta,\phi)^2 + F_x(\theta,\phi)^2}$$

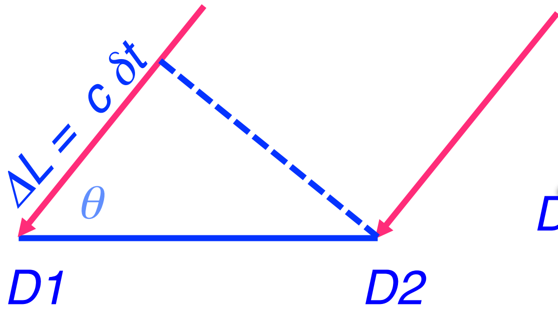


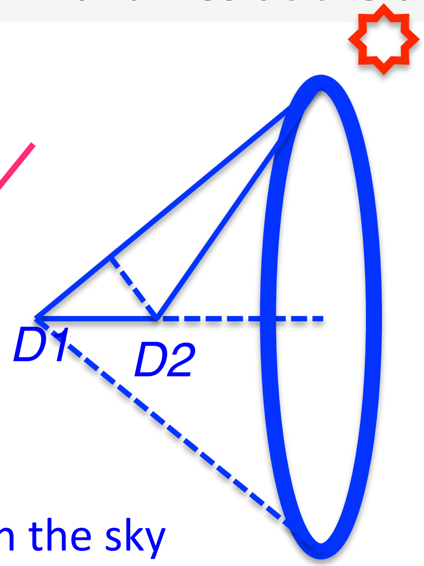
- Single GW detector is a **good all-sky monitor**, nearly omni-directional
  (the transparency of Earth to GWs)

- But does not have good directional sensitivity, **not a pointing instrument**!
  It has a very poor angular resolution (about 100 degrees)

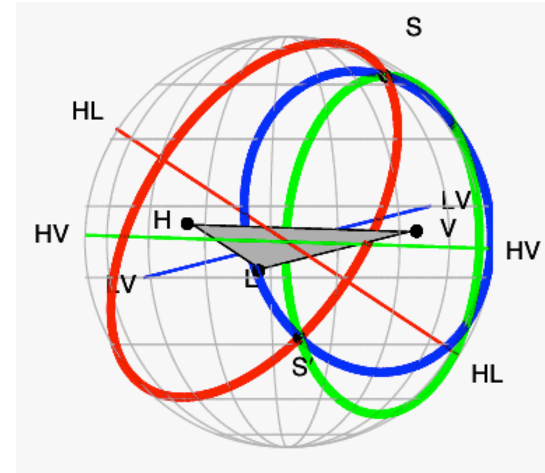
The source localization requires a network of GW detectors

*The **sky position** of a GW source is mainly **evaluated by triangulation**, measuring the differences in signal arrival times at the different network detector sites*

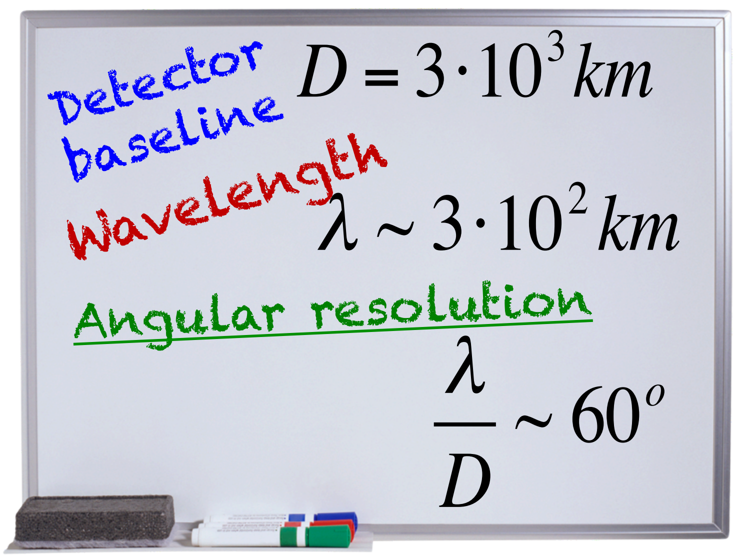




2-detector → anulus in the sky



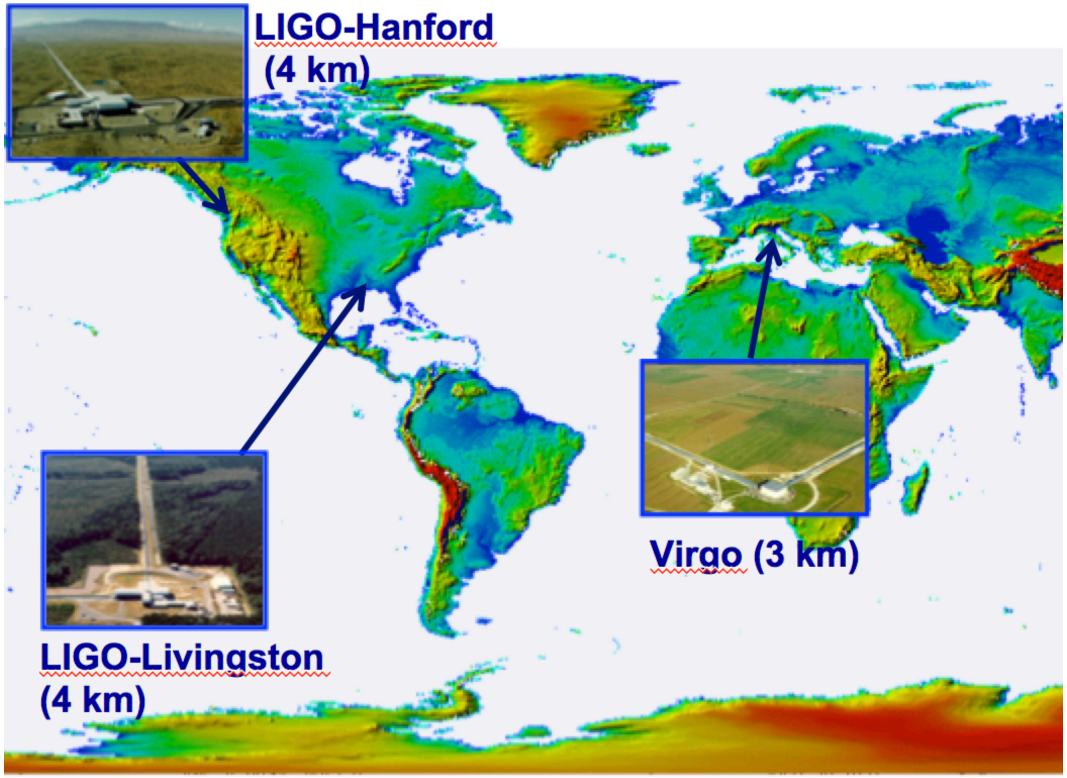
3-detectors → localize



The GW lengths are comparable to Earth diameter

→ *longer baseline and greater number of the sites* distributed *worldwide* significantly improve *the sky-localization capabilities!*

Other benefits of a network of GW detectors



Improvements:

- Sensitivity
- Observation time, and sky coverage
- In determining the polarization
- Ability to reconstruct the GW source parameters
- False alarm rejection thanks to coincidence

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

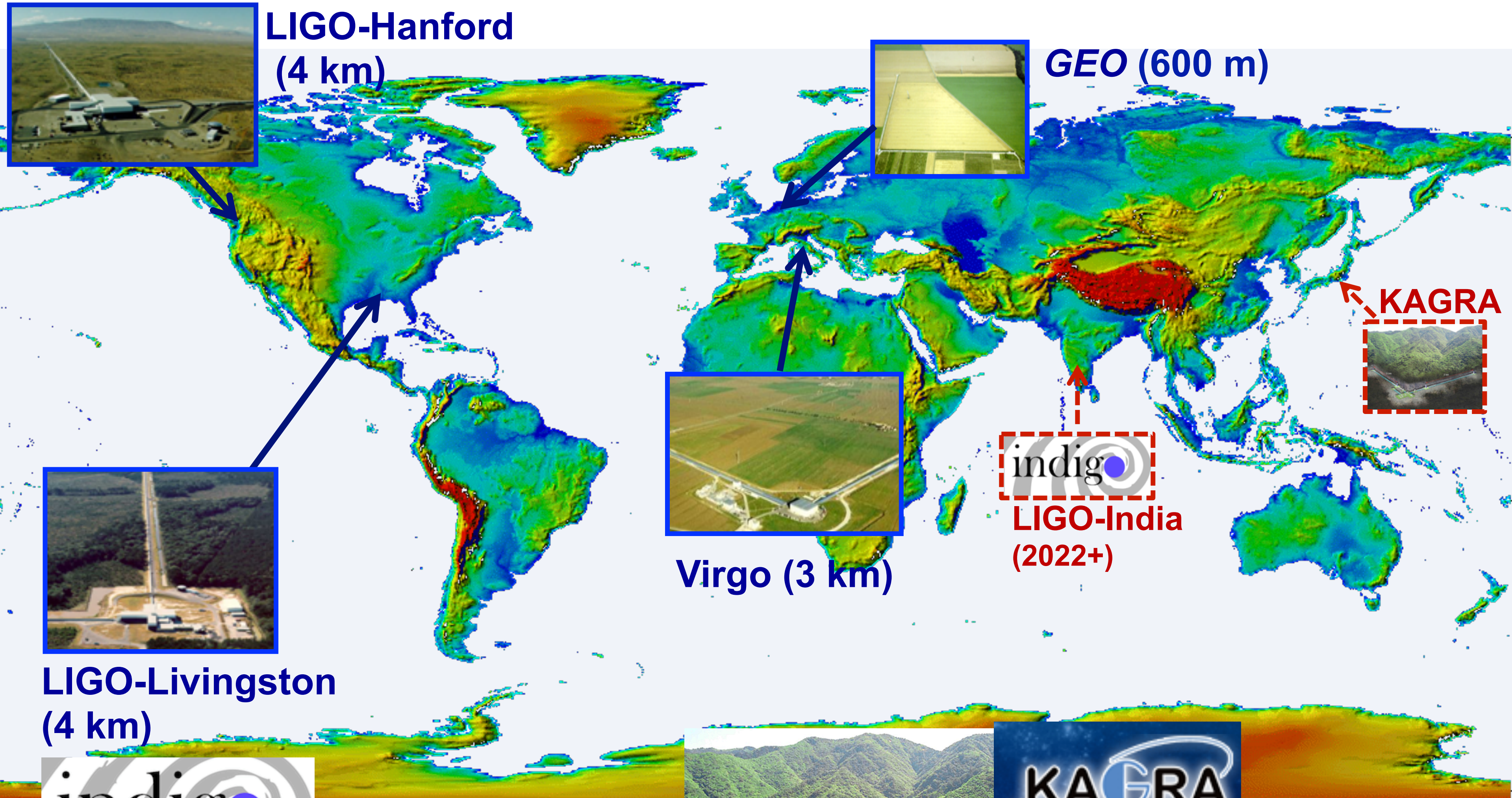
Advanced LIGOs and **Virgo** will observe the sky (10-1000 Hz) as a **single network** aiming at the **first direct detection of GWs**

Example of sky-localization capabilties

NS-NS with SNR=7 in each of the LIGOs and Virgo:

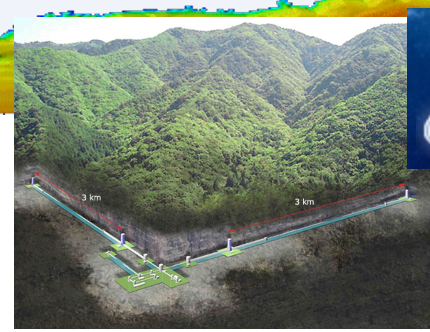
- best case localization of **20 deg^2** (signal is directly over the plane of network)
- median of **40 deg^2** **(Fairhurst 2009)**

Near Future Gravitational Wave Detectors



indigo

Move one of the two LIGO detectors in Hanford to India



KAGRA

Underground detector in the Kamioka mine: 3km length,
– Cryogenic mirrors (2nd phase)

Astrophysical sources detectable by the ground-based GW detectors

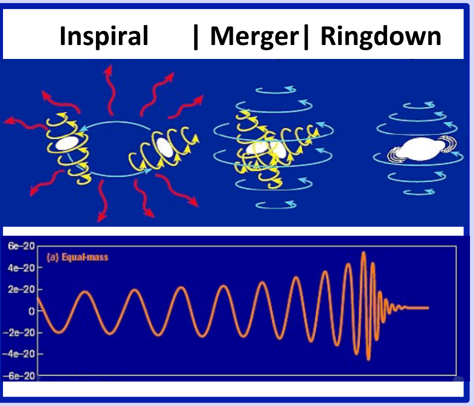
- Some science results of the Initial LIGO/Virgo
- Prospects for the advanced detectors

"Transient" GW sources detectable by LIGO/Virgo

"**Transient GW signal**": signal with duration in the detector sensitive band significantly shorter than the observation time and that cannot be re-observed

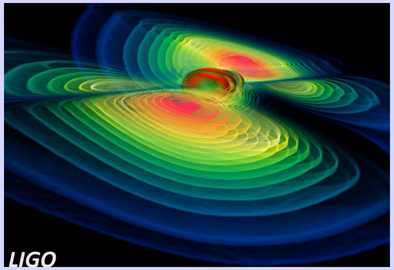
Coalescence of Compact Objects

Neutron-Stars and/or Black-Holes

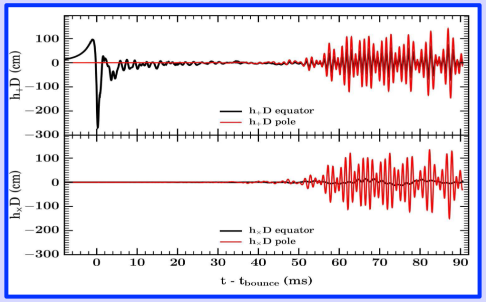


Binary containing a NS:
- **Inspiral** dominant phase
- **GW emission** enters sensitive band (> 50 Hz) **< 20 s before merger**
- **Energy emitted in GW: ~$10^{-2} M_o c^2$**

Initial LIGO/Virgo
Binary containing a NS detectable to ~50 Mpc likely rate **0.02 yr^{-1}**



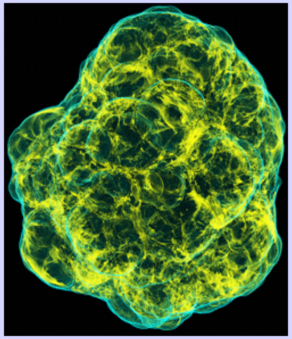
Core-collapse of Massive Stars



Ott, C. 2009, CQG, 26

Energy emitted in GW uncertain: **10^{-8} - 10^{-4} $M_o c^2$**

Initial LIGO/Virgo
Detectable within a fraction of the Milky Way (10 kpc)



Ott et al. 2013, ApJ, 768

Advanced Era GW-detectors (ADE)

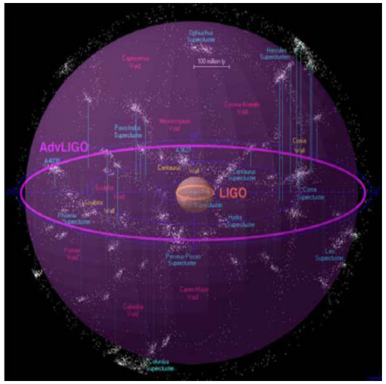
LIGO-H

LIGO-L

Virgo

LIGO and **Virgo** detectors
are currently being **upgraded**

boost of sensitivity
by a **factor of ten**
(of 10^3 in number of detectable sources)



Advanced era
Detection rates of compact binary coalescences

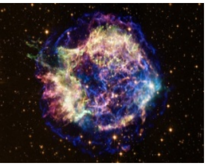
	Source	Low yr^{-1}	Real yr^{-1}	High yr^{-1}	Max yr^{-1}
	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
Advanced	BH-BH	0.4	20	1000	

(Abadie et al. 2010, CQG 27)

Mass: NS = 1.4 Mo
BH = 10 Mo

Advanced era
Sky location and orientation averaged range

197 Mpc for NS-NS
410 Mpc for NS-BH
968 Mpc for BH-BH



Core-Collapse Supernovae

2-4 yr^{-1} EM-observed within **20 Mpc**

Rate of GW-detectable events unknown

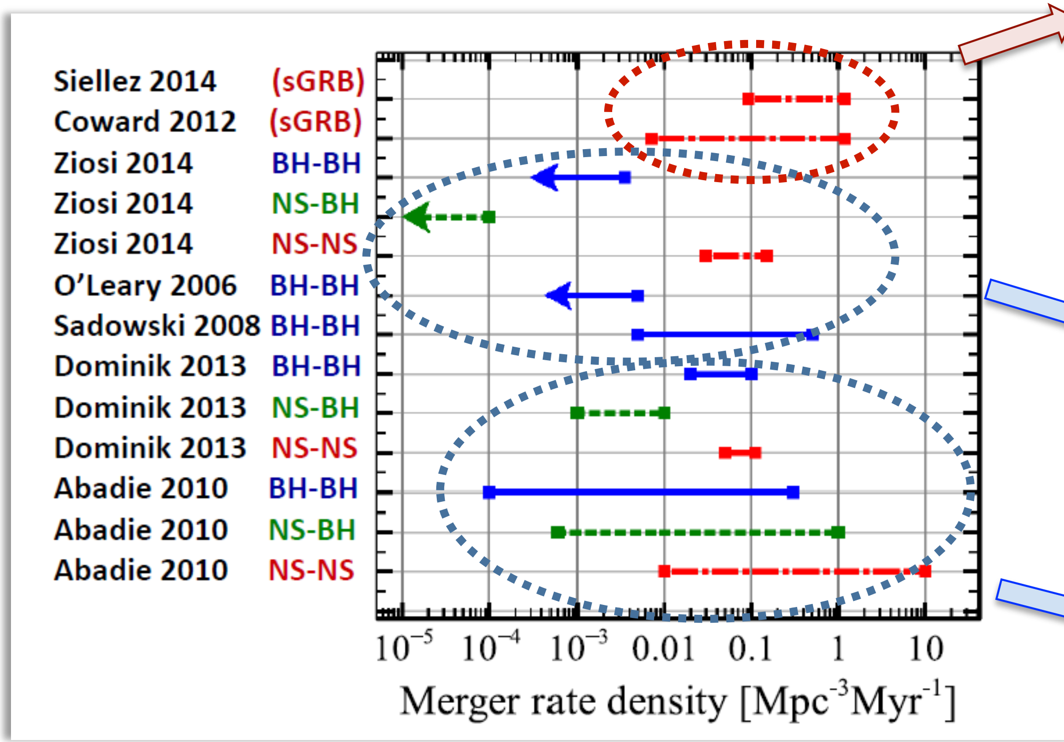
GW-signal detectable **< Milky Way** (Ott et al. 2012, Phy.R.D.)
few Mpc (Fryer et al. 2002, ApJ, 565)

Optimistic models **10 - 100 Mpc** (Piro & Pfahl 2007)
(Fryer & New 2011)

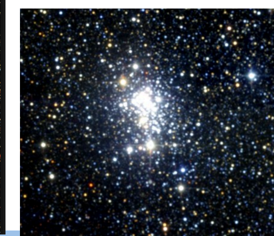
Compact object merger rates

Merger rates of BH-BH, NS-BH, NS-NS

Ziosi et al. 2014, *MNRAS*, 441



Gamma-ray Burst Observations



N-body and Montecarlo

Globular Star cluster

& Young Star Clusters

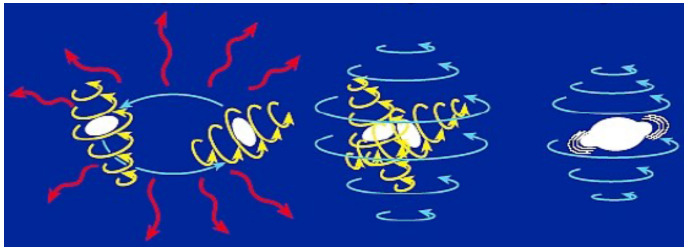
Population Synthesis Code

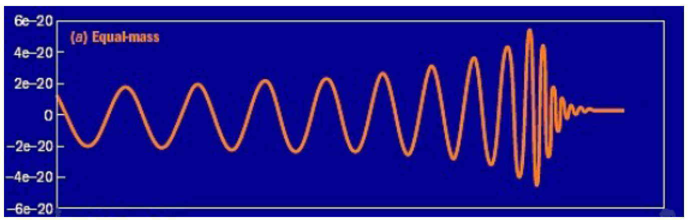
Binaries form and evolve isolated

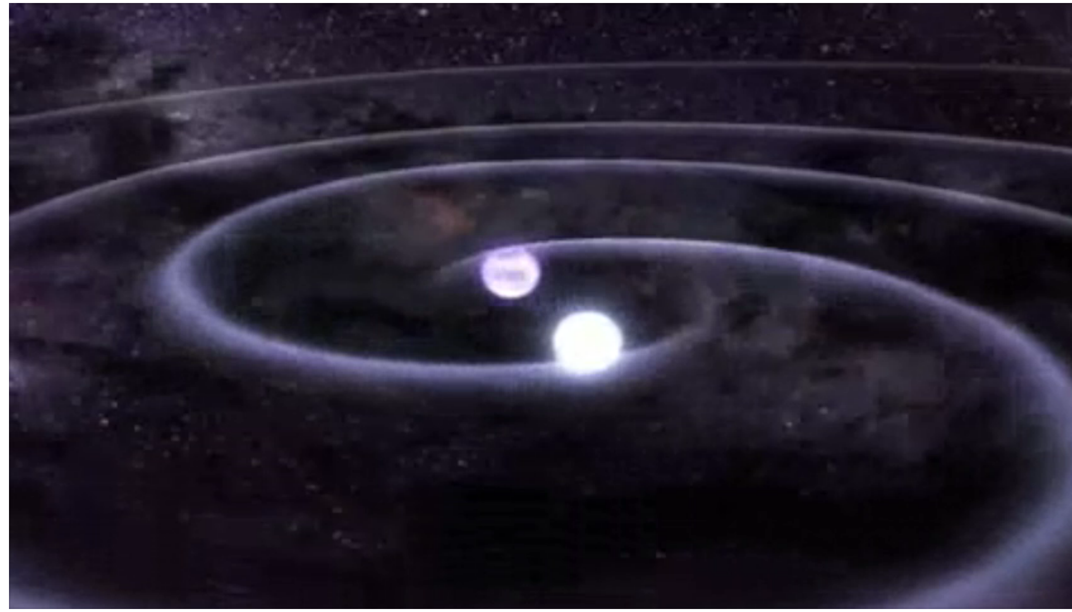
Rates very poorly constrained:

- only 9 observed binary NS-NS sytems
- never observed NS-BH and BH-BH

Inspiral Merger Ring-down

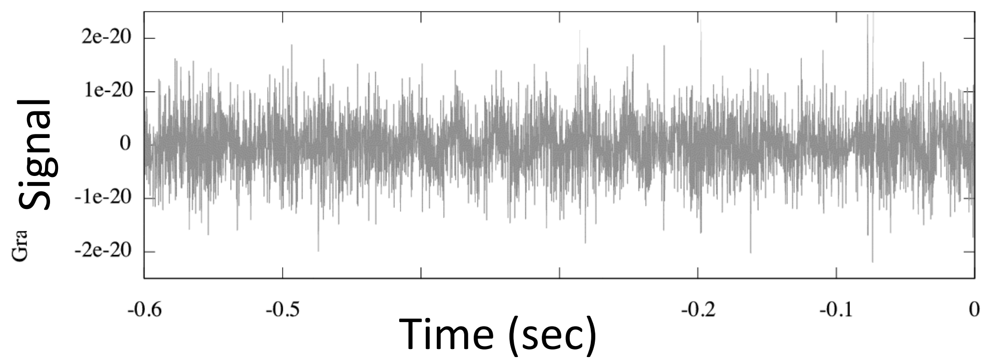






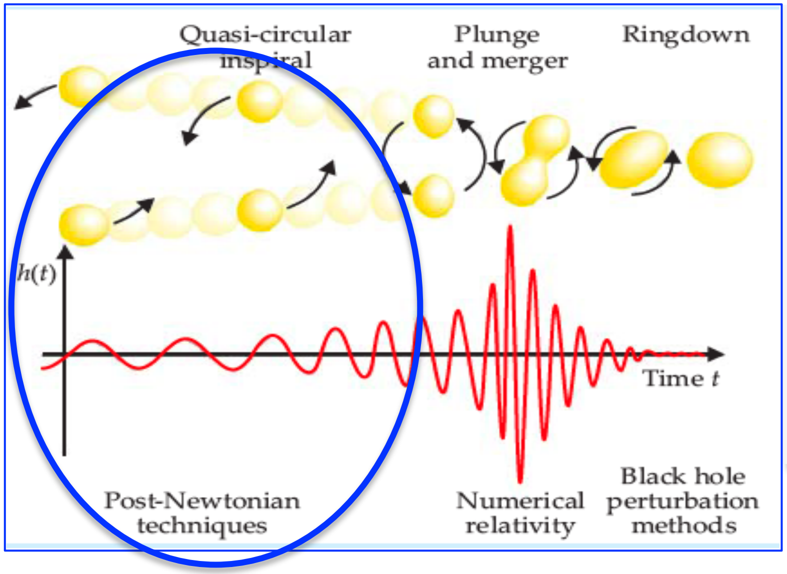
The signal is embedded

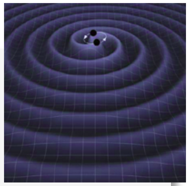
in the detector noise



Which analysis to extract the signal?

Coalescence of NS-NS, NS-BH, BH-BH – Search by "Matched Filtering"





The waveforms depend on

- ***intrinsic parameters**: **masses** and **spins** of the binary system (plus eccentricity, NS compactness, tidal deformability)*
- ***extrinsic parameters** that describe location, distance, merger time and system orientation with respect to an observer*

Detection phase: Known waveform → **MATCHED FILTERING**

- using templates for a range of intrinsic parameters (masses and spin)
- "Extrinsic" parameters absorbed in overall amplitude

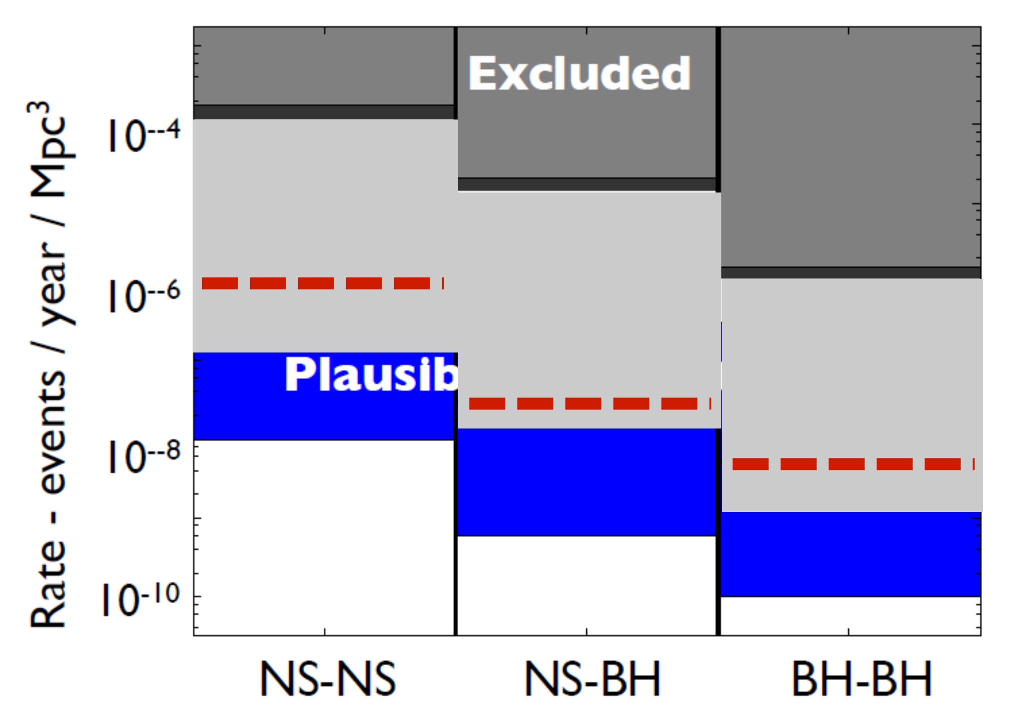
After confident detection → ***Source PARAMETER RECONSTRUCTION:***

- Techniques to explore 15-dimensional parameter space and find most likely values
- Measure masses, spins, distance, sky, location, orientation, ...

Initial LIGO/Virgo upper limit compact binary rates

Upper limits on the rate of low mass compact binary coalescence total mass 2-25 Mo

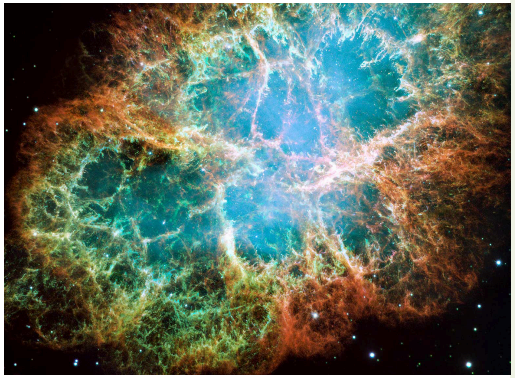
Abadie et al. 2012, *Phys. Rev. D*, 85



Mass: NS = 1.35 Mo
BH = 10 Mo

The upcoming years are very exciting to observe for the first time BH-NS and BH-BH, to constrain stellar evolution model and shed light on the birth and evolution of BHs

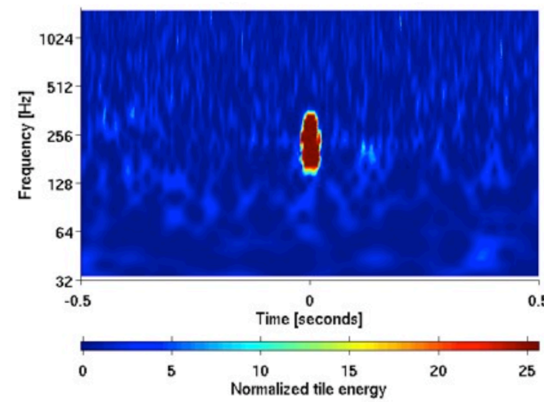
Unmodeled GW transients



Transient sources:

- Core-collapse of massive stars
- Cosmic strings
- Neutron star instabilities
- ...
- ... the unknown

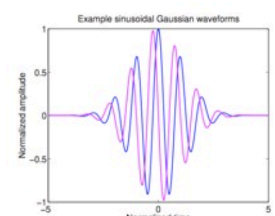
Poorly modeled
→ Can't use matched filtering

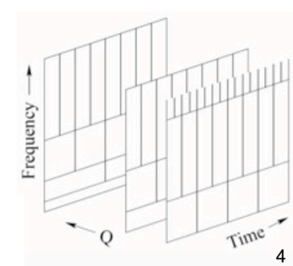


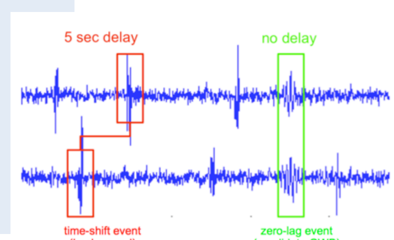
Detection without unknown waveform
→ **LOOK FOR "EXCESS POWER"**

All-sky, all-time search for transient increase in power in some time-frequency region, minimal assumptions:

1. Duration: 1 to 100 ms (characteristic time scale for stellar mass objects)
2. Frequency: 60 to 2000 Hz (determined by detector's sensitivity)
3. **Signal appears coherently** in multiple detectors, consistent with antenna pattern → coincidence, coherent statistics, sky location

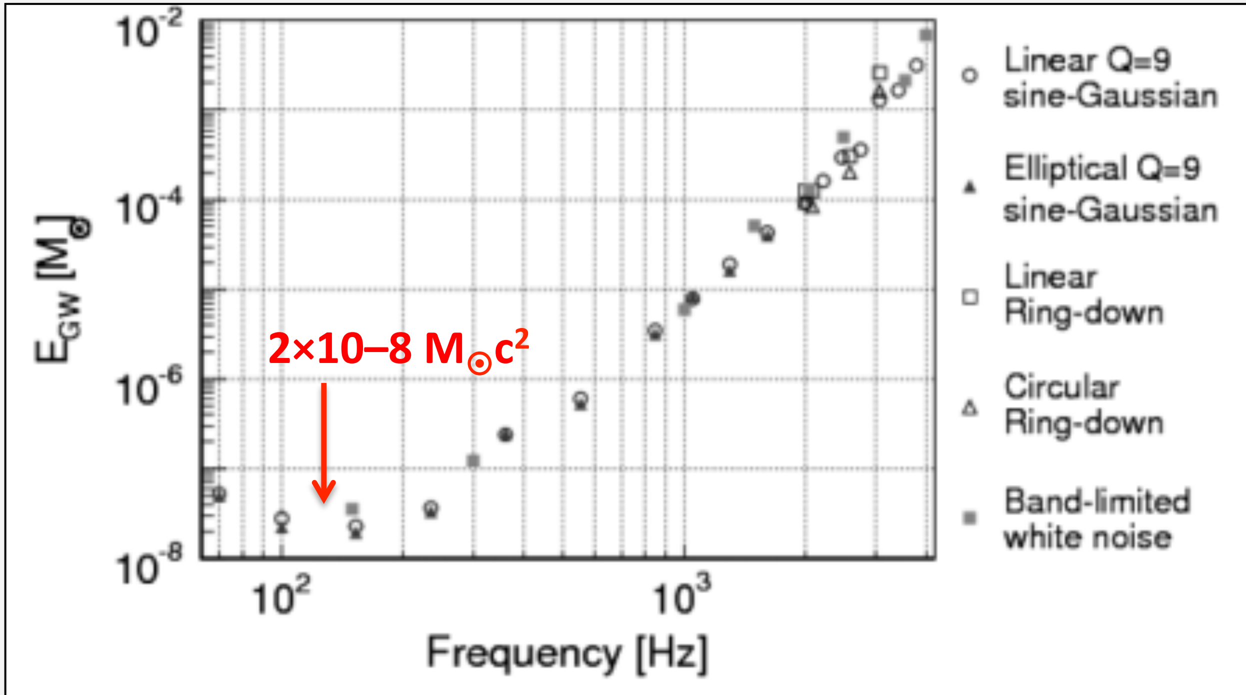






Initial LIGO/Virgo burst sensitivity

Energy emitted in GW at a distance of 10 kpc for the tested waveforms



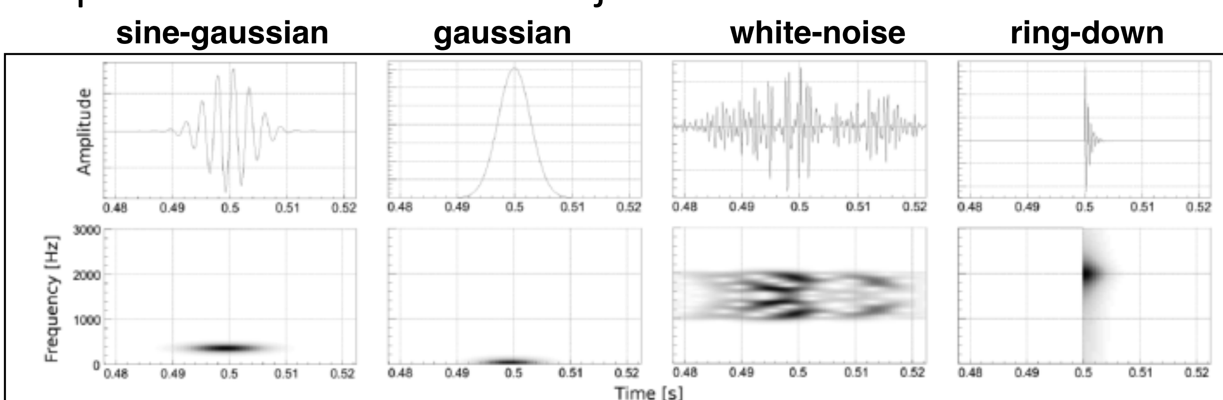
GW energy in short (< 1 s) **pulse from galactic center**, detectable with 50% probability.

Distance scaling:

$E_{GW} \propto D^2$

(so, need ~$3x10^6$ more E_{GW} for a signal from the Virgo to be detectable)

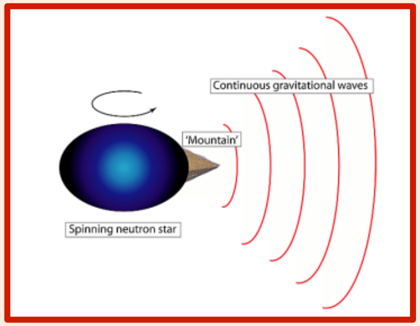
Representative waveforms injected into data for simulation studies

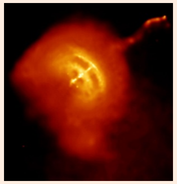


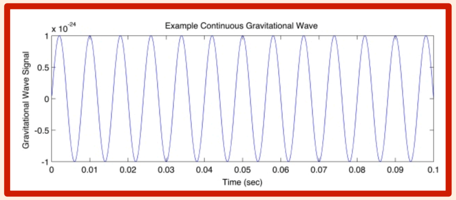
Abadie 2012, PRD, 85,122007

Continuous GW signal

Single Neutron Star





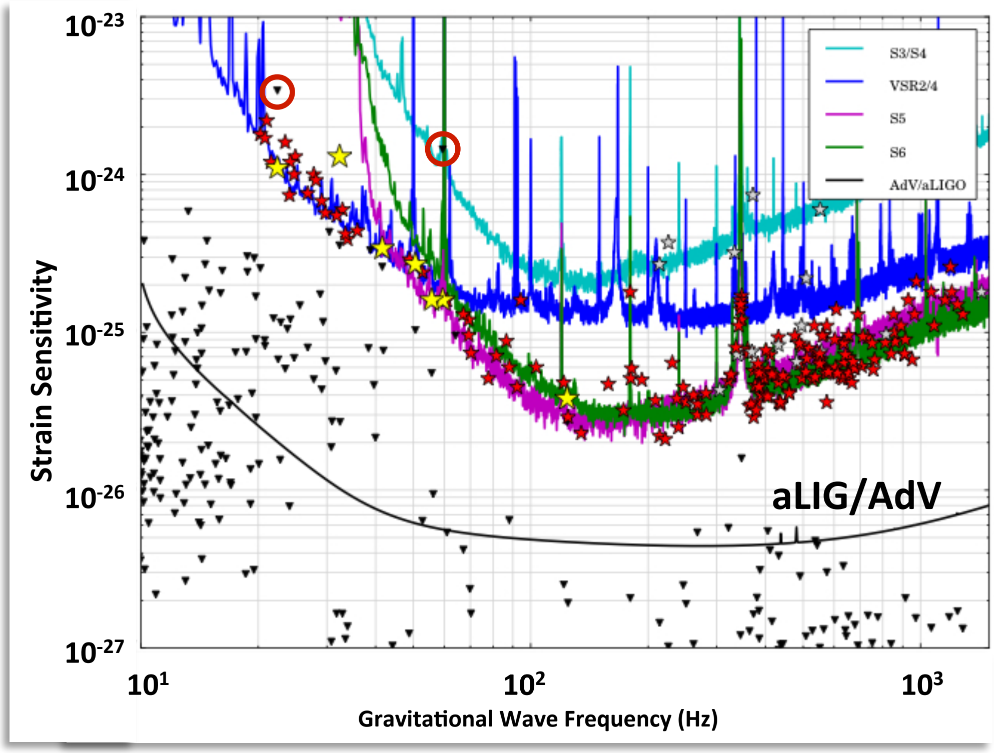


→ *Non-axisymmetric spinning NS emit sources emit quasi-periodic waves whose frequency changes slowly*

→ *Weakness of signal requires long observation times (years) in order to accumulate SNR to ensure detection*

→ Searches for GWs:

- *within parameter windows of know pulsars **TARGETED SEARCH***
- *all sky and all frequencies **ALL SKY SEARCH***

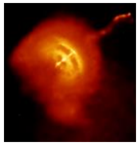


GW amplitude upper limits

from 195 known Pulsars

Crab limit *at 1% of total energy loss!*

Ellipticity: $\varepsilon < 8.6 \times 10^{-5}$

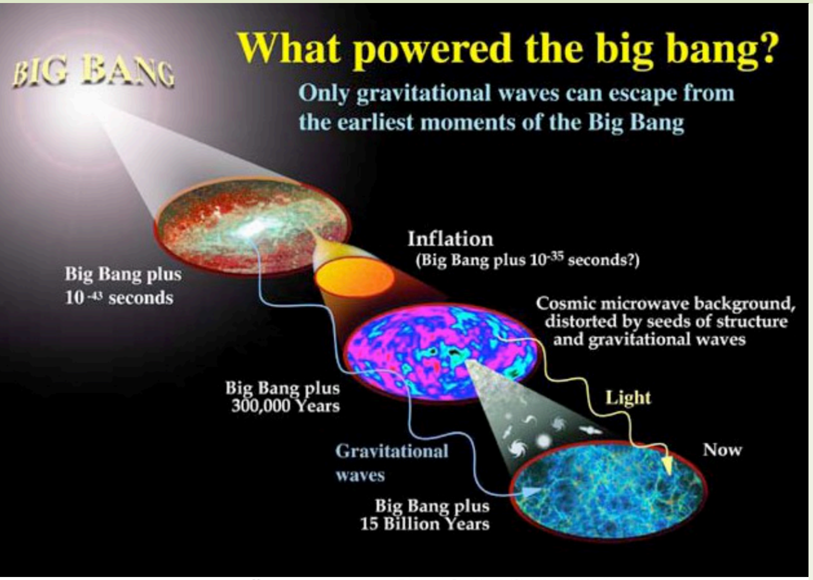


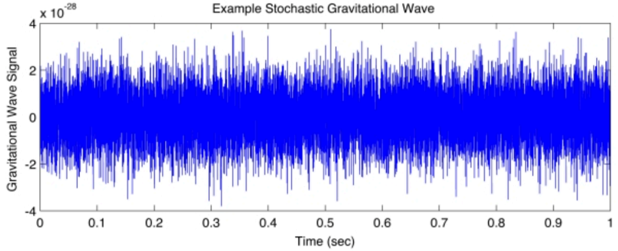
Vela limit *at 10% of total energy loss!*

Ellipticity: $\varepsilon < 6 \times 10^{-4}$

Aasi et al. 2014, ApJ, 785

Stochastic background



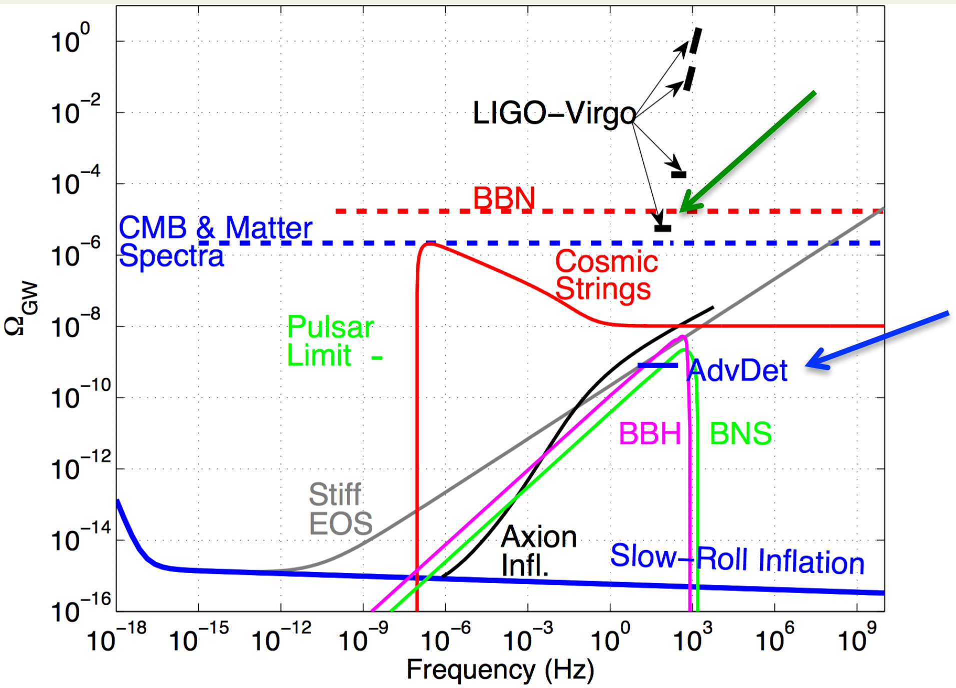


- ➢ *Superposition of many incoherent, unresolvable sources of GWs*
- ***Astrophysical**: summing contributions from compact binaries, rotating neutron stars, magnetars, and supernovae across the universe.*
- ***Cosmological**: early universe signatures –*
- *inflation, Cosmic (super)strings, alternative cosmologies*
- ➢ *A single detector observes stochastic background just like weak noise within the detector noise*
- ➢ *Search method → cross-correlation between network detectors*

LIGO-Virgo limit surpasses indirect limit from Big Bang nucleosynthesis:
in the frequency band 41.5–169.25 Hz

$$\Omega_{GW} \leq 5.6 \times 10^{-6}$$

Aasi et al. 2014, PRL,113
Abbott et al. 2009, Nature, 460

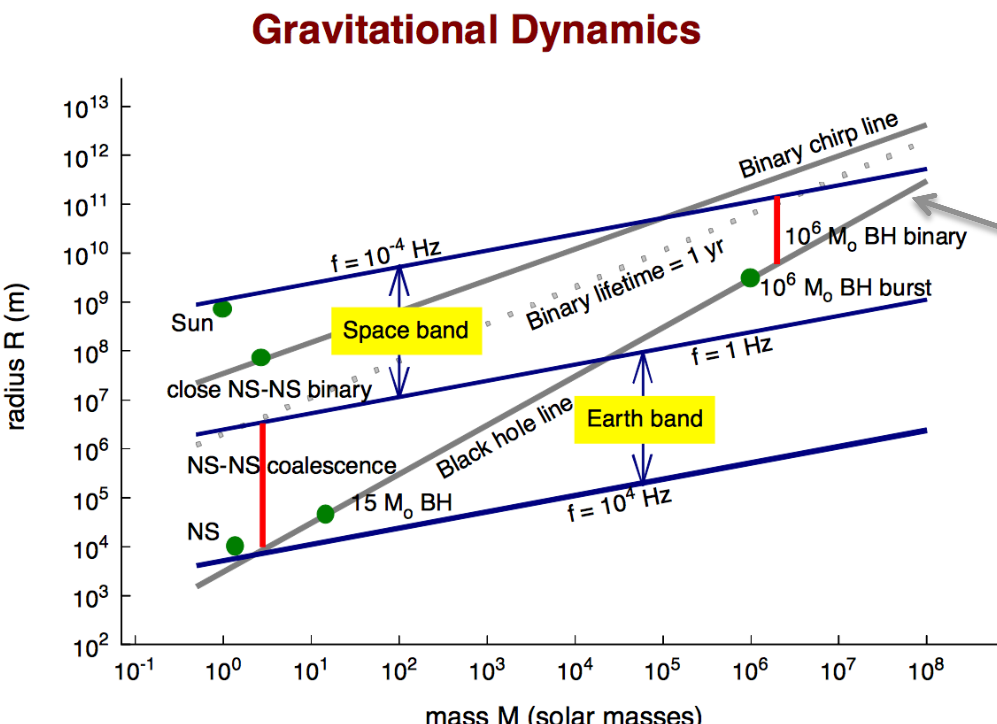


Tomorrow other scientific results on multi-messenger astronomy!

Extra slides

The natural frequency for a self-gravitating body is $$f = \sqrt{\frac{G < \rho >}{4\pi}}$$

Where <ρ>is the mean density of mass-energy in the source $$< \rho > = \frac{3M}{4\pi R^3}$$



Schutz - 1999

GWs:

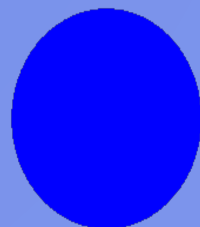
- between 1 and 10^4 Hz accessible to ground-based detectors
- lower frequencies only from space

Line marking the black-hole boundary: R = 2M. There are no objects below this line.

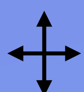
This line restricts ground-based to looking at stellar-mass objects.
Nothing over a mass of about $10^4 M_\odot$ can radiate above 1 Hz.

Simplified Interferometric Gravitational Wave Detector

*Spatial distortion from a **plus and a cross** polarized GW*

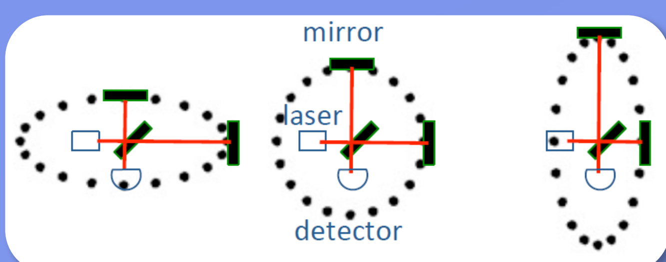


Polarization "Plus"



"Cross"

*The length change is measured interferometrically by using a **laser light beam***



Suspended mirrors as test mass