# Gravitational wave searches: an overview

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University of Glasgow

Astronomy group seminar,
University of Southampton, Jan 2015

LIGO-DCC G1500072

# 1. Gravitational wave (GW) background

# What are gravitational waves?

- Gravitational waves are a direct prediction of Einstein's General Theory of Relativity
- Solutions to (weak field) Einstein equations in vacuum are wave equations

$$\left(-\frac{\partial^2}{\partial t^2}+\nabla^2\right)h^{\mu\nu}=-16\pi T^{\mu\nu}$$

Vacuum so stress-energy tensor $T^{\mu\nu}=0$

$$\left(-\frac{\partial^2}{\partial t^2}+\nabla^2\right)h^{\mu\nu}=0$$

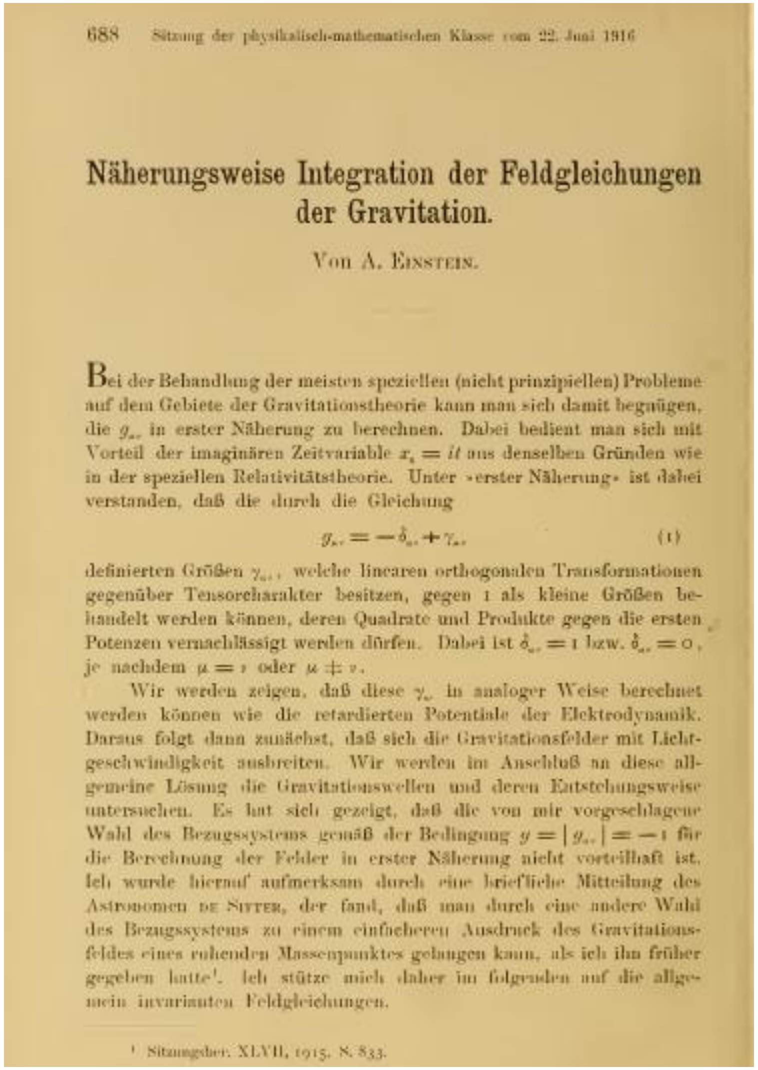
$$h^{\mu\nu}=A^{\mu\nu}\exp\left(ik_\mu x^\mu\right)$$

- "Ripples in space-time"

# What are GWs?

- Einstein first predicted GWs in 1916 paper
- This had a major error – the waves carried no energy!

Einstein, “Näherungsweise Integration der Feldgleichungen der Gravitation“, *Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften,* 1916



688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

## Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \tag{1}$$

definierten Größen $\gamma_{\mu\nu}$, welche linearen orthogonalen Transformationen gegenüber Tensorcharakter besitzen, gegen 1 als kleine Größen behandelt werden können, deren Quadrate und Produkte gegen die ersten Potenzen vernachlässigt werden dürfen. Dabei ist $\delta_{\mu\nu} = 1$ bzw. $\delta_{\mu\nu} = 0$, je nachdem $\mu = \nu$ oder $\mu \neq \nu$.

Wir werden zeigen, daß diese $\gamma_{\mu\nu}$ in analoger Weise berechnet werden können wie die retardierten Potentiale der Elektrodynamik. Daraus folgt dann zunächst, daß sich die Gravitationsfelder mit Lichtgeschwindigkeit ausbreiten. Wir werden im Anschluß an diese allgemeine Lösung die Gravitationswellen und deren Entstehungsweise untersuchen. Es hat sich gezeigt, daß die von mir vorgeschlagene Wahl des Bezugssystems gemäß der Bedingung $g = |g_{\mu\nu}| = -1$ für die Berechnung der Felder in erster Näherung nicht vorteilhaft ist. Ich wurde hierauf aufmerksam durch eine briefliche Mitteilung des Astronomen de Sitter, der fand, daß man durch eine andere Wahl des Bezugssystems zu einem einfacheren Ausdruck des Gravitationsfeldes eines ruhenden Massenpunktes gelangen kann, als ich ihn früher gegeben hatte[1]. Ich stütze mich daher im folgenden auf die allgemein invarianten Feldgleichungen.

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[1] Sitzungsber. XLVII, 1915, S. 833.

# What are GWs?

- Corrected in 1918 paper which introduced the now famous “*quadrupole formula*”

Einstein, “Über Gravitationswellen“, *Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften,* 1918

154 Gesamtsitzung vom 14. Februar 1918. — Mitteilung vom 31. Januar

## Über Gravitationswellen.

Von A. Einstein.

(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden[1]. Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.

Wie damals beschränke ich mich auch hier auf den Fall, daß das betrachtete zeiträumliche Kontinuum sich von einem »galileischen« nur sehr wenig unterscheidet. Um für alle Indizes

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \tag{1}$$

setzen zu können, wählen wir, wie es in der speziellen Relativitätstheorie üblich ist, die Zeitvariable $x_4$ rein imaginär, indem wir

$$x_4 = it$$

setzen, wobei $t$ die »Lichtzeit« bedeutet. In (1) ist $\delta_{\mu\nu} = 1$ bzw. $\delta_{\mu\nu} = 0$, je nachdem $\mu = \nu$ oder $\mu \neq \nu$ ist. Die $\gamma_{\mu\nu}$ sind gegen 1 kleine Größen, welche die Abweichung des Kontinuums vom feldfreien darstellen; sie bilden einen Tensor vom zweiten Range gegenüber Lorentz-Transformationen.

### § 1. Lösung der Näherungsgleichungen des Gravitationsfeldes durch retardierte Potentiale.

Wir gehen aus von den für ein beliebiges Koordinatensystem gültigen[2] Feldgleichungen

$$-\sum_{\alpha}\frac{\partial}{\partial x_\alpha}\begin{Bmatrix}\mu\nu\\ \alpha\end{Bmatrix}+\sum_{\alpha}\frac{\partial}{\partial x_\nu}\begin{Bmatrix}\mu\alpha\\ \alpha\end{Bmatrix}+\sum_{\alpha\beta}\begin{Bmatrix}\mu\alpha\\ \beta\end{Bmatrix}\begin{Bmatrix}\nu\beta\\ \alpha\end{Bmatrix}-\sum_{\alpha\beta}\begin{Bmatrix}\mu\nu\\ \alpha\end{Bmatrix}\begin{Bmatrix}\alpha\beta\\ \beta\end{Bmatrix}$$
$$= -\kappa\left(T_{\mu\nu}-\frac{1}{2}g_{\mu\nu}T\right). \tag{2}$$

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[1] Diese Sitzungsber. 1916, S. 688 ff.

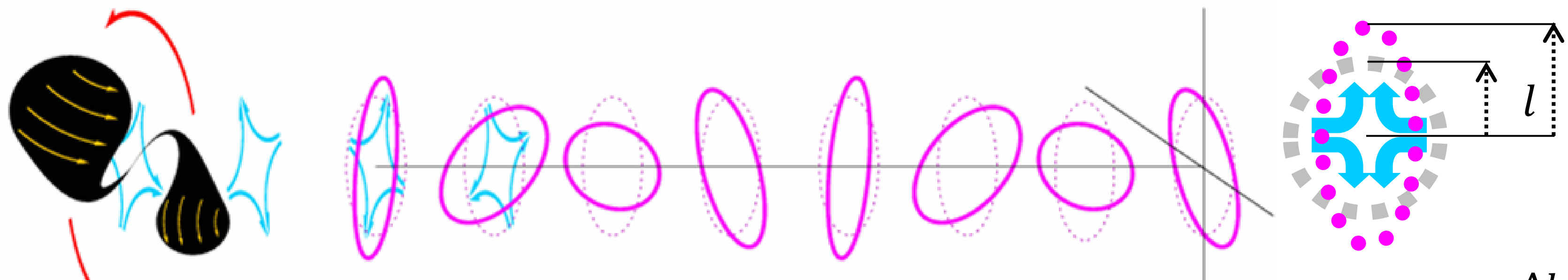
[2] Von der Einführung des »λ-Gliedes« (vgl. diese Sitzungsber. 1917, S. 142) ist dabei Abstand genommen.

# What are GWs

Source: Bulk Motion Produces Changing Tidal Field

Oscillating Tidal Field Propagates (Unobstructed) to Observer

Observer Detects Distortion Strain



Strain: $h = \frac{\Delta l}{l}$

Quadrupole formula:

$$h(t) = \frac{2}{r}\frac{G}{c^4}\ddot{I}(t)$$

mass quadruple

$8\text{x}10^{-45}$ small number!

source distance ($1/r$ - amplitude not power!)

# What are GWs?

$$h(t) = \frac{2}{r}\frac{G}{c^4}\ddot{I}(t)$$

mass quadruple

$8\mathrm{x}10^{-45}$

source distance ($1/r$ - amplitude not power!)

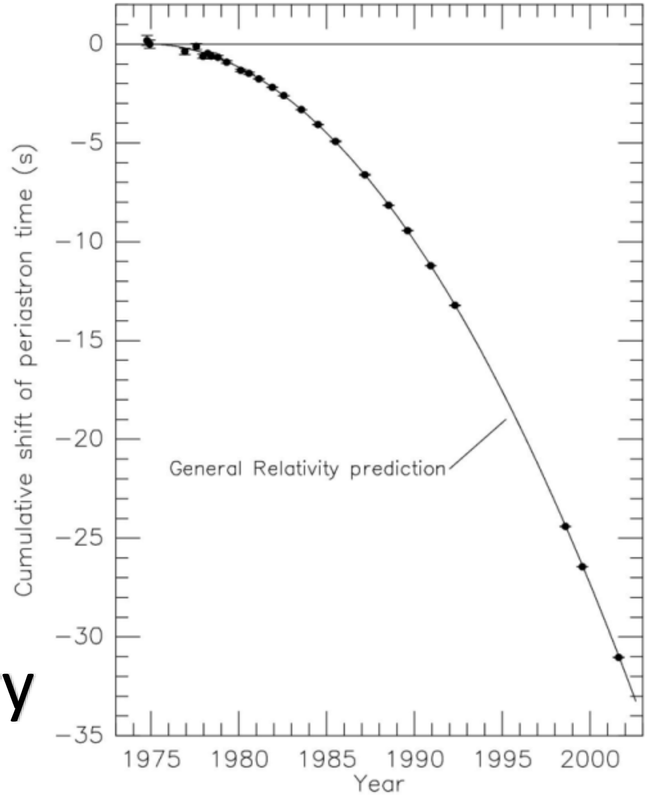
For two 1.4 $M_{\odot}$ neutron stars near coalescence at a distance of 10 Mpc $h \sim 1.4 \times 10^{-22}$

Displacement measured by 4km long detector $\sim 5.6 \times 10^{-19}$m - about 1/10000th diameter of a proton, or measuring change in distance to α Centauri to ~1/10th diameter of a human hair!

- Detectable gravitational waves (GWs) will only come from the most massive and energetic systems in the universe e.g. black hole binaries, pulsars, supernova, GRBs, etc

# Evidence for GWs

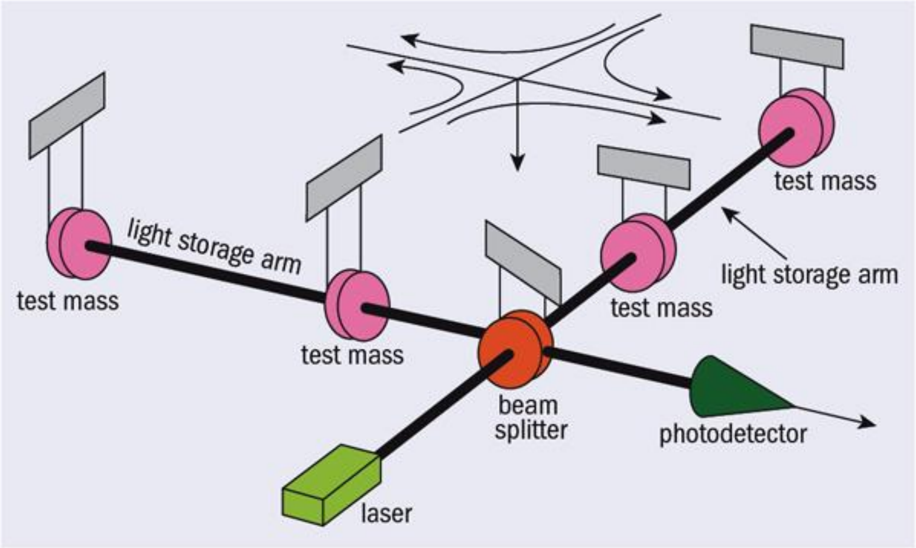
- GR works!
  - Gravitational lensing
  - Perihelion precession of Mercury
  - Shapiro delay
  - Gravitational time dilation
  - Frame dragging
- Hulse-Taylor pulsar and other binary neutron star systems are losing energy exactly as predicted through GW emission

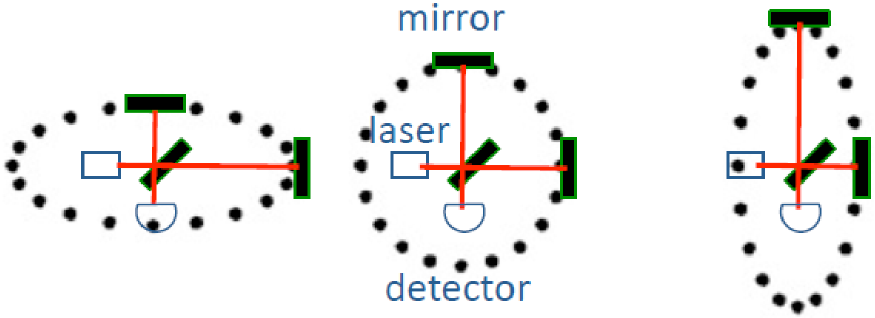


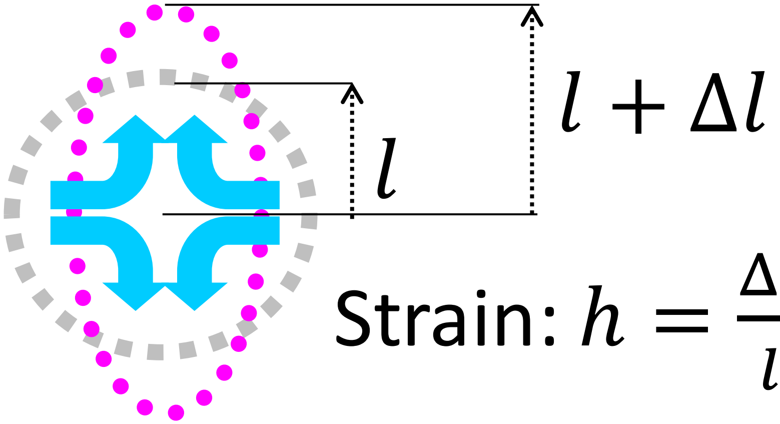
# 2. Detection and detectors

# GW detection basics

- Measure displacement between two freely falling test masses (i.e. the suspended mirrors at the end of an interferometer’s arms)
- Detectors measure strain: larger arm length ➞ more sensitive

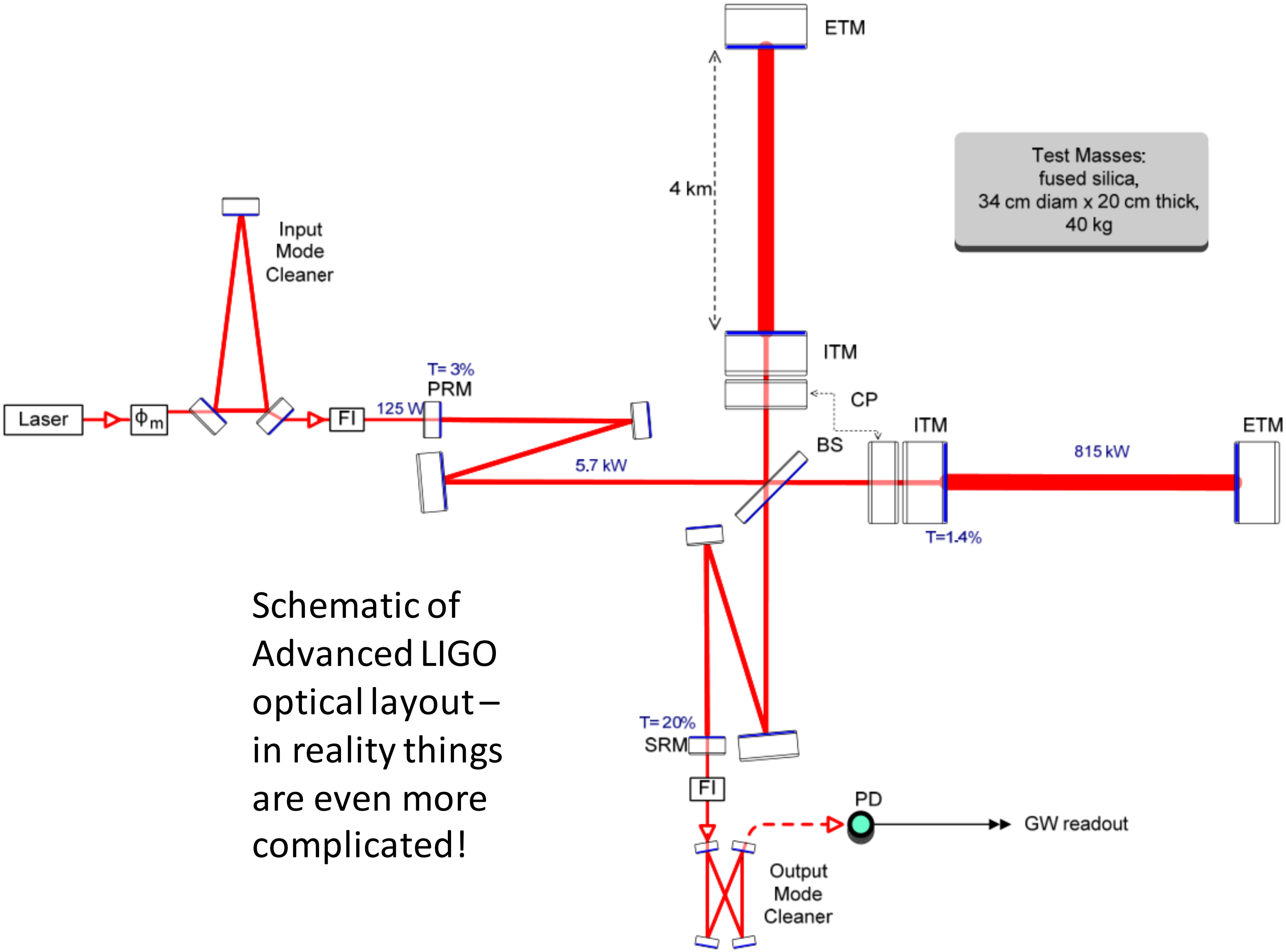






Strain: $h = \frac{\Delta l}{l}$

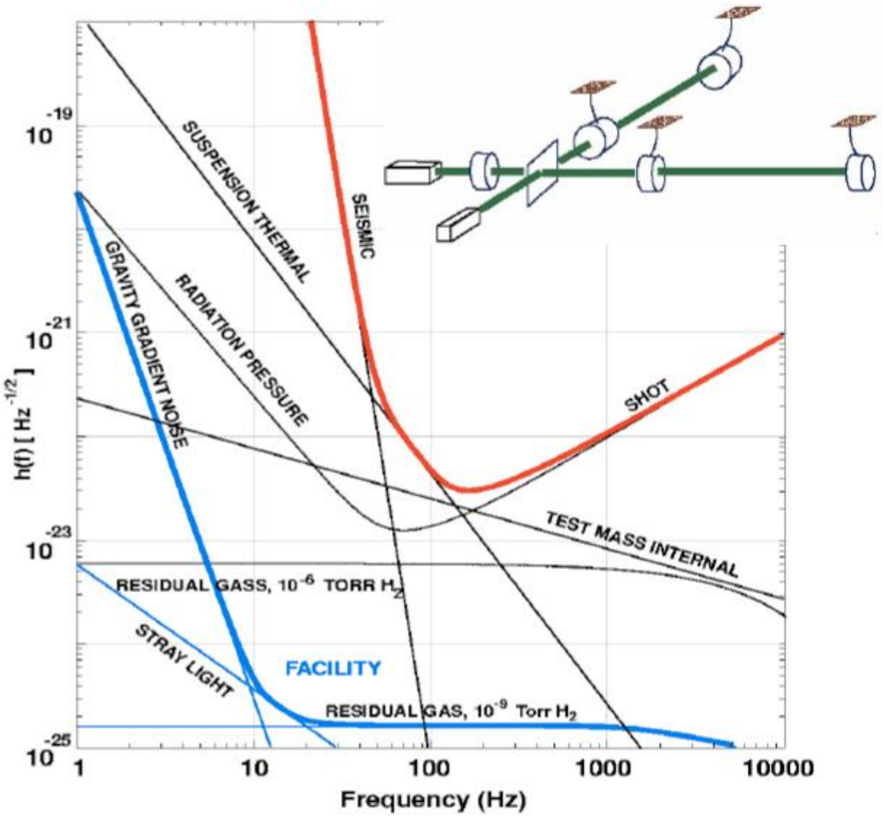
# GW detection basics



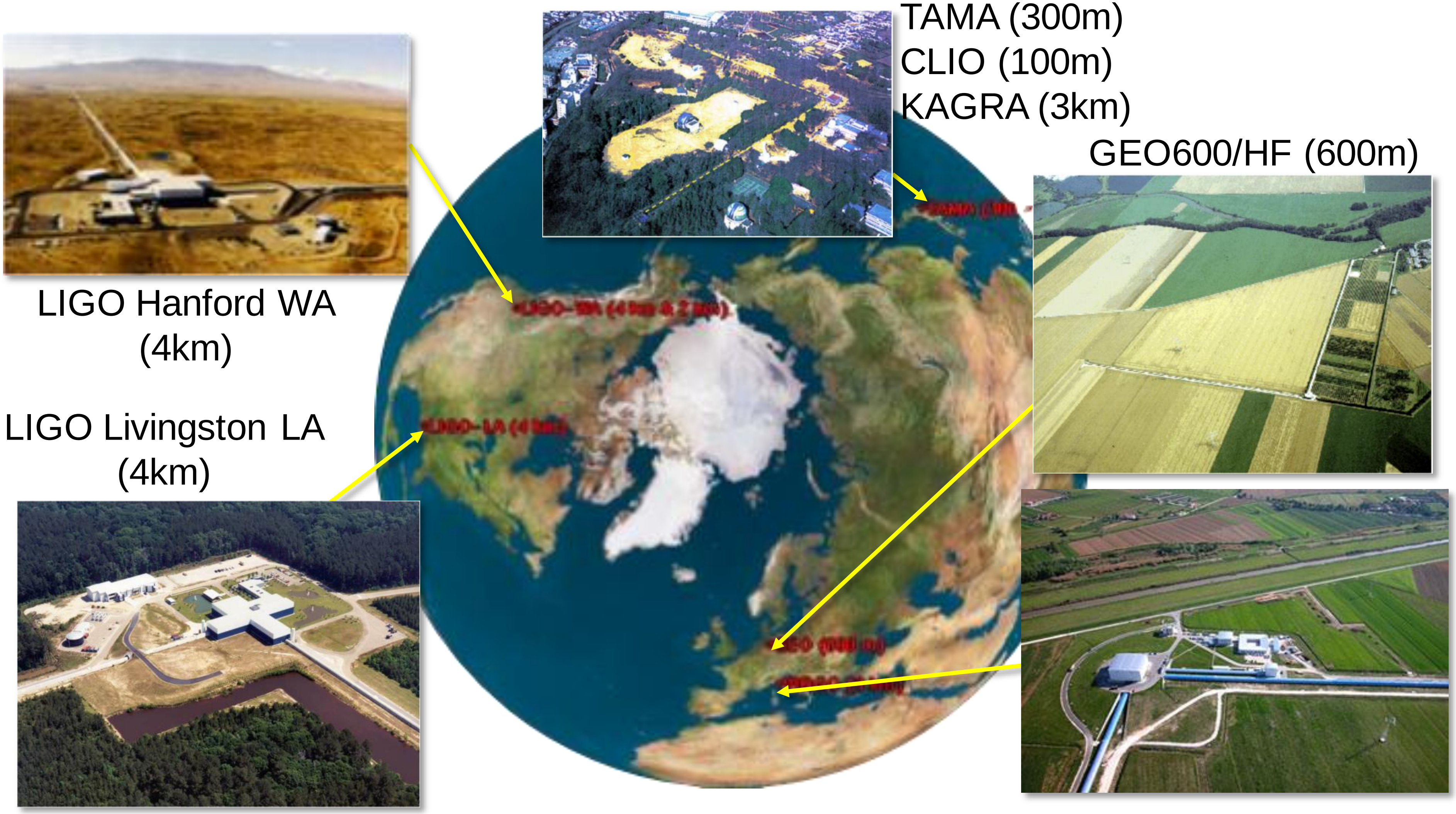
Schematic of Advanced LIGO optical layout – in reality things are even more complicated!

# Noise sources

- Many noise sources to overcome
  - Pendulum suspension isolates masses from seismic motion (low frequency <100Hz)
  - High quality factor masses, mirror coatings, suspensions reduces thermal noise in detection band (low-mid frequency 10s-100s Hz)
  - High laser power reduced laser shot noise (high frequencies > 100s Hz)
    - power recycling - keep as much light in interferometer arms as possible (few W input laser ➡ few kW in arms)



# Worldwide detector network



TAMA (300m)
CLIO (100m)
KAGRA (3km)

GEO600/HF (600m)

LIGO Hanford WA
(4km)

LIGO Livingston LA
(4km)

Virgo (3km)

LIGO

# LIGO Scientific Collaboration

LSC

Trinity University
University of Maryland
Andrews University
Washington State University
California State University Fullerton
indigo
ANU The Australian National University
Texas Tech University
R·I·T
ICTP SAIFR
Montana State University
Sonoma State University
University of the West of Scotland UWS
Montclair State University
清華大學 Tsinghua University
American University Washington, DC
Michigan
University of Glasgow
1754
NASA Goddard Space Flight Center
Whitman College
LSU
University of Strathclyde
CITA–ICAT
ACU
UTB TSC
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Massachusetts Institute of Technology
Southern University and Agricultural & Mechanical College
The University of Western Australia
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University of Minnesota
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Georgia Tech
Syracuse University
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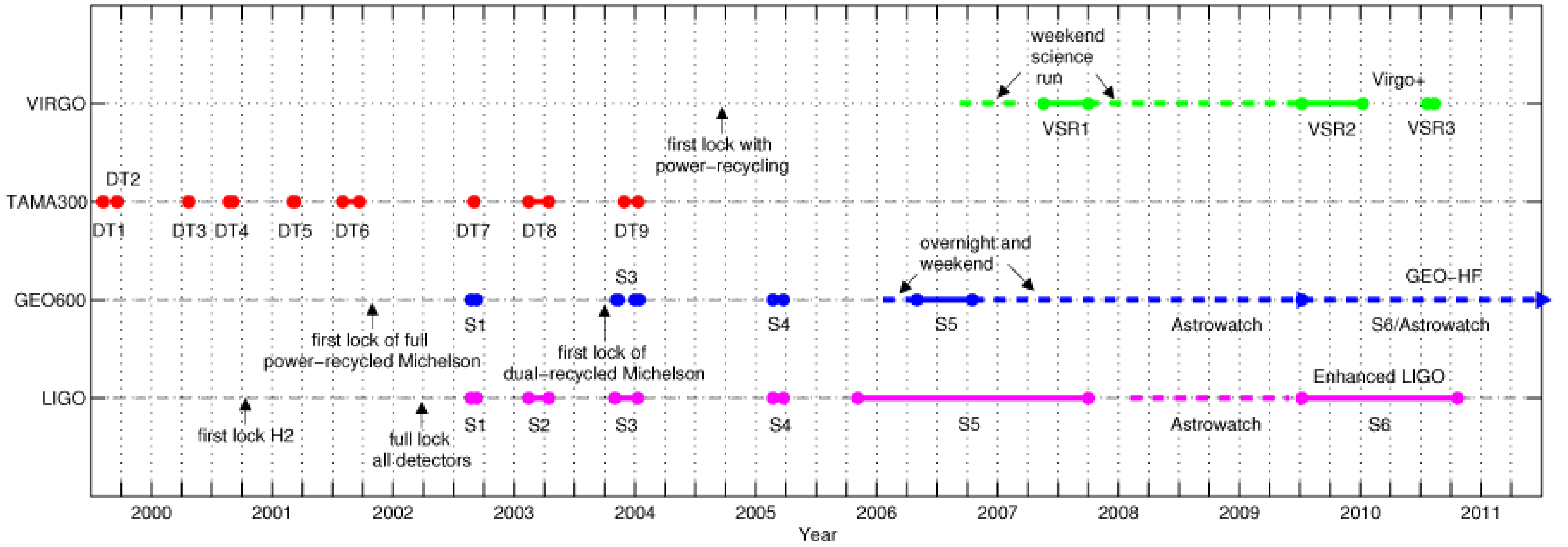
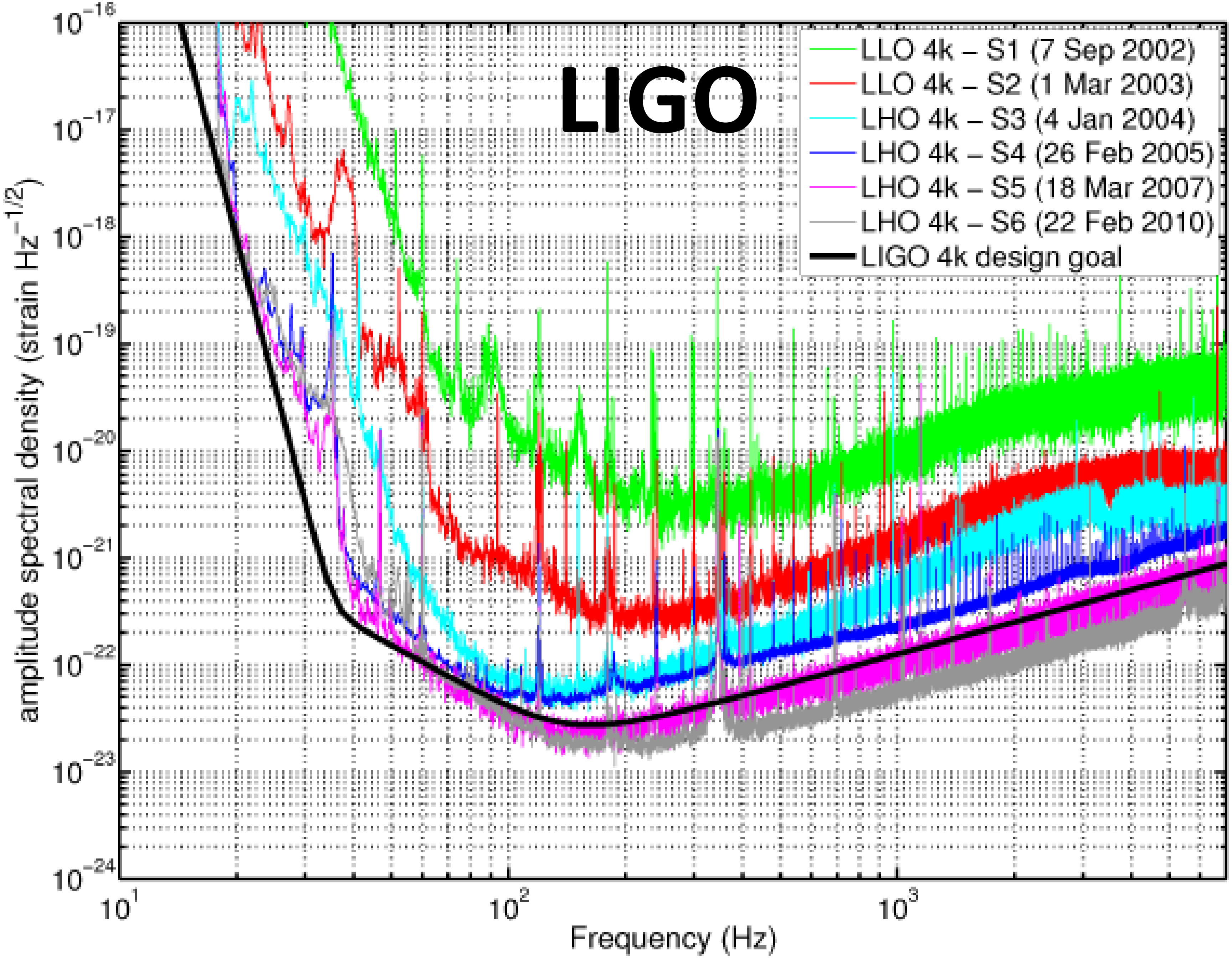
Universitat de les Illes Balears
UF University of Florida
University of Wisconsin UW Milwaukee
Korean Gravitational-Wave Group
ACIGA
University of Southampton
Penn State
Leibniz Universität Hannover
Hobart and William Smith Colleges
Science & Technology Facilities Council Rutherford Appleton Laboratory

# "Initial" and "Enhanced" detectors

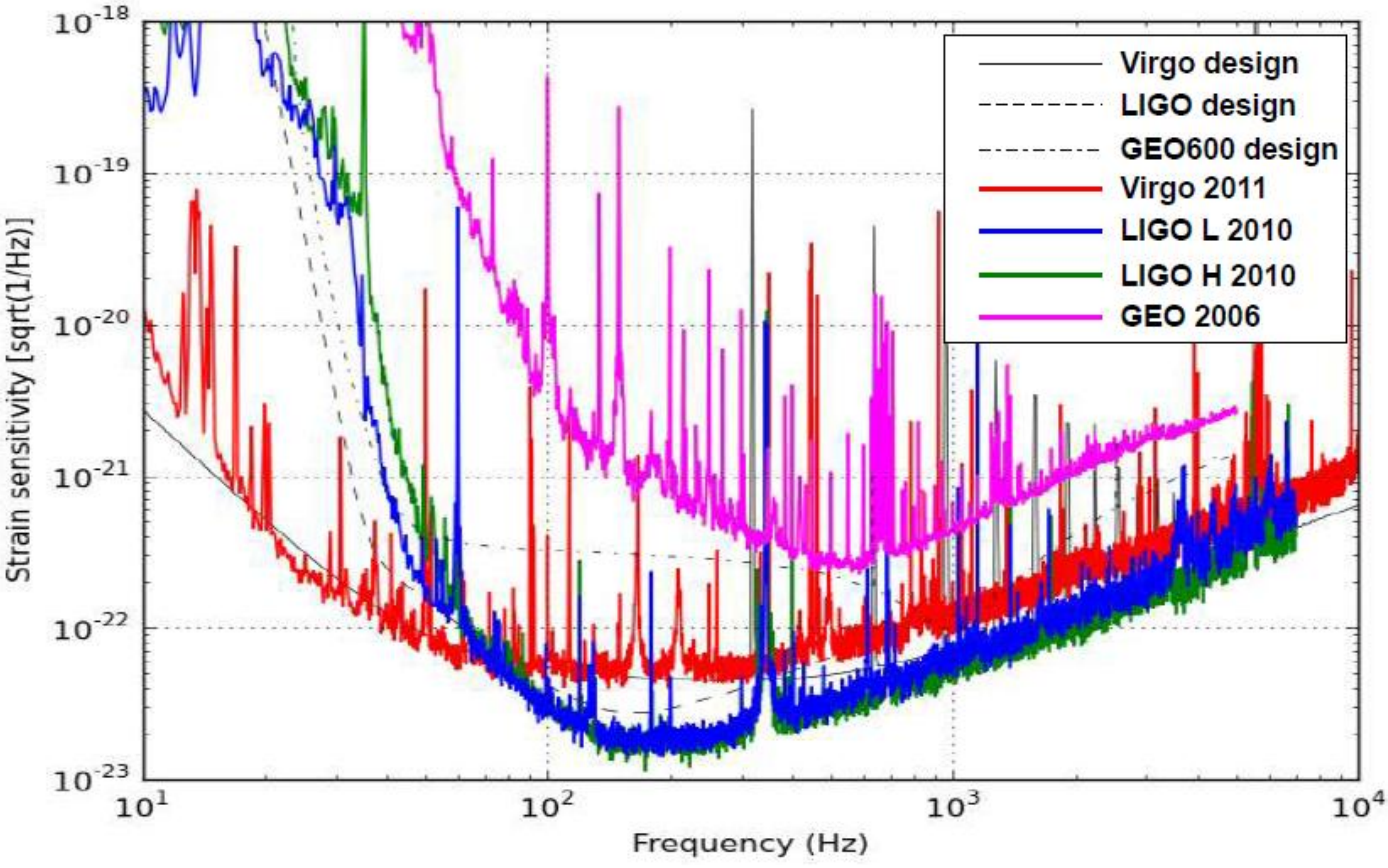
- Since 2001 the initial generation of interferometric detectors have been through periods of science data taking
- 6 major science runs producing astrophysical results up to 2011
- Enhanced LIGO/Virgo+/GEO-HF tested some "Advanced" technology



# LIGO


LLO 4k – S1 (7 Sep 2002)
LLO 4k – S2 (1 Mar 2003)
LHO 4k – S3 (4 Jan 2004)
LHO 4k – S4 (26 Feb 2005)
LHO 4k – S5 (18 Mar 2007)
LHO 4k – S6 (22 Feb 2010)
LIGO 4k design goal
amplitude spectral density (strain Hz$^{-1/2}$)
$10^{-16}$
$10^{-17}$
$10^{-18}$
$10^{-19}$
$10^{-20}$
$10^{-21}$
$10^{-22}$
$10^{-23}$
$10^{-24}$
$10^{1}$
$10^{2}$
$10^{3}$
Frequency (Hz)

# Detector network



# "Horizon distance" sensitivity

Often express detector sensitivity as the maximum distance to which we could observe the coalescence of two 1.4 solar mass neutron stars optimally oriented to the detector at an SNR of 8 (an angle averaged version can be obtained by dividing by ~2.3)

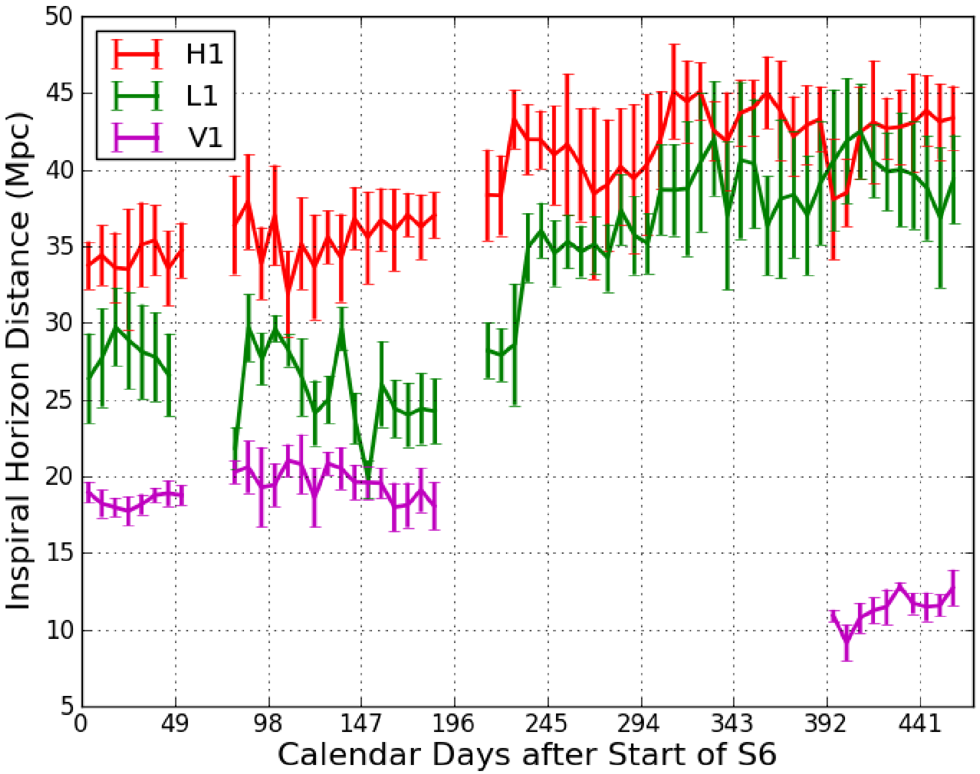


Figure for S6/VSR1,2,3 from LSC & Virgo, arXiv:1203.2674

# 3. GW searches and science

# GW searches

1. **Bursts**
   - Any transient (e.g. < 1 sec) (potentially unmodelled) source of excess power
2. **Compact binary coalescences (CBC)**
   - late stage neutron star or black hole binary inspirals, mergers and ring-downs with well-modelled signal
3. **Continuous [waves] (CW)**
   - Any long duration quasi-monochromatic signal
4. **Stochastic background**
   - Coherent stochastic signals

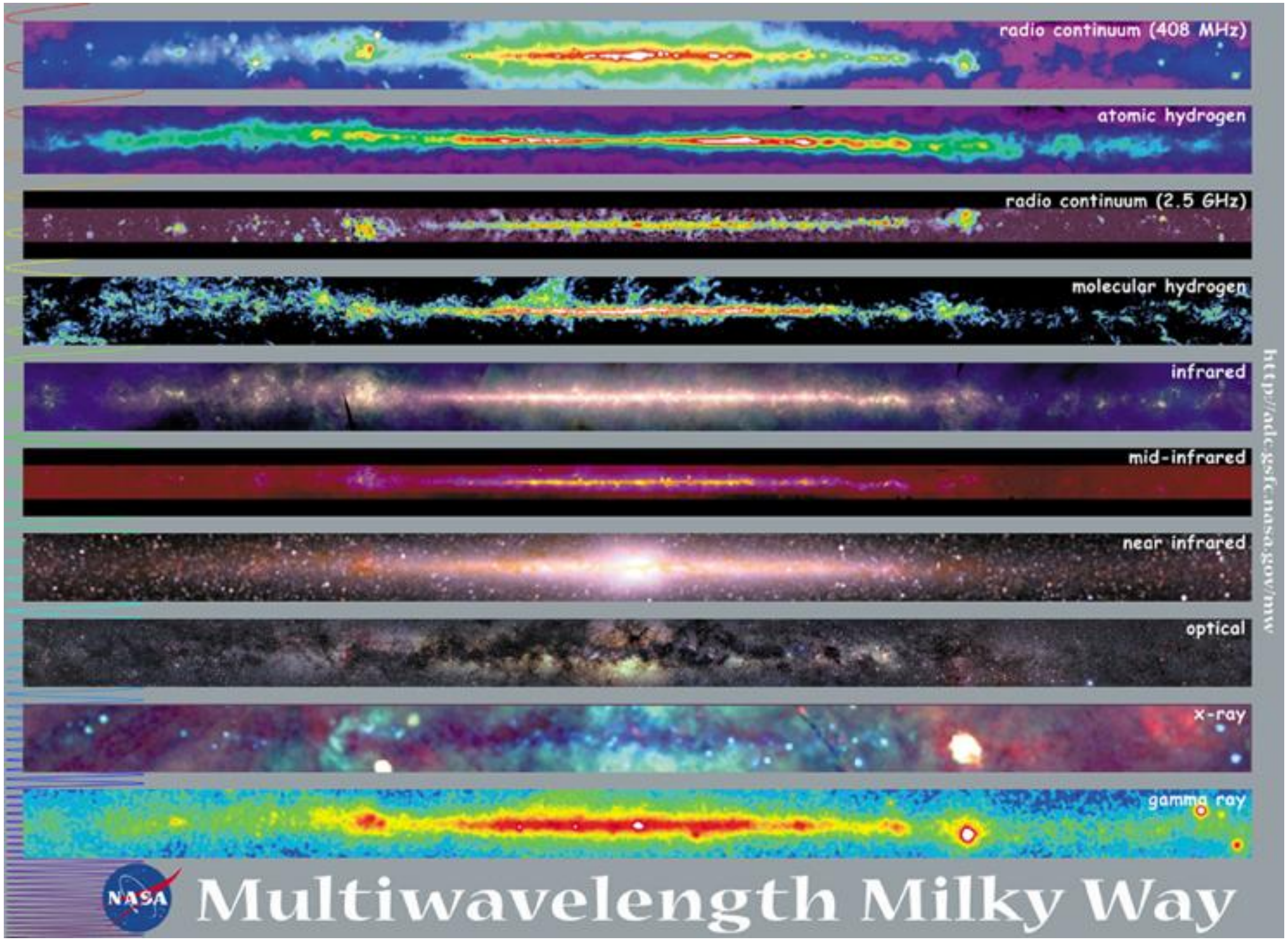
Not broken down by the astrophysical source type (e.g. neutron stars can be CBC, burst, CW and stochastic emitters), but by waveform and the optimal search strategy

# GW sources

1. **Bursts**
   - Core-collapse supernova, compact object coalescence, neutron star/black-hole vibrational modes, cosmic strings, …
2. **Compact binary coalescences (CBC)**
   - final stages of coalescence, merger and ring-down of binary neutron stars, binary black holes, or neutron star-black hole binaries
3. **Continuous [waves] (CW)**
   - deformed galactic neutron stars, …
4. **Stochastic background**
   - Cosmological background, astrophysical background of unresolved sources (e.g. binary systems)

# Why? Science with GWs

- “New window on the universe”!

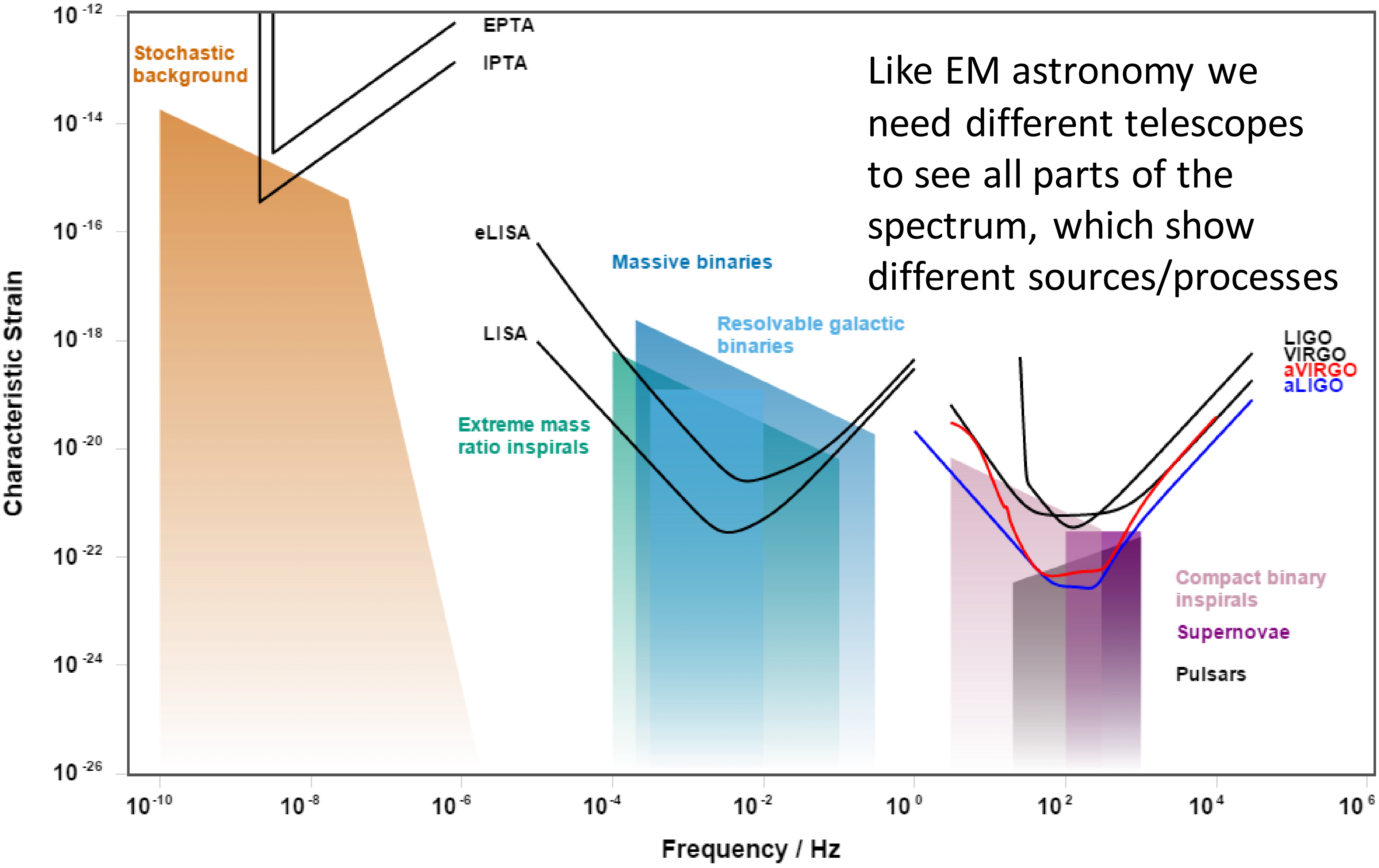


\+ GWs

spanning 20 orders of magnitude in wavelength

# GW spectrum

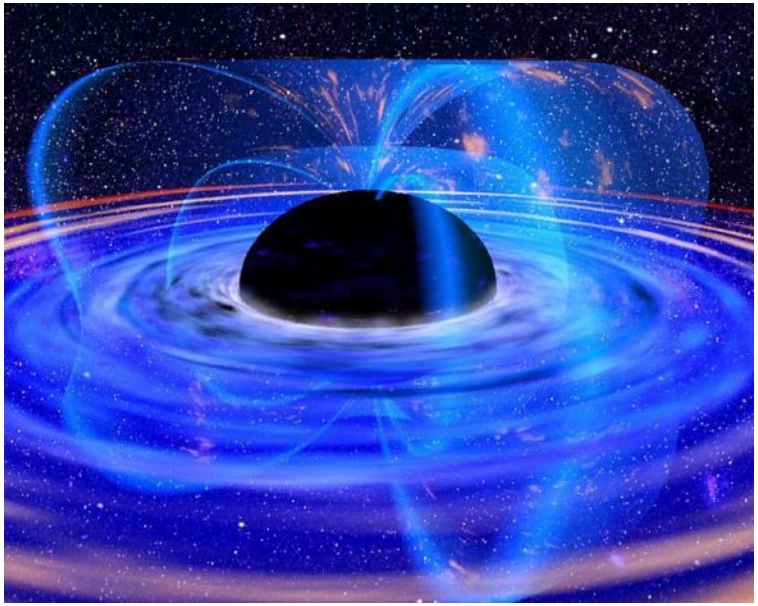
Image credit: Moore, Cole & Berry, http://rhcole.com/apps/GWplotter/

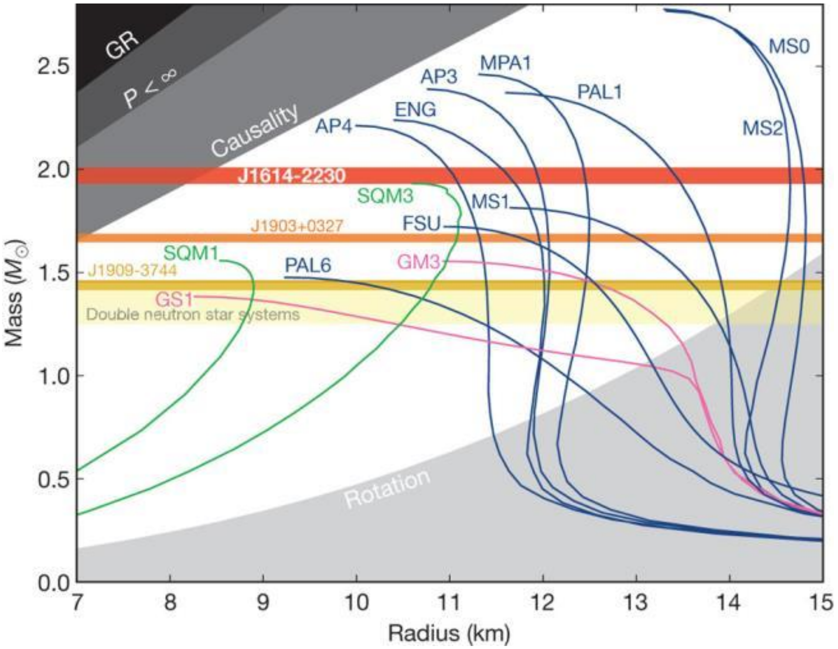


Like EM astronomy we need different telescopes to see all parts of the spectrum, which show different sources/processes

# Science with GW

- Fundamental physics:
  - What are the properties of GWs?
    - speed of GWs (massive gravitons?)
    - are there more than 2 polarisation states?
  - Is GR the correct description of gravity?
    - precision tests of correctness of GR in strong field regime
    - are black holes as GR predicts (“no-hair” theorem)?
  - Behavior of matter at nuclear densities and pressures
    - what is the composition of neutron star?

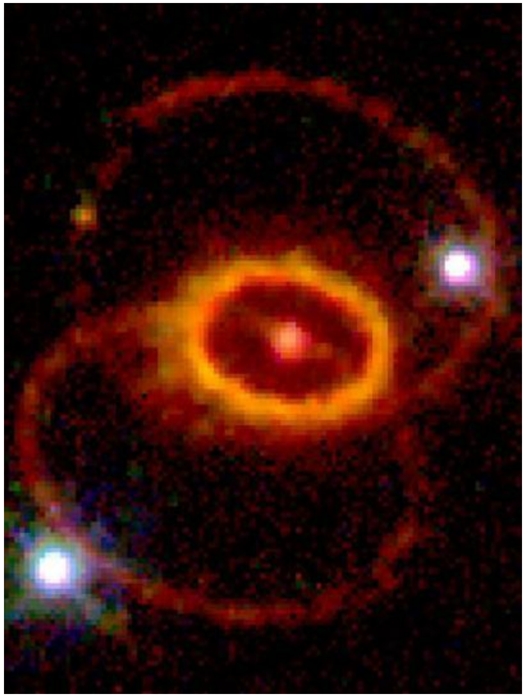




Neutron star EOS: Credit: Demorest *et al*, *Nature* 467, 1081-1083 (2010)

# Science with GWs

- Astronomy and astrophysics:
  - population studies (local and high redshift):
    - black holes (stellar mass, intermediate mass (do they exist?), supermassive) and neutron stars
      - massive star formation history
      - galaxy formation history
    - galactic white dwarf and neutron star binary numbers
  - Gamma-ray burst (GRB) central engine:
    - compact binary coalescence, hypernova?
  - Core collapse supernova:
    - what exactly happens during explosion?
  - Neutron stars and magnetars:
    - are they deformed?
    - why do they glitch?

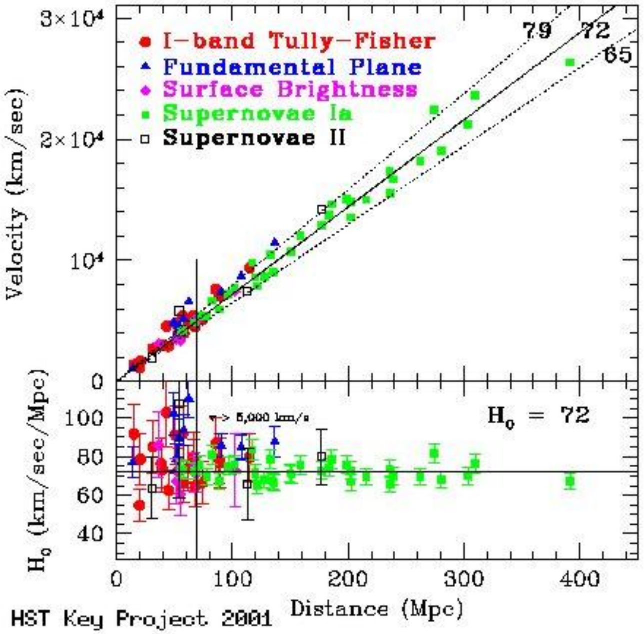


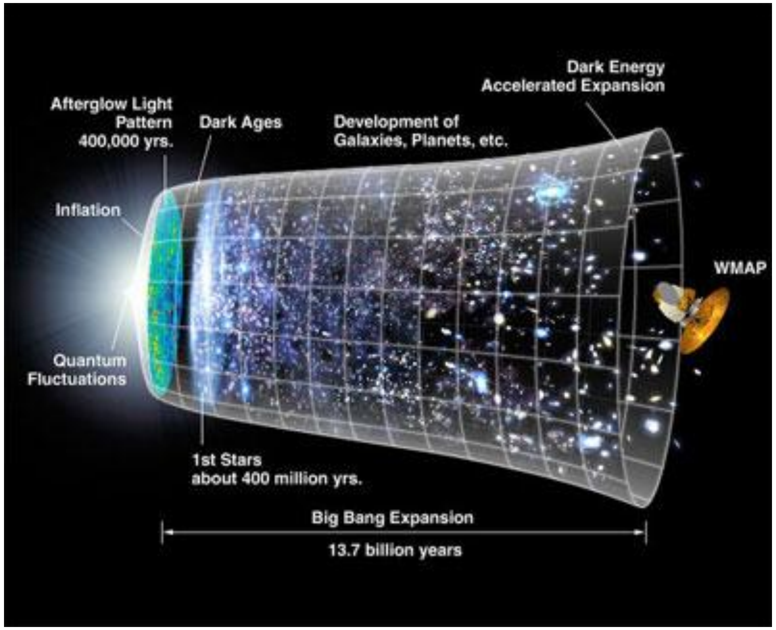
(ESA/STScI), HST, NASA

See "Physics, Astrophysics and Cosmology with Gravitational Waves"
B.S. Sathyaprakash and Bernard F. Schutz
http://www.livingreviews.org/lrr-2009-2

# Science with GWs

- Cosmology:
  - precise measurements of history of cosmic acceleration to z~10! without relying on “cosmic distance ladder” - standard sirens
  - cosmological stochastic background:
    - probe $<10^{-14}$s after big bang!
    - inflation?
    - cosmic strings from phase transitions?



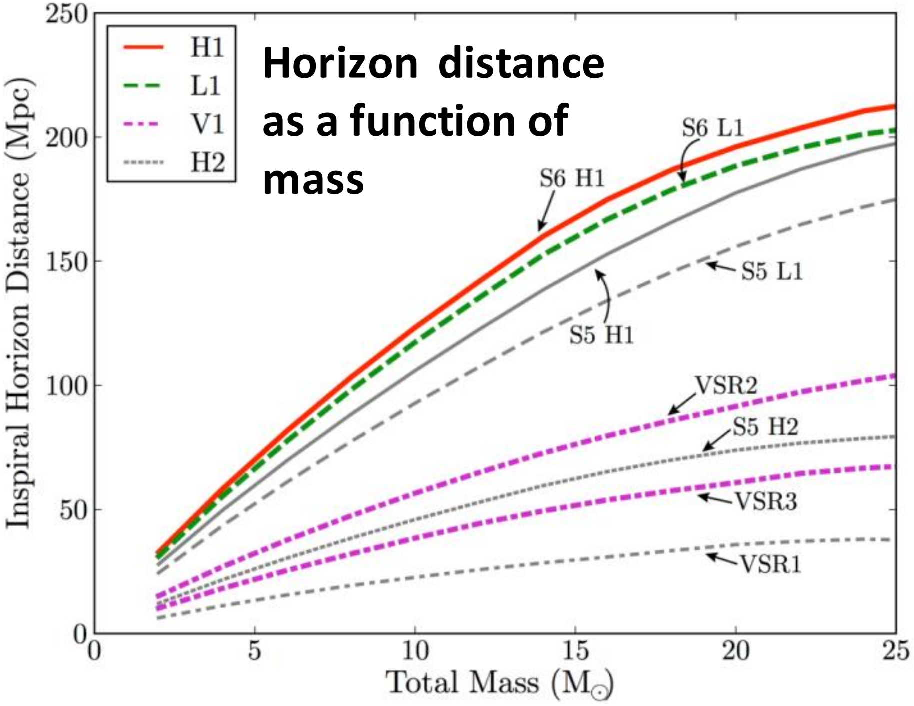


Credit: NASA

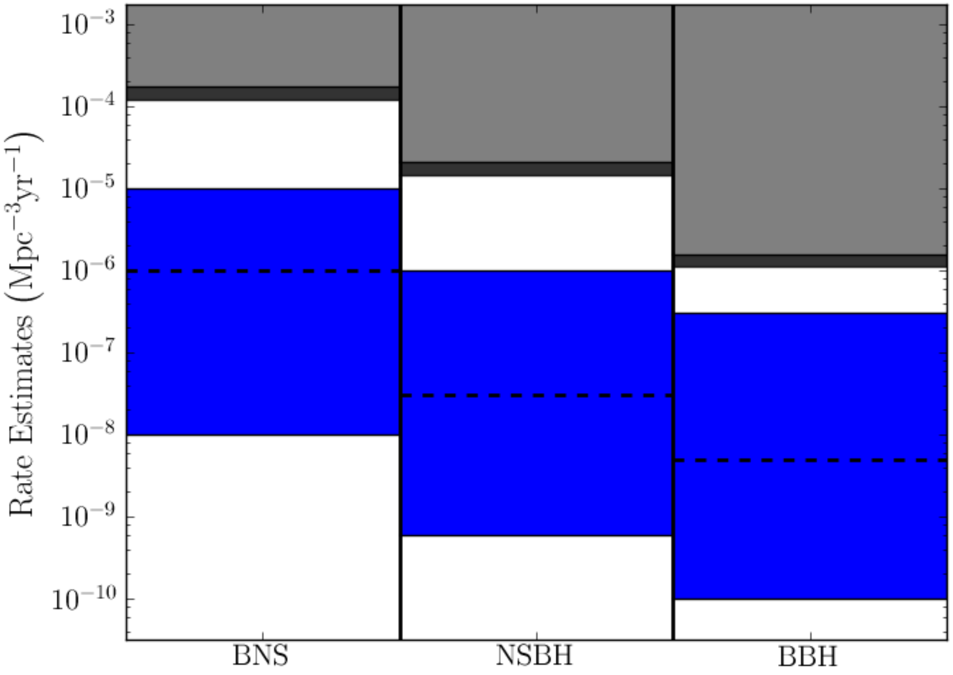
# Results "highlights"

See http://www.ligo.org/science/outreach.php for a selection of summaries of LIGO/Virgo results

- Low-mass (binaries with total mass between 2-25 solar masses) CBC search using LIGO S6 and Virgo VSR2 data



**Horizon distance as a function of mass**



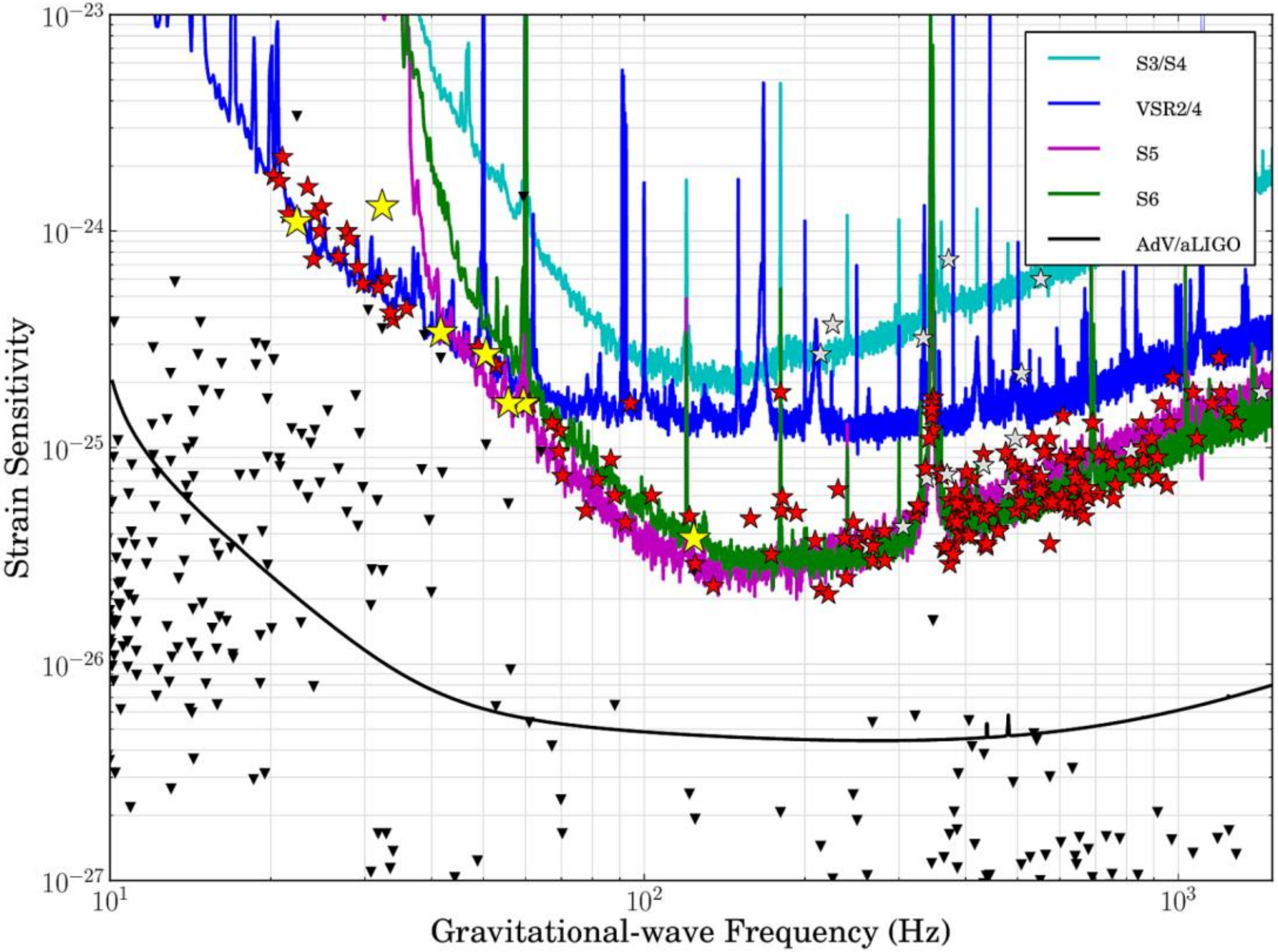
**Event rate limits for different systems**

Abadie *et al*, *PRD* 85, 082002 (2012) arXiv:1111.7314

# Results “highlights”

Aasi *et al*, ApJ 785, 2, 119 (2014)
arXiv:1309.4027

- Searching for GWs from known pulsars



# Results “highlights”

Aasi *et al*, ApJ 785, 2, 119 (2014)
arXiv:1309.4027

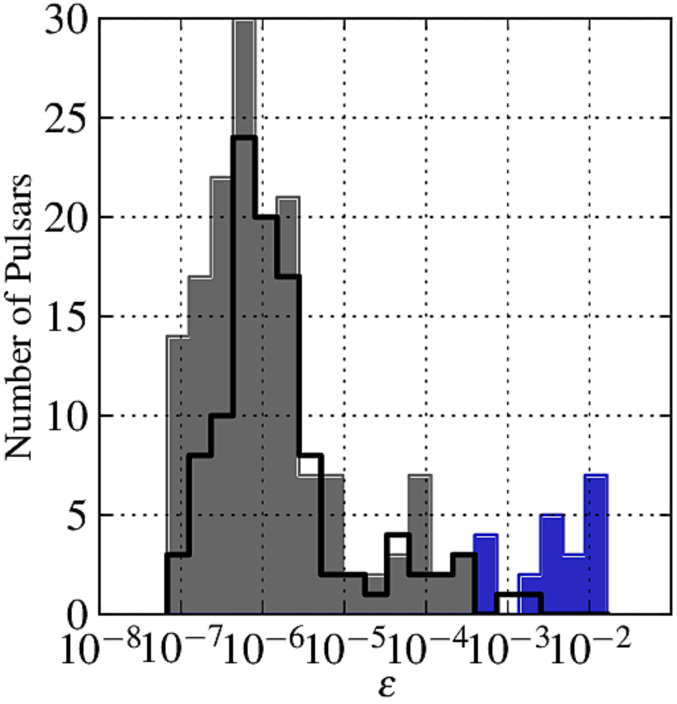
- Searching for GWs from *known* pulsars

Strain $h = 4.2 \times 10^{-26} \epsilon_{-6} I_{38} f_{100}^{2} r_{\mathrm{kpc}}^{-1}$

$\epsilon_{-6}$: ellipticity (per $10^{-6}$)
$I_{38}$: principle mom. of inertia (per $10^{38}\mathrm{kgm}^2$)
$f_{100}$: rotation freq. (per 100 Hz)
$r_{\mathrm{kpc}}$: distance (kpc)

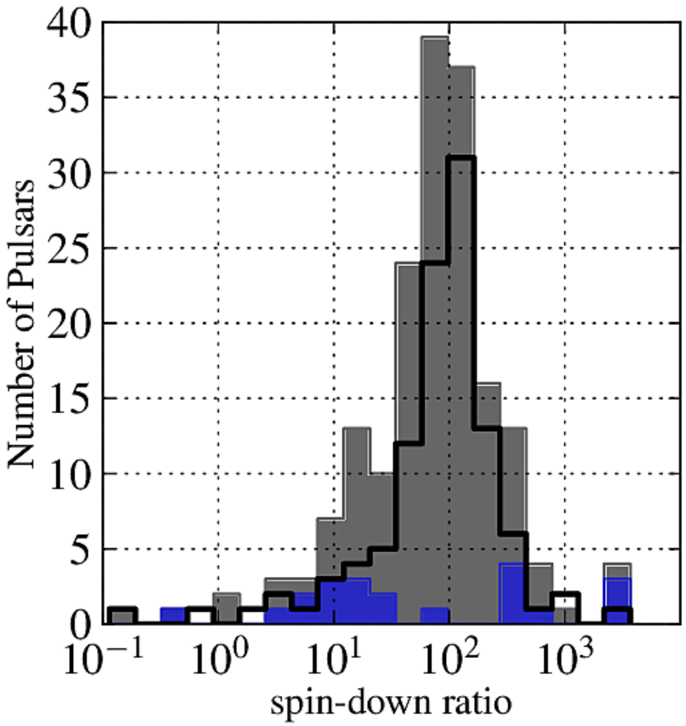
Spin-down limit: spin-down luminosity = GW luminosity

$$h_{sd} = 2.5 \times 10^{-25} I_{38} \left|\dot{f}_{-11}\right|^{1/2} f_{100}^{-1/2} r_{\mathrm{kpc}}^{-1}$$



Ellipticity and mom. of inertia (or combined as mass quadrupole) are EOS dependent

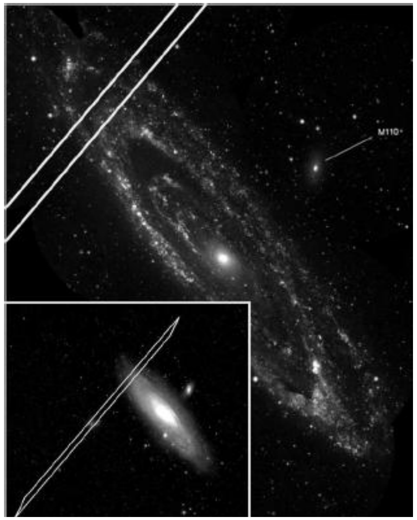
Currently we expect $\epsilon_{max} \sim 10^{-4}$ for ‘exotic’ quark stars, $\sim 10^{-5}$ for ‘normal’ NS, but more likely to be $< 10^{-7}$



# Results “highlights”

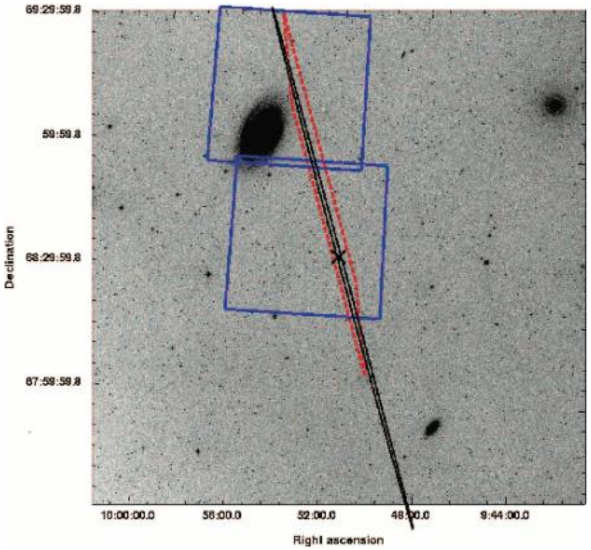
Abbott *et al*, *ApJ* 681, 2, (2008)
arXiv:0711.1163
Abadi *et al*, *ApJ* 755, 1, 2 (2012)
arXiv:1201.4413

- Exclusion of compact binary mergers being sources of two short GRBs in M31 and M81 during S5



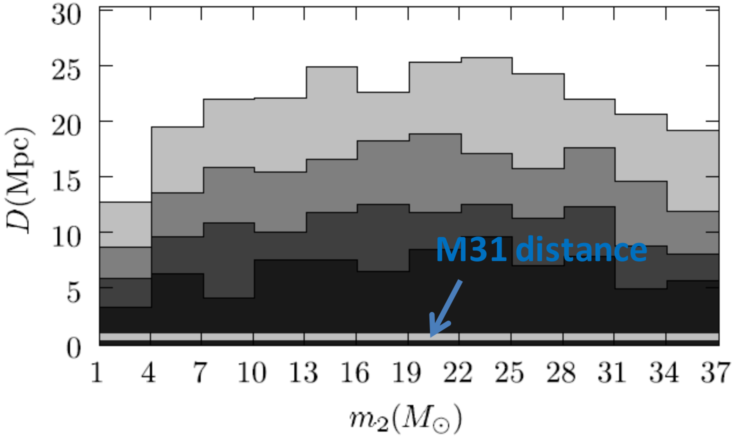
GRB 070201
M31 (0.78 Mpc)

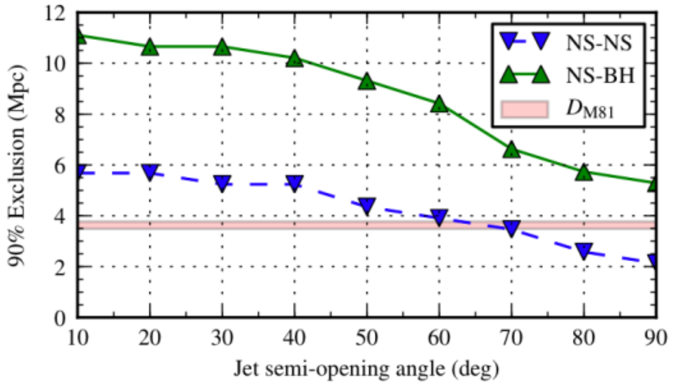
Darkest contour: 90% exclusion distance for CBC signal as a function companion mass



GRB 051103
M81 (3.6 Mpc)

90% exclusion distance for CBC signal as a function of GRB jet opening angle



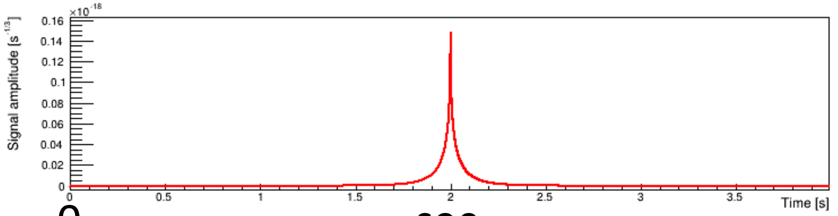


# Results "highlights"

Aasi *et al*, *PRL* 112, 131101, (2014)
arXiv:1310.2384

- Do cosmic strings exist? Search for GW bursts from string cusps using LIGO & Virgo data constrained loop size parameter, string tension and probability of loop interation

Cusp GW waveform



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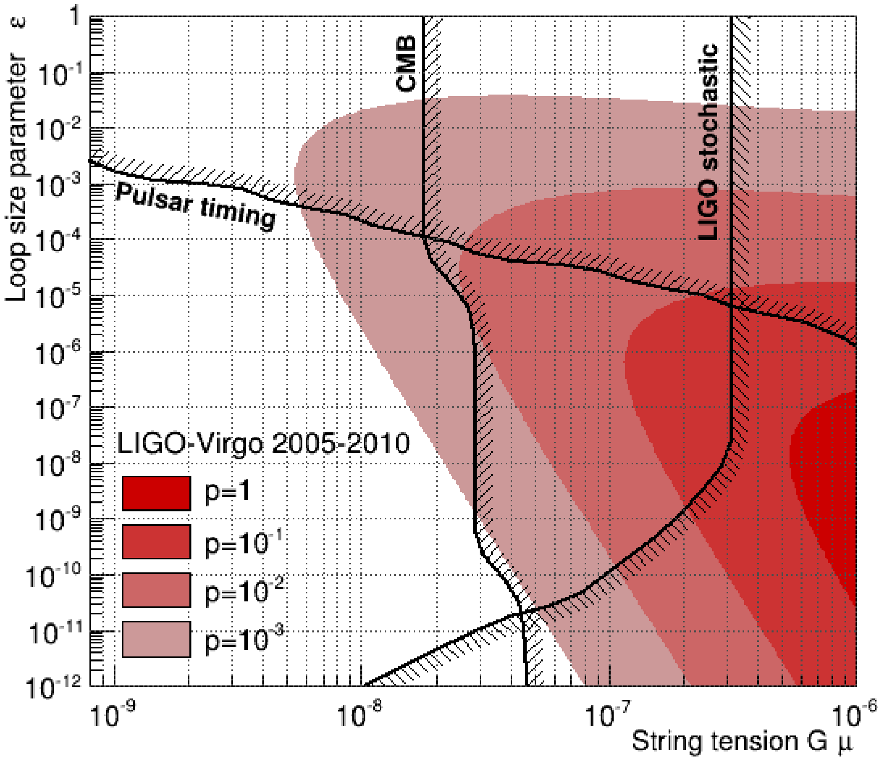
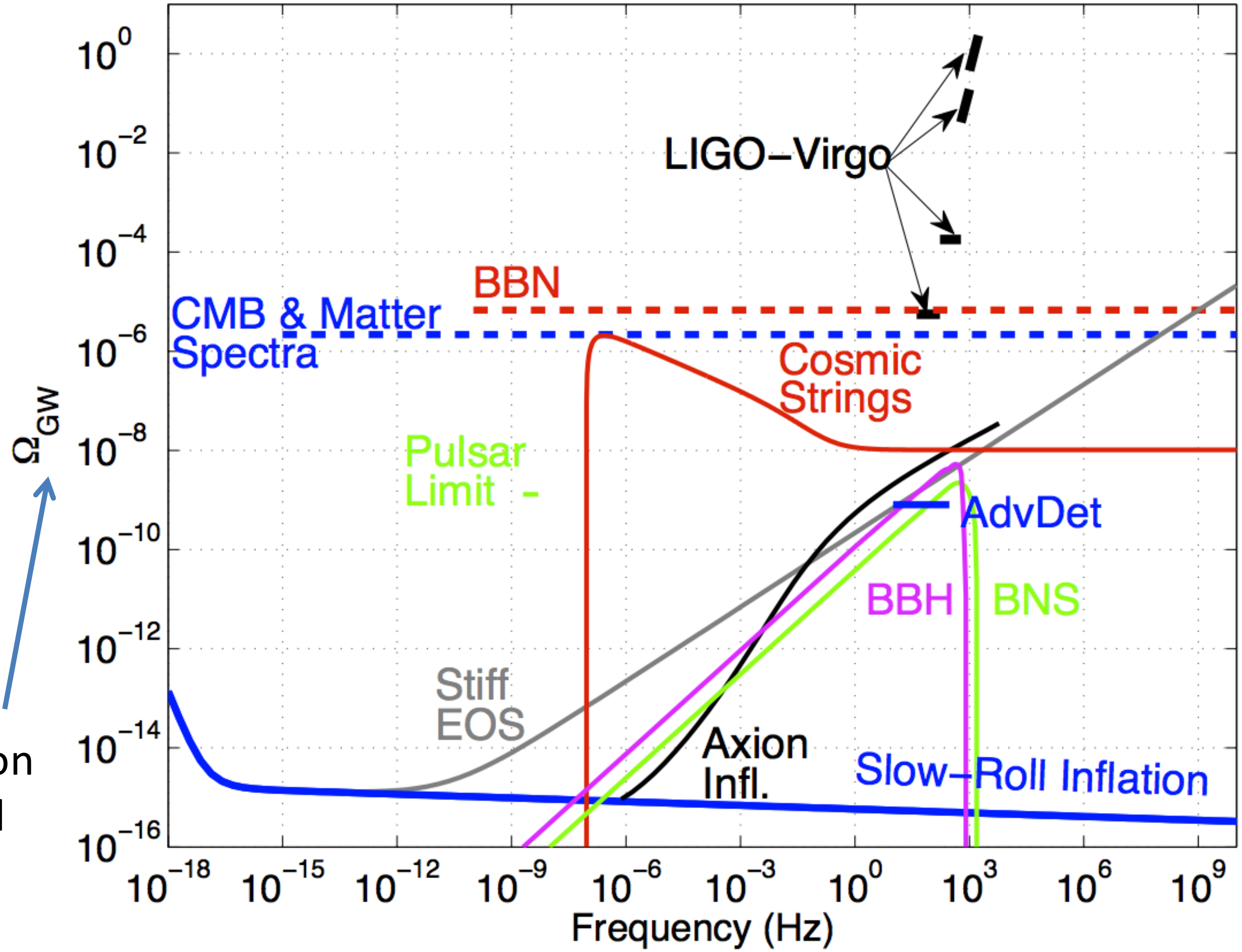


# Results “highlights”

- Search for cosmological stochastic background – results beat constraints from big bang nucleosynthesis



GW energy density (fraction of the critical density)

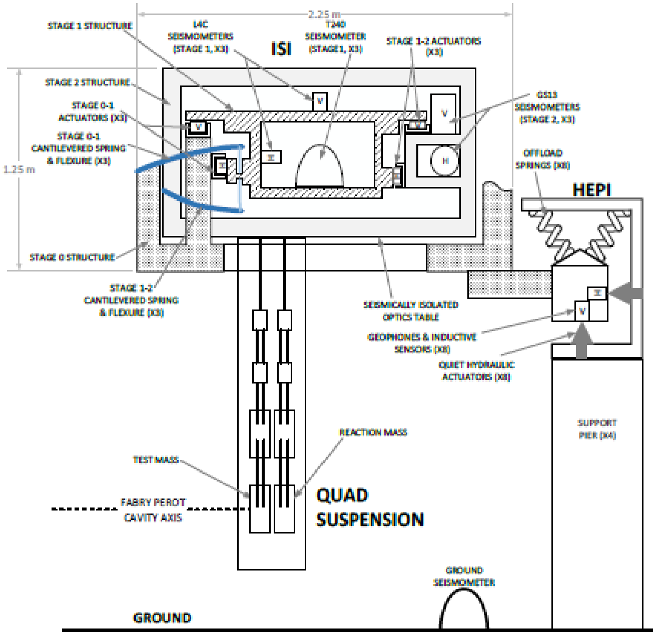
# Some other searches…

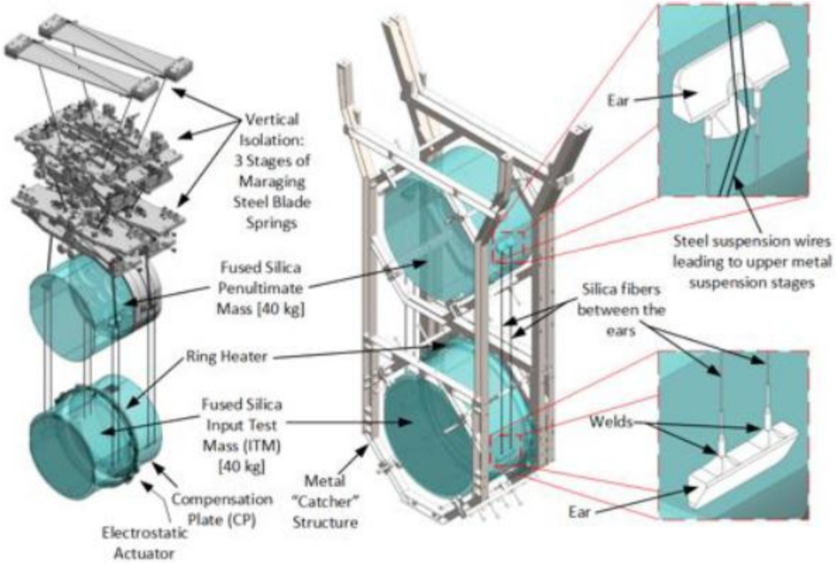
- GWs associated with 100s of long and short GRBs
- Burst searches associated with neutrino observatories (e.g. IceCube)
- Follow-up of GW triggers with optical telescopes
- Searches for high mass (10s of solar mass) CBC signals
- All-sky and directed (Cas A, galactic centre, Sco-X1) searches for CWs from neutron stars
- [see http://www.ligo.org/science/outreach.php]

# 4. Advanced detectors

# Advanced LIGO/Virgo

- LIGO -> Advanced LIGO (aLIGO)
- Virgo -> Advanced Virgo (AdV)
- Aim to achieve order of magnitude sensitivity improvements over initial detectors and push sensitive band down to 10Hz
- Main upgrades (aLIGO [similar for AdV]):
  - Higher laser power (~10W -> ~100W)
  - Larger test masses (10kg -> 40 kg)
  - Monolithic fused silica suspensions
  - Active seismic isolation
  - Improved mirror coatings

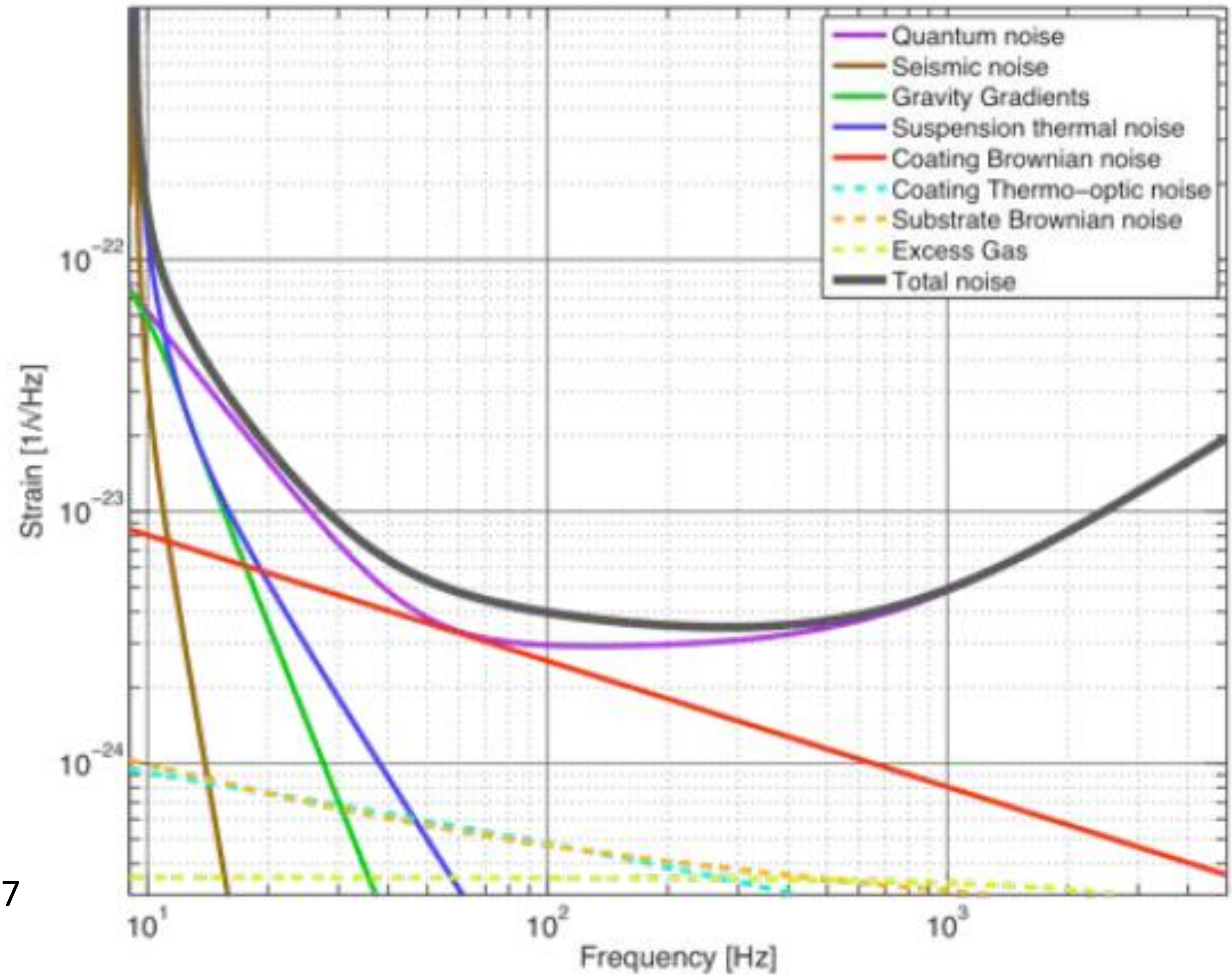




aLIGO see e.g. LSC, arXiv:1411.4547

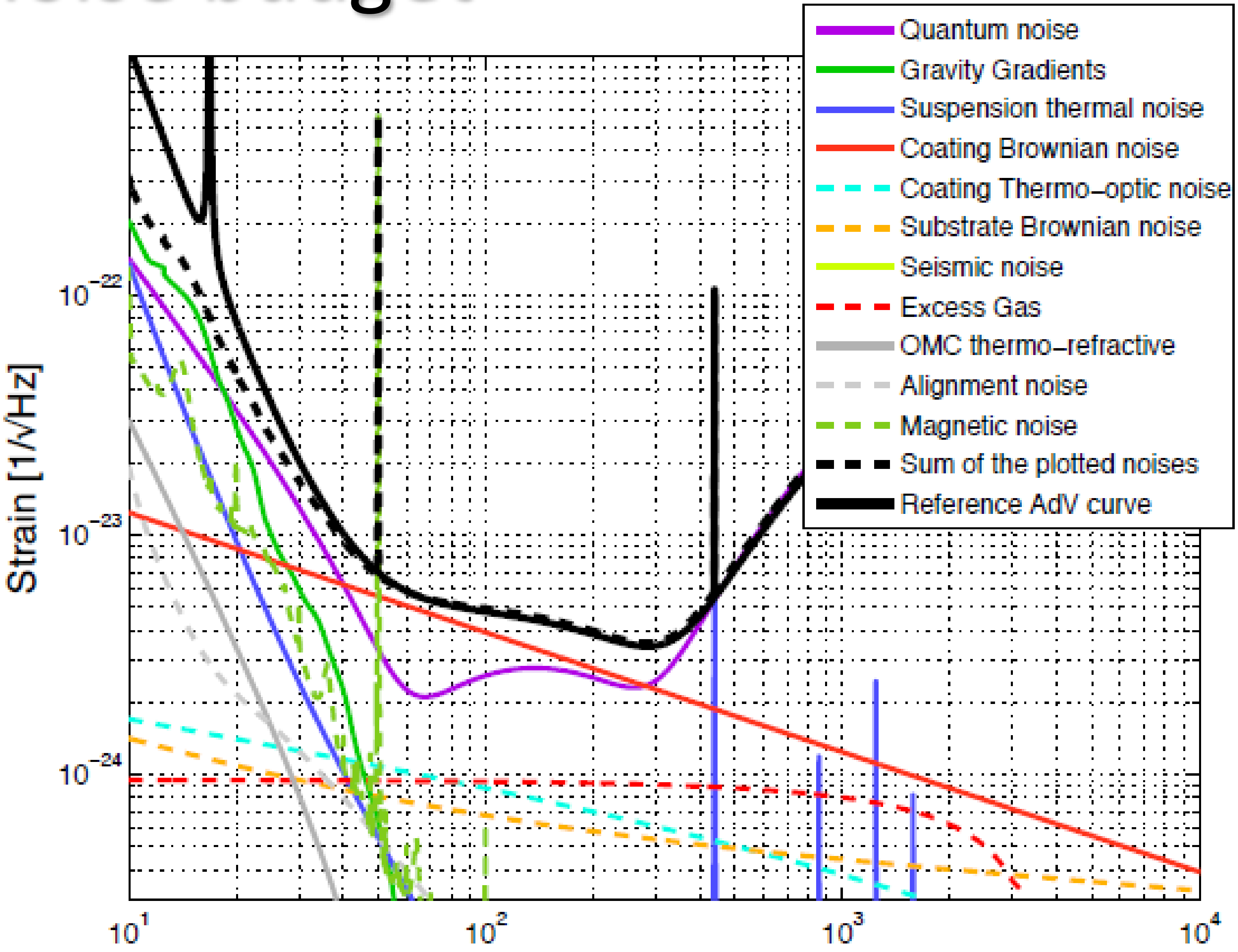
AdV see e.g. Acernese *et al*, arXiv:1408.3978

# aLIGO noise budget



The LSC,
arXiv:1411.4547

# AdV noise budget

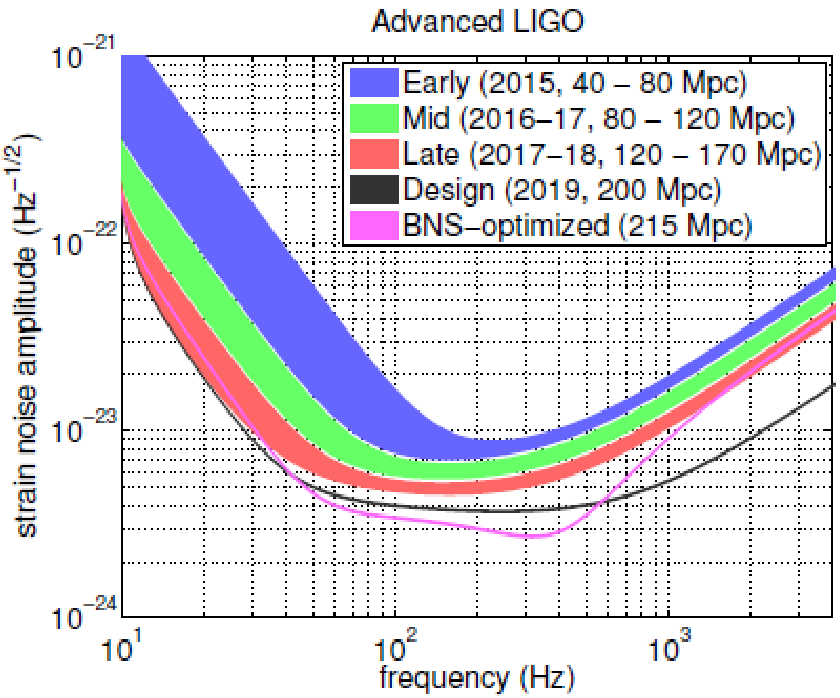


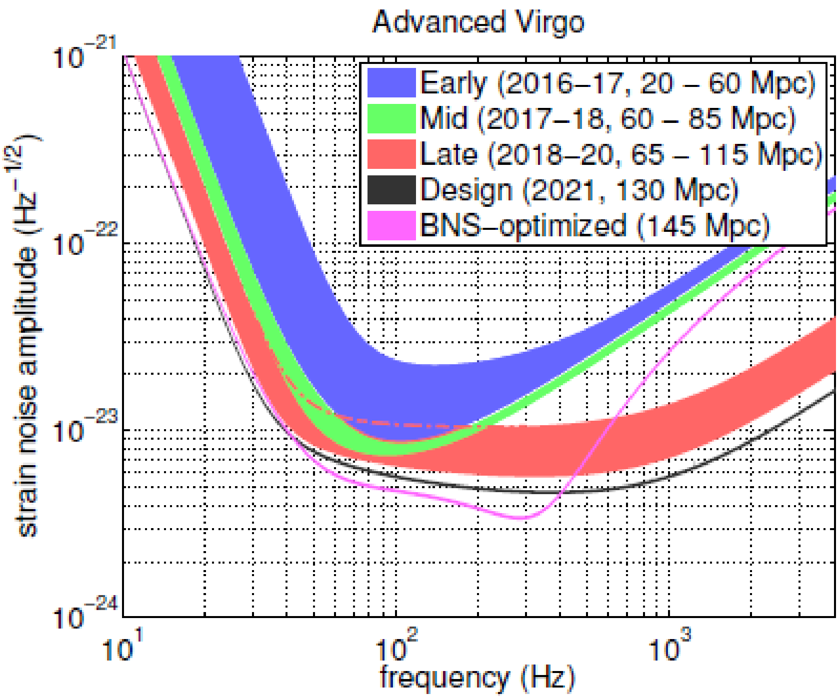
Acernese *et al*,
arXiv:1408.3978

# Observing schedule (estimate)

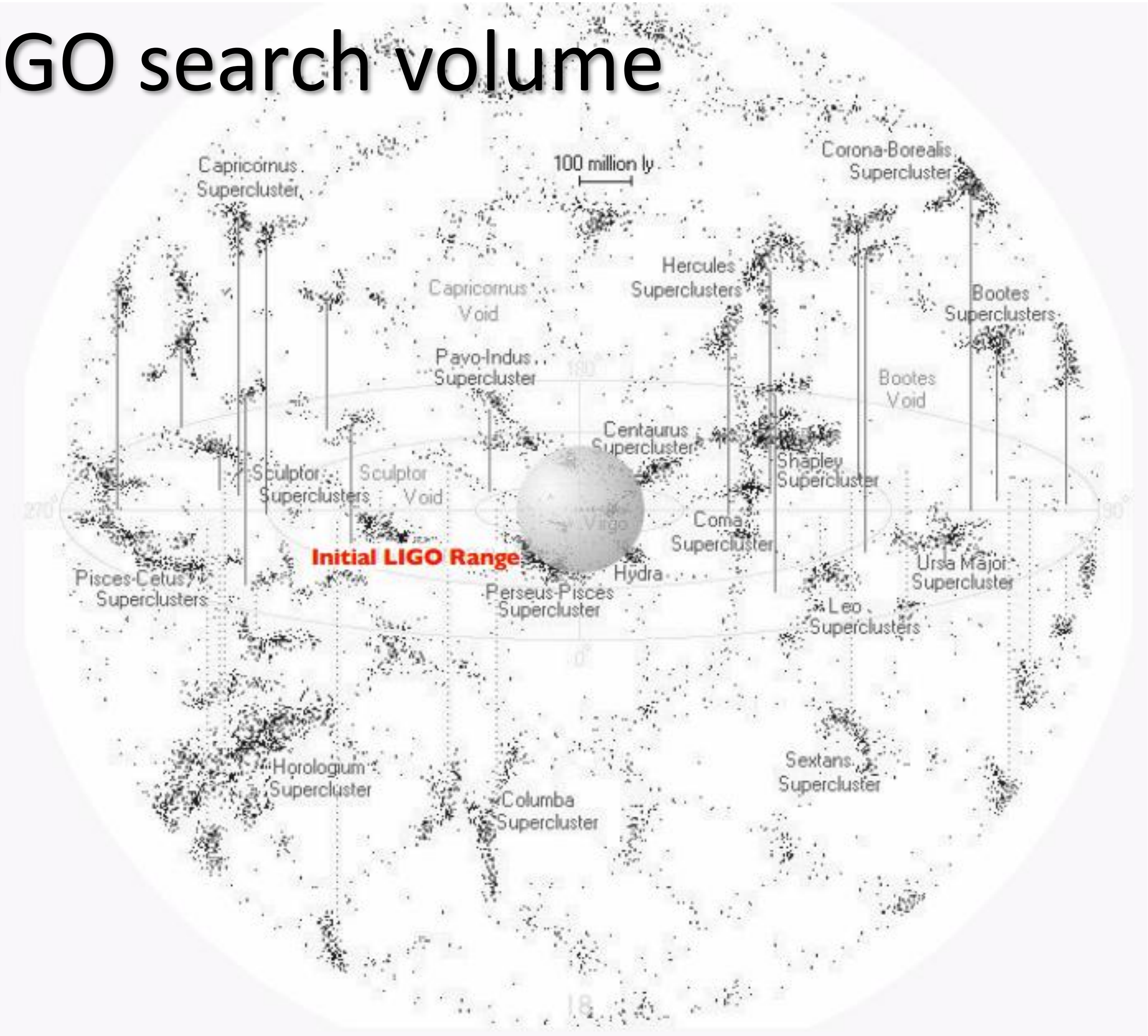
Aasi *et al*, arXiv:1304.0670

- 2015: 3 month run with two aLIGO detectors (potentially with AdV)
- 2016-2017: 6 month run with aLIGO and AdV
- 2017-2018: 9 month run with aLIGO and AdV
- 2019 onwards: 3 detector network at design sensitivity
- 2022: 4 detectors including LIGO India (or 5 with KAGRA)





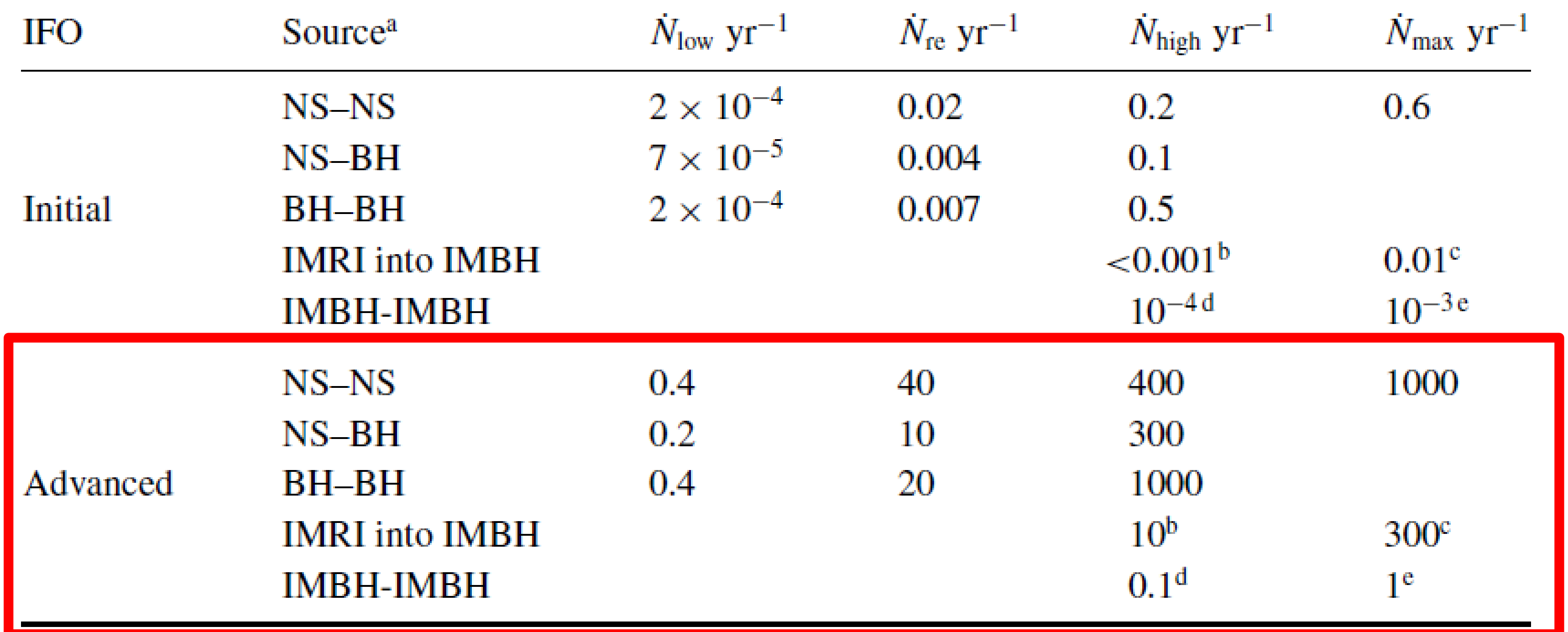
# aLIGO search volume



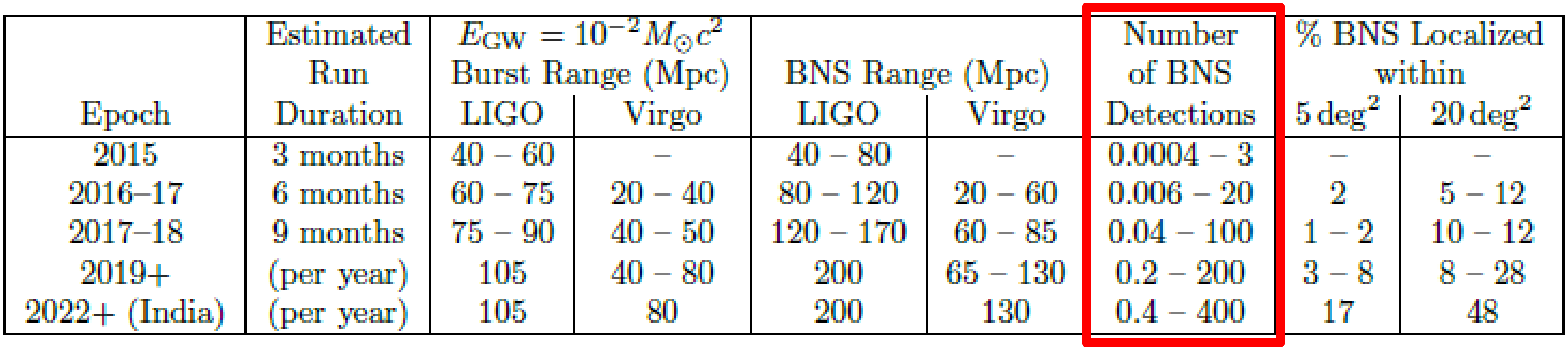
# Rate estimates for CBCs

See Aasi *et al*, arXiv:1304.0670 & Abadie *et al*, CQG, 27, 173001 (2010) arXiv:1003.2480

Assuming design sensitivity and 3 aLIGO detectors



| IFO | Source[a] | $\dot{N}_{\rm low}$ yr$^{-1}$ | $\dot{N}_{\rm re}$ yr$^{-1}$ | $\dot{N}_{\rm high}$ yr$^{-1}$ | $\dot{N}_{\rm max}$ yr$^{-1}$ |
|---|---|---|---|---|---|
| | NS–NS | $2 \times 10^{-4}$ | 0.02 | 0.2 | 0.6 |
| | NS–BH | $7 \times 10^{-5}$ | 0.004 | 0.1 | |
| Initial | BH–BH | $2 \times 10^{-4}$ | 0.007 | 0.5 | |
| | IMRI into IMBH | | | <0.001[b] | 0.01[c] |
| | IMBH-IMBH | | | $10^{-4}$[d] | $10^{-3}$[e] |
| | NS–NS | 0.4 | 40 | 400 | 1000 |
| | NS–BH | 0.2 | 10 | 300 | |
| Advanced | BH–BH | 0.4 | 20 | 1000 | |
| | IMRI into IMBH | | | 10[b] | 300[c] |
| | IMBH-IMBH | | | 0.1[d] | 1[e] |

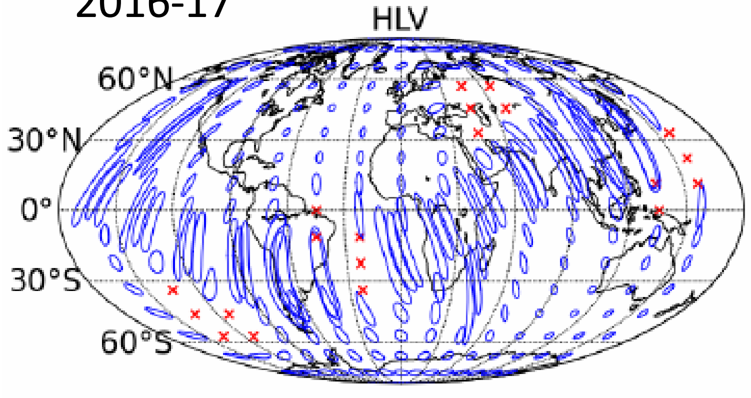


| Epoch | Estimated Run Duration | $E_{\rm GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc) LIGO | Virgo | BNS Range (Mpc) LIGO | Virgo | Number of BNS Detections | % BNS Localized within 5 deg$^2$ | 20 deg$^2$ |
|---|---|---|---|---|---|---|---|---|
| 2015 | 3 months | 40 – 60 | – | 40 – 80 | – | 0.0004 – 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 |

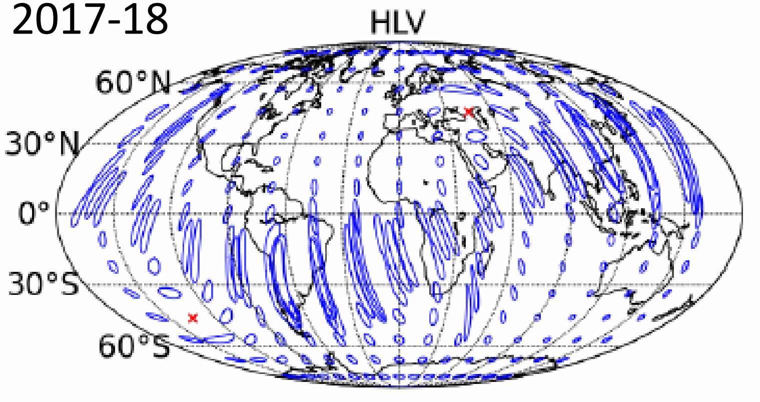
# Sky localisation

- For CBC and burst searches sky localisation is important to do EM follow-up (multi-messenger astronomy)

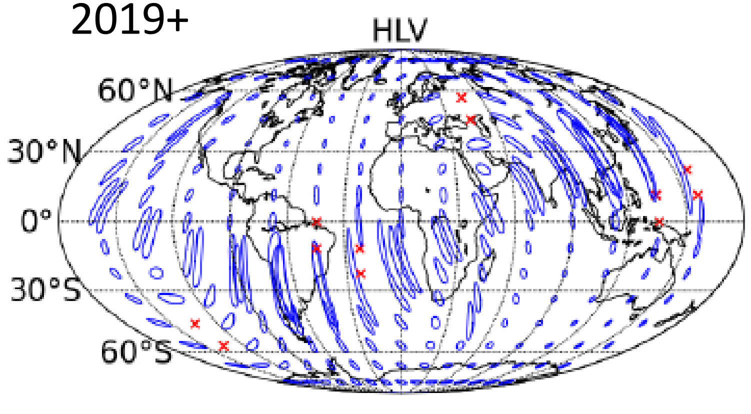
2016-17



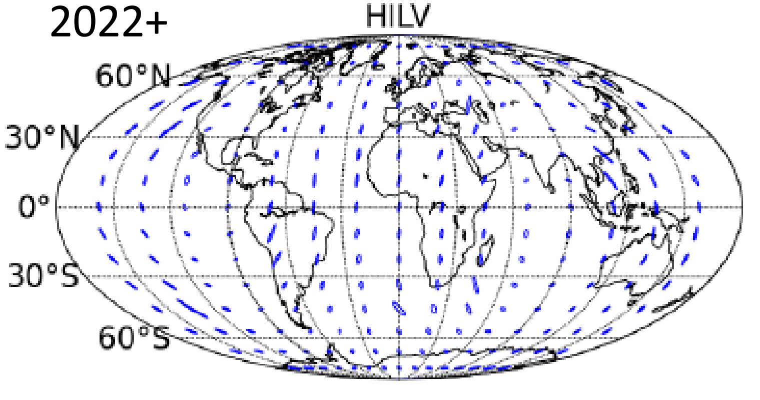
2017-18



2019+



2022+



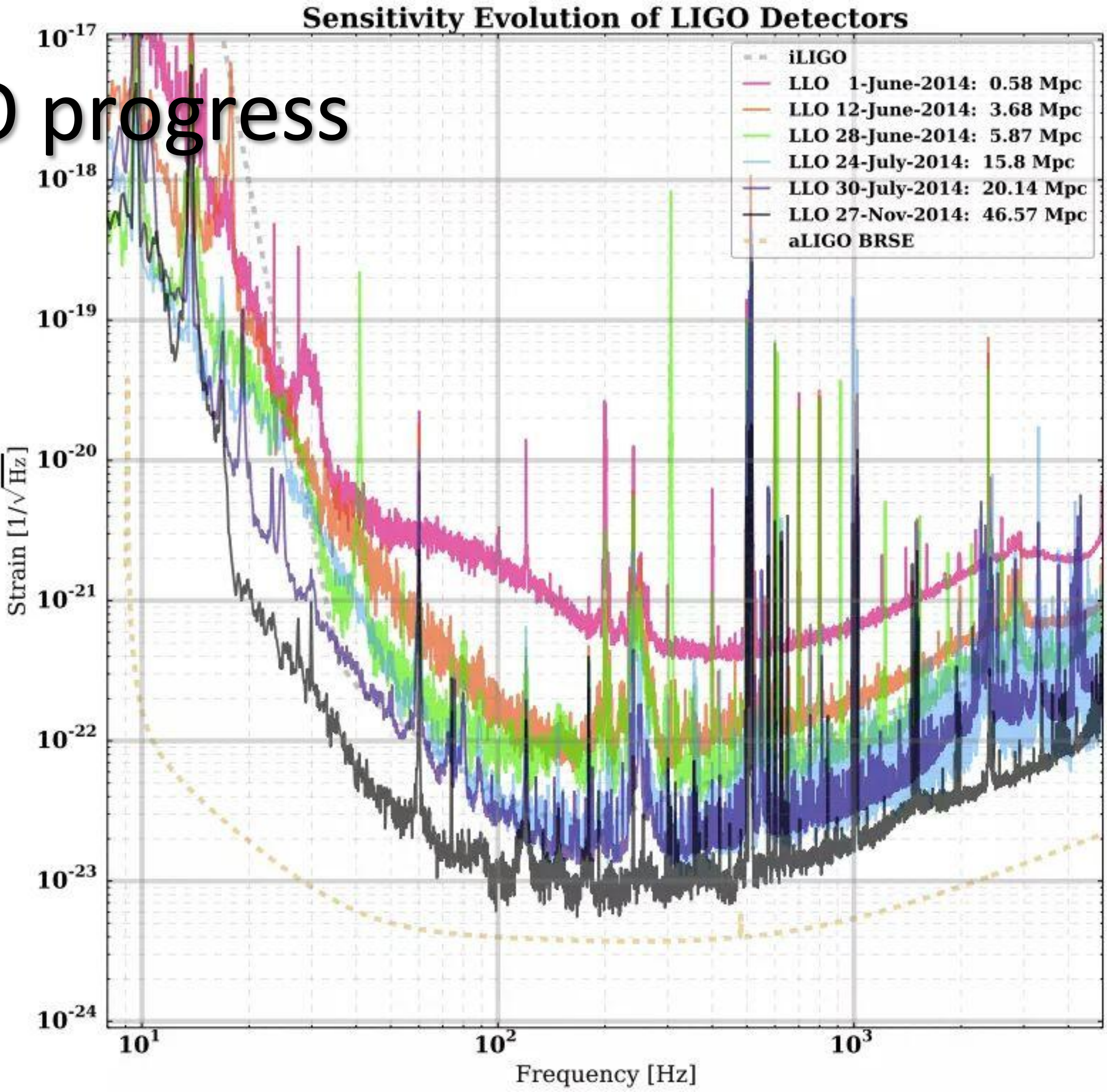
Sky localisation accuracy using triangulation (90% confidence regions) for face-on BNS – increase in sensitivity doesn't make much difference, adding another detector does

Aasi *et al*, arXiv:1304.0670

Can do a bit better with full parameter estimation (see e.g. Singer *et al*, arXiv:1404.5623)

# aLIGO progress

Looking good for observing run 1 (O1) in mid-to-late 2015



# Summary

- No direct detections of GWs yet
- Lots of exciting science can be uncovered with GWs
- Searches for many source types are well tested on initial GW detector data
- Advanced detectors are on schedule to begin observations this year
- Possible first detections by end of the decade