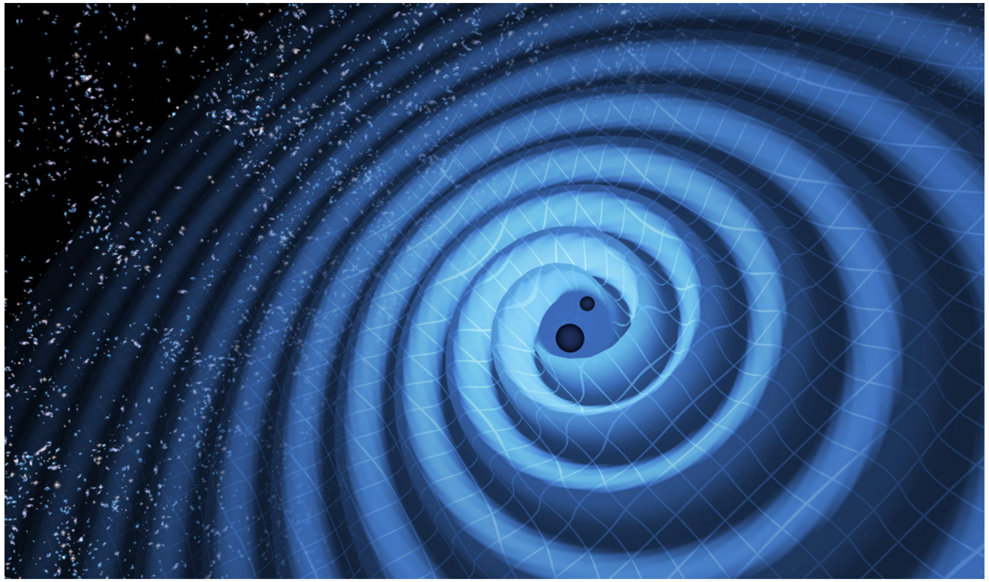
Overview of the gravitational waves search programs

- Gravitational Waves
- Ground detectors
- GW150914
- Space detector
- The pulsar timing arrays

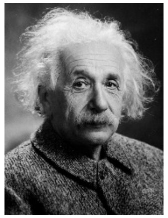


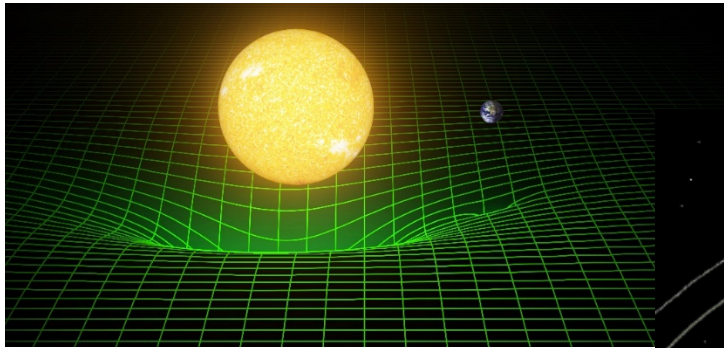
Benoit Mours (LAPP – Annecy)

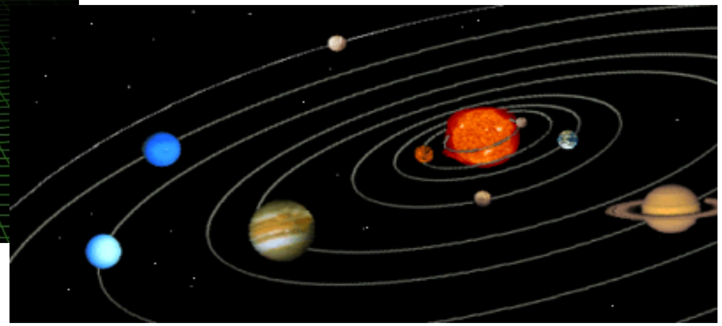
ESIPAP

January 23rd, 2017

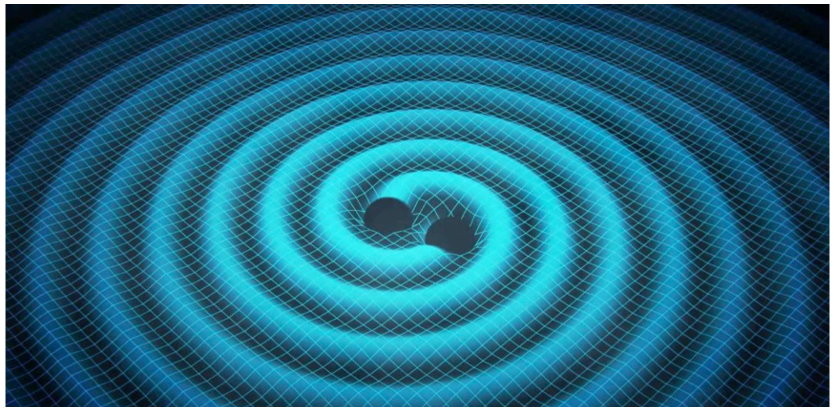
Gravitational waves?





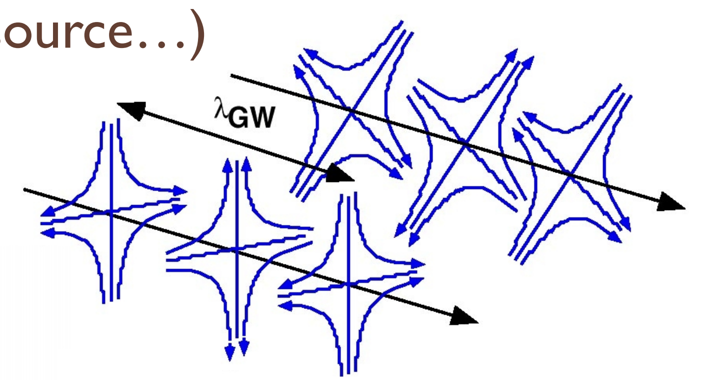


- General relativity:
  - Mass curve space
  - Gravitational force: effect of space curvature
  - J.A.Wheeler : ***"Space tells matter how to move and matter tells space how to curve"***
  - Extreme case: black hole
- GW: fluctuations of space time deformations that propagate
  - Ripples in the curvature of space-time



Gravitational waves effect and generation

- GW Effect
  - Change the distance between freely-falling test masses: $h=2\delta L/L$
    - Small perturbation to a flat space (away from source…)
  - Quadrupolar emission; two polarizations



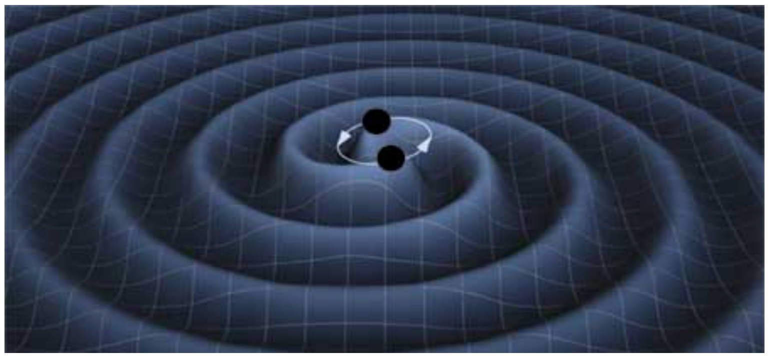
- Accelerated mass→ Gravitational waves

$$h \approx \frac{G}{c^4}\frac{E_{ns}}{r}$$

"Non spherical" kinetic energy

distance to the source

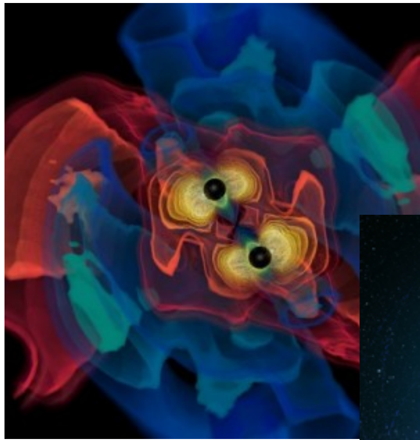
$\sim 10^{-44}\ \mathrm{m^{-1}\ kg^{-1}\ s^{2}}$



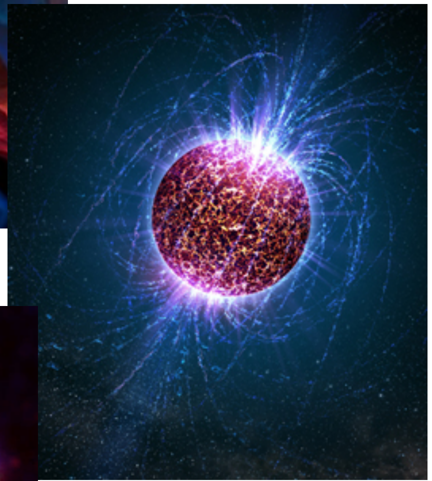
  - No way for lab generation
  - Astrophysical sources:
    - two orbiting objects as typical source
- Small effect → requires large instruments

Astrophysical sources of GW

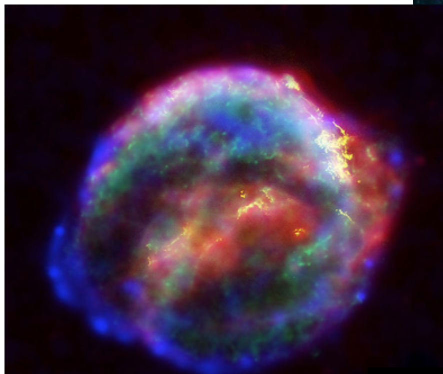
- Binary system
  - Need to be compact to be observed by ground based detectors
    - Neutron stars, black holes
  - Signal well modeled by rates not well known
- Spinning neutron stars
  - Nearly monotonic signals
  - Long duration
  - Strength not well known
- Asymmetric explosion
  - Like supernovae core collapse
  - “burst” transient
  - Not well modeled
- Cosmic gravitational wave background
  - Residual of the big bang/inflation
  - Stochastic background
  - Could be overlapped by superposition of transients



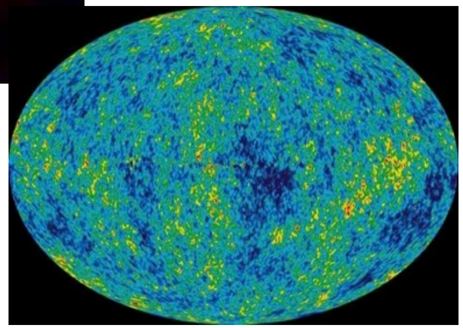
Credit: AEI, CCT, LSU



Casey Reed, Penn State

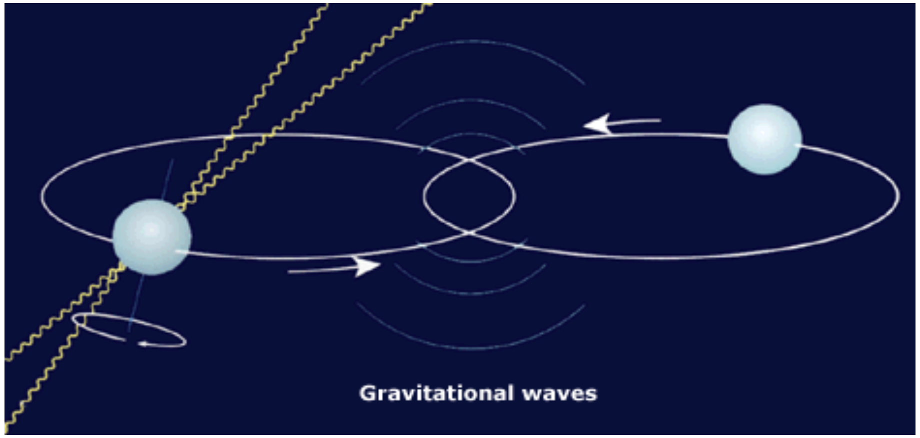


Credit: Chandra X-ray Observatory

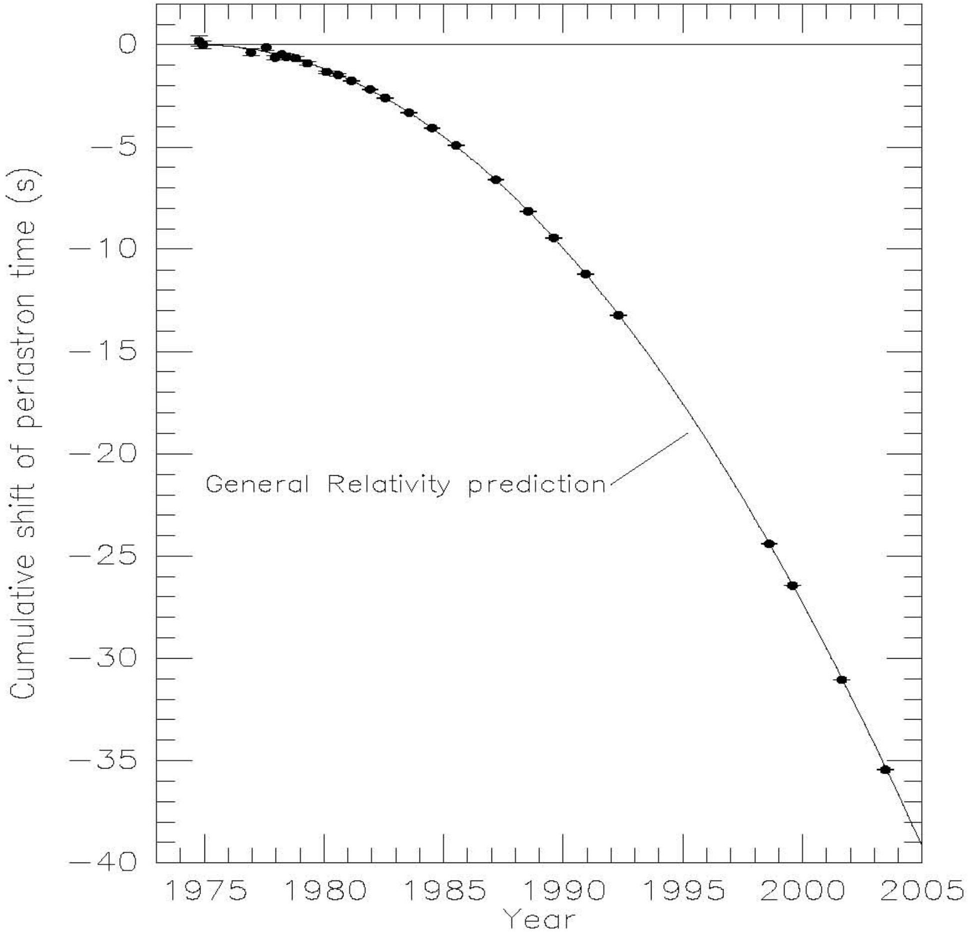


NASA/WMAP Science Team

Indirect evidence: PSR 1913+16



- Binary system of neutron stars
- One neutron star is a radio pulsar
- Discovered in 1975 by Hulse and Taylor
- Studied by Taylor, Weisberg and co.
- Decay of the orbital period compatible with GW emission



$$\dot{P}_{observe} / \dot{P}_{predit} = 1.0013 \pm 0.0021$$

Why searching for GW?

Gravitation

Sources

Universe

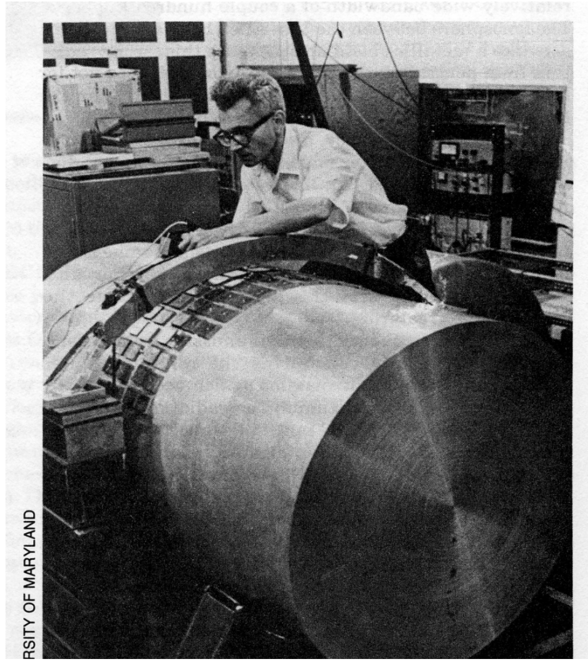
- GW generated by powerful mass acceleration
  - Very energetic events in the Universe
  - Gravitational waves probe event dynamics
- Gravitation only clue to 96% of Universe contents
  - Gravitational waves probe gravitation in new regime

General Relativity

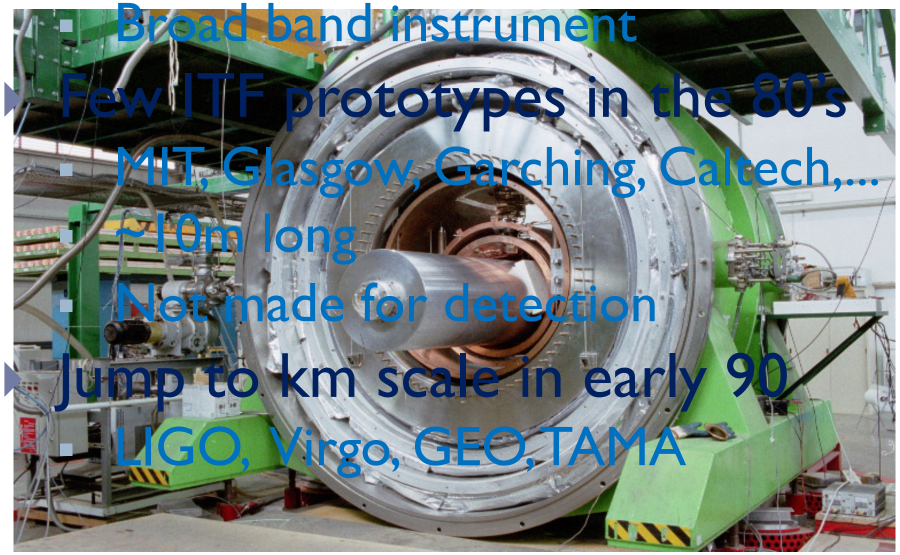
Astrophysics

Cosmology

GW: a bit of history



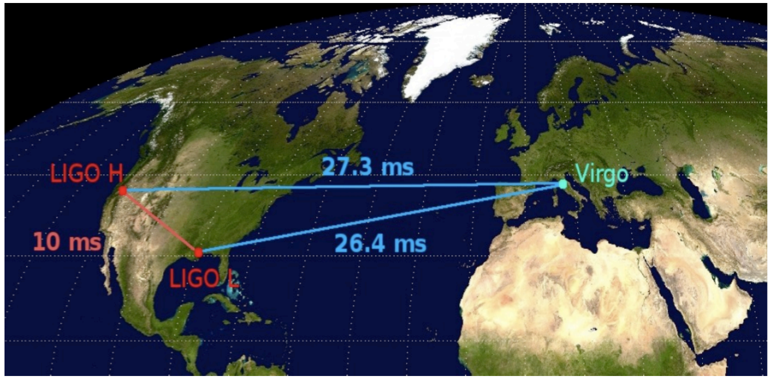
- Joseph Weber invents the bar detector
  - First claim for detection in 1969… but contested
  - Triggered large interest, at least 18 bars in 8 countries
- Evolve to cryogenic resonant bars ('80-'90)
- Bar not enough sensitivity:
  - h : few 10^{-21} 1/sqrt(Hz) @ 900Hz
- ITF started in the 70's (Germany, Rai Weiss)
  - Broad band instrument
- Few ITF prototypes in the 80's
  - MIT, Glasgow, Garching, Caltech,…
  - ~10m long
  - Not made for detection
- Jump to km scale in early 90
  - LIGO, Virgo, GEO, TAMA

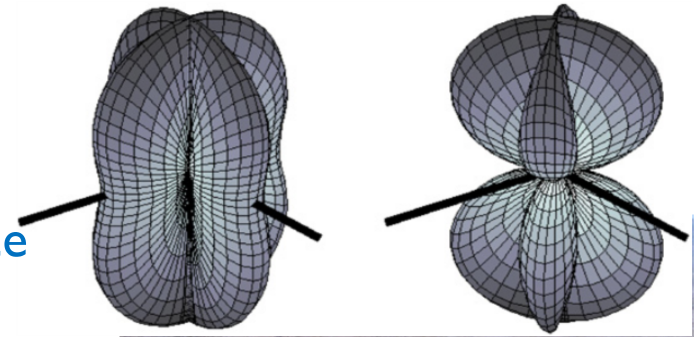


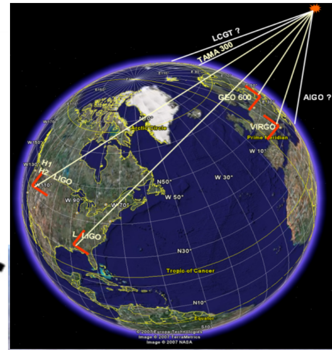
S_h (1/ $\sqrt{\text{Hz}}$)

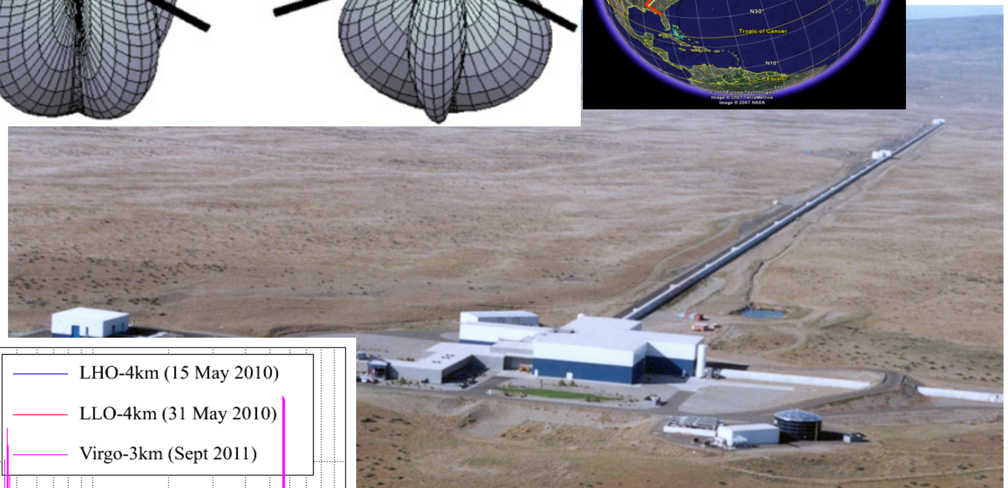
Virgo construction

LIGO-Virgo : a worldwide network

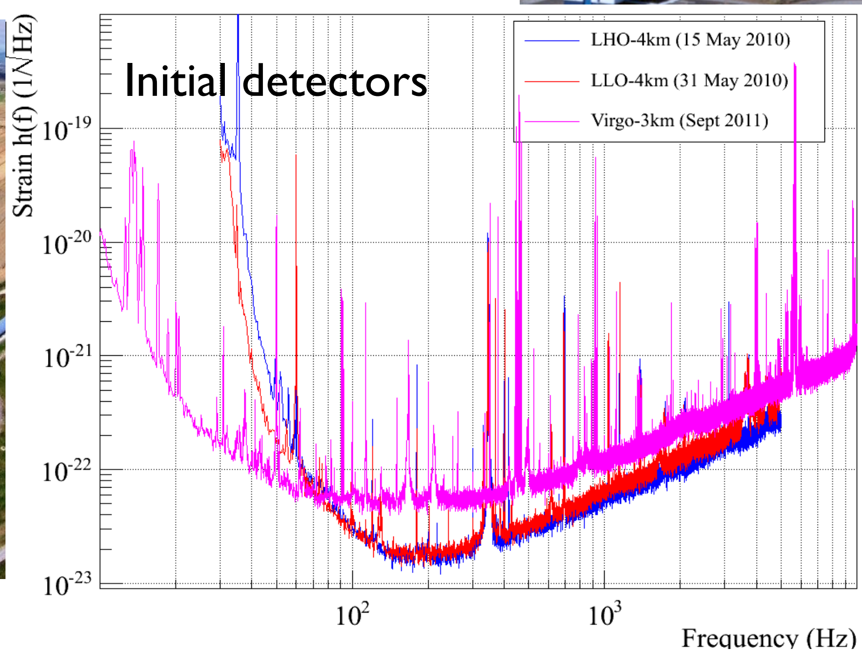




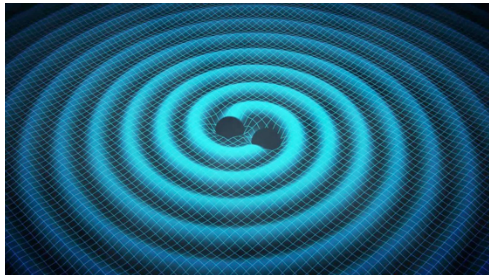




- Detectors have wide beam antenna
  - → Network for signal validation, source localization, duty cycle…
- LIGO and Virgo agreement for joint data analysis and collaboration since 2007
- Common runs with initial detectors

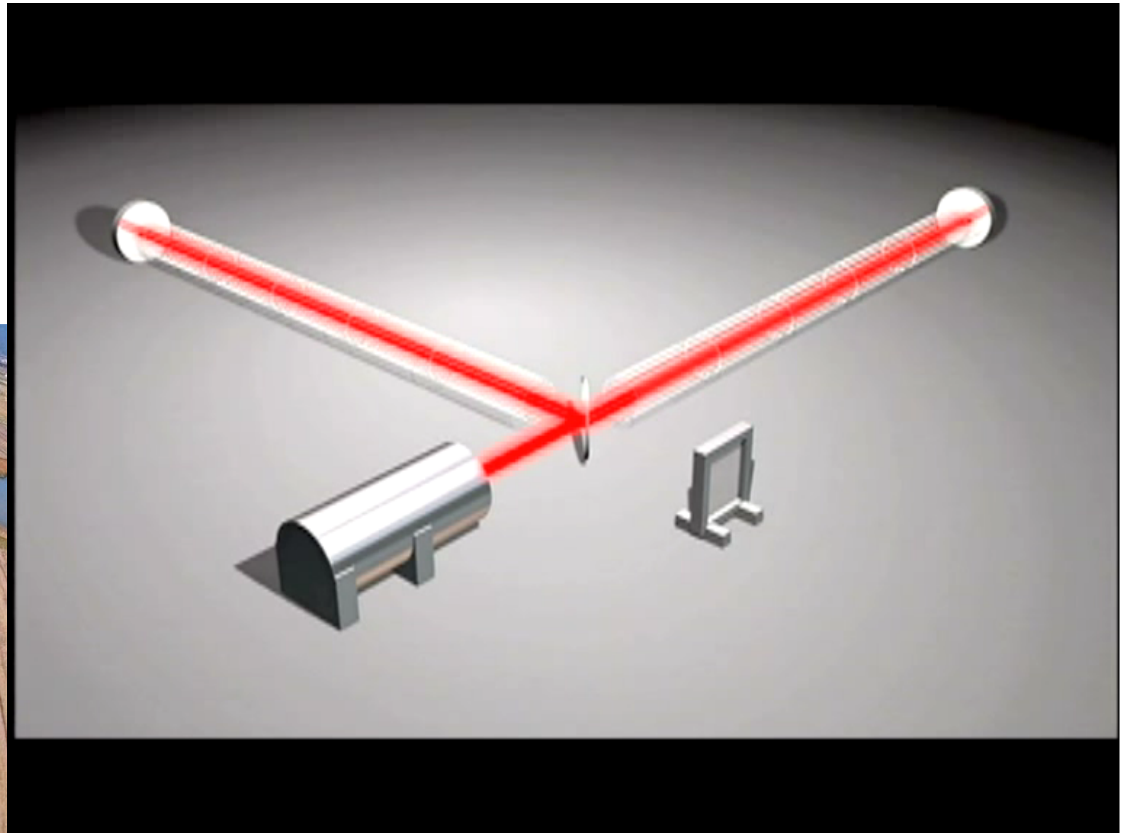


Why building *large* interferometer to detect GW?



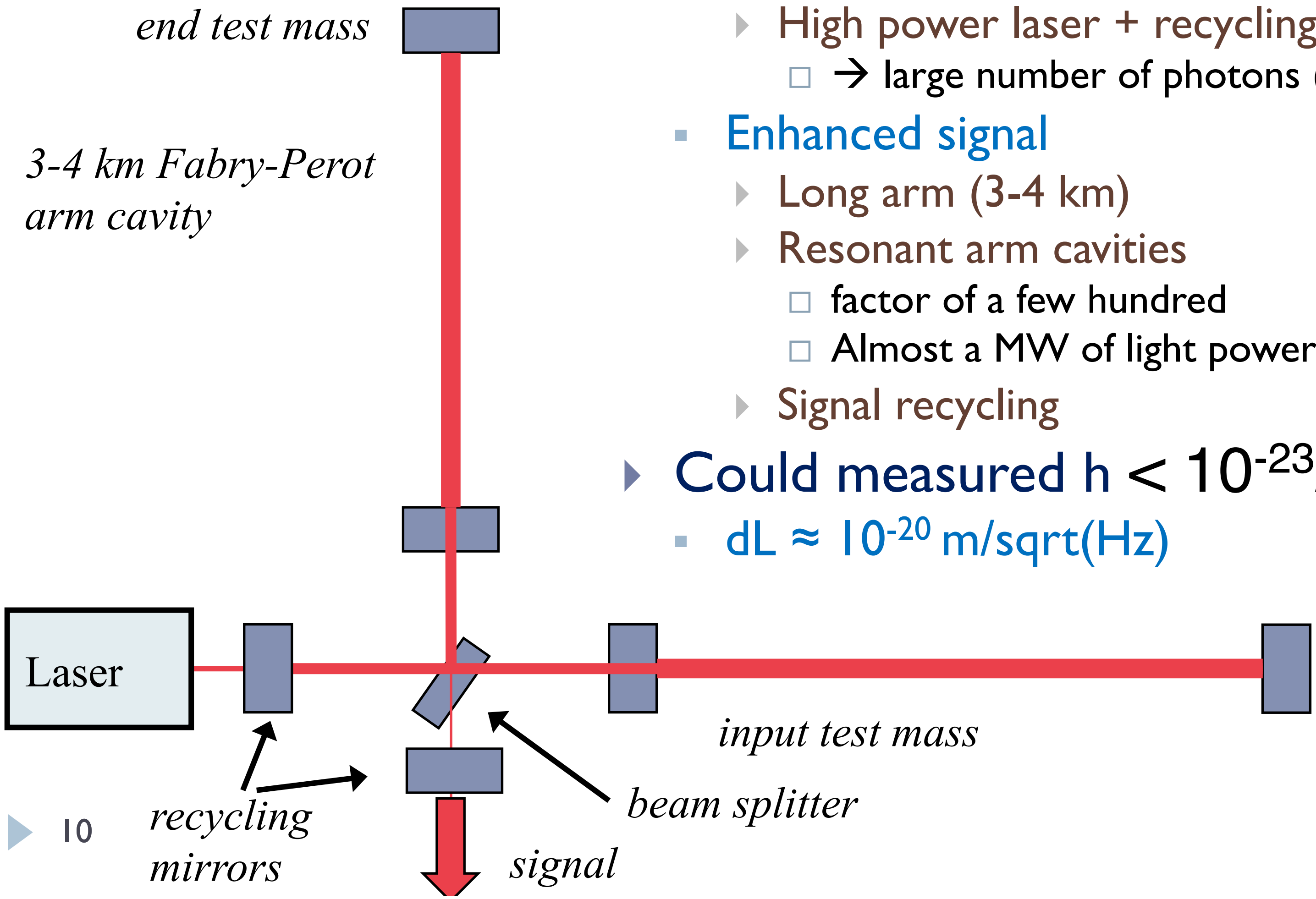
- GW: very weak effect on earth:
  - Sensitivity : $h = \dfrac{\delta L}{L} \leq 10^{-21}$
  - Need to measure small displacements over large distances

    ➔ Large interferometers and challenging technologies



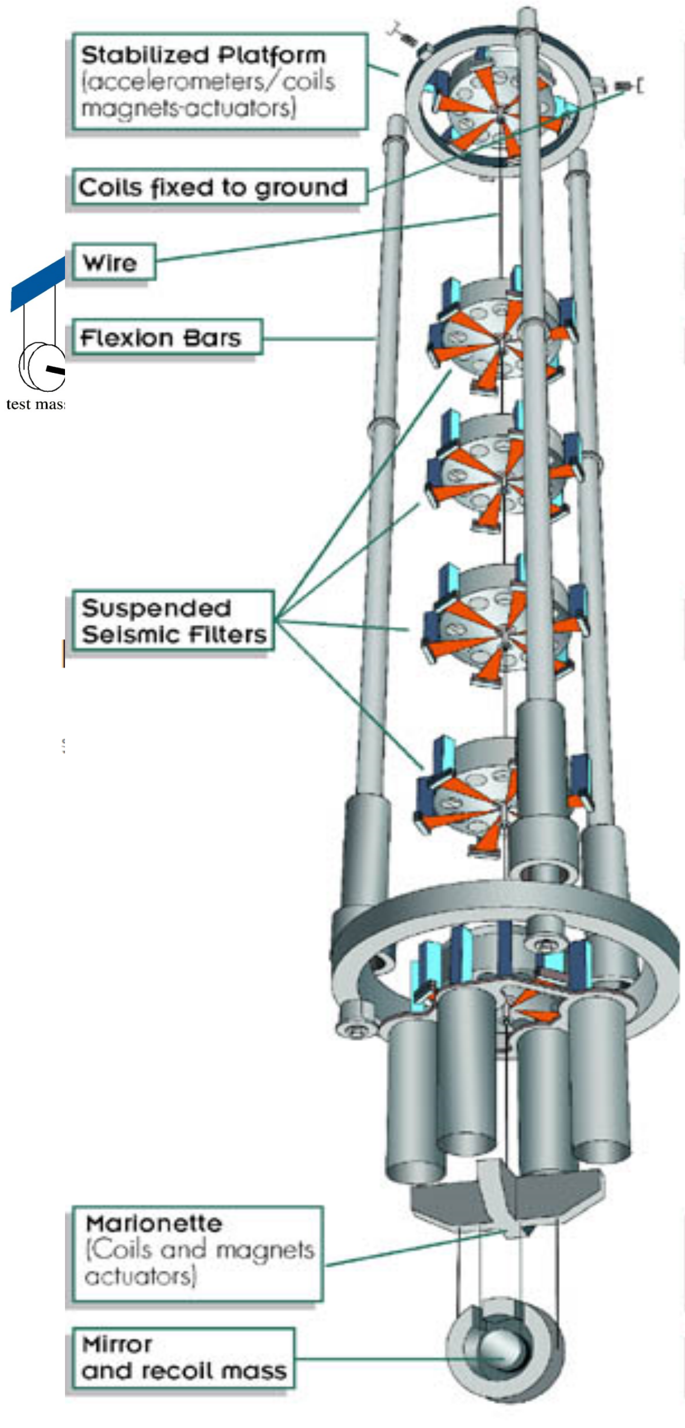
Optical configuration and sensitivity

- Sensitivity
  - Interferometer = sensitive measurement
    - Interferometer: laser wavelength 10^{-6}m
    - High power laser + recycling
      - → large number of photons (few kW on BS)
  - Enhanced signal
    - Long arm (3-4 km)
    - Resonant arm cavities
      - factor of a few hundred
      - Almost a MW of light power
    - Signal recycling
- Could measured h < 10^{-23}/sqrt(Hz)
  - dL ≈ 10^{-20} m/sqrt(Hz)



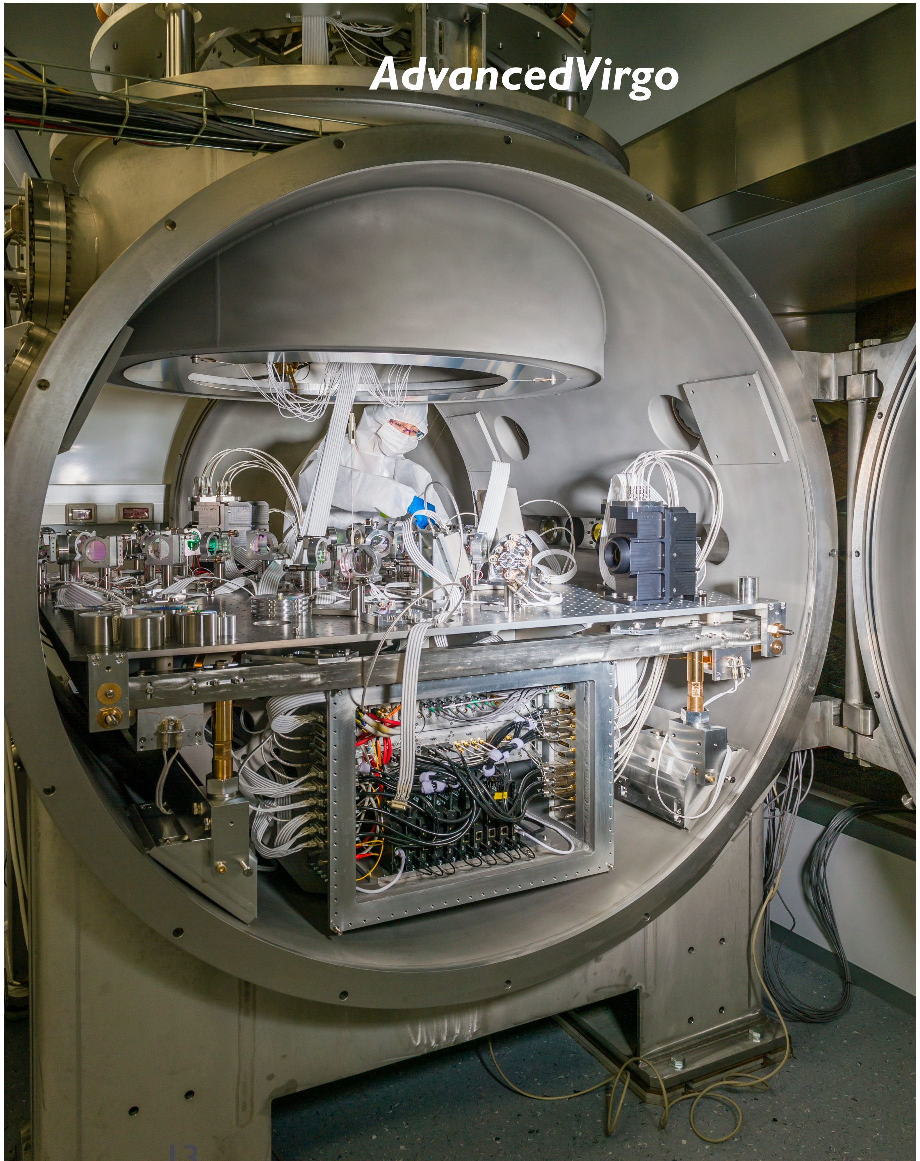
Getting motionless mirrors…

- The mirrors are our test masses
  - Mirror are suspended:
    - "free" test masses above pendulum frequency
- The ground motion ("seimic noise") is large
- The earth is curved
  - Need isolation in all degrees of freedom
  - Horizontal to vertical coupling > 2.10^{-4}
- Need complex isolation system
- Mirrors thermal noise becomes an issue
  - Low loss material
  - Large beams



LIGO and Virgo are complex detectors

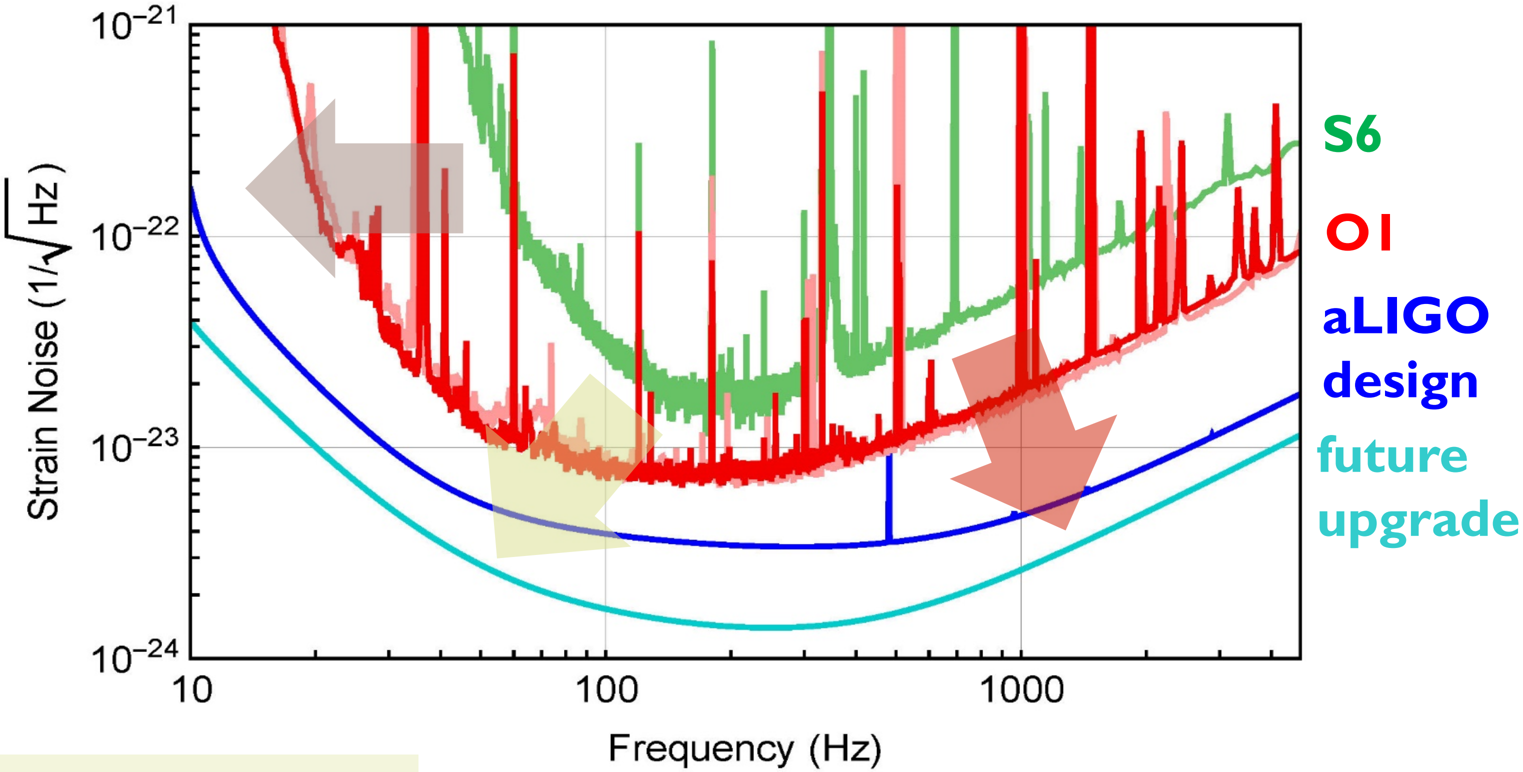
Initial to Advanced detector: example detection



- Detection bench role:
  - Filters and conditions dark fringe light to eliminate contaminating noise
- Moved from classical optical table to in-vacuum suspended bench with ultra-low scatter, high efficiency

From 1st to 2nd generation

Seismic noise
Improved
seismic isolation

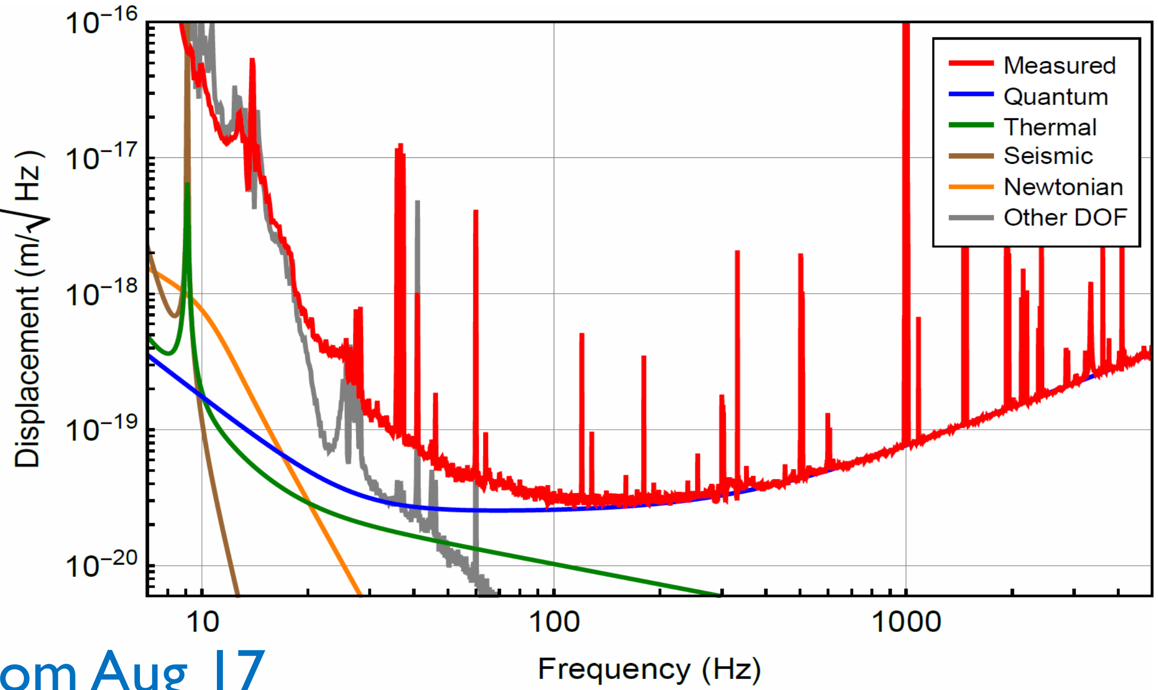


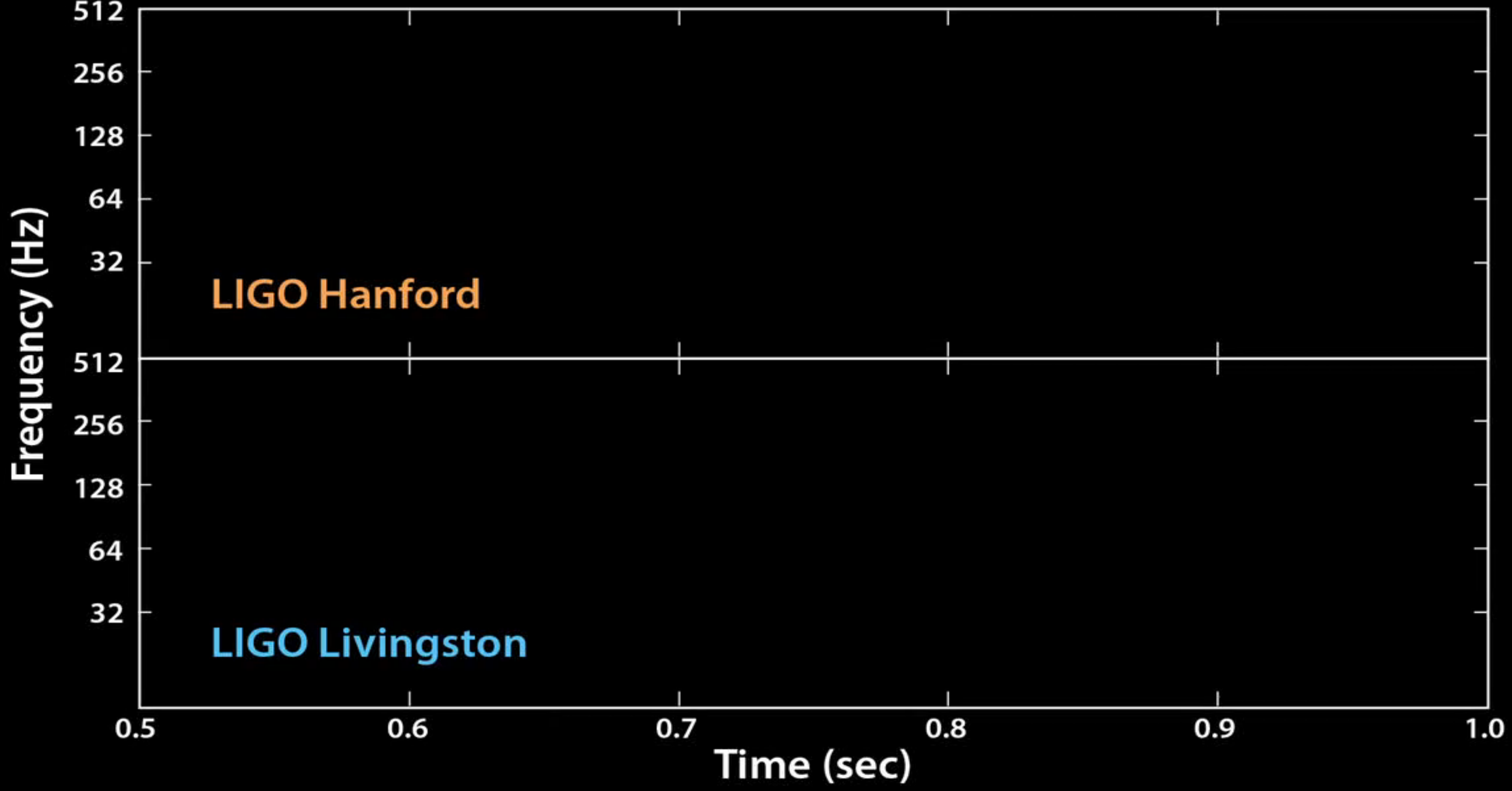
Thermal noise
Monolithic suspensions
Improved mirror coatings
Larger beam size

Quantum noise
Signal recycling
DC detection
Higher laser power
Thermal compensation

Advanced LIGO O1run

- Similar sensitivities for H1 and L1
  - 3-4 times better than in 2010 in 100 Hz – 300 Hz band
- O1: Sep 2015 – Jan 2016
  - Preceded by engineering run from Aug 17
  - Stable data taking from Sep 12
  - O1 scheduled to start on Sep 18
    - When fully ready with calibration / hardware injections / EM follow-up alerts / computing

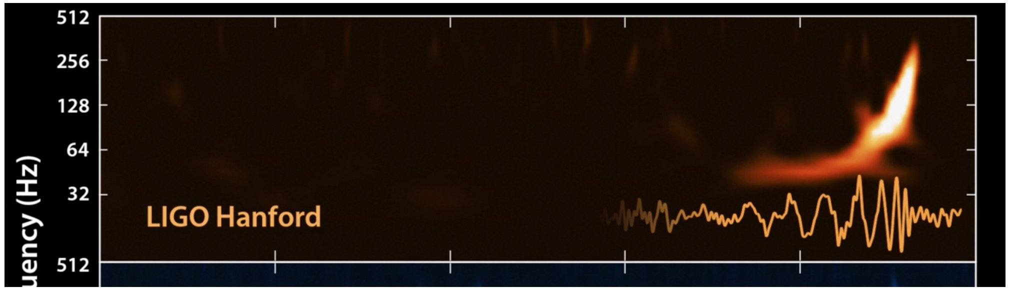




INTRODUCING♪

GW150914♪

09.14.15 | 09:50:45 UTC | 29 +36 $M_{\odot}$, SNR 24 | proud parents, LIGO & Virgo Collaborations



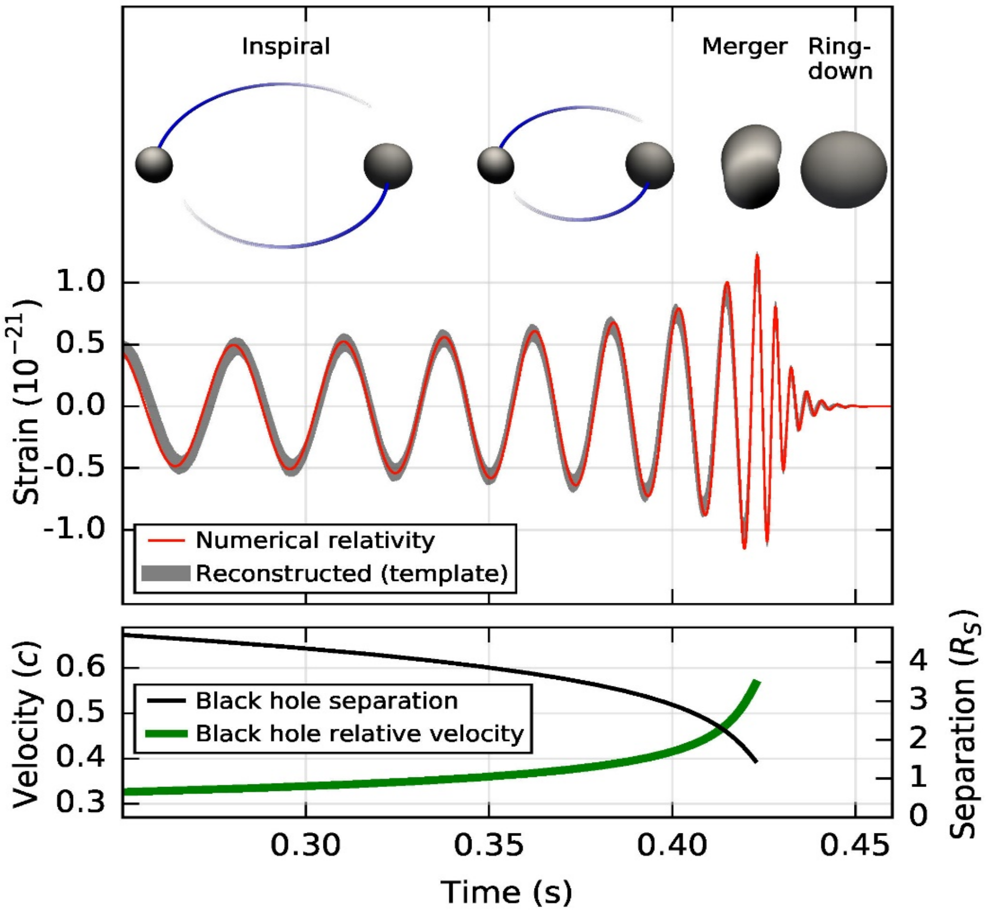
Evidence for BBH merger

- Over 0.2 s, frequency and amplitude increase from 35 Hz to 150 Hz (~ 8 cycles)
  - GW-driven of two orbiting masses
  - Inspiral evolution characterized by chirp mass

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$

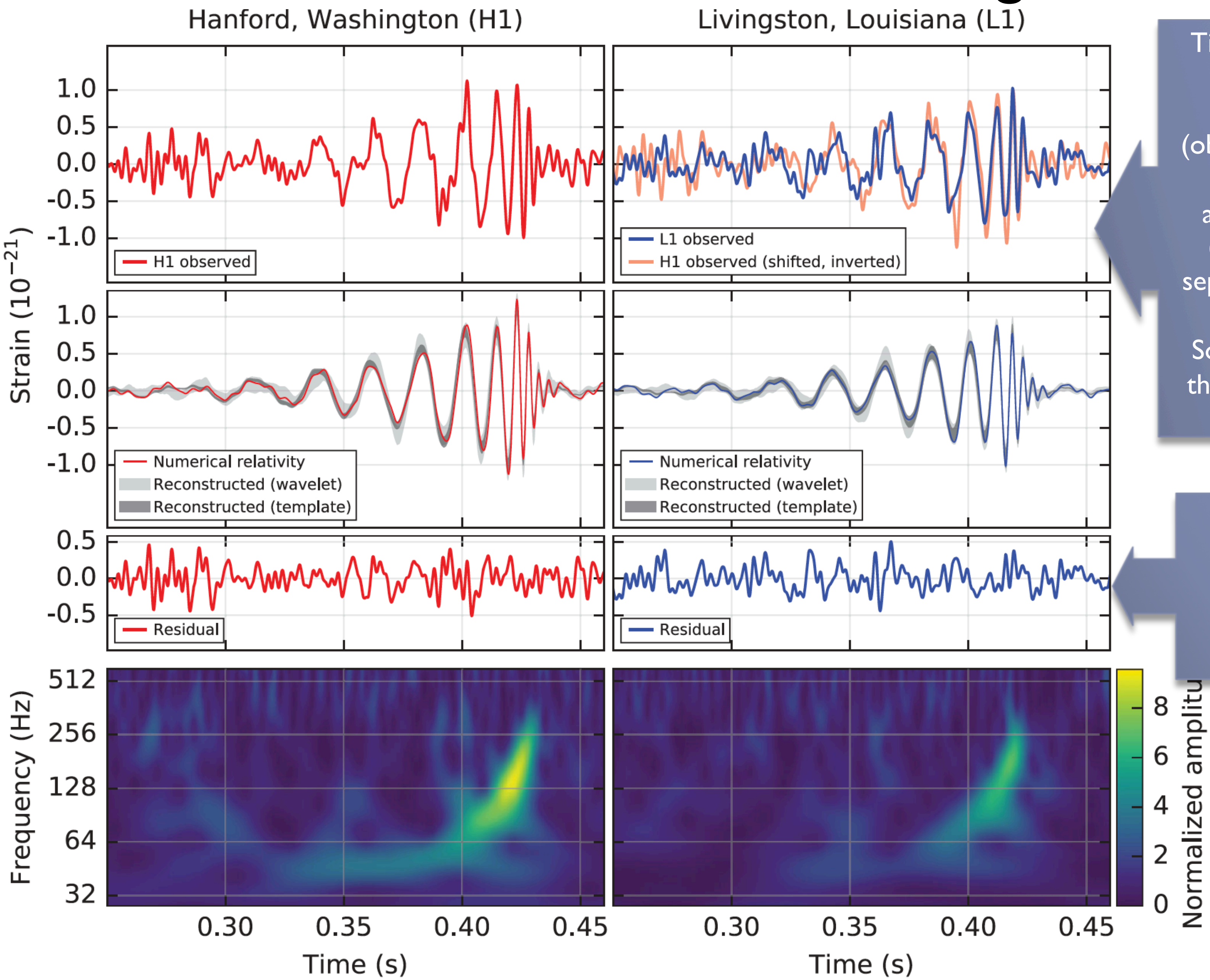
$$\mathcal{M} \simeq 30 M_\odot \qquad M = m_1 + m_2 \gtrsim 70 M_\odot$$

  - Modulation of amplitude gives nonaligned spin components
  - Keplerian separation gets close to Schwarzschild radius
  - Very close and very compact objects
    - BNS too light,
    - NSBH would merge at lower frequencies
- Decay of waveform after peak consistent with damped oscillations of BH relaxing to final stationary Kerr configuration
  - But SNR too low to claim observation of quasi normal modes



$$R_S = 2GM/c^2 \gtrsim 210 \text{ km}$$

Signal consistency

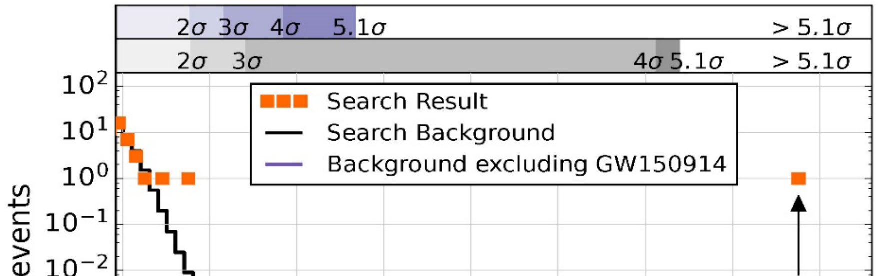


Time trace from Hanford and Livingston;
Hanford inverted (observatory orientation is 90),
and shifted by 7.1 msec (the observatories are separated by 10 msec time of flight).
Source is in an annulus in the Southern hemisphere.

Real time-series data, minus best fit GR waveform:
Shows only noise in residual.

Compact Binary Coalescence Search: BBH result

- Match filtering search
  - Relies on accurate model of waveform
  - Extract maxima in SNR time series $\rho(t)$

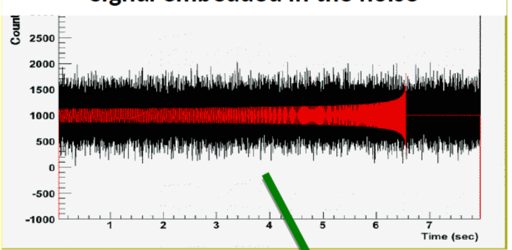


een single
rom GW150914
detector

n GW150914 to

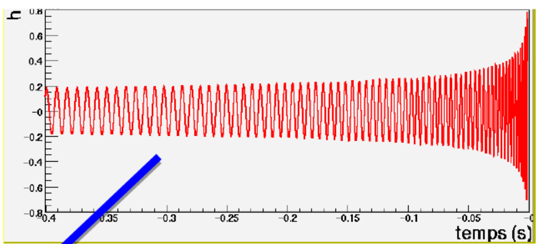
- Matched filtering = weighted intercorrelation signal/template

Signal embedded in the noise



$\otimes$

Template



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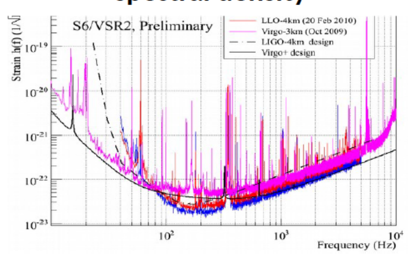
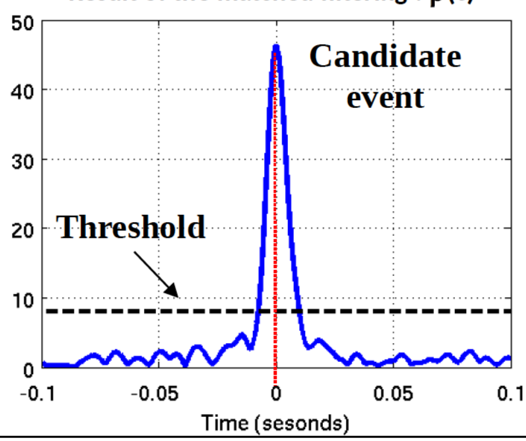
Detectors noise spectral density



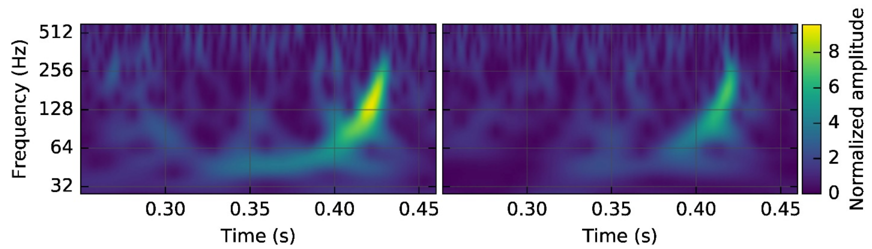
$$\langle \tilde{a}, \tilde{T} \rangle = 2\left[\int_0^\infty \frac{\tilde{a}(f).\tilde{T}^*(f)}{S_n(f)} \mathrm{d}f + \mathrm{c.c.}\right]$$

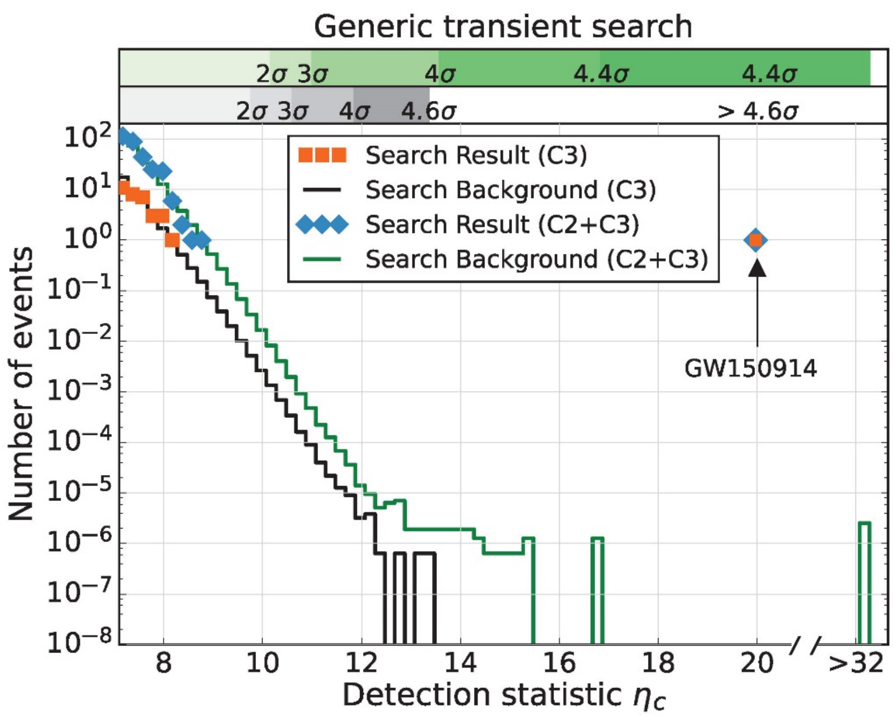
Result of the matched filtering : ρ(t)



Generic Transient Search

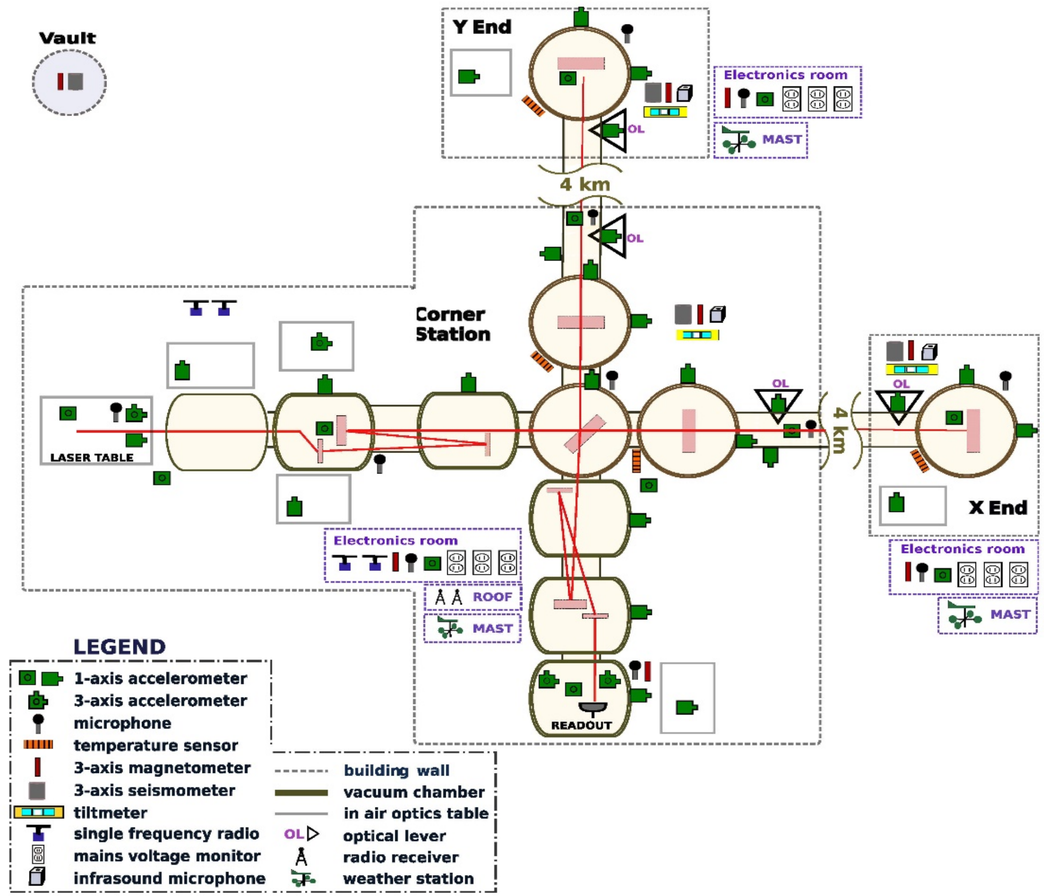
- Identifies coincident excess power in time-frequency representation of h(t)
  - Frequency < 1 kHz
  - Duration < a few seconds
- Detection statistic based on the coherent signal energy
  - Obtained by cross-correlation
- Signal divided into 3 search classes
  - Based on their time-frequency morphology
  - C3: events with frequency increasing with time
    - CBC like
- GW150914 loudest event in C3 search
  - Significance measured from time slides





Environment vetting

- Monitoring of detectors physical environment performed with array of sensors
  - Seismometers, accelerometers, microphones, magnetometers, radio receivers, weather sensors, AC-power line monitors, cosmic ray detector
    - ~10^5 channels for each detector
  - Used to characterize couplings and identify / veto transient disturbances
  - Special attention to possible correlated sources of noise
    - Global electromagnetic noise
- Environmental origin for GW150914 ruled out
  - Excess power in any auxiliary channel too small by factor > 17 to account for GW150914 amplitude
    - Would not match signal morphology anyway

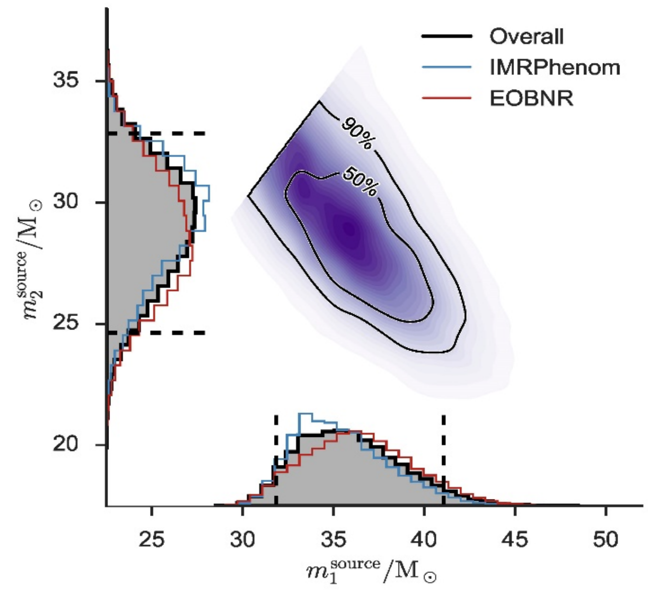


GW150914 Parameter Estimation: Intrinsic Parameters

- Encoded in GW signal
  - Inspiral
    - Leading order: chirp mass
    - Next to leading order: mass ratio, spin components // orbital angular momentum
    - Higher orders: full spin DOF
  - Additional spin effect
    - If not // orbital angular momentum: orbital plane precession
      ➔ Amplitude and phase modulation
  - Merger and ringdown
    - Primarily governed by final black hole mass and spin
    - Masses and spins of binary fully determine mass and spin of final black hole in general relativity
- Masses
- Spins
  - Weak/tight constraints on individual/final

$$a_{\mathrm{f}} = 0.67^{+0.05}_{-0.07}$$

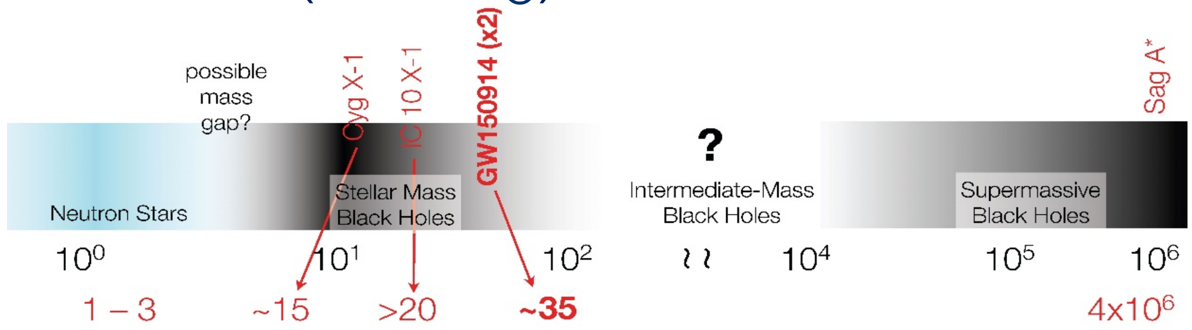
- Radiated energy $3.0^{+0.5}_{-0.5}\ \mathrm{M}_{\odot}c^2$
- Peak luminosity $3.6^{+0.5}_{-0.4} \times 10^{56}\ \mathrm{erg\,s^{-1}} = 200^{+30}_{-20}\ \mathrm{M}_{\odot}c^2/\mathrm{s}$

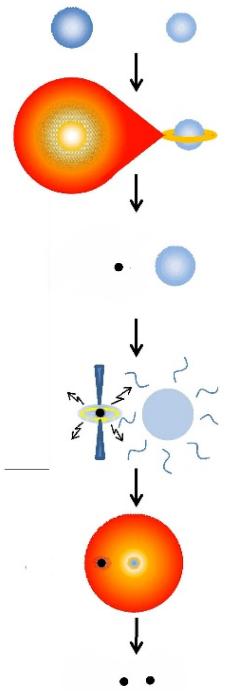


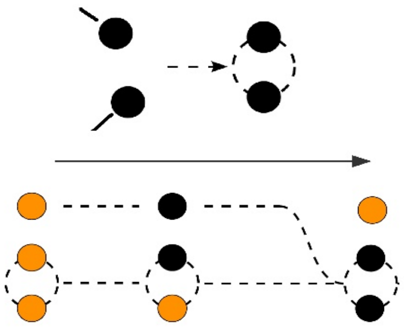
Source-frame total mass $M^{\mathrm{source}}/\mathrm{M}_{\odot}$	$64.8^{+4.6\pm1.0}_{-3.9\pm0.5}$
Source-frame chirp mass $\mathcal{M}^{\mathrm{source}}/\mathrm{M}_{\odot}$	$27.9^{+2.1\pm0.4}_{-1.7\pm0.2}$
Source-frame primary mass $m_1^{\mathrm{source}}/\mathrm{M}_{\odot}$	$35.7^{+5.4\pm1.1}_{-3.8\pm0.0}$
Source-frame secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_{\odot}$	$29.1^{+3.8\pm0.2}_{-4.4\pm0.5}$
Source-fame final mass $M_{\mathrm{f}}^{\mathrm{source}}/\mathrm{M}_{\odot}$	$61.8^{+4.2\pm0.9}_{-3.5\pm0.4}$

Astrophysical Implications

- Relatively heavy stellar-mass black holes (> 25 $M_\odot$) exist in nature
  - Implies weak massive-star winds
  - Formation in environment with low metallicity



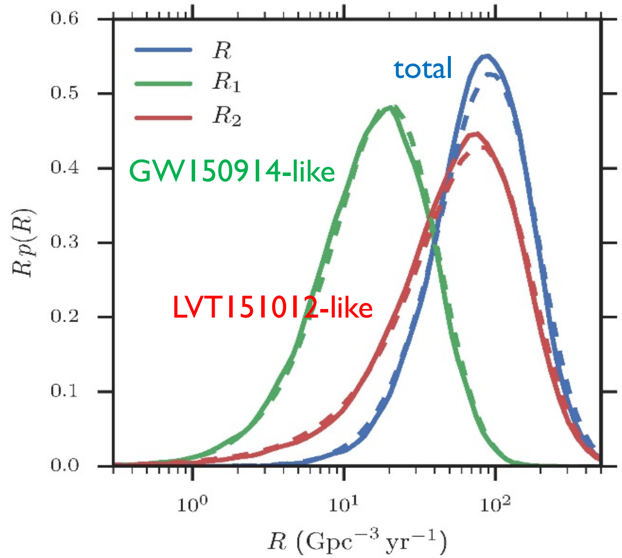


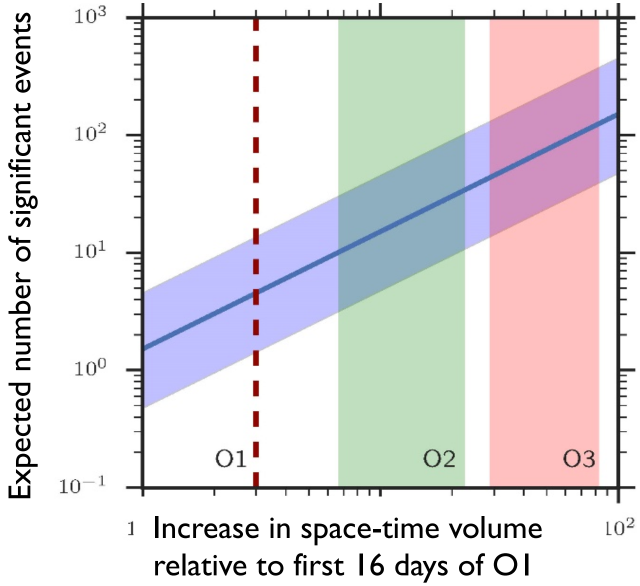


- Binary black holes form in nature
  - GW150914 does not allow to identify formation path
  - From isolated binaries vs dynamical capture in dense star clusters
    - Spin information may be able to tell in the future
- BBHs merge within age of Universe at detectable rate
  - Inferred rate consistent with higher end of rate predictions

Rate of BBH mergers

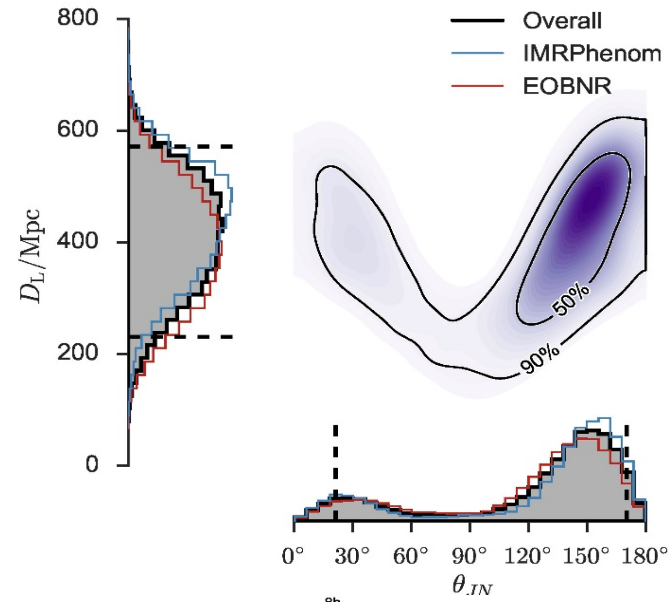
- Previous rate estimates based on EM observations and population modelling
  - R ~ 0.1 – 300 $Gpc^{-3}\ yr^{-1}$
- Previous LIGO-Virgo rate upper limits
  - R < 140 $Gpc^{-3}\ yr^{-1}$ for GW150914 parameters
- Astrophysical rate inference involves
  - Counting signals in experiment
  - Estimating sensitivity to population of sources
    - Depends on (hardly known) mass distribution
- Low statistics and variety of assumptions yield broad rate range
  - R ~ 2 – 400 $Gpc^{-3}\ yr^{-1}$
- Can project expected number of highly significant events as a function of surveyed time-volume

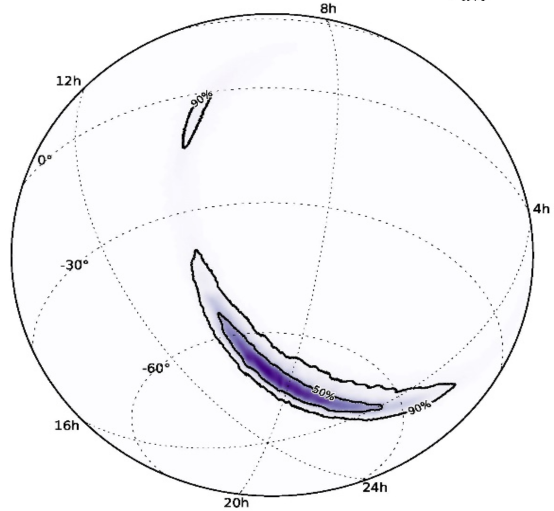




GW150914 Extrinsic Parameters

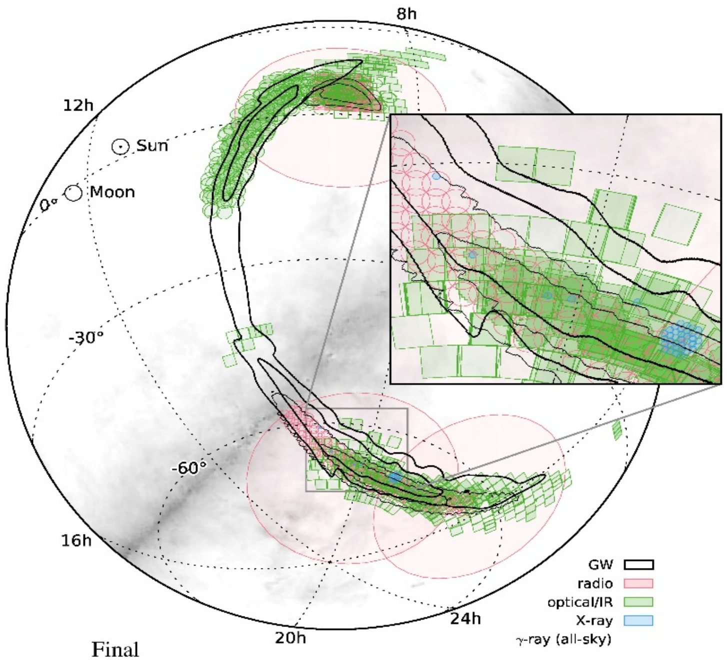
- A mix of things we can measure and things we can guess
  - Amplitude depends on masses, distance, and geometrical factors
    - Distance – inclination degeneracy
    - Distant sources with favorable orientations are preferred
    - $D_{\mathrm{L}} = 410^{+160}_{-180}\ \mathrm{Mpc}$ $\quad z = 0.09^{+0.03}_{-0.04}$
  - Source location inferred primarily from time of flight $6.9^{+0.5}_{-0.4}\ \mathrm{ms}$, amplitude and phase consistency
    - Limited accuracy with two detector network
    - Sky locations with good detector response are preferred
    - 2-D 90% credible region is 590 deg^2
    - 3-D uncertainty volume is 10^7 Mpc^3
      ~ 10^5 Milky Way equivalent galaxies

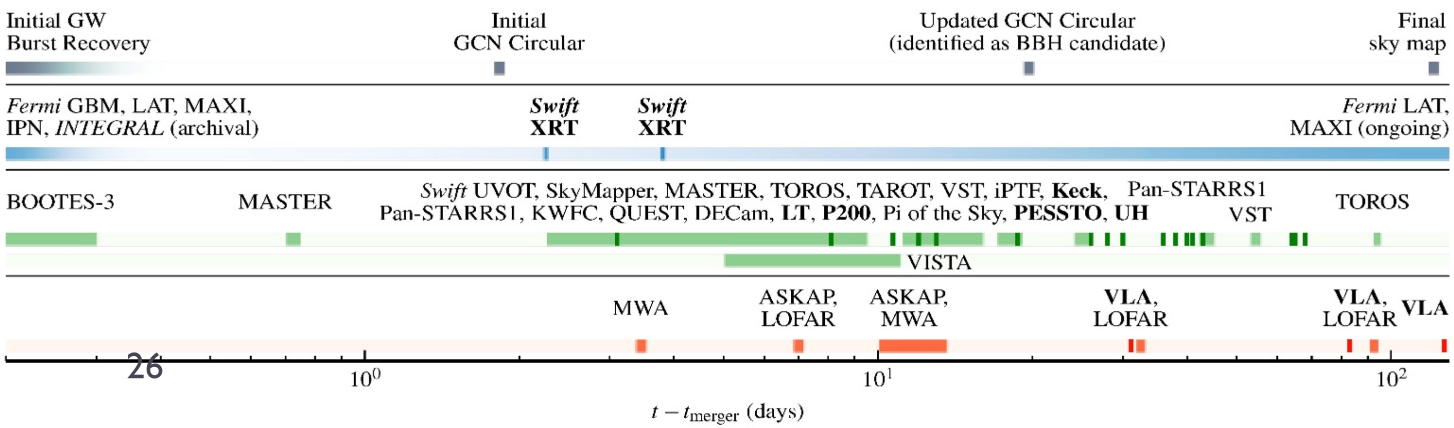




Electromagnetic follow-up

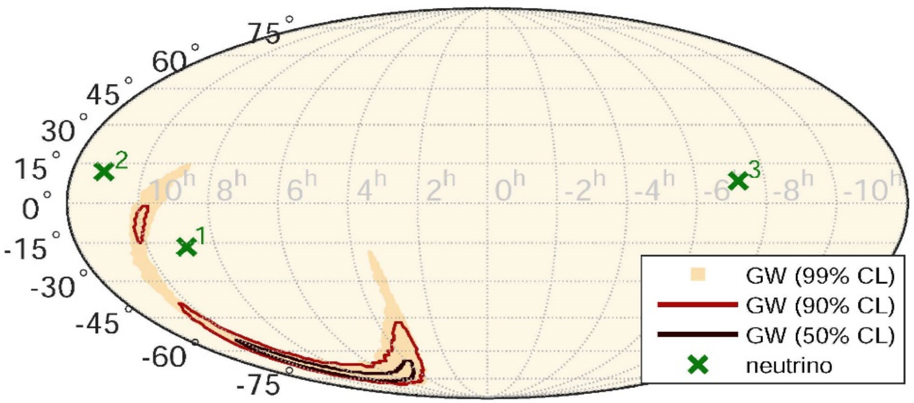
- LVC called for EM observers to join a follow-up program
  - LIGO and Virgo share promptly interesting triggers
  - 70 MoUs, 160 instruments covering full spectrum
    - from radio to very high energy gamma-rays
- 25 teams reported follow-up observation of GW150914





High-Energy Neutrino Follow-up

- Search for coincident high energy neutrino candidates in IceCube and ANTARES data
  - HEN ν expected in (unlikely) scenario of BH + accretion disk system
  - Search window ± 500 s



- No ν candidate in both temporal and spatial coincidence
  - 3 ν candidates in IceCube
  - 0 ν candidate in ANTARES
  - Consistent with expected atmospheric background
  - None of ν candidates directionally coincident with GW150914

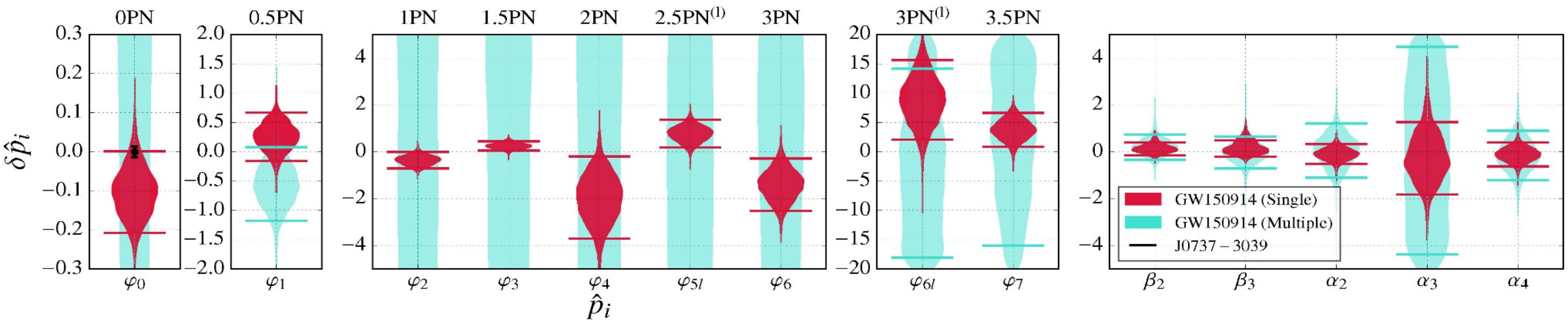
- Derive direction dependent ν fluence upper limit
- Derive constraint on total energy emitted in ν by the source
  - $$E^{ul}_{\nu,tot} \sim 10^{52}\text{–}10^{54} \left(\frac{D_{gw}}{410\,\mathrm{Mpc}}\right)^2 \mathrm{erg}$$

Testing GR with GW150914 (I)

- Most relativistic binary pulsar known today
  - J0737-3039, orbital velocity: $v/c \sim 2 \times 10^{-3}$
- GW150914
  - Strong field, non linear, high velocity regime: $v/c \sim 0.5$
- Loud-*ish* SNR allows some coarse tests
  - Check residuals after subtraction of best-fit waveform are consistent with instrumental noise
  - Waveform internal consistency check
  - Evidence for deviation from General Relativity in waveform ?
  - Bound on graviton mass

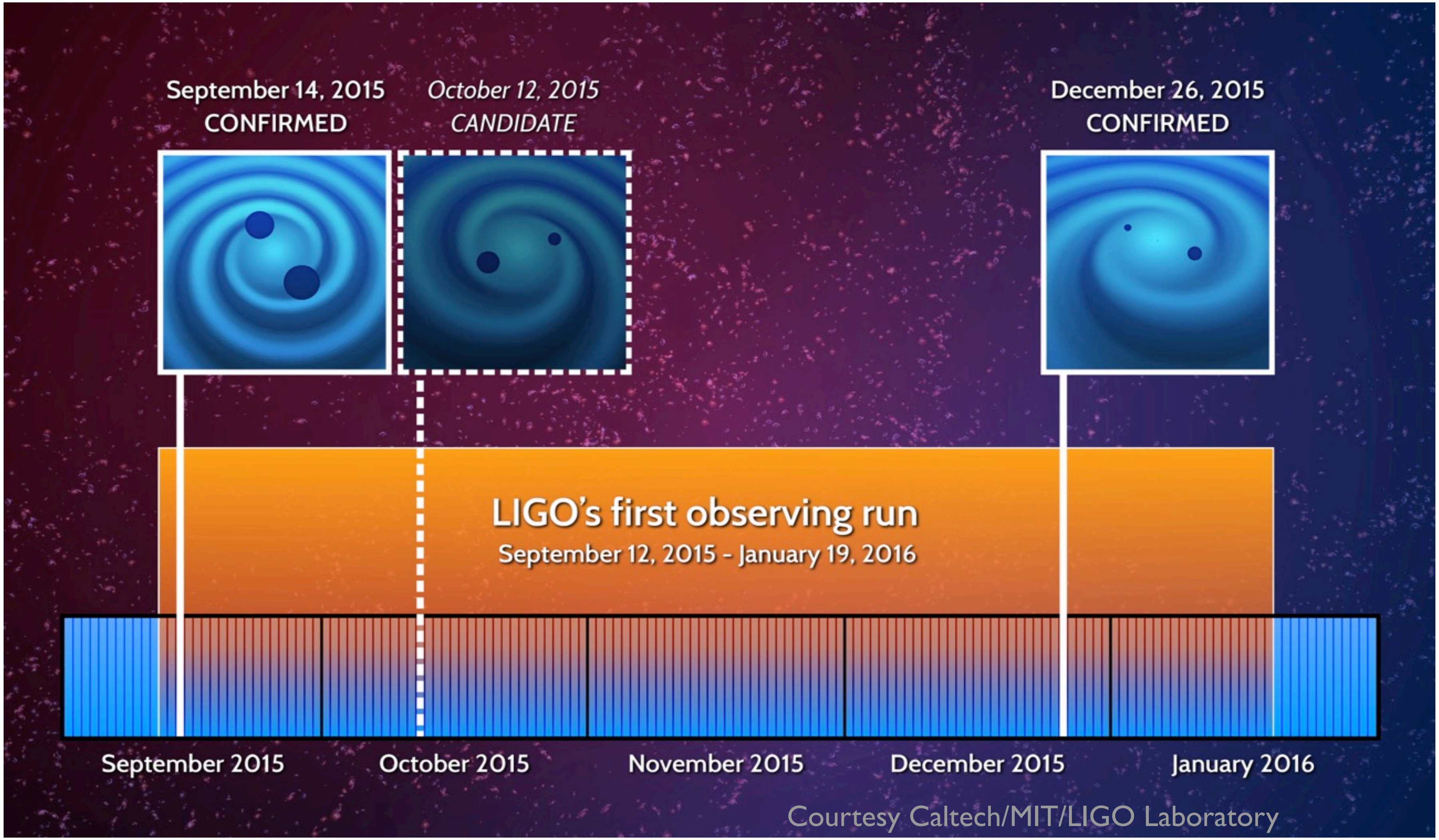
Testing GR with GW150914 (II)

- No evidence for deviation from GR in waveform



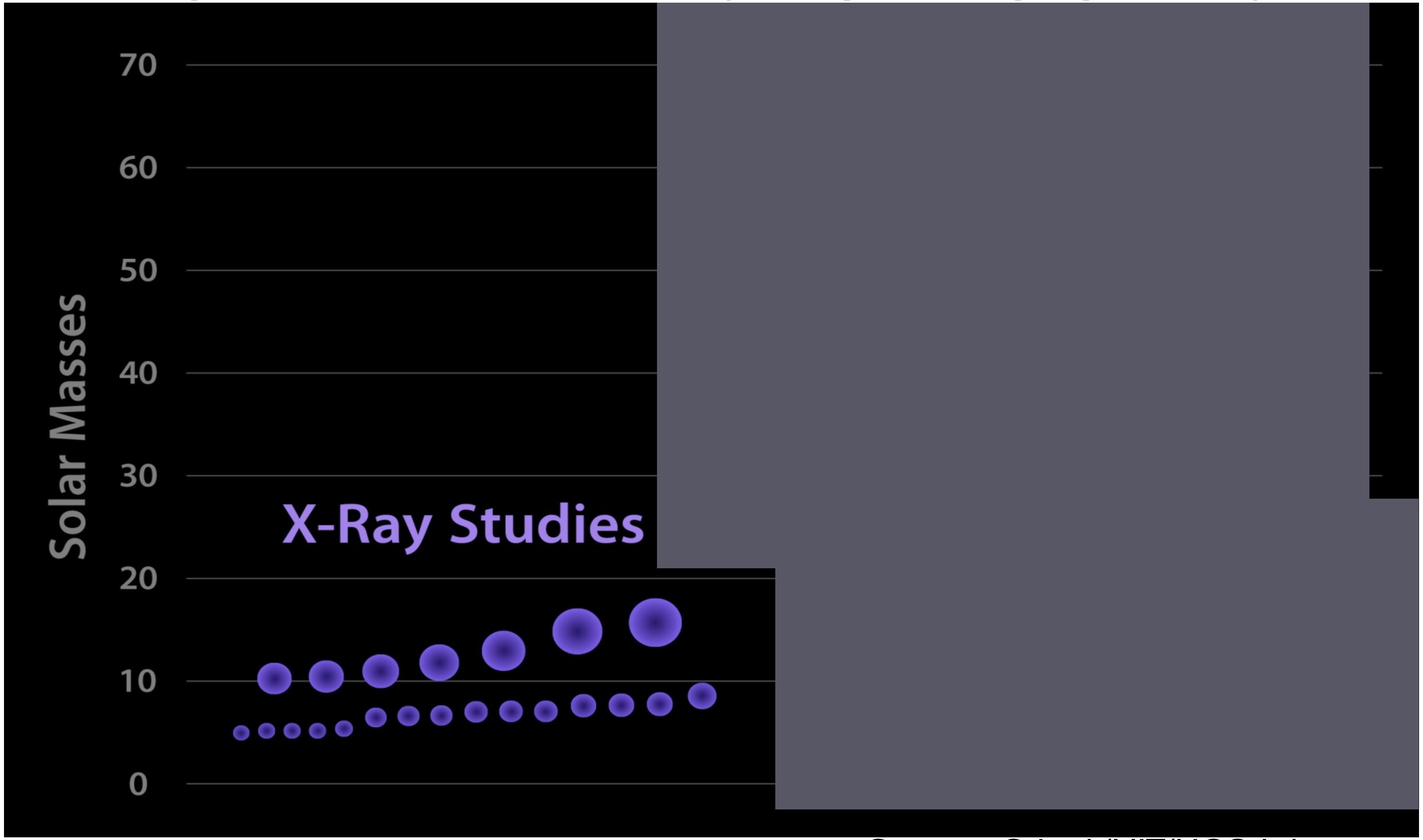
- No evidence for dispersion in signal propagation
  - $$\left(\frac{v}{c}\right)^2 = 1 - \left(\frac{hc}{\lambda_g E}\right)^2 \qquad \lambda_g > 10^{13} \text{ km}$$
  - $$m_g \leq 1.2 \times 10^{-22} \text{ eV/c}^2$$
  - More constraining than bounds from Solar System and binary pulsar observations
  - Less constraining than model dependent bounds from large scale dynamics of galactic clusters and weak gravitational lensing observations

Events Observed During O1



Census of Black Holes in the Universe

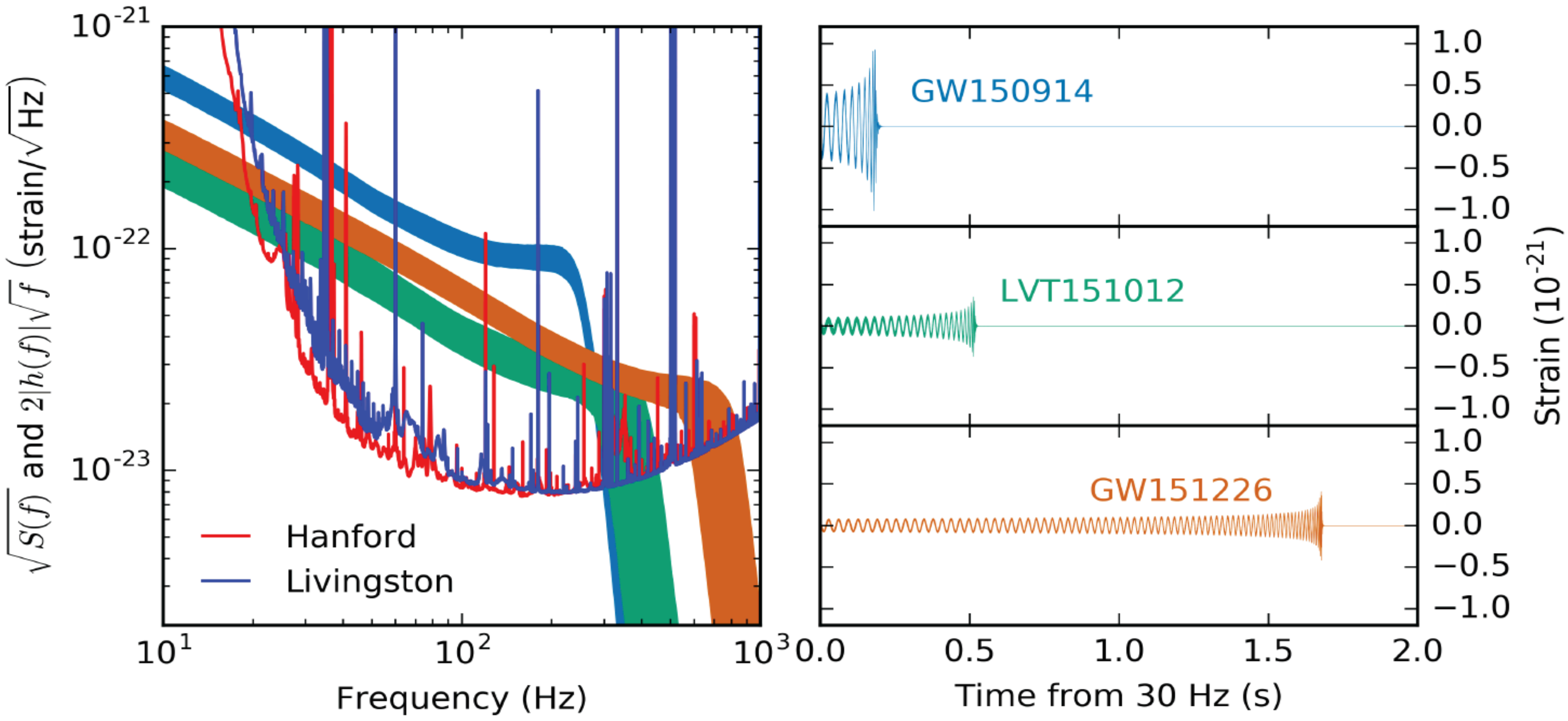
- Previously known black holes (X-ray binary systems)



Courtesy Caltech/MIT/LIGO Laboratory

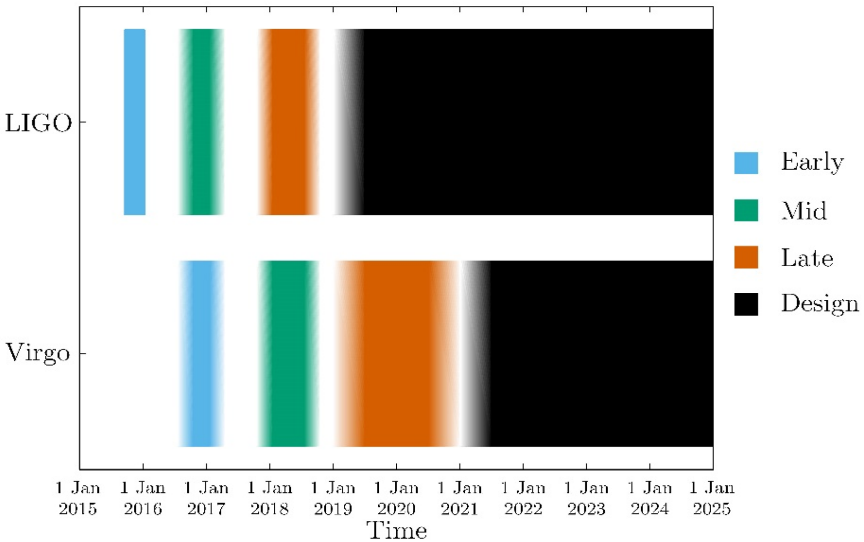
Frequency dependence of 3 events compared to the LIGO sensitivity

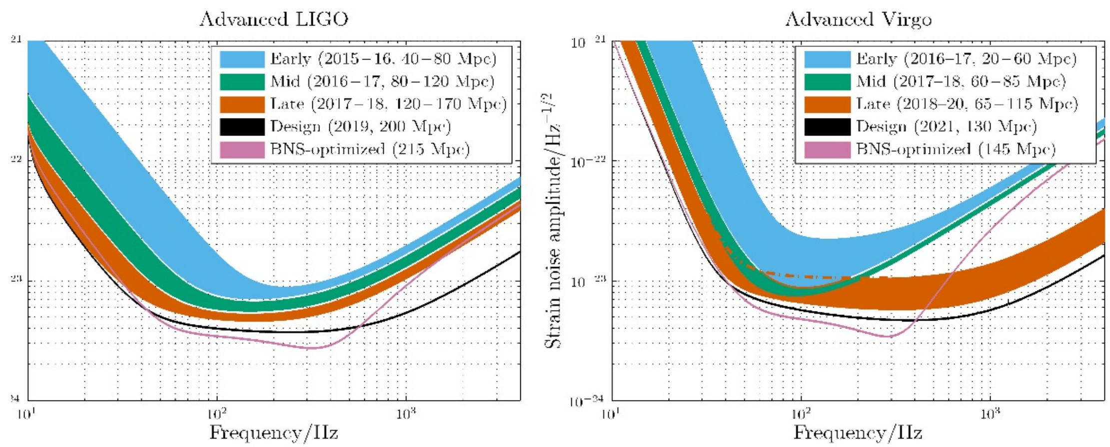
https://arxiv.org/abs/1606.04856



Outlook: Future Data

- Virgo installation in progress: expect to take data this year

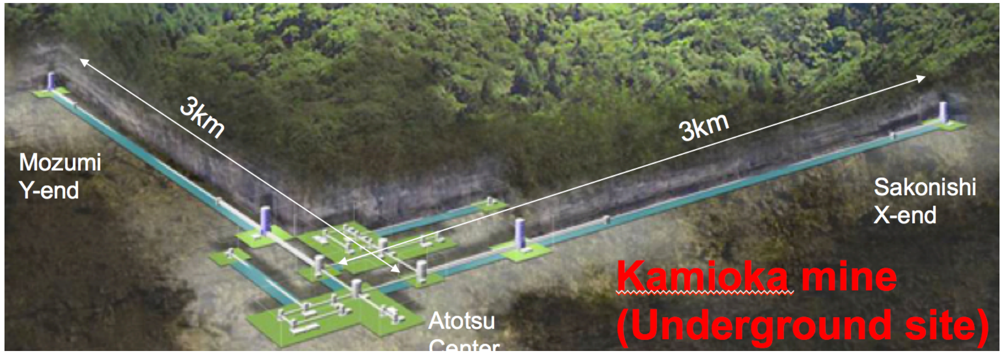




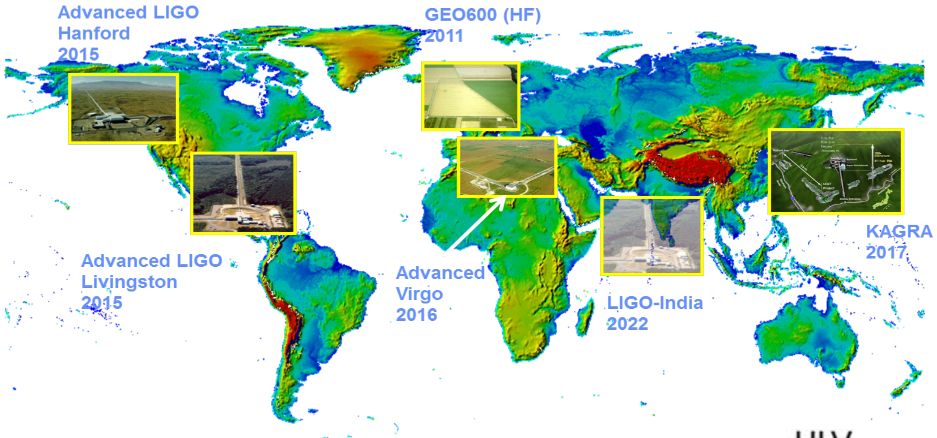
Epoch			2015 – 2016	2016 – 2017	2017 – 2018	2019+	2022+ (India)
Estimated run duration			4 months	6 months	9 months	(per year)	(per year)
Burst range/Mpc		LIGO	40 – 60	60 – 75	75 – 90	105	105
		Virgo	—	20 – 40	40 – 50	40 – 80	80
BNS range/Mpc		LIGO	40 – 80	80 – 120	120 – 170	200	200
		Virgo	—	20 – 60	60 – 85	65 – 115	130
Estimated BNS detections			0.0005 – 4	0.006 – 20	0.04 – 100	0.2 – 200	0.4 – 400
90% CR	% within	5 deg^2	< 1	2	> *1 – 2*	> *3 – 8*	> *20*
		20 deg^2	< 1	14	> *10*	> *8 – 30*	> *50*
		median/deg^2	480	230	—	—	—
searched area	% within	5 deg^2	6	20	—	—	—
		20 deg^2	16	44	—	—	—
		median/deg^2	88	29	—	—	—

New large interferometers in construction

- KAGRA:
  - 3km underground in Japan
  - Infrastructure completed
  - Science data around 2020-2021

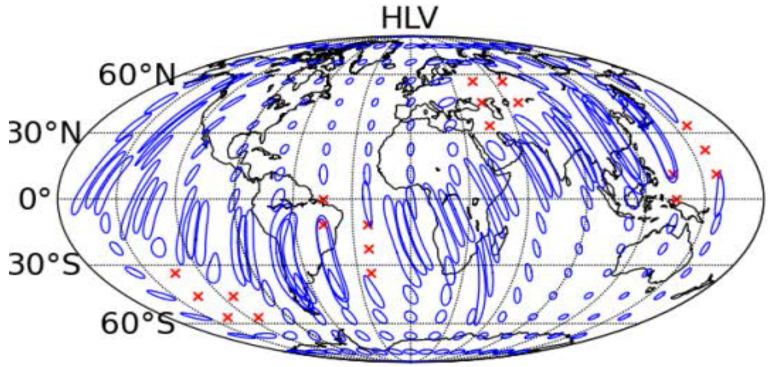


- LIGO-India:
  - Third LIGO interferometer installed in India
  - Site acquisition in progress
  - Science data around 2024

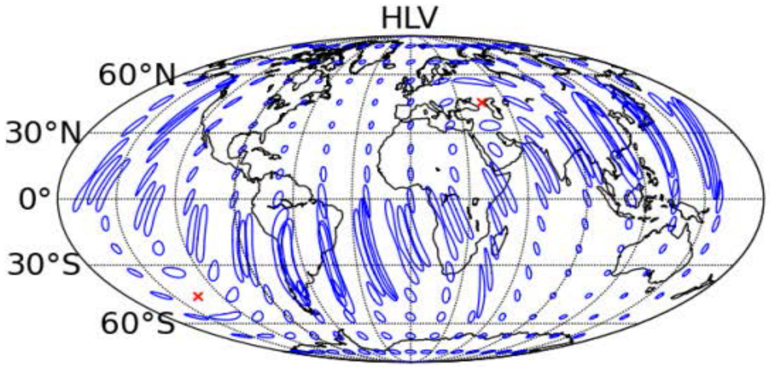


Future Localization Prospects

Face-on BNS
@ 80 Mpc

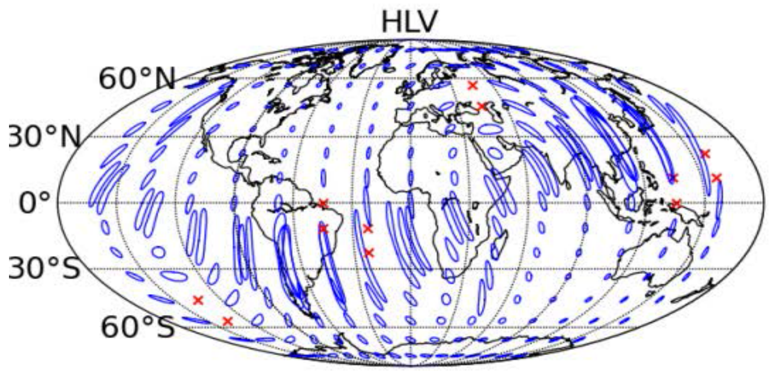


2016-17

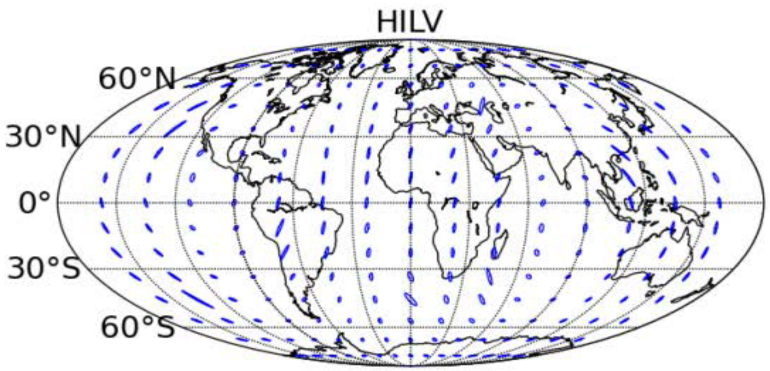


2017-18

Face-on BNS
@ 160 Mpc



2019+



2022+

Ground-based GW detectors

- 1st generation interferometric detectors
  - Initial LIGO, Virgo, GEO600

Unlikely detection

Science data taking
First rate upper limits
Set up network observation

➢ Enhanced LIGO, Virgo+

Improved sensitivity

Laid ground for multi-messenger astronomy

❑ 2nd generation detectors
  ➢ Advanced LIGO, Advanced Virgo, GEO-HF, KAGRA

VOUS ÊTES ICI

First detection

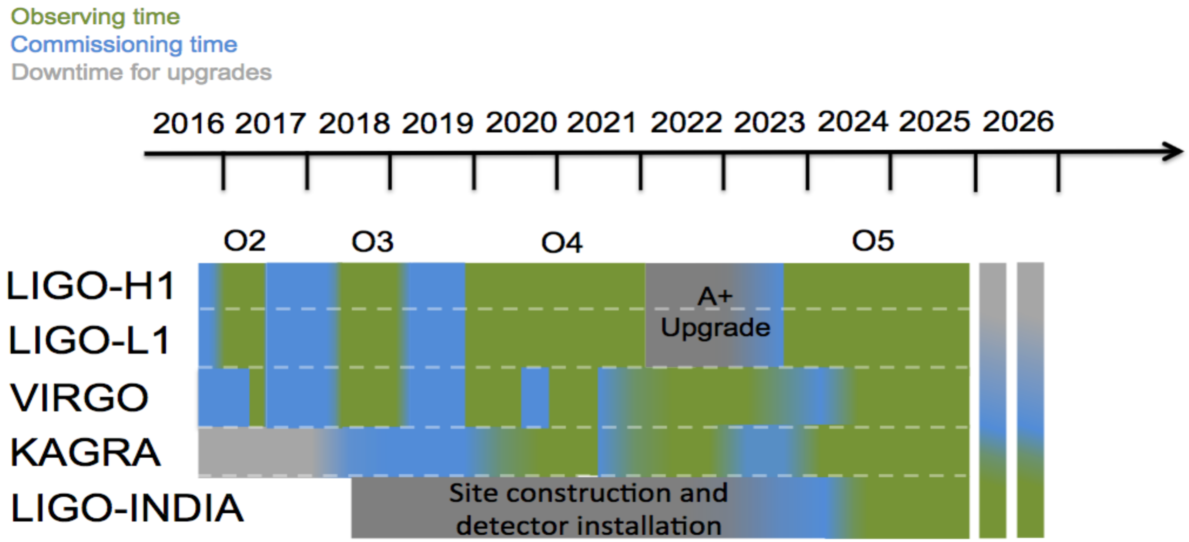
Toward routine observation
GW astronomy

2.5 G

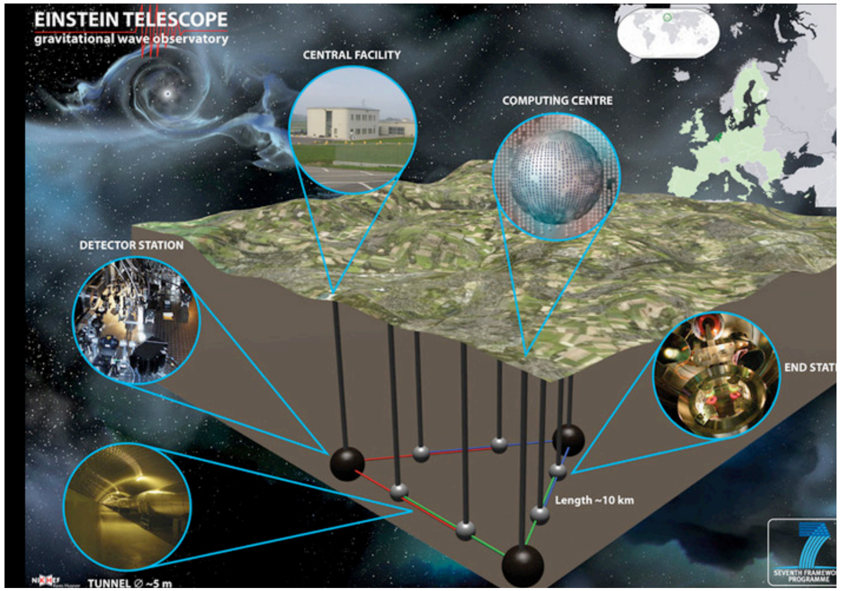
❑ 3rd generation detectors
  ➢ Einstein Telescope, Cosmic Explorer

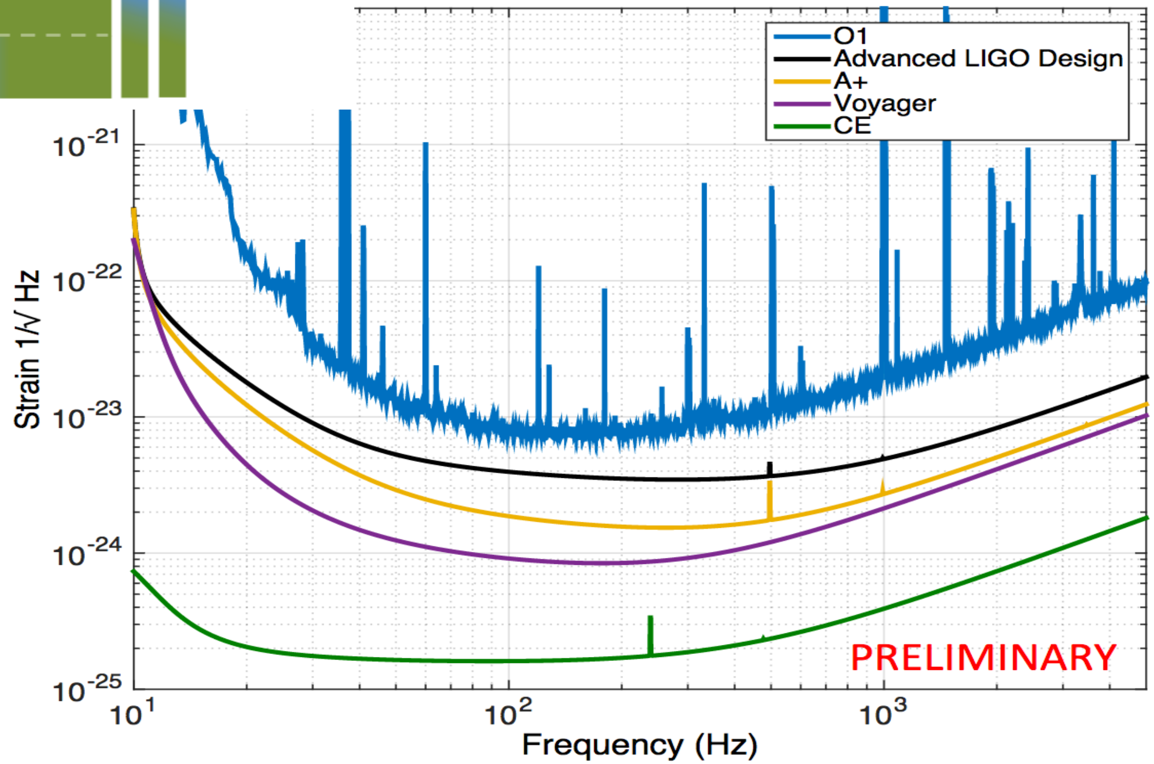
Thorough observation of Universe with GW

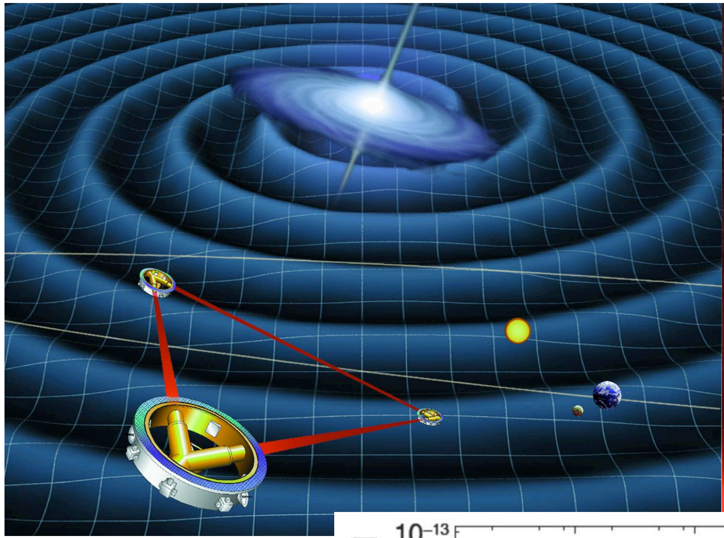
Network evolution

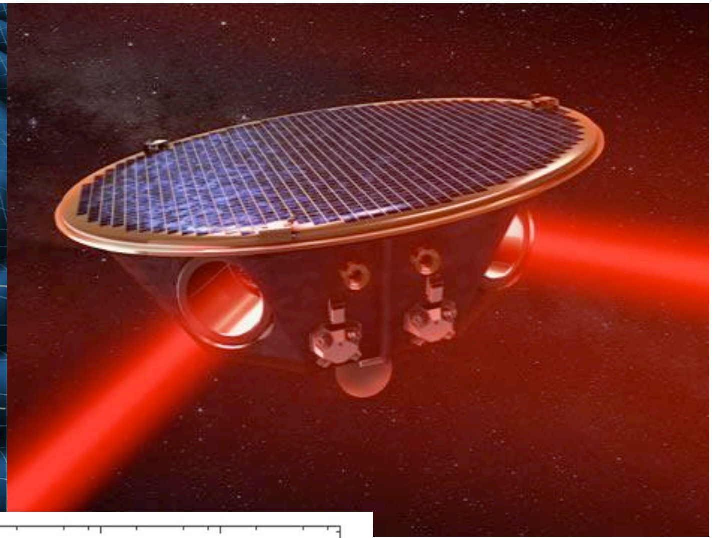


- Example of LIGO possible evolutio
  - LIGO-T1500293
- Einstein telescope: an underground third generation detector

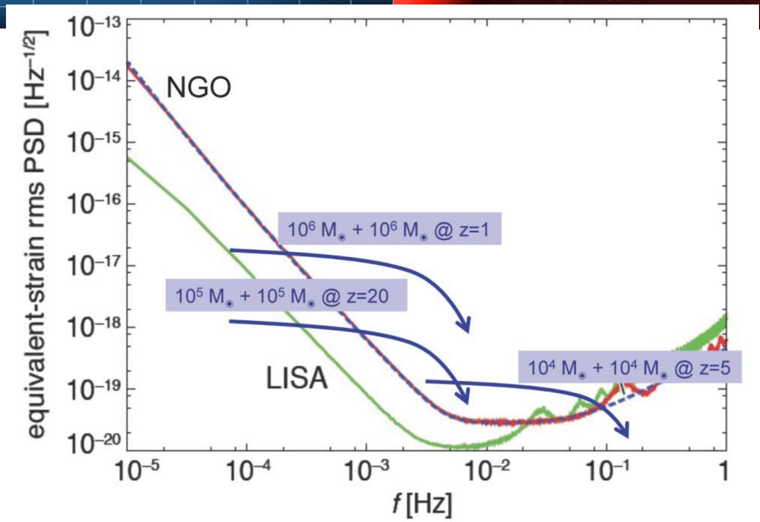








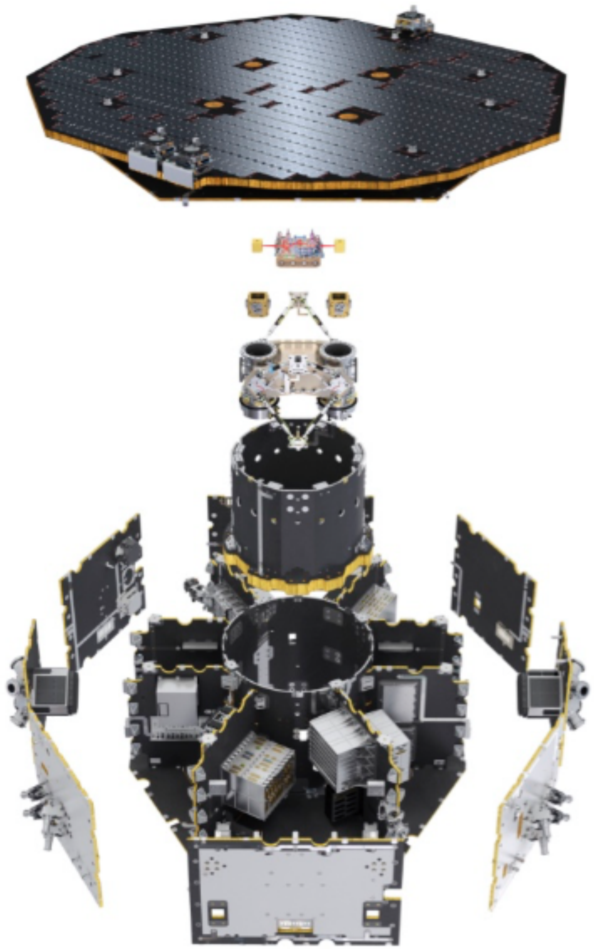
eLISA
LISA pathfinder



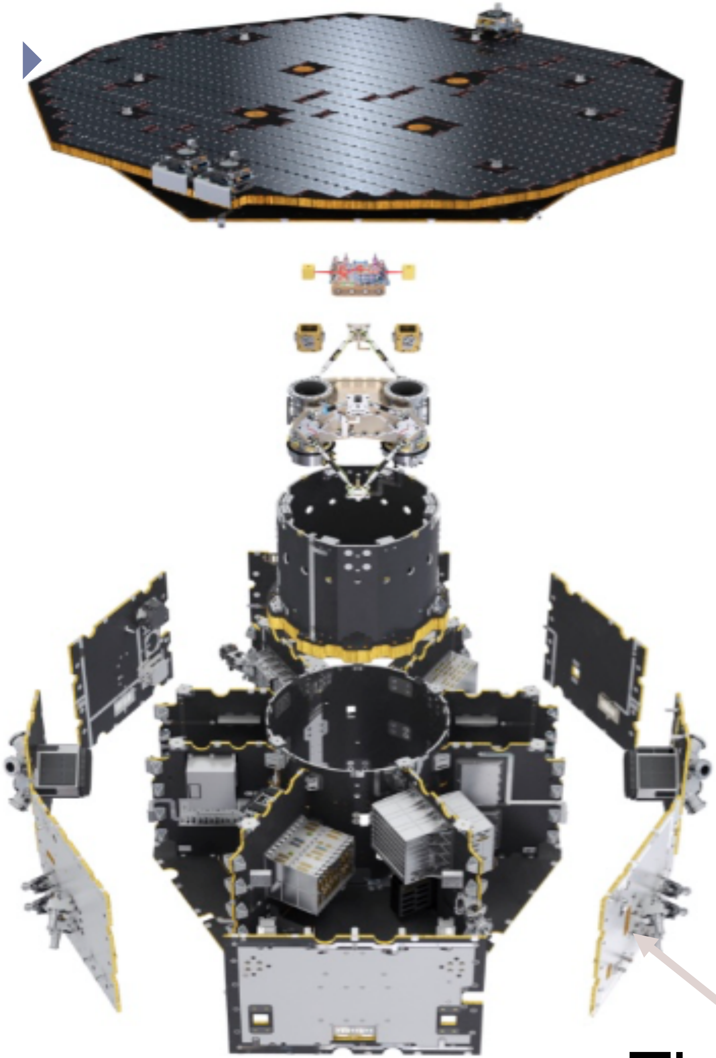
- Super-massive black holes and large structure formation
- White-dwarf binary systems in the Galaxy
- Cosmology, ultra-strong gravity tests

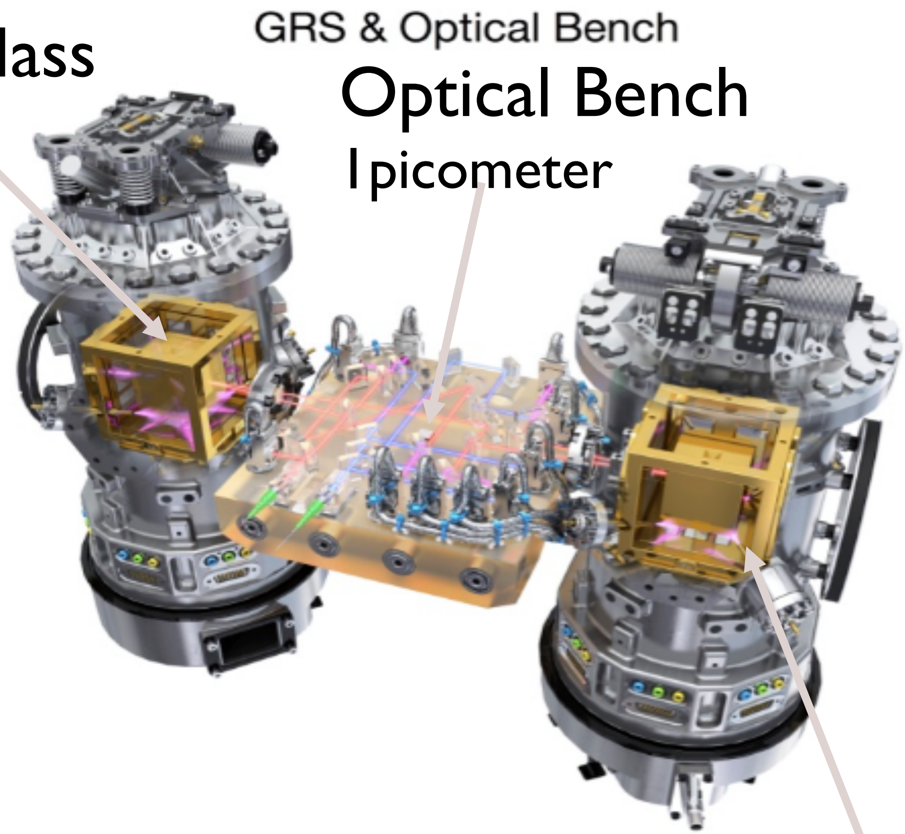
LISA Pathfinder

- LISA Pathfinder is a mission that will demonstrate the possibility of "Free Fall" in space at the level of $\approx 10^{-14}$ m s^{-2}, around 1 mHz
- The 2 "Test Masses" of LPF are protected from solar pressure by the satellite.
- A set of μ-thrusters allows to keep the SC centered on the TMs
- A number of effects have to be minimized:
  - The static gravitational potential between the TMs and the SC,
  - Residual links of the TMs w.r.t the SC via the residual vacuum,
  - Cross talk between various electrostatic actuators,
  - TM charging by Cosmic rays that is eliminated by UV illumination,
  - Temperature fluctuations ,
  - Magnetic field fluctuations,
  - …



LisaPathfinder : A technological demonstrator





Test Mass

Optical Bench

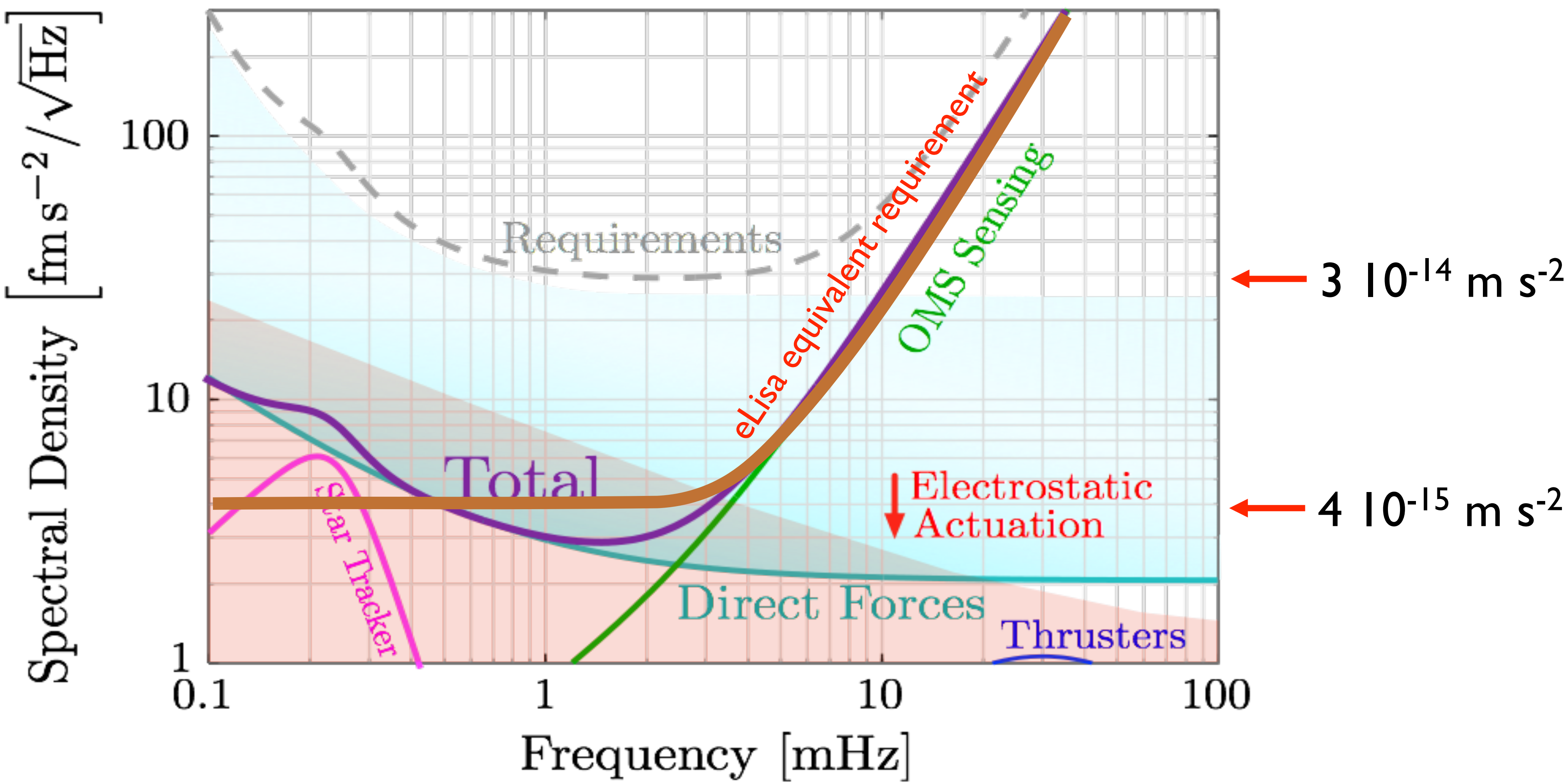
1picometer

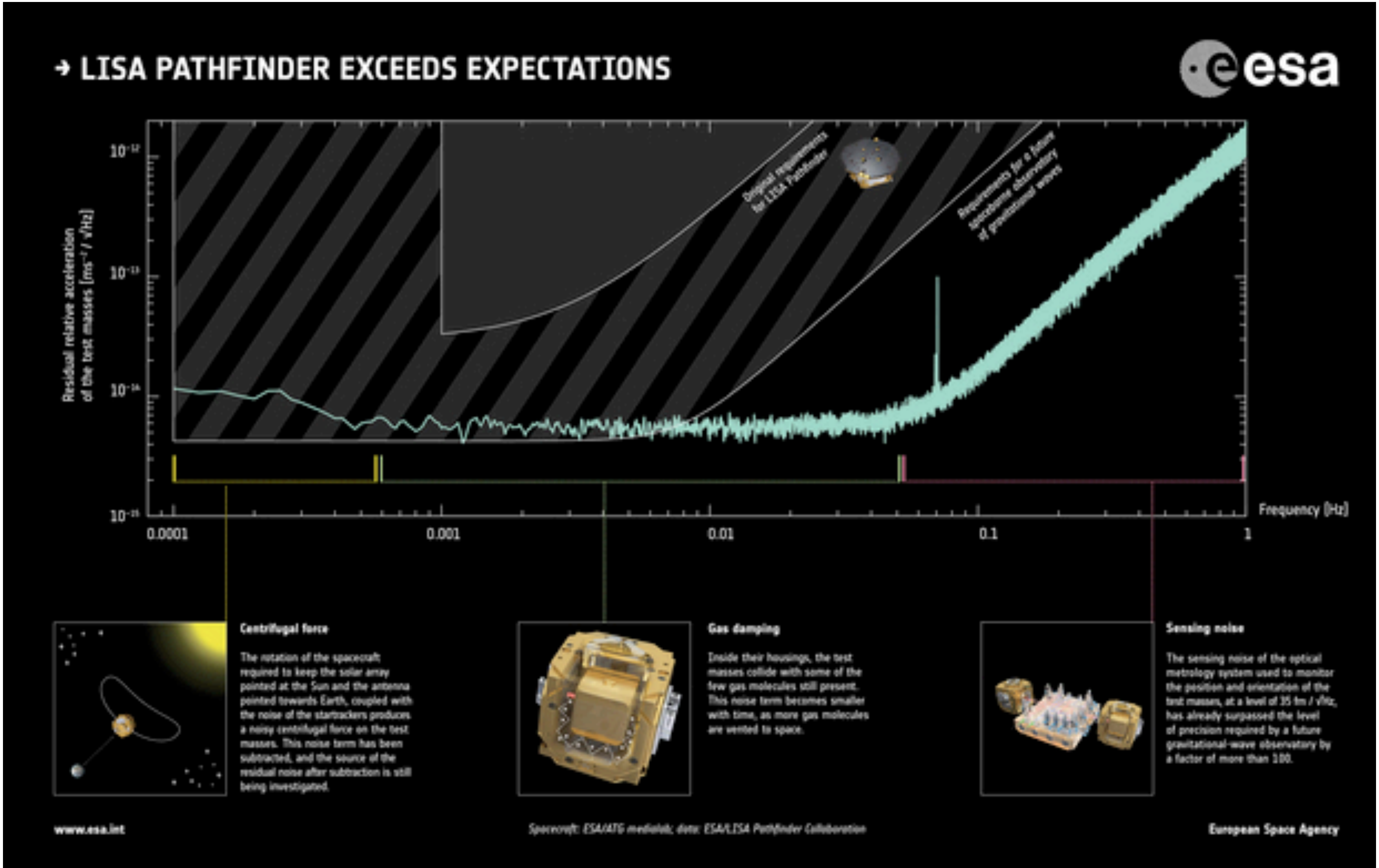
UV illuminatio

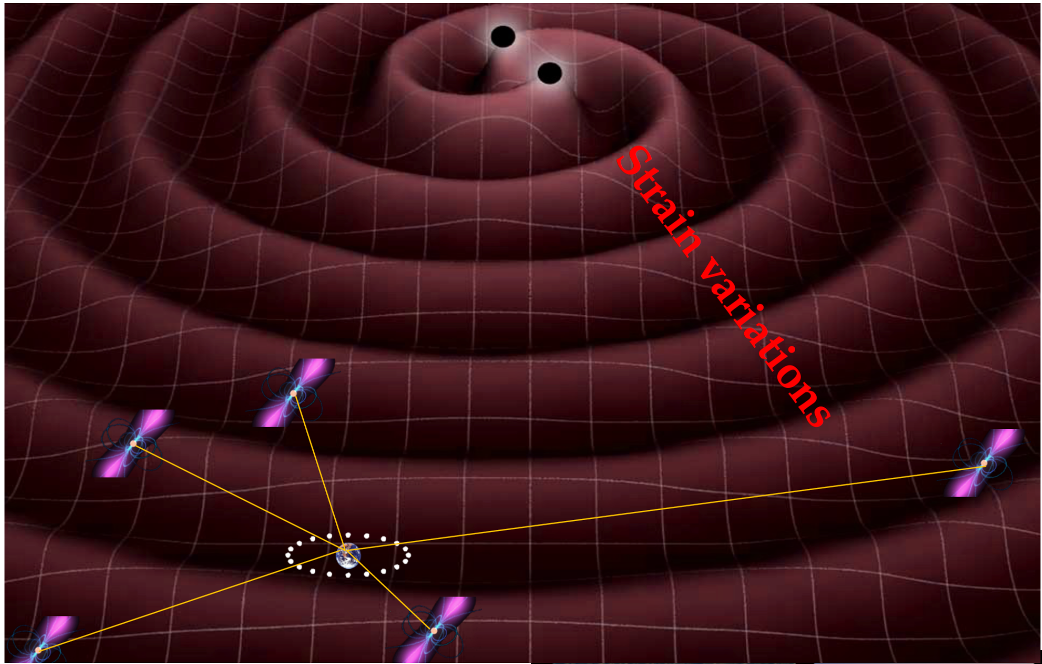
The micro-thrusters

Cold Gas (μ-Newton)

Goal of LISA Pathfinder



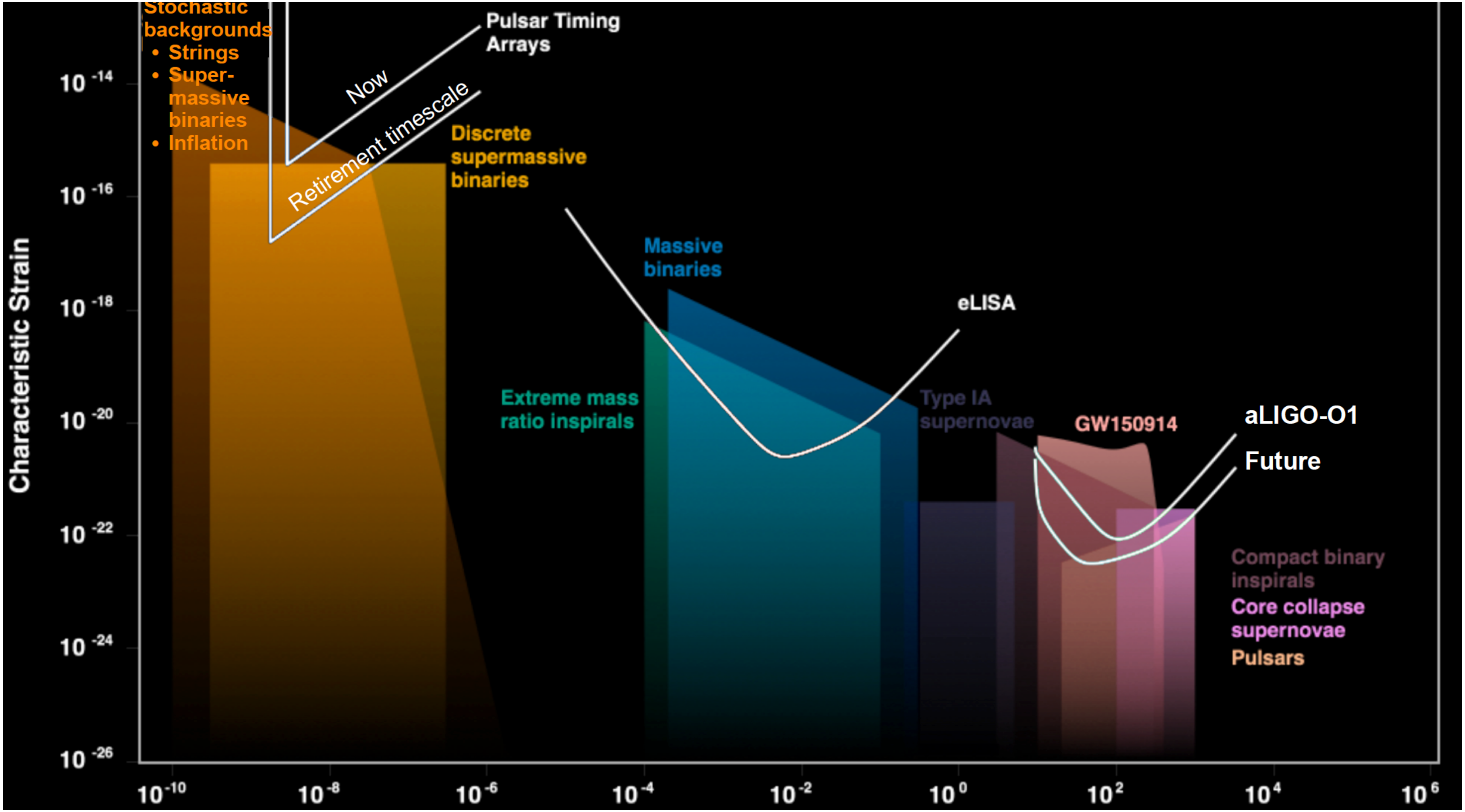

→ LISA PATHFINDER EXCEEDS EXPECTATIONS
esa
Residual relative acceleration of the test masses [ms⁻² / √Hz]
Original requirements for LISA Pathfinder
Requirements for a future spaceborne observatory of gravitational waves
Frequency [Hz]
0.0001
0.001
0.01
0.1
1
Centrifugal force
The rotation of the spacecraft required to keep the solar array pointed at the Sun and the antenna pointed towards Earth, coupled with the noise of the startrackers produces a noisy centrifugal force on the test masses. This noise term has been subtracted, and the source of the residual noise after subtraction is still being investigated.
Gas damping
Inside their housings, the test masses collide with some of the few gas molecules still present. This noise term becomes smaller with time, as more gas molecules are vented to space.
Sensing noise
The sensing noise of the optical metrology system used to monitor the position and orientation of the test masses, at a level of 35 fm / √Hz, has already surpassed the level of precision required by a future gravitational-wave observatory by a factor of more than 100.
www.esa.int
Spacecraft: ESA/ATG medialab; data: ESA/LISA Pathfinder Collaboration
European Space Agency



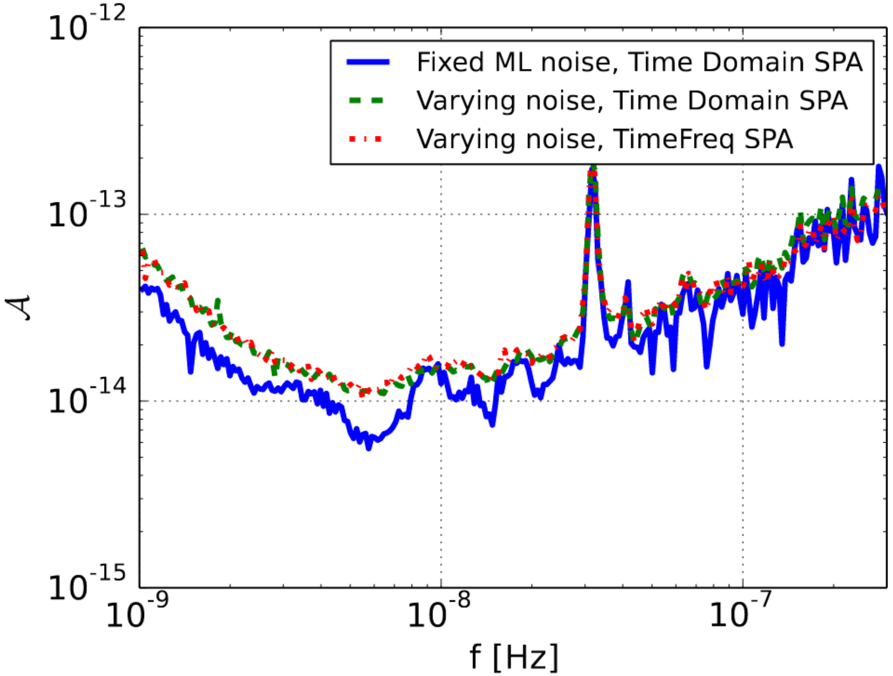
Pulsar Timing Arrays

- **North American Nanohertz Observatory for Gravitational Waves** (NANOGrav, North America)
- **European Pulsar Timing Array** (EPTA, Europe)
- **Parkes Pulsar Timing Array** (PPTA, Australia)

A wider range



Examples of 2015 EPTA results



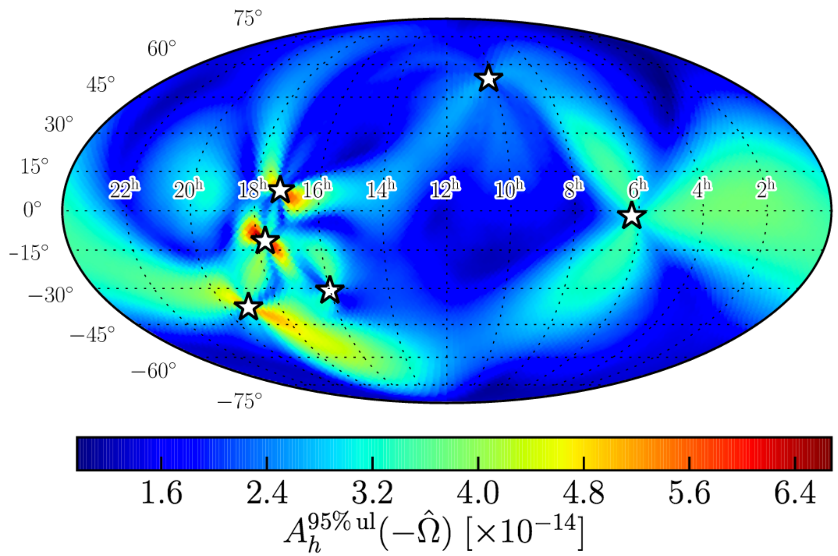
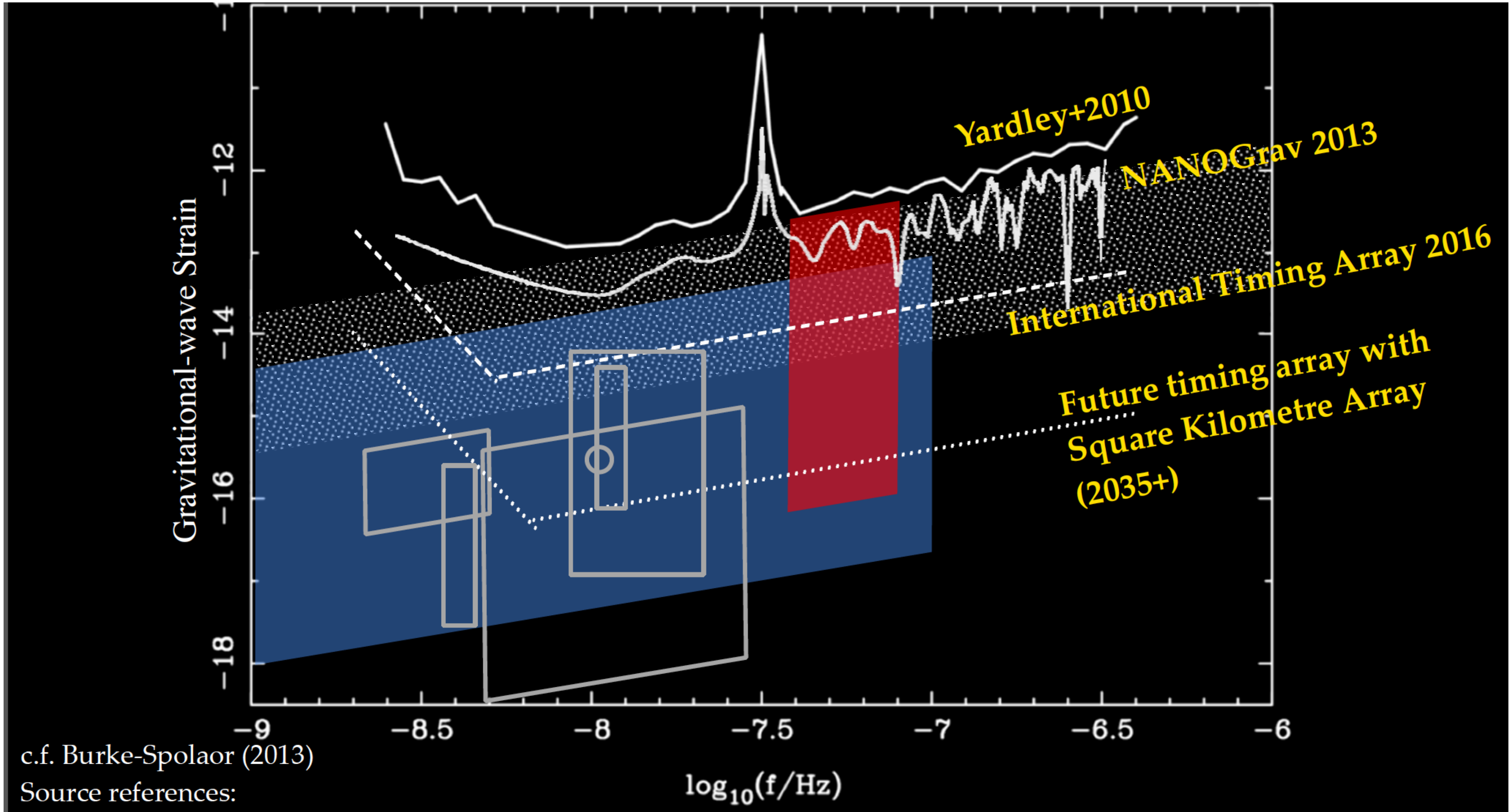


FIG. 2: 95% upper limits on the GW strain amplitude in each pixel. These limits are obtained by mapping from the Bayesian MCMC-sampled cross-correlation values to a pixelated ORF basis ($N_{\mathrm{pix}} = 12288$). White stars show the pulsar locations.

- Limits on continuous GW from Individual Supermassive Black Hole Binaries
- Limits on anisotropy in the nanohertz stochastic GW background

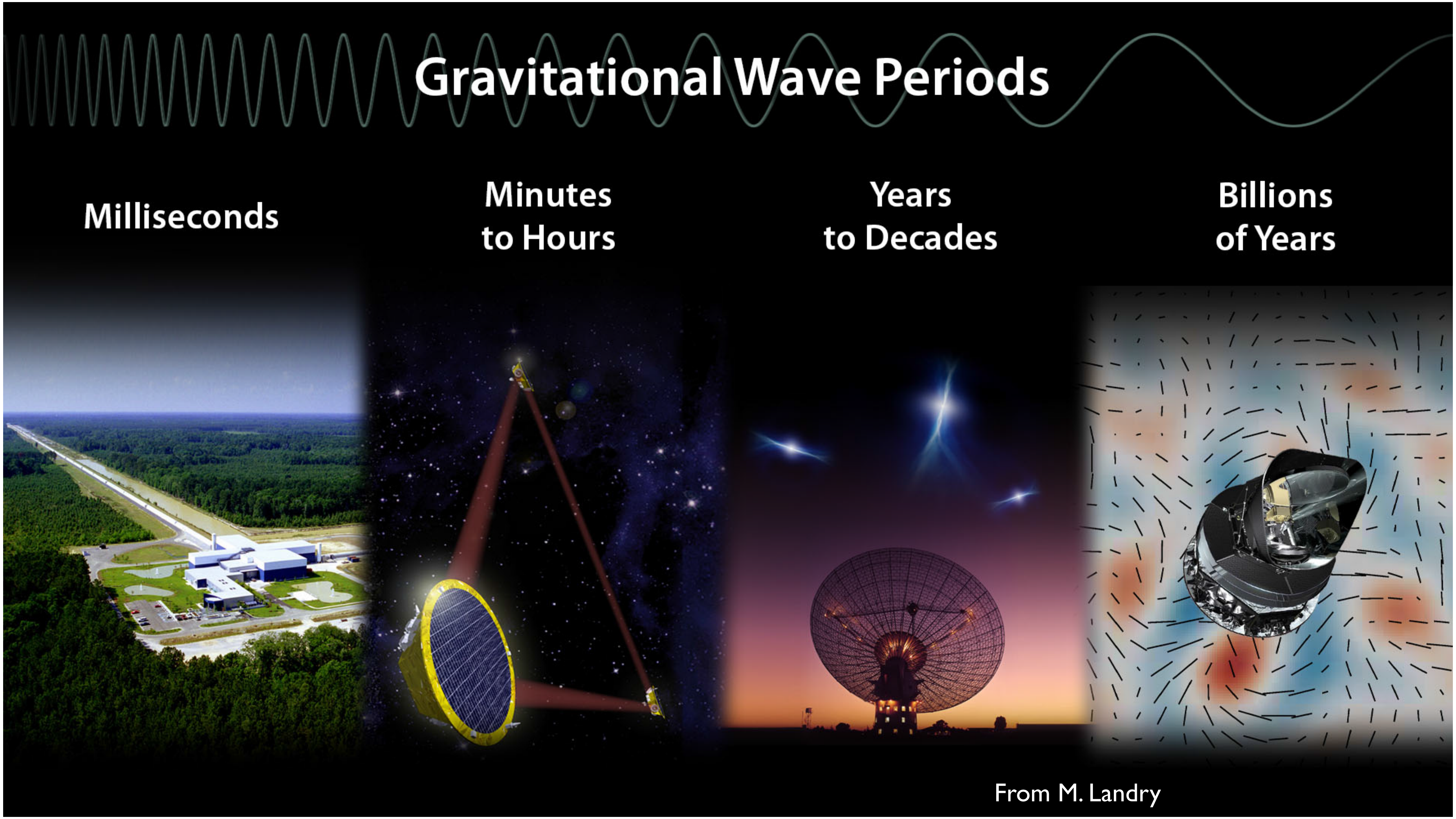
Pulsar timing arrays: what next…



c.f. Burke-Spolaor (2013)
Source references:
Sundelius+97, Britzen+10, Decarli+10, Kudryavtseva+11, Eracleous+12, Carpineti+12, Bon+12, Ju+13, Sudou+03, Iguchi+10, Graham+15, Liu+15

Conclusion

- Second generation ground-based GW detectors came back online, with amazing sensitivity
  - The LIGO detectors observed the beautifully clear and loud signal GW150914 and GW151226
  - This discovery opens up two new paths
    - Testing gravitation in uncharted territory
    - Gravitational wave astronomy
  - Eagerly waiting for – and striving for –Advanced Virgo to join the network and the fun
- LISA Pathfinder: very good results
- Pulsar timing array: the next surprise?
- … Primordial GW from CMB polarization?


Gravitational Wave Periods
Milliseconds
Minutes to Hours
Years to Decades
Billions of Years
From M. Landry