Gravitational Waves: where we are, where we go

Fulvio Ricci

New Frontiers in Theoretical Physics
Cortona (Arezzo) May 23-26, 2018

Talk Outline

- Where we are
    - ➢ Discoveries
    - ➢ Status of the detectors
- Where we go
    - ➢ Upgrades and new detectors
    - ➢ Looking for new physics
- Conclusion

Discoveries

Searching for Compact Binary Coalescences

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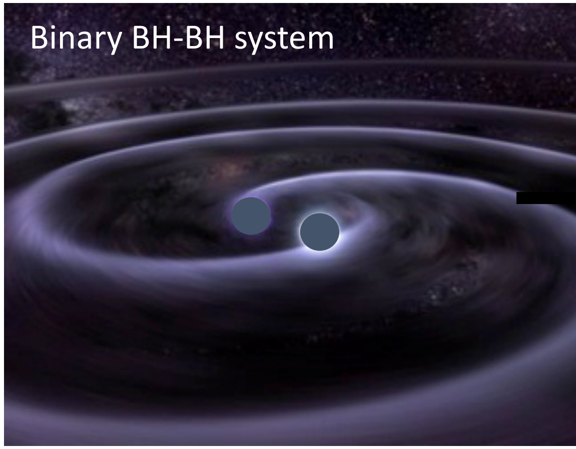
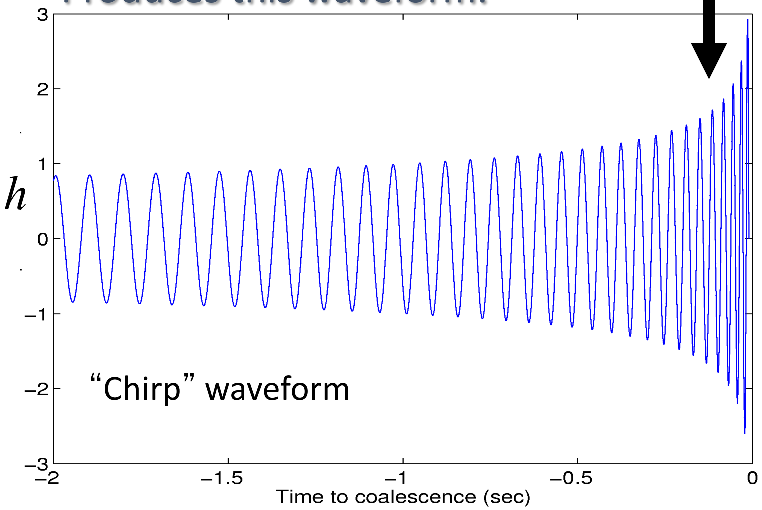
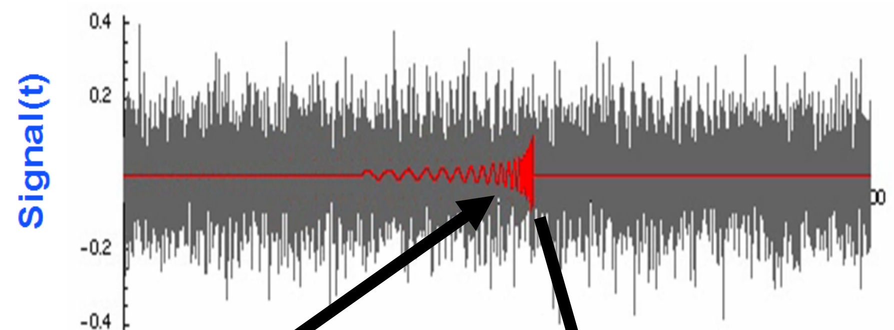
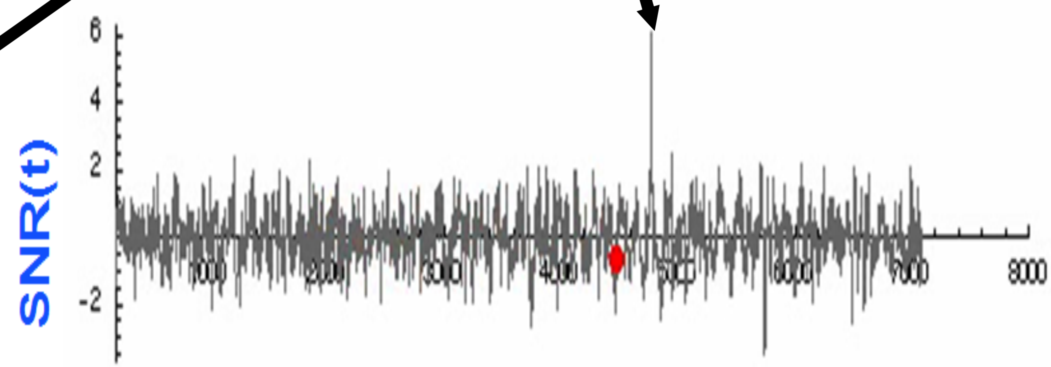


Produces this waveform:



Buried in this noise stream:

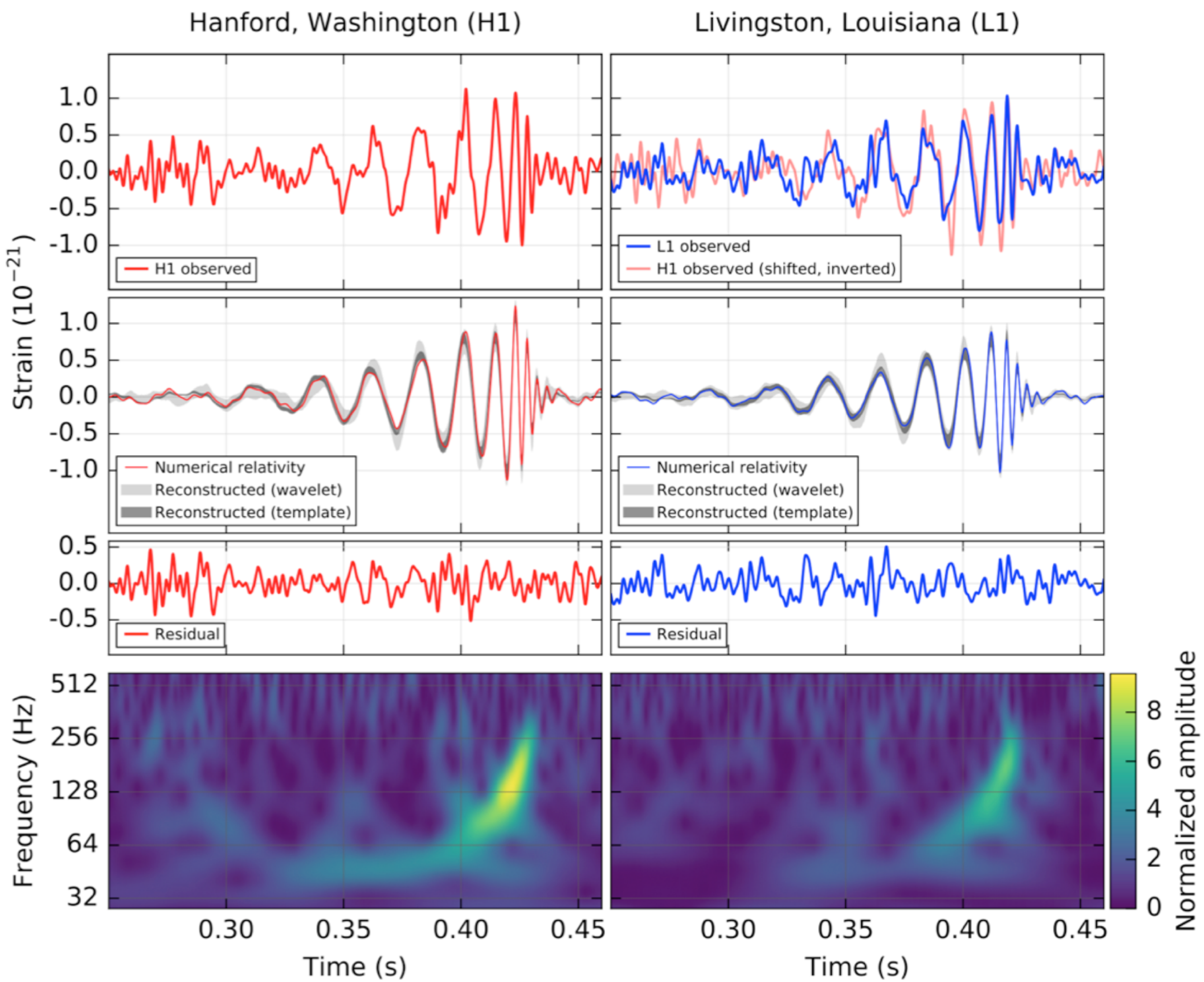




We use different methods (in this case optimal Wiener filtering using matched templates) to pull these signals from the noise

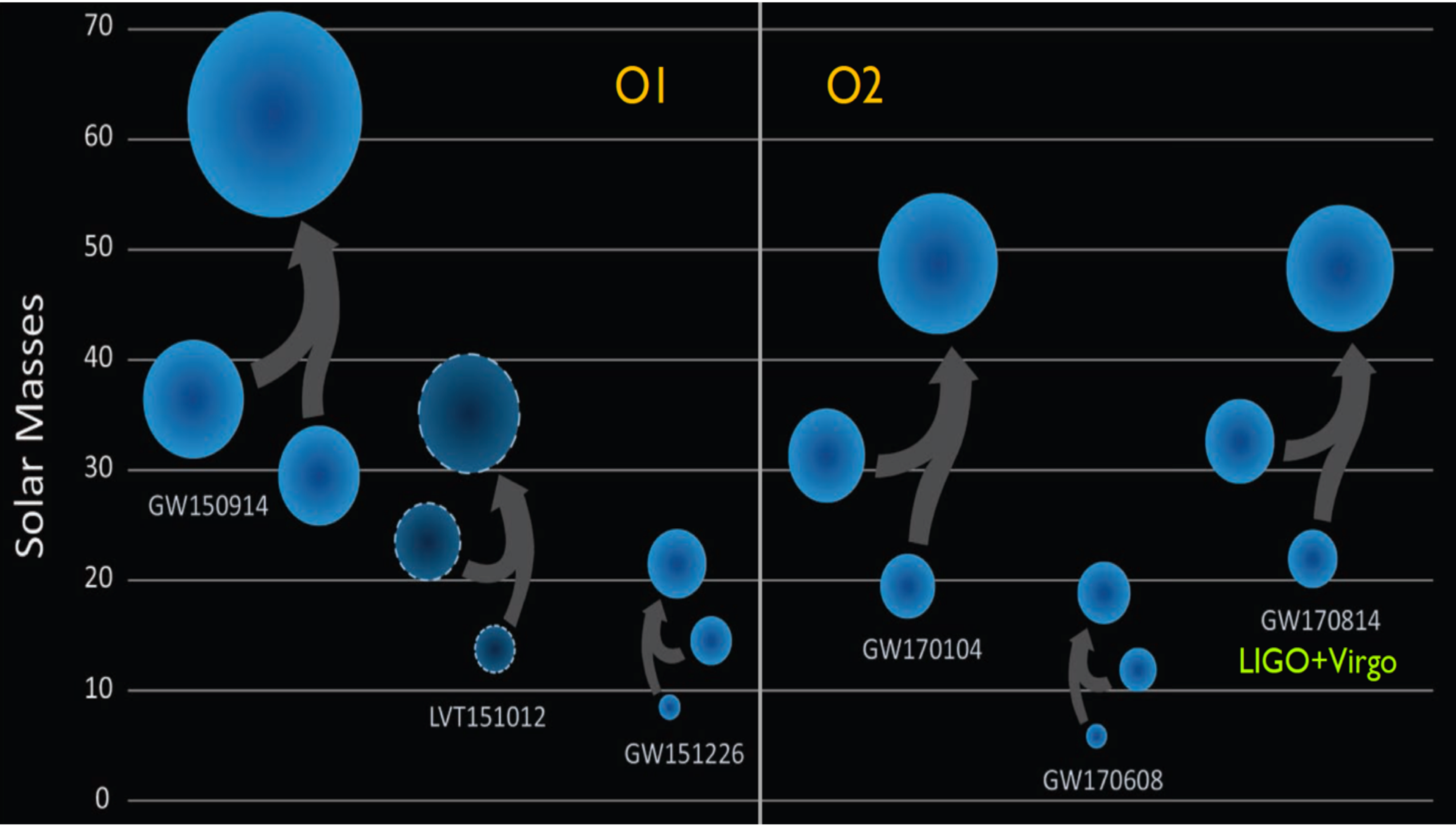
The problem is that non-astrophysical sources also produces signals (false positives)

GW150914 – the first event - a binary Black Hole



Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, "Observation of Gravitational Waves from a Binary Black Hole Merger" Phys. Rev. Lett. 116, 061102 (2016)

Black hole mergers detected by LIGO & VIRGO



Analysis of O2 not completed yet !

In particular, Virgo data cleaning still on the way!

Astrophysical Implications of LIGO-Virgo BH Mergers

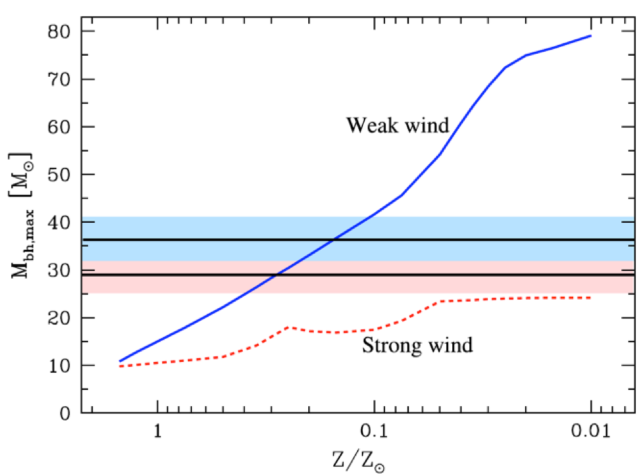
- Stellar mass binary black hole systems exist!
- Stellar mass binary black hole systems can merge in less than a Hubble time.
- ***First observation of 'heavy' stellar mass (> 25 $M_{\odot}$) black holes***
- Heavy mass BBH system most likely formed in a low-metallicity environment: < ½-¼ $Z_{\odot}$

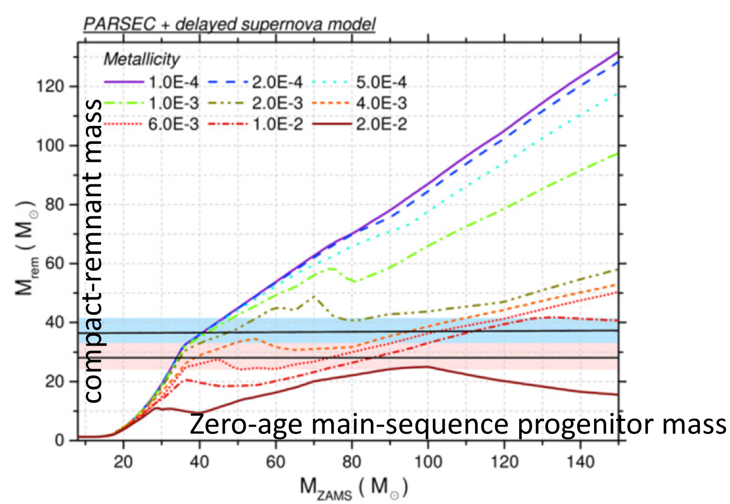
Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, "Astrophysical Implications of the Binary Black-Hole Merger GW150914", ApJL, 818, L22, 2016 ;"The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914", arXiv:1602.03842

What to expect in the future:

- Determination of mass and spin spectrum of black holes
  - Confirm or rule out dark matter scenarios??
- **Determine preferred formation channels: isolated binary evolution vs dynamical capture in dense stellar environments**

Dependence of maximum BH mass on metallicity for the old (strong) and new (weak) massive star winds



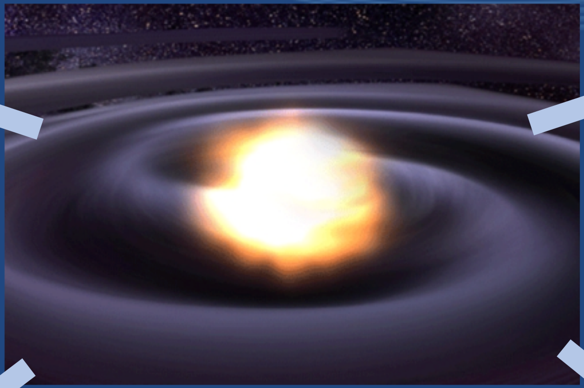


Multi-messenger Astronomy with Gravitational Waves and Light

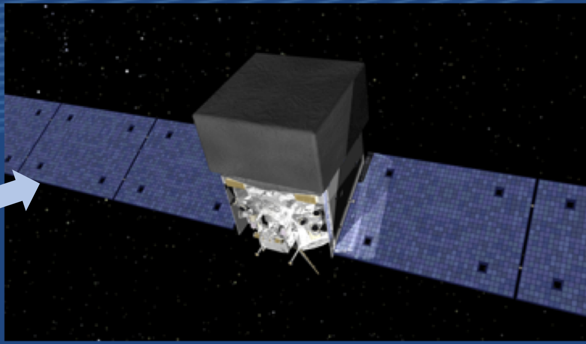
The First Detection of a Binary Neutron Star Merger

Multi-messenger Astronomy with Gravitational Waves

Binary Neutron Star Merger

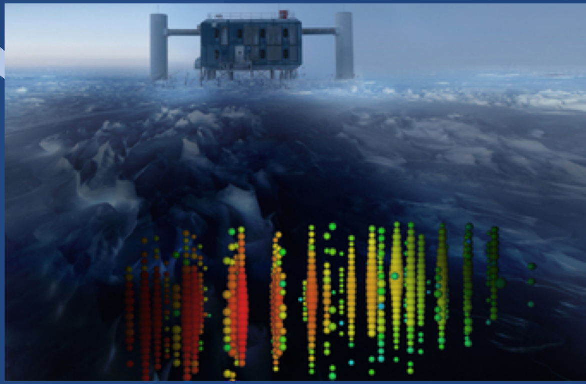


Gravitational Waves



X-rays/Gamma-rays

Visible/Infrared Light



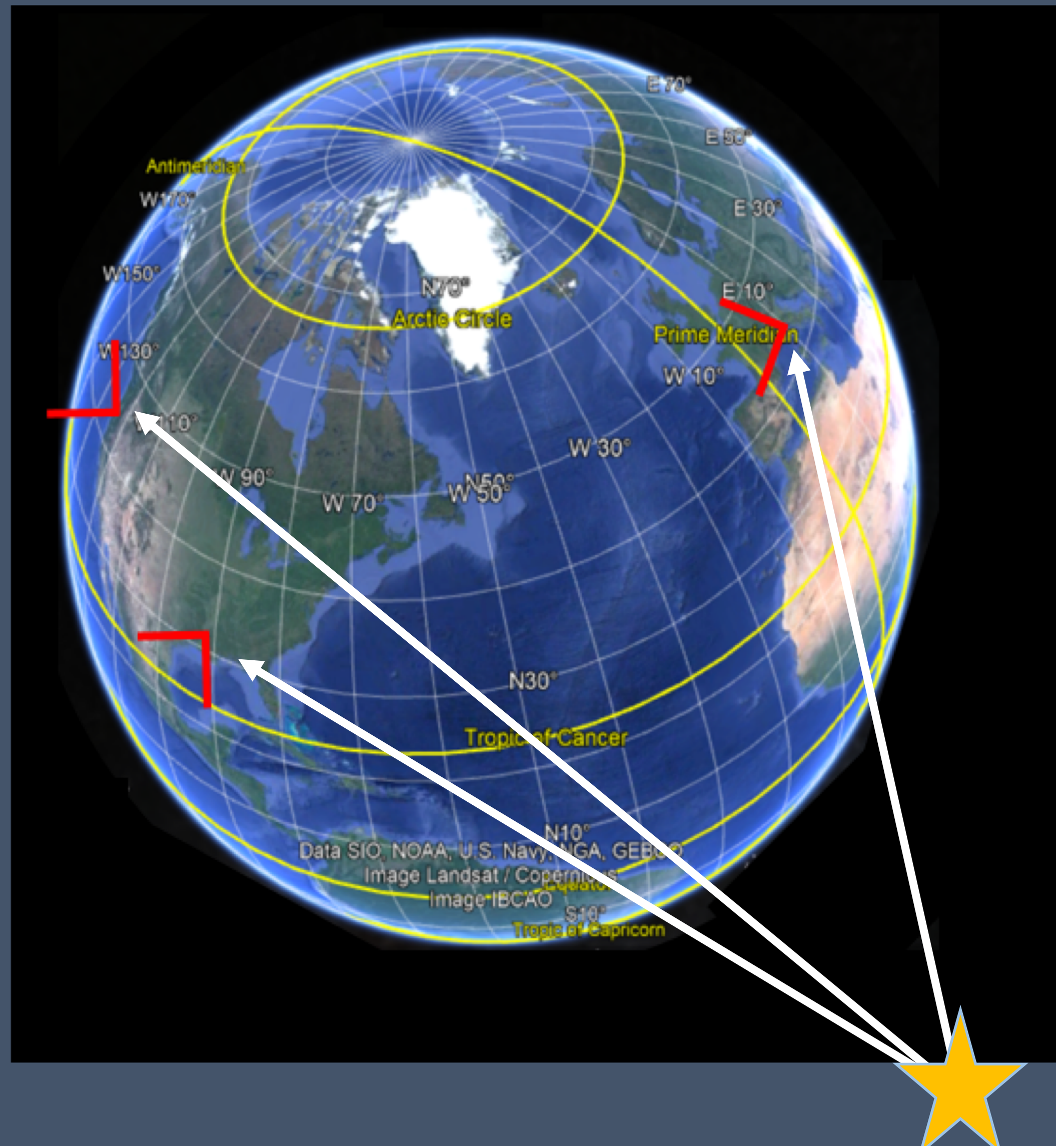
Neutrinos

Radio Waves

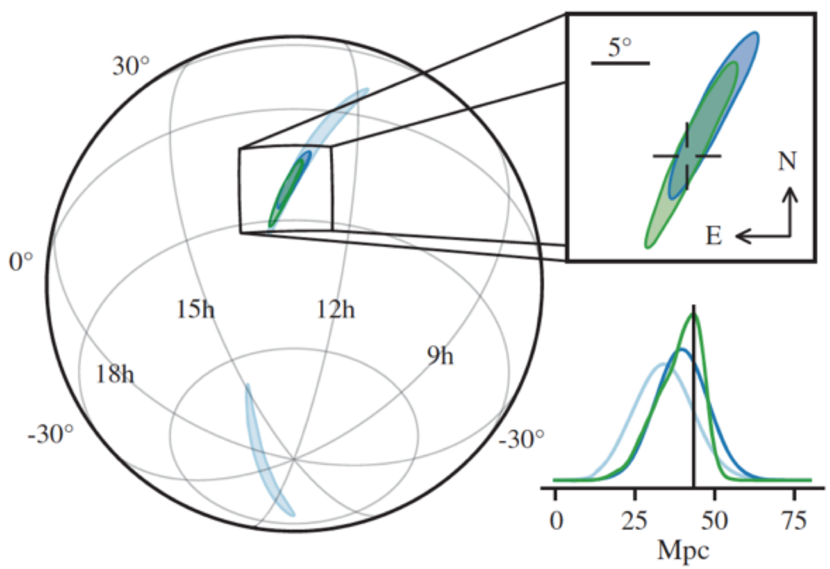

Virgo, Cascina, Italy


LIGO, Livingston, LA

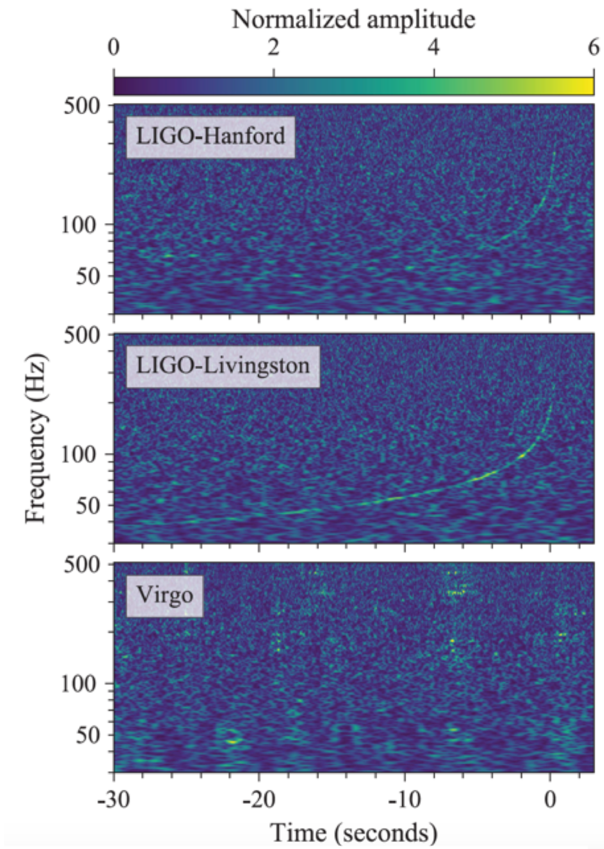

LIGO, Hanford, WA


Antimeridian
Arctic Circle
Prime Meridian
Tropic of Cancer
Tropic of Capricorn
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat / Copernicus
Image IBCAO

GW170817: The First Detected Binary Neutron Star Merger



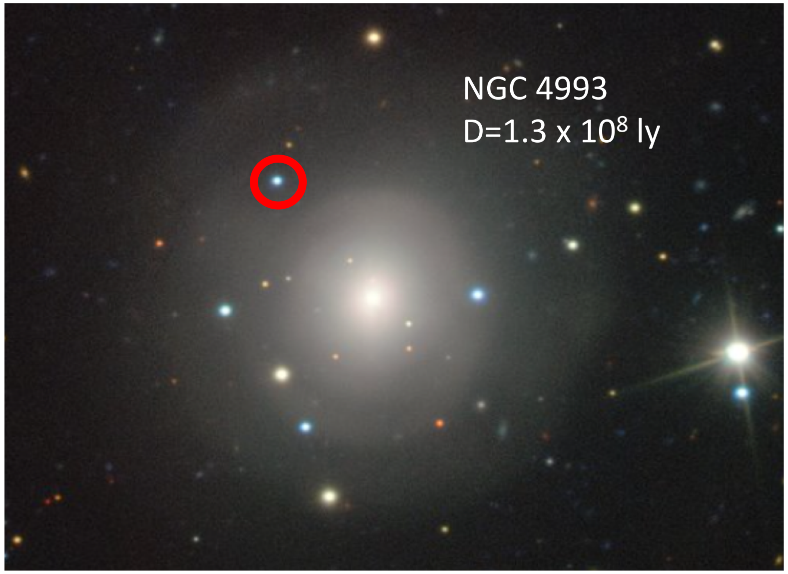
Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, “GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral” Phys. Rev. Lett. 161101 (2017)



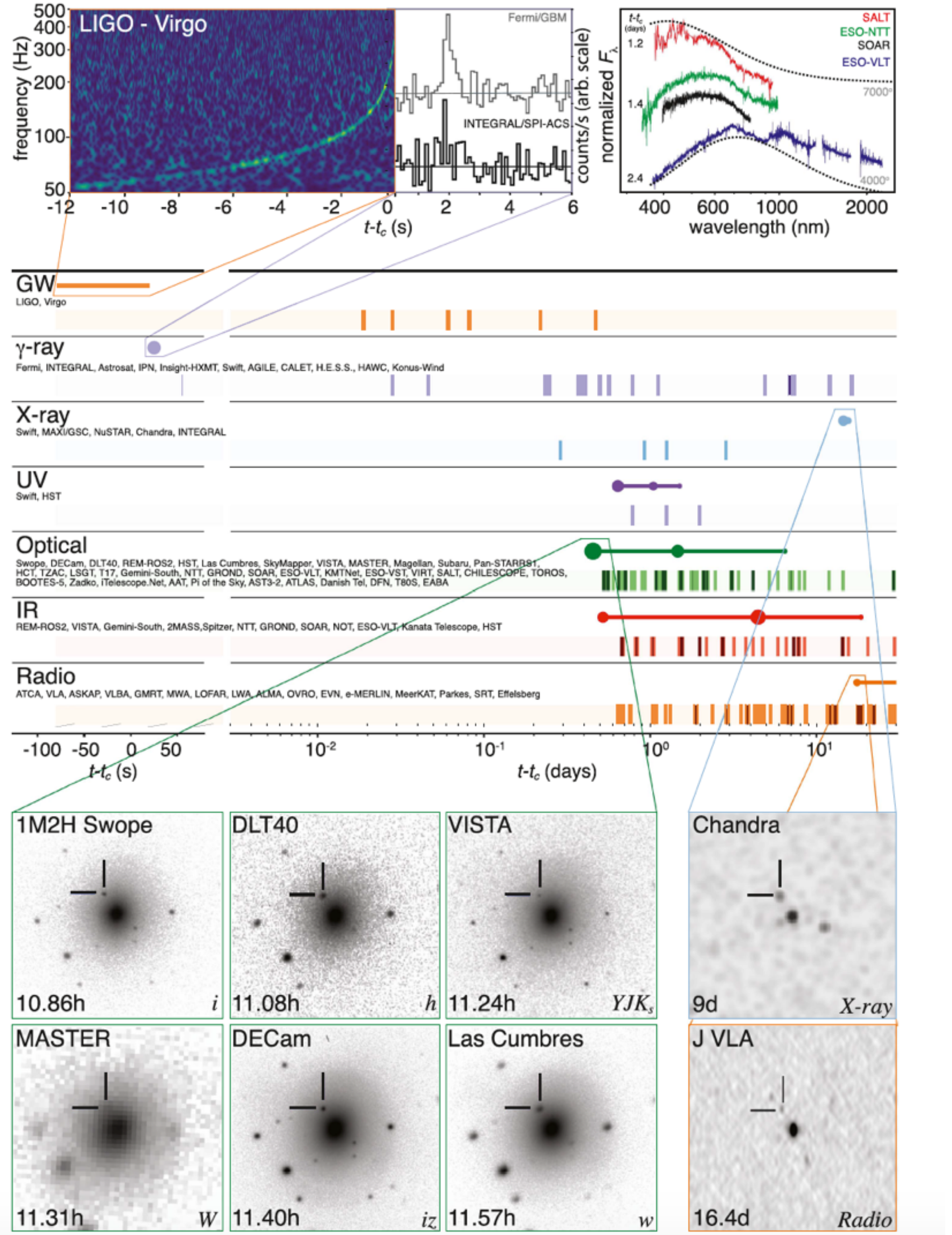
	Low-spin priors ($\|\chi\| \leq 0.05$)	High-spin priors ($\|\chi\| \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance D_{L}	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

Observations Across the Electromagnetic Spectrum!

Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, “Multi-messenger Observations of a Binary Neutron Star Merger” Astrophys. J. Lett., 848:L12, (2017)



Credit: European Southern Observatory Very Large Telescope

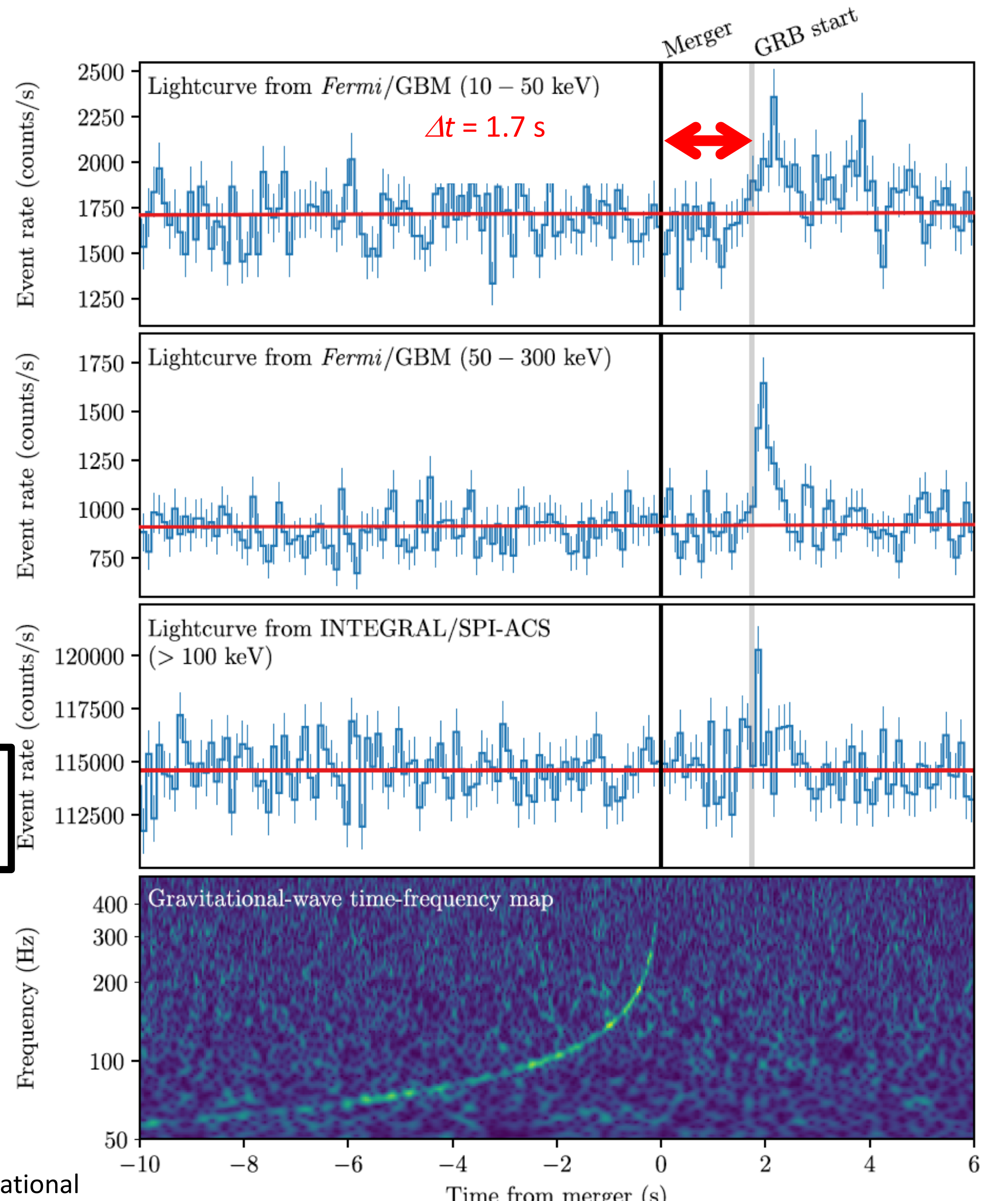


Are Gravitons Massless?

- GW170817 provides a stringent test of the speed of gravitational waves
- Δt =1.74 +/- 0.05 s $\quad \frac{v_{GW} - c}{c} \approx \frac{c\Delta t}{D}$
- $D \approx 26$ Mpc
  - Conservative limit – use 90% confidence level lower limit on GW source from parameter estimation

$$\boxed{-3 \times 10^{-16} \leq \frac{v_{GW} - c}{c} \leq +7 \times 10^{-16}}$$

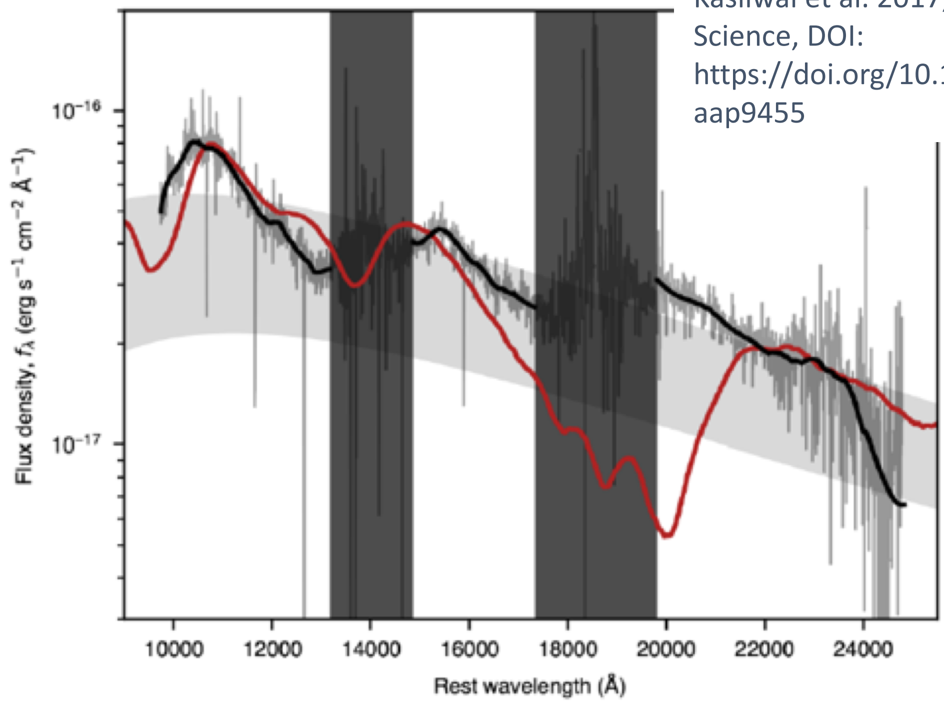
- GW170814 also puts limits on violations of Lorentz Invariance and Equivalence Principle



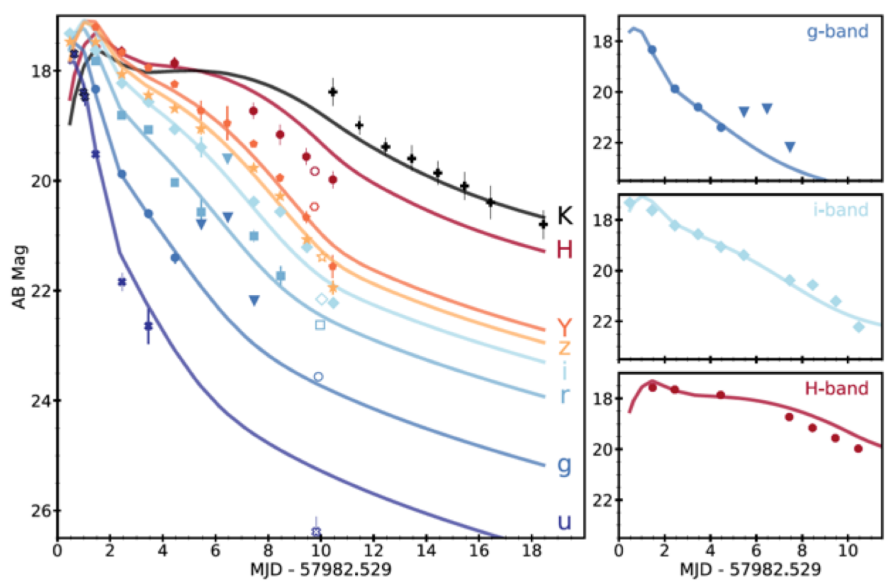
LIGO Scientific Collaboration and Virgo Collaboration, Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A" Astrophys. J. Lett., 848:L13, (2017)

BNS Mergers Produce Kilonovae

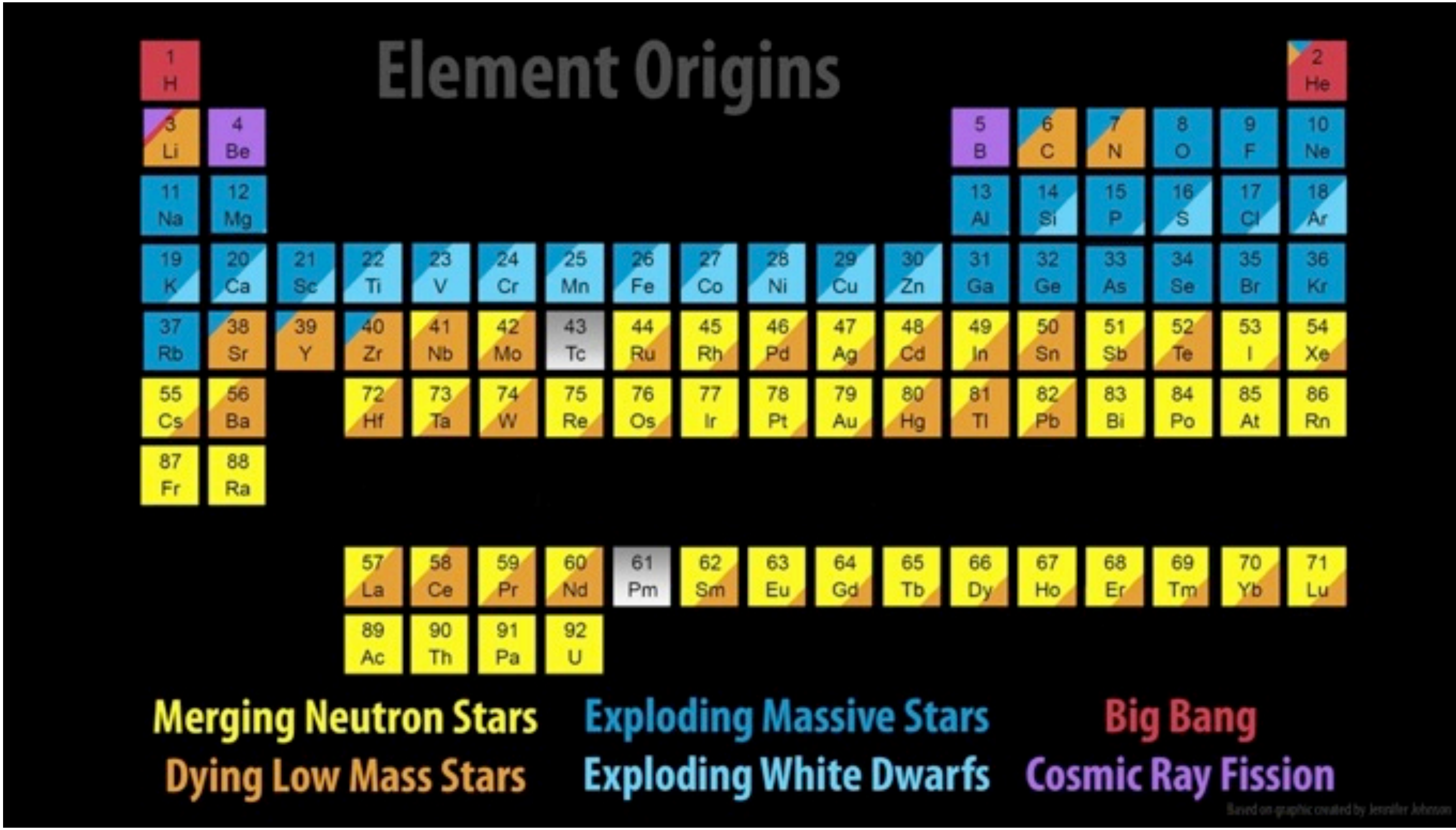
- Electromagnetic follow-up of GW170817 provides strong evidence for kilonova model
  - kilonova - isotropic thermal emission produced by radioactive decay of rapid neutron capture (‘r-process’) elements synthesized in the merger ejecta
- Spectra taken over 2 week period across all electromagnetic bands consistent with kilonova models
  - “Blue” early emission dominated by Fe-group and light r-process formation; later “red” emission dominated by heavy element (lanthanide) formation
- Recent radio data prefers ‘cocoon’ model to classical short-hard GRB production



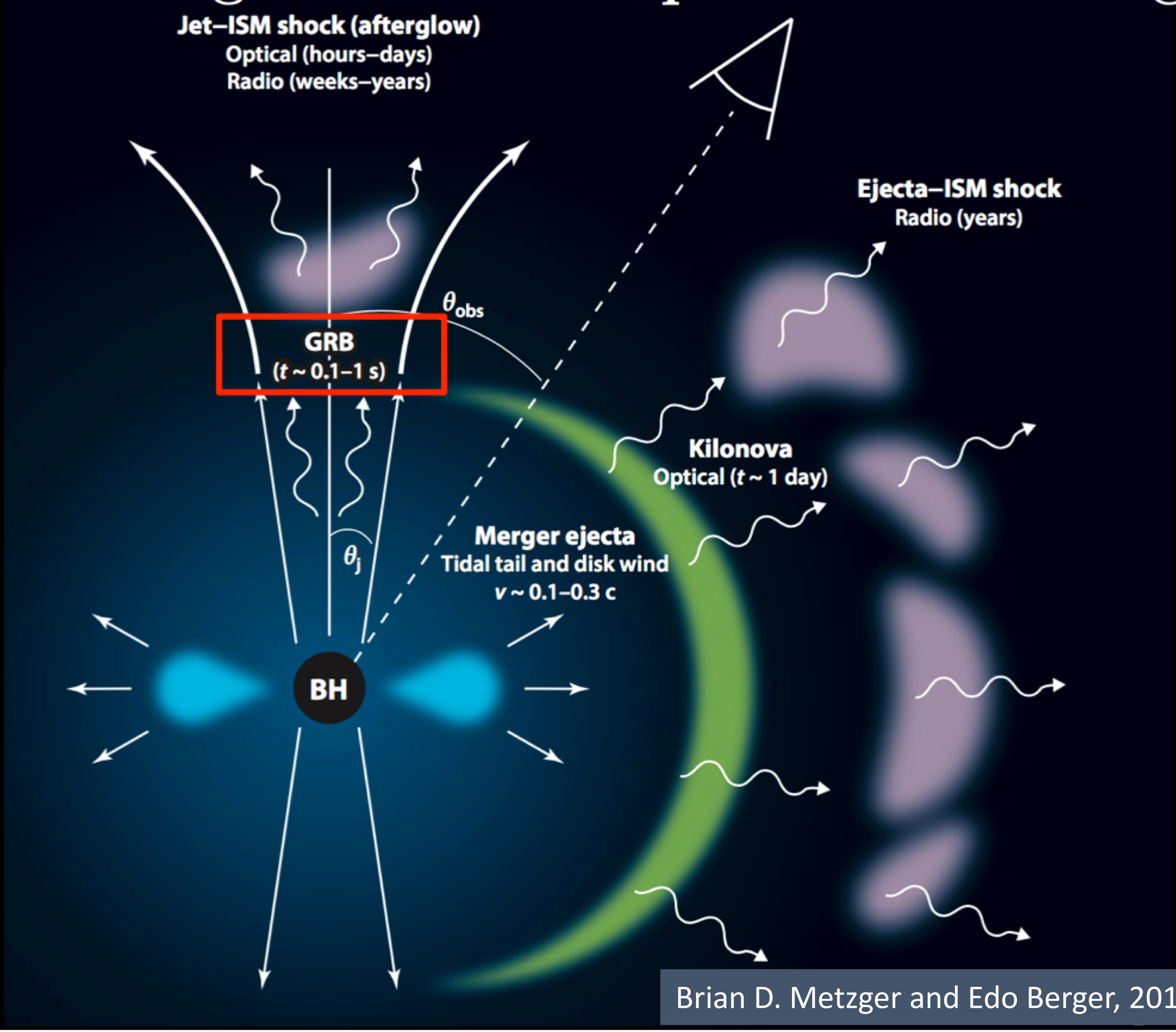
Kasliwal et al. 2017, Science, DOI: https://doi.org/10.1126/science.aap9455



Cowperstwaite, et al. 2017, Ap. J. Lett. DOI: https://doi.org/10.3847/2041-8213/aa8fc7


Element Origins
1 H
2 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe
55 Cs
56 Ba
72 Hf
73 Ta
74 W
75 Re
76 Os
77 Ir
78 Pt
79 Au
80 Hg
81 Tl
82 Pb
83 Bi
84 Po
85 At
86 Rn
87 Fr
88 Ra
57 La
58 Ce
59 Pr
60 Nd
61 Pm
62 Sm
63 Eu
64 Gd
65 Tb
66 Dy
67 Ho
68 Er
69 Tm
70 Yb
71 Lu
89 Ac
90 Th
91 Pa
92 U
Merging Neutron Stars
Exploding Massive Stars
Big Bang
Dying Low Mass Stars
Exploding White Dwarfs
Cosmic Ray Fission
Based on graphic created by Jennifer Johnson

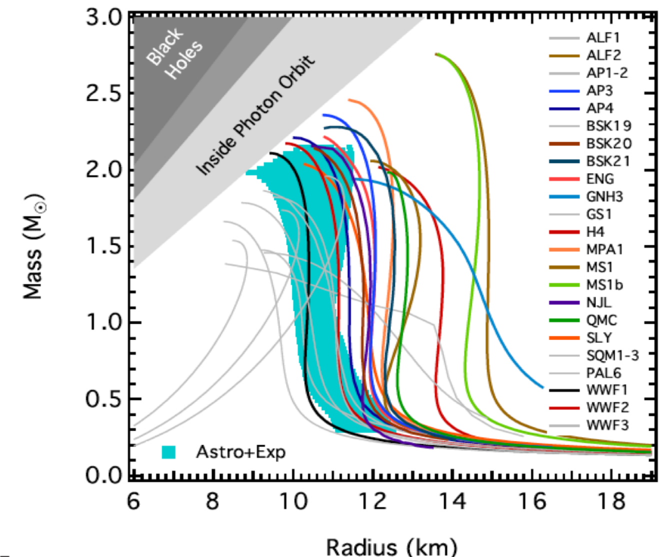
Electromagnetic Counterparts of NS Mergers



Brian D. Metzger and Edo Berger, 2012

Constraining the Neutron Star Equation of State with GW170817

Ozel and Friere (2016)

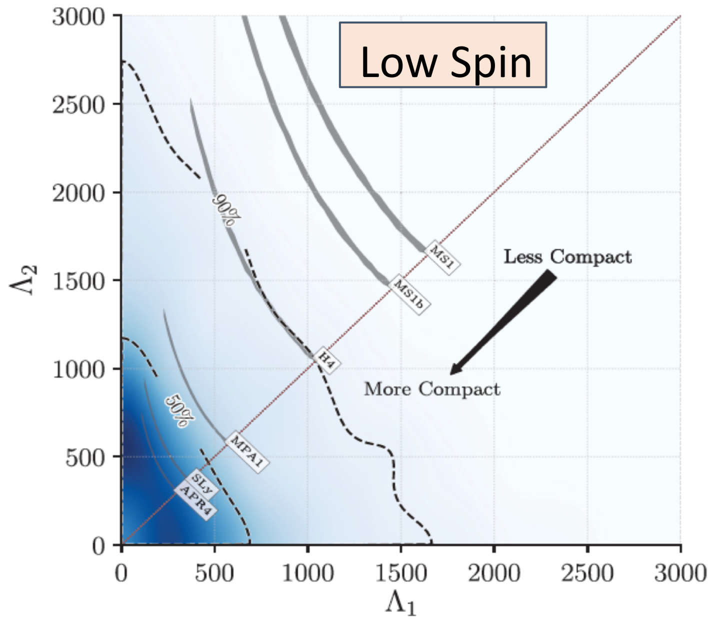


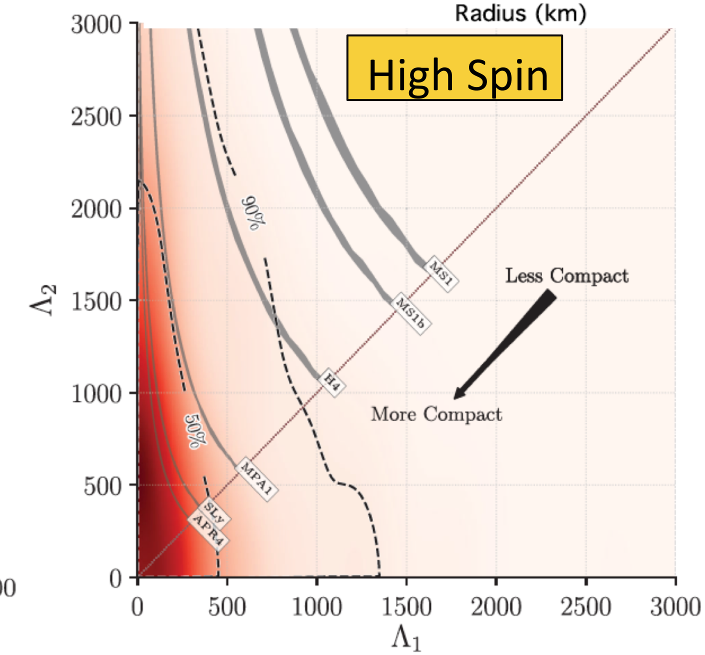
- Gravitational waveforms contain information about NS tidal deformations → allows us to constrain NS equations of state (EOS)
- Tidal deformability parameter:

$$\Lambda = \frac{2}{3} k_2 \left(\frac{R}{M} \right)^5$$

- GW170817 data consistent with softer EOS → more compact NS

Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral" Phys. Rev. Lett. 161101 (2017)





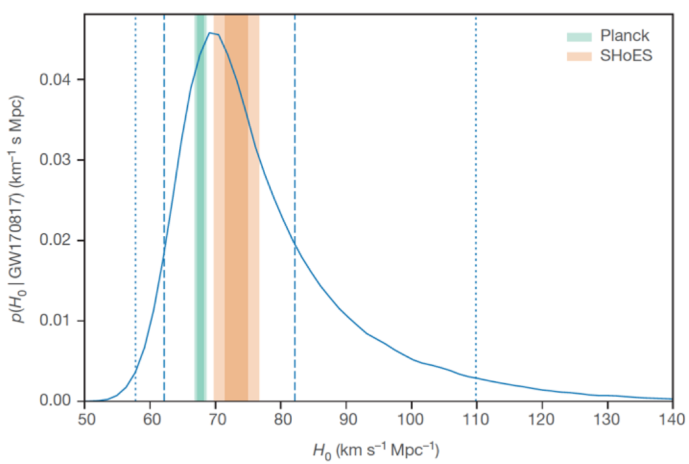
A gravitational-wave standard siren: measurement of the Hubble constant

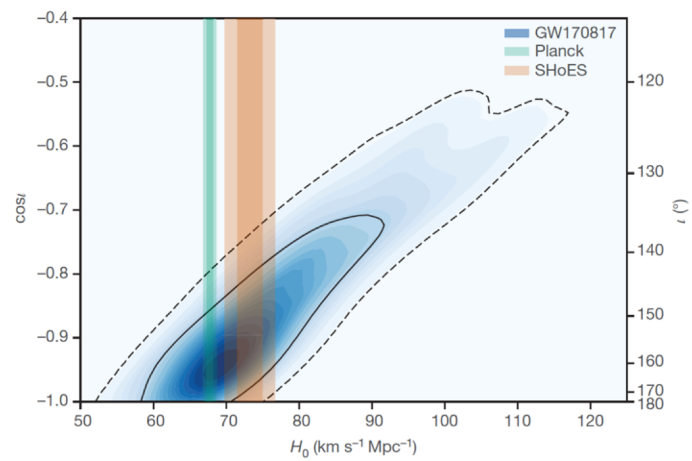
- Gravitational waves are 'standard sirens', providing absolute measure of luminosity distance d_L
- can be used to determine H_0 directly if red shift is known:

$$c\,z = H_0\,d_L$$

- … without the need for a cosmic distance ladder!

$\boxed{H_0 = 70\ (+12,\ -\ 8)\ \mathrm{km/s/Mpc}}$

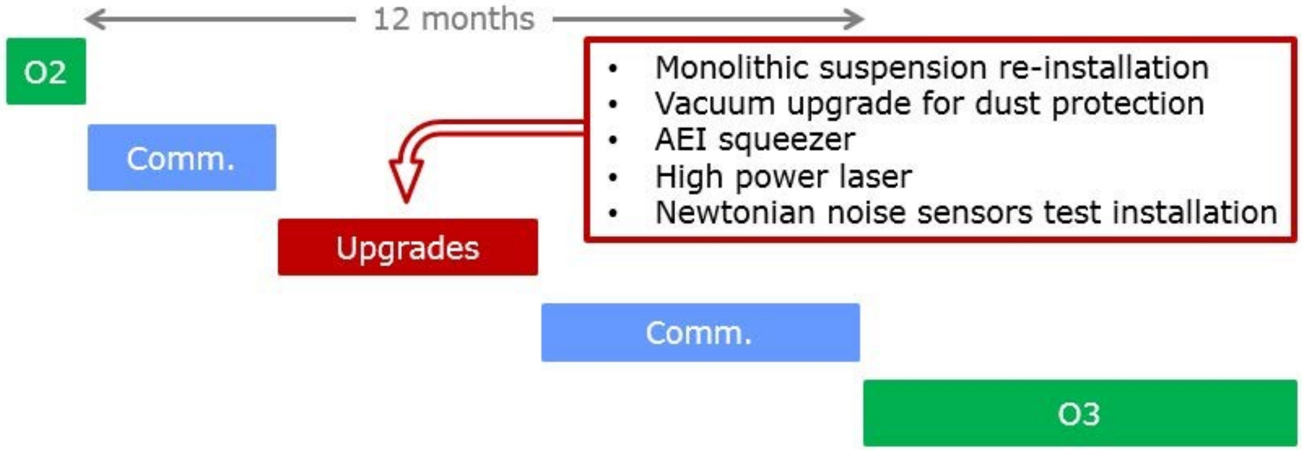




Abbott, et al., LIGO-Virgo Collaboration, 1M2H, DeCAM GW-EM & DES, DLT40, Las Cumbres Observatory, VINRO UGE, MASTER Collaborations, A gravitational-wave standard siren measurement of the Hubble constant", *Nature* 551, 85–88 (2017).

Status of the Virgo detector

From O2 to O3



New minimal target sensitivity: ***60 Mpc*** at horizon for a NSNS 1.4 M at SNR=8

Main benefit should come from putting back the monolithic suspension

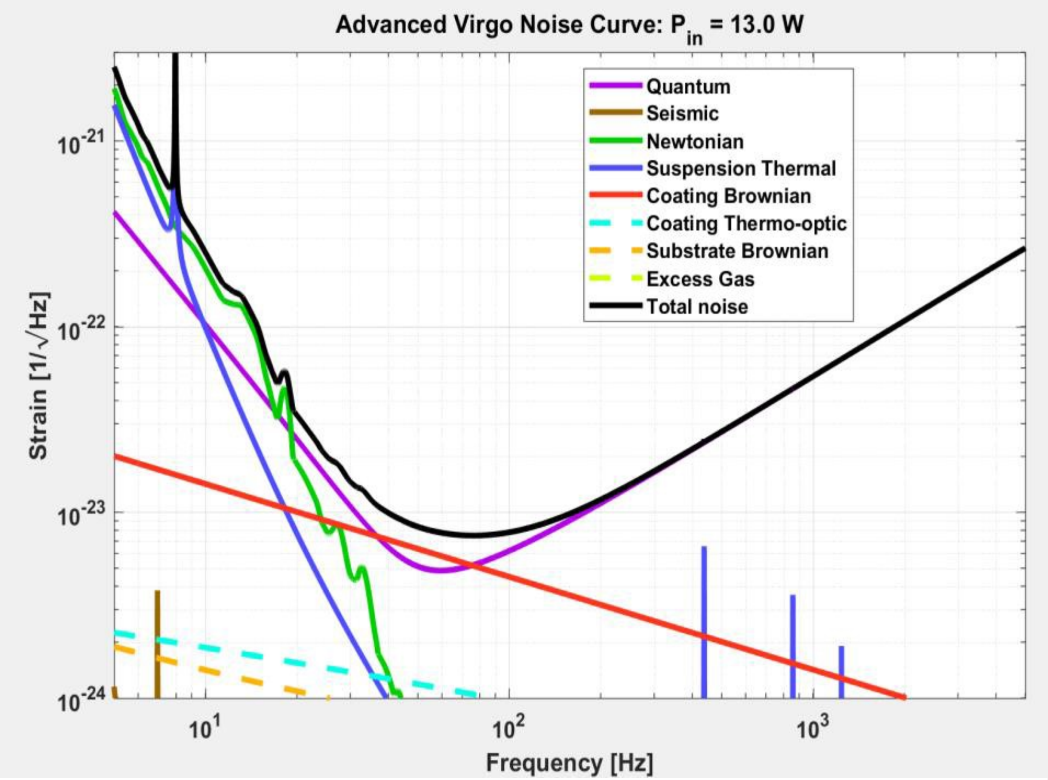
Removing the steel wire thermal noise from noise budget gives a 20 Mpc range increase

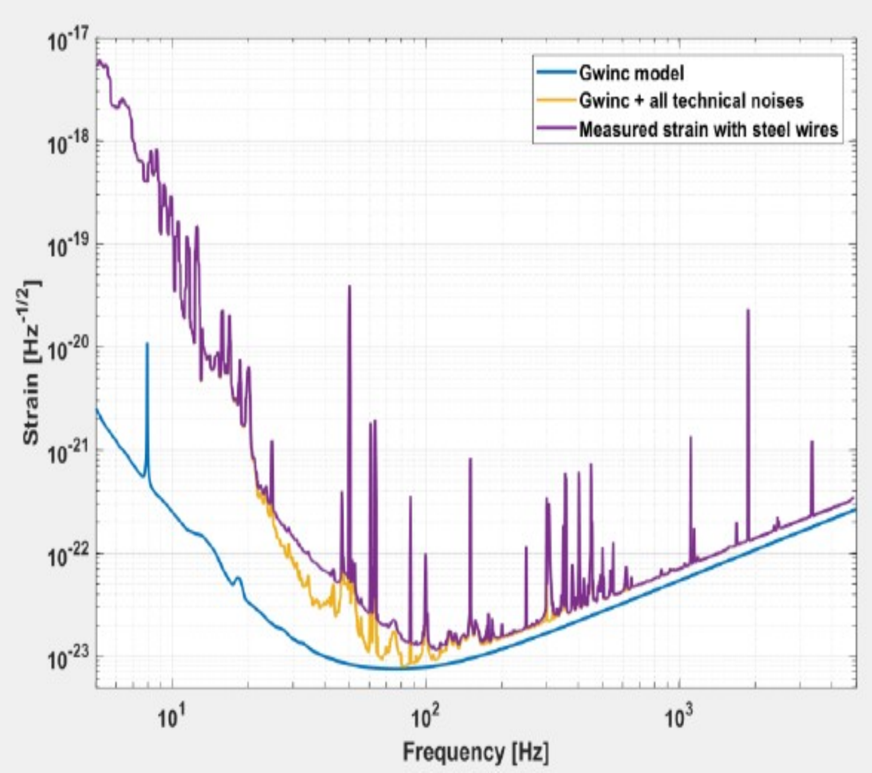
Theoretical limit of this configuration:
100 Mpc *@13W and without squeezing bench*

Main criteria applied to choose the new parts to be installed:
just those new elements that they don't require long commissioning time

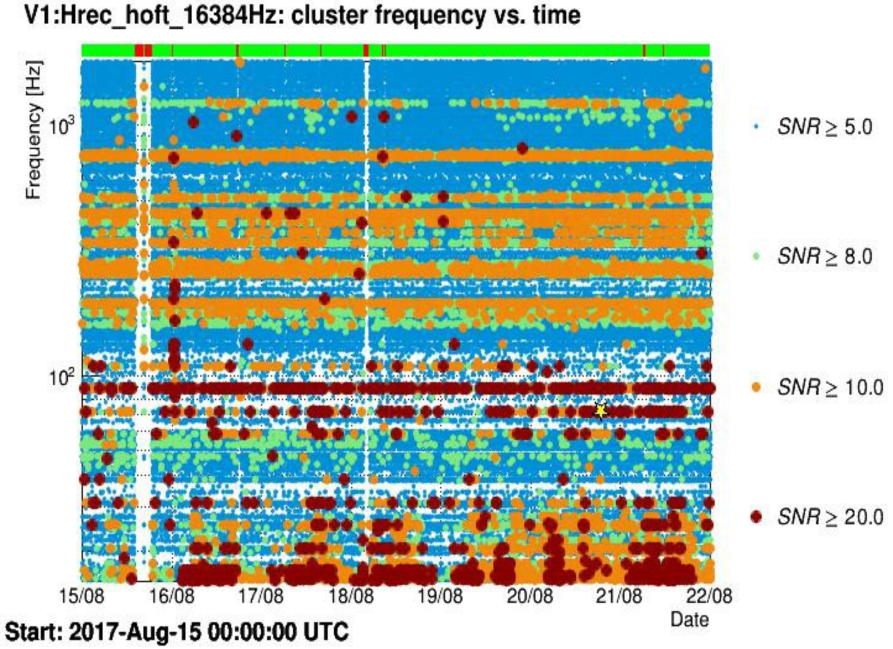
Sensitivity prediction: theoretical and experimental one i.e. intrinsic noise of the detector and technical noises

To beat technical noises we need time for commissioning !!!



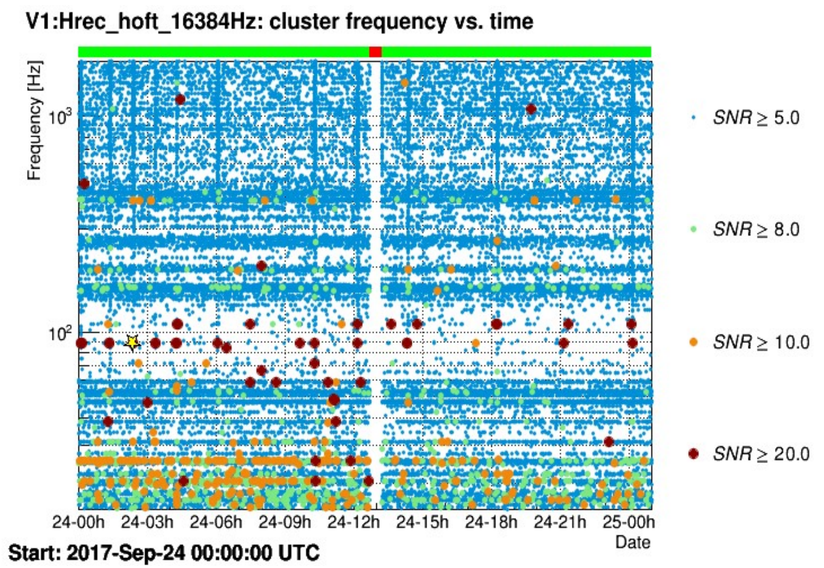


Pre- installation: commissioning to cure glitches

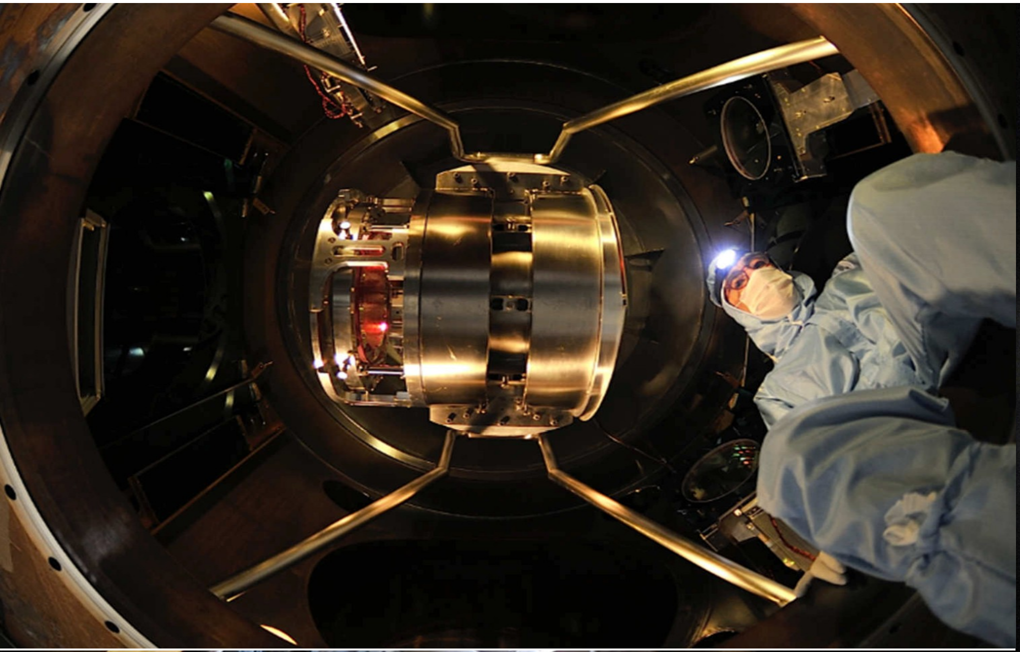


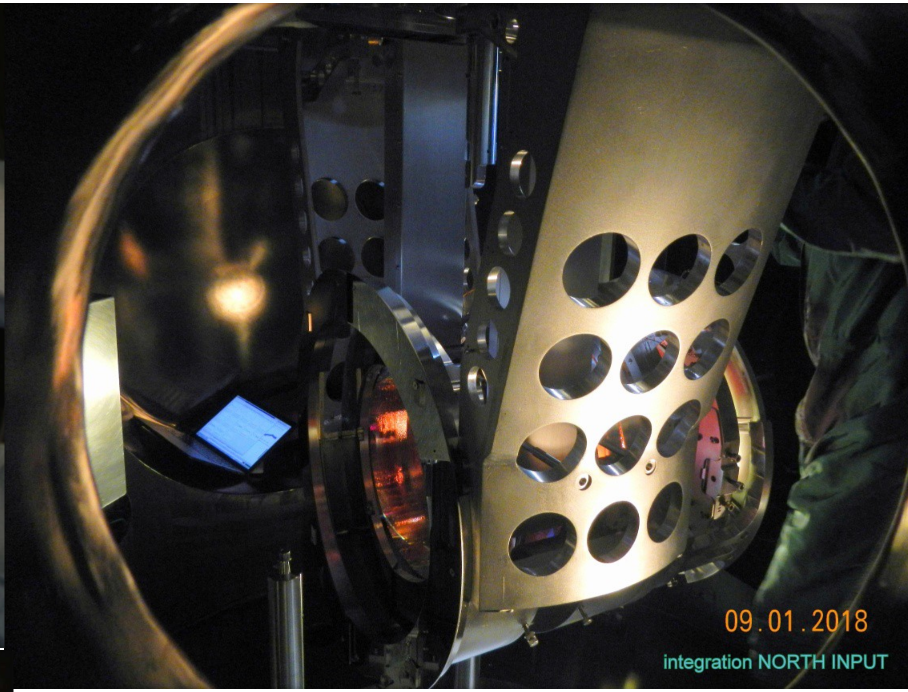
During O2

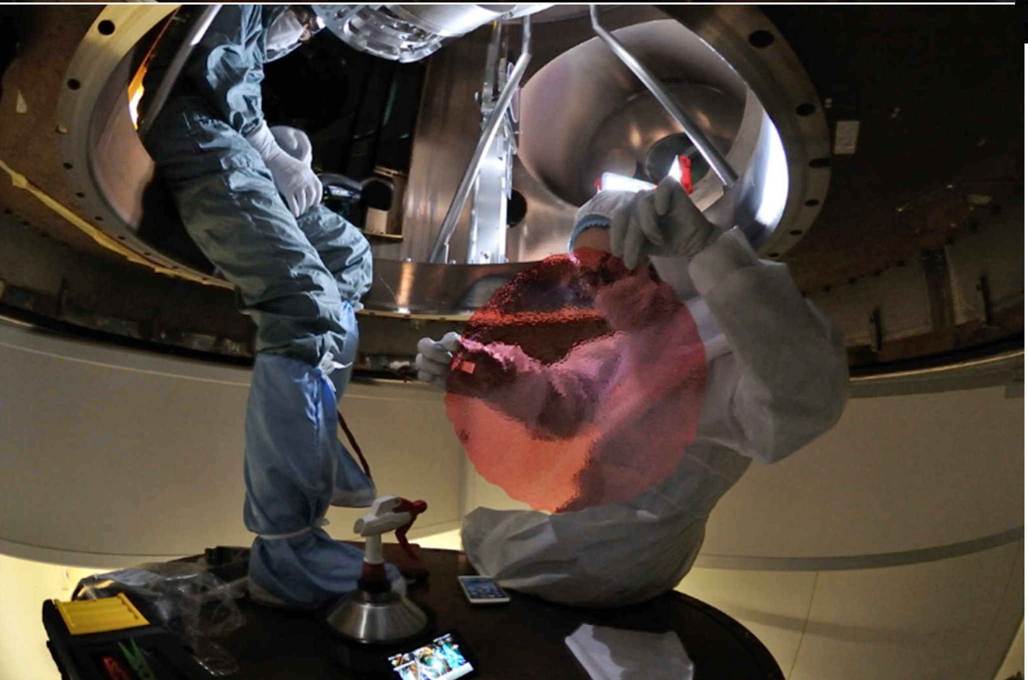
Post O2



Monolithic suspensions are back







Done in less than four months

- Arm valves closed on Nov 27, reopen March 19
- Include two weeks of commissioning
- Faster than scheduled

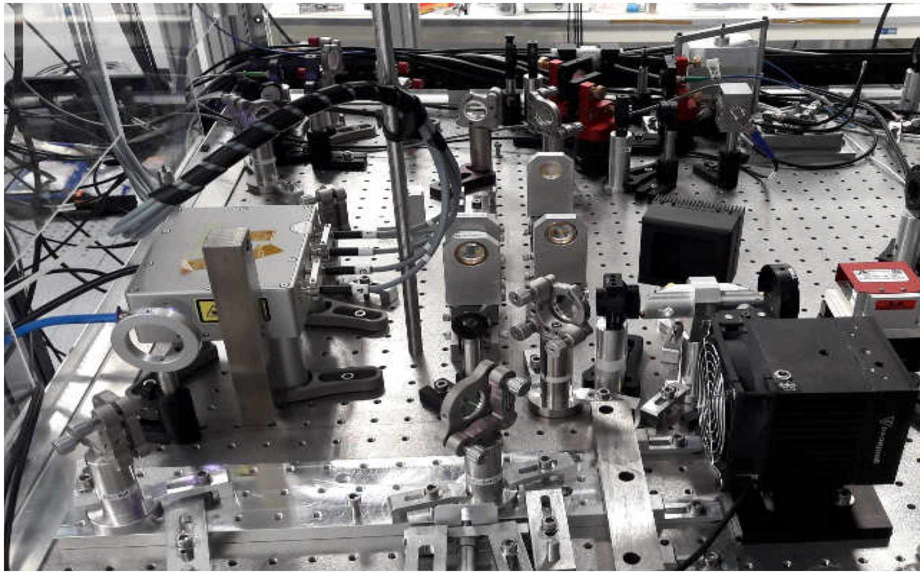
Installation: additional highlights

Squeezing bench provided by AEI –
MAX Planck
14 – 15 dB squeezed vacuum
(then when we match to the main interferometer
significant loss in the gain are added)

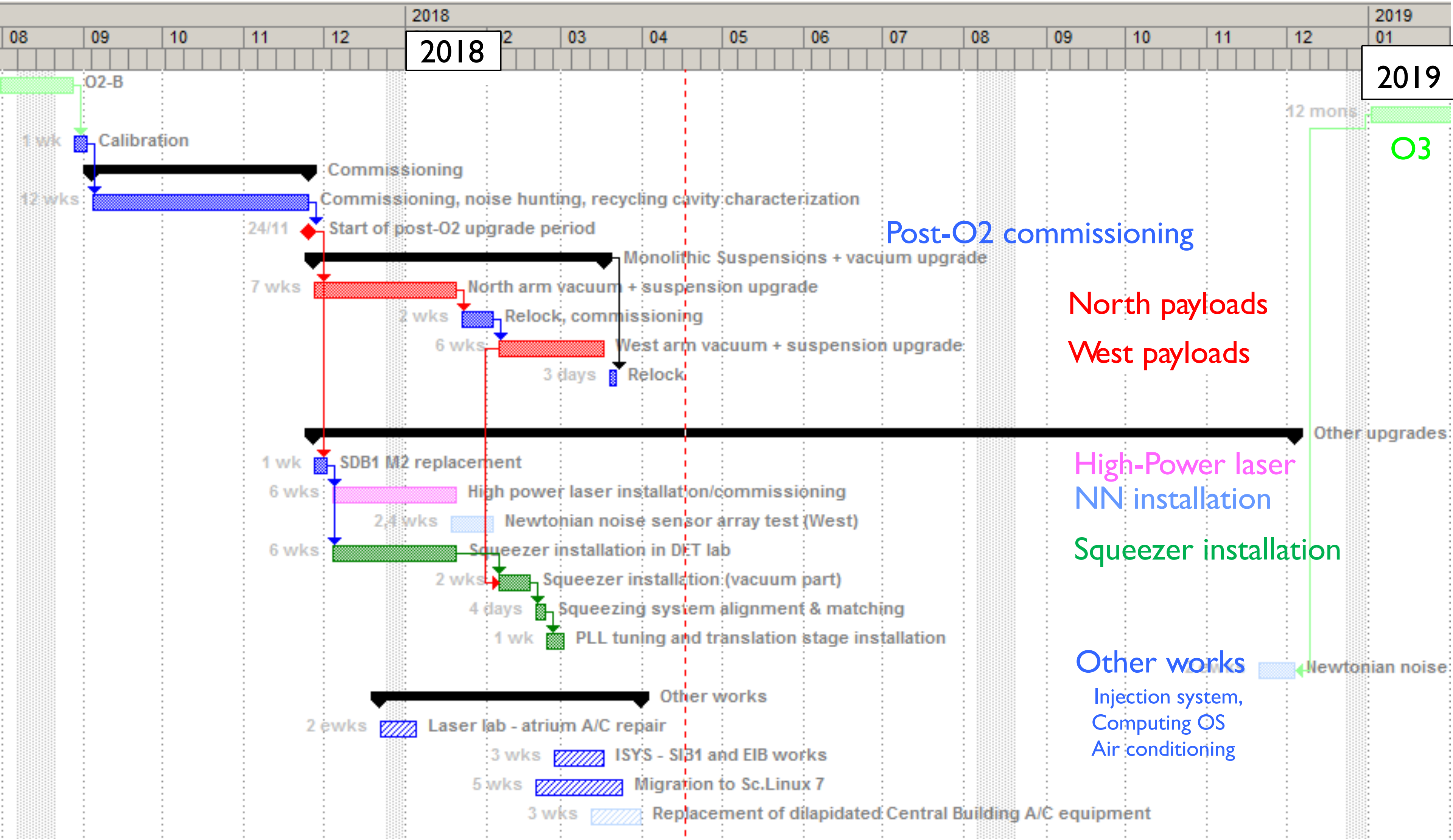
Stray light hunting restarted adding extra baffles

New laser amplifier 70 W ➔ 100 W
New pre-mode cleaner

We can inject in the ITF up to 50 W



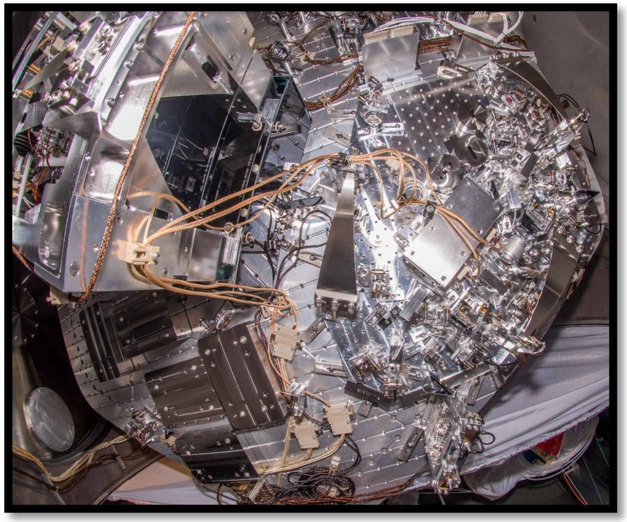
Planning toward O3



Status of aLIGO detectors

LIGO status: major hardware upgrade at both LIGO sites

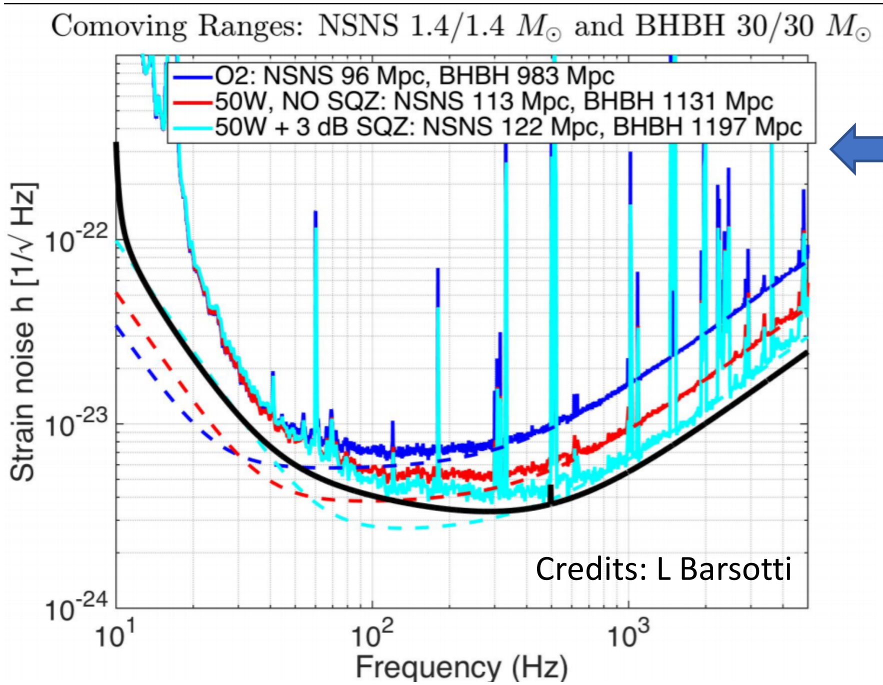
- High power
- Laser noise
- Squeezing
- Signal recycling mirror change



- Stray light control
- Electric field sensors
- Test mass replacements

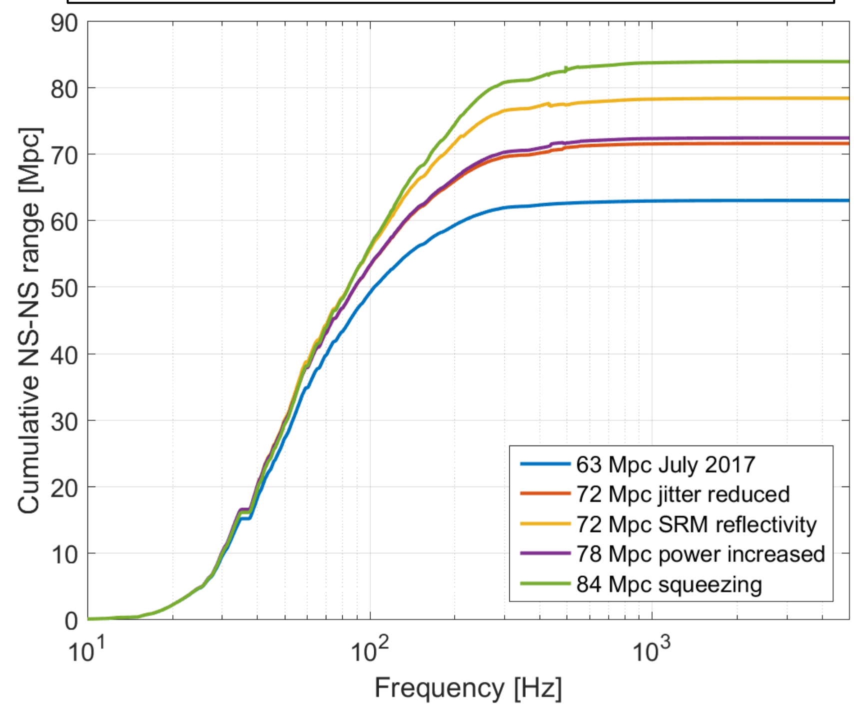
Pre and post installation of the new baffles

Projection of noise improvements from high power and squeezing: 120 Mpc



Livingston case

New installations and corresponding sensitivity improvements



Hanford needs to improve low frequency noise in order to reach sensitivity goal for next observing run

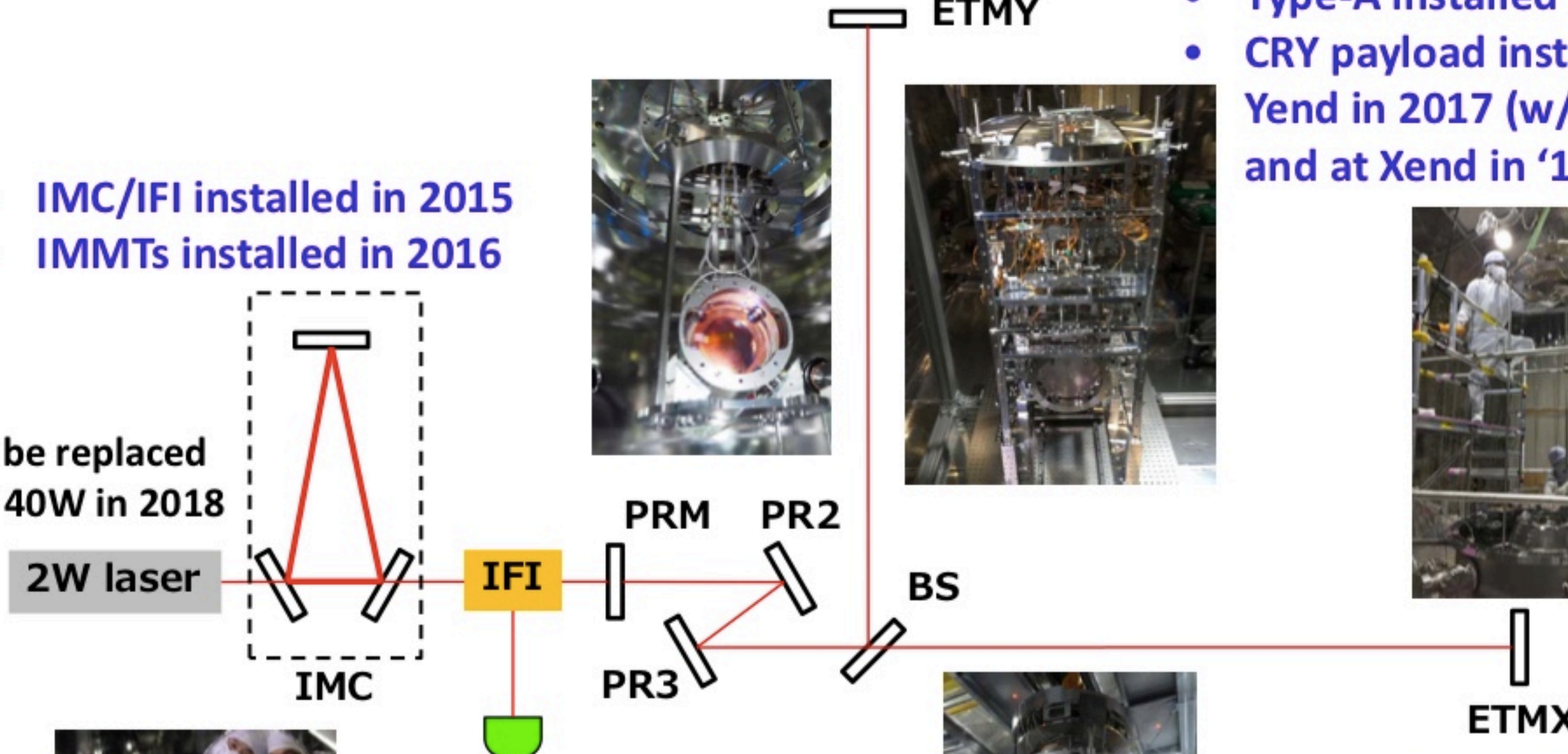
KAGRA: a new partner will join soon the network

KAGRA project

Kamioka mine, Japan

3 km, underground, cryogenic detector (20 K)
waiting for funding

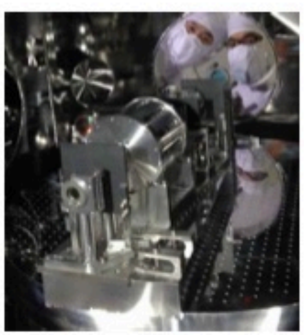
Installation status



To be replaced by 40W in 2018

- IMC/IFI installed in 2015
- IMMTs installed in 2016

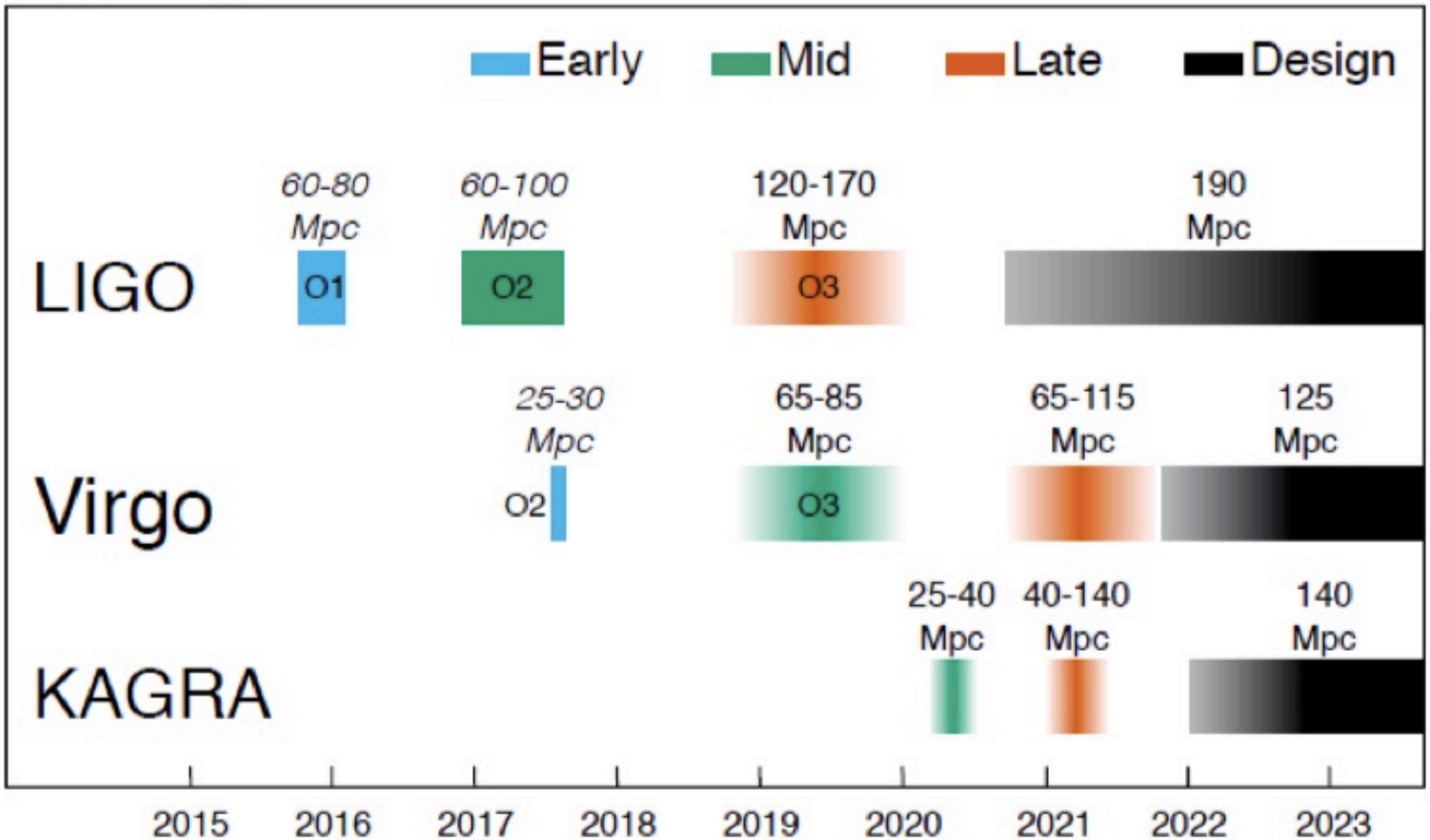
- Type-A installed in 2017
- CRY payload installed at Yend in 2017 (w/spare TM) and at Xend in ‘18 Mar.



- PRMs intalled in 2017 (Type-Bp suspension)
- BS installed in 2017 (Type-B suspension)

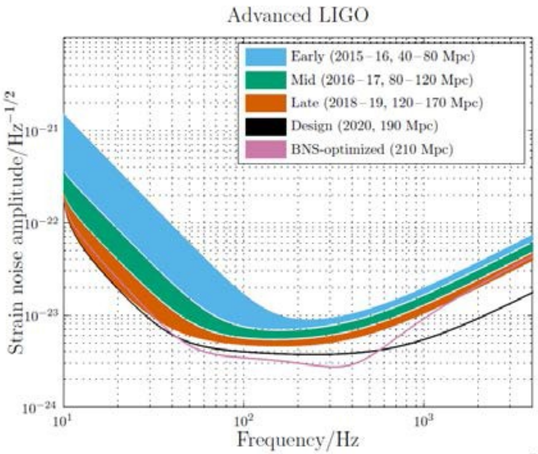
- Yend in vac ‘18/Jan
- ETMY cooled ‘18 Feb (currently T=18K)
- Center in vac ‘18/Mar
- Xend in vac ’18/Apr

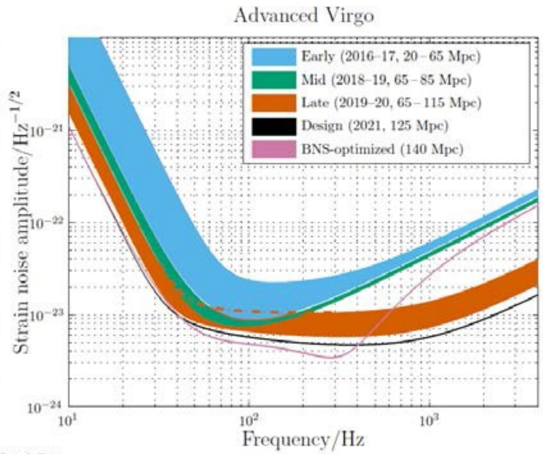
KAGRA status and plan

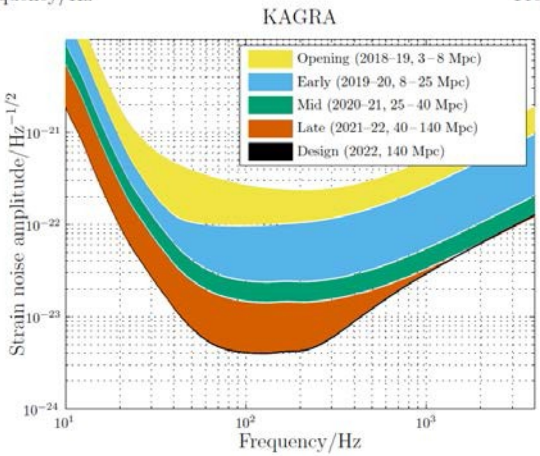


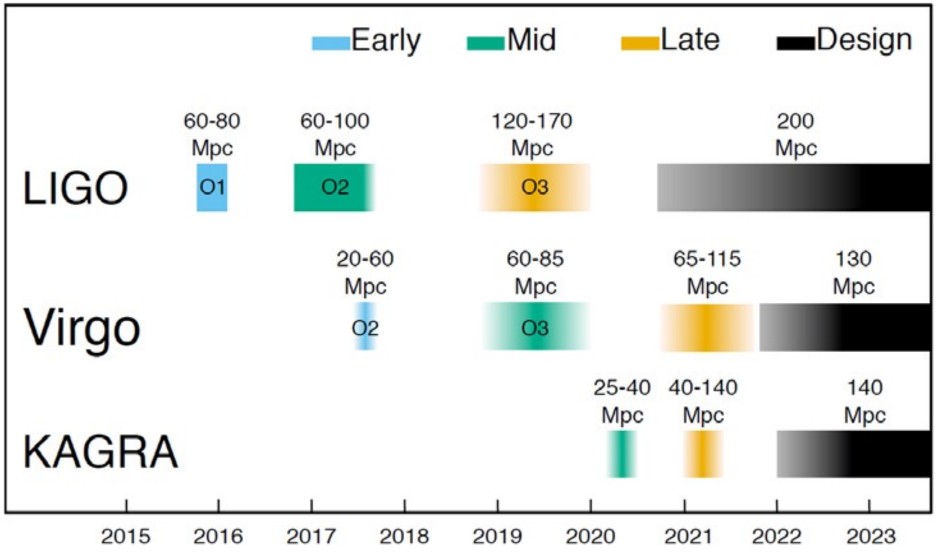
KAGRA collaboration has agreed to somehow accelerate the schedule to join O3 in 2019.

Future Upgrades and new detectors









..and LIGO India plans to come online in 2024-2025

arXiv:1304.0670
Living Rev Relativ (2016) 19

What next?

2.5 G: a set of upgrades capable of enhancing the sensitivities of the current detectors (event rate 5-10x)

- AdV+ in Europe; A+ in USA
  - Timeline: ~2024
  - Cost: ~20÷30 M€

3 G: new infrastructures/detectors capable of reaching the early universe. One order of magnitude gained in sensitivity wrt 2G

- Timeline: ~2030
- Cost > 1 G€

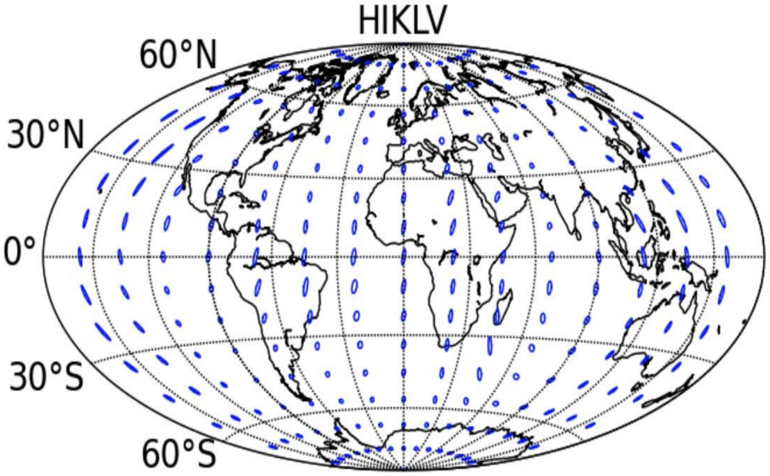
- Einstein Telescope: EU for a nested assembly of co-located interferometers, 10 km long
  - underground
  - bandwidth extended to 1 Hz
  - cryogenics

- Cosmic Explorer: US idea for a 40 km interferometer

Current discussion in GWIC (Gravitational Wave International Committee) for a strong action coordinated at a global international level

Middle term: Advanced Virgo+ (AdV+)

LIGO and Virgo expected upgrade to 2.5 G at mid 2020s with a localization capability of 60% of sources within 10 deg^2 sources



New results expected in

- fundamental physics
- astrophysics
- cosmology
- nuclear physics

Upgrades split in two phases:

Phase 1: BNS range up to 160 Mpc

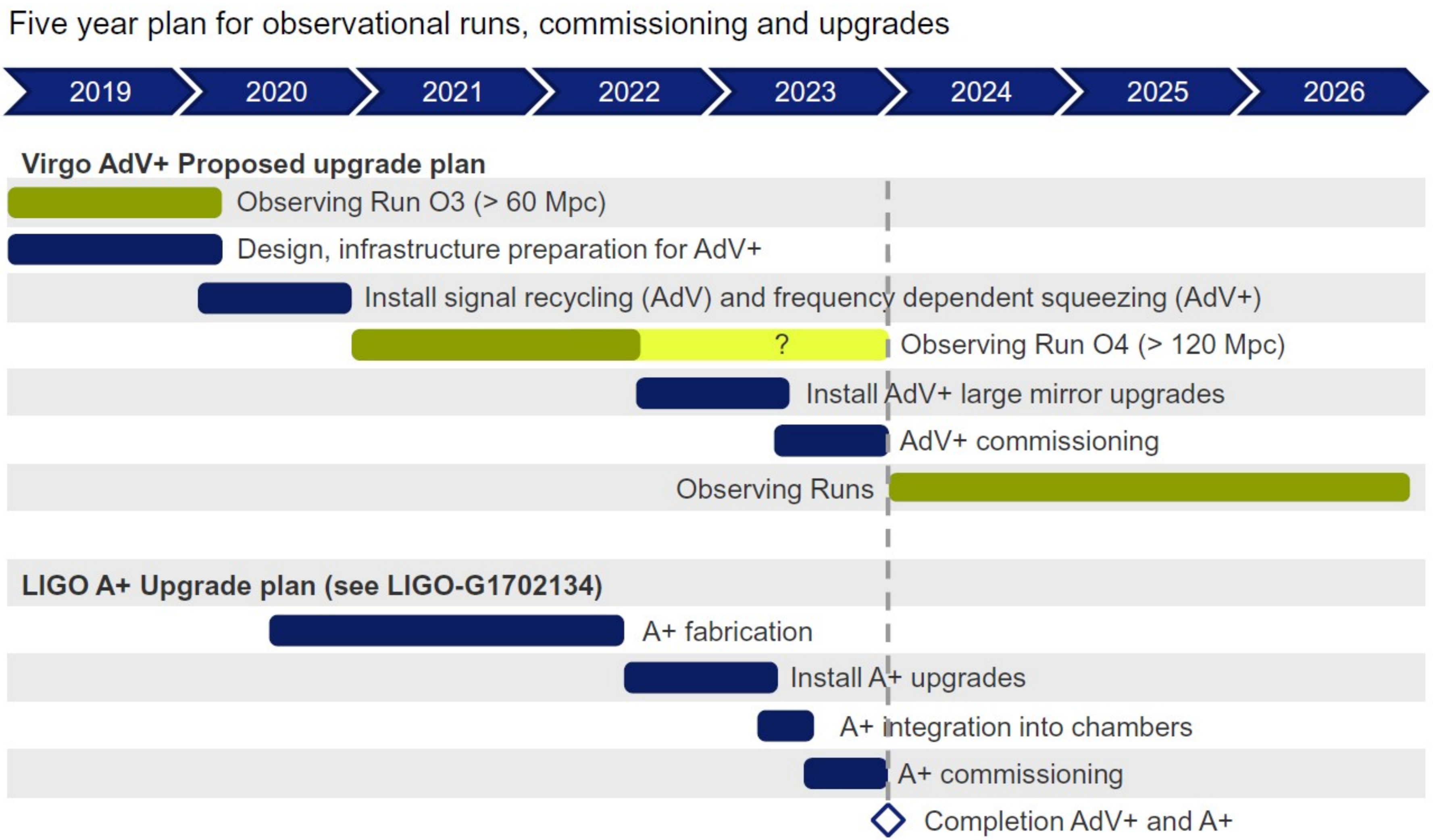
- frequency dependent squeezing
- newtonian noise cancellation

Phase 2: BNS range up to 260 (300) Mpc

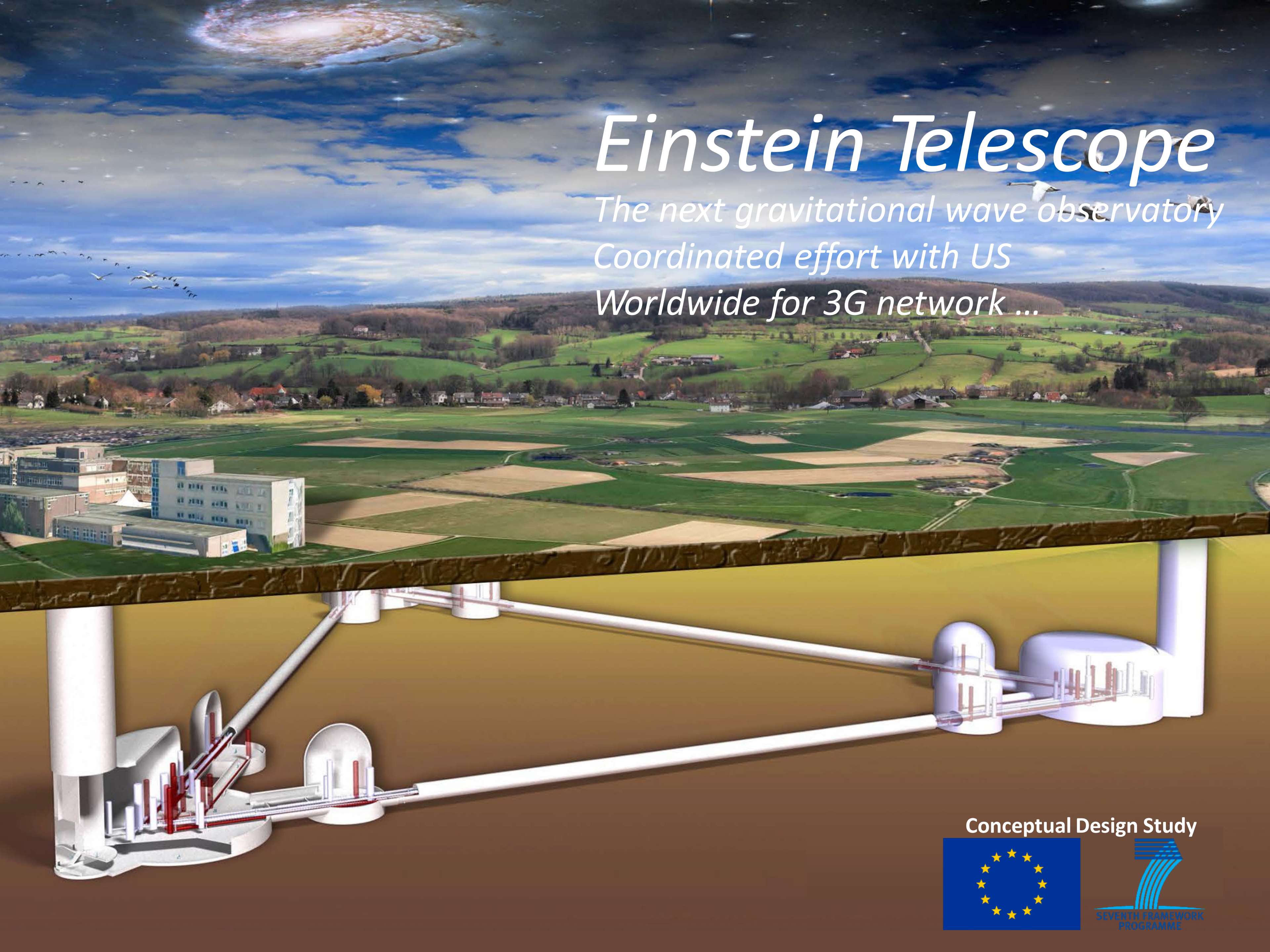
- new larger mirrors
- factor 3 of coating thermal noise reduction

Bridge to future 3G GW - stepping stone to 3G detector technology

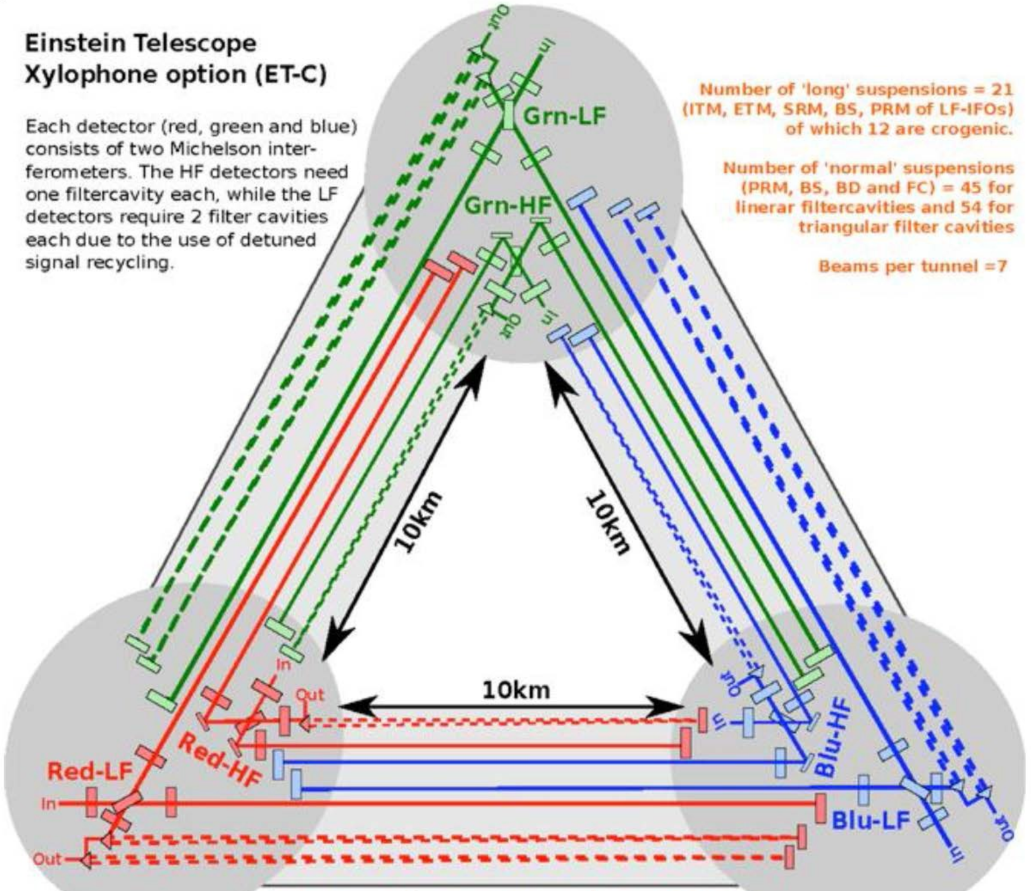
AdV+ tentative timeline



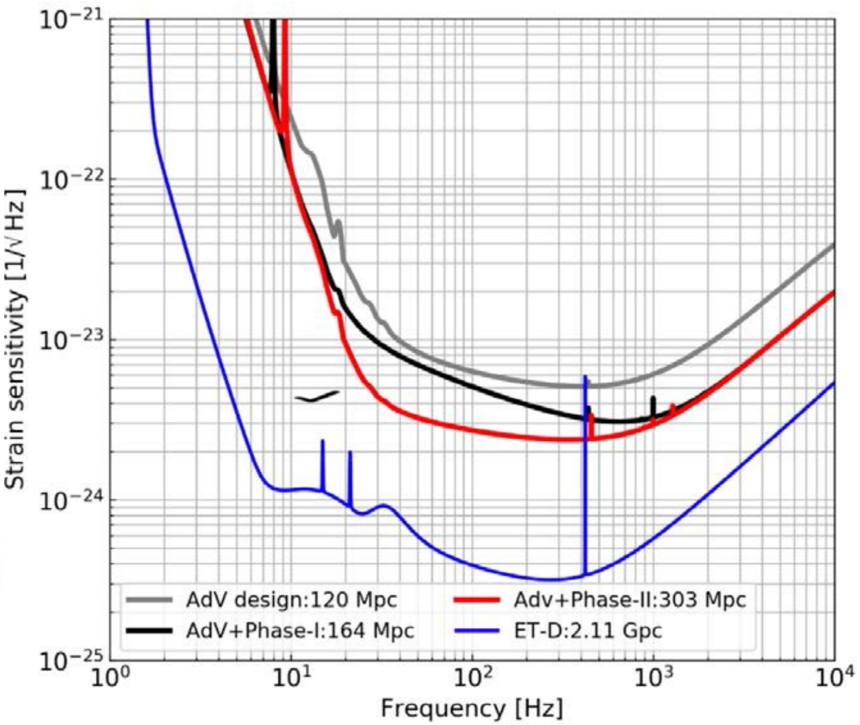
Note: duration of O4 has not been decided at this moment


Einstein Telescope
The next gravitational wave observatory
Coordinated effort with US
Worldwide for 3G network …
Conceptual Design Study
SEVENTH FRAMEWORK PROGRAMME

EINSTEIN TELESCOPE



ET Design Study, 2011

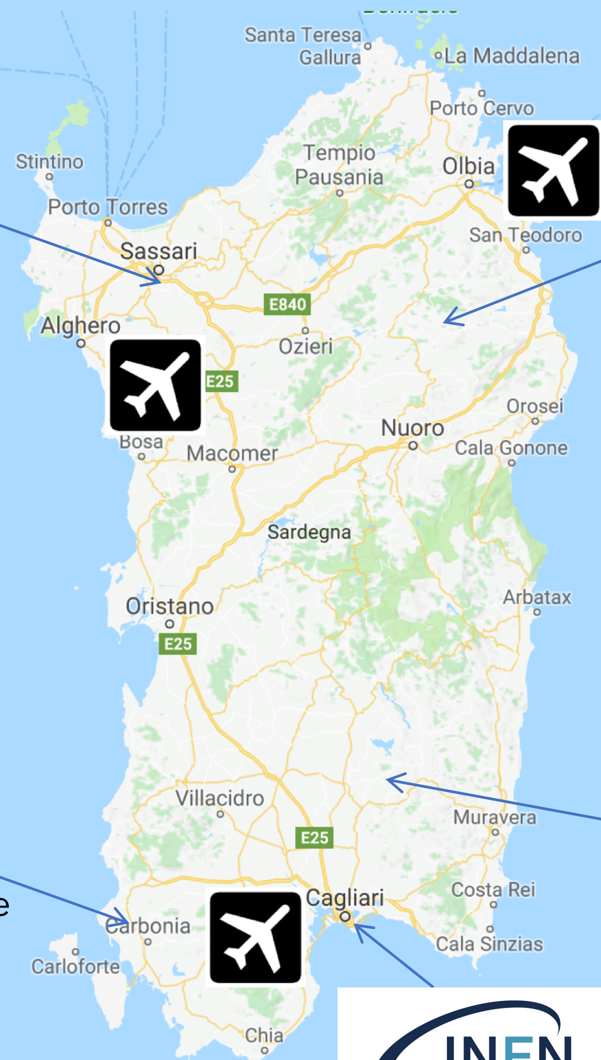


Our Proposal is to have ET inSARDINIA

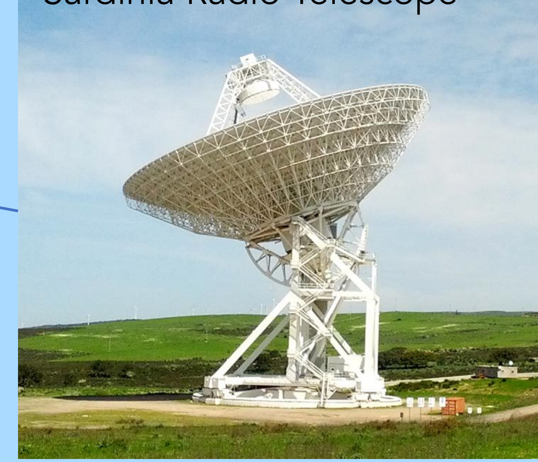
uniss
UNIVERSITÀ DEGLI STUDI DI SASSARI

50′ drive from Olbia airport to the Sos Enattos mine (85 km)

ET EINSTEIN TELESCOPE



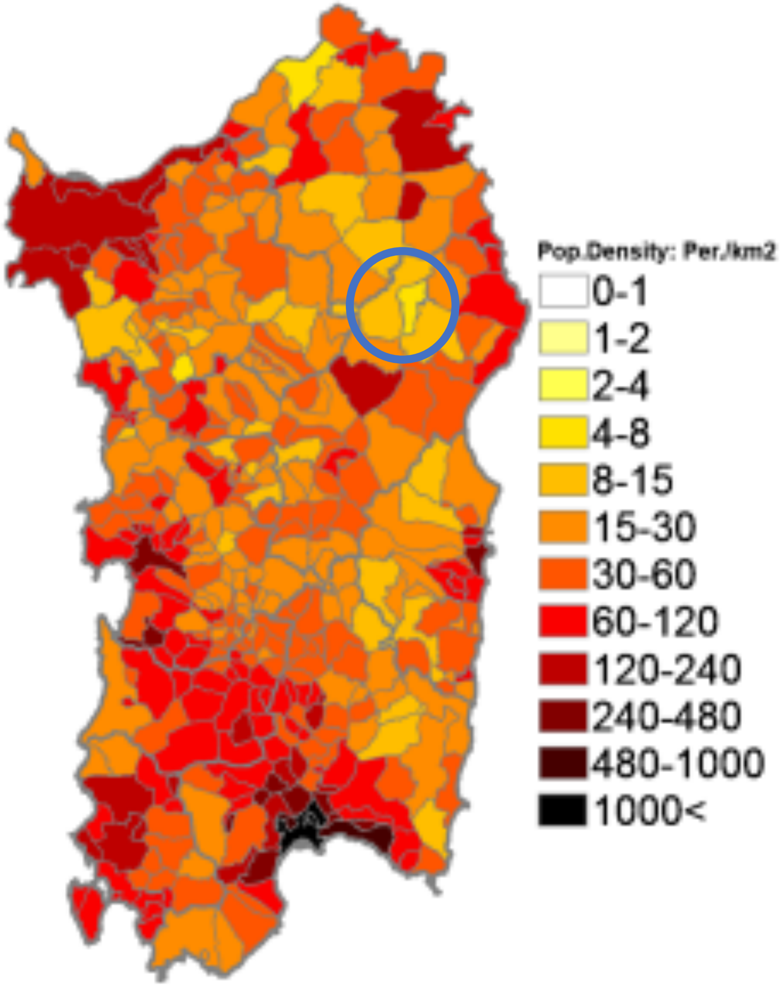
"ARIA" PROJECT
(for the Gran Sasso Dark Side DM detector)

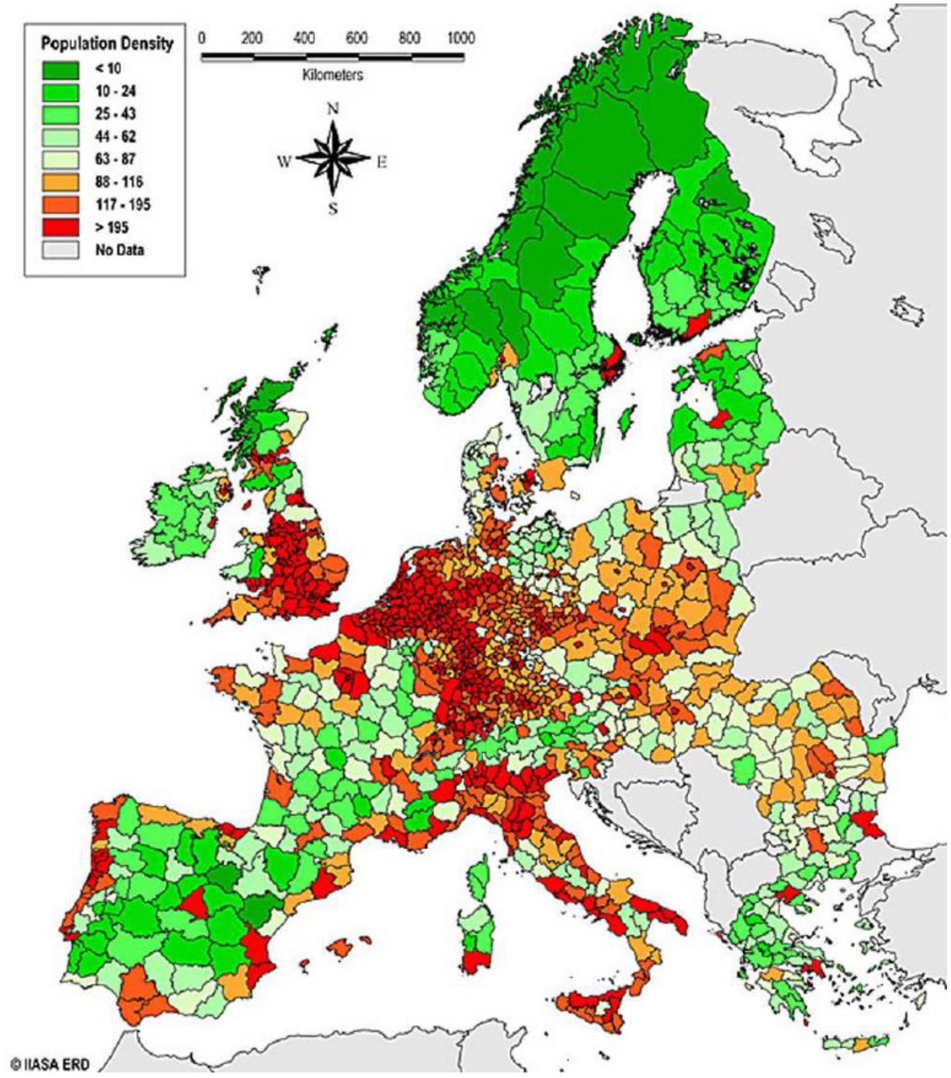


Sardinia Radio Telescope

INFN
Istituto Nazionale di Fisica Nucleare

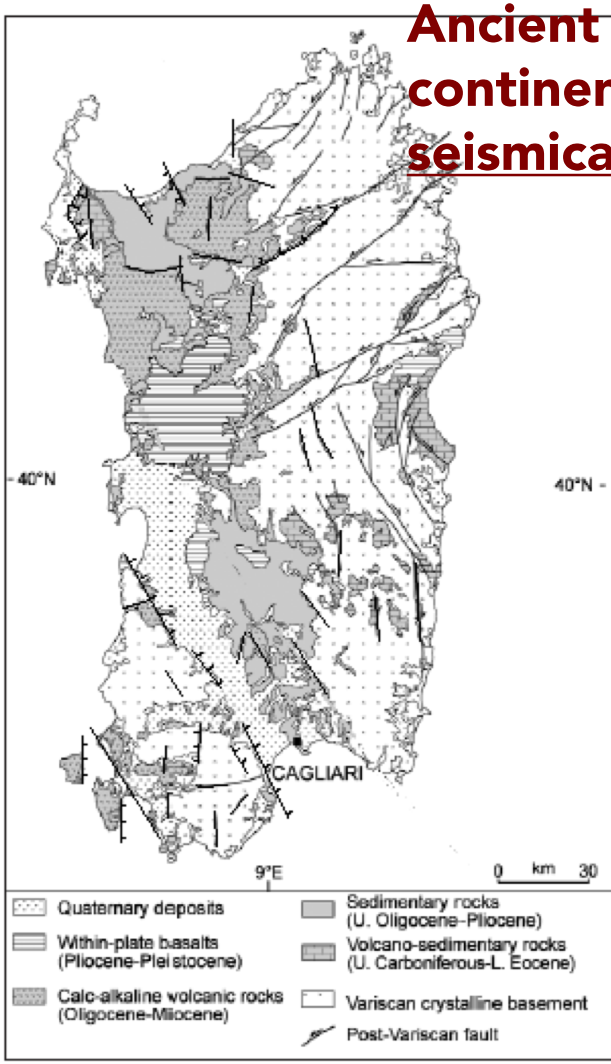
POPULATION DENSITY

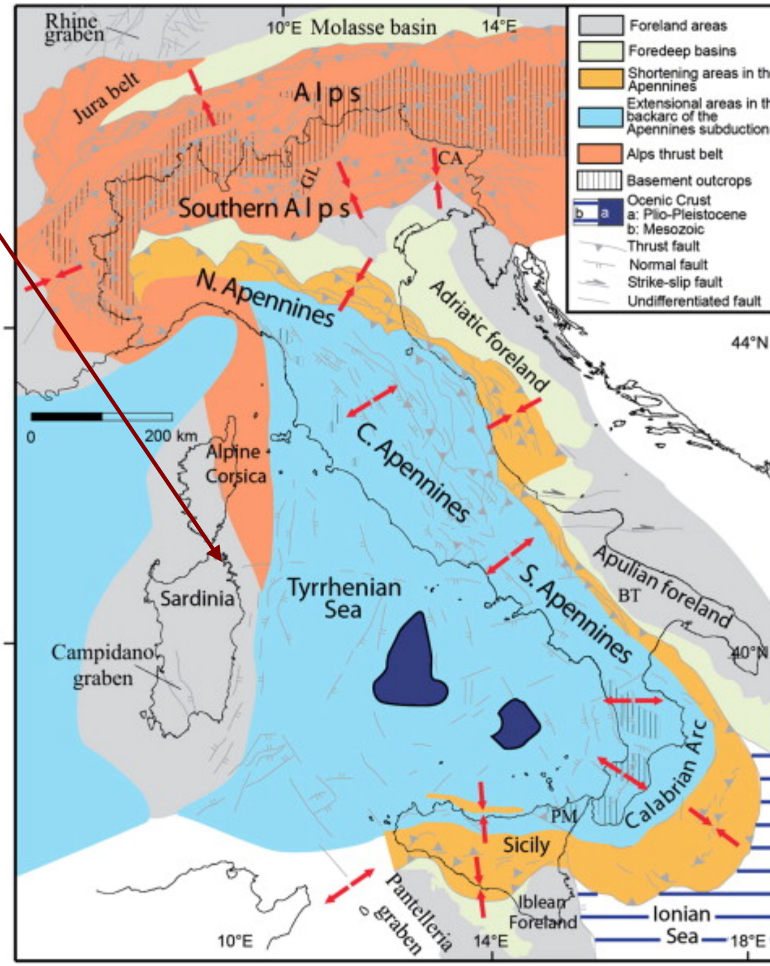




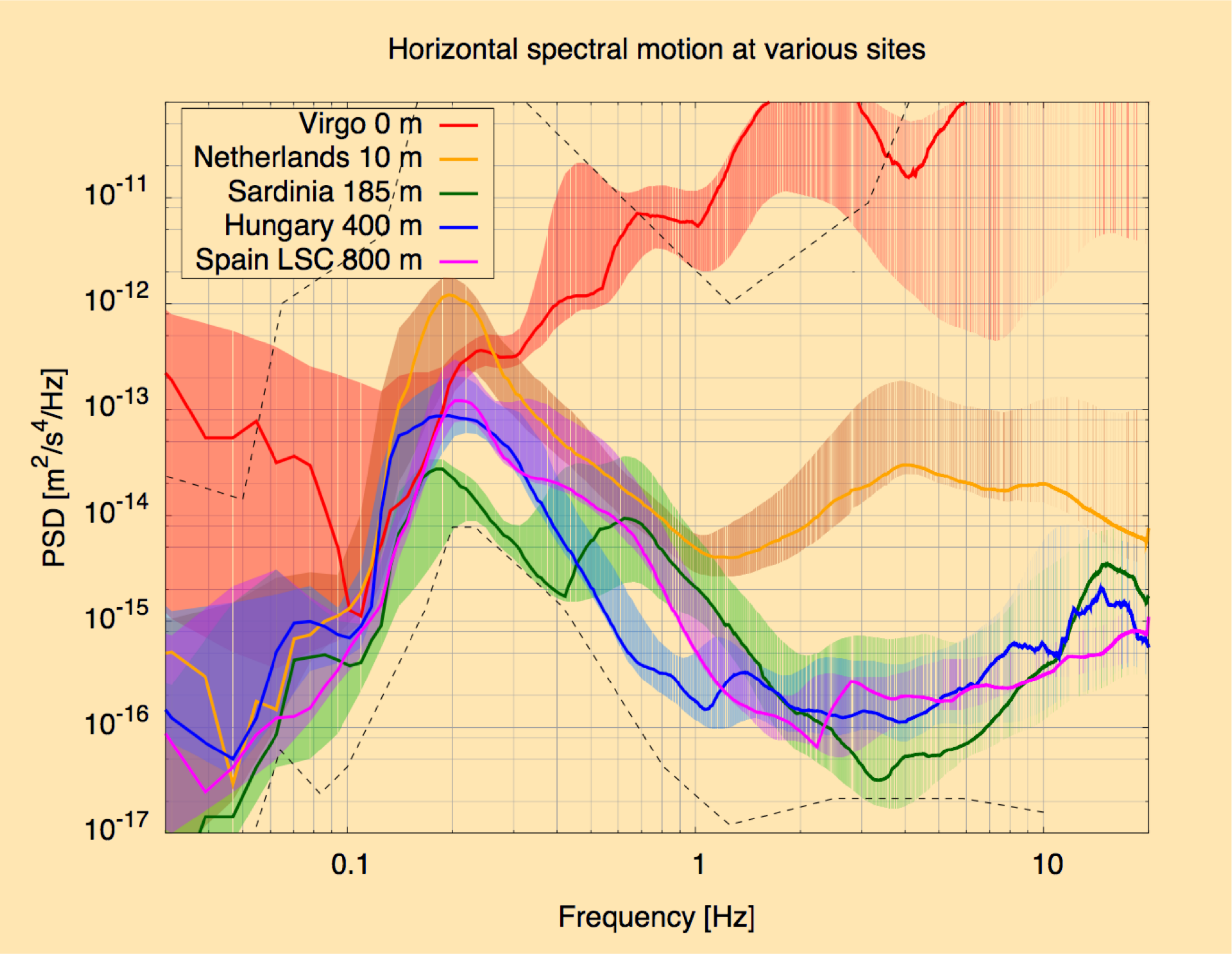
LOCAL GEOPHYSICS

Ancient rocks, European continental landmass: seismically quiet





SEISMIC MEASUREMENTS



More details are in Naticchioni et al. :

Microseismic studies of an underground site for a new interferometric gravitational wave detector

Class. Quantum Grav. **31** (2014) 105016 (20pp) doi:10.1088/0264-9381/31/10/105016

ITALY GOVERNMENT SUPPORT

17 MEuros for AdV+, ET R&D and support of the Sos Enattos candidature

ONDE GRAVITAZIONALI: MIUR, INFN E UNISS CANDIDANO LA REGIONE SARDEGNA A OSPITARE IL FUTURO OSSERVATORIO INTERNAZIONALE

Pubblicato: 22 Febbraio 2018

COMUNICATO CONGIUNTO MIUR/INFN/REGIONE SARDEGNA/UNISS_Il Ministero dell'Istruzione, dell'Università e della Ricerca sosterrà la candidatura della Regione Sardegna a ospitare un Centro europeo per l'Osservatorio delle onde gravitazionali nella miniera di Sos Enattos a Lula. Il MIUR, la Regione, l'Istituto Nazionale di Fisica Nucleare e l'Università di Sassari hanno firmato un Protocollo d'intesa finalizzato a mettere in atto ogni iniziativa utile a favorire l'insediamento della infrastruttura Einstein Telescope nell'Isola, anche con lo scopo di entrare nella lista delle infrastrutture di ricerca riconosciute a livello europeo. Il progetto era stato presentato lo scorso 7 febbraio a Roma alla ministra Valeria Fedeli dal presidente della Regione Francesco Pigliaru e dall'assessore della Programmazione

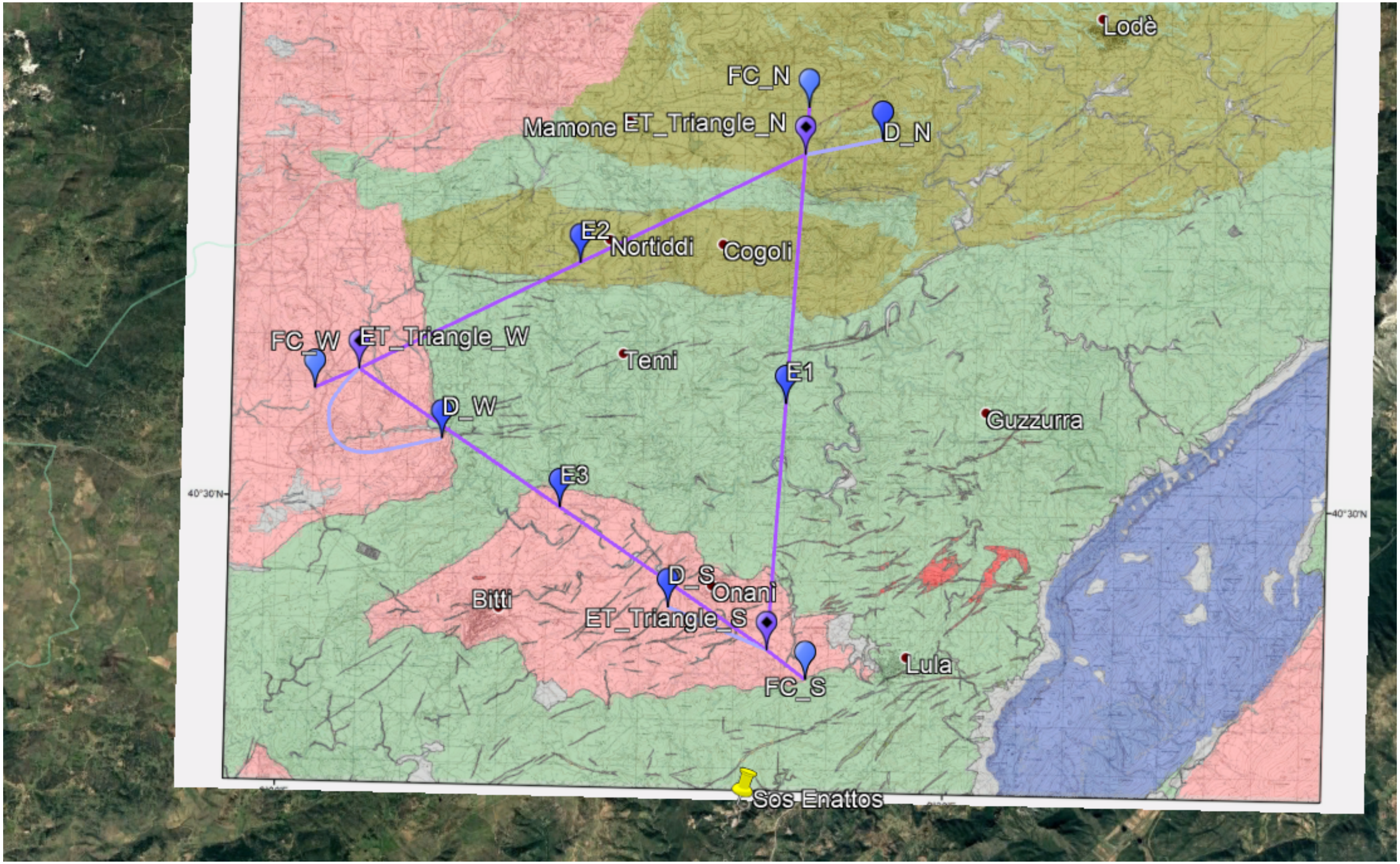
Ministero dell'Istruzione dell'Università e della Ricerca

REGIONE AUTÒNOMA DE SARDIGNA
REGIONE AUTONOMA DELLA SARDEGNA

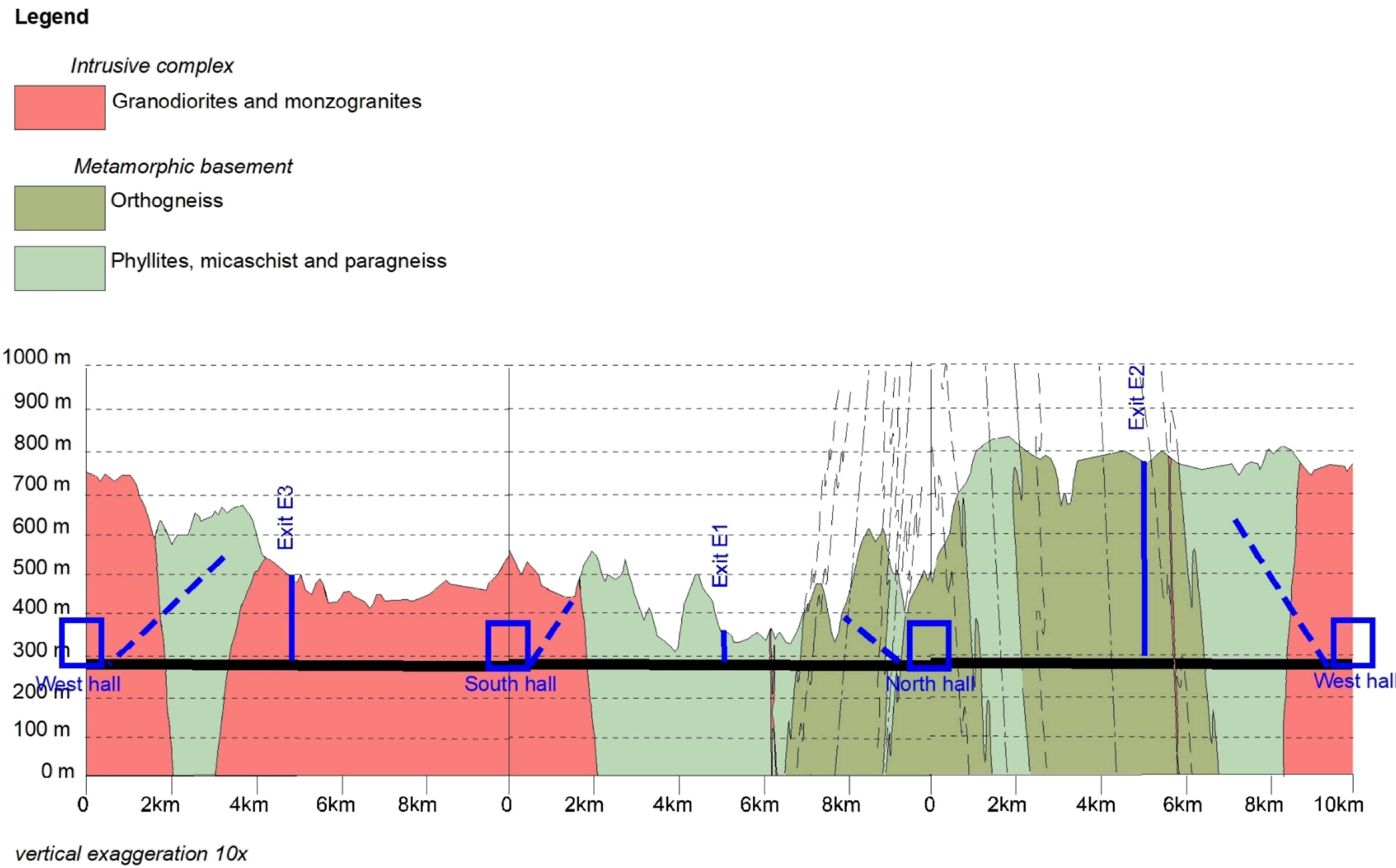
INFN Istituto Nazionale di Fisica Nucleare

uniss UNIVERSITÀ DEGLI STUDI DI SASSARI

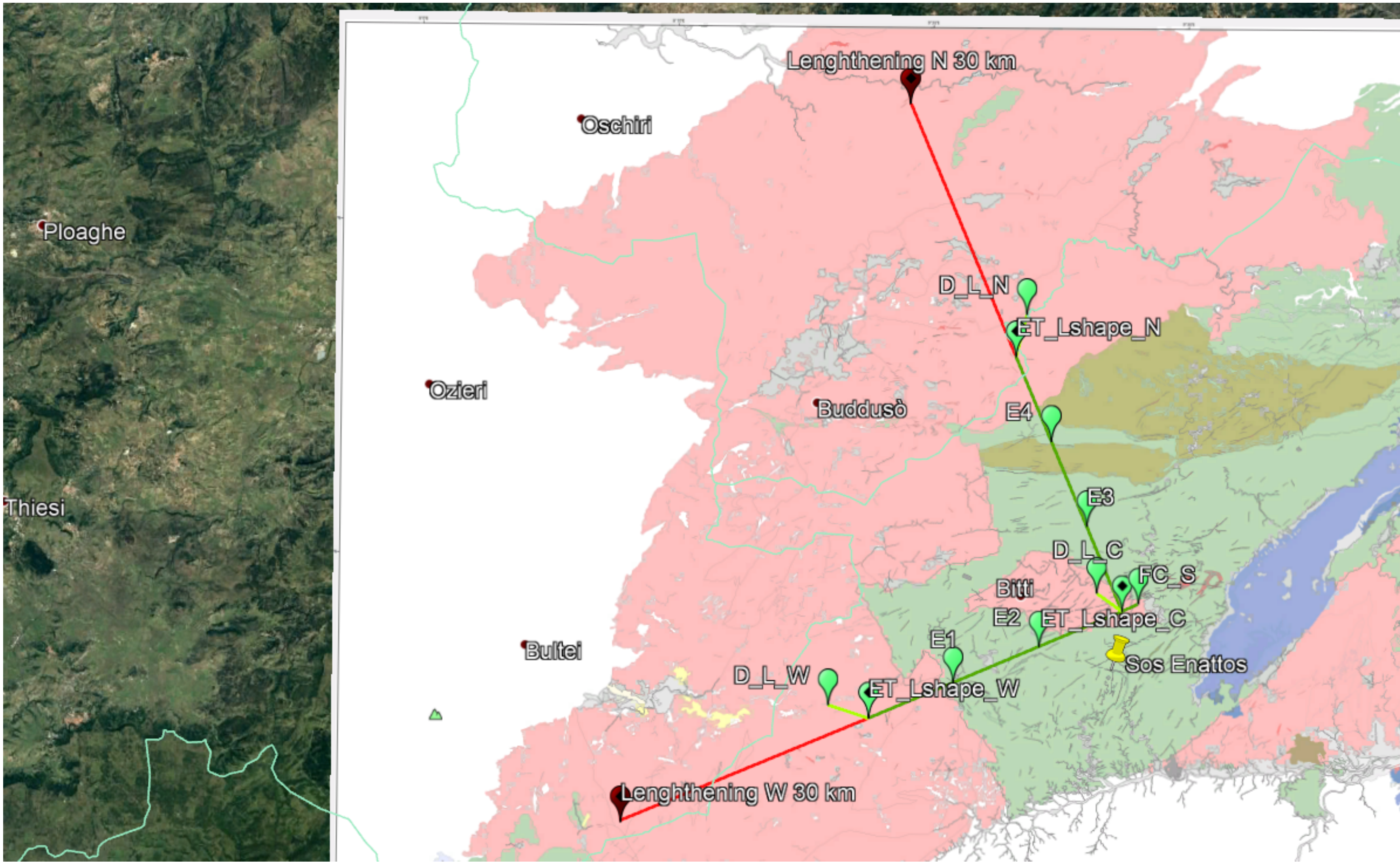
LOCATION - TRIANGLE



GEOLOGICAL SECTIONS



LOCATION - L



Lenghthening N 30 km
Oschiri
Ploaghe
D_L_N
ET_Lshape_N
Ozieri
Buddusò
E4
E3
Thiesi
D_L_C
FC_S
Bitti
E2
ET_Lshape_C
E1
Bultei
Sos Enattos
D_L_W
ET_Lshape_W
Lenghthening W 30 km

A robust R&D program for ET

An R&D program, focused on some crucial technologies, will pave the way for the realization of the next generation of instruments:

- the improvement of the VIRGO seismic attenuation system, to improve the low frequency sensitivity and to maintain the INFN historic leadership in this field
- the design, construction and test of a cryogenic payload
- the development of innovative frequency dependent squeezing techniques, to reduce quantum noise;
- the improvement of the (optical and mechanical) losses of the mirrors' coatings, to reduce thermal noise

New Physics with the 3G detectors

New Physics with the New Detector

- Black holes through cosmic history

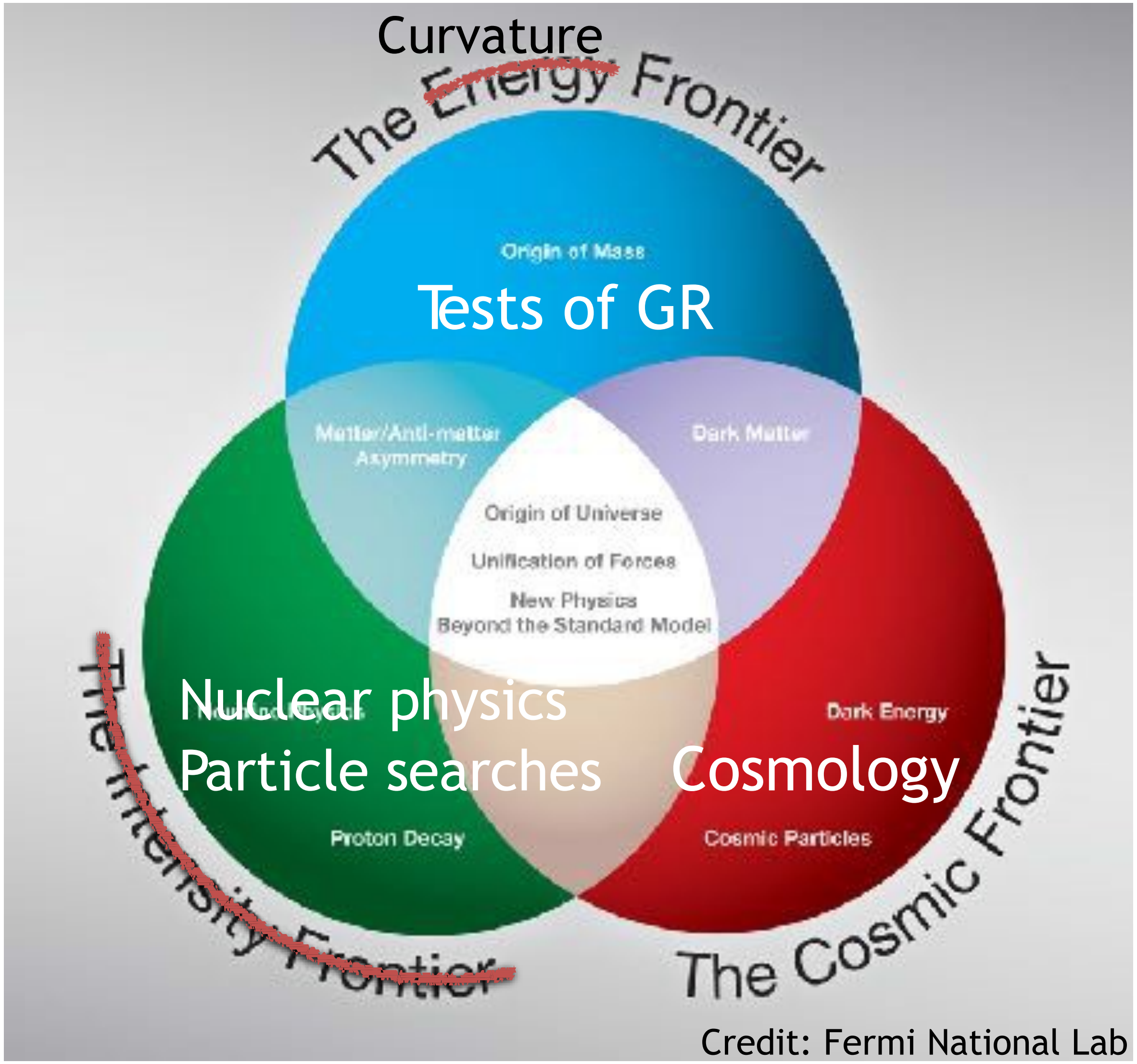
Formation, evolution and growth of black holes and their properties

- Understanding extremes of physics
  - Structure and dynamics of neutron stars
  - Physics of extreme gravity

- Probing the transient Universe

Gamma ray bursts, gravitational collapse and Supernovae

Extreme Physics



Credits Aaron Zimmerman

BBH population study

The detected signals confirmed the existence of black holes with masses larger than 20 $M_\odot$

- ❖ How many black holes? Which size? How are they formed?
- ❖ How metallicity environment influence the formation ? (stellar wind depends on metallicity)

Two models for the binary black hole formation:

- ✓ Two object formed and exploded at the same time from two stars➔ similar spins with the same orientation
- ✓ Black holes in a stellar cluster sink to the center of the cluster and pair up ➔ spin randomly oriented

- ➢ Do it exist miniature black holes ?

  They may have formed immediately after the Big Bang. Rapidly expanding space may have squeezed some regions into tiny, dense black holes less massive than the sun.

BBH population study: from 2G to 3G

Under a simplified hypothesis of a uniform distribution of BBH creation on the universe history

With a 3G detector we expect

- $10^5\ y^{-1}$ BBH
- SNR ~ 10^4 for rare events

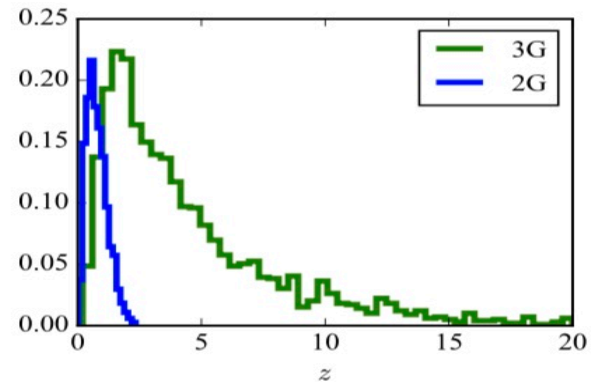


FIG. 2. The redshift distribution of detectable events with a 2-detector network of advanced detectors at design (2G) or CE-like (3G). Note that the two curves use different y scales to improve clarity.

- ➢ Population study biased in function of the achievable SNR

GW signal amplitude depends on $\mathcal{M}^{5/2}$

$\mathcal{M}$ = *chirp mass* = $(m_1 m_2)^{3/5} / (m_1 + m_2)^{1/5}$

Higher $\mathcal{M}$ ➔ easier detection

GW signal duration decreases ***with*** $M_{tot} = m_1 + m_2$

Too massive systems ➔GW signals at frequency out of the detector bandwidth

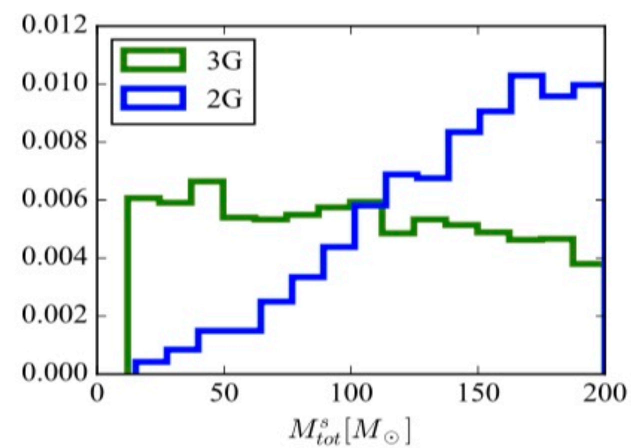


FIG. 3. The source-frame total mass distribution of detectable events with a 2 interferometers network of advanced detectors at design (2G) or CE-like (3G).

In addition the signals detected depend on the redshifted masses M (1+z)

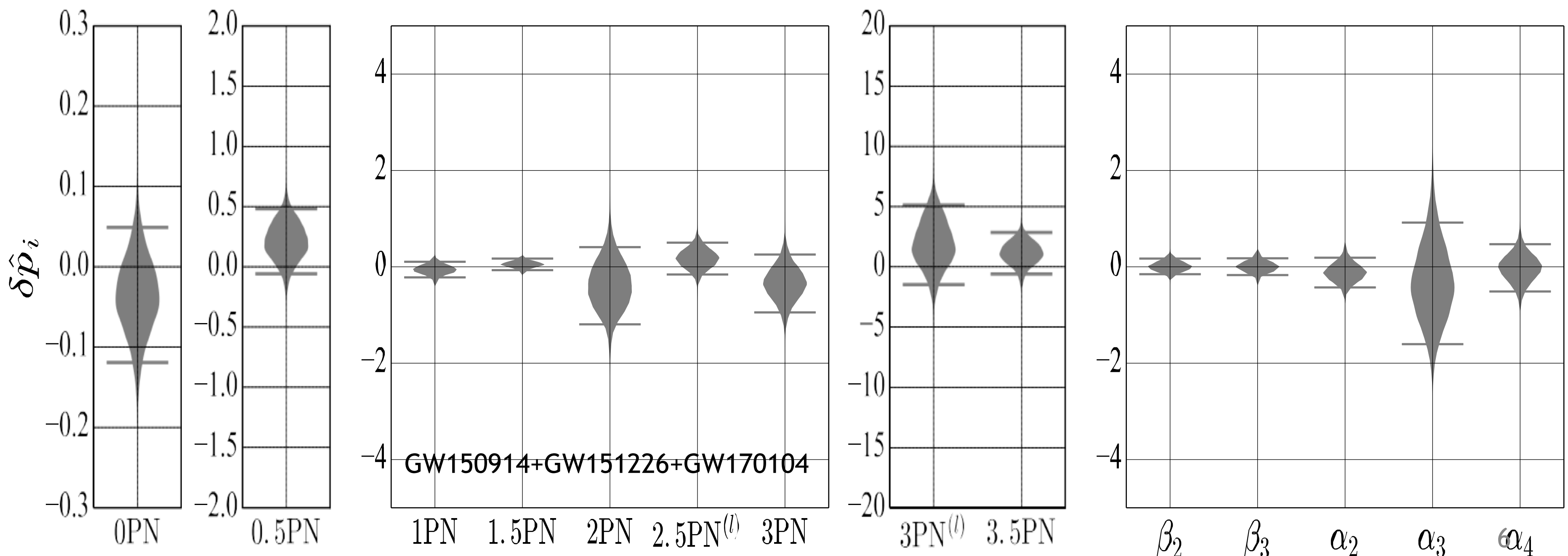
Salvatore Vitale, Phys. Rev. D 94, 121501 (2016)

Testing GR: example via Post Parametrized Expansion

Phenom consistency test $h(f) = A(f,\vec{\theta})e^{i\Psi(f,\vec{\theta})}$

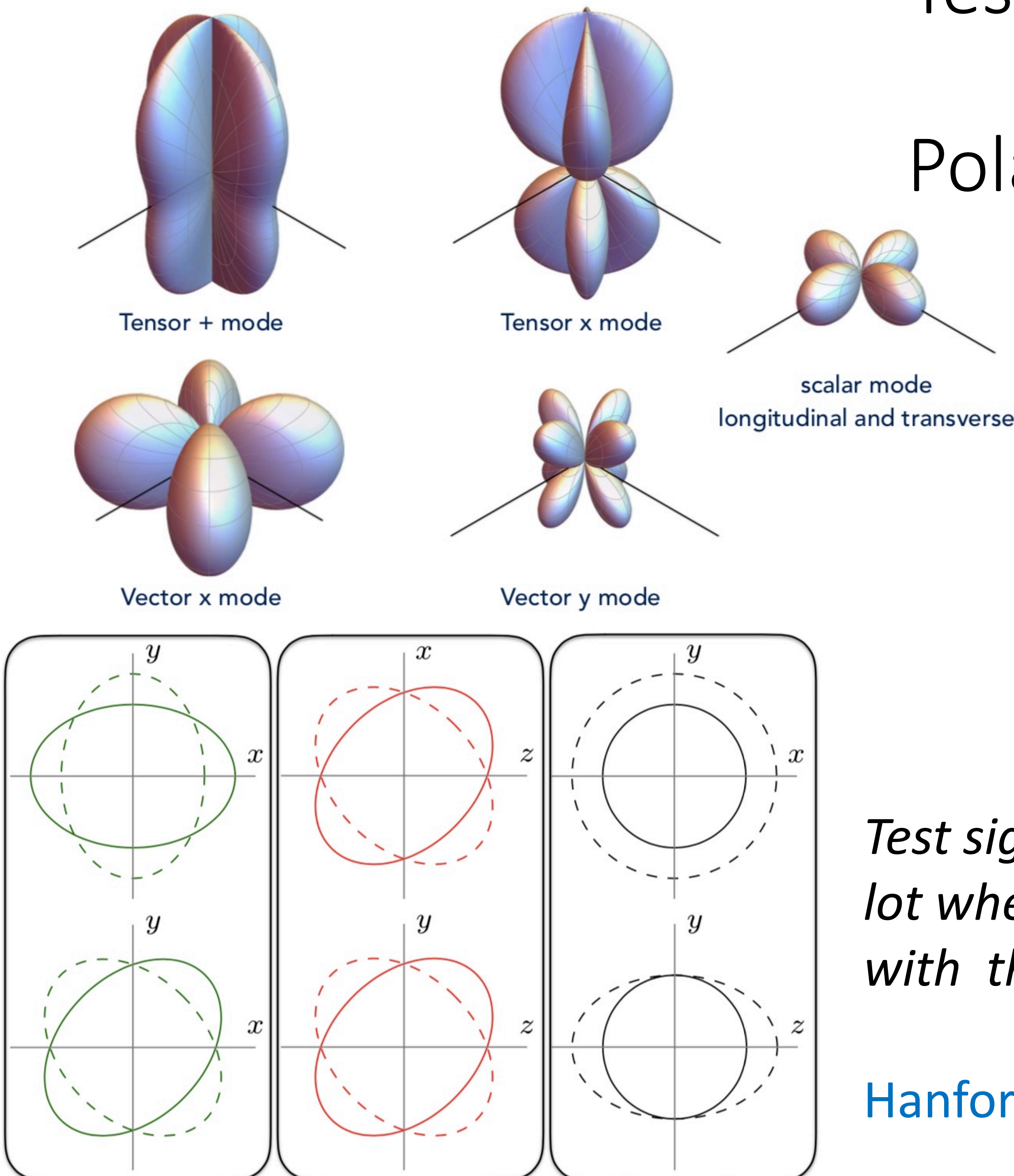
$$\Psi = f^{-5/3}\sum_{i=0}^{7} p_i(\vec{\theta})f^{i/3} + (\log\text{terms})$$

$$p_i \to p_i(1+\delta\hat{p}_i)$$



PRL 118, 221101 (2017)

Testing GR via Polarization



GW170814 result

Bayes factors:

- 1:200 , i.e. purely vector disfavoured vs purely tensor
- 1:1000 i.e. purely scalar disfavoured vs purely tensor mode

Test significance will improve a lot when it will be carried on with the extended network

Hanford-Livingston-KAGRA-Virgo

Looking ahead for tests of GR

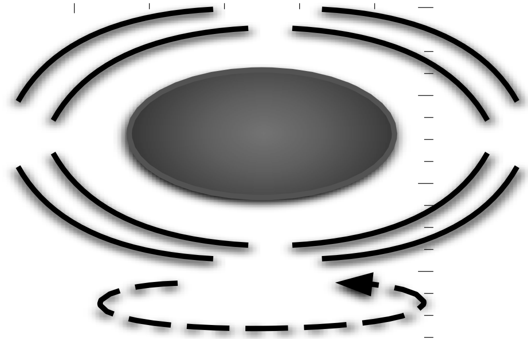
- Precision era ahead: modeling challenges
  - Part in 10^{-4} -10^{-5} waveform accuracy
  - Predictions from non-GR mergers

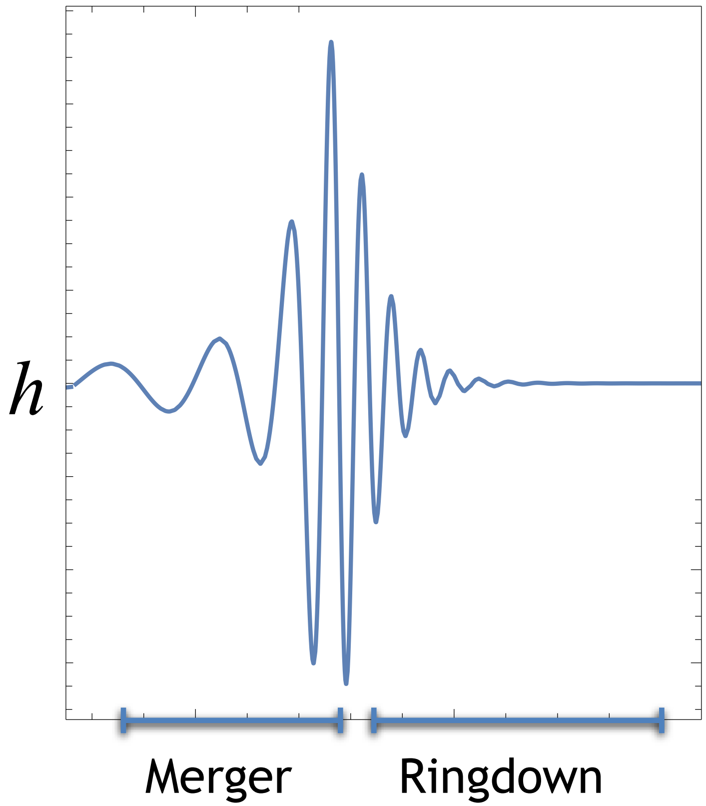
More work on mapping constraints to theory

- Beyond leading order PPE

- New ideas/new events lead to dramatic constraints
- Target measurements to rule out classes of non- GR theories

Ringdown of a Kerr Black hole





Scheel et al. PRD (2009)

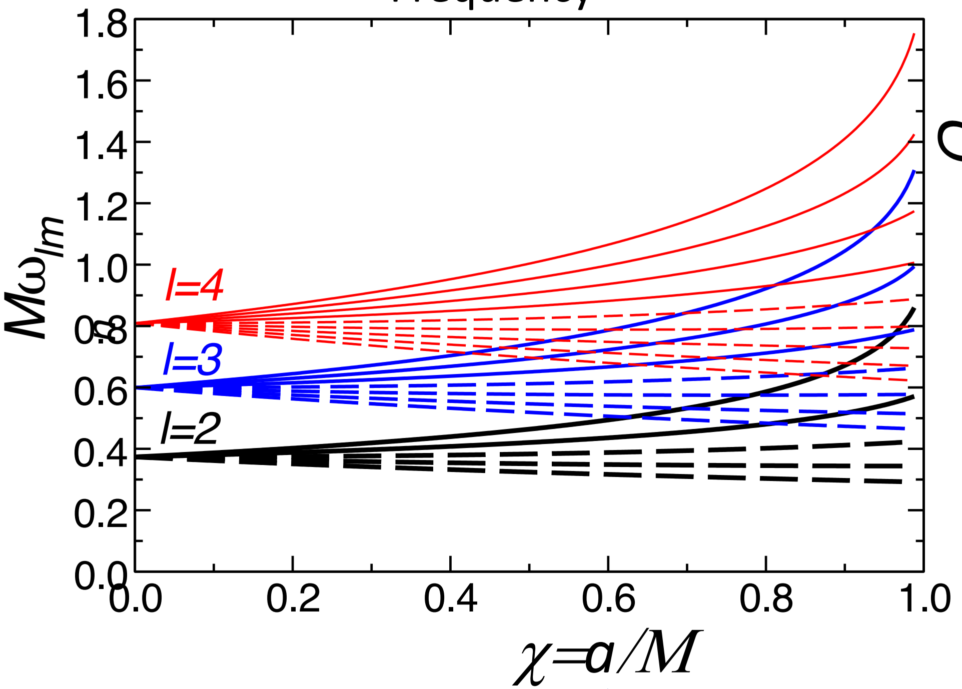
The spectrum of Quasi Normal Modes (QNM) is characterized only by the BH mass and angular momentum.

The detection of a few modes from the ringdown signal can allow for precision measurements of the BH mass and spin

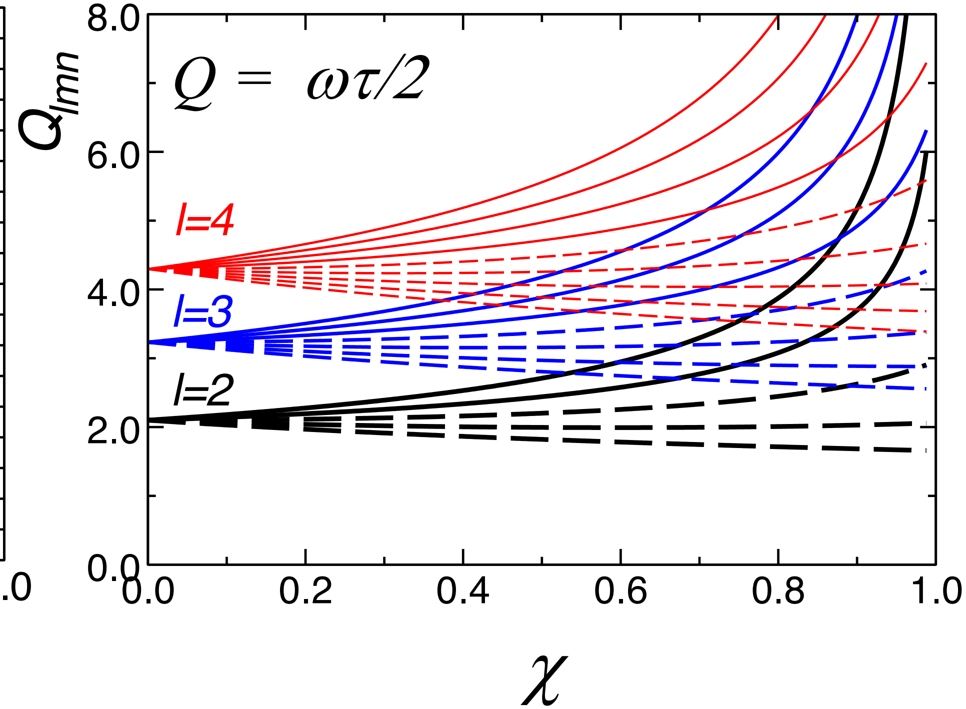
In addition the detection of higher multipole moments can be used to perform null- hypothesis tests of the no-hair theorems of general relativity

Black hole spectroscopy

Frequency



Quality Factor



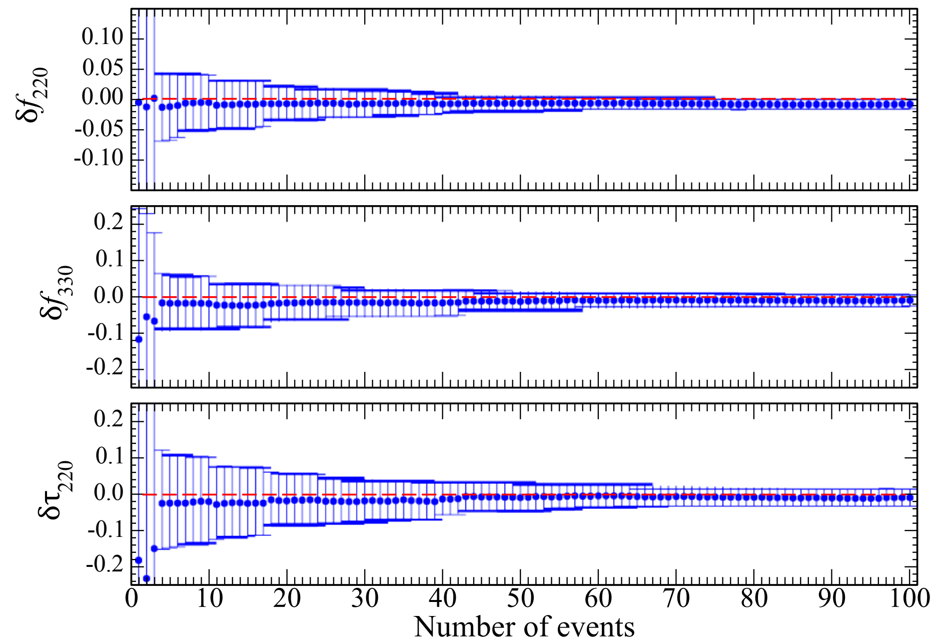
a =*J*/*M* ➔ Kerr rotation parameter

(ω,τ) ➔ (M, χ)

Berti,Cardoso, Starinets (2009)

BH spectroscopy with the future detectors

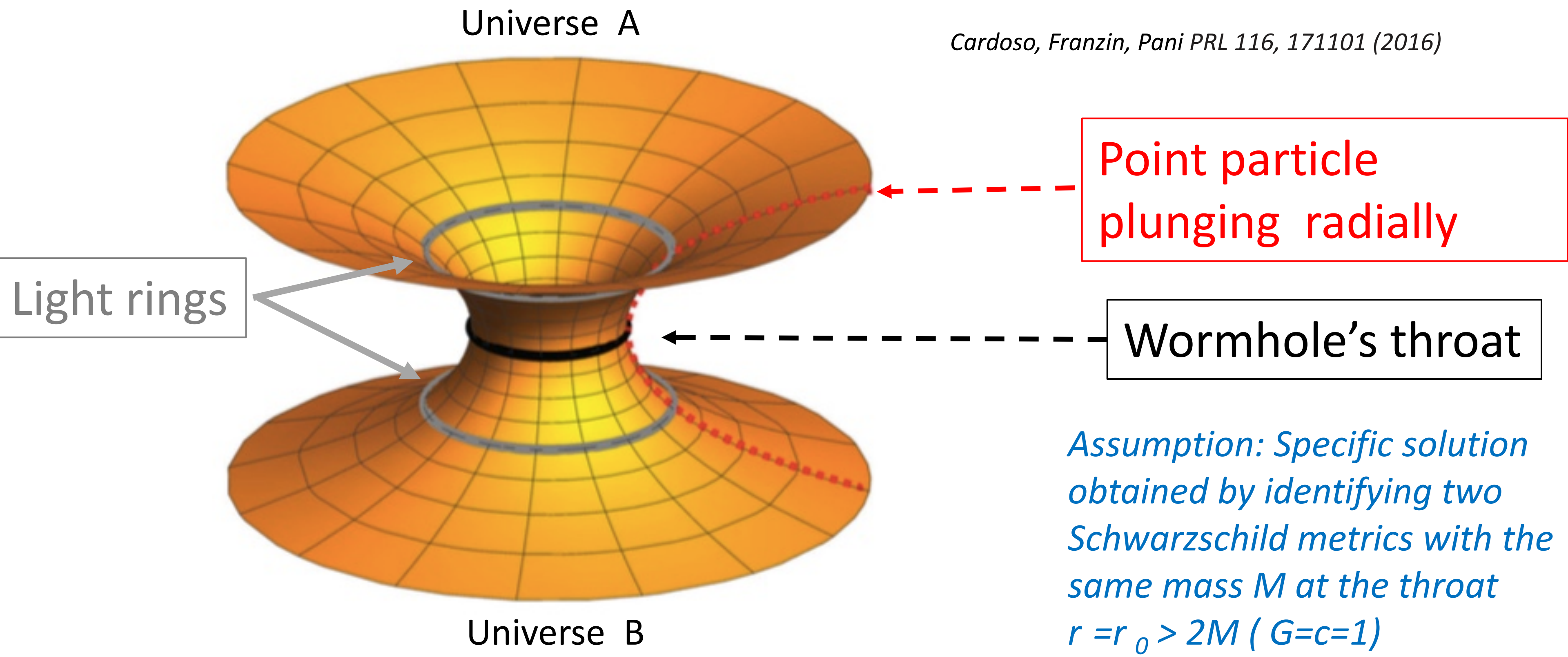
- 3G and LISA detectors ideal for ringdown
- High-SNR events will give individual tests
- Combine many events: both 2G and 3G provide stronger constraints on GR
- Practical in active development



$$f_{lmn} = f_{lmn}^{\mathrm{GR}}(1 + bf_{lmn})$$

Brito, Buonanno, Raymond arXiv:1805.00293

QNM to Probe Wormhole Spacetime



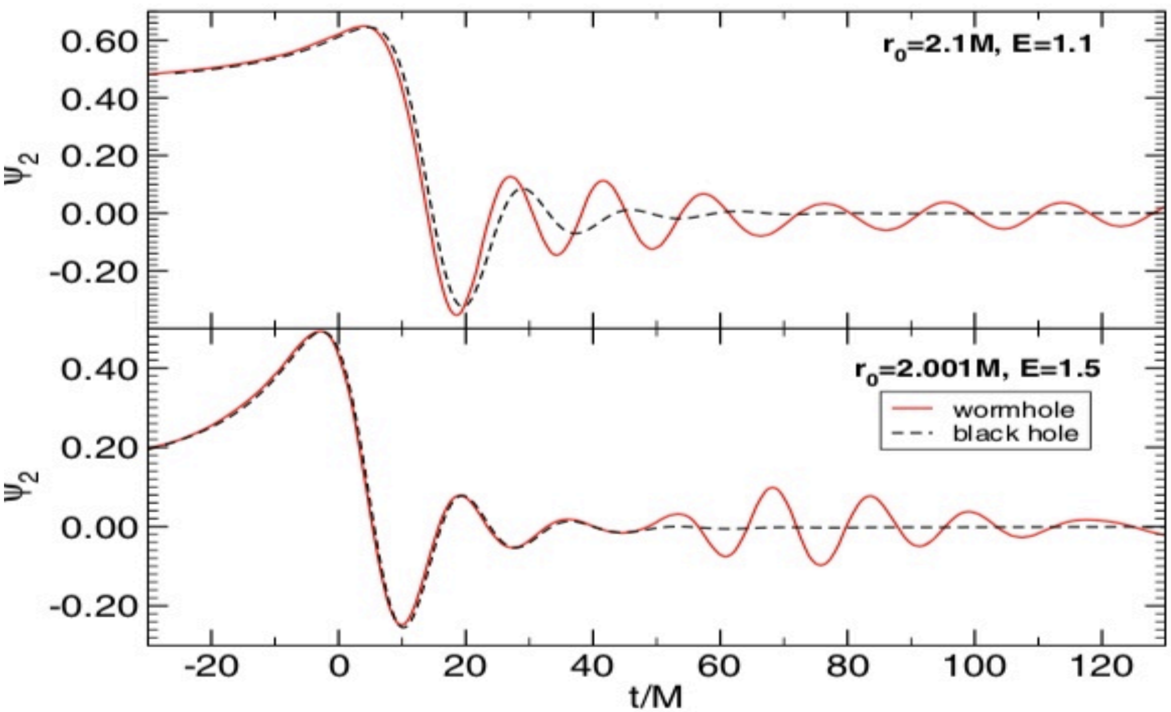
Cardoso, Franzin, Pani PRL 116, 171101 (2016)

Assumption: Specific solution obtained by identifying two Schwarzschild metrics with the same mass M at the throat $r = r_0 > 2M$ (G=c=1)

A point particle plunges radially and emerges in another "universe". When the particle crosses each of the light rings curves, <u>it excites QNM characteristic modes</u> trapped between the light-ring potential wells

Comparison of the GW waveform between the BH and wormhole case

- Particle plunging into a Schwarzschild BH with the energy E compared to the particle crossing a traversable wormhole



GW waveforms comparison for different values of E.

The BH waveform was shifted in time to account for the dephasing due to the light travel time from the throat to the light ring

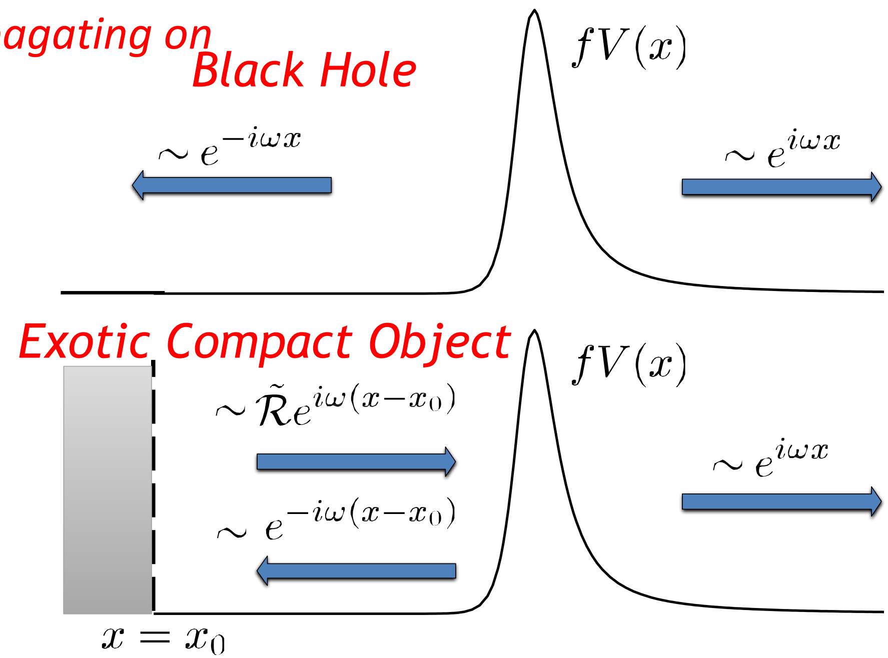
Echoes from compact objects

Event horizon ➔ the heart of the BH information paradox

BH in a quantum theory of gravity ➔ an open question

Horizonless alternatives to BH: gravastars, boson stars, wormholes,…………….

Reflecting boundary condition for a waves propagating on



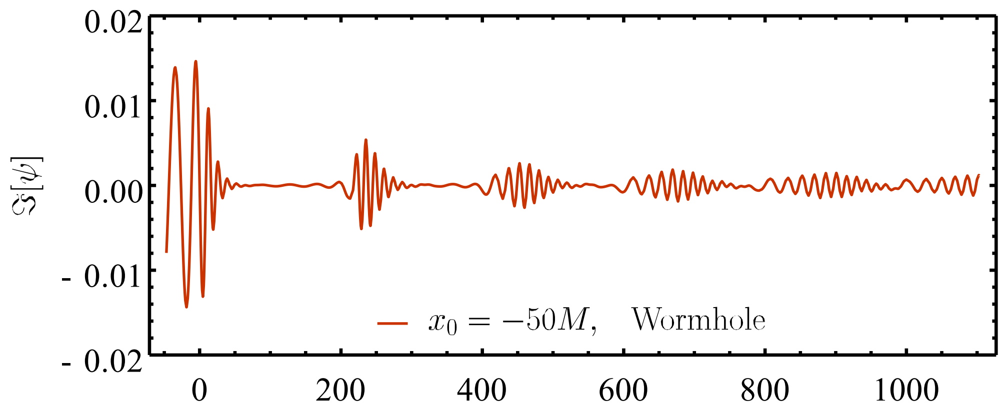
- Exotic compact objects (ECOs): resemble BHs
- But are not perfectly absorbing
- Parametrize by reflecting barrier
- Initially ringdown normally
- Waves going into the horizon become “echoes”

Cardoso, Franzin, Pani, PRL 116, 171101 (2016)
Mark, Zimmerman, Du, Chen, PRD 96, 084002 (2017)

Echoes from compact objects

- Exotic compact objects (ECOs): resemble BHs
- But are not perfectly absorbing
- Parametrize by reflecting barrier
- Initially ringdown normally
- Then it contains a train of decaying echo pulses

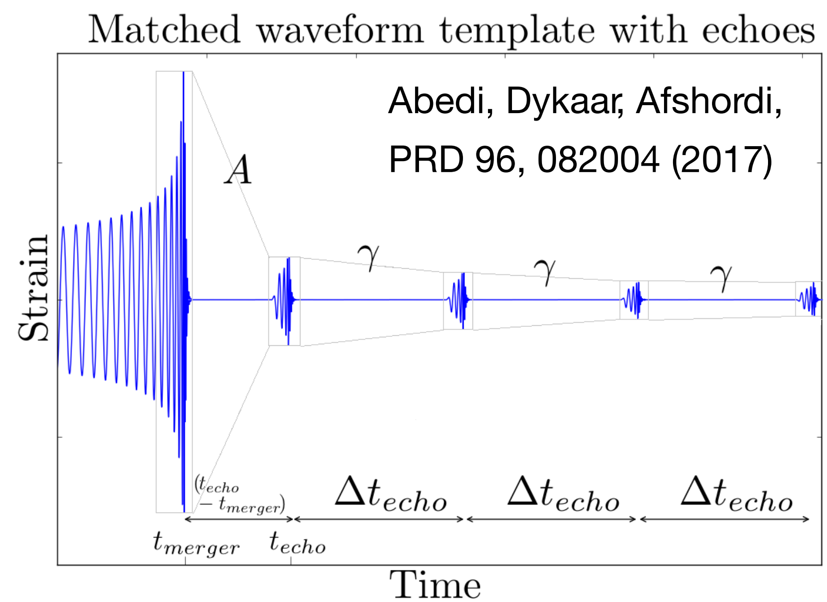
Cardoso, Franzin, Pani, PRL 116, 171101 (2016)
Mark, Zimmerman, Du, Chen, PRD 96, 084002 (2017)



Time delay between the echoes is related to the ECO compactness while the decay and shape of each pulse encodes the reflective properties of the ECO

Echos Searches

- Exotic compact objects (ECOs): resemble BHs
- But are not perfectly absorbing
- Parametrize by reflecting barrier
- Initially ringdown normally
- Waves going into the horizon become "echoes"



Event	[19]	original 16s (32s)	widened priors 16s (32s)
GW150914	0.11	0.199 (0.238)	0.705 (0.365)
LVT151012	-	0.056 (0.063)	0.124
GW151226	-	0.414 (0.476)	0.837
(1,3)	-	0.159	0.801
(1,2,3)	0.011	0.020 (0.032)	0.18 (0.144)

Abedi, Dykaar, Afshordi 1701.03475

Conklin, Holdom, Ren 1712.06517

Abedi, Afshordi 1803.10454

Westerwick et al.1712.09966

Ashton et al. 1612.05625

Tsang et al. 1804.04877

BH and particle physics

- With a stellar mass BH we have a new precision tool that may diagnose the presence of new light (10^{-20} 10^{-10} eV) and weakly interacting bosonic particles

- When such a particle's Compton wavelength is comparable to the horizon size of a rotating BH,

$$\lambda_C \gtrsim R_s$$

the super radiance effect spins down the BH, populating bound orbits around the BH with an exponentially large number of particles

- The BH already detected by LIGO/Virgo can act as attractors of QCD axions of the upper end of a mass range, which covers the parameter space for the QCD axion

GW interferometer as detector of new elementary particles

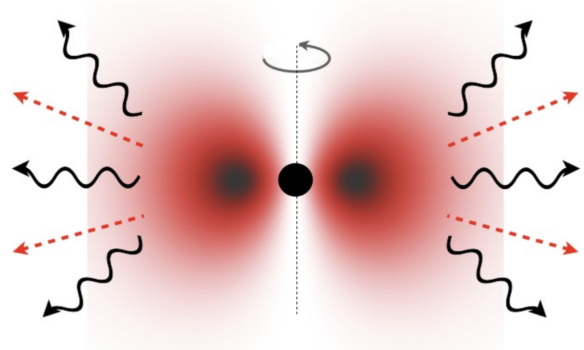
In this proposed scenario black holes develop clouds of axions

The axion cloud will emit ~monocromatic GWs

Depending on the mechanism, these might be visible to tens of Mpc (Arvanitaki+ 1604.03958)

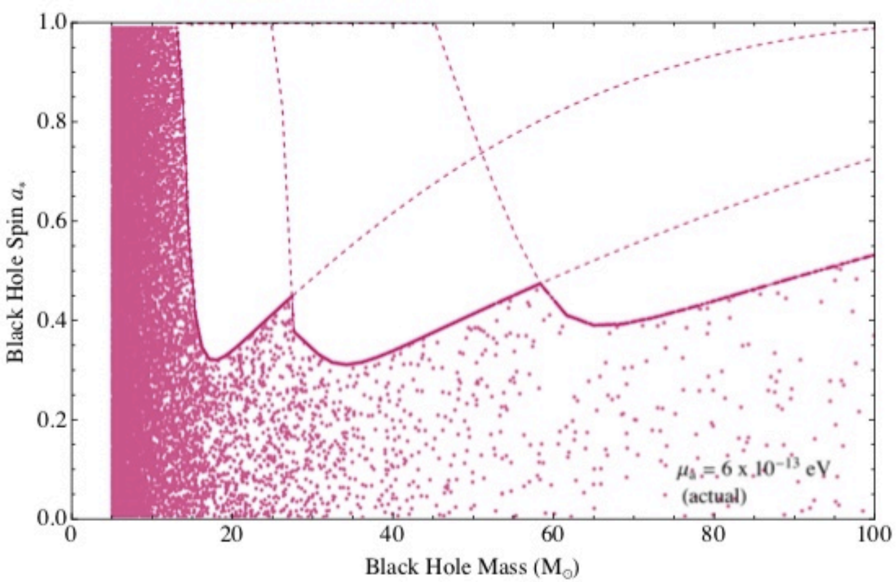
We can follow-up newly formed BHs and look for this signal.

Source-frame frequency depends on the mass of the axion
(Detected frequency will be redshifted)

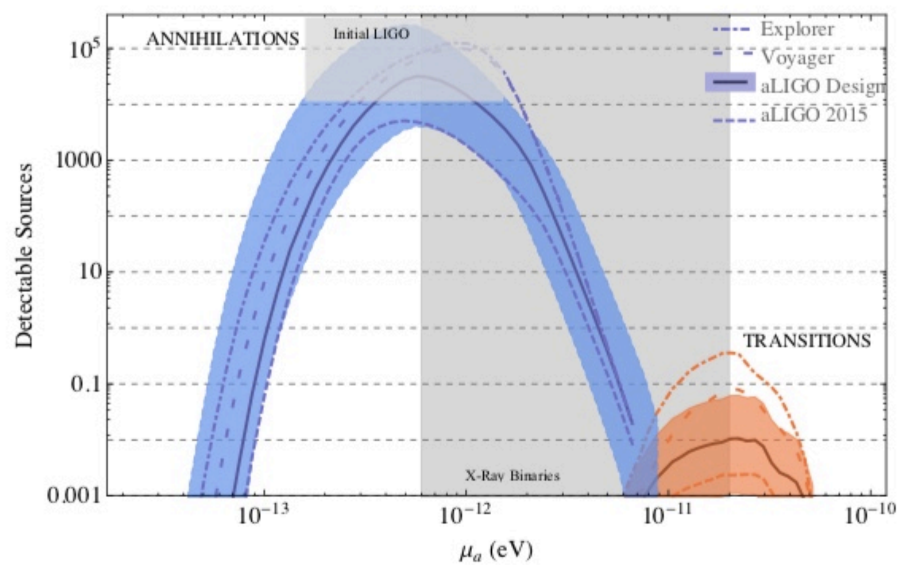


Searching for ultra-light particles

μ_a = 10^{-10} - 10^{-14} eV $\longrightarrow$ $\lambda_C = 10 - 10^5$ km



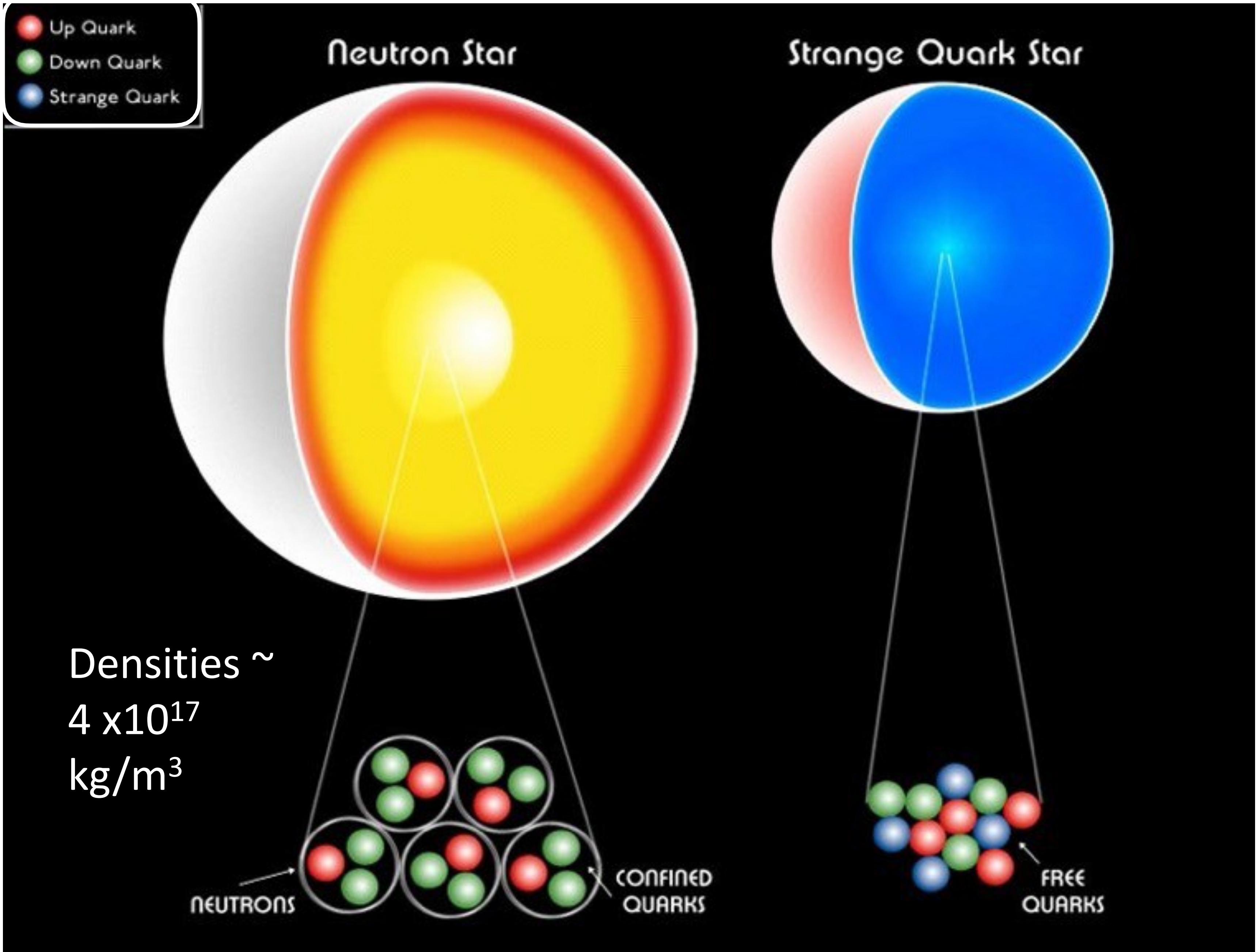
Population inferences



Direct searches

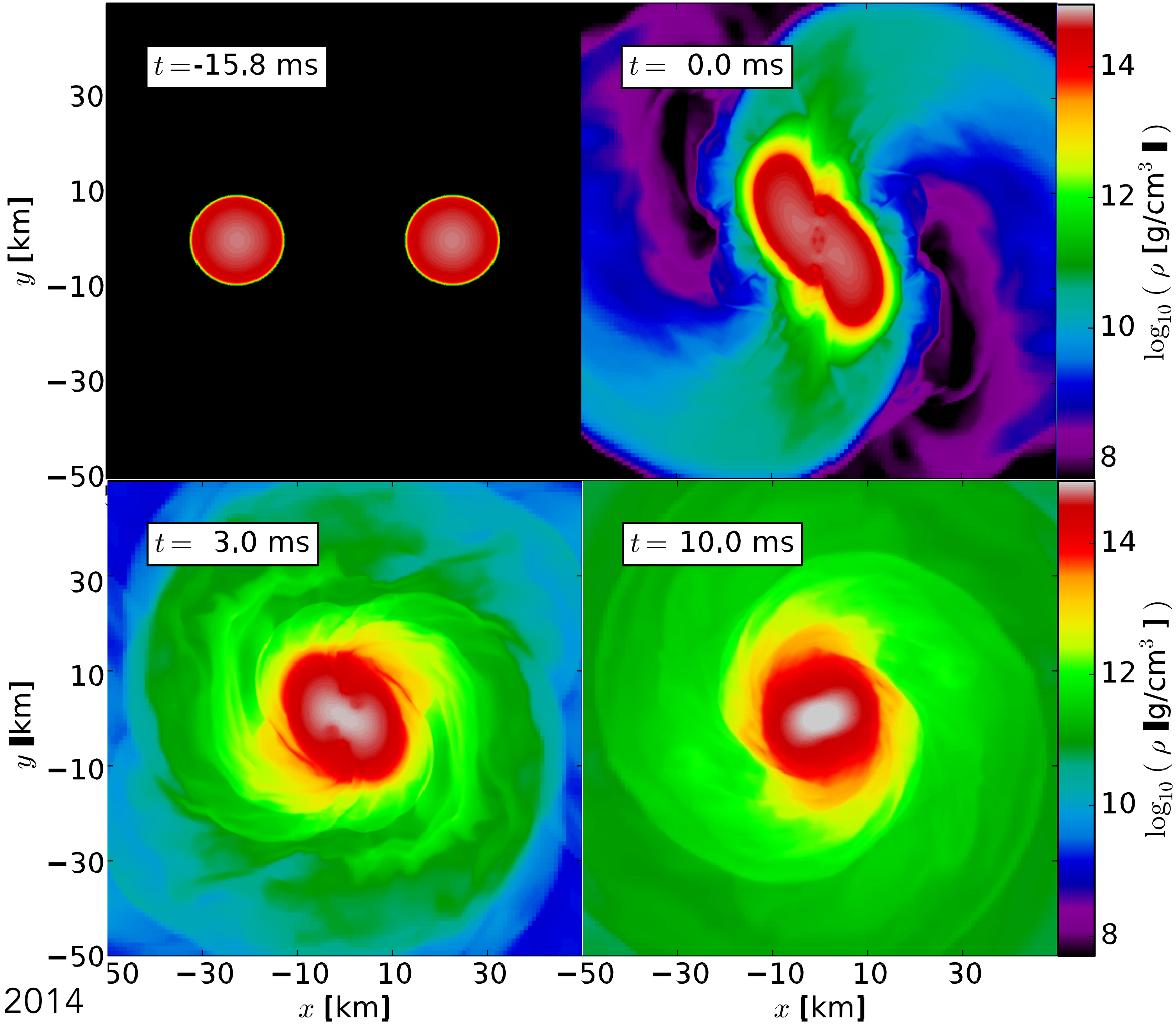
Arvanitaki et al.,
Phys. Rev. D 95, 043001 (2017)

Measuring the EOS of dense nuclear matter



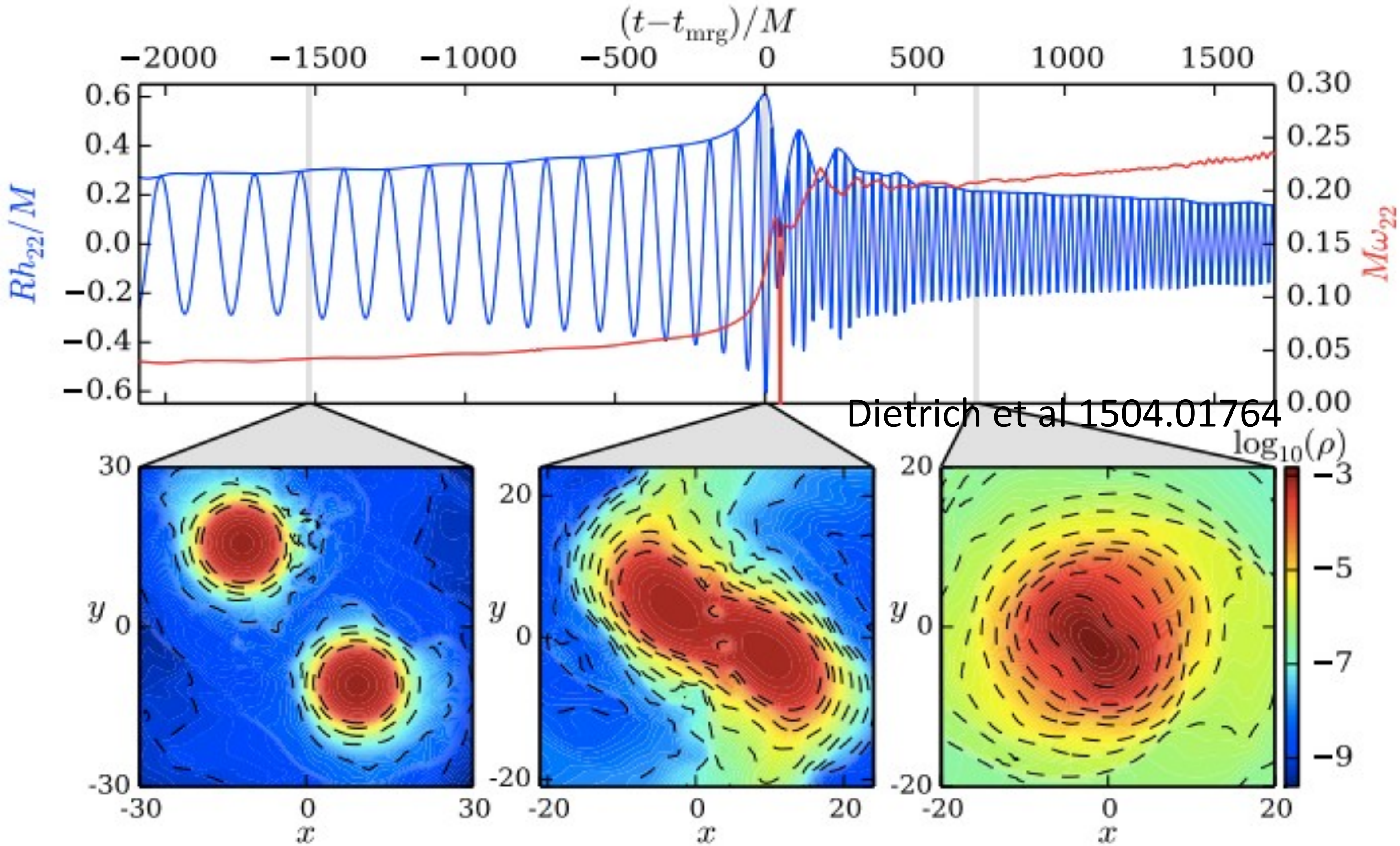
Densities ~ 4 x10^{17} kg/m^3

Binary Neutron Star Merger



Takami+ 2014

The waveform



Dietrich et al 1504.01764

- Tidal field ε of one companion induces a quadrupole moment Q in the other
- In the adiabatic approximation $Q_{ij} = - \lambda(m)\, \varepsilon_{ij}$ $\lambda(m) = 2/3\, k(m)\, R^5(m)$

λ(m) ➔ tidal deformability (size of the quadrupole deformation/strength of external field),
$k_2(m)$ ➔ Love number, R ➔ NS radius

Waveform: Tidal term +…….

A contribution at 5 PN ➔ $(v/c)^5$

$$\Psi(v) = \Psi_{\rm PP}(v) + \Psi_{\rm tidal}(v),$$

$$\begin{aligned}\Psi_{\rm tidal}(v) \; = \; & \frac{3}{128\eta} v^{-5} \sum_{A=1}^{2} \frac{\lambda_A}{M^5 X_A} \Big[-24\left(12 - 11X_A\right) v^{10} \\ & + \frac{5}{28}\left(3179 - 919X_A - 2286X_A^2 + 260X_A^3\right) v^{12} \\ & + 24\pi(12 - 11X_A) v^{13} \\ & -24\left(\frac{39927845}{508032} - \frac{480043345}{9144576} X_A + \frac{9860575}{127008} X_A^2 \right. \\ & \left. - \frac{421821905}{2286144} X_A^3 + \frac{4359700}{35721} X_A^4 - \frac{10578445}{285768} X_A^5 \right) v^{14} \\ & + \frac{\pi}{28}\left(27719 - 22127X_A + 7022X_A^2 - 10232X_A^3\right) v^{15} \Big]\end{aligned}$$

$X_A = m_A/M, \; A = 1,2, \;$ and $\; \lambda_A = \lambda(m_A)$

$X_A = m_A/M, \; A = 1,2, \;$ and $\; \lambda_A = \lambda(m_A)$

..........Quadrupolar Term

$$\Psi_{\mathrm{QM}}(v) = -\frac{30}{128\eta}\sigma_{\mathrm{QM}} v^{-1},$$

$$\sigma_{\mathrm{QM}} = -\frac{5}{2}\sum_{A=1,2} q_A \left(\frac{m_A}{M}\right)^2 \left[3(\hat{\chi}_A \cdot \hat{L})^2 - 1\right]$$

$$\simeq \frac{5}{2}\sum_{A=1,2} a(m_A) \left(\frac{m_A}{M}\right)^2 \left[3(\hat{\chi}_A \cdot \hat{L})^2 - 1\right] \chi_A^2$$

$$q \simeq -a\chi^2,$$

$$\mathcal{C} = 0.371 - 3.91 \times 10^{-2} \ln \frac{\lambda}{m^5} + 1.056 \times 10^{-3} \left(\ln \frac{\lambda}{m^5}\right)^2$$

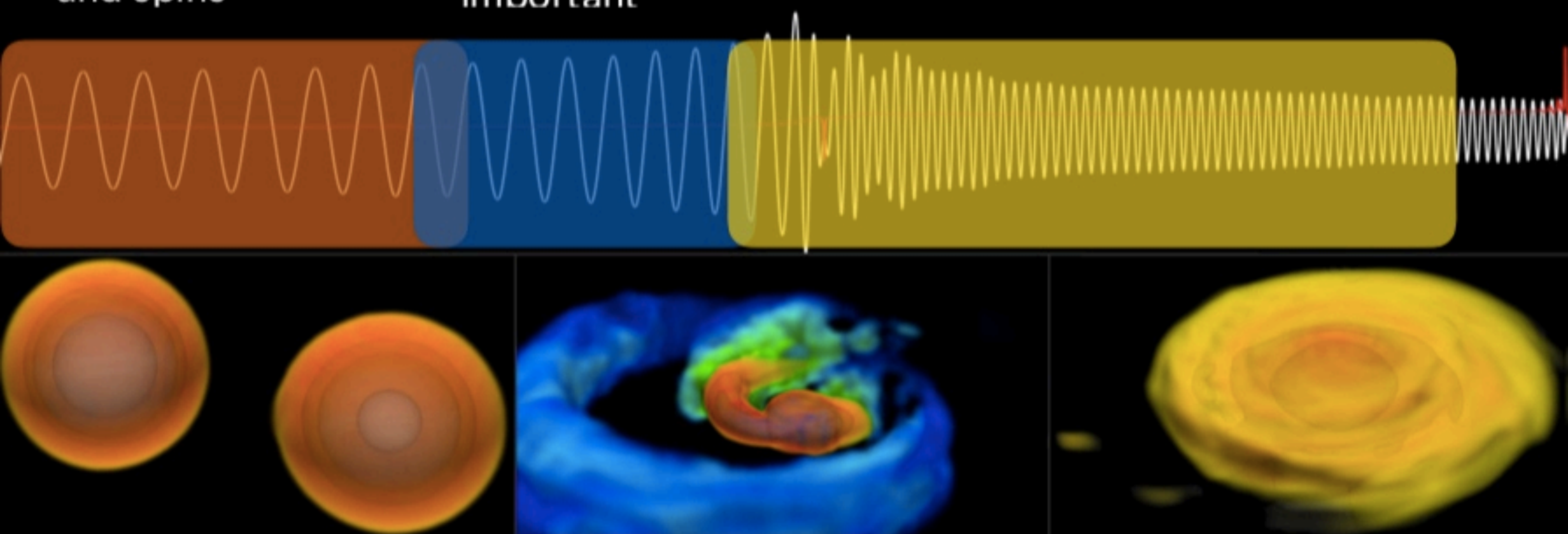
PHYSICAL EFFECTS IN BINARY NEUTRON STAR COALESCENCE WAVEFORMS

Credits: Sebastiano Bernuzzi

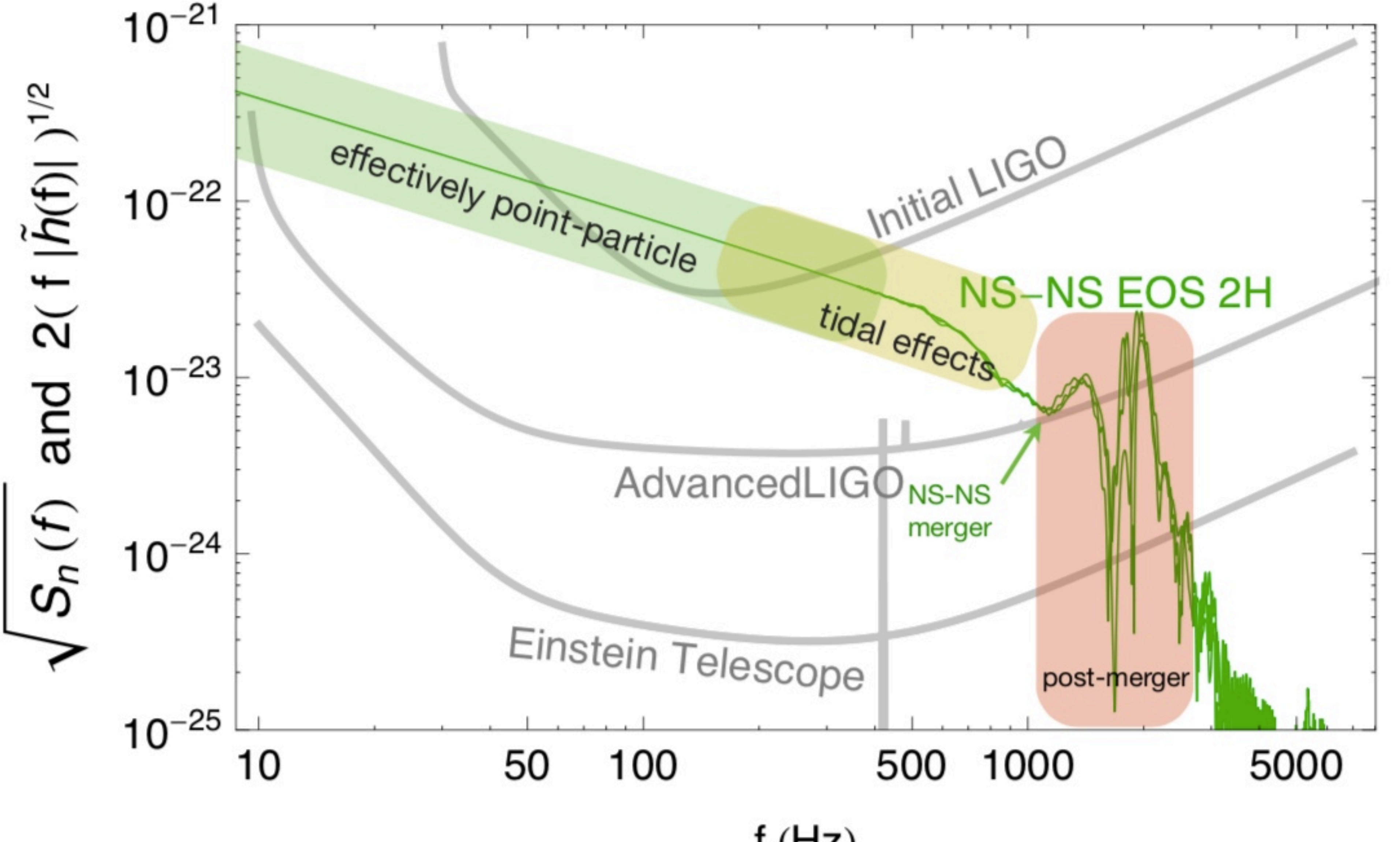
dominated by gravitational radiation back reaction - masses and spins

tidal effects appear at high PN order, dynamical tides might be important

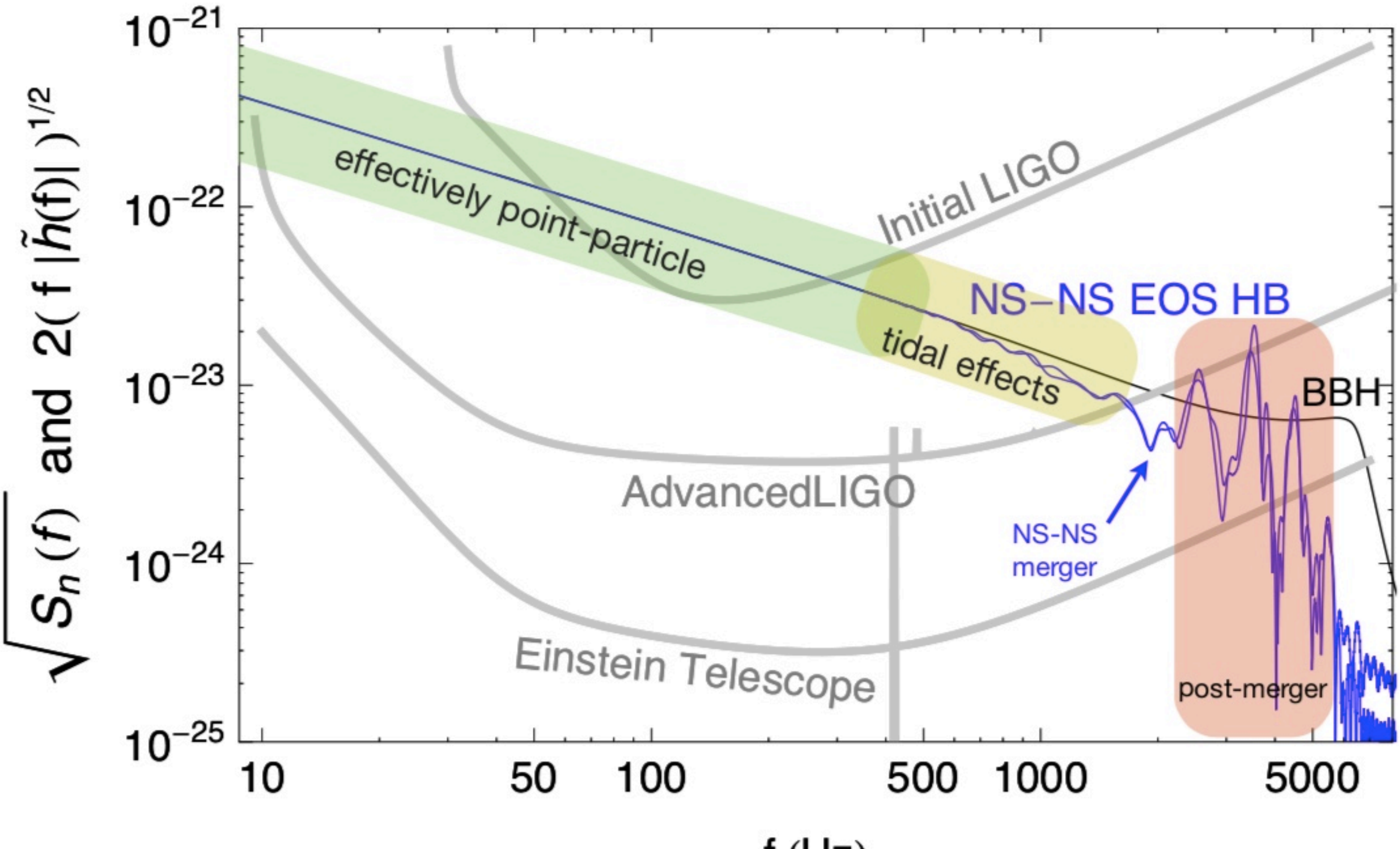
complex physics of the merger remnant, multi-messenger source, signature of neutron star EoS



Hard NS EOS


$\sqrt{S_n(f)}$ and $2(f\,|\tilde{h}(f)|)^{1/2}$
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
effectively point-particle
Initial LIGO
tidal effects
NS–NS EOS 2H
AdvancedLIGO
NS-NS
merger
Einstein Telescope
post-merger
10
50
100
500
1000
5000
f (Hz)

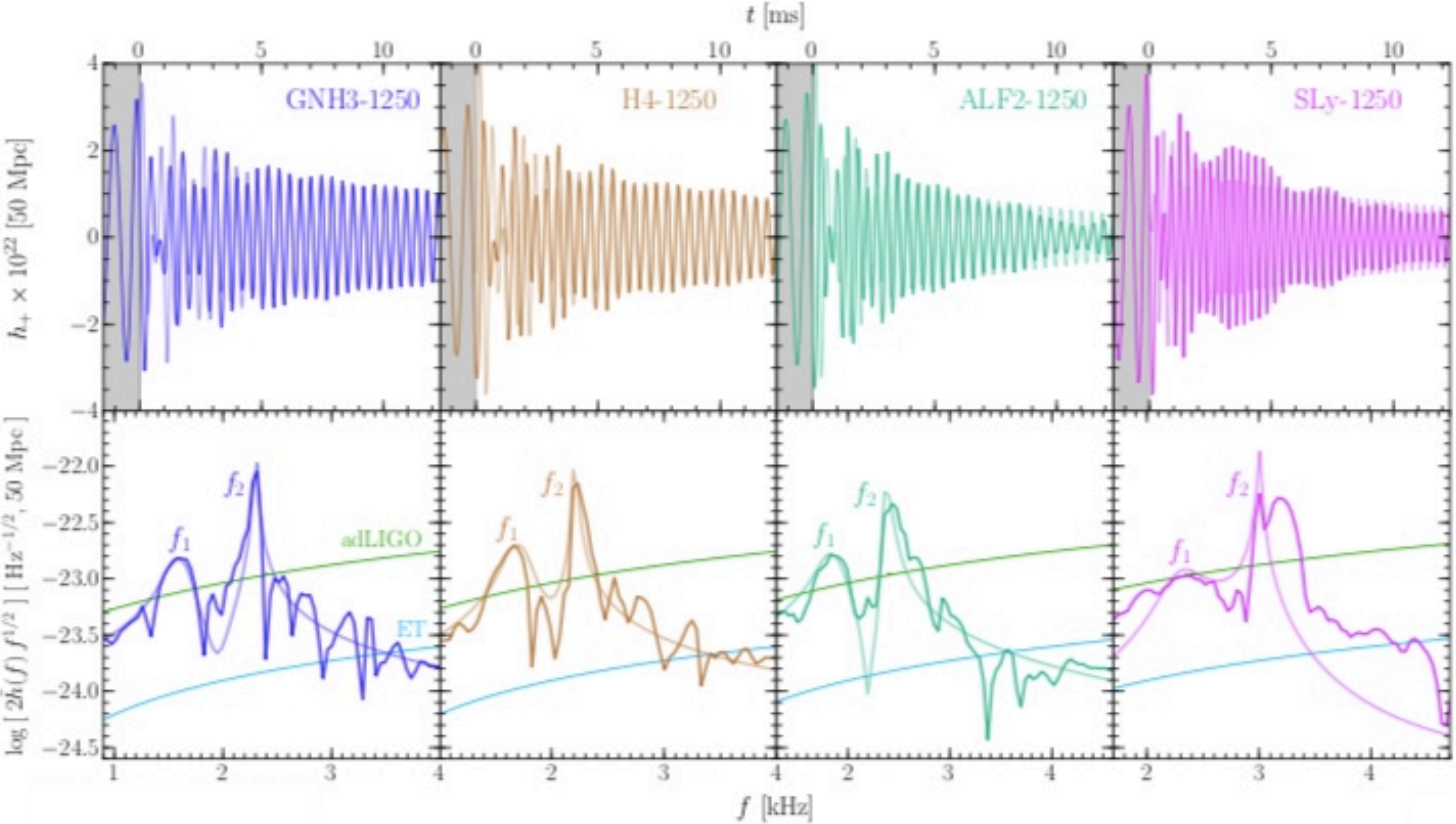
Soft NS EOS



10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
$\sqrt{S_n(f)}$ and $2(f\,|\tilde{h}(f)|)^{1/2}$
effectively point-particle
Initial LIGO
NS−NS EOS HB
tidal effects
BBH
AdvancedLIGO
NS-NS
merger
Einstein Telescope
post-merger
10
50
100
500
1000
5000

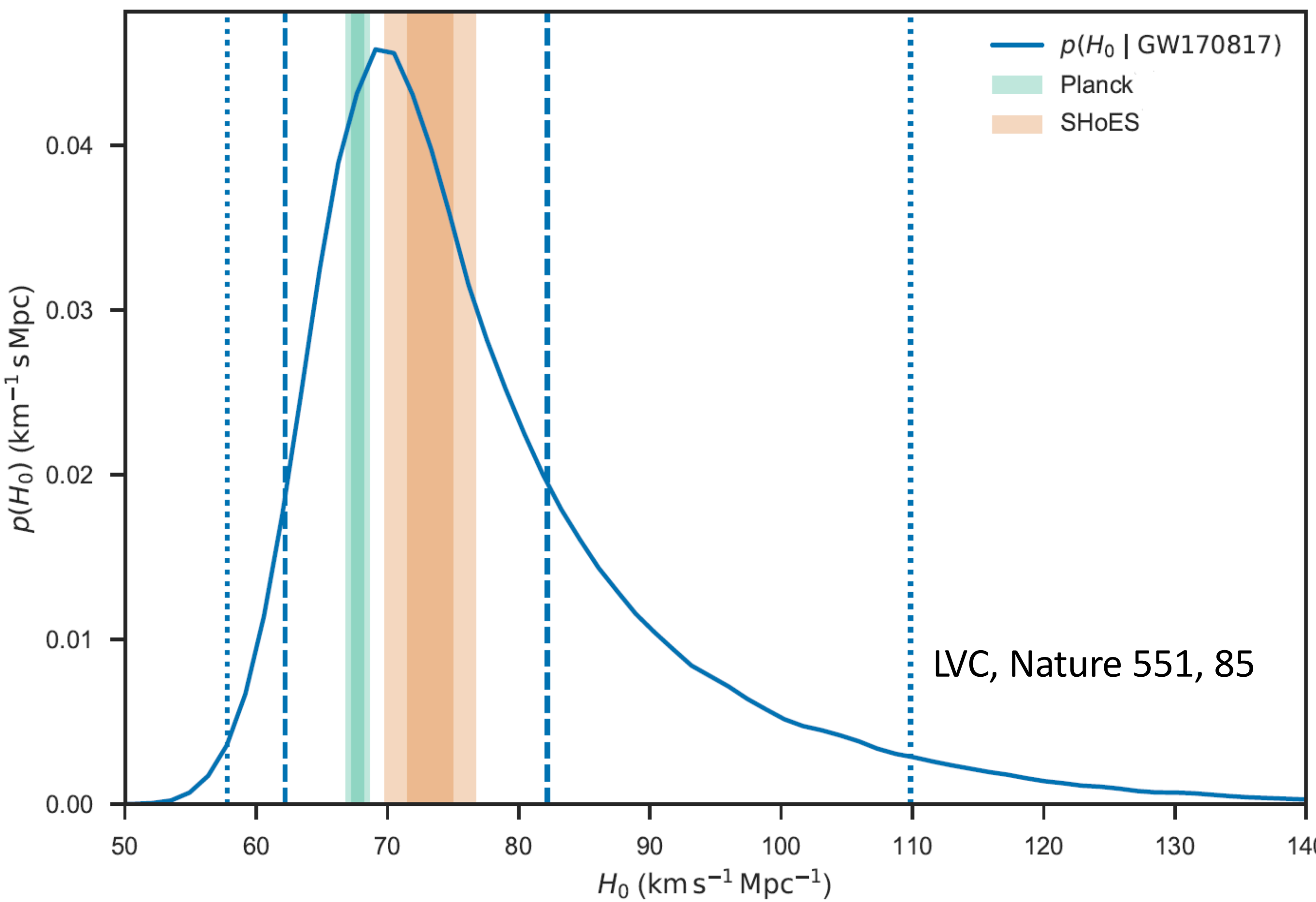
Post Merger Modelling

$$h(t) = \alpha \exp(-t/\tau_1)\left[\sin(2\pi f_1 t) + \sin(2\pi(f_1 - f_{1\epsilon})t) + \sin(2\pi(f_1 + f_{1\epsilon})t)\right] + \exp(-t/\tau_2)\sin(2\pi f_2 t + 2\pi\gamma_2 t^2 + \pi\beta_2).$$



GW170817: first result on cosmology

•LVC measurement ➔ 14% (1σ) uncertainty
- ~11% GW luminosity distance
- ~3% peculiar velocity of the galaxy



Cosmology

To measure the cosmology one needs luminosity distance *and* redshift of the source

$$D_L(z) = \begin{cases} \frac{(1+z)}{\sqrt{\Omega_k}} \sinh[\sqrt{\Omega_k} \int_0^z \frac{dz'}{H(z')}] & \text{for} \quad \Omega_k > 0 \\ (1+z) \int_0^z \frac{dz'}{H(z')} & \text{for} \quad \Omega_k = 0 \\ \frac{(1+z)}{\sqrt{|\Omega_k|}} \sin[\sqrt{|\Omega_k|} \int_0^z \frac{dz'}{H(z')}] & \text{for} \quad \Omega_k < 0 \end{cases}$$

$$H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_k (1+z)^2 + \Omega_\Lambda E(z, w(z))}$$

$$E(z, w(z)) = (1+z)^{3(1+w_0+w_1)} e^{-3w_1 z/(1+z)}$$

Usually, GWs provide the distance

How do we get the redshift?

How to get the redshift information

- If the CBC produces an EM counterpart (e.g. GRB) (Sathyaprakash+ CQG 27 215006, Nissanke+ 1307.2638)
- If one knows the neutron star (NS) equation of state (Read & Messenger PRL 108 091101; Del Pozzo+ 1506.06590)

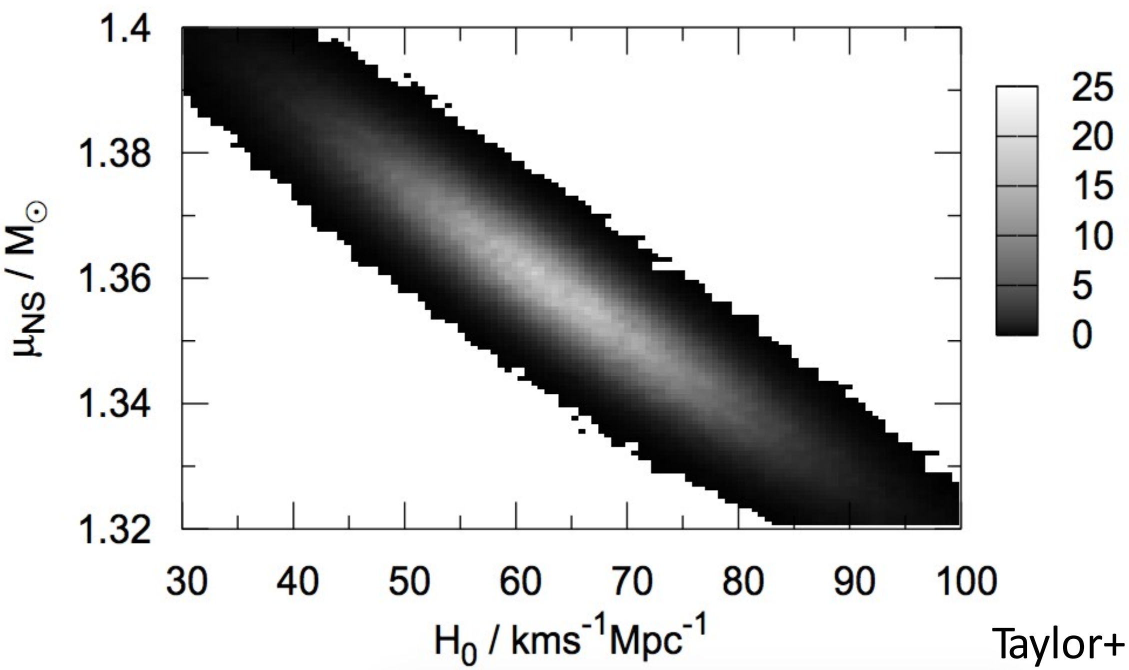
  GW phase encodes the equation of state of neutron stars and it depends on the source-frame masses. If the EOS is known through other means (EM) one can measure both source-frame and redshifted masses, hence get the redshift
- If the post-merger signal is observed (Messenger+ PRX 4, 041004)

  Compare the measured redshifted frequency of the post merger phase with expected frequency gives redshift.
- If the shape of NS mass distribution is known (Taylor+ PRD 85 023535; Taylor & Gair PRD 86, 023502)
- Even if no EM is found, but there is a reliable galaxy catalog (Schutz, Nature 1986, Del Pozzo PRD 86 043011)

Neutron stars mass distribution

- Neutron star masses are expected to lie in a narrow range

- If one knew the shape of mass distribution could compare measured (redshifted) masses with expected ones, and infer the redshift



Taylor+ PRD 85 023535

Conclusion

Conclusion

- The installation phase of the new parts is ended in Virgo and (almost) in LIGO
- We are back in the commissioning phase to prepare he new run that we plan to start at the beginning of 2019
- We prepared already plans for future upgrades a+ and AdV+ paving the way for the construction of the new 3 G detectors
- New GW detectors will open a new era in Astronomy and fundamental physics


Thanks for the attention
The future will be rich of new surprises and conundrums to be solved

Extra Slides

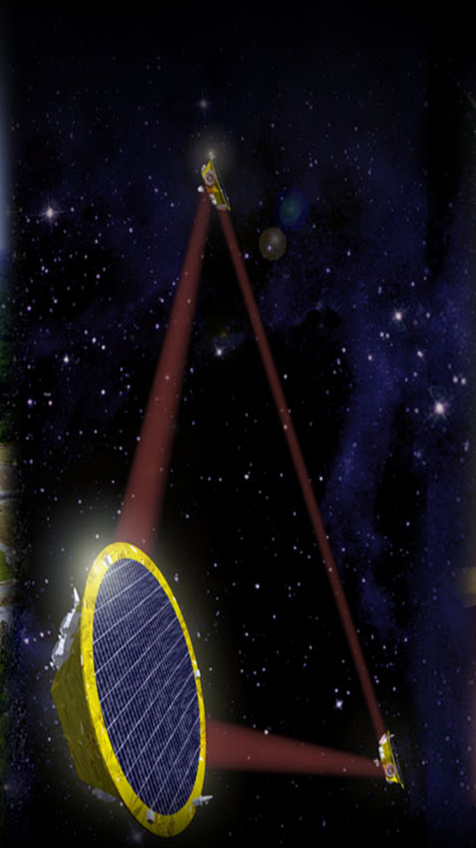
Gravitational Wave Periods

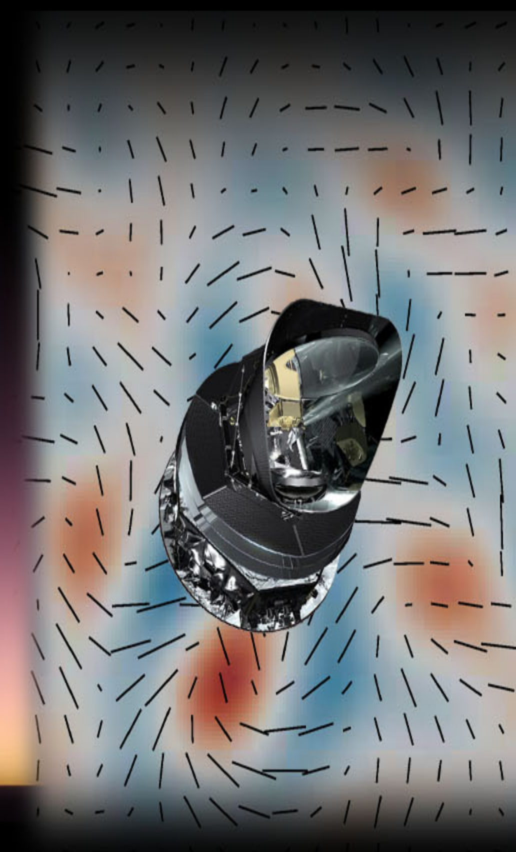
Milliseconds

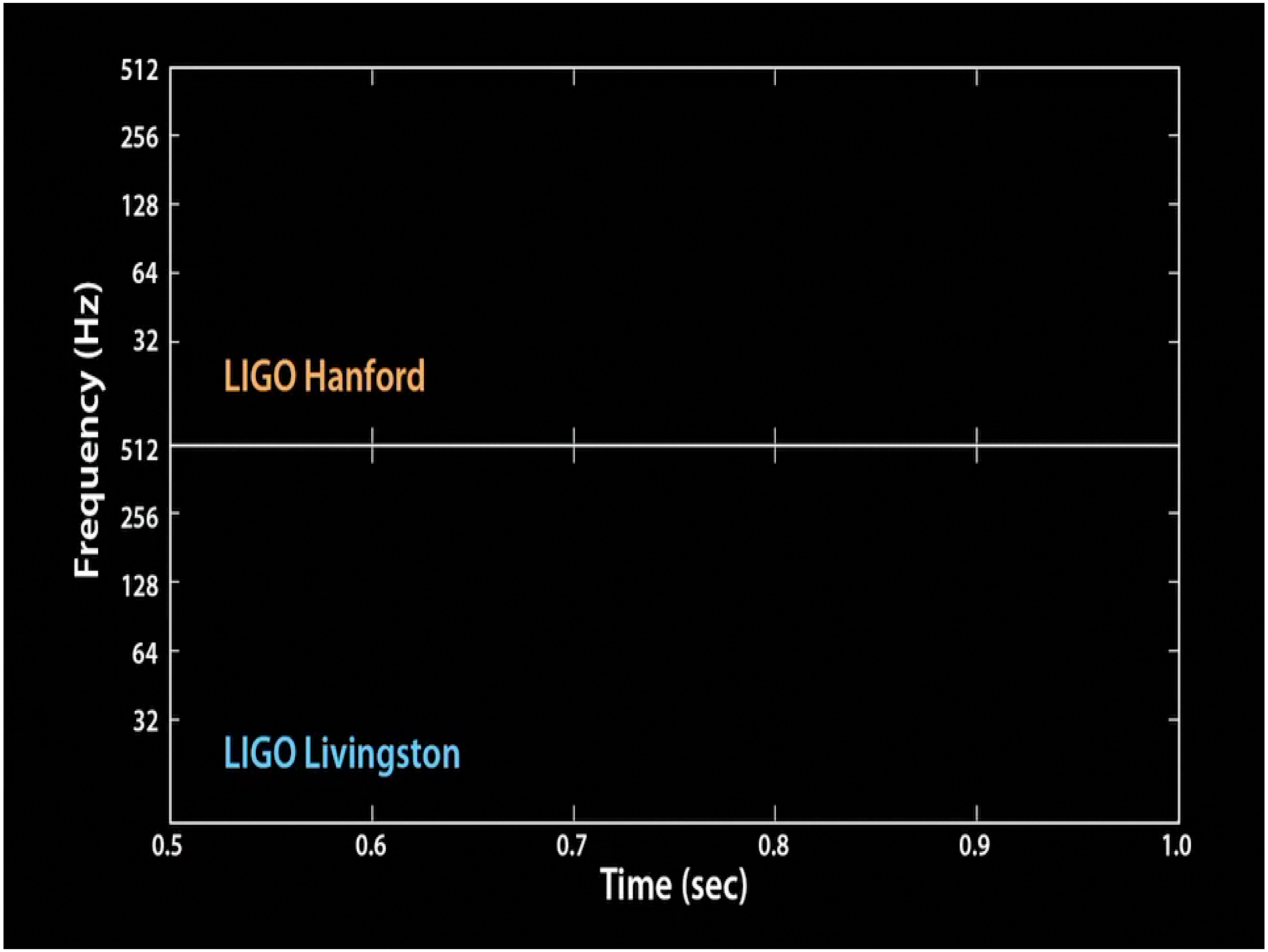
Minutes to Hours

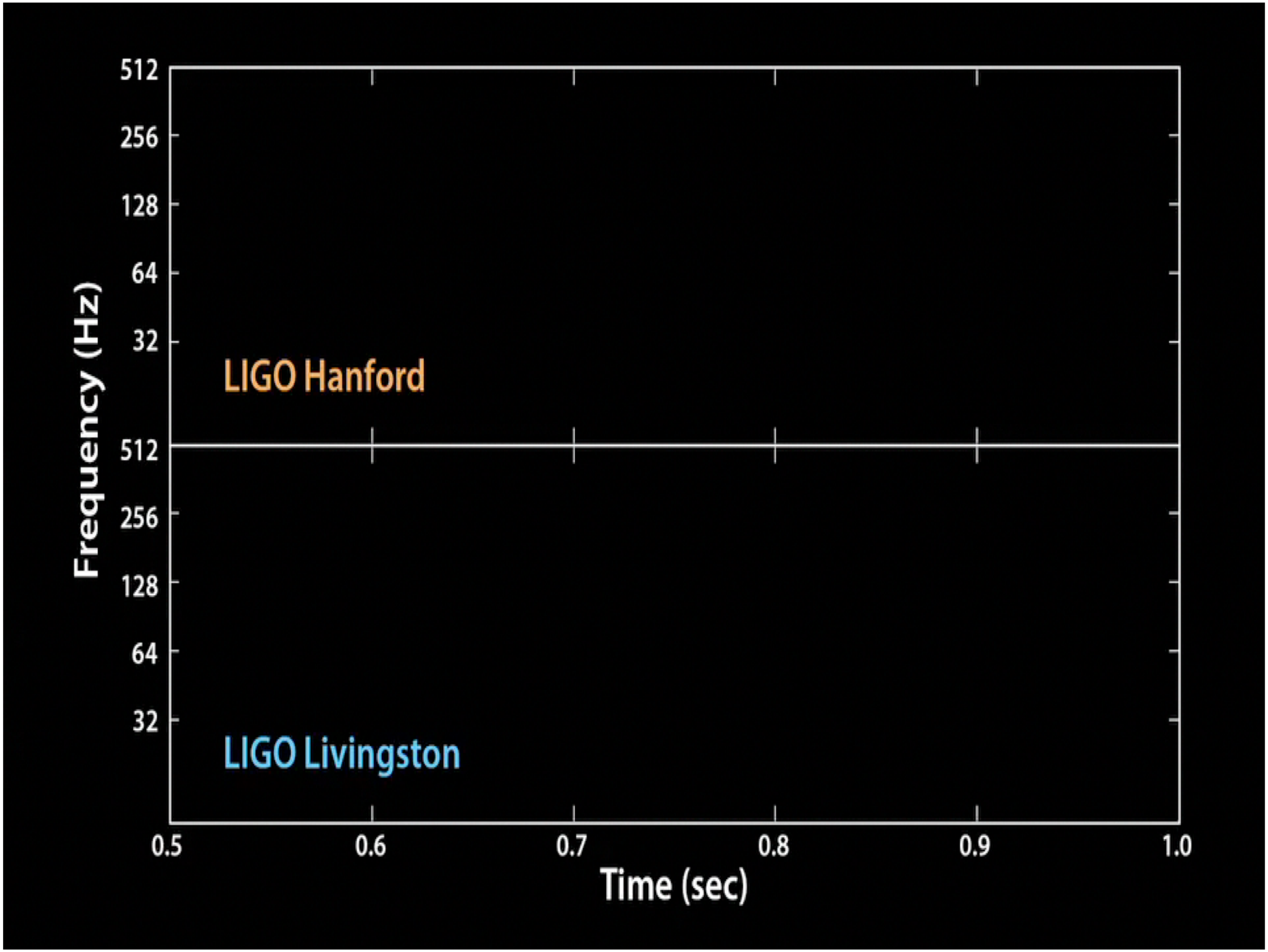
Years to Decades

Billions of Years






512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)


512
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LIGO Hanford
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