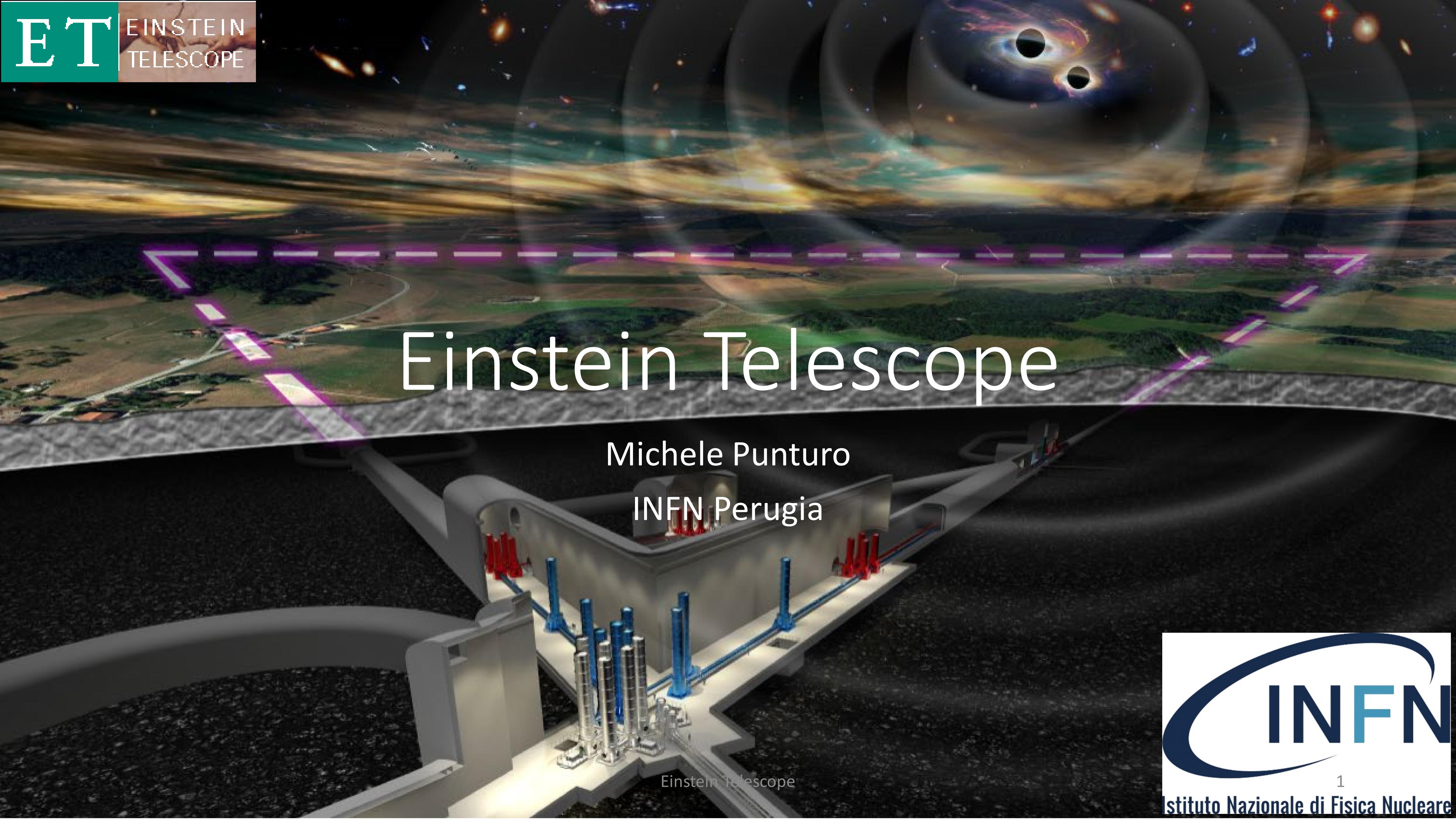


Einstein Telescope

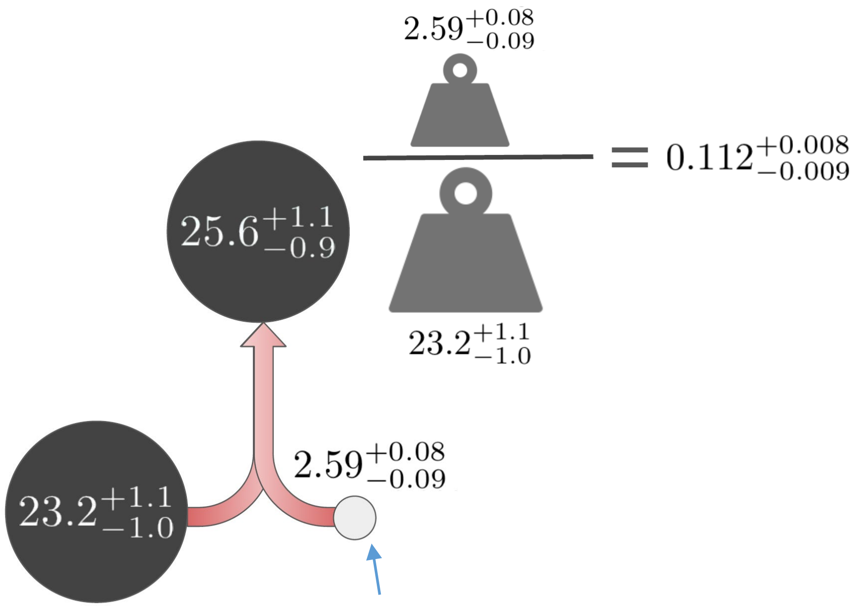
Michele Punturo

INFN Perugia

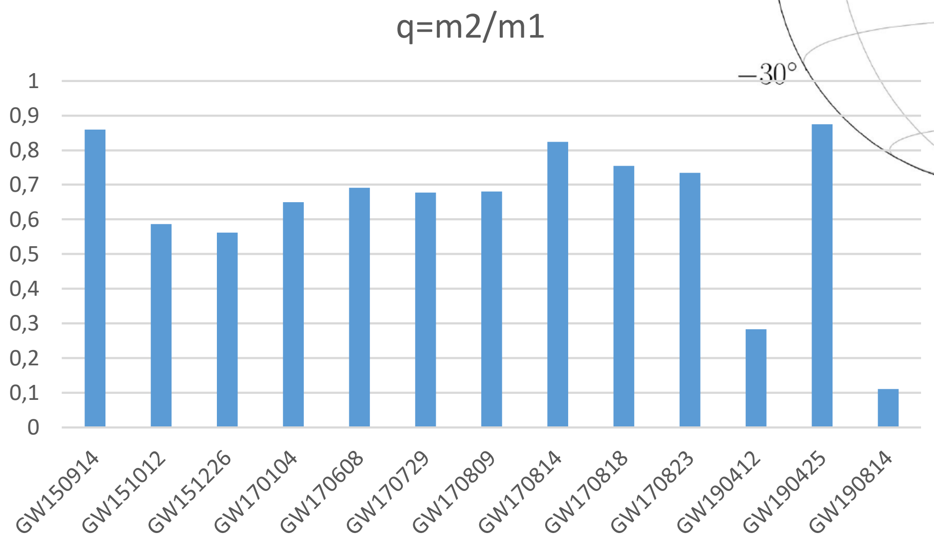
Let start from the Advanced detectors

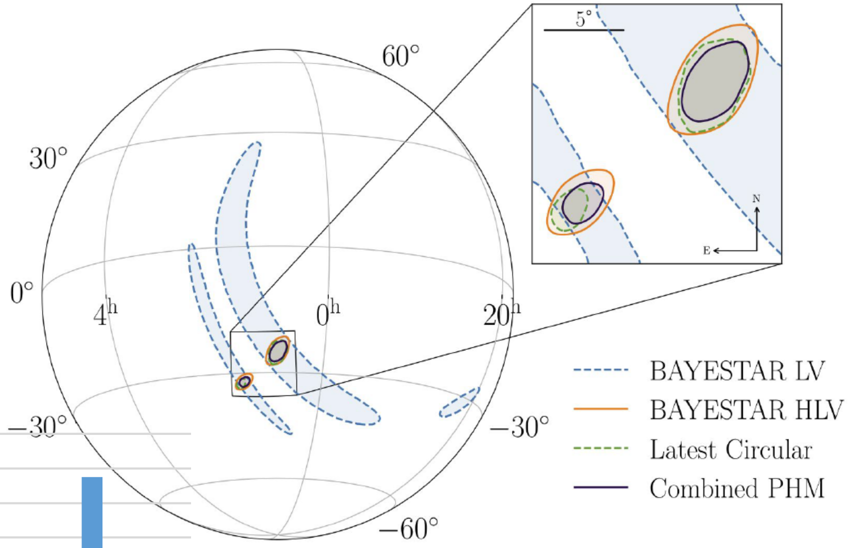
GW190814 – Loud event

- Detected online by Livingstone and Virgo, Hanford in commissioning mode, but undisturbed
  - Hanford data recovered offline
  - Best localised source (green skymap 23 deg^2)
  - The most mass asymmetric GW event detected



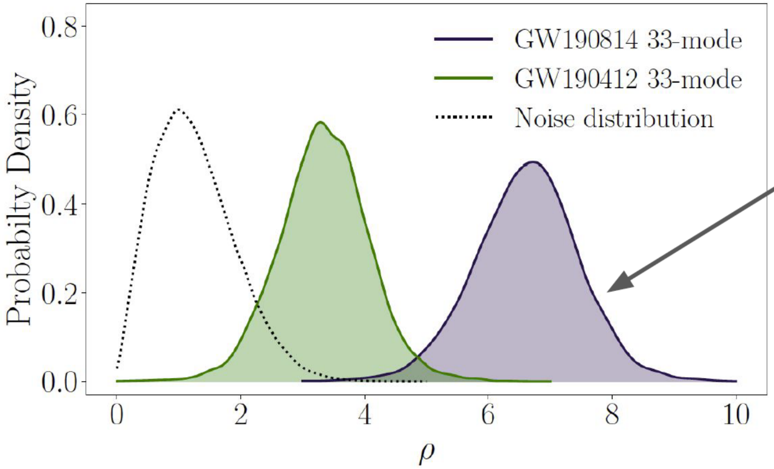
What is M_2?



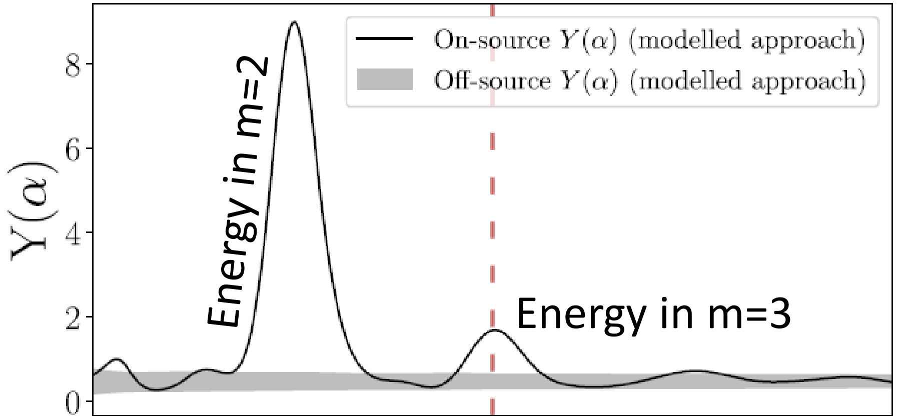


GW190814 – Higher order multipoles

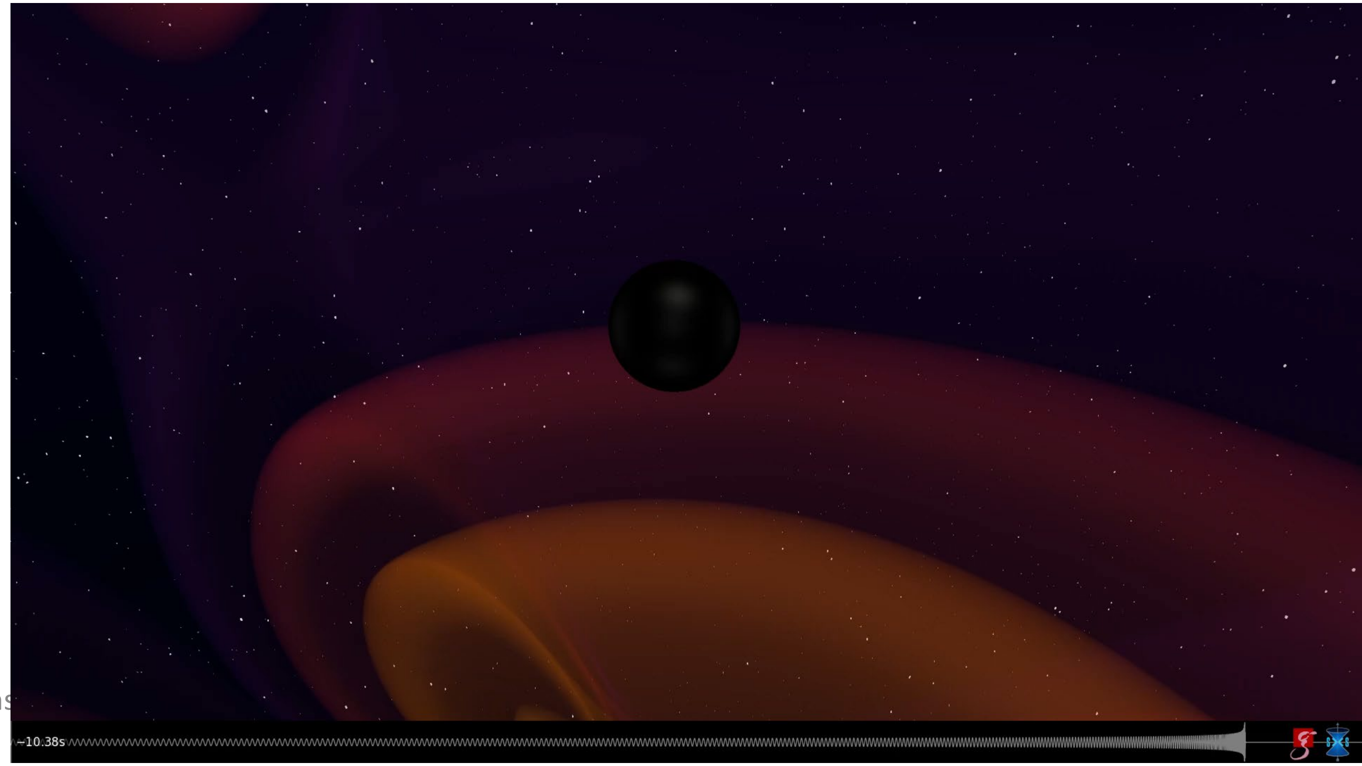
- Being the mass distribution so asymmetric:



GW190814 has the strongest evidence for Higher order multiples that we have ever detected.



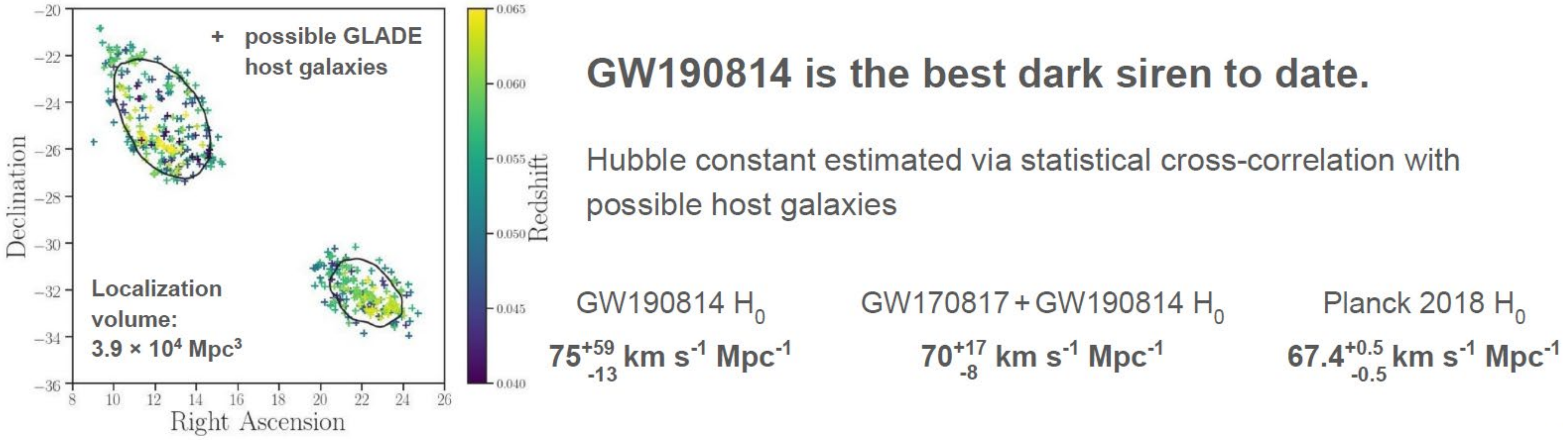
SNR in 33 multipole nearly as high as the total SNR of GW151012



- Test of GR on strongly asymmetric mass distribution (GR “validated”)

GW190814 - Cosmology with GW signal only

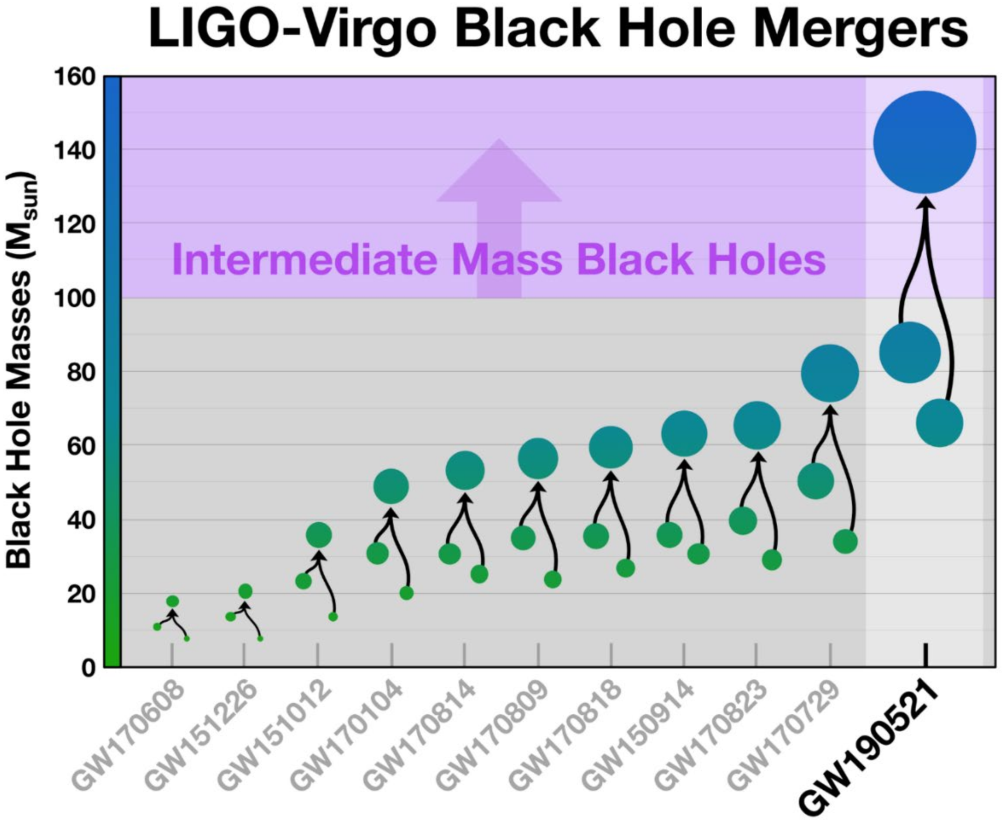
- The localisation of GW190814 is so good that it is possible to attempt a H_0 measurement only with GW signal (and galaxies catalogues):



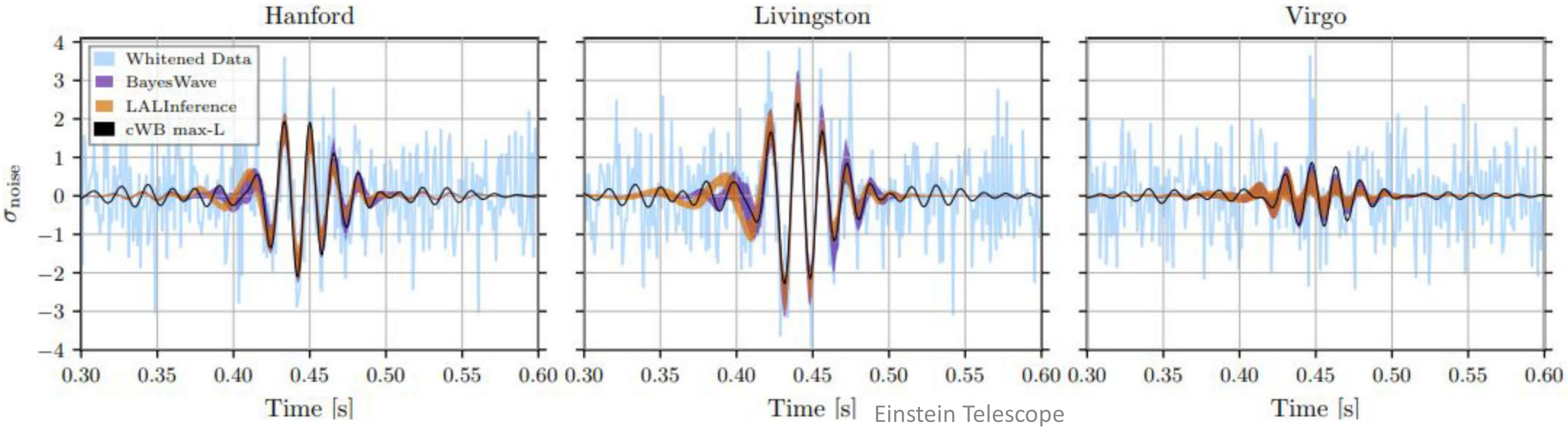
GW190521

$M_1 = 85^{+21}_{-14} M_\Theta$, $M_2 = 66^{+17}_{-18} M_\Theta$
at $z \sim 0.82$ (5.3Gpc)
Remnant $M_f = 142^{+28}_{-16} M_\Theta$

- Very special event:
  - M_1, the black hole that should not exist
  - M_f, the first IMBH ever seen

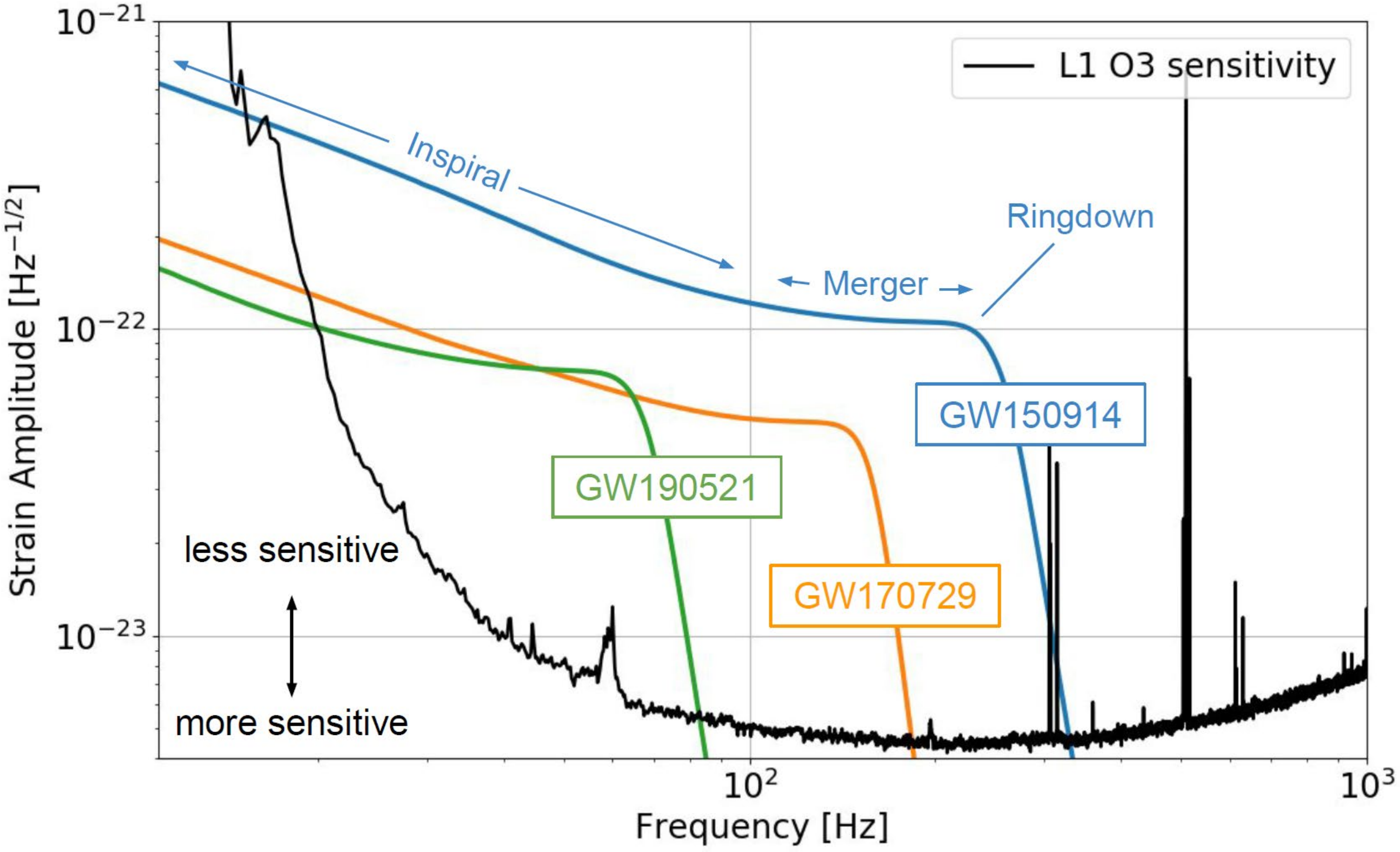


Phys. Rev. Lett. 125, 101102 (2020)
Astrophys. J. Lett. 900, L13 (2020)



Where is the chirp?

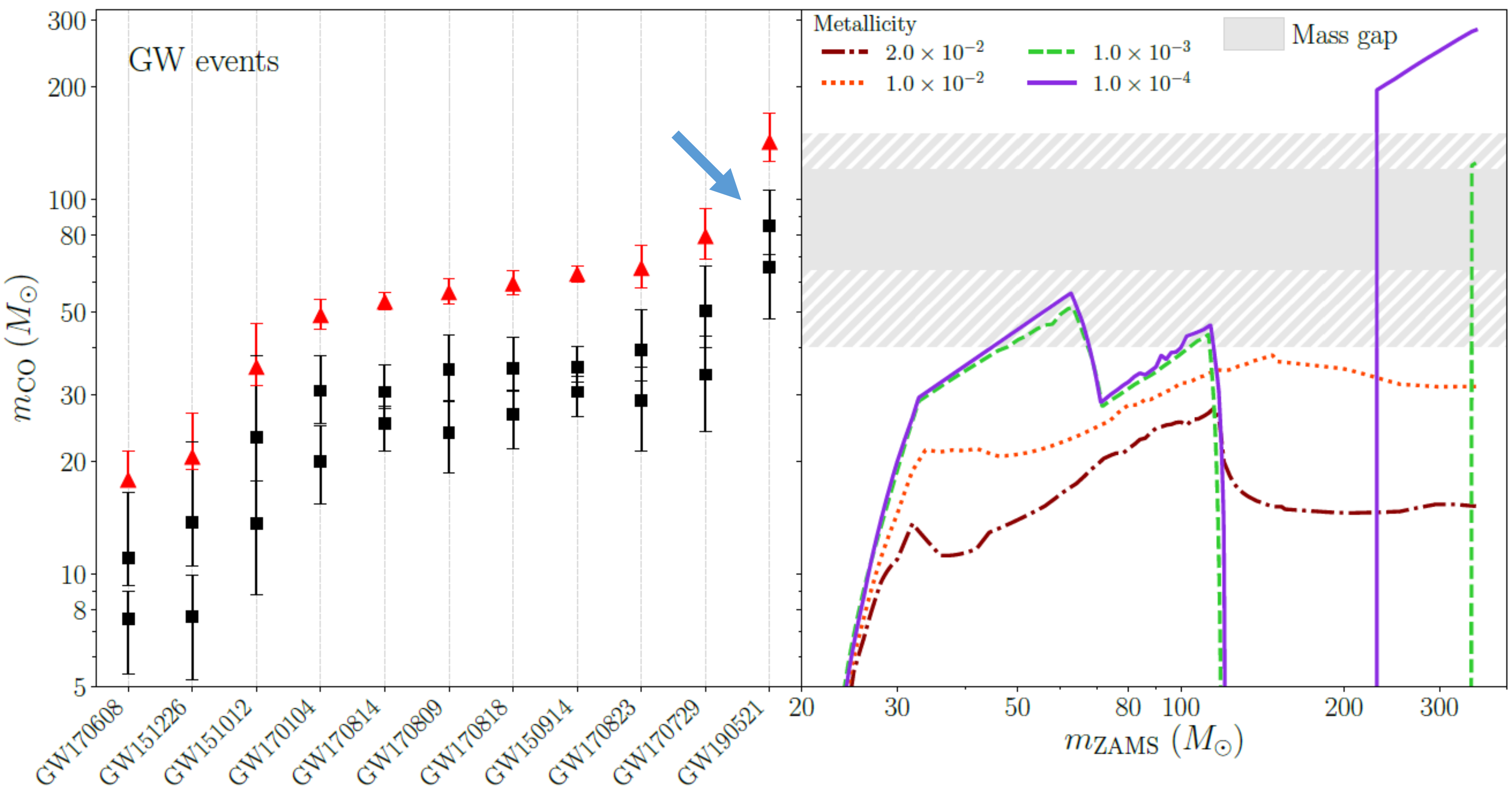
GW190521: LIGO-Virgo sensitivity to the BBH merger



- Higher masses correspond to lower frequency GW emission

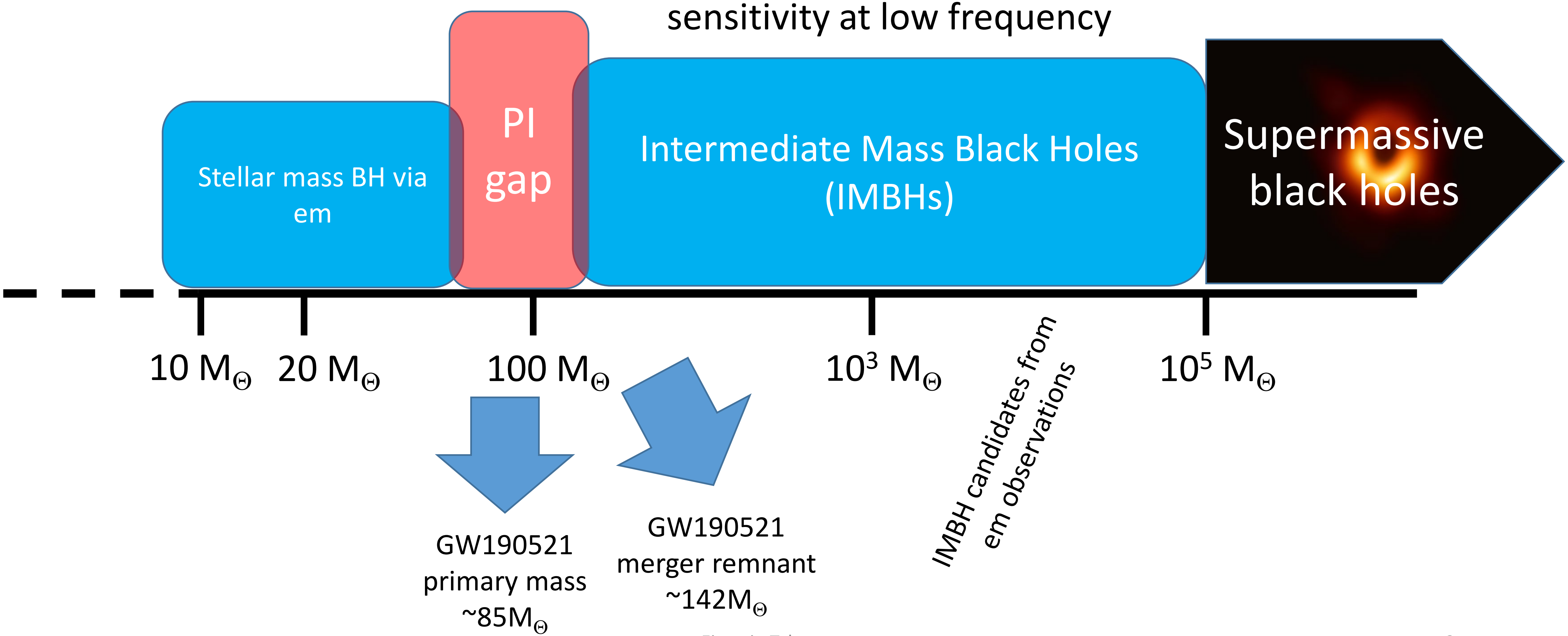
GW190521: M_1, what is that?

- M_1 has a mass of $M_1 = 85^{+21}_{-14} M_{\Theta}$
  - It falls in the upper gap for black hole formation, due to Pair Instability (PI) and Pulsation Pair Instability (PPI)



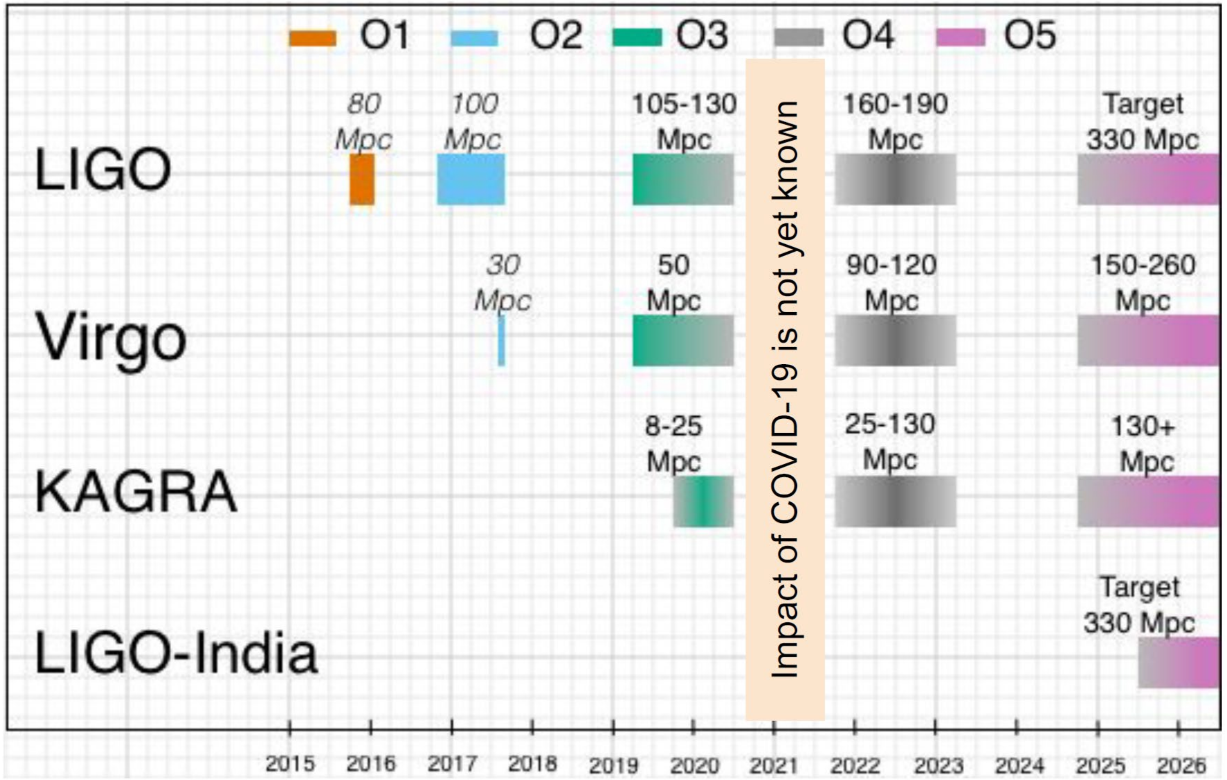
BH masses

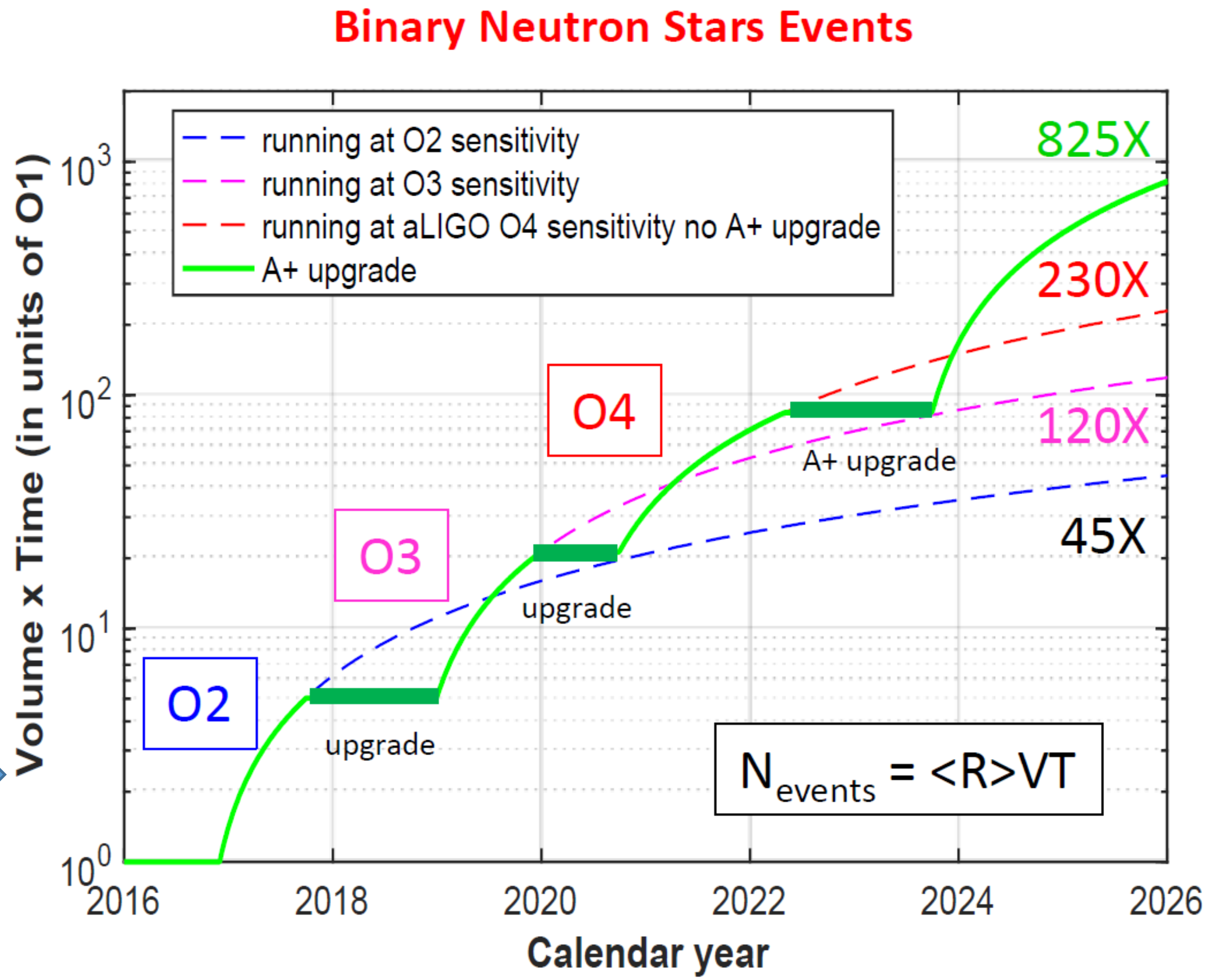
LIGO & Virgo will have marginal access to IMBH because of the “seismic wall” limiting the sensitivity at low frequency



Next Future

Plans for LIGO-KAGRA-Virgo runs





HEPP physicists?

Luminosity $\mathcal{L}$

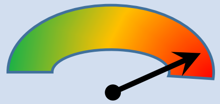
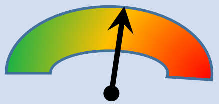
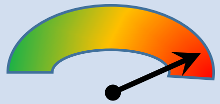
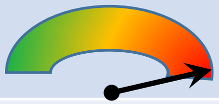
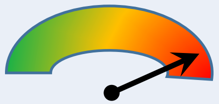
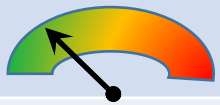
Branching ratio $\mathcal{R}$

- <R> average astrophysical rate
- V volume of the universe probed → $(\text{Range})^3$
- T coincident observing time

What Next?

2029 outlook

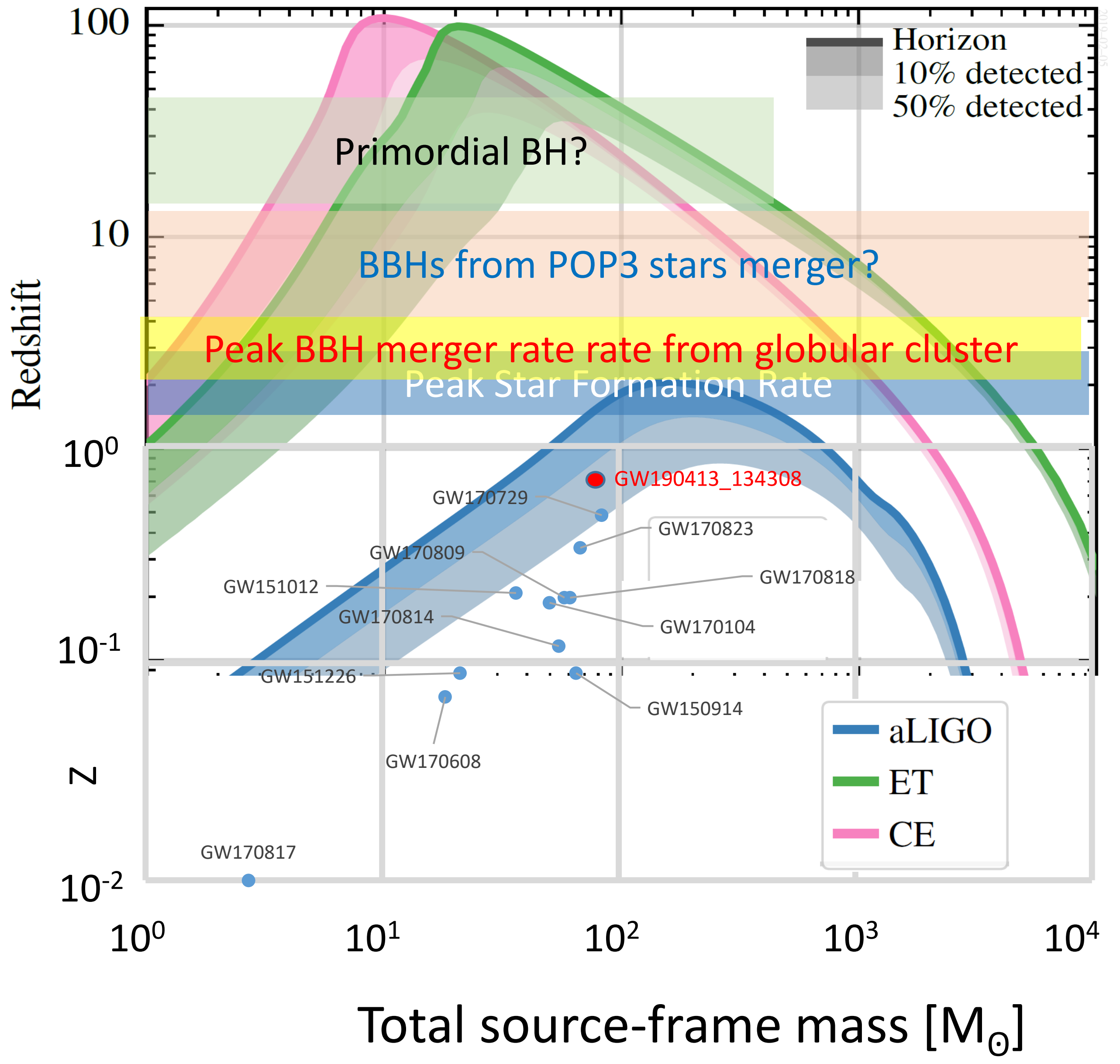
- In 2029 we will have a really heterogeneous 2.xG network
  - The concepts of “obsolescence” and “limit of the infrastructure”, that are driving the quest for new research infrastructures (rather more than a new detector) apply differently to the different continents

Continent	Detector	Obsolescence	Limits	
America	LIGO H1			
	LIGO L1			
Europe	GEO600			
	Virgo			
Asia	KAGRA			
	LIGO India			

OK, all done?

- aLIGO and AdV achieved awesome results with a reduced sensitivity
- When they will reach or over-perform their nominal sensitivity can we exploit all the potential of GW observations?

- 2nd generation GW detectors will explore local Universe, initiating the precision GW astronomy, but to have cosmological investigations a factor of 10 improvement in terms detection distance is needed



GWTC-1: A gravitational-wave transient catalog of compact binary mergers observed by LIGO and Virgo during the first and second observing runs - arXiv:1811.12907 [astro-ph.HE]

Detection distance of GWD

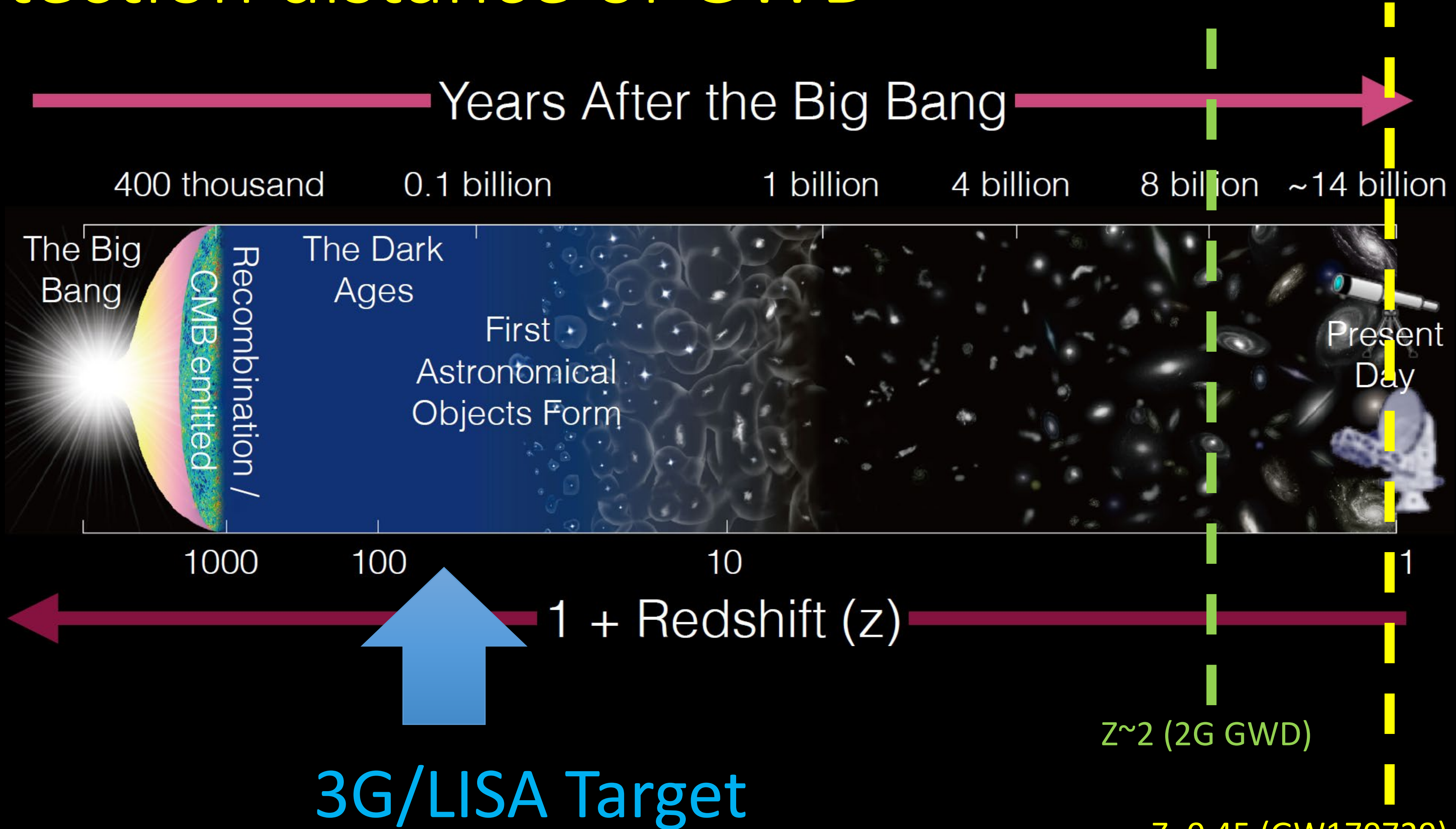
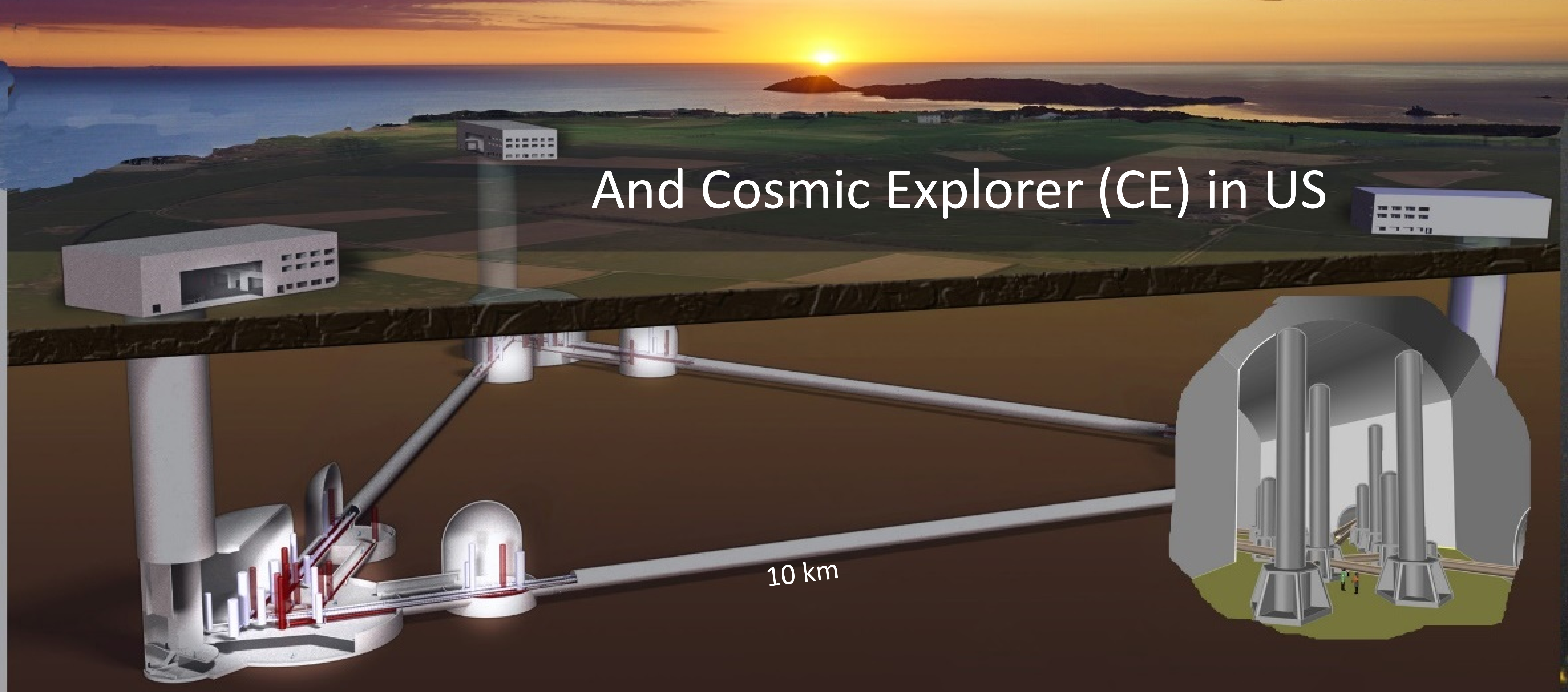


Image credit: NAOJ/ALMA http://alma.mtk.nao.ac.jp/

The Einstein Telescope

ET EINSTEIN TELESCOPE



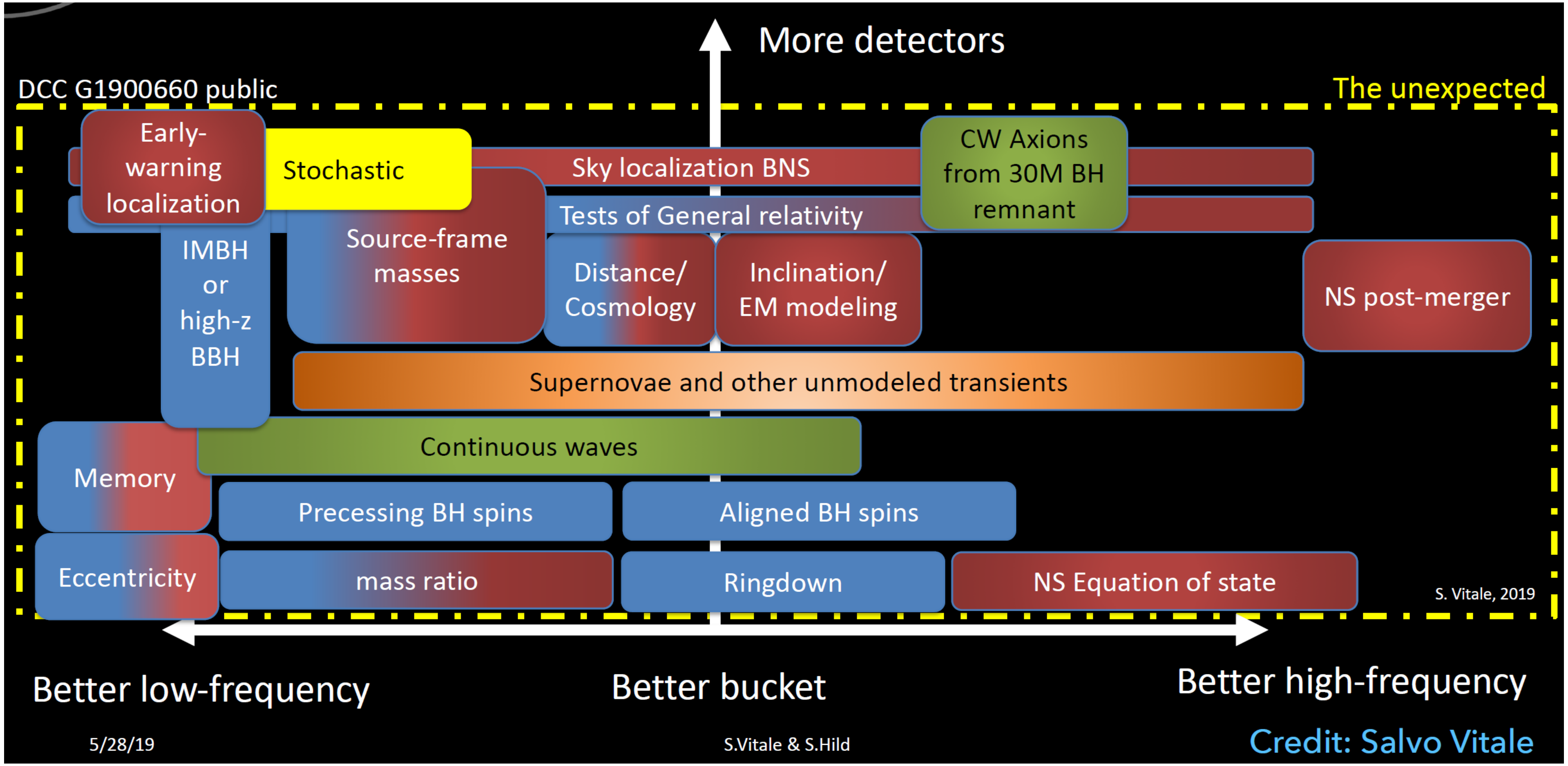
And Cosmic Explorer (CE) in US

The 3G/ET key points

- ET is THE 3G new GW observatory
    - 3G: Factor 10 better than advanced (2G) detectors
    - New:
        - We need a new infrastructures because
            - Current infrastructures will limit the sensitivity of future upgrades
            - In 2030 current infrastructures will be obsolete
    - Observatory:
        - Wide frequency, with special attention to low frequency (few HZ)
            - See later
        - Capable to work alone (characteristic to be evaluated in the international scenario)
            - (poor) Localization capability
            - Polarisations (triangle)
            - High duty cycle: redundancy
        - 50-years lifetime of the infrastructure
            - Compliant with the upgrades of the hosted detectors

Wideband or Narrow band?

- The design of the ET observatory is driven by the physics objectives
  - At what frequency are they?



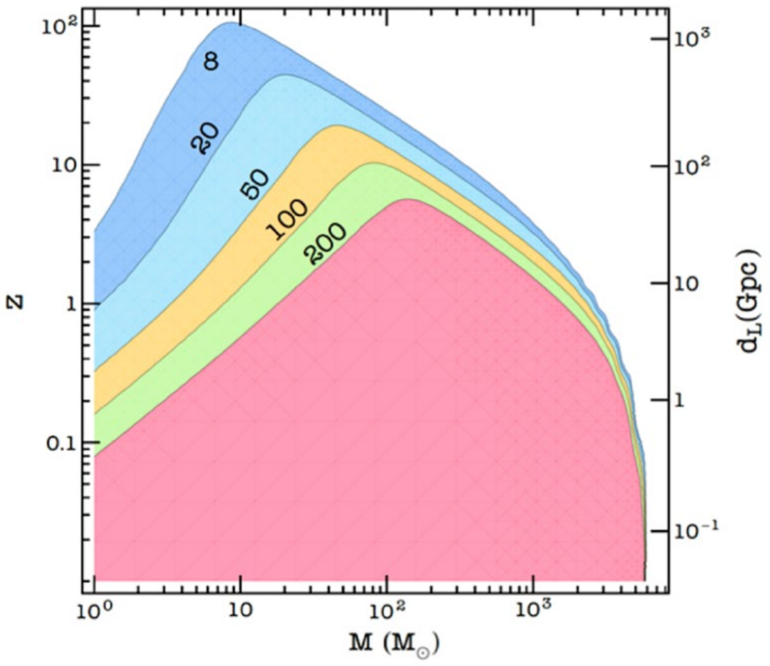
Everywhere!

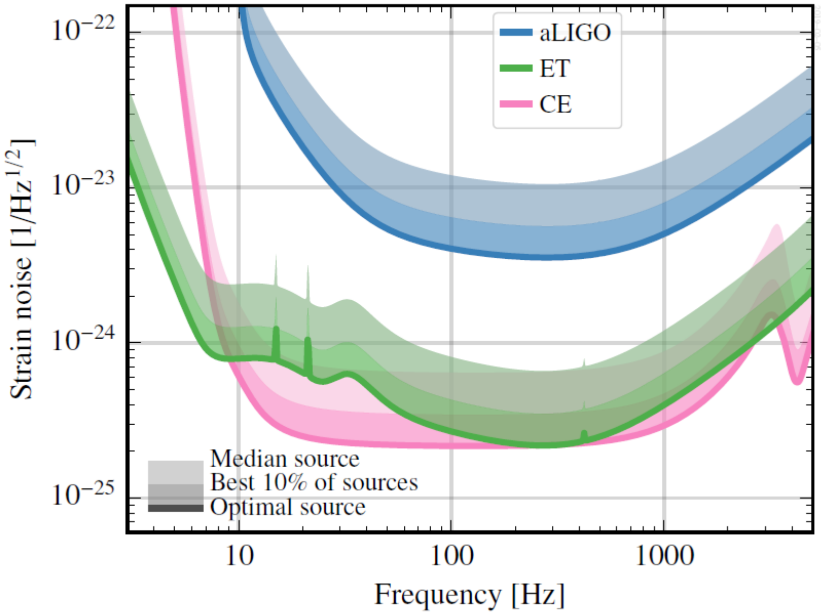
We need a wide band observatory

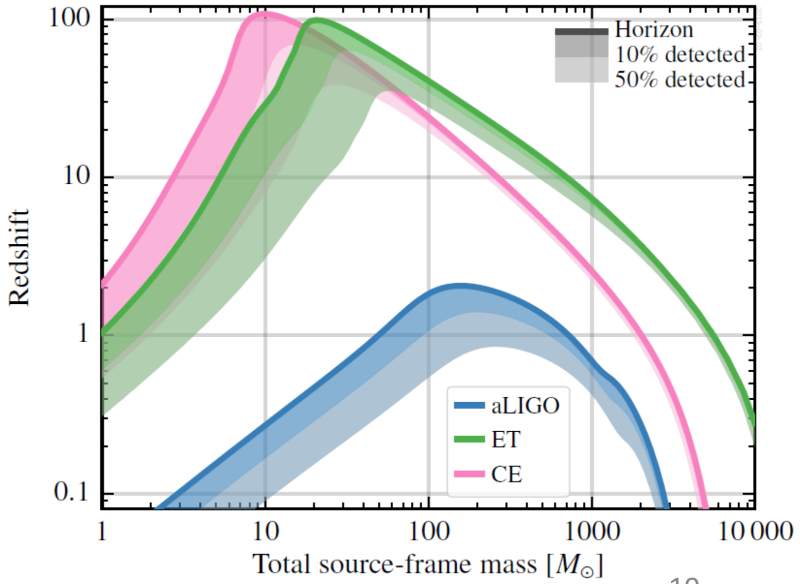
(with special attention to low frequency)

Key performances expected in ET

- BBH up to z~50
  - 10^6 BBH/year
  - Masses $M_T \gtrsim 10^3 M_\Theta$
- BNS to z~2
  - 10^5 BNS/year
  - Possibly O(10-100)/year with e.m. counterpart
- High SNR







ET science targets

- A recent science case study for ET is here:
  - M.Maggiore et al, JCAP, 2020, 03, pp.050. ⟨10.1088/1475-7516/2020/03/050⟩
  - Hereafter a short list

- Astrophysics
  - Black Hole physics
  - Neutron star physics
  - Multi-messenger astronomy
  - Core Collaps Sne
  - Isolated NS

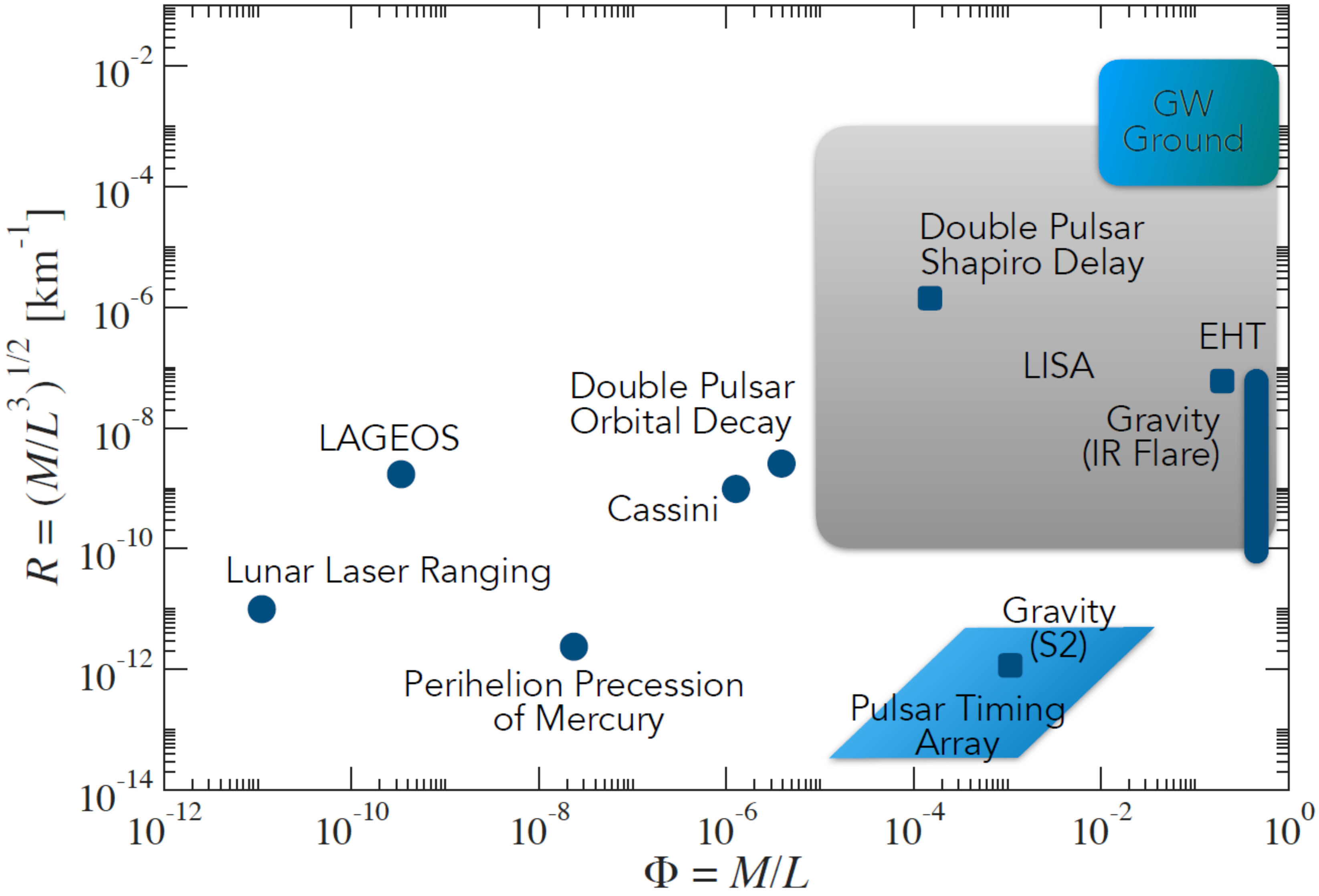
- Fundamental physics
  - Testing GR
    - Perturbative regime
      - Inspiral phase of BH, post Newtonian expansion
    - Strong field regime
      - Physics near BH horizon
      - Exotic objects
  - QCD
    - NS interior structure
  - Dark matter
    - Primordial black holes
    - Axions
  - Dark Energy
    - DE equation of state
    - Modified propagation of GW

- The “Unexpected”
  - ???

Probing GR in strong field conditions

- BBH coalescences allow to test GR in strong field conditions

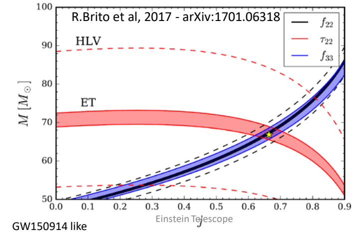
Yunes N. et al.
Phys. Rev. D 94, 084002 (2016)
Edited by ET science case team

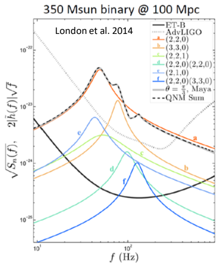


What I will **not** talk about

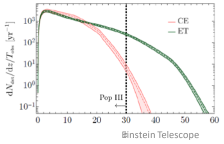
Probing multiple populations of BH: PBHs

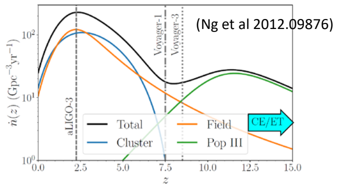
- We have different BBH populations:
  - binary stellar evolution in galactic fields
  - dynamical formation through multi-body interactions in star clusters or AGN

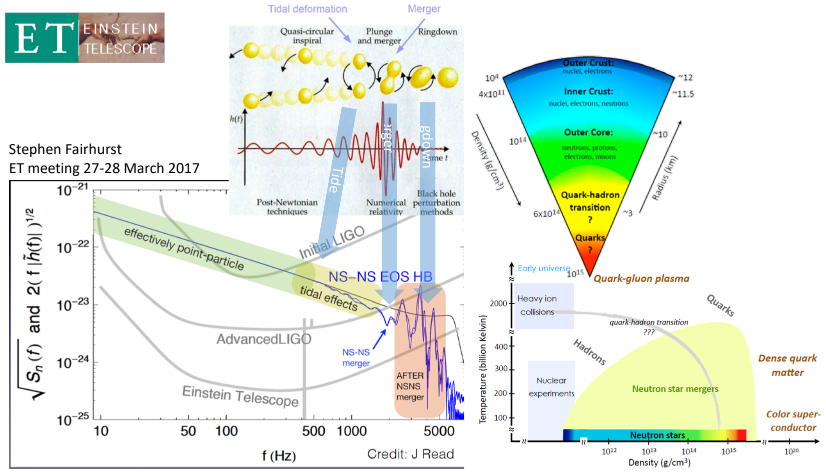




$N_{det}^{ET}(z > 30) = 1315^{+305}_{-168}\,\text{yr}^{-1}$







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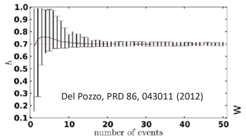
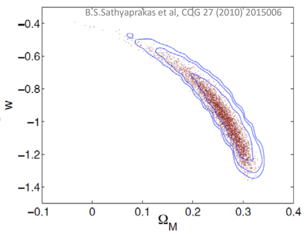
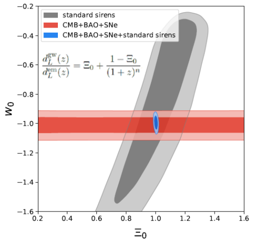
- A fraction (about 10^3/year?) of the BNS will have a electromagnetic counterpart (thanks also to new telescopes like THESEUS, E-ELT, …





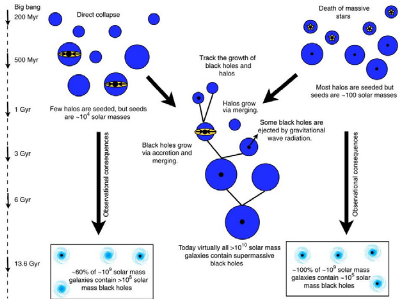


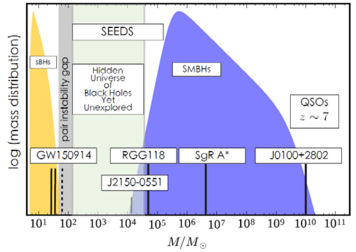
$$D_L(z) = \frac{c(1+z)}{H_0}\int_0^z \frac{dz}{[\Omega_M(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)}]^{1/2}}$$

Investigating the DE sector in modified theories of gravity

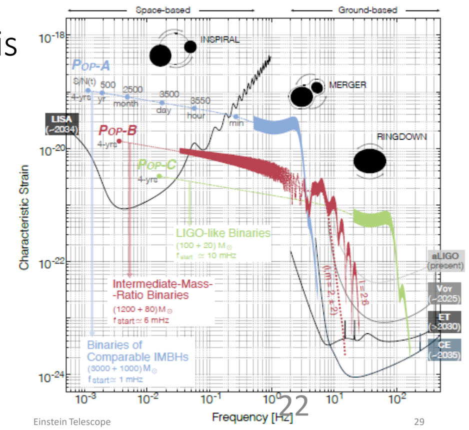
Seeds and Supermassive Black Holes

- Supermassive Black Holes (SMBHs) are present at the center of many galaxies:
  - What is their history? How they formed? What are the seeds?





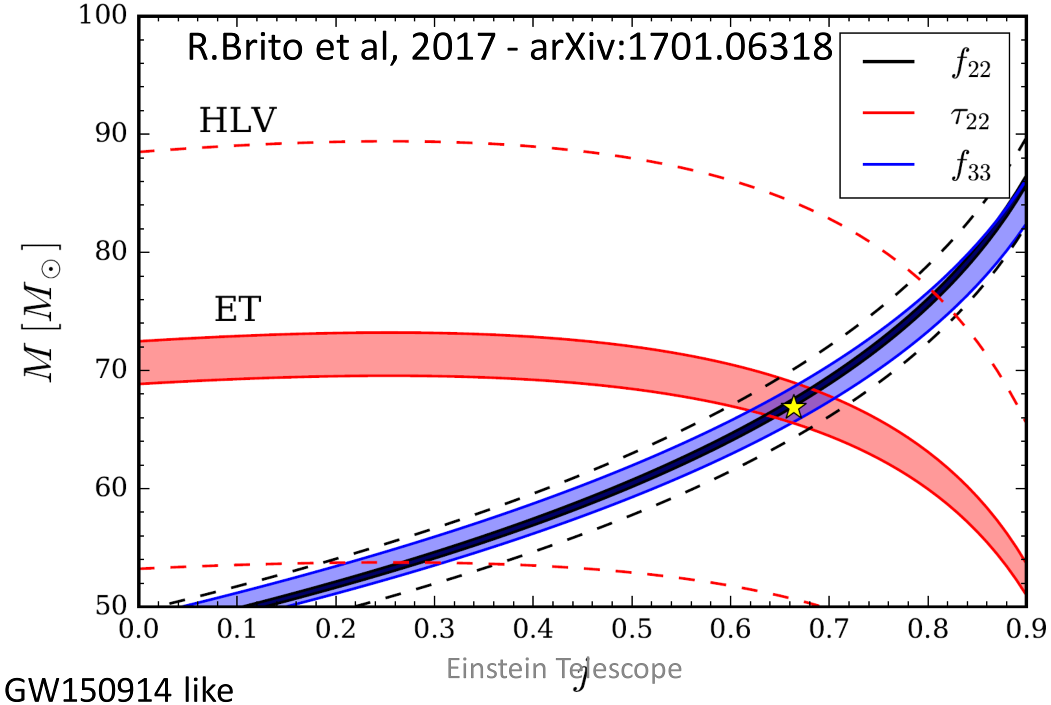
is



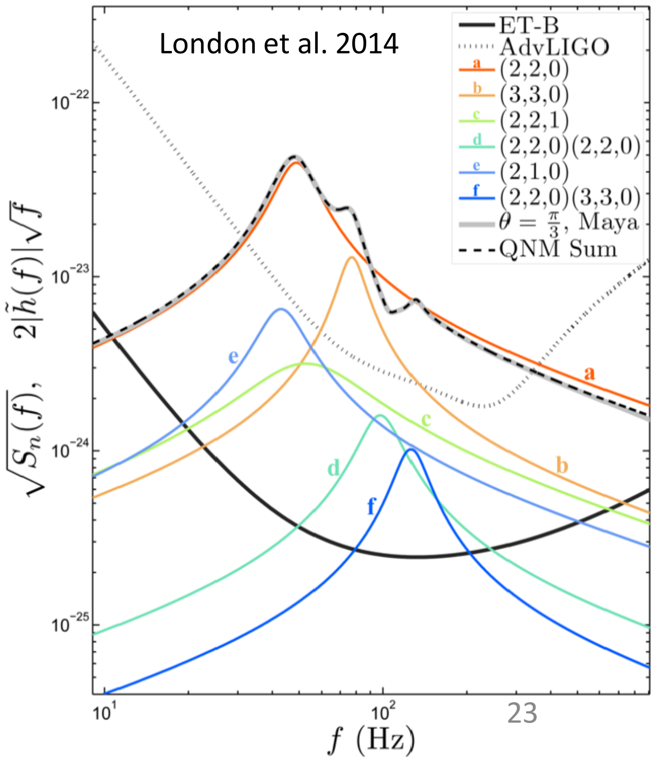
Extreme gravity

- In GR, no-hair theorem predicts that BHs are described only by their mass and spin (and charge)
  - However, when a BH is perturbed, it reacts (in GR) in a very specific manner, relaxing to its stationary configuration by oscillating in a superpositions of quasi-normal modes, which are damped by the emission of GWs.
  - A BH, a pure space-time configuration, reacts like an elastic body → Testing the "elasticity" of the space-time fabric
  - Exotic compact bodies could have a different QN emission and have echoes

- In ET accurate BH spectroscopy already from single events
- 10^4-10^5 events/yr with detectable ringdown
- 20-50 events/yr with detectable higher modes



350 Msun binary @ 100 Mpc

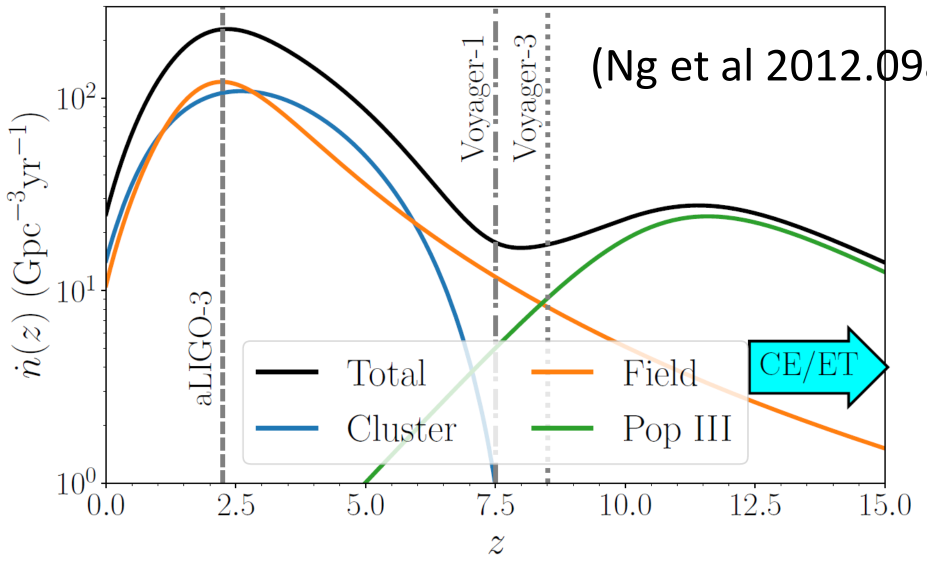


J=J/M^2 dimensionless spin

GW150914 like

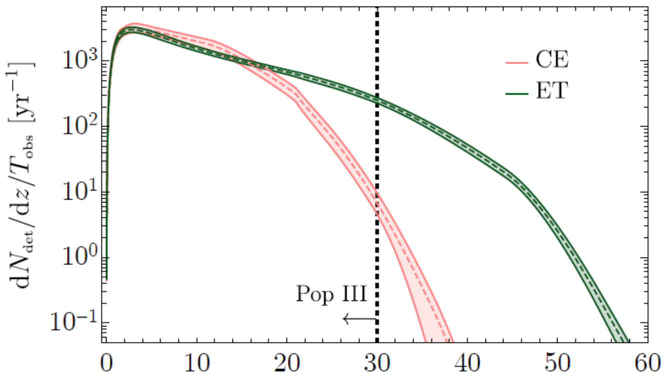
Probing multiple populations of BH: PBHs

- We have different BBH populations:
  - binary stellar evolution in galactic fields
  - dynamical formation through multi-body interactions in star clusters or AGN
  - from Population III (Pop III) stars
    - BHs from Pop III stars peak at z≃12 and could form binaries (and merge) up to z≃25-30 (conservatively)
  - Primordial blackholes
    - Any BBH merger at z>30 (very conservatively) will be of primordial origin
    - ET reaches z~50 !!



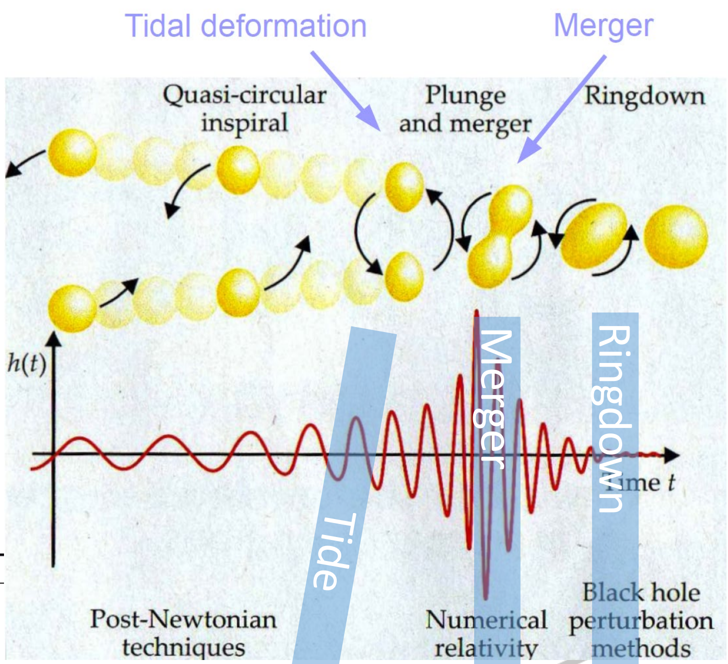
(Ng et al 2012.09876)

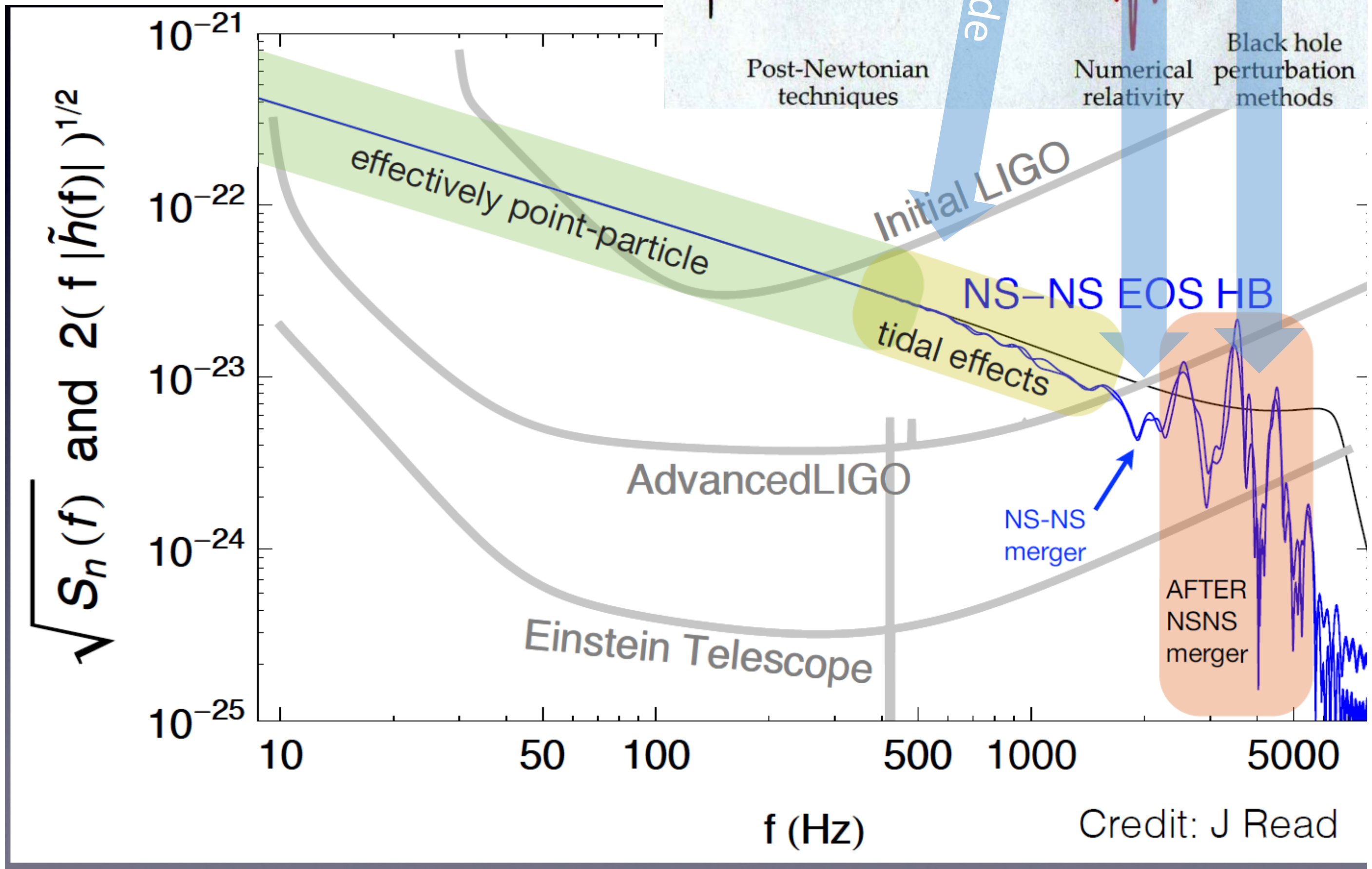
$$N_{\rm det}^{\rm ET}(z>30) = 1315^{+305}_{-168}\,{\rm yr}^{-1}$$

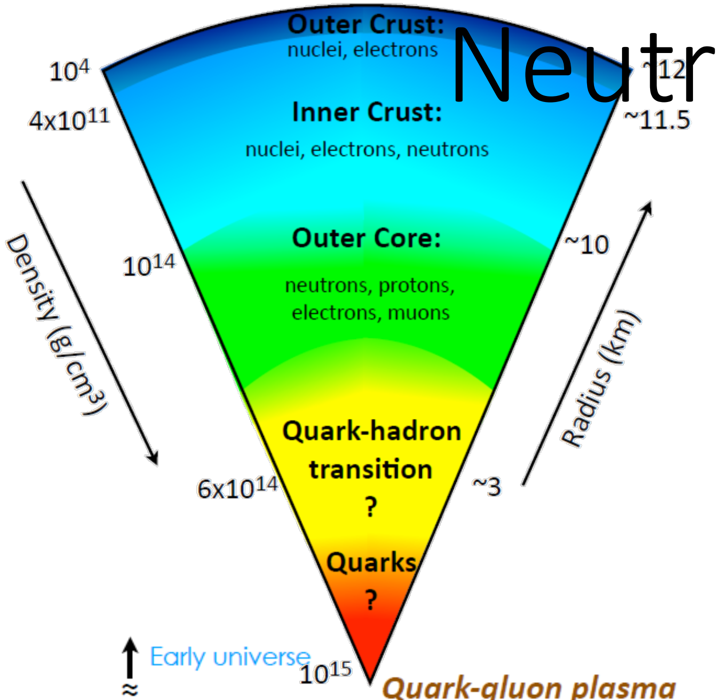


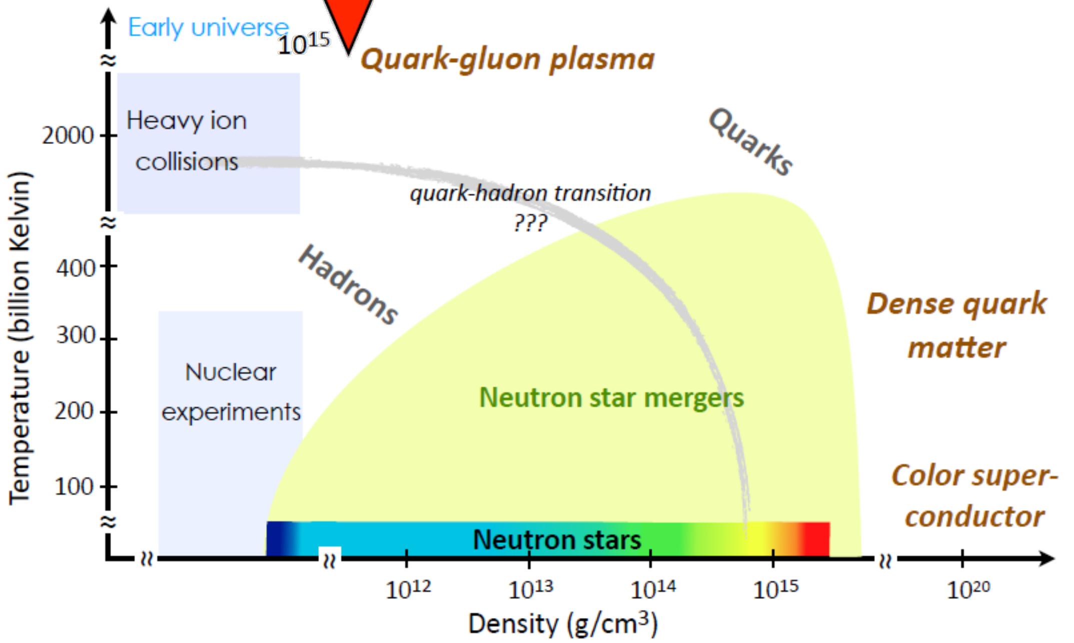
QCD -Structure of a Neutron Star

Stephen Fairhurst
ET meeting 27-28 March 2017









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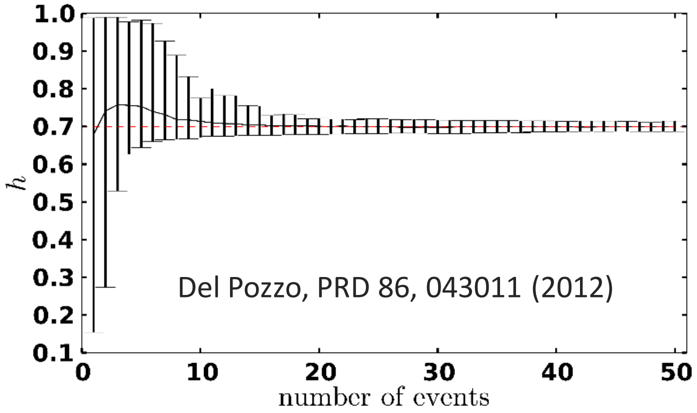
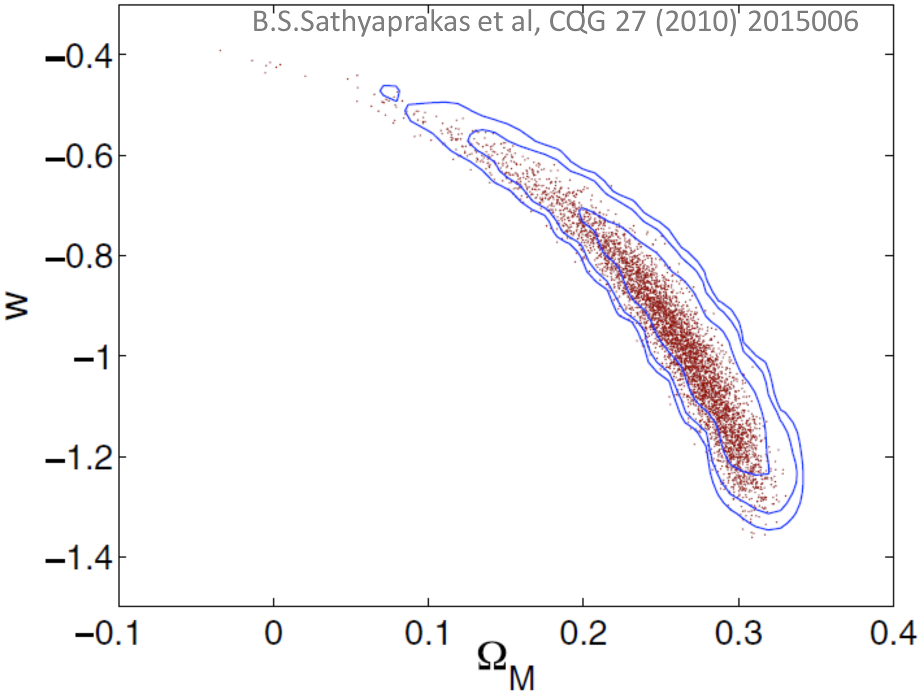
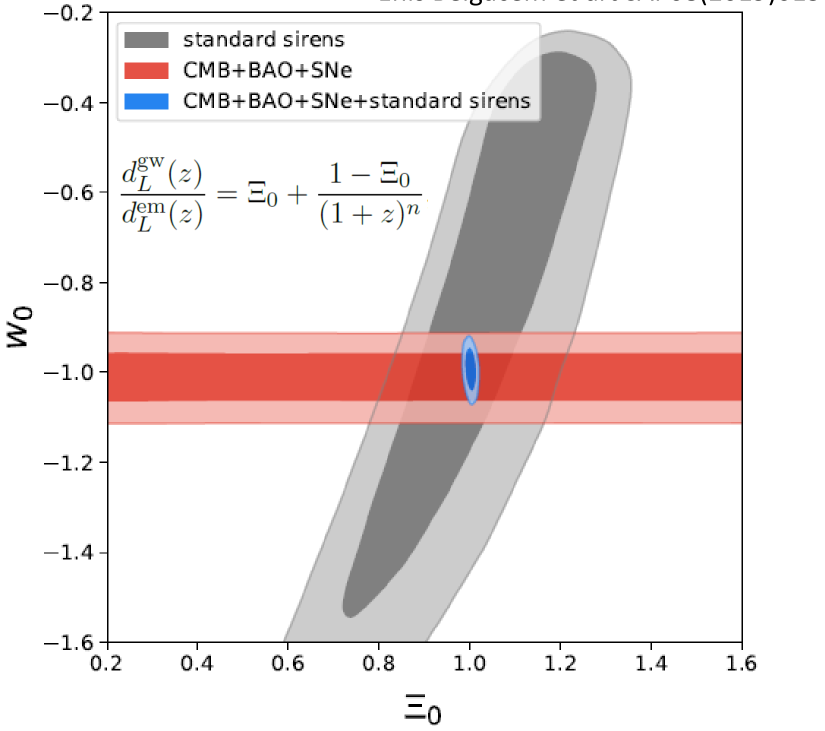




Enis Belgacem et al JCAP08(2019)015



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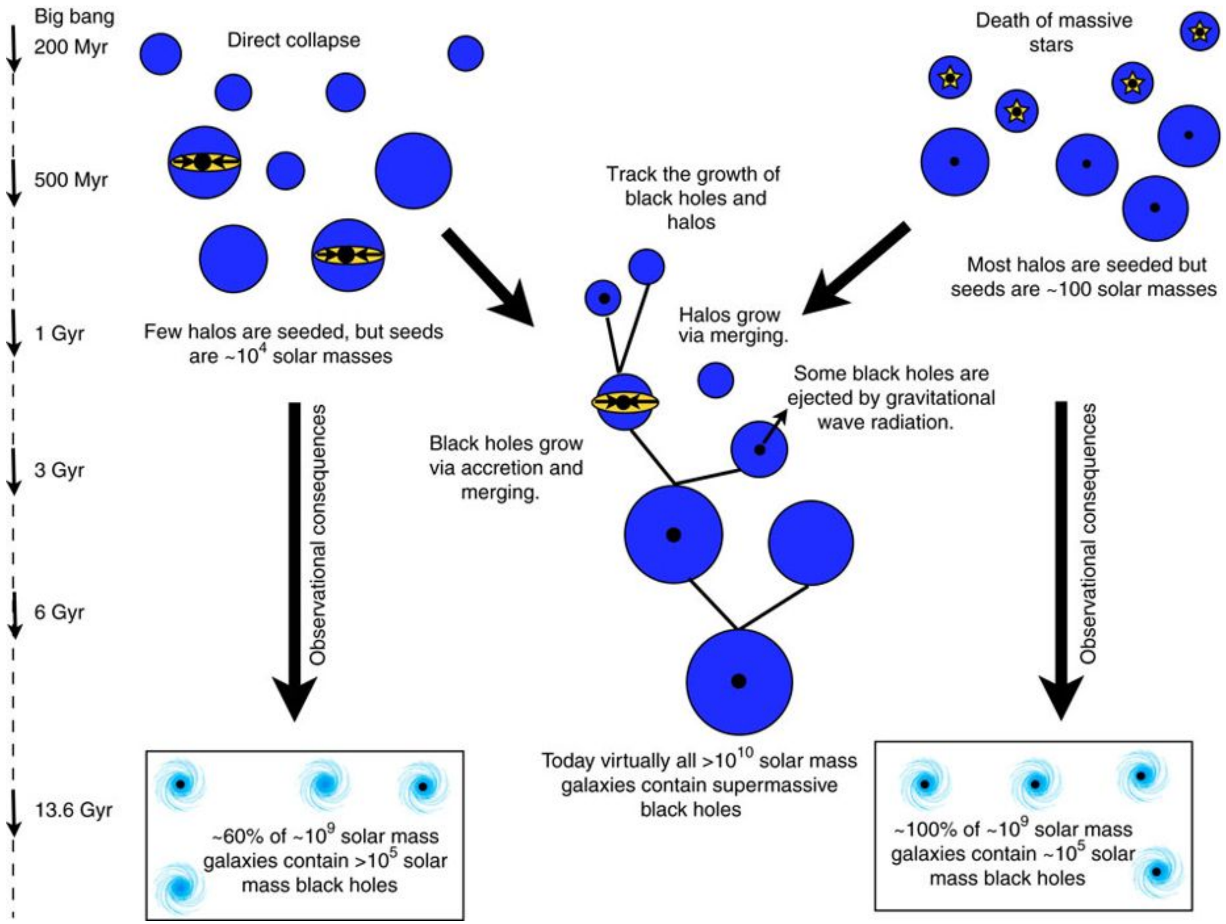
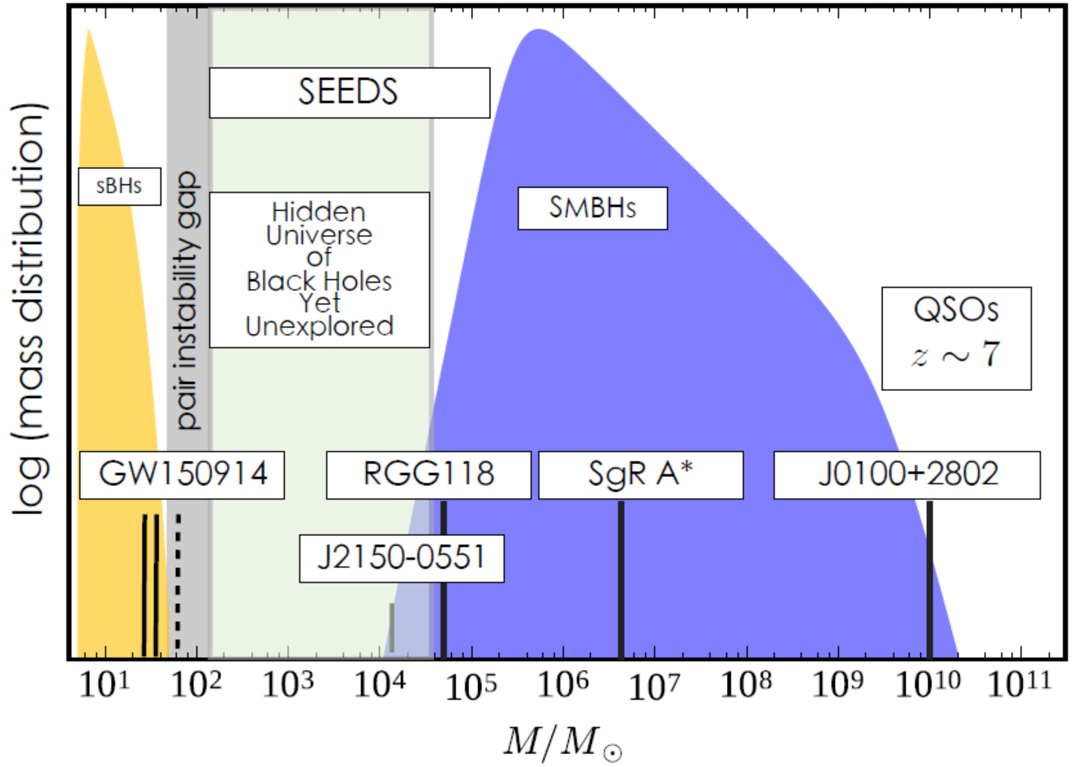
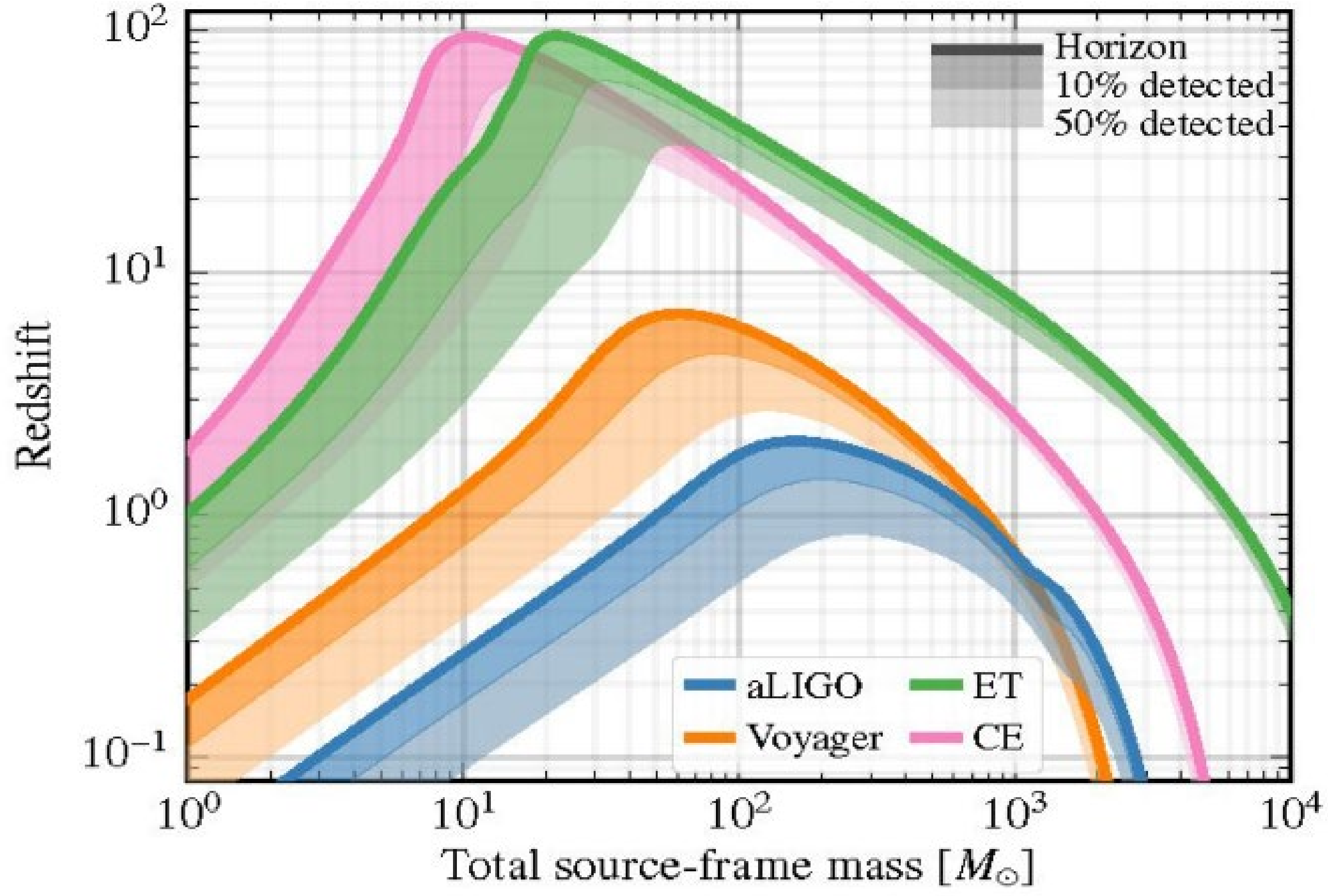
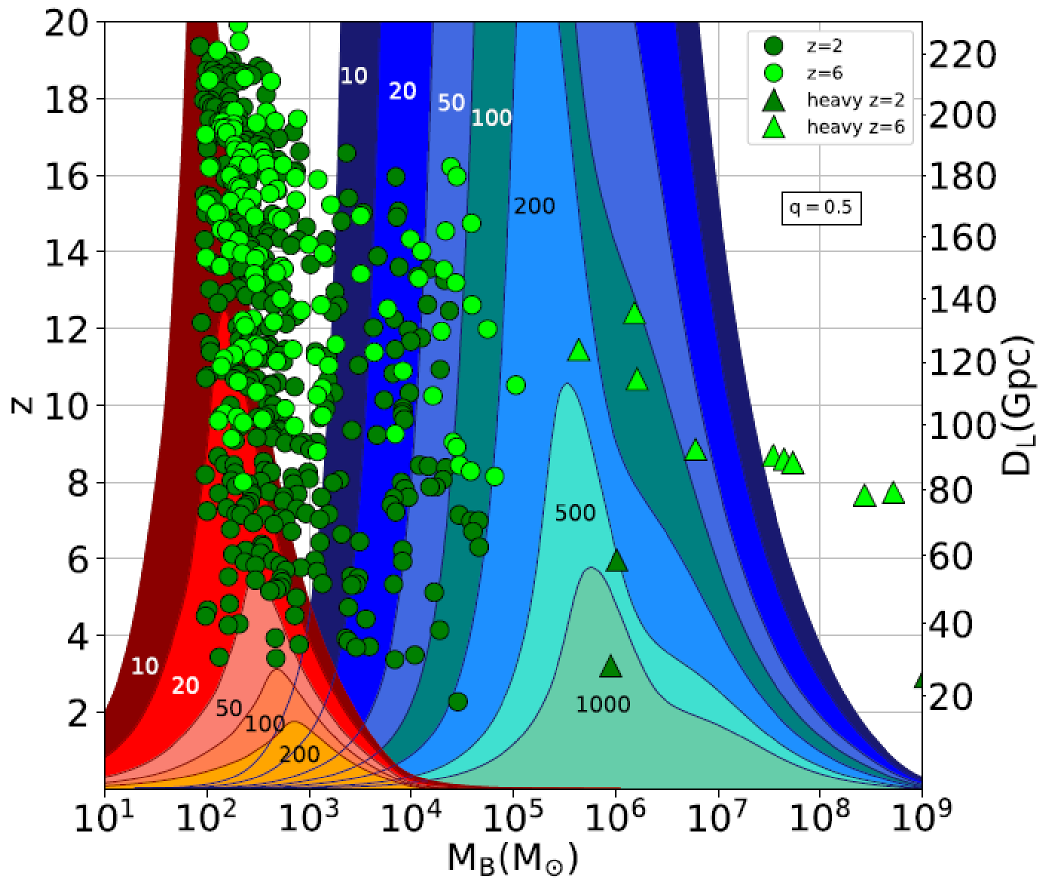




Seeds and Supermassive Black Holes

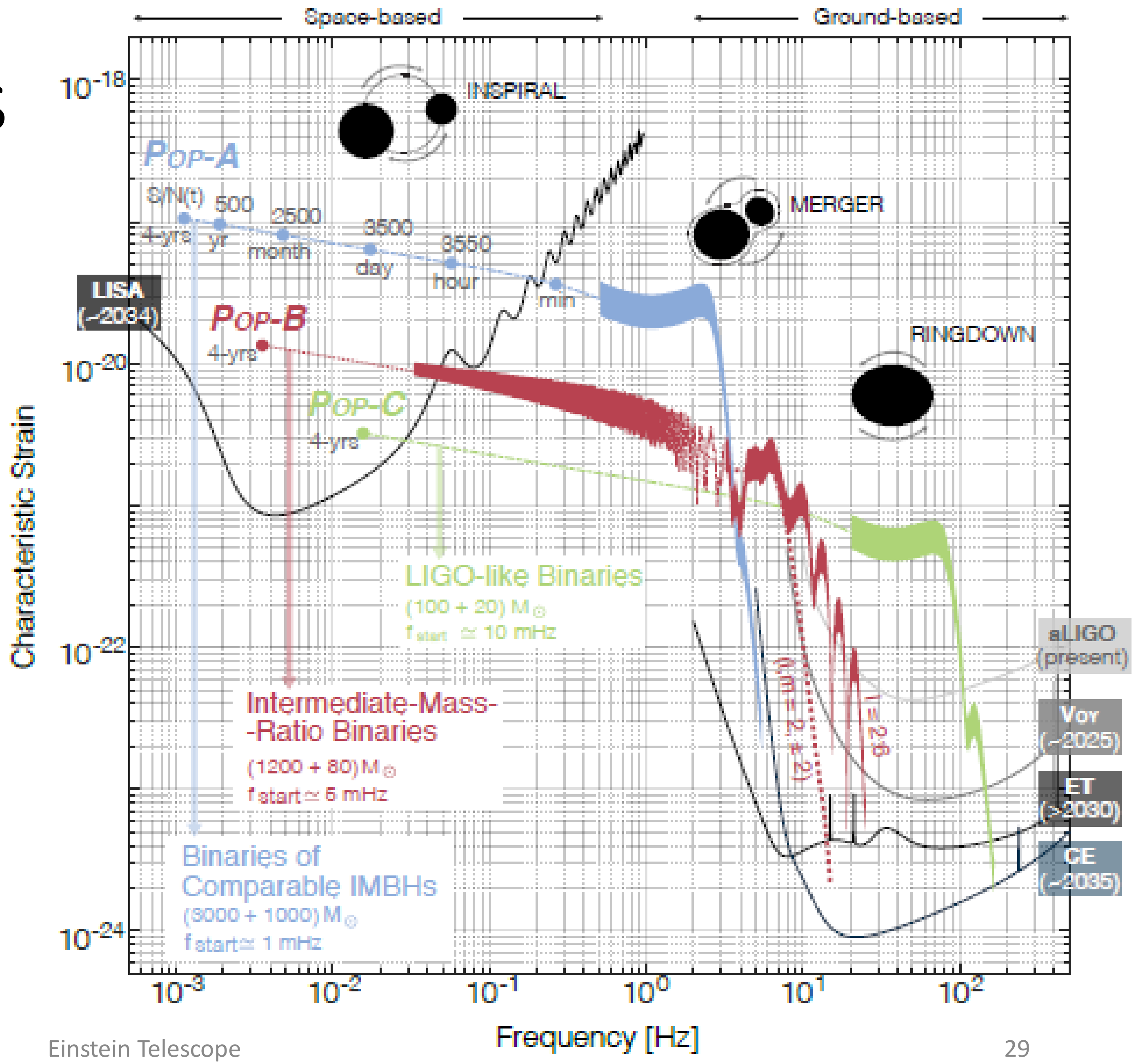
- LISA will detect the coalescences of SMBHs, but what about the seeds?



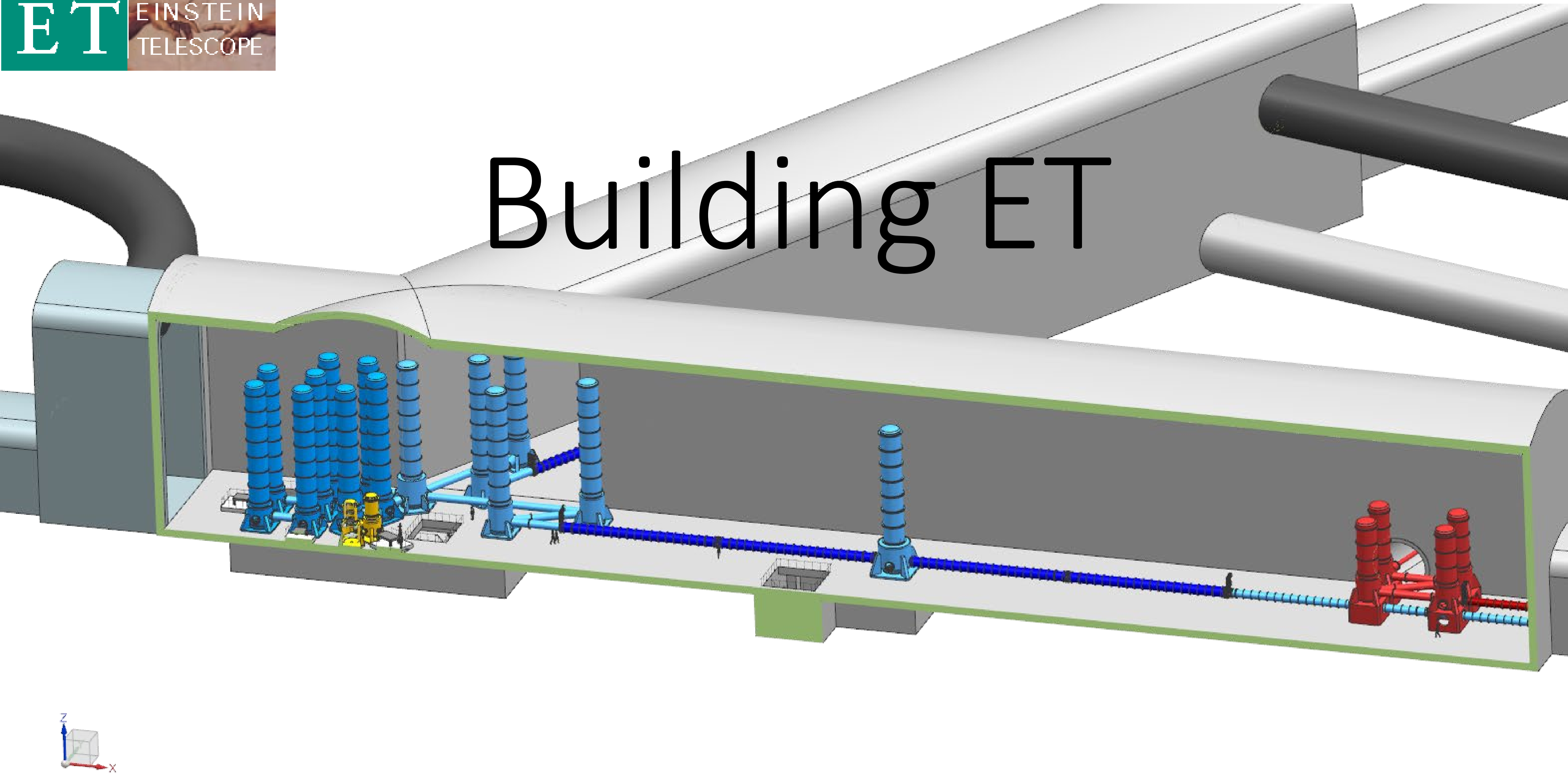


Multi-Band analysis

- Space based GW observatory and terrestrial GW observatory can observe different phases of the coalescence of specific sources (IMBH)
  - Localisation
  - GR tests



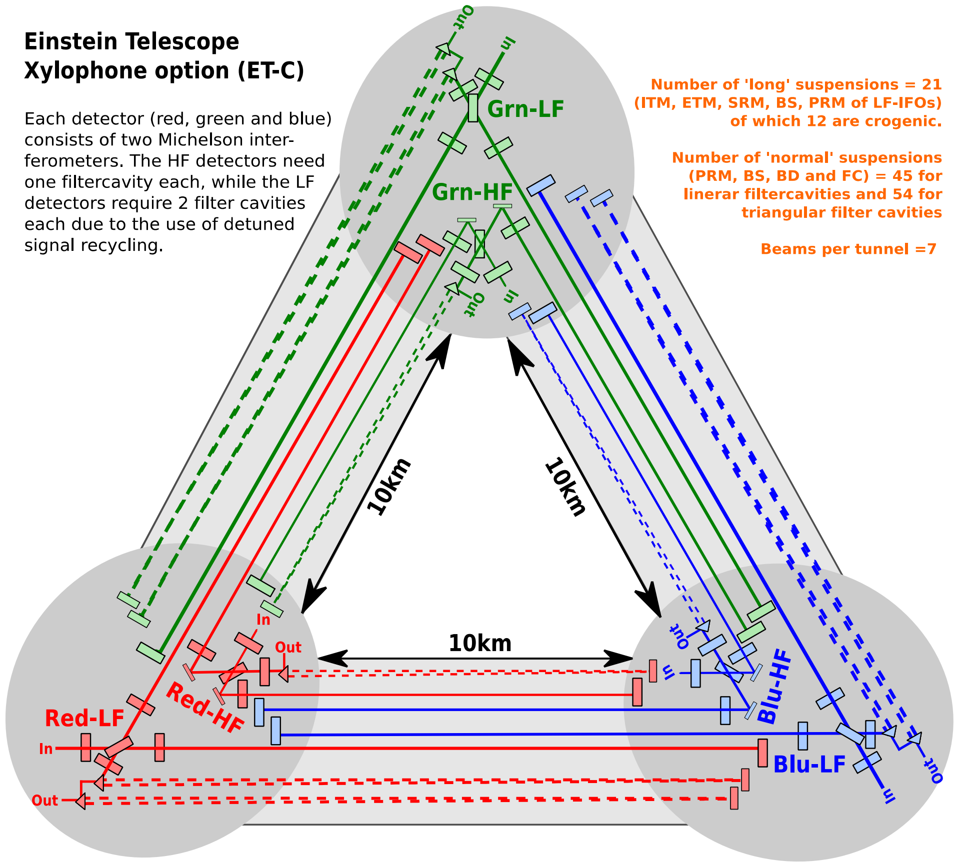
Building ET



ET Key ingredients

Factor 10 better sensitivity in a wide range of frequency
with a specific attention to low frequency (<10Hz)

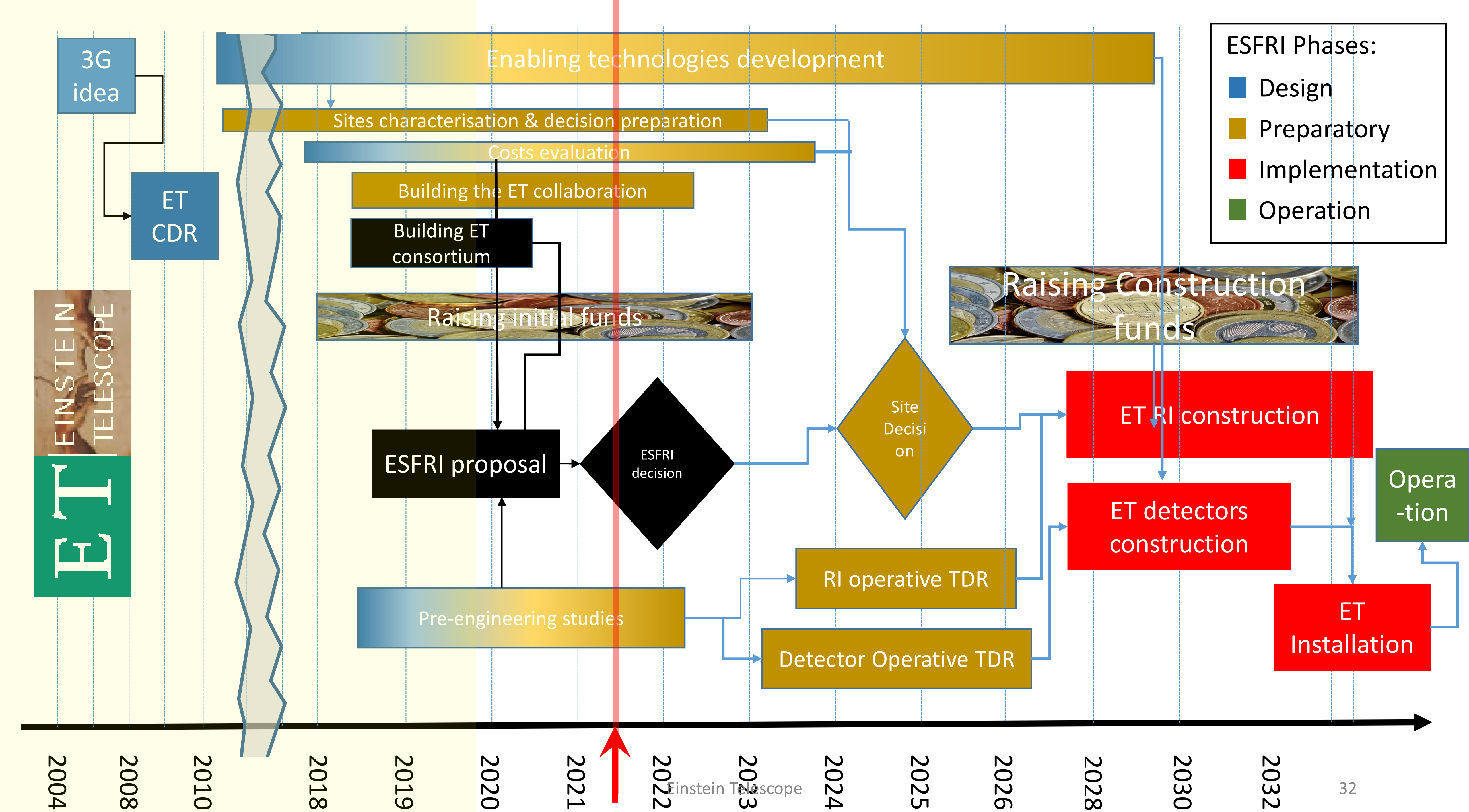
- Einstein Telescope is a 3rd generation Gravitational Wave Observatory
  - It is, first of all, a new Research Infrastructure



- Capable to host ET and its upgrades
- Capable to host 4G, 6G, …

Observation (rather than detection) is the core business:

Requirements	Design Specifications
Wide frequency range	Xylophone (multi-interferometer) Design
Massive black holes (LF focus)	Underground
Localisation capability	Cryogenic
(more) Uniform sky coverage	Triangular shape
Polarisation disentanglement	Multi-detector design
High Reliability (high duty cycle)	Longer arms
High SNR	


ESFRI Phases:
Design
Preparatory
Implementation
Operation
3G idea
ET CDR
EINSTEIN TELESCOPE
ET
Enabling technologies development
Sites characterisation & decision preparation
Costs evaluation
Building the ET collaboration
Building ET consortium
Raising initial funds
ESFRI proposal
ESFRI decision
Site Decision
Raising Construction funds
ET RI construction
ET detectors construction
Opera-tion
RI operative TDR
Pre-engineering studies
Detector Operative TDR
ET Installation
2004
2008
2010
2018
2019
2020
2021
2022
2023
2024
2025
2026
2028
2030
2032

ESFRI Roadmap

European Strategy Forum on Research Infrastructures

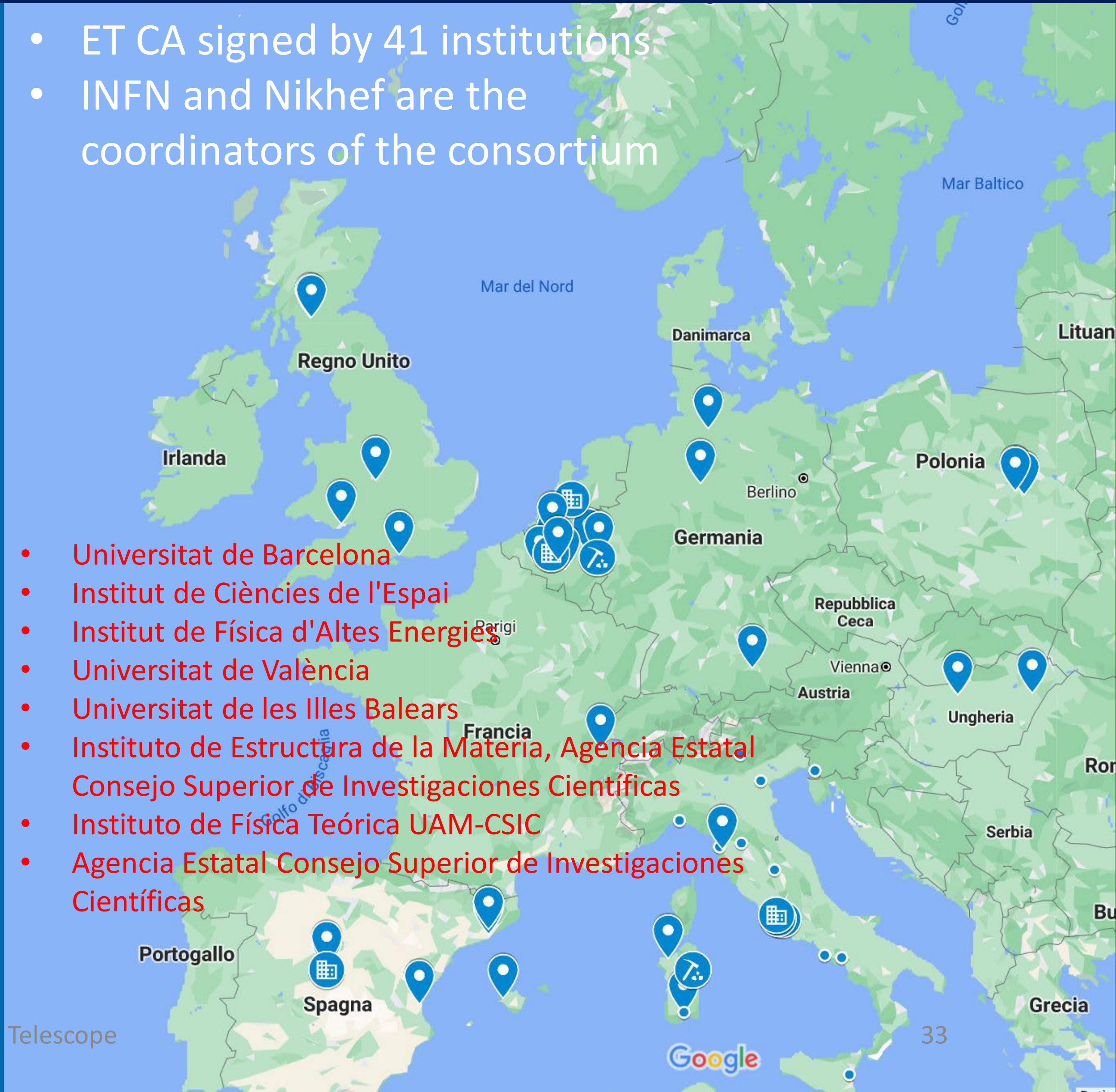
EINSTEIN TELESCOPE

Proposal submitted by:

- **Italy** (Lead Country)
- Netherlands
- Belgium
- Spain
- Poland

- ET CA signed by 41 institutions
- INFN and Nikhef are the coordinators of the consortium

- Universitat de Barcelona
- Institut de Ciències de l'Espai
- Institut de Física d'Altes Energies
- Universitat de València
- Universitat de les Illes Balears
- Instituto de Estructura de la Materia, Agencia Estatal Consejo Superior de Investigaciones Científicas
- Instituto de Física Teórica UAM-CSIC
- Agencia Estatal Consejo Superior de Investigaciones Científicas

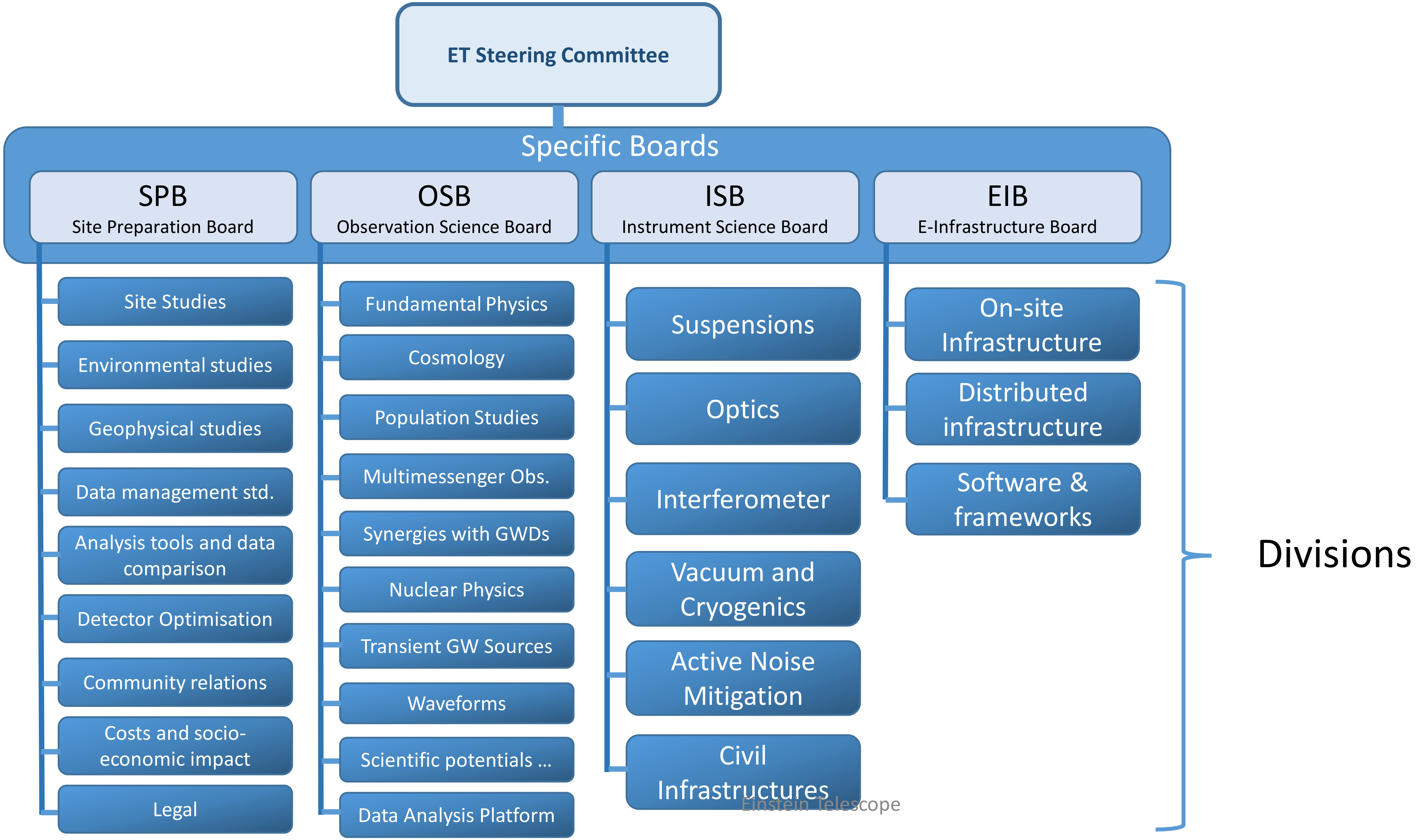


European Strategy Forum on Research Infrastructures

ESFRI Roadmap 2021: next steps

- OPEN CALL FOR PROPOSALS - 25 September 2019 ✓
- SUBMISSION OF PROPOSALS - 9 September 2020 ✓
- CRITICAL QUESTIONS & INVITATION TO HEARINGS – February-March 2021 ✓
- HEARING – April 14 2021 ✓
- ESFRI FORUM DECISION - June-September 2021
- ESFRI ROADMAP LAUNCH - October - November 2021

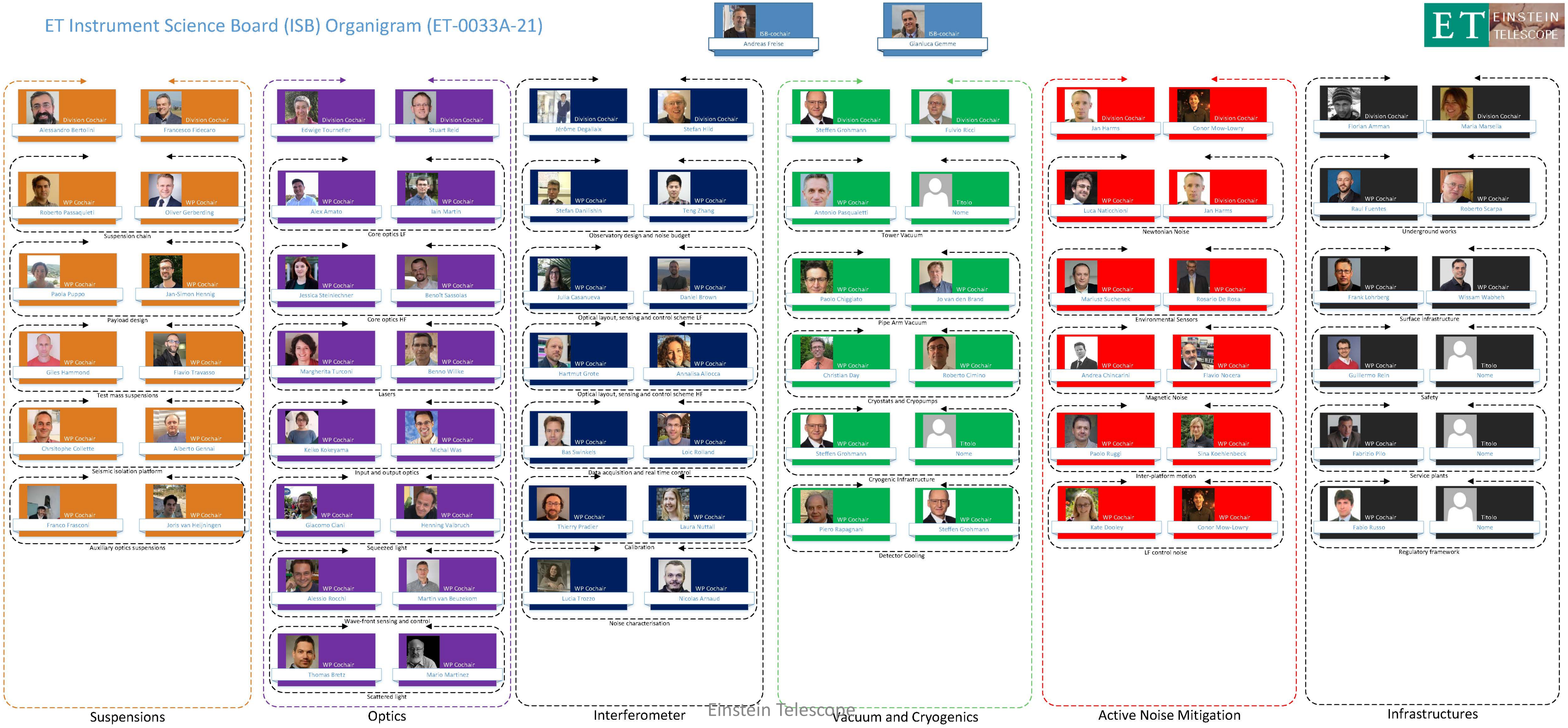
ET collaboration current organisation



ESFRI

ISB: Instrument Science Board

ET Instrument Science Board (ISB) Organigram (ET-0033A-21)

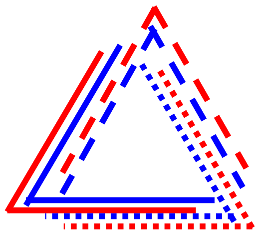


Q1: Enabling Technologies

ESFRI

ET EINSTEIN TELESCOPE

- The multi-interferometer approach asks for two parallel technology developments:



- **ET-LF:**
  - Underground
  - Cryogenics
  - Silicon (Sapphire) test masses
  - Large test masses
  - New coatings
  - New laser wavelength
  - Seismic suspensions
  - Frequency dependent squeezing

- **ET-HF:**
  - High power laser
  - Large test masses
  - New coatings
  - Thermal compensation
  - Frequency dependent squeezing

Challenging engineering

New technology in cryo-cooling

New technology in optics

New laser technology

High precision mechanics and low noise controls

High quality opto-electronics and new controls

Evolved laser technology

Evolved technology in optics

Highly innovative adaptive optics

High quality opto-electronics and new controls

OSB: Observational Science Board

Marica Branchesi - Michele Maggiore - Ed Porter

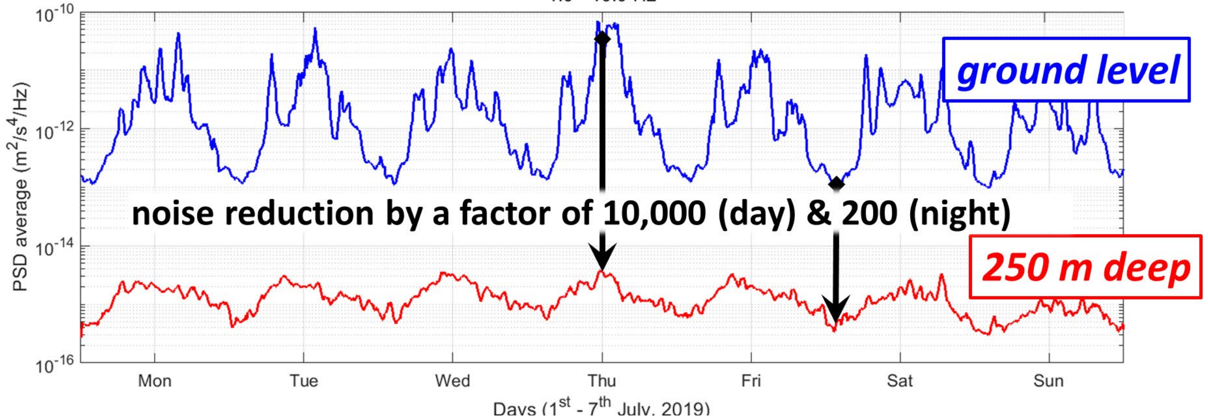
Fundamental physics	Cosmology	Population Studies	MM observations	Synergies w. other GW observ.	Nuclear physics	Transient GW Sources	Waveforms	Science Potential	DA platform
Physics near BH horizons	Dark Energy	Predictions of population of astrophysical origin	ET / high-energy	Synergies with 2G+ detector	EoS of NSs in isolated systems	Predictions for Supernovae	Waveforms relevant for ET	Science potential for various detector configurations	DA platform
Tests of GR	Dark matter	Predictions of primordial BHs	ET / optical	Synergies with CE, 3G	EoS in NSs in binary systems	Predictions for magnetars	Improvement of waveforms for BBH	Common tools	
Exotic compact objects	Estimation of cosmological parameters	Stochastic backgrounds of astrophysical origin	ET / radio	Synergies with LISA	Nucleo-synthesis in BNS mergers	Predictions for cosmic string bursts	Improvement of waveforms for NSBH		
	Modifications of gravity at cosmological scales		ET / neutrinos				Improvement of waveforms for BNS		
	Stochastic background of cosmological origin								

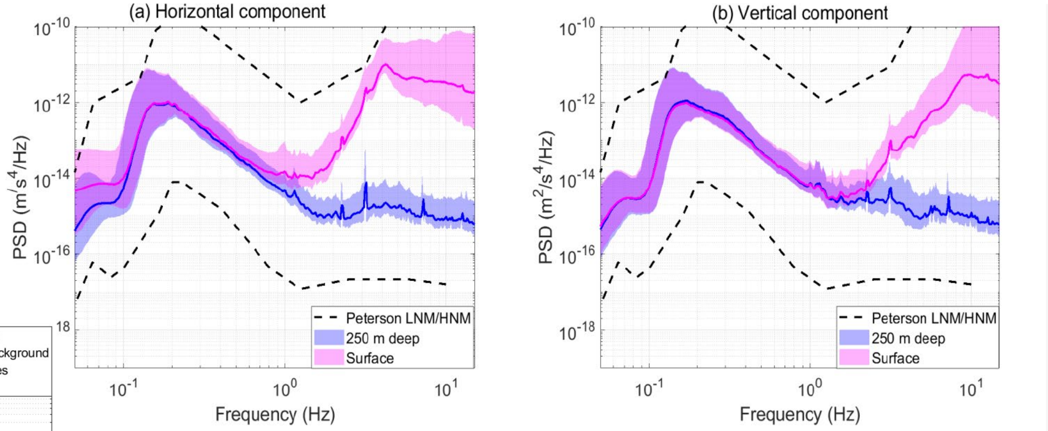
SPB: ET sites under characterisation

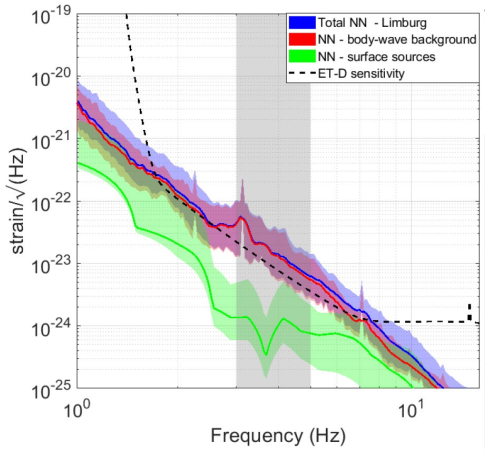
Euregio Meuse-Rhine

- A 250-m deep borehole has been excavated and equipped
  - Seismic data under acquisition and analysis
- 3-5 other boreholes expected
- Extensive active and passive site characterisation with sensor arrays in 2021
- Good seismic noise attenuation given by the particular geological structure
- ET pathfinder centre under construction
- 15+15M€ funding through Interreg grants

H.Lueck – GWADW 2021







Soumen Koley, GWADW 2021

SPB: ET sites under characterisation

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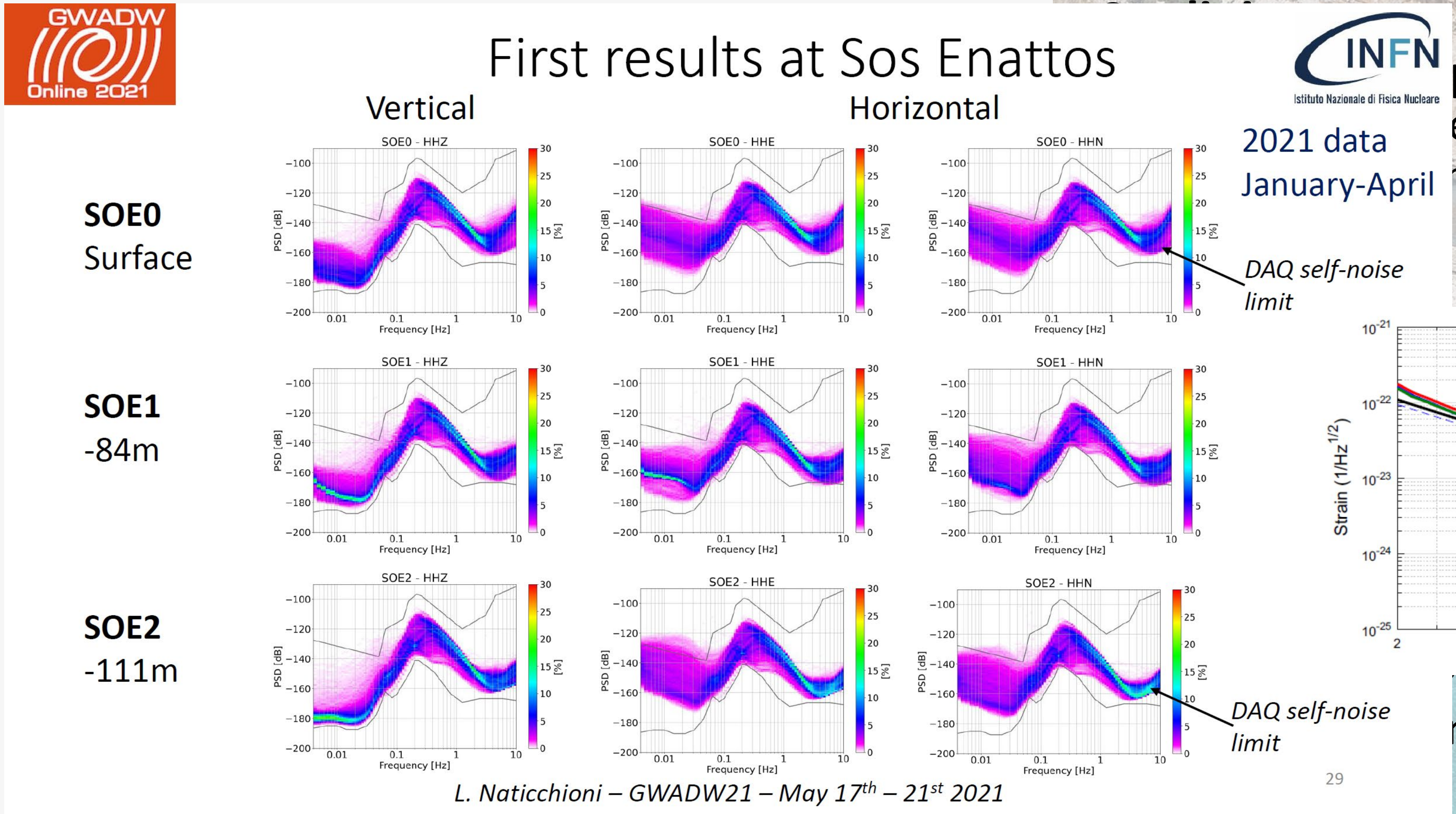
Sardinia

- Long standing characterisation of the mine in one of the corners continuing
  - Seismic, magnetic and acoustic noise characterisation ongoing at different depth in the mine
- Underground laboratory under construction (SarGrav)
- A 290m borehole has been excavated and it will be equipped
- A second borehole to be excavated in the summer 2021
- Intense & international surface investigations programme in Summer 2021
- 17+3.5+1+11M€ funding through national and regional funds

SPB: ET sites under characterisation



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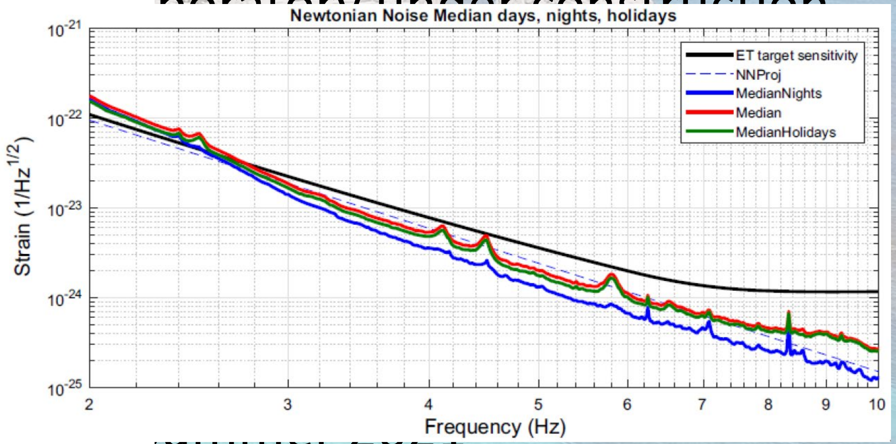
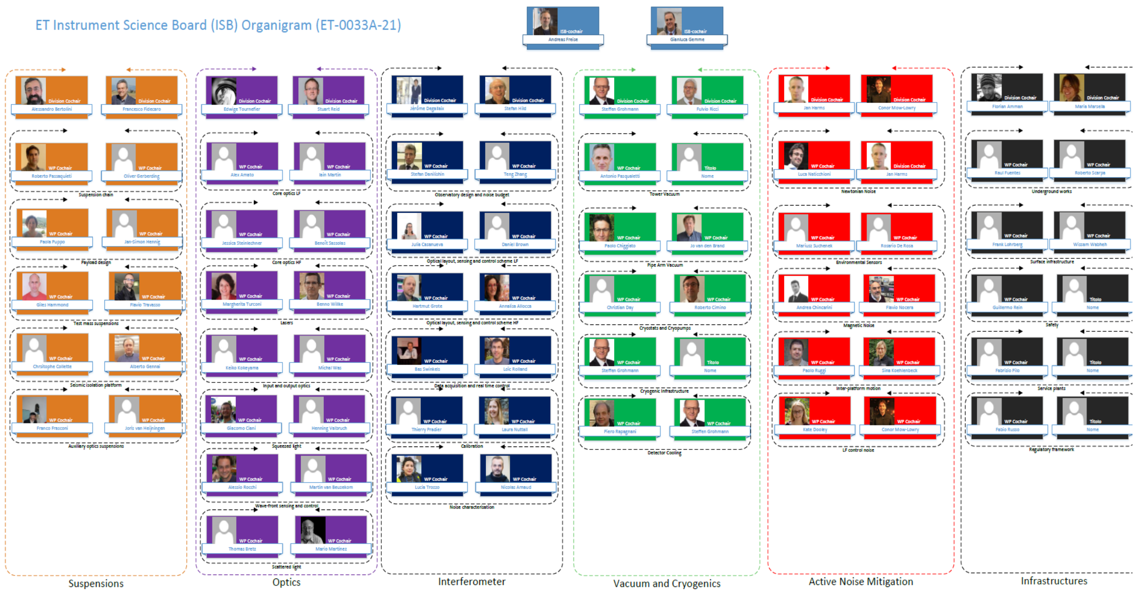


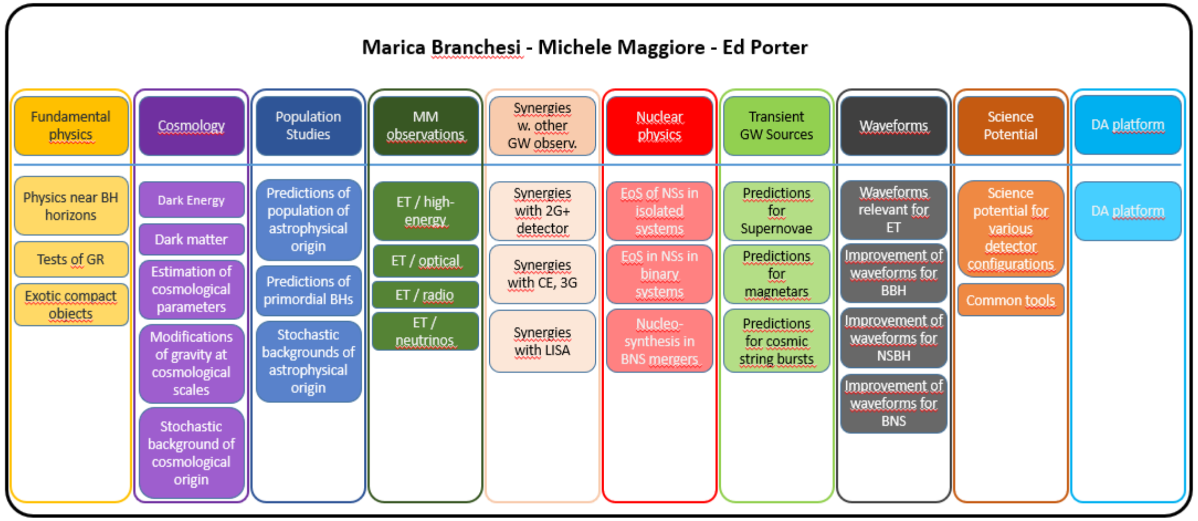
nding through national and

-L.Naticchioni e tal.,***Characterization of the Sos Enattos site for the Einstein Telescope***,**JPCS**1468,2020
-M.DiGiovanni et al.,***A seismological study of the Sos Enattos Area–the Sardinia Candidate Site for the Einstein Telescope***, **SRL**,2020https://doi.org/10.1785/0220200186
-A.Allocca et al.,***Seismic glitchness at Sos Enattos site: impact on intermediate black hole binaries detection efficiency***, **EPJP**,2021https://doi.org/10.1140/epjp/s13360-021-01450-8

Instrument Science Board



Observational Science



How to join?

If you are interested in contributing, please get in touch with one of the division or working group chairs

Check out the ISB webpage: https://wiki.et-gw.eu/ISB/WelcomePage

The Instrument Science Board (ISB) is described in more detail in:
https://apps.et-gw.eu/tds/ql/?c=15709
https://apps.et-gw.eu/tds/ql/?c=15707

END