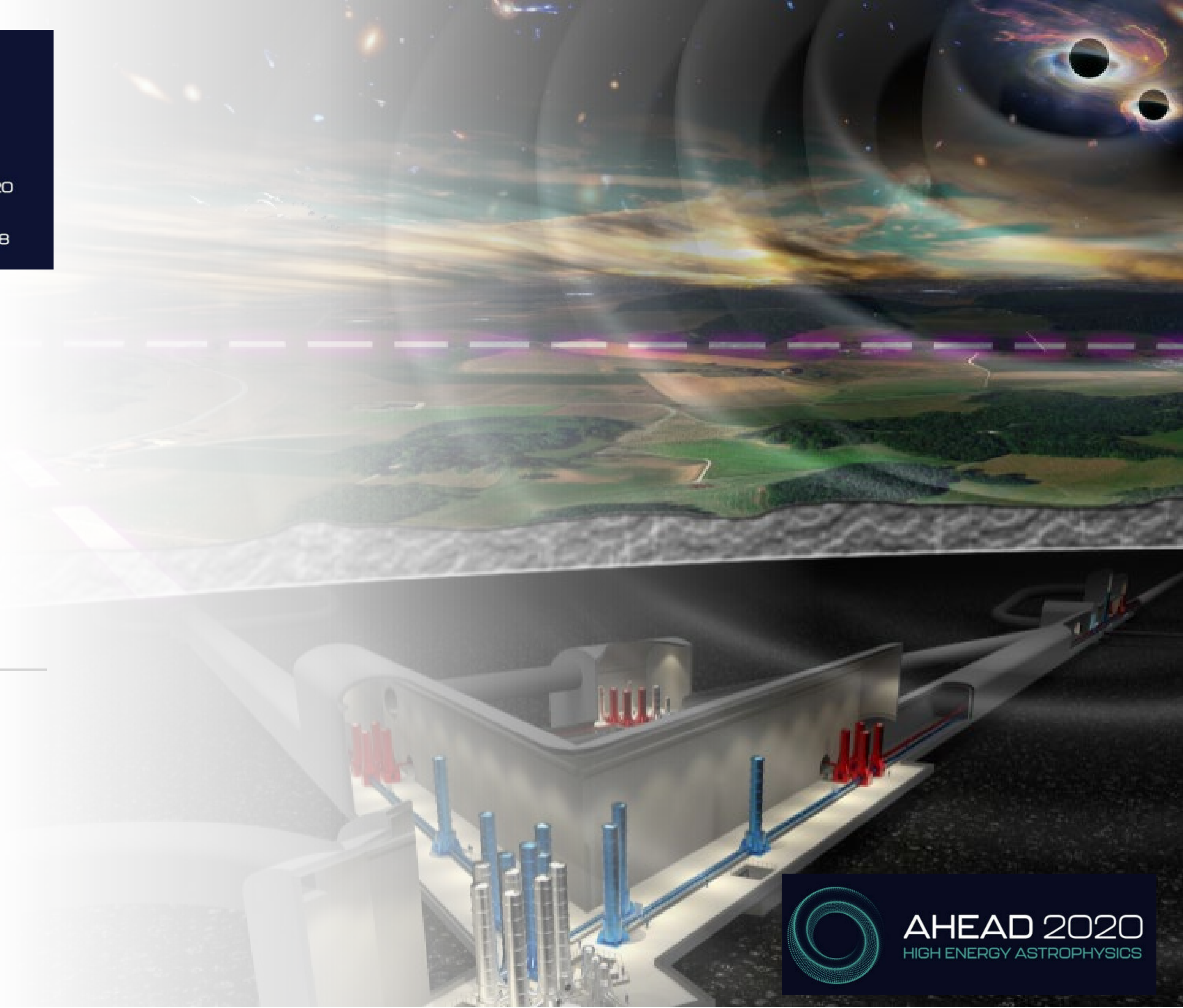
EINSTEIN TELESCOPE

Funded by the Horizon 2020 Framework Programme of the European Union Grant Agreement No. 871158



Einstein Telescope

Status and Perspectives

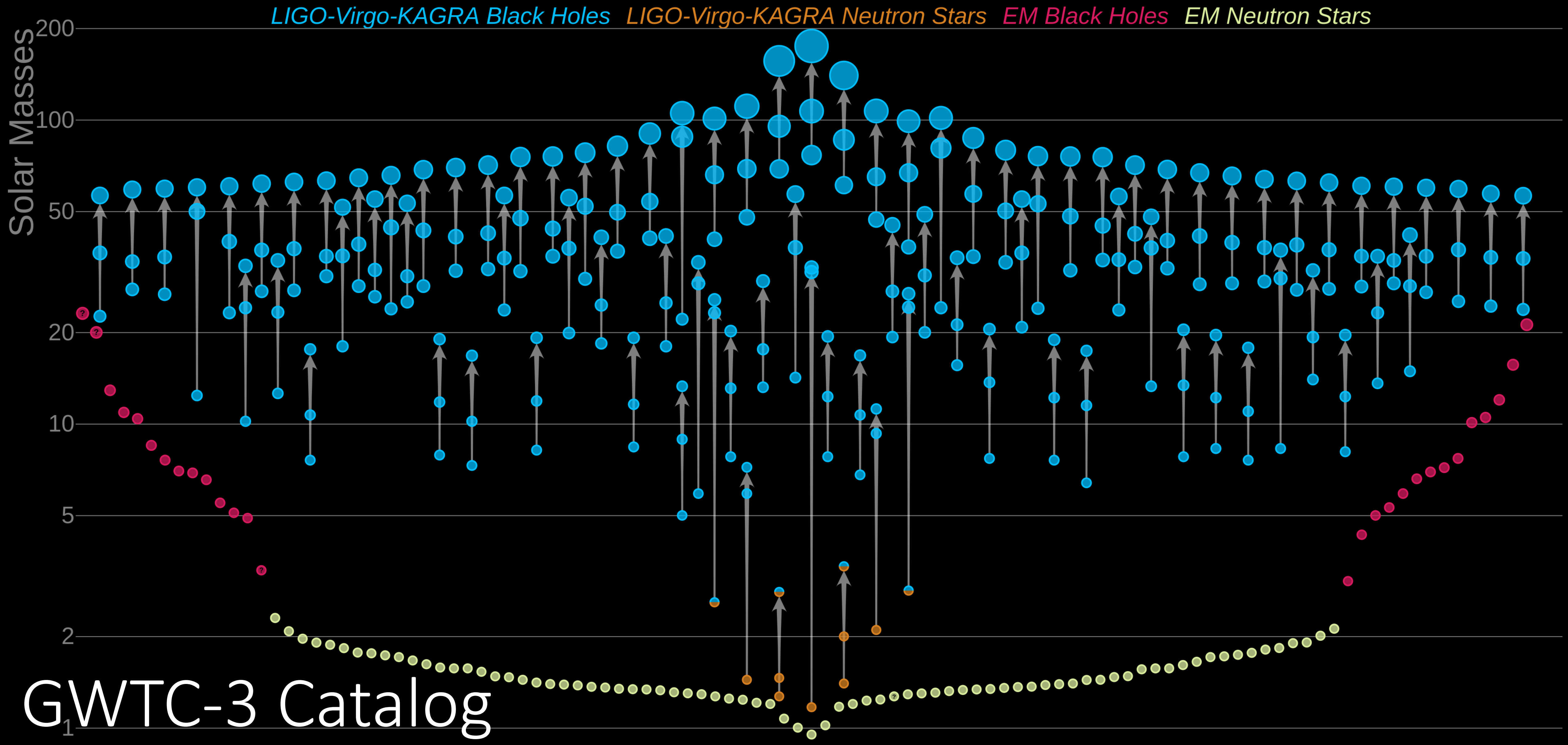
Michele Punturo

INFN Perugia

Istituto Nazionale di Fisica Nucleare

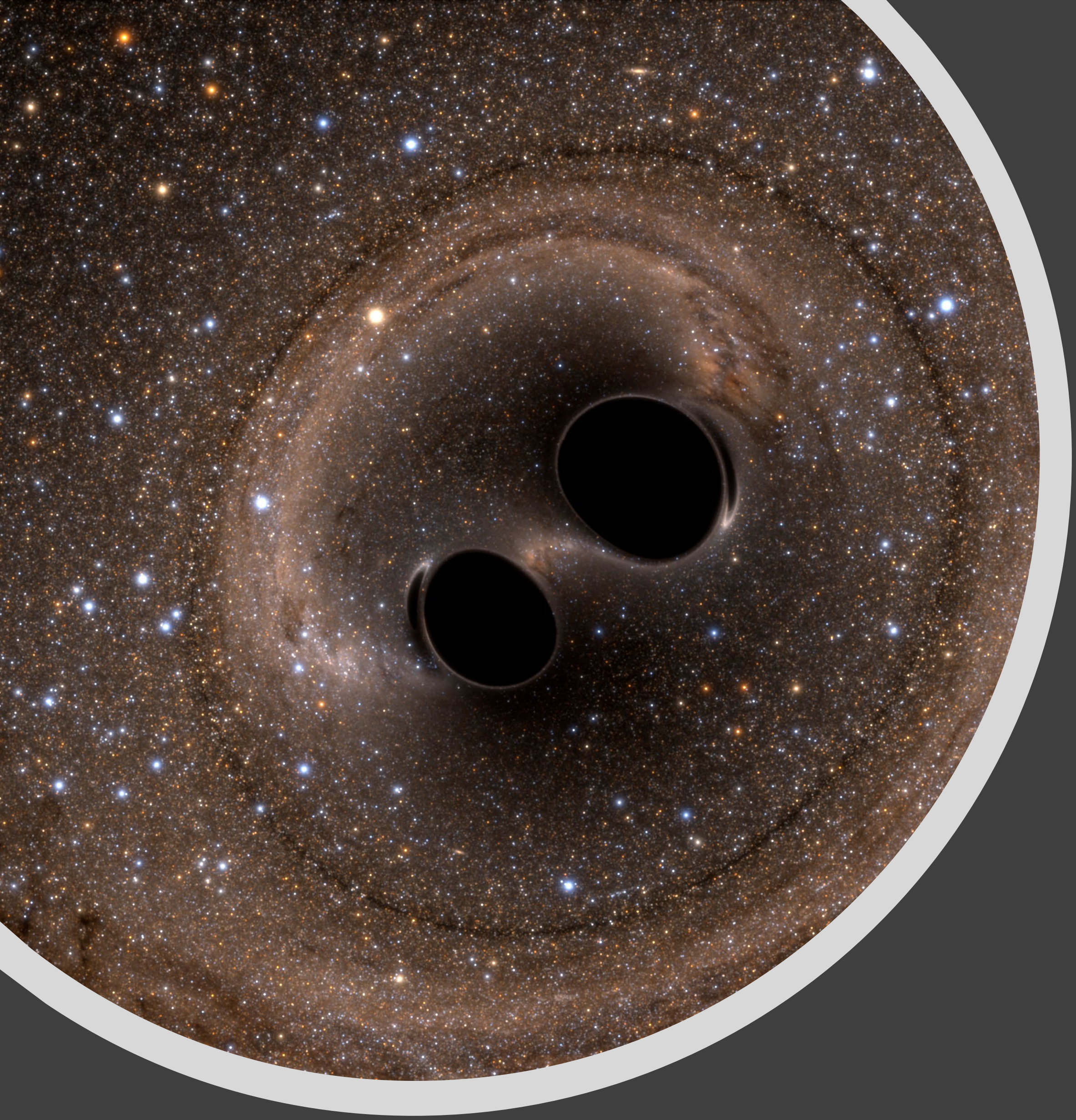
AHEAD 2020
HIGH ENERGY ASTROPHYSICS

Masses in the Stellar Graveyard



GWTC-3 Catalog

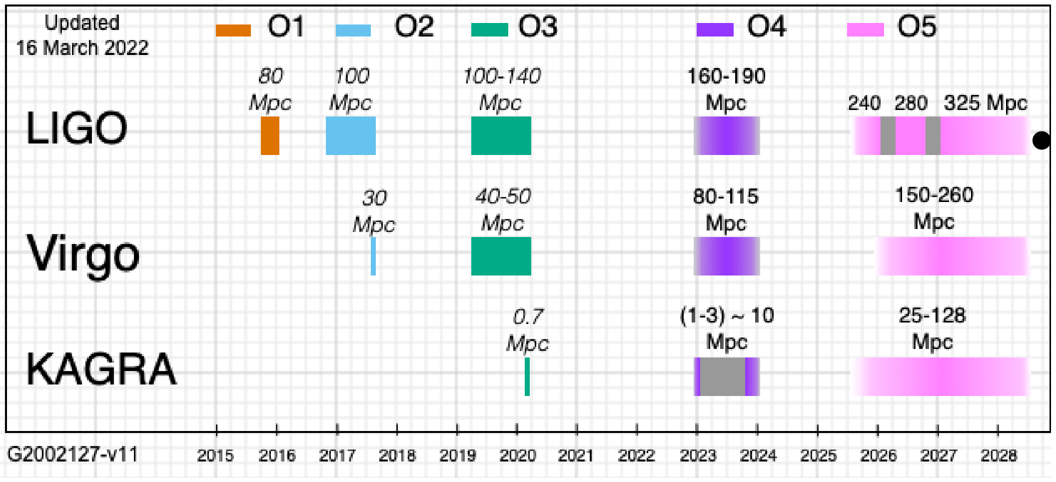
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern



Monumental successes of the Advanced detectors

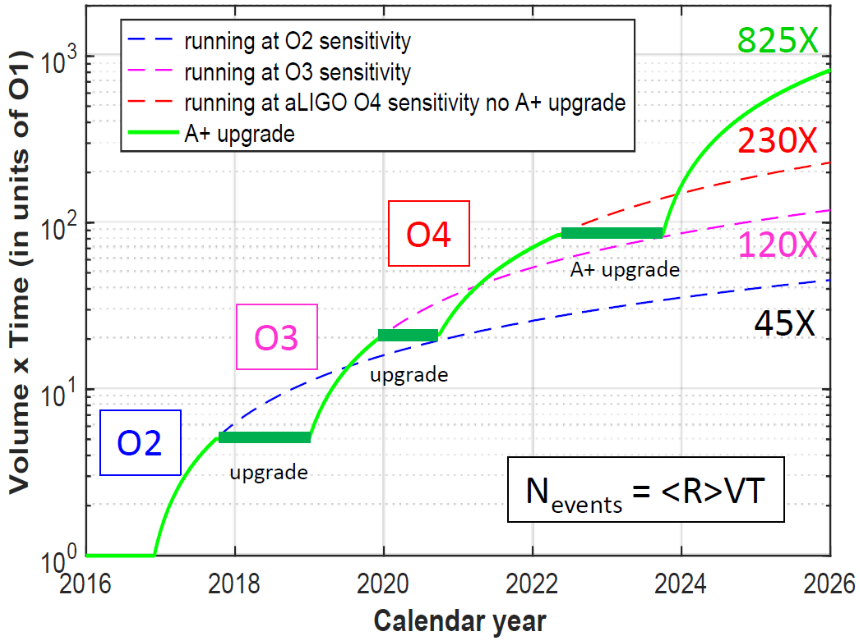
- First detection of GWs from a BBH system (GW150914)
  - Physics of BHs
- First detection of GWs from a BNS system (GW170817)
  - Birth of the multimessenger astronomy with GWs
  - Costraining EOS of NS
- Localisation capabilities of a GW source
- Measurement of the GW propagation speed
- Test of GR
- Alternative measurement of H_0
- GW polarisations
- Intermediate mass black hole (GW190521)

Near future

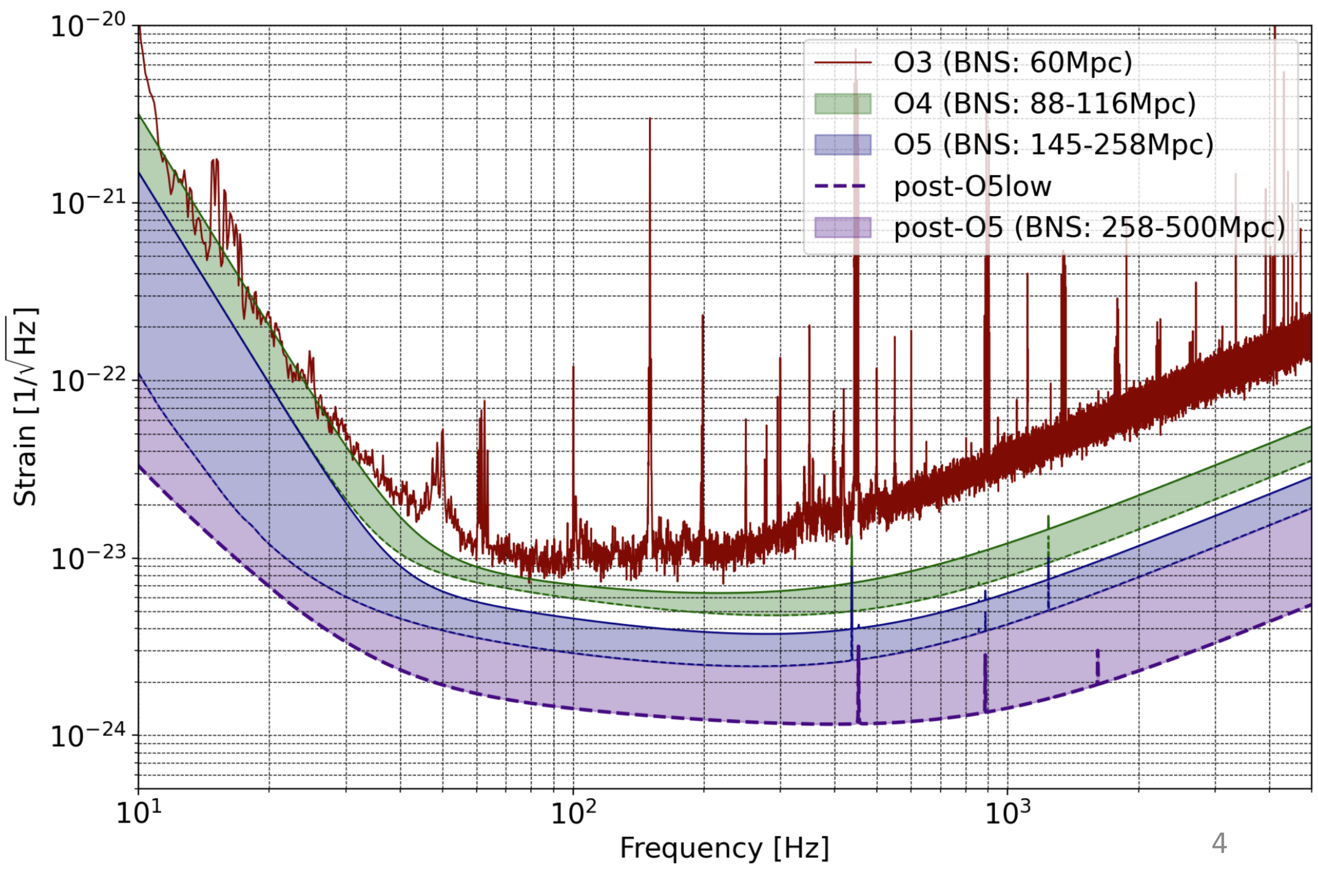


- O4 run, including the Advanced LIGO, Advanced Virgo and KAGRA detectors should start March 2023
- Current detectors have a well defined plan of upgrades and science runs

Binary Neutron Stars Events



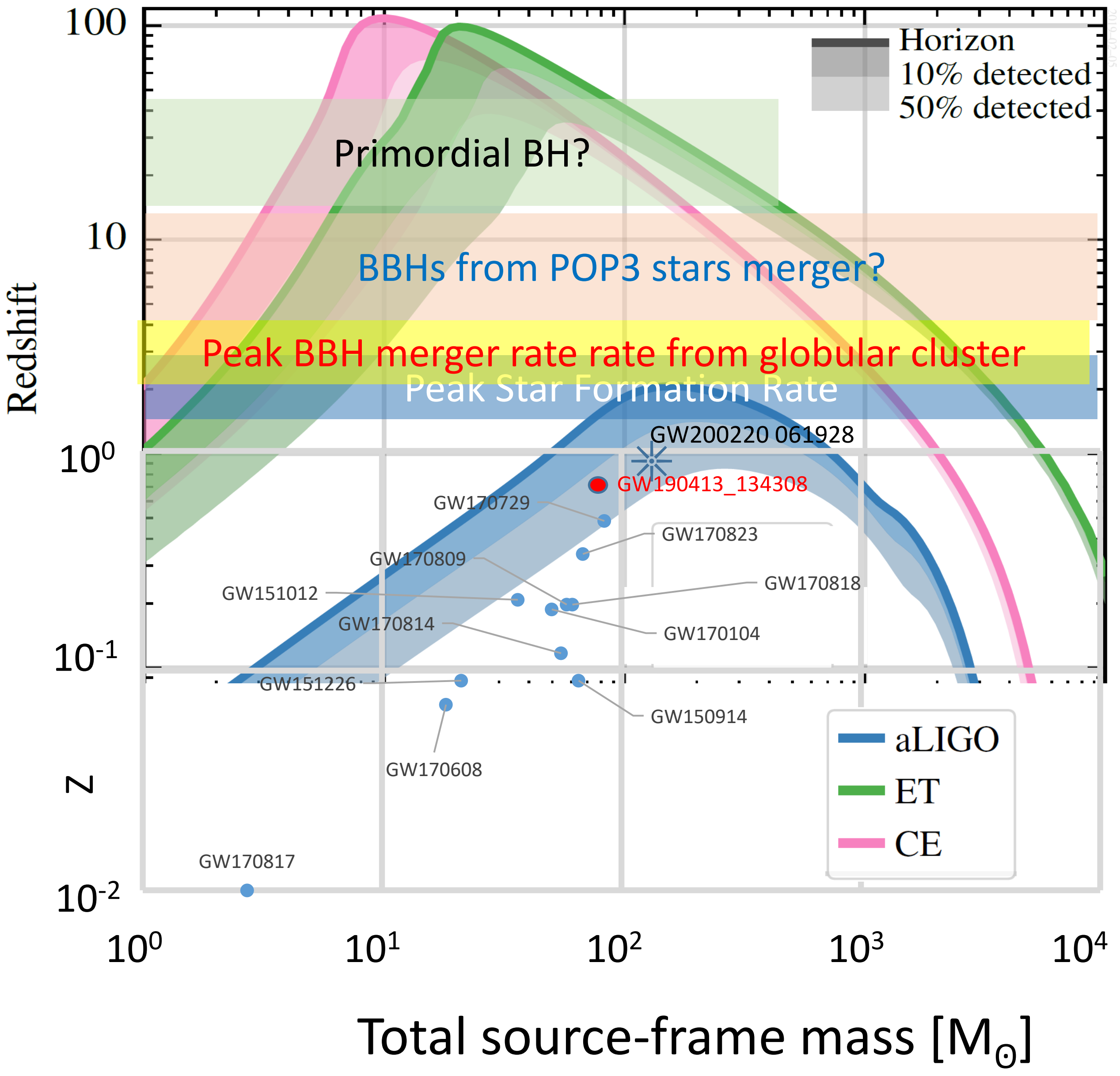
AdV sensitivity evolution from O3 to post-O5



OK, all done?

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

- 2nd generation GW detectors will explore the local Universe, even in their post-O5 configuration, initiating precision GW astronomy, but to have cosmological investigations a factor of 10 improvement in terms detection distance is needed



Detection distance of GWD

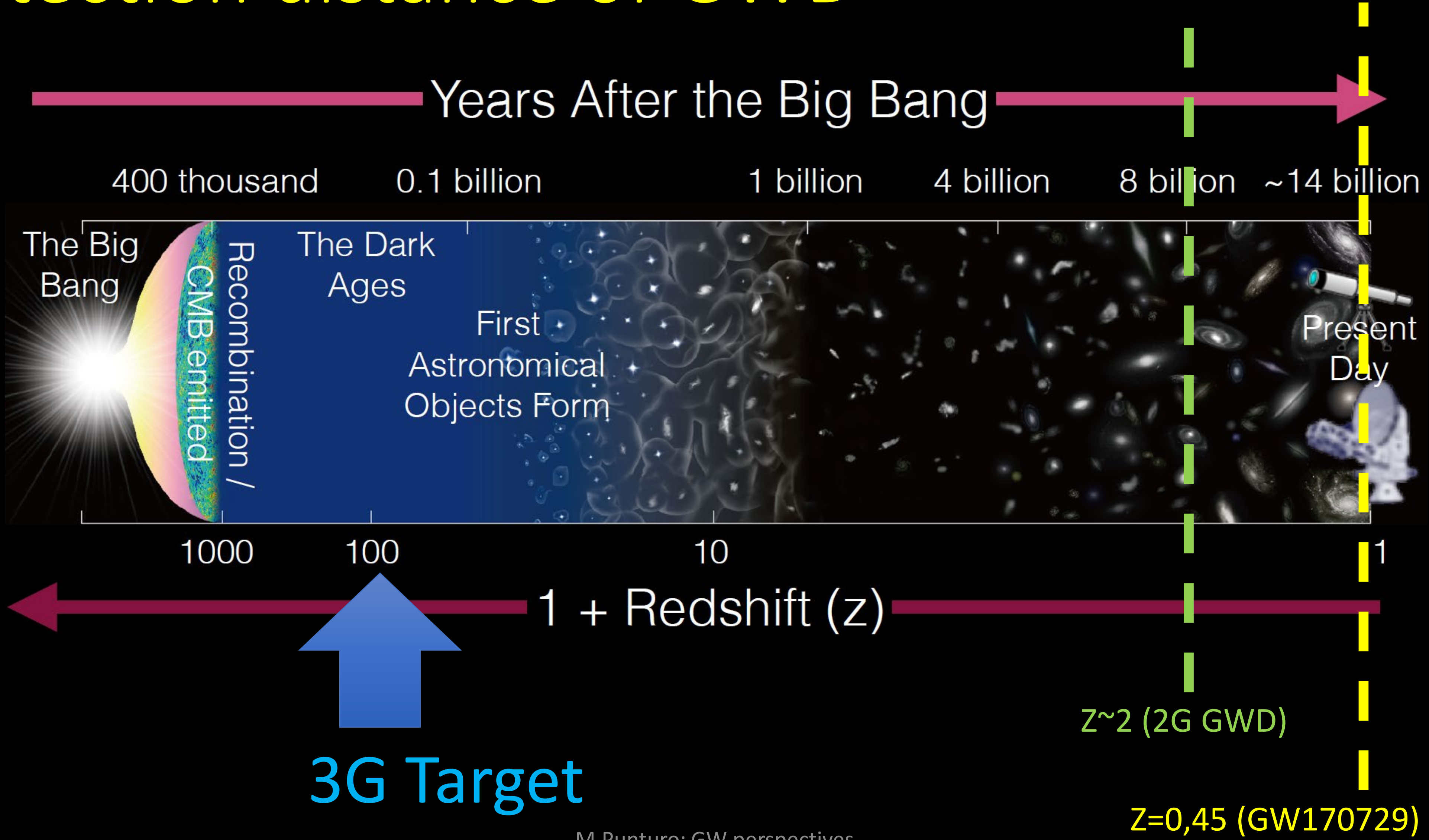
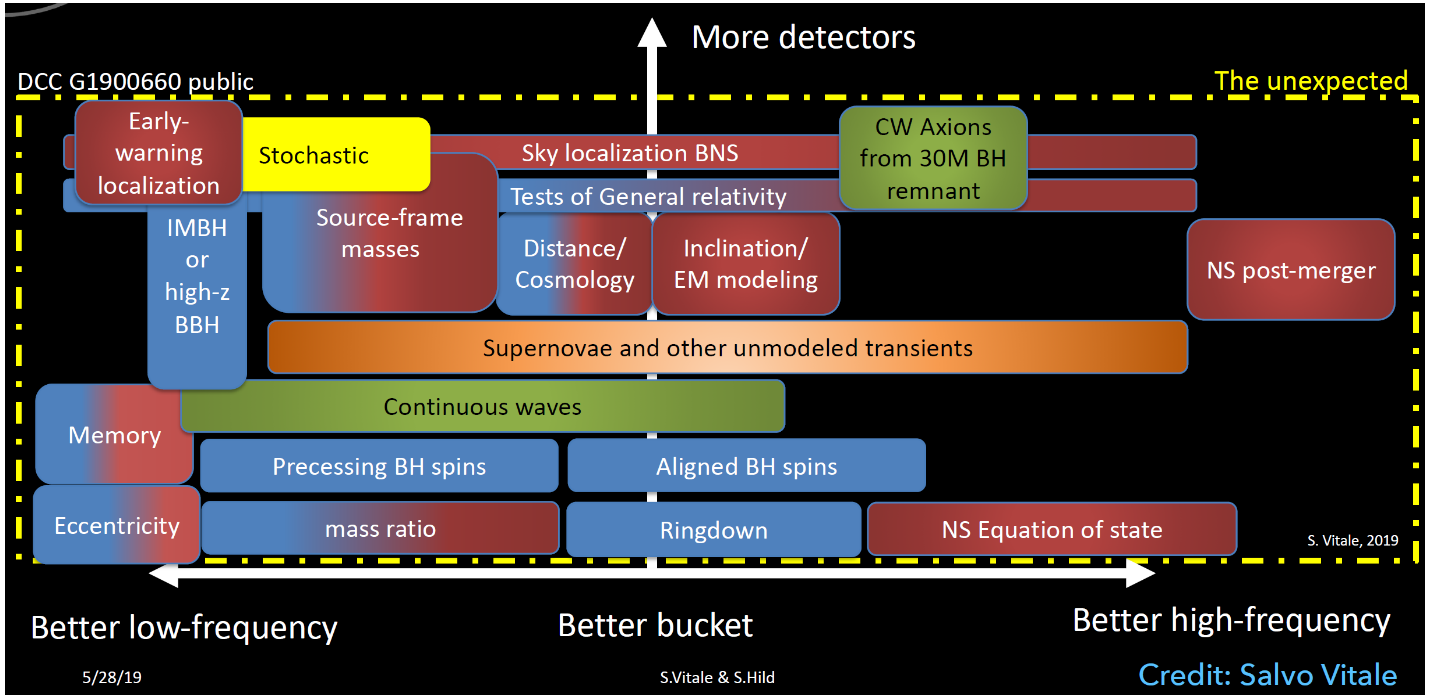


Image credit: NAOJ/ALMA http://alma.mtk.nao.ac.jp/

Where to look for new physics?

- Terrestrial interferometric detectors have access roughly to the [few, few×10^3] Hz frequency interval of the GW signal
- GW sources produce signals in different GW ranges
- Discovery machines must have the widest possible frequency range
- Precision measurement machines should have the best sensitivity
- 3G GW observatories must have both



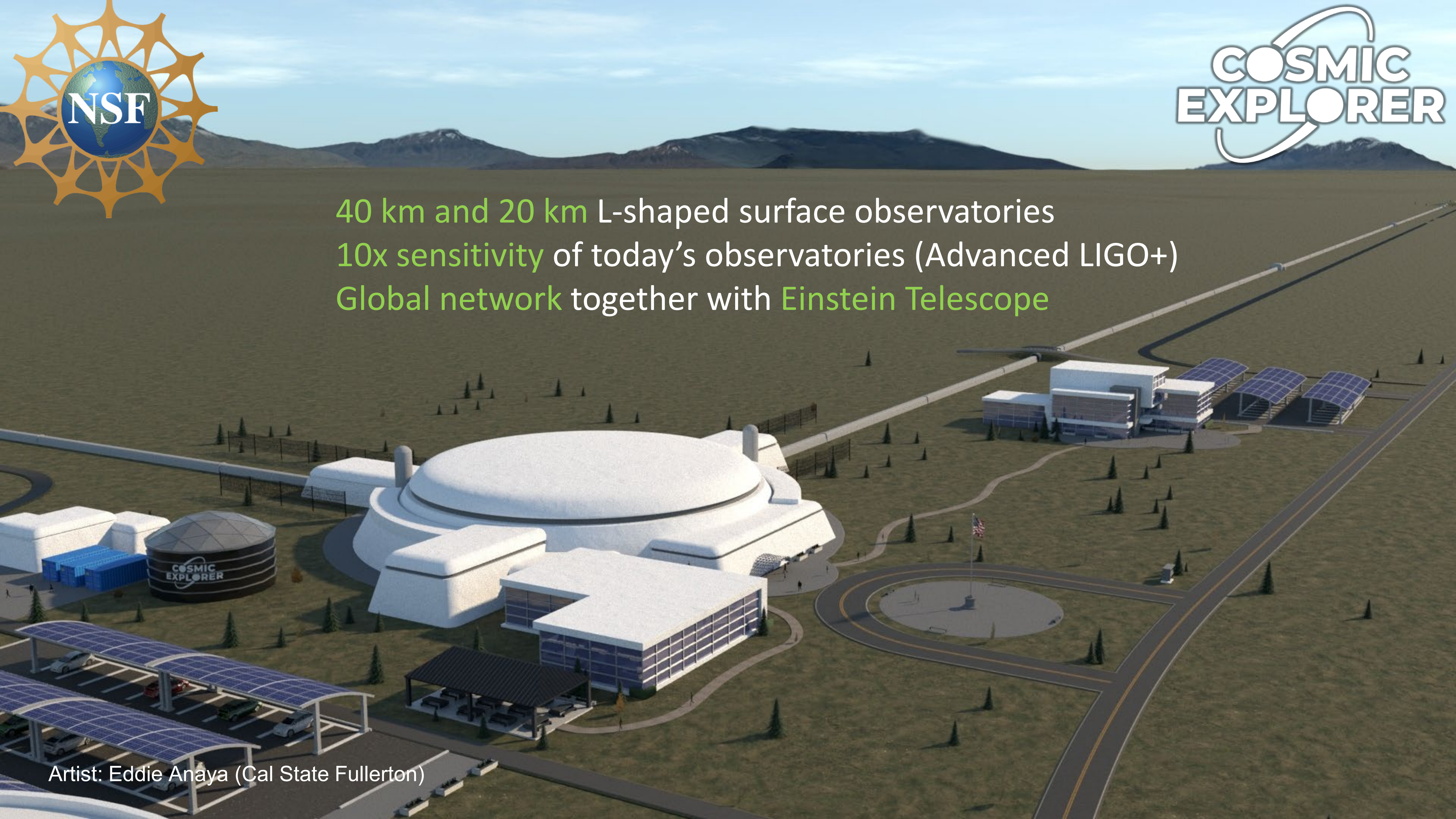
Einstein Telescope (ET)

≥ 10km

Corner halls depth about 200m

ET pioneered the idea of a 3rd generation GW observatory:

- A new infrastructure capable to host future upgrades for decades without limiting the observation capabilities
- A sensitivity at least 10 times better than the (nominal) advanced detectors on a large fraction of the (detection) frequency band
- A dramatic improvement in sensitivity in the low frequency (few Hz – 10Hz) range
- High reliability and improved observation capability
- Polarisation disentanglement

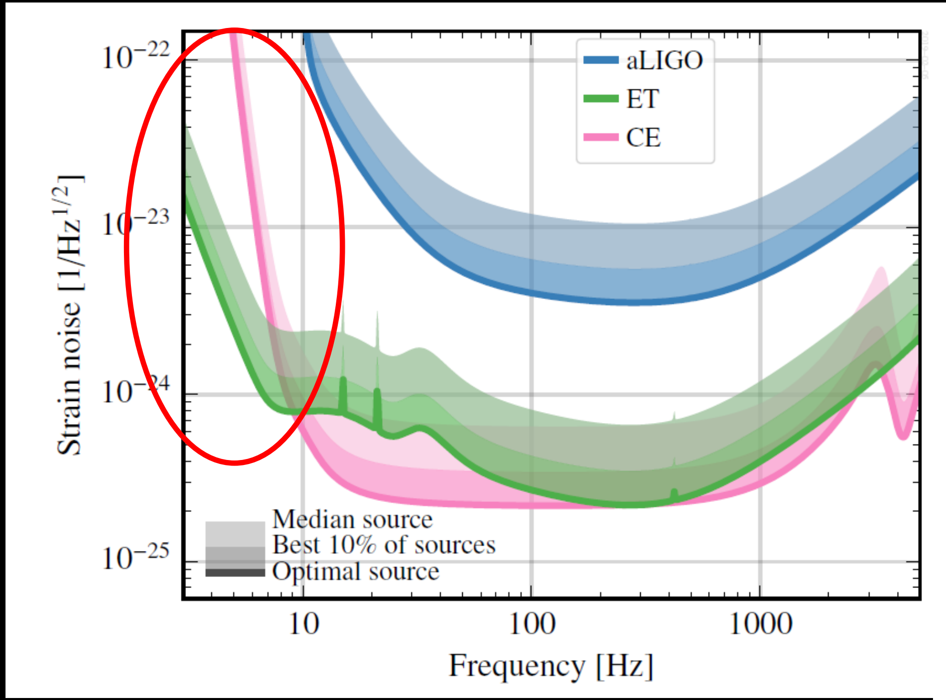


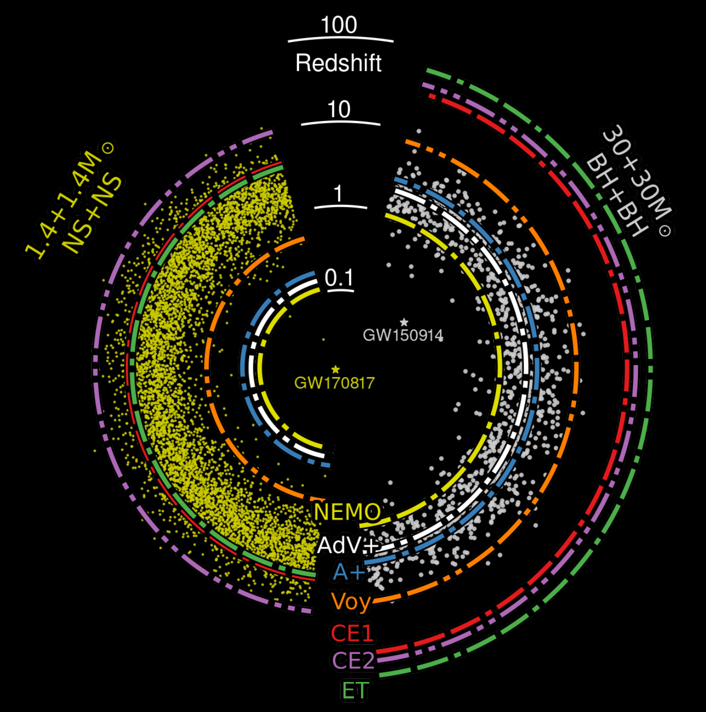
40 km and 20 km L-shaped surface observatories
10x sensitivity of today's observatories (Advanced LIGO+)
Global network together with Einstein Telescope

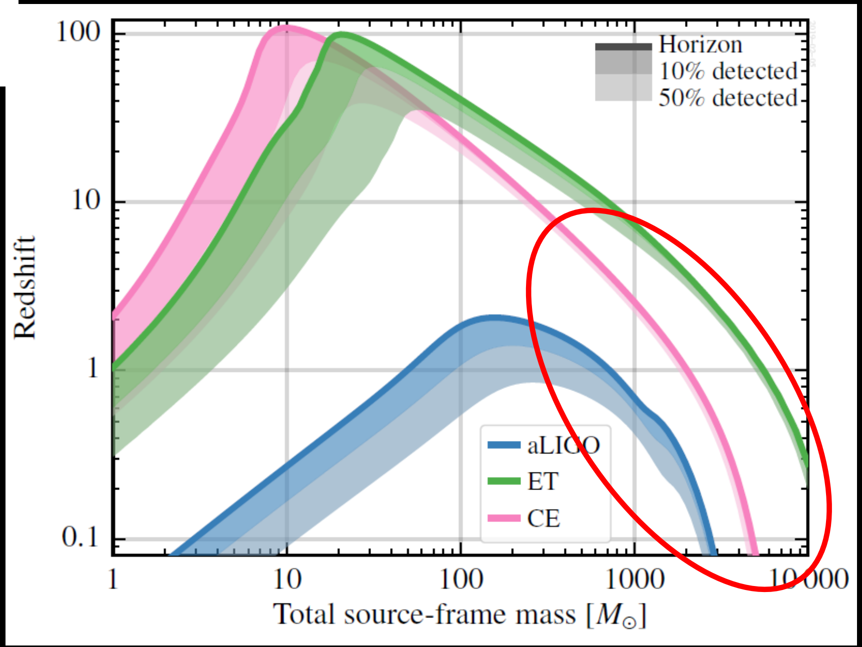
Artist: Eddie Anaya (Cal State Fullerton)

Observation performance of ET & CE

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





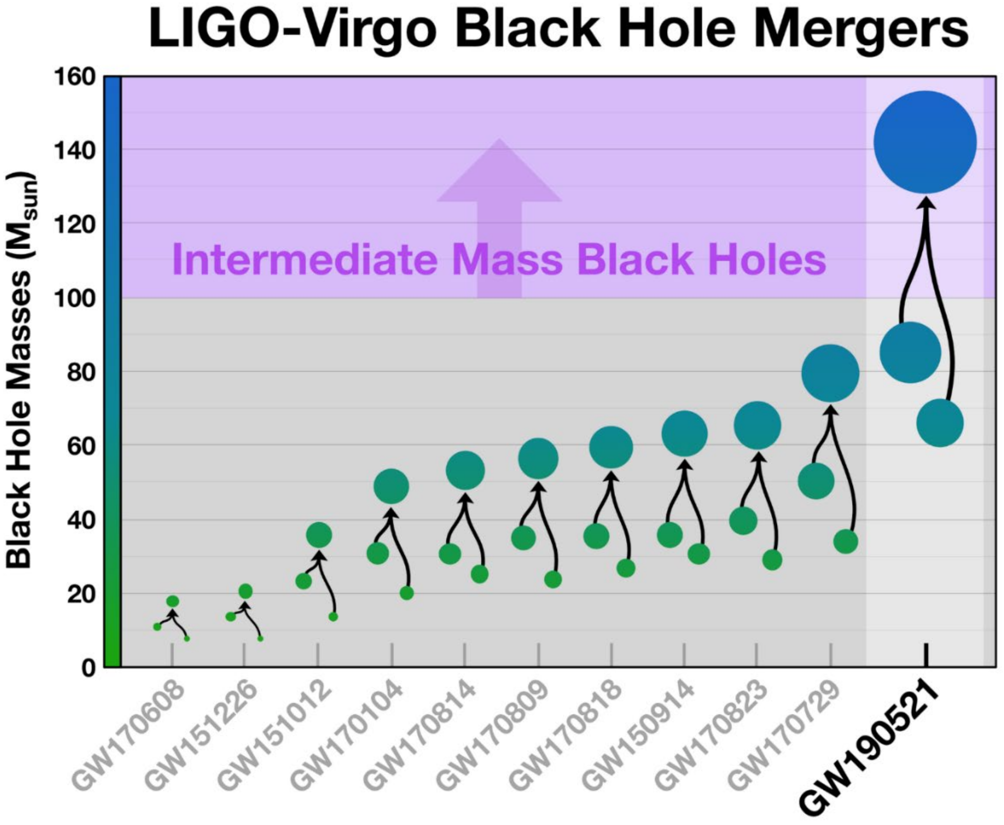


Why low frequency focus?

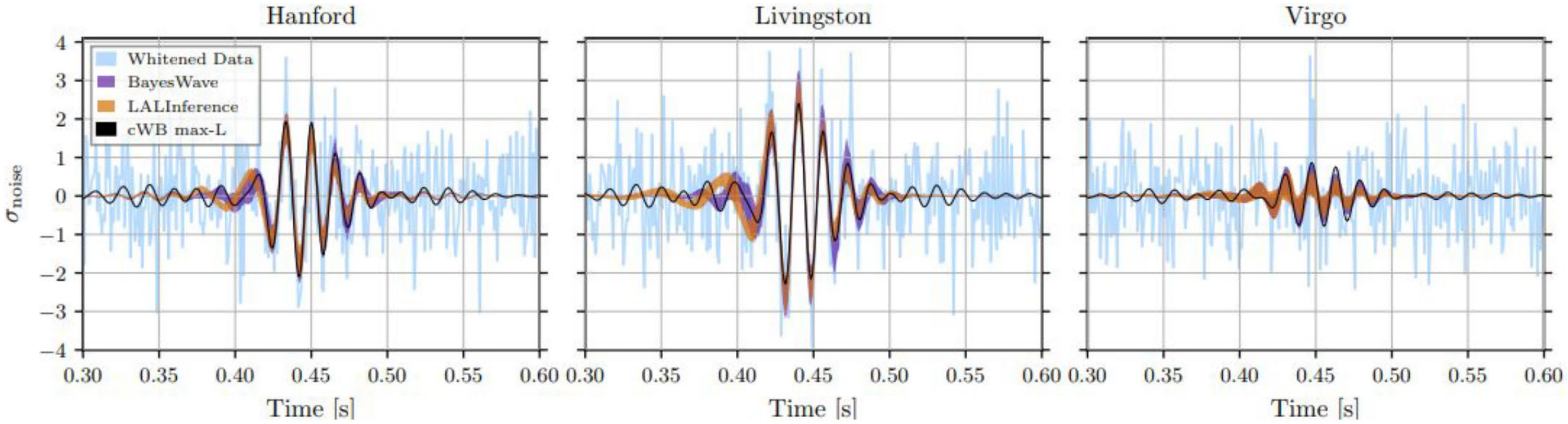
GW190521

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

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

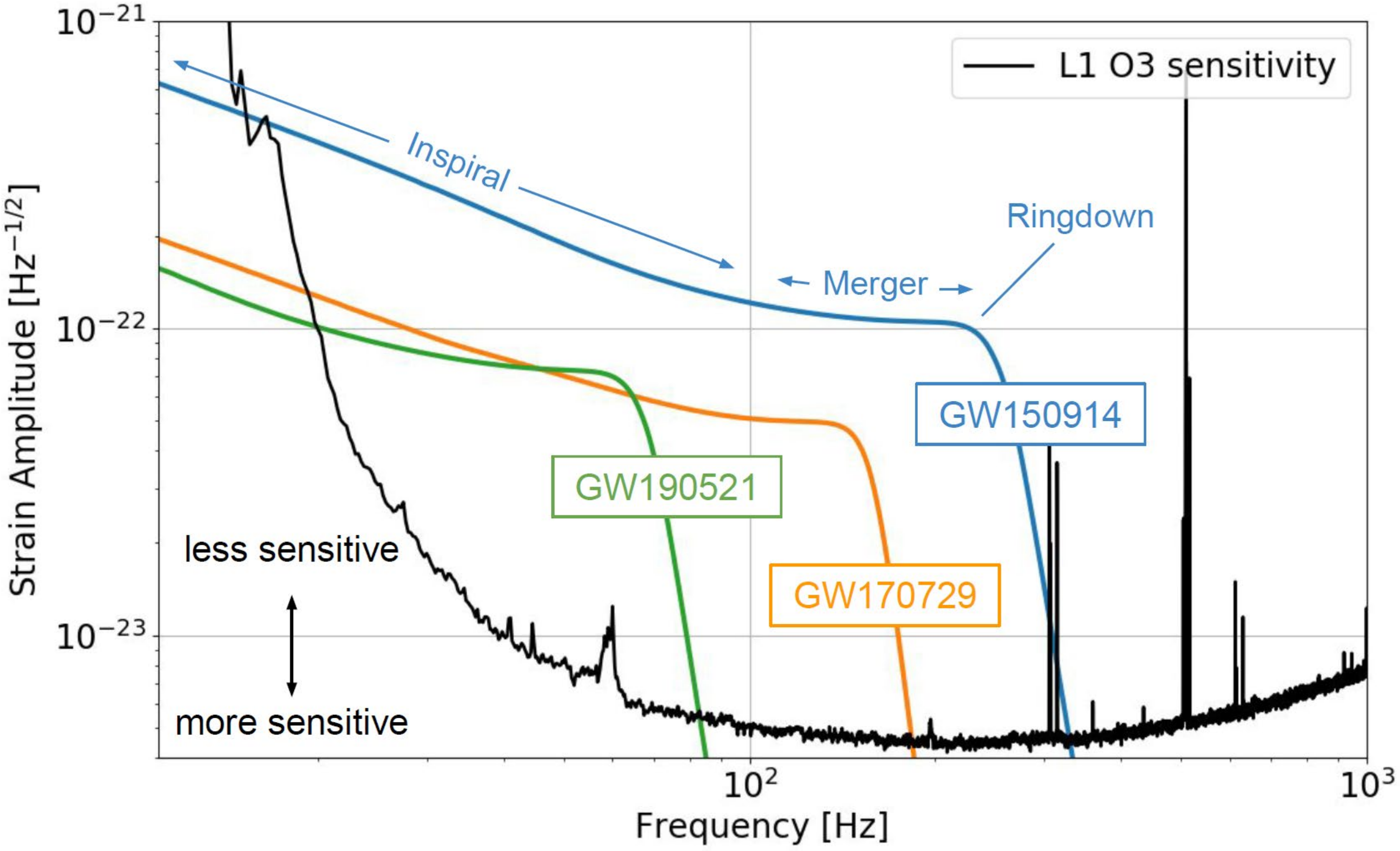


Phys. Rev. Lett. 125, 101102 (2020)
Astrophys. J. Lett. 900, L13 (2020)



Where is the chirp?

GW190521: LIGO-Virgo sensitivity to the BBH merger



- Higher masses correspond to lower frequency GW emission

ET Science in a nutshell

ASTROPHYSICS

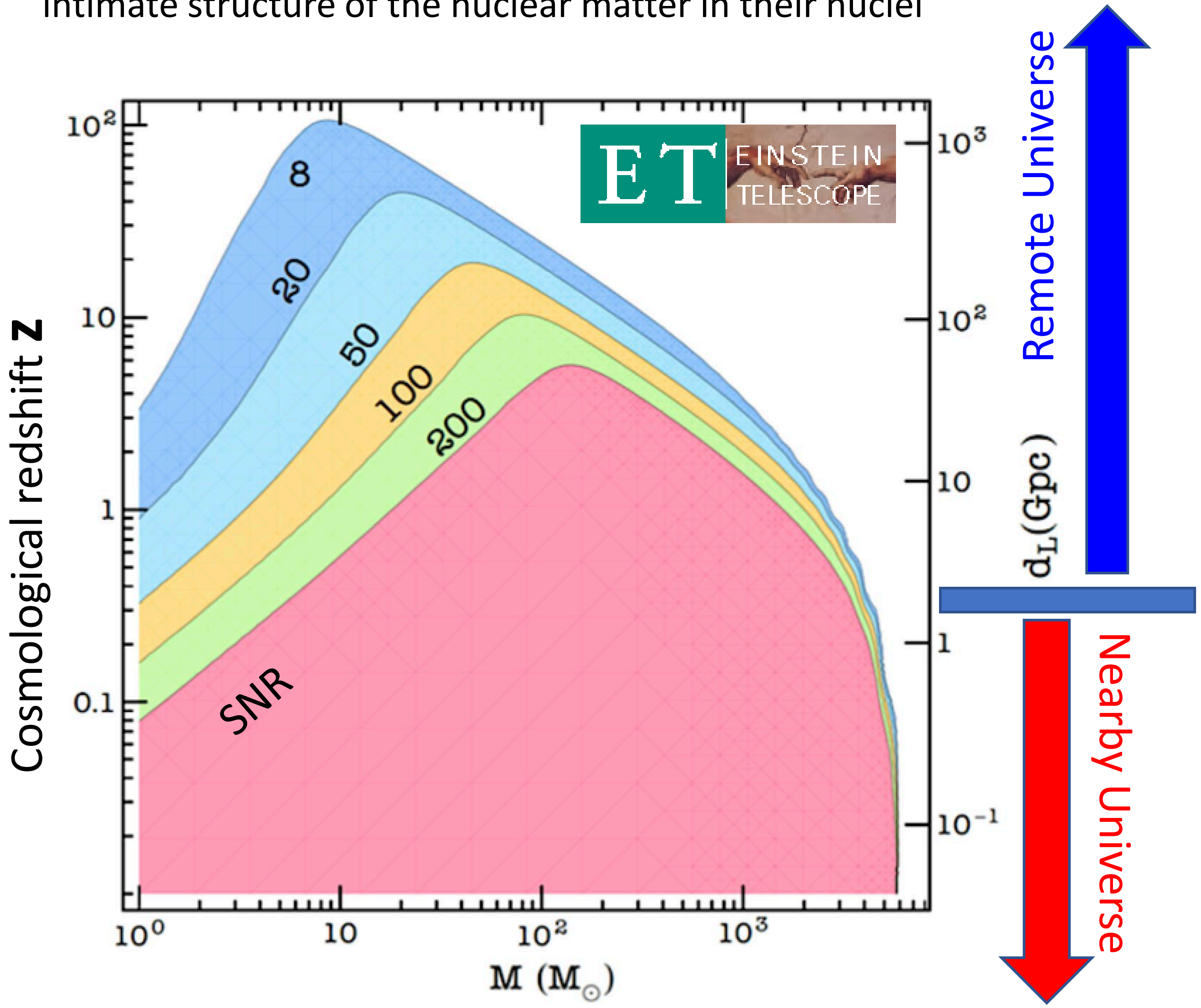
- **Black hole properties**
  - origin (stellar vs. primordial)
  - evolution, demography
- **Neutron star properties**
  - interior structure (QCD at ultra-high densities, exotic states of matter)
  - demography
- **Multi-band and -messenger astronomy**
  - joint GW/EM observations (GRB, kilonova,...)
  - multiband GW detection (LISA)
  - neutrinos
- **Detection of new astrophysical sources**
  - core collapse supernovae
  - isolated neutron stars
  - stochastic background of astrophysical origin

FUNDAMENTAL PHYSICS AND COSMOLOGY

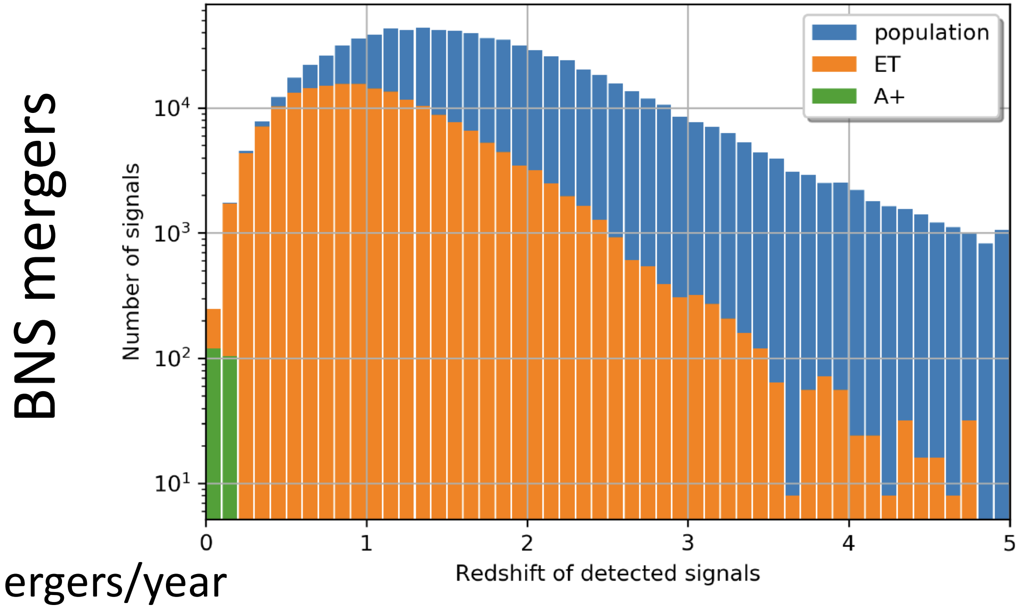
- **The nature of compact objects**
  - near-horizon physics
  - tests of no-hair theorem
  - exotic compact objects
- **Tests of General Relativity**
  - post-Newtonian expansion
  - strong field regime
- **Dark matter**
  - primordial BHs
  - axion clouds, dark matter accreting on compact objects
- **Dark energy and modifications of gravity on cosmological scales**
  - dark energy equation of state
  - modified GW propagation
- **Stochastic backgrounds of cosmological origin**
  - inflation, phase transitions, cosmic strings

ET Science in a nutshell

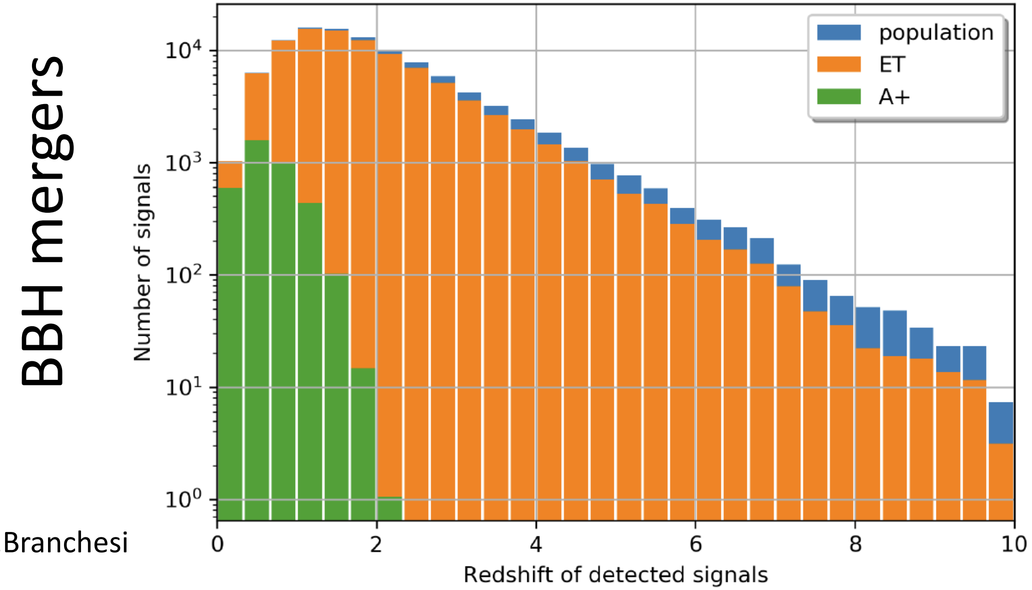
- ET will explore almost the entire Universe listening the gravitational waves emitted by black hole, back to the dark ages after the Big Bang
- ET will detect, with high SNR, hundreds of thousands coalescences of binary systems of Neutron Stars per year, revealing the most intimate structure of the nuclear matter in their nuclei



Compact Object Binary Populations



O(10^5) mergers/year

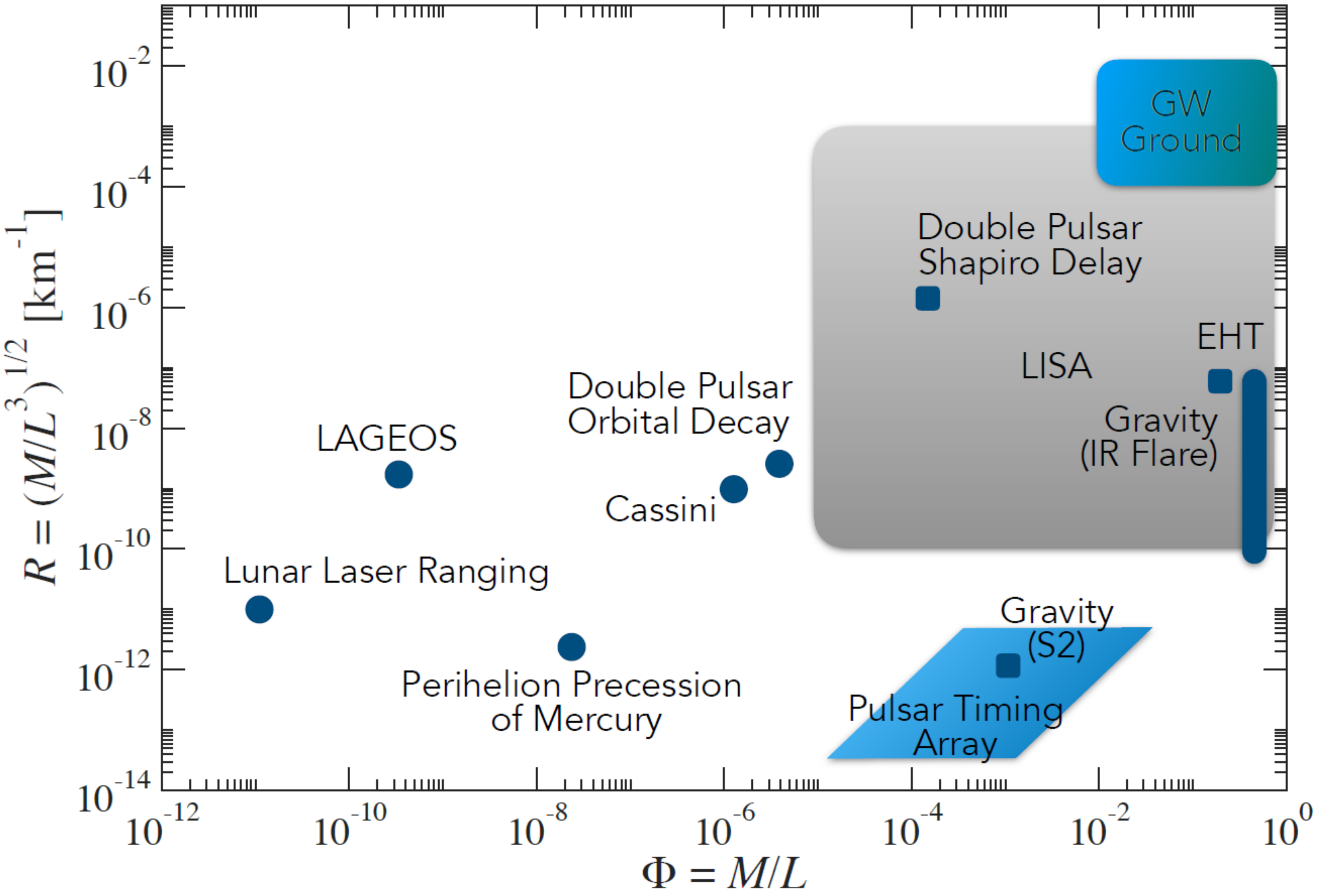


Credit: M.Branchesi

GWs are 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



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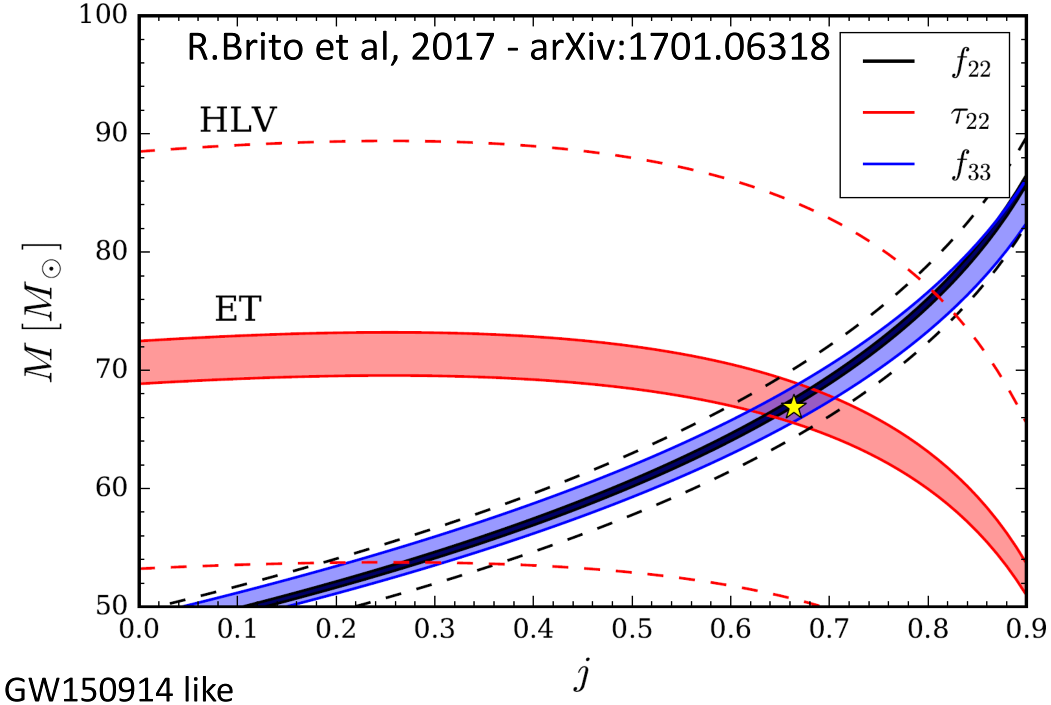
Extreme gravity

- 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

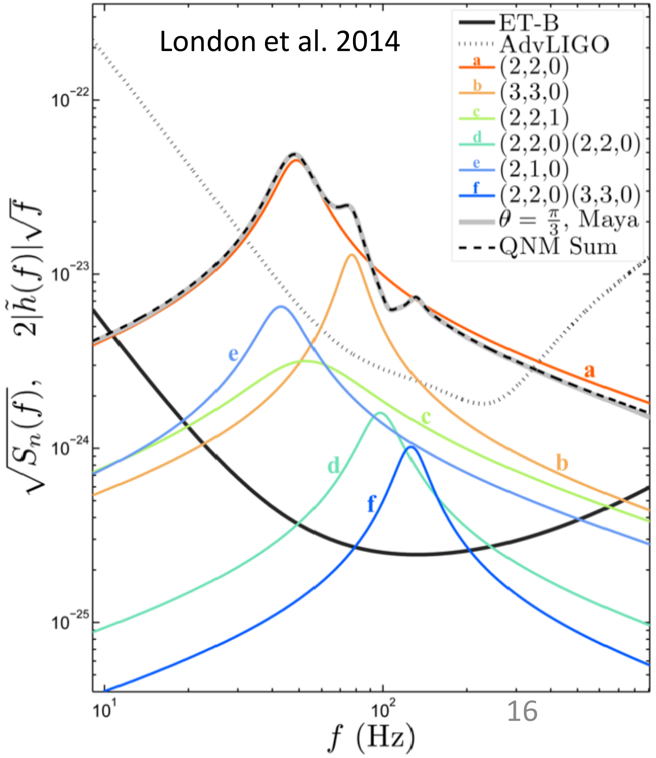
ET will resolve QN emission by BH

J=J/M² dimensionless spin



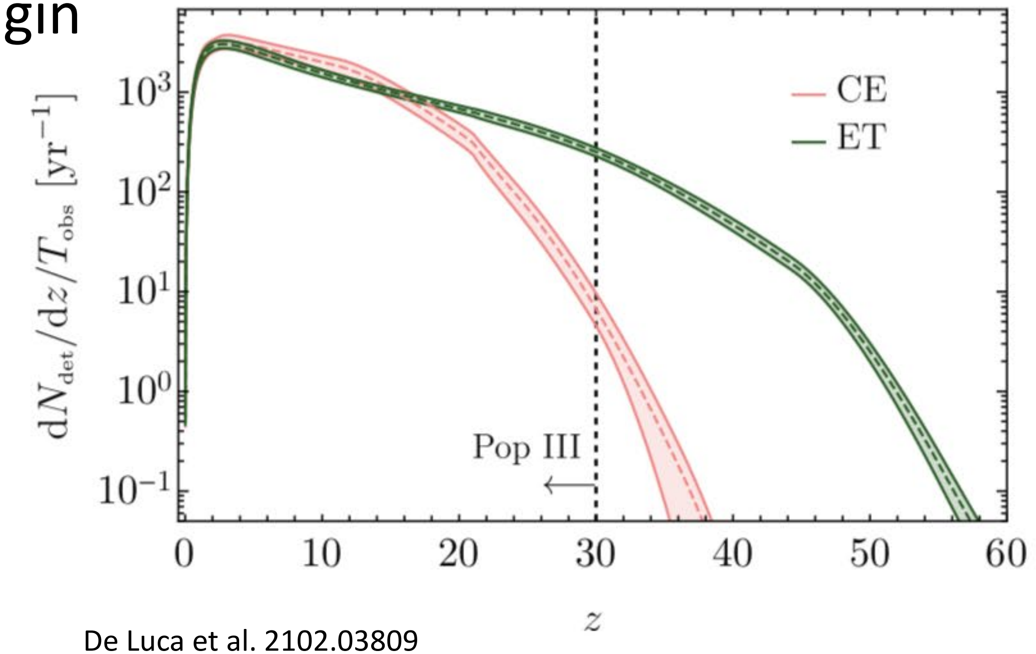
GW150914 like

350 Msun binary @ 100 Mpc



Primordial BHs

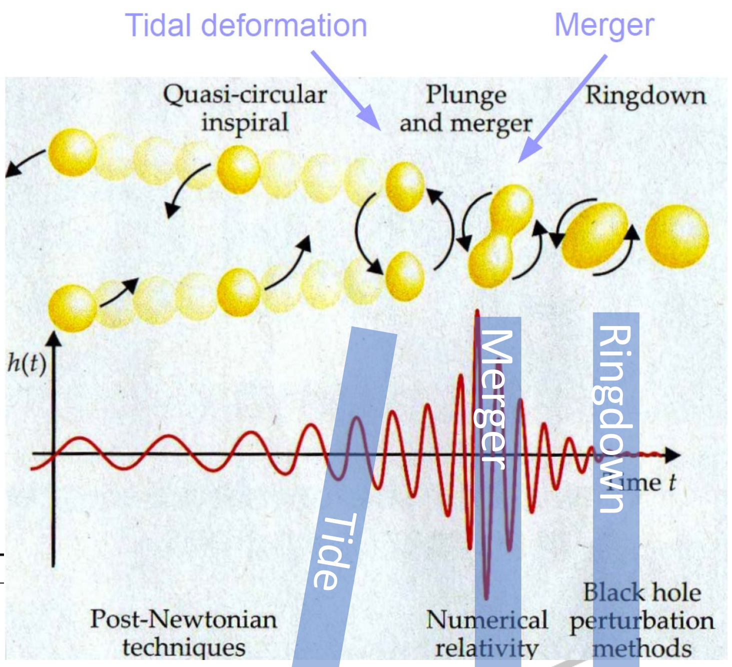
- ET (and CE) will detect BH well beyond the SFR peak z~2
  - comparing the redshift dependence of the BH-BH merger rate with the cosmic star formation rate it will be possible to disentangle the contribution of BHs of stellar origin from that of possible BHs of primordial origin (whose merger rate is not expected to be correlated with the star formation density)
  - Any BBH merger at z>30 will be of primordial origin

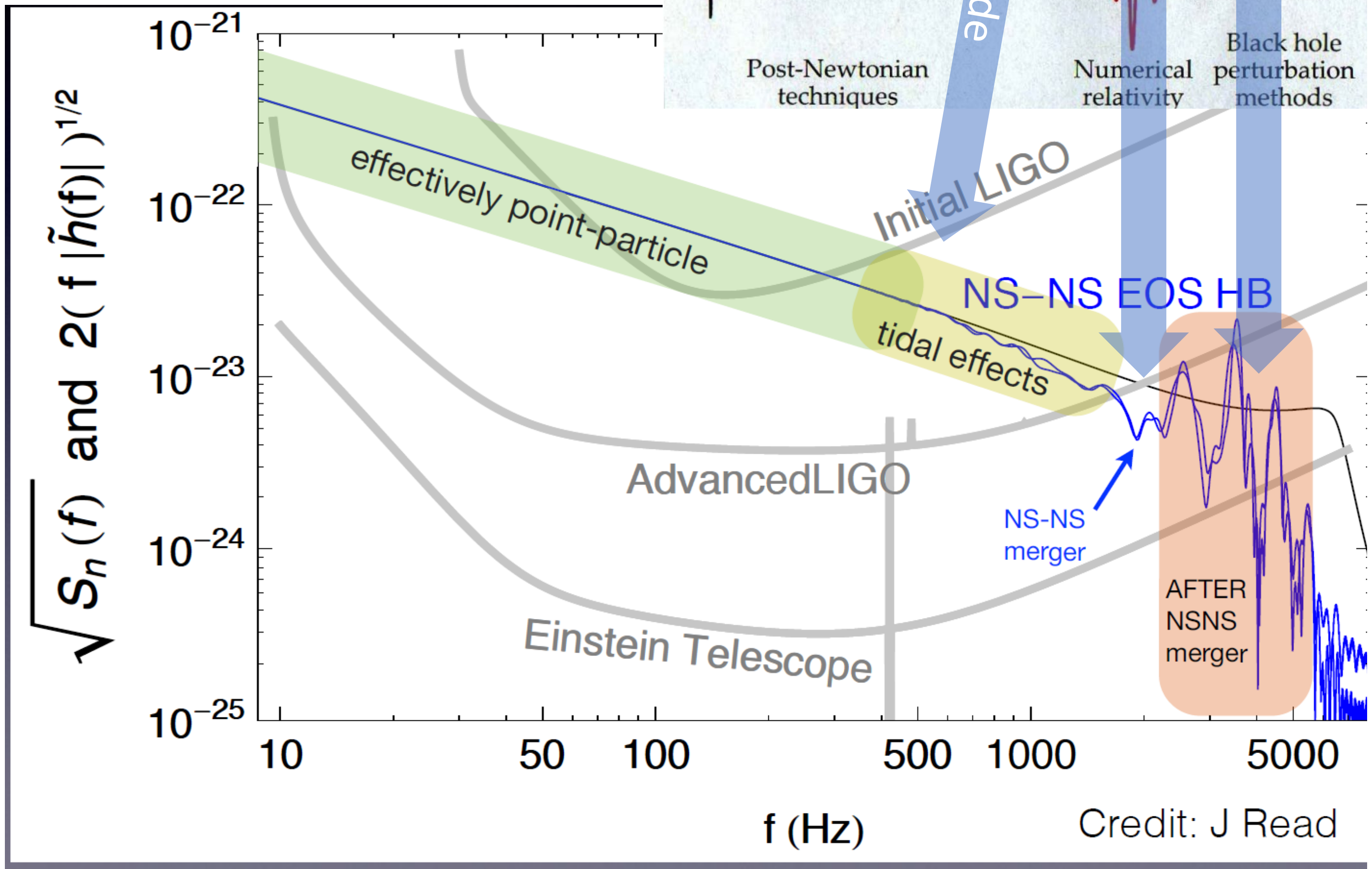


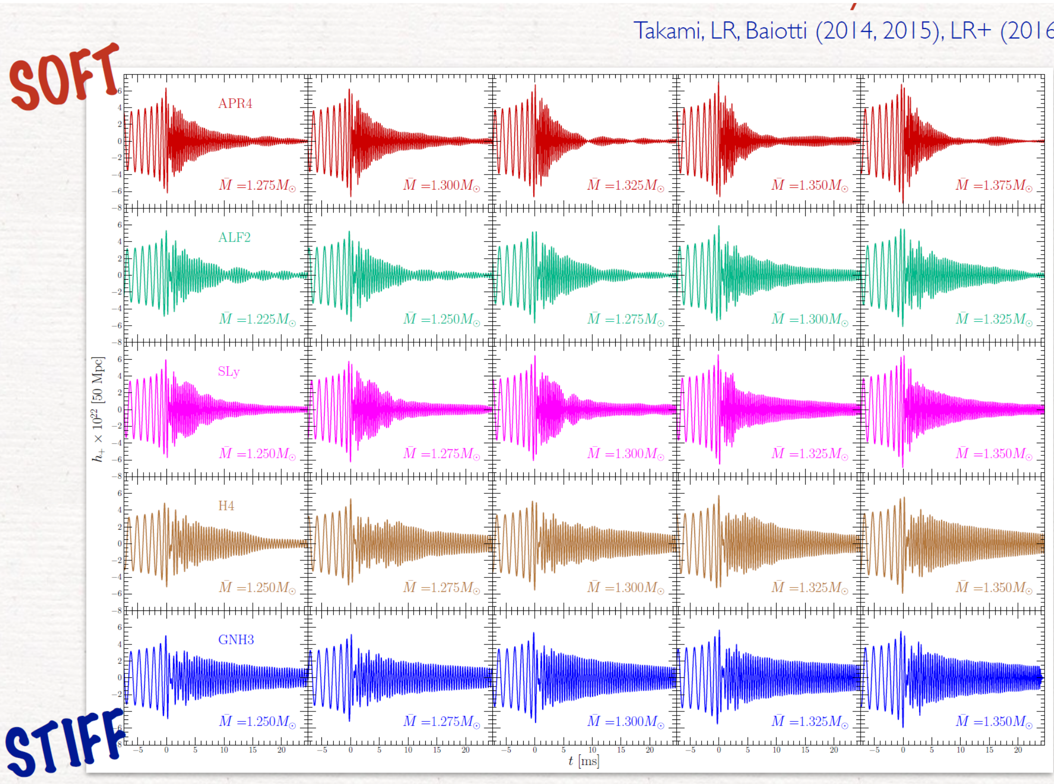
De Luca et al. 2102.03809

Structure of a Neutron Star

Stephen Fairhurst
ET meeting 27-28 March 2017

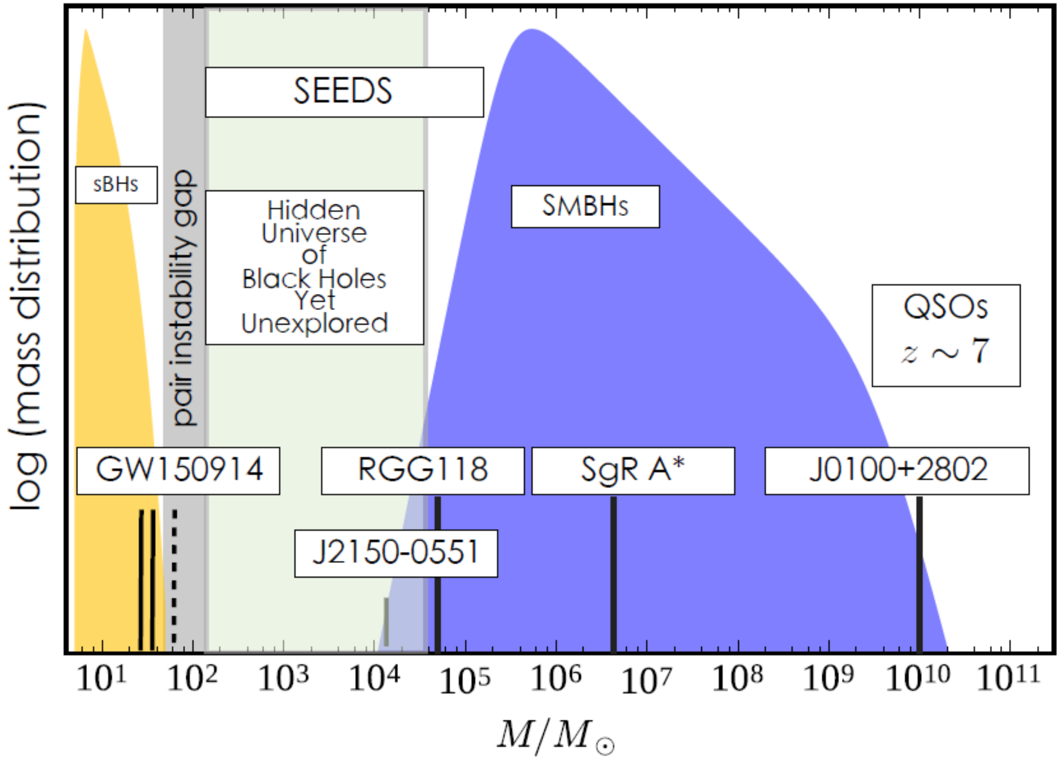


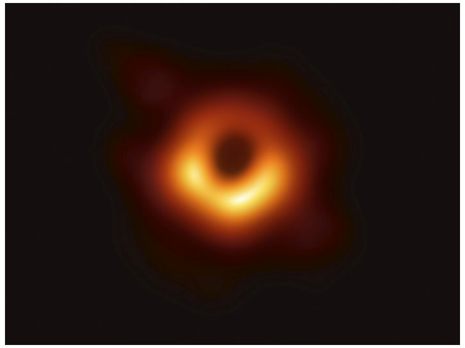


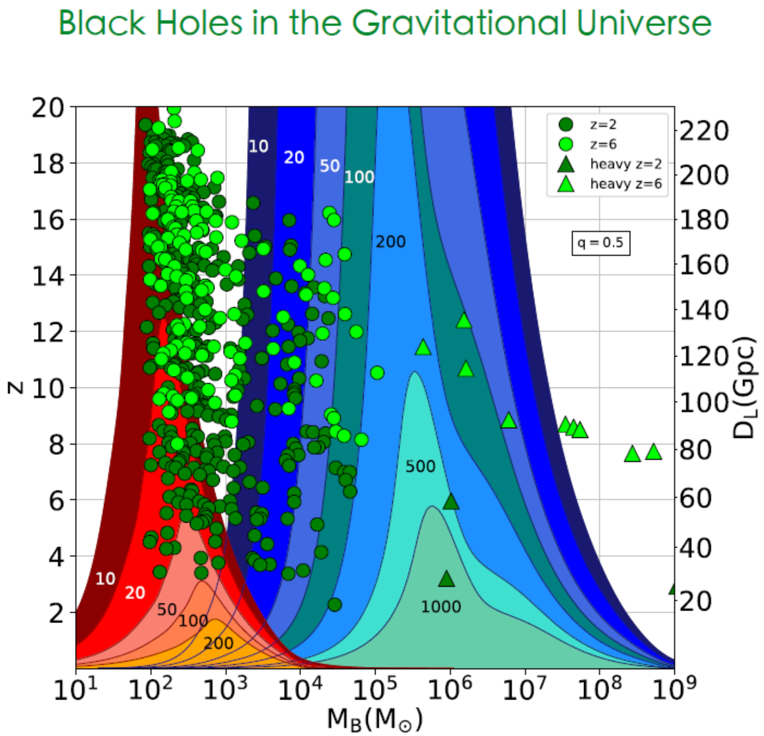


Seeds and Supermassive Black Holes

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

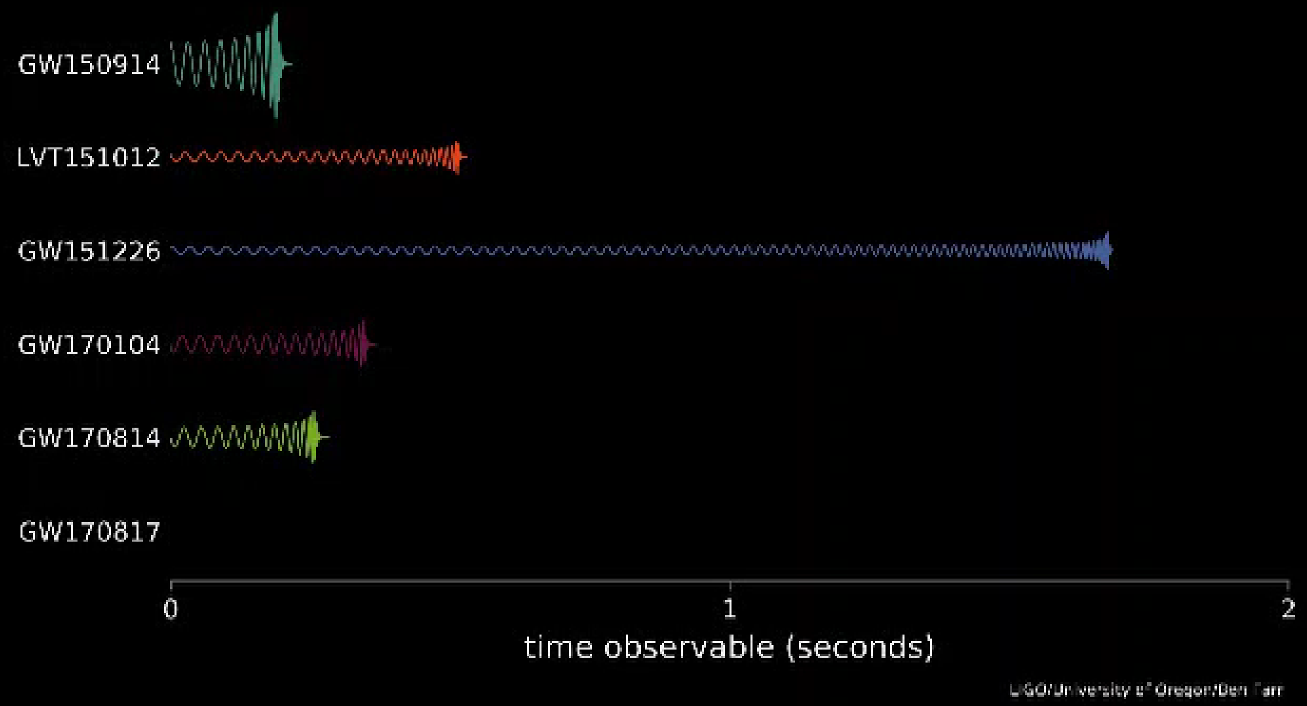


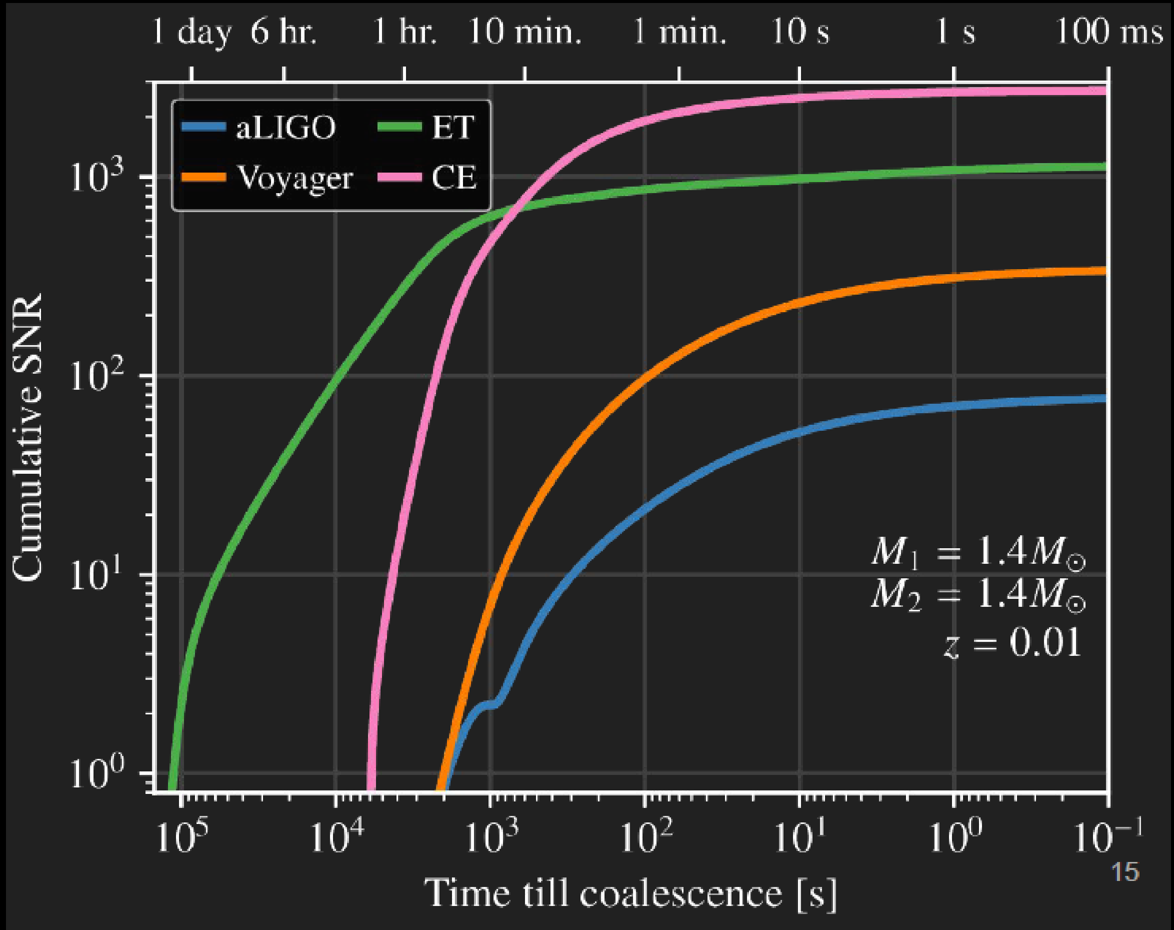




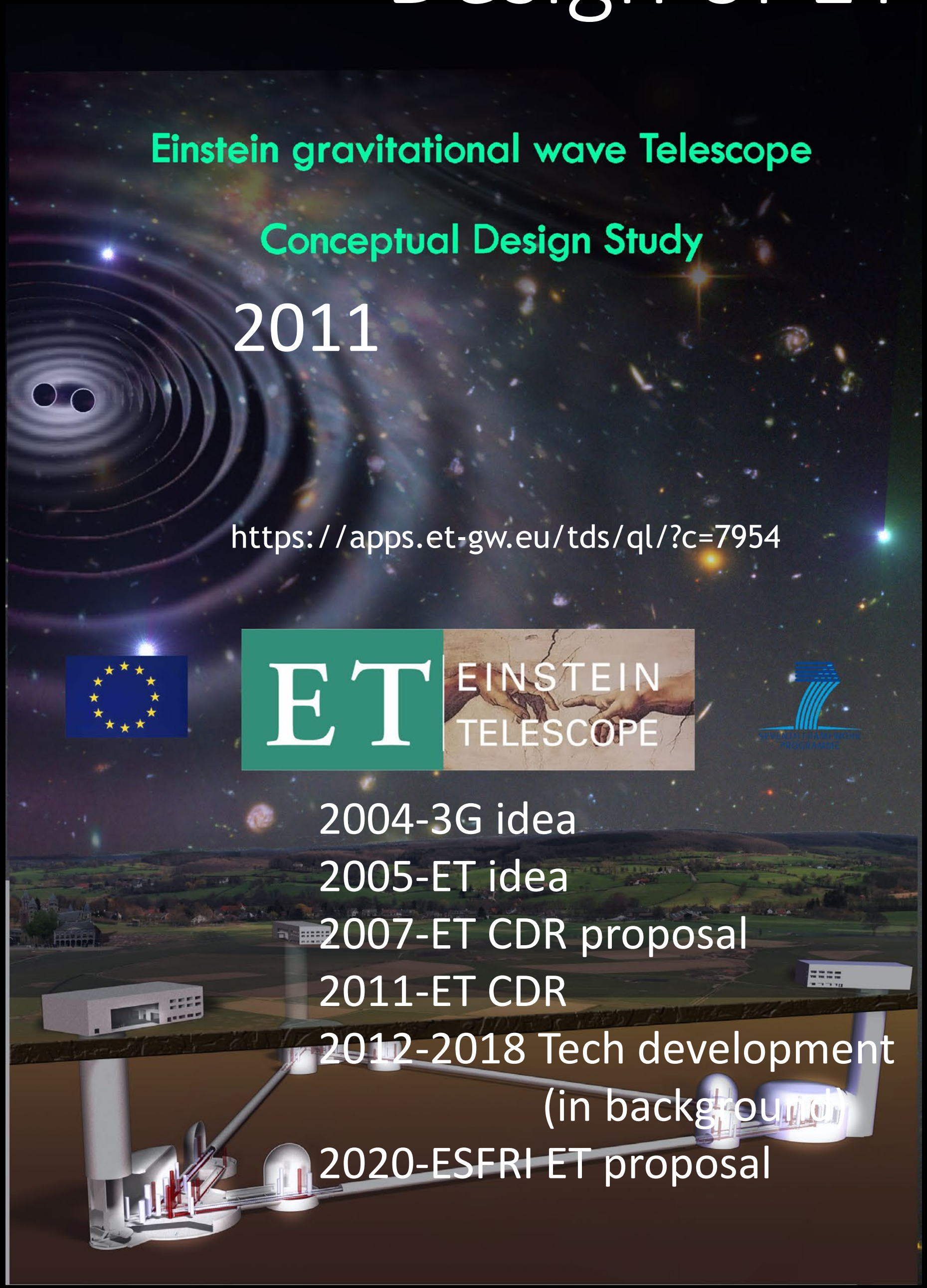
Low frequency: Multi-messenger astronomy

- If we are able to cumulate enough SNR before the merging phase, we can trigger e.m. observations before the emission of photons
- Keyword: low frequency sensitivity:



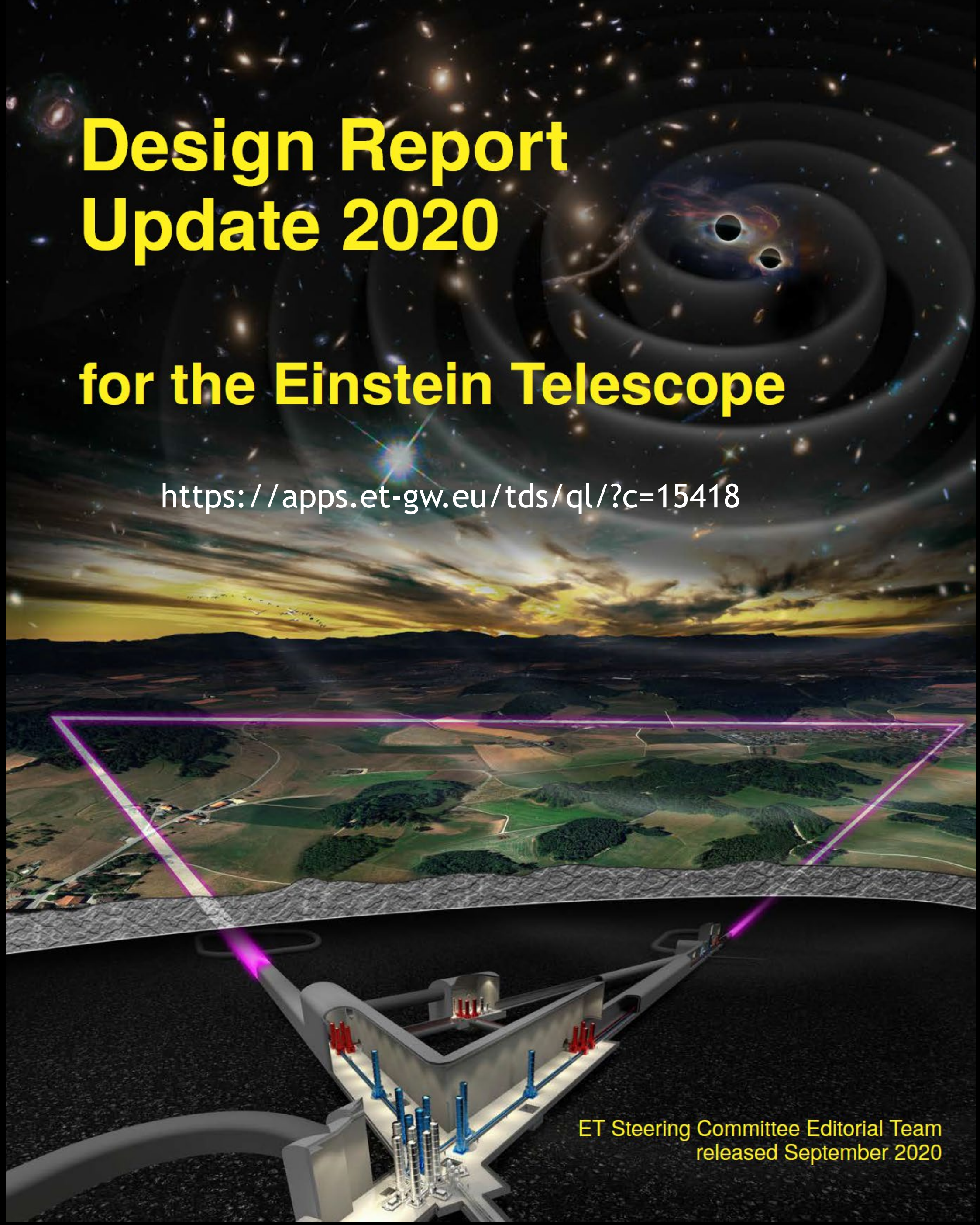


Design of ET



2004-3G idea
2005-ET idea
2007-ET CDR proposal
2011-ET CDR
2012-2018 Tech development
(in background)
2020-ESFRI ET proposal

ESFRI



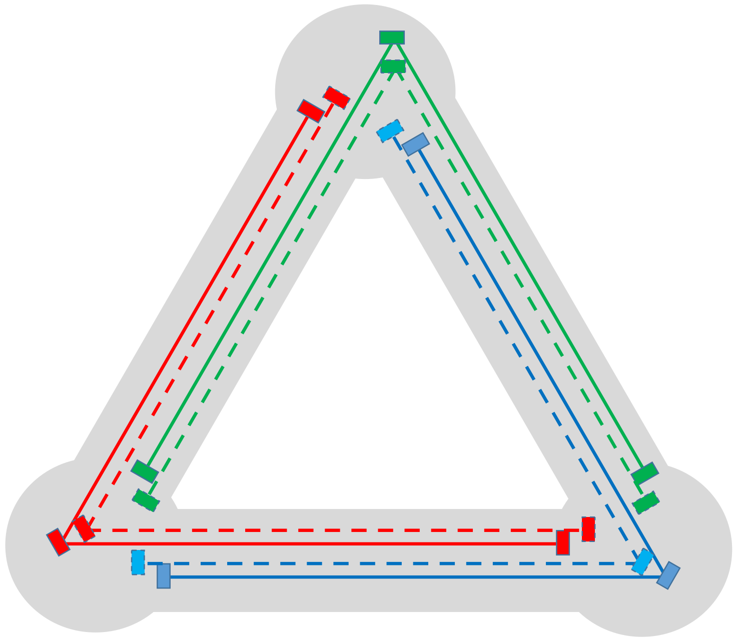
ET key elements

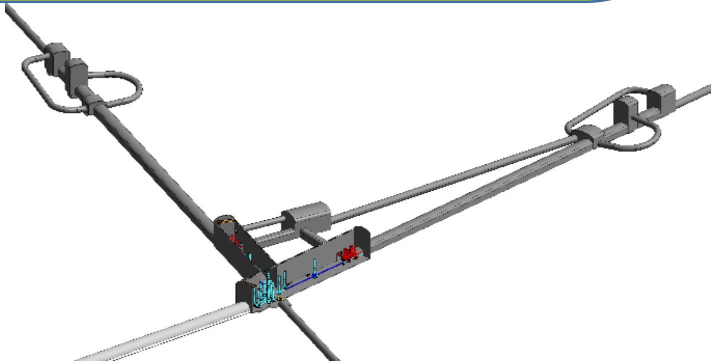
Requirements

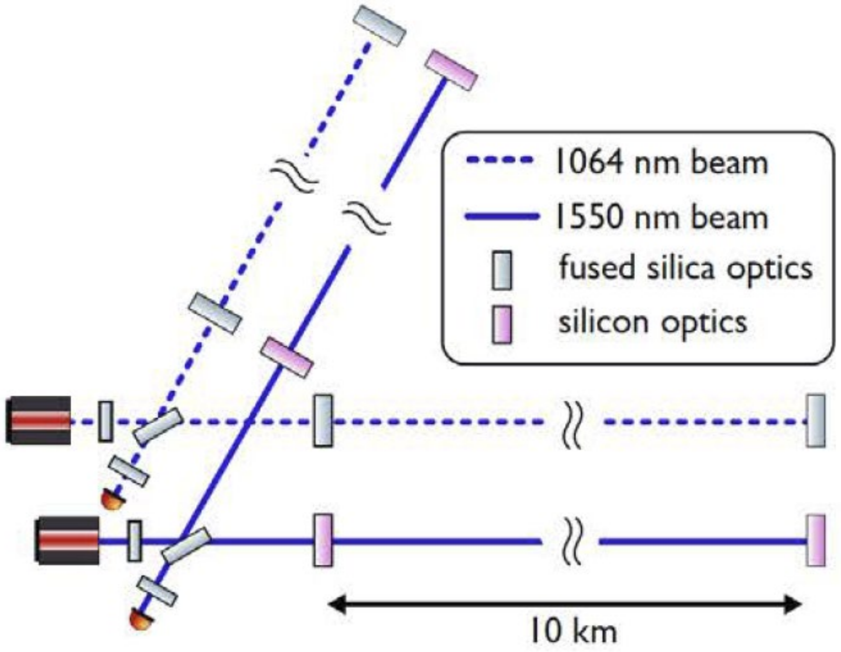
- Wide frequency range
- Massive black holes (LF focus)
- Localisation capability
- (more) Uniform sky coverage
- Polarisation disentanglement
- High Reliability (high duty cycle)
- High SNR

Design Specifications

- Xylophone (multi-interferometer) Design
- Underground
- Cryogenic
- Triangular shape
- Multi-detector design
- Longer arms







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ET Enabling Technologies

- 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

Parameter	ET-HF	ET-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10-20 K
Mirror material	fused silica	silicon
Mirror diameter / thickness	62 cm / 30 cm	45 cm/ 57 cm
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase (rad)	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1×300 m	2×1.0 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	TEM_{00}	TEM_{00}
Beam radius	12.0 cm	9 cm
Scatter loss per surface	37 ppm	37 ppm
Seismic isolation	SA, 8 m tall	mod SA, 17 m tall
Seismic (for $f > 1$ Hz)	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$
Gravity gradient subtraction	none	factor of a few

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

Challenging Engineering: key points

- **~30km of underground tunnels**
  - Safety (fire, cryogenic gasses, escape lanes, heat handling during the vacuum pipe backing)
  - Noise (creeping, acoustic noise, seismic noise, Newtonian noise)
  - Minimisation of the volumes, but preservation of future potential)
  - Water handling, hydro-geology and tunnels inclination
  - Cost
- **Large caverns**
  - In addition to the previous points:
  - Stability
  - Cleanliness
  - Thermal stability
  - Ventilation and acoustic noise

Cryo-cooling

ET operative temperature ~10K

Key issues

- Acoustic and vibration noises
- Laser absorption and heat extraction
- Cleanliness and contamination
- Cooling time (large masses, commissioning time, …)
- Infrastructures
- Technology (gasses or cryo-coolers)
- Materials
- Safety

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Low Frequency special focus

- Underground infrastructure
- 17m tall seismic filtering suspensions
    - Large impact on cavern engineering and costs
- R&D in active-passive filtering systems and seismic sensors

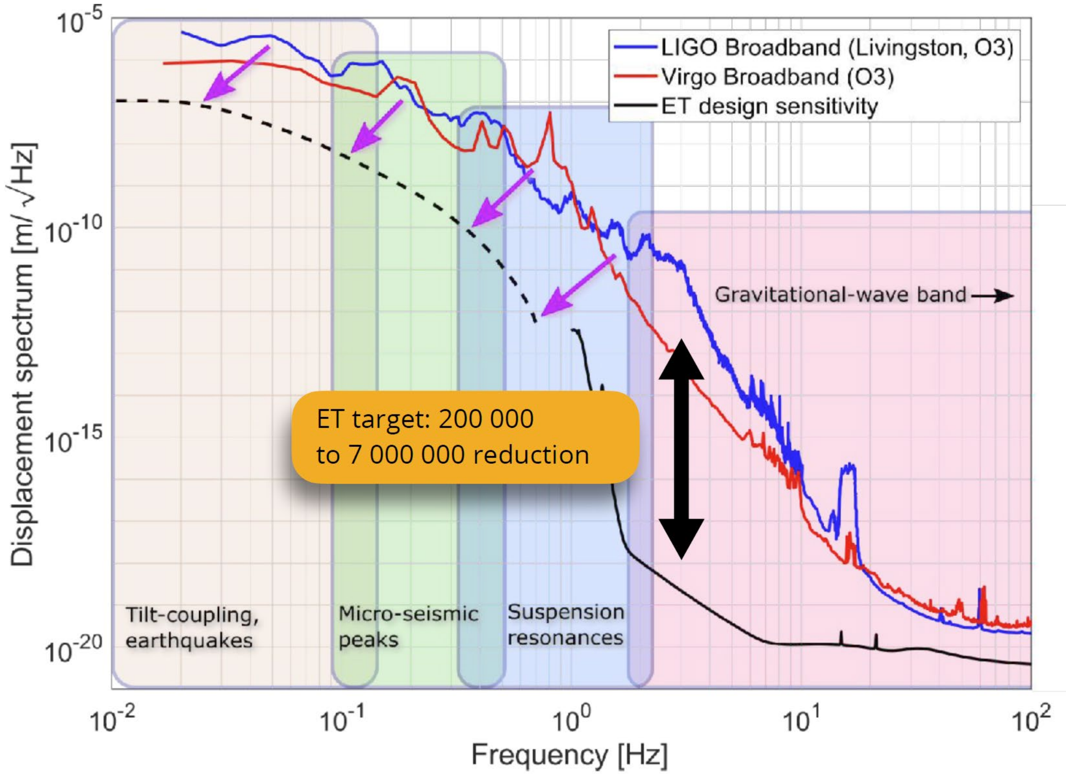
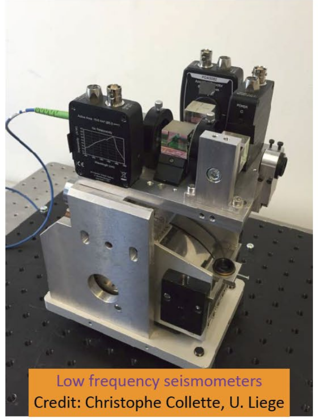
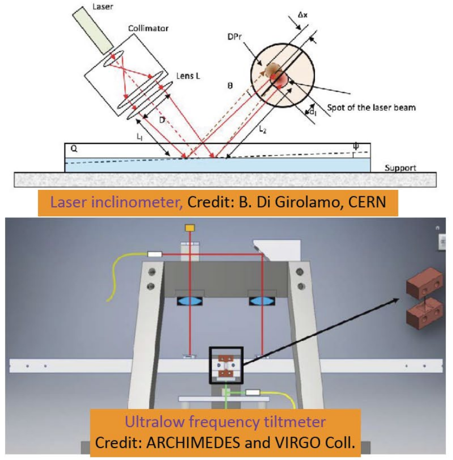


Image: Conor Mow-Lowry

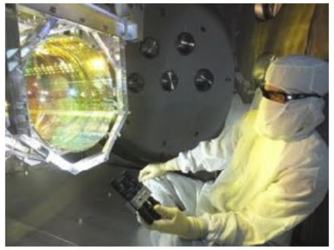
Credits: A.Freise

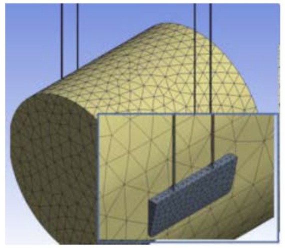




Credits: A.Freise

New Optics



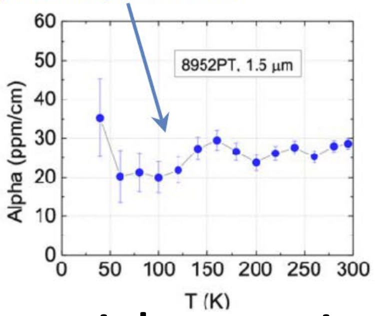


Advanced LIGO – 40 kg / ET 200 kg

Nikon SiO_2

Absorption of “best 45 cm” MCZ Si: 1.5um

Stanford/Glasgow/Berkeley/Caltech 2019



- Substrates Challenge:
  - Substrate (ET-HF silica / ET-LF silicon) of 200 kg-scale, diam≥45cm, with required purity and optical homogeneity/abs.
  - Silicon Challenge:
    - Czochralski (CZ) method produced test masses could have the required size, but show absorption excesses due to the (crucible) contaminants
    - Float Zone (FZ) produced samples show the required purity, but of reduced size (20cm wrt ≥45cm required)
    - Magnetic Czochralski (mCZ) could be the possible solution?
- Coating Challenge:
  - major challenge over recent years:
    - Amorphous dielectric coating solutions often either satisfy thermal noise requirement (3.2 times better than the current coatings) **or** optical performance requirement (less than 0.5ppm) – not both
    - AlGaAs Crystalline coatings could satisfy ET-LF requirements, but currently limited to 200mm diameter.

New Laser and Opto-Electronic Technology

Virgo and LIGO developed CW low noise lasers at 1064nm

- In ET-HF their evolution toward higher power will be investigated

In ET-LF we will use a different wavelength because of the Silicon test masses:

- λ=1.55μm or 2μm?

New electro-optic components:

- High quantum efficiency photodiodes
- Low absorption e.o.m.
- Low dissipation faraday isolators

Other relevant challenges

- Auxiliary optics, adaptive optics and thermal compensation of optical aberrations
- Precision mechanics, alignment and positioning
- **Vacuum** (*the largest volume under UHV in the World*):
  - More than 120km of vacuum pipes
    - ~1 m diameter, total volume 9.4×10^4 m^3
    - 10^{-10} mbar for H_2, 10^{-11} mbar for N_2 and less than 10^{-14} mbar for Hydrocarbons
  - Joint development with CERN involving ET and CE
- Low noise controls
- Computing
  - Computation intensive, not data intensive
- Governance & Organisation

ESFRI Roadmap

European Strategy Forum on Research Infrastructures

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ESFRI partners:

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

The ET-PP (preparatory phase) funded by EU commission with 3.45M€: t0=01/09/2022

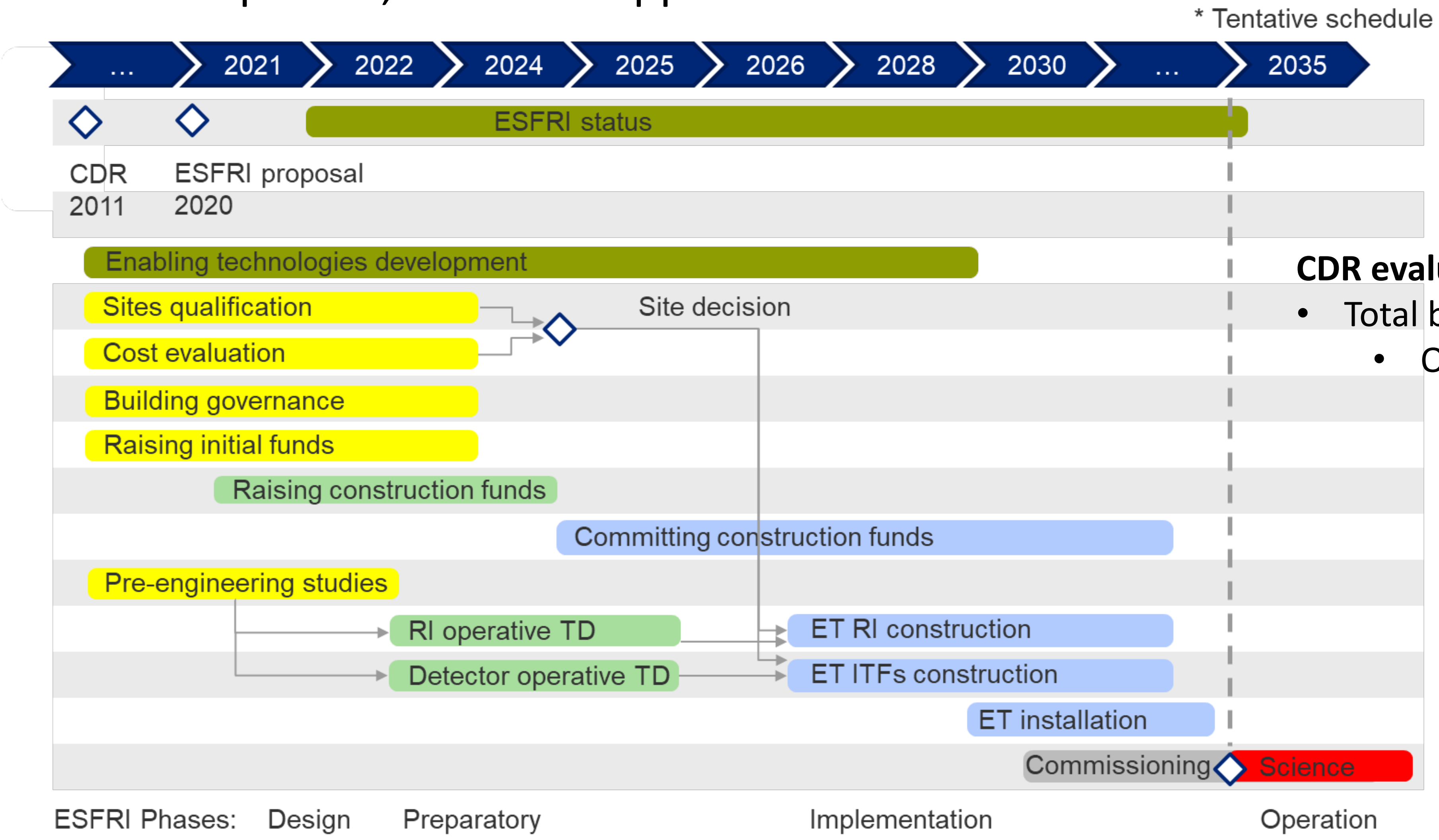
It includes also agencies and institutions belonging to:

- **Austria**
- **France**
- **Germany**
- **Hungary**
- **Switzerland**
- **UK**

- ET CA originally signed by 41 institutions
  - Consortium currently coordinated by INFN and Nikhef

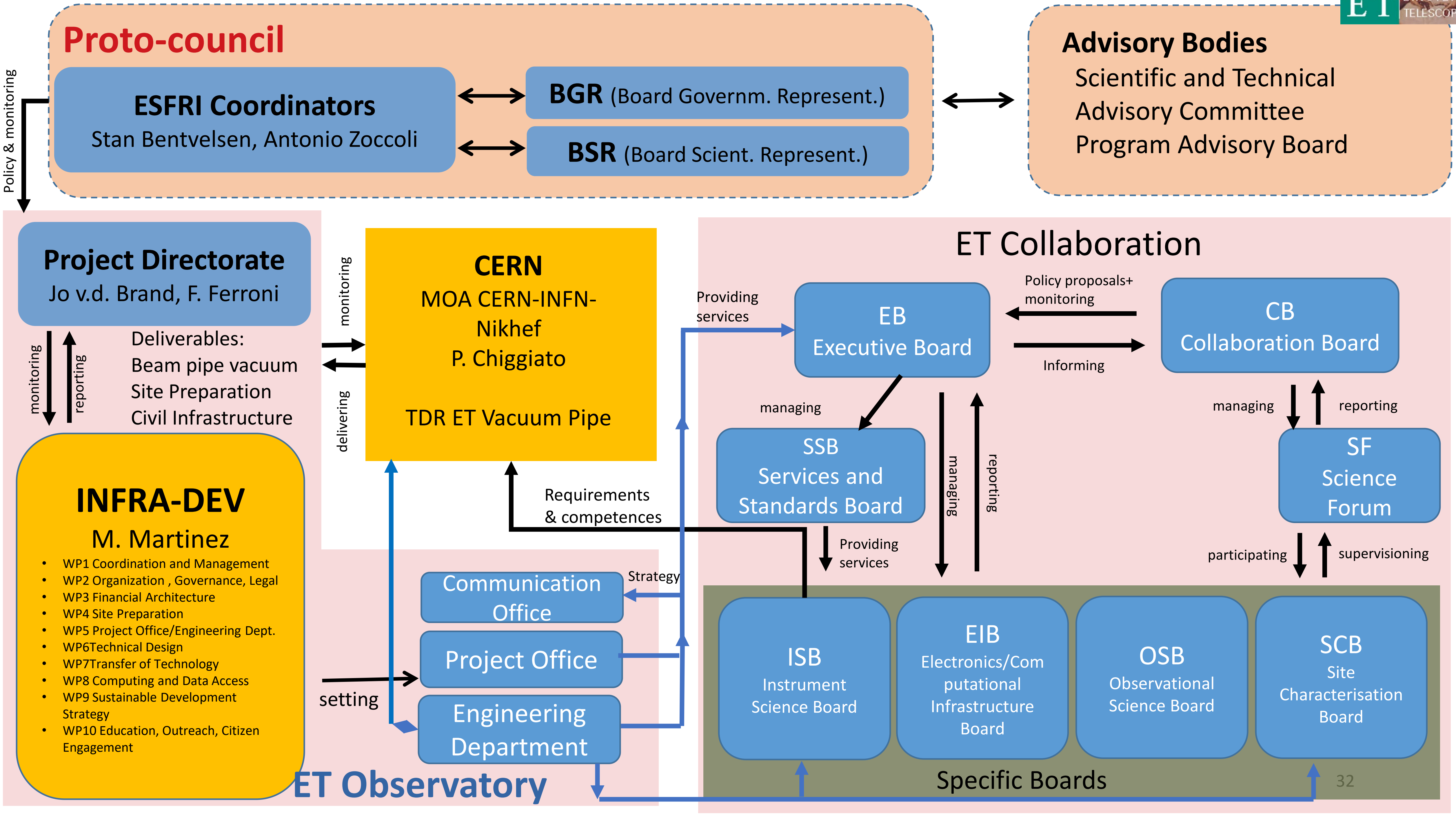
ET timeline

- ET timeline presented to ESFRI
  - As expected, the ESFRI approval boosted the activities at all the levels:
    - Scientists
    - Agencies
    - Governments



CDR evaluations:

- Total budget ~ 2G€
  - Observatory budget ~ 1.7G€
    - Infrastructure Budget:
      - Civil infrastructure: ~930M€
      - Vacuum system: ~570M€



Proto-council
ESFRI Coordinators
Stan Bentvelsen, Antonio Zoccoli
BGR (Board Governm. Represent.)
BSR (Board Scient. Represent.)
Advisory Bodies
Scientific and Technical
Advisory Committee
Program Advisory Board
Policy & monitoring
Project Directorate
Jo v.d. Brand, F. Ferroni
monitoring
reporting
Deliverables:
Beam pipe vacuum
Site Preparation
Civil Infrastructure
monitoring
delivering
CERN
MOA CERN-INFN-
Nikhef
P. Chiggiato
TDR ET Vacuum Pipe
INFRA-DEV
M. Martinez
• WP1 Coordination and Management
• WP2 Organization , Governance, Legal
• WP3 Financial Architecture
• WP4 Site Preparation
• WP5 Project Office/Engineering Dept.
• WP6Technical Design
• WP7Transfer of Technology
• WP8 Computing and Data Access
• WP9 Sustainable Development Strategy
• WP10 Education, Outreach, Citizen Engagement
Requirements
& competences
Communication Office
Strategy
Project Office
setting
Engineering Department
ET Observatory
ET Collaboration
Providing services
EB
Executive Board
Policy proposals+
monitoring
Informing
CB
Collaboration Board
managing
managing
reporting
reporting
SSB
Services and Standards Board
managing
SF
Science Forum
Providing services
participating
supervisioning
ISB
Instrument Science Board
EIB
Electronics/Computational Infrastructure Board
OSB
Observational Science Board
SCB
Site Characterisation Board
Specific Boards

ET Collaboration formed

https://indico.ego-gw.it/event/411/

Official Birth of the ET Collaboration

XII ET Symposium, Budapest on June 7th - 8th

More than 400 scientists,

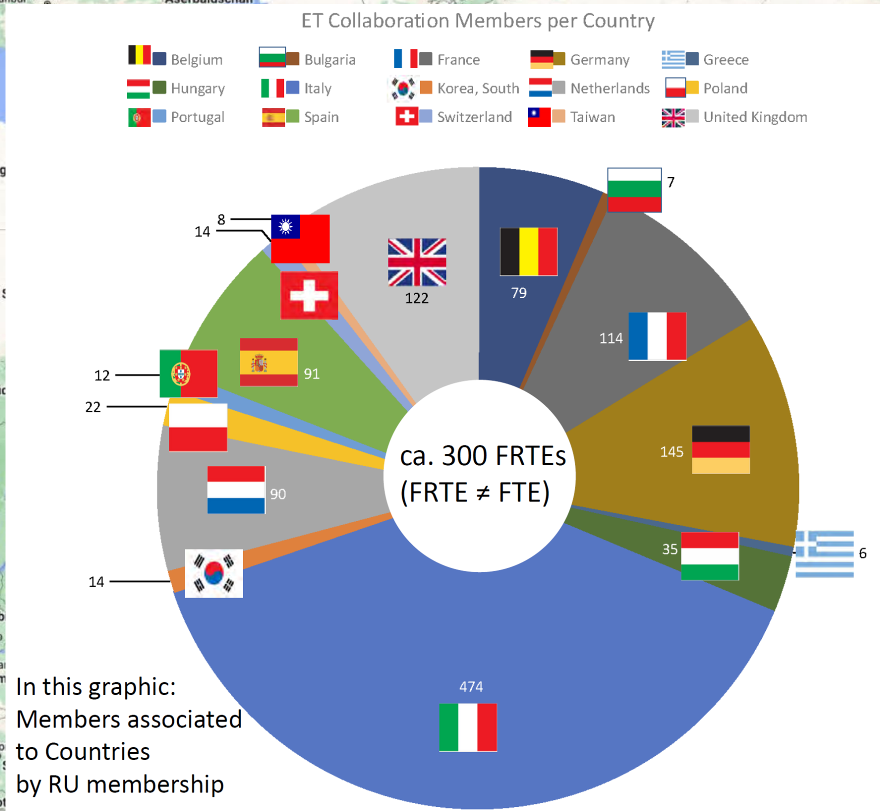
out of >1200 members of the Collaboration,

attended the meeting in person or remotely.

The Einstein Telescope Collaboration

EINSTEIN TELESCOPE

- **The ET Collaboration was formed on 8.6.2022 @ XII ET Symposium Budapest**
- **80 Research Units**
- **Ca. 1250 members**
- **Member Database is being set up**



ET site(s)

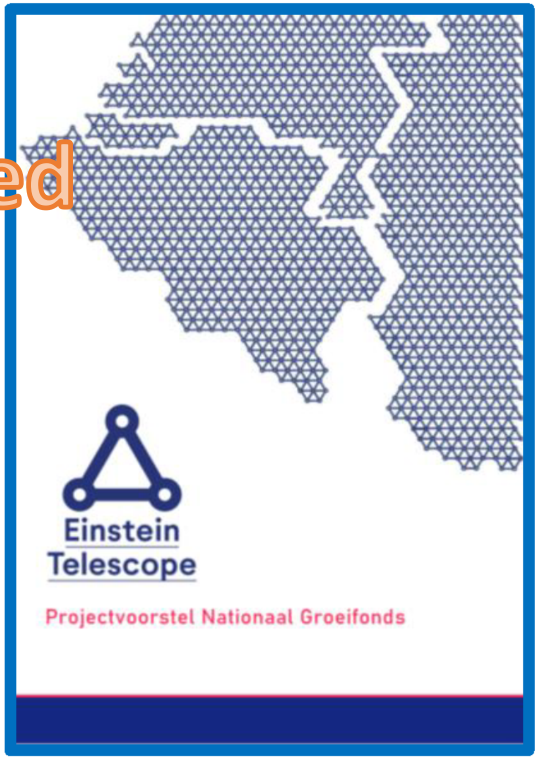
- Currently there are two sites, in Europe, candidate to host ET:
  - The Sardinia site, close to the Sos Enattos mine
  - The EU Regio Rhine-Meusse site, close to the NL-B-D border
- A third option in Saxony (Germany) is under discussion
- Sites are investigated through
  - seismic noise measurements on surface, in boreholes and in mine (Sardinia)
  - Magnetic and ambient noises measurements
  - Geophysical and geotechnical characterizations
  - …
- Large funds needed to elaborate and propose the candidature of the sites

Einstein Telescope in Euregio Meuse-Rhine (EMR)

approved

Connected institutions in:
Belgium,
Germany &
the Netherlands

Nationaal Groeifonds (the Netherlands)



Emphasis on potential socio-economic Impact

Submitted by OCW Ministry
(EZK Ministry support)

Supported by ~70 Dutch Industries/institutions

In October 2021 the Netherlands submitted large funding proposal within context of the '*Nationaal Groeifonds*'. Decision in April 2022.

Includes 42 M€ for geology, R&D & organization
as well as possible Dutch share towards ET realization

ETIC – Einstein Telescope Infrastructure Consortium

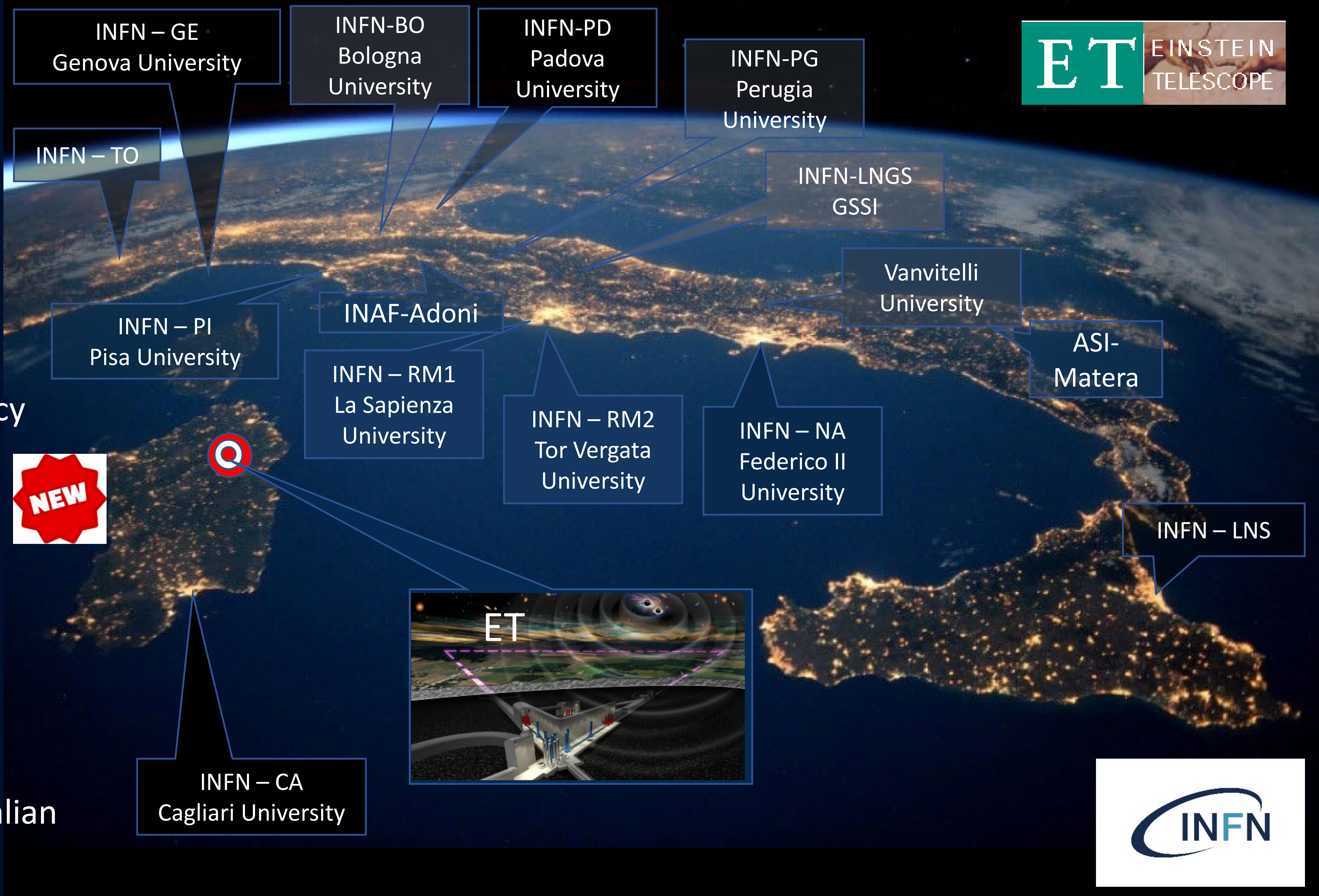
Next Generation EU (PNRR) Investment focused on ET enabling technology and Sardinian site candidature support

Leaded by INFN,
Partners:
11 Universities
INAF and Italian Space Agency

<u>Budget 50M€ approved</u>

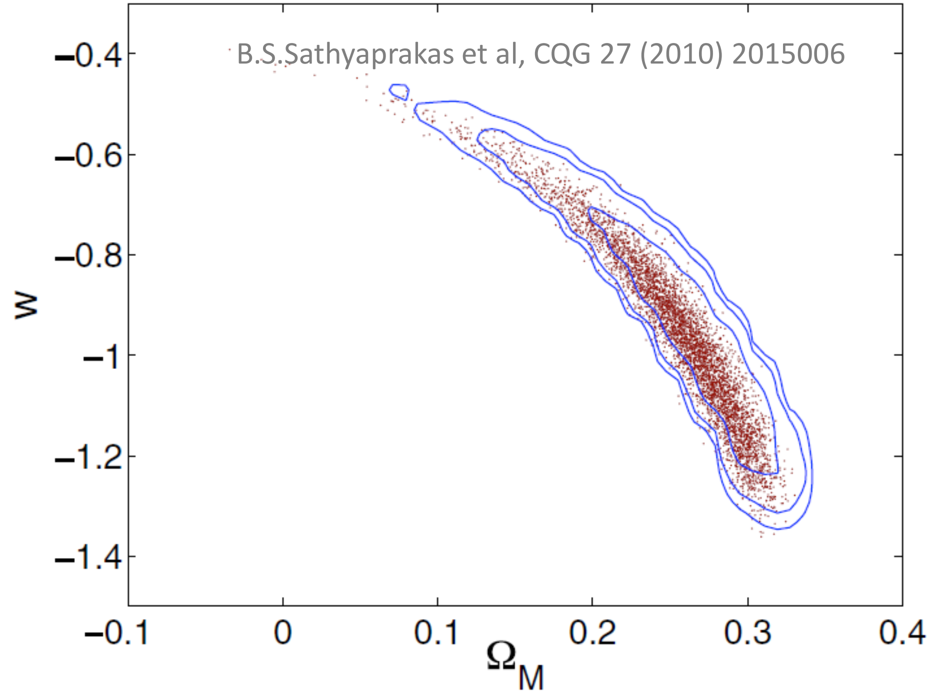
Start of the project:
1st December 2022

Discussion ongoing with the Italian Government on an Italian share toward ET realization



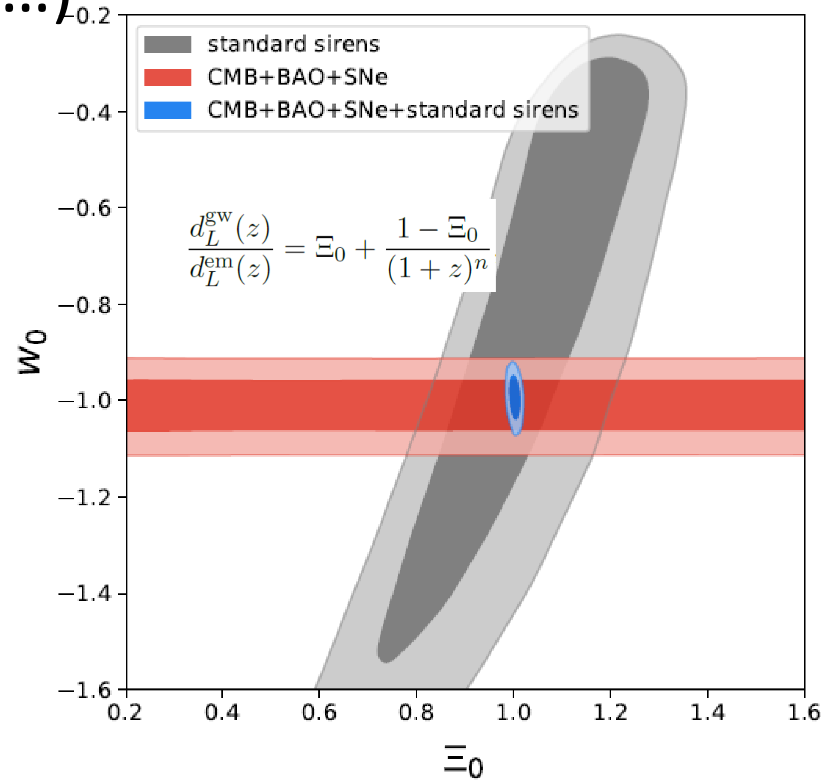
Cosmology/Cosmography with ET

- ET will reveal 10^5 BBH/BNS coalescences per year
- A fraction (about 10^3/year) of the BNS will have a electromagnetic counterpart (thanks also to new telescopes like THESEUS, E-ELT, …)



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

Enis Belgacem et al JCAP08(2019)015

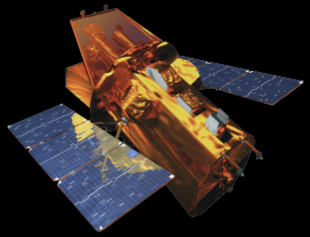


Investigating the DE sector in modified theories of gravity

Multimessenger Astronomy

ET EINSTEIN TELESCOPE

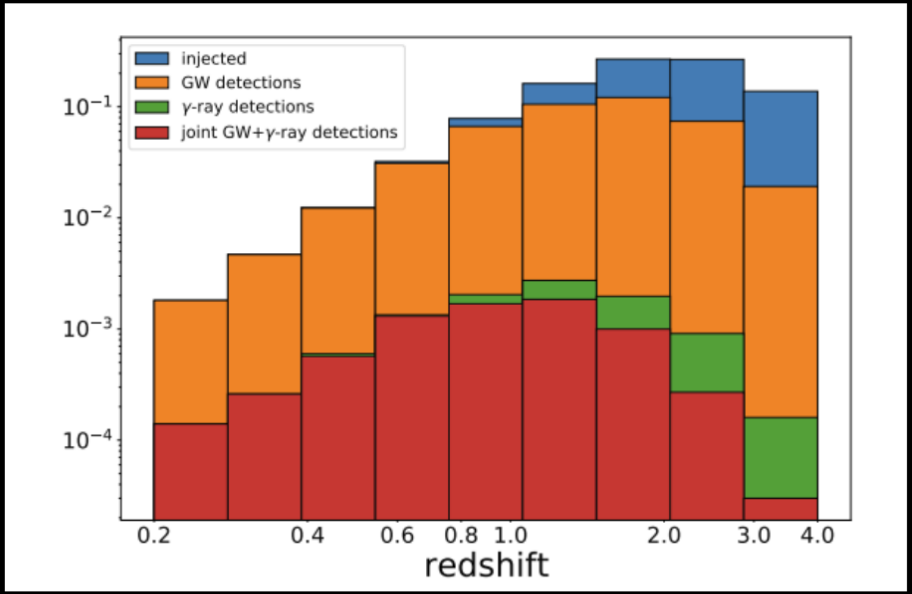
- GW + γ-ray joint detection per year (credits: M.Branchesi)



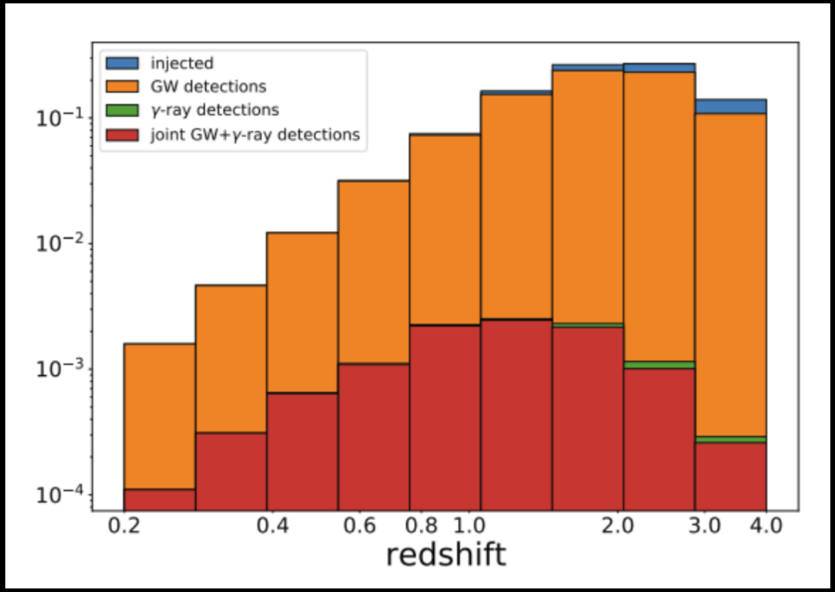
A large fraction of detected short GRB will have a GW counterpart!

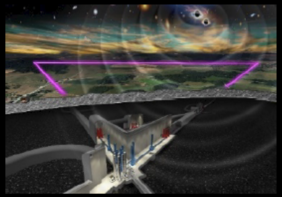
$N/Ntot_{inj}$

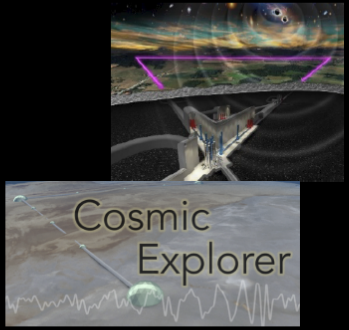
Fermi-GBM+ET



Fermi-GBM+(ET+CE)



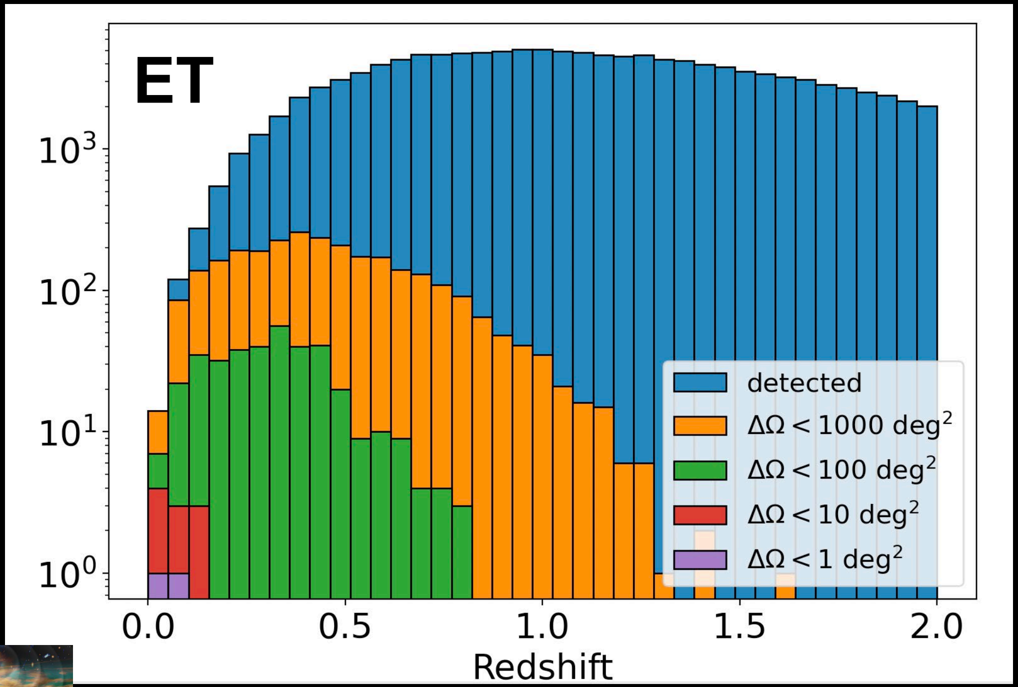


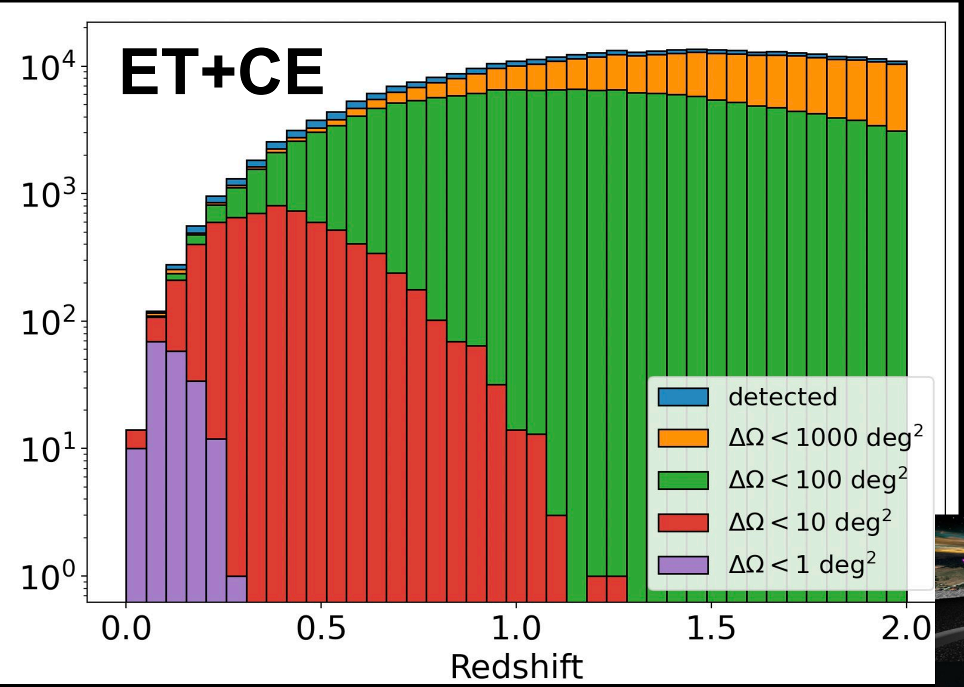


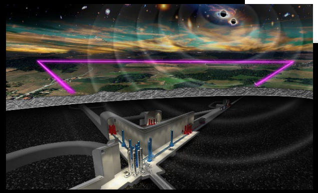
Simulation of 10^5 BNS with $0° < \vartheta_v < 10°$

ET Localisation Capabilities

credits: M.Branchesi







ET low frequency sensitivity makes possibile to localize BNS!

O(100) detection per year with sky-localization (90% c.r.)<100 deg^2 (early warning alerts!)

O(1000) detection per year with sky-localization (90% c.r.)<10 deg^2

ET-Italia collaboration

- The ET-Italia collaboration is composed by 18 INFN units, several university groups belonging to more than 11 universities, INAF, INGV and ASI research groups
- In the figure, yellow marks are corresponding to the INFN groups, blue marks to the ETIC OUs