JENAS 2022 – Madrid – 2-6 May 2022

Gravitational Wave Probes of Fundamental Physics

On behalf of the steering committee:

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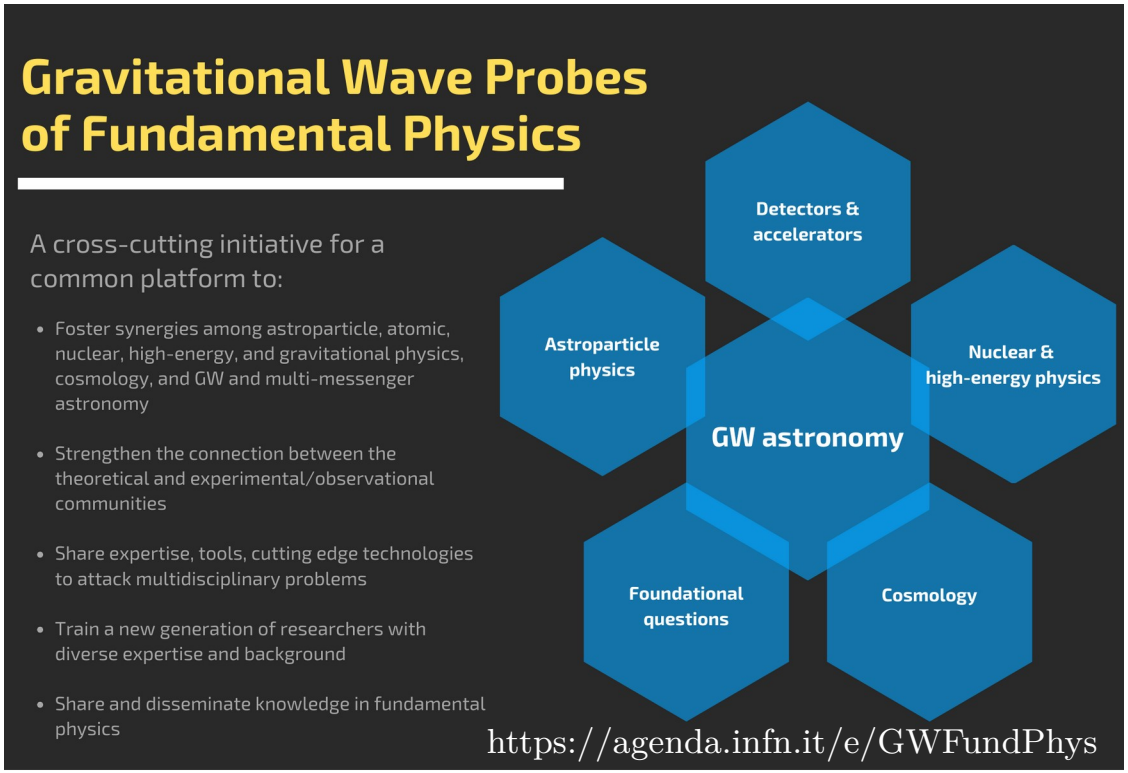
* Coordinators



Paolo Pani

Sapienza University of Rome & INFN Roma1

https://web.uniroma1.it/gmunu

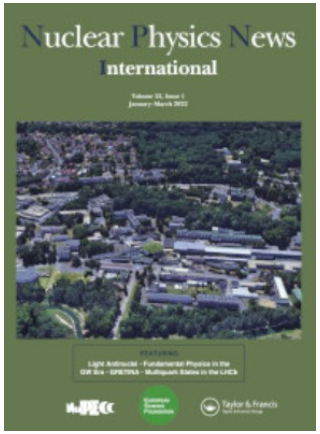
Outline

1. Science of the GW-FP initiative

2. Current and future activities

3. Overview on the science of the Einstein Telescope (ET)

GW science: much more than Astro



feature article

Fundamental Physics in the Gravitational-Wave Era

Sonja Bernitt[1], Gianfranco Bertone[2], Vitor Cardoso[3], Roberto Emparan[4], Tetyana Galatyuk[5], Aleksi Kurkela[6], Ann-Cecilie Larsen[7], Marlene Nahrgang[8], Samaya Nissanke[2], Paolo Pani[9], Rafael Porto[10], Antonio Riotto[11], and Stephan Rosswog[12]

April 2022

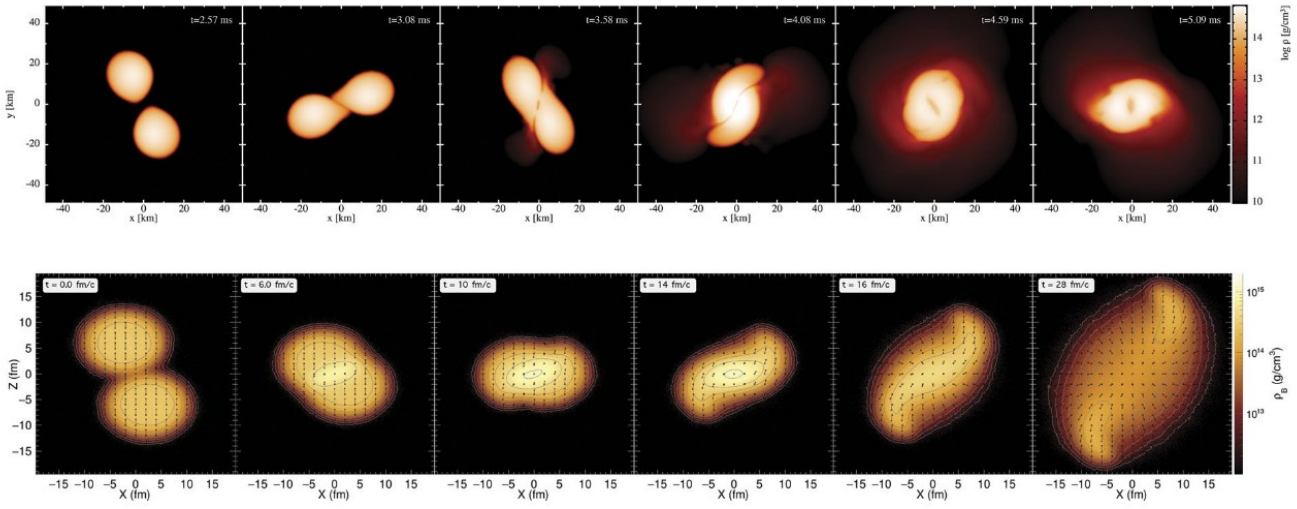
- GW revolution opened new avenues for fundamental physics:
  - Matter under extreme conditions
  - Multimessenger astronomy: role of nuclear and atomic physics
  - GWs & Cosmology
  - Fundamental problems in high-energy and gravitational physics
- Multidisciplinary, cross-cutting effort at the interface between different communities → synergies, complementarities, community building

Matter under extreme conditions

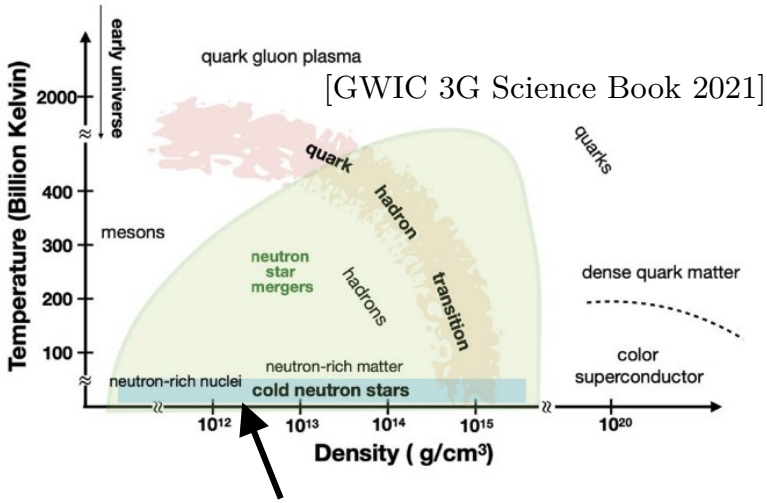
GWs from binary neutron-star mergers provide a way to investigate strongly interacting matter at ultra-high density, temperature, and isospin

- Equation of state (EoS) & phase structure in the core (hyperons? quarks?)
- Temperature and densities comparable to heavy-ion collisions
- Single ET detection will constrain EoS at unprecedented levels

Neutron-star merger [Rosswog-Diener CQG 2021]



Heavy-ion collision [HADES, Nature Physics 2019]

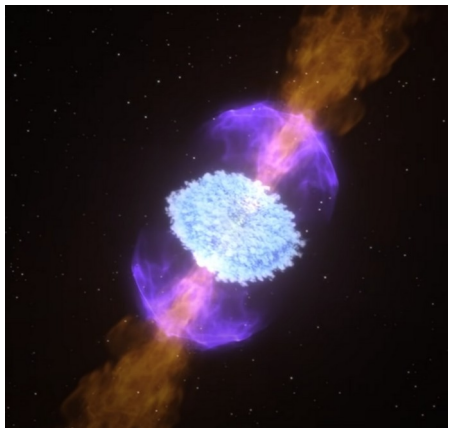


[GWIC 3G Science Book 2021]

Synergies to explore quark-hadron phase transition

Nuclear/Atomic physics & Multimessenger

EM counterpart of GW170817 is the strongest evidence to date of heavy-element nucleo-synthesis through the r-process



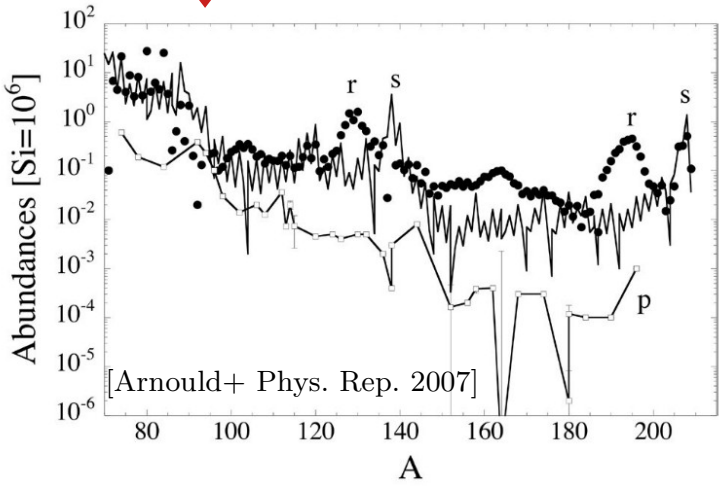
Nuclear theory
for neutron-rich, unstable nuclei

Kilonova ⟷ large-scale nuclear network calculations

5K+ nuclei; 50K+ reactions

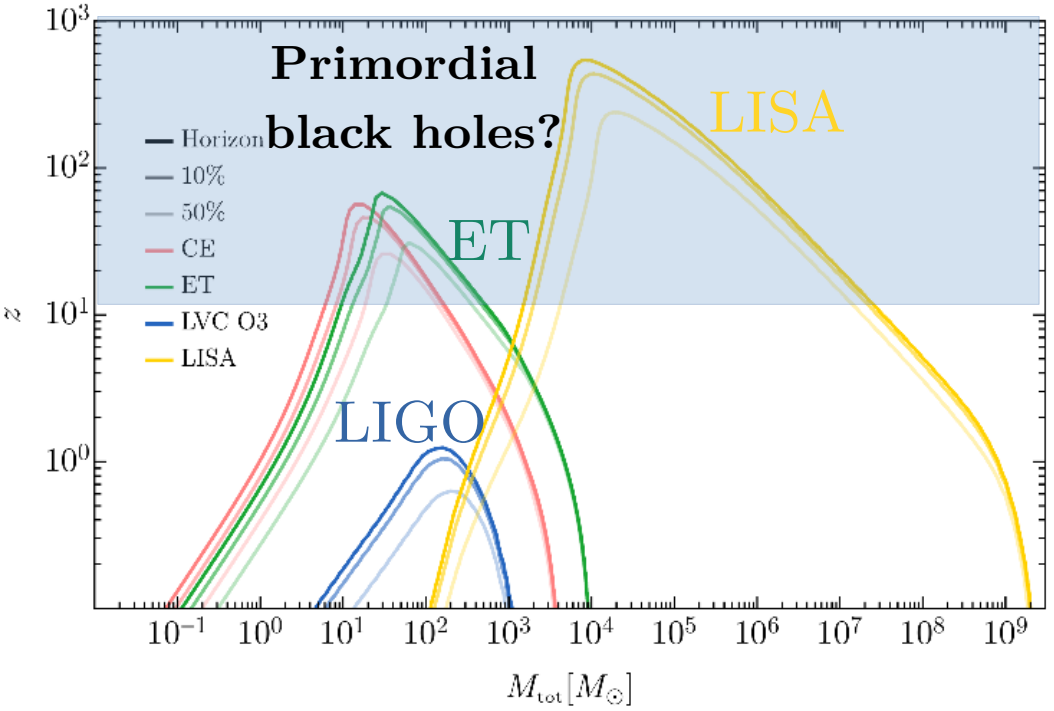
Appearance and detectability of kilonovae strongly depends on atomic physics

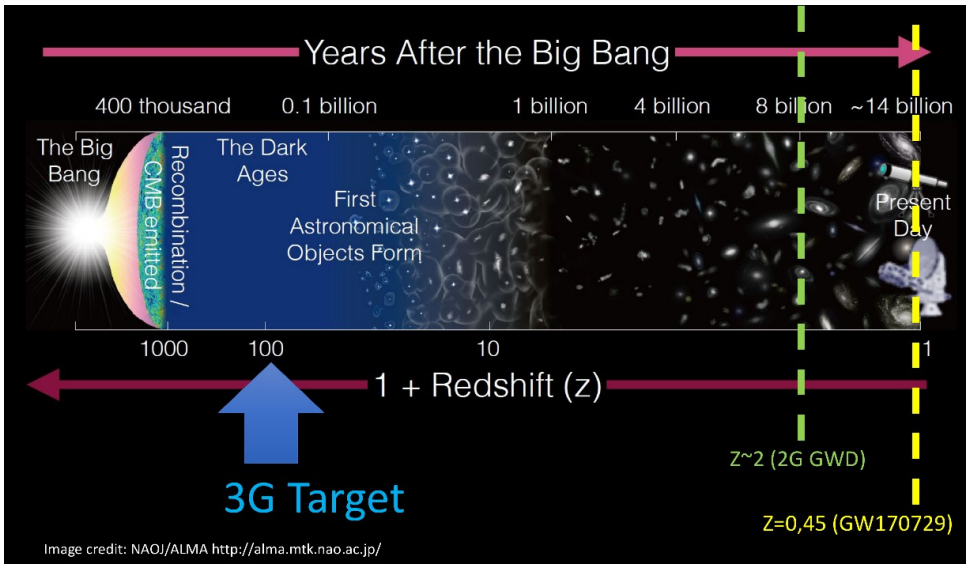
Future X-ray missions (XRISM, Athena, NICER, GRAVITY) → high-res spectra



GWs & Cosmology

- GW standard sirens at large redshift can measure **Hubble constant** and shed light on **dark energy** and **modified gravity**
- Stochastic GW background → **inflation** and **phase transitions**
- 3G/LISA: unique discovery machines for **primordial black holes** (may be 100% of the dark matter)



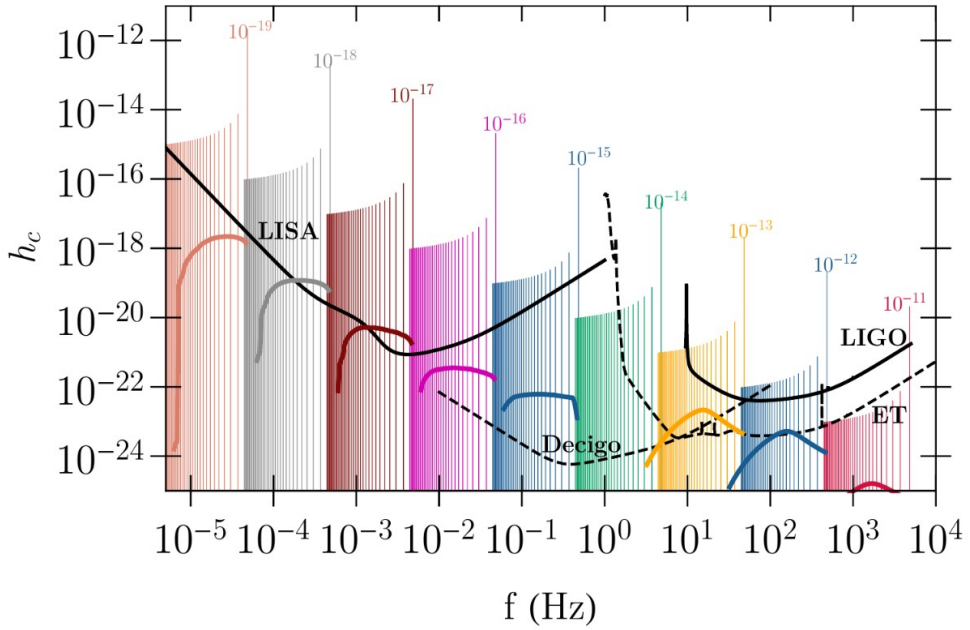


Fundamental Physics and GWs

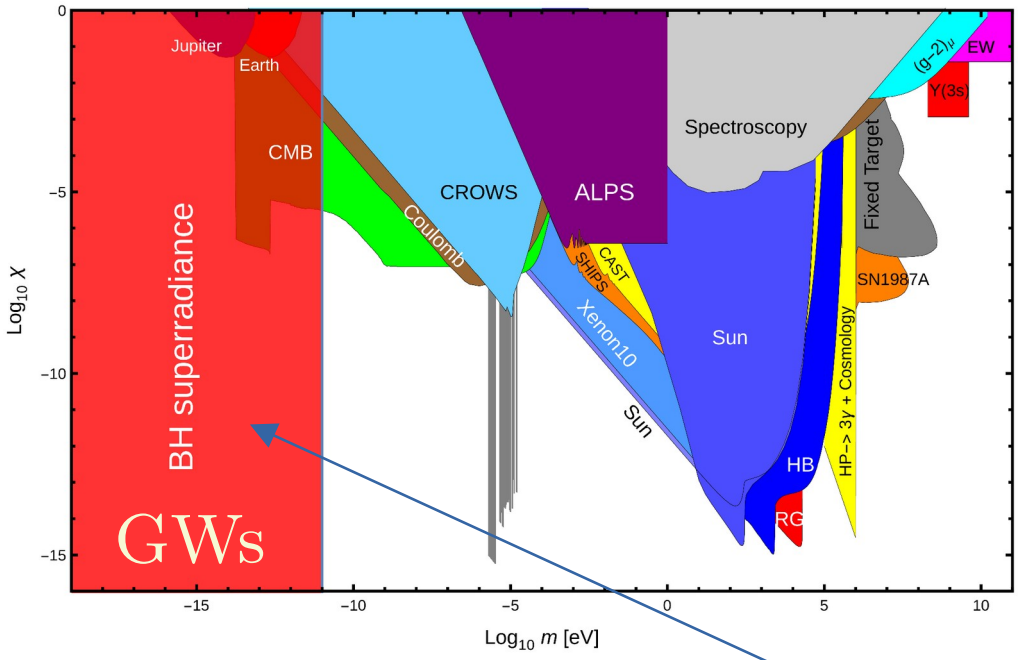
- GWs searches for dark matter & new fundamental fields
- Classical and quantum extensions of General Relativity
- Hep techniques to compute waveforms (eg. EFT, scattering amplitudes)

GWs from ultralight dark matter

(axion ALPs, dark photons, ...)



Constraints on dark photons



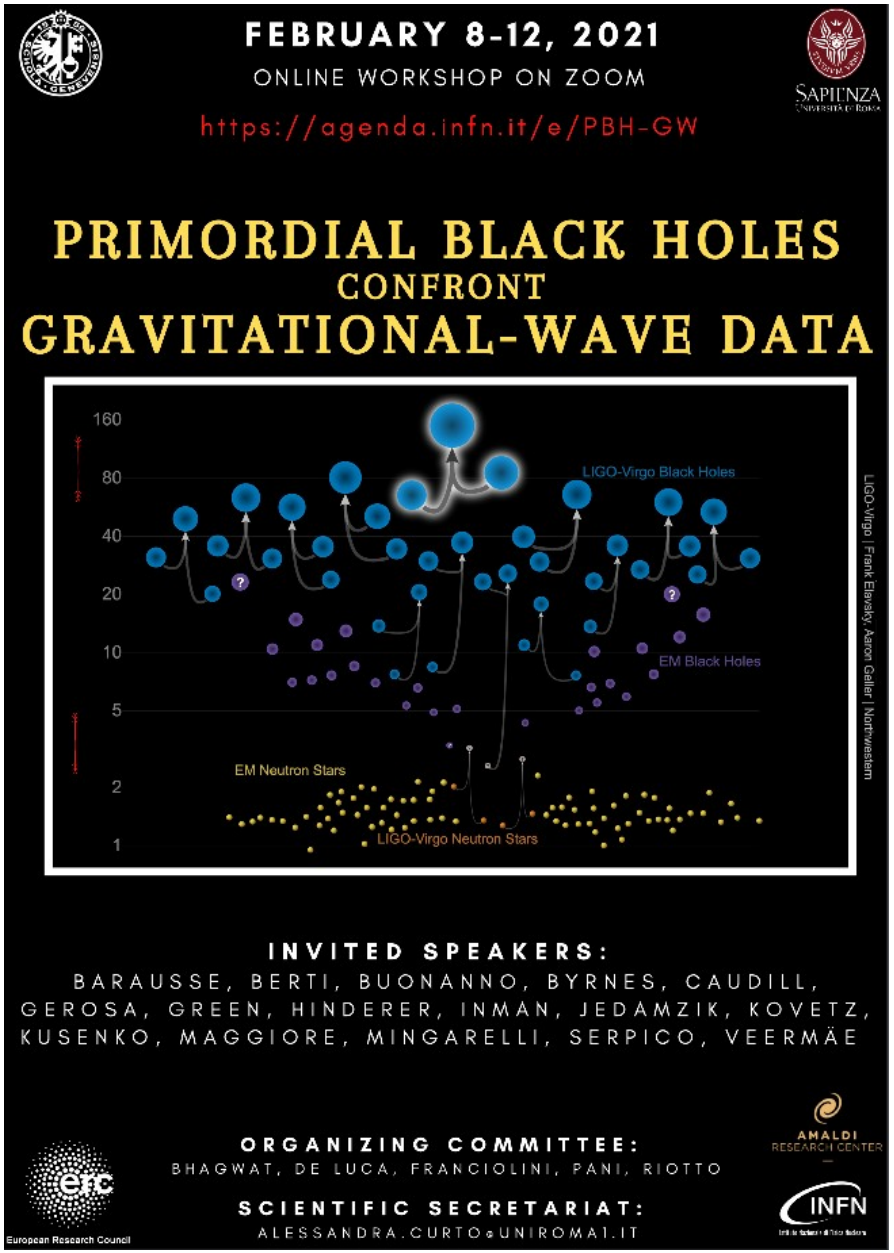
Detectable also in the DM "nightmare" scenario! (i.e. ~no coupling to SM)

Arvanitaki+ PRD 2014; Brito+ PRL 2017-2020; Baumann+ PRD 2020, PRL 2022

GW probes of dark matter

Bertone+ 2020

Community building



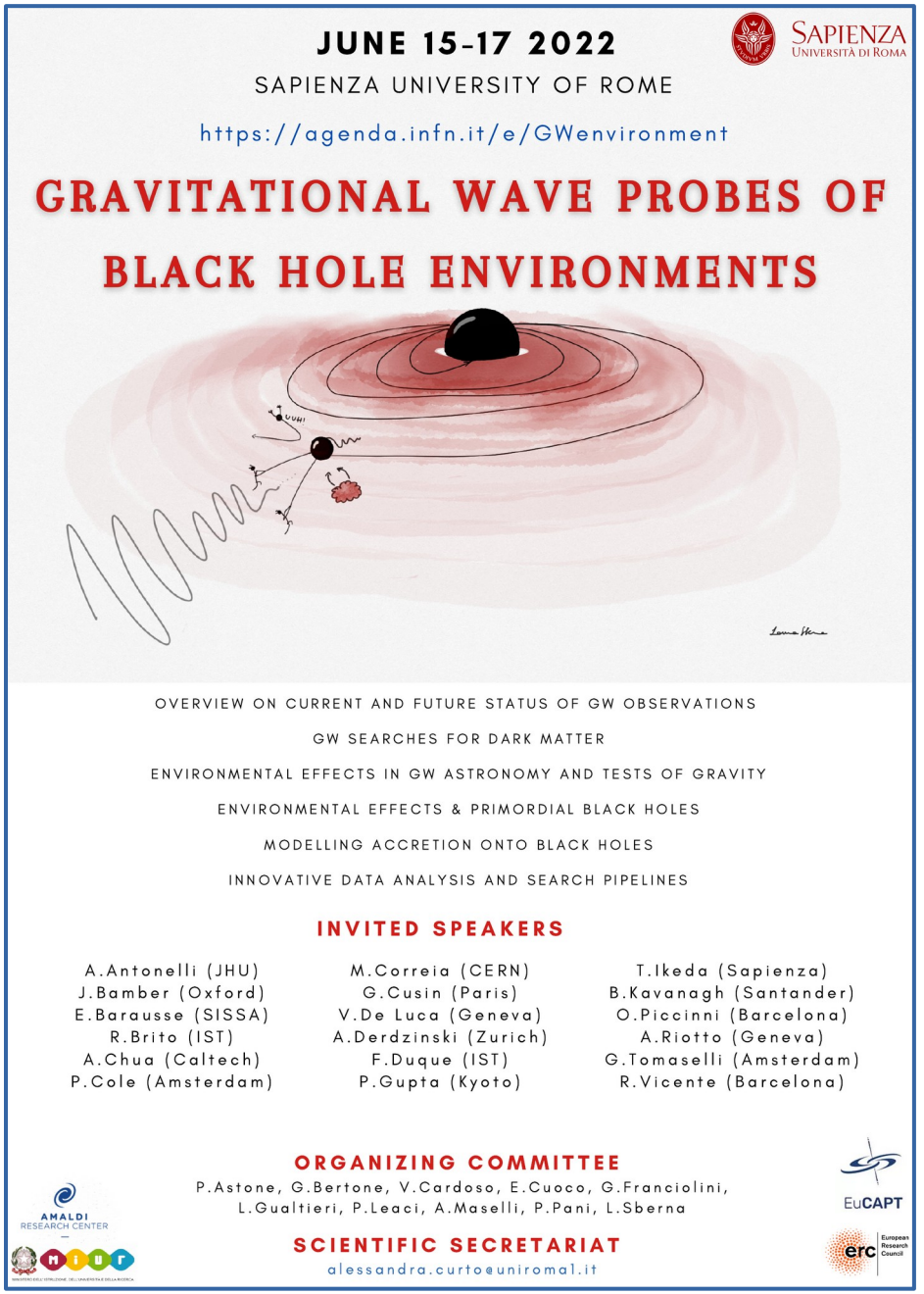
200+ (online) participants

Brought together experts from GW, hep, & Cosmo communities

Connection with EuCAPT

https://agenda.infn.it/e/GWenvironment

Expected ~100 (in-person) participants



GWSci: a COST Action proposal

	Astrophysics	GR dynamics & Modeling	Cosmology	Fundamental Physics
Black Holes and their binaries	MBH growth; AGN spectroscopy; BBH formation channels; BH masses/spins, supernovae; ...	Inspiral: pN, EOB, EFT, amplitudes; phenom. Models; nonlinear dynamics in and beyond GR; ...	Nature of DM and DE; structure formation; primordial BHs; standard sirens; ...	BH hair & new fields; tests of GR; near-horizon quantum effects; nature of DM; ...
Neutron Stars and their binaries	Multimessenger astrophysics; EOS; NS structure; gamma ray bursts; kilonovas; ...	NS microphysics & imprint on GW; dynamical tides; postmerger oscillations; MHD ...	Multimessenger astrophysics and cosmological parameters; nature of DM; ...	EOS; QCD phase transitions; quark deconfinement; tests of GR & LV; new fields; ...
IMRIs & EMRIs	Dense stellar environments; EM counterparts; IMRI formation; MBH low redshift evolution, ...	BH perturbations & self force; Resonant and Environmental effects; Numerical Relativity ...	Standard sirens & cosmological parameters; nature of DM; primordial BHs; ...	BH hair & new fields, tests of GR; near-horizon quantum effects; nature of DM; ...
GW Backgrounds, Foregrounds, and Bursts	High redshift sources; GW confusion; hyperbolic encounter rates and parameters; ...	GWs from Cosmic Strings; Stochastic GWs; GWs from hyperbolic encounters; ...	Inflation; early universe phase transitions; cosmic strings; primordial BHs; ...	Early universe phase transitions; boson clouds; tests of GR & LV; ...

GR: General Relativity, **AGN**: Active Galactic Nucleus, **BH**: black hole, **BBH**: BH binary, **MBH**: Massive BH, **NS**: Neutron Star, **DM/DE**: Dark Matter/Energy, **EM**: Electromagnetic, **EOB**: Effective one-body, **EFT**: Effective Field Theory, **LV**: Lorentz Violations, **EOS**: Equation of State, **pN**: post-Newtonian, **QCD**: Quantum chromodynamics

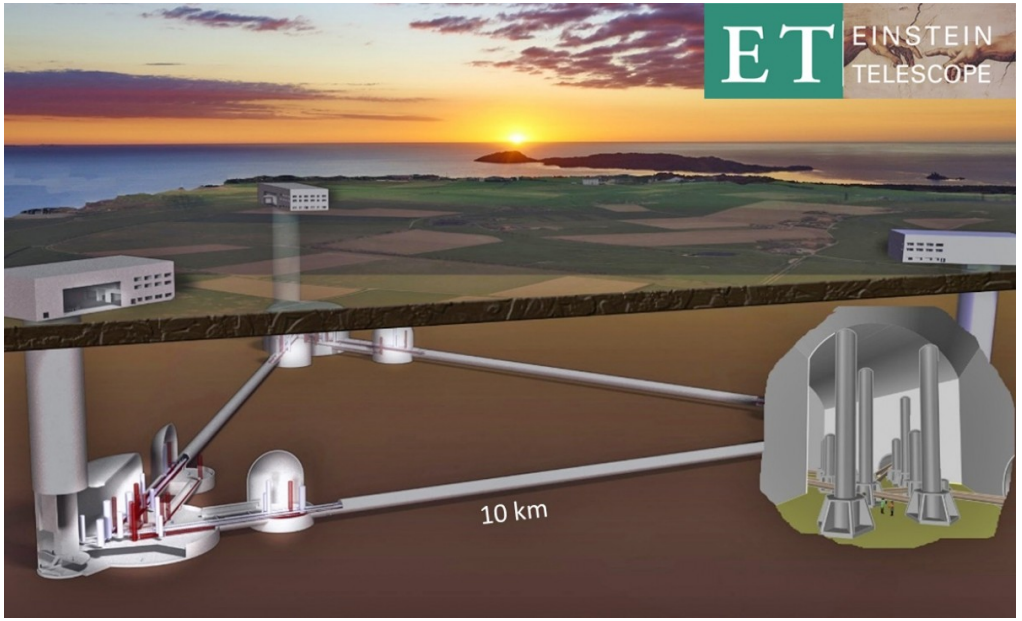
cost
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

- Budget: ~0.5M EUR (workshops, dissemination, scientific visits, esp. ECRs)
- Submitted in Oct 2021 – Results expected in May 2022

Einstein Telescope (ET)

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

- New infrastructure capable to host future upgrades for **decades** without limiting the observation capabilities (~50yr time scale)
- Sensitivity **at least 10 times better** than (nominal) adv. detectors on a large fraction of the (detection) frequency band
- Dramatic improvement in sensitivity at **low frequency (few Hz – 10Hz) range** → intermediate-mass black holes
- **High reliability** and improved observation capability
- **Standalone localization** & polarization disentanglement

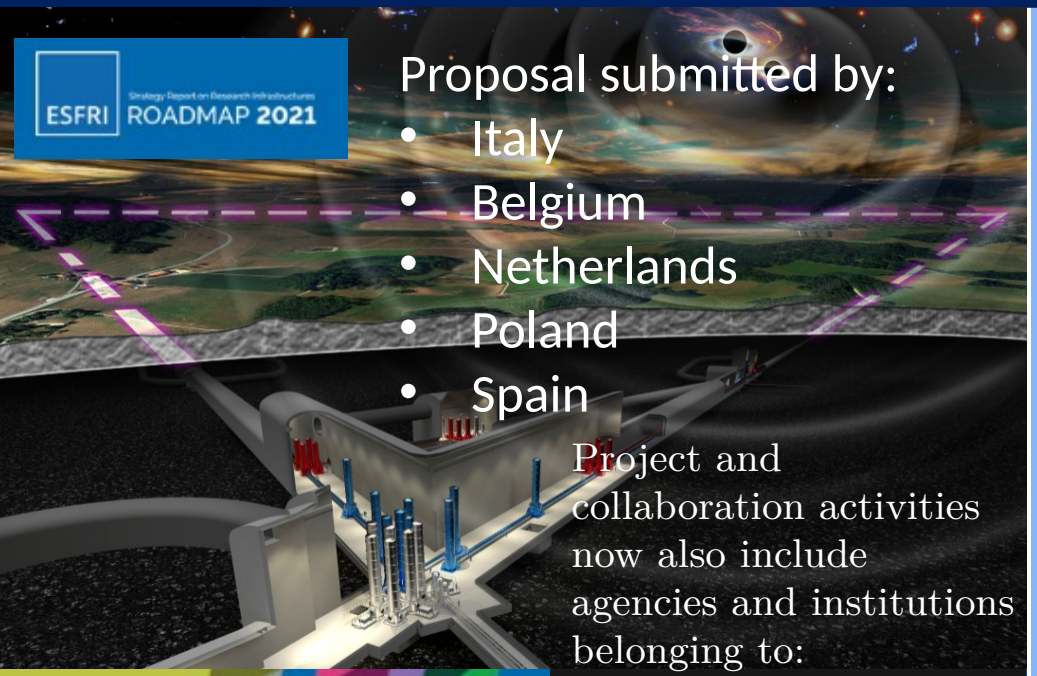


Both precision physics and discovery machine!

European Strategy Forum on Research Infrastructures

ESFRI Roadmap

ET EINSTEIN TELESCOPE



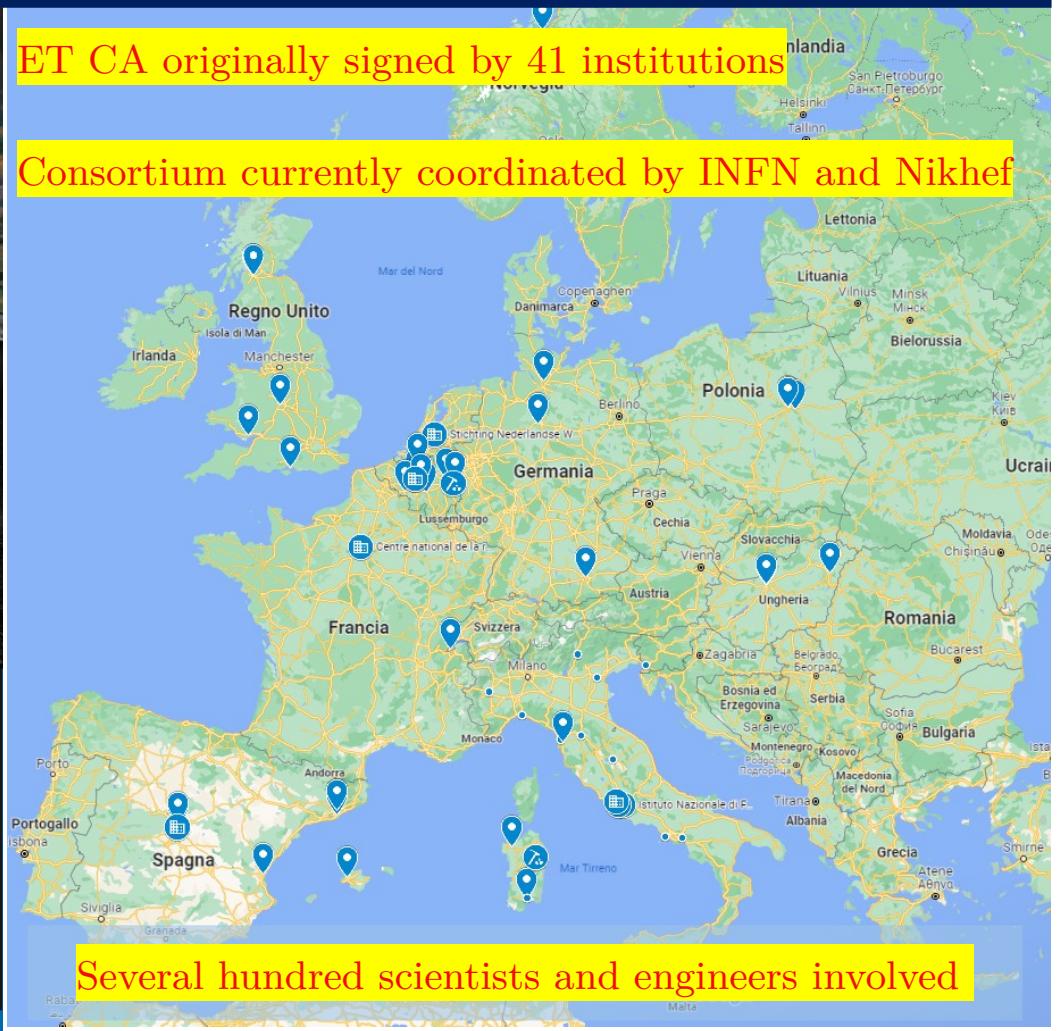
Proposal submitted by:

- Italy
- Belgium
- Netherlands
- Poland
- Spain

Project and collaboration activities now also include agencies and institutions belonging to:

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

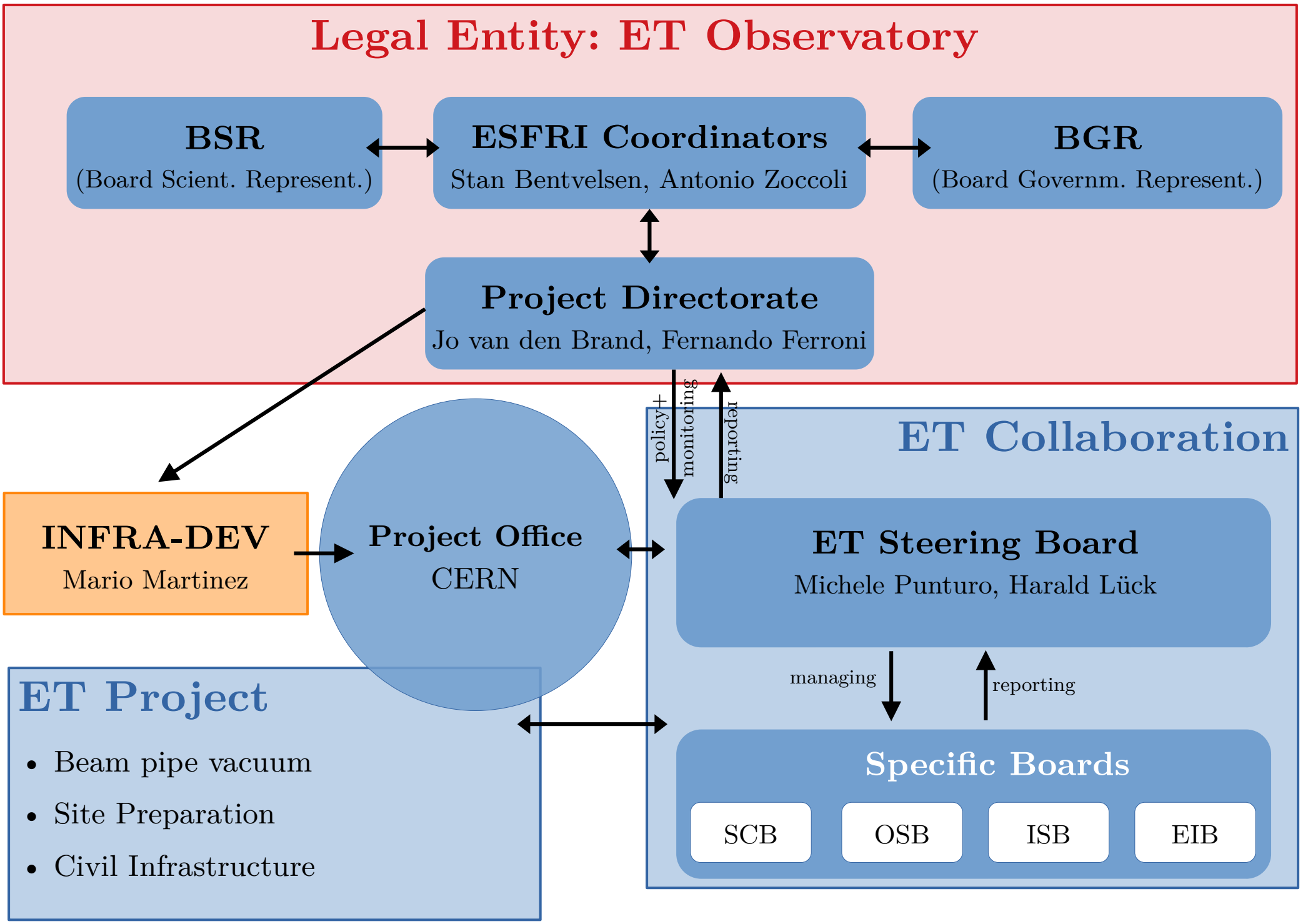
Large preparatory funds available in some country (IT, NL, …), an EU INFRA-DEV proposal just approved with a grant of 3.45M€ and an EU INFRA-TECH proposal has been just submitted



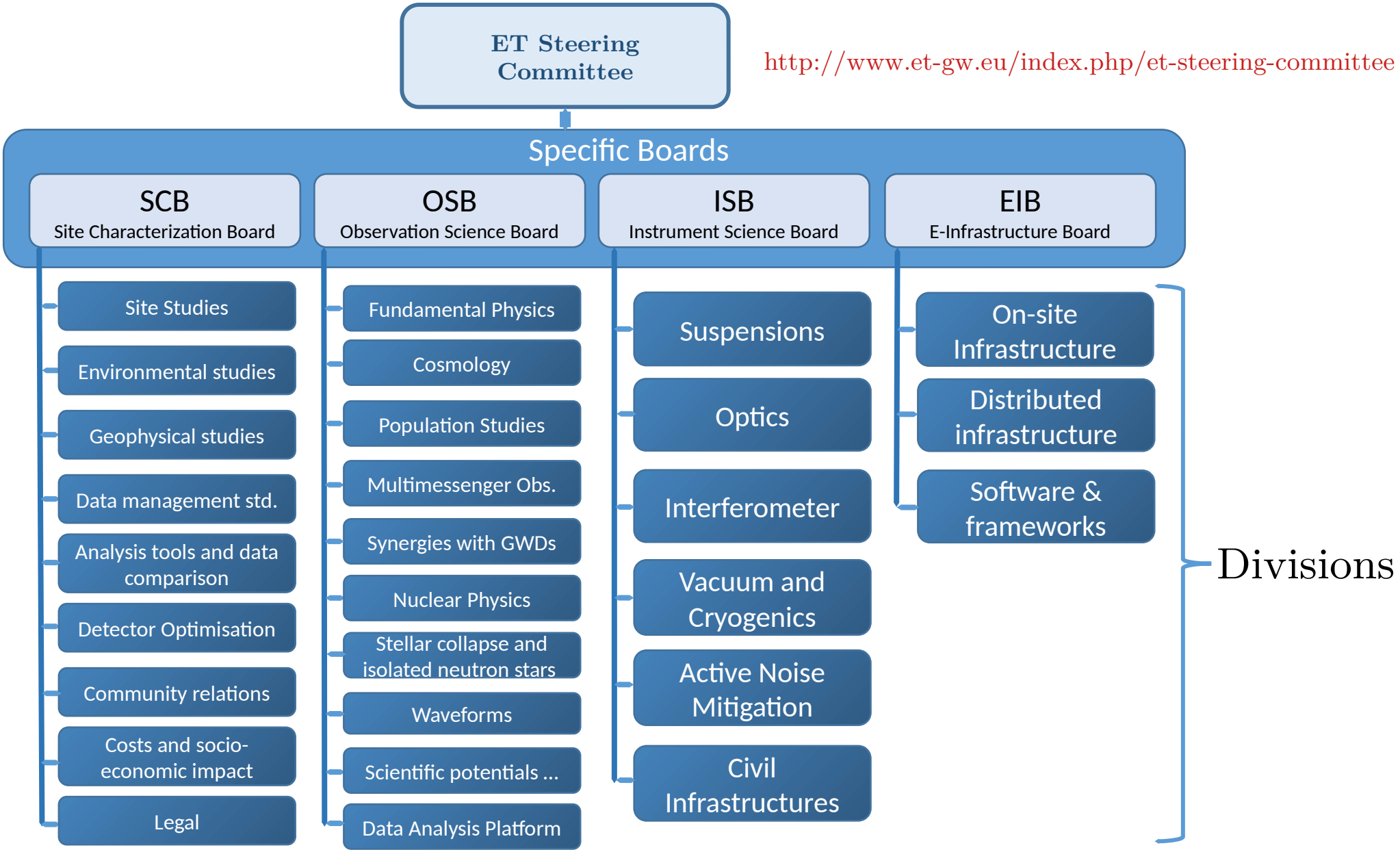
- NL: intended investment of 42M€ for geology, R&D, organization

(+ 870M€ reserved in case of Dutch construction)

- Similar investments under discussion in IT (outcome expected by June 2022)


Legal Entity: ET Observatory
BSR
(Board Scient. Represent.)
ESFRI Coordinators
Stan Bentvelsen, Antonio Zoccoli
BGR
(Board Governm. Represent.)
Project Directorate
Jo van den Brand, Fernando Ferroni
policy+
monitoring
reporting
ET Collaboration
INFRA-DEV
Mario Martinez
Project Office
CERN
ET Steering Board
Michele Punturo, Harald Lück
managing
reporting
Specific Boards
SCB
OSB
ISB
EIB
ET Project
Beam pipe vacuum
Site Preparation
Civil Infrastructure

ET Collaboration: current organization



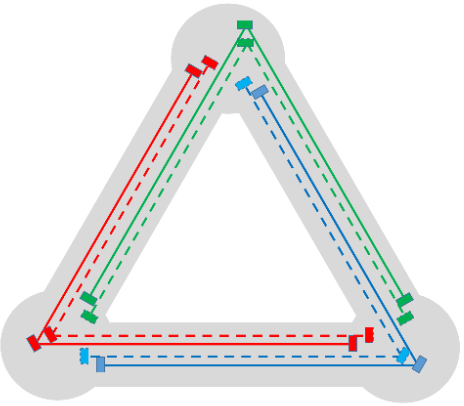
XII ET Symposium

XII Einstein Telescope Symposium

Budapest June 7-8, 2022
Formal birth of the ET collaboration

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

ET key elements

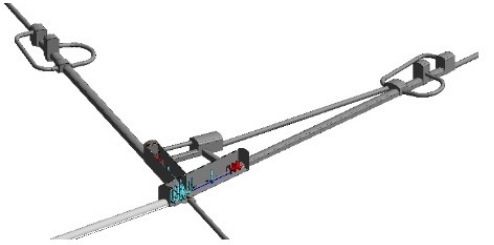


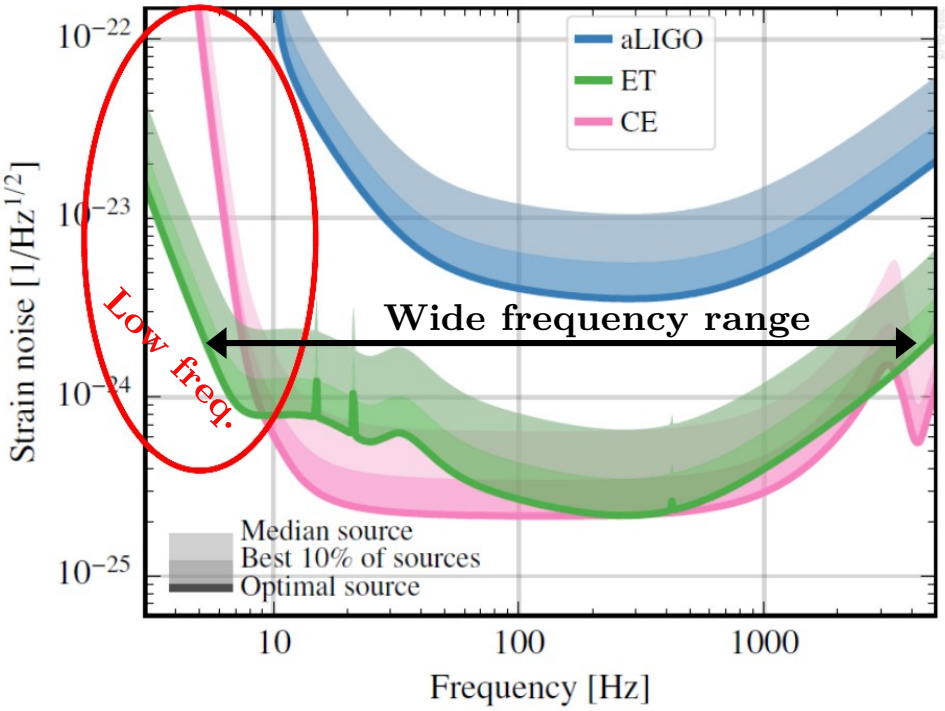
Requirements

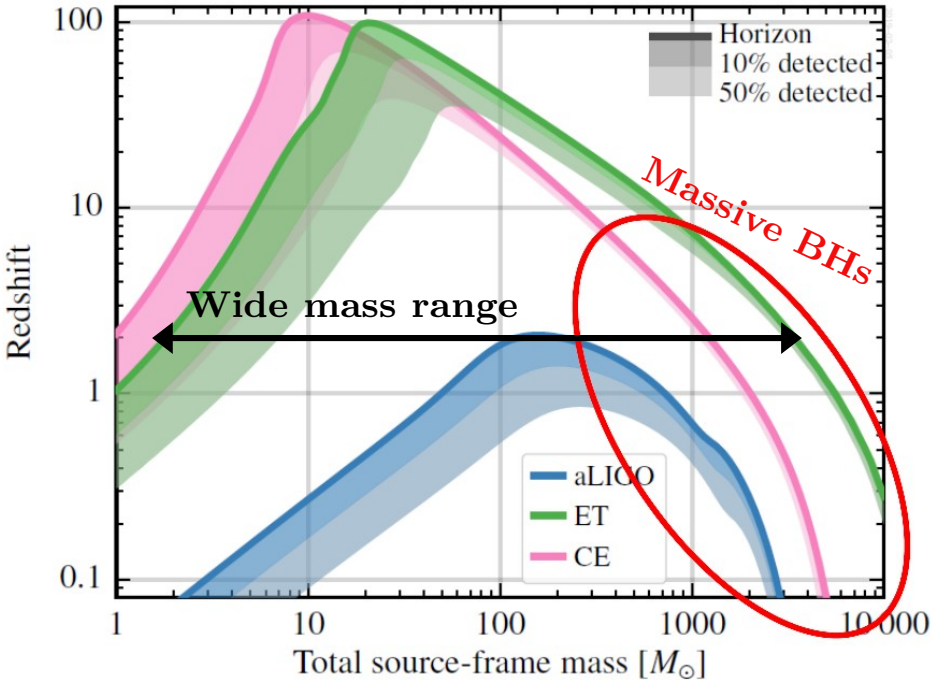
- Wide frequency range
- Low-frequency sensitivity
- Localization capability
- (more) Uniform sky coverage
- Polarization disentanglement
- High reliability (high duty cycle)
- High SNR

Design specifications

- Xylophone (multi-interferometer) design
- Underground
- Cryogenic
- Triangular shape
- Longer arms (>10km)







ET science in a nutshell

Astrophysics:

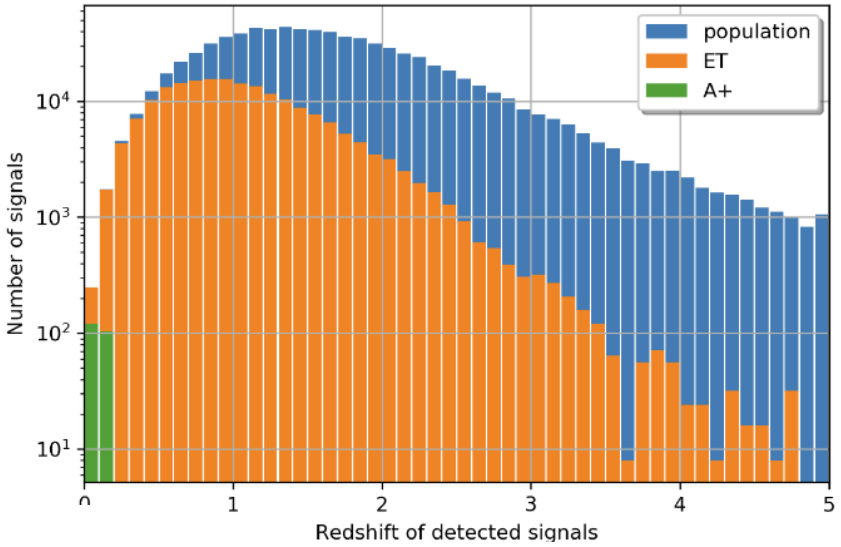
- **Black hole properties**
  - Origin (stellar vs primordial)
  - Evolution, demography
- **Neutron star properties**
  - Interior structure (QCD at ultra-high densities, exotic states of matter)
  - Demography
- **Multi-band and -messanger astronomy**
  - Joint GW/EM observations (GRBs, kilonova)
  - Multiband GW detection (LISA)
  - Neutrinos
- **Detection of new astrophysical sources**
  - Core-collapse supernovae
  - Isolated neutron stars
  - Stochastic background of astrophysical origin

Fund. physics & cosmology:

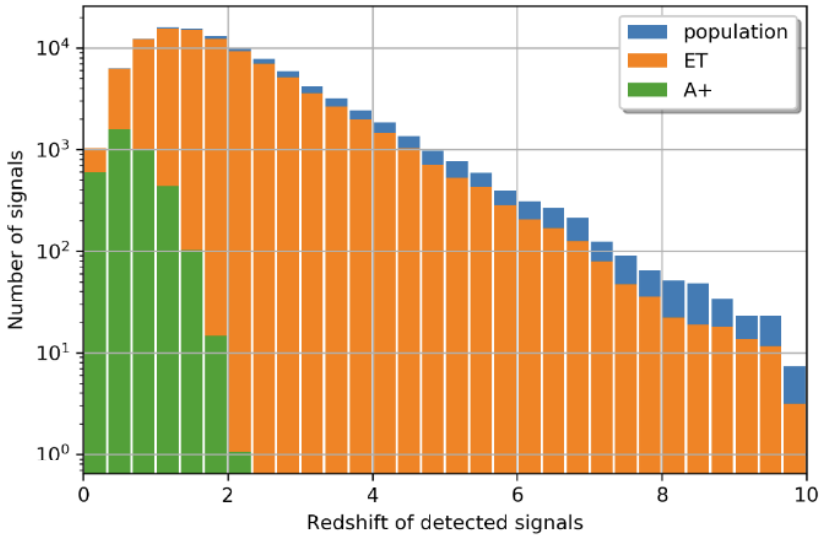
- **The nature of compact objects**
  - Near-horizon physics
  - Tests of no-hair theorem
  - Exotic compact objects
- **Tests of General Relativity**
  - Post-Newtonian expansion
  - Strong-field regime
- **Dark matter**
  - Primordial black holes
  - Axion clouds, environment
- **Dark energy & modified gravity**
  - Dark energy equation of state
  - Modified GW propagation
- **Stochastic background of cosmological origin**
  - Inflation, phase transistion, cosmic strings

BH & NS demography: 10^5 events/yr (1 event every 5min)

BNS mergers

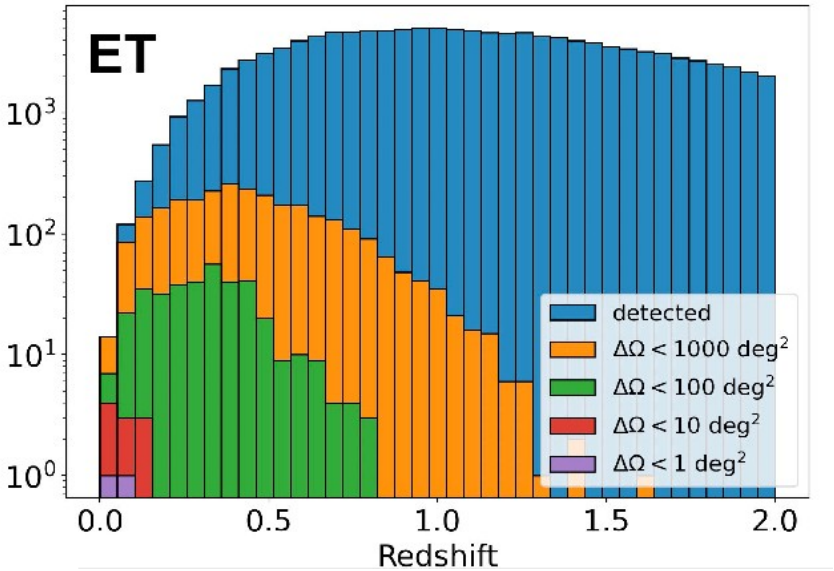


BBH mergers

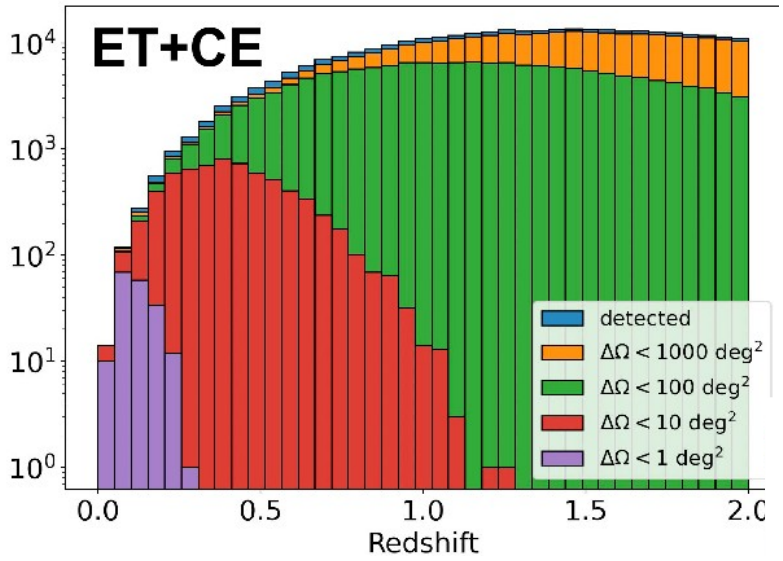


credits: M.Branchesi

Low-freq. sensitivity → localization & early alerts

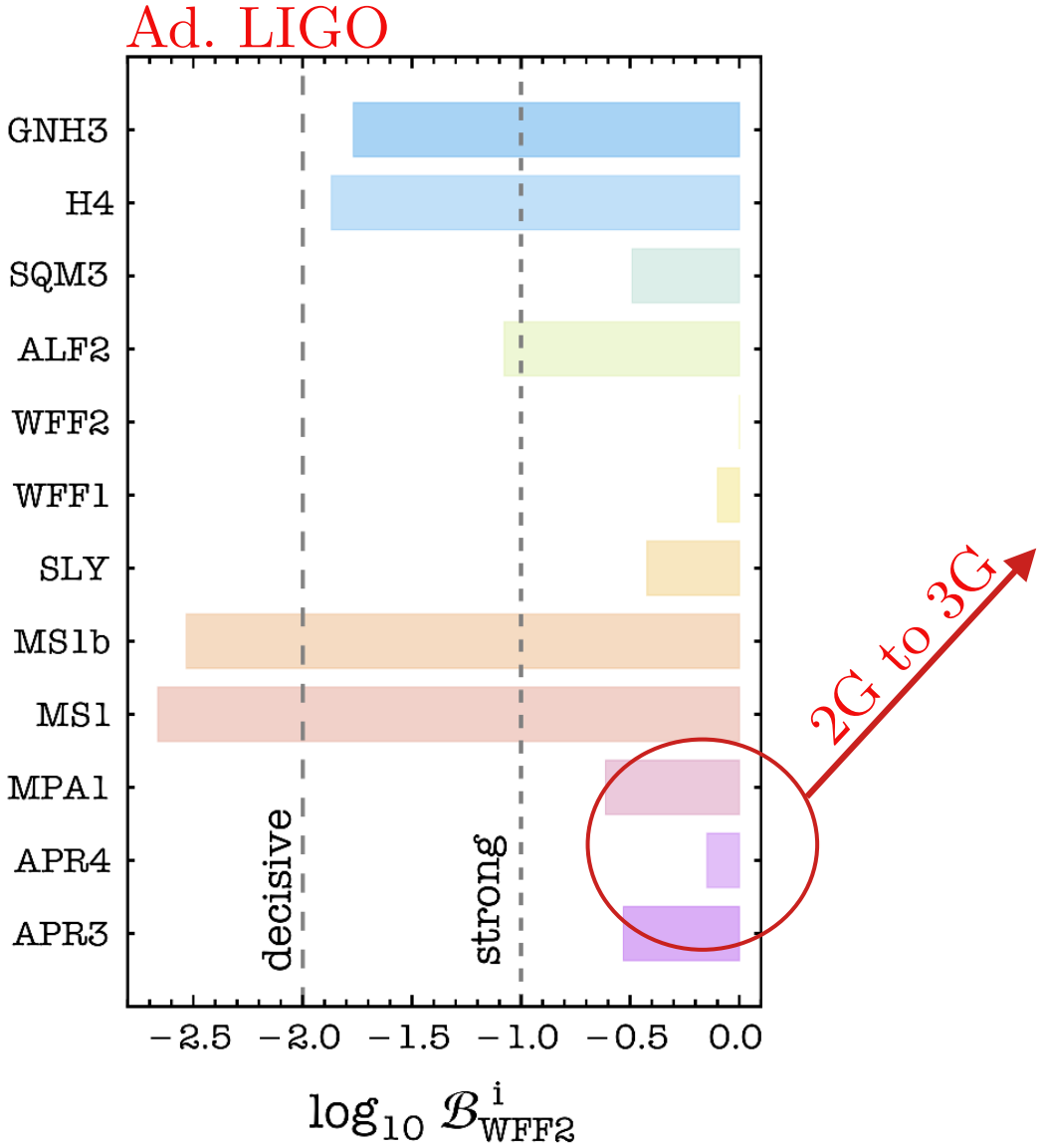


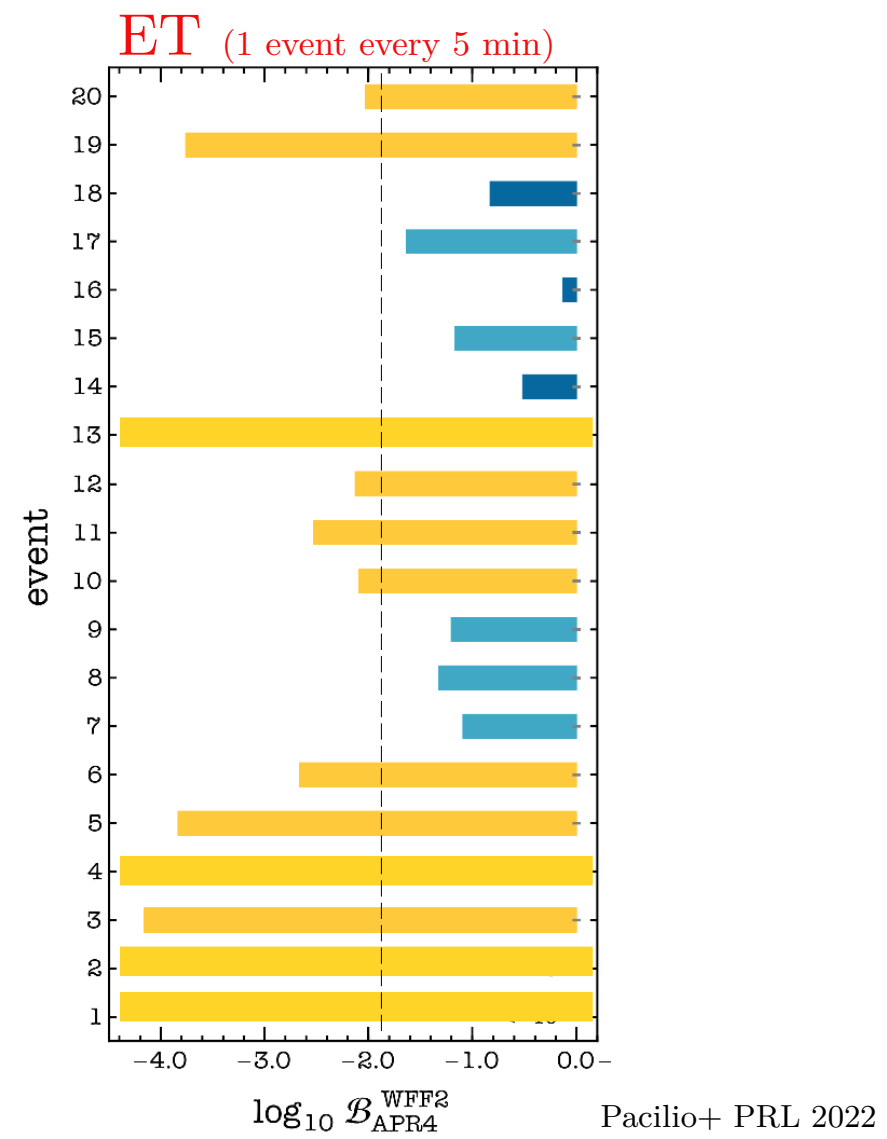
O(100) events/yr with sky-localization <100 deg^2



O(1000) events/yr with sky-localization <10 deg^2

EoS constraints with ET





2G to 3G

Pacilio+ PRL 2022

GW170817 with LIGO/Virgo
→ limited constraining power

GW170817-like in ET
→ rule out most EoS

Outlook of the Initiative

- Work in progress:
  - Contribution to ET science (OSB Divisions & Blue Book)
  - Contribution to LISA science (FP & Cosmo WGs)
  - Workshop organizations
- Goals for the future:
  - Fund raising
    - Short-term Scientific Missions
    - Training next-gen of leaders in GW physics
    - Software Repositories
  - Organization of working groups and recurrent meetings

Thanks for the attention!

XII Einstein Telescope Symposium

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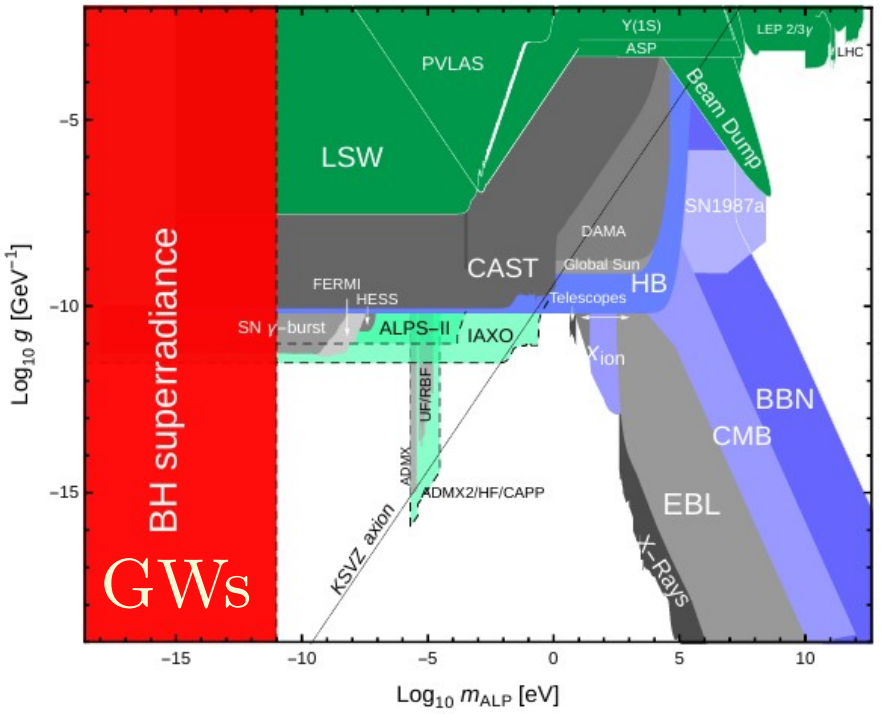
Backup slides

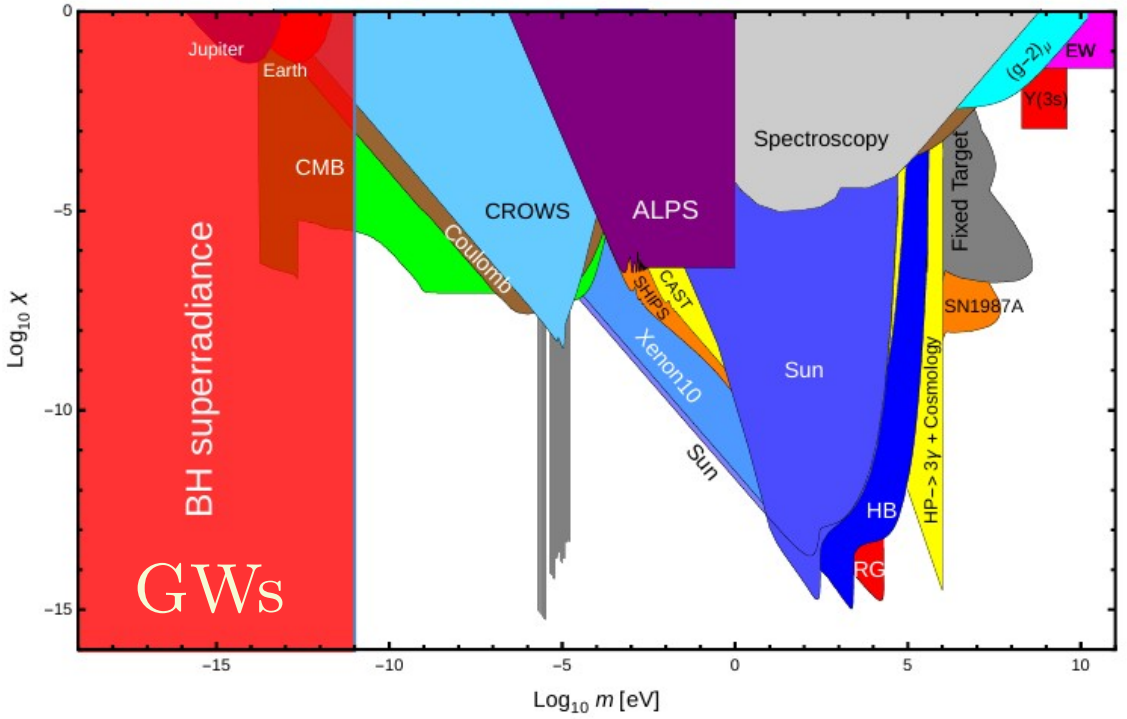
"Nothing is More Necessary than the Unnecessary" [cit.]

GW searches for ultralight dark matter

Axion-like particles (ALPs)



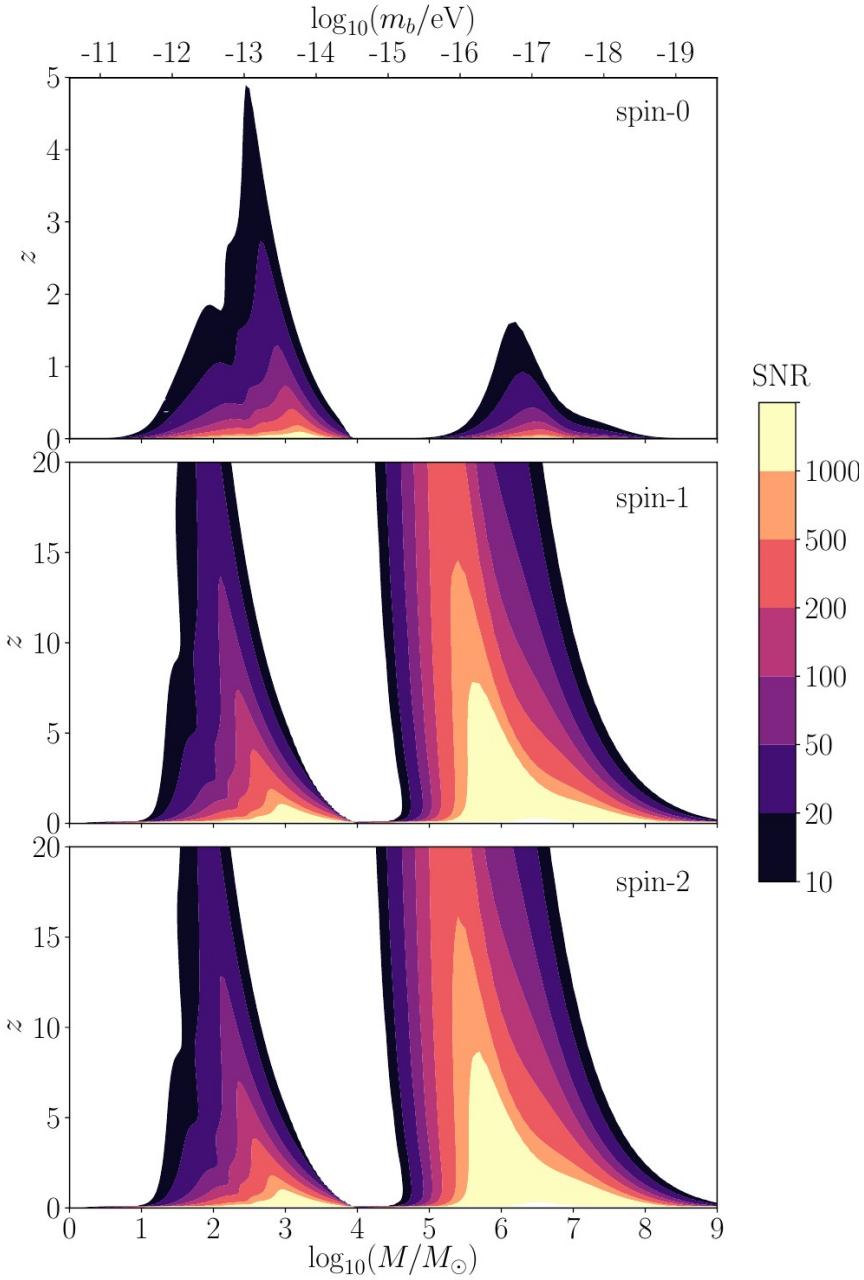
Dark photons



GW constraints do not require dark-matter couplings to SM!

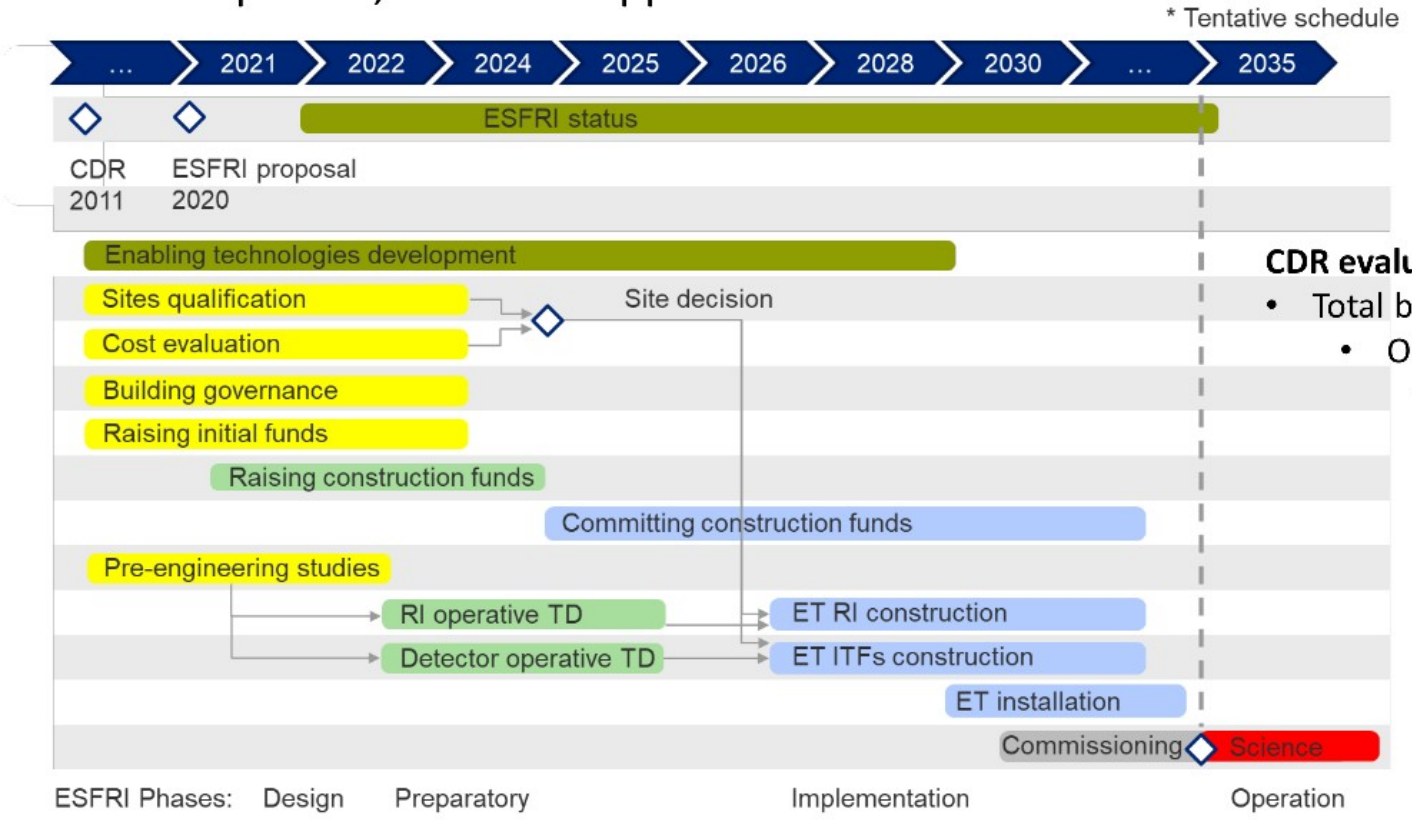
ET-LISA horizon for ultralight DM

ET/LISA will be sensitive to ultralight dark matter around *any* black hole in the Universe!



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€

ET site(s)

- Currently there are two European candidate sites to host ET:
  - The Sardinia site, close to the Sos Enattos mine
  - The EU Regio Rhine-Meusse (Limburg) site, close to the NL-B-D border
- A third option in Saxony (Germany) is under discussion