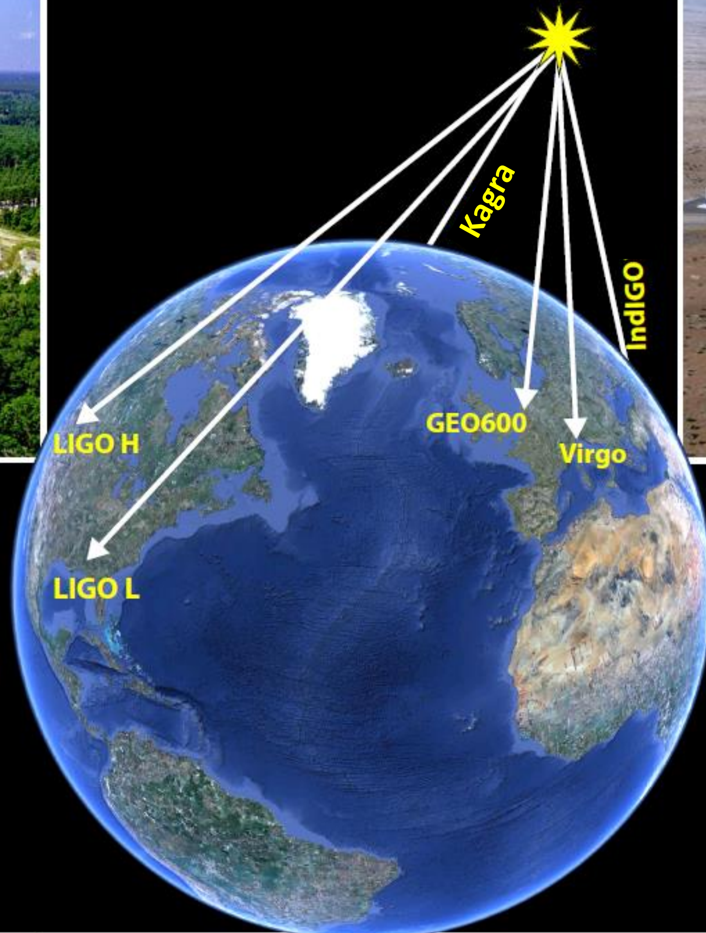
From 2G to 3G GW detectors

Jo van den Brand, Nikhef and VUA,
jo@nikhef.nl
Joint Gravitational Waves and CERN Meeting, CERN, September 1, 2017



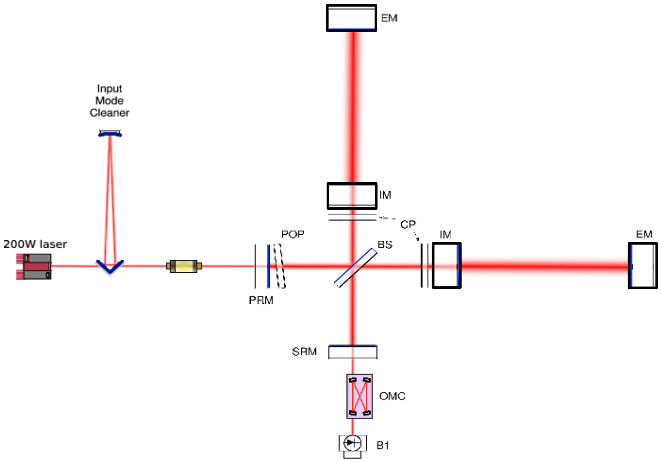
Advanced LIGO started in Sep. 2015

Virgo joined in 2017

Kagra joins 2020
LIGO India?

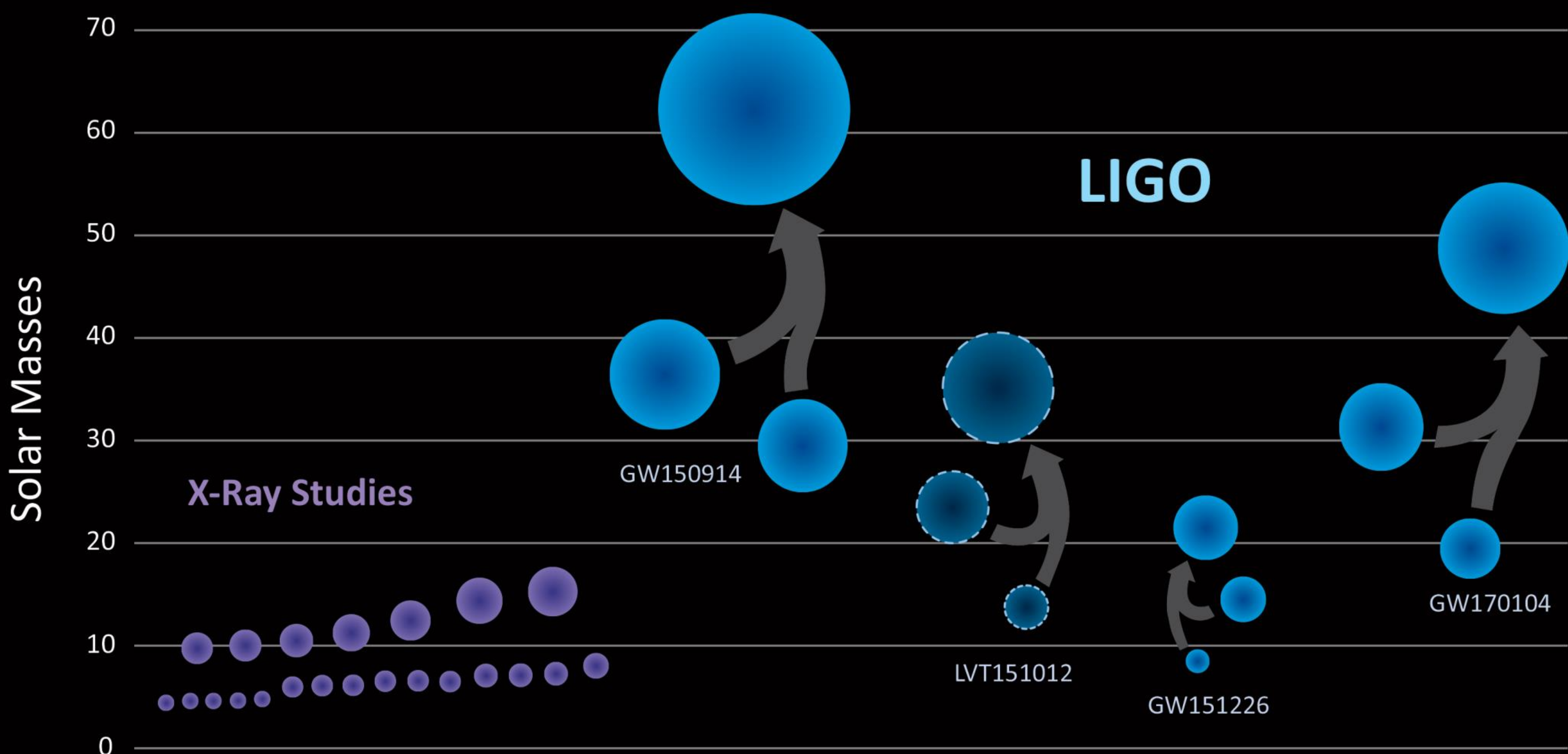
2G detectors

The LIGO and Virgo gravitational wave detectors are power recycled interferometer with Fabry-Perot cavities in their arms



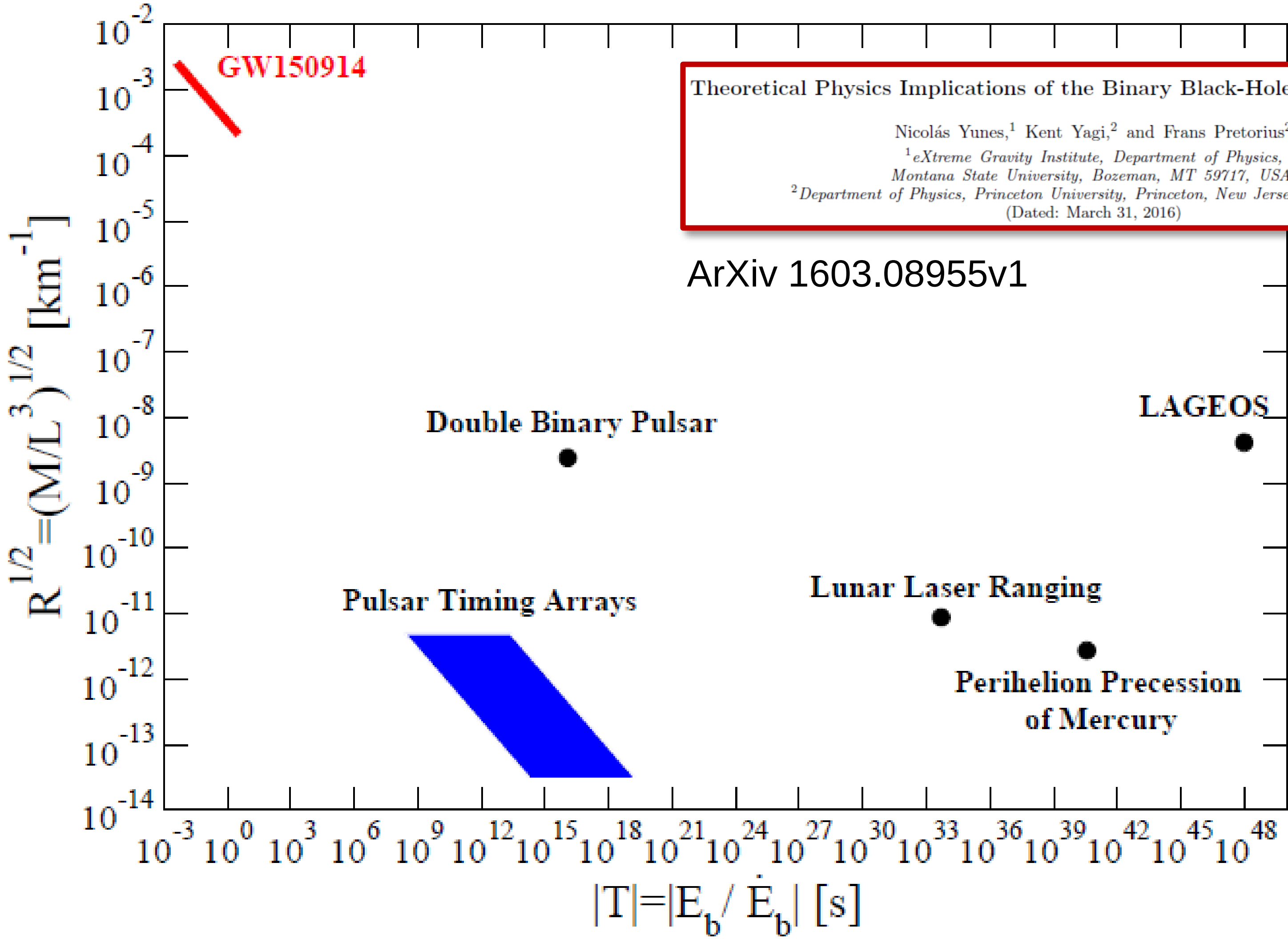
Virgo gravitational wave antenna

Black Holes of Known Mass



Allows to explore GR in the strong-field regime

Curvature-radiation reaction time-scale phase space sampled by relevant experiments. E_b is the characteristic gravitational binding energy and $\dot{E}_b$ is the rate of change of this energy



Theoretical Physics Implications of the Binary Black-Hole Merger GW150914

Nicolás Yunes,[1] Kent Yagi,[2] and Frans Pretorius[2]

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(Dated: March 31, 2016)

ArXiv 1603.08955v1

Exotic compact objects

Gravitational waves from coalescence of two compact objects is the Rosetta Stone of the strong-field regime. It may hold the key and provide an in-depth probe of the nature of spacetime

Quantum modifications of GR black holes

- Motivated by Hawking's information paradox
- Firewalls, fuzzballs, EP = EPR, …

Fermionic dark matter

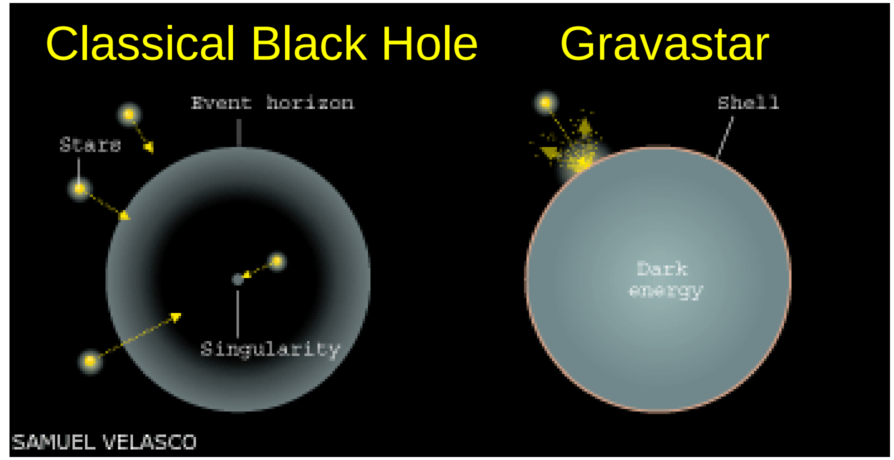
- Dark matter stars

Boson stars

- Macroscopic objects made up of scalar fields

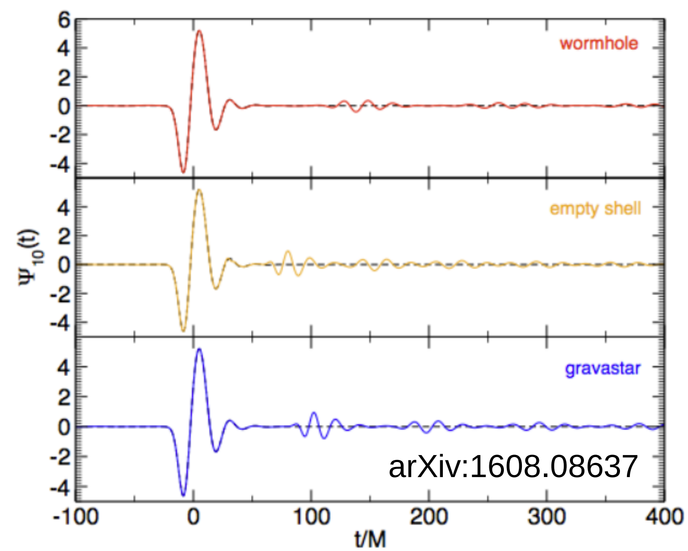
Gravastars

- Objects with de Sitter core where spacetime is self-repulsive
- Held together by a shell of matter
- Relatively low entropy object



GW observables

- Inspiral signal: modifications due to tidal deformation effects
- Ringdown process: use QNM to check no-hair theorem
- Echoes: even for Planck-scale corrections $\Delta t \approx -nM \log\frac{l}{M}$



General Relativity passes first precision tests

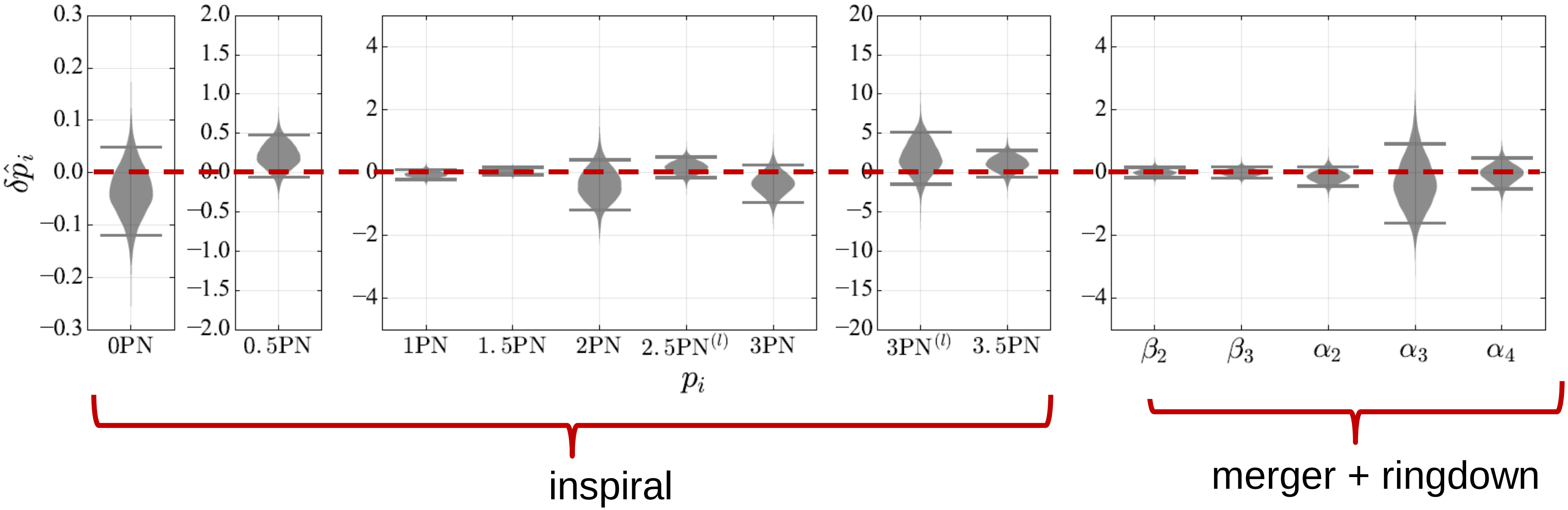
Our Bayesian analysis allows combination of different events in order to improve hypothesis testing

Orbital phase (post Newtonian expansion): $\Phi(v) = \left(\frac{v}{c}\right)^{-5} \sum_{n=0}^{\infty} \left[\varphi_n + \varphi_n^{(l)} \ln\left(\frac{v}{c}\right)\right] \left(\frac{v}{c}\right)^n$

Inspiral PN terms $\varphi_j, j = 0,..,7$ and logarithmic terms $\varphi_{jl},\ j = 5, 6$
Intermediate and merger-ringdown β_i and α_i

GW back-reaction, spin-orbit, spin-spin couplings, …

GW150914 + GW151226 + GW170104



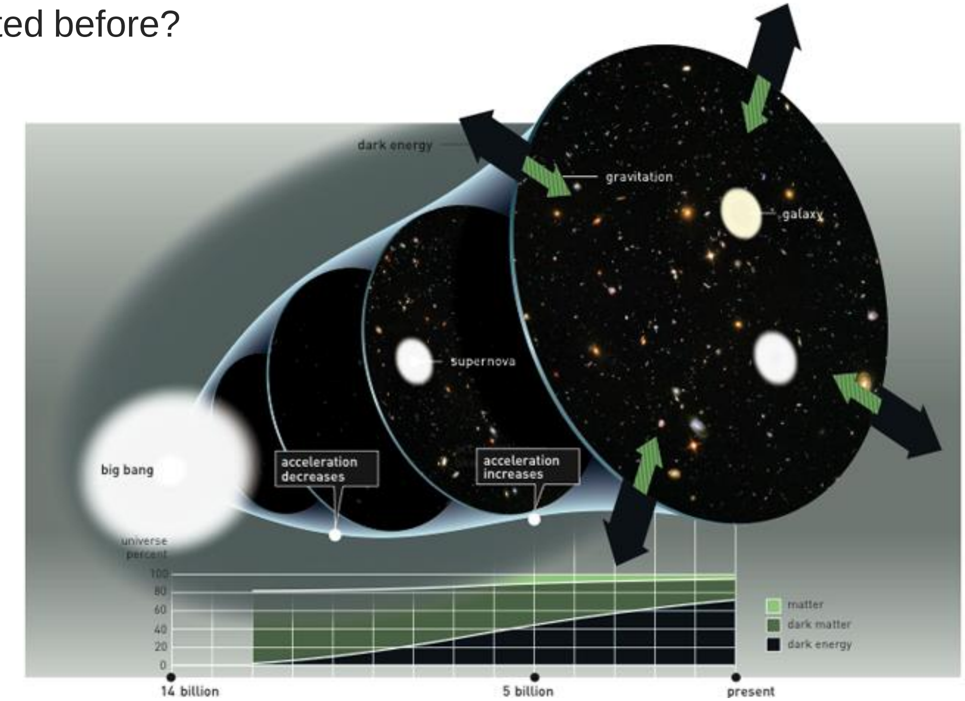
What does it all mean? What’s next?

Gravity

Gravity is the least understood fundamental interaction with many open questions. Should we not now investigate general relativity experimentally, in ways it was never tested before?

Gravity

- Main organizing principle in the Universe
  - Structure formation
- Most important open problems in contemporary science
  - Acceleration of the Universe is attributed to dark energy
  - Standard Model of Cosmology features dark matter
  - Or does this signal a breakdown of general relativity?



Large world-wide intellectual activity

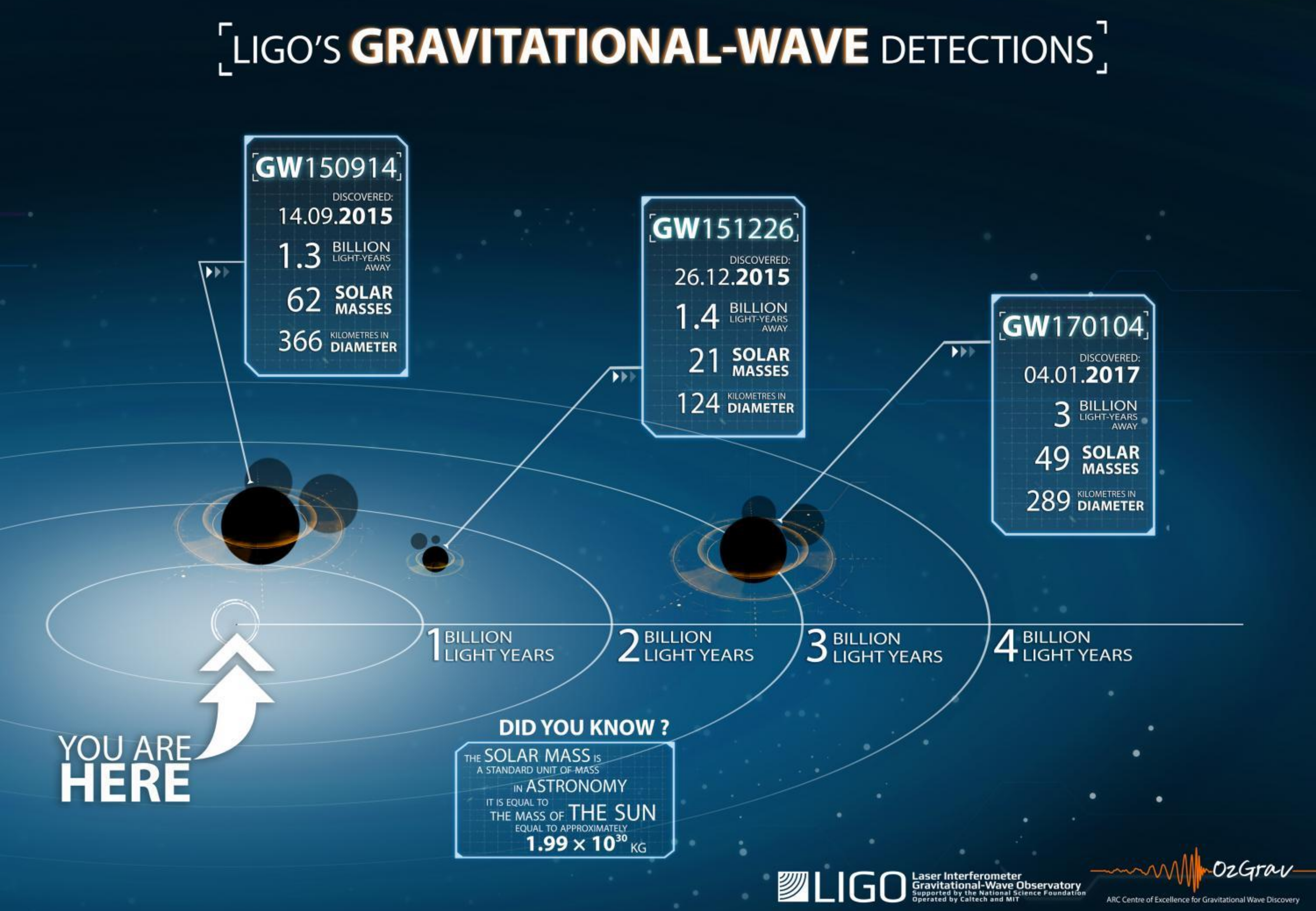
- Theoretical: combining GR + QFT, cosmology, …
- Experimental: astronomy (CMB, Euclid, LSST), particle physics (LHC), dark matter searches (Xenon1T), …

Gravitational waves

- Dynamical part of gravitation, all space is filled with GW
- Ideal information carrier, almost no scattering or attenuation
- The entire universe has been transparent for GWs, all the way back to the Big Bang

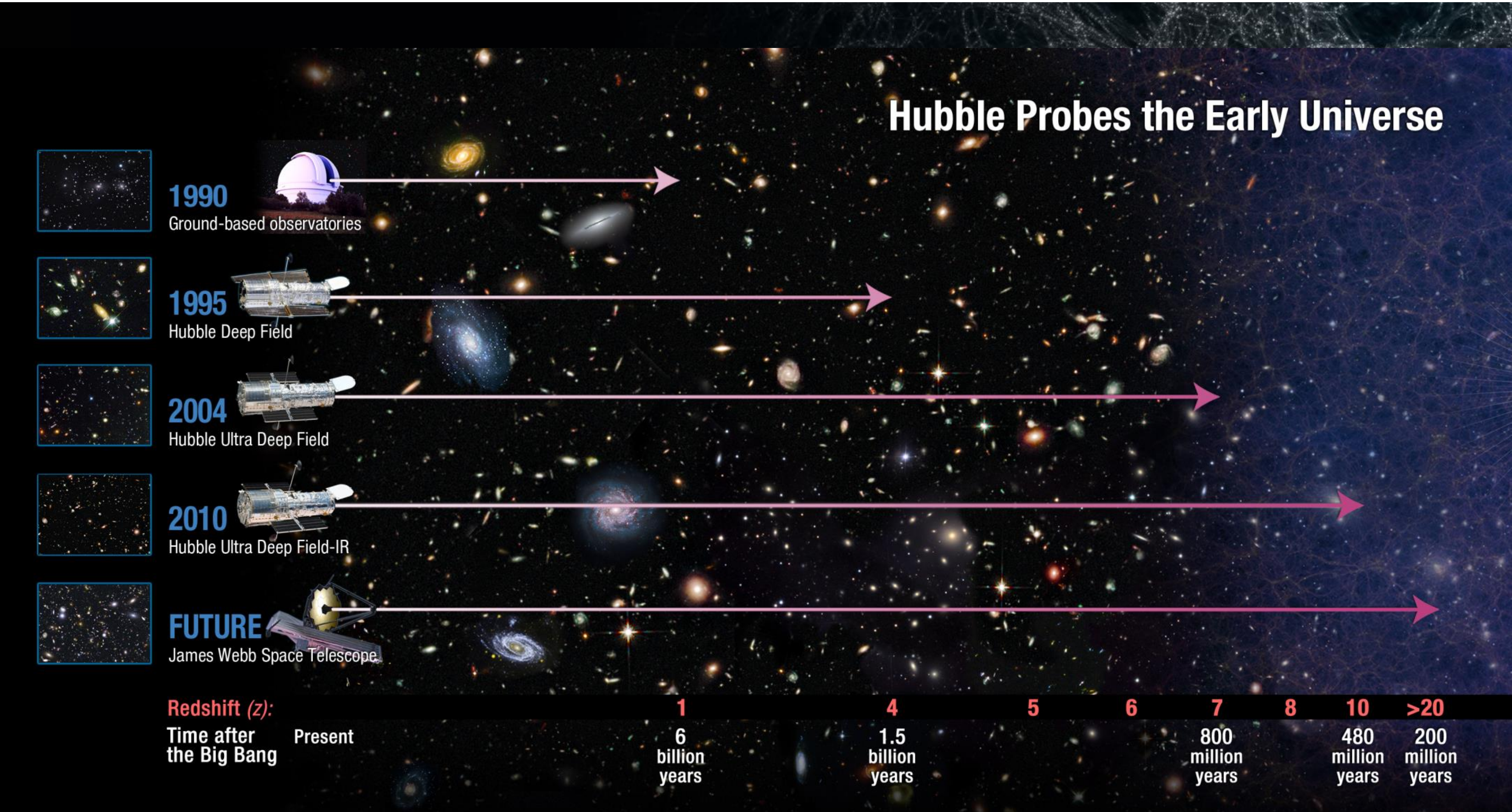
Gravitational wave science can impact

- Fundamental physics: black holes, spacetime, horizons
- Cosmology: dark energy


LIGO'S GRAVITATIONAL-WAVE DETECTIONS
GW150914
DISCOVERED: 14.09.2015
1.3 BILLION LIGHT-YEARS AWAY
62 SOLAR MASSES
366 KILOMETRES IN DIAMETER
GW151226
DISCOVERED: 26.12.2015
1.4 BILLION LIGHT-YEARS AWAY
21 SOLAR MASSES
124 KILOMETRES IN DIAMETER
GW170104
DISCOVERED: 04.01.2017
3 BILLION LIGHT-YEARS AWAY
49 SOLAR MASSES
289 KILOMETRES IN DIAMETER
1 BILLION LIGHT YEARS
2 BILLION LIGHT YEARS
3 BILLION LIGHT YEARS
4 BILLION LIGHT YEARS
YOU ARE HERE
DID YOU KNOW ?
THE SOLAR MASS IS A STANDARD UNIT OF MASS IN ASTRONOMY
IT IS EQUAL TO THE MASS OF THE SUN
EQUAL TO APPROXIMATELY 1.99×10^{30} KG
LIGO Laser Interferometer Gravitational-Wave Observatory
Supported by the National Science Foundation
Operated by Caltech and MIT
OzGrav
ARC Centre of Excellence for Gravitational Wave Discovery

Probing the early Universe

It is important to study the early Universe in the “dark ages”, before first stars have formed. For example, Einstein Telescope can observe BBH mergers up to redshifts of about 20



Science drives the design requirements for 3G

Questions for new facilities as Cosmic Explorer and Einstein Telescope

Do we want to observe all BBH mergers in the Universe?

- Do we want to collect high statistics (e.g. a million BBH events) distributed over a large z-range ($z < 20$)?
- Do we really need 3G, or is an upgrade of existing facilities within site constrains sufficient?

Do we want to do precision science, and can we combine information from multiple events?

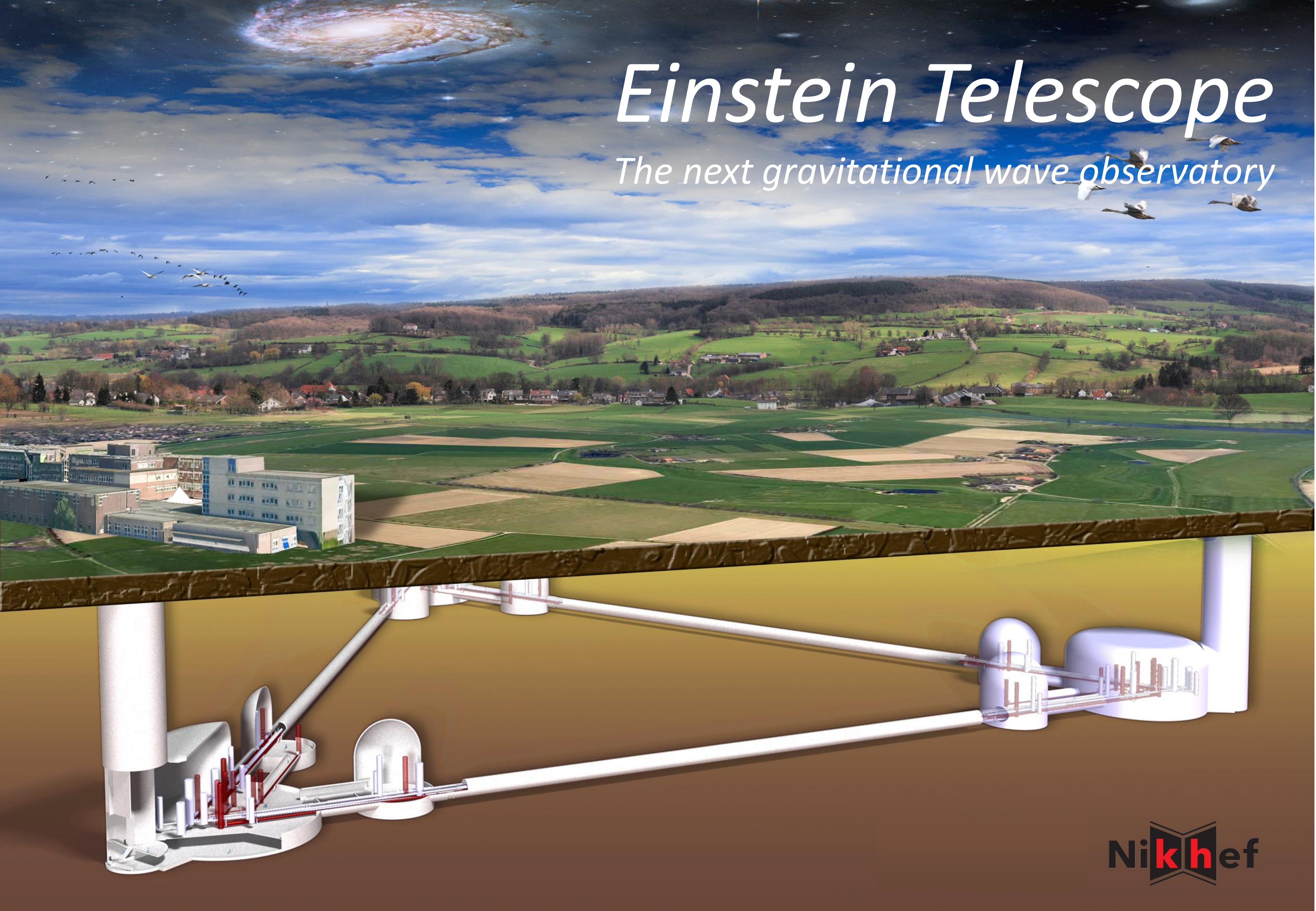
- Are our waveform models robust for stacking, e.g. to sub-per-mille precision on PN terms?
- Can we face-up to the computing challenge?
- Do we prefer events a few high-SNR events (thus long arms), or can we combine lower SNR events?

Do we want to constantly observe the entire sky with high pointing precision?

- Correlate high statistics GW data with other (e.g. EM) observations (SKA-II, LSST, Theseus, …)
- One L-shaped sensitive instrument, or one triangular detector? Or do we need a 3G network?

For how long do we want to observe our signals?

- How important is it to predict a merger minutes in advance to prepare for EM follow-up?
- Importance of studying spin-precession effects? What about IMRIs? Sensitivity for high-z events?
- What should be our low-frequency cut-off? Do we need to go underground for seismic and Newtonian noise?

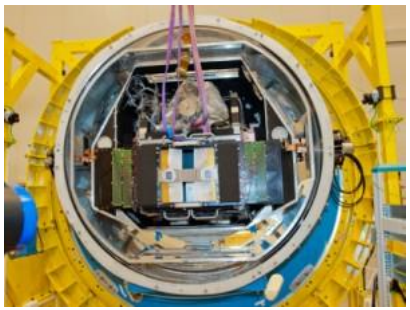

Einstein Telescope
The next gravitational wave observatory
Nikhef

What technologies are required for Einstein Telescope?

Third generation GW facilities pose extreme technological demands, that must be developed specially for this application. The involvement and expertise of CERN would be an enormous asset

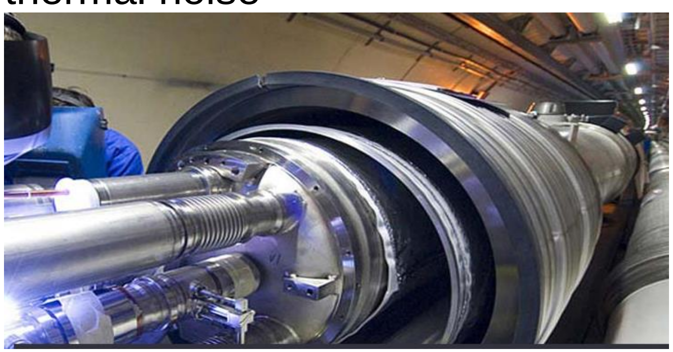
For Einstein Telescope significant underground construction is foreseen

Measuring and attenuating vibrations to extremely low levels



Optics, coatings, special materials, laser technology, semiconductor technology

Cryogenic technology to suppress thermal noise



Vacuum technology: ET will be one of the biggest vacuum systems worldwide

How to get from 2G to 3G?

Vision beyond Advanced Virgo

The collaboration has discussed a path from Advanced Virgo to Einstein Telescope

Sensitivity of Advanced Virgo will be improved further within current infrastructure limits

- Additional hardware implementations are planned: MS, FDS, HPL, SR
  - Main limits: mirror thermal noise and quantum noise
- New ideas are under study
  - Larger beam and larger mirrors, and better coatings
  - Newtonian noise subtraction, and improved suspensions

Phased approach

- Phase I: achieve design sensitivity (2017 – 2021)
- Phase II: achieve maximum sensitivity within infrastructure limits (2021 – 2025)
- Phase III: optimize AdV in view of a new available infrastructure (> 2025)

From Advanced Virgo to Einstein Telescope

- Scientific excellence with the network of advanced detectors: LIGO, Virgo, KAGRA
- Vigorous and international R&D program focused on third generation with spin-off to advanced detectors
- Position Virgo as an attractive international gateway to GW science

Strategic decision of EU agencies on their commitment for ground-based GW science is required

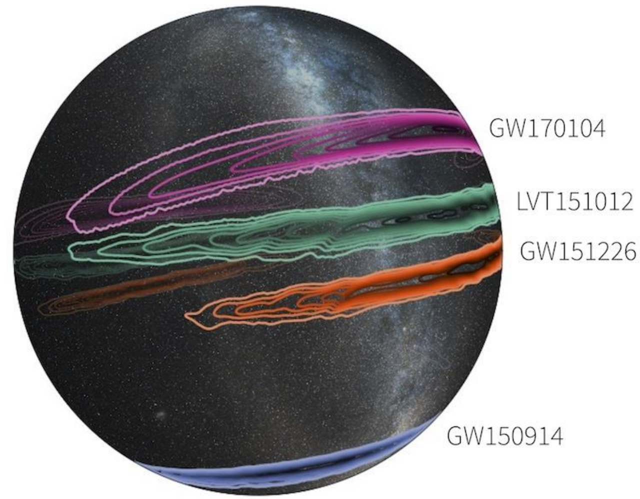
- Important roles for ApPEC and GWIC

Virgo as third node in the GW global network

We made a promise to deliver Virgo as the third node in a world-wide network for GW detection

Added scientific value of Virgo in the network

- Increase data volume
- Increase of sky coverage
- Improvement of sky location of sources
- Measurement of GW polarization
- Improvement in distance measurement
- Three-fold coincidence measurement for increased robustness
- Improvement in parameter estimation



Sensitivity evolution in BNS range (see VIR-0136A-16)

• Early	2016 – 17	20 – 60 Mpc
• Mid	2017 – 18	60 – 85 Mpc
• Late	2018 – 20	65 – 115 Mpc
• Design	2021	130 Mpc
• BNS-optimized		145 Mpc

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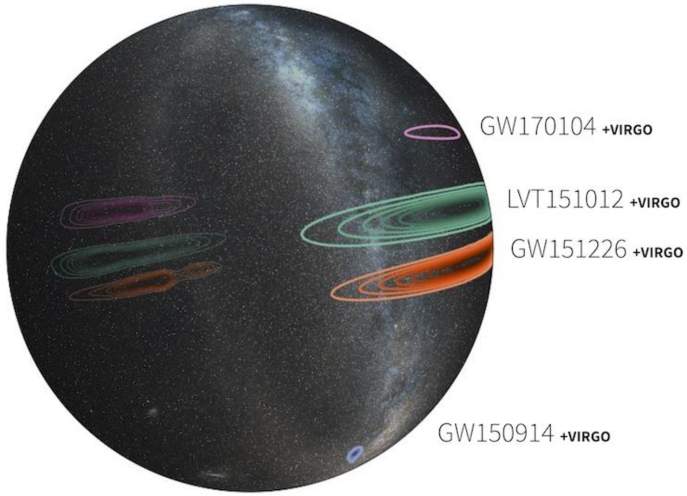

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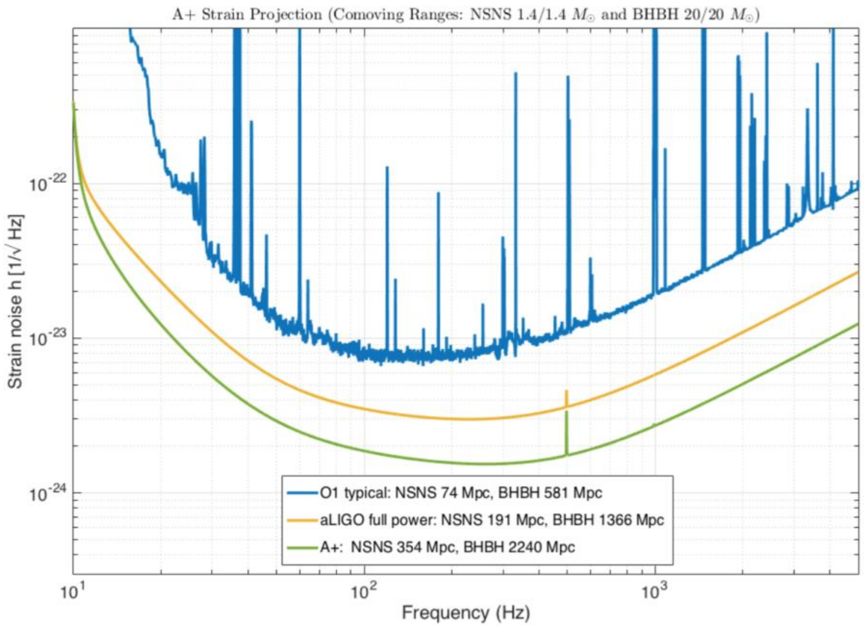
Multi-messenger astronomy

- BNS, BHNS

Upgrade path for 2G

LIGO and Virgo are aiming at mid and long-term upgrades to exploit the current facilities. Laser power, FDS, reduction of coating loss angle. But also heavier test masses, … Towards z = 1 for BBH



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Prospects for doubling the range of Advanced LIGO

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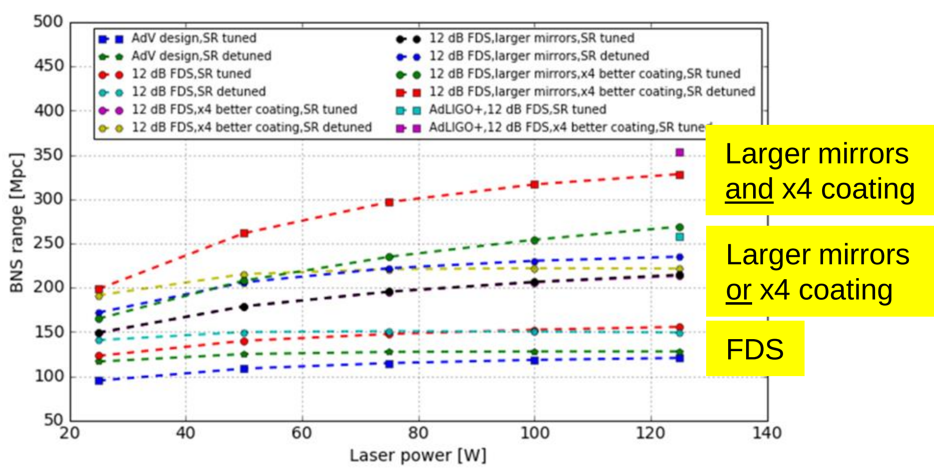
(Received 29 October 2014; published 16 March 2015)



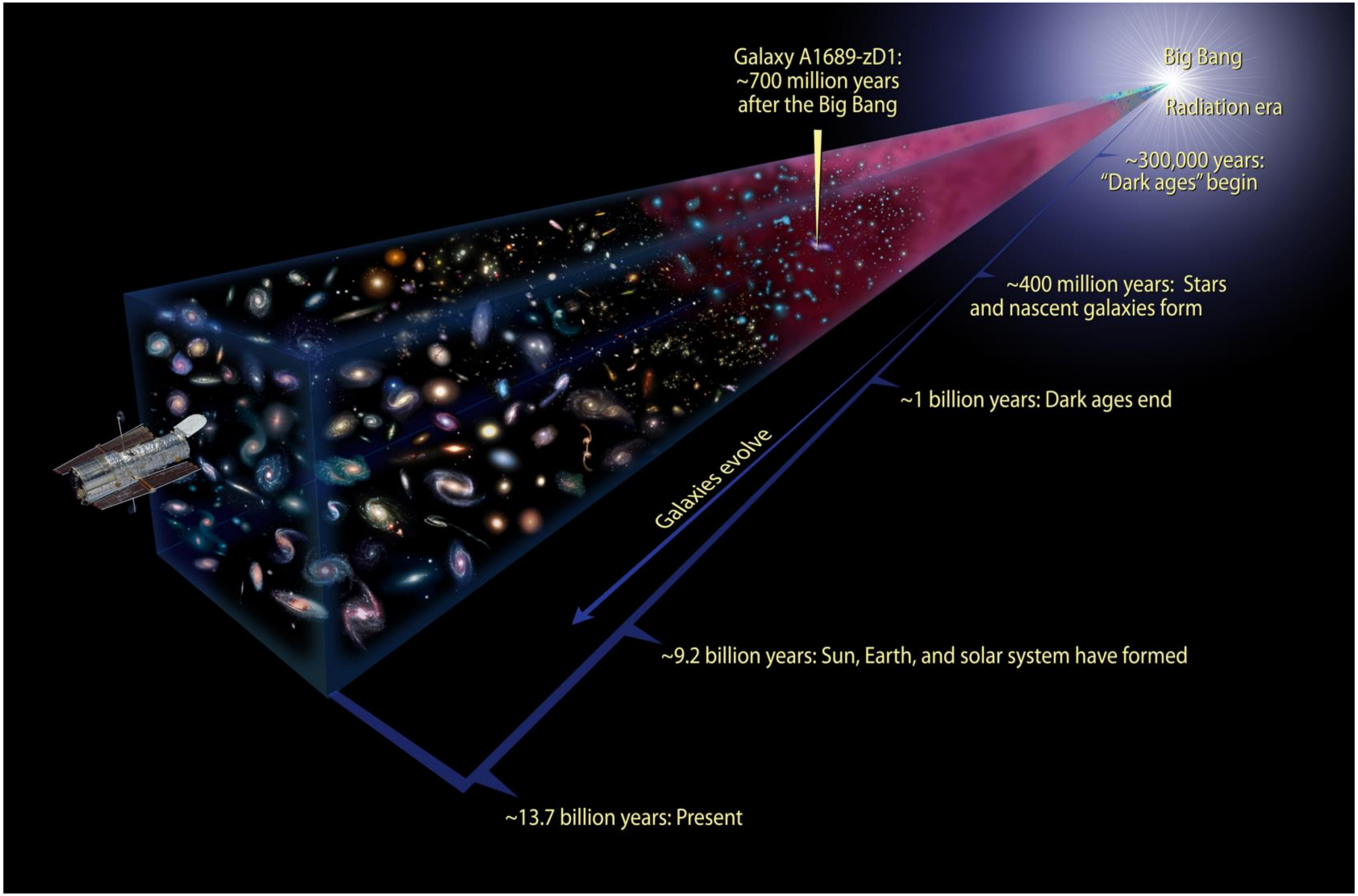
A Vision Beyond the Advanced Virgo Project

VIR-0136A-16

The VIRGO collaboration
September 2016

How far do you want to go?

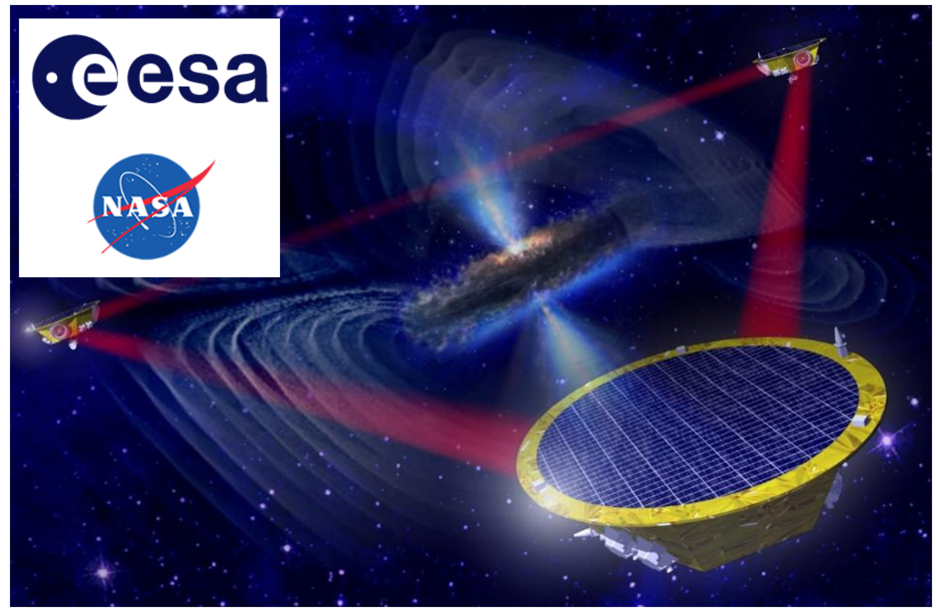
Einstein Telescope can observe BBH mergers up to red shifts of about 20. Explore the dark ages …



Credit: NASA, ESA, and A. Feild (STScI)

Next step in gravitational wave research

LIGO and Virgo are operational. LIGO-India and KAGRA in Japan under construction. ESA launches LISA in 2034. Einstein Telescope CDR financed by EU, strong support by APPEC



Gravitational wave research

- LIGO and Virgo operational
- LIGO-India and KAGRA under construction
- ESA and NASA select LISA
- Pulsar Timing Arrays, such as EPTA and SKA
- Cosmic Microwave Background radiation

Einstein Telescope

- Design financed by EU in FP7
- APPEC gives GW a prominent place in the new Roadmap and especially the realization of ET

Next steps

- Organize the community and prepare a credible plan for EU funding agencies
- ESFRI Roadmap

What is needed now?

Einstein Telescope requires that major players in fundamental science are acting in consort so that we together make this unique opportunity for an iconic project a reality

How can we develop a fruitful collaboration with CERN?

- An innovative R&D program must be defined to address key technologies
- Collaboration to study scientific issues of common interest
- Develop the international science/governance case for ET: GWIC (Summer 2018)
- Come to a common strategy that will lead to an ESFRI request (2019)
- A unique chance for Europe, but support from CERN will make the difference

European Strategy Forum
on Research Infrastructures
ESFRI