Il ruolo delle onde gravitazionali nella futura strategia particellare

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Grazie ai contributi di:
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2015-2017: Scientific revolution

he detection of GW has been a huge scientific achievement, result of a century f efforts, but actually it is the beginning of a new era in the observation of the Jniverse

he discoveries announced by LIGO and Virgo are crucial milestones in Science:

- GW150914:
  - the first direct detection of GW. Confirmation of the Einstein's prediction of GW. Discovery/ Confirmation of the existence of stellar mass black holes. Birth of the experimental physics of the gravitation in strong field and of the astrophysics of stellar mass black holes
- GW170814:
  - The first detection in a network of 3 GW detectors of GW emitted by the coalescence of black holes. The first test of GW polarisation. The birth of the gravitational wave astronomy and astrophysics thanks to the localisation capability.
- GW170817:
  - The first detection of the GW emitted by the coalescence of two Neutron Stars. Test of GR versus alternative theories of gravity. The birth of the multi-messenger astronomy and astrophysics with GW

Network of GW detectors

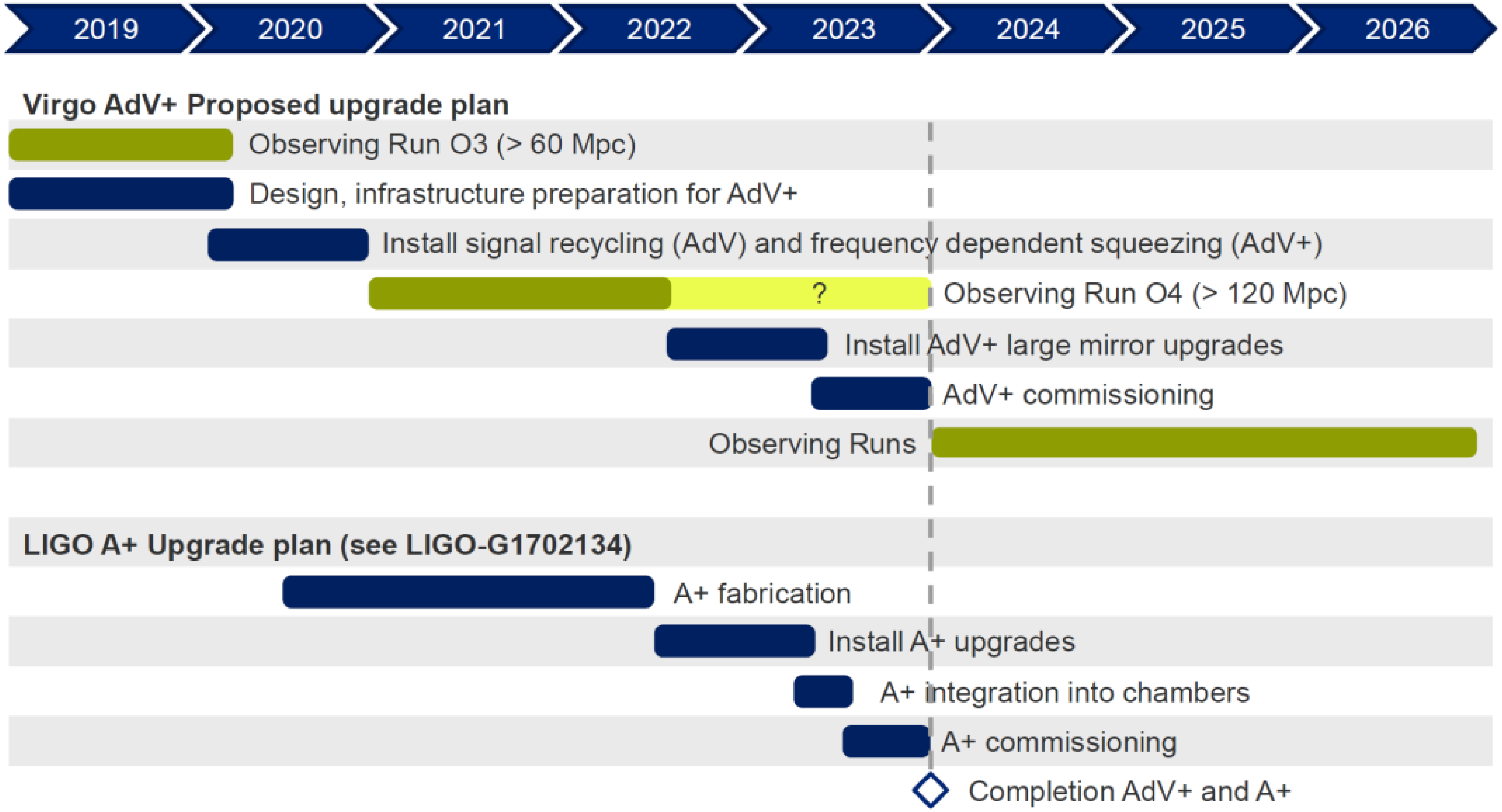
O Scientific Collaboration:
- 1263 collaborators (including GEO)
- 20 countries
- 3 computing centres
- ~1.5 G$ of total investment

Virgo Collaboration:
- 343 collaborators
- 8 countries
- 5 computing centres
- ~0.42 G€ of total investment

KAGRA Collaboration:
- 260 collaborators
- 12 countries
- 5 computing centres
- ~16.4 G¥ of construction

Short term evolutions

Five year plan for observational runs, commissioning and upgrades



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

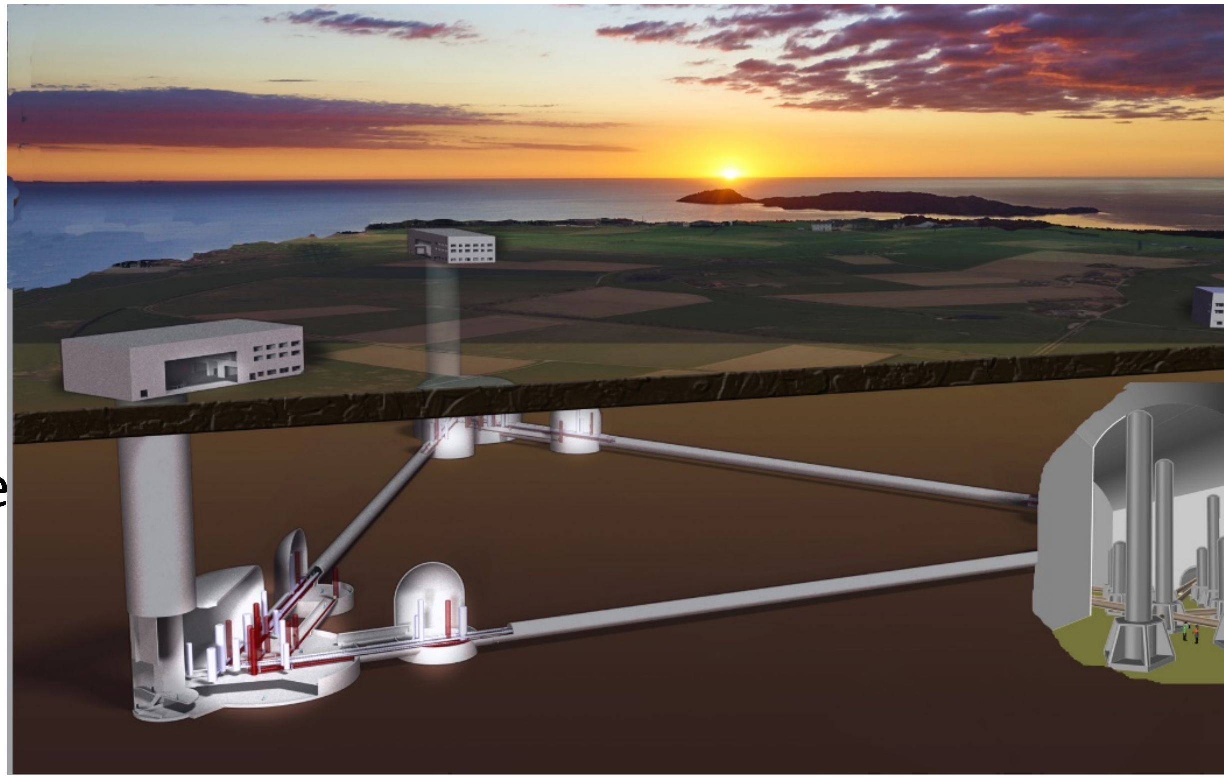
VIR-0943A-17

What Next?

e worldwide GW community elaborated a roadmap for the next 15-20 year

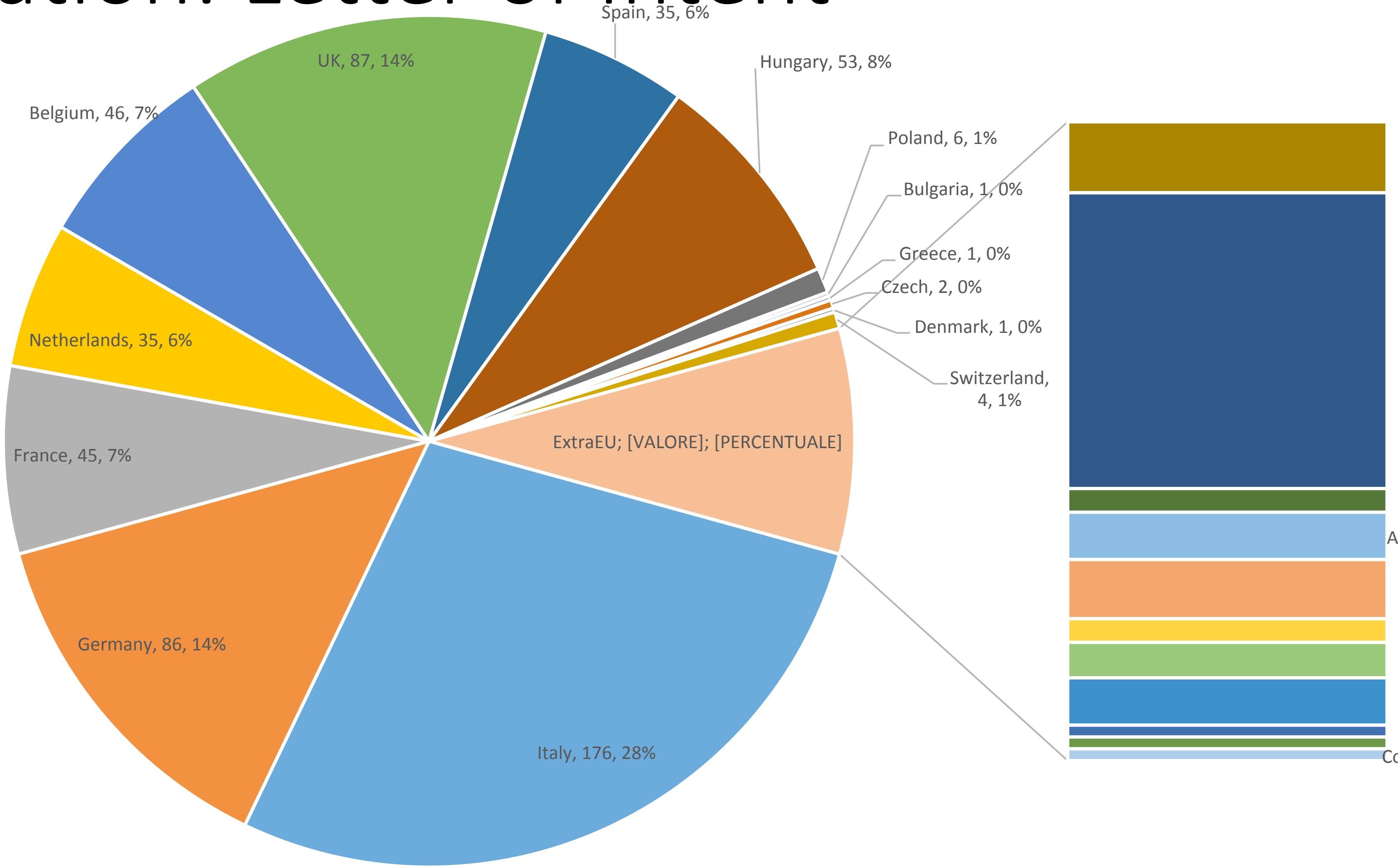
rrent detectors will be updated in order to “listen” better and further, unti
e limits of the current infrastructures will be reached

- Virgo will achieve these limits earlier than LIGO
- For this reason the European GW community started well in advance (2004/2008) to elaborate the future perspectives
- ET: Einstein Telescope
  - 3rd generation GW observatory
  - Site location in Europe under discussion
- US GW community is now following with the Cosmic Explorer idea
- A worldwide coordination is under definition thanks to a global committee (GWIC-3G)



ET collaboration: Letter of Intent

- ddressed to all the ientists and gineers interested the 3G GW ience and chnology
- e signatories (636 rsons, the 3rd of ptember) obably will ecome the future embers of the ET llaboration

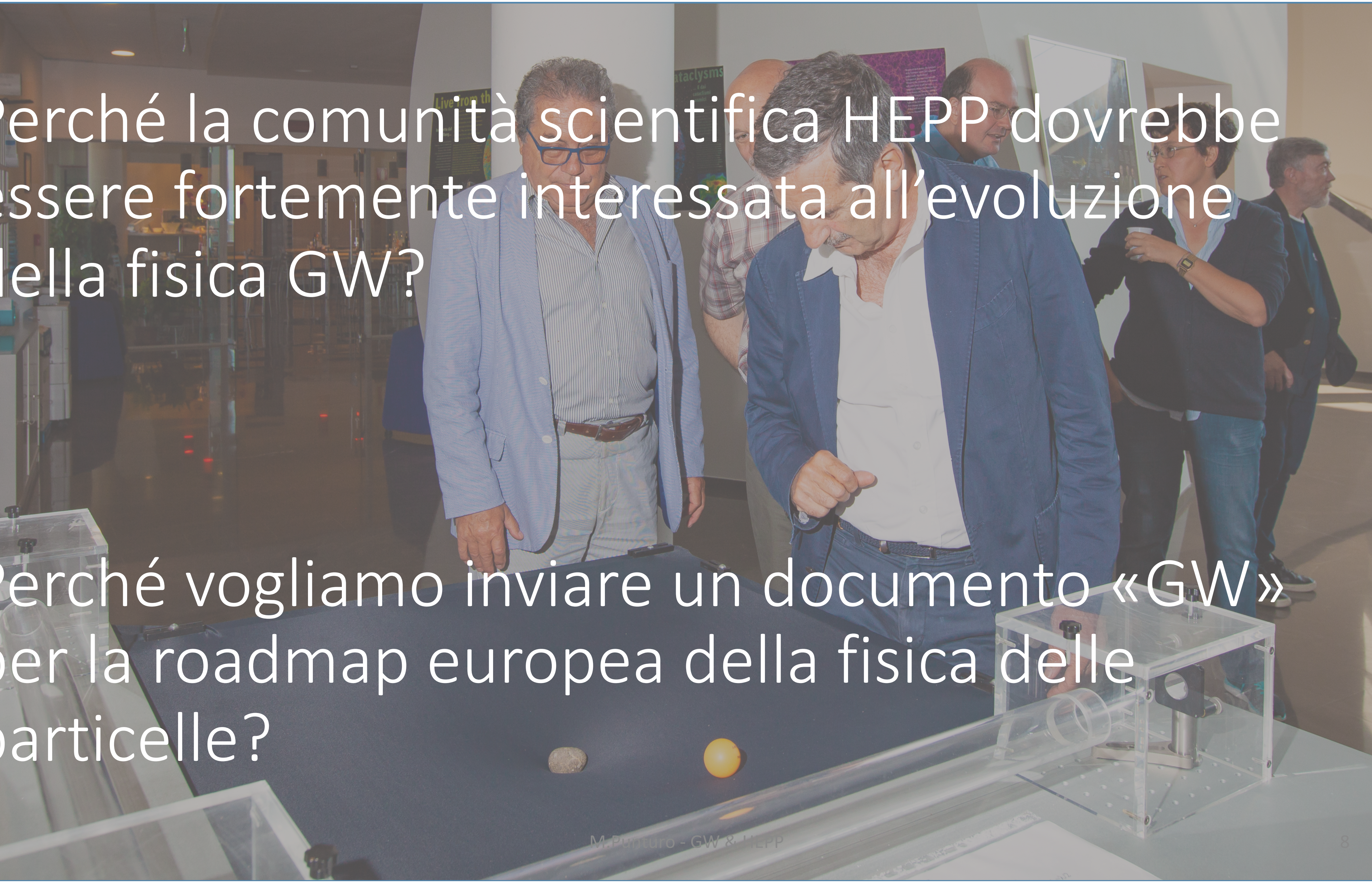


http://www.et-gw.eu/index.php/letter-of-intent

ET: the project roadmap

has a clearly defined project roadmap, presented to APPEC:

- 2018 Form the ET collaboration
- 2019 ESFRI roadmap
  - In Nov 2018 ET and the GW GRI (Global Research Infrastructure) will be presented as case study to the body GSO (Group of Senior Officer)
  - We need to define the site selection parameters before to submit the proposal
    - The requirement to be compliant with alternative design options (Δ vs L) could be a crucial point
- 2021-2022 Site Selection
  - Technical/political activity
  - Requirements need to be compared with the site characteristics through an intense experimental activ the next 3 years
- 2023 Full Technical Design Report ← Here, the design options are frozen
- Cost definition
- 2025 Infrastructure realization start (excavation, ….)
- 2030 -2031 end of infrastructure construction, beginning of installation
- 2032+: installation / commissioning / operation



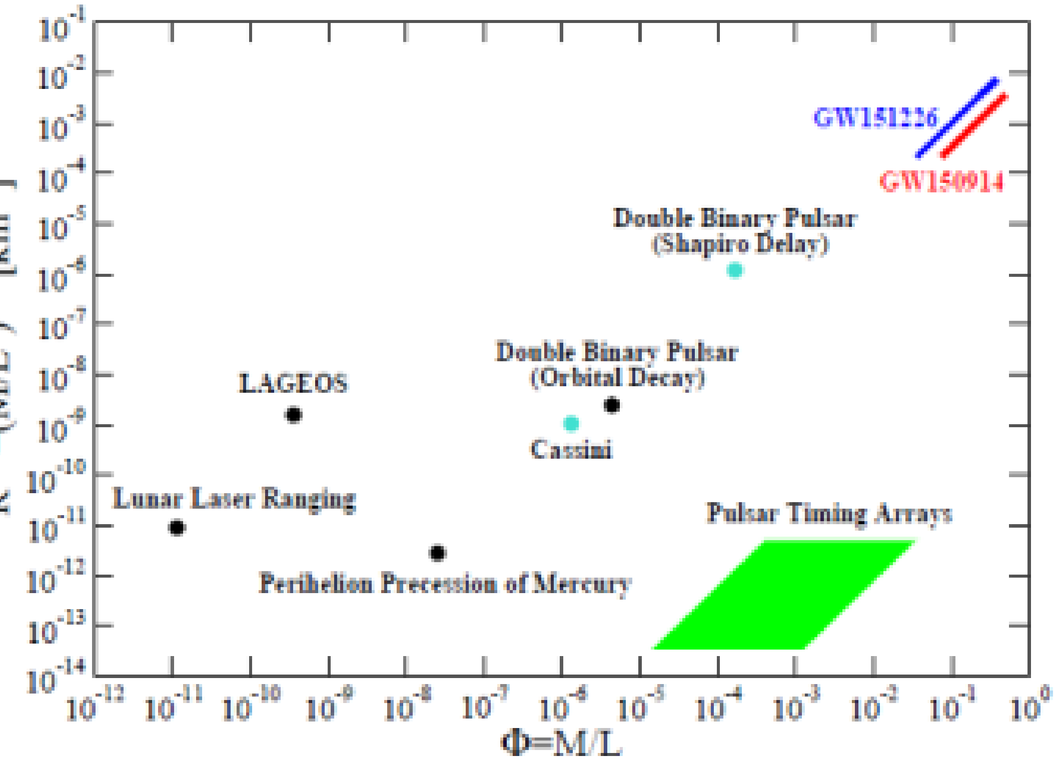
Perché la comunità scientifica HEPP dovrebbe essere fortemente interessata all’evoluzione della fisica GW?

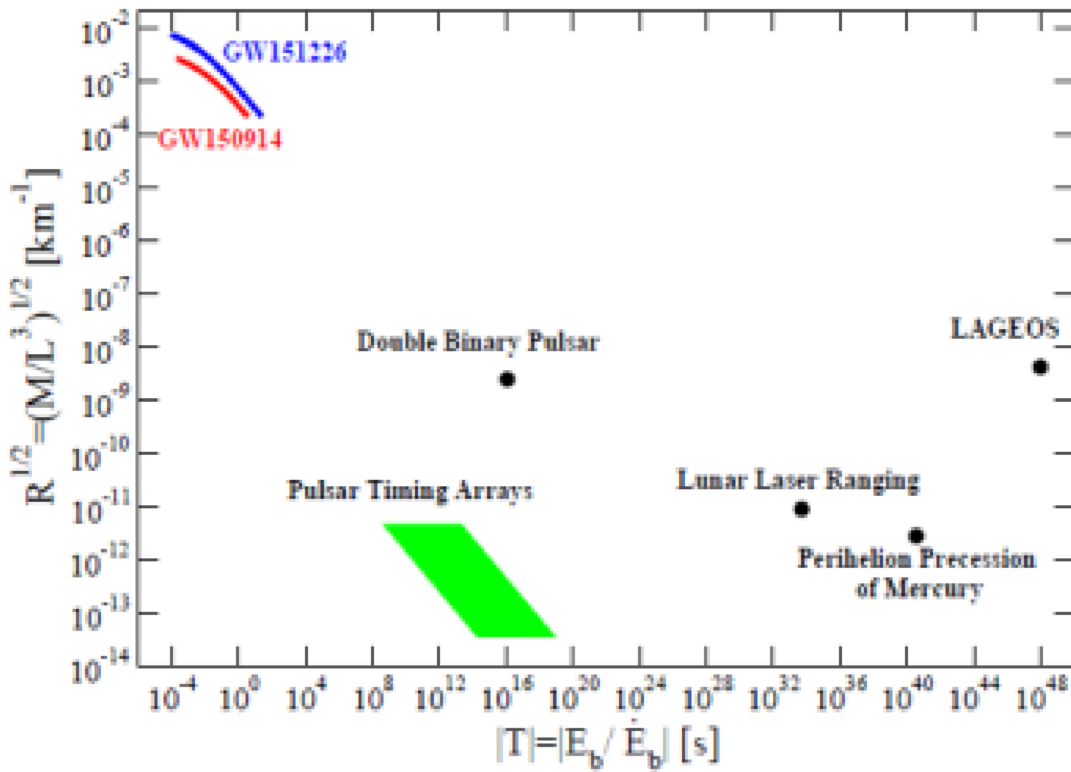
Perché vogliamo inviare un documento «GW» per la roadmap europea della fisica delle particelle?

HEPP and GW physics similitudes & synergies

imilitudes

- Both HEPP and GW physics evolutions are aiming to
  - High rates (events pileup ↔ astrophysical stochastic background)
  - High energy





Yunes N. et al.
Phys. Rev. D 94, 084002 (2016)

HEPP and GW physics similitudes & synergies

ynergies

- There are strong synergies in the Physics and Technologies in the two fields
- Physics: GW → HEPP
- Technology: HEPP → GW

Physics

Technology

ome of the questions addressed by GW (AdV+, ET)

- ndamental questions in Gravity:
  - New/further tests of GR
  - Exploration of possible alternative theories of Gravity
  - How to disprove that Nature black holes are black holes in GR (e.g. non tensorial radiation, quasi normal modes inconsistency, absence o horizon, echoes, tidal deformability, spin-induced multipoles)

  HEPP Fundamental interactions, Dark matter, dark energy

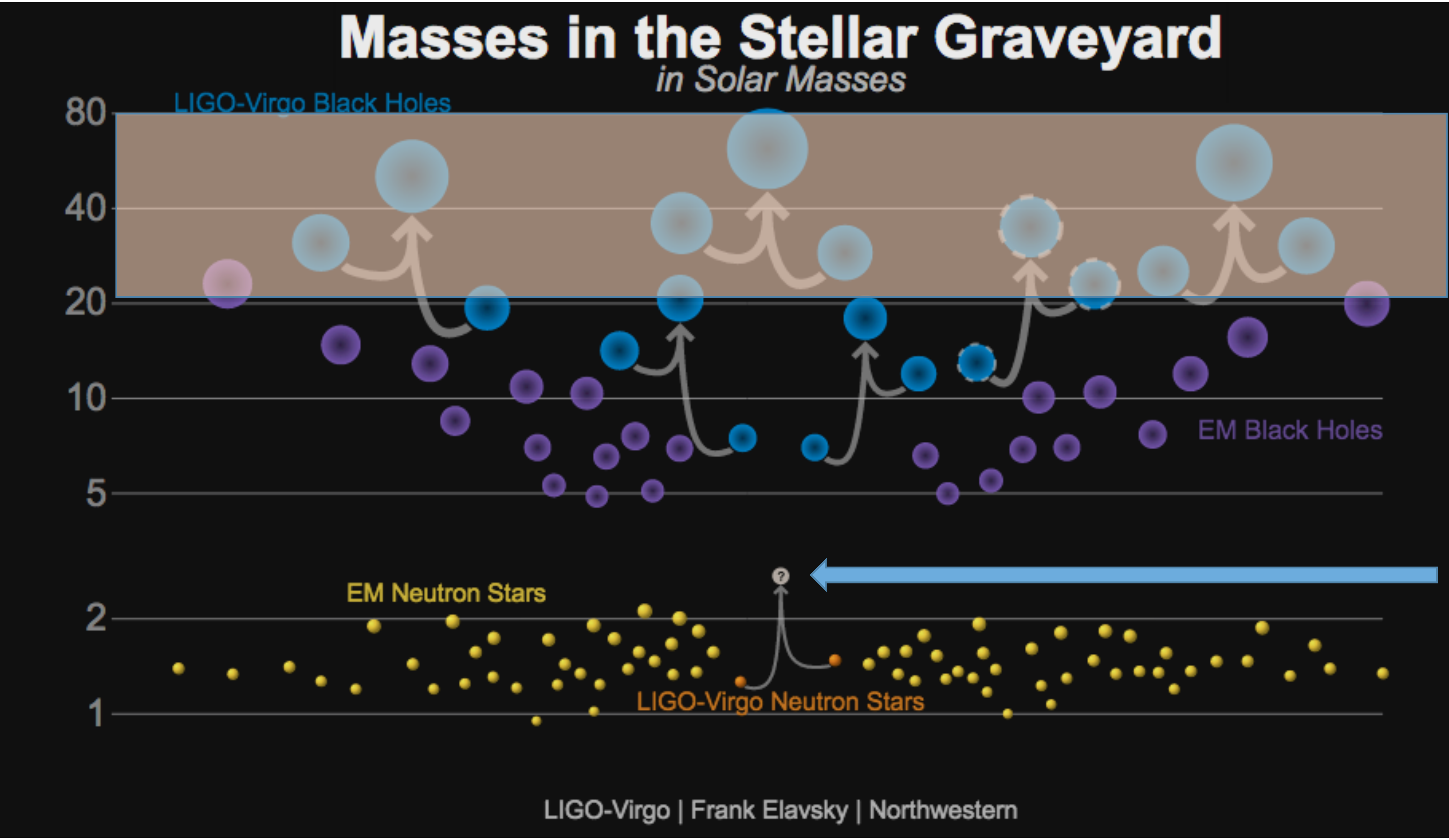
- ndamental questions in particle physics
  - Axions and ultralight particle through the evaluation of the consequences of new interactions, their impact on two bodies mechanics, in population and characterisics of BHs, NSs

  HEPP Inflation, additional interactions, dark matter

- obing the EOS of neutron stars **HEPP** Nuclear physics, quark-gluon plasma
- otic objects and phenomena (cosmic strings, exotic compact objects: boson stars, strange stars/gravastars, …)
- smology and Cosmography with GWs **HEPP** Cosmology
- curate Modelling of GW waveforms
- / models in alternative theory of gravitation **HEPP** Cosmology
- e population of compact objects discovered by GWs is the same measured by EM? Selection effects on BHs and NSs
- hat is the explosion mechanism in Supernovae? **HEPP** Nuclear physics
- hat is the history of SuperMassive black holes?
- / Stochastic Background? Probing the big bang? **HEPP** Cosmology, inflation
- ultimessenger Astronomy in 3G? **HEPP** Astroparticle, GRB, Neutrino Physics

Dark Matter?

GO-Virgo detections



New
famil
of BH

A BH
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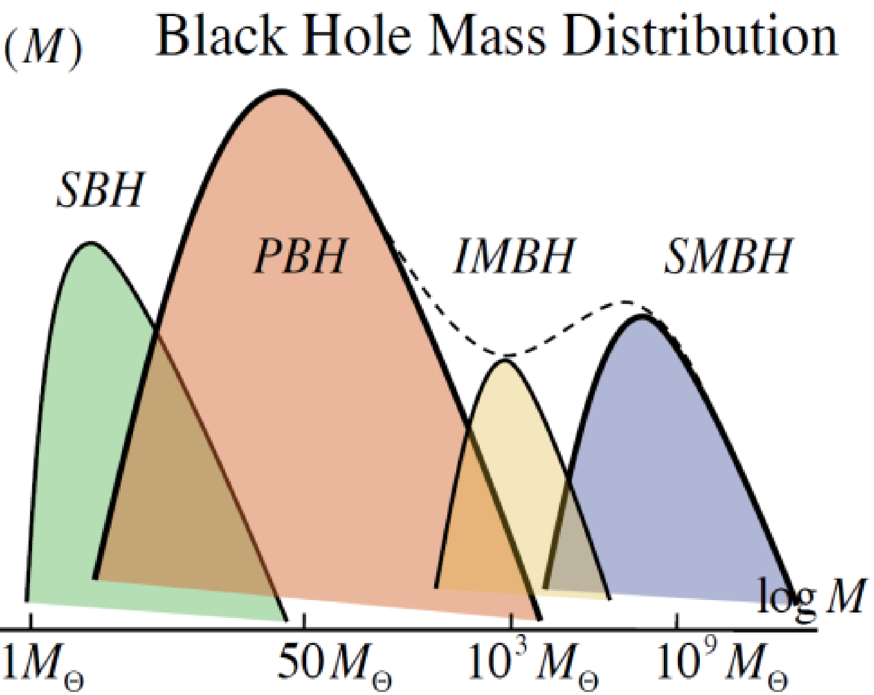
Primordial Black holes as Dark Matter (element?)

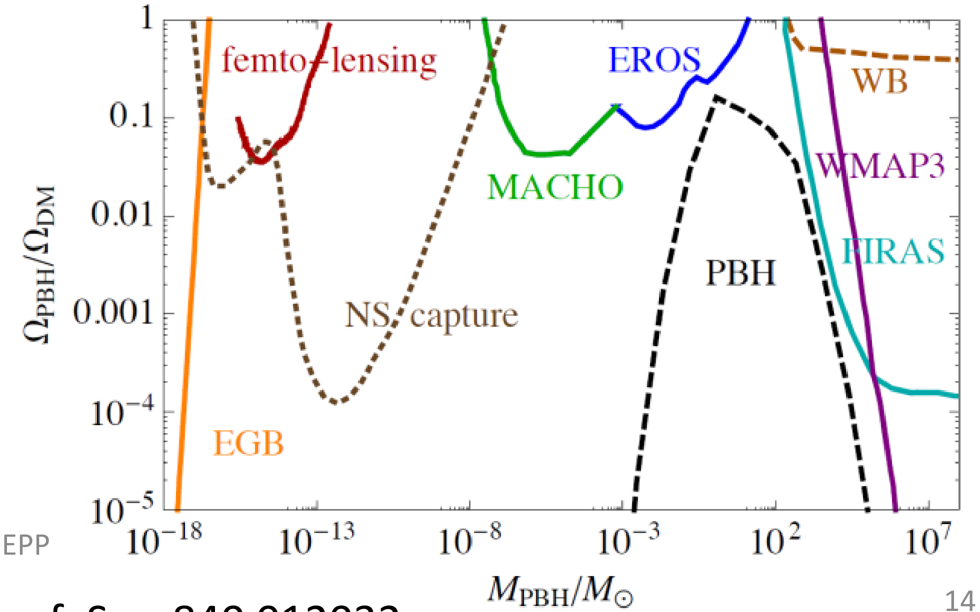
Gravitational dynamics of galaxies and clusters is indicating a mass excess in the galaxies halo

$T_{\mu\nu}^{WIMP}$ $T_{\mu\nu}^{axion}$

$$G_{\mu\nu} = \frac{8\pi G}{c^4}\left(T_{\mu\nu} + T_{\mu\nu}^{DM}\right)$$

$T_{\mu\nu}^{BH}$

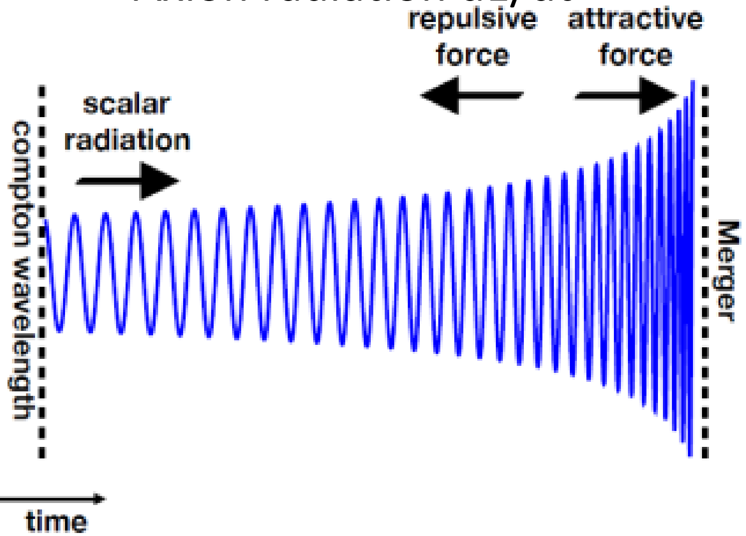




Juan García-Bellido 2017 J. Phys.: Conf. Ser. 840 012032

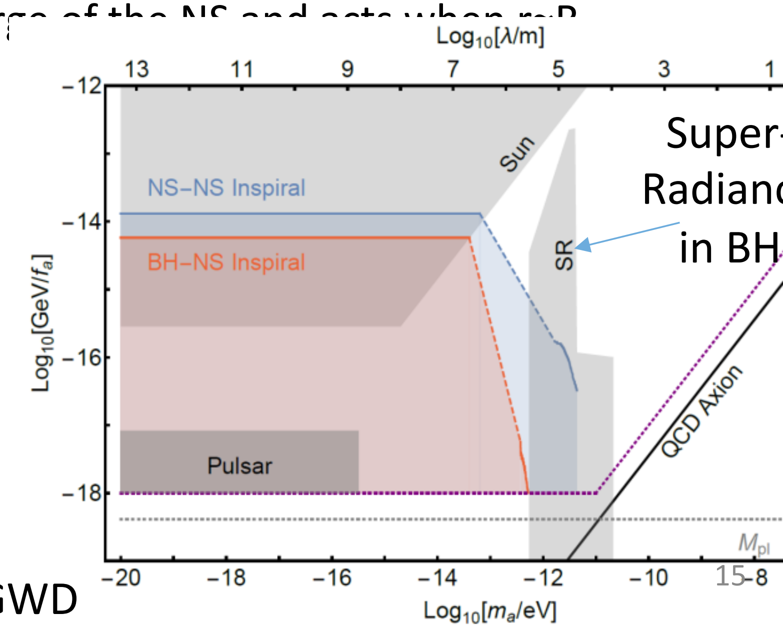
ions and GW

- he introduction of light scalar fields is a possible extension of the Particle standar odel
  - Axions could be a component of the dark matter or dark energy
  - Axions could provide an inflation mechanism
- hat GW could tell about Axions? BNS and spinning BH (Super-Radiance)
- xions, coupled to matter, can mediate new long range interactions between mpact bodies:
  - They modify the dynamics of the coalescence and merging of BNS through two mechanisms
    - Axion mediated force $\boldsymbol{F}=\frac{Q_1 Q_2}{4\pi r^2} e^{-r/\lambda_a}\, \hat{r}$ where $Q=\pm 4\pi(\pi f_a R_{NS})$ are the scalar charges of the NS
      - The force can be attractive or repulsive according to the scalar charg
    - Axion radiation dE/dt

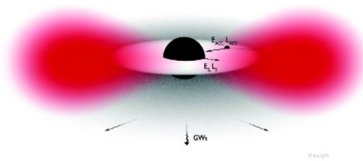


Junwu Huang et al.
arXiv:1807.02133v1

2G GWD



Black Hole Superradiance

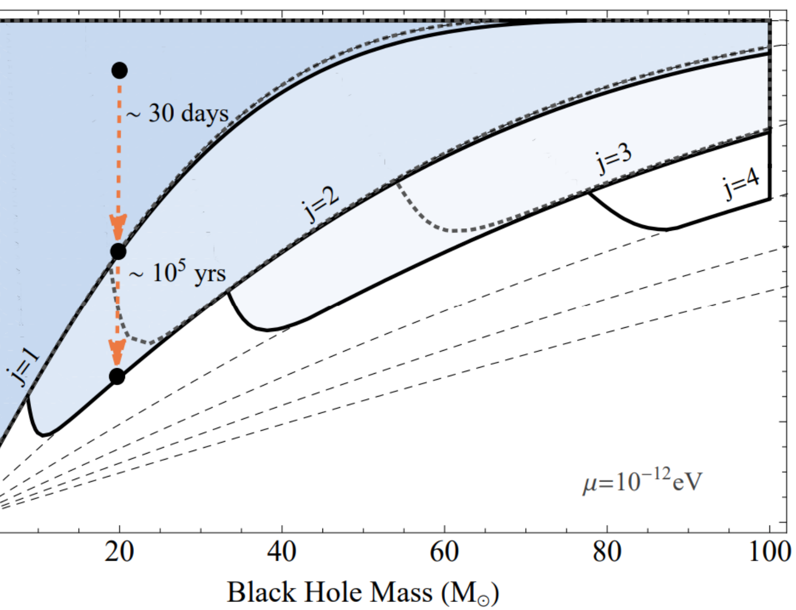


hen the Compton wavelength $\hbar/(m_s c)$ of the light bosons (axions) of mass m_s in a oud surrounding a black hole is comparable to the size of the BH ($R=2GM/c^2$), a ravitational atom" is formed

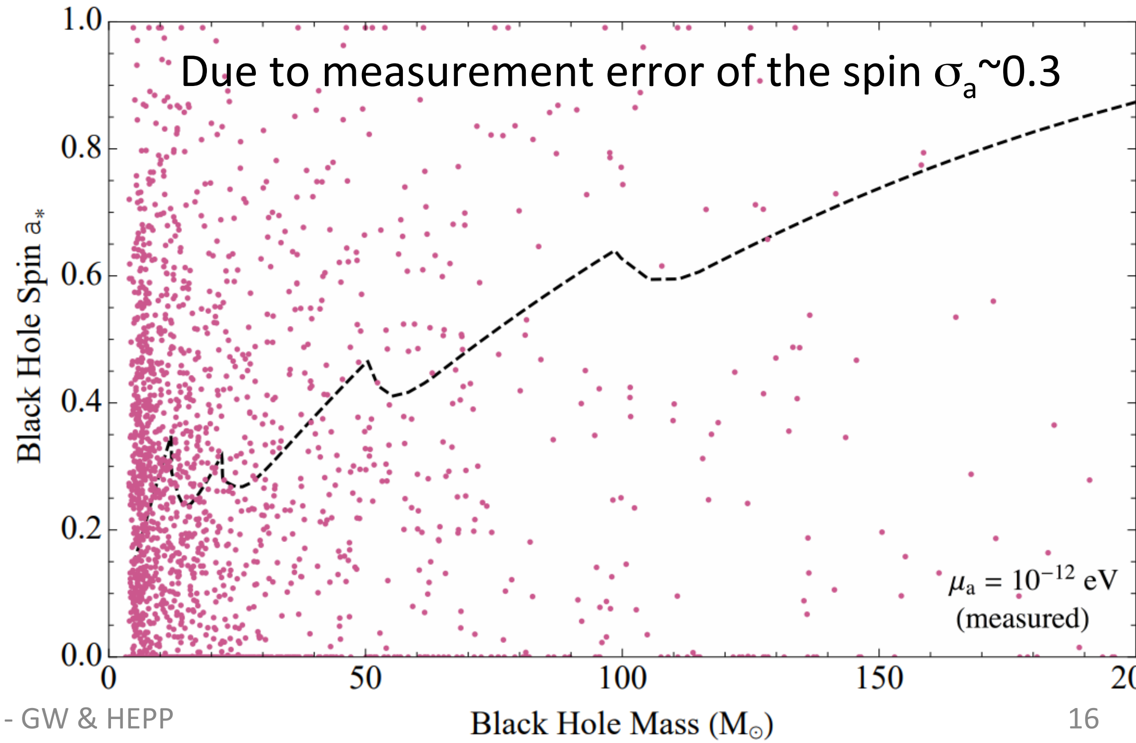
- The bosonic field trapped by its mass around the BH, under certain circumstances, can produce emissi (lasing) of a quasi-monochromatic GW extracting energy from the angular momentum of the BH

e emitted wave can be either detected directly or as stochastic background, but the m eresting approach is statistical

yakhtar, Masha et al. Phys.Rev. D96 (2017)



←bold vector, dotted scalar $\mu=10^{-12}$eV)



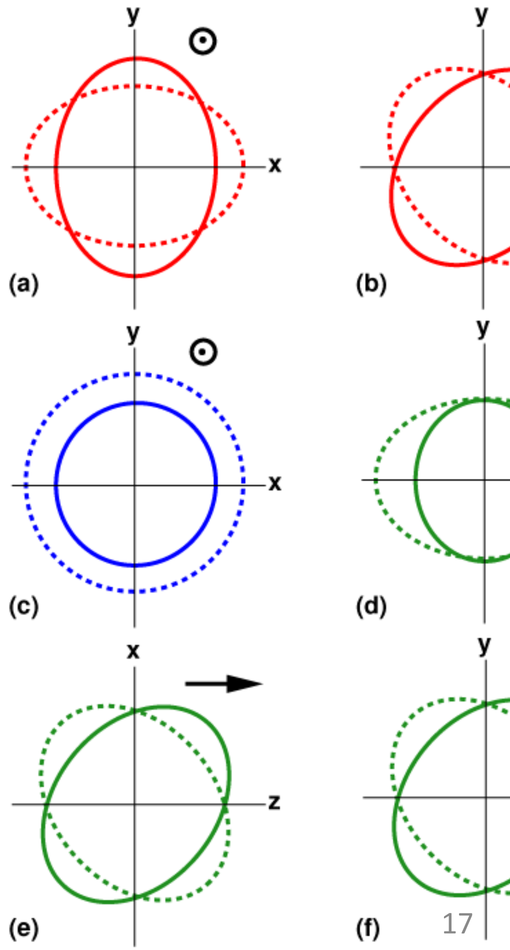
Alternative theories of Gravity

et go back to the Einstein Field Equation:

- Maybe it is possible to match the dynamics mimed by DM modifying the gravity (curvature)

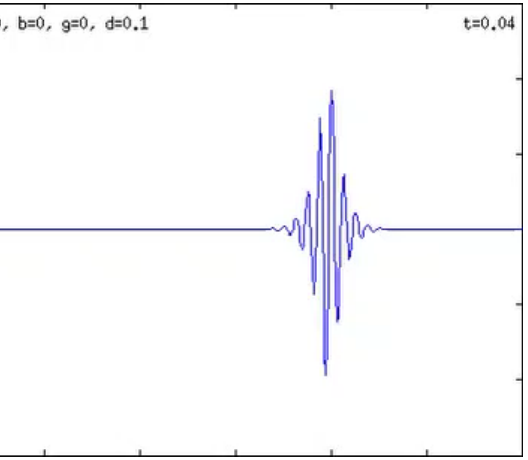
$$G_{\mu\nu} + G_{\mu\nu}{}' = \frac{8\pi G}{c^4} T_{\mu\nu}$$

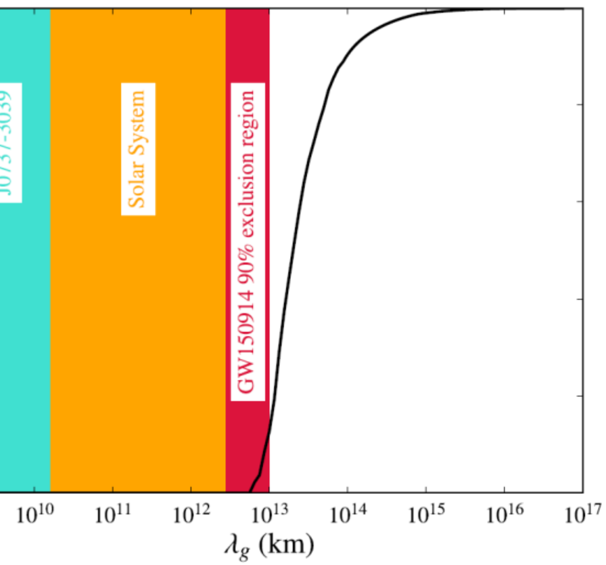
- Alternative theories of gravity; they could predict massive graviton, different propagation velocity of em and GW, extra polarisations of GW (2 in GR, up to 6 in modified gravity)
- Present and future GW detectors are setting stringent limits
  - GW170814:
    - Thanks to the presence of Virgo has been possible the evaluate the contribution of extra polarisations in the detected GW resulted strongly disfavoured



Is the Graviton massless?

the graviton has mass>0 the GW propagates slowly and with dispersion





- Dispersion relation: $E^2 = p^2c^2 + m_g^2c^4$
- $\lambda_g = h/(m_g c)$
- Thanks to **GW170104**, measured at about 3 billions of light years it is possible to set an upper limit:

$$\lambda_g > 1.6\times10^{13}\,km \Rightarrow \quad m_g < 7.7\times10^{-23}\,eV/c^2$$

Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update

γ (photon) $\qquad I(J^{PC}) = 0,1(1^{--})$

γ MASS

Results prior to 2008 are critiqued in GOLDHABER 10. All experimental results published prior to 2005 are summarized in detail by TU 05.

The following conversions are useful: 1 eV = 1.783×10^{-33} g = 1.957×10^{-6} m_e; $\lambda\!\!\!^{-}_C = (1.973 \times 10^{-7}$ m)$\times$(1 eV/m_γ).

VALUE (eV)	CL%	DOCUMENT ID	TECN	COMMENT
<1 × 10^{-18}		[1] RYUTOV 07		MHD of solar wind

ultimessenger Astronomy and Fundamental Physics

he beginning of the multimessenger astronomy, marked by GW170817
lowed several fundamental physics tests

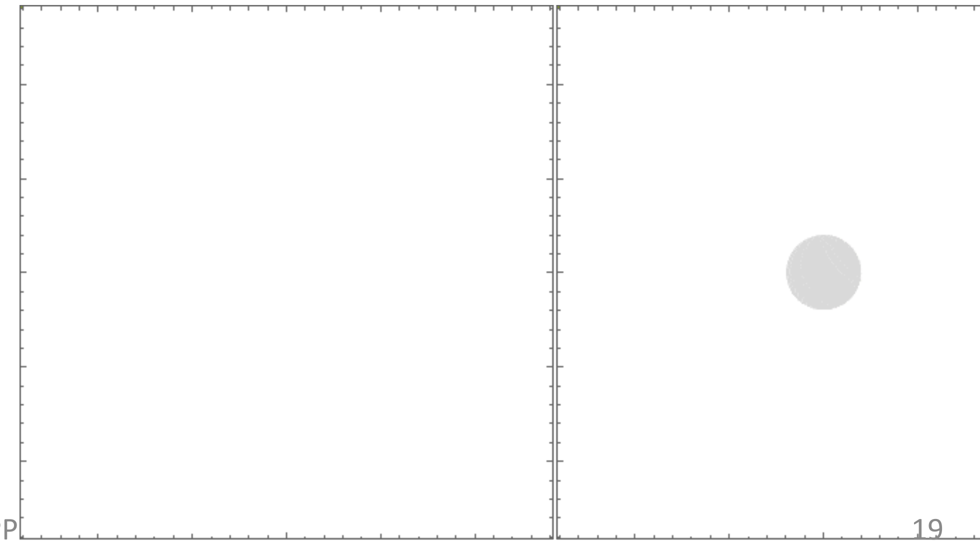
- Constrain the difference of speed between γ and GW: $-3\times10^{-15} \leq \frac{v_{GW} - v_{\gamma}}{v_{\gamma}} \leq 7\times10^{-16}$
- Test the equivalence principle and discard families (tensor-scalar) of alternative theo of gravity
  - Shapiro effect predicts that the propagation time of massless particles in curved spacetime, i.e., through gravitational fields, is slightly increased with respect to the flat spacetime case:

$$\delta t_{\mathrm{S}} = -\frac{1+\gamma}{c^3}\int_{\mathbf{r}_\mathrm{e}}^{\mathbf{r}_\mathrm{o}} U(\mathbf{r}(l))dl,$$

servation point
ission point
gravitational
ootential

$$-1.2\times10^{-6} \leq \gamma_{\mathrm{GW}} - \gamma_{\mathrm{EM}} \leq 2.6\times10^{-7}$$

factor γ parametrises the departure from the
tein General Relativity where $\gamma\downarrow GW =$
$EM = 1$



Dark Energy and Dark Matter after GW170817

0817 had consequences for our understanding of Dark Energy and Dark Matter

GWs: many models of modified gravity ruled out!

	Viable after GW170817 (c_g=c)	Not Viable after GW170817 (c_g≠c)
Horndeski ↓	General Relativity	Quartic/quintic Galileon
	Quintessence/K-essence	"Fab-Four"
	K-mouflage	de Sitter Horndeski
	Brans-Dicke/f(R)	$G_{\mu\nu}\phi^{;\mu}\phi^{;\nu}$, Gauss-Bonnet
Beyond H. ↓	DHOST with A_1=0=B_i=G_5	DHOST with A_1≠0 or B_i≠0 or G_5≠0
	Derivative Conformal	Quintic GLPV

Also, e.g.,
- Massive gravity

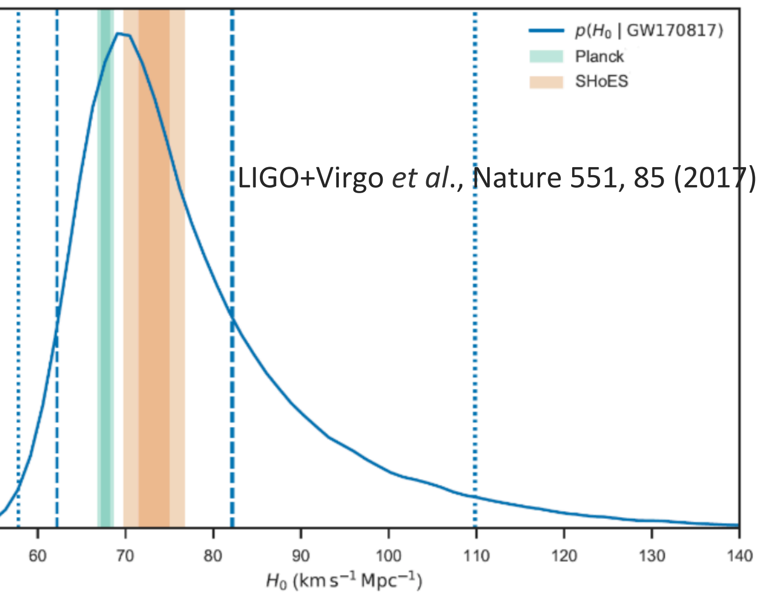
Also strongly affected:
- Vector Dark Energy
- Einstein Aether theories
- Some sectors of Horava gravity
- TeVeS
- MOND-like theories
- Generalized PROCA theories

See, e.g., Ezquiaga & Zumalacarregui '17; Baker et al. '17; Creminelli & Vernizzi '17

Nicola Bartolo, private communi

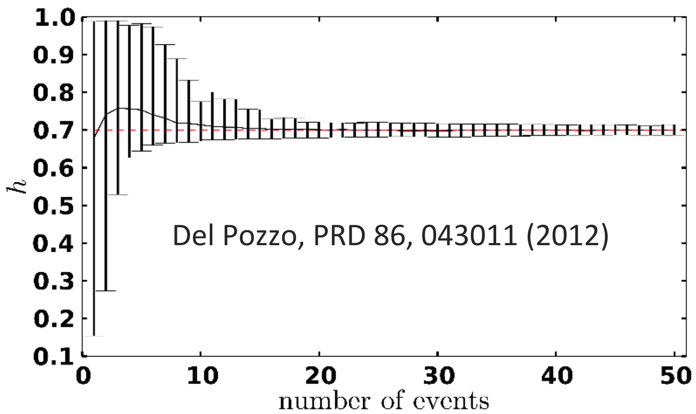
Cosmology with GW

- W by coalescence of compact bodies are standard ~~candles~~ sirens
- W170817 has been the first taste of the potential of the multimessenger tronomy in cosmology:
  - Measure of the Hubble constant with an independent method $H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,M}$

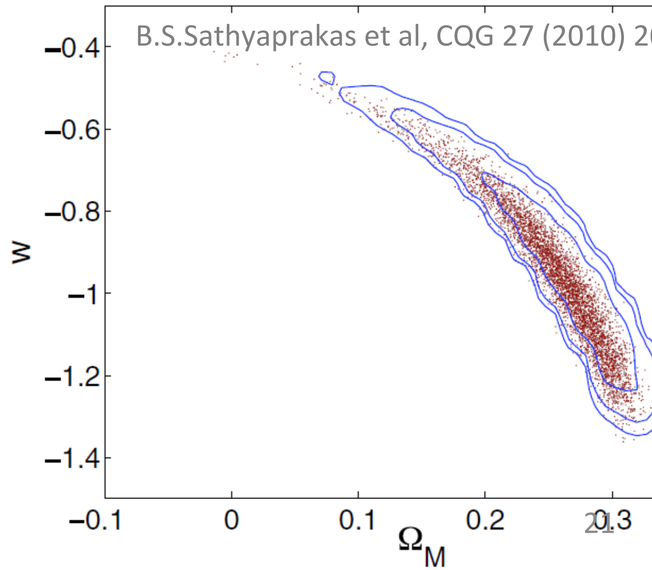


LIGO+Virgo *et al.*, Nature 551, 85 (2017)

- ET will reveal thousands of BNS coalescence:
  - Test of the cosmological model



Del Pozzo, PRD 86, 043011 (2012)



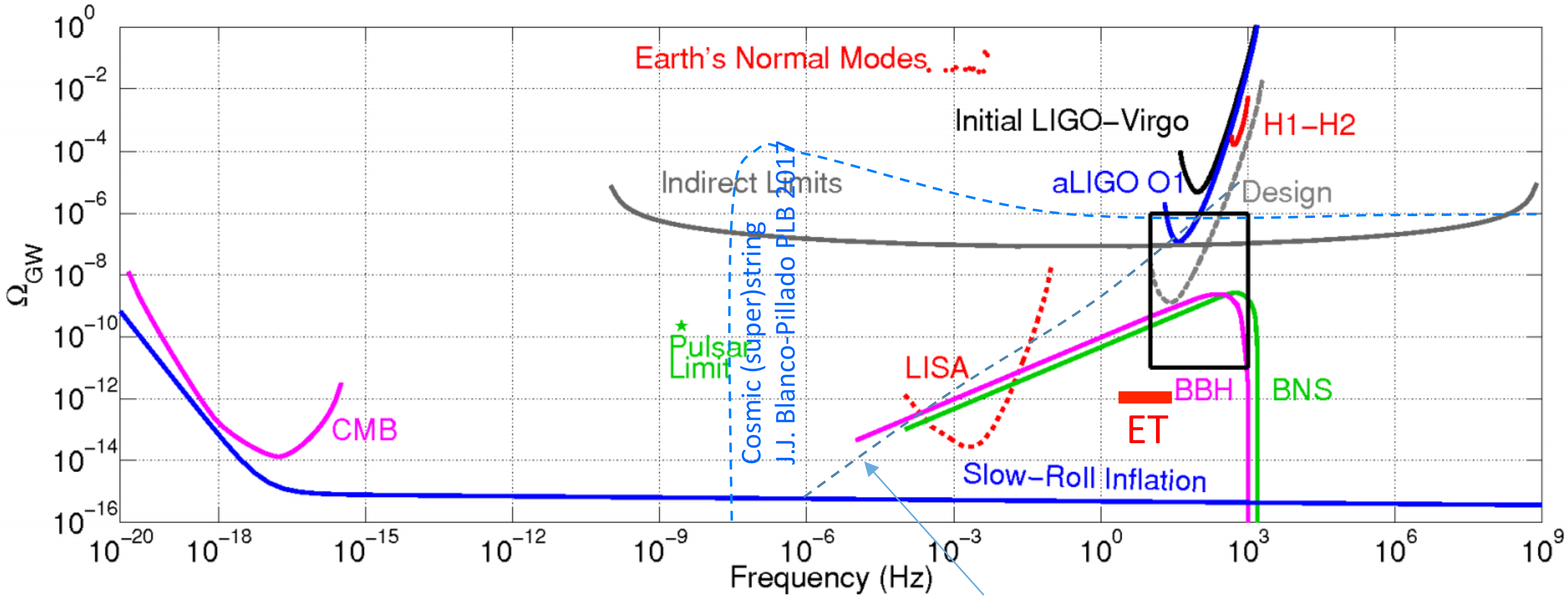
B.S.Sathyaprakas et al, CQG 27 (2010) 2

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

GW Stochastic Background and inflation

flation, reheating, preheating models could be distinguishible in the GW stochastich ckground in case of some blue-shift mechanism

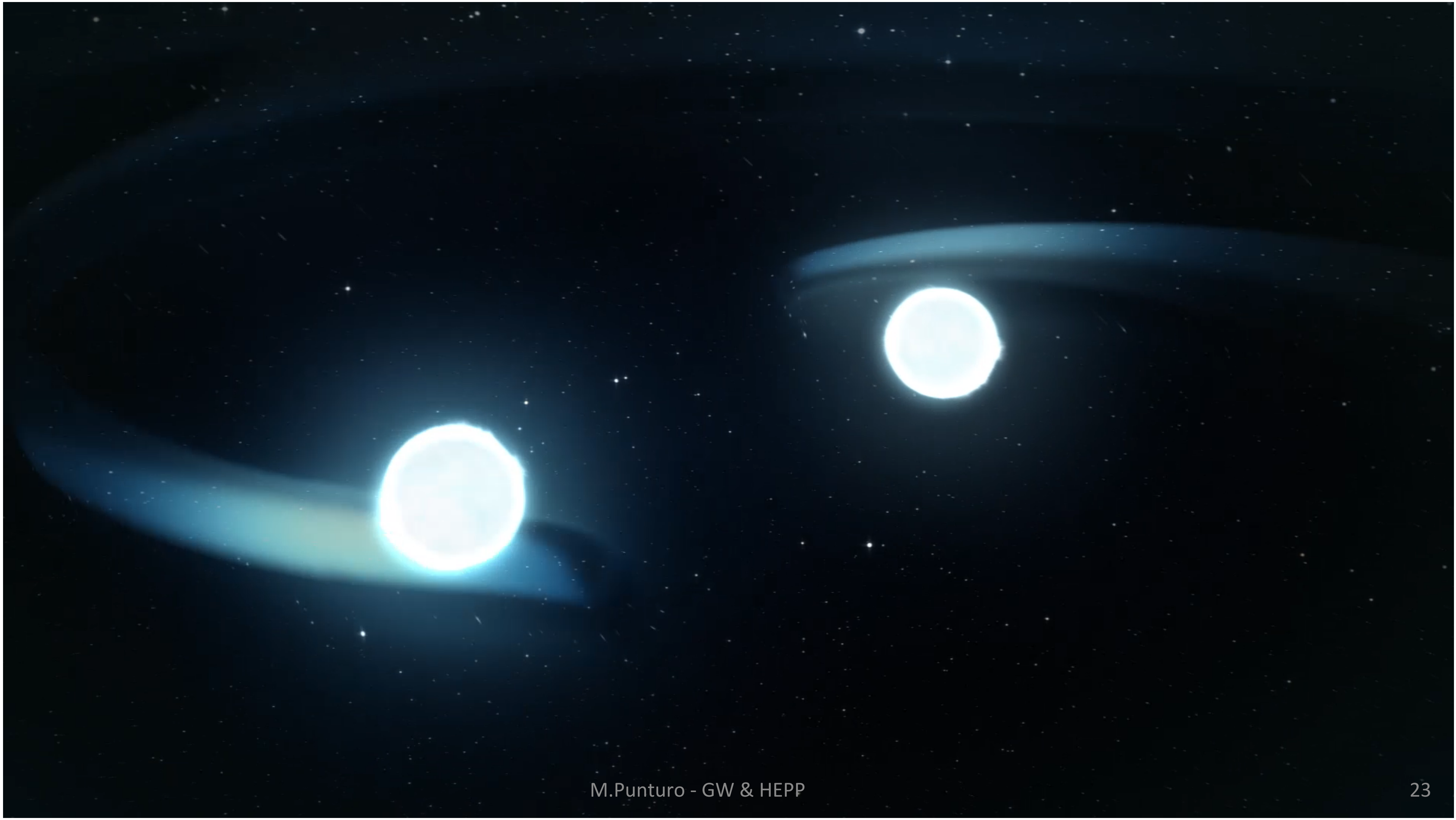
- information on: new additional degrees of freedom, interactions and/or new symmetry patterns underlying high energy physics of early universe

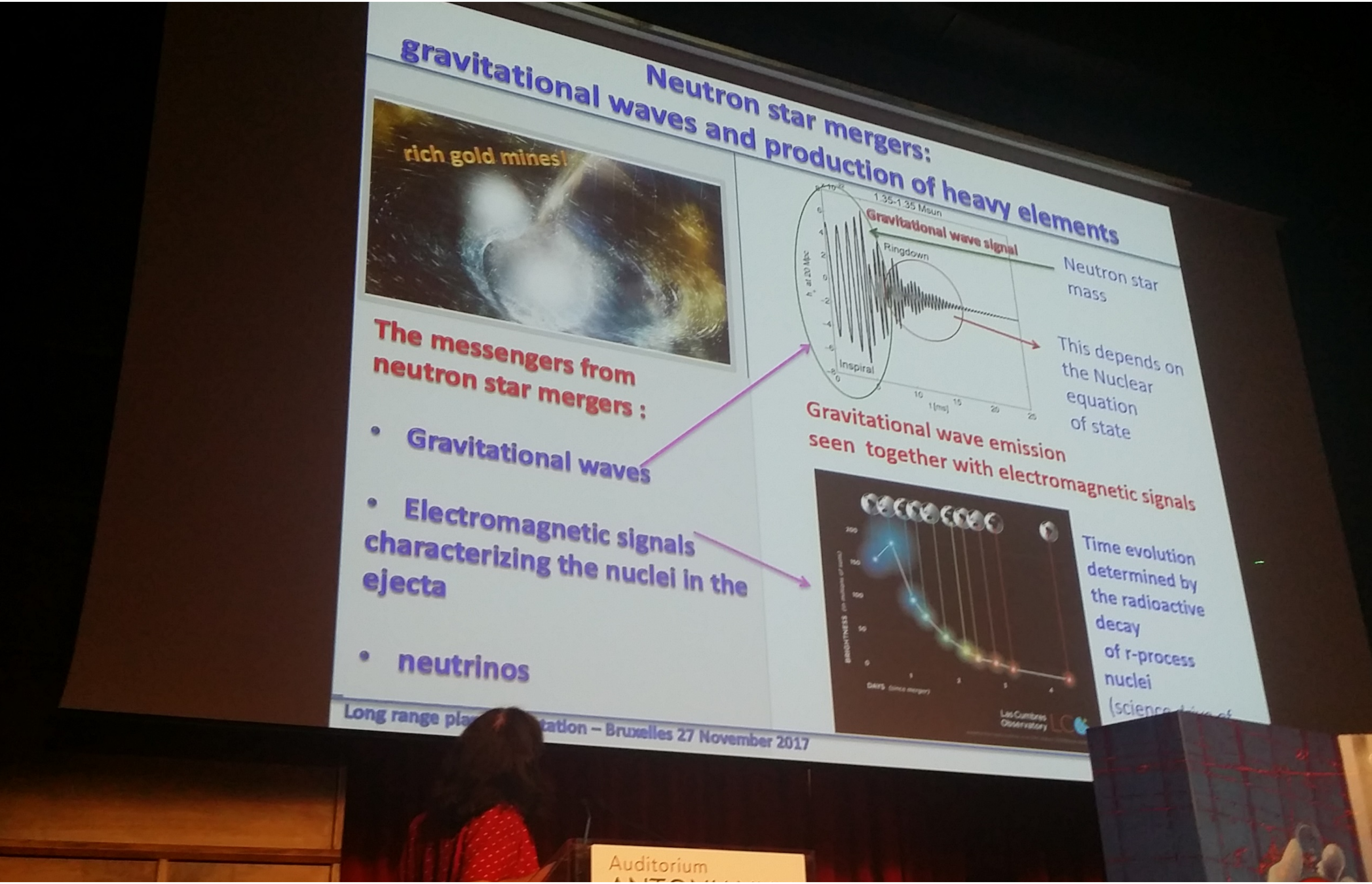


ot, B.P. et al, Phys Rev Lett 118 (12), 2017, 121101

Axion inflation
(see for example V. Domcke arXiv:1704.03464)

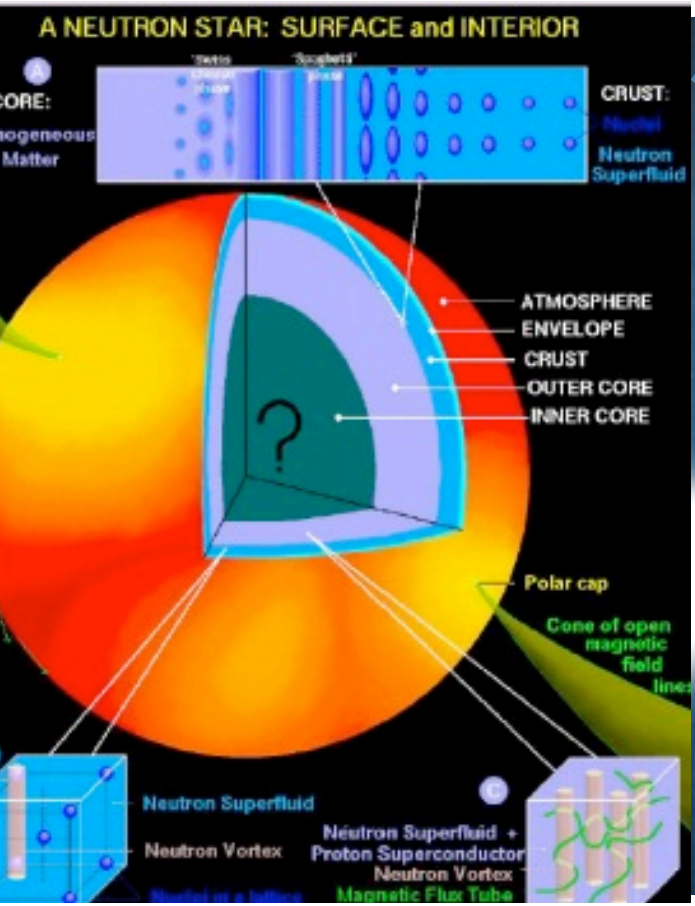
Our Collider

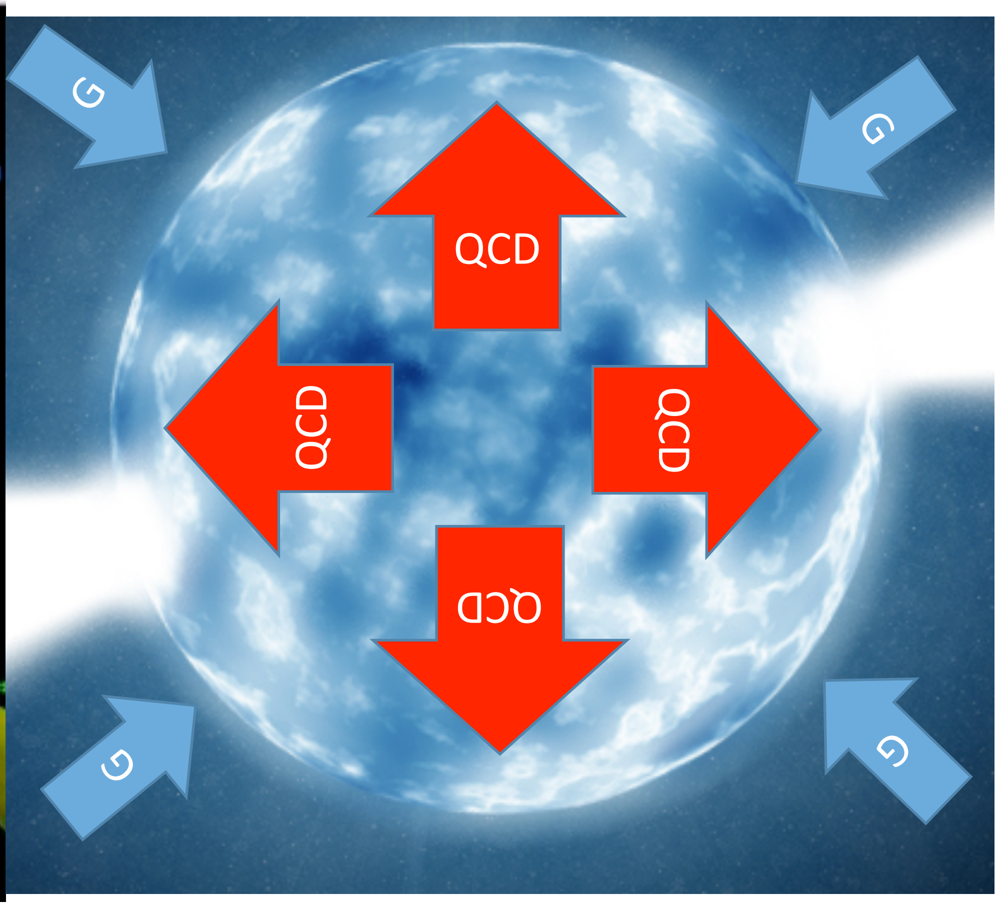


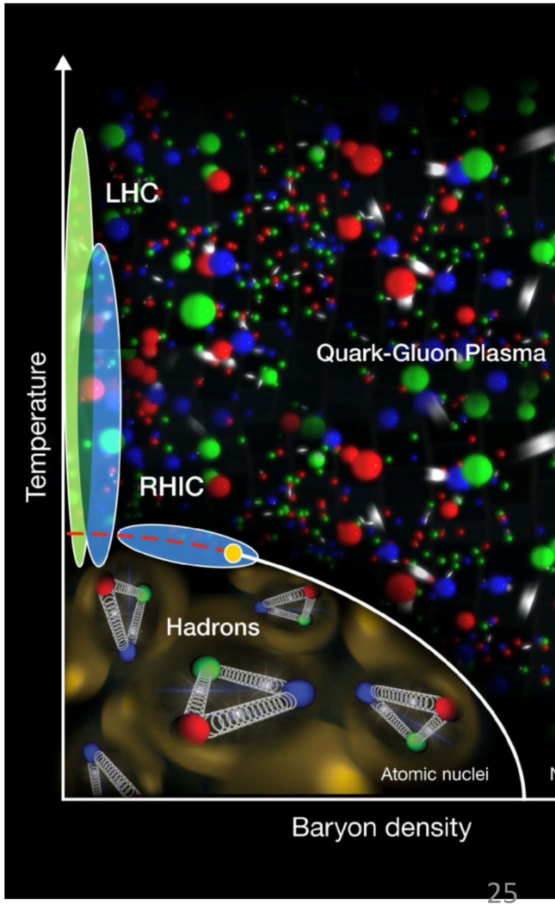

Neutron star mergers:
gravitational waves and production of heavy elements
rich gold mines!
The messengers from neutron star mergers :
• Gravitational waves
• Electromagnetic signals characterizing the nuclei in the ejecta
• neutrinos
1.35-1.35 Msun
Gravitational wave signal
Ringdown
Inspiral
Neutron star mass
This depends on the Nuclear equation of state
Gravitational wave emission seen together with electromagnetic signals
Time evolution determined by the radioactive decay of r-process nuclei
Las Cumbres Observatory
tation – Bruxelles 27 November 2017
Auditorium

Neutron Star is a nuclear physics lab

- eutron stars are an extreme laboratory for nuclear physics
  - The external crust is a Coulomb Crystal of progressively more neutron-reach nuclei
  - The core is a Fermi liquid of uniform neutron-rich matter ("Exotic phases"? Quark-Gluon plas



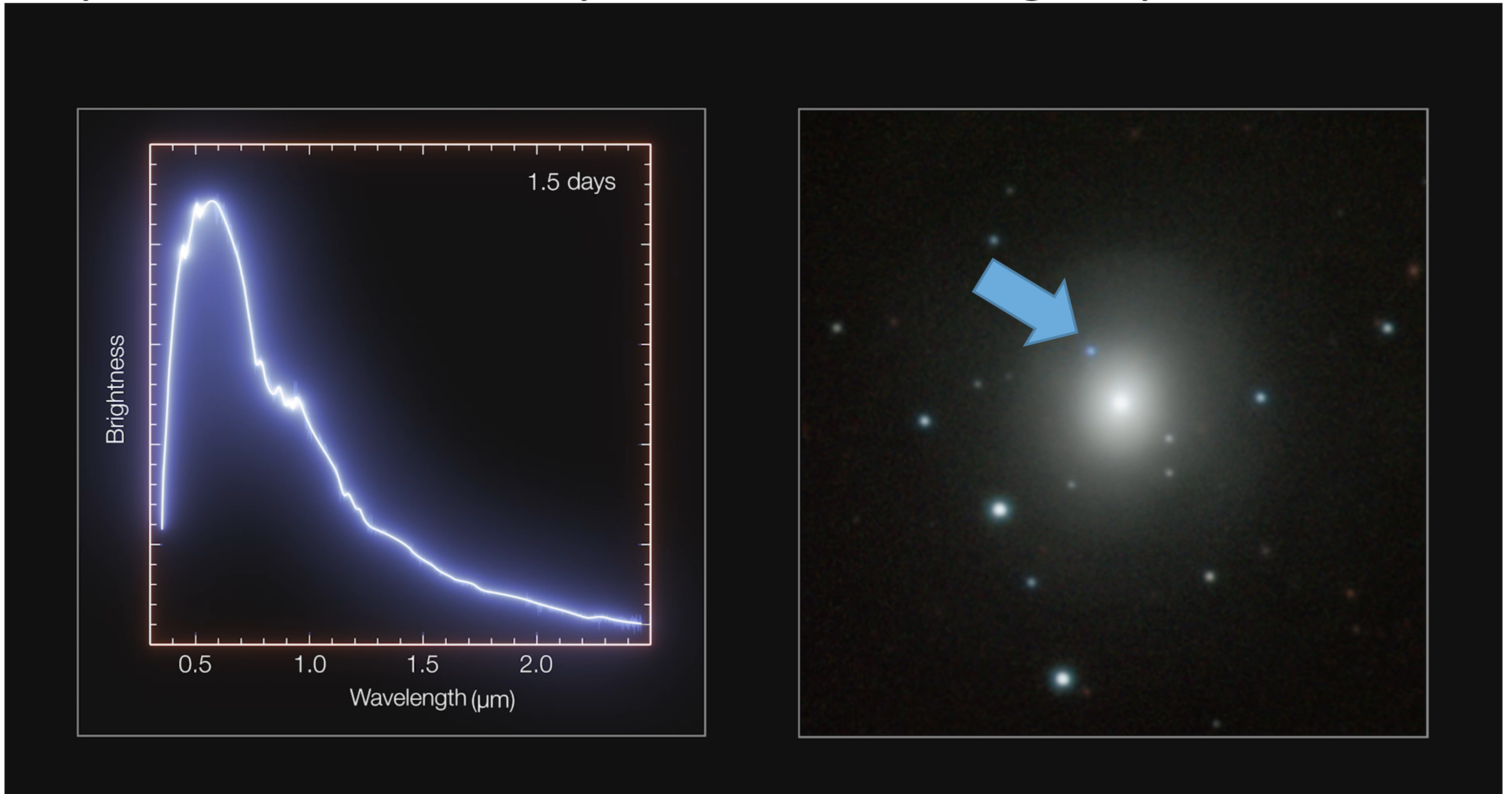




GW170817: Nuclear Physics “experiment”

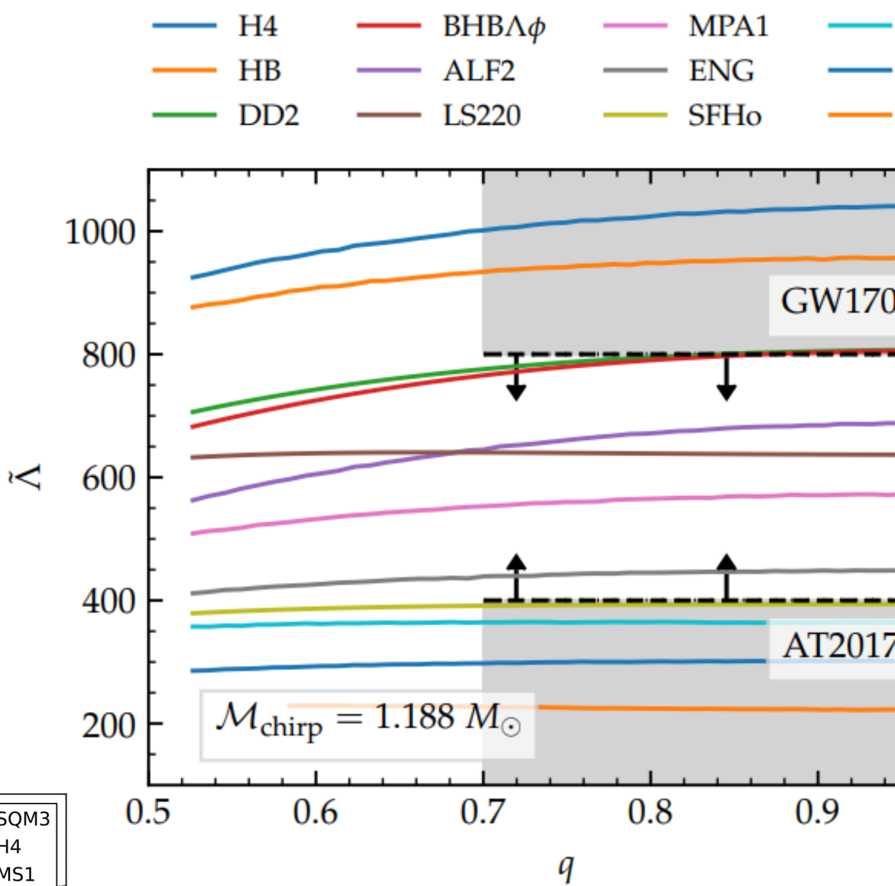
e collision of two NS in GW170817 has been a complex nuclear physics
periment, where it has been possible

- The accurate measure the mass and radius of the NS through the tidal deformation of the star → Constrain the EOS
- To observe the production of heavy elements through r-processes



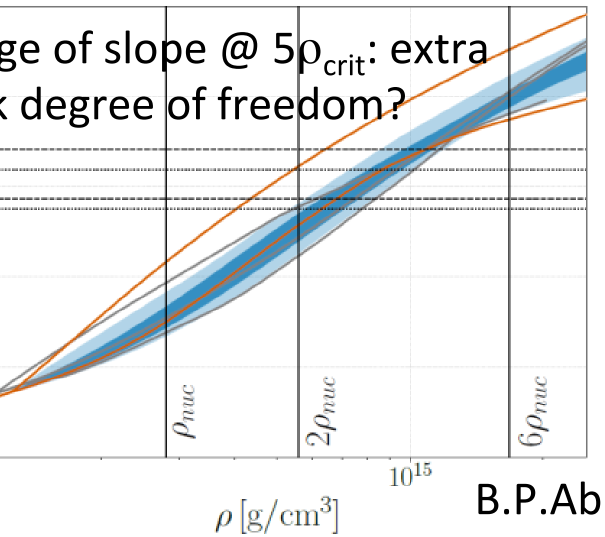
Constraining the NS EOS

- Measuring the tidal deformation through the dephasing in the GW signal is possible to constrain the EOS of the NS
- Adding the em information helps to impose more stringent constrain
  - Knowing the EOS it is possible to describe the status of the matter in the over-critical pressure condition in the NS

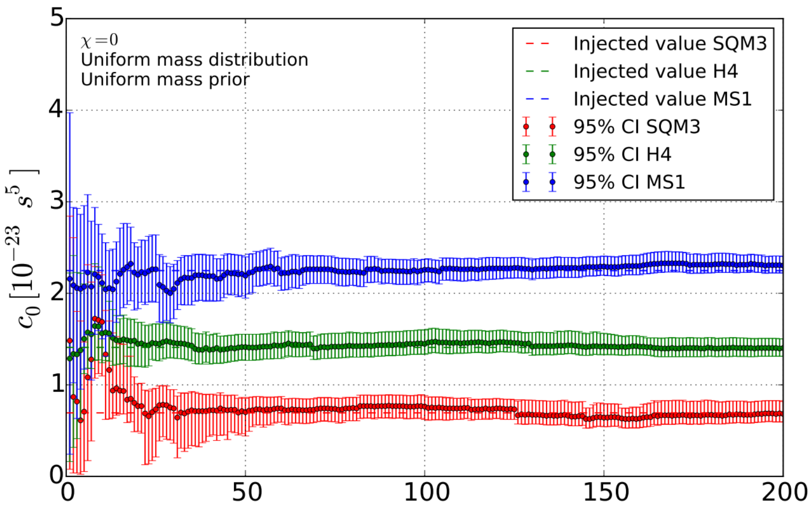


D. Radice et al. (APJ Letters, 852, 2, 20

ge of slope @ 5ρ_{crit}: extra
k degree of freedom?



B.P.Abbott et al., arXiv:1805.11581v1



M. Agathos et al, Phys. Rev. D 92, 023012 (2015)

Technologies HEPP → GW

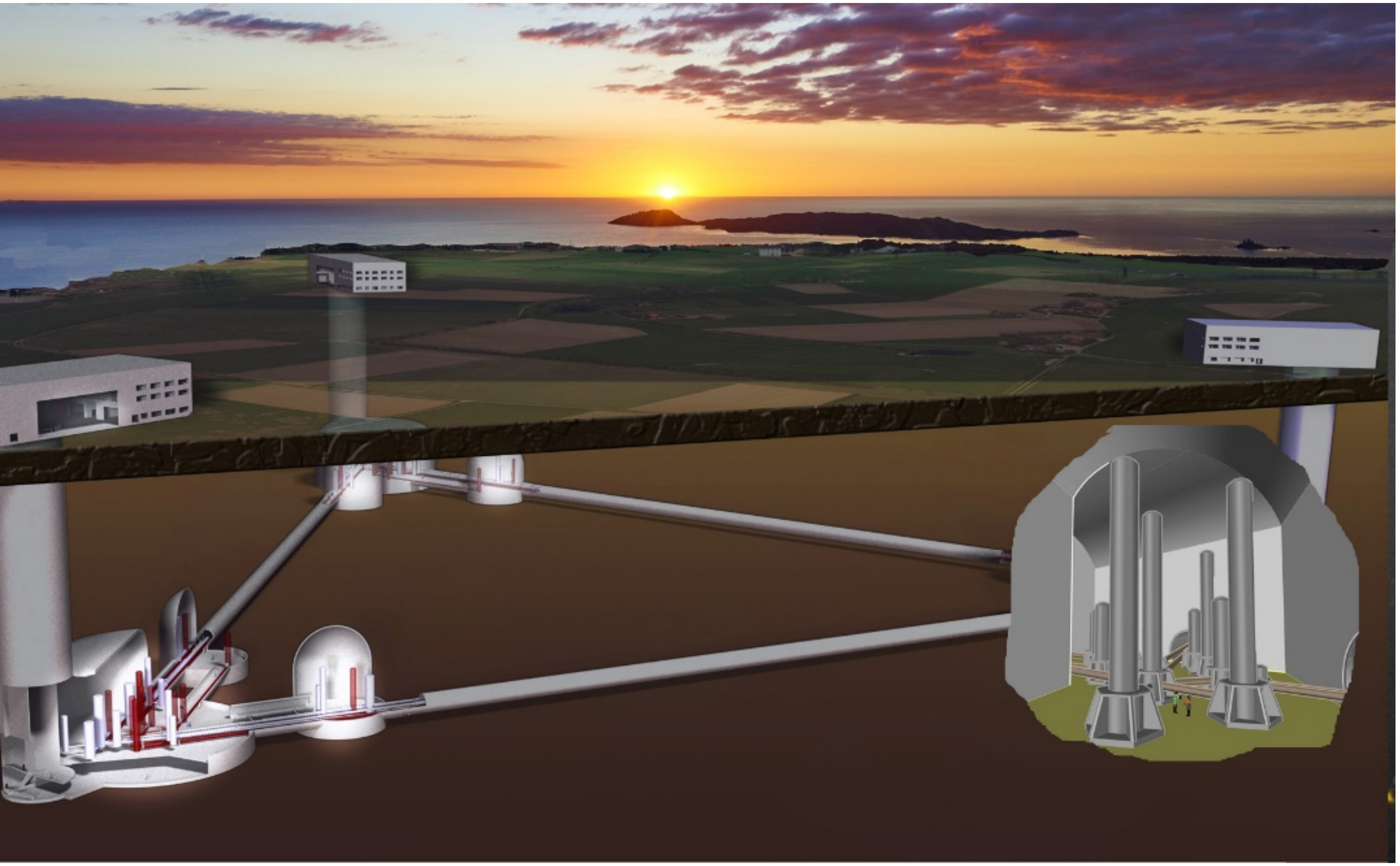
urrent and future GW detectors can hugely benefit of the technologies eveloped at CERN for HEPP

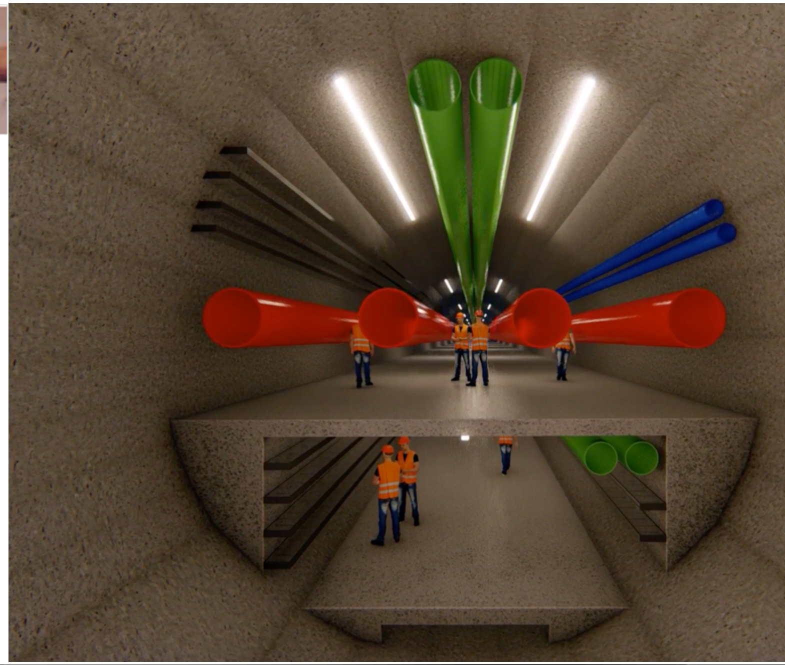
T needs from CERN/HEPP:

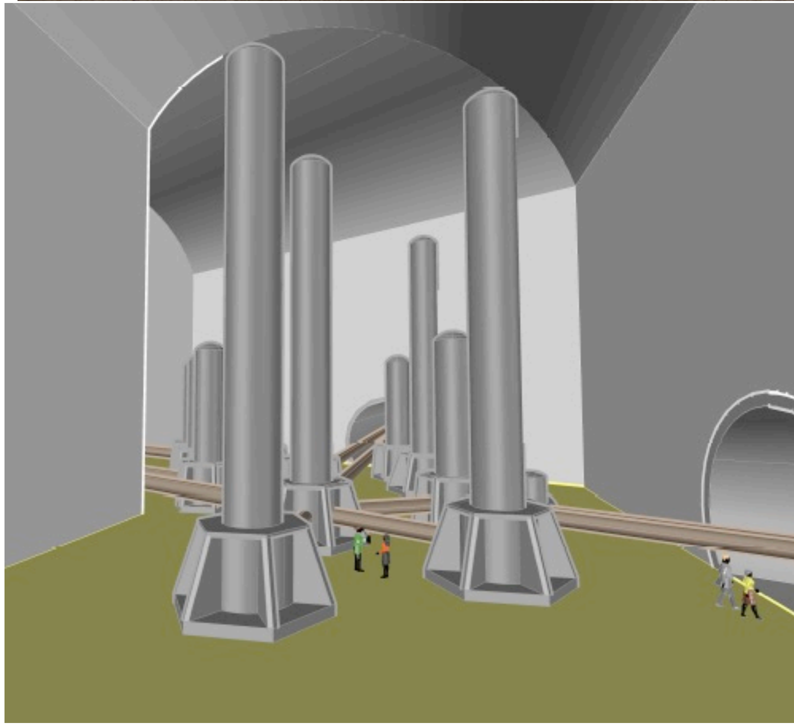
- Underground infrastructures
  - Civil Engineering
- Cryogenics (~10K)
  - Large, underground plants, low noise
    - Controls, Safety, handling
- Vacuum (<10^{-10} mbar)
  - ET, the largest volume under vacuum
    - Controls, safety, handling
- Material and surface science
  - Special materials, surface treatments
- Electronics/Data acquisition
  - Monitoring, timing, high rate DAQ
- Computing
  - Data handling, computing methods, GRID, GPUs

ET infrastructure

' will be a complex research infrastructure that
eed the expertise developed at CERN and at
e LNGS







Cryogenics

- We need to cool down at 10K:
  - large masses (300kg)
  - without touching them in the operative phase
  - Having a cooling time relatively short (few days)
  - Without introducing vibration
  - Without polluting the surfaces
  - Having an “open” cryostat
- In an underground facility
  - Safety issues
  - Accessibility issues

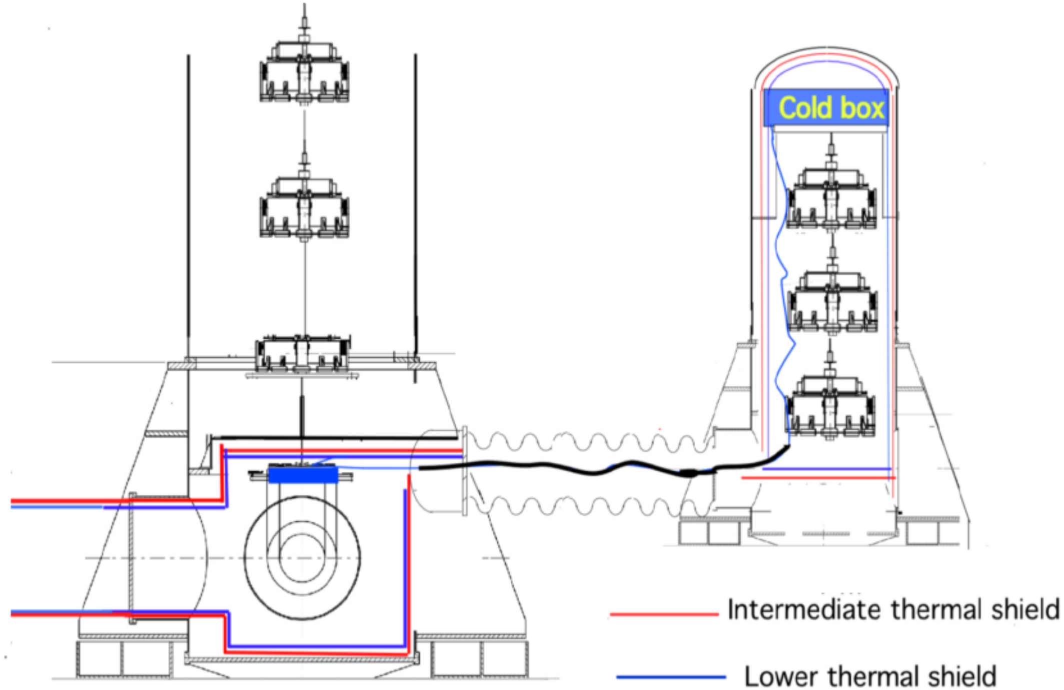


Figure 96: Scheme of the cryostats needed for cooling a test-mass of the LF-interferometer.

Vacuum and Material/Surface science

Vacuum

- ET will be the largest volume under vacuum
- The cost of the vacuum plant will one of the cost driver
  - New solutions?
- Low noise vacuum systems
- Low contamination pumps

Material/Surface science

- Coatings for the mirrors
- Ionization issues
- Surface treatments for the apparatuses under vacuum

Electronics/DAQ - Computing

Electronics/DAQ

- HEPP experience in handling large quantity of experimental data
- Low noise digital and analog electronics:
  - Modulation
  - Timing
  - Actuation and sensing
  - Photosensing
- DAQ

Computing

- HTC and HPC paradigms
  - GPUs
- Data management
  - Rucio, Dirac, …
  - Data lake
- GRID, Cloud, Virtualisation
- Data preservation

overnance: HEPP → GW

/e want to realise a global network of 3G observatories

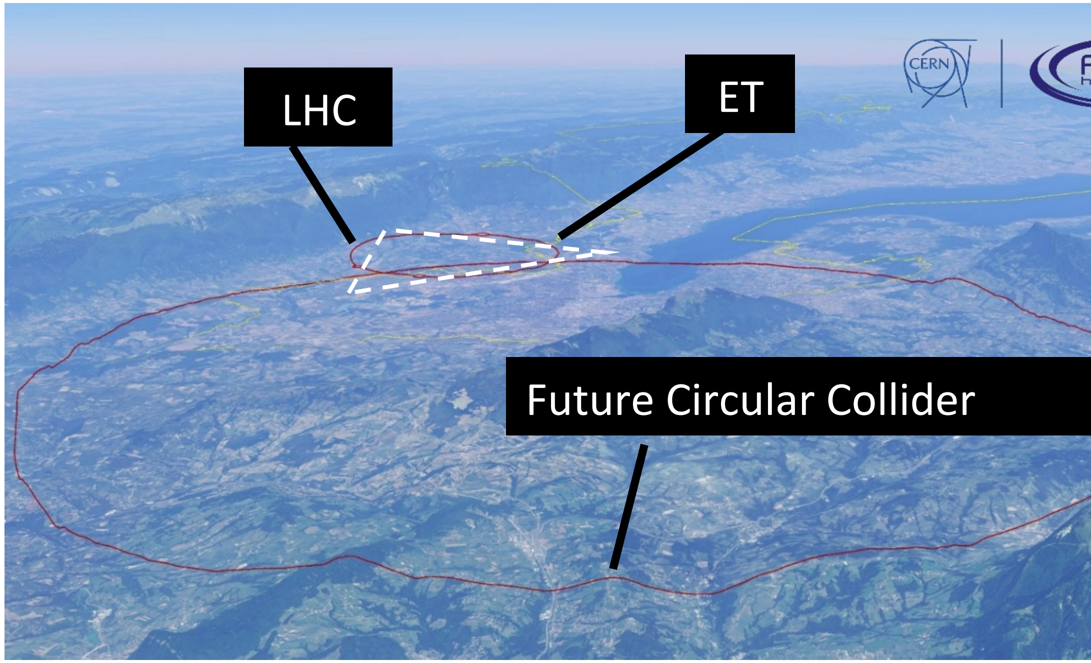
nstein Telescope will be the pioneer of this global research nfrastructure

urrently we are organised as a “collaboration of collaborations”, ut we are aiming to a more structured governance:

- HEPP community is an example to emulate and CERN could be more thar a model
  - Synergies in science and technologies are evident
  - A direct involvement of CERN in ET is a valid option to be investigated

onclusions

- the CERN/HEPP roadmap GWs have a ear scientific role
  - Many synergies to be explored by scientists of both the disciplines
    - That should appear in the CERN roadmap: devote a chapter/paragraph to this subject
- EPP technologies are of extreme interest nd importance for the future of GW, pecially for ET
  - An engagement of the HEPP community in GW research is more than welcome: it is necessary!
    - Moral suasion in HEPP to approach GW
    - Stimulate opportunities for joint developments
      - Attract initiative?
- overnance model developed at CERN could e an example for ET and the global network 3G observatory
  - The interest of CERN on this subject needs to be further investigated and stimulated
    - Propose a direct involvement of CERN in the 3G governance



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