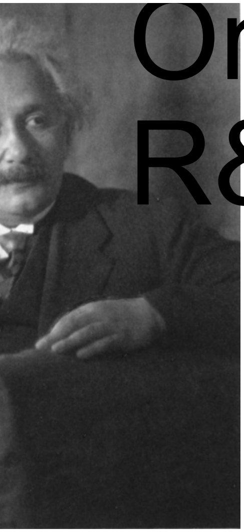
La frontiera delle onde gravitazionali: Einstein Telescope

Michele Punturo

INFN Perugia

per le collaborazioni Virgo ed ET INFN

One century of research, study and R&D



R

1937 equazione corretta GW

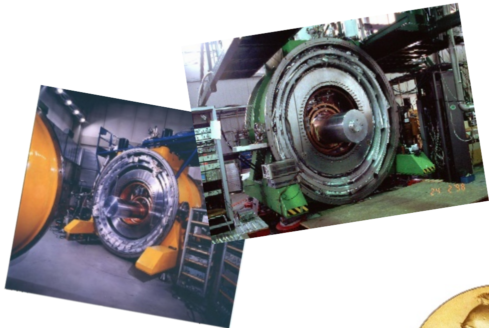
1918

V

1957 GW trasportano energia

1966 Inizio era sperimentale con la barra risonante di J.Weber

1974 Osservazione binaria pulsar PSR B1913+16 (premio nobel 1993 Hulse & Taylor)



’80-’90: Barre risonanti criogeniche

1986: B.Schutz (standard sirens), PPN templates …

1993

1994: Approva-zione sigla INFN Virgo

1999+ Templates: EOB, Numerical relativity

1999+ Inizio operazioni interferometri LIGO e Virgo (+4y)

2015: Inizio operazione aLIGO: Scoperta GW

Final targ

2017 Inizio operazioni Advanced Virgo: GW da coalescenza BNS

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

How it has been possible?

2015-2017: Sc… n

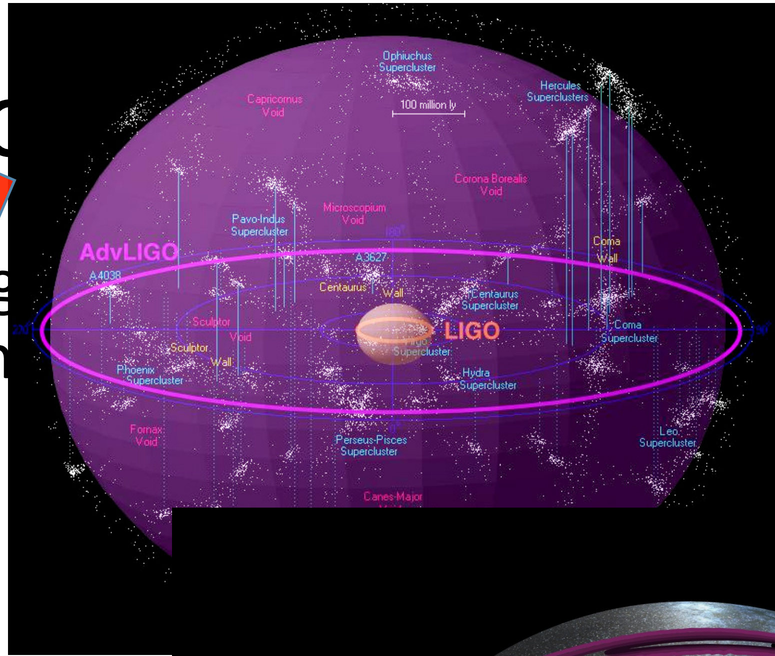
he detection of GW has been a huge … esult of a century of efforts, but actually it is the begin… servation of the Universe

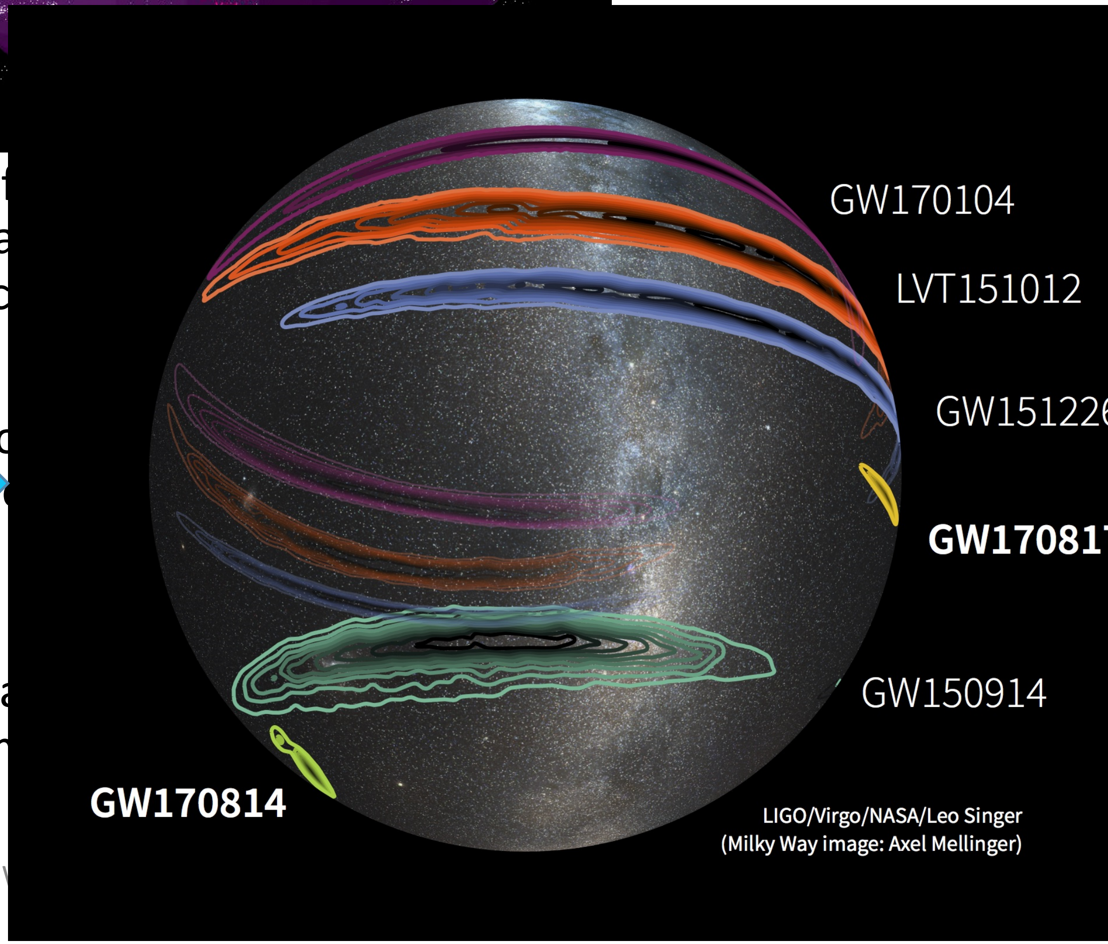
New generation of detectors with largely improved sensitivity

he discoveries announced by LIGO …

- GW150914: LIGO VIRGO
  - the first direct detection of GW. Confirmation of … Confirmation of the existence of stellar mass bla… gravitation in strong field and of the astrophysic…
- GW170814: LIGO VIRGO
  - The first detection in a network of 3 GW detecto… The first test of GW polarisation. The birth of th… thanks to the localisation capability.
- GW170817: LIGO VIRGO
  - The first detection of the GW emitted by the coa… alternative theories of gravity. The birth of the m…

3 detectors with comparable sensitivity





Network of GW detectors

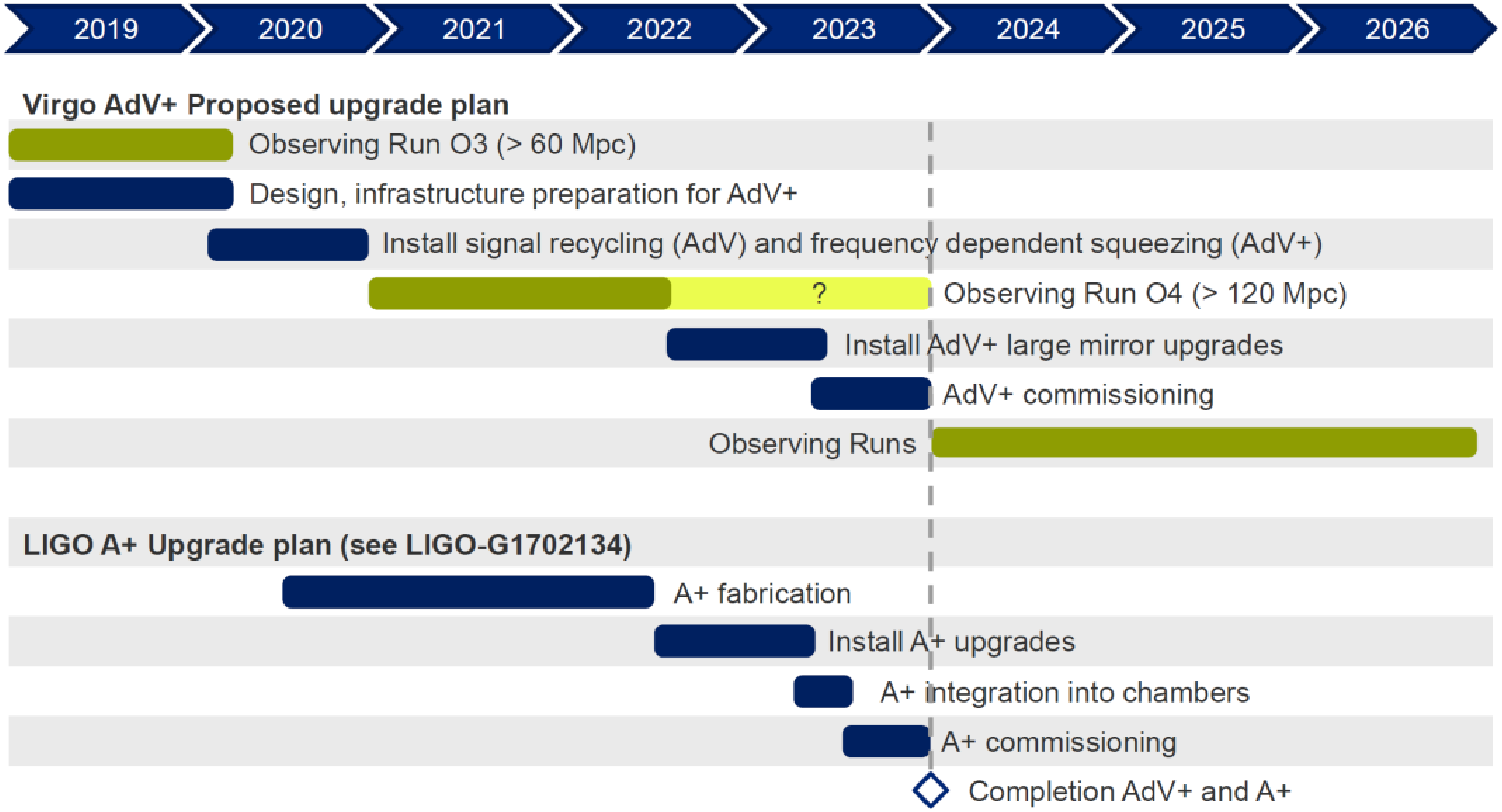
Scientific Collaboration:
- 1263 collaborators (including GEO)
- 20 countries
- 3 computing centres
- ~1.5 G$ of total investment

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

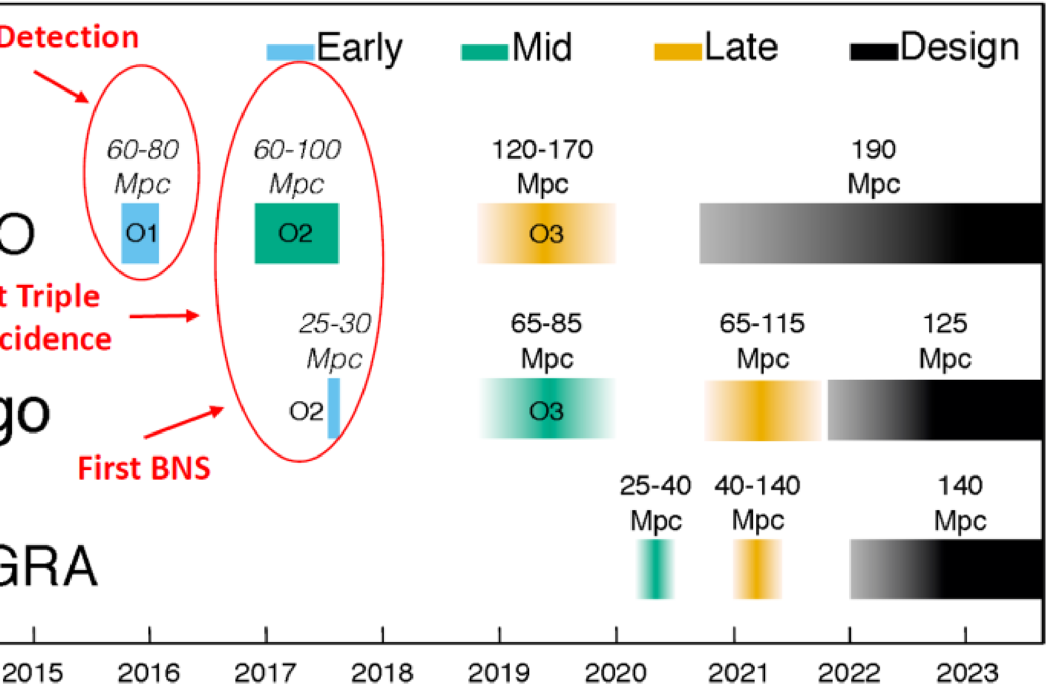


Note: duration of O4 has not been decided at this moment

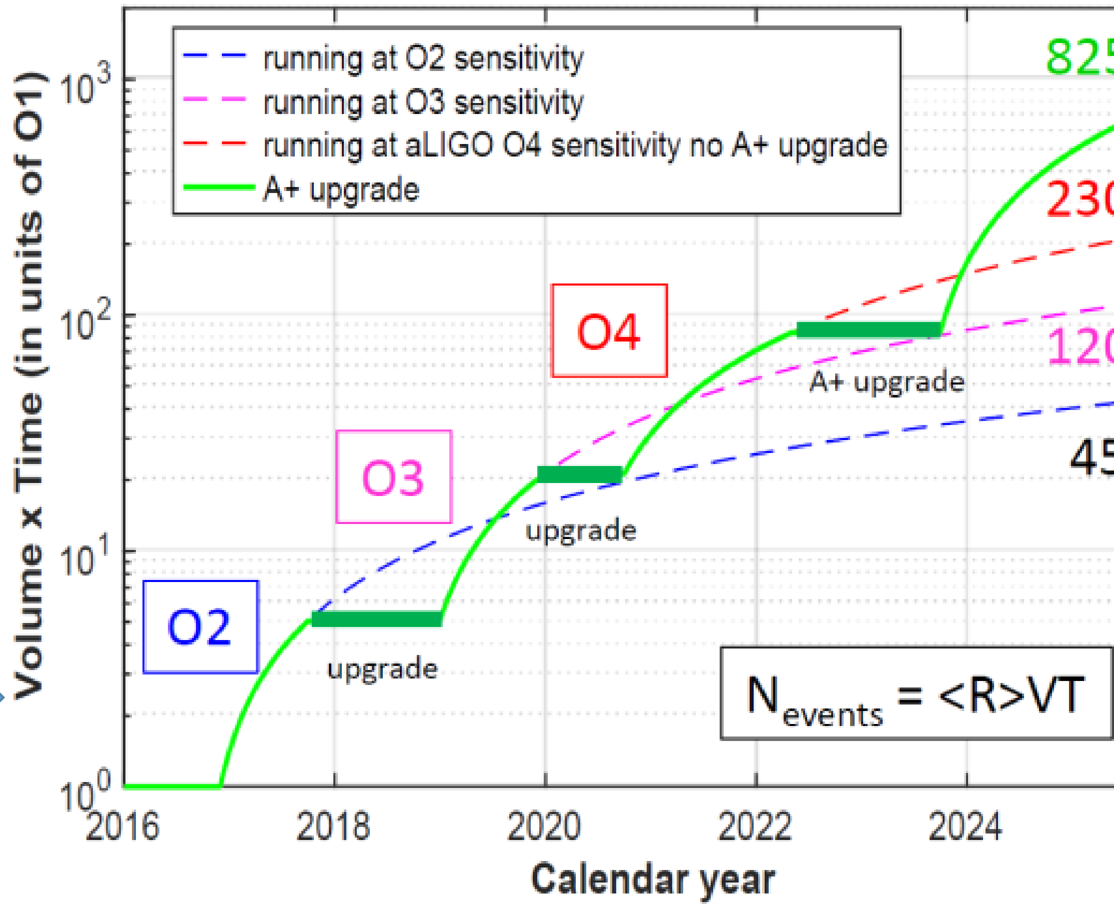
VIR-0943A-17

Plans for LIGO-KAGRA-Virgo runs

arXiv: 1304.0670v4 KAGRA & LIGO & VIRGO



Binary Neutron Stars Events

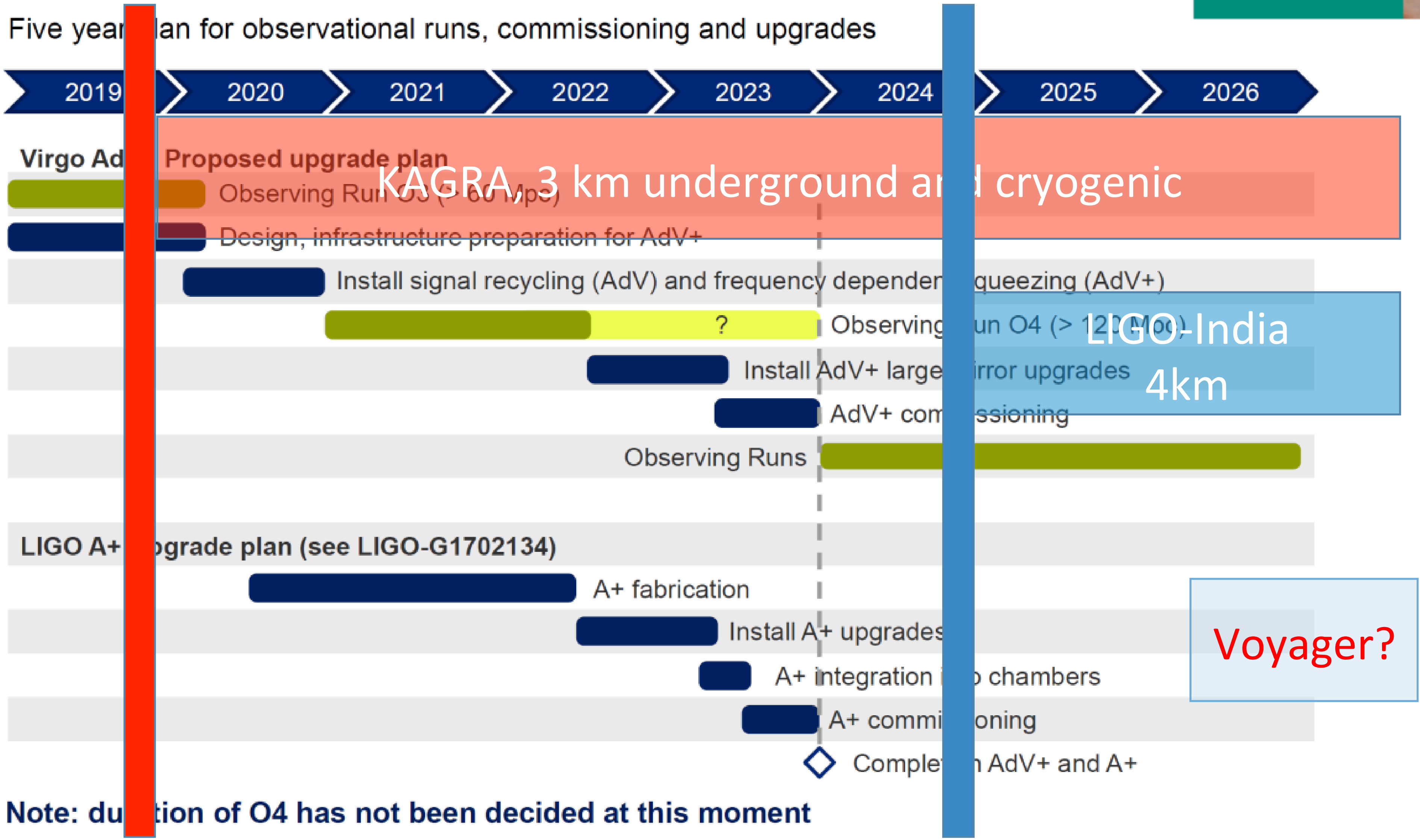


HEPP physicists?

- Luminosity L
- Branching ratio R

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

Short term evolutions

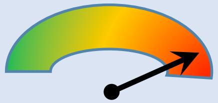
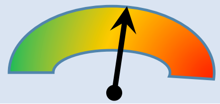
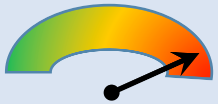
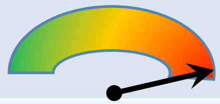
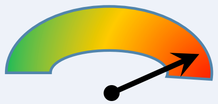
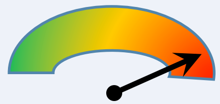
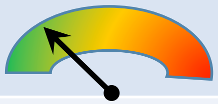
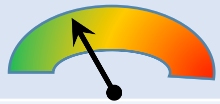


VIR-0943A-17

2029 outlook

n 2029 we will have a really heterogeneous 2.xG network

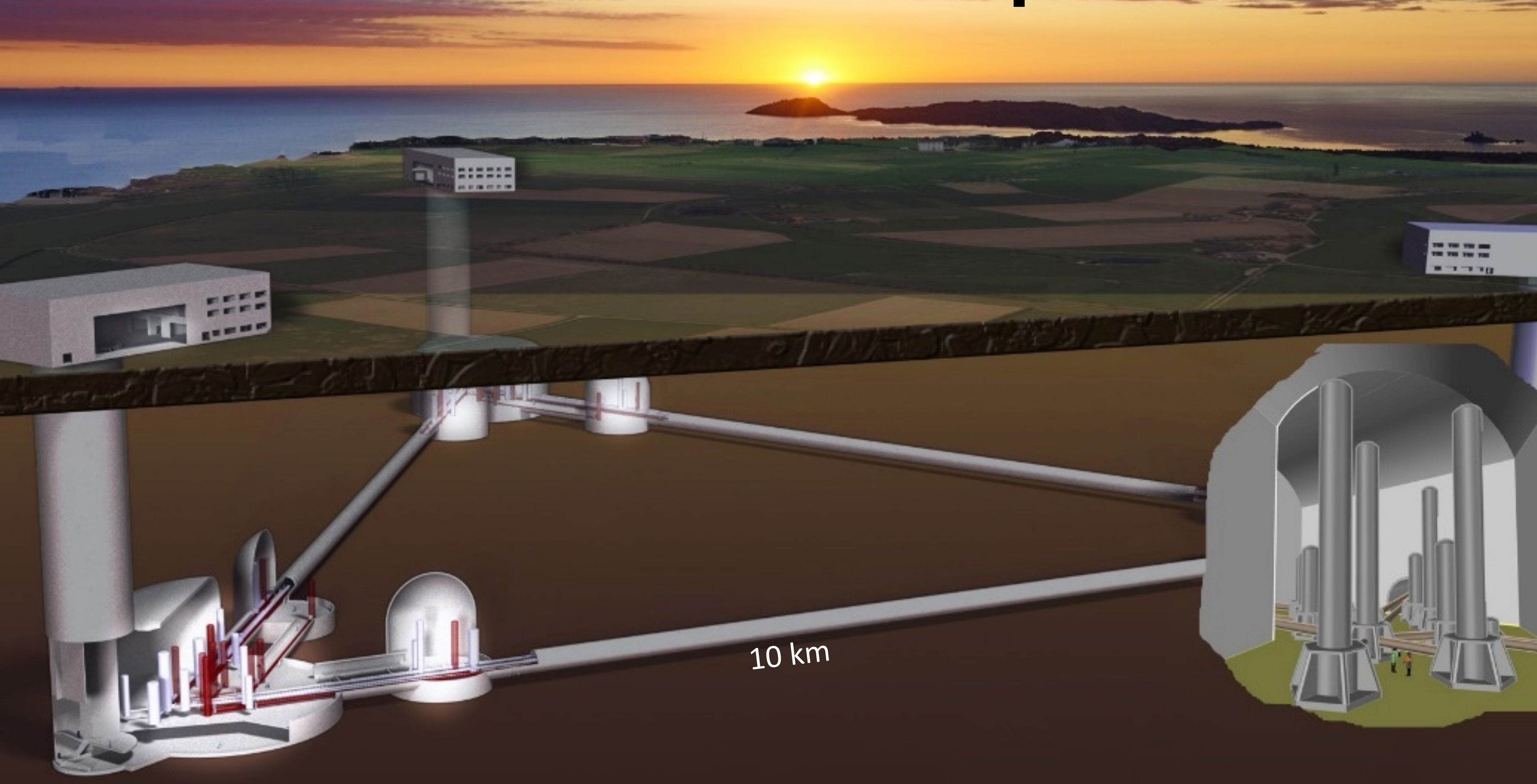
- The concepts of "obsolescence" and "limit of the infrastructure", that are driving th quest for new research infrastructures (rather more than a new detector) apply differently to the different continents

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

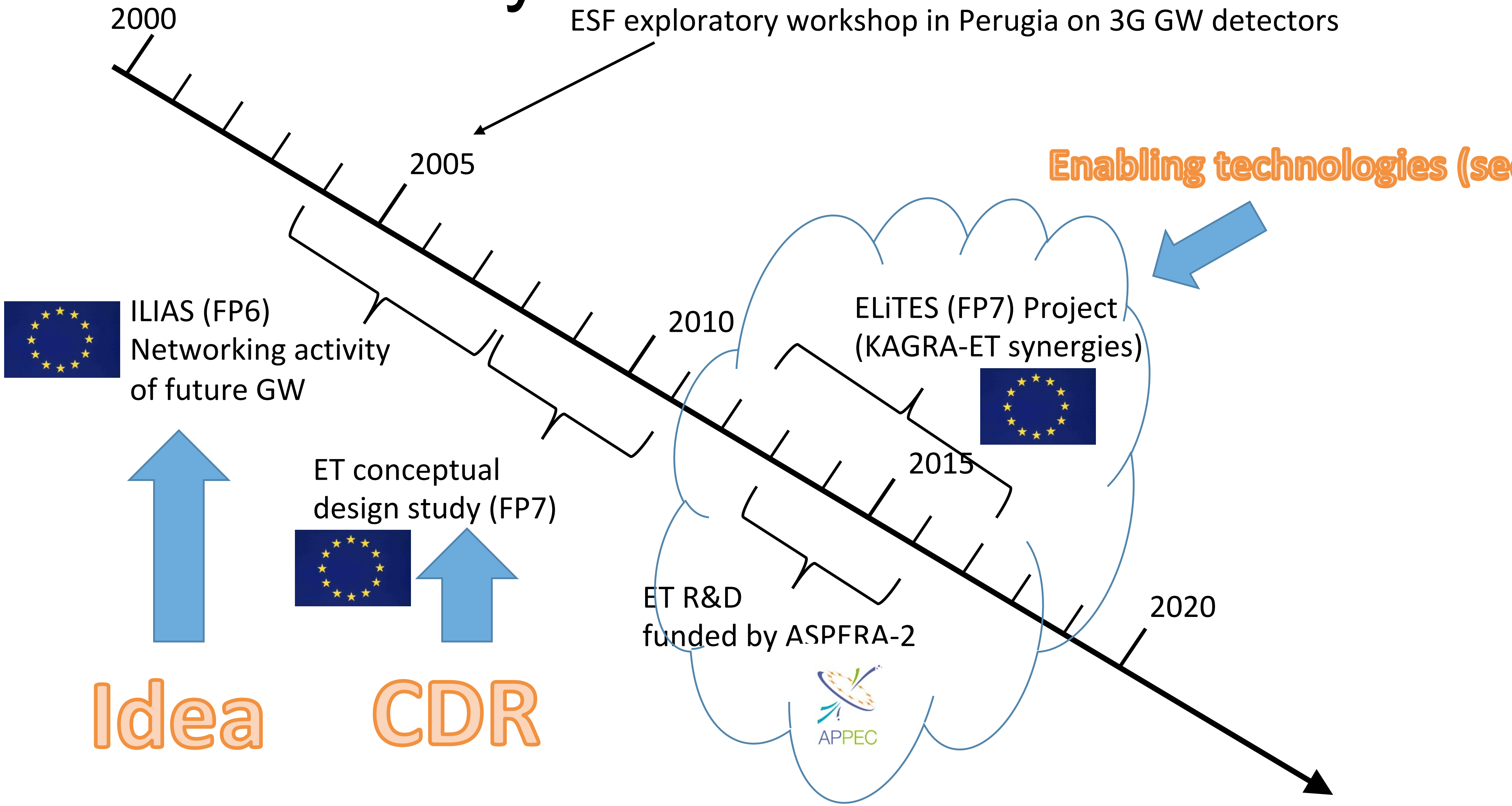
How to keep a scientific relevance in Europe?

Risk: Obsolescence and limits of the European Infrastructures in a 20 years timeline

The Einstein Telesco



ET history


2000
ESF exploratory workshop in Perugia on 3G GW detectors
2005
Enabling technologies (se
ILIAS (FP6)
Networking activity
of future GW
2010
ELiTES (FP7) Project
(KAGRA-ET synergies)
2015
ET conceptual
design study (FP7)
ET R&D
funded by ASPERA-2
APPEC
2020
Idea
CDR

ET: Science targets

ome of the questions addressed by GW
dV+, 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

HEPP Inflation, additional interactions, dark matter

- 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

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

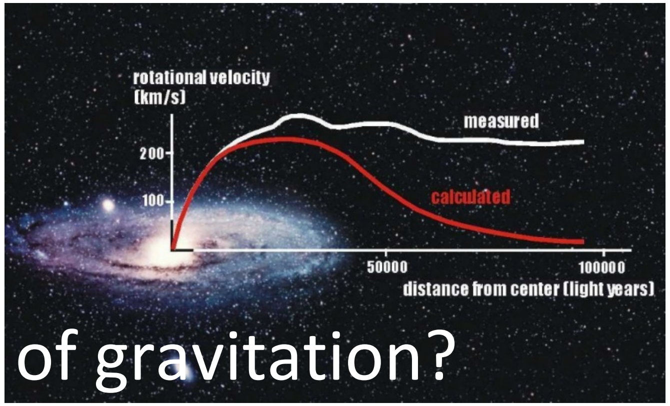
hat is the history of SuperMassive black holes?

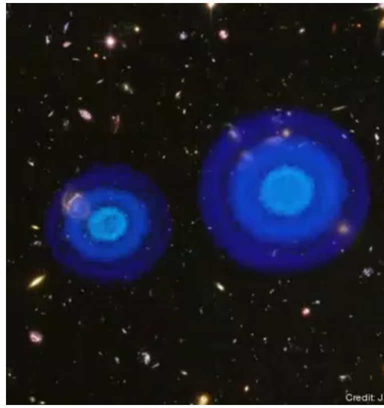
/ Stochastic Background? Probing the big bang? **HEPP** Cosmology, inflation

ultimessenger Astronomy in 3G? **HEPP** Astroparticle, GRB, Neutrino Physics

HEPP-INFN Strategy meeting

ome of the fundamental estions





- Einstein's General Relativity THE theory of gravitation?
  - Test of GR
  - Polarisations
  - Mass of the "graviton"
- o we need Dark Matter?
  - Wimps, Axions or black holes?

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

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

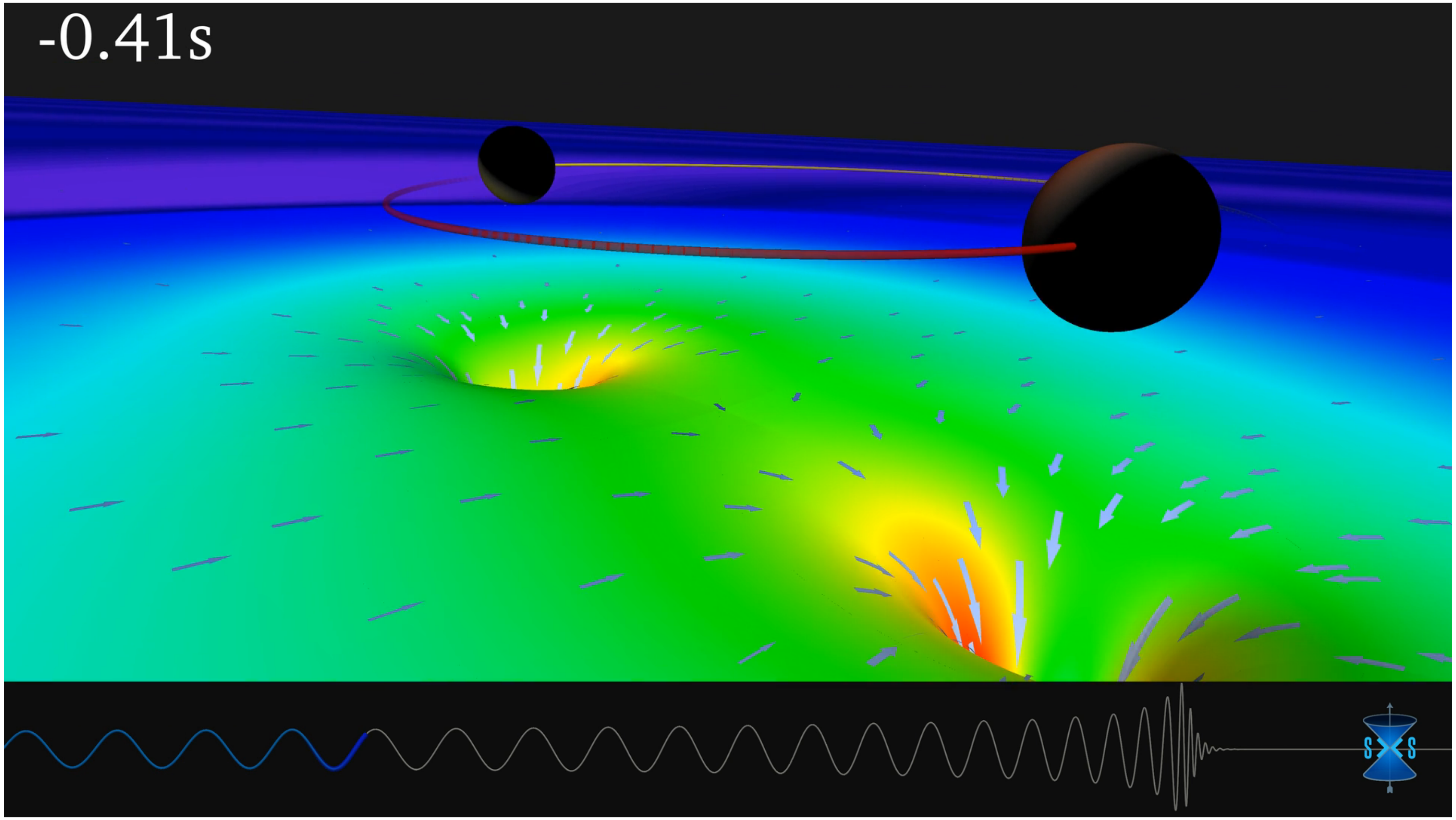
- o we need Dark Energy?
  - Alternative theories of Gravity

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

Alternative theories of Gravity

- e Neutron Stars "strange"?
  - EOS of NS

GW150914 … e BBH coalescences



Probing GR in strong field conditions

BH
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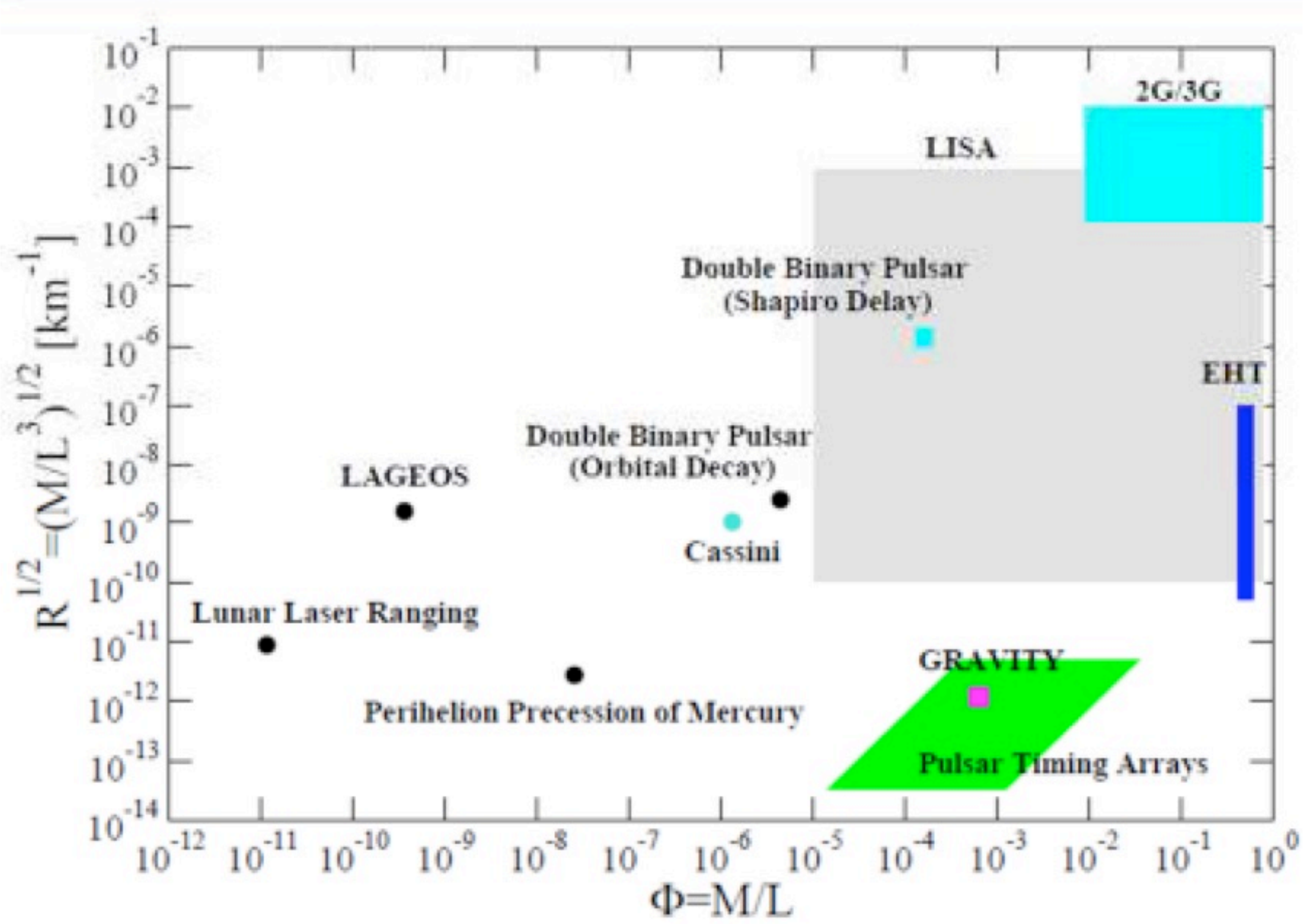
es N. et al.
. Rev. D 94, 084002 (2016)
ed by ET science case team



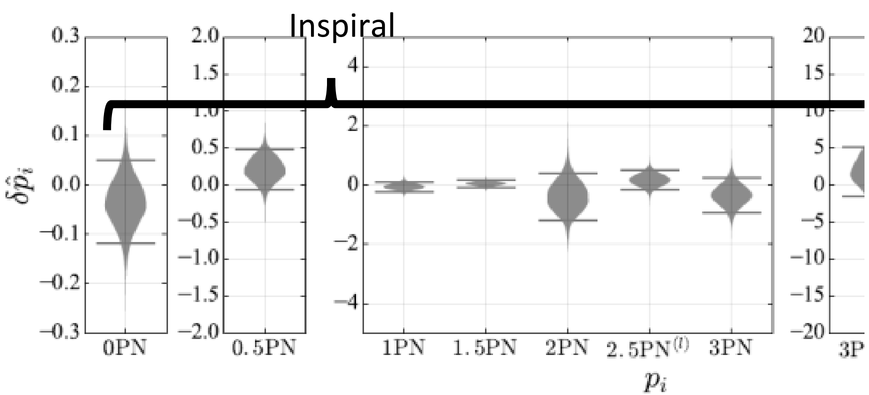
Test of GR: PN approximation

Going in strong field regime, allow to constrain eventual discrepancies with respect to PN approximation of the GR

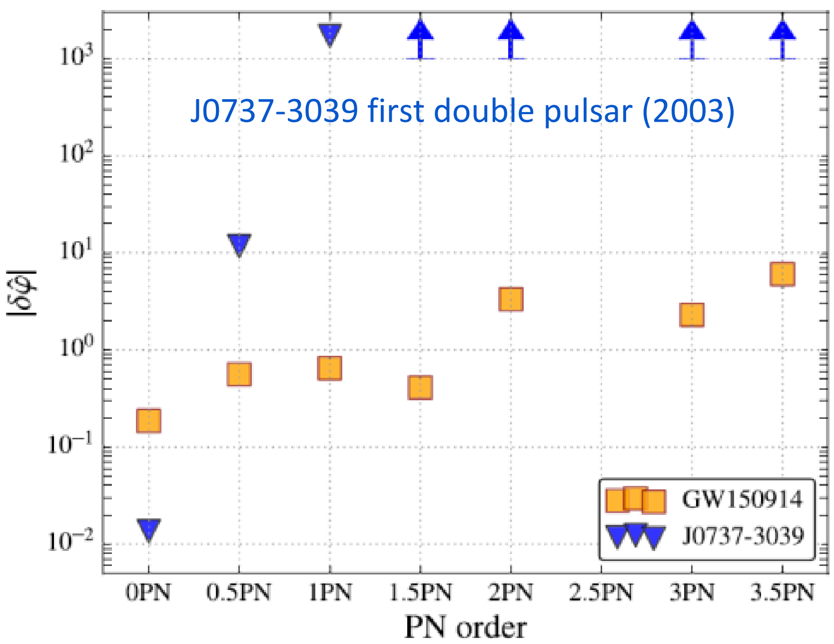
BBH template

$$\Psi(f) = 2\pi f t_c - \varphi_c - \frac{\pi}{4} + \sum_{j=0}^{7}\left[\psi_j + \psi_j^{(l)} \ln f\right] f^{(j-5)/3},$$

$$\psi_j \rightarrow (1 + \delta p_j)\psi_j$$



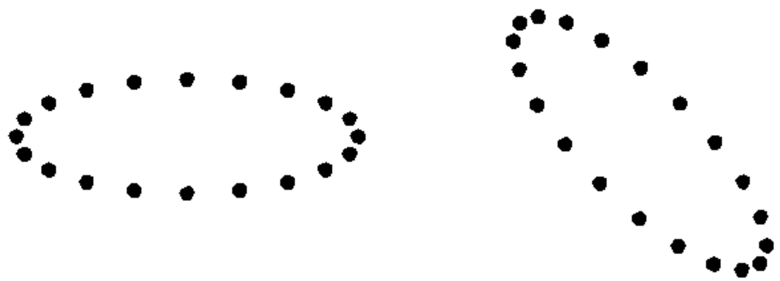
B. P. Abbott et al. (LIGO Scientific and Virgo Collaboration)
Phys. Rev. Lett. 118, 221101 – supplement material

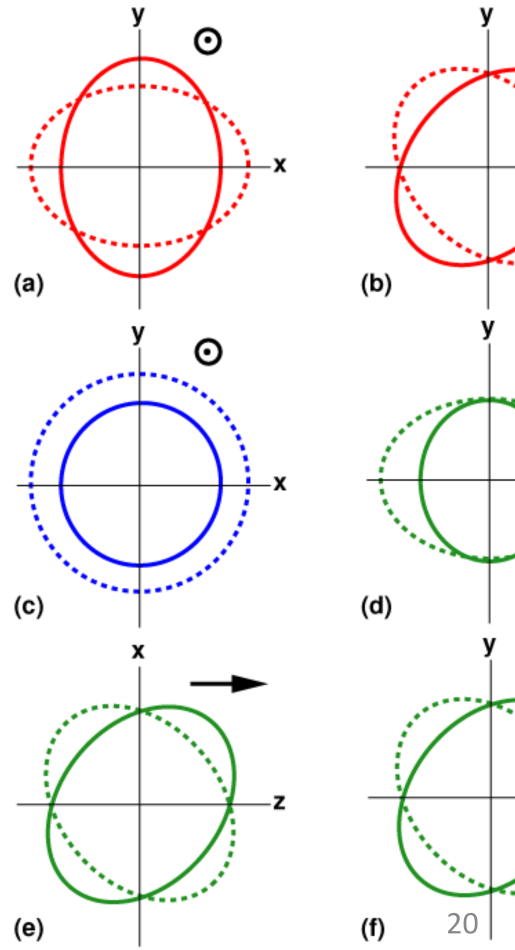


Alternative theories of Gravity: polarisations

R predicts a tensorial nature of GW with two polarisations

- Alternative theories of gravity could predict extra polarisations of GW (up to 6)

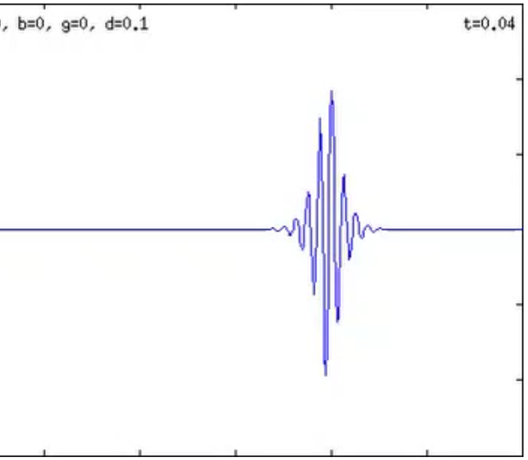


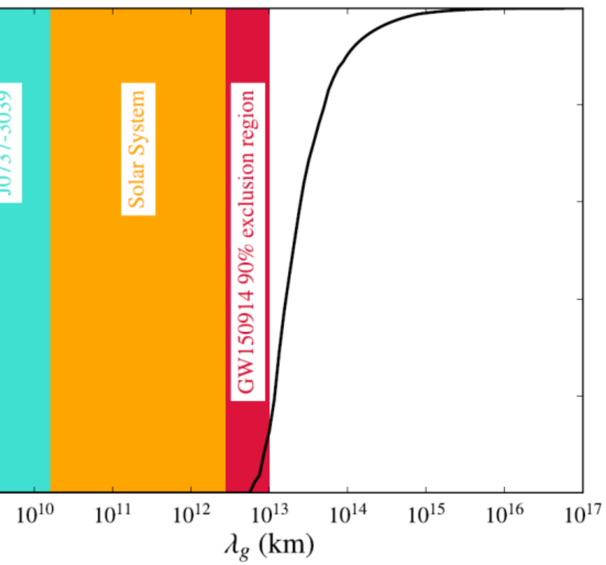


- Present and future GW detectors are setting stringent limits
  - GW170814:
    - Thanks to the presence of Virgo has been possible the evaluate the contribution of extra polarisations in the detected GW resulted strongly disfavoured

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) $I(J^{PC}) = 0,1(1^{--})$

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)×(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 hysics

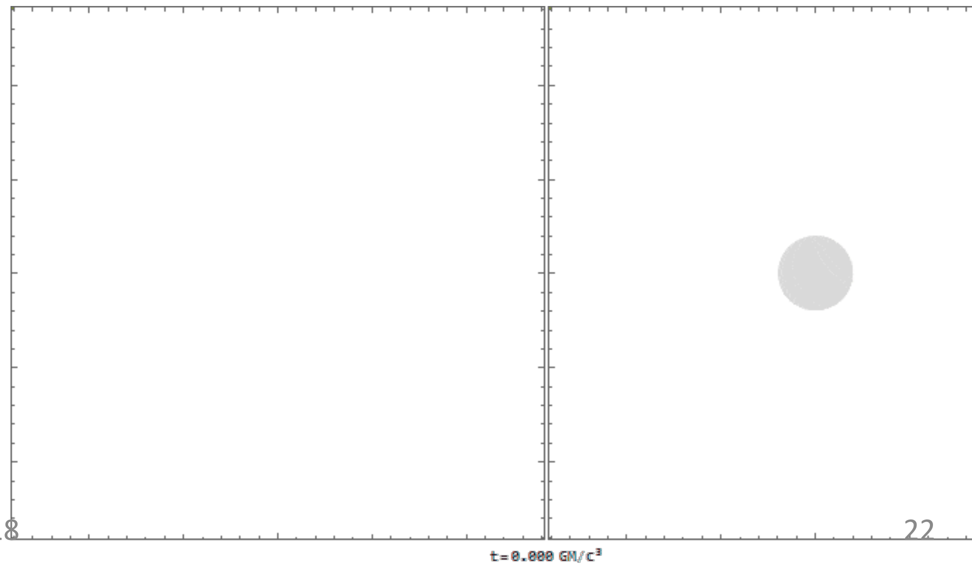
he beginning of the multimessenger astronomy, marked by GW170817 llowed several fundamental physics tests

- 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:

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

servation point
ission point
gravitational
potential

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



γ factor parametrises the coupling of the sity energy with the curvature; in the Einstein eral Relativity $\nu\downarrow GW = \nu\downarrow EM = 1$

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 ($c_g \neq c$)
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 $A_1\neq0$ or $B_i\neq0$ or $G_5\neq0$
	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

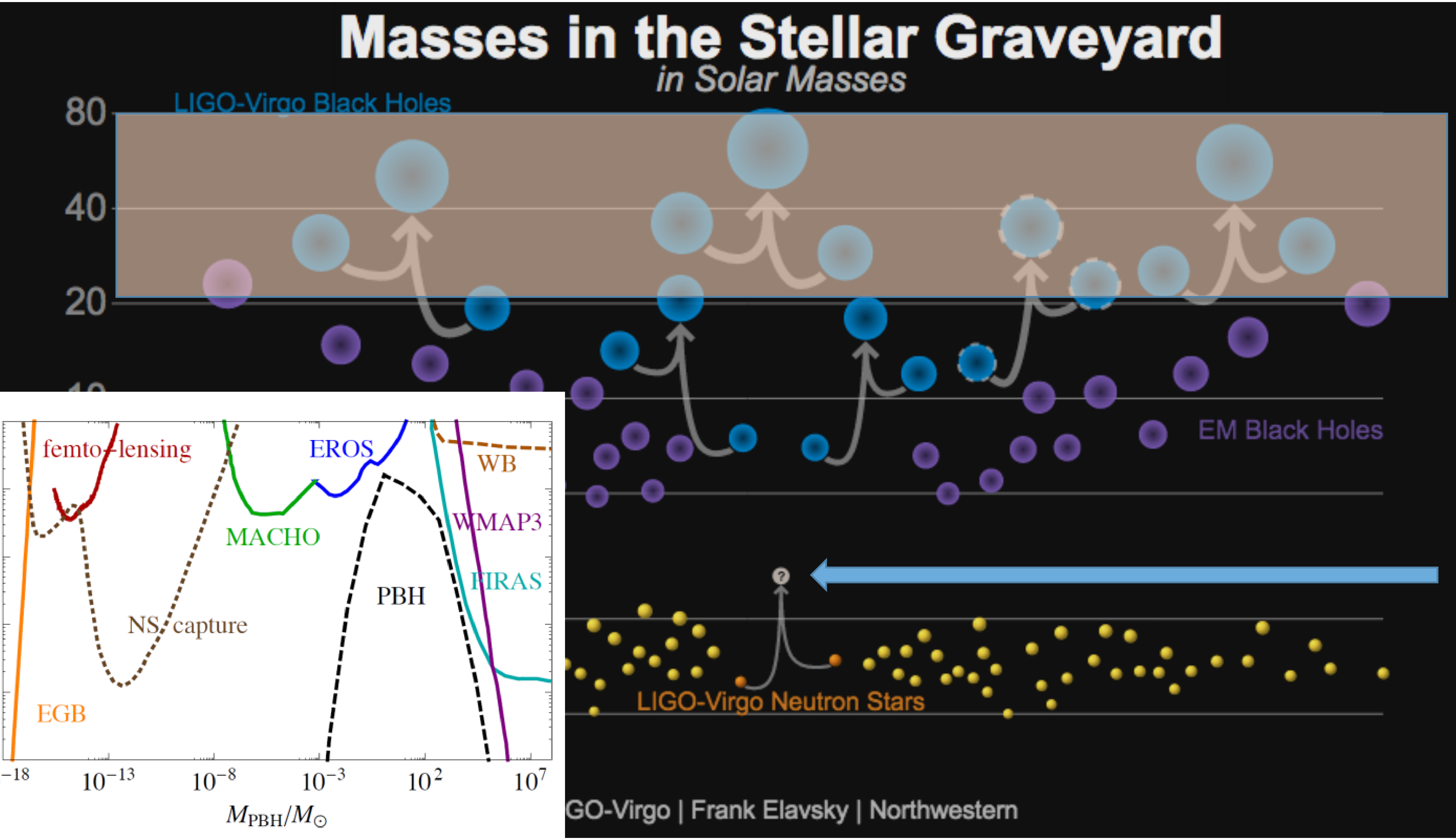
Ok, the Dark Matter paradigm seems strengthened

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

But what kind of Dark Matter? $G_{\mu\nu} = \frac{8\pi G}{c^4}\left(T_{\mu\nu} + T_{\mu\nu}^{DM}\right)$

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

GO-Virgo detections



New
fami
of BH

A BH
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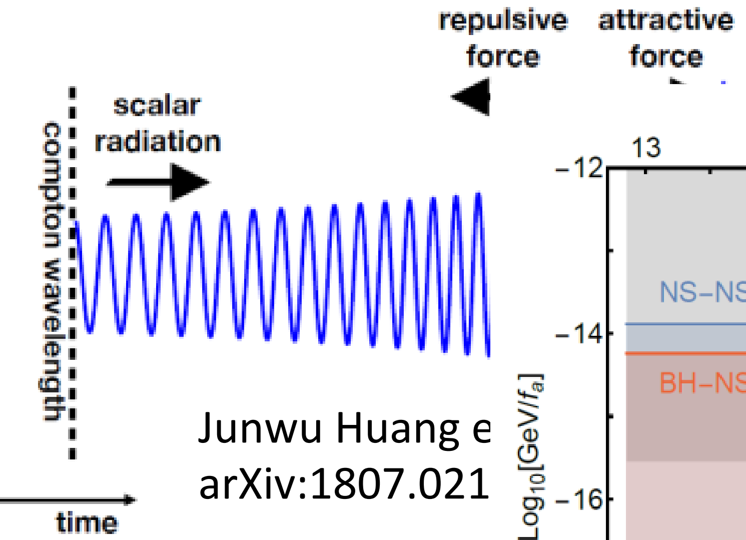
arcía-Bellido 2017 J. Phys.: Conf. Ser. 840 012032

xions and GW

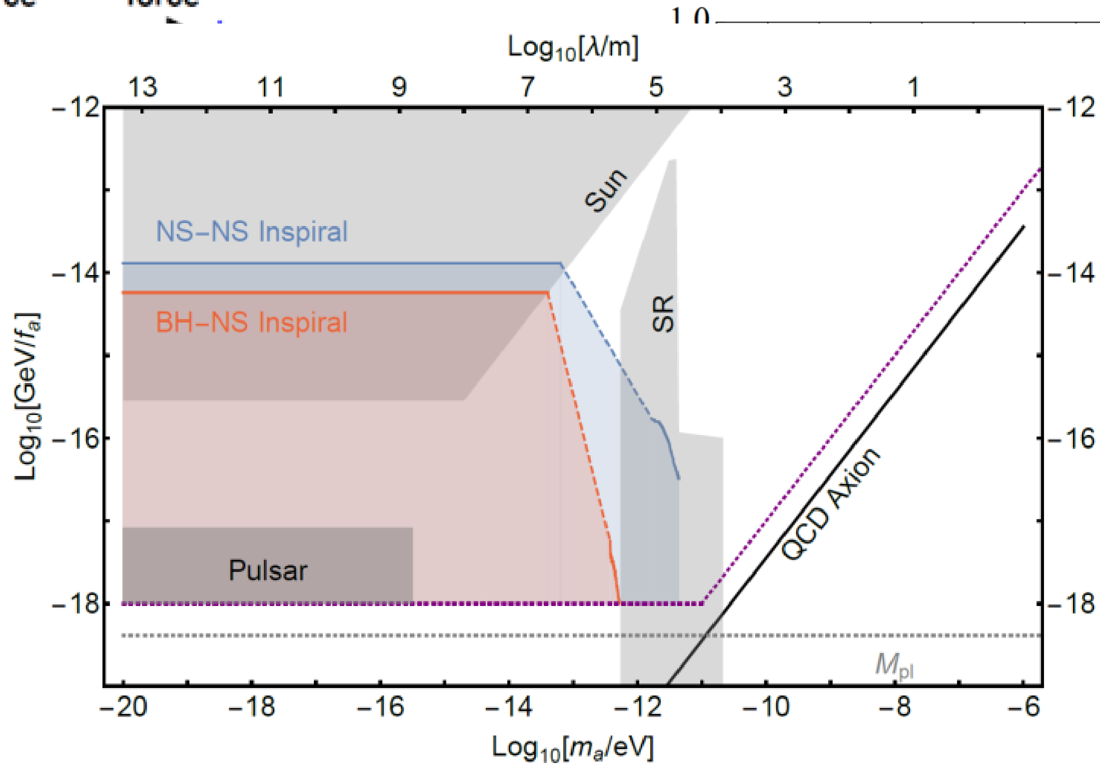
xions or, in general, light scalar fields are a possible extension of the Particle andard model and they could be a component of the dark matter or dark energy
- Axions could provide an inflation mechanism

hat GW could tell about Axions?

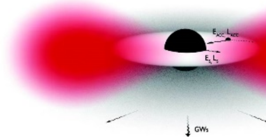
BNS coalescence

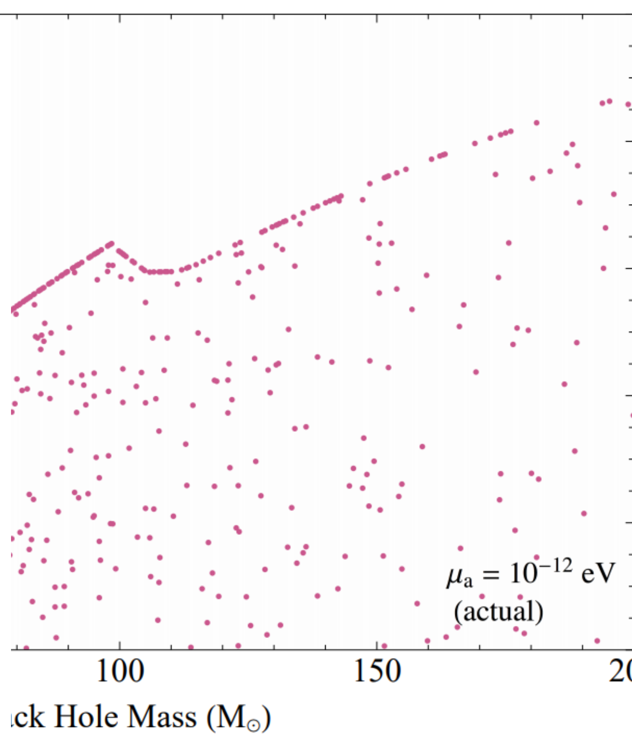


Junwu Huang e
arXiv:1807.021



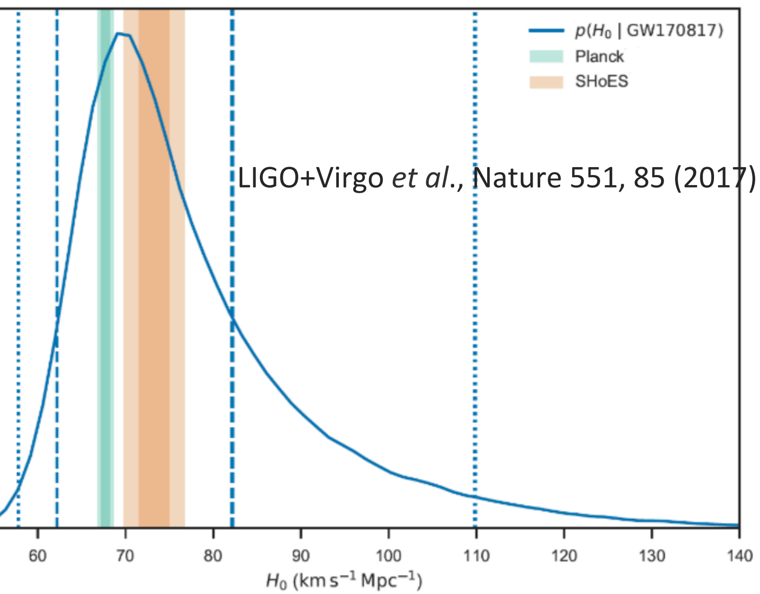
BH superradiance



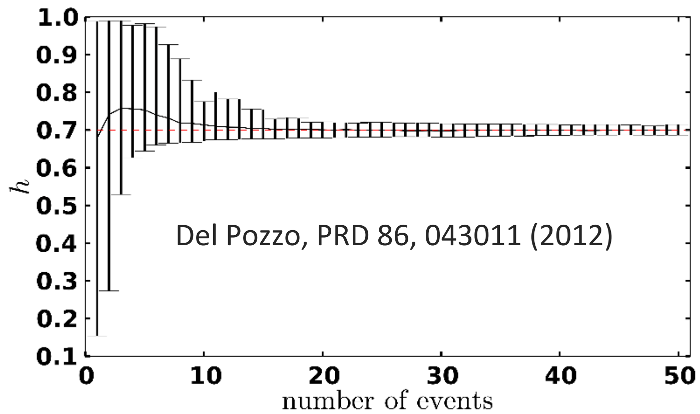


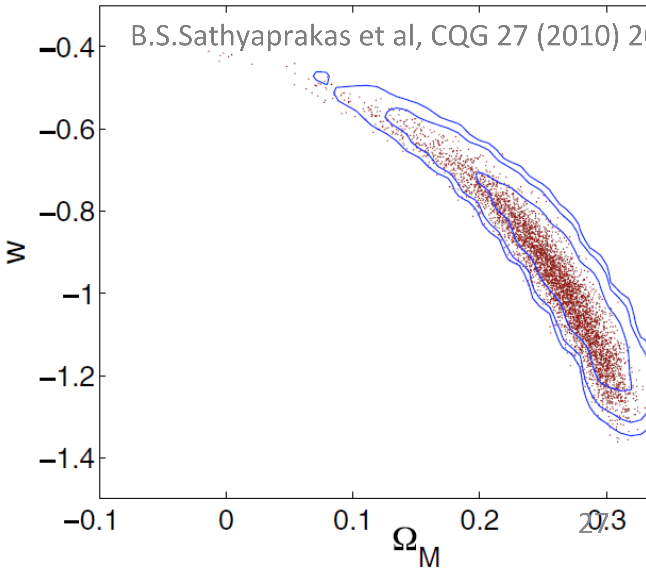
Cosmology with GW

- 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 $H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,M}$



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



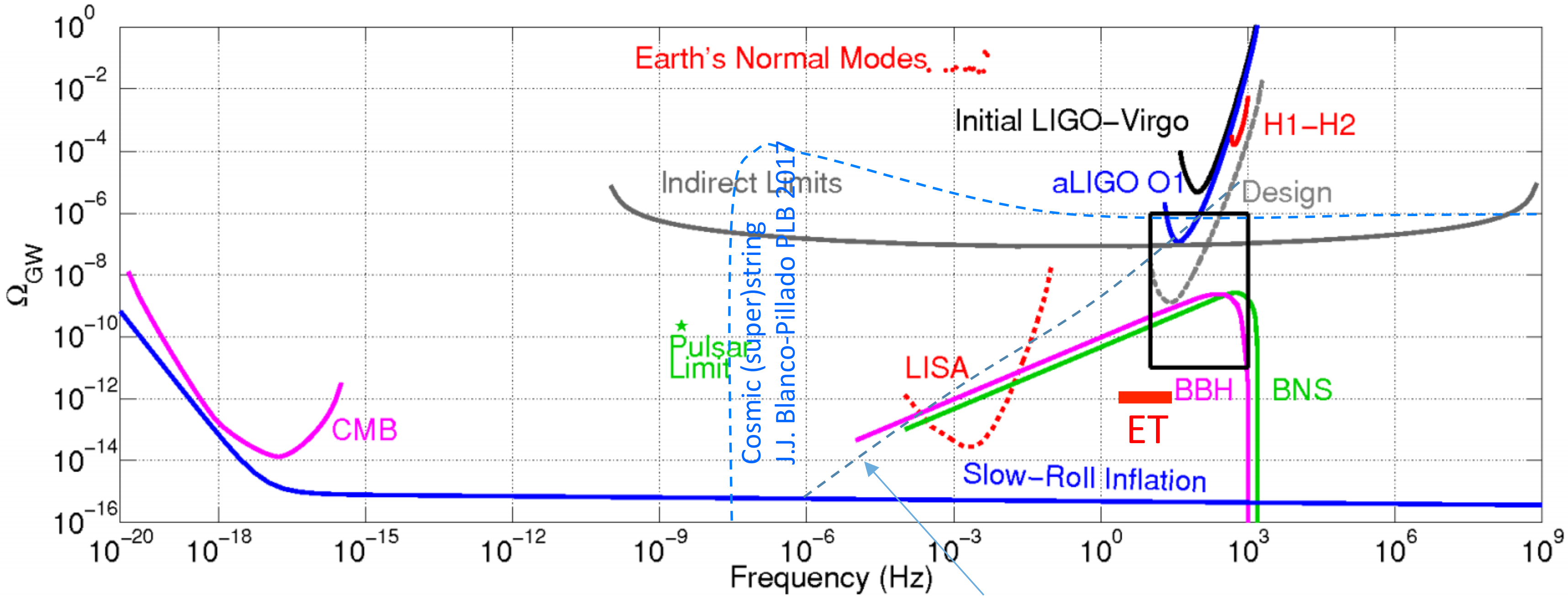


$$D_L(z) = \frac{c(1+z)}{H_0}\int_0^z \frac{dz}{[\Omega_M(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)}]^{1/2}}$$

GW Stochastic Background and inflation

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

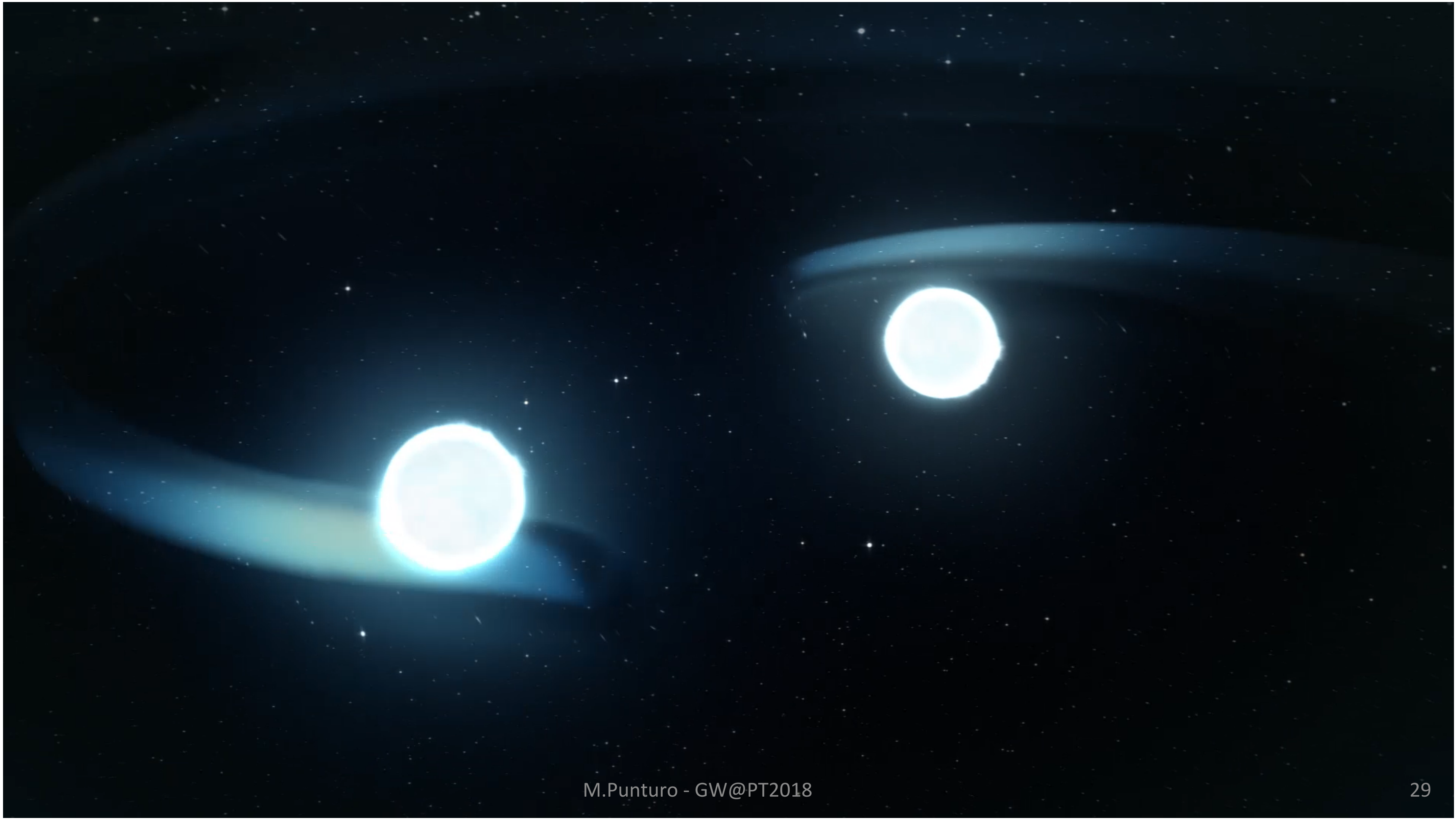
- information on: new additional degrees of freedom, interactions and/or new symmetry patterns underlying high energy physics of early universe



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

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

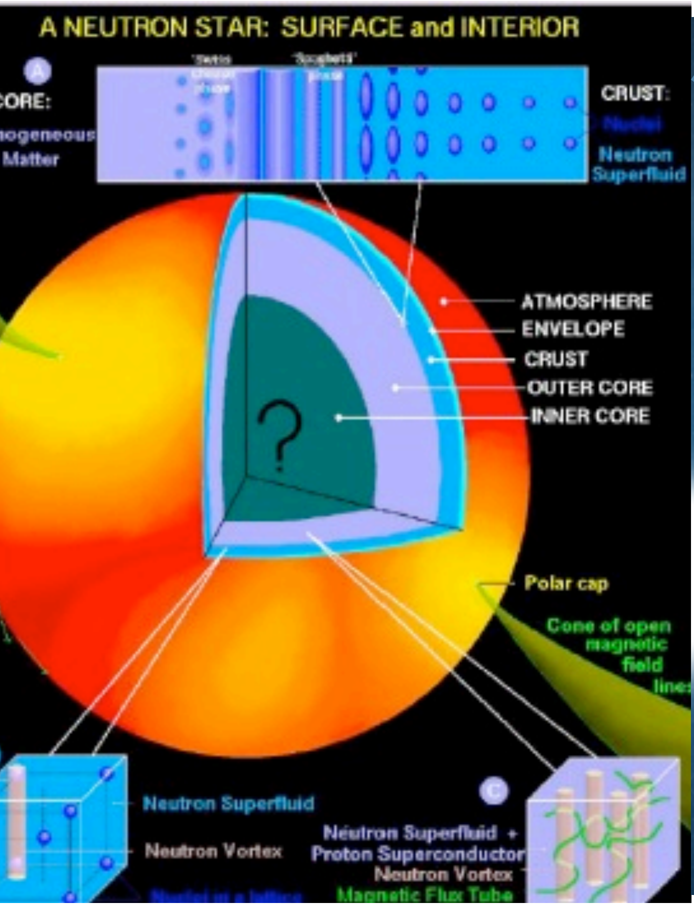
Our Collider

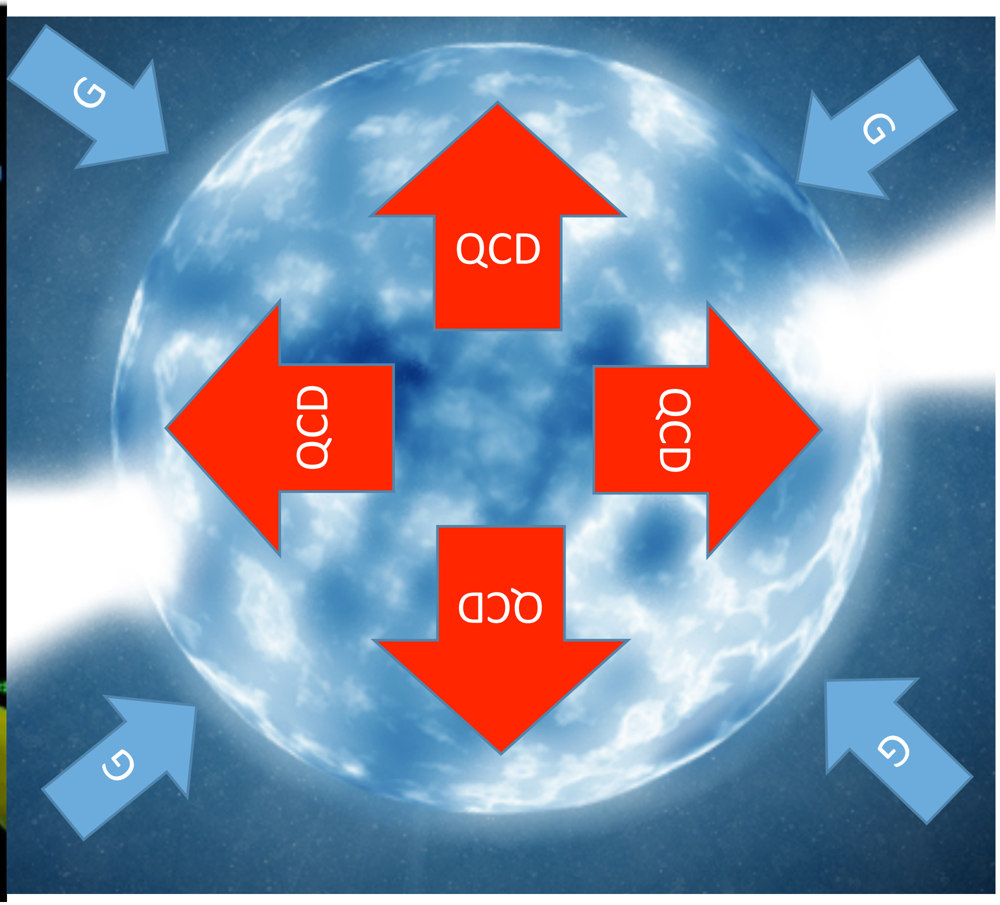


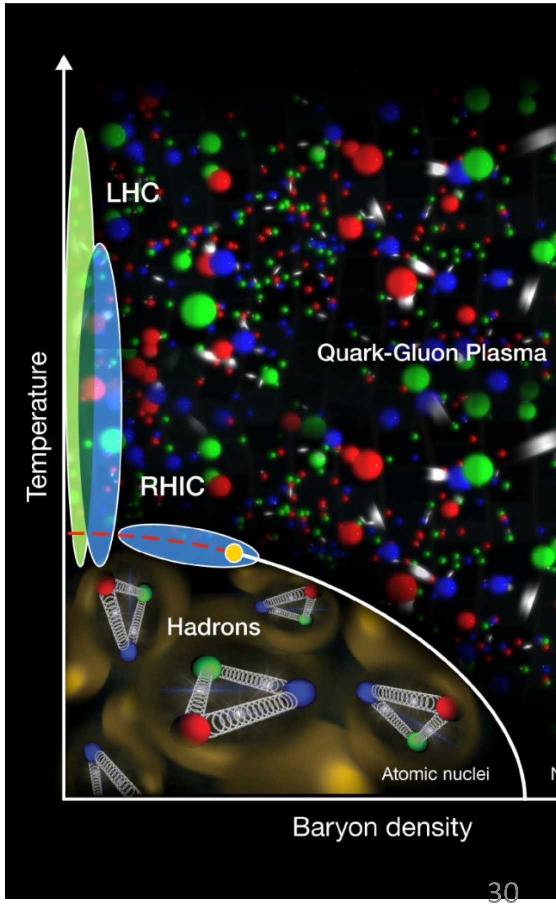
Neutron Star is a nuclear physics lab

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



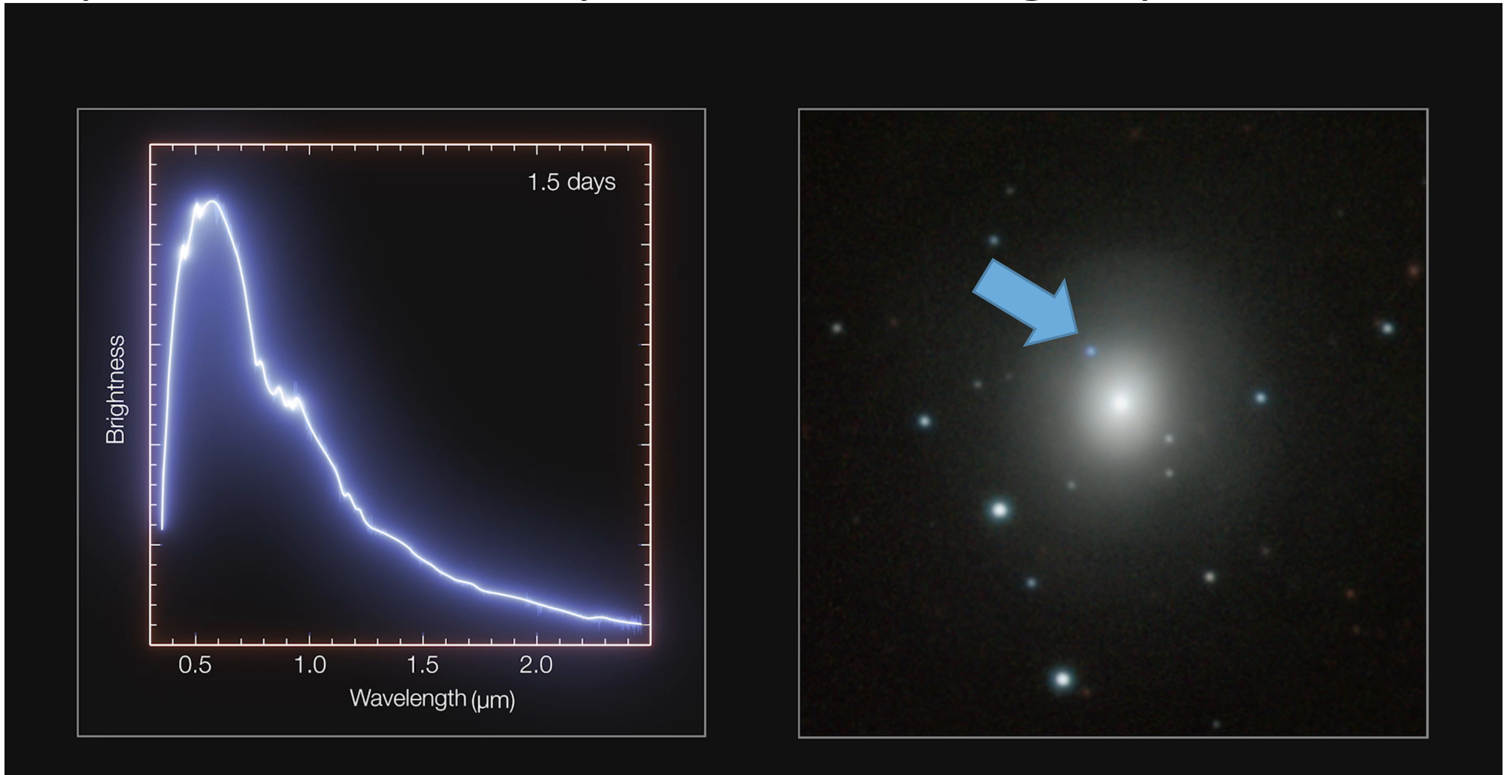




GW170817: Nuclear Physics “experiment”

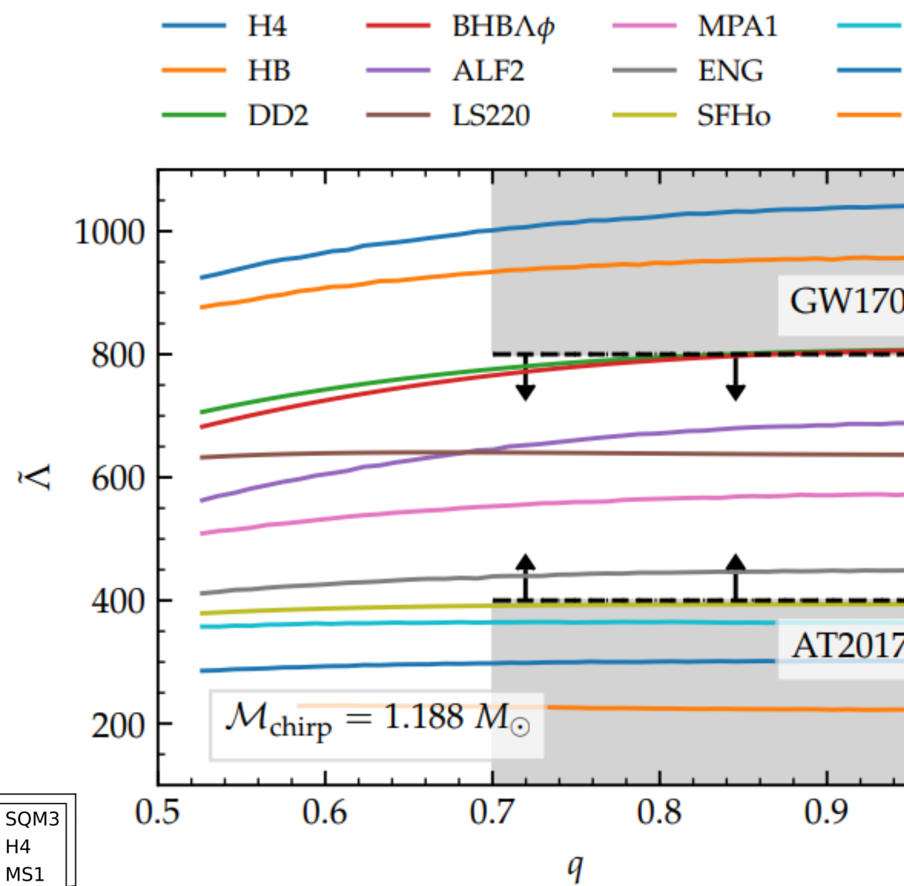
e collision of two NS in GW170817 has been a complex nuclear physics periment, where it has been possible

- 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

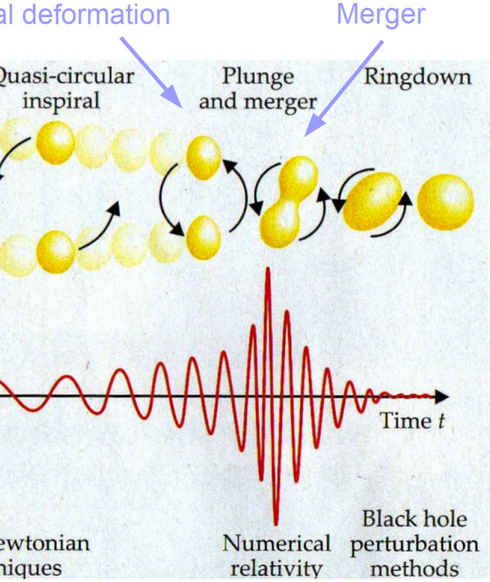


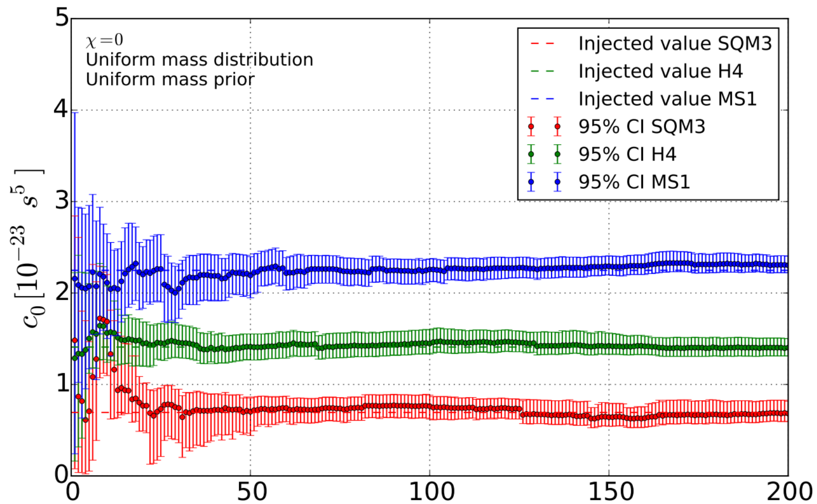
Constraining the NS EOS

- leasuring the tidal deformation through the ephasing in the GW signal is possible to onstrain the EOS of the NS
- dding the em information helps to impose ore 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



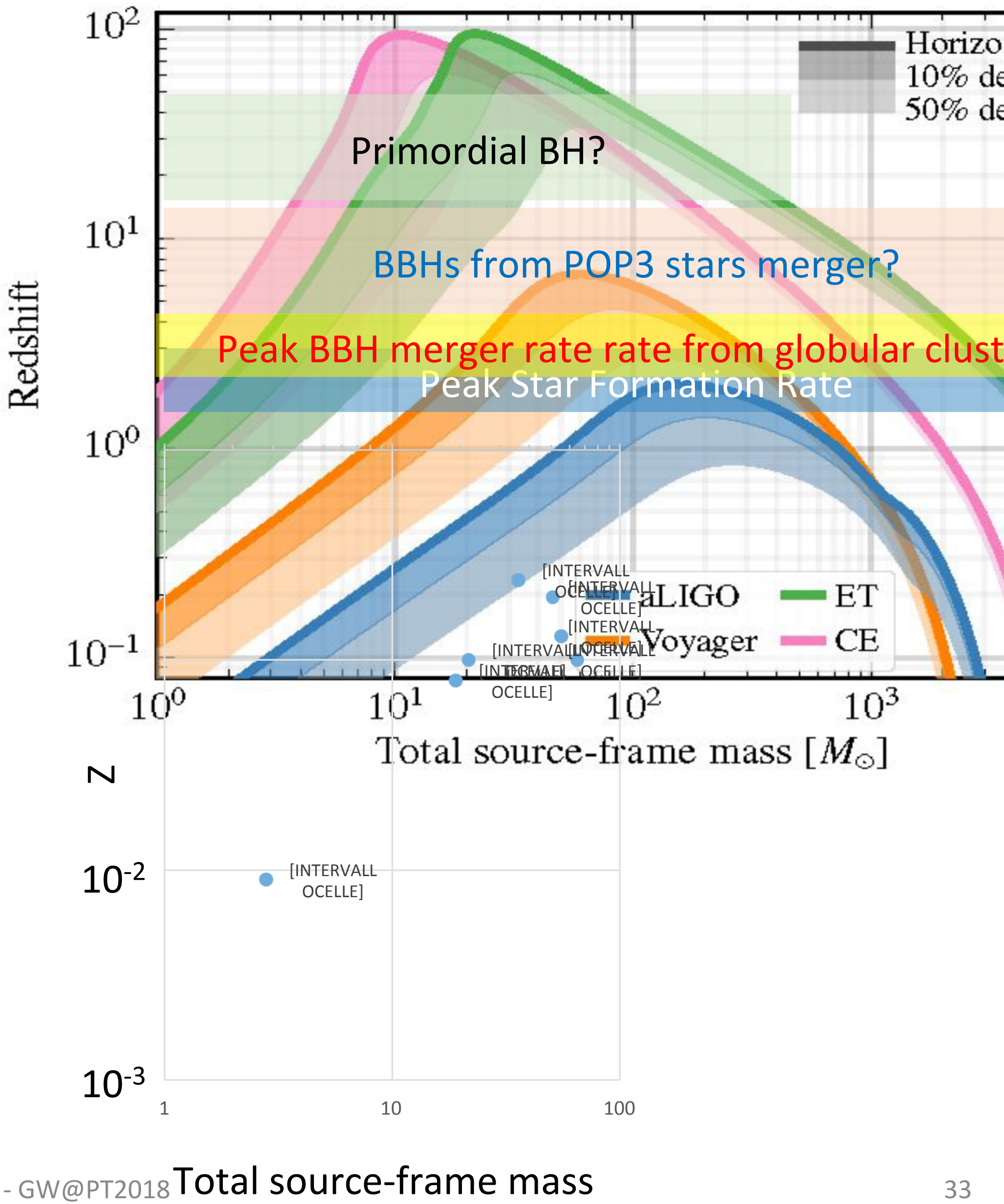


M. Agathos et al, Phys. Rev. D 92, 023012 (2015)

K, all done?

LIGO and AdV achieved awesome results with a educed sensitivity
Vhen they will reach or over-perform their nominal ensitivity can we exploit all the potential of GW bservations?

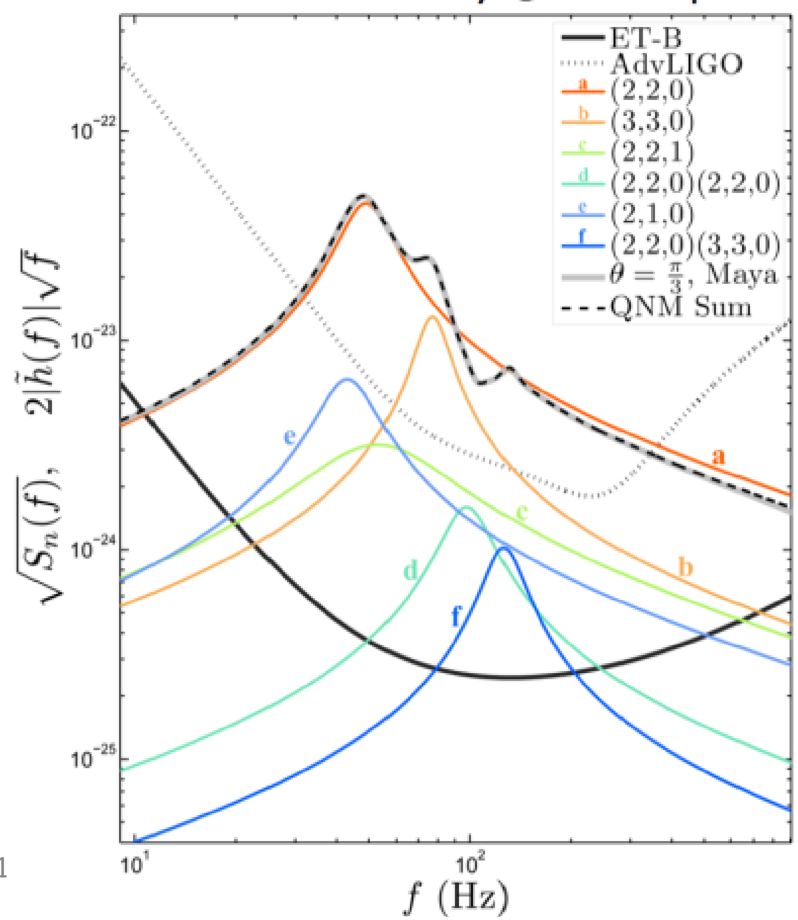
nd generation GW detectors will explore local Jniverse, initiating the precision GW astronomy, but o have cosmological investigations a factor of 10 mprovement in terms detection distance is needed



Extreme gravity

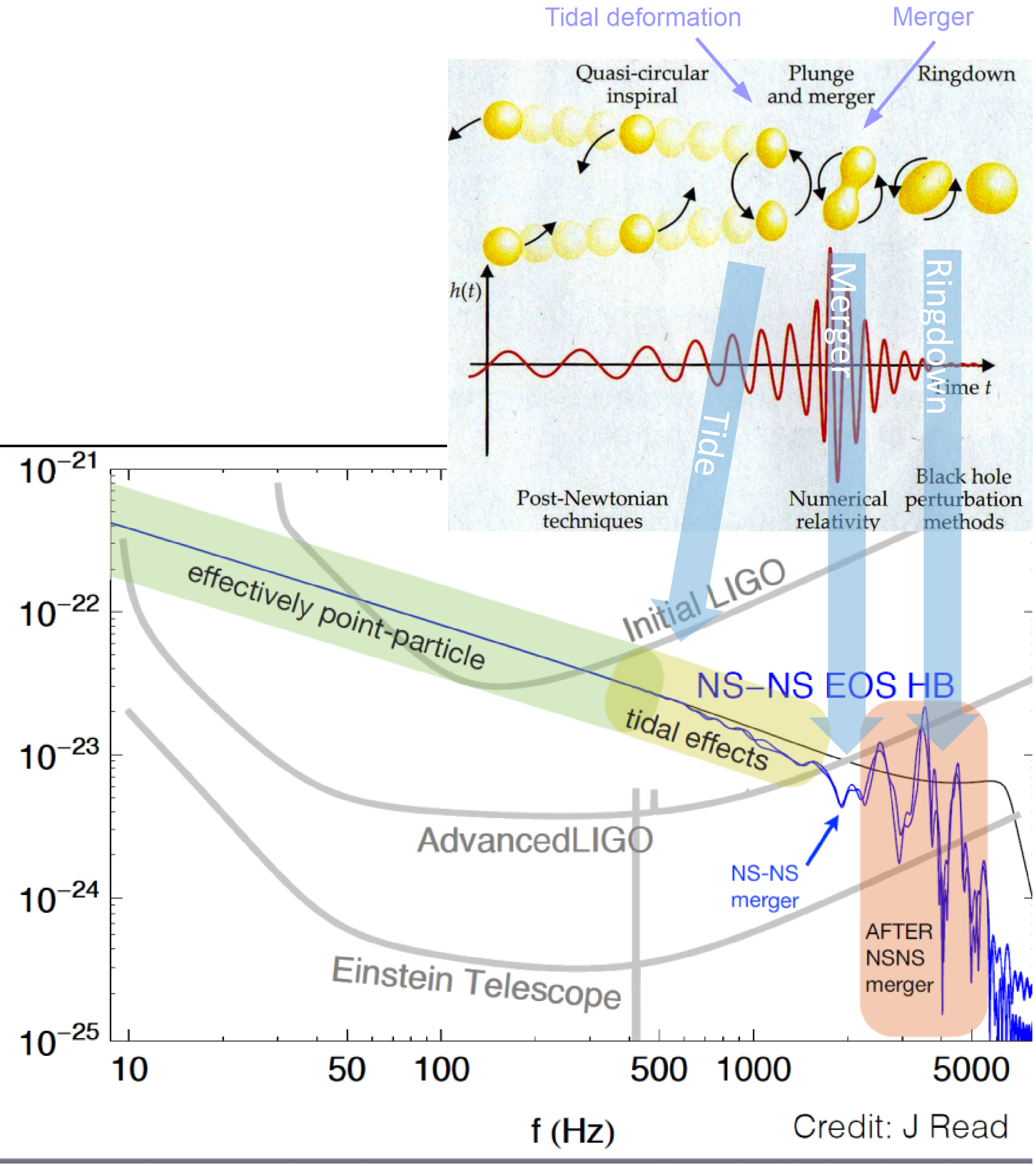
- But, are the massive objects seen by aLIGO and AdV really GR-BBH?
  - Unable to disentangle the QNM
  - Do exotic compact objects (Boson stars, strange stars) exists?
  - Do singularities and event horizons really forms?

350 Msun binary @ 100 Mpc



London et al. 2014

Structure of a Neutron Star



Stephen Fairhurst
ET meeting 27-28 March 2017

Realising ET
Where we are?

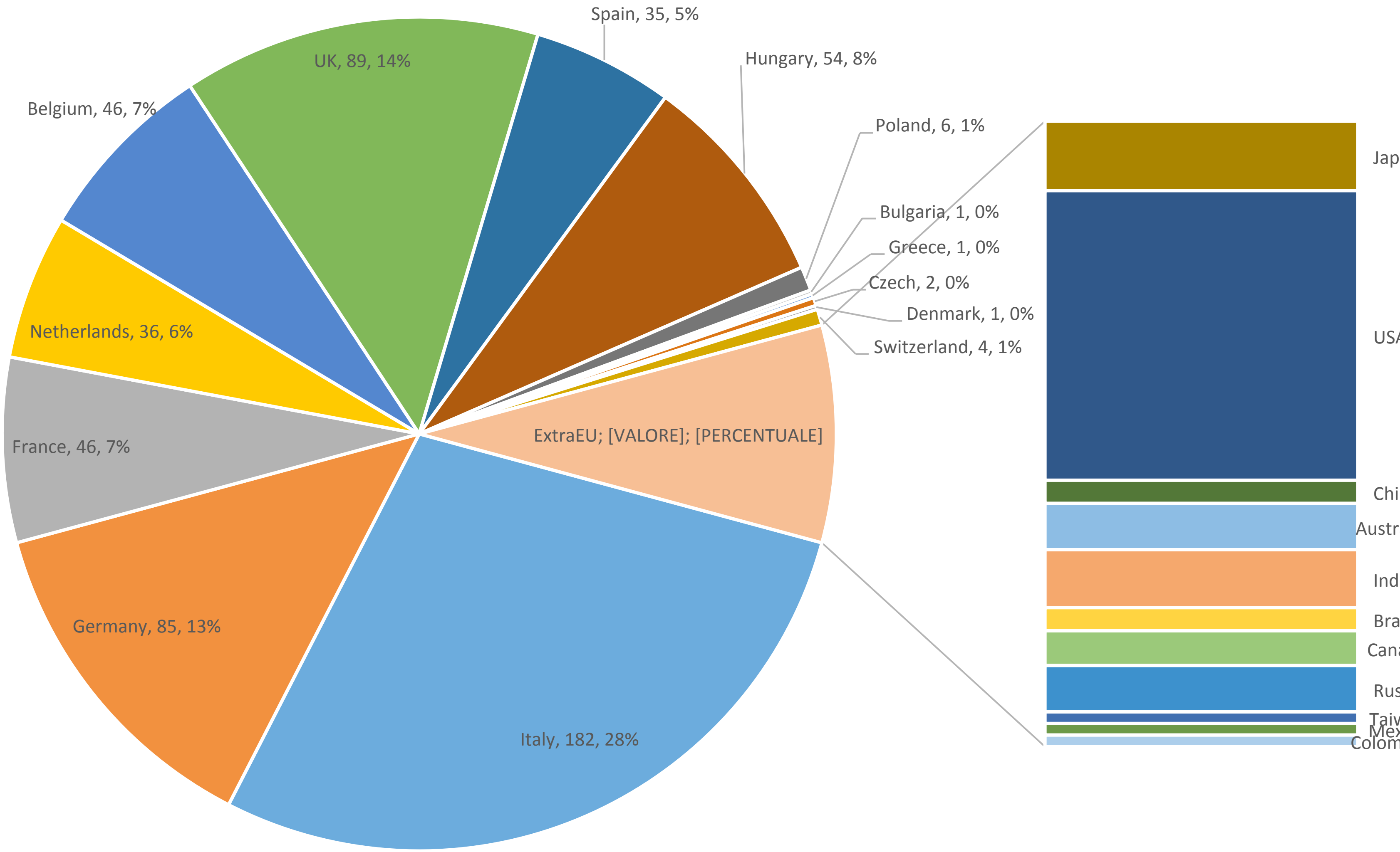
ET: project roadmap

 has a clearly defined project roadmap, presented to APPEC:

- 2018-2019 Form the ET collaboration
- 2019-2020 ESFRI roadmap
  - In Apr 2019 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
- 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

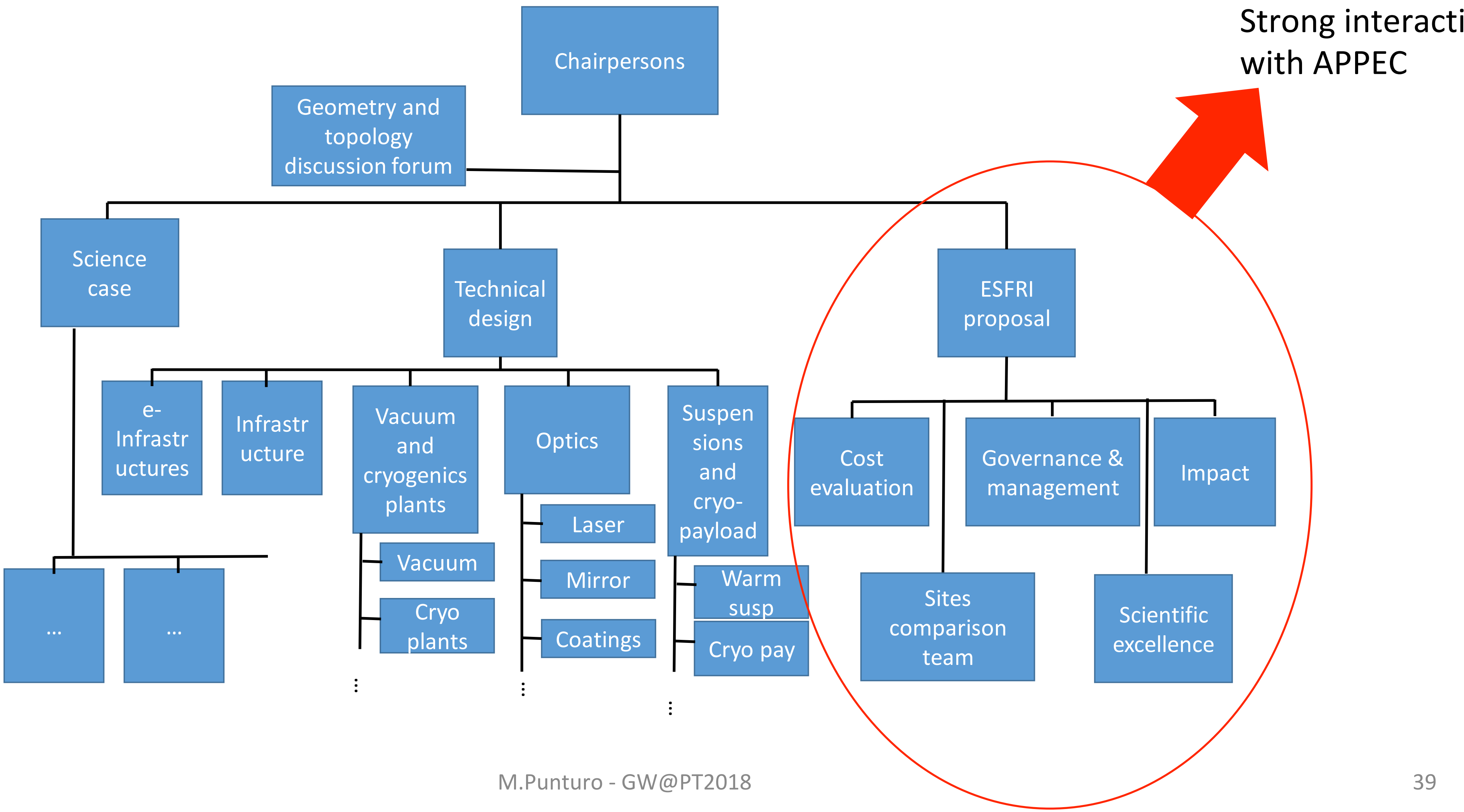
ET collaboration: Letter of Intent

- ddressed to all the
ientists and
gineers interested
the 3G GW
ience and
chnology
- e signatories (642
ersons, the 3rd of
ctober) probably
ll become the
ture members of
e ET collaboration

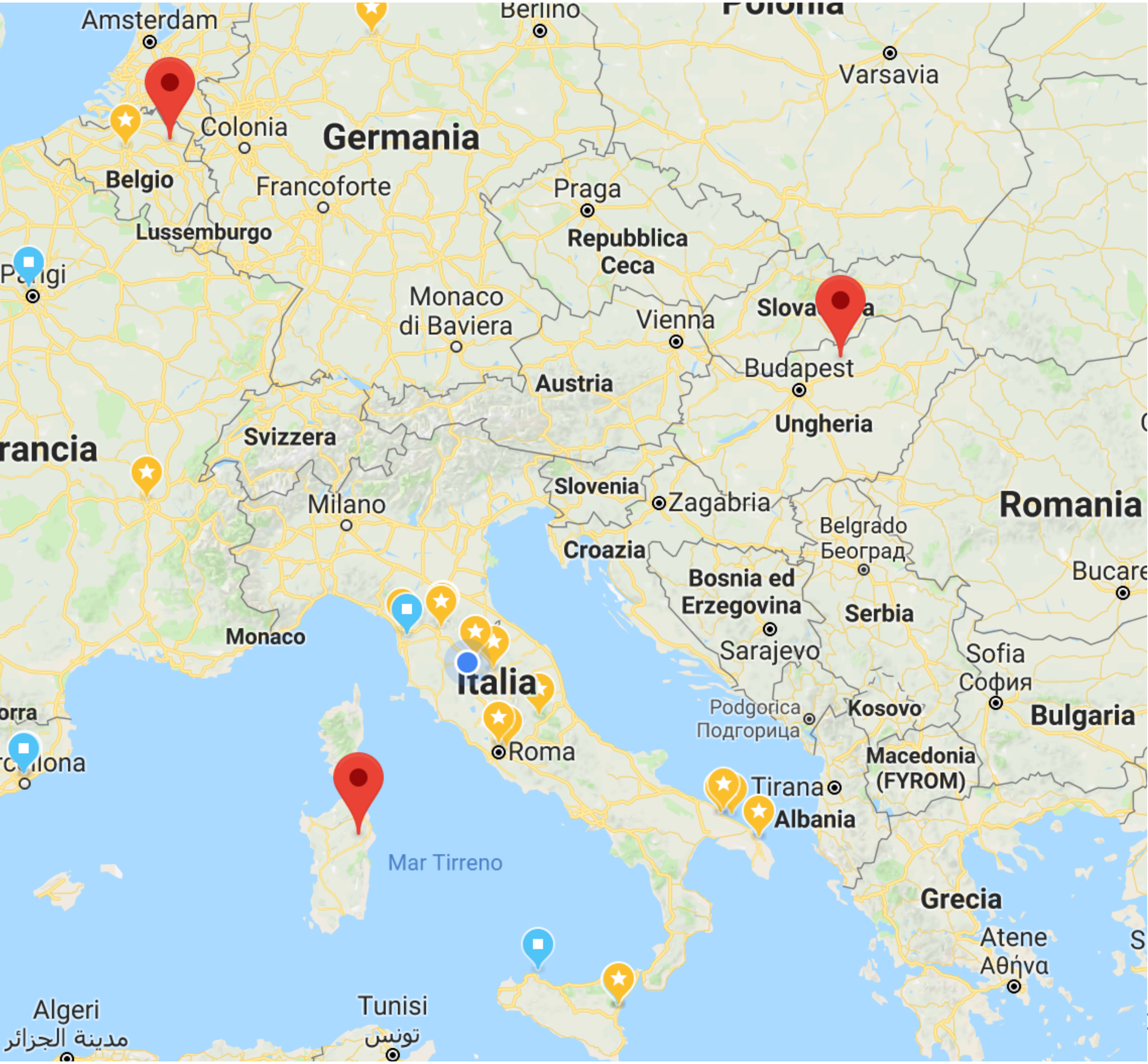


http://www.et-gw.eu/index.php/letter-of-intent

The Executive Board

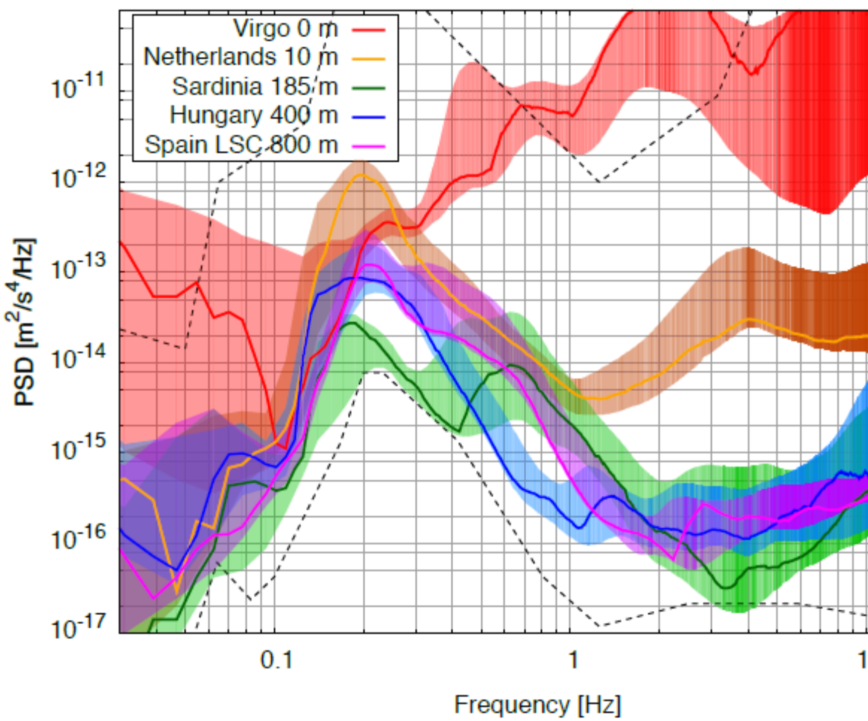


T site: 3 candidates



- What are the technical selection parameters
- How the site in Sardinia matches these parameters
  - Complete the site qualificat

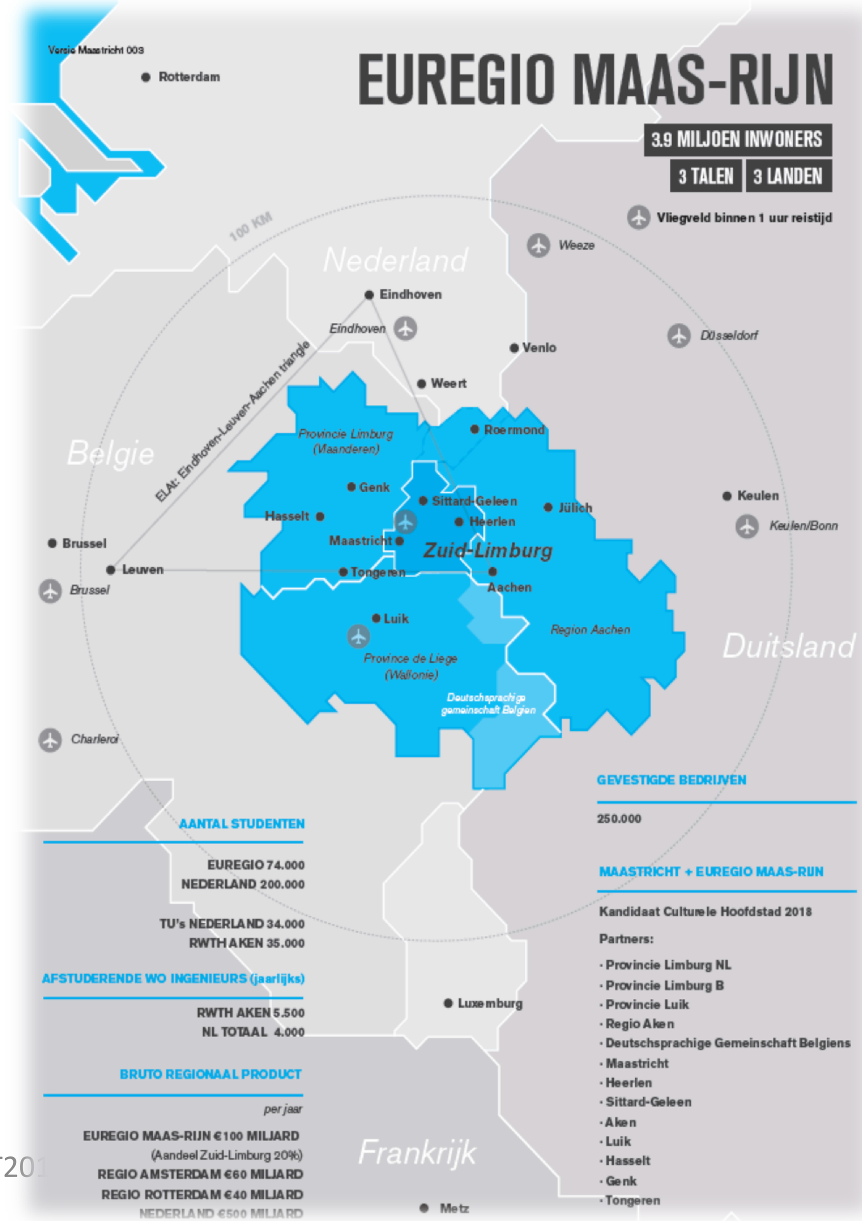
Horizontal spectral motion at various sites



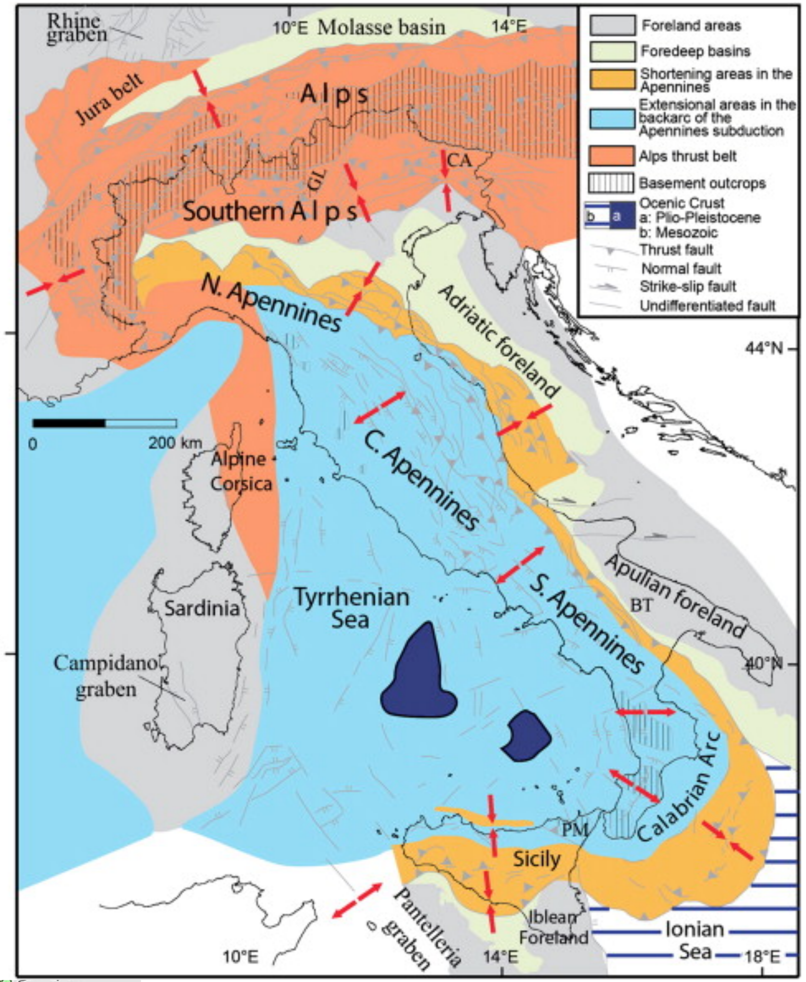
M.
GW

EUREGIO MEUSE-RHIN

- proposal to realize ET in the Limburg area
- strong asset: a detector hosted by 3 untries (B-D-NL)
- tial funding (4-6M€) by NL and B

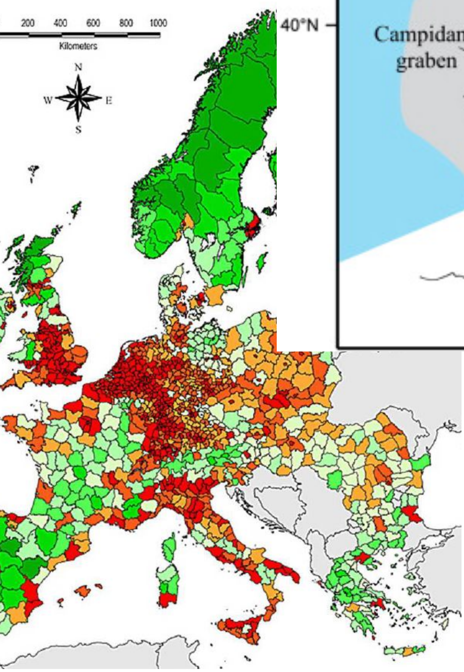


SOS ENATTOS

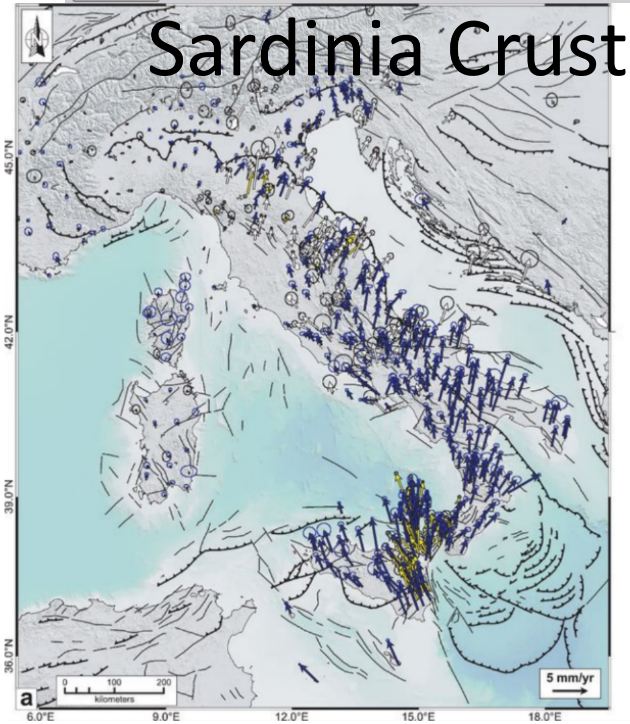


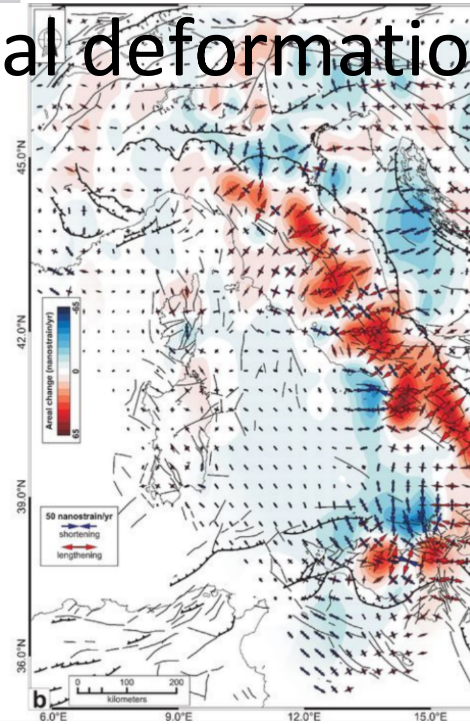
2 earthquakes M>1.5 in the last 10 yea

https://earthquake.usgs.gov/

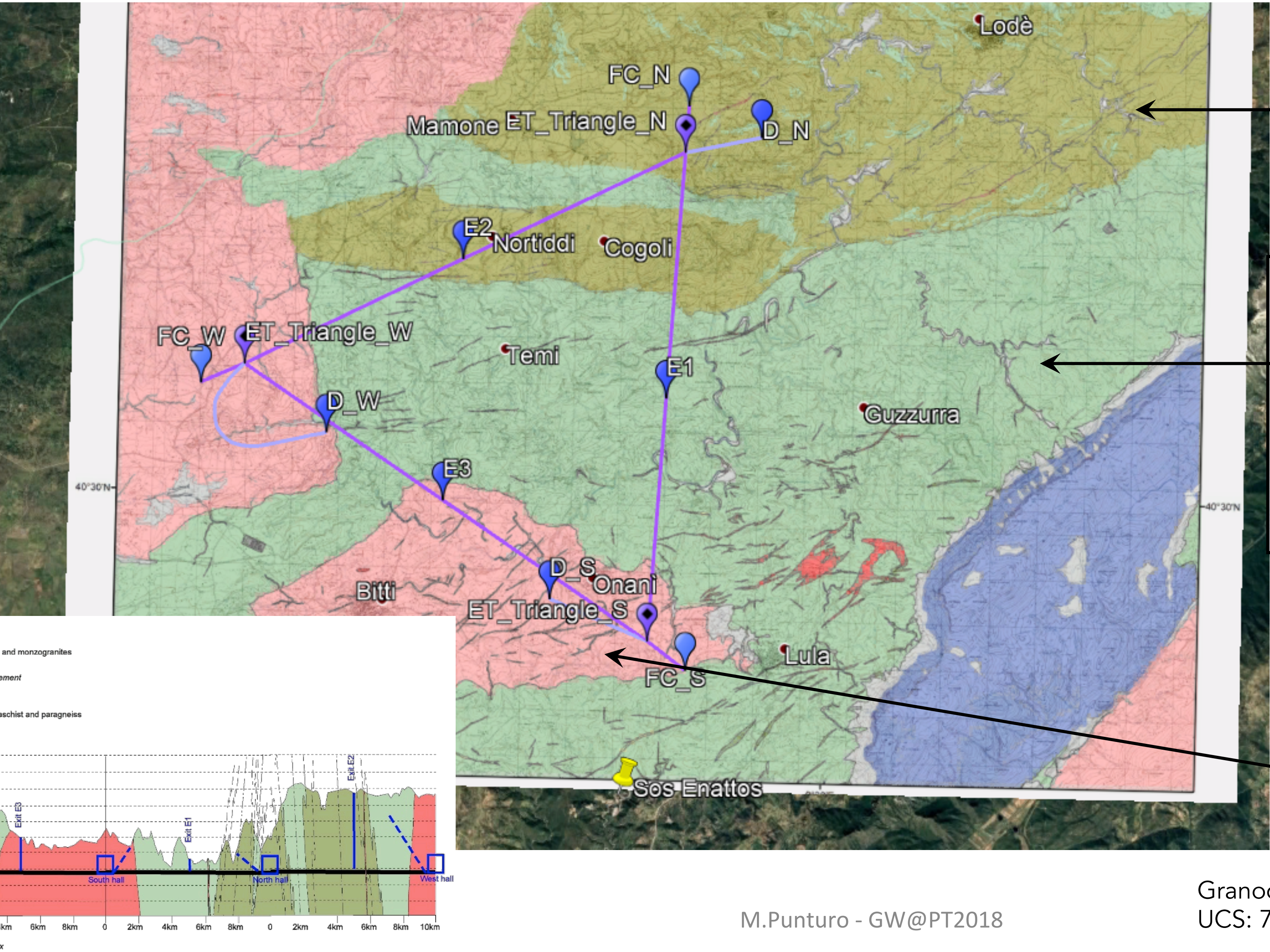


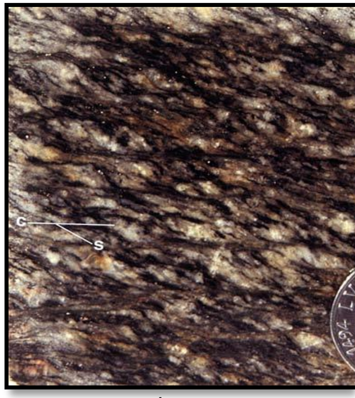
Sardinia Crustal deformatio



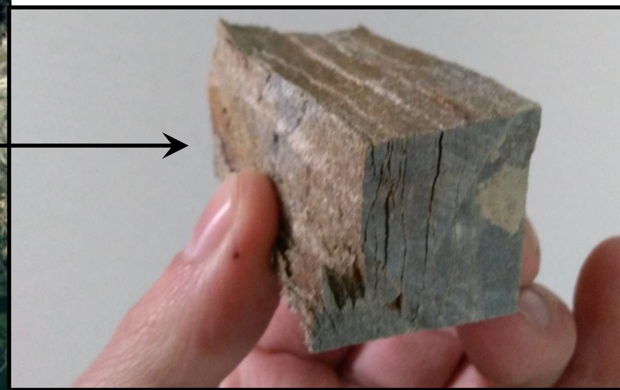


LOCATION - TRIANGLE

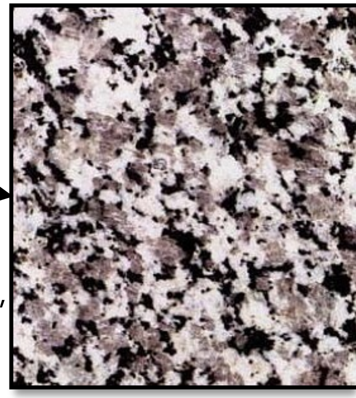




Orthogneiss "Loc
UCS: 92.6/60.8 M



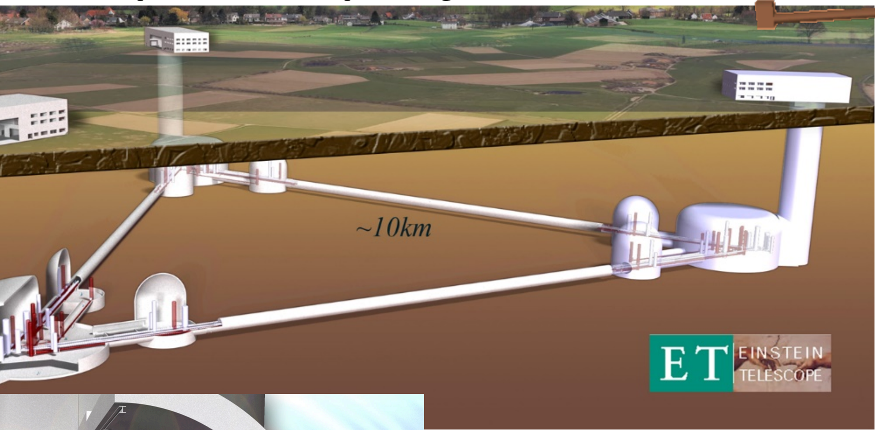
Micaschist – Paragneiss - Quartzite
UCS: 9.9/8.8 MPa

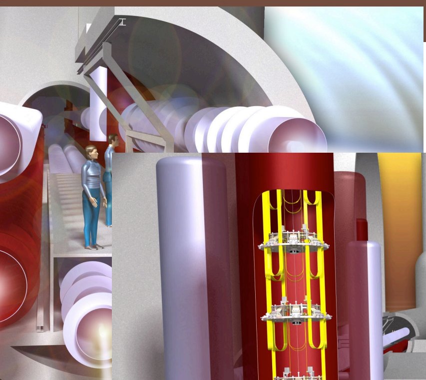


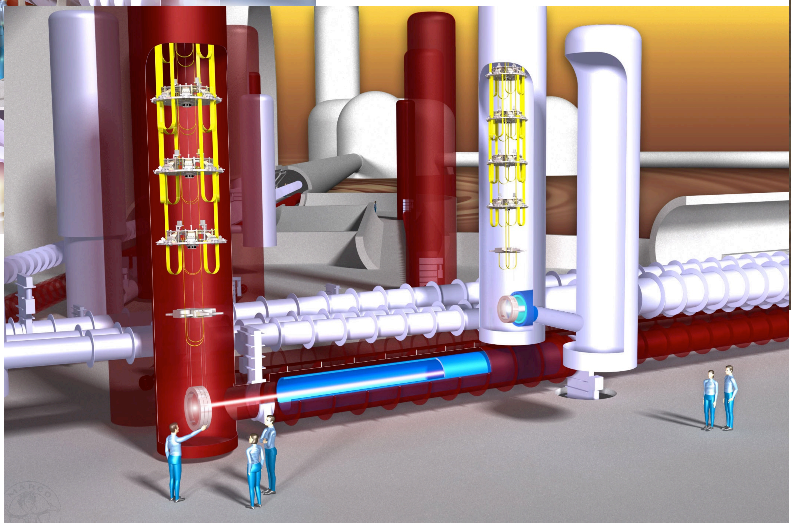
Granodiorite "Bitti type"
UCS: 72.1 MPa

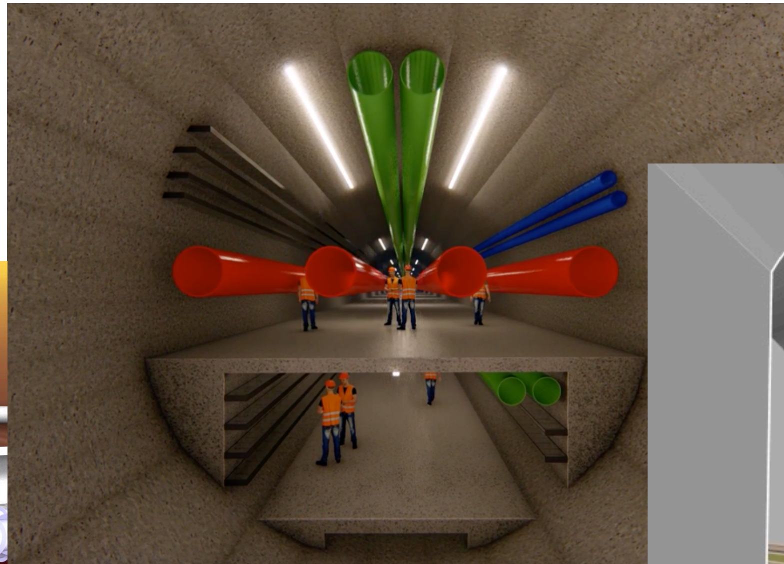
From the conceptual to the technical design

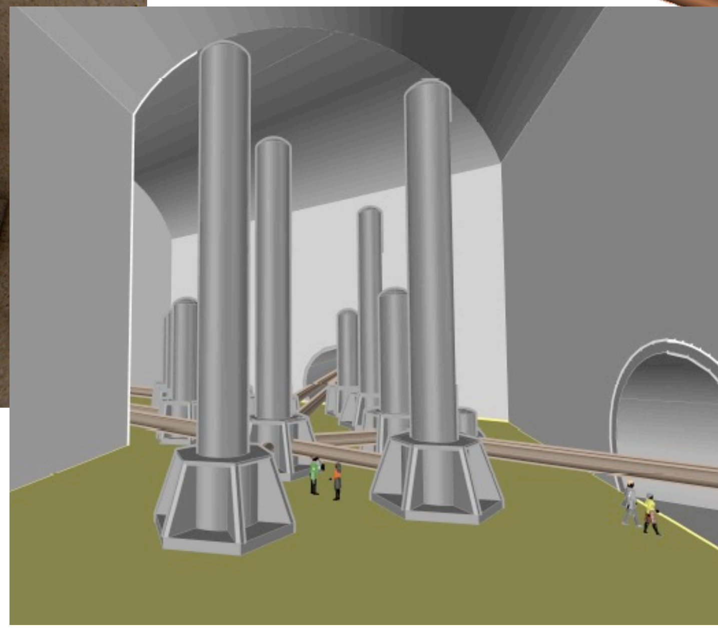
urrently our efforts are addressed to transform the ET infrastructure
oncept in a project











EINSTEIN TELESCOPE

Activities at/for Sos Enattos site

- We need to qualify the site with seismic and environmental measures
- We need to put the seed for the future ET infrastructure
- Thanks to the support of the Regione Sardegr we are realising an underground lab (SarGrav all the experiments that need very low level o seismic and environmental noise
- CSN2 funded a fundamental physics experime for measuring the relationship between vacuu fluctuations and gravity
  - Archimedes

Financial resources: Italy

Italian government promised 17M€ for the upgrade of AdV and the candidature of Sos Enattos for ET

- 5,5M€ have been delivered to INFN in the 2018 FOE
- A good fraction is used to support AdV+
- A part of the remaining budget will be used to support Sos Enattos candidature

Regione Sardegna provided 1M€ for Sos Enattos activities

- Sassari University

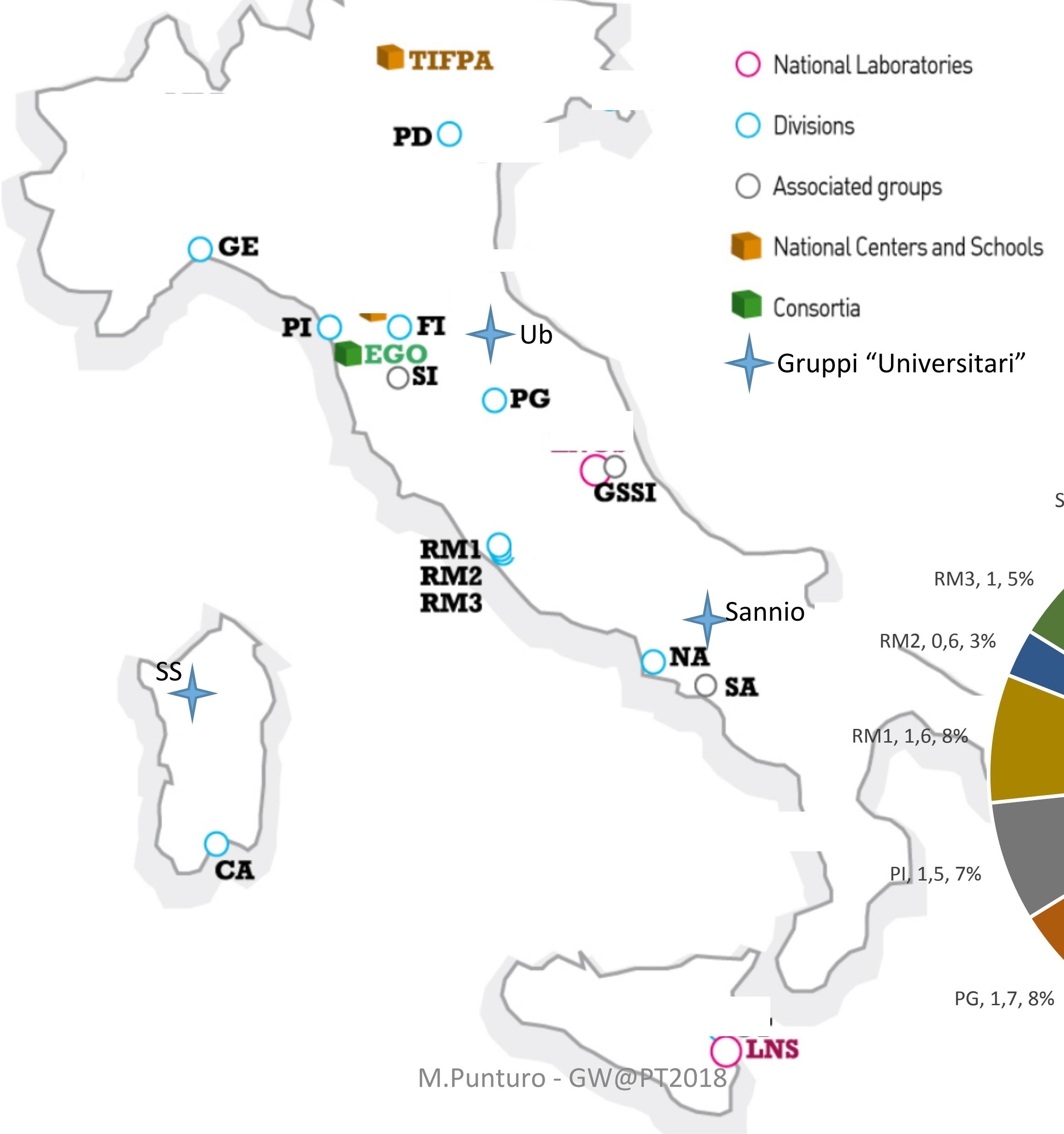
Comunicati stampa

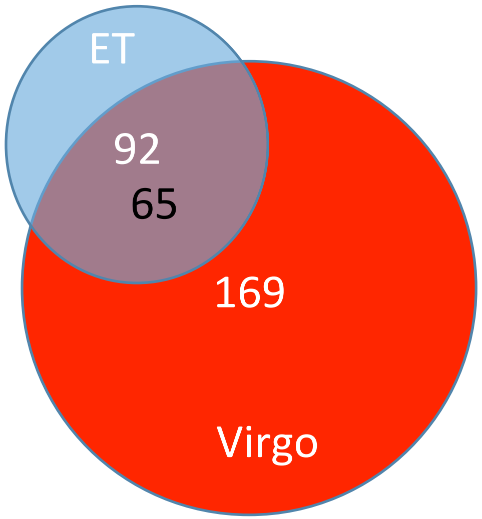
22 FEBBRAIO 2018

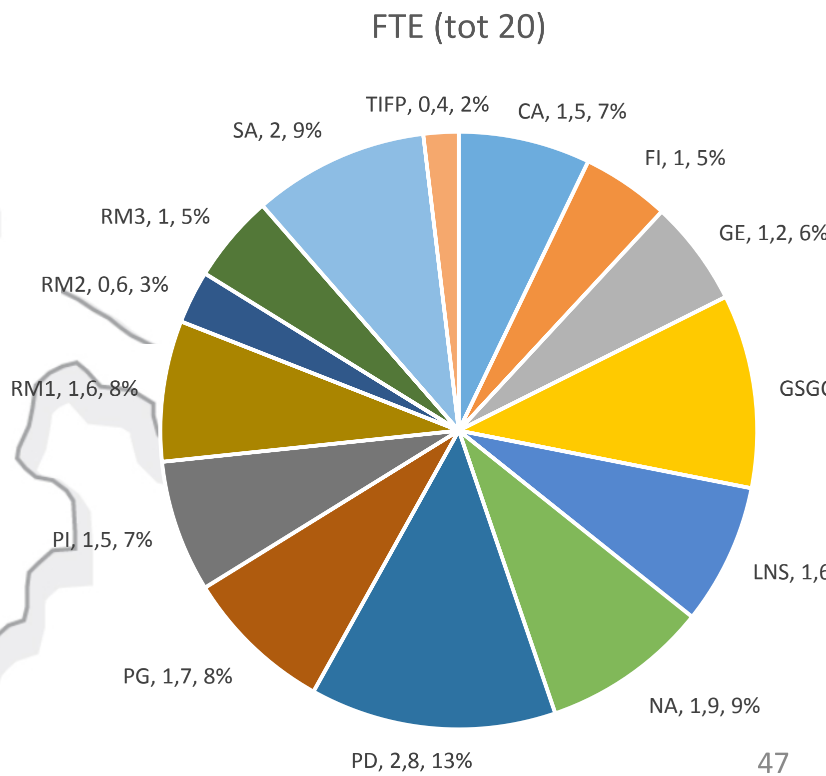
ONDE GRAVITAZIONALI: MIUR, INFN E UNISS CANDIDANO LA REGIONE SARDEGNA A OSPITARE IL FUTURO OSSERVATORIO INTERNAZIONALE

COMUNICATO CONGIUNTO MIUR/INFN/REGIONE SARDEGNA/UNISS_Il Ministero dell'Istruzione, dell'Università e della Ricerca sosterrà la candidatura della Regione Sardegna a ospitare un Centro europeo per l'Osservatorio delle onde gravitazionali nella miniera di Sos Enattos a Lula. Il MIUR, la Regione, l'Istituto Nazionale di Fisica Nucleare e l'Università di Sassari hanno firmato un Protocollo d'intesa finalizzato a mettere in atto ogni iniziativa utile a favorire l'insediamento della infrastruttura Einstein Telescope nell'Isola, anche con lo scopo di entrare nella lista delle infrastrutture di ricerca riconosciute a livello europeo. Il progetto era stato presentato lo scorso 7 febbraio a Roma alla ministra Valeria Fedeli dal presidente della Regione Francesco Pigliaru e dall'assessore della Programmazione Raffaele Paci, ricevuti al Miur insieme al presidente dell'Istituto Nazionale di Fisica Nucleare Fernando Ferroni e al rettore dell'Università di Sassari Massimo Carpinelli

CSN2:ET Italia



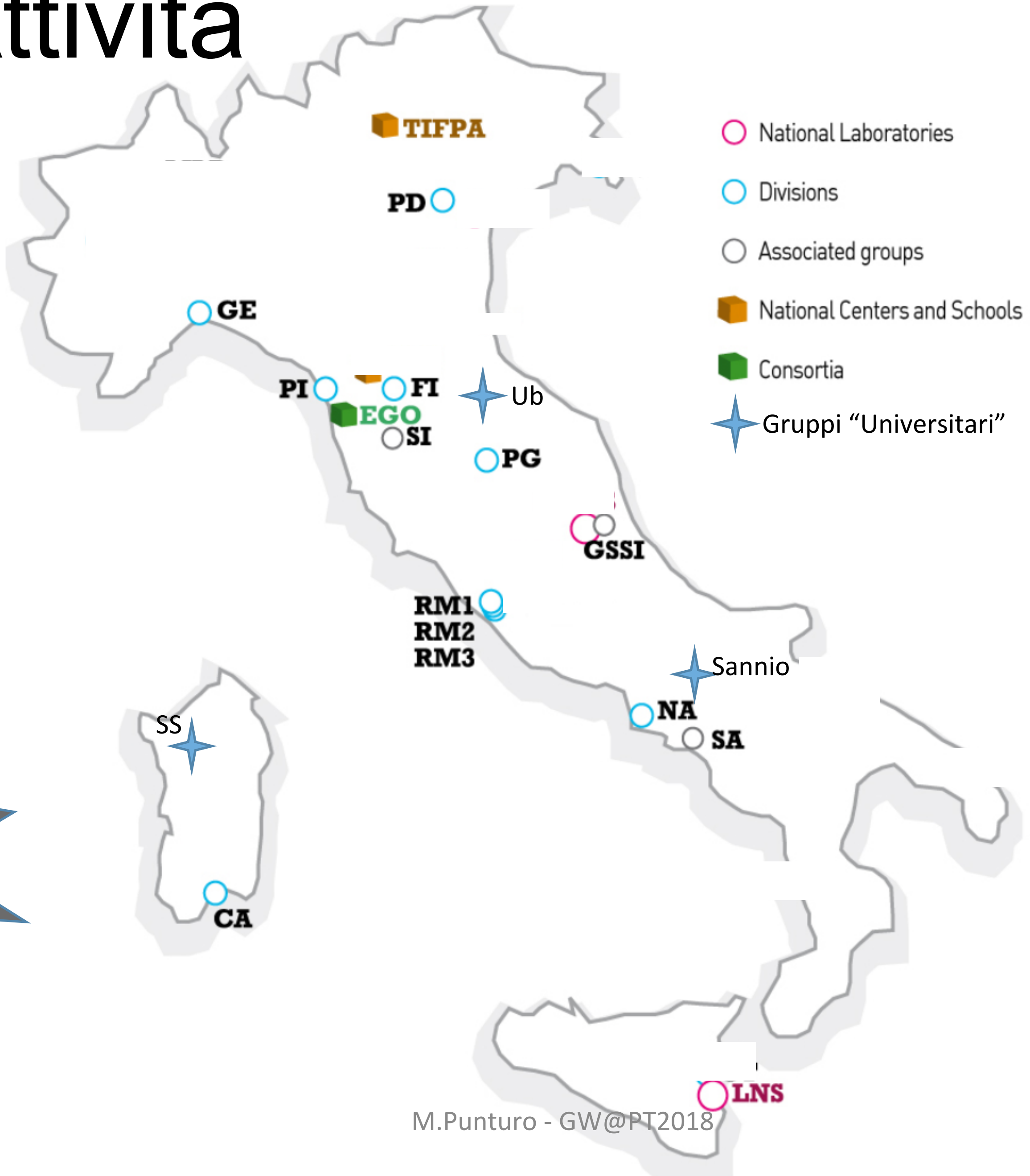




Attività

A1: Management Internazionale

A2: Qualificazione e candidatura del sito



A4: Science Case

A3: Enabling technologies

Einstein Telescope

01/02/1940 – 16/11/2017