The future of Gravitational wave detection is passing through Sardinia……

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on behalf of the ET Collaboration

Slide credits: G. Losurdo, S Hild, F Linde, H Lück, M Punturo, B Sathyaprakash, M Vasuth, …

OUTLINE

INTRODUCTION

WHY 3G? WHY NOW?

- LIGO and Virgo both have facility-imposed limits on sensitivity
  - length, on surface site, obsolescence
  - At best a factor 3 in sensitivity can be gained wrt to the “advanced” LIGO/Virgo
- We are ready to realize infrastructure compatible with the development of the interferometric detectors for decades
- The first and second generations have required ~15 years between the concept and the operation
- 3G detector:
  - extend by ~10x the distance of sight wrt to the “advanced detectors”
  - entend the bandwidth towards lower frequencies (1 Hz target)
- EINSTEIN TELESCOPE: concept developed in a FP7 Design Study, involving France, Germany, Italy, the Netherland, UK
  - today the ET community also involves Belgium Hungary, Poland, Spain, …

SCIENCE CASE

Extreme matter
Extreme gravity
Extreme universe

A NEW WINDOW ON GRAVITY

- Precision tests of alternative theories
  - black hole dynamics “we are studying geometry..”
  - polarizations
  - graviton mass
  - Lorentz invariance
- Exotic compact objects
- BH QNM
- Black holes populations and related open questions

Detector	GW150914 SNR	QNM SNR
O1	25	7
Advanced LIGO	80	20
LIGO-India ALIGO+ (2024)	250	80
ET (2030)	800	200
Cosmic Explorer (2034)	2400	800

BBH population study

The detected signals confirmed the existence of black holes with masses larger than $60\,M_{\odot}$

- ❖ How many black holes? Which size? How are they formed?
- ❖ How metallicity environment influence the formation ? (stellar wind depends on metallicity)

Two models for the binary black hole formation:

- ✓ Two object formed and exploded at the same time from two stars➔ similar spins with the same orientation
- ✓ Black holes in a stellar cluster sink to the center of the cluster and pair up ➔ spin randomly oriented

- ➢ Do it exist miniature black holes ?

  They may have formed immediately after the Big Bang. Rapidly expanding space may have squeezed some regions into tiny, dense black holes less massive than the sun.

BBH population study: from 2G to 3G

EINSTEIN TELESCOPE

Under a simplified hypothesis of a uniform distribution of BBH creation on the universe history

With a 3G detector we expect

- 10^5 y^{-1} BBH
- SNR ~ 10^4 for rare events

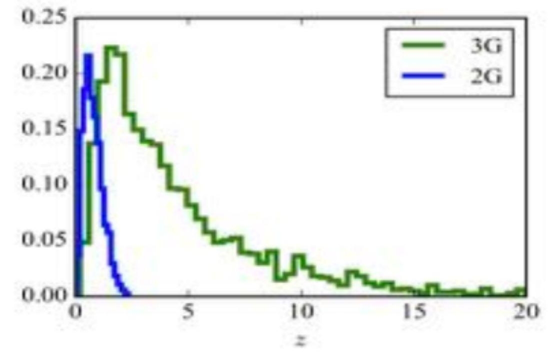


FIG. 2. The redshift distribution of detectable events with a 2-detector network of advanced detectors at design (2G) or CE-like (3G). Note that the two curves use different y scales to improve clarity.

- ➢ Population study biased in function of the achievable SNR

GW signal amplitude depends on $\mathcal{M}^{5/2}$

$\mathcal{M}$ = chirp mass = $(m_1 m_2)^{3/5} / (m_1 + m_2)^{1/5}$

Higher $\mathcal{M}$ ➔ easier detection

GW signal duration decreases ***with*** $M_{tot} = m_1 + m_2$

Too massive systems ➔GW signals at frequency out of the detector bandwidth

In addition the signals detected depend on the redshifted masses M (1+z)

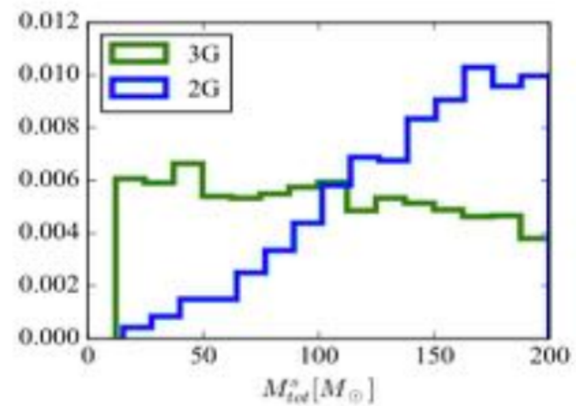


FIG. 3. The source-frame total mass distribution of detectable events with a 2 interferometers network of advanced detectors at design (2G) or CE-like (3G).

Salvatore Vitale, Phys. Rev. D 94, 121501 (2016)

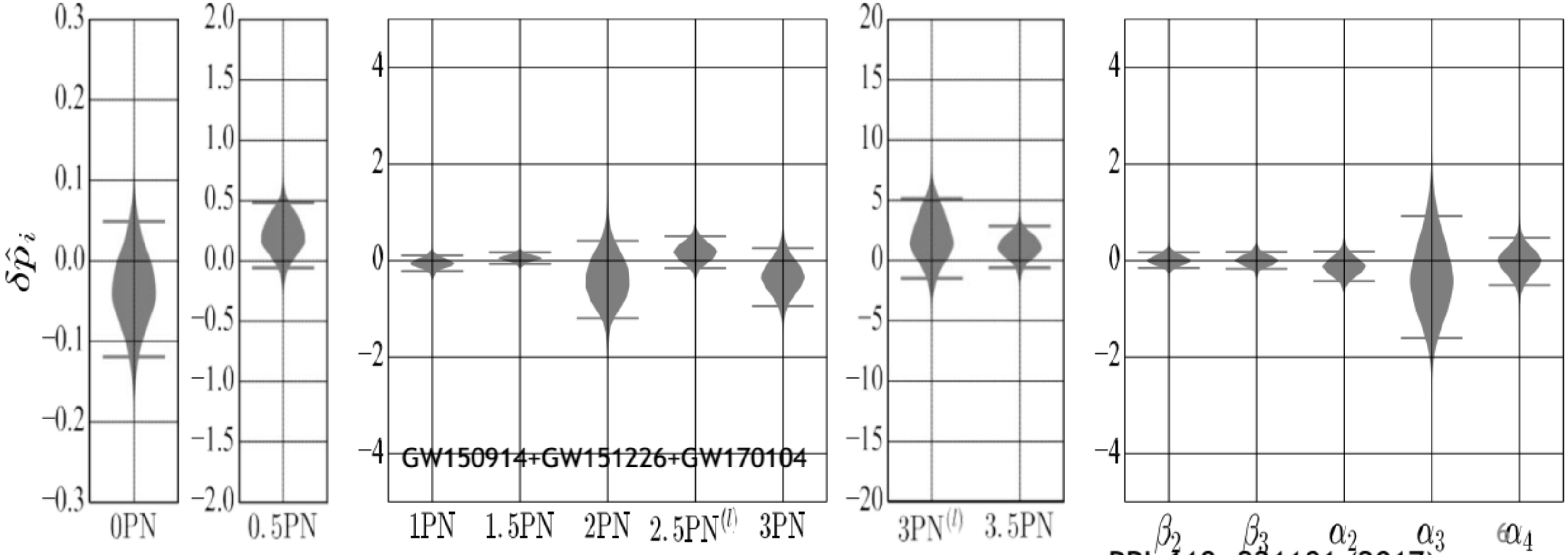
Testing alternative teories to General Relativity via Post Newtonian Parametric Expansion

Phenom consistency test

$$h(f) = A(f,\vec{\theta})e^{i\Psi(f,\vec{\theta})}$$

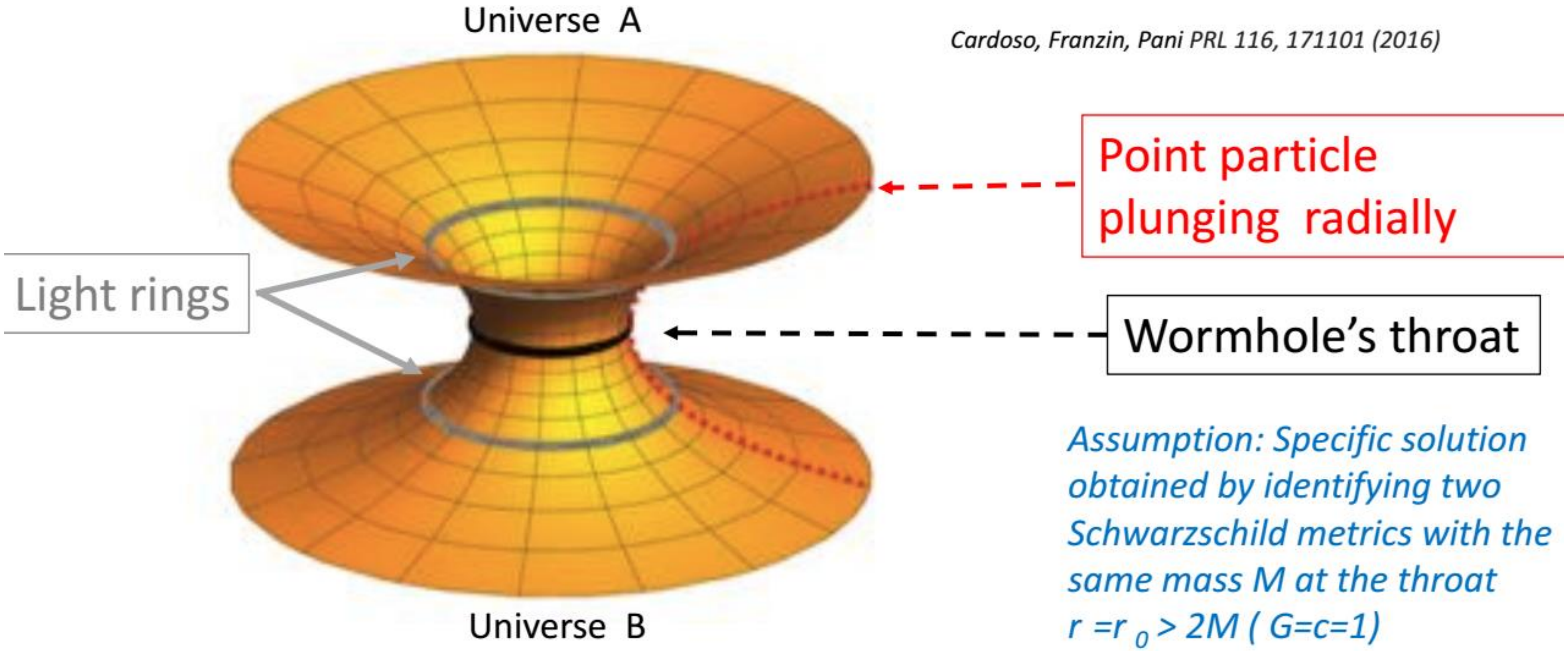
$$\Psi = f^{-5/3}\sum_{i=0}^{7} p_i(\vec{\theta})f^{i/3} + (\log \text{terms})$$

$$p_i \rightarrow p_i(1+\delta\hat{p}_i)$$



PRL 118, 221101 (2017)

The Exotic Universe : Quasi Normal Modes to Probe Wormhole Spacetime



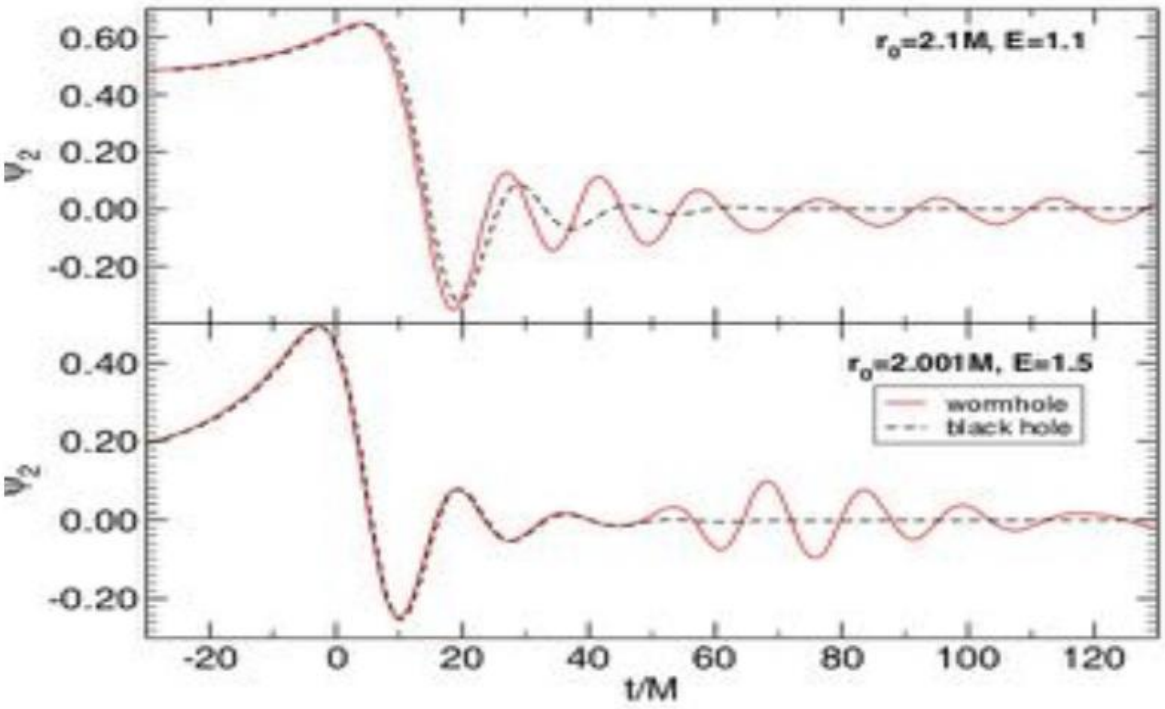
Cardoso, Franzin, Pani PRL 116, 171101 (2016)

Assumption: Specific solution obtained by identifying two Schwarzschild metrics with the same mass M at the throat $r = r_0 > 2M$ (G=c=1)

A point particle plunges radially and emerges in another "universe". When the particle crosses each of the light rings curves, it excites QNM characteristic modes trapped between the light-ring potential wells

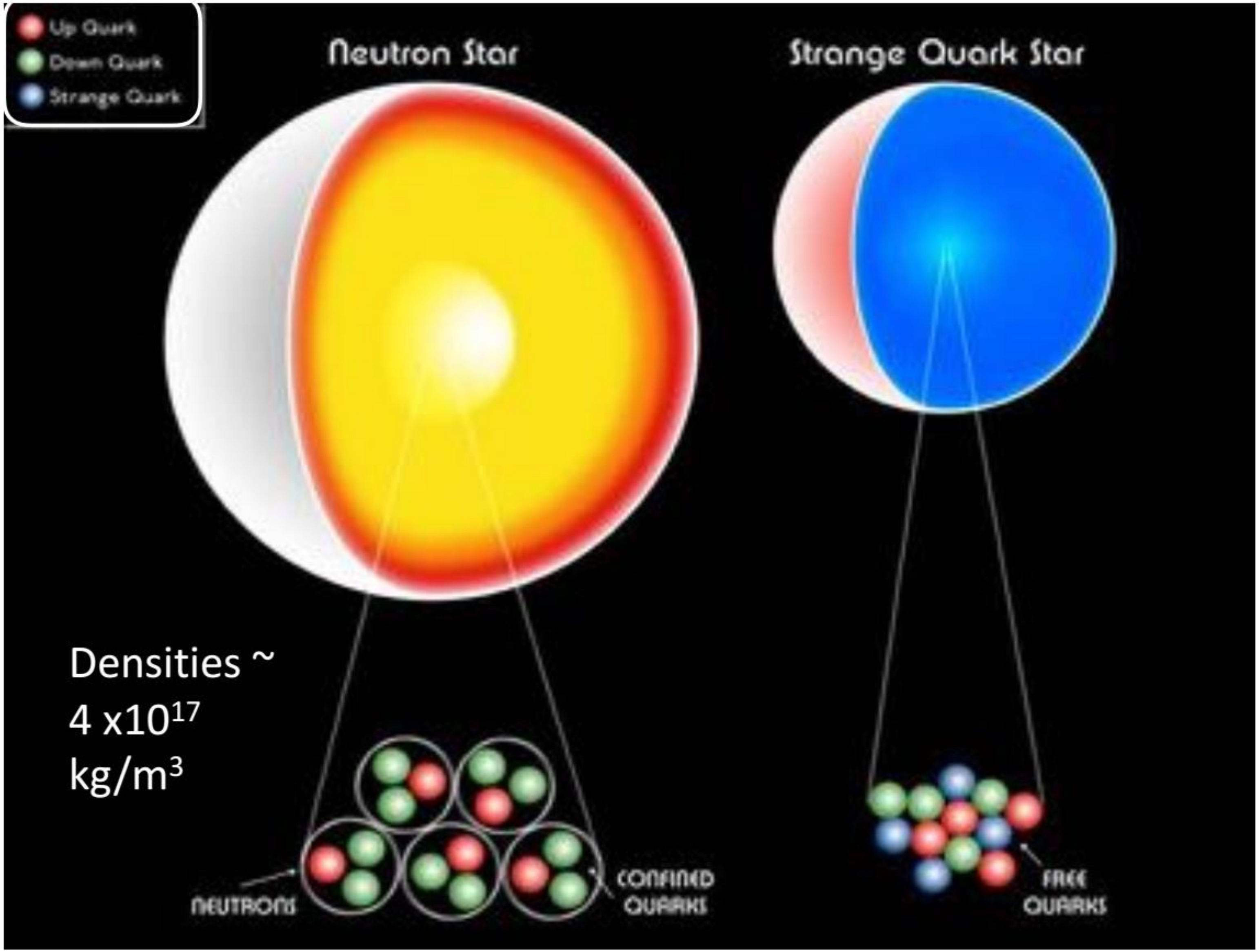
Comparison of the GW waveform between the BH and wormhole case

- Particle plunging into a Schwarzschild BH with the energy E compared to the particle crossing a traversable wormhole



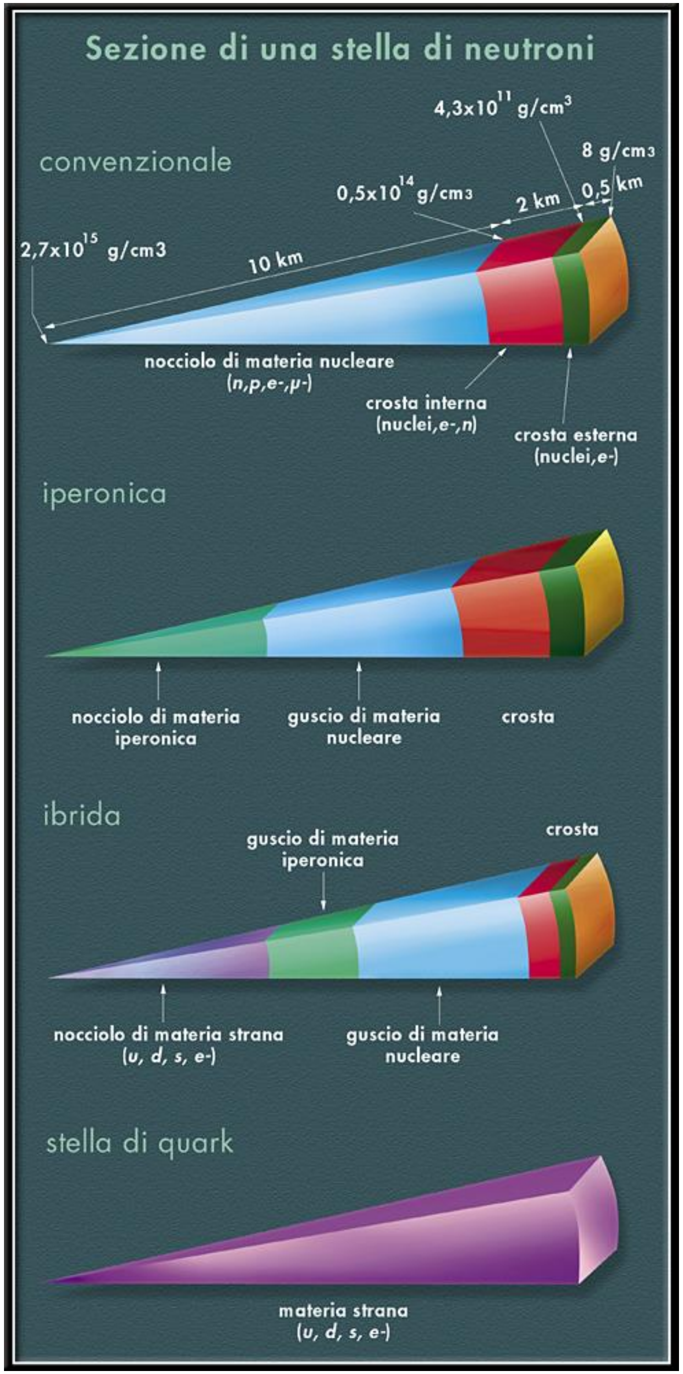
GW waveforms comparison for different values of E.

The BH waveform was shifted in time to account for the dephasing due to the light travel time from the throat to the light ring



Measuring the EOS of dense nuclear matter

“Neutron Stars”



Nucleon Stars

Hyperon Stars

Hybrid Stars

Strange Stars

Why is it very likely to have hyperons in the core of a Neutron Star?

- **The central density of a Neutron Star is “high”:**
- $n_c \approx (4 - 10)\, n_0$ $(n_0 = 0.17\ fm^{-3})$

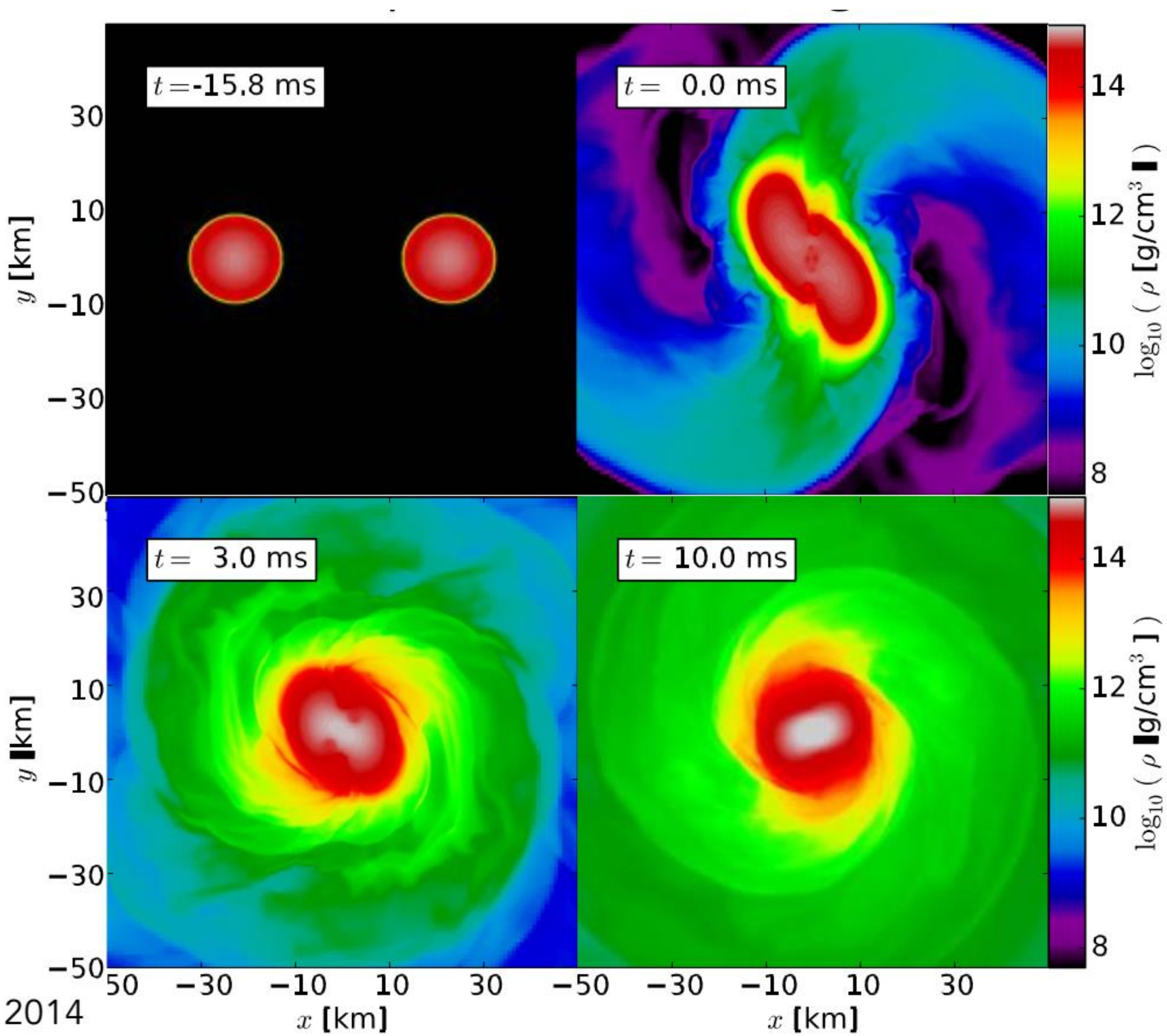
above a threshold density, $n_{cr} \approx (2 - 3)\, n_0$, weak interactions in dense matter can produce strange baryons (hyperons)

$n + e^- \rightarrow \Sigma^- + \nu_e$

$p + e^- \rightarrow \Lambda + \nu_e$ etc.

A. Ambarsumyan, G.S. Saakyan, (1960)
V.R. Pandharipande (1971)

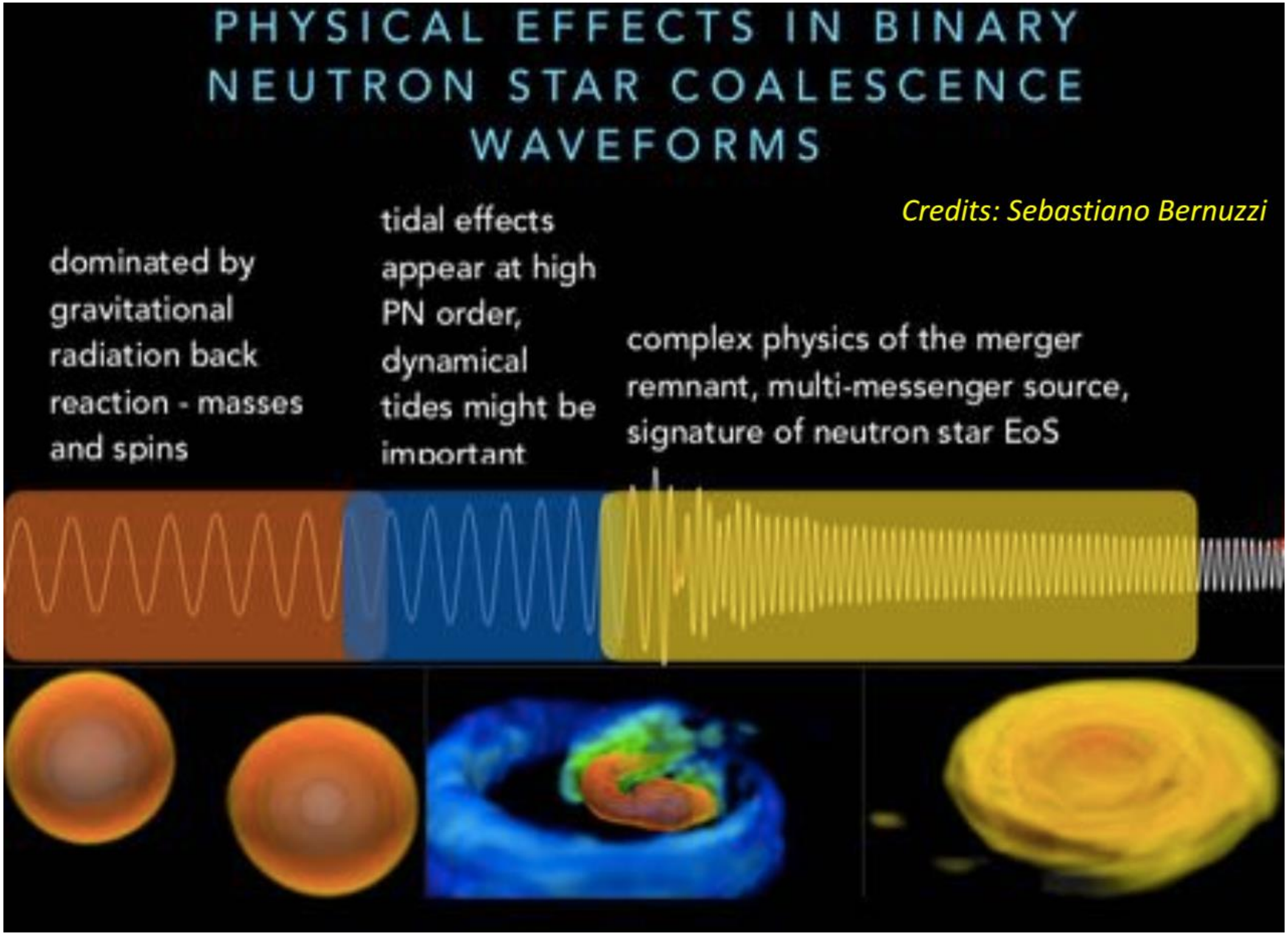
Binary Neutron Star Merger



Takami+ 2014

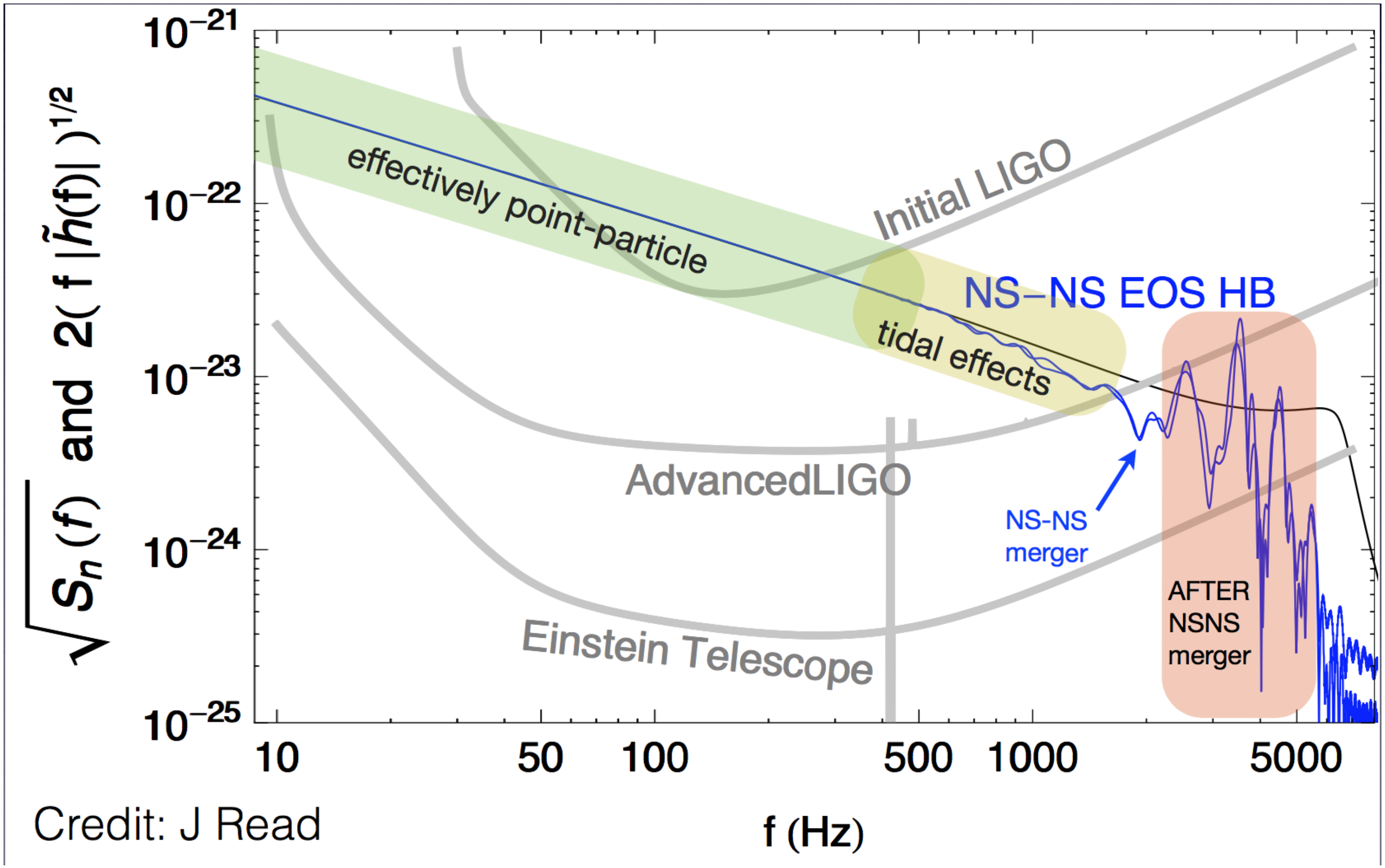
EXTREME MATTER

WE ARE ABLE TO COMPUTE THE WAVEFORMS FOR THE VARIOUS EOS



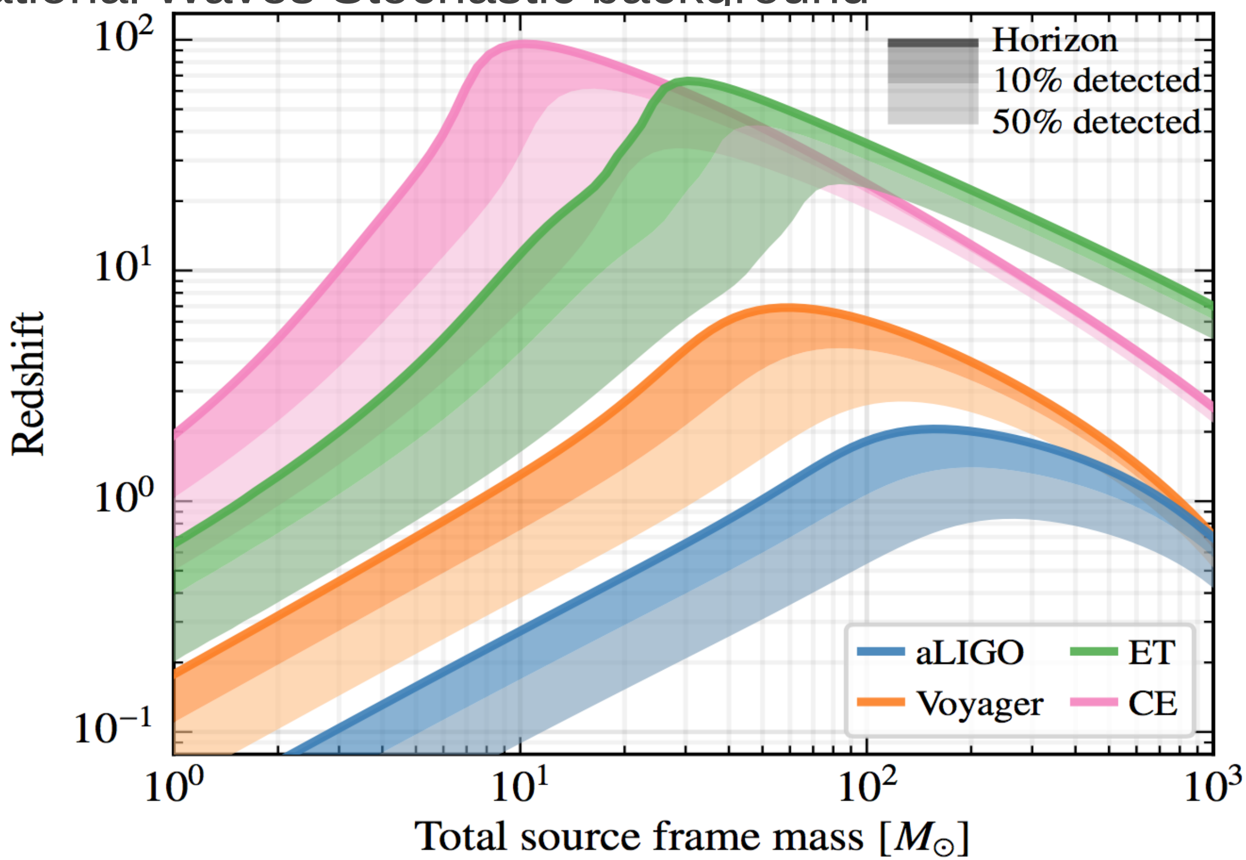
EXTREME MATTER

A 3G DETECTOR IS NEEDED TO MEASURE WHICH EOS IS THE RIGHT ONE



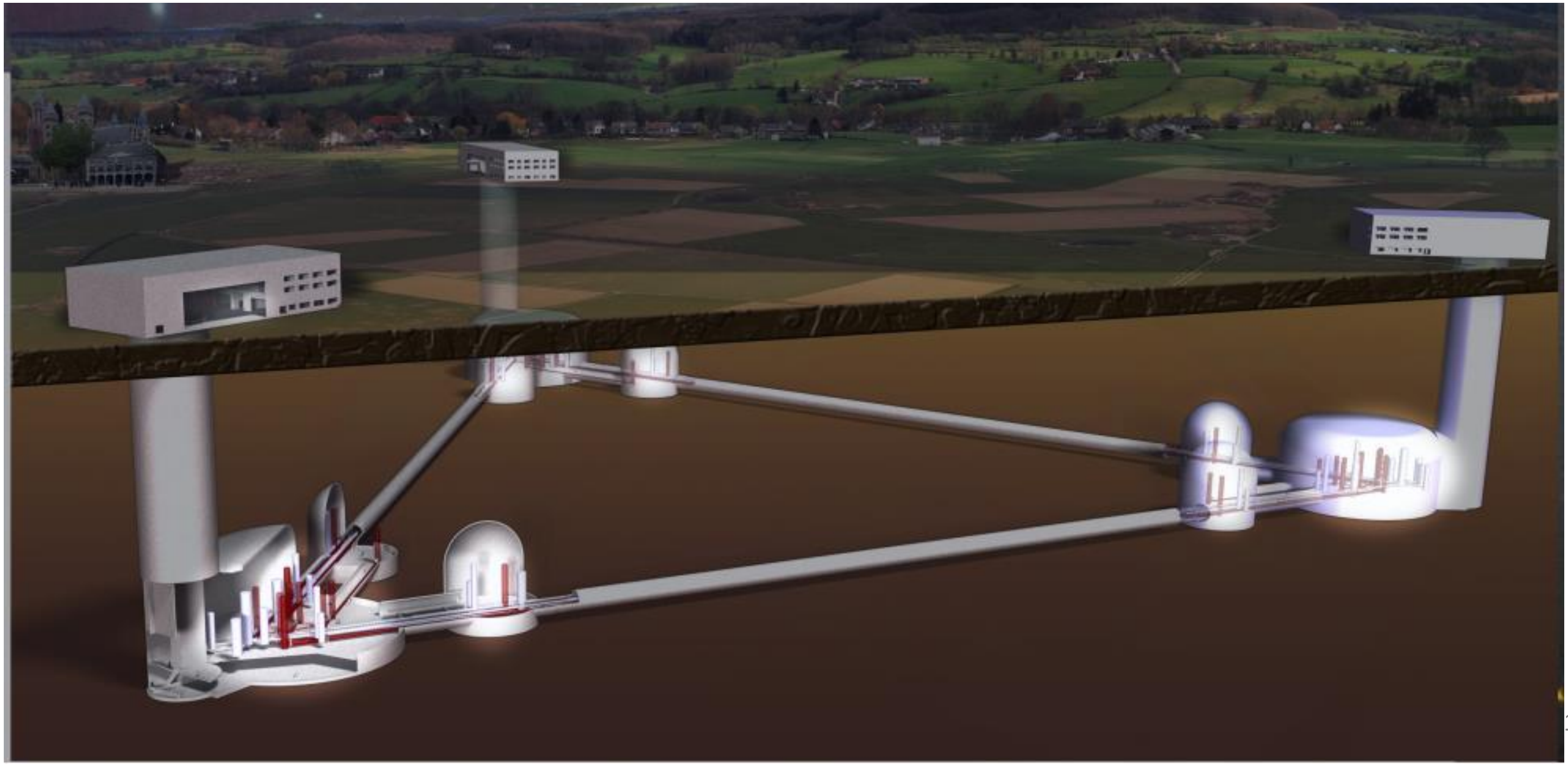
EXTREME UNIVERSE

- Exploring gravity at the remote region of the Universe
- Hubble parameter
- Gravitational Waves Stochastic background

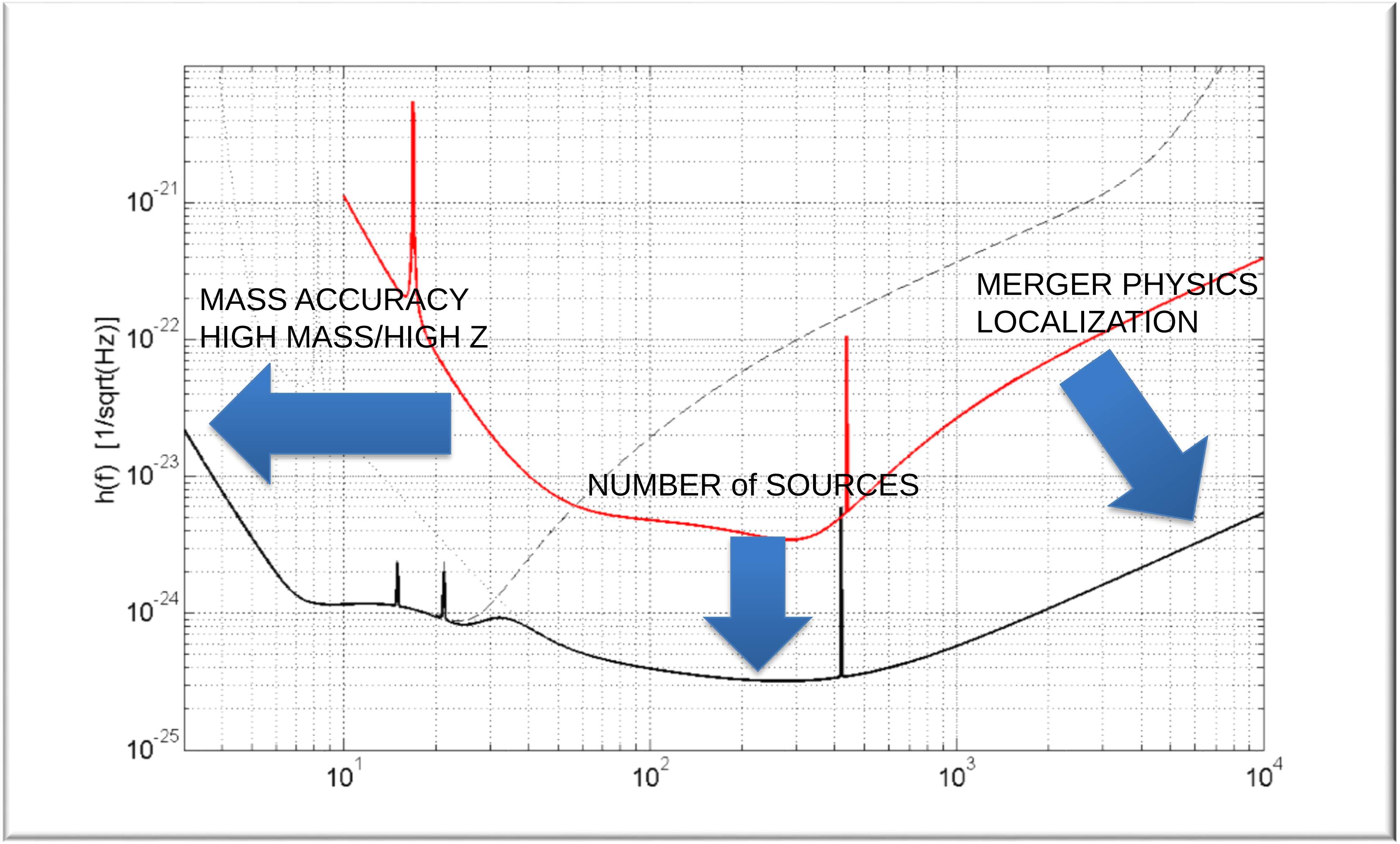


ET CONCEPT

Longer
Cryogenic
Underground



SENSITIVITY GOAL



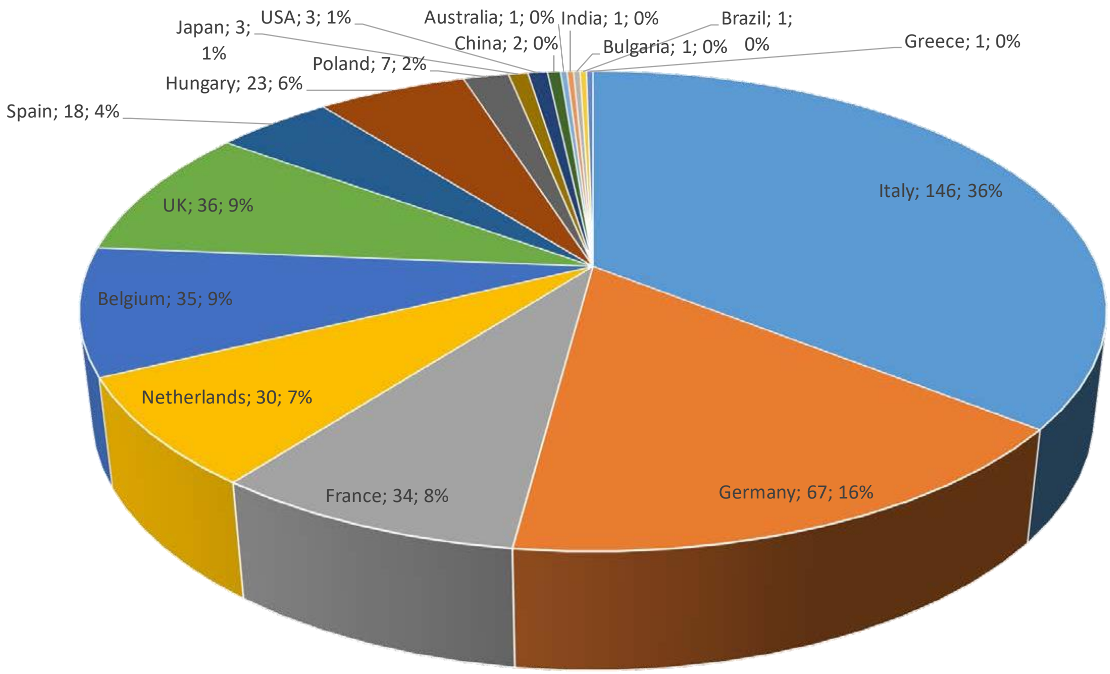
TECHNOLOGIES

- HF DETECTOR
  - “standard” superattenuators
  - large fused silica mirrors (for large beams)
  - high power, frequency dependent squeezing
  - standard laser (1064 nm)
- LF detector
  - “extreme” superattetuators (1 Hz goal)
  - newtonian noise subtraction
  - large silicon mirrors, silicon suspensions, cryogenics (test mass @10 K)
  - new wavelength (1550 nm)
  - low power, frequency dependent squeezing)

- Aggressive R&D program needed

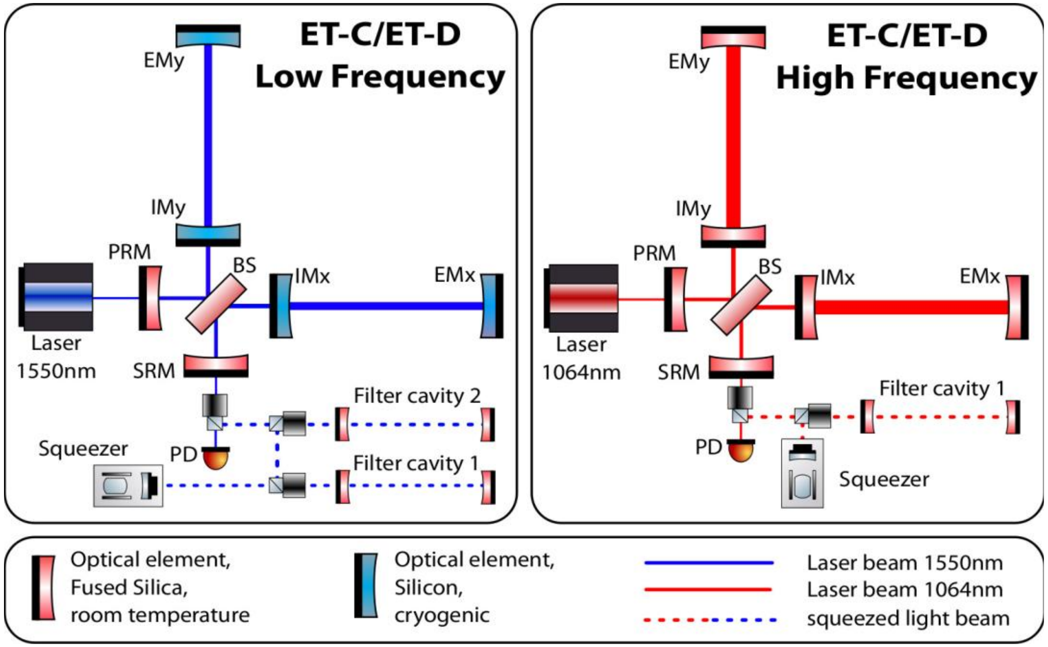
ET COLLABORATION

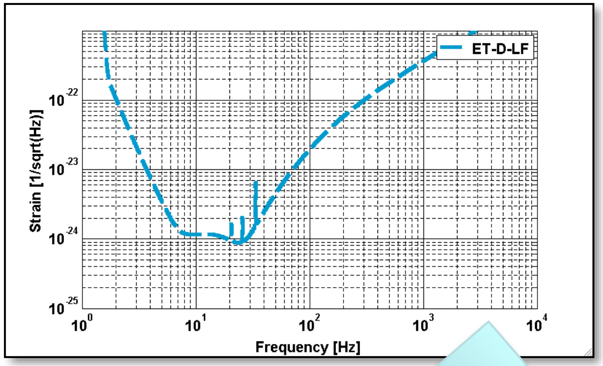
- Call for interested launched at the ET Symposium (May 19-20)
- Adhesions by individual scientists (>400 so far)
- Committee or representatives nominated to write the Collaboration statute and the governance rules

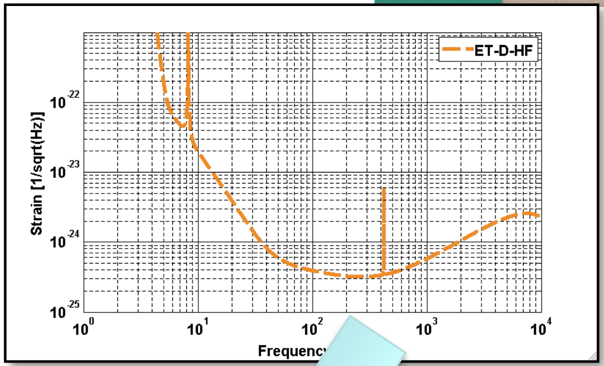


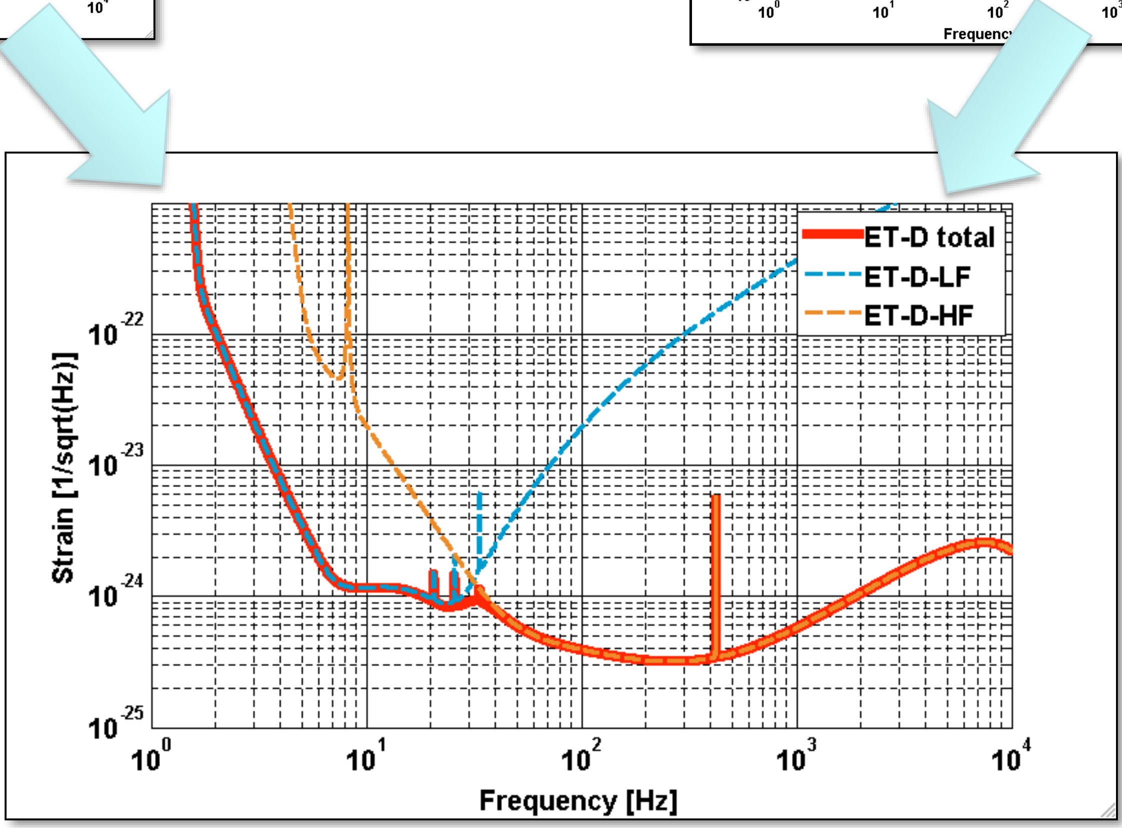
INITIAL ET IDEA to WIDEN THE BAND: XYLOPHONE (Two slightly different detectors in the same site)

- Improving al low and high frequency with a single detector is very challenging
  - HF requires more laser power
  - LF requires cold mirrors
- Idea: split the detection band over 3 “specialized” instruments



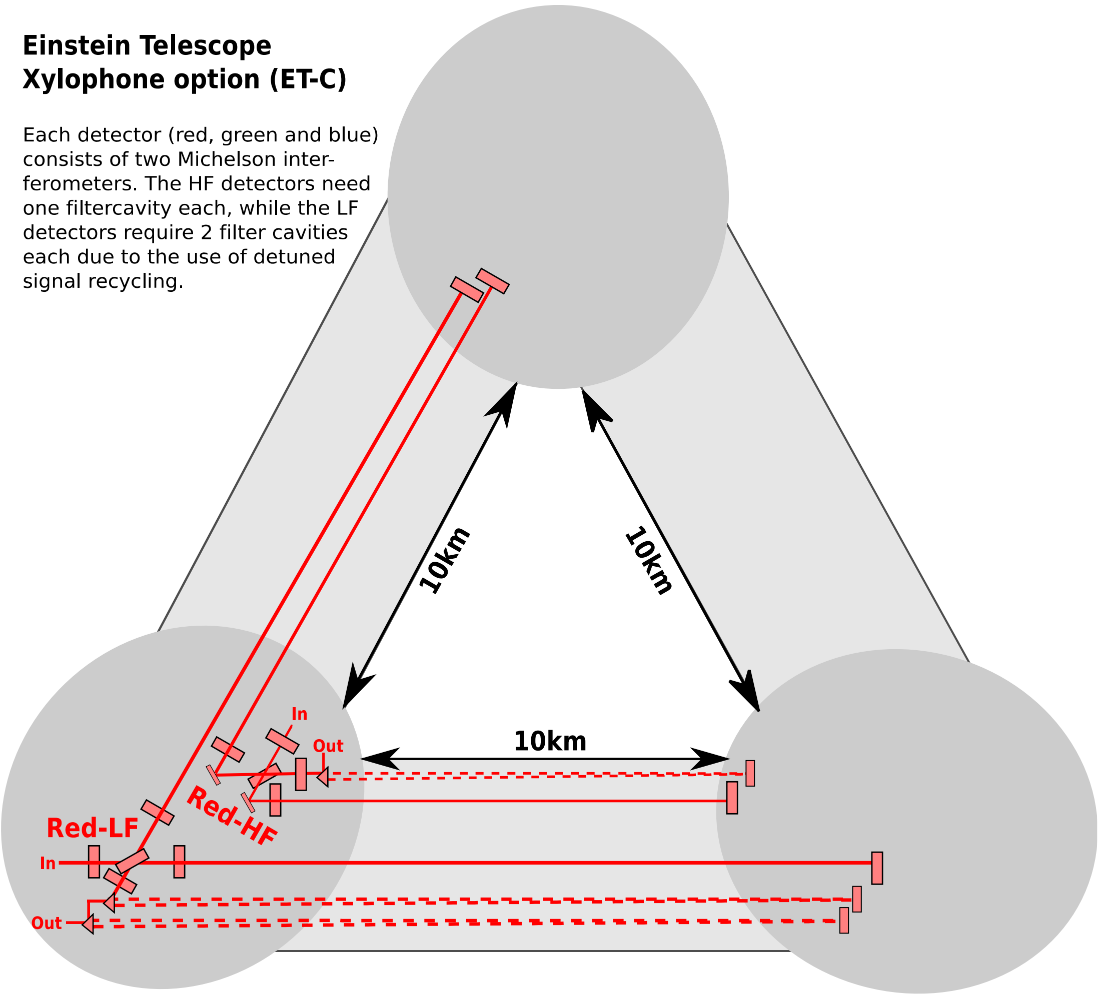

ET-D-LF
Strain [1/sqrt(Hz)]
Frequency [Hz]


ET-D-HF
Strain [1/sqrt(Hz)]


ET-D total
ET-D-LF
ET-D-HF
Strain [1/sqrt(Hz)]
Frequency [Hz]

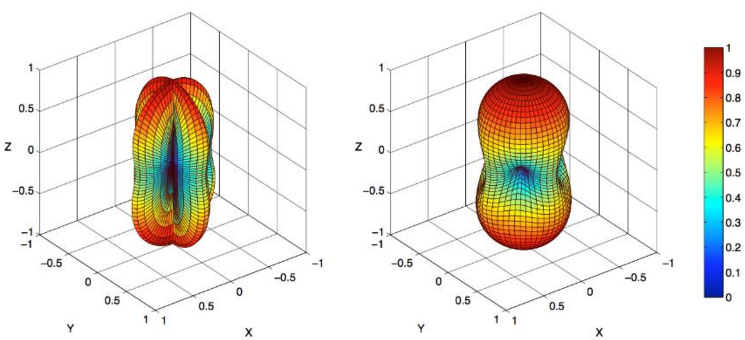
INITIAL IDEA OF ET
STAND-ALONE OBSERVATORY

- Start with a single (xylophone) detector

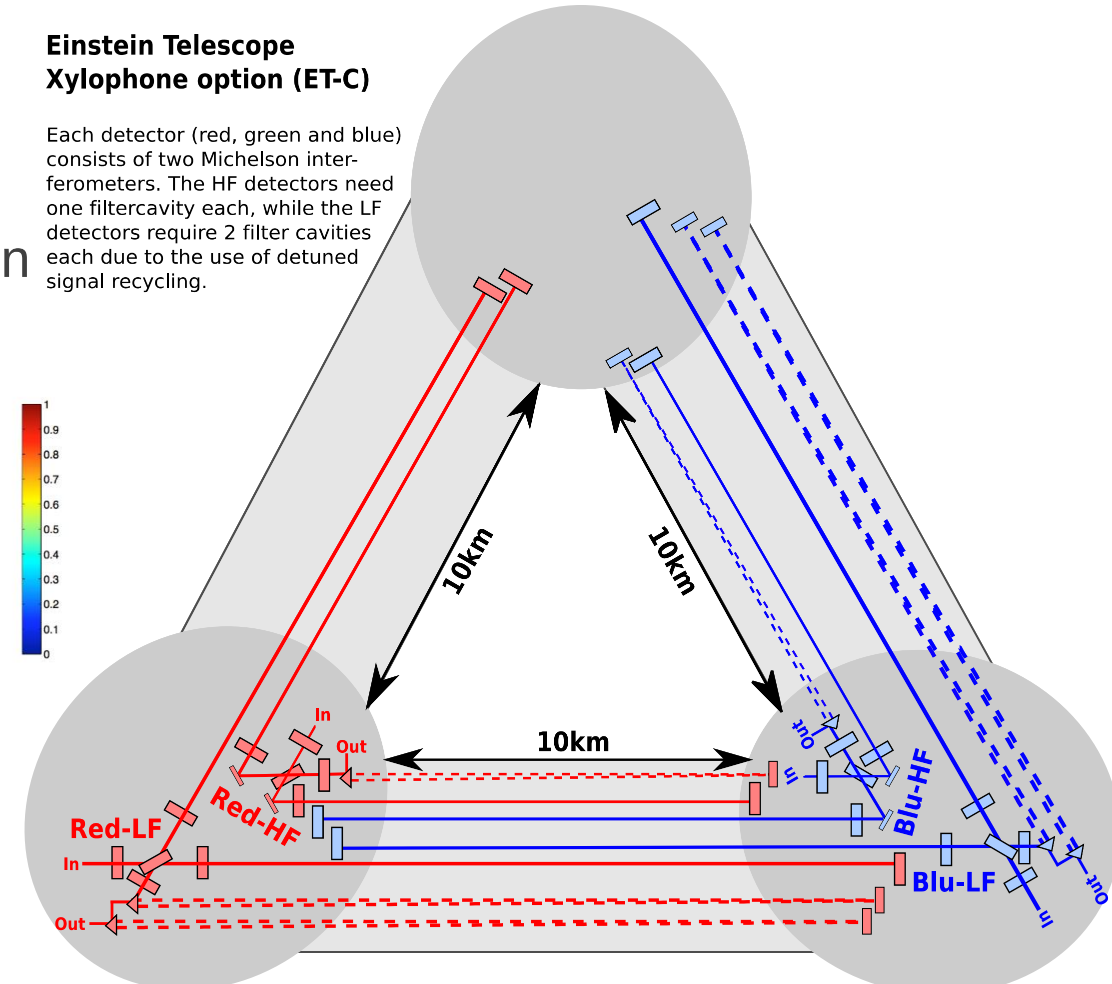


STAND-ALONE OBSERVATORY

- Start with a single (xylophone) detector
- Add a second one to fully resolve polarization

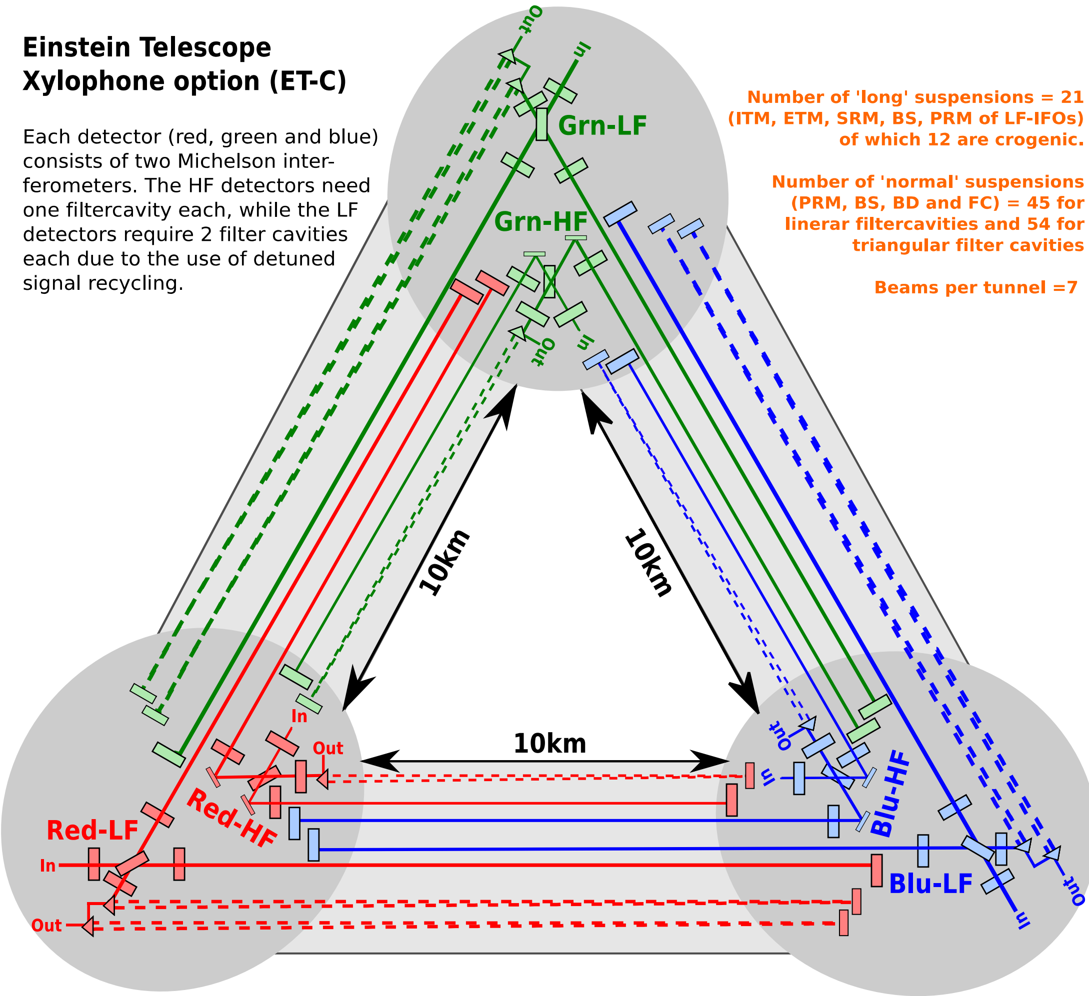


Antenna pattern for a polarized GW: simple “L” (left) vs Triangle (right)

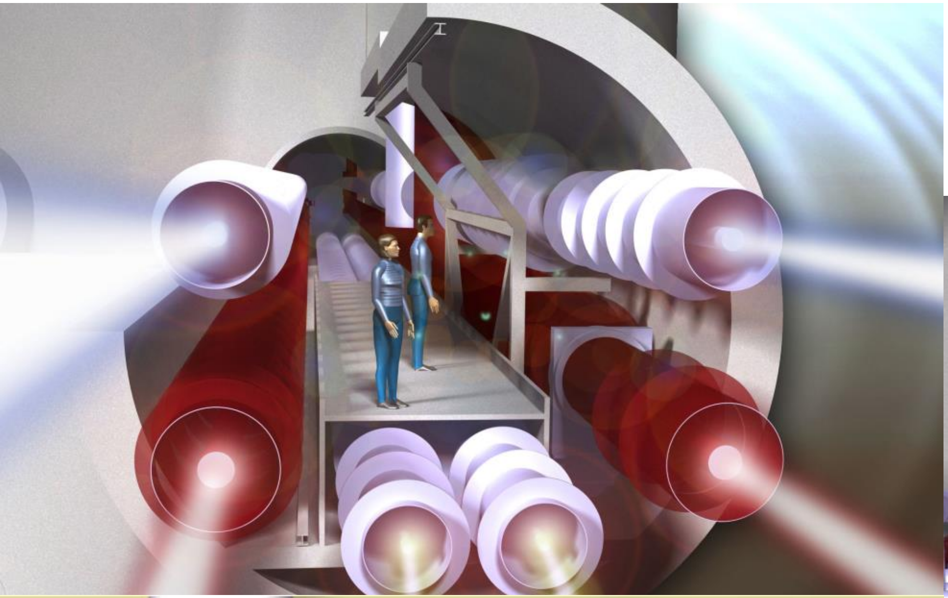


STAND-ALONE OBSERVATORY

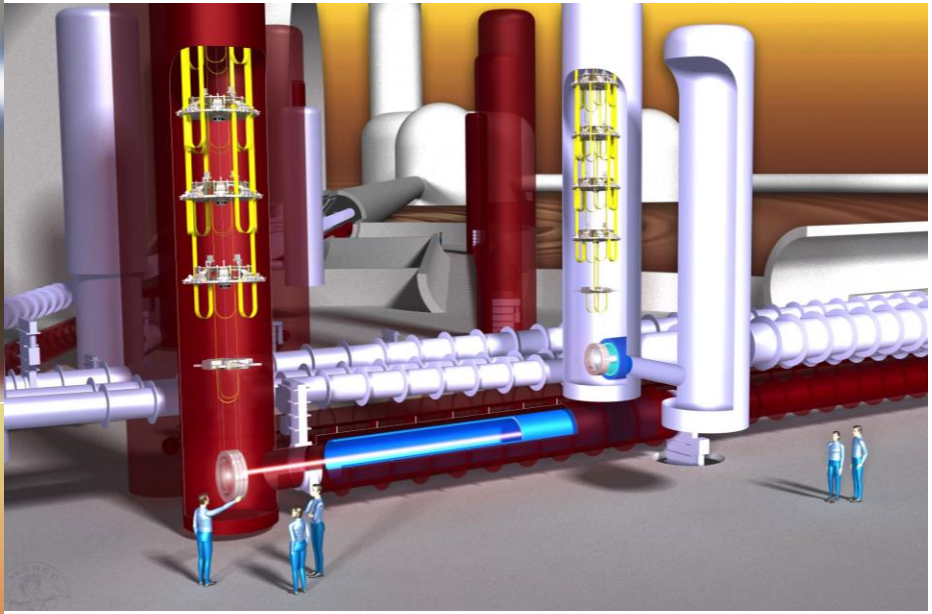
- Start with a single (xylophone) detector
- Add a 2nd one to fully resolve polarization
- Add a 3rd one for null stream and redundancy

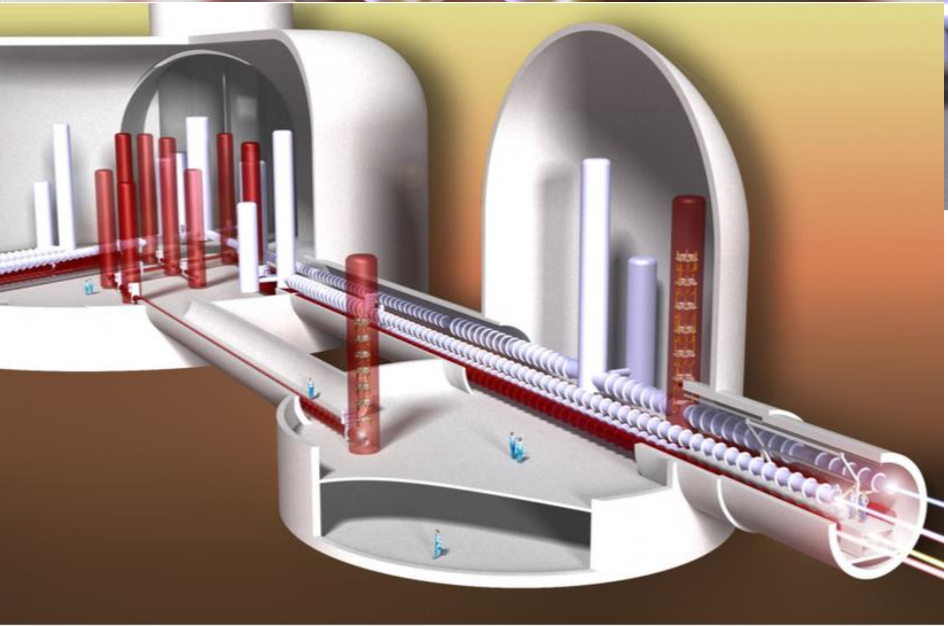


ET INFRASTRUCTURE CONCEPT



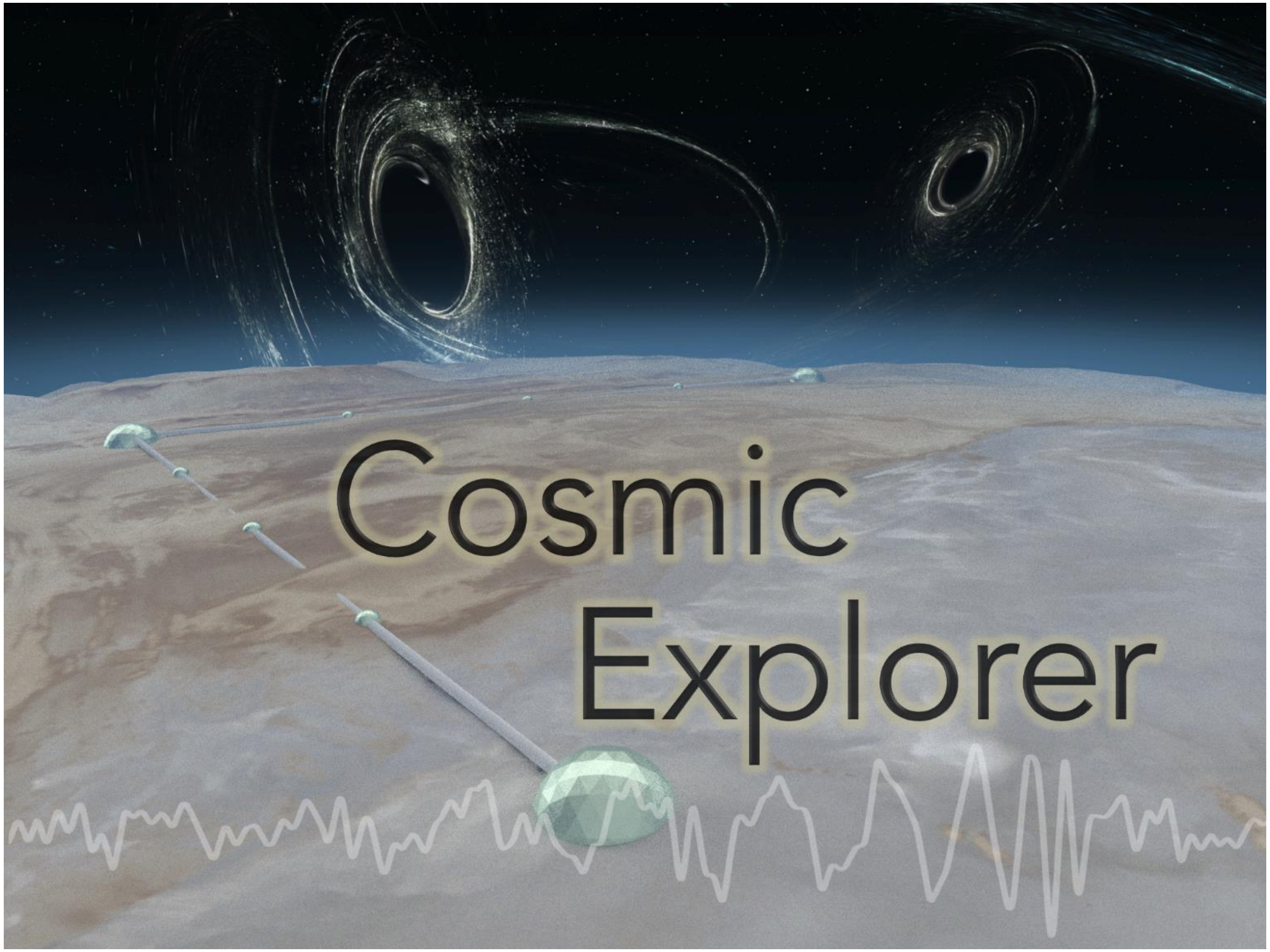
ET DESIGN STUDY, 2011





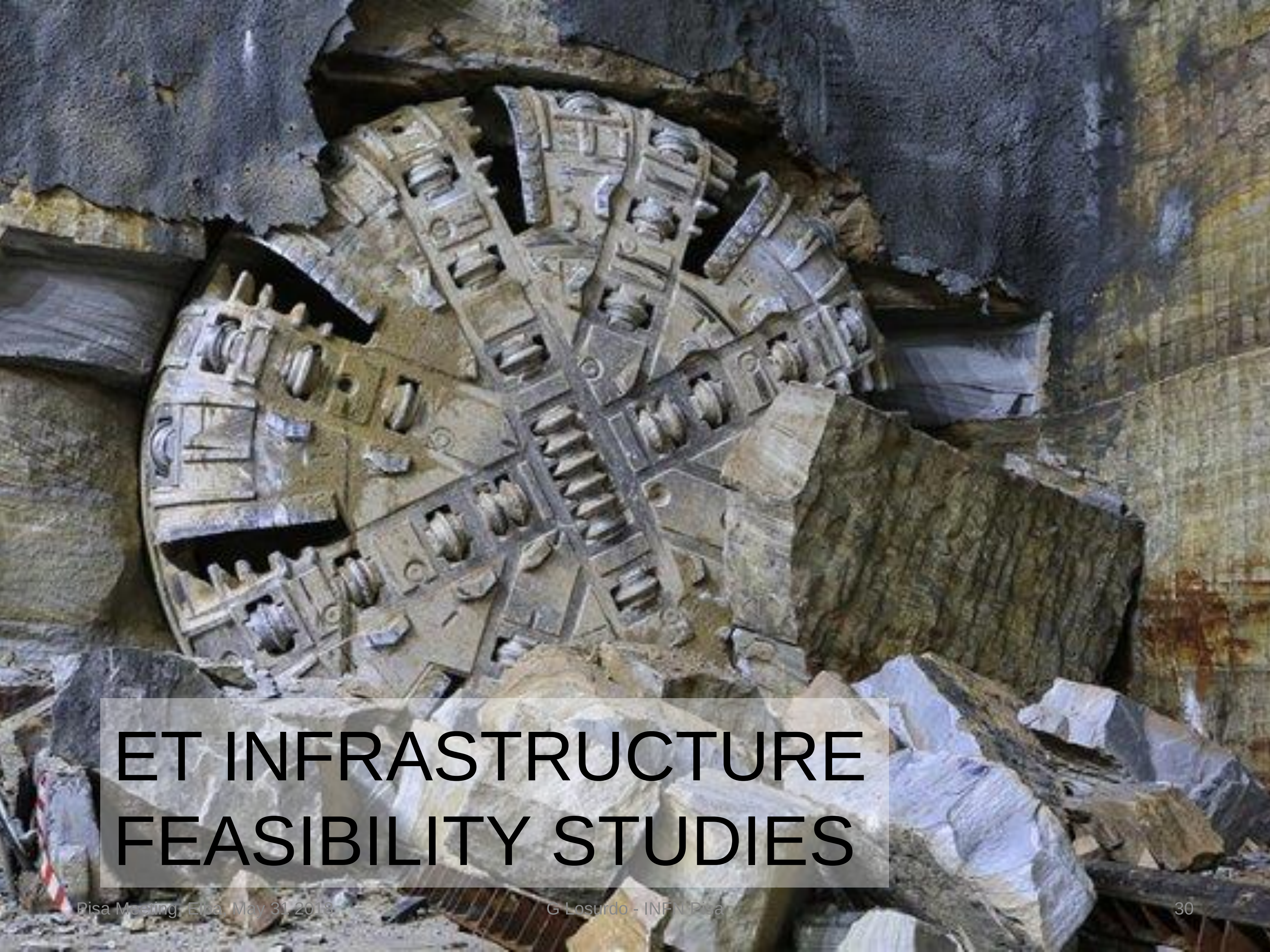
PLANS IN THE US

40 km ON-SURFACE DETECTOR



TOWARDS A 3G NETWORK

- ET-3G idea is spreading in the world
  - A similar scale GW observatory concept (Cosmic Explorer) is currently under consideration in the US
  - Or other designs that may emerge
  - **ET is being reconsidered under this new light as a “not alone” observatory**
- A global approach to coordinate the efforts toward a Global Research Infrastructure vision is underway
  - Bottom-Up approach: GWIC-3G
    - Through the “Gravitational Wave International Committee”, scientists have established a coordination team named GWIC-3G (see next slide) that is investigating the future network of 3G observatory from several points of view: addressing its scientific potential, the technological development needed, the opening and growing of the scientific community, the relationship with the funding agencies and the governance model to be adopted.
  - Top-Down approach: GWAC
    - Funding agencies supporting or interested in GW research activities have established the “Gravitational Wave Agencies Correspondents”, an information exchange forum to develop higher-level coordination

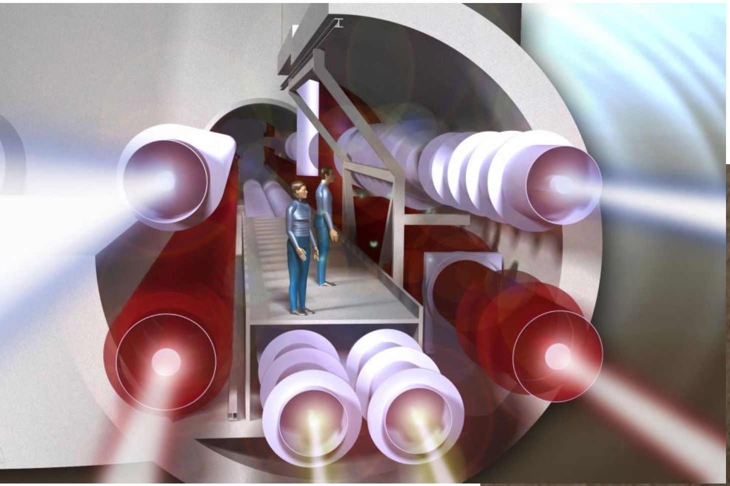


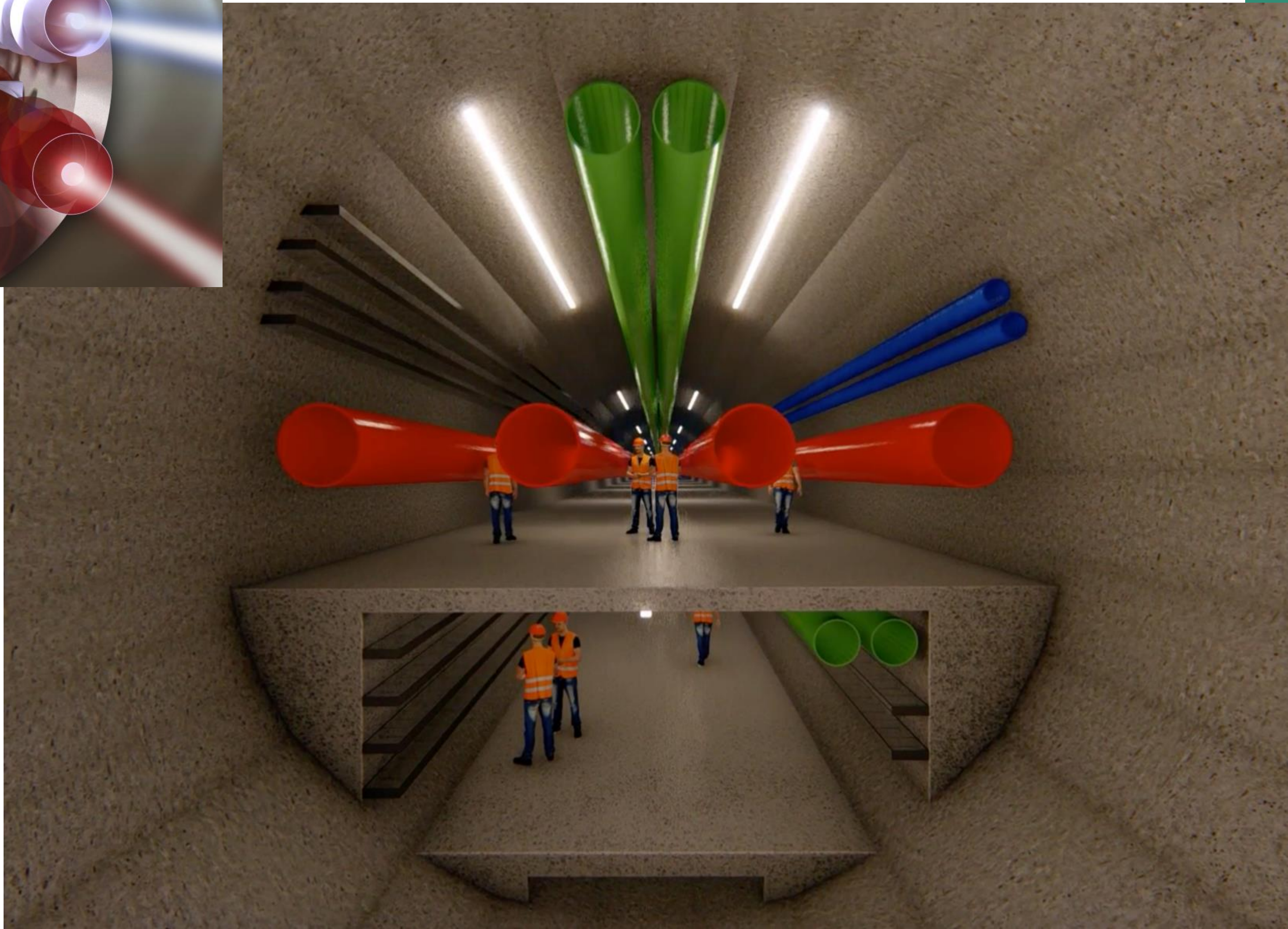
ET INFRASTRUCTURE FEASIBILITY STUDIES

TUNNEL

- Golden rules:
  - a new (and expensive) infrastructure must not be born short in space
  - avoid as much as possible complex arrangements
- We tried to fit the ET xylophone configuration in a underground infrastructure making realistic assumptions
  - space required for working around the pipes (e.g. welding the modules)
  - avoid vertical arrangement of the ITF
  - include realistic tower footprint
  - WARNING: things might get even more complex (e.g. space required by cryogenics)
- To further offload the tunnel we have moved the filter cavities into shorter (1 km), dedicated tunnels
  - this is a working hypothesis, to be discussed by the detector design teams
- The resulting tunnel diameter is ~2x larger wrt ET book

TUNNEL - $\oslash_{in}$ 10m

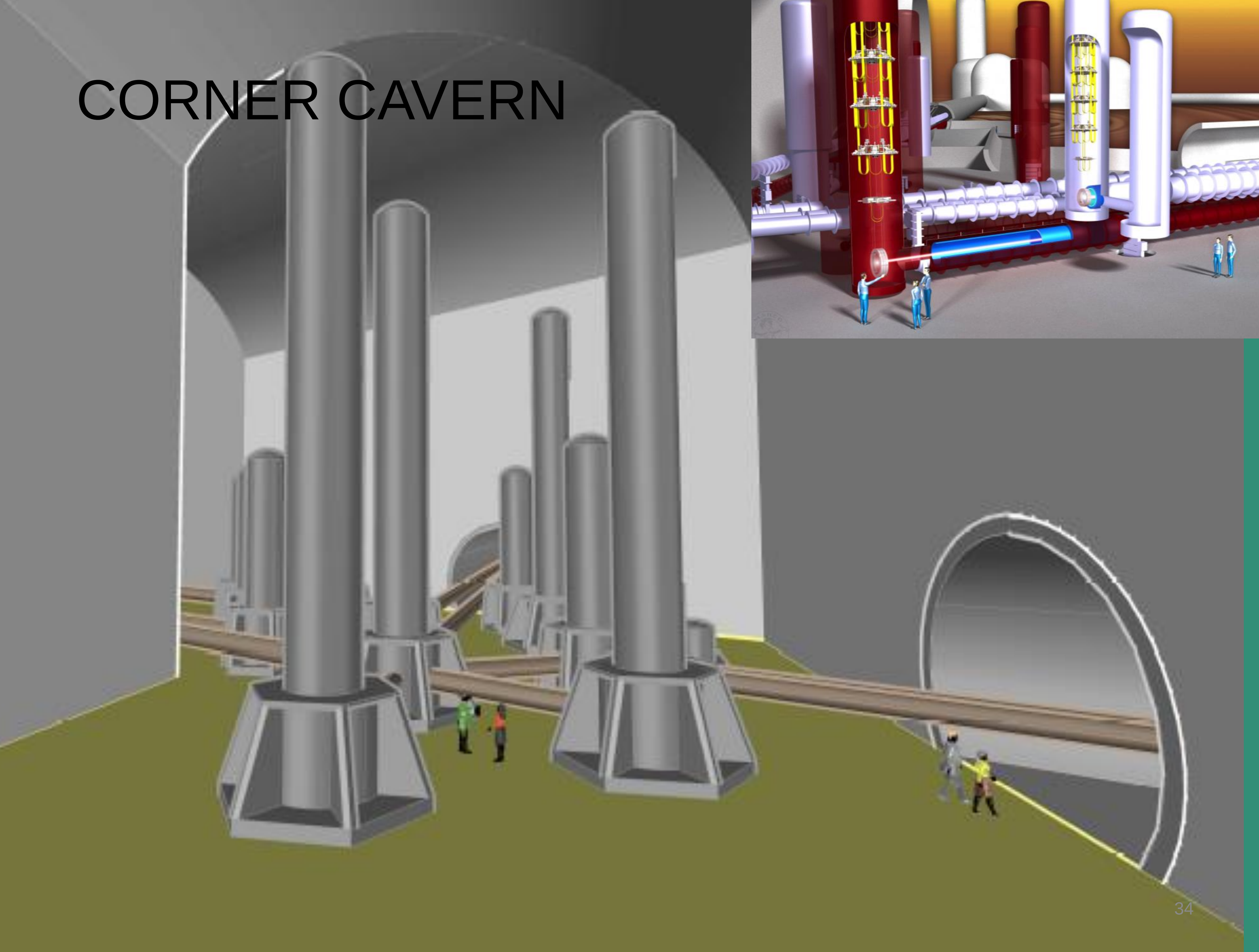




CAVERNS AND ACCESS

- Big caverns are a challenge
  - structure stability
  - atmospheric NN
- 65m diameter (ET concept) would be the largest cavern in the world
  - We have studied solutions to reduce the volume while maintaining the infrastructure flexibility and development potential
- Big shafts are expensive and challenging for civil engineering
  - We have designed downhill accesses to the infrastructure and smaller diameter shafts for safety accesses

CORNER CAVERN



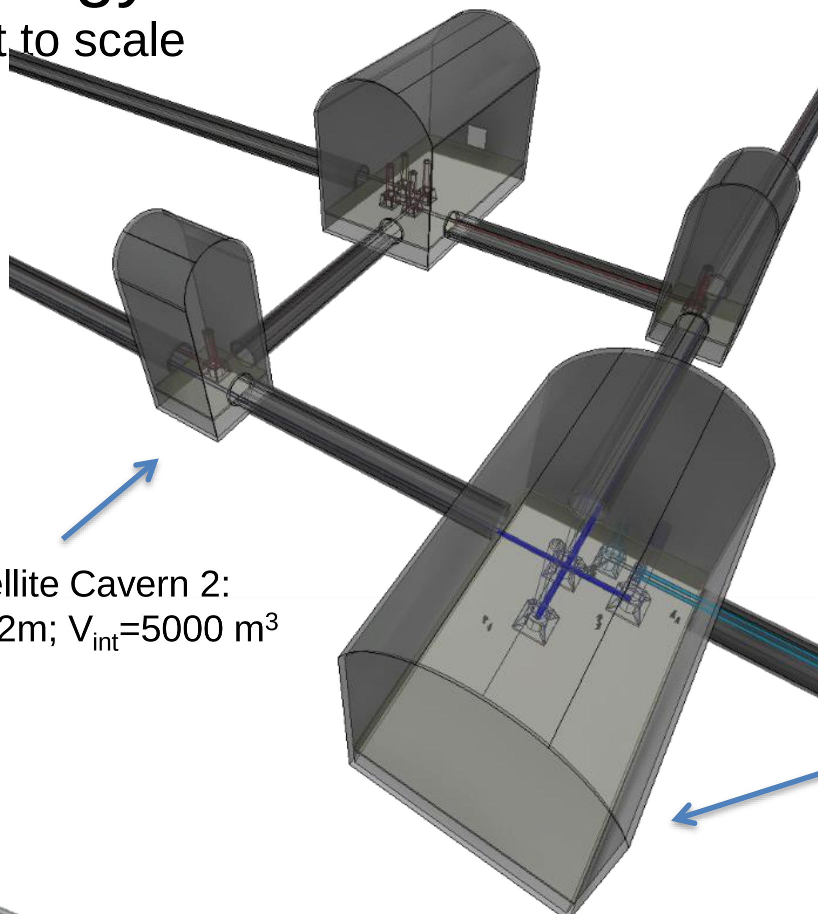
THE "L" GEOMETRY OPTION

- There are top-level arguments which may push towards changing the baseline topology
  - ET was conceived as a stand-alone observatory
  - **The ideal perspective is to have a 3G network**
  - **We are working for a global governance of a 3G effort**

- We have studied the scenario of a 15 km L-shaped ET
  - smaller tunnel diameter (5.5 instead of 10 m)
  - smaller caverns
  - less complexity
- Overall, in this scenario the cost of the infrastructure would be about one half of the full triangle

ET L Topology – Main Infrastructure

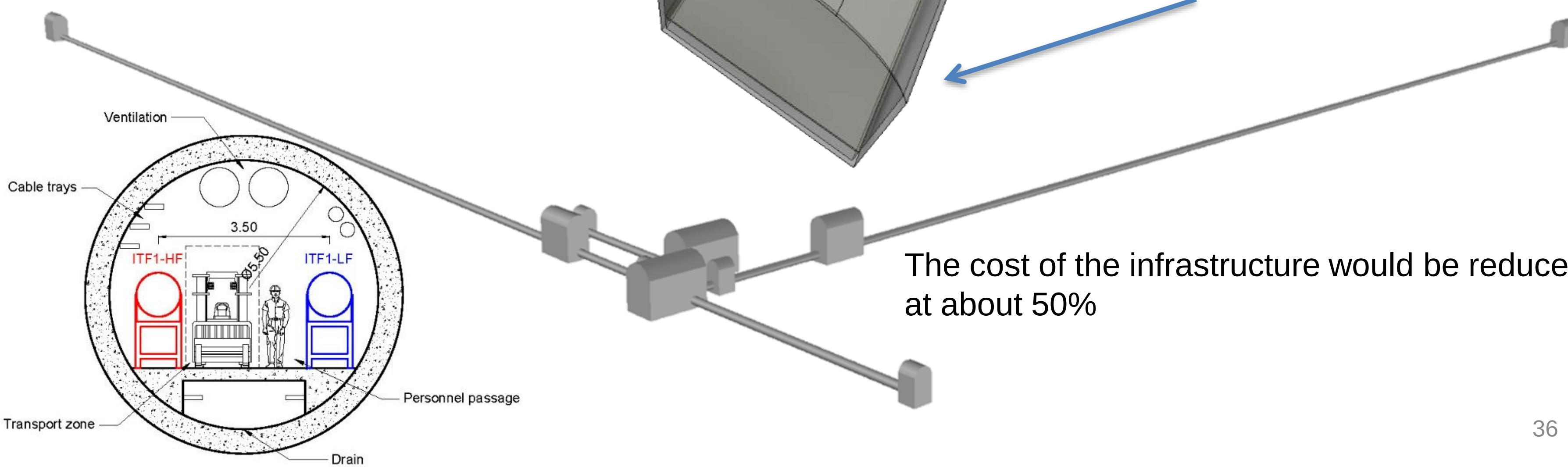
Heights are not to scale



CENTRAL AREA SPLIT
IN 4 CAVERNS TO REDUCE
VOLUMES (AND NN)

Satellite Cavern 2:
H=22m; V_{int}=5000 m^3

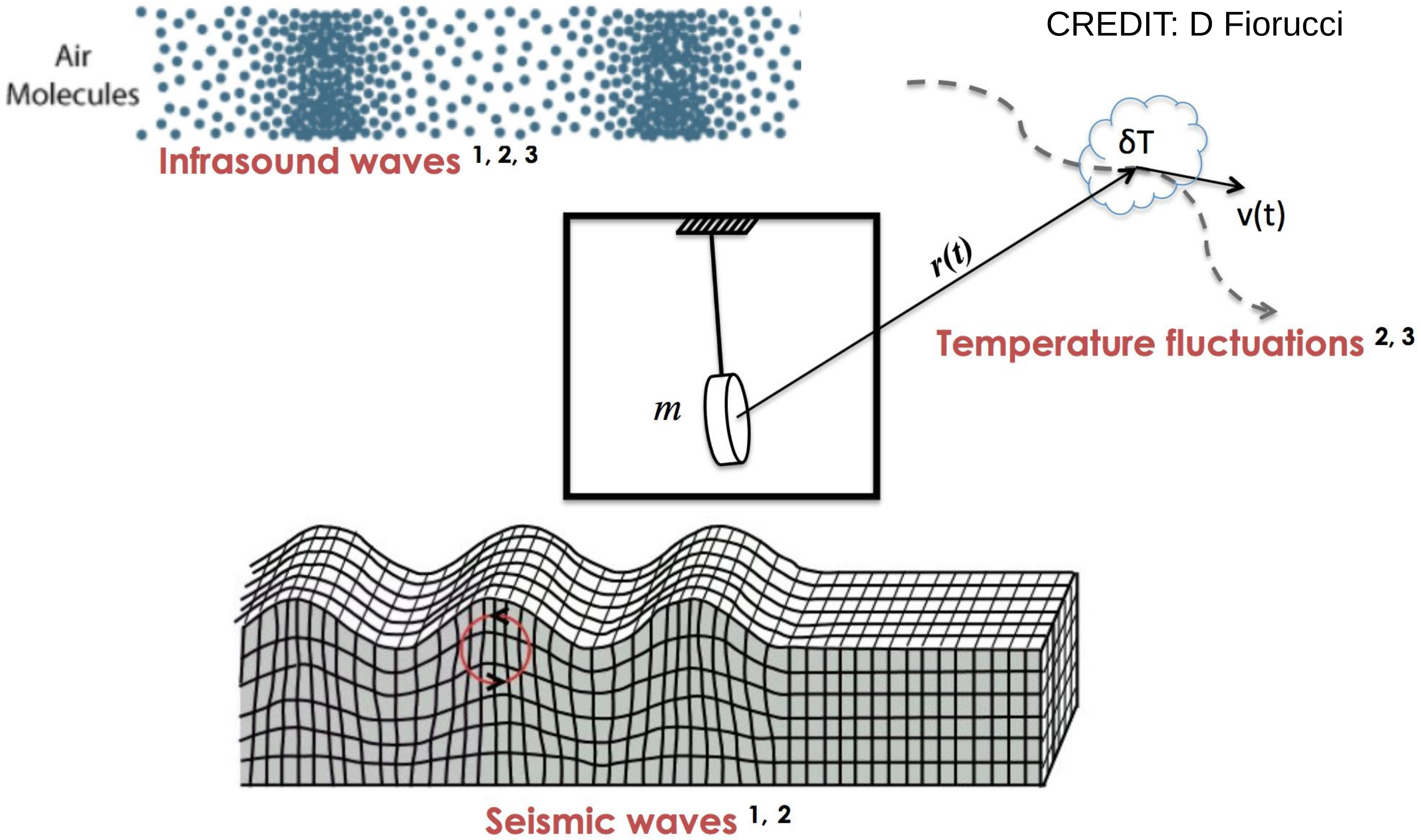
Main Cavern:
H=36m; V_{int}=55000 m^3



The cost of the infrastructure would be reduced at about 50%

Underground: why and where ?

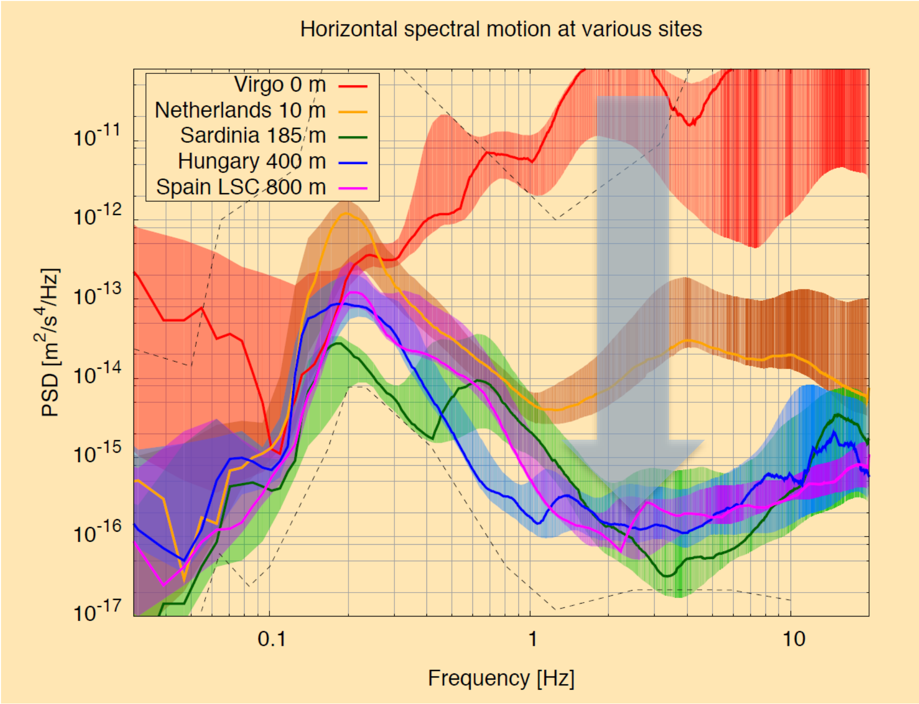
Newtonian Noise



[1] Saulson Phys. Rev. D **30**, 732, [2] J. Harms Terrestrial Gravity Fluctuations,
[3] Creighton CQG. **25** (2008) 125011, C.Cafaro, S. A. Ali arXiv:0906.4844 [gr-qc]

WIDEN THE BAND: UNDERGROUND

- Limitations to LF sensitivity
  - newtonian noise
  - rejection of seismic noise
- Both can be eased by going underground



noise at 2 Hz reduced by
~2 orders of magnitude

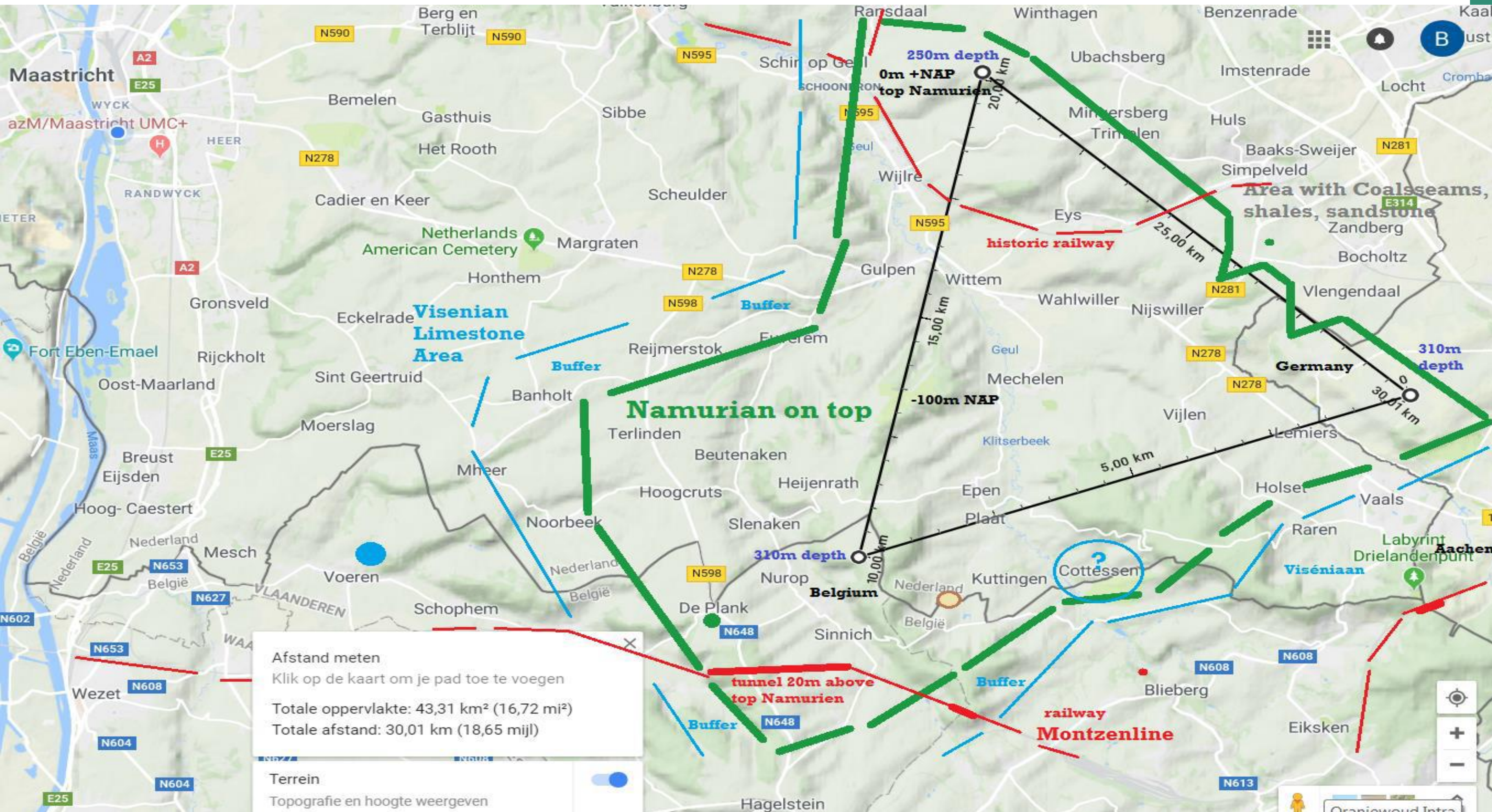
CANDIDATE SITES

Limburg (NL)

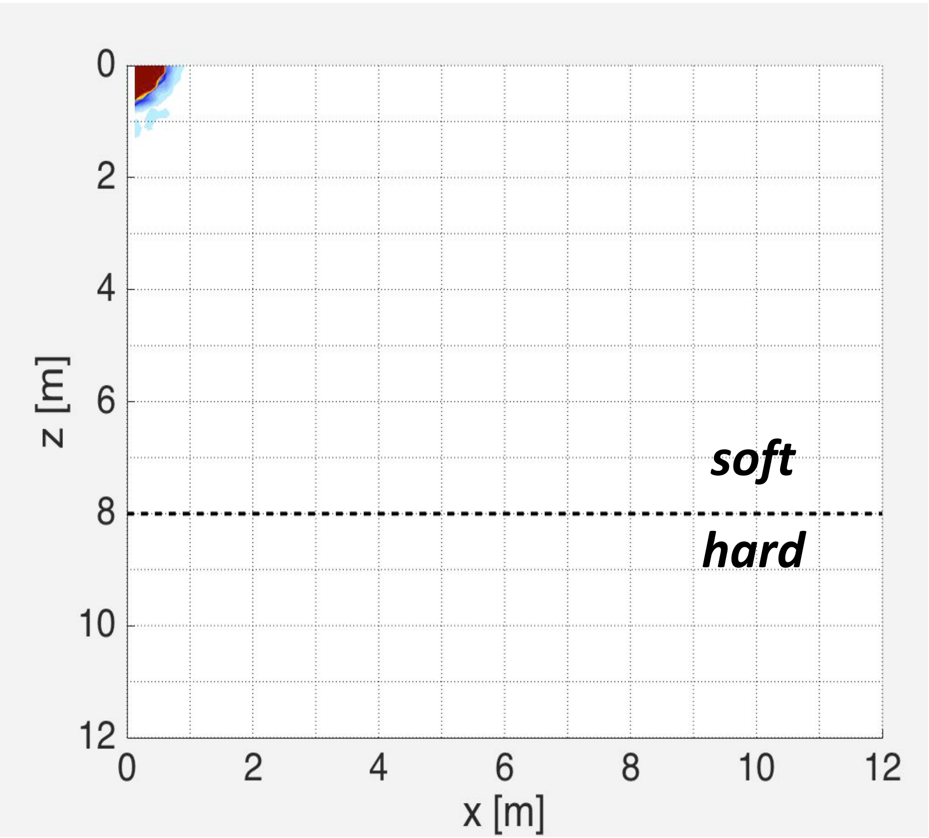
Matra (HU)

Sos Enattos (I)

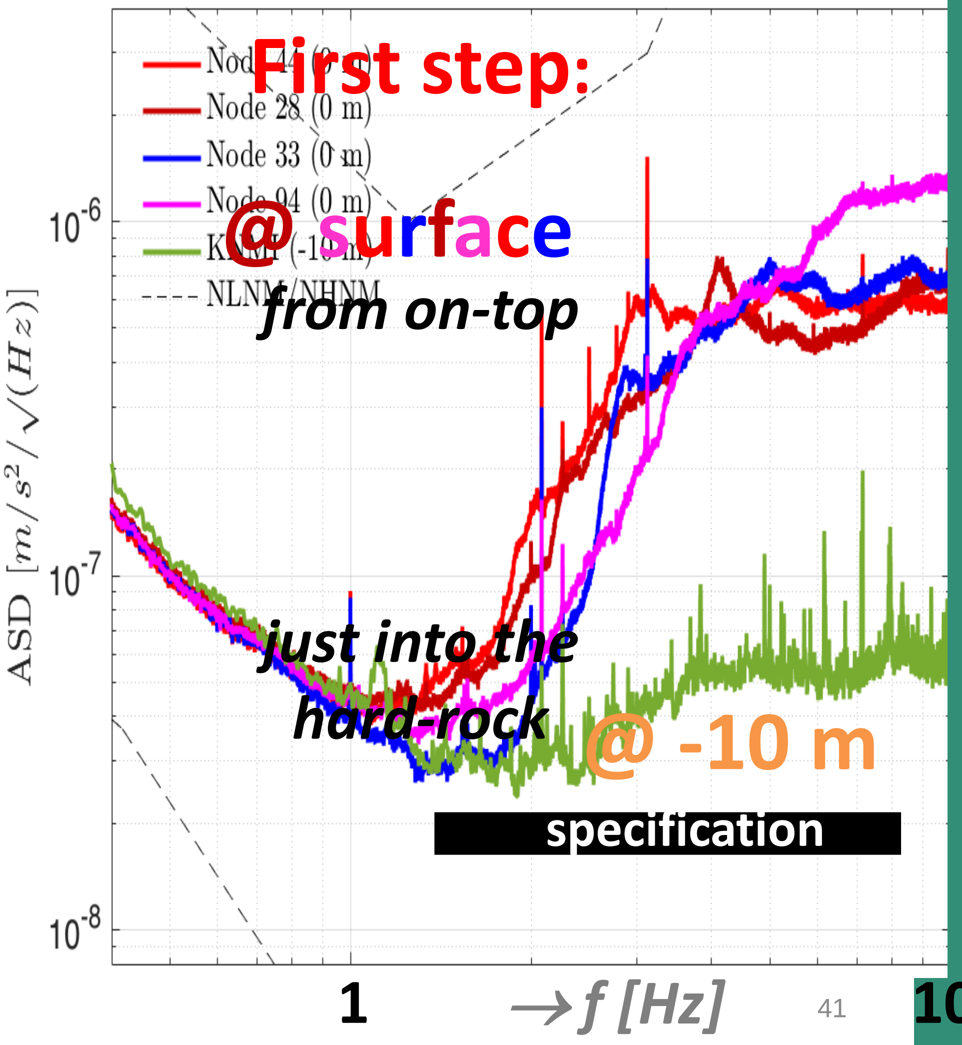
Limburg (NL-B-D)



Soft top layer on top of hard rock ..

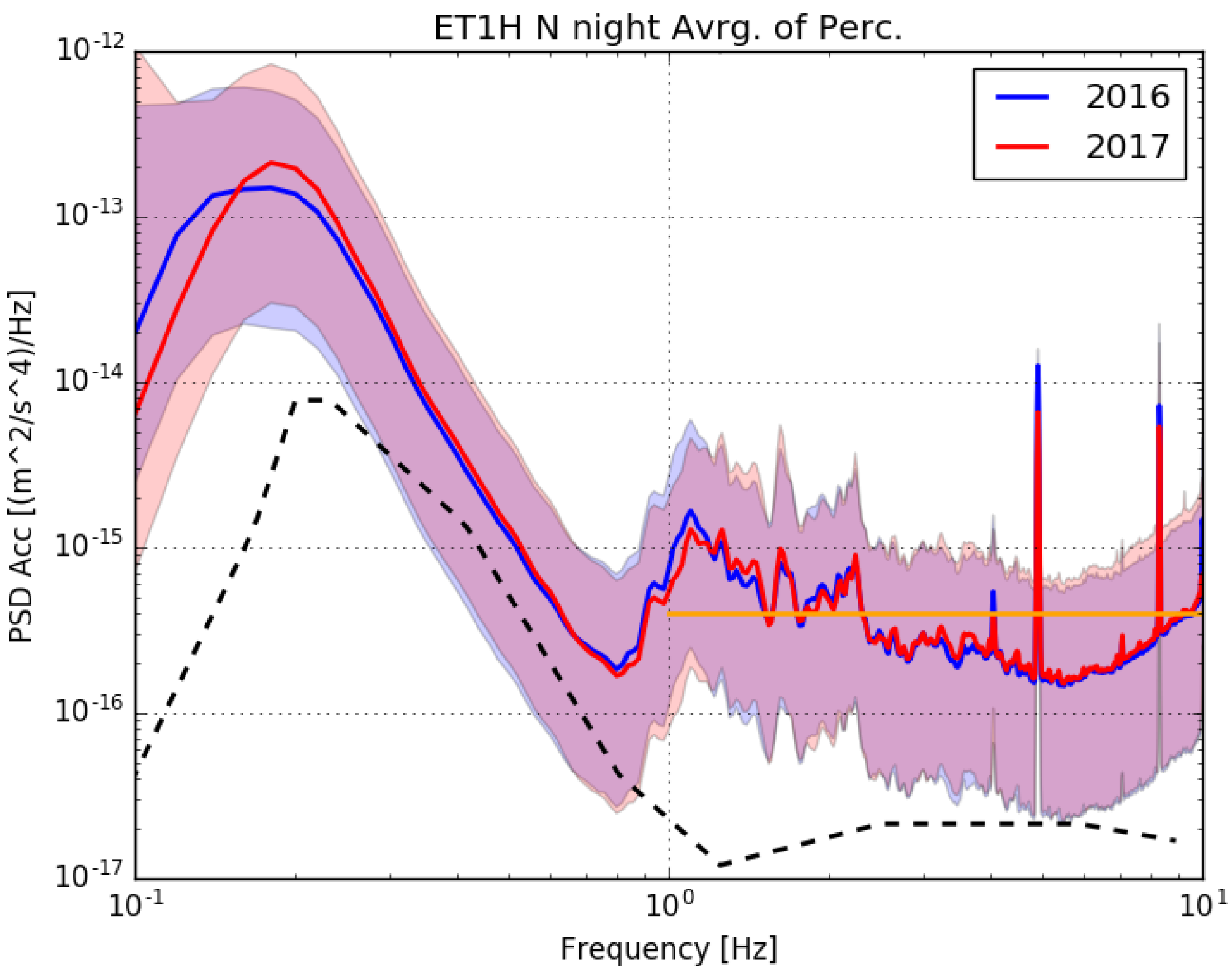


Only measurement so far ...



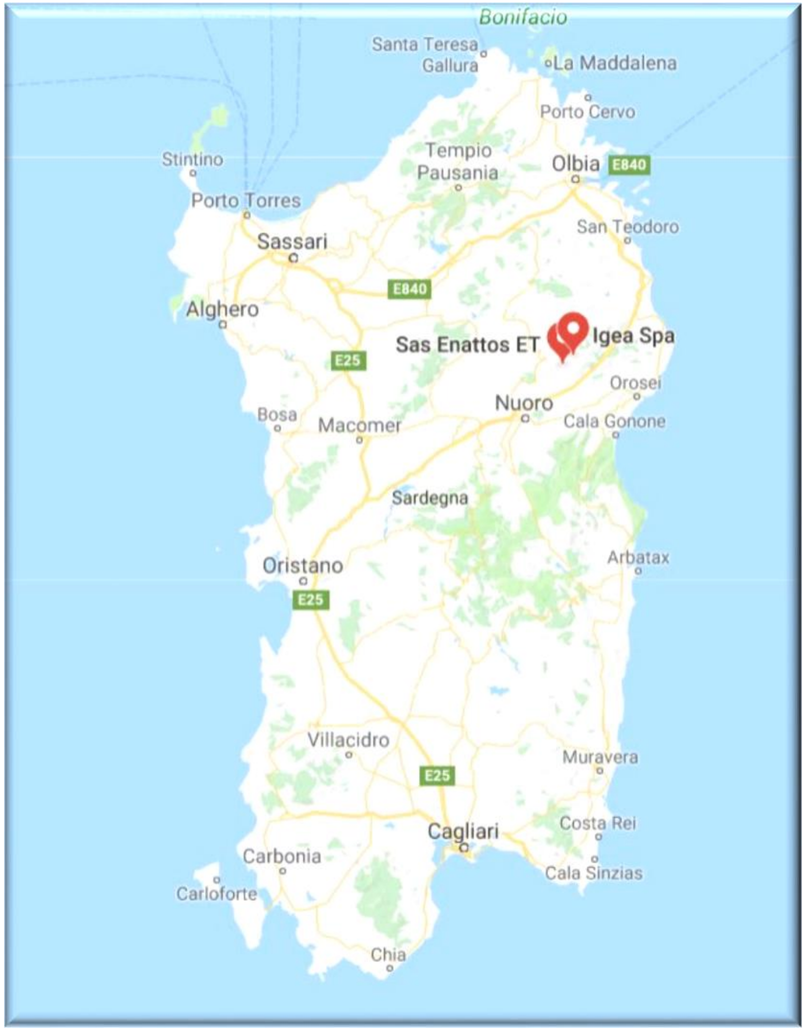
MATRA MOUNTAINS

- Small underground lab (-88m) realized and used for seismic measurements
- Two years of seismic data available


ET1H N night Avrg. of Perc.
2016
2017
PSD Acc [(m^2/s^4)/Hz]
Frequency [Hz]
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-1}
10^{0}
10^{1}

SOS ENATTOS

Offically candidated by Italy on May 19-20th at the ET sysmposium

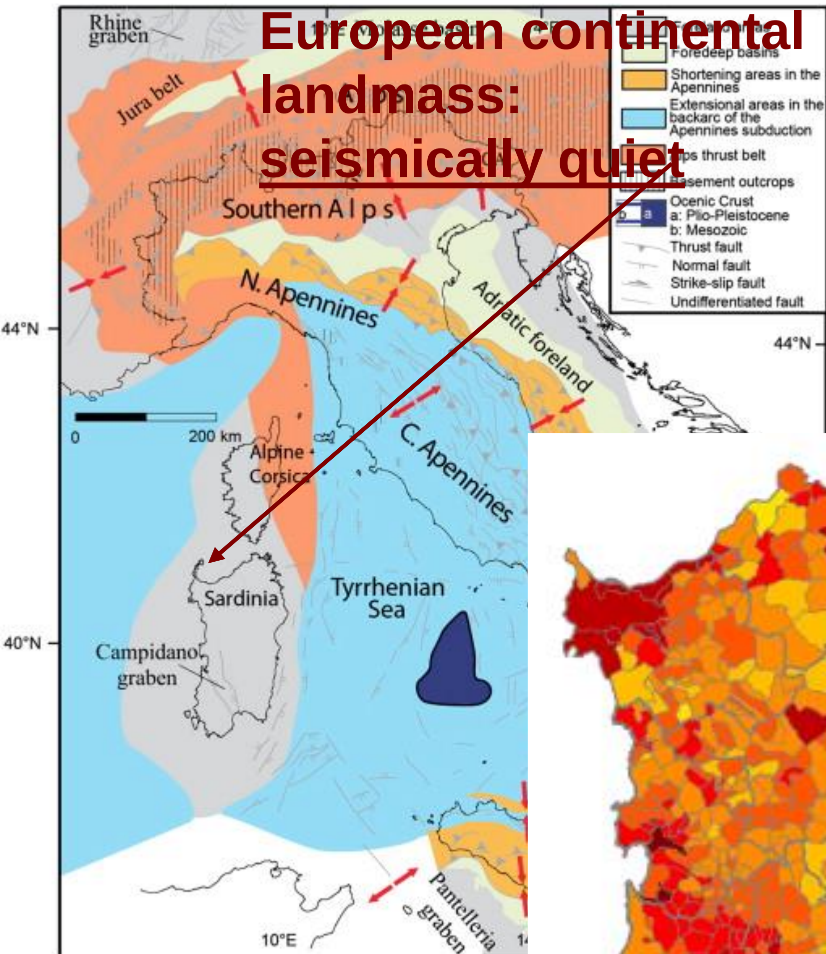


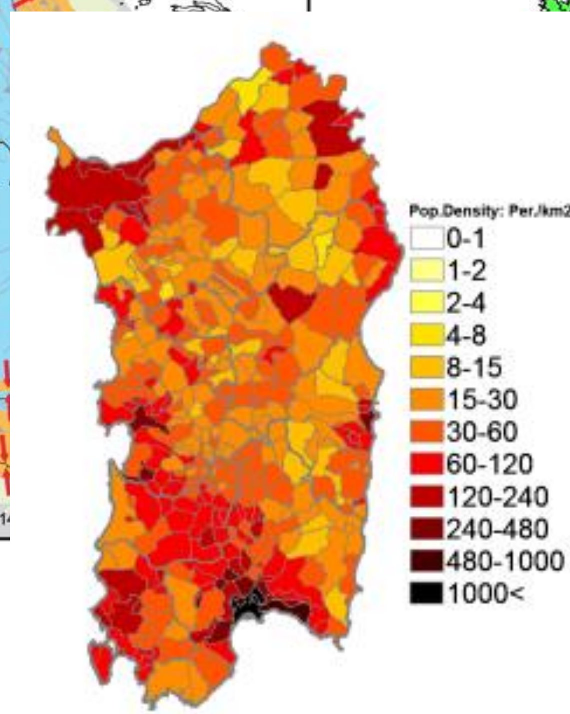
A quiet site!
Low seismic – No antropic noise

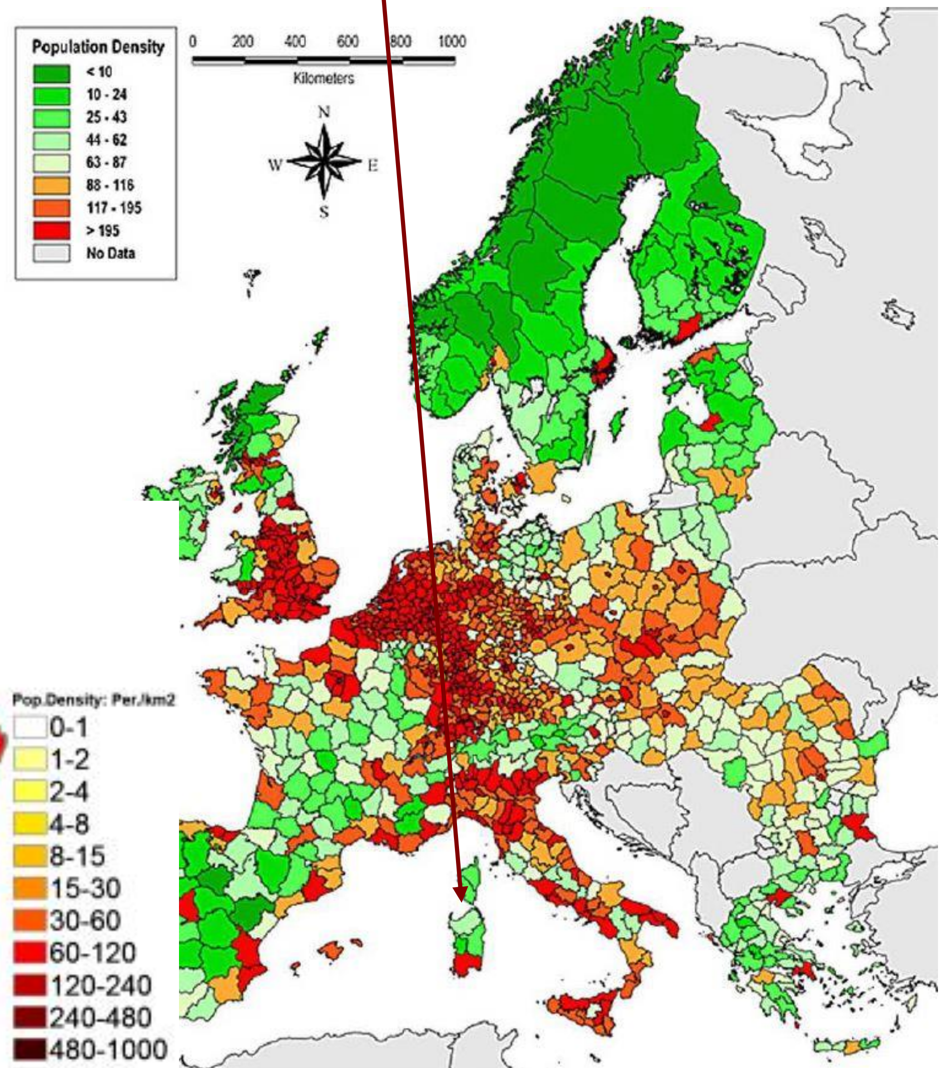
AREA ASSETS

One of the least populated areas in EU

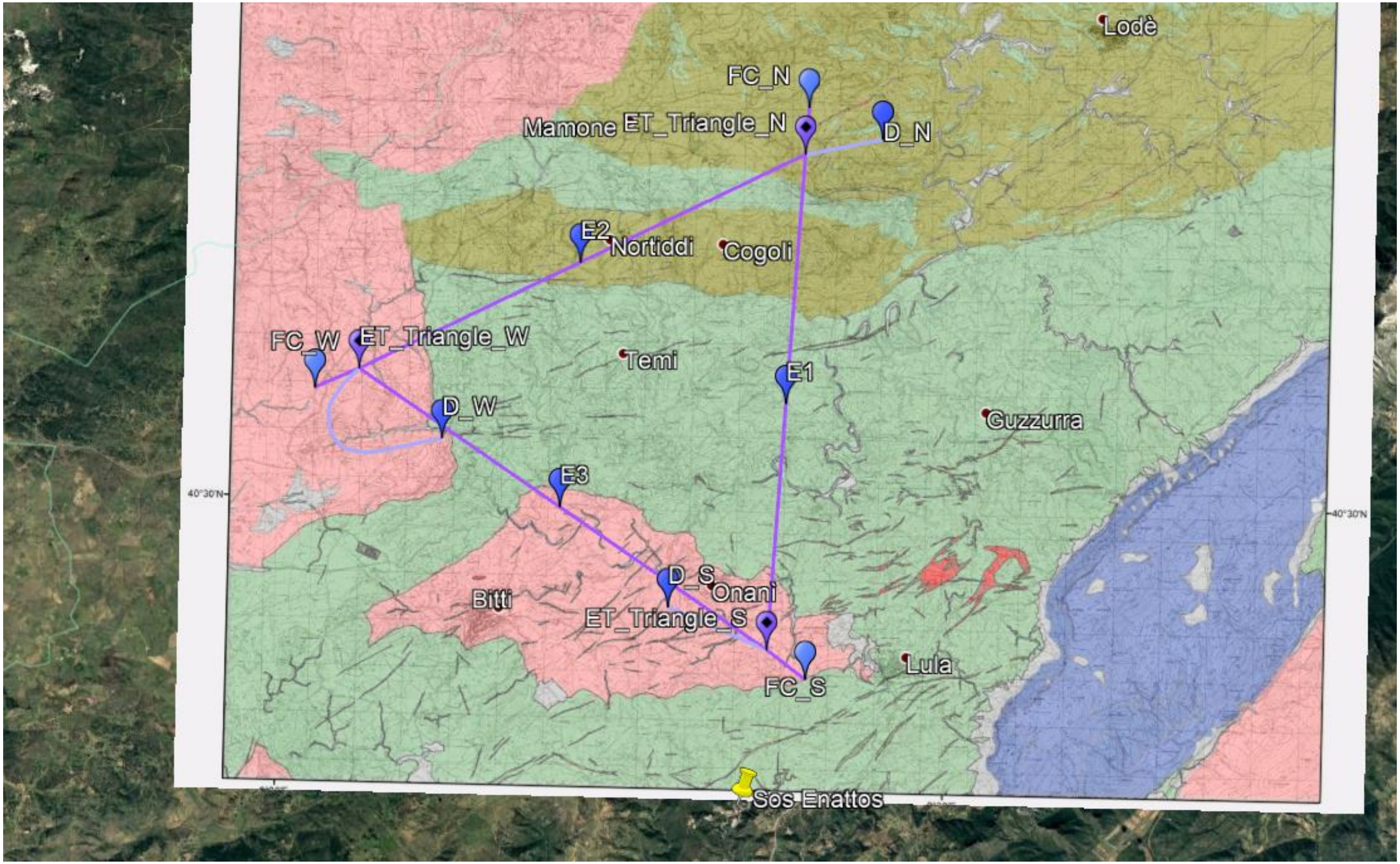
Ancient rocks, European continental landmass: seismically quiet







LOCATION - TRIANGLE



GEOLOGICAL SECTIONS

Legend

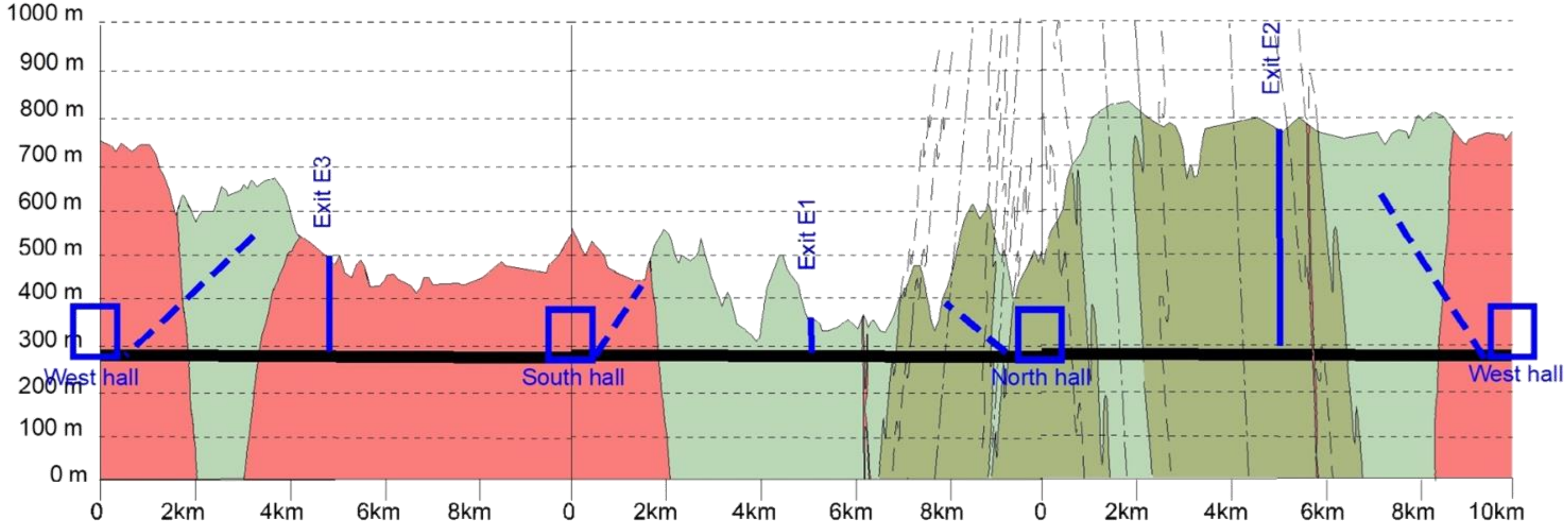
Intrusive complex

Granodiorites and monzogranites

Metamorphic basement

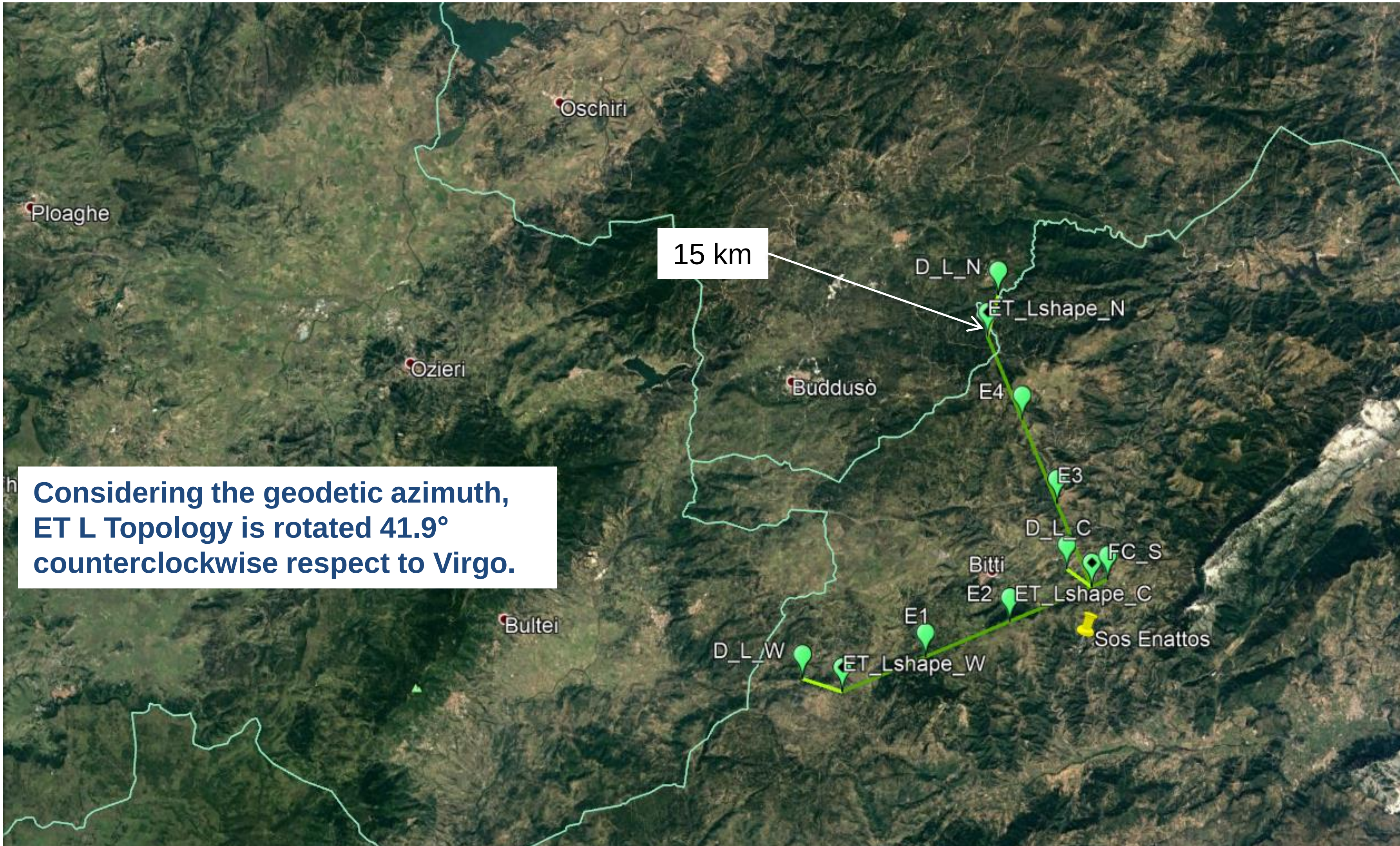
Orthogneiss

Phyllites, micaschist and paragneiss



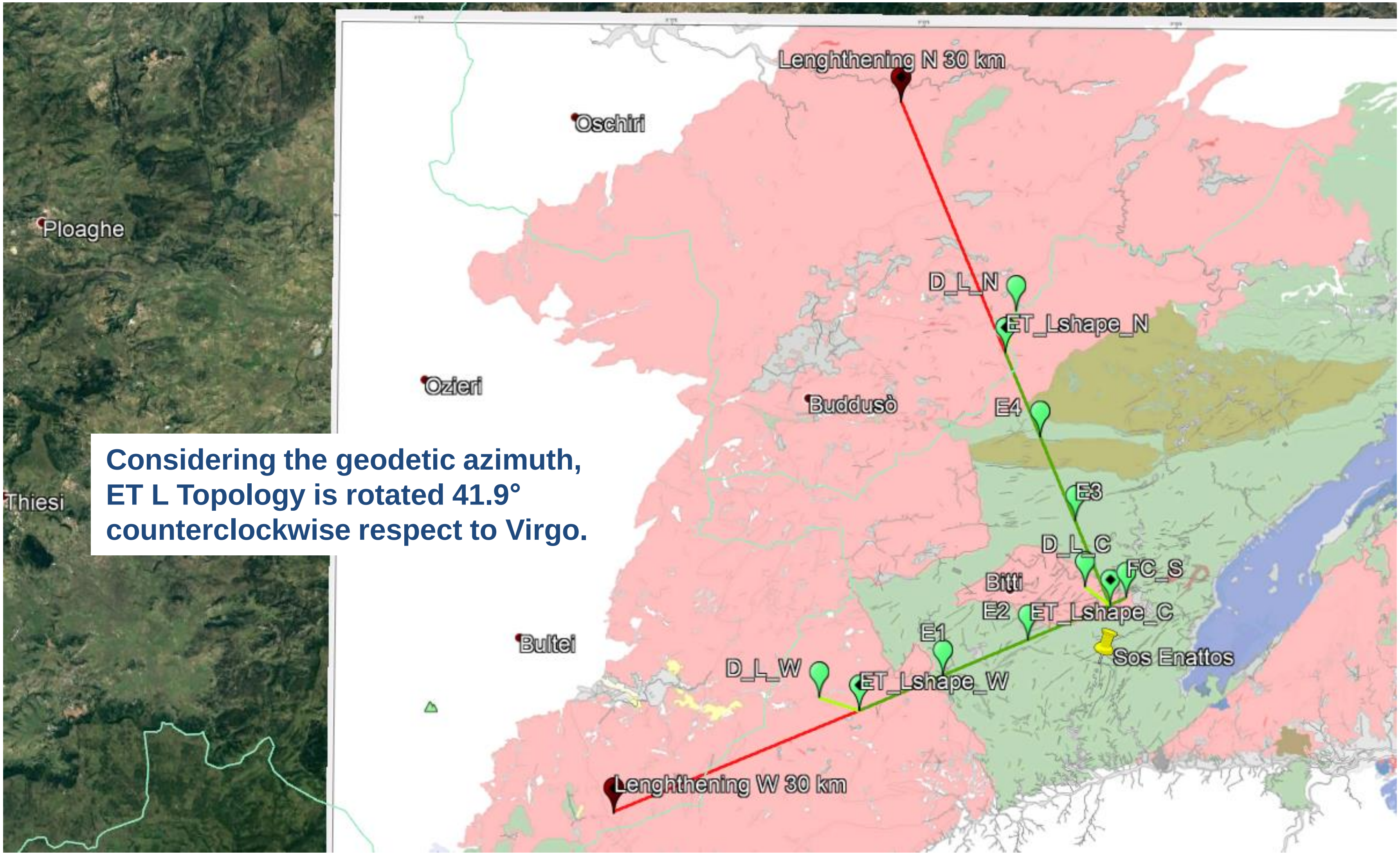
vertical exaggeration 10x

LOCATION - L



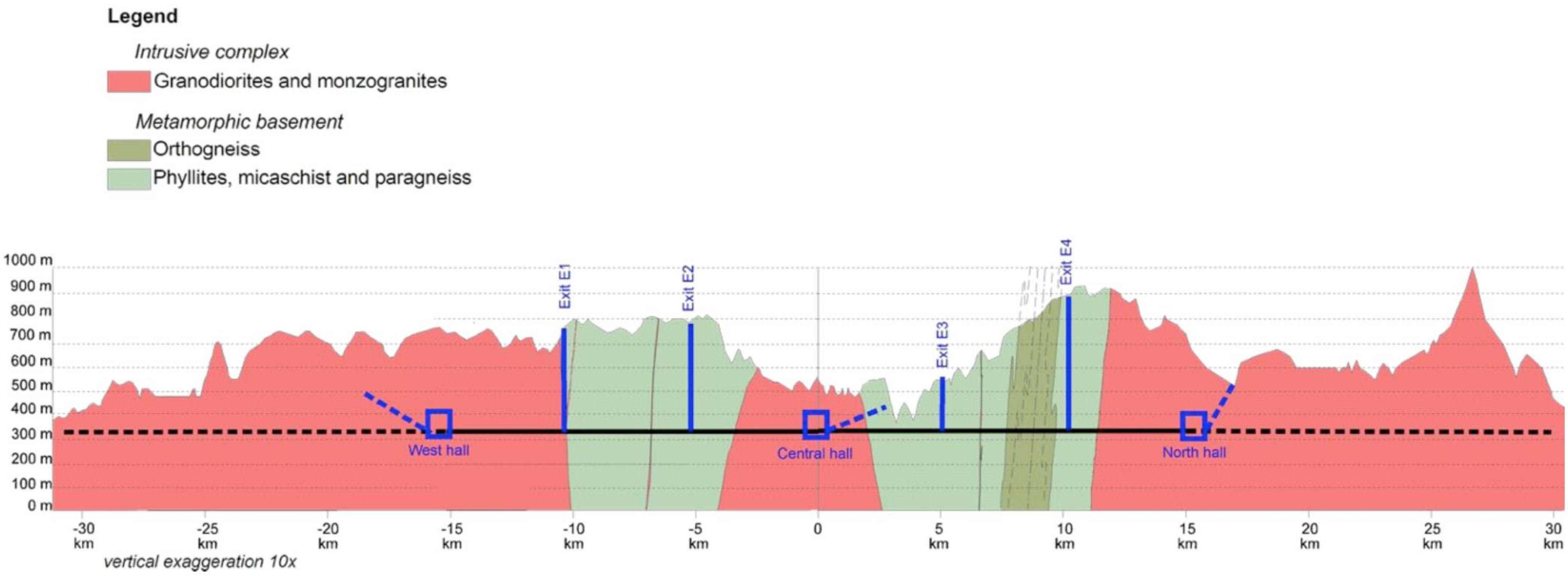
Considering the geodetic azimuth, ET L Topology is rotated 41.9° counterclockwise respect to Virgo.

LOCATION - L



Considering the geodetic azimuth, ET L Topology is rotated 41.9° counterclockwise respect to Virgo.

GEOLOGICAL SECTIONS - L

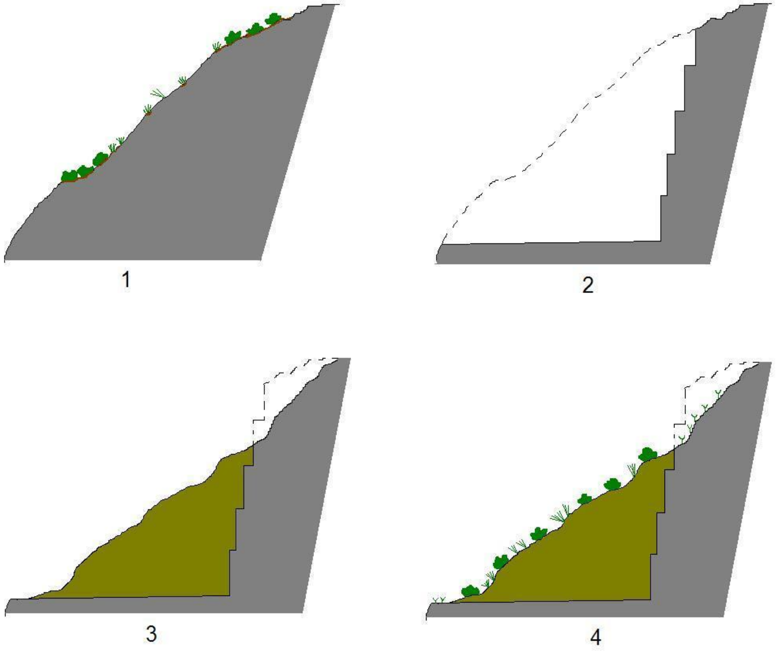


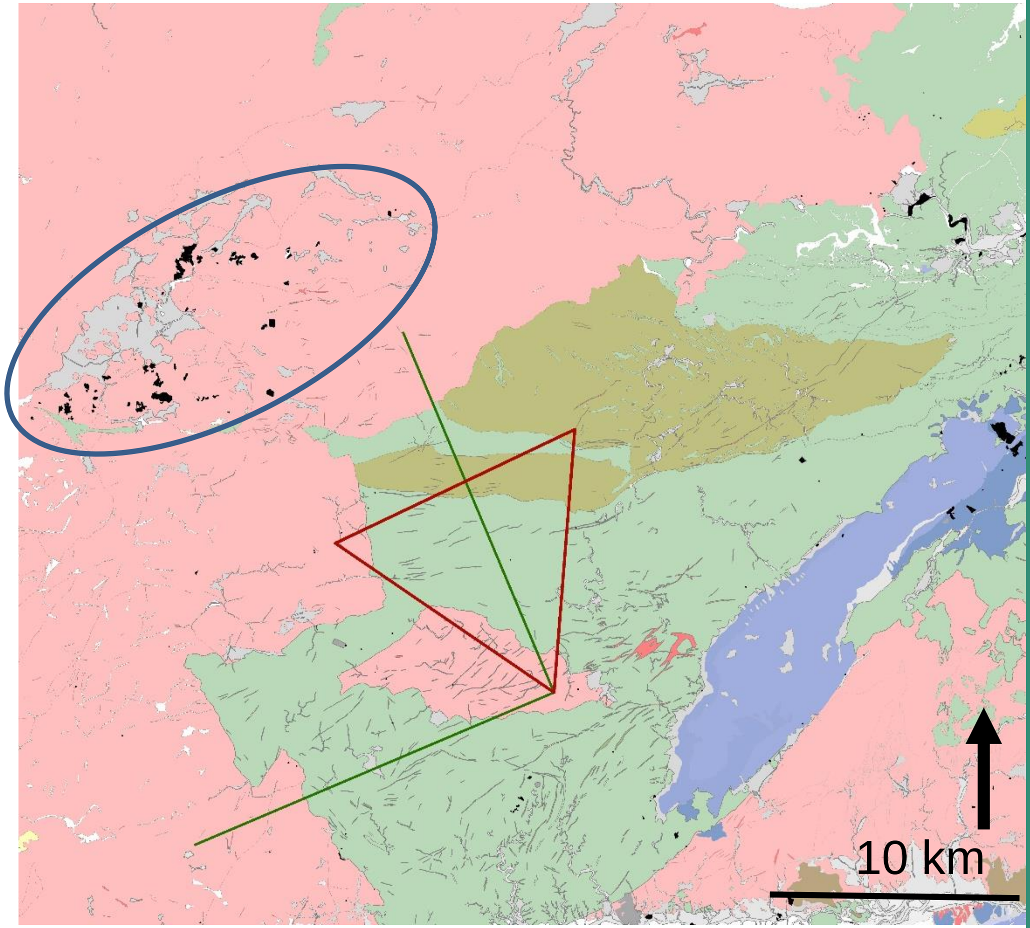
ET@SosEnattos L Topology could be lengthned untill arms of ~30 km with the present height.

Lowering the interferometer further would allow length up to 40 km.

ENVIRONMENTAL ISSUES

The excavated rock could be employed in the recovery of the nearby quarry sites.
The quarried surfaced in the Buddusò District (granite extraction) covers ~2 Mm^2.
The muck produced by the excavations could be used for landscape rehabilitation.





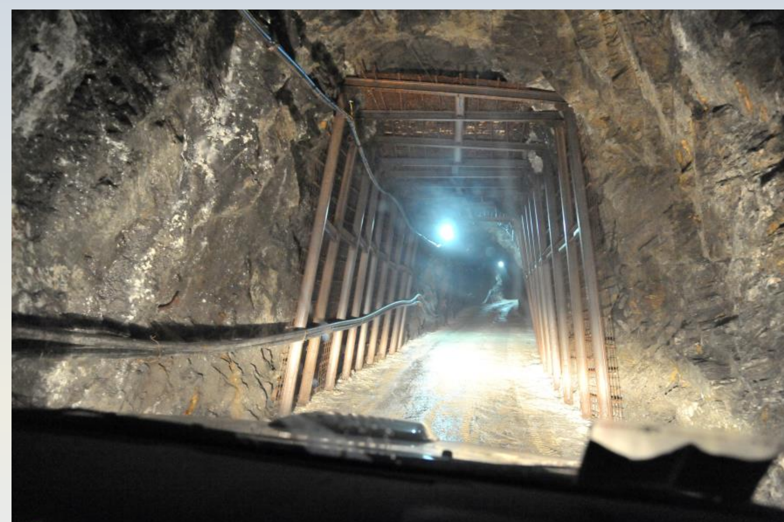
SAR-GRAV a seed Undergorung Gravitational Laboratory

- An agreement as been signed in 2017 to create the SAR-GRAV Laboratory. The mine is property of Regione Sardegna throught the consortium IGEA. The infrastrucure has been funded by regione Sardegna and INFN and INGV (Istituto Nazionale Geofisica e Vulcanologia) will use.
- The underground laboratory will be approximately 200 m^2. The design of the laboratory is done in collaboration among the civil engeneering of IGEA and INFN scientists.

SAR-GRAV and the measure of the weight of vacuum

- The experiment Archimedes devoted to the measure of the weight of vacuum fluctuations will be the first experiment hosted in the underground laboratory
- Hopefully it has been a seed for working toward ET

Works have started on surface building – enlargement of the cavern expected to start in few weeks from now



Caverna 110 m sotto terra raggiungibile con auto.

ITALY GOVERNMENT SUPPORT

EINSTEIN TELESCOPE

17 Meuros for AdV+, ET R&D and support of the Sos Enattos candidature

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

Pubblicato: 22 Febbraio 2018

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

Ministero dell'Istruzione dell'Università e della Ricerca

REGIONE AUTÒNOMA DE SARDIGNA
REGIONE AUTONOMA DELLA SARDEGNA

INFN
Istituto Nazionale di Fisica Nucleare

uniss
UNIVERSITÀ DEGLI STUDI DI SASSARI

ESFRI (European Strategy Forum on Research Infrastructures)

- For European GW community it is crucial to enter in the 2020 update of the ESFRI roadmap
- Update window: Jan-Aug 2019
- We need to define the political support and financial committment:
  - **Lead Country/Entity**
  - Partecipating countries/entities
  - Inclusion in National research infrastructure roadmap (when applicable)
  - Cost estimates and repartition
- No need to choose the site in the proposal

COST AND TIMELINE

- The realization of the ET observatory may cost 1-1.5 GEuros. Final cost TBD on the basis of
  - final choice of geometry and length
  - TDR

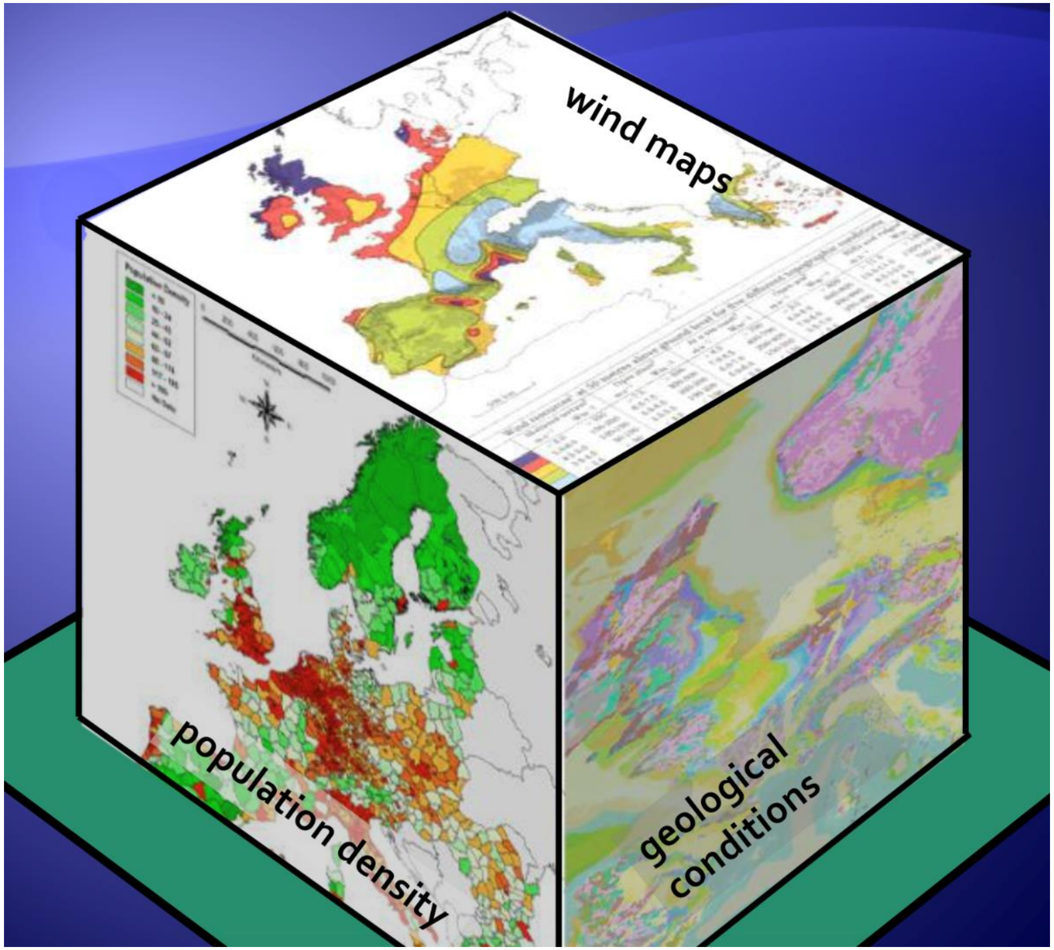
- TIMELINE:
  - 2021-22: site selection
  - 2023-24: TDR
  - 2025: infrastructure realization start
  - 2030-31: commissioning start
  - 2032+: operation

Conclusion

- Surely the present moment is fascinating for studying gravity and its relation with astrophysics and particle physics
- ET is a great opportunity for the italian community that can profit of the huge heritage built in the past decades….but a lot of work remains to be done to make this opportunity a reality
- The hope is to really have a third generation GW detectors in Europe in the next decade

SITE SELECTION

POLITICAL SUPPORT



LOGISTICS

…

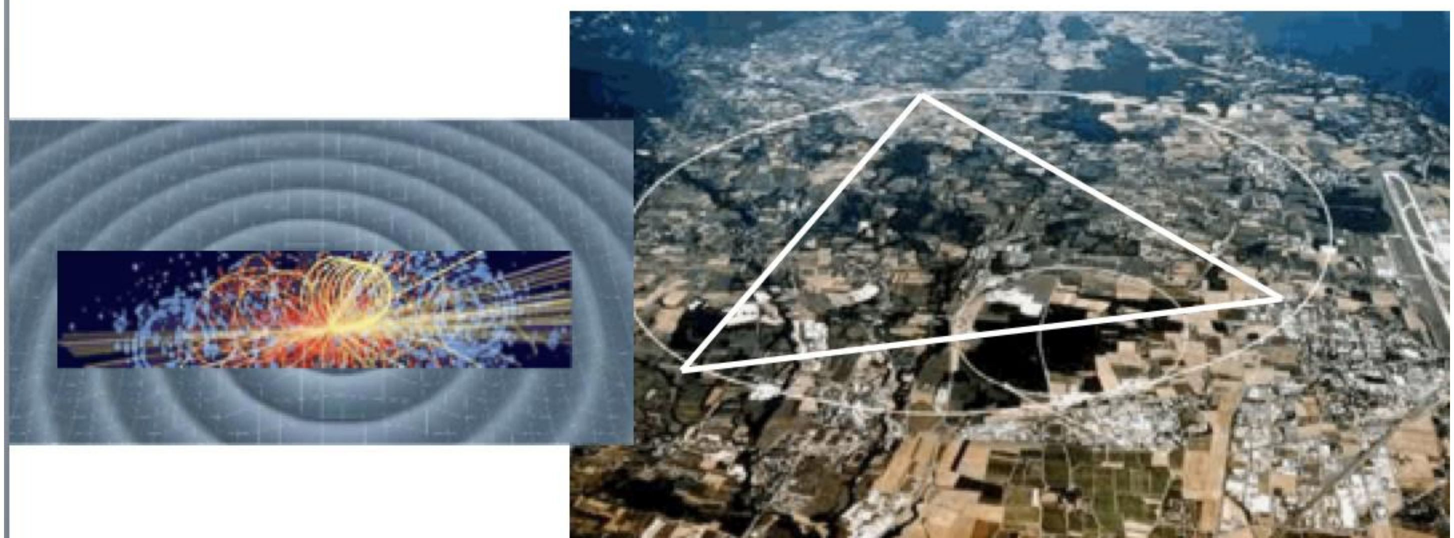
ET AND THE INTERNATIONAL FRAMEWORK

CERN

NOT A GOOD SITE FOR ET BUT….

The Great Unification...in Europe

If we cannot put the fundamental interactions into the same theory...
we can at least put them in the same place!



EAP Town Meeting – Munich, Nov. 23, 2005   G.Losurdo – Firenze-Urbino 24

THE POSSIBLE ROLE OF CERN

- The GW community looks at CERN as model to many extents
- We have a lot to learn:
  - Model of governance
  - Management of big projects
  - Technology: underground infrastructure, vacuum, cryogenics
- …

Conclusions

GF Giudice, CERN 9/2017

- GW physics is awesome
- Our sciences have much in common
- More than ever, particle physics needs exchange with other sciences
- GW physics has much to offer to particle physics and CERN

(tests of GR, search for ECOs, primordial BH as DM, early-universe phase transitions, cosmological stochastic bkgrd, search for light particles through superradiance, QCD in extreme conditions, …)

CONCLUSIVE REMARKS

- Science case for ET is compelling
- If not now…: great window of opportunity opened by recent discoveries
- A world wide coordination effort on 3G detectors being pursued
  - Europe is ahead
- A lot of room for collaboration/exchange with high energy physics community

SPARES

BH and particle physics

- With a stellar mass BH we have a new precision tool that may diagnose the presence of new light (10^{-20} 10^{-10} eV) and weakly interacting bosonic particles

- When such a particle's Compton wavelength is comparable to the horizon size of a rotating BH,

$$\lambda_C \gtrsim R_s$$

the super radiance effect spins down the BH, populating bound orbits around the BH with an exponentially large number of particles

- The BH already detected by LIGO/Virgo can act as attractors of QCD axions of the upper end of a mass range, which covers the parameter space for the QCD axion

GW interferometer as detector of new elementary particles

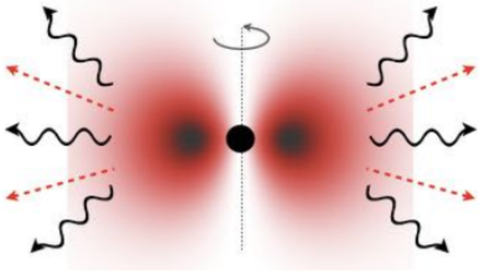
In this proposed scenario black holes develop clouds of axions

The axion cloud will emit ~monocromatic GWs

Depending on the mechanism, these might be visible to tens of Mpc (Arvanitaki+ 1604.03958)

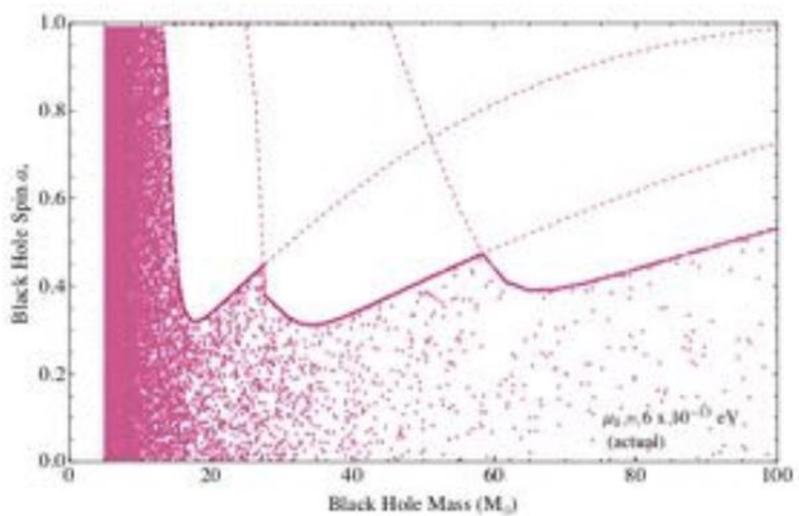
We can follow-up newly formed BHs and look for this signal.

Source-frame frequency depends on the mass of the axion
(Detected frequency will be redshifted)

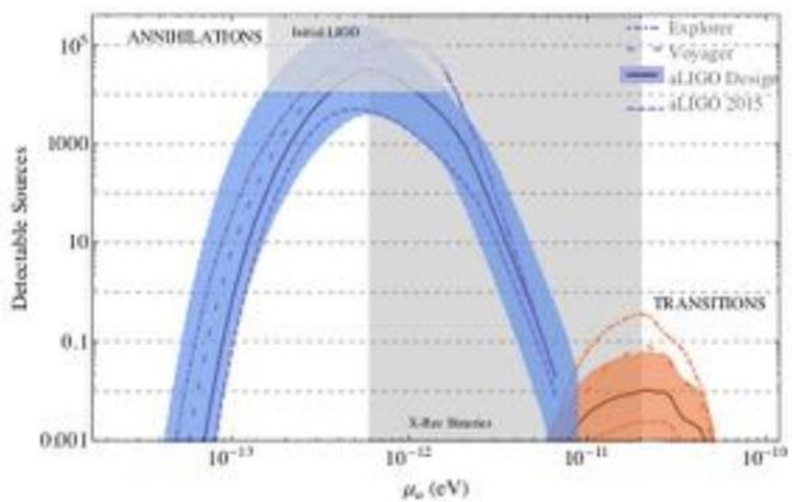


Searching for ultra-light particles

μ_a = 10^{-10} - 10^{-14} eV → λ_C = 10 - 10^5 km



Population inferences



Direct searches

Arvanitaki et al.,
Phys. Rev. D 95, 043001 (2017)