

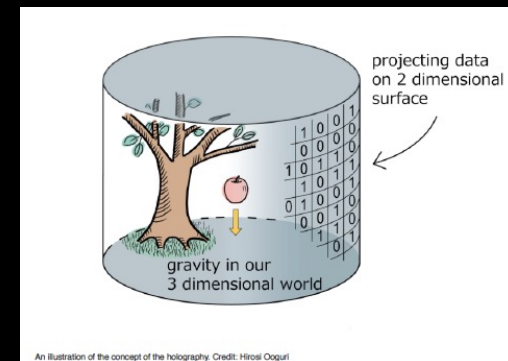
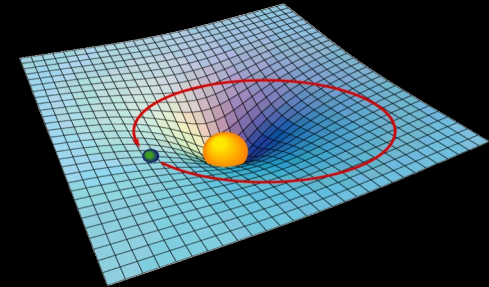
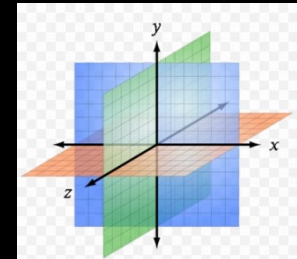
# 50 years of EGO LMA



**S. K. Katsanevas EGO Director**  
**24 November 2022**

# 3 concepts of space-time-matter

- 1. Newton** Space and time a fixed eternal frame( Sensorium dei). *“It is inconceivable that inanimate brute matter should without the mediation of something else which is not material, operate upon and affect other matter without mutual contact”; Hypotheses non-fingo.*
- 2. Einstein** Space-time is a deformable medium. Mass and Energy deform space-time around them and inversely they follow the deformed paths inside it (the metaphor of the swimmer of Deleuze). Space and time depend on the M/E context. Gravitational Waves can be produced by violent phenomena
- 3. Bohr, Shrodinger, Dirac, ...** Quantum Mechanics, Quantum Field Theory, Strings,Holography, Entanglemenent. Space-time is an “emmergent” product of the relation. (Also Leibnitz) Physics Nobel of 2022



# The Chapel Hill Conference

Could the waves be a coordinate effect only, with no physical reality? Einstein didn't live long enough to learn the answer.

In **January 1957**, the U.S. Air Force sponsored the *Conference on the Role of Gravitation in Physics*, a.k.a. the Chapel Hill Conference, a.k.a. GR1.

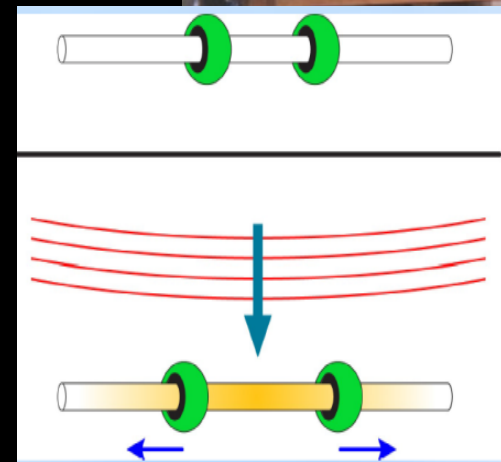
The organizers were Bryce and Cecile DeWitt. 44 of the world's leading relativists attended.

**The "gravitational wave problem" was solved there, and the quest to detect gravitational waves was born.**

(Pirani, Feynman and Babson)

Sticky bead argument (Feynman)

The history of detection a history of persistence and managing uncertainty



# *Only extremely violent phenomena can produce detectable GW*

Consider ~30 solar mass binary  
Merging Black Holes

–  $M = 30 M_{\odot}$

$R = 100 \text{ km}$

$f = 100 \text{ Hz}$

$r = 3 \cdot 10^{24} \text{ m (500 Mpc)}$

$$h = \Delta L / L \approx \frac{4\pi^2 GMR^2 f_{orb}^2}{c^4 r} \Rightarrow h \sim 10^{-21}$$

Credit: T. Strohmayer and D. Berry

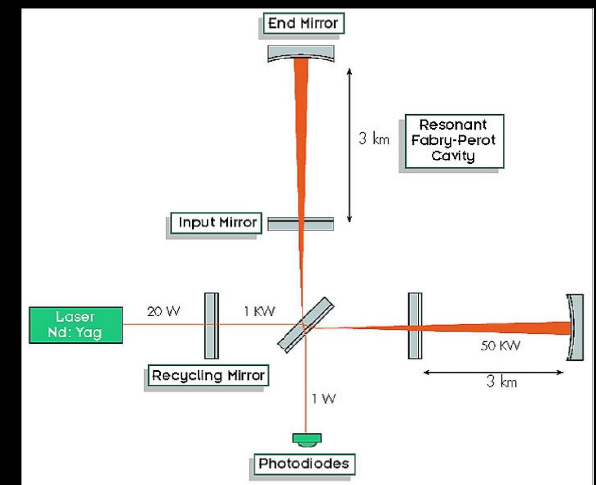
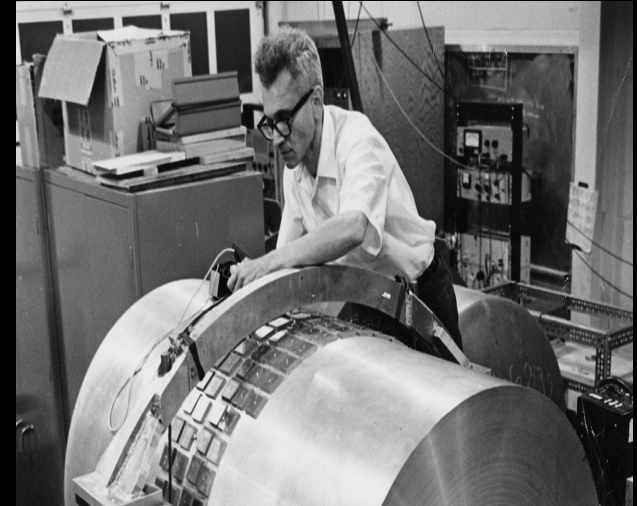
$\Delta L$  by 1/1000 of a proton radius in a distance  $L$  of 1 km



# Gravitational Waves

## The last 100 years

- 1915 Einstein : Mass/Energy deform space-time
- 1916-1918 Einstein: “Space-time quakes” can be produced by violent phenomena
- 1937 Einstein and Rosen “On Gravitational waves”
- 1957 Pirani/Feynman (Chappel conference) GW can transmit energy and thus be detected
- 1960-1970’s J. Weber first bar detectors (1972 Apollo deployment at the Moon)
- 1967-1968 R. Weiss, K. Thorne, Drever first interferometers
- 1974 R. Hulse and J.Taylor binary pulsars emit GW (Nobel 1993)
- 1984-1994 US: LIGO proposal period → G. Barish LIGO director at 1994
- 1987-1994 EU: Virgo proposal period → A.Giazotto, A. Brillet
- 2015 First detection of GW by LIGO and Collaboration LIGO-Virgo
- 2017 First multi-messenger event BNS detection by LIGO-Virgo



# Virgo and EGO the first 50 years

A. Giazotto

1972 SMA R&S

1982 CNRS:INGN starts working on S MA

1993-1994 CNRS and INFN approve VIRGO

1997 Construction starts near Pisa

**2000 Foundation of EGO (CNRS, INFN)**

**2002 SMA EGO MoA**

**2003 Inauguration of Virgo (+10y)**

2004-2006 Commissioning of Virgo

2006 Netherlands joins EGO as an Observer

2007 Start of Virgo science runs

2007 LIGO-Virgo “a single machine”

**2009 EGO Council approves AdVirgo (+16y)**

2010's Polish, Hungarian and Spanish groups join AdVirgo

**2017 First Virgo-LIGO detection (+24y)**

2019 Declared Historical milestone by IEEE

**2020 EGO Council approves AdVirgo+ (+27y)**

A. Brillet



# SMA EGO Moa 20 wears

In the frame of the Virgo project the “Institut de Physique Nucleaire de Lyon” (IPNL) through the “Service des Materiaux Avancés” (SMA) performed some important R&D for the realisation of the high performance coatings required by Virgo and realized a unique large coating facility. This Virgo facility was to a large extent funded by the Virgo budget shared in a proportion of 45/55% between CNRS and INFN. The total investment in equipment done under Virgo budget is about 2500 k€ for the coater, 850 k€ for the test instrumentation and 2360 k€ for the building. About 1200 k€ have also been invested in R&D at the beginning of the Virgo program.

The SMA Virgo facility is in operation since 2001 and consists in addition to the building with its technical facilities, of a 2m class coating plant with its ancillary equipment, a class 1 clean room and a test instrumentation which was developed in collaboration with ESPCI, another member of the Virgo collaboration.

**THE VIRGO PROJECT**

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Dipartimento di Fisica  
dell'Università di Pisa

C. BRADASCHIA  
R. DEL FABBRO  
A. DI VIRGILIO  
A. GIAZOTTO  
H. KAUTZKY  
V. MONTELATI  
D. PASSUELLO

INFN Sez. di Napoli  
Dipartimento di Scienze Fisiche  
dell'Università di Napoli

F. BARONE  
L. DI FIORE  
L. MILANO  
G. RUSSO  
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delle Università  
di Salerno e di Napoli

M. CAPOZZI  
M. LONGO  
M. LOPS  
L. PINTO  
G. ROTOLI

CNR Frascati

F. FULIGNI  
V. IAFOLLA  
G. NATALE

Instituto de Fisica <sup>1</sup>. USP, Instituto Astronomico e Geofisico<sup>2</sup> - USP,  
Centro Brasileiro de Pesquisas Fisicas<sup>3</sup> - CNPQ, Observatorio  
Nacional- CNPQ<sup>4</sup>, Instituto de Fisica GW- UniCAMP.<sup>5</sup>

M. S. D. CATTANI<sup>1</sup>  
J. A. F. DE FREITAS PACHECO<sup>2</sup>  
C. O. ESCOBAR<sup>1</sup>  
C. A. GÁLVAO<sup>3</sup>  
N. O. SANTOS<sup>4</sup>  
A. TURTELLI JR<sup>5</sup>  
W. VELLOSO<sup>2,\*</sup>

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CNRS-Lab. de Gravitation  
et de Cosmologie Relativiste  
Orsay - Paris

A. BRILLET  
O. CREGUT  
P. HELLO  
C.N. MAN  
P.T. MANII  
A. MARRAUD  
D. SHOEMAKER  
J-Y. VINET

CNRS-Université Paris 6

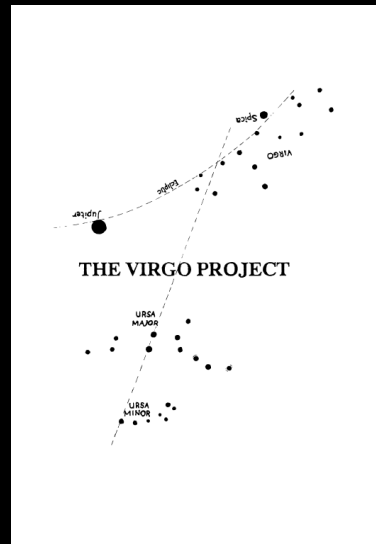
J.M. AGUIRREGABIRIA  
H. BEL  
J-P. DURUISSEAU  
G. LE DENMAT  
M. TOURRENC

Groupe d'Astrophysique  
Relativiste  
Observatoire de Meudon

T. DAMOUR  
S. BONAZZOLA  
J.A. MARCK  
Y. GOURGHOULON

University of Illinois  
at Urbana, USA

L.E. HOLLOWAY



THE VIRGO PROJECT

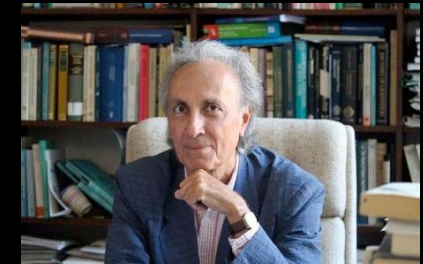
En France



Alain Brillet



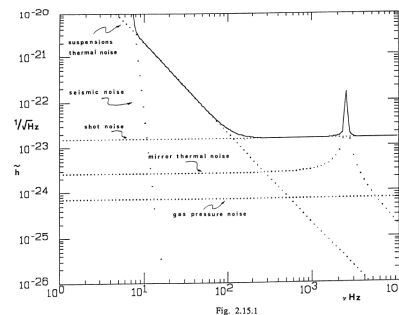
Patrick Fleury



Tibault D'Amour

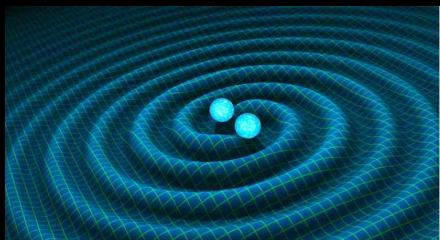


Jean-Marie Mackowski





# The Advanced Virgo antenna

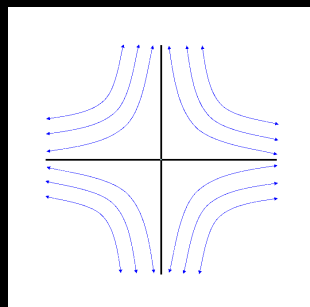


$L_1 + \Delta L; L_2 - \Delta L$

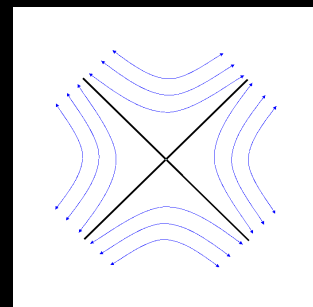
$L_1$

The most stable « standard » meter on earth  
 Sensitive to space deformations of  $10^{-18}$  m

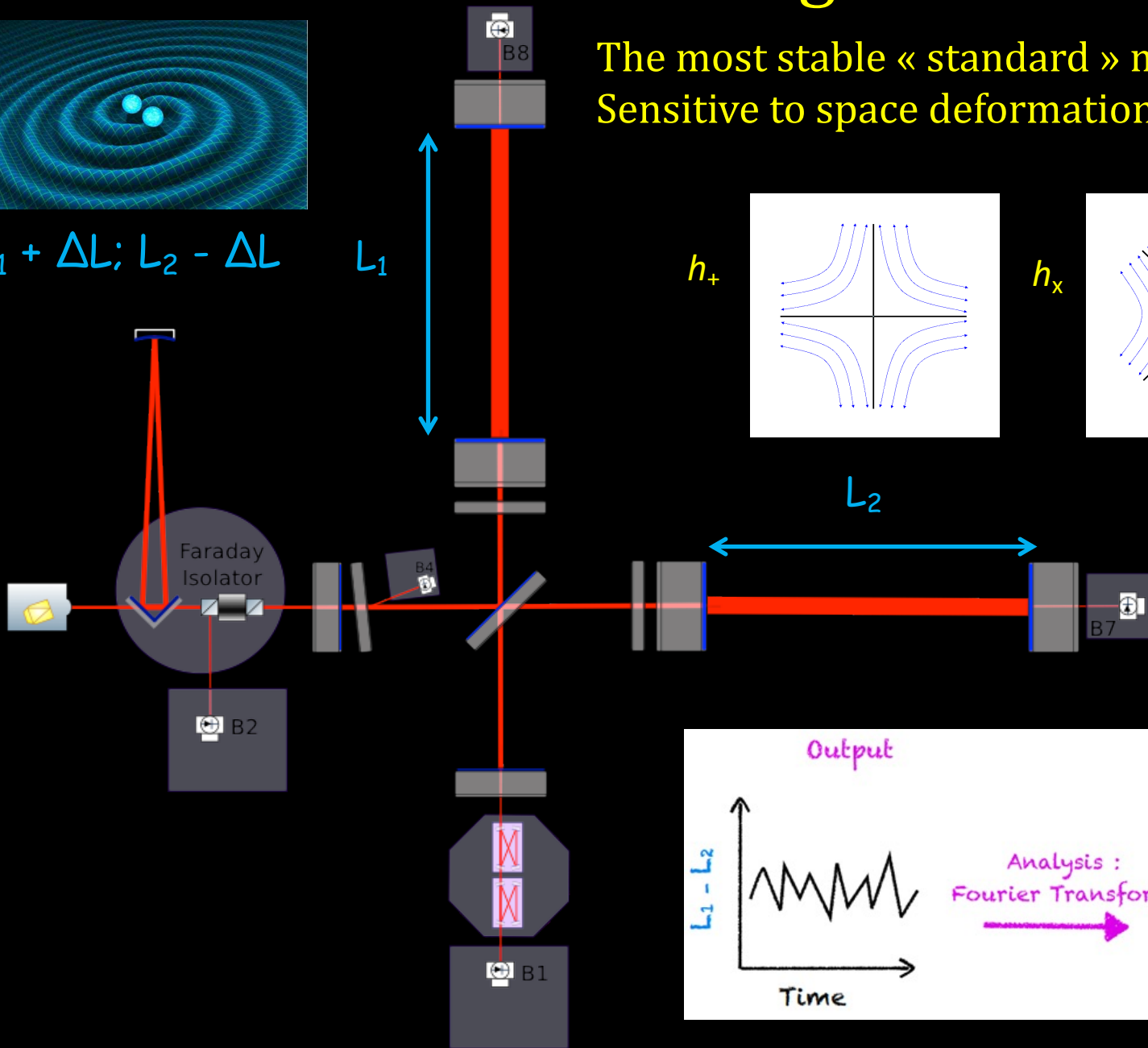
$h_+$



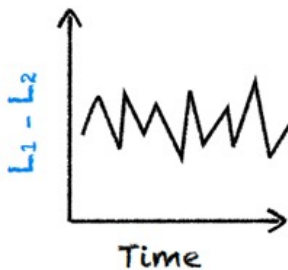
$h_x$



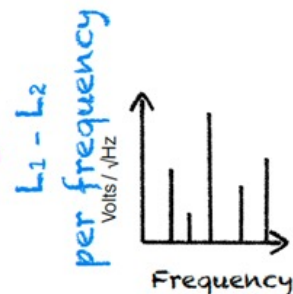
$L_2$



Output



Analysis :  
 Fourier Transform

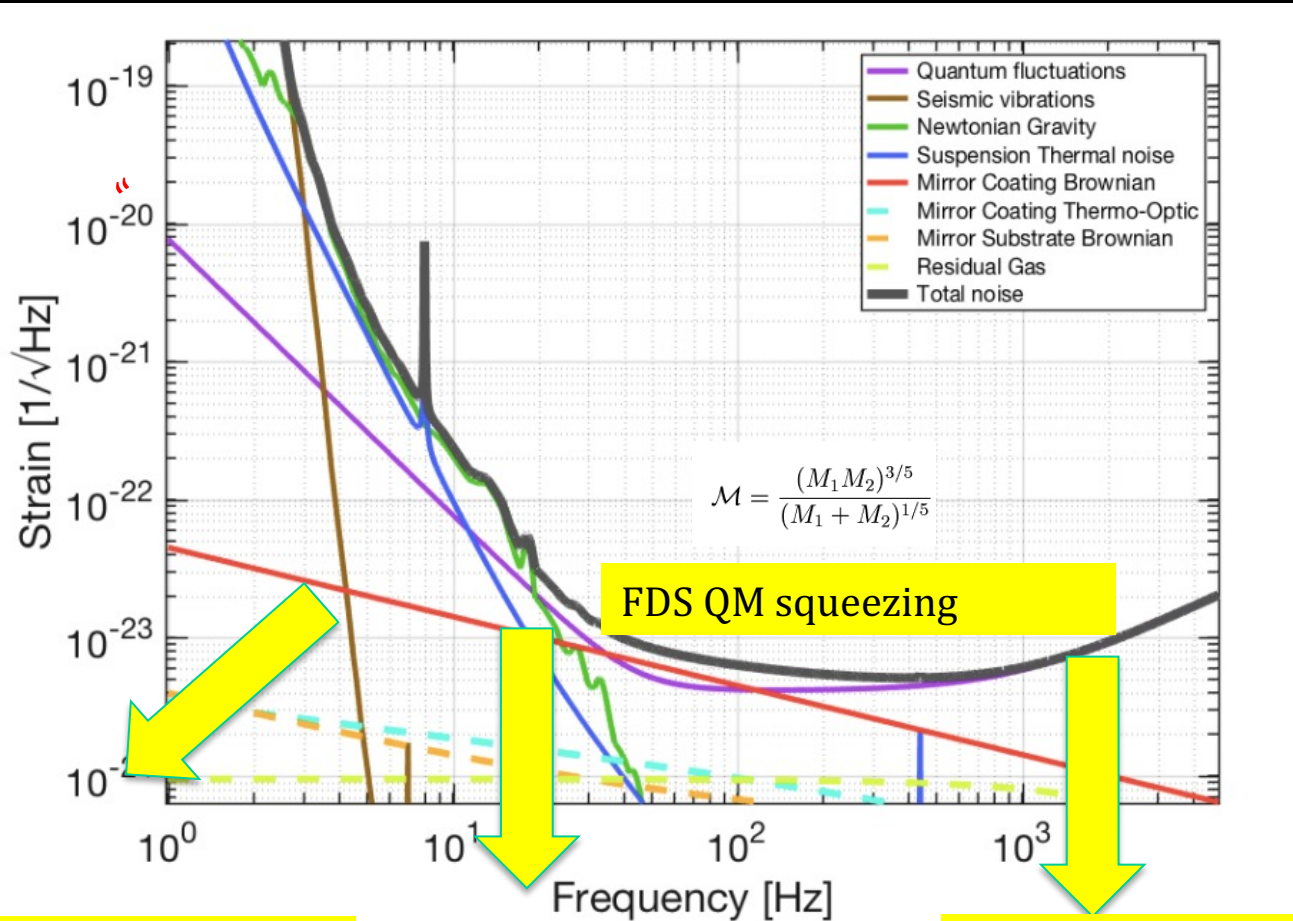


# A long fight against Noise

“Il Satana rumore” A. Giazotto (La musica nascosta del’Universo”  
 (Albinoni)

## Noise hunt:

- From mechanical vibrations, to
- Thermodynamic limits, to
- Quantum limits
- There is no such thing as silence. There is always sound. So, I hear this little sound. I hear myself breathing. Whether I am always listening, or I am speaking, or I just stop speaking. **John Cage**
- The preservation of life is not a matter of energy it is a matter of signal over noise. **Freeman Dyson**

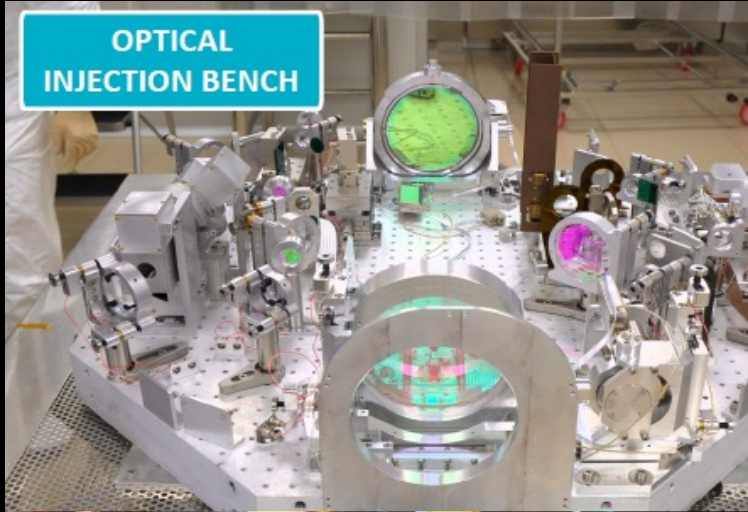


Low Freq Front Suspensions, Env noise

Thermal Front Mirrors, Payloads

Quantum Front High Intensity Laser beam

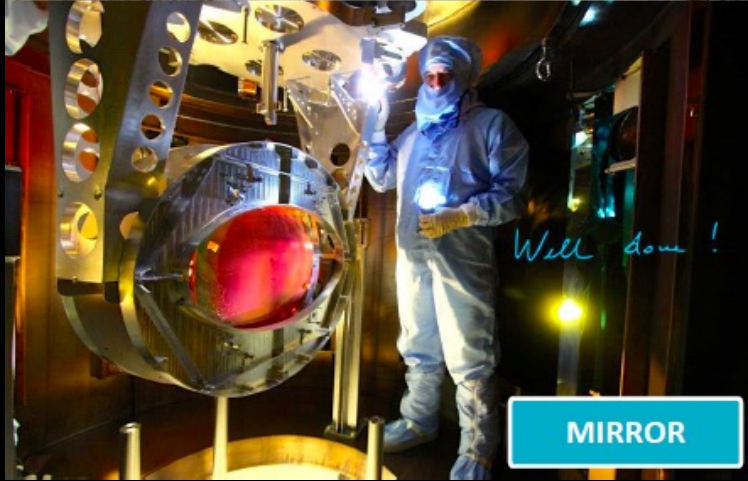
# Technology



OPTICAL INJECTION BENCH

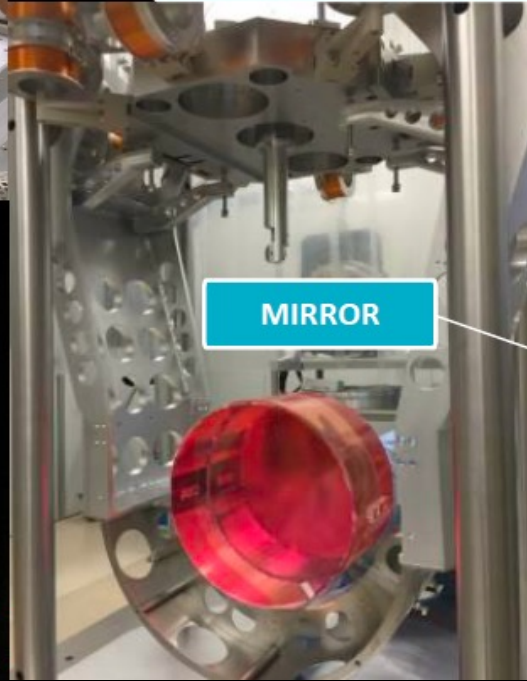


ULTRA-HIGH VACUUM PIPE  
 $10^{-10}$  mbar, 6800 m<sup>3</sup>

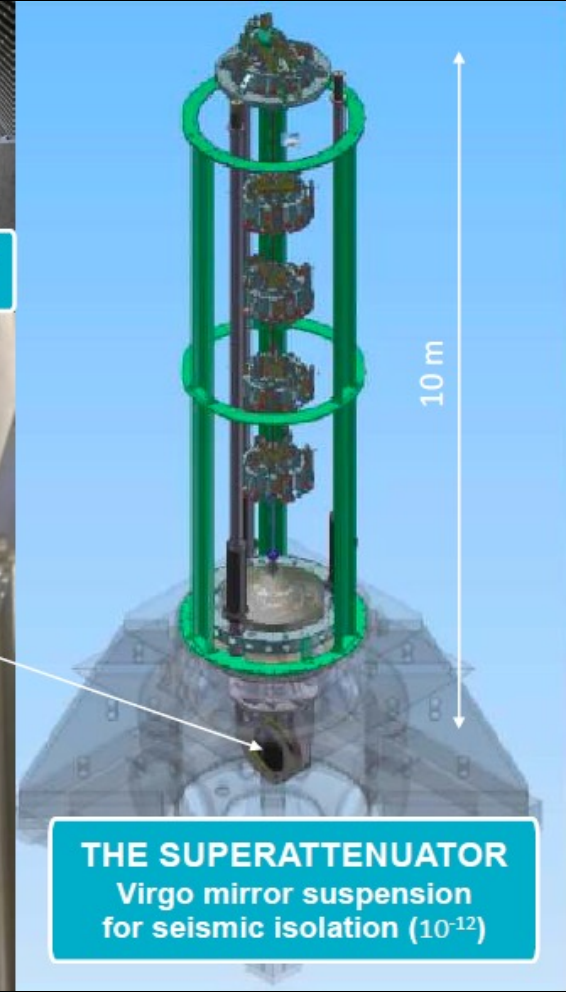


MIRROR

*Well done!*



MIRROR



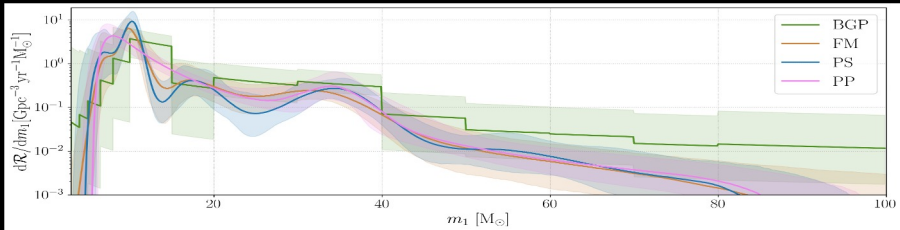
THE SUPERATTENUATOR  
Virgo mirror suspension  
for seismic isolation ( $10^{-12}$ )

10 m

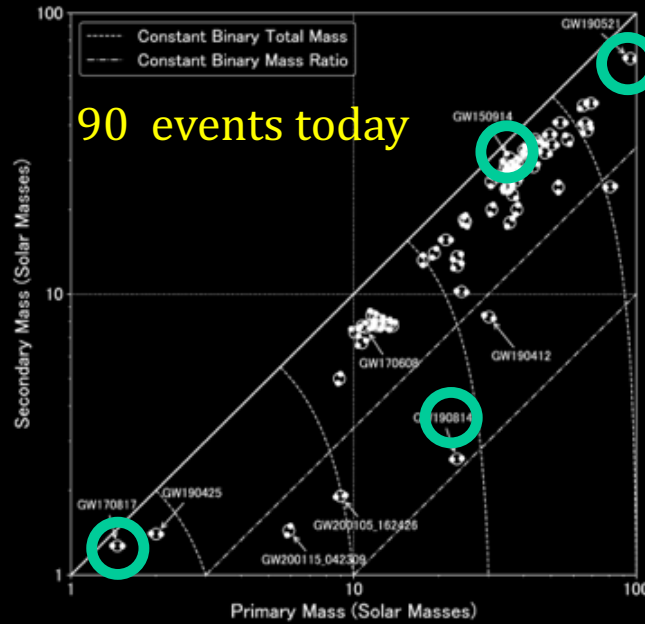


# Today 90 events

## Astrophysics

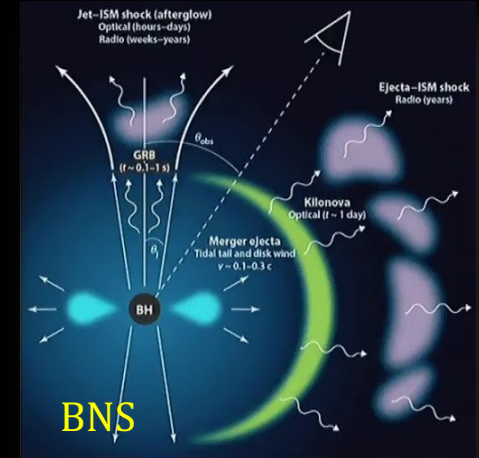


BNS  $13\text{-}1900 \text{ Gpc}^{-3} \text{yr}^{-1}$   
 NSBH  $7.4\text{-}320 \text{ Gpc}^{-3} \text{yr}^{-1}$   
 BBH  $17.3\text{-}45 \text{ Gpc}^{-3} \text{yr}^{-1}$

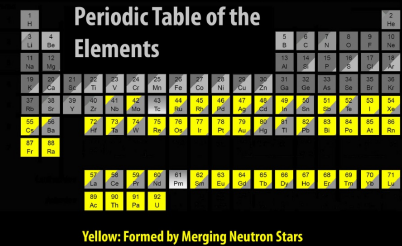


90 events today

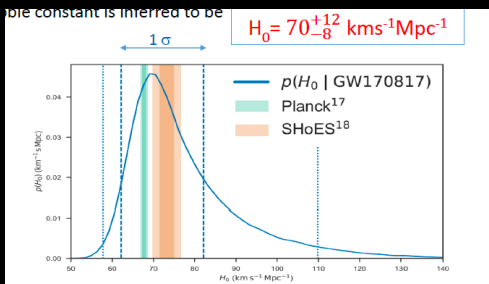
## Multimessenger Astrophysics



## Nuclear Physics



## Cosmology (Hubble tension)



## In the future: A+/ET/CE /LISA

- Dark Matter and Energy
- Primordial Universe
- Star and Galaxy evolution
- High density environments

## Fundamental Physics

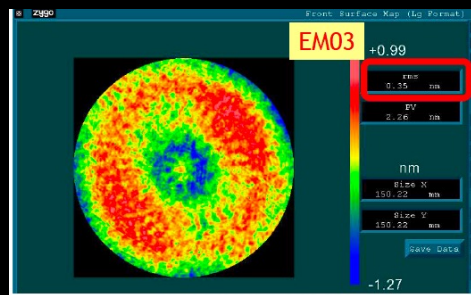
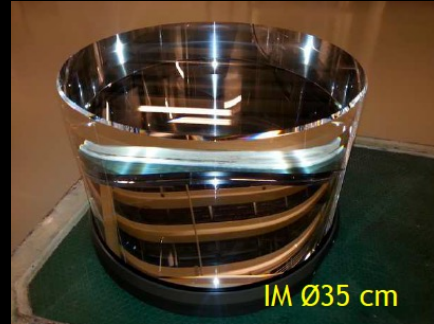
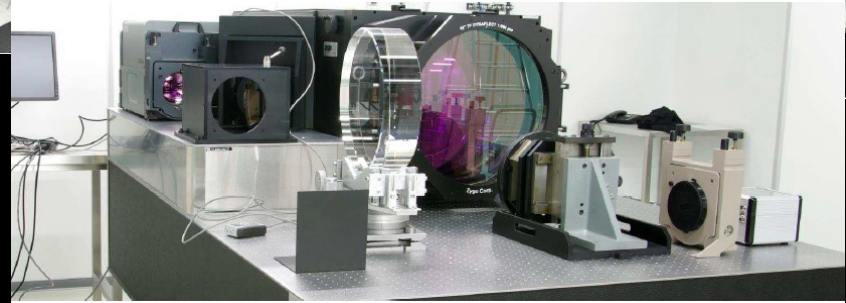
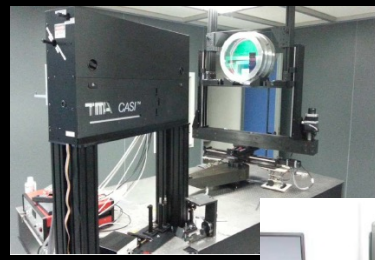
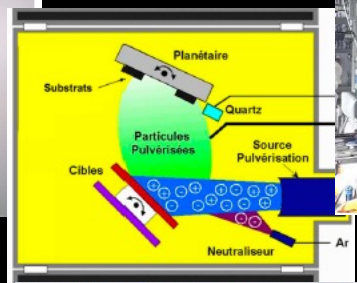
$$-3 \times 10^{-15} \leq \frac{\Delta v}{v_{EM}} \leq +7 \times 10^{-16}$$

GWs propagate at the speed of light to within  $1:10^{15}$ !  
 LVC 2017, APJL, 848, L13



# Mirrors → Laboratoire des Matériaux Avancés (LMA) Provides Coating for all LVK mirrors 30 Years Anniversary 24 November

- ❑ UNIQUE IN THE WORLD
- ❑ National Platform IN2P3 /CNRS @the campus of UCBLyon 1
- ❑ Infrastructure realized for the needs of Virgo
- ❑ Constructed also mirrors of LIGO (crown jewels) and KAGRA
- ❑ Expertise
- ❑ Coatings (low losses), materials
- ❑ Metrology (Optical, mechanical)
- ❑ Machines
- ❑ Ion Beam Sputtering (3)
- ❑ Ion Assisted Deposition
- ❑ Metrology



High reflective mirror transmission 4 ppm at 1064 nm

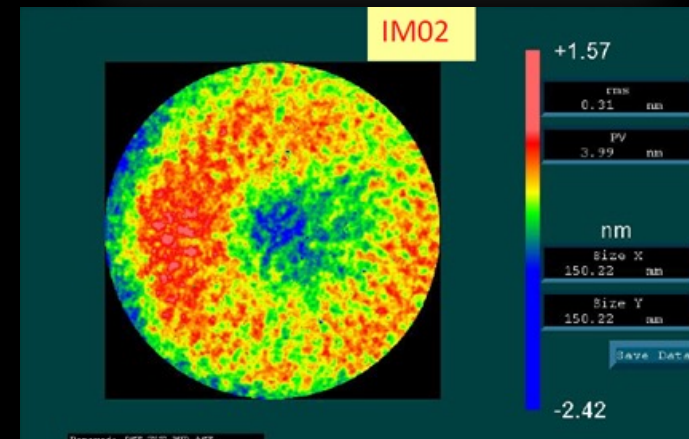
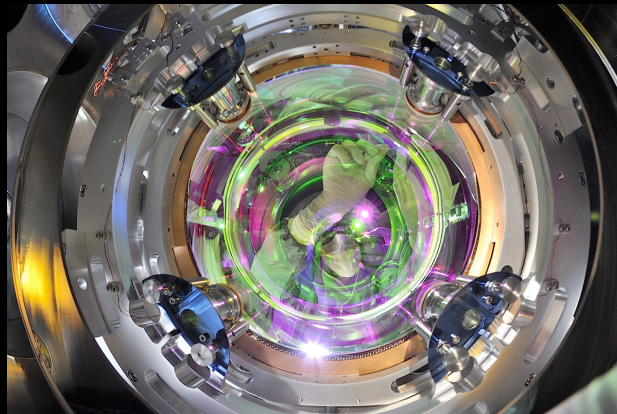
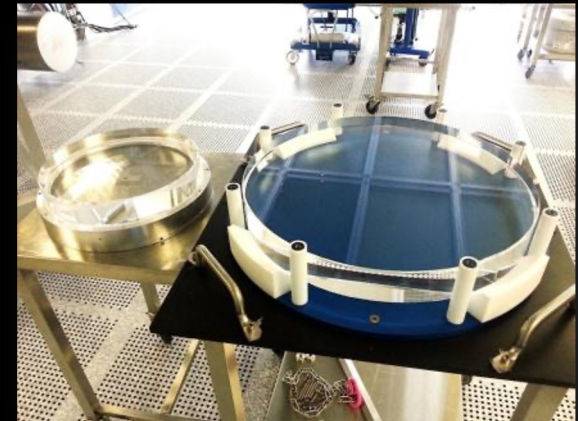
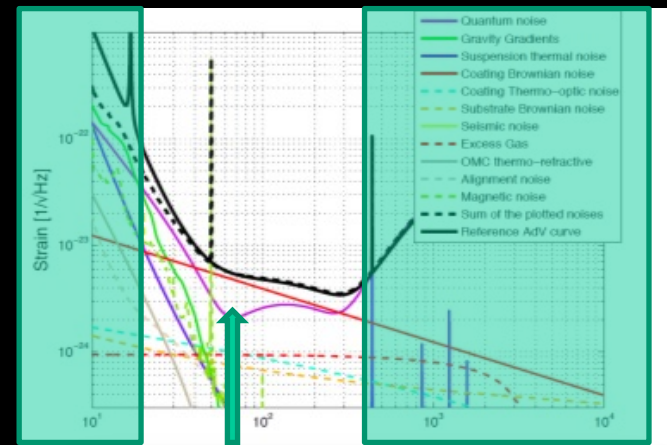
# II. Mid-frequency Noise

- Thermal noise → Mirrors
  - Coming from mirror coatings and suspensions
- Reduced by: *Larger beam spot* (sample larger mirror surface)
- Test masses suspended by fused silica fibers (low mechanical losses)
- Mirror coatings engineered for low losses

Reflectivity > 99.999%

Absorptivity < 1ppm, Scattering < 10 ppm

Flatness < 0.5 nm



# O4-O5 V\_next : what do we expect

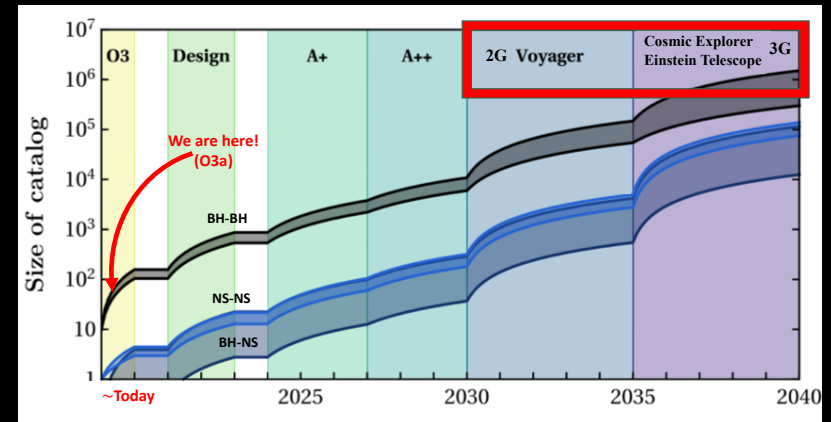
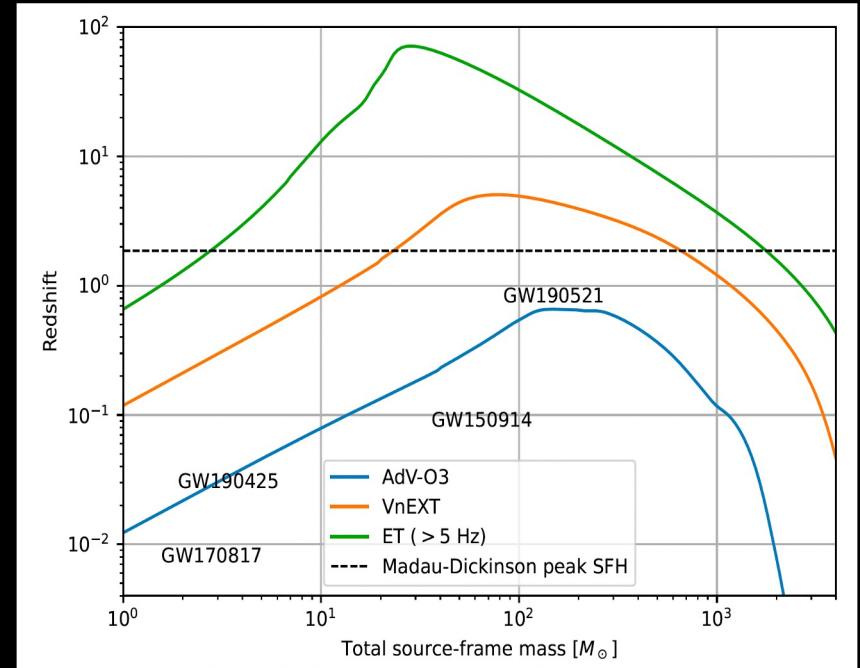
## Binary detection rates

- O3 ~ 1 / 5 days
- O4 ~ 1 / day
- O5 ~ 3 / day
- Vnext 1 / 2h ?

**SNR = 8 on each detector**

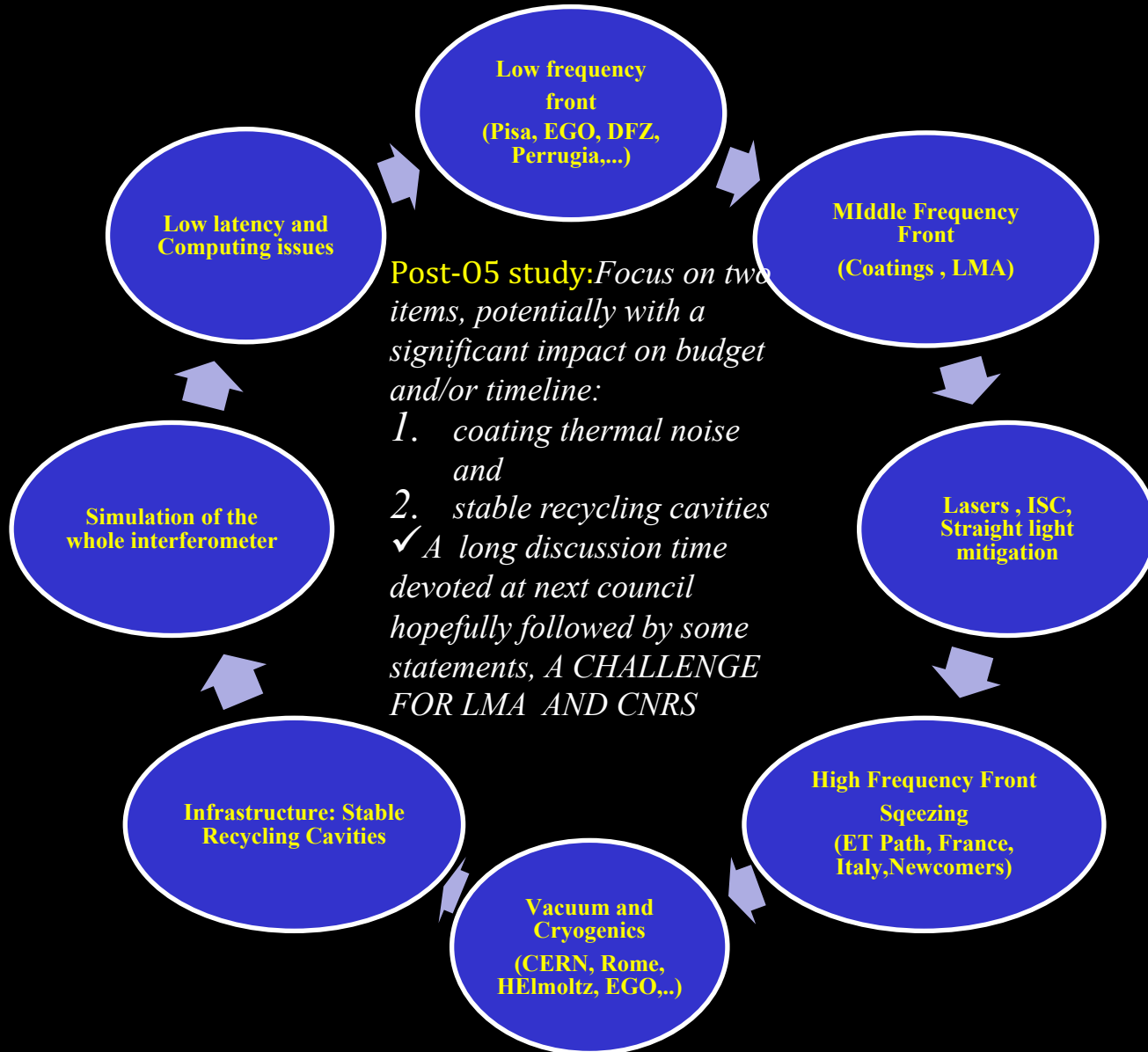
D	BNS per year	Comment
100 Mpc	1	GW170817 is once per decade event
175 Mpc	4 - 7	Most likely for O4 ?
300 Mpc	30	Game changing number : O5 + Rubin Observatory ToO

See Mandel & Broekgaarden 2022, LRR





# V\_Next Challenges on many interconnected fronts, but also many opportunities for increase of VirgO/EGO partnership



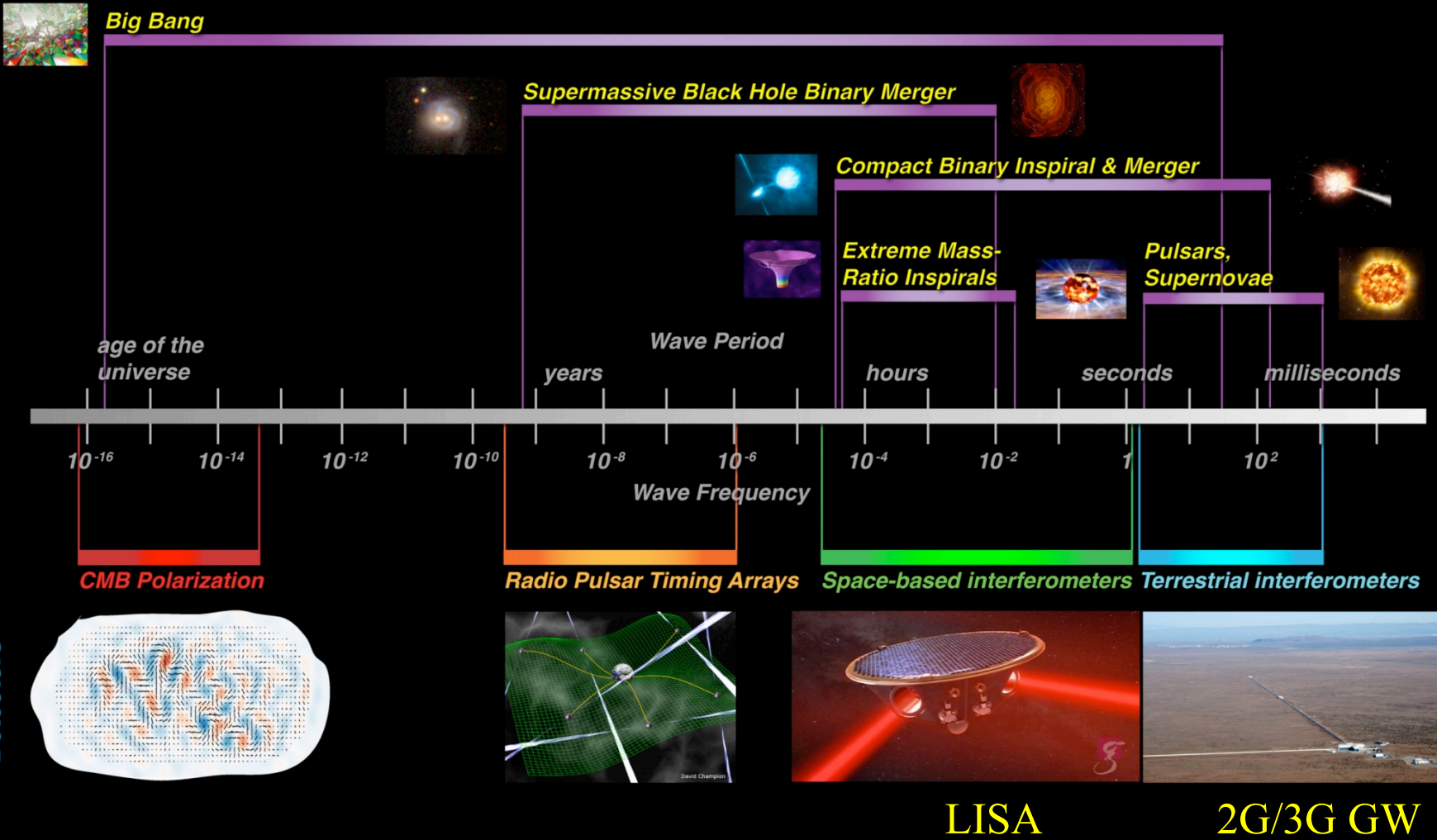


# Gravitational Waves « Frequency Domain » Analysis

The Gravitational Wave Spectrum

Sources

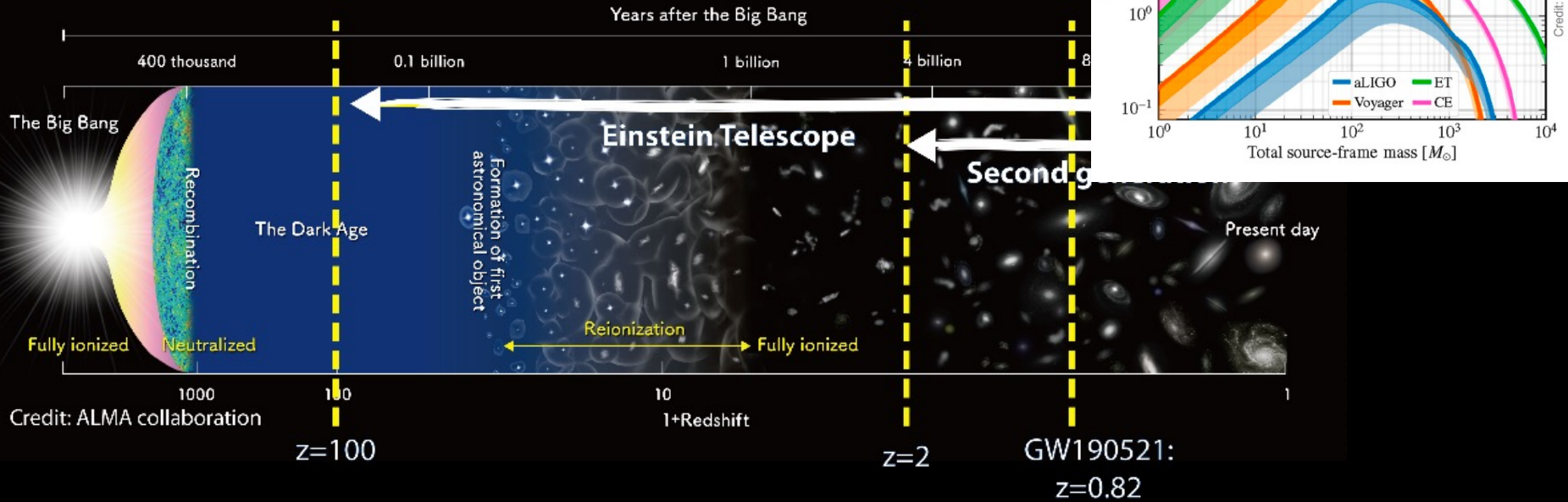
Detectors



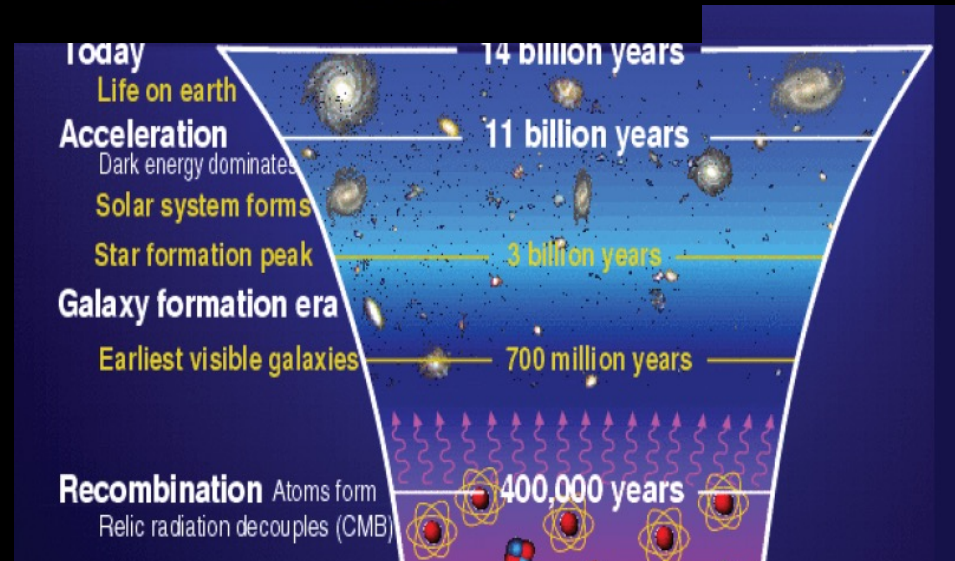
LISA

2G/3G GW

## Detection horizon for black-hole binaries

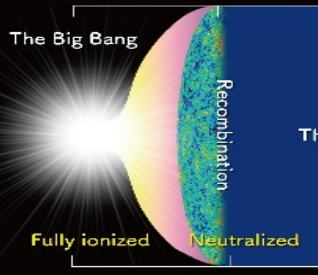


7. First Galaxy and Population III (primordial BH?) formation era
8. Star formation, Reionisation Modern Galaxy and formation and evolution
9. Dark Energy Domination
10. Today





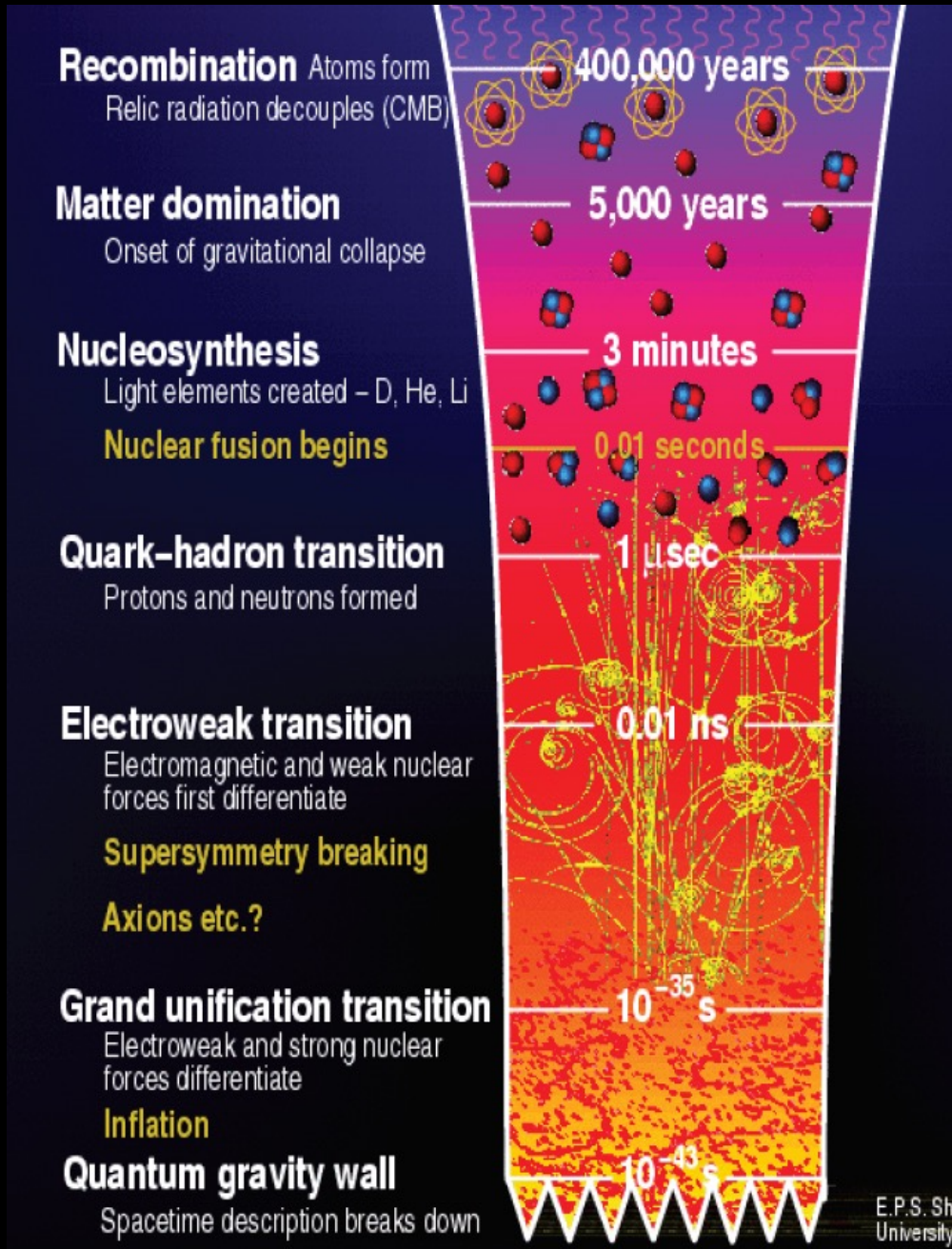
400 thousand



Credit: ALMA collaboration

The first 400.000 years Cosmology up to the recombination wall  
**GW a dominant probe**

1. **Inflation**
2. **Grand Unification Transition:** Electroweak and Strong interaction differentiate
3. **Quark-hadron Transition:** Protons and Neutrons form
4. **Nucleosynthesis Transition :** Light elements (D,He, LI) form
5. **Matter Domination Transition:** Onset of gravitational collapse
6. **Recombination Transition:** Atoms form, Universe becomes transparent relic radiation decouples and travels to earth (CMB)



The 2 years delay of 93-94 should not be repeated because of European discussions should not be repeated

see Smoot et al paper and the most recent Adele de la Rana

## Das Deutsche Zentrum für Astrophysik

2 Standorte für Forschung, Technologie, Digitalisierung



2

Landespressekonferenz Sachsen | 30.09.2022



## SPB: ET sites under characterisation



### Euregio Meuse-Rhine

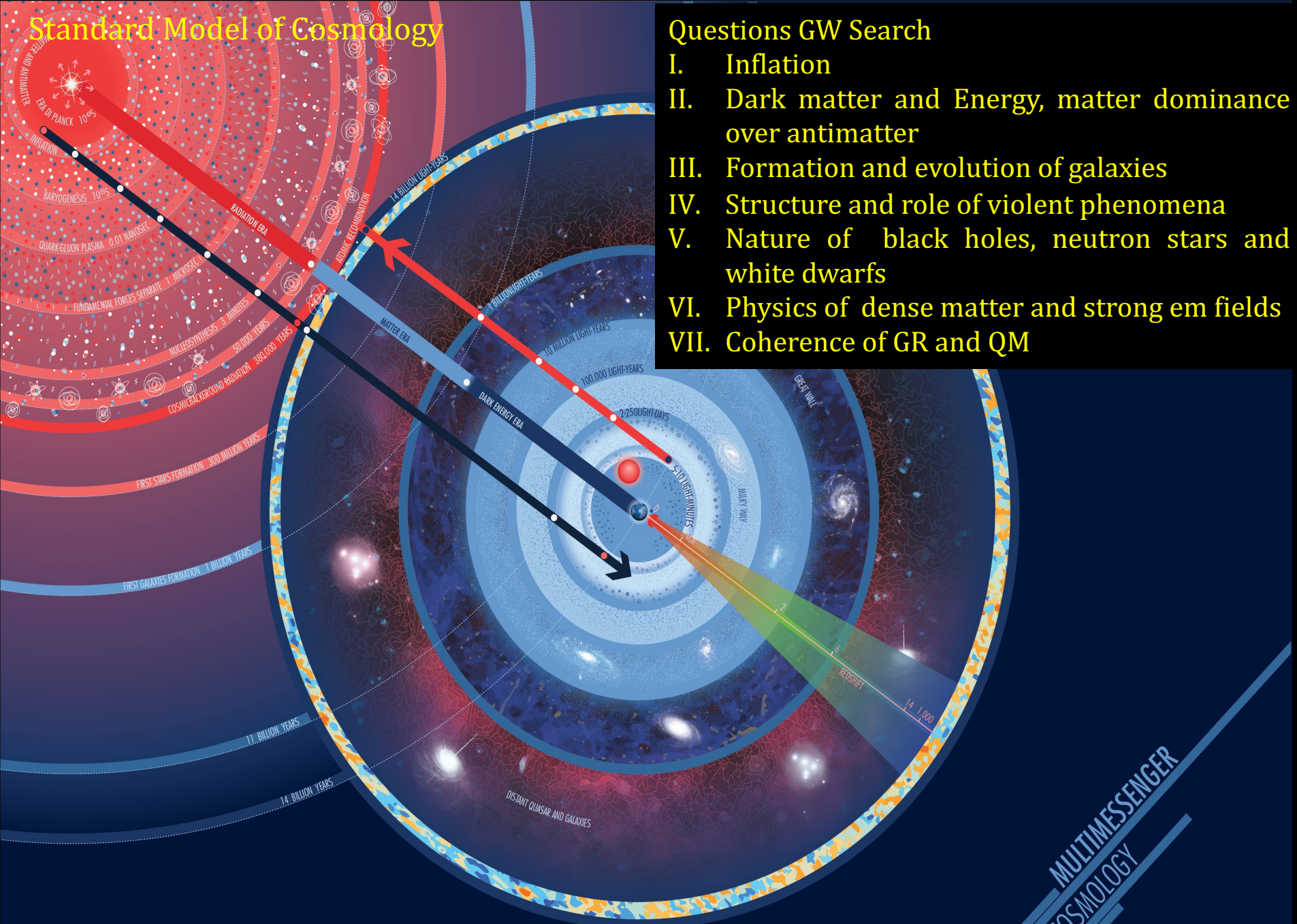
- A 250-m deep borehole has been excavated and equipped
  - Seismic data under acquisition and analysis
- 3-5 other boreholes expected
- Extensive active and passive site characterisation with sensor arrays in 2021
- Good seismic noise attenuation given by the particular geological structure
- ET pathfinder centre under construction
- ~30M€ funding through Interreg grants

### Sardinia

- Long standing characterisation of the mine in one of the corners continuing
  - Seismic, magnetic and acoustic noise characterisation ongoing at different depth in the mine
- Underground laboratory under construction (SarGrav)
- Two ~290m boreholes have been excavated and they will be equipped in the next weeks
- Intense & international surface investigations programme in Summer/Fall 2021
- ~30M€ funding through national and regional funds



# Standard Model of Cosmology



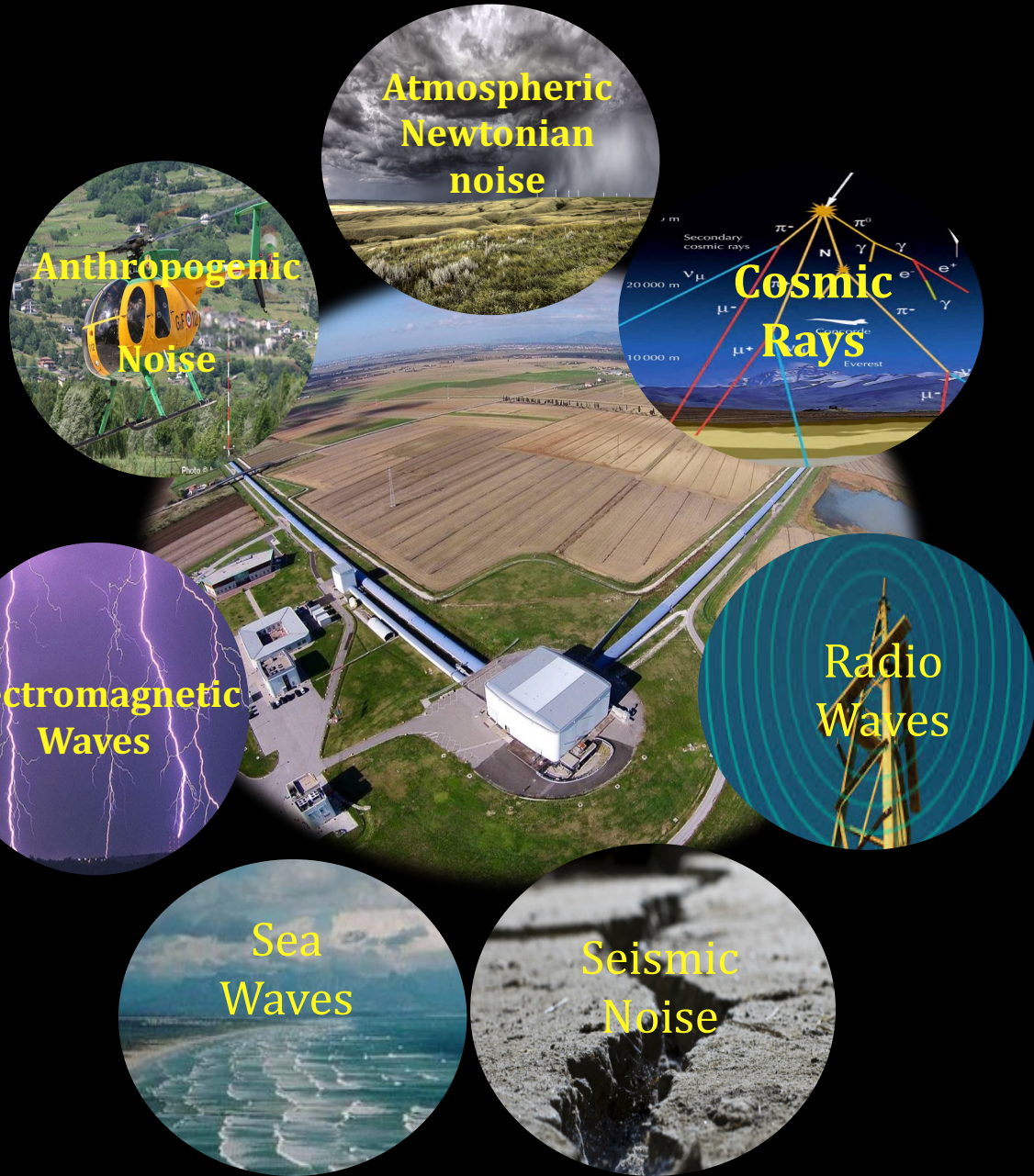
## Questions GW Search

- I. Inflation
- II. Dark matter and Energy, matter dominance over antimatter
- III. Formation and evolution of galaxies
- IV. Structure and role of violent phenomena
- V. Nature of black holes, neutron stars and white dwarfs
- VI. Physics of dense matter and strong em fields
- VII. Coherence of GR and QM

MULTIMESSENGER  
COSMOLOGY

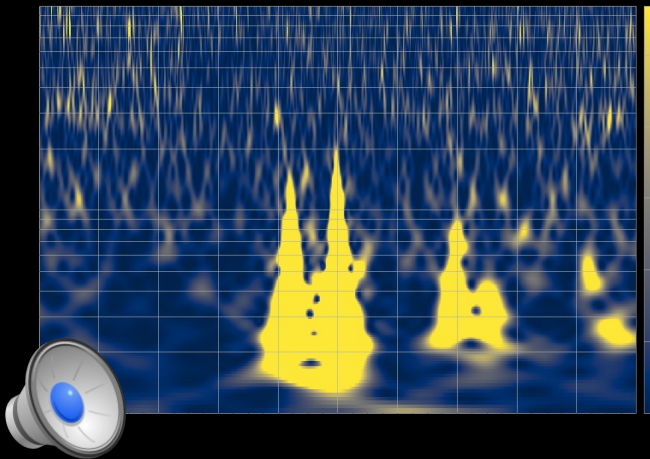


# Imbedding of Virgo/EGO in the Environment



# Inclusion for augmenting humanities perception capabilities from Multi-Messenger to Multi-sensorial

- From multi-messenger to multisensorial apprehension of reality
- Not only increasing inclusion . Also increasing the researchers discrimination power of signal over background through the use of sound.



Recent Nature Editorial, and NAture Astronomy published 6 articles on sonification 18 Nov.

Stressing the pioinnering role of WAnd Diaz-MERced

Editorials

---

## nature

---

### Sounds of the stars: how scientists are listening in on space

**In astronomy, the use of sound instead of light is breaking down barriers to participation and providing insight into the Universe.**

conveyed details of the physics of these stellar explosions. When, in early 2020, the pandemic meant she was unable to get to a 3D printer, she shifted to working on sonification. In August, NASA tweeted about the sound of the black hole at the centre of the Perseus galaxy cluster; the attached file has since been played more than 17 million times. In the same month, Arcand and others converted some of the first images from the James Webb Space Telescope into sound. They worked under the guidance of people who are blind and visually impaired to map the intensity and colours of light in the headline-grabbing pictures into audio. These maps are grounded in technical accuracy. The sonification of an image of gas and dust in a distant nebula, for instance, uses loud high-frequency sounds to represent

## Editorial

<https://doi.org/10.1038/s41550-022-01848-z>

## Hearing is believing

Check for updates

**For blind and visually impaired astronomers, sonification of data creates opportunities for research and outreach. But for everyone, this Focus issue lays out the benefits of complementing vision-based data analysis tools with data sonification.**

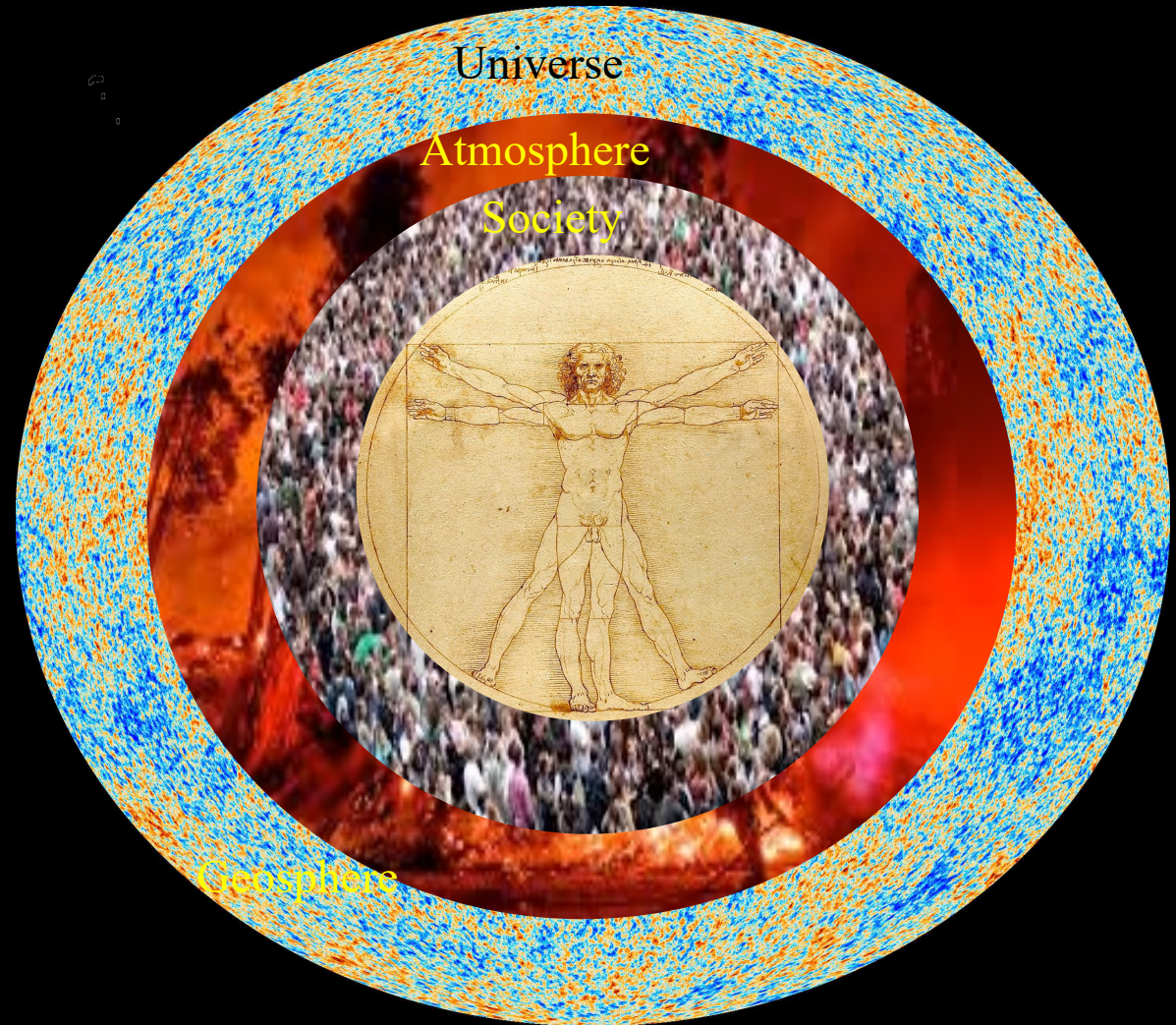
accessibility. In their Q&A, Jake Noel-Storr and Michelle Willebrands interview four blind or visually impaired researchers working in astronomy research, education and outreach: Nicolas Bonne, Cheryl Fogle-Hatch, Garry Foran and Enrique Perez-Montero. These days very few astronomers travel to observatories, yet the image of an astronomer as someone gazing into a telescope persists. This

from perception to experience. The authors consider the main motivations for their community: what can be learned from the sound experience; where are they heading in terms of improved or new tools; and how to evaluate the usefulness, usability and desirability? Within this broader context, astronomers can develop accessible, well-designed and multi-purpose tools that can be assessed



# Conclusion the 4 cosmos

Les translucides mains du Juif  
 polissent Dans la pénombre le  
 dur cristal et  
 Le soir qui se meurt n'est que  
 froid et peur. (Chaque soir aux  
 autres soirs ressemble.) Les  
 mains et l'espace de jacinthes,  
 Qui pâlisent aux confins du  
 ghetto, N'existent guère pour  
 l'homme paisible Qui rêve d'un  
 diaphane labyrinthe.  
 La gloire ne le trouble point,  
 vague Reflet d'un rêve au rêve  
 d'un miroir, Ni les tendres et  
 craintives amours. Libre du  
 mythe et de la métaphore Il  
 polit le cristal : carte infinie  
 De Celui qui est toutes ses  
 étoiles. **Jorge Luis Borges,**  
*Spinoza, 1964*



Que le monde soit cosmos fut une des décisions constitutives de notre histoire intellectuelle  
**H. Blumenberg**