Technological challenges at a Third Generation gravitational wave detector

Mátyás Vasúth

MTA Wigner RCP

Gravitational Physics Research Group

Wigner VIRGO Group

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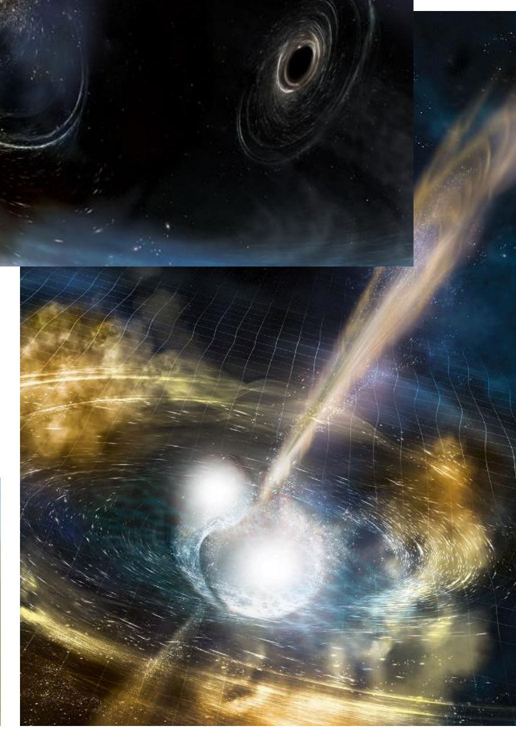
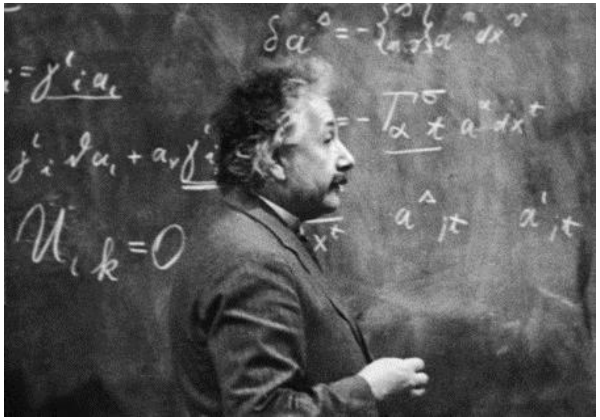
Introduction

- GWs, multi messenger astronomy
- NS sources
- GW detectors
- 3G, technological challenges

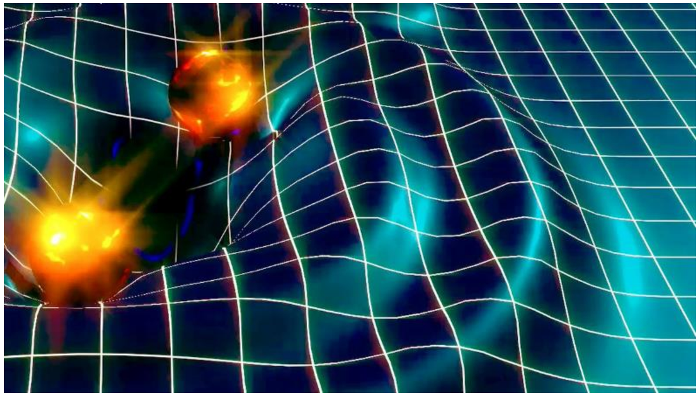


Ripples in spacetime



- General relativity, connects the curvature of spacetime with the matter content, its motion and properties

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

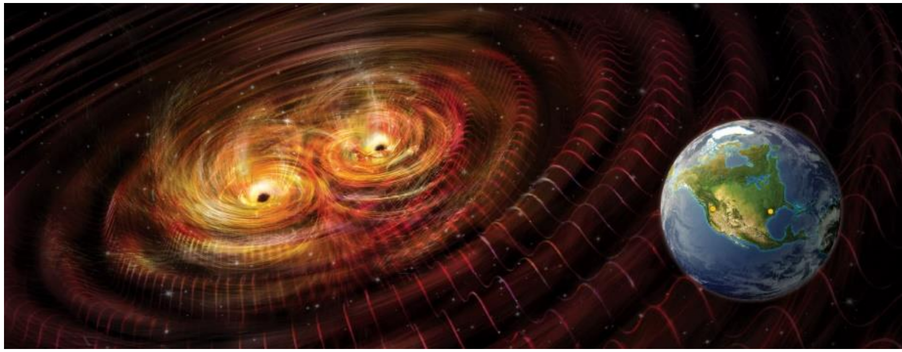


- Gravitational waves, change of gravitational field, ripples of spacetime, propagating with the speed of light

- Linear approximation, far from the source GWs are described as the perturbation of the flat metric

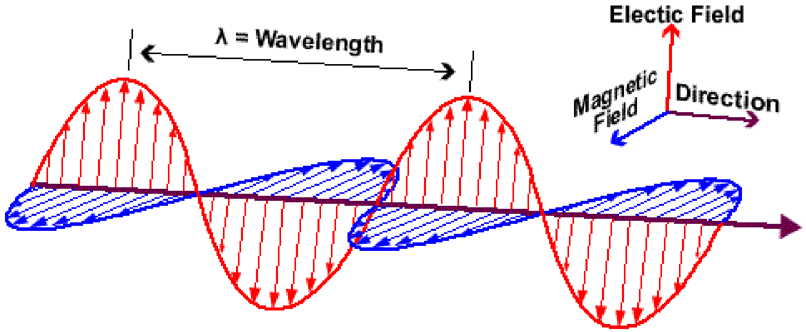
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$\eta^{\rho\sigma} h^{\mu\nu}{}_{,\rho\sigma} = -16\pi\tau^{\mu\nu}$$

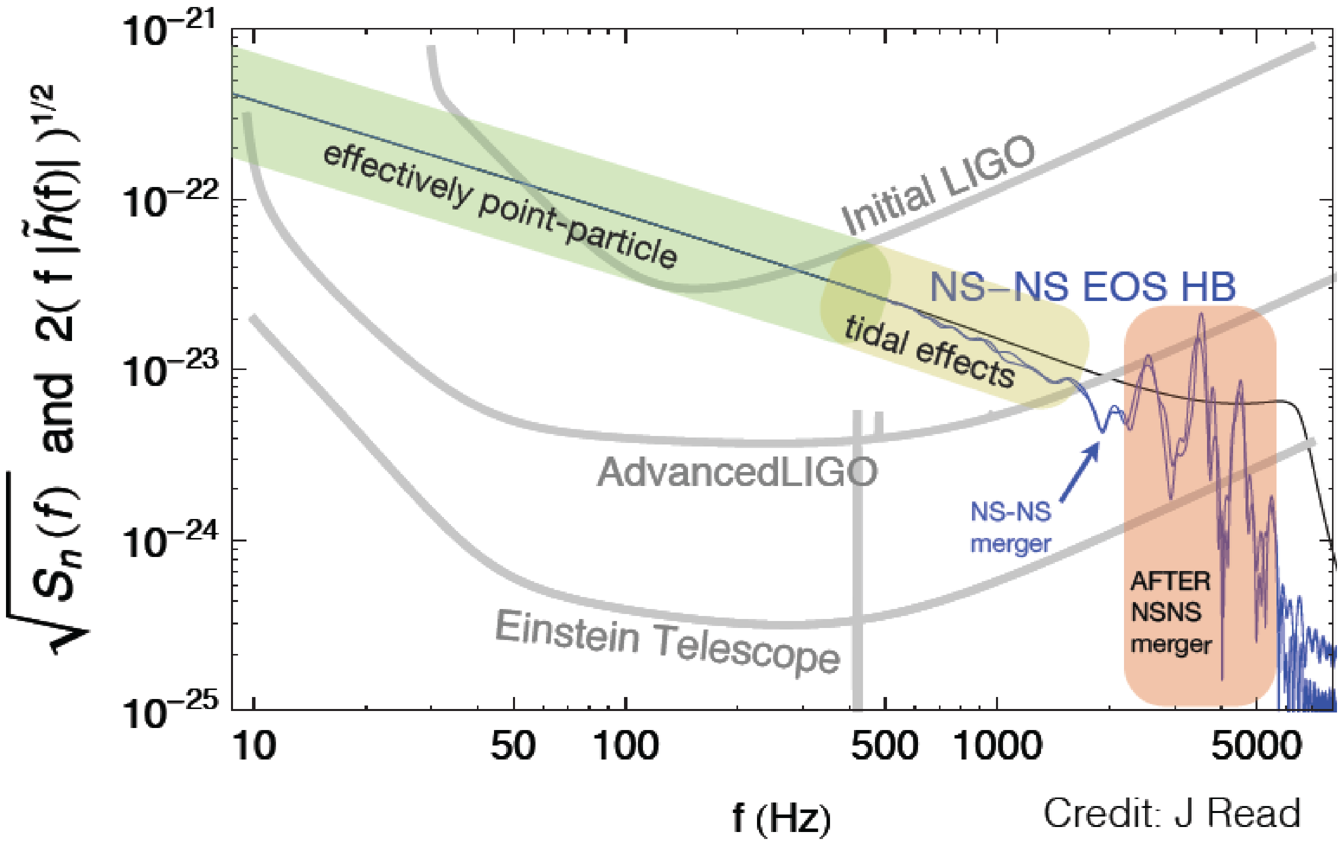


Gravitational / electromagnetic interaction

- Fundamental interactions
- Weak, attracting / much stronger, charges
- Source: masses / separated charges
- GWs: accelerating motion of masses, its wavelength is typically larger than the spatial extent of the source, weakly interacting, similar to sound
- EM: moving charges, its wavelength is smaller than the spatial extent of the source, strong interaction with matter, imaging

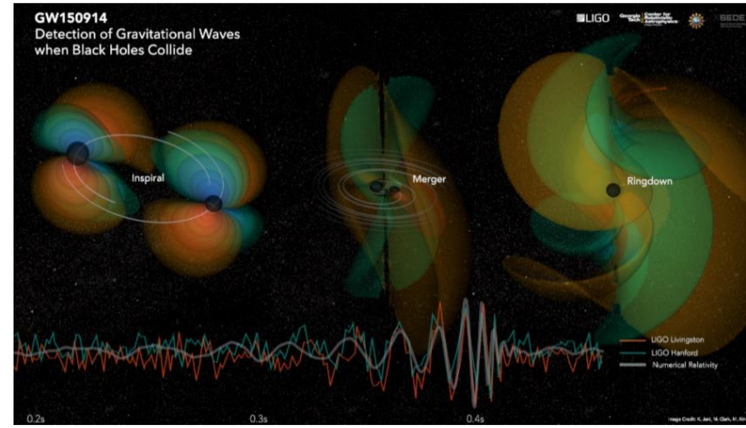


BNS sources, EM counterpart



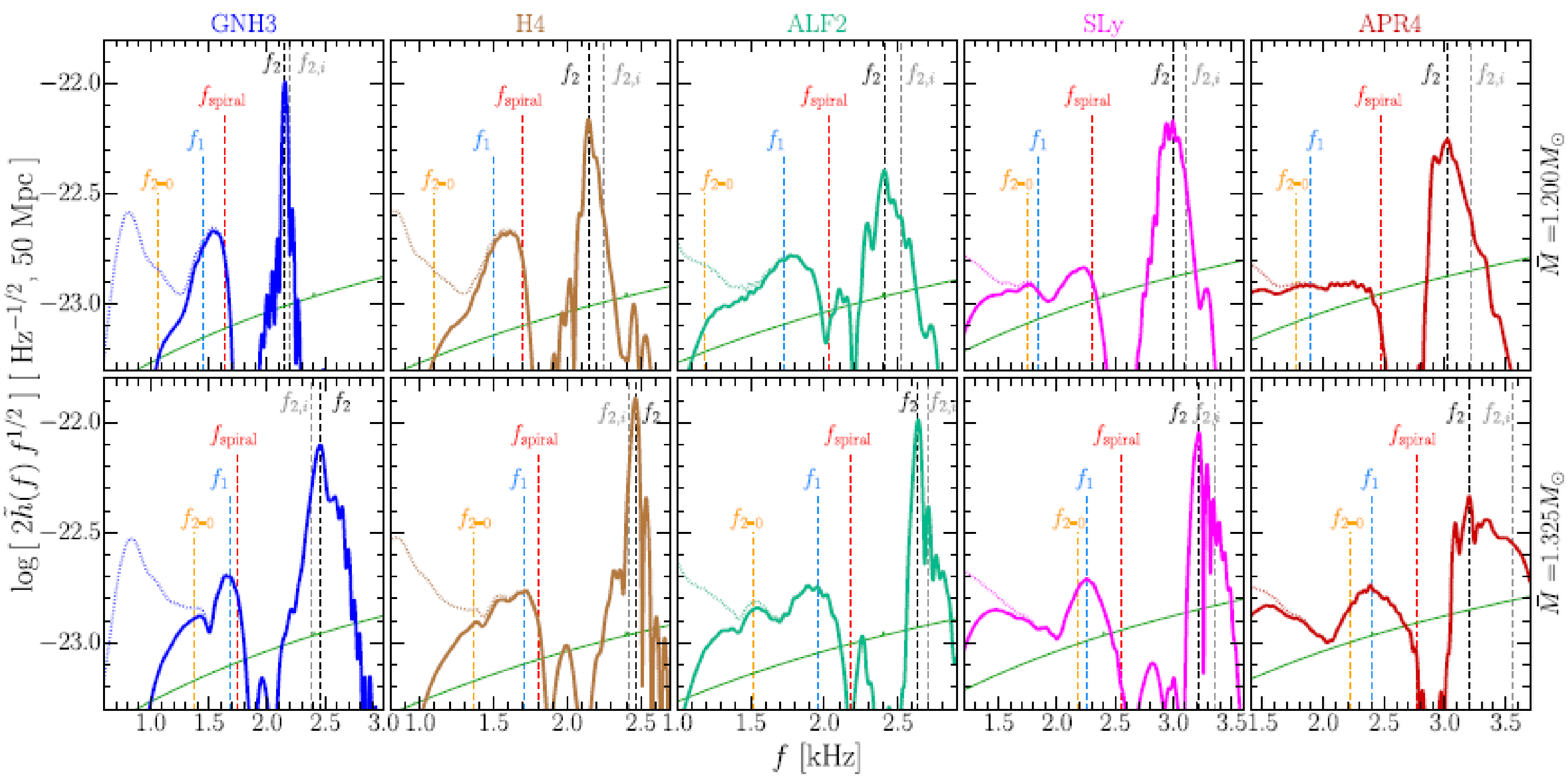
Credit: J Read

Waveforms



- Numerical evolution
  e.g. LORENE, KADATH

- GR and hydrodynamics
  e.g. Rezzola and Takami, 2016



Waveforms

Favata, 2014

- Stationary Phase Approximation

$$\tilde{h}_{\mathrm{T}}(f) = \mathcal{A} f^{-7/6} e^{i\Psi_{\mathrm{T}}(f)}$$

- GW phase

$$\Psi_{\mathrm{T}}(f) = \phi_c + 2\pi f t_c + \frac{3}{128\eta v^5}\Big(\Delta\Psi^{\mathrm{pp}}_{3.5\mathrm{PN}} + \Delta\Psi^{\mathrm{spin}}_{3\mathrm{PN}} + \Delta\Psi^{\mathrm{ecc.}}_{2\mathrm{PN}} + \Delta\Psi^{\mathrm{tidal}}_{6\mathrm{PN}} + \Delta\Psi^{\mathrm{tm}}_{6\mathrm{PN}}\Big)$$

- NS tidal love number: ~ few hundred

  for black holes: 0

$$\Delta\Psi^{\mathrm{tidal}}_{6\mathrm{PN}} = -\frac{39}{2}\tilde{\Lambda} v^{10} + v^{12}\left(\frac{6595}{364}\delta\tilde{\Lambda} - \frac{3115}{64}\tilde{\Lambda}\right)$$

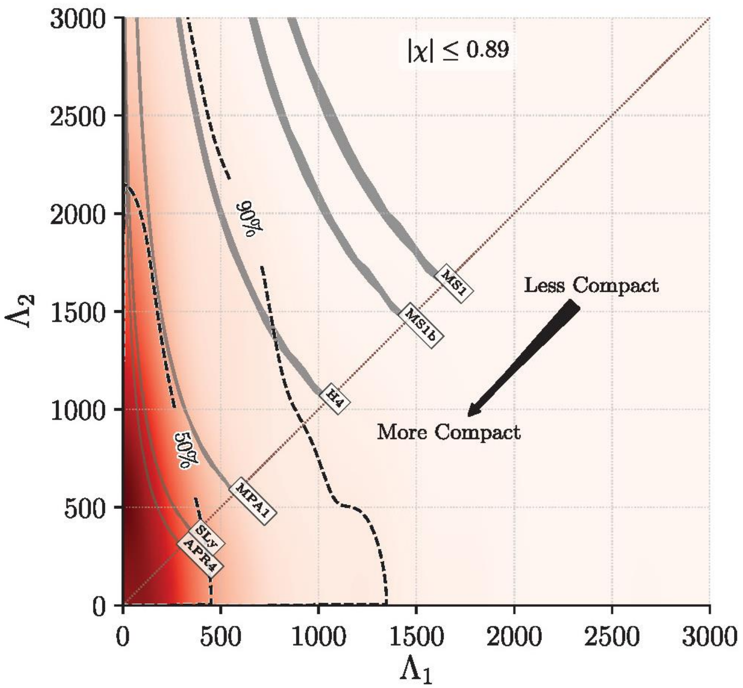
First BNS merger – GW170817

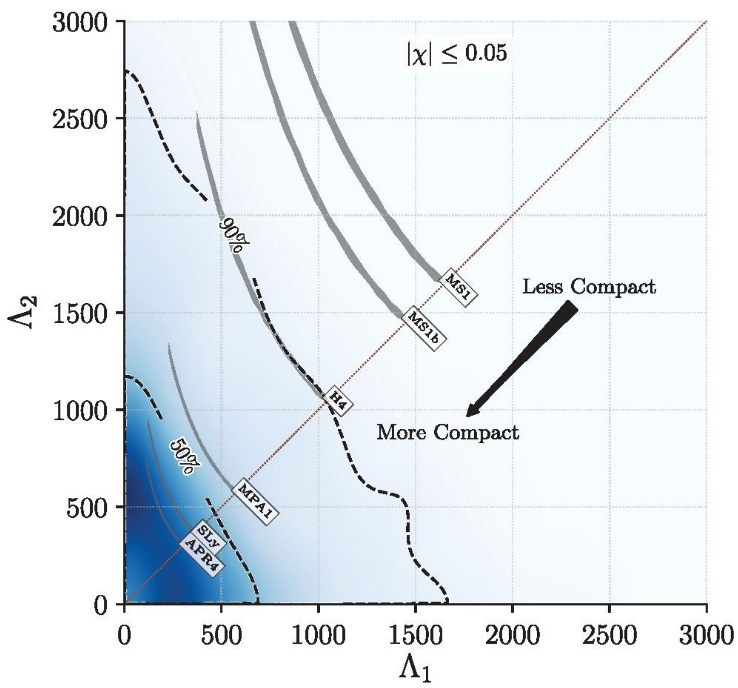
- The tidal field of the companion induces a mass-quadrupole moment

$$\Lambda = (2/3)k_2[(c^2/G)(R/m)]^5$$

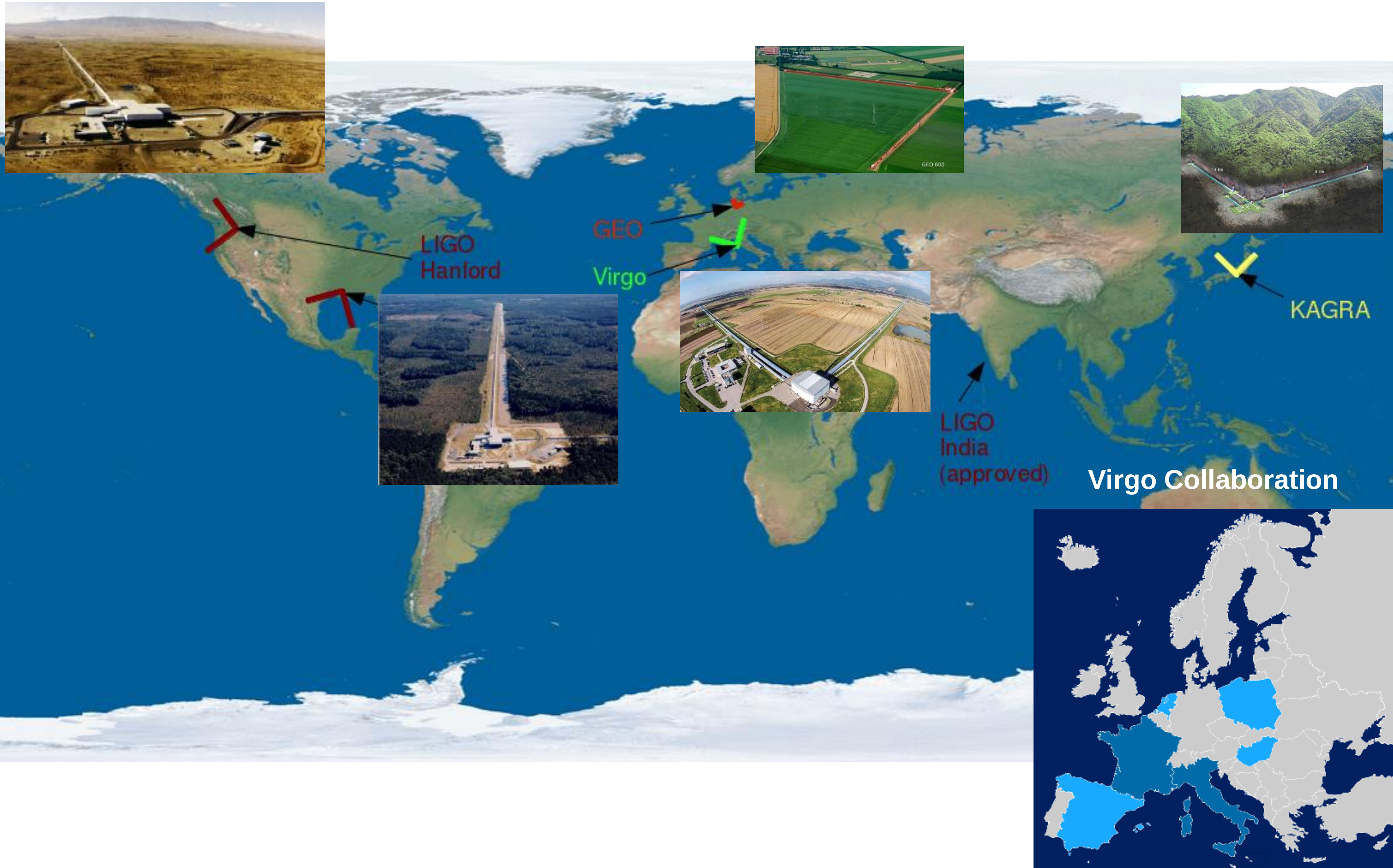
- Tidal deformability
Λ ~ quadrupole moment / external tidal field

- Measurements disfavor EOS that predict less compact stars



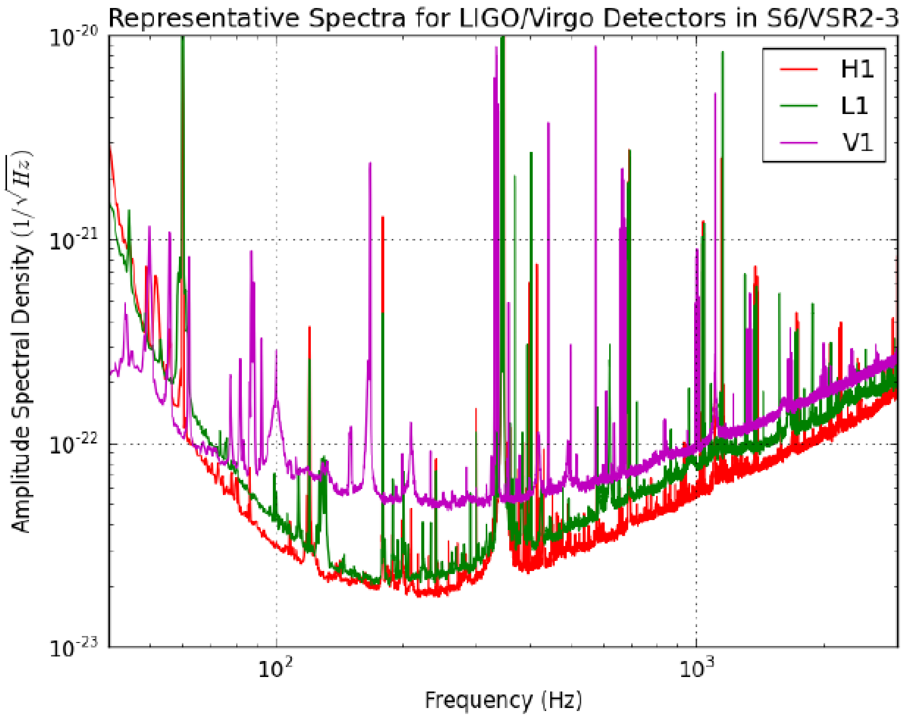


Observatories worldwide

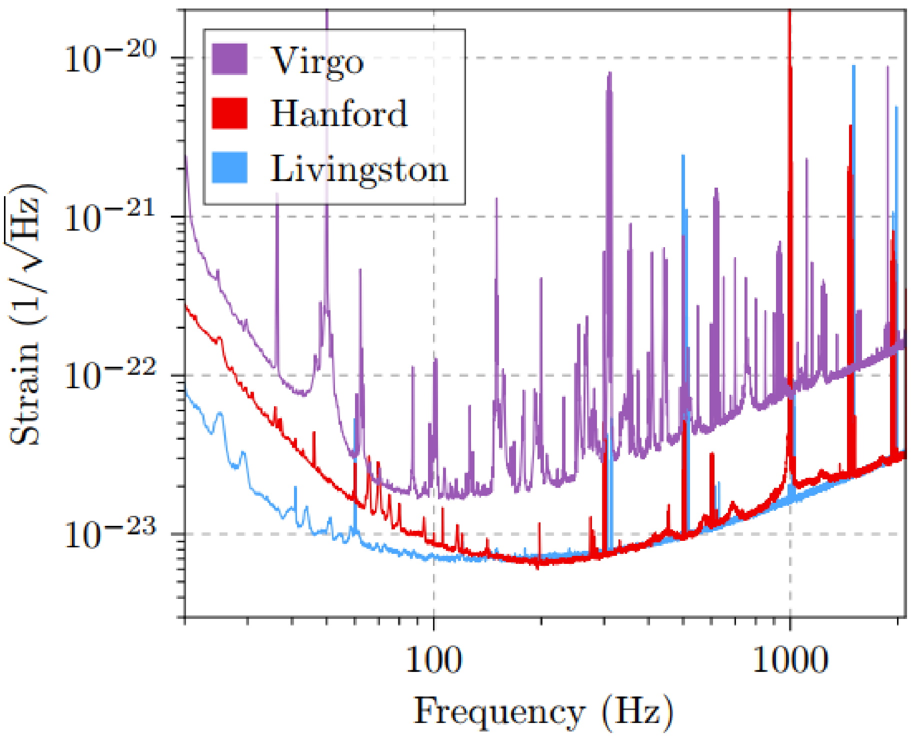


Sensitivity of GW detectors

- Sensitivity of first (2009 - 2010) and second (2017) generation detectors

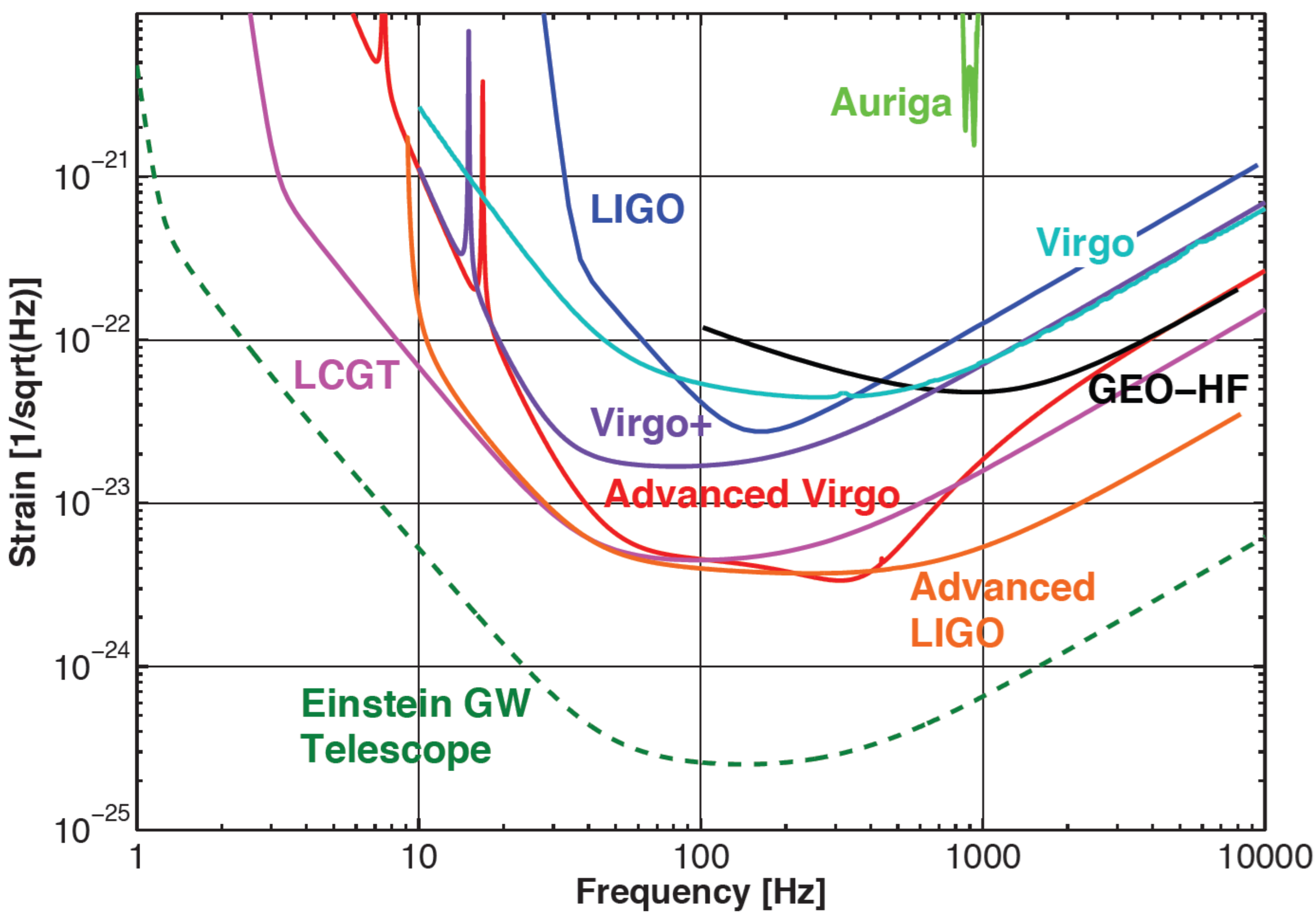


LVC, 2012



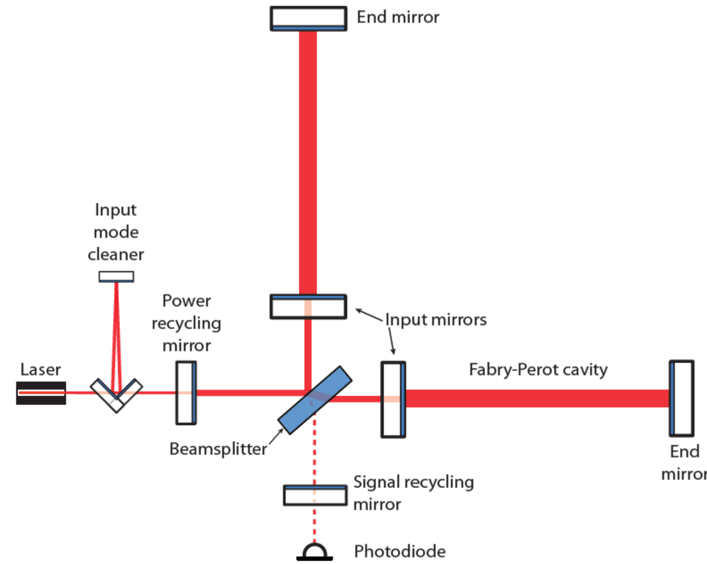
PRL **119**, 141101 (2017)

Sensitivity of GW detectors

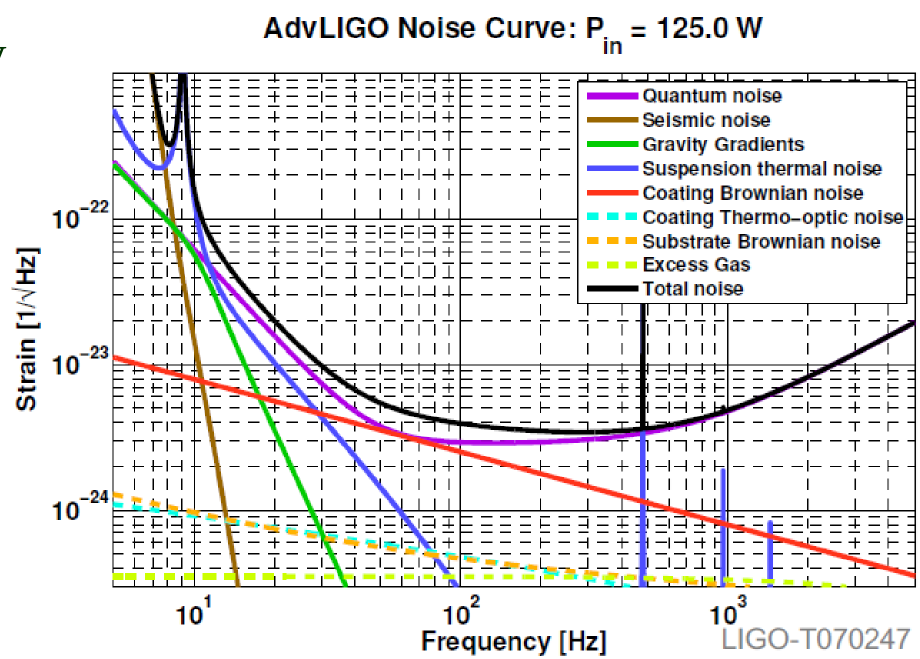


Evolution of interferometers

- 2nd generation, VIRGO, LIGO
  - Dark fringe operation
  - Power recycling
  - Fabry-Perot arm cavities
  - Input mode cleaning
  - Signal recycling
  - Squeezed light

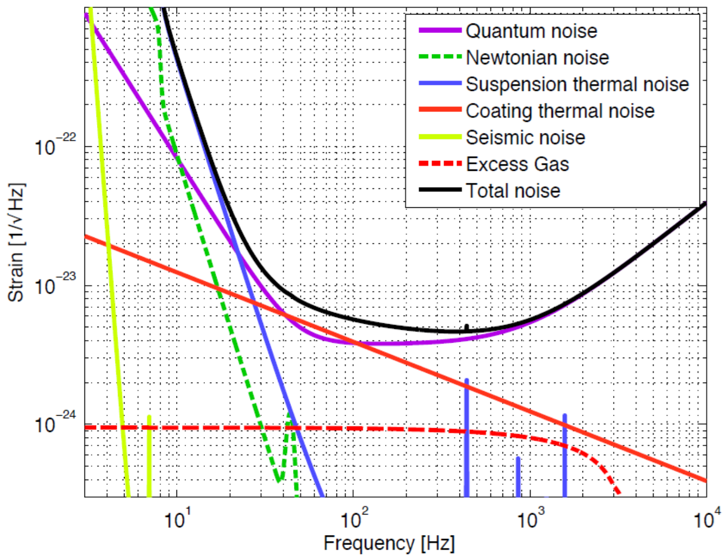


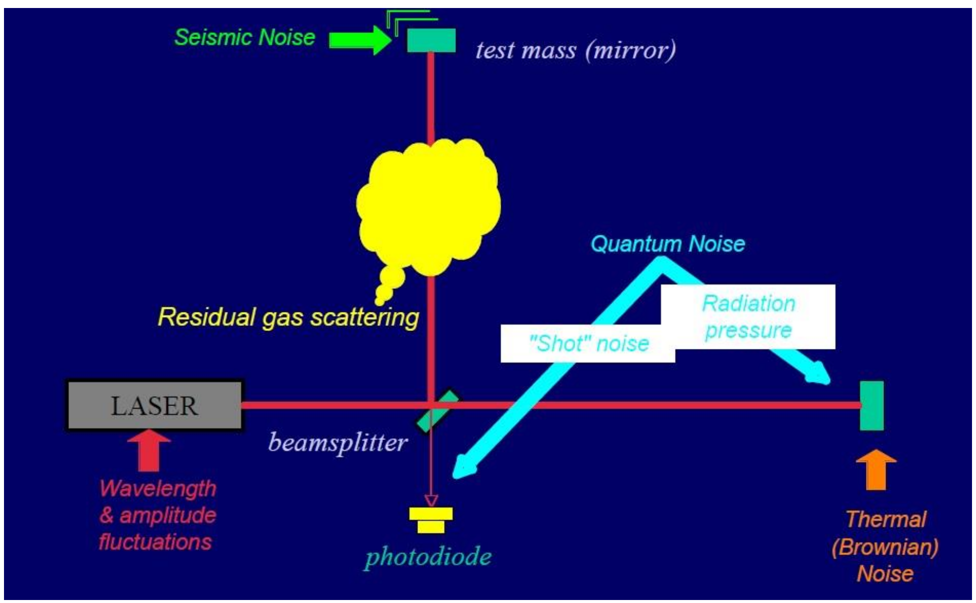
- 3rd generation, e.g. ET, 10 x sensitivity improvement
  - Larger laser, 125 W → 500 W
  - Bigger mirrors, 30 kg → 210 kg
  - Longer arm, 3,4 km → 10 km
  - Cooling, 290 K → 20 K
  - Underground operation

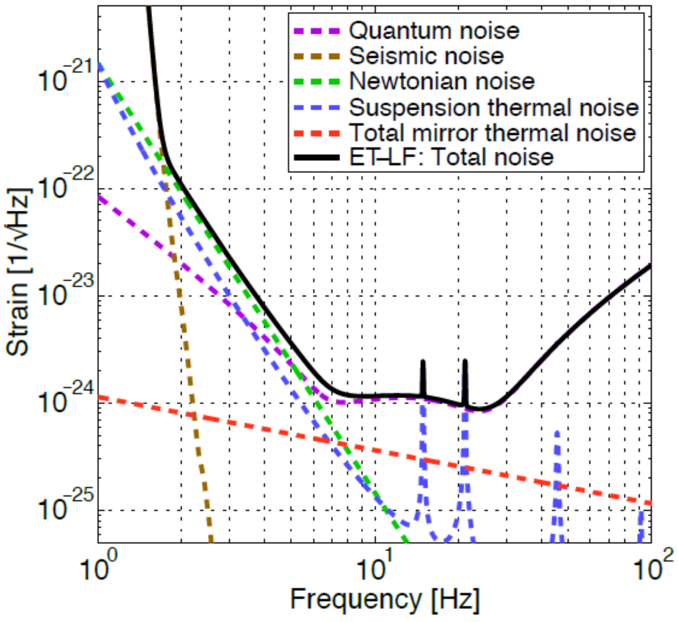


Noise sources

- Photon shot noise, radiation pressure noise: quantum noise
- Thermal noise: coating and suspension
- Residual gas scattering
- Seismic noise
- Newtonian noise

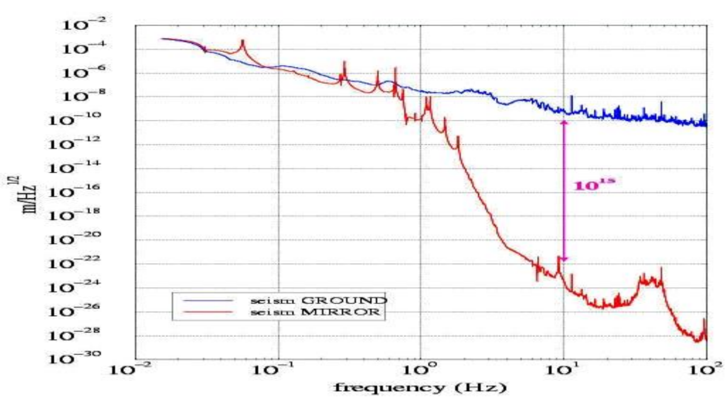


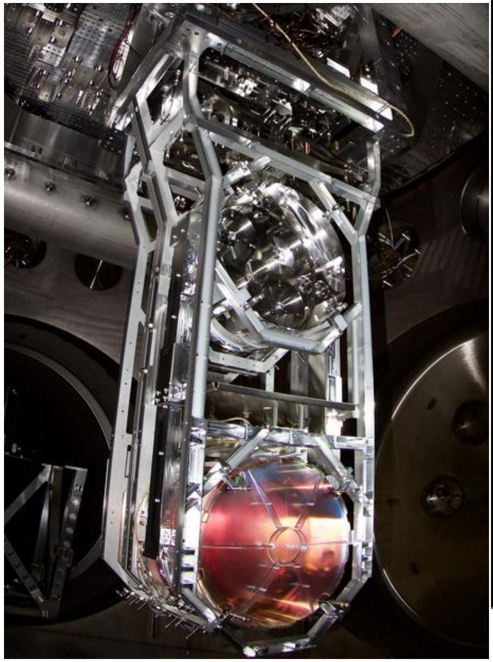


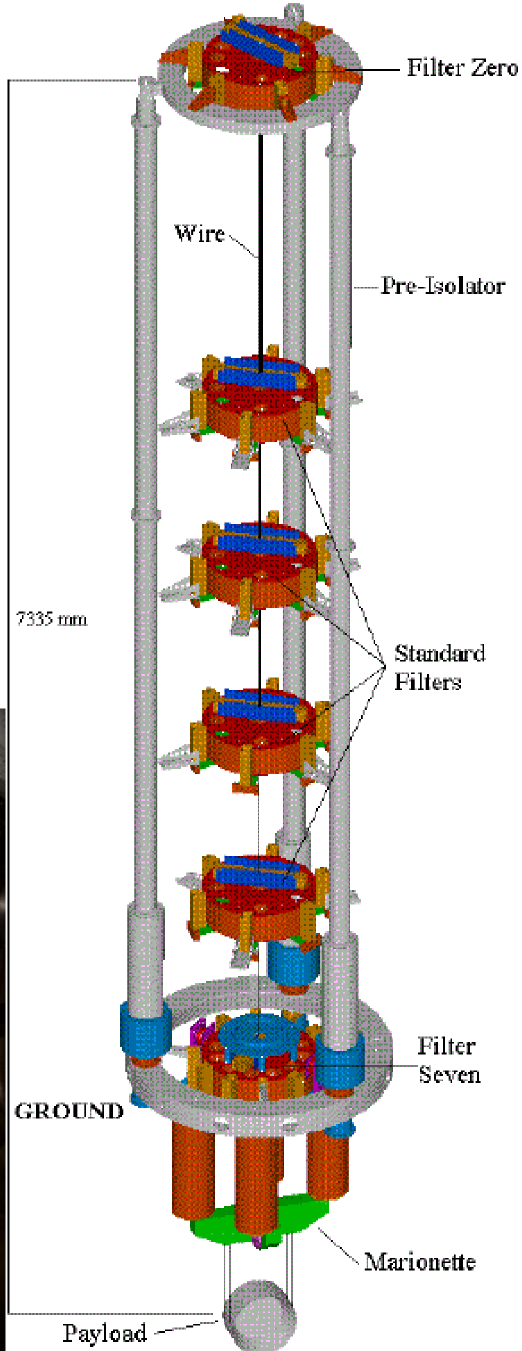


Attenuation of seismic noise

- Seismic noise is a limiting factor for ground based interferometers
- In VIRGO the mirror suspension system (Super Attenuator, SA) reduces seismic noise transmission below 100 Hz, multistage pendulum, measured attenuation upper limit 10^{15} at 10 Hz, active control below 4 Hz and passive above
  - Inverted pendulum
  - 6 or 2 seismic filters
  - Payload/mirror
- aLIGO: quadruple pendulum active isolation

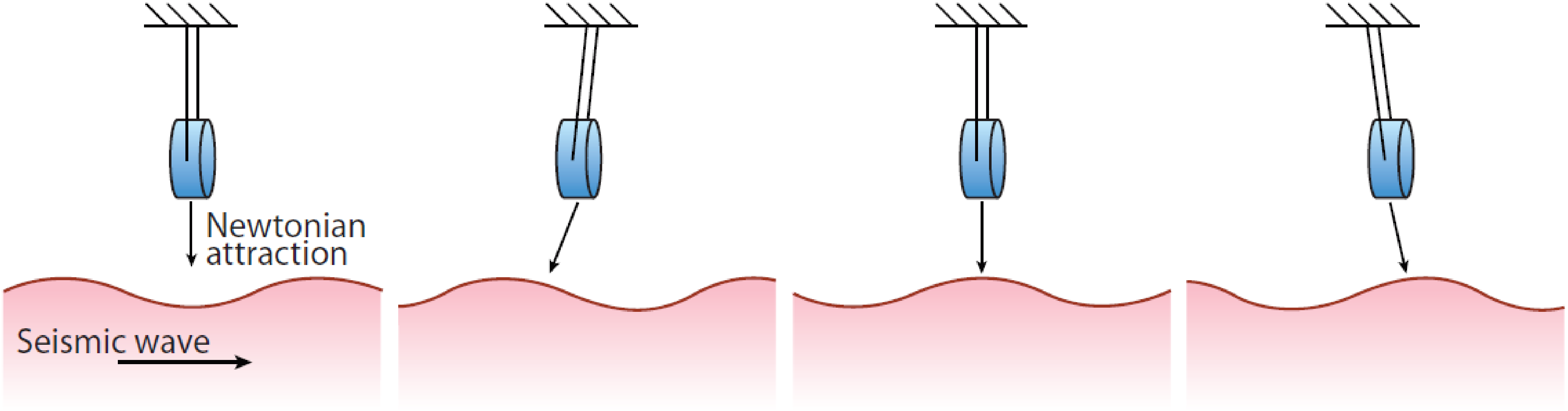






Newtonian noise

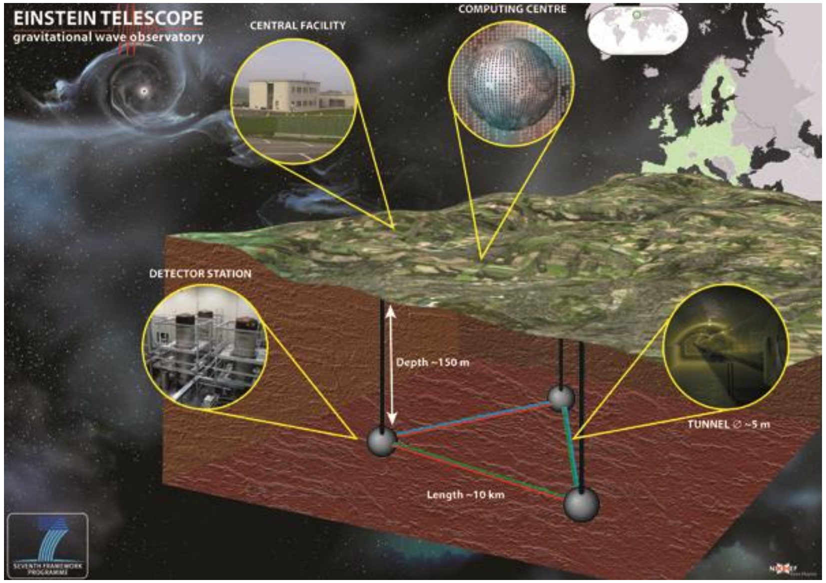
- Direct coupling to mirrors
- Seismological sources: P-S and Rayleigh waves
- Active filtering, continuum theory and measured transfer function
- Direct measurements of rock deformation

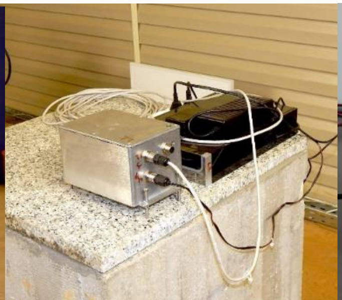


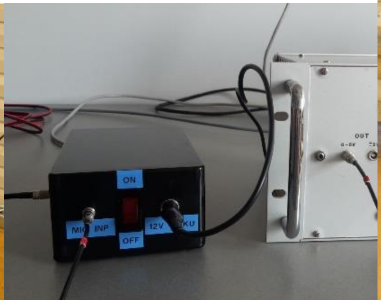
Further improvements

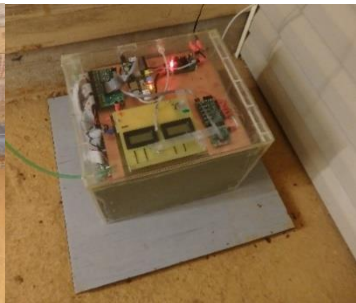
- Continuing observations and upgrades
- International efforts for 3rd generation detectors

  Gravitational **W**ave **I**nternational **C**ommittee
- Long term observations: Mátra Gravitational and Geophysical Laboratory



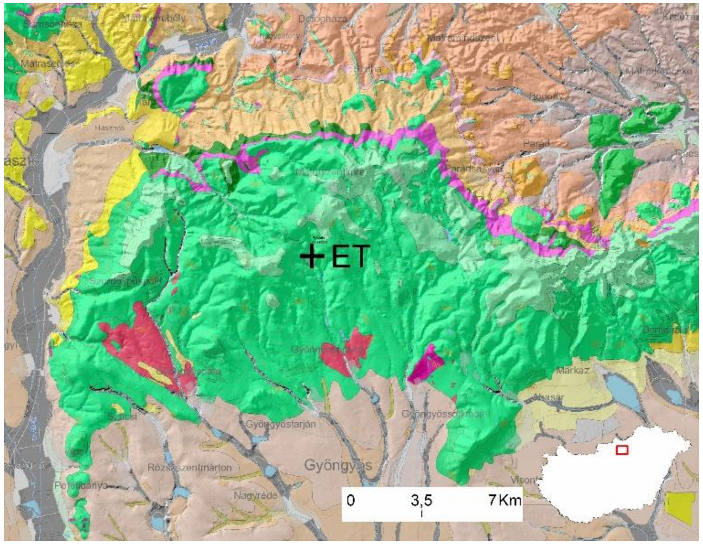


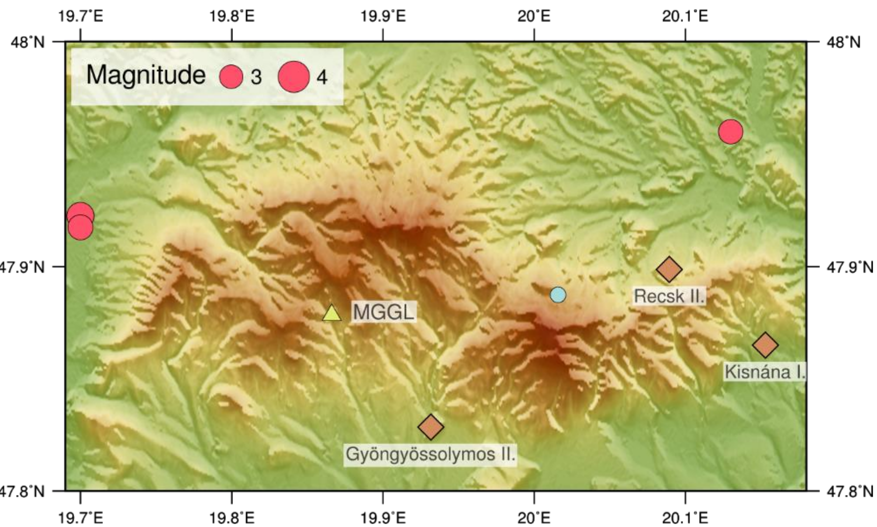


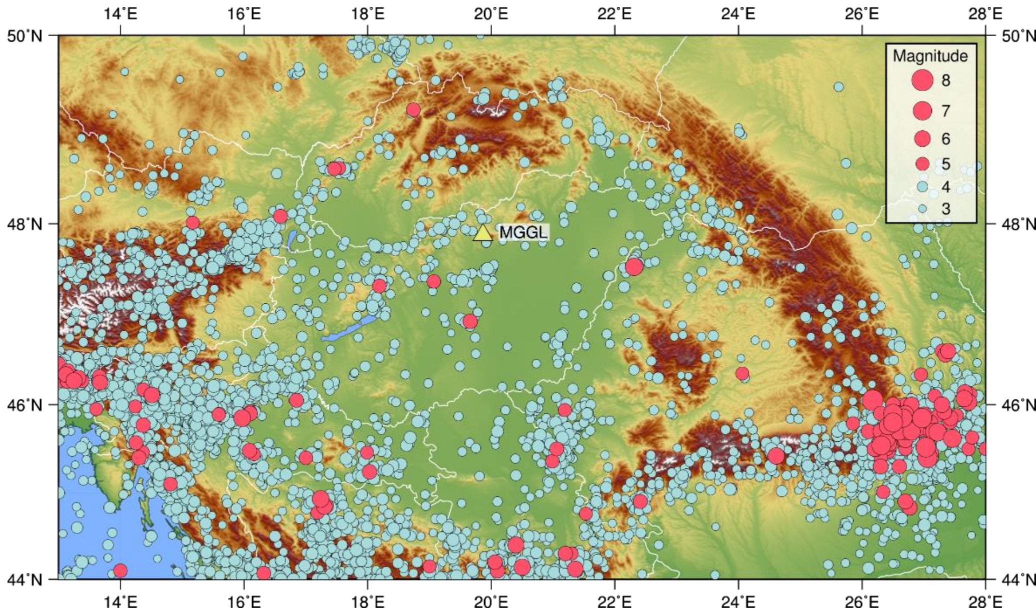


Mátra Mountain

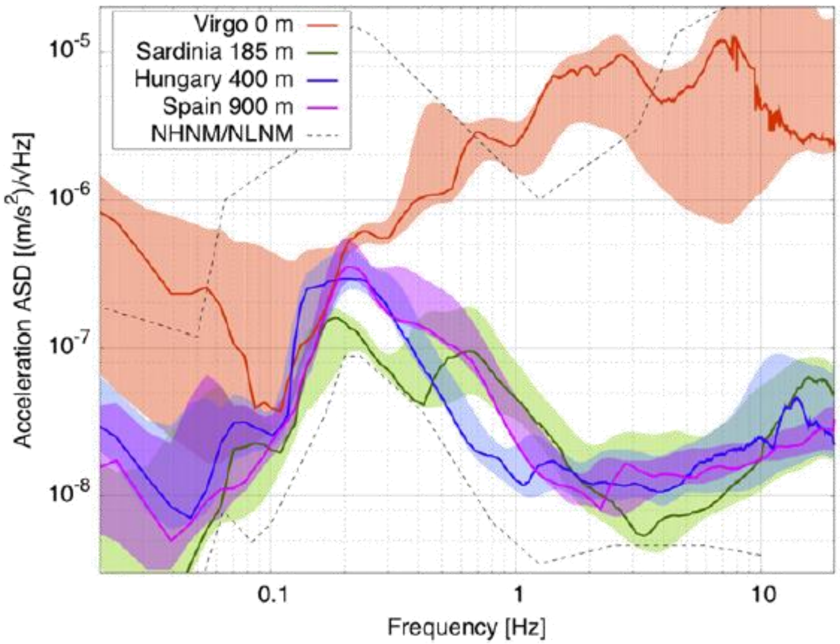
- Various andesite types from same geological era, limestone basis
- Local seismicity level
  - 3 earthquakes in the last 200 ys
- Explosions nearby
  - 91 between 03.2016 – 12.2017

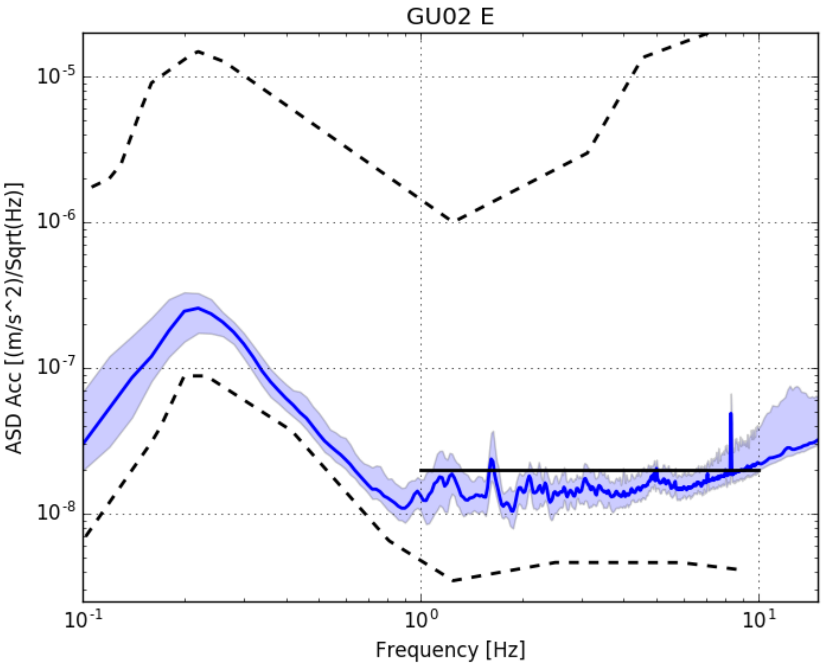






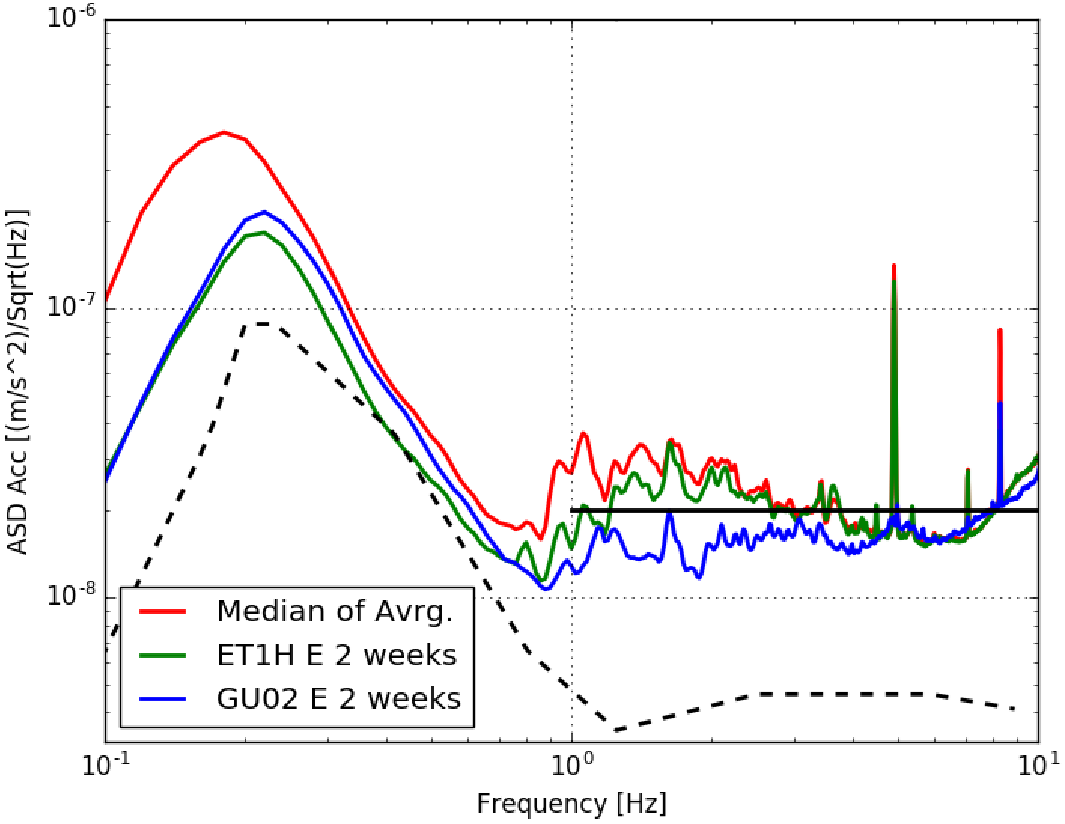
Optimal noise level





- Left: Baker et.al. (2015), short term, Right: Somlai et.al. (2018), 2 weeks
- Plotted: Acceleration ASD, 10 – 90 percentiles (stripe), and the mode (line)
- Cumulative characteristics, rms_{2Hz}
  - Beker et.al. (2011): 0.082 nm (5 days)
  - Somlai et.al. (2018): 0.083 nm (2 weeks)

Characteristic noise level



- Blue: -404 m, 2 weeks, rms_{2Hz} = 0.083 nm
- Green: -88 m, 2 weeks, rms_{2Hz} = 0.133 nm
- Red: -88 m, 547 days, rms_{2Hz} = 0.148 nm

Andesite properties

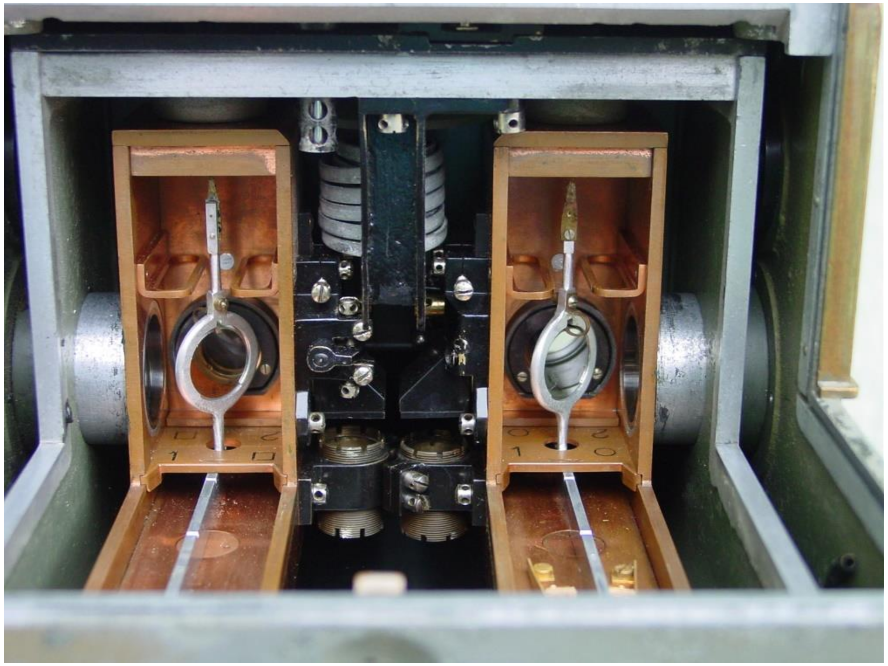
- Rigid but not elastic
- Dynamic and static elastic moduli: rheology

$$\tau_s \dot{\sigma}_s + \sigma_s = E_{2s} \ddot{\varepsilon}_s + E_{1s} \dot{\varepsilon}_s + E_{0s} \varepsilon_s$$

	Young [MPa]	Poisson [-]
Dynamic	38.6	0.18
R-static	28	0.22
R-dynamic	43	0.35

- τ = 2-80 s, relaxation time scales
- frequency dependent rock properties: damping and propagation speeds

Jánossy pit, Eötvös balance measurements

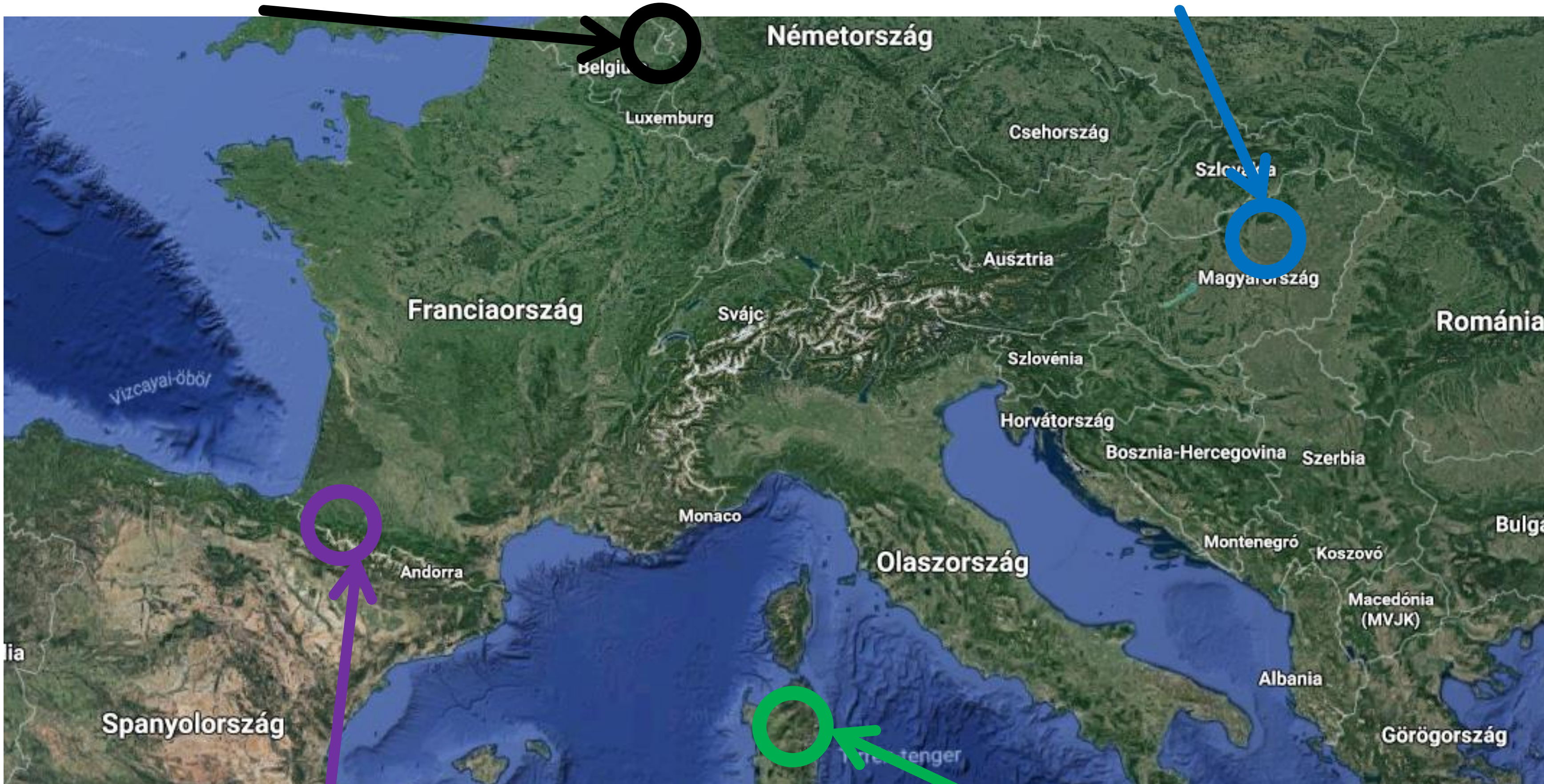


- Wigner RCP and BME
- Aim: Newtonian noise, Eötvös year, equivalence principle

Site selection

Liege (German, Belgian, Dutch)

Mátra (Hungary)

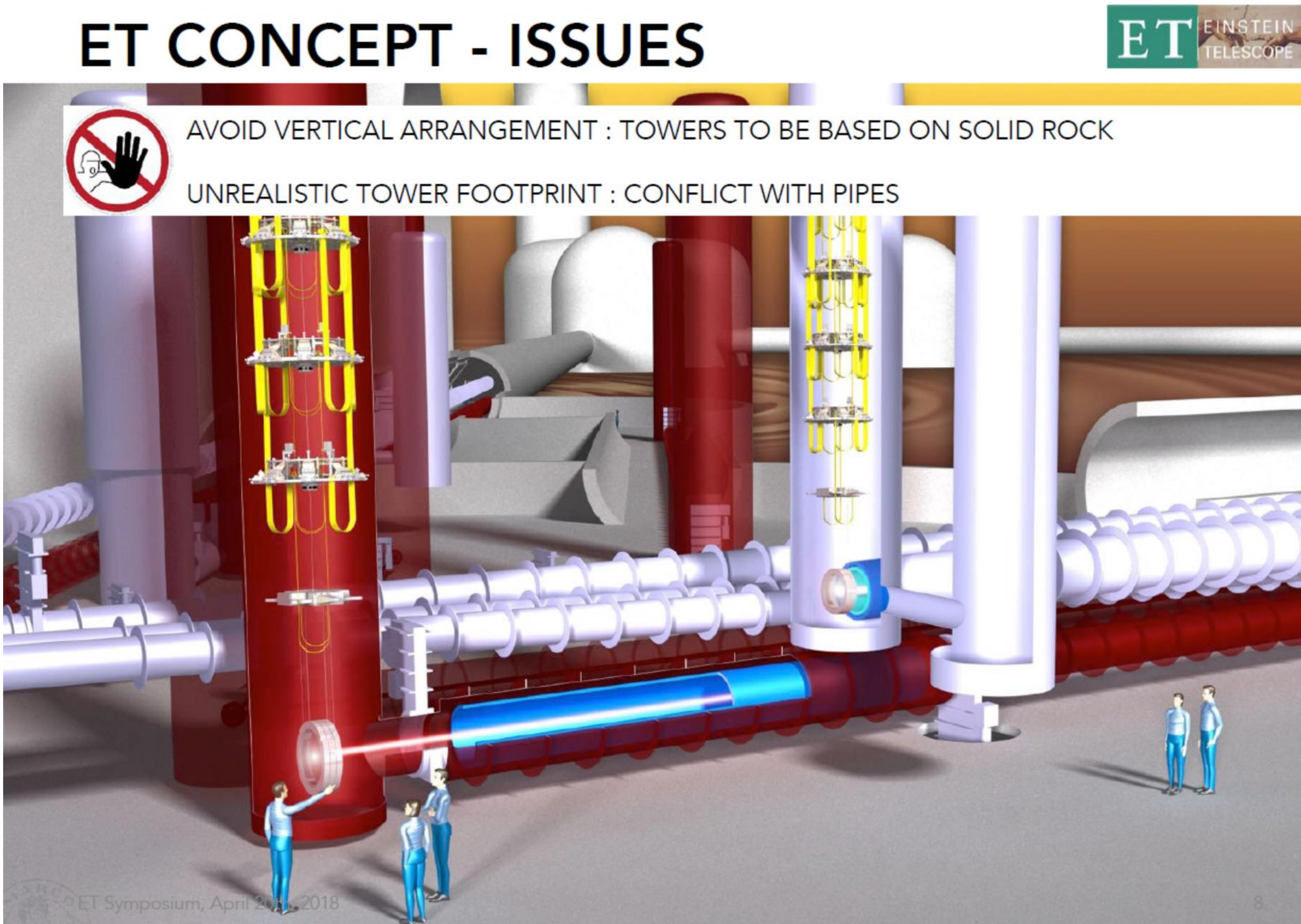


LSC, Canfranc (Spain)

Sardinia (Italy)

Preliminary design study: Italy

Preliminary design study: Italy

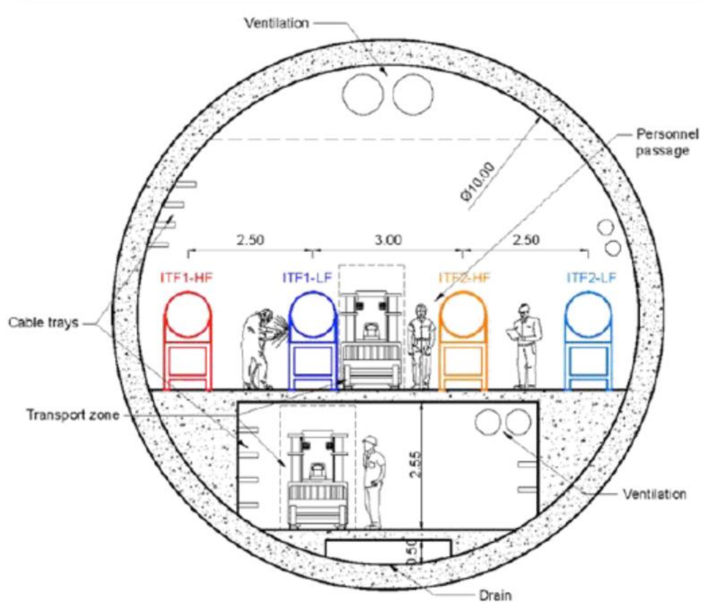


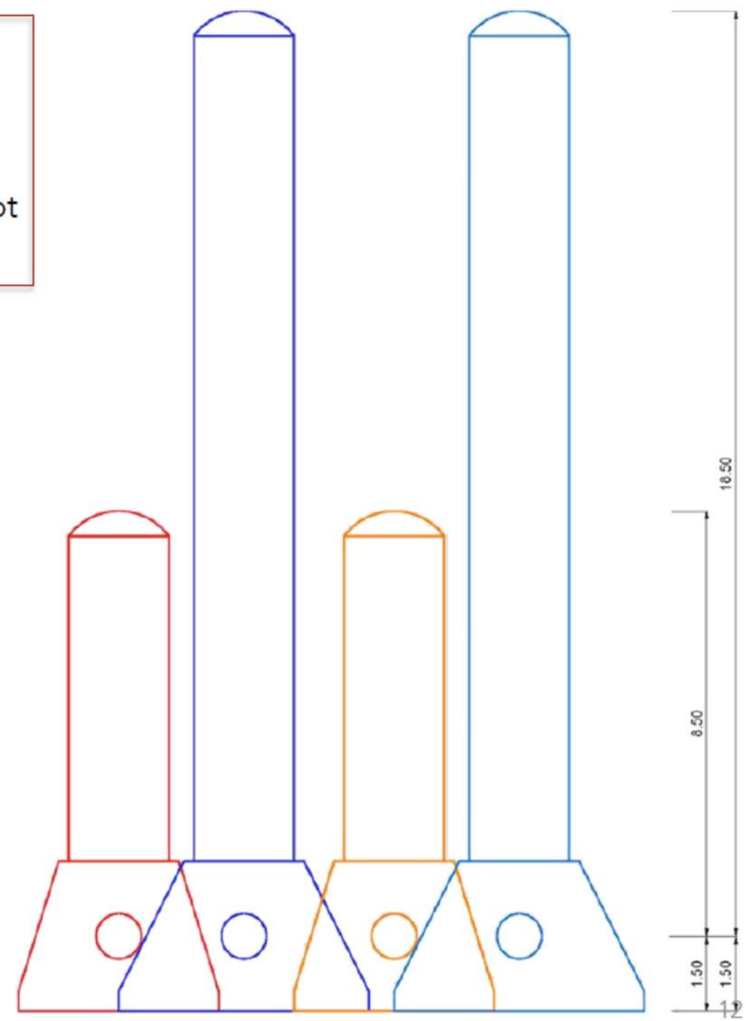
Preliminary design study: Italy

TUNNEL SECTION

Realistic tower bases force to shift pipes horizontally

Our assumption is probably optimistic since cryostats and auxiliary instrumentation are not taken into account





COST ESTIMATE - ET book p. 313
Underground Infrastructure

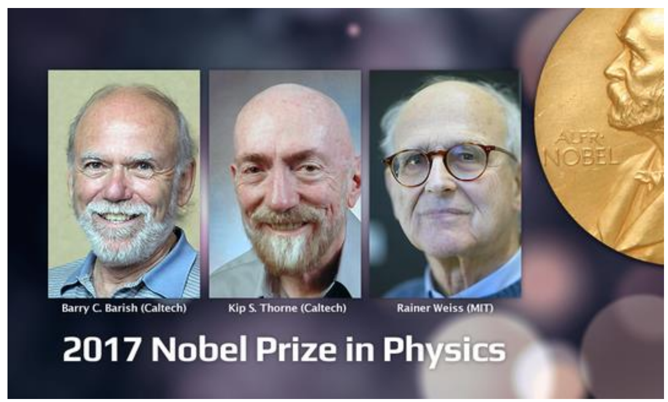
Conceptual Design	**ET-0106C-10 p.313**	
Configuration:	**Xylophone - Triangular**	

Total Excavation (net volume) [Mm³]	**1.742**
Total Cost [M€]	**451**
Contingency 30%	**135**

ID	Item Description	Comment	nr.	Ø-H-Sur.	W	L	Quantity	Un. cost	SubTotal
				[m] [m^2]	[m]	[m]	[m^3]	[k€/m^3] [k€/m]	[k€]
1	Main Tunnel excavation	D=6.5m, D_inner 5.5 m, 30 km		6.5		30000	994988	0.2589	257602
2	Auxiliary Tunnel excavation	D=7.0m, D_inner 6.0 m, 1.8 km		7.0		1800	69237	0.2589	17925
	57 pumping/bake-out areas	L=10m W=12m H=6m	57	6.0	11	10	16983	0.2589	4397
3		(minus tunnel volume)							
5	Main Caverns	#3: D=65m, Hmed=30m	3				298496	0.2589	77281
6	Satellite Caverns	#6: D=30m, Hmed=30m	6				127170	0.2589	32924
7	Main Shafts	#3: D=20m; depth 200m	3	20.0		200	188400	0.2589	48777
8	Auxiliary Shafts	#3: D=10m; depth 200m	3	10.0		200	47100	0.2589	12194

- No excavation factor considered
- No safety exit along tunnels considered
- Shafts 200m deep for materials and equipment transportation (unrealistic during construction)
- Contingency 30% added to total budget

Thank you for your attention !



The Wigner Virgo group

- Member of the Collaboration since 2005
- Waveform templates, search algorithms, GPU
- Data analysis **PyCBC**, data management
- Einstein telescope
- Outreach

I. Rácz

G. Debreczeni
VDASC coordinator 2013-15

M. Egri-Nagy

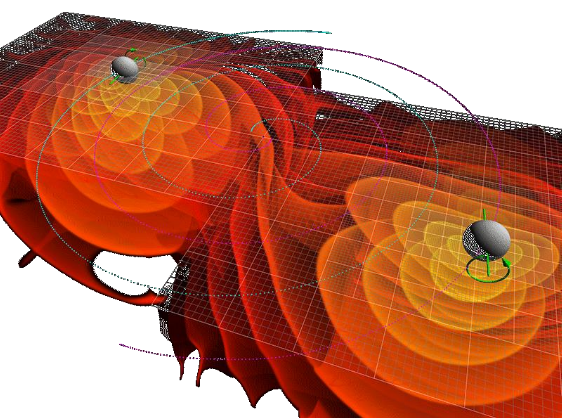
D. Berényi

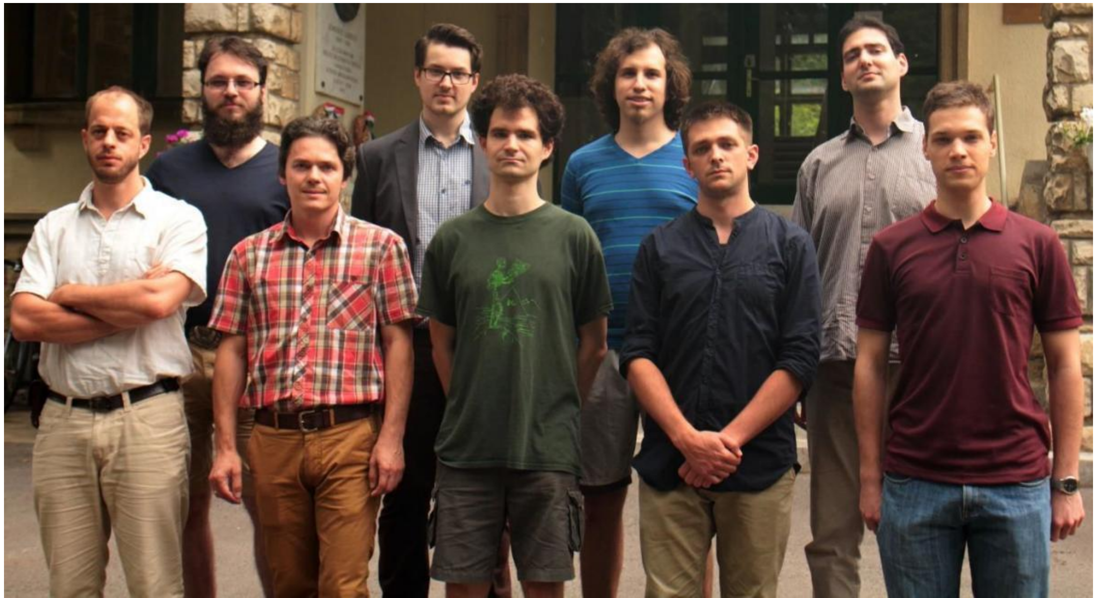
B. Kacskovics

L. Somlai

J. Maróti

A. Balogh





GW / multi-messenger astronomy