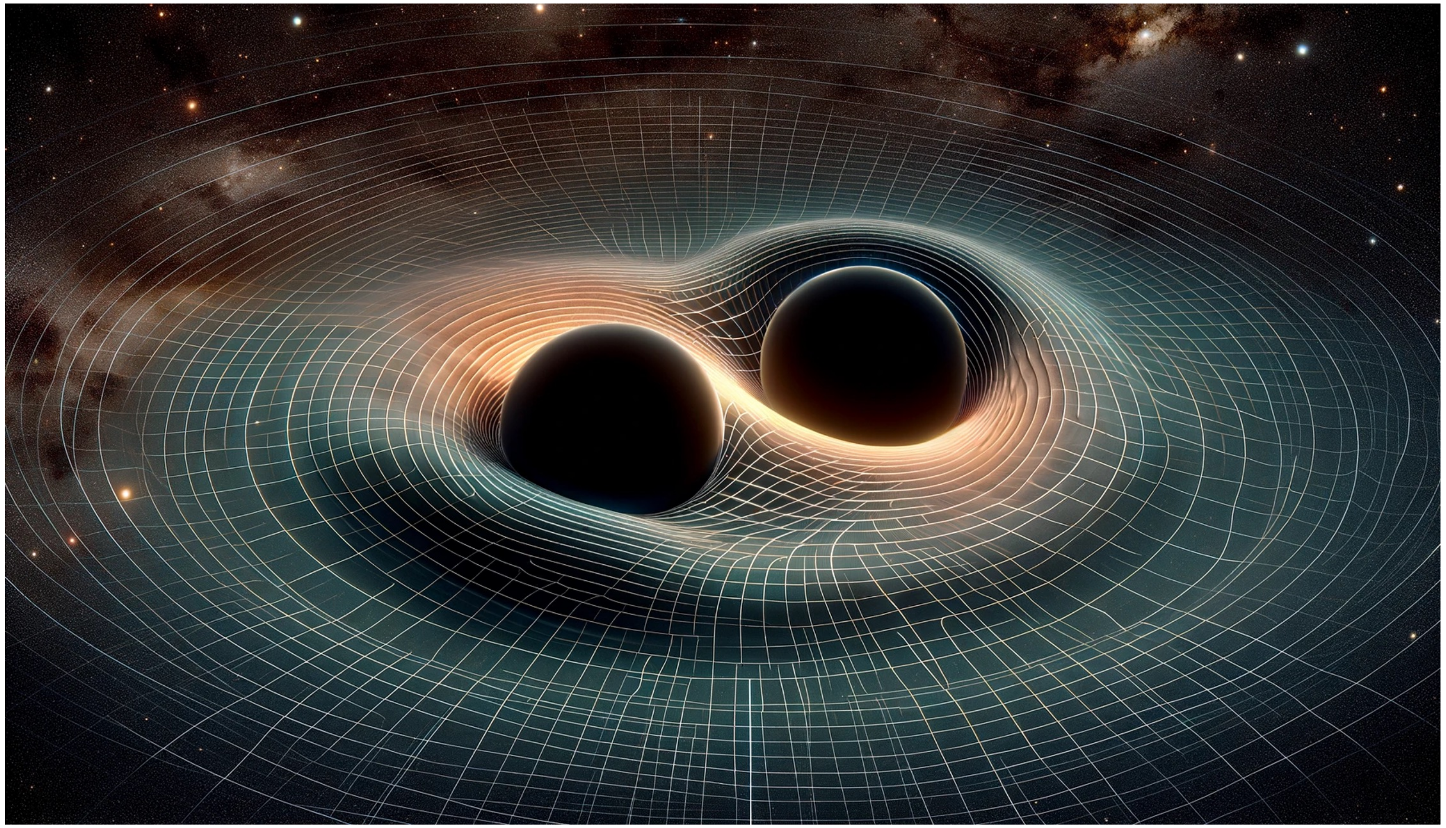
Austrian Roadmap Round Table Meeting



Gravitational waves

Gianluca Inguglia

10/06/2024

HEPHY
INSTITUT FÜR HOCHENERGIEPHYSIK

ÖAW
ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

ET EINSTEIN TELESCOPE

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What are gravitational waves?

Gravitational waves are ripples (or perturbations) in the space-time geometry that are predicted by Einstein theory of general relativity:

Flat Minkowski metric

Energy-impulse tensor, source of space-time deformations

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

$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{g_{\mu\nu} R}{2}$$

Deformation (Einstein) tensor, effect of the space-time deformation

$$g_{\mu\nu} = \eta_{\mu\nu} + \mathbf{h}_{\mu\nu}, if \left| h_{\mu\nu} \right| \ll 1 \rightarrow \left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) h_{\mu\nu} = 0$$

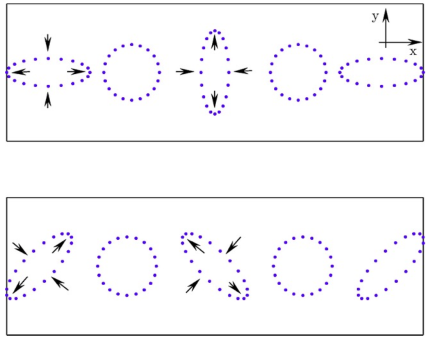
Small perturbation

Wave equation

$$h_{\mu\nu}(z,t) = e^{i(\omega t - kz)} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

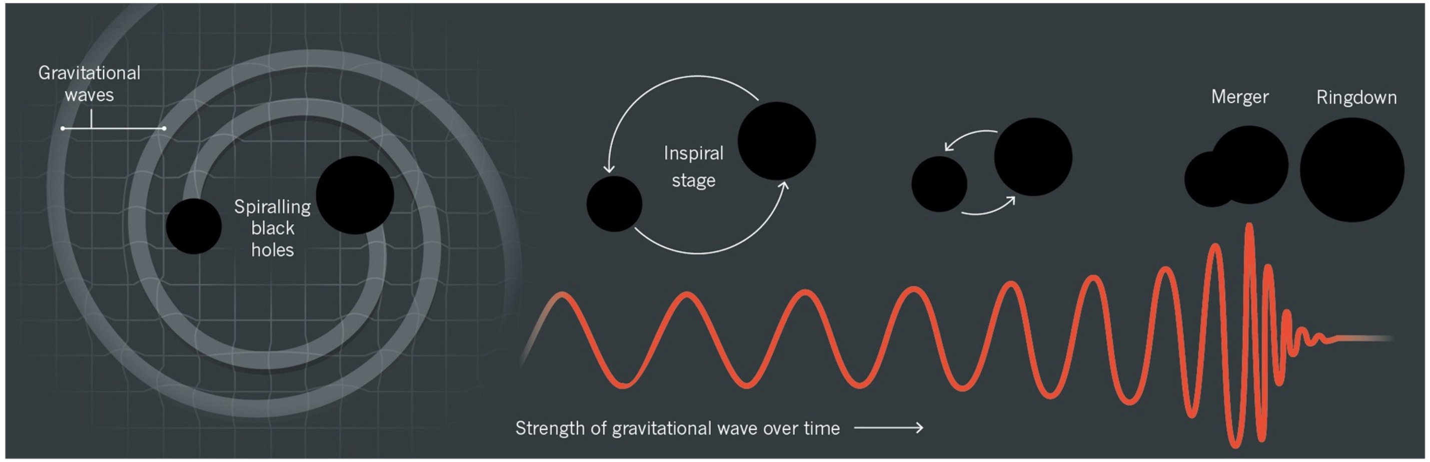
$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

Distance between 2 points

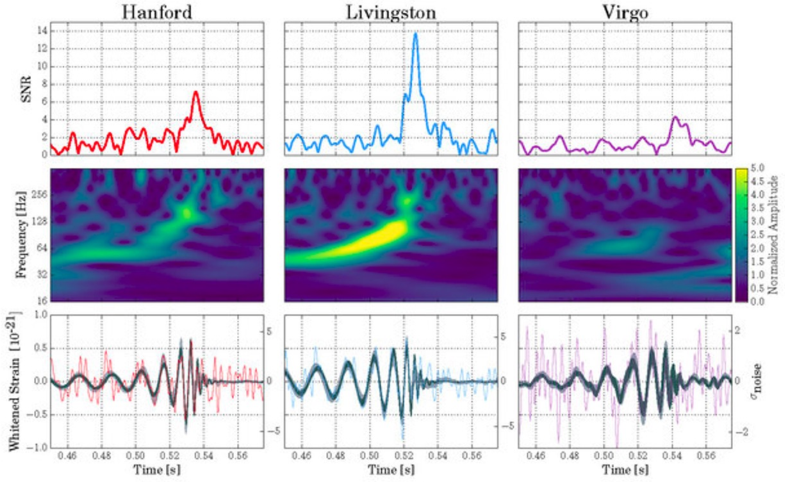


Gravitational wave propagating in the z-direction with 2 polarizations: x and +

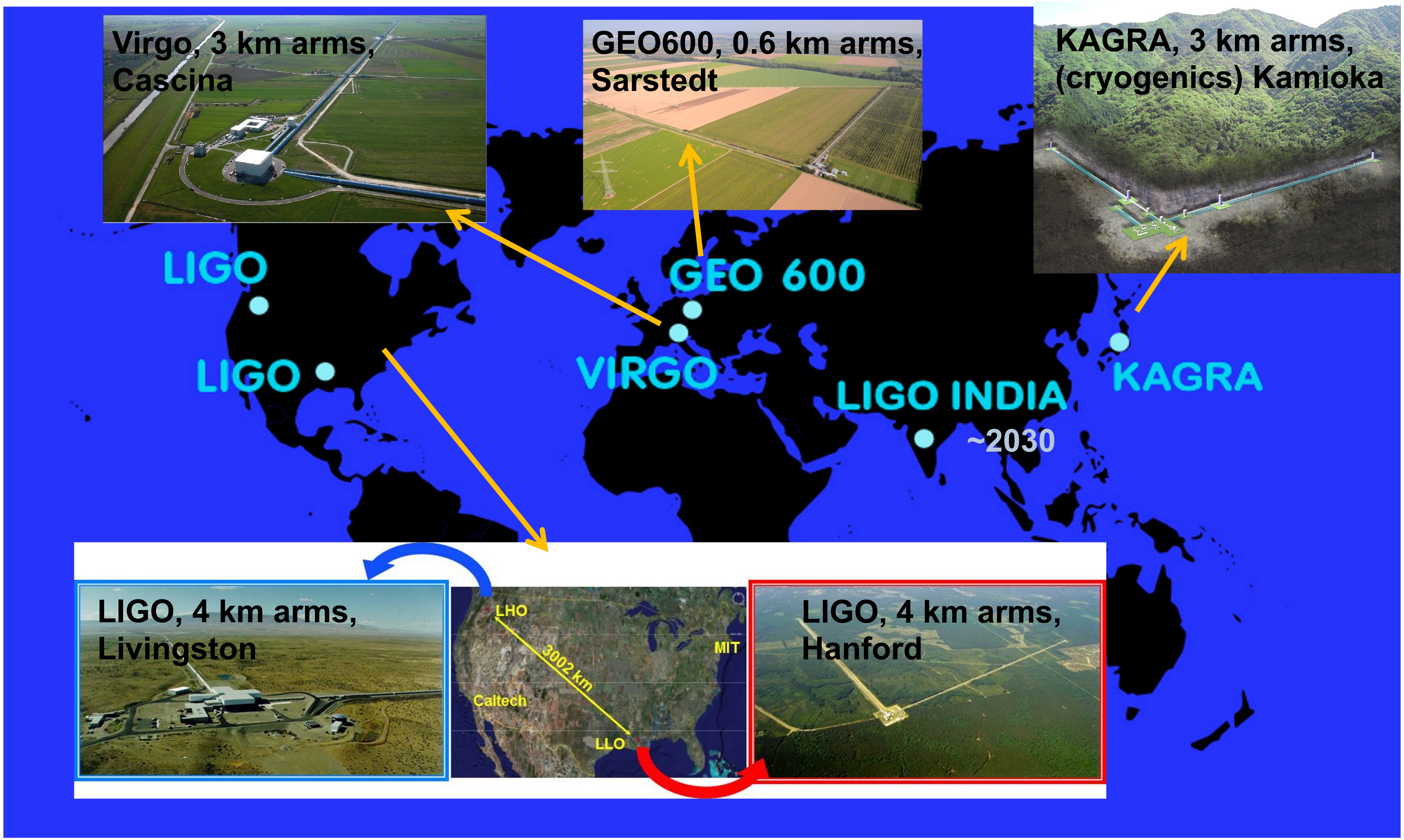
Gravitational waves emerge from specific motions of massive objects in space (for example compact binaries)

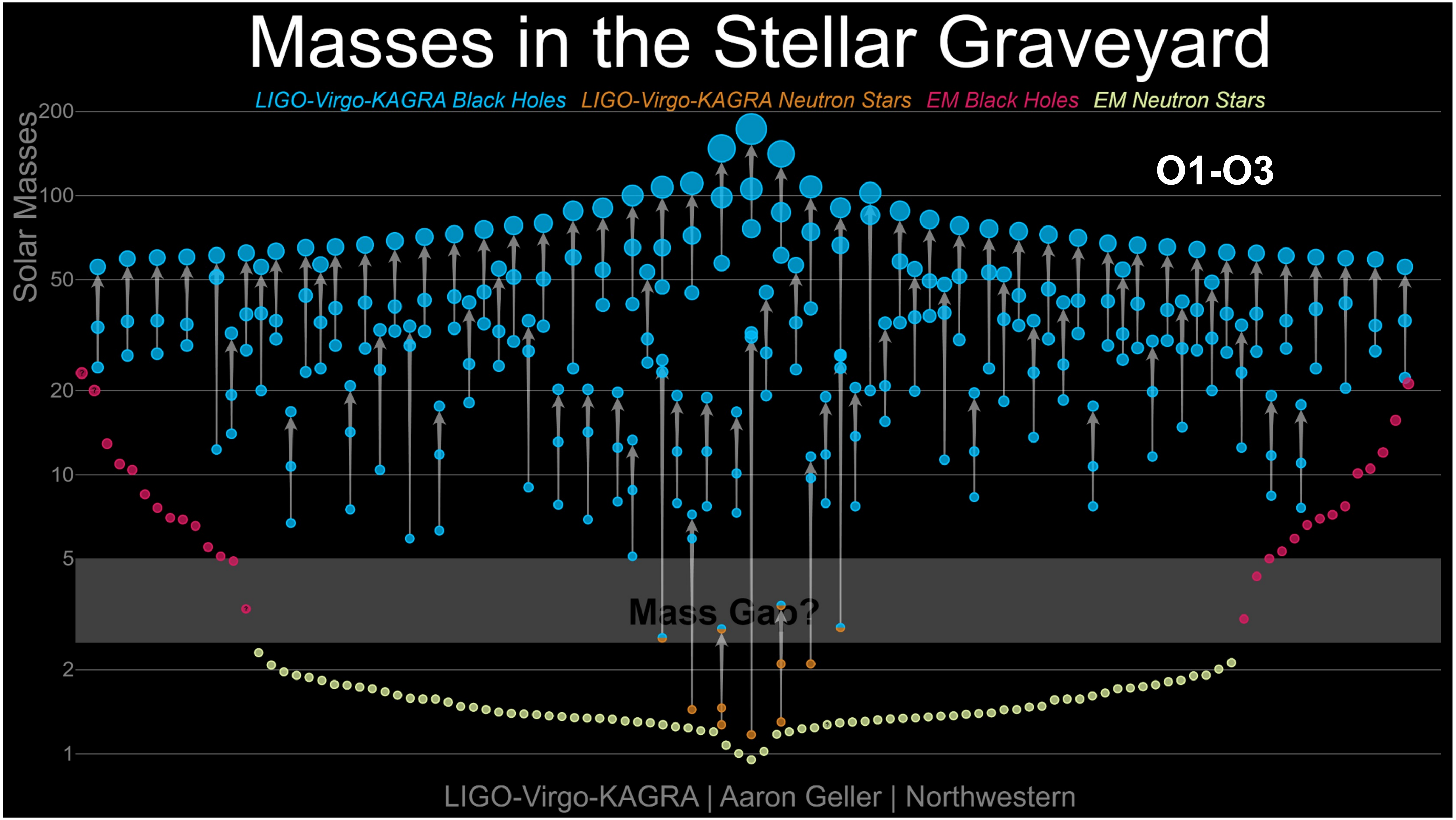


GW170814

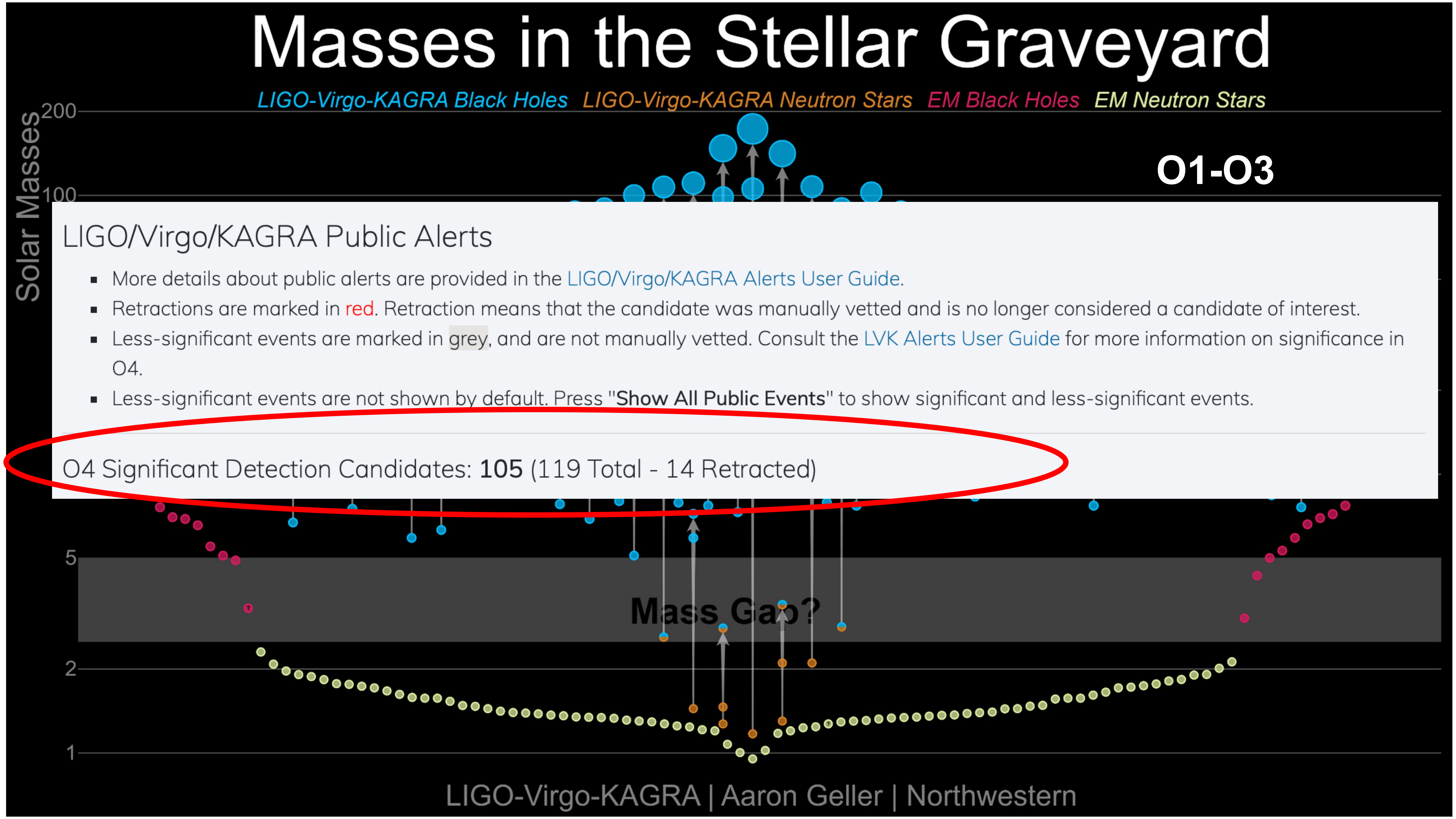


Current network of 2-G GW detectors



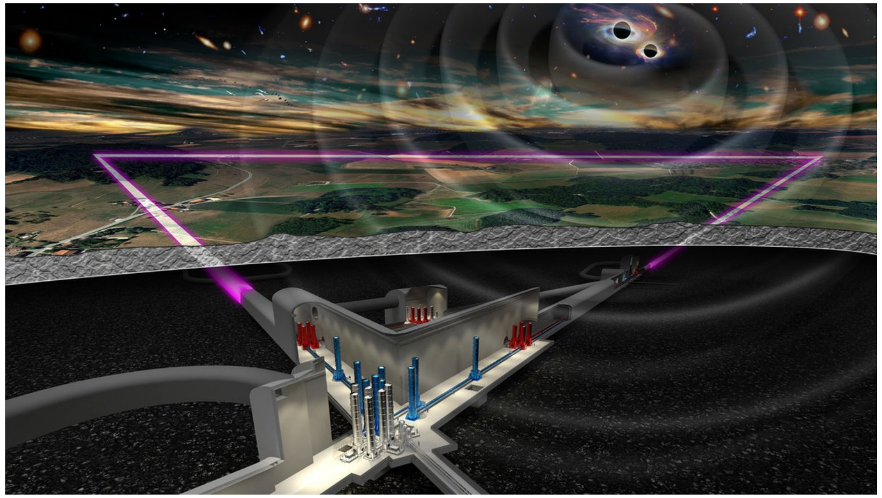


*Check the GWTC 3 population study and the recent GW230529_181500



*Check the GWTC 3 population study and the recent GW230529_181500

3-G GW detector in EU, the Einstein Telescope



Third-generation gravitational wave observatory consisting of

- 3 nested GW detectors arranged in a triangular shape
- 10 KM long arms per detector (vs. 3/4 of Virgo/LIGO)

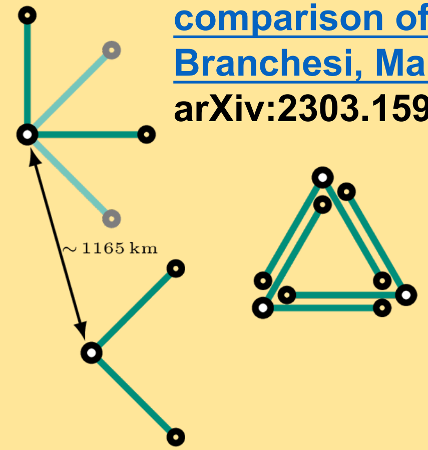
- Each detector will have 2 interferometers working at
- low frequency (~2-40 Hz) →low laser power, cryogenic mirrors
- High frequency(40-several kHz) →high laser power, room temperature

To reduce gravity gradient **noise** and seismic noise (hence improving sensitivity at low frequencies)
ET will be built underground (current design is 200m)
Two (+1) candidate sites to host the telescope, with ongoing site characterization work

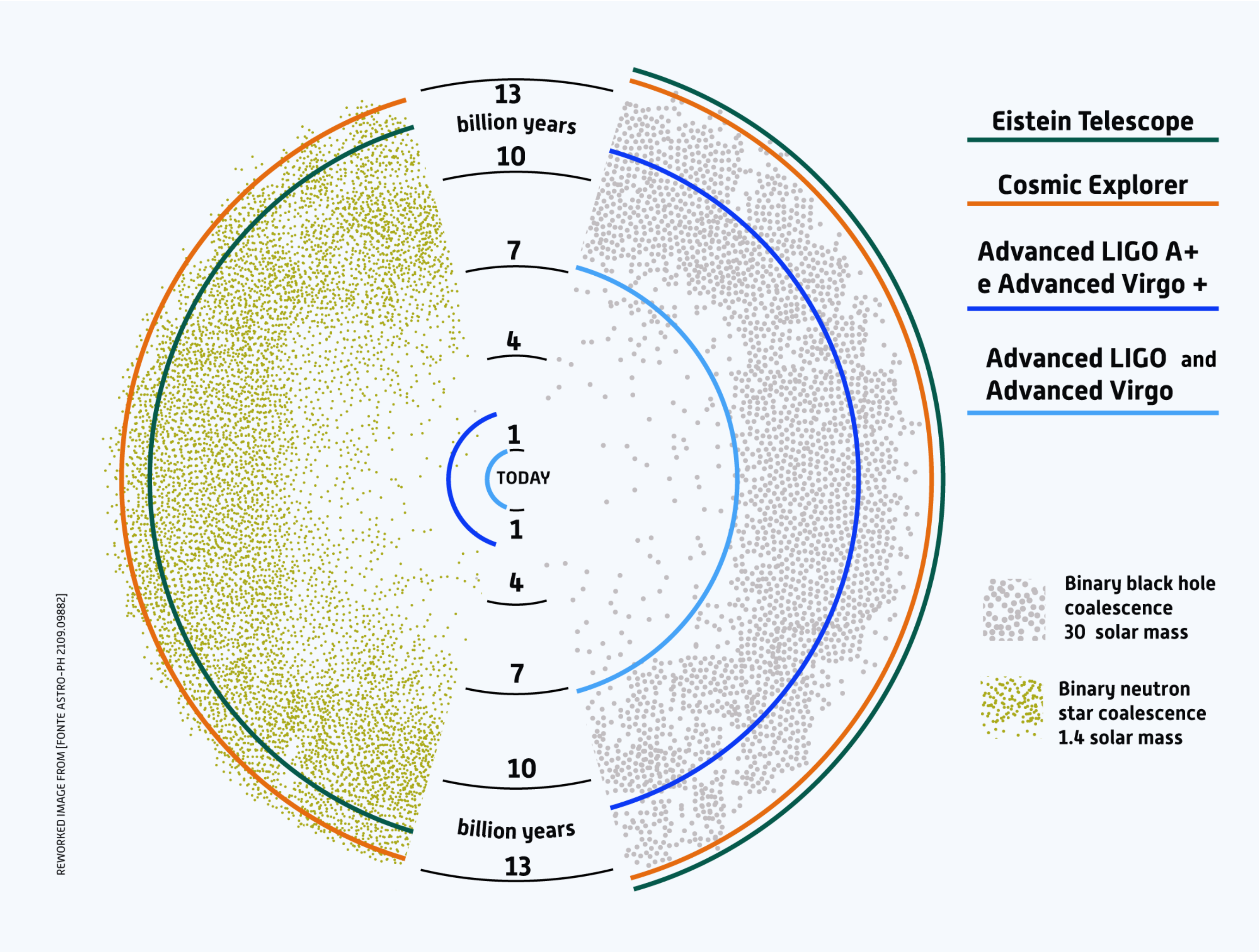
- Sardegna, Sos Enattos mine
- Euregio Meuse-Rhine
- Saxony (under discussion)

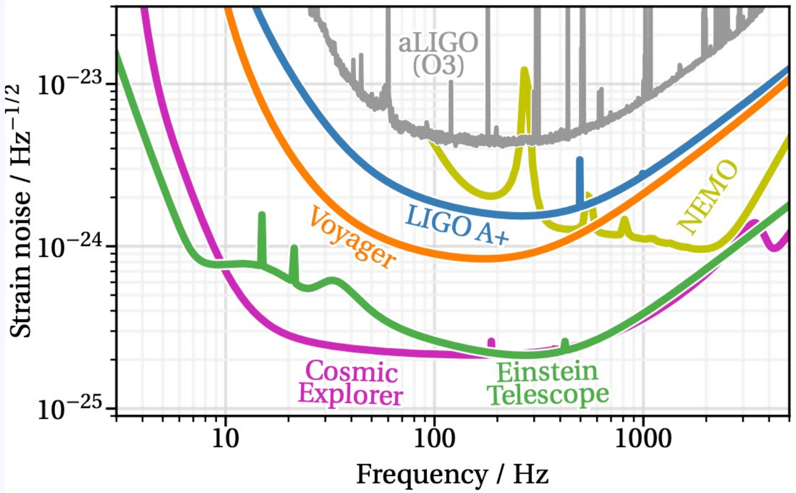
Why 3 detectors? Because it will be sensitive to both polarisations rather than their linear combination. However, a second option with two L-shaped antennas at ~1000 km distance and with a 45 deg angle wrt each other has better sensitivity overall

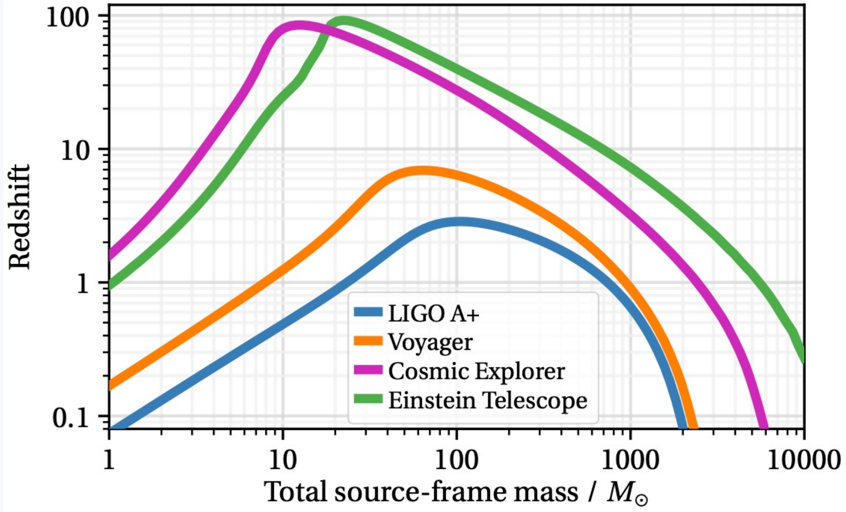
Science with the Einstein Telescope: a comparison of different designs – Branchesi, Marica et al – arXiv:2303.15923 ET-0084A-23



Why a 3-G GW of detectors?







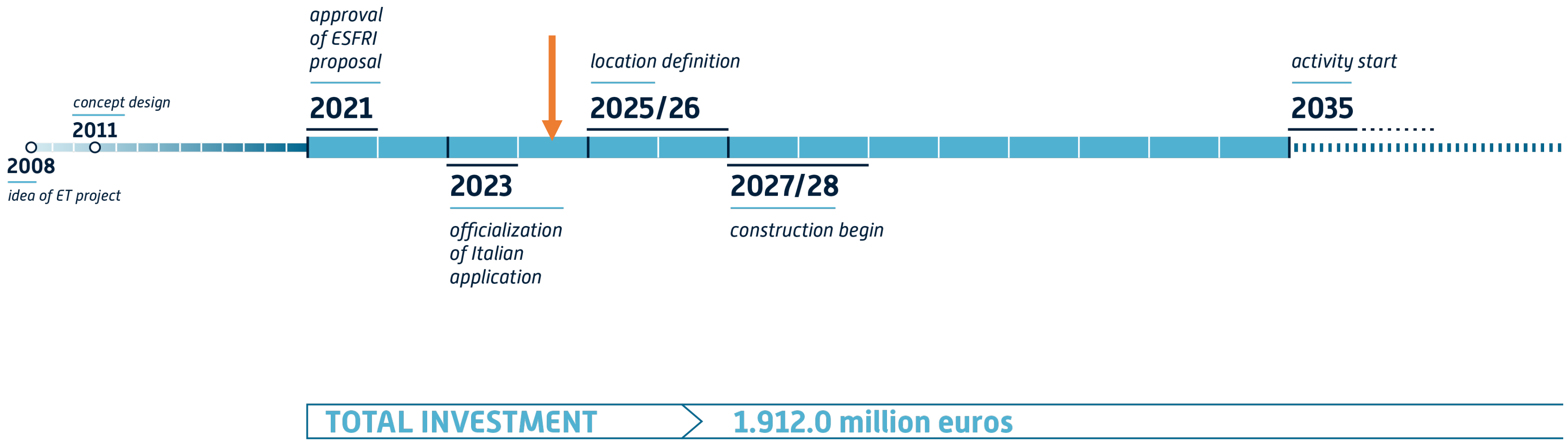
Activities at HEPHY have recently started

- HEPHY participate in ET, in collaboration with the group of Prof. M. Mapelli from Heidelberg University
  - Contributions to the Observational Science Board (various divisions).
  - Participation in the ET bluebook (on ArXiv in September).
  - Topics: intermediate-mass black holes, (fast) alert generation, population studies, etc.

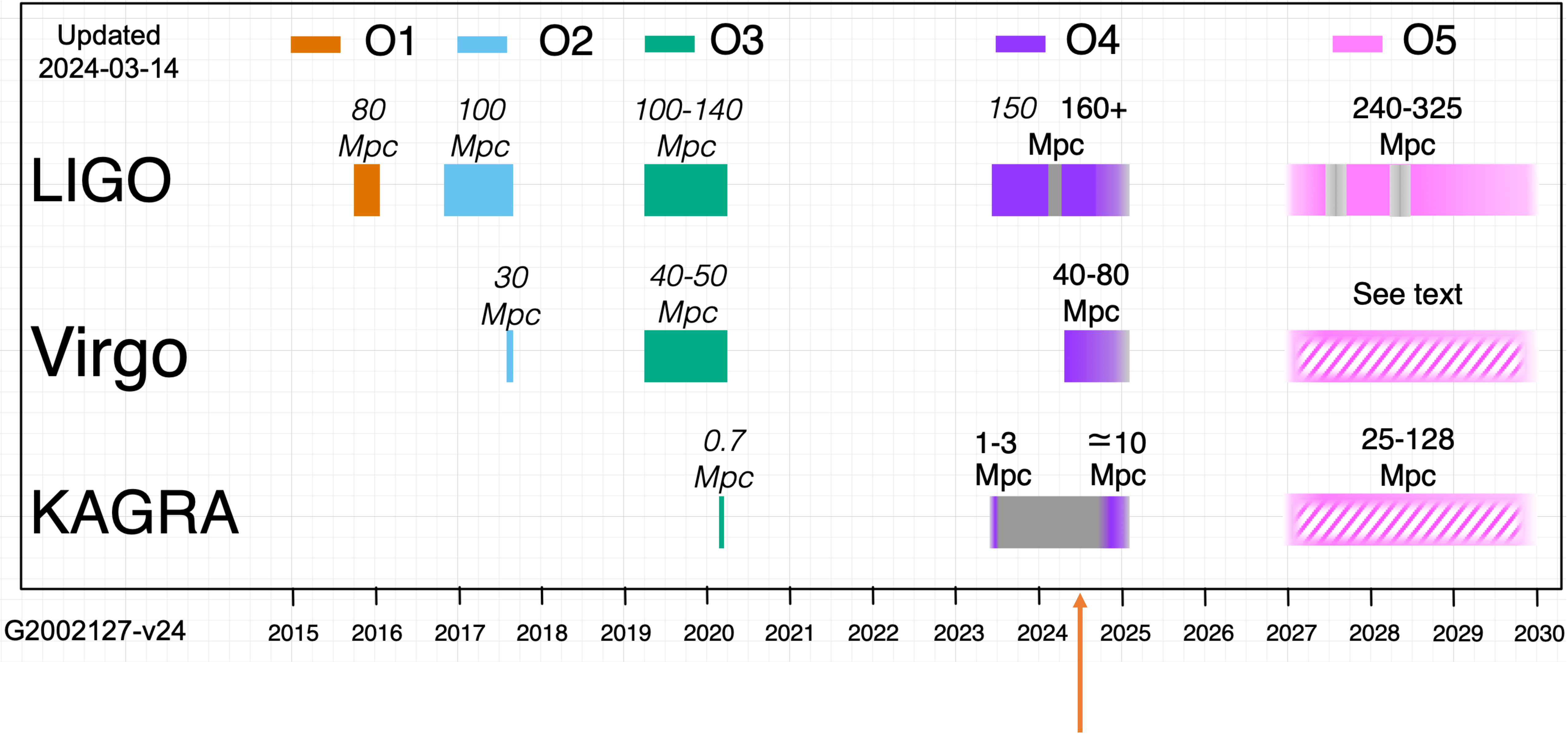
- A local ET research unit in Vienna is planned and will be formed in the future
  - synergies possible with various Austrian institutes (ISTA, Leoben, Linz, Uni Wien, Uni Innsbruck).
  - synergies with other HEPHY groups (electronics, machine learning).

- HEPHY will also join Virgo in the coming months and participate in the analysis of data

- ISAPP 2025 Summer School on "Gravitational waves, from theory to detection" will take place in Vienna in July 2025.



Backup material


Updated 2024-03-14
O1
O2
O3
O4
O5
LIGO
80 Mpc
100 Mpc
100-140 Mpc
150
160+ Mpc
240-325 Mpc
Virgo
30 Mpc
40-50 Mpc
40-80 Mpc
See text
KAGRA
0.7 Mpc
1-3 Mpc
≃10 Mpc
25-128 Mpc
G2002127-v24
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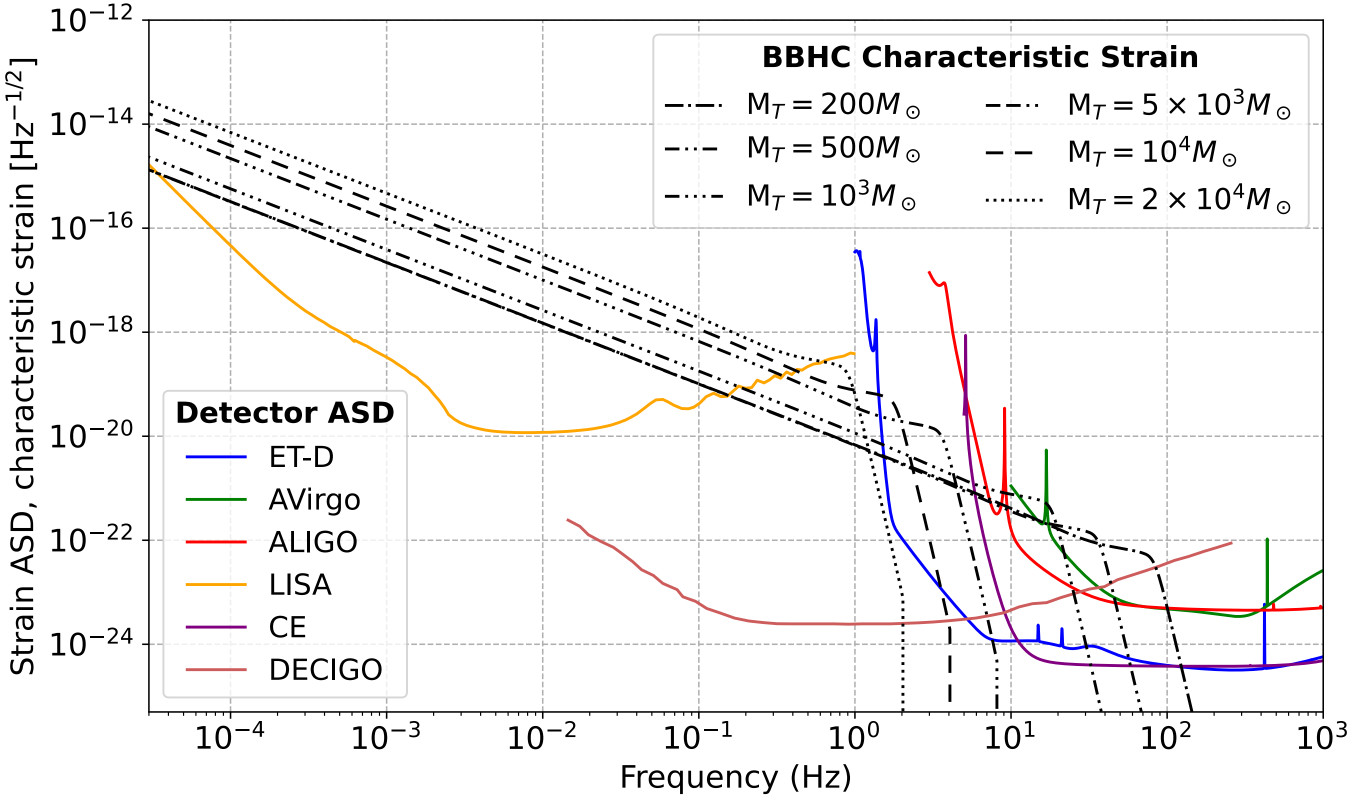
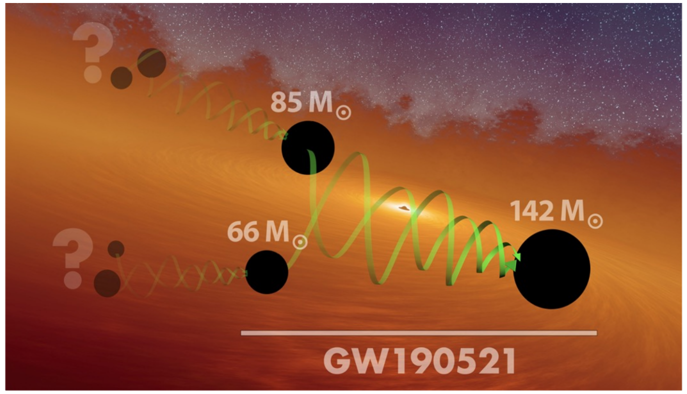
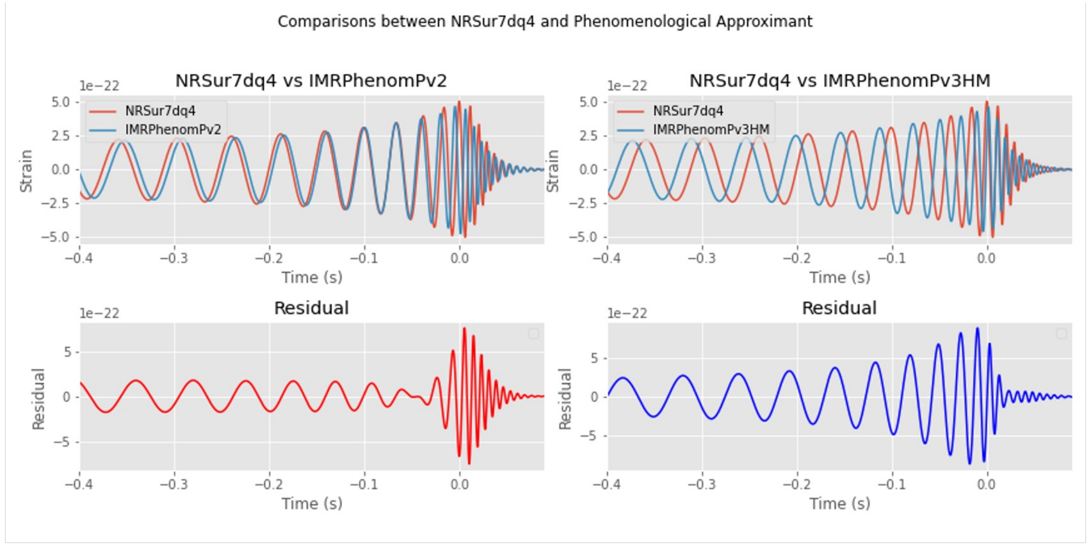
IMBH GW signals and detector sensitivities: mass and distance insights

Preliminary study, uses **IMRPhenomD** as waveform approximant.
Unofficial sensitivity curves obtained from https://dcc.ligo.org/LIGO-T1500293/public



The inspiral phase of IMBHs' coalescence will be for years within the sensitive region of LISA who can in turn provide details to ET: multiband GW studies!

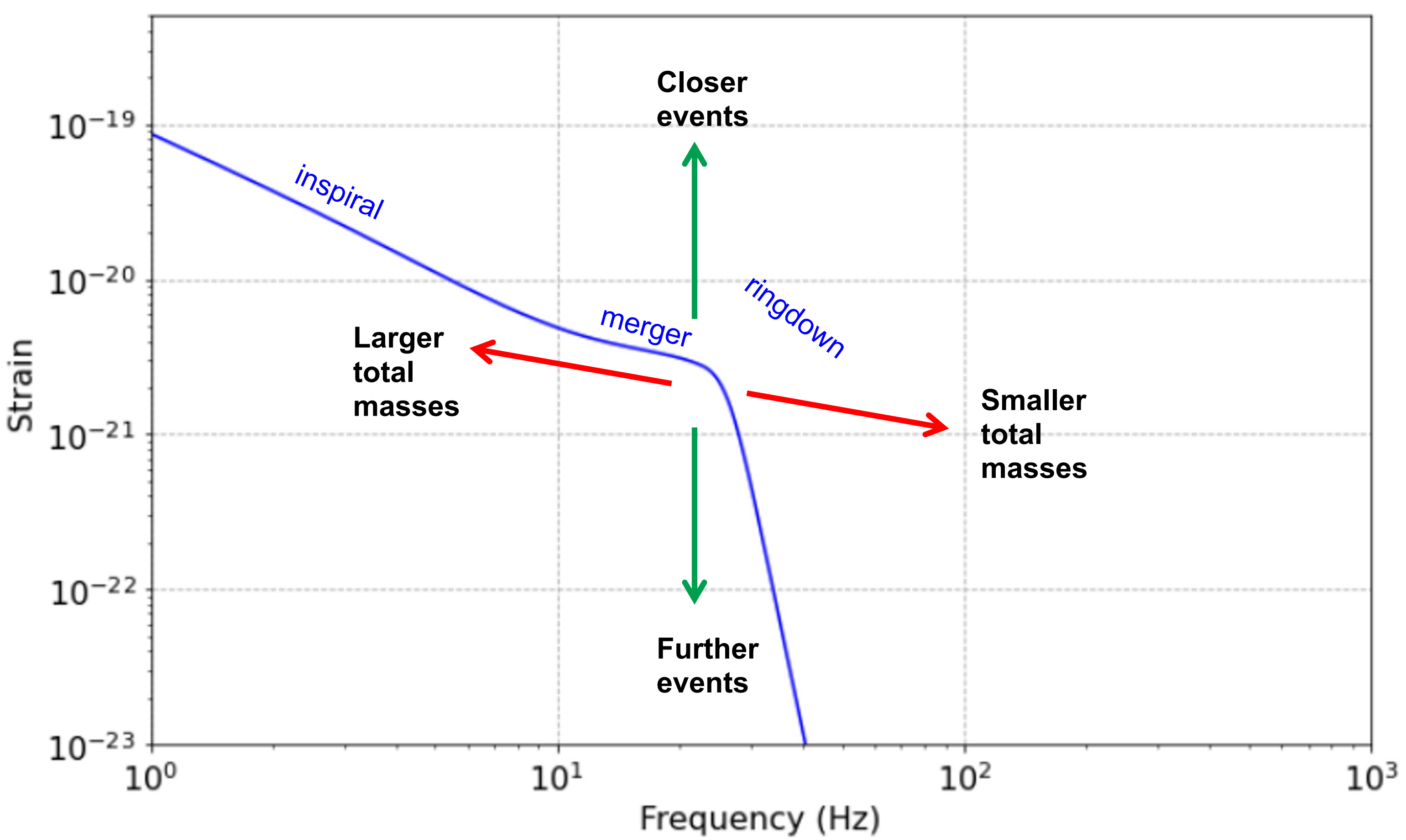




Preliminary results presented at the ET Symposium in Maastricht, May 6-10

Different approximants produce very different waveforms, with differences as large as the original GW amplitude. Higher order modes becomes not negligible.

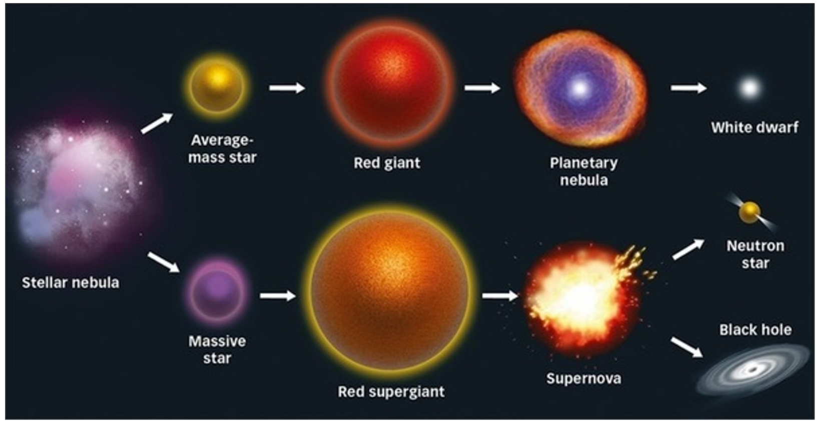
Effects of mass and distance on GW strain signals from compact binary coalescence



Stellar, supermassive and intermediate-mass black holes

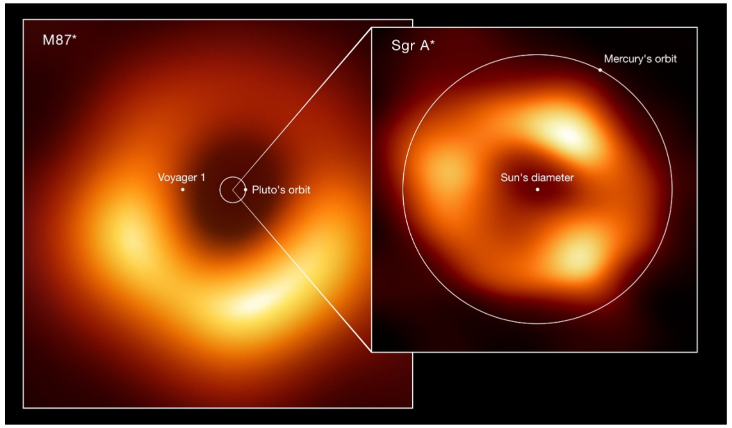
Stellar black holes (SBHs)

- Masses ranging from 5* to few x10 M⊙
- Forms in the final stage of evolution of stars from stellar collapse
- Can exist isolated or in binary systems



Supermassive black holes (SMBHs)

- Very large masses of $10^6 – 10^9$ M⊙
- Typically located in the center of galaxies
- Grow through accretion disk of gas and dust around them
- Core of AGNs



Intermediate-mass black holes (IMBHs)

- Masses of the order of $10^2 – 10^5$ M⊙
- Various models for their origin – no general consensus (ex. population III stars vs. hierarchical mergers)
- Difficult to detect. How do we even know they exists?

SBH IMBH SMBH M⊙

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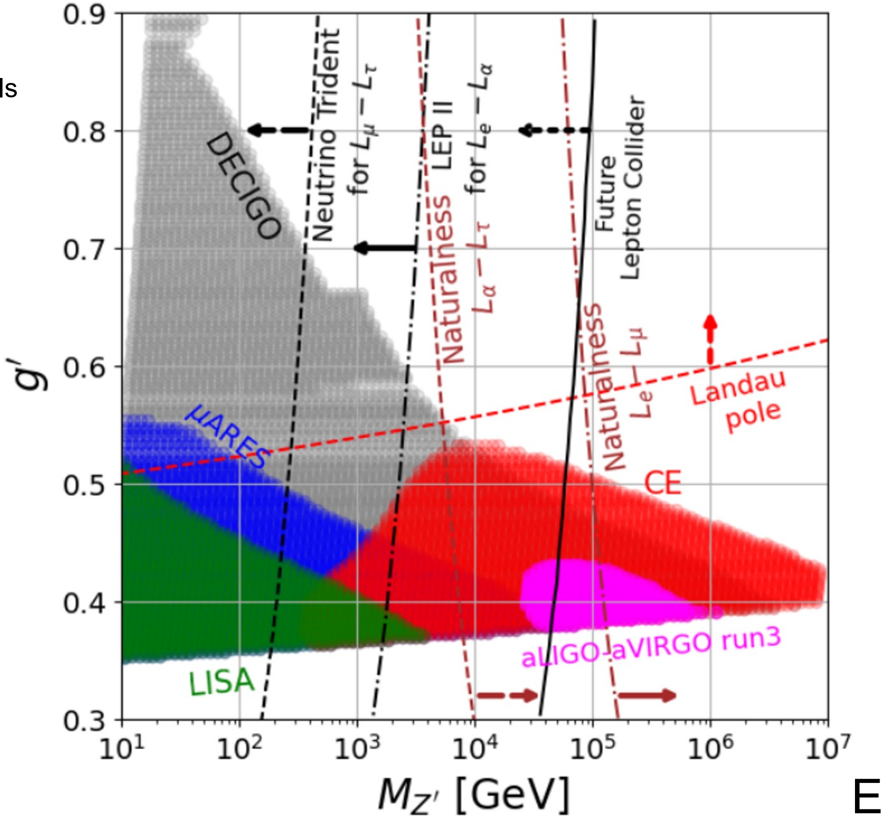
Gravitational waves probing fundamental physics, leptophilic Z’

First-order phase transition if scalar sector is conformally invariant:

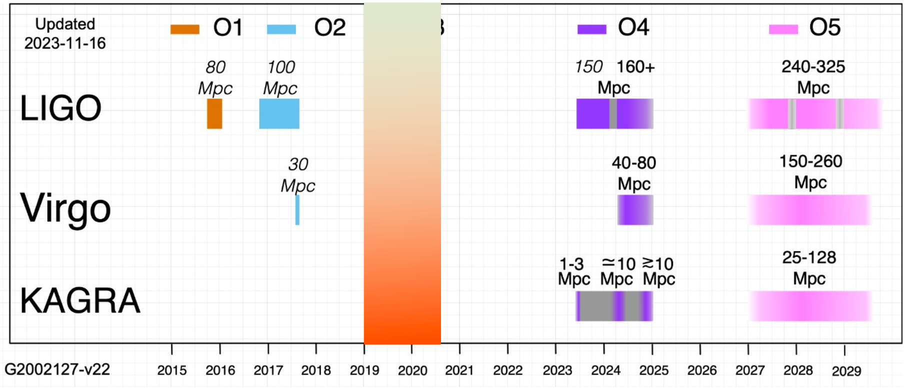
$$V_{\rm tree} = \lambda_H (H^\dagger H)^2 + \lambda(\Phi^\dagger \Phi)^2 - \lambda'(\Phi^\dagger \Phi)(H^\dagger H)\,.$$

Leptophilic Dark Portals

Bhupal Dev



[Dasgupta, BD, Han, Padhan, Wang, Xie, 2308.12804 (JHEP ’23)]



This data used

We are here

Enhanced sensitivity with already available new set of data

- Heavy boson fields might be responsible for phase transitions, strong enough to generate gravitational waves → stochastic, not observed so far → set upper limits
- New, complementary, way with respect to typical HEP measurements with even more accessible parameter space.
- More analysis methodologies and results can be expected in the very near future.