

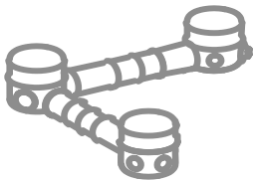
Challenges for next-generation ground-based detectors at low frequencies

Artem Basalaev

Max Planck Institute for Gravitational Physics (AEI Hannover)

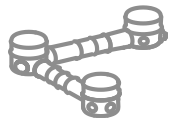
Belgian-Dutch Gravitational Wave meeting

7 October 2026



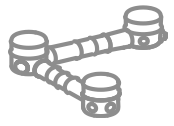
Leibniz
Universität
Hannover



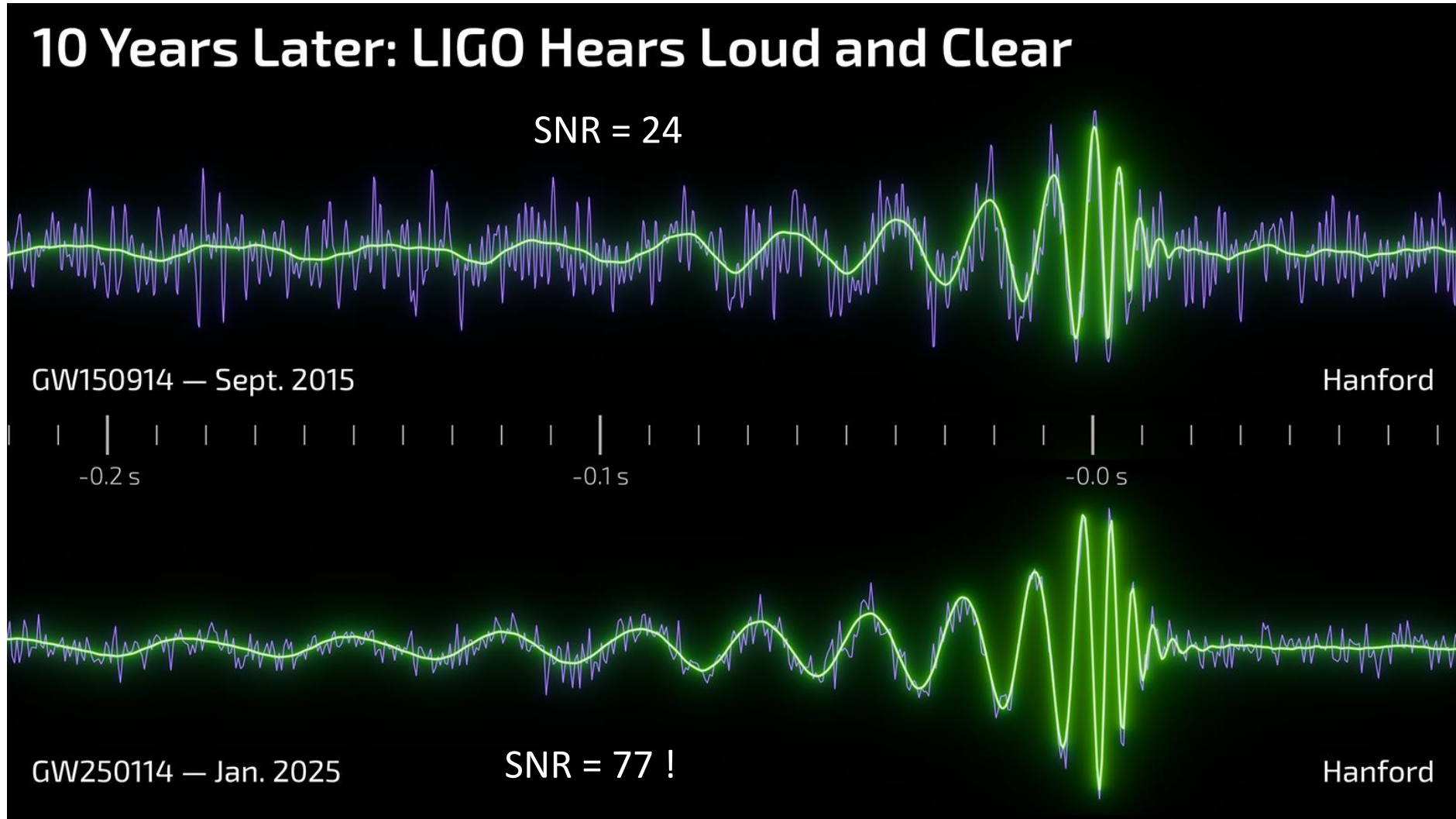


Outline

- Where we are today
- Future of GW detection landscape
- Why do we need LF? Sources at low frequencies
- Noise at LF and how to deal with them:
 - Technical noises
 - Quantum noise
- Detector design: can we do it as before?



Gravitational waves: from discovery to precision



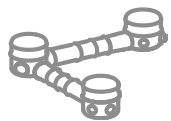
Both events:

- 30-40 $M_{\odot}$
- 3B light years away

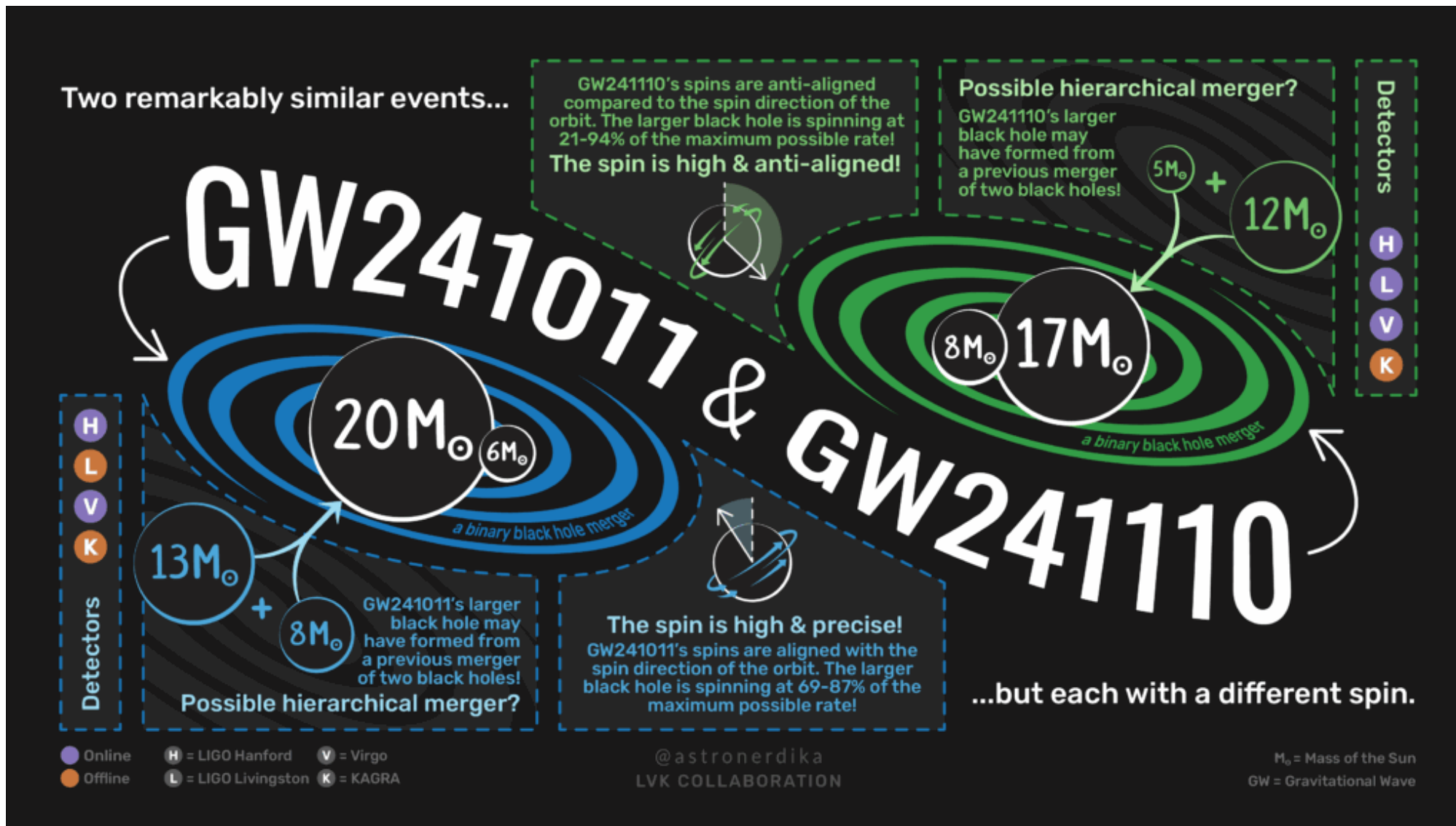
Resolved ringdown:
Hawking Area Law
tested at $>3.4\sigma$!

[LVK Collab. Phys. Rev. Lett. 136, 041403](#)

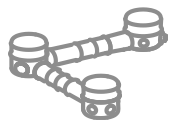
Credit: [LIGO/J. Tisso \(GSSI\)/R. Hurt \(Caltech-IPAC\)](#)



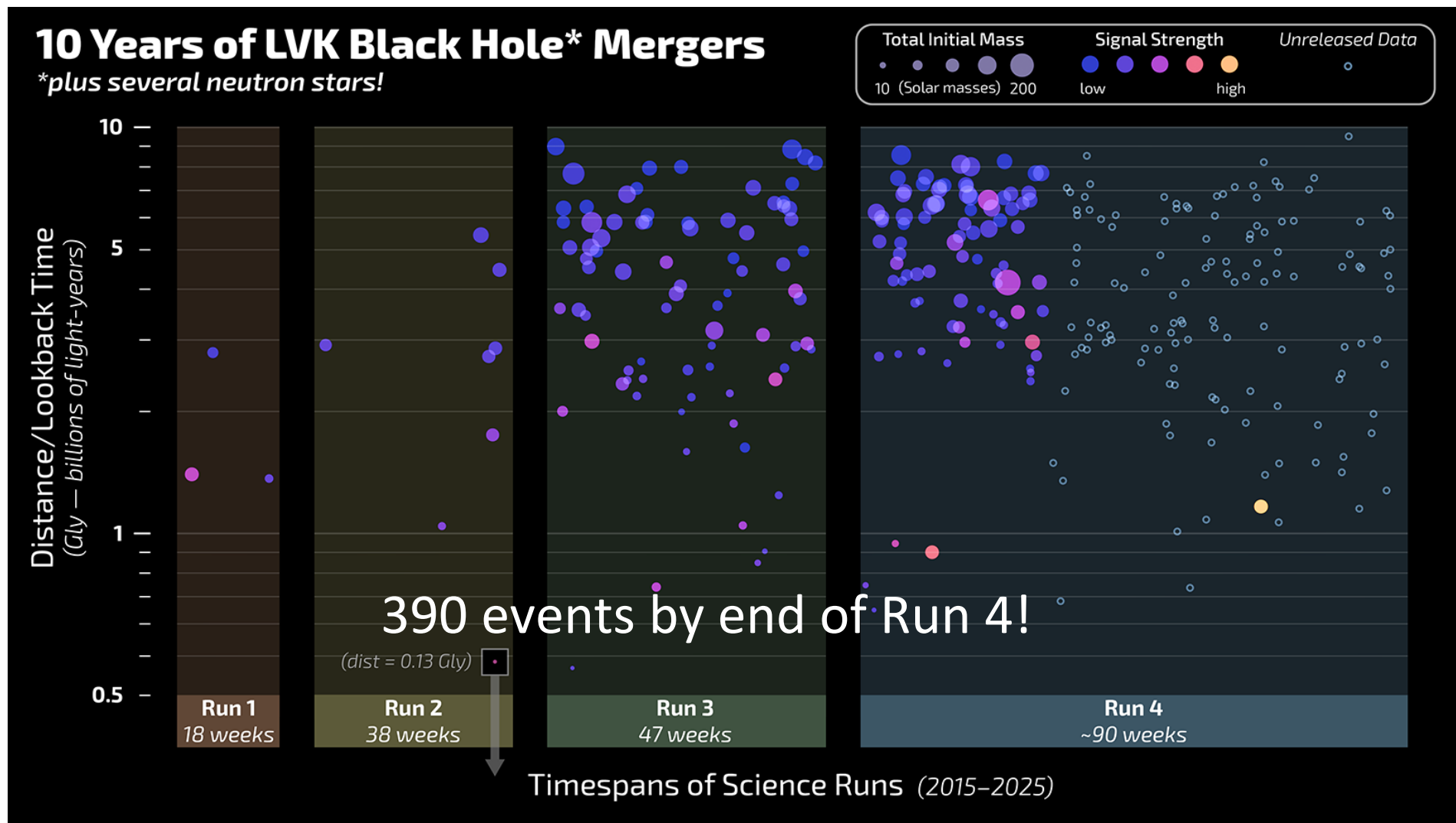
Gravitational waves: from discovery to precision



Credit: S. Galaudage/LVK



Gravitational waves: from discovery to precision

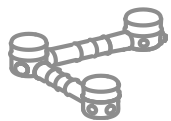


- A detection
~every 3 days in
Run 4!
- Best constraint on
Hubble constant
with GW

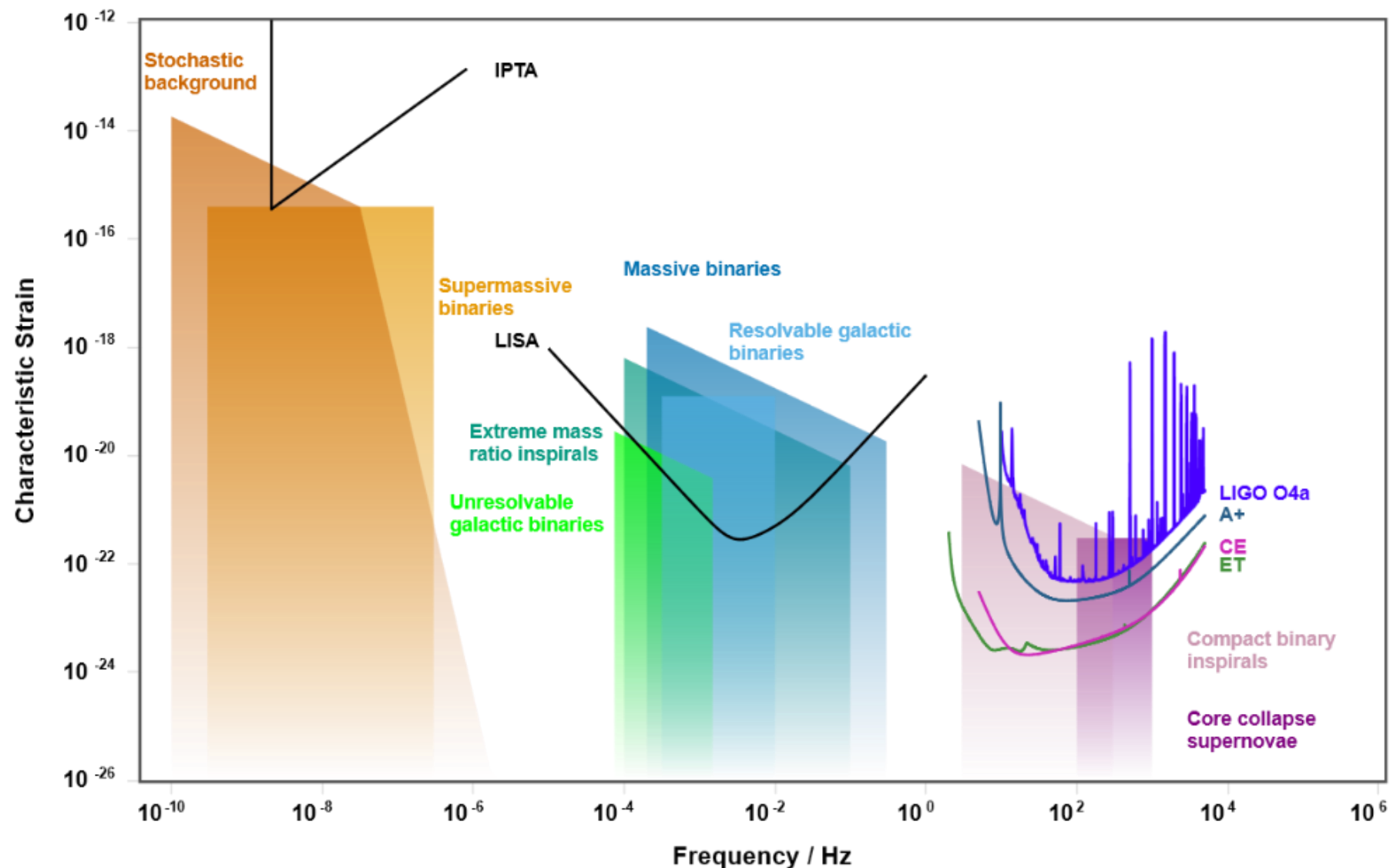
[\[arXiv:2605.27227\]](https://arxiv.org/abs/2605.27227)

Credit: LIGO/Caltech/MIT/R. Hurt (IPAC)

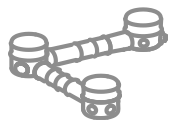
Future GW detection landscape



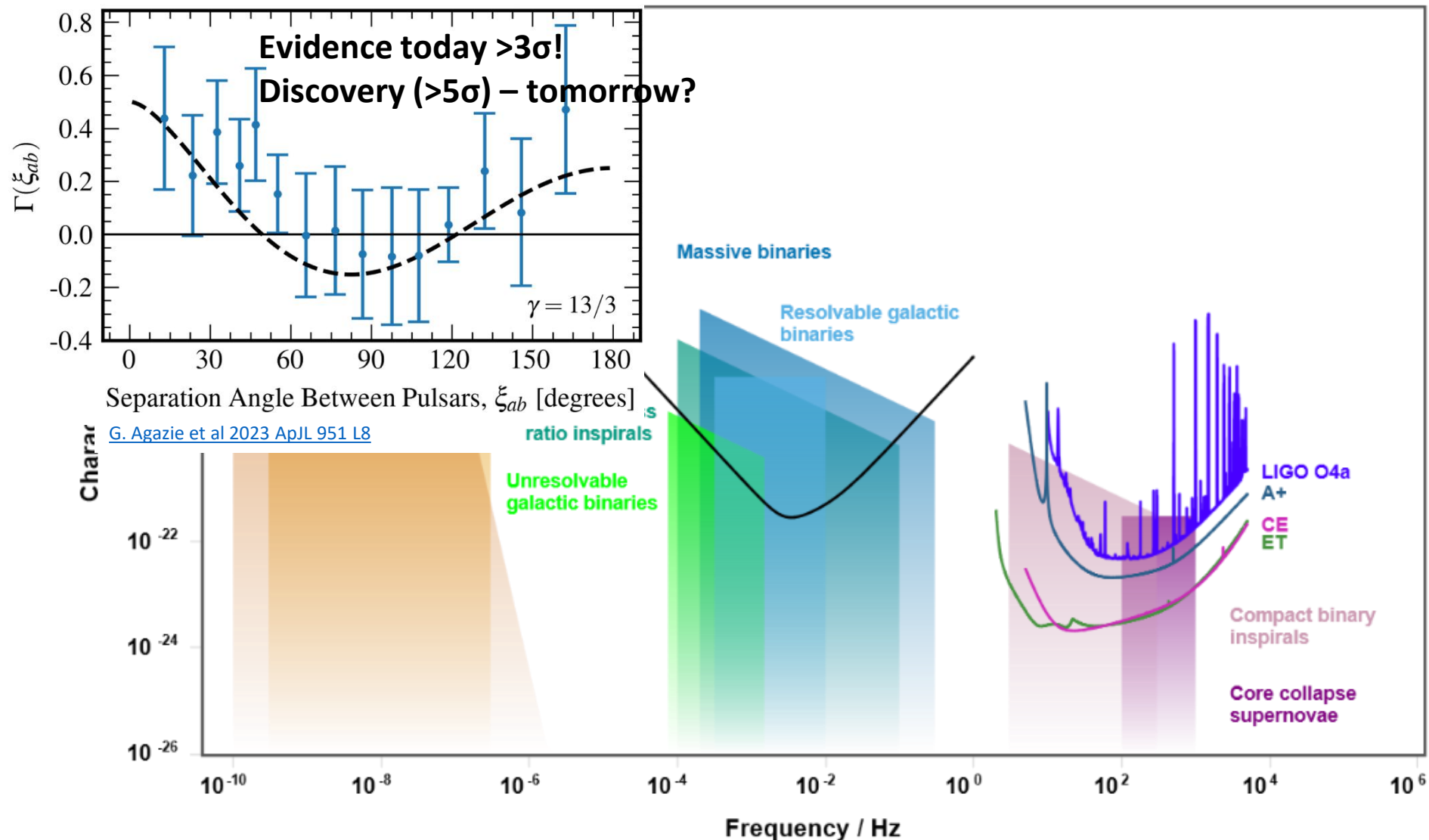
(Loud!) Future of GW detection



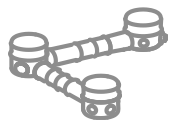
C. Moore, R. Cole and C. Berry with GWPlotter, with updated [CE](#), [ET](#) and [LIGO L1 O4a](#) sensitivities



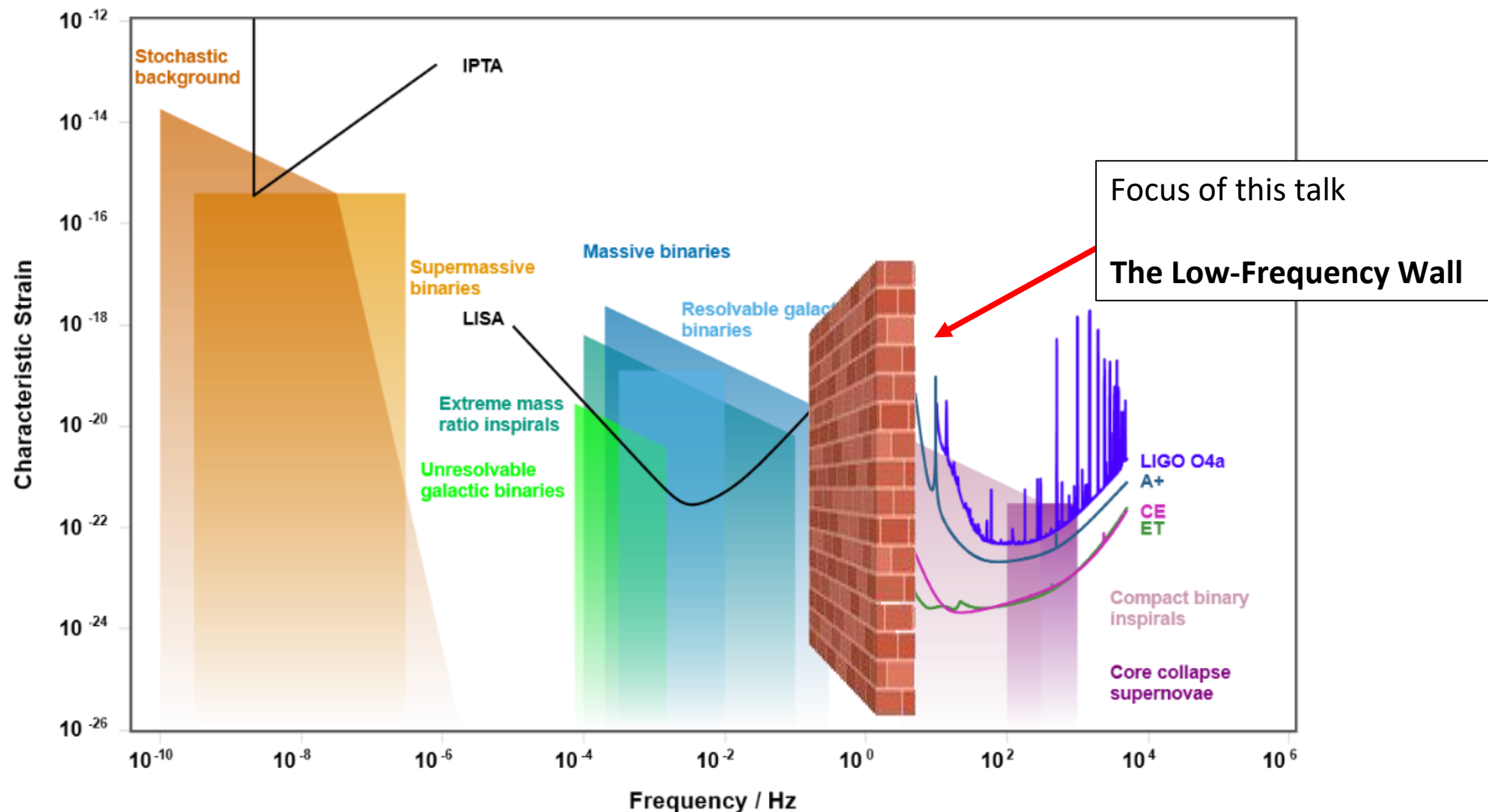
(Loud!) Future of GW detection



[C. Moore, R. Cole and C. Berry with GWPlotter](#), with updated [CE](#), [ET](#) and [LIGO L1 O4a](#) sensitivities



(Loud!) Future of GW detection



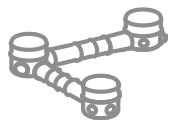
C. Moore, R. Cole and C. Berry with GWPlotter, with updated [CE](#), [ET](#) and [LIGO L1 O4a](#) sensitivities

Why LF?
Sources at low frequencies



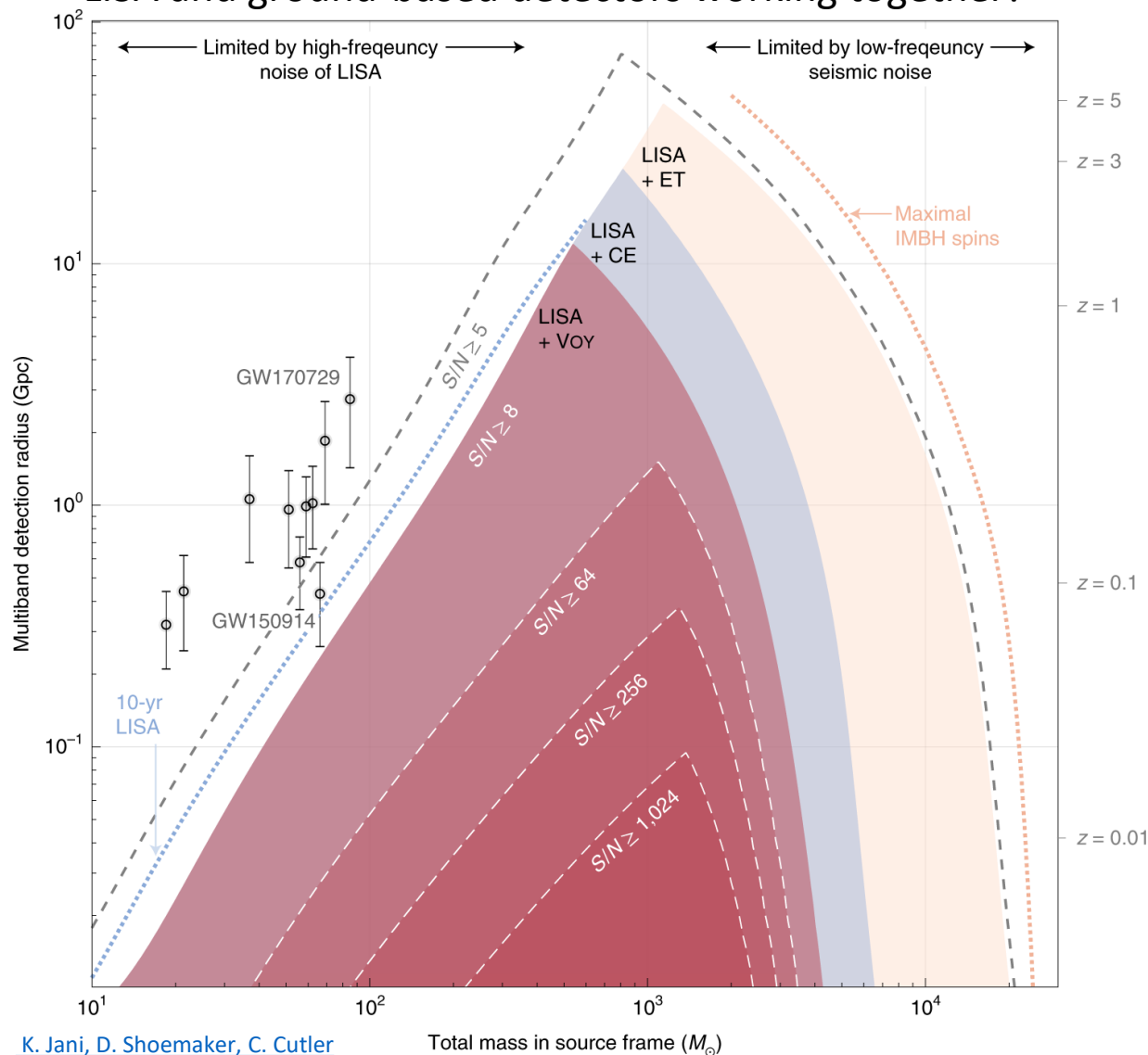


- Self-force inspiral-merger-ringdown waveforms from flux-balance laws by *Loïc Honet*



Sources at low frequencies

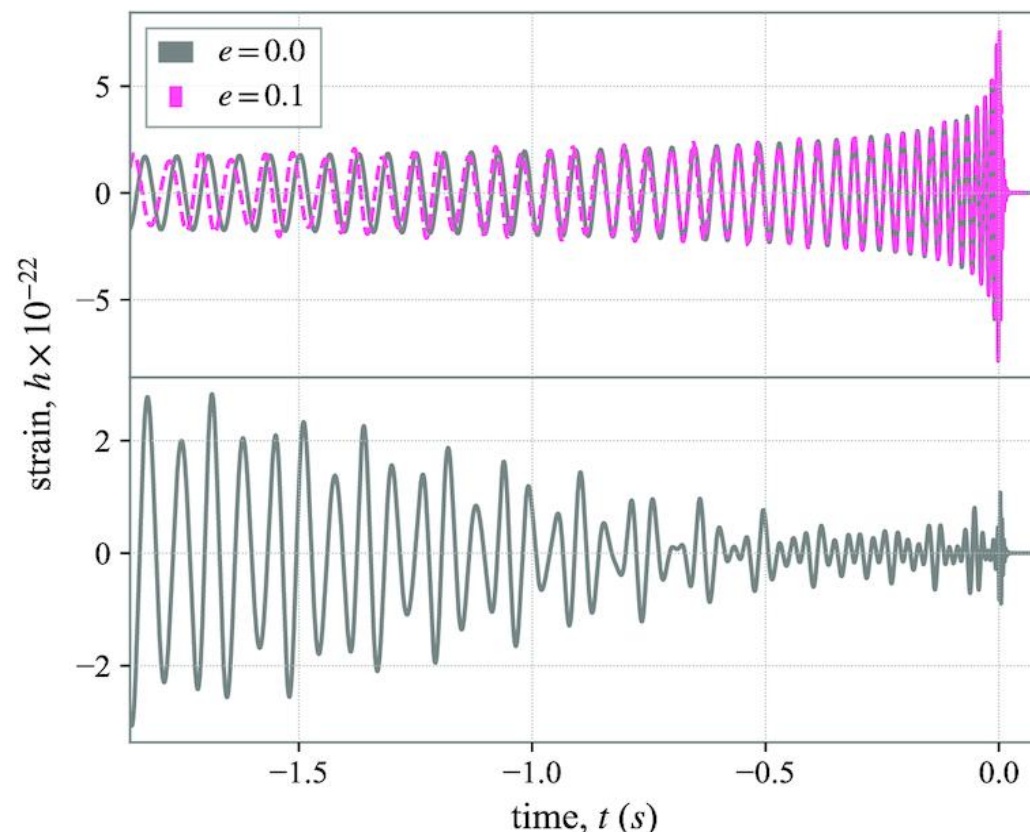
LISA and ground-based detectors working together!



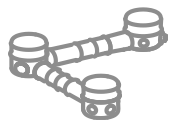
[K. Jani, D. Shoemaker, C. Cutler](#)
[Nat Astron 4, 260–265 \(2020\)](#)

Total mass in source frame ($M_{\odot}$)

- As a merger approaches, the orbits circularize
- Critical detection band <10 Hz
- a single event with $e > 0.1$ near merger = **dynamical formation**

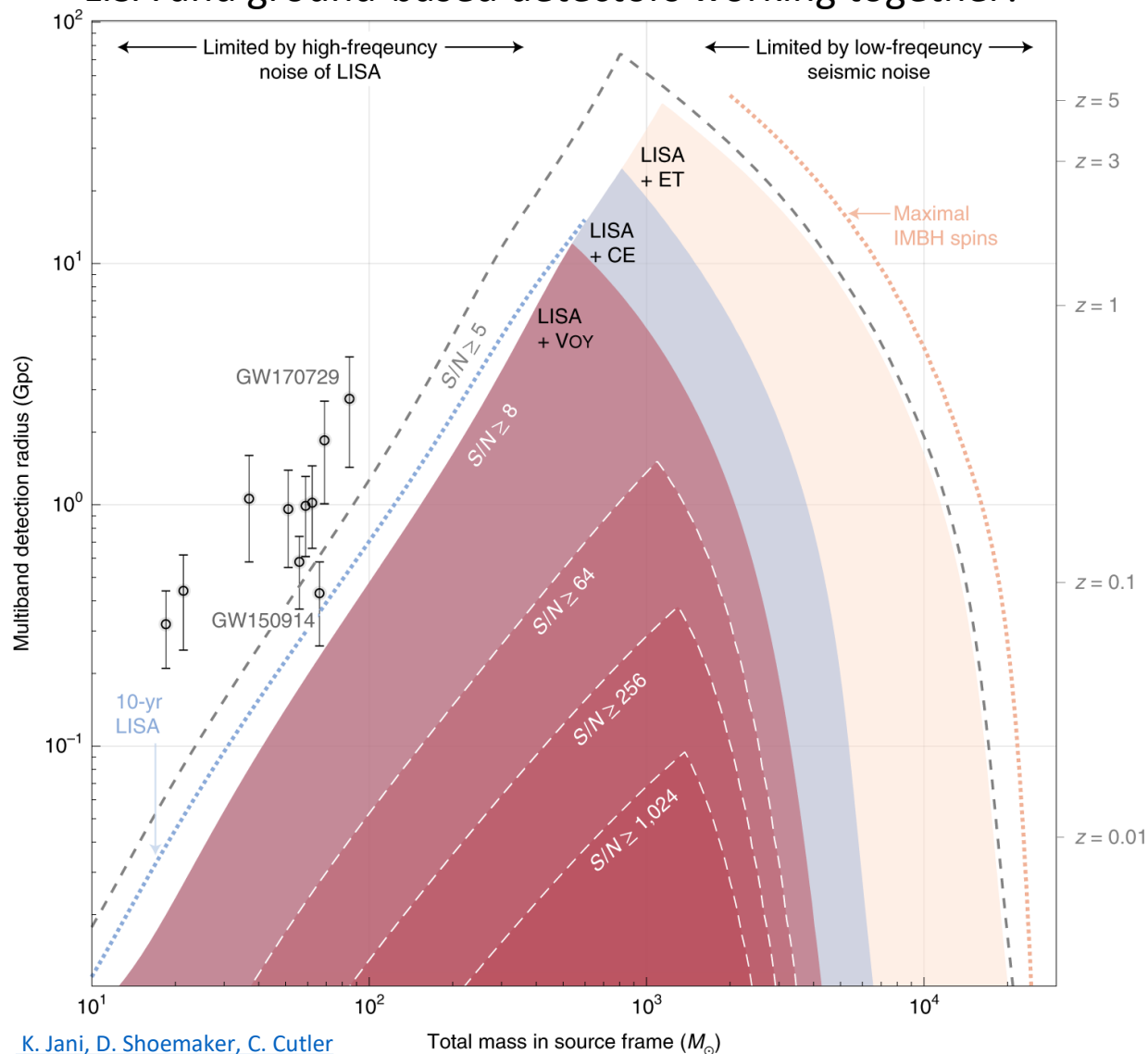


[I. M. Romero-Shaw, P. D. Lasky, E. Thrane 2019 MNRAS 490 5210](#)



Sources at low frequencies

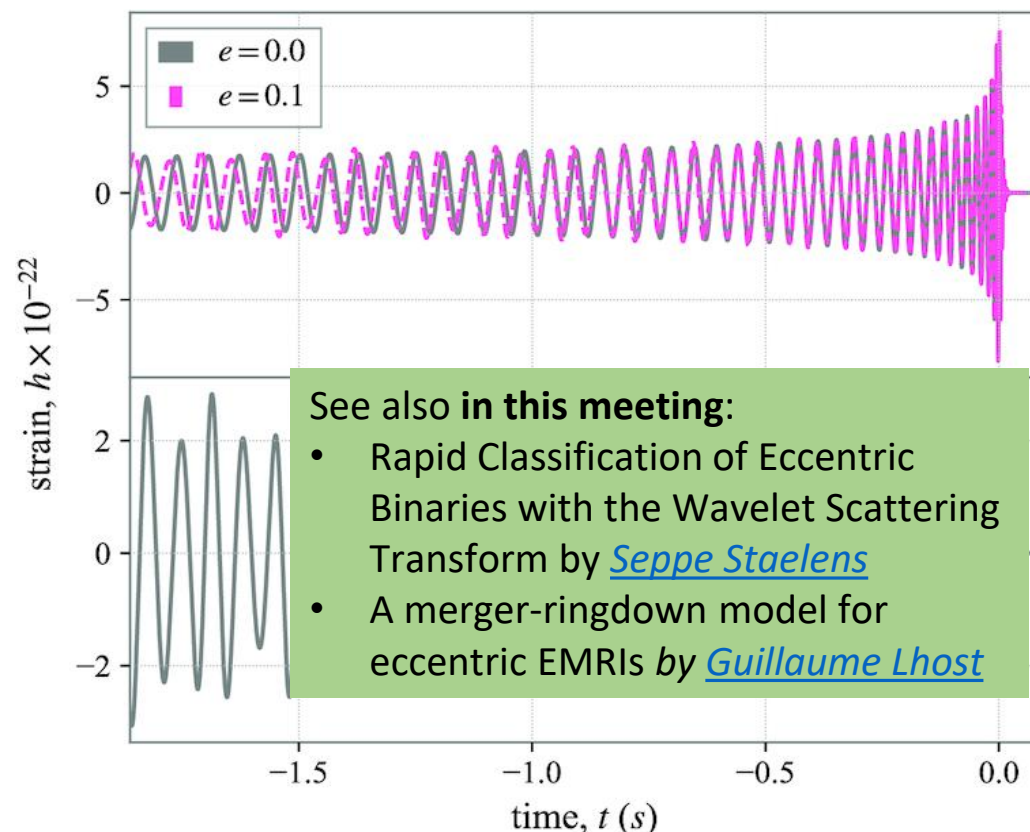
LISA and ground-based detectors working together!



[K. Jani, D. Shoemaker, C. Cutler](#)
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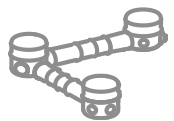
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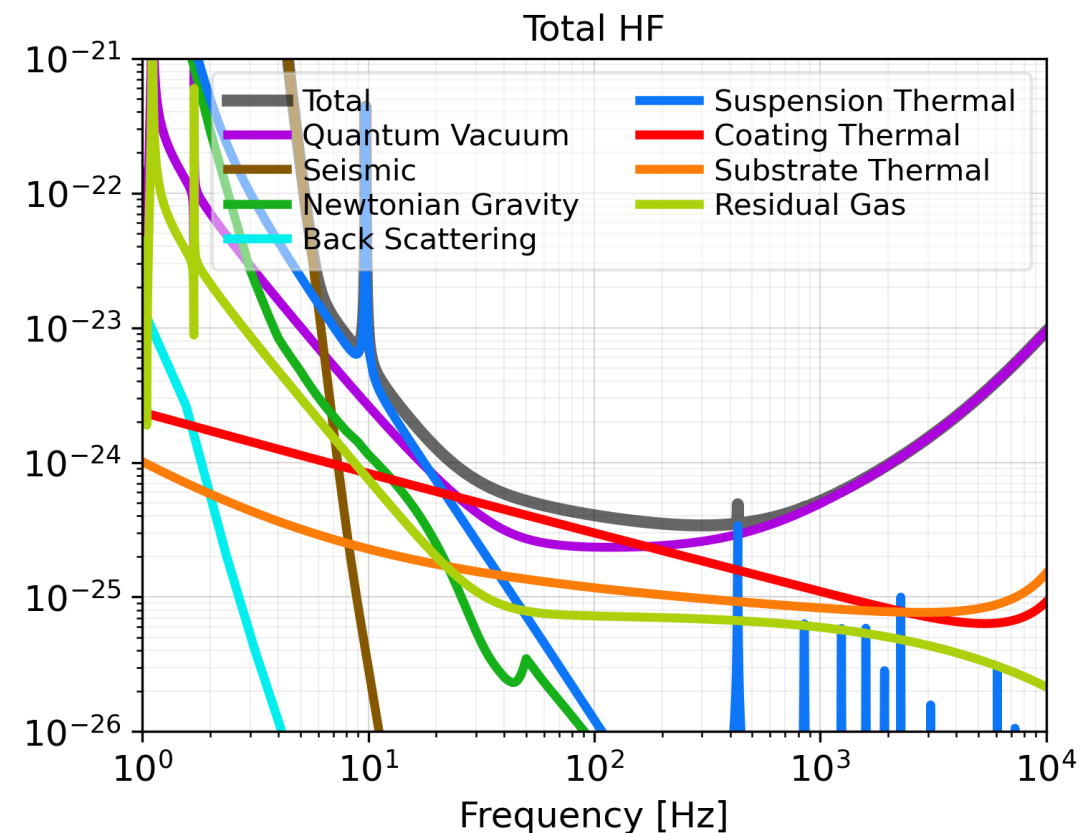
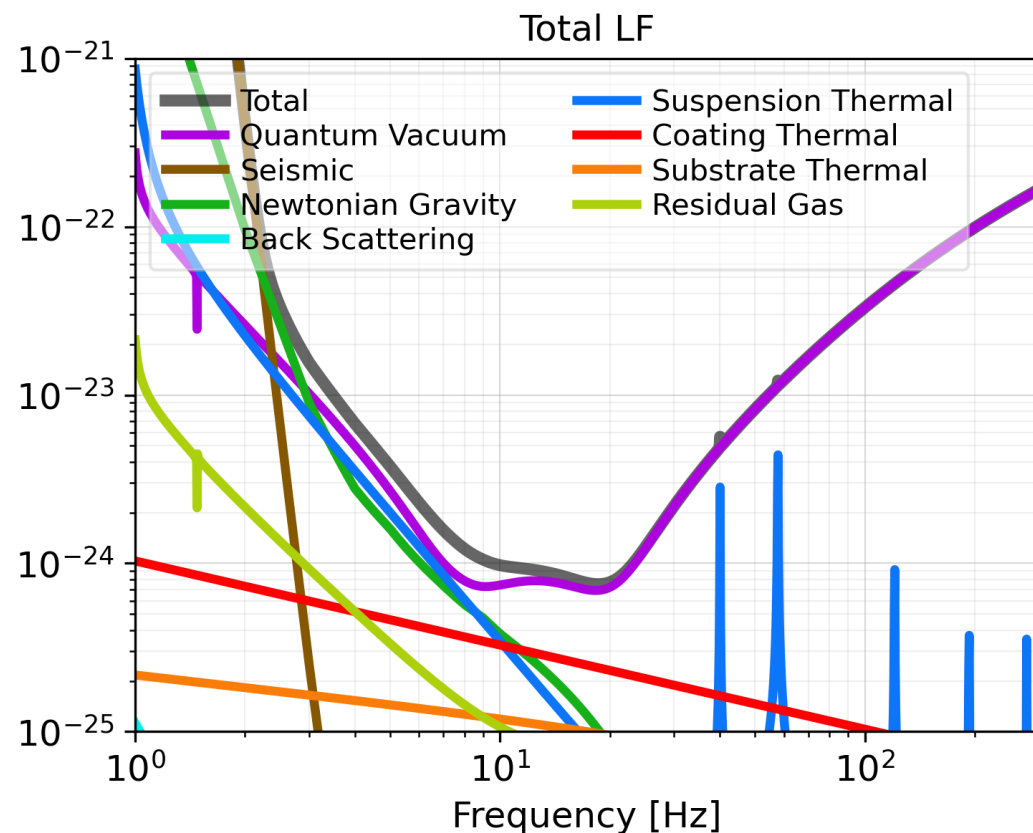


[I. M. Romero-Shaw, P. D. Lasky, E. Thrane 2019 MNRAS 490 5210](#)

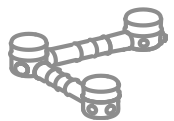
How LF?
Noise at low frequencies



How to get there: ET noise budget



[ET Sensitivity curves: gitlab.et-gw.eu/pub/et-sensitivity-curves/](https://gitlab.et-gw.eu/pub/et-sensitivity-curves/)



Newtonian noise: hard to model, site-dependent!

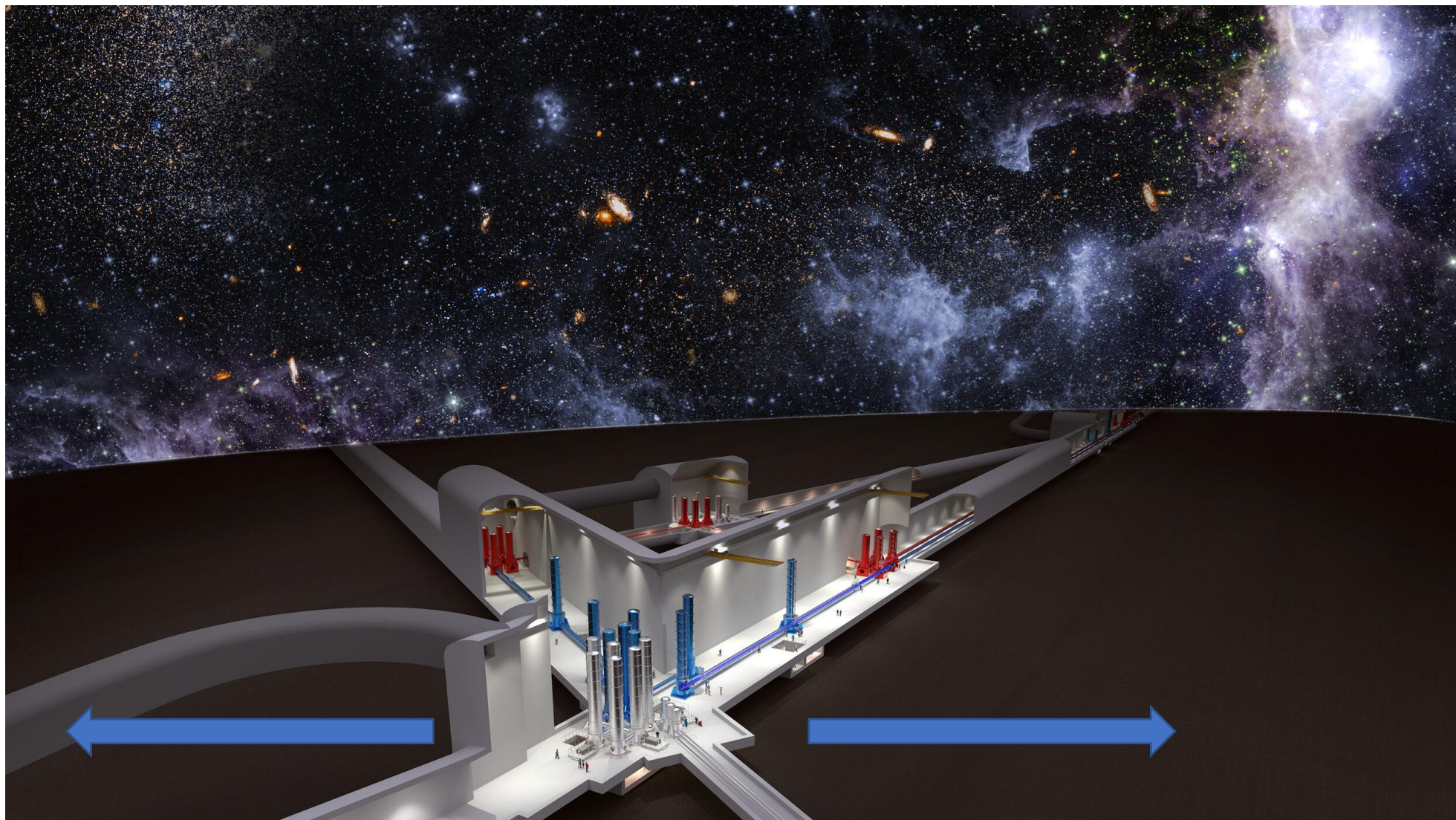
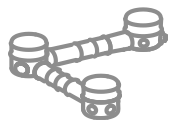


Image: <https://einstein telescope.eu>



Newtonian noise: hard to model, site-dependent!

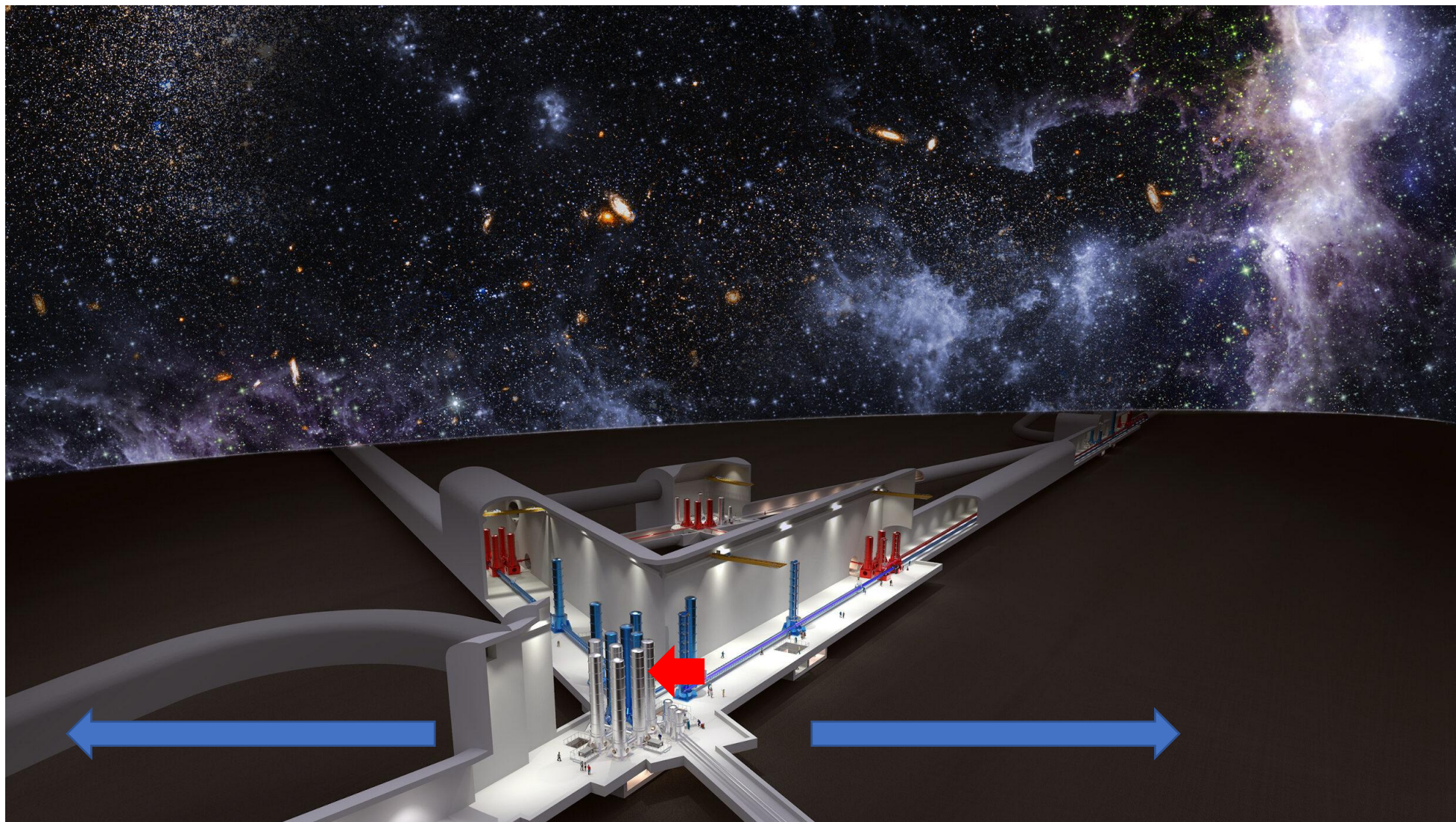
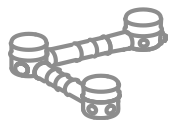


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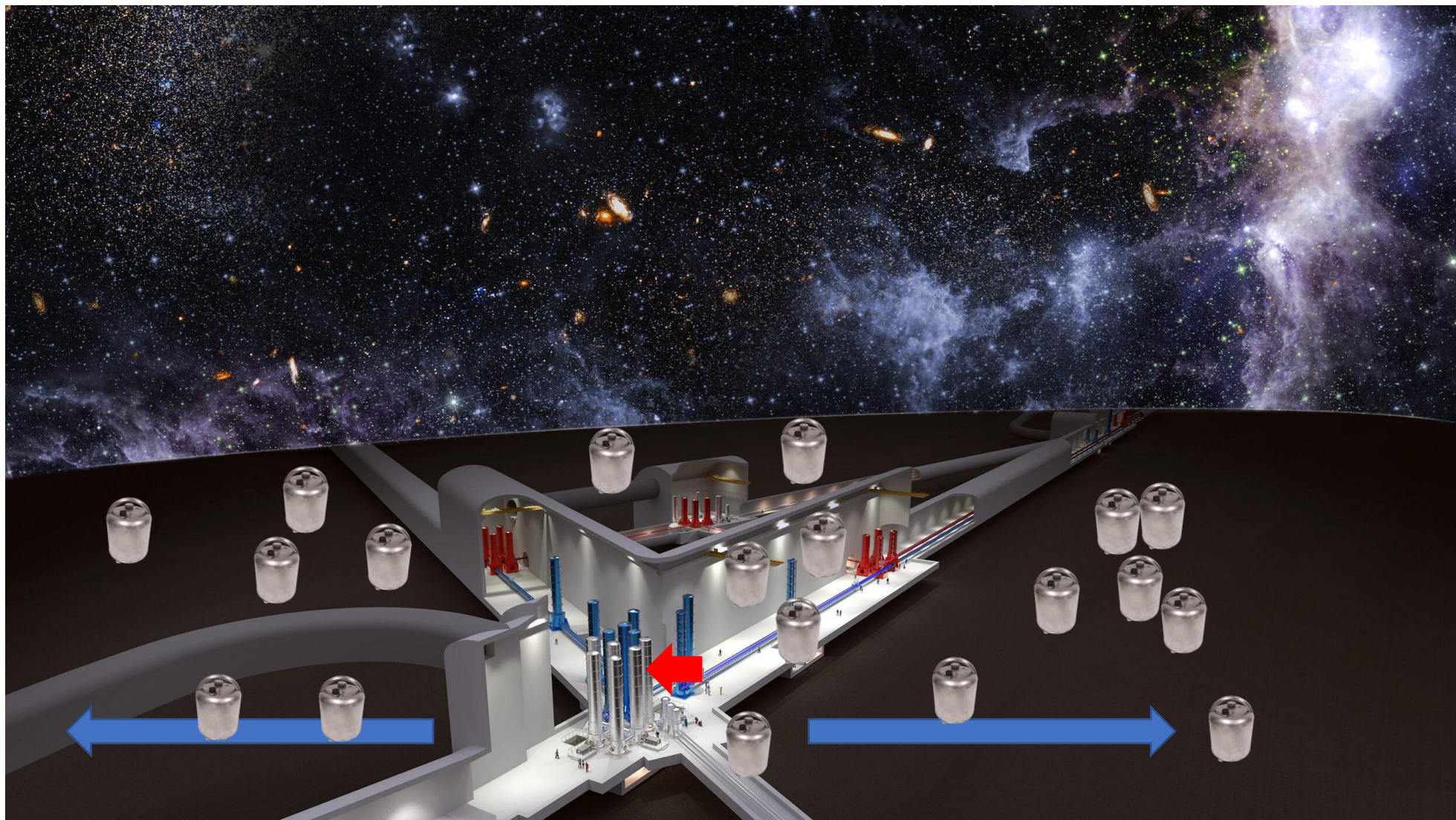
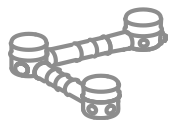


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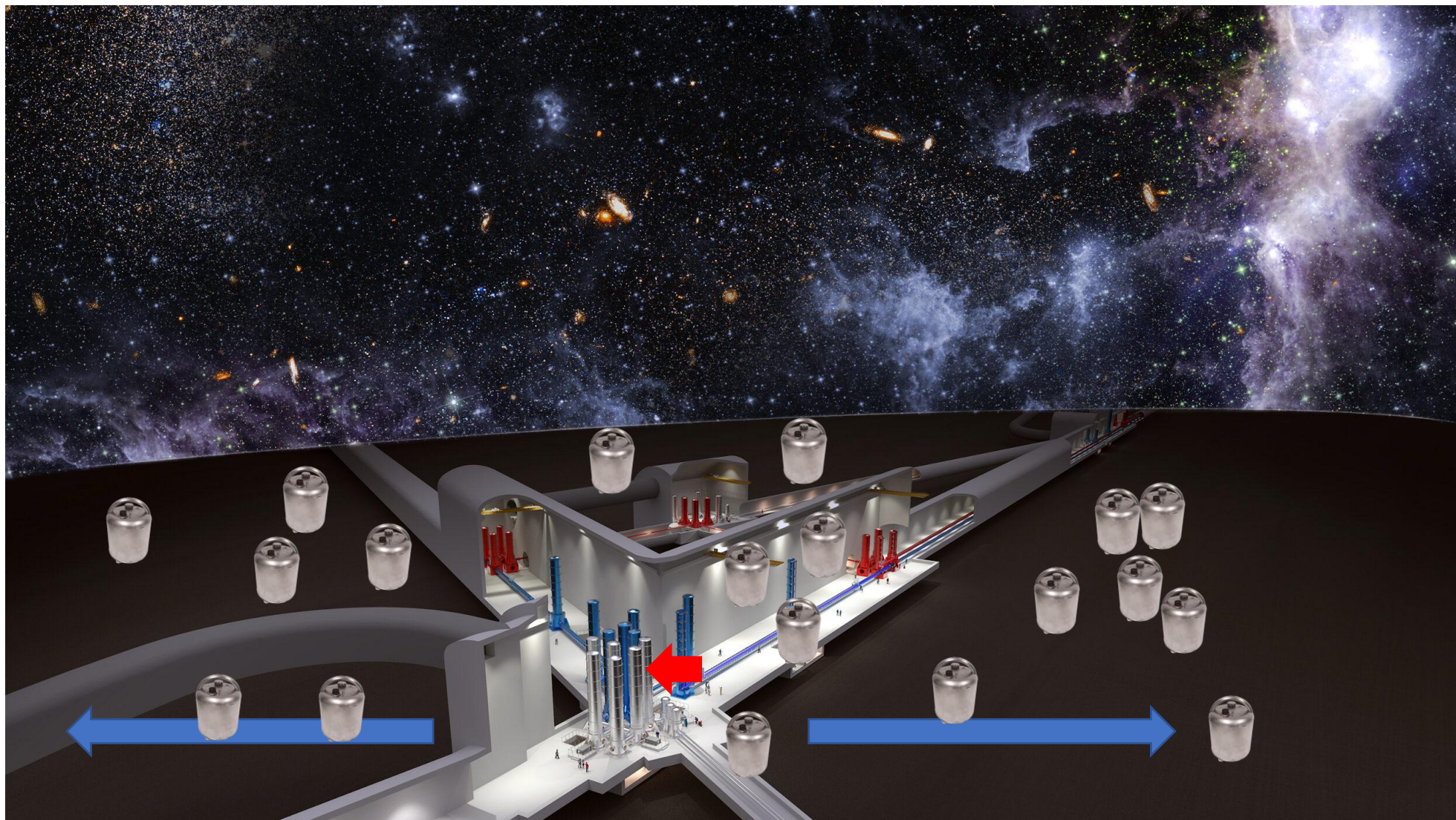
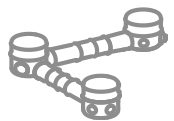
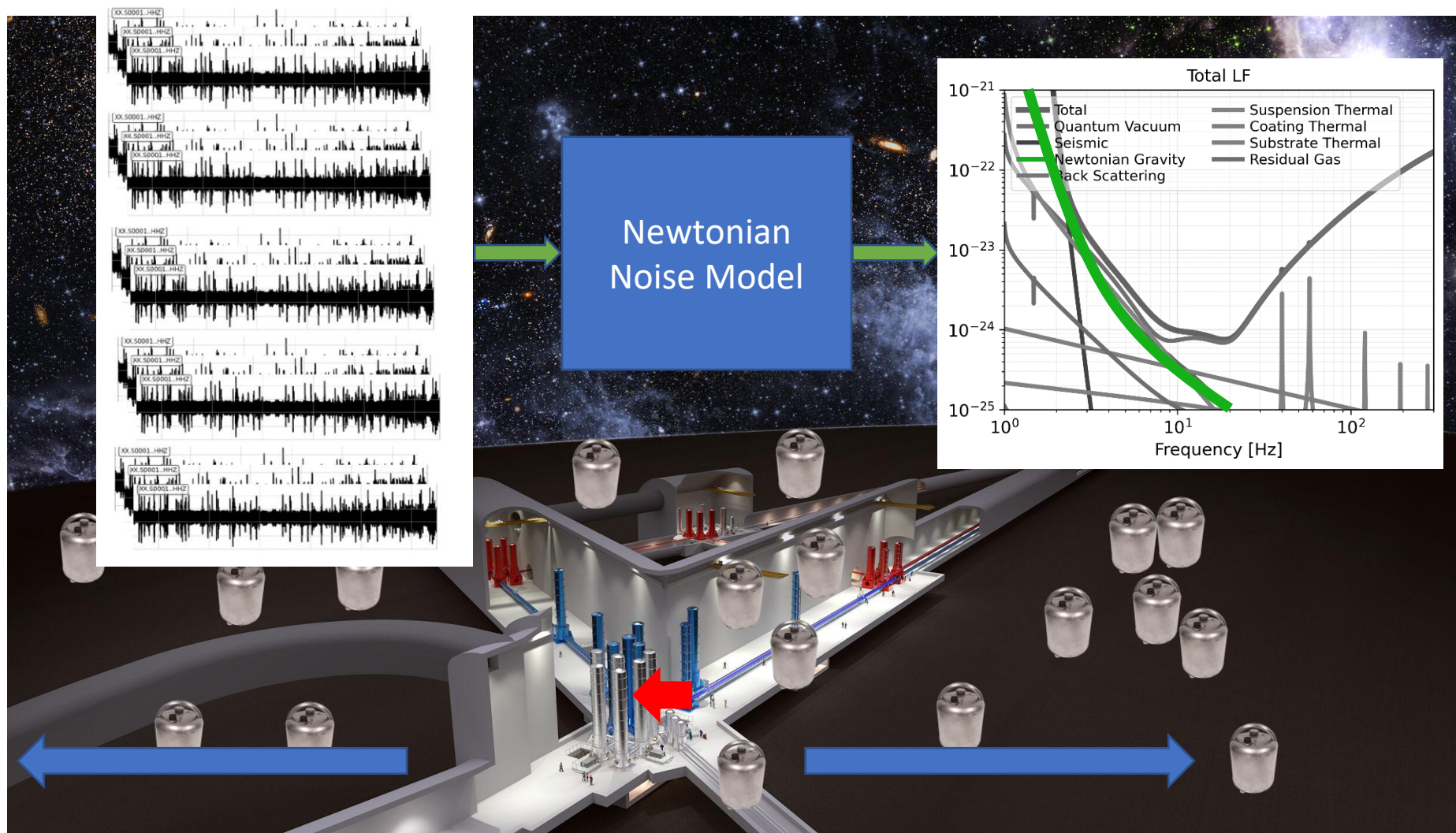


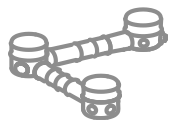
Image: <https://einstein Telescope.eu>



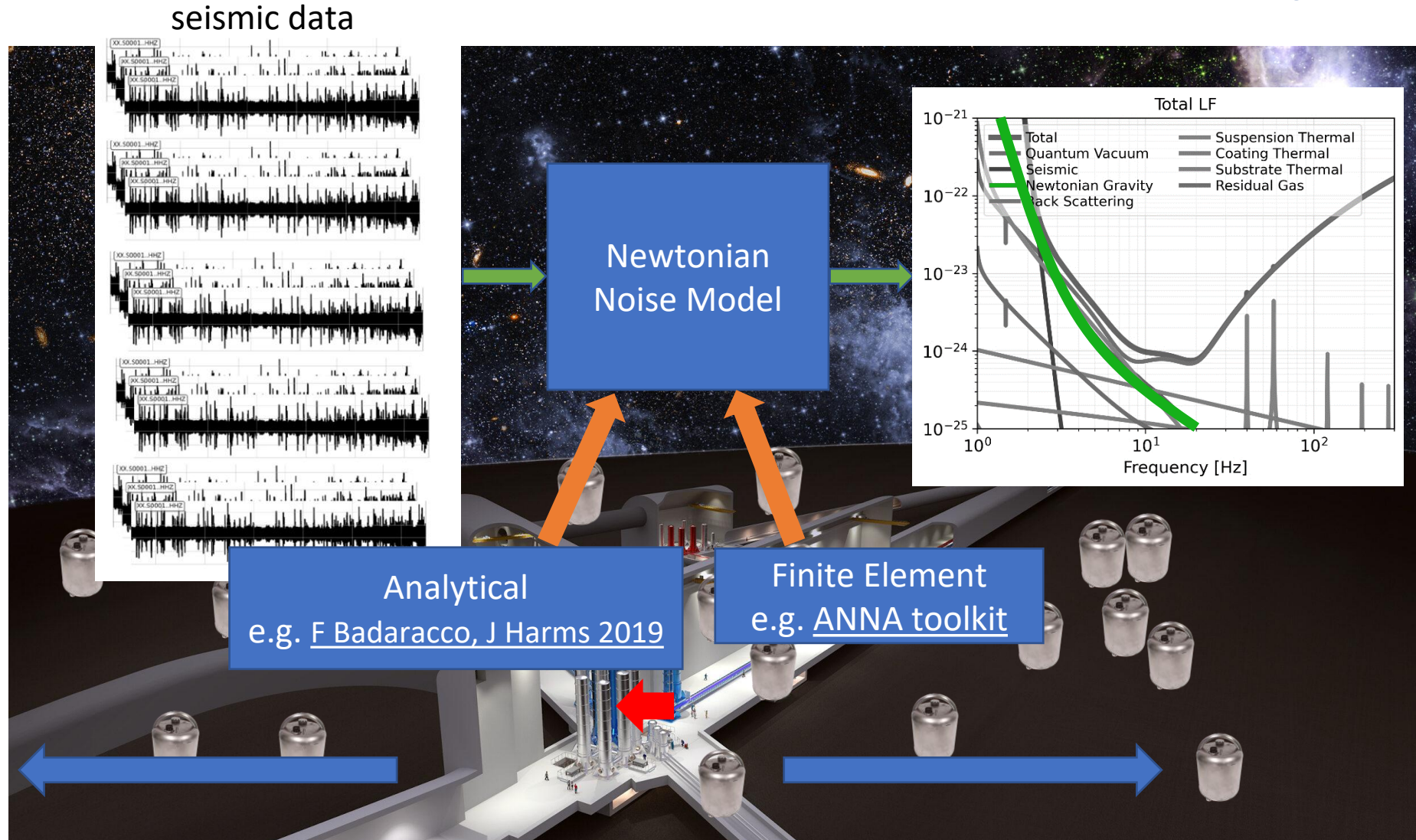
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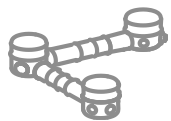
seismic data



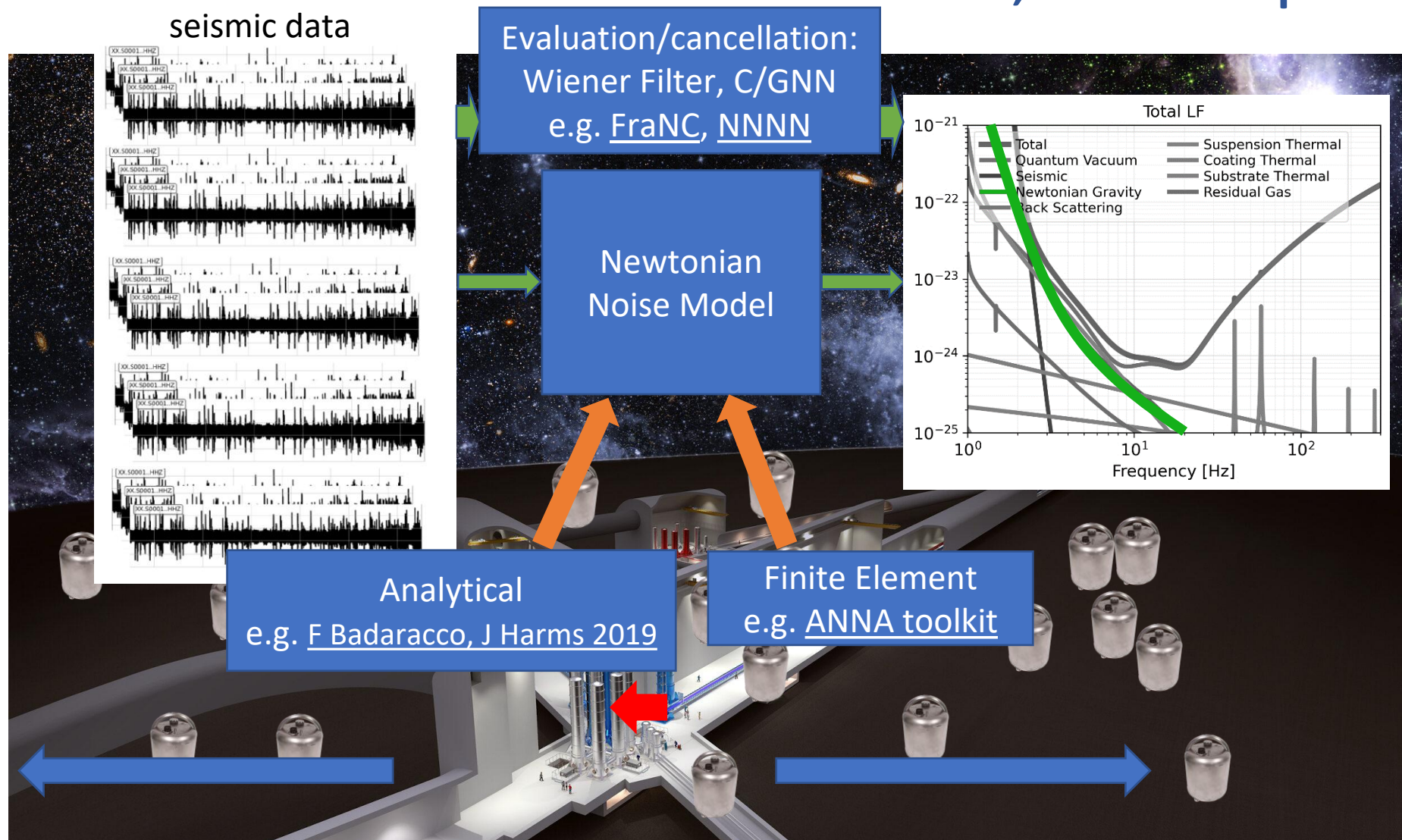


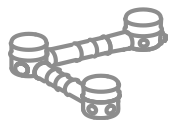
Newtonian noise: hard to model, site-dependent!





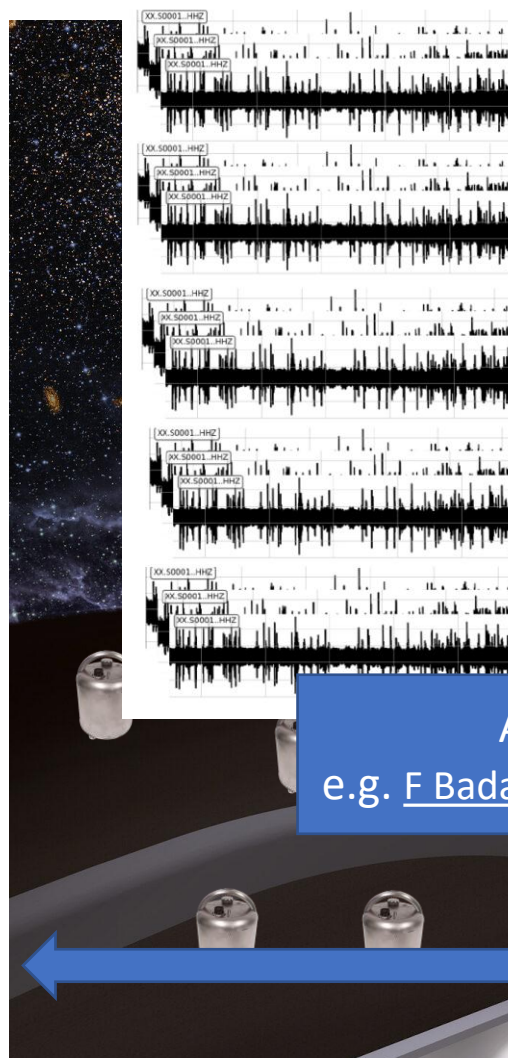
Newtonian noise: hard to model, site-dependent!





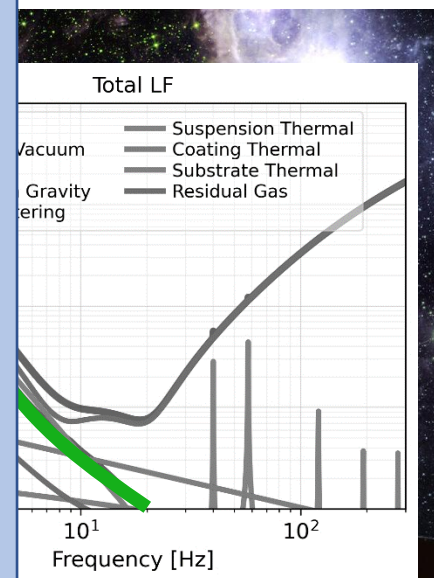
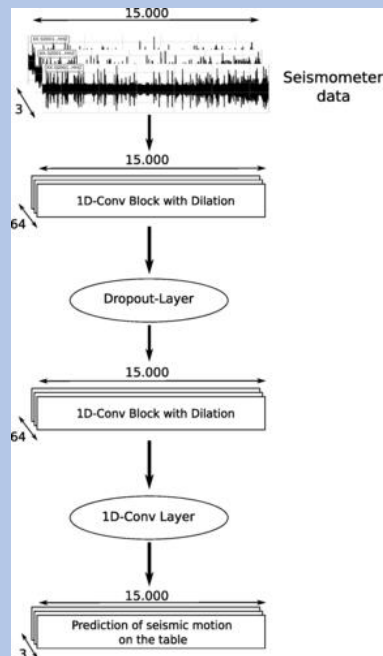
Newtonian noise: hard to model, site-dependent!

seismic data



e.g. F Bada

Characterizing seismic isolation using convolutional neural networks and Wiener filters

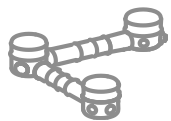


Basalaev, Feldhusen, Gerberding
Phys. Rev. Applied 23, 044056 2025

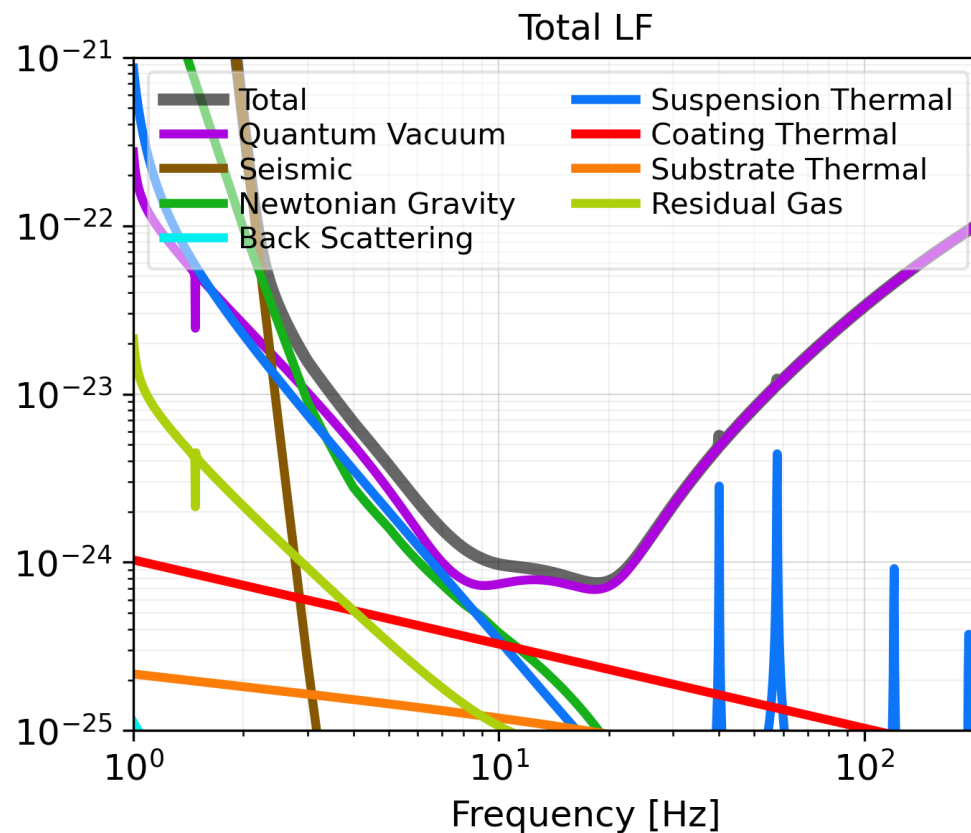
Tip: Wiener filters for arbitrary time series can be found in Spicy package



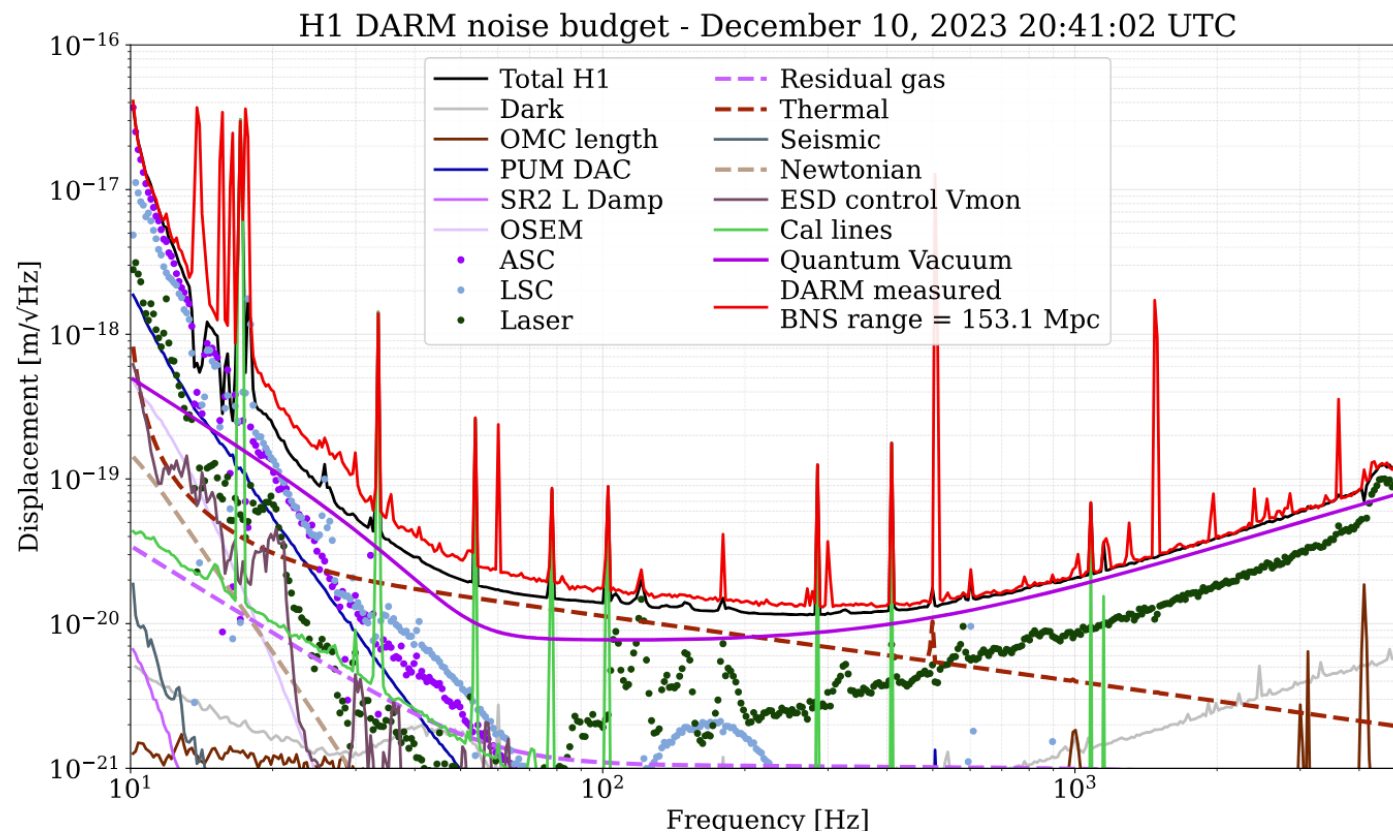
<https://pyda-group.gitlab.io/spicy>



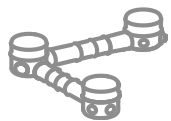
Seismic noise: harder than it seems



[ET Sensitivity curves: gitlab.et-gw.eu/pub/et-sensitivity-curves/](https://gitlab.et-gw.eu/pub/et-sensitivity-curves/)

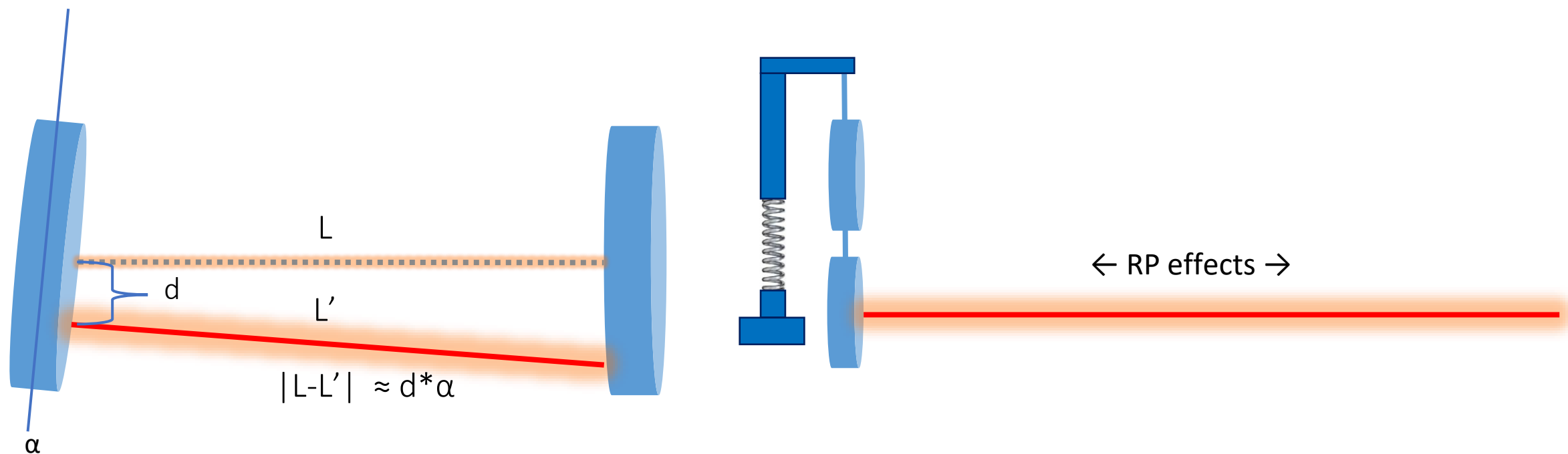


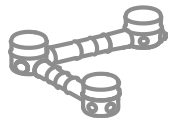
<https://noisebudget.docs.ligo.org/aligoNB/>



Controlled Suspension – source of noise

- Biggest: **angular sensing noise** due to tilt-to-length coupling of the interferometer
- **length sensing noise** also contributes
- Coupling is **nonlinear**! (bi-linear as first approximation)
- A lot of things become entangled: suspension design, local position sensors on suspension, controls of suspension, interferometer optical layout, global control...
- **Many of these can only be measured currently, not reliably modelled**





Controlled Suspension – source of noise

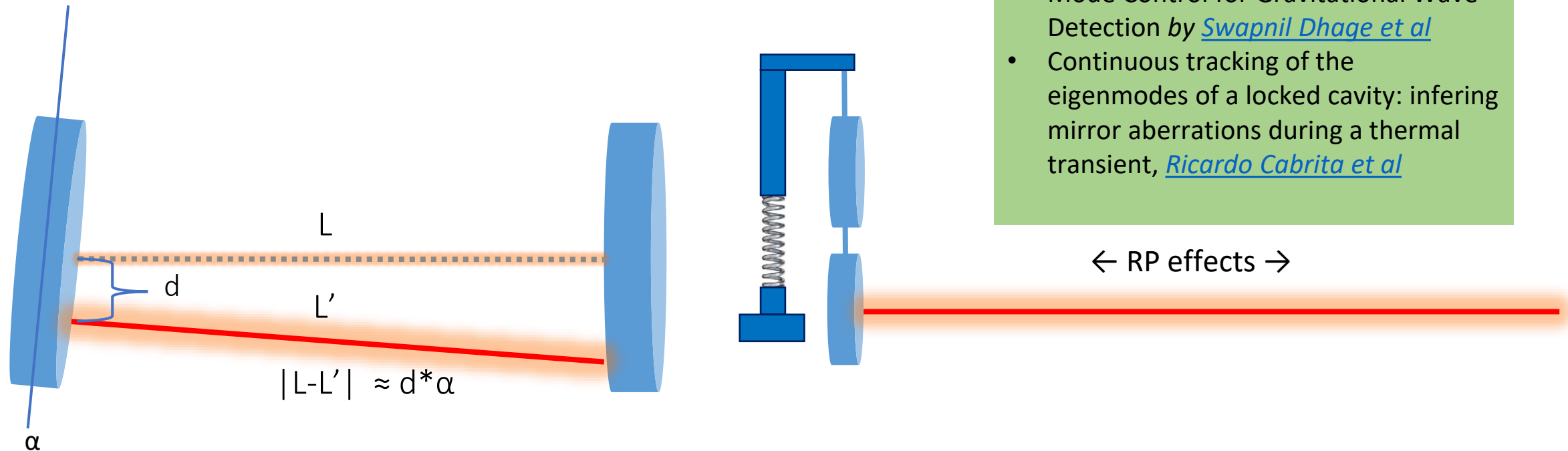
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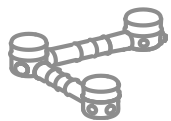
See also in **this meeting**:

- [Workshop on ET Modelling](#)

For **high power** issues:

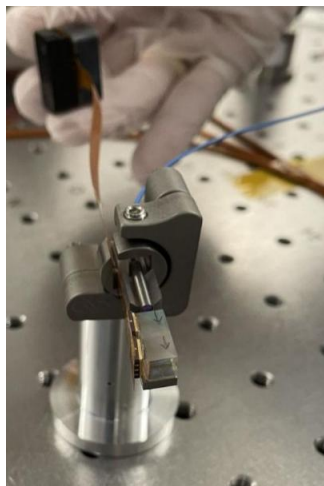
- Demonstrating Transverse Optical Mode Control for Gravitational Wave Detection by [Swapnil Dhage et al](#)
- Continuous tracking of the eigenmodes of a locked cavity: inferring mirror aberrations during a thermal transient, [Ricardo Cabrita et al](#)





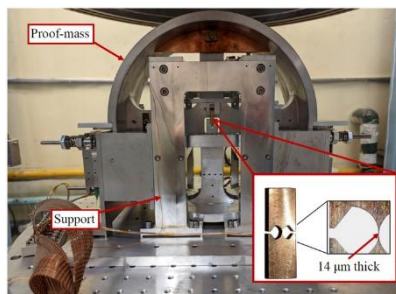
Interferometric sensors

- New technology, but already maturing. Sub-pm sensitivities shown
- From compact (COBRI, HoQI, ...) to 6D (Compact 6D,...); measuring translations and/or tilts directly

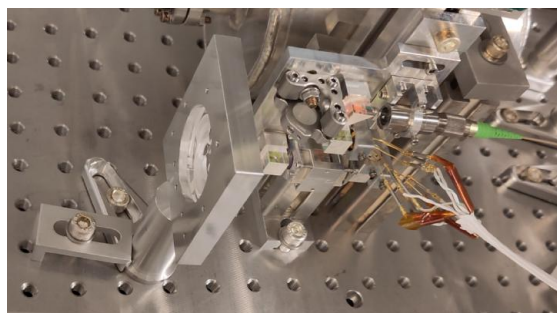


COBRI

[Gerberding, Isief Sensors 2021, 21\(5\), 1708, LIGO-G2602021](#)



CRS [Ross et al Rev. Sci. Instrum. 94, 094503 \(2023\)](#)



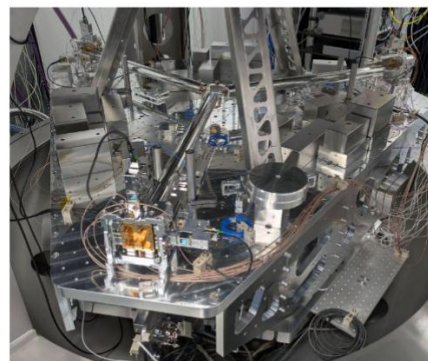
HoQI [Cooper et al 2018 Class. Quantum Grav. 35 09500](#)
+ High-Q silica resonator

[J J Carter et al 2025 Class. Quantum Grav. 42 185001](#)



LPS sensing head undergoing testing

[Ubhi et al Phys. Rev. Lett. 137, 031401](#)



Omnisens

[Mow-Lowry, Martynov 2019 Class. Quantum Grav. 36 245006 ET-0328A-26, LIGO-G2601974](#)

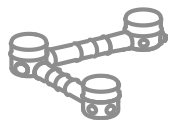


C-6D undergoing installation at MIT LASTI facility

See also in **this meeting**:

- Cryogenic Interferometric Inertial Sensor for next-generation gravitational-wave detectors, [M. Zeoli](#)
- Addressing coupling limitation in low-frequency active isolation systems with Fiber-Optic Gyroscopes, [B. Thibaut](#)

(...and more, not listed!)



... and prototypes to test them (+ more)



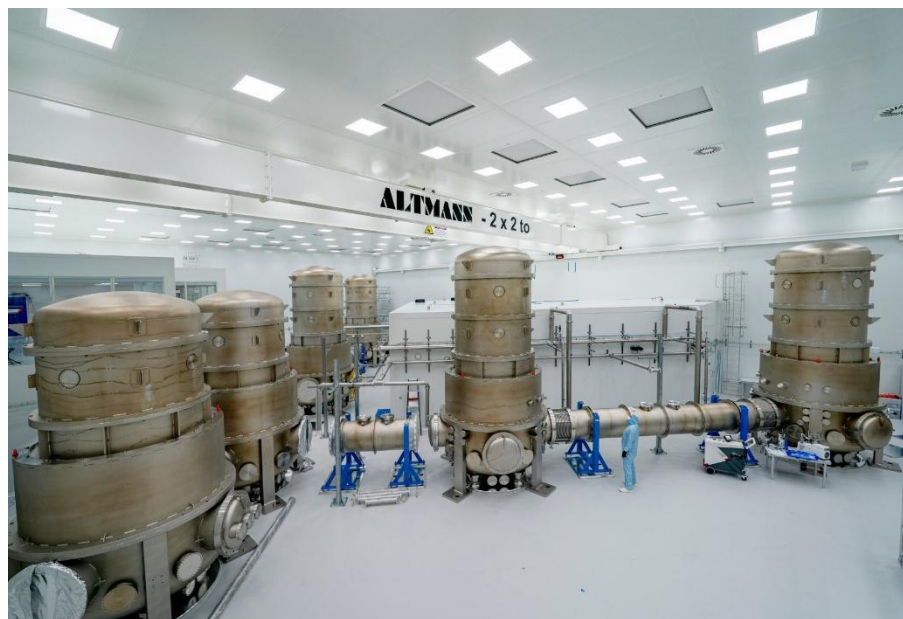
10 m Prototype AEI Hannover/LUH



E-TEST



“VATIGrav” chamber
in Hamburg

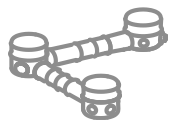


ET Pathfinder

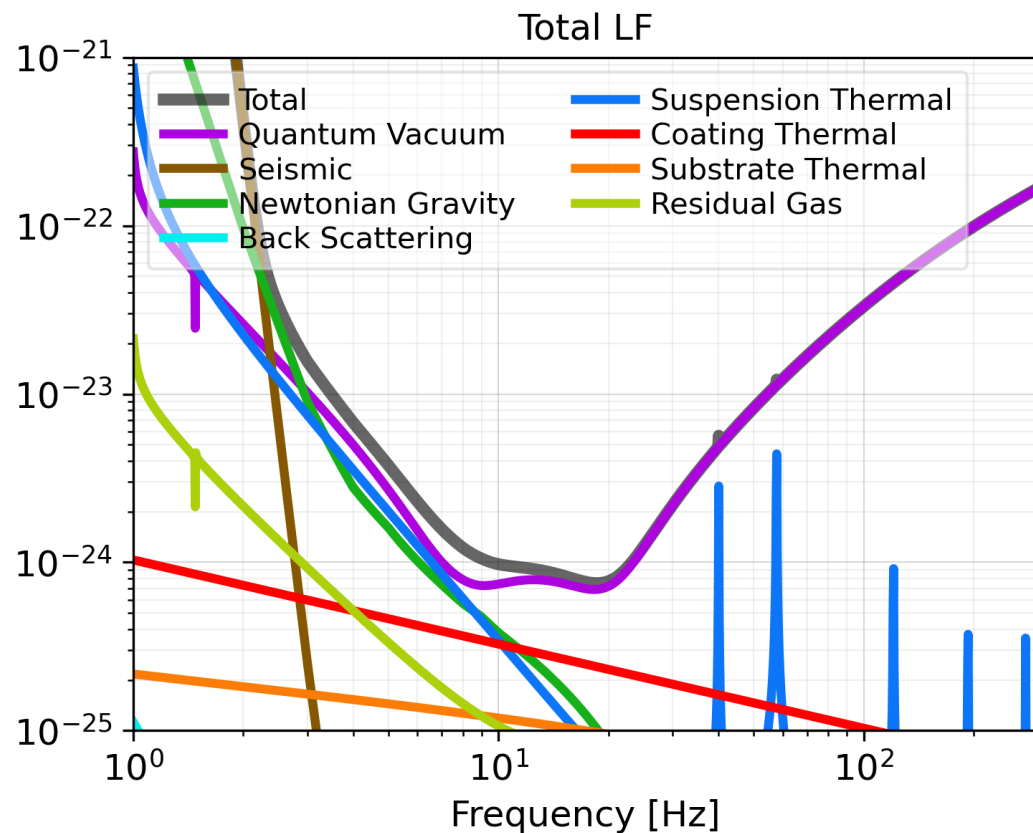
(...and many more, not listed)

See also in **this meeting**:

- ETpathfinder: prototyping low-frequency technologies for the Einstein Telescope by [E. Van den Bossche](#)
- ET-CRISTAL - Seismic Isolation Update, [T Giordano](#)



Quantum noise



[ET Sensitivity curves: gitlab.et-gw.eu/pub/et-sensitivity-curves/](https://gitlab.et-gw.eu/pub/et-sensitivity-curves/)

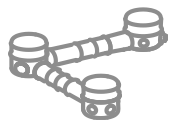
- Shot Noise
- Quantum Radiation Pressure Noise

$$S_h(\Omega) = \frac{8}{L^2} \left[S_{\text{SN}}(\Omega) + 2\Re[\chi^*(\Omega)S_{\text{CC}}(\Omega)] + |\chi(\Omega)|^2 S_{\text{QRPN}}(\Omega) \right]$$

$$S_{\text{SN}}(\Omega)S_{\text{QRPN}}(\Omega) - |S_{\text{CC}}(\Omega)|^2 \geq \frac{\hbar^2}{4\eta(\Omega)}$$

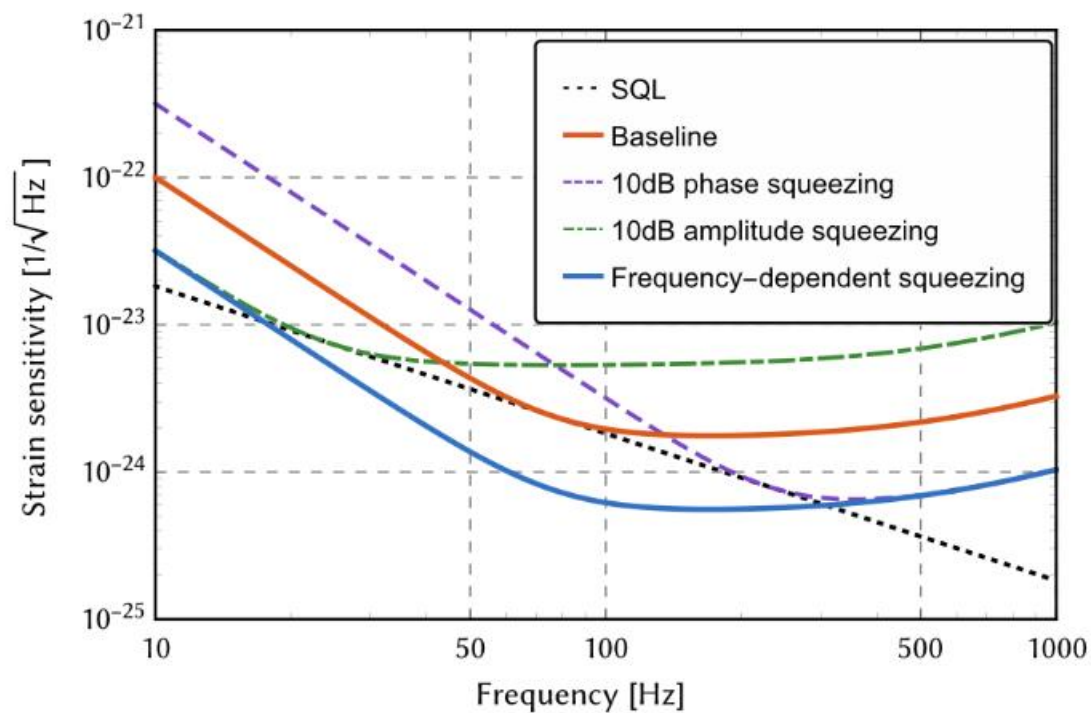
- There's optimal power at which SN = QRPN = min noise
- Locus of these points = Standard Quantum Limit (SQL)

[Korobko Galaxies 2025, 13\(1\), 11](#)

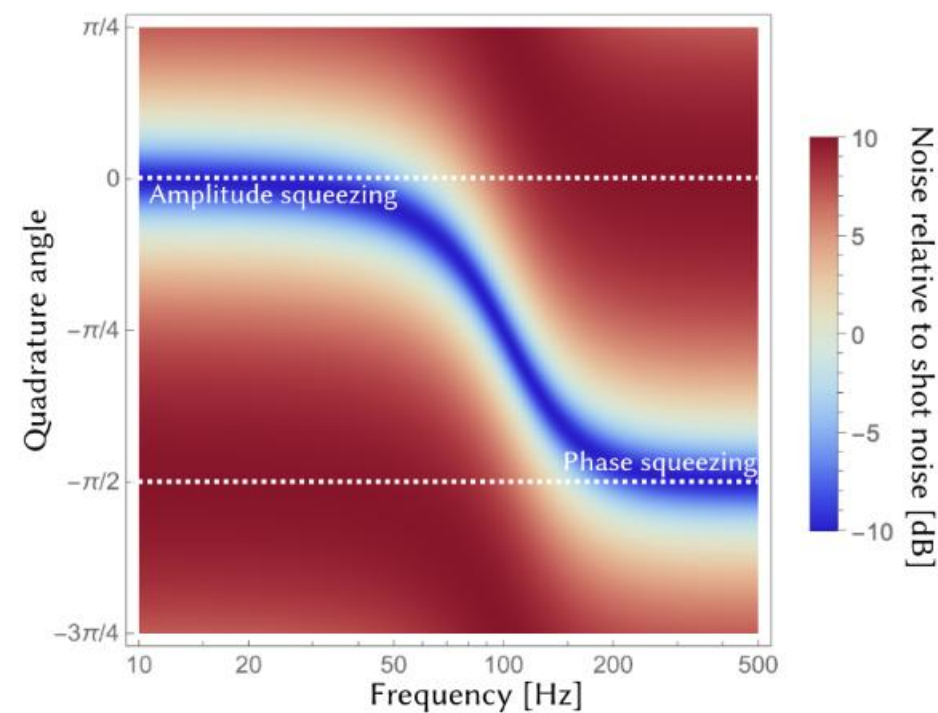


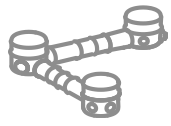
Quantum Noise: squeezing

Illustration of frequency-dependent squeezing (**not** ET-LF)



[Korobko Galaxies 2025, 13\(1\), 11](#)

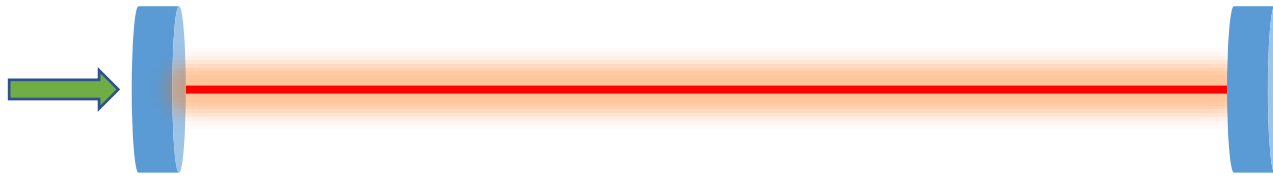


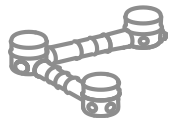


Quantum noise: optical spring

Optical Spring effect

- Detune cavity from resonant condition





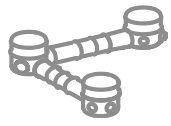
Quantum noise: optical spring

Optical Spring effect

- The field amplitude in the detector cavities becomes dependent on the position of the arm cavity mirrors (cavity length)



$$P_c = \frac{P_0}{1 + \delta^2}$$



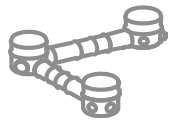
Quantum noise: optical spring

Optical Spring effect

- This position is influenced by the radiation pressure force, which itself depends on the field amplitude



$$P_c = \frac{P_0}{1 + \delta^2}$$



Quantum noise: optical spring

Optical Spring effect

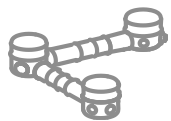
- This effect resonantly enhances the sensitivity at the **optical spring frequency**



$$P_c = \frac{P_0}{1 + \delta^2}$$

$$k_{OS} = \frac{2}{c} \frac{dP_c}{dx} = \frac{2}{c} \frac{dP_c}{d\delta} \frac{d\delta}{dx}$$

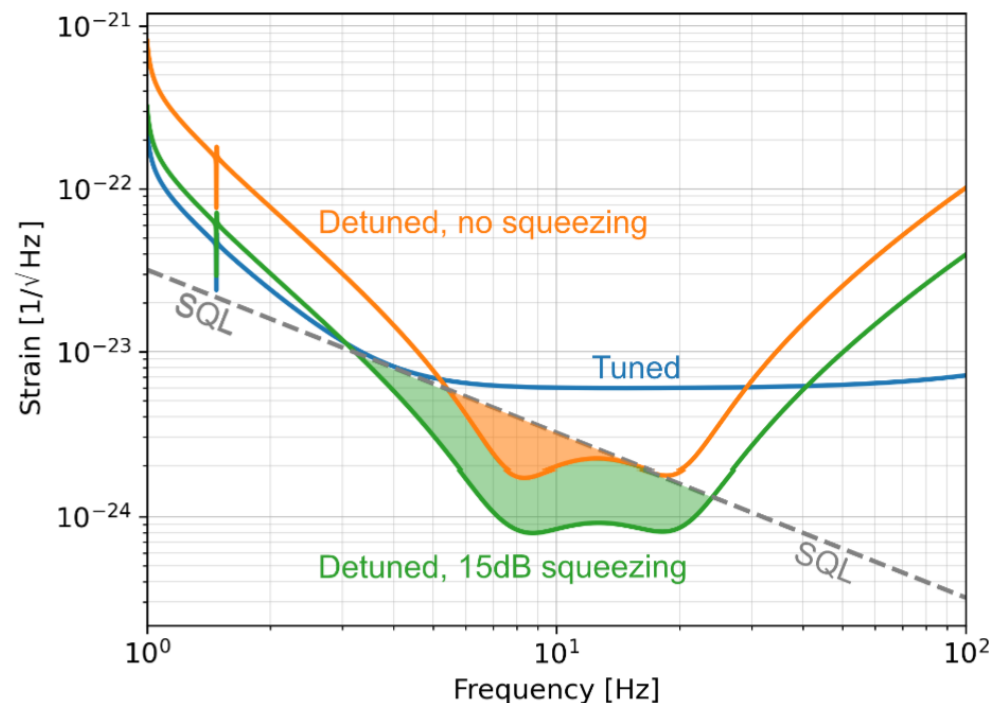
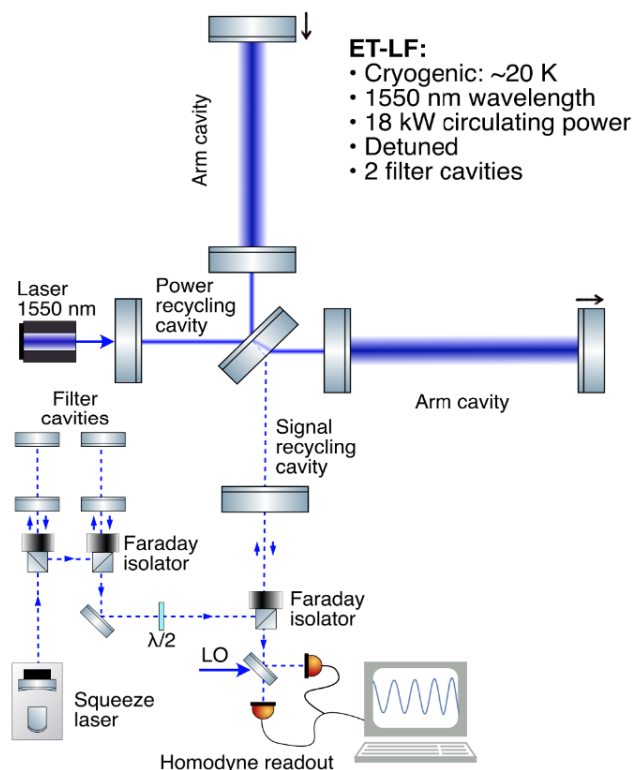
- Challenge: the system becomes **intrinsically unstable**
- **Control** in a large-scale detector **remains an open question**



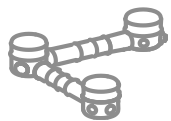
Quantum noise: optical spring

Optical Spring effect

- ET is a **dual-recycled FPMI**, optical spring by **detuning SRC** and has **double dip**

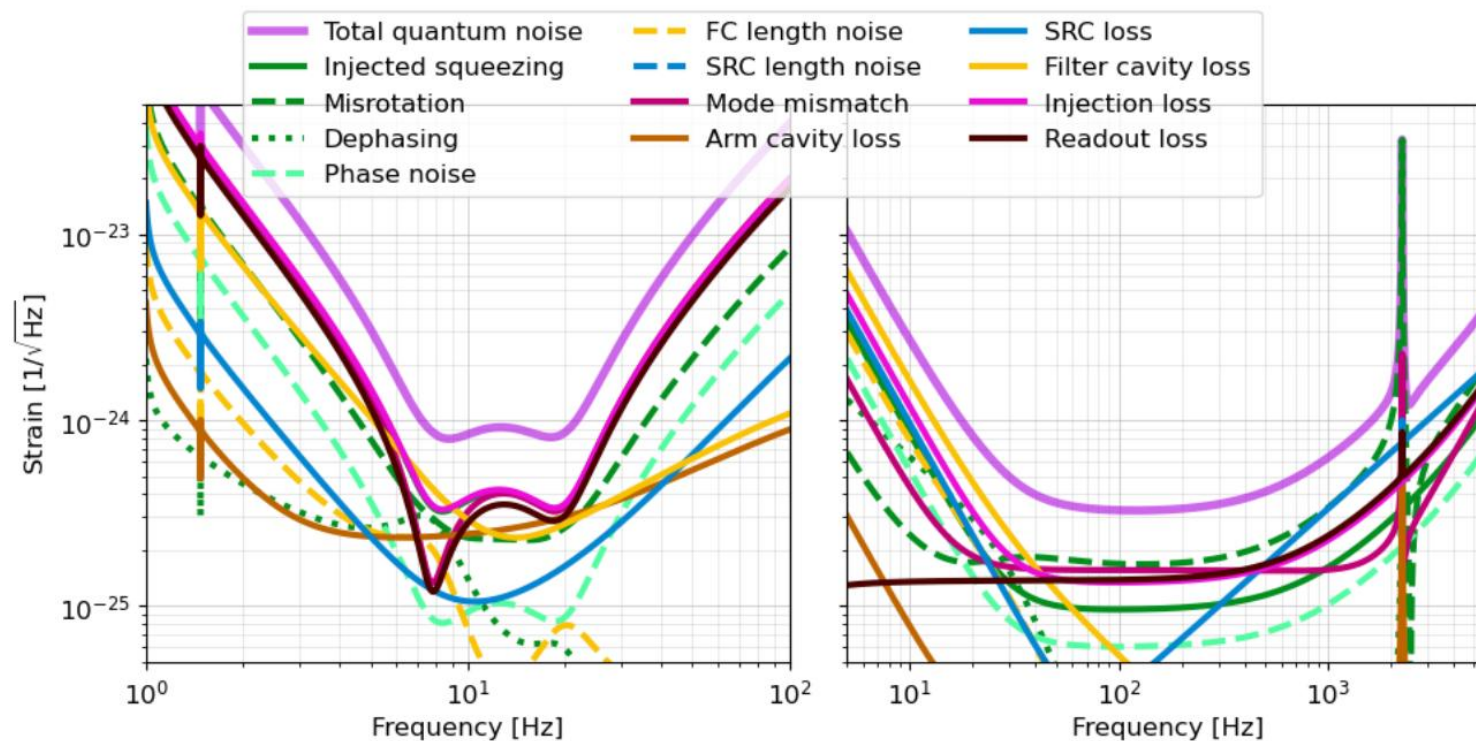


[Korobko Galaxies 2025, 13\(1\), 11](#)

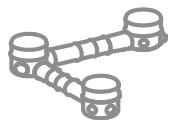


Quantum noise: optical spring vs squeezing

- 2 **extremely long filter cavities (5 km!)** are a big risk for ET-LF
- **FC loss is already dominating** and may be highly optimistic!
- **Pro:** optical spring does not need FC
- **Con:** possible control issues

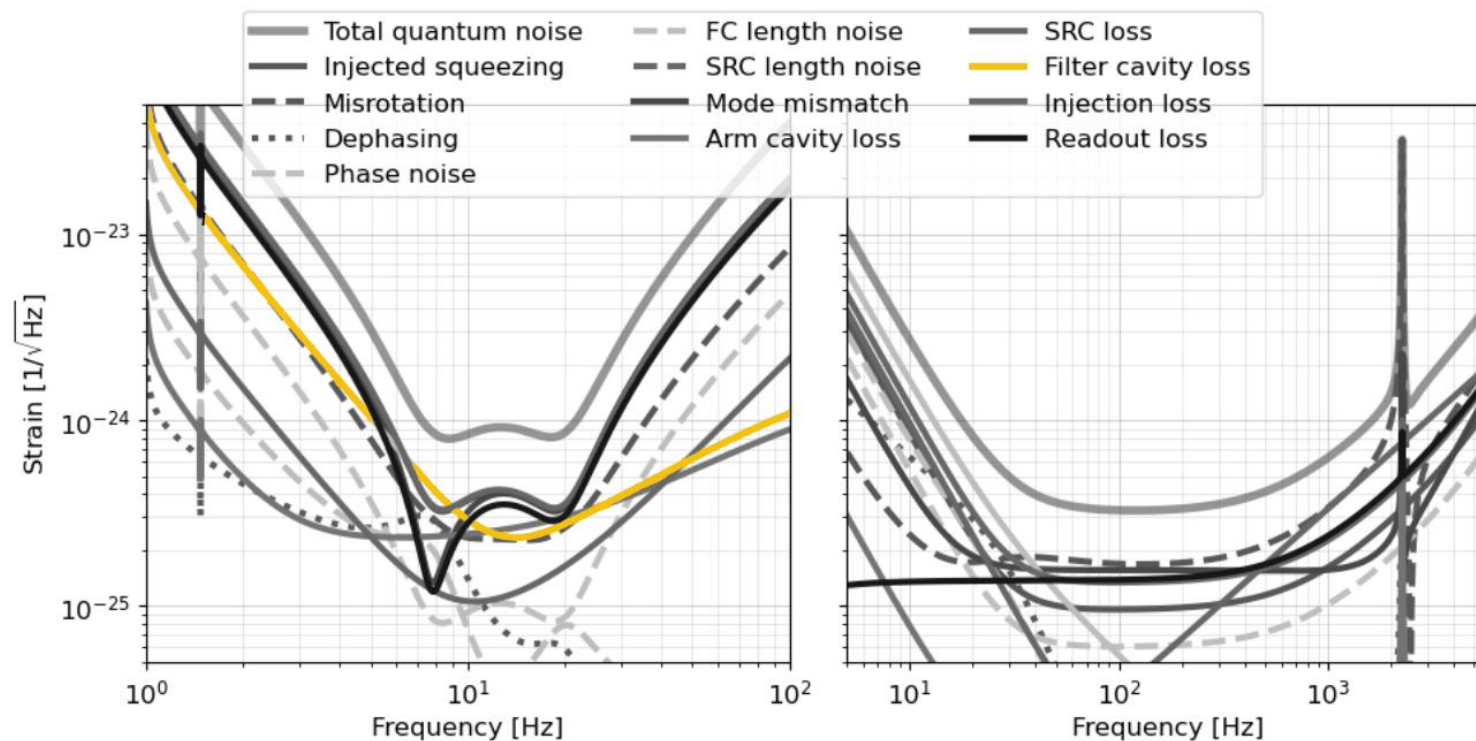


[Korobko Galaxies 2025, 13\(1\), 11](#)

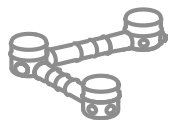


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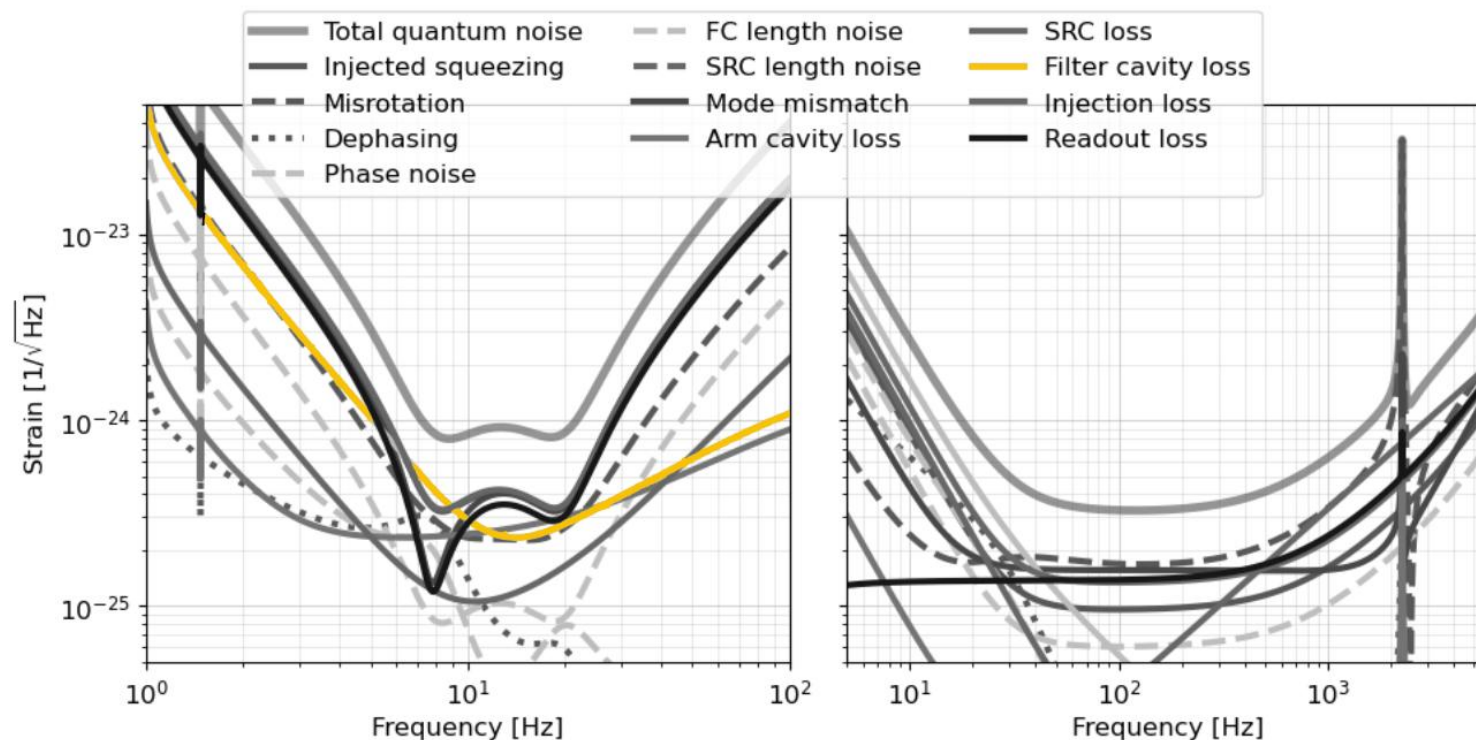


[Korobko Galaxies 2025, 13\(1\), 11](#)



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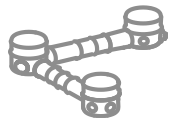
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[Korobko Galaxies 2025, 13\(1\), 11](#)

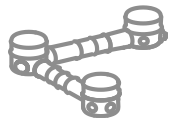
Bonus: optical spring in principle allows **dynamic tuning of sensitivity**

[Aronson et al Opt. Lett. 49 \(24\), 2024](#)



Summary so far

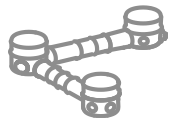
- Where we are today
- Future of GW detection landscape
- Why do we need LF? Sources at low frequencies
- Noise at LF and how to deal with them:
 - Technical noises
 - Quantum noise
- Detector design: can we do it as before?



Designing detectors of the future

- Making a detector such as ET a success is an enormous challenge
- In the past, many of the problems were **tackled individually by separate research groups**
- Perhaps this approach does not work anymore because of **extremely low tolerances for underperformance**
- **What is the solution?**

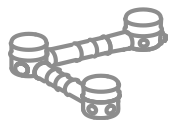
Digital Twin?



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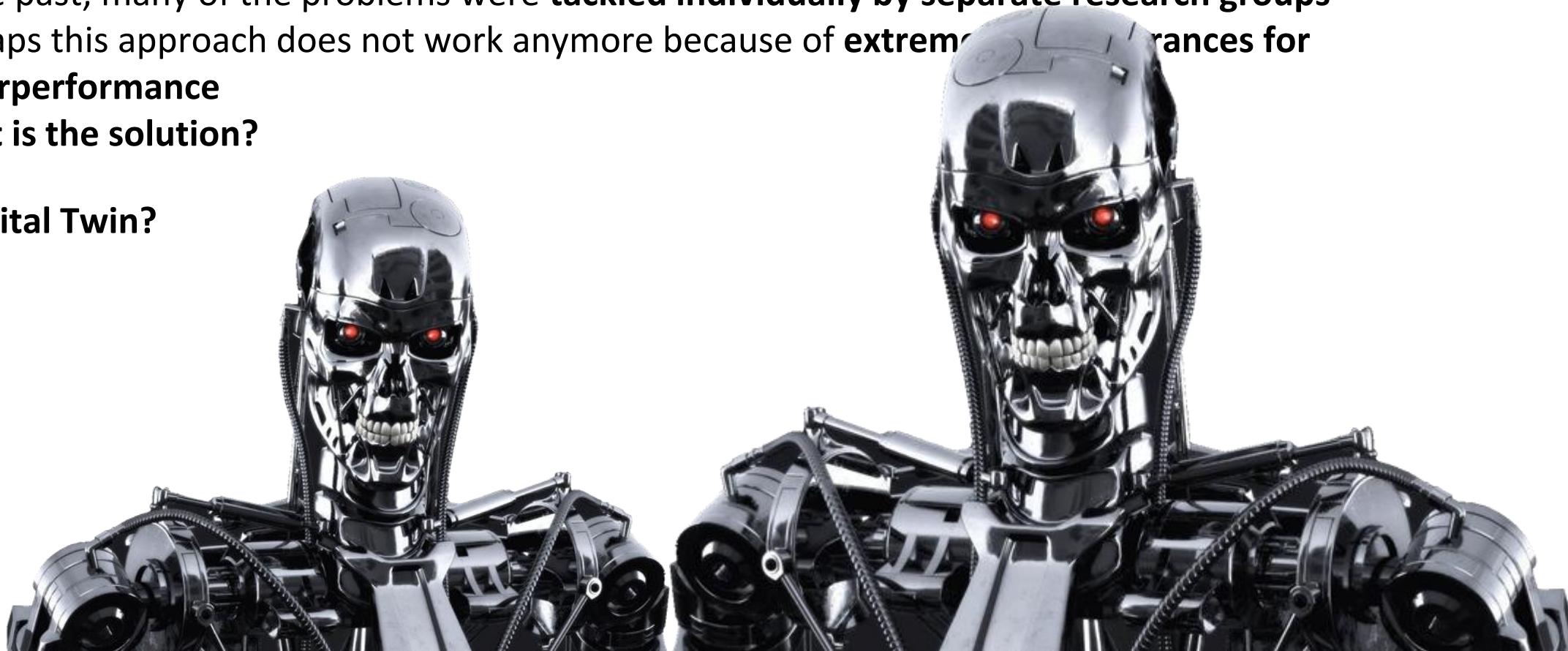
Digital Twin? AI?

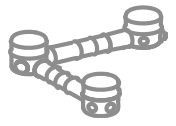


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AI Digital Twin?





Designing detectors of the future

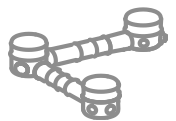
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In my opinion: **we have to set up processes to efficiently work together:**

- **Common formats and standards** for our documents and software tools
- E.g. git **version control, review** and discussion with Issues
- Preferably **public, open-source, documented** software.
- Always leave a **possibility for integration** (common formats!) but **divide responsibility**
- More **interaction between experimentalists and data analysts**
- *Perhaps one day*: full-chain modelling of the detector, from each noise source to DARM

Inspirations:





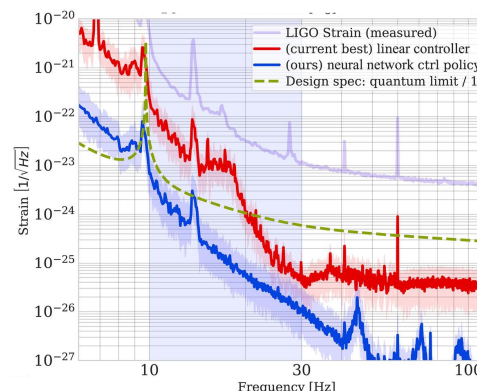
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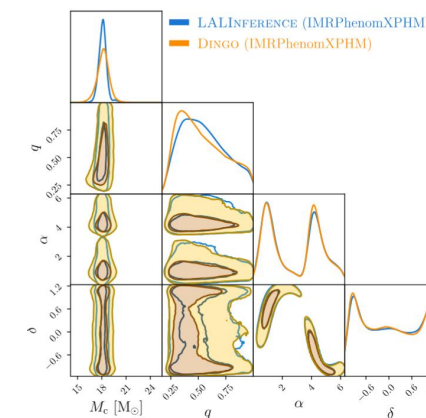
What about AI?

- I'm worried that some of us trust it too blindly. AI is here to help, not to replace us. If we don't anymore understand the process, are we still doing science? *Is it still science?*
- I'm optimistic, but we have to keep it under control.

Inspirations:



[Jonas Buchli et al. Science 389,1012-1015\(2025\)](#)



[Dax et al, Phys. Rev. Lett. 130, 171403](#)

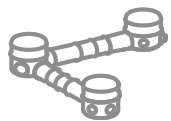


The future is bright. And LOUD!

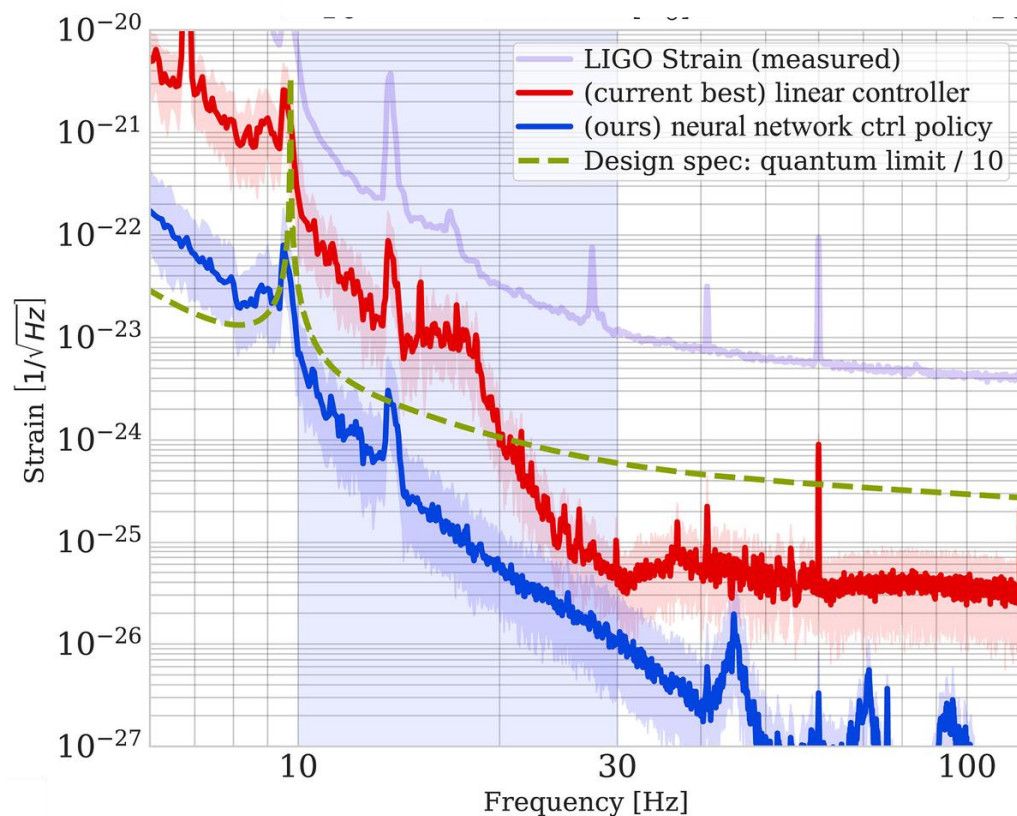


The future is bright. And LOUD!

Merci de votre attention!



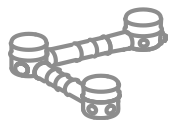
AI success stories (I)



[Jonas Buchli et al. Science 389,1012-1015\(2025\)](#)

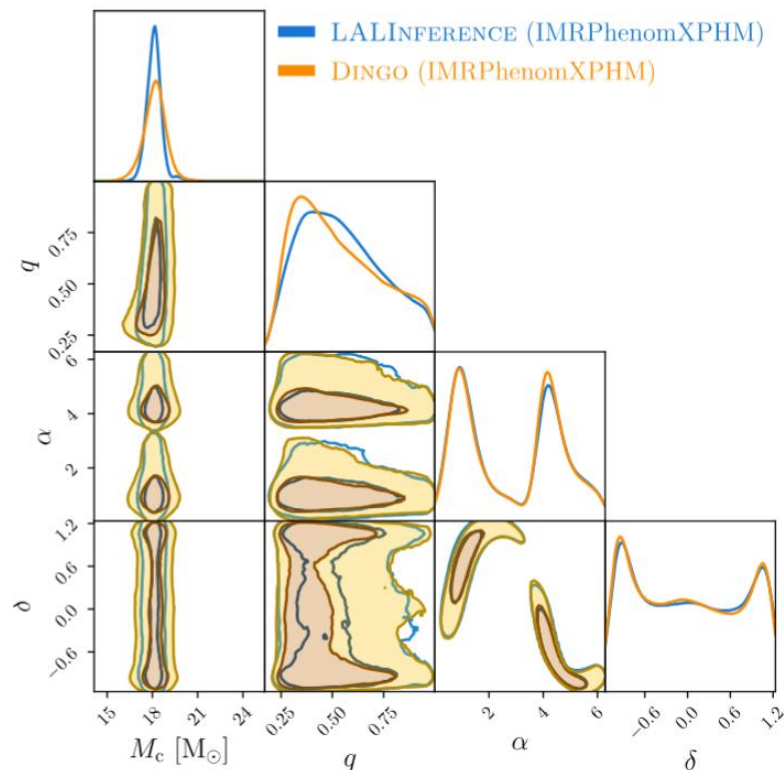
- AI controller deployed at LLO
- Can't prove stability analytically
- But **very extensive** testing on simulation
- And a proof in real world – **it works!**

In engineering tasks, AI enhances what we do if we can easily test the outcome, and be sure it is reliable, even if how we don't fully "understand" how it gets there



AI success stories (II)

Neural Importance Sampling for Rapid and Reliable Gravitational-Wave Inference



- generate a rapid proposal for the Bayesian posterior using neural networks
- attach importance weights based on the underlying likelihood and prior

AI is only used to increase sampling efficiency, but does not affect accuracy of the inference! Where we can't easily check AI output (inference itself) we don't trust it

[Dax et al, Phys. Rev. Lett. **130**, 171403](#)