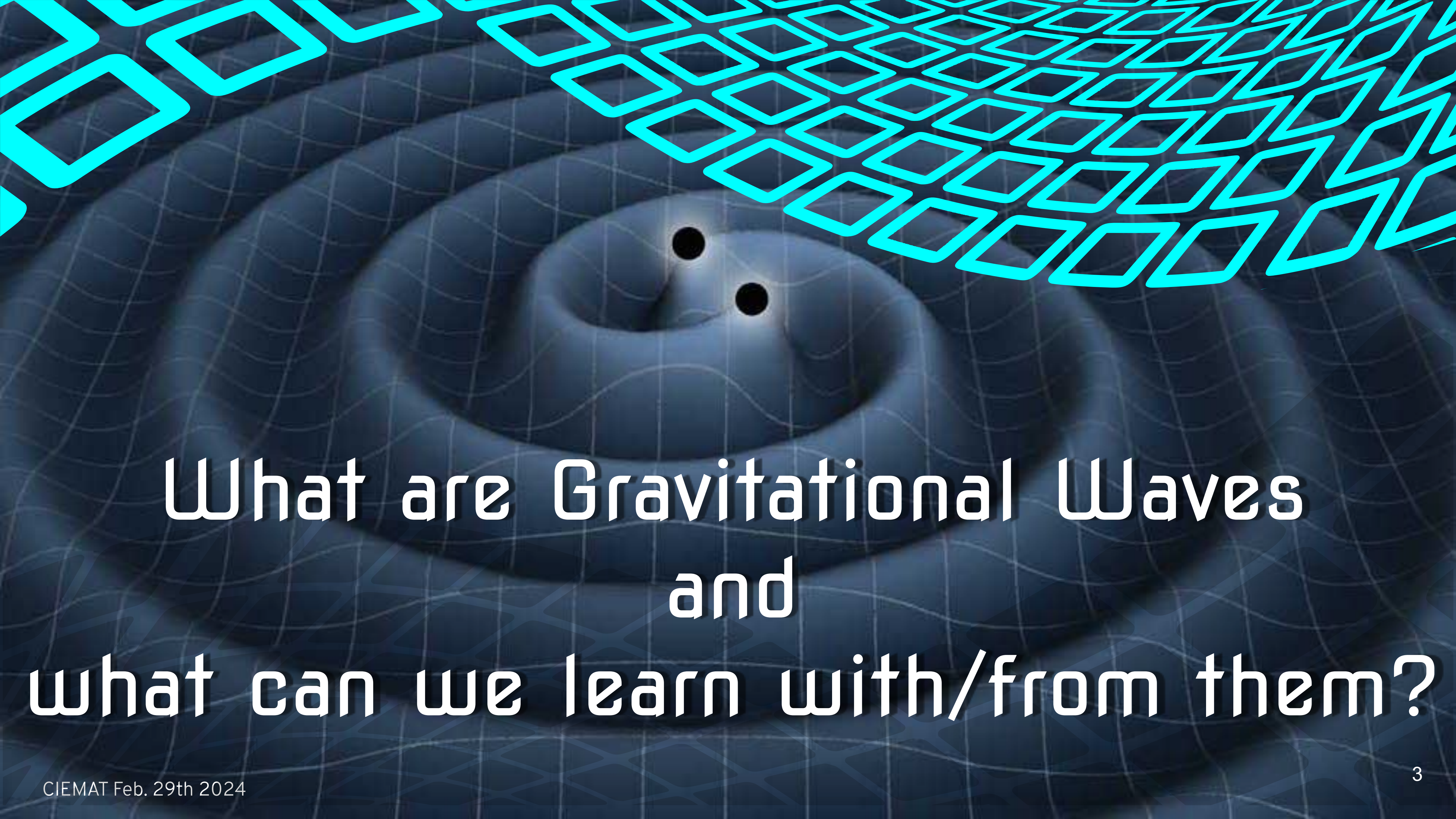
Gravitational Waves At CIEMAT

CIEMAT Feb. 29th 2024

Outline

- What are GW and what can we learn with/from them?
- How are they detected.
- CIEMAT Group and goals.
- Activities in Virgo.
- The future: E.T



What are Gravitational Waves
and
what can we learn with/from them?

What's a gravitational wave

Traveling linear perturbations in the metric due to the acceleration of a mass distribution with a non-vanishing quadrupole or higher order moment.

Einstein equations

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Weak field

$$g_{\mu\nu} = \delta_{\mu\nu} + h_{\mu\nu} + O(G^2)$$

And copy from electromagnetism

Simplest case

Point like, equal masses

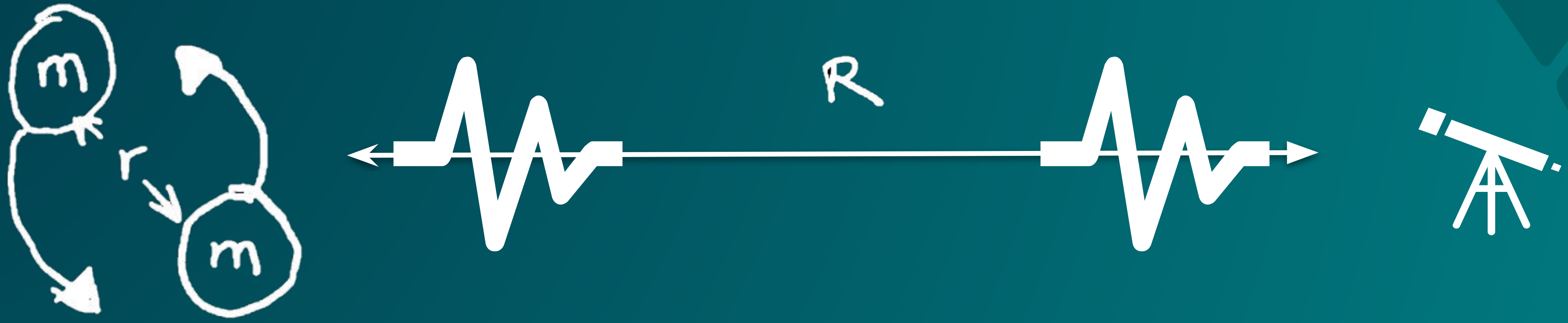
Newtonian stable orbit

Frequency of the orbit

$$\omega \sim \frac{m^{1/2}}{r^{3/2}}$$

Key messages

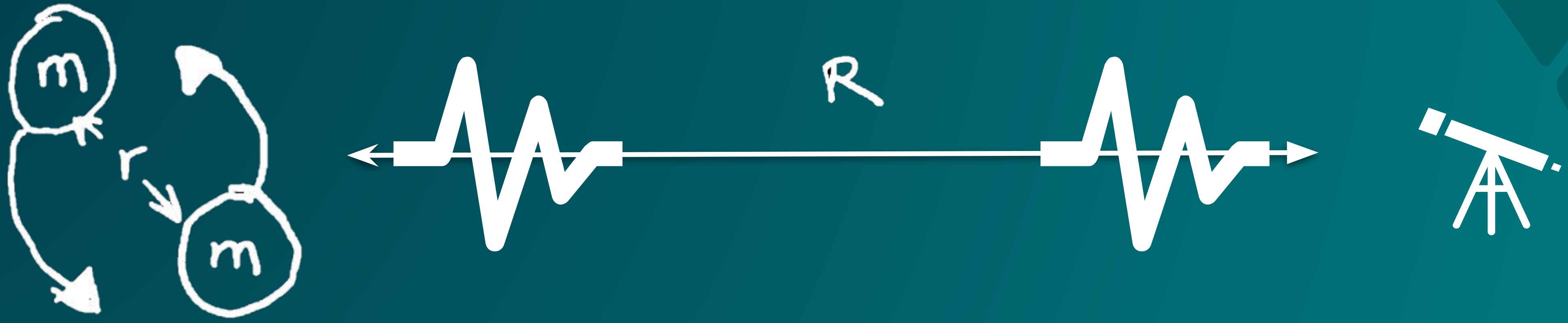
(remember… copy from elecromagnetism)



$$h_{\mu\nu} \sim \frac{\omega^2 m r^2}{R}$$

Key messages

(remember… copy from elecromagnetism)



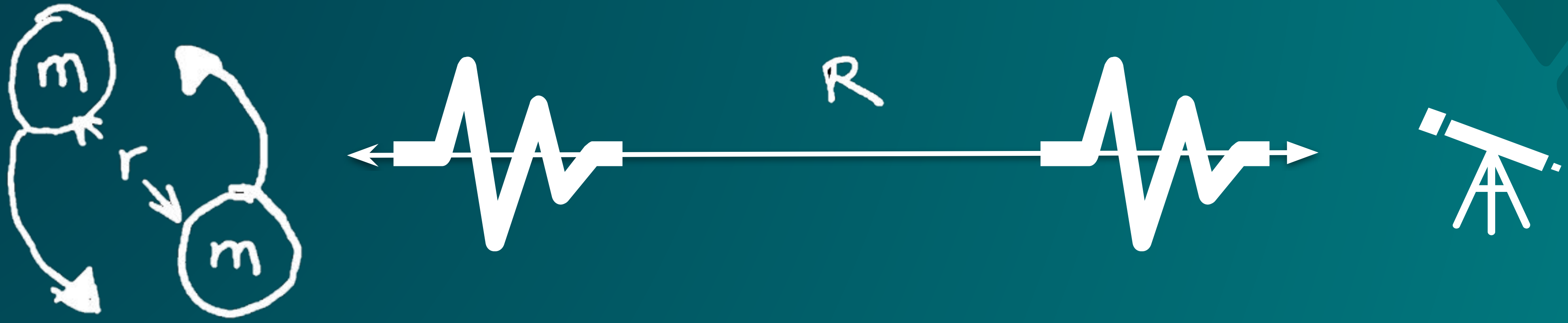
$$h_{\mu\nu} \sim \frac{\omega^2 m r^2}{R}$$

Quadrupole instead dipole

(source is 2-tensor instead of vector)

Key messages

(remember… copy from elecromagnetism)



$$h_{\mu\nu} \sim \frac{\omega^2 m r^2}{R}$$

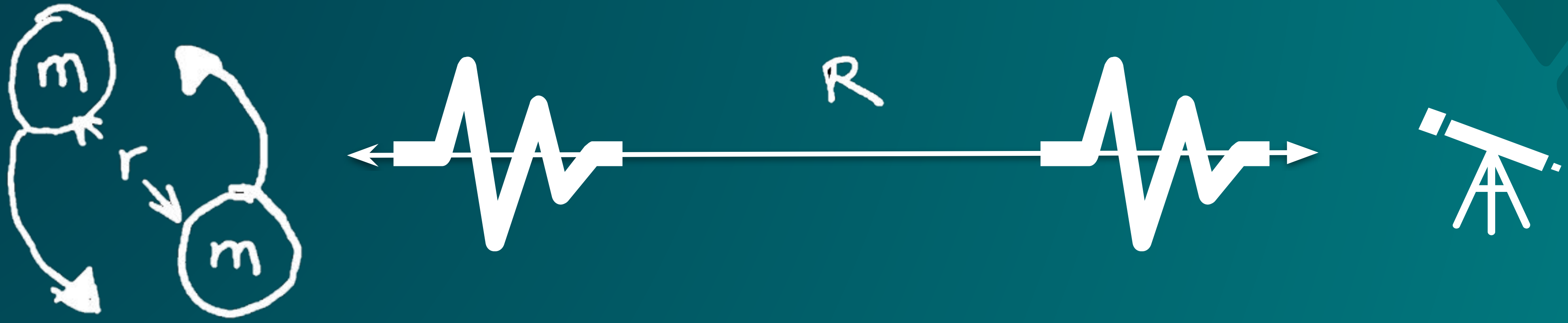
$$\omega \sim \frac{m^{1/2}}{r^{3/2}}$$

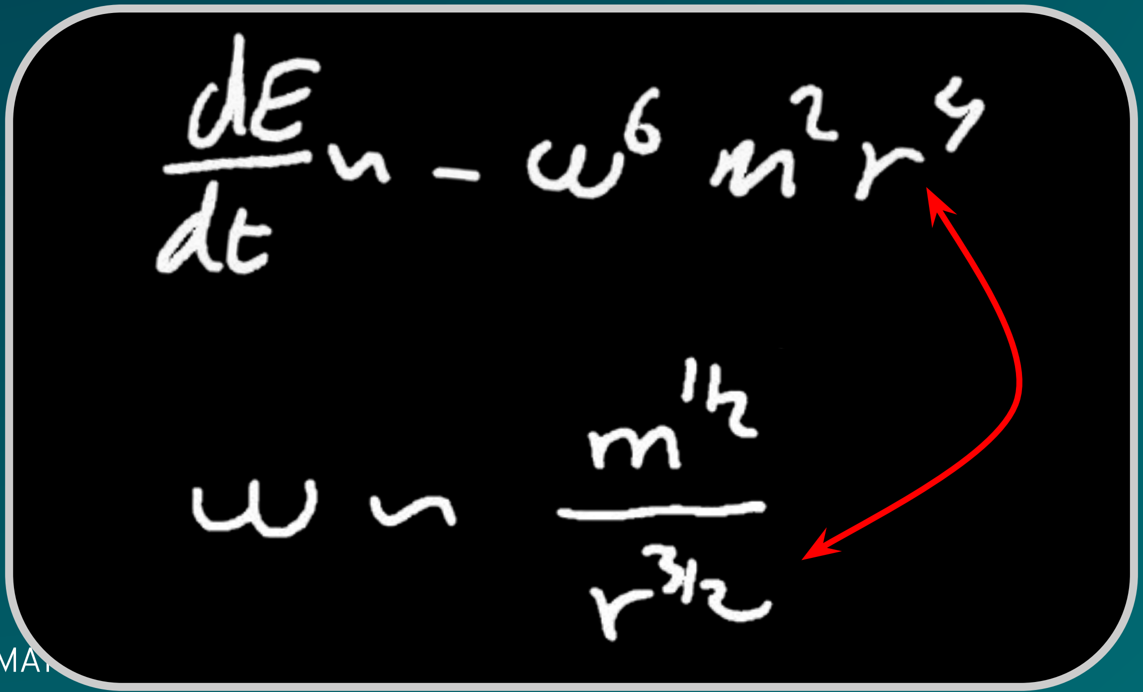
Amplitude only depends on
- Mass
- Frequency (observable)
- Distance

… for a single mode

Key messages

(remember… copy from elecromagnetism)





$$\frac{dE}{dt} \sim -\omega^6 m^2 r^4$$

$$\omega \sim \frac{m^{1/2}}{r^{3/2}}$$

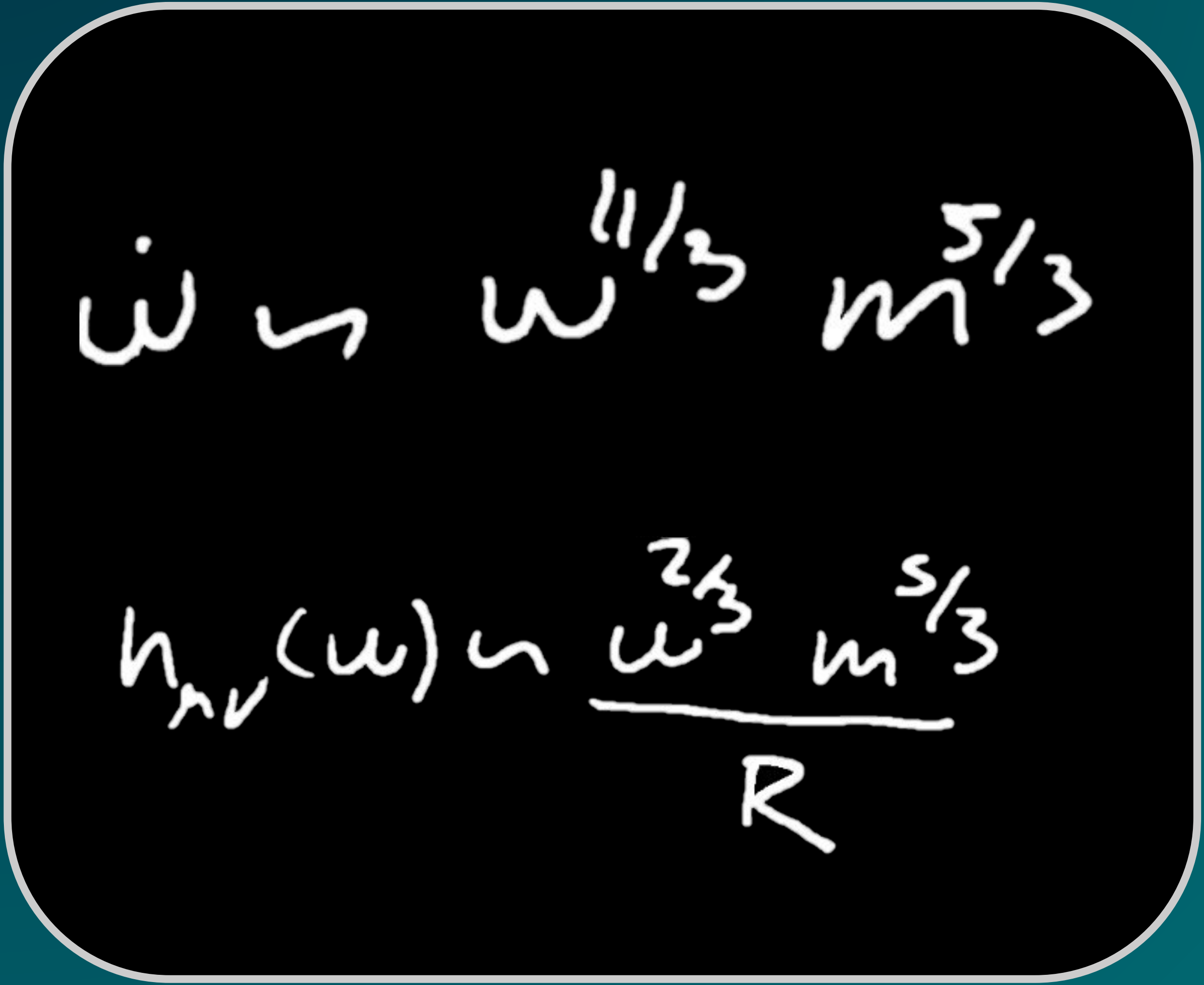
Emitted energy only depends on

- Mass
- Frequency (observable)

… and modifies the distance (so the frequency)

Key messages

(remember… copy from elecromagnetism)



$$\dot{\omega} \sim \omega^{11/3} m^{5/3}$$

$$h_{\mu\nu}(\omega) \sim \frac{\omega^{2/3} m^{5/3}}{R}$$

Measure the GW frequency and its variation with time to get the mass

Use mass and frequency to get the distance from the amplitude of the GW

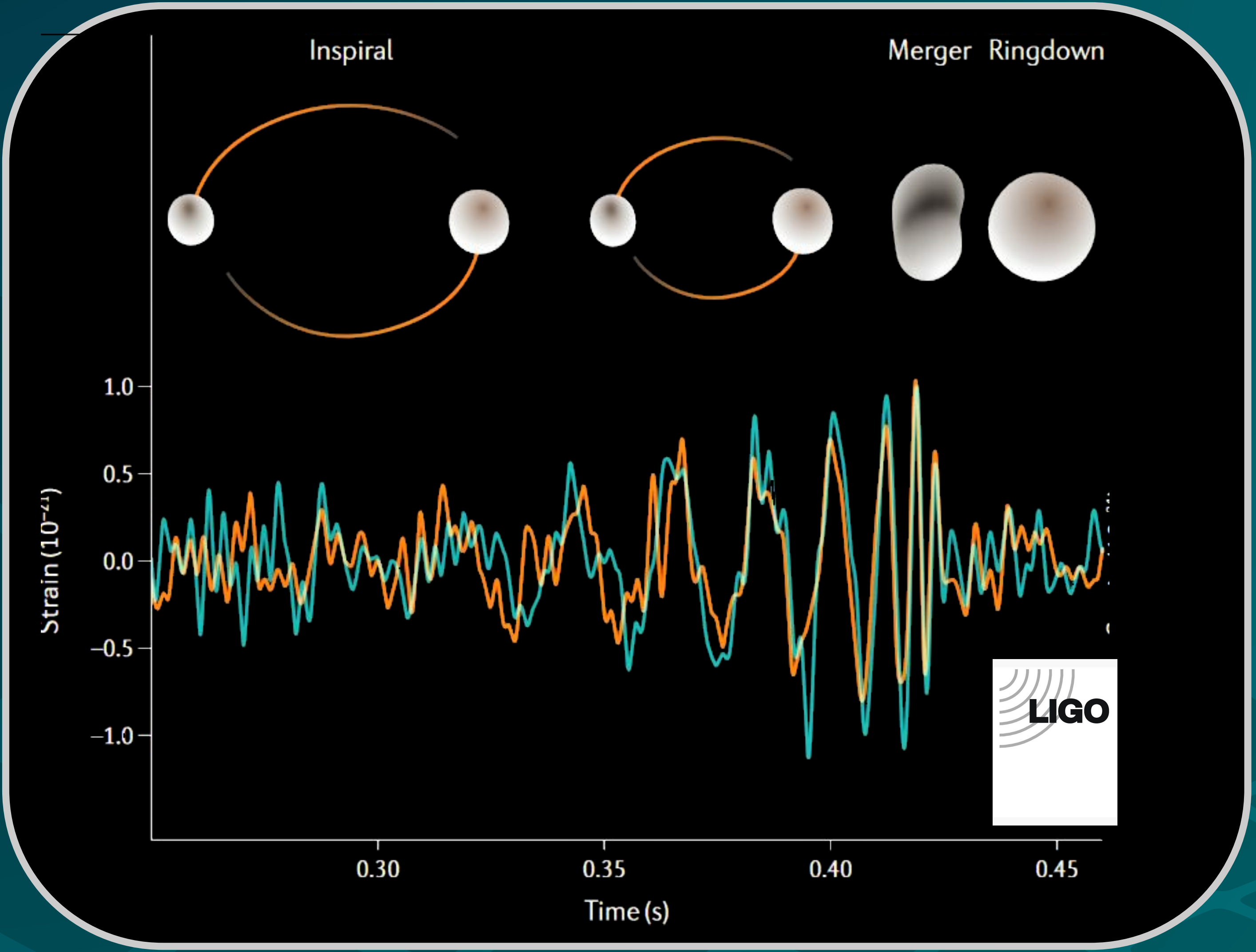
Some words of caution

Life is much more complicated:

- These relationships break down when the speed of the bodies get close to **c**
  - This happens when the distance is of the order of the Schwarzschild radius
- Spin of the bodies plays a role: there are more than a single mode in reality
- For different body masses, things get a bit more complicated (but not too much)
- The emission is not isotropic, so the measured amplitude depends on where it is observed w.r.t. the orientation of the orbit.

… and this are just the most obvious oversimplifications.

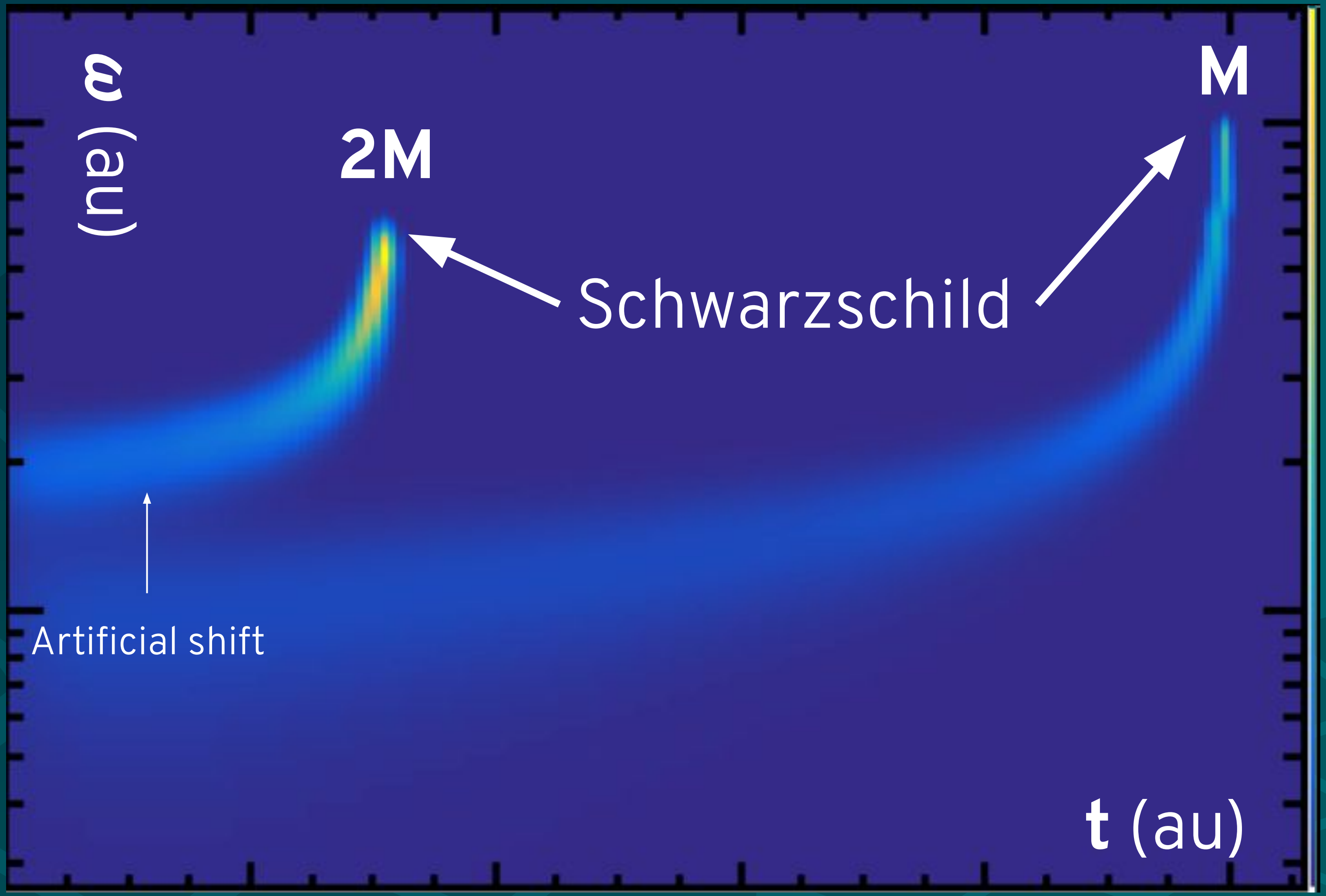
An academic example of event



With >1 detector time delay estimates direction.

... but is is (again) more complicated

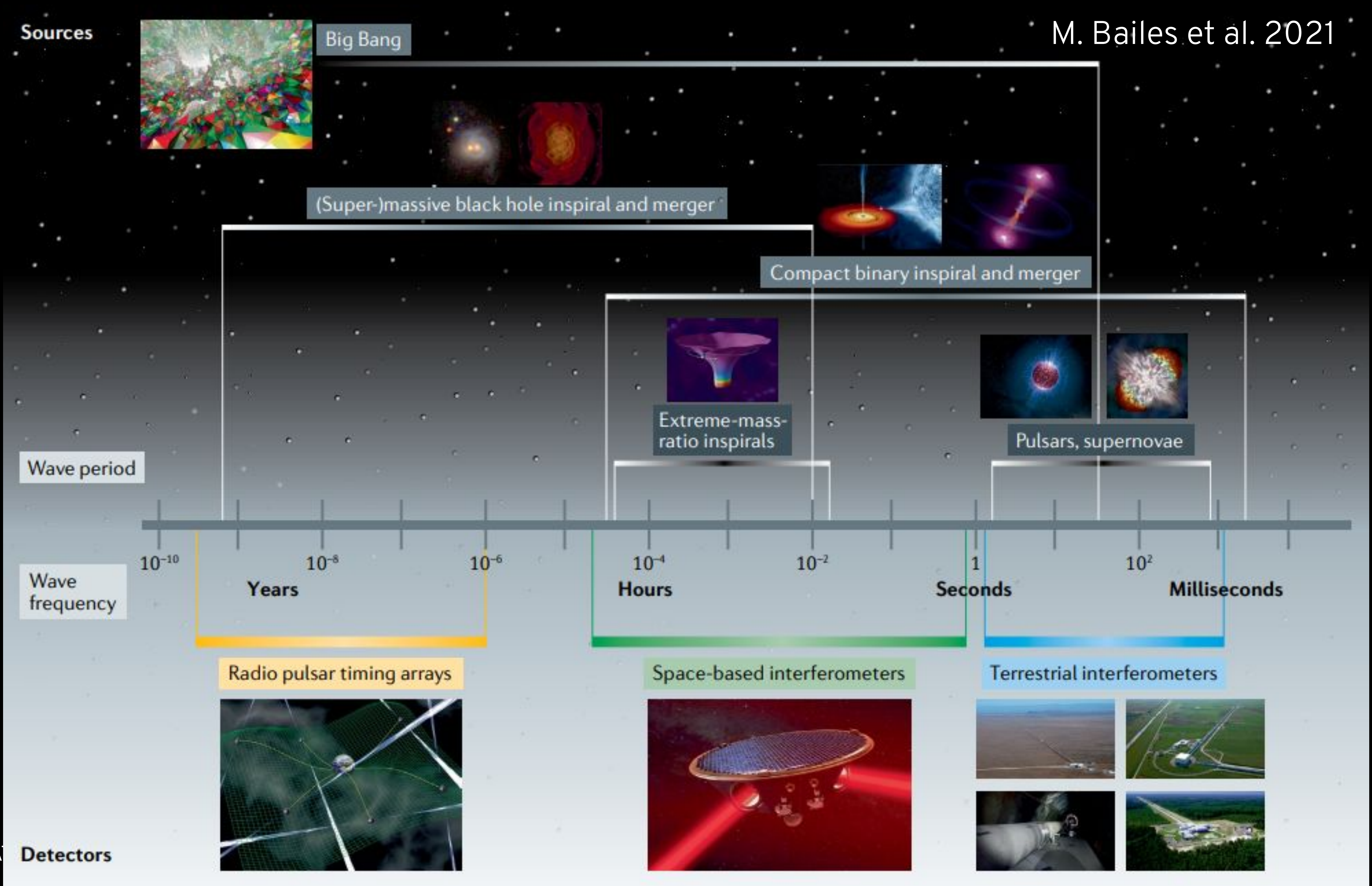
An academic example of event



Usually the analysis makes uses of the Q-transform of the signal.

Fancy name for freq vs time vs amplitude

M. Bailes et al. 2021



Physics topics

What is the physics of stellar core collapse? How often do core-collapse supernovae occur?

What is the equation of state, and what are the radii, of neutron stars?

What are the multi-messenger emission mechanisms of high-energy transients (gamma-ray bursts and kilonovae)?

How do binary black holes of tens of solar masses form and evolve?

How did super-massive black holes at the cores of galactic nuclei form and evolve and what were their seeds and demographics?

Are black hole spacetimes as predicted by general relativity?

Physics topics

Are there any signatures of horizon structure or other manifestations of quantum gravity accessible to gravitational-wave observations?

Is dark matter composed, in part, of primordial black holes, or must it be composed solely from exotic matter such as axions or dark fermions?

What is the expansion rate of the Universe?

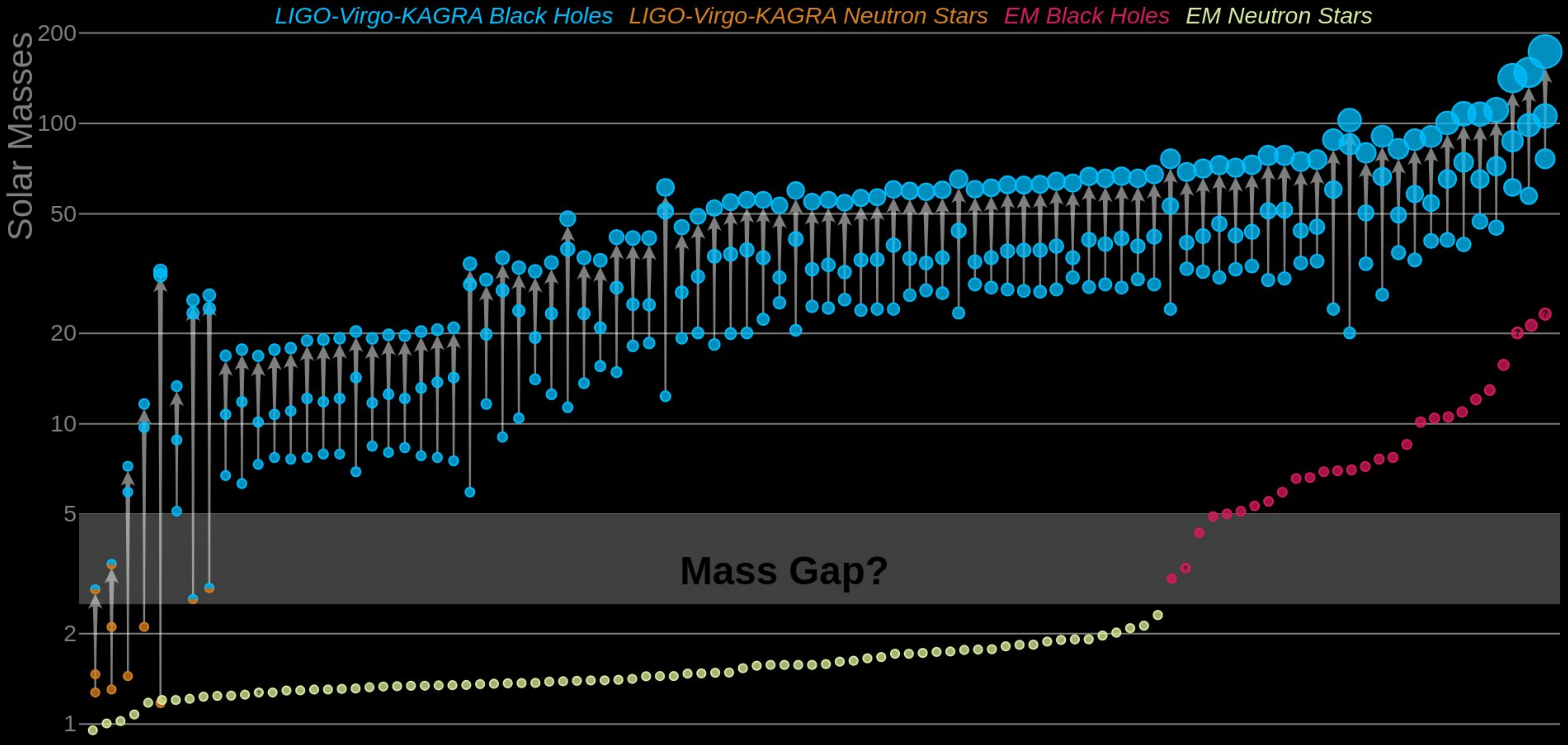
What is the nature of dark energy?

Is there a measurable gravitational-wave stochastic background due to phase transitions in the early Universe?

How does gravity behave in the strong/highly dynamical regime?

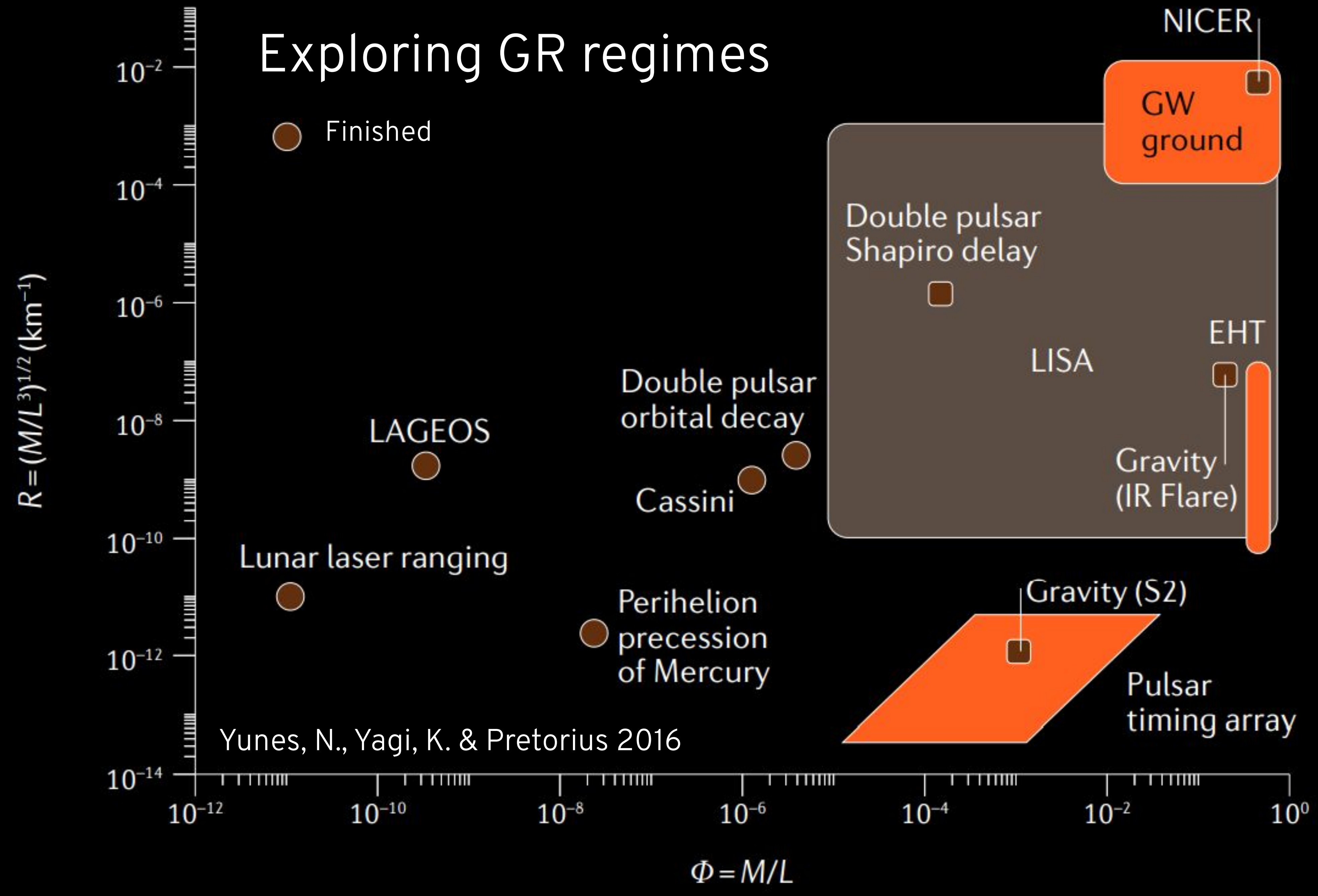
Are black holes, neutron stars and white dwarfs the only compact objects in our Universe, or are there even more exotic objects?

Masses in the Stellar Graveyard

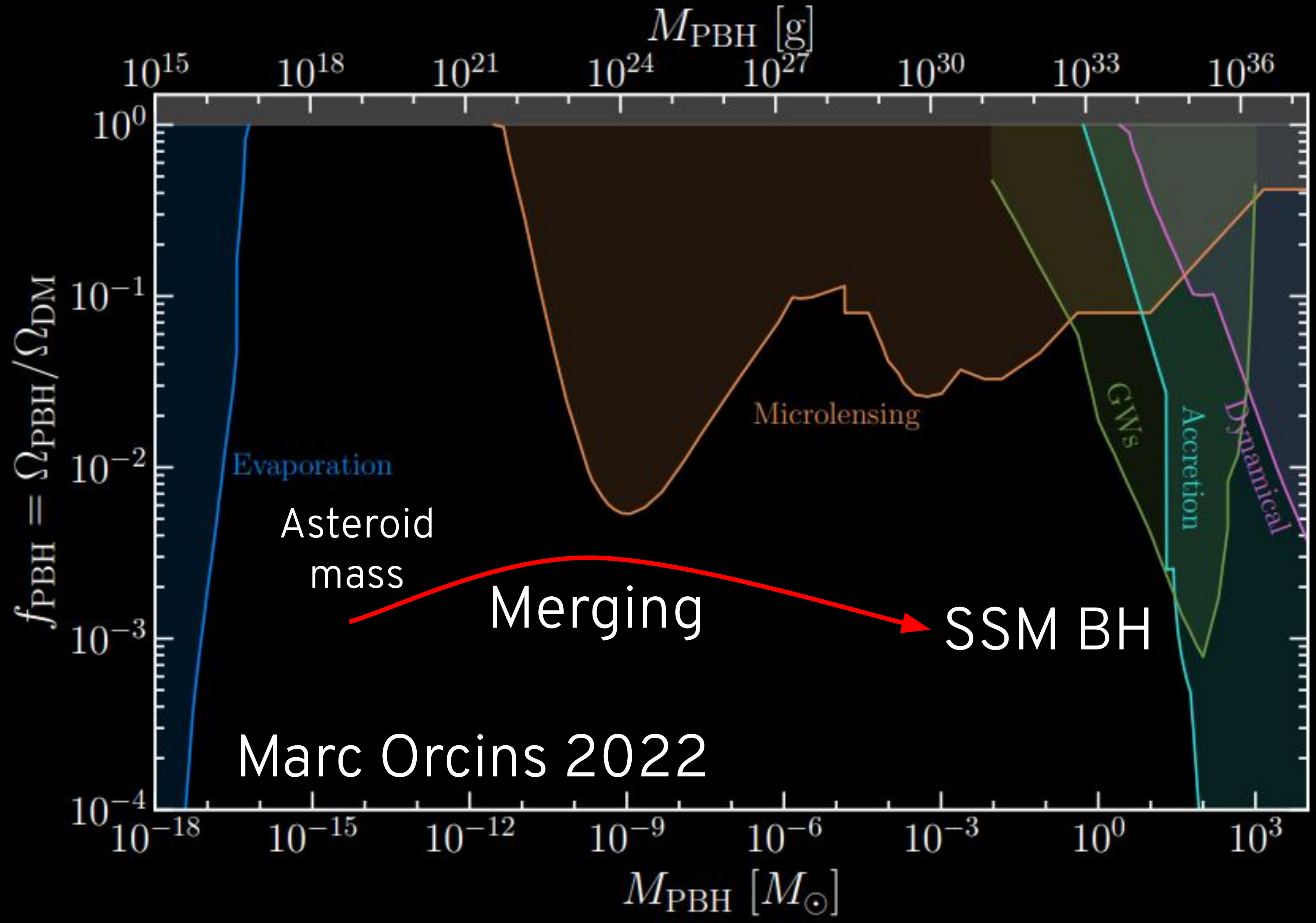


LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Exploring GR regimes



Yunes, N., Yagi, K. & Pretorius 2016



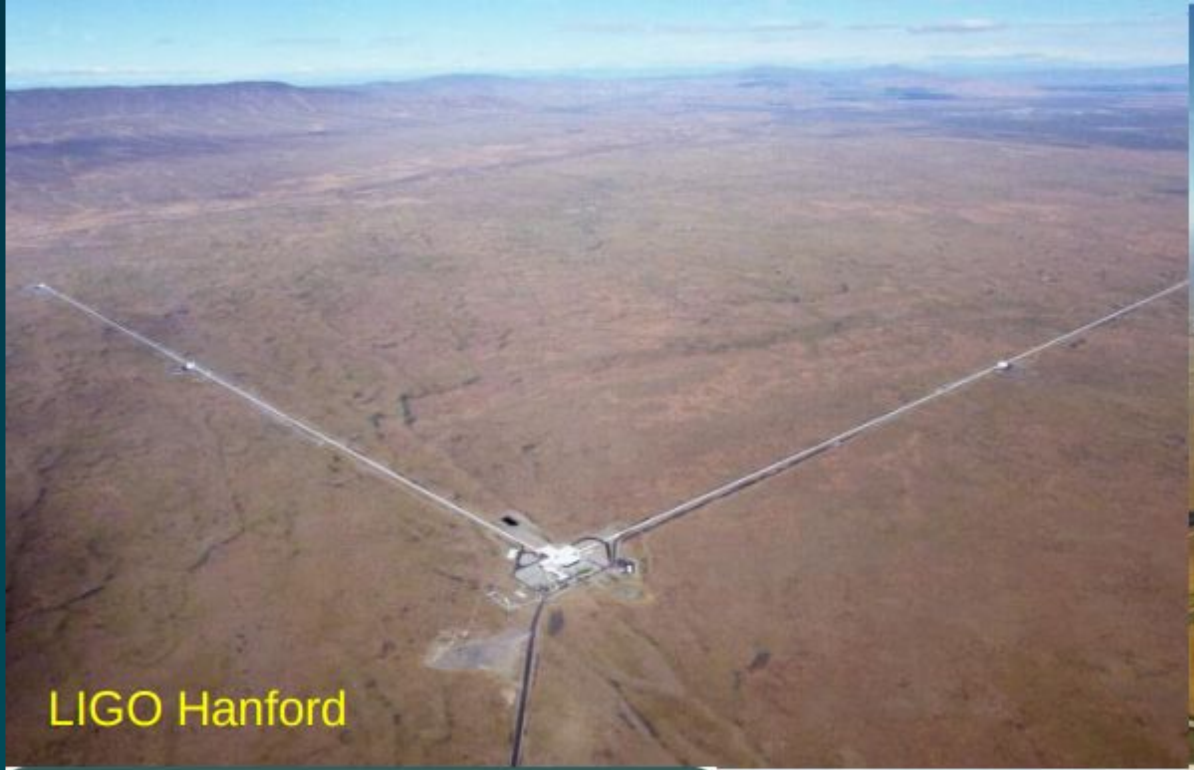
Asteroid
mass

Merging

SSM BH

Marc Orcins 2022

How are GW detected in Advanced Interferometers?


LIGO Hanford


VIRGO

KAGRA


LIGO Livingston

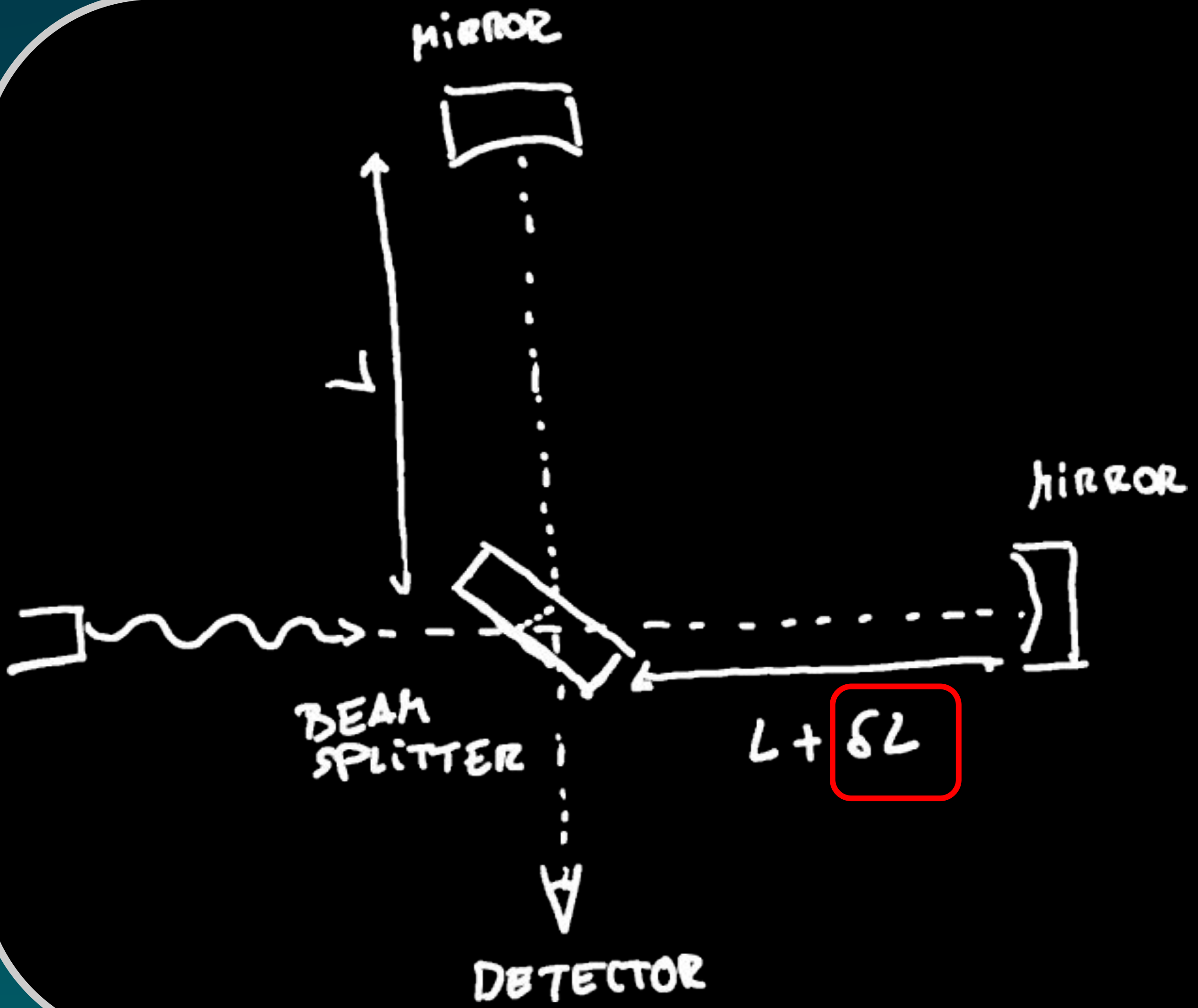
GEO600

What's the magnitude of the problem?

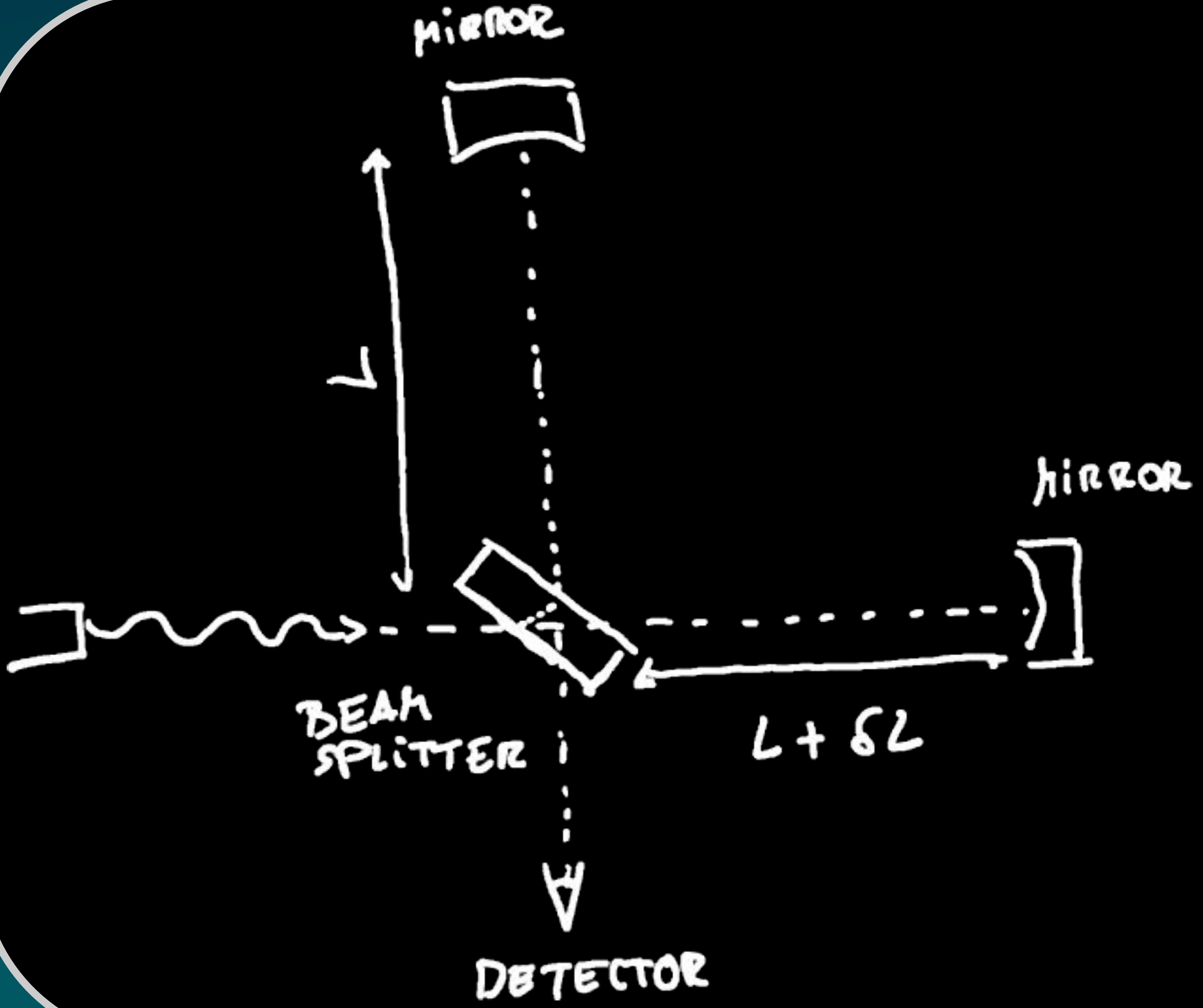
Measure changes in the length between two points:

$$\underbrace{\frac{\Delta L}{L}}_{\text{Best precision reached with interferometers}} \simeq h \simeq \frac{G}{c^4}\,\frac{Mv^2}{R} \simeq 10^{-22}\underbrace{\left(\frac{M}{M_\odot}w\right)^{4/3}\left(\frac{r_{pc}}{R}\right)}_{\text{These can only add few zeroes}}$$

Measuring with an interferometer



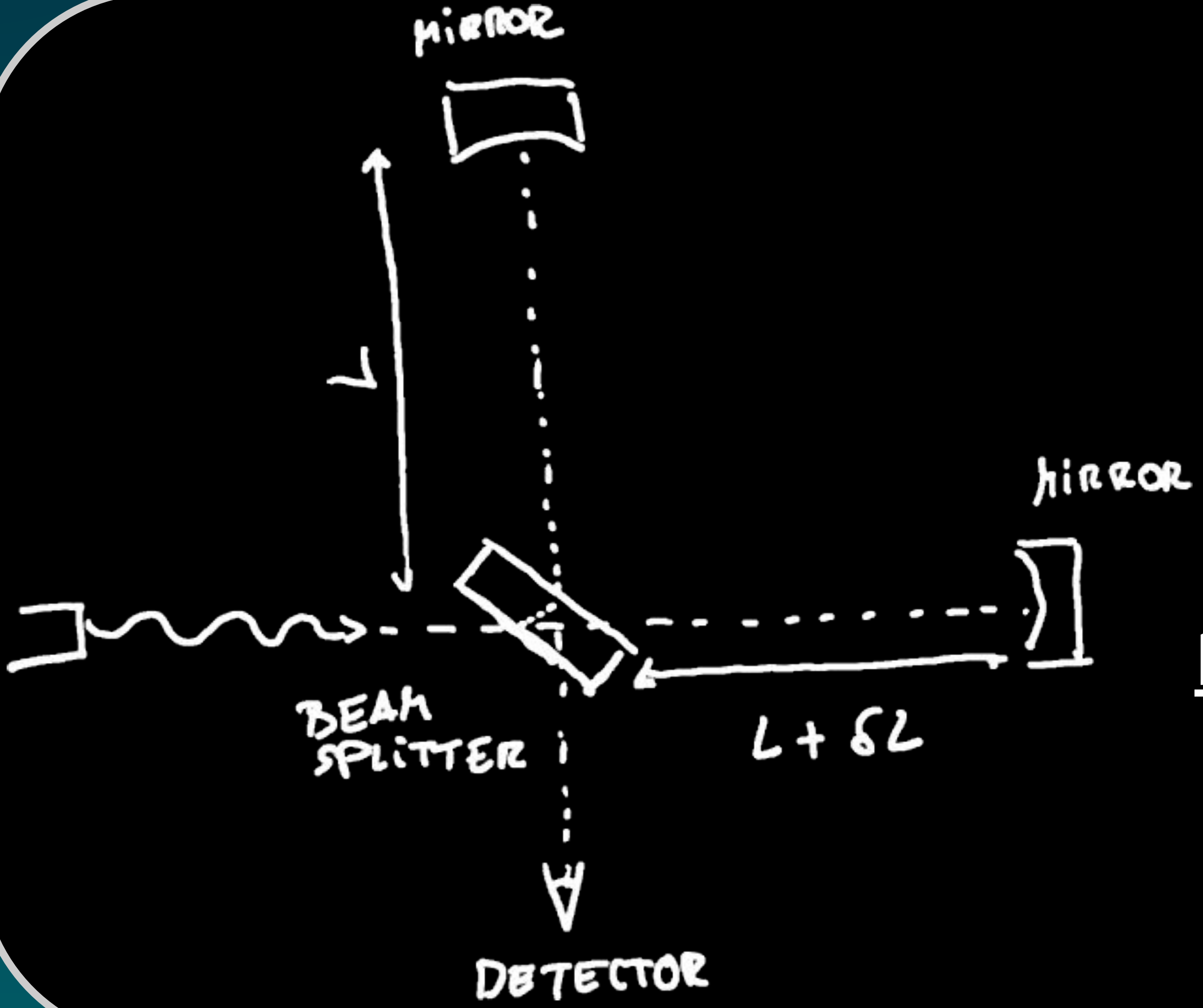
Measuring with an interferometer



$$P_{det.} \sim P_{laser}\left(\phi(L) - \phi(L+\delta L) + k\right)$$

Linear relation
with phases

Measuring with an interferometer



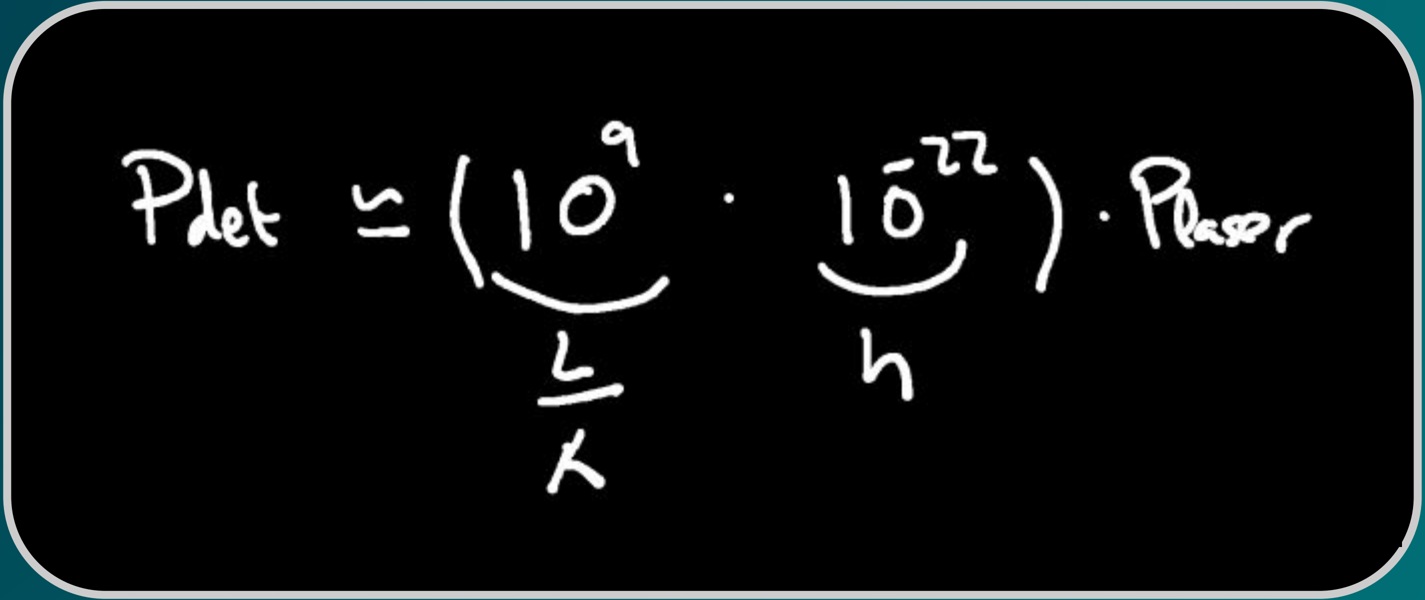
$$P_{det.} \sim P_{laser}\left(\phi(L) - \phi(L+\delta L) + k\right)$$

$$\phi(L+\delta L) - \phi(L) \sim \frac{4\pi}{\lambda}\frac{L}{2}h$$

h (strain) signal is amplified by

$$\frac{L}{\lambda} \sim \frac{10^{3}}{10^{-6}}$$

Measuring with an interferometer



$$P_{det} \simeq \left(\underbrace{10^{9}}_{\frac{L}{\lambda}} \cdot \underbrace{10^{-22}}_{h}\right) \cdot P_{laser}$$

Requires a extremely stable and powerful laser:

- Relative error due to Poisson fluctuations has to be smaller 10^{-13}
- For 100Hz sampling window this goes to the 10MW scale
    - Most powerful continuous laser are at the 10kW scale, so no way.

How to solve the problem?

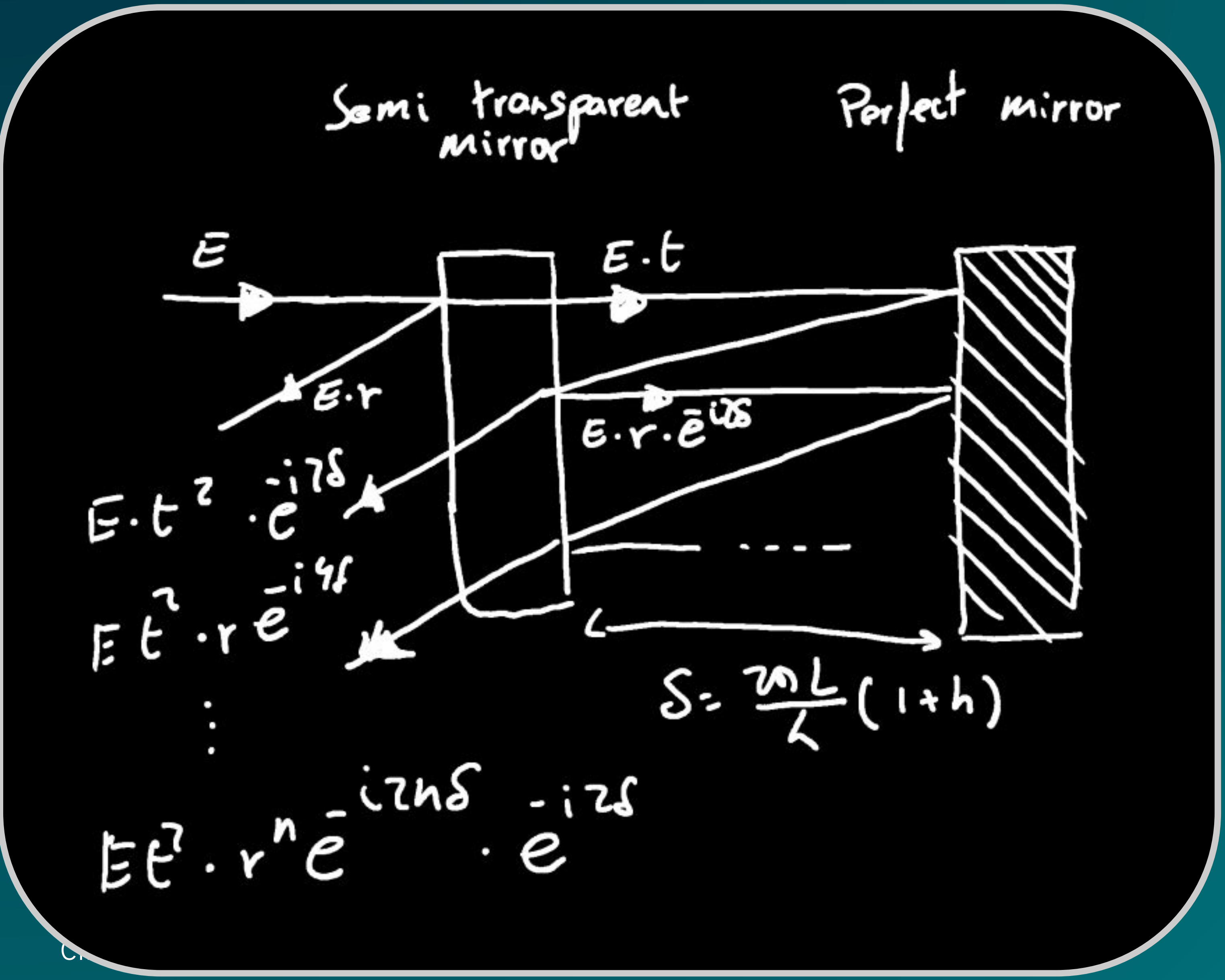
$$\frac{L}{\lambda} \sim \frac{10^{3}}{10^{-6}}$$

Increase L as much as possible:

- By keeping the photons as long as possible in the interferometer arms.

Introducing optical cavities!

Optical cavities



Trap the laser between mirrors.

Expectations:

The phase is multiplied by the number of reflections.

The amplification increases in the same way.

Optical cavities

$$E_{out} = E\cdot r + E t^2 e^{-2i\delta} \sum_{n=0}^{\infty} r^n e^{-2i\delta n}$$

$$\frac{E_{out}}{E_{in}} = e^{-i2\delta\frac{1+r}{1-r}}$$

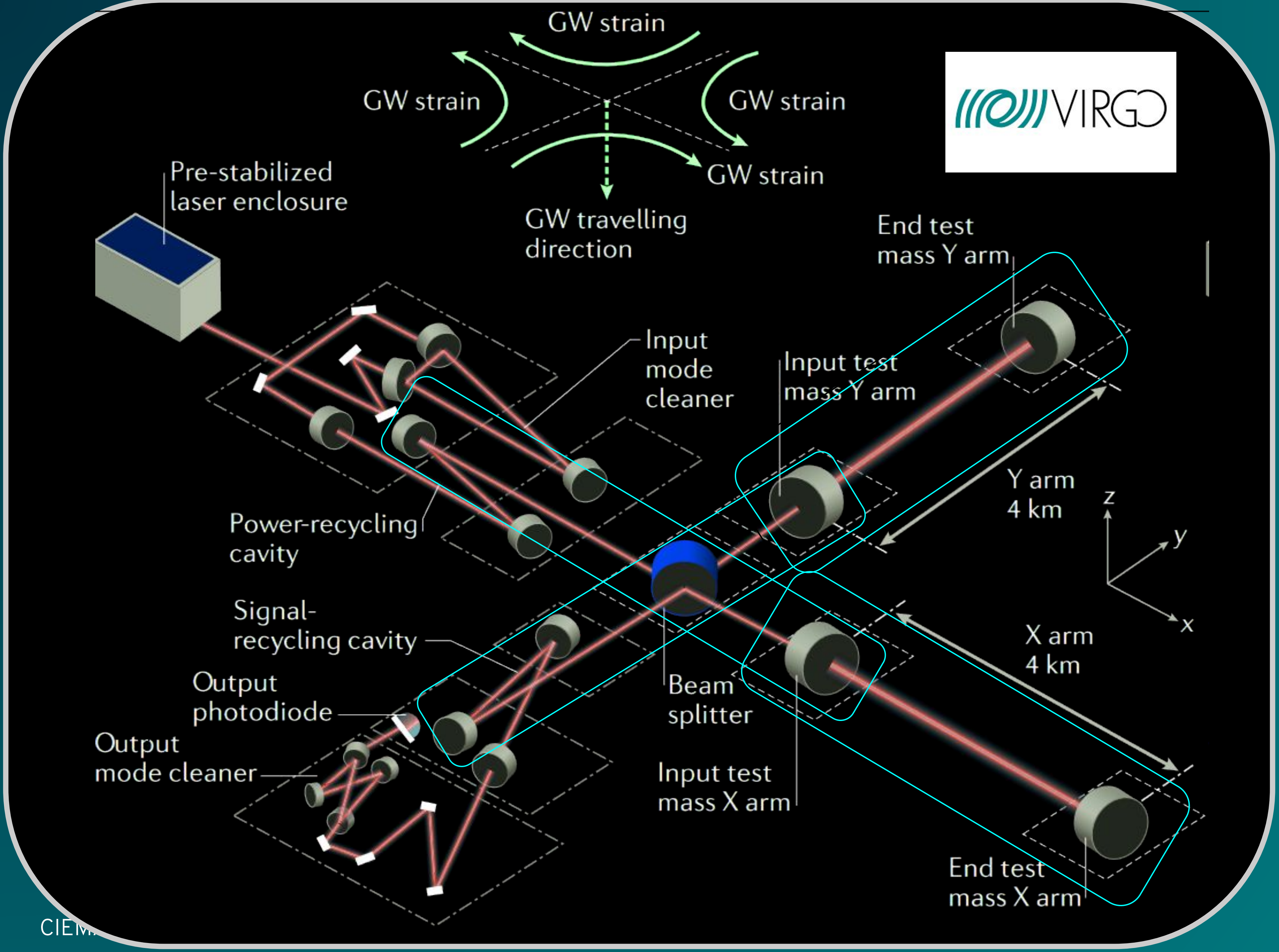
FOR

$$2\delta = \frac{4\pi L}{\lambda} + \frac{2\pi L h}{\lambda} \simeq 2k\pi$$

For r~1 there is a huge enhancement.

This trick can be used in several places in the interferometer.

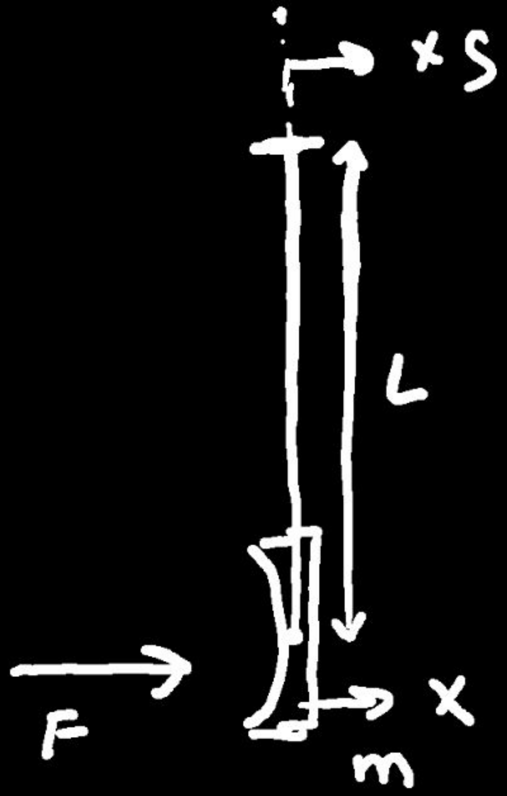
And it can be used to suppress unwanted modes of the laser.



Effective arm length increased ~1000 folds

So a laser of ~10 W Is OK!

Noise sources

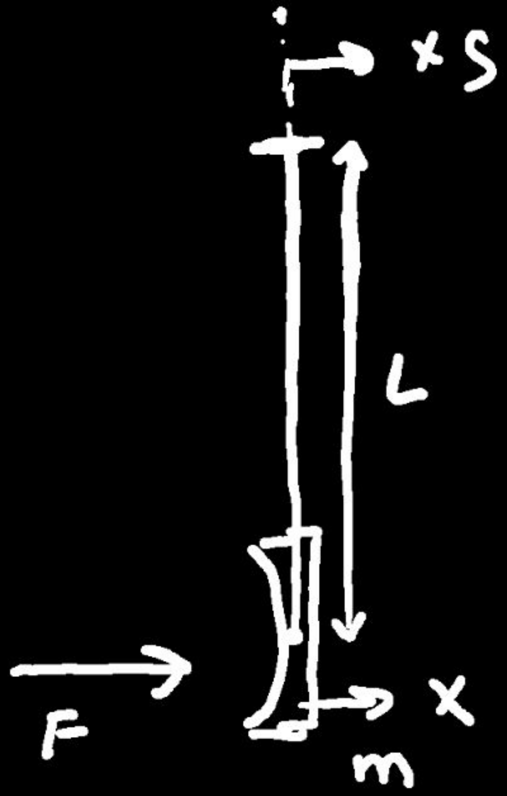


$$x = \frac{\frac{F}{m} + \omega_0^2 x_s}{\omega_0^2 - \omega^2}$$

$$\omega_0^2 = \frac{g}{L}$$

Noise sources

Seismic noise + Thermal noise

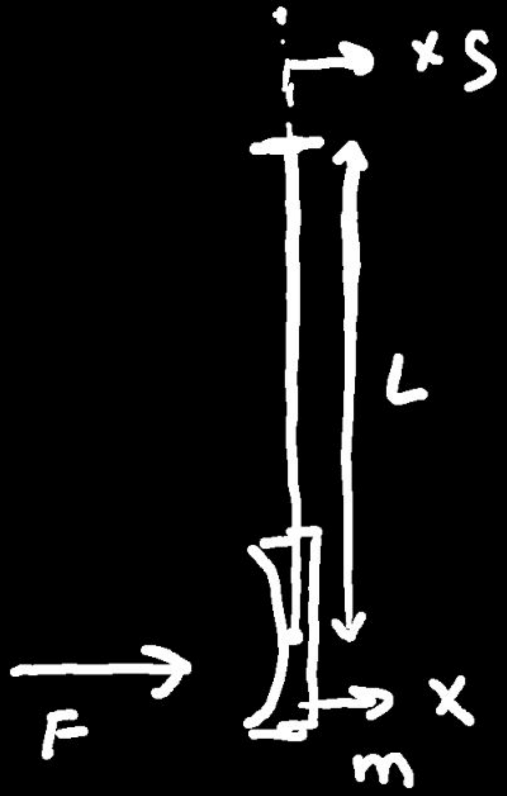


$$X = \frac{\frac{F}{m} + \boxed{\omega_0^2 x_s}}{\omega_0^2 - \omega^2}$$

$$\omega_0^2 = \frac{g}{L}$$

Noise sources

Fluctuations in radiation pressure



$$x = \frac{\boxed{\frac{F}{m}} + \omega_0^2 x_s}{\omega_0^2 - \omega^2}$$

$$\omega_0^2 = \frac{g}{L}$$

Quantum noise

$$\Delta N \sim \sqrt{\frac{\lambda\, P_{laser}}{\omega}}$$

Poisson fluctuations

$$\Delta F \sim \frac{1}{\lambda} \cdot \Delta N \cdot \omega$$

Transfer of momentum
per foton

1/ integration time

Quantum noise

$$\Delta N \sim \sqrt{\frac{\hbar P_{laser}}{\omega}}$$

$$\Delta l \sim \frac{\Delta F}{m\omega^2} \sim \frac{1}{\omega^{3/2} m}\sqrt{\frac{P}{\hbar}}$$

Radiation pressure noise

Quantum noise

$$\Delta l \sim \frac{\Delta F}{m\omega^2} \sim \frac{1}{\omega^{3/2} m}\sqrt{\frac{P}{\lambda}}$$

$$\Delta N \sim \sqrt{\frac{\lambda P_{laser}}{\omega}}$$

$$\Delta l \sim \frac{\Delta N}{N} \cdot \lambda \sim \sqrt{\frac{\lambda}{P}}\, \omega^{1/2}$$

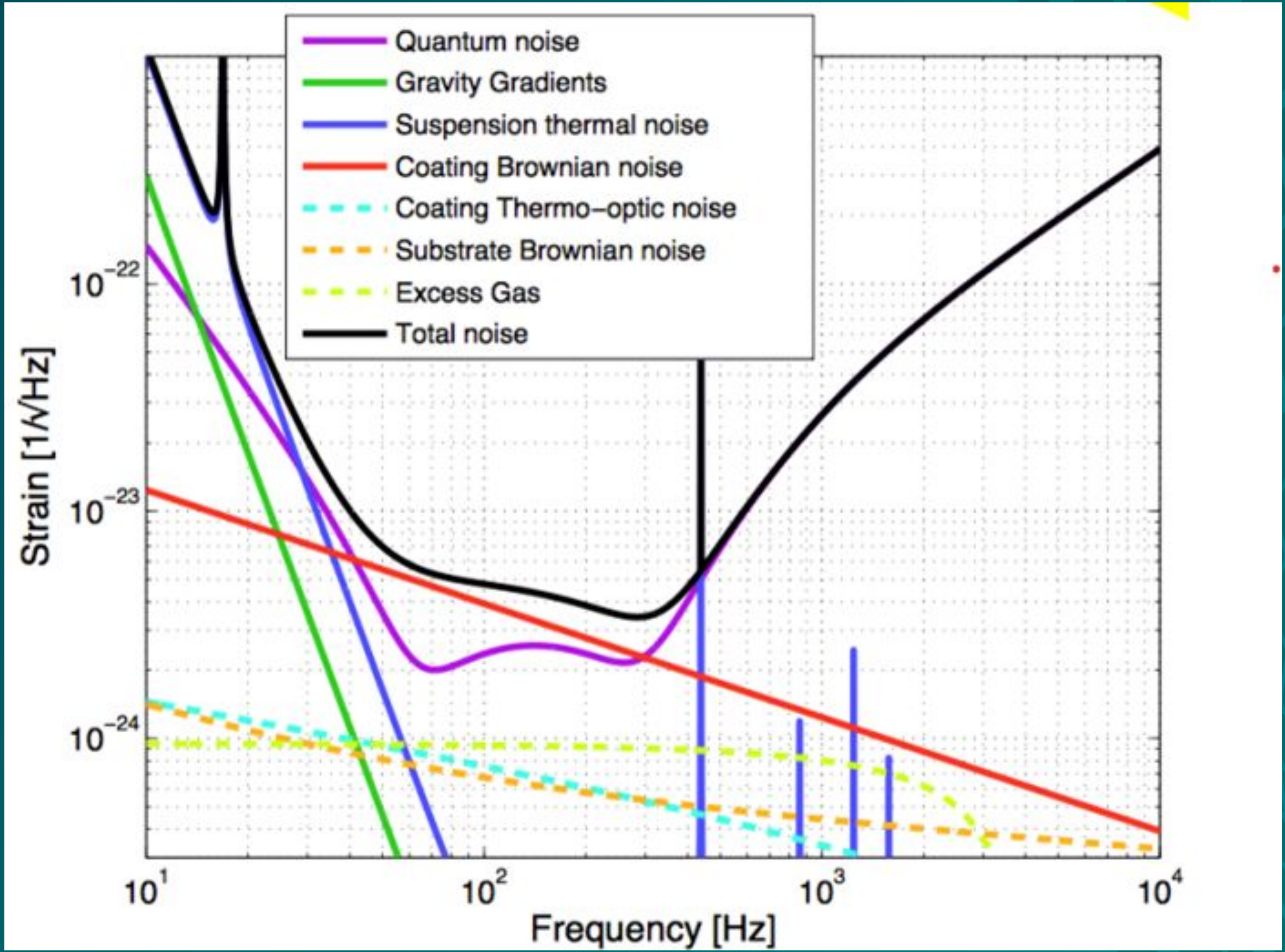
Photon counting noise

Quantum noise

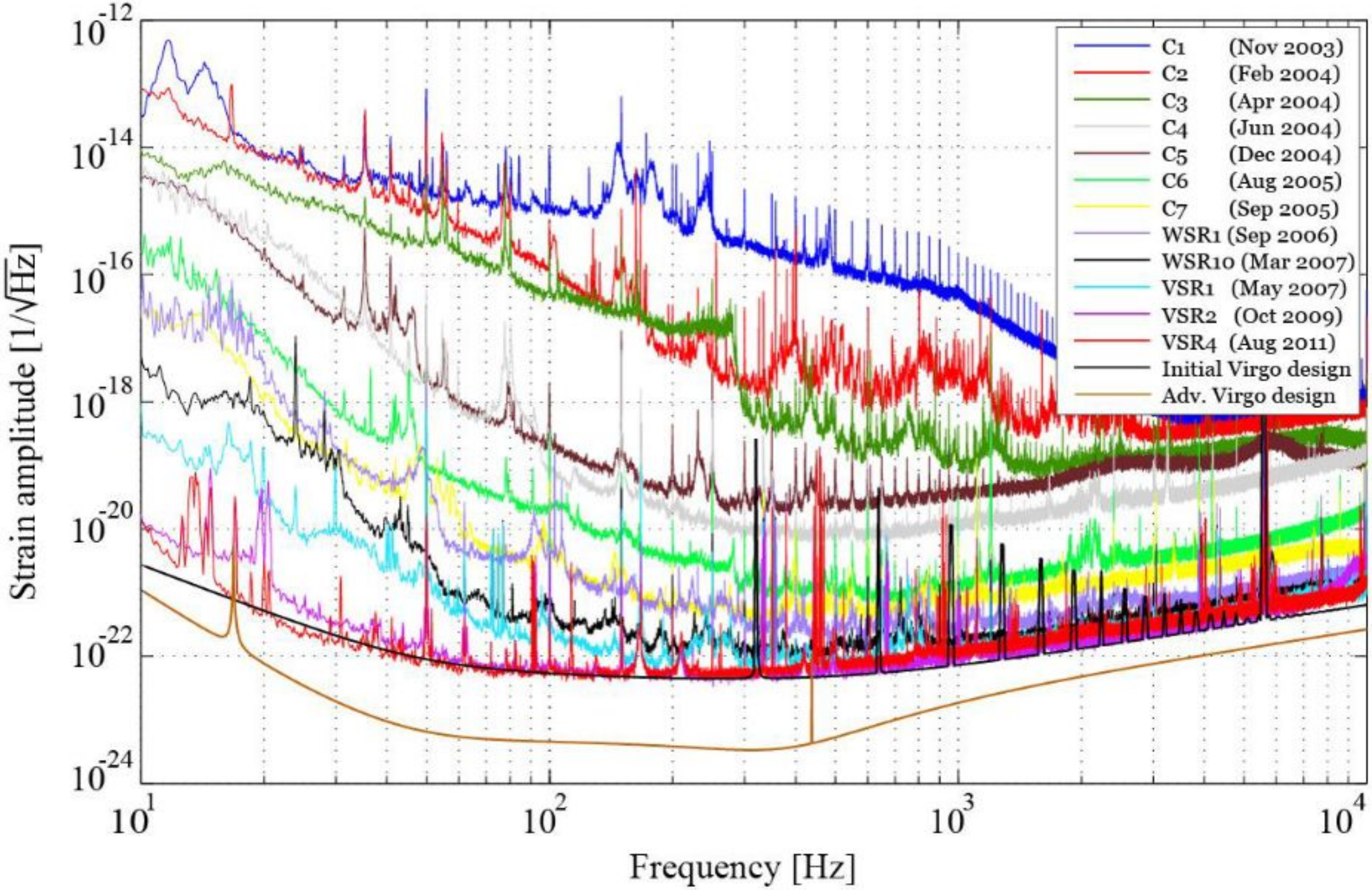
Poisson fluctuations in the number of photons:

$$\delta L \sim \frac{1}{\omega^{3/2}}\sqrt{\frac{P_{laser}}{\lambda}}$$

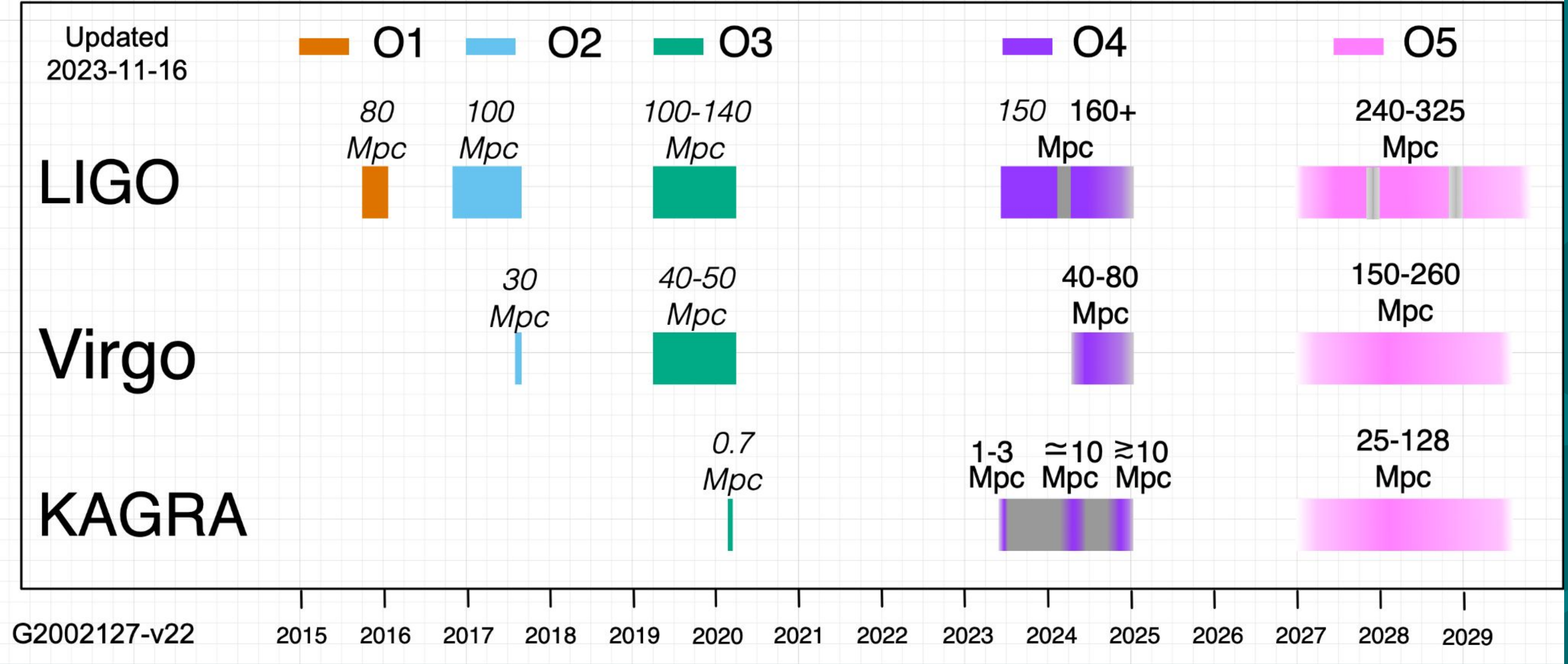
$$\delta L \sim \frac{\delta P_{det}}{P_{laser}} \sim \sqrt{\frac{\lambda}{P_{laser}}}\,\omega^{1/2}$$



Virgo: sensitivity evolution



Ligo-Virgo-Kagra timeline.



Activities in Virgo

Participants

Daniel Beltran

Upgrade of IMC

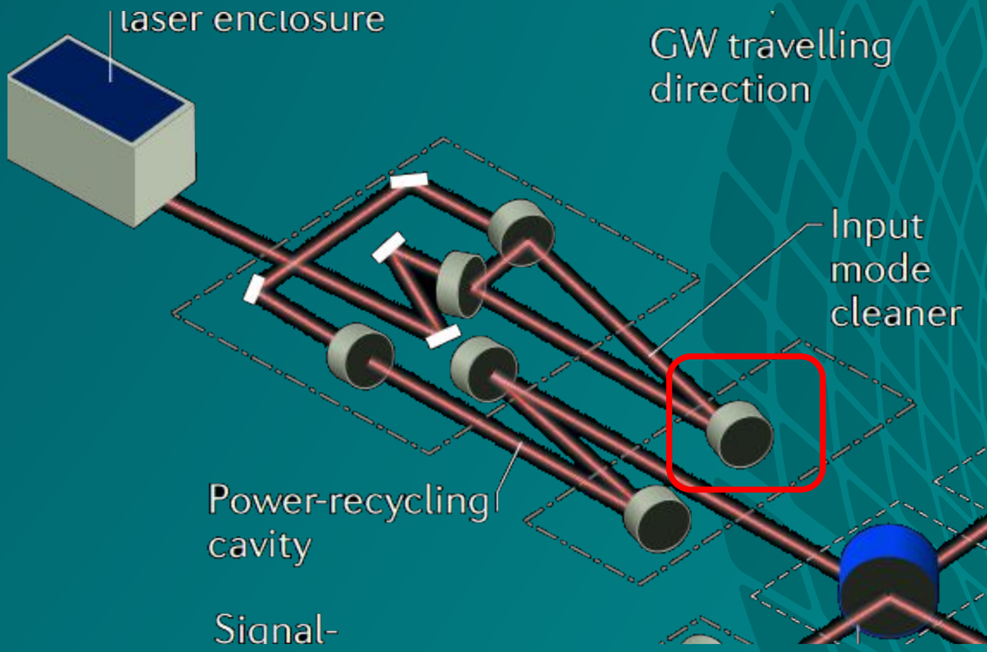
Upgraded IMC payload for O5

Motivations for a new payload:

- Add a ring heater to the IMC Payload to control the curvature of the mirror

Tasks:

- Study the impact of adding the ring heater to the IMC Payload
- Design a new dummy mass structure
- Manufacturing the needed parts
- Help during the test and installation

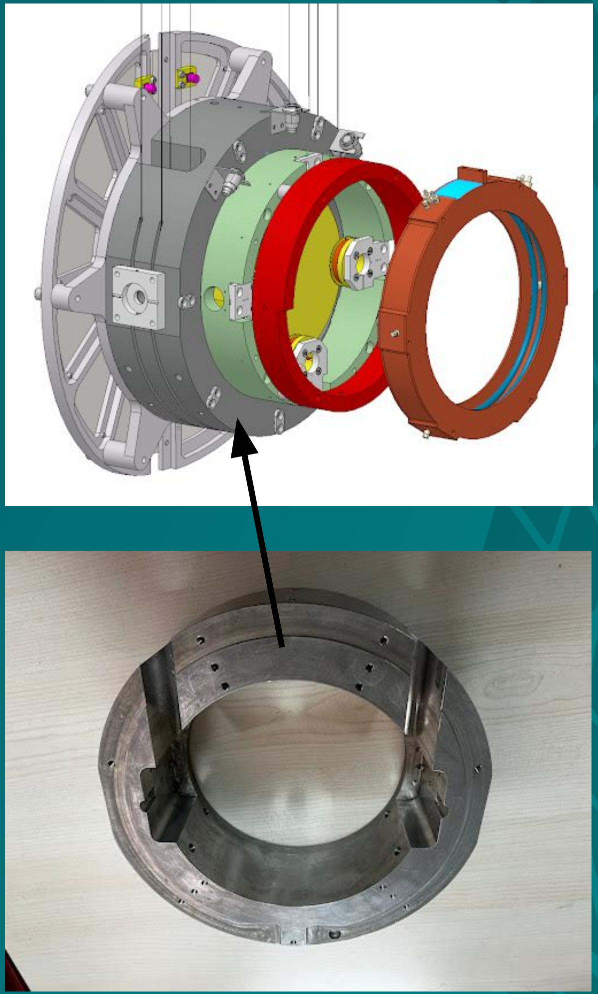


Upgraded IMC payload for O5

A preliminary study has been initiated by facing up the 3D models of the IMC system and the Ring Heater to identify affected components.

Additionally, physical properties of materials are being added to evaluate the impact on the center of gravity of the final assembly.

The manufacture of a Reference Mass part has begun in our mechanical workshops in order to evaluate the difficulties and necessary precisions.

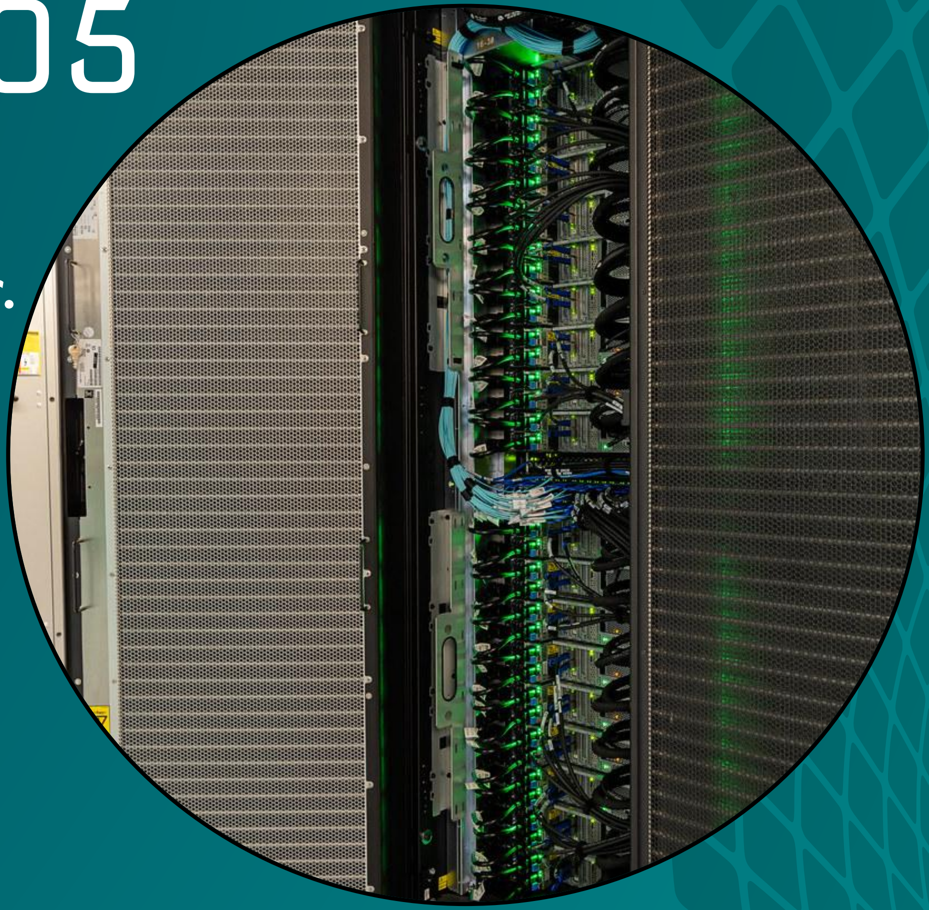


Low latency cluster for O5

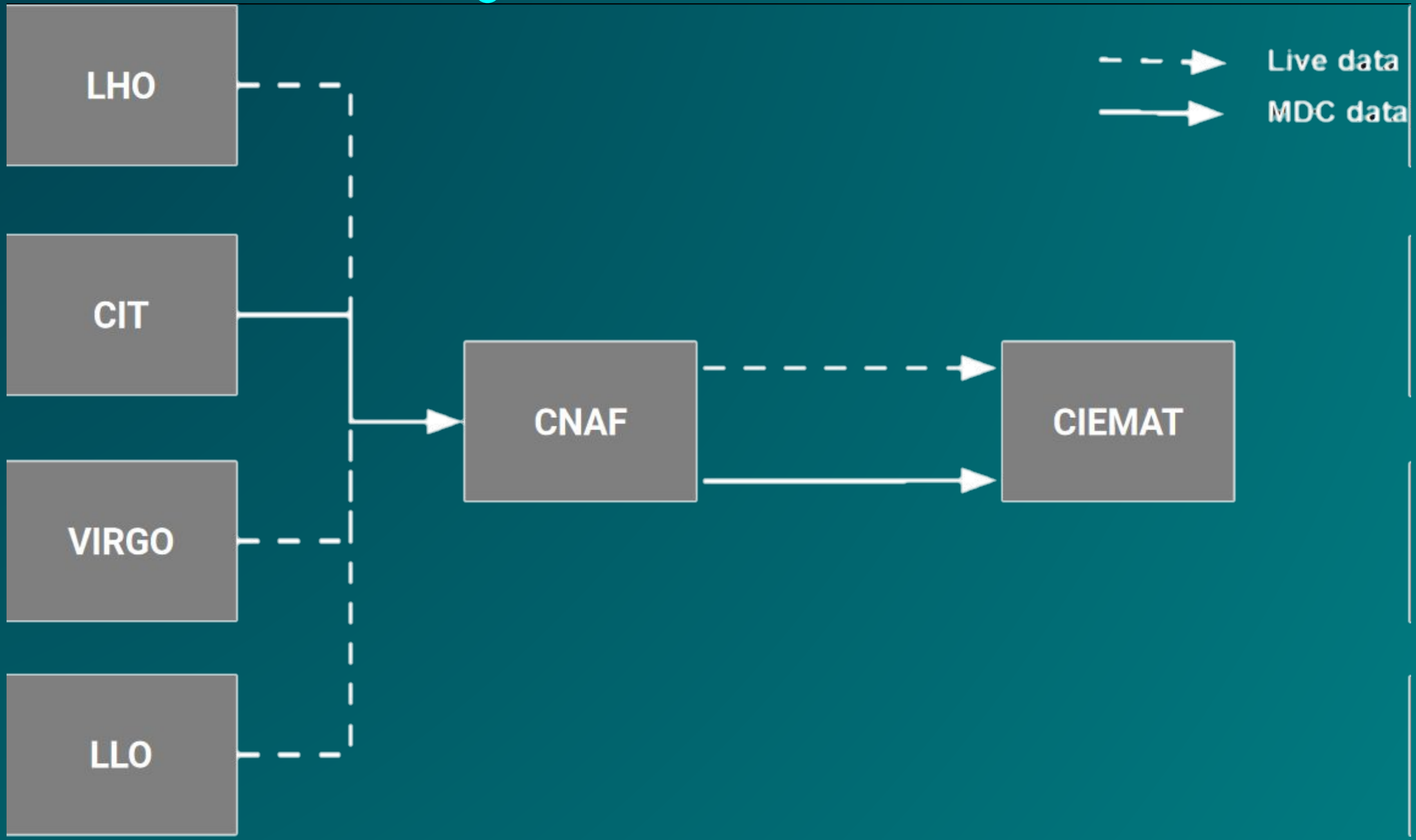
CIEMAT provides and hosts a low-latency computing cluster.

Aims to run analysis pipelines to provide a fast response (alarm) to the astroparticle communities.

Complementary to the the ones running locally in Virgo



Low latency cluster



Computing resources for VIRGO/LIGO

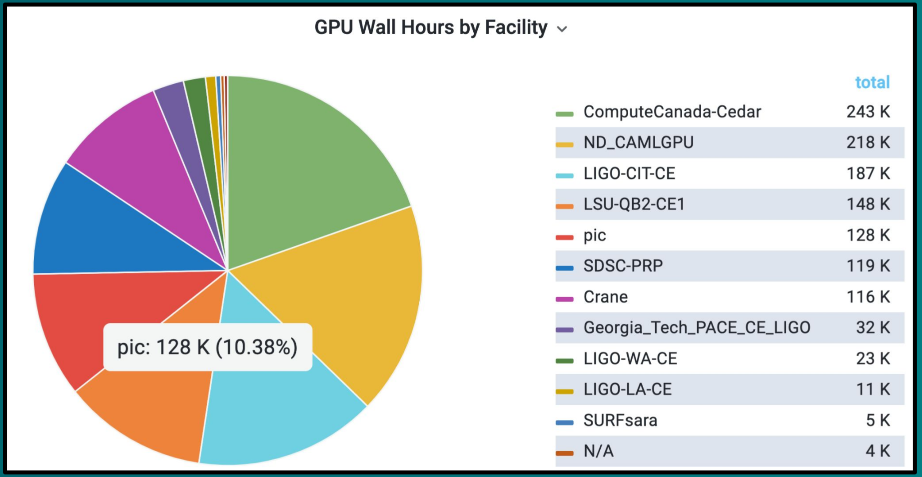
Joined the LIGO/VIRGO Grid in Summer 2019.

- Site integration was fast and painless, thanks to common sw stack with LHC and others.

CPU and GPU access through HTCondor. Transparent & efficient access to sw and data through CVMFS.

Overall contribution: 10% of the CPU (EU) and GPU (Global) to VIRGO/LIGO

- Opportunistic resources only



GPU Wall Hours by Facility

	total
ComputeCanada-Cedar	243 K
ND_CAMLGPU	218 K
LIGO-CIT-CE	187 K
LSU-QB2-CE1	148 K
pic	128 K
SDSC-PRP	119 K
Crane	116 K
Georgia_Tech_PACE_CE_LIGO	32 K
LIGO-WA-CE	23 K
LIGO-LA-CE	11 K
SURFsara	5 K
N/A	4 K

Low latency cluster

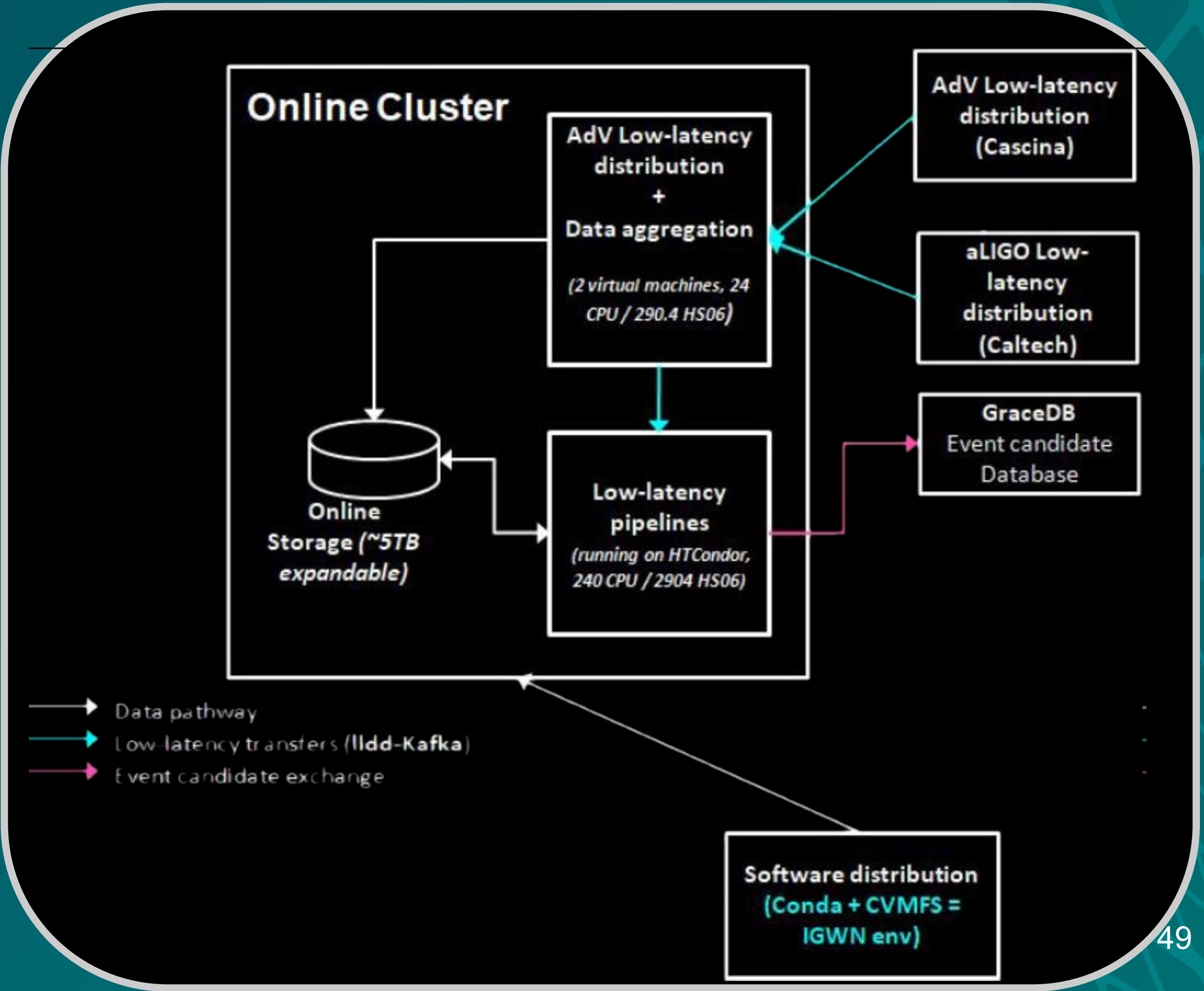
2 Main servers/ submission machines

7 Worker nodes (startd's of the HTCondor pool)

72 cores per node

256 GB (3.55 GB per core)

CVMFS software/ data



Online Cluster

AdV Low-latency distribution + Data aggregation *(2 virtual machines, 24 CPU / 290.4 HS06)*

Online Storage *(~5TB expandable)*

Low-latency pipelines *(running on HTCondor, 240 CPU / 2904 HS06)*

AdV Low-latency distribution (Cascina)

aLIGO Low-latency distribution (Caltech)

GraceDB Event candidate Database

Software distribution (Conda + CVMFS = IGWN env)

→ Data pathway

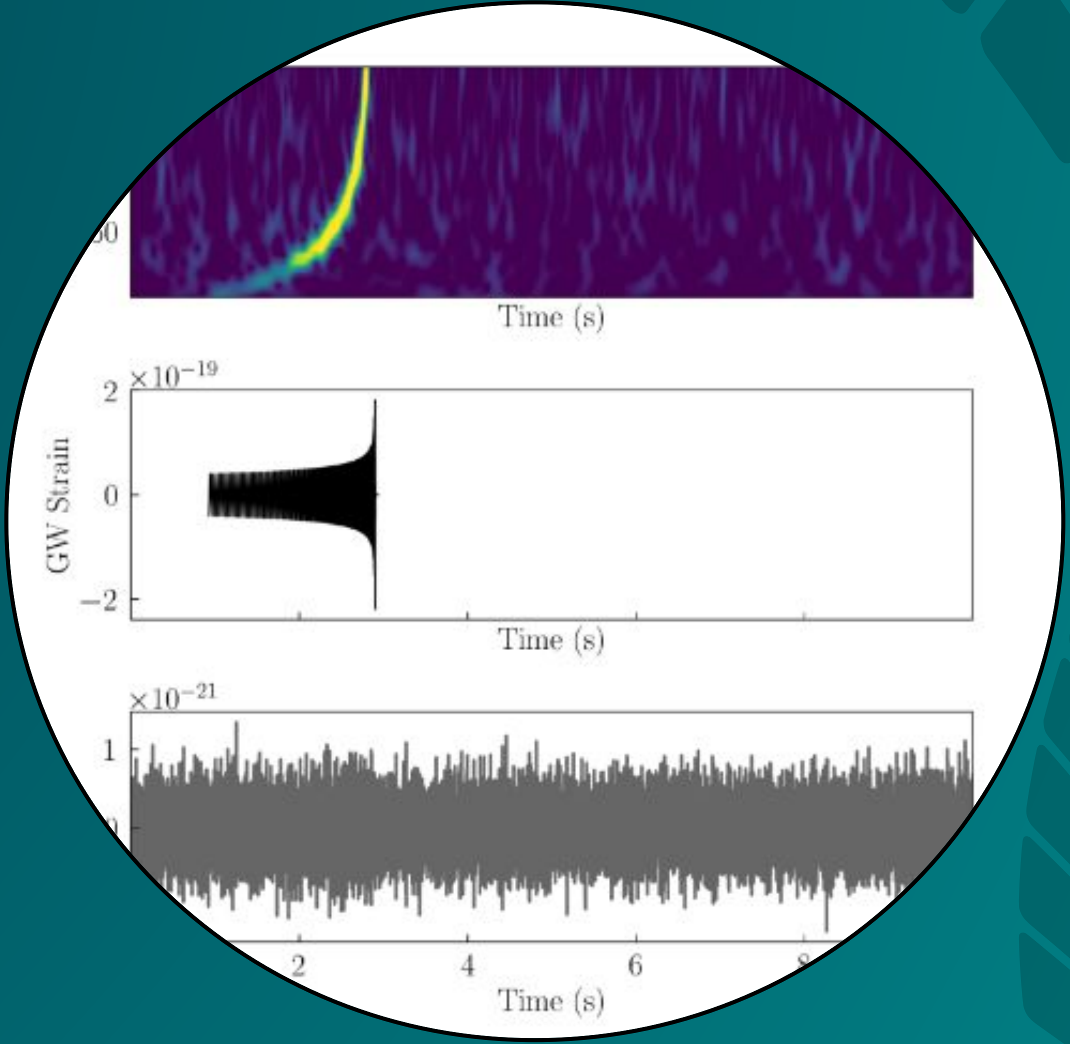
→ Low-latency transfers (lldd-Kafka)

→ Event candidate exchange

Analysis

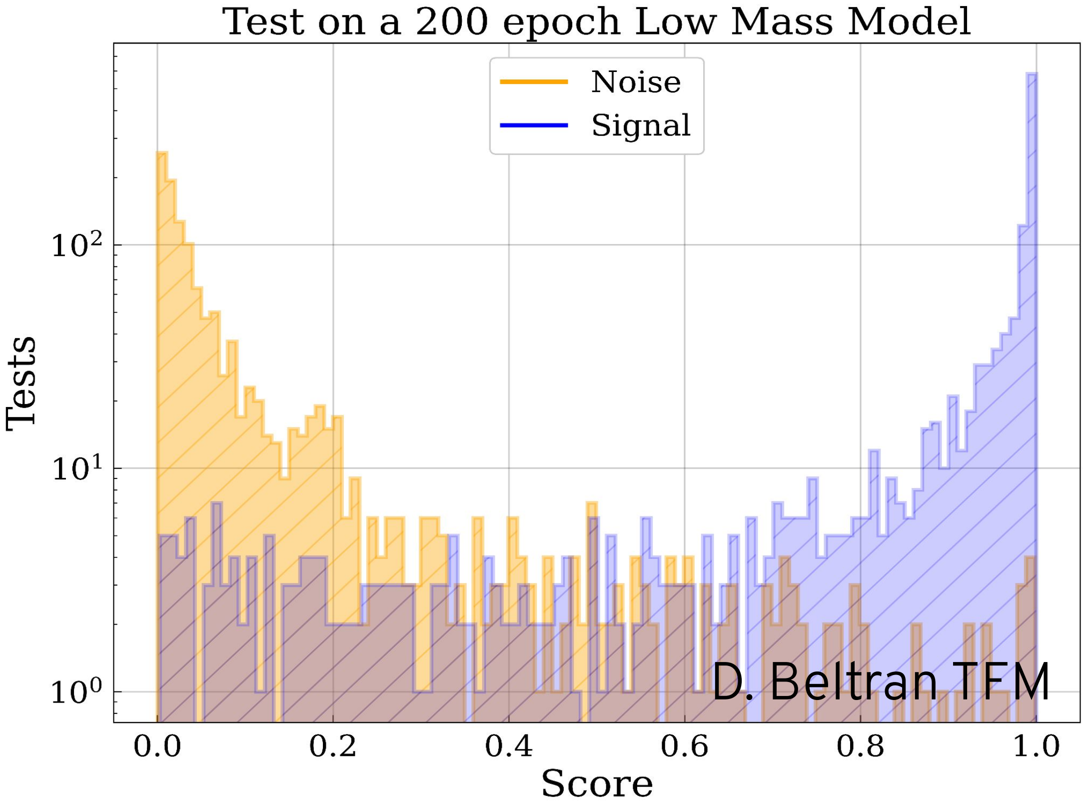
SSM events detection and reconstruction:

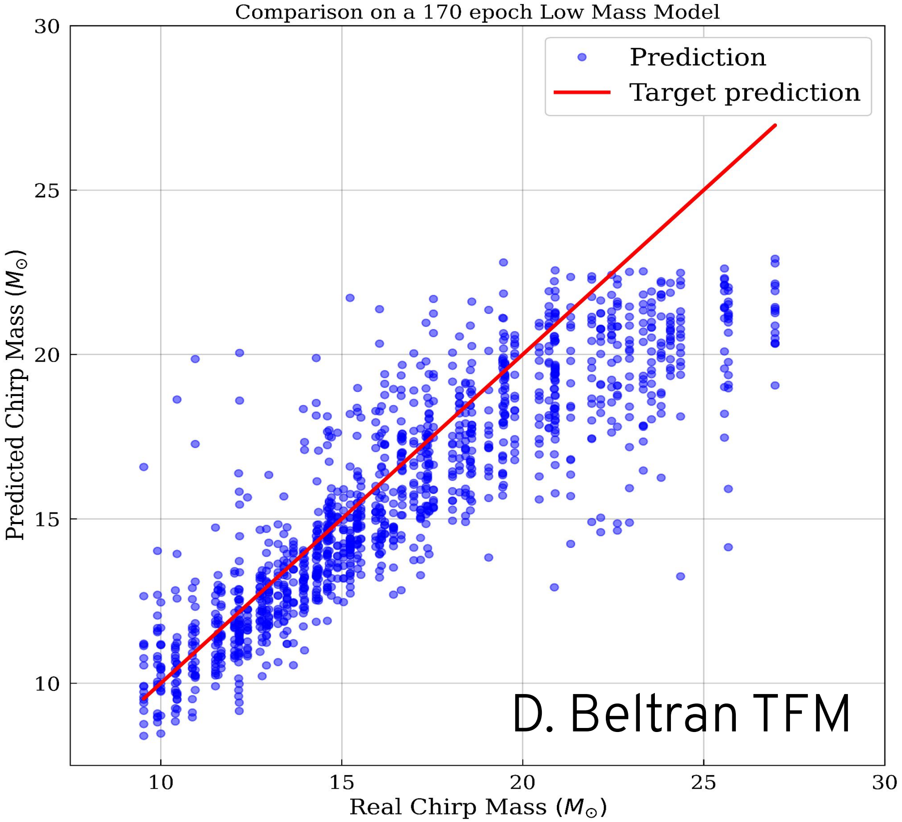
- Goal: search for PBH
- Start with studies based in simulated events.
- Currently learning the business.



Regression and classification with Virgo public data and codes

As part of a pipeline: benchmark for low-latency

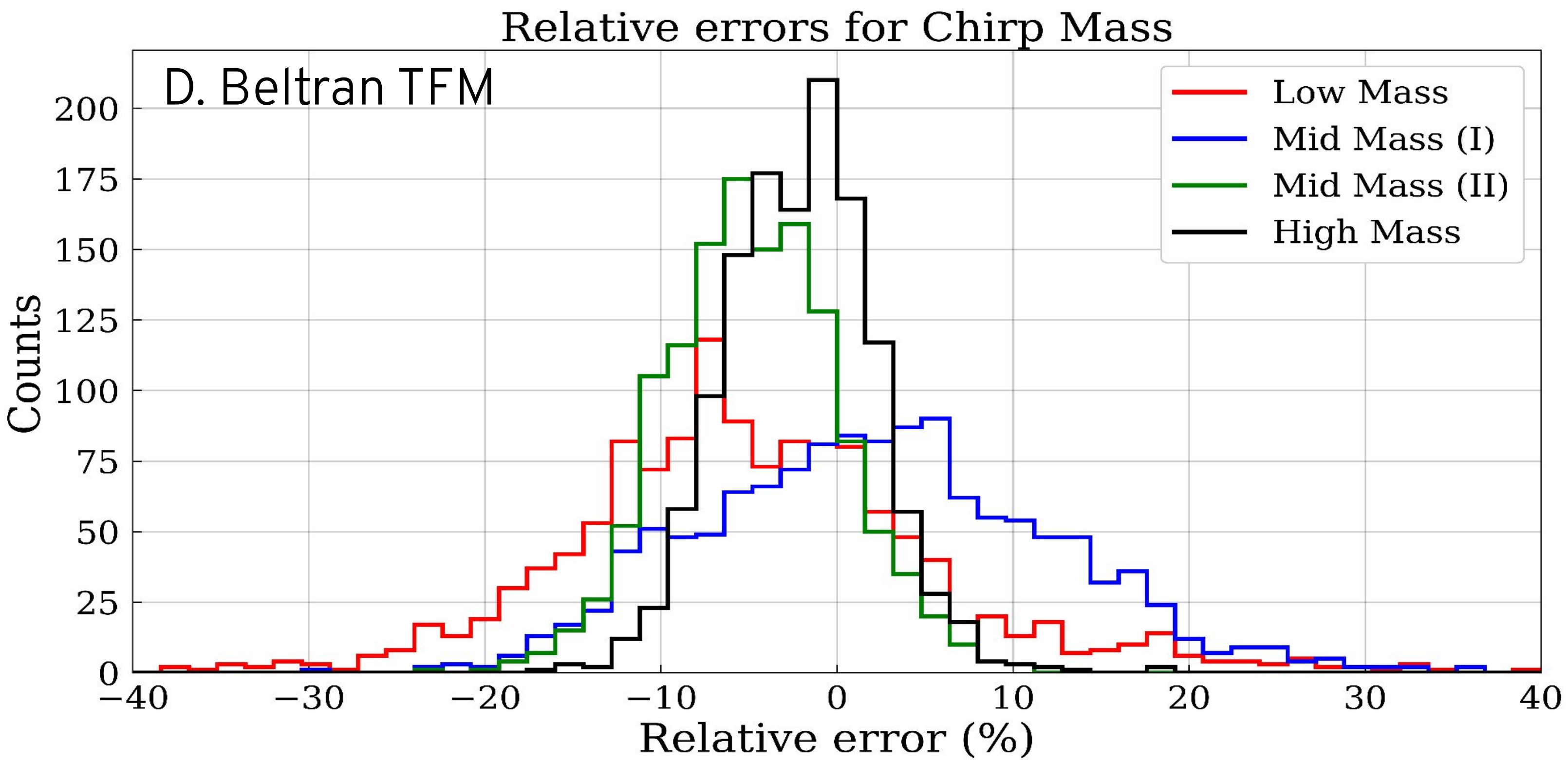




Regression and classification with Virgo public data and codes

As part of a pipeline:
benchmark for low-latency

Chirp Mass regressor

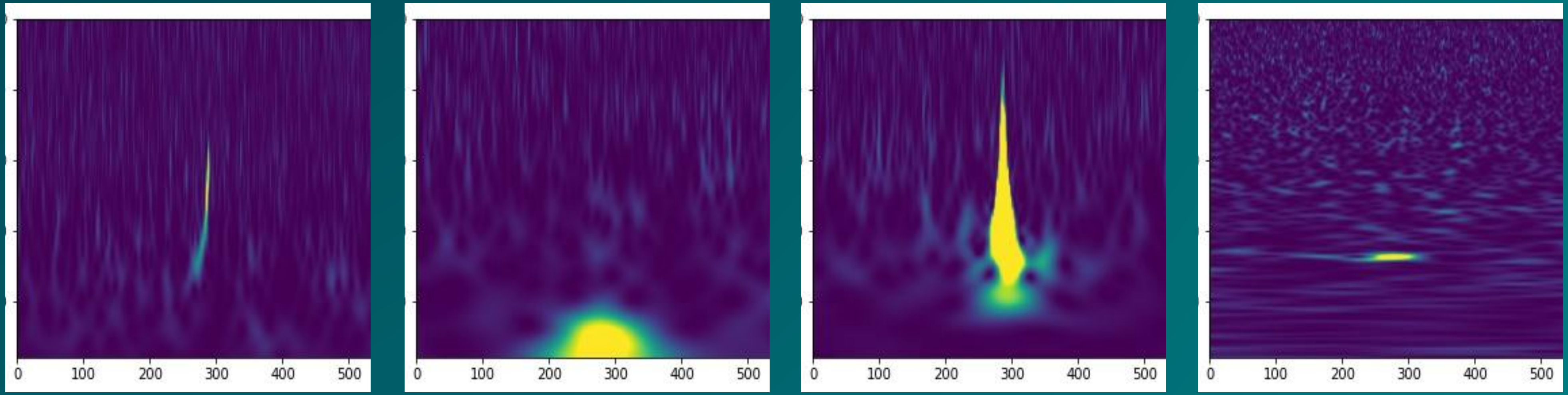


Going deep (first baby steps)

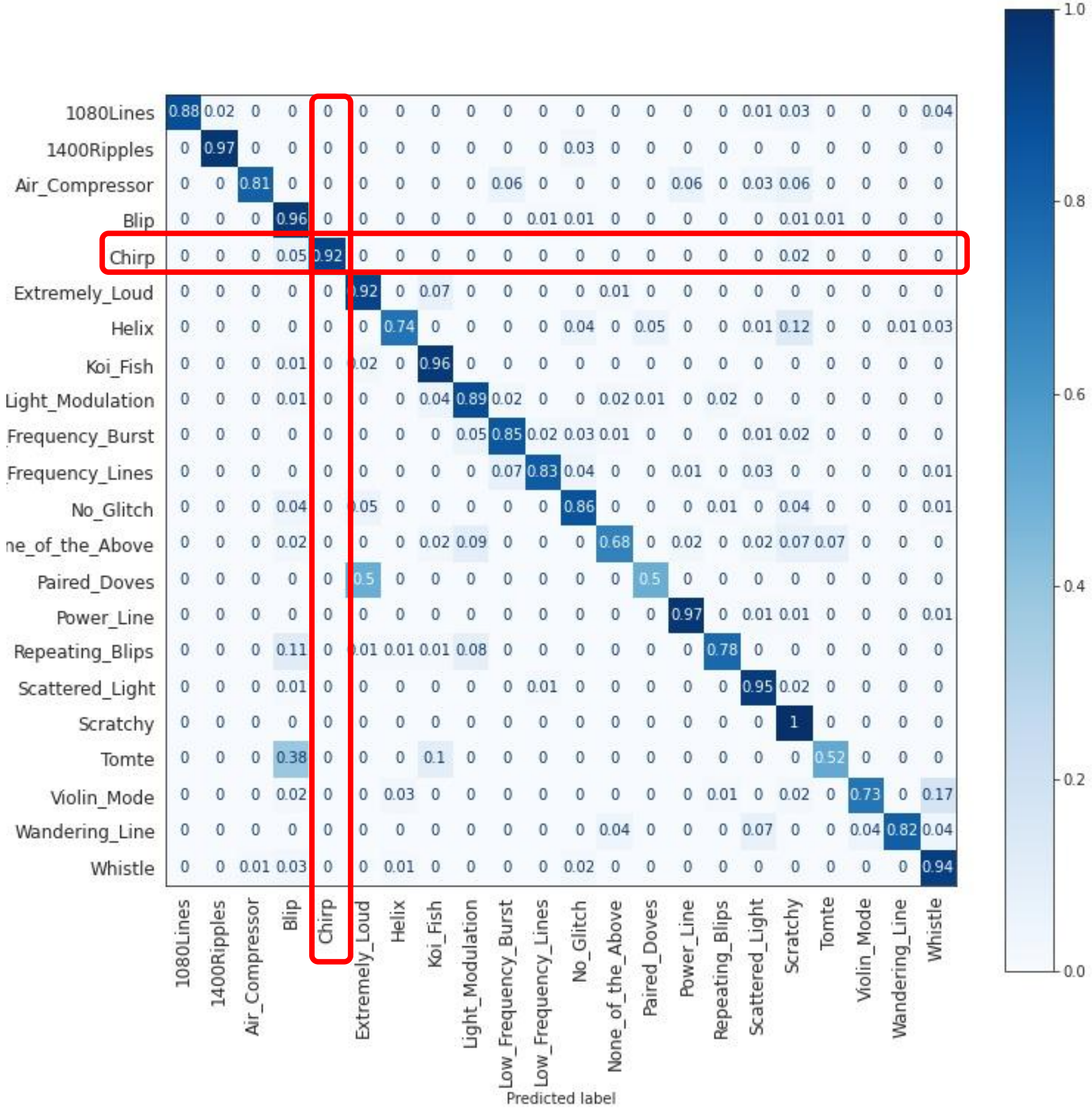
Ligo simulated events lasting from 0.5 to 4 seconds

1 (signal)+21 (noise) classes.

Based in Q-transform images

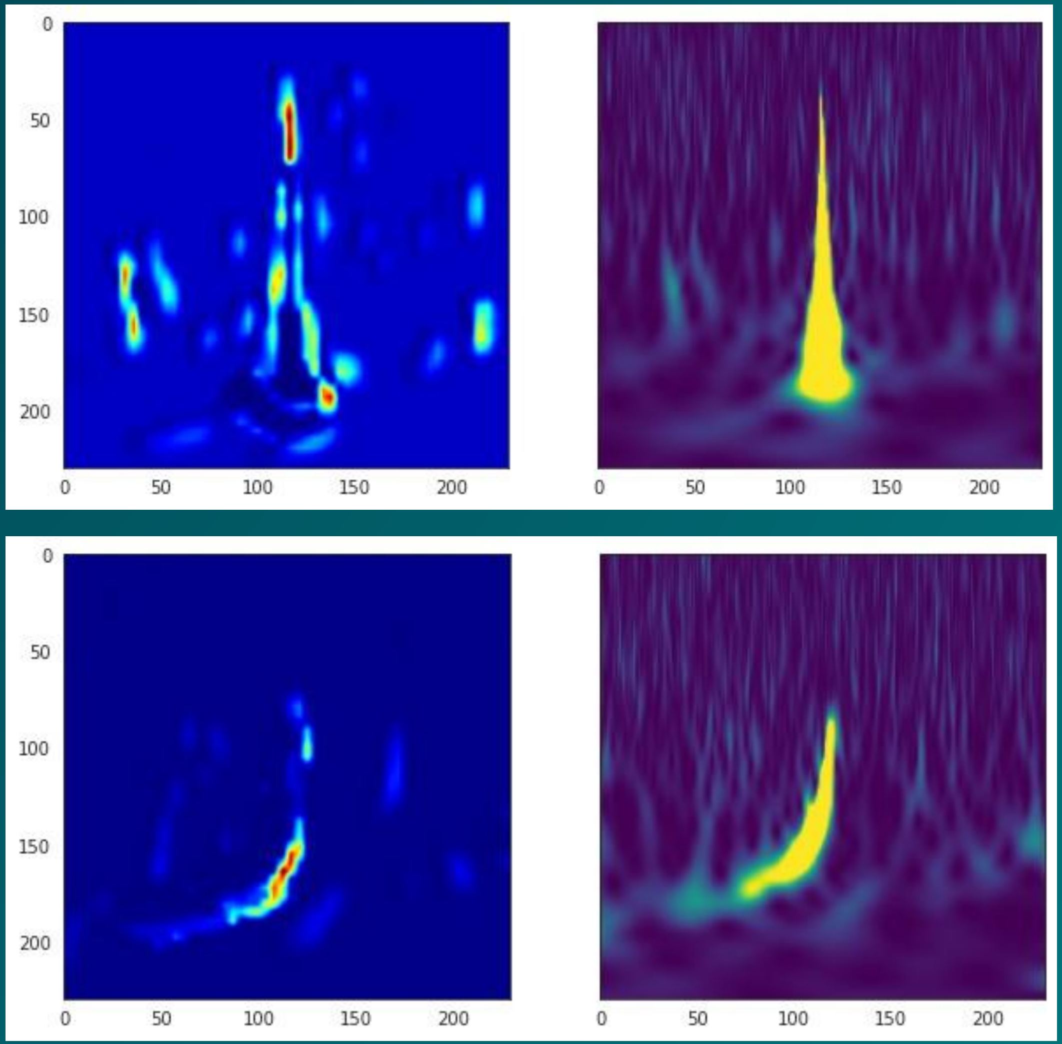


Confusion matrix



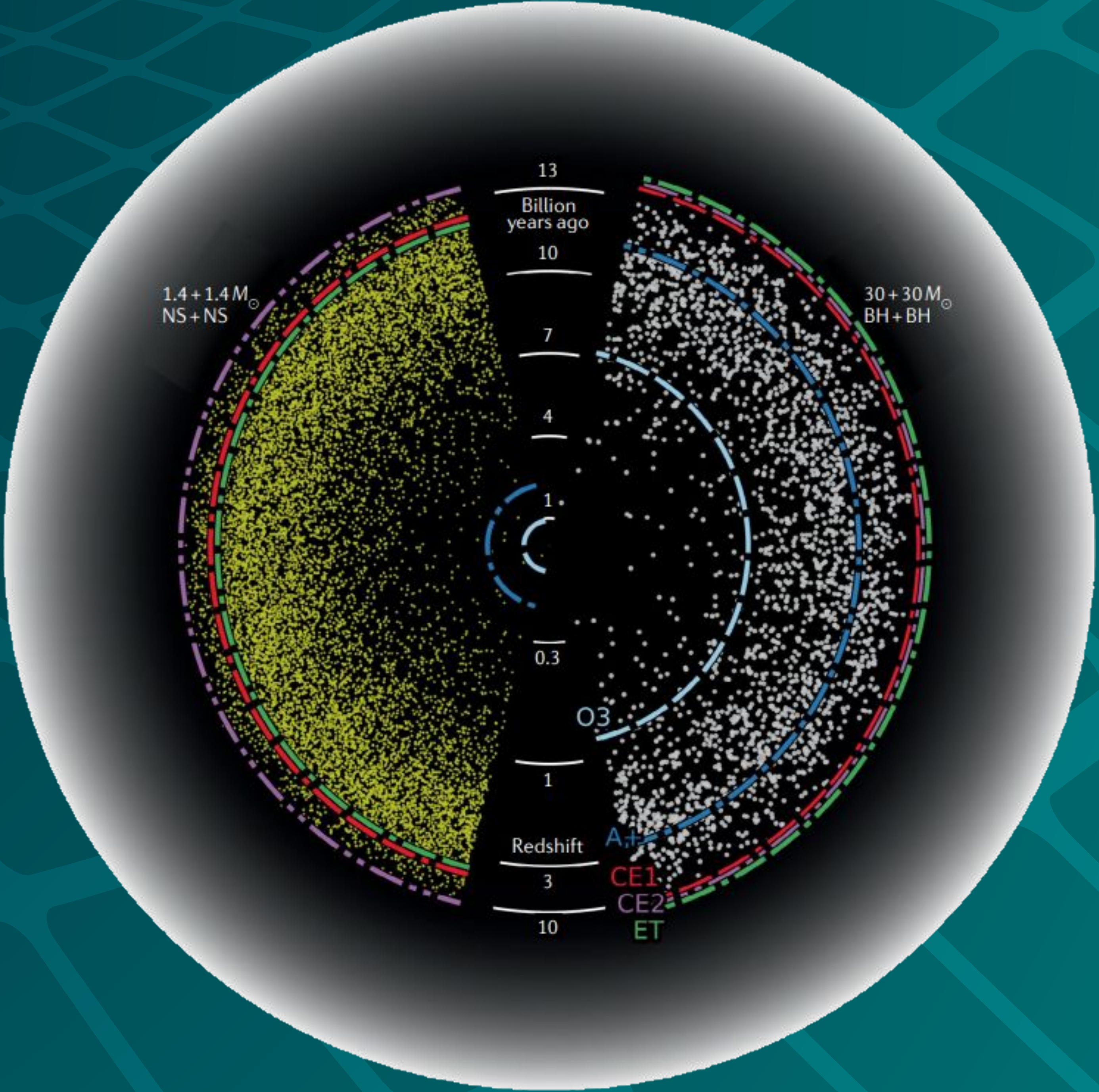
	1080Lines	1400Ripples	Air_Compressor	Blip	Chirp	Extremely_Loud	Helix	Koi_Fish	Light_Modulation	Low_Frequency_Burst	Low_Frequency_Lines	No_Glitch	None_of_the_Above	Paired_Doves	Power_Line	Repeating_Blips	Scattered_Light	Scratchy	Tomte	Violin_Mode	Wandering_Line	Whistle
1080Lines	0.88	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0.03	0	0	0	0.04
1400Ripples	0	0.97	0	0	0	0	0	0	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0
Air_Compressor	0	0	0.81	0	0	0	0	0	0	0.06	0	0	0	0	0.06	0	0.03	0.06	0	0	0	0
Blip	0	0	0	0.96	0	0	0	0	0	0	0.01	0.01	0	0	0	0	0	0.01	0.01	0	0	0
Chirp	0	0	0	0.05	0.92	0	0	0	0	0	0	0	0	0	0	0	0	0.02	0	0	0	0
Extremely_Loud	0	0	0	0	0	0.92	0	0.07	0	0	0	0	0.01	0	0	0	0	0	0	0	0	0
Helix	0	0	0	0	0	0	0.74	0	0	0	0	0.04	0	0.05	0	0	0.01	0.12	0	0	0.01	0.03
Koi_Fish	0	0	0	0.01	0	0.02	0	0.96	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Light_Modulation	0	0	0	0.01	0	0	0	0.04	0.89	0.02	0	0	0.02	0.01	0	0.02	0	0	0	0	0	0
Frequency_Burst	0	0	0	0	0	0	0	0	0.05	0.85	0.02	0.03	0.01	0	0	0	0.01	0.02	0	0	0	0
Frequency_Lines	0	0	0	0	0	0	0	0	0	0.07	0.83	0.04	0	0	0.01	0	0.03	0	0	0	0	0.01
No_Glitch	0	0	0	0.04	0	0.05	0	0	0	0	0	0.86	0	0	0	0.01	0	0.04	0	0	0	0.01
ne_of_the_Above	0	0	0	0.02	0	0	0	0.02	0.09	0	0	0	0.68	0	0.02	0	0.02	0.07	0.07	0	0	0
Paired_Doves	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0
Power_Line	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.97	0	0.01	0.01	0	0	0	0.01
Repeating_Blips	0	0	0	0.11	0	0.01	0.01	0.01	0.08	0	0	0	0	0	0	0.78	0	0	0	0	0	0
Scattered_Light	0	0	0	0.01	0	0	0	0	0	0	0.01	0	0	0	0	0	0.95	0.02	0	0	0	0
Scratchy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Tomte	0	0	0	0.38	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0.52	0	0	0
Violin_Mode	0	0	0	0.02	0	0	0.03	0	0	0	0	0	0	0	0	0.01	0	0.02	0	0.73	0	0.17
Wandering_Line	0	0	0	0	0	0	0	0	0	0	0	0	0.04	0	0	0	0.07	0	0	0.04	0.82	0.04
Whistle	0	0	0.01	0.03	0	0	0.01	0	0	0	0	0.02	0	0	0	0	0	0	0	0	0	0.94

Understanding why

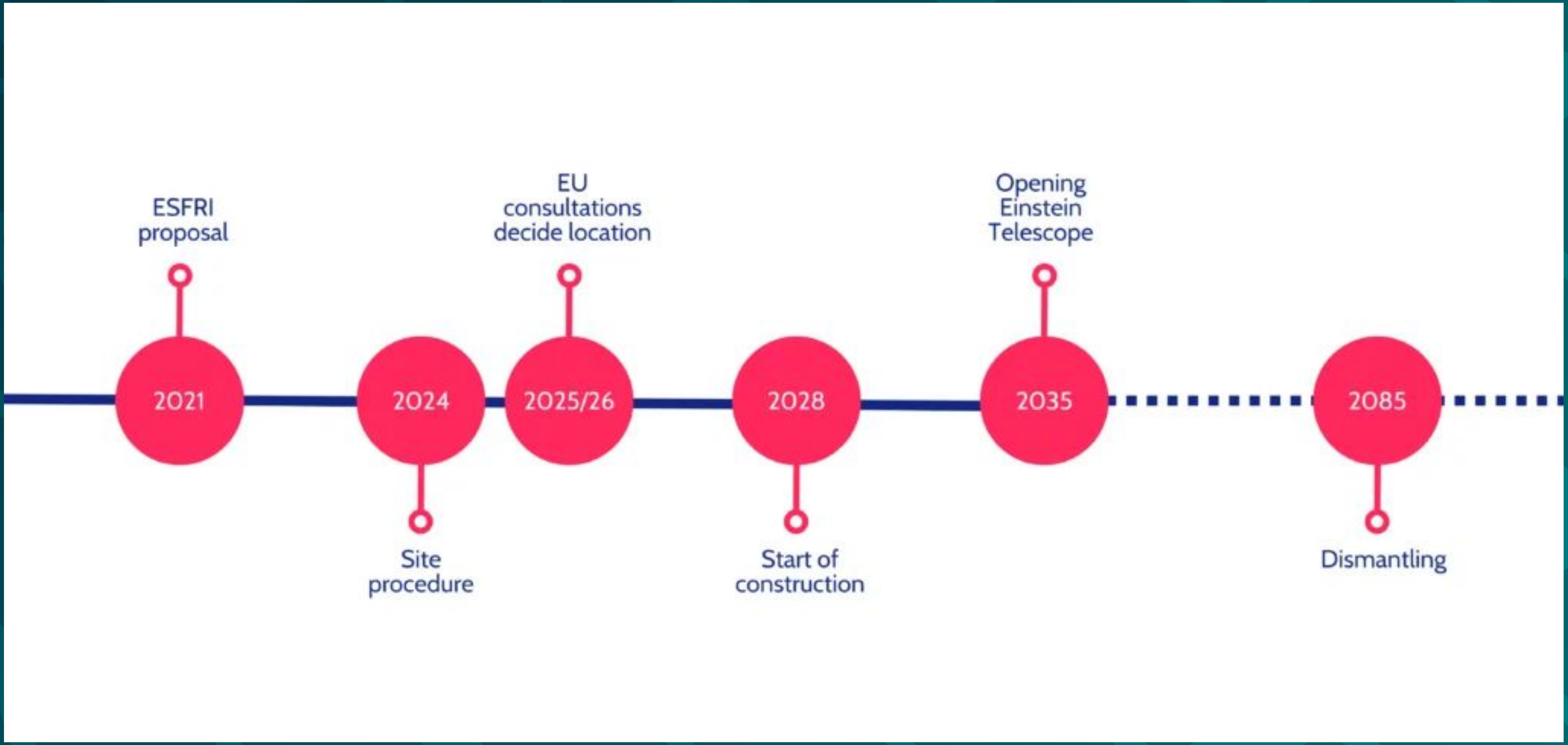


Einstein Telescope

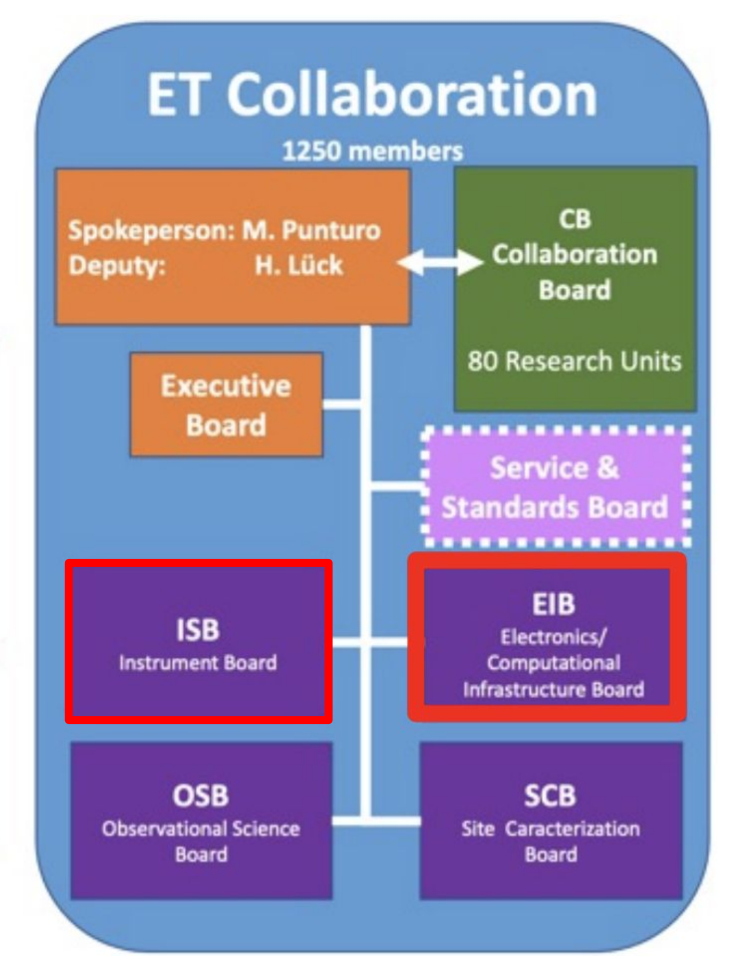
The future


13
Billion years ago
10
7
4
1
0.3
1
Redshift
3
10
1.4 + 1.4 $M_\odot$
NS + NS
30 + 30 $M_\odot$
BH + BH
O3
A+
CE1
CE2
ET

The future


ESFRI proposal
2021
2024
Site procedure
EU consultations decide location
2025/26
2028
Start of construction
Opening Einstein Telescope
2035
2085
Dismantling

Einstein Telescope Computing



ET Collaboration
1250 members

Spokeperson: M. Punturo
Deputy: H. Lück

CB
Collaboration
Board

80 Research Units

Executive
Board

Service &
Standards Board

ISB
Instrument Board

EIB
Electronics/
Computational
Infrastructure Board

OSB
Observational Science
Board

SCB
Site Caracterization
Board

We participate in the ET e-Infrastructure Board (EIB)

EIB mandate: "*...to design, create and operate an evolving, efficient and functional e-infrastructure environment at a reasonable cost for the collaboration.*"

Initial focus:

- Prepare a plan of the studies and activities that need to be undertaken for the development of the ET computing.
- Propose a computing model and its updates to the collaboration.

EIB Organization

EIB Chairs: Stefano Bagnasco (INFN), Patrice Verdier (IP2I Lyon - IN2P3)

ET-PP WP8 leaders: Achim Stahl (U. Aachen), Sergi Girona (BSC) + Nadia Tonello (BSC)

- Division 1: Software, frameworks, and data challenge support, Andres Tanasijczuk (UCL)
- Division 2: Services and Collaboration Support, Antonella Bozzi (EGO)
- **Division 3: Computing and data model, Resource Estimation**, Gonzalo Merino (PIC/CIEMAT)
- Division 4: Multimessenger alerts infrastructure, Steven Schramm (Université de Genève)
- TTG: Technology Tracking working Group, Sara Vallero (INFN Torino)

Liaison with OSB Div. 10: John Veitch (University of Glasgow)

Joint WP8+EIB weekly call for coordination

EIB Div3 – Computing Model

The challenge: The most obvious difference between ET with respect to 2nd Gen interferometers data is the increased event rate, thanks to the much improved sensitivity.

- 2G event rates ~ 100 events per year → ET event rates 100,000 events per year.
- The challenge is in the computing (CPU/GPU resources and algorithms) not the data volumes.

Div3 **Initial Tasks:**

- Analysis of current Gen2 detectors computing models
  - identification of bottlenecks and areas that will require evolution
- Methods to address ET analysis challenges
  - Analysis acceleration (incl. ML), signals overlap, continuous signals, low-frequency …
- Requirements from theory
  - Numerical simulations, waveform models development

ET Mock Data Challenge

The ET collaboration will use a rolling program of Mock Data Challenges (MDCs) to provide qualitative and quantitative input on ET computing resource needs before operations begin.

Realistic simulated data containing instrumental noise + GW signal from population of sources at the output of E1, E2 and E3 has been produced and it is available for people to analyze.

Goals:

- Use this data to test, develop, optimize data analysis pipelines and parameter estimation.
- Stress-testing the current computational infrastructure.

Thank You!

INFRA_DEV ET-PP

Horizon Europe project for ET Preparatory Phase (Sep 2022 - Sep 2026)

- Address fundamental prerequisites for the approval, construction and operation of ET.

WP8 is the computing and data access work package.

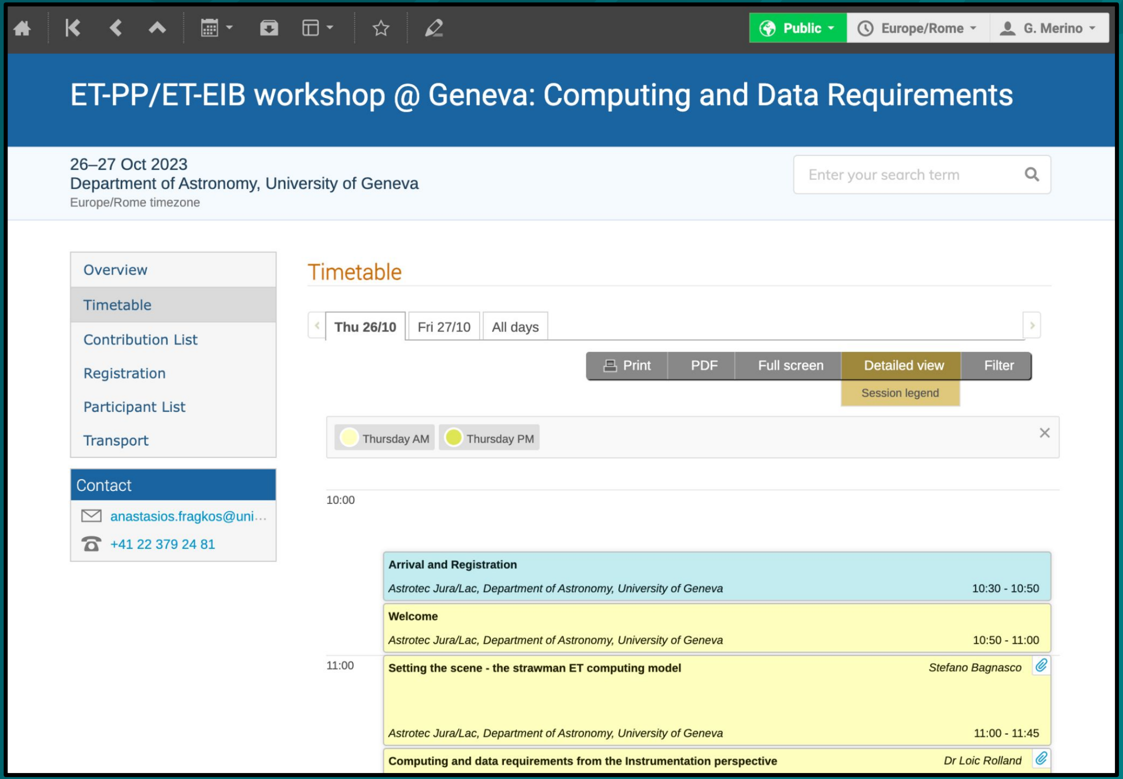
Coordinated work with ET EIB.

ET-PP WP8

A first workshop was organized to gather information for preparing the first deliverable:

“Workflows Requirements collection and constraints: computing and data”

The document is currently under internal review.



ET-PP/ET-EIB workshop @ Geneva: Computing and Data Requirements

26–27 Oct 2023
Department of Astronomy, University of Geneva
Europe/Rome timezone

Timetable

Contact
anastasios.fragkos@uni…
+41 22 379 24 81

10:00

Arrival and Registration
Astrotec Jura/Lac, Department of Astronomy, University of Geneva 10:30 - 10:50

Welcome
Astrotec Jura/Lac, Department of Astronomy, University of Geneva 10:50 - 11:00

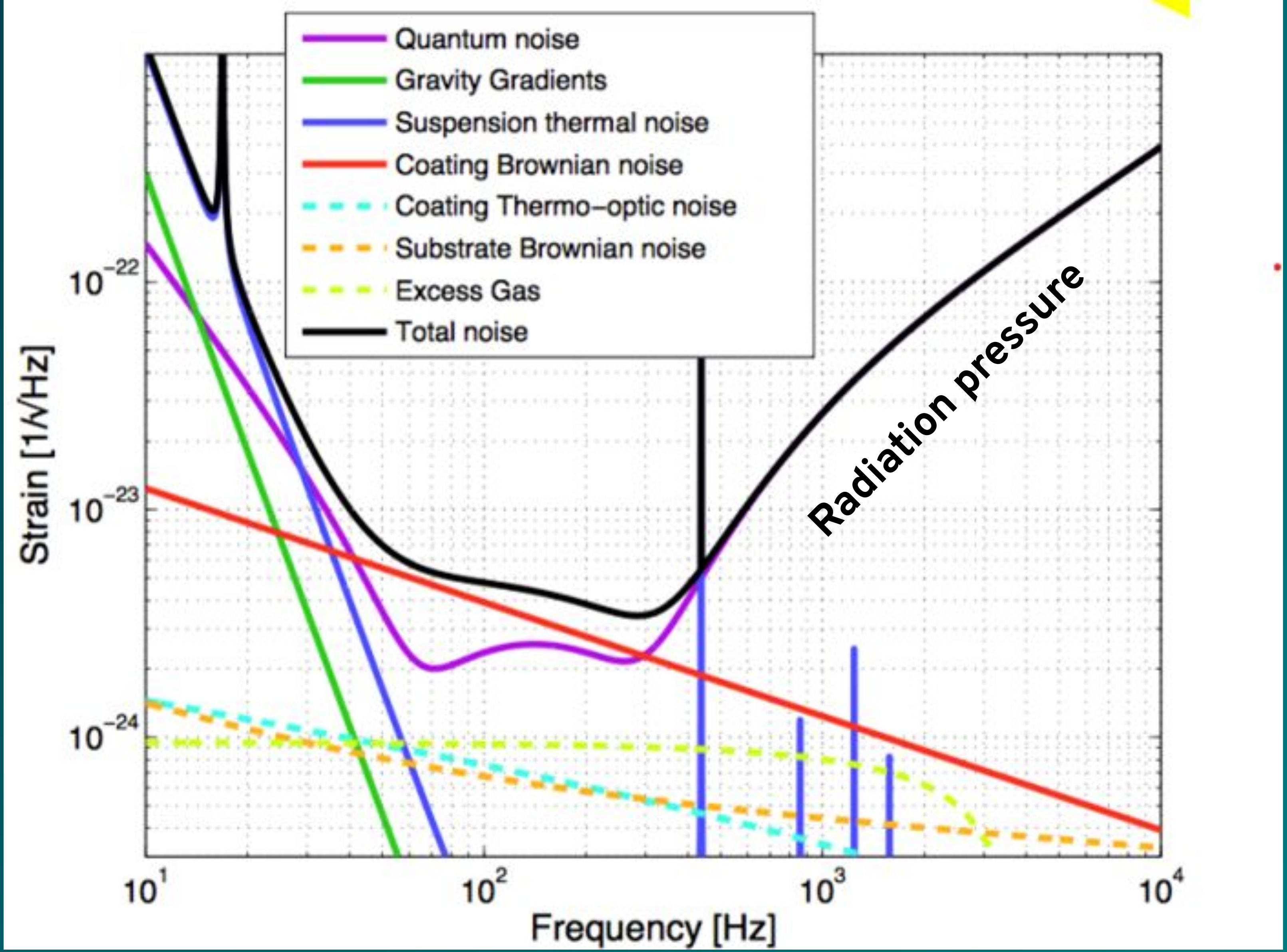
11:00

Setting the scene - the strawman ET computing model *Stefano Bagnasco*
Astrotec Jura/Lac, Department of Astronomy, University of Geneva 11:00 - 11:45

Computing and data requirements from the Instrumentation perspective *Dr Loic Rolland*

CIEMAT Feb. 29th 2024

Noise budget



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