Optomechanical parametric instabilities study for Virgo

David Cohen[1] dcohen@lal.in2p3.fr
PhD director: Nicolas Arnaud[1,2]
Co-supervisor: Thibaut Jacqmin[3]
[1]LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, F-91898 Orsay, France
[2]European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy
[3]Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, F-75005 Paris, France

Monday the 25th of November 2019

© Wikimedia commons

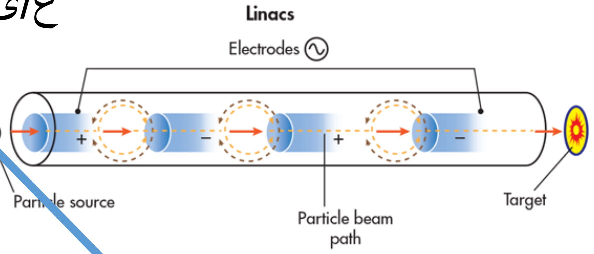
Introduction

Gravitational waves basics

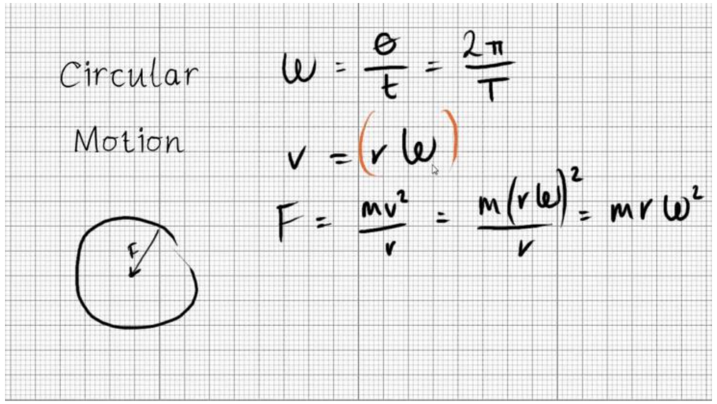
How to detect gravitational waves

Detections

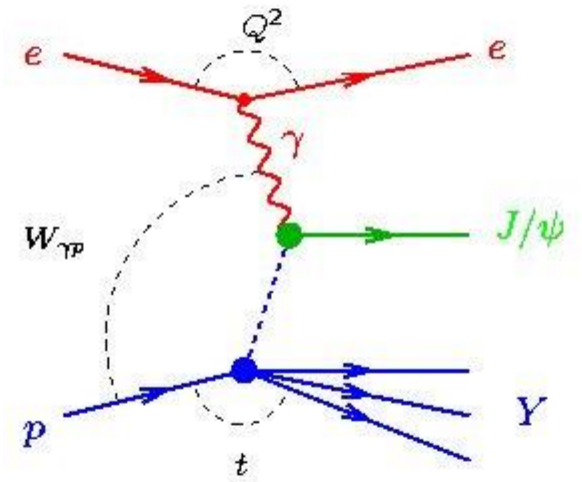
u/d/c/s/t/b
e⁻/ν/μ⁻
γ/W/ȷ/Њ/Ɣ/Щ/Ъ/א/מ/ڽ/ڠ



© Symmetry Magazine



© YouTube - Useful Equations in Particle Physics - A Level Physics Revision



© DESY - H1 Collab., A. Aktas et al., Phys Lett B568 (2003) 205-218 , 06/03

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\psi + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) + \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.$$

© Nikolai Schwerg (GNU FDL 1.2, not modified)

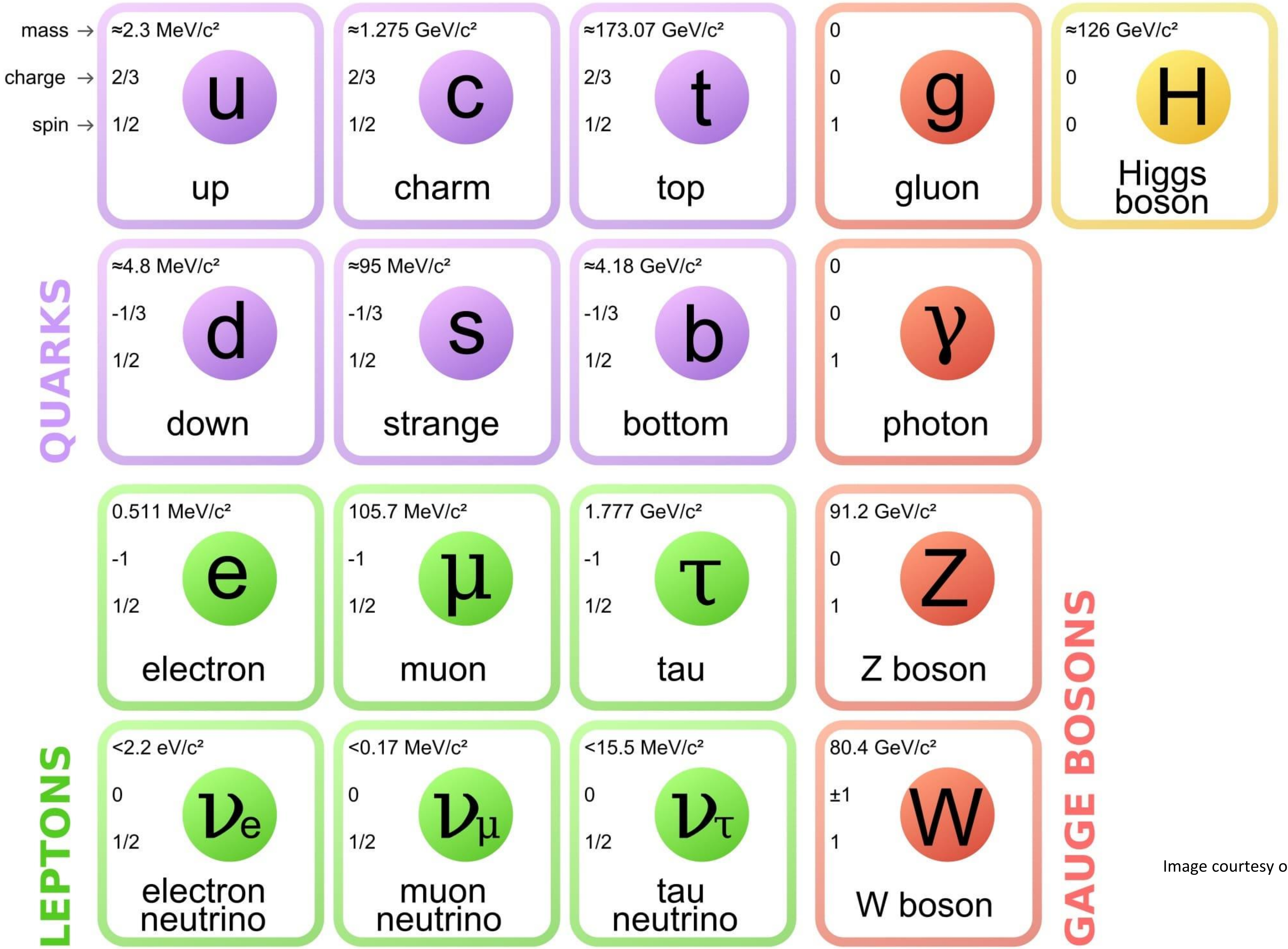
© Jean-Grégoire Ducoin

© CERN

© Maximilien Brice (CERN)

© The Virgo collaboration/CCO 1.0

© The Virgo collaboration



mass → charge → spin →	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	
	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson	
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson	GAUGE BOSONS

Image courtesy of Wikimedia Commons.

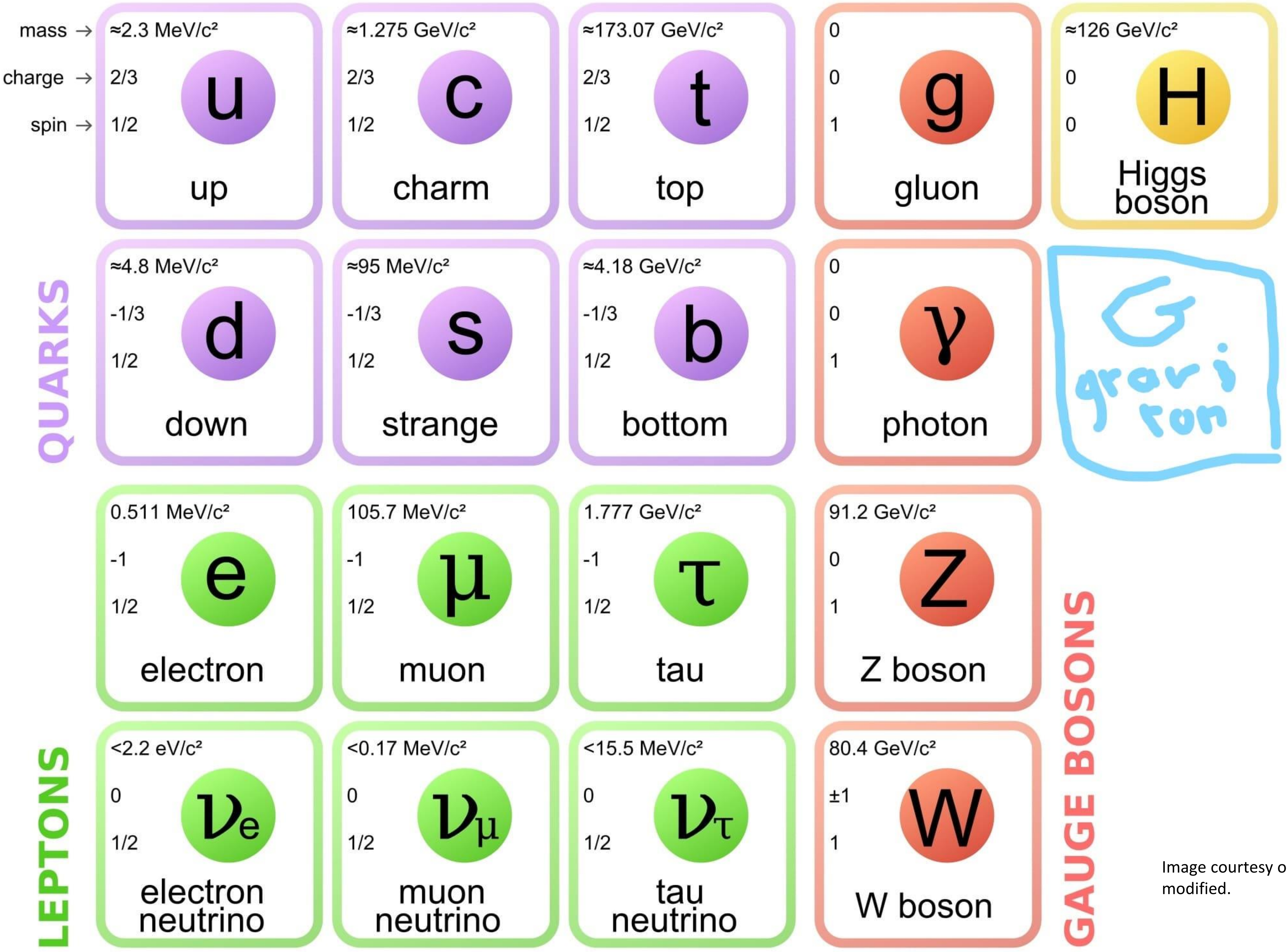
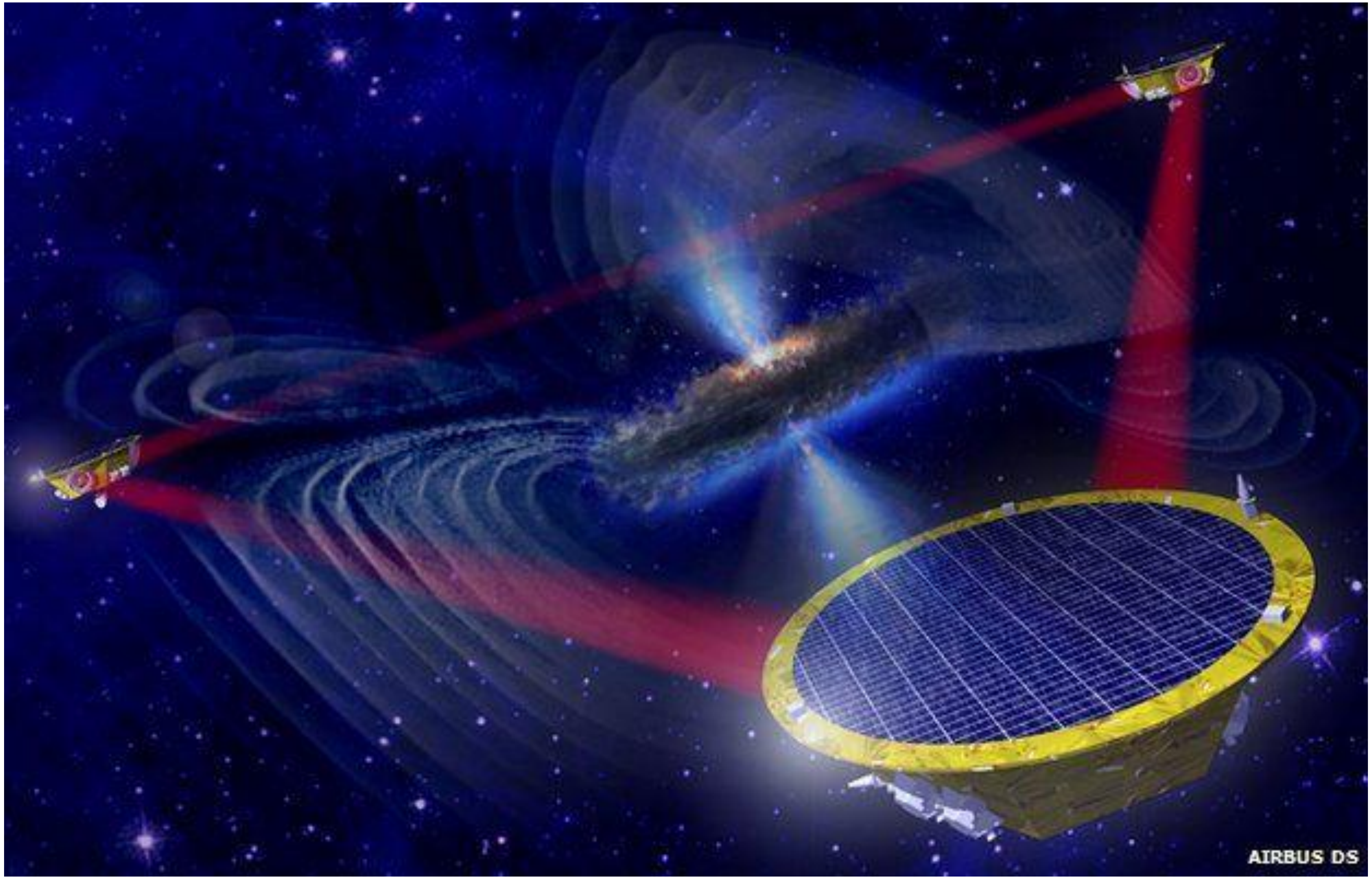


Image courtesy of Wikimedia Commons, modified.


AIRBUS DS

Gravitational waves (GW): basics

- Ripples of the curvature of spacetime: ‘space tells matter how to move […] matter tells space how to curve’ (Misner, Thorne & Wheeler, in Gravitation, 1973).
- Emitted by accelerating massive bodies; travel at the speed of light.
- Stretch and squeeze an object; the larger the object, the more it stretches as:

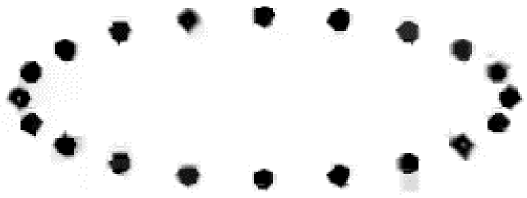
$$\frac{\delta L}{L_0} = \frac{h}{2}$$

where L_0 is the length of the object, δL the length variation due to the GW, and h the GW strain amplitude.

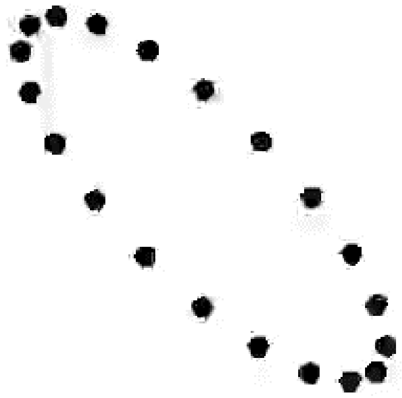
This $\frac{\delta L}{L_0}$ is what is actually measured to get to the GW strain amplitude h.

Gravitational waves (GW): basics

- Transverse waves ➔ similar to tidal effect



+ polarisation



+ polarisation

GW strain amplitude

- Einstein formula:

$$h \approx \frac{2}{r}\frac{G}{c^4}\frac{MR^2}{T^2} \approx \frac{\delta L}{L_0}$$

with $G = 6.67408 \times 10^{-11}\, m^3.kg^{-1}.s^{-2}$

$c = 2.99792 \times 10^{8}\, m.s^{-1}$

➔ h is… extremely small!!

1st detector condition

A gravitational wave detector has to be very sensitive!!

Sources luminosity

- The gravitational-wave luminosity of a source can be written as:

$$L \sim \frac{c^5}{G}\, \epsilon^2 \left(\frac{R_S}{R}\right)^2 \left(\frac{v}{c}\right)^6$$

where ε is the source asymmetry, R_S the Schwarzschild radius (describing the compactness of the source) , *R* the source radius, and *v* its velocity.

➔ to be a good GW emitter, a source needs to be **asymmetric** ($\varepsilon \sim 1$), **compact** ($R_S/R \sim 1$), and **relativistic** ($v/c \sim 1$).

➔ astrophysical events

Neutron Stars merger

Black Holes merger

Superr

Kouign-amann

© Daniel Mettoudi

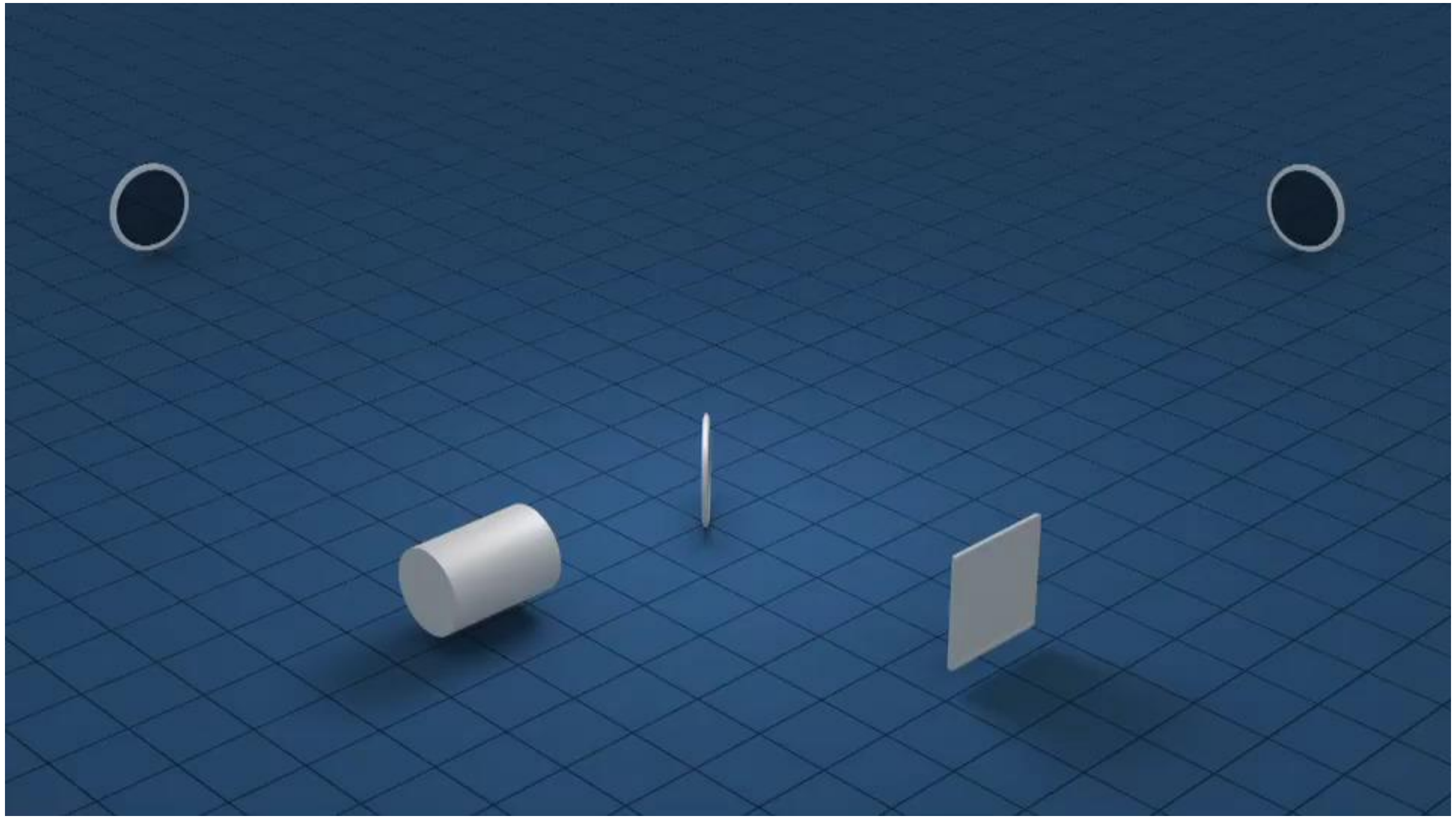
© NASA, ESA, J. Hester and A. Loll (Arizona State University)

© SXS Collaboration/Canadian Institute for Theoretical Astrophysics/SciNet

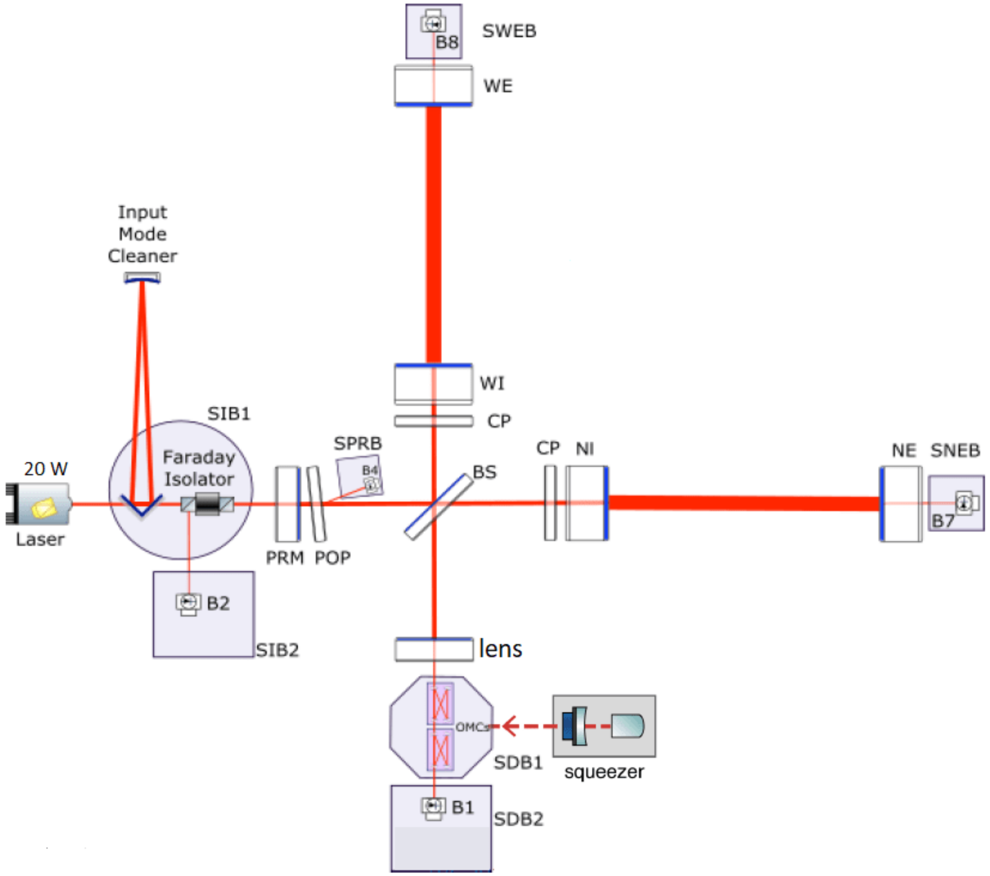
Outline

- Introduction
  - Gravitational waves basics
  - How to detect gravitational waves?
  - Detections
- Three-mode parametric instabilities

Ground-based interferometer for GW detection



What is Virgo?



- Michelson interferometer (ITF)
  → **direct detection** of gravitational waves
- 3 km arms with **Fabry-Perot** cavities to increase the light path
- Working point @ **dark fringe** (destructive interferences)
- **Power Recycling mirror** that reflects the light back to the ITF increasing the power in the ITF.
- Real-time active control of the working point:
  Sensing: **photodiodes**
  Actuation: **mirrors**, **suspensions**, **laser**
- Large optics (mirrors) contained in **superattenuator towers (inverted pendulums)**. They are the test masses that perceive the space-time variations induced by GW.
- Small optics (telescopes, photodiodes) on **suspended benches**
- Laser:
  wavelength = **1064 nm**
  input power = **12-25 W continuous**

Outline

- Introduction
  - Gravitational waves basics
  - How to detect gravitational waves?
  - Detections
- Three-mode parametric instabilities

Observation Runs

- For any GW detector, observation phases last for a certain time, called an Observation run.
- Between two Observation runs, GW detectors are upgraded.
- The first detection GW150914 occurred during the Observation run 1 (O1). The first triple detection GW170814 occurred during O2.
- **Since 1 April 2019, O3 has started** and will last for a whole year. At present, only potential candidates to GW events have been recorded and one will need several months for confirmation.


09/2015 – 01/2016: LIGO

11/2017 – 08/2018: LIGO
08/2018: + Virgo

04/2019 – 10/2019: LIGO/Virgo

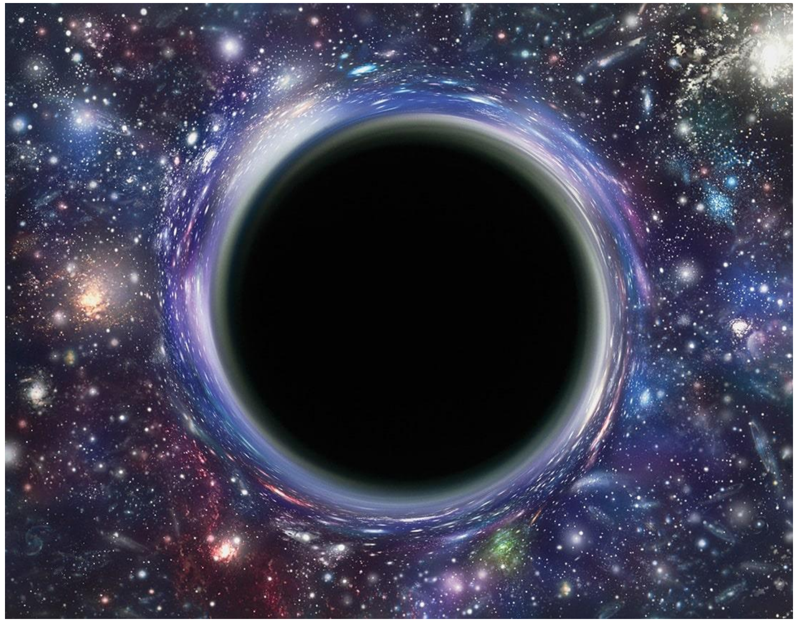
11/2019 – 04/2020 LIGO/Virgo

A couple of interesting links

Virgo news: http://www.virgo-gw.eu/

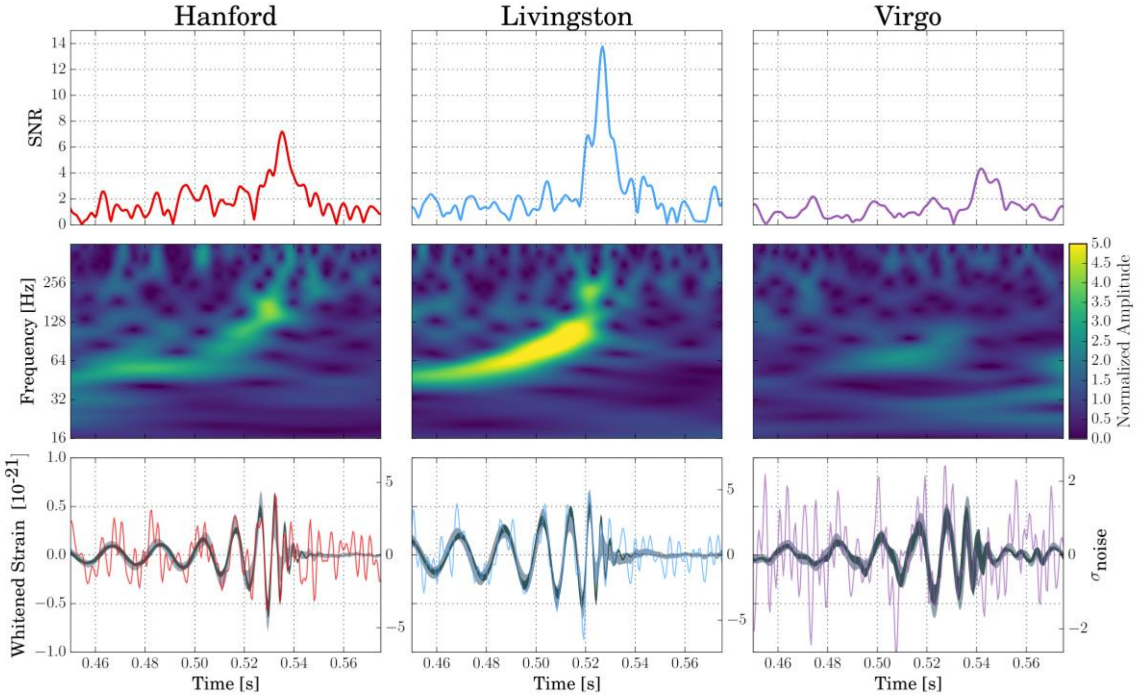
Potential candidates: https://gracedb.ligo.org/superevents/public/O3/

App to keep track of the latest gravitational wave alerts: http://chirp.sr.bham.ac.uk



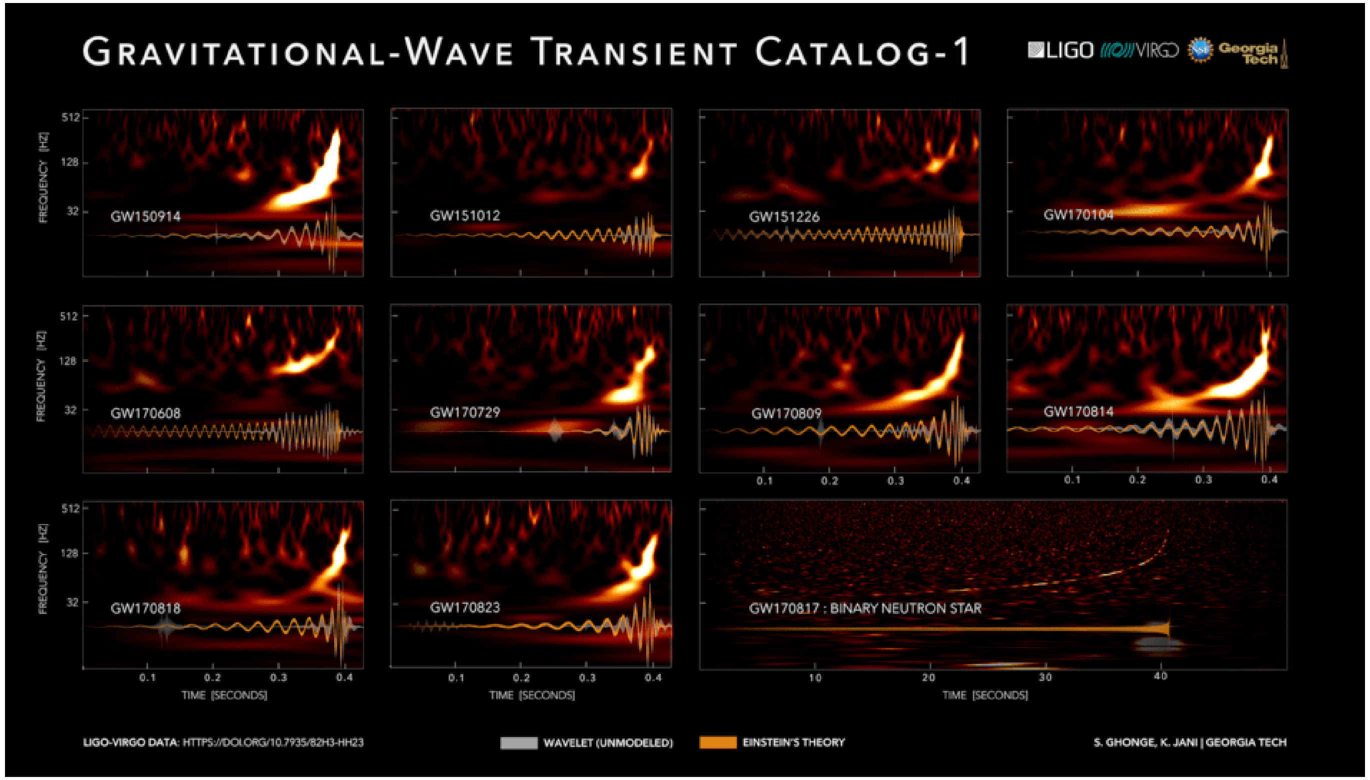
© Mehau Kulyk/Science Photo Library

Detections



GW170814: the **first triple detection** (LIGO + Virgo) of a **binary black hole merger**

Detections



LIGO Scientific Collaboration and Virgo Collaboration/Georgia Tech/S. Ghonge & K. Jani, CC BY-SA 4.0, not modified

2nd detector condition

A gravitational wave detector system control has to be very stable!!

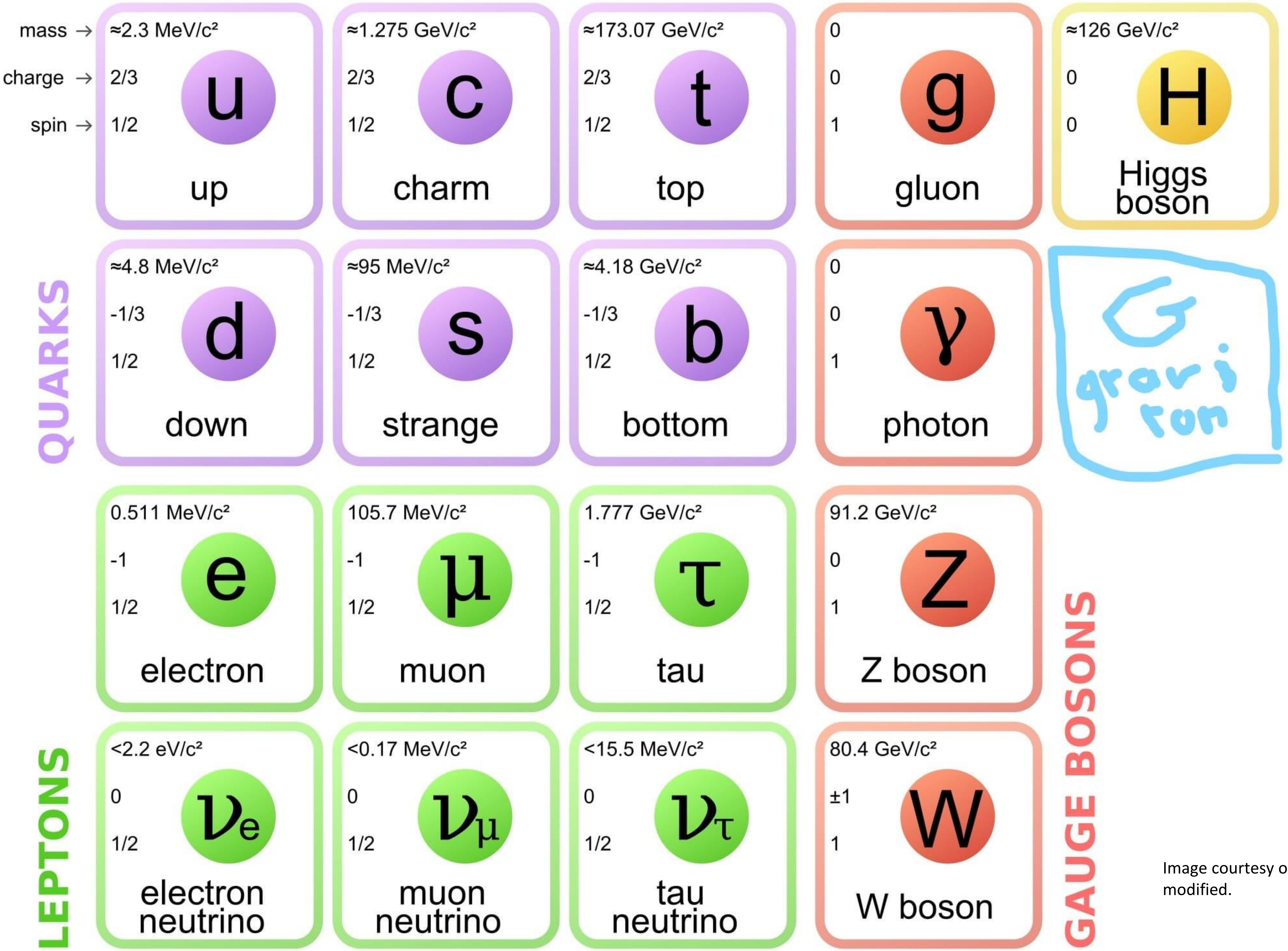


Image courtesy of Wikimedia Commons, modified.

Three-mode parametric instabilities

AKA only 'parametric instabilities' (PI)

Parametric gain

There are many sources of noise that limit the interferometer sensitivity (hence its observable range). One of the fundamental ones is the shot noise, describing the discontinuous property of photons (Poisson distribution):

$$\tilde{h} \propto P_{laser}^{-1/2}$$

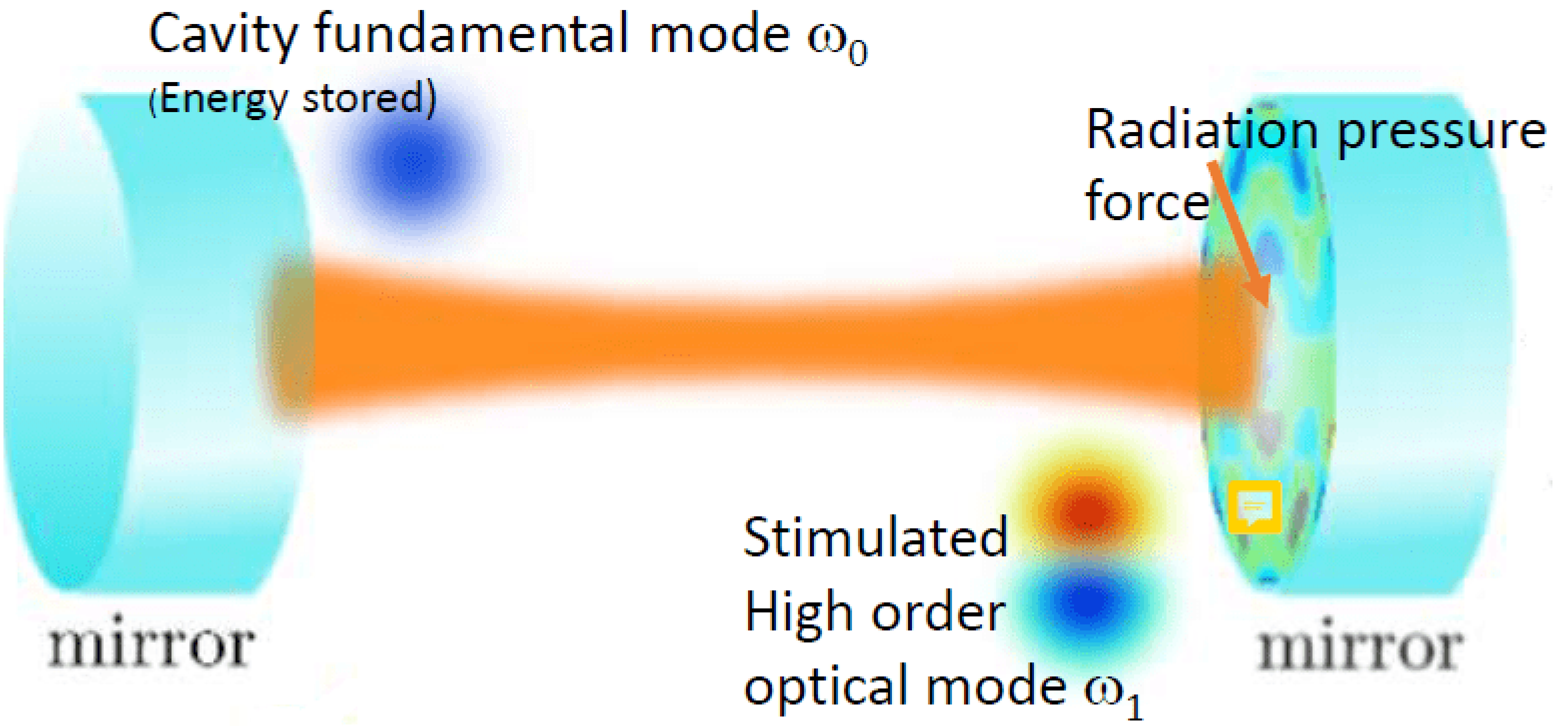
So, the higher the laser power, the lower the noise, the higher the sensitivity.

However, the three-mode (or optomechanical) parametric instability gain (explained right after), is proportional to the laser power input:

$$R_m \propto P_{laser}$$

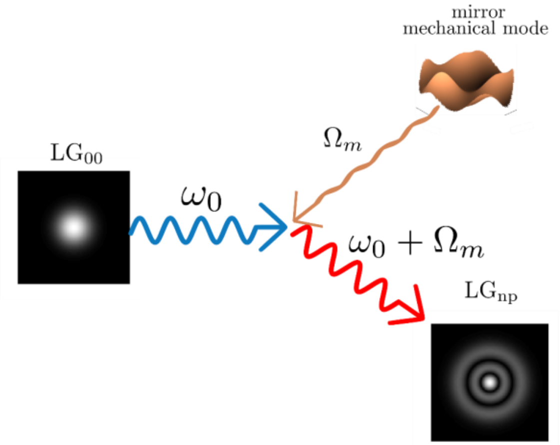
So, the higher the laser power, the higher the instability, the lower the stability (control of the interferometer).

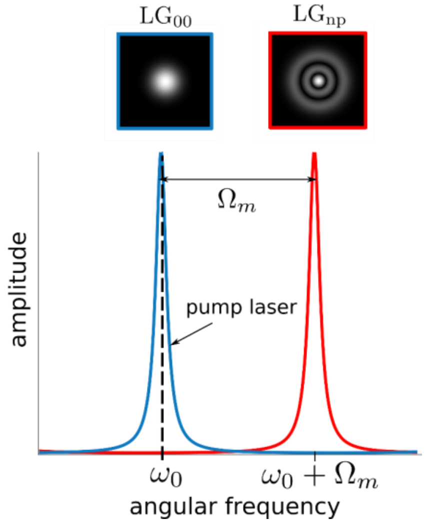
3-mode interaction



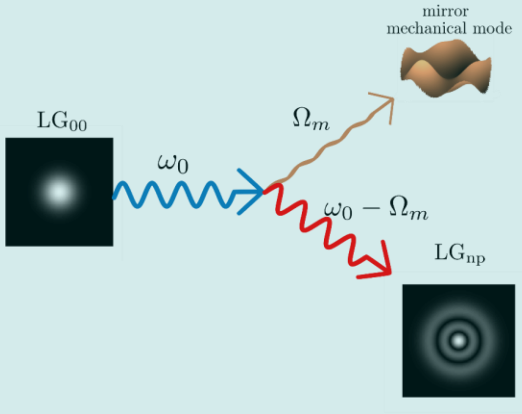
3-mode interaction

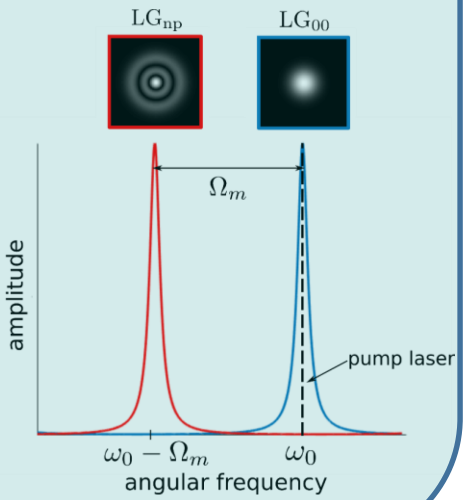
Anti-Stokes process: cooling





Stokes process: heating

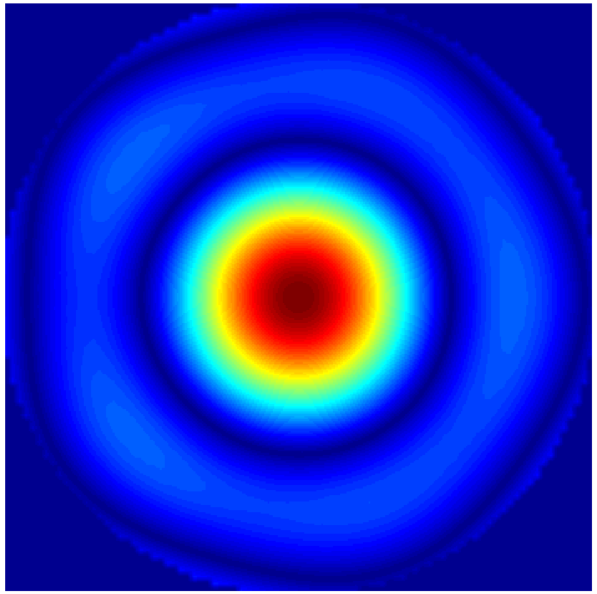


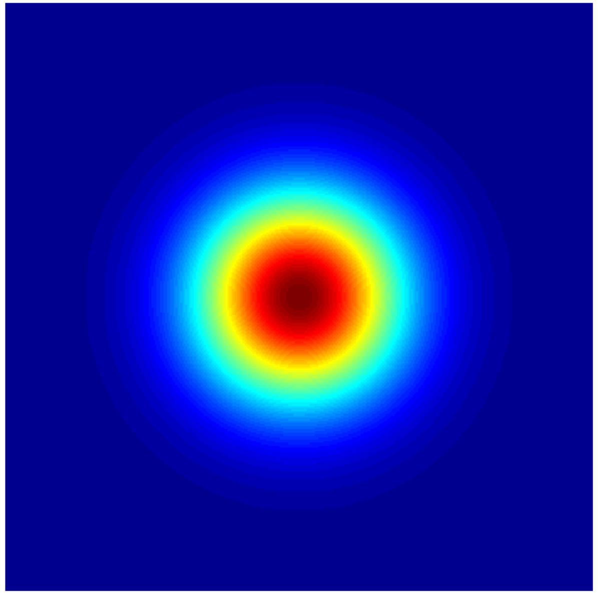


Mechanical and optical modes overlap

Mechanical mode

Optical mode





Parametric gain

mechanical mode quality factor

power travelling through the arm (Fabry-Perot cavity)

optical gain (function of mechanical mode frequency, cavity lengths, Gouy phase, mirror reflectivities)

$$R_m \propto \frac{Q_m P_{arm}}{M\omega_m^2\lambda} \sum_{all\ beam\ modes\ n} \{optical\ gain\}_n \times \{overlap\}_{n,m}$$

mass of the mirrors

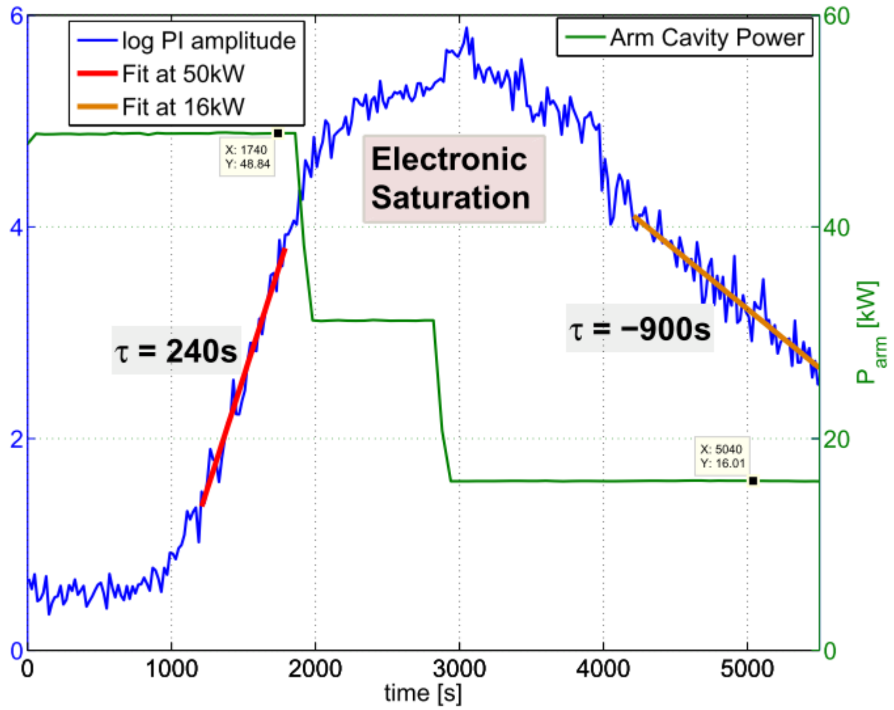
mechanical mode pulsation

laser wavelength

spatial overlap between optical mode and mechanical mode

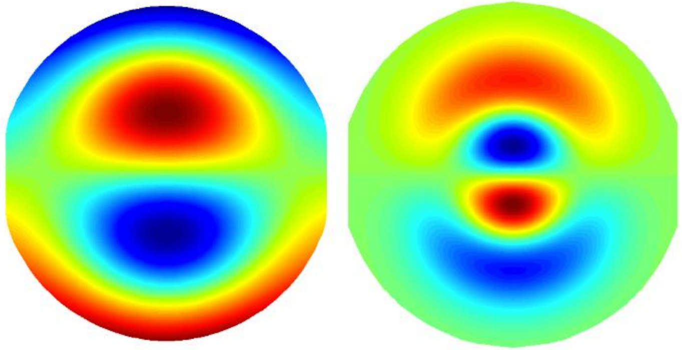
The mechanical mode is unstable if its parametric gain R_m is higher than 1.

Parametric instabilities (PI) at LIGO



$$\tau_m = \frac{2Q_m}{\omega_m(R_m - 1)}$$

The instability rings up until the electronics begins to saturate, at which point the control of the interferometer is lost. Before the electronic saturation, the growth was long enough for them to try to decrease the laser power input.

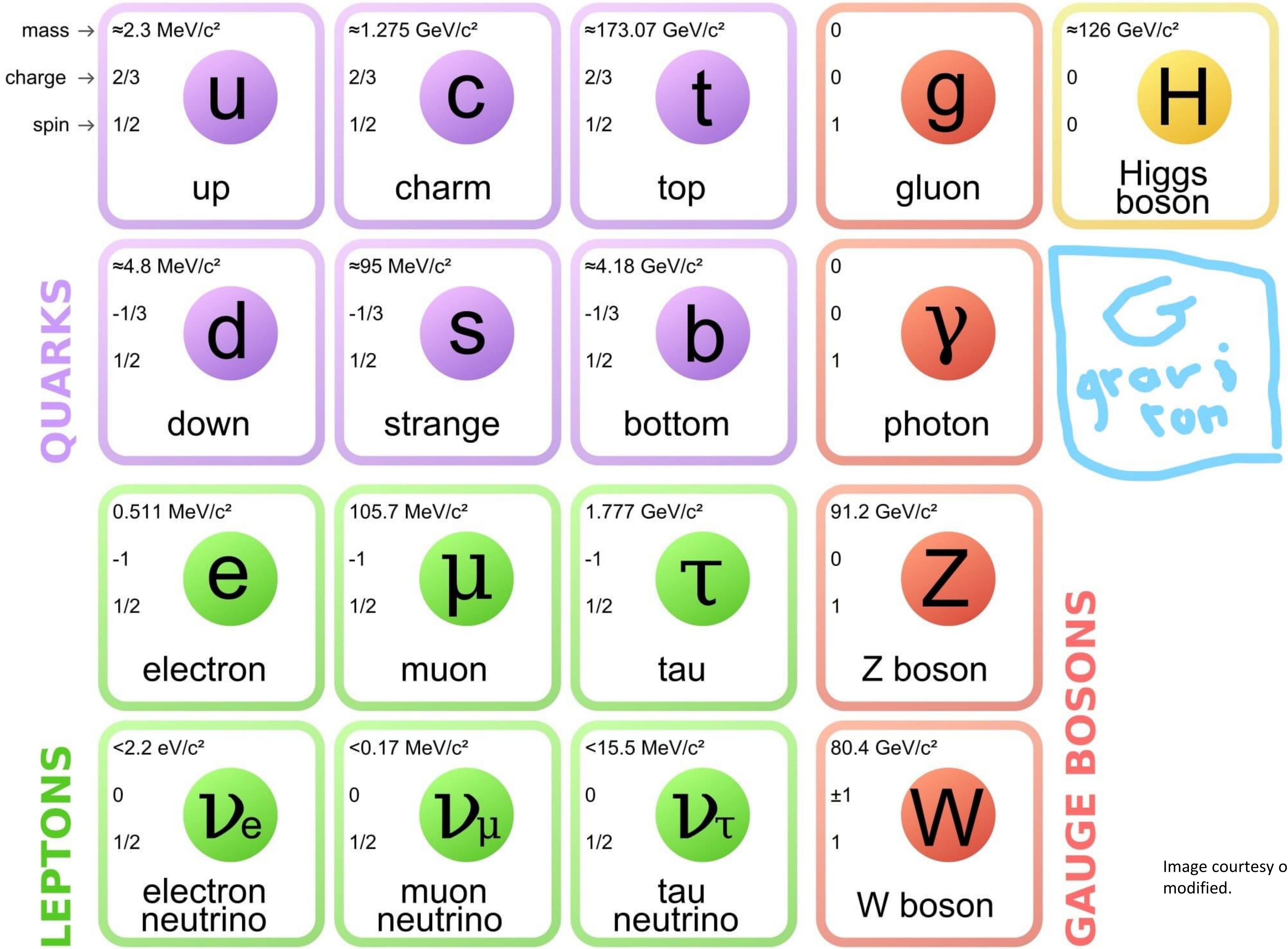


Mechanical mode (15.5 kHz)

Optical Mode

The mechanical mode and the optical mode responsible for the PI.

Evans et al, *Phys. Rev. Lett.* 114.16 (2015): 161102



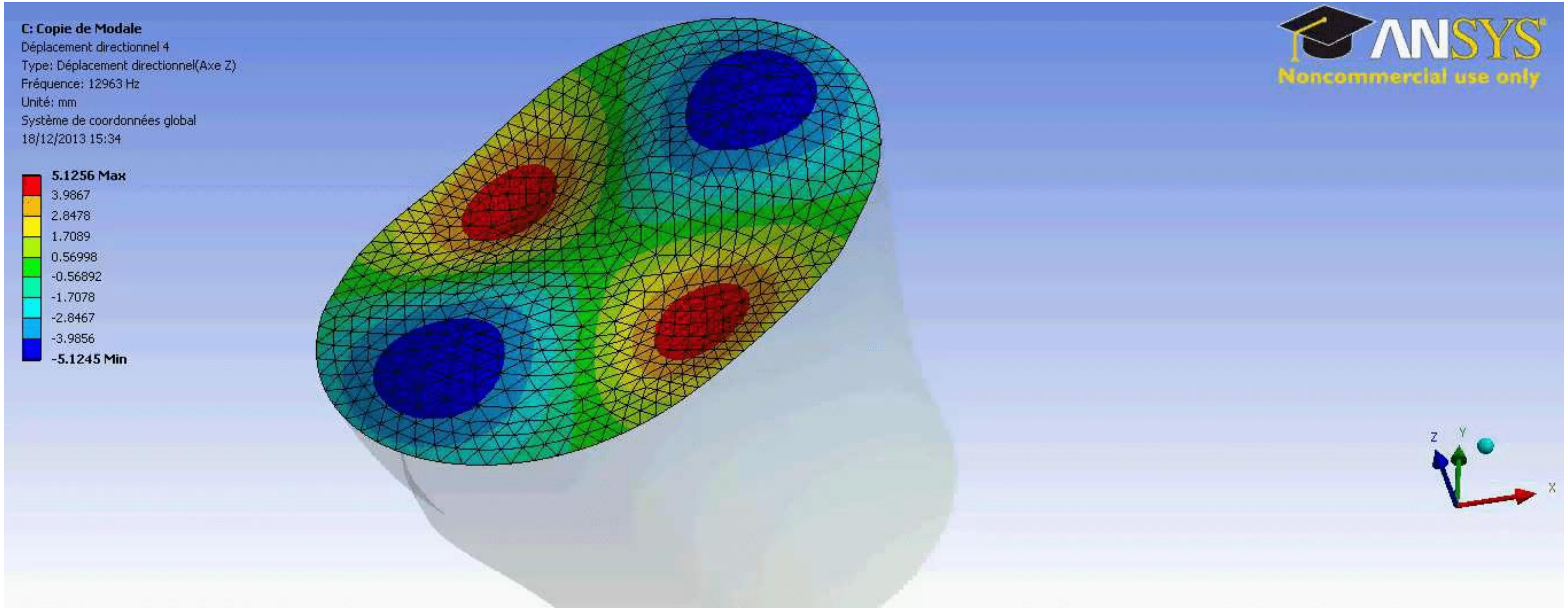
mass → charge → spin →	≈2.3 MeV/c² 2/3 1/2 u up	≈1.275 GeV/c² 2/3 1/2 c charm	≈173.07 GeV/c² 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c² 0 0 H Higgs boson
QUARKS	≈4.8 MeV/c² -1/3 1/2 d down	≈95 MeV/c² -1/3 1/2 s strange	≈4.18 GeV/c² -1/3 1/2 b bottom	0 0 1 γ photon	G graviton
	0.511 MeV/c² -1 1/2 e electron	105.7 MeV/c² -1 1/2 μ muon	1.777 GeV/c² -1 1/2 τ tau	91.2 GeV/c² 0 1 Z Z boson	GAUGE BOSONS
LEPTONS	<2.2 eV/c² 0 1/2 ν_e electron neutrino	<0.17 MeV/c² 0 1/2 ν_μ muon neutrino	<15.5 MeV/c² 0 1/2 ν_τ tau neutrino	80.4 GeV/c² ±1 1 W W boson	

Image courtesy of Wikimedia Commons, modified.

Outline

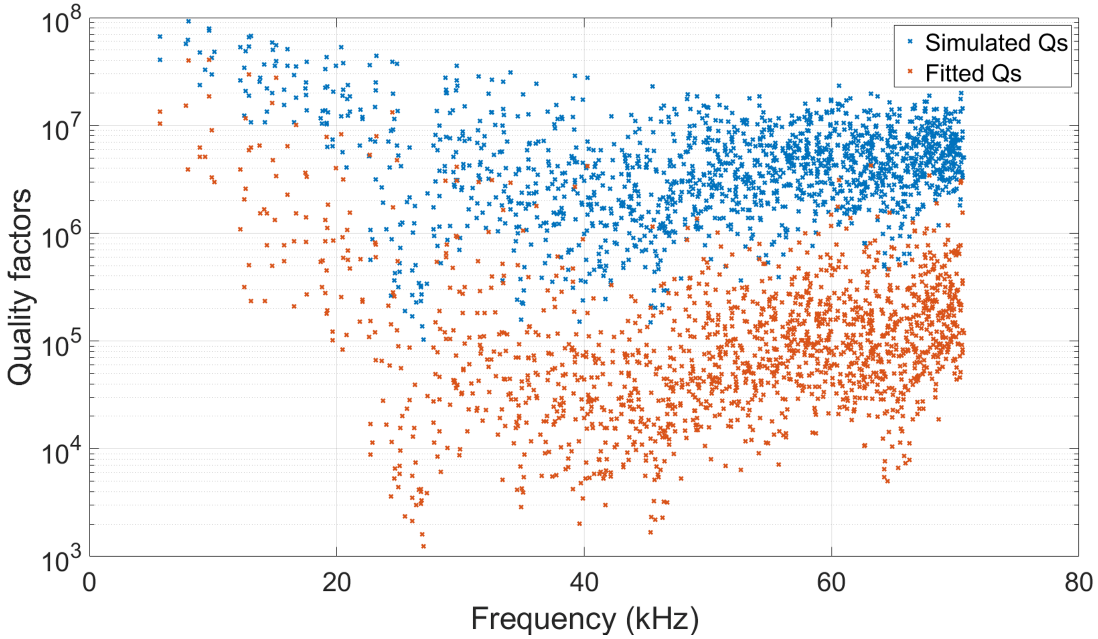
- Introduction
  - Gravitational waves basics
  - How to detect gravitational waves?
  - Detections
- Three-mode parametric instabilities
  - Basics
  - At Virgo

Mechanical modes computation



C: Copie de Modale
Déplacement directionnel 4
Type: Déplacement directionnel(Axe Z)
Fréquence: 12963 Hz
Unité: mm
Système de coordonnées global
18/12/2013 15:34

Mechanical modes' quality factors (Qs)



- On the left panel are displayed two different sets of Qs. The 'fitted' ones are closer to the real ones, because they were fitted from a measurement.
- A new set is being measured: so far, measured Qs are even lower than the 'fitted' ones.
- LIGO mirrors' mechanical modes have higher Qs.

Recall of the parametric gain relation

$$R_m \propto \frac{Q_m P_{arm}}{M\omega_m^2\lambda} \sum_{all\ beam\ modes\ n} \{optical\ gain\}_n \times \{overlap\}_{n,m}$$

These are lower than those ‘fitted’, which are lower than those ‘simulated’, which are lower than those from LIGO! → Virgo is less likely to face PI!

Homemade code for PI computation

- Analytical method taken from Evans *et al*. "A general approach to optomechanical parametric instabilities." *Physics Letters A*374.4 (2010): 665-671

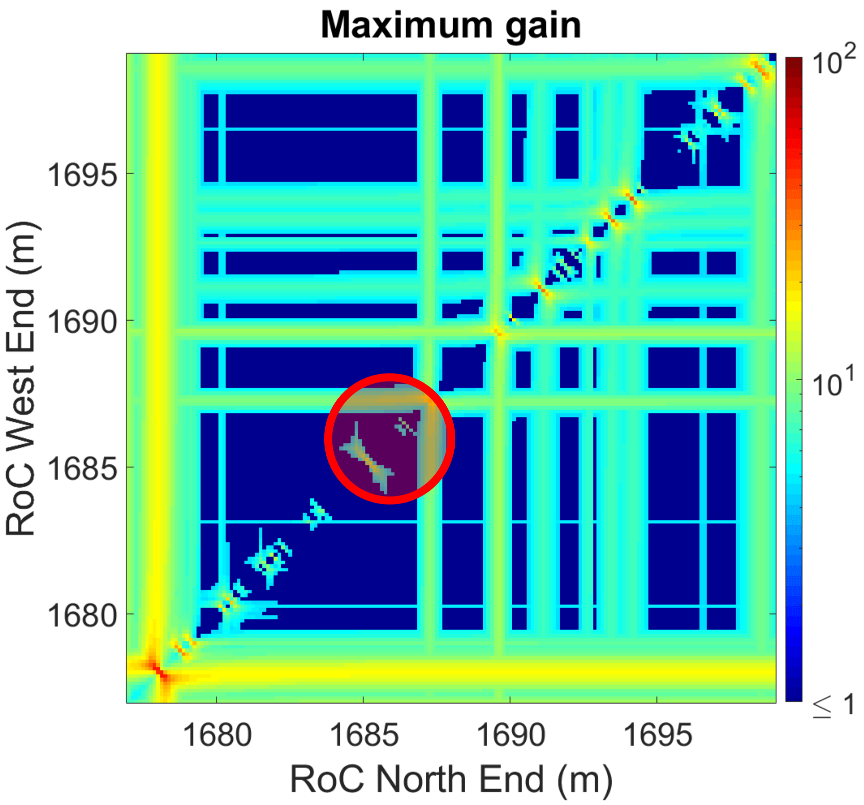
➔Matlab Oriented Object Programming (OOP) code

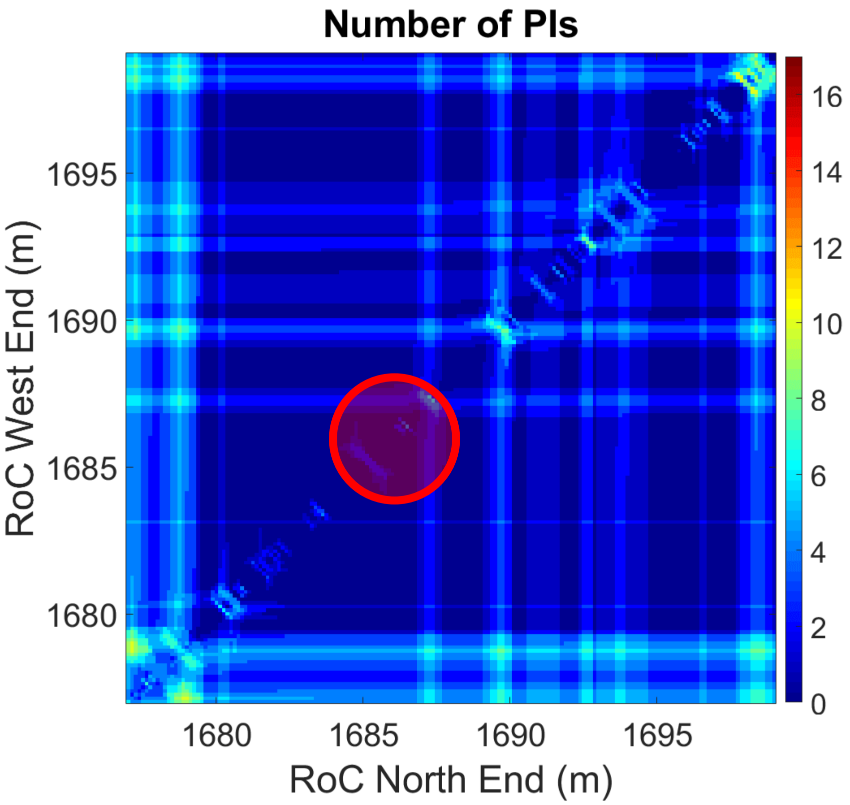
\+

Graphical User Interface (GUI)

What kind of results do we get?

With all mechanical Q factors set to 10^7



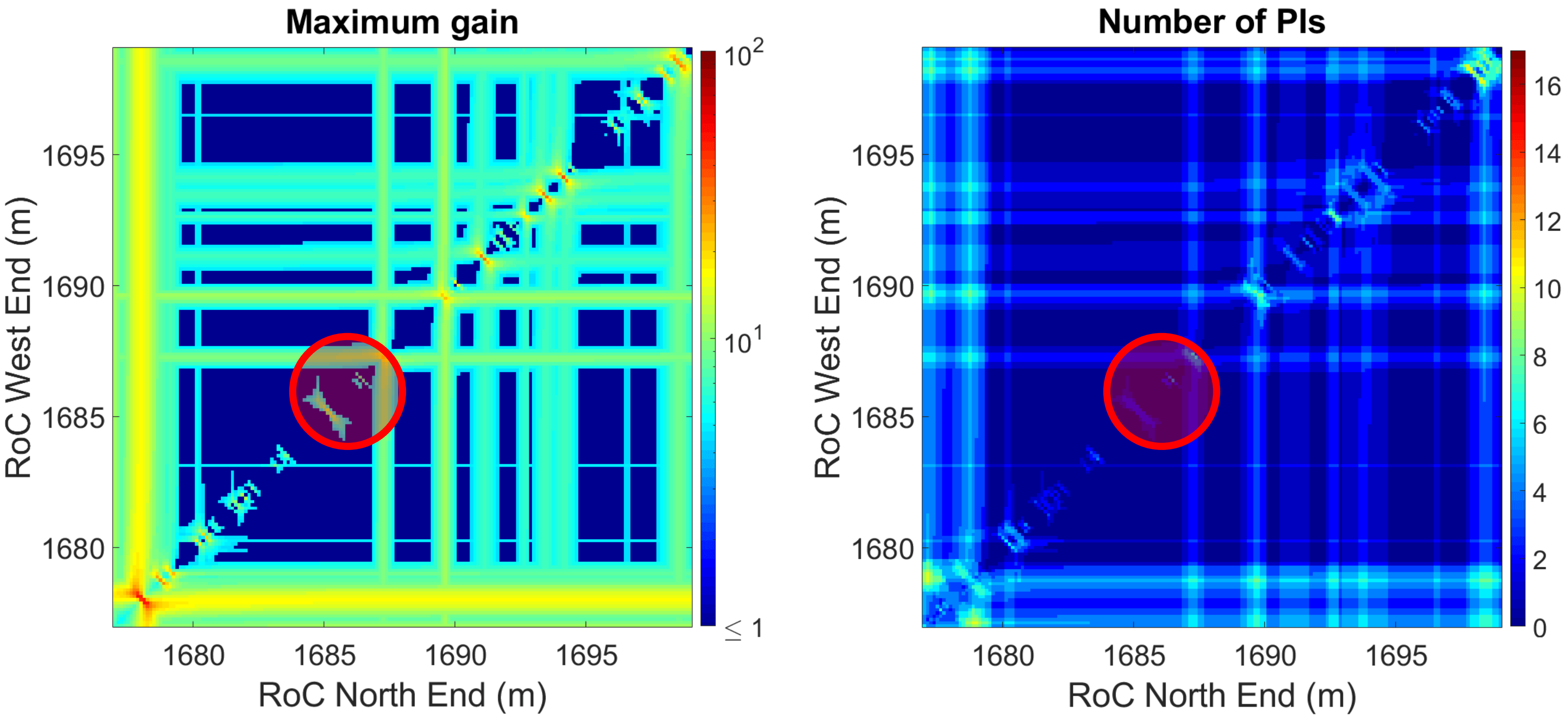


Radii of curvatures (RoC) of the two END mirrors are scanned over a chosen range in order to take various uncertainties into account.

The Virgo working point (WP) has been measured: around 1686 m for both END mirrors.

What kind of results do we get?

With all mechanical Q factors set to 10^7

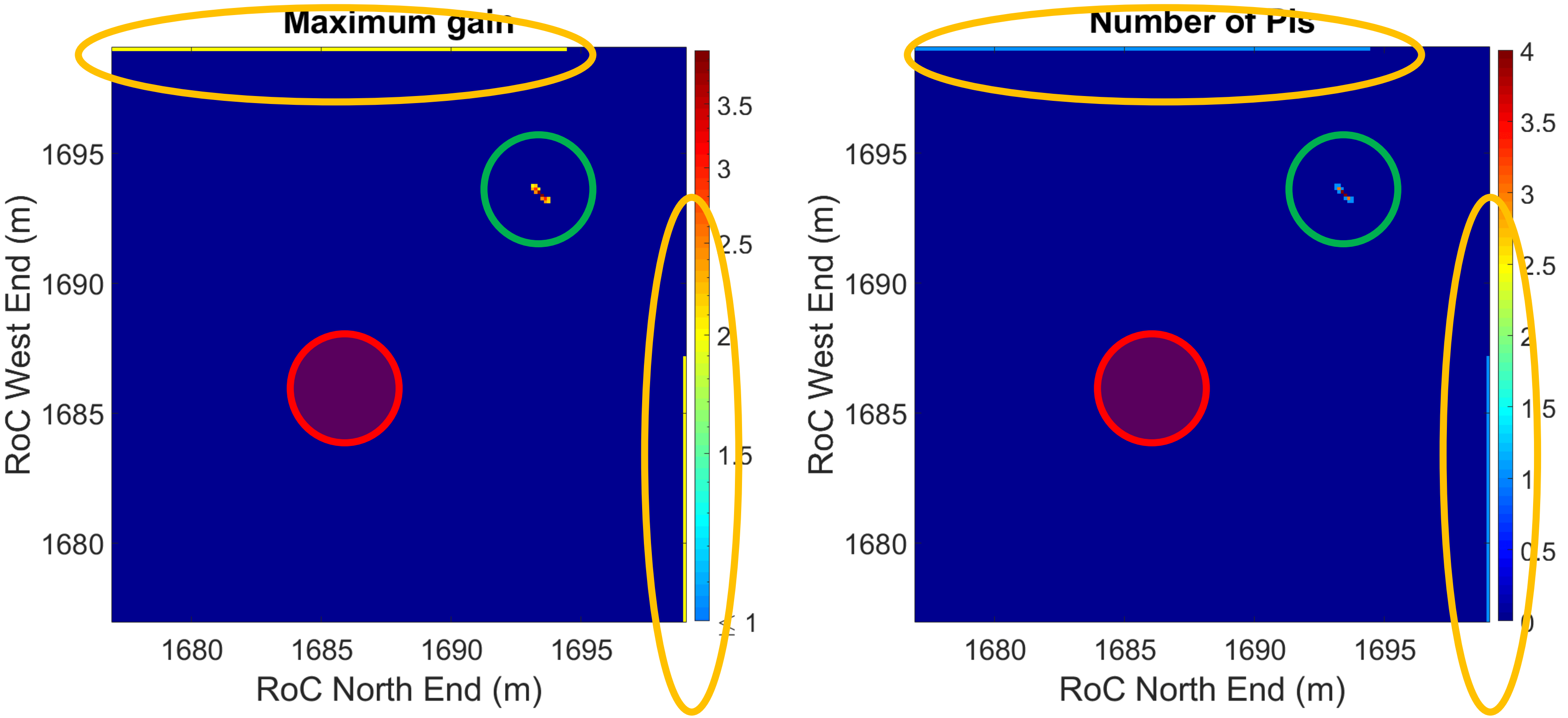


For each configuration (here it is a position in terms of radius of curvature), there are from 0 to less than 20 unstable mechanical modes.

Each mechanical mode resonates at a certain radius of curvature. So one can get back to the unstable mode thanks to this kind of map.

What kind of results do we get?

With all ‘fitted’ quality factors

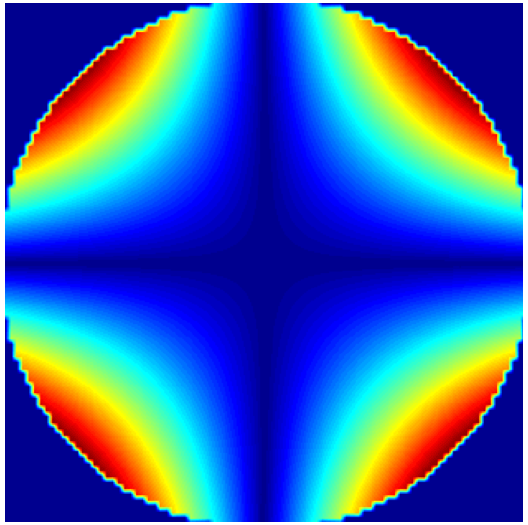


In a more real situation, Virgo should not face any PI for the O3 setting, as one can see here. This is mainly due to the very low mechanical Qs.

The two unstable mechanical modes, the **12.516 kHz**, and the **12.914 kHz**, are quite far away from the **WP**.

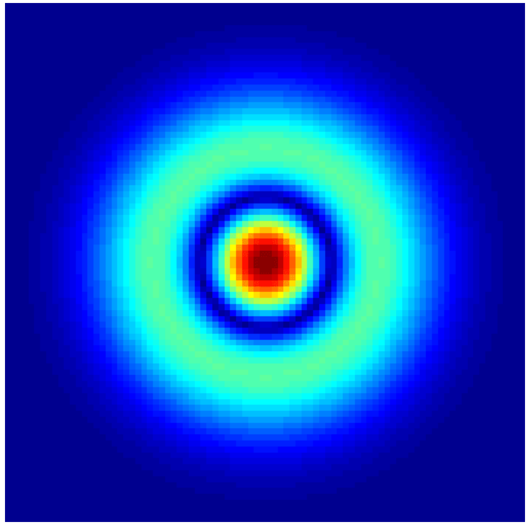
What kind of results do we get?

Mechanical mode

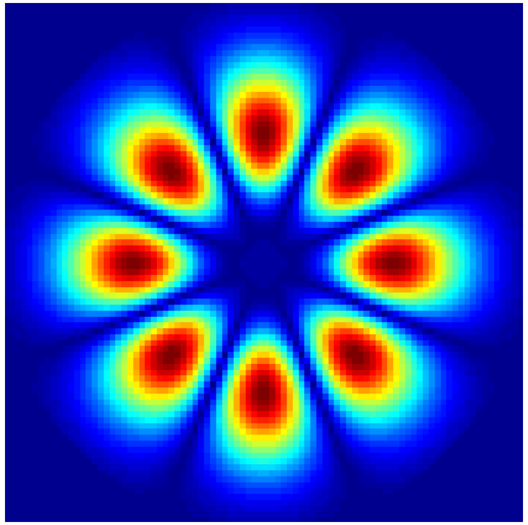


12.516 kHz

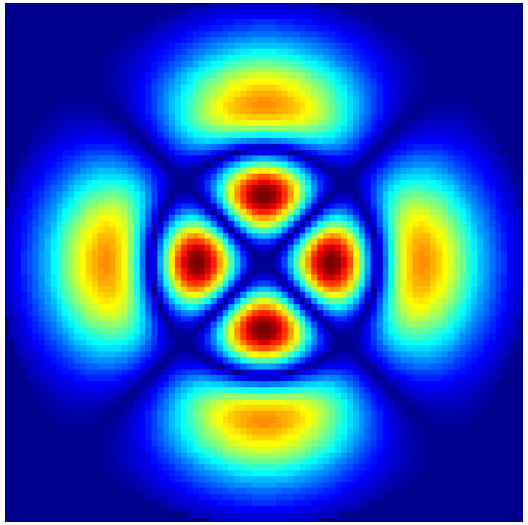
Main contributing optical modes



Order 2



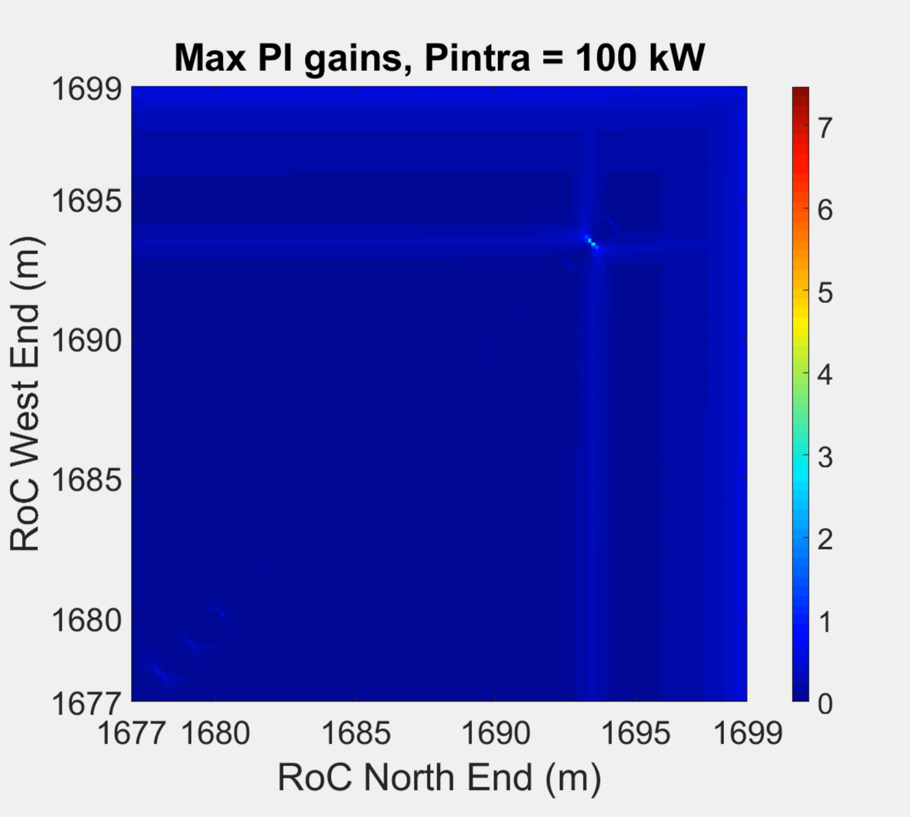
Order 4

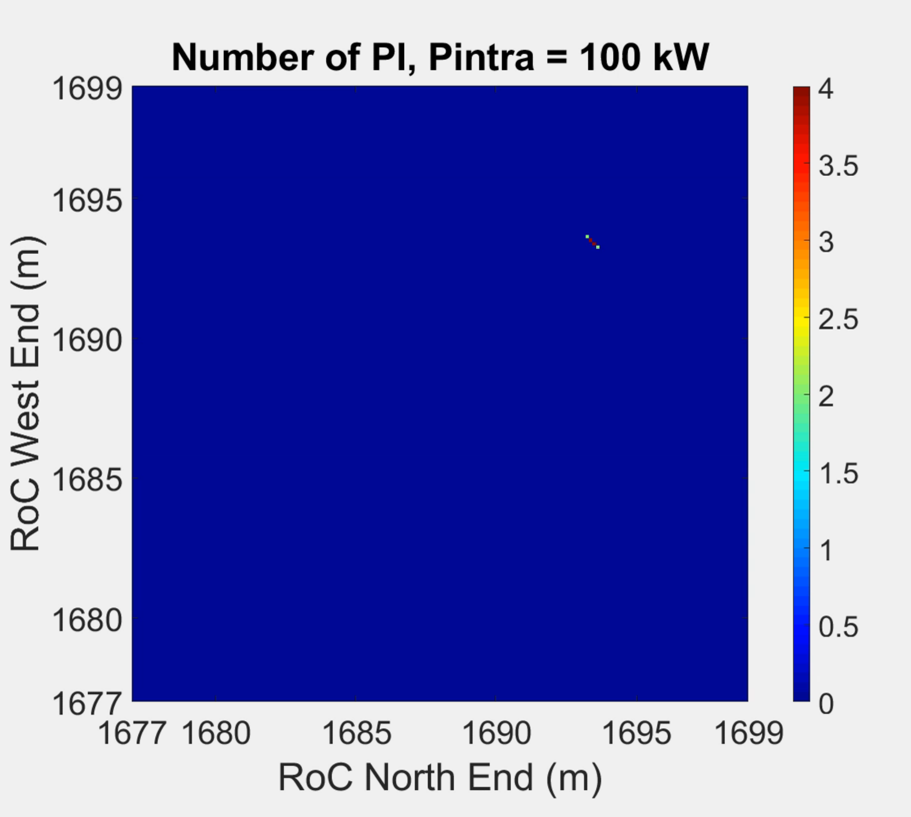


Order 4

As one can see, the overlap is not obviously the main contributor to the parametric gain.
The optical gain plays an important role as well!

Evolution of the instabilities when the input power increases



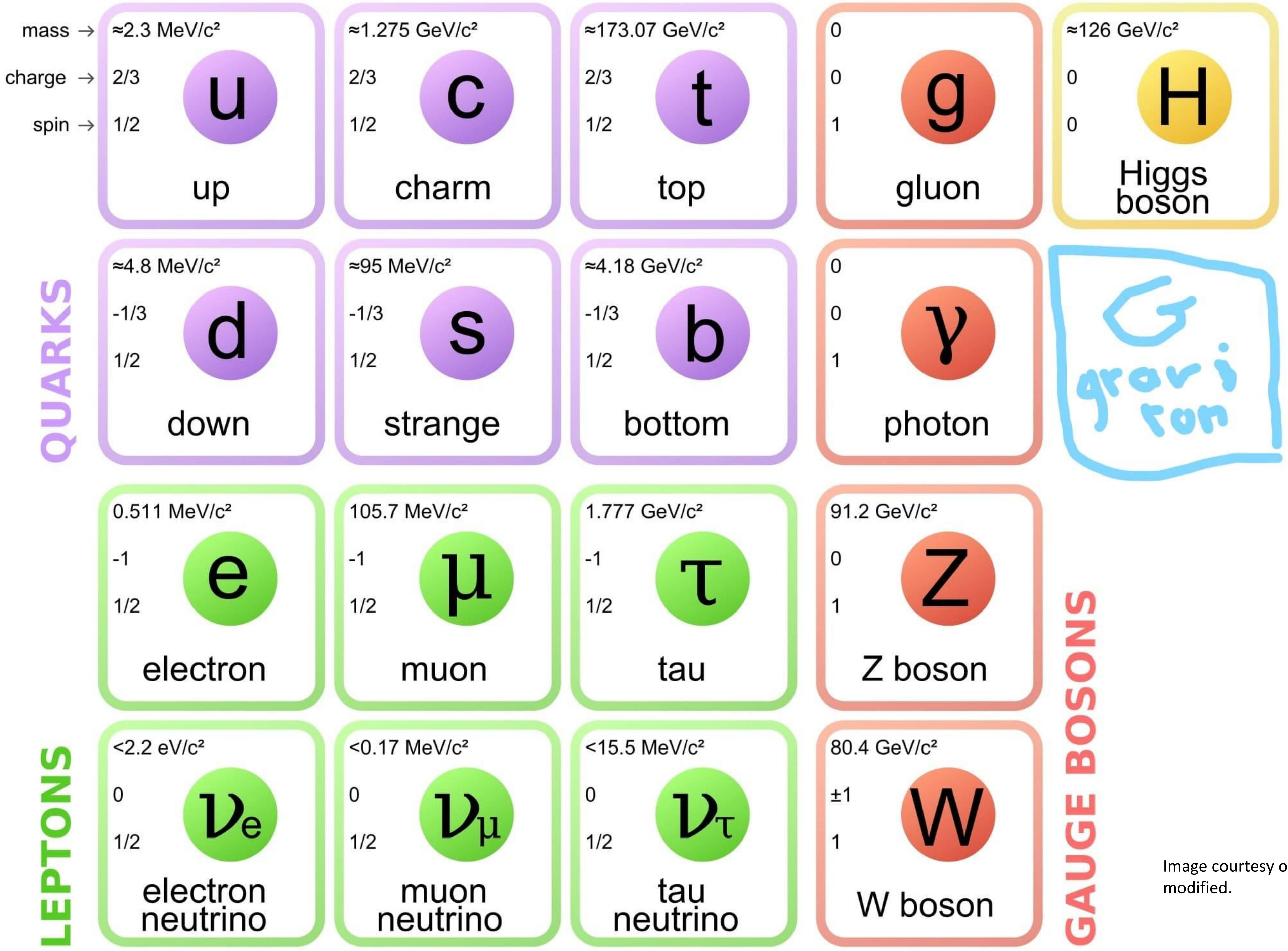


At present

- Virgo has never observed any optomechanical parametric instabilities so far. Our simulations helped endorse the fact that none is foreseen with the current O3 configuration.
- With the same configuration, the intracavity power can be increased up to about 1500 kW.
- However, the next Virgo configurations should be quite different.

Next steps

- Perform a simulation for the O4 configuration, that is with a higher laser power input, and with an extra mirror, thus creating a new optical cavity in the interferometer (Signal Recycling Cavity).
- Perform a simulation for the O5 configuration, that is with an even higher laser power input, and new mirrors.
- Perform a simulation for the LIGO configuration as an extra sanity check. Indeed, they observed some of these instabilities at LIGO, therefore we should be able to find them with our program.



mass → charge → spin →	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	G graviton
	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson	GAUGE BOSONS
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson	

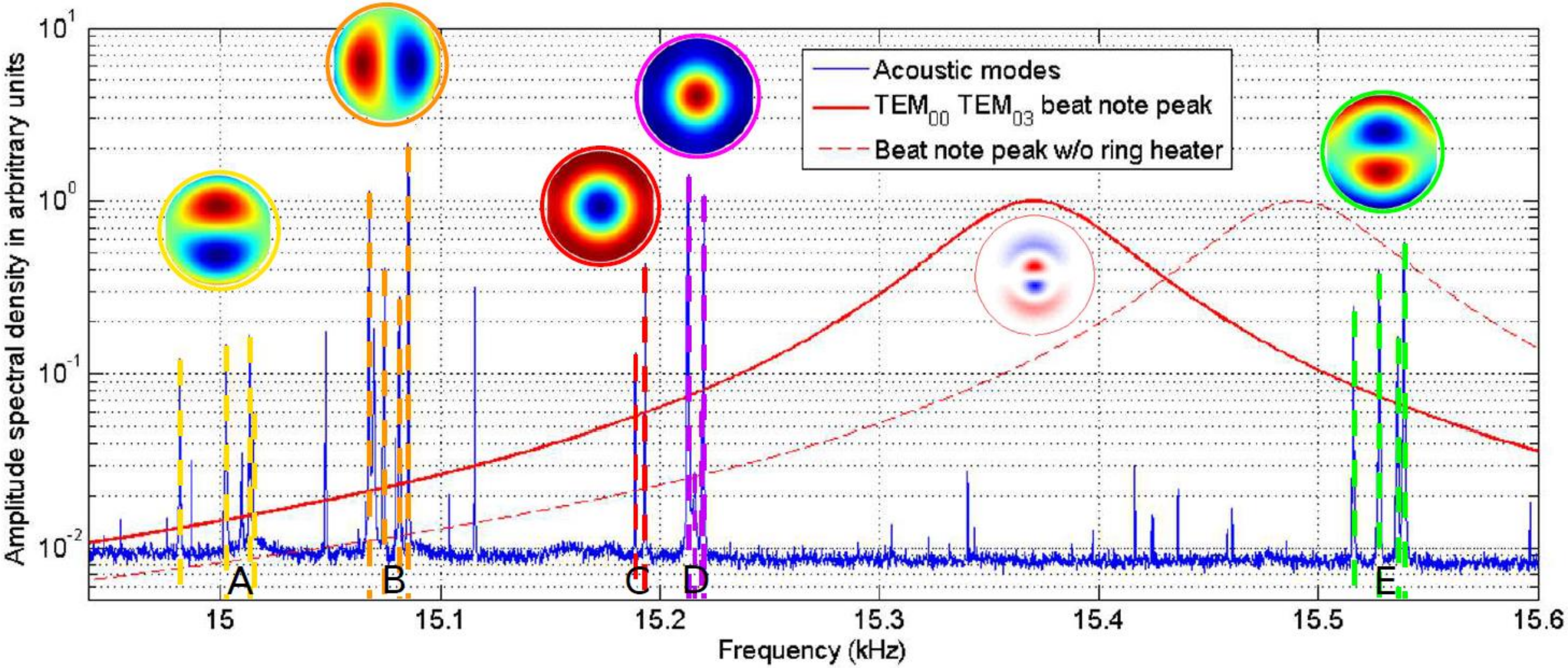
Image courtesy of Wikimedia Commons, modified.

trugarez

[/tʁy.ˈga.ʁe/]

Spare slides

Mitigation

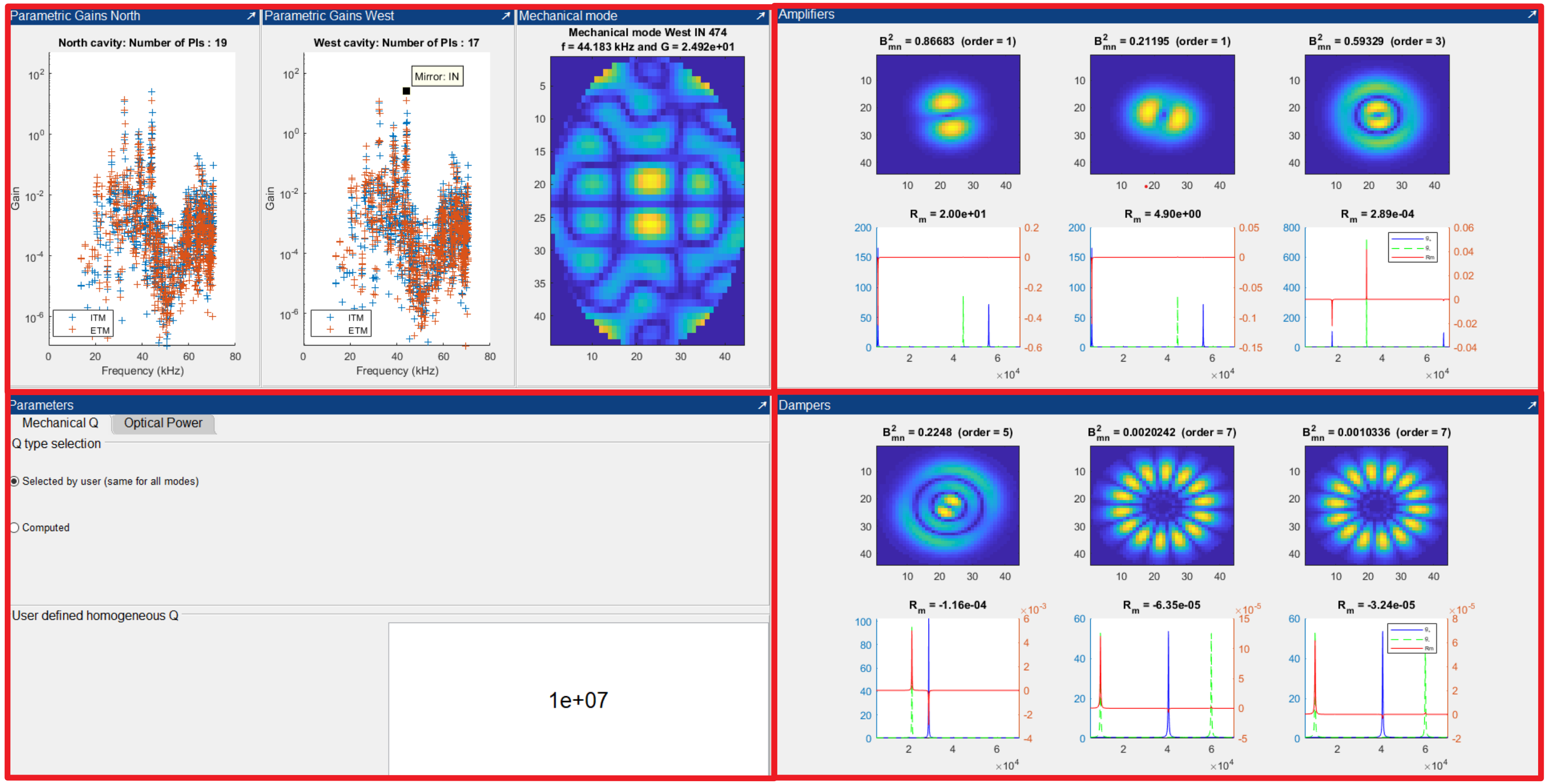


10^{1}
10^{0}
10^{-1}
10^{-2}
Amplitude spectral density in arbitrary units
Acoustic modes
TEM_{00} TEM_{03} beat note peak
Beat note peak w/o ring heater
A
B
C
D
E
15
15.1
15.2
15.3
15.4
15.5
15.6
Frequency (kHz)

GUI for commissioners

PI gains + associated mechanical mode to the selected PI

Settings panel



Q type selection

● Selected by user (same for all modes)

○ Computed

User defined homogeneous Q

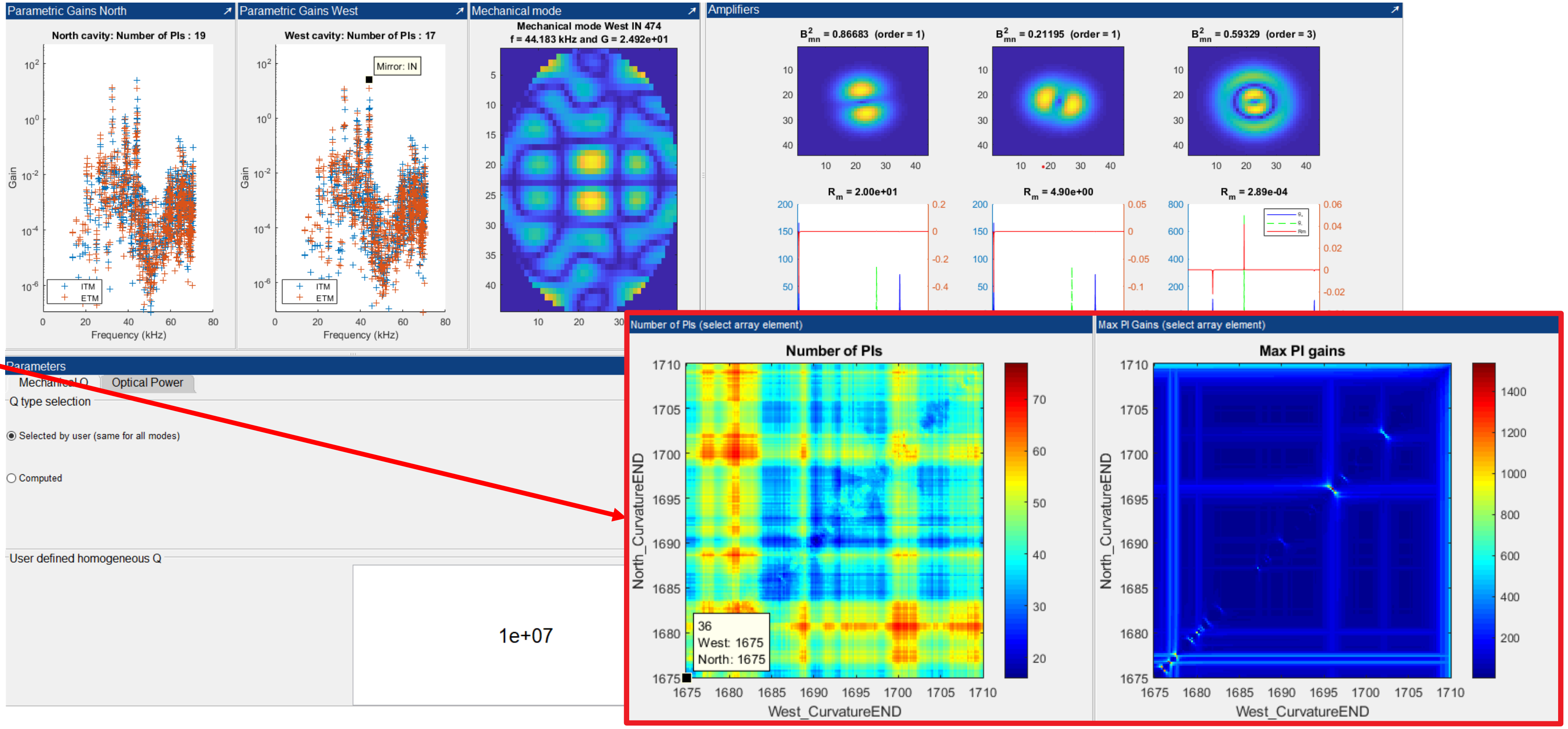
1e+07

Optical modes amplifiers contributing the most to the select PI

Optical modes dampers contributing the most to the select PI

GUI for commissioners

Panel to select the interferometer configuration, ie selecting both END mirrors RoCs
→ the first panel is modified accordingly



Parameters

Mechanical Q | Optical Power

Q type selection

● Selected by user (same for all modes)

○ Computed

User defined homogeneous Q

1e+07