Advanced Virgo commissioning challenges

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on behalf of the Virgo collaboration

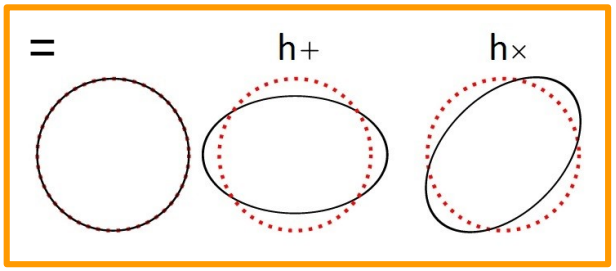
GW detectors network

- **Effect** on Earth of the passage of a GW → *change on the distance between test masses*

Differential effect:

$$\delta L \sim h \cdot L$$

GW amplitude



Test mass:

mass that senses only the gravitational force

MICHELSON INTERFEROMETER + SUSPENDED MIRRORS

- **GW detectors network** → allow localization of GW sources

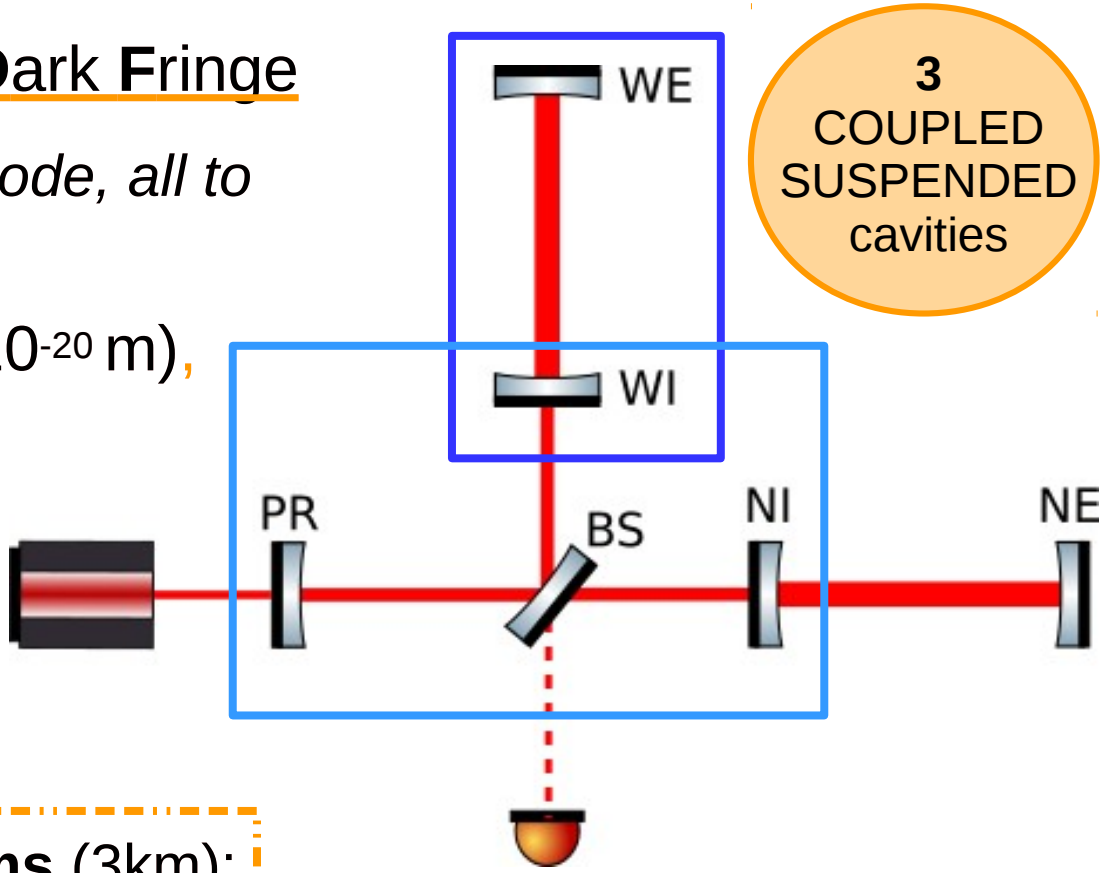
1st generation of GW detectors

- **Working point:** Michelson in **D**ark **F**ringe

  (No light goes back to the photodiode, all to the laser)

- GW passage will cause a δL (10^{-20} m), *spoiling the DF*

Simple Michelson **not enough sensitivity!!**



3 COUPLED SUSPENDED cavities

1) **Fabry-Perot cavities in the arms** (3km): increase the optical path ~400km!

2) **Power Recycling cavity:** increase the circulating power

1st generation instruments did not make any detection

Better sensitivity needed: **10 times more!**

2nd generation: Advanced Virgo

⇧ Increase the gain of the optical cavities:

- Arm cavities F = 450 (3x more than Virgo+)
- Power Recycling cavity gain = 37.5 (~30 in Virgo+)

⇩ Reduce fundamental noises:

- ***Increase the mirror masses***
- ***Geometry of the arm cavities*** changed → waist in the middle to increase beam size on the mirrors

⇩ Reduce diffused light

- Detection benches *suspended* and in *vacuum*
- New system of *baffles* in strategic places to *absorb diffused light*

⇩ Power Recycling cavity *more marginally stable*

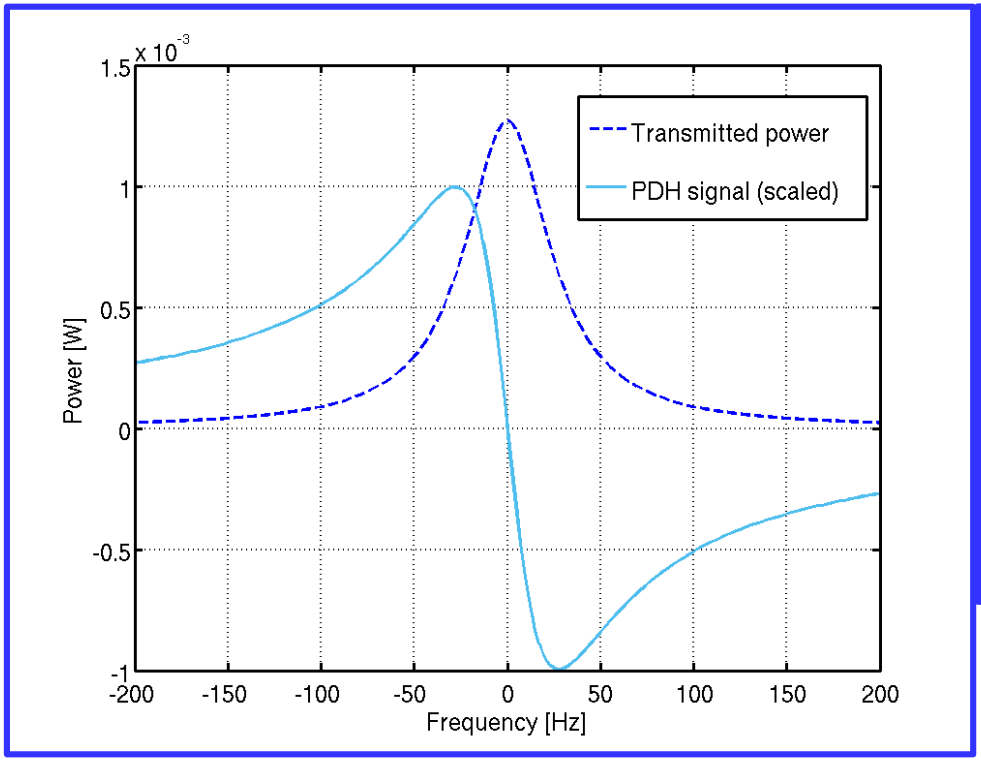
- *Thermal Compensation System* improved to deal with the PRC stability and with the future High Power Laser
  - ➔ *Ring Heater / Central Heating*

Arm cavities: Longitudinal control

- **Suspended mirrors + seismic noise** → cavity length is *continuously changing*
- We need to keep the cavities on their resonance point → **feedback control loop** is applied to the suspension system
  - **Error signal** that gives information about how far we are from the working point → Pound-Drever-Hall technique

RF phase modulation

- Create **sidebands** non-resonant in the arms (6MHz) → phase reference
- Error signal → beating sideband/carrier



Good error signal fulfills:

- Linear
- Bipolar
- Crosses zero at resonance

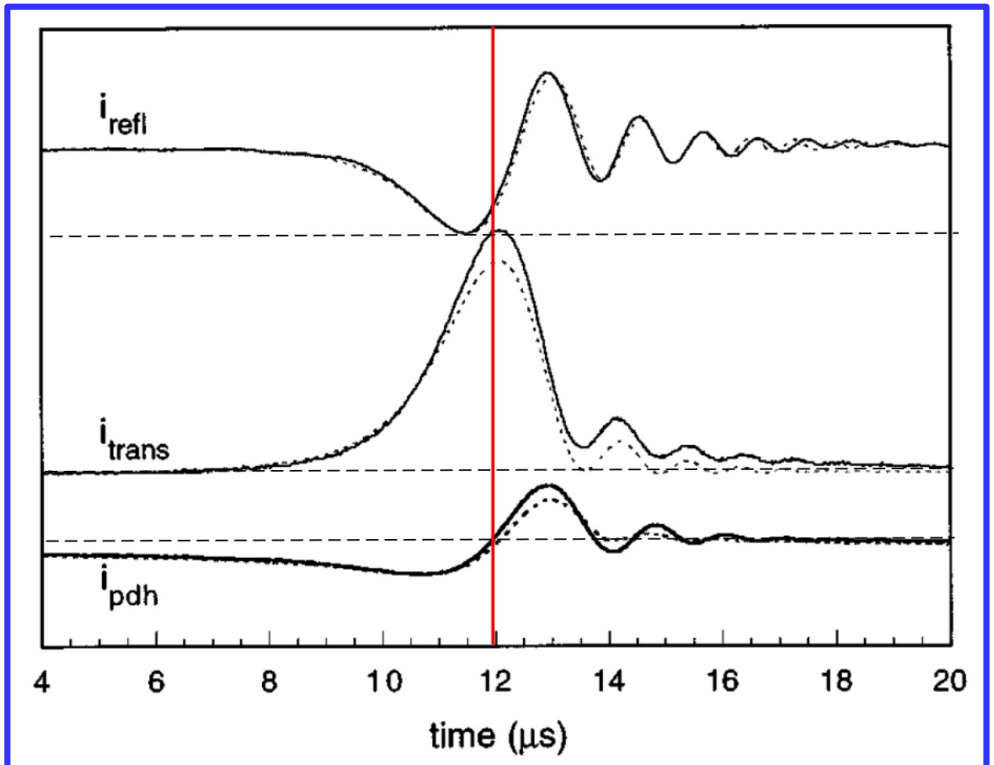
Arm cavities: Dynamical effects

- When a laser beam reaches a *swinging mirror* → **Doppler effect**
- The error signal gets distorted when the Doppler effect that *piles up each round-trip, reaches* ~linewidth of the cavity → **RINGING**

- Suspended cavities → mirrors free motion ~1um/s rms
- $V_{critical}$ is ~0.14 um/s for AdV arm cavities (10x smaller than in Virgo+)

Feedback loop can not be engaged with such an error signal!

NEED a new lock strategy!



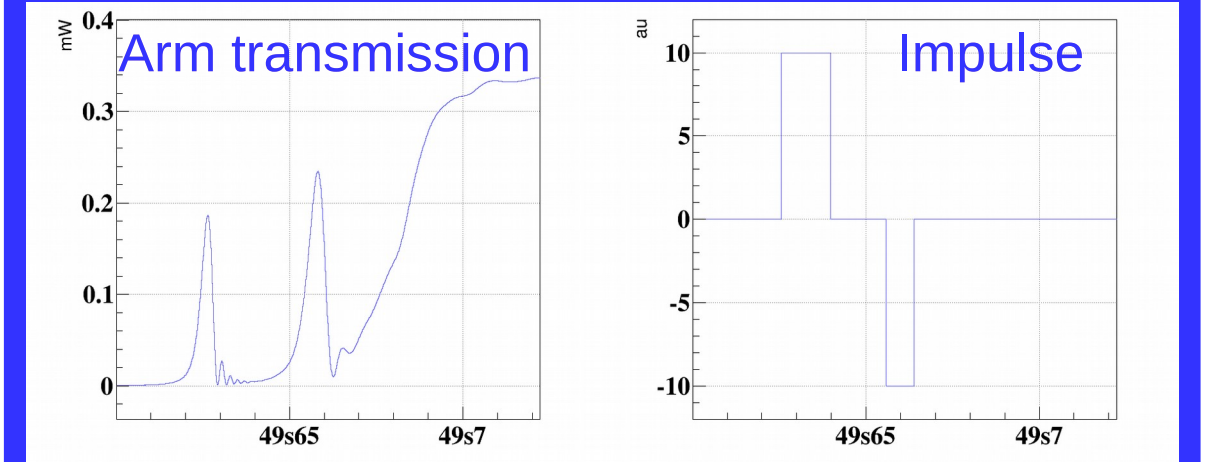
Wrong zero-crossing **+** asymmetrical around working point

Arm cavities: Guided Lock

- **Guided Lock** was first tested in Caltech (1995) and further improved in TAMA. *Already tested in Virgo+*.

Measure the *resonance crossing velocity* **online** and apply a *single extended impulse* with the maximum force available in order to bring the cavity *back to the resonance* but with a *lower velocity*

- Challenge is to <u>estimate the velocity online</u> → *slope of the PDH*
  - ✗ Needs **calibration** and a power law **correction for high velocities!**



In the *early stages of commissioning* this is **too demanding**

✔ **The arm cavities <u>first lock was on 24-05-2016</u> but the lock status was *not very robust***

Arm cavities: Guided Lock II

ALTERNATIVE method:

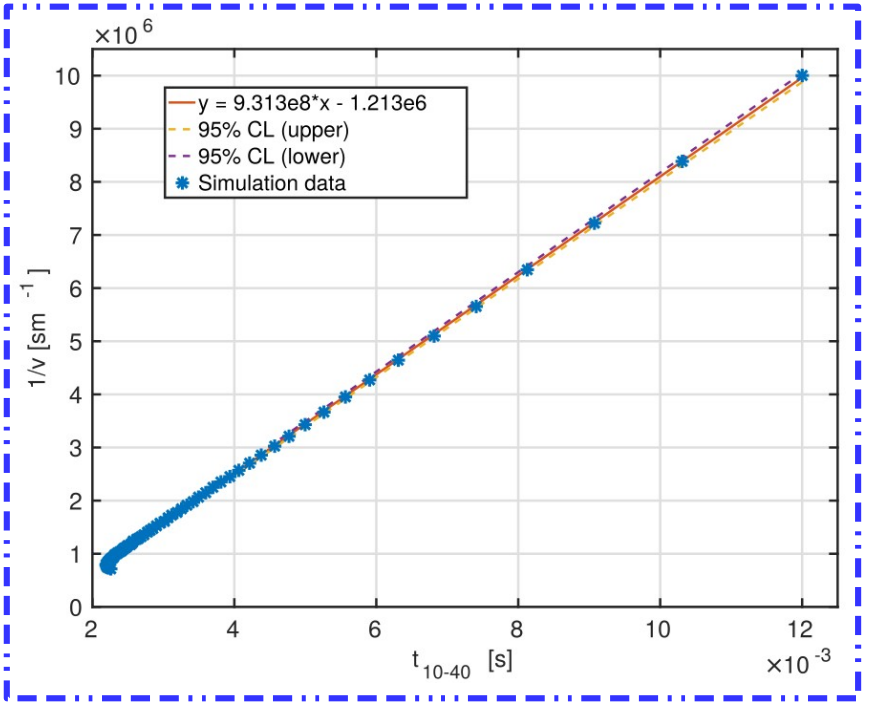
- **Time interval** necessary to pass from 10% to 40% of the transmitted cavity power on resonance
- Simulations showed that it exist a **linear relationship between 1/v and $\Delta t_{10\text{-}40}$**

ADVANTAGES:

- ✔ The velocity is calculated before passing the resonance → **Increase efficiency**
- ✔ No need of calibration, already **physical units**

DISADVANTAGES:

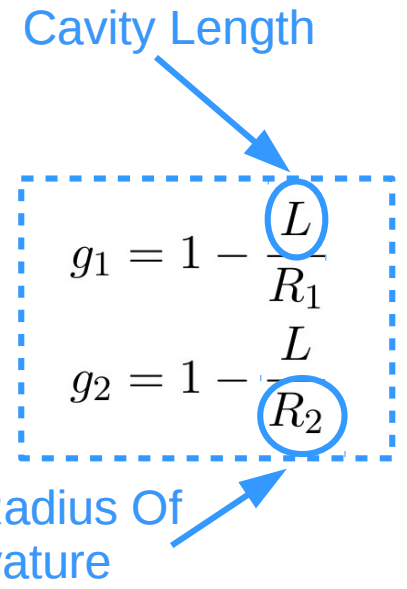
- ✗ **Loss of linearity** ~1.2 um/s → doesn't introduce high error, 20%
- ✗ Velocity at which the cavity **build-up does not reach 40%** of the maximum power, 1.4 um/s



SUCCESSFULLY IMPLEMENTED!

Power Recycling Cavity Stability

- An optical cavity is **stable** when it exists a Gaussian beam that can resonate inside it.
  - **Geometrical** considerations only: $0 < g_1 g_2 < 1$
- PRC is even **more marginally stable** ($1-g_1g_2$ ~0.19e-5) than in Virgo+ ($1-g_1g_2$ ~4e-5)



WHAT DOES IT MEAN ?

HOMs resonate very close to the fundamental mode → **very sensitive to misalignments and/or mismatch**

- Simulations showed that for 0.15urad of misalignment we lose 80% of the slope of our error signal → **feedback loop can not survive**

SOLUTION

Add a **higher RF** modulation frequency (119MHz) that has a **lower finesse** and so is *less sensitive to misalignment*

Actual Power Recycling Cavity

- PR Mirror RoC is *optimized for High Power Laser* (200W)
- With present power, **RoC is ~70m far away**

The PRC is "marginally unstable"

WHAT DOES IT MEAN ?

In theory, it does not exist any Gaussian beam that can resonate inside it

- *In practice* we are very close to the stability region so the main effect is that it is not able to select the fundamental mode because the HOMs are too close → **Very high presence of HOMs inside the interferometer**

Thermal Compensation System's aim is to **bring the PRC to stability** and **compensate for any optical imperfection** to avoid HOMs

- » ***TCS heats up the different optics in order to change their radius of curvature***
- » *Thermal transients are very long* and in order to commission this subsystem **we need a working interferometer!**

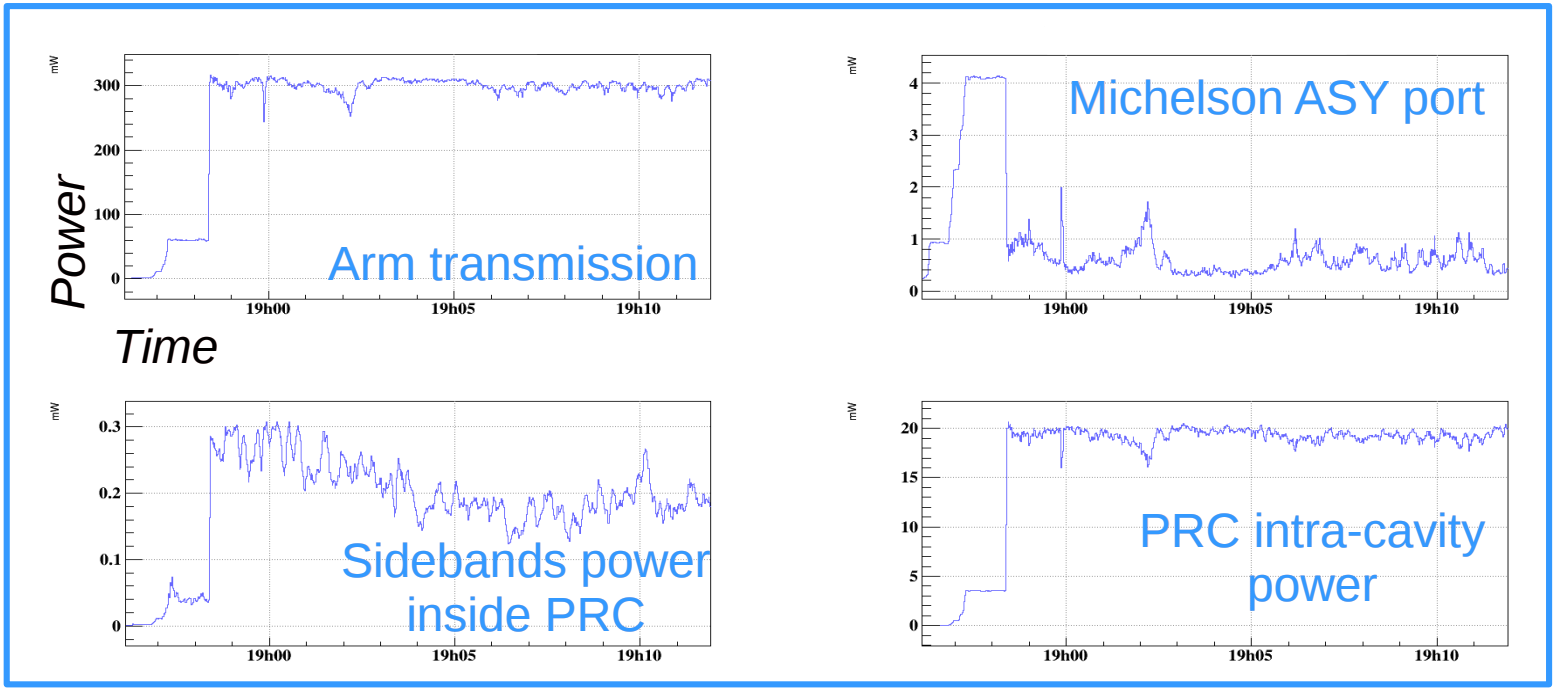
Control of the Full ITF

- Commissioning of an “unstable” interferometer is tricky because:
  - **Modal simulations do not work** for this type of cavities → specific simulations are under development (DarkF / Oscar / FOG / SIS)
  - **Alignment quadrants work only if the HOMs of 1st order are dominant** → otherwise the quadrant see all the HOMs and does not provide useful information
    - Also increases the difficulty of commissioning the quadrants themselves
  - Carrier is cleaned by the arm cavities but not the sidebands → **recycling gain of the sidebands is not very stable**, difficult to evaluate their performance

Despite this we have managed to **reach DF in a repeatable and robust way**

Towards a stable Dark Fringe

- So far we have reached **1.5h of lock in Dark Fringe! (~ 70kW inside the arm cavities!)**



- **High RF frequency** → stabilizes the control despite angular fluctuations
- Alignment loops → only to *prevent the alignment drifts*
  - End mirrors and PR mirror

Future challenges

- **TCS commissioning to** reach PRC stability
  - Act on PR and Input Mirrors → maximize sidebands recycling gain
- Engage the **alignment** control loops → avoid the slow alignment drifts allowing long lock periods
- **Measure the sensitivity** → noise hunting period

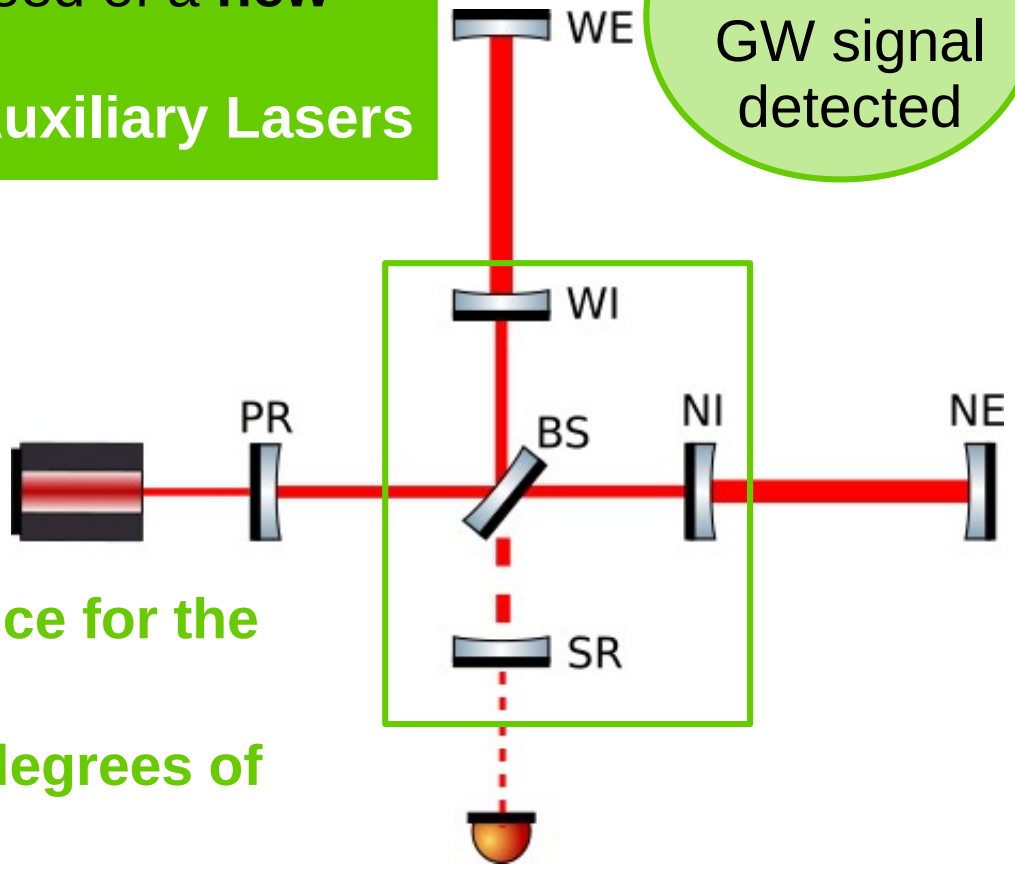
Adding 1 mirror to the system

- One of the next possible upgrades is to install a new mirror in order to increase the sensitivity at high frequency → **Signal Recycling Mirror**

Additional cavity to be controlled!

- Extra coupling between DOFs → need of a **new control strategy**
- Already implemented in LIGO → **Auxiliary Lasers**

Aim: maximize the GW signal detected



CONTROL STRATEGY:

1) Send a **green laser beam** to control the arm cavities independently from the rest of the interferometer

2) Lock the arm cavities **out of resonance for the main laser** *(lower Finesse)*

3) Control the remaining **three central degrees of freedom**

4) Bring the cavities to their **resonance for the main laser**

Summary

- **Increase of the Finesse** on the arm cavities
  - New lock strategy succesfully implemented
- PRC close to instability
  - **1.5h of lock achieved** → high RF frequency + drift control
  - Further stabilize the lock → *TCS* + *alignment full bandwidth*
- Close to start **noise hunting** → Join O2
- Working on further sensitivity improvements → **new challenges are coming!**

THANK YOU