New alignment scheme for KAGRA and future GW detectors

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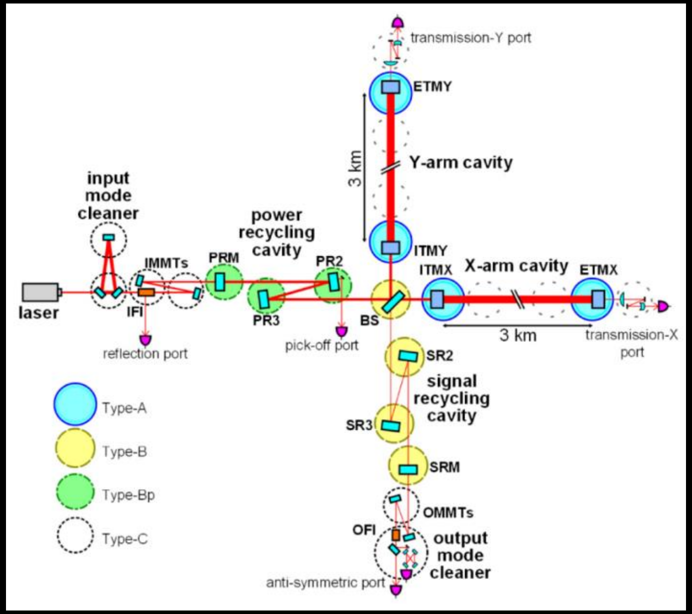
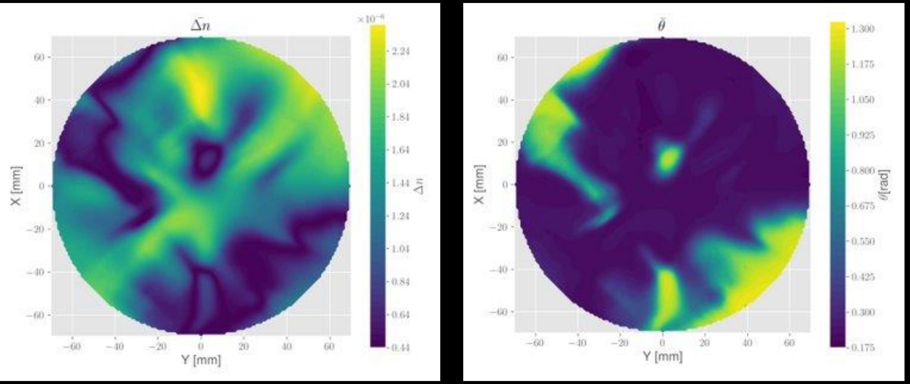
KAGRA detector

- KAGRA is a 2.5-generation gravitational wave detector
  - Similar optical layout and scale as advanced LIGO and Virgo detectors
  - **Underground**
  - **Cryogenic -> crystalline test-masses** (ITMx/y , ETMx/y)

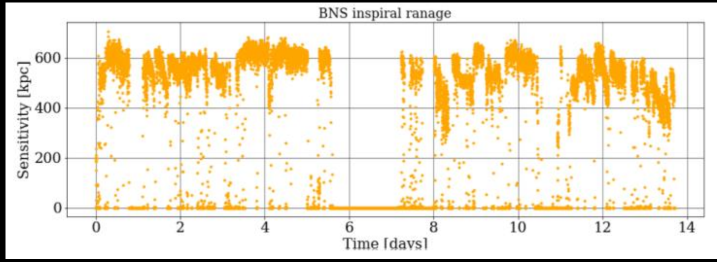


- KAGRA test-masses are made of sapphire
  - Imperfect growth caused non-uniform birefringence



- Next generation of gravitational wave detectors will use crystalline test-masses that could also be affected by birefringence

O3GK performances



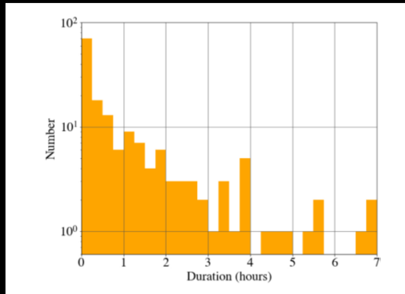


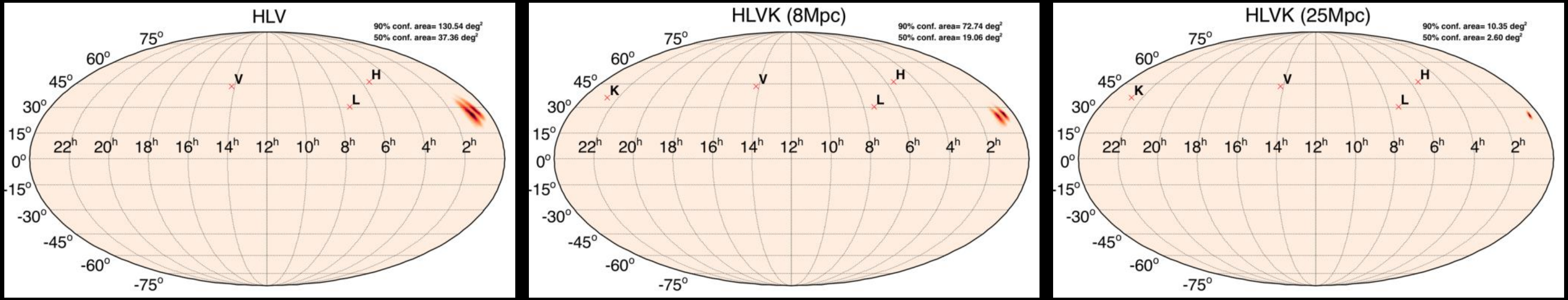
Fig. 3. Histogram of the operational duration during O3GK.

Performance of the KAGRA detector during the first joint observation with GEO 600 (O3GK)

- Shorter run (O3GK) together with GEO600
  - KAGRA median BNS range ~0.6 MPc
  - KAGRA duty-cycle ~53%
  - Majority of observation time shorter than ~15mn

'We expect to improve the operational duration once the global angular control system with wavefront sensors is implemented.'

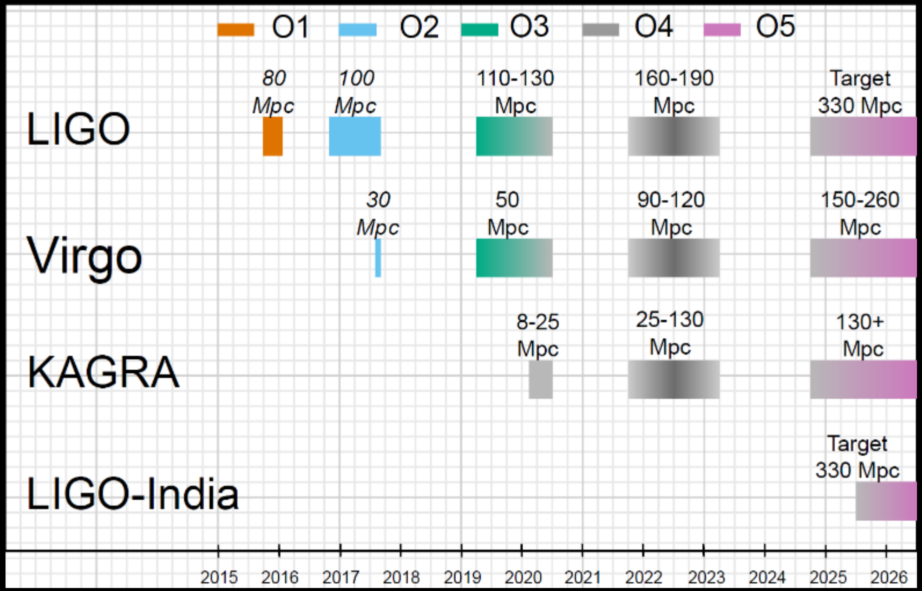
- However, KAGRA high duty-cycle and BNS range will be mandatory to improve events sky localization



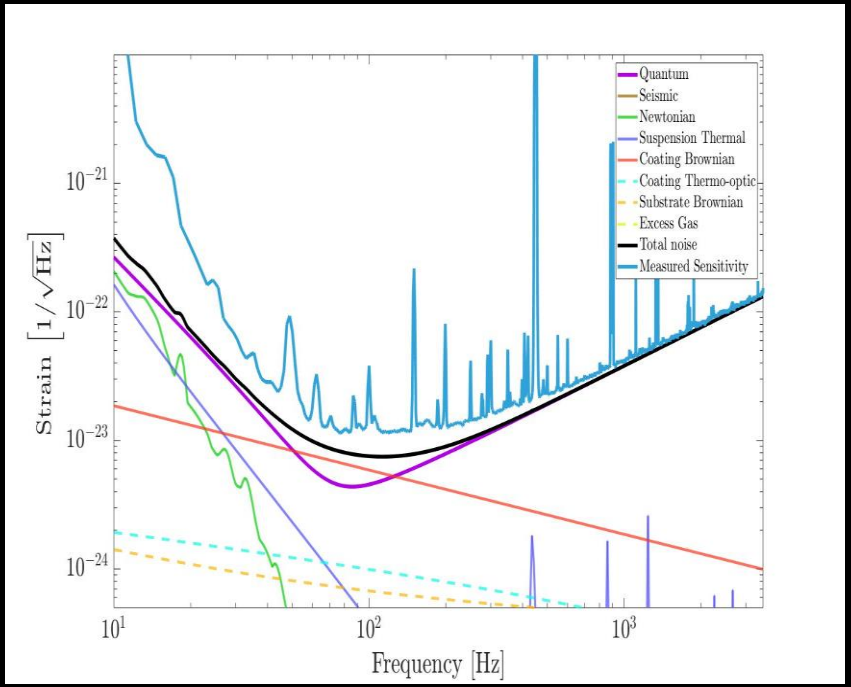
O3 simulation, S. Haino , JGW-G1910190-v14

Sensitivity and observing runs

Schedule as of 2020



Virgo O3a sensitivity



Detection rate ∝ $range^3 . duration$

- There is a broad variety of 'technical noises' that can drastically affect the detector performances
- Their reduction and characterization is crucial for current and future detectors
- Misalignment(s) is one of the numerous technical noises

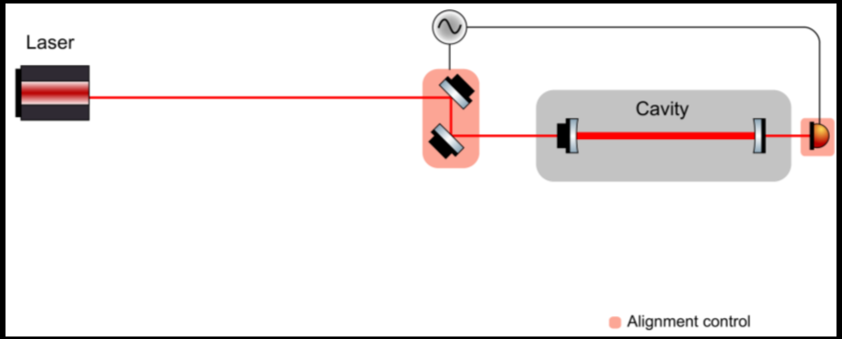
Dithering based alignment

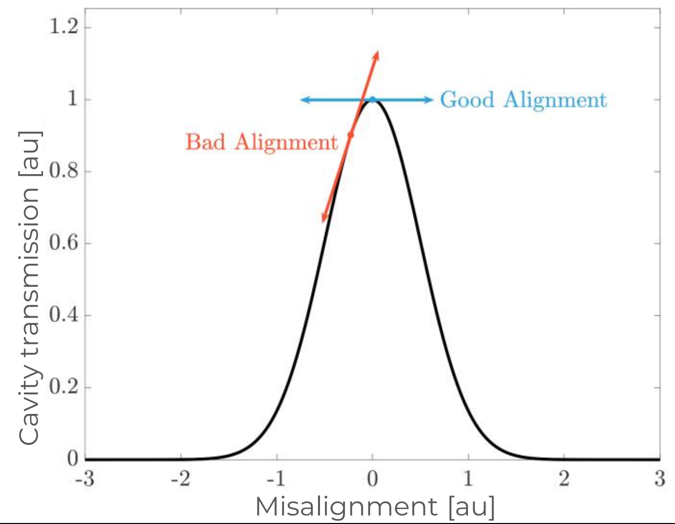
- Modulate input beam direction

  - Misaligned : transmitted power modulated at same frequency
    Aligned : transmitted power modulated at twice this frequency

  - Error signal = transmitted power at modulation frequency

- In KAGRA :
  - modulation applied on heavy suspended mirrors
    - Small bandwidth : easier to lose control
  - Requires permanent beam direction modulation
    - Decreased sensitivity

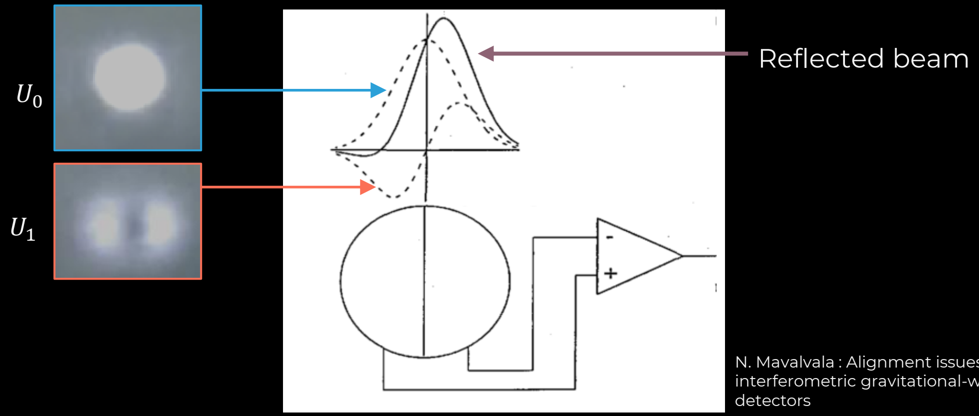




Wavefront sensing based alignment

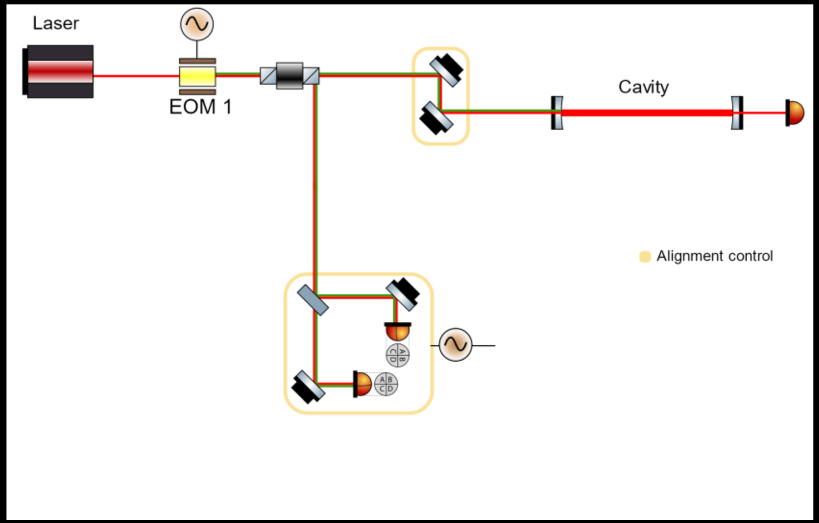
- If input beam is aligned with the cavity :
  - Coupling to cavity fundamental mode (U_0)
- If input beam is misaligned with the cavity :
  - Coupling to cavity first higher order mode (U_1)

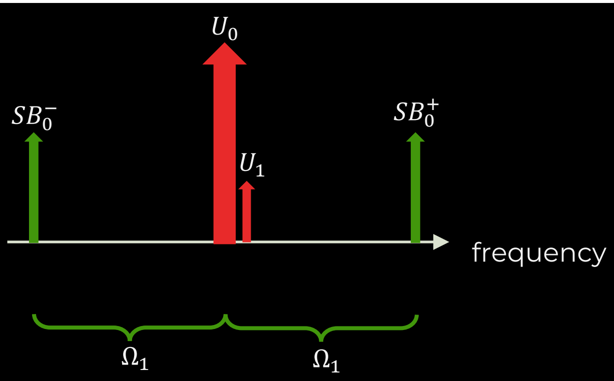
- Using quadrant photodiode can distinguish between them



N. Mavalvala : Alignment issues in laser interferometric gravitational-wave detectors

- Requires a reference field (generally a sideband from EOM1 : SB_0) to extract this information
  - Does not resonate inside the cavity

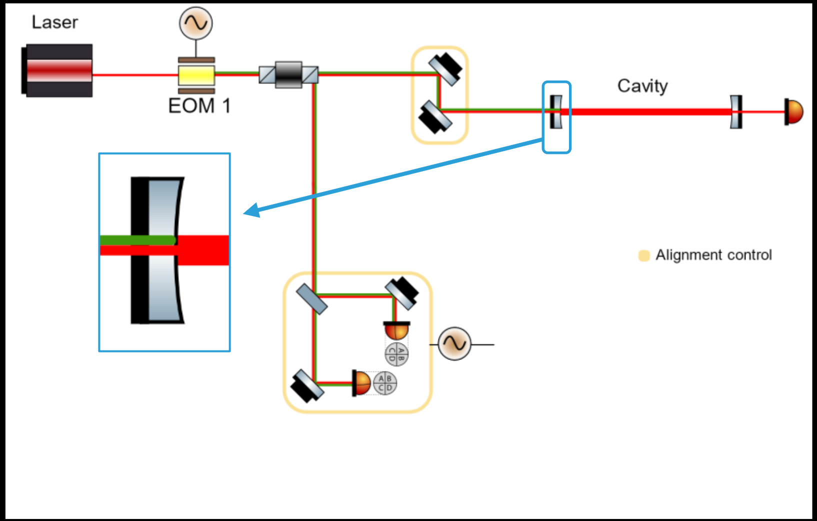




Demodulation at Ω_1 : $SB_0 . U_1$ alignment control signal

Cavity with birefringent mirrors

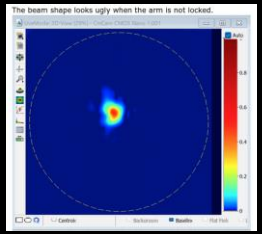
- Input and end mirrors of the cavity are birefringent :
  - All the beam going through input mirror
  - Both affected by mirror substrate birefringence



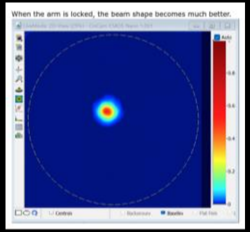
- In reflection of the cavity :
  - Interference between directly reflected beam with beam circulating inside the cavity cancels the birefringence effect (Lawrence effect)

- **BUT** the sideband does not circulate inside the cavity :
  - Affected by birefringence
  - Generates sidebands higher-order mode

Direct reflection



Direct reflection + circulating beam

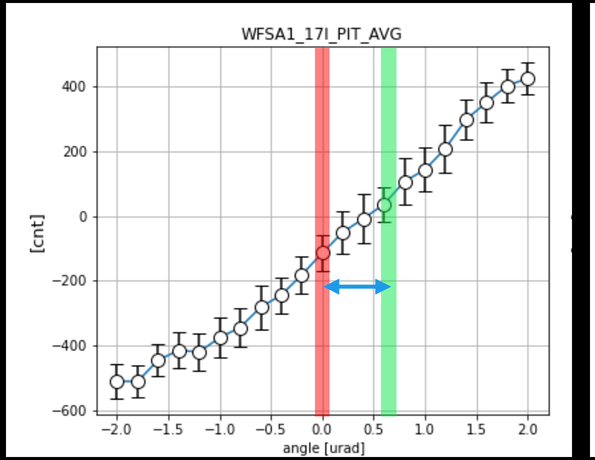


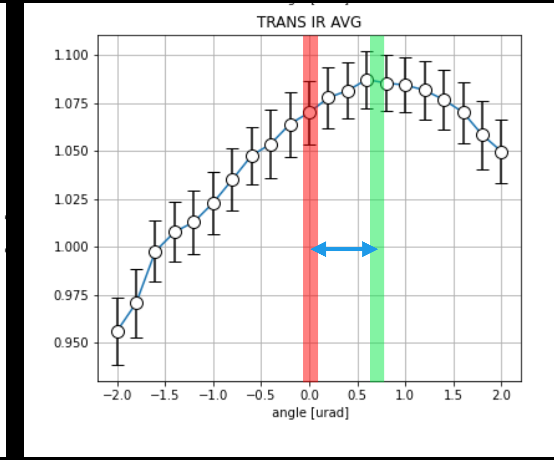
Klog 22213

Wavefront sensing with birefringence

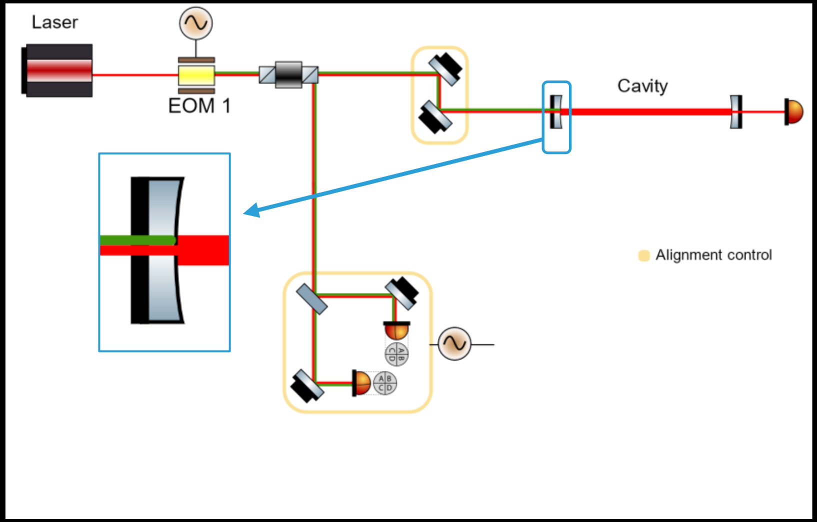
- Input mirror birefringence :
  - Almost no effect on main beam
  - Higher-order modes coupling of sideband (SB_n)

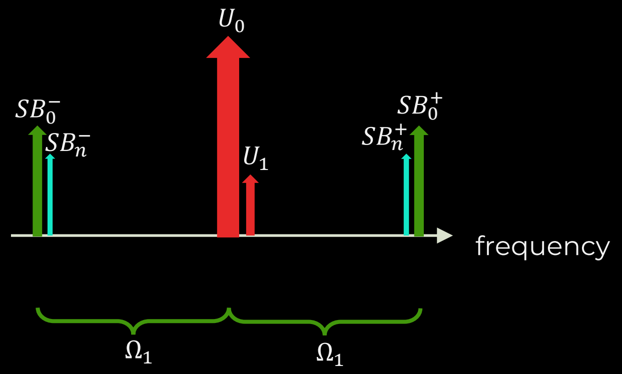
- Distorted reference for the wavefront sensing :
  - Position dependent offset on alignment control signal





JGW-G2314755-v6





Optimal alignment from signal at Ω_1

Best alignment from transmitted power

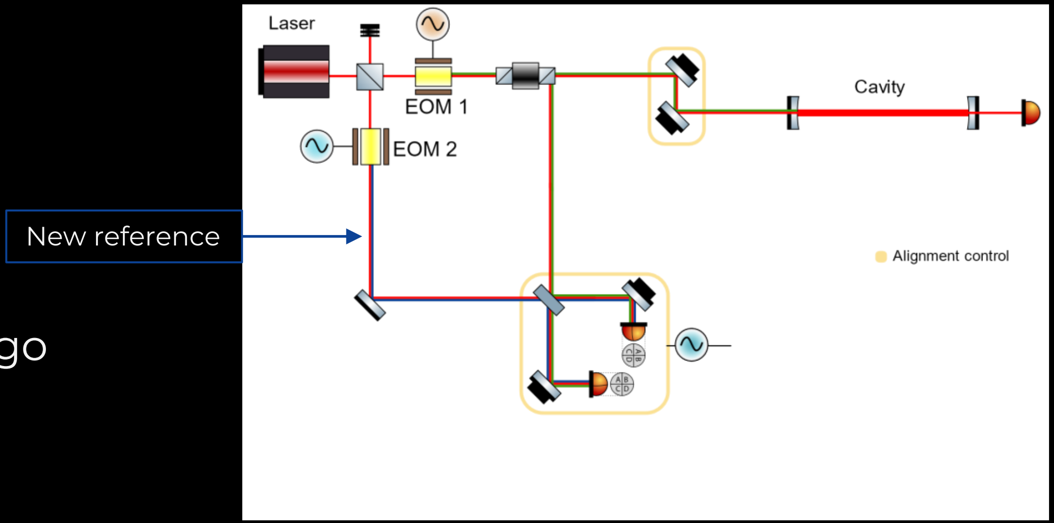
Birefringence offset

At $\Omega_1 : SB_0 \,.\, U_1 + SB_n \,.\, U_0$

Cavity alignment signal + Birefringence effect

A new reference beam

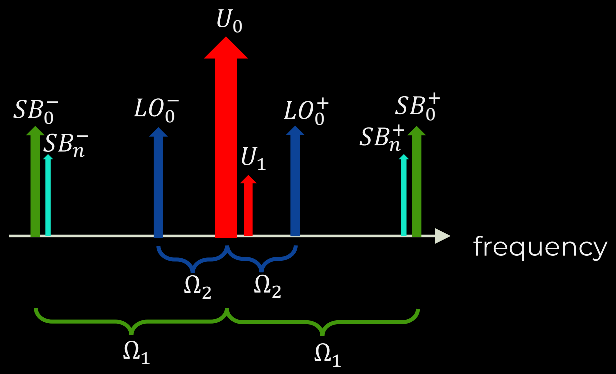
- We propose to use a new external reference beam
  - Does not interact with the cavity
    - No birefringence effect
  - Similar external reference beam used in LIGO and Virgo
    - Monitoring sideband



  - Generate a sideband at a new frequency Ω_2

At $\Omega_2 : LO_0 \,.\, U_1$ — Cavity alignment signal

At $\Omega_1 : SB_0 \,.\, U_1 + SB_n \,.\, U_0$ — Cavity alignment signal + Birefringence effect



  - Can also reconstruct the birefringence effect

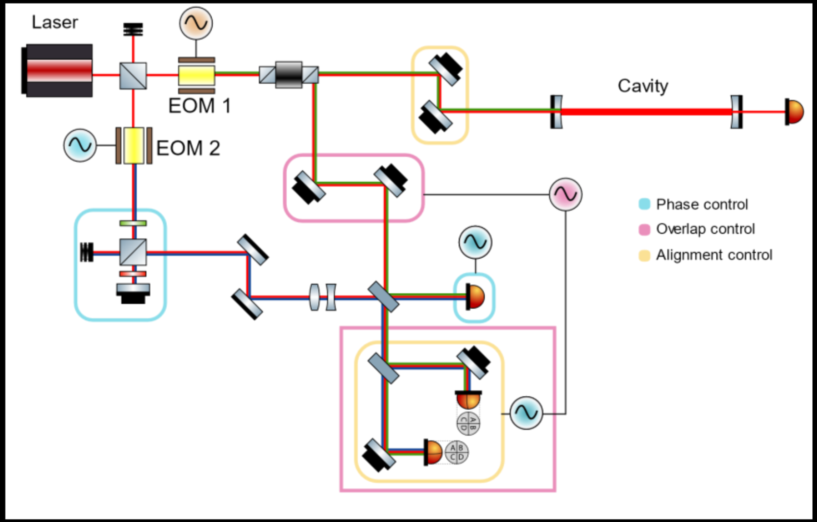
Reference controls

- Need to insure that the external beam is a good reference to perform wavefront sensing
  - Requires phase control
  - Requires overlap control

- Phase control :
  - To maximize SNR
  - Can be controlled using an additional photodiode and a phase shifter

- Overlap control :
  - To avoid mis-identification (coupling) of alignment
  - Alignment control using 2 dithering mirrors
  - Control from demodulation at dithering freq. of alignment signal

  - Mode-matching :
    - To maximize SNR, avoid coupling
    - High quality telescope
    - Should be stable over time but could be checked with additional cavity



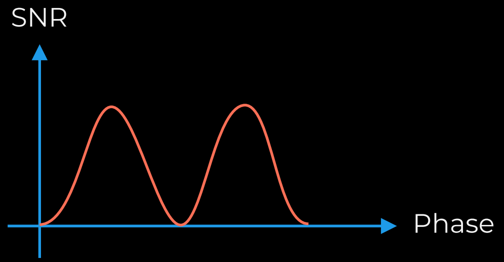
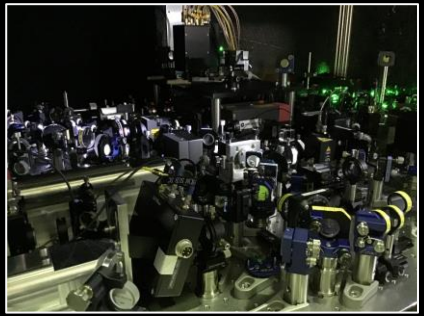
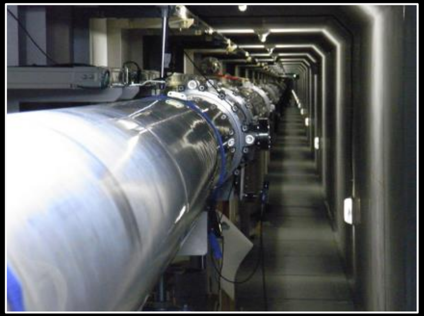


Table-top demonstration at NAOJ

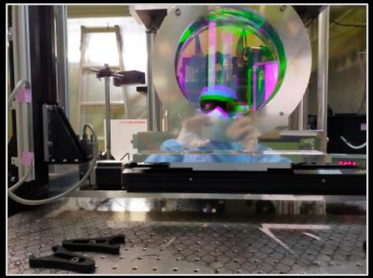
- NAOJ was hosting TAMA300 gravitational wave detector
  - 300m long arm
  - Most sensitive detector in ~2000
  - Operation stopped in 2011

- Currently hosting
  - Frequency-dependent squeezing experiment
  - Absorption/Birefringence mirror characterization





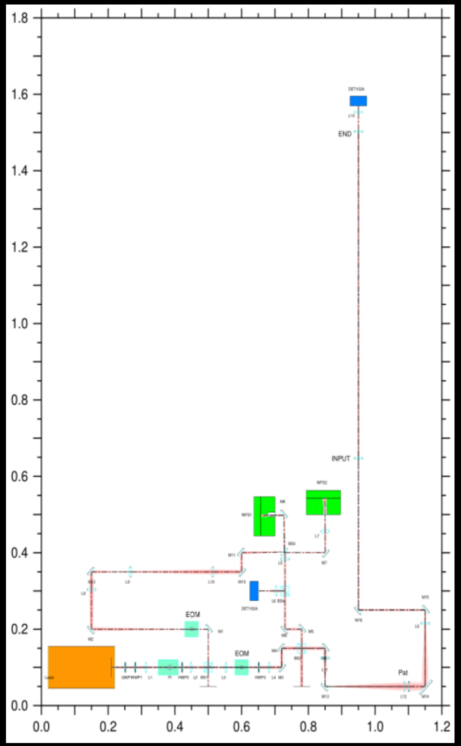
- Several components available
  - Optics at 1064mn and 532 nm
  - Electronics and mechanics
  - Data acquisition system

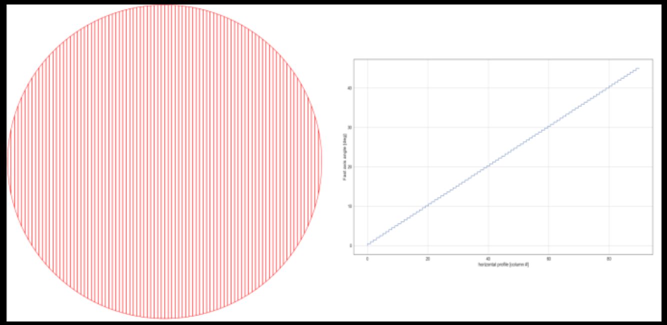


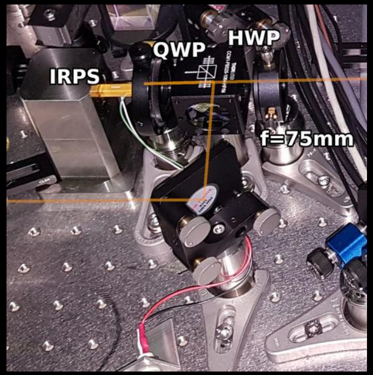
- Goal :
  - Demonstrate our new alignment signal
  - Confirm our simulations to estimate KAGRA, (ET, CE) coupling

Table-top demonstration status

- Designed a small optical cavity to reproduce KAGRA arm cavity parameter
  - Cavity mirrors will arrive in ~1 month
  - Can not use sapphire as birefringence is too uniform for small sample
  - Custom made birefringent plate to simulate a controlled birefringence of input mirror
- Overall optical scheme ready
  - Most of the components from TAMA300/frequency-dependent squeezing experiment
- Phase control
  - Use same design as frequency-dependent squeezing experiment
- Overlap control
  - Strategy already tested
  - Component available
- Quadrant photodiode
  - Use same design as KAGRA ones







Conclusion

- KAGRA will play a crucial role in gravitational wave and mutli-messenger astronomy
- Current performances and duty-cycle highly affected by test-masses birefringence
  - Might also affect next generation of gravitational wave detectors
- We propose a new alignment scheme using an external reference beam
- The table-top demonstration design is ready
  - Installation to start in April
- If successful we could install it in KAGRA with minimal modifications of the detector and control