Lessons learned with Virgo

Romain Gouaty, on behalf of the Virgo Collaboration

- **The context: Virgo latest upgrades**
- **Performances of the Virgo Super Attenuators**
- **Experience with the mirror payload**
- **Handling thermal effects in recycling cavity**
- **Diffused light**
- **Problems with the mirror radii of curvature**
- **Central Heating Radius of Curvature Correction (CHRoCC)**
- **Tuning of the arm asymmetries**
- **Understanding of the Virgo sensitivity**

Virgo overview since 2007

Virgo ➔ Virgo+

Virgo+ ➔ Virgo+ with monolithic suspensions

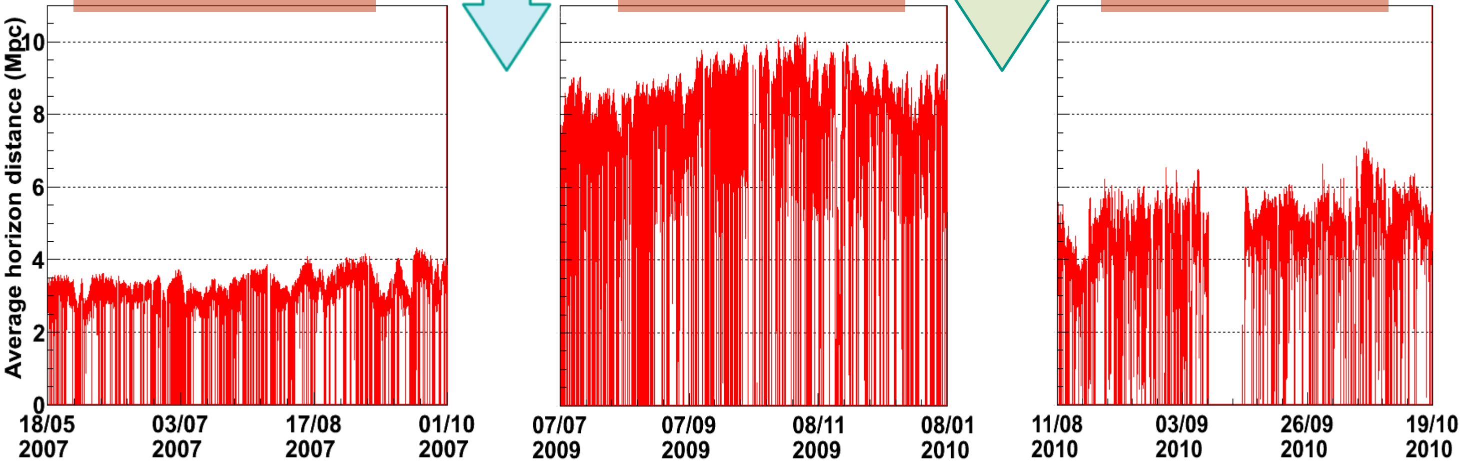
Commissioning

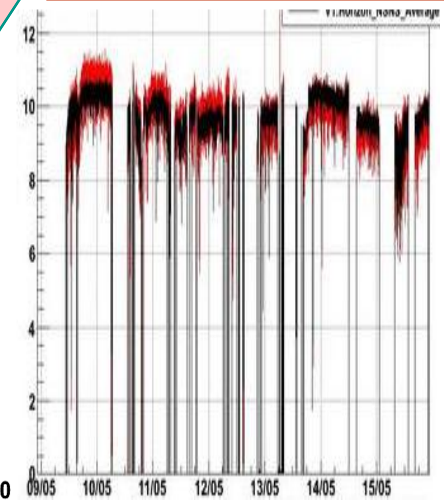
May 2011 (1 week of commissioning)

VSR1 (2007)

VSR2 (2009)

VSR3 (2010)





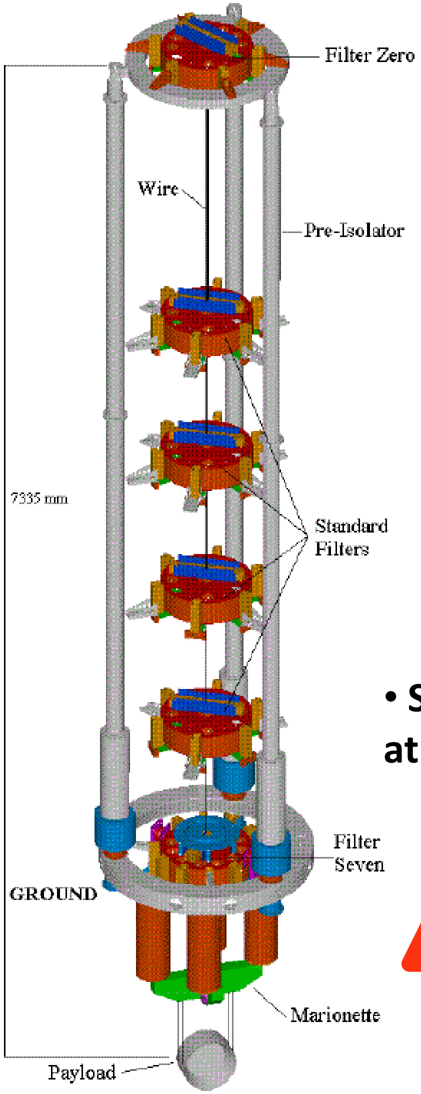
Good stability also recovered (can hold locks of 24 hours)

- **Thermal Compensation System**
- Injected power 8 ➔ 17 W
- Dump **diffused light**

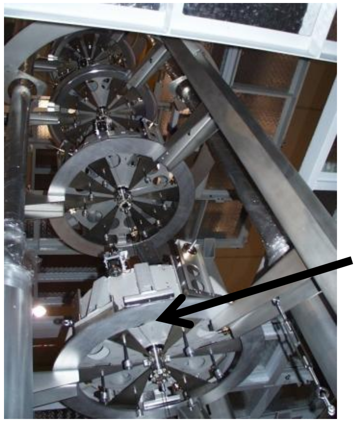
- Increase arm finesse 50 ➔150
- **Monolithic suspensions**

- **Correction of mirror curvature**
- Dump diffused light
- Other noise hunting…

Virgo Super Attenuators

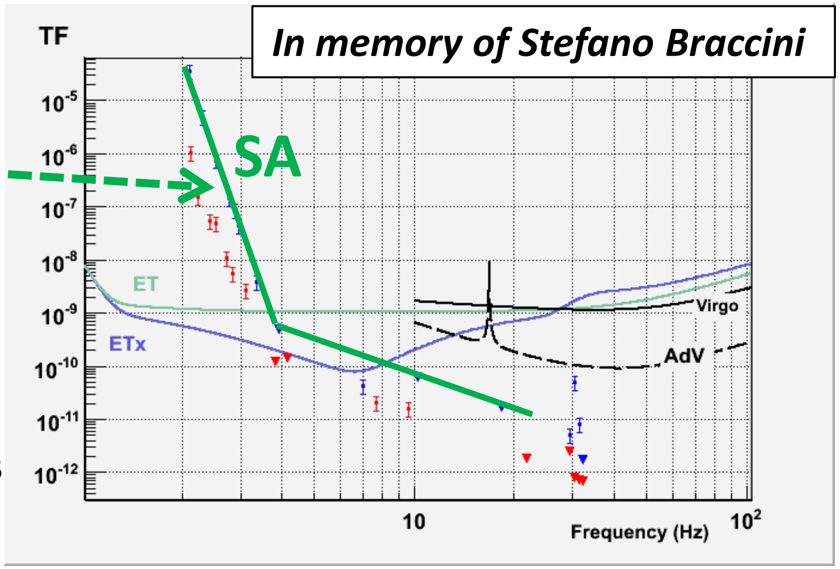


On site measurements of seismic isolation give upper limits below Advanced Virgo requirements

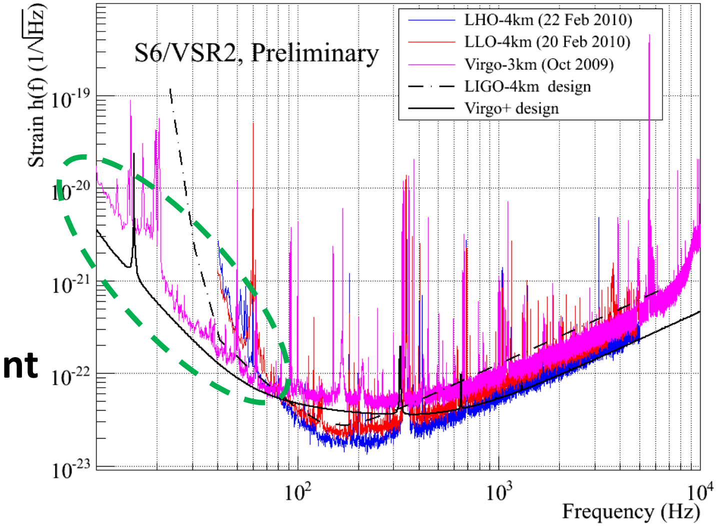


Blade Springs

In memory of Stefano Braccini



- SA helped Virgo to reach good sensitivity at low frequency (< 60 Hz)

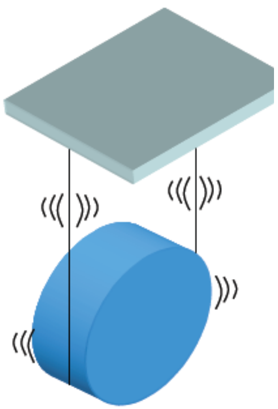


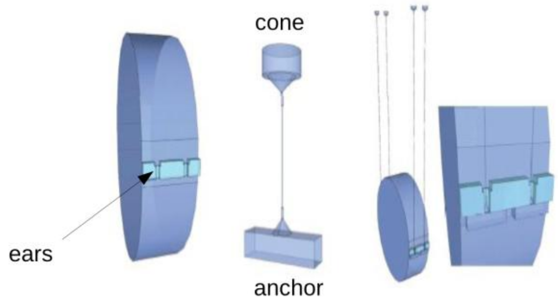
Lesson learned:

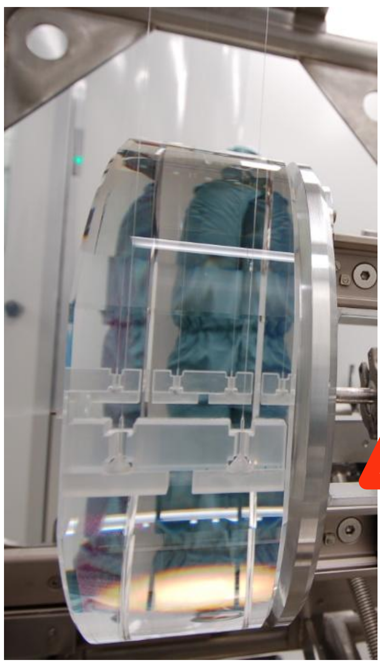
Super Attenuators robust and efficient

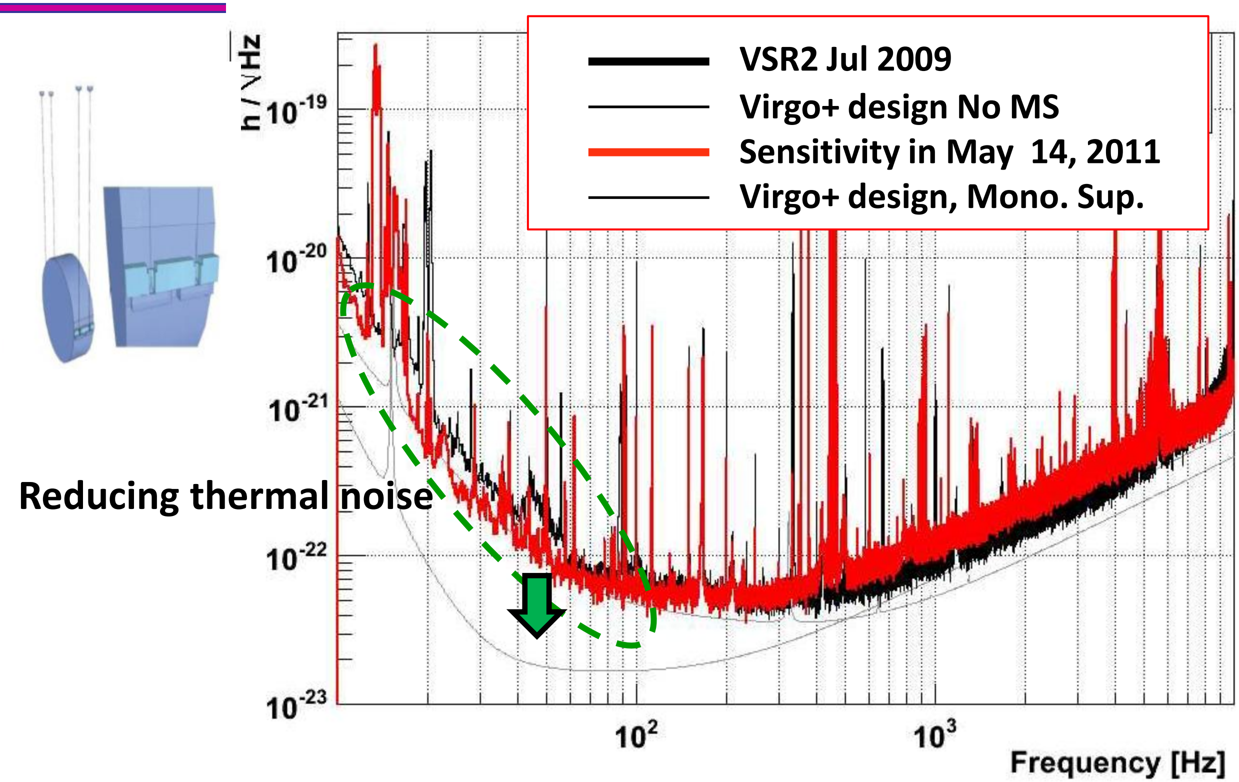
⇒ Ready for Advanced Virgo

Experience with the payload:
Monolithic suspensions









- Installation of monolithic fused silica susp. for the 4 arm mirrors (spring 2010)

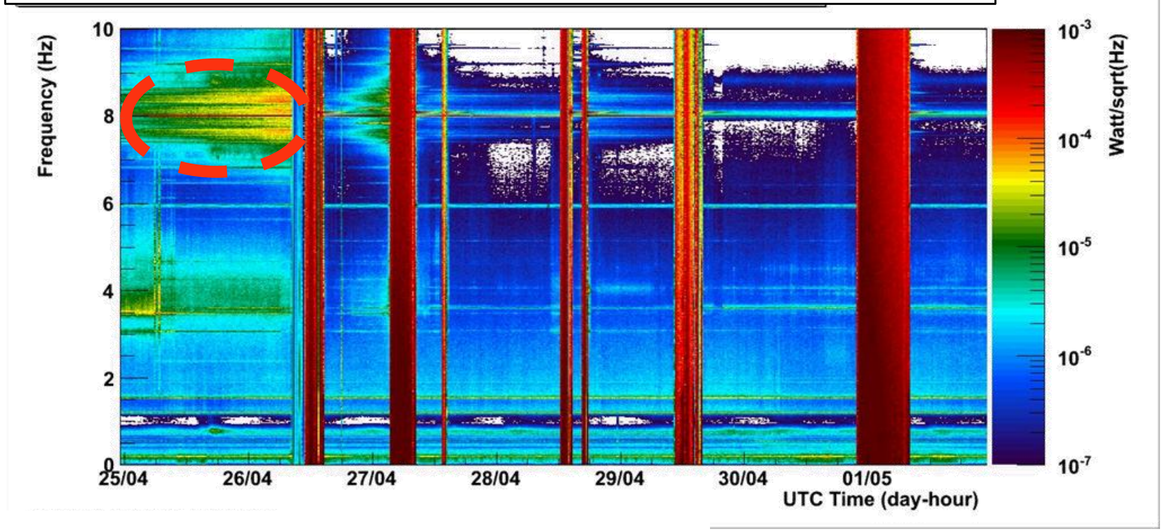
Lesson learned: **No robustness or control problems experienced with monolithic suspensions ⇒ Risk reduction for Advanced Virgo**

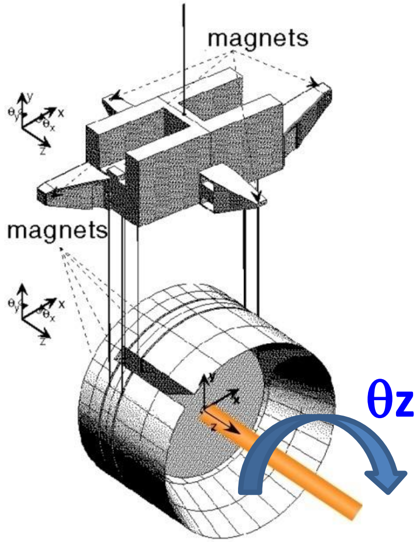
- **Sensitivity at 20-80 Hz sometimes beating design without Mono. Sup.**
- **Still far from expected thermal noise limit (instrumental + unknown noises)**

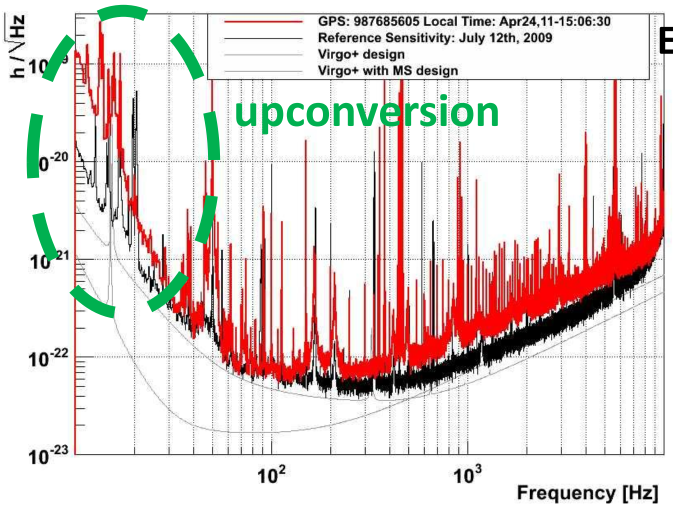
With best sensitivity, Vela Spin Down Limit could now be reached within 10 days with 95% CL (was about 65 days during VSR2) *arXiv:1104.2712v2*

Experience with the payload:
Mechanical resonances

Time-frequency spectrum of the dark fringe signal







Example of problem with payload resonances:

θz resonance (8Hz) some times gets excited during lock acquisition

Caused noise up-conversion in 10-40 Hz region

Lot of work in understanding how to damp it or not to excite it

Lesson learned: Design of payload is critical

A small modification can have important consequences

Learning how to handle them is a long process

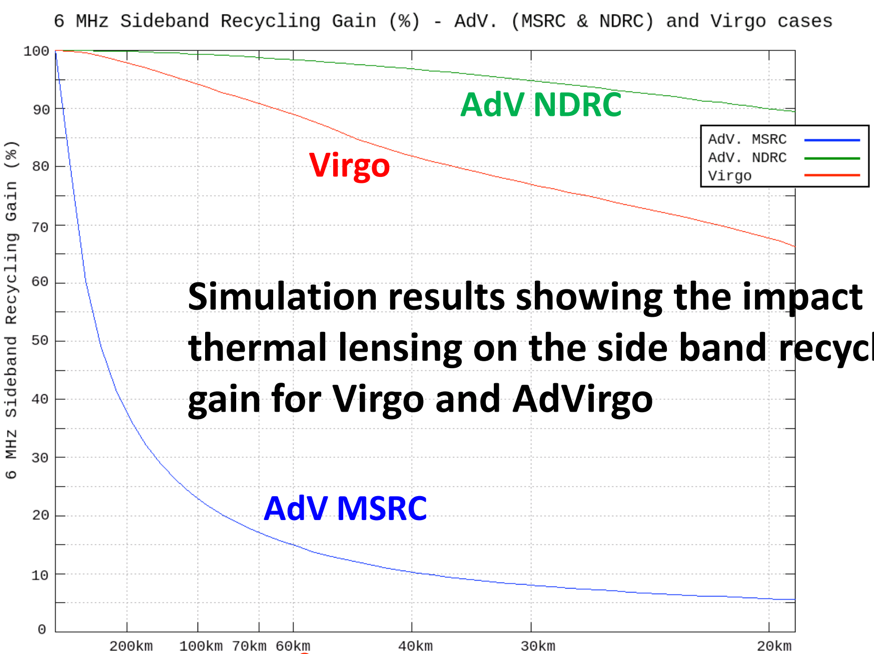
Thermal effects in recycling cavity

- **Thermal lensing** due to absorption in input mirrors
- Sensitivity of **Marginally Stable Cavity** to this effect

⇒ Changes recycling gain of the side bands

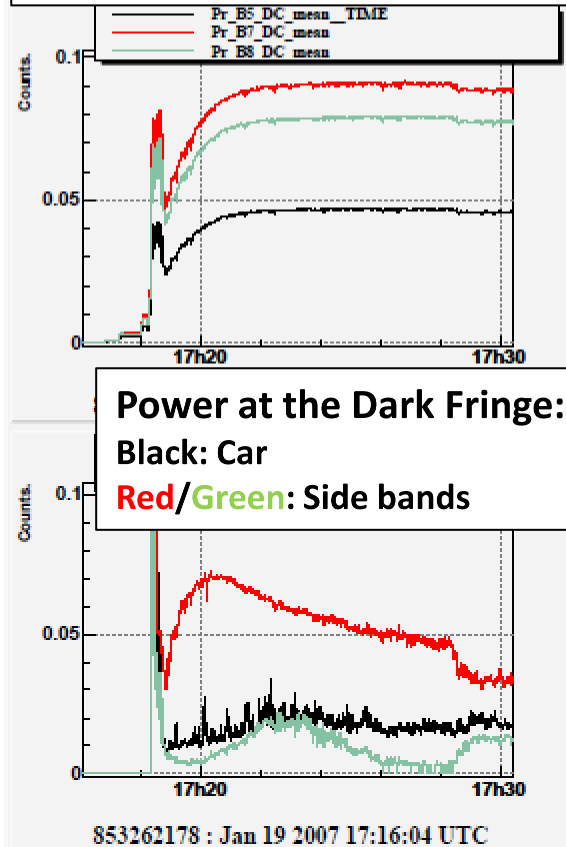
⇒ Was the main responsible for thermal transients after lock acquisition (observed during Virgo commissioning and VSR1)

⇒ **Impact on control loops and sensitivity**



Simulation results showing the impact of thermal lensing on the side band recycling gain for Virgo and AdVirgo

Car powers in the cavities



Power at the Dark Fringe:
Black: Car
Red/Green: Side bands

Large amount of commissioning time spent to deal with thermal effects

Lesson learned: the need for Thermal Compensation

Thermal Compensation System

Installation of Thermal Compensation System (TCS): 2008

- Upgrade necessary to start Virgo+ (VSR2) with increased injected power (8W to 17 W)
- CO_2 laser sent on the High Reflectivity surfaces of the Input Test Masses

Annular heating obtained with an "AXICON" (lens with conical surfaces)

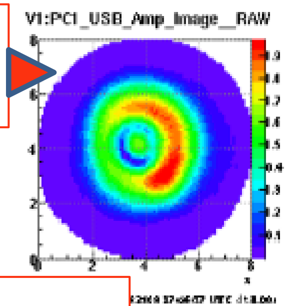
⇒ Recover a good recycling gain for the side bands

(ITF optical gain increased by 50% with 14.5 Watts input power)

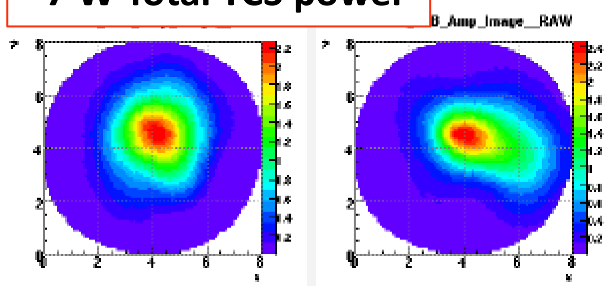
⇒ Recover gaussian side bands at the dark fringe

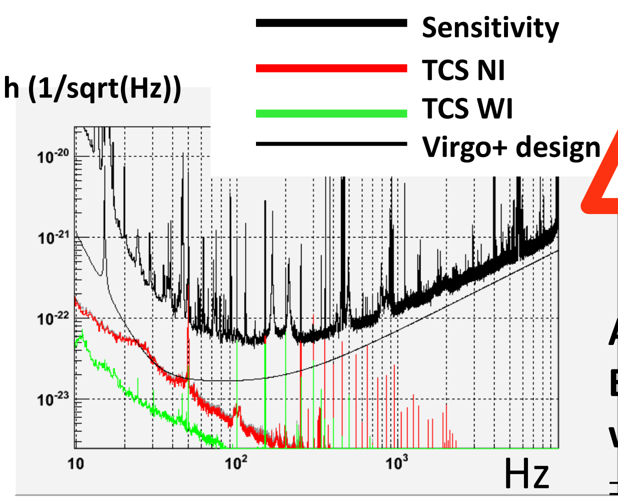
⇒ Robust system, noise reduction with power stabilization

Side band image NO TCS, 12 W IFO



7 W Total TCS power





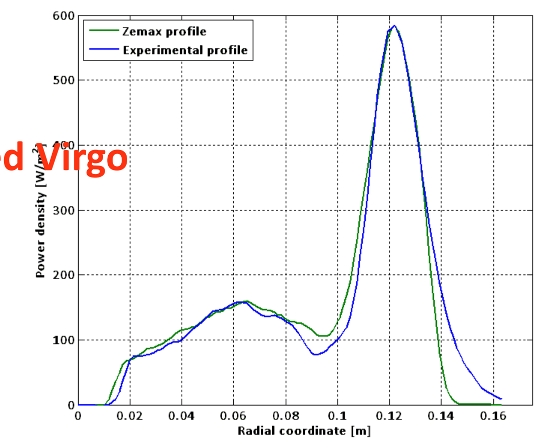
Lesson learned:

Good experience with Virgo TCS will be even more crucial for Advanced Virgo

AdV R&D:

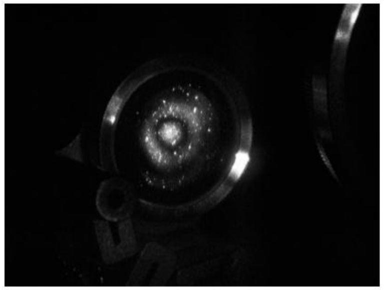
Encouraging results obtained in laboratory with "double axicon "

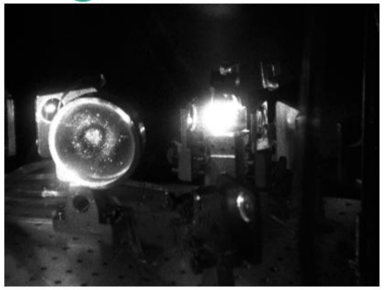
⇒ Obtain an optimal heating pattern



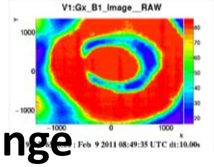
Problem of excess light at the dark port (2010-2011)

Problem started after installation of monolithic suspensions and mirrors replacement (spring 2010)





Degradation of the interferometer contrast due to waist mismatch between the arm cavities (powerful Laguerre Gauss mode)



⇒ **Large amount of power at the dark fringe** (before Output Mode Cleaner): 2-3 Watts

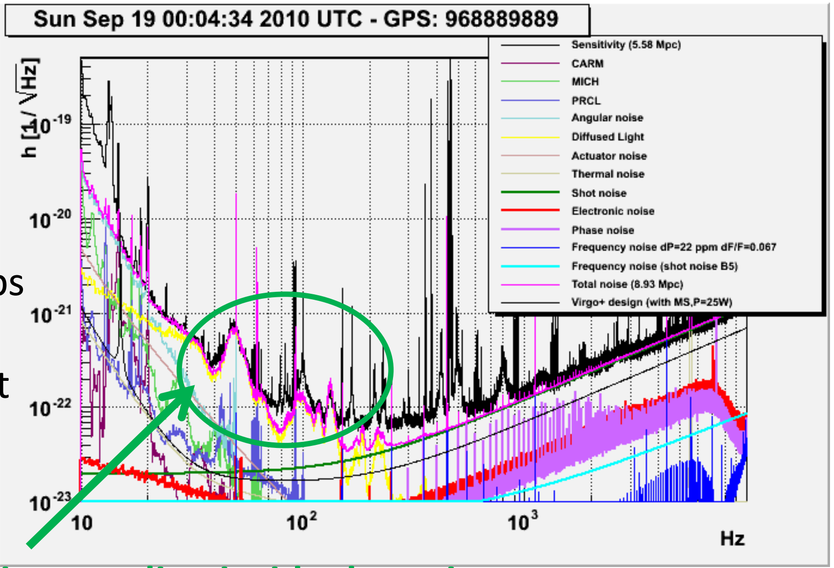
Consequences:

- HOMs spoiling error signals used in alignment control loops
- HOM near TEM00 making lock of OMC difficult

⇒ Locking more complex, no well defined ITF working point

- **Increases diffused light on the detection optics**

⇒ **Strong impact on VSR3 sensitivity**



30-200 Hz: sensitivity limited by diffused light noise coupling inside detection tower

⇒ Partly fixed by adding a beam dump at the OMC reflection

Lesson learned: **large HOM power at dark port must be avoided**

⇒ makes ITF controllability very difficult and worsens sensitivity (despite OMC)

Radii of Curvature (RoC) of the new End Mirrors

	ROC before coating (m)	ROC after coating (m)
Specification	3450 +- 100	
North End	3368	3273
West End	3496	3403

- **Both RoC asymmetry and absolute value of RoCs changed**
- Optical simulation: shows importance of **mode degeneracy inside Fabry-Perot cavities**

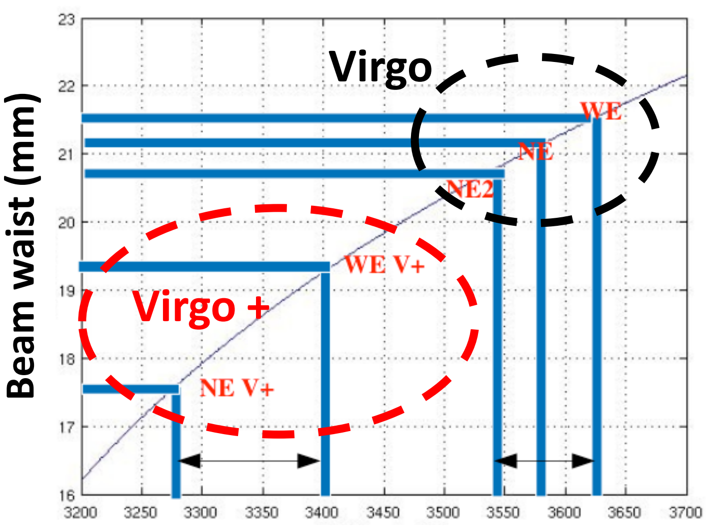
⇒ **Can lead to large round trip losses and loss asymmetry**

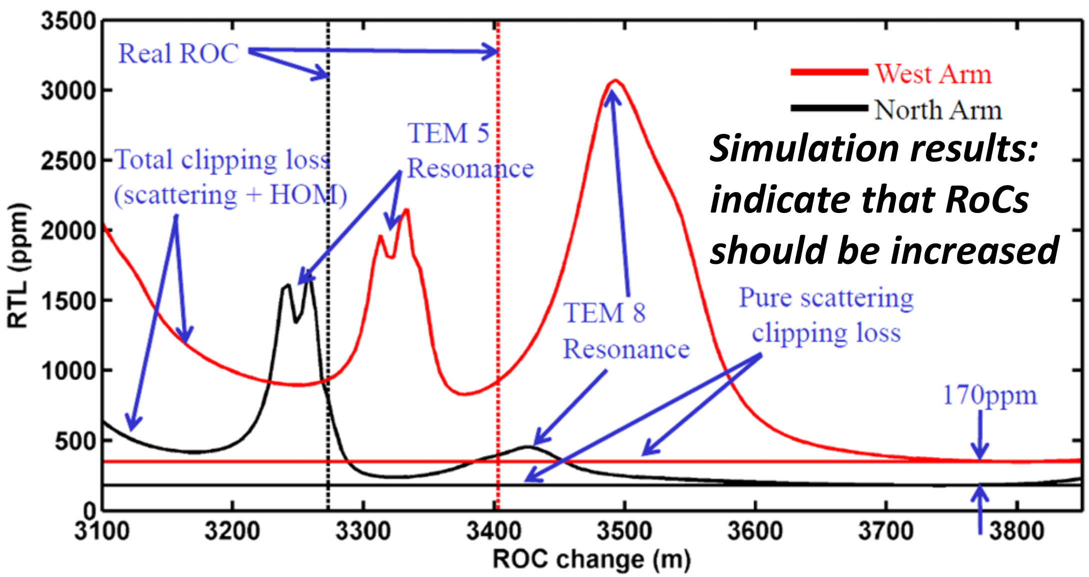
⇒ **Increase contrast defect and presence of high HOMs**

- **Lesson learned:**

- RoC specifications were set uncorrectly

- Avoid dangerous regions (mode degeneracy)



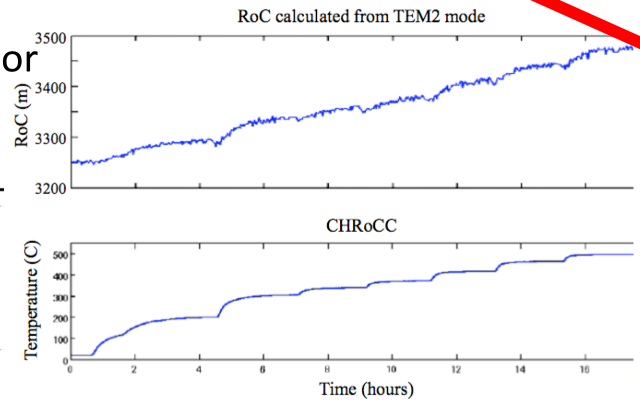


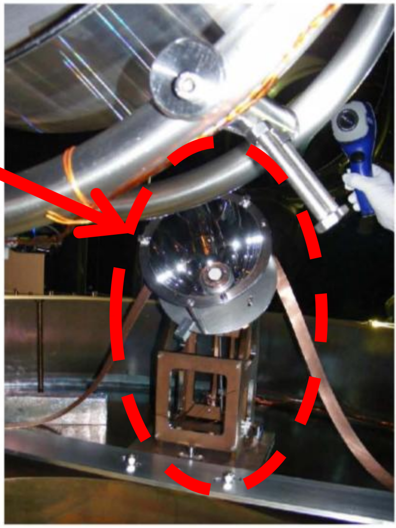
Correction of the mirror RoCs

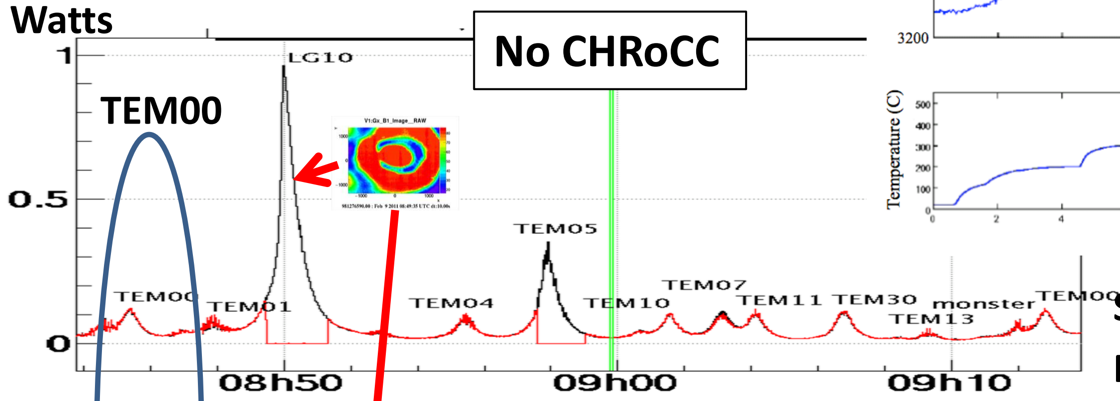
See Richard Day's talk on Thursday afternoon

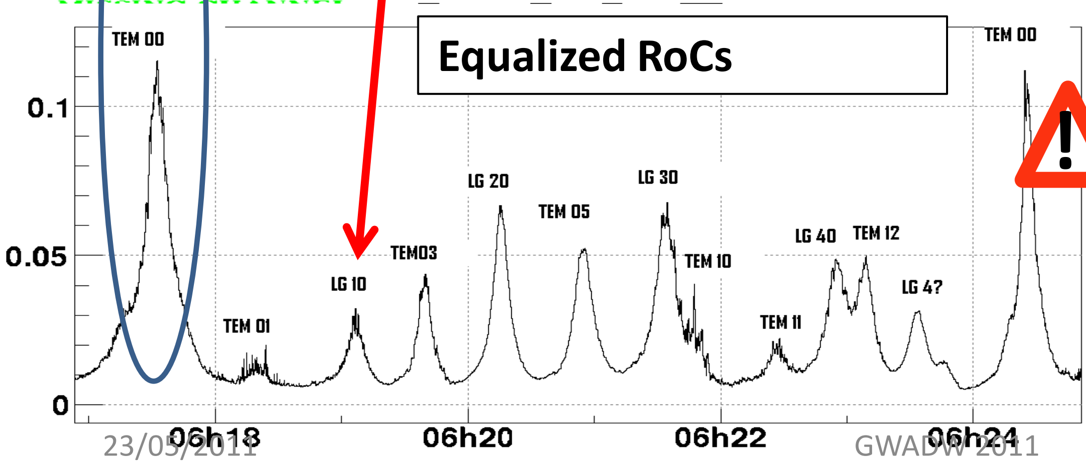
Central Heating Radius of Curvature Correction (CHRoCC)

- **Increase End Mirror RoC by projecting heat pattern onto center of mirror's HR surface.**
- In-vacuum heat projector with ellipsoidal reflector
- Installed at NE(WE) in Dec 2010 (March 2011)









Scan of the Output Mode Cleaner:

Probe mode content of dark fringe beam

$\Rightarrow$ Dark fringe power (High Order Modes) reduce by a factor ~5

Lesson learned:

CHRoCC is successful in equalizing RoCs and avoiding HOM mode degeneracy

BUT: this working point leads to a worse contrast defect

Tuning of ITF asymmetry is tricky!

Impact of arm asymmetries

Arm asymmetries play a crucial role:

- For interferometer **contrast defect** (impact on error signals, shot noise, …)
- For **coupling of laser frequency noise** (Common Mode Rejection Factor)

Simple model assuming effective loss asymmetry ΔP and finesse asymmetry ΔF

$$CMRF(f) = \frac{F}{2\pi}\Delta P \frac{f_{cav}}{f_{recy}} \frac{1 + j\frac{f}{f_{cav}}}{1 + j\frac{f}{f_{recy}}} + \frac{\Delta F}{F} \frac{1}{1 + j\frac{f}{f_{cav}}}$$

Complex coupling between RT losses & RoCs

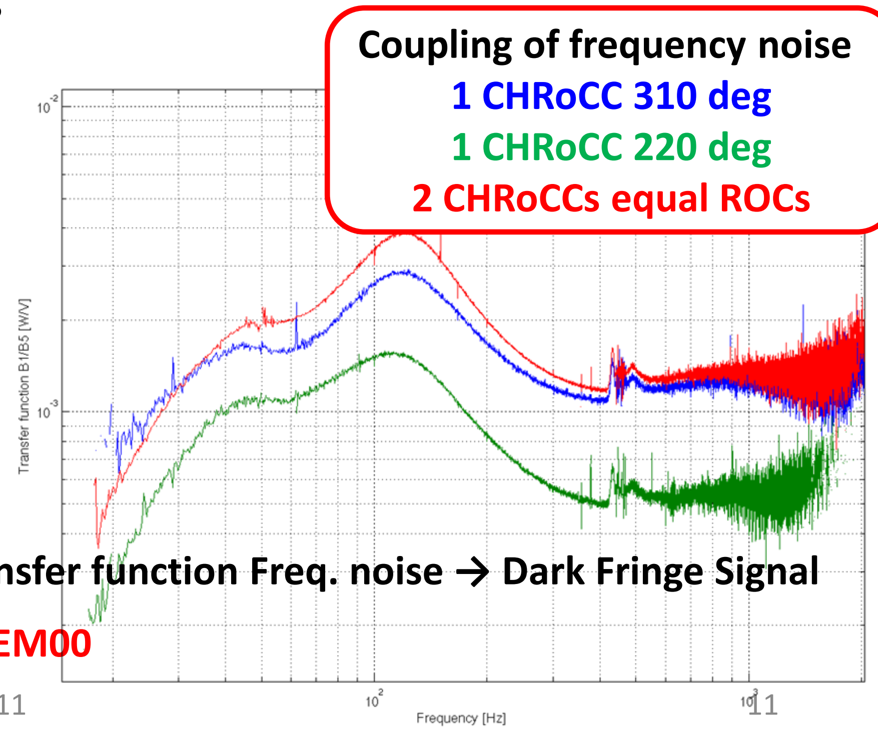
⇒ difficult to model

Sensitivity depends on the asymmetries seen by the TEM00 mode

With equalized RoCs:

ΔP = 680 ppm (≈30 ppm during VSR3)

⇒ Large coupling of laser frequency noise



Transfer function Freq. noise → Dark Fringe Signal

<u>Lesson learned</u>:

Tune RoCs to minimize effective loss asymmetry ΔP on TEM00

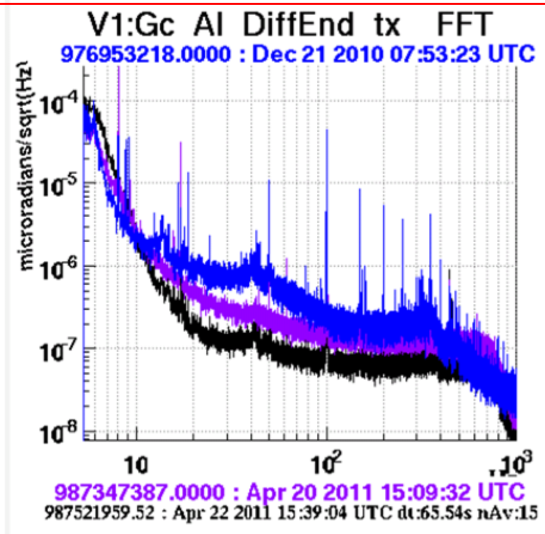
Reaching the ITF working point

Best ITF working point is a trade-off between:

- Minimization of loss asymmetry on TEM00, ΔP: 680 → 80 ppm
⇒ **Strong reduction of frequency noise**

- Maintain RoCs in a region without HOM degeneracy, with moderate RoC asymmetry
⇒ **Error signals for alignment control loops still of good quality**

Blue curve: RoCs as in VSR3
Purple curve: equalized RoCs
Black curve: new working point

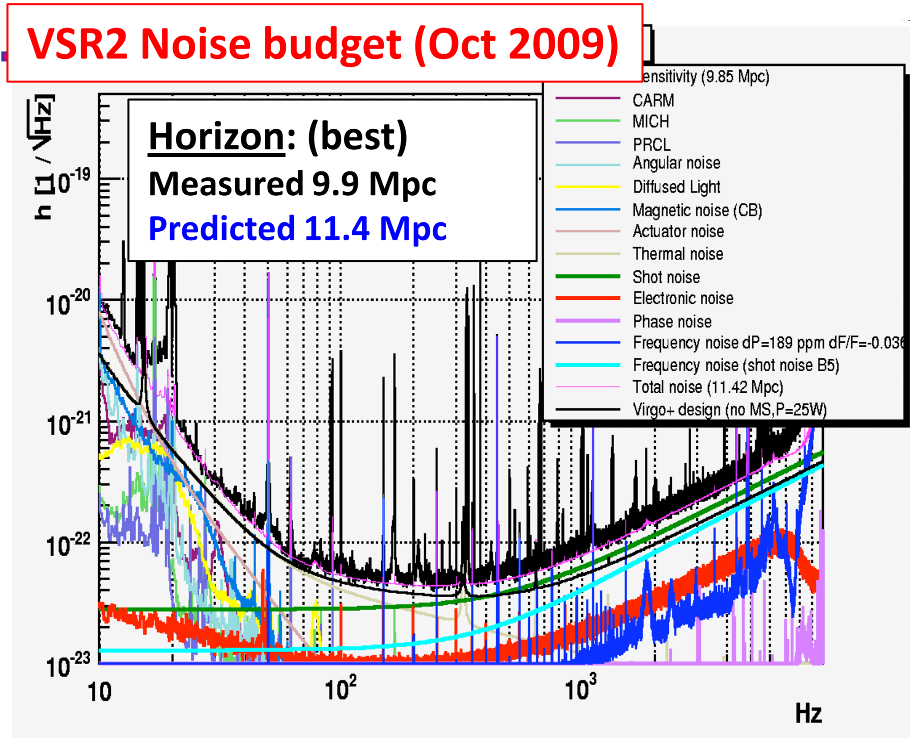


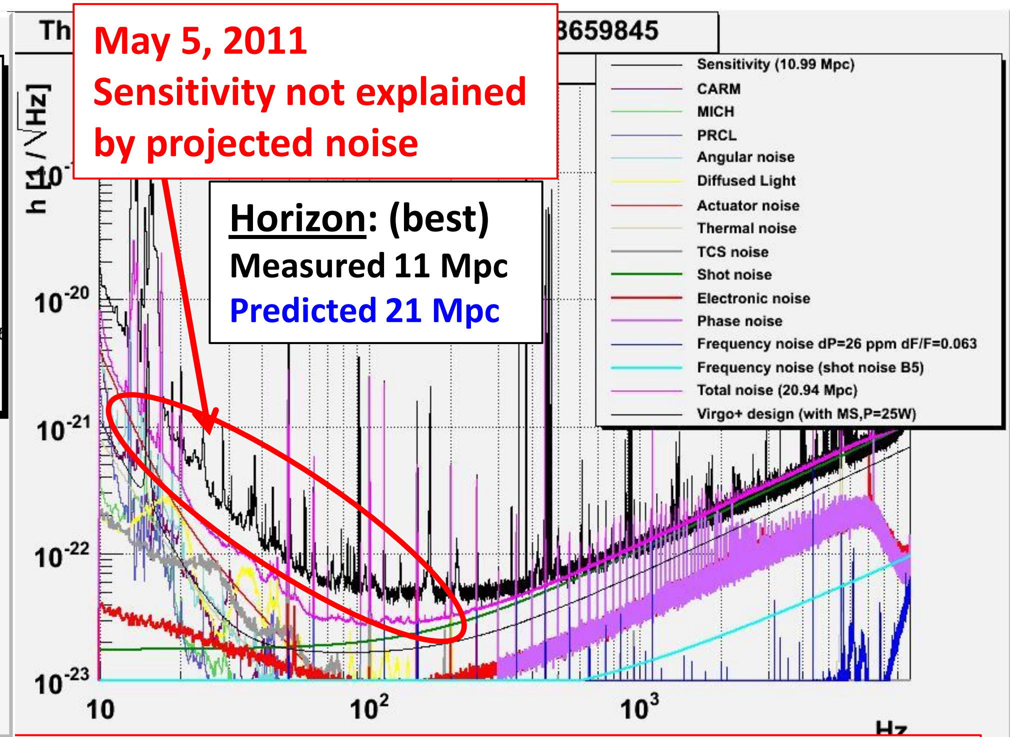
⇒ **CHRoCC allowed to recover a horizon up to ~11 Mpc**
⇒ **A successful development, risk reduction for Advanced Virgo**

BUT:
Power at the dark port is still high (~1 Watt before OMC) due to cavity losses asymmetry
⇒ **Impact of mirror defects cannot be fully cured by CHRoCC**

Main Lessons learned:
- **CHRoCC has allowed us to find a stable ITF working point**
- **Increased quality optics is still mandatory for Advanced Virgo**

Understanding of the Virgo sensitivity





- **VSR2 sensitivity was very near design, and noise seemed to be well understood**

⇒ **A validation of Virgo technologies**

- **Current situation: noise budget does not explain sensitivity below 300 Hz**
- Noise hunting has been significantly slowed down by RoC issues
- Not all diffused light has been understood
- Possible non linear effects not taken into account
- Noise coupling very sensitive to ITF alignment, not fully understood
- A lot of mistery remains ⇒ **going beyond initial design might reveal us some surprises…**

A reminder: Virgo chronology

2003 — End of the Virgo construction

2004

2005 — Initial Virgo commissioning

2006

2007

VSR1

2008 — Commissioning and upgrade to Virgo+ (1^{st} part)

2009

VSR2 – Initial Virgo design sensitivity reached

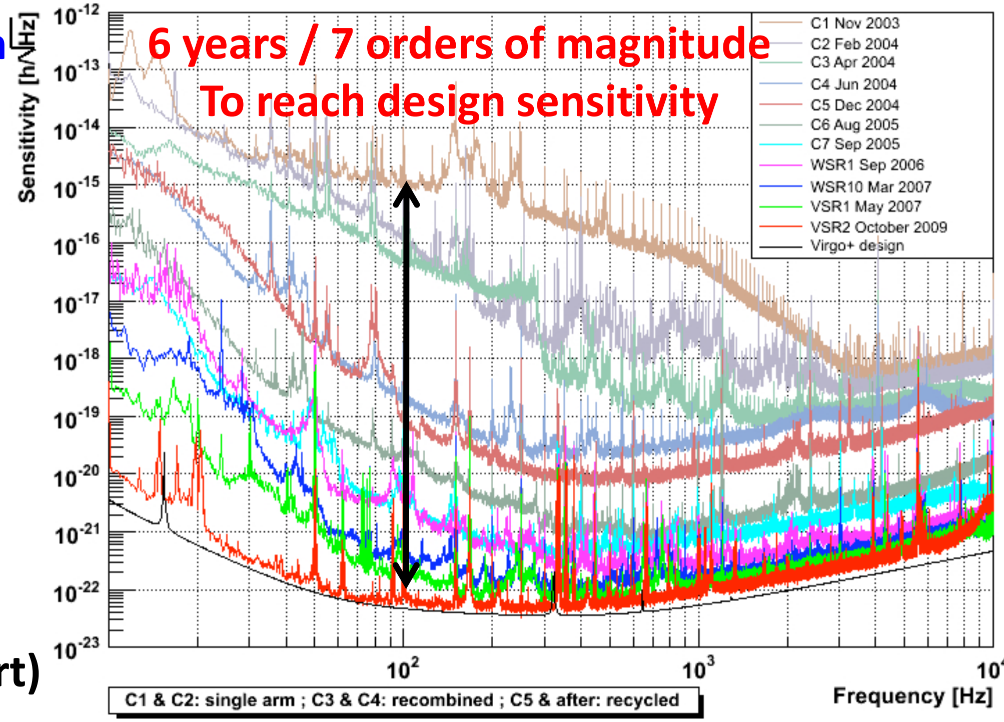
2010 — Upgrade to Virgo+ (2^{nd} part)

VSR3

2011 — Commissioning

Summer 2011: VSR4

Fall 2011 shutdown, start of Advanced Virgo construction



Conclusion: "Lessons of the lessons"

- Initial Virgo has been successfully implemented and design sensitivity reached (after 6 years of commissioning)

⇒ A validation of Virgo technologies

- Virgo+ : several upgrades that provide risk reduction for advanced Virgo

⇒ Dealing with thermal effects, mirror RoC defects, monolithic suspensions

- We learned that our way to put specifications on Virgo mirrors needed to be improved

⇒ Full optical simulations are needed

- Reaching the target sensitivity:

⇒ Generally, it is not only one effect but the sum of several effects that need to be cured

⇒ Going beyond initial sensitivity, we might have to face "unknown" noises

- Commissioning is a long and complex phase

⇒ This should be taken into account for Advanced Detectors

Advertisements

See Richard Day’s talk on “CHRoCC”, Thursday afternoon

See Robert Ward’s talk on “Advanced Virgo design”, Friday morning

Comparison Virgo/Virgo+ mirrors