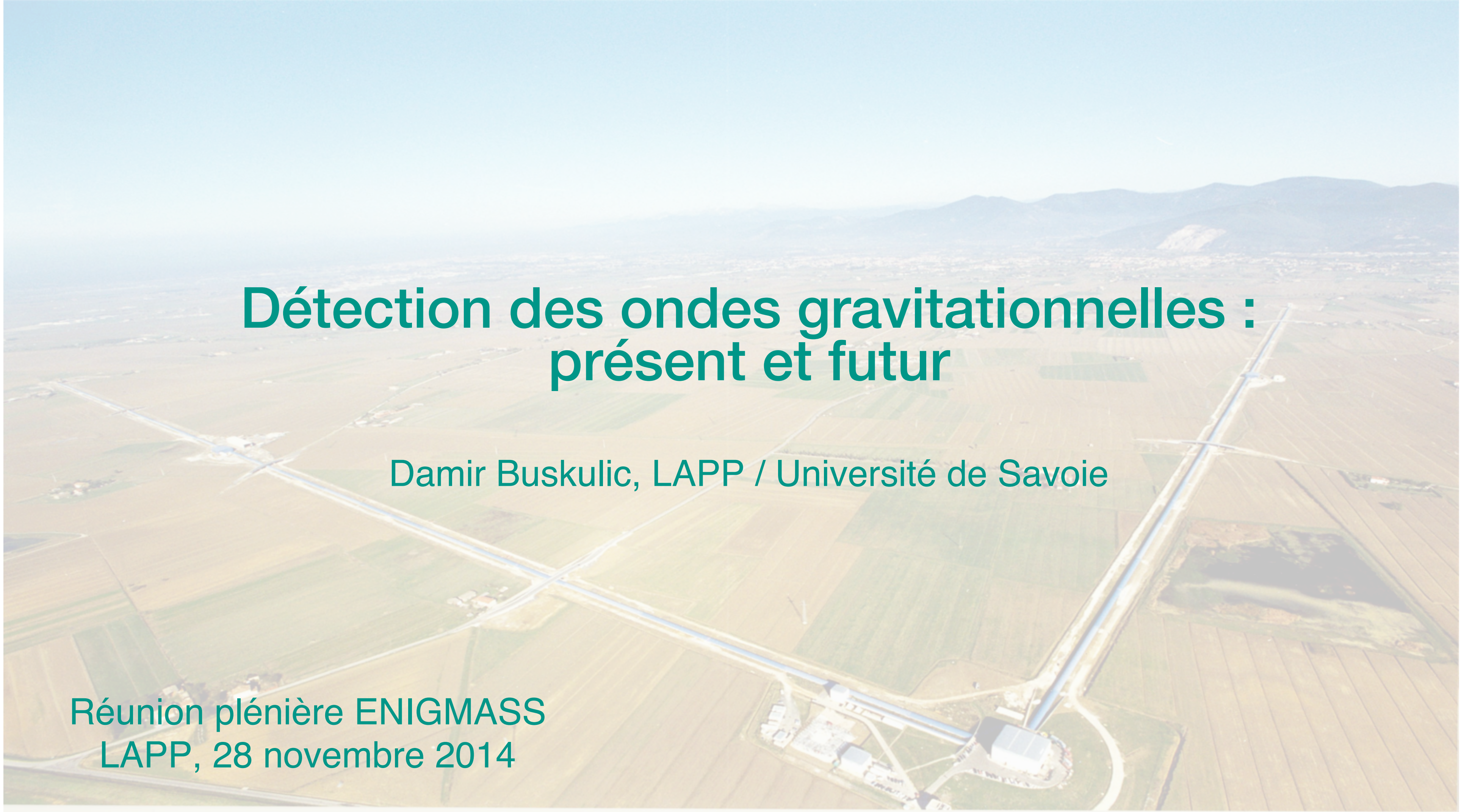


# Détection des ondes gravitationnelles : présent et futur

Damir Buskulic, LAPP / Université de Savoie

Réunion plénière ENIGMASS
LAPP, 28 novembre 2014

# Introduction

Gravitation

- GW are perturbations of space-time that propagate
  - In GR : speed = c, quadrupolar, 2 transverse polarizations
  - Very faint when they reach our detectors $h \propto \frac{G}{c^4} \cdot \frac{1}{D}$
- GW generated by powerful mass acceleration
  - Very energetic events in the Universe
  - GW probe event dynamics
- Gravitation is the only clue to 96% of matter in the Universe
  - GW probe gravitation in new regime

General Relativity

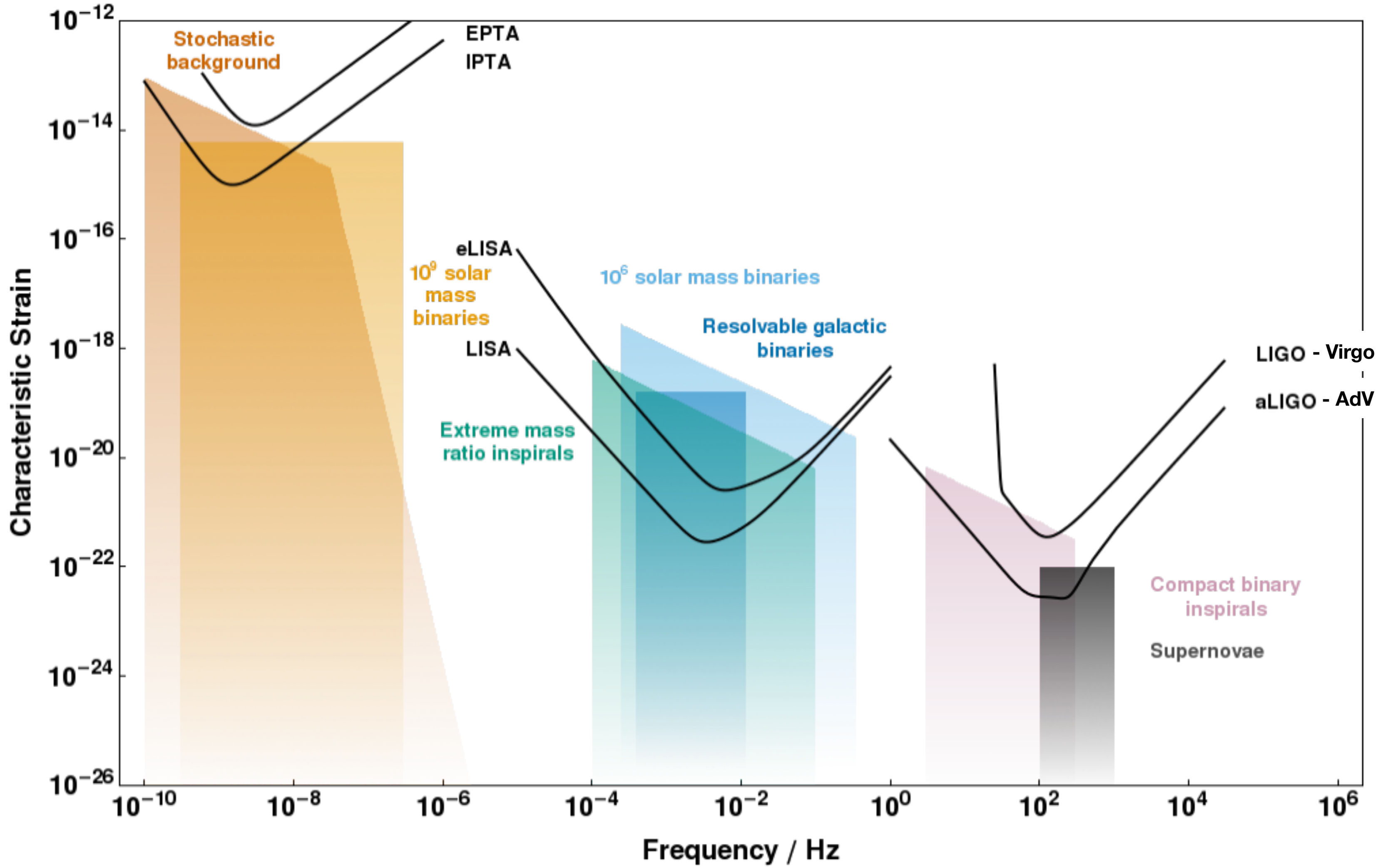
Sources

Universe

Astrophysics

Cosmology

# Gravitational wave spectrum



# Ground-based interferometers

- 1st generation interferometric detectors
  - Initial LIGO, Virgo, GEO600

Unlikely detection

Science data taking
First rate upper limits
Set up network observation

- Enhanced LIGO, Virgo+

Improved sensitivity

Lay ground for multi-messenger astronomy

VOUS ÊTES ICI

- 2nd generation detectors
  - Advanced LIGO, Advanced Virgo, GEO-HF, KAGRA
  - 2.5

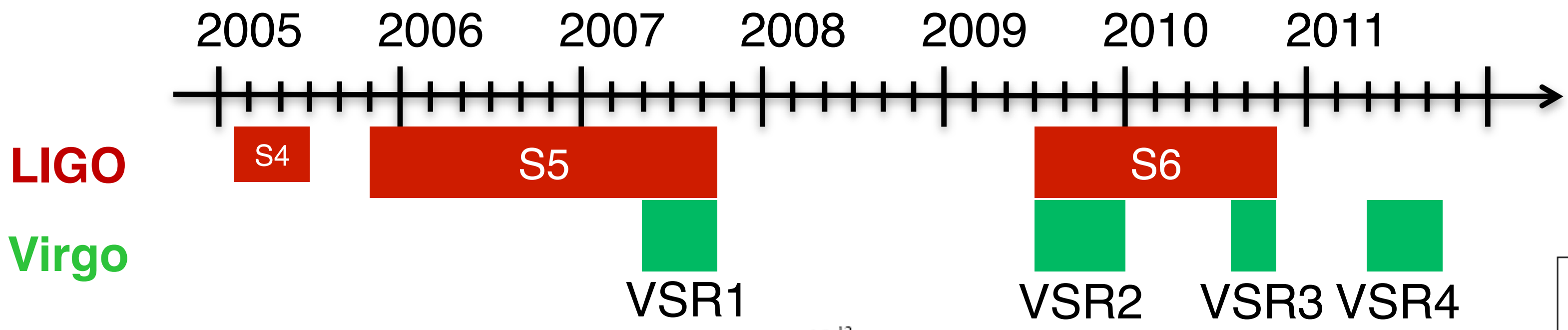
Likely detection

Routine observation
➡ GW astronomy

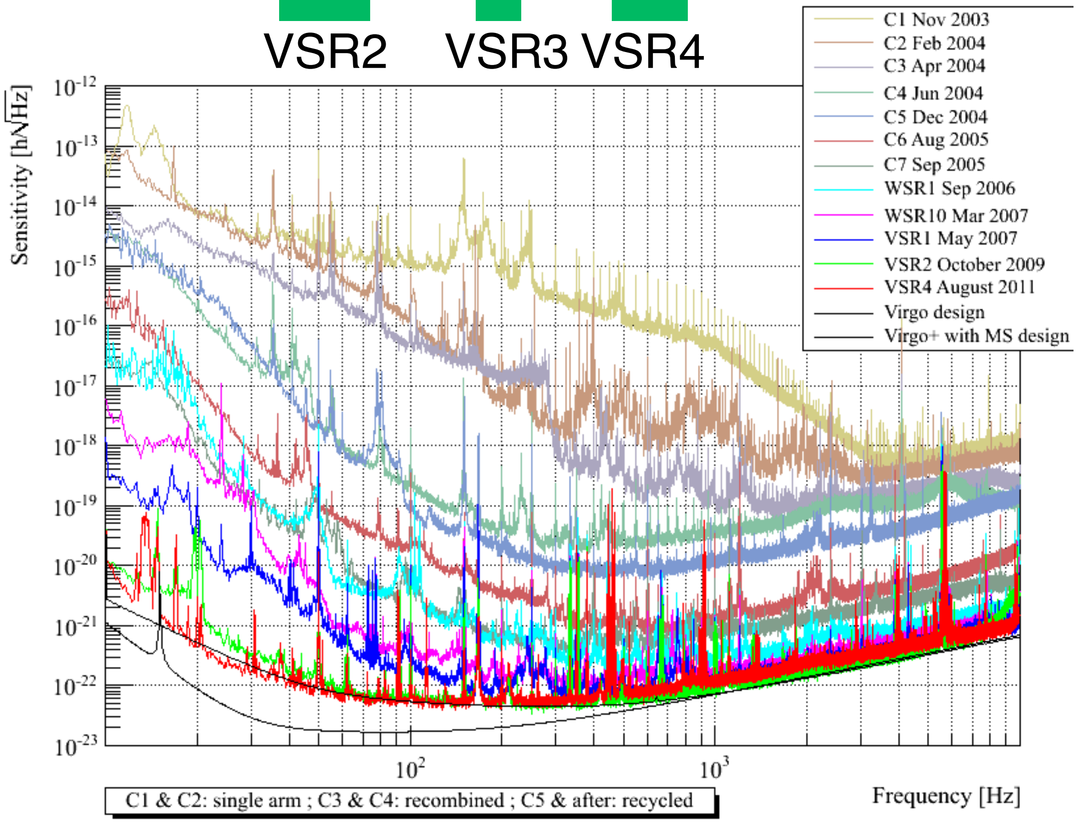
- 3rd generation detectors
  - Einstein Telescope, US counterpart to ET

Thorough observation of Universe with GW

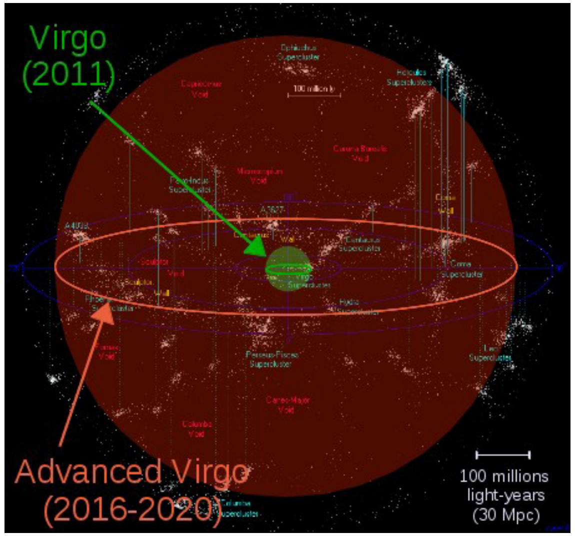
# 1$^{st}$ generation




- Operating detectors at their nominal sensitivities took years of effort
- Long science data taking
- No detection, but some science!

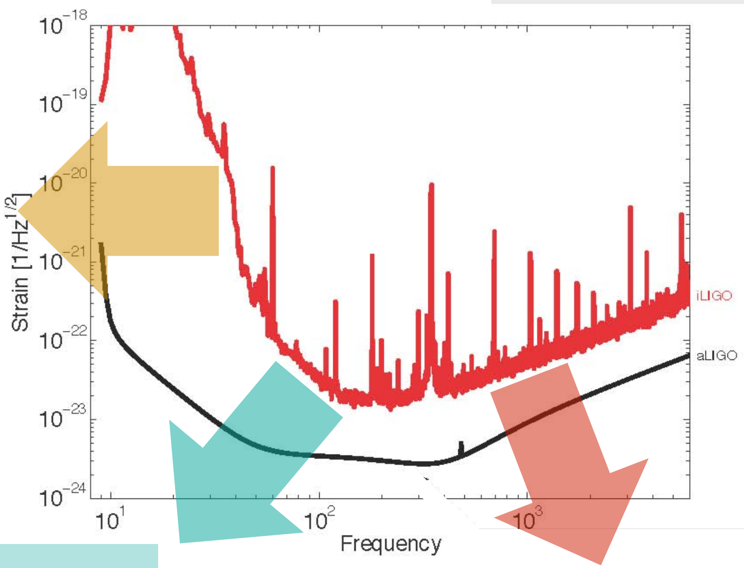


# $2^{nd}$ generation (I)




x10 distance
x1000 volume
*More in a day of observation than in a year…*

**Seismic noise**
Improved seismic isolation

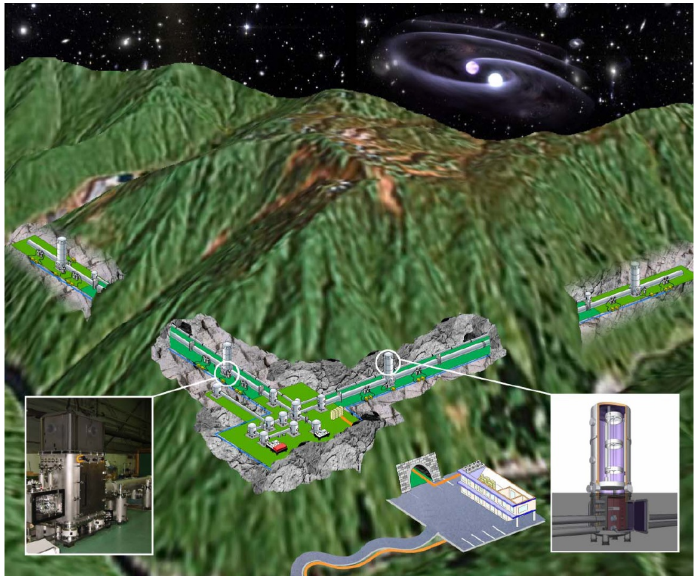


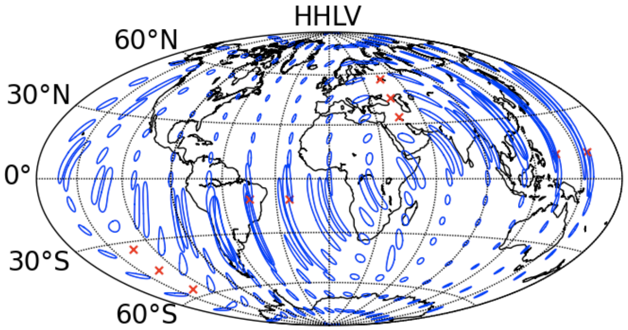

**Thermal noise**
Monolithic suspensions
Improved mirror coatings
Larger beam size

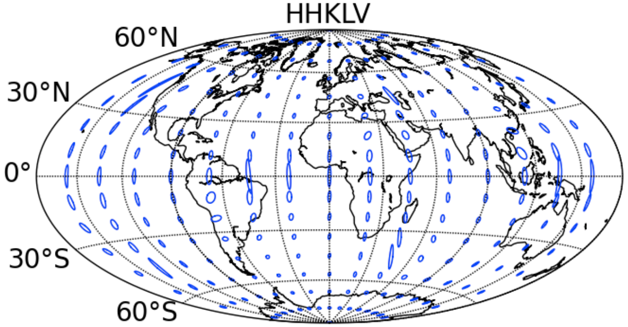
**Quantum noise**
Higher laser power
Thermal compensation
Signal recycling
DC detection

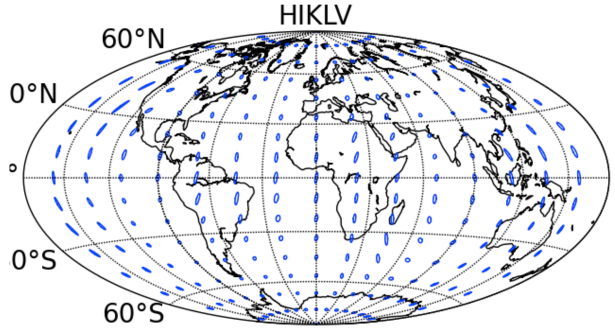
# 2nd generation (II)

- Towards an extended detector network
  - KAGRA in Japan -> 2019 ?
  - Third LIGO detector located in India -> 2020 ?
  - Duty cycle
    - ~80% at best for one detector
    - ~50% for three detectors in coincidence
  - Sky coverage
  - Source localization capability





# Main types of searches

- Compact Binary Coalescences (CBC)
  - Reconstruction of the parameters (direction, masses, spins)
  - All sky
  - Or targeted
    - Short Gamma Ray Bursts
- Burst sources
  - Supernovae, cosmic strings
  - All sky
  - Or targeted
    - Long Gamma Ray Bursts, SGR flares, high energy neutrinos …
- Continuous waves (spinning neutron stars)
  - All sky, single or binary neutron stars
  - Targeted
    - Known pulsars
- Stochastic background

LAPP

# Multi-messenger astronomy

- Many science goals require combining information
  - GW with electromagnetic and/or particle observation
- Search for electromagnetic counterparts to GW
  - Low latency pipelines produce events, sky maps
    - » Bursts
    - » CBC ← LAPP
  - Alerts sent to partners for followup
    - » E.M. telescopes or satellites : 51 MoU signed
  - During S6/VSR2/3 : tested sending of alerts
- Search for GW counterparts to E.M.
  - Targeted searches
  - Radio astronomers
    - » -> information for pulsar targeted searches
- Search for GW – Neutrino counterparts

# CBC detection rates 1st and 2d gen.

$$\mathcal{R}_{det} \propto R.\Gamma.T$$

Taux astrophysique

Nombre de galaxies atteignables

Temps d'observation

« Realistic » rates

TABLE V: Detection rates for compact binary coalescence sources.

| IFO | Source[a] | $\dot{N}_{\rm low}$ yr$^{-1}$ | $\dot{N}_{\rm re}$ yr$^{-1}$ | $\dot{N}_{\rm high}$ yr$^{-1}$ | $\dot{N}_{\rm max}$ yr$^{-1}$ |
|---|---|---|---|---|---|
| Initial | NS-NS | $2 \times 10^{-4}$ | 0.02 | 0.2 | 0.6 |
| | NS-BH | $7 \times 10^{-5}$ | 0.004 | 0.1 | |
| | BH-BH | $2 \times 10^{-4}$ | 0.007 | 0.5 | |
| | IMRI into IMBH | | | $< 0.001^b$ | $0.01^c$ |
| | IMBH-IMBH | | | $10^{-4\,d}$ | $10^{-3\,e}$ |
| Advanced | NS-NS | 0.4 | 40 | 400 | 1000 |
| | NS-BH | 0.2 | 10 | 300 | |
| | BH-BH | 0.4 | 20 | 1000 | |
| | IMRI into IMBH | | | $10^b$ | $300^c$ |
| | IMBH-IMBH | | | $0.1^d$ | $1^e$ |

Realistic rates do get substantial for advanced detectors
BBH visible up to 1 Gpc

# Science with GW from compact binaries

- General Relativity
  - Test theory in strong field
  - Test/constrain alternative gravity theories
- Astrophysics
  - Measure merger rates
    - As a function of parameters
  - Inform source distribution
    - Masses, spins, spatial distribution
  - Study effect of matter in BNS waveform
  - Short, hard GRBs
    - Confirm or rule out merger progenitor
- Cosmology
  - CBC inspirals as standard sirens
    - Independent measurement of Hubble constant

*Challenges*

→ Sensitivity

→ Waveforms

Known, but large parameter space, not fully explored yet

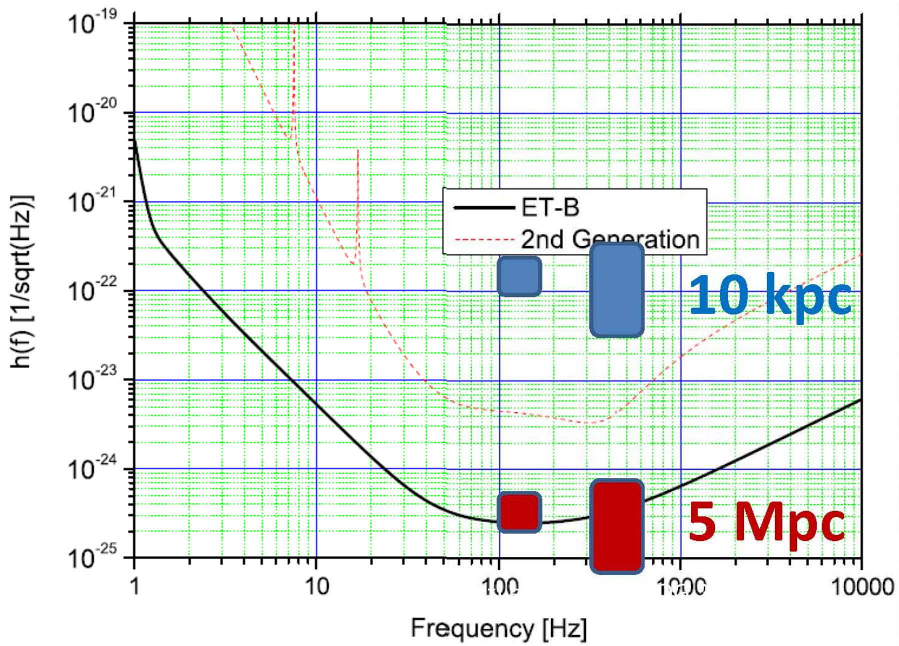
→ Multi-messenger astronomy

Combine information from GW, electromagnetic and/or particle observations.

# Burst GW: supernovae

- Galactic rate of core-collapse SN ~1 per 30-50 years
  - Within reach of 2nd generation detectors, but rare
  - (Lack of) detection will constrain SN mechanisms
- Expect 1 within 5 Mpc every 2-5 years
  - Needs 3rd generation detectors

Sensitivity estimated with Dimmelmaier et al. waveforms (bounce mechanism)



# Continuous waves: initial detectors

## GW upper limits beating spin-down limit for two pulsars

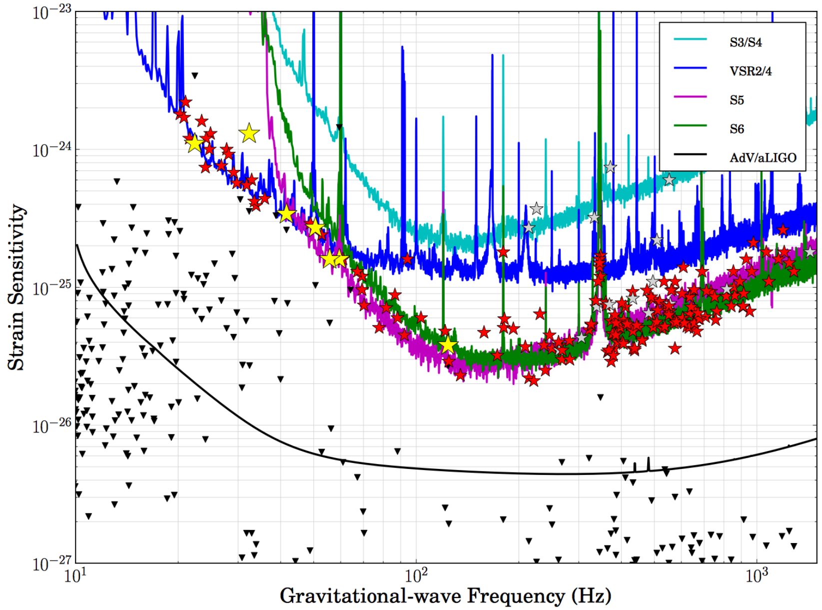
- Crab @ ~60 Hz (LIGO data)
  - GW energy < 1% of spin-down energy
  - $\varepsilon < 8.6\times10^{-5}$
- Vela @ ~22 Hz (Virgo data)
  - GW energy < 10% of spin-down energy
  - $\varepsilon < 6\times10^{-4}$

## Other targeted searches

- 195 known millisecond and young pulsars with LIGO S6 and Virgo VSR3/4 data
  - Best h limit $2.1\times10^{-26}$
    - J1910–5959D, 221 Hz
  - Best $\varepsilon$ limit $7.0\times10^{-8}$
    - J2124–3358, 406 Hz, 0.3 kpc

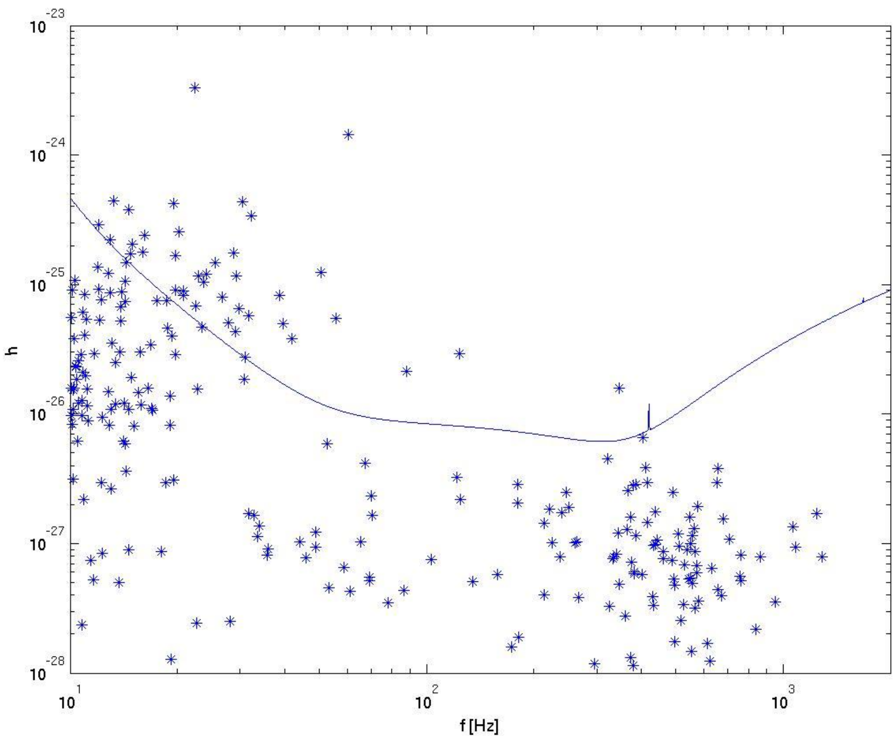
## All-sky searches

- S5 LIGO data
- At high frequency, sensitive to $\varepsilon = 10^{-6}$ up to ~500 pc

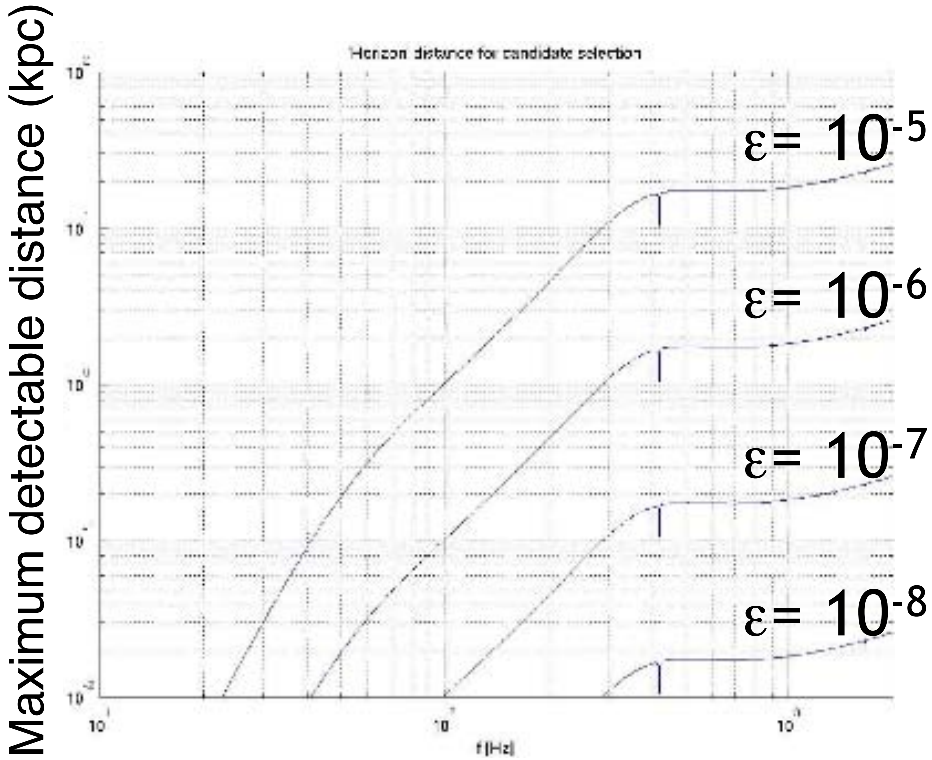


# Continuous waves: advanced detectors

Minimum detectable amplitude with 1yr observation of Advanced Virgo, compared to spin-down limits of known pulsars



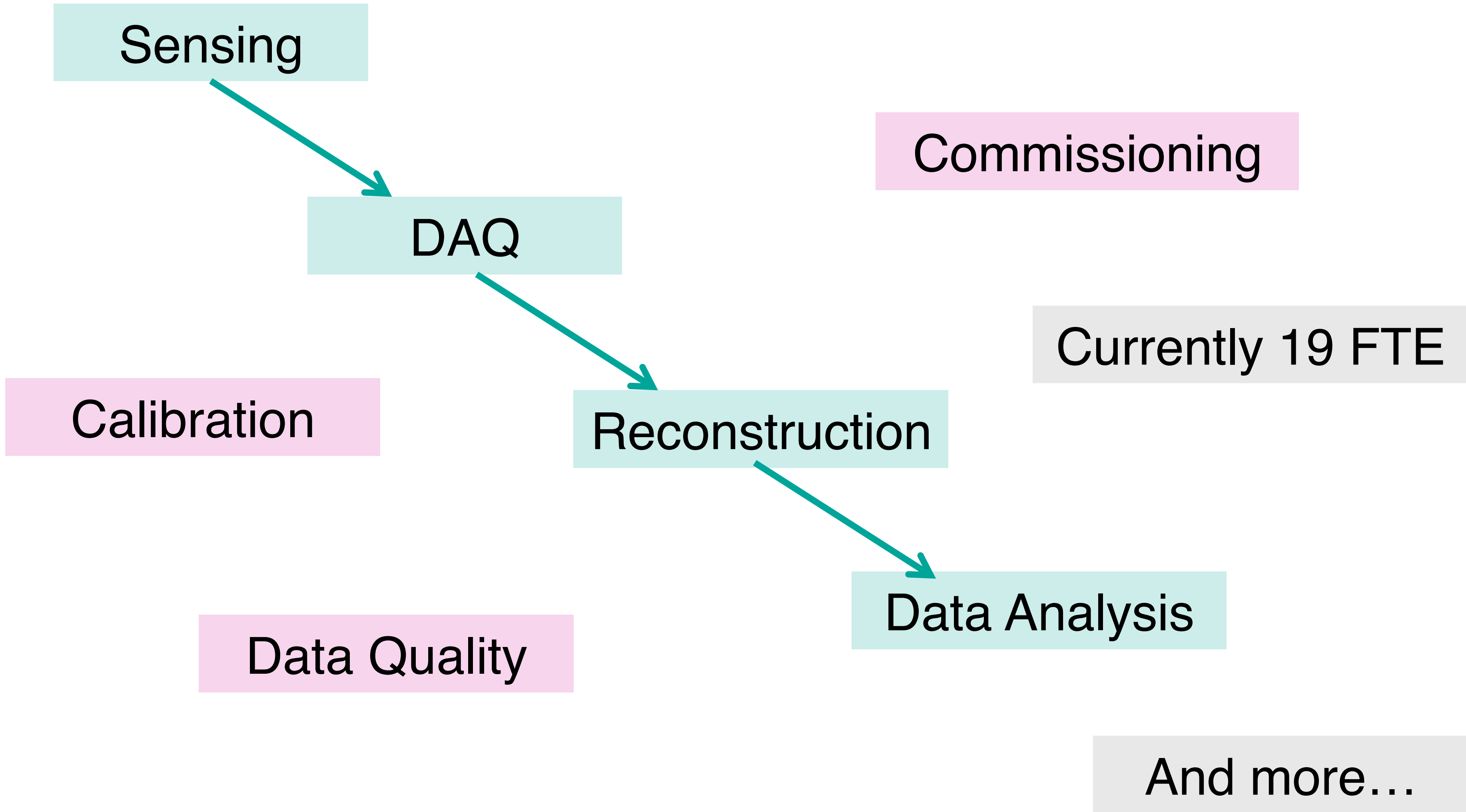

Significant fraction of the Galaxy probed for large ellipticities



# Analysis program for the coming years

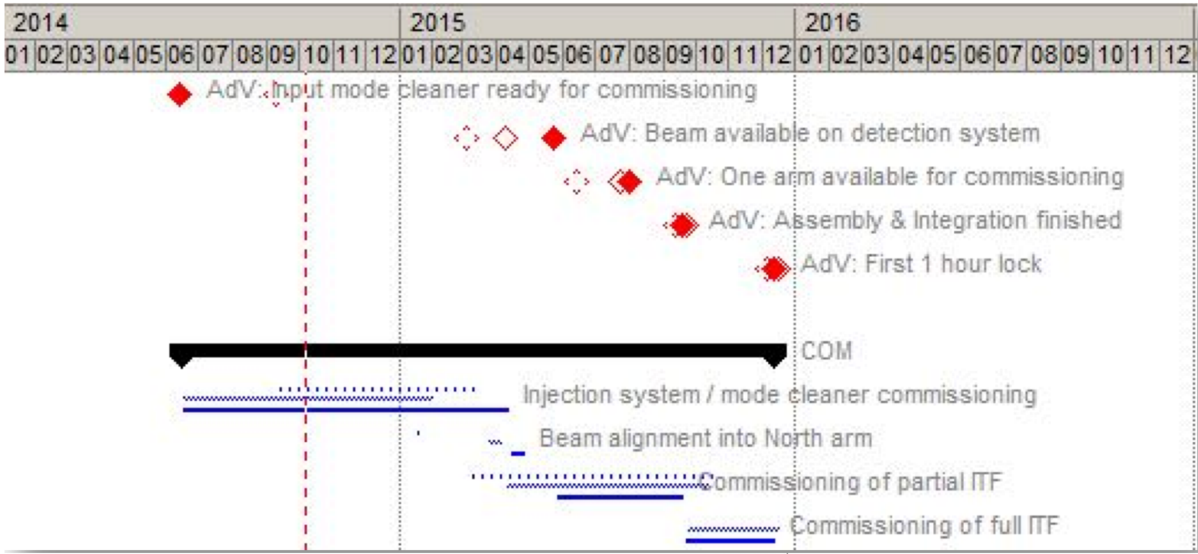
- Analysis pipelines should be ready for day 1
  - Especially low latency pipelines
  - Observational run 1 (O1 - LIGO only) : starts september 2015
  - Common LIGO-Virgo Observational run 2 (O2) : mid-2016
  - Calibration/Reconstruction
  - Detector characterization and Data Quality
- Post-doc of Thomas Adams funded by ENIGMASS
  - Work on our CBC low latency pipeline
- E.M. followup optmisation/strategy
- Longer term future depends on detections and results

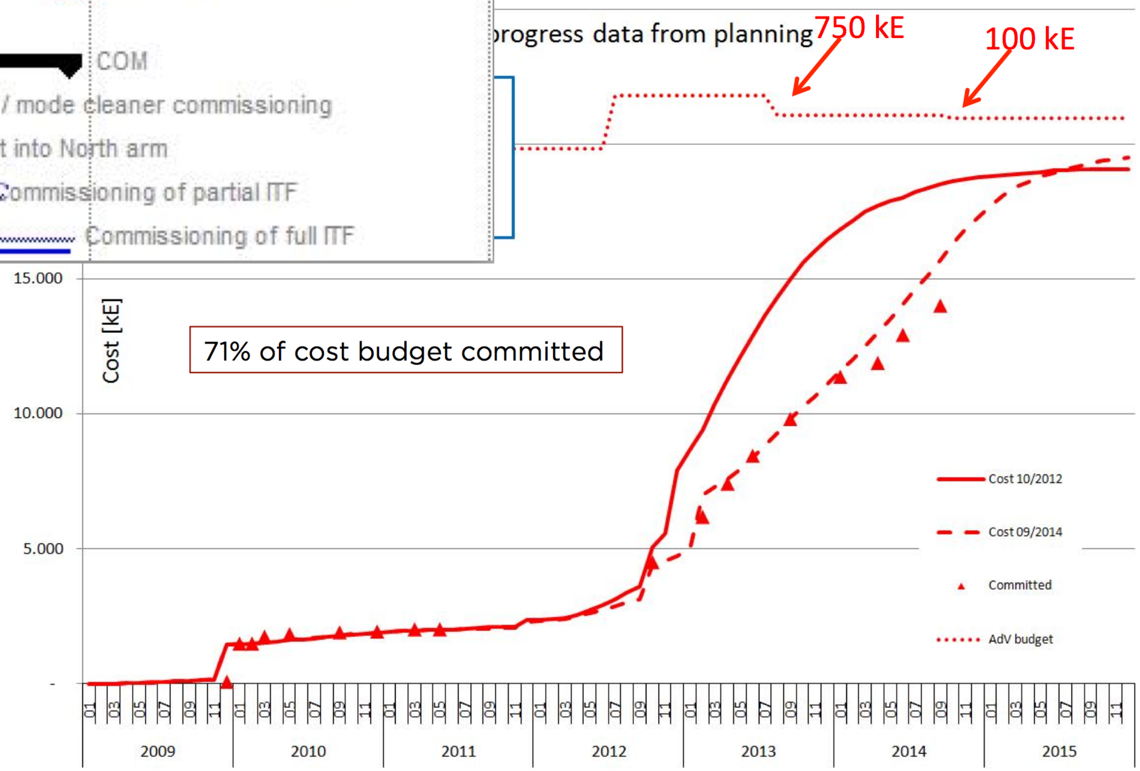
# AdV @ LAPP



Sensing
DAQ
Reconstruction
Data Analysis
Commissioning
Currently 19 FTE
Calibration
Data Quality
And more…

# AdV planning & progress

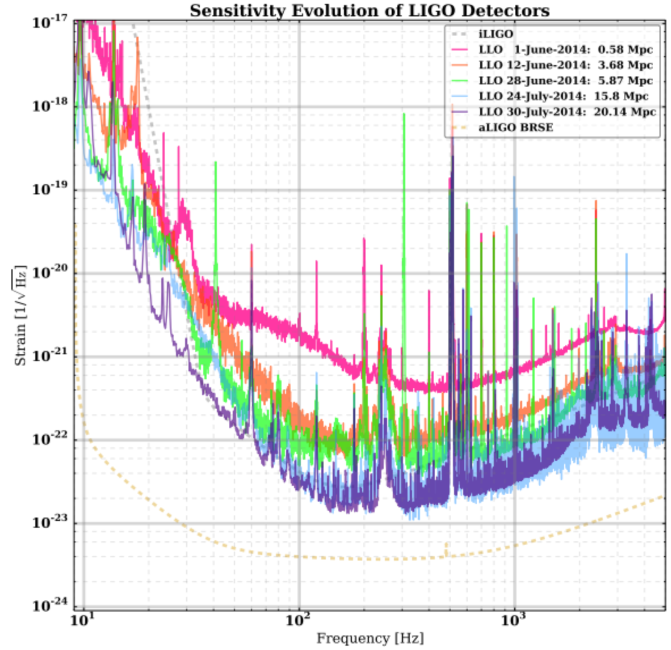



- Input mode cleaner locked
- Detector installation is progressing steadily

# aLIGO status

- Commissioning of the L1 (Livingston) interferometer
  - Interferometer locked on May 26
  - NS-NS Horizon = 36 Mpc at end of september
- Installation of H1 (Hanford) completed
  - Commissioning started
- Ahead of schedule for some tasks
- Engineering Run 6 starts december 8
  - 10 days
  - L1 participates, hopefully also H1



# Conclusion

- The coming years will be very exciting times
  - We are confident that the detection of GW is nearing

- Second generation detectors
  - Should start observational data taking end 2015 (LIGO) – mid 2016 (LIGO + Virgo)
  - On schedule for LIGO, as well as Virgo
  - A lot of different data analysis opportunities
    - » CBC, Continuous waves, Bursts
    - » Multi-messenger astronomy

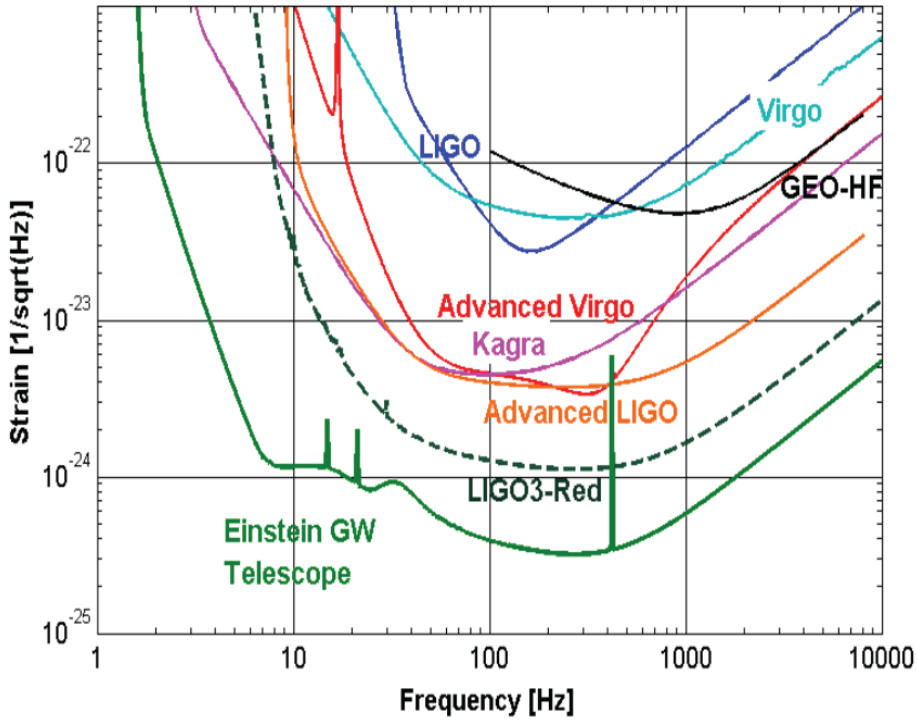
- Still a lot of work needed to make it happen
  - Commissioning of the detectors
  - Reconstruction/Calibration/Detector characterisation are important
  - Continued developpement of the analysis pipelines

- And then, followup of the events that we will detect

Diapos supplémentaires

# AdV+

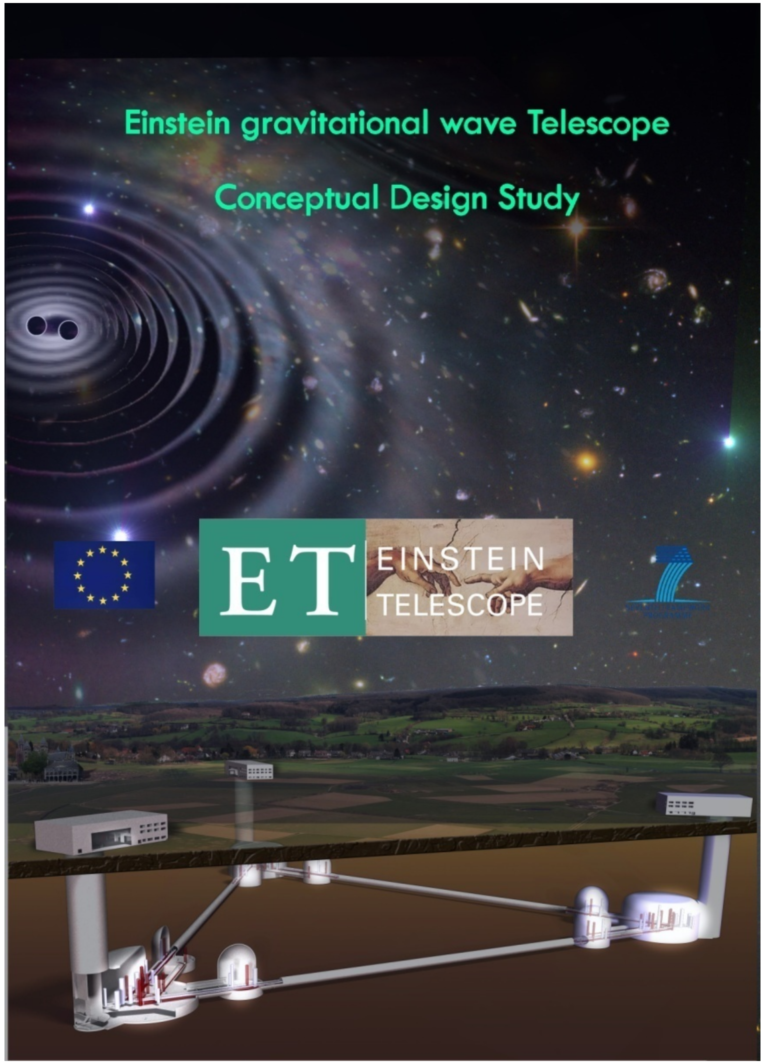
- Room for improvement within infrastructure
- Examples:
  - Subtract gravity gradient noise
  - Increase mirror weight
  - Increase length of final pendulum stage
  - Improve fiber geometry
  - Improve coating materials
  - Larger beam size
    - » Larger mirrors, different beam shape
  - More powerful laser
    - » Change wavelength
  - Squeezing
  - Cryogenics
  - …



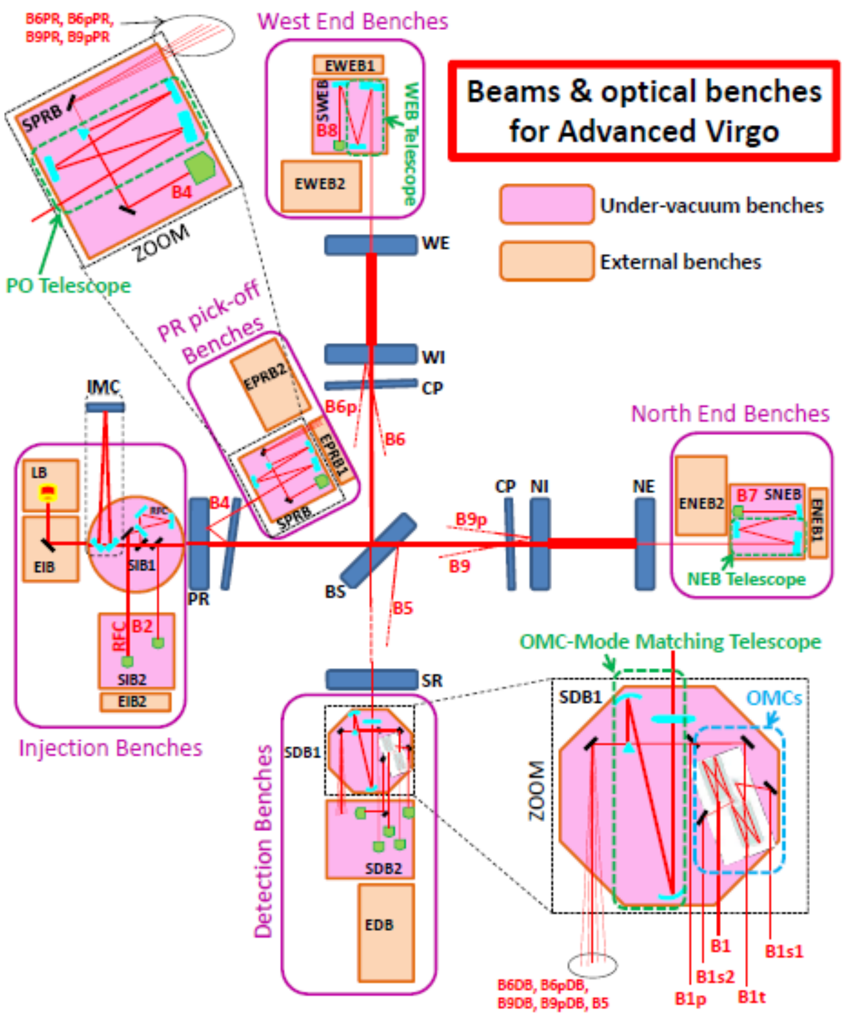

- Need to fight fundamental noises but also technical noises
- Brainstorming started in LIGO three years ago: LIGO-3G
  - Broadband sensitivity improvement by a factor of 3-5 ➔ event rate x 25-100
- Need for sustained technical effort after AdV is installed

# $3^{rd}$ generation

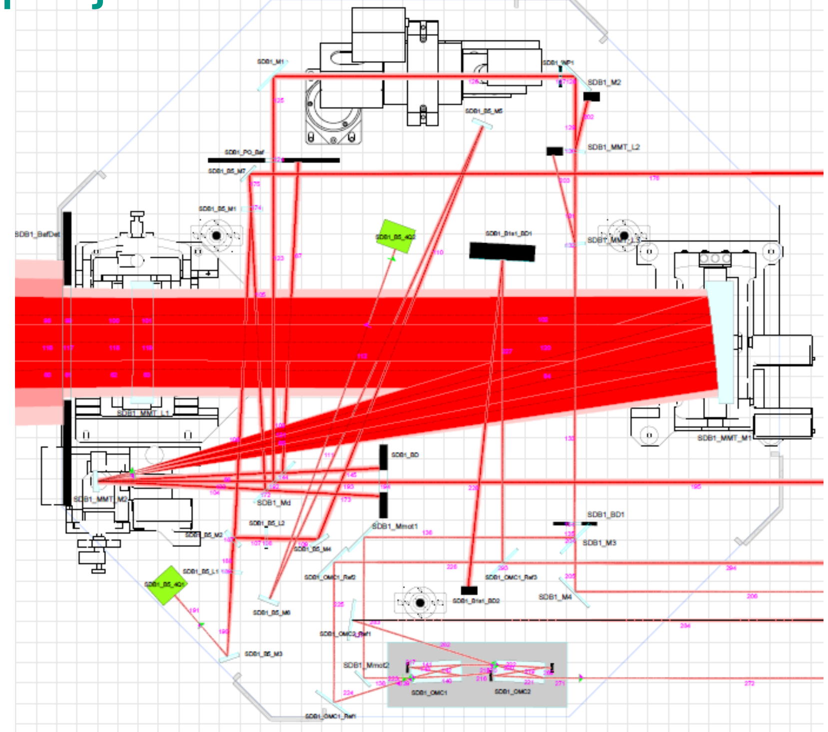
- Sensitivity
  - 10x better than $2^{nd}$ generation
  - Bandwidth starting at 1 Hz
  - BNS / BBH to z ~ 4 / 10
- Configuration
  - Several large interferometers (30km?)
  - Underground
- Improved technologies
  - Cryogenic, mirrors, laser, squeezing…
- Status
  - ASPERA roadmap
  - FP7 Design Study
    - » 2008-2011
  - Construction?
    - » Probably not before 1st detection



# AdV @ LAPP: DET (I)

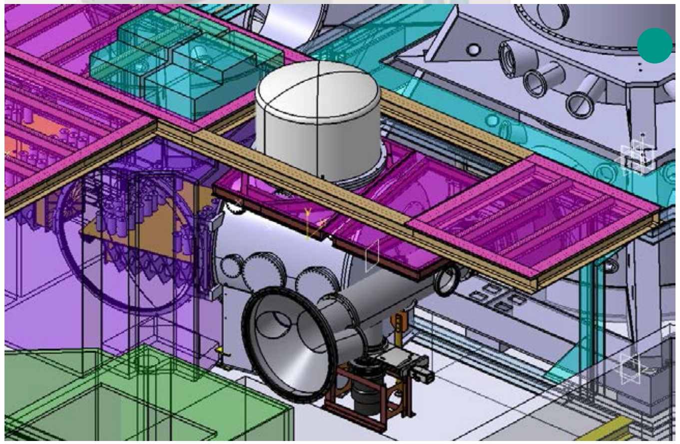



- More benches suspended in vacuum for AdV
- Optics is only one angle of the project

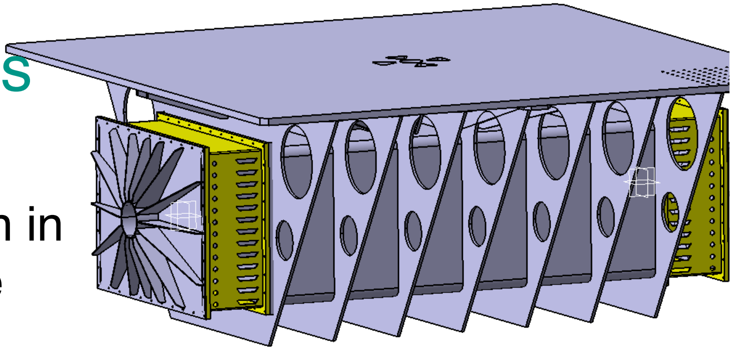


# AdV @ LAPP: DET (II)

- Vacuum chambers designed @ LAPP
  - First two delivered early 2013 at LAPP & NIKHEF
  - Three installed at Virgo
- On-going study for on site integration

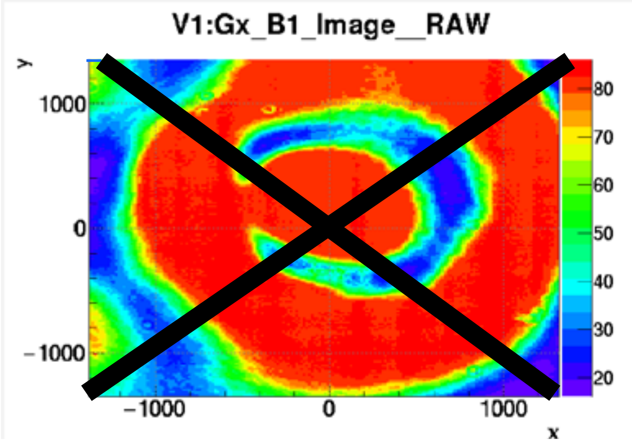


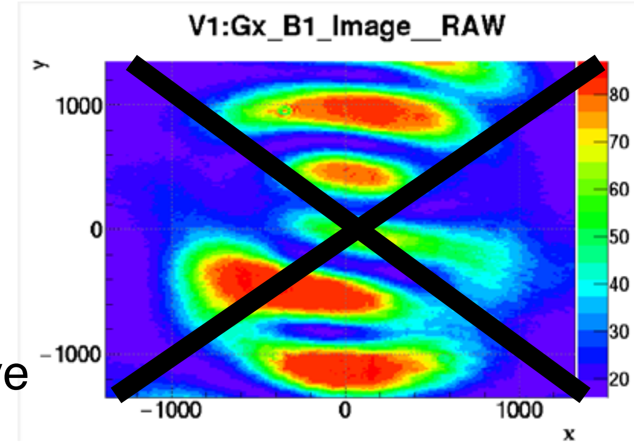
- Optical benches holding containers for electronics
  - Thermal dissipation in vacuum is an issue
  - Local controls

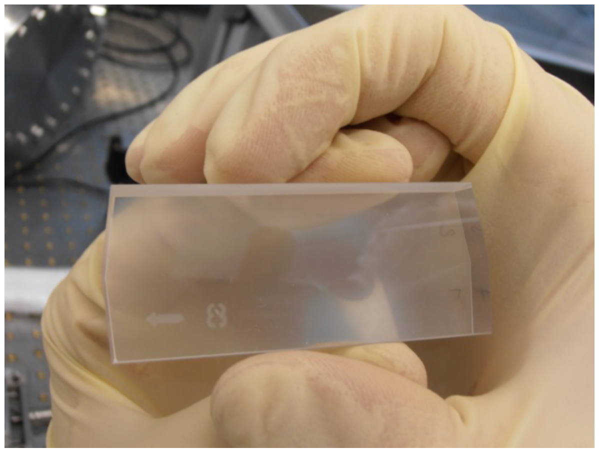


# AdV @ LAPP: DET (III)

- Output mode-cleaner is a crucial element for sensitivity (shot noise)
  - ◆ Filter high order modes generated by beam mismatch, misalignments and astigmatism
  - ◆ New for AdV : filter RF side-bands for DC detection
- Final prototype being characterized and hopefully validated



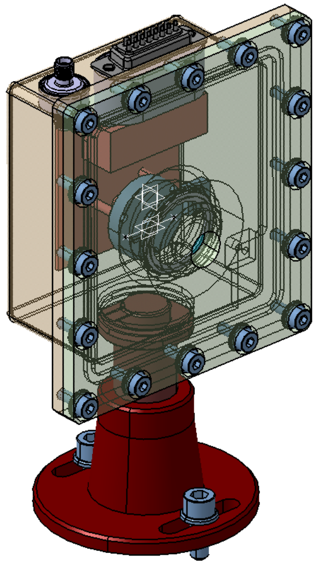



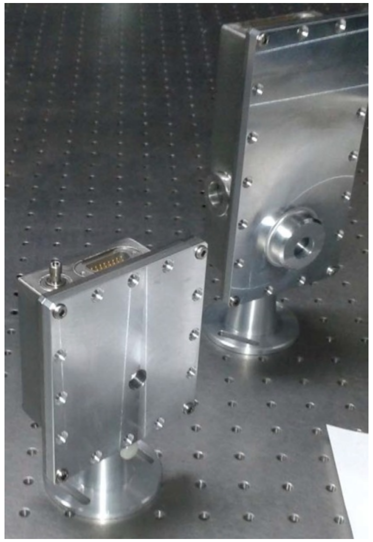



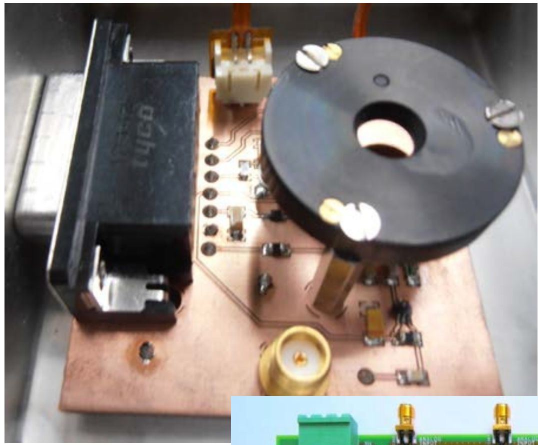
- Cavity kept on resonance with thermal control
  - ◆ Accuracy crucial to keep thermo-refractive noise low
  - ◆ Not the only sensitive part of detection system : scattered light, electronics… ⚠

# AdV @ LAPP: DET (IV)

- Photodiodes
  - Main beam & auxiliary beams
  - For detection & controls
- Readout and demodulation electronics
  - Low noise, large dynamics

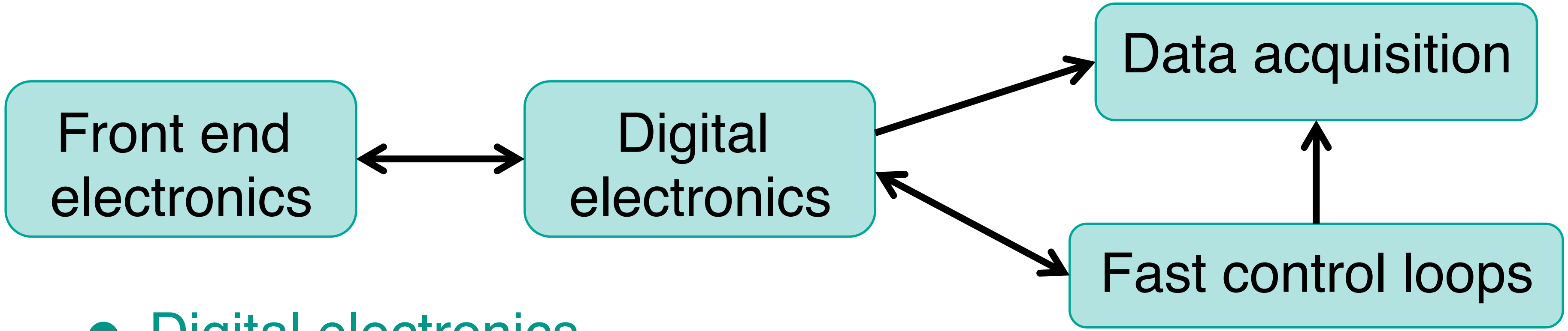







- In air in sealed boxes on benches in vacuum

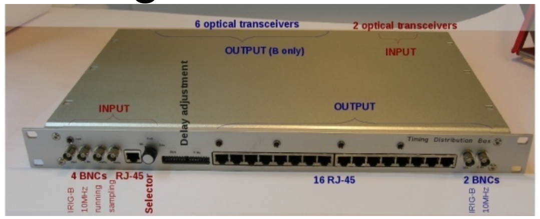
# AdV @ LAPP: DAQ (I)



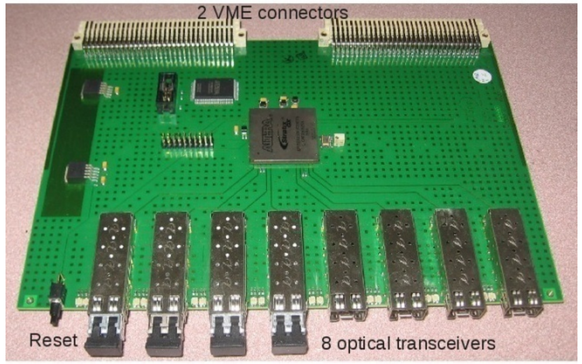

- Digital electronics
  - ADCs
  - DACs
  - Video
  - Digital demodulation
  - Photodiode control
- Calibration
- Network for data exchange and fast controls
  - Optical fibers
  - Timing
  - Multiplexing
  - Real time PCs
- Major upgrade for Virgo+, follow-up developments for AdV

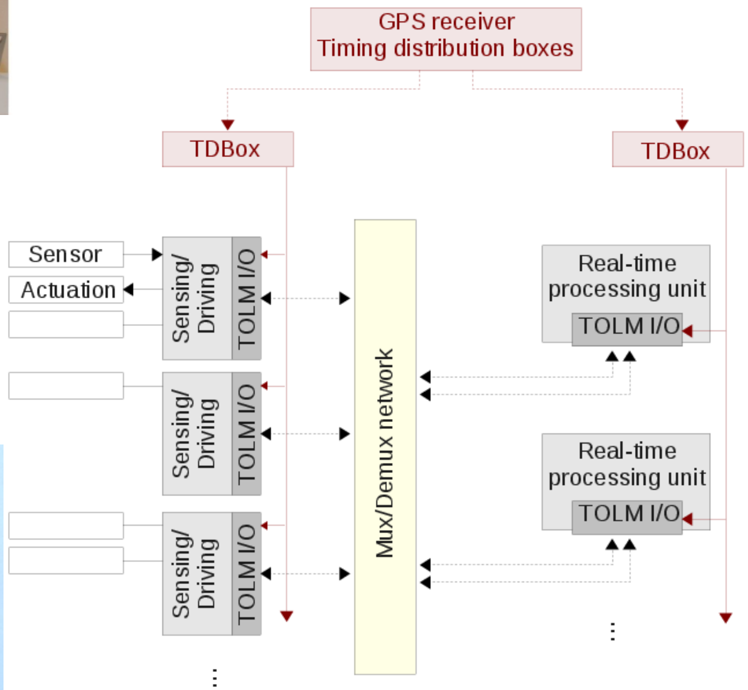
# AdV @ LAPP: DAQ (II)

## Timing distribution box

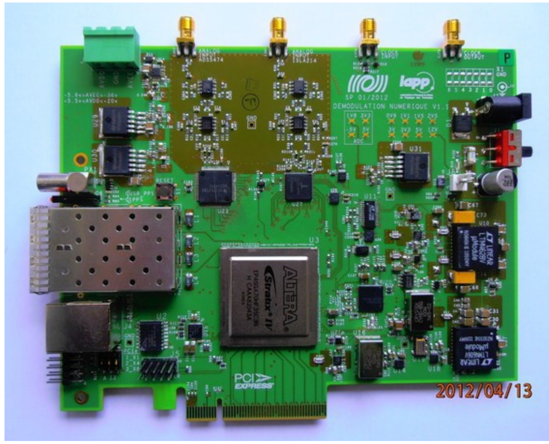



## Mux/demux boards



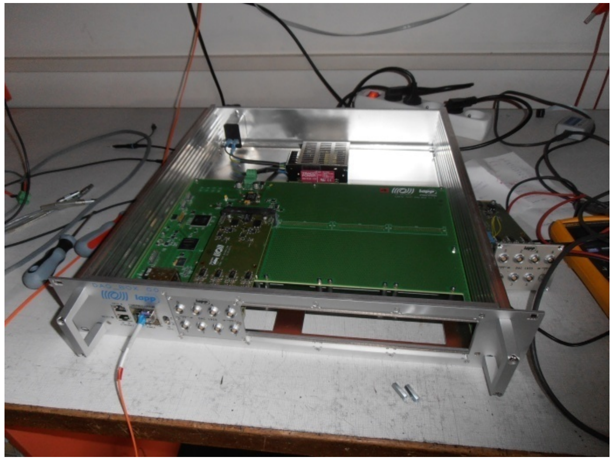

## TOLM with PCIe interface (prototype)



New real time PCs

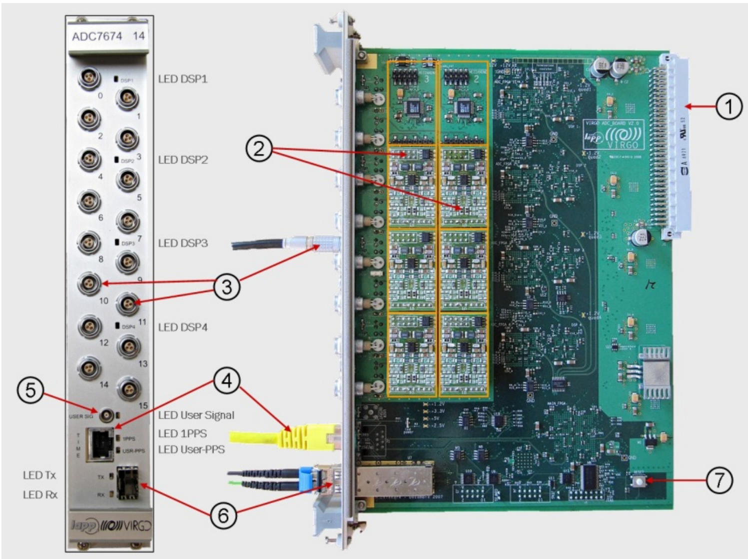
# AdV @ LAPP: DAQ (III)

- DAQ-box
  - Generic mother board hosting serveral functional mezzanines
    - ADC, DAC, demodulation, photodiode control, camera control



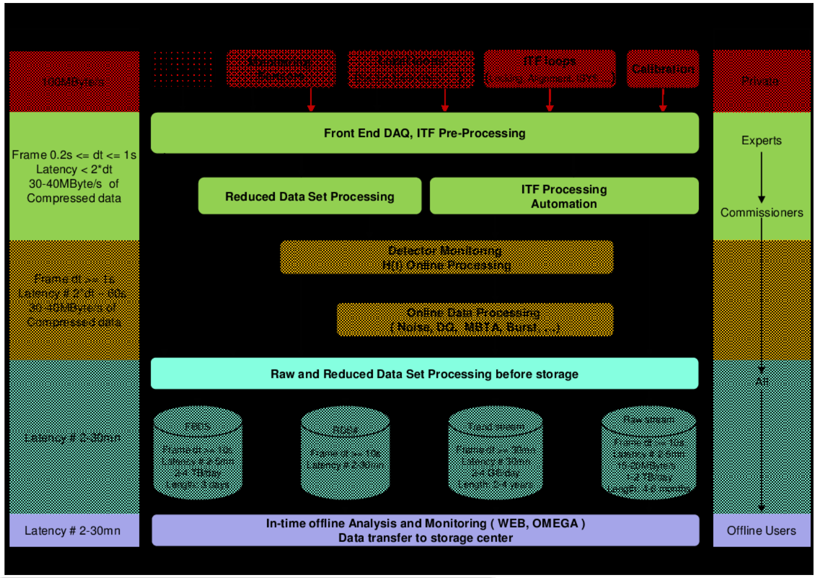
DAC mezzanine

Virgo+ ADC board ➔ ADC mezzanine for AdV

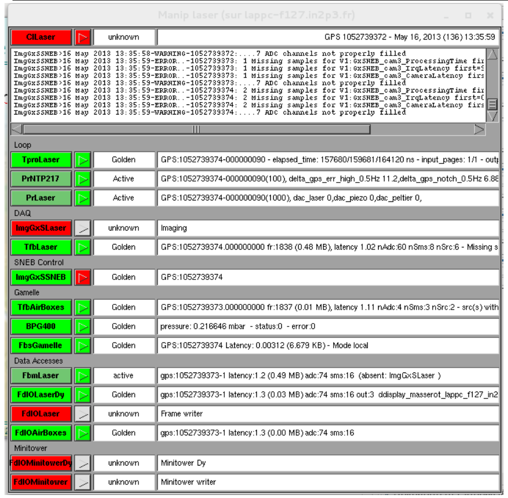


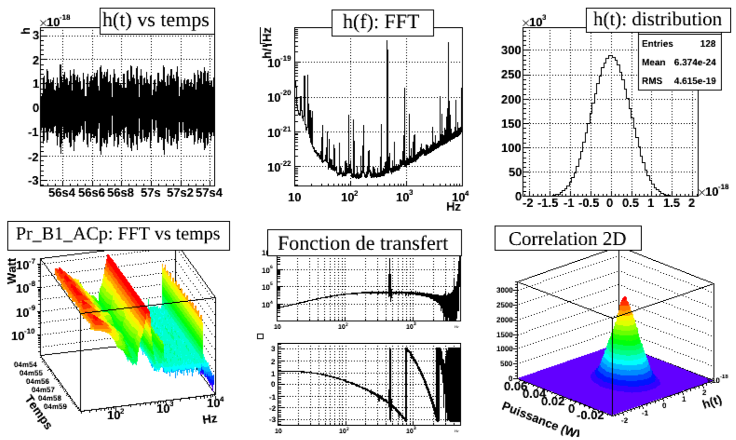

Virgo+ camera box ➔ camera mezzanine for AdV

# AdV @ LAPP: DAQ (IV)




- DAQ software
- Online processes control GUI
- Data display
- Monitoring web pages






# AdV @ LAPP: coating robot

- Robot for corrective coating @ LMA of AdV mirrors
  - Accurate positioning of mirrors in vacuum for corrective coating process ➔ improve surface quality
  - Delivered at LMA in summer 2011
  - Successfully tested

# From commissioning to data analysis

- Assembling ➔ Commissioning ➔ Data taking
  - Prepare carefully, be prepared to face the unpredictable
  - LAPP contribution: DET commissioning, noise hunting, control optimization…
- Calibration and h(t) reconstruction
- Virgo data quality
  - Detector characterization, online veto production
- Online search for compact binary coalescences
  - Follow-up of S6-VSR3 effort
  - To allow EM counterpart search
  - Real time CBC pipeline developed @ LAPP