Advanced VIRGO and the network of advanced detectors: status of art

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INFN - Sezione di Roma

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Talk outline

- A bit of history
- GW Science from the first generation
- The new generation of advanced detectors
  - Advanced Virgo: new hardware
  - Advanced LIGO: new hardware
- The first science run of the advanced detector era
- The future
- Conclusion

H1- Hanford – Washington state

Virgo – Cascina (Pisa) – EGO site

GEO600 – Hannover - Germany

L1- Livingston – Louisiana state

A bit of history

- *The **LIGO** project was approved in **1992** and inaugurated in **1999**. Built at a cost of almost $3x10^8$ $, LIGO was the largest single enterprise ever undertaken by the foundation. It started the operation in 2002.*
- **VIRGO** was formally proposed in 1989 and approved in 1993. The construction was divided in two step: it started in 1996 and then completed in 2003. The first science run is date 2007. The total investment done by CNRS and INFN was almost 8×10^7 $.
- ***GEO600** was proposed in 1994. Since September 1995 this British-German GW detector was under construction. The first science run was performed in 2002. In 2013 Squeezing light was used over one complete year!*
- First attempt to exchange data and mix the data analysis groups started in 2004. The formal **MoU of data sharing and common analysis** among **GEO-LIGO-VIRGO** was signed in **2007**.

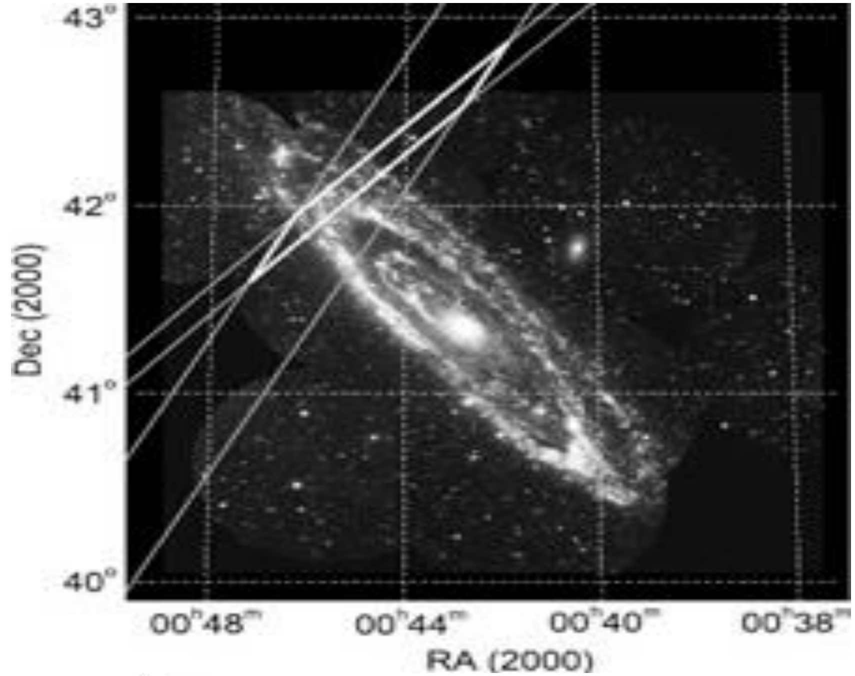
GW Science From First Generation

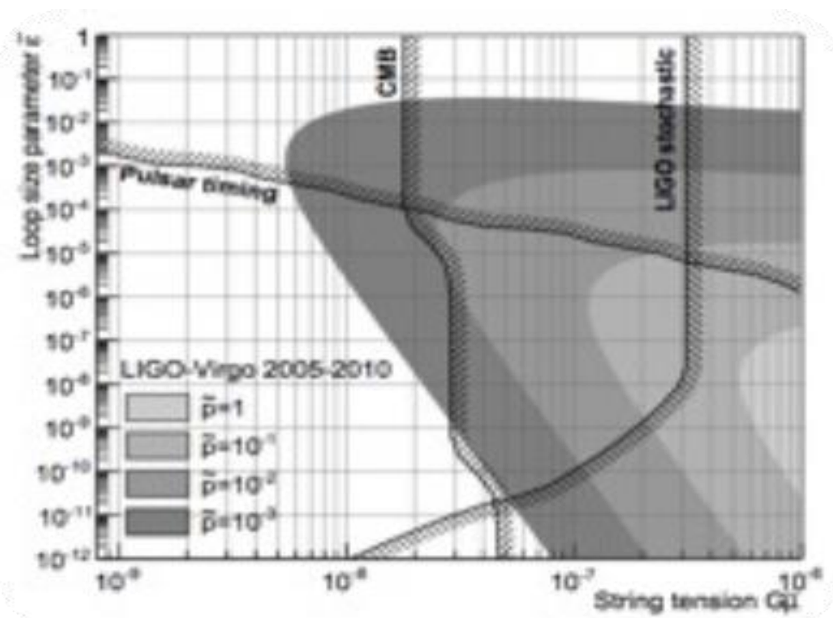
Non-detection of nearby GRBs
GRB070201 [**ApJ 681 (2008) 1419**]
GRB051103 [**ApJ 755 (2012) 2**]

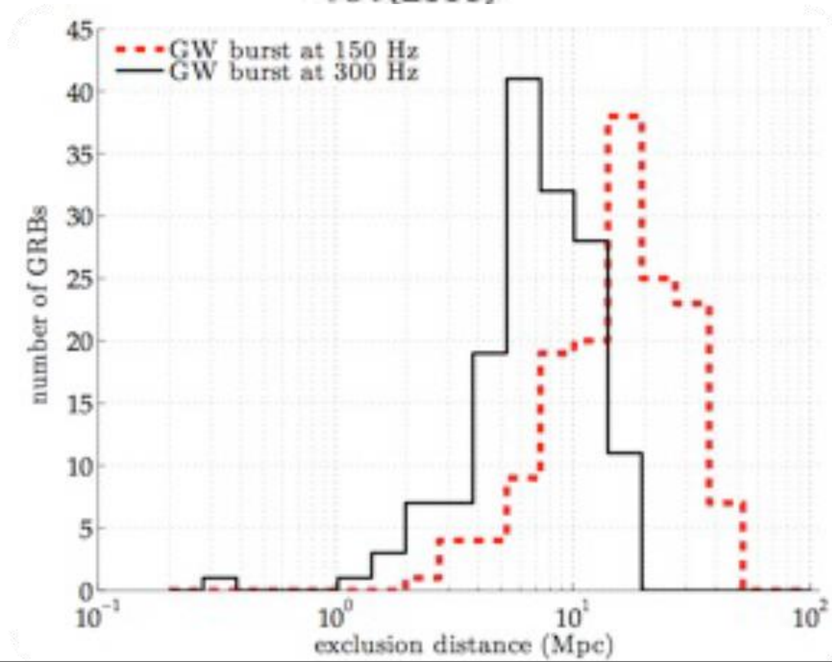
GW constraints for magnetars
[**ApJ 734 (2011) L35**]

GRB population constraints
[**ApJ 760 (2012) 12, PRL 113 (2014) 011102**]

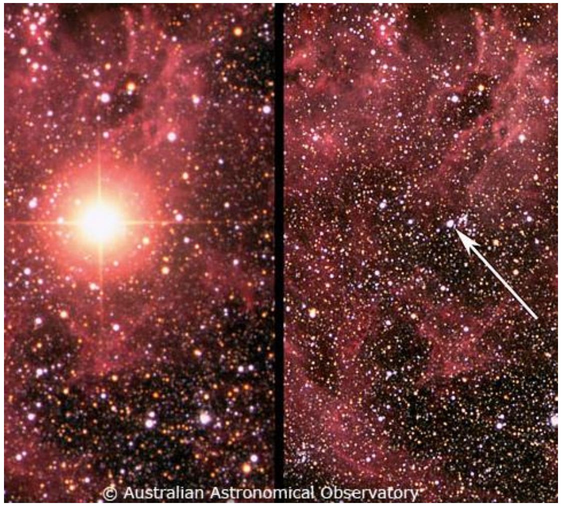
Cosmic strings [**PRL 112 (2014) 131101**]

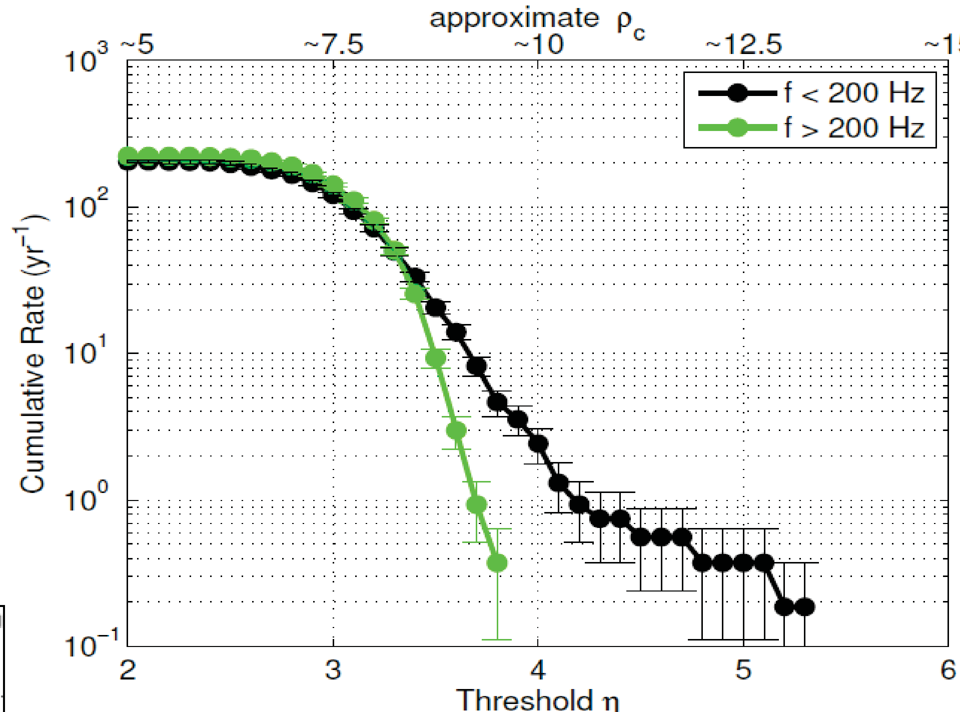




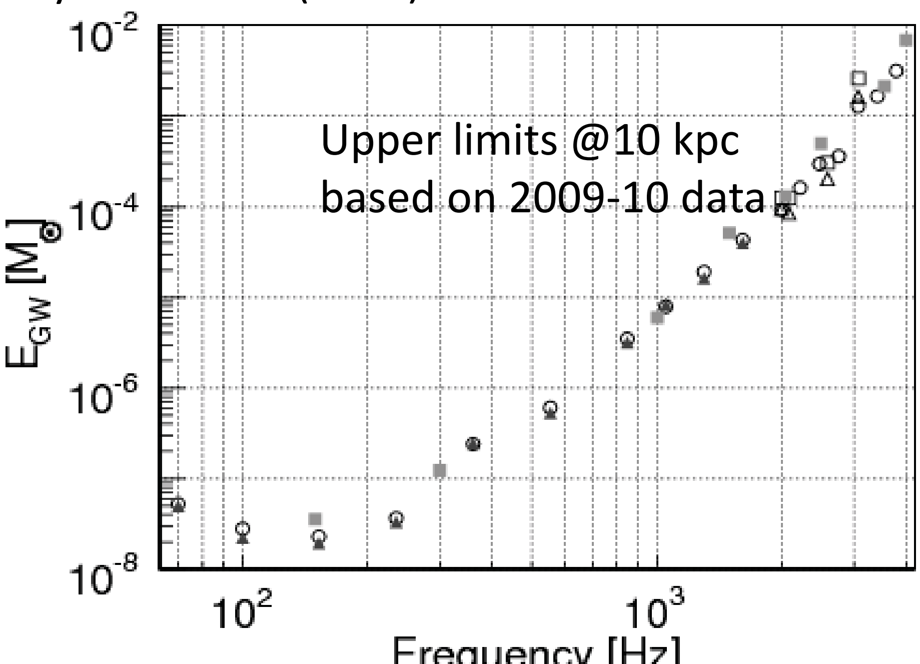


Burst unmodeled searches





Phys. Rev D 85 (2012) 122007



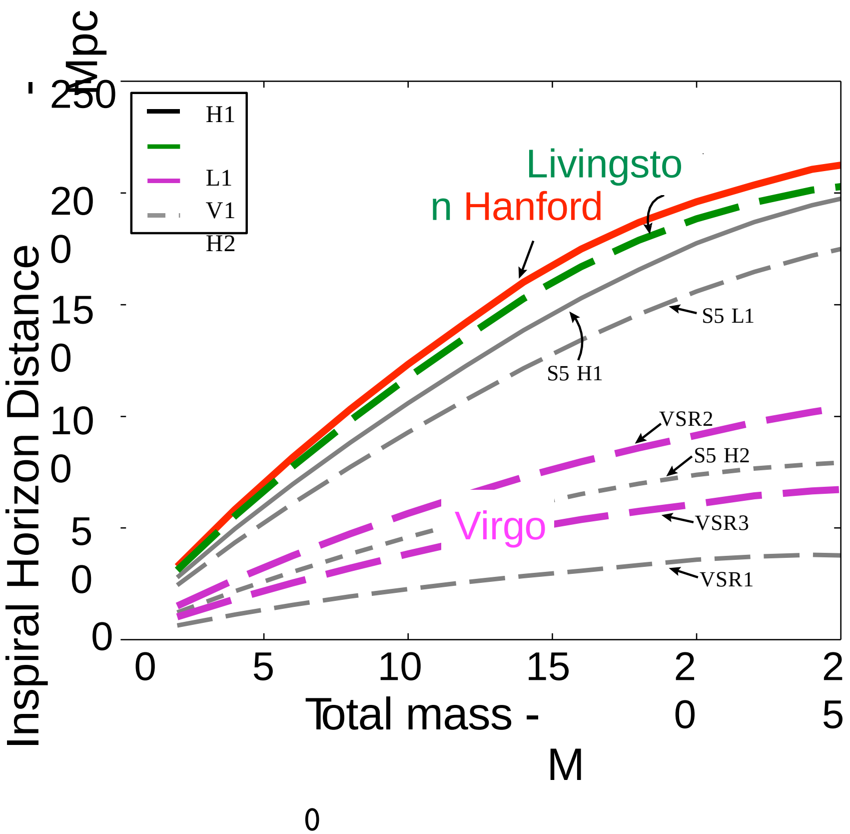
$$h_{rss} = \sqrt{\int |h_+(t)|^2 + |h_\times(t)|^2}$$

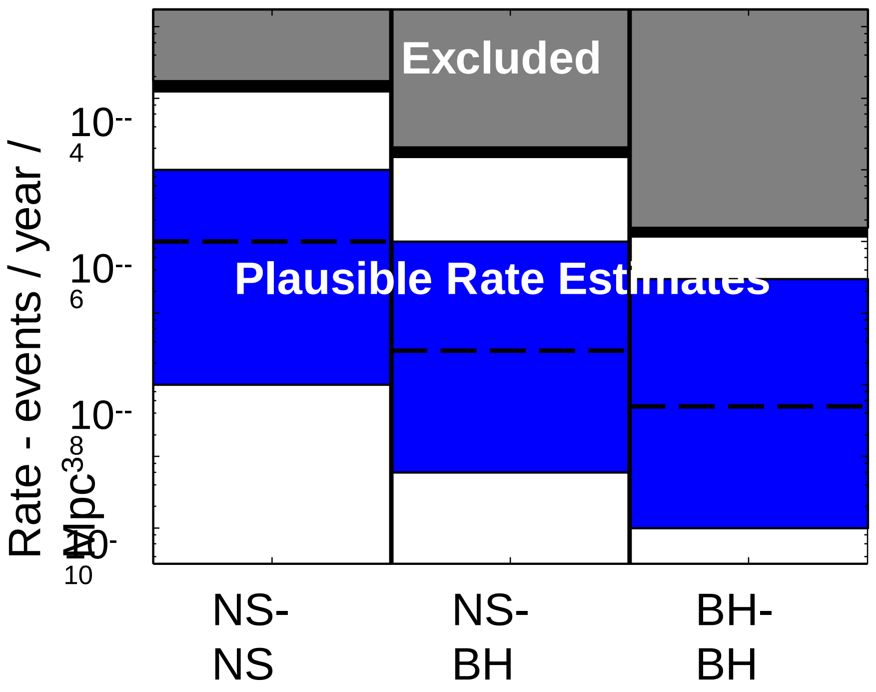
Numerical simulations for galactic supernovae:

E_{GW} 10^{-7} - 10^{-4} $M_\odot c^2$

GW Science From First Generation (2005-2011)

PRD 85 (2012) 08202



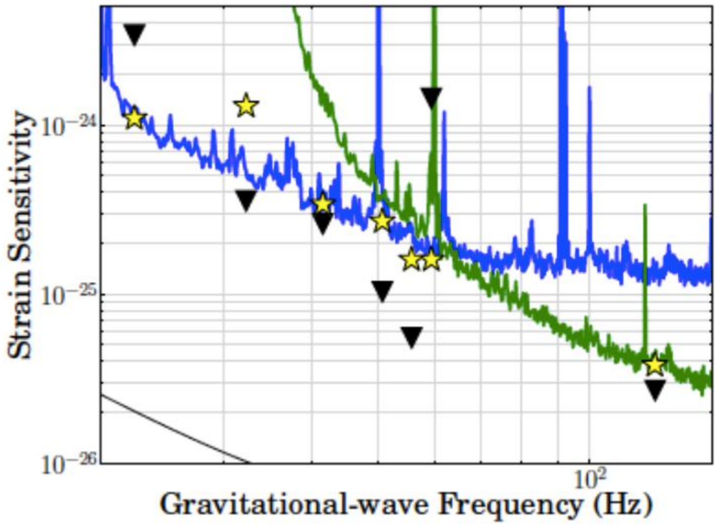


CW and stochastic signal searches

- **For Crab and Vela pulsars we are below the "spin-down limit"**: constrain the fraction of spin-down energy due to GW J0534+2200

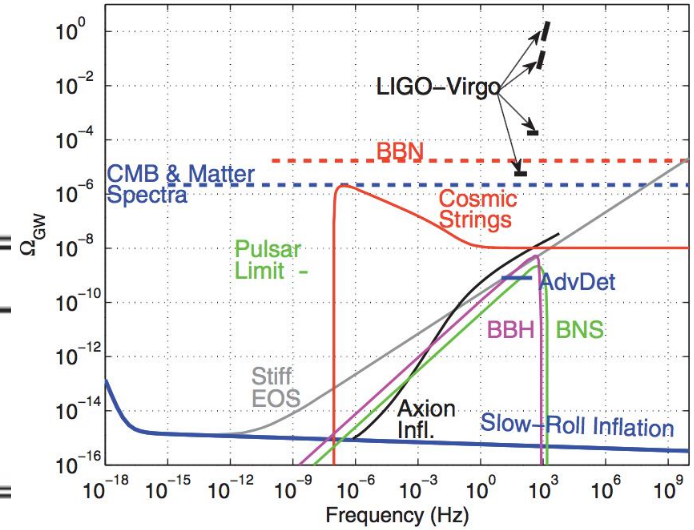
 [Aasi et al. ApJ 2014]

Pulsar	$h_{95\%}$	ε
J0534+2200	1.8(1.6)x10^{-25}	9.7(8.6)x10^{-5}
J0835-4510	1.1(1.0)x10^{-24}	6.0(5.5)x10^{-4}



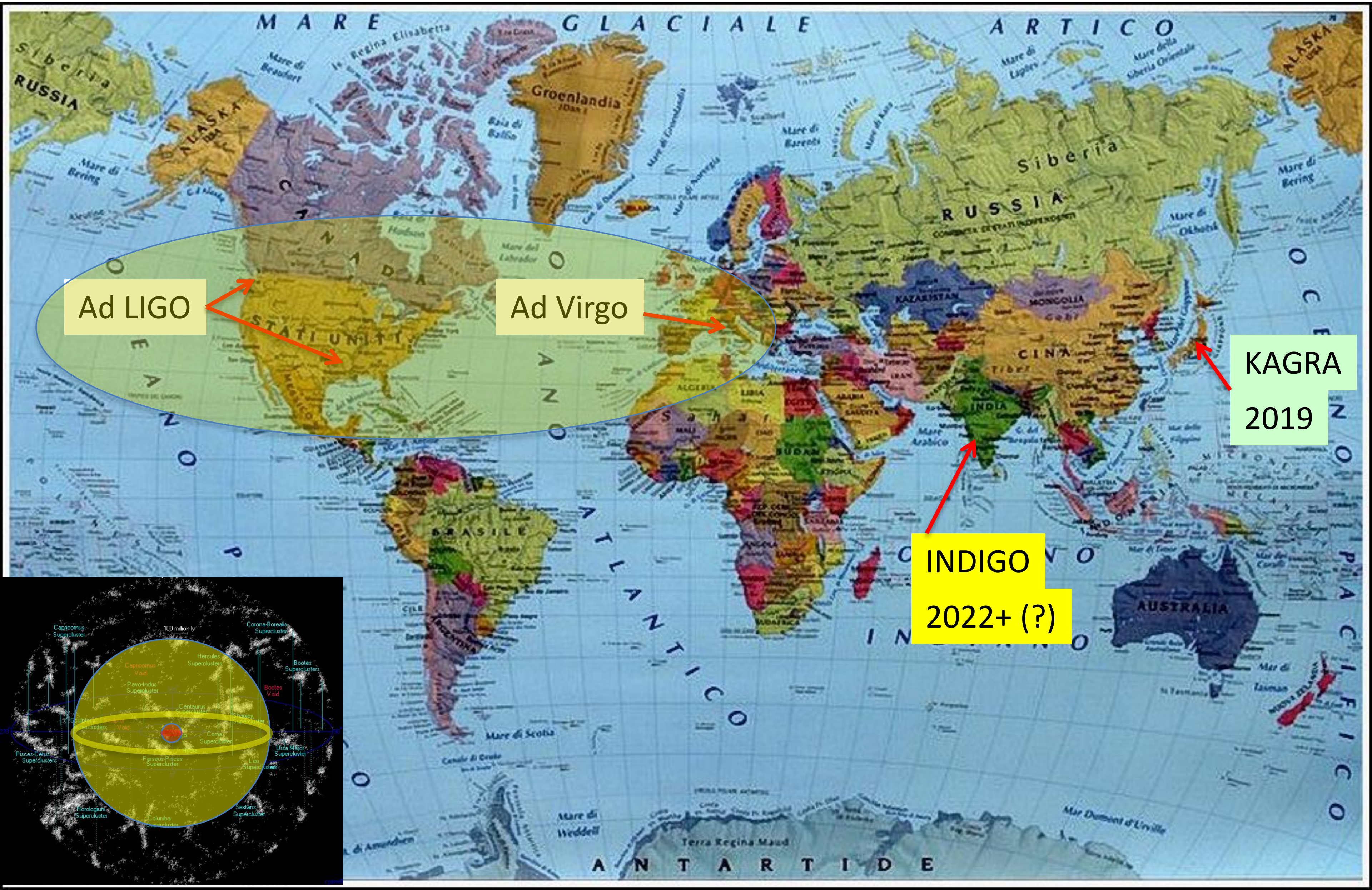
- Upper Limits on the Stochastic Gravitational-Wave Background [PRL 113, 231101 (2014)]

Frequency (Hz)	f_{ref} (Hz)	α	Ω_α
41.5–169.25	...	0	$(-1.8 \pm 4.3) \times 10^{-6}$
170–600	...	0	$(9.6 \pm 4.3) \times 10^{-5}$
600–1000	900	3	0.026 ± 0.052
1000–1726	1300	3	-0.077 ± 0.53



The new generation of advanced detectors

The GW network of the Advanced detectors

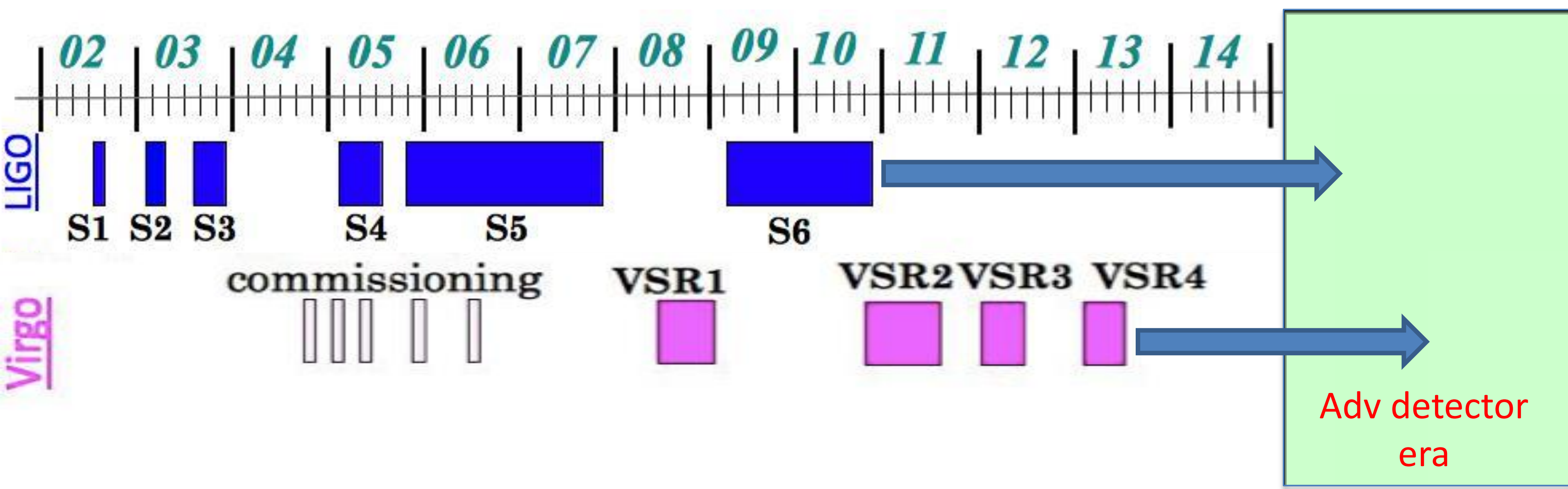


ADVANCED LIGO (aLIGO)

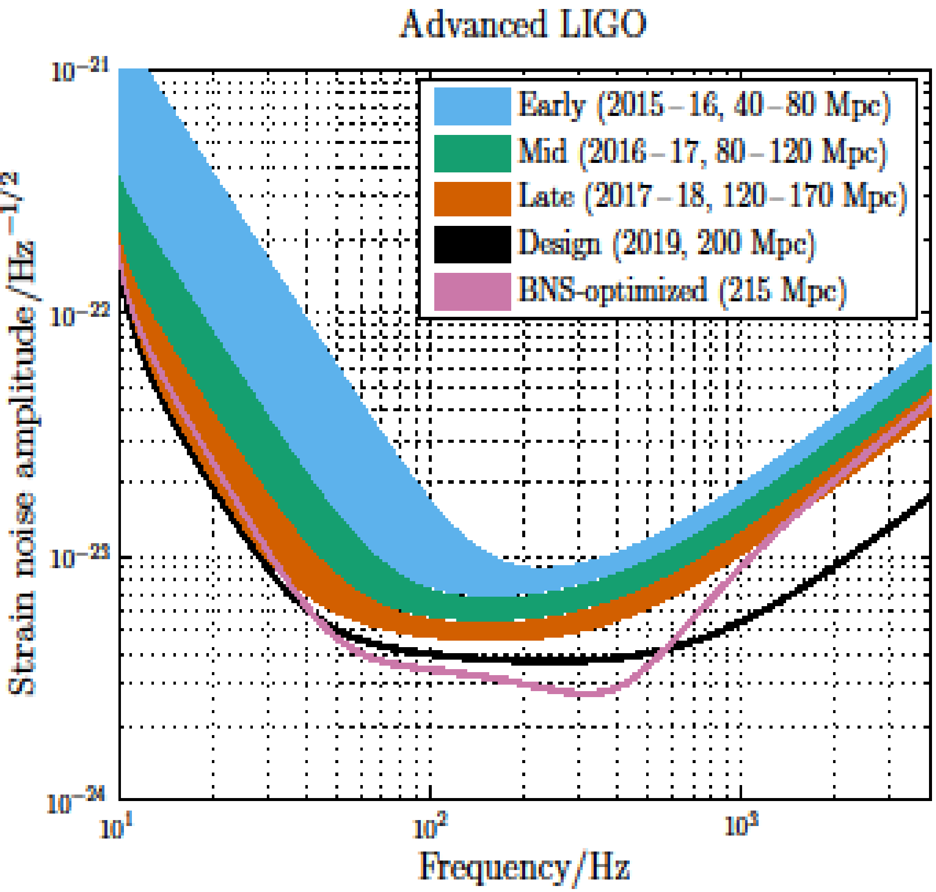
- ✓ Project funded: April 2008
- ✓ Project start: 2010
- ✓ Funding: >205 M$
- ✓ Installation completed: June 2014
- ✓ First science run: O1 Aug 2015

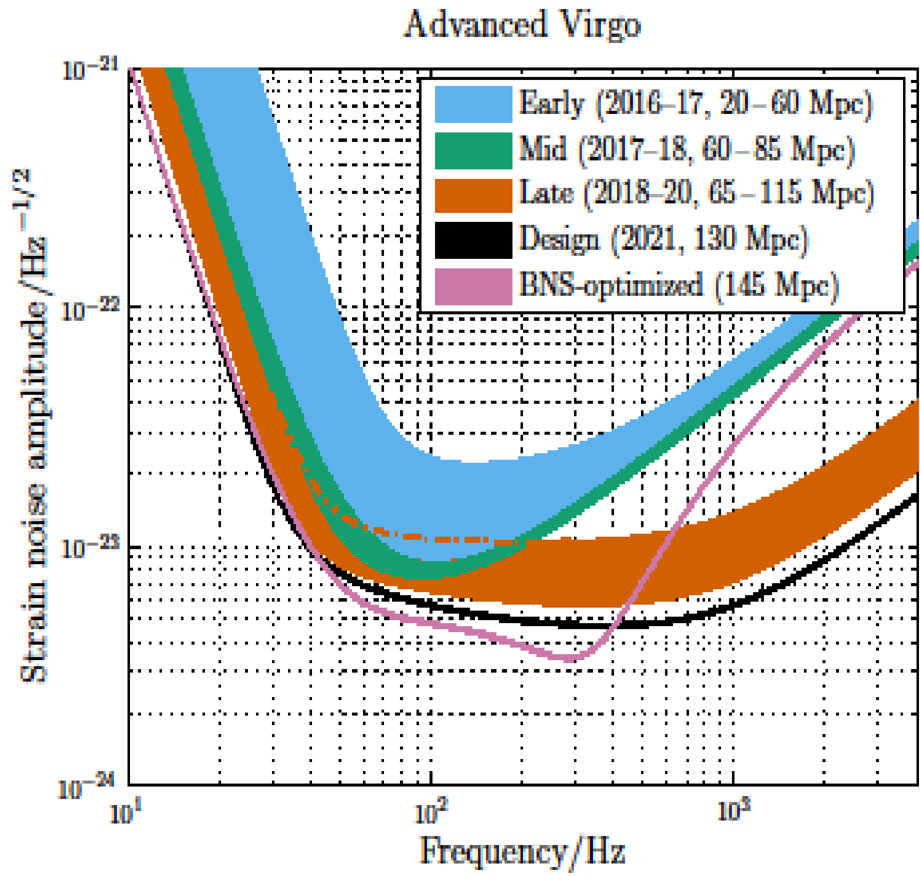
ADVANCED VIRGO (AdV)

- ✓ Project funded: Dec 2009
- ✓ Project start: 2012
- ✓ Funding: 23 M€
- ✓ Installation completed: early 2016
- ✓ First science run: O2 ~Sep 2016

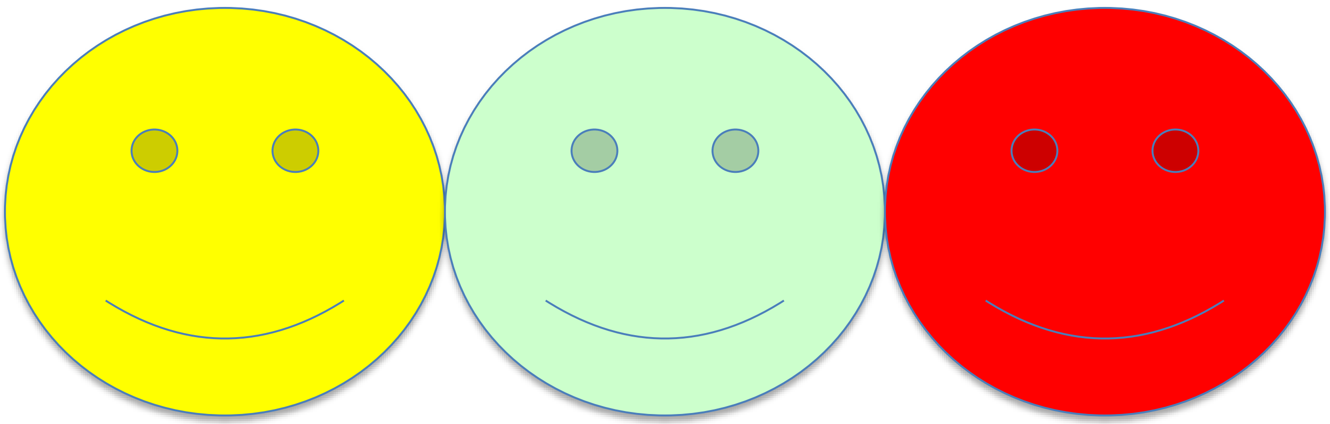


Sensitivity in the early phase and beyond

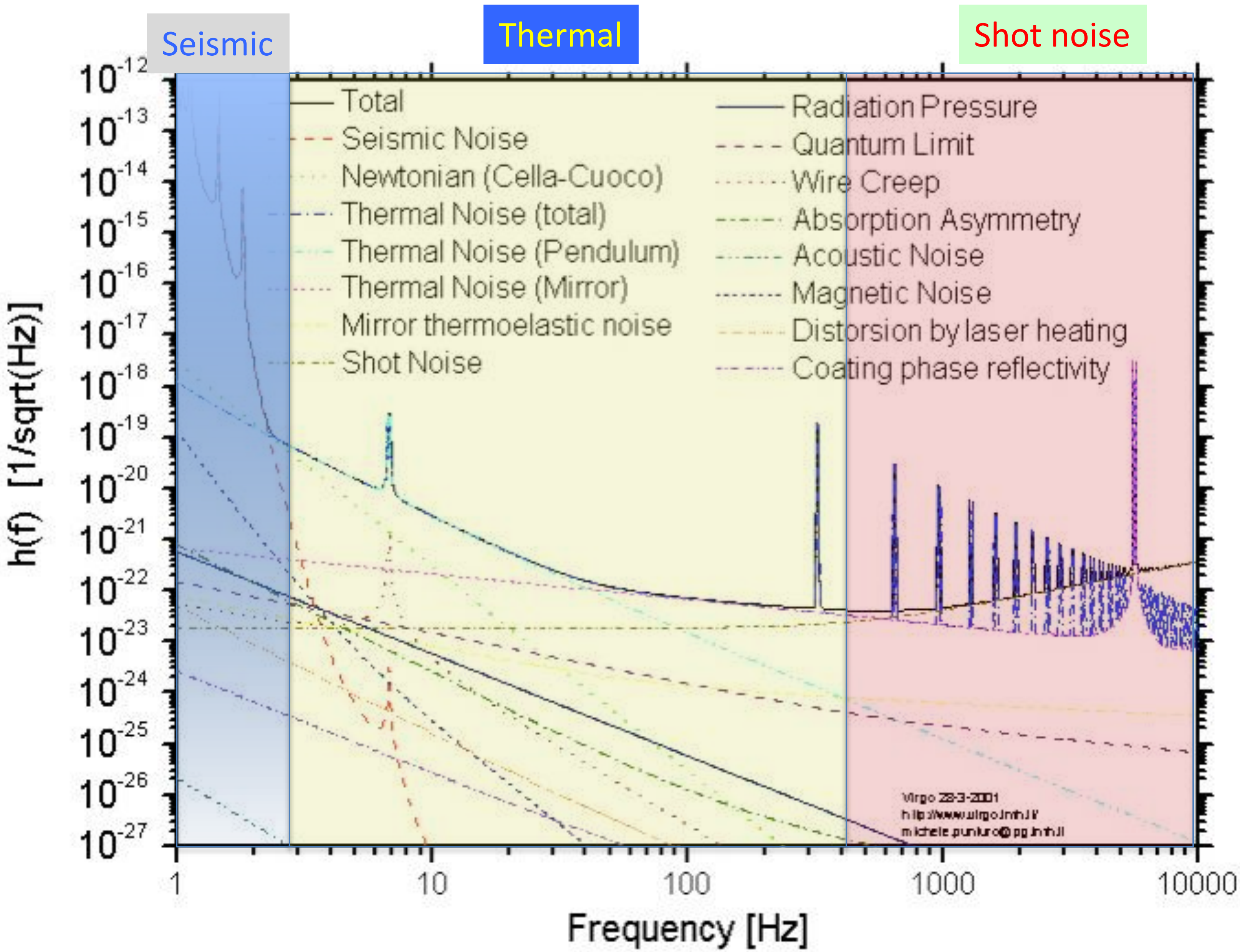




AdVirgo: hardware highlights

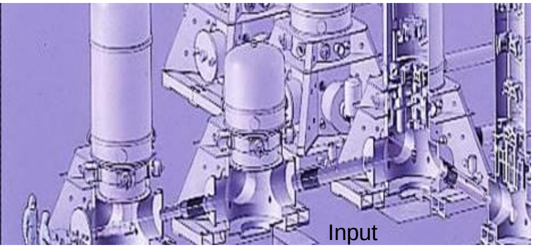


Fast *Good* *Cheap*

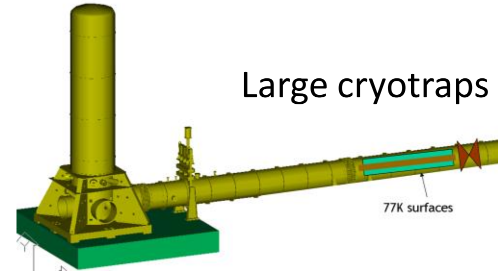

Seismic
Thermal
Shot noise
Total
Seismic Noise
Newtonian (Cella-Cuoco)
Thermal Noise (total)
Thermal Noise (Pendulum)
Thermal Noise (Mirror)
Mirror thermoelastic noise
Shot Noise
Radiation Pressure
Quantum Limit
Wire Creep
Absorption Asymmetry
Acoustic Noise
Magnetic Noise
Distorsion by laser heating
Coating phase reflectivity
h(f) [1/sqrt(Hz)]
Frequency [Hz]
1
10
100
1000
10000

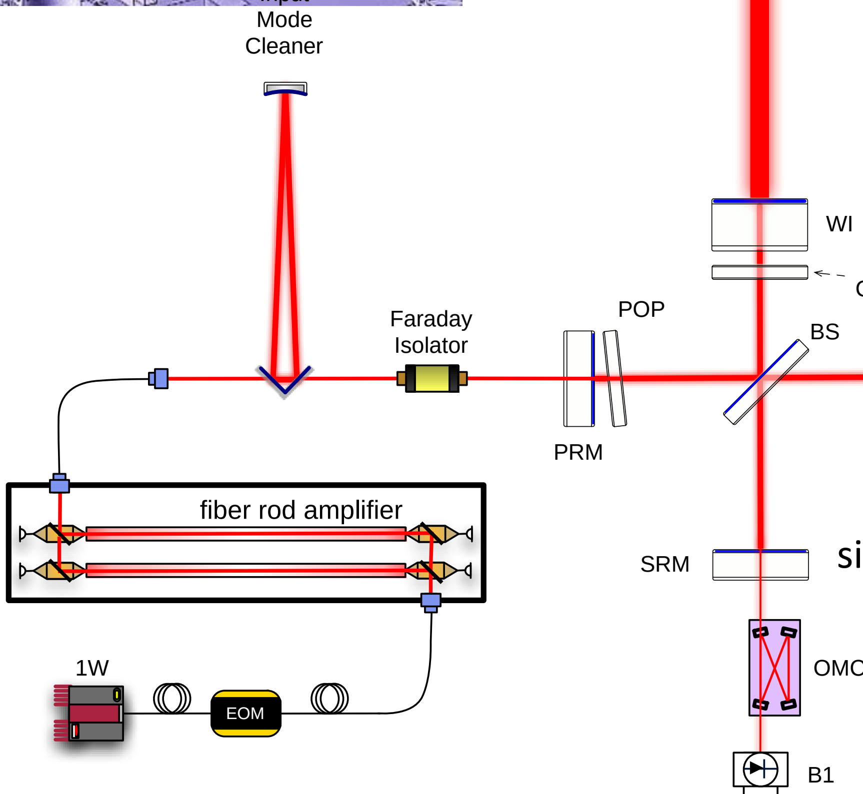
Ad Virgo in a nutshell

Larger central vacuum links



Large cryotraps





heavier mirrors
(42 kg)

larger beam waist

signal recycling

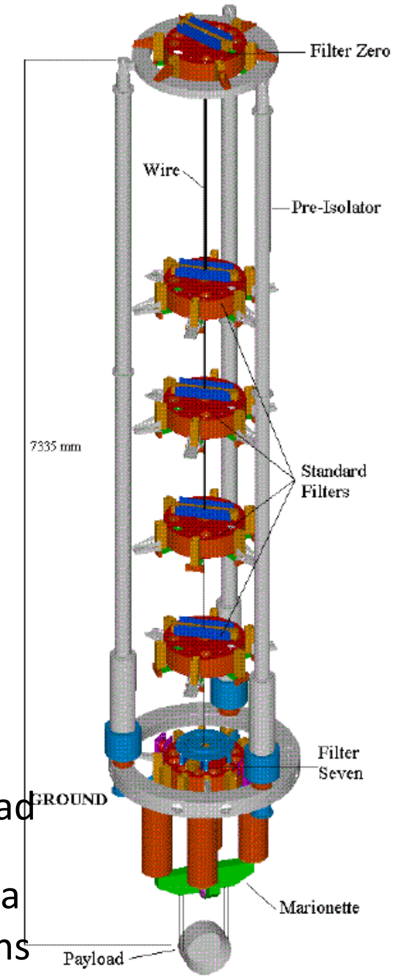
high power SSL

DC detection

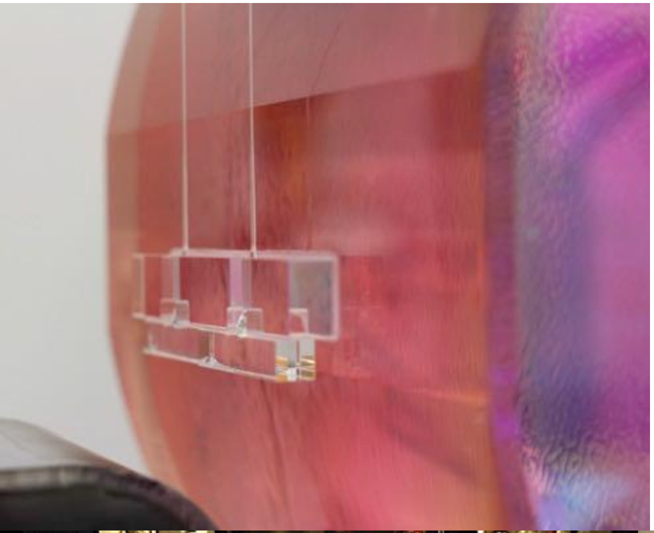
new IP
tilt control

new payload

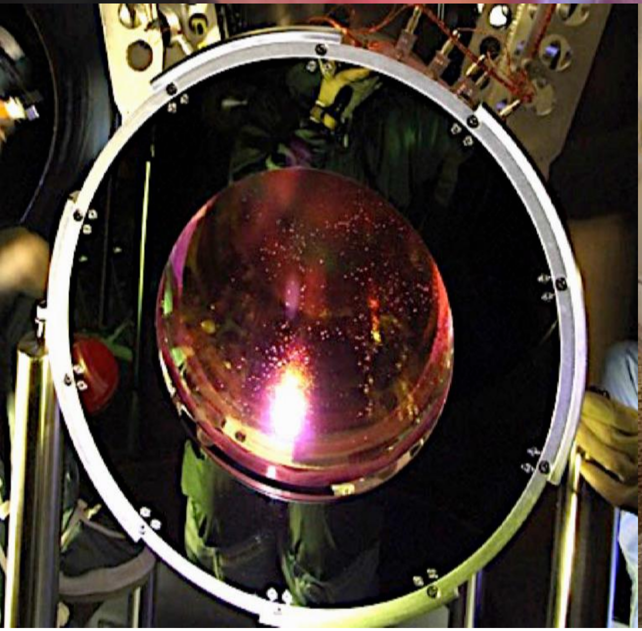
fused silica
suspensions

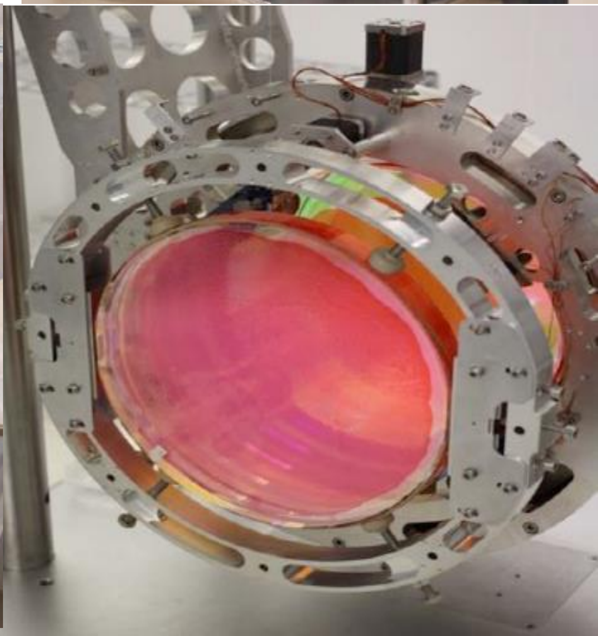


TEST MASS PAYLOAD

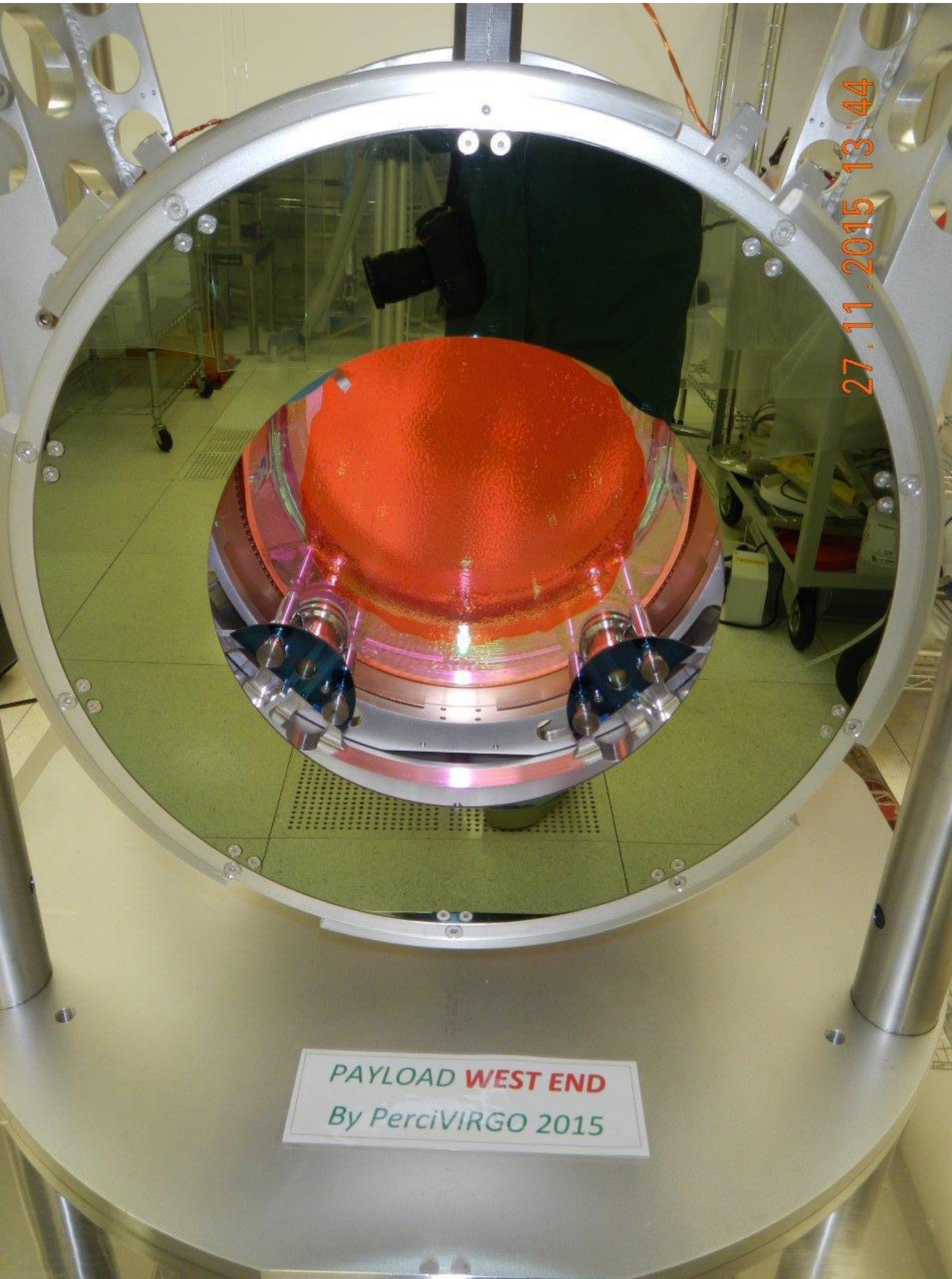


A major technical challenge:
complex integration of many key parts.

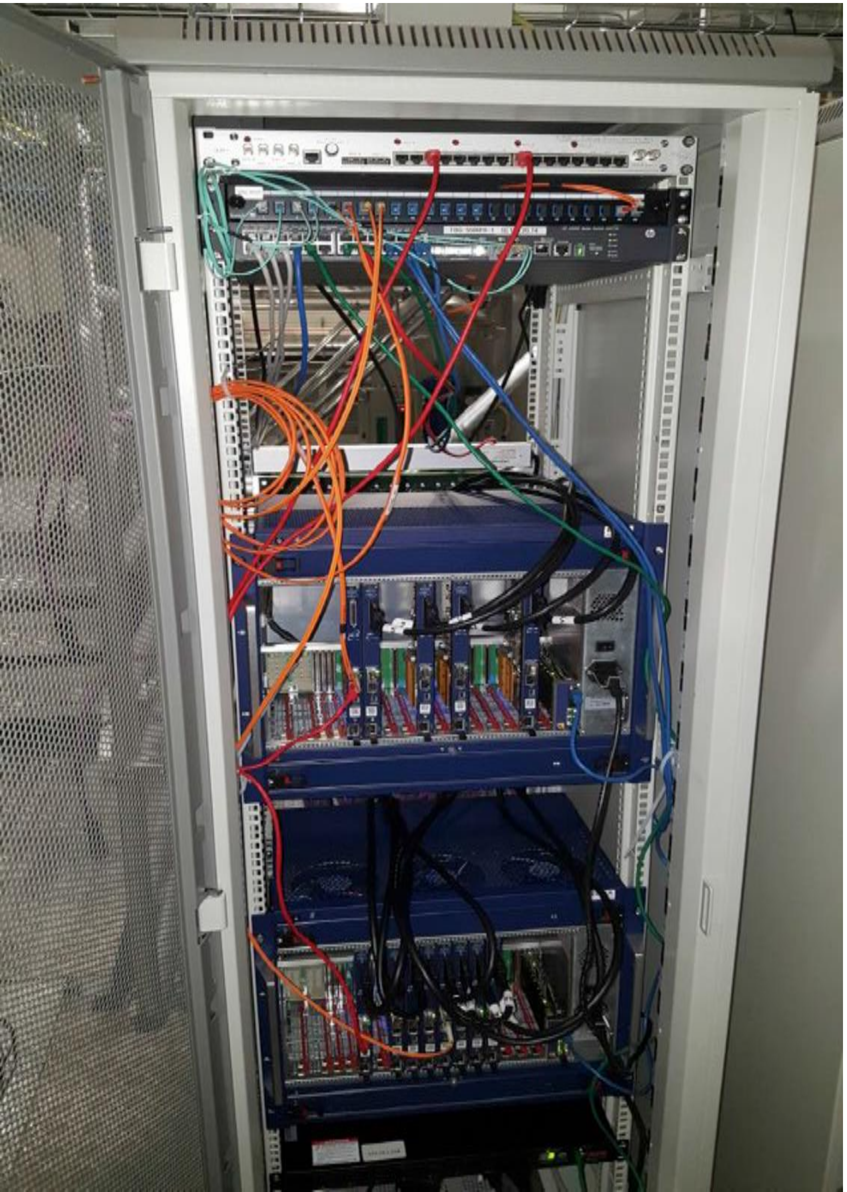




The last two payloads ready for the installation

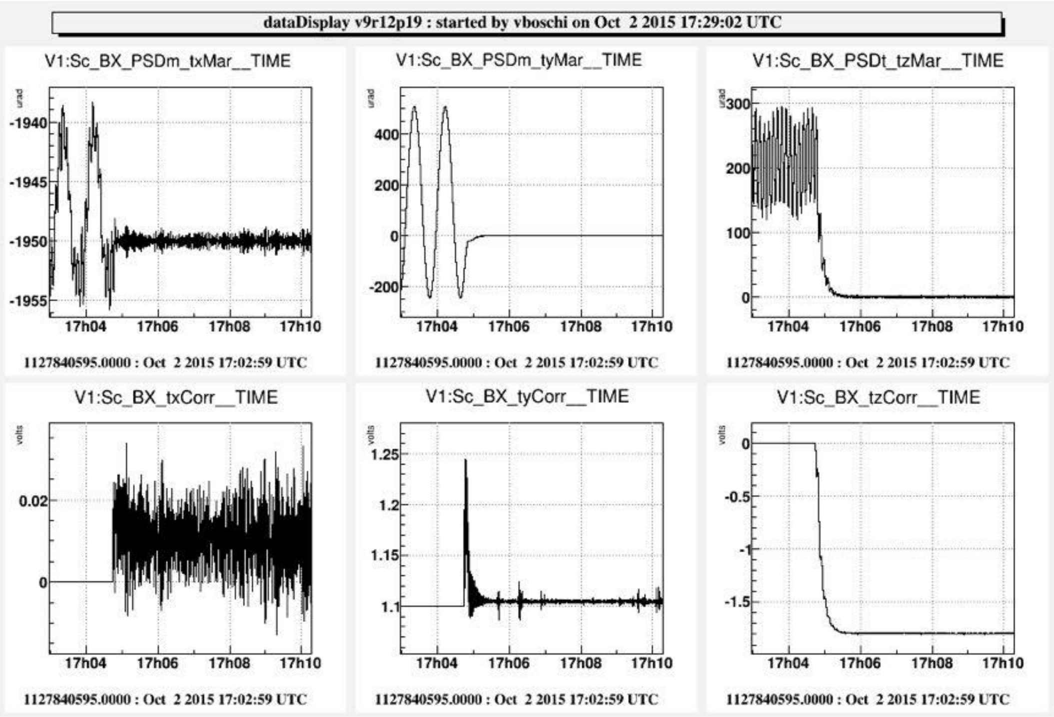


New SAT electronics in place

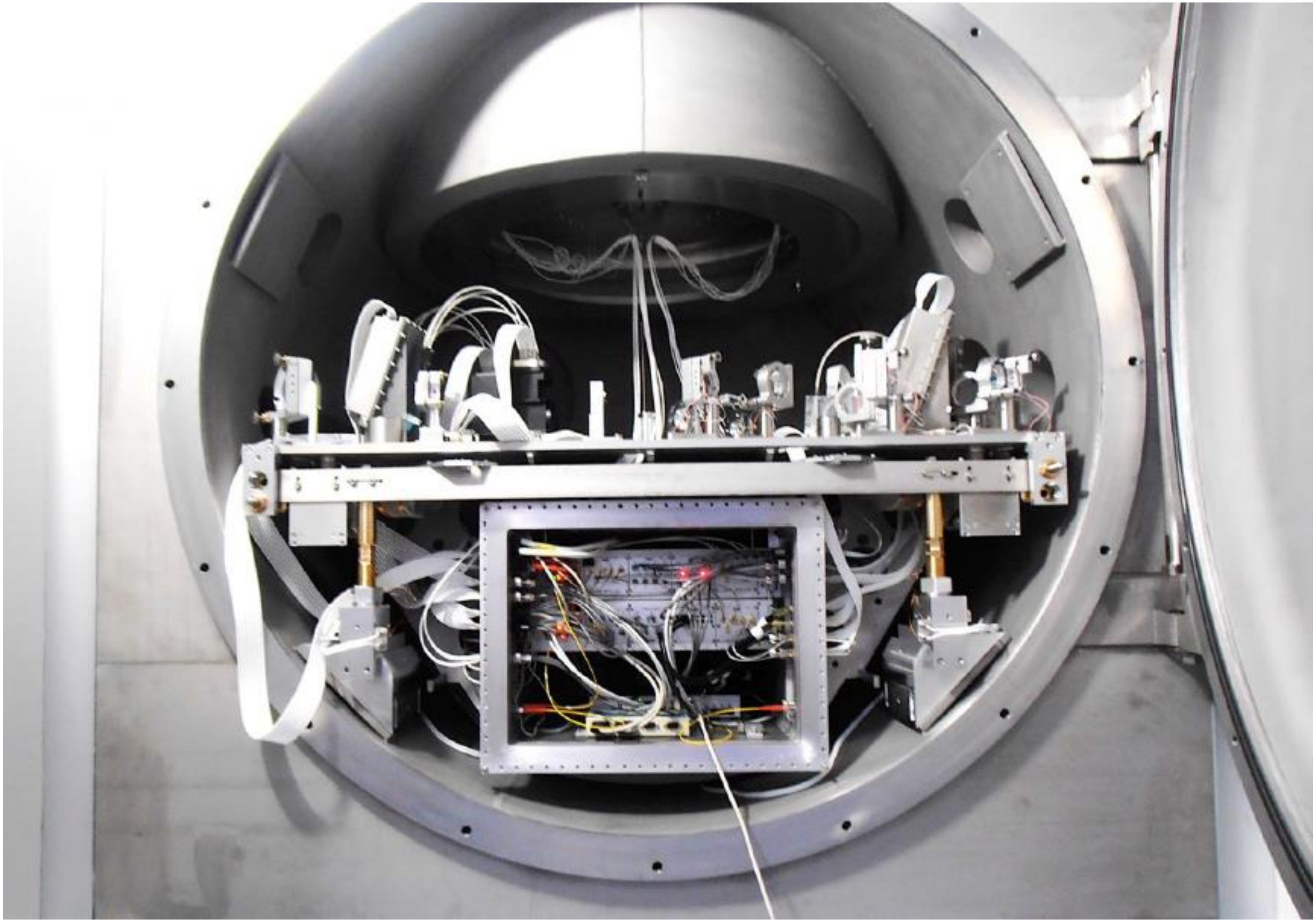


Test on the beam splitter suspended to the superattenuator

Mirror fully controled



Putting in vacuum all the photodiodes



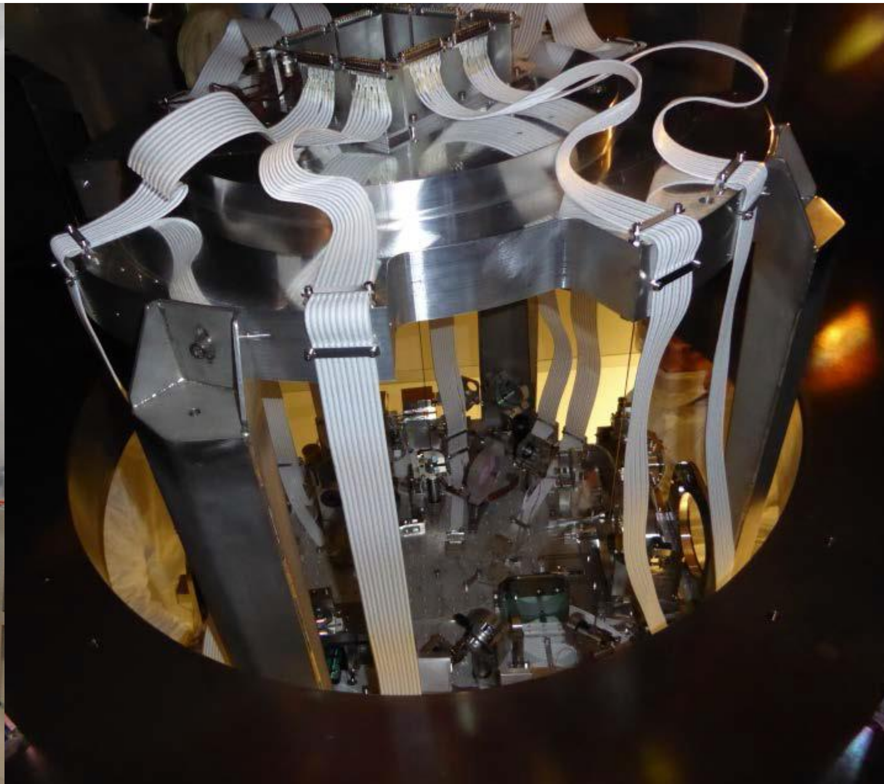
SIB2 & SPRB INSTALLED

SDB2 & SNEB IN PREPARATION

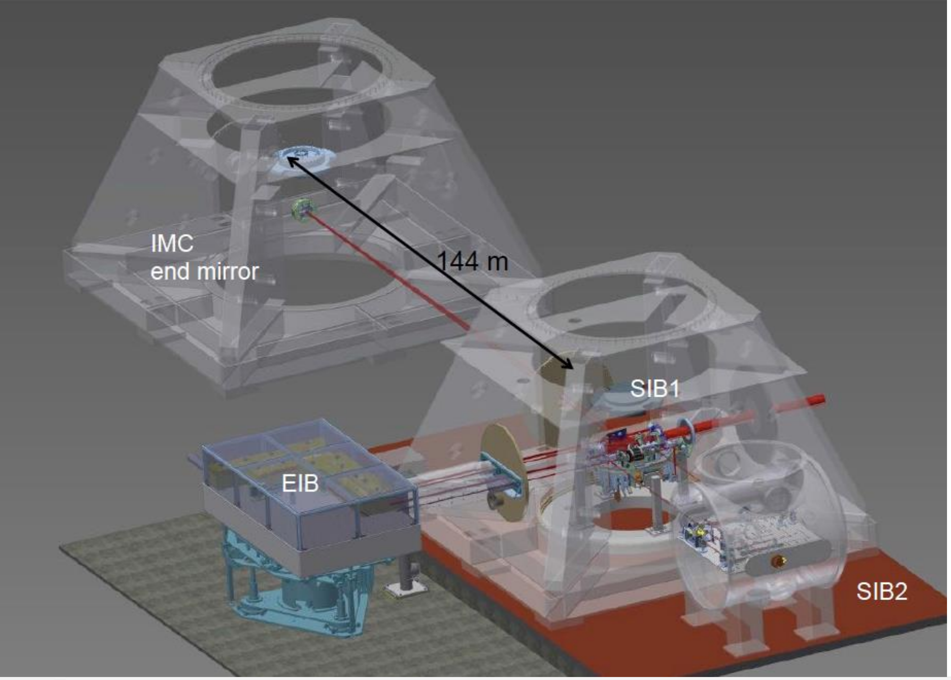
Output Mode Cleaner

New Output Mode Cleaner developed for DC detection
→ must filter out high order modes and « control beams »
→ made of two monolithic cavities in series
→ cavity length thermally controlled + PZT

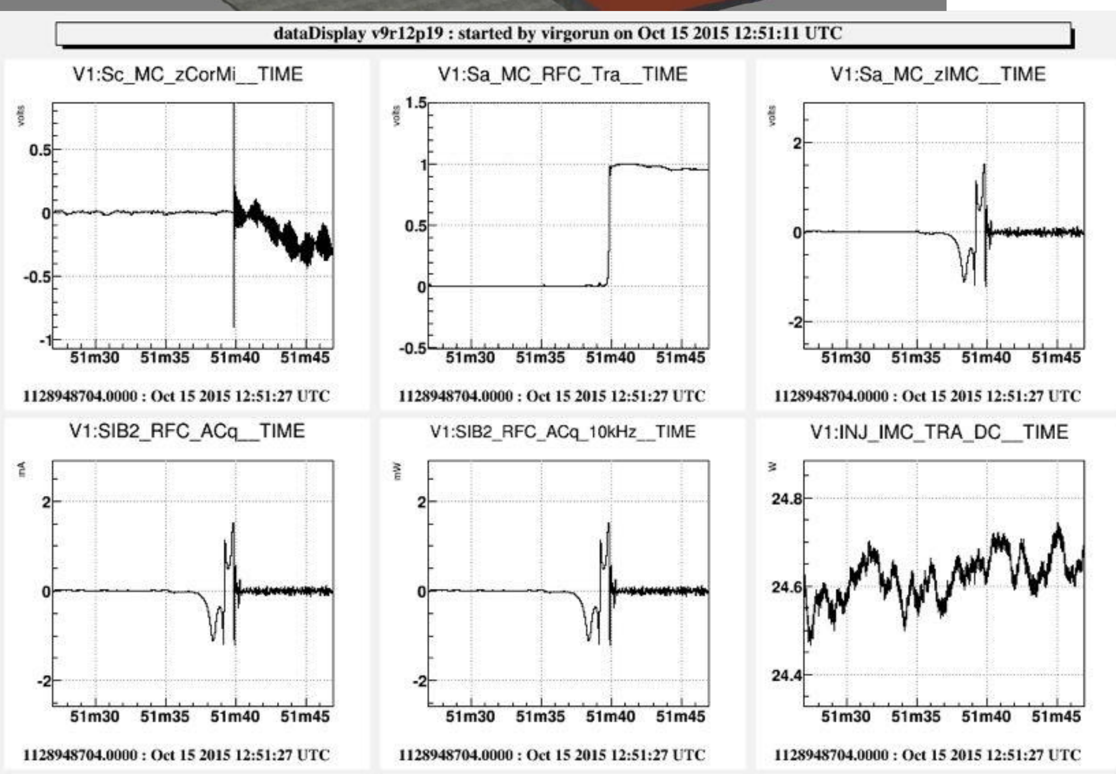
- OMC tested and integrated on its optical bench with output telescope
- OMC bench inserted in its tower

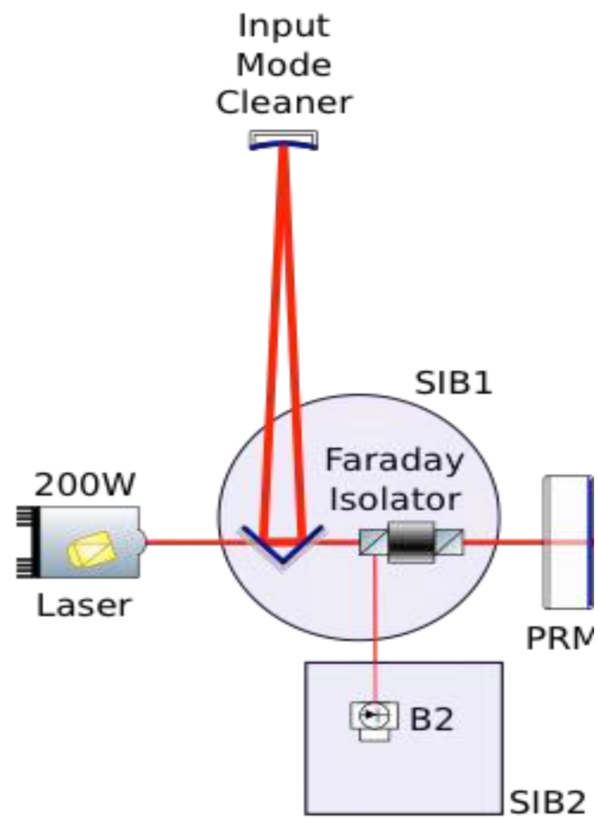



First successful test of the digital demodulation chain



Locking of the reference cavity

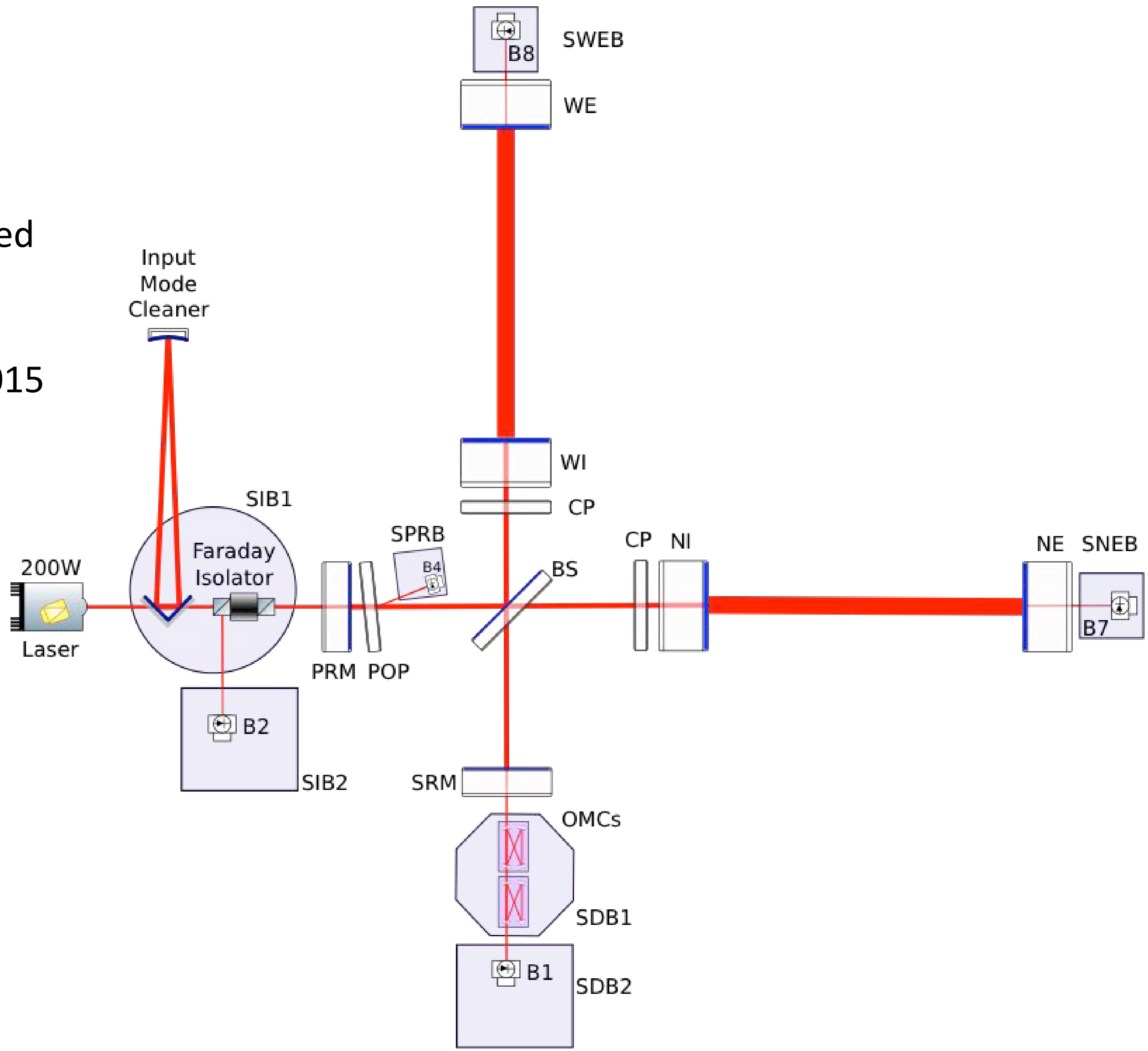




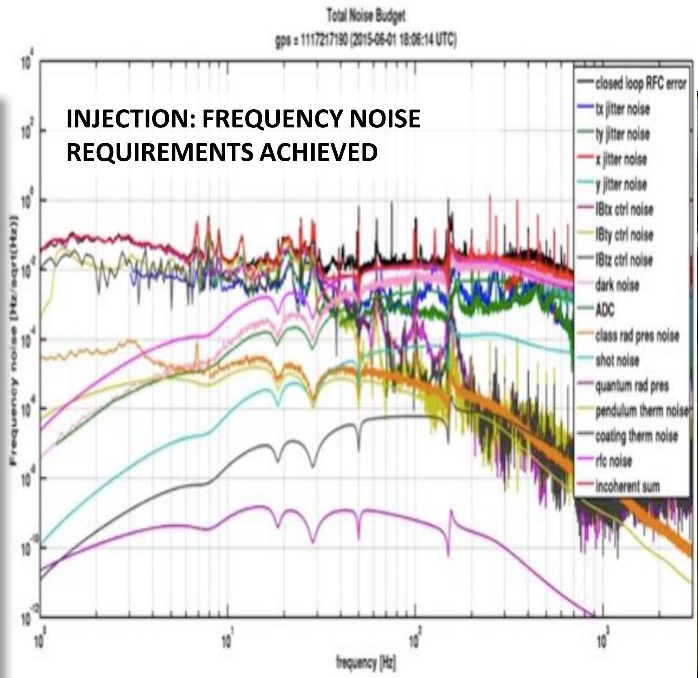
Mid December 2015: installation status

BS/NI controlled
PR installed
SR ready for installation
NE ready for installation
WE ready for installation
SDB1/SIB2/SPRB integrated
SDB2 installed

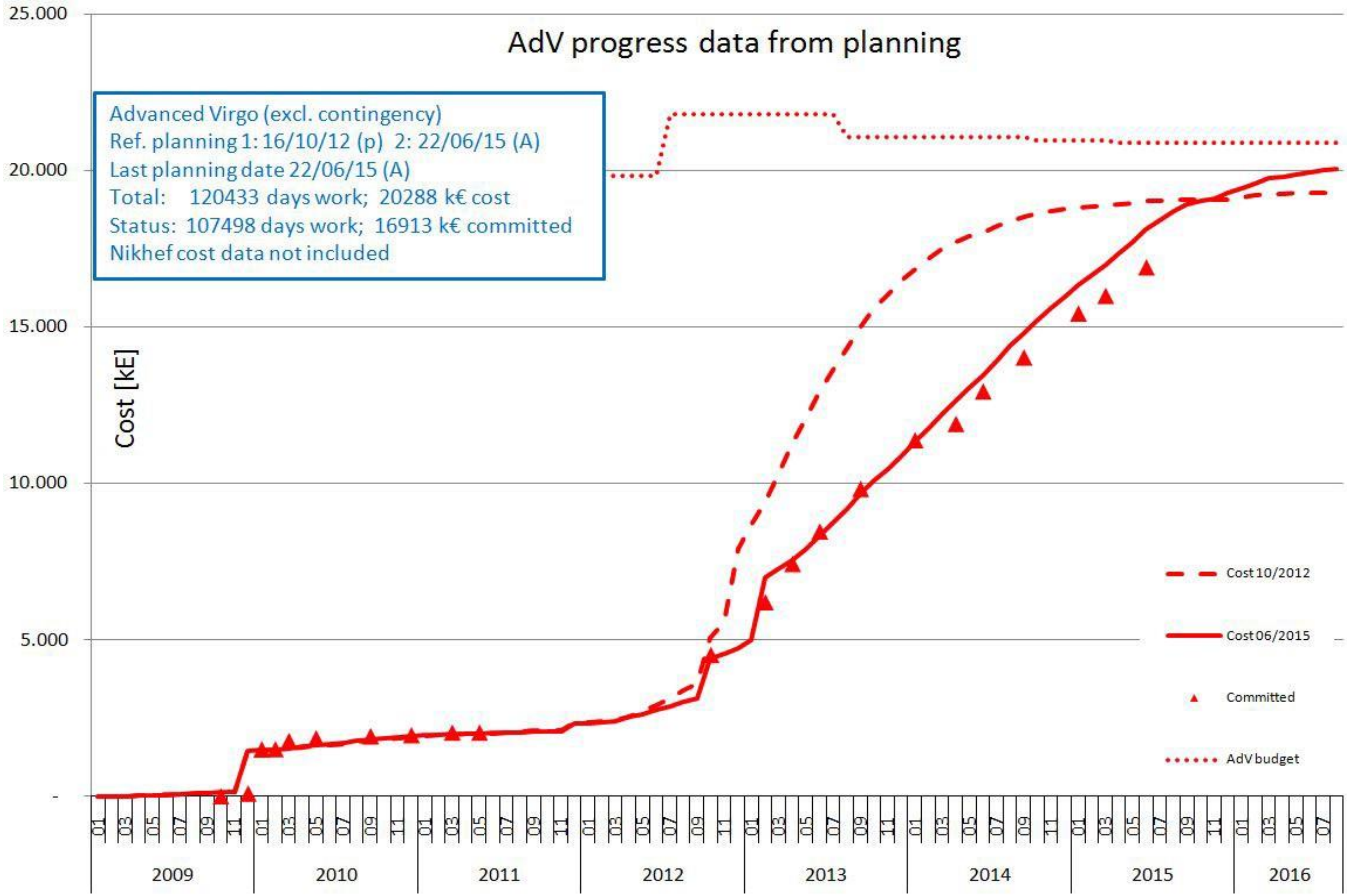
WI installed on August 2015
Failure last week
To be reinstalled



AdV - Integration Activities



AdV Commitment Profile



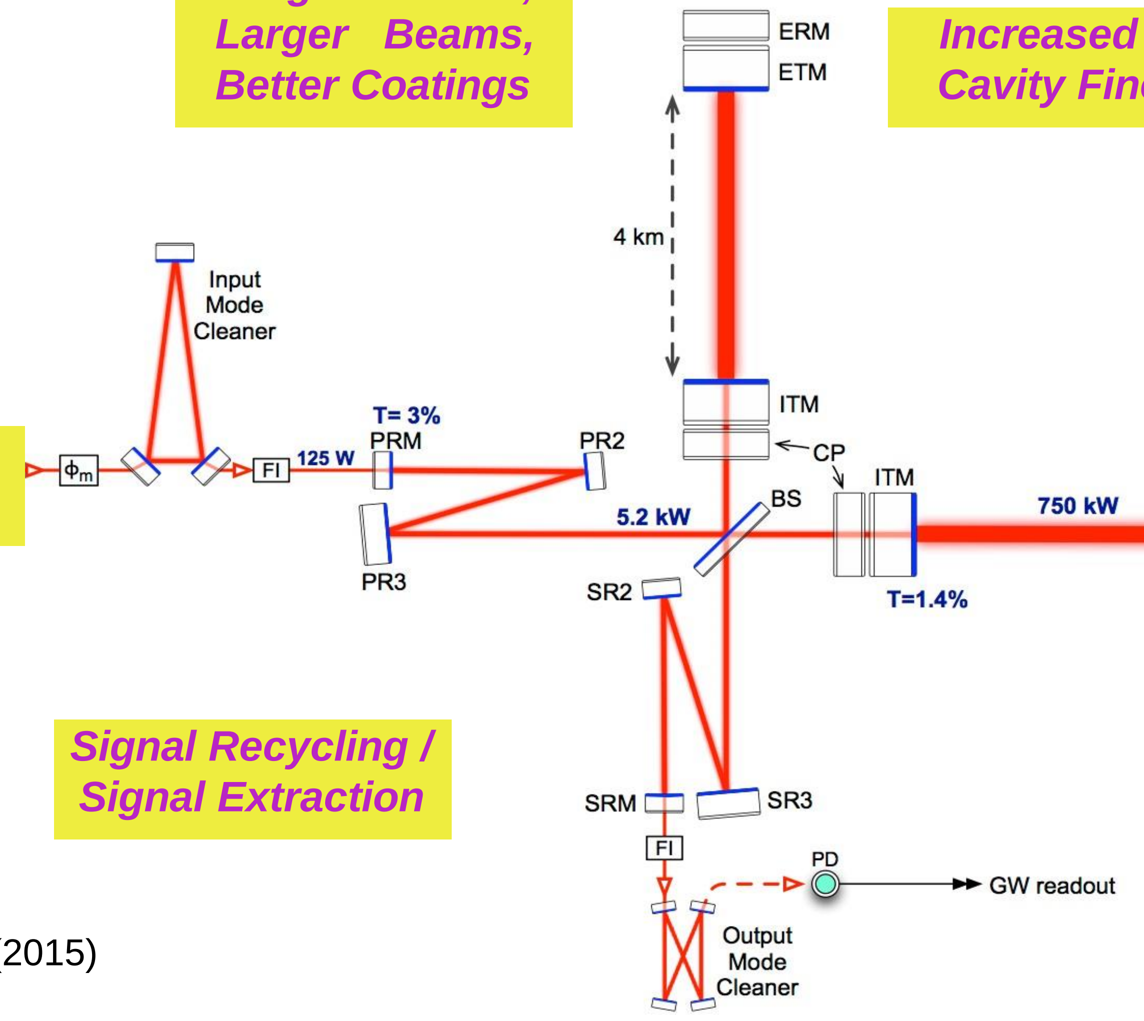
aLIGO: hardware highlights

From LIGO to aLIGO

Larger Mirrors, Larger Beams, Better Coatings

Increased Arm Cavity Finesse

Increased Laser Power



Signal Recycling / Signal Extraction

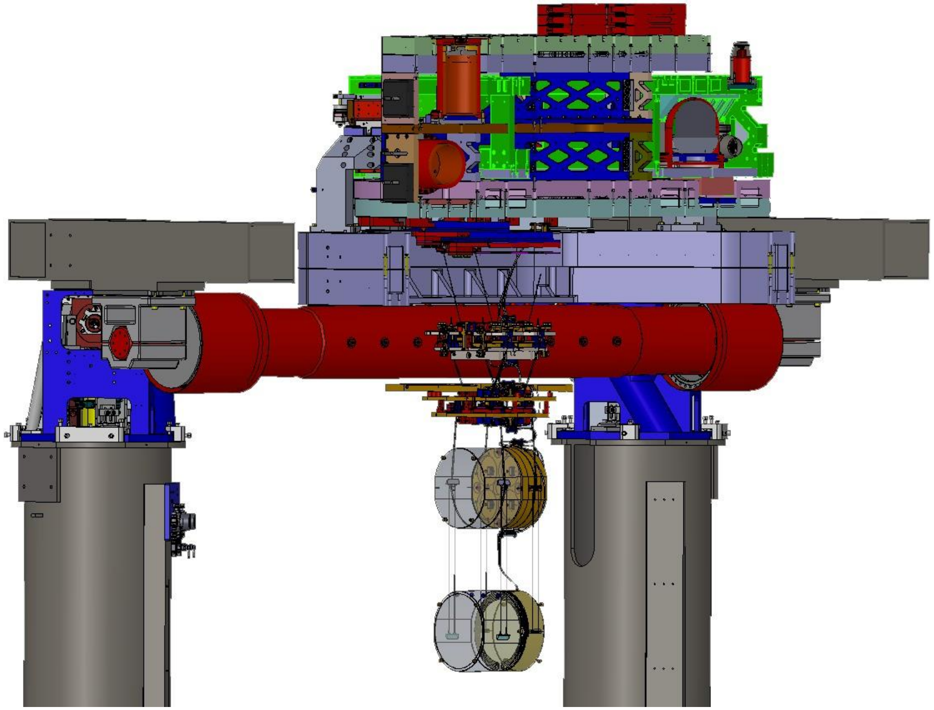
Big Investment in Seismic Isolation and Suspensions

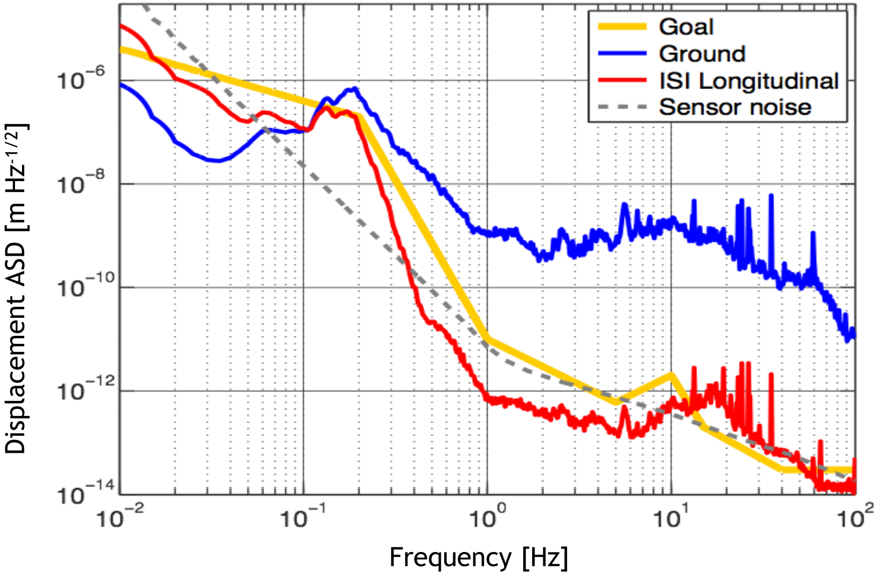
CQG 32 105102 (2015)

Credits to D. Hoak

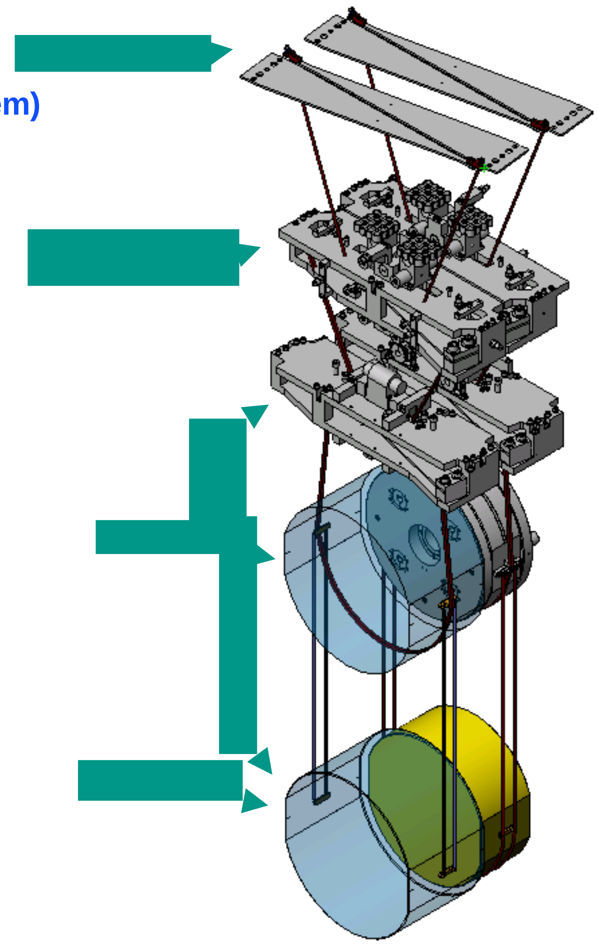
Active Seismic Isolation for in-vacuum Optical Tables

Credits to D. Hoak





Four-stage monolithic suspensions larger mirrors

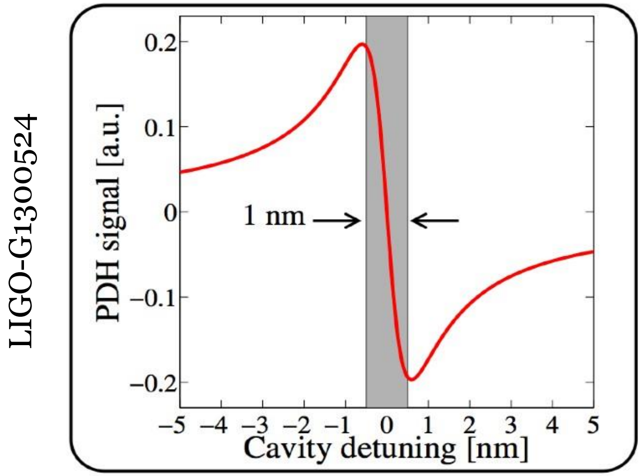


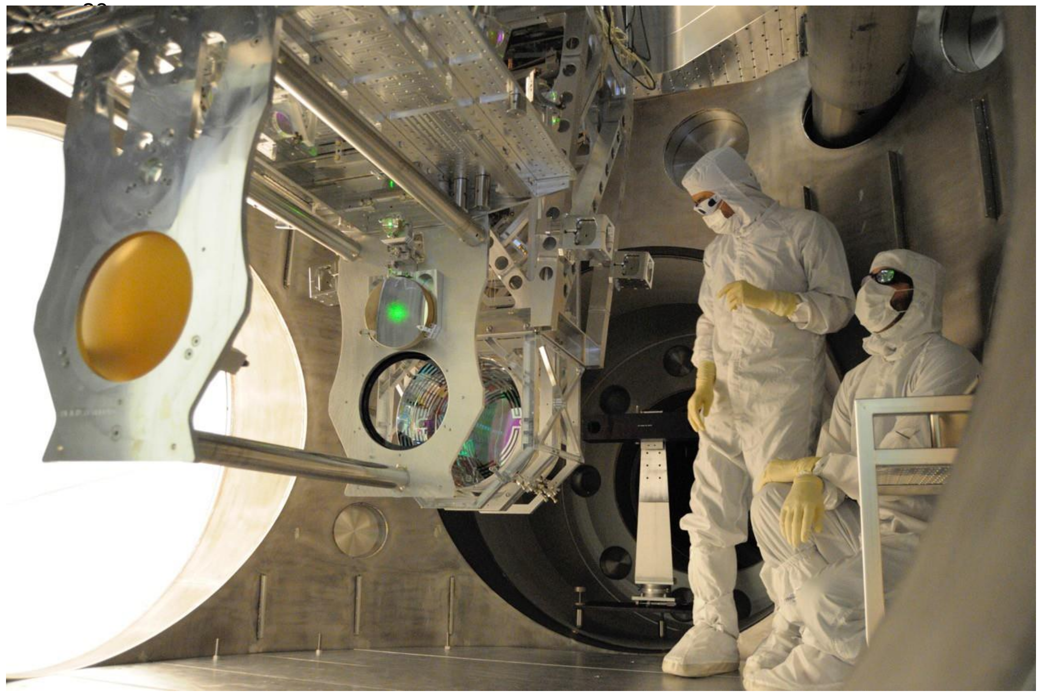
Credits to D. Hoak

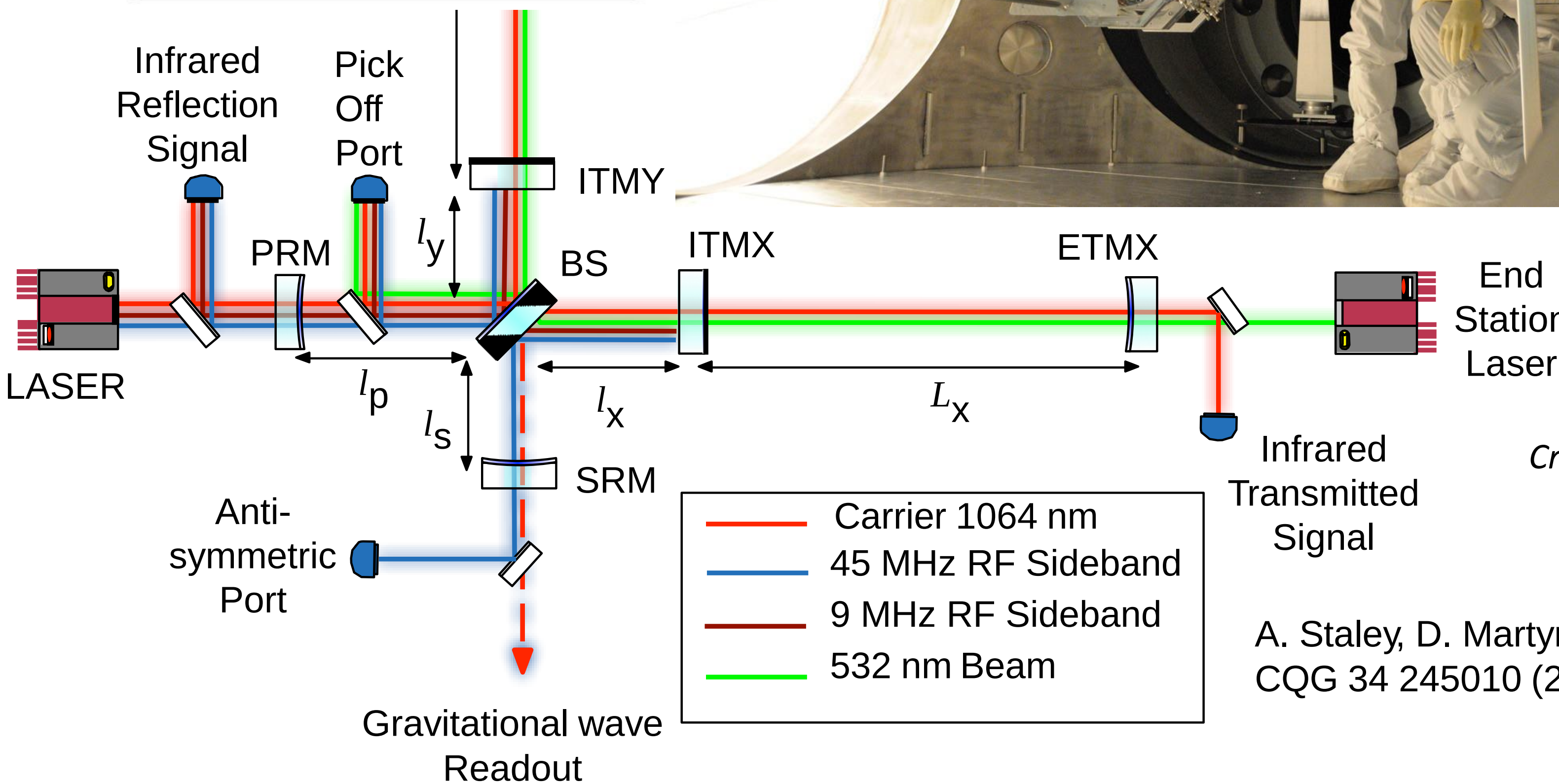
10x more laser power —> Reduced shot noise

Larger test masses —> Larger beam size —> Coating thermal noise coupling is reduced
—> Less sensitive to radiation pressure noise from increased power

Arm Length Stabilization



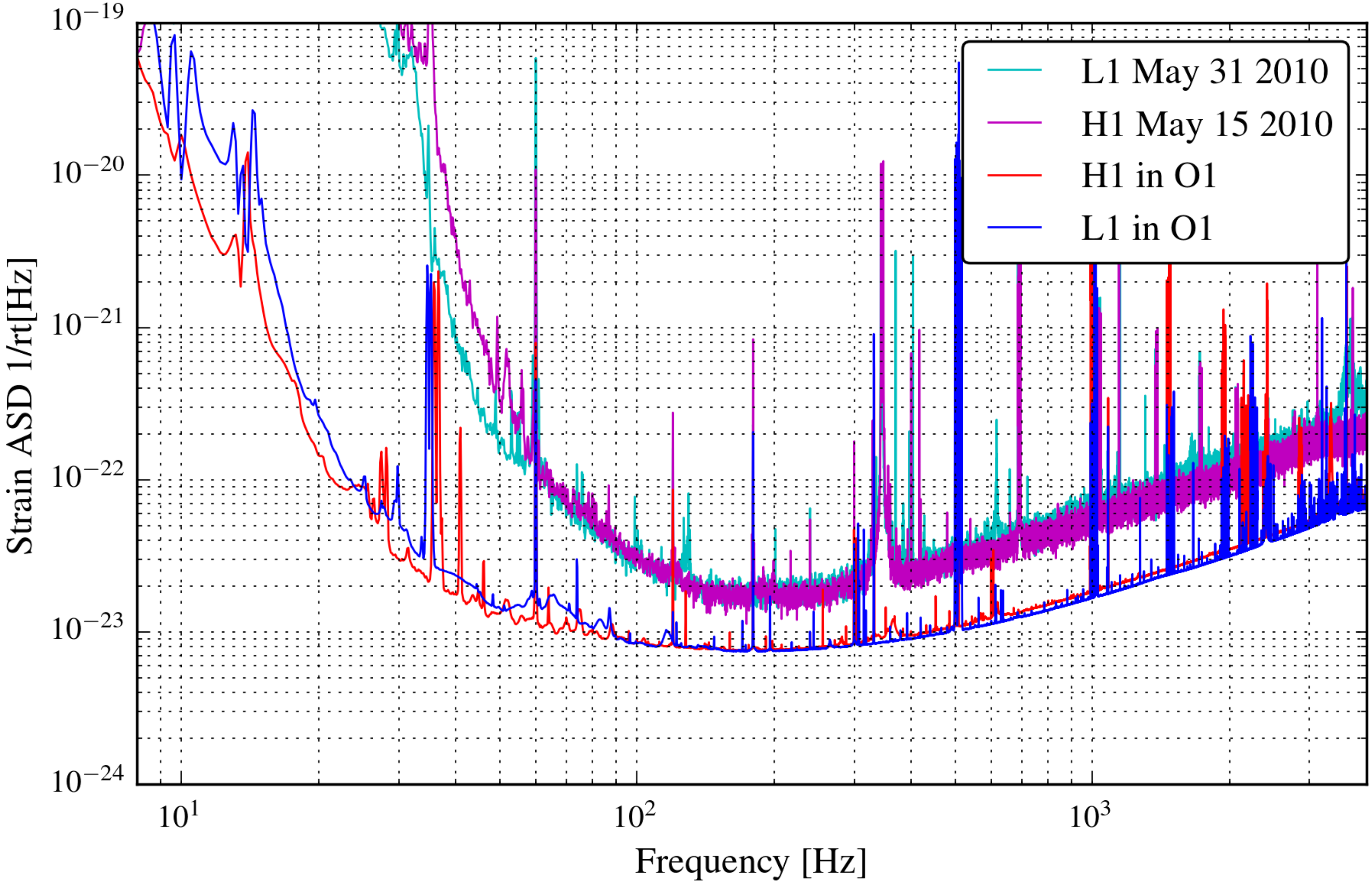




Credits to D. Hoak

A. Staley, D. Martynov et al., CQG 34 245010 (2015)

From LIGO to aLIGO: Sensitivity improvements



Advanced LIGO completed

- *The Advanced LIGO dedication ceremony was held at Hanford on May 19, 2015*

NSF Director, Dr. France Cordova

Attendees enjoying a tour of H1 installation

(Photos: Kim Fetrow)

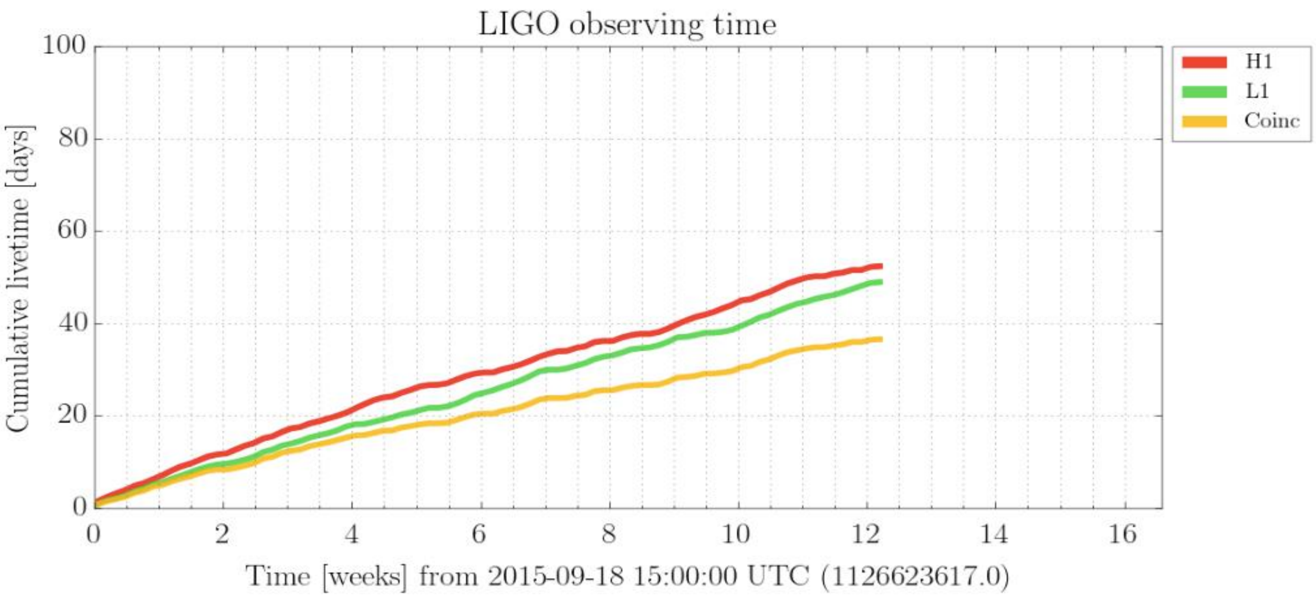
- *Several engineering run have been concluded. These have been devoted to the fine tuning of the detectors and to refine several procedures, as detector characterization, calibration..etc…*
- ***Then, the first science run O1 was started !***

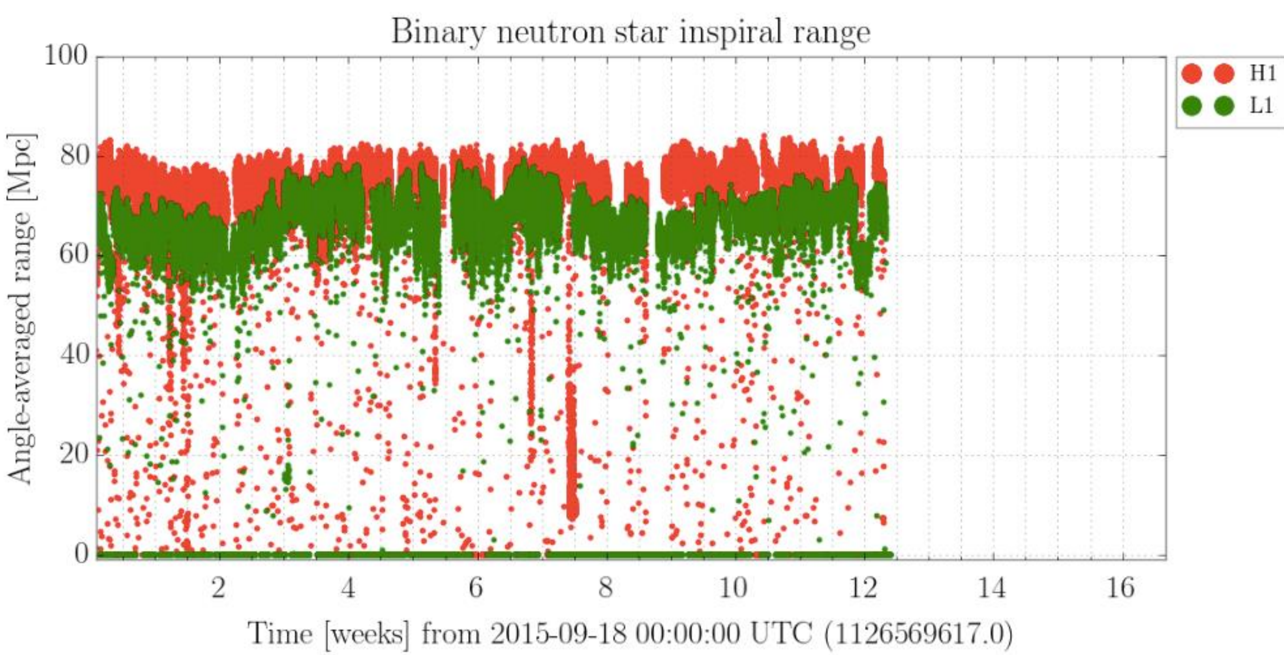
The first science run of the advanced detector era

Status of O1

- Advanced LIGO in observational mode since August 2015

- End of O1: January 16, 2015





The joint LSC/Virgo data analysis is ongoing

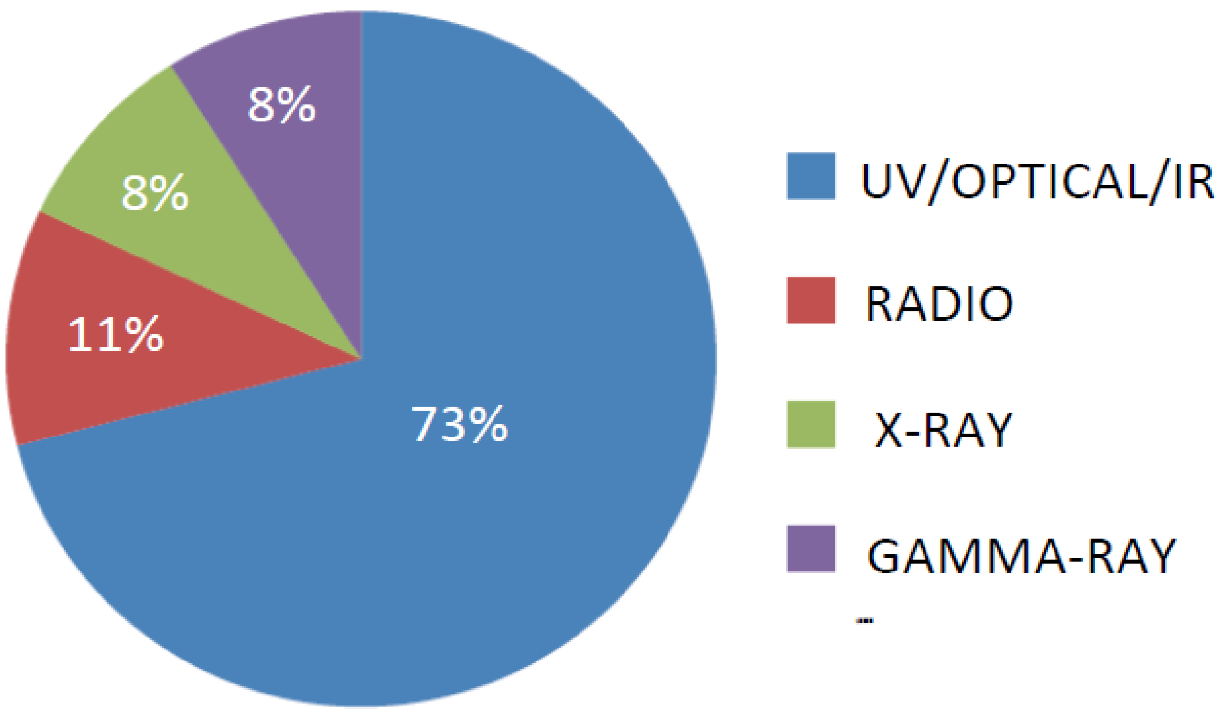
Results expected for the end of January 2016 / beginning of February

Joint LSC/Virgo em follow up program in action

EM follow-up program started

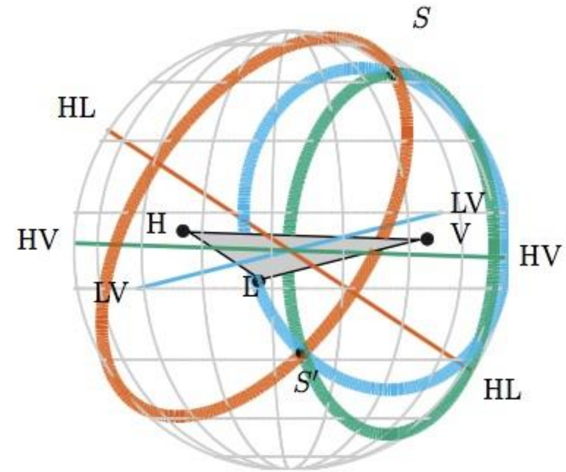
(72 MoU signed with astronomical groups, 160 instruments, 20 countries)

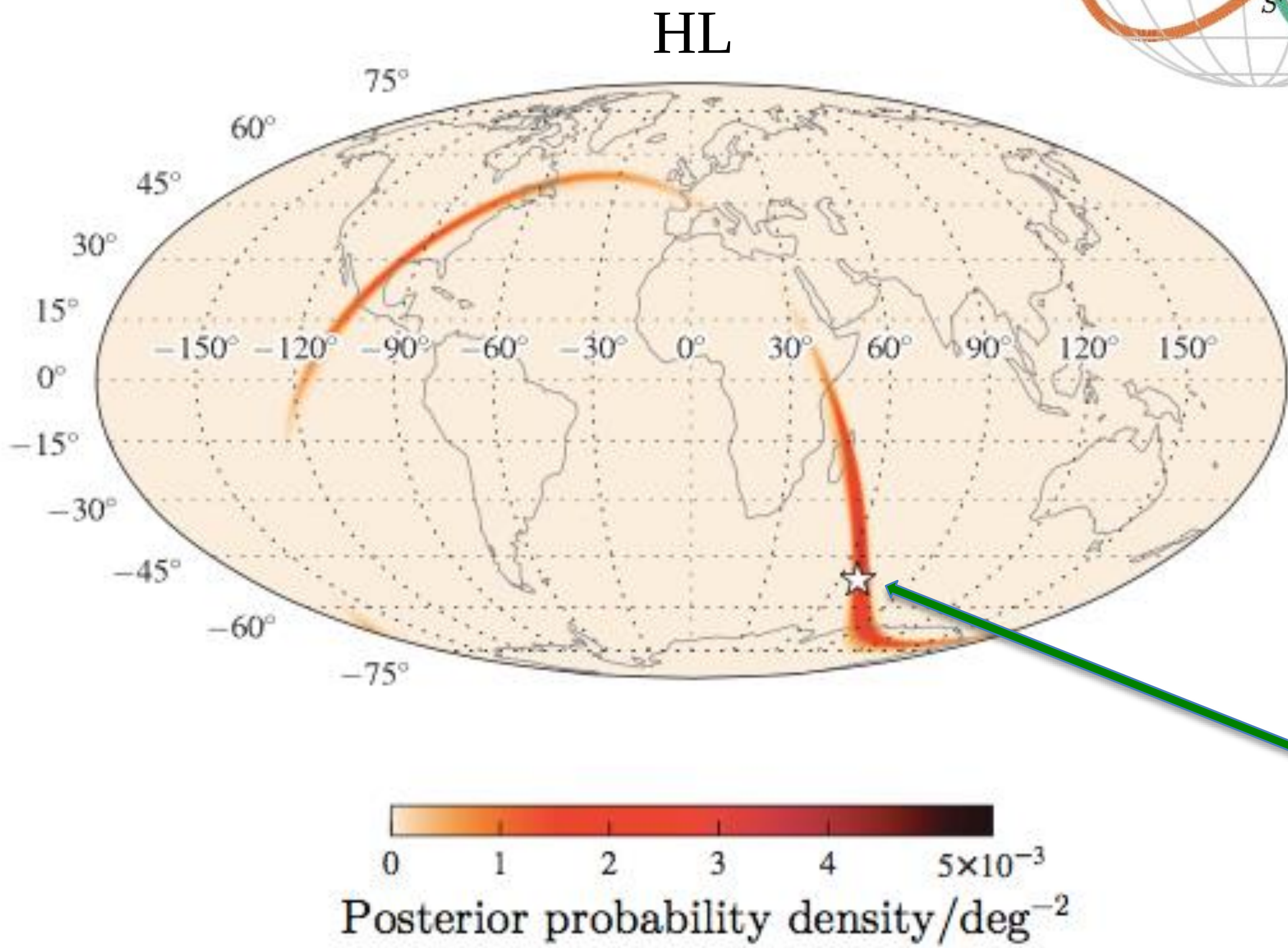
62 groups with observational capabilities ready for O1



Permanent LIGO and Virgo shifts organized to analyze data and sent the alerts!

Transient Source Localization





Injected signal

The future

Future actions

•aLIGO will end the run on January 16th

•VIRGO will start the commissioning at the beginning of next year, even before the end of the integration (commissioning of the 3 km North cavity)

•The commitment is to operate the three interferometers at the same time during O2, scheduled in the second part of 2016

•In view of O2 a third call for participation to the em follow up program is open.

Third call for participation to the em follow up

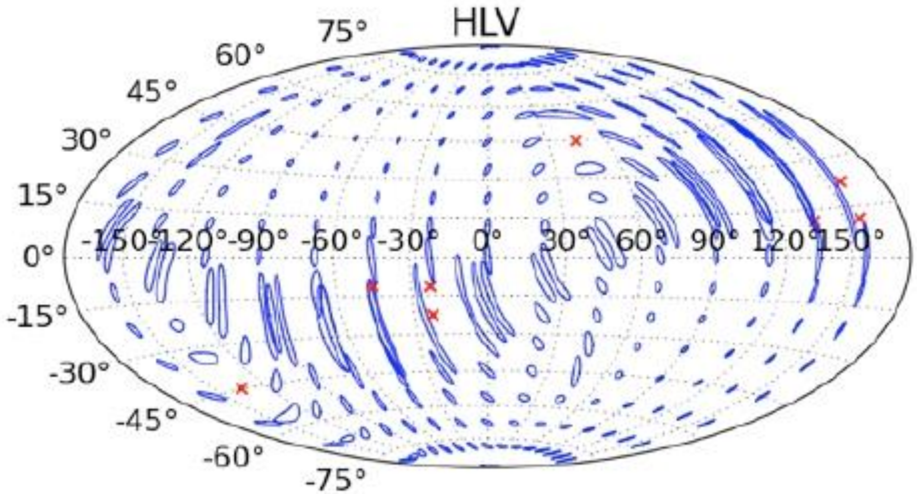
•*Identification and follow up of electromagnetic counterparts of gravitational wave candidate events*

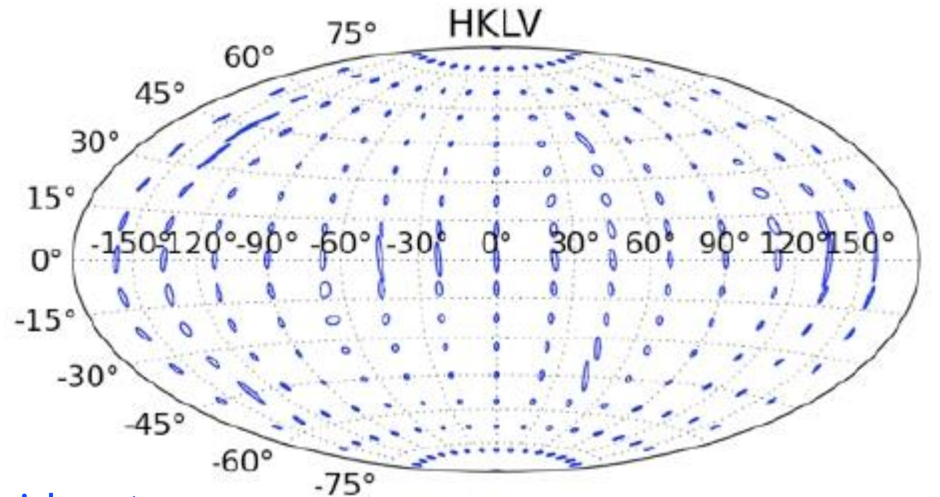
•Call for proposals to sign the standard MoU with LVC has been issued in December 2015

•*Deadline February 7, 2016*.

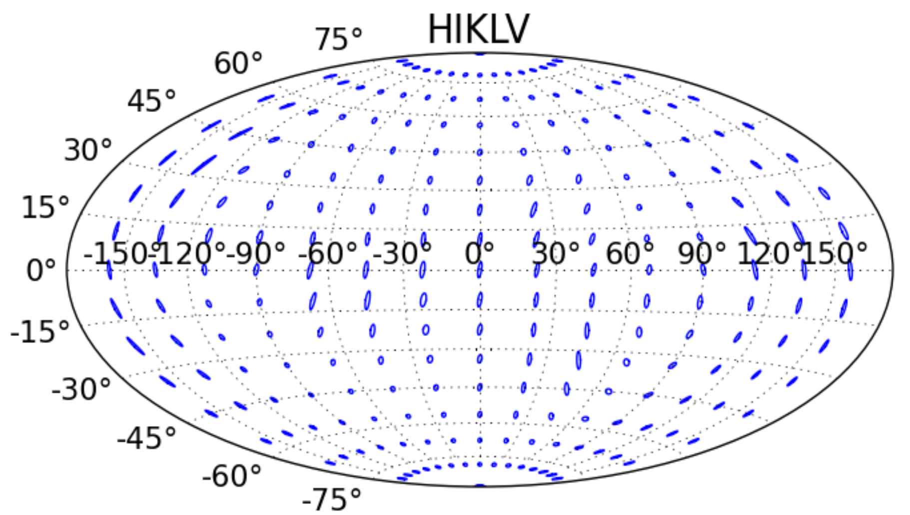
http://www.ligo.org/scientistsGWEMalerts.php#sthash.b7G5v2T3.dpuf

Transient Source Localization



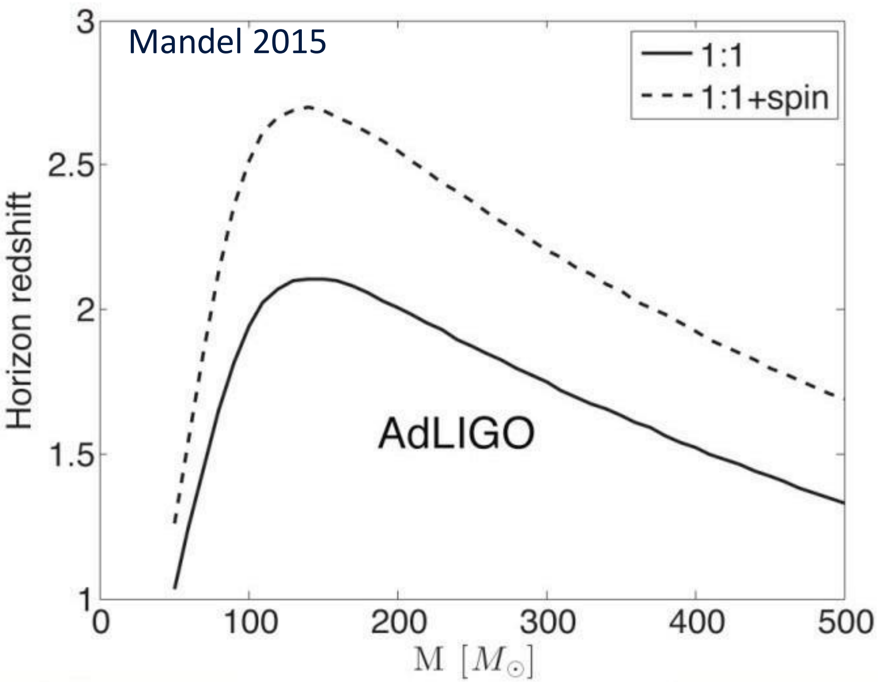


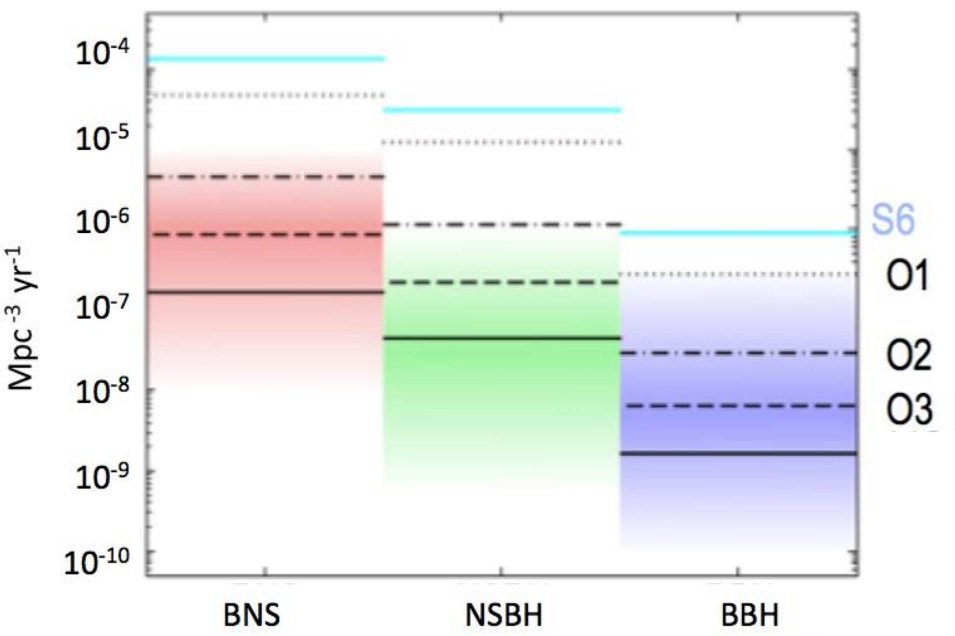
Credit: S. Fairhurst



Compact Coalescing Binaries

Detection perspectives with advanced detectors Phys. Rev D85 (2012) 082002





Epoch		2015	2016–2017	2017–2018	2019+	2022+ (India)
Estimated run duration		3 months	6 months	9 months	(per year)	(per year)
BNS range/Mpc	LIGO	40–80	80–120	120–170	200	200
	Virgo	–	20–60	60–85	65–130	130
BNS detections		0.0004–3	0.006–20	0.04–100	0.2–200	0.4–400

Probe beyond local universe
100 $M_\odot$ + 100 $M_\odot$ BBH visible out to ~16 Gpc at design sensitivity (~5 Gpc in O1), even further if the source is spinning

Conclusion

- VIRGO: although several difficulties are delaying the installation we are confident to start the commissioning soon.
- LIGO: the O1 run will end I the middle of January. An aggressive plan for commissioning is in place mainly focused to improve the sensitivity in the low frequency range.
- The goal for 2016 is to run the three interferometer at the same time in O2.


Finis

Extra slides

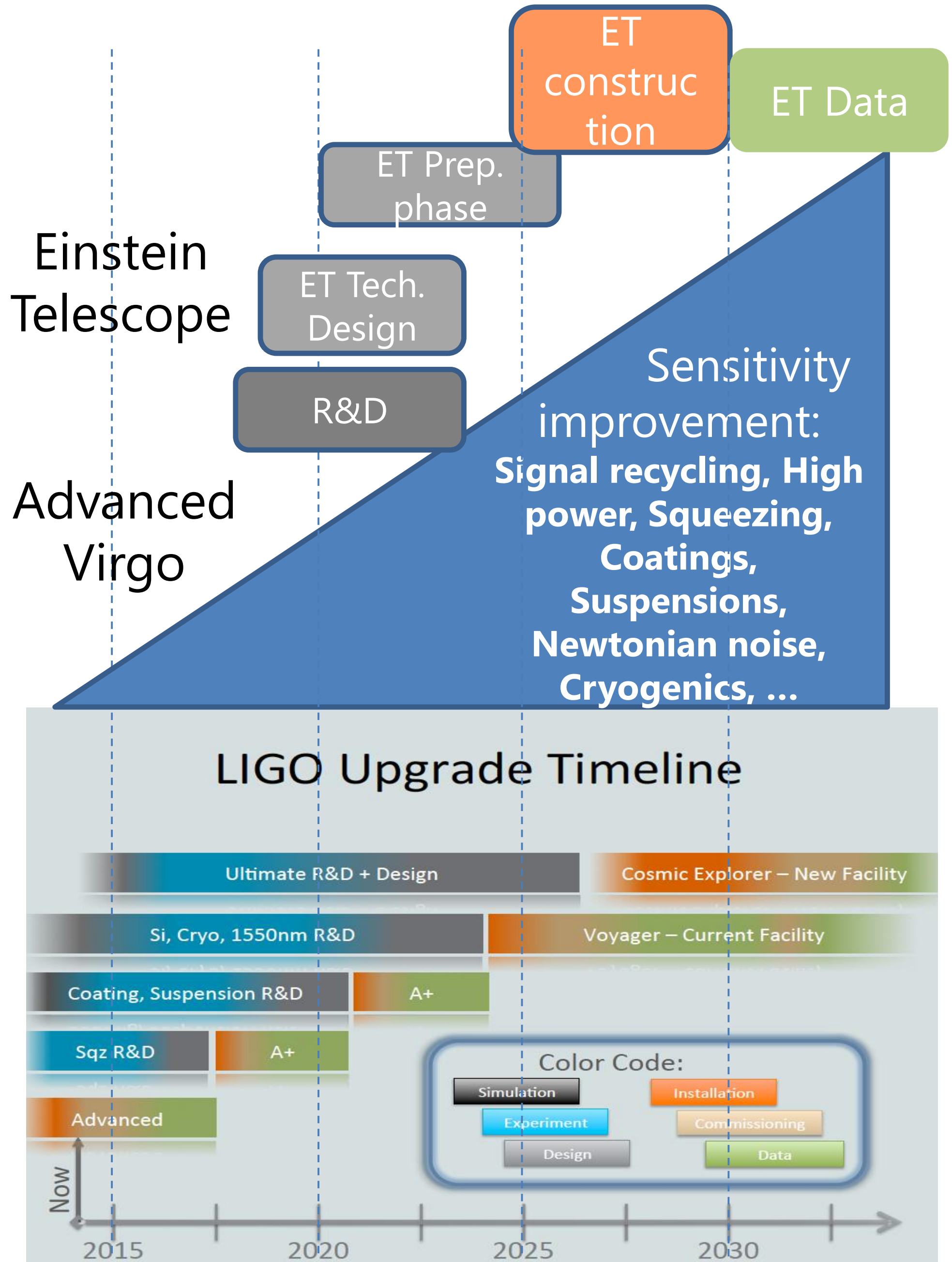
PATH to 3RD GENERATION

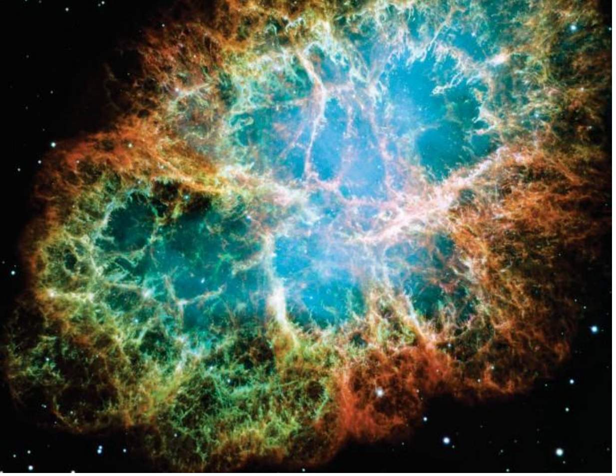
Towards the era of GW astronomy and astrophysicis:

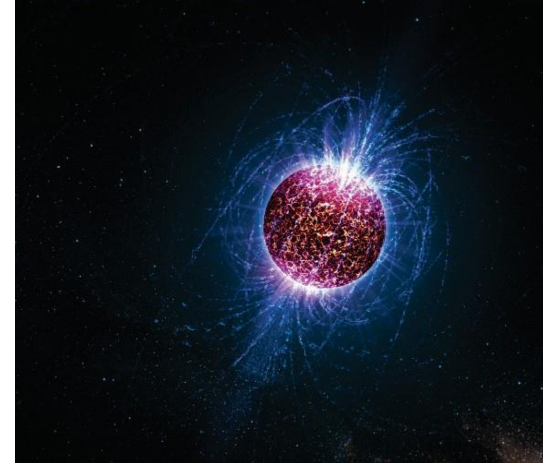
- ✓ Investigate the nuclear state of the matter above the critical density through the observation of the coalescence of NS-NS and NS-BH
- ✓ Study the GR and alternative gravitation theories in regime of medium or intense gravitational field, like in stellar mass BH coalescence
- ✓ Test of the cosmological model of the universe through the multimessenger observation of NS-NS and NS-BH coalescences

From the network of Adv. detectors to a system of observatories to routinely observe high SNR events:

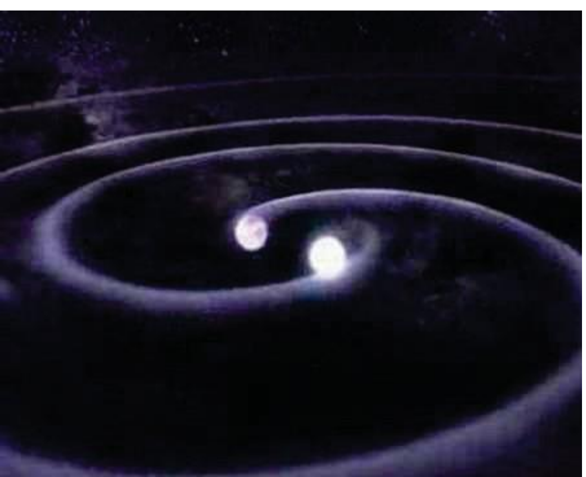
- ✓ Einstein Telescope and the future network of observatories (Cosmic Explorer in USA)
- ✓ New technologies

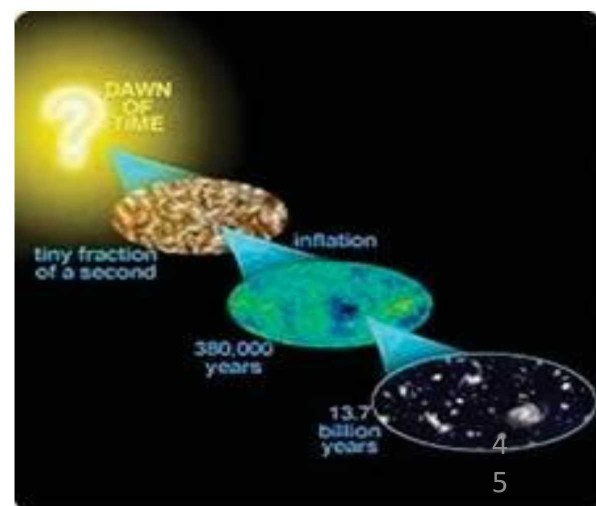




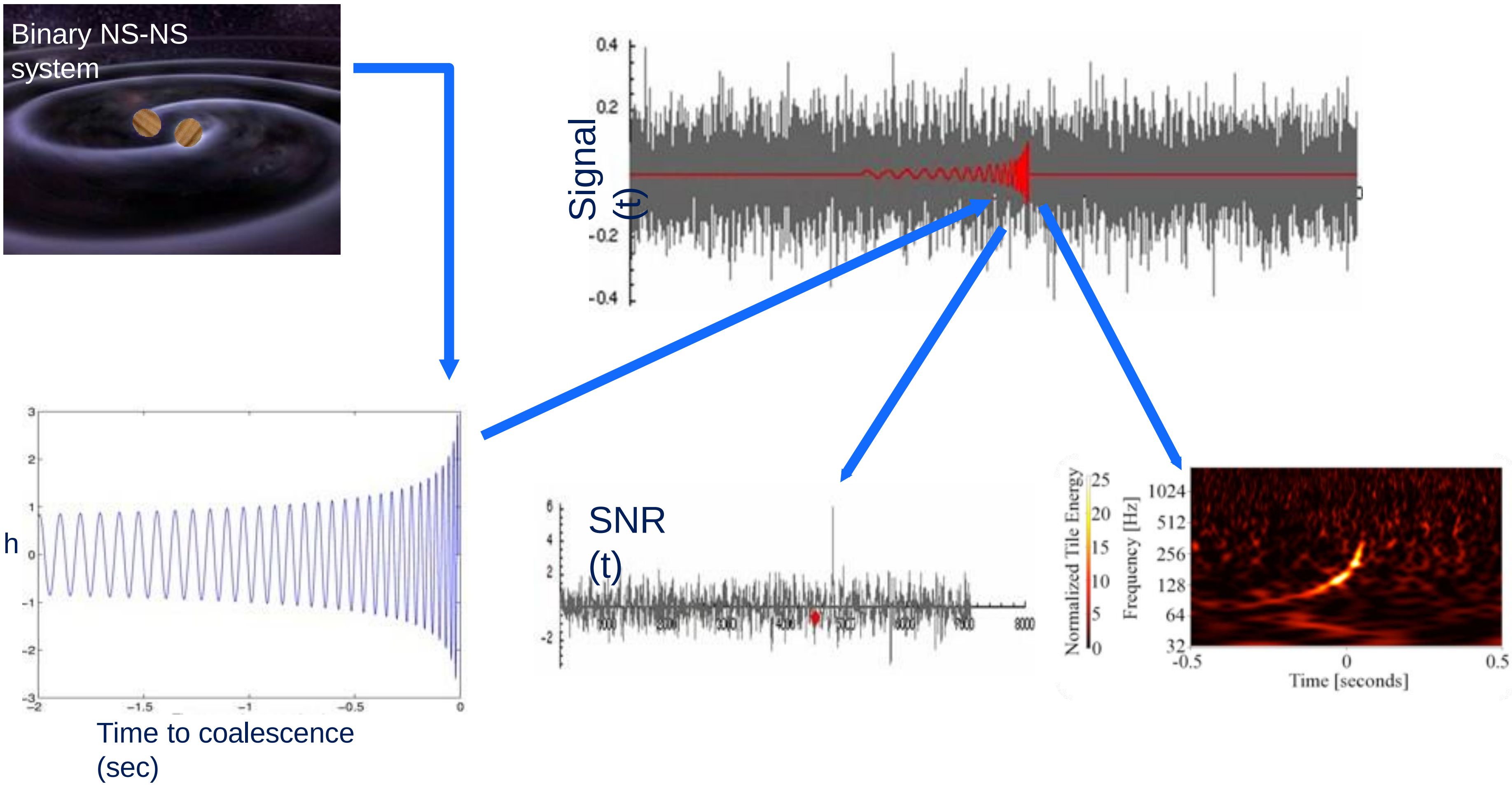


Hunting the GW signals in the Advanced Detector era

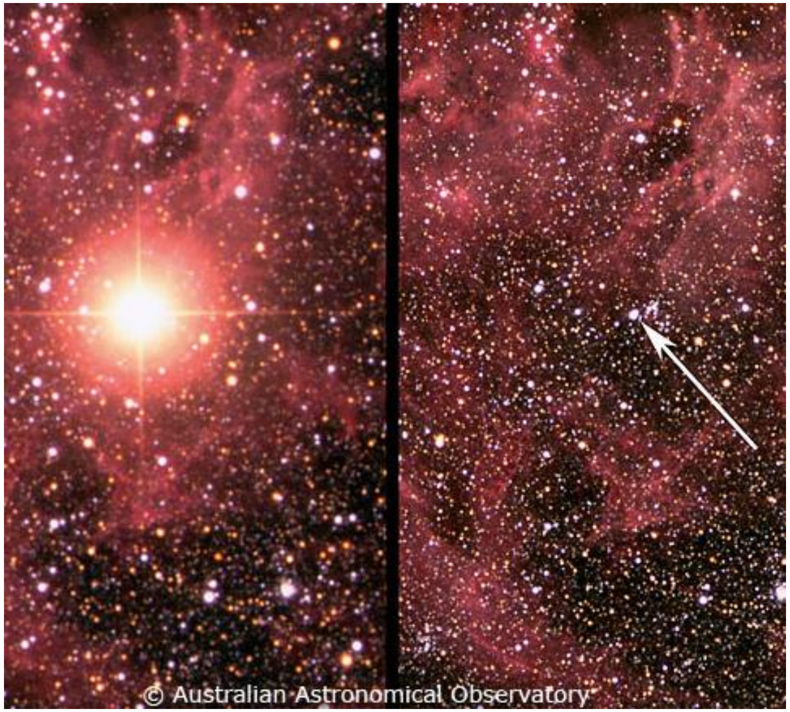




What Might the First Direct GW Detection Look Like?



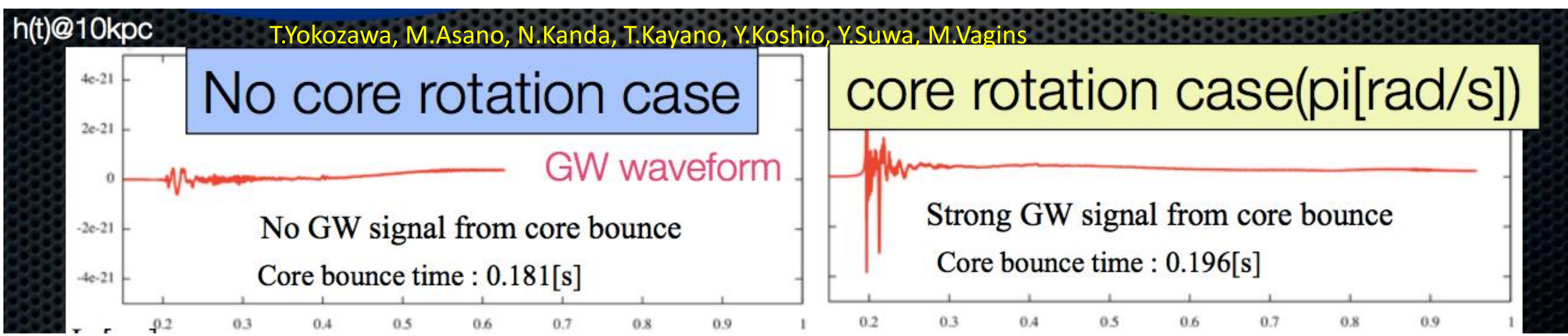
Core-collapse Supernovae



Core collapse dynamics and GW emission difficult to predict

Numerical models

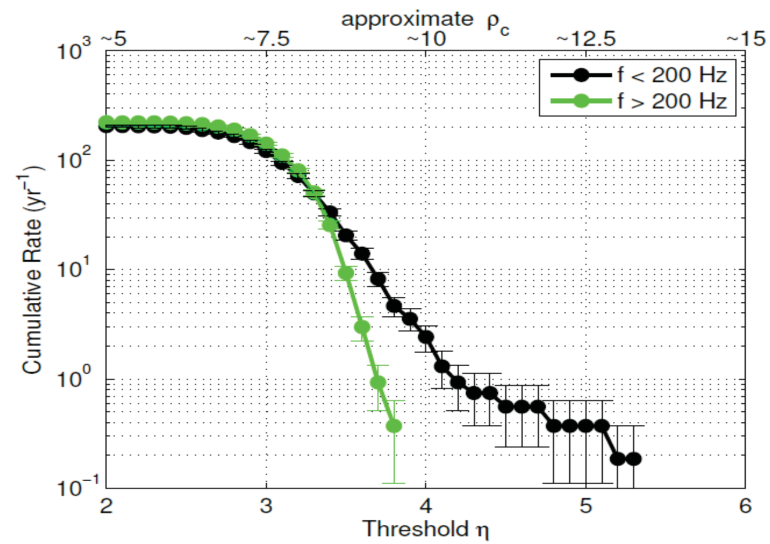
$E_{GW} \sim 10^{-11} – 10^{-12}\, M_\odot\, c^2$



Burst unmodeled searches

Robust search algorithm

- Require coherent signals in multiple detectors, using direction-dependent antenna response
- Look for excess power in time-frequency space using wavelet decomposition
- Data quality and vetoes are crucial to keep background under control



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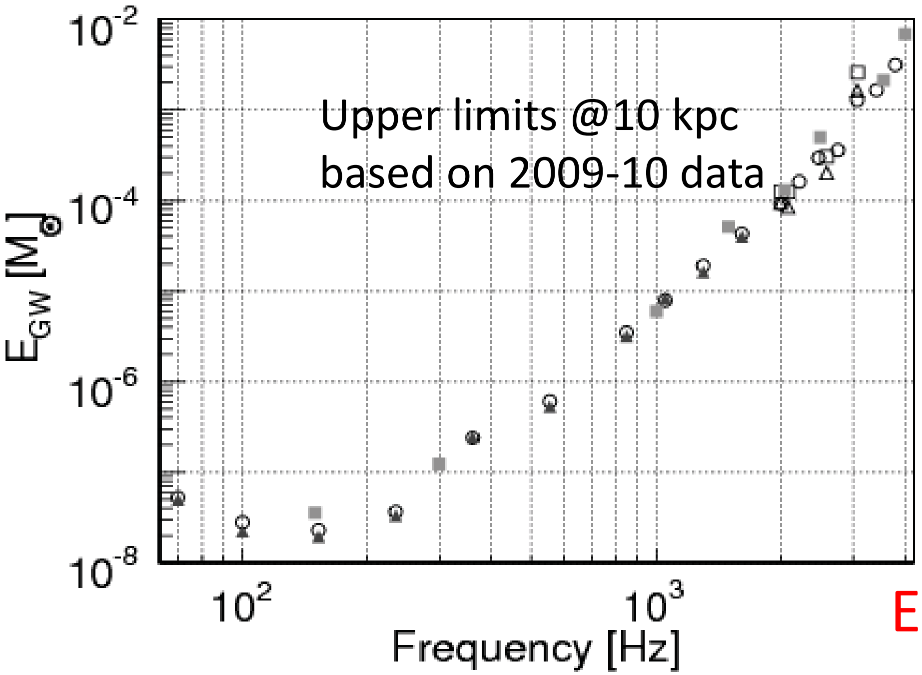
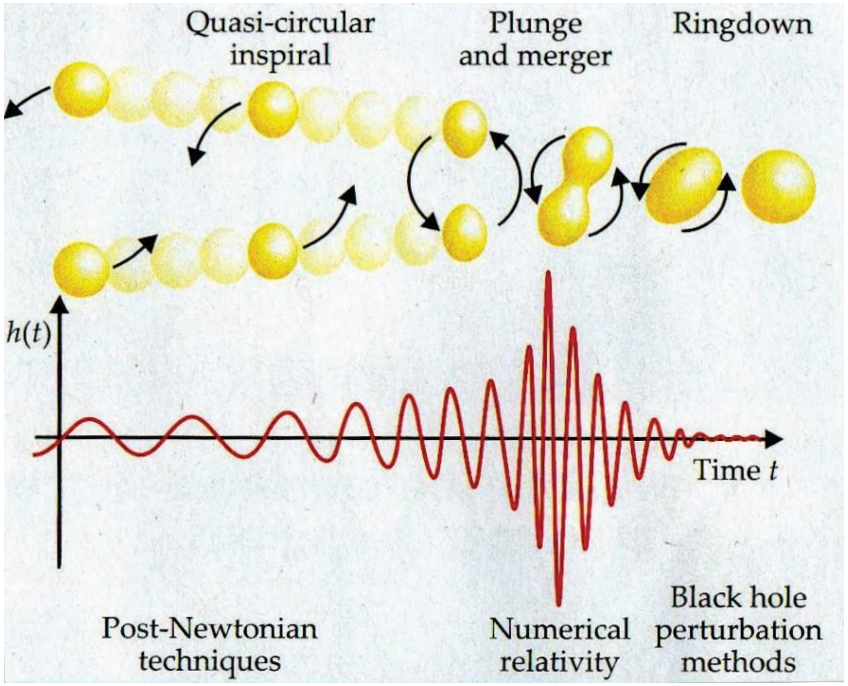


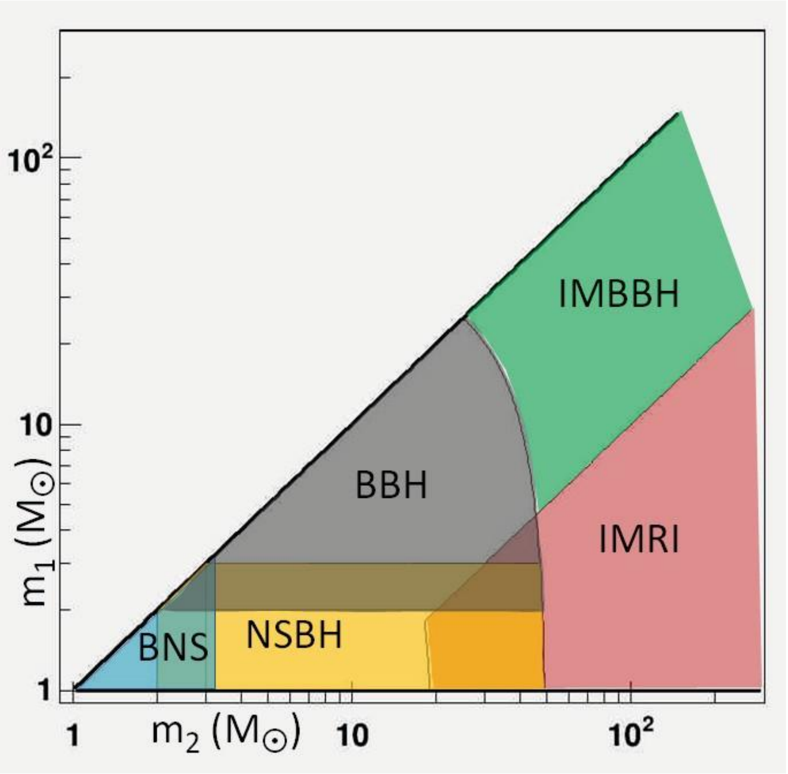
Advanced detectors will probe

$$h_{rss} = \sqrt{\int |h_+(t)|^2 + |h_\times(t)|^2} \sim 10^{-23}$$

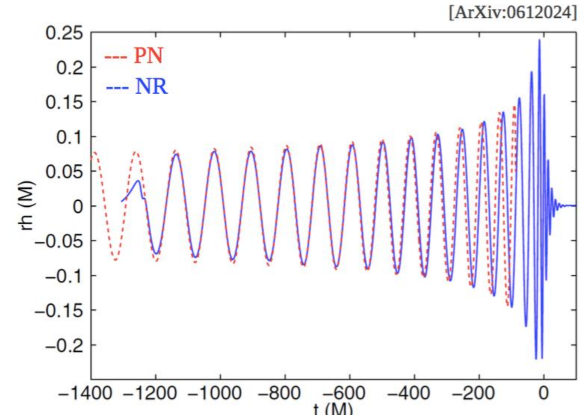
$E_{GW} \sim 10^{-9}\, M_\odot c^2$ @ 10 kpc, 100-200 Hz

CBC searches

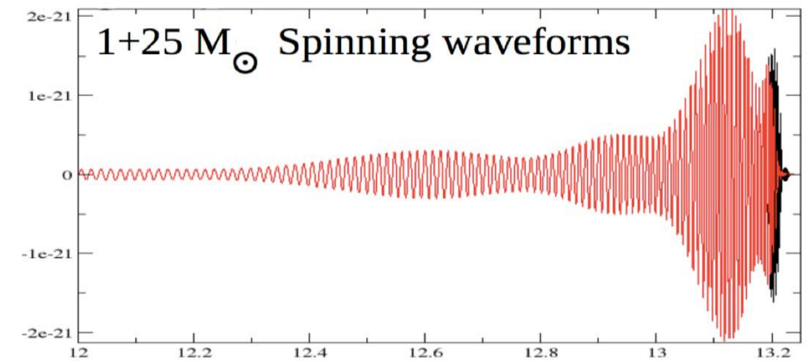




- Searches use waveform predictions to perform matched filtering
- Searches organized as a function of source types and technical specifics (waveforms)



Waveform zoology



- Mass regime: low and high+mass mass ratio)
- Spin contribution

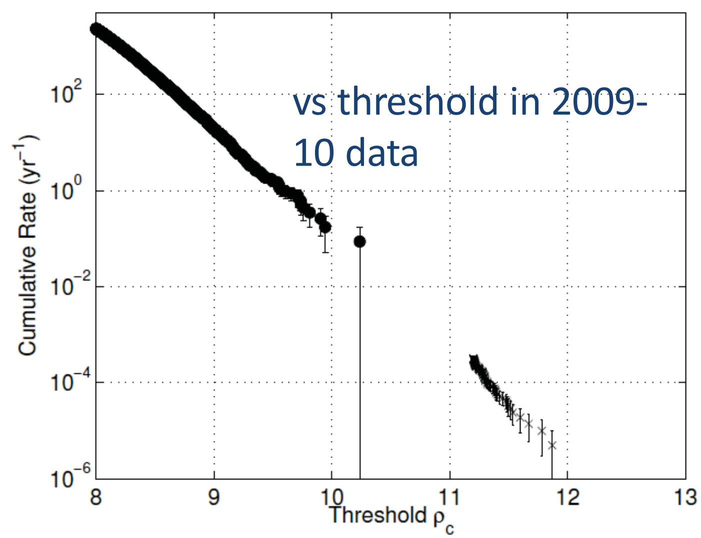
	Approximations	Spins
Low mass $(M_{tot} < 12 M_\odot)$	BNS case SNR dominated by the inspiral phase. Waveforms accurate until PN approx. breaks	For initial detectors: spin could be neglected. Advanced LIGO/Virgo: spin 0.015 - 0.1 → 3%-25% mismatch. Aligned spins is still OK?
High mass $(M_{tot} > 12 M_\odot)$	For masses higher than 50 Msun, merger and ring-down contribute dominantly → need full waveform inspiral + merger + ring-down (IMR) Use of NR waveforms for merger.	BH spins is likely maximal Spin precession effects can be large. Spins cannot be neglected for Advanced LIGO/Virgo

CBC search

Waveforms

- Ideally: Account for inspiral + merger + ringdown, with precessing spins, tidal effects, higher harmonics, eccentricity… and with fast computation
- Not everything matters everywhere in the parameter space
  - Some aspects are more crucial for parameter estimation than for detection
- Progress still needed to fully explore the spin - mass ratio space for IMR waveforms

CBC false alarm rate

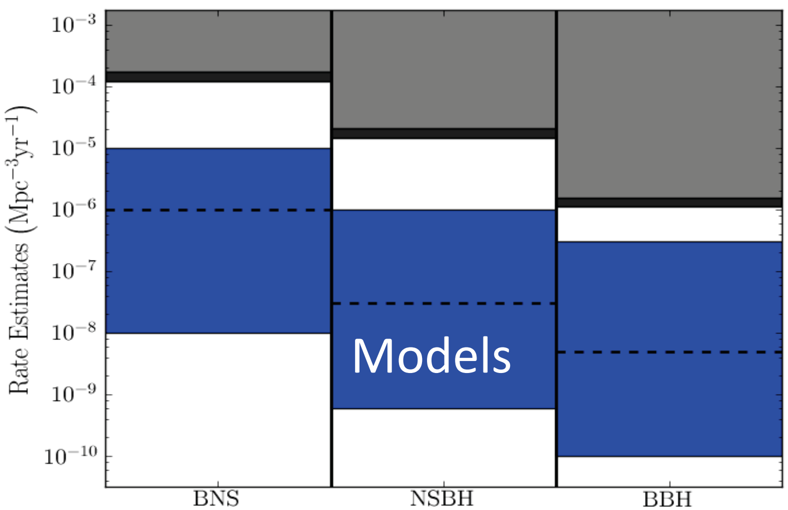


Getting the background under control

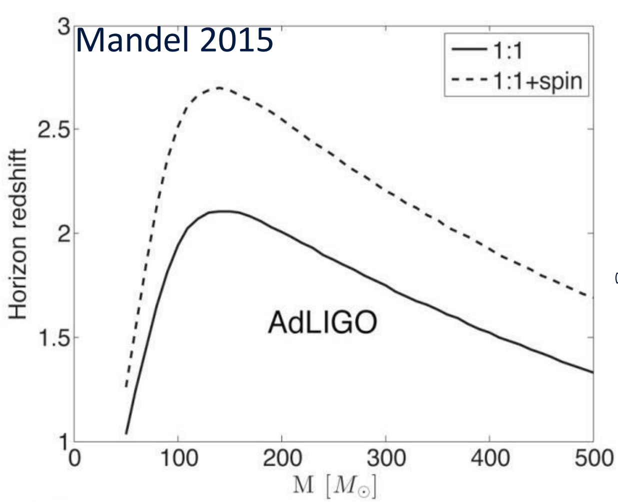
- Signal based consistency cuts
- Data quality and vetoes
- A winning combo that brought the background close to Gaussian level in past searches
- Advanced detectors are new detectors
  - Data quality not granted a priori!
- Explore new techniques: multivariate classifiers

Compact Coalescing Binaries

Initial detectors rate upper limits and detection perspectives with advanced detectors Phys. Rev D85 (2012) 082002



IFO	Source[a]	$\dot{N}_{low}$ yr^{-1}	$\dot{N}_{re}$ yr^{-1}	$\dot{N}_{pl}$ yr^{-1}	$\dot{N}_{up}$ yr^{-1}
	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
Advanced	BH-BH	0.4	20	1000	
	IMRI into IMBH			10^b	300^c
	IMBH-IMBH			0.1^d	1^e

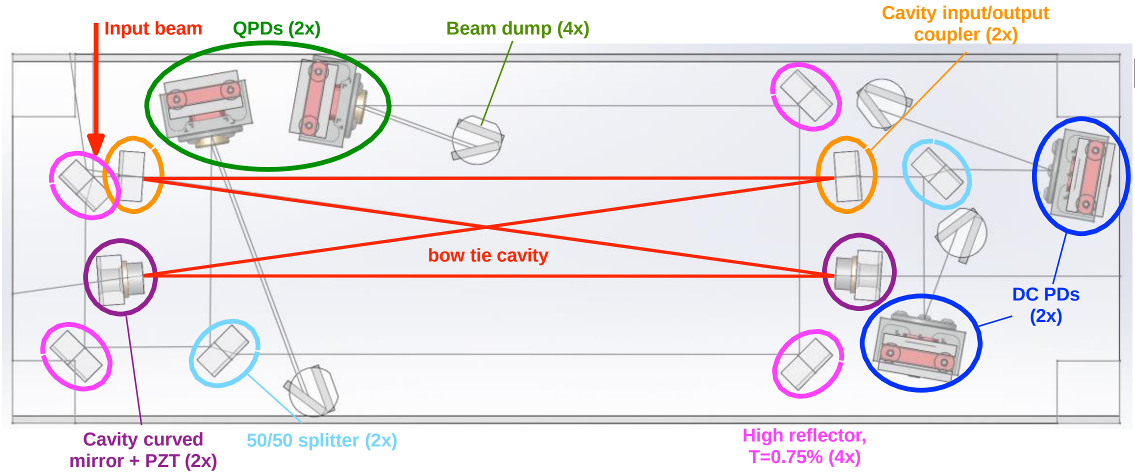


Epoch		2015	2016 – 2017	2017 – 2018	2019+	2022+ (India)
Estimated run duration		3 months	6 months	9 months	(per year)	(per year)
BNS range/Mpc	LIGO	40 – 80	80 – 120	120 – 170	200	200
	Virgo	—	20 – 60	60 – 85	65 – 130	130
BNS detections		0.0004 – 3	0.006 – 20	0.04 – 100	0.2 – 200	0.4 – 400

Probe beyond local universe

- 100 M⊙ + 100 M⊙ BBH visible out to ~16 Gpc at design sensitivity (~5 Gpc in O1), even further if the source is spinning

Output Mode Cleaner

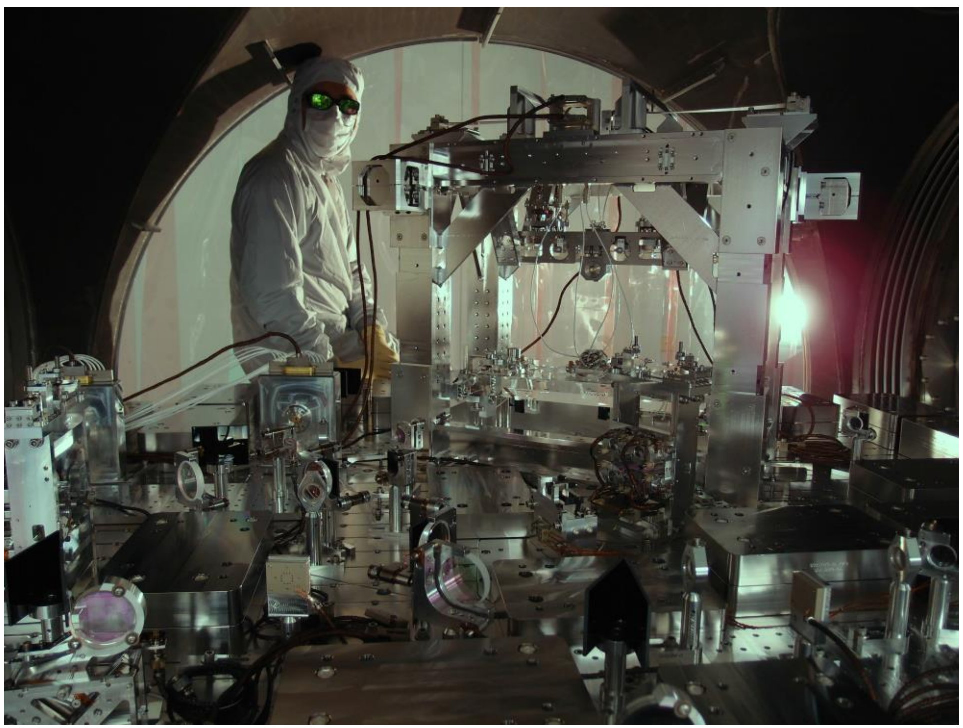


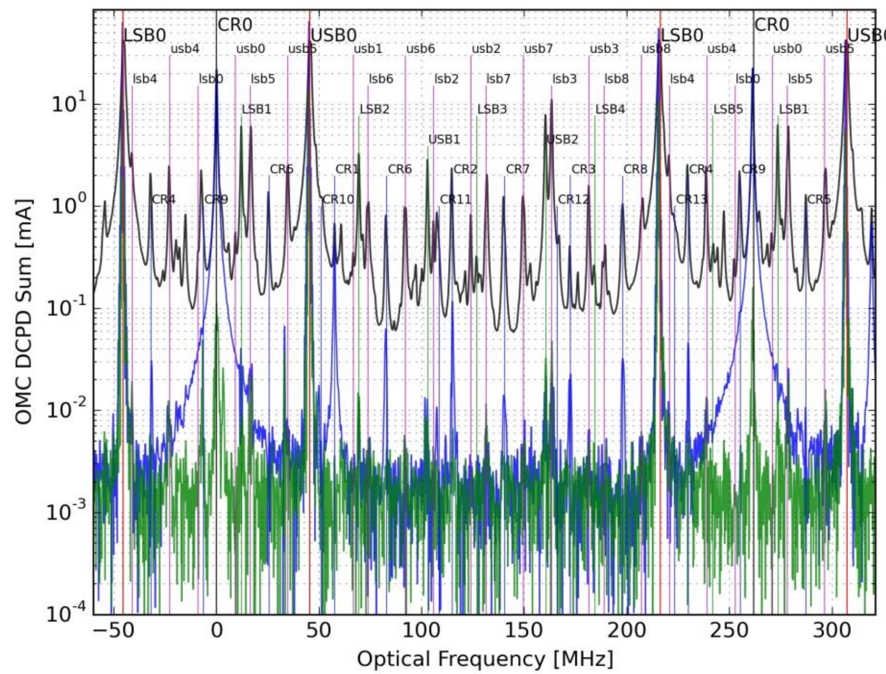
By K. Arai et al., T1000276

Finesse: 390, FSR: 261 MHz
TMS spacing: 0.219 x FSR PZT actuation range: 2.4 x FSR

Results from mode scans in full lock:

- Carrier mode-matching ~99%
- Carrier contrast defect ~70ppm





Credits to D. Hoak