Advanced Virgo

INFN

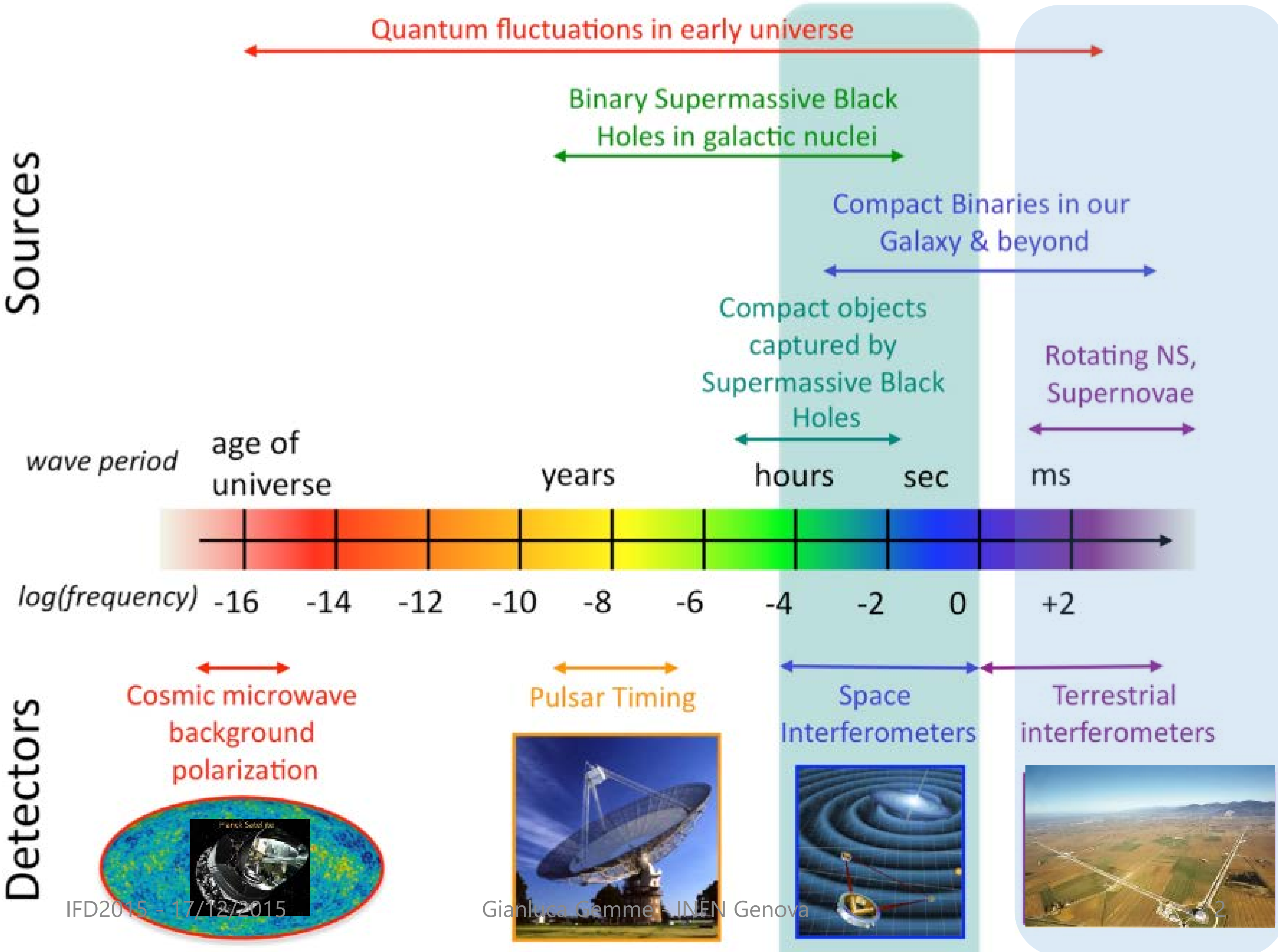
TECHNOLOGIES FOR FUTURE GRAVITATIONAL WAVES DETECTORS (ON EARTH)

what NEXT?

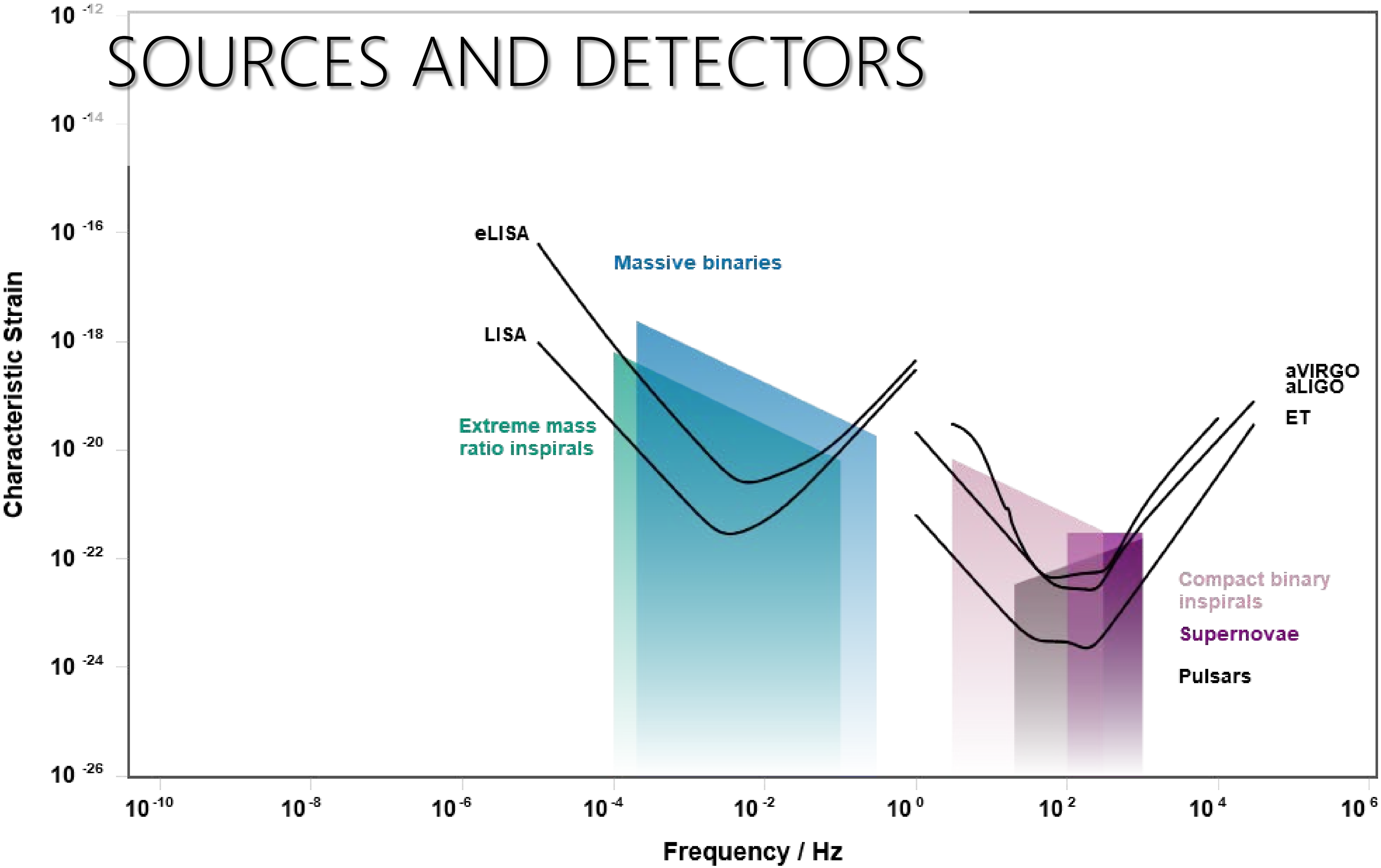
IFD2015
17/12/2015

Gianluca Gemme
INFN Genova

The Gravitational Wave Spectrum

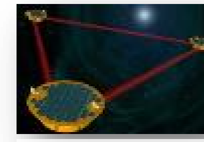


SOURCES AND DETECTORS



 http://rhcole.com/apps/GWplotter/

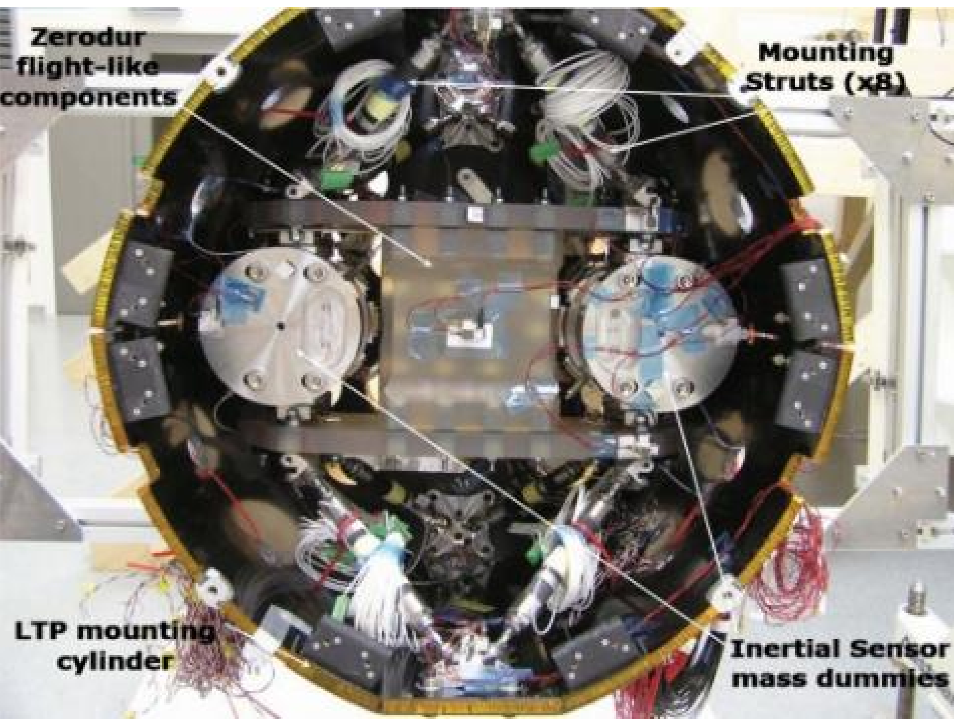
WORLDWIDE NETWORK OF GW DETECTORS



(e)LISA
~2034

LISA Technology Package

Pictures: ESA/ATG Medialab



ADVANCED VIRGO

- Advanced Virgo (AdV): upgrade of the Virgo interferometric detector
- Participated by scientists from France and Italy (former founders of Virgo), The Netherlands, Poland and Hungary
- Funding approved in Dec 2009 (21.8 ME + Nikhef in kind contribution)
- Construction in progress. End of installation: fall 2015
- First science data in 2016
- Part of the international network (MoU with LSC)

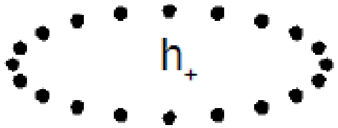
5 European countries
19 labs, ~200 authors

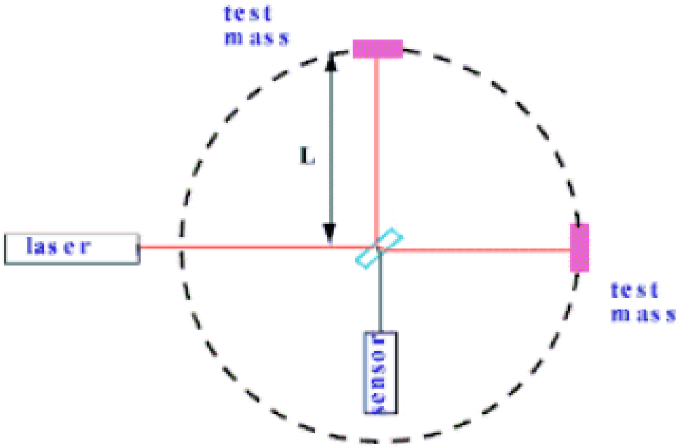
APC Paris
ARTEMIS Nice
EGO Cascina
INFN Firenze-Urbino
INFN Genova
INFN Napoli
INFN Perugia
INFN Pisa
INFN Roma La Sapienza
INFN Roma Tor Vergata
INFN Trento-Padova
LAL Orsay – ESPCI Paris
LAPP Annecy
LKB Paris
LMA Lyon
NIKHEF Amsterdam
POLGRAW(Poland)
RADBOUD Uni. Nijmegen
RMKI Budapest

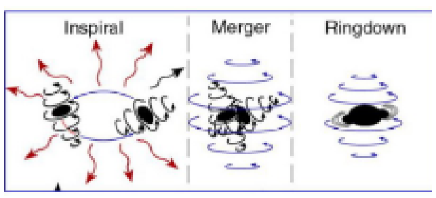
1-slide primer on gravitational waves

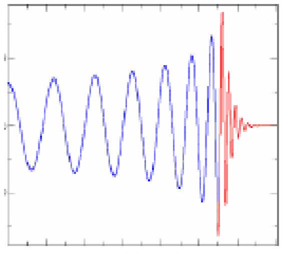
- Gravitational waves GW
  - Propagating space-time distorsions predicted by General Relativity
  - Goal: **measure GW directly (*in situ*)**
- Kilometric Michelson interferometer
  - Measure relative difference in optical path length to $h_{\text{noise}} \sim 10^{-21}$ **, or 10^{-18} m** over km
  - Sensitive from few 10th Hz to few kHz
- Target distant astrophysical sources
  - Typically: binaries of stellar mass compact objects (neutron star or black hole)

    $h_{\text{signal}} \sim 10^{-21}$ from NS–NS at 15 Mpc





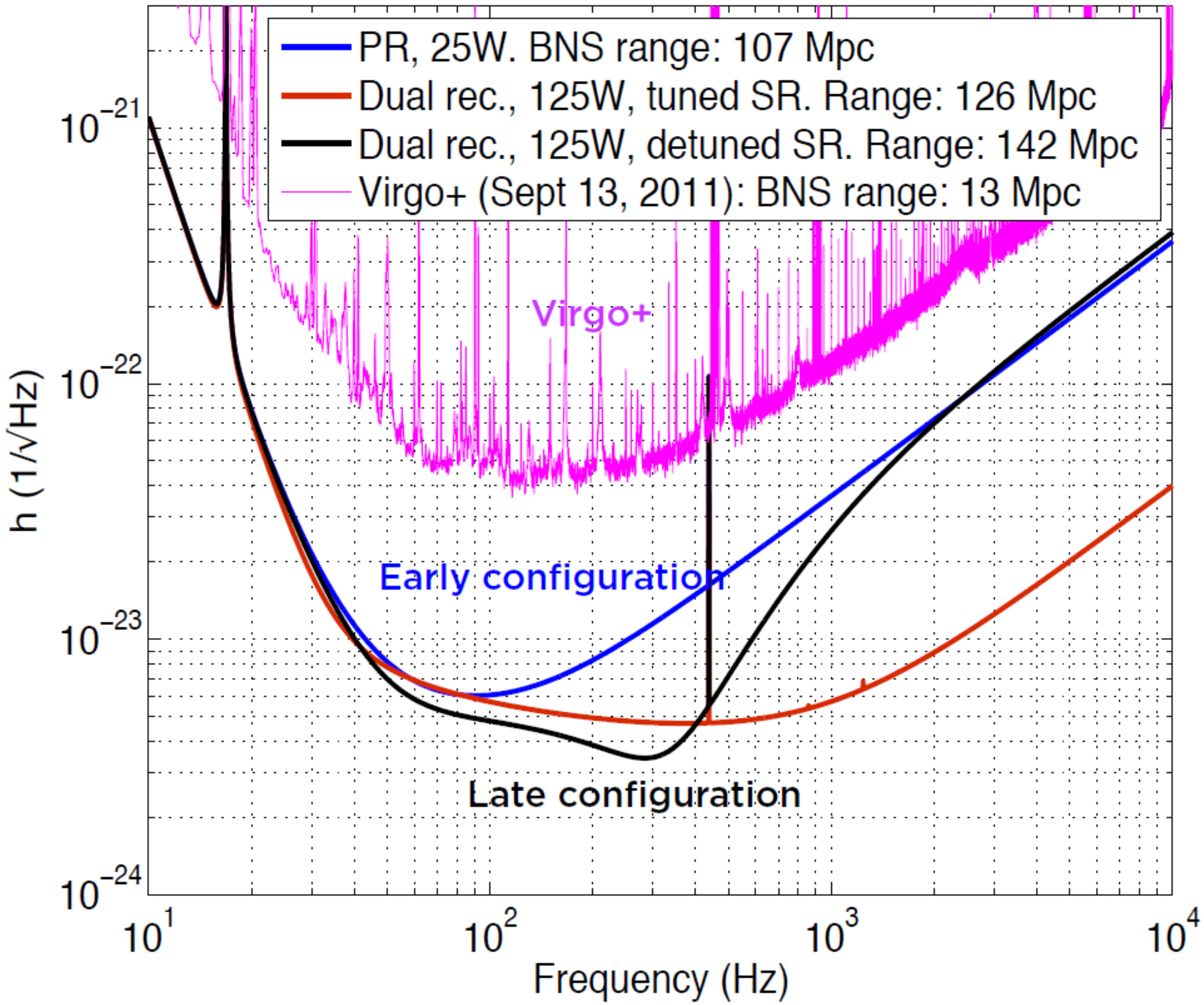




$$h(t) = \frac{\delta L(t)}{L} \propto \delta\Phi(t)$$

CREDIT:
E. Chassande-Mottin

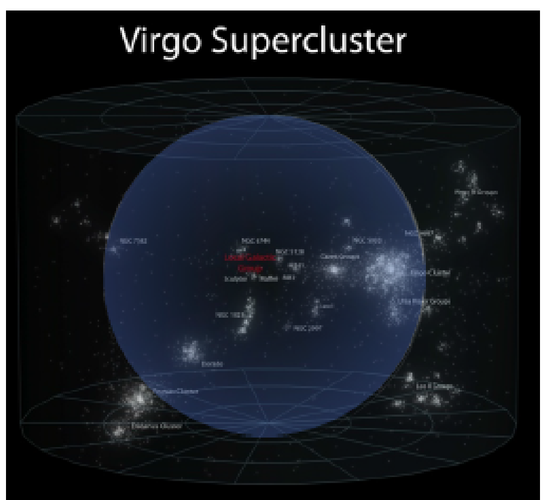
SENSITIVITY

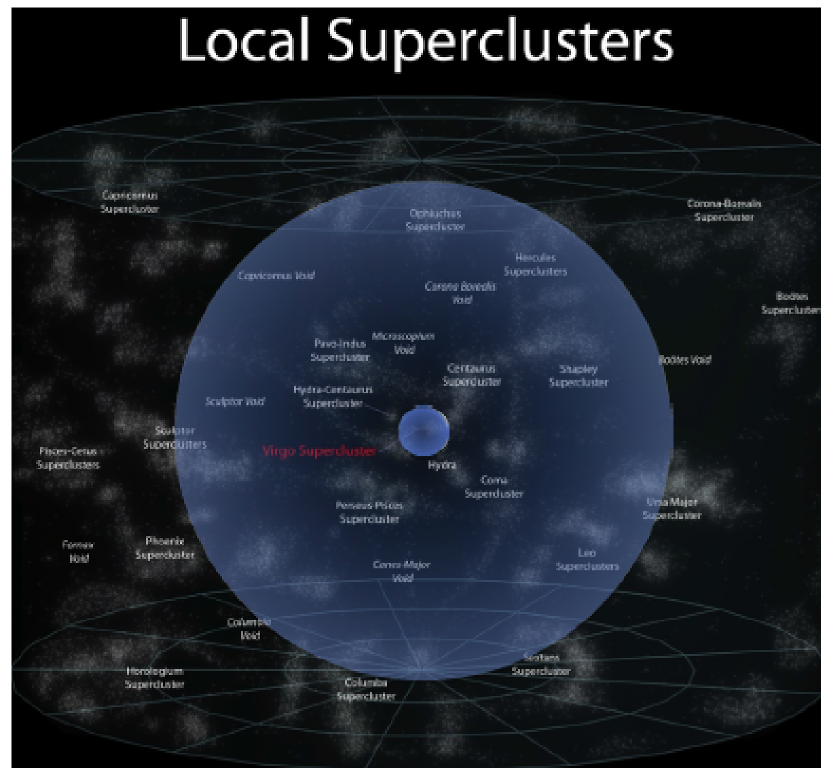


SCIENTIFIC REACH

- Up-coming advanced detectors are **~10 x more sensitive**, will **reach about 100,000 galaxies**
- Events happen once every 10,000 years per galaxy…
- NS-NS detection rate order of

  1 per month





CREDIT:
E. Chassande-Motttin

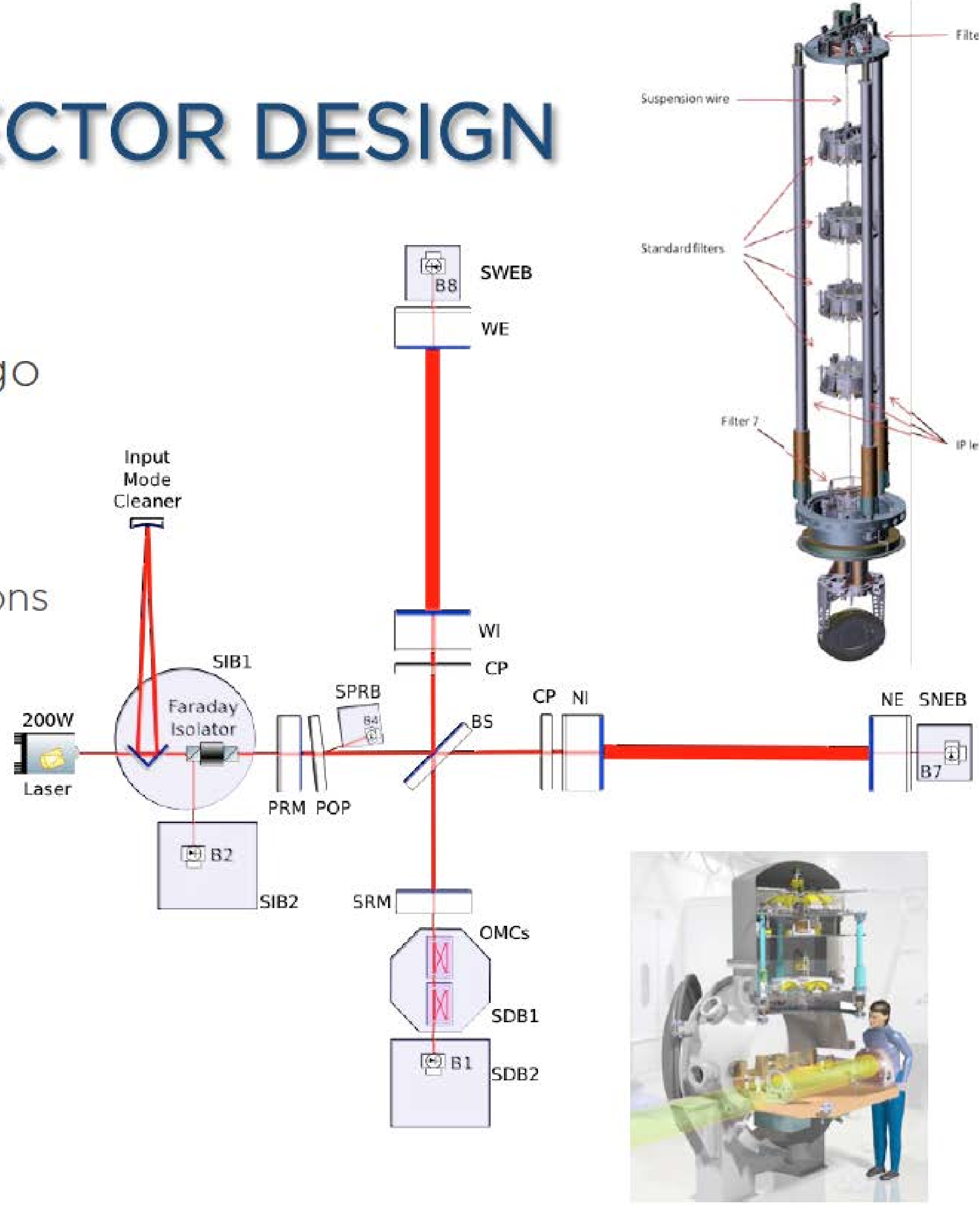
Initial reach

Advanced reach

ADV DETECTOR DESIGN

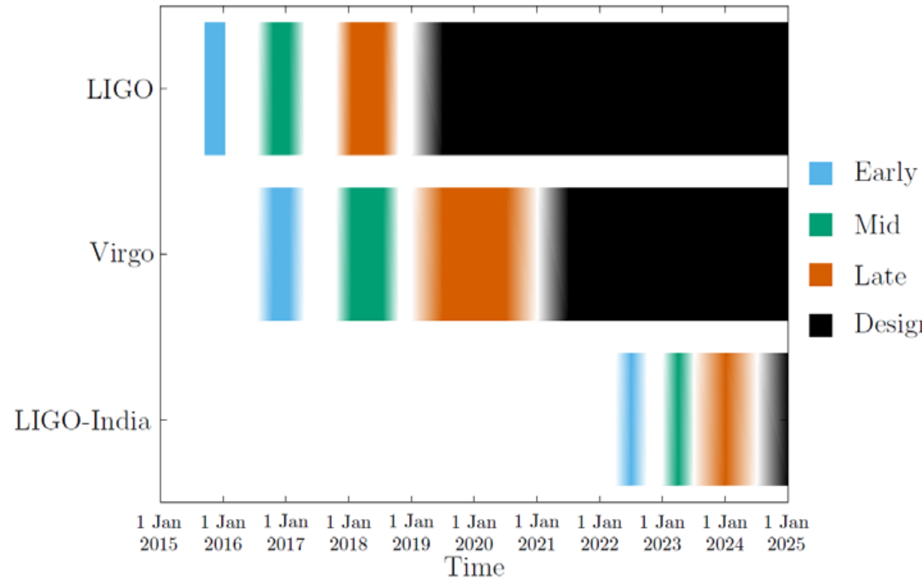
- TDR released in 2012
- MAIN CHANGES wrt Virgo
  - larger beam
  - heavier mirrors
  - higher quality optics
  - thermal control of aberrations
  - stray light control
  - *200W laser*
  - *signal recycling*

(200W laser and signal recycling: 2017/18)



ADV: STATUS & SCHEDULING

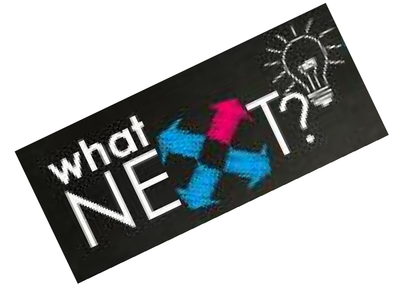
- Budget: 88% of project cost committed
- End of the assembling expected at the beginning of next year
- Pre-commissioning of some of the apparatuses already started



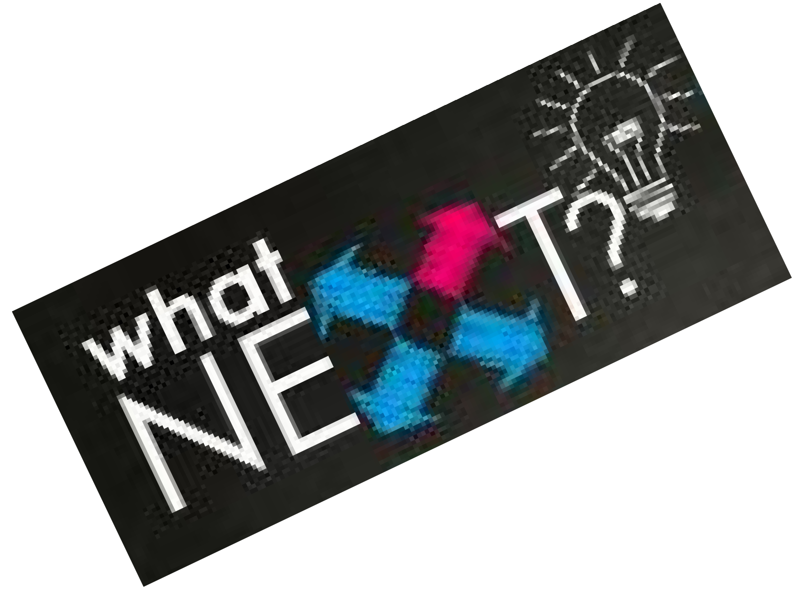
Main Goal:

Join aLIGO in the 2016 science run

ADVANCED VIRGO: WHAT NEXT?



- PHASE 1 (~2017- 2019):
  a collection of "*minor*" upgrades to AdV to reach design sensitivity
  - high laser power, signal recycling, frequency independent squeezing, parametric instabilities, …
- PHASE 2 (~10 years from now):
  the best we can do in the current infrastructure
  - frequency dependent squeezing, better coatings, heavier masses, gravity noise cancellation, …
- PHASE 3 (>2025)
  ET: a new infrastructure
  - increased length (~10km), underground, cryogenics, new materials, topology, xylophone, …

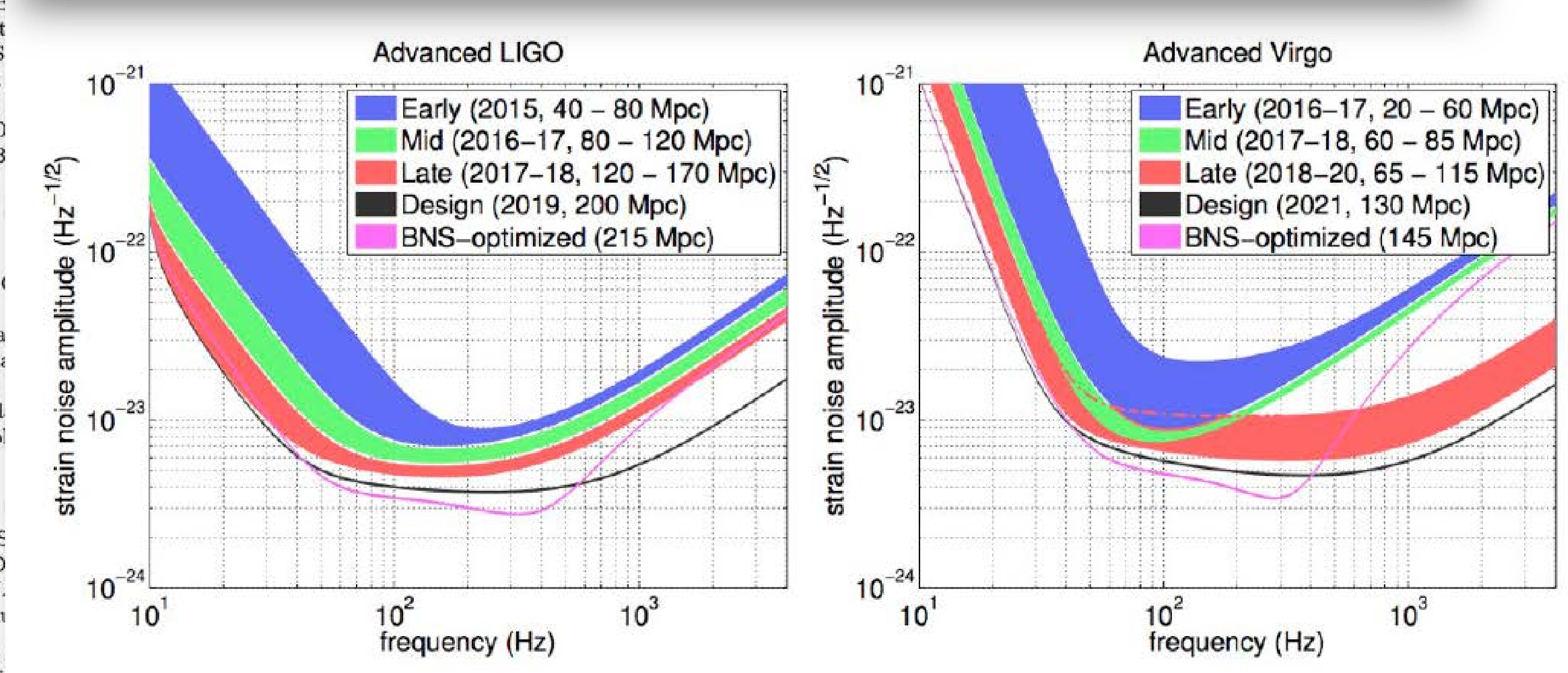


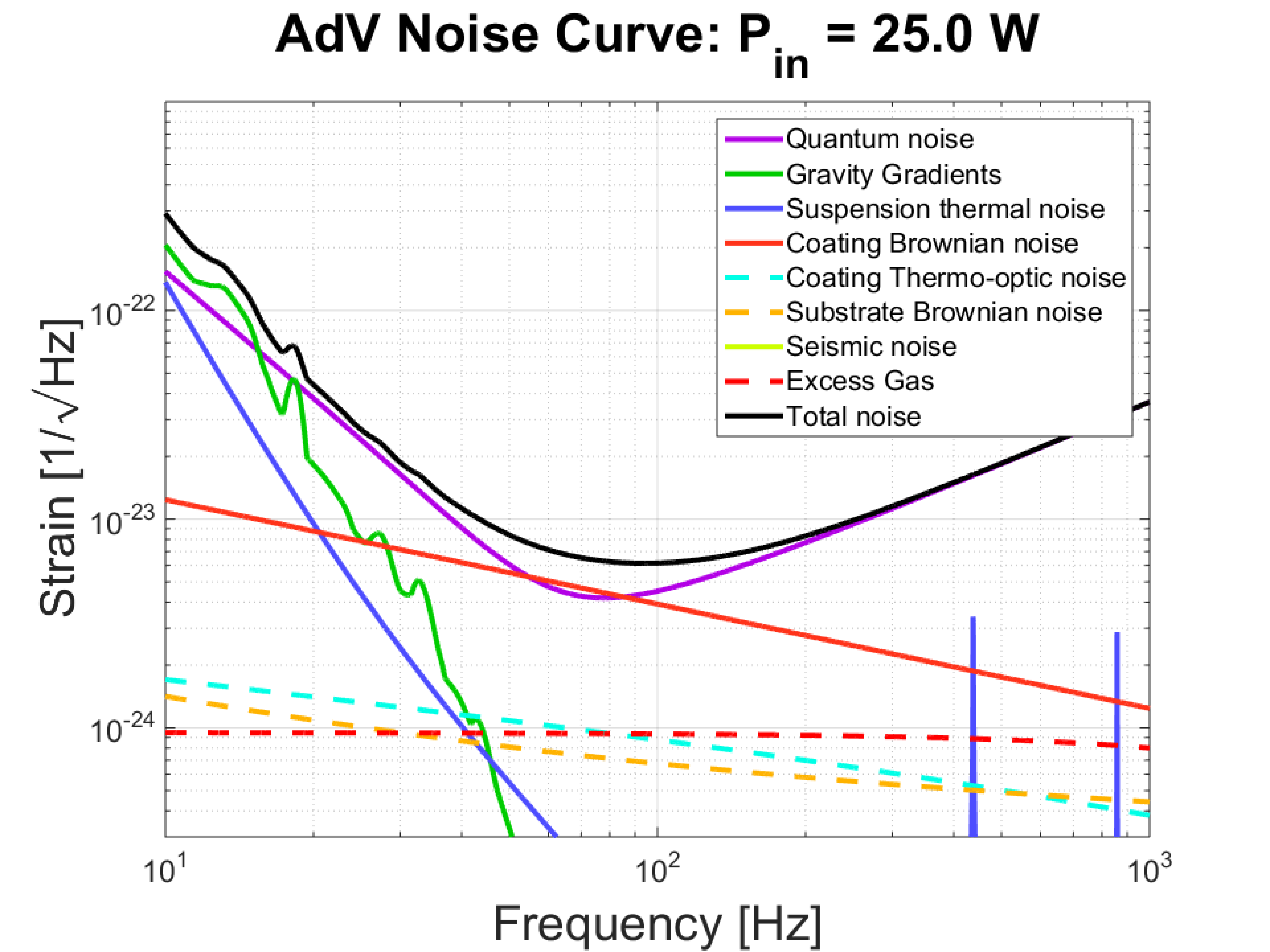
PHASE 1 (~2017- 2019)

a collection of "*minor*" upgrades to AdV to reach design sensitivity

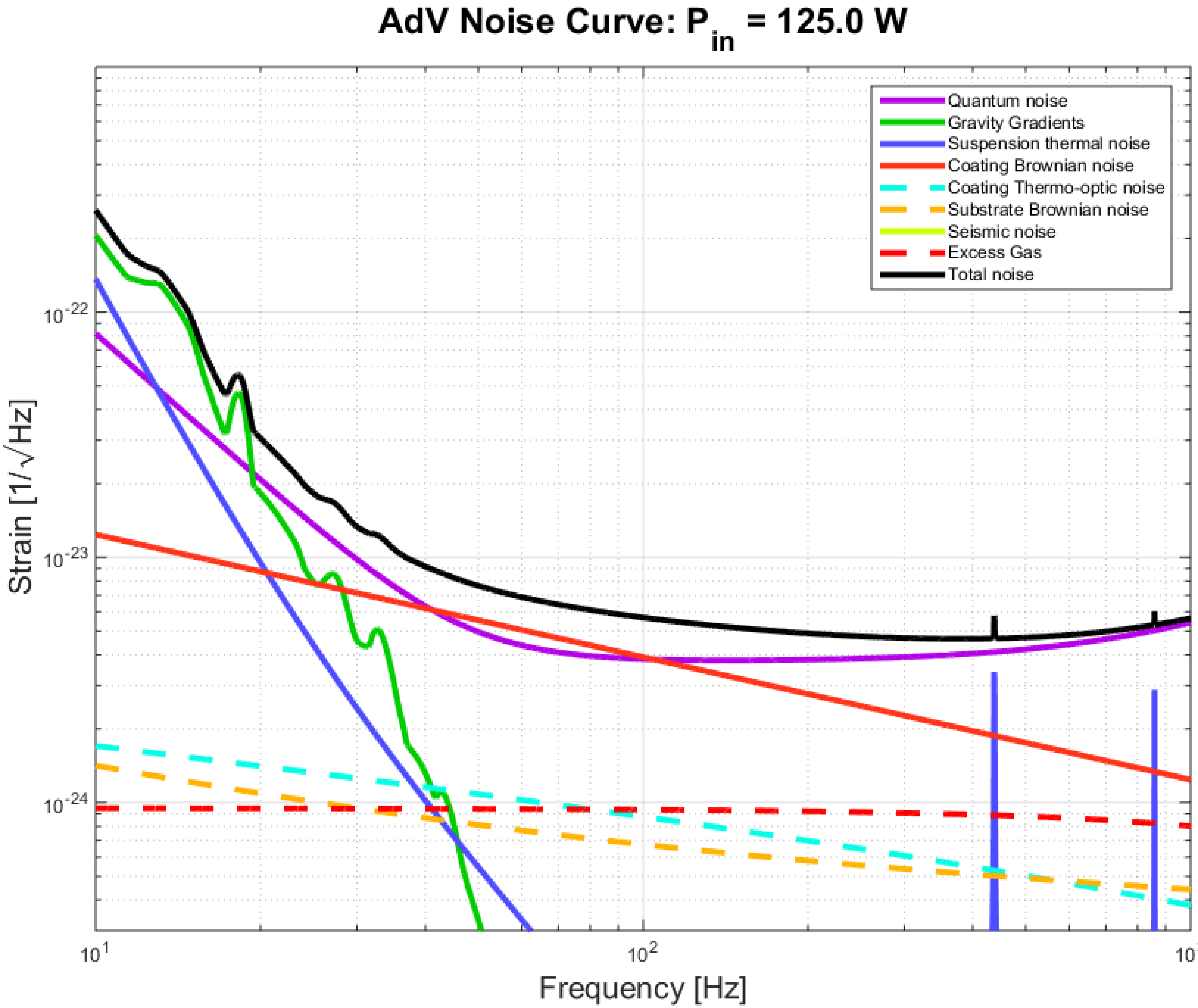
SENSITIVITY EVOLUTION

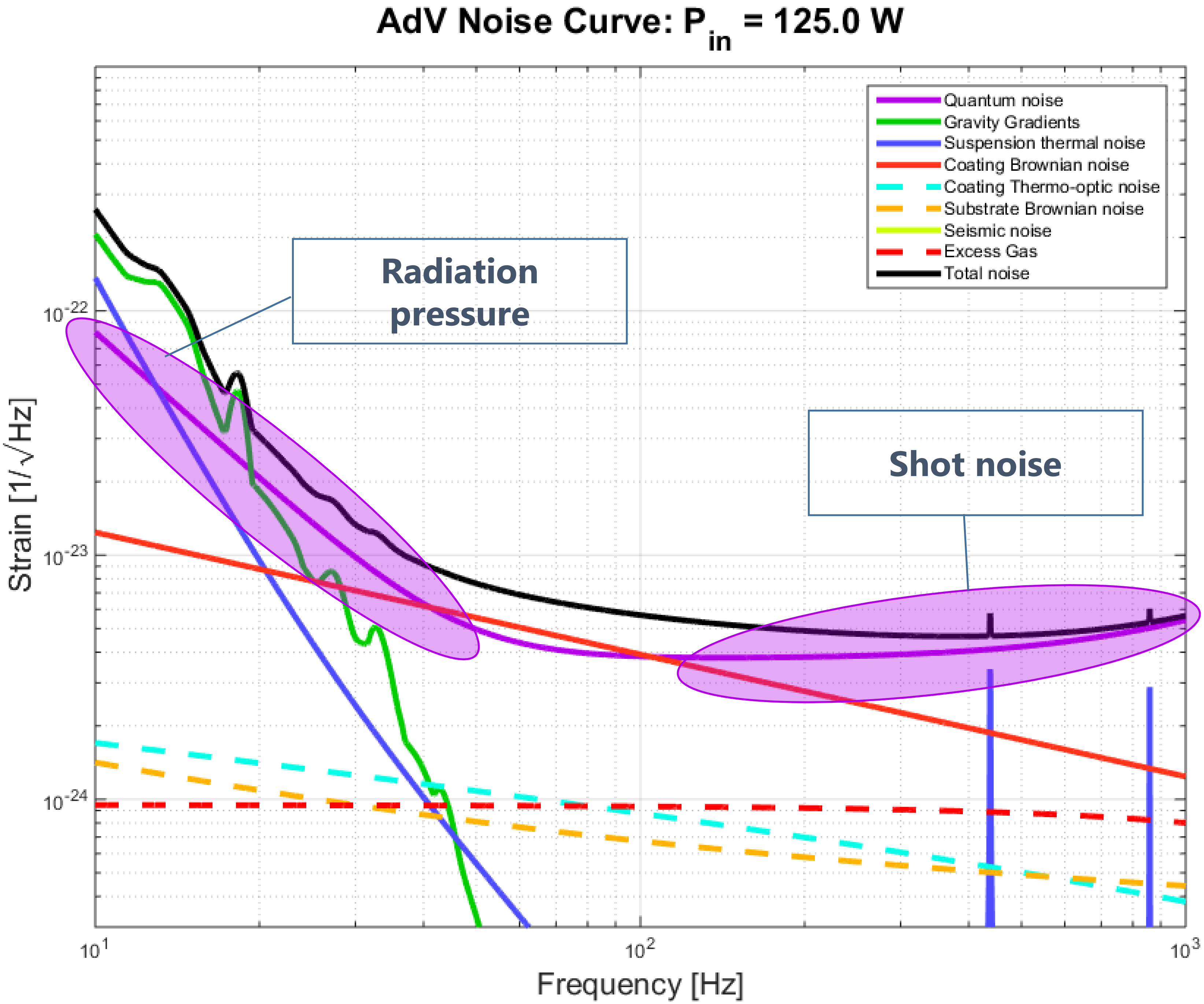
Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48





AdV Noise Curve: P in = 25.0 W
Quantum noise
Gravity Gradients
Suspension thermal noise
Coating Brownian noise
Coating Thermo-optic noise
Substrate Brownian noise
Seismic noise
Excess Gas
Total noise
Strain [1/√Hz]
10-22
10-23
10-24
10 1
10 2
10 3
Frequency [Hz]


AdV Noise Curve: P_in = 125.0 W
Quantum noise
Gravity Gradients
Suspension thermal noise
Coating Brownian noise
Coating Thermo-optic noise
Substrate Brownian noise
Seismic noise
Excess Gas
Total noise
Strain [1/√Hz]
Frequency [Hz]
10^-22
10^-23
10^-24
10^1
10^2
10^3



AdV Noise Curve: P_{in} = 125.0 W
Quantum noise
Gravity Gradients
Suspension thermal noise
Coating Brownian noise
Coating Thermo-optic noise
Substrate Brownian noise
Seismic noise
Excess Gas
Total noise
Radiation pressure
Shot noise
Strain [1/√Hz]
Frequency [Hz]
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}

QUANTUM NOISE IN OPTICAL MEASUREMENTS

- Measurement process
  - Interaction of light with test mass
  - Counting signal photons with a photodetector
- Noise in measurement process
  - Poissonian statistics of force on test mass due to photons
    ➔ radiation pressure noise (RPN)
    (amplitude fluctuations)

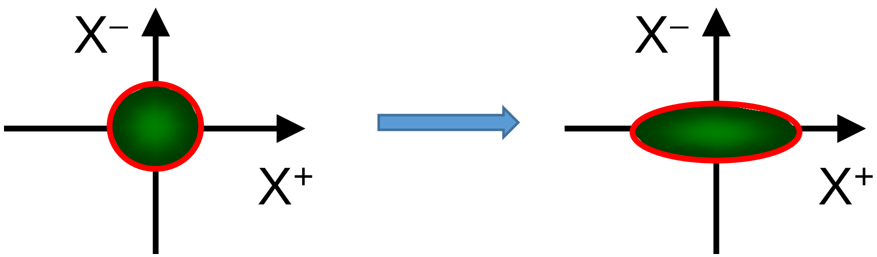
$$h(f) \propto \sqrt{\frac{1}{P_{bs}}}$$

  - Poissonian statistics of counting the photons ➔ shot noise (SN)
    (phase fluctuations)

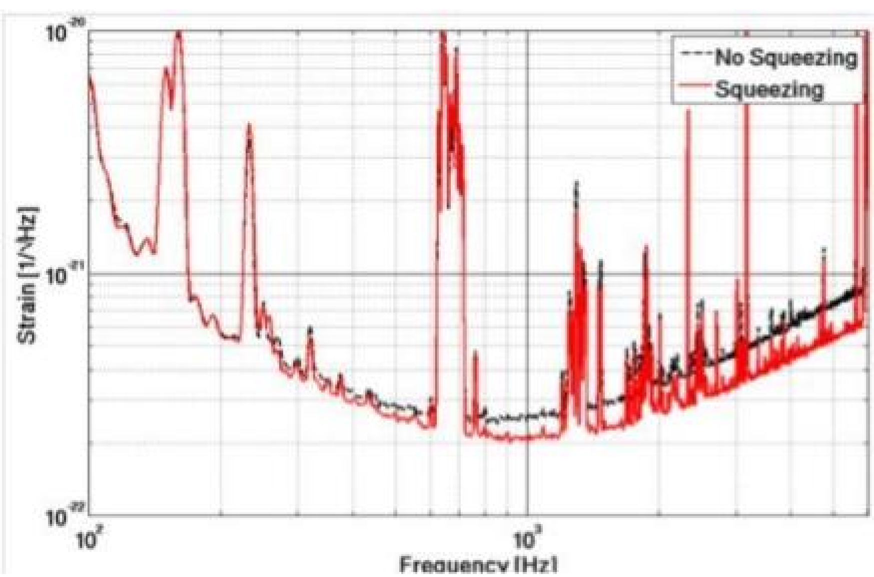
$$h(f) \propto \sqrt{\frac{P_{bs}}{Mf^4}}$$

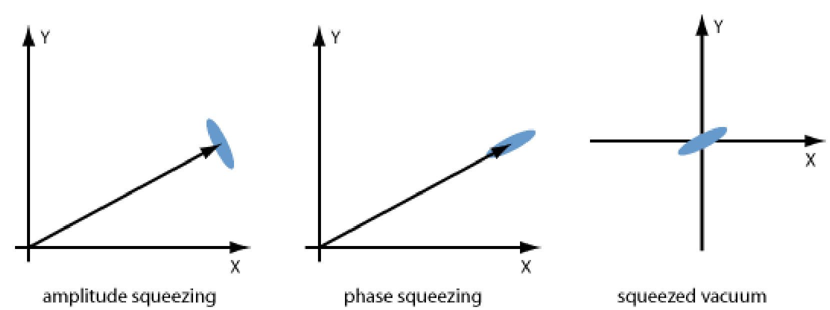
➔ Optimal input power depends on frequency

SQUEEZED INPUT VACUUM STATE IN MICHELSON INTERFEROMETER



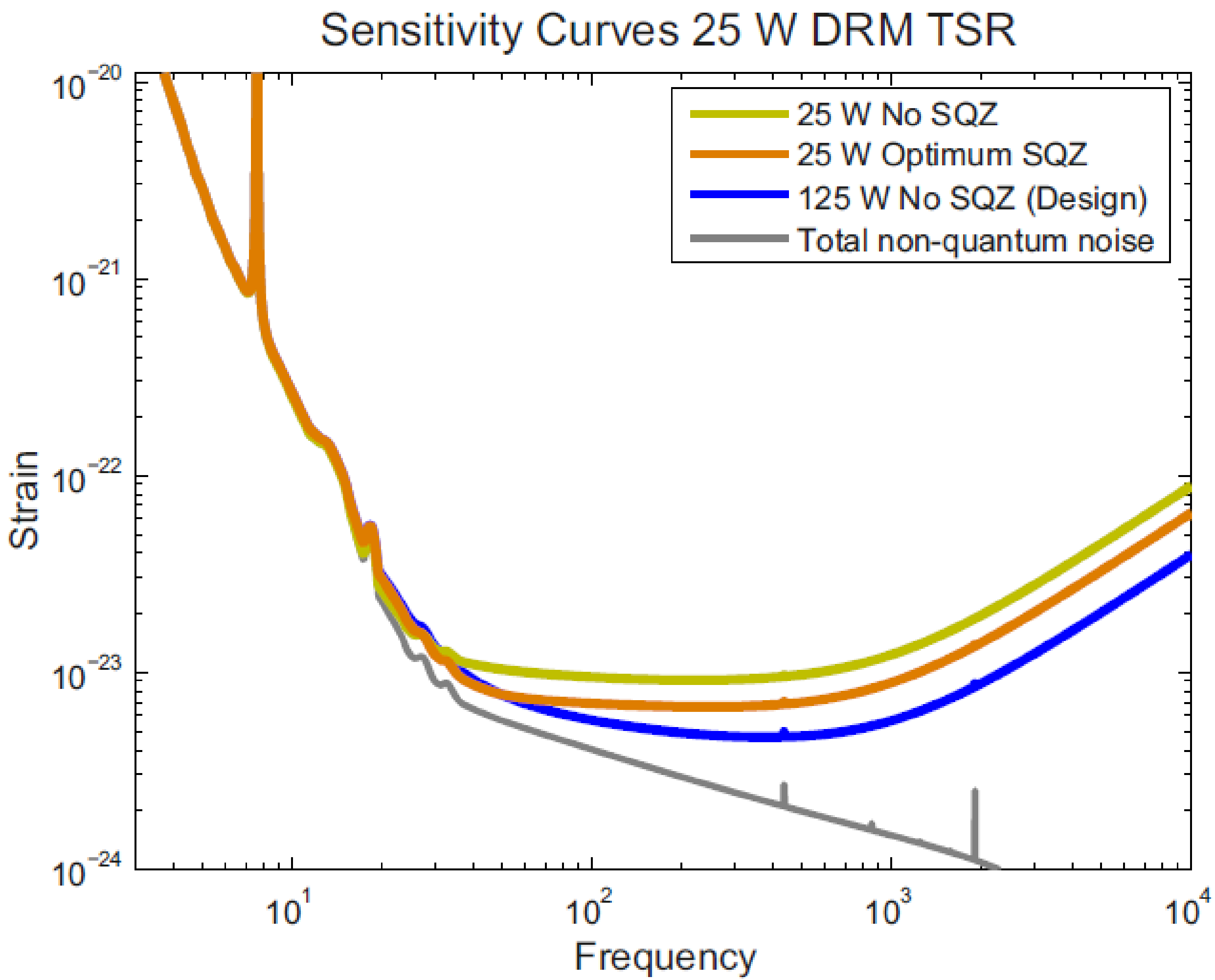
- GW signal in the phase quadrature
- Orient squeezed state to reduce noise in phase quadrature

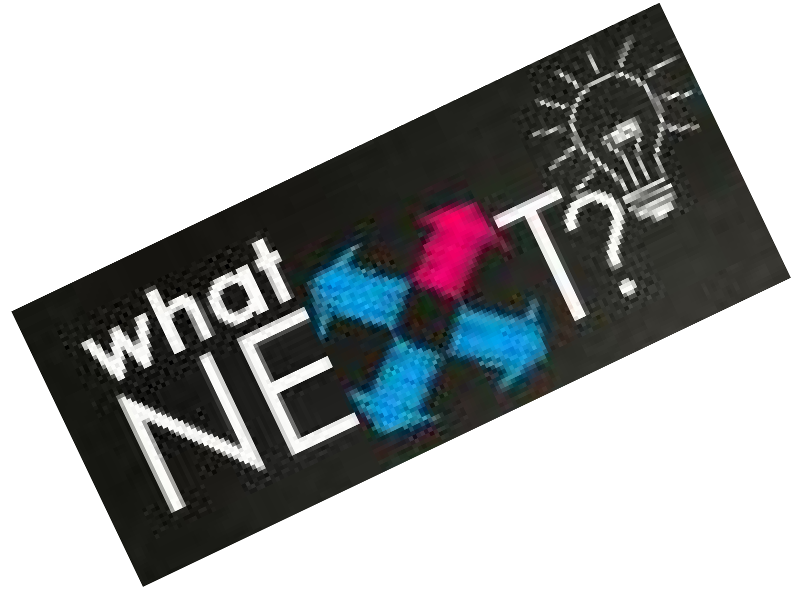




CREDIT: N. Mavalvala & GEO600

FREQUENCY INDEPENDENT SQUEEZING





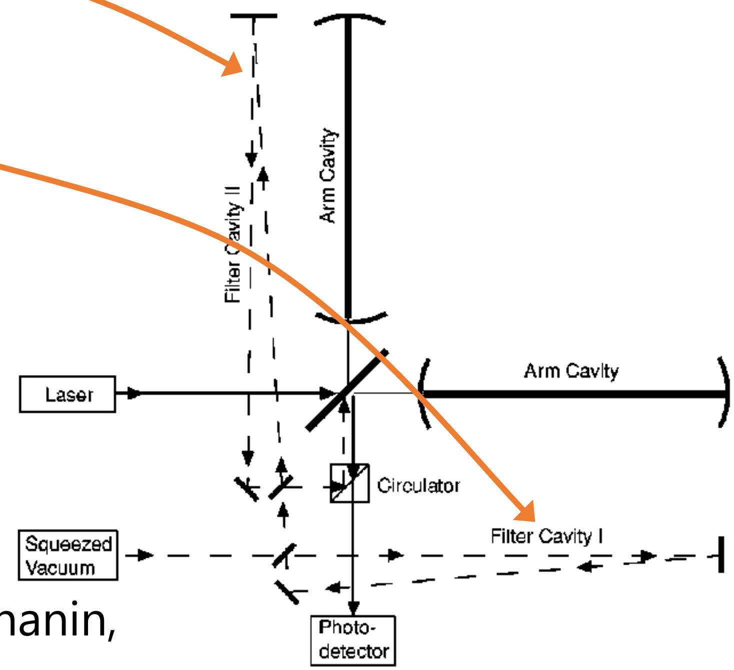
PHASE 2 (~10 YEARS FROM NOW)

the best we can do in the current infrastructure

REALIZING A FREQUENCY-DEPENDENT SQUEEZE ANGLE

- Filter cavities
- Difficulties
  - Low losses
  - Highly detuned
  - Multiple cavities

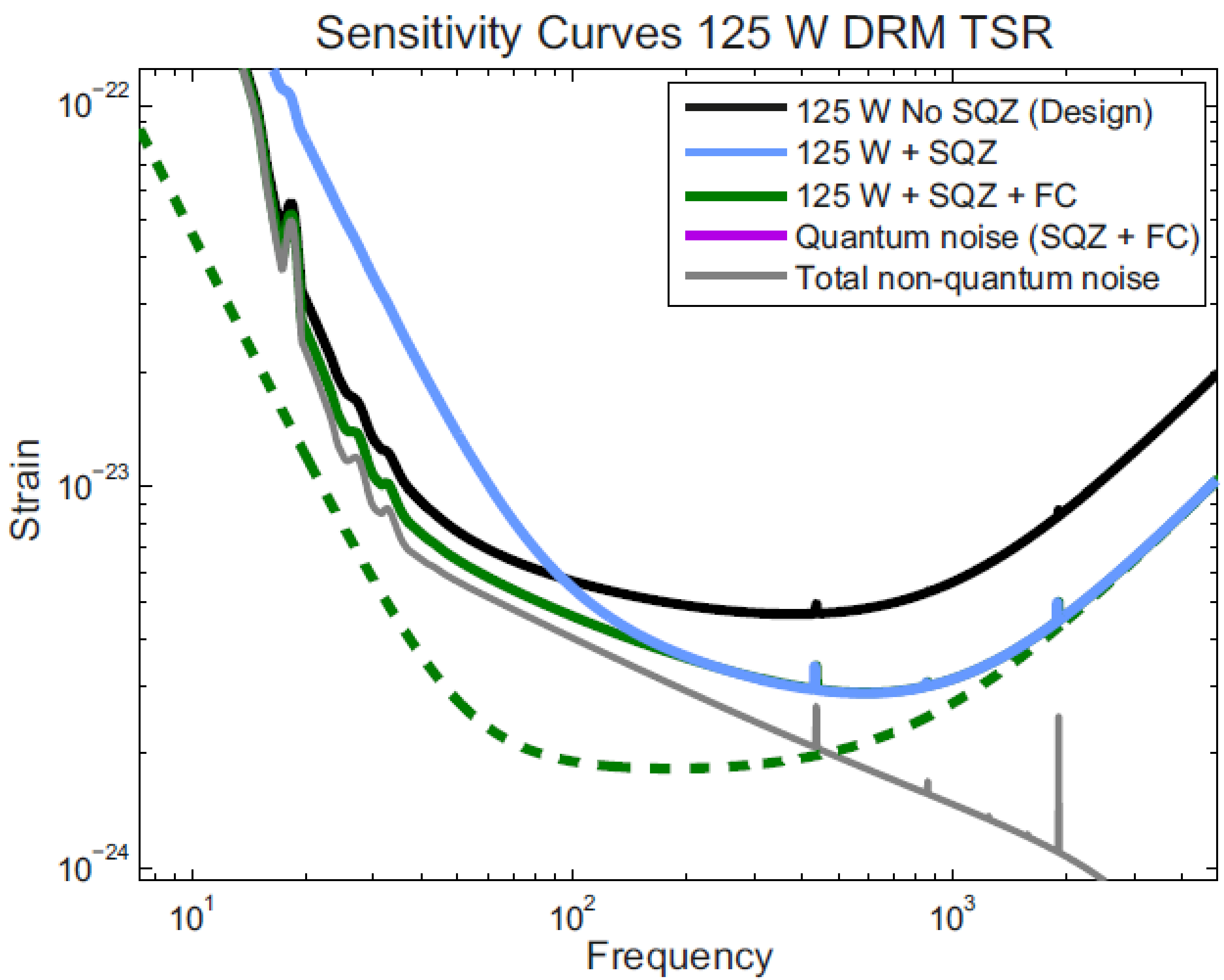
filter cavities



- Conventional interferometers →
  - Kimble, Levin, Matsko, Thorne, and Vyatchanin, Phys. Rev. D **65**, 022002 (2001).
- Signal tuned interferometers →
  - Harms, Chen, Chelkowski, Franzen, Vahlbruch, Danzmann, and Schnabel, gr-qc/0303066 (2003).

CREDIT: N. Mavalvala

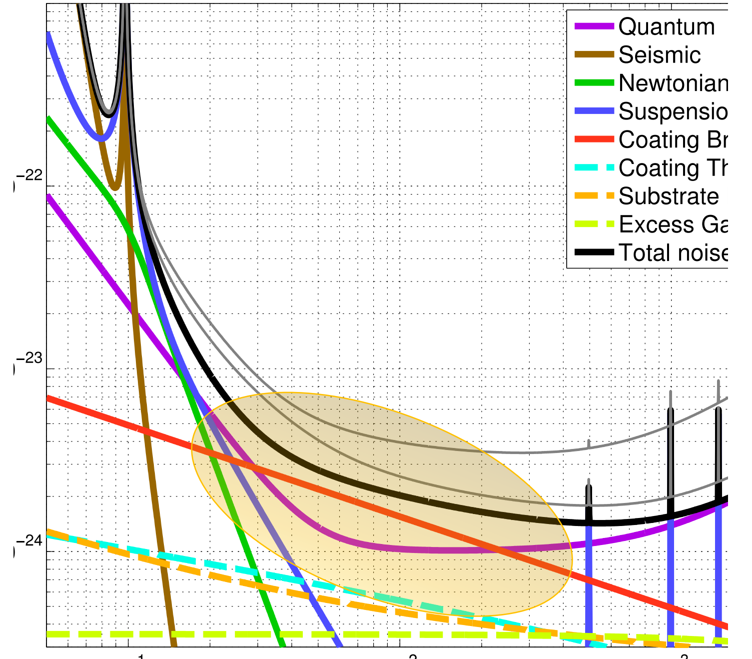
FREQUENCY DEPENDENT SQUEEZING

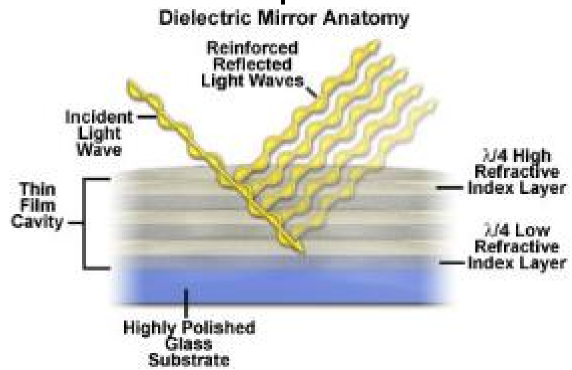


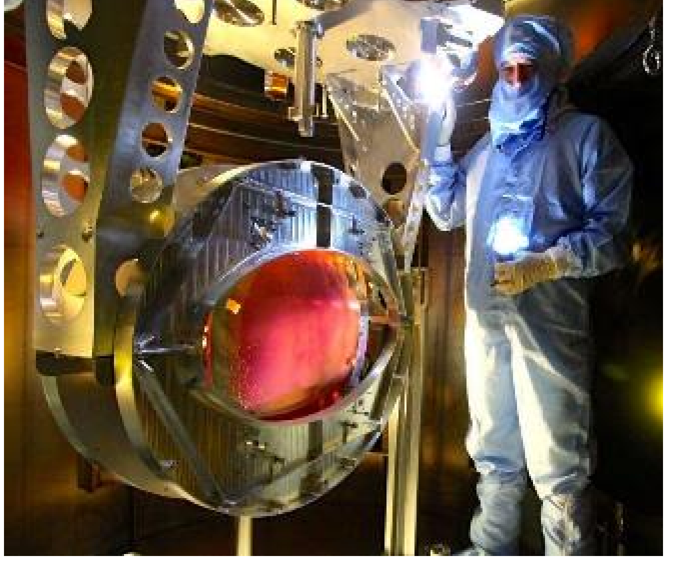
CREDIT: S. Chua

COATINGS ARE LIMITING

- “Improved” coatings are NOT something we know how to make
- The frequency dependent squeezing IS something we know how to make
- We only see BIG benefits when we combine squeezing with better coatings (in current facilities)
- Coatings will be problem unless we make very optimistic assumptions, and go cryogenic…



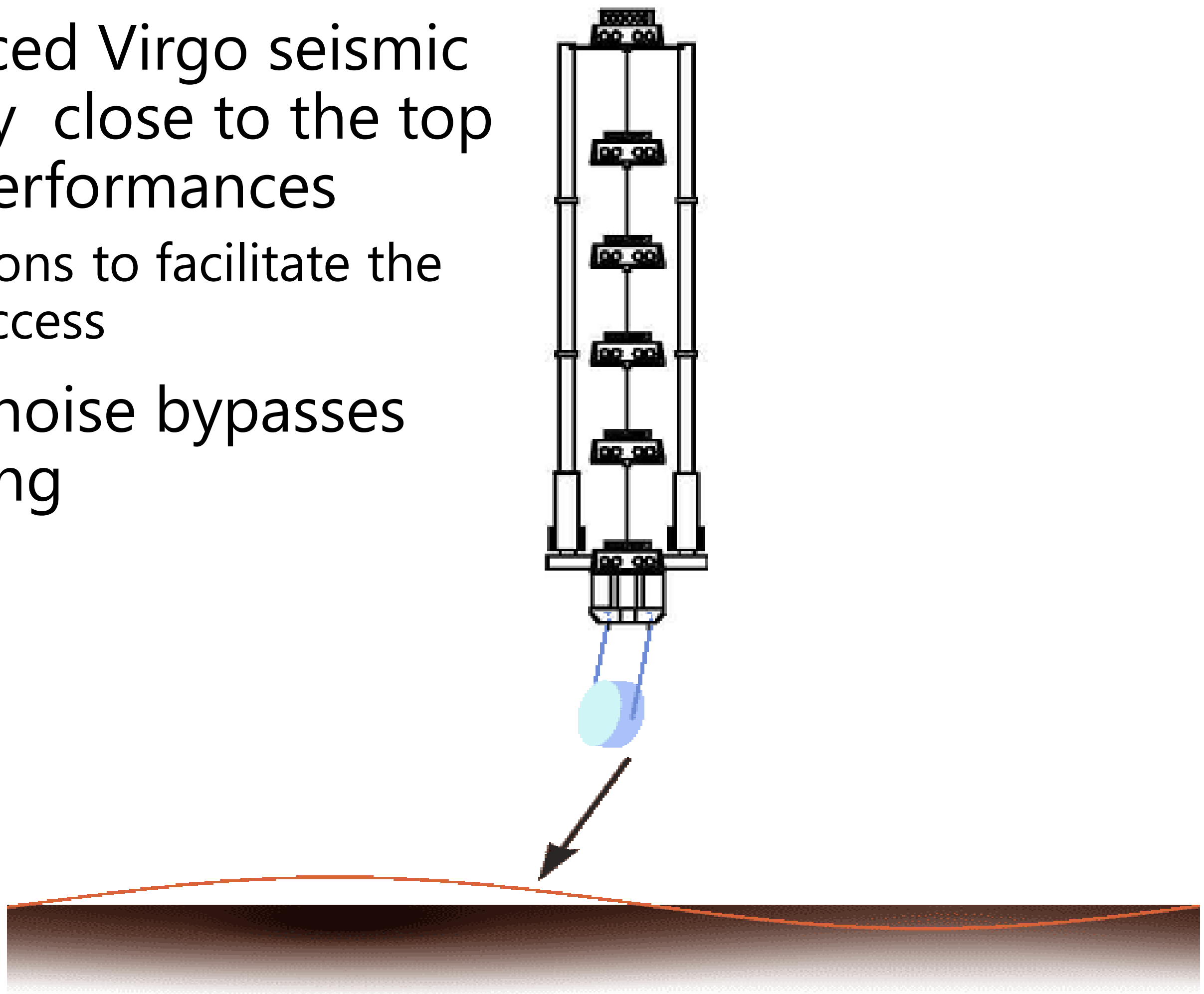




 CREDIT: M. Evans

SEISMIC AND NEWTONIAN NOISES

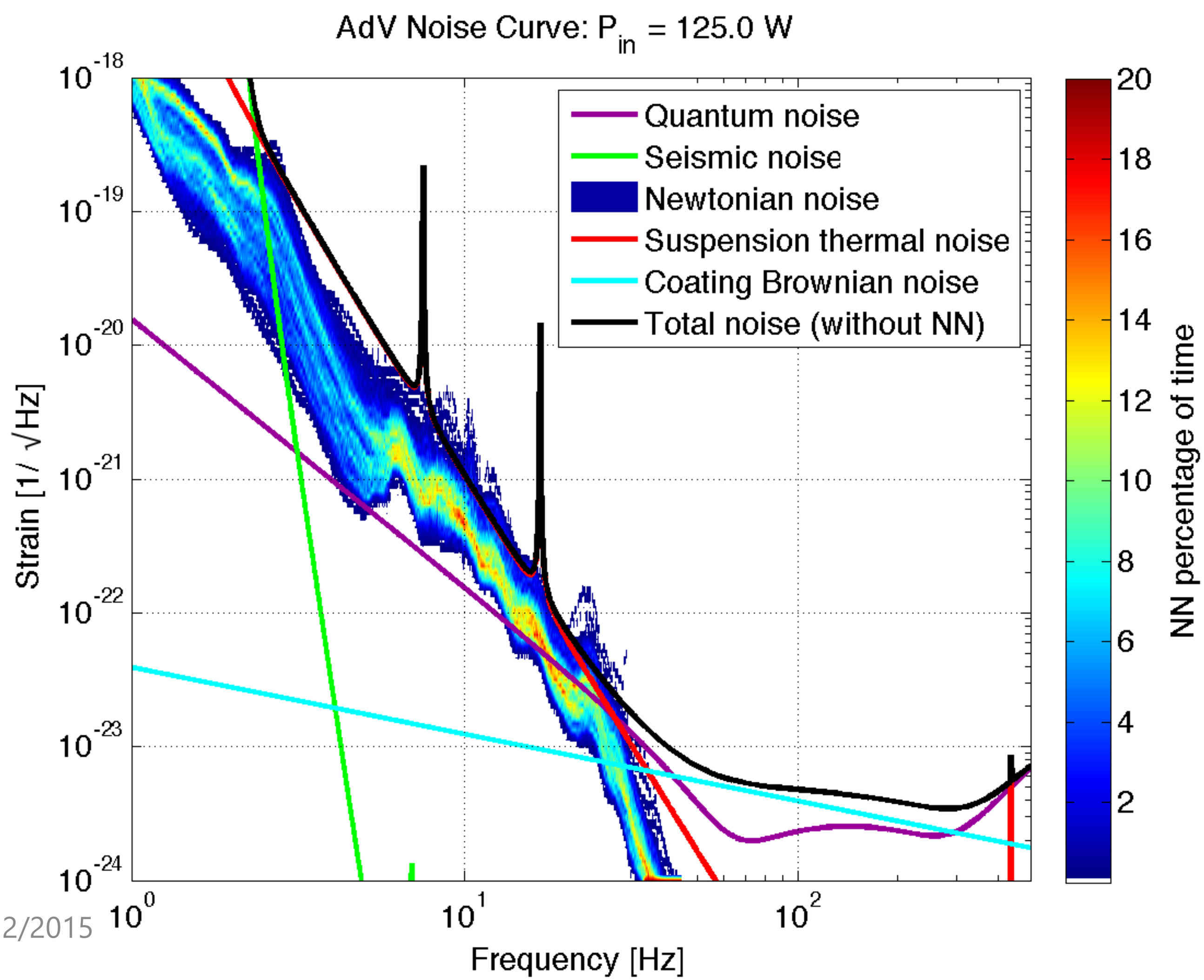
- Virgo and advanced Virgo seismic filtering is already close to the top of the possible performances
  - Longer suspensions to facilitate the low frequency access
- Gravity gradient noise bypasses the seismic filtering



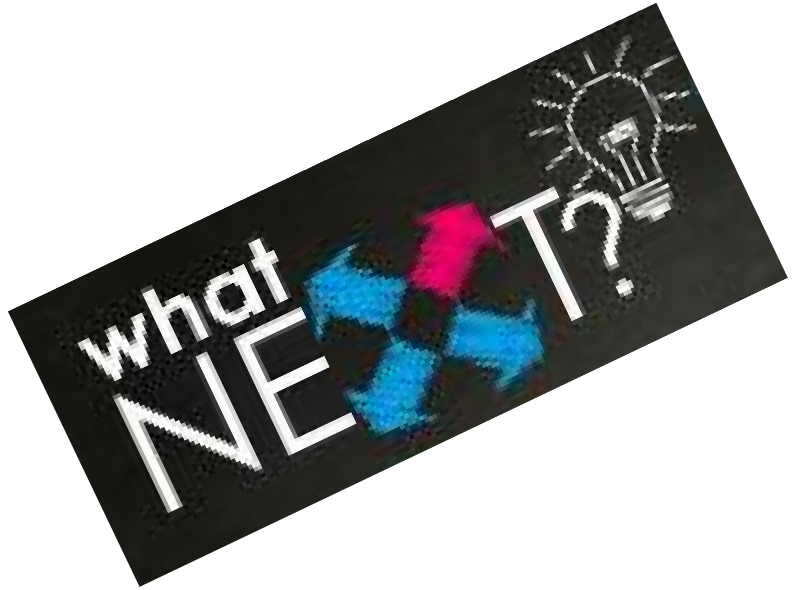
Credit M.Lorenzini

GRAVITY GRADIENT NOISE IN ADV

- The GGN noise could limit the AdV sensitivity during high seismic activity days:



M. Punturo (VIR-0073B-12)
M.Beker (GWADW 2012

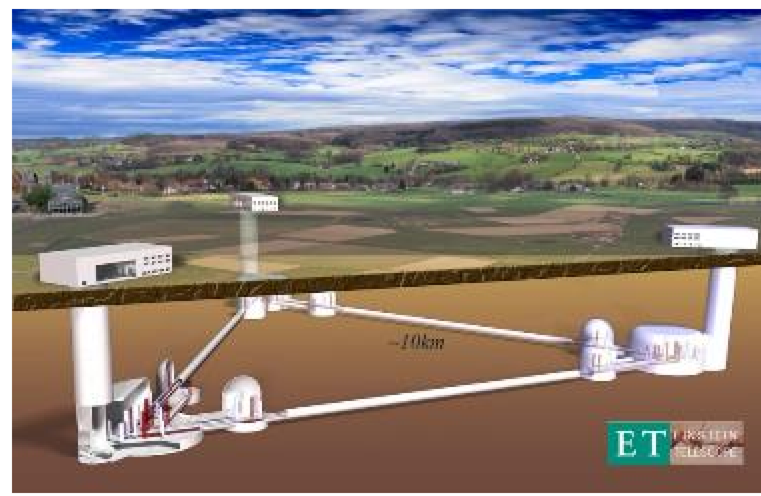


PHASE 3 (>2025)

ET: a new infrastructure

THE EINSTEIN TELESCOPE PROJECT

- Design study of ET funded by the European Commission under FP7
  - interest primarily focused on the Infrastructure rather than on the detector and its technologies
  - The infrastructure should no limit the sensitivity of the future hosted detectors
    - Size
    - Environmental noises (mainly, seismic and GGN)
  - ET absorbed and developed many concepts in GW detectors:
    - Underground and cryo-compatible facility, pioneered in Japan by CLIO and KAGRA
    - Triangular geometry, concept used in LISA
    - Xylophone configuration



Data collected from these sites

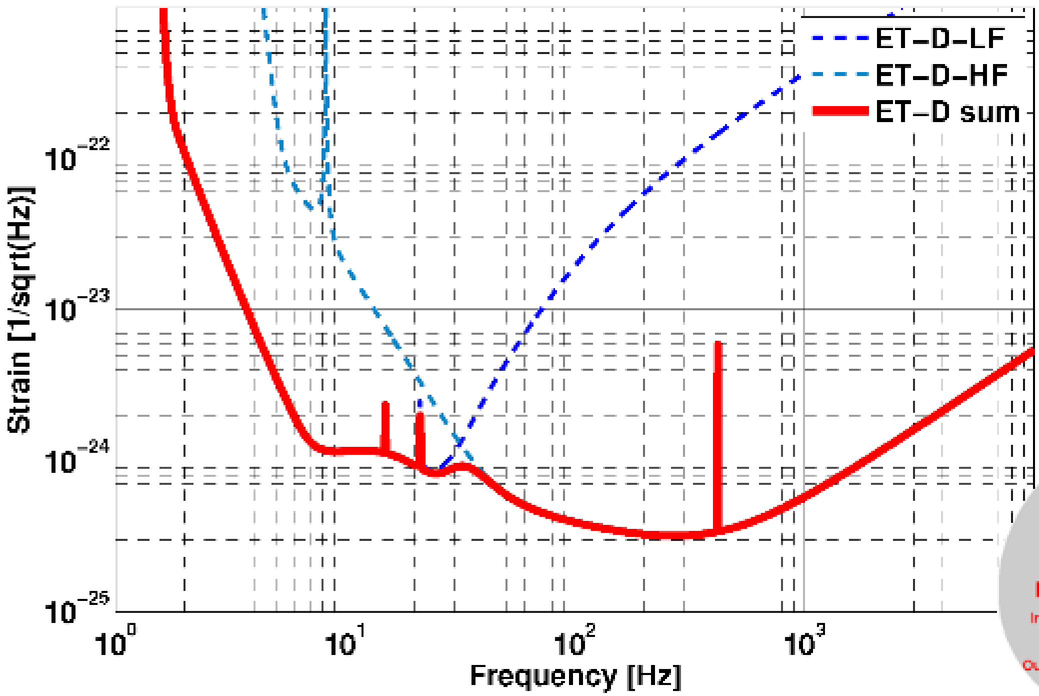
3rd party data obtained and analyzed from these sites

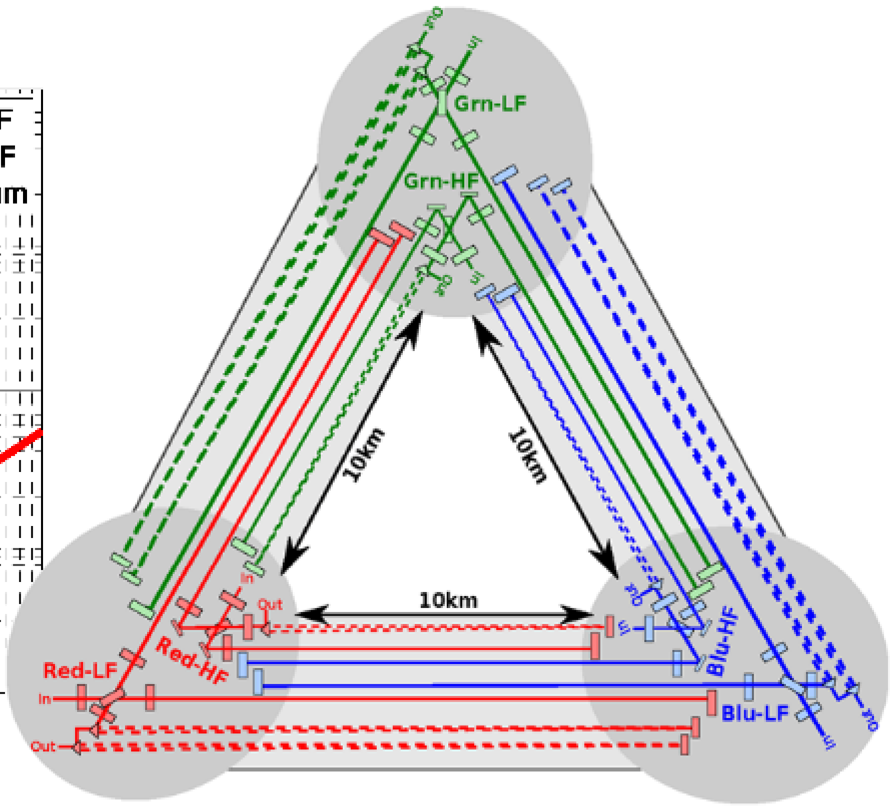
UNDERGROUND VS ON THE SURFACE

- A milestone of the ET design study has been setting an underground infrastructure
- KAGRA is underground
- Some idea for the US 3G detector describes a detector on the surface
- Underground advantages:
  - Seismic noise reduction
  - Seismic and Atmospheric Newtonian noise reduction
  - Environmental noise reduction
  - But do we really master these concepts?
    - J. Harms, *Living Rev. Relativity*, **18**, (2015), 3

XYLOPHONE DESIGN

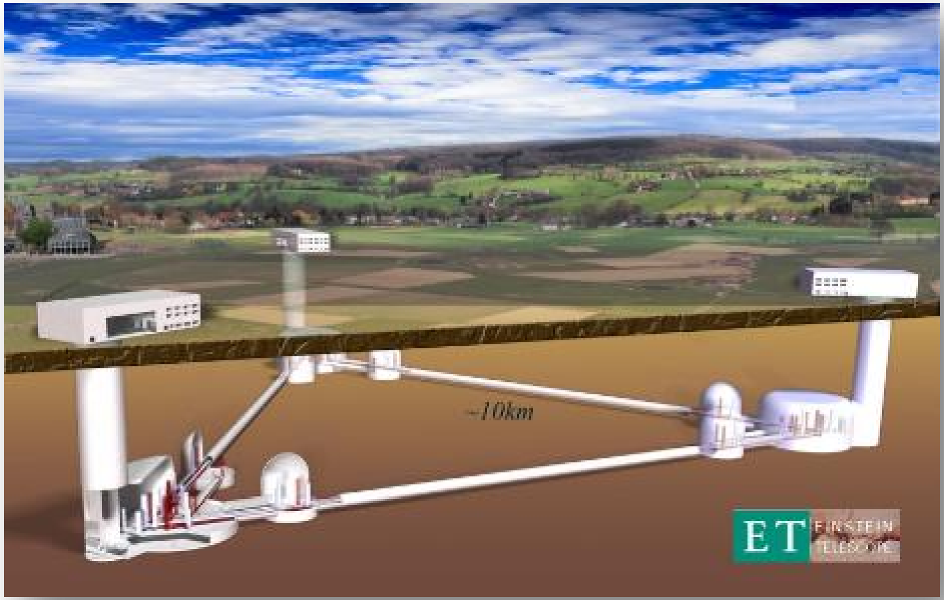
- The issues raised by the cross-compatibility between all these technologies:
  - ET implements a Xylophone approach, where the overall sensitivity is given by the combination of the performances of two “frequency specialised” interferometers





ET TECHNOLOGIES

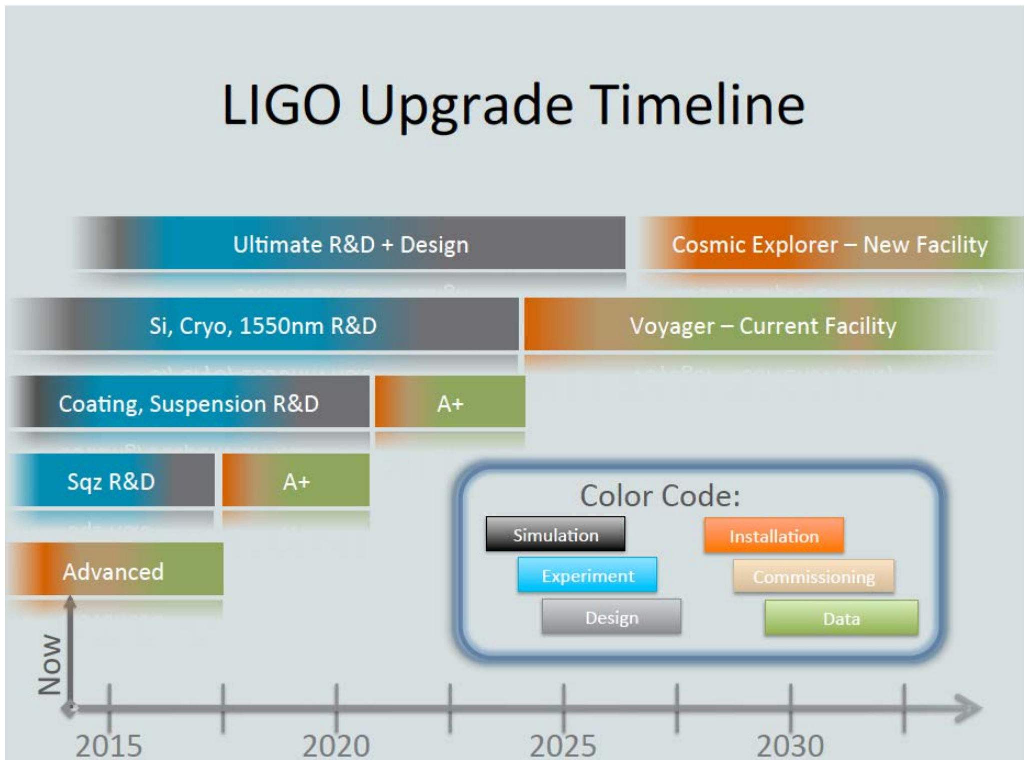
- The ET design study focused on the “research infrastructure”, designing an observatory able to host the evolution of the GW detectors in the next decades
- Enabling technologies:
  - Very Low Frequency <~10Hz
    - Passive vs active seismic attenuation
    - Newtonian noise subtraction
  - Low and medium frequency
    - Cryogenics
      - Cooling technologies
      - Optical materials: (ultra pure) Silicon
      - Laser wavelenght (1550 nm or >2μm?)
      - Coatings materials
  - Medium and high frequency
    - High power lasers
    - Frequency dependent squeezing
    - New topologies (speedmeter?)



3G: NOT ONLY AN EU IDEA

LIGO

A possible path in the US



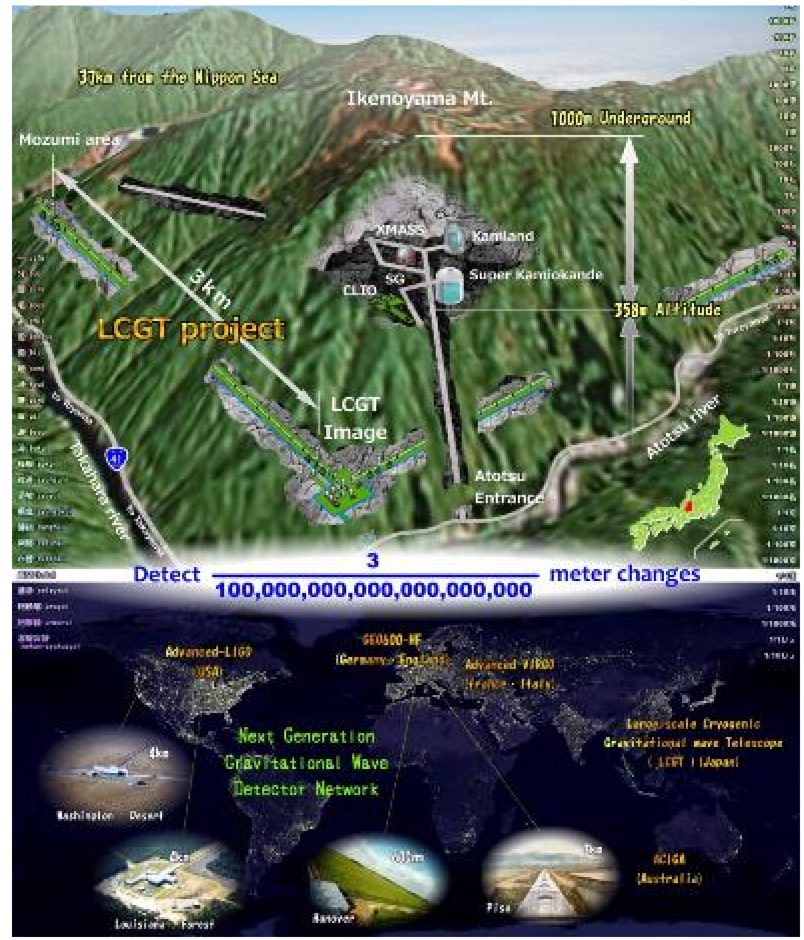
LIGO-G15000xxx-v1

LIGO Laboratory

6

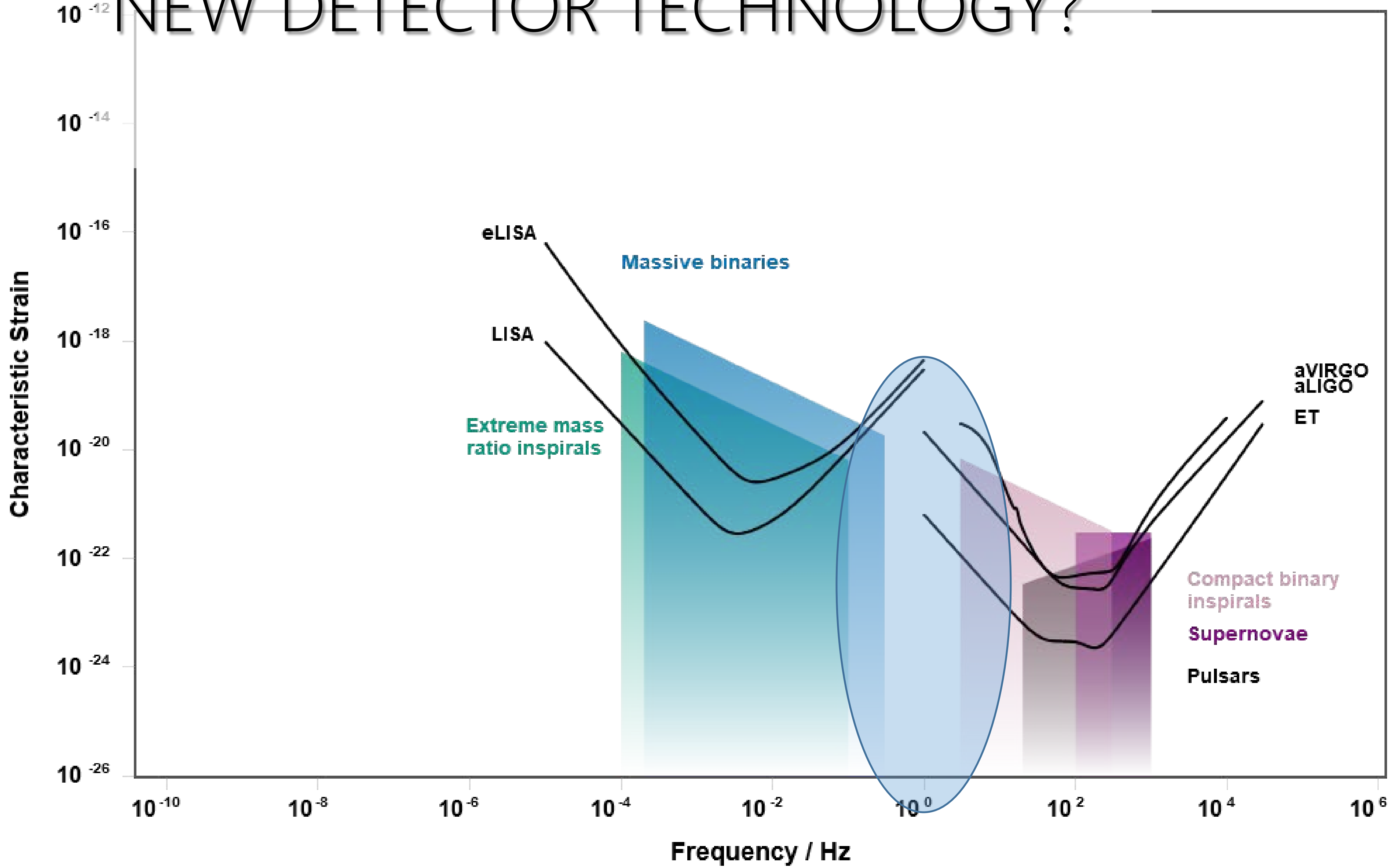
SYNERGIES WITH KAGRA

- The Japanese detector, under construction, KAGRA is pioneering the development of an underground infrastructure and of the cryogenic interferometer for GW detection
- For ET is mandatory to have a synergy with KAGRA
- A 4 years European-Japanese joint project “ELiTES” supported by European Commission under FP7-IRSES is started in 2013
    - Exchange of scientists focused mainly on cryogenic issues common to ET and KAGRA



	Virgo	AdV	aLIGO	ET
1985	R&D			
1990	White Paper, CDR (1989)			
	R&D Approval (1994)		R&D	
1995	Final Design, TDR (1995) Beginning Infrastructure (1996)			
2000		R&D	CDR (1999)	
	Completion installation Detector (2003)	First AdV sensitivity projection (2004)	R&D	
2005		AdV White Paper, CDR (2005)		First Idea (2005)
	Scientific data taking (2007)	Approval (2009)	Funding (2006) Building (2008)	R&D
2010	Decommissioning (2011)	First orders (2010) TDR (2012)		CDR (2011)
			Installing completion (2014)	R&D
2015		Completion Installation (2015) First data taking (2016)	Data taking (2015)	
2020				TDR ?
2025				Construction ?

NEW DETECTOR TECHNOLOGY?

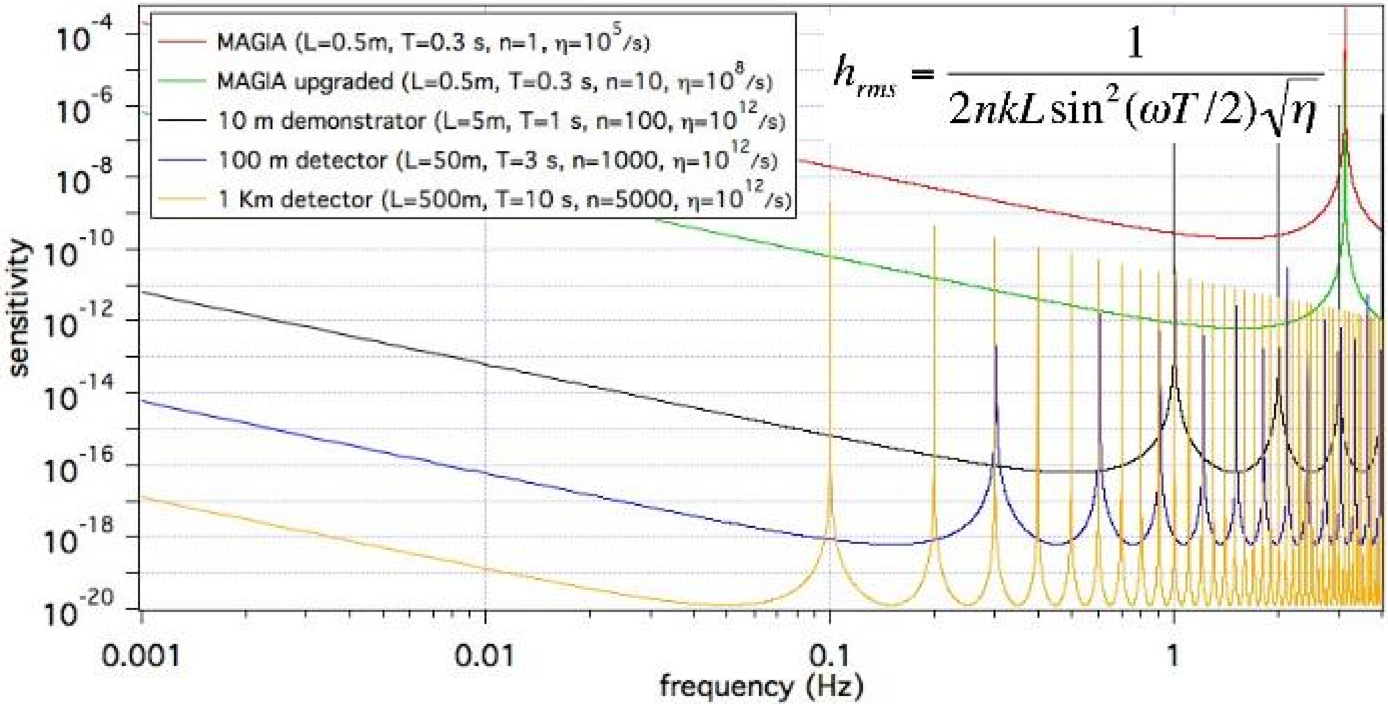


 http://rhcole.com/apps/GWplotter/

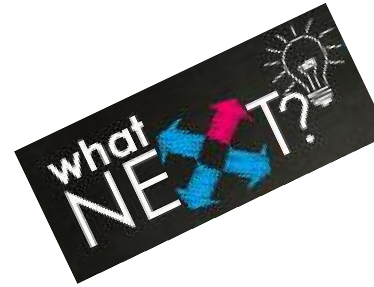
AI & GW

- Possible advantage of atom interferometers:
  - no thermal noise
  - excellent rejection of seismic noise
  - tuning of sensitivity function
  - potentially sensitive below 1 Hz
- Complementary to terrestrial optical detectors (Virgo, LIGO)
  - E.g. characterization/compensation of Newtonian noise in terrestrial detectors
  - Possible hybrid schemes (atoms in optical interferometers, see E3S 4, 01004 [2014])

G. M. Tino and F. Vetrano, Class. Quant. Grav. **24** (2007)
G. M. Tino and F. Vetrano, Gen. Relativ. Gravit. **43**, 2037 (2011)
P. W. Graham et al., Phys. Rev. Lett. **110**, 171102 (2013)
F. Vetrano et al., Int. J. Mod. Phys. **23**, 135 (2013)
F. Vetrano and A. Viceré, Eur. Phys. J. C **73**, 2590 (2013)



CONCLUSIONS



- A strong claim for a full-featured LISA mission (the results of LISA-PF will be a crucial milestone)
- On earth: three-phase scenario
  - Short term (~2017-2019) – well defined technologies. In some cases (squeezing) need to finalize design soon for the integration in the existing infrastructure
  - Medium term (~2025) – R&D effort already started, needs to be finalized. Hopefully first detections will tell us where to concentrate our efforts
  - Long term (>2025) – after first detections. Some infrastructure requirements already established. Needs a focused, coordinated effort (worldwide) to finalize some key concepts:
    - Topology
    - Underground/on surface
    - 3G Network/mixed 3G-2G
    - Working temperature/Materials
    - The role of AI
- Advanced Virgo TDR https://tds.ego-gw.it/ql/?c=8940
  ET Design Study https://tds.ego-gw.it/ql/?c=7954
  ET symposium - Florence, 2-3 Feb 2016
  https://events.ego-gw.it/indico/conferenceDisplay.py?confId=34