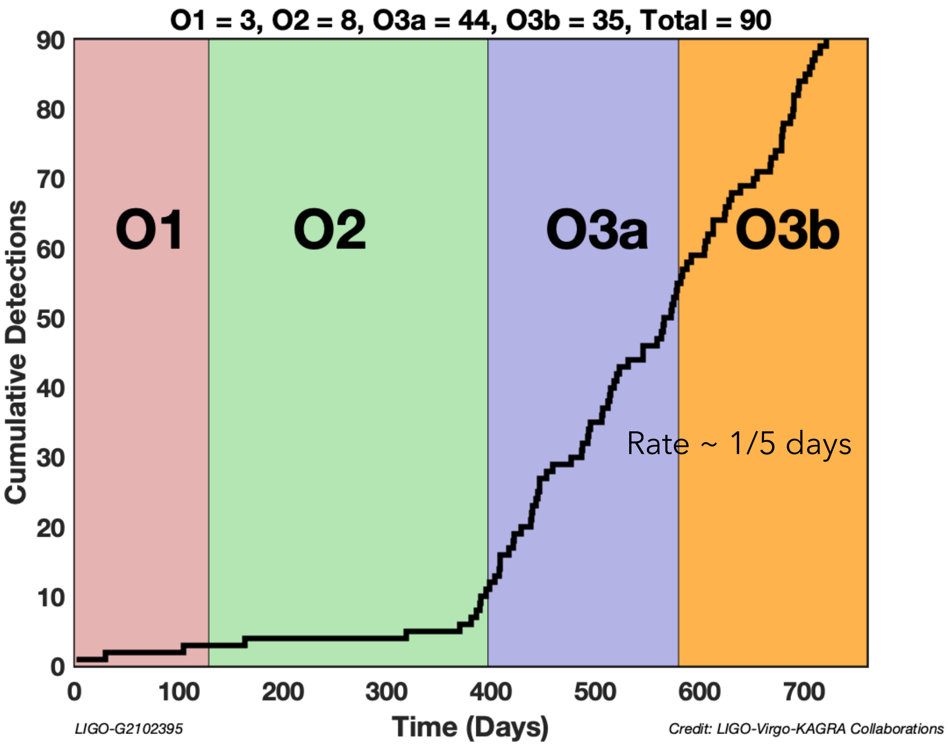
GRAVITATIONAL WAVE DETECTORS
bridging the generation gap

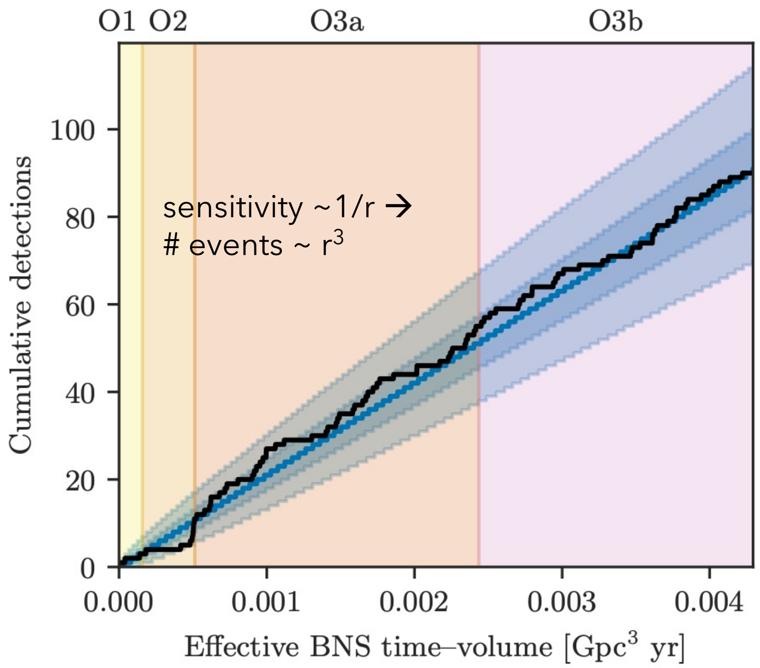
Giovanni Losurdo – INFN Pisa
LIGO/Virgo/KAGRA Coll.

Virgo Spokesperson

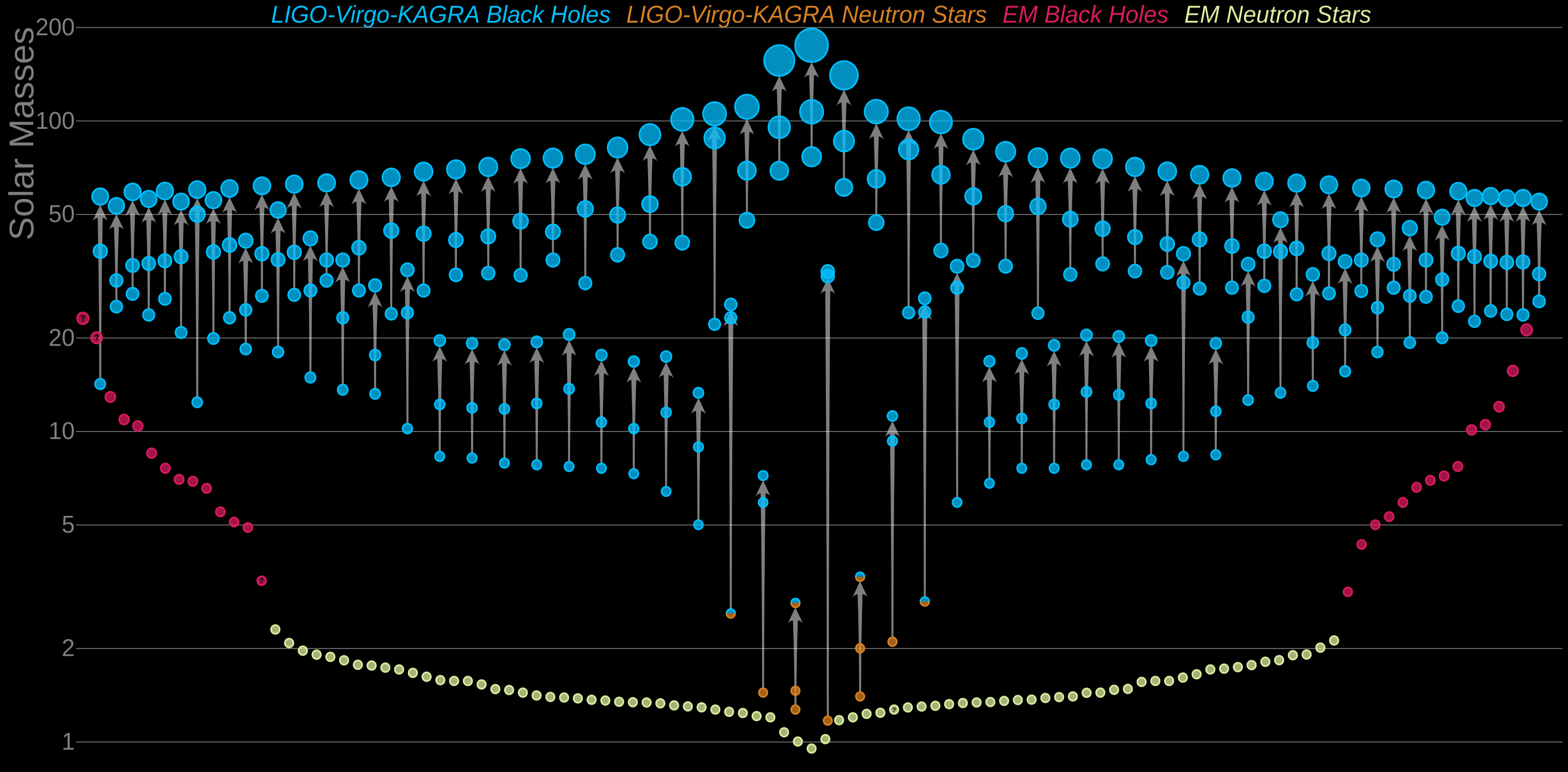
SO FAR



from GWTC-3, arXiv:2111.03606



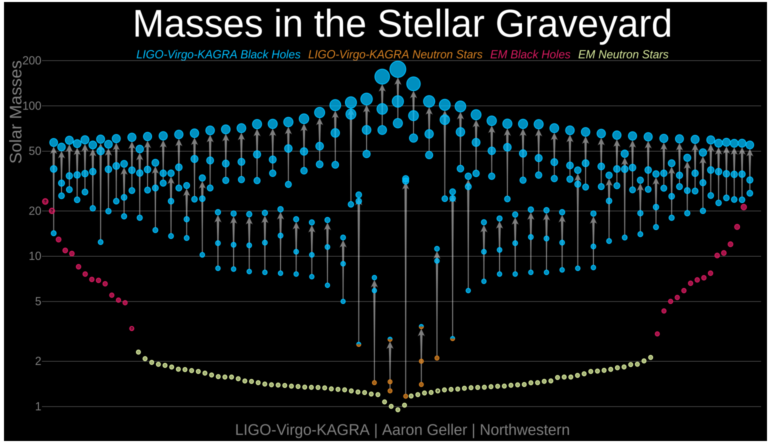
Masses in the Stellar Graveyard



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

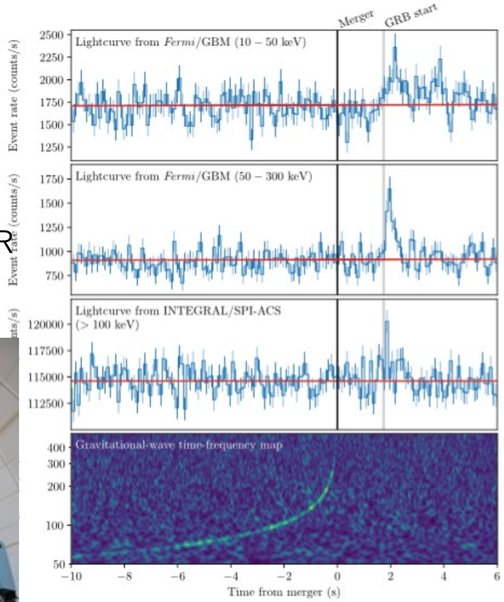
SCIENCE WITH GW (I)

ApJL, 848:L13

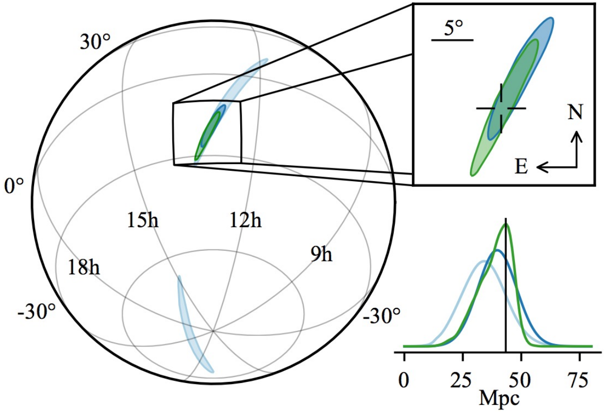


NEW OBJECTS/
NEW POPULATIONS

MULTIMESSENGER
OBSERVATIONS

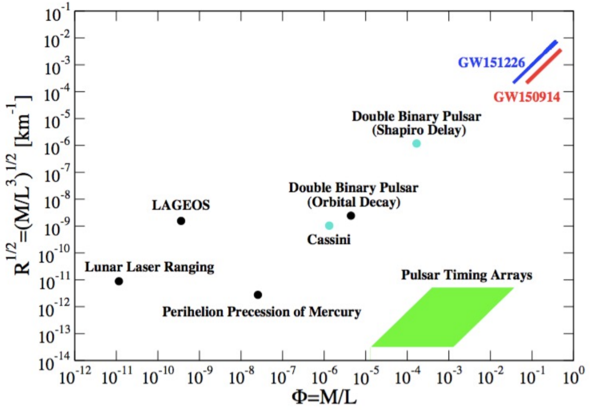


ALERTS FOR
E.M. OBS



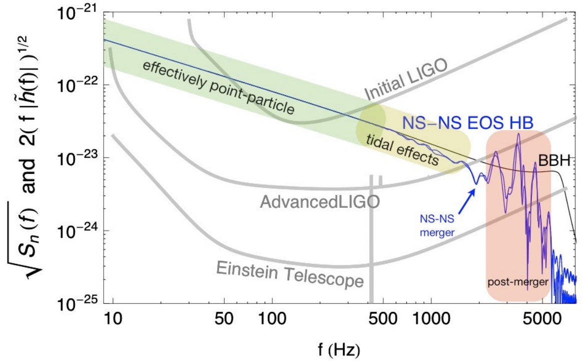
ApJL, 848:L12

SCIENCE WITH GW (II)



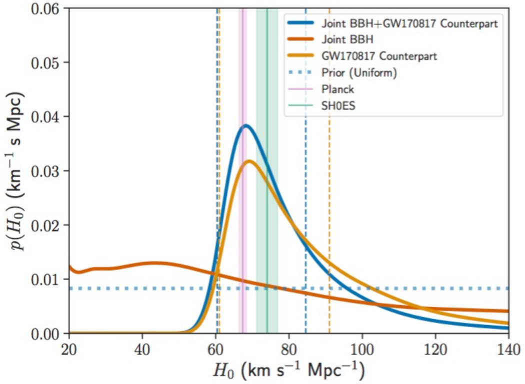
TESTS OF GRAVITY IN EXTREME CONDITIONS

EXTREME STATES OF MATTER

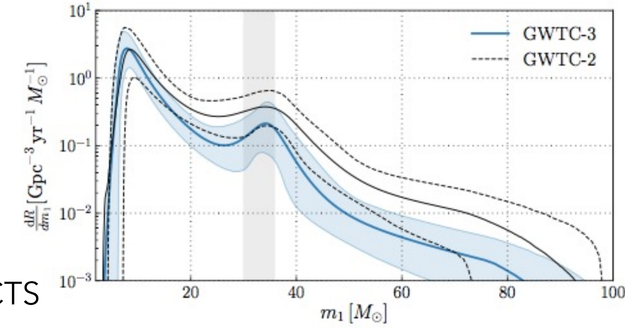


COSMOLOGY

arXiv:2111.03604



POPULATION OF COMPACT OBJECTS



arXiv:2111.03606

FROM ONE TO MANY: POPULATIONS

- Entering in the «statistical information driven» regime
  - NSBH binaries
  - Lower mass gap
  - NS mass distribution
  - Substructure in BBH mass distribution
  - BBH rate evolution with redshift
- Providing data for many studies

https://arxiv.org/abs/2111.03634

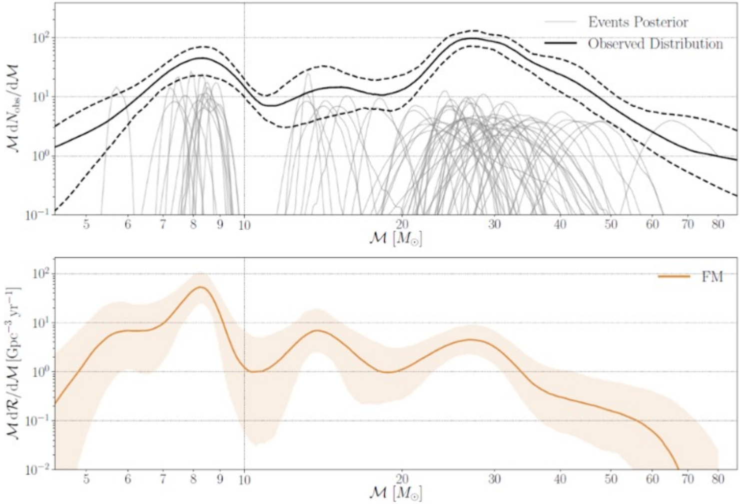
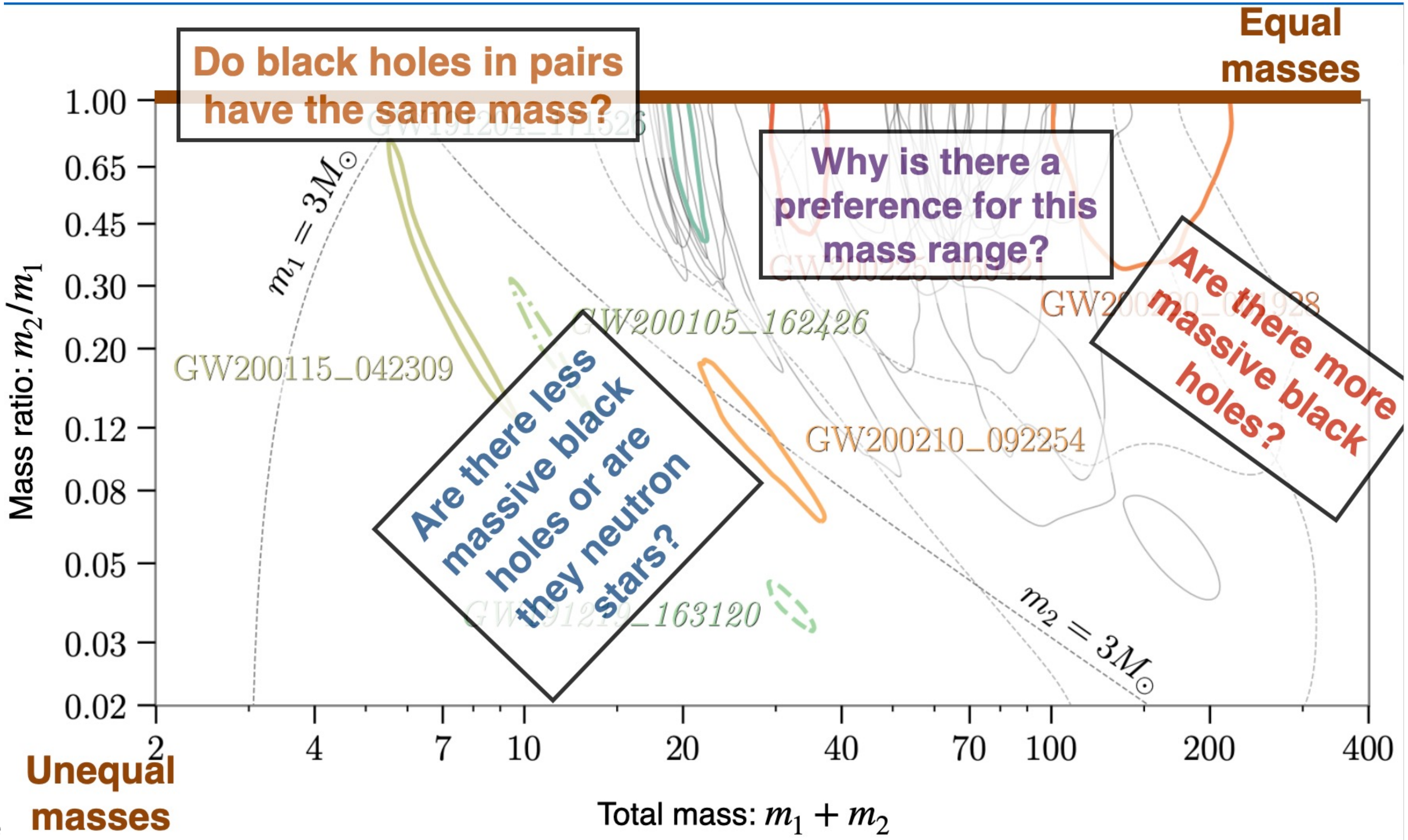


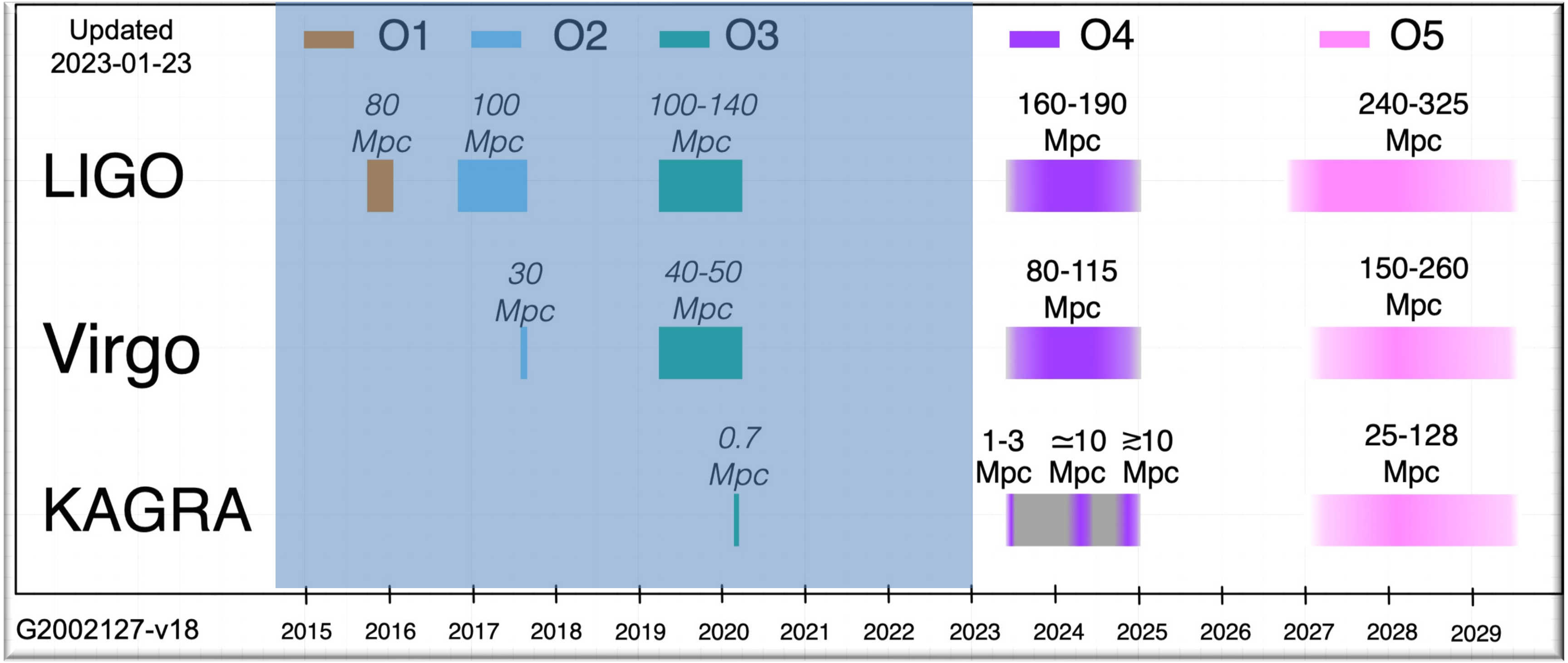
Figure credit: K Chatziannou

BH masses

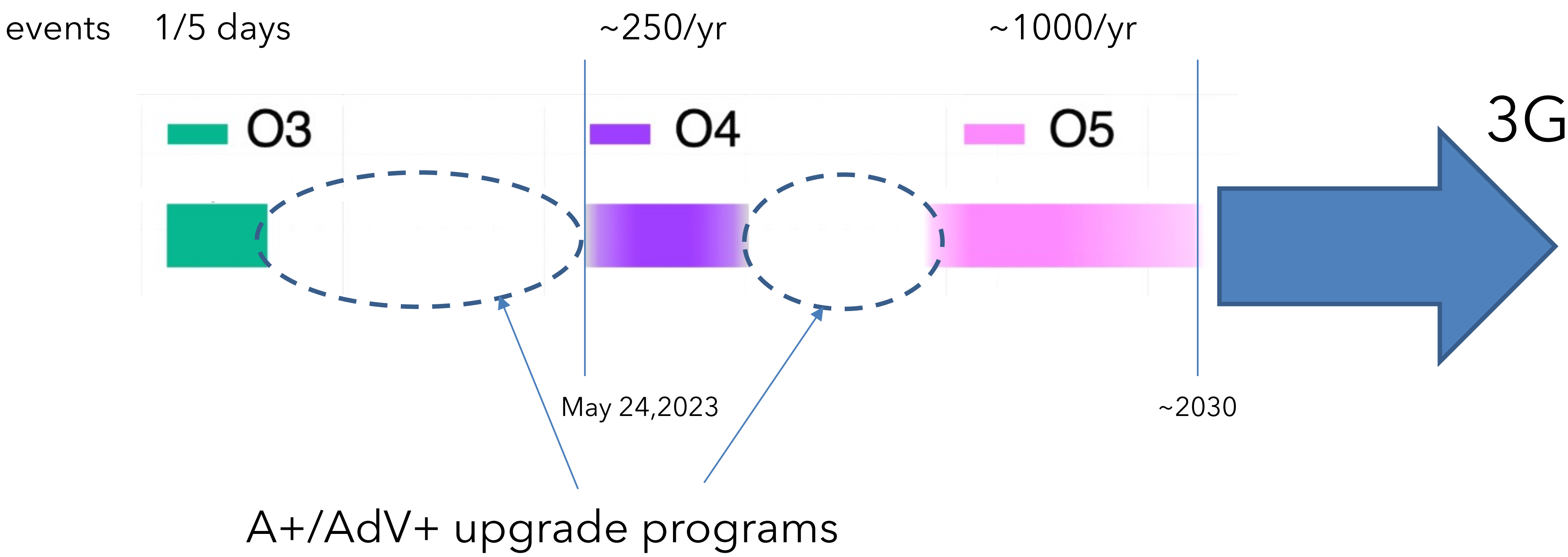
arXiv:2111.03604

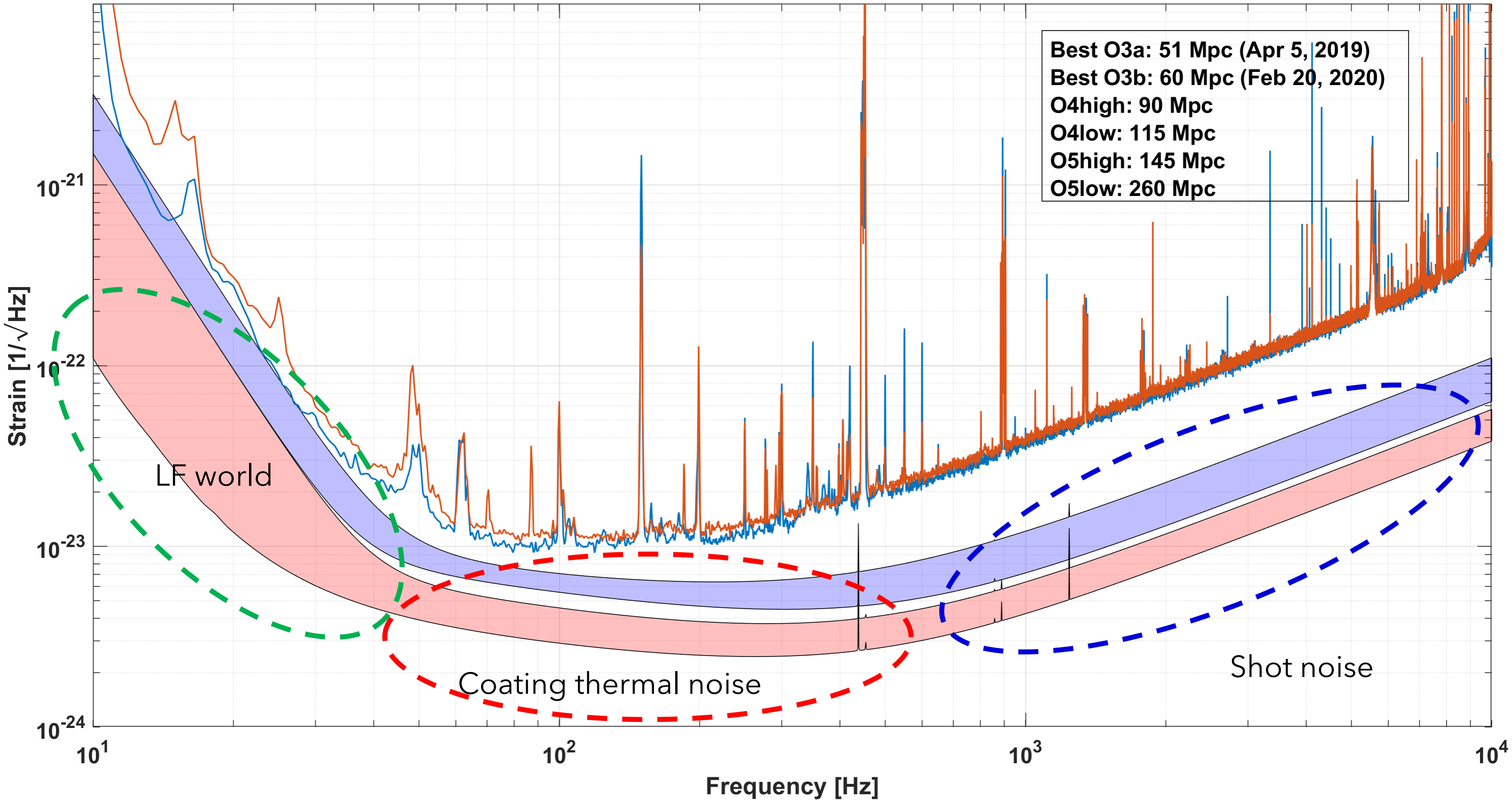


MID-TERM

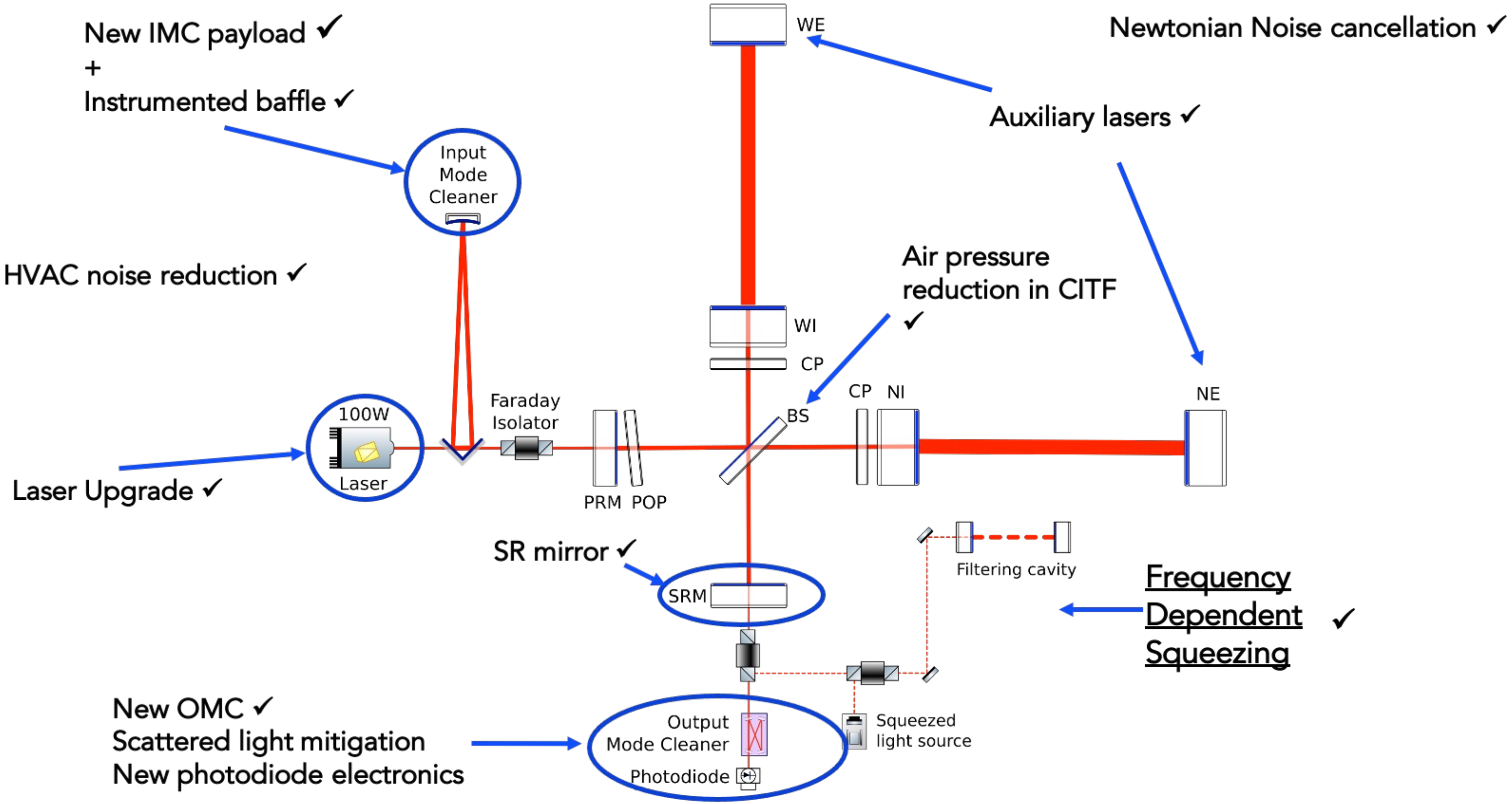

Updated
2023-01-23
O1
O2
O3
O4
O5
LIGO
80 Mpc
100 Mpc
100-140 Mpc
160-190 Mpc
240-325 Mpc
Virgo
30 Mpc
40-50 Mpc
80-115 Mpc
150-260 Mpc
KAGRA
0.7 Mpc
1-3 Mpc
≃10 Mpc
≳10 Mpc
25-128 Mpc
G2002127-v18
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029

MAIN FIGURES



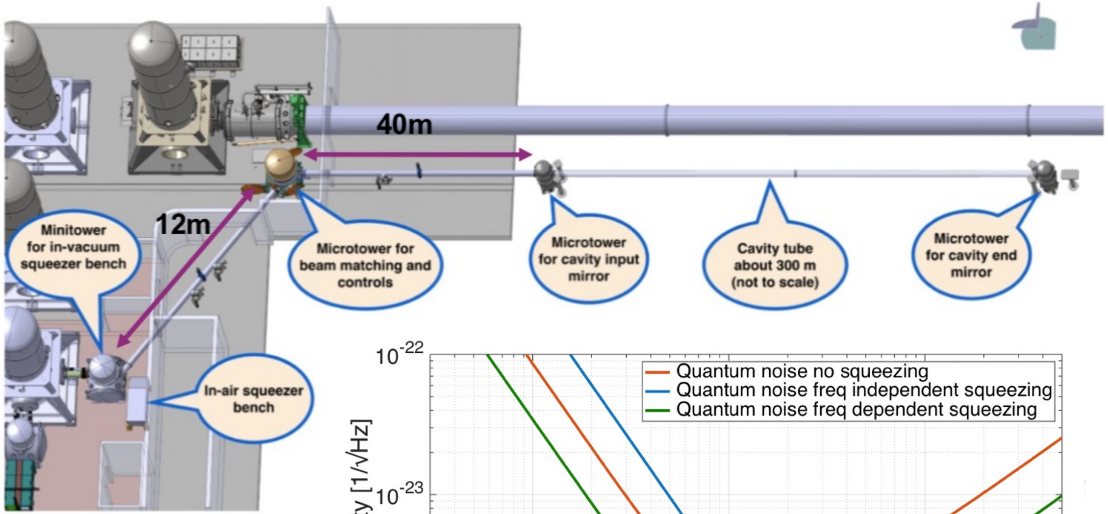

Best O3a: 51 Mpc (Apr 5, 2019)
Best O3b: 60 Mpc (Feb 20, 2020)
O4high: 90 Mpc
O4low: 115 Mpc
O5high: 145 Mpc
O5low: 260 Mpc
Strain [1/√Hz]
Frequency [Hz]
LF world
Coating thermal noise
Shot noise

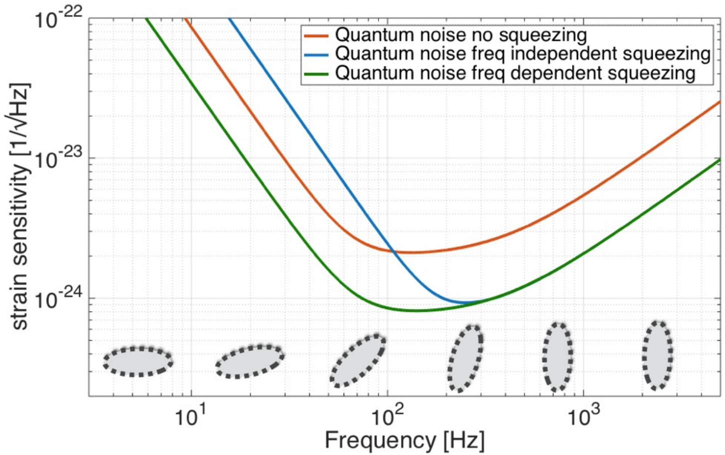
AdV+/Phase 1



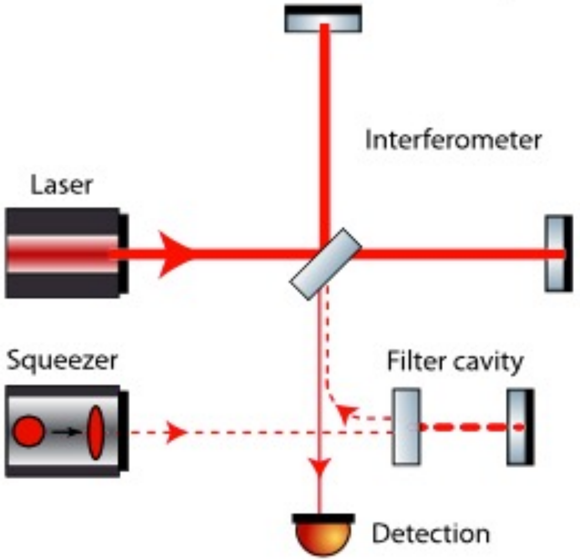
New IMC payload ✓
+
Instrumented baffle ✓
Input
Mode
Cleaner
HVAC noise reduction ✓
100W
Laser
Laser Upgrade ✓
Faraday
Isolator
PRM
POP
WE
WI
CP
BS
CP
NI
NE
Newtonian Noise cancellation ✓
Auxiliary lasers ✓
Air pressure
reduction in CITF
✓
SR mirror ✓
SRM
Filtering cavity
Frequency
Dependent
Squeezing
✓
New OMC ✓
Scattered light mitigation
New photodiode electronics
Output
Mode Cleaner
Photodiode
Squeezed
light source

KEY TECHNOLOGIES FOR ADV+



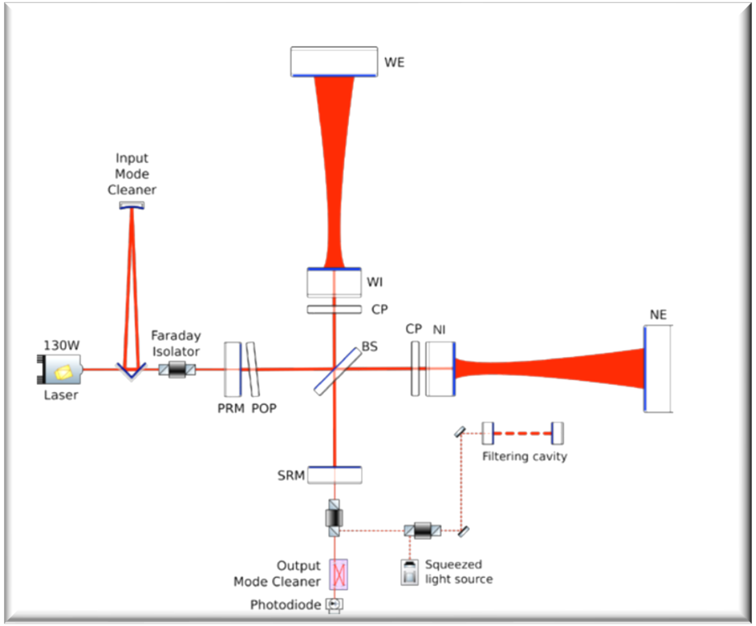


FREQUENCY DEPENDENT SQUEEZING FOR WIDEBAND QUUANTUM NOISE REDUCTION



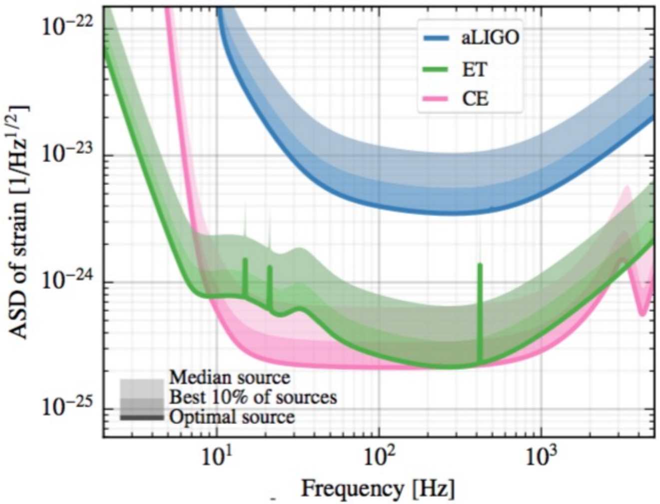
KEY TECHNOLOGIES FOR ADV+

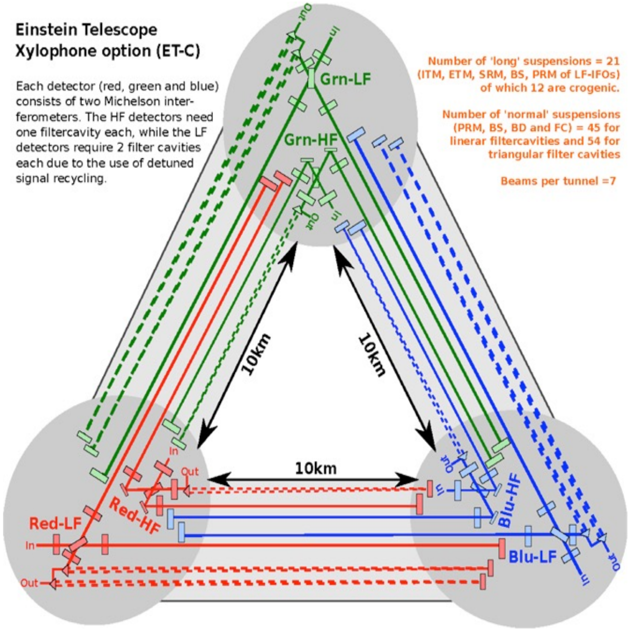
100 KG MIRRORS, IMPROVED COATINGS

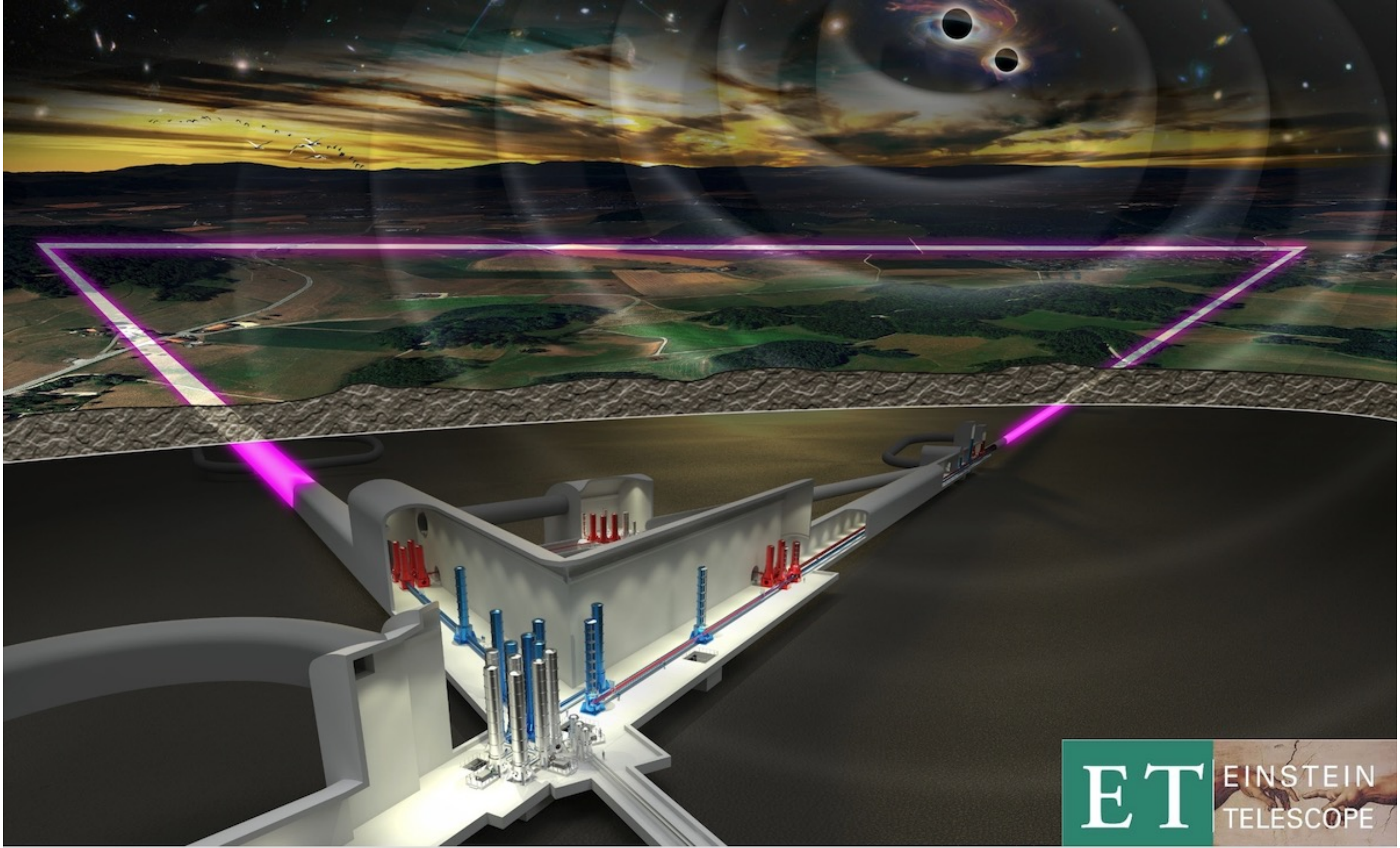


Einstein Telescope

- Underground infrastructure, 10km long
- 3 nested couples of interferometers
  - ET-HF: room temperature, high power, enhancing HF sensitivity
  - ET-LF: cryo, low power, enhancing LF sensitivity






ET
EINSTEIN
TELESCOPE

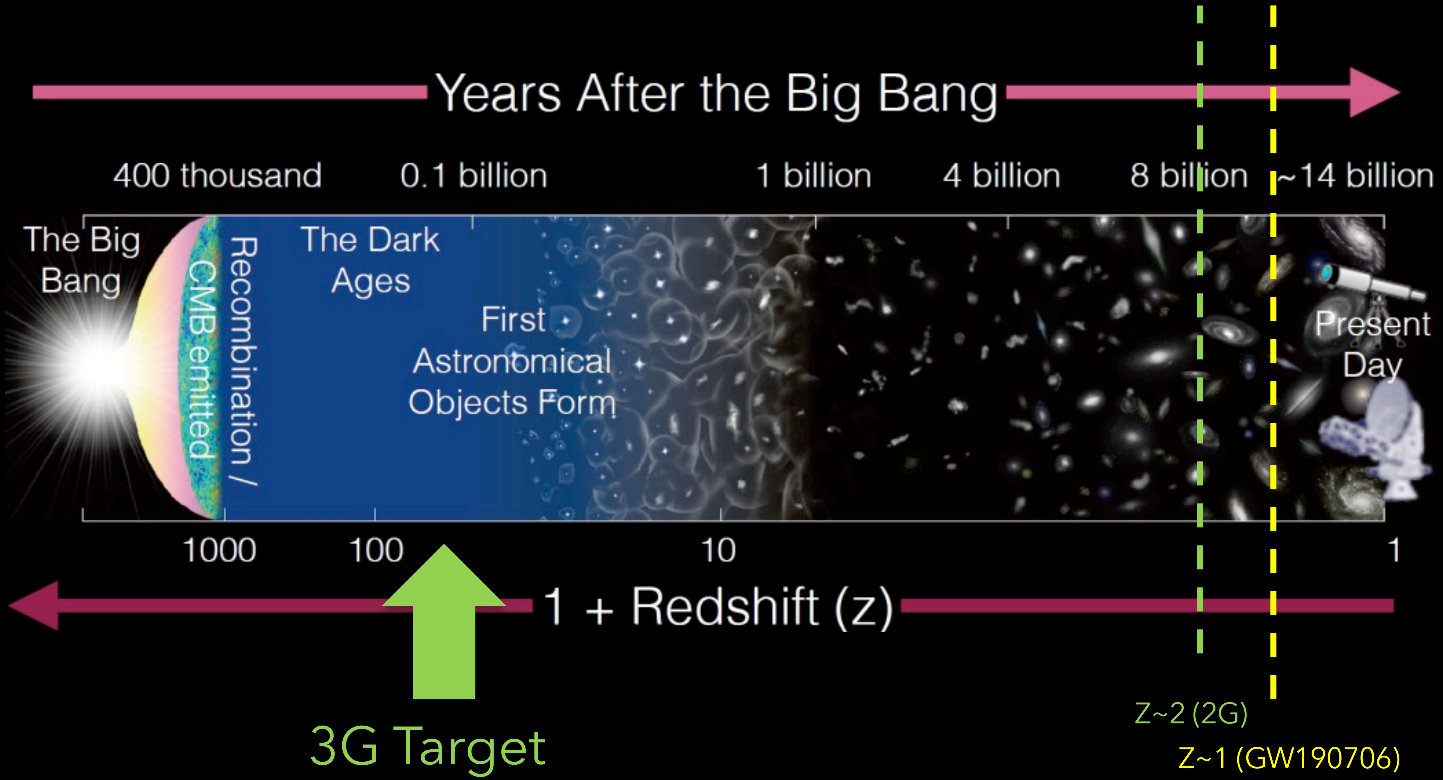


Image credit: NAOJ/ALMA http://alma.mtk.nao.ac.jp/

ET Enabling Technologies

ET EINSTEIN TELESCOPE

Credit: M Punturo

- The multi-interferometer approach asks for two parallel technology developments:
- **ET-LF:**
  - Underground
  - Cryogenics
  - Silicon (Sapphire) test masses
  - Large test masses
  - New coatings
  - New laser wavelength
  - Seismic suspensions
  - Frequency dependent squeezing
- **ET-HF:**
  - High power laser
  - Large test masses
  - New coatings
  - Thermal compensation
  - Frequency dependent squeezing

Parameter	ET-HF	ET-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10-20 K
Mirror material	fused silica	silicon
Mirror diameter / thickness	62 cm / 30 cm	45 cm/ 57 cm
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase (rad)	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1×300 m	2×1.0 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	TEM_{00}	TEM_{00}
Beam radius	12.0 cm	9 cm
Scatter loss per surface	37 ppm	37 ppm
Seismic isolation	SA, 8 m tall	mod SA, 17 m tall
Seismic (for $f > 1$ Hz)	$5 \cdot 10^{-10}\ m/f^2$	$5 \cdot 10^{-10}\ m/f^2$
Gravity gradient subtraction	none	factor of a few

Left column (ET-LF):
- Challenging engineering
- New technology in cryo-cooling
- New technology in optics
- New laser technology
- High precision mechanics and low noise controls
- High quality opto-electronics and new controls

New Technologies

Right column (ET-HF):
- Evolved laser technology
- Evolved technology in optics
- Highly innovative adaptive optics
- High quality opto-electronics and new controls

Innovation

- ET will start taking data in >2035
  - For Virgo and LIGO it took one decade to reach initial detector's target sensitivity
- Existing detector will still play a crucial role for ~ a decade after O5
- Two possible approaches:
  - Stay at the O5 sensitivity and observe for a long time
  - Upgrade and observe later at a better sensitivity

$$\# \text{ EVENTS} \propto d^3 \, T$$

- If you have the technology and money for a significant upgrade, then do it

VIRGO_NEXT

IS A NEW UPGRADE POSSIBLE?

- Are there developments on key technologies promising a significant enhancement of the sensitivities?
- Yes. R&D is making progress and a new push will come from ET
- Areas for synergies:
  - Better coatings
  - Higher squeezing level
  - High power laser
  - Control of thermal effects
  - Newtonian noise subtraction
  - Reduction of low frequency noises

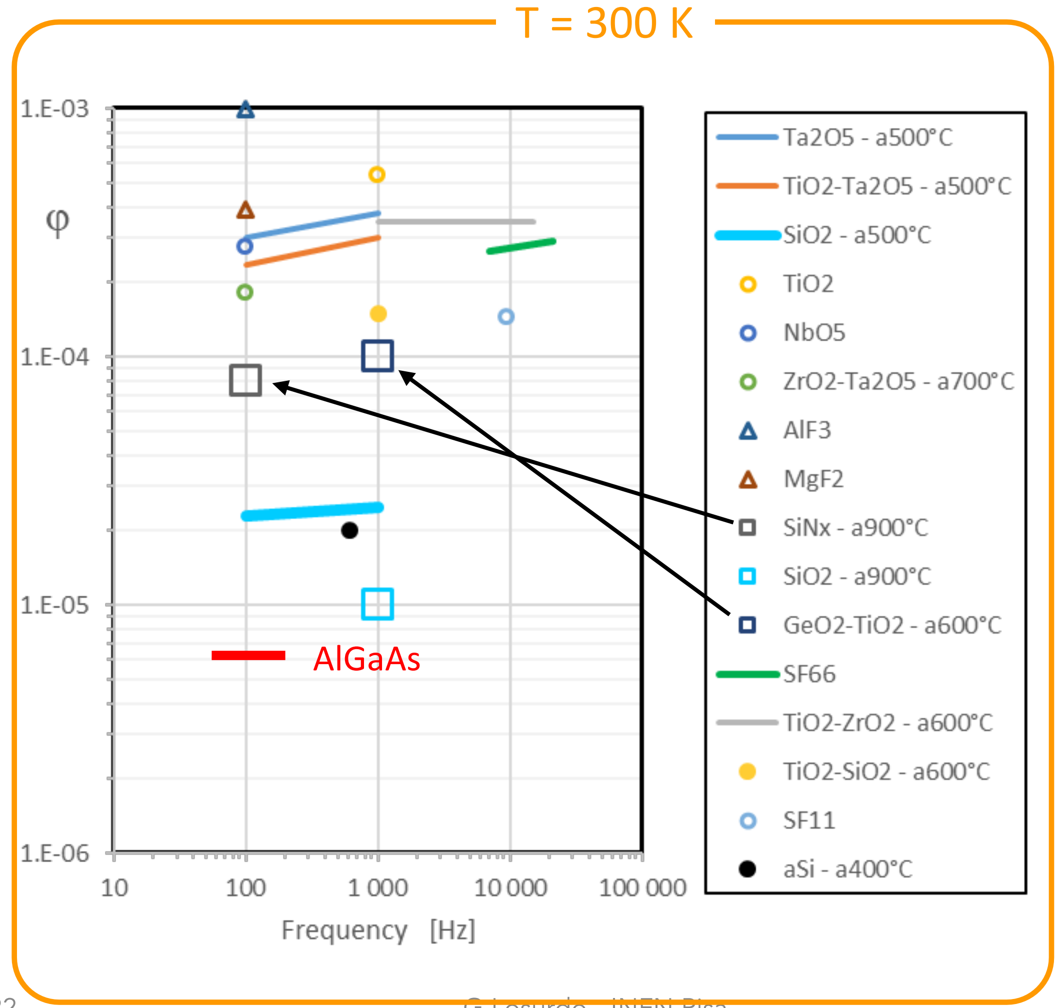
A NEW UPGRADE: GOALS

- Continue/extend the Virgo/LIGO science program until the advent of 3G detectors
  - ~ x2 sensitivity improvement wrt AdV+
- Intermediate step in technology developments between 2G+ and 3G
  - Framework: same Virgo wavelength, room temperature, "same" infrastructure
  - Risk reducer for Einstein Telescope
  - Strong synergies on common R&Ds
- Keeps the community together, allows to form a new generation of GW interferometry experts

COATING RESEARCH

- Coating thermal noise remains the main offender in GW detector sensitivity
- 20 yrs R&D on amorphous materials within Virgo/LIGO has produced incremental progress. Still aiming to a breakthrough
- Three main lines open
  - New amorphous materials
  - Crystalline oxides
  - Crystalline AlGaAs
- Significant loss reduction achieved on small samples of AlGaAs, but large samples are not available so far
- All the 3 lines requires significant investments
  - Synergy with ET is crucial

Credit: G Cagnoli
VIR-1070A-22



LF NOISE

- At 3 Hz ET is O(10^6) better than today's detectors
- Virgo_nEXT can be a key to understand/tackle LF noises
  - Sensing/controls
  - Environmental
  - Scattered light
  - …

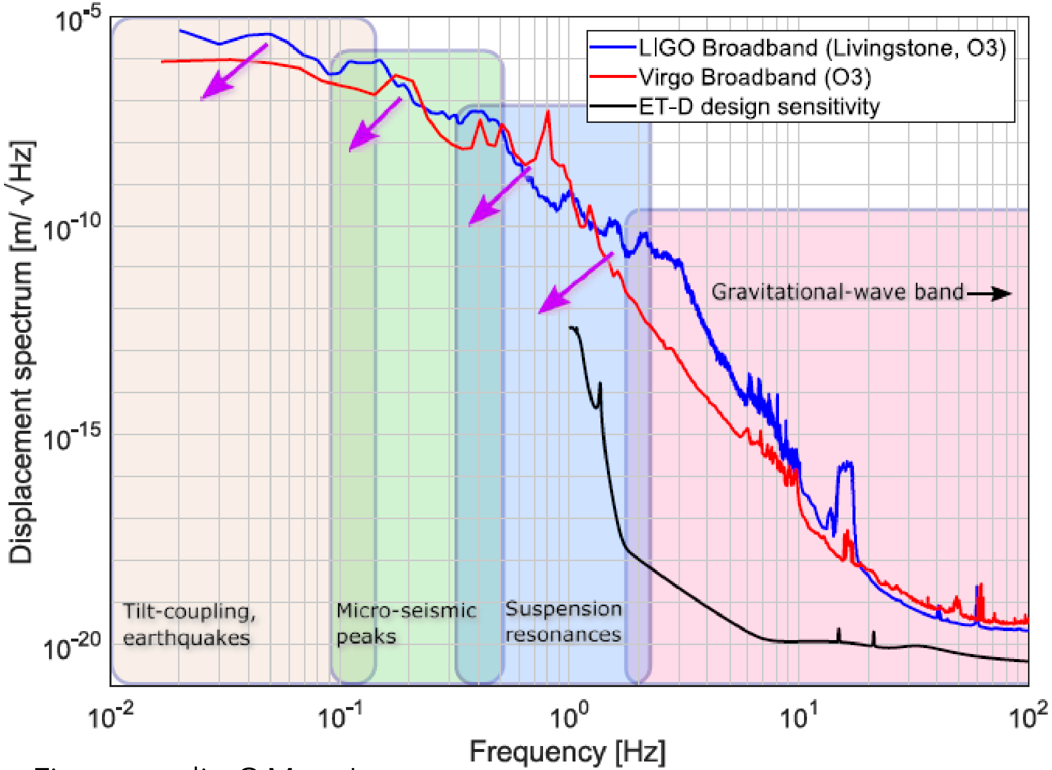


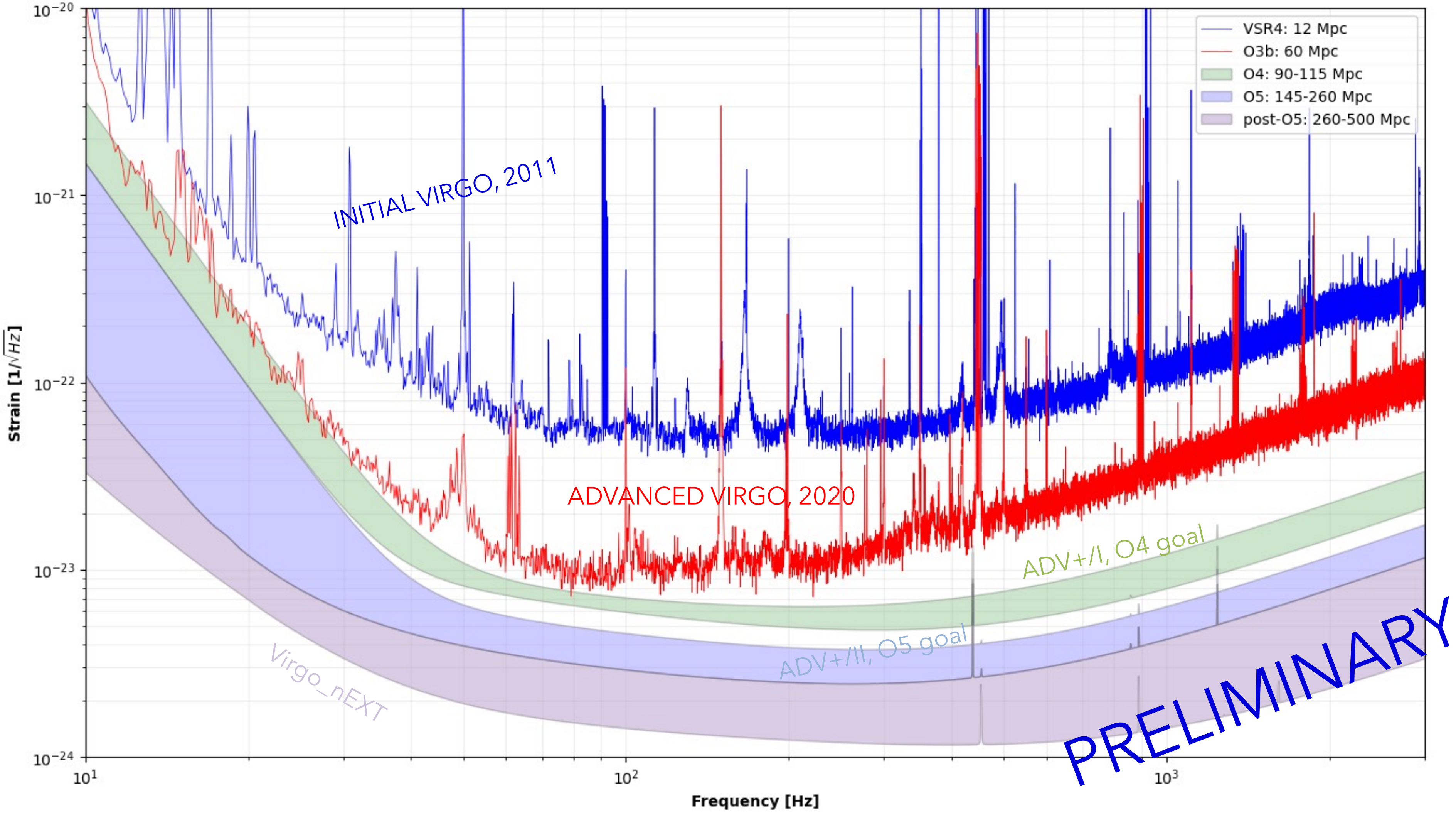
Figure credit: C Mow-Lowry

SOME FIGURES

	AdV+ best	V_next best	ET HF
Power inj.	125 W	277 W	500 W
Arm power	390 kW	1.5 MW	3 MW
FDS detected	6 dB	10 dB	10 dB
Mirror mass	42/105 kg	105 kg	200 kg
beam radius	49/91 mm	91 mm	120 mm
coating losses	5.4e-5	6e-6	1.25e-5
NN reduction	1/5	1/5	0-1/3

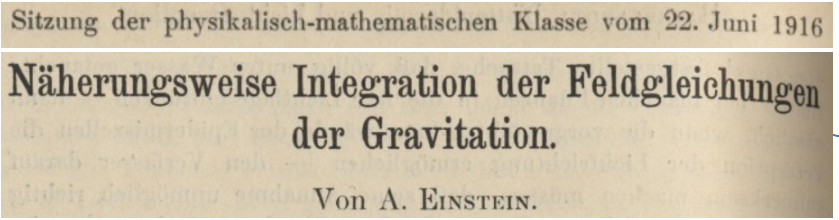
Virgo_nEXT STATUS

- A concept study has been submitted to (and endorsed by) the funding agencies
- A Design Team (coordinated by V Fafone – INFN) is being set up to produce a baseline design within 18 months
- An "Early R&D plan" will be submitted to the agencies in the next months
- Discussing with LIGO and ET for coordination on R&D and schedule



VSR4: 12 Mpc
O3b: 60 Mpc
O4: 90-115 Mpc
O5: 145-260 Mpc
post-O5: 260-500 Mpc
INITIAL VIRGO, 2011
ADVANCED VIRGO, 2020
ADV+/I, O4 goal
ADV+/II, O5 goal
Virgo_nEXT
PRELIMINARY
Strain [1/√Hz]
Frequency [Hz]
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}

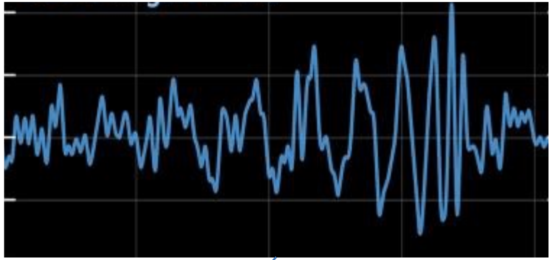
CONCLUSIVE REMARKS


Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

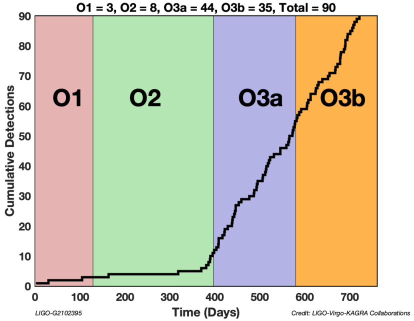
Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

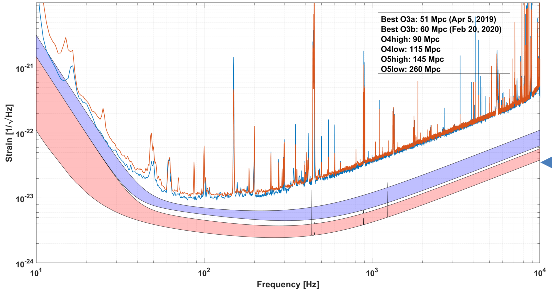
100 years



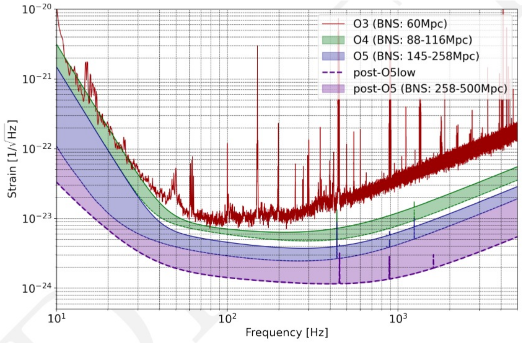
5 yrs



→ 2030



2030 →



2035 →