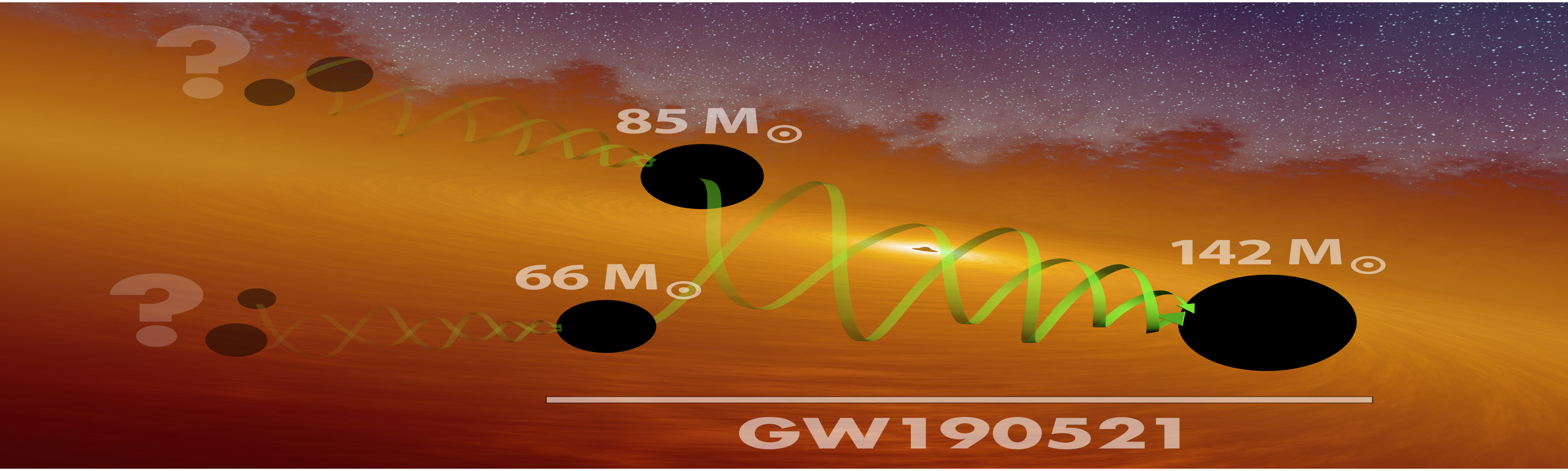
The Gravitational Wave Universe

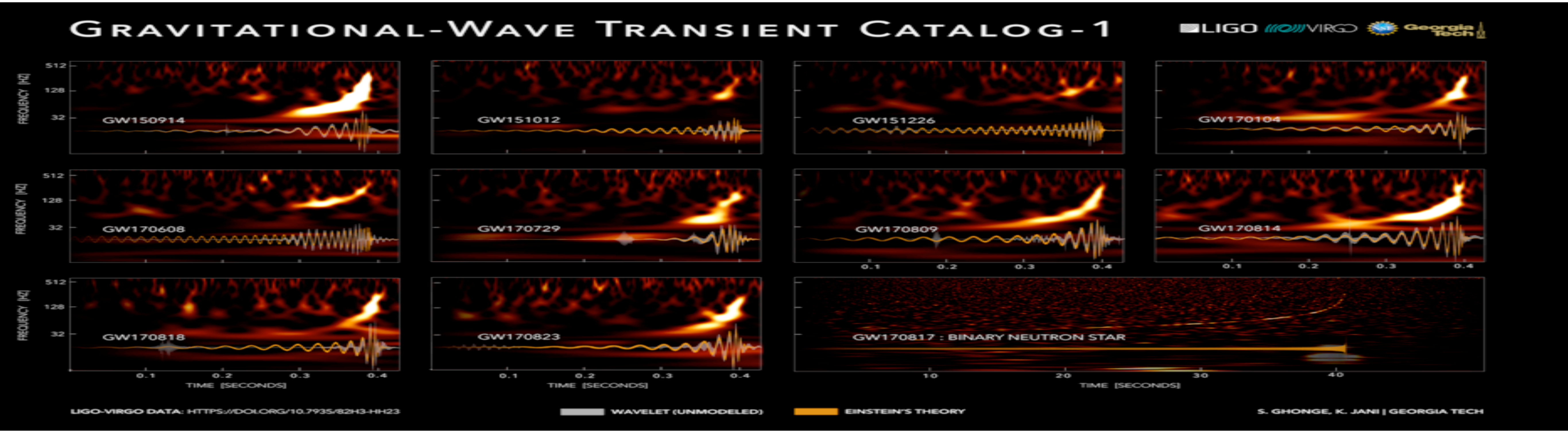
Ed Porter
APC/CNRS



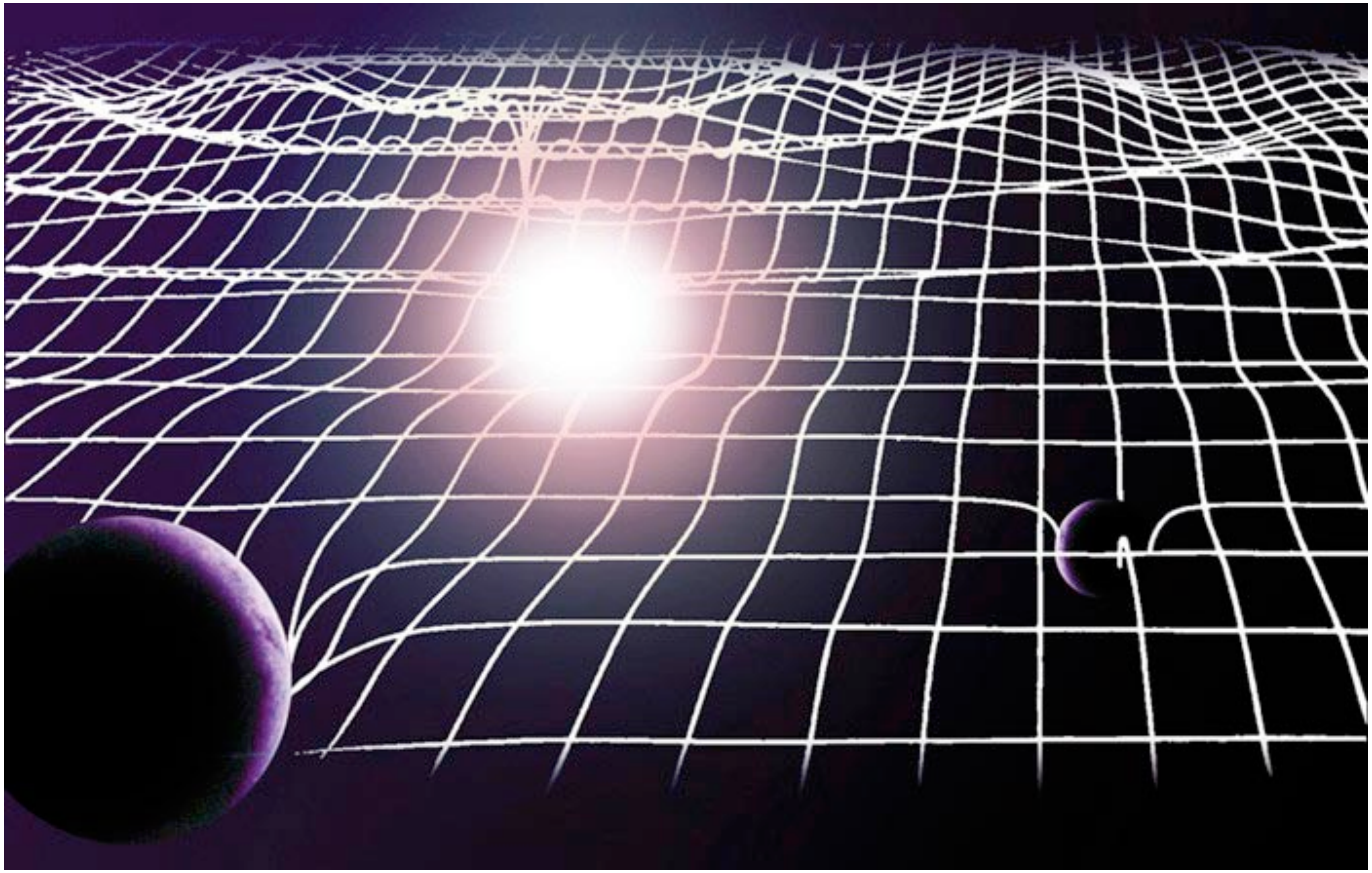
Outline

- Gravitational Waves
- Active GW experiments
- The future of GW astronomy

GWs and the LVK Observation Runs

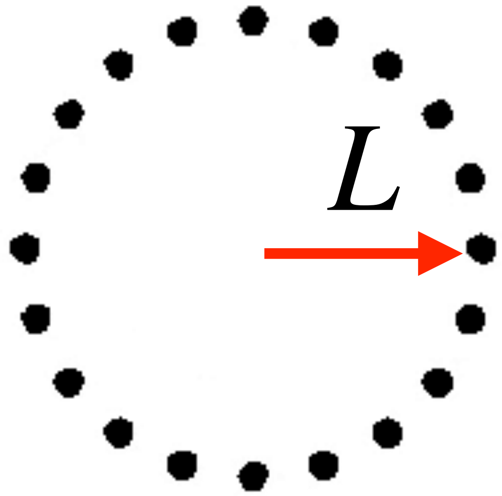


Gravitational Waves

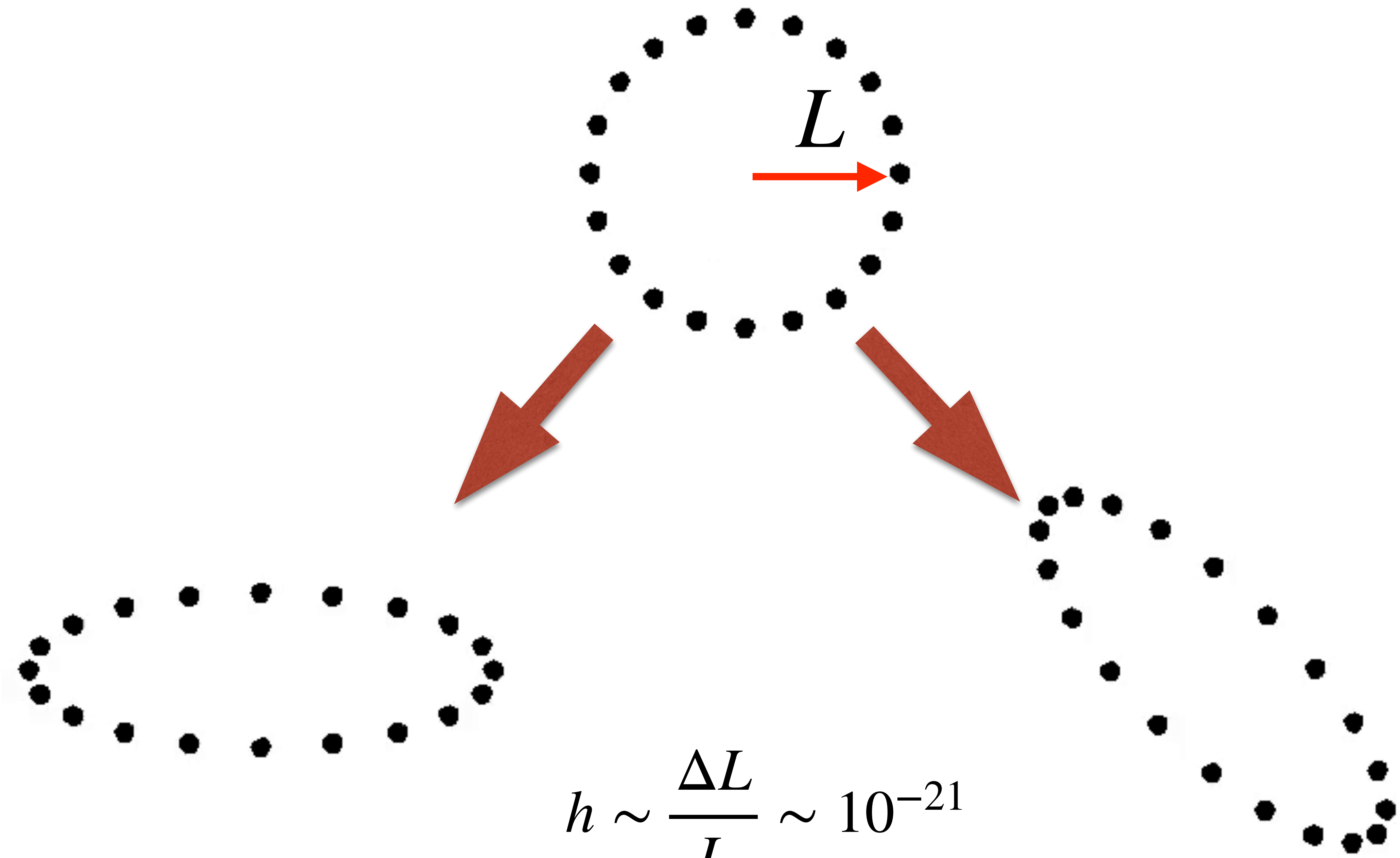


$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \quad |h_{\mu\nu}| << 1$$

GW Polarizations

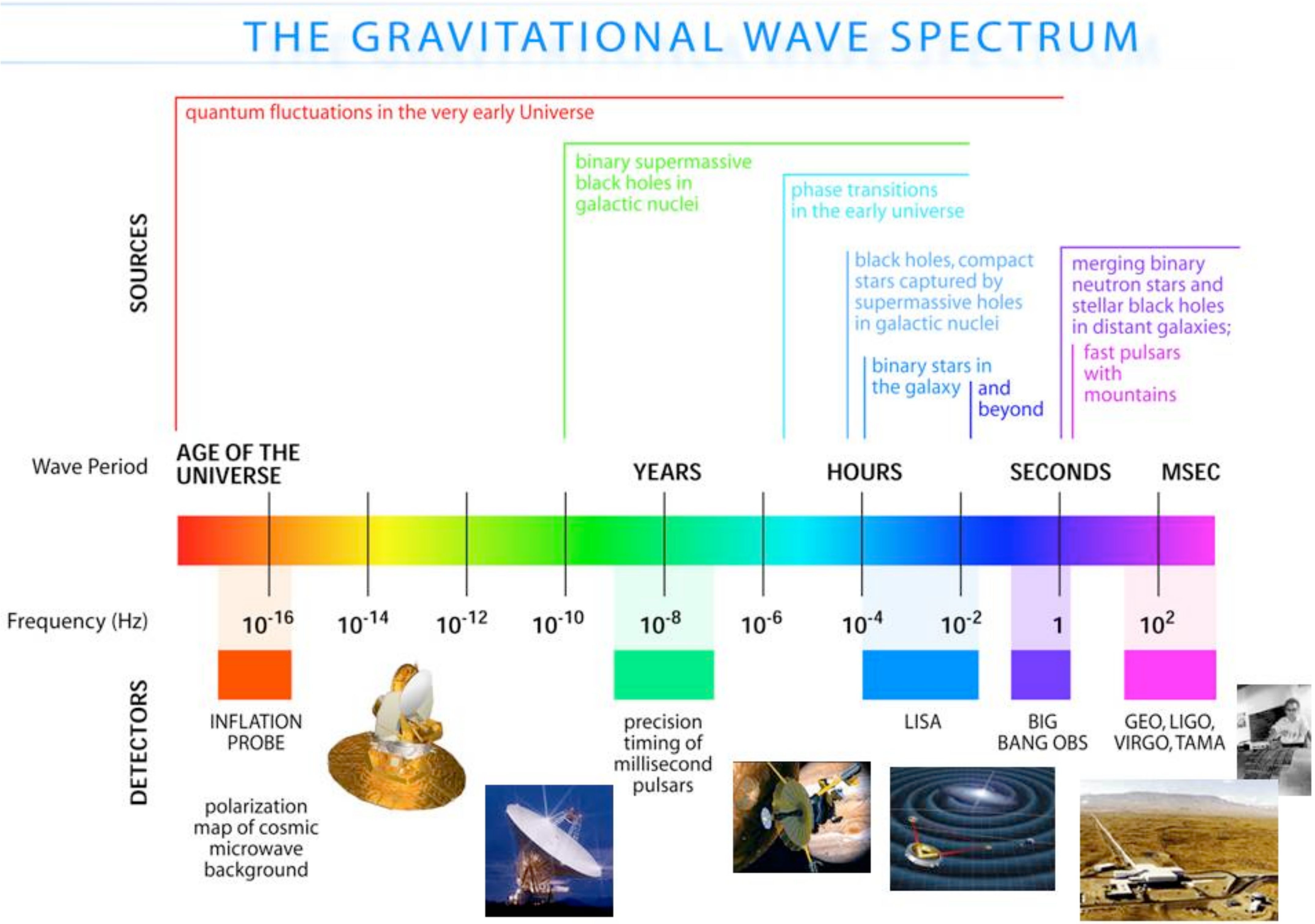


GW Polarizations

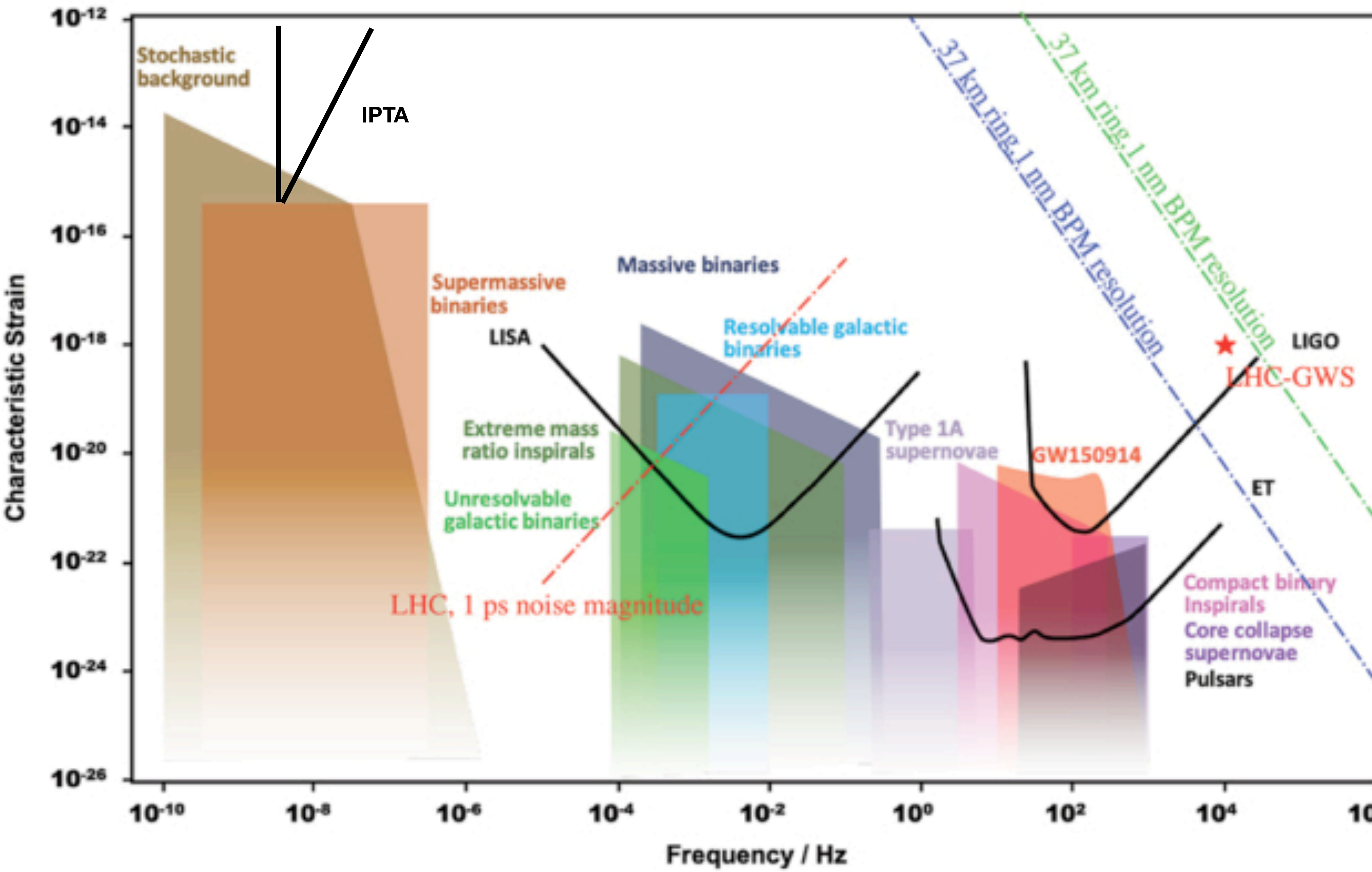


$$h \sim \frac{\Delta L}{L} \sim 10^{-21}$$

GW Spectrum

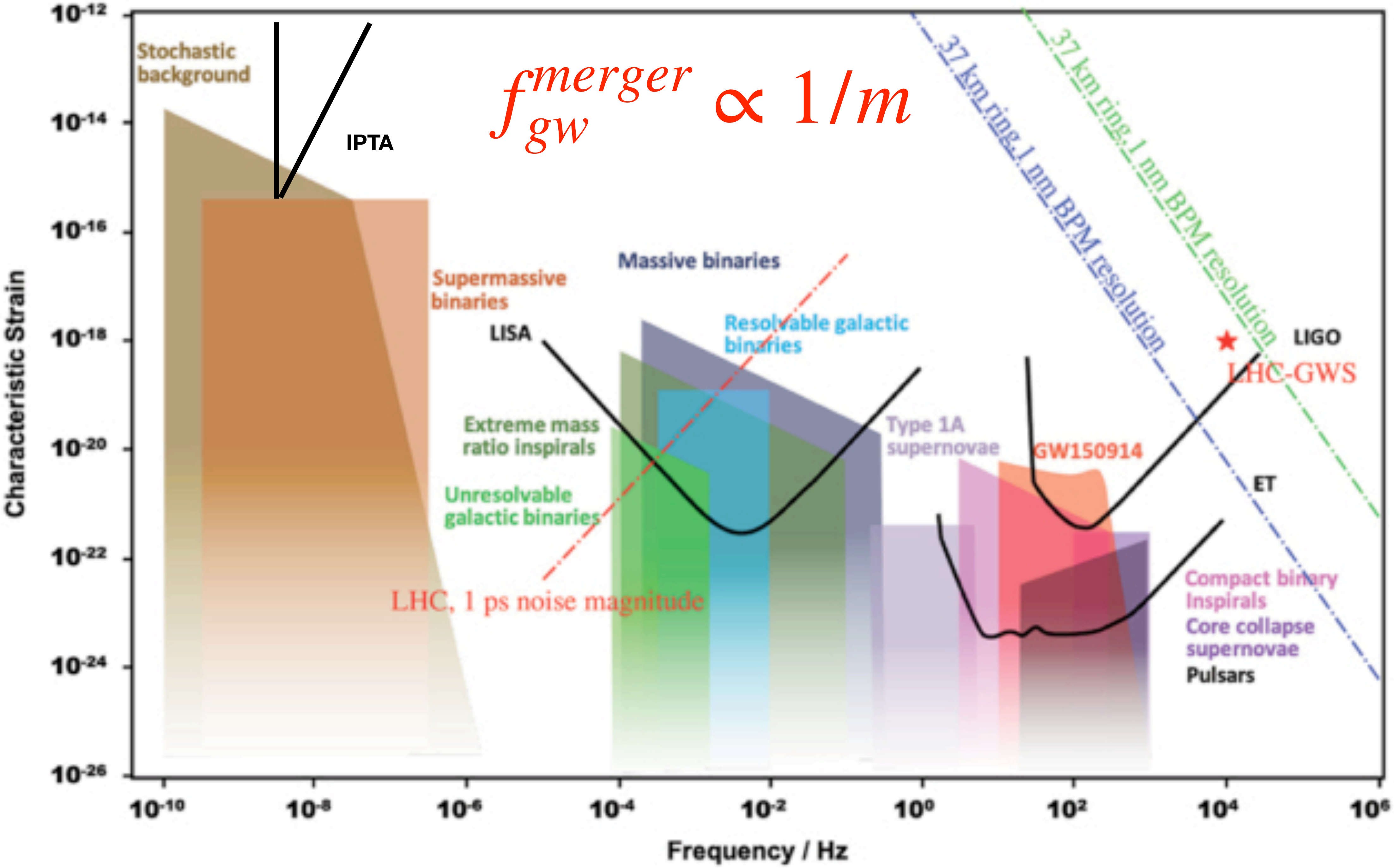

THE GRAVITATIONAL WAVE SPECTRUM
SOURCES
quantum fluctuations in the very early Universe
binary supermassive black holes in galactic nuclei
phase transitions in the early universe
black holes, compact stars captured by supermassive holes in galactic nuclei
binary stars in the galaxy
and beyond
merging binary neutron stars and stellar black holes in distant galaxies;
fast pulsars with mountains
Wave Period
AGE OF THE UNIVERSE
YEARS
HOURS
SECONDS
MSEC
Frequency (Hz)
10-16
10-14
10-12
10-10
10-8
10-6
10-4
10-2
1
102
DETECTORS
INFLATION PROBE
polarization map of cosmic microwave background
precision timing of millisecond pulsars
LISA
BIG BANG OBS
GEO, LIGO, VIRGO, TAMA

GW Spectrum



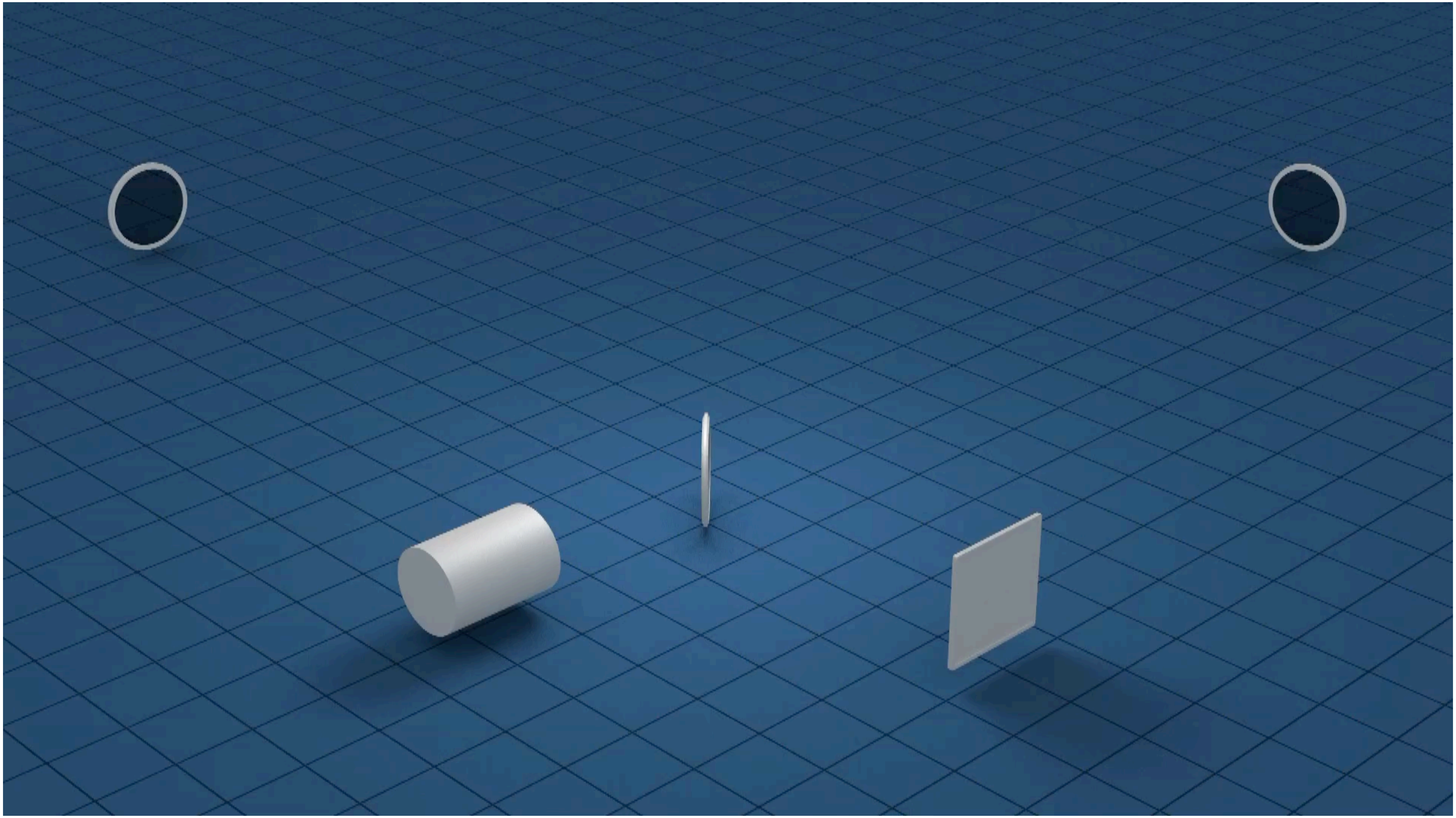
Characteristic Strain
Frequency / Hz
Stochastic background
IPTA
Supermassive binaries
Massive binaries
LISA
Resolvable galactic binaries
Extreme mass ratio inspirals
Unresolvable galactic binaries
LHC, 1 ps noise magnitude
Type 1A supernovae
GW150914
LIGO
LHC-GWS
ET
37 km ring,1 nm BPM resolution
37 km ring,1 nm BPM resolution
Compact binary Inspirals
Core collapse supernovae
Pulsars

GW Spectrum

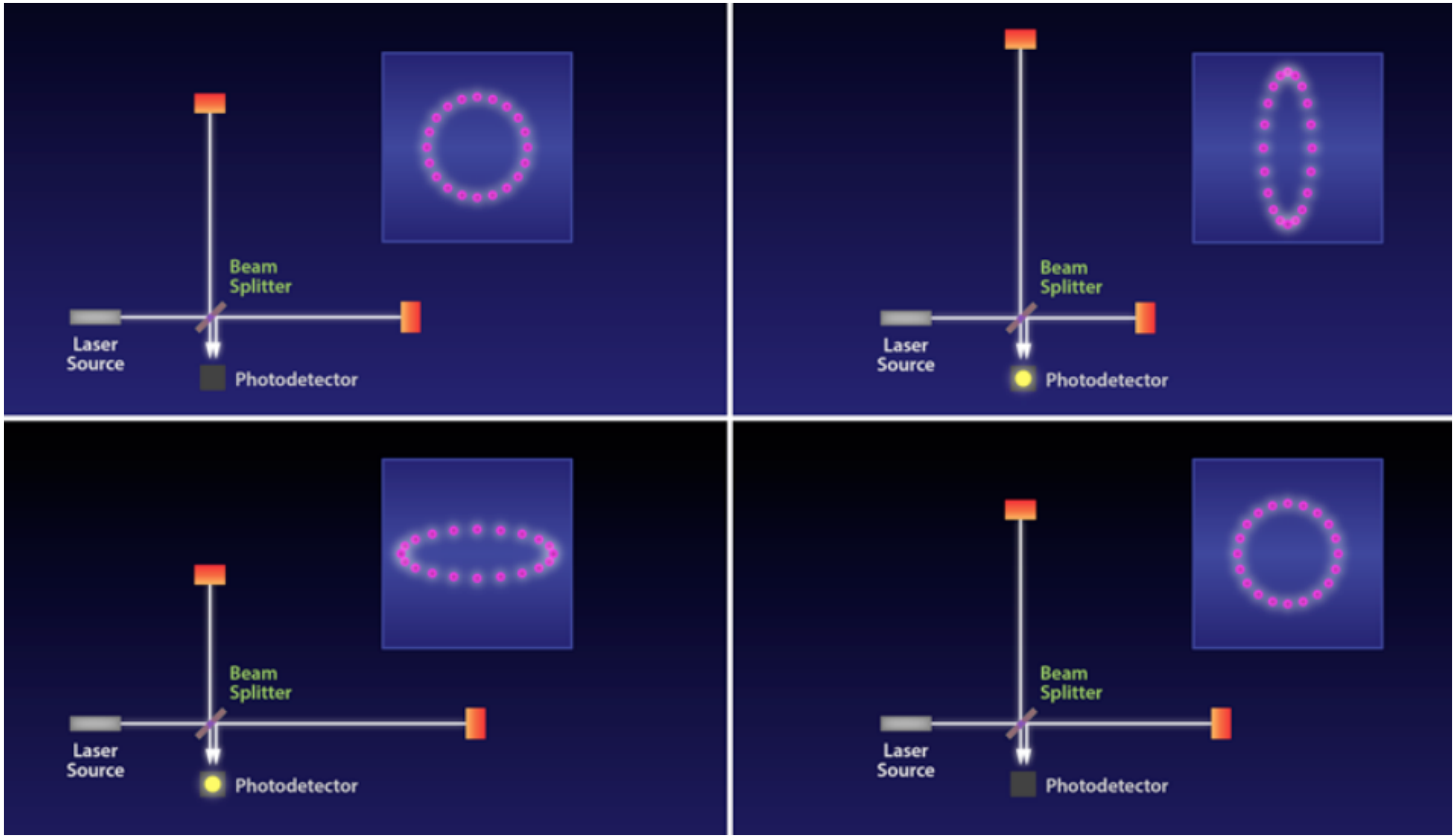


so, the lower the frequency, the higher the mass

GW IFO



GW IFO



$$\Delta L \sim hL \sim 10^{-21} 10^{3} m \sim 10^{-18} m$$

Detecting GWs

GWs are analogous to 1D sound waves

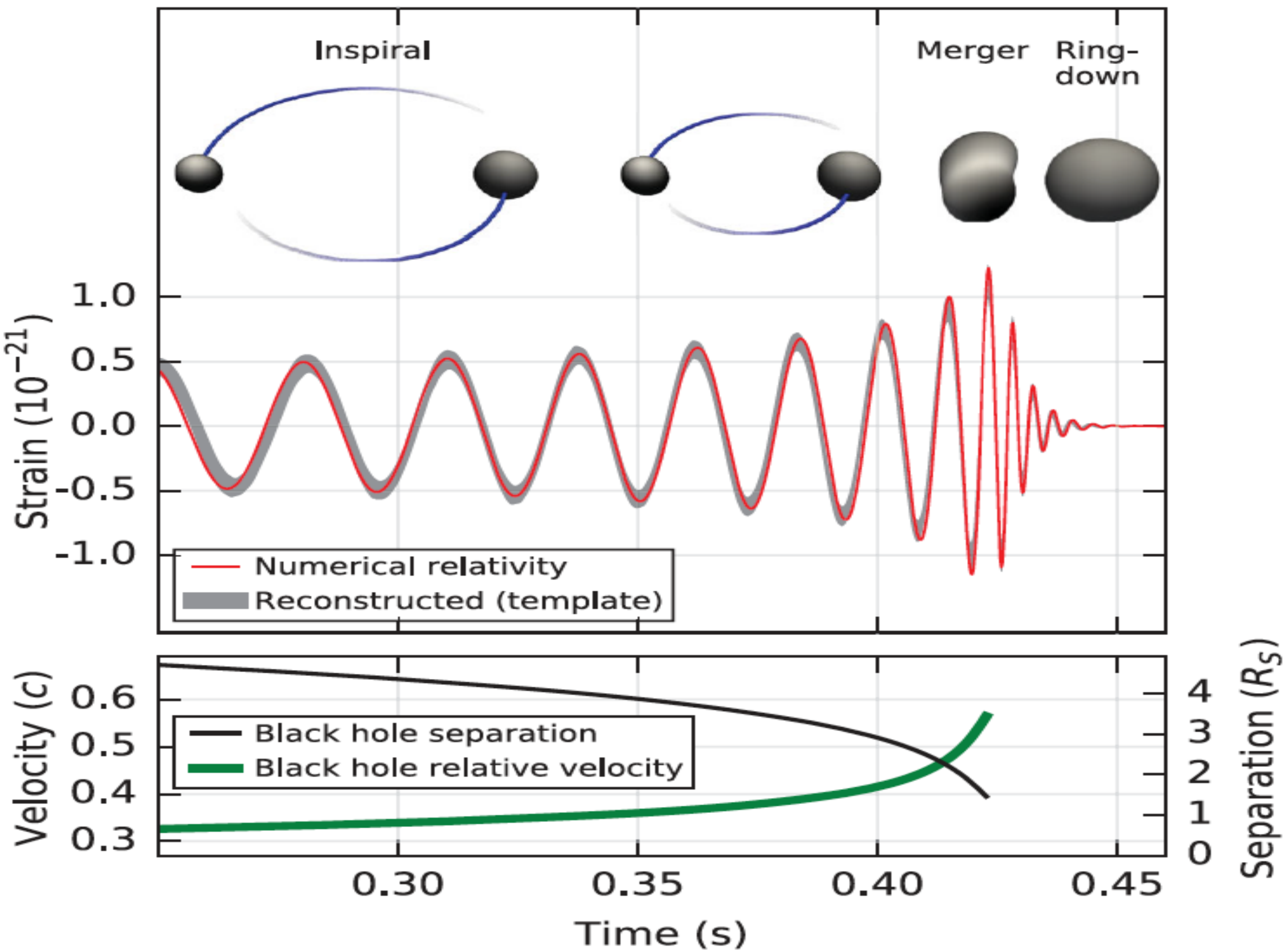
A matched filter is an optimal linear filter for signals buried in noise

Very sensitive to phase evolution

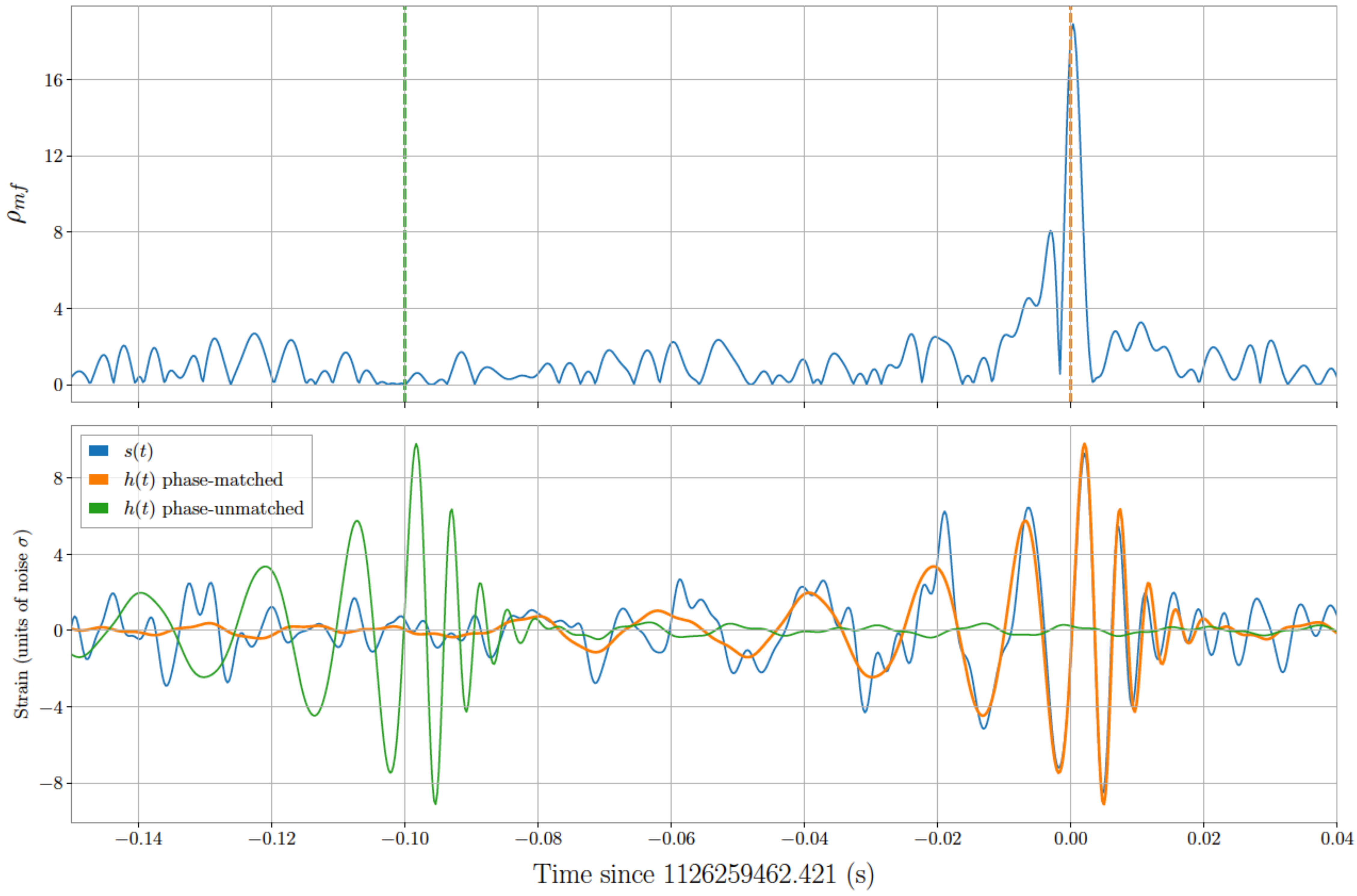
Need very accurate models of the waveform

As the noise in the detector is not constant, the analysis is conducted in the Fourier domain

Detecting GWs

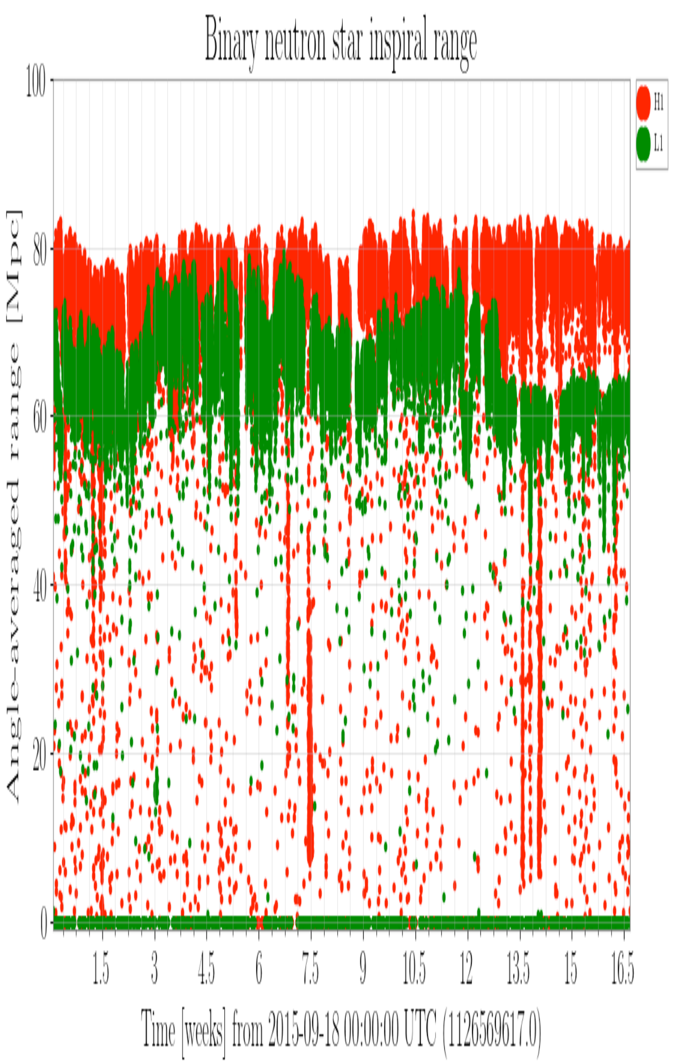


GW Detection

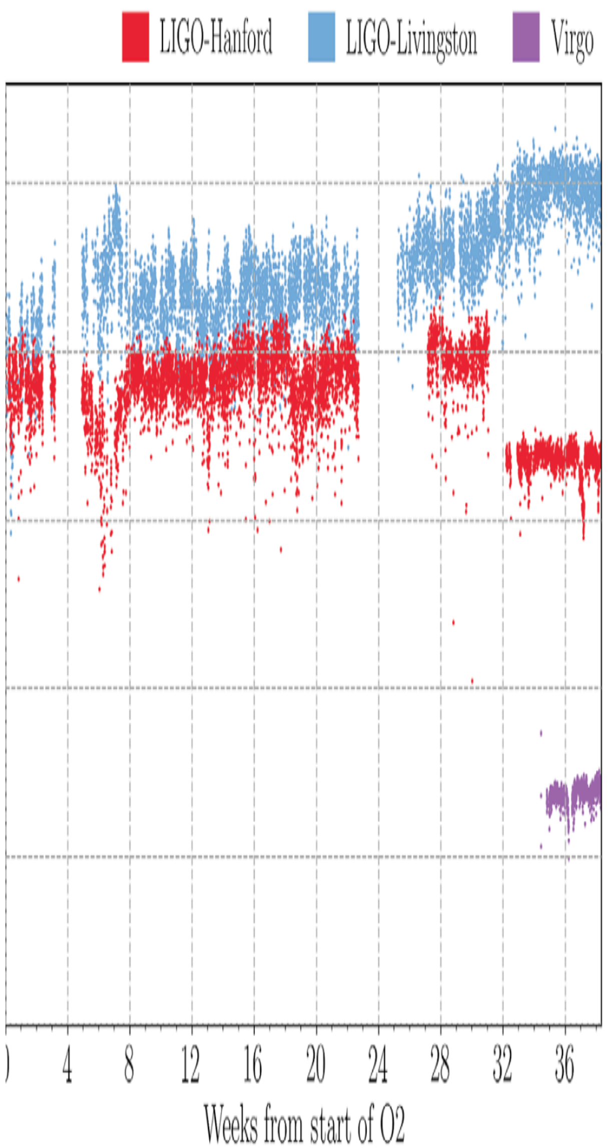


BNS Range O1-O3

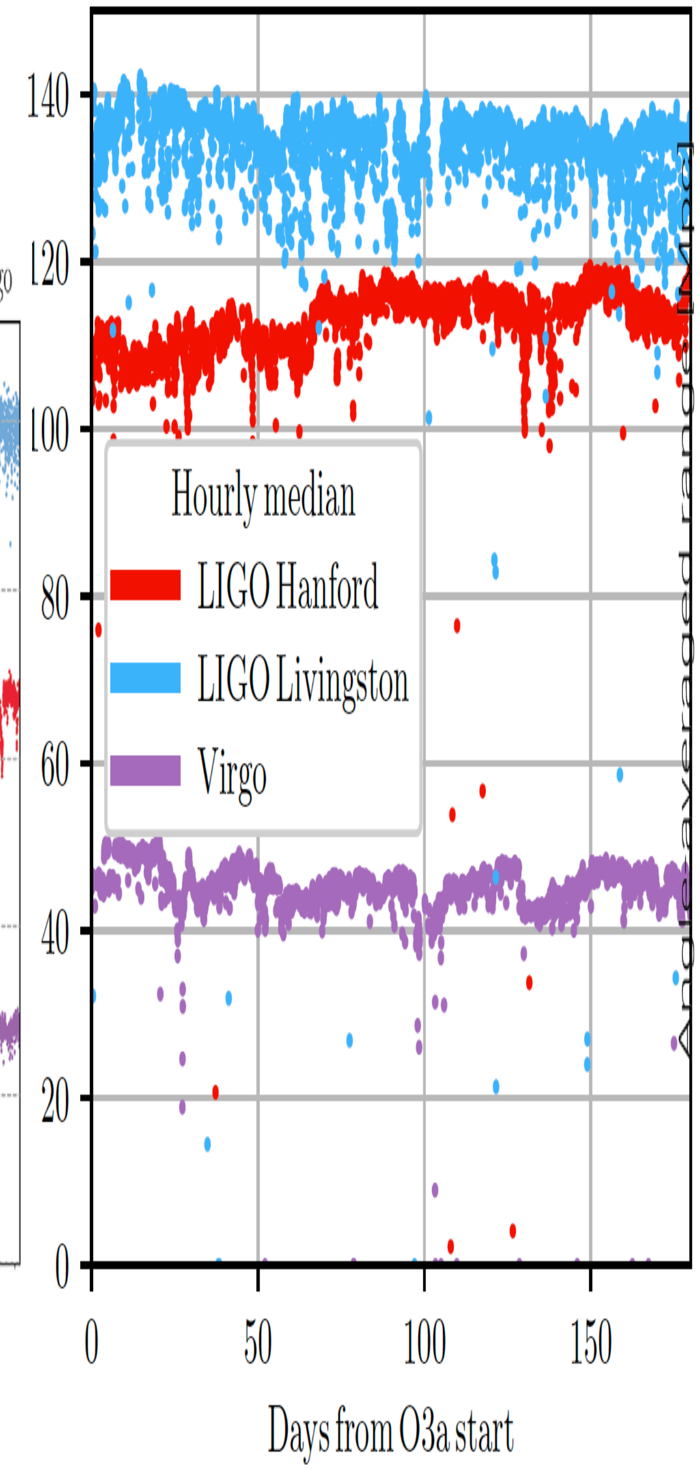
O1

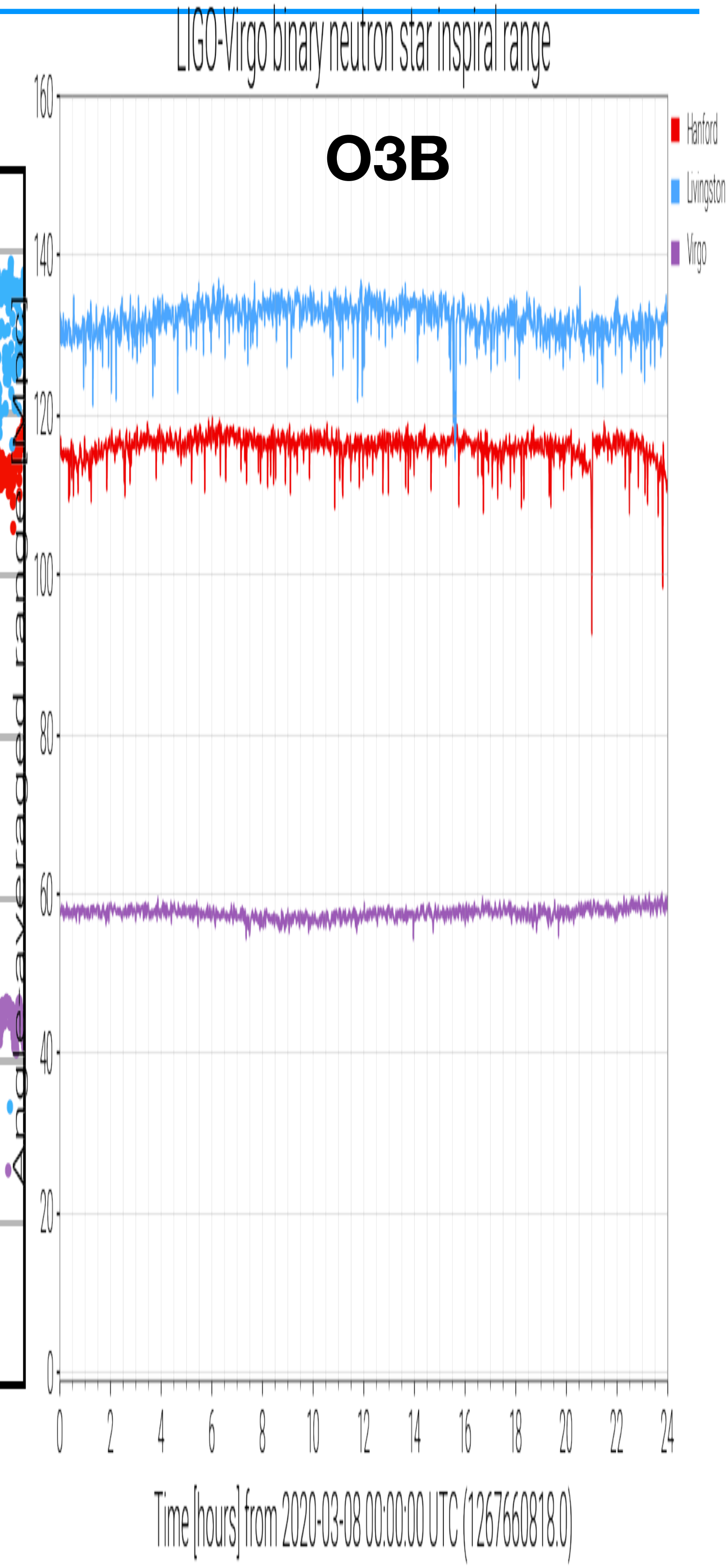


O2

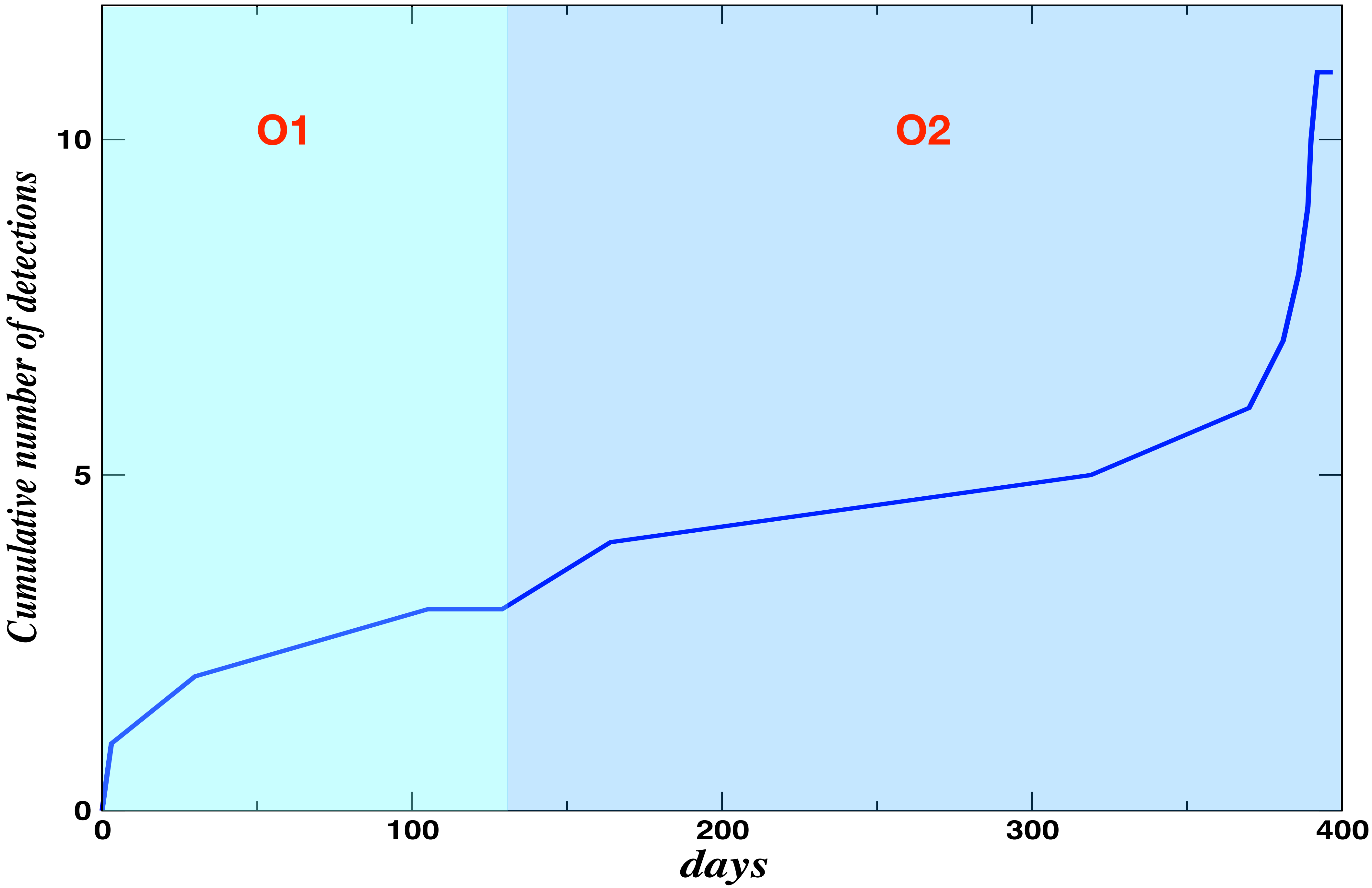


O3a

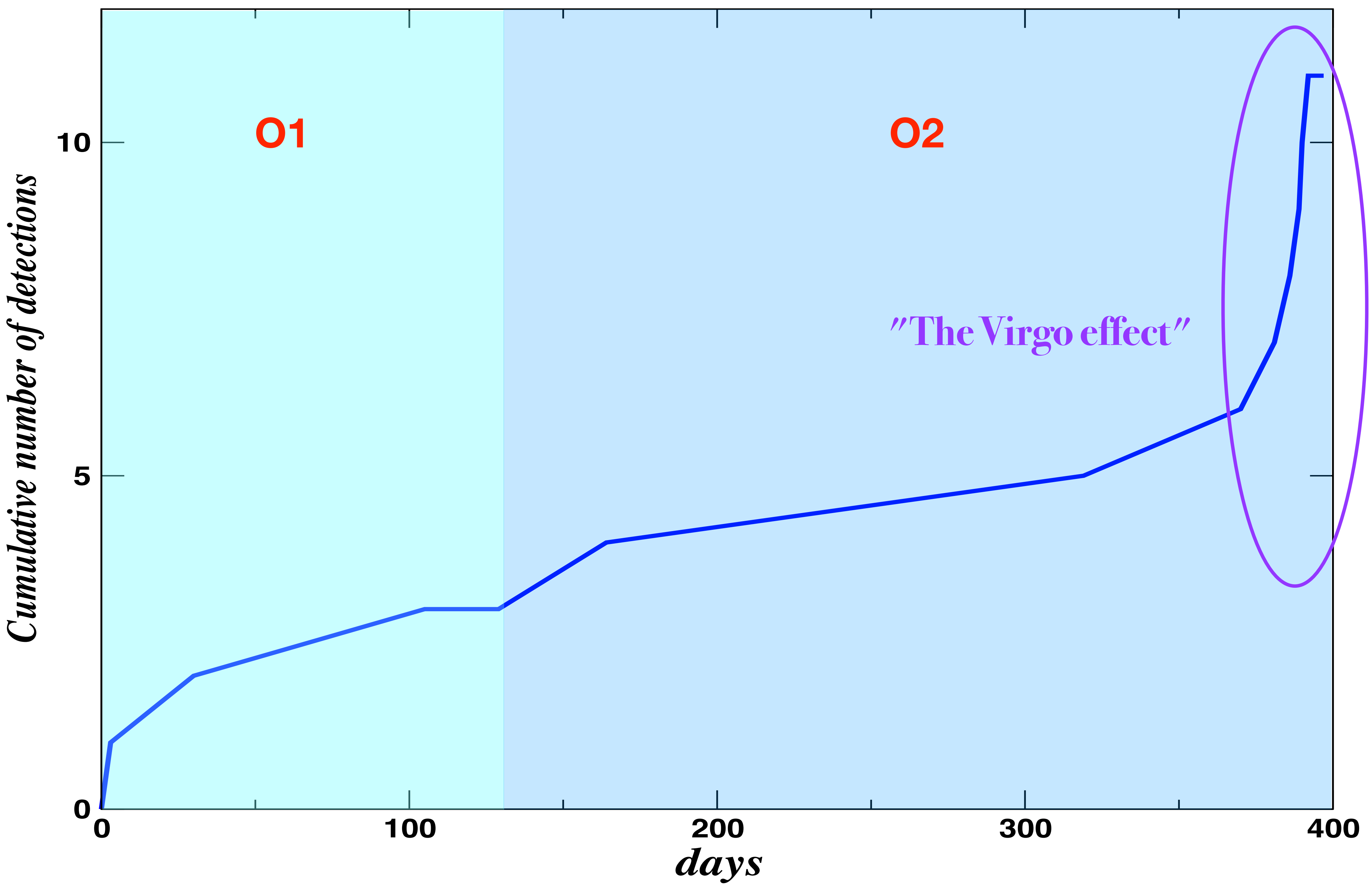




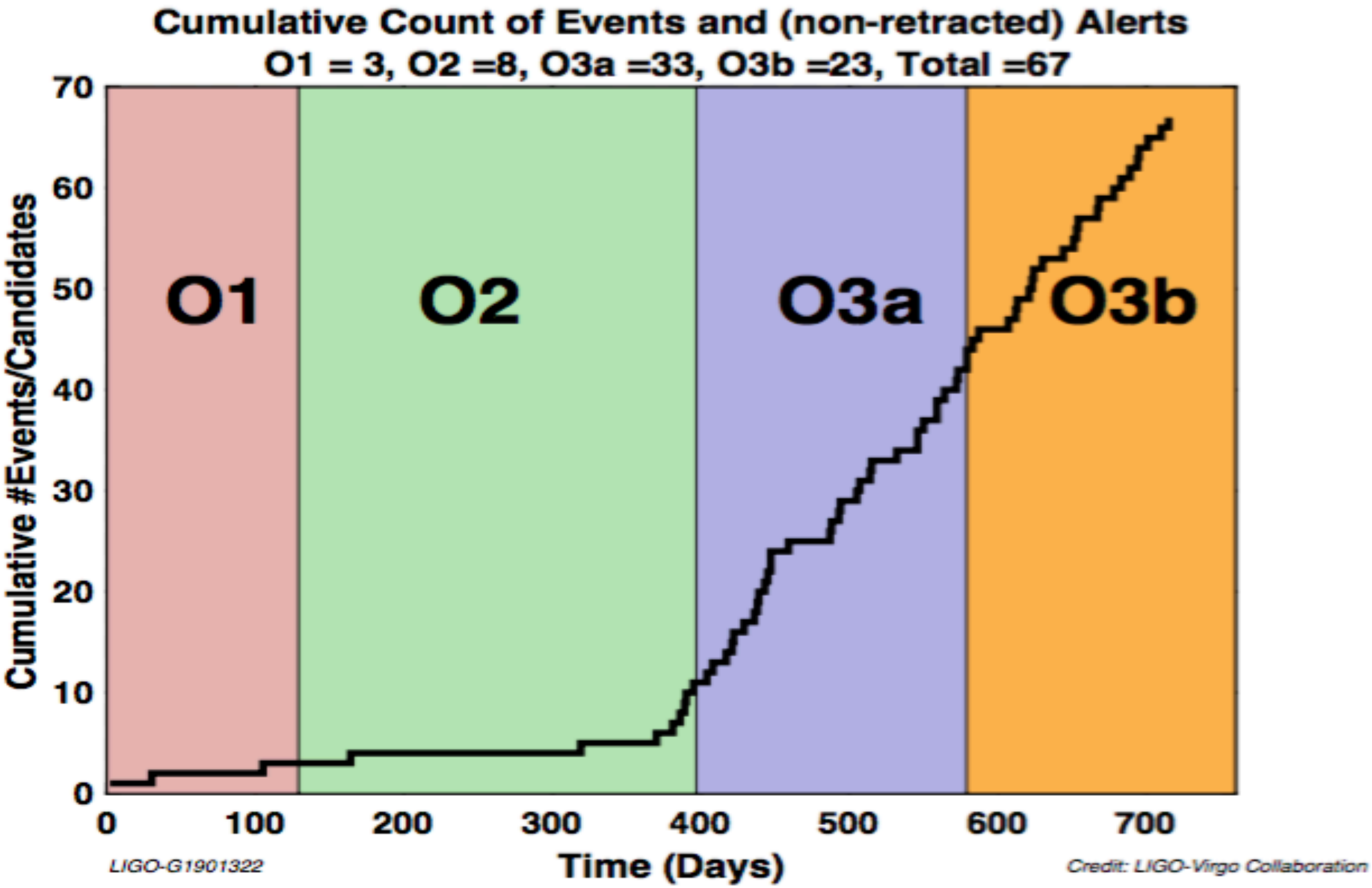
GW Detections



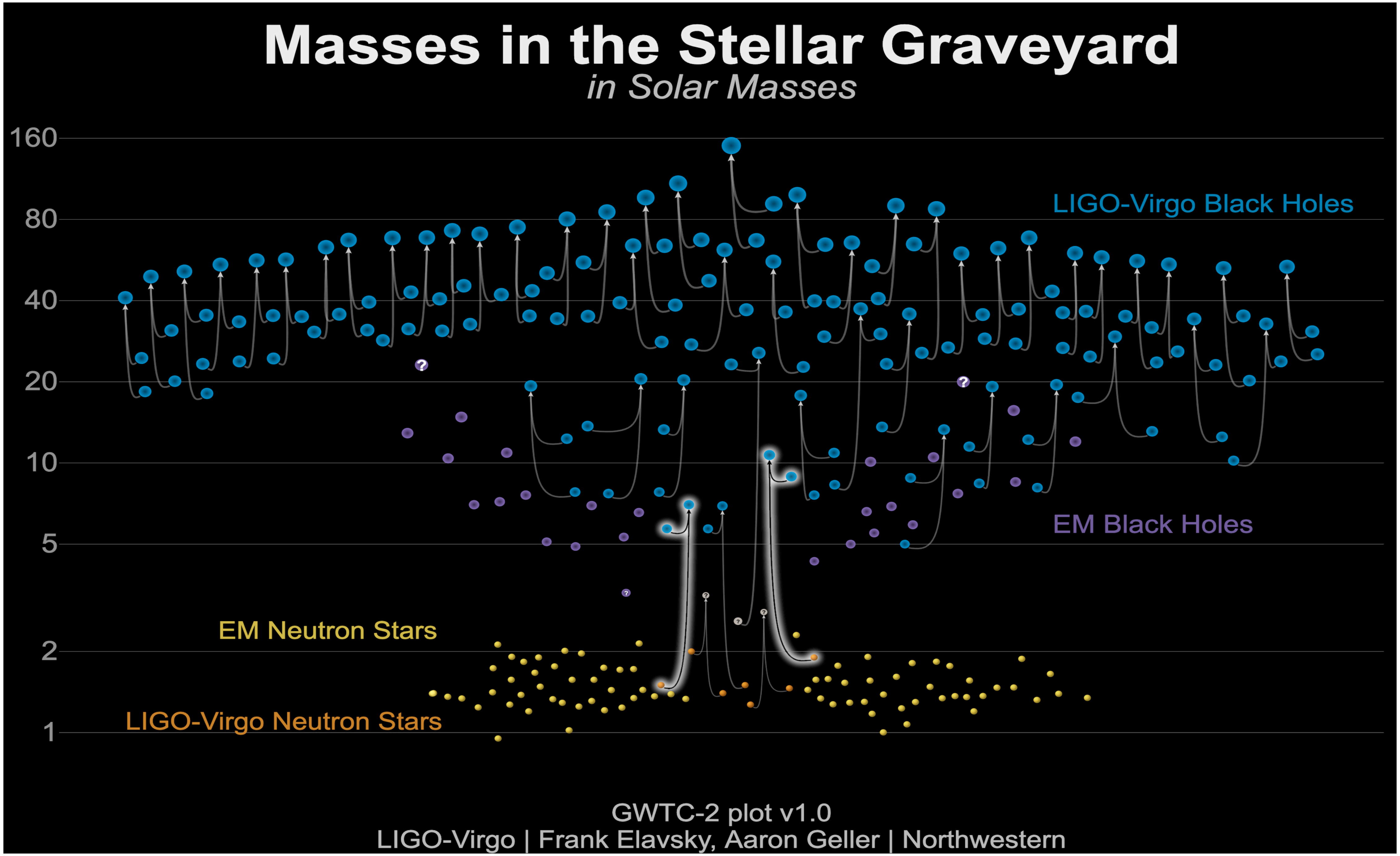
GW Detections



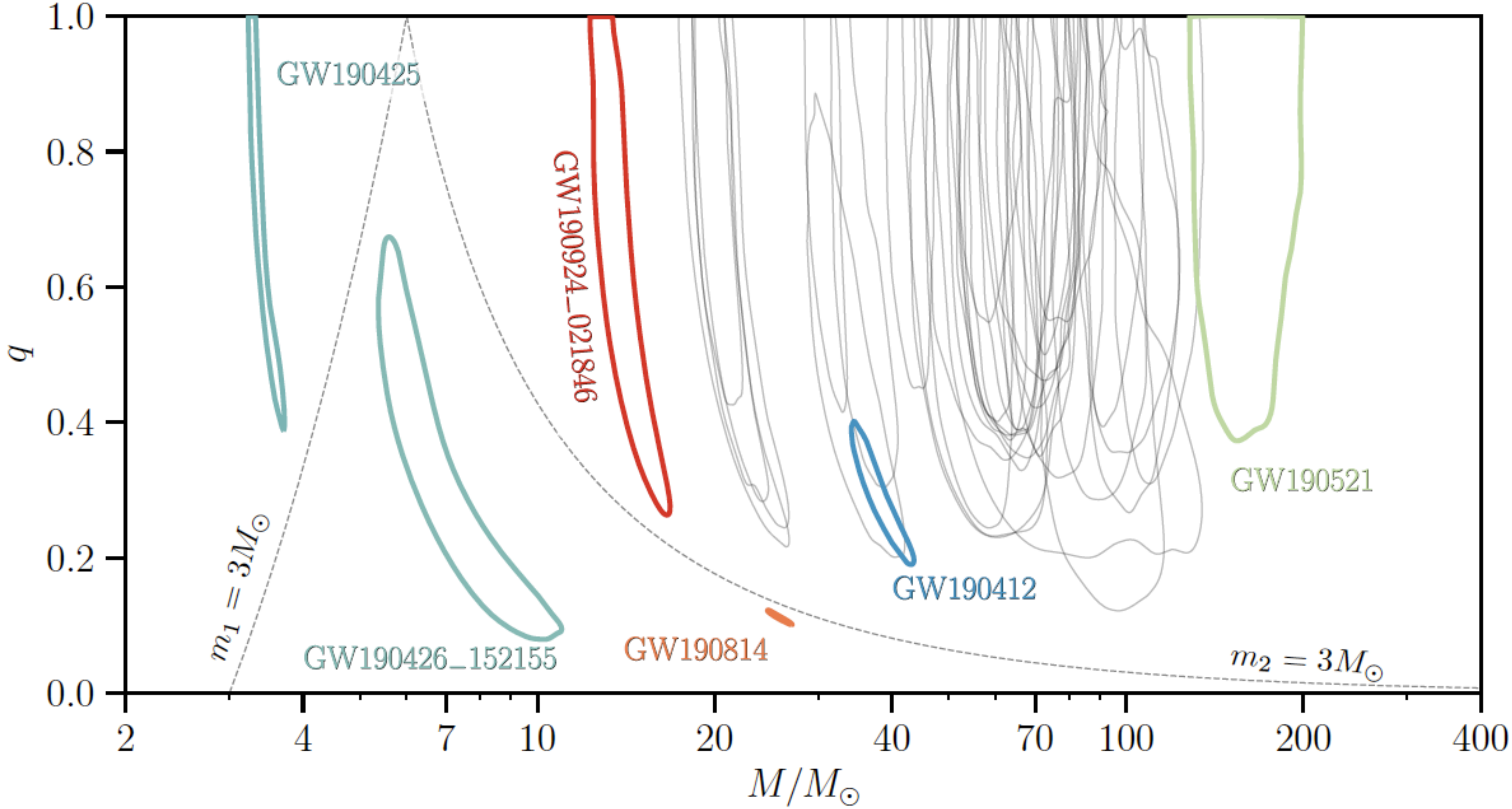
GW Detections



GW Detections

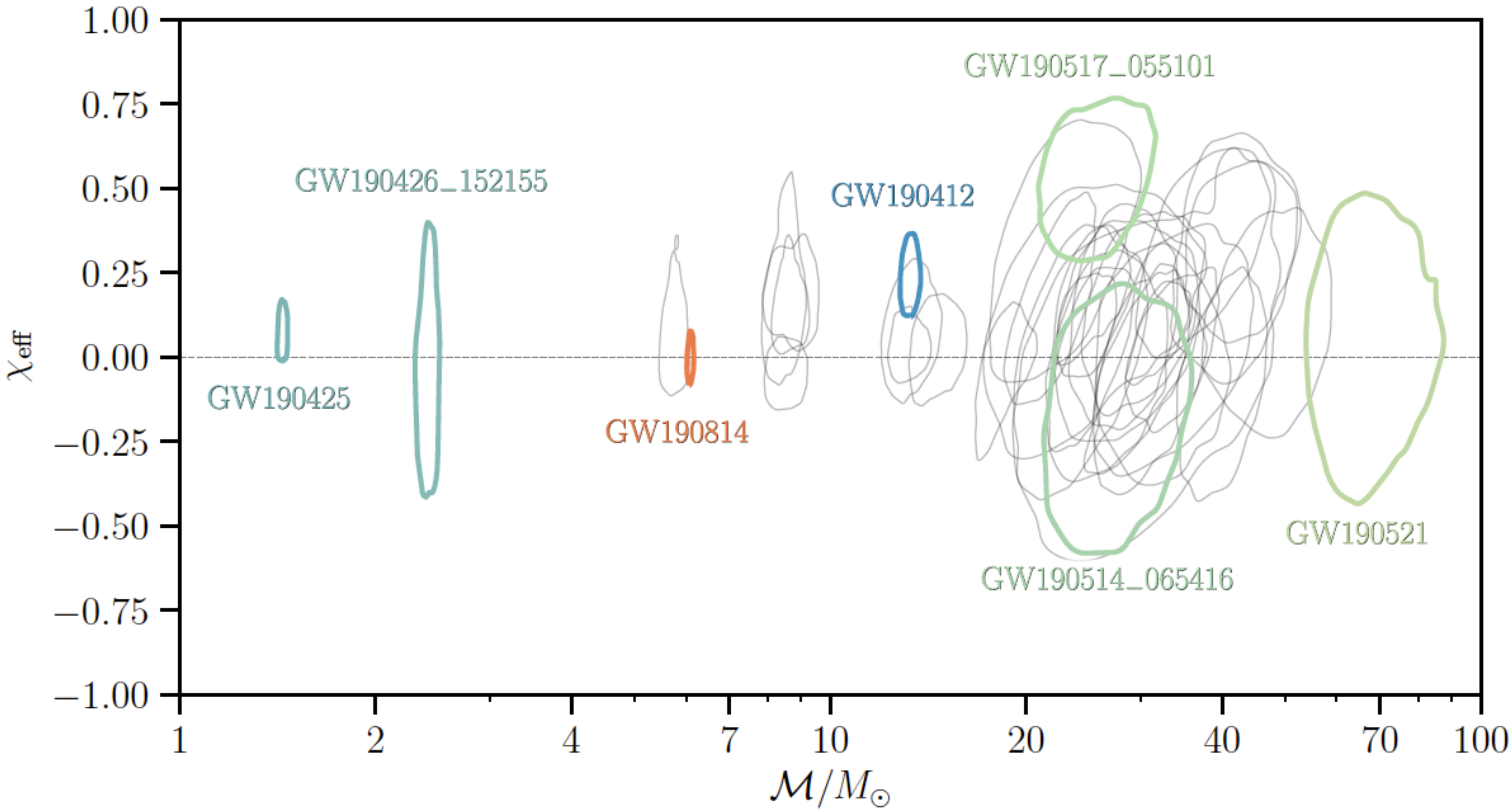


O3a Masses



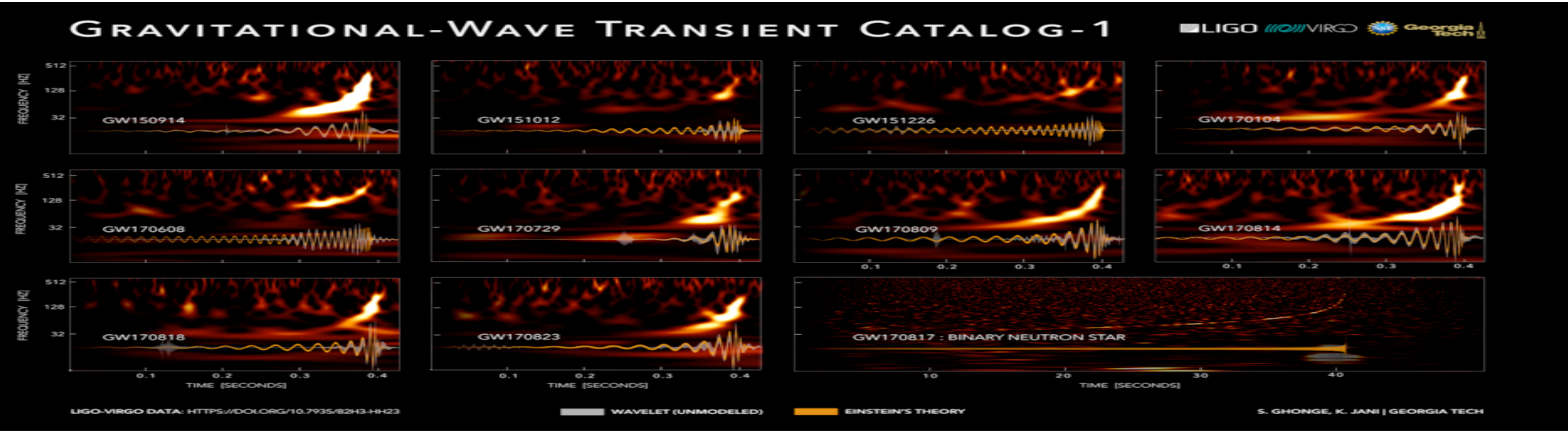
Abbott et al, arXiv:2010.14527(2020)

O3a spins

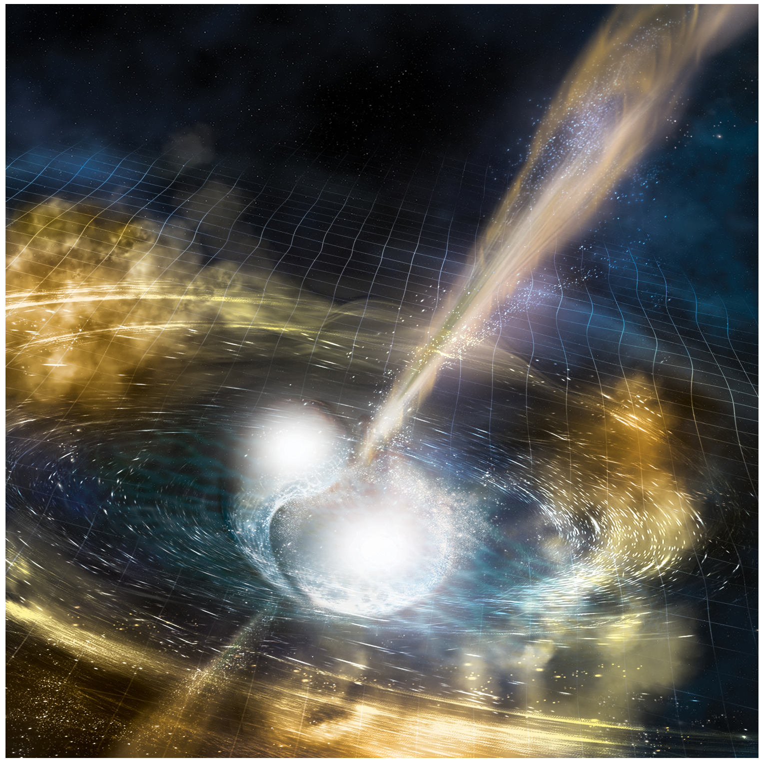


Abbott et al, arXiv:2010.14527(2020)

Exceptional Events



GW170817

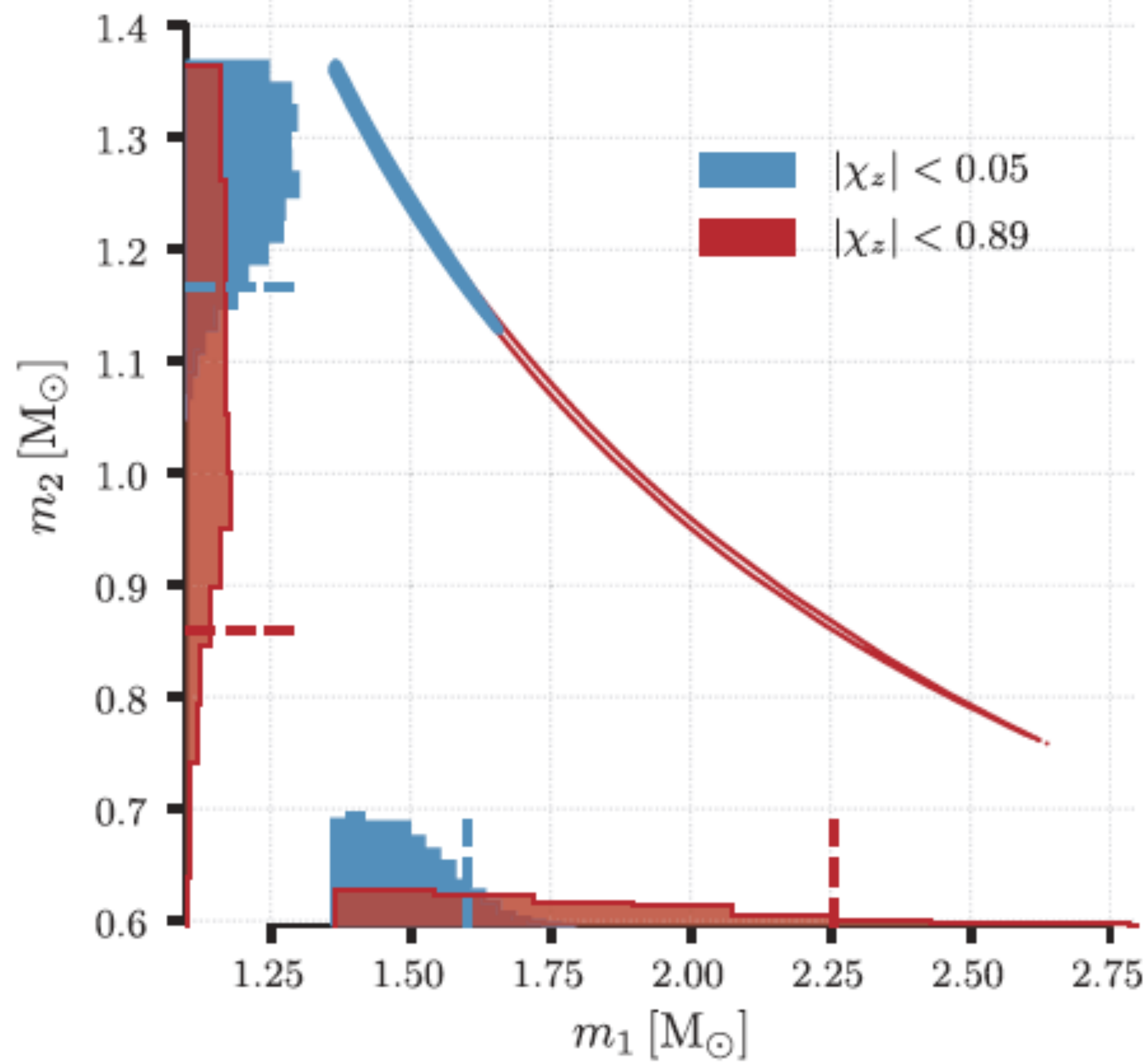


- Detected Aug. 17, 2017
- Brightest GW event yet seen (SNR=32)
- Lasted 100s / 3000 cycles in the detector
- Sky error of 28 deg^2
- Luminosity distance of 40 Mpc
- Multiple EM confirmations in gamma, x-ray, optical, radio
- Confirmation of the link between BNS mergers and SGRBs
- Event associated with galaxy NGC 4993 and kilonova AT2017gfo

GW170817

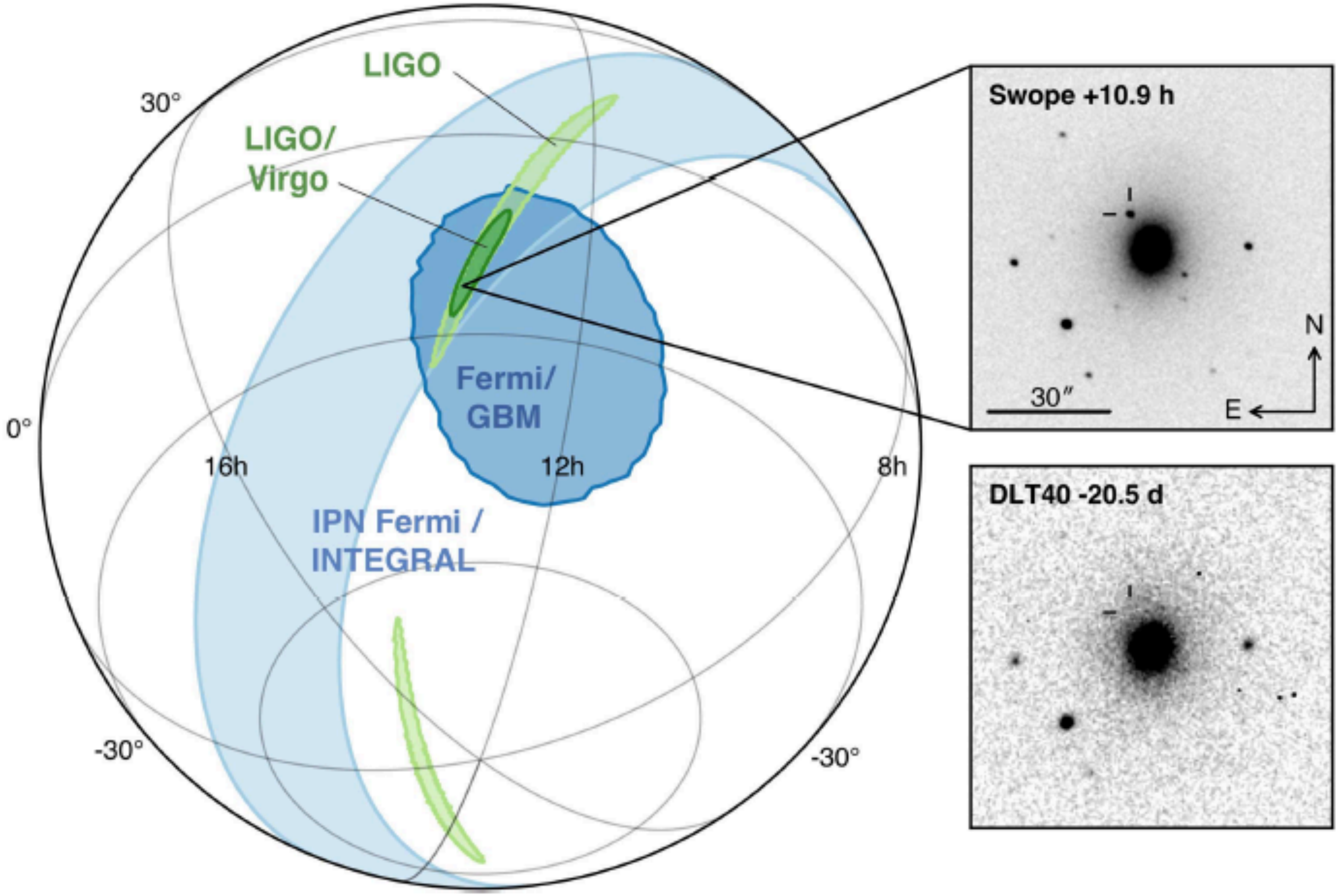
Chirp mass well constrained

Component masses affected by degeneracy between q and the aligned spin components



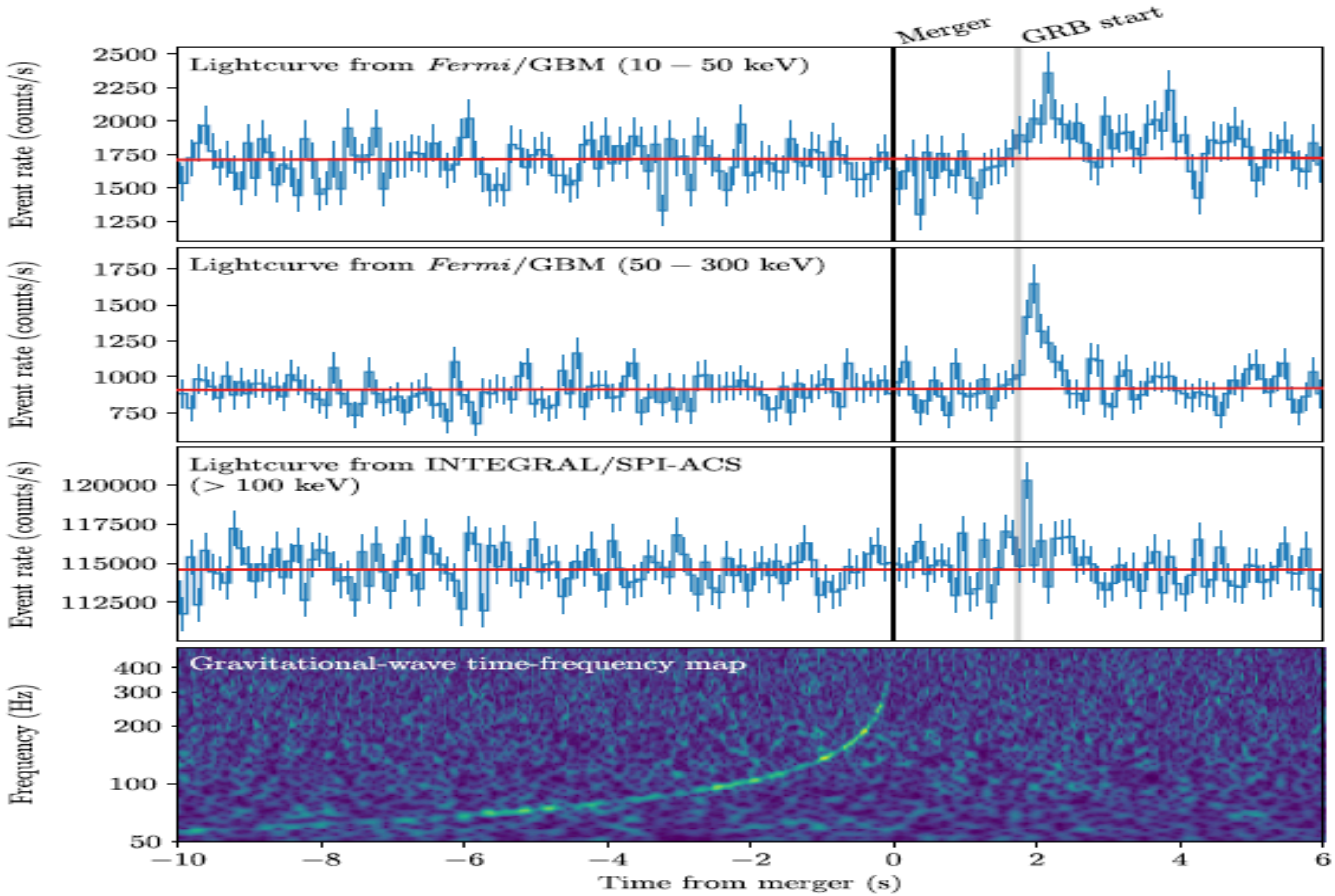
Abbott et al, PRL 119, 161101 (2017)

GW170817



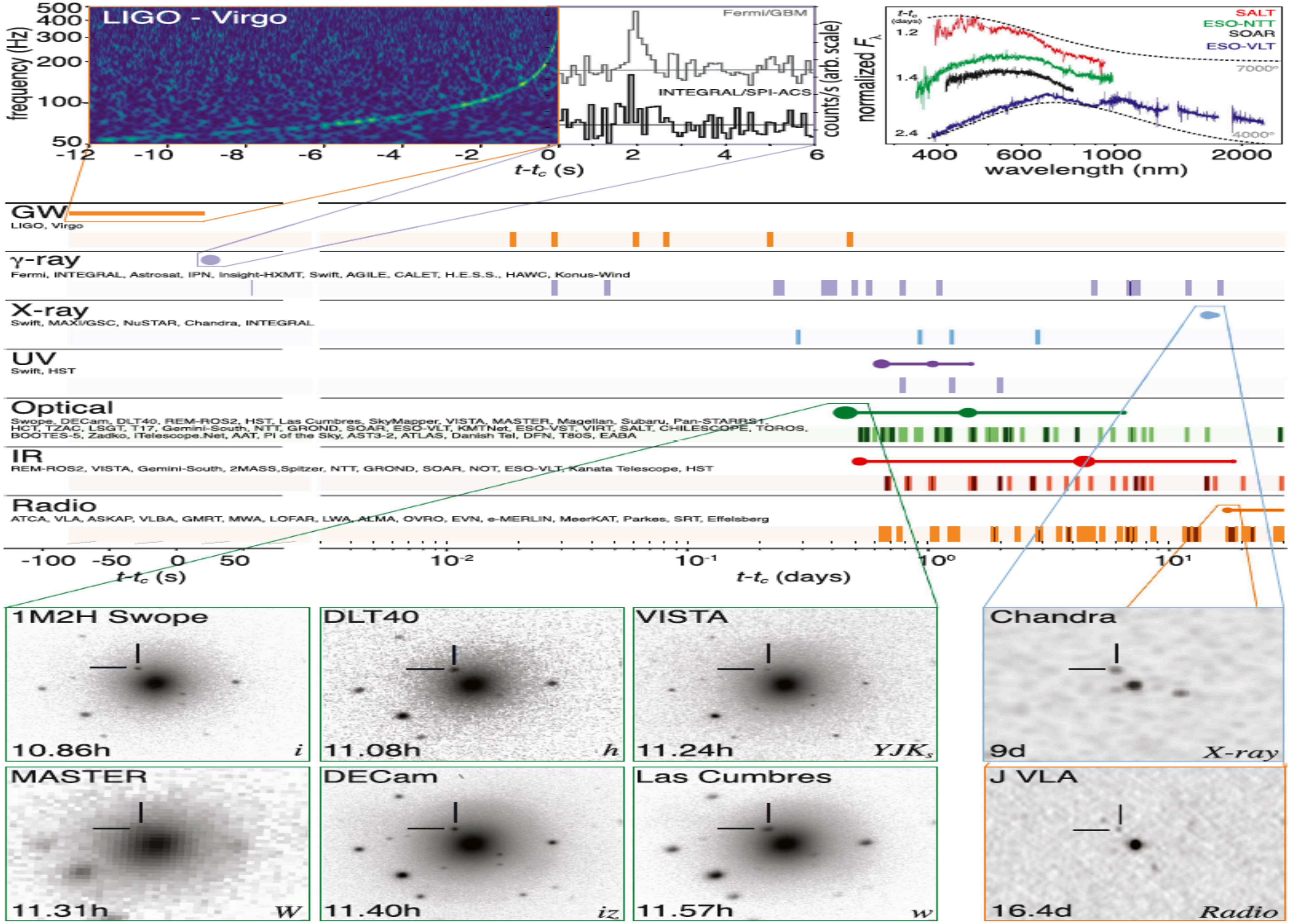
LIGO
LIGO/
Virgo
30°
0°
16h
12h
8h
-30°
-30°
Fermi/
GBM
IPN Fermi /
INTEGRAL
Swope +10.9 h
30″
N
E
DLT40 -20.5 d

GW170817/GRB170817A



Abbott et al, ApJ Letters 848, L13 (2017)

GW170817



LIGO - Virgo
frequency (Hz)
t-t_c (s)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
normalized F_λ
wavelength (nm)
SALT
ESO-NTT
SOAR
ESO-VLT
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
IR
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
t-t_c (days)
1M2H Swope
10.86h
DLT40
11.08h
VISTA
11.24h
Chandra
9d
X-ray
MASTER
11.31h
DECam
11.40h
Las Cumbres
11.57h
J VLA
16.4d
Radio

GW170817

- The time delay between the GW and GRB detections over 130×10^6 Lyrs was

$$\Delta t = (1.74 \pm 0.05)\, s$$

- Defining the fractional difference between the speed of light and GWs as

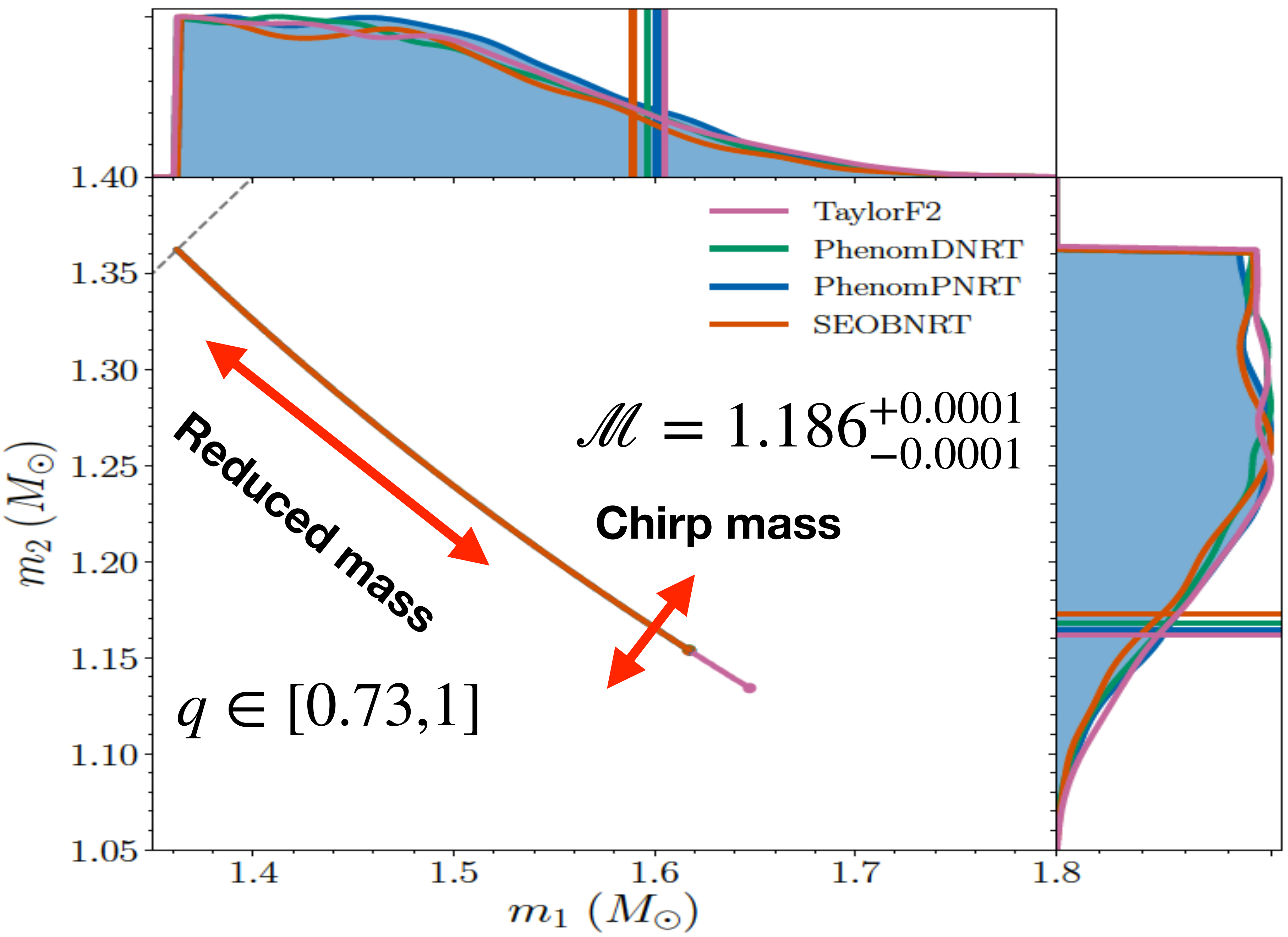
$$\frac{c_g - c}{c} \approx c \frac{\Delta t}{D_L}$$

- We find the following constraint

$$-3 \times 10^{-15} \leq \frac{\Delta c}{c} \leq 7 \times 10^{-16}$$

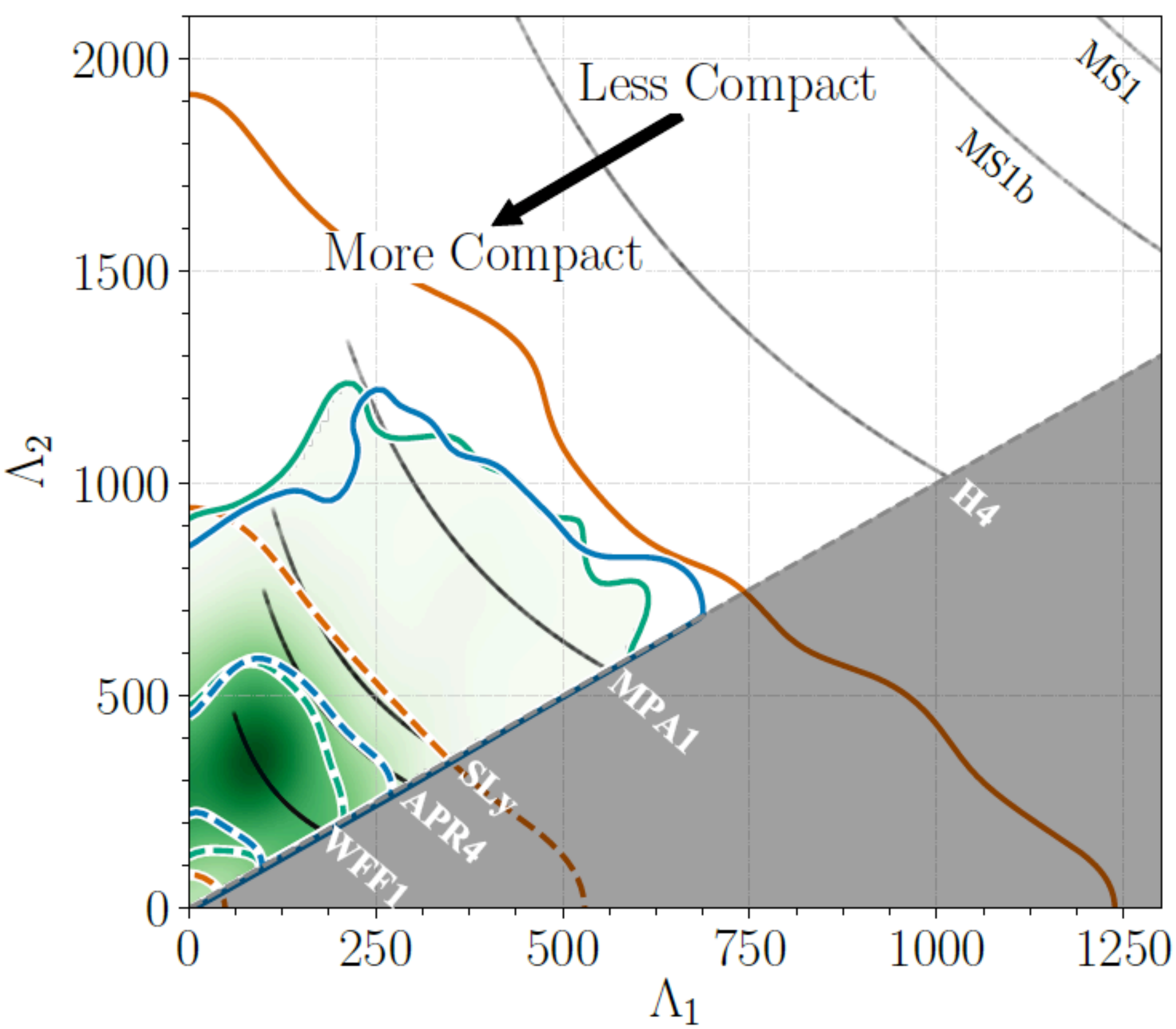
- Large consequences for cosmological theories

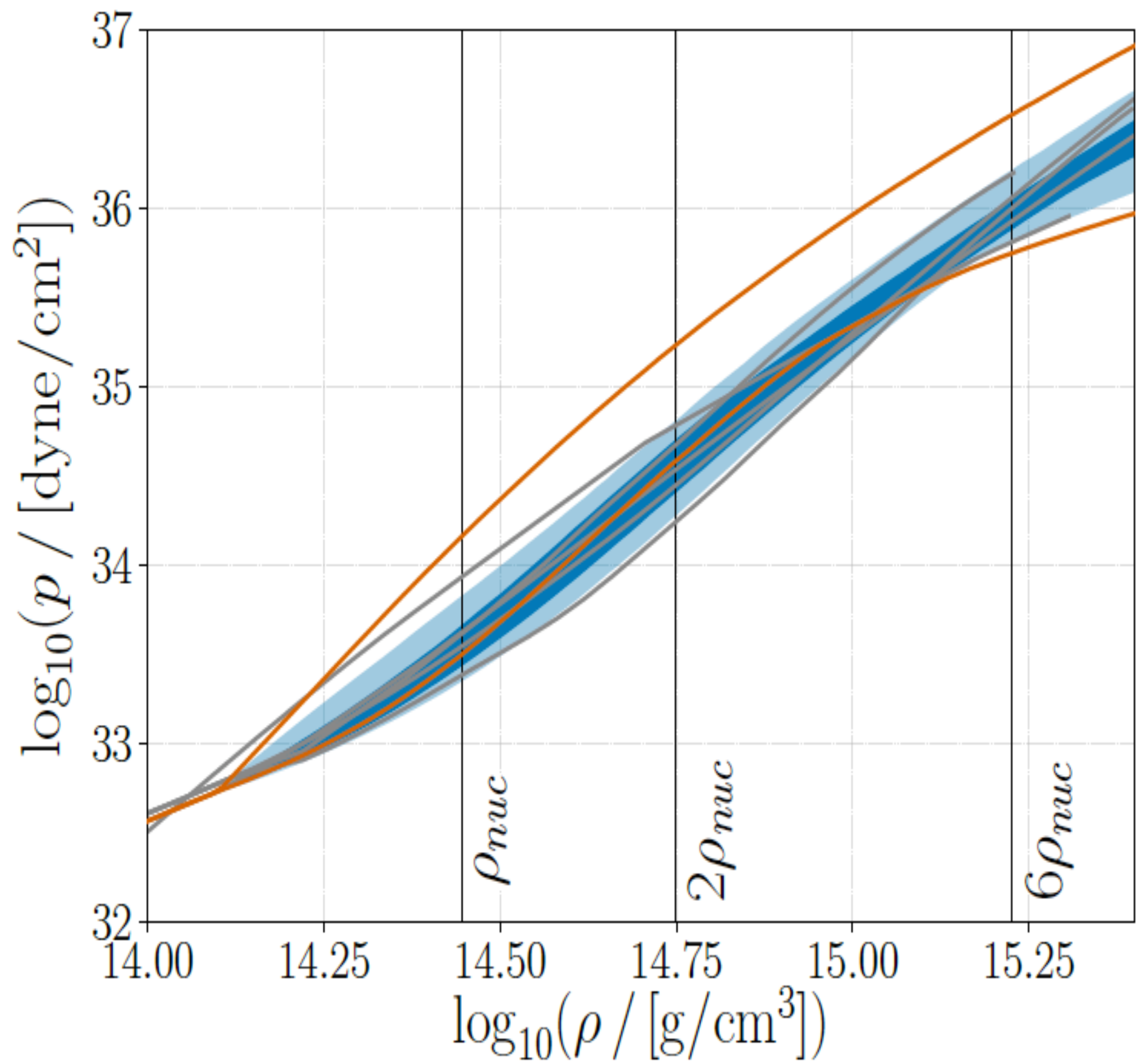
GW170817



Abbott et al, arXiv:1805.11579 (2018)

GW170817



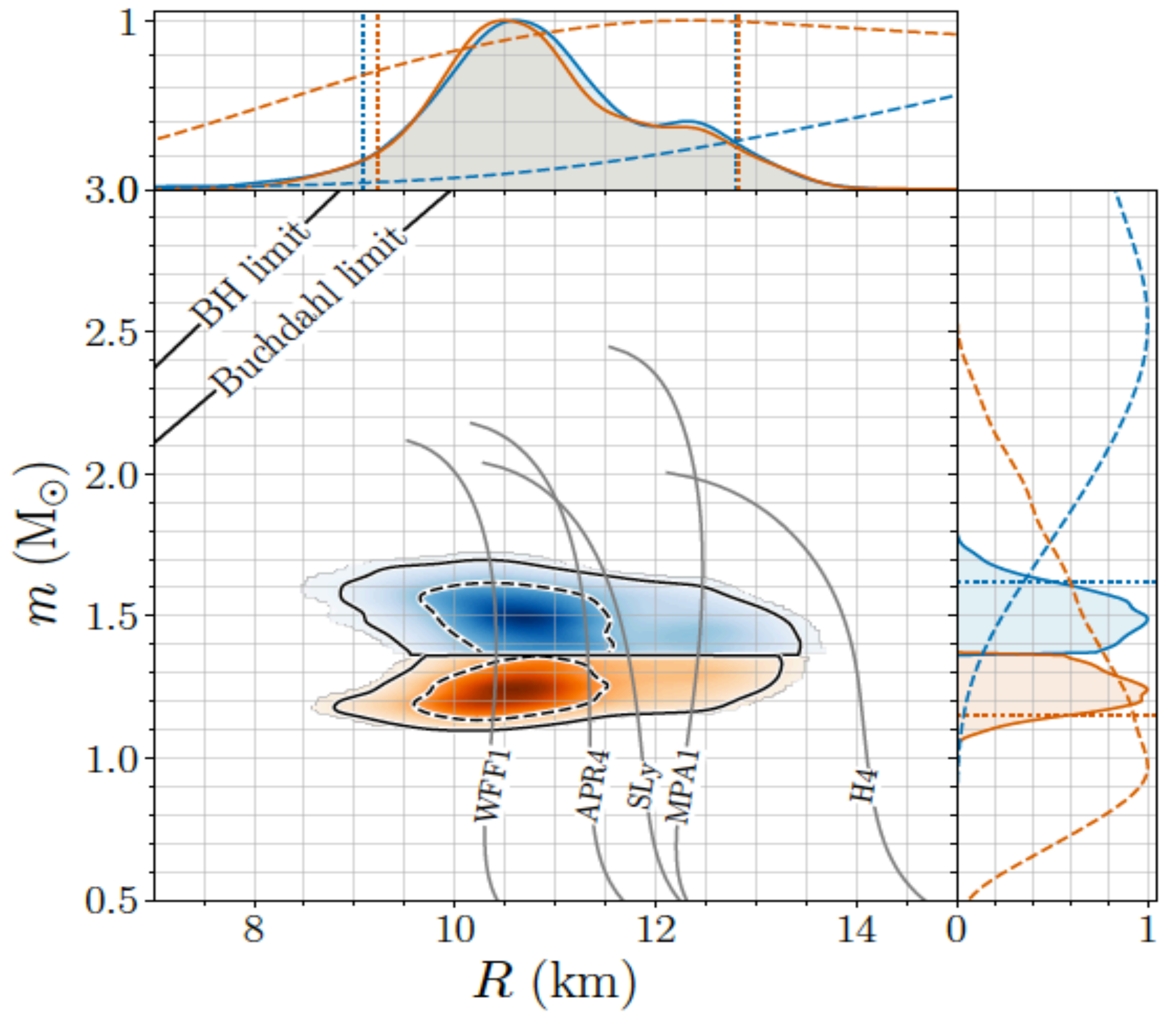


$$\Lambda_{1.4} = 190^{+390}_{-120}$$

$$p(2\rho_{nuc}) = 3.5^{+2.5}_{-1.7} \times 10^{34}\, dyne\, cm^{-2}$$

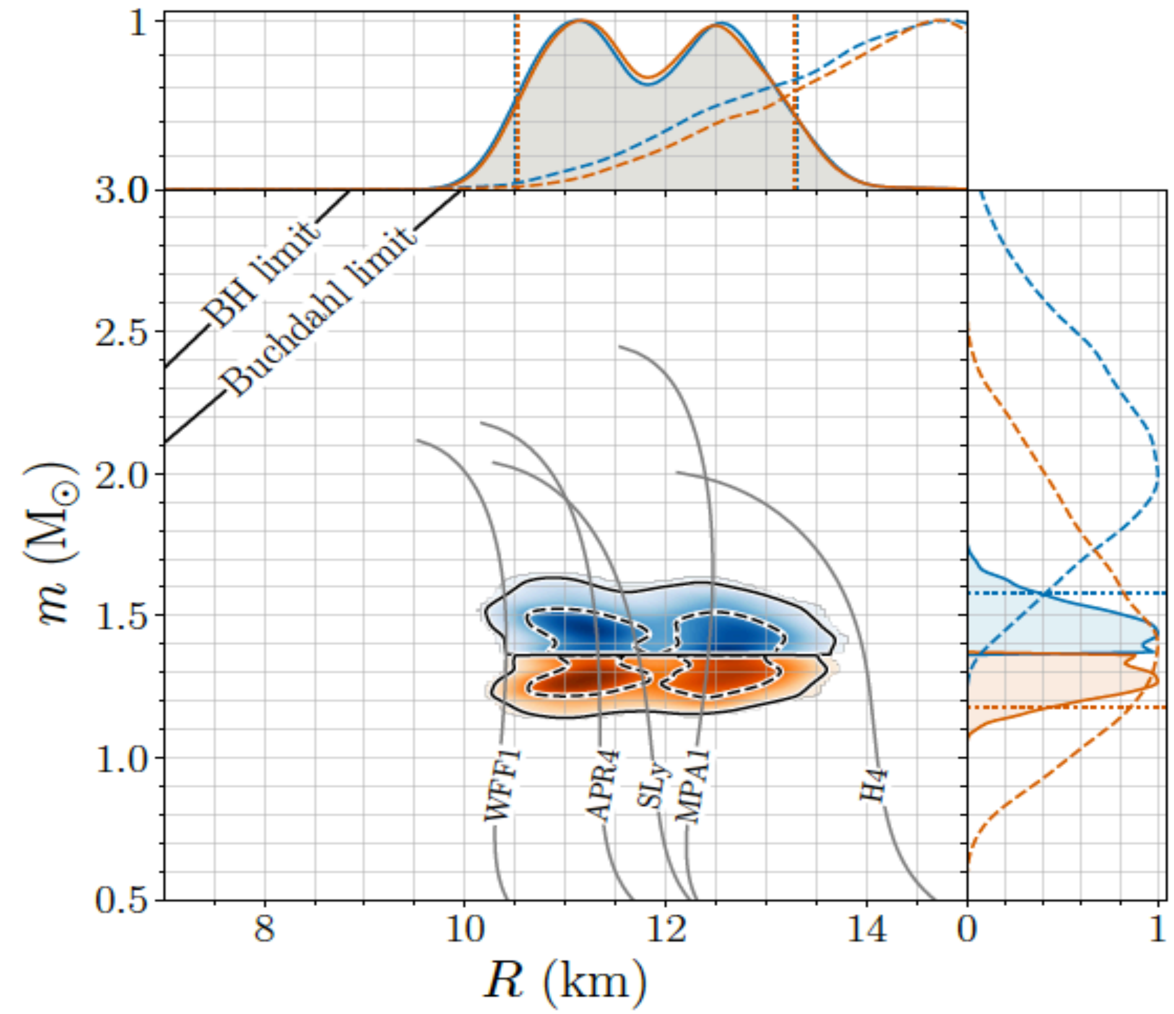
GW170817

EOS-ins (GW only)



$$R_1 = 10.8^{+2.0}_{-1.7}\,km$$
$$R_2 = 10.7^{+2.1}_{-1.5}\,km$$

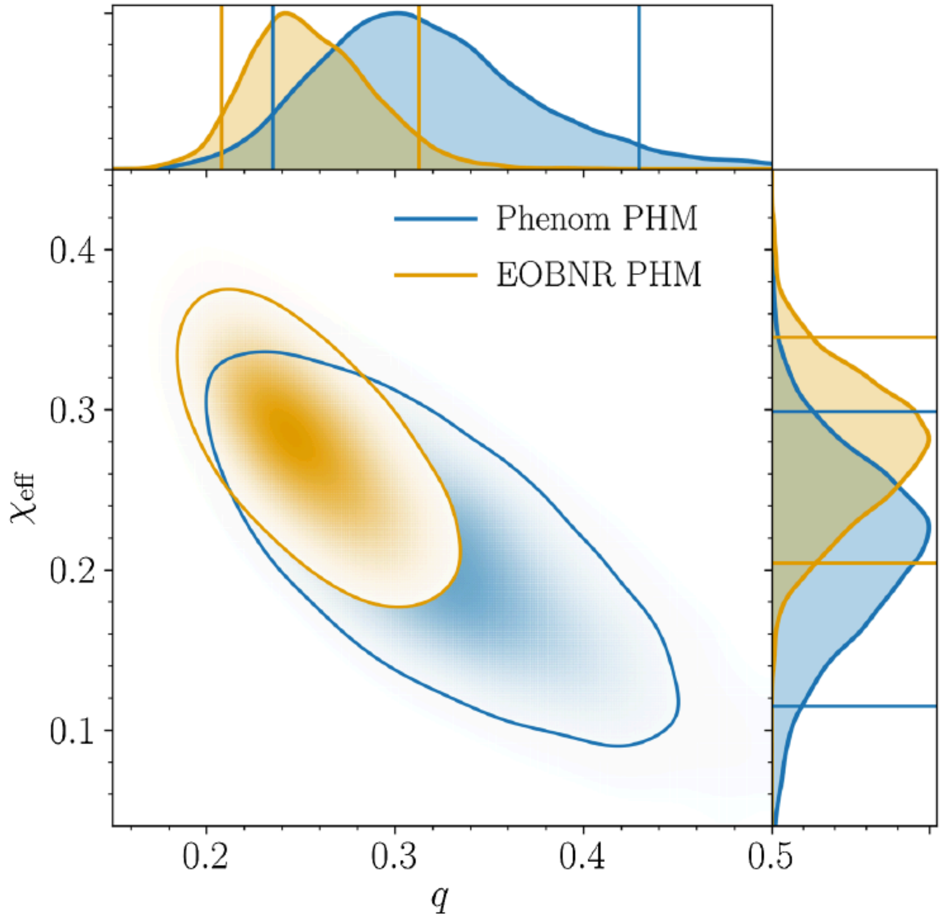
Spec.Param + max. NS mass (GW + EM)



$$R_1 = 11.9^{+1.4}_{-1.4}\,km$$
$$R_2 = 11.9^{+1.4}_{-1.4}\,km$$

GW190412

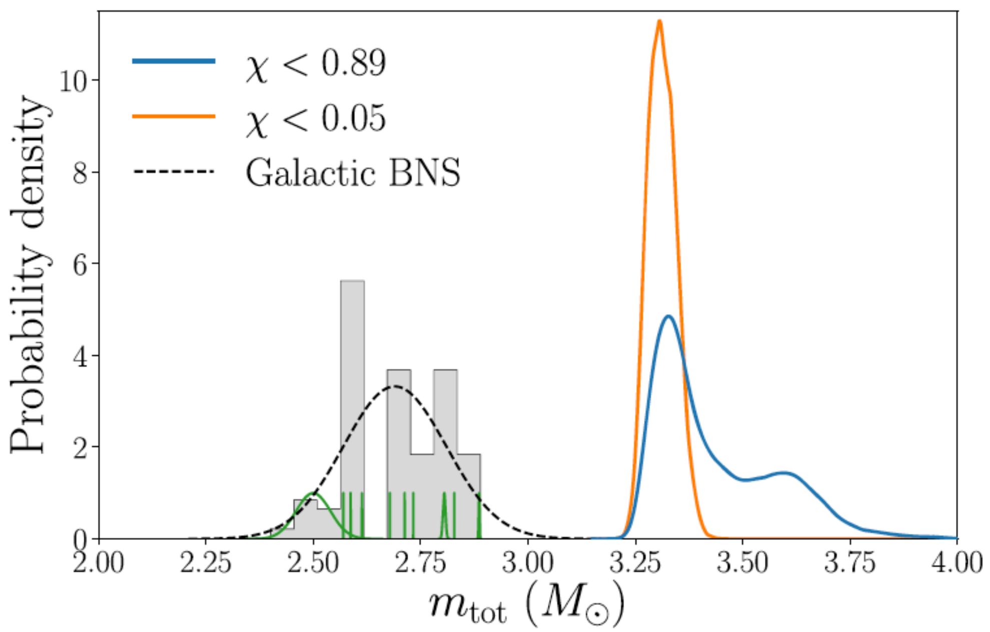
- BBH with $(m_1, m_2) = (30, 8)\ M_\odot$
- $D_L = 740\ Mpc,\ z = 0.15$
- Most asymmetric system
- First evidence of higher order multipoles as predicted by GR



Abbott et al, Phys.Rev.D 102, 043015 (2020)

GW190425

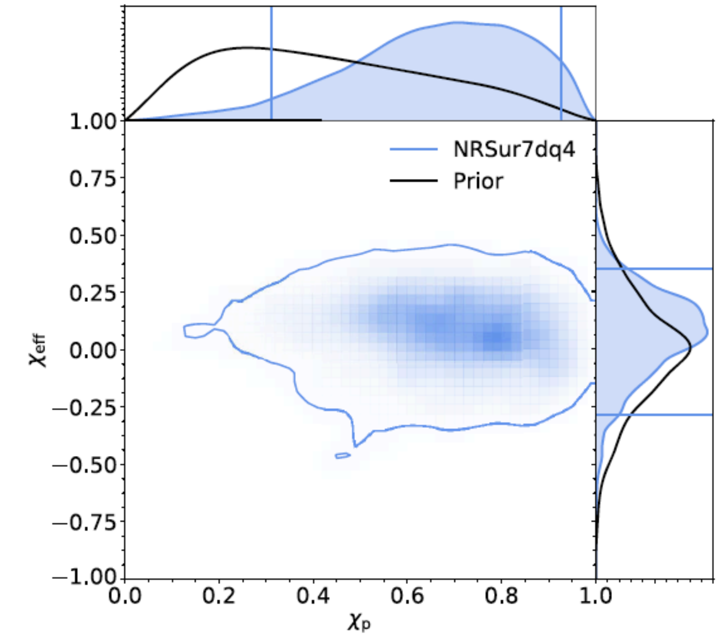
- Potential BNS system
- Total mass of $3.4\ M_\odot$
- Masses significantly larger than any other known BNS
- Cannot rule out BBH using GWs

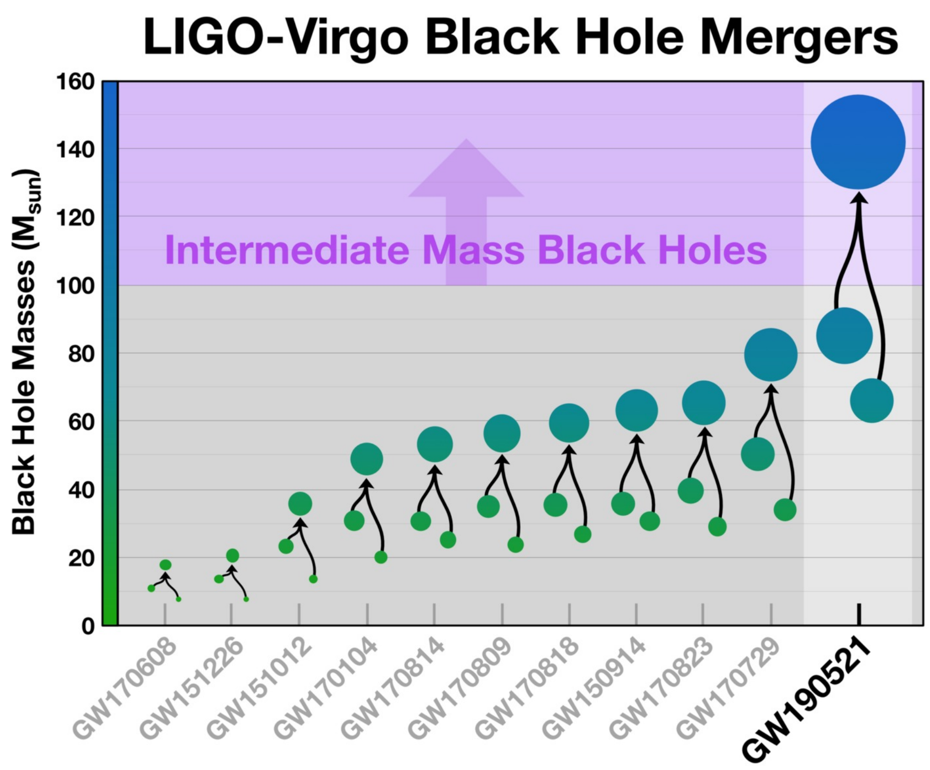


Abbott et al, ApJ Letters 892, L3 (2020)

GW190521

- BBH with $(m_1, m_2) = (85, 66)\ M_\odot$
- Primary is sitting in the pair-instability mass gap
- Remnant has a mass of $142\ M_\odot$
- First evidence of an IMBH formation
- Strong evidence for precession
- Formation channel unclear

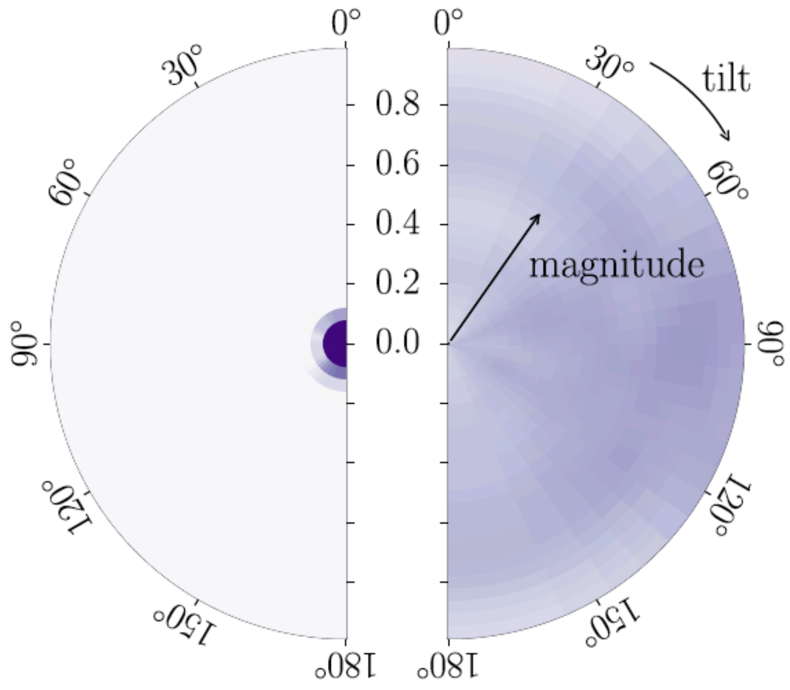




Abbott et al, Phys.Rev.D 125, 101102 (2020)

GW190814

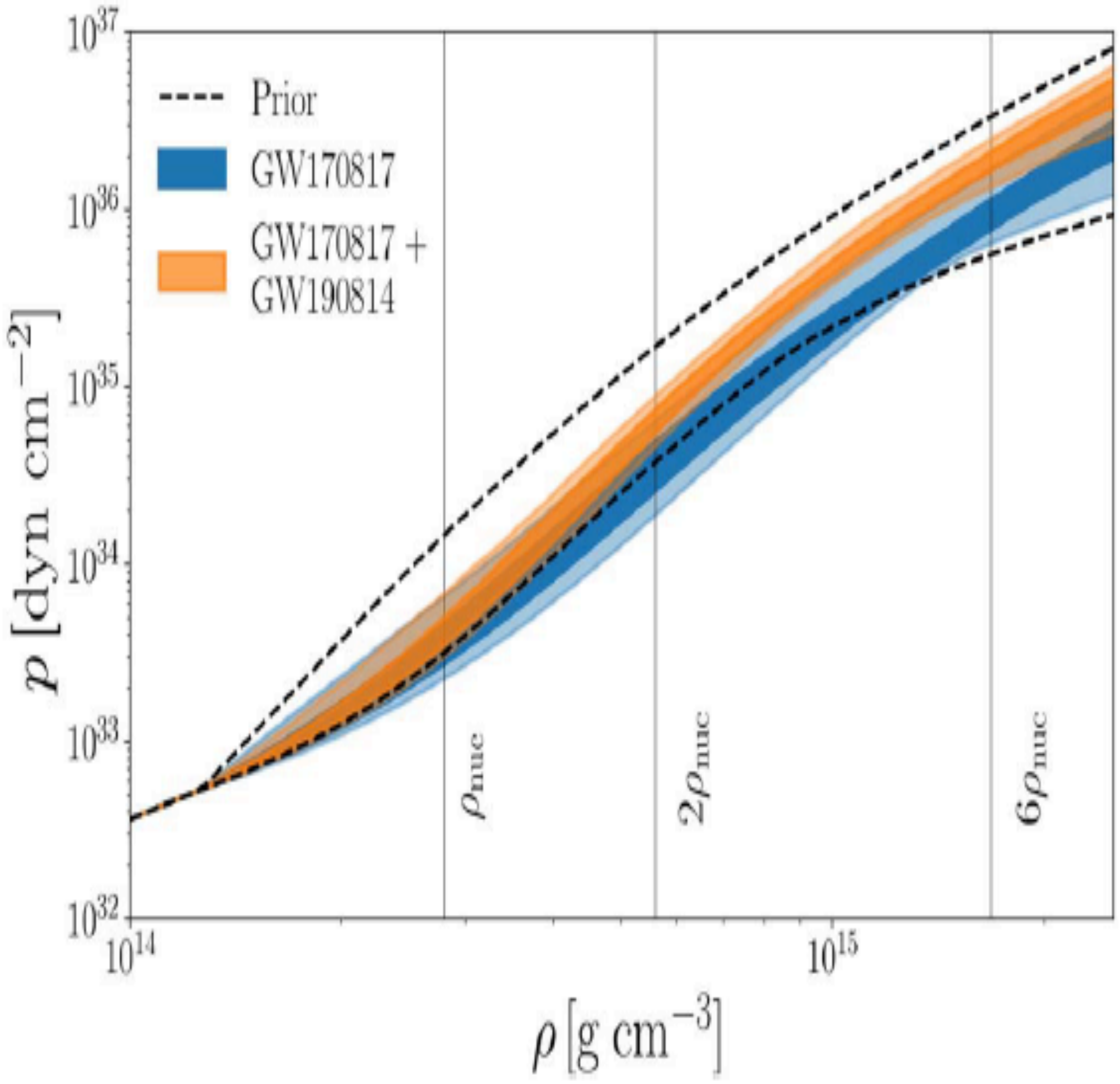
- $(m_1, m_2) = (23, 2.6)\ M_\odot$
- Secondary object in lower mass gap of $2.5\text{-}5\ M_\odot$
- Either lightest BH or heaviest NS ever detected
- If this is a new class of binary, $R = 1\text{-}23\ Gpc^{-3}\ yr^{-1}$
- Spin of secondary object is unconstrained
- Could be a highly rotating NS, BH or something more exotic



Abbott et al, ApJ Letters 896, L44 (2020)

Neutron star EOS

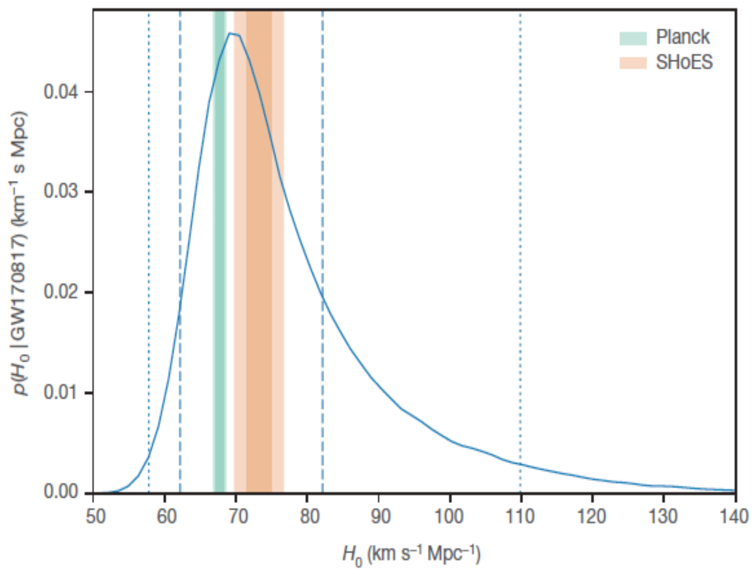
- GW190814 was a much lower SNR event
- More distant (*241 Mpc*)



Abbott et al, ApJ Letters 896, L44 (2020)

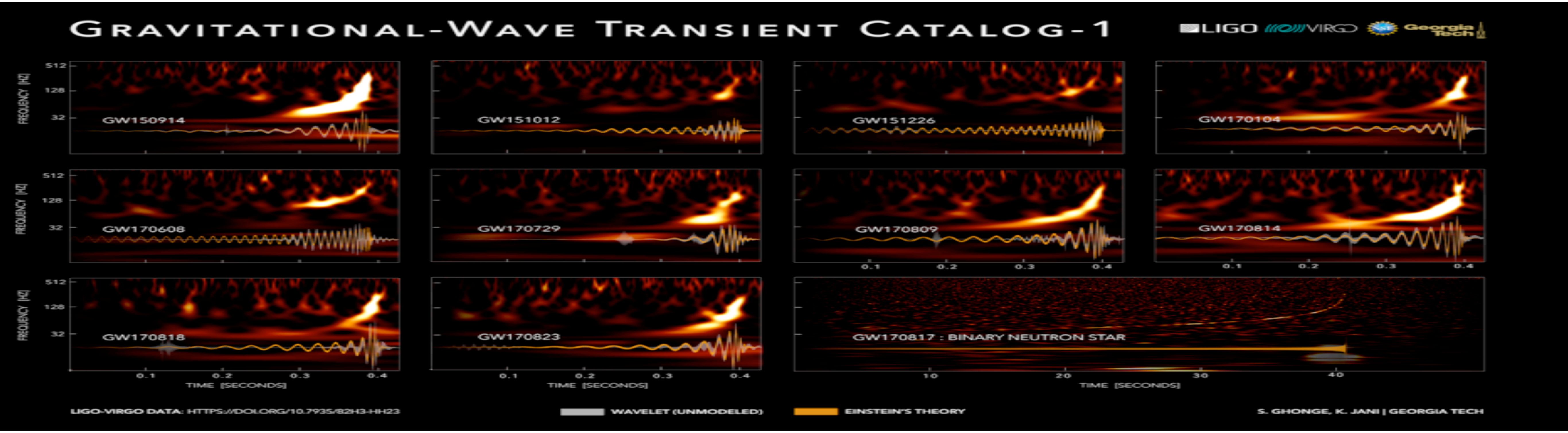
Cosmology

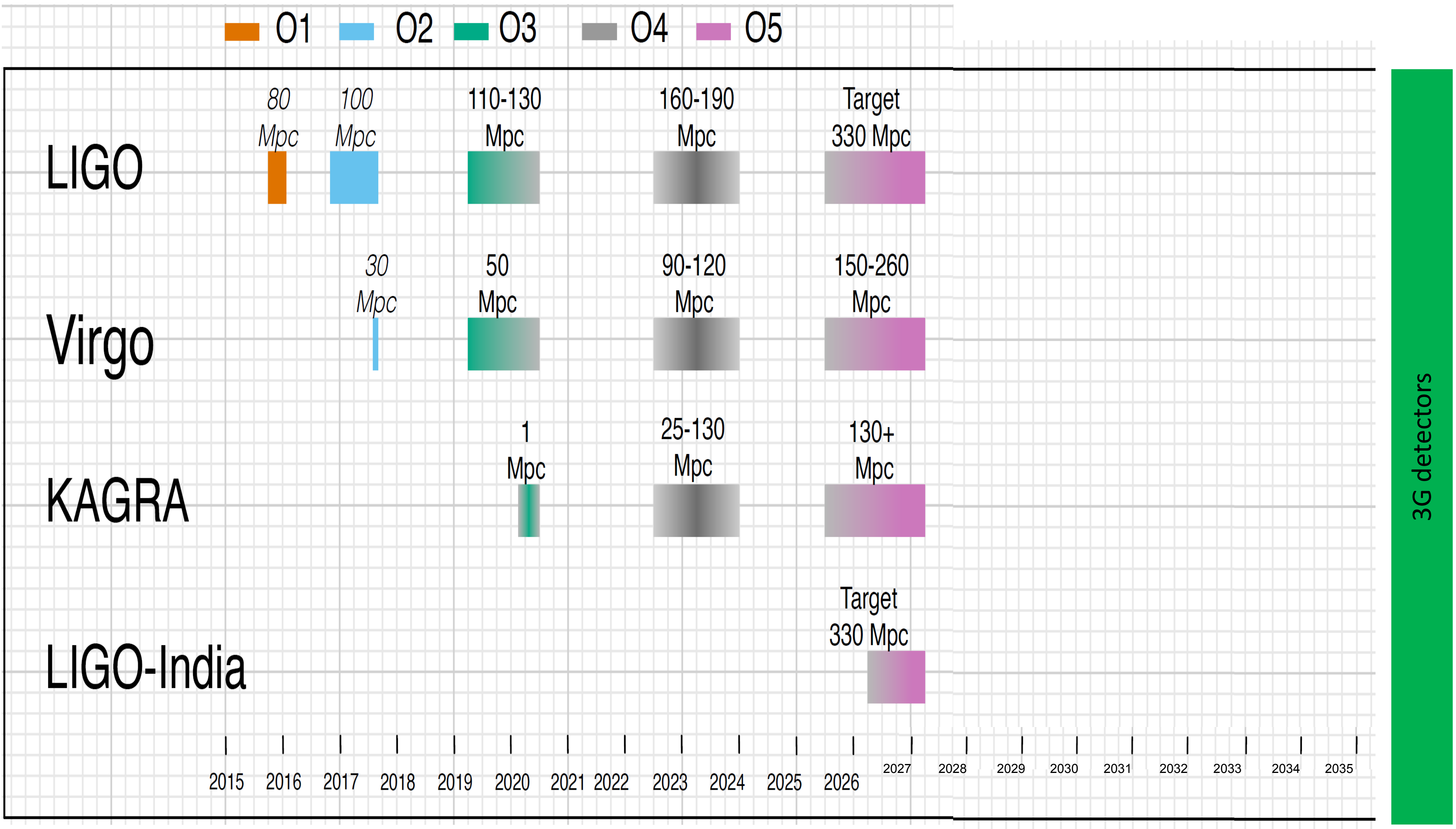
- Estimate Hubble's constant using standard sirens
- No cosmic distance ladder needed $h(t) \sim \frac{1}{D_L}$
- Best with EM counterpart
- Statistical method for "dark" sirens
  - e.g GW170817 : $H_0 = 69^{+22}_{-8}\, km\, s^{-1}\, Mpc$
  - +GW190814 : $H_0 = 70^{+17}_{-8}\, km\, s^{-1}\, Mpc$



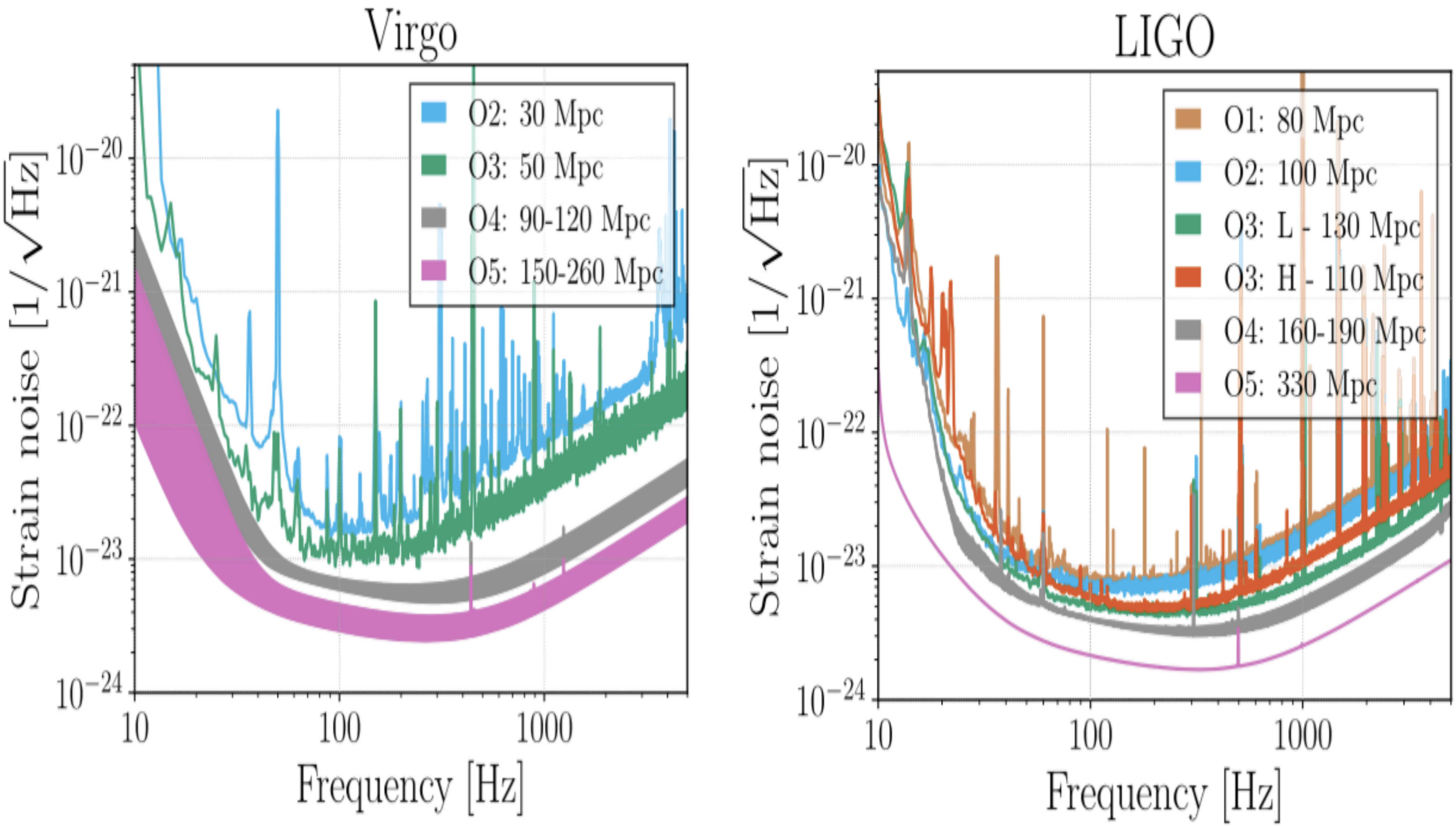
Abbott et al, Nature (2017)

Evolution to O4/O5+




O1
O2
O3
O4
O5
LIGO
80 Mpc
100 Mpc
110-130 Mpc
160-190 Mpc
Target 330 Mpc
Virgo
30 Mpc
50 Mpc
90-120 Mpc
150-260 Mpc
KAGRA
1 Mpc
25-130 Mpc
130+ Mpc
LIGO-India
Target 330 Mpc
2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035
3G detectors

O4/O5

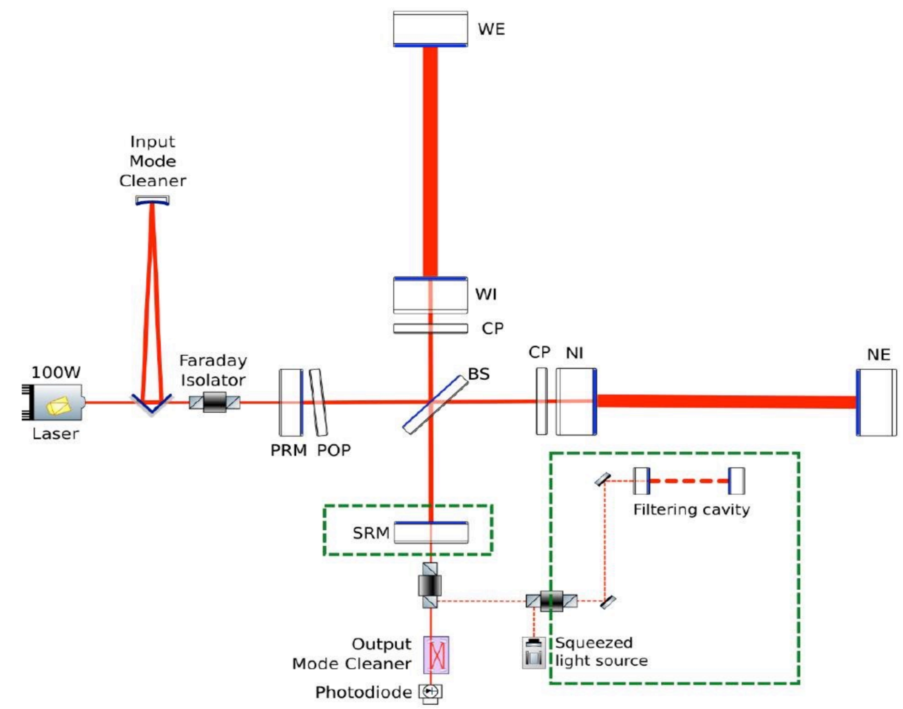

Virgo
O2: 30 Mpc
O3: 50 Mpc
O4: 90-120 Mpc
O5: 150-260 Mpc
Strain noise [1/√Hz]
Frequency [Hz]
LIGO
O1: 80 Mpc
O2: 100 Mpc
O3: L - 130 Mpc
O3: H - 110 Mpc
O4: 160-190 Mpc
O5: 330 Mpc
Strain noise [1/√Hz]
Frequency [Hz]

Advanced Virgo+

Coordinated strategy with Advanced LIGO

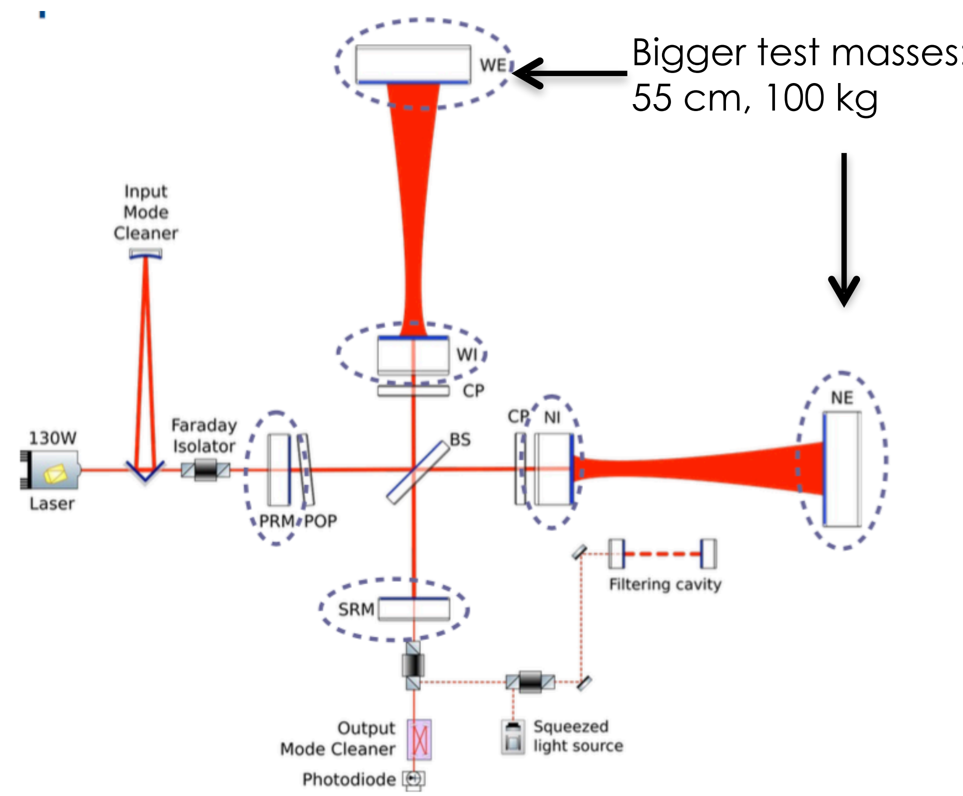
Phase 1:

- Use signal recycling (used by Adv LIGO in O3)
- Increase laser power from 26W to 40W
- Use frequency dependent squeezing



Phase 2:

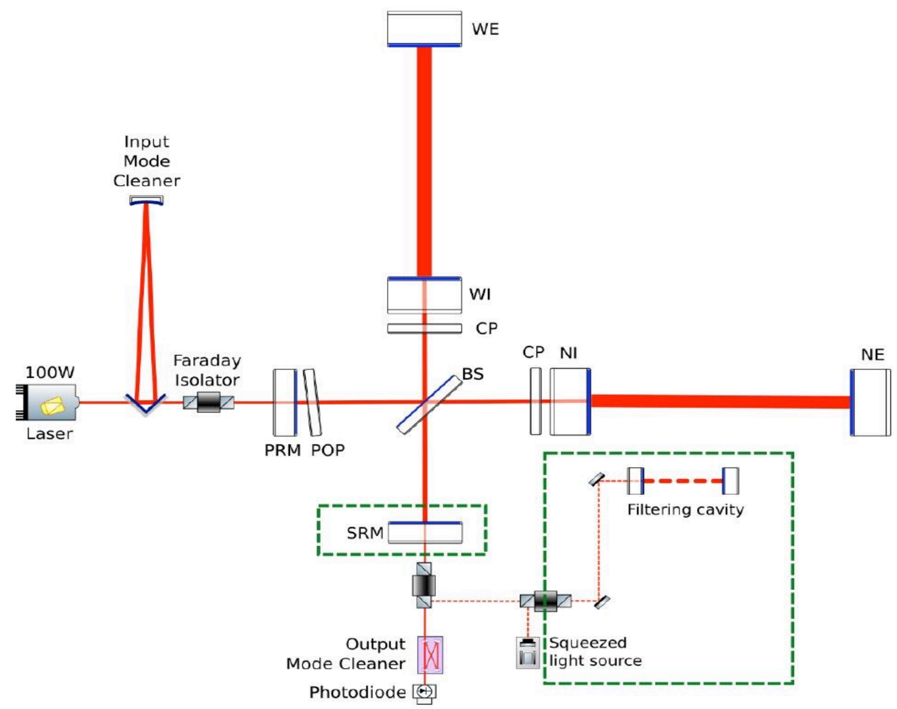
- Increase beam size on end test masses
- R&D on coating mechanical / optical properties
- Quantum noise reduction
- Laser power increase from 40W to 80W

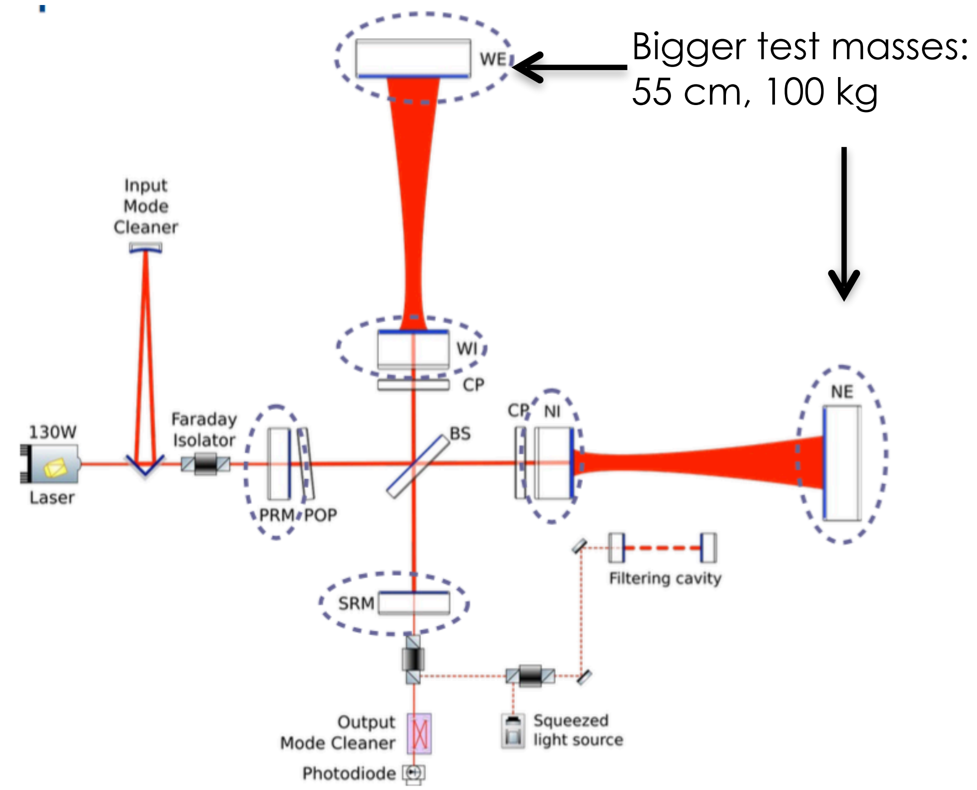


Advanced Virgo+

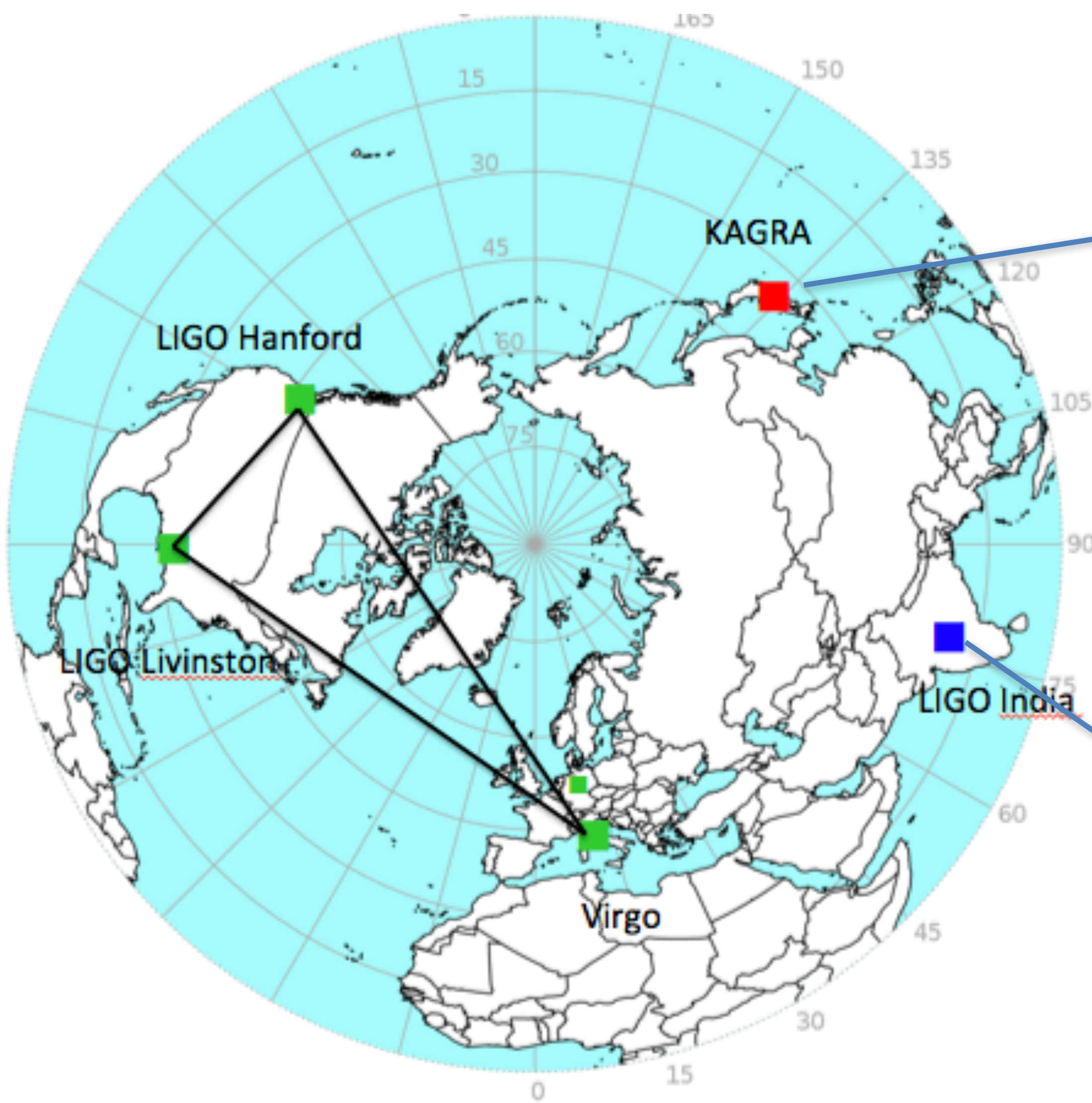
At present:

- The IFO and filter cavity has been locked
- Noise hunting will take place in 1st half of 2022
- O4 starting date to be announced in Nov.
- Most likely, second half of 2022





Kagra & LIGO India

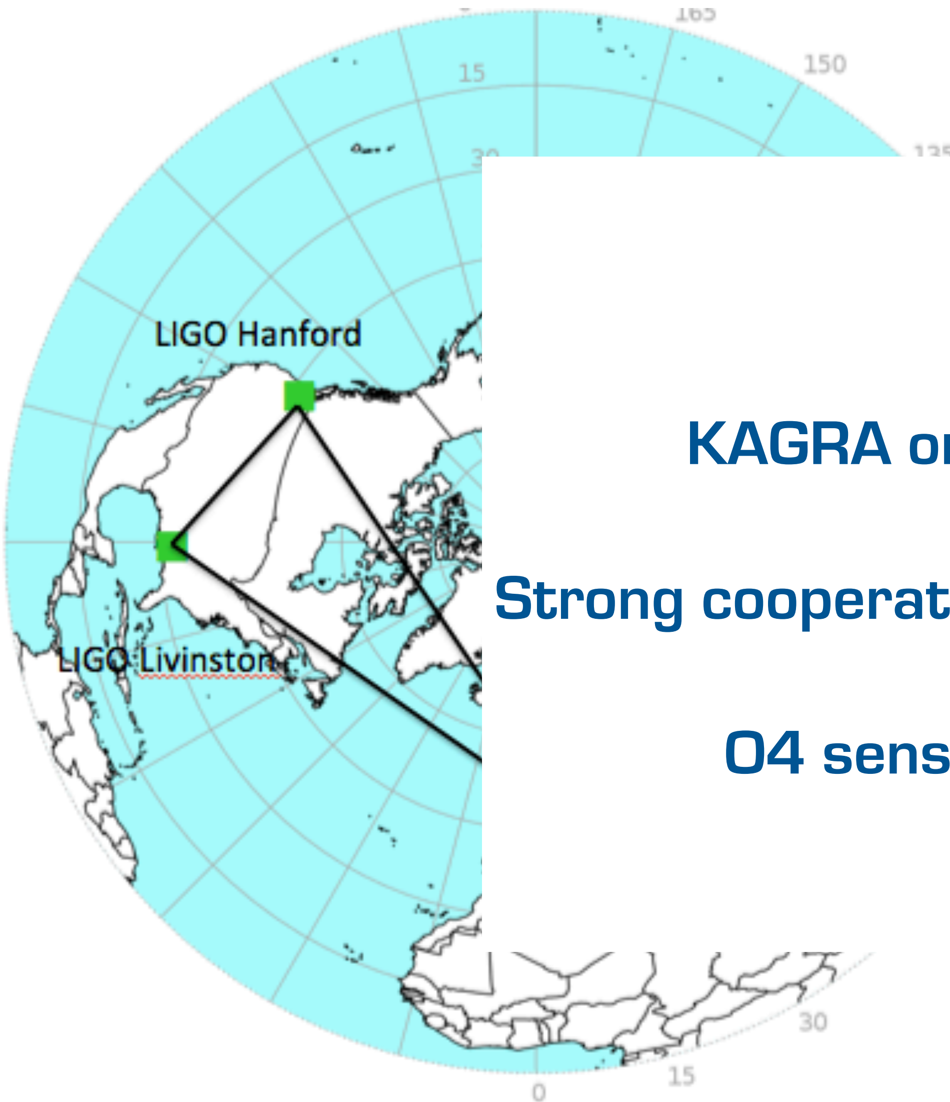


KAGRA

https://gwcenter.icrr.u-tokyo.ac.jp/en/

LIGO India

Kagra & LIGO India



KAGRA on track to join O4.

Strong cooperation on data analysis etc.

O4 sensitivity uncertain

KAGRA

ter.icrr.u-tokyo.ac.jp/en/

LIGO India

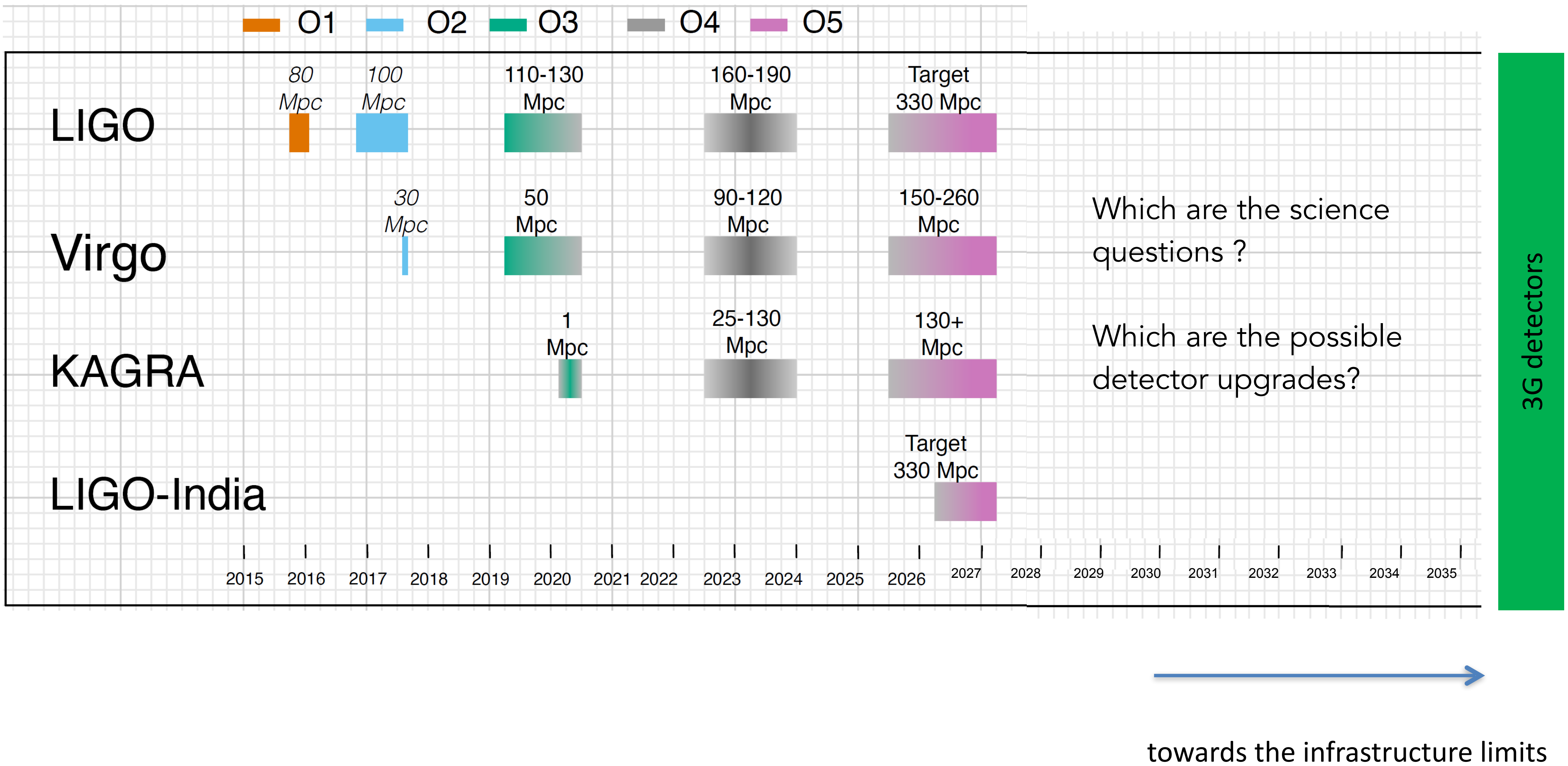
O4/05 detection range

		O1	O2	O3	O4	O5
BNS Range (Mpc)	aLIGO	80	100	110 – 130	160 – 190	330
	AdV	-	30	50	90 – 120	150 – 260
	KAGRA	-	-	8 – 25	25 – 130	130+
BBH Range (Mpc)	aLIGO	740	910	990 – 1200	1400 – 1600	2500
	AdV	-	270	500	860 – 1100	1300 – 2100
	KAGRA	-	-	80 – 260	260 – 1200	1200+
NSBH Range (Mpc)	aLIGO	140	180	190 – 240	300 – 330	590
	AdV	-	50	90	170 – 220	270 – 480
	KAGRA	-	-	15 – 45	45 – 290	290+
Burst Range (Mpc)	aLIGO	50	60	80 – 90	110 – 120	210
$[E_{GW} = 10^{-2} M_{\odot} c^2]$	AdV	-	25	35	65 – 80	100 – 155
	KAGRA	-	-	5 – 25	25 – 95	95+
Burst Range (kpc)	aLIGO	15	20	25 – 30	35 – 40	70
$[E_{GW} = 10^{-9} M_{\odot} c^2]$	AdV	-	10	10	20 – 25	35 – 50
	KAGRA	-	-	0 – 10	10 – 30	30+

O4 Event number predictions

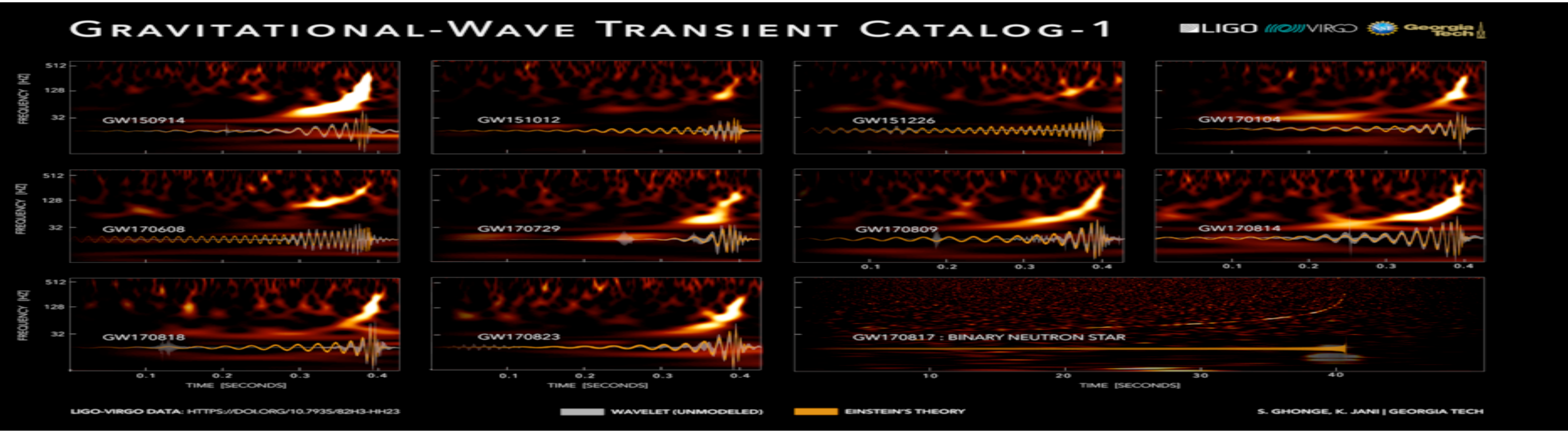
Observation Run	Network	Expected BNS Detections	Expected NSBH Detections	Expected BBH Detections
O3	HLV	1^{+12}_{-1}	0^{+19}_{-0}	17^{+22}_{-11}
O4	HLVK	10^{+52}_{-10}	1^{+91}_{-1}	79^{+89}_{-44}
		Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.
O3	HLV	270^{+34}_{-20}	330^{+24}_{-31}	280^{+30}_{-23}
O4	HLVK	33^{+5}_{-5}	50^{+8}_{-8}	41^{+7}_{-6}
		Comoving Volume (10^3 Mpc^3) 90% c.r.	Comoving Volume (10^3 Mpc^3) 90% c.r.	Comoving Volume (10^3 Mpc^3) 90% c.r.
O3	HLV	120^{+19}_{-24}	860^{+150}_{-150}	16000^{+2200}_{-2500}
O4	HLVK	52^{+10}_{-9}	430^{+100}_{-78}	7700^{+1500}_{-920}

Post-O5

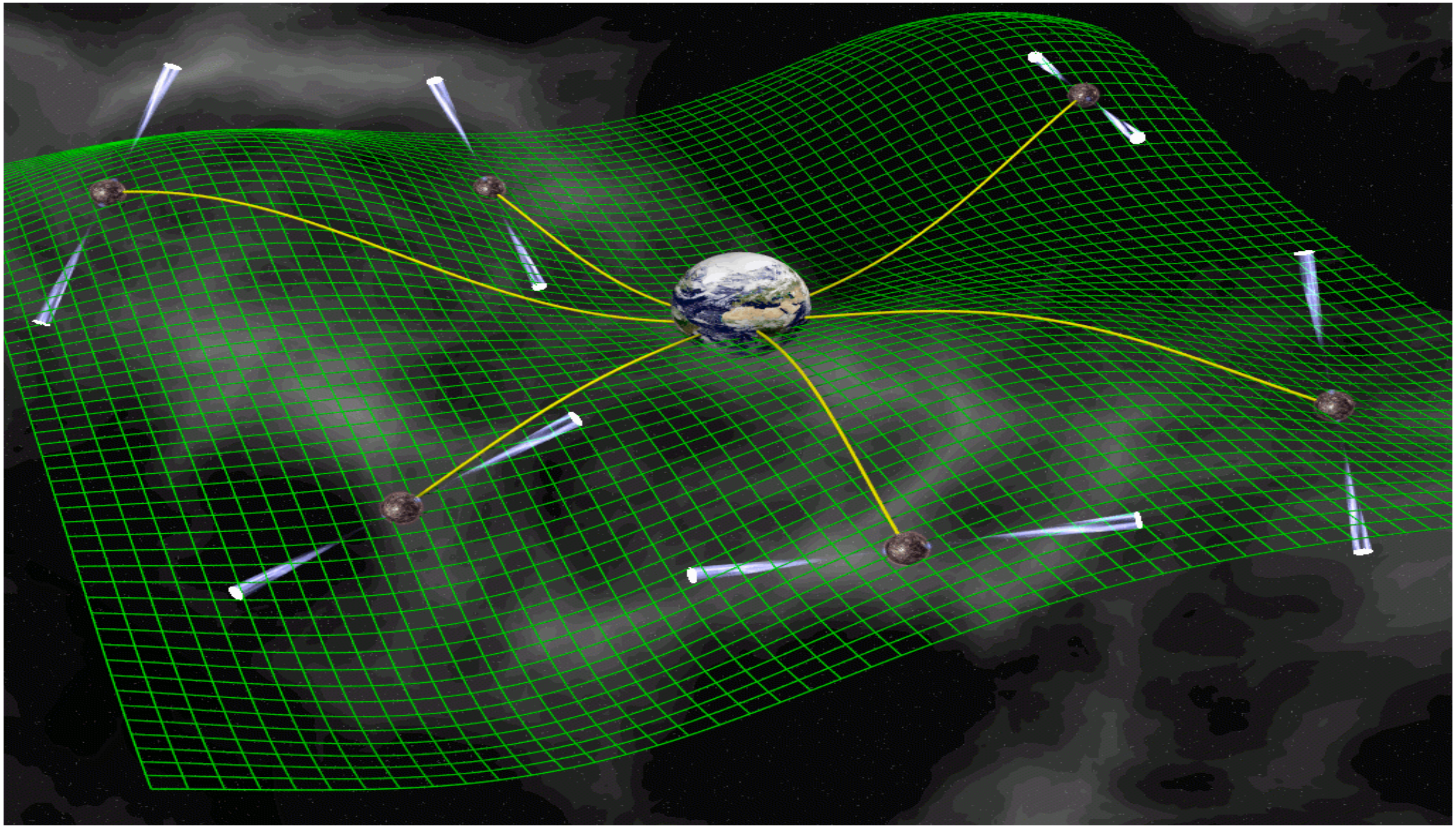


O1 O2 O3 O4 O5
LIGO
80 Mpc
100 Mpc
110-130 Mpc
160-190 Mpc
Target 330 Mpc
Virgo
30 Mpc
50 Mpc
90-120 Mpc
150-260 Mpc
KAGRA
1 Mpc
25-130 Mpc
130+ Mpc
LIGO-India
Target 330 Mpc
2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035
Which are the science questions ?
Which are the possible detector upgrades?
3G detectors
towards the infrastructure limits

Other/Future GW Experiments



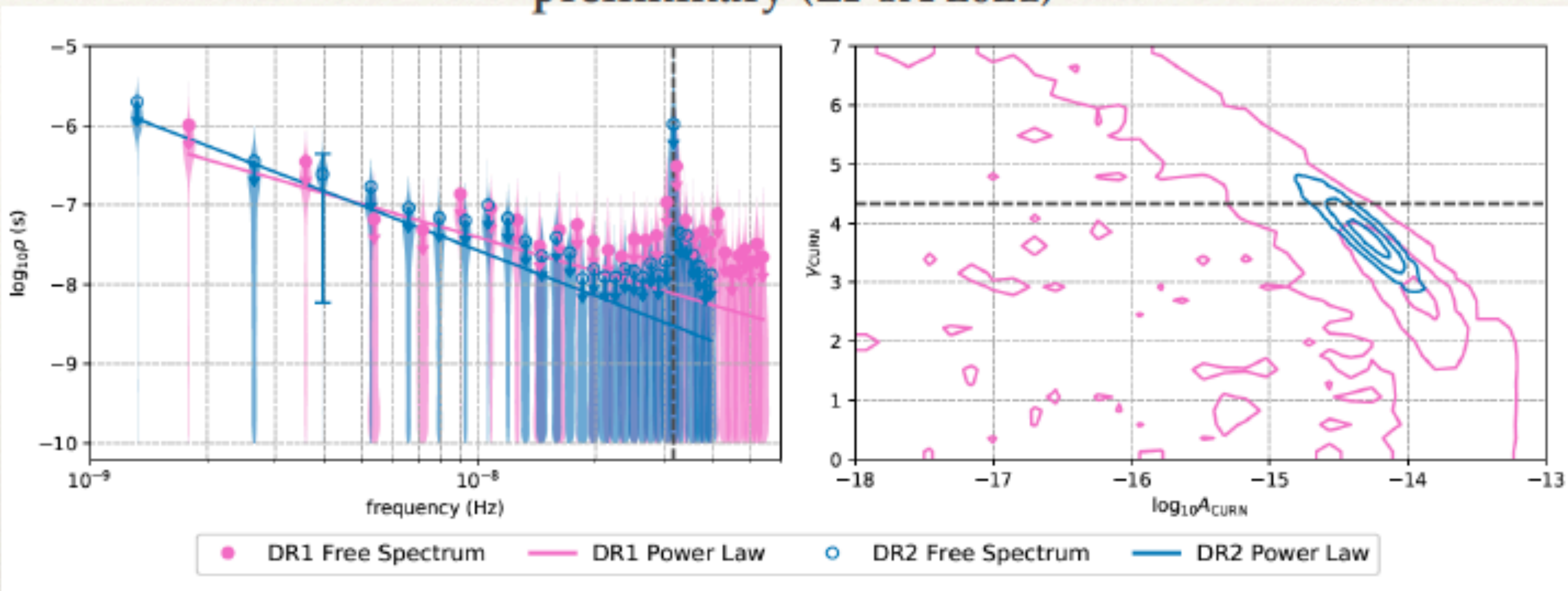
IPTA

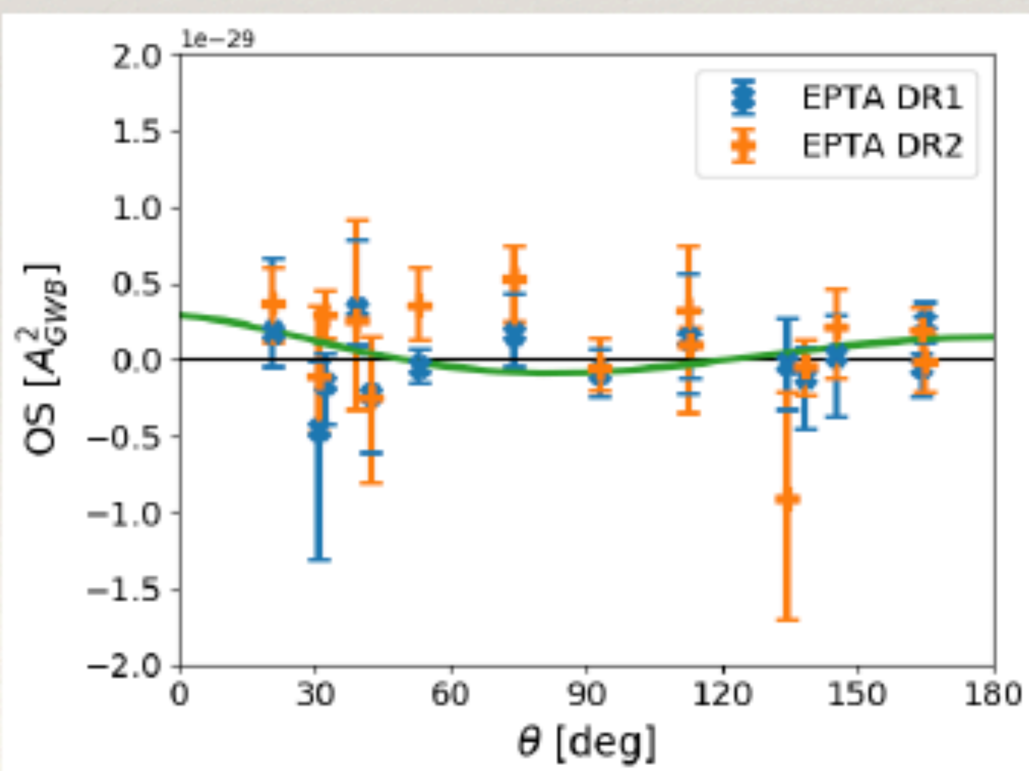


Idea is to use highly stable millisecond pulsars as GW beacons in the nano-Hertz range
Main target is widely separated SMBHBs

Common red noise in EPTA data

preliminary (EPTA 2021)





There is a strong statistical support for presence of common red noise

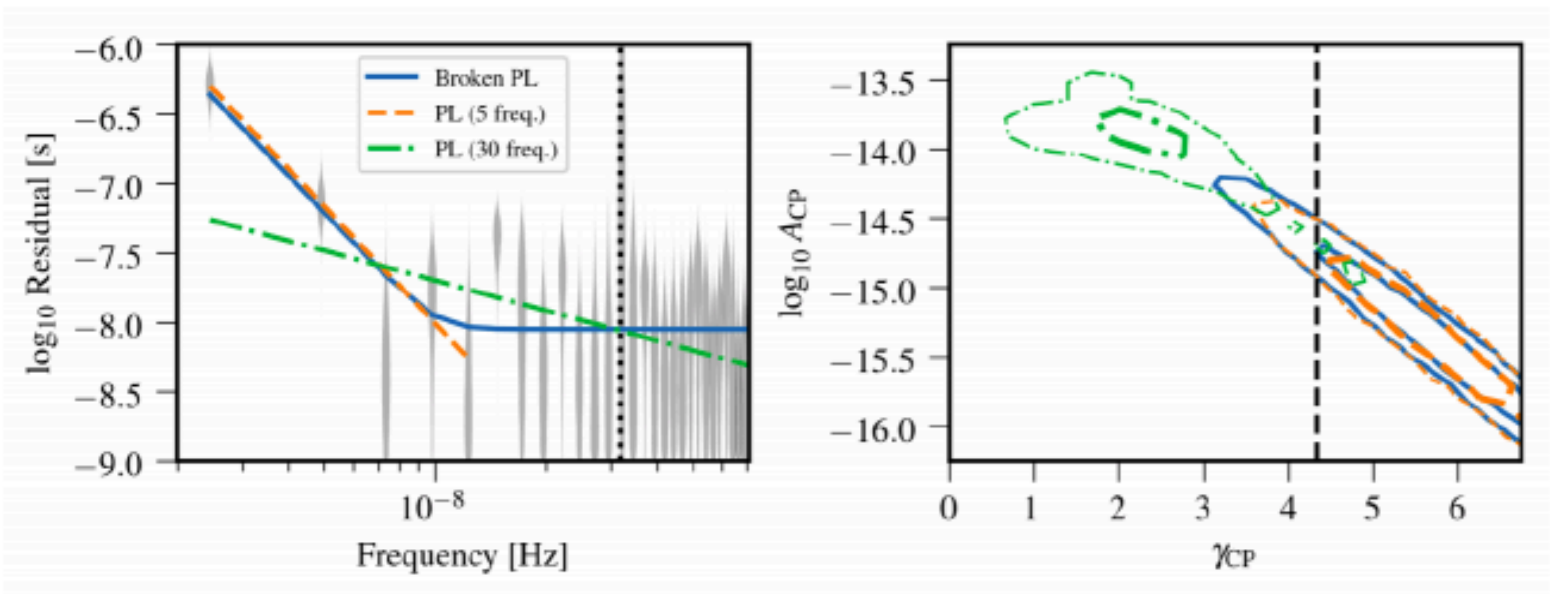
$$S(f) = A_{rn} f^{-\gamma}$$

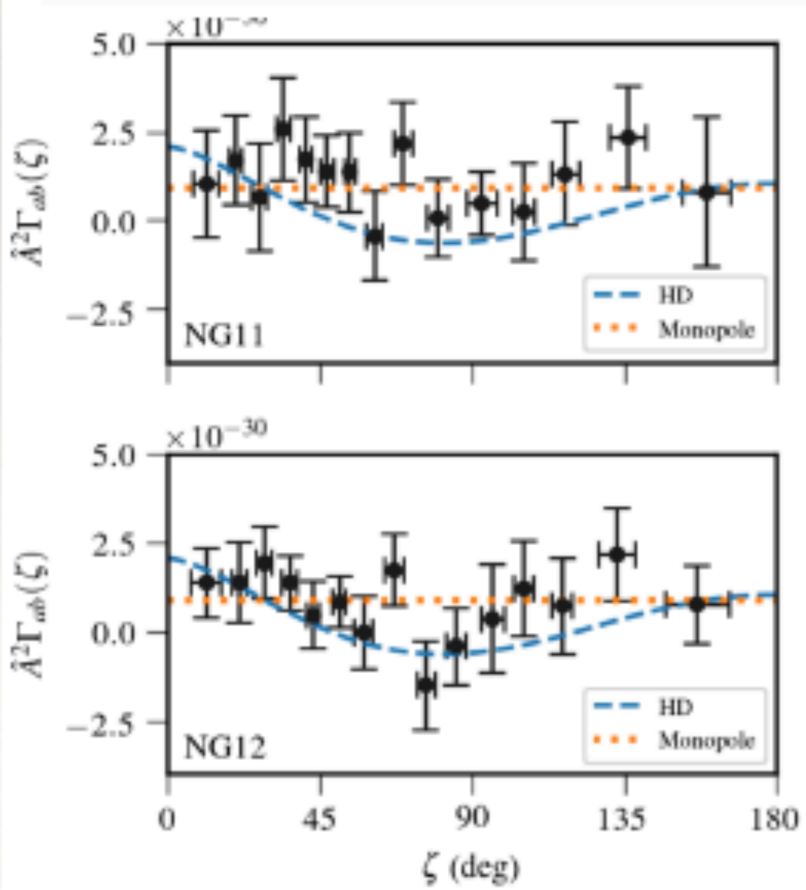
common, uncorrelated red noise

Credit: S Babak

NanoGrav 12.5 yrs data result

[Arzoumanian+ 2020]





There is a strong statistical support for presence of common red noise

$$S(f) = A_{rn} f^{-\gamma}$$

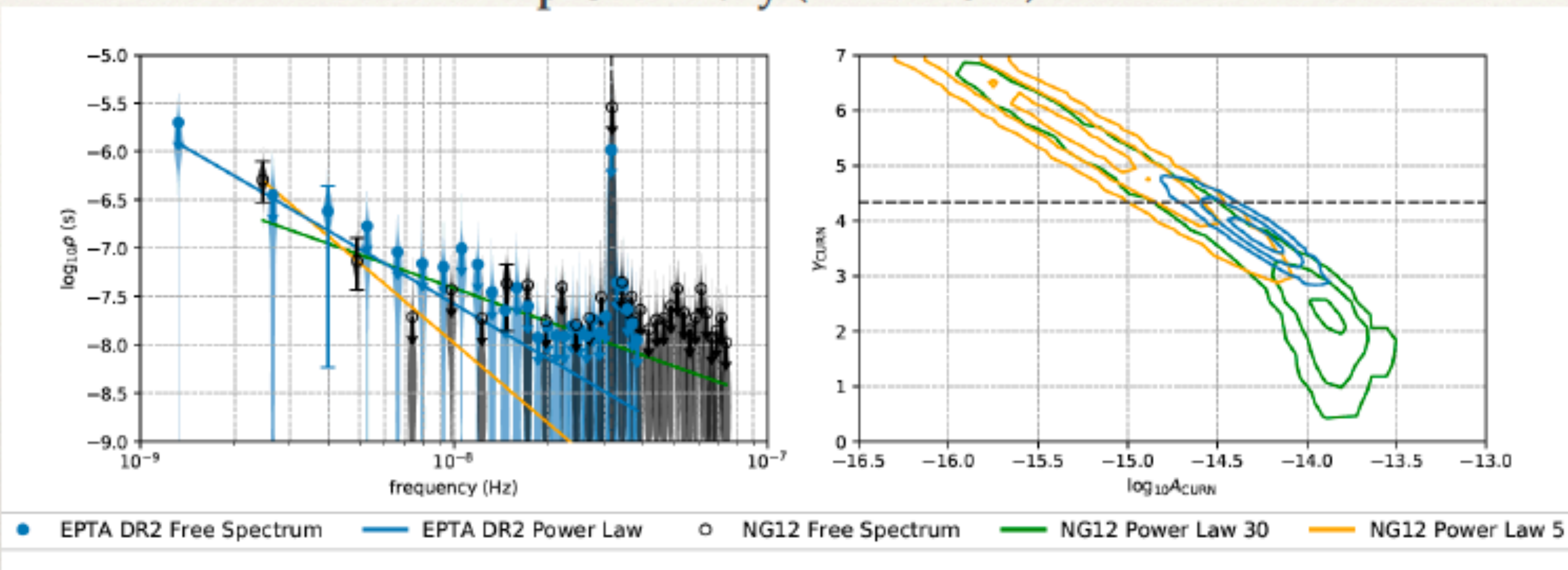
common, uncorrelated red noise

Credit: S Babak

Common uncorrelated red noise

NanoGrav , EPTA and PPTA support presence of a common red noise

preliminary (EPTA 2021)



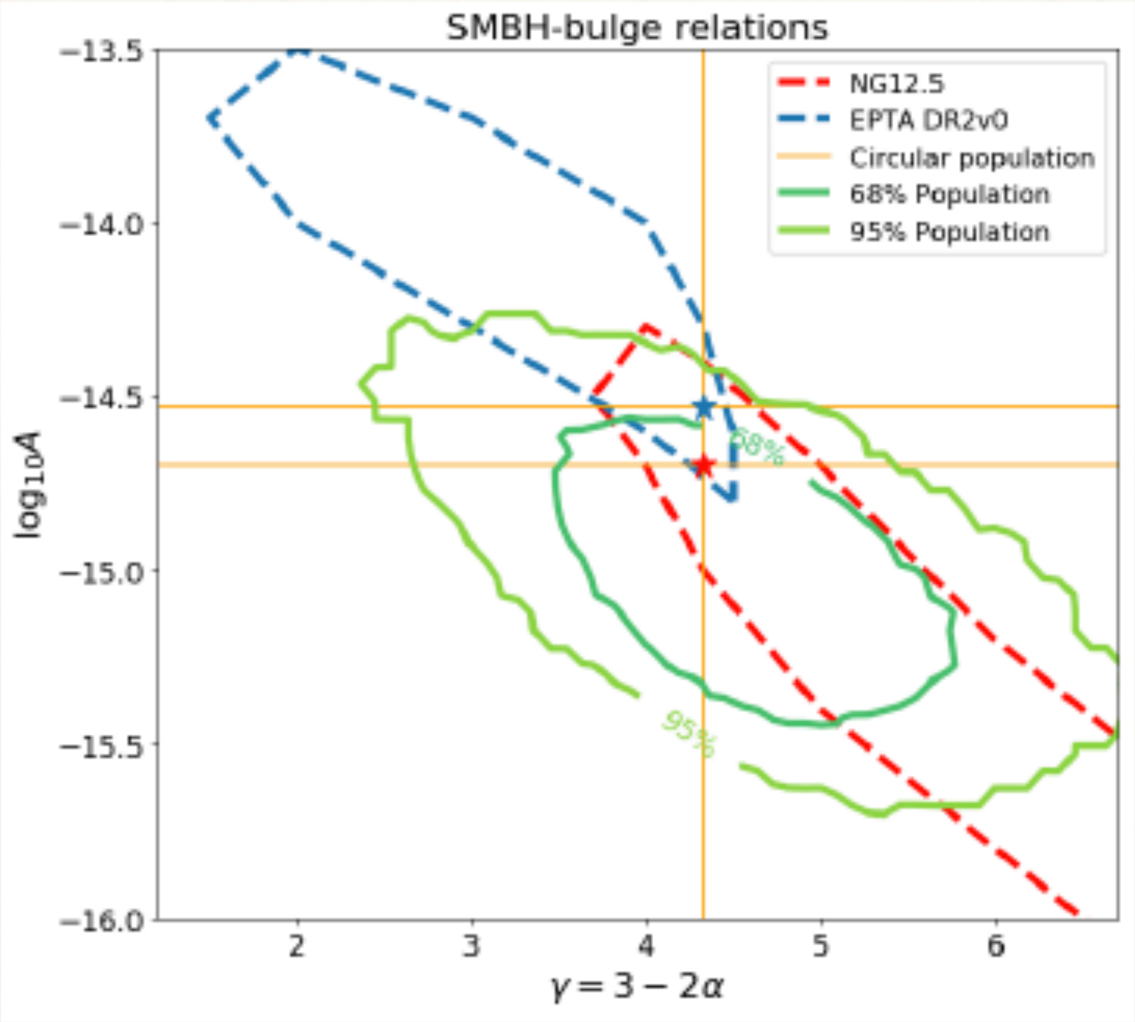
Bayesian analysis: model selection (hypothesis testing)

Odd ratio: $$O(M_1, M_2) = \frac{p(M_1|d)}{p(M_2|d)} = \frac{p(d|M_1)}{p(d|M_2)} \frac{\pi(M_1)}{\pi(M_2)}$$

Bayes factor

Credit: S Babak

Can it be GW from SMBHs?

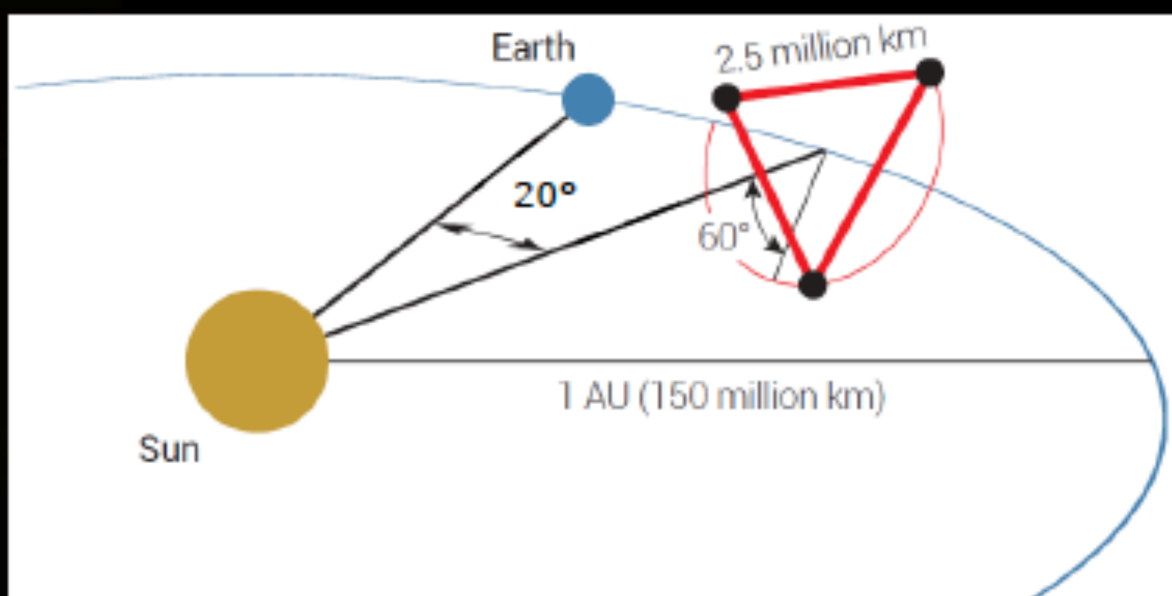


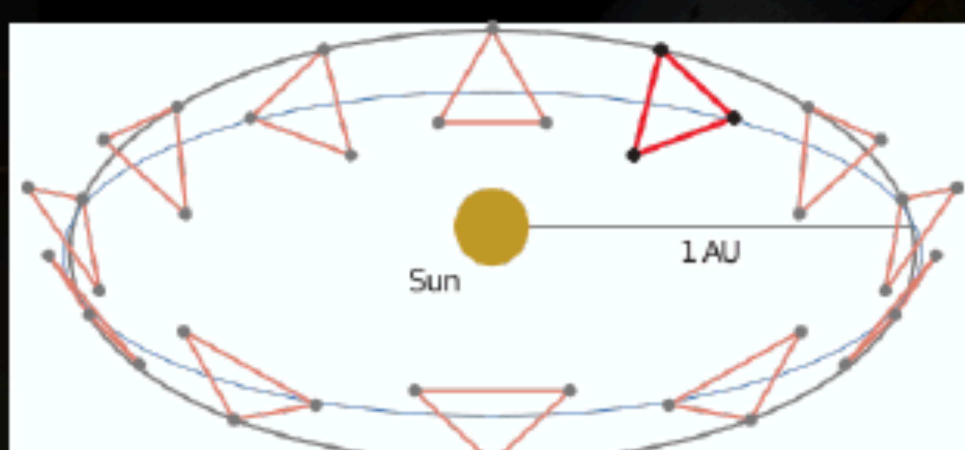
- Analytic prediction: spectral index
- Simulation of SMBHB populations is shown as green contours: wide range spectral indices
- Results of NanoGrav and EPTA are consistent with spectral index from the population of SMBHBs

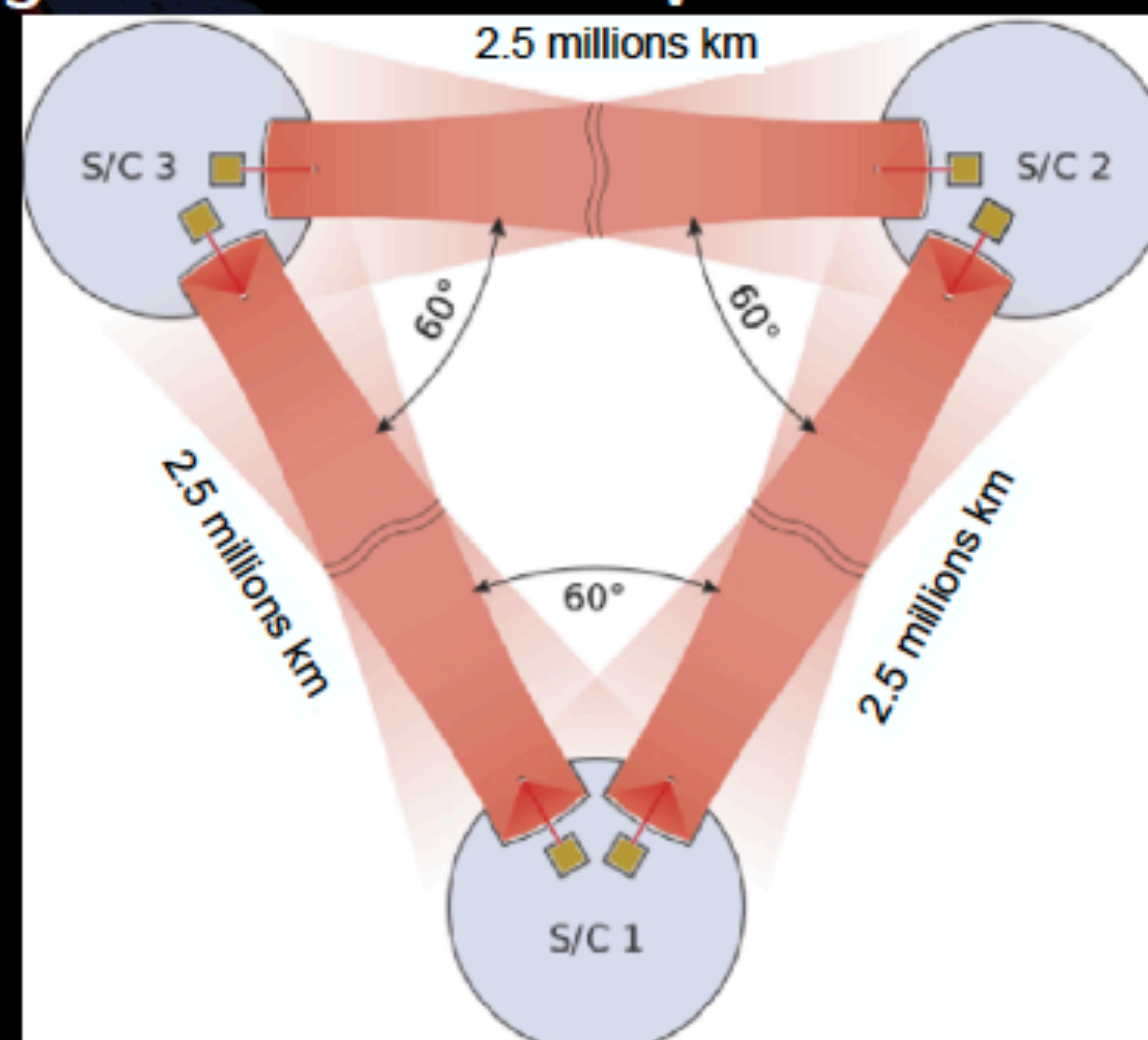
Credit: S Babak

LISA mission

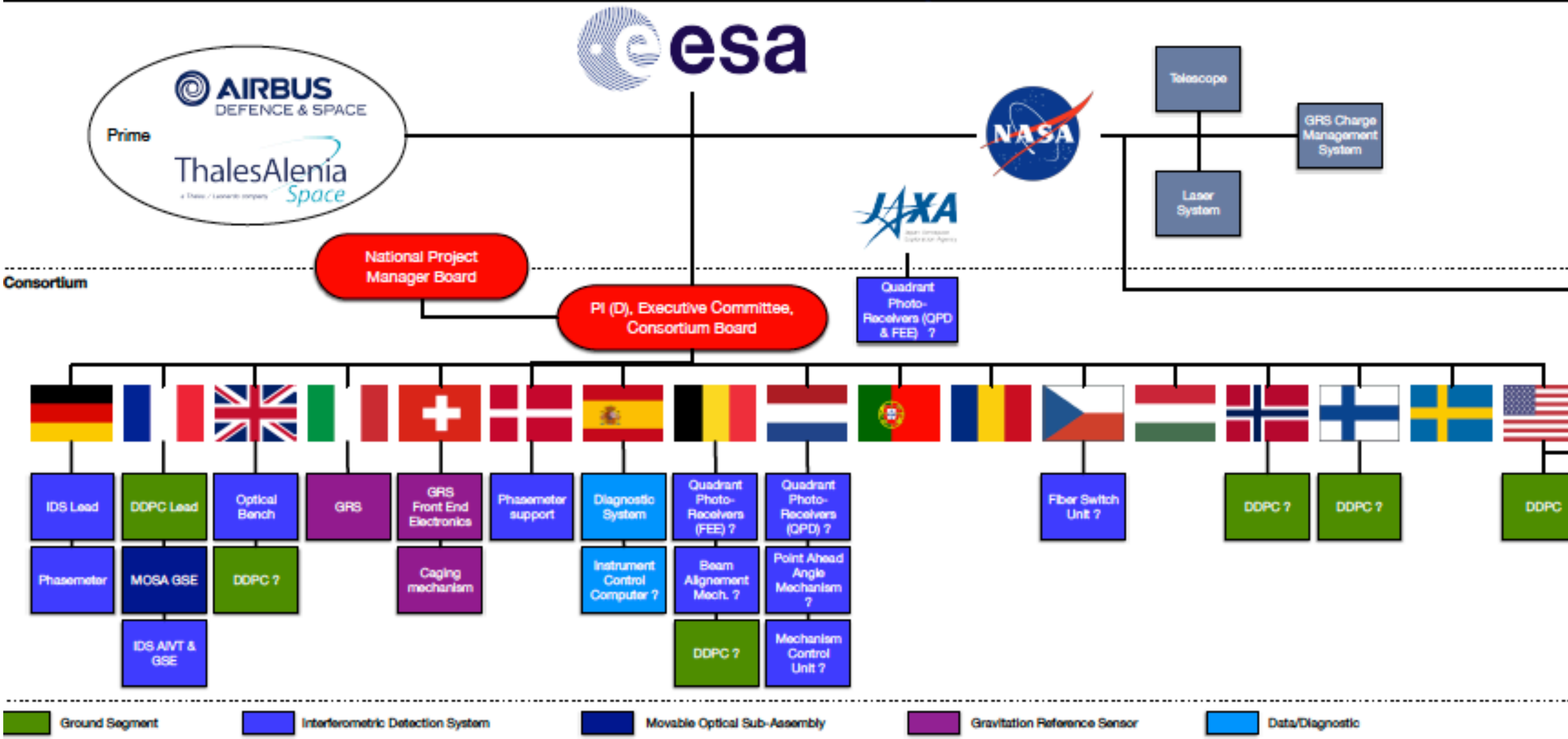
- Laser Interferometer Space Antenna
- 3 spacecrafts on heliocentric orbits and distant from 2.5 millions kilometers
- Goal: detect relative distance changes of 10^{-21}: few picometers





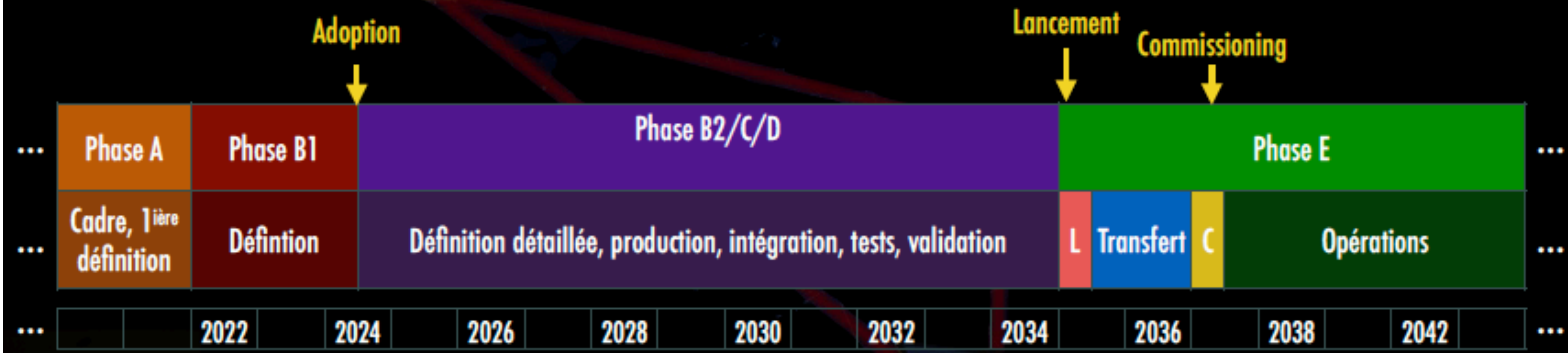


LISA organisation



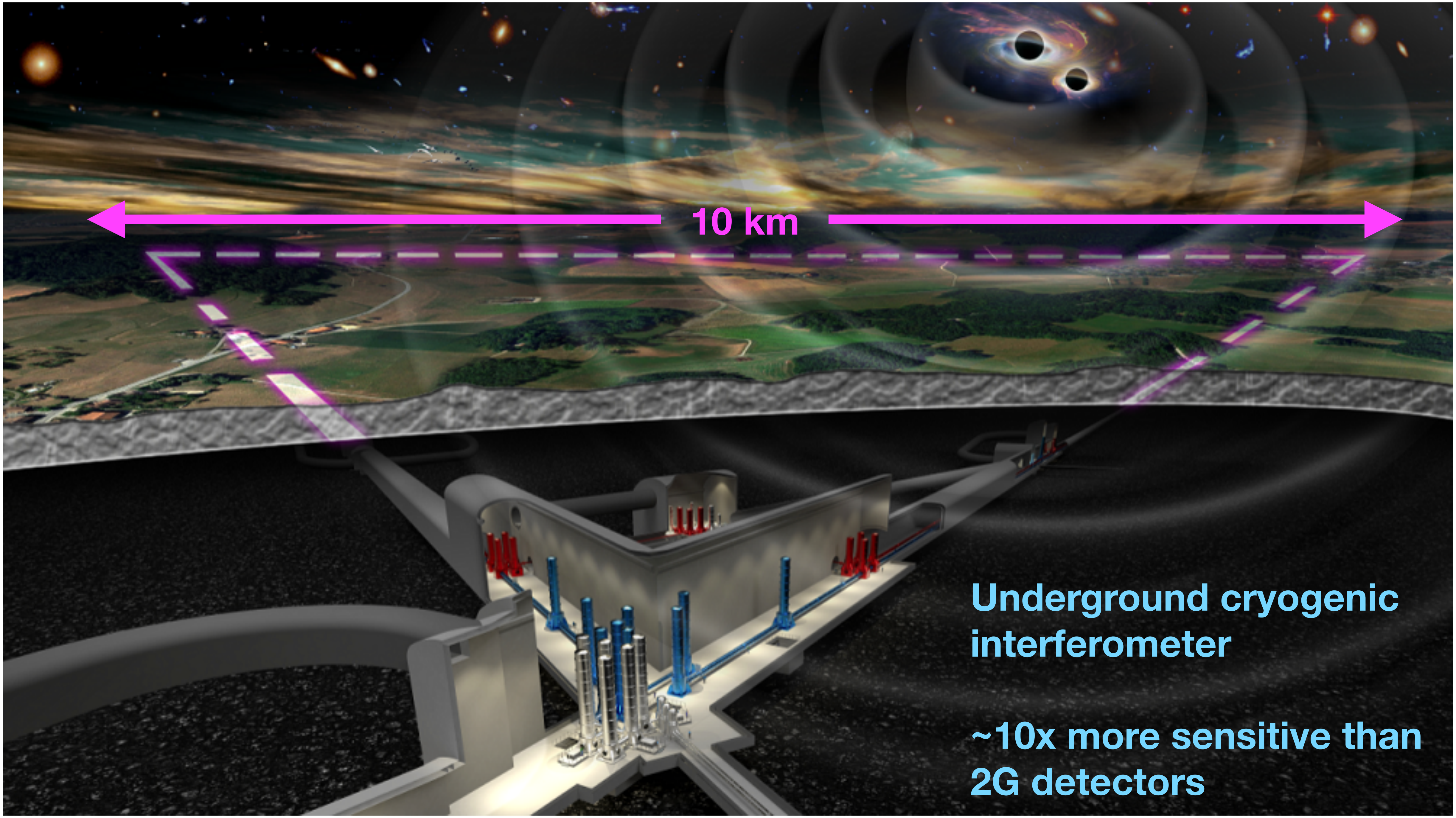
- LISA Consortium 1460 members:
  - 698 "full members" committing time
  - 762 associates participating to the 5 WGs: Astrophysics, Cosmology, Fundamental Physics, LISA Data Challenge, Waveforms

Planning & status

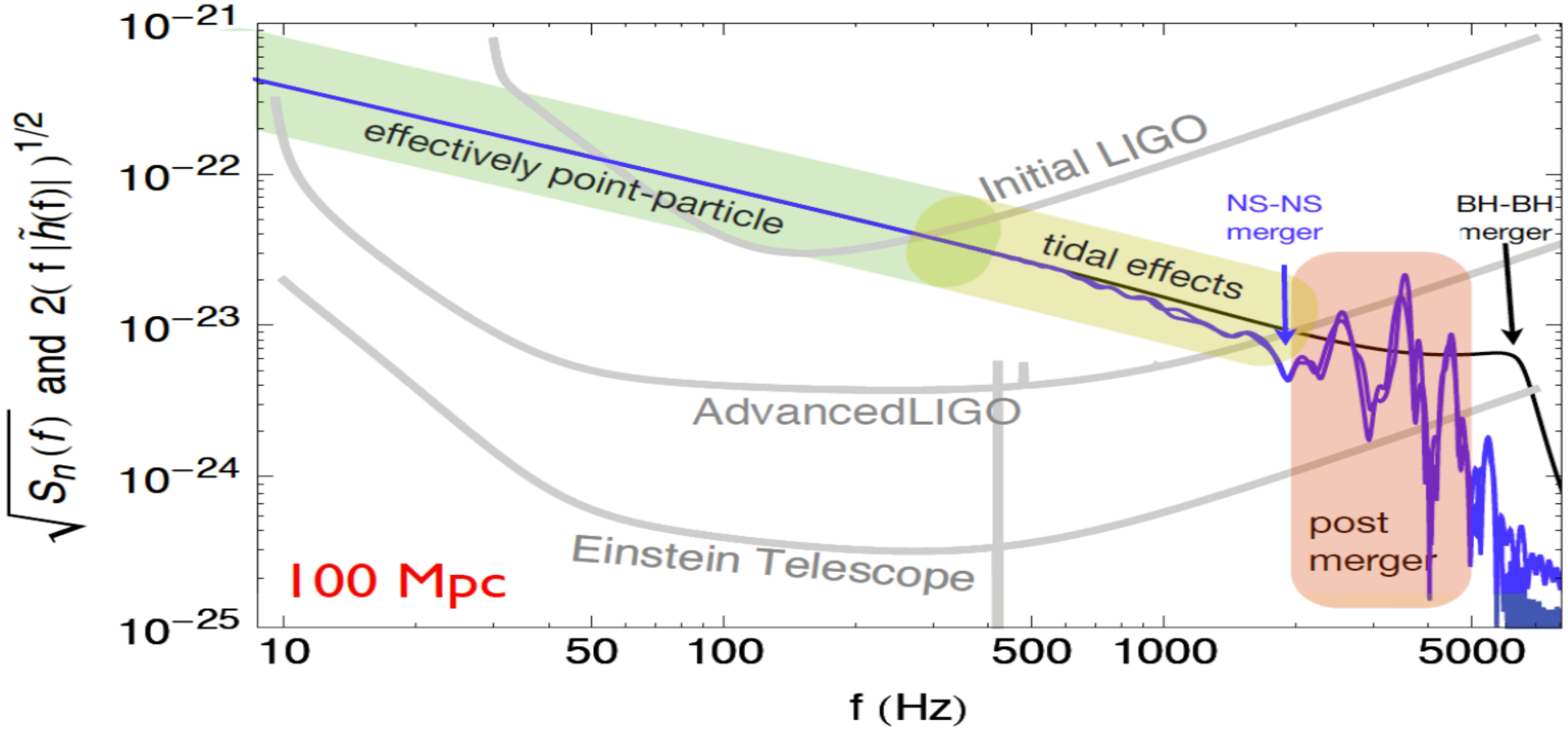


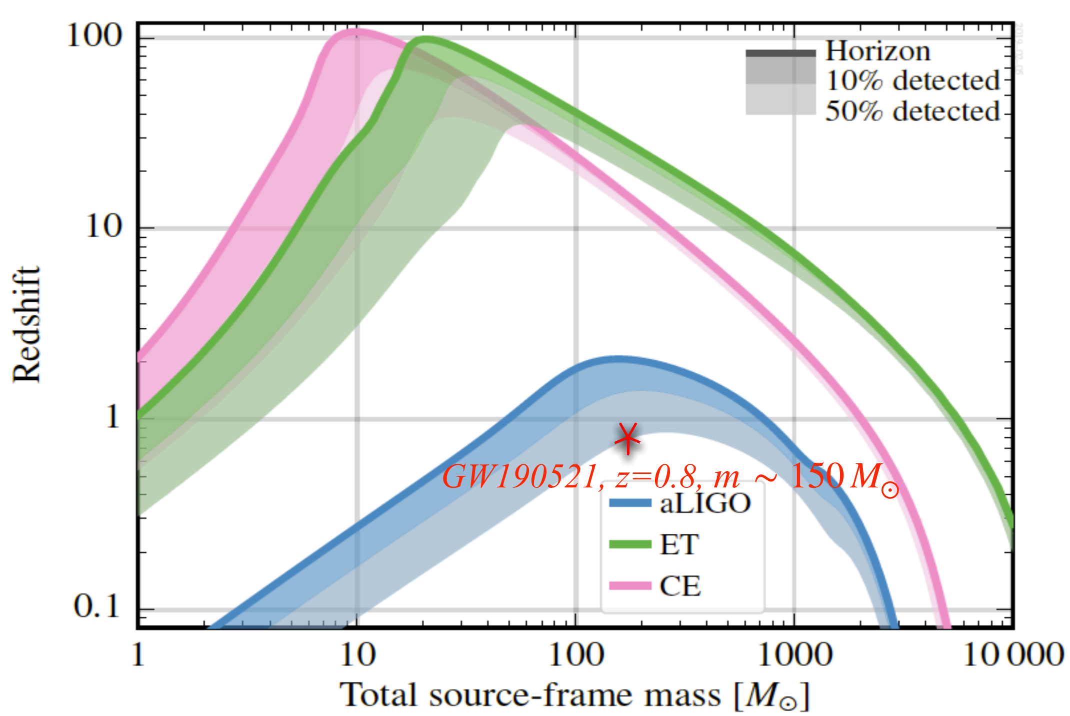
- Now: end of phase A with ESA Mission Formulation Review (October to December 2021)
- ESA Adoption end 2023
- Launch mid-2030
- Long building phase: 6 core subsystems (MOSA)
- Building of some model for subsystem already started

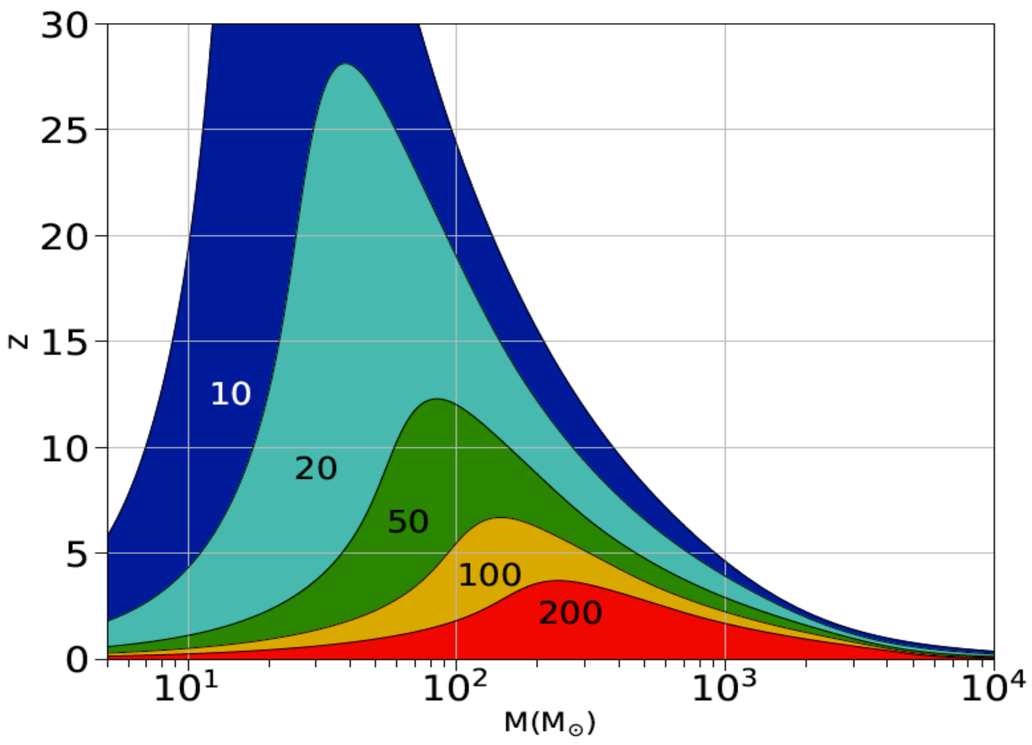
Einstein Telescope



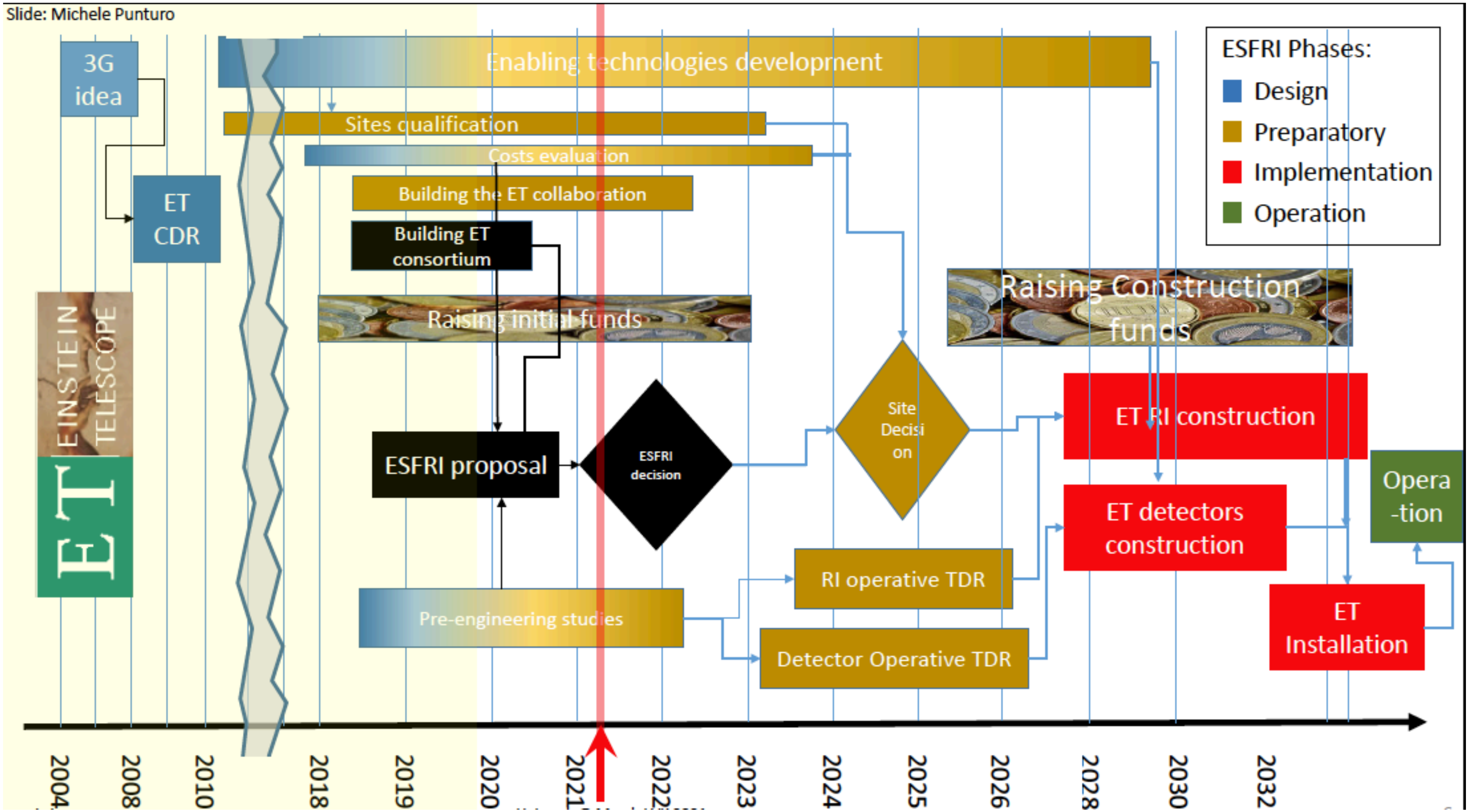
Einstein Telescope







ET Timeline



Slide: Michele Punturo
3G idea
ET CDR
EINSTEIN TELESCOPE
ET
Enabling technologies development
Sites qualification
Costs evaluation
Building the ET collaboration
Building ET consortium
Raising initial funds
ESFRI proposal
ESFRI decision
Pre-engineering studies
Site Decision
RI operative TDR
Detector Operative TDR
Raising Construction funds
ET RI construction
ET detectors construction
ET Installation
Opera-tion
ESFRI Phases:
Design
Preparatory
Implementation
Operation
2004
2008
2010
2018
2019
2020
2021
2022
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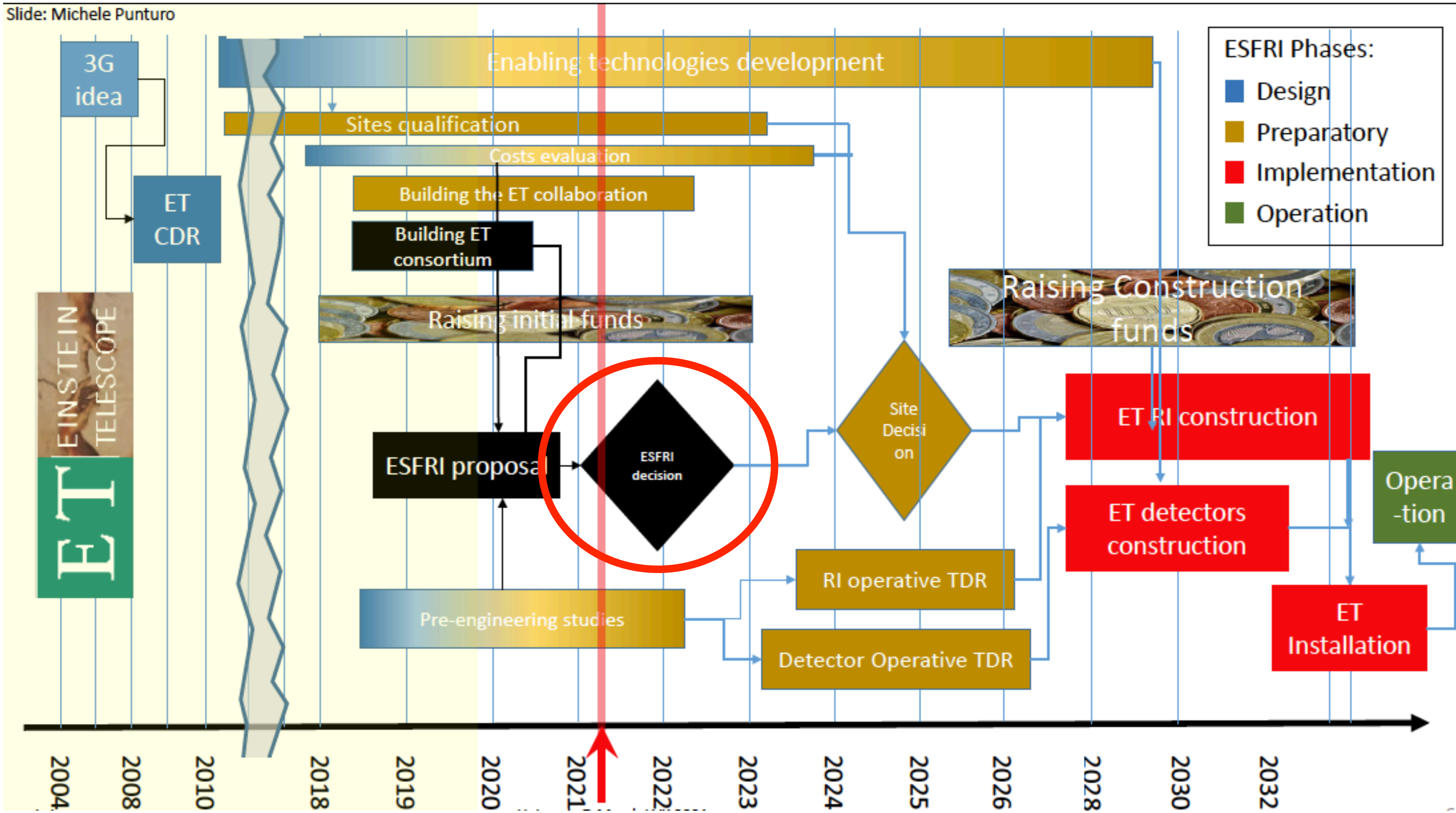
2030
2032

ET Timeline



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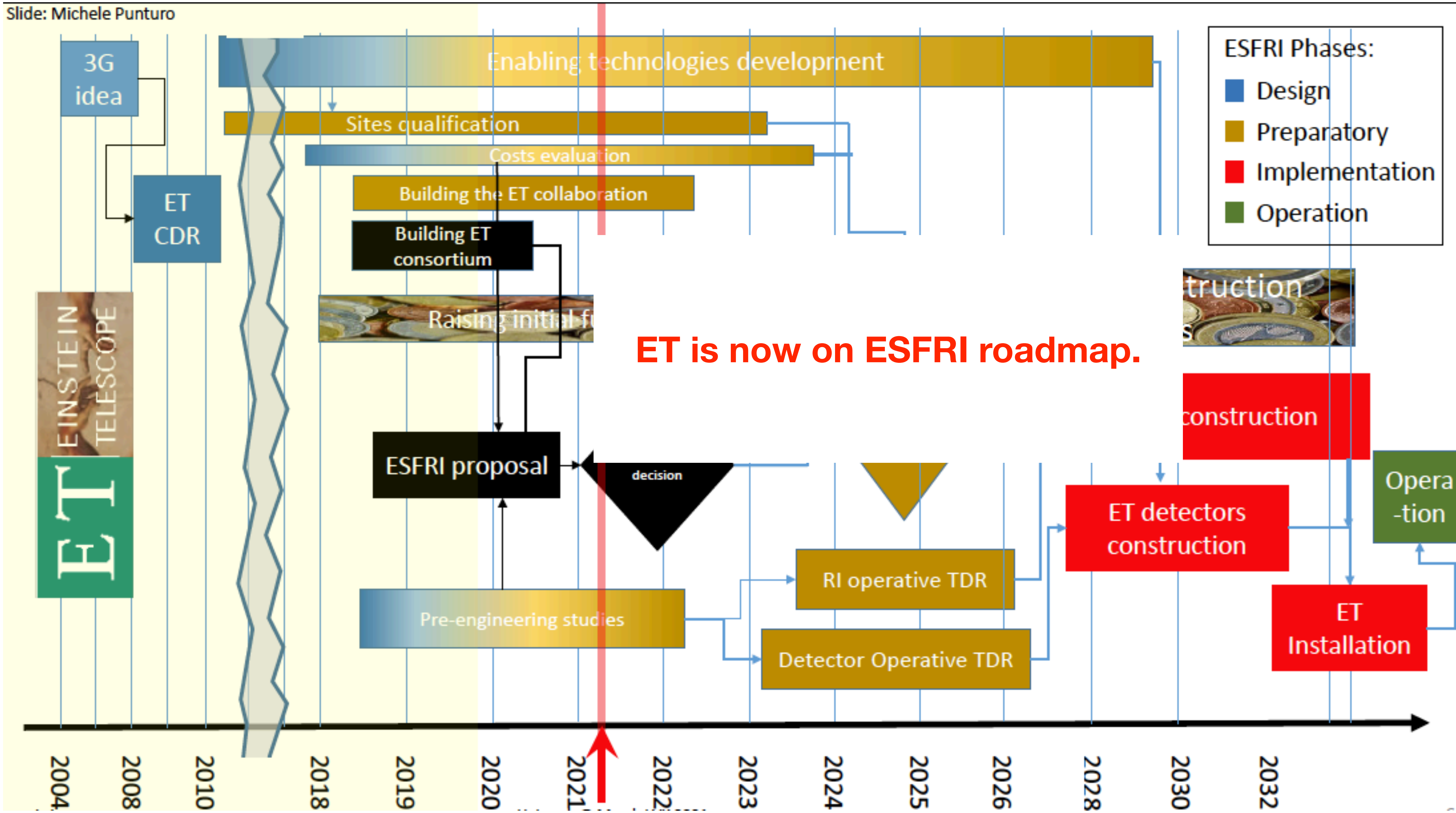
2032

ET Timeline



ET is now on ESFRI roadmap.

Einstein Telescope

- Currently putting together the collaboration
- A steering committee exists and meets weekly
- Chairs have been assigned to various working groups
- Working groups themselves are currently being organised
- Close collaboration with members of Cosmic Explorer, as well as LIGO, Virgo and KAGRA

Einstein Telescope

ET Working Groups

SPB:

Coordinate on-site activities

Formulate site specifications

Choice of site

EIB:

Define computing resources

Study computing models

Possible synergies

ISB:

ET-TDR for infrastructures and detector

Identify missing technologies

Plan R&D activities

OSB:

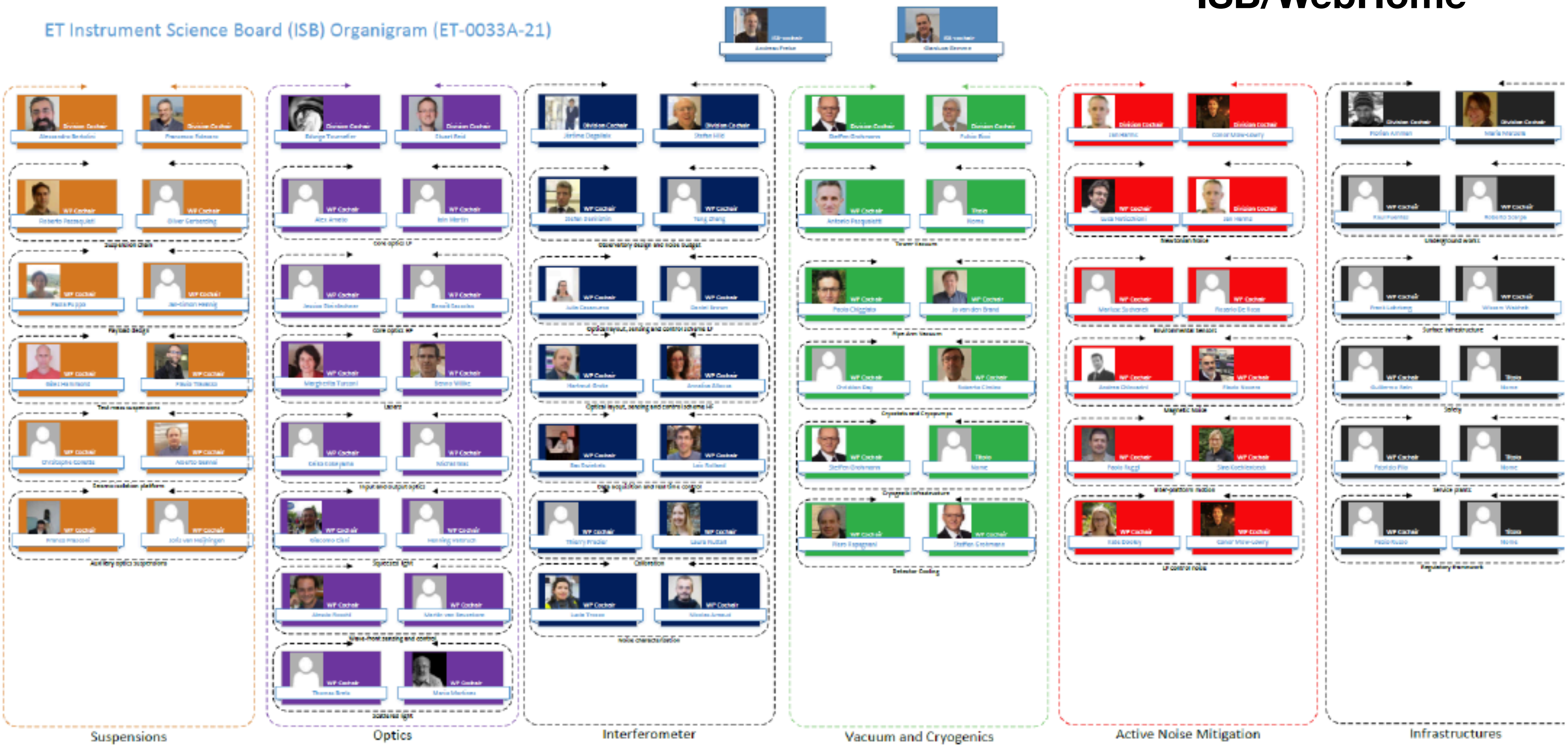
ET science case

Prepare DA requirements

Evaluate computing requirements

ET-ISB

https://wiki.et-gw.eu/ISB/WebHome



ET-OSB

Marica Branchesi - Michele Maggiore - Ed Porter

Fundamental physics	Cosmology	Population Studies	MM observations	Synergies w. other GW observ.	Nuclear physics	Transient GW Sources	Waveforms	Science Potential	DA platform
Physics near BH horizons	Dark Energy	Predictions of population of astrophysical origin	ET / high-energy	Synergies with 2G+ detector	EoS of NSs in isolated systems	Predictions for Supernovae	Waveforms relevant for ET	Science potential for various detector configurations	DA platform
Tests of GR	Dark matter	Predictions of primordial BHs	ET / optical	Synergies with CE, 3G	EoS in NSs in binary systems	Predictions for magnetars	Improvement of waveforms for BBH	Common tools	
Exotic compact objects	Estimation of cosmological parameters	Stochastic backgrounds of astrophysical origin	ET / radio	Synergies with LISA	Nucleo-synthesis in BNS mergers	Predictions for cosmic string bursts	Improvement of waveforms for NSBH		
	Modifications of gravity at cosmological scales		ET / neutrinos				Improvement of waveforms for BNS		
	Stochastic background of cosmological origin								

ET-OSB

- Investigate the science case for ET, especially for different configurations
- Develop more sophisticated waveform models, incorporating higher order modes, EOS, and possible deviations from GR
- Investigate population models at near and high redshift, and the consequence for stochastic backgrounds
- Develop an infrastructure for MMA, as well as a deep connection with external telescopes/facilities
- Investigate fundamental physics in the vicinity of compact objects, dark energy and dark matter, and the existence of exotic objects such as primordial black holes
- Investigate cosmology at high redshift, including networks of cosmic strings, and precise estimates of Hubble's constant.
- Develop DA tools and analyses for CBCs, and transient events such as SN, cosmic string kinks/cusps etc.
- Develop synergies with other GW observatories, i.e. 2G, Cosmic Explorer, LISA

ET-OSB: Div S

- The goal of Div S is to build a bridge to comunicate, coordinate and collaborate with other neutrino and electromagnetic observatories.
- Div S is governed by the OSB chairs, the MMA division chairs, plus a representative from each experiment

High-energy

- SVOM
- Einstein Probe
- GECAM
- eXTP
- Athena
- Mission concept THESEUS
- Mission Concept TAP
- Mission Concept GAMOW Explorer
- HERMES constellation
- AMEGO

UV/Optical/infra-red

- Vera Rubin Observatory
- ULTRASAT
- JWST
- The Nancy Roman Telescope
- ESO : NTT+SOXS
- ESO : VLT (optical and NIR instrumentation)
- ESO : ELT
- ESO: 4MOST
- Euclid (indirect synergy)
- WAVE
- DESI

RADIO

- SKA
- VLBI
- VLA(?)

Very High Energy

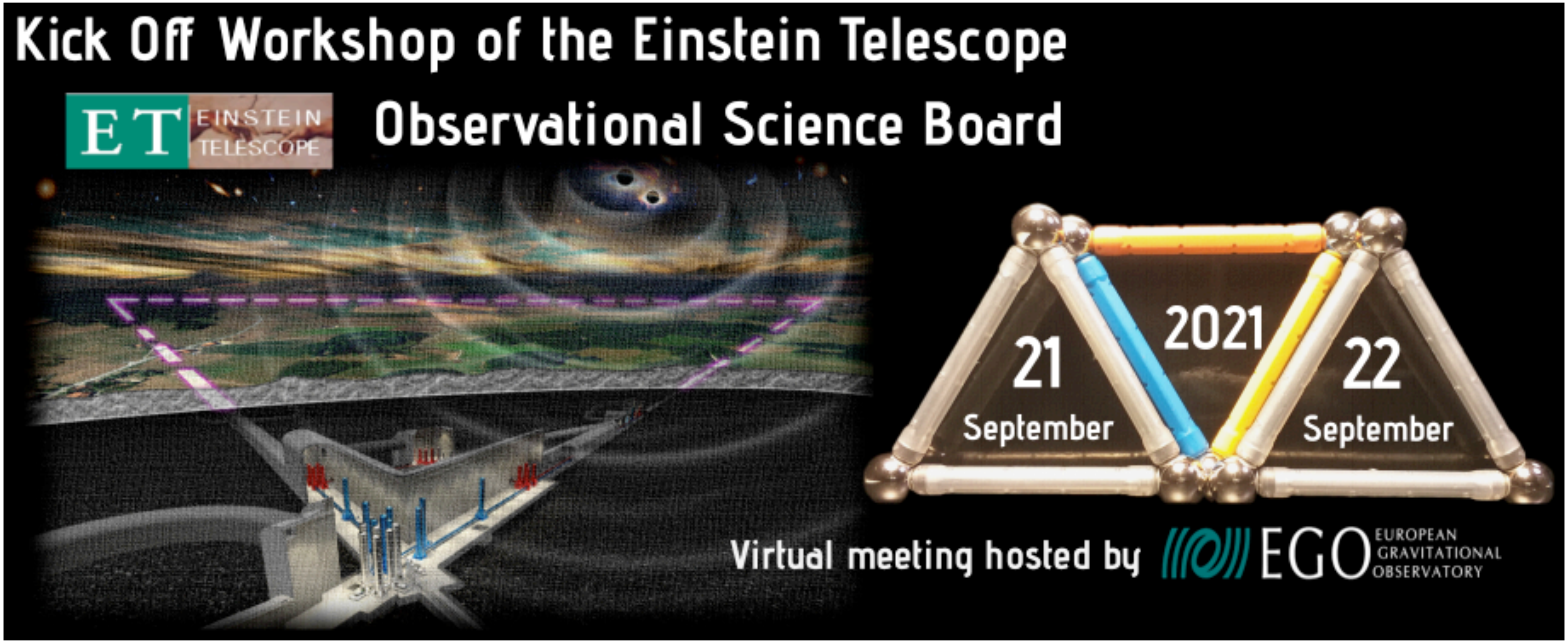
- CTA

NEUTRINO EXPERIMENTS

- Heper-Kamiokande
- KM3NET
- Ice-Cube/GEN 2

+ ESO, ESA, European collaborations such as ENGRAVE, and European infrastructure/networks such as ESCAPE/AHEAD2020 etc.

ET-OSB



https://indico.ego-gw.it/event/240/

Currently 447 participants

Conclusion

- For the LVK, O3 was a great success

- Lots of surprises (and questions)
  - was GW190425 a BNS or is there a BH in the system?
  - how did GW190521 form? is it a 2nd generation merger?
  - Is the low mass companion of GW190814 a NS, a BH or something else?

- O4 will be even more fruitful (and challenging)

- Plans have begun for O5/O5+
- IPTA may have detected evidence of GWs
- ET is now on ESFRI roadmap and is in the process of building the collaboration
- Operations expected mid-2030s
- LISA is planned for launch mid-2030s