GWs now and future

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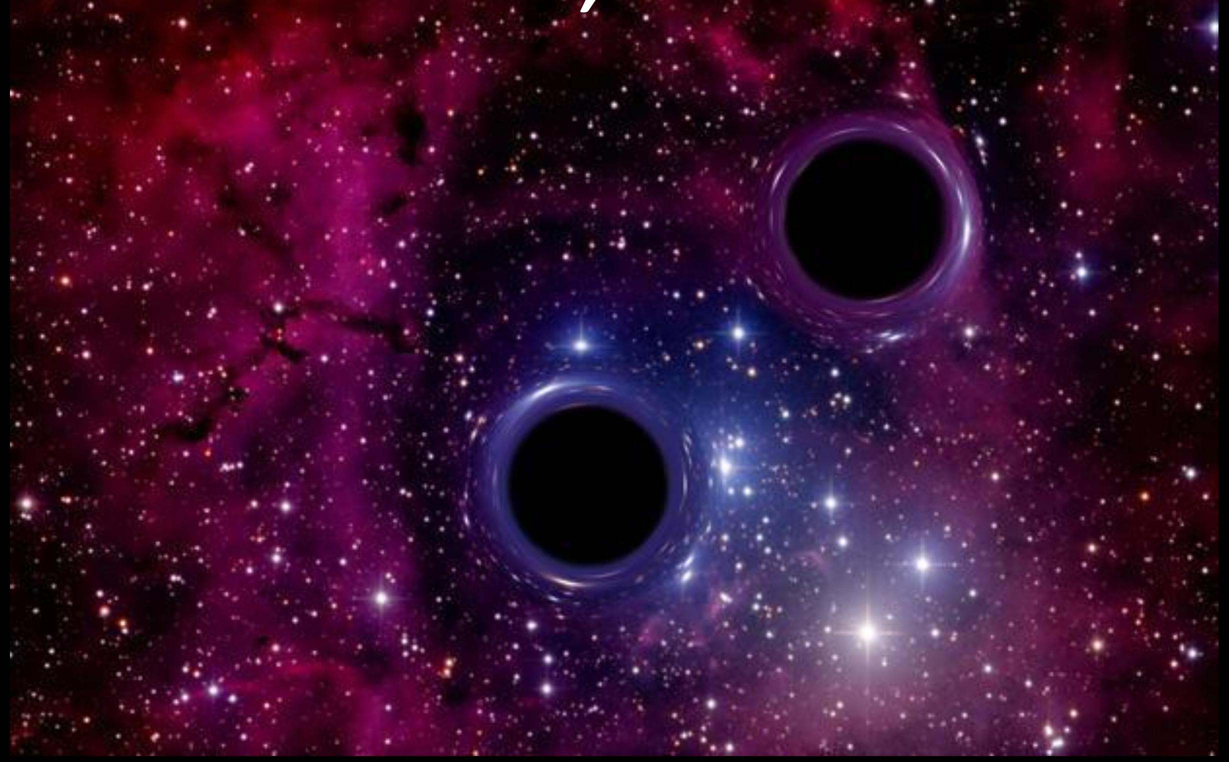
34th Rencontres de Blois on "Particle Physics and Cosmology", Blois, France, 19th May 2023

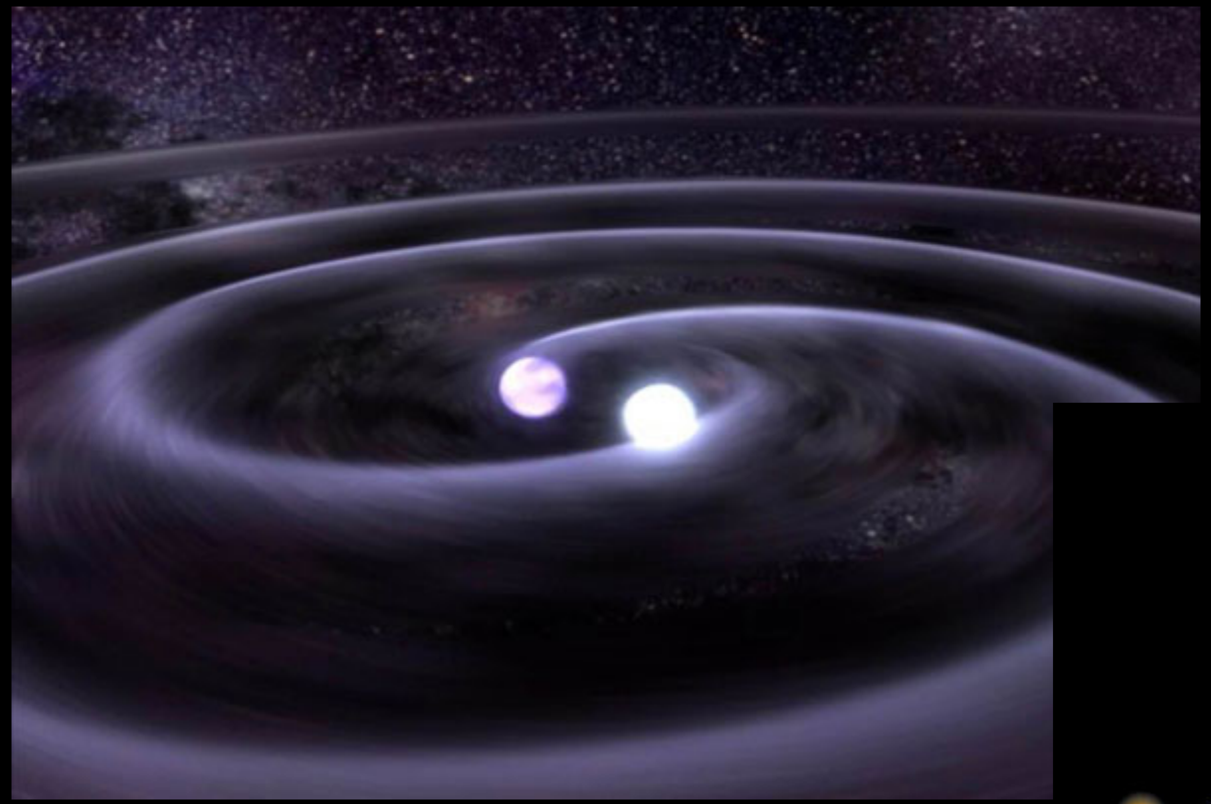
Outline

- Overview of LVK results
  - Populations and O3 catalogue
  - Test of General Relativity
  - Kilonova & NS EoS
  - Search for Continuous GWs
  - Search for Stochastic Signals
  - Dark Matter Searches
  - Use of DL algorithms
- Post-O5
- The 3rd Generation worldwide scenario
- The Einstein Telescope
- Final notes

Sources of GWs

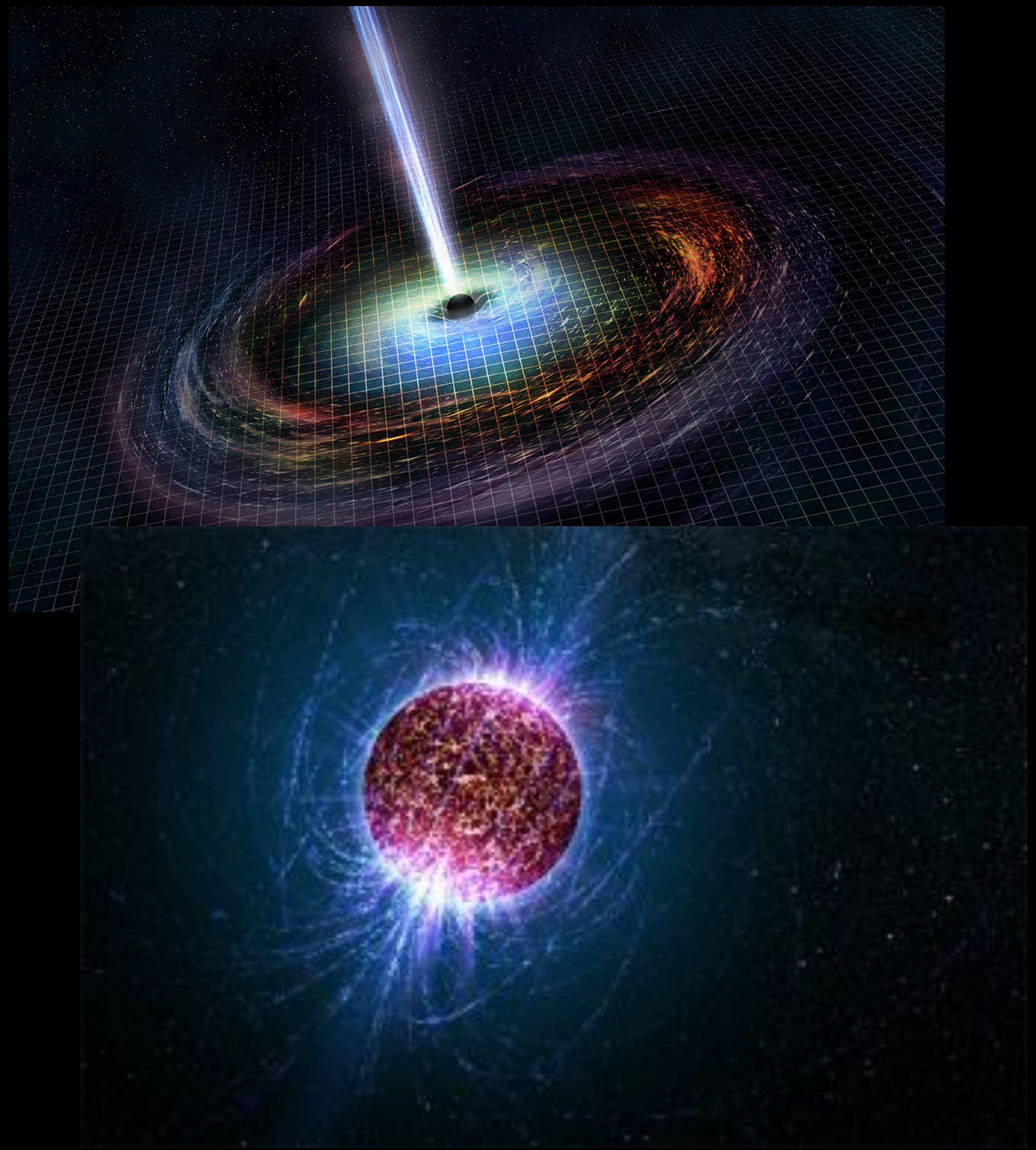
Binary systems
(Black holes, Neutron Stars)



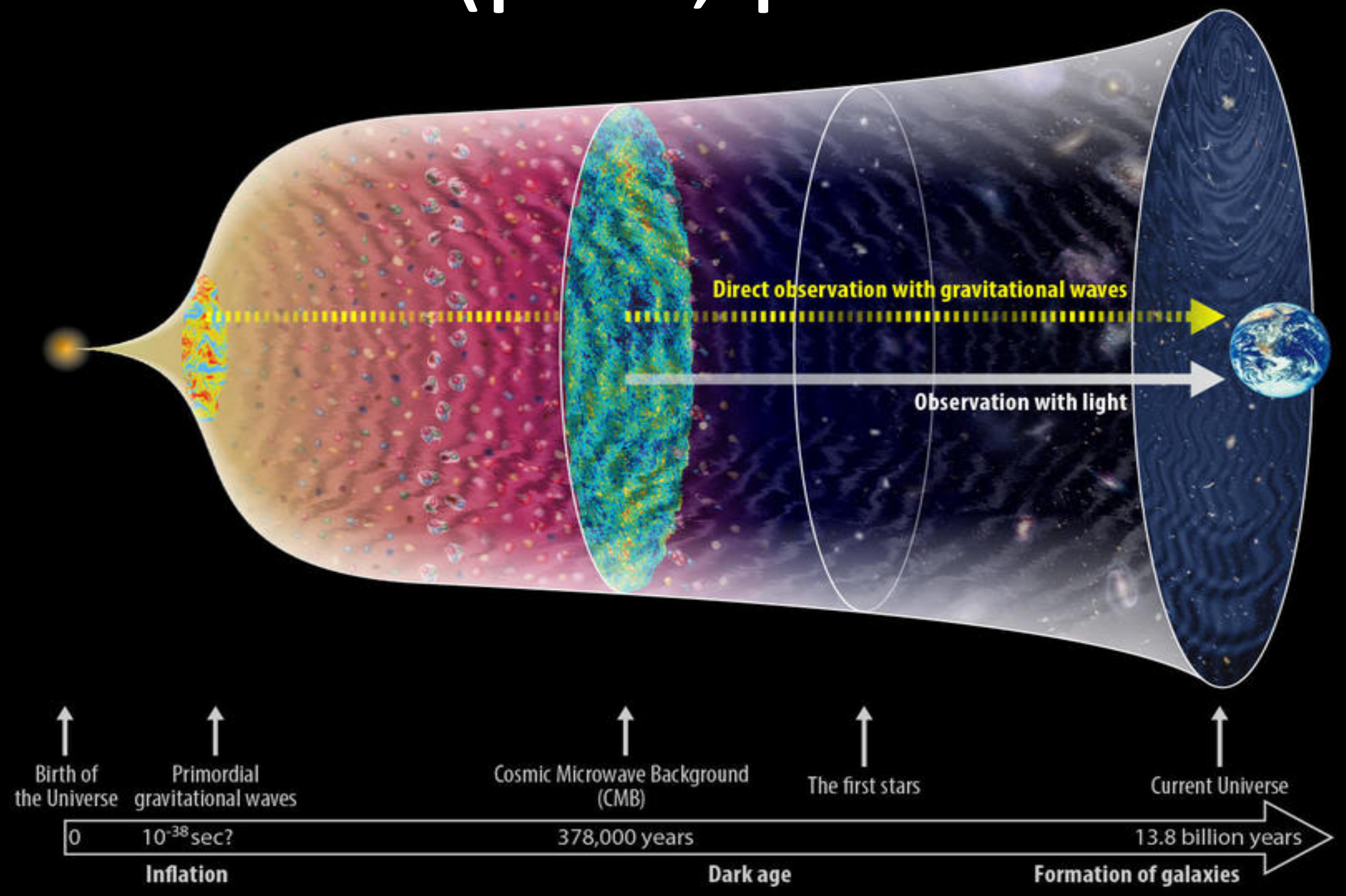


Stellar collapse
(supernovae)

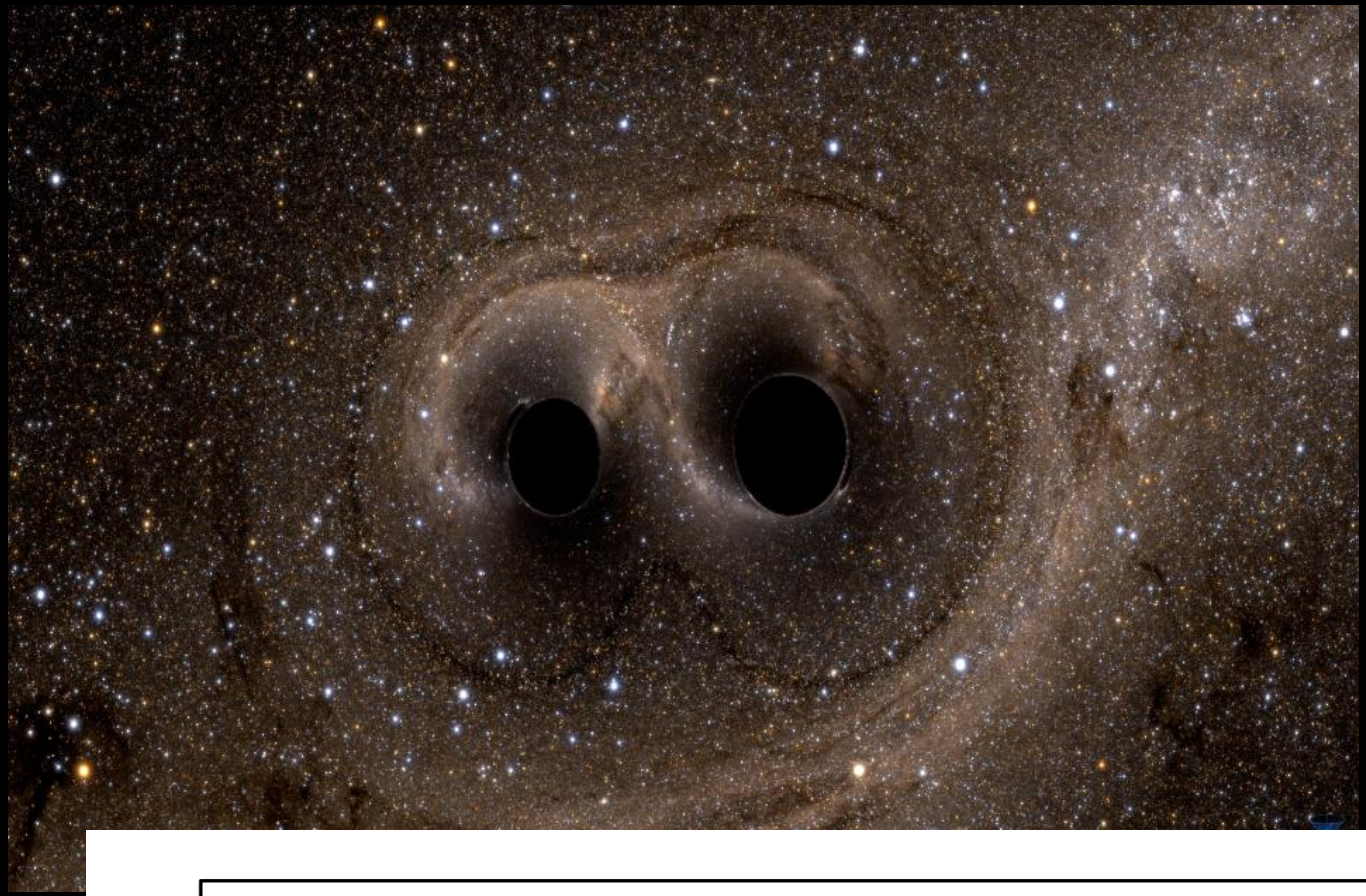
Pulsars



Stochastic Signals
(pBH, phase transitions, astrophysics)



Black hole Binary



$m_1 = m_2 = 30\ M_\odot$

Distance = 100 km

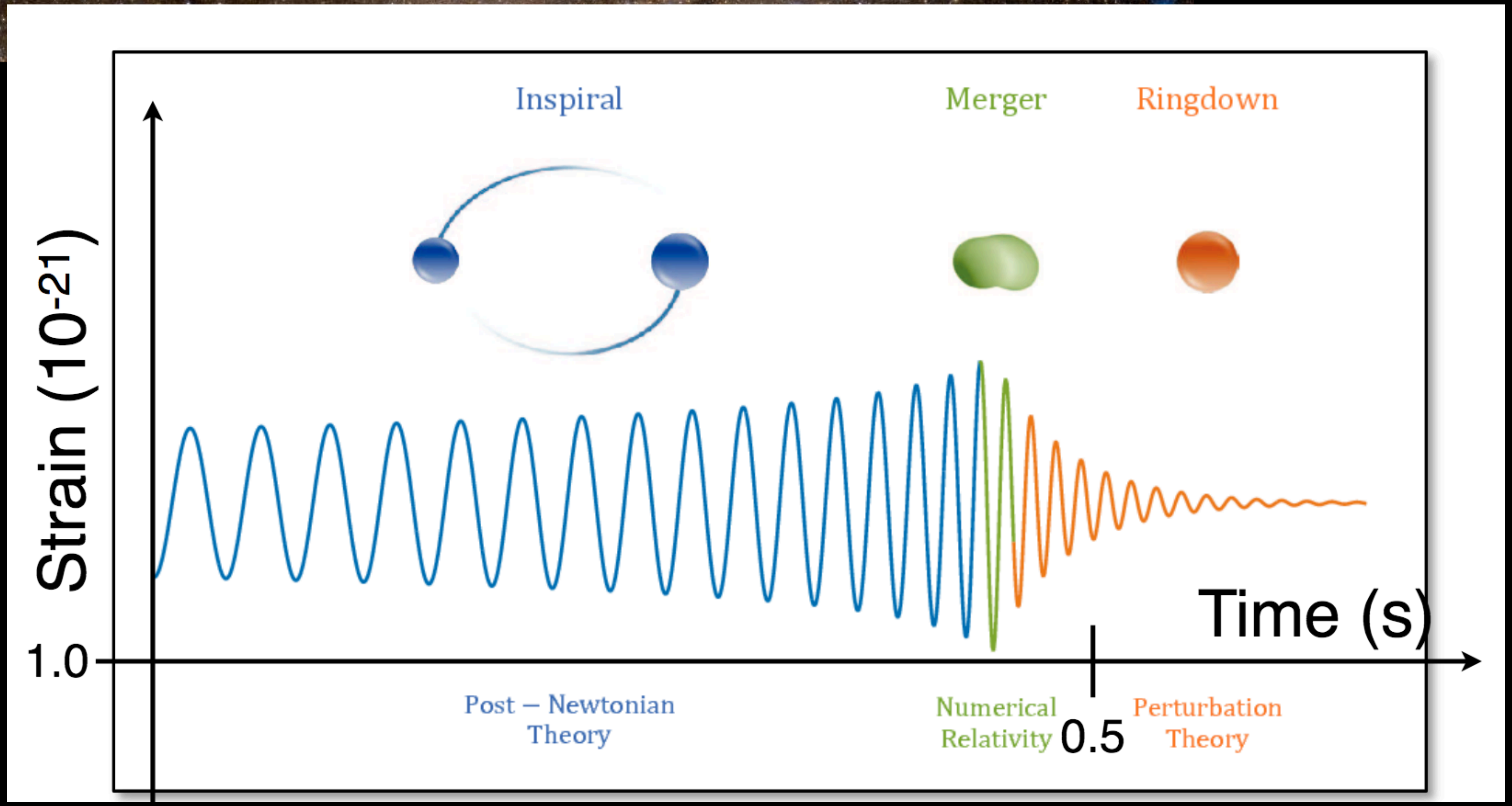
frequency = 100 Hz

$r = 3\ 10^{24}$ m (500 Mpc)

1 Mpc = 31 x 10^{18} km

0.0000000000000000000001

$h \sim 10^{-21}$



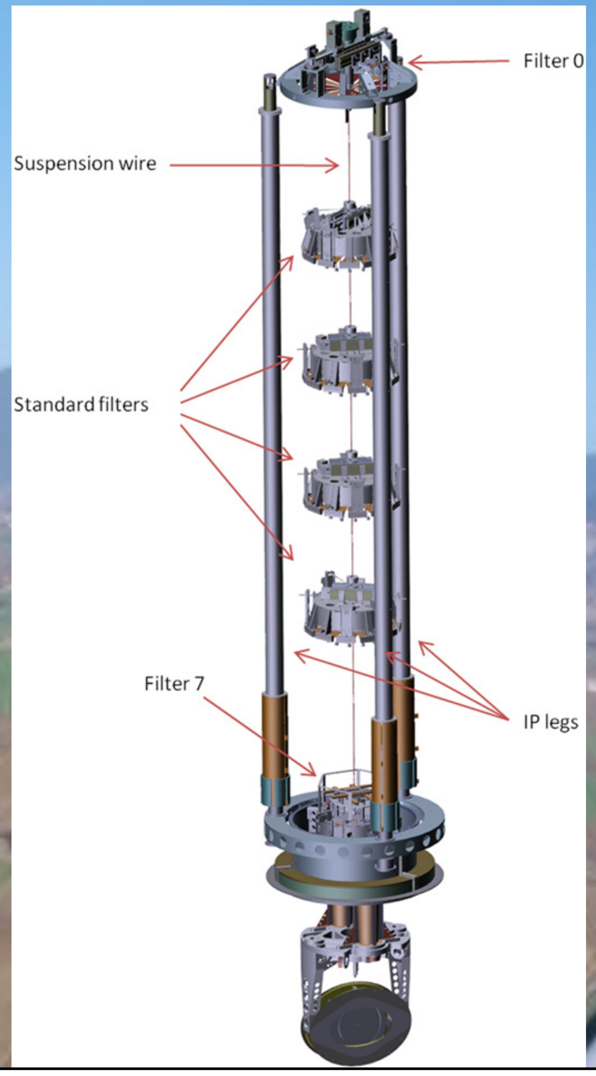
Interferometers

The interferometers act as a network

- Allows for a precise positioning in the sky
- Veto against fakes and employs correlations to search for stochastic signals

VIRGO @ EGO

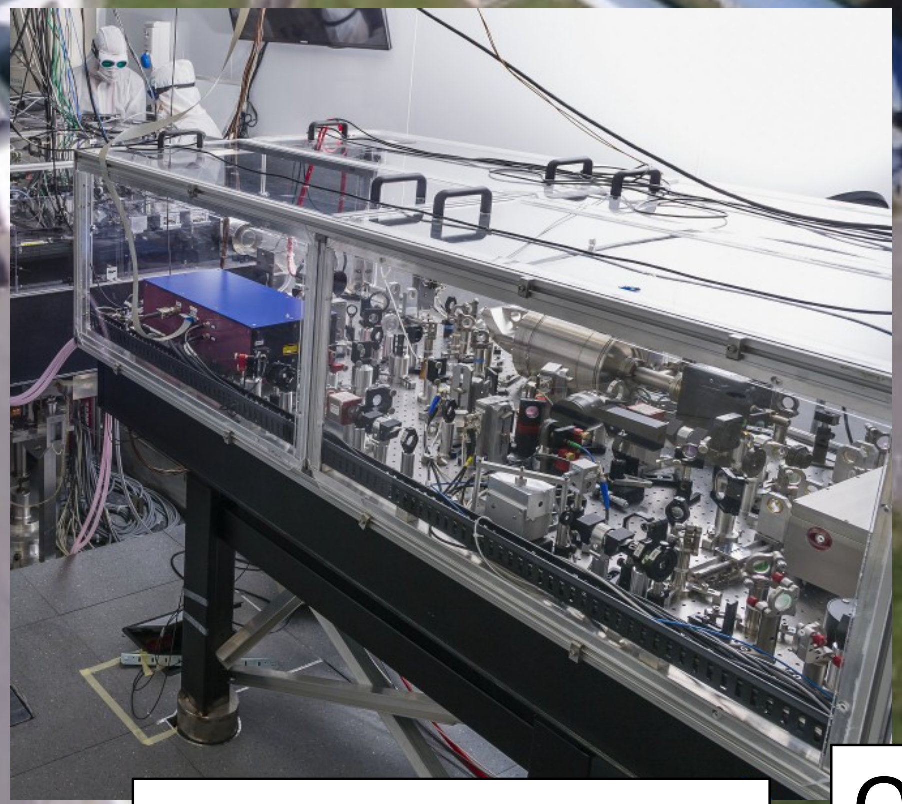
UHV to avoid pressure fluctuations



Complex attenuators
With a power of $1/10^{14}$

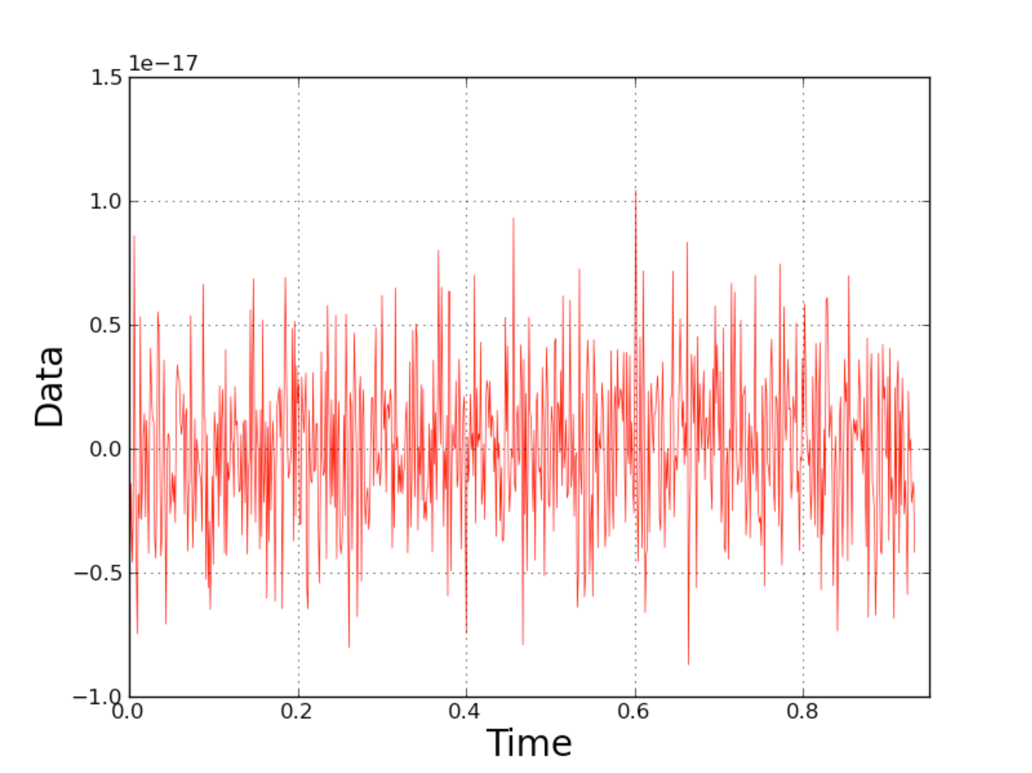
Almost perfect mirrors
99.9995 % reflection)

Complex network of sensors to
monitor the environment



Powerful lasers

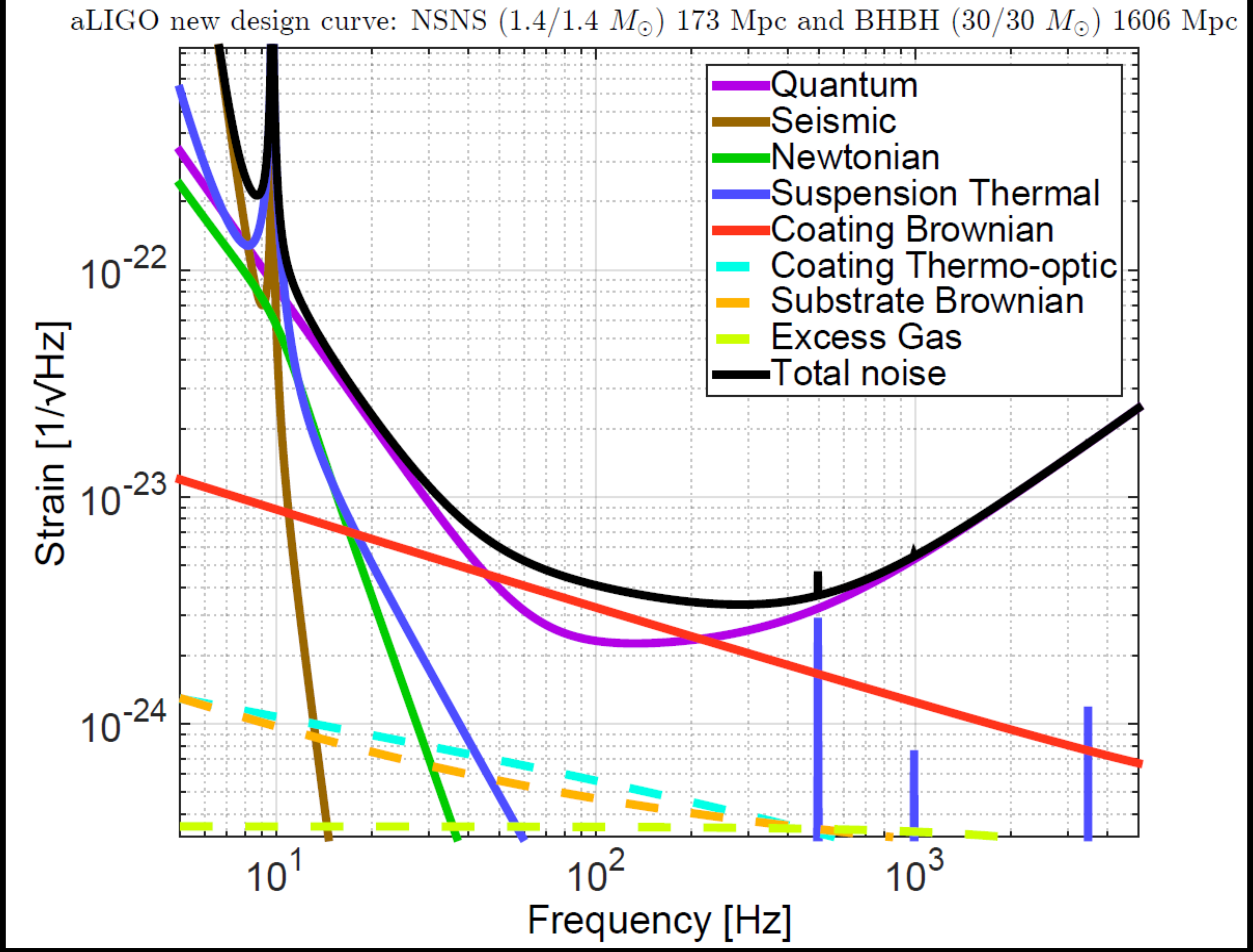
Quantum Squeezing



Sensitivity

$$s(t) = n(t) + h(t)$$

$$\tilde{n}(f) = \int dt\ n(t)\ e^{-2\pi i f t}$$



Power spectral density

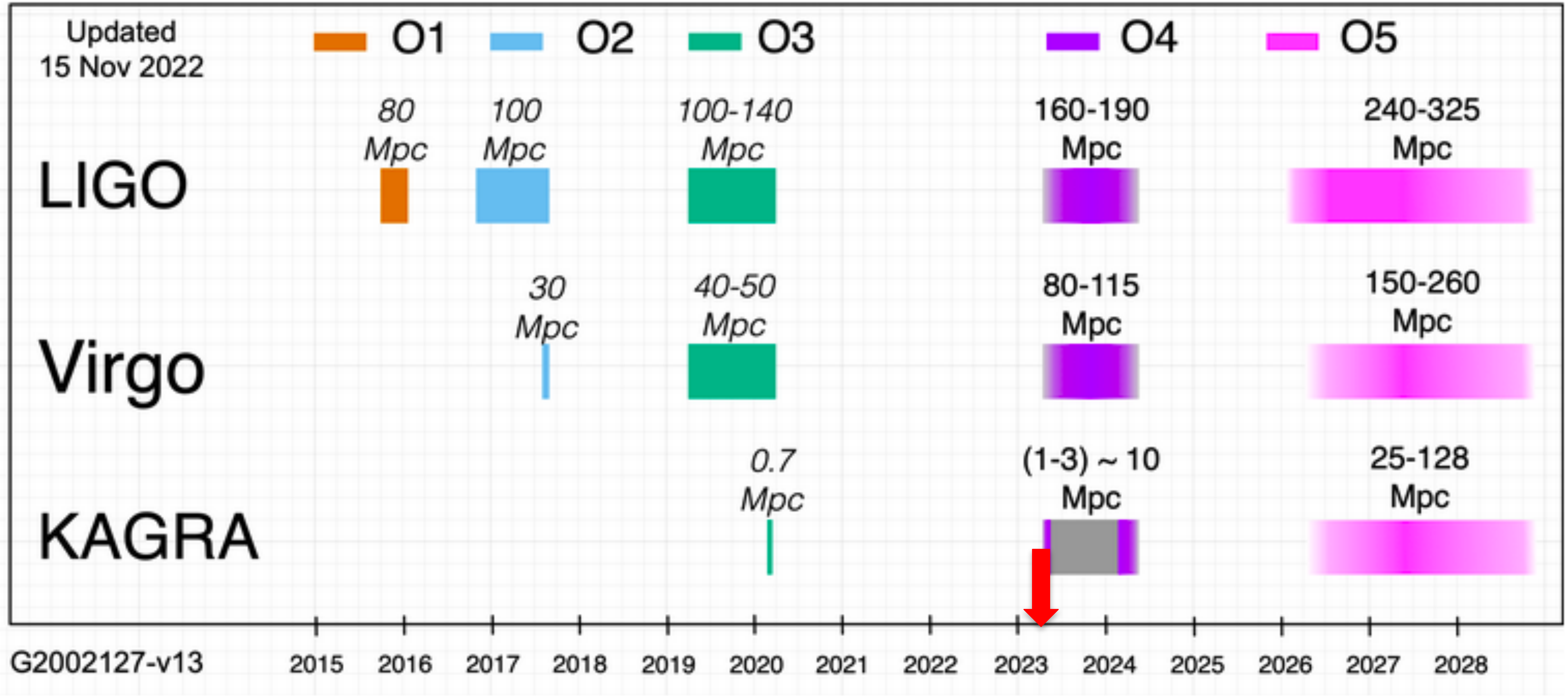
$$S(f) = |\tilde{n}(f)|^2$$

Energy per unit frequency
in time series at frequency f

Amplitude spectral density

$$\sqrt{S(f)} \sim \frac{\text{strain}}{\sqrt{\text{Hz}}}$$

LIGO/Virgo/KAGRA Schedule



O4 observation run expected to start on May 24th 2023 (18 months duration)

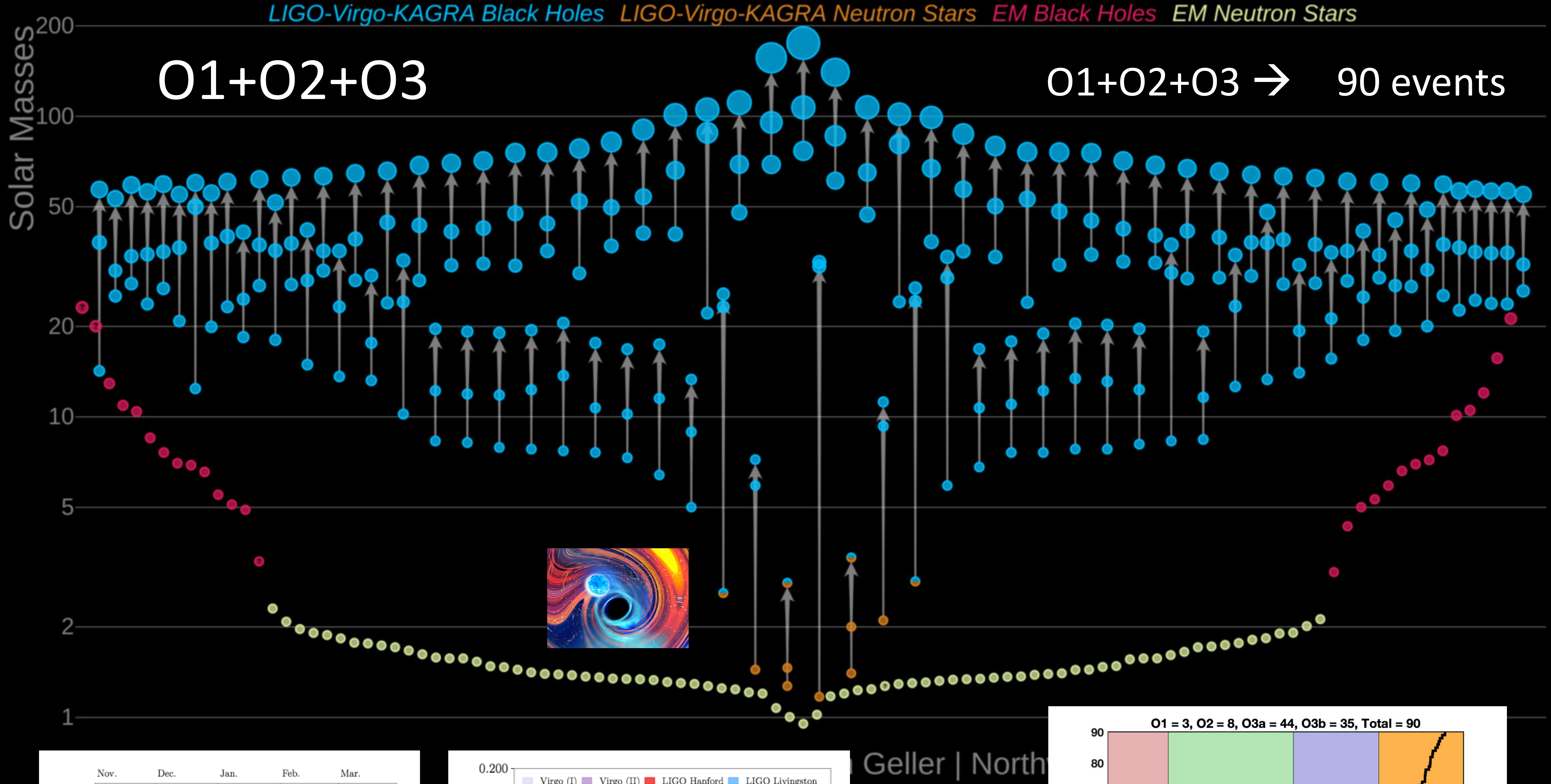
The KAGRA sensitivity is limited and it will join for first month.

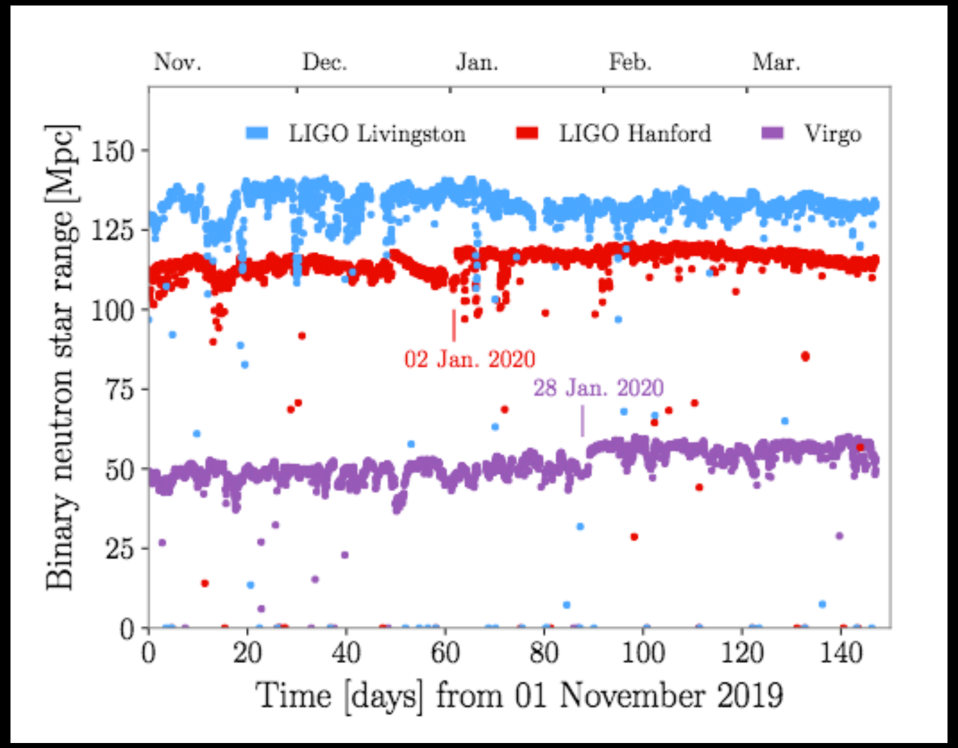
Virgo decided to delay its participation until sensitivity improves

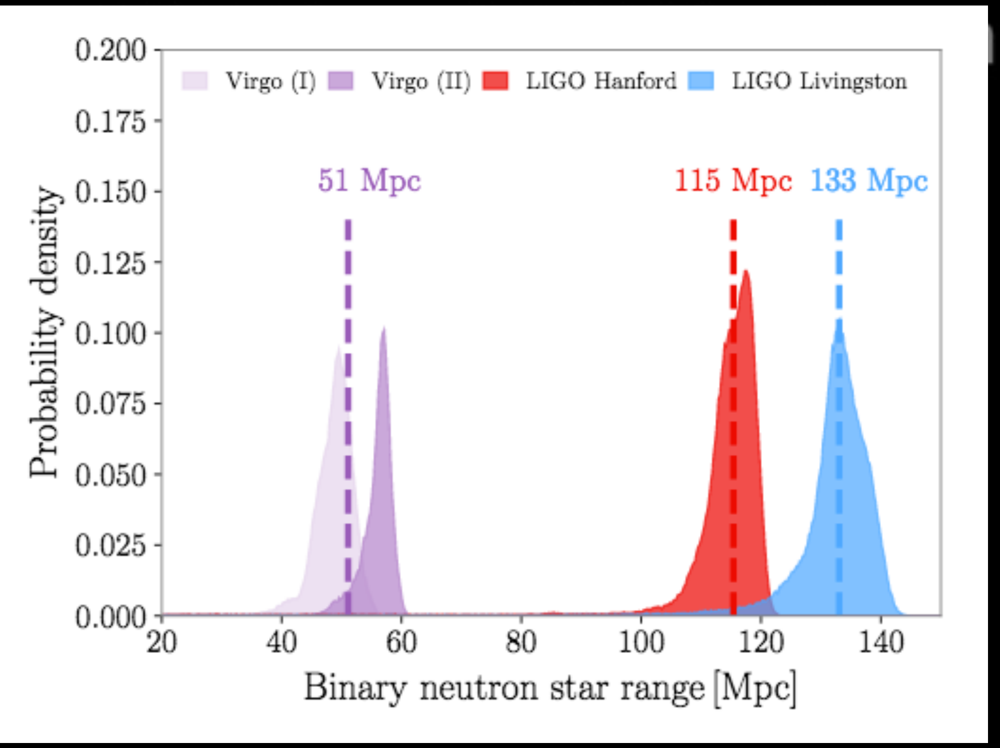
Masses in the Stellar Graveyard

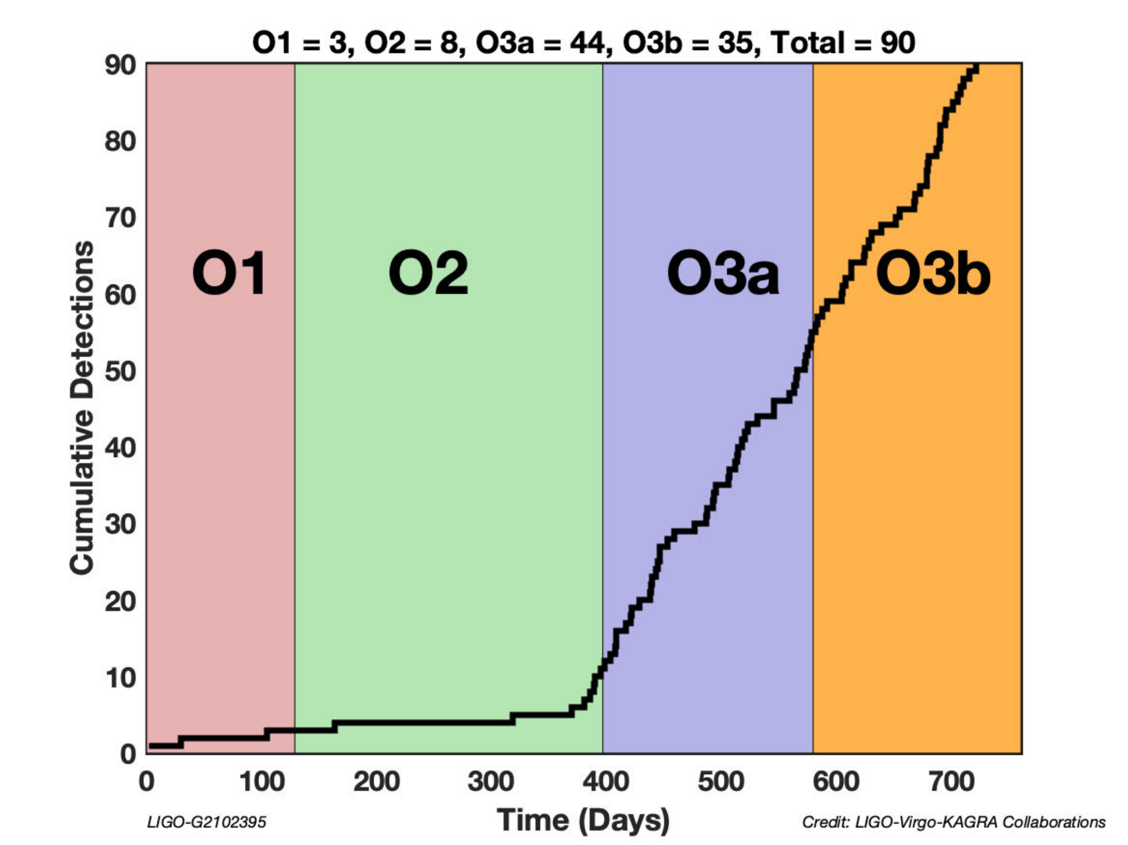
O1+O2+O3

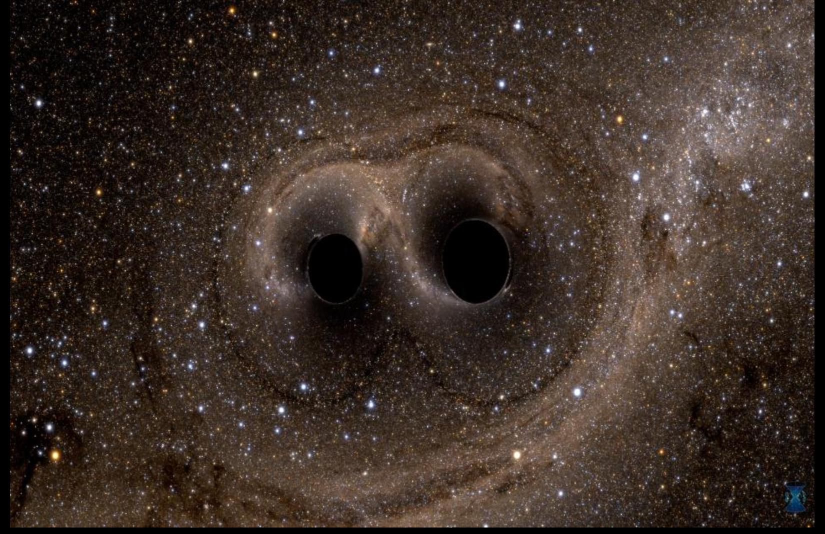
O1+O2+O3 → 90 events



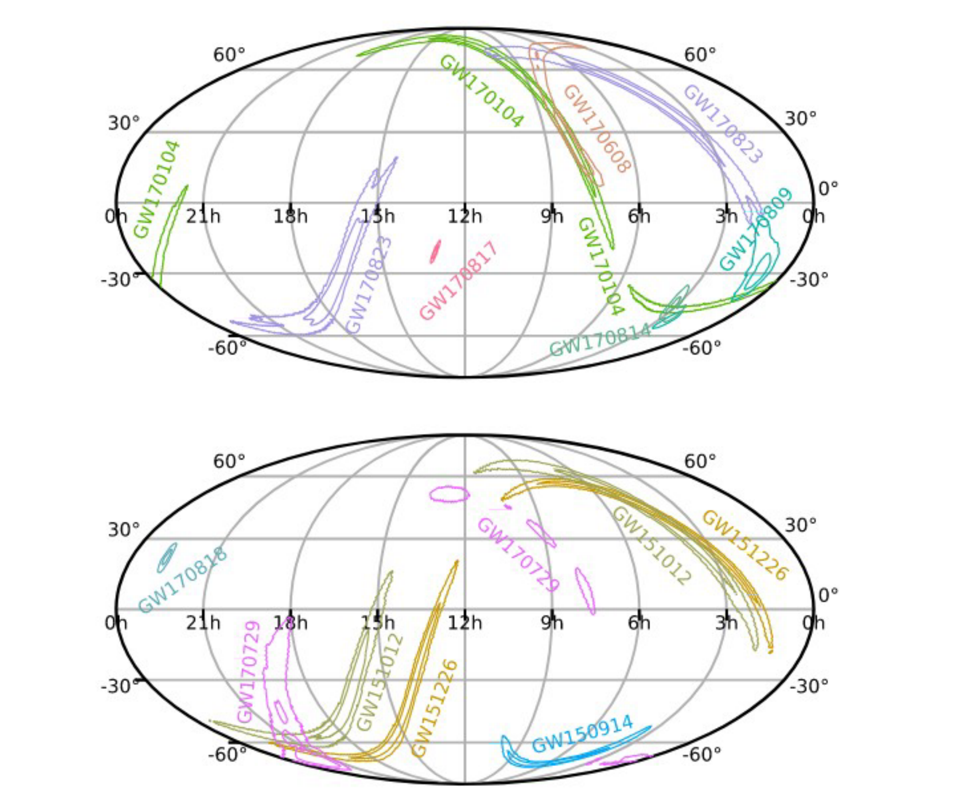




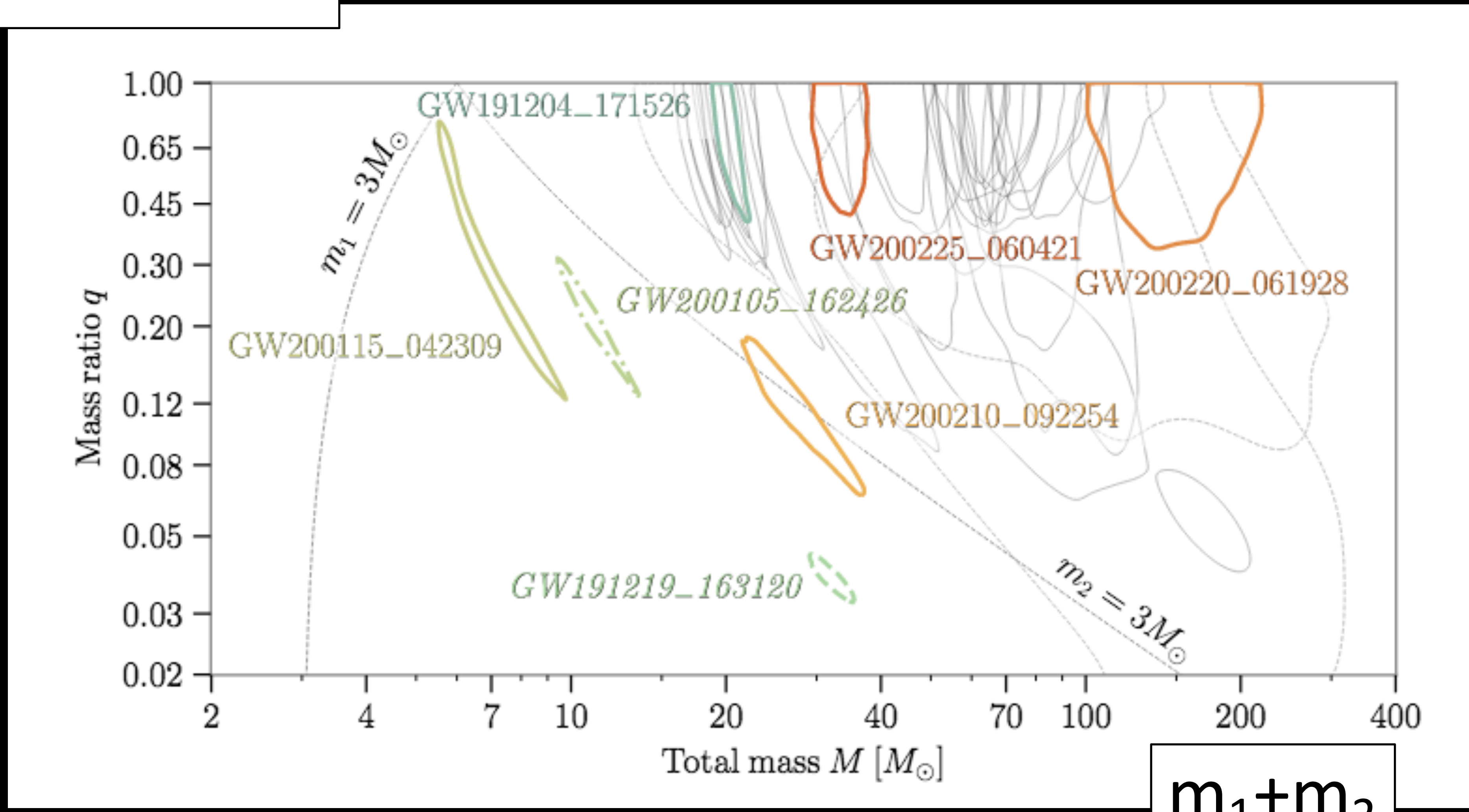




Population Studies (I)

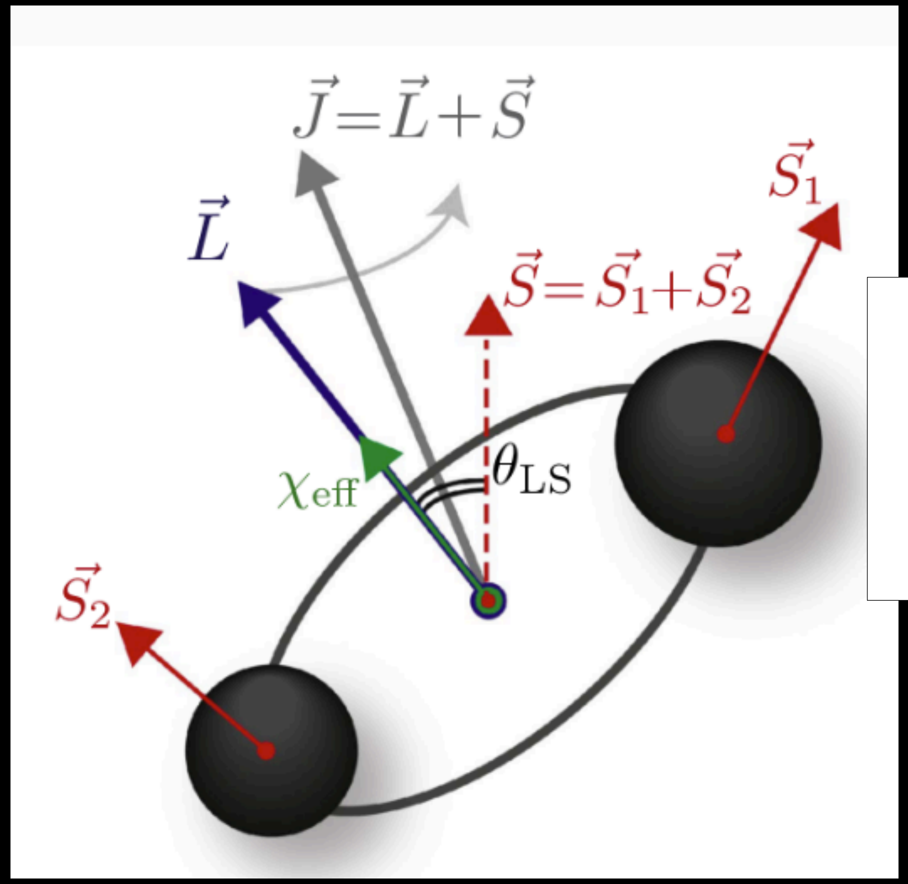


$q = m_2/m_1$

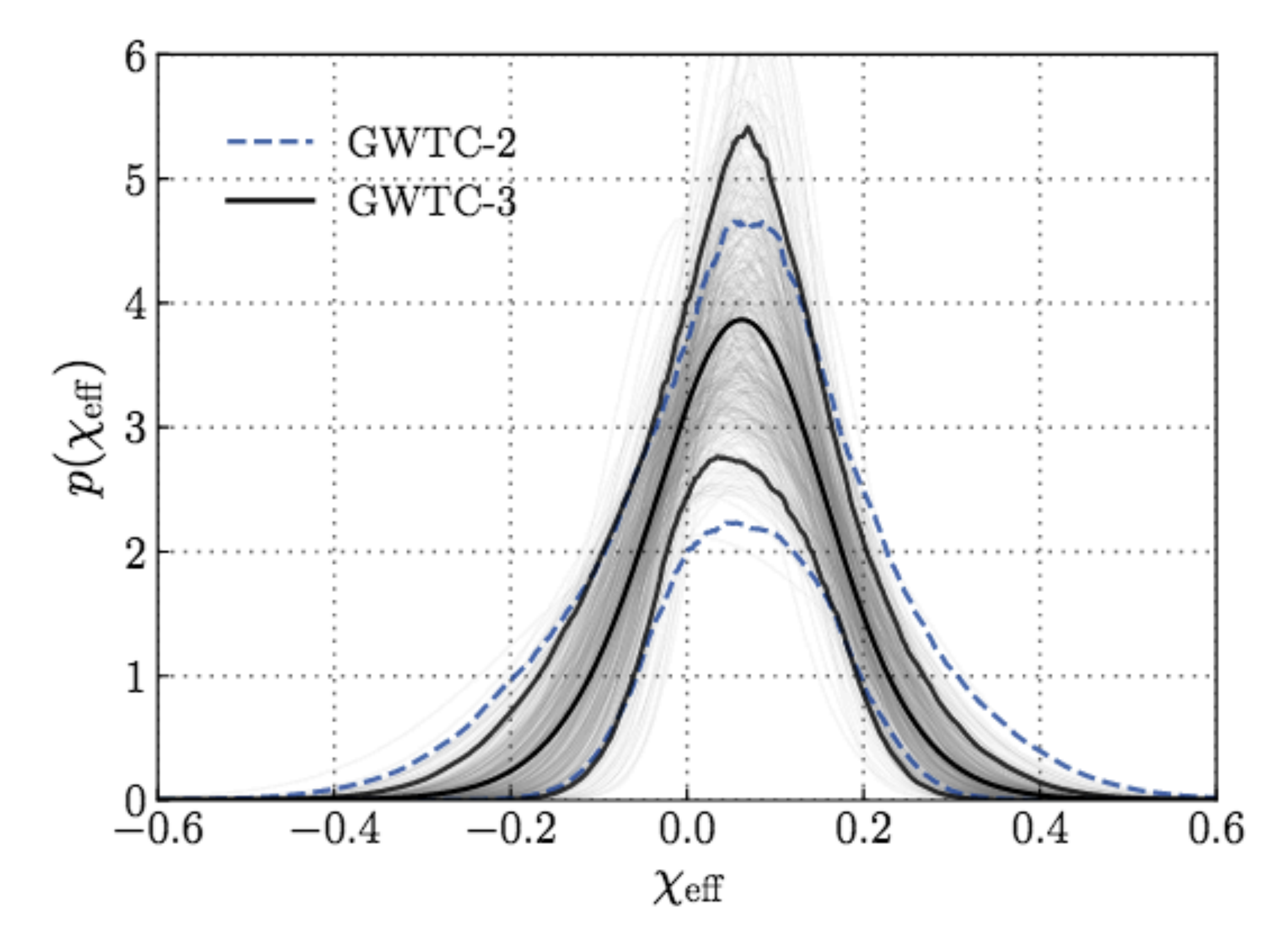


m_1+m_2

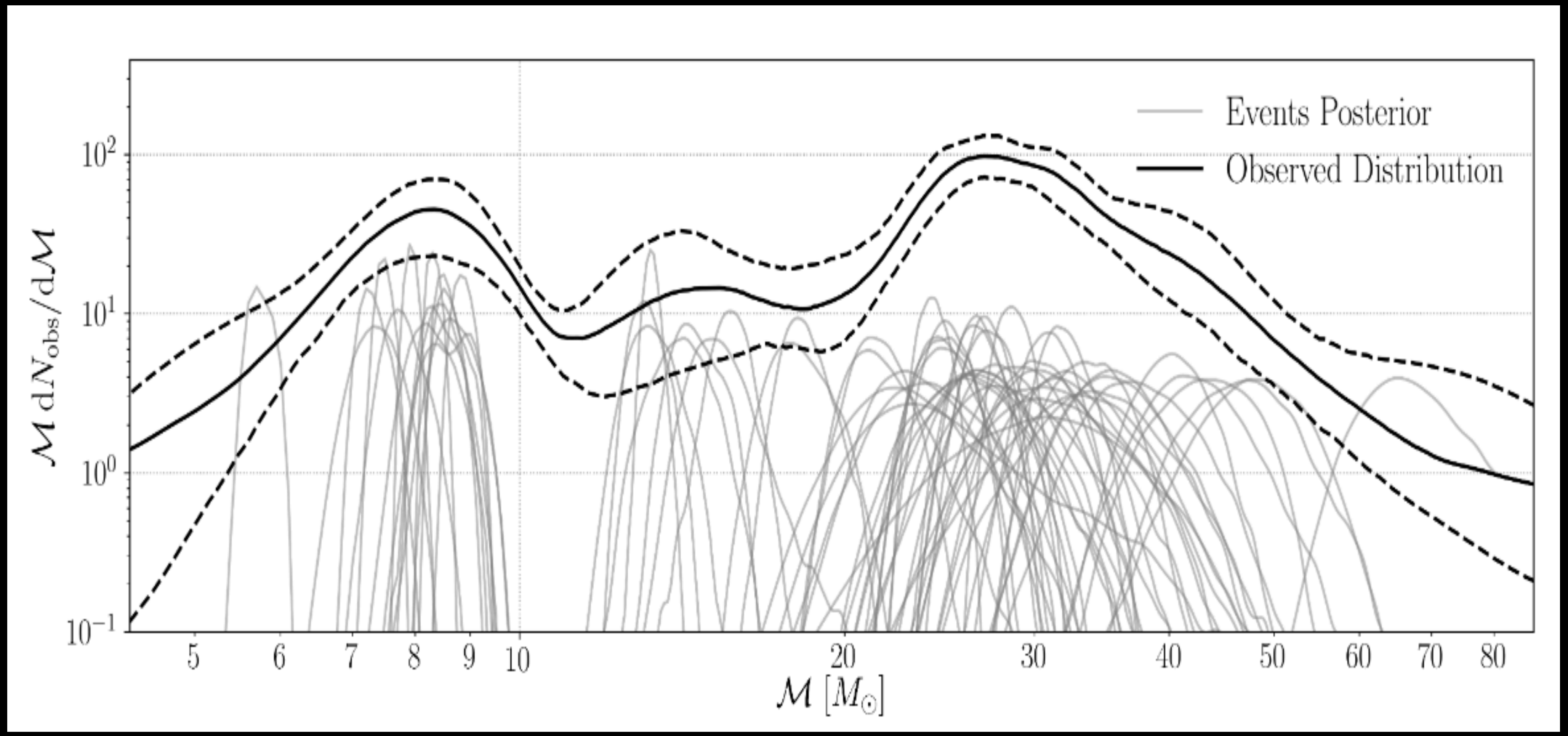
- Still large uncertainty in sky location.
- Binaries with clear asymmetric masses ($q < 1$).
- Indication of spin-orbit precession.
- Points to different production mechanism.



$$\chi_{\rm eff} = \frac{(m_1\vec{\chi}_1 + m_2\vec{\chi}_2)\cdot\hat{L}_{\rm N}}{M}$$



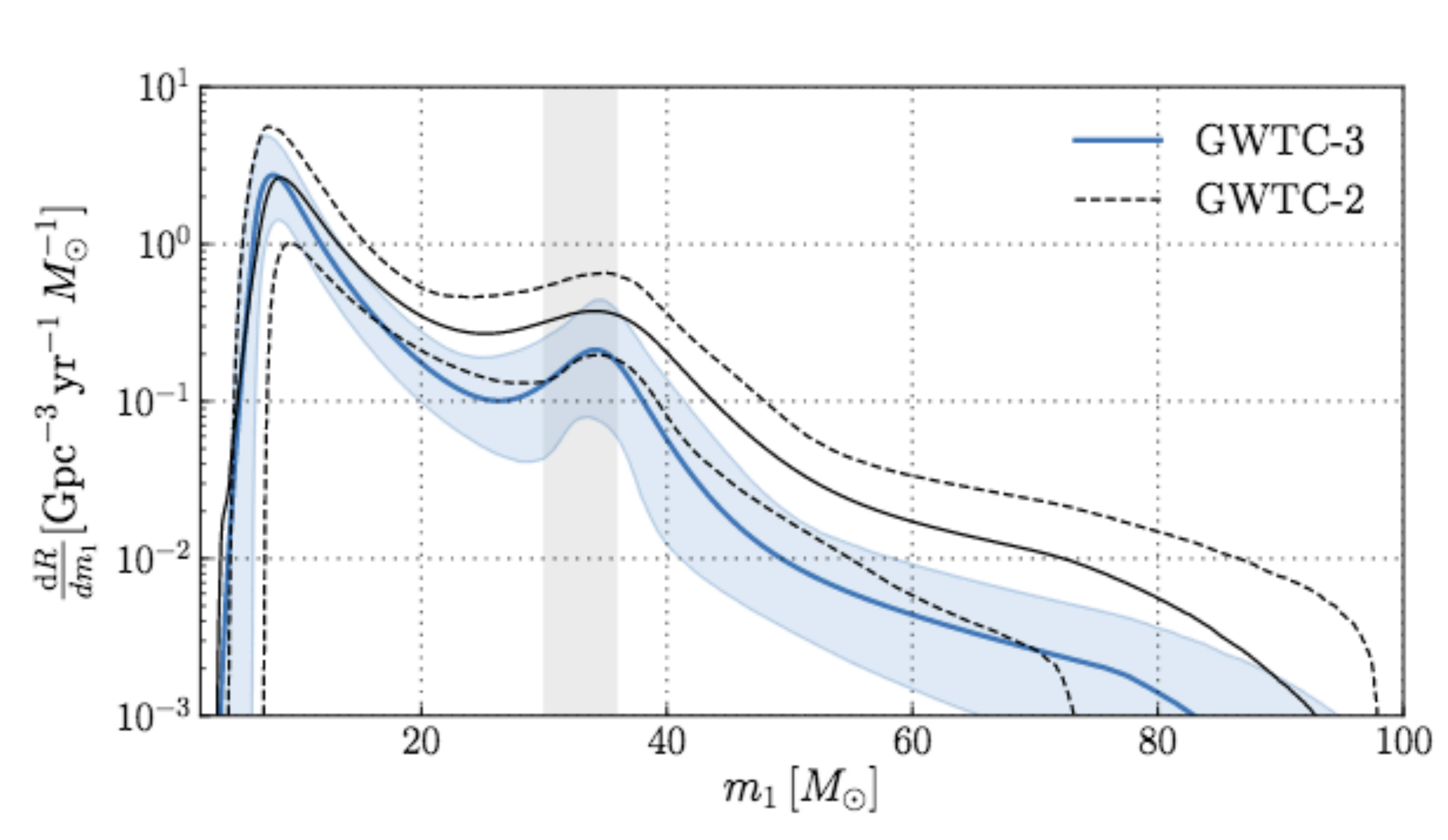
Population studies (II)

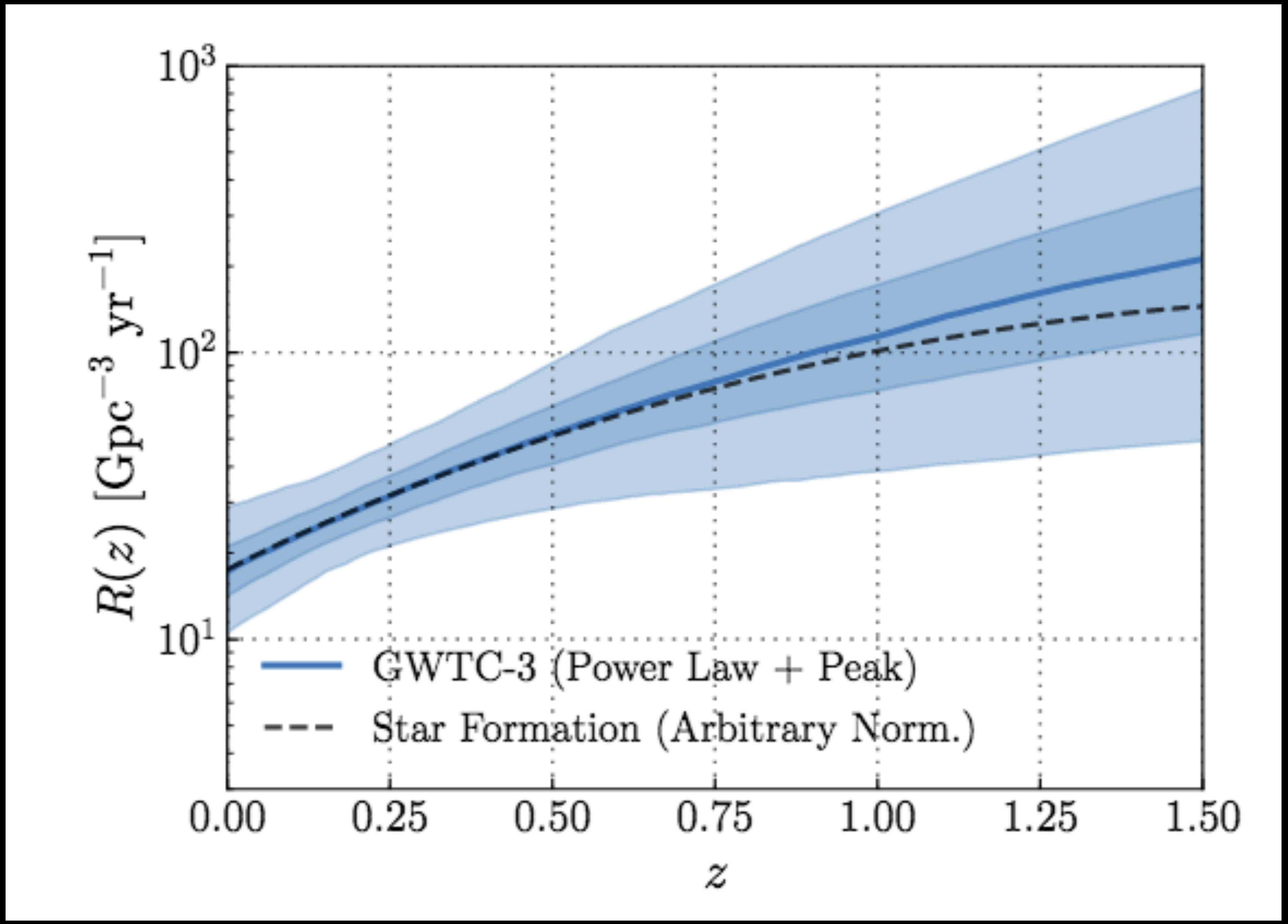


$$M_{ch} = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}}$$

First differential distributions
→ Start resolving different populations

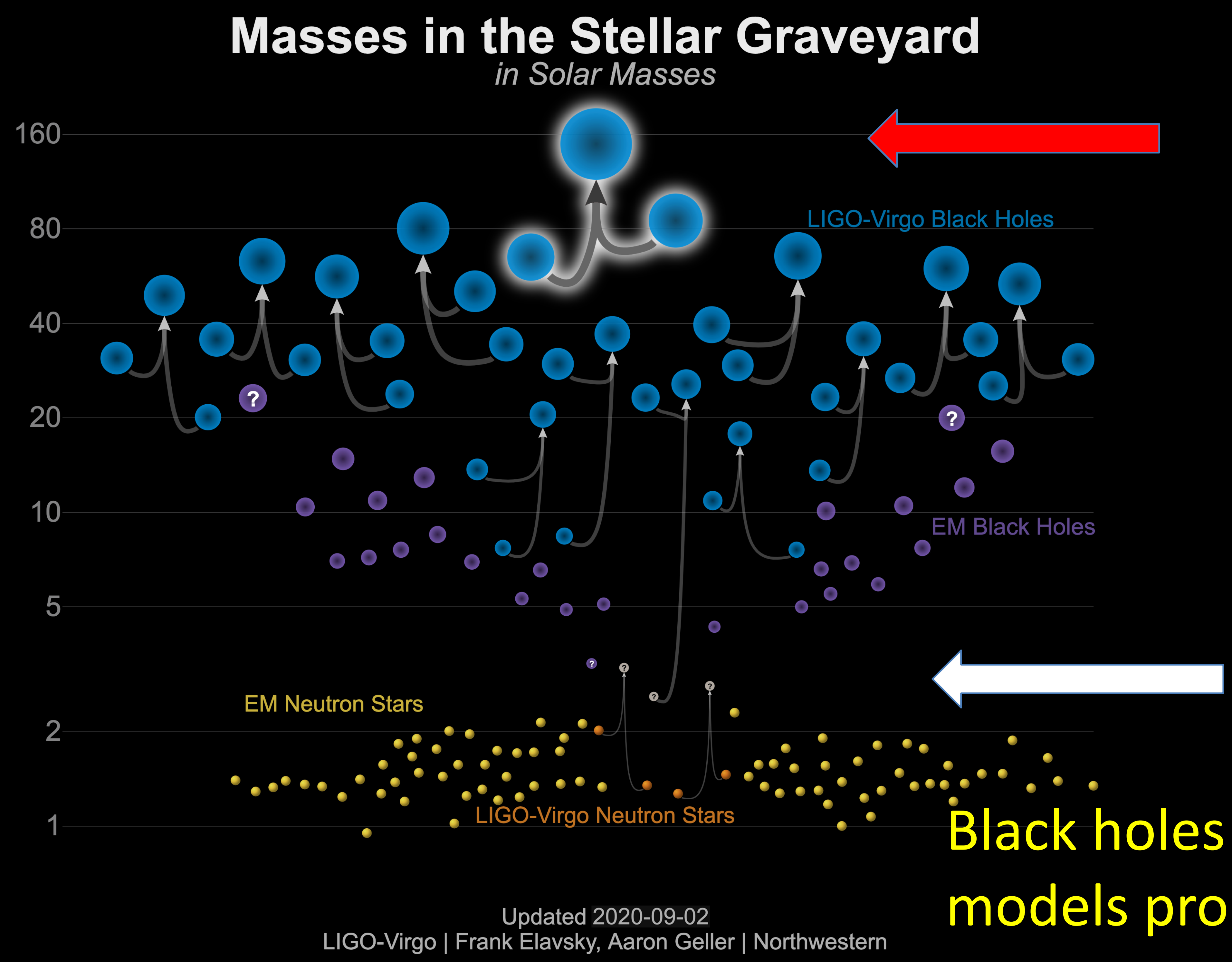
Population vs z consistent with star formation models (limited to small redshifts)

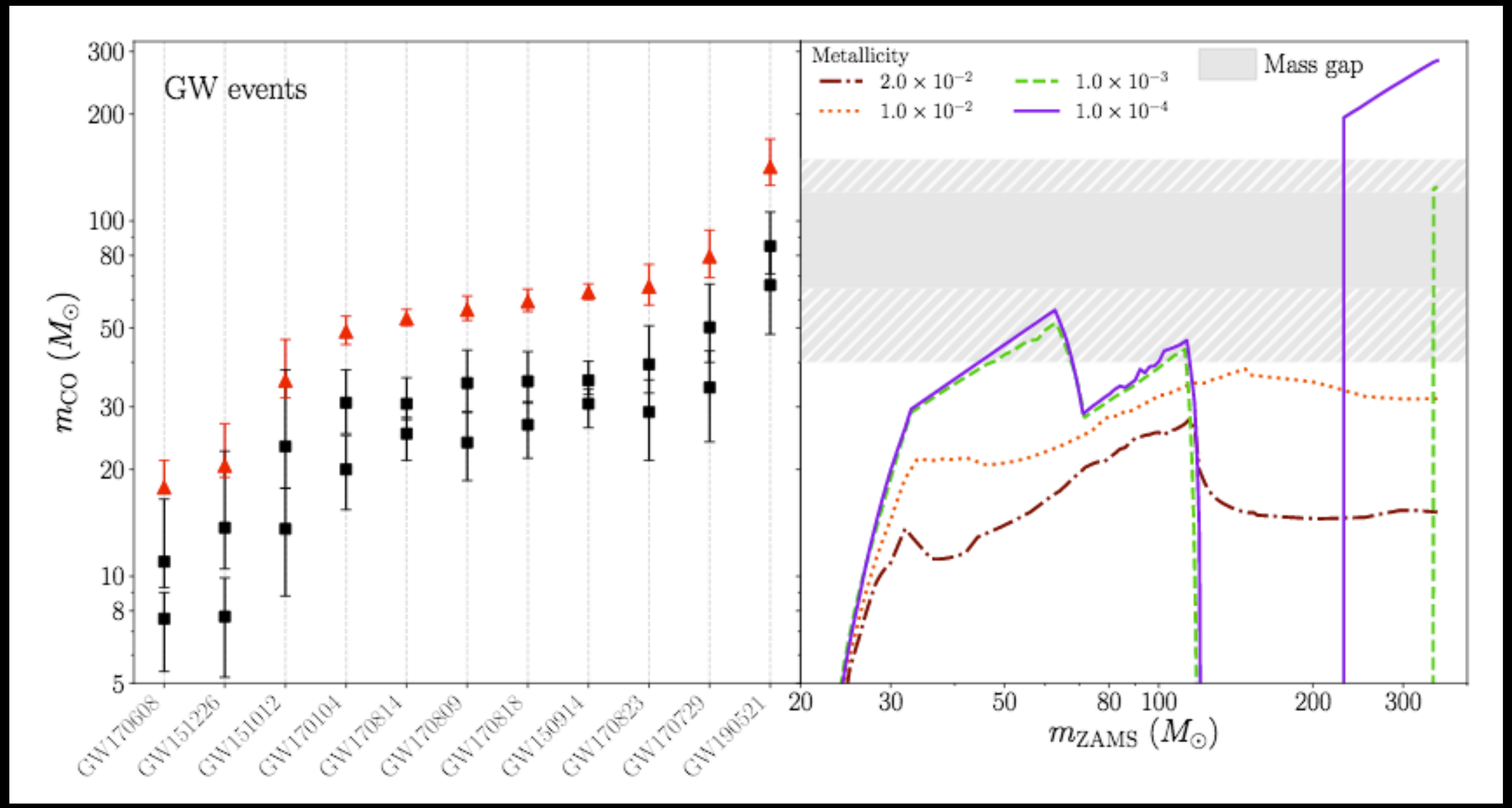


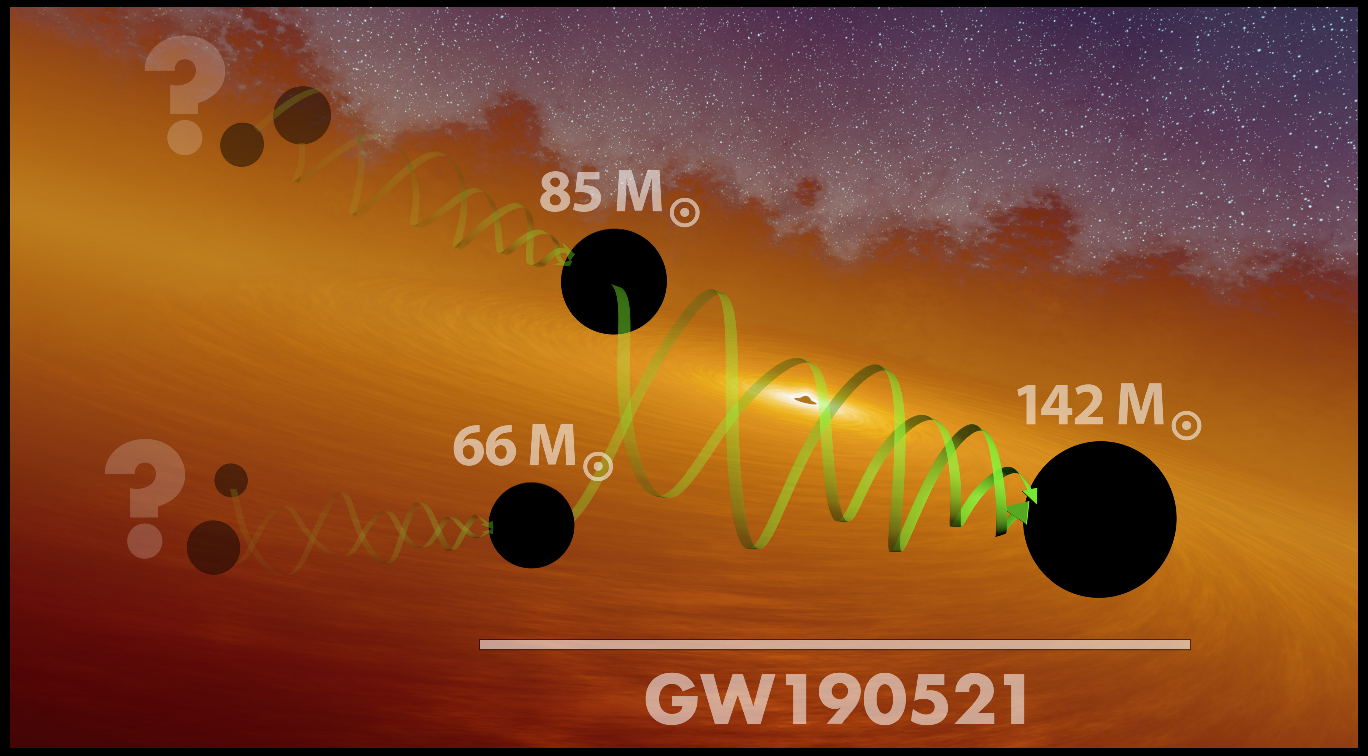


Event in the "mass gap"

(GW190521)





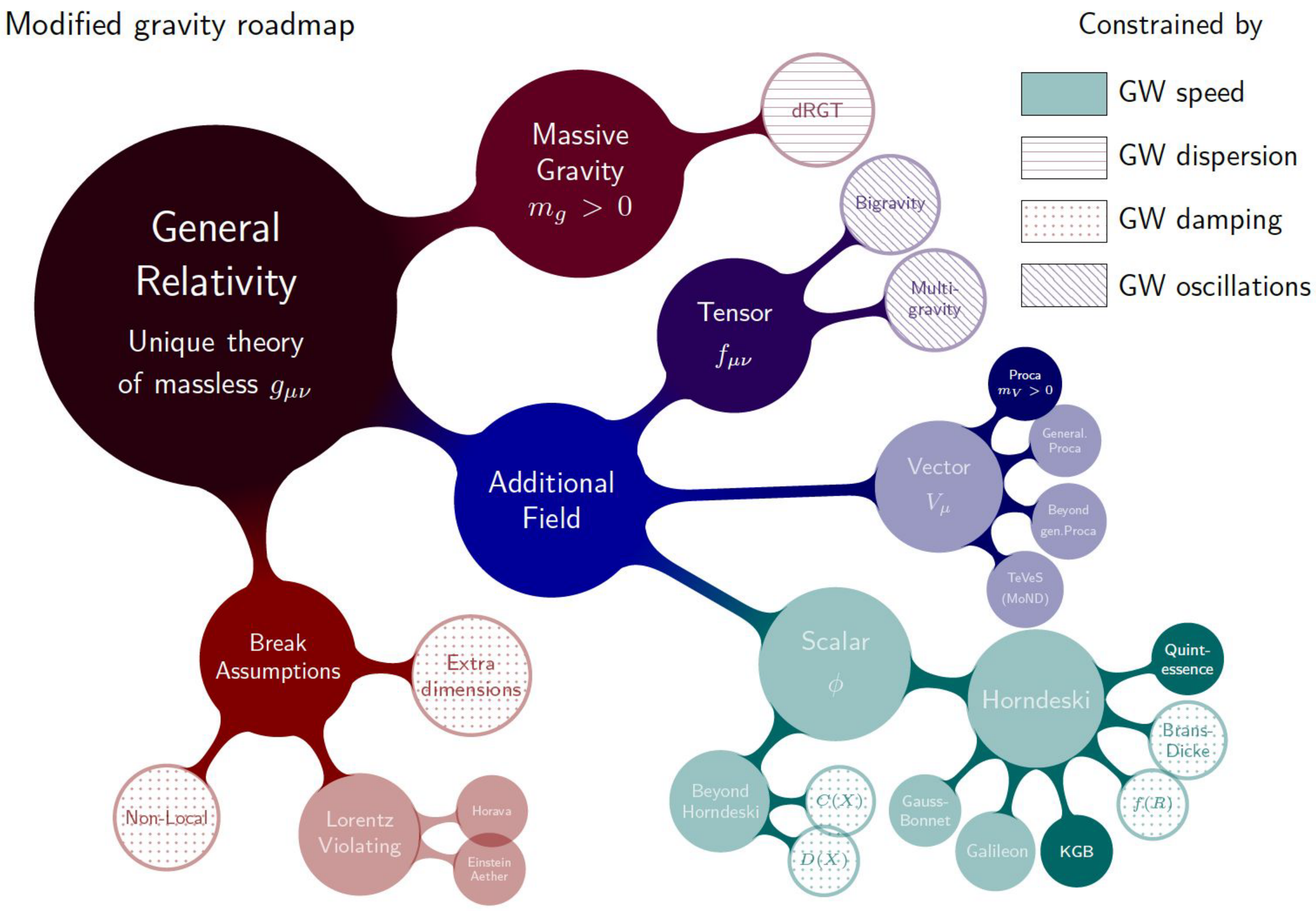


Black holes in the "mass gap" where stellar evolution models prohibit their presence

- Product of successive black hole mergers?
- Review of stellar evolution models?
- Primordial origin of black holes?

Production of a 142 M_{sun} black hole Illustrates how very massive BH can be produced

Tests of General Relativity

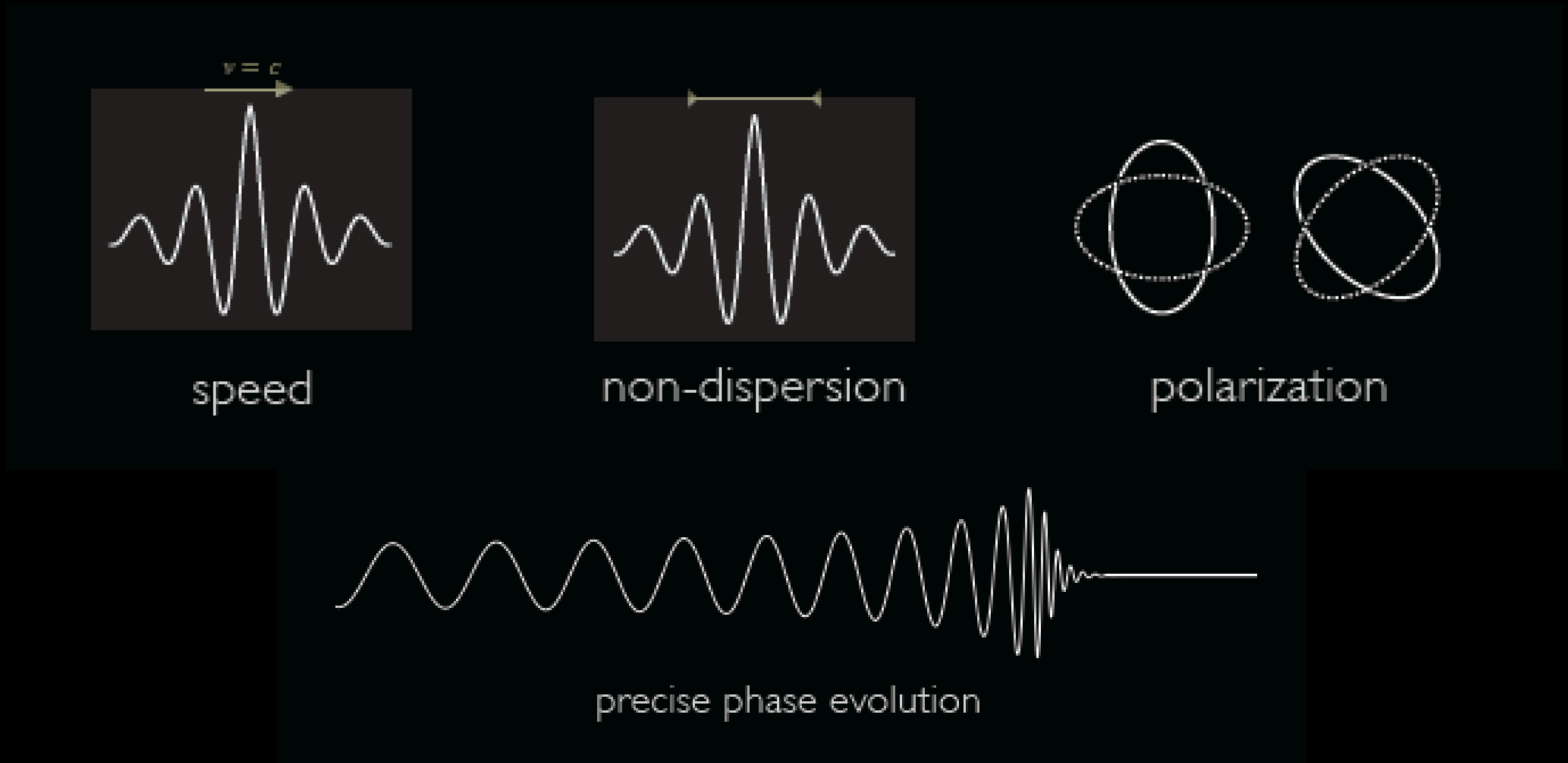


https://arxiv.org/pdf/2112.06861.pdf

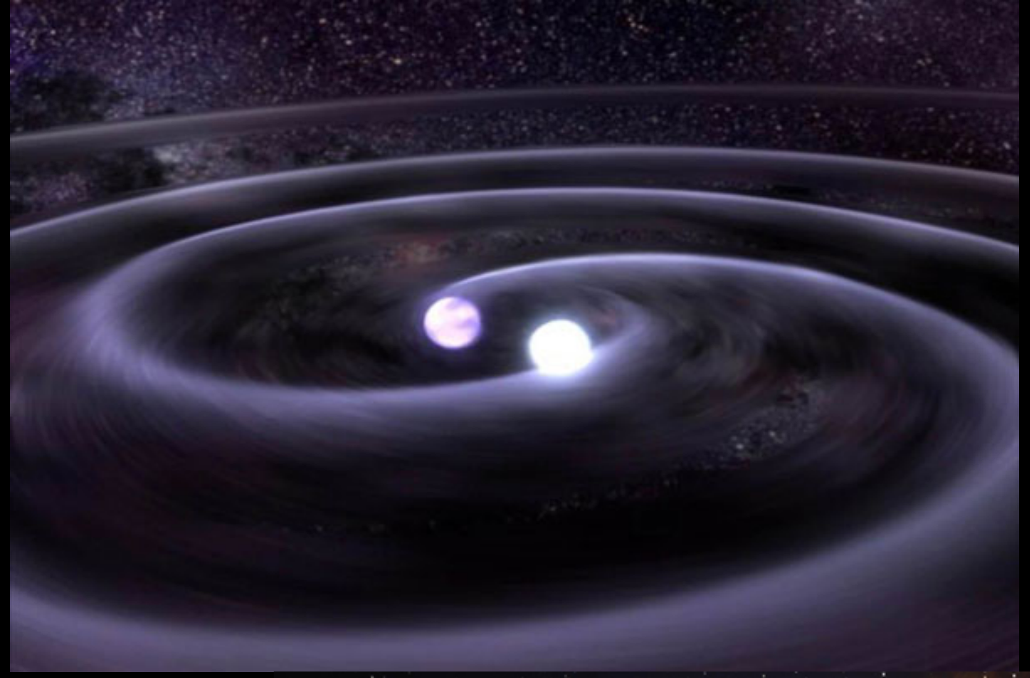
e-Print: 2112.06861

Test of General relativity

GR provides very precise predictions on wave velocity, non-dispersion, polarizations (+,x) and waveform (phase evolution)



Speed of Gravity

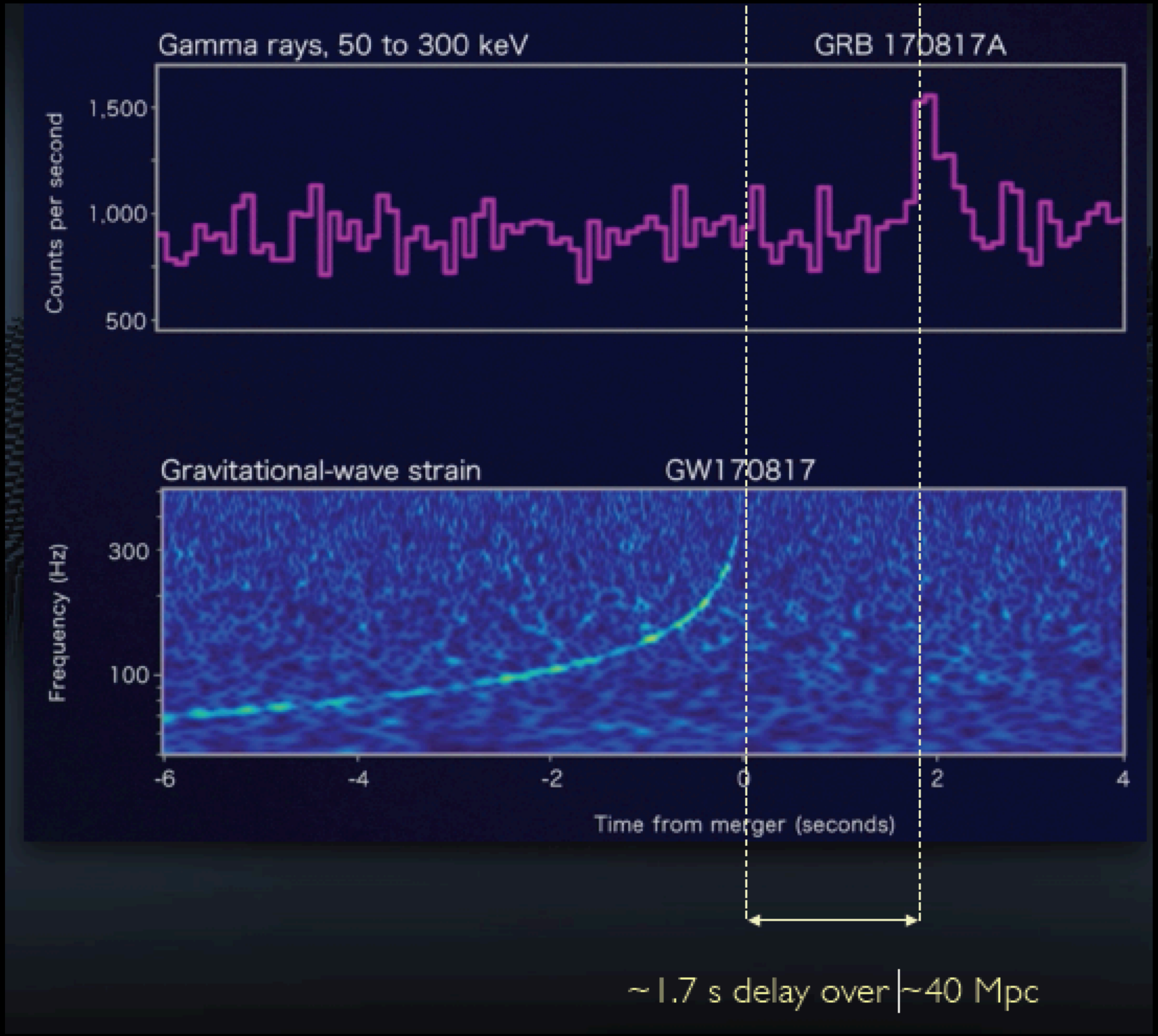


Time of arrival of GW and EM

GW170817

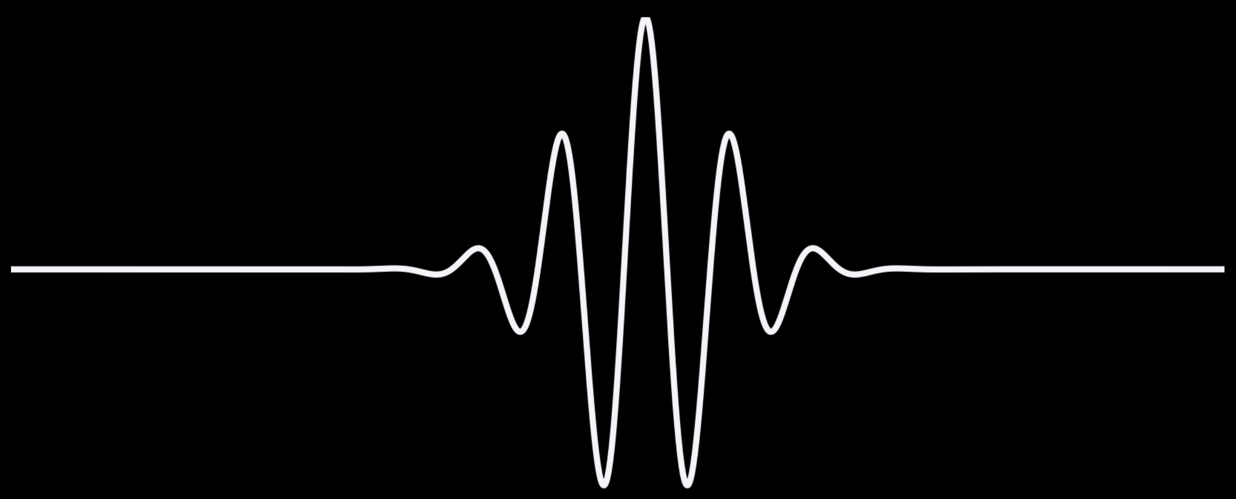
$$-3 \times 10^{-15} \leq c_{gw}/c - 1 \leq 7 \times 10^{-16}$$

Abbott+2017 [arxiv:1710.05834]

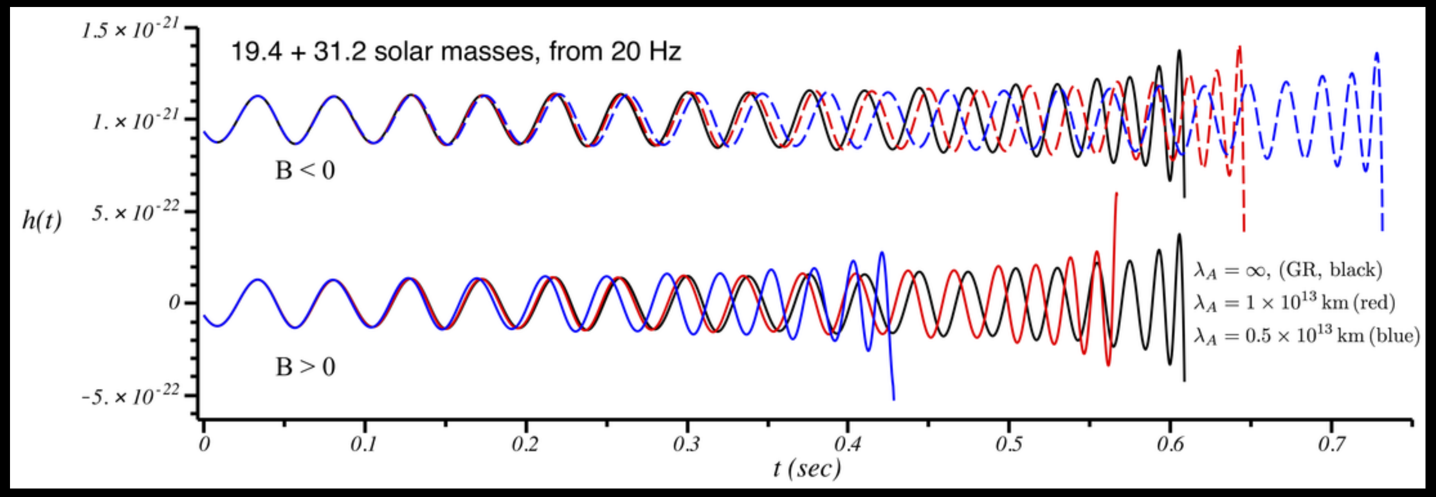


Introduces severe constrains to models with modified GR at cosmological scales
Baker+2017 [arxiv:1710.06394], Creminelli+2017 [arxiv:710.05877], Ezquiaga+2017 [arxiv:1710.05901], Sakstein+2017 [arxiv:1710.05893

Dispersion



Propagation velocity will depend on the frequency (Low frequencies slower)



Taking into account cosmology translates into modified waveforms with dephasing effects

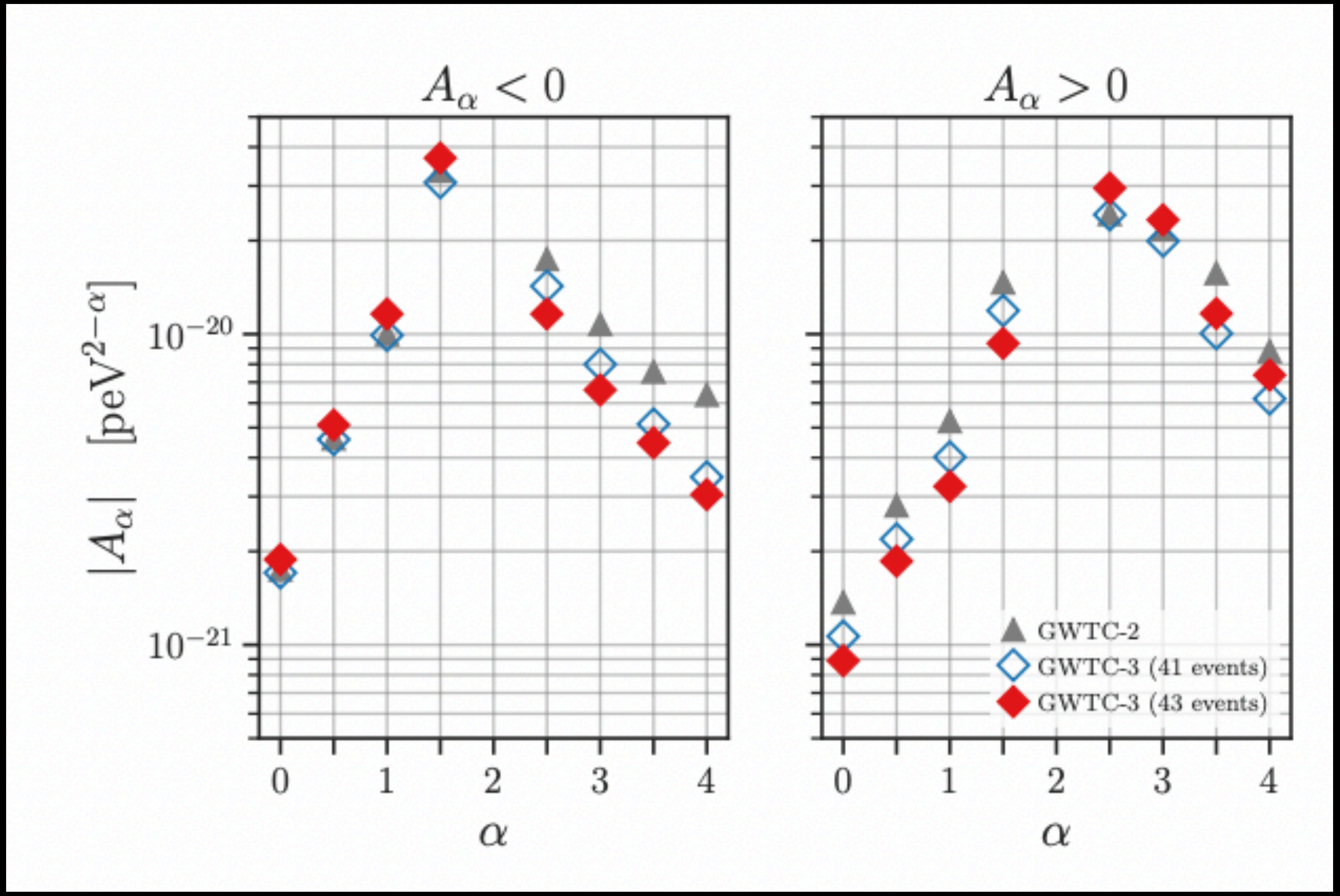
$$m_g = \sqrt{A_0}/c^2$$

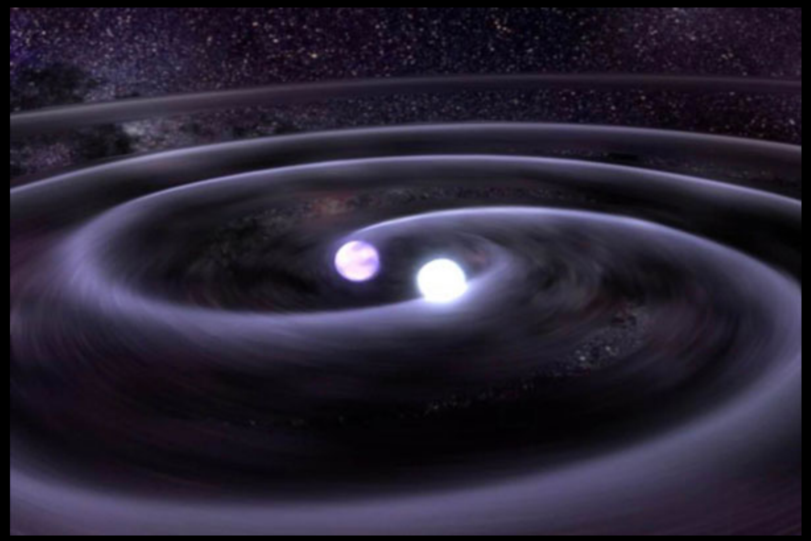
$$m_g \leq 1.27 \times 10^{-23} \mathrm{eV}/c^2$$

$$E^2 = p^2c^2 + A_\alpha p^\alpha c^\alpha$$

$$g_{\mu\nu}p^\mu p^\nu = -m_g^2 - \mathbb{A}|p|^\alpha$$

Effective approach to cover different models beyond GR





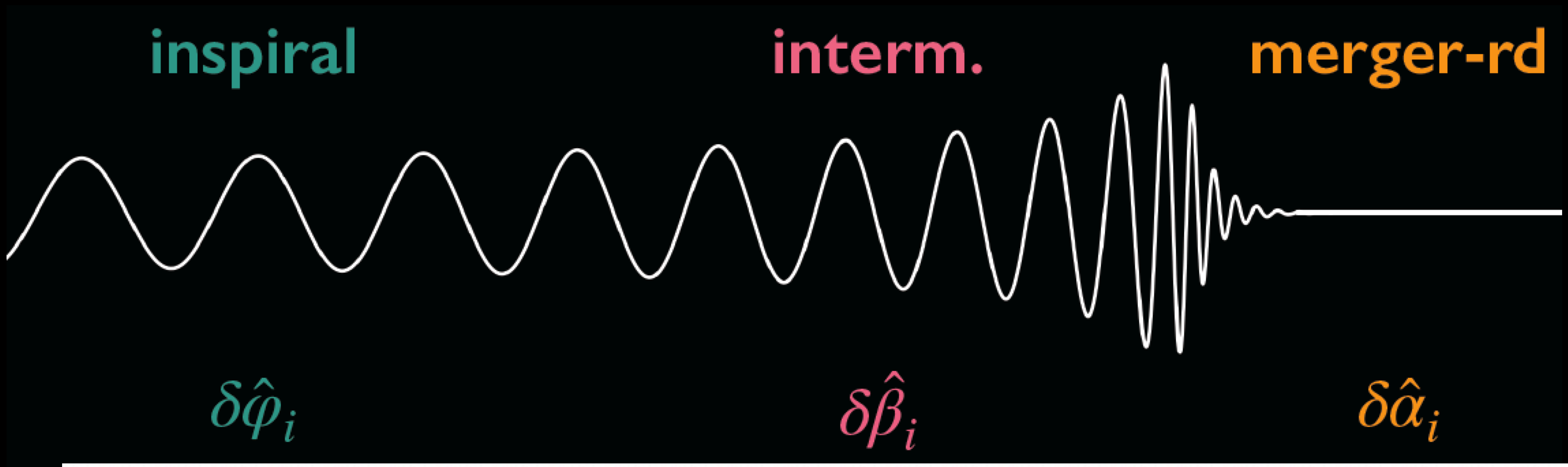
Waveform

Express inspiral phase as a series expansion in the orbital velocity v (f ~ v³/M)

GW tails

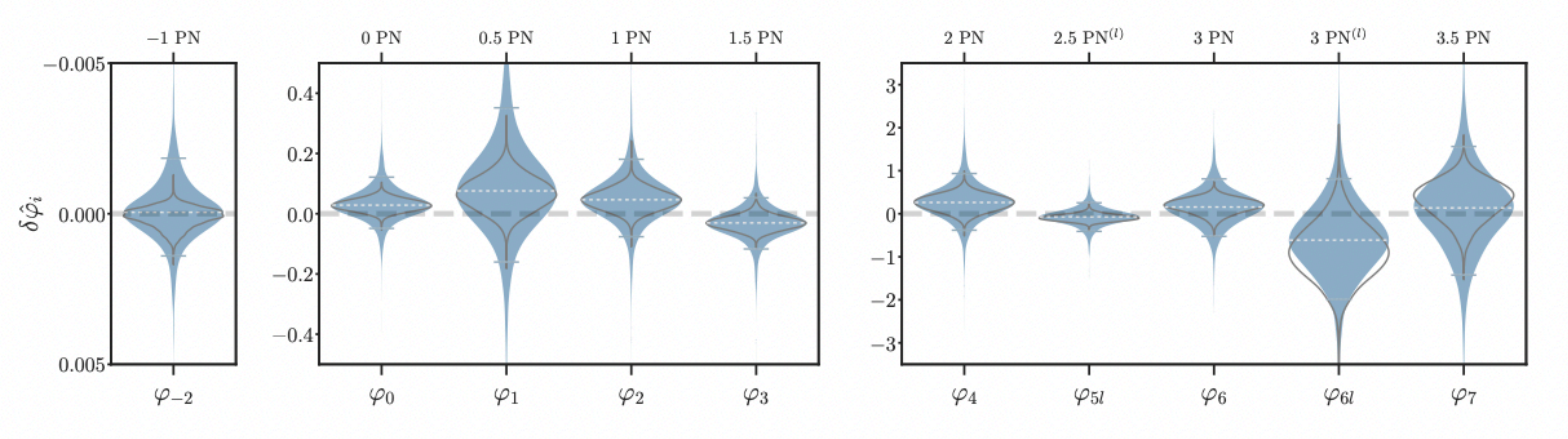
$$\Phi(v) = \left(\frac{v}{c}\right)^{-5}\left[\varphi_0 + \varphi_1\left(\frac{v}{c}\right) + \varphi_2\left(\frac{v}{c}\right)^2 + \ldots + \varphi_{5l}\ln\left(\frac{v}{c}\right)\left(\frac{v}{c}\right)^5 + \ldots + \varphi_7\left(\frac{v}{c}\right)^7\right]$$

0PN + 0.5PN + 1PN + … + 2.5PN$^{(l)}$ + … + 3.5PN

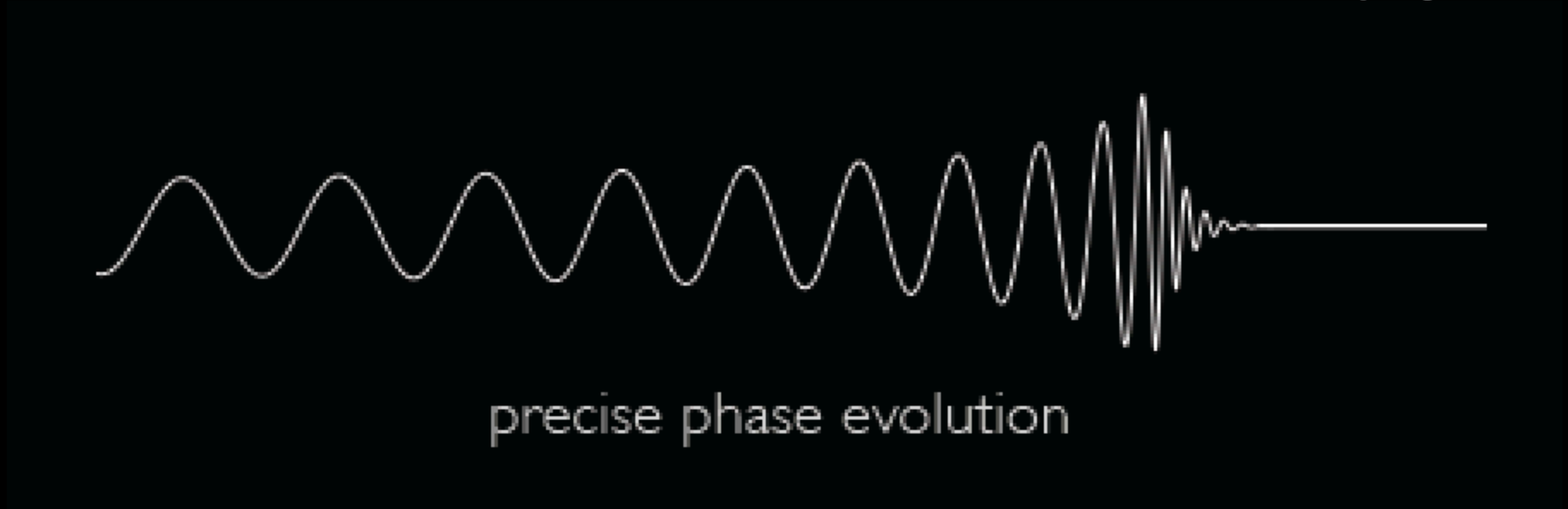


$$p_i \rightarrow \left(1 + \delta\hat{p}_i\right) p_i$$

Consistent with GR

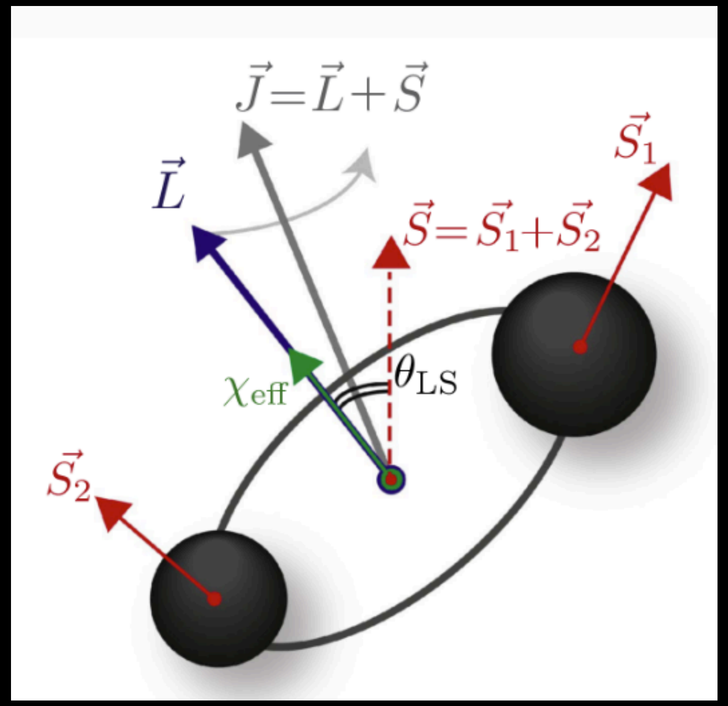


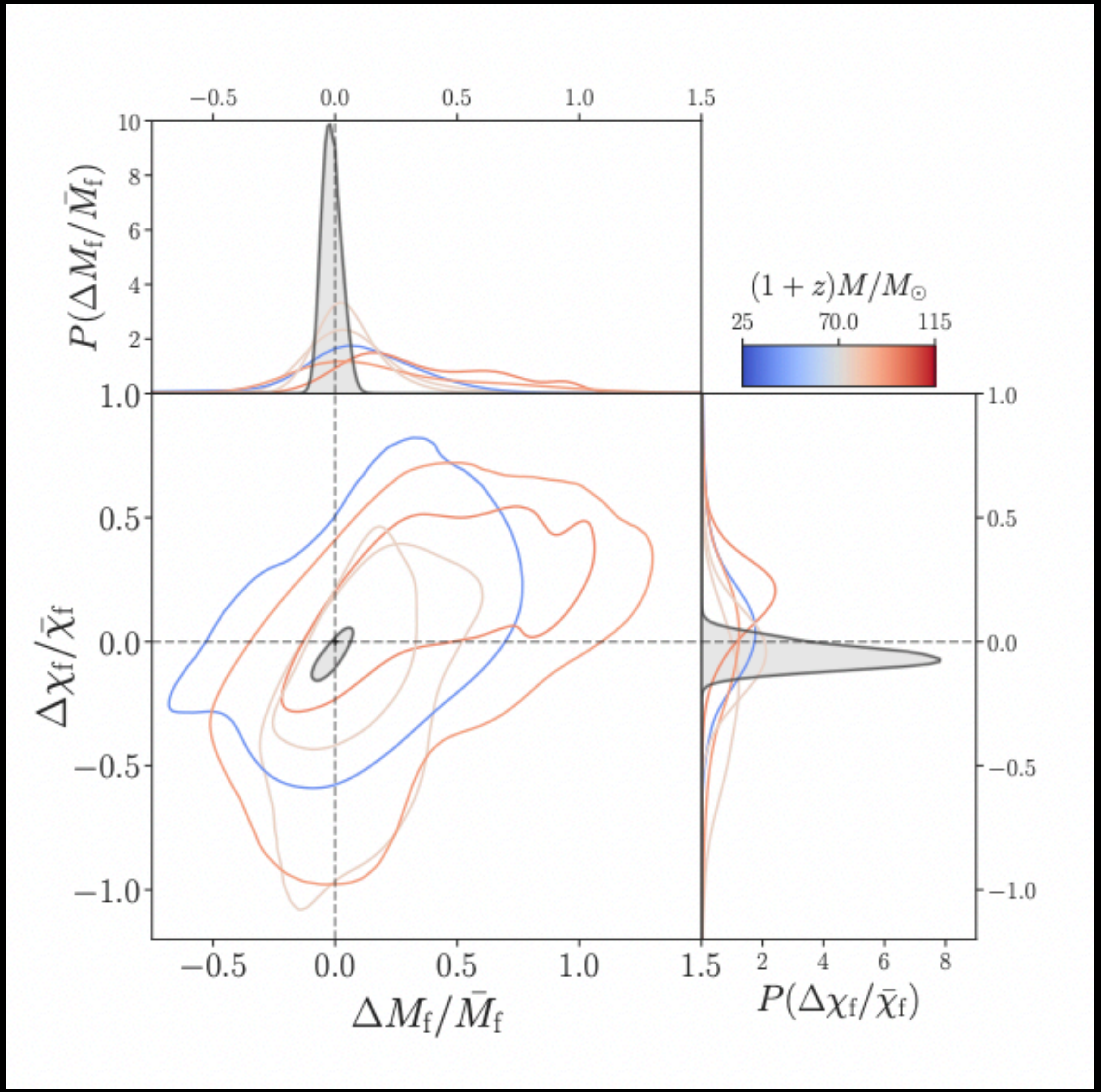
Inspiral–merger–ringdown consistency test



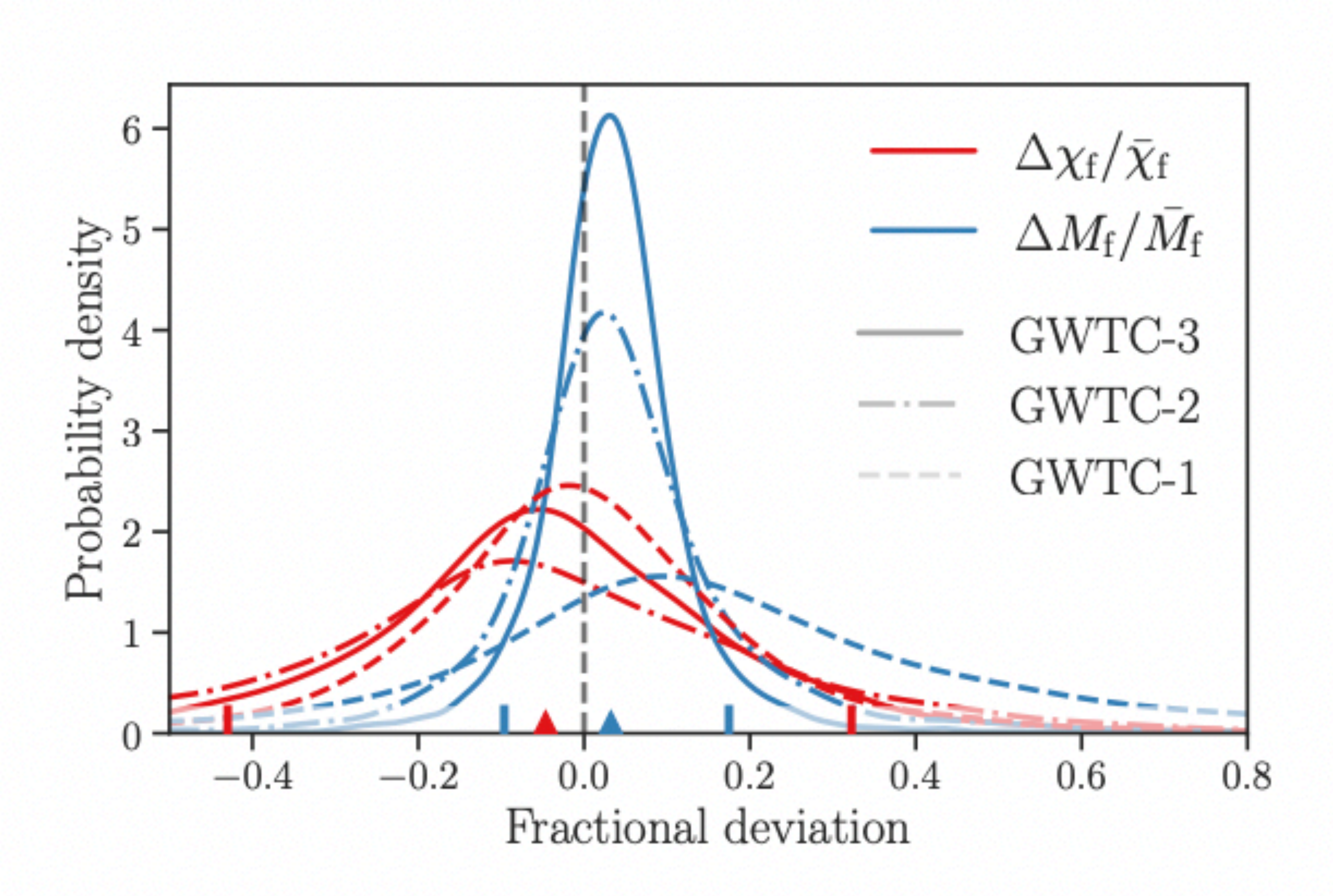
$$\frac{\Delta M_f}{\bar{M}_f} = 2\frac{M_f^{insp} - M_f^{postinsp}}{M_f^{insp} + M_f^{postinsp}},$$

$$\frac{\Delta \chi_f}{\bar{\chi}_f} = 2\frac{\chi_f^{insp} - \chi_f^{postinsp}}{\chi_f^{insp} + \chi_f^{postinsp}},$$





Determining the remnant mass and
Spin using different parts of the waveform



Tests for Exotic Objects

The spin-induced multipole moments take unique values for black holes given their mass and spin. At leading order:

$$Q = -\kappa \chi^2 m^3$$

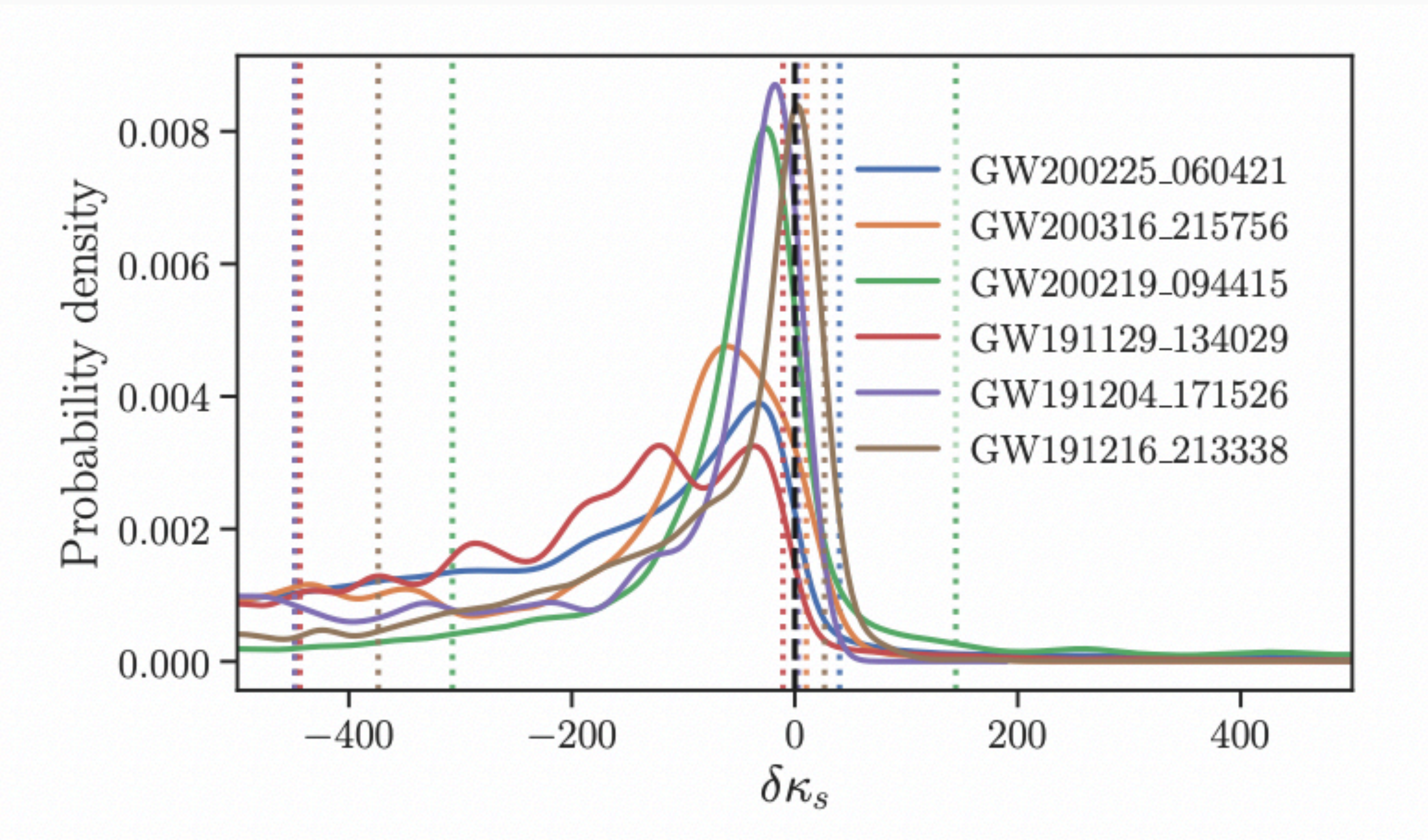
For BH -> k=1

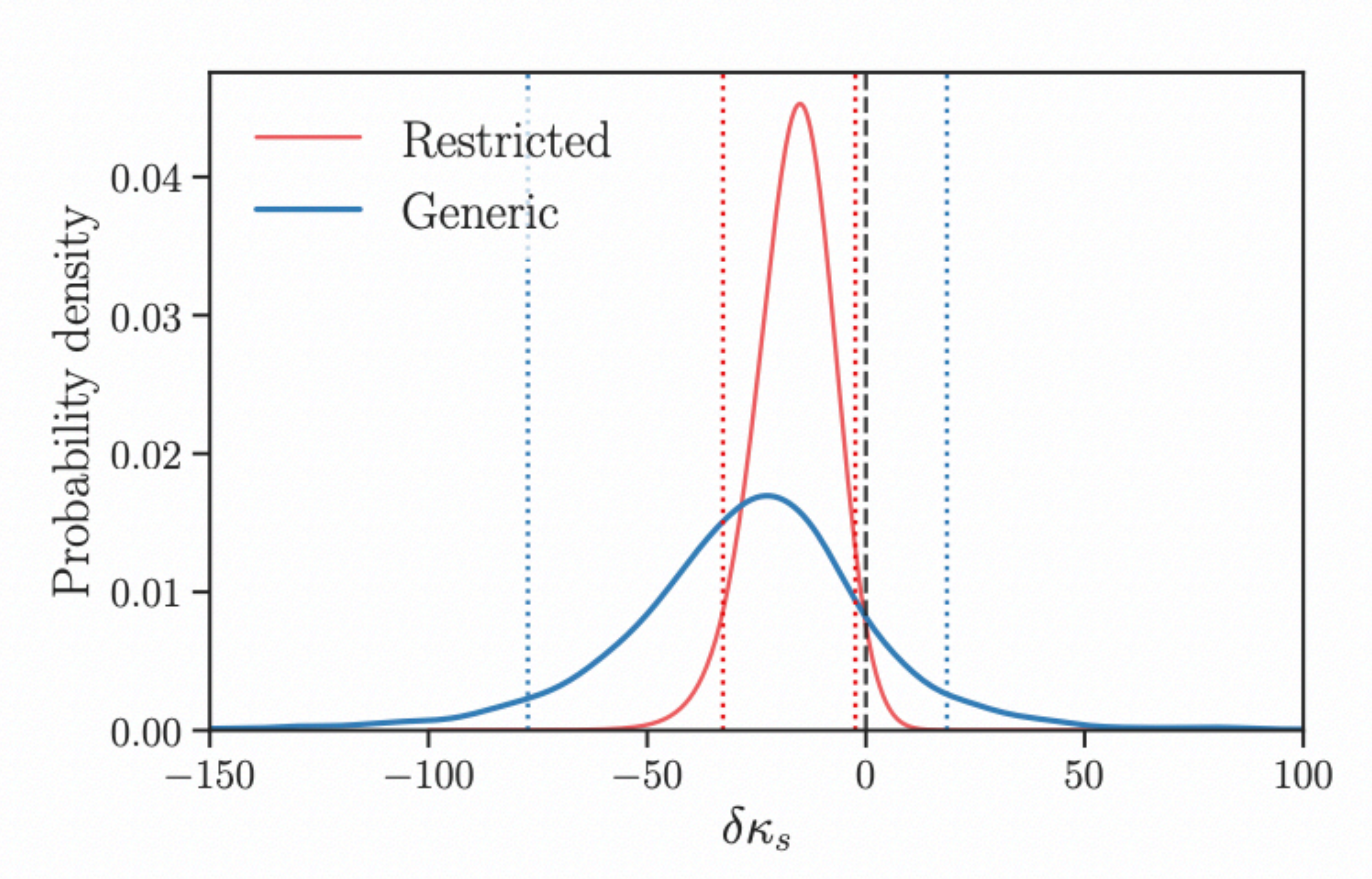
Values very different from 1 would indicate the presence of exotic objects

We look from deviations using the symmetric and asymmetric decomposition of the primary and secondary components'spin-induced quadrupole moment parameters
—> translate into modified PN expansion of inspiral phase

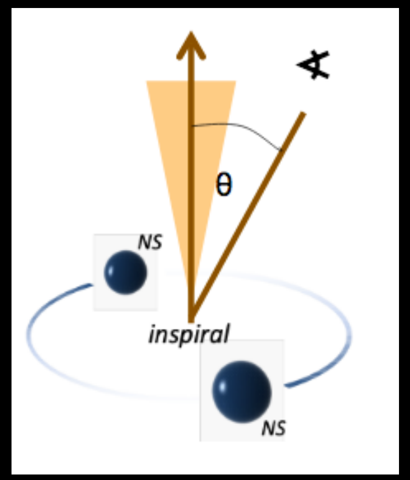
$$\kappa_s = (\kappa_1 + \kappa_2)/2$$
$$\kappa_a = (\kappa_1 - \kappa_2)/2$$

Consistent with BH hypothesis

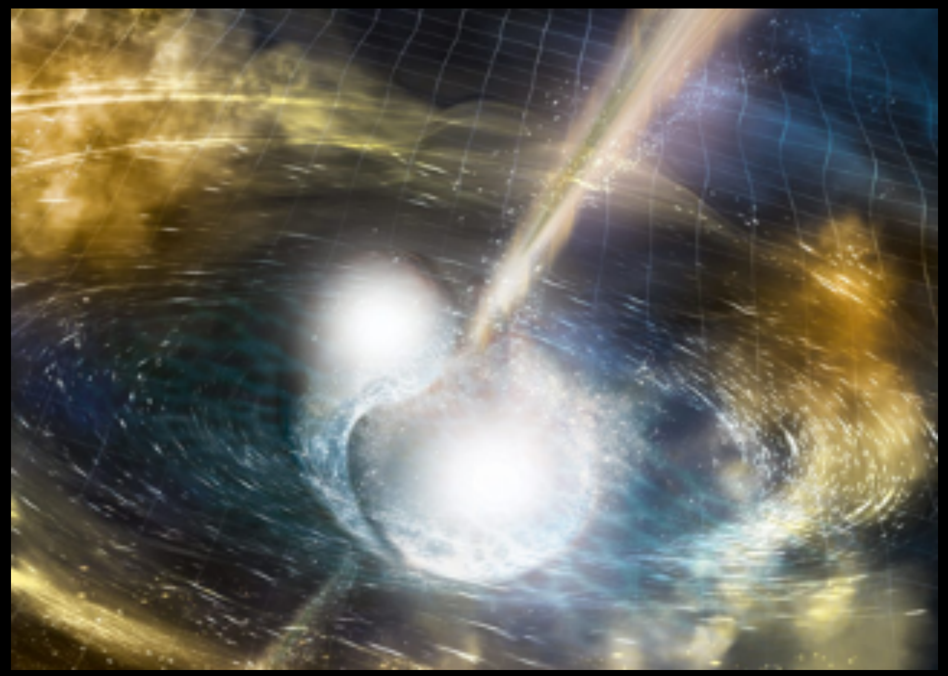


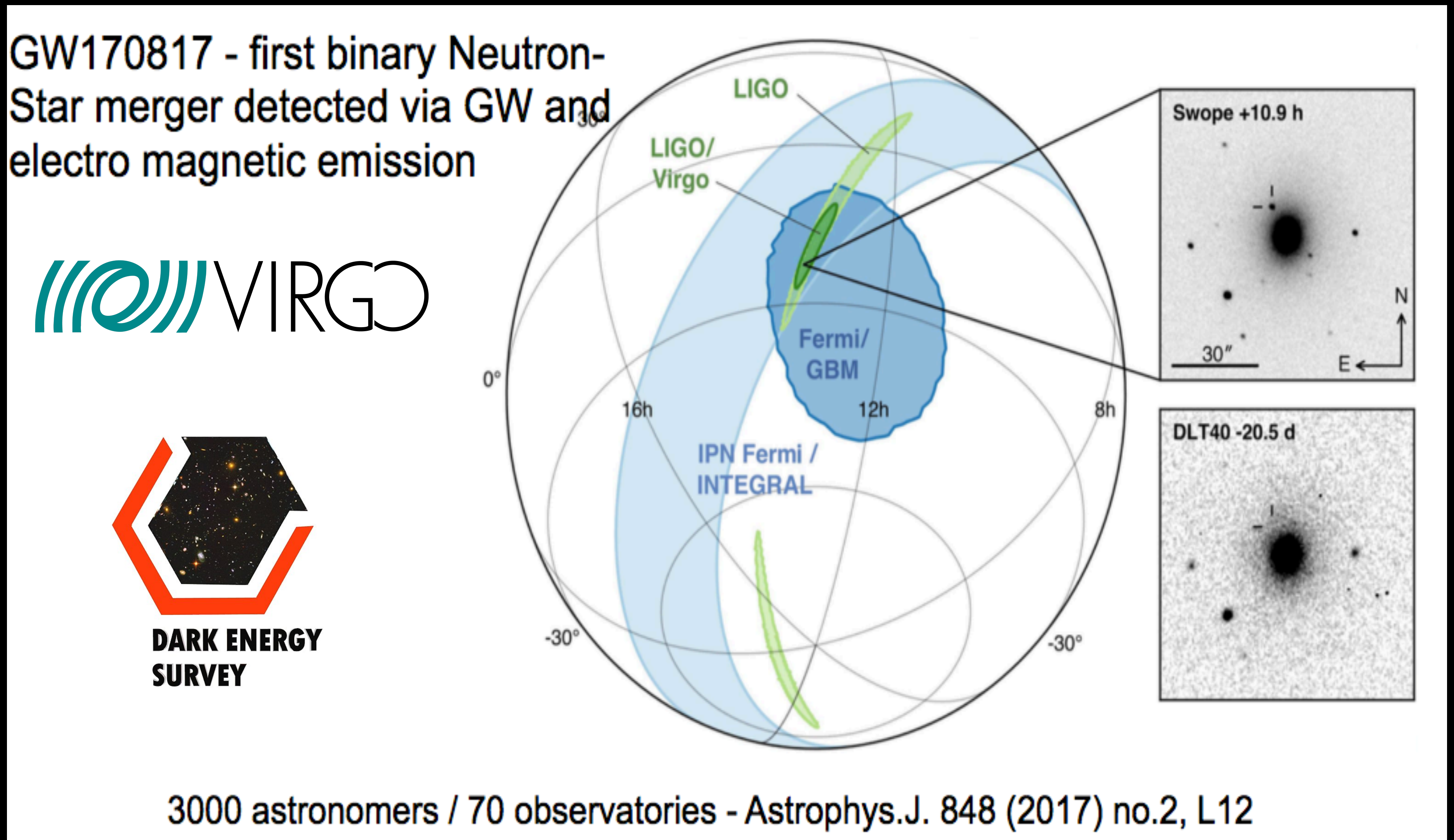


Neutron Star Collisions



Confirmed BNS as origin for some GRBs





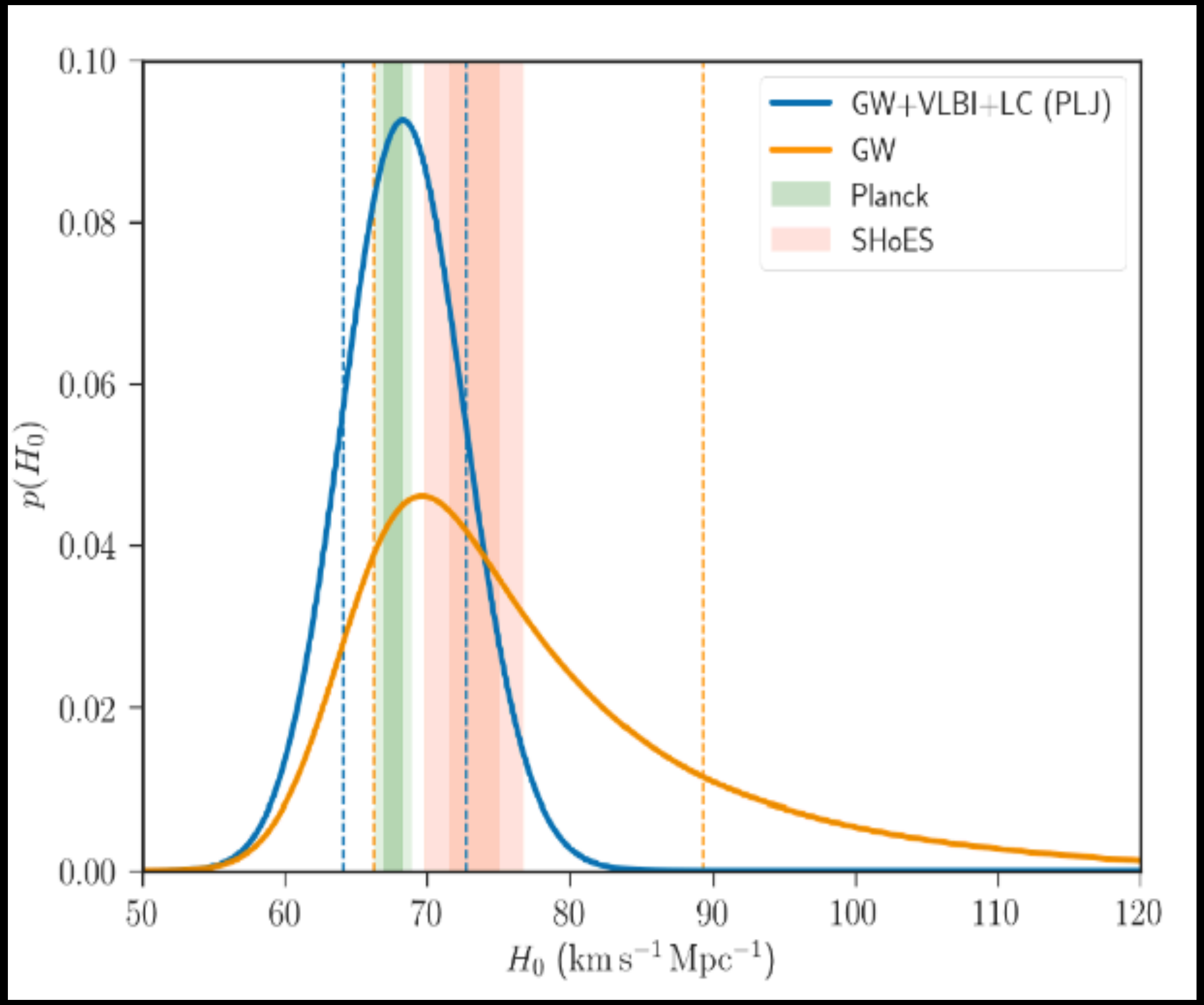
Few events of BNS will allow for few % precision in the determination of H_0

Observation with GWs and EM optics

$$v_H = H_0\, d \quad \text{(GW + EM)}$$

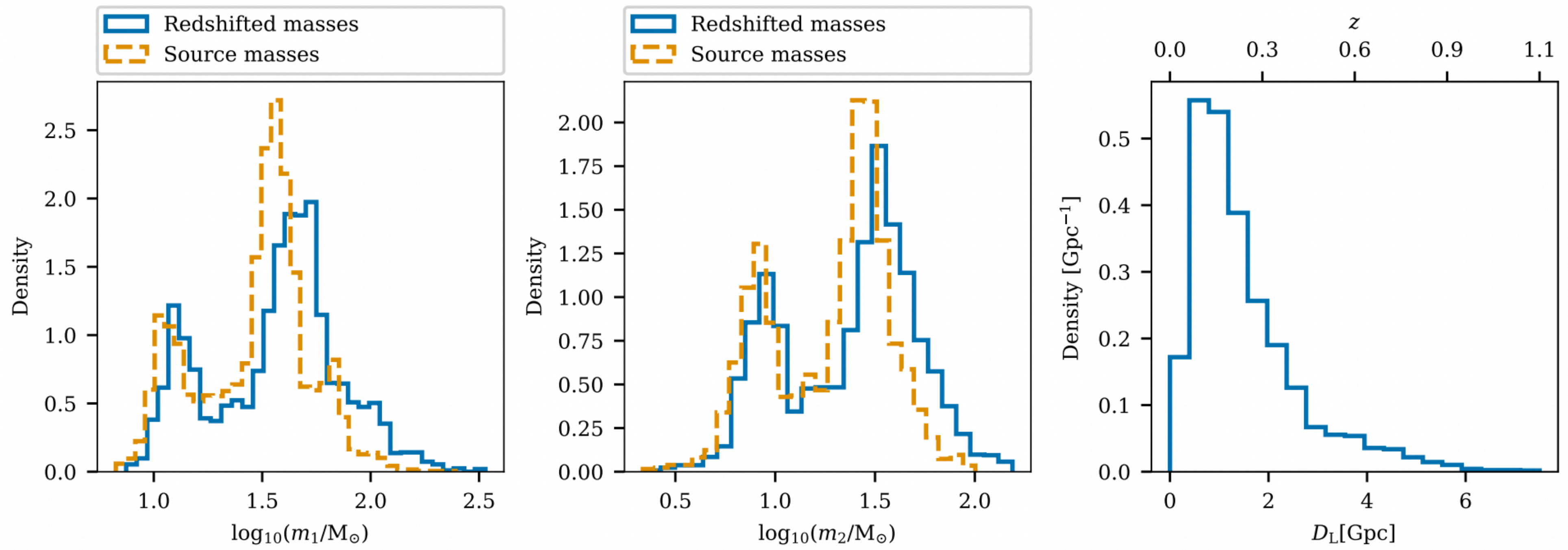
Direct measurement of Hubble parameter H_0

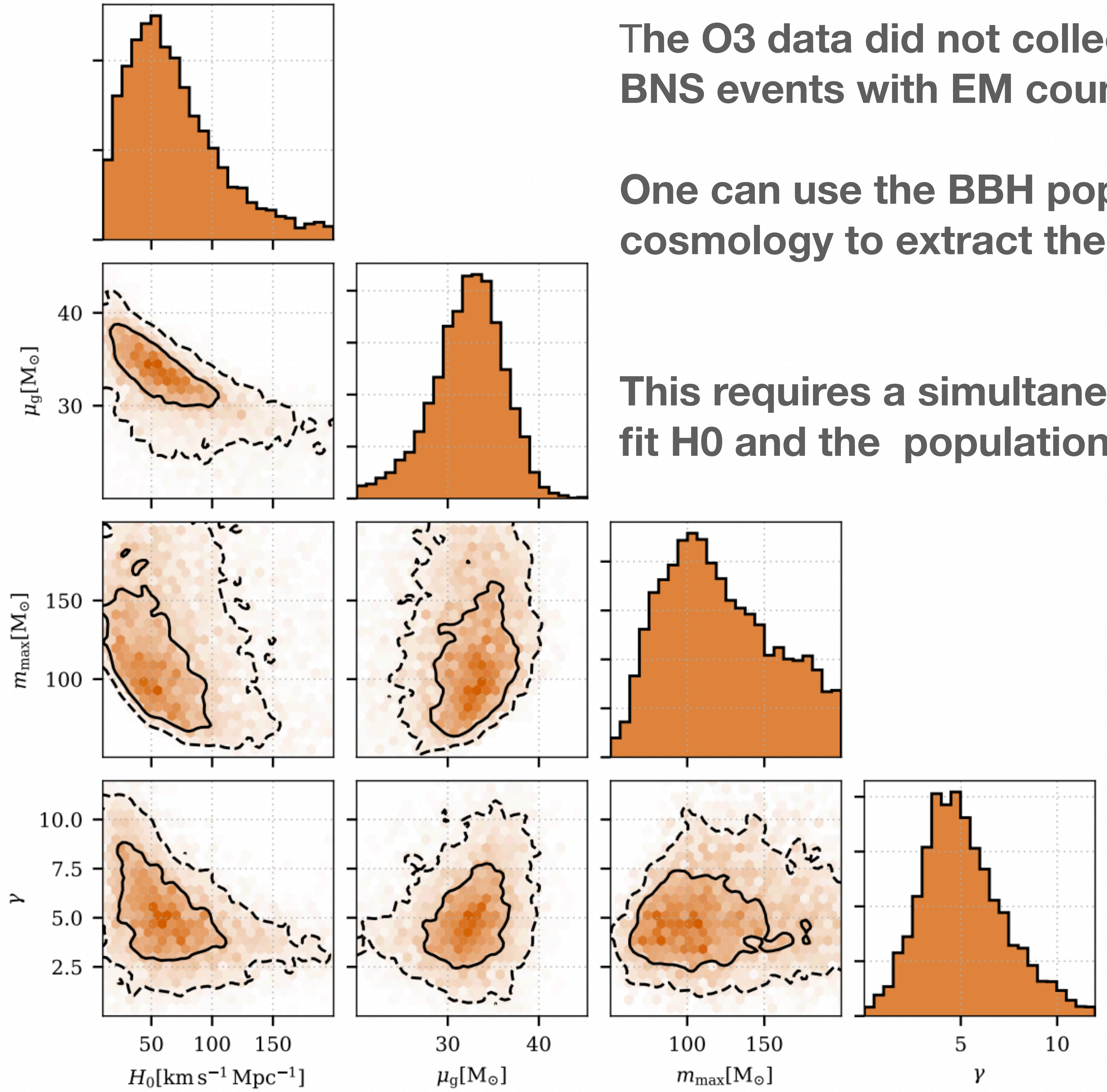
$$H_0 = 69 \pm 5 \mathrm{kms^{-1}Mpc^{-1}}$$



Cosmology

$$m_i = \frac{m_i^{\mathrm{det}}}{1 + z(D_{\mathrm{L}}; H_0, \Omega_{\mathrm{m}}, w_0)}$$

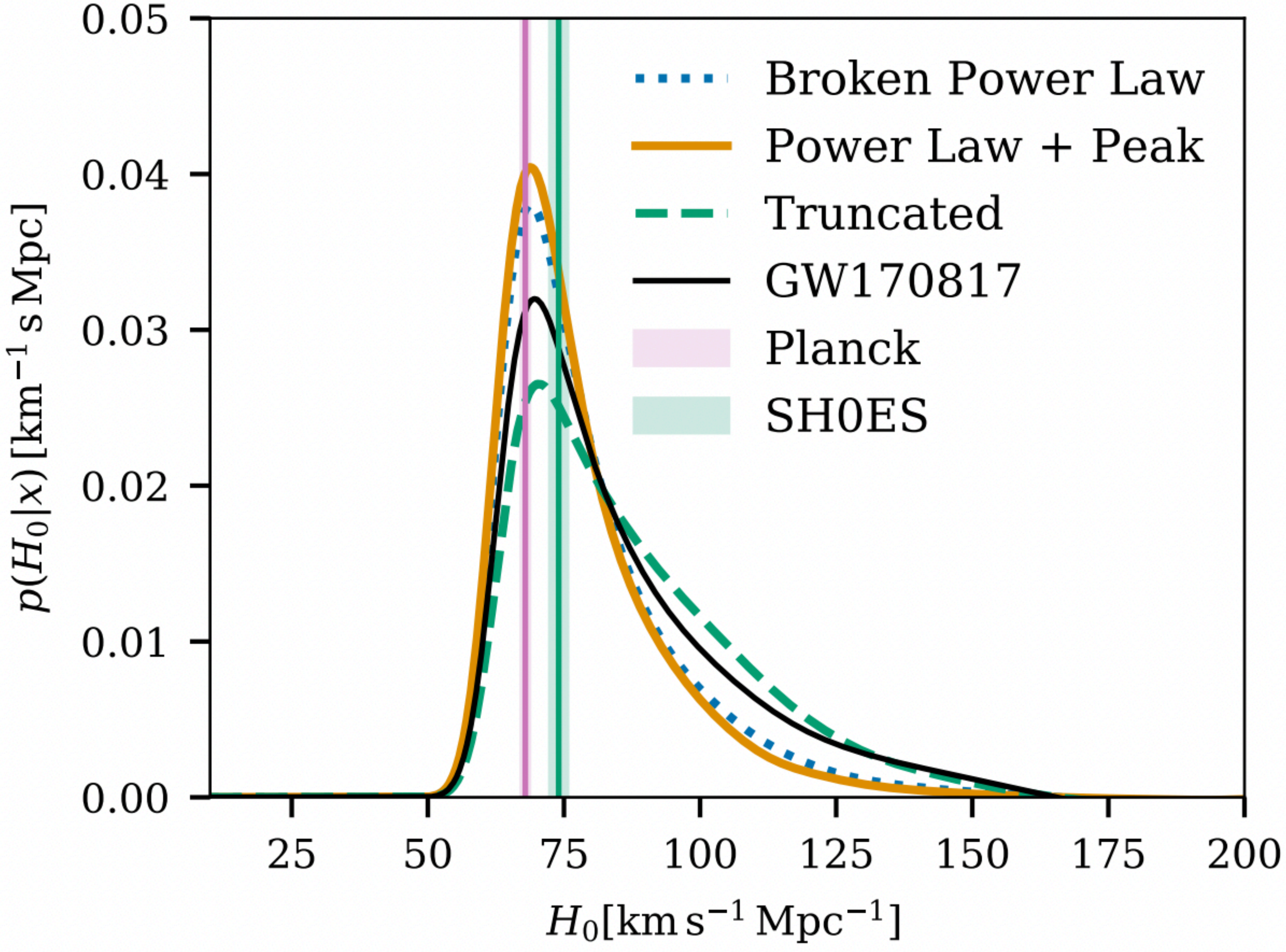




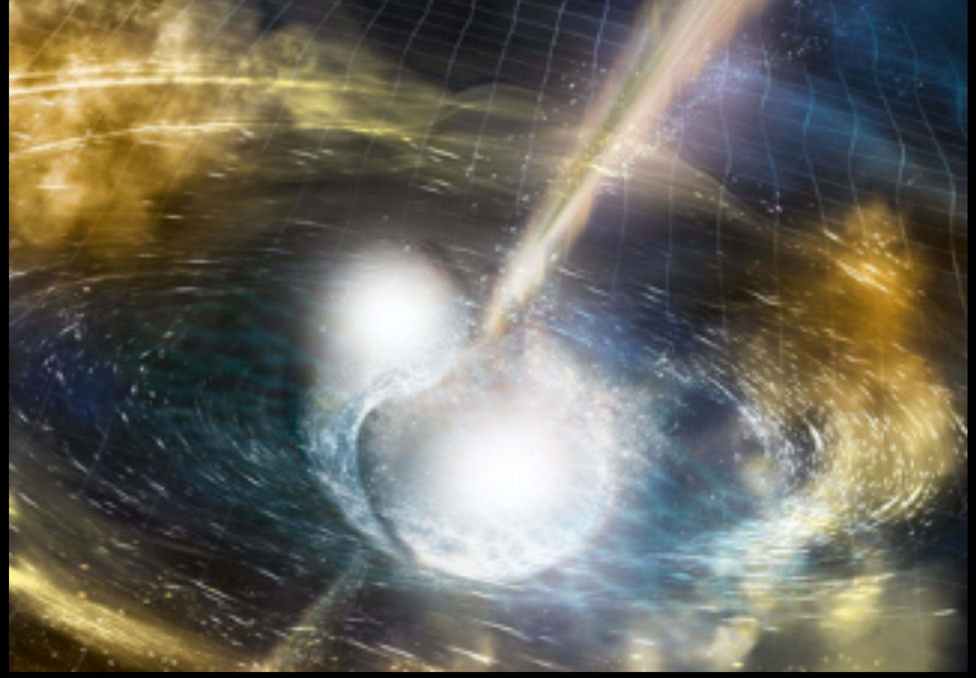
The O3 data did not collect more BNS events with EM counterparts

One can use the BBH population and cosmology to extract the H0 value

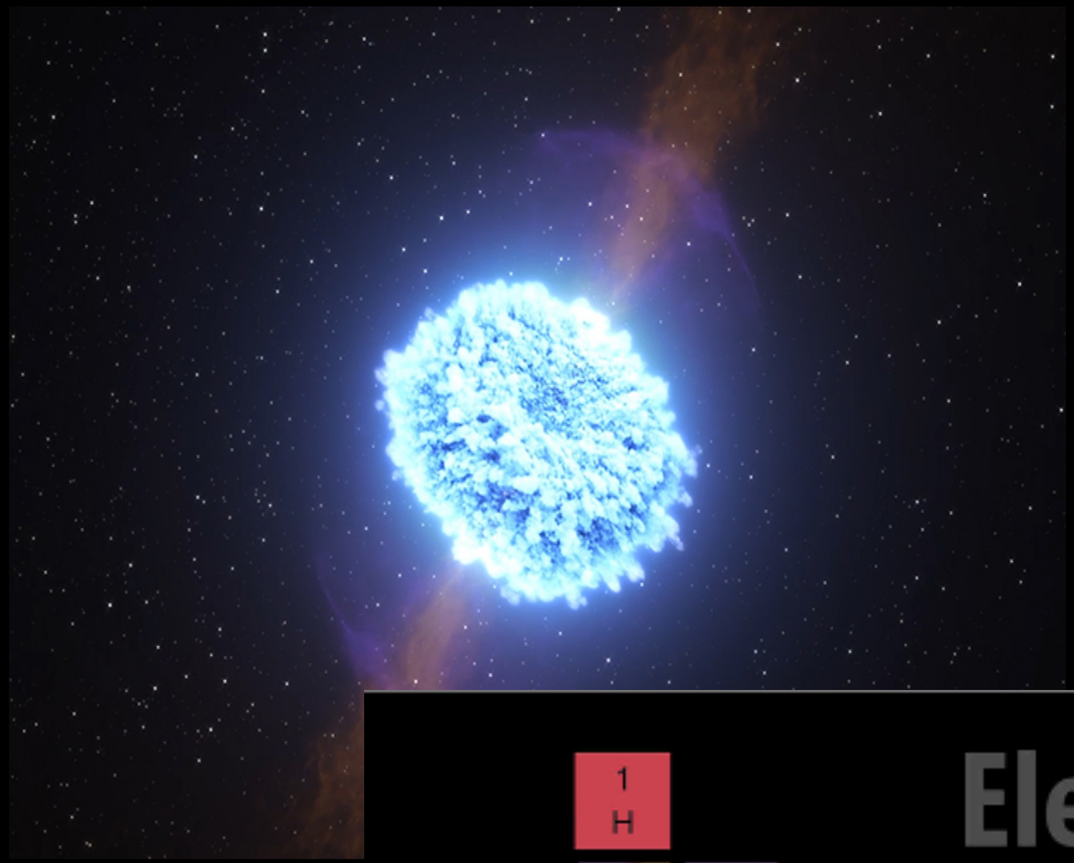
This requires a simultaneous fit H0 and the population parameters



Kilonova

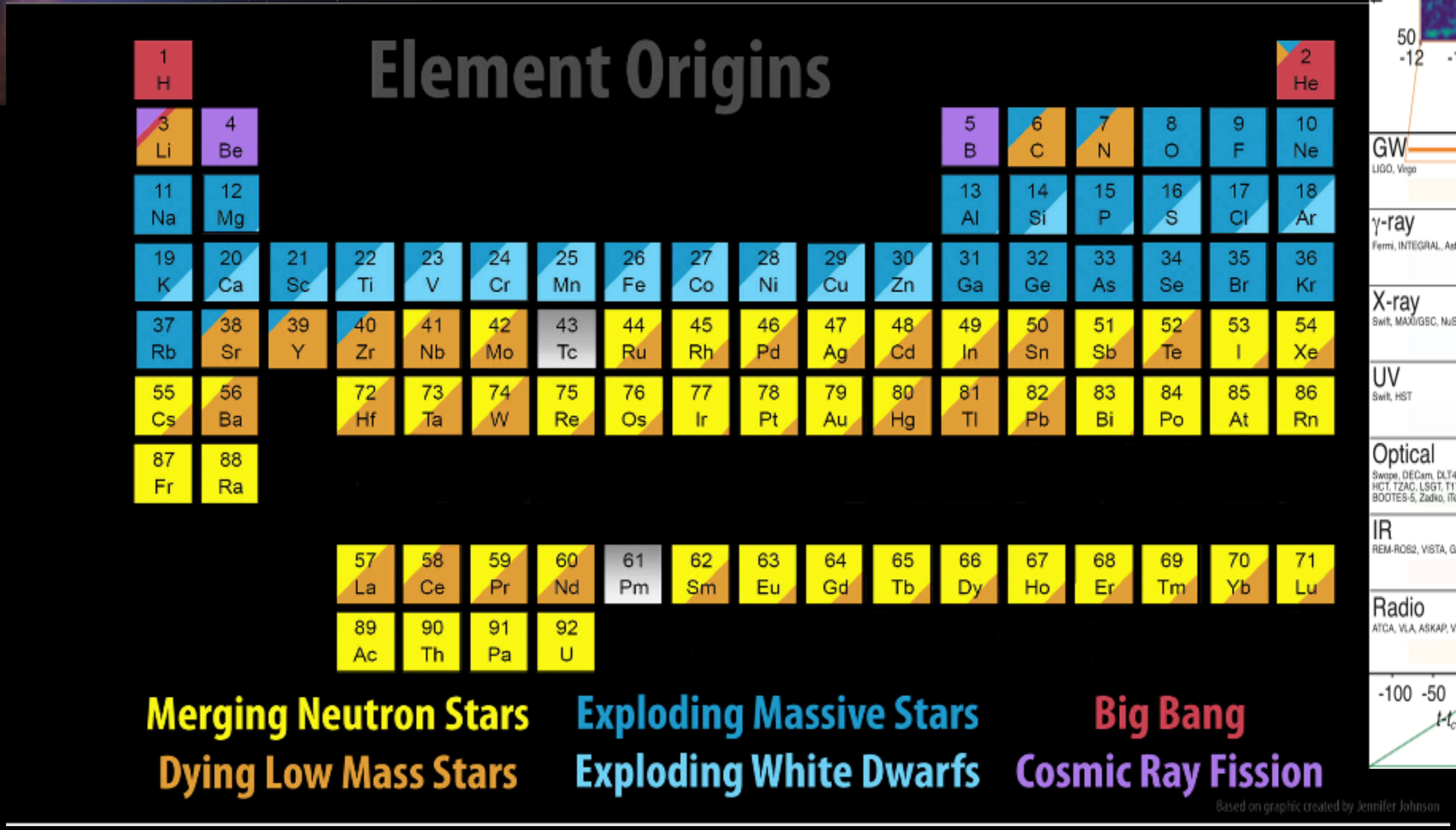


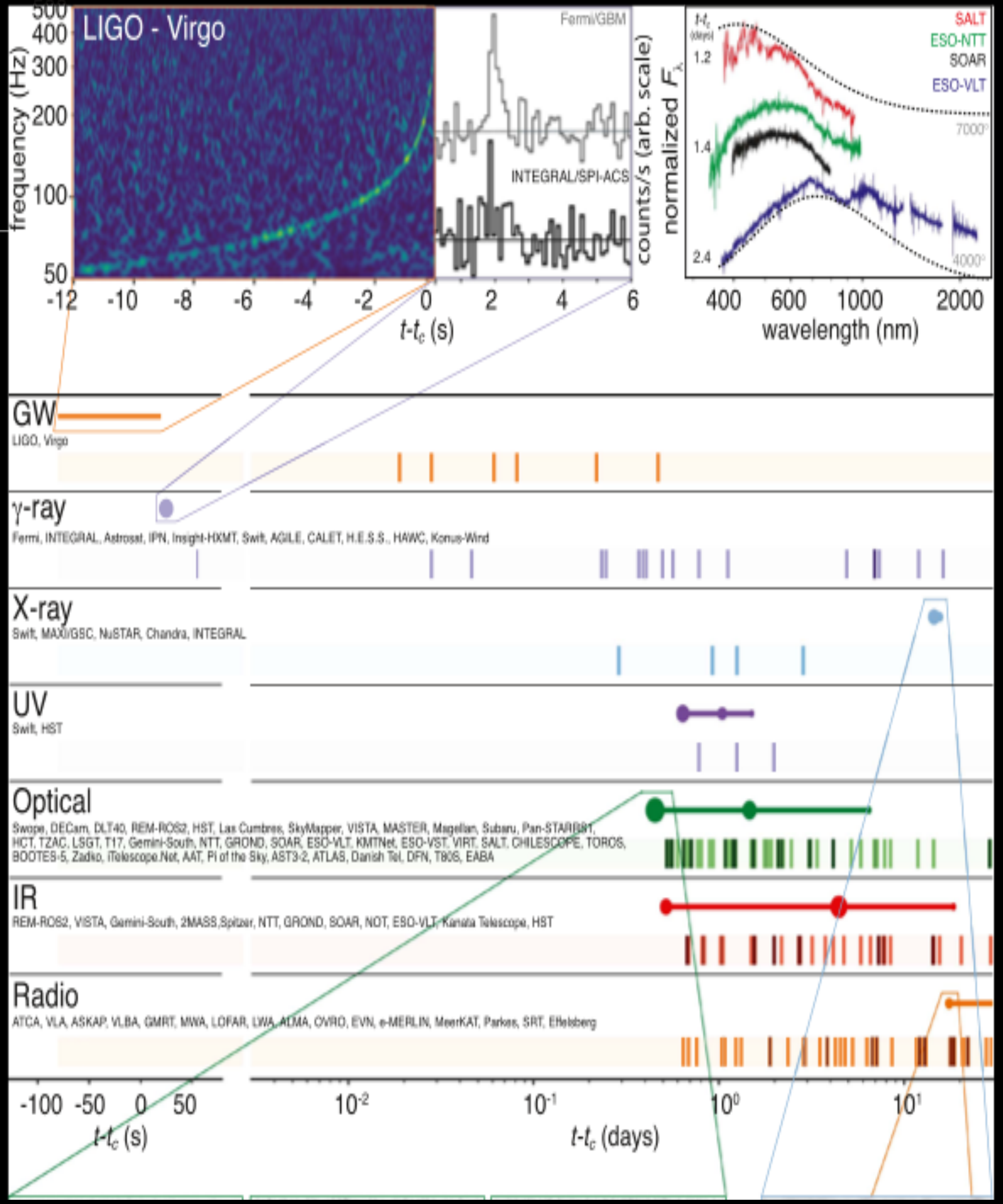
Open the door for studying EoS of neutron stars → data already disfavor some models



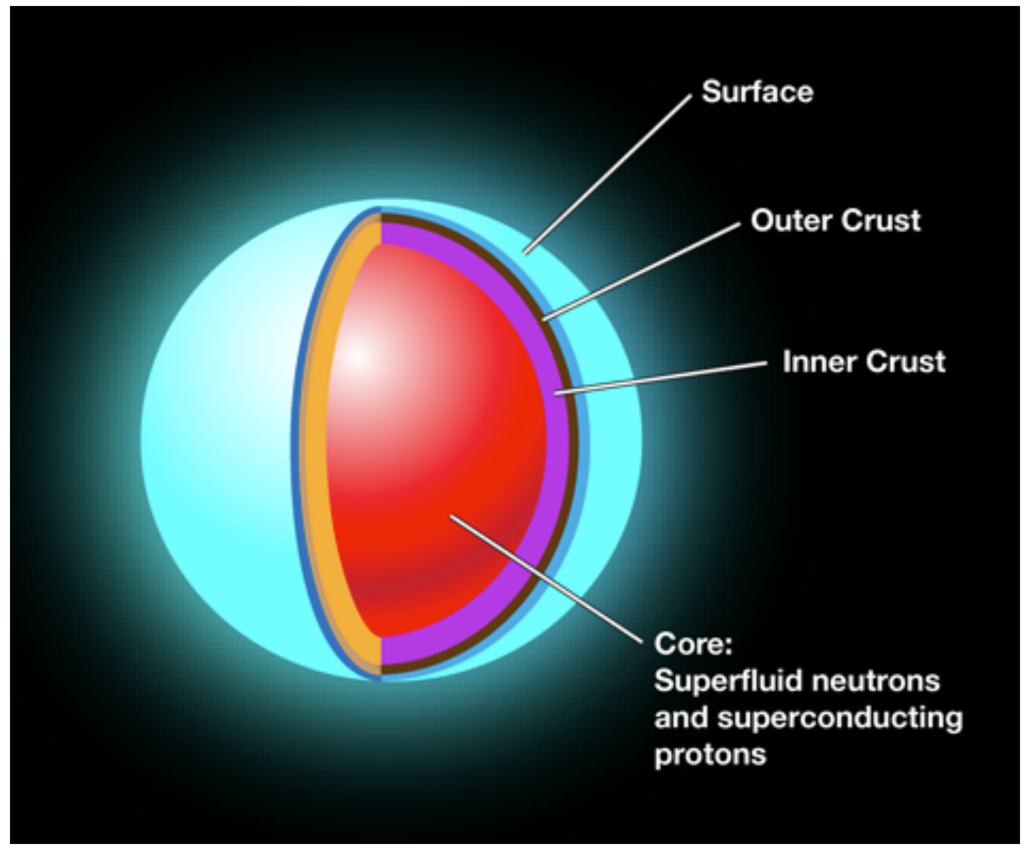
Shows the production mechanism of heavy elements

Initiates an era of multi-messenger approach

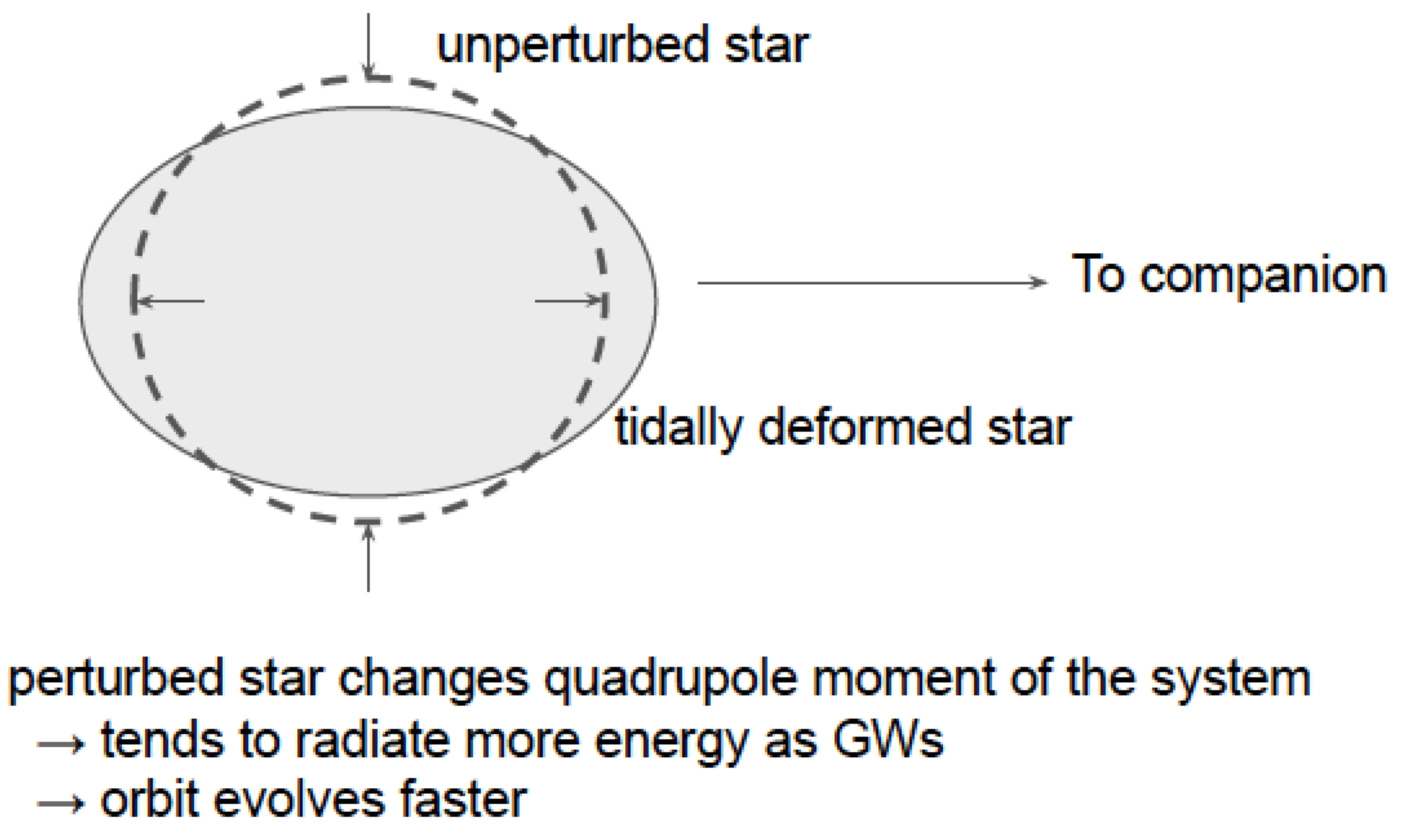


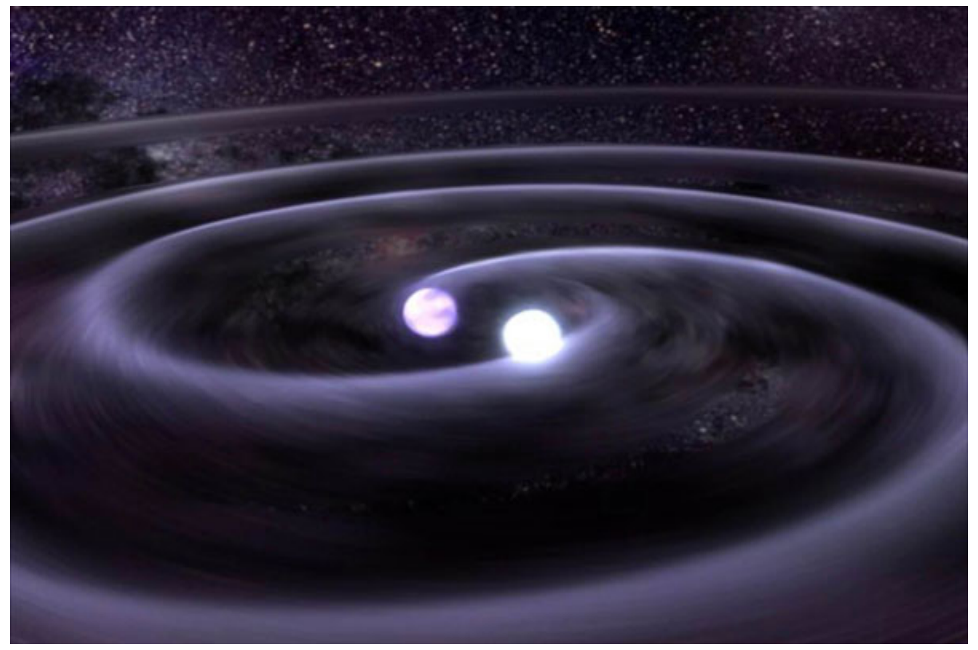


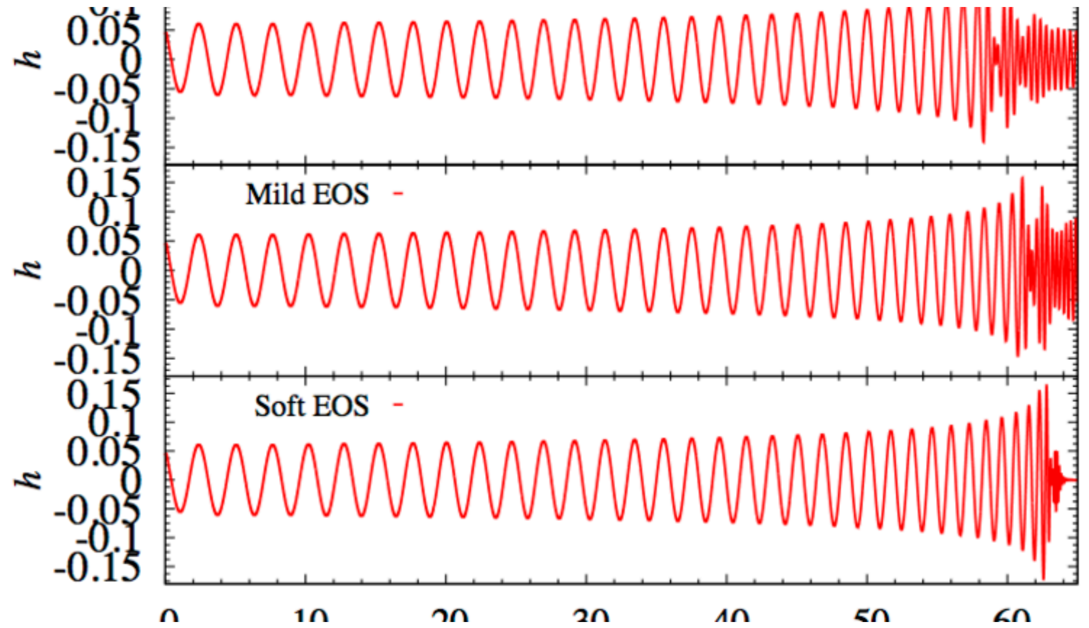
Neutron stars

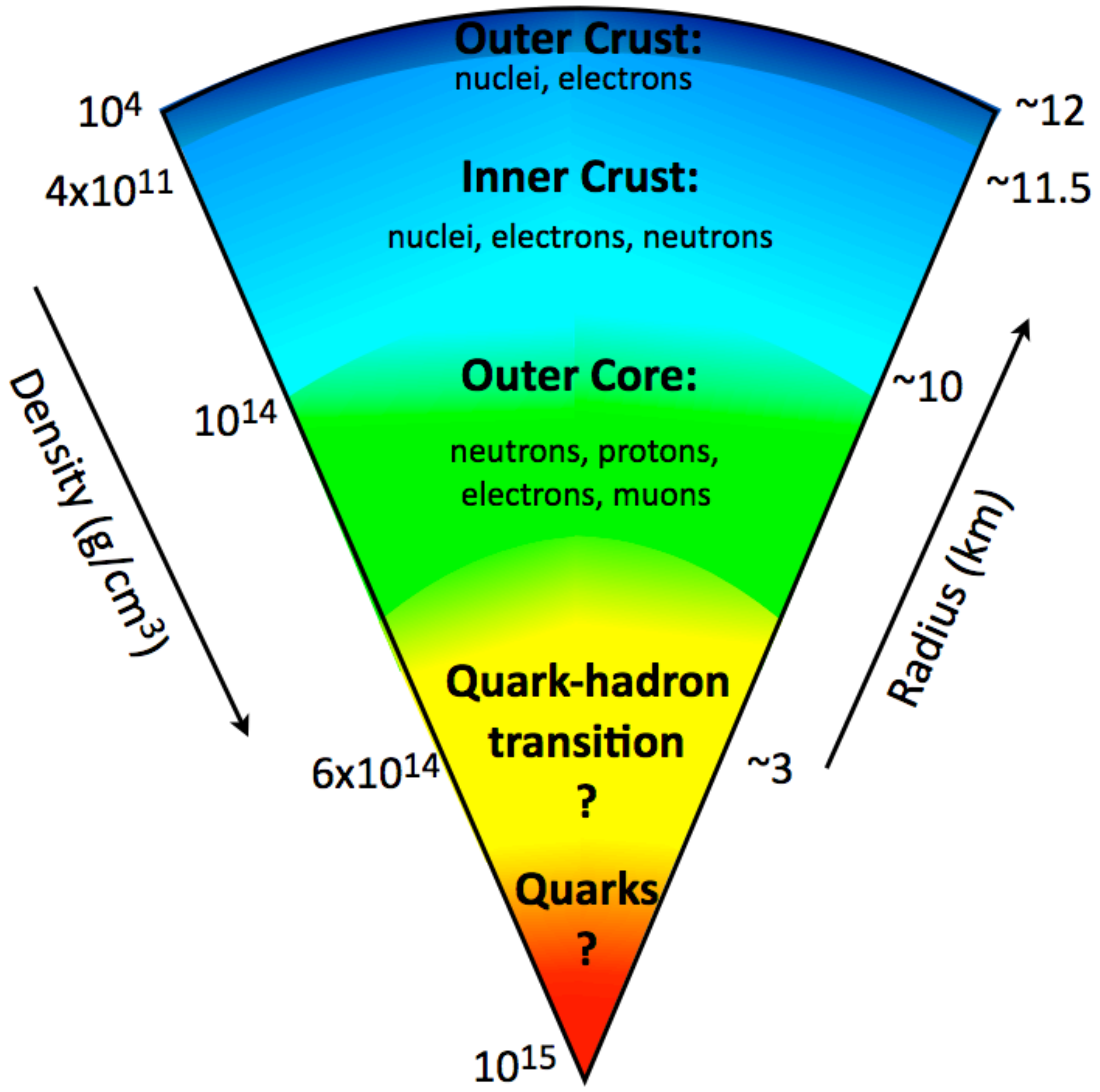


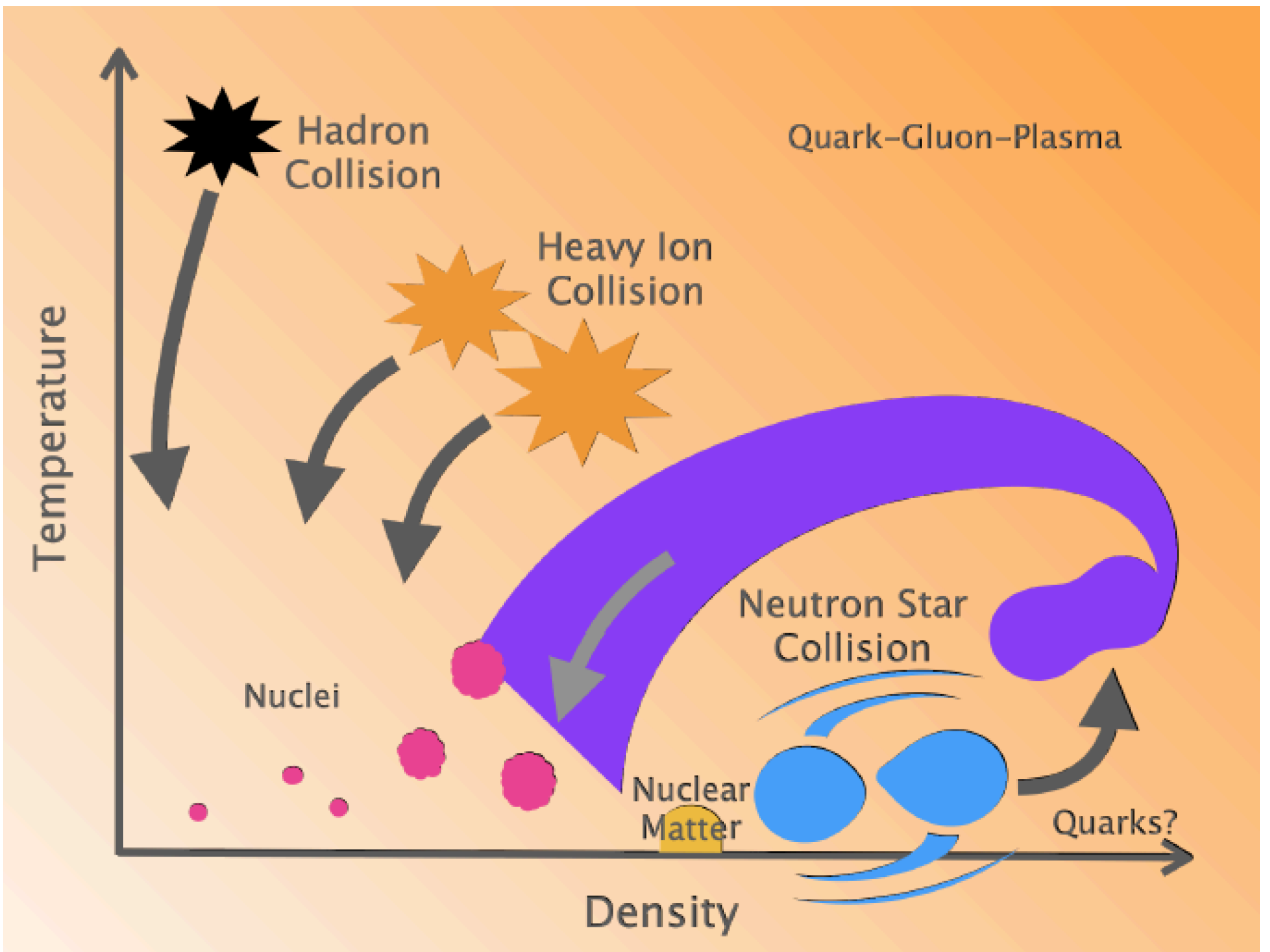
1-2 solar masses is an object with a diameter of 20KM (1/70000 the size of the sun)





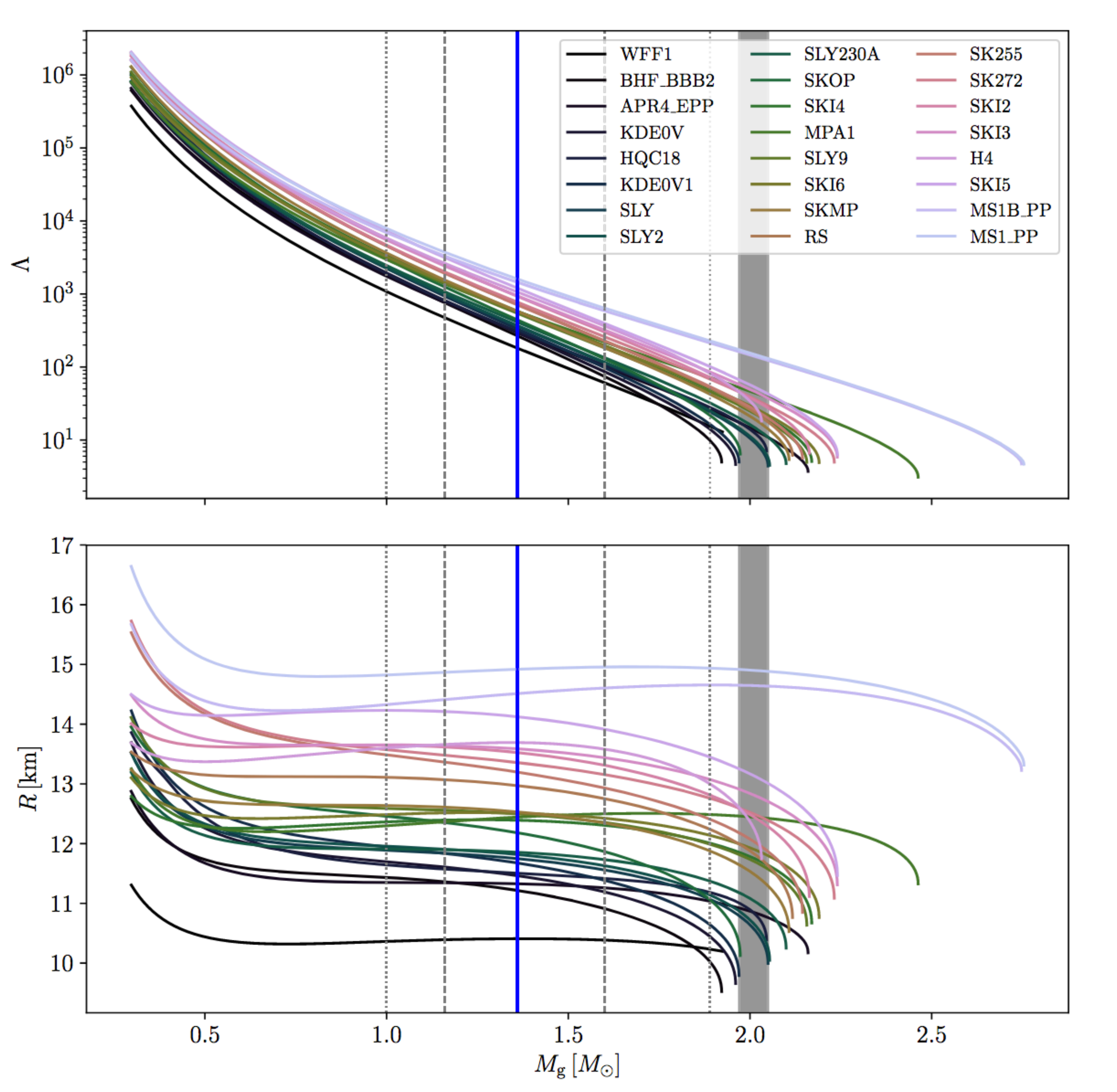






The study of neutron star mergers allows to study the equation of state of the star involving QCD in very dense and high regimes temperatures.

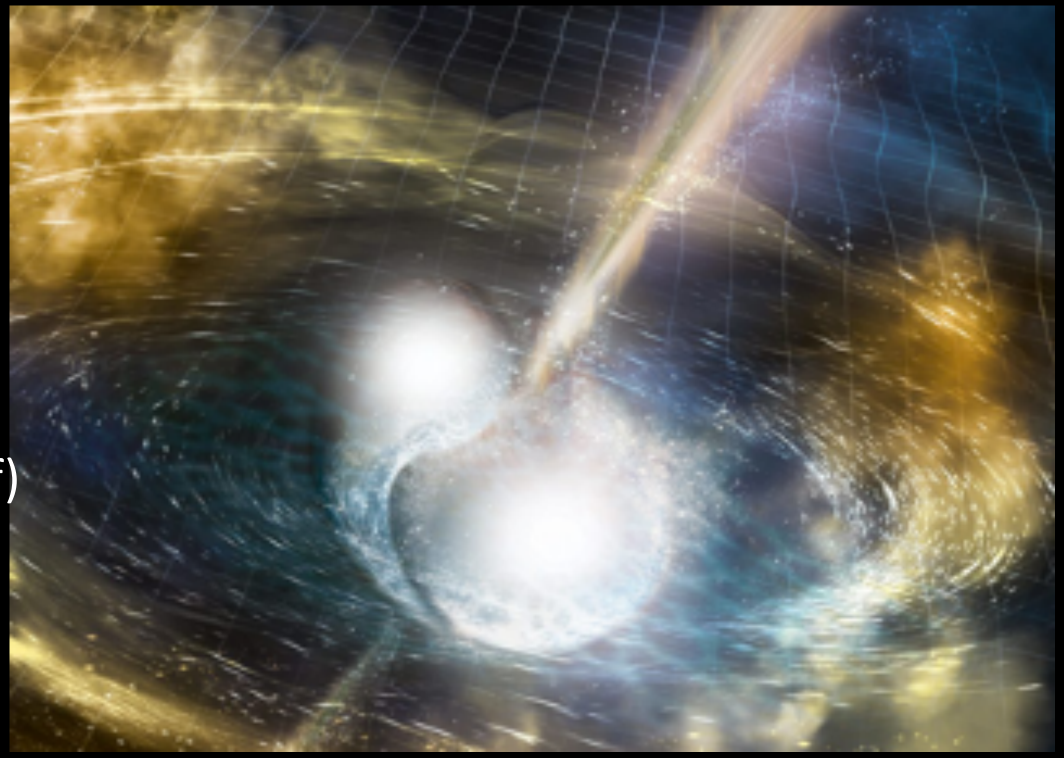
Class. Quantum Grav. 37 (2020) 0450060817



NS EoS

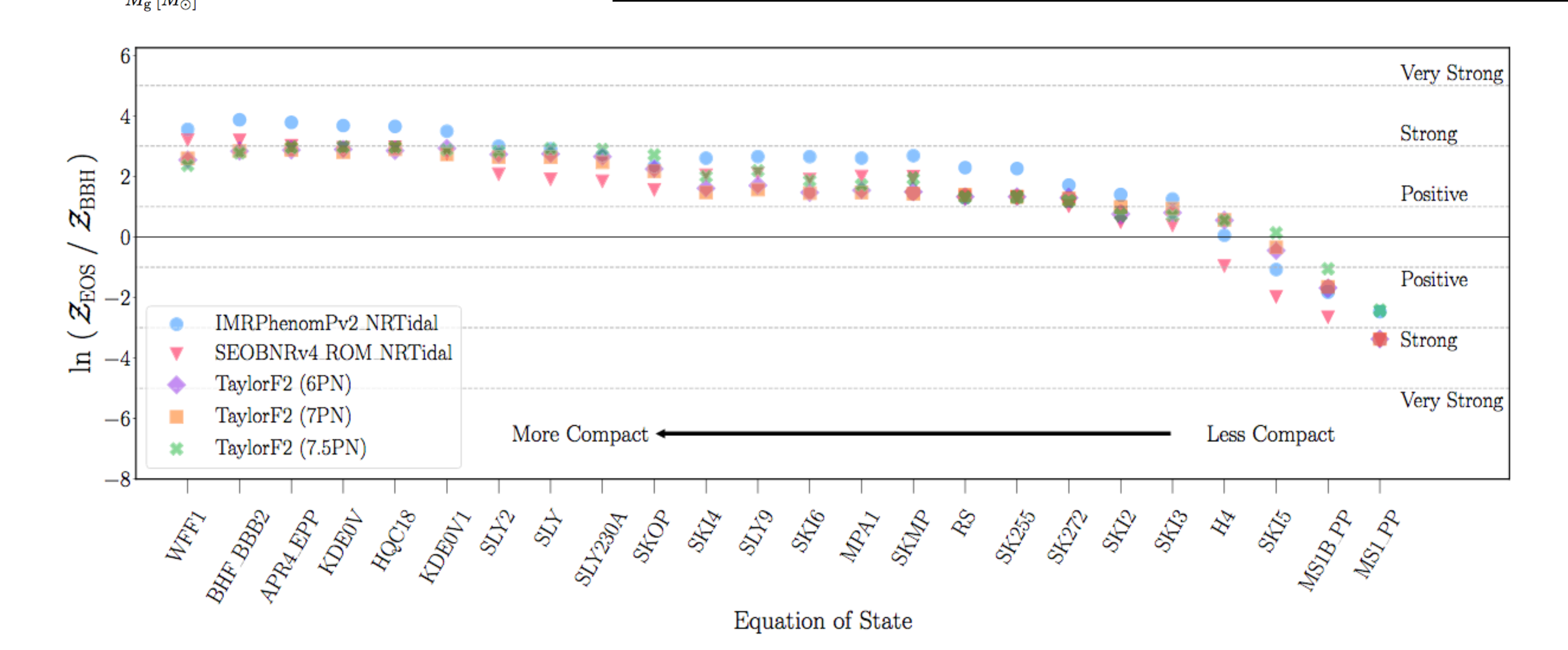
GW170817

(https://arxiv.org/pdf/1805.11581.pdf)

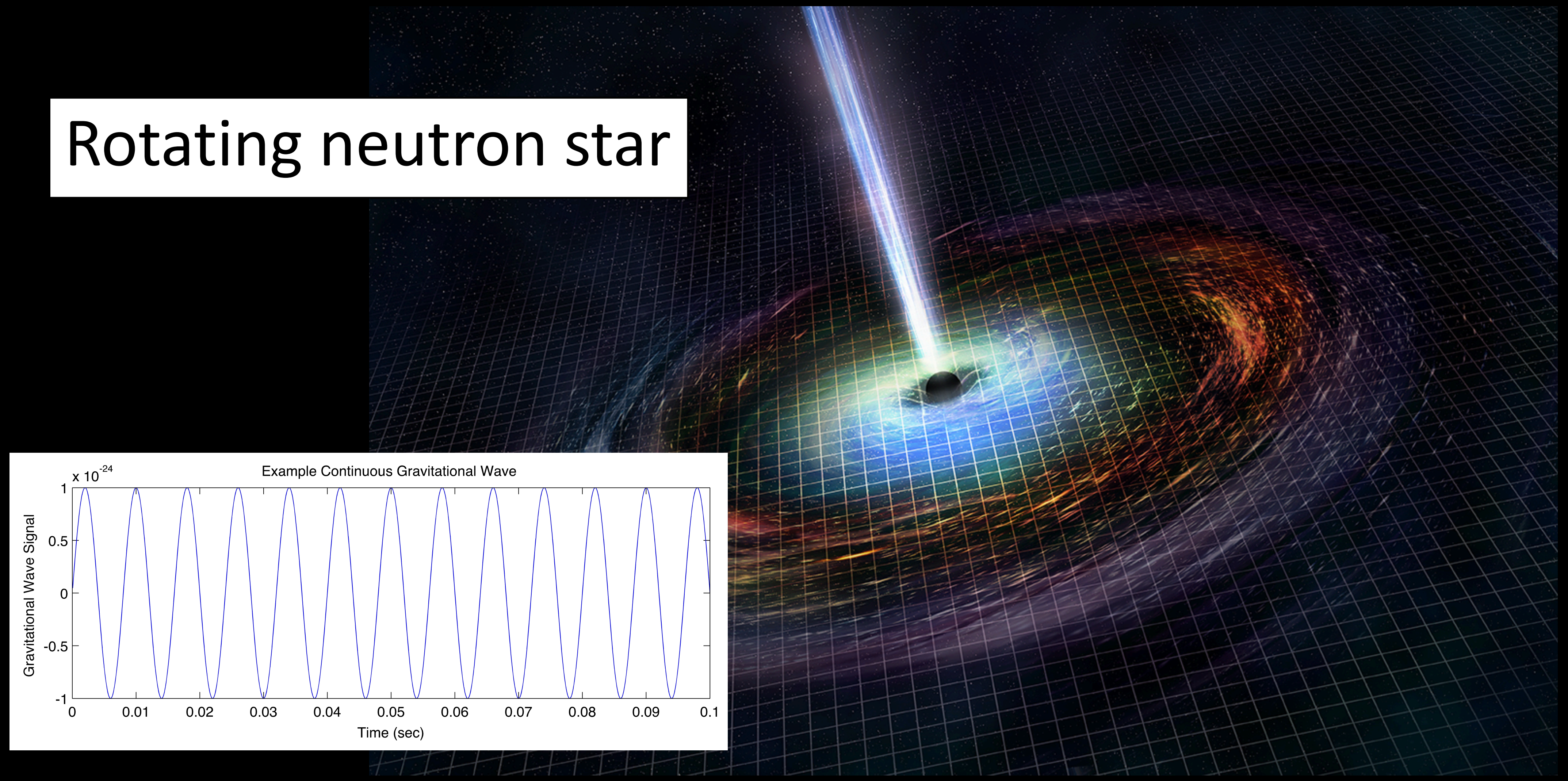


“deformability”
and radius vs mass

The data did have the power to exclude some (few) of the EoS models for NS



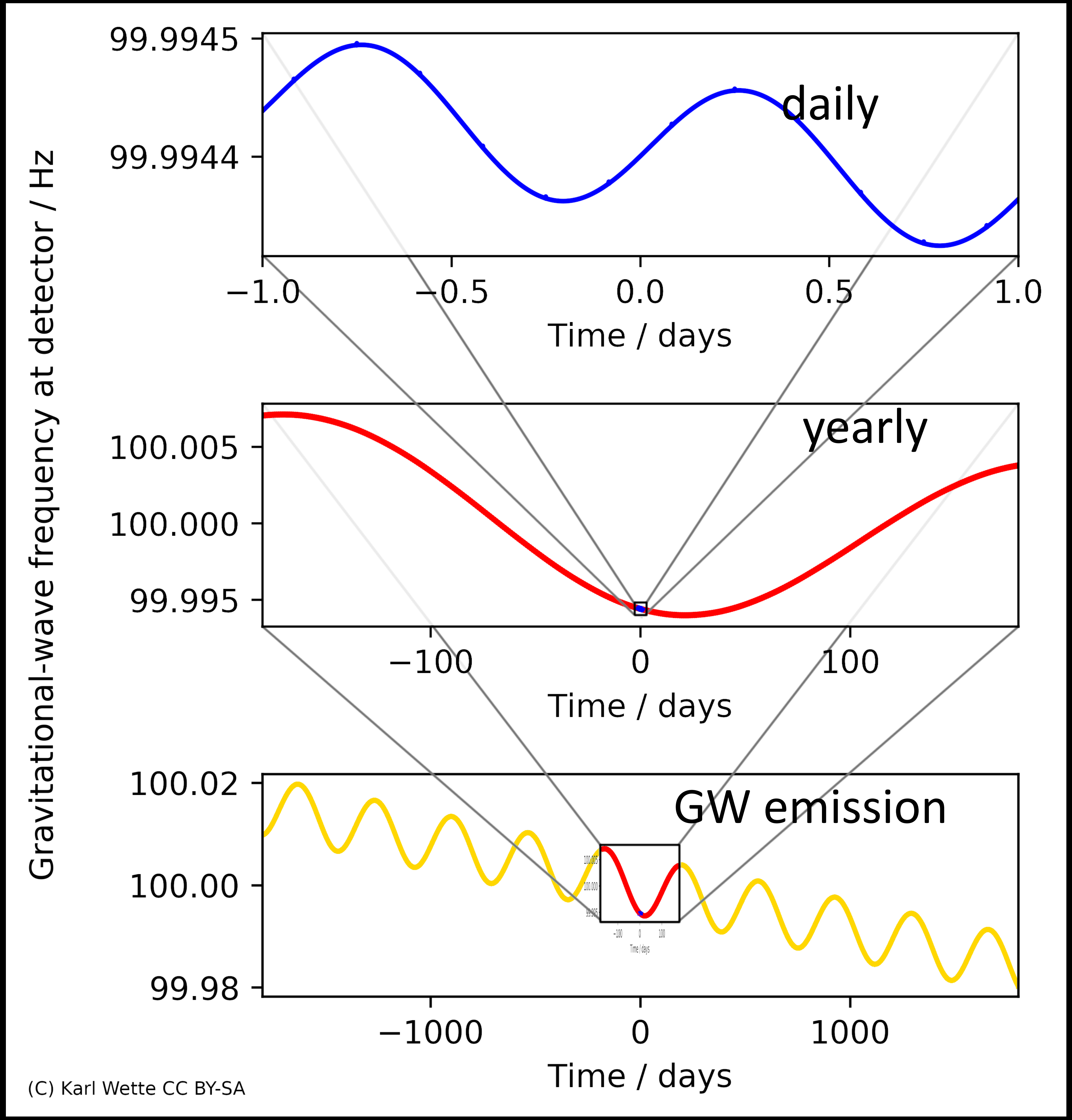
Continuous GW Searches



The search for continuous GWs is known to be extremely difficult.. needs to analyze the year-long data in a shot (matched filtering is not feasible)

→ Tracking all possible frequency changes makes the search a computational challenge (Doppler modulation)

→ Requires sophisticated algorithms



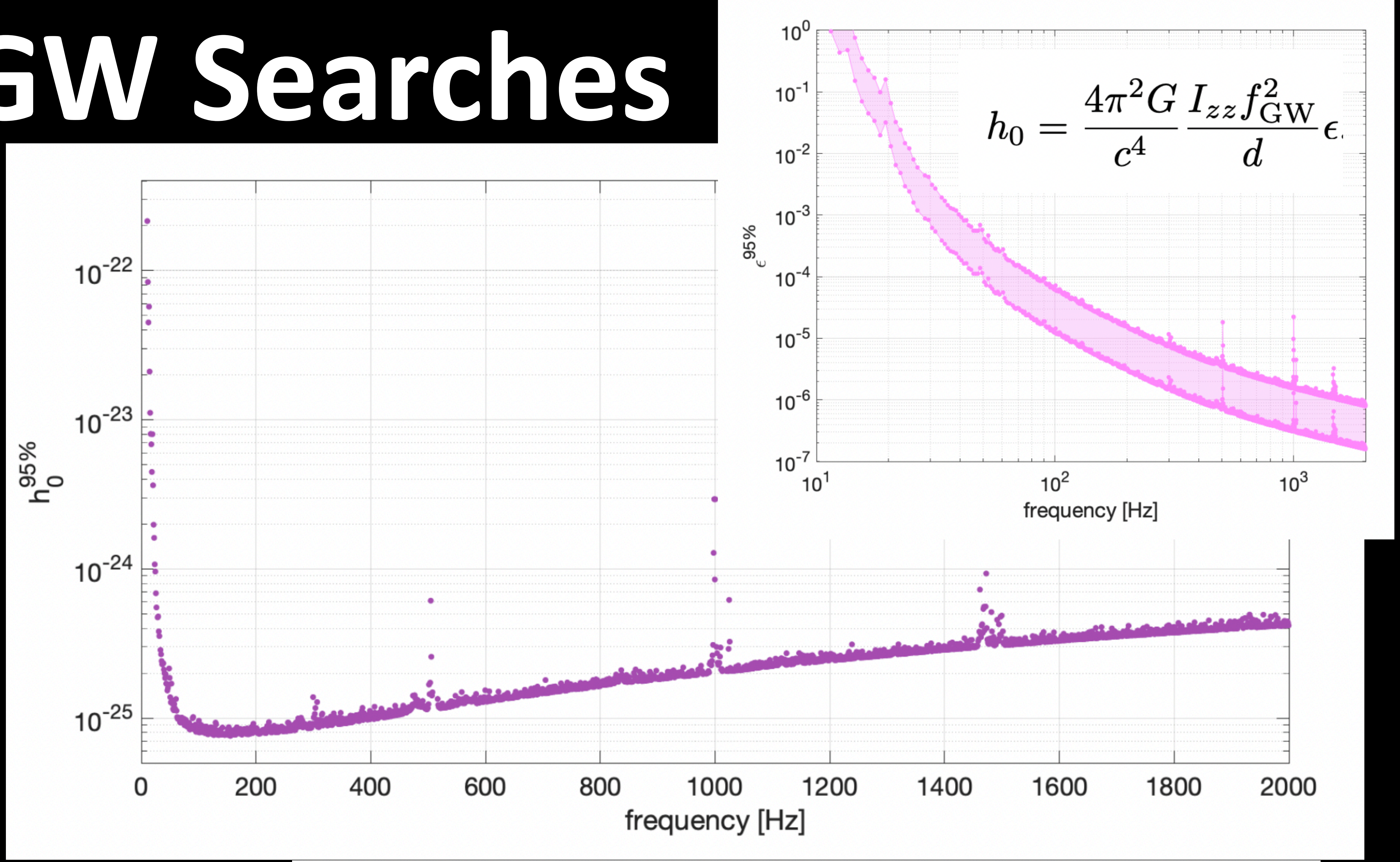
Continuous GW Searches

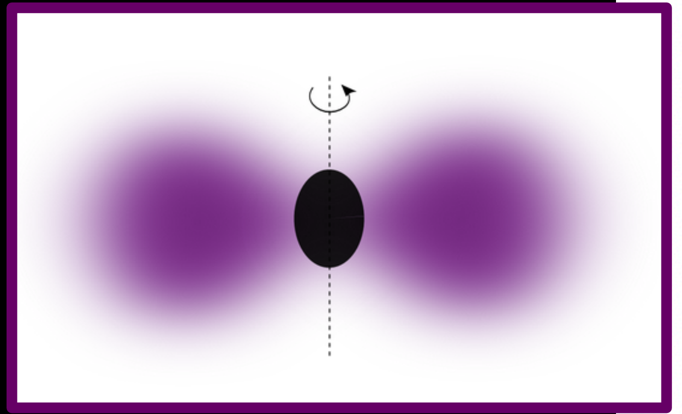
Phys.Rev.D 106 (2022) 4, 042003

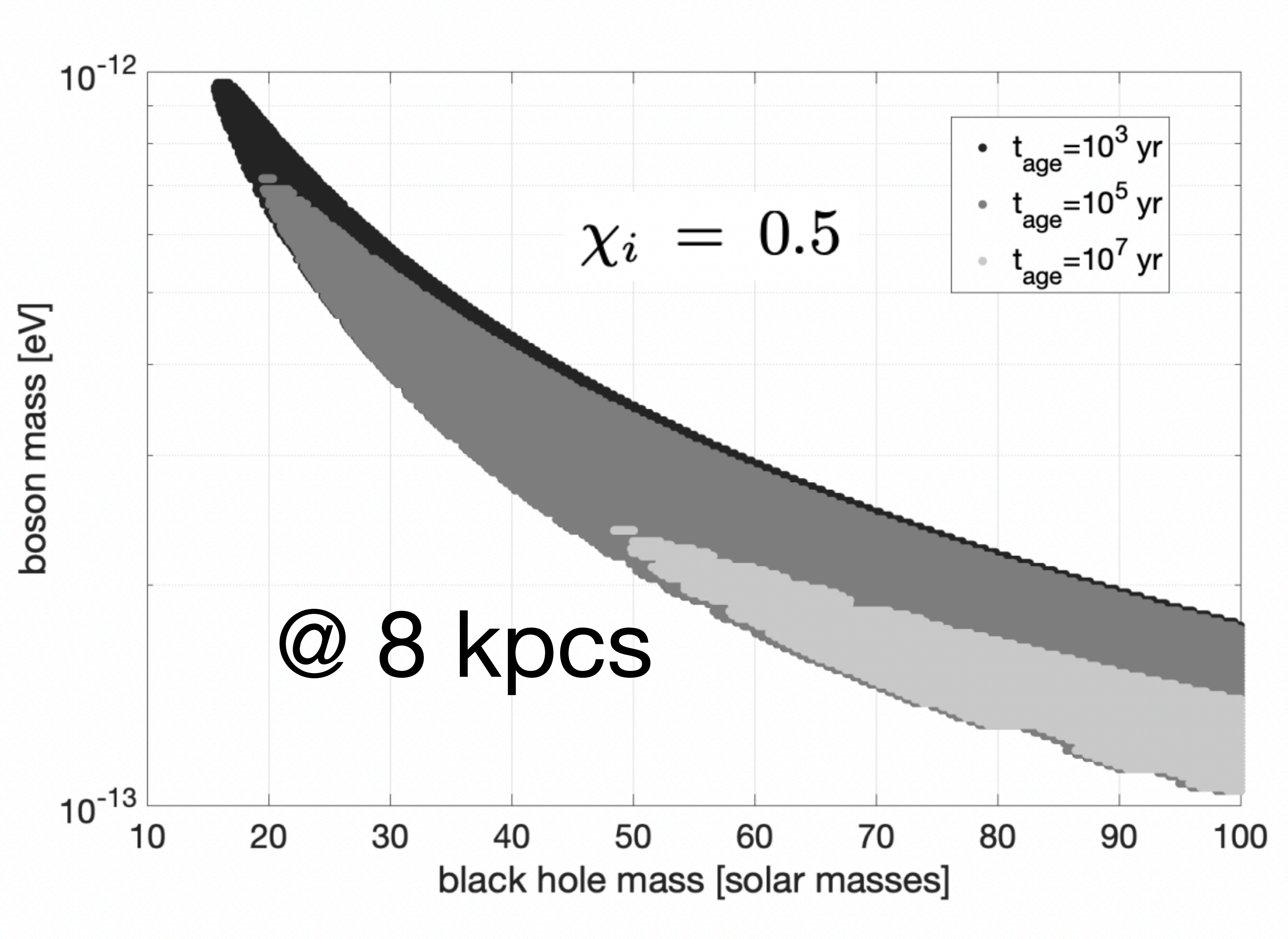
No signal found yet

- A plethora of analyses looking for signals from continuous GW emissions.
  - **From Milky Way Center**
  - All-sky searches of isolated NS
  - Known Pulsars & supernovae remnants
  - Boson Clouds around spinning BH

—> large uncertainty on quoted limits due to BH age & population details

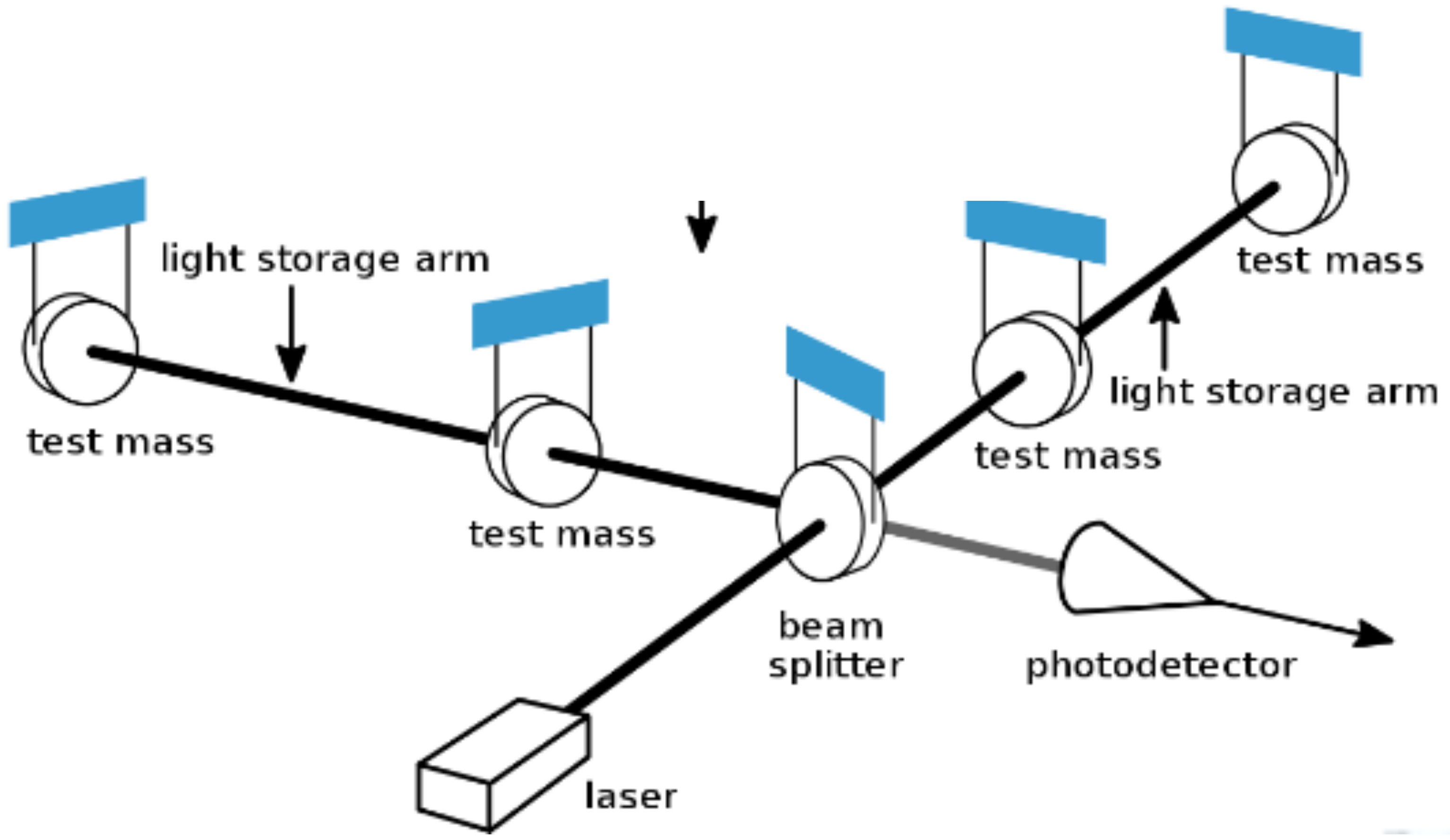






Phys.Rev.D 105 (2022) 10, 102001

Dark Photons



- The interferometer acts as a Direct Detection DM experiment due to the interaction of the dark photons with the mirrors.

$$\mathcal{L} = -\frac{1}{4\mu_0}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2\mu_0}\left(\frac{m_A c}{\hbar}\right)^2 A^\mu A_\mu - \epsilon e J^\mu A_\mu$$

$$\langle h^2_{\rm total}\rangle = \langle h^2_D\rangle + \langle h^2_C\rangle.$$

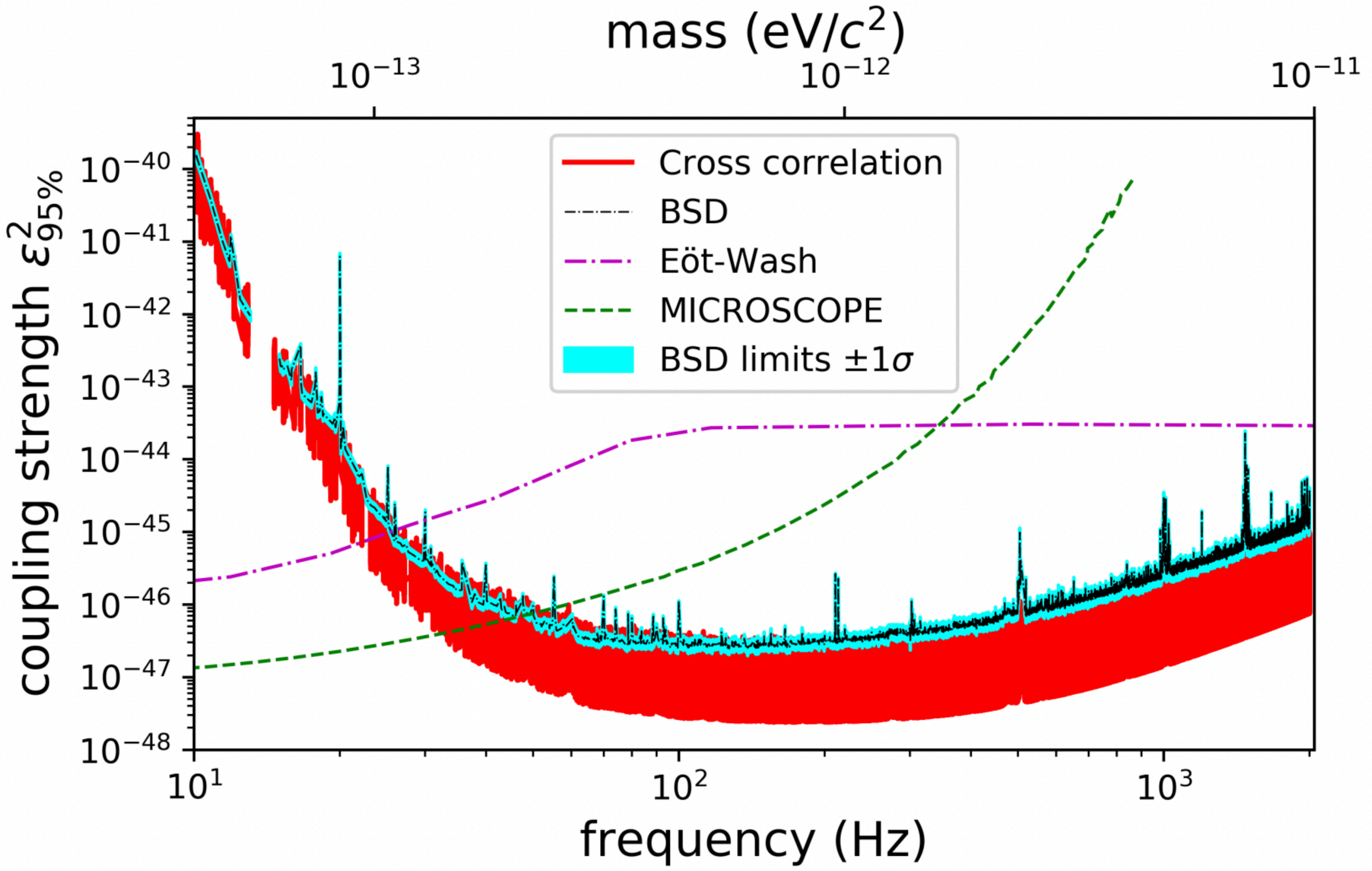
- The experiment put limits on the couplings vs mass

- A continuous dark photon flux interacts with the mirrors leading to a next signal that mimic a GW continuous signals

- Different contributions

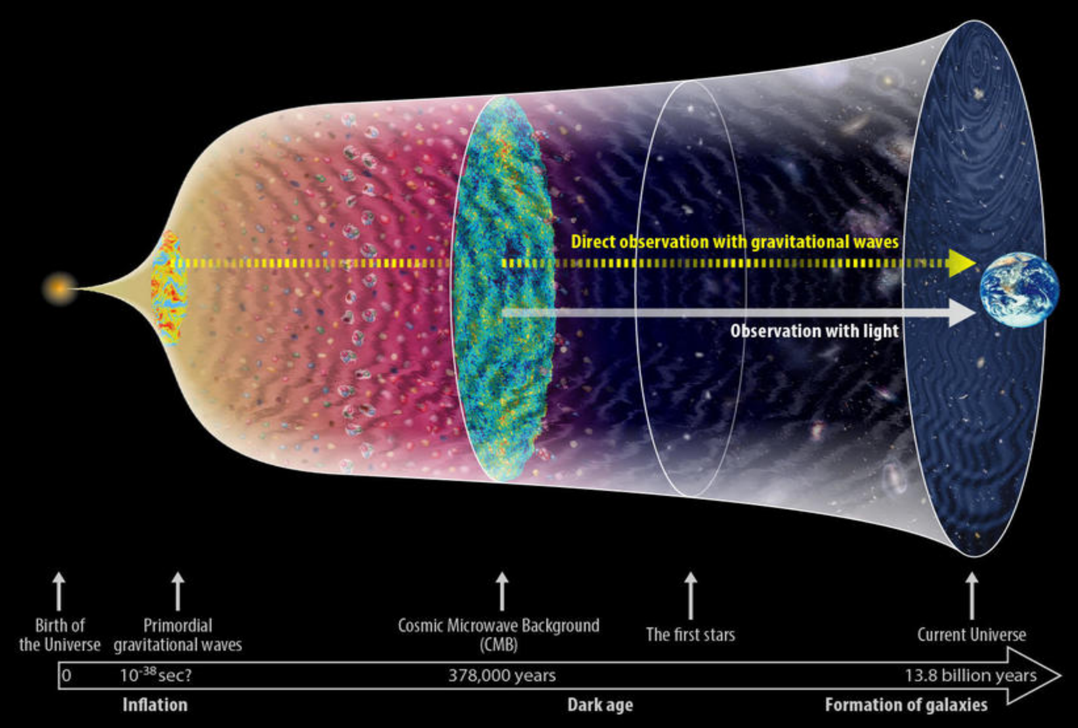
$$\sqrt{\langle h^2_C\rangle} = \frac{\sqrt{3}}{2}\sqrt{\langle h^2_D\rangle}\frac{2\pi f_0 L}{v_0}, \simeq 6.58\times 10^{-26}\left(\frac{\epsilon}{10^{-23}}\right)$$

$$\sqrt{\langle h^2_D\rangle} = C\frac{q}{M}\frac{v_0}{2\pi c^2}\sqrt{\frac{2\rho_{\rm DM}}{\epsilon_0}}\frac{e\epsilon}{f_0} \simeq 6.56\times 10^{-27}\left(\frac{\epsilon}{10^{-23}}\right)\left(\frac{100\text{ Hz}}{f_0}\right)$$

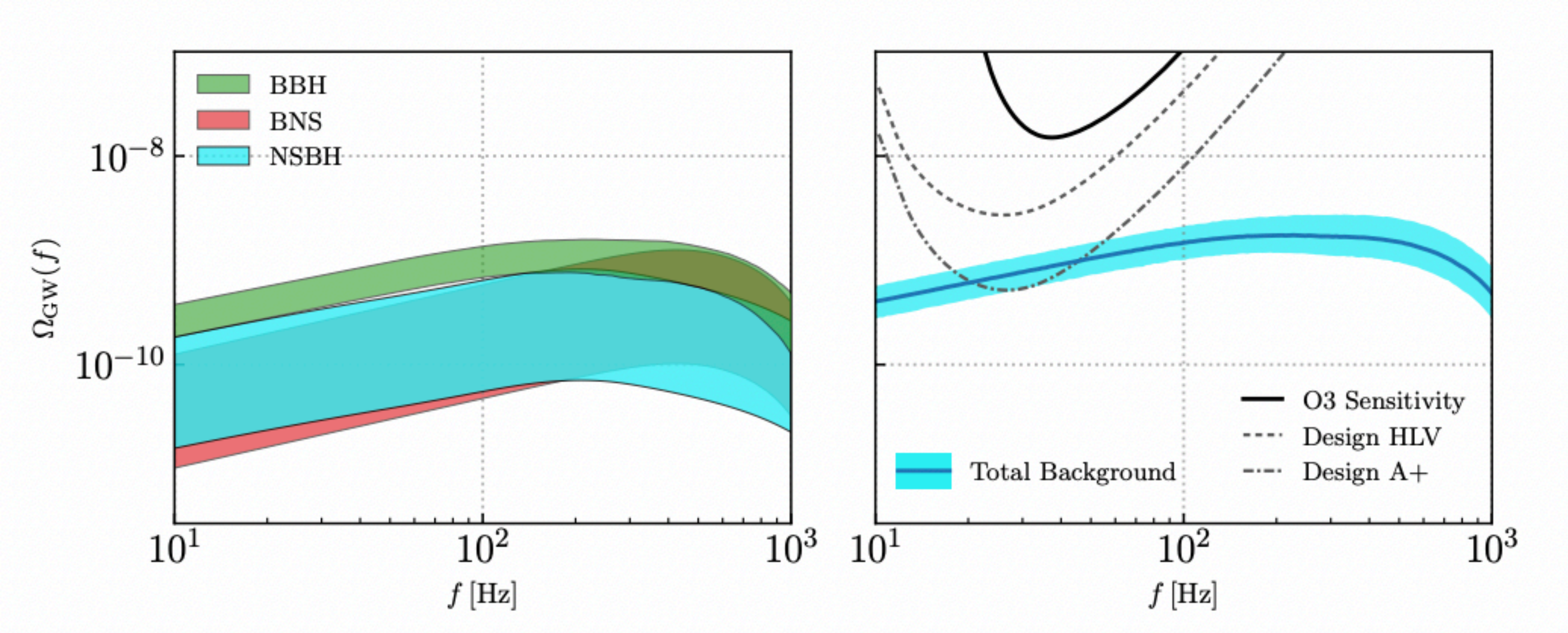


Stochastic GW search

$$\Omega_{\mathrm{GW}}(f) = \frac{f}{\rho_c}\frac{\mathrm{d}\rho_{\mathrm{GW}}}{\mathrm{d}f}$$

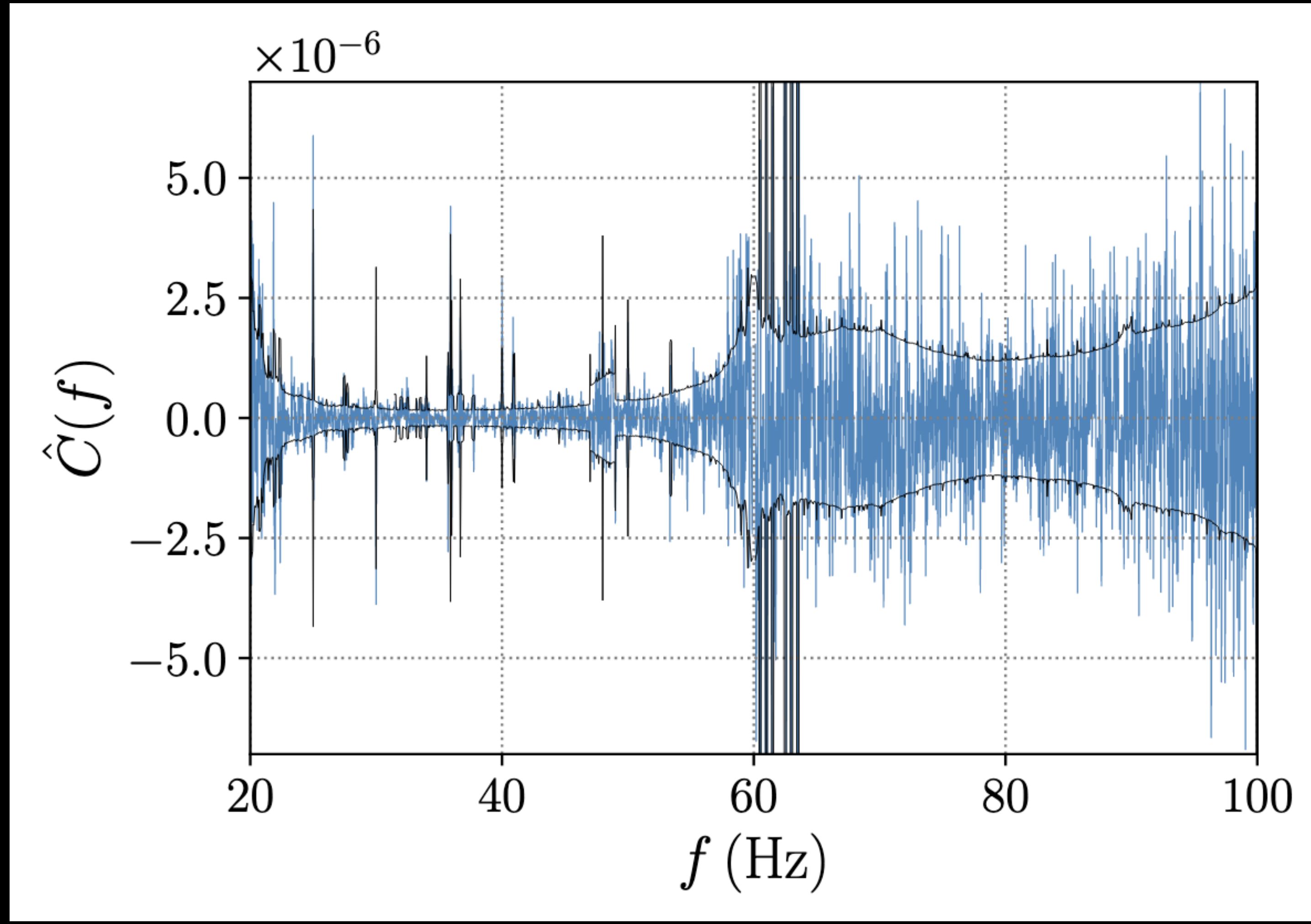


$\Omega_{\mathrm{GW}}(f)$



Using correlations across pairs of interferometers assuming uncorrelated noise.

$$\hat{C} = \frac{\sum_{IJ} \hat{C}^{IJ} \sigma_{IJ}^{-2}}{\sum_{IJ} \sigma_{IJ}^{-2}}, \quad \sigma^{-2} = \sum_{IJ} \sigma_{IJ}^{-2}$$



Assuming a signal with given frequency dependence

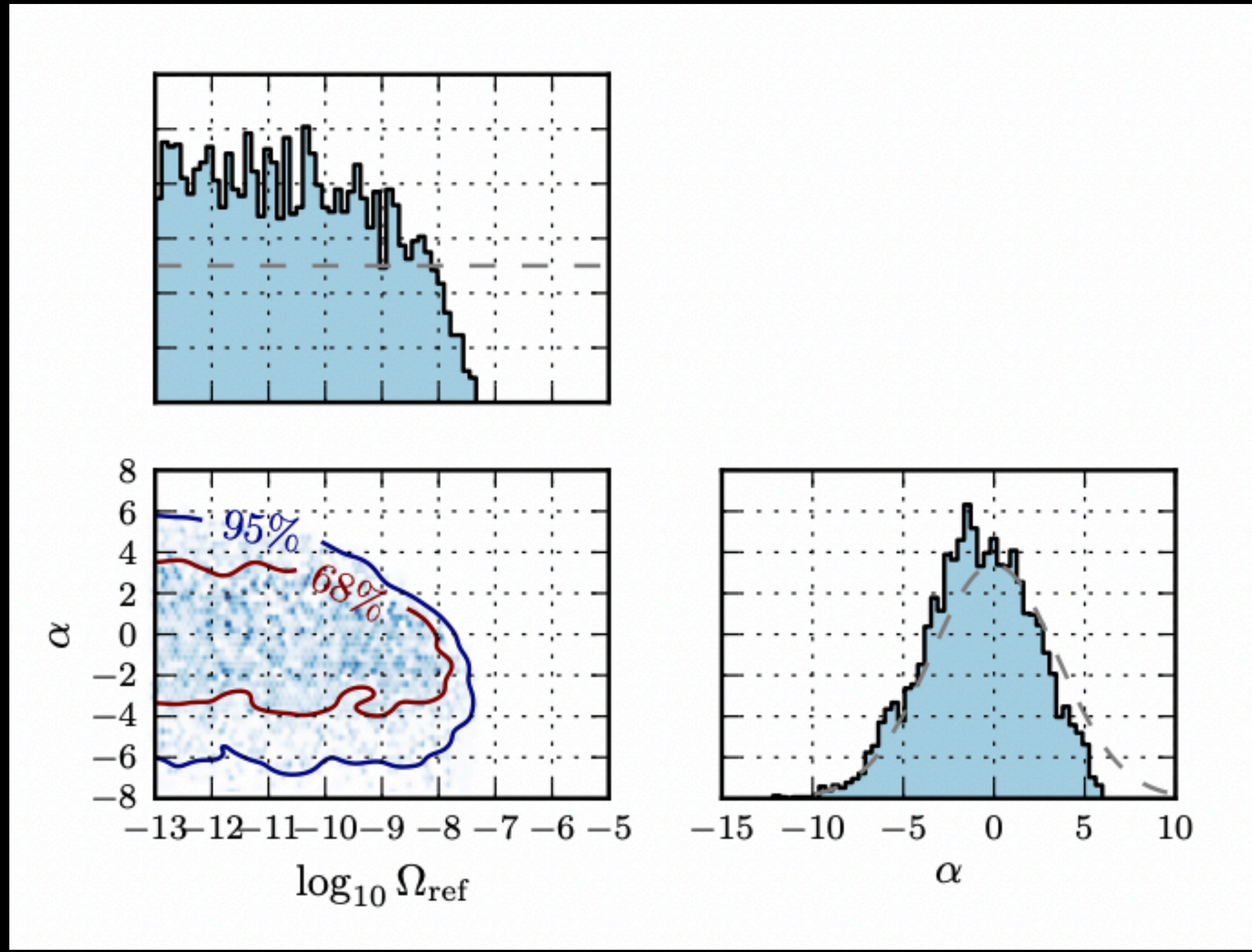
$$\Omega_{\mathrm{GW}}(f) = \Omega_{\mathrm{ref}} \left(\frac{f}{f_{\mathrm{ref}}}\right)^{\alpha}$$

Frat frequency spectrum:

$$\Omega_{\mathrm{GW}} \leq 5.8 \times 10^{-9}$$

Astrophysics : alpha = 2/3

$$\Omega_{\mathrm{GW}}(f) \leq 3.9 \times 10^{-10}$$



LIGO / Virgo with the sensitivity to observe first signs of astrophysical origin in the next years.

Phys. Rev. Lett. 126, 151301

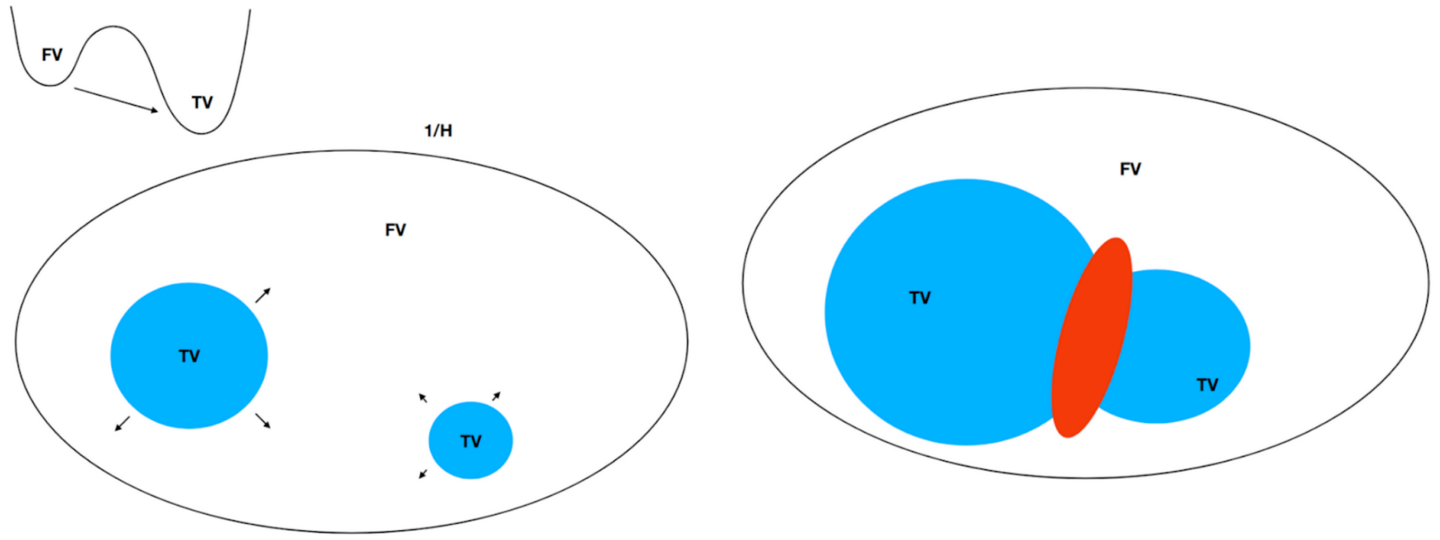
First Order Phase Transitions

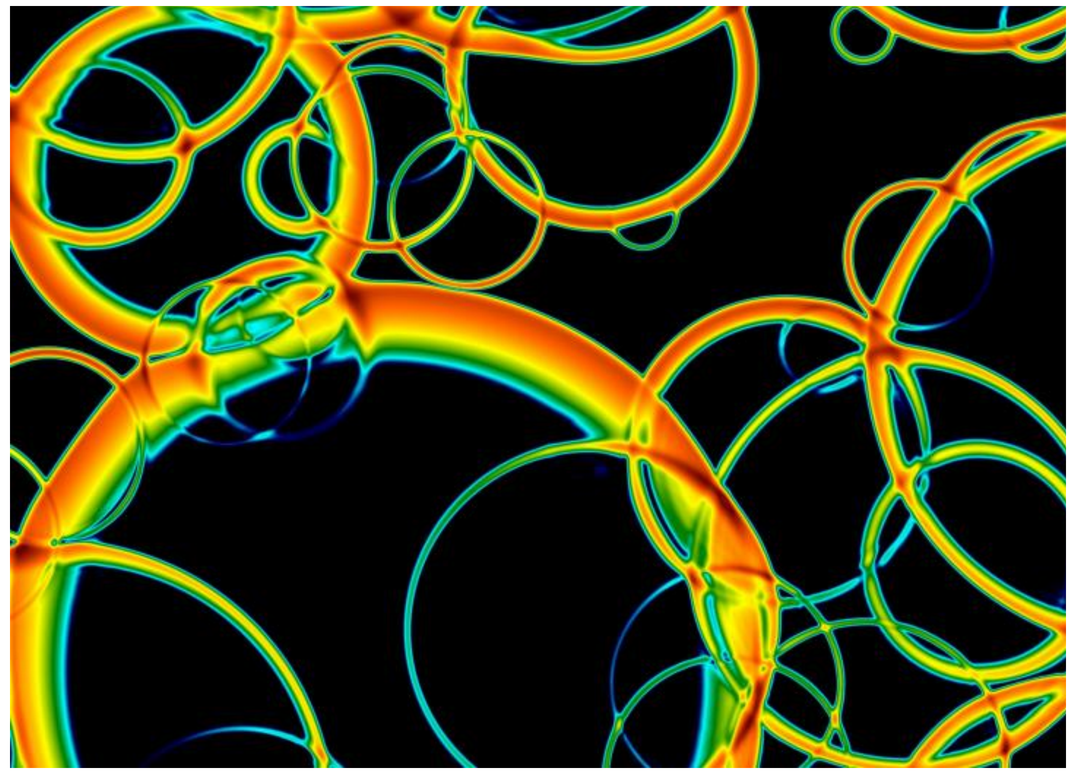
Three sources of GWs:

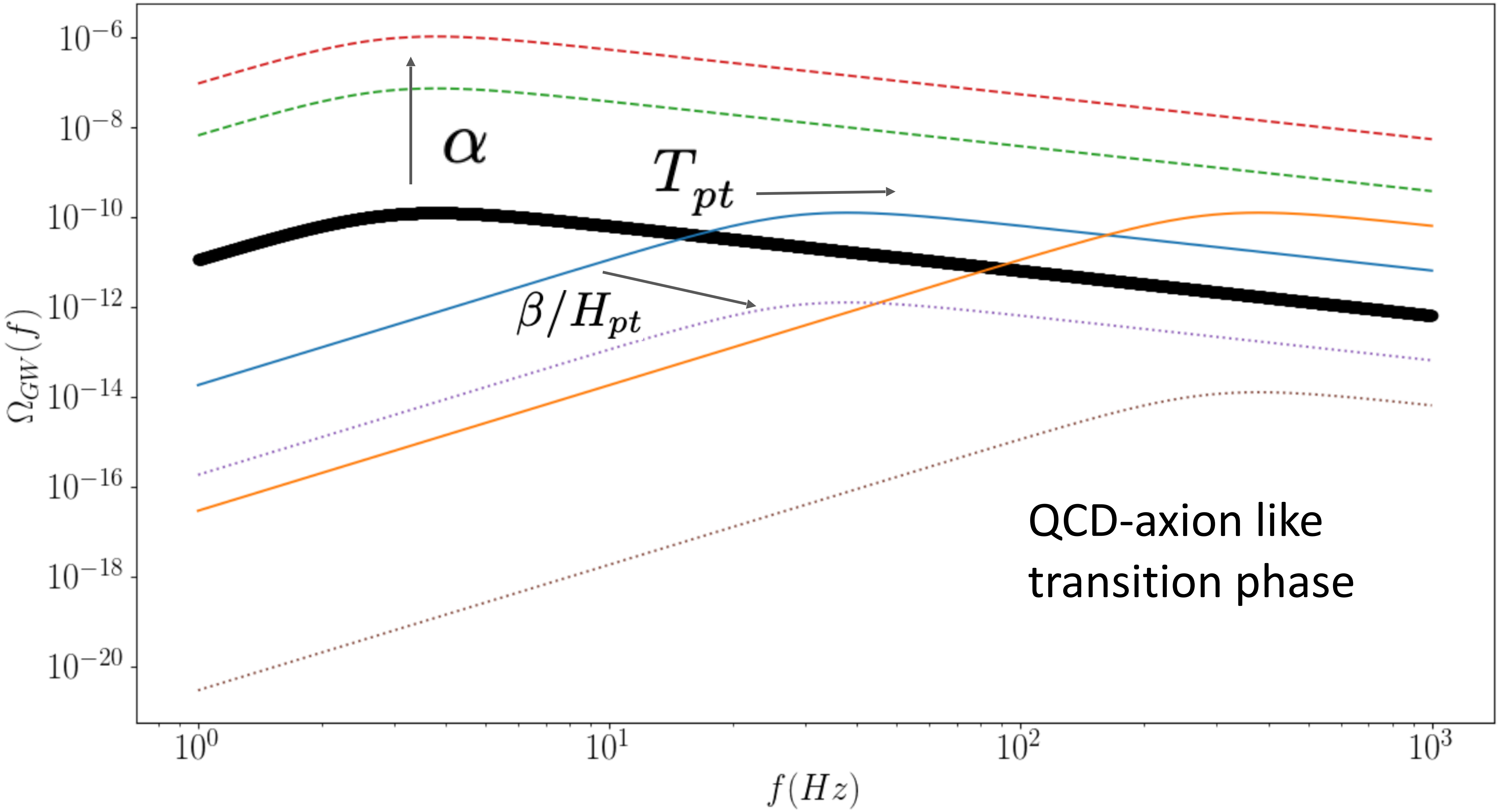
- Bubble collisions (BC): Ω_{coll}
- Sound waves (SW): Ω_{sw}
- Turbulence: Ω_t negligible.

Parameters

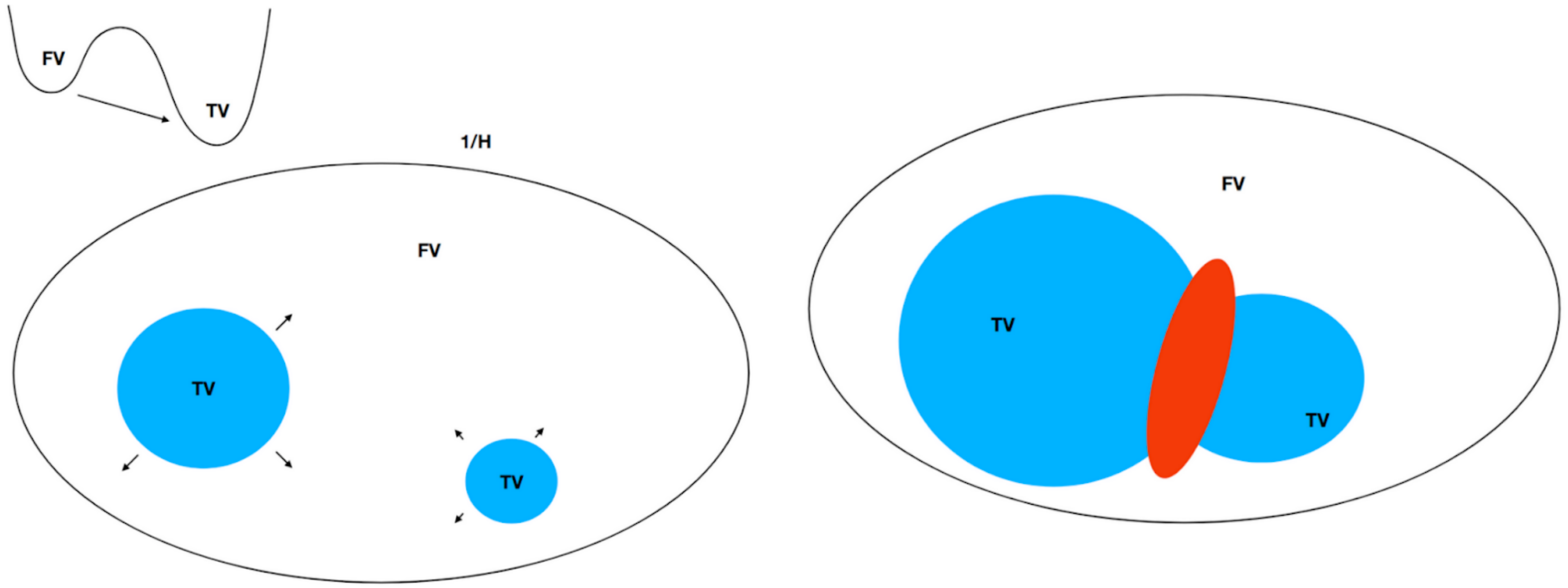
- Transition temperature: T_{pt}
- Inverse duration of the FOPT: β/H_{pt}
- Strength of the FOPT: α
- Bubble wall velocity: v_w
- Efficiency of the FOPT: κ_ϕ κ_{sw}

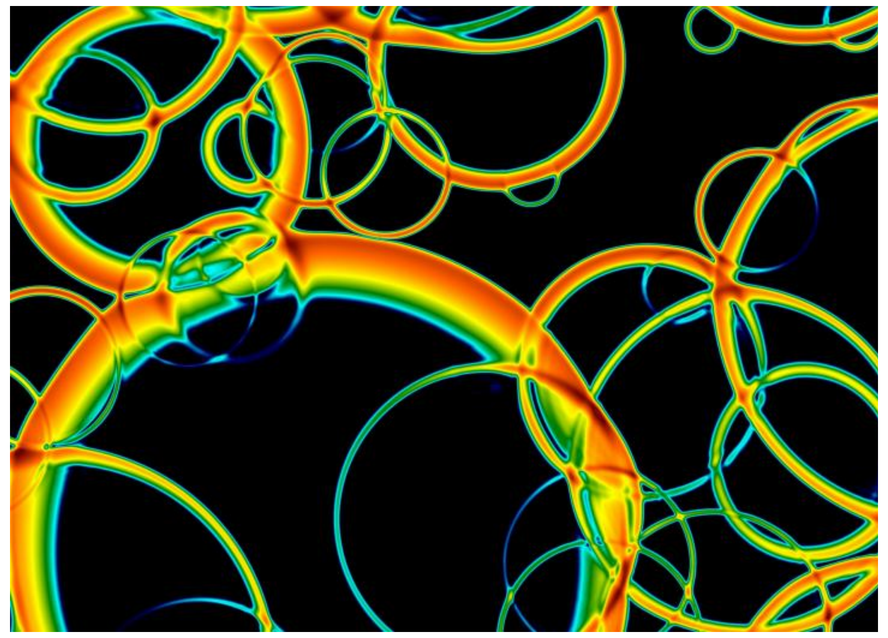


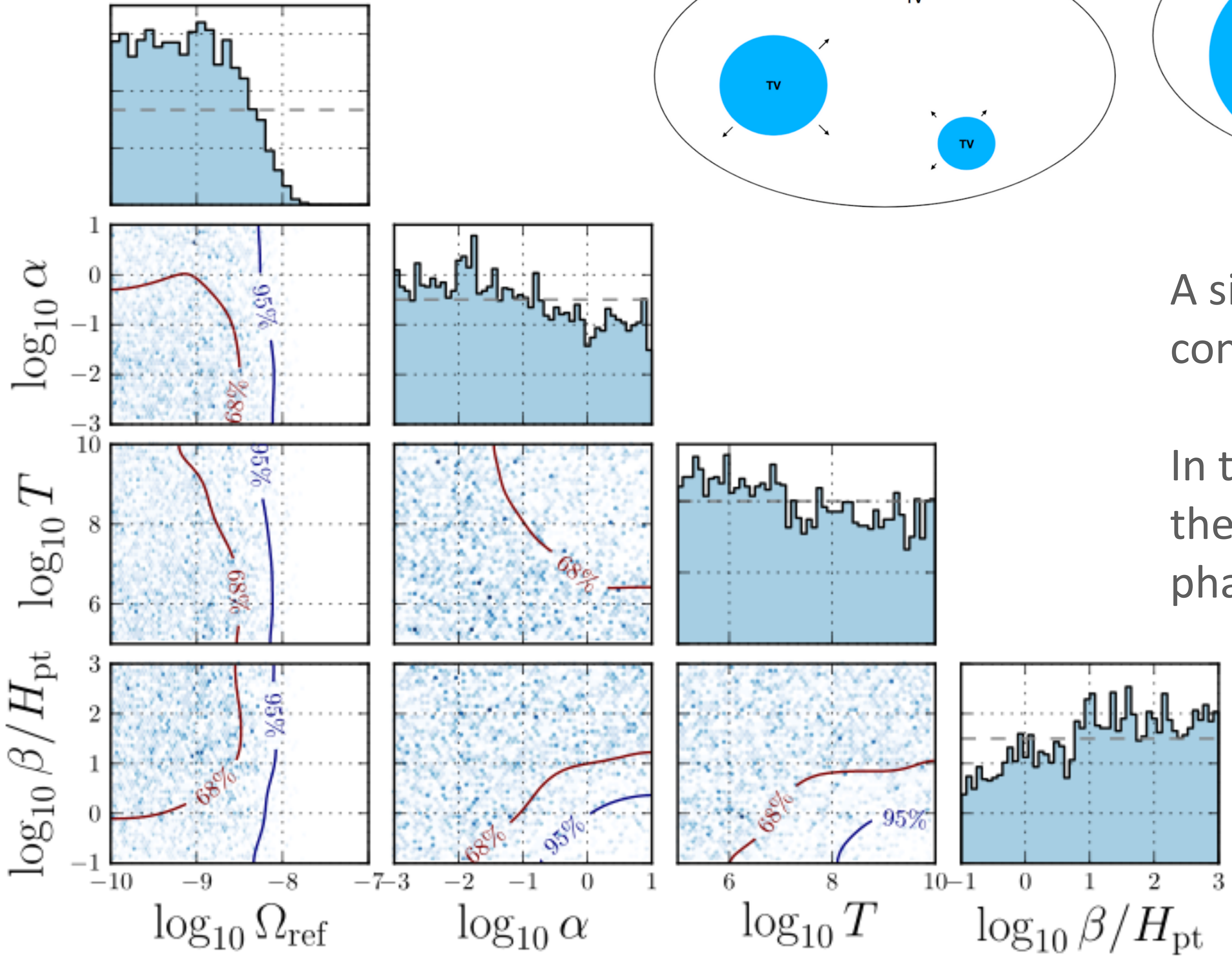




Phys. Rev. Lett. 126, 151301







A simultaneous fit is performed on CBC contributions and contributions from FOFT

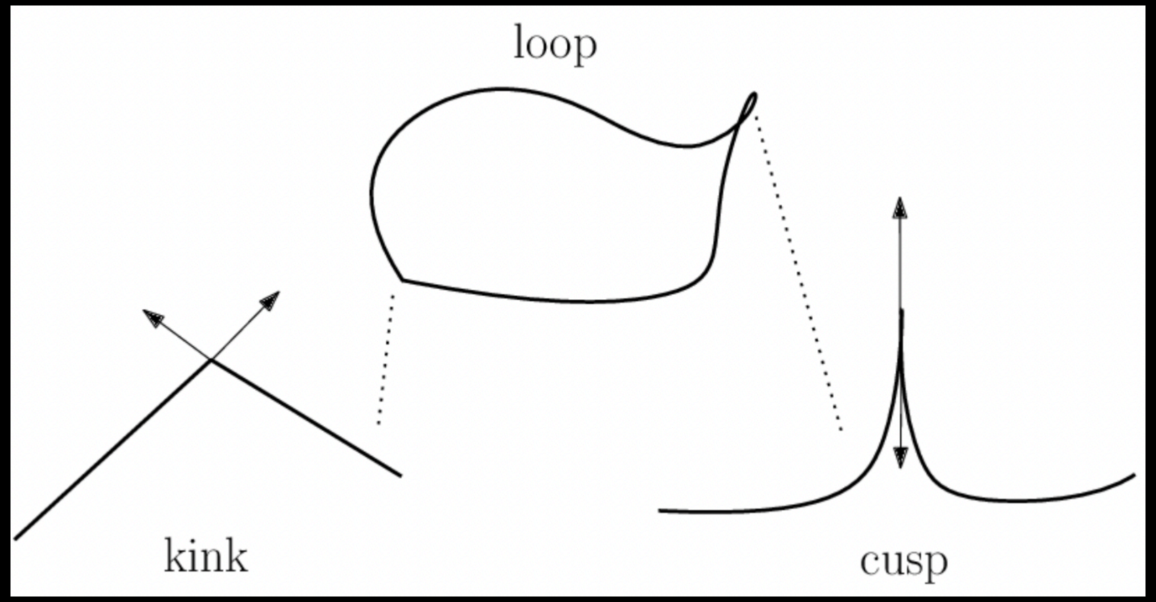
In the case of GWs from bubble collisions the data shows sensitivity in part of the phase space considerer at very large temperatures

Search for Cosmic Strings

https://arxiv.org/pdf/2101.12248.pdf

Topological defects from phase transitions at the GUT scale

GWs produced from collisions of cusps, kink and kink-kink on loops (different frequency dependence)

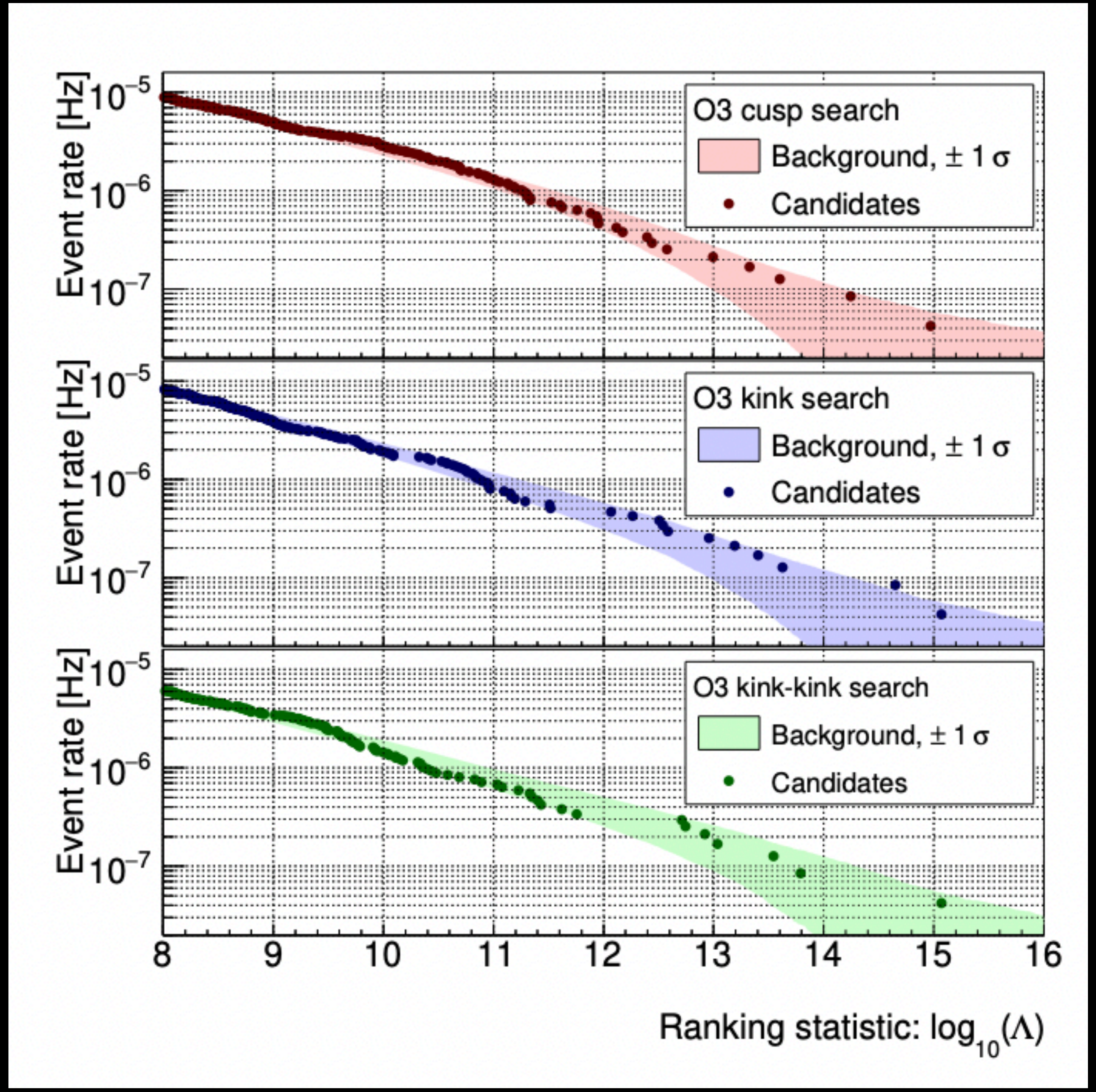


$$h_i(\ell, z, f) = A_i(\ell, z) f^{-q_i}$$

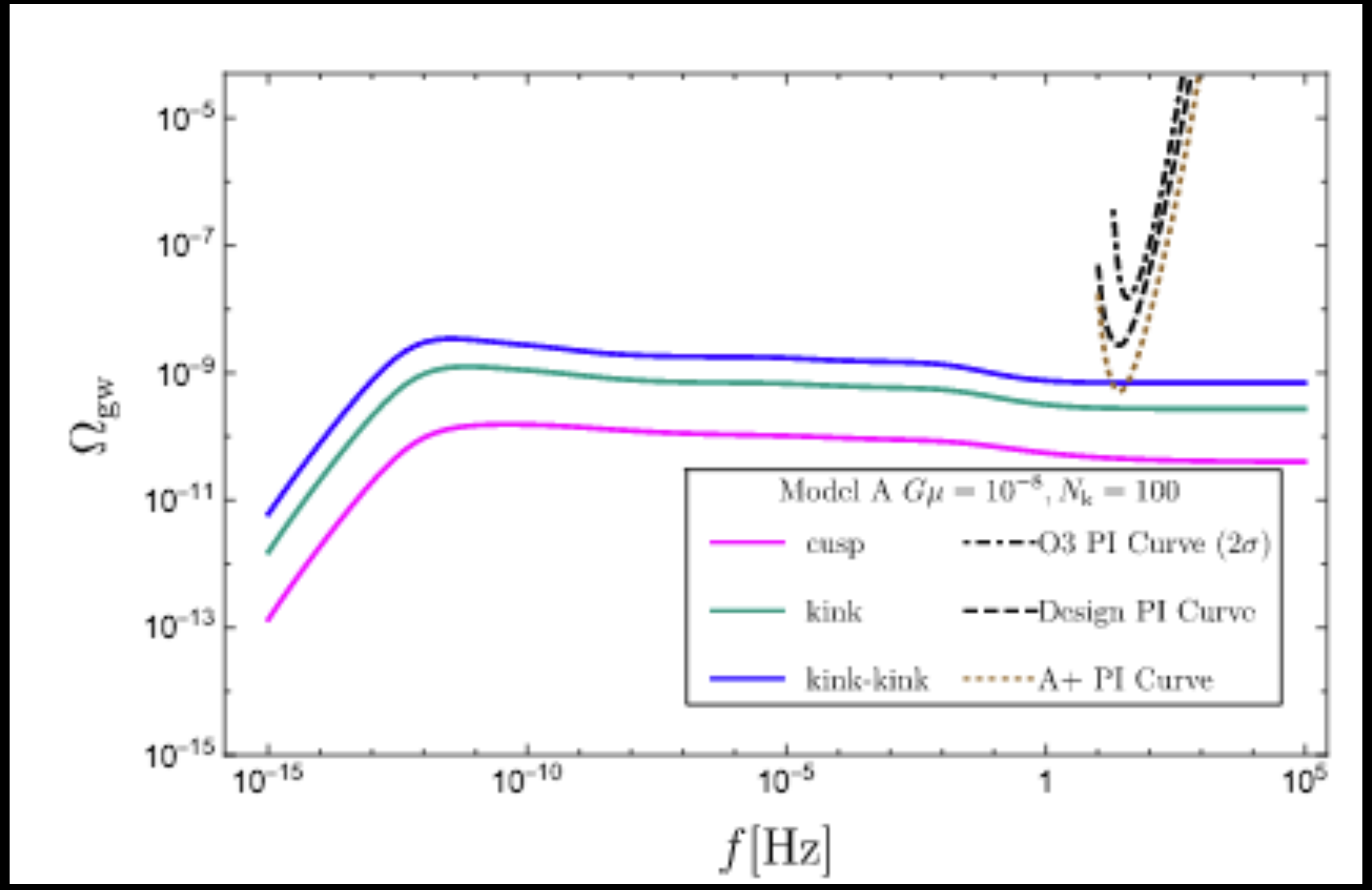
$$A_i(\ell, z) = g_{1,i} \frac{G\mu\, \ell^{2-q_i}}{(1+z)^{q_i-1} r(z)}$$

$$G\mu \sim (\eta/M_{\rm Pl})^2$$

BURST SIGNALS



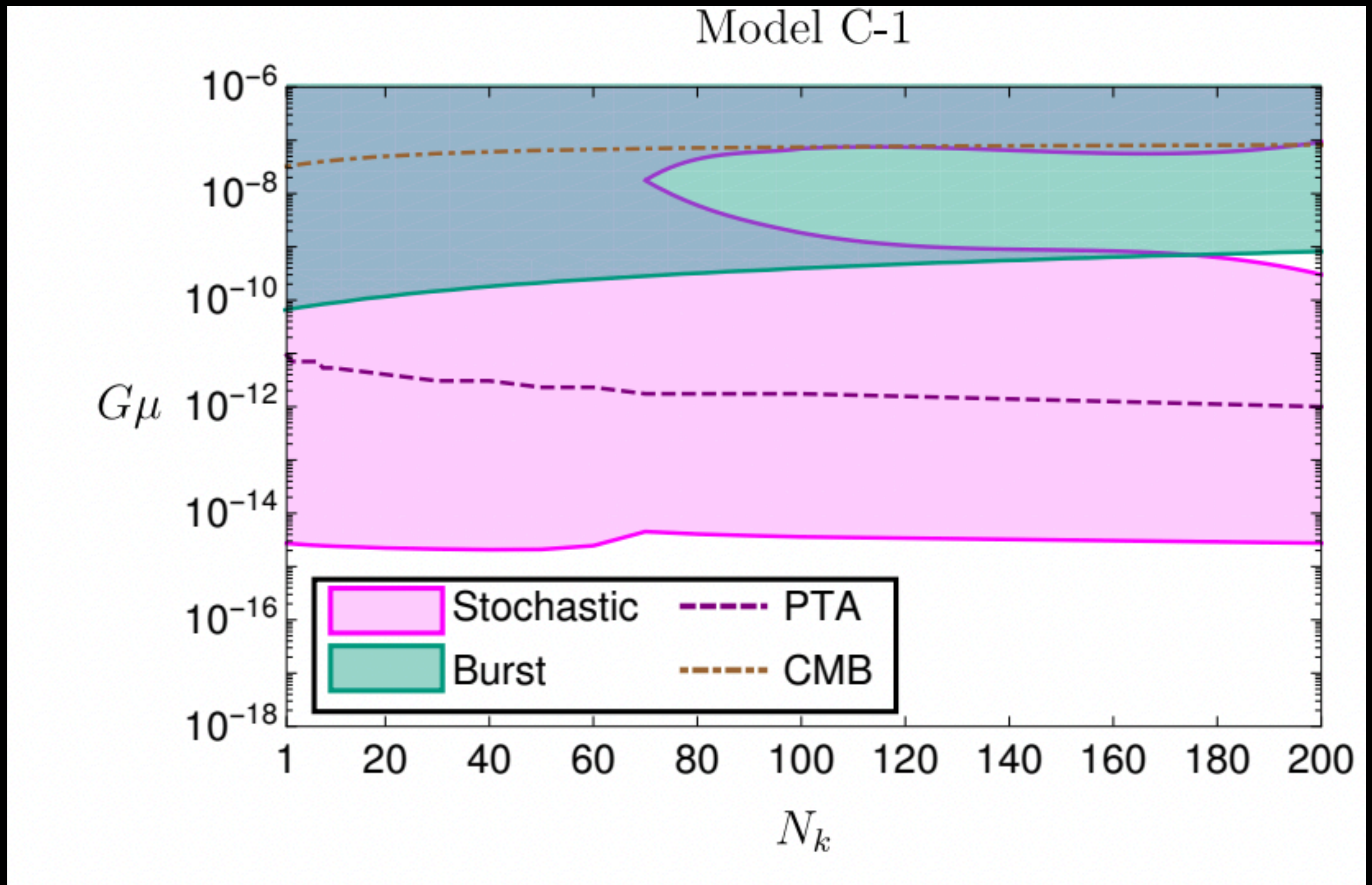
STOCHASTIC SIGNALS



Burst and Stochastical Signals

Null results expressed in terms of different models governing the formation of the string loops

95% CL on string tension vs N-kinks



Stochastic signals in pBH formation

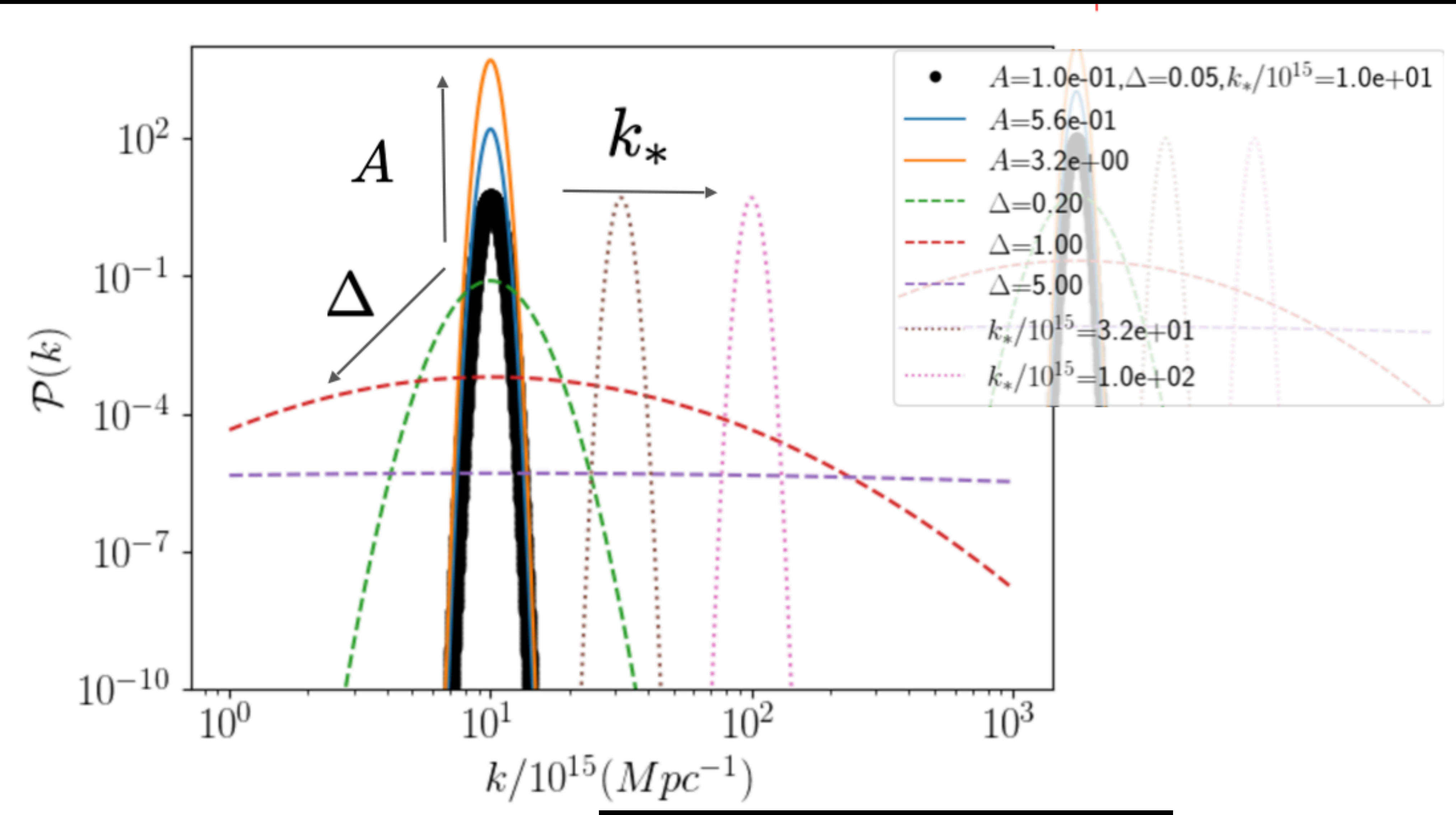
Scalar induced GW background

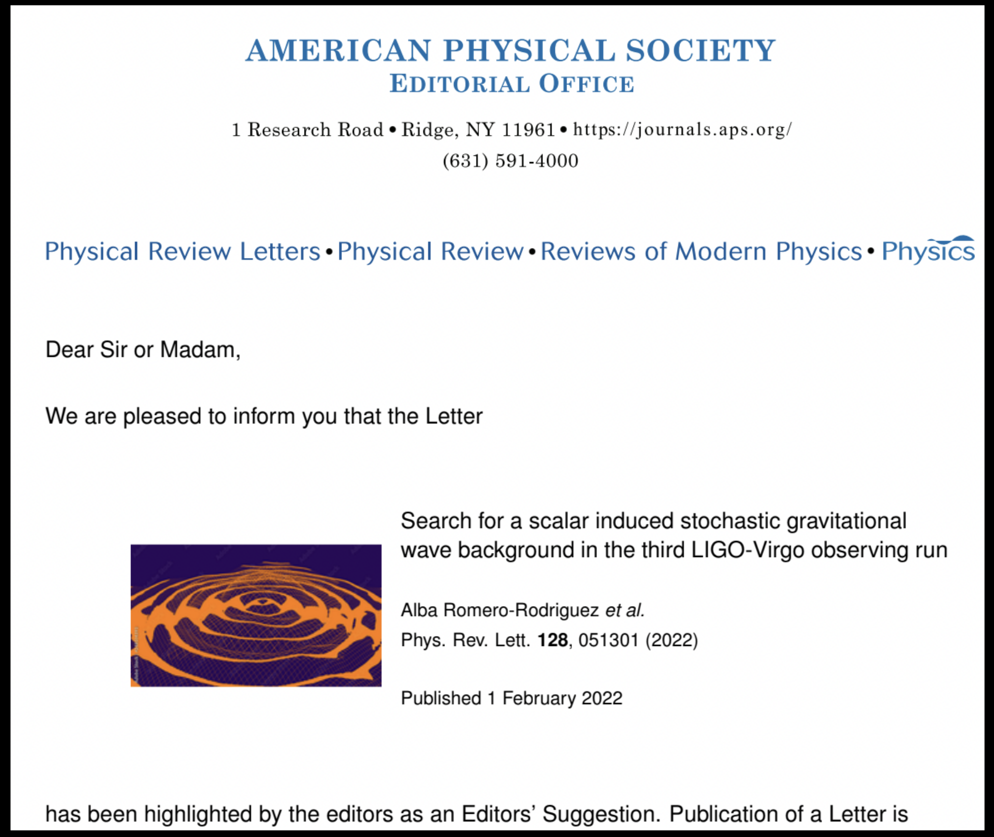
Integrated power of the peak

Location of the peak

$$\mathcal{P}_\zeta(k) = \frac{A}{\sqrt{2\pi}\Delta} \exp\left[-\frac{\ln^2(k/k_*)}{2\Delta^2}\right]$$

Width of the peak





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Dear Sir or Madam,

We are pleased to inform you that the Letter

Search for a scalar induced stochastic gravitational wave background in the third LIGO-Virgo observing run

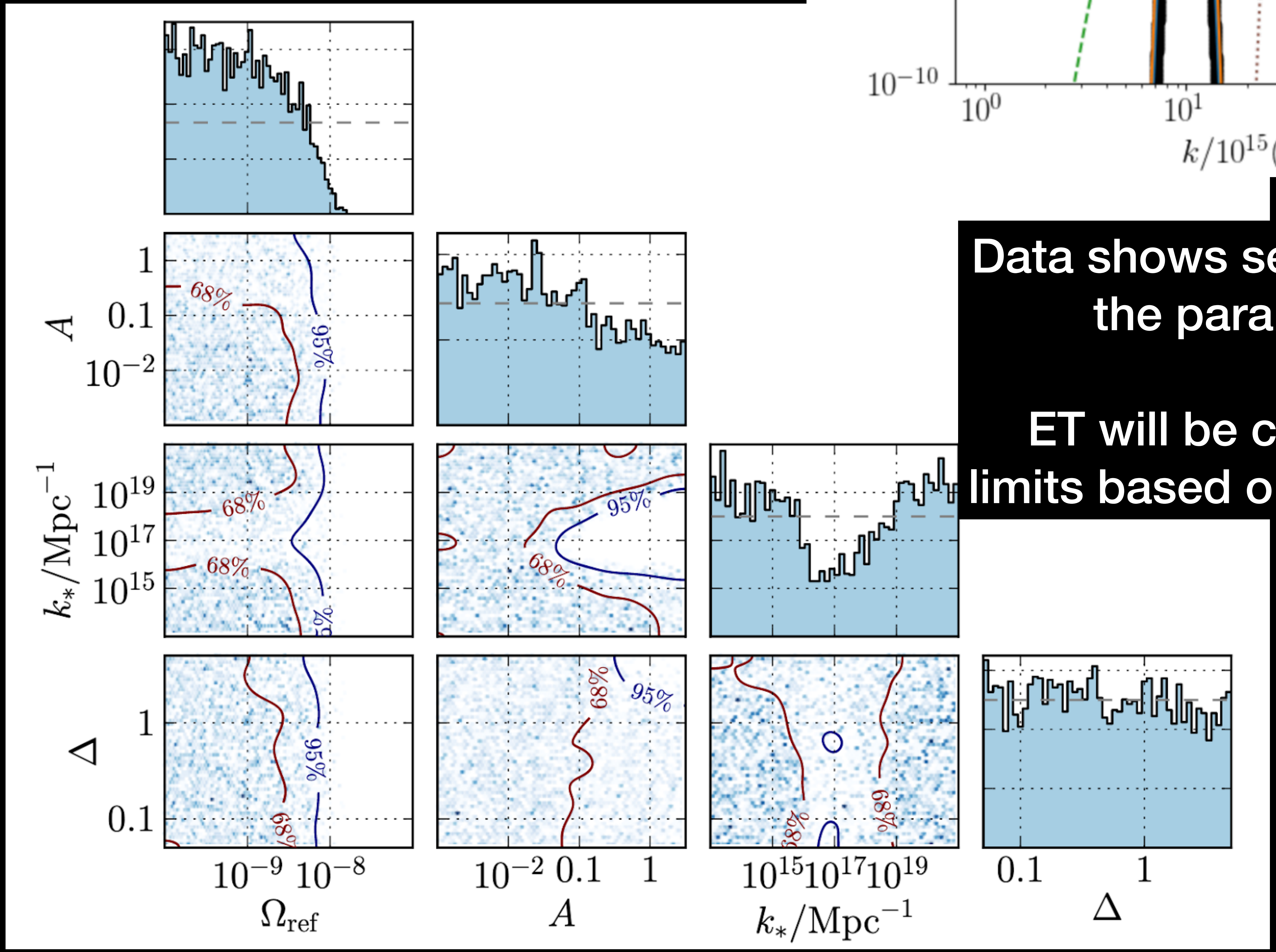
Alba Romero-Rodriguez *et al.*

Phys. Rev. Lett. **128**, 051301 (2022)

Published 1 February 2022

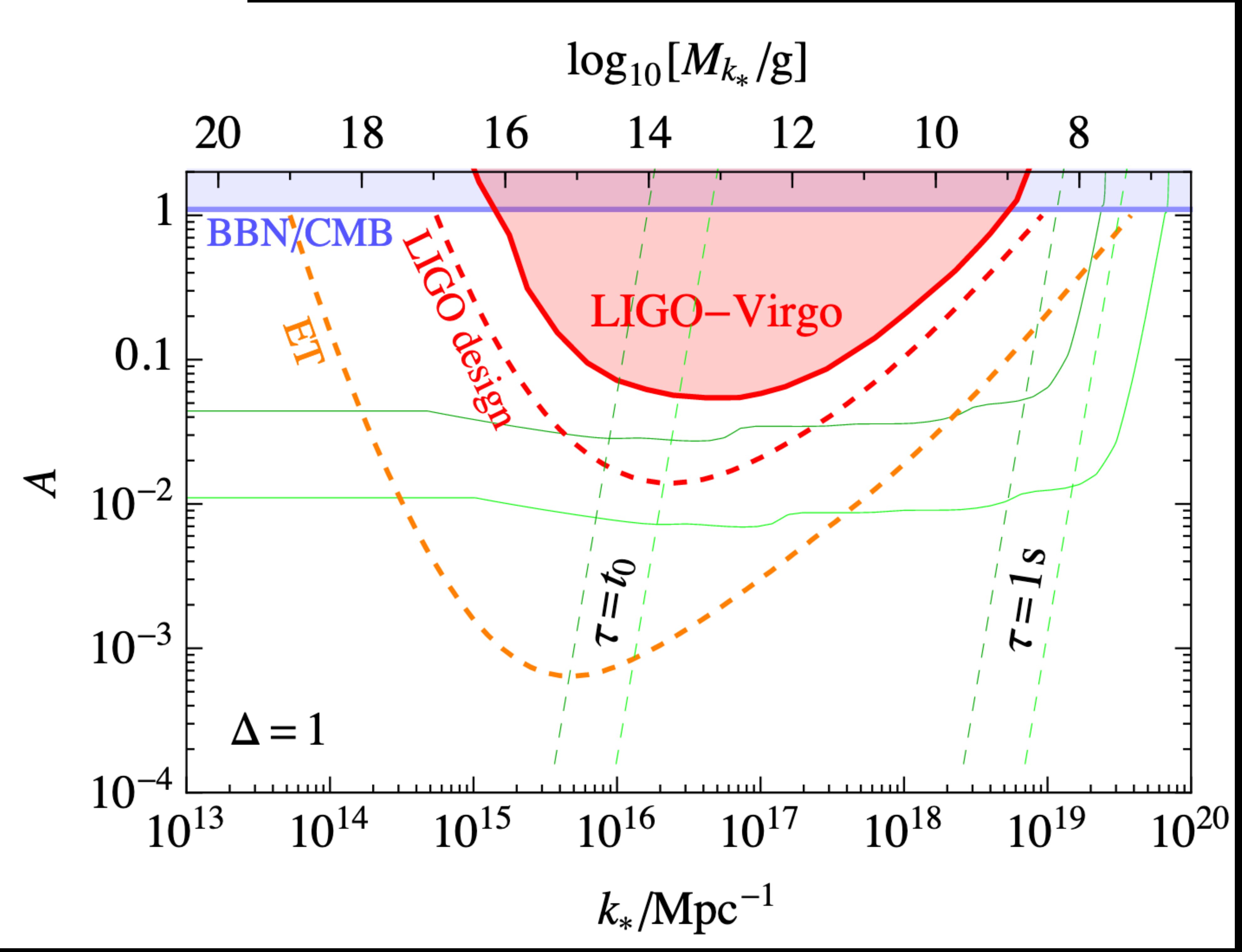
has been highlighted by the editors as an Editors' Suggestion. Publication of a Letter is

Phys. Rev. Lett., vol. 128, p. 051301 (2022)



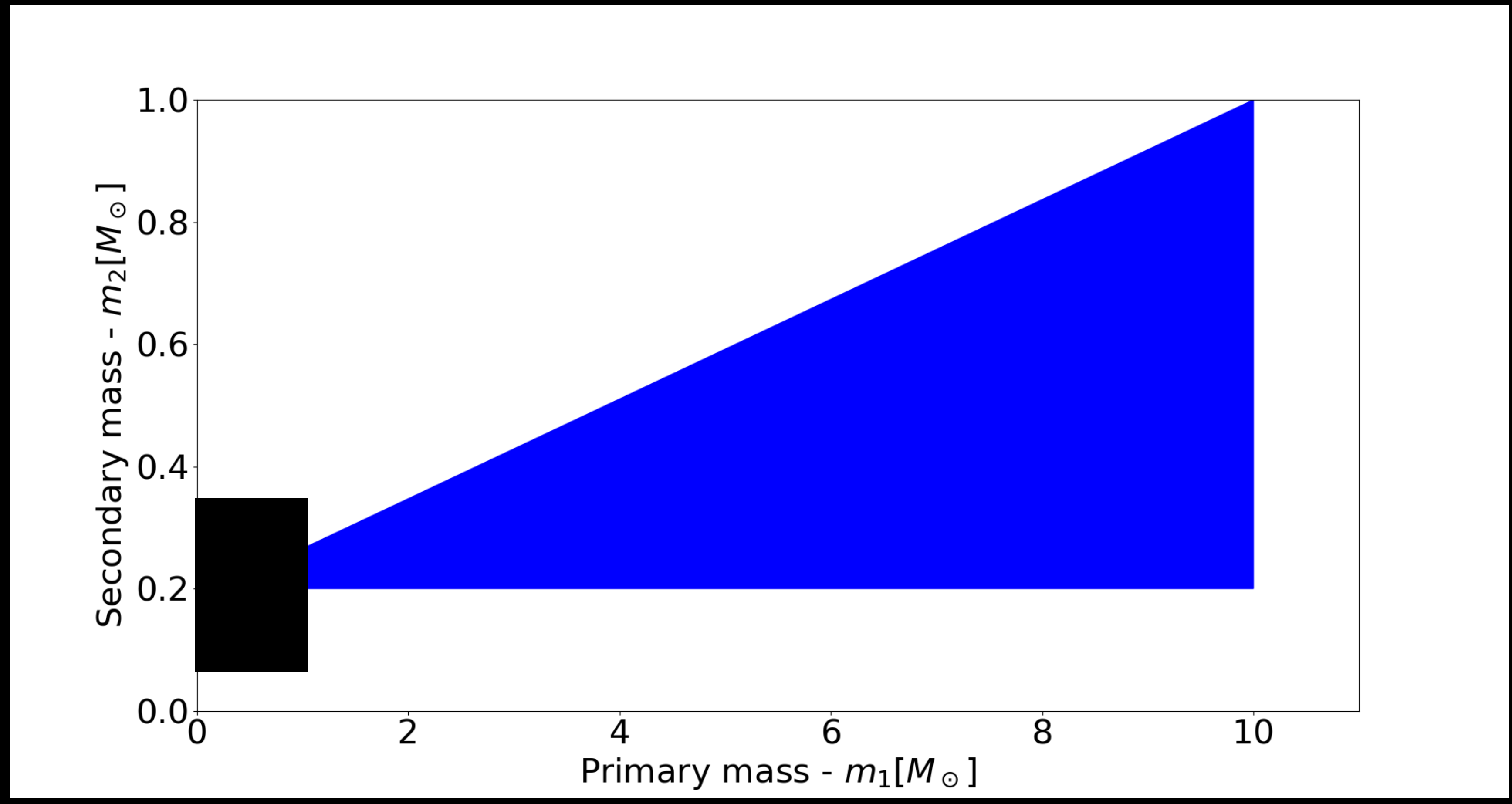
Data shows sensitivity in part of the parameter space

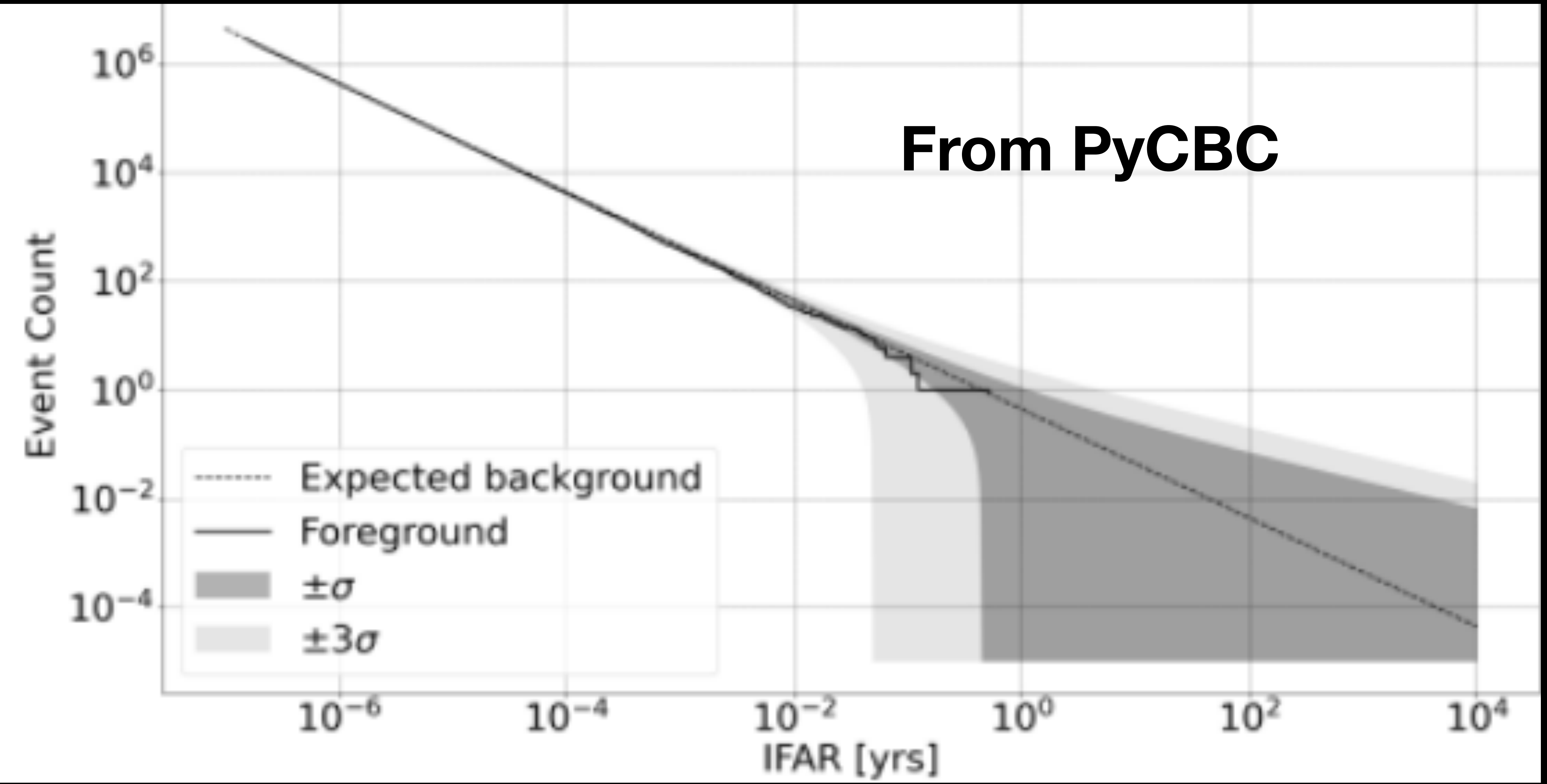
ET will be competitive with limits based on PBH abundance

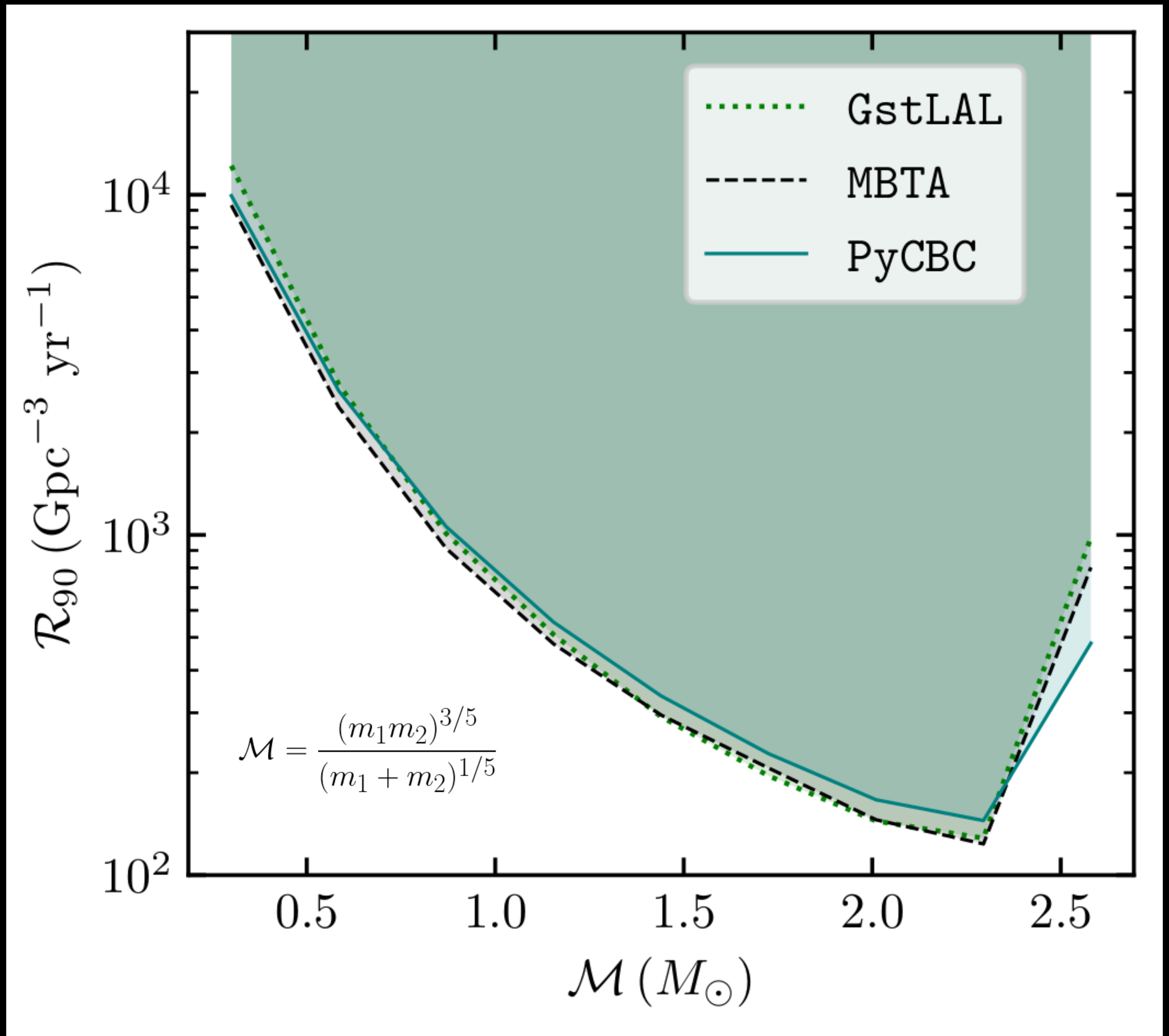


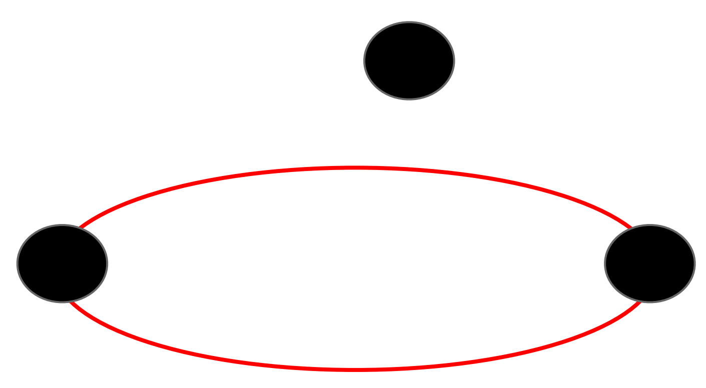
Search for subsolar mass BHs

- Targeted searches for binary systems with subsolar components -> primordial origin
- Motivated by pBHs possible DM candidate
- No significant event is found

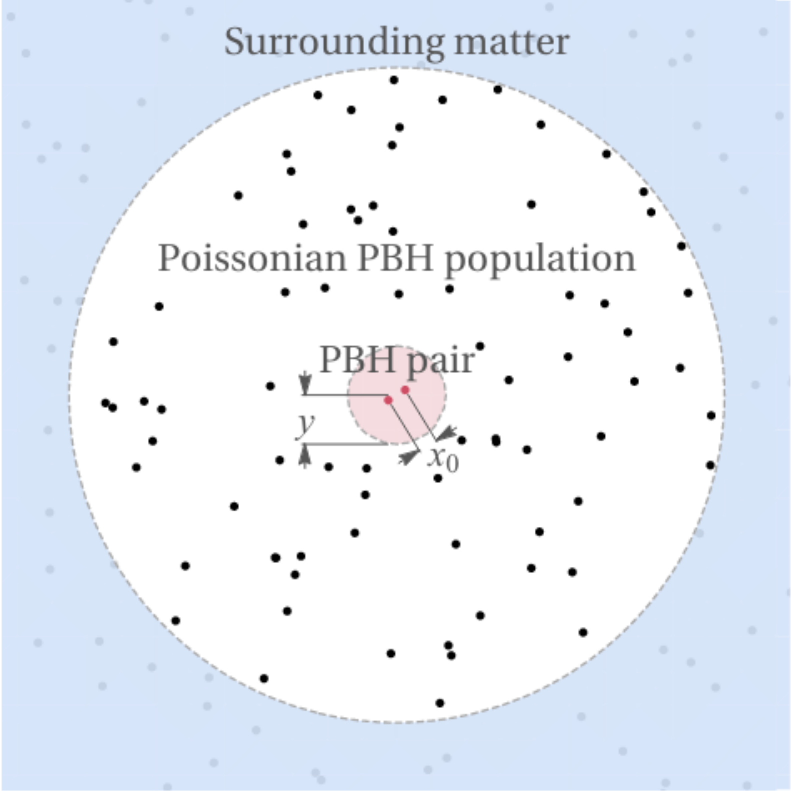








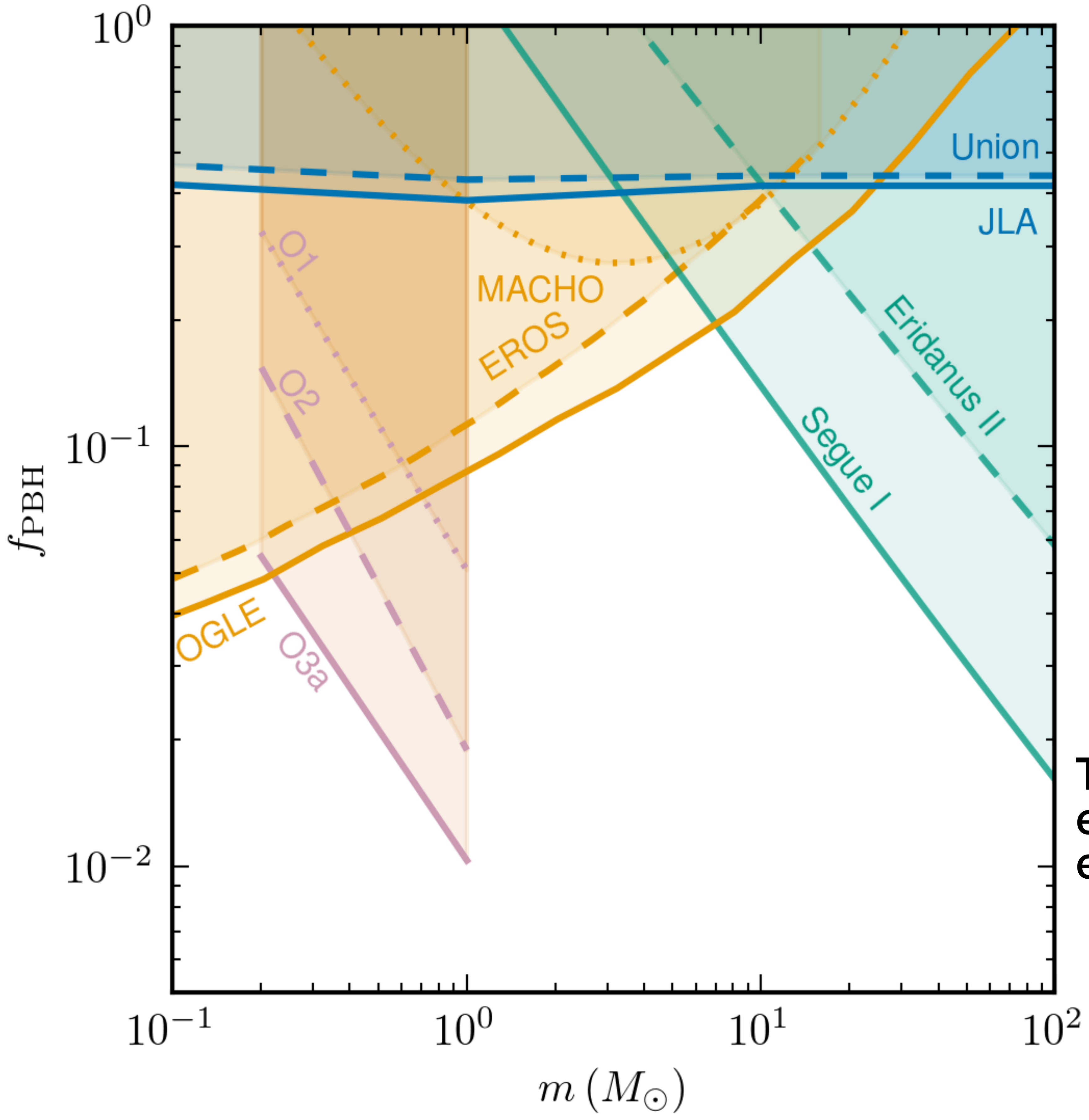
Search for subsolar mass BHs



2212.01477 [astro-ph.HE]

Translated into limits on fraction of DM density in pBHs
using models that predict the presence of PBH binaries
and w/wo environmental effects via the inclusion of suppression factors

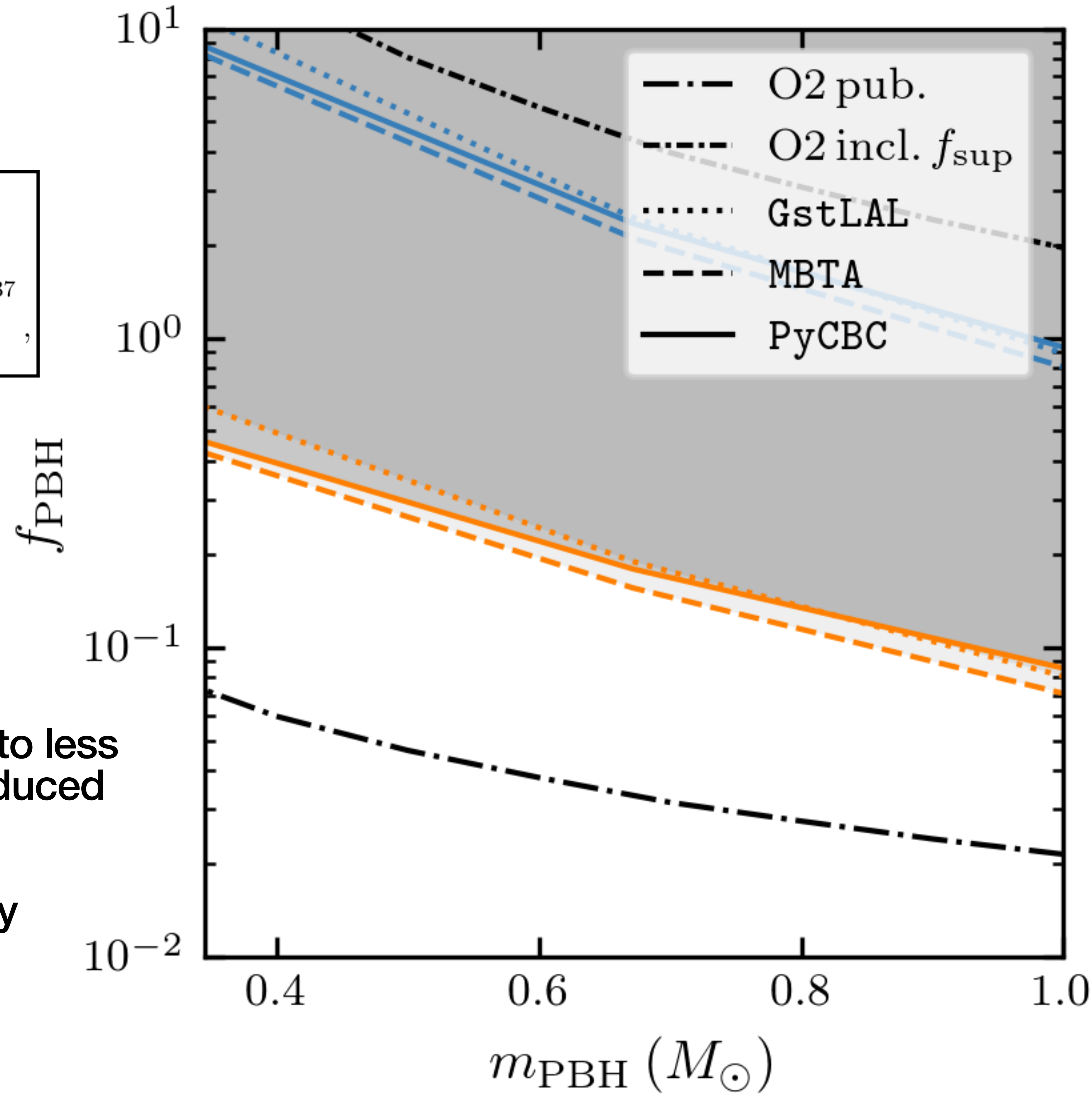
—> Very model dependent on the pBH formation mechanism & mass distribution



$$\frac{\mathrm{d}\mathcal{R}^{\rm PBH}}{\mathrm{d}\ln m_1 \mathrm{d}\ln m_2} = 1.6\times10^6\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}\times f_{\rm sup} f_{\rm PBH}^{53/37} f(m_1)\times f(m_2)\left(\frac{m_1+m_2}{M_\odot}\right)^{-32/37}\left[\frac{m_1 m_2}{(m_1+m_2)^2}\right]^{-34/37},$$

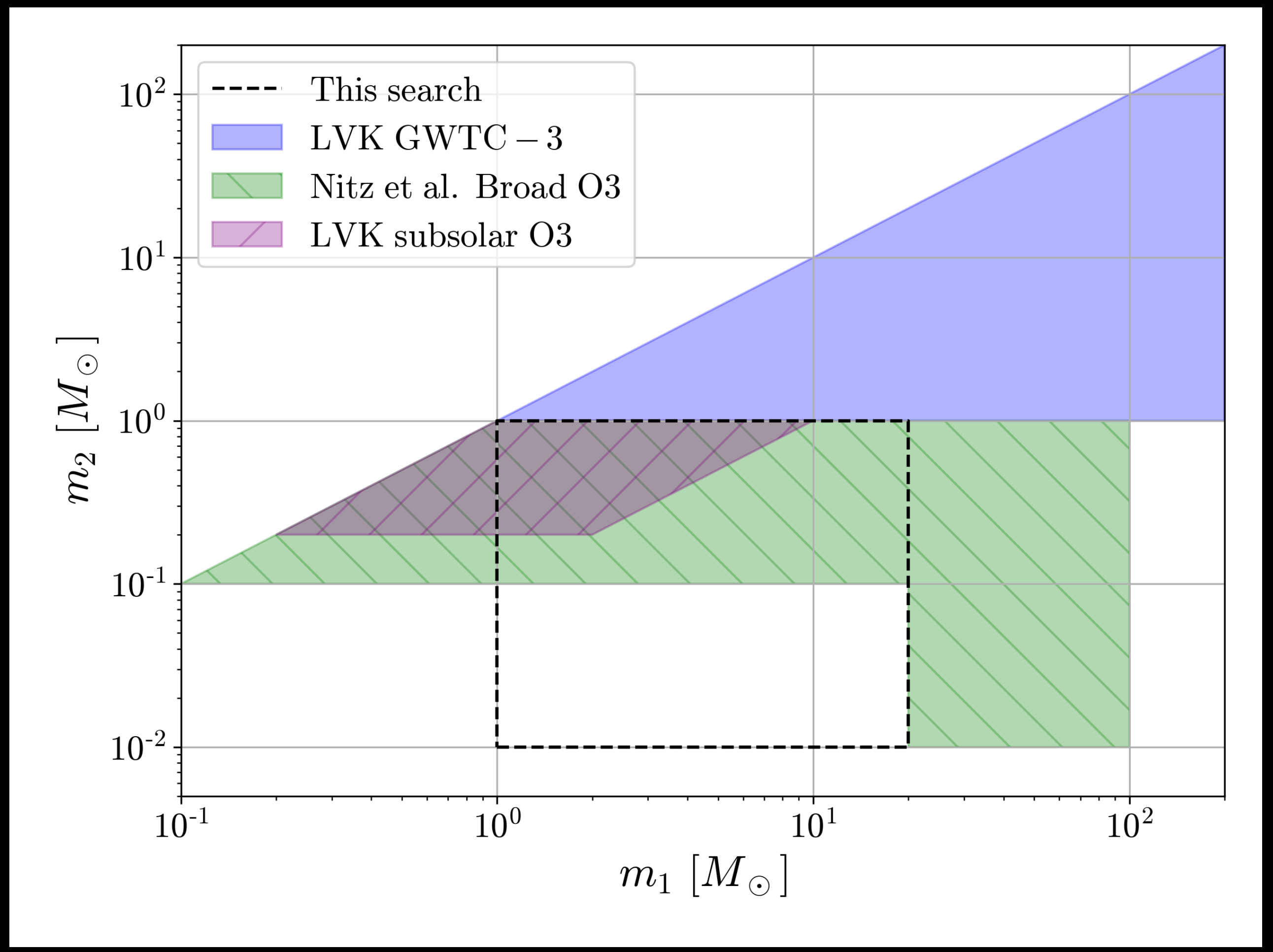
The inclusion of environmental effects leading to less efficient formation of the binary system and reduced expected population t translates into

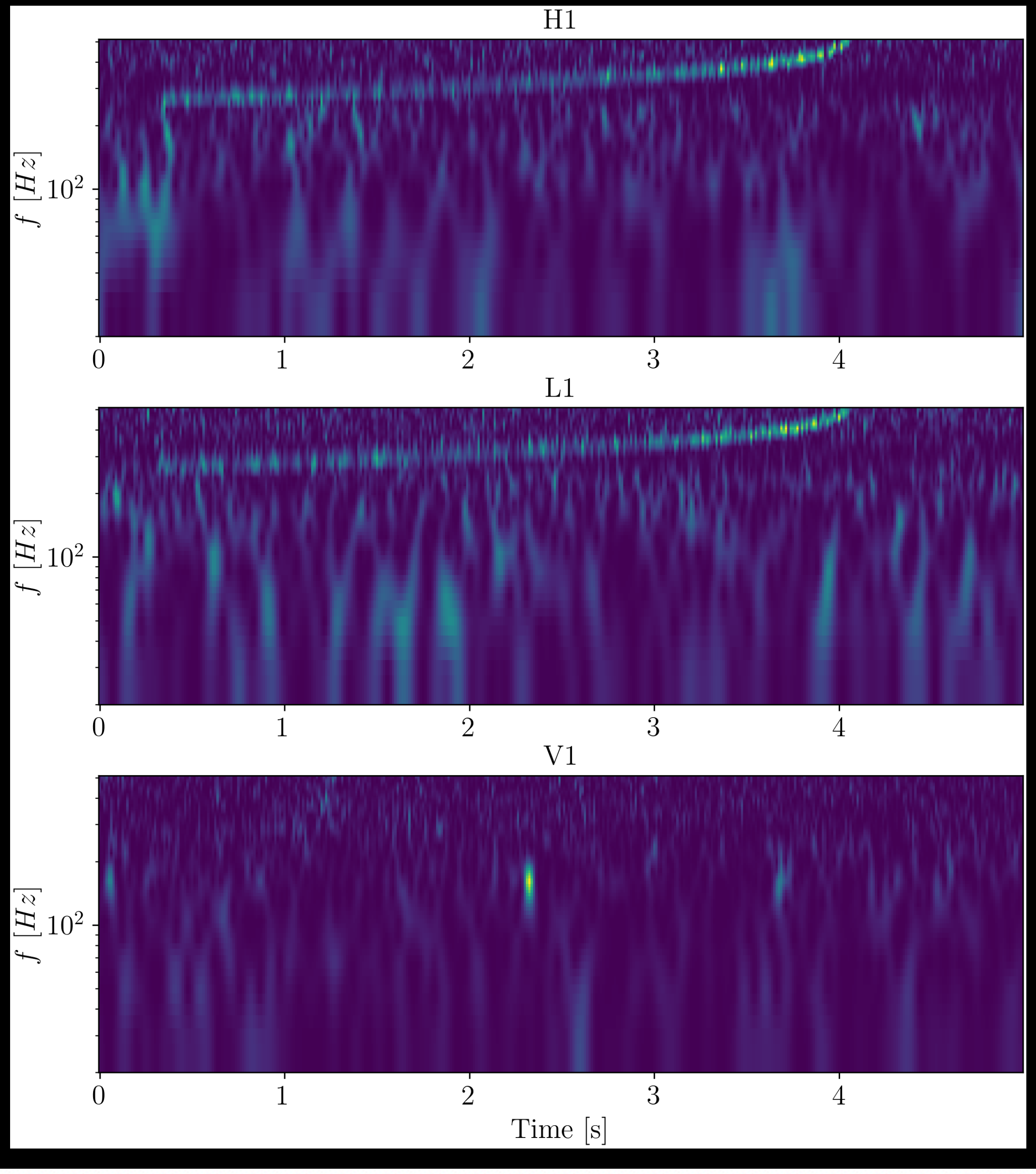
much weaker bounds on fraction of DM density

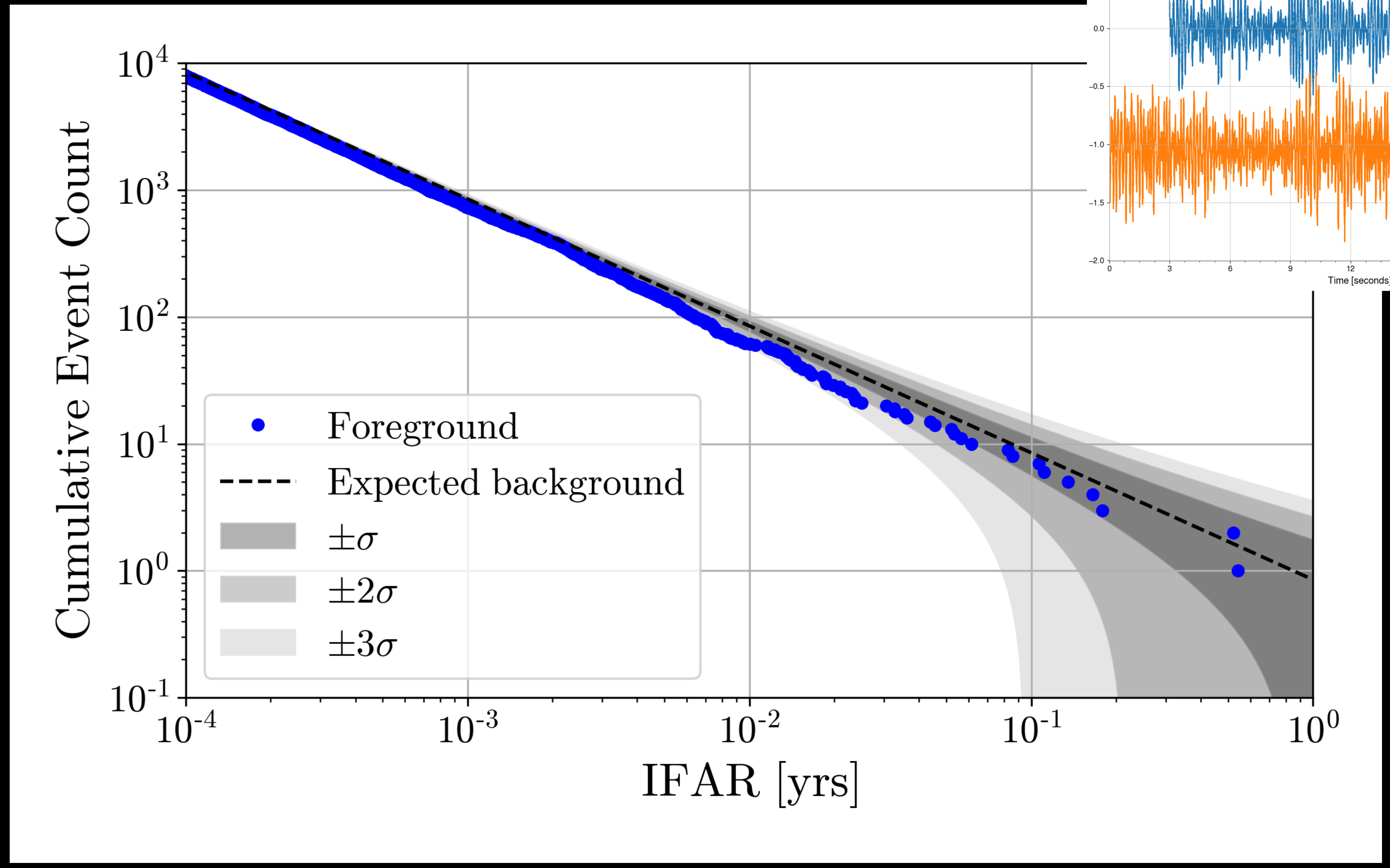


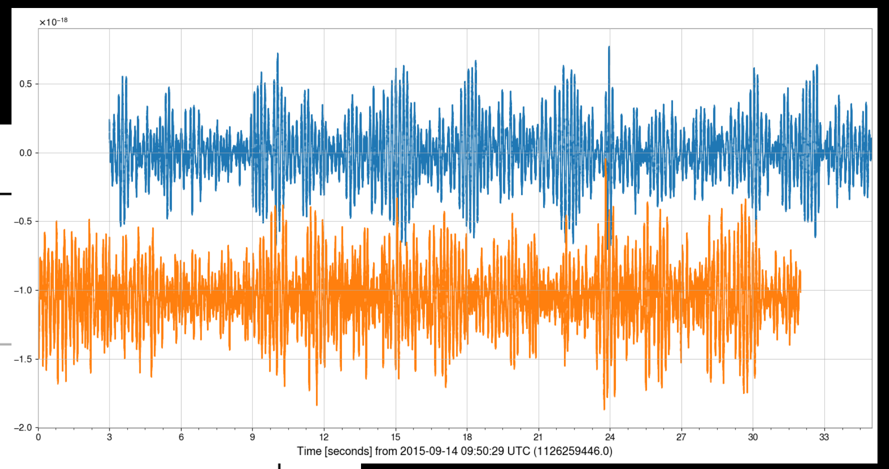
Phys. Rev. D 103, 062004 (2021)

Search for pBH using DL





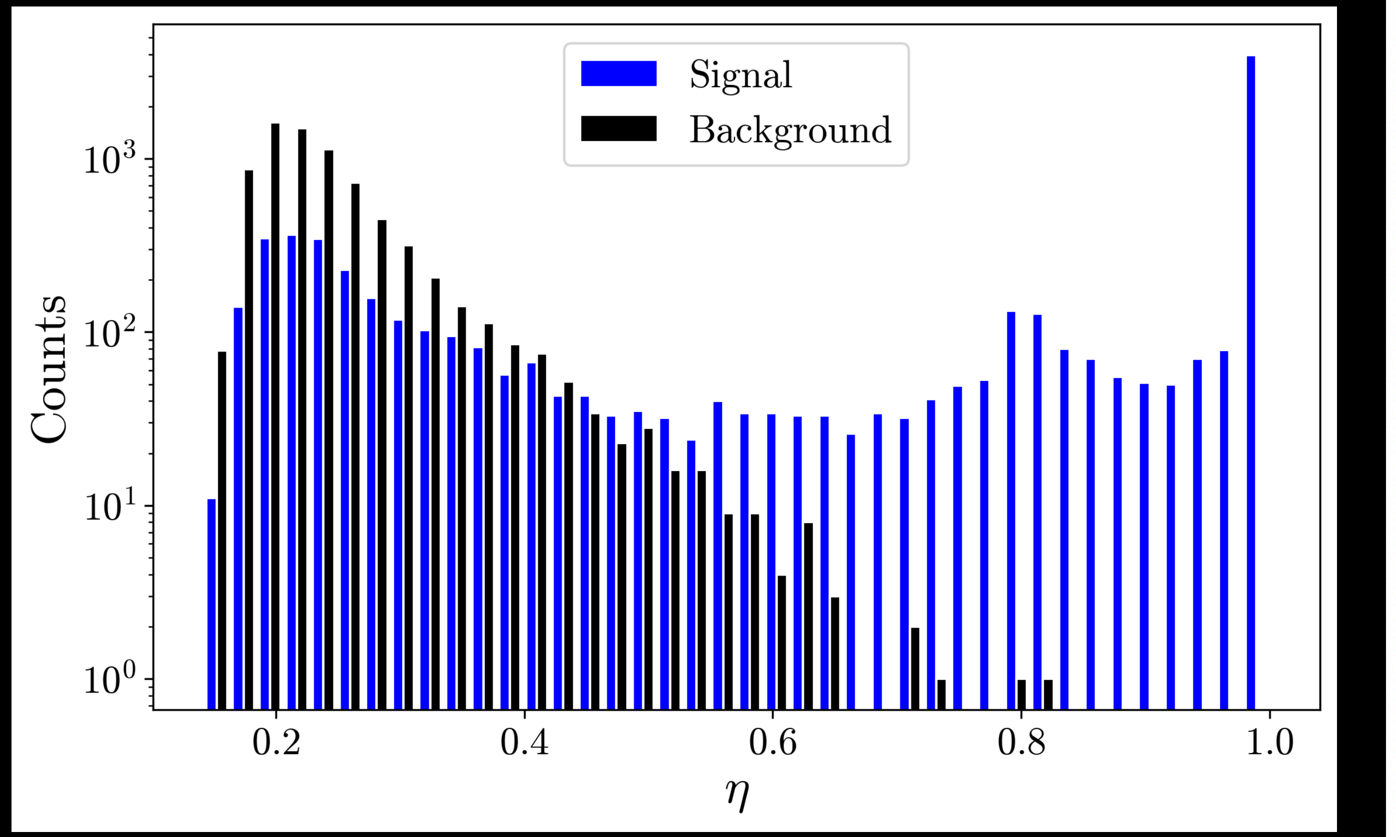


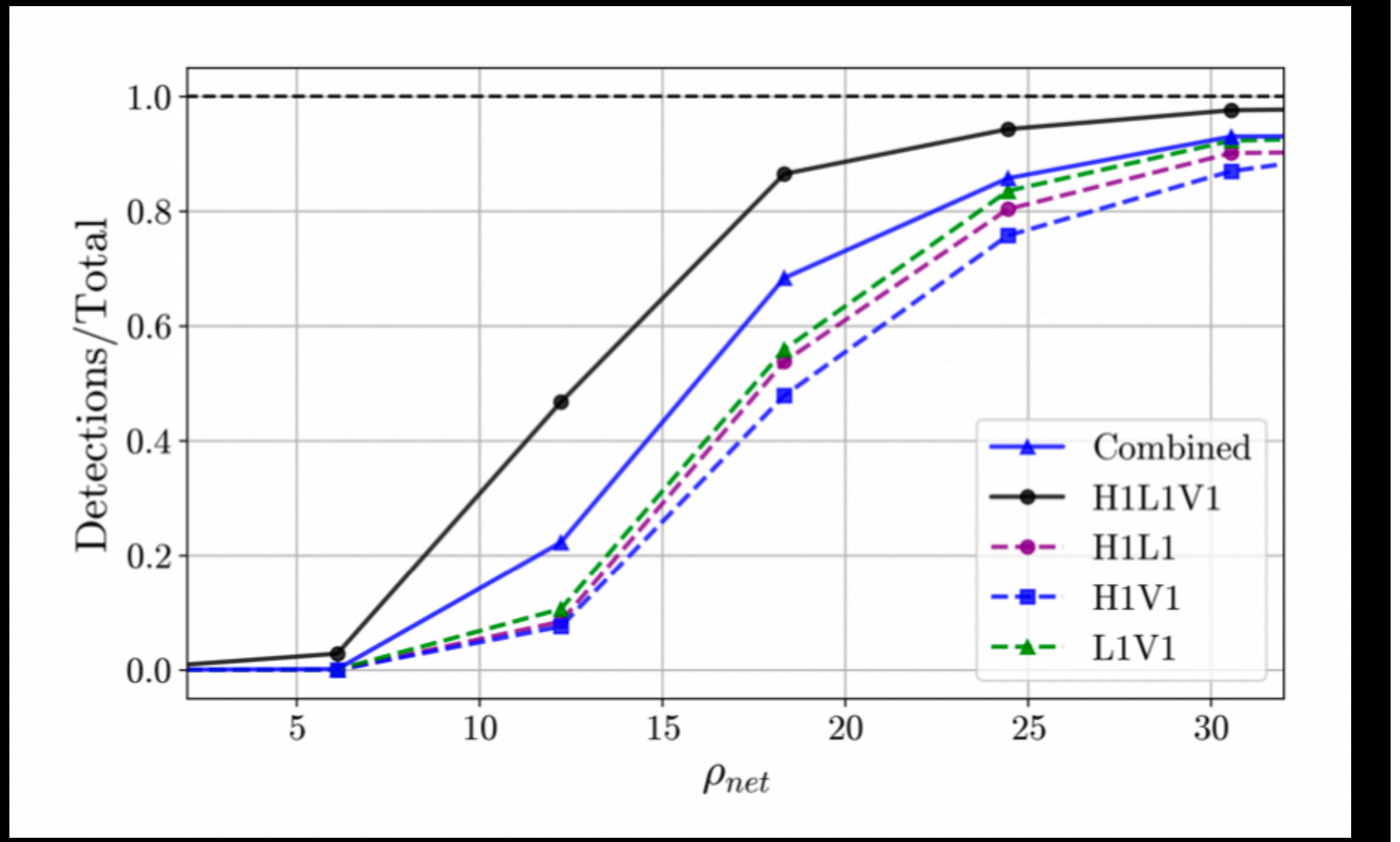


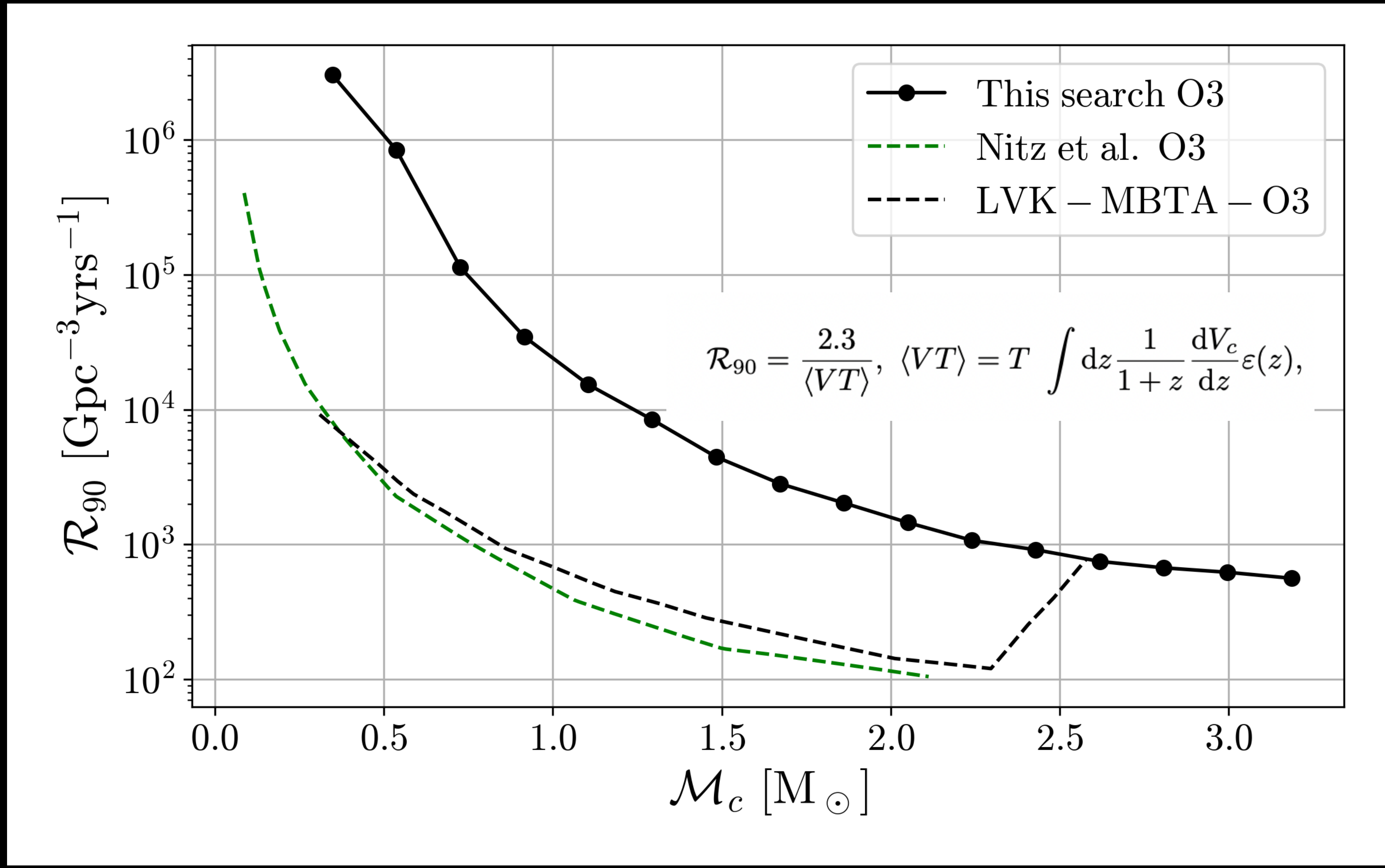
Convoluted NN focused on very asymmetric binary mass configurations

Using simultaneously Ligo and Virgo data as input during training process to limit fakes

This however effectively reduced the observation time to L-V overlapped (1/2)

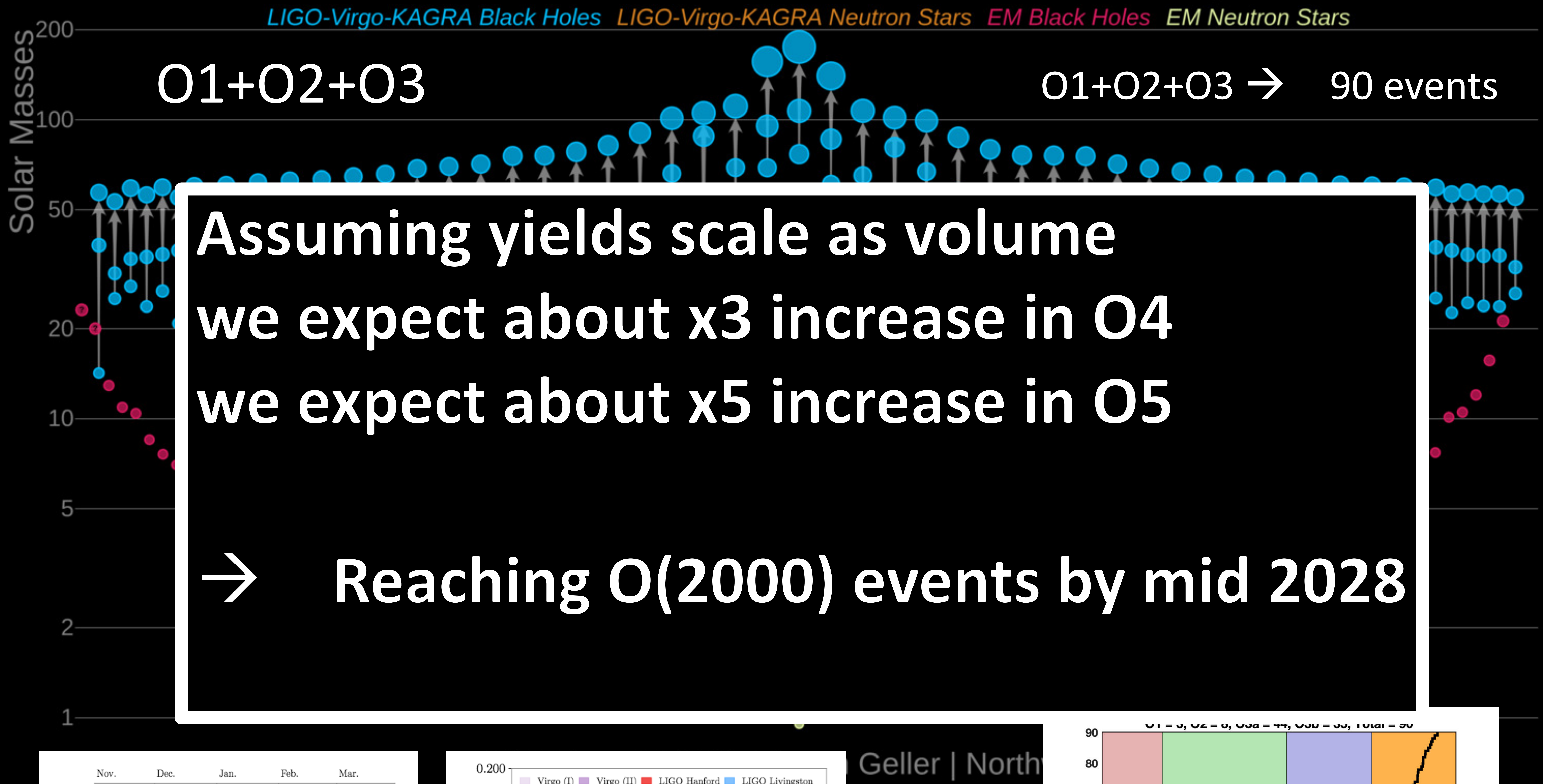






A scan over the whole data in steps of 5s images (overlap of 2.5 s) gives no significant iFAR values beyond expected background fluctuations

Masses in the Stellar Graveyard

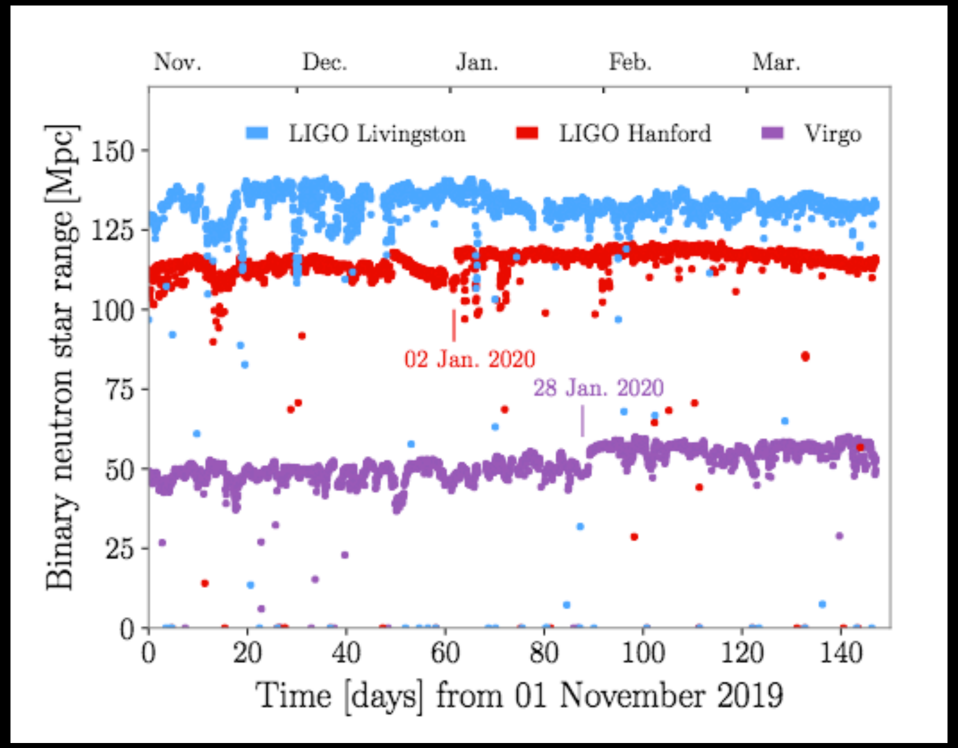


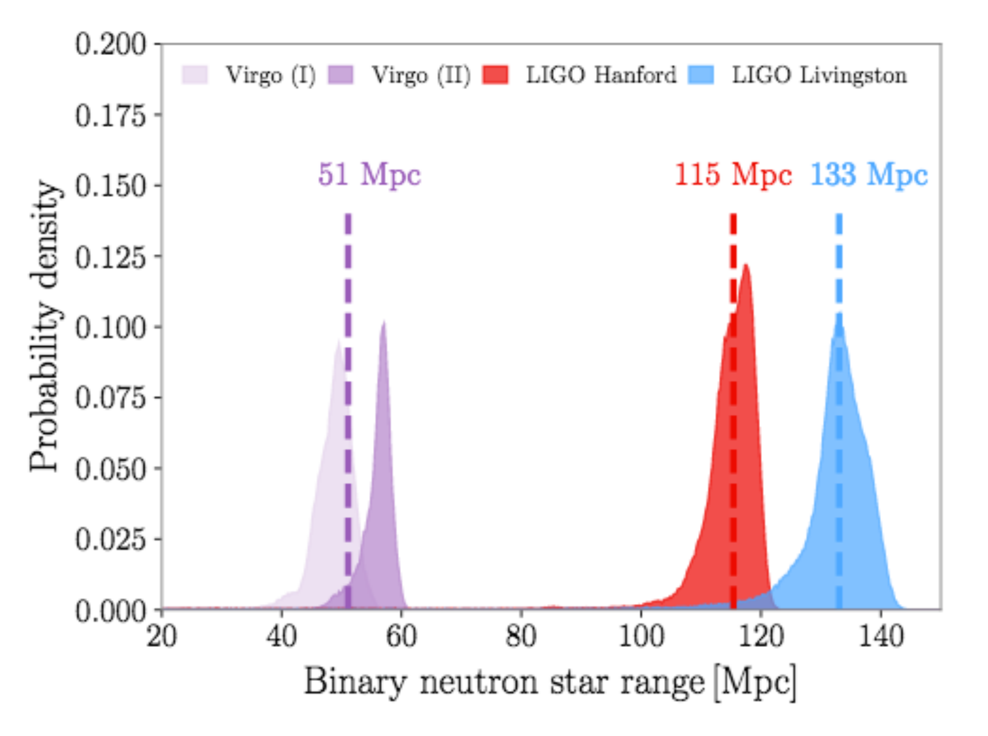
O1+O2+O3

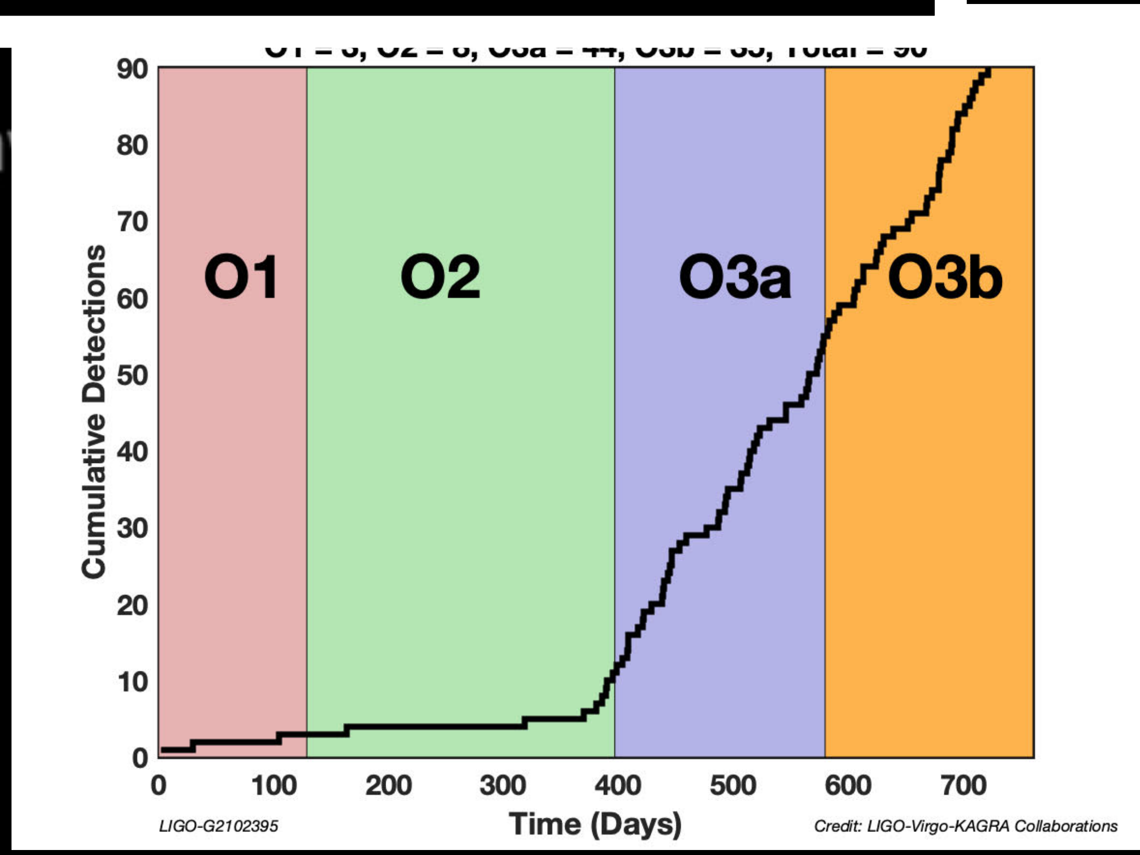
O1+O2+O3 → 90 events

Assuming yields scale as volume
we expect about x3 increase in O4
we expect about x5 increase in O5

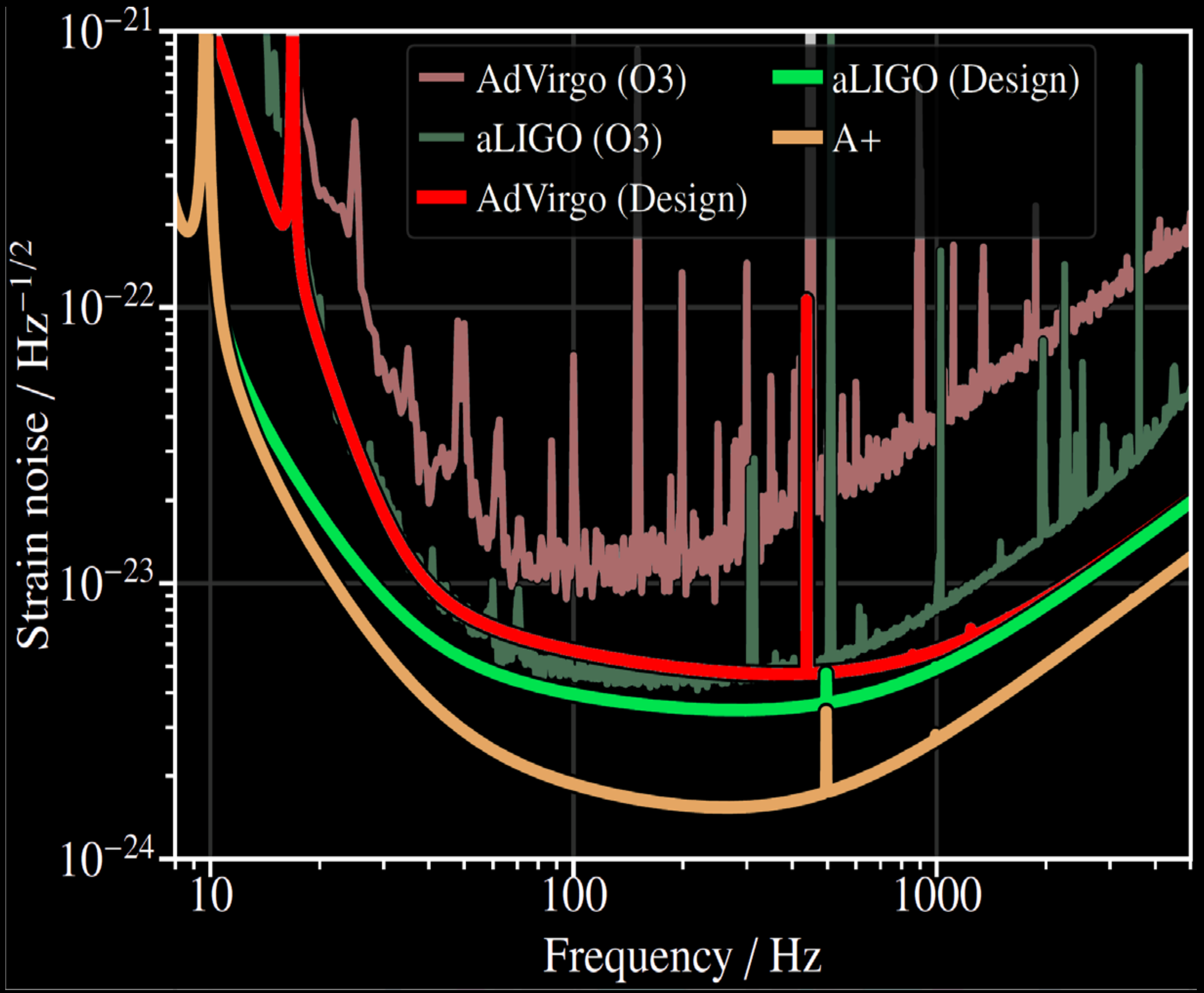
→ Reaching O(2000) events by mid 2028

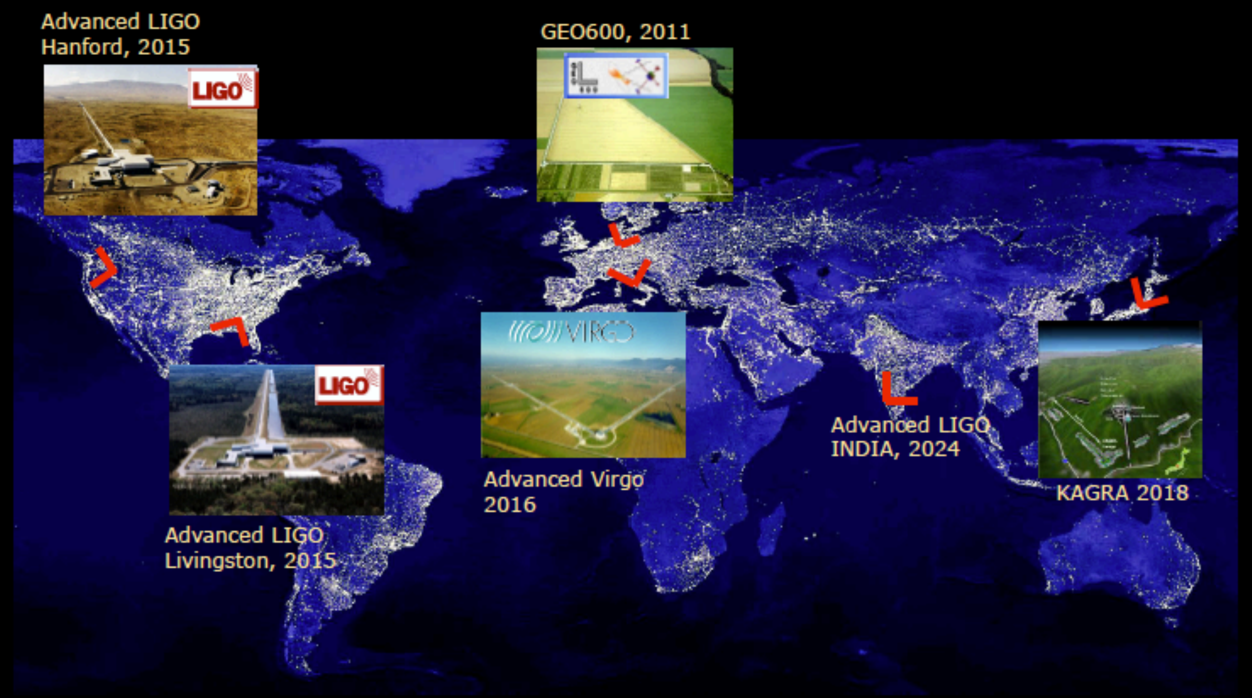






2G sensitivity

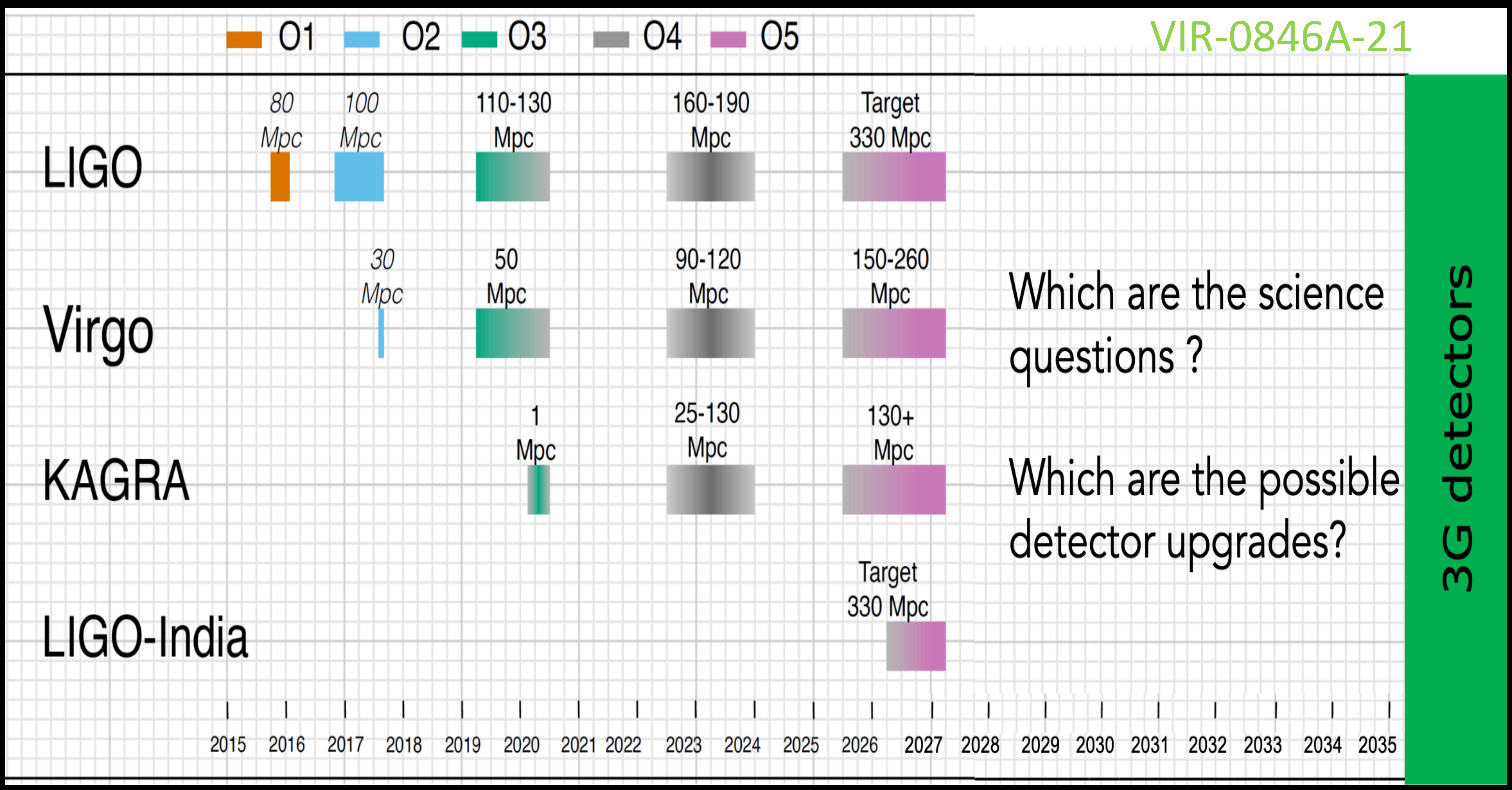




In the next 5 years the 2G Interferometers will reach their design sensitivity…

Ongoing discussion to extend the 2G program towards 2030s

What does the future hold?



**e.g.
ET ESFRI
applications
mentions
operation
period
of 2035-2085**

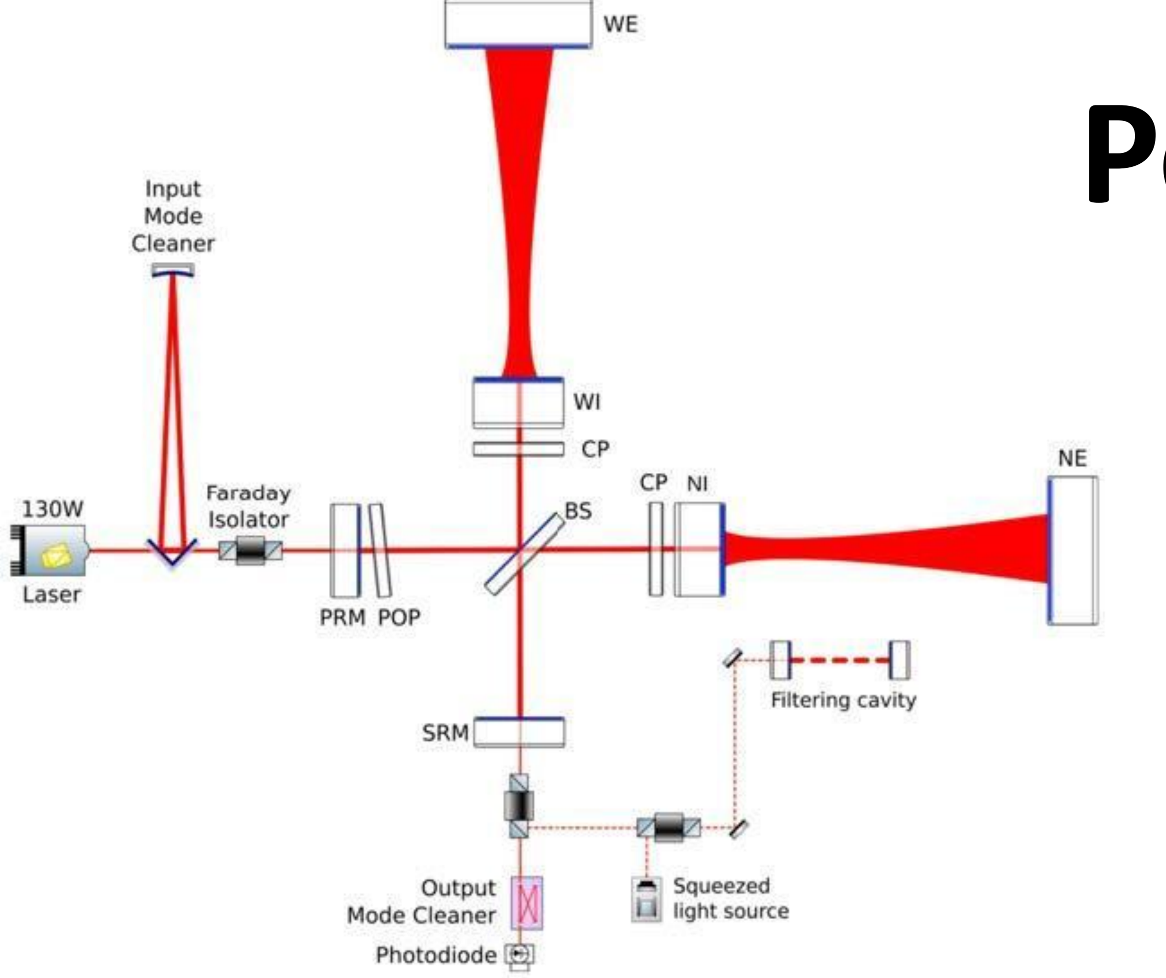
**A+, AdVirgo+, KAGRA, LIGO India
= Well underway**

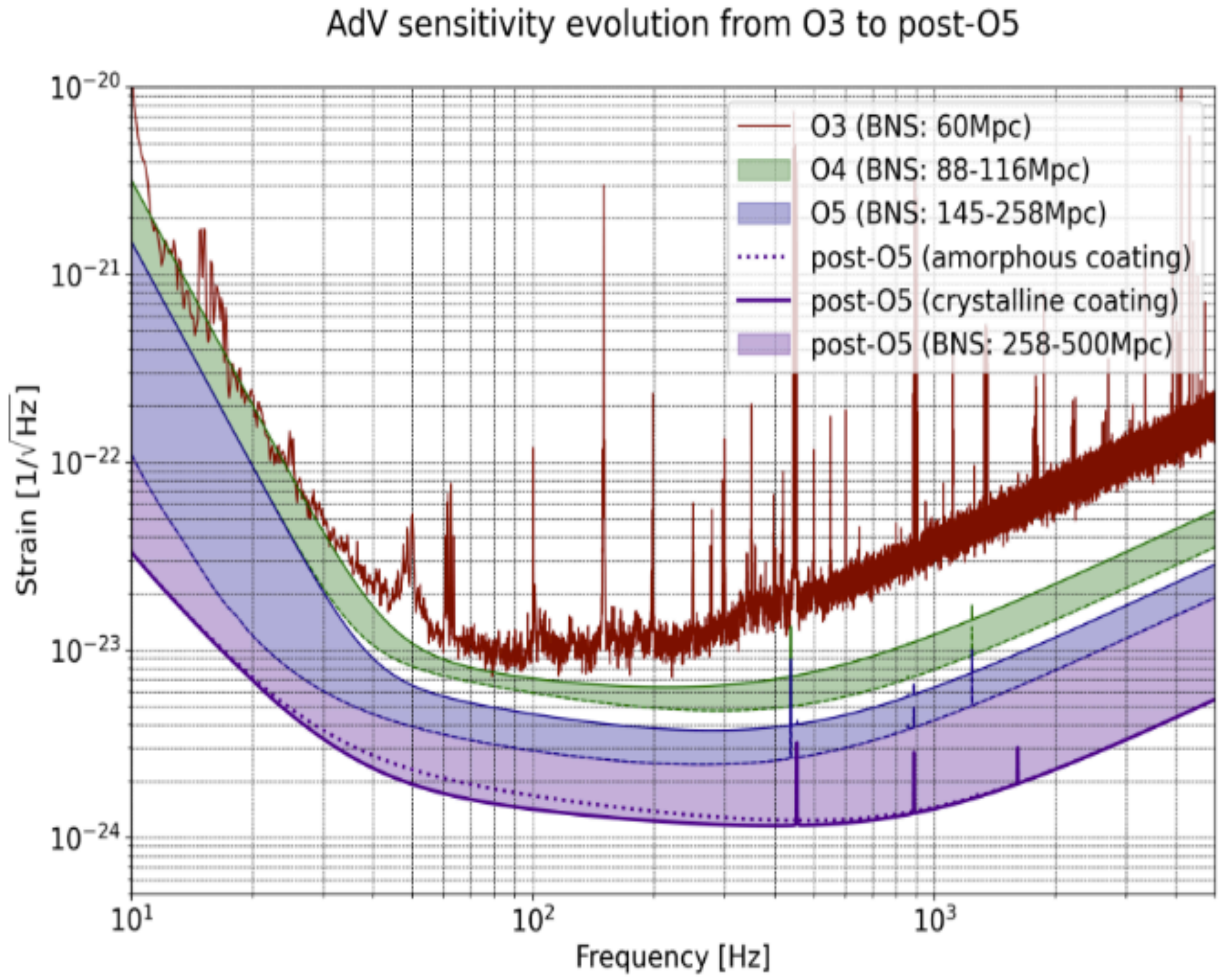
Post O5 (after mid 2028) planning just started

New facilities
**ET, CE, NEMO
…**

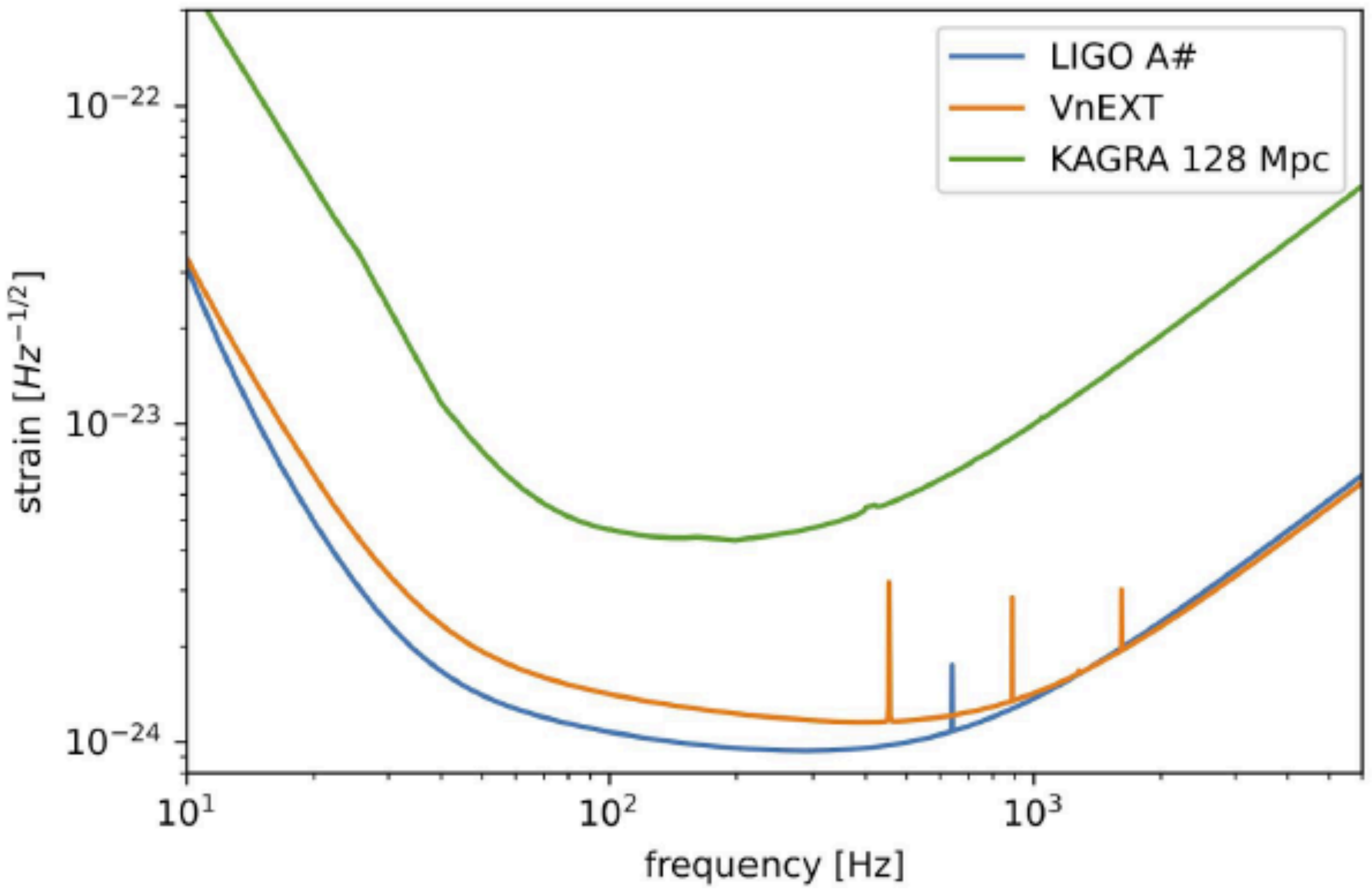
Footnote on O4:
It is not yet possible to give a definitive start date for O4, as there are some continued supply chain delays and the impact of COVID continues. We can say at this time that the O4 observing run will not begin before August 2022. We expect to be able to give a better estimate for the start of O4 by 15 September 2021 and will issue an update then.

Post-O5





This bring you to 2030s entering then into diminishing returns regime for 2G experiments



Higher laser power → 1.5 MW

Heavier test masses → 100 Kg

Improved coatings

Refine quantum squeezing

Improve suspensions

Improve seismic isolation

→ Fact 2 improvement on sensitivity

→ Factor 10 improvement in rates

→ O (3k€) events in one year

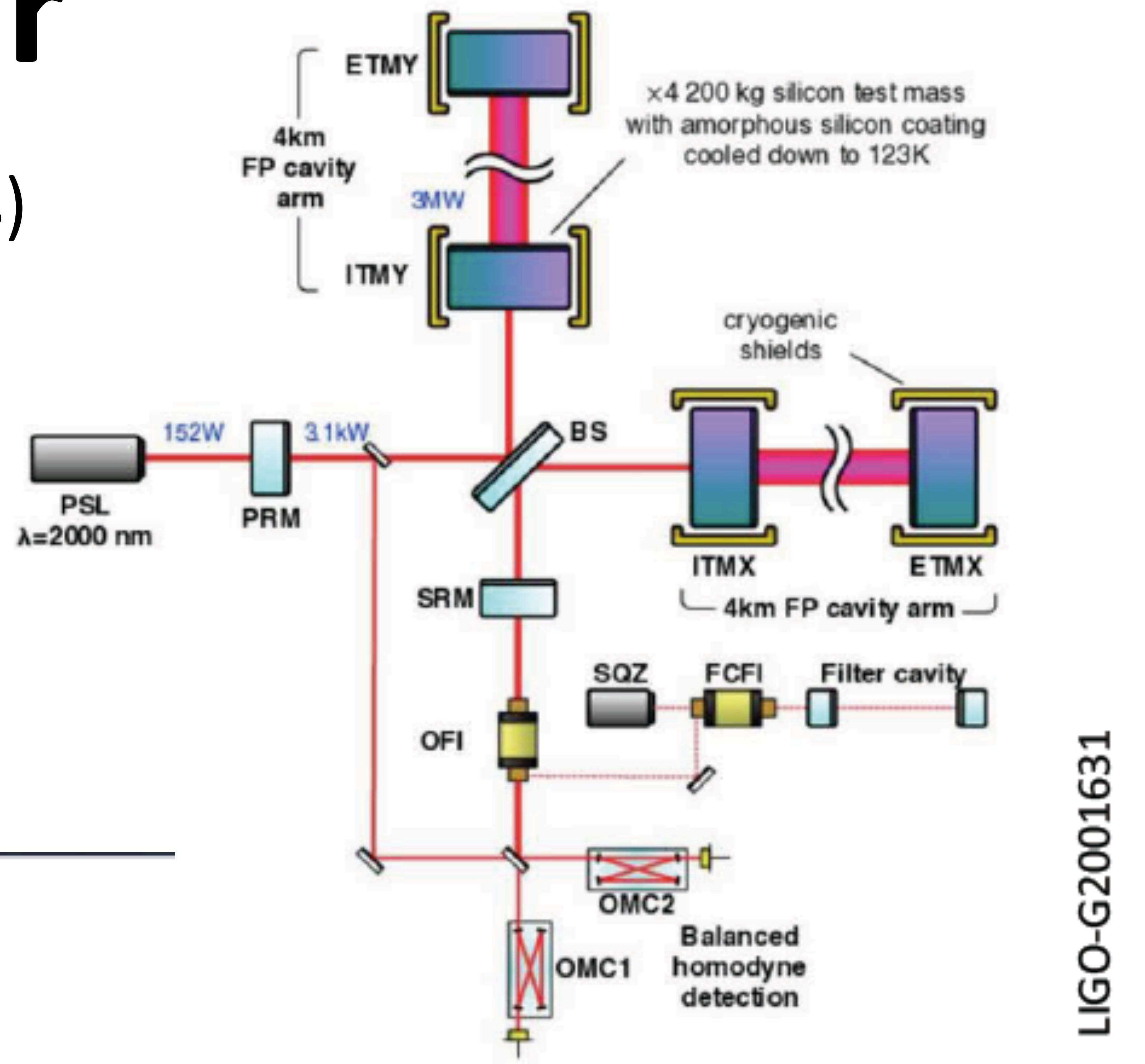
→ Reaching BNS up to 500 – 600 Mpcs

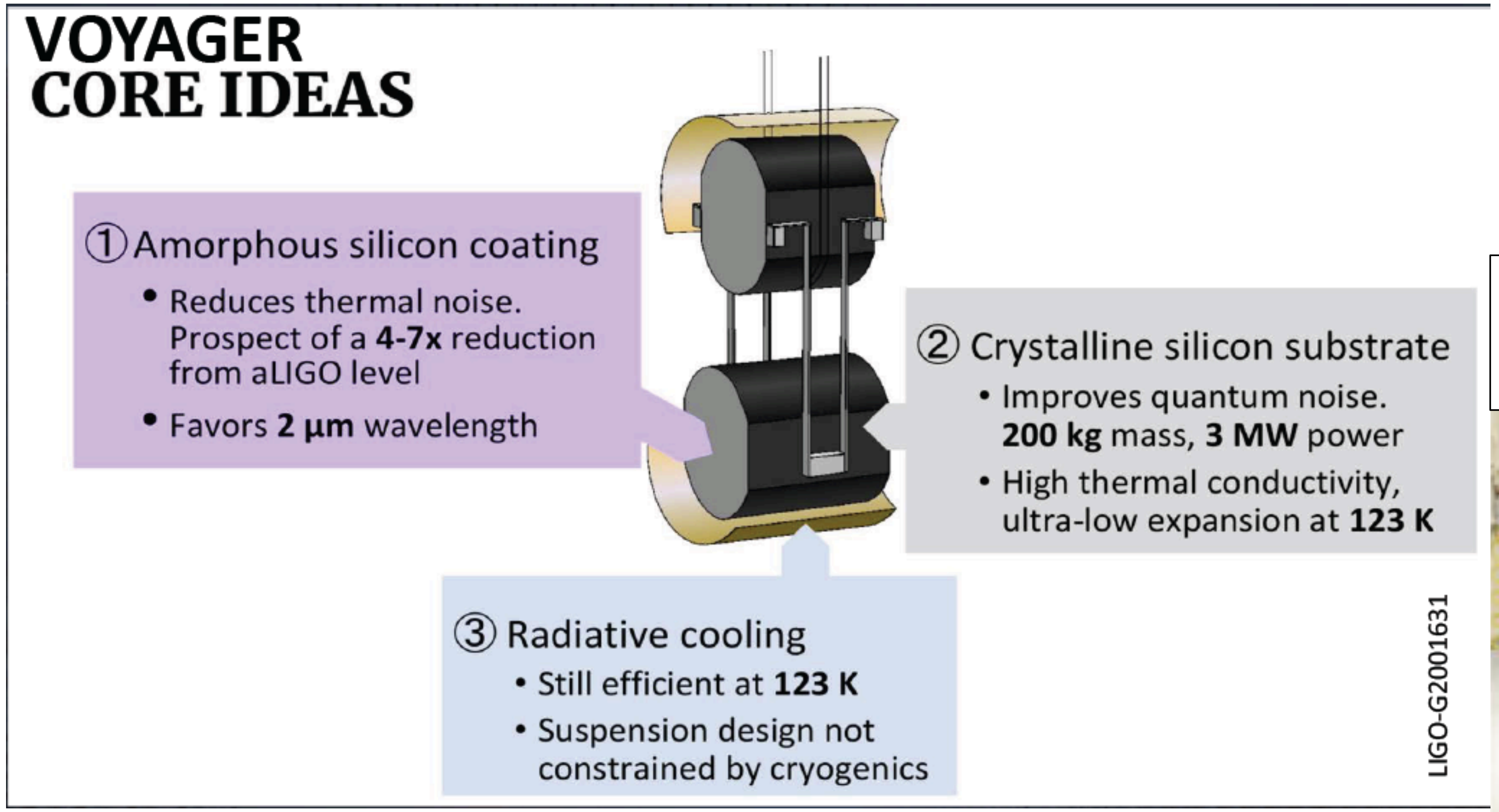
Voyager

Further upgrade of LIGO
Factor x3 improved in reach for BNS (1100 Mpcs)

Going cryogenic temperatures (123K)
Larger masses with new substrate material
Different wavelength (2000 nm)

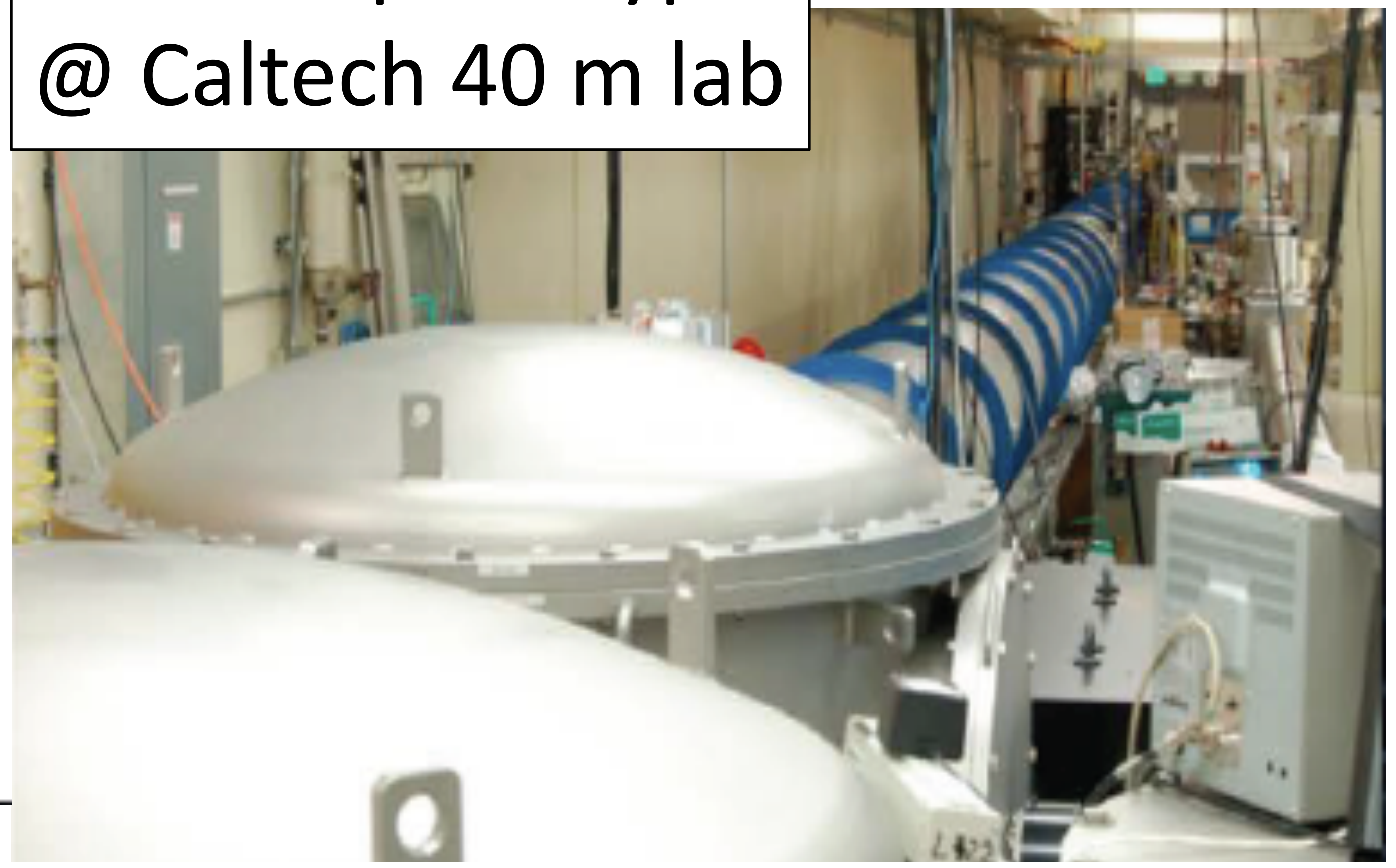
Planned for the next decade (2025 --)



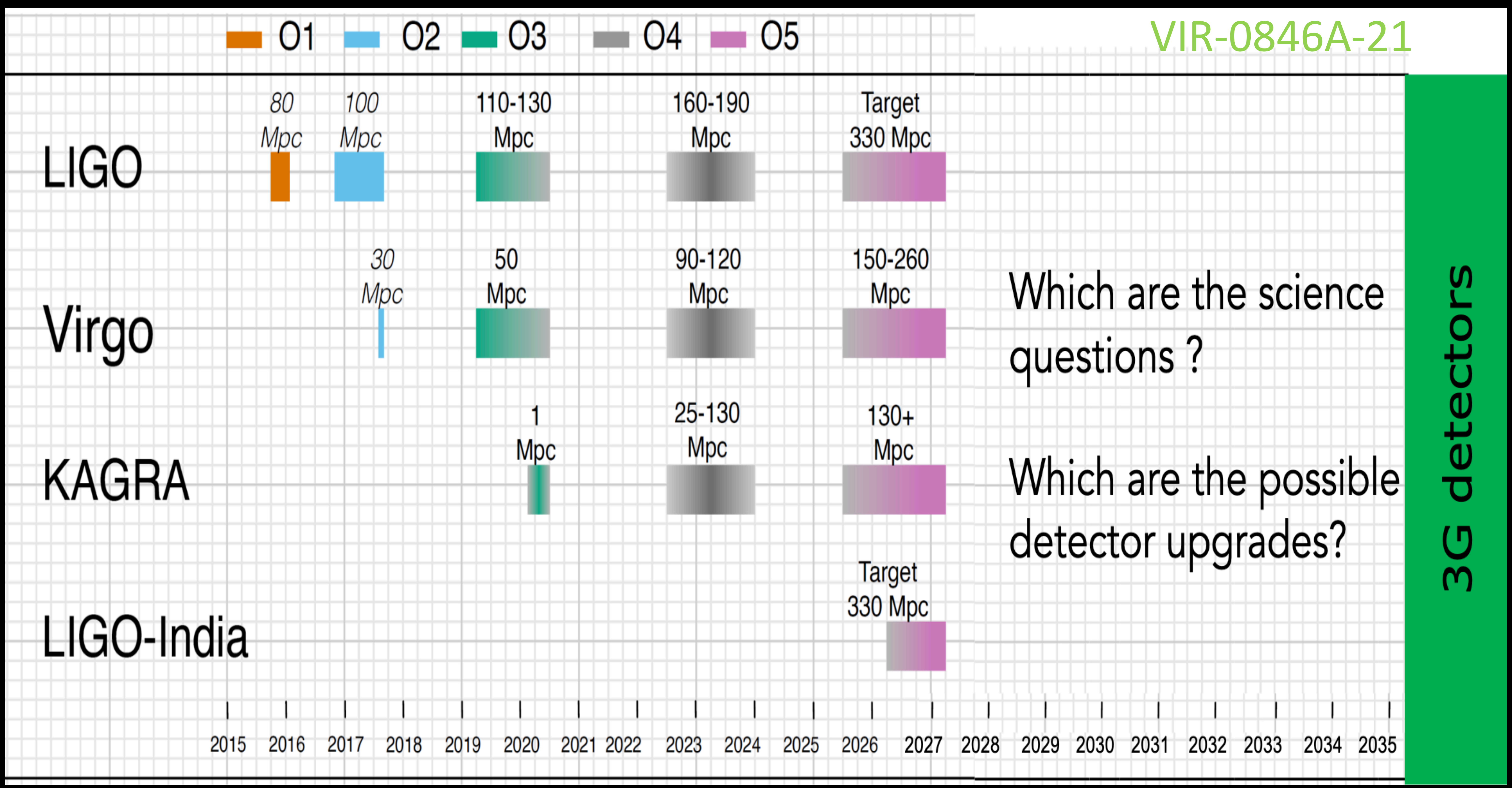


https://dcc.ligo.org/public/0142/T1700231

Mariner prototype
@ Caltech 40 m lab



What does the future hold?



e.g.
ET ESFRI applications mentions operation period of 2035-2085

Footnote on O4:
It is not yet possible to give a definitive start date for O4, as there are some continued supply chain delays and the impact of COVID continues. We can say at this time that the O4 observing run will not begin before August 2022. We expect to be able to give a better estimate for the start of O4 by 15 September 2021 and will issue an update then.

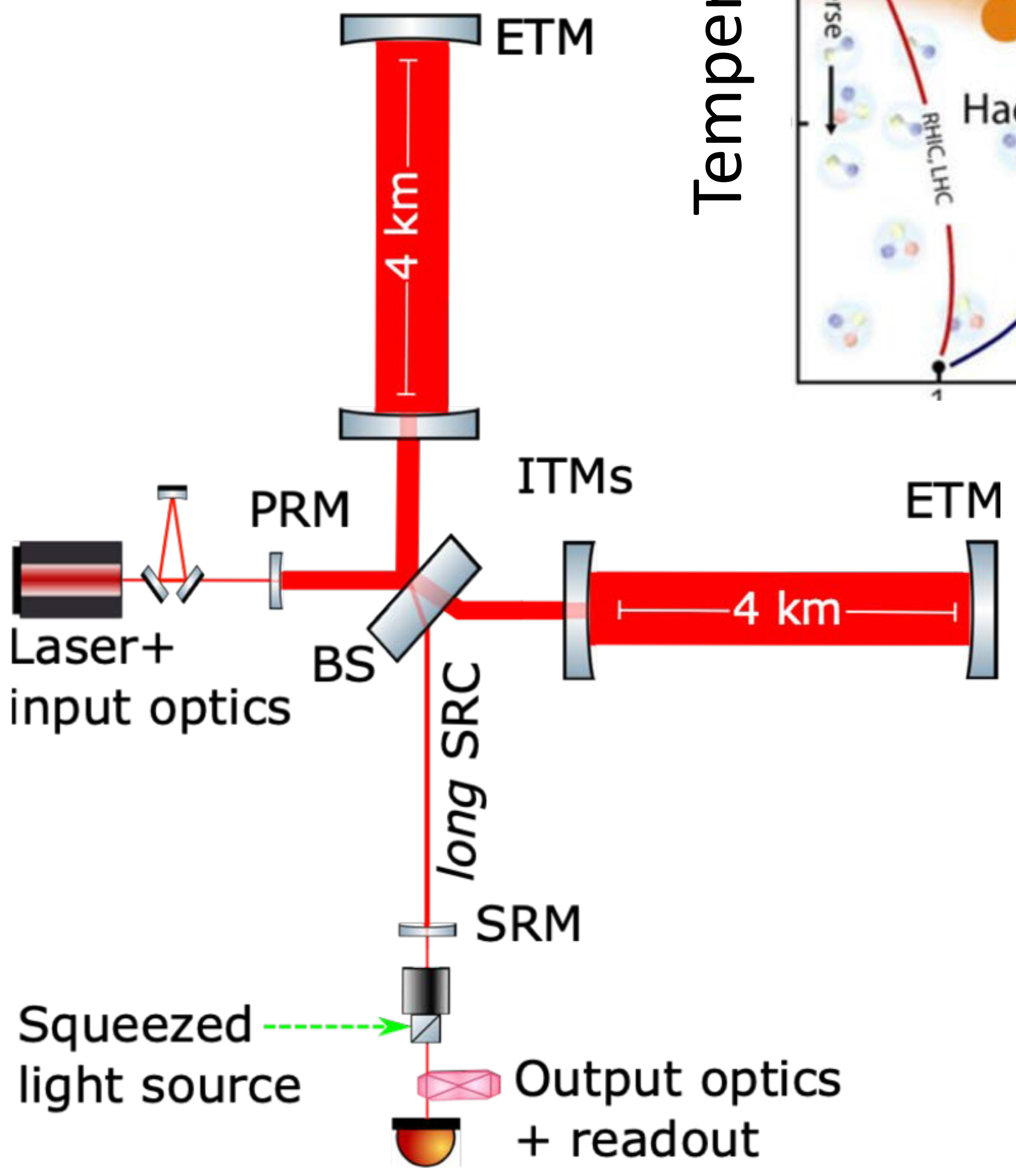
A+, AdVirgo+, KAGRA, LIGO India = Well underway

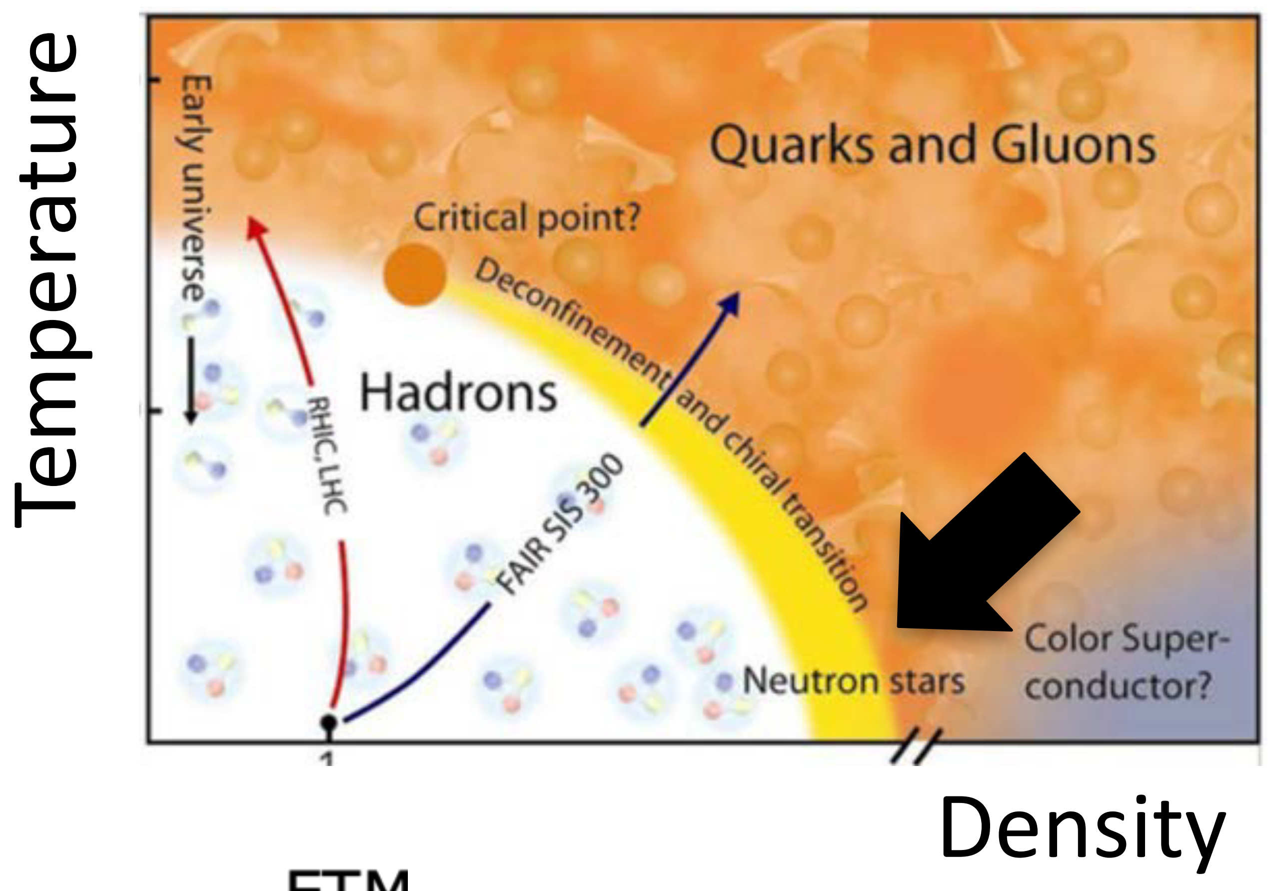
Post O5 (after mid 2028) planning just started

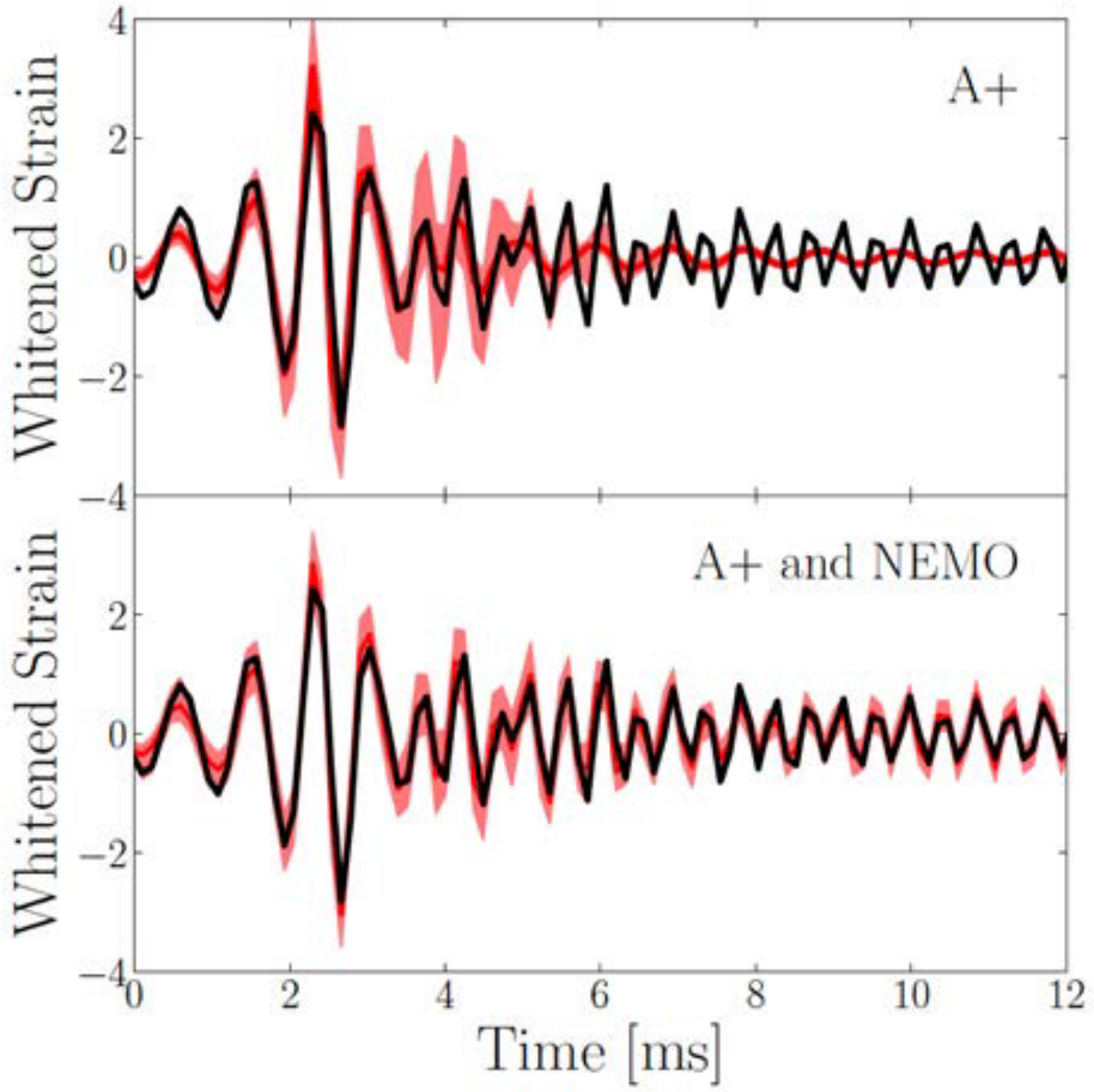
New facilities
ET, CE, NEMO
…

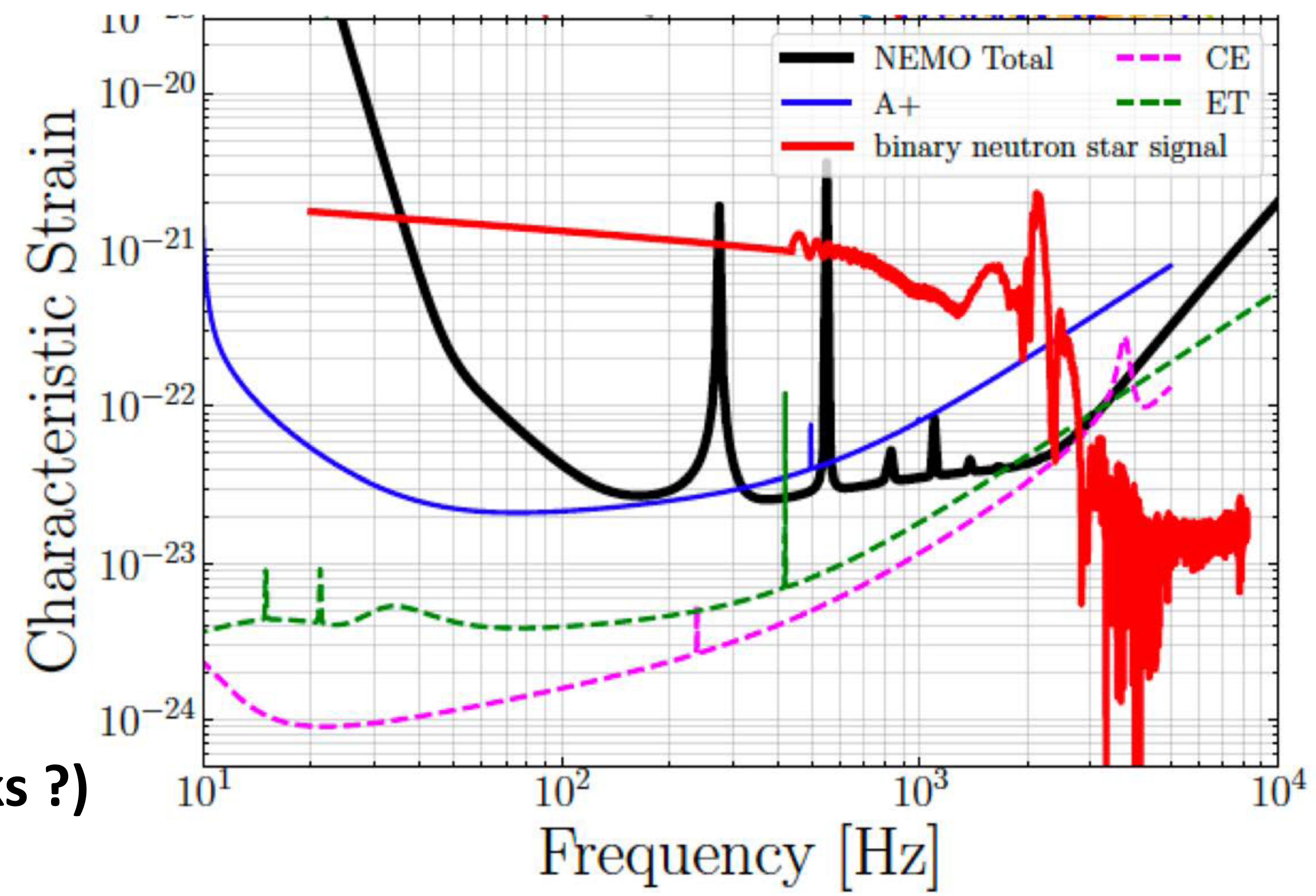
NEMO

NEMO paper : doi:10.1017/pasa.2020.39







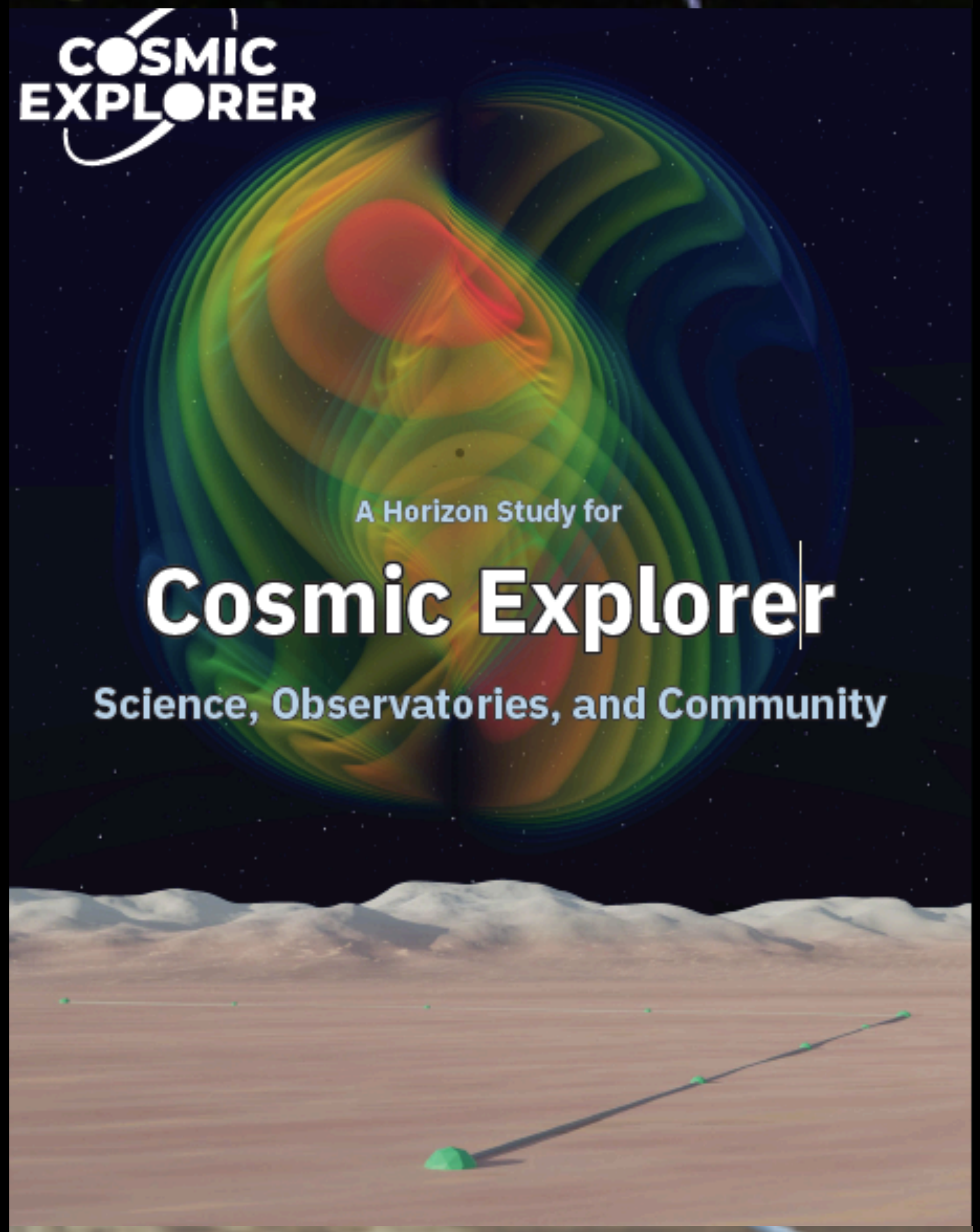


Focused on very high (kHz) frequency and post-merger BNS phenomena

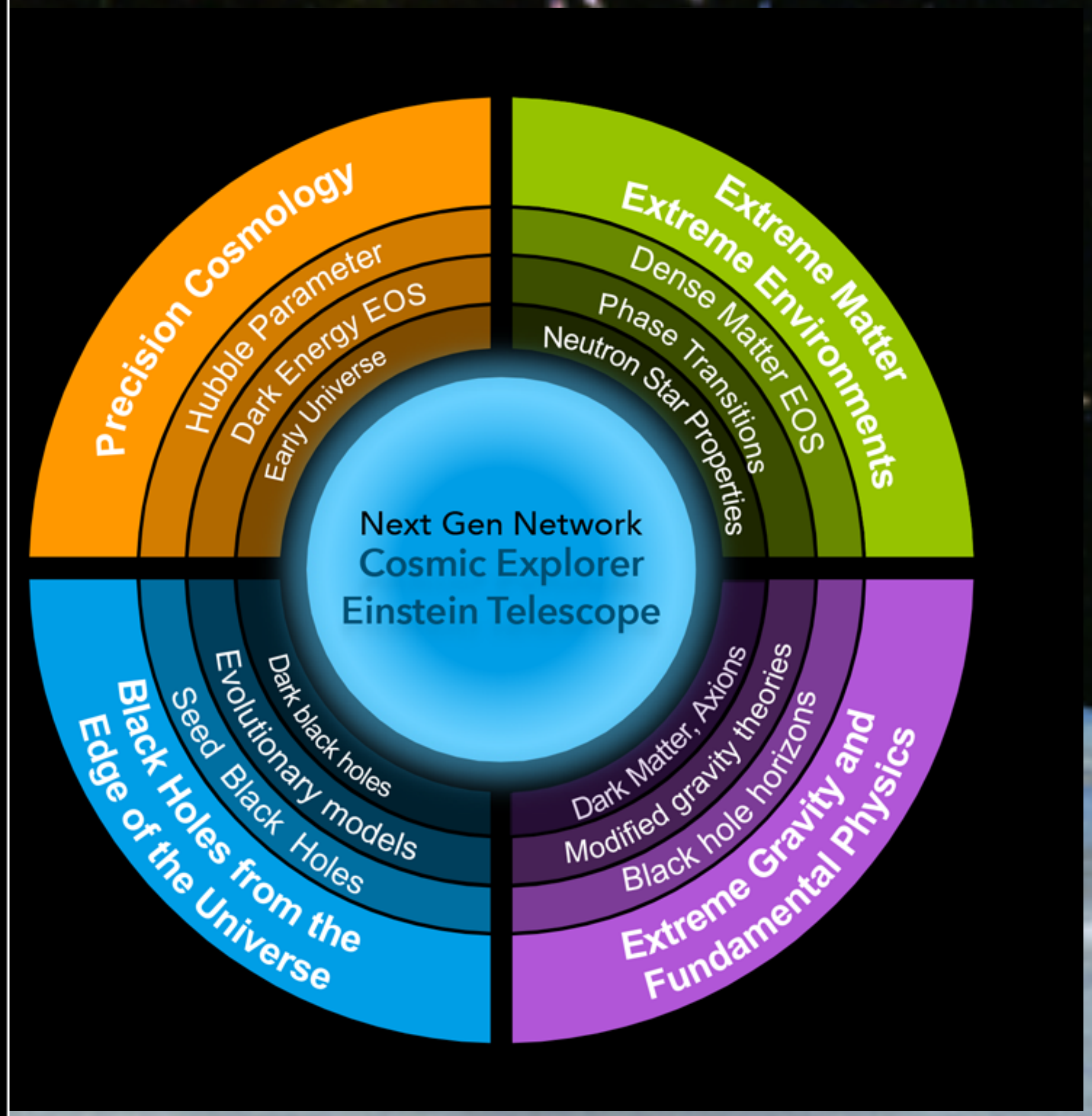
→ QCD in very dense systems

→ Phase transitions (Deconfined quarks ?)

Cosmic Explorer (USA)



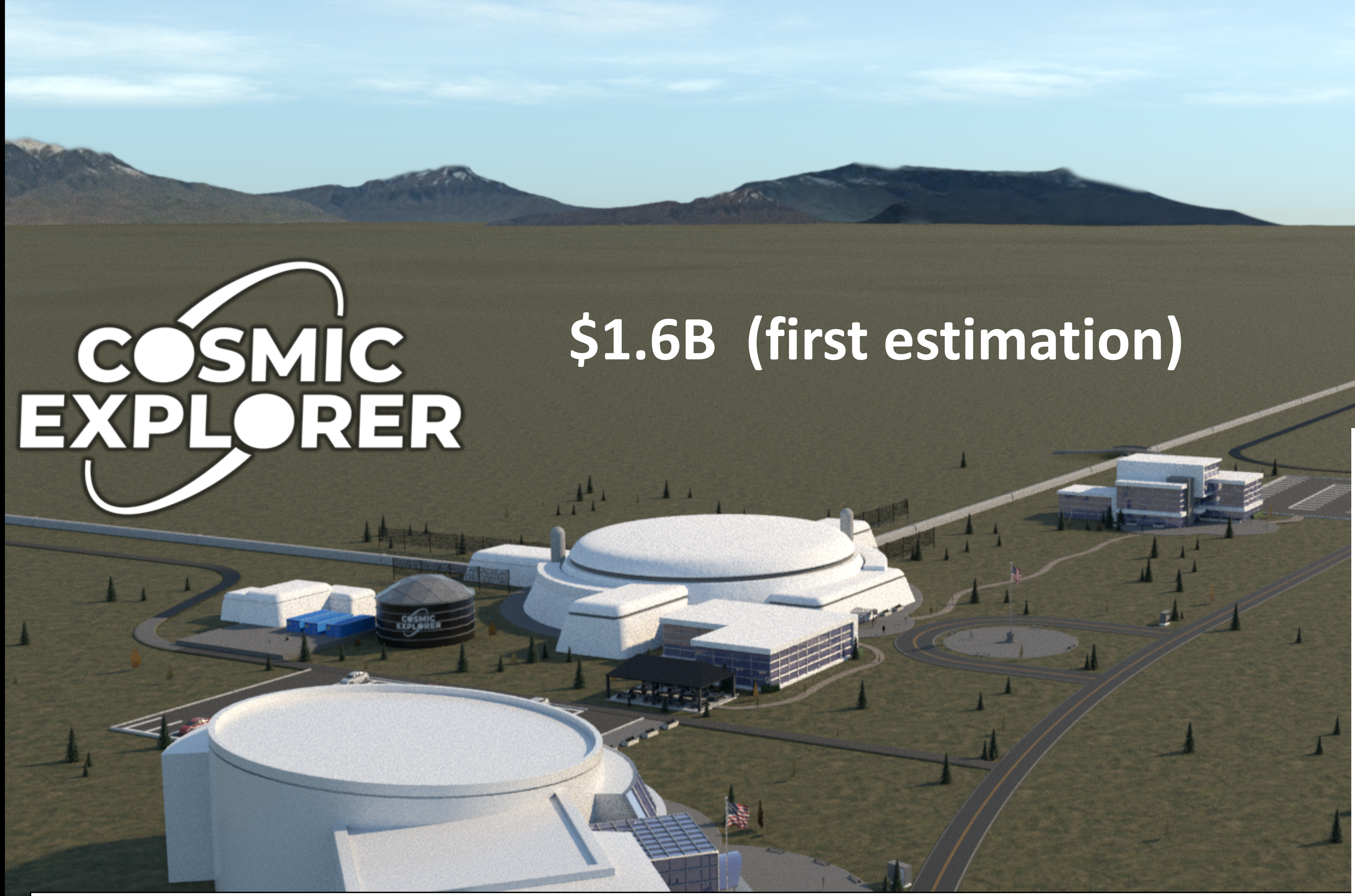
tps://cosmicexplorer.org/

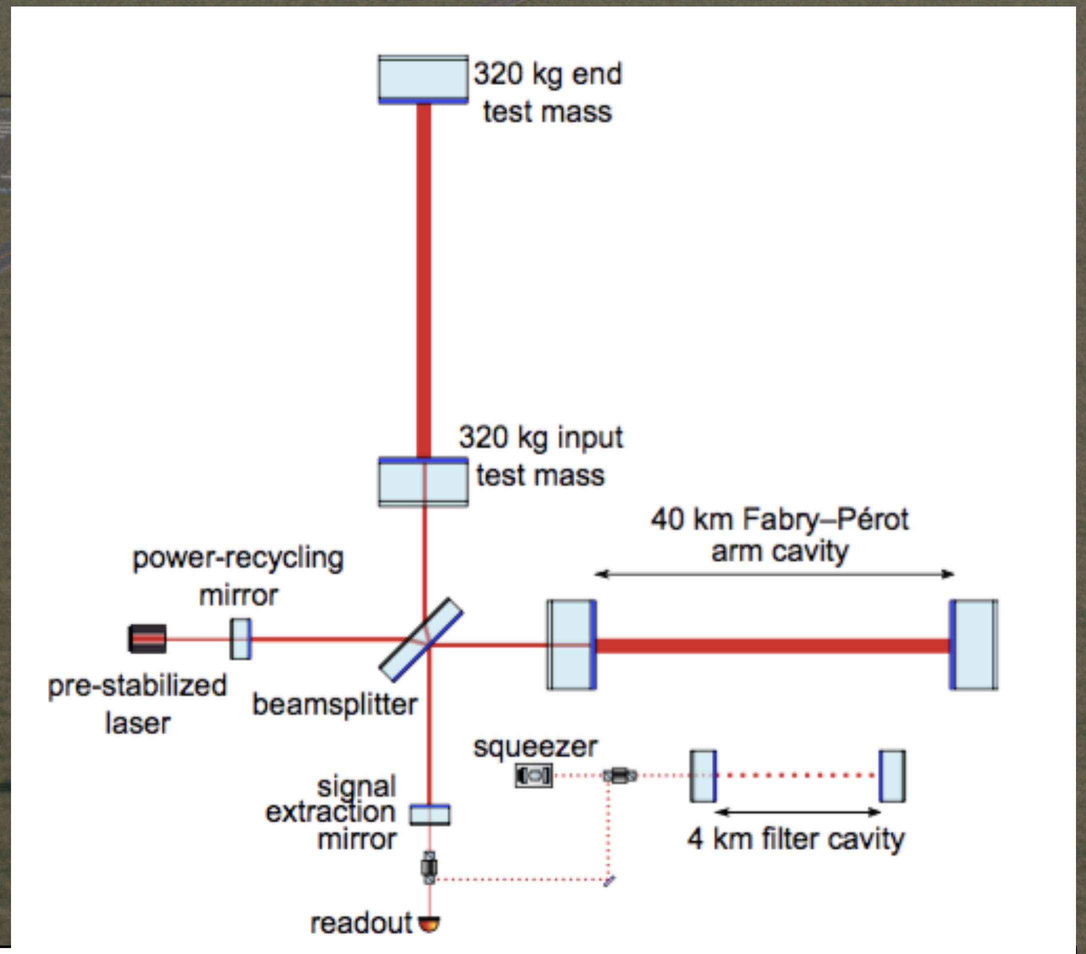


http://dcc.cosmicexplorer.org/CE-P2100003/public

COSMIC EXPLORER

$1.6B (first estimation)





Two widely separated, L-shaped surface facilities in the US:

- A 40 km detector optimized for deep, broadband sensitivity
- A 20 km detector tuned to neutron-star post-merger signals

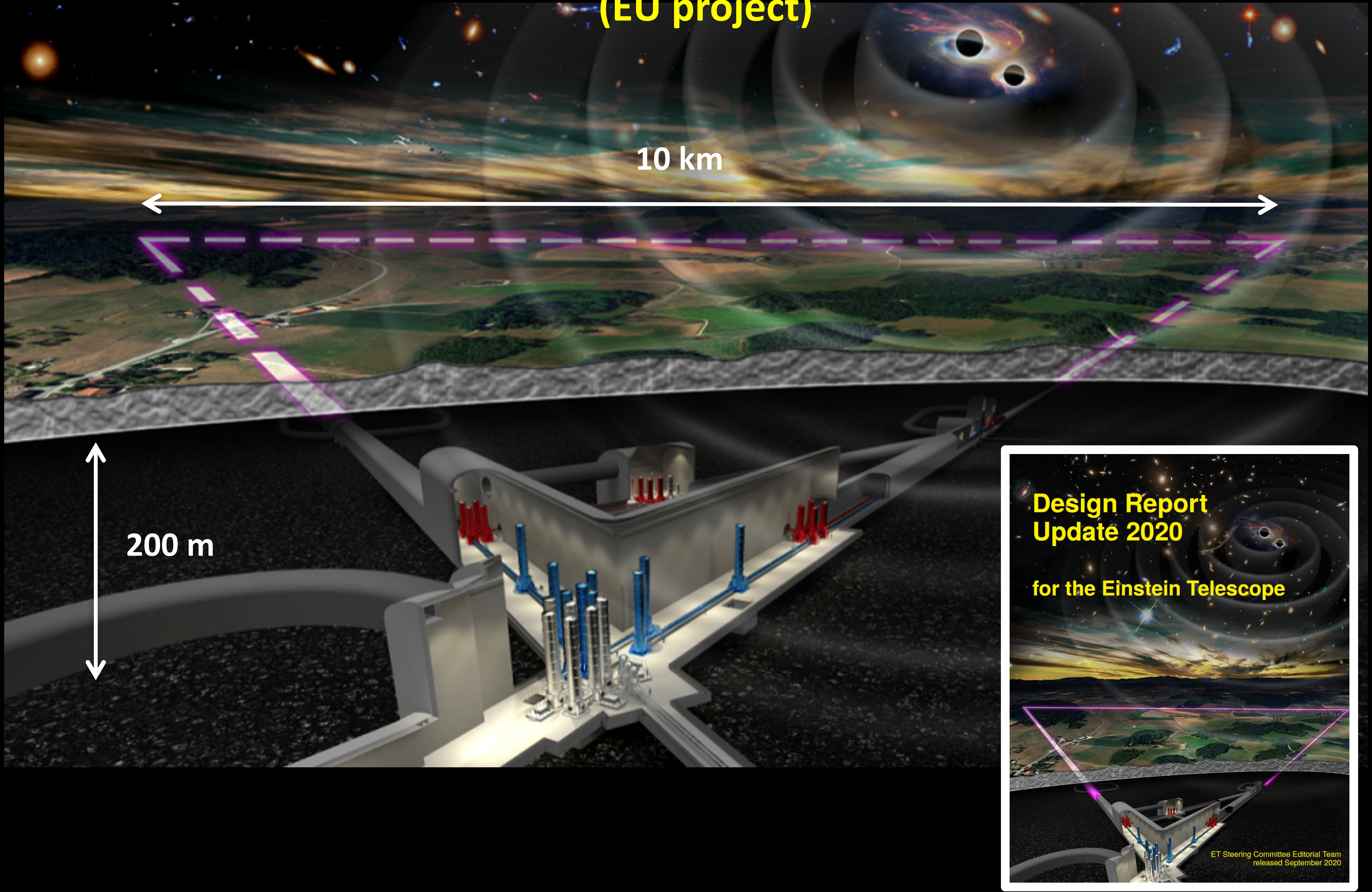
Two facilities improve localization and polarization information

Cosmic Explorer will extend LIGO A+ technology **(room-temp silica, 1 μm laser)**, with Voyager technology **(123 K silicon, 2 μm laser)** as a secondary option

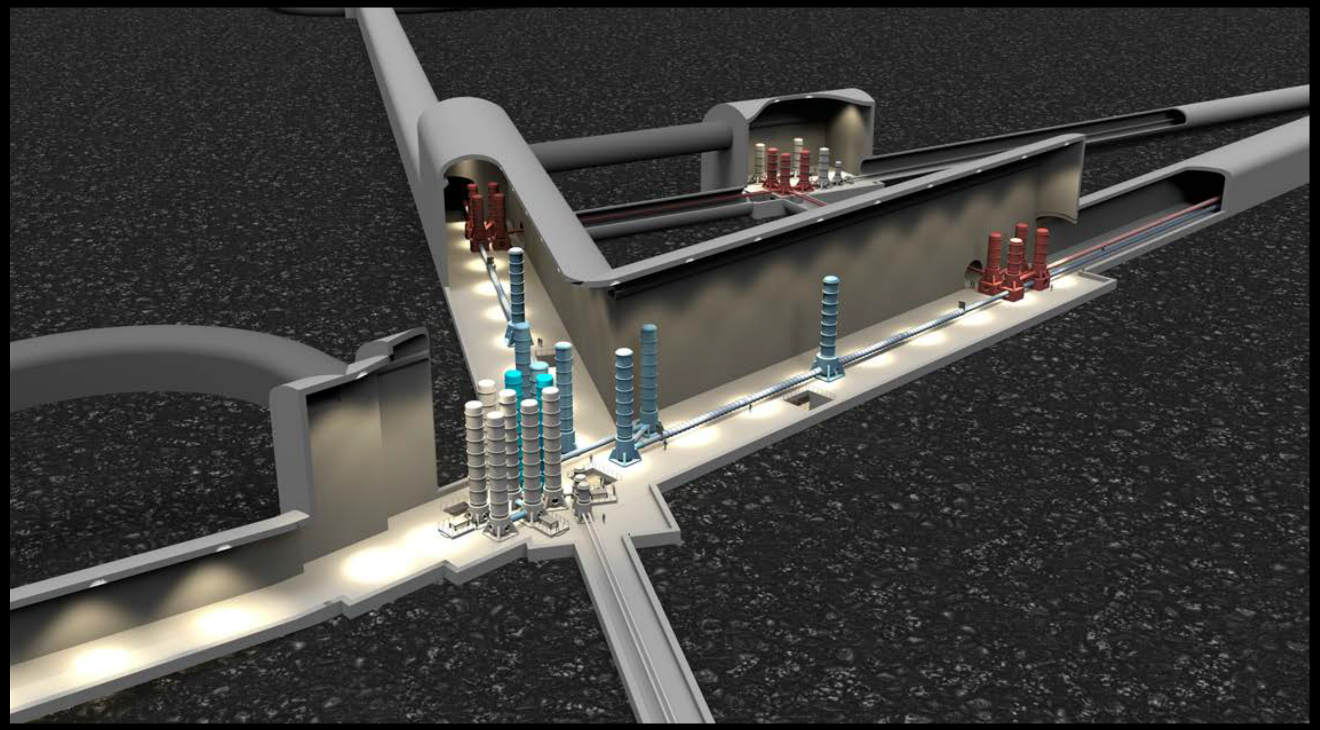
The Einstein Telescope

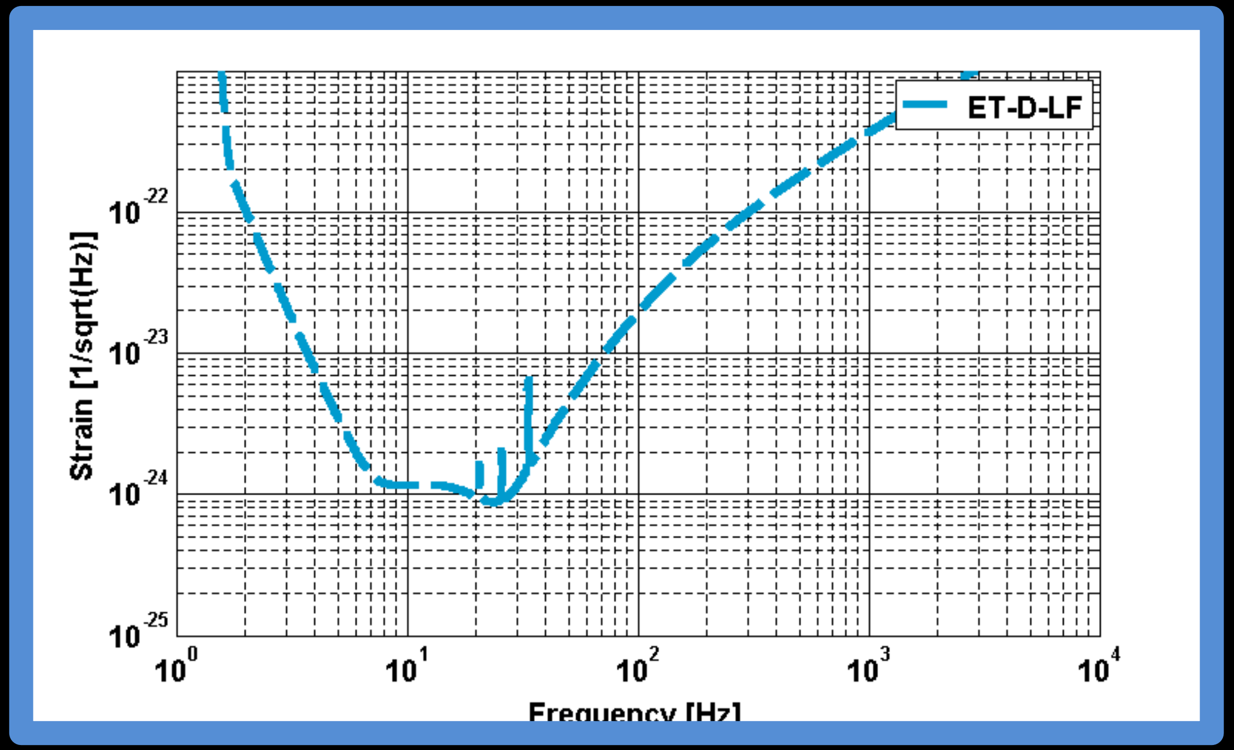
http://www.et-gw.eu/

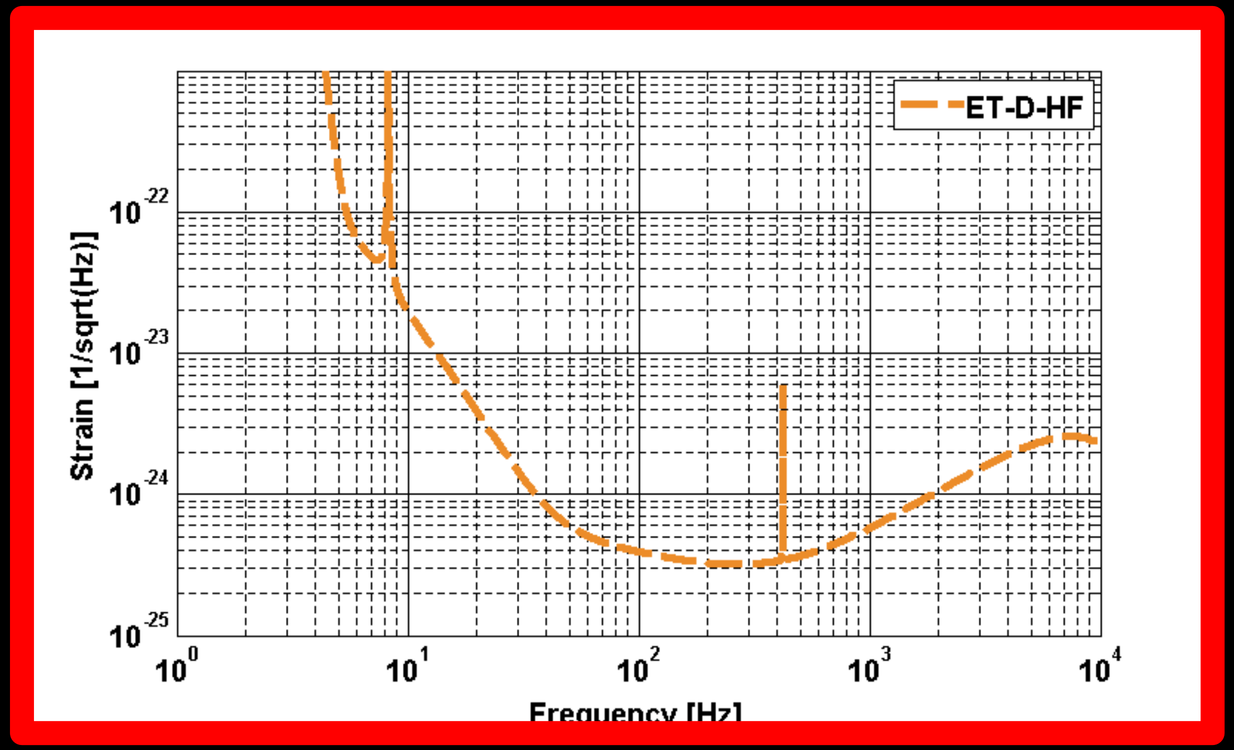
(EU project)

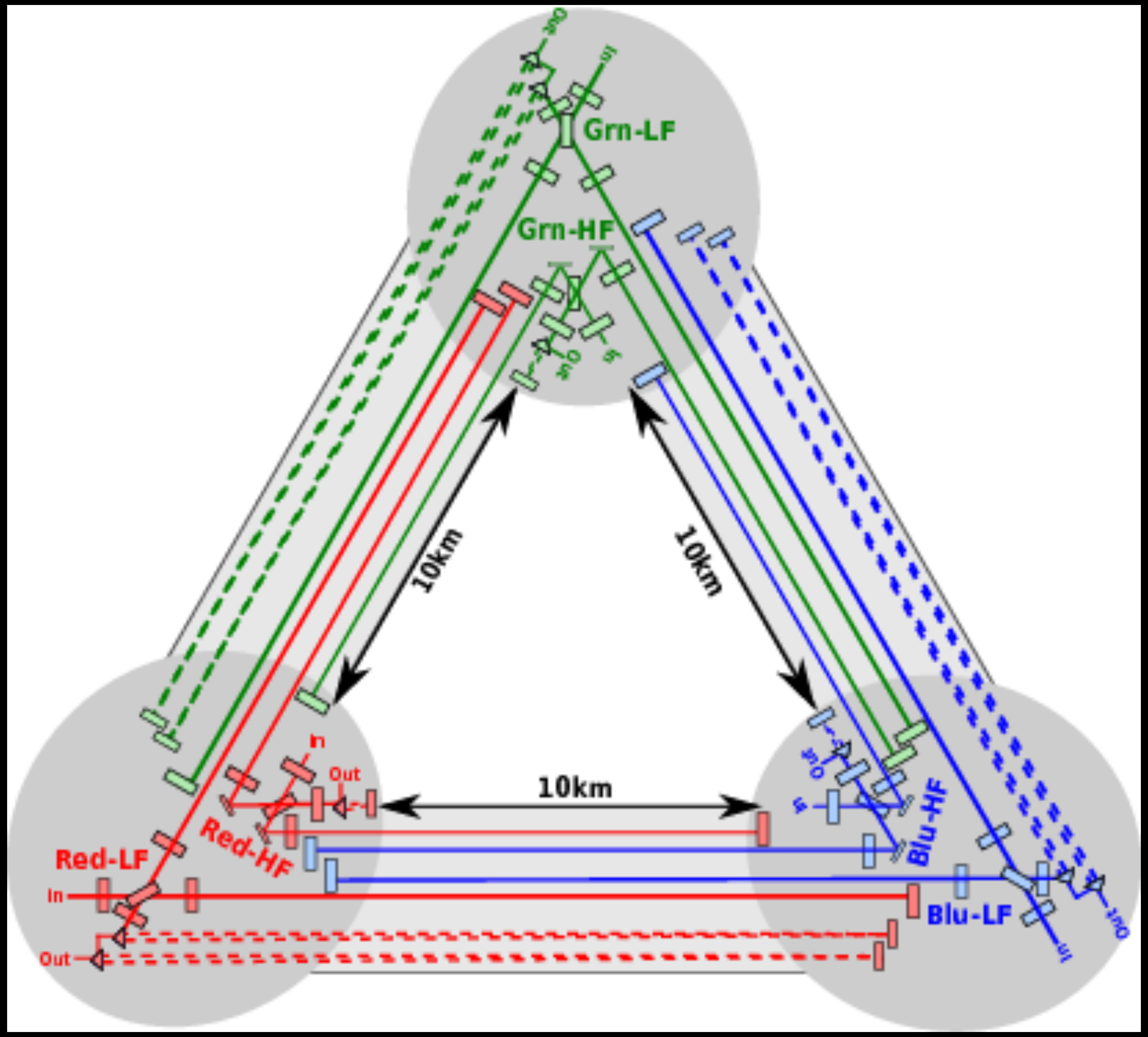


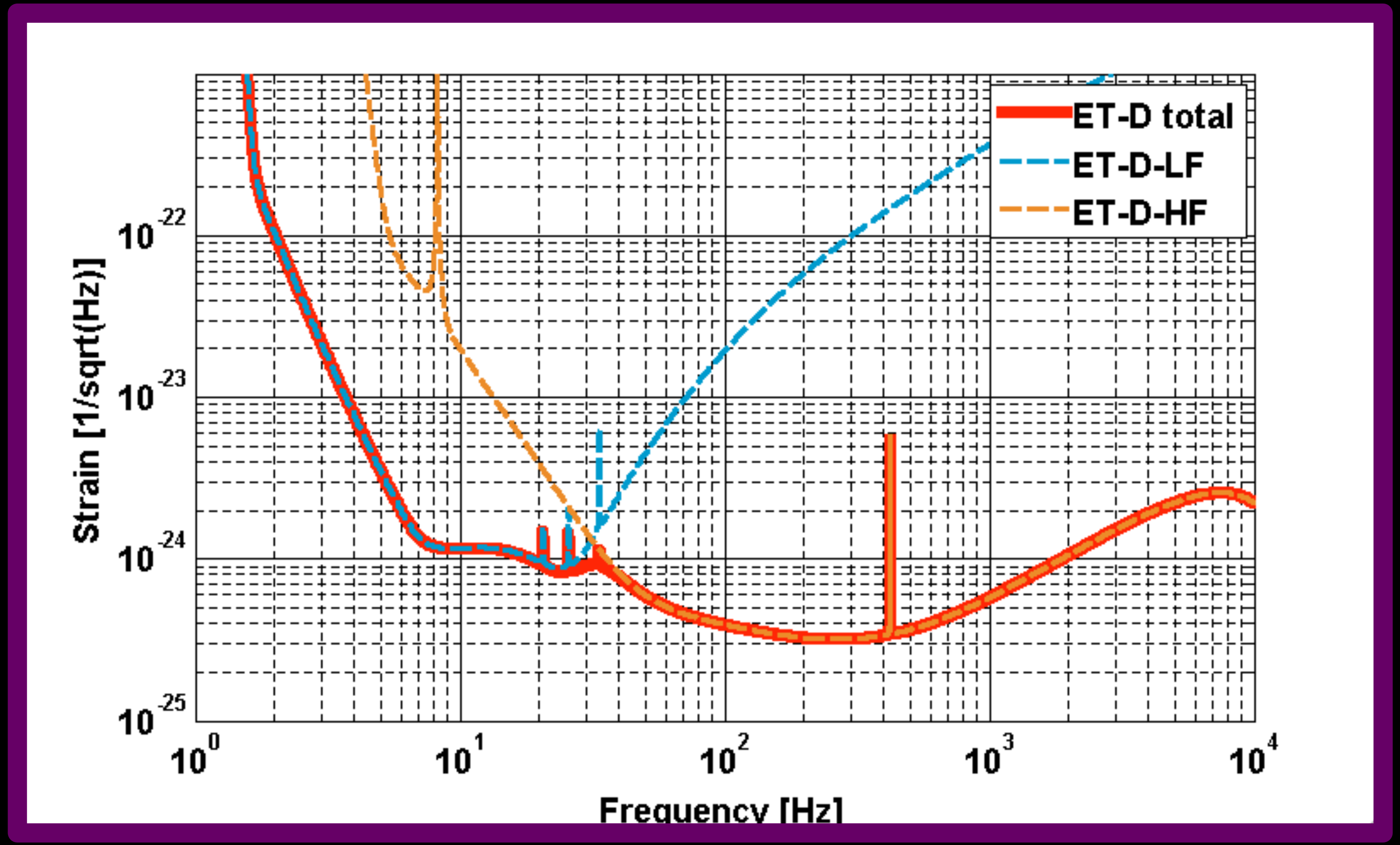
Einstein Telescope (6 in 1) Xylophone





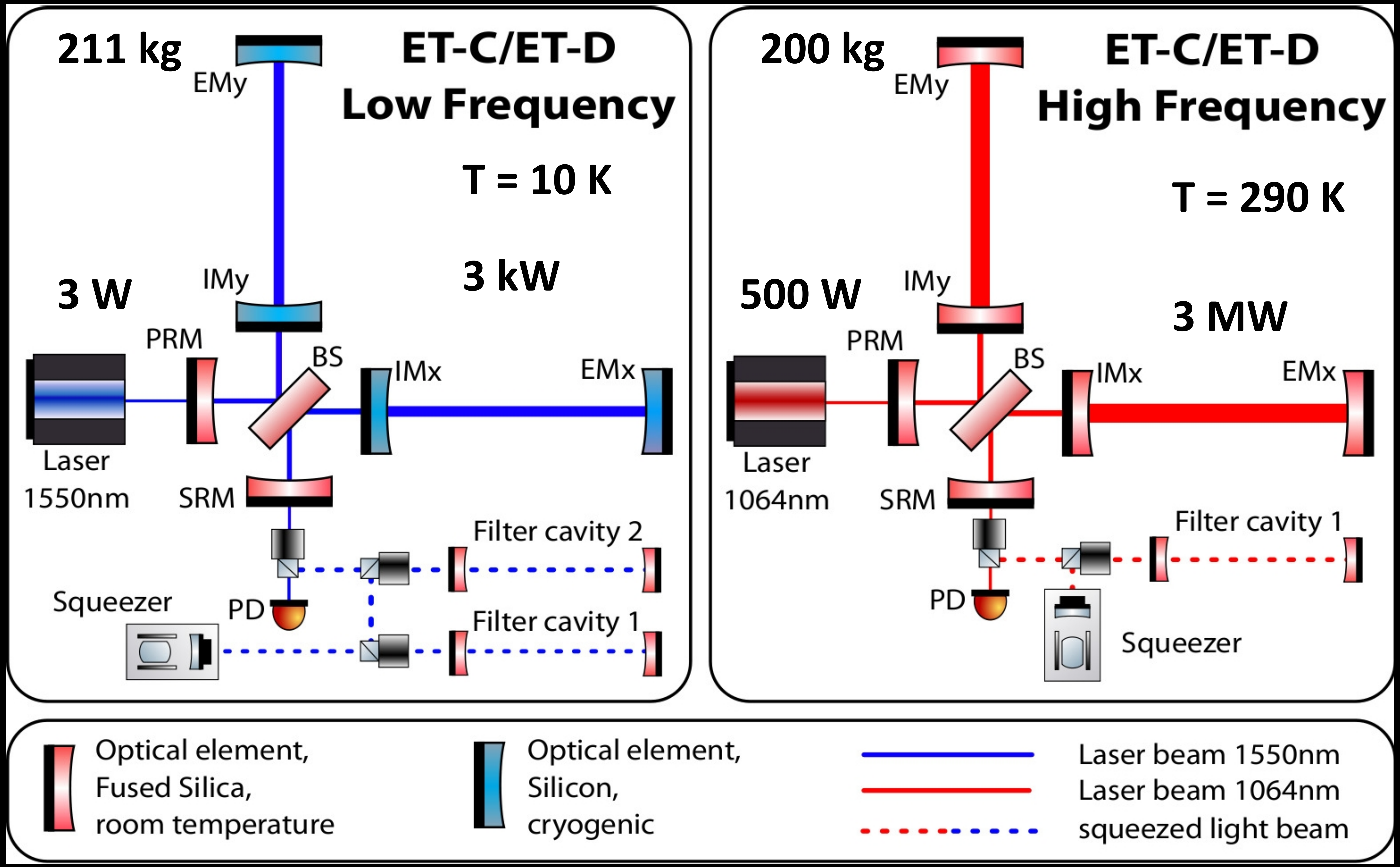






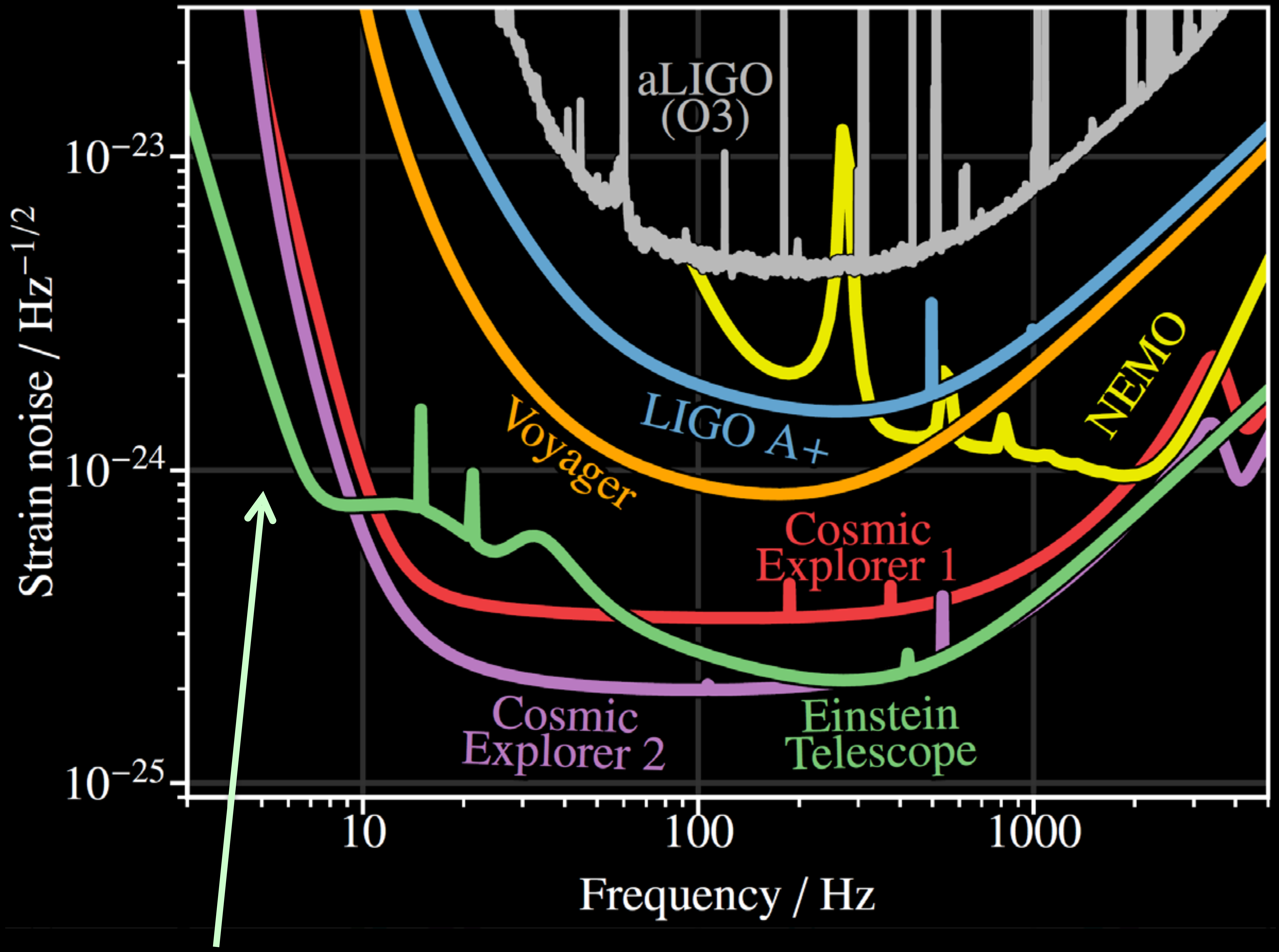
Each interferometer decoupled into 2 devices independent for the best sensitivity to low and high frequency

2G → ET

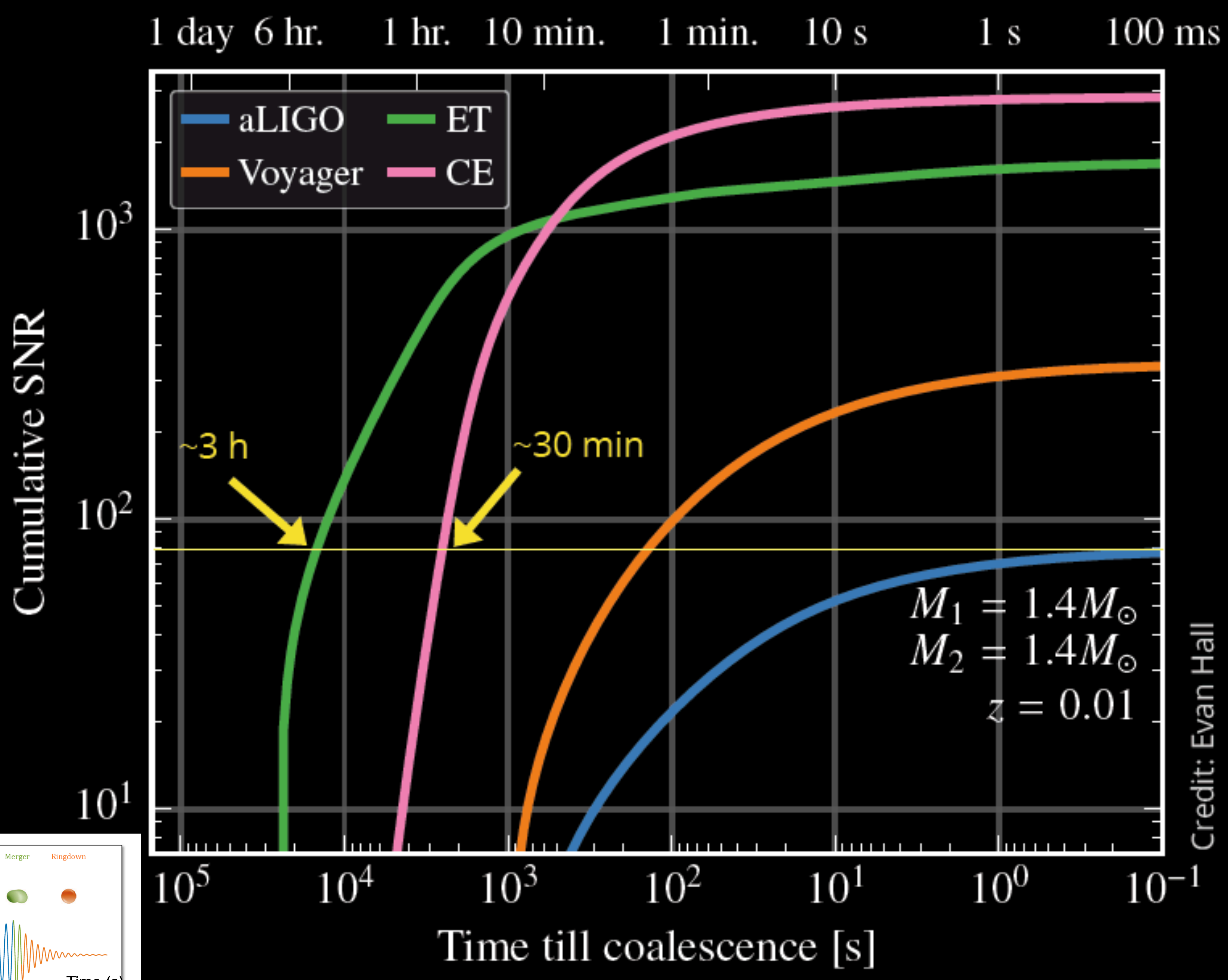


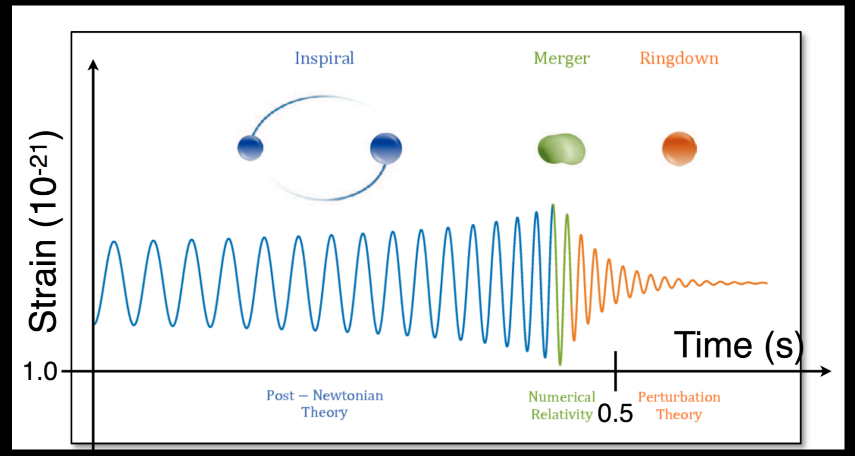
Underground
Cryogenic
Silicon mirrors
1550 nm (Si transparent)
New optical coatings
New suspensions / seismic controls

More powerful lasers
Larger fused silica mirrors
1064 nm (silica transparent)
New optical coatings
New thermal compensation systems



About one order of magnitude improvement w.r.t 2G detectors and an extended sensitivity to low frequencies

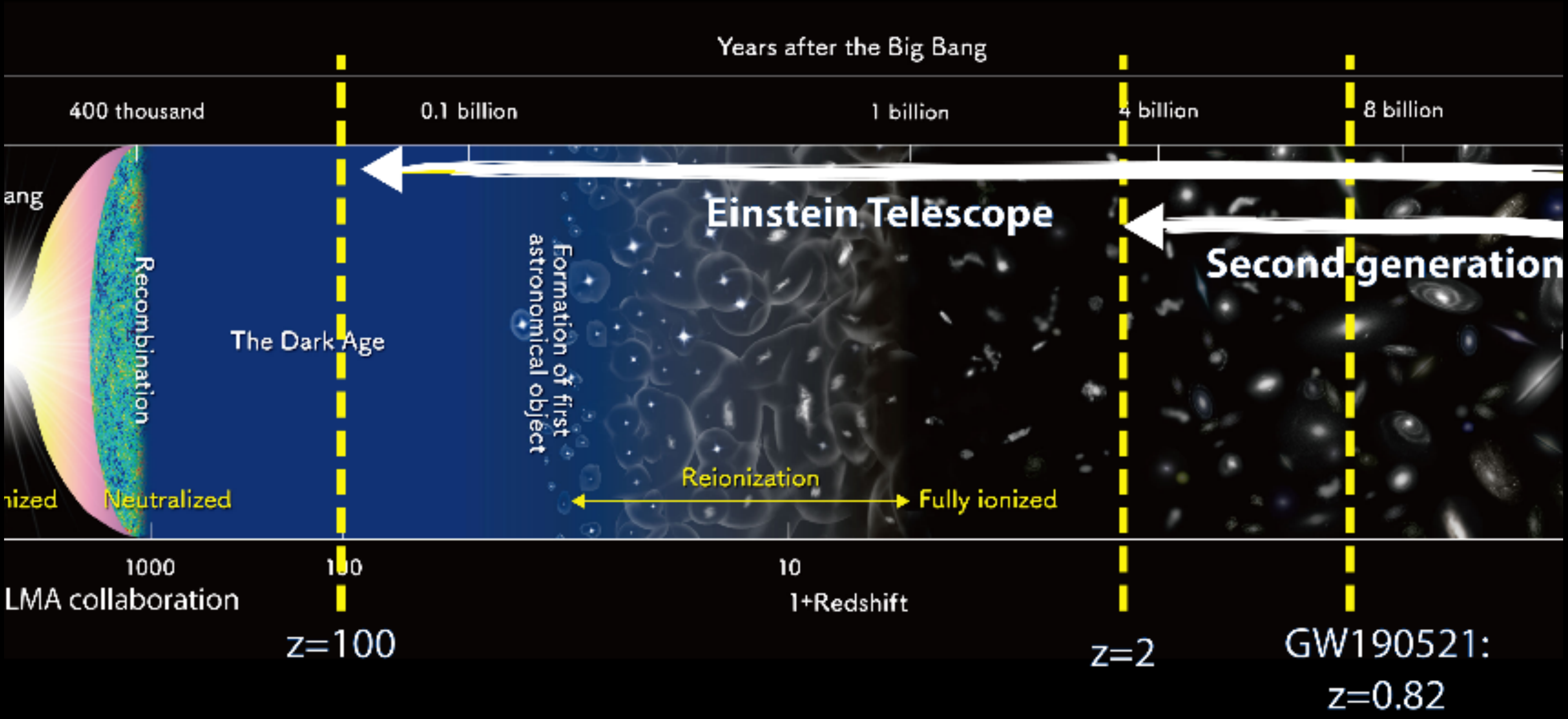




The sensitivity at low frequencies allows for an early detection

→ Very relevant for precise GR tests and facilitates the EM follow-ups.

Detection horizon for black-hole binaries



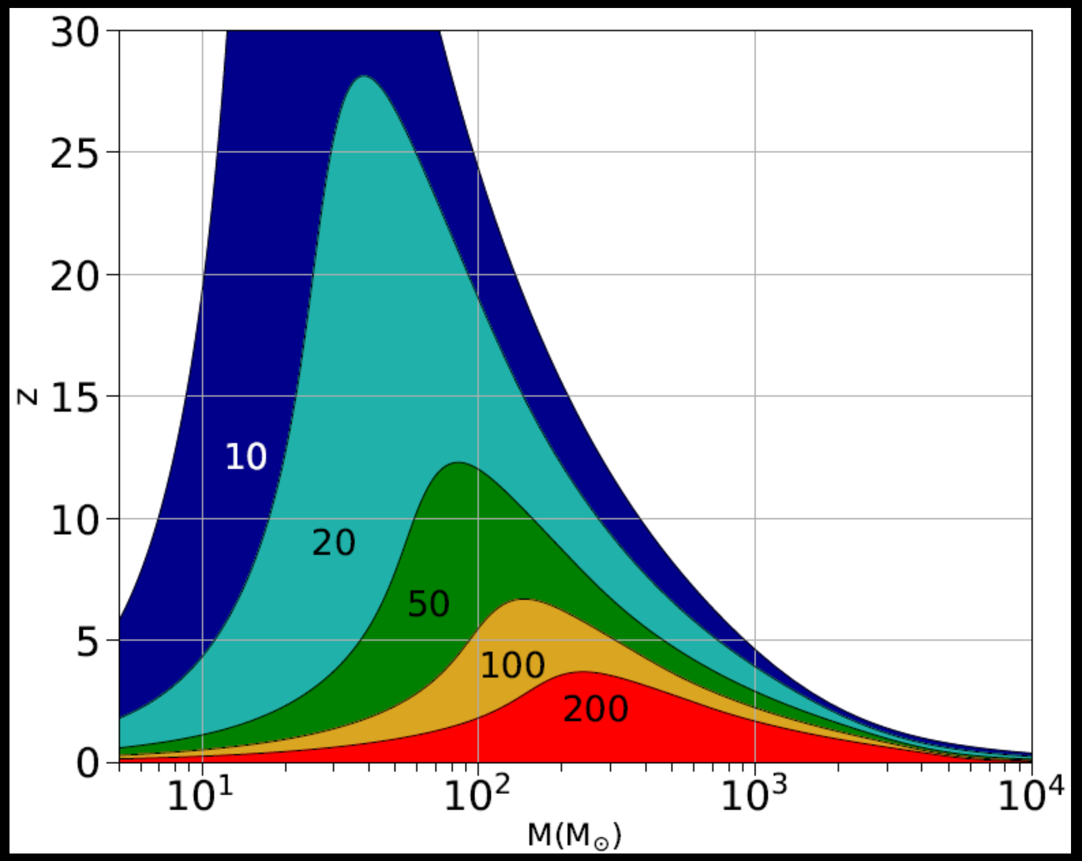
Huge rate of detections (about 1 per minute)

Extended redshift coverage up to the Dark Age

- Test for primordial BH origin
- Cosmology & Cosmography

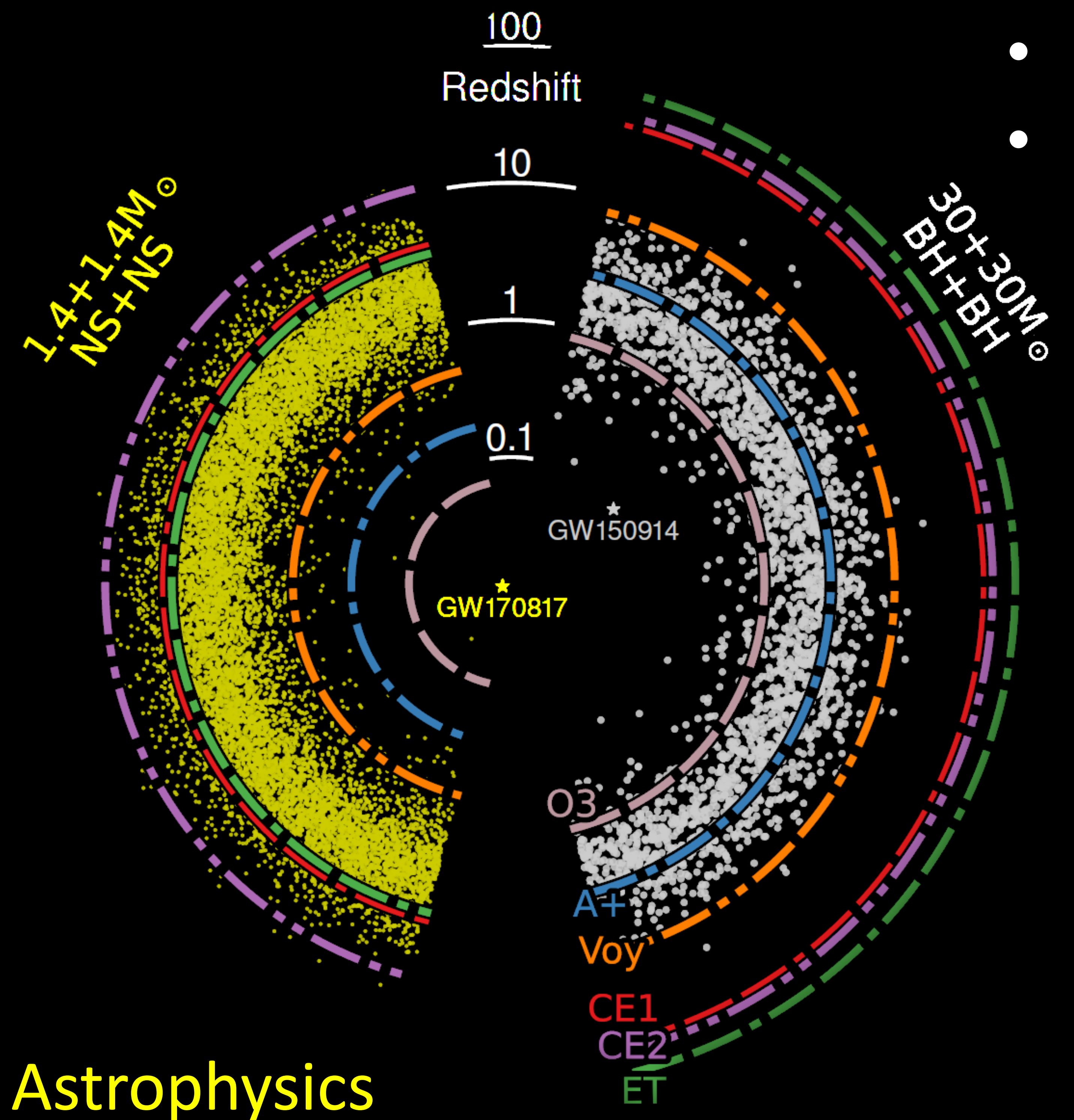
Many events with very large Signal-to-Noise ratios

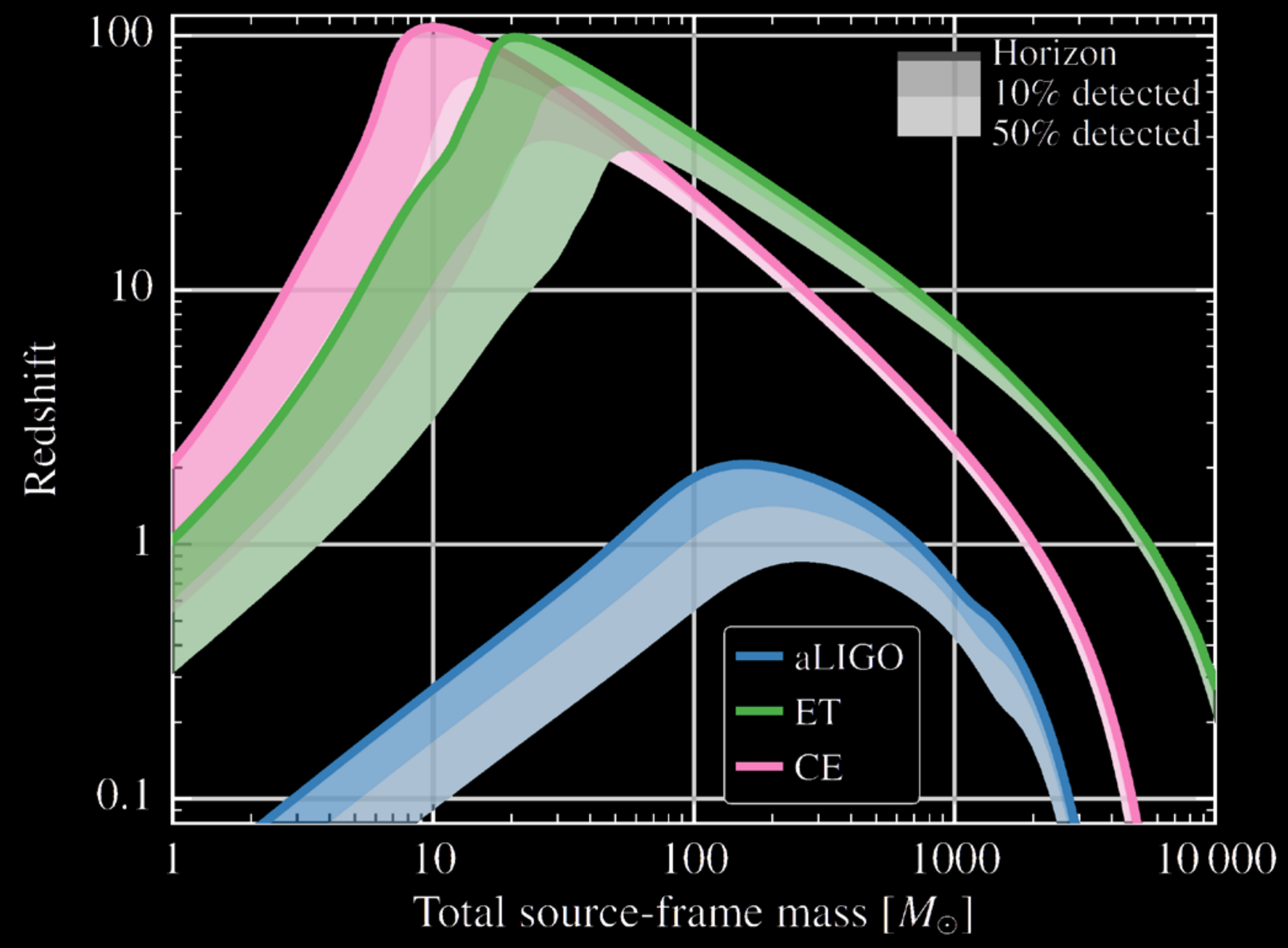
- Precision tests of GR predictions and detailed BH studies



Listening the whole Universe

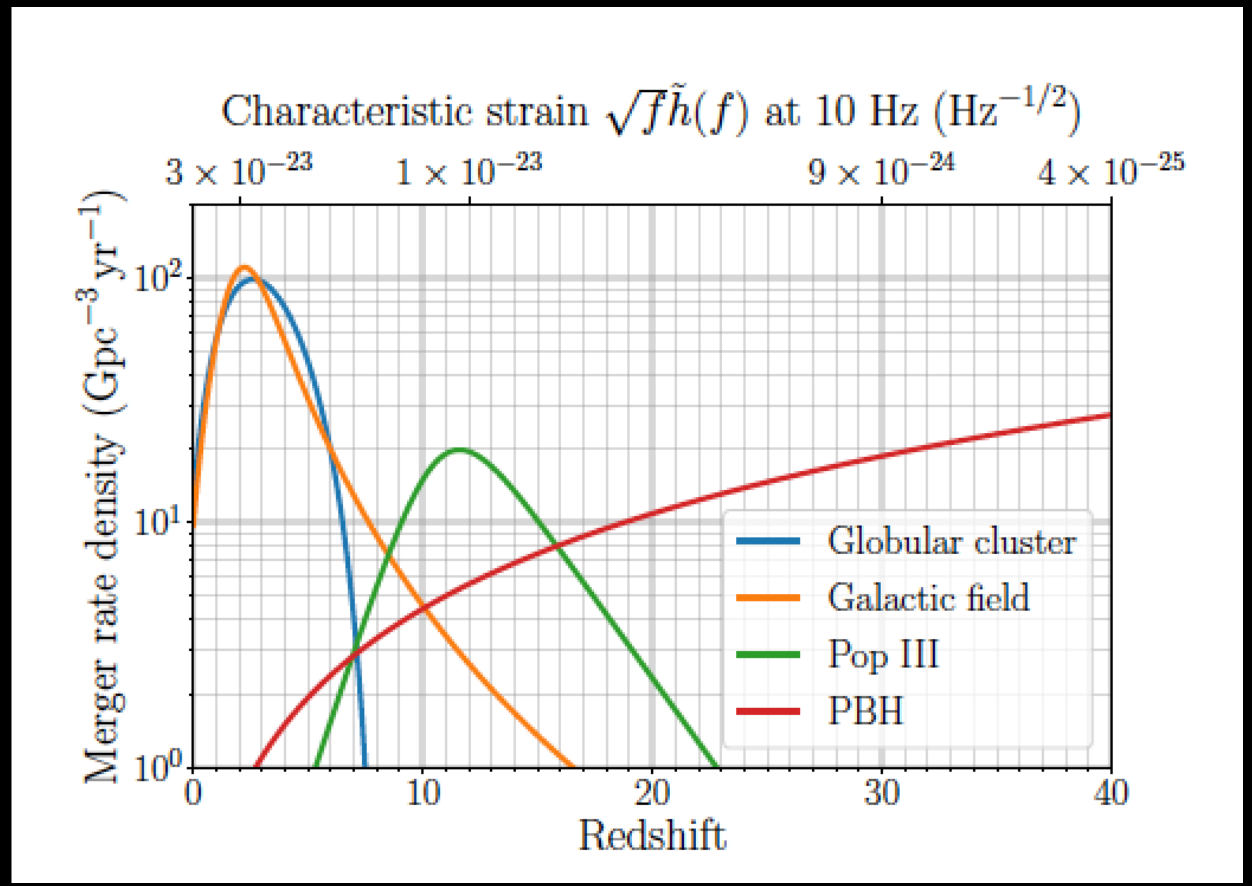
- 10^6 BH-BH / year up to z ~20 (230 Gpcs) and 10^3 M_{sol}
- 10^5 NS-NS / year up to z~2
- O(10^2 – 10^3) GW events with EM counterparts





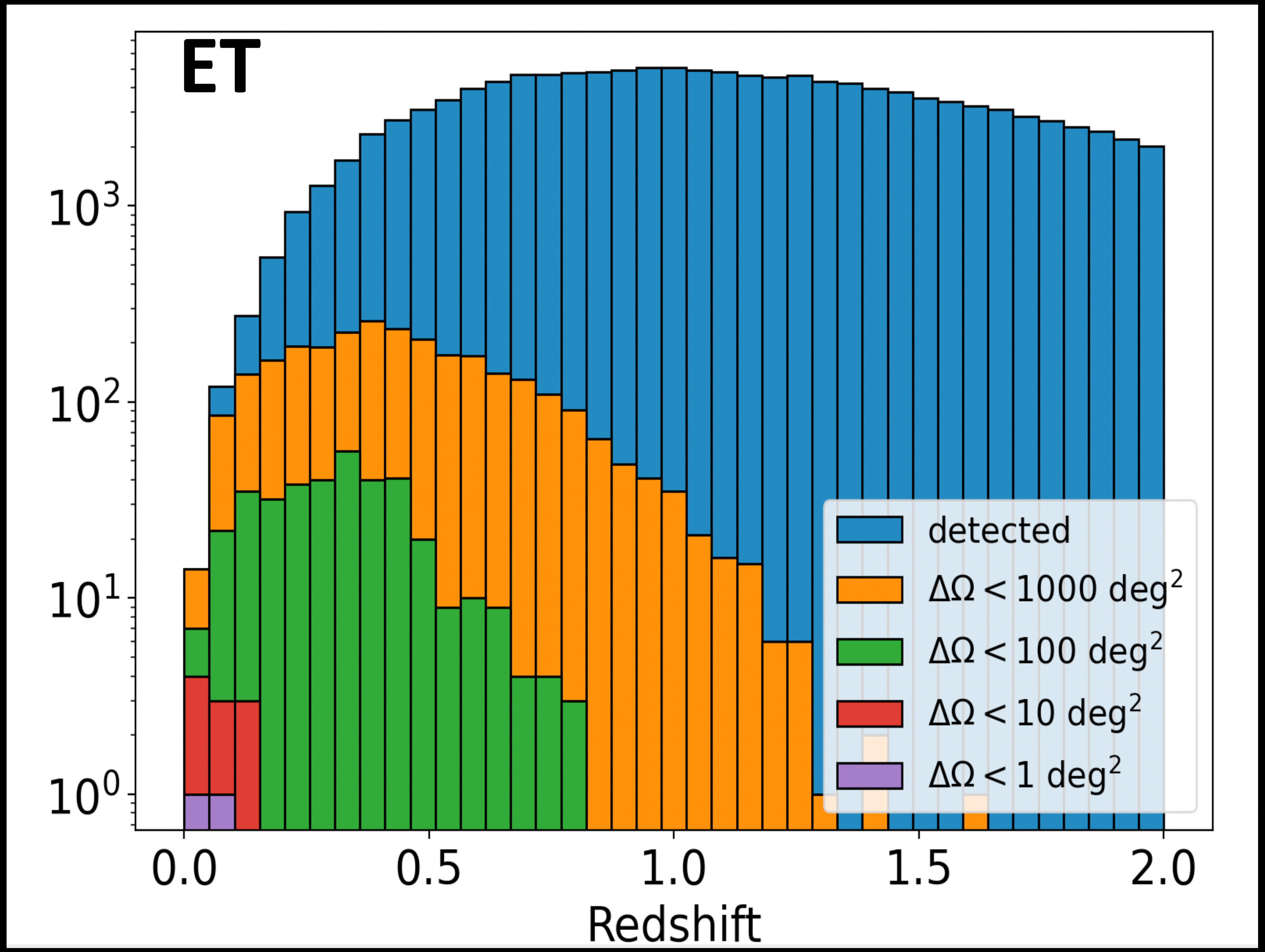
Astrophysics

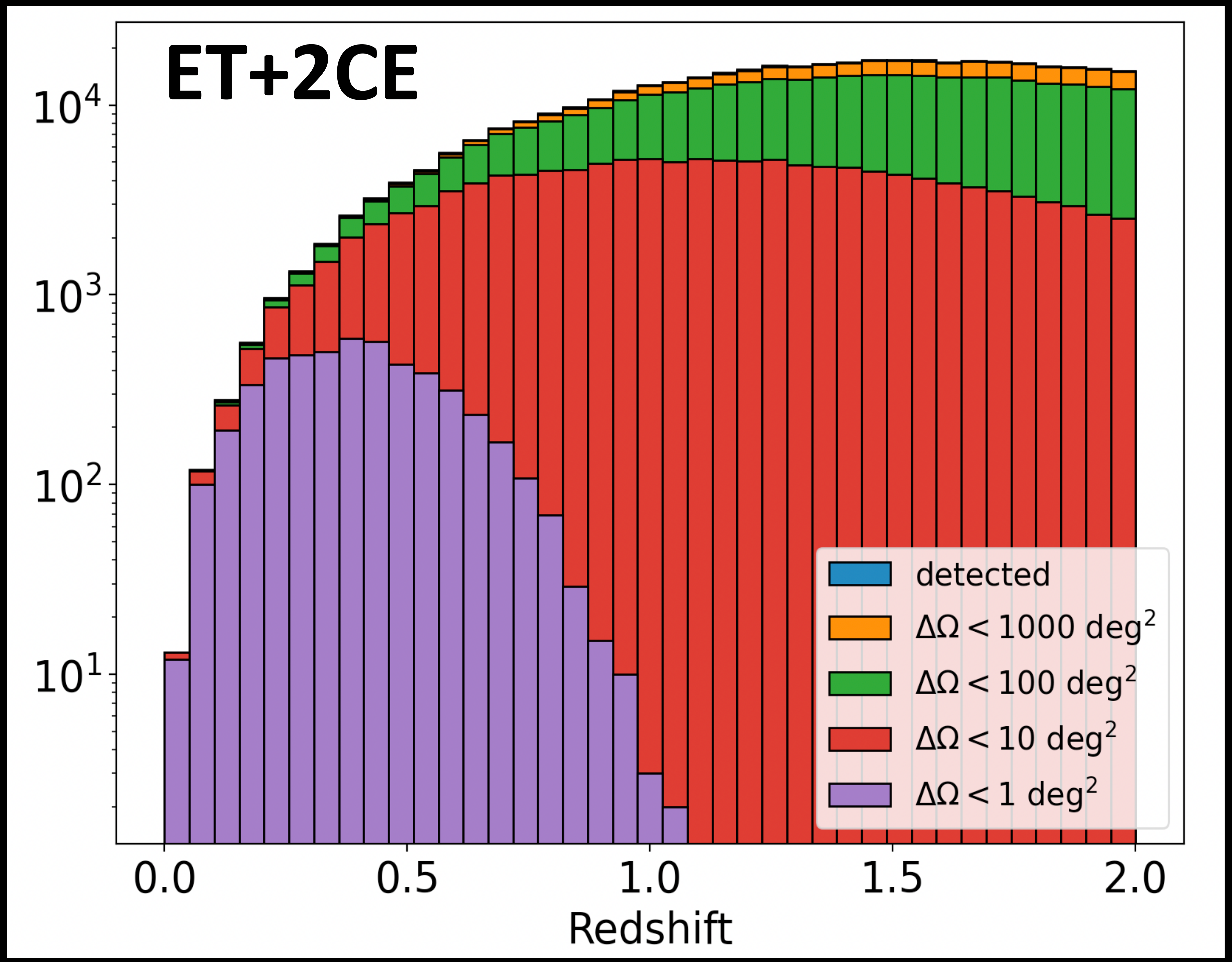
- BH demography and evolution
- Primordials? Stellar?
- Are BHs part of the dark matter?
- Supernovae, Pulsars, Stochastic signals
- Properties of neutron stars
- Multi Messenger: Optical, Neutrinos, Gamma Rays



M. Branchesi (OSB)

Sky localization

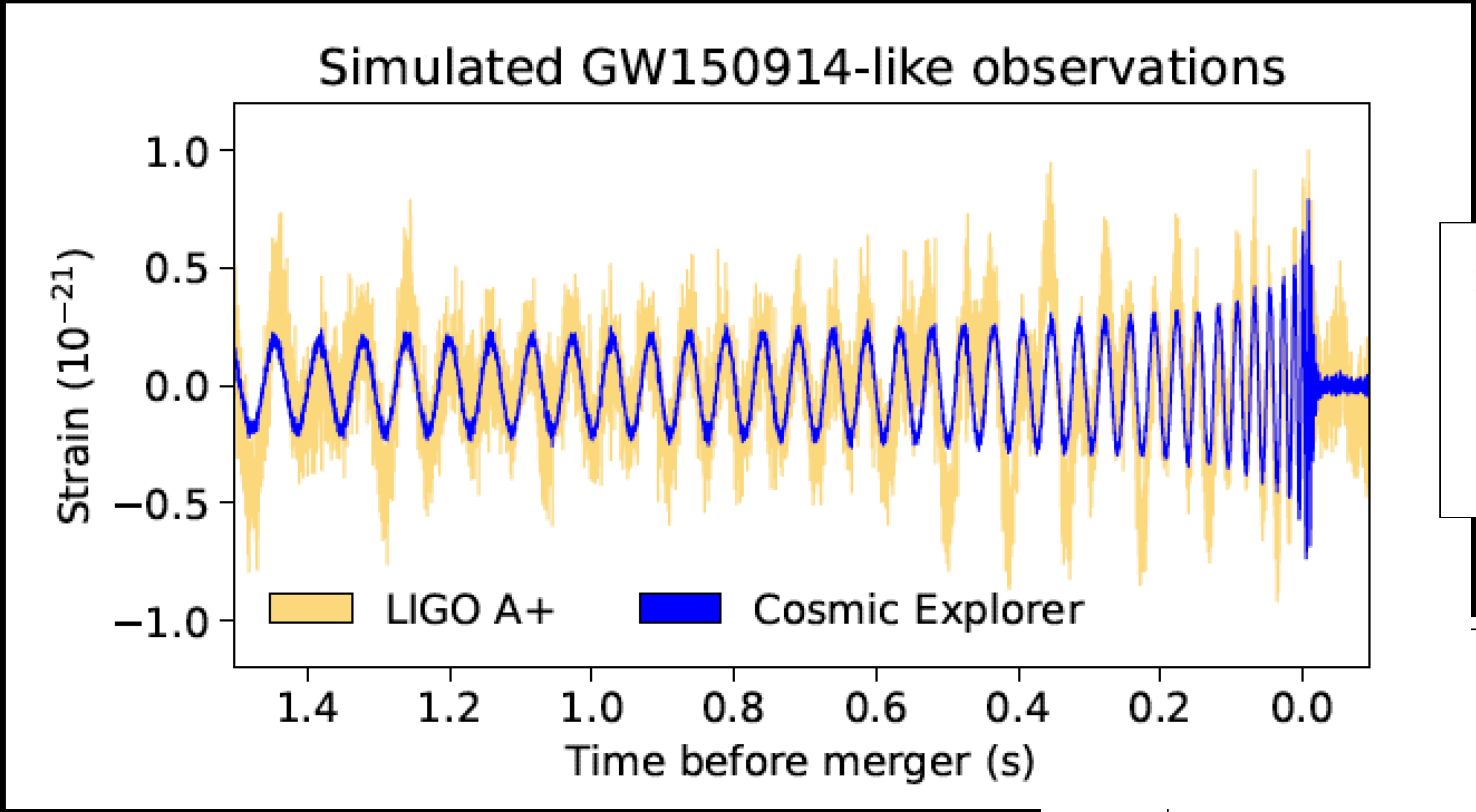




ET only configuration would allow for O(100) events / year with a sky-localizations (90% CL) < 100 deg²

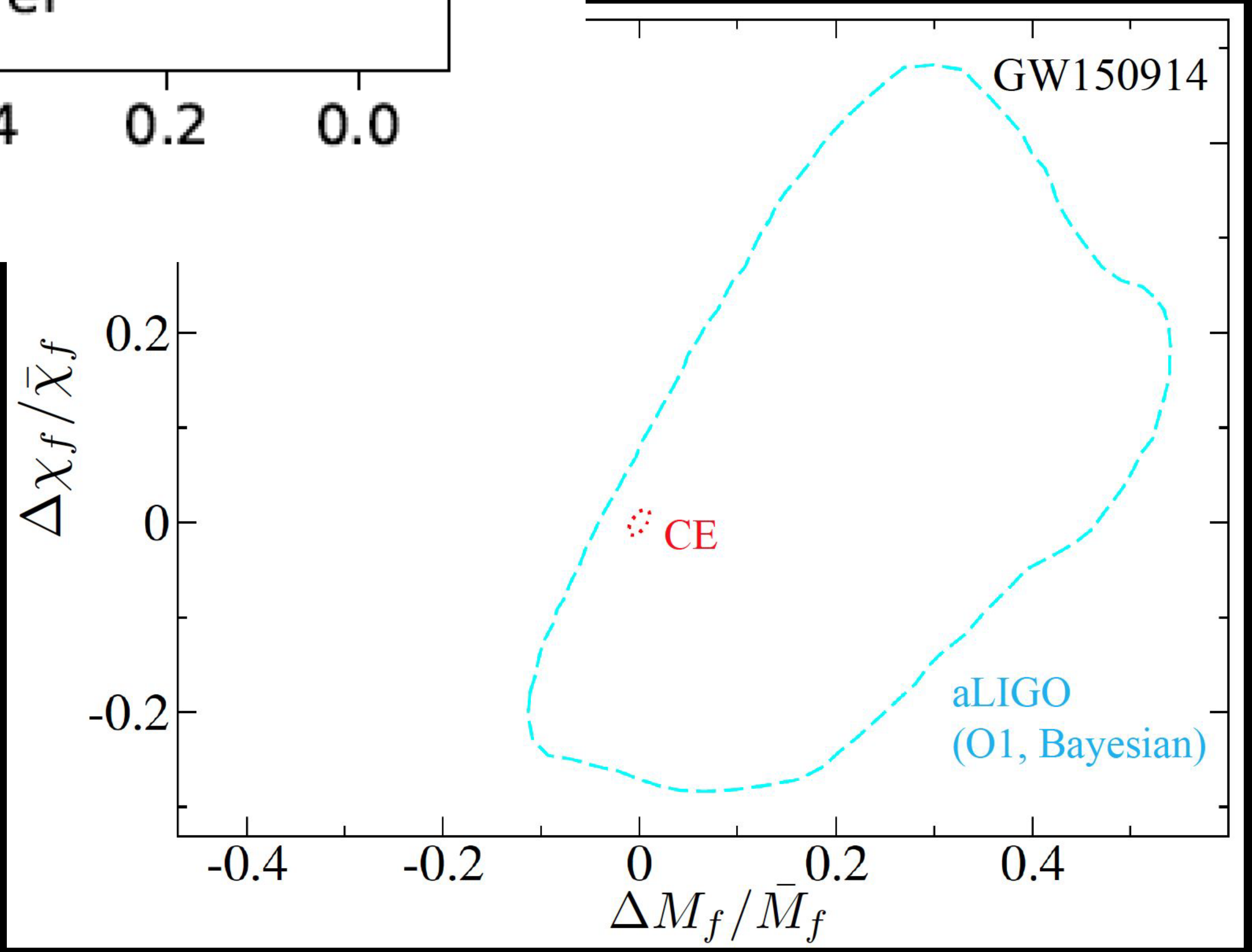
ET + 2 CE configuration would allow for O(1000) events / year with a sky-localizations (90% CL) < 1 deg²

General Relativity Tests (cont.)

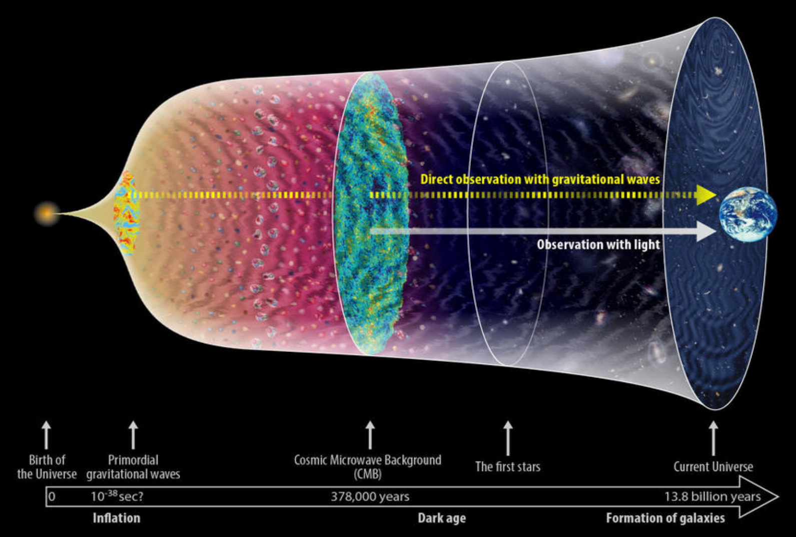


$$\frac{\Delta M_{\rm f}}{\bar{M}_{\rm f}} = 2\frac{M_{\rm f}^{\rm insp} - M_{\rm f}^{\rm postinsp}}{M_{\rm f}^{\rm insp} + M_{\rm f}^{\rm postinsp}},$$

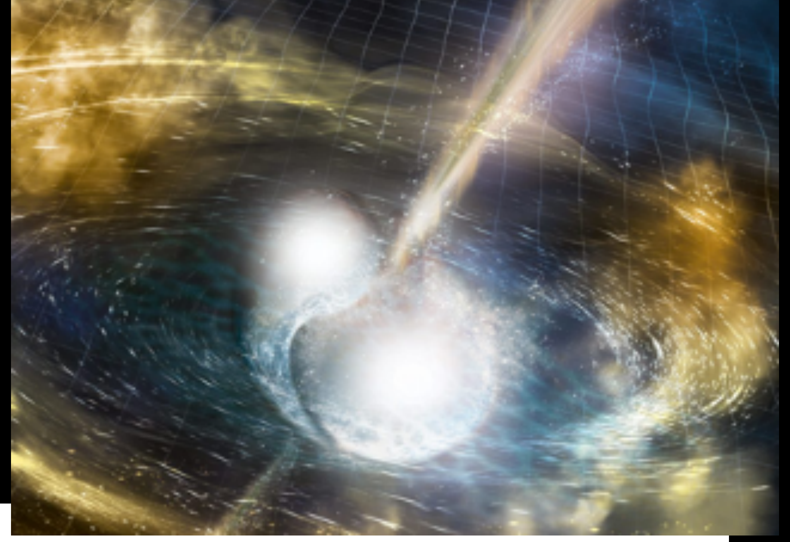
$$\frac{\Delta \chi_{\rm f}}{\bar{\chi}_{\rm f}} = 2\frac{\chi_{\rm f}^{\rm insp} - \chi_{\rm f}^{\rm postinsp}}{\chi_{\rm f}^{\rm insp} + \chi_{\rm f}^{\rm postinsp}},$$



The huge boost in sensitivity and SNR allows for precise tests of GR improving by 2 orders of magnitude compared to 2G results.



Cosmology

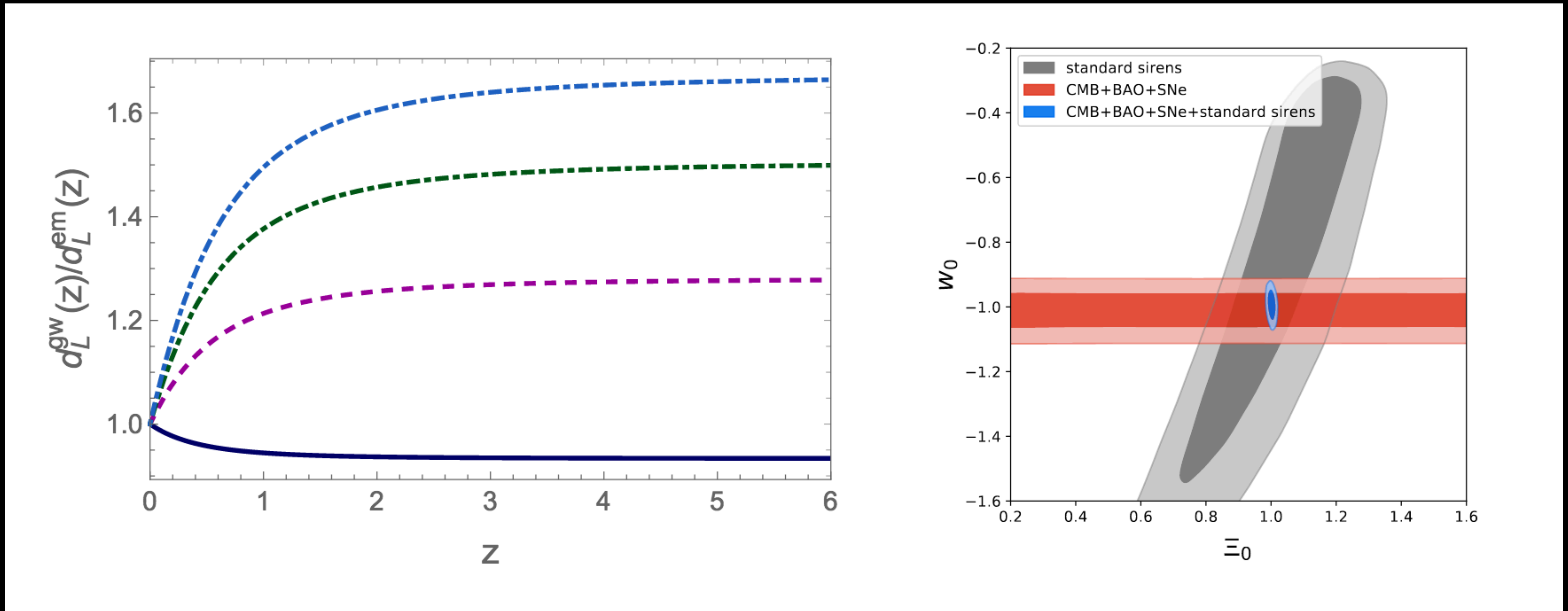


$$d_L(z) = \frac{1+z}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_M(1+z')^3 + \frac{\rho_{\rm DE}(z')}{\rho_0}}},$$

Relationship between light distance and redshift contains information on high redshift cosmology

$$\frac{d_L^{\rm gw}(z)}{d_L^{\rm em}(z)} = \Xi_0 + \frac{1-\Xi_0}{(1+z)^n}$$

in models beyond GR



After a few years and collecting a few hundred BNS events ET can do a rigorous test.

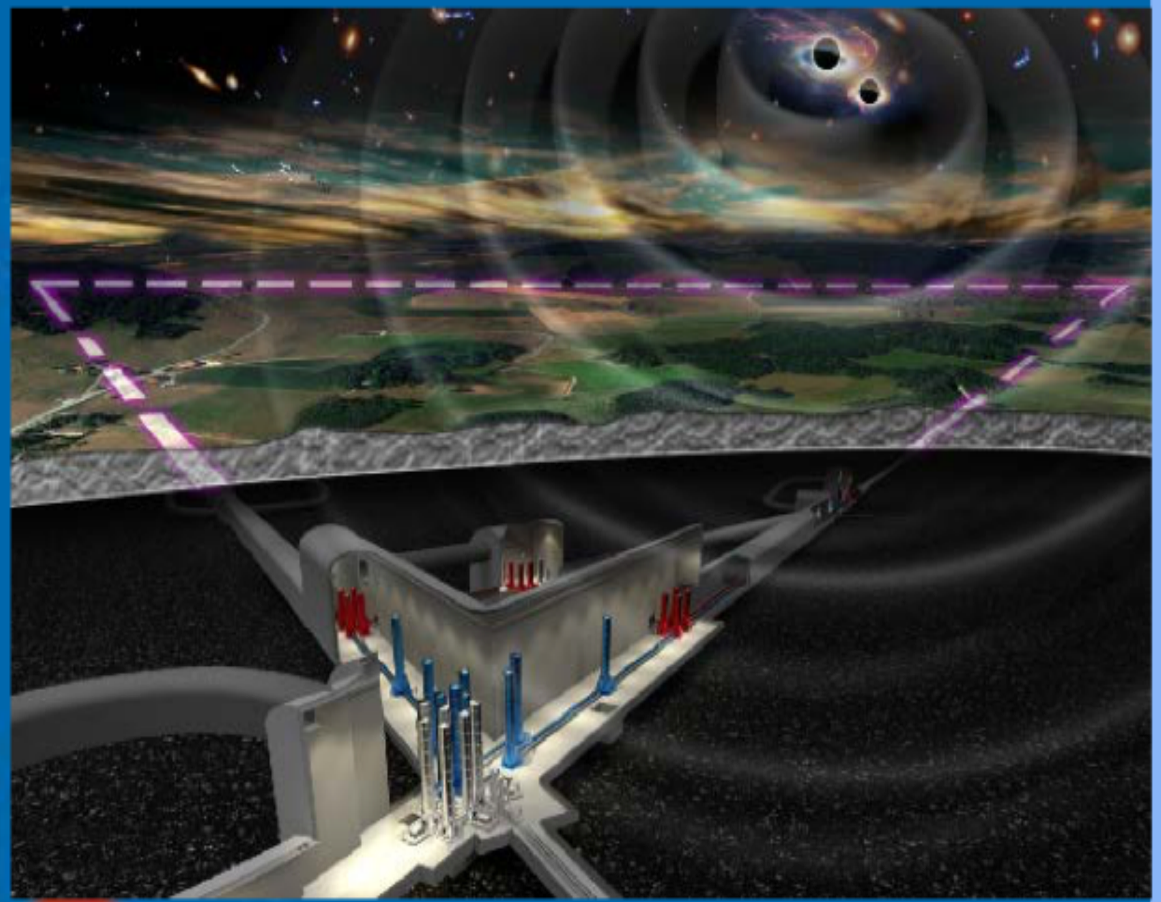
ET on the ESFRI roadmap

European Strategy Forum on Research Infrastructures

EINSTEIN TELESCOPE

ESFRI | ROADMAP 2021

https://www.et-gw.eu/



Project submitted by:

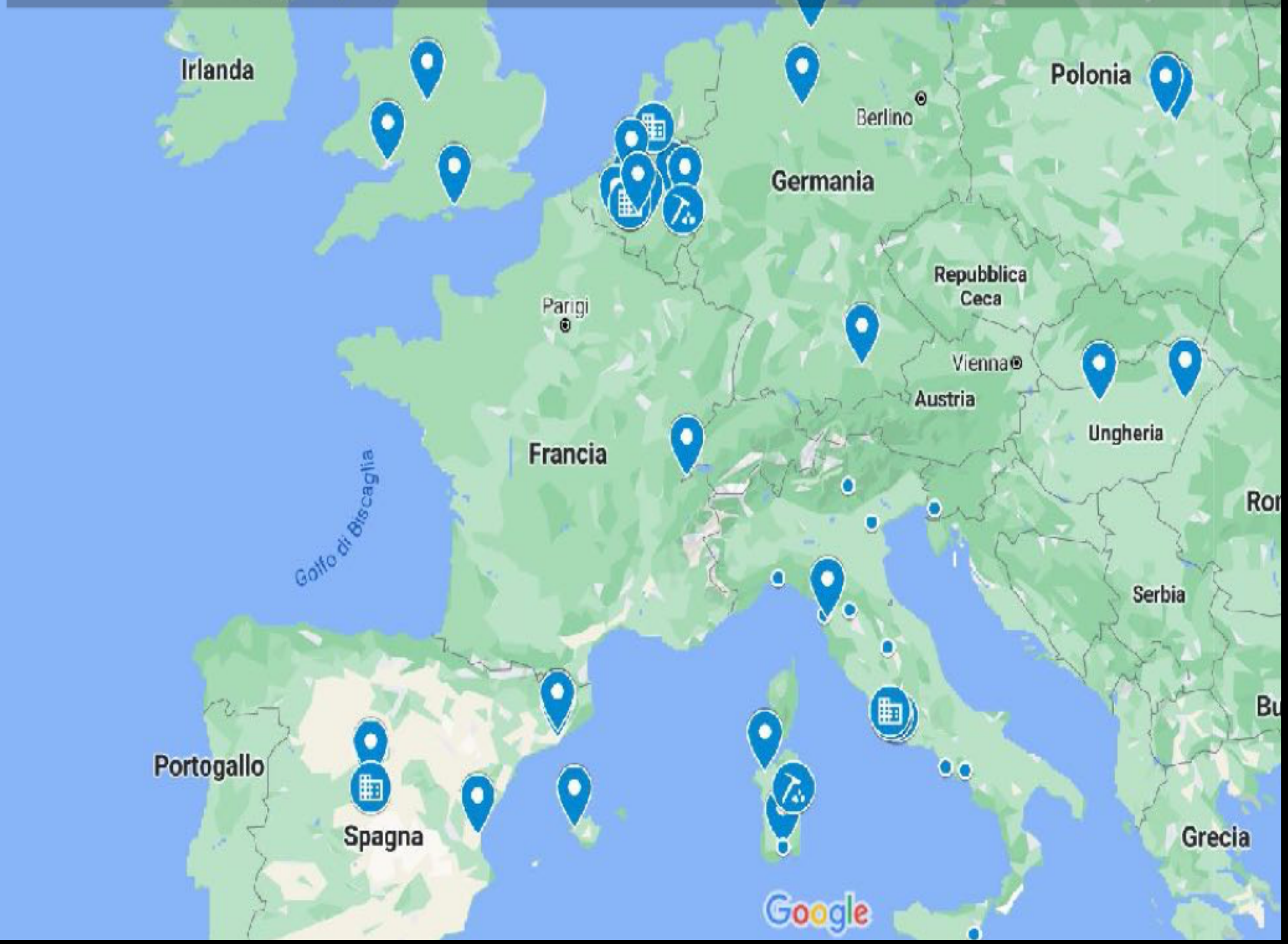
- **Italy** (Lead Country)
- Netherlands
- Belgium
- Spain
- Poland

30/06/2021:

ET is on the ESFRI roadmap!

ET Consortium

- ET CA signed by 41 institutions
- INFN and Nikhef are the coordinators of the consortium
- Funding expected in the next months by the governments in the frontline
- EU funding for the Preparatory Phase in 2022

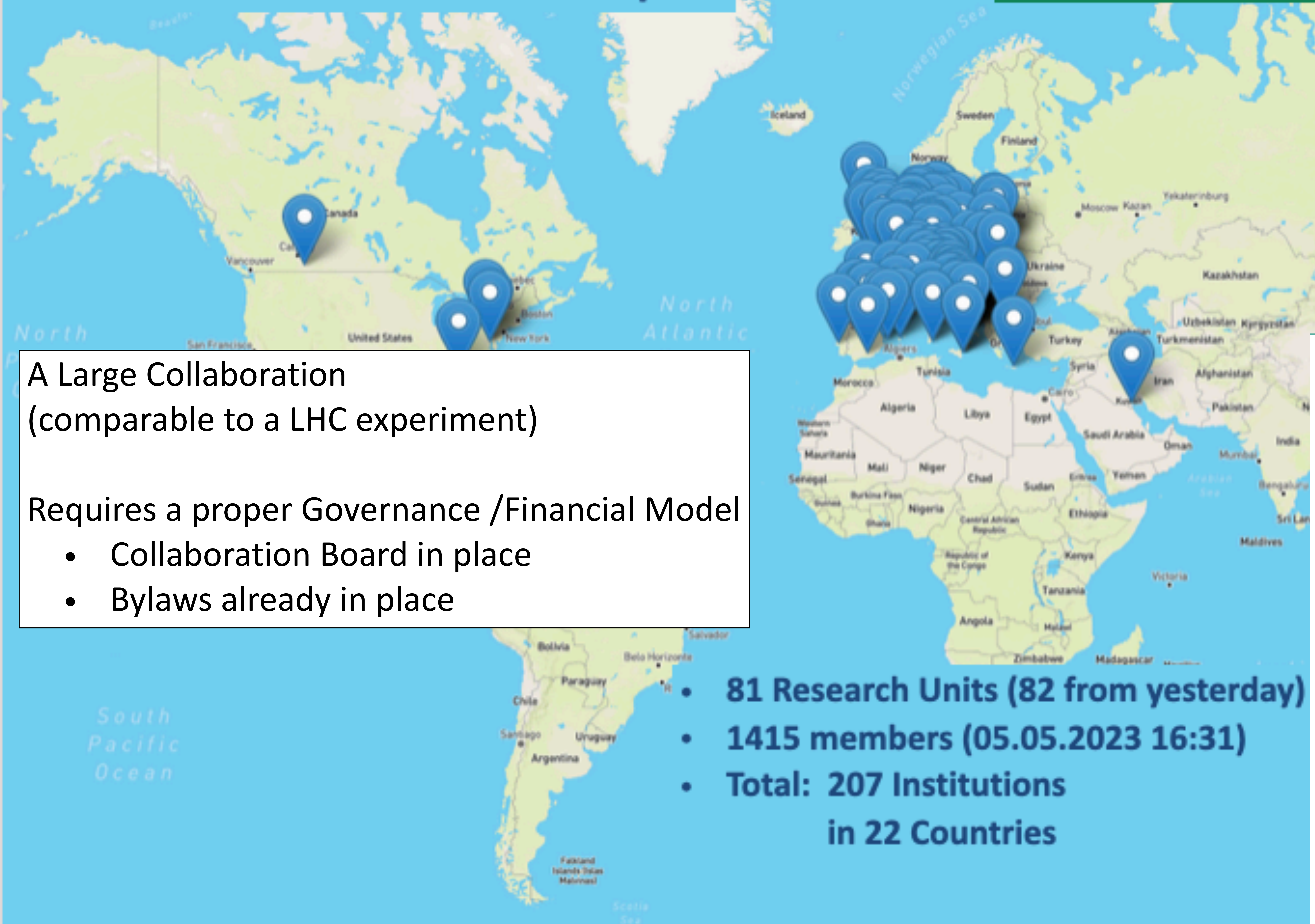


The Einstein Telescope Collaboration

ET EINSTEIN TELESCOPE

ET Member‘s affiliation map

- **ET member database** (https://apps.et-gw.eu/etmd/)

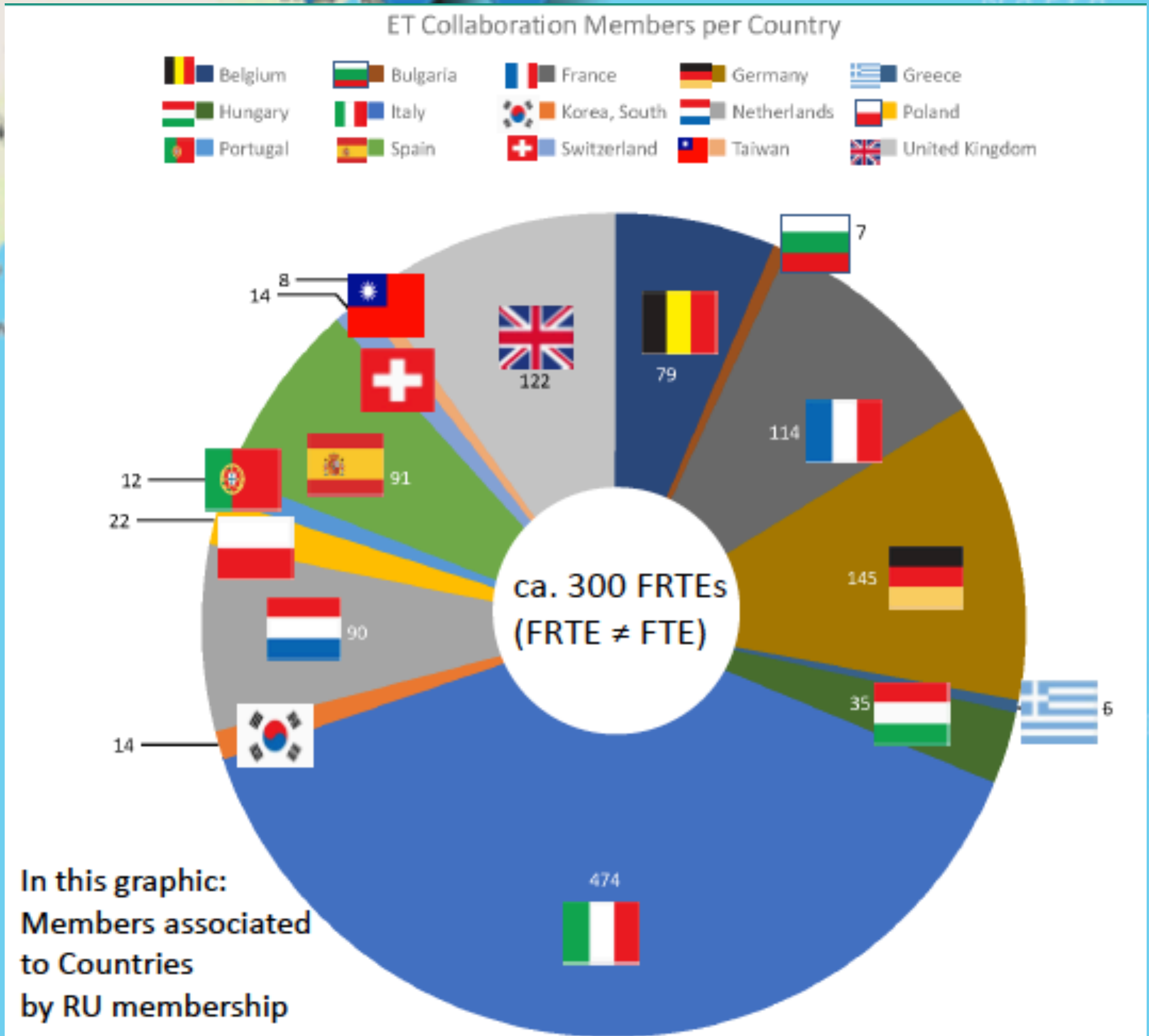


A Large Collaboration
(comparable to a LHC experiment)

Requires a proper Governance /Financial Model

- Collaboration Board in place
- Bylaws already in place

- **81 Research Units (82 from yesterday)**
- **1415 members (05.05.2023 16:31)**
- **Total: 207 Institutions in 22 Countries**



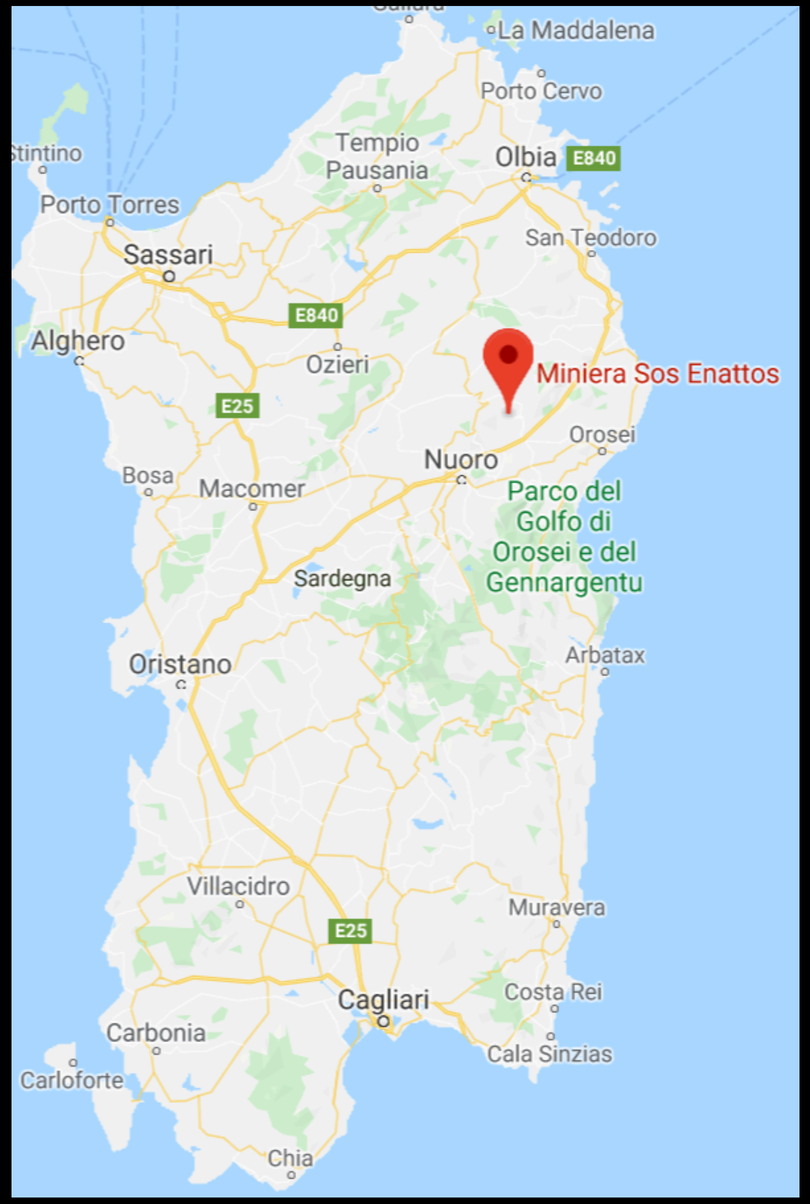
Locations ?

30 M€ investment
ETparthfinder

Intensive studies
@ Limburg,
@ Sardinia
@ Saxony
For characterize seismic,
environmental noise, etc ...

@ Limburg area (border NL-B-D)
→ Promoted by Nikhef

30 M€ investment
Lab in construction



?

@ Sardinia
→ Promoted by INFN

@ Germany is very present in ET and ETpathfinder
They foresee a large investment in the following years

→ Exploring Saxony as a possibility
→ Ongoing geological characterization of the site

https://www.deutscheszentrumastrophysik.de/de

News from Germany

Big Science Business Forum 2022

German Center of Astrophysics in Saxony became a reality → now approved

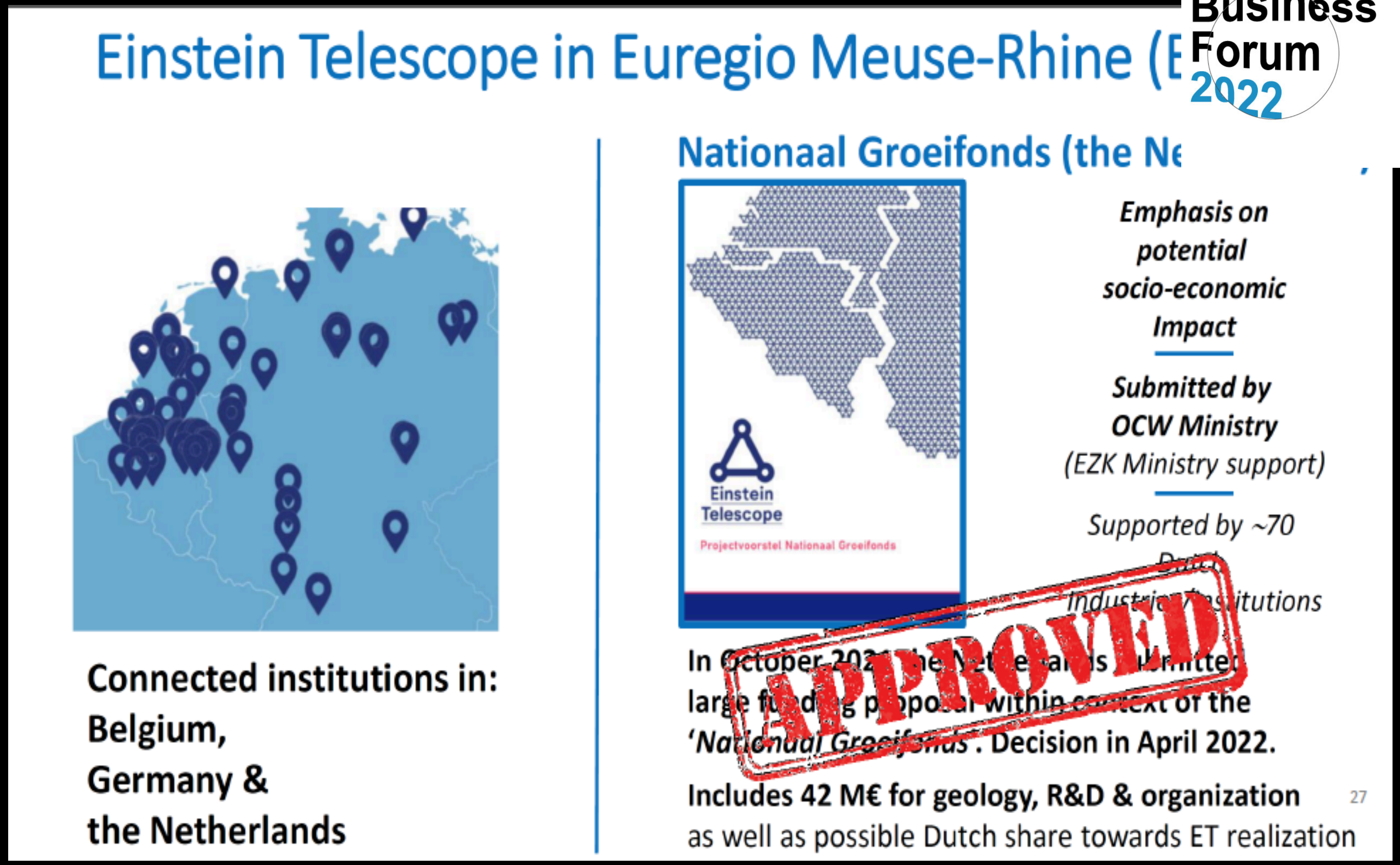
→ Big Data for Astroparticle physics
→ Technology (Si-sensors, Optics)
→ **One of the main missions related to ET**

Thirdly, the settlement of the European gravitational wave observatory **"Einstein Telescope"**, which is already being planned, is to be examined in the granite stock of Upper Lusatia. **"The granite stock offers ideal conditions, the construction of the telescope under the earth's surface would tie in with the mining tradition of the region and would be an international lighthouse project,"** explains **Christian Stegmann, DESY director for astroparticle physics and supporter of the DZA.**

Rising Construction Funds

Big Science Business Forum 2022

In the Netherlands a formal request of 900M€ for ET@ Maastricht **has been approved** by the Science Minister to the NL Government



Italy approved a 50M€ project for enabling technologies and additional 350M€ for supporting ET@ Italy **has been secured** plus rece explicit support by italian Presidency for ET@Italy

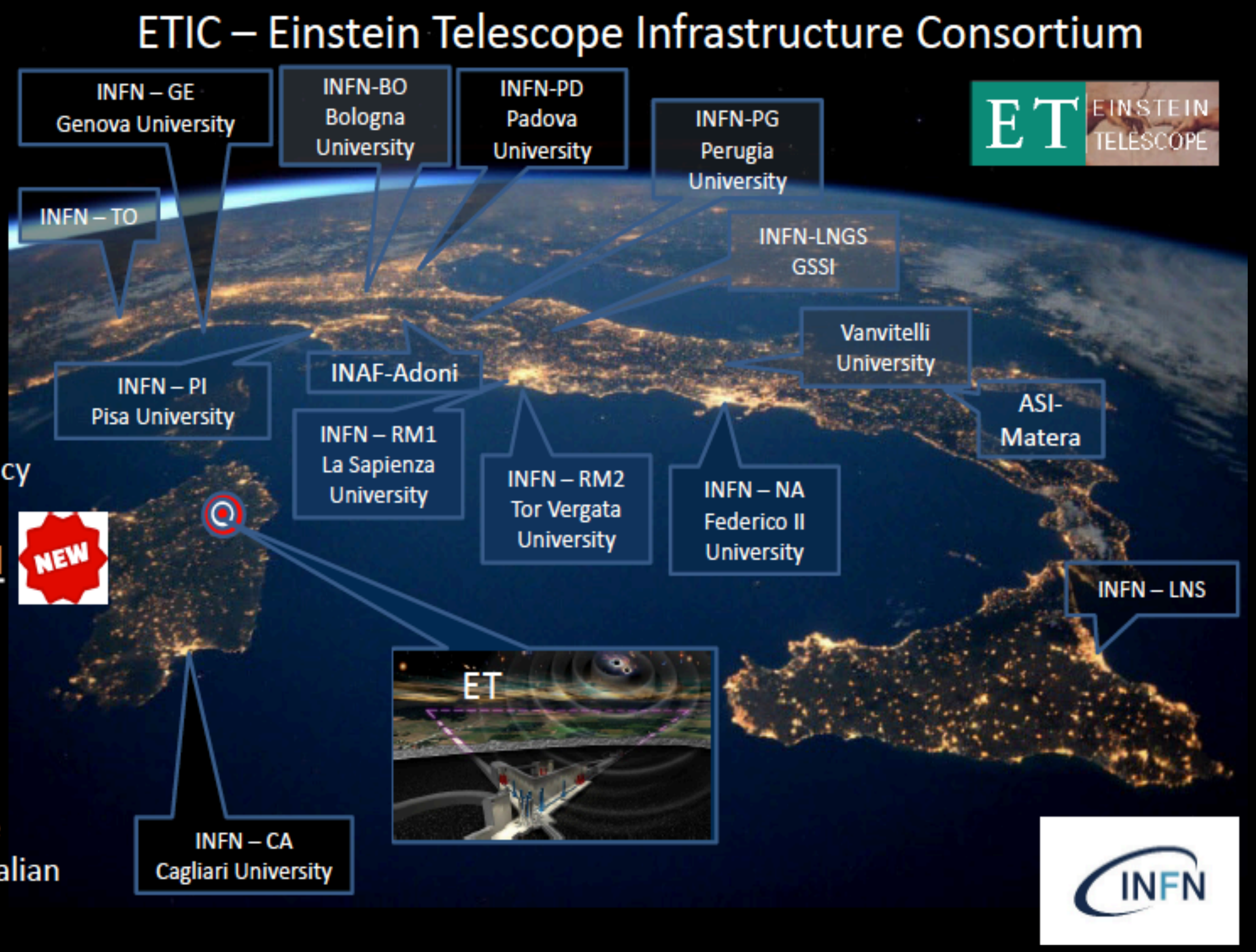
Next Generation EU Investment focused on ET enabling technology and Sardinian site candidature support

Leaded by INFN,
Partners:
11 Universities
INAF and Italian Space Agency

Budget 50M€ approved NEW

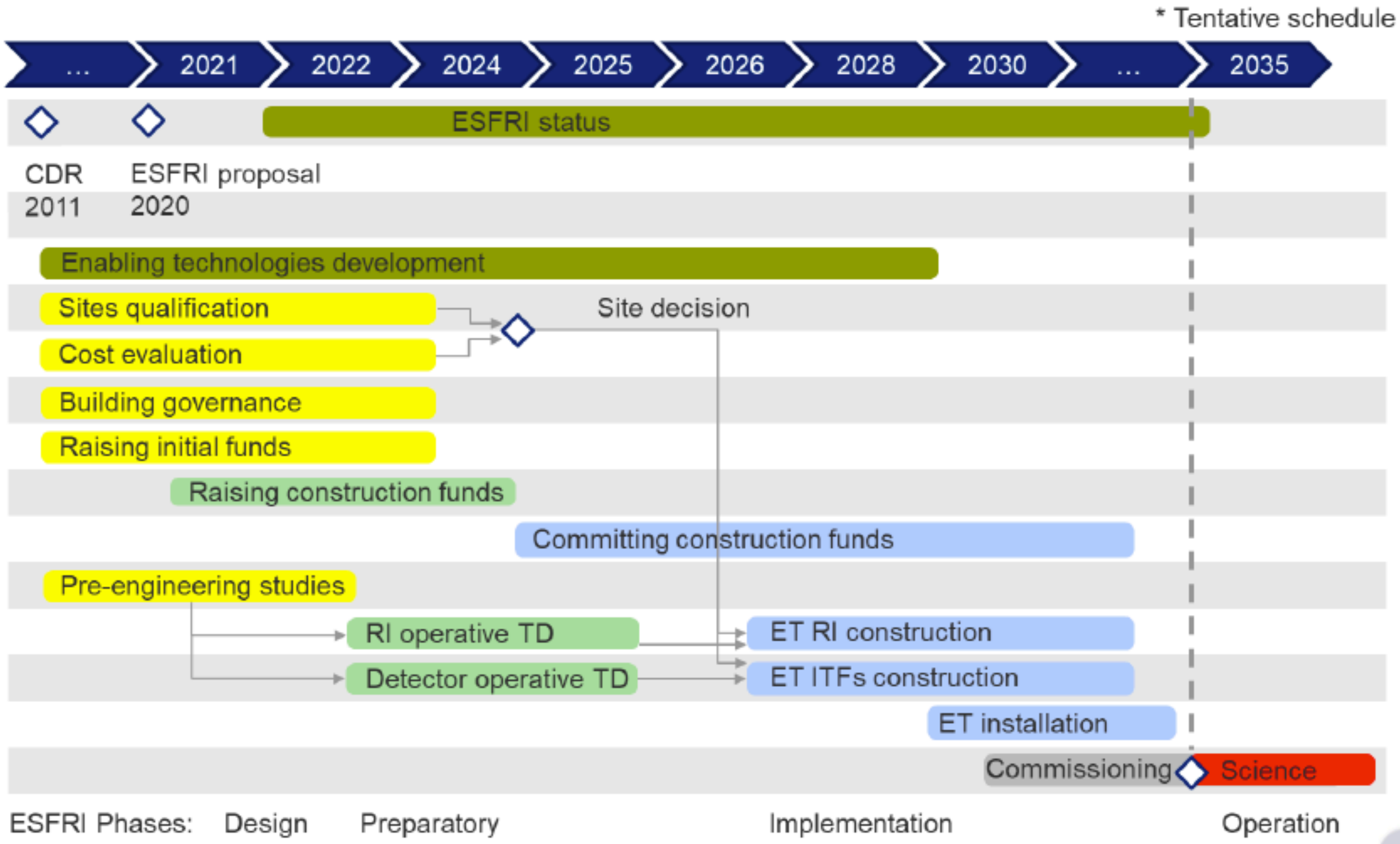
Start of the project:
1st December 2022

Discussion ongoing with the Italian Government on an Italian share toward ET realization



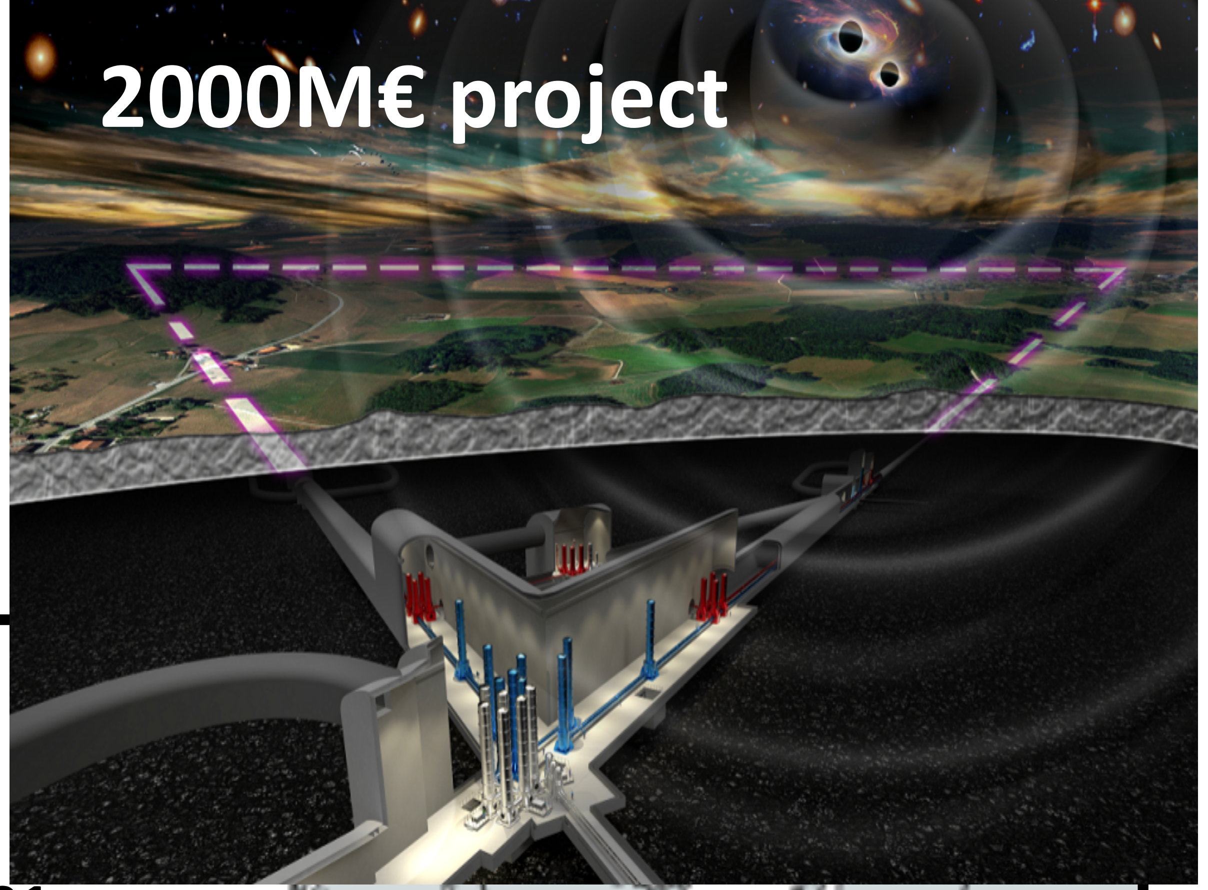
Time to discuss the level of financial involvement by other EU countries in ET for the following decade

ESFRI: project timeline



ET project is now entering the preparatory phase

Einstein Telescope as ESFRI



European Commission | Funding & tender opportunities
Single Electronic Data Interchange Area (SEDIA)

SEARCH FUNDING & TENDERS ▾ HOW TO PARTICIPATE ▾ PROJECTS & R

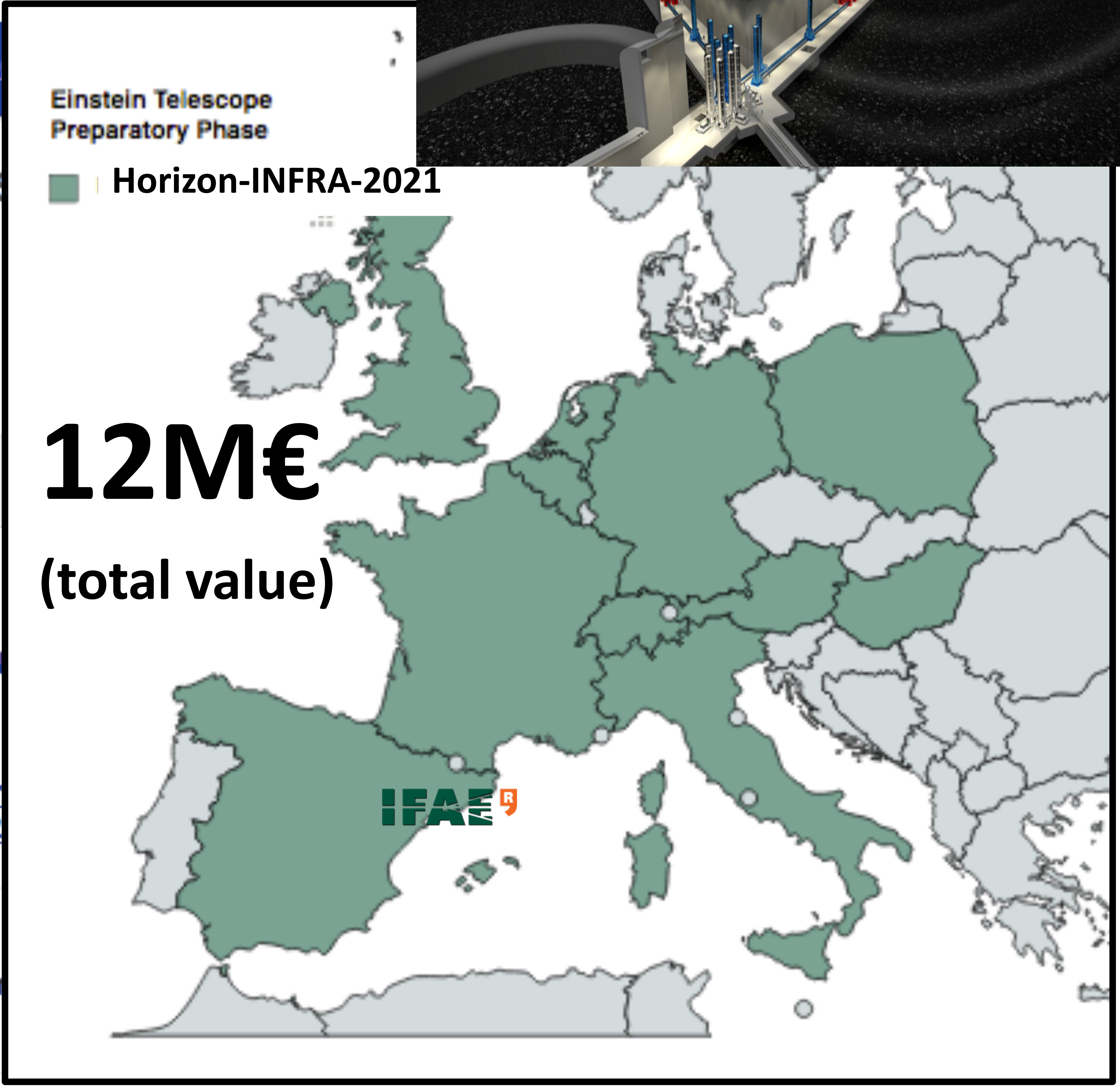
Preparatory phase of new ESFRI research infras

Goals for ET Preparatory Phase

- Governance
- Financial architecture/plan/framework
- ET legal entity
- Final ET design and cost evaluation
- Site or sites selection
- Construction funding
- User services
- Computing model
- Sustainability

3.45M€
(approved)

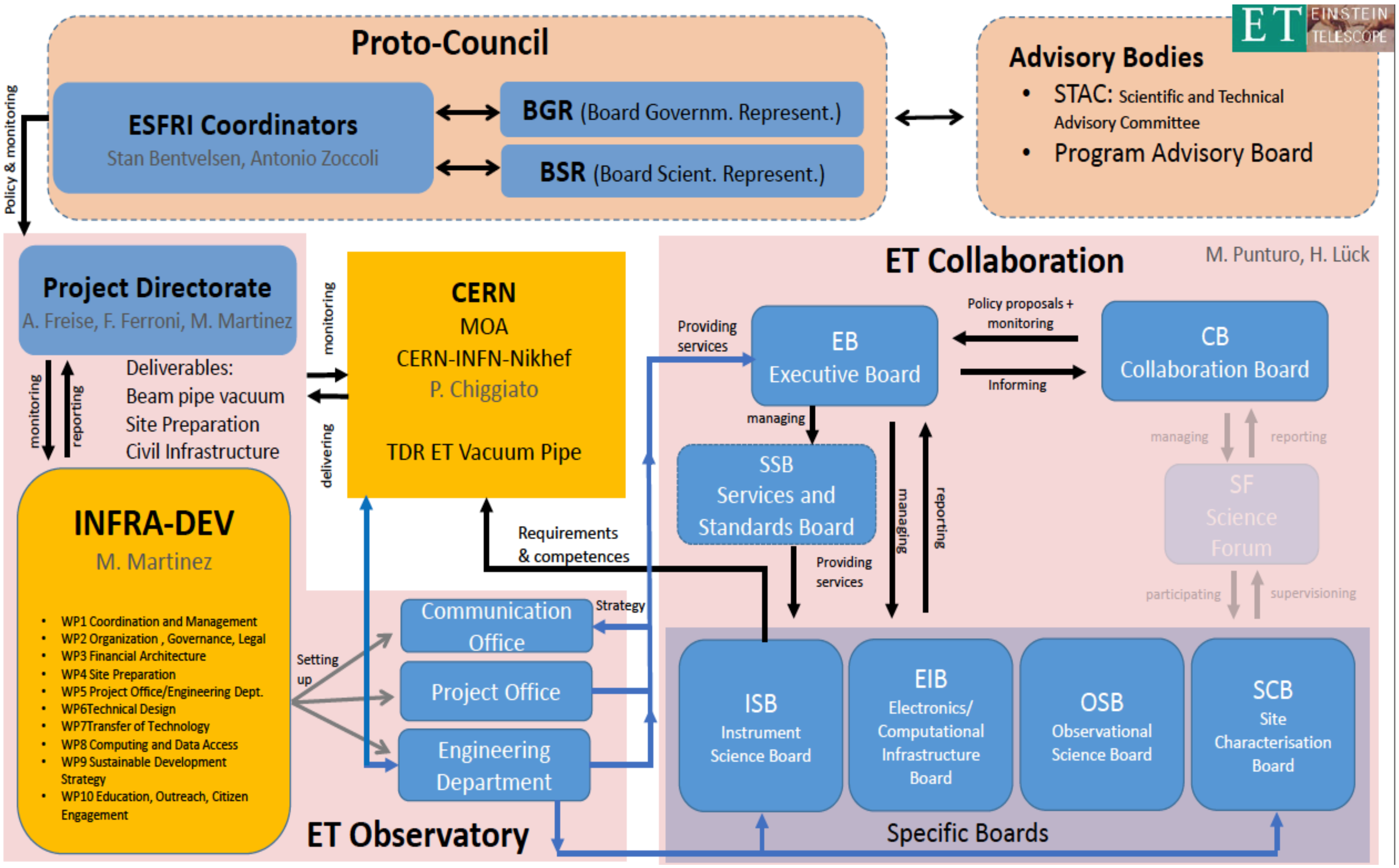
Get support



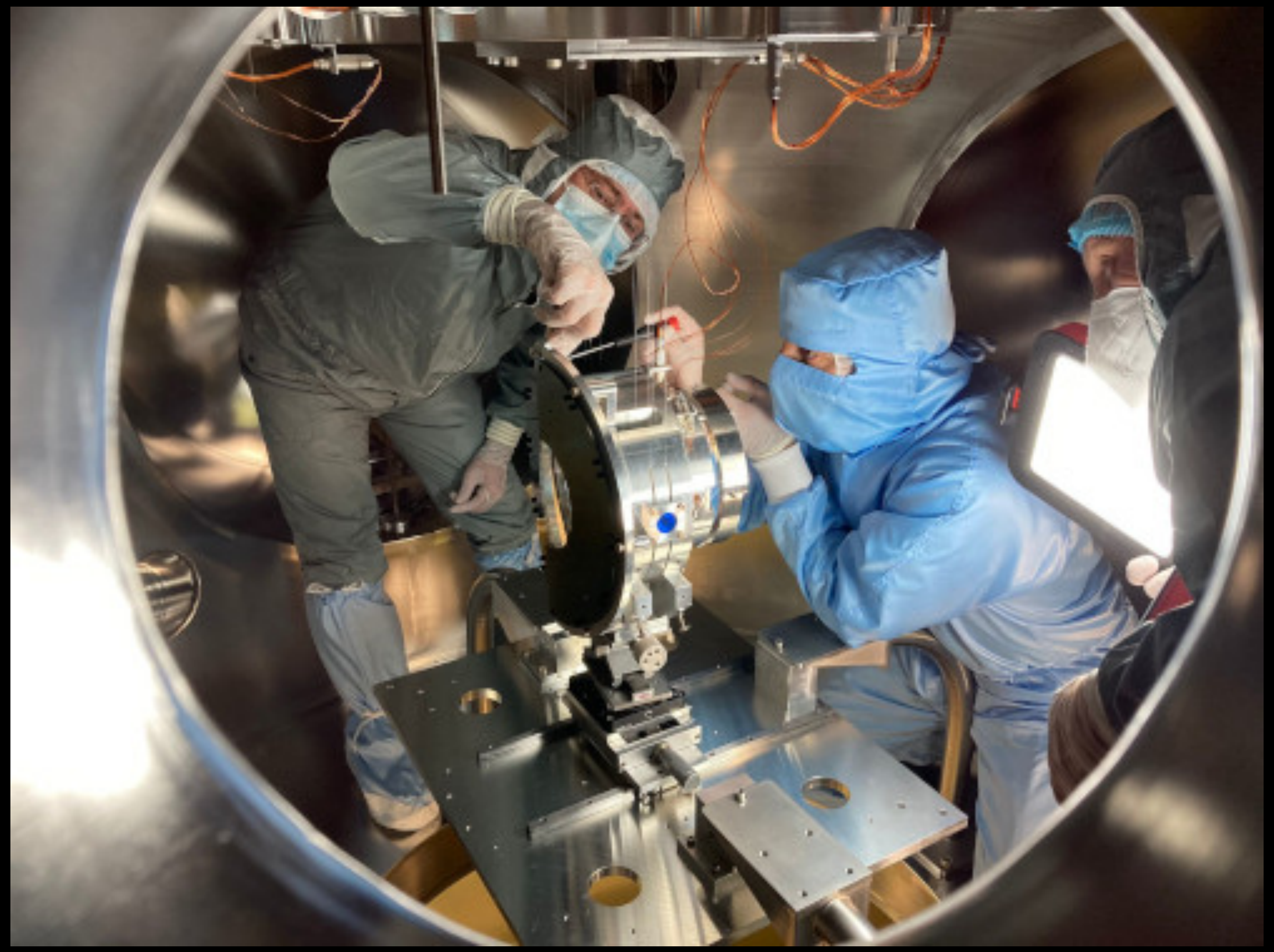
Einstein Telescope Preparatory Phase (ET-PP) in 2022 – 2026
HORIZON-INFRA-DEV EU Project coordinated by IFAE

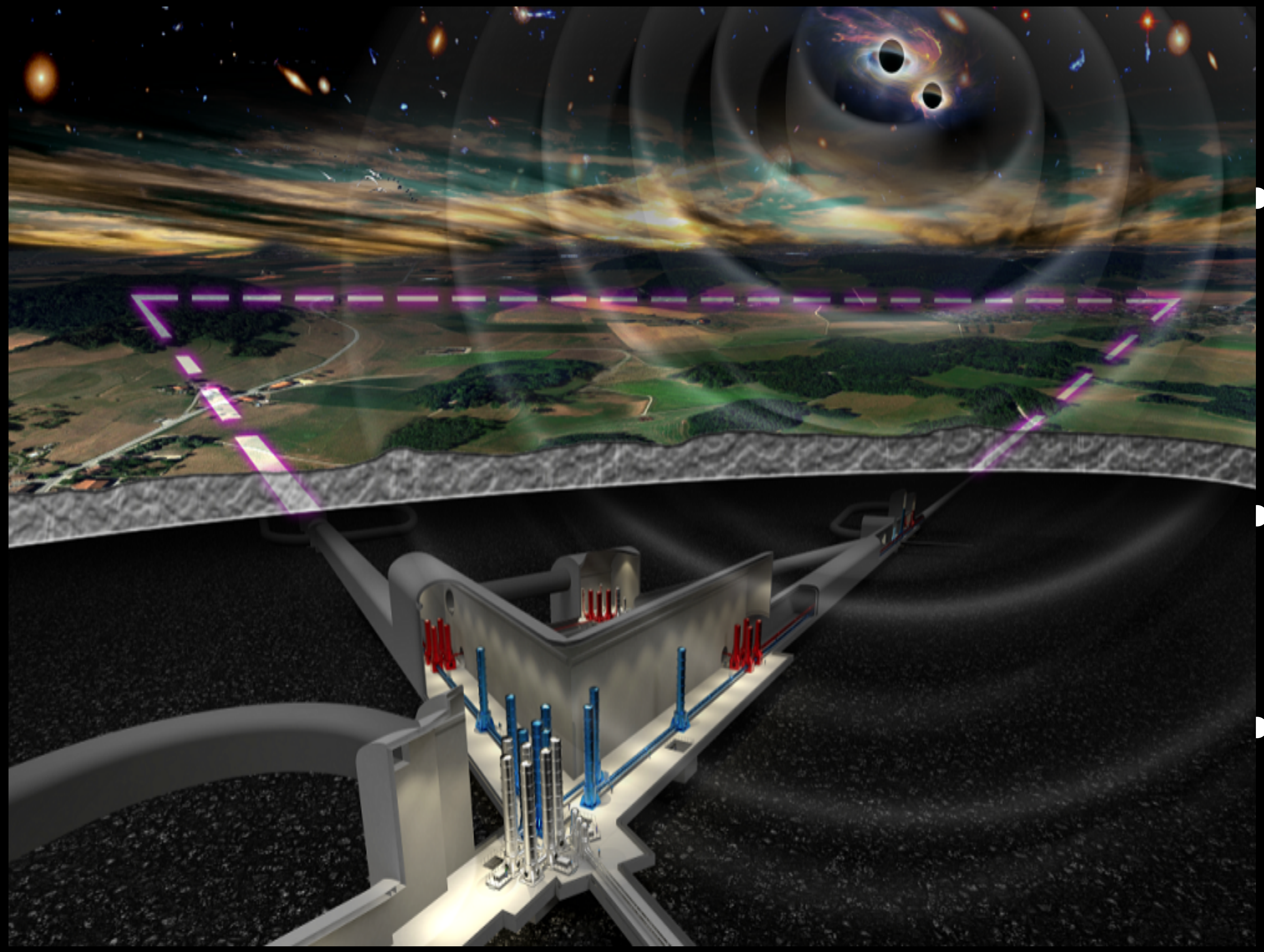
→ **Project started 1st September 2022 (https://etpp.ifae.es)**

ET-PP Preparatory Phase



Final notes





- The field of gravitational waves is / will be one of the main lines of research in Fundamental Physics, Astrophysics and Cosmology in the coming decades.
- New window to the early universe and inflation.
- Detailed study of BHs and NSs.
- After the success of LIGO / Virgo, it is time to prepare for the next generation.
- ET is the leading EU 3G project today…and
- Enormous synergies with HEP experiments