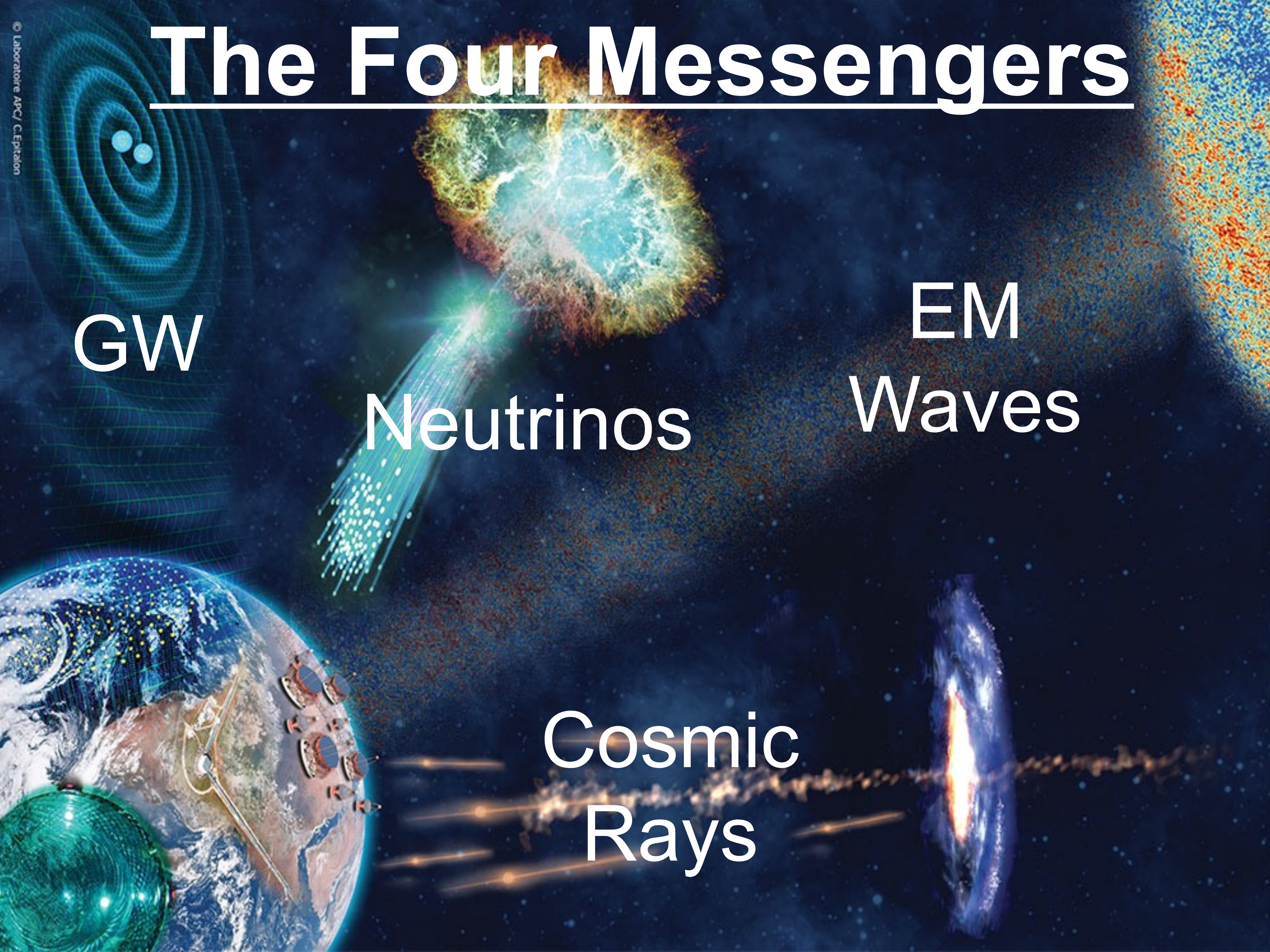
Einstein Telescope Science Case

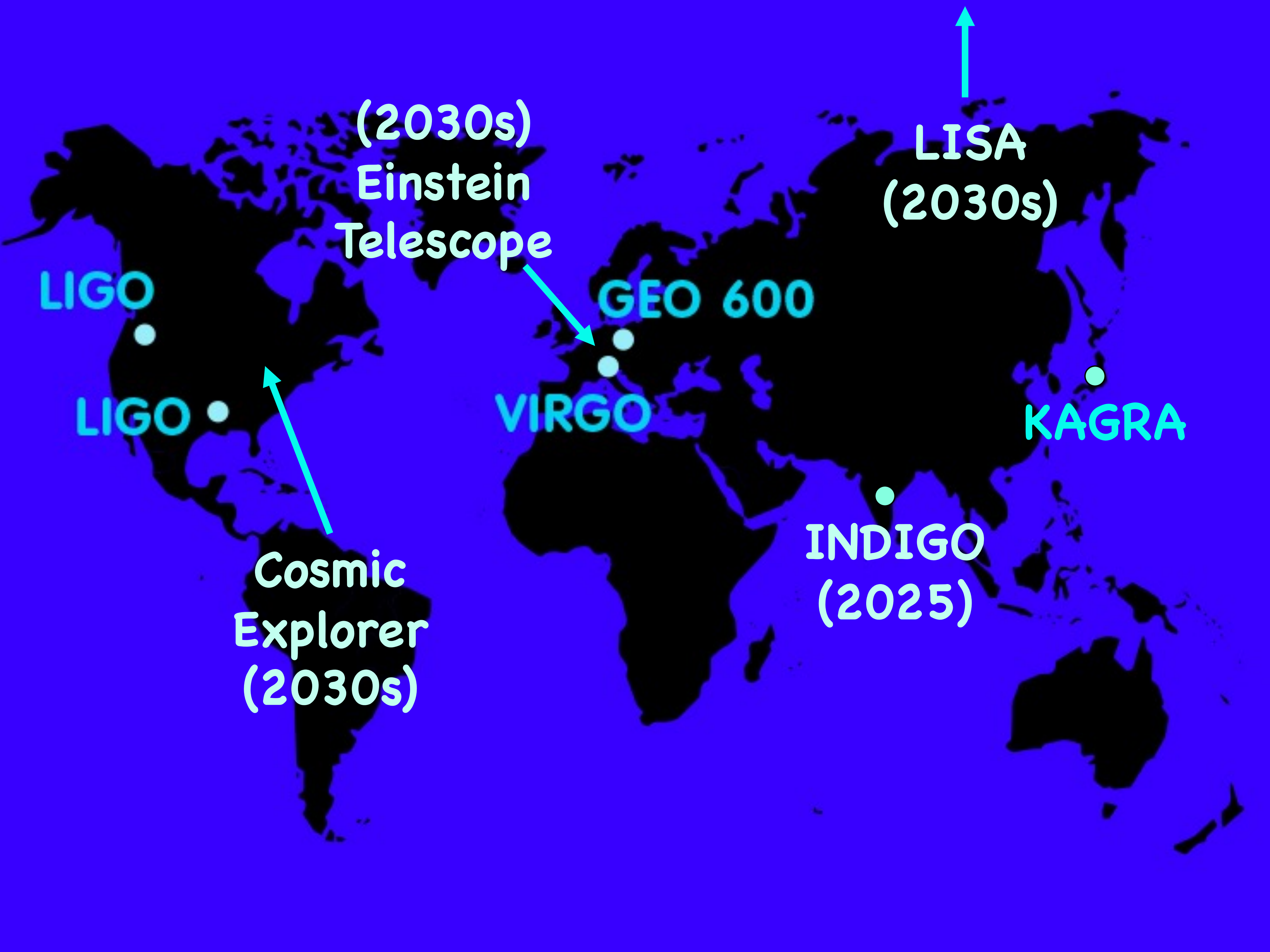
Juan García-Bellido (IFT-UAM/CSIC)

Madrid, 8th Oct 2021

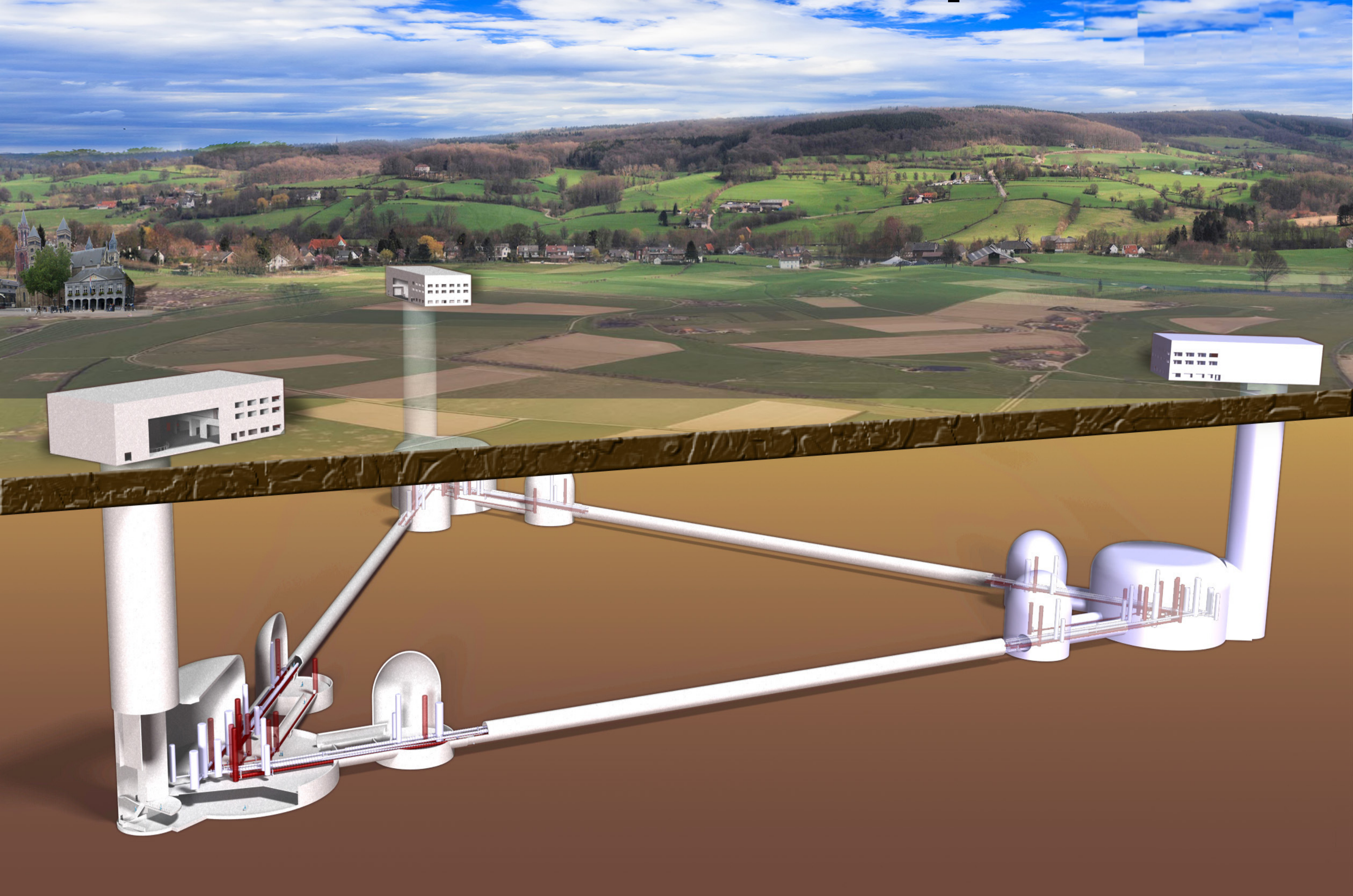
[Based on ET CDR 2019 &
ET Obs Science Board 21-22 Sep 2021
https://indico.ego-gw.it/event/240/]

CSIC
Consejo Superior de Investigaciones Científicas
Excelencia Severo Ochoa
ift Instituto de Física Teórica UAM-CSIC
UAM Universidad Autonoma de Madrid

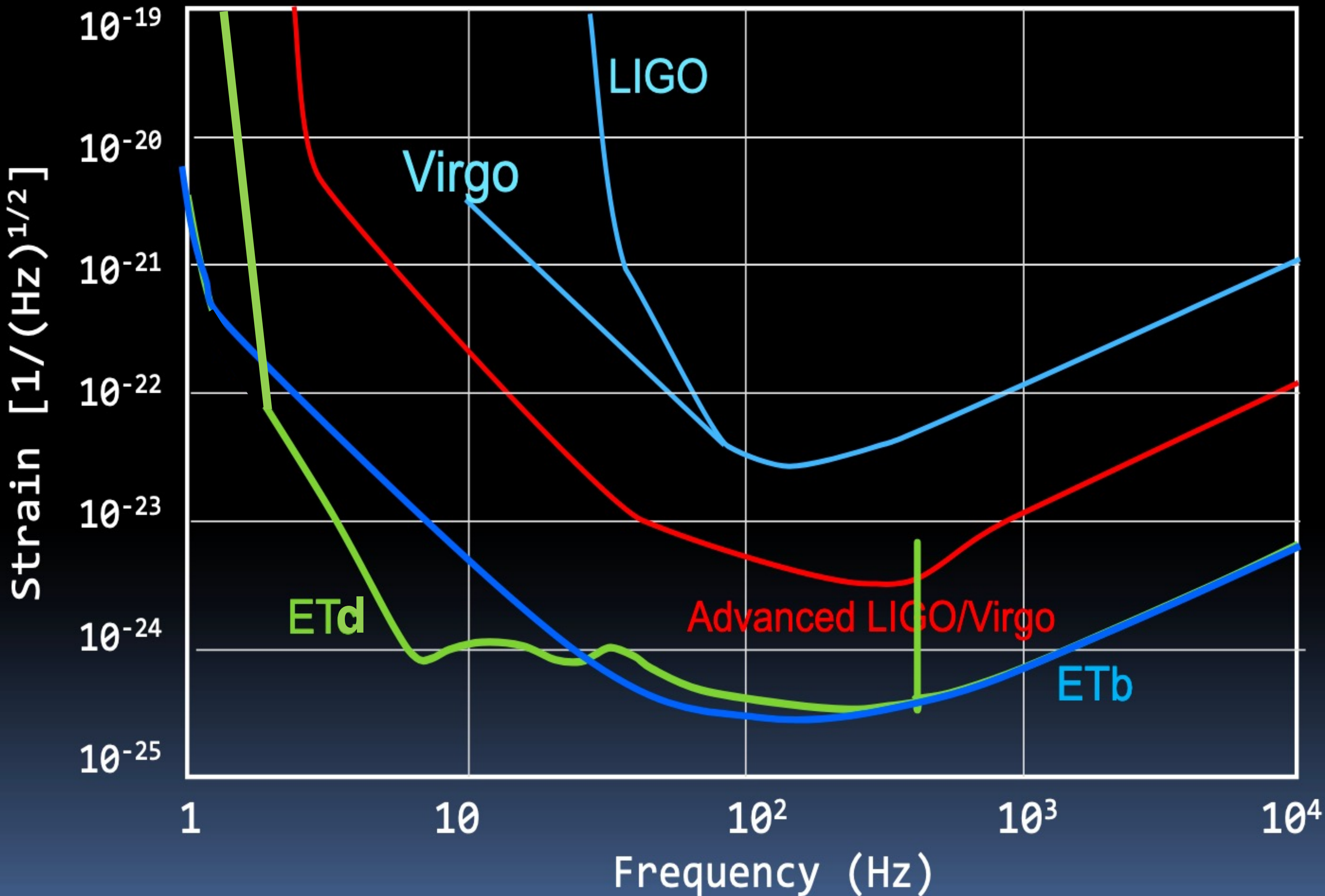

The Four Messengers
GW
Neutrinos
EM
Waves
Cosmic
Rays
© Laboratoire APC/ C.Epitalon


(2030s)
Einstein
Telescope
LISA
(2030s)
LIGO
GEO 600
LIGO
VIRGO
KAGRA
INDIGO
(2025)
Cosmic
Explorer
(2030s)

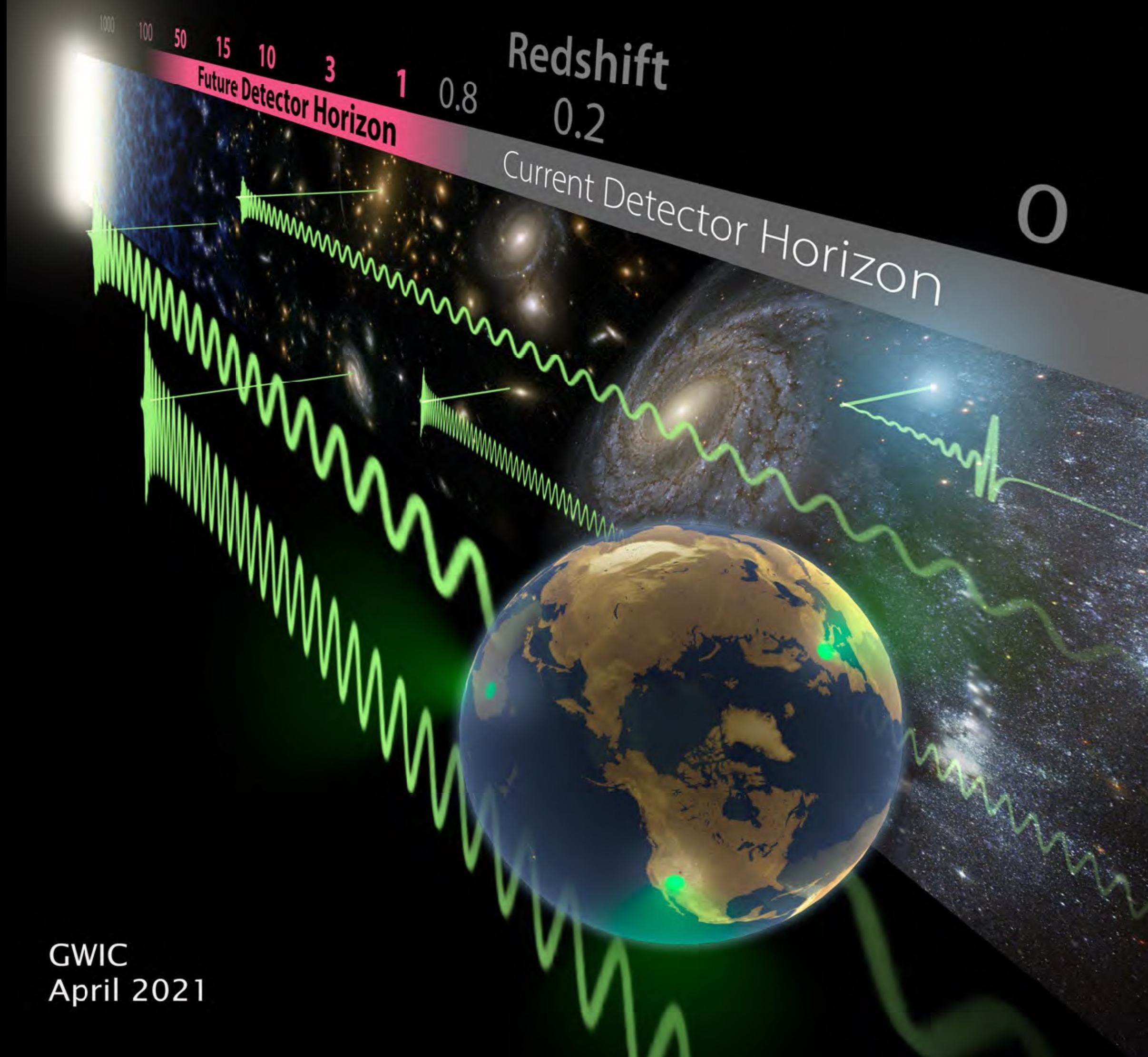
Einstein Telescope



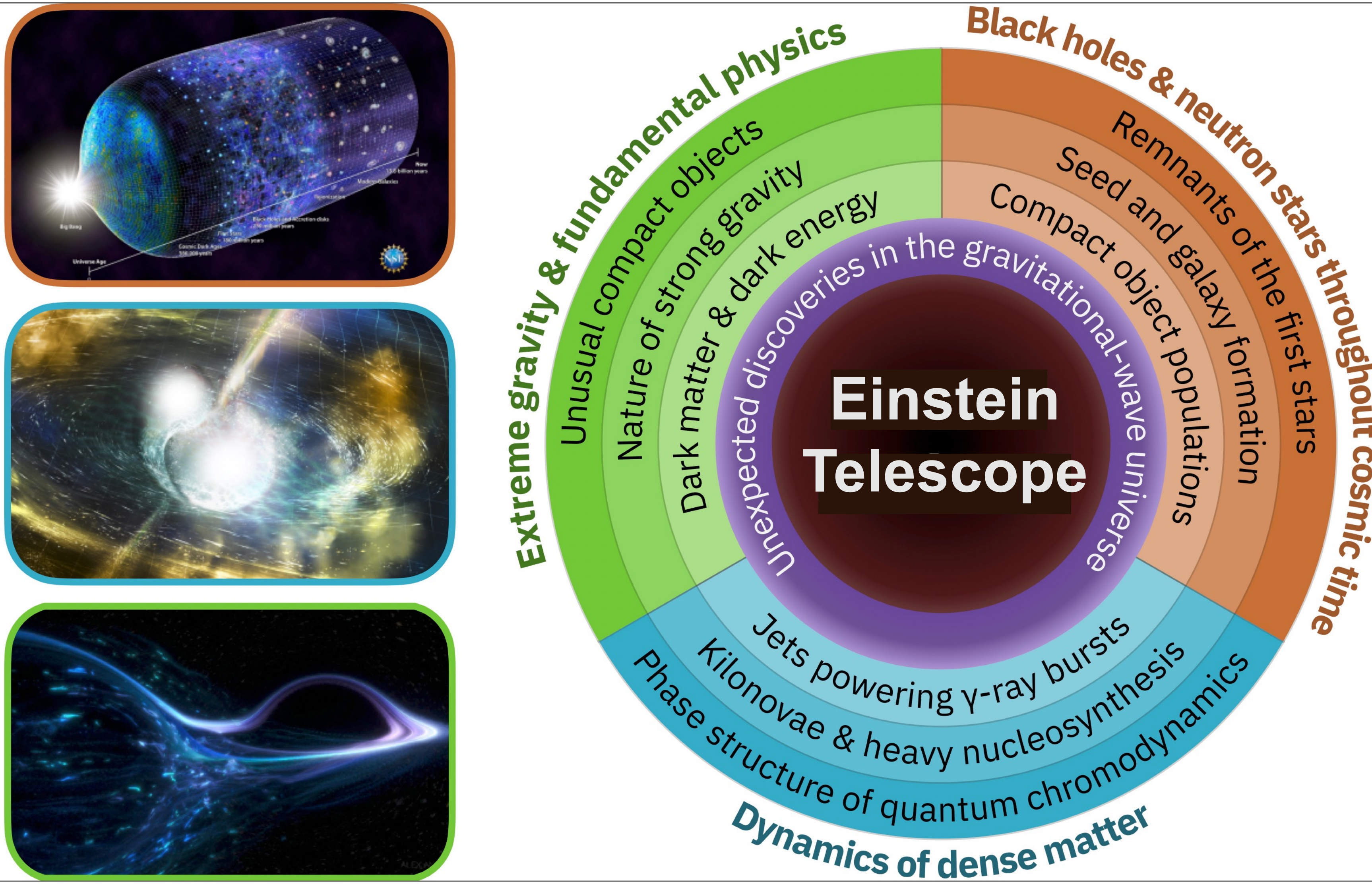
Sensitivity ET vs LIGO



Expanding the Reach of Gravitational Wave Astronomy to the Edge of the Universe



GWIC
April 2021


Einstein Telescope
Unexpected discoveries in the gravitational-wave universe
Extreme gravity & fundamental physics
Unusual compact objects
Nature of strong gravity
Dark matter & dark energy
Black holes & neutron stars throughout cosmic time
Remnants of the first stars
Seed and galaxy formation
Compact object populations
Dynamics of dense matter
Jets powering γ-ray bursts
Kilonovae & heavy nucleosynthesis
Phase structure of quantum chromodynamics

Main Scientific Objectives

- Fundamental Physics and tests of GR
  - Nature of Gravity and Compact Objects
  - Black Holes and the nature of Dark Matter
- Astrophysics of compact objects
  - Black Hole Binaries
  - Neutron Stars and Supernovae
  - Multi-messenger Astrophysics
- Cosmology and Cosmography
  - Stochastic Backgrounds
  - Cosmological parameters

Probing Gravity at all scales

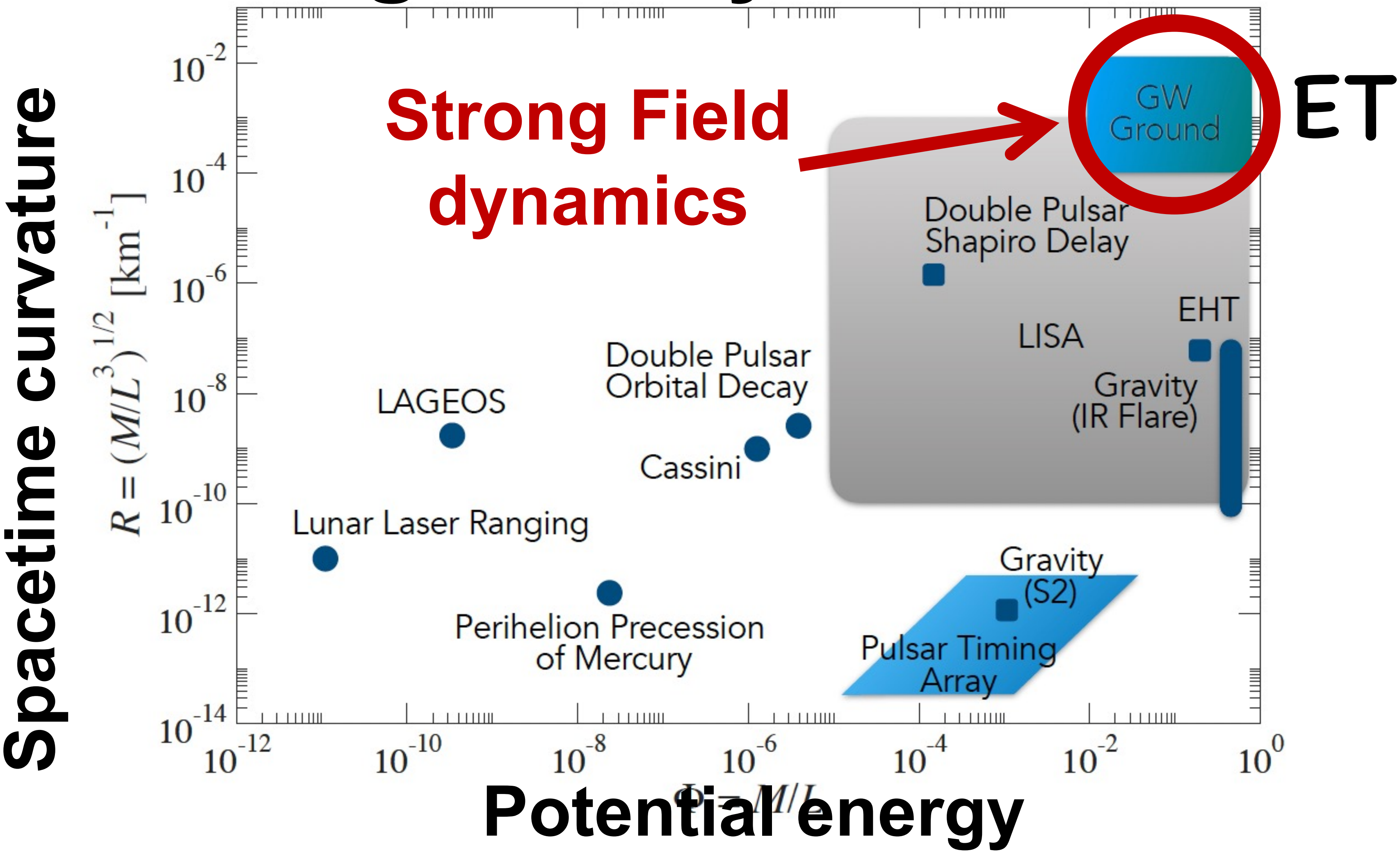
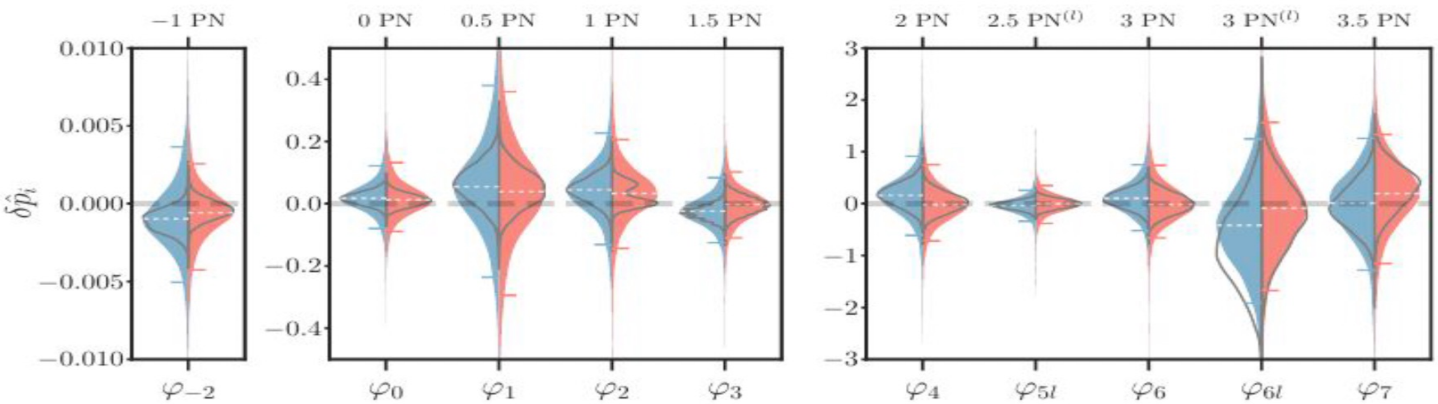
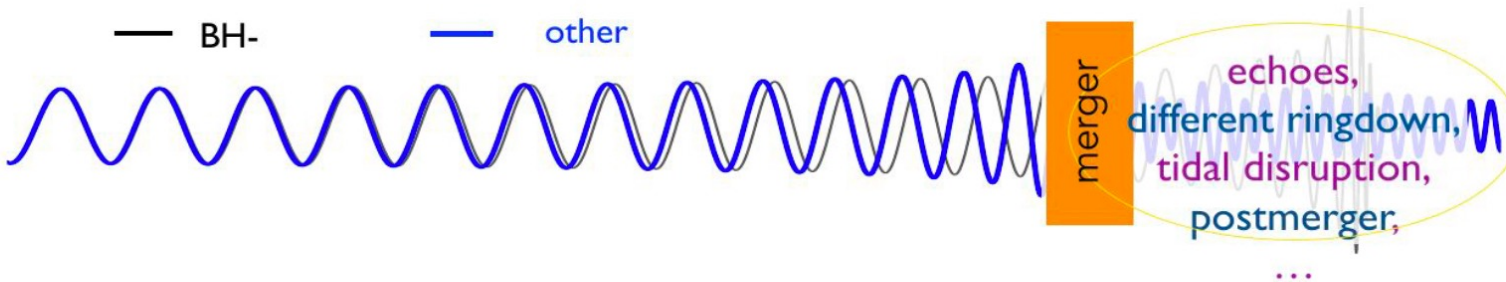


Figure 8. Probing gravity at all scales: illustration of the reach in spacetime curvature versus potential energy targeted by different kinds of observations. M and L are the characteristic mass and length involved in the system or process being observed. The genuinely strong-field dynamics of spacetime manifests itself in the top right of the diagram. The label EHT refers to the Event Horizon Telescope. From ref. [86].

Tests Gravity & Compact Objects



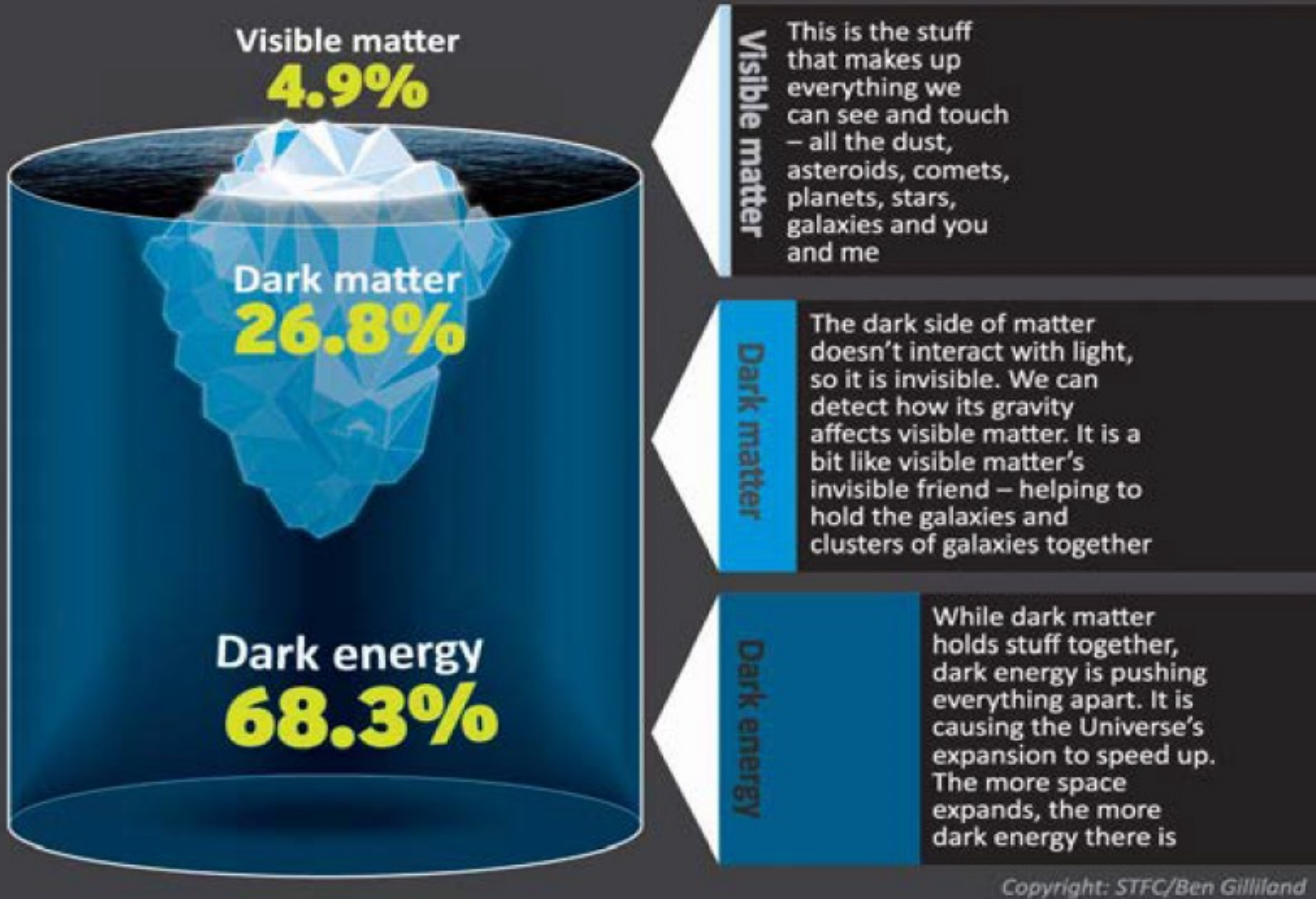


~point masses: same signal for all objects

tidal effects* + *multipolar structure

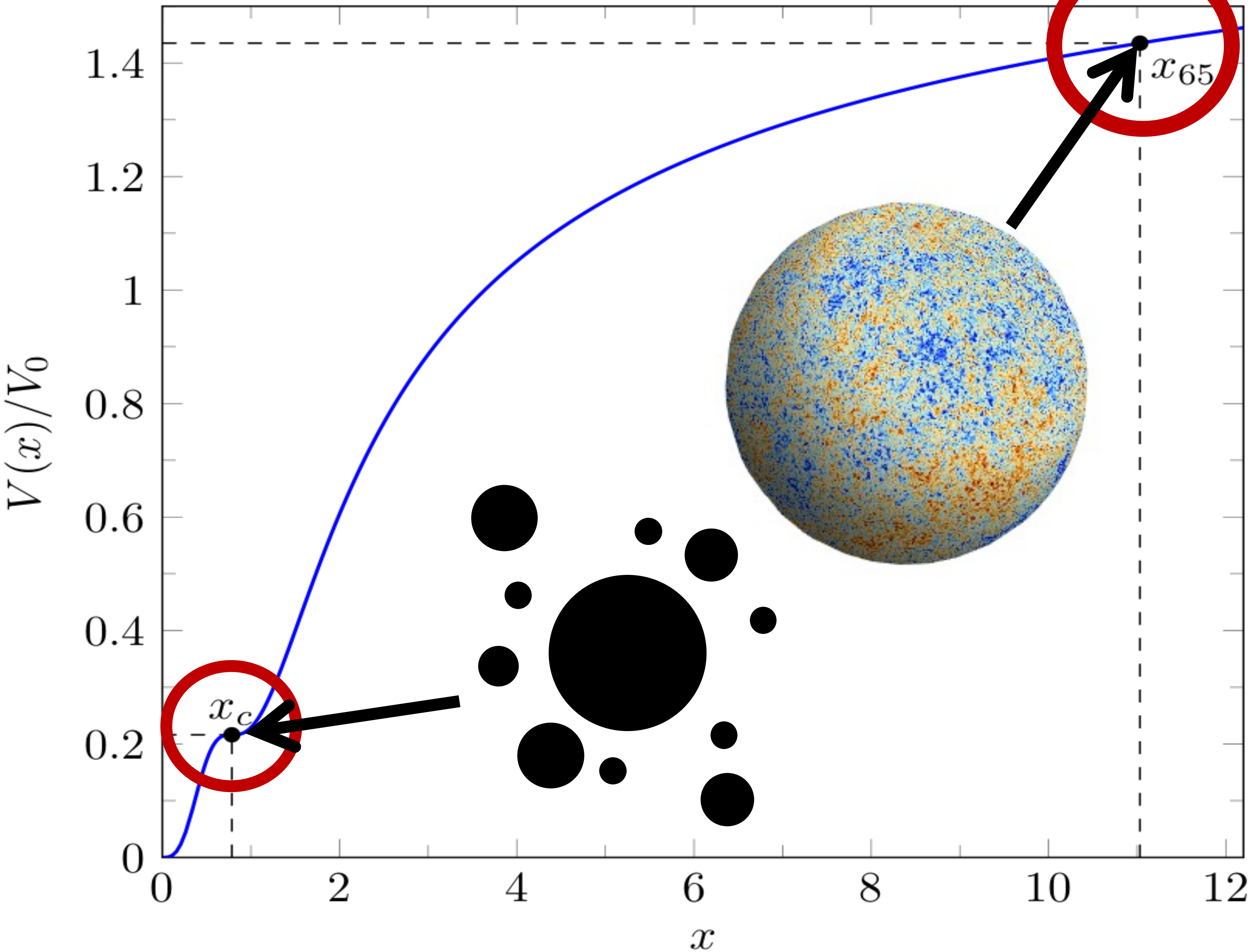
absence of horizon ***absorption effects***

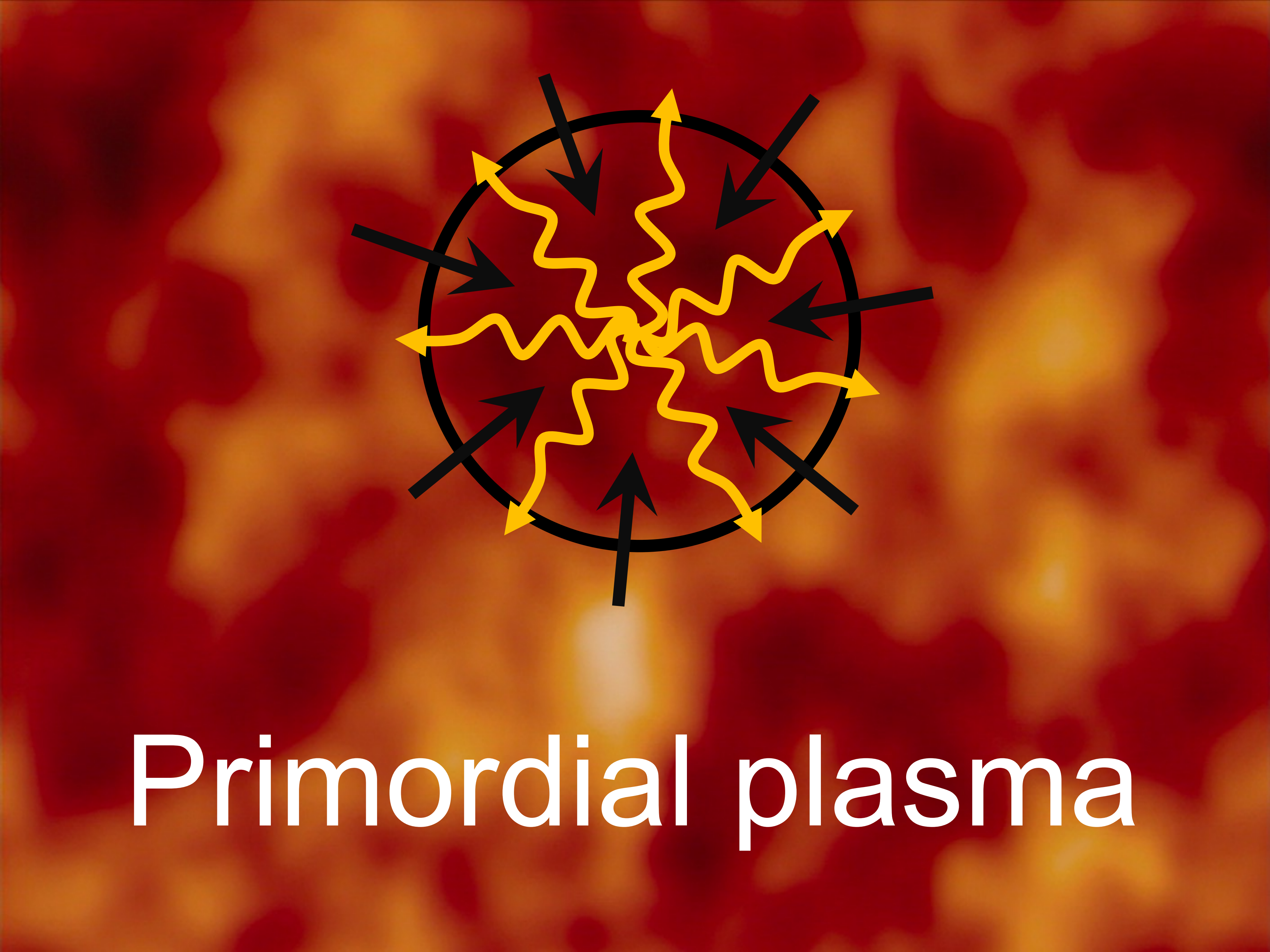
echoes



Universe Components

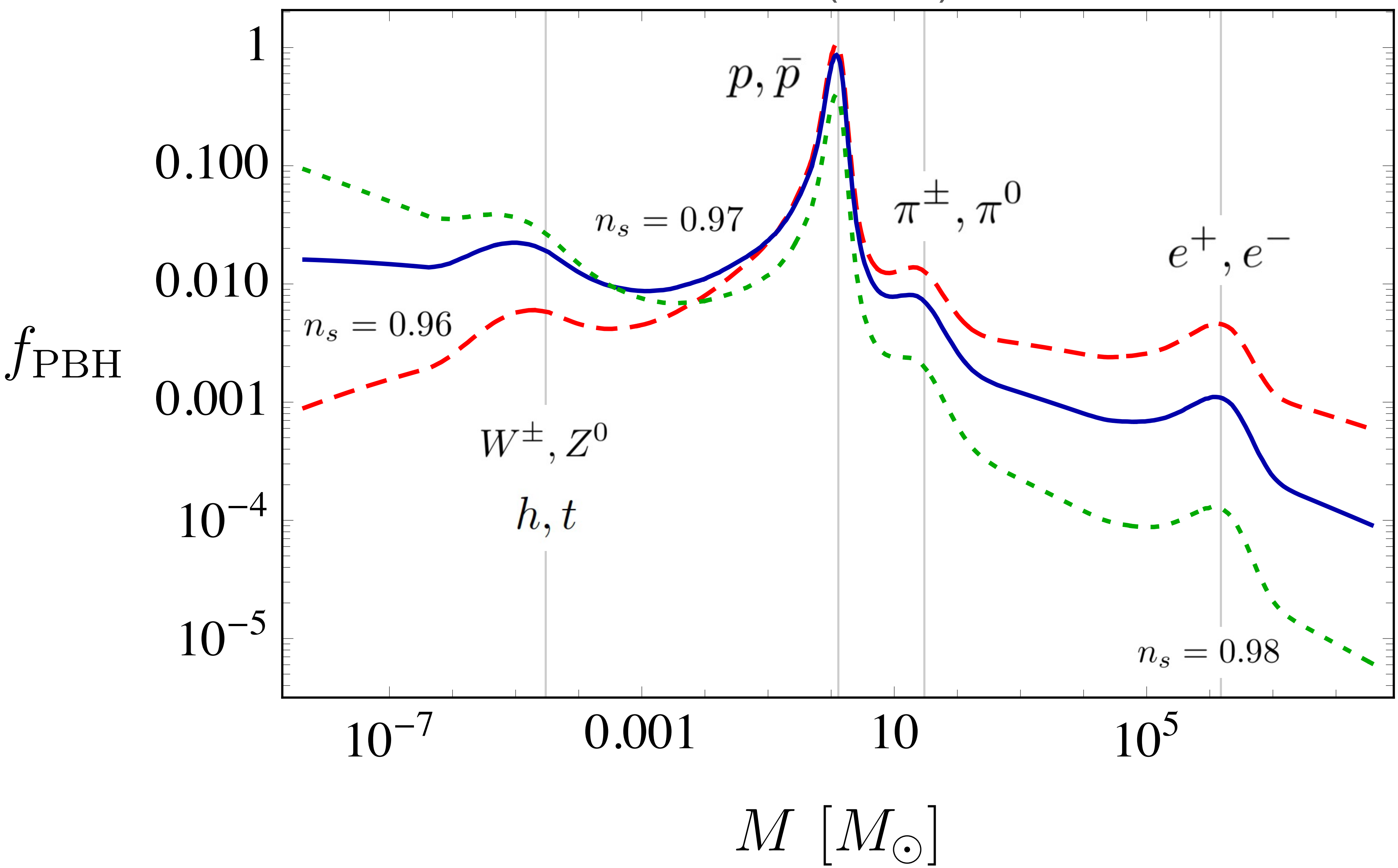
Primordial Black Holes = DM



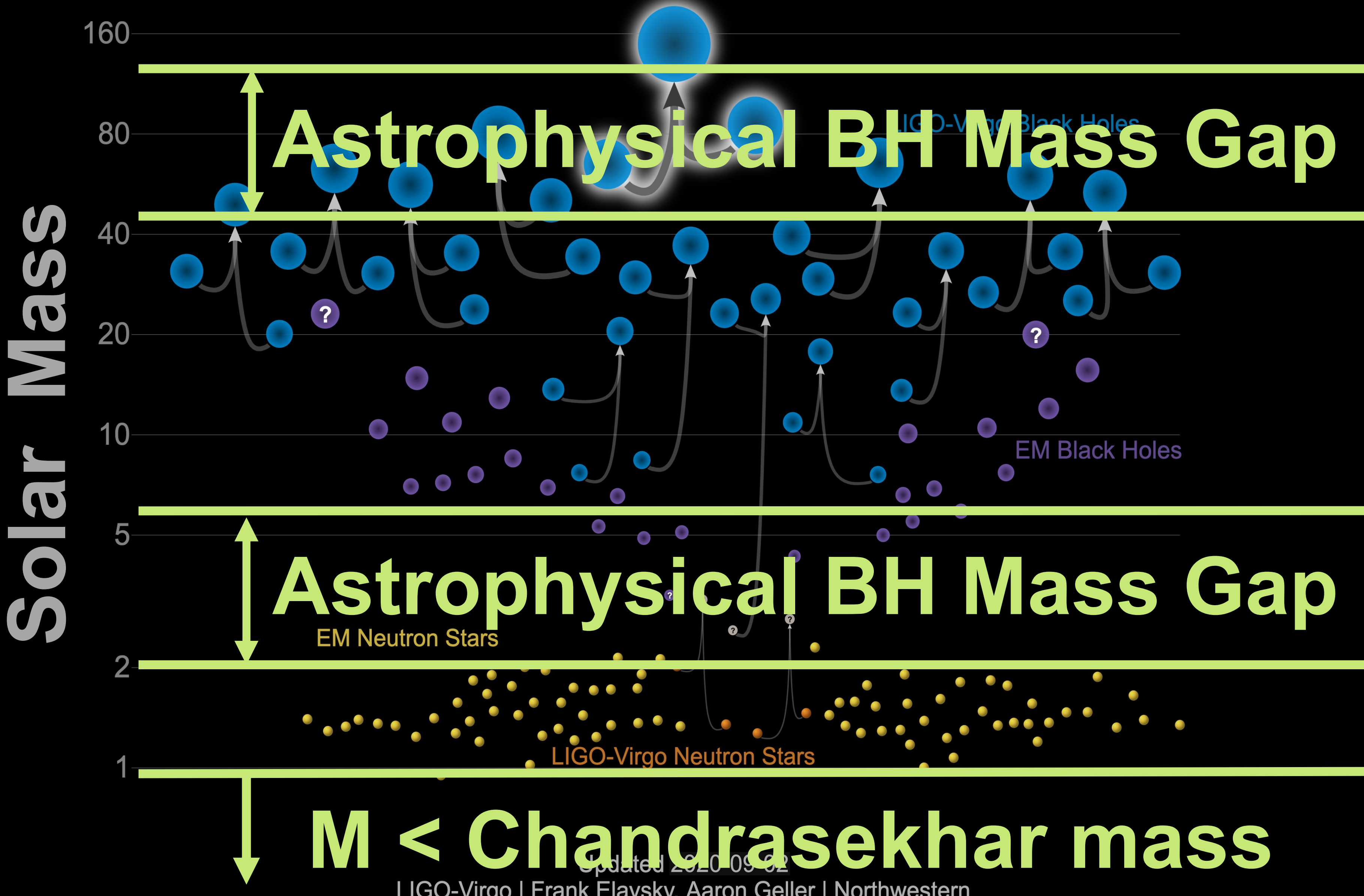

Primordial plasma

PBH mass spectrum

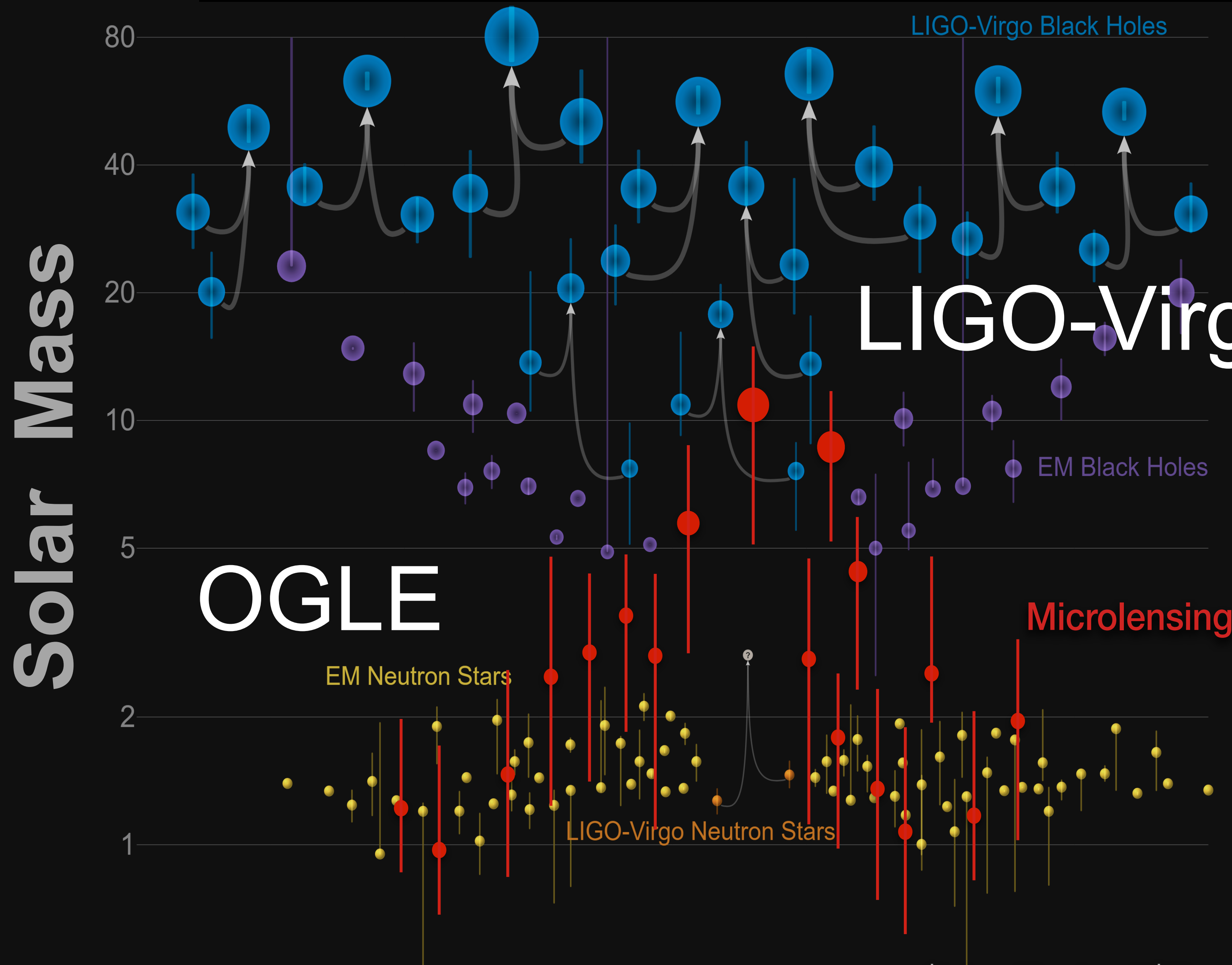
Carr, Clesse, JGB, Kühnel (2019)



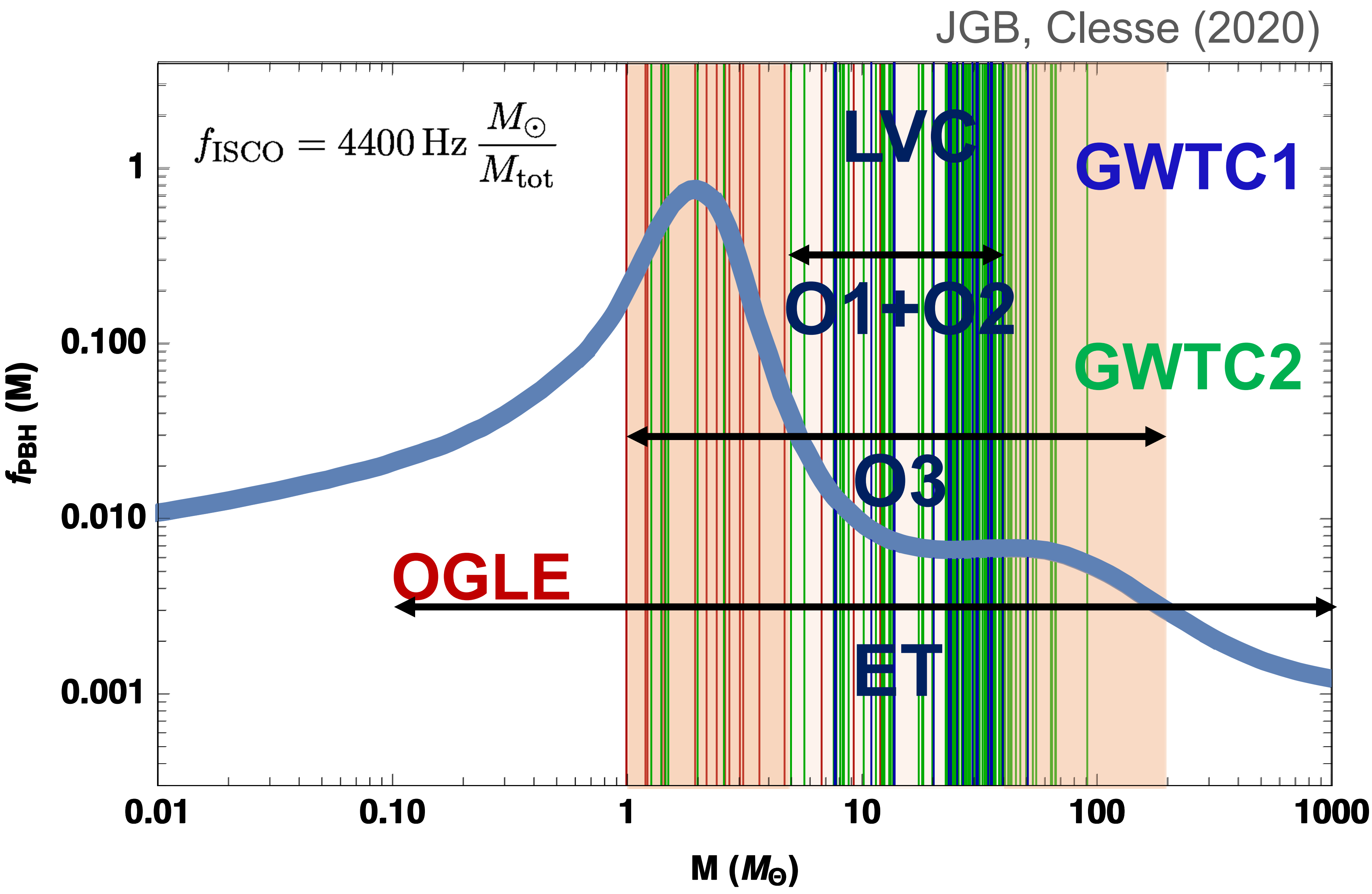
Black Holes and Neutron Stars



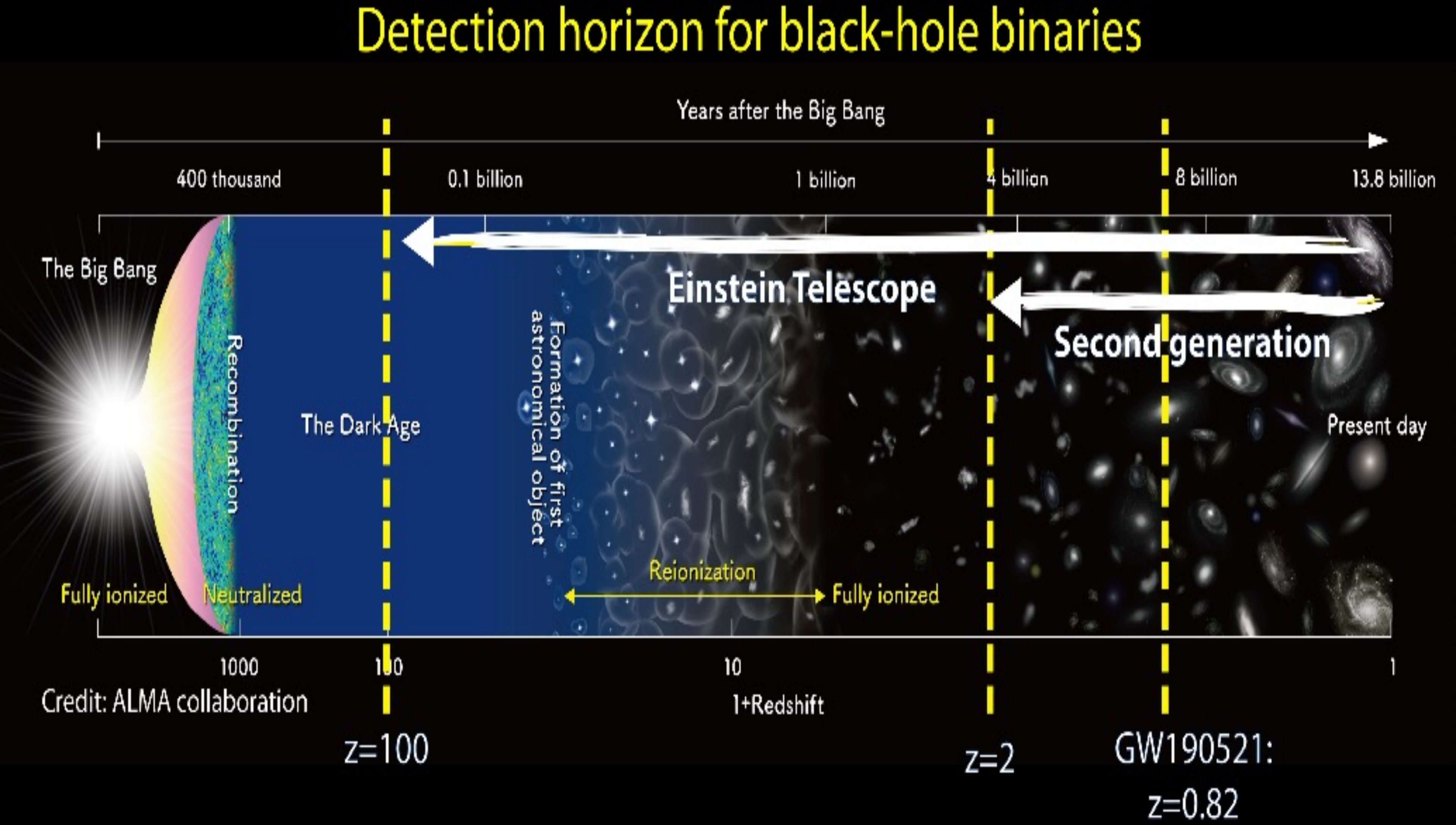
Black Holes and Neutron Stars



Model prediction: mass spectrum



Einstein Telescope (G3)



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Black Hole Binaries

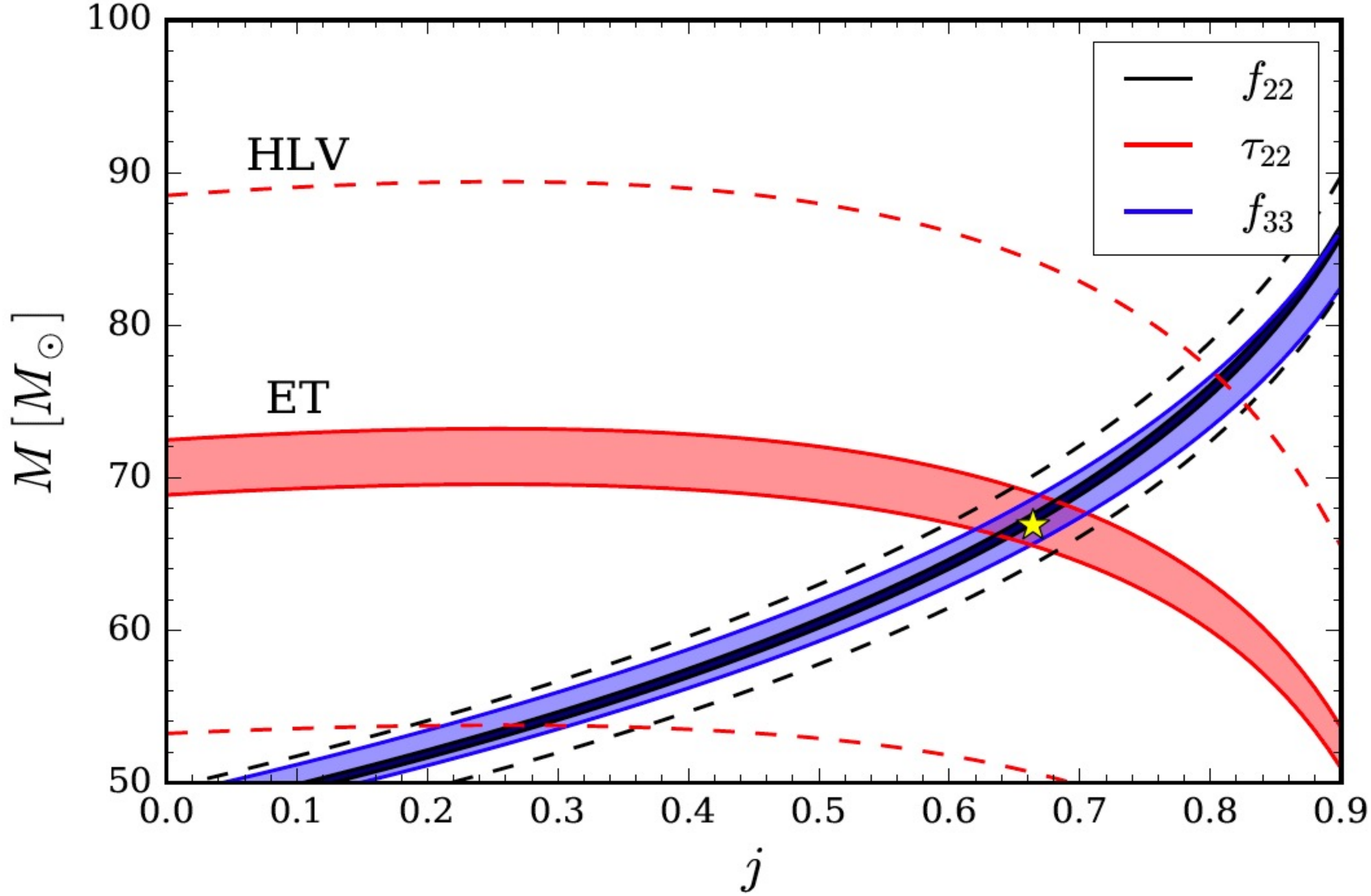
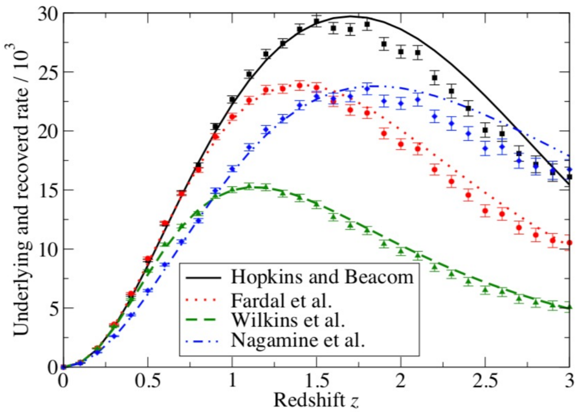


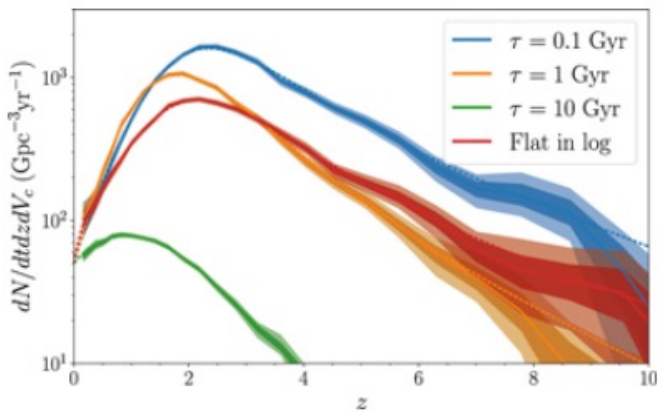
Figure 9. Testing the nature of black holes by using two quasi-normal modes and checking that the characteristic frequencies f_{22} and f_{33} and the damping time τ_{22} are consistent with each other, given that for ordinary black holes these can only depend on two numbers, namely the final mass M and final spin j. The estimates are for the "ringdown" of the remnant black hole arising from a binary similar to the source of GW150914. The dashed curves marked HLV are the 95% confidence regions one would obtain from Advanced LIGO-Virgo, while the colored bands are for ET. The star indicates the true values of M and j. Figure adapted from ref. [89].

Tracking Star Formation & Multiple BBH Populations

✧ Distinguish star formation models up to z~10

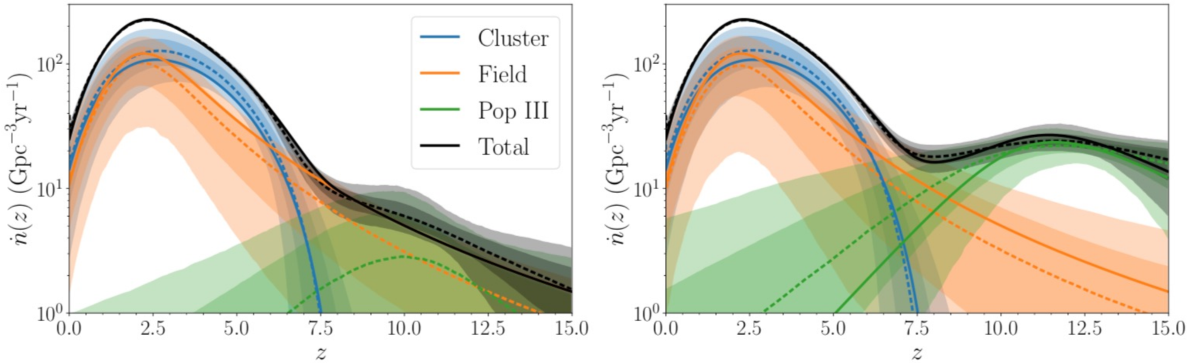


ET Design Study (2011)



Vitale *et al* 2019 *ApJL* **886** L1

✧ Reconstruct history of multiple BBH channels incl. Pop III mergers



(a) $f_{\rm III} = 0$ (b) $f_{\rm III} = 0.024$

Ng *et al* 2021 *ApJL* **913** L5

Binary Neutron Stars Mergers

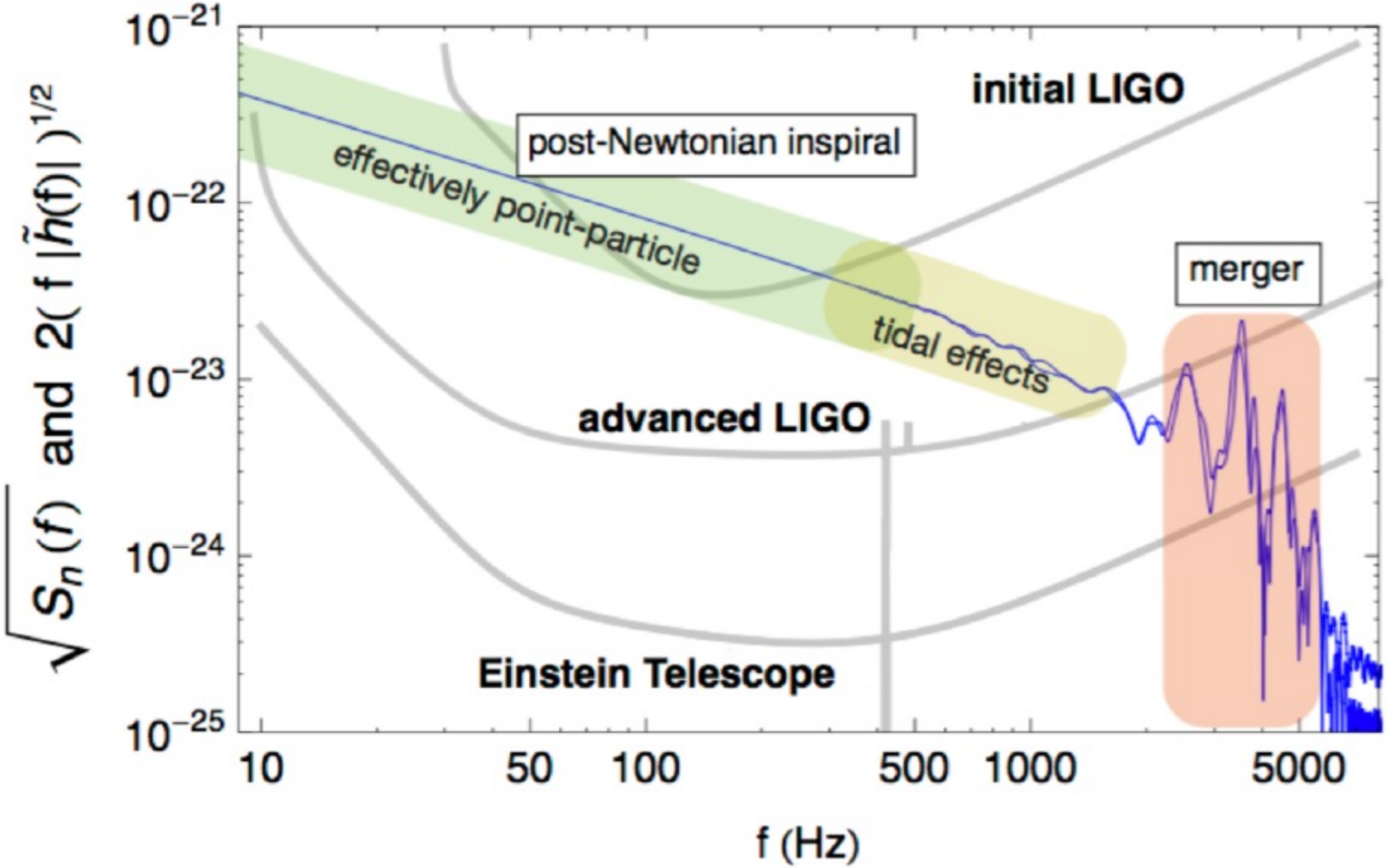


Figure 4. Gravitational wave signal from a NS-NS merger at a distance 100 Mpc, as it sweeps across the detector-accessible frequency range. Figure from [37] (adapted from an original figure by J. Read, based on data from [38]).

Neutron Stars and QCD phases

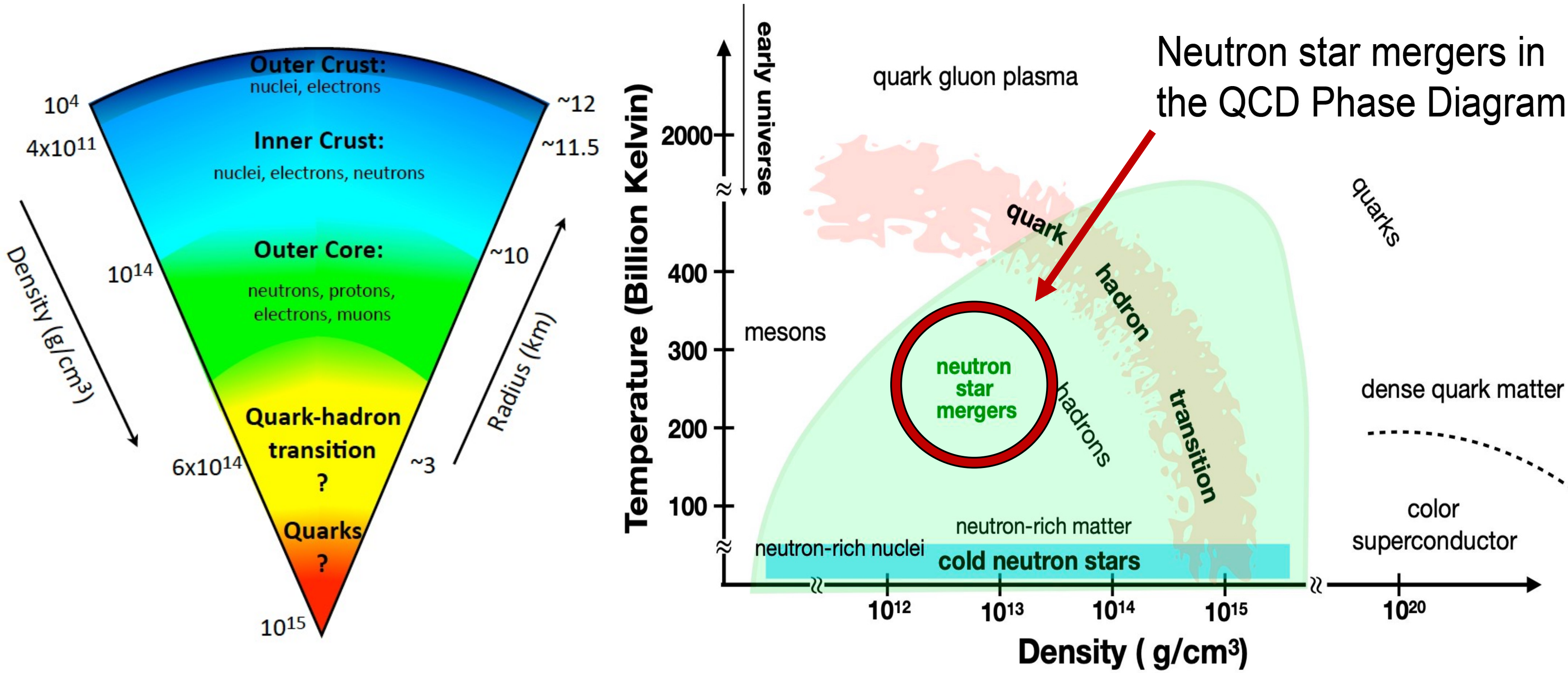
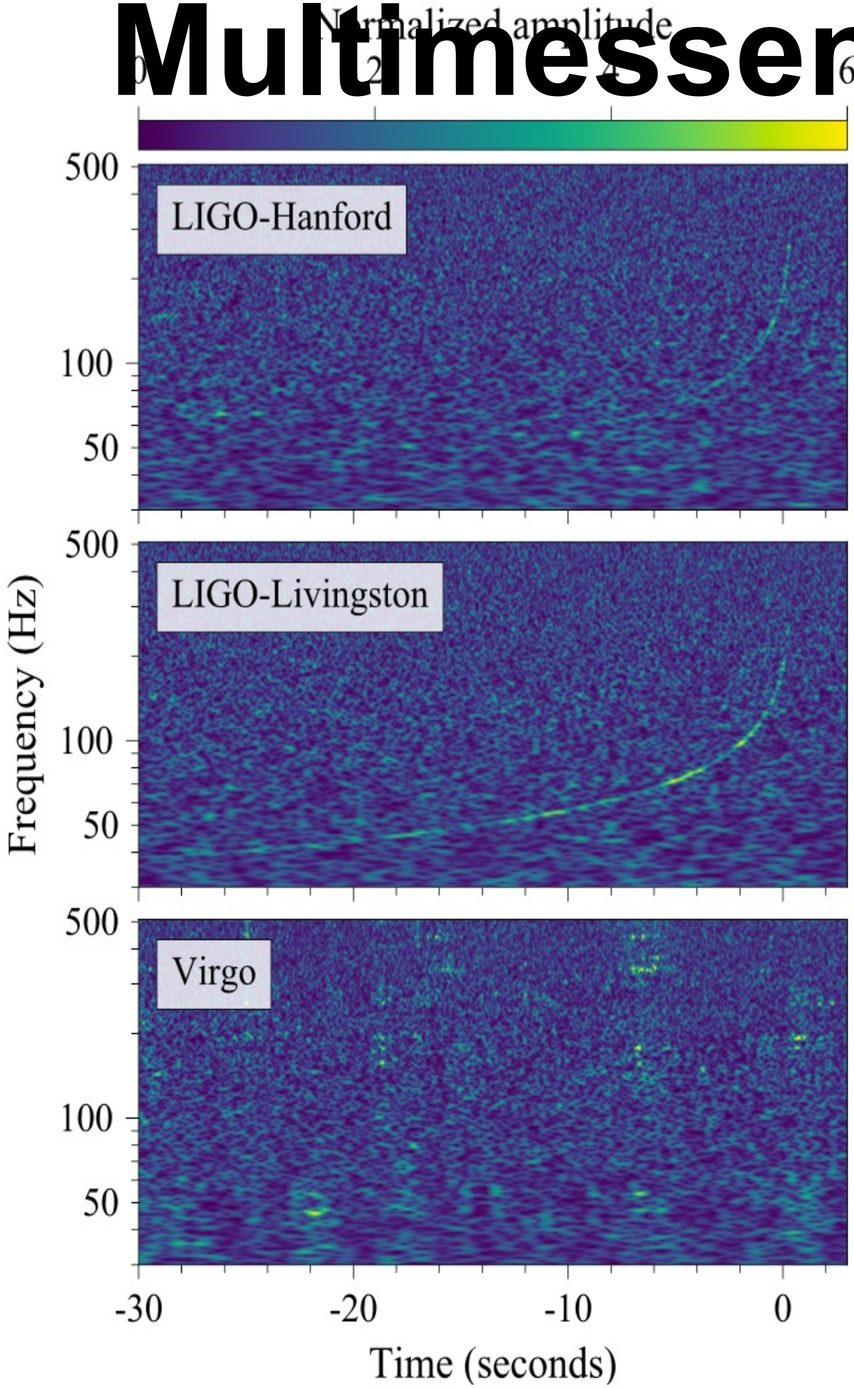
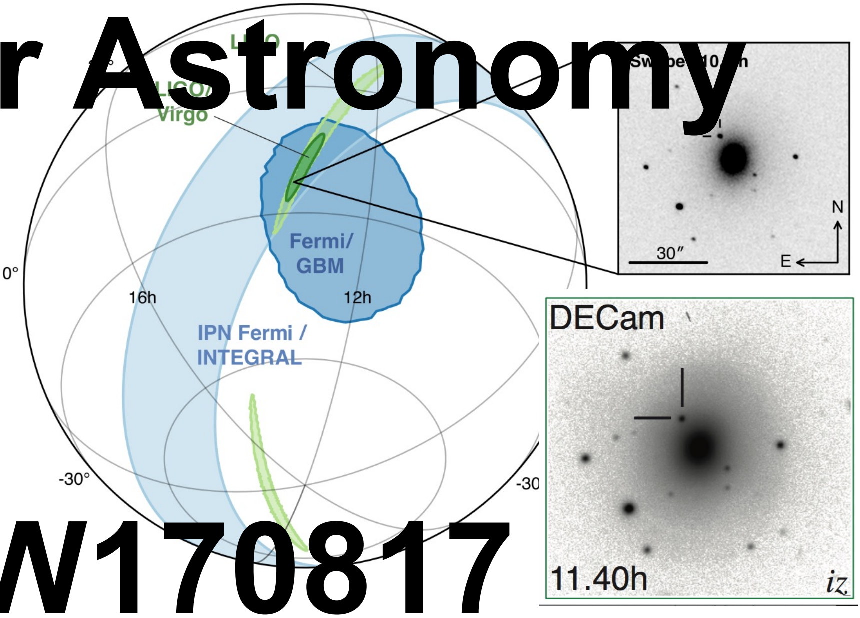


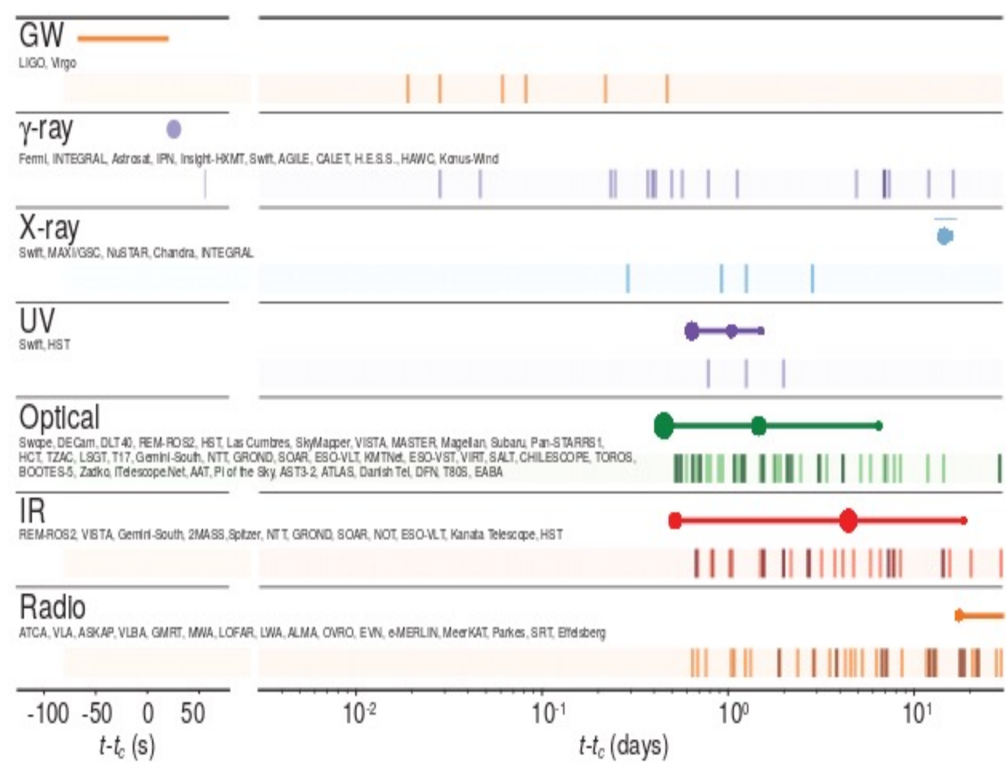
Figure 3. Left: Conjectured interior structure of a neutron star. Right: Matter encountered in neutron stars and binary mergers explores a large part of the QCD phase diagram in regimes that are inaccessible to terrestrial collider experiments.

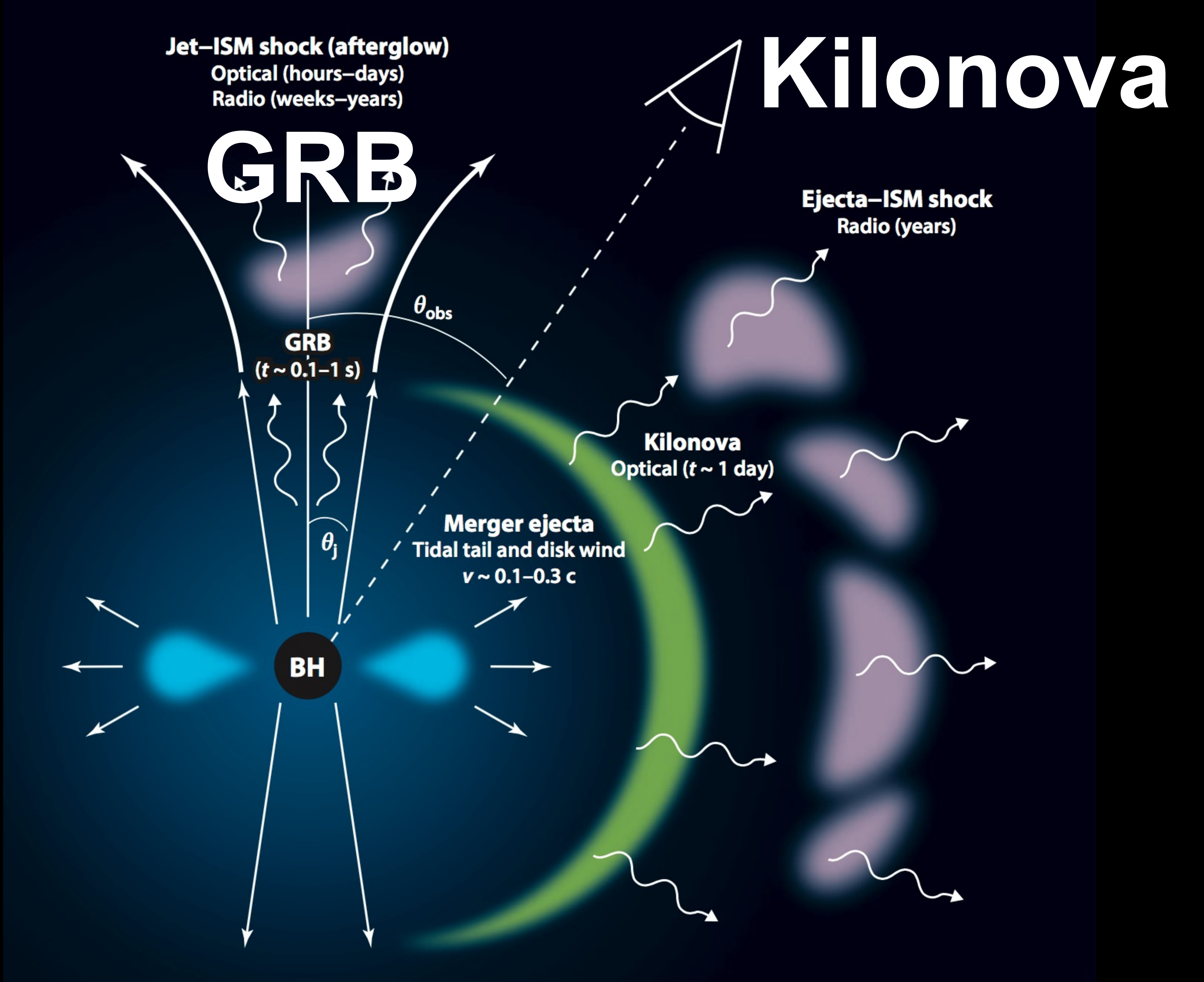
Multimessenger Astronomy



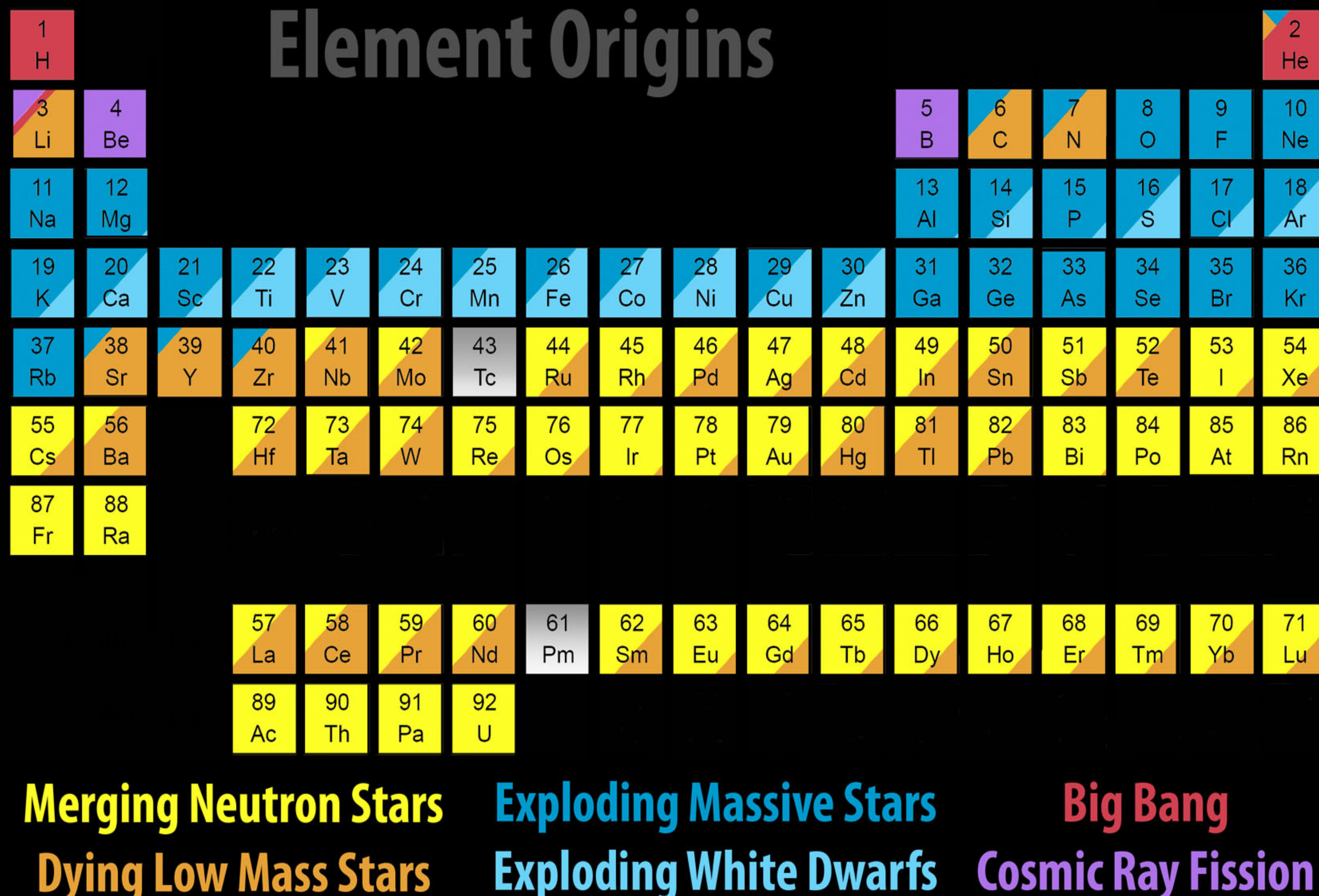


GW170817





Kilonova
Jet–ISM shock (afterglow)
Optical (hours–days)
Radio (weeks–years)
GRB
Ejecta–ISM shock
Radio (years)
θ_{obs}
GRB
(t ~ 0.1–1 s)
Kilonova
Optical (t ~ 1 day)
Merger ejecta
Tidal tail and disk wind
v ~ 0.1–0.3 c
θ_j
BH



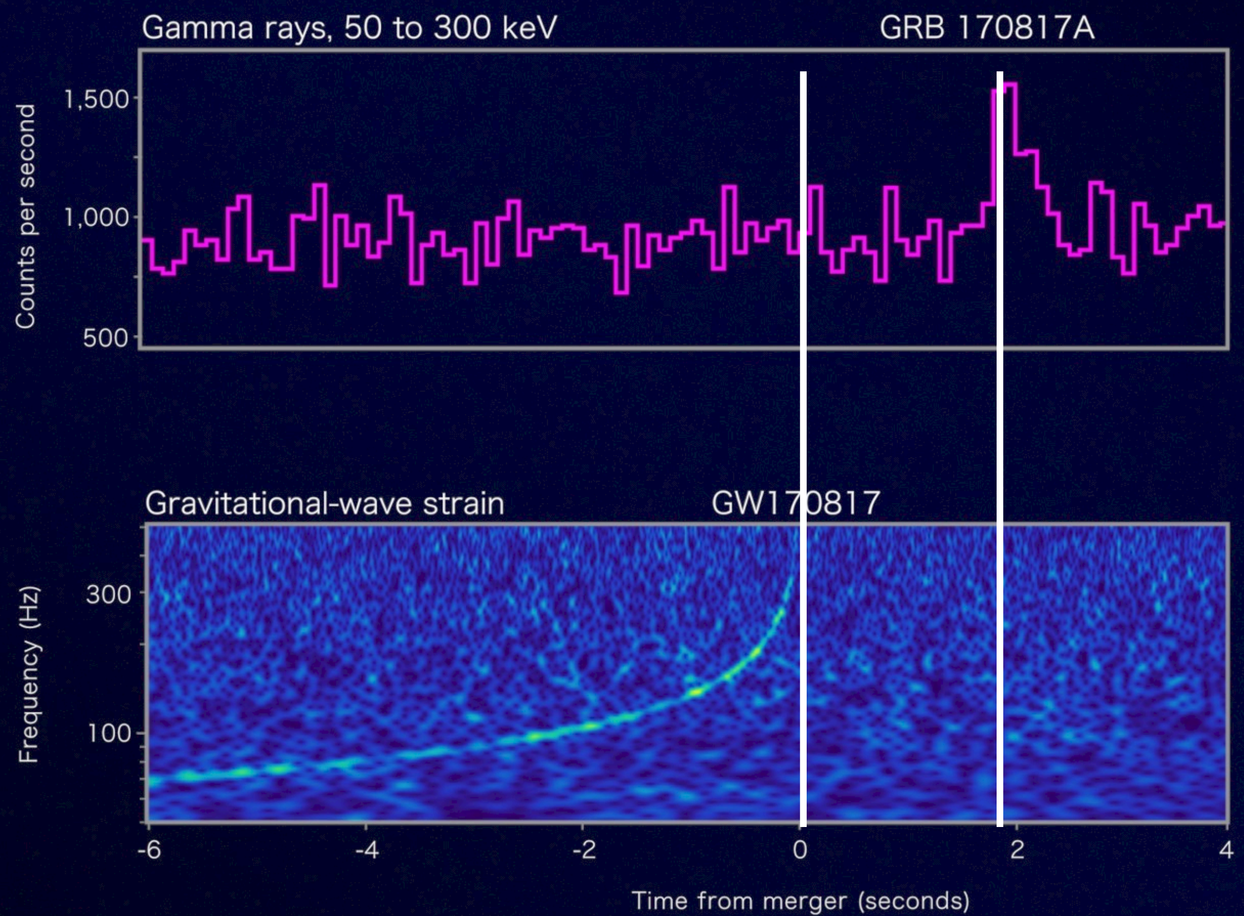
Based on graphic created by Jennifer Johnson

$c_{gw} = c_{em}$

(1.7 s in 144 Myrs)

Fermi

LIGO



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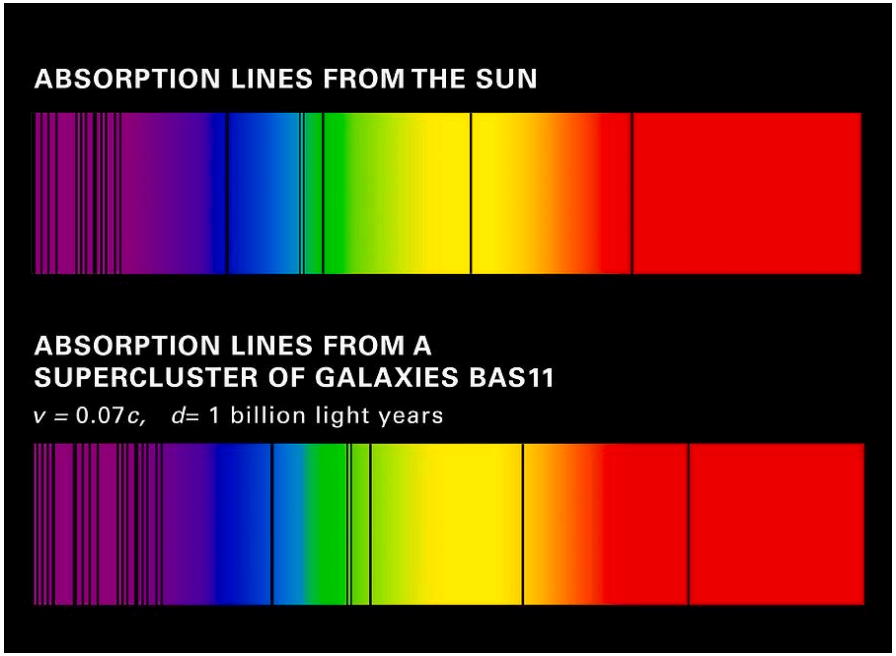
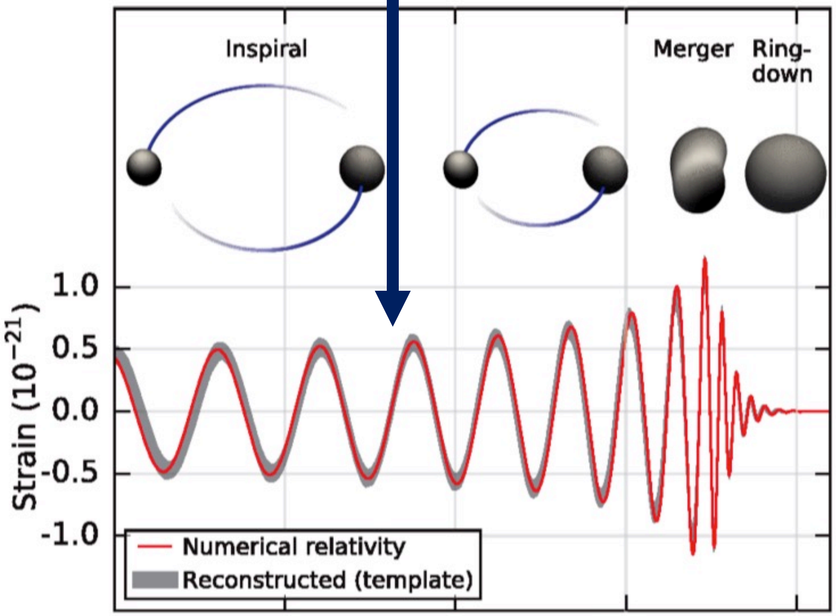
Universe Expansion

Hubble Law

$$H_0 d_L = z$$

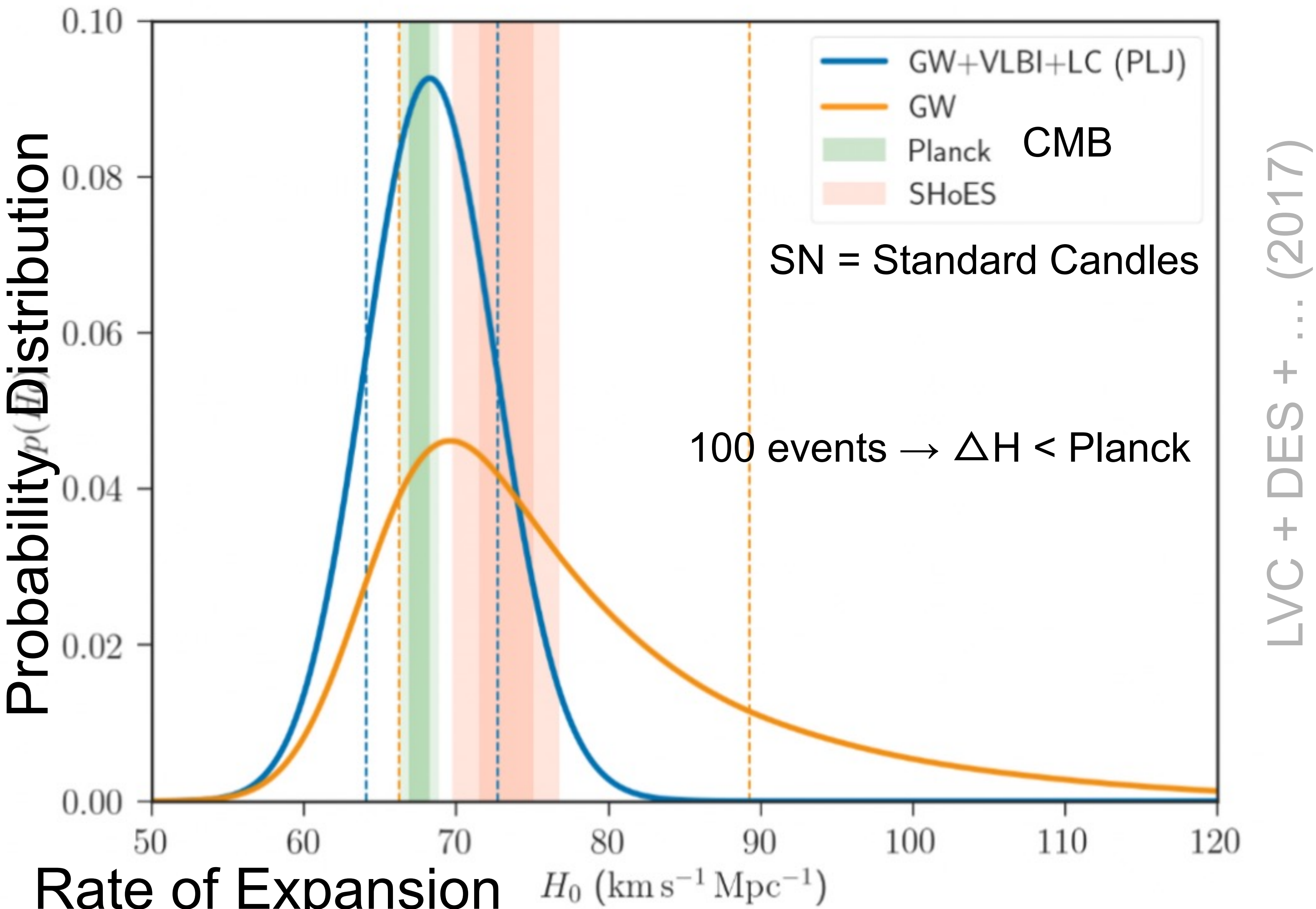




NGC4993

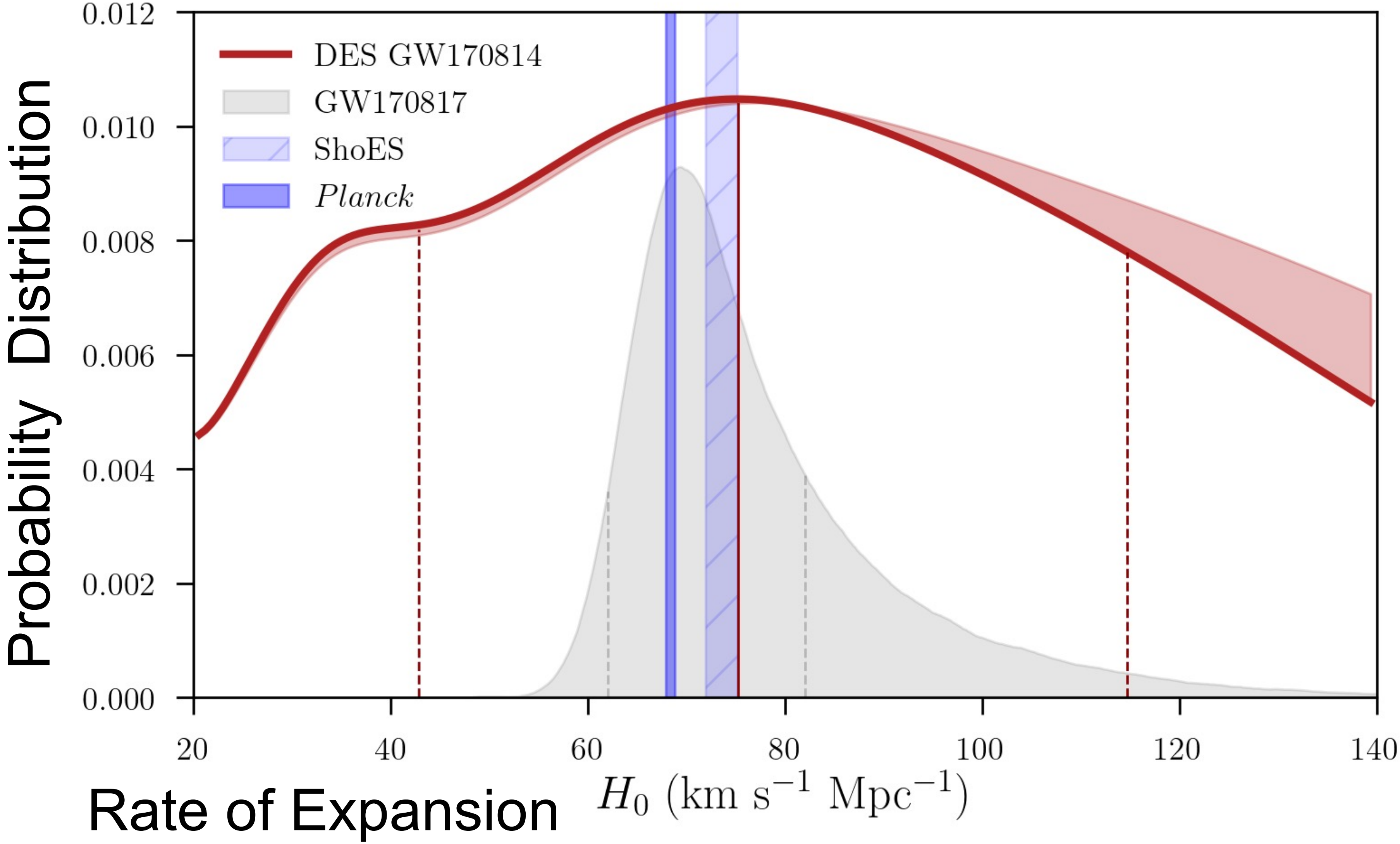
z = 0.009727

GW = Standard Sirens



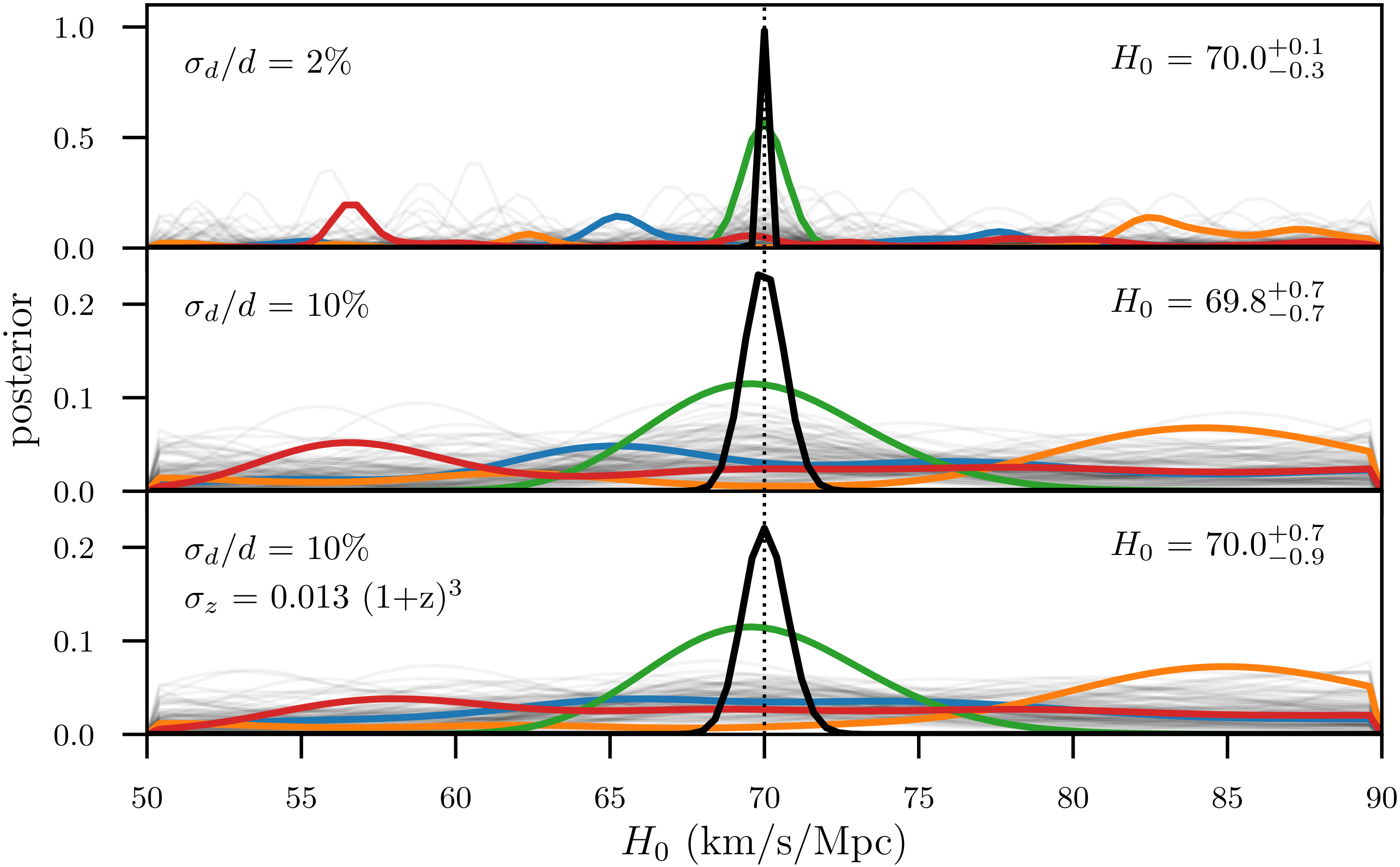
GW = Dark Sirens

Soares-Santos, Palmese, JGB et al. (2019)

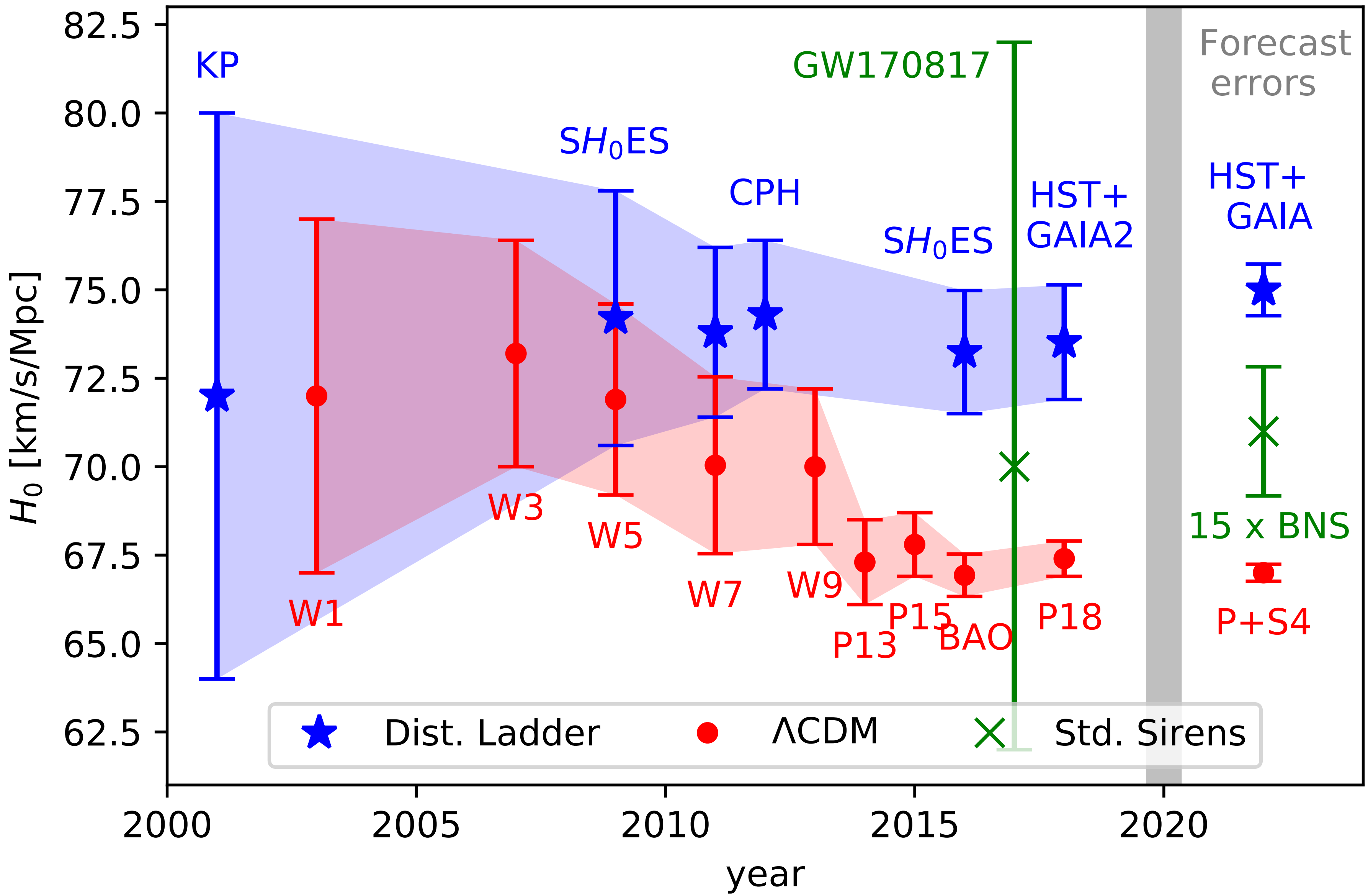


GW = Dark Sirens

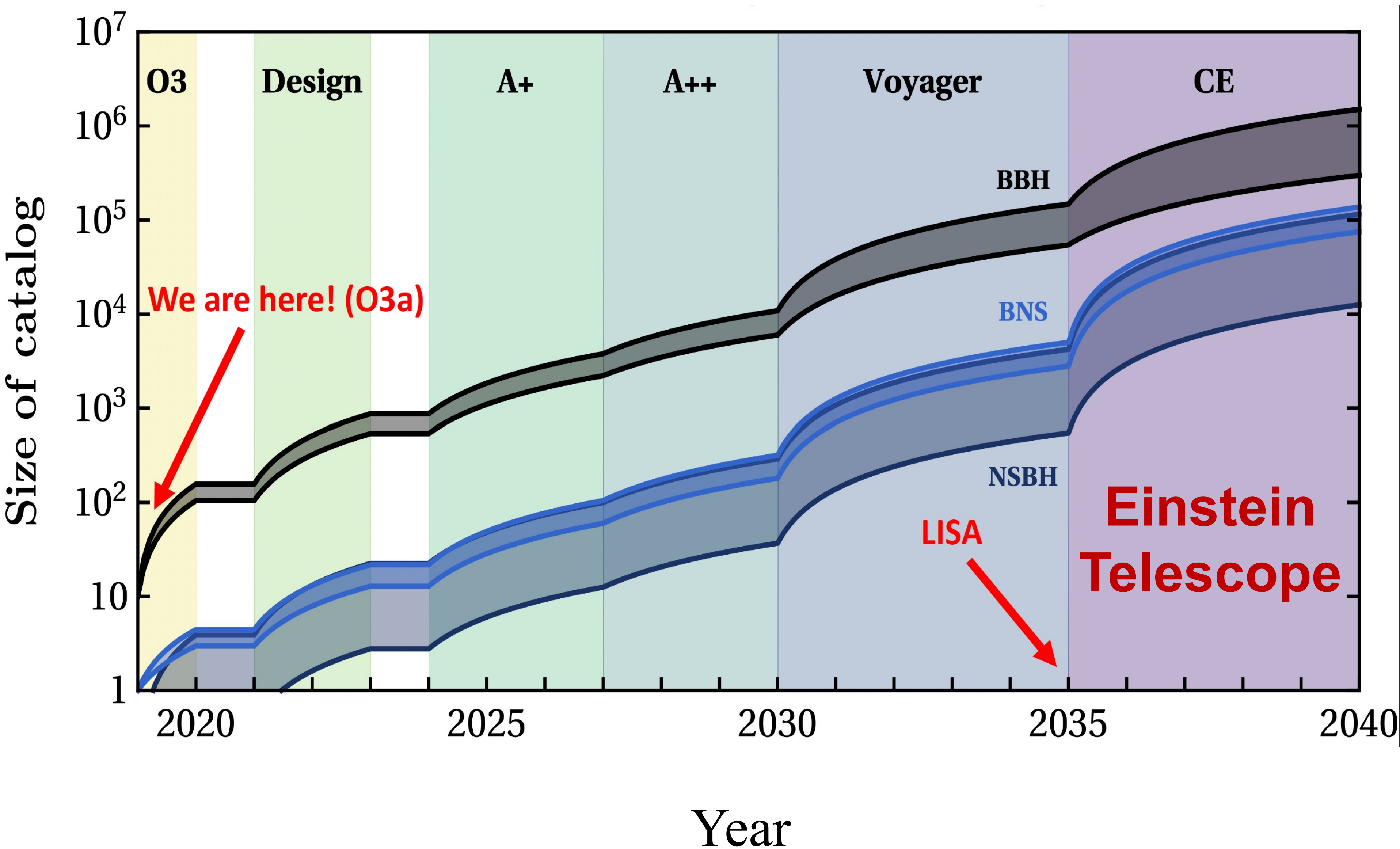
Soares-Santos, Palmese, JGB et al. (2019)



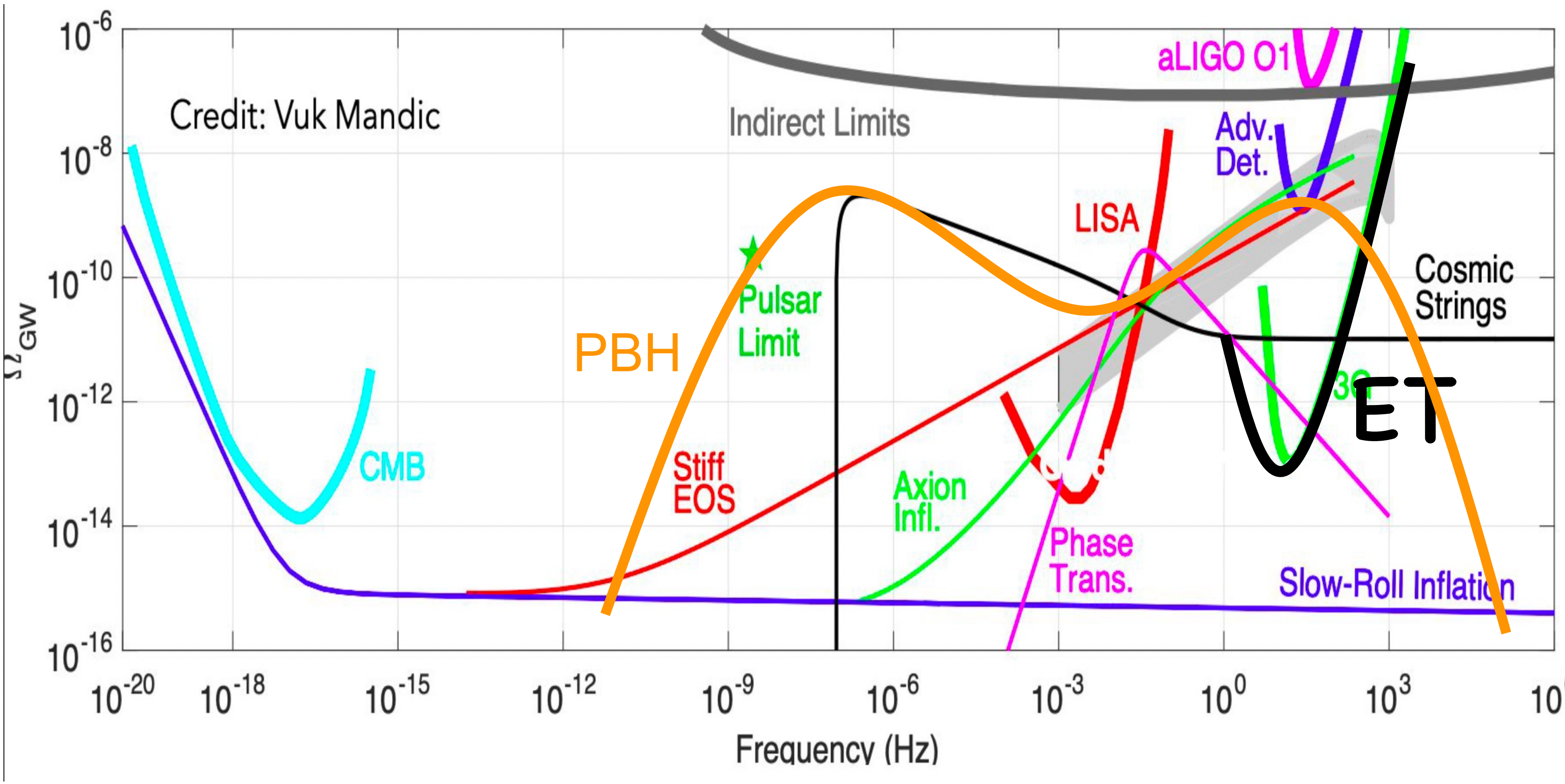
H_0 tension: Future prospects



Expected BBH, BNS, NSBH

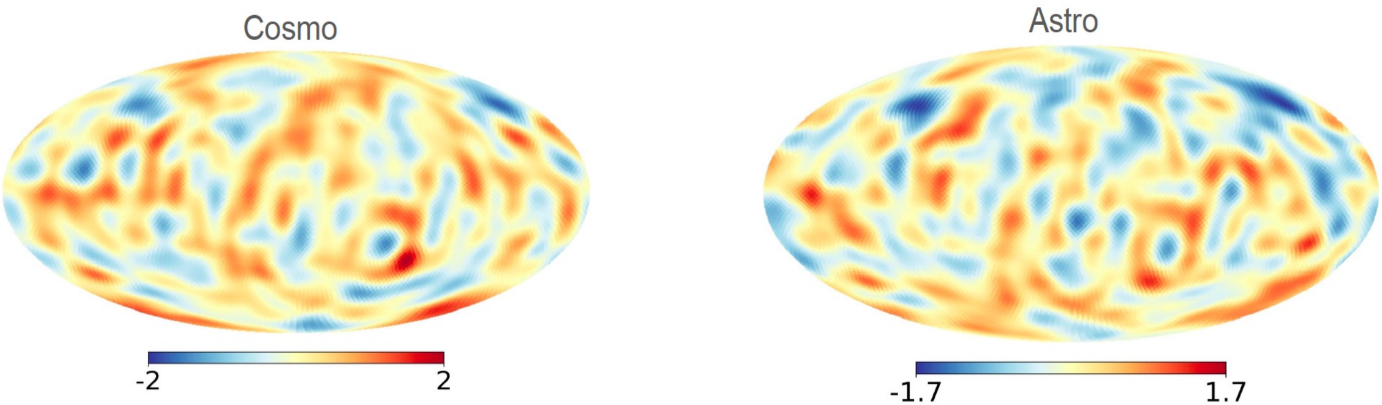


Stochastic GW Background



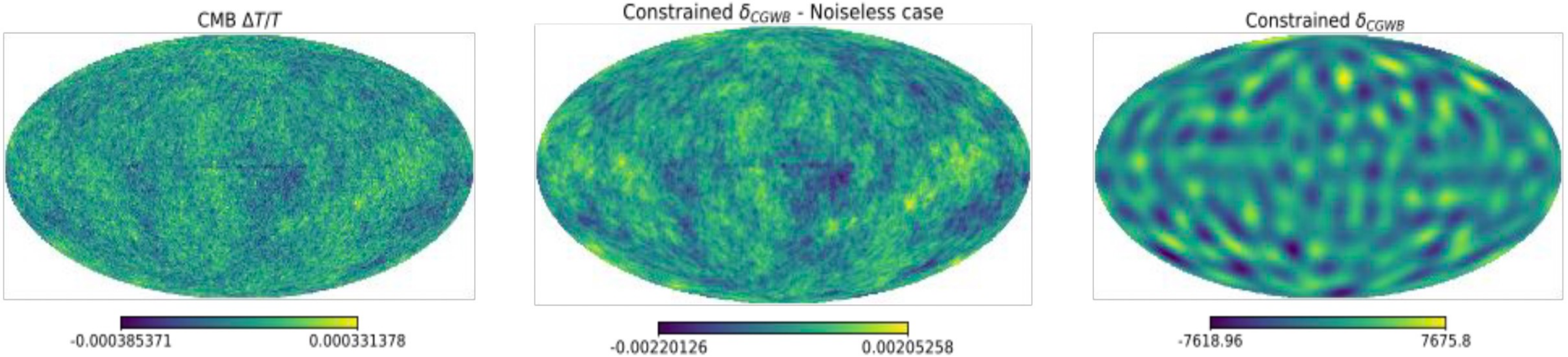
Mapping the SGWB with ET

The ET improved resolution will allow to have a better mapping of the GW "sky"



Sky map from LIGO O1

Extra information from the GWB x CMB cross correlation



SGWB constrained maps obtained from high resolution CMB Planck maps

Conclusions

- Third Generation GW interferometers are inevitable. The question is when and where?

- The Science Case is very clear:
  - Fundamental Physics
  - Astrophysics
  - Cosmology

- How big is our community?
- Do we have the momentum?

Gravitational Waves