LVK O4 - Science Case

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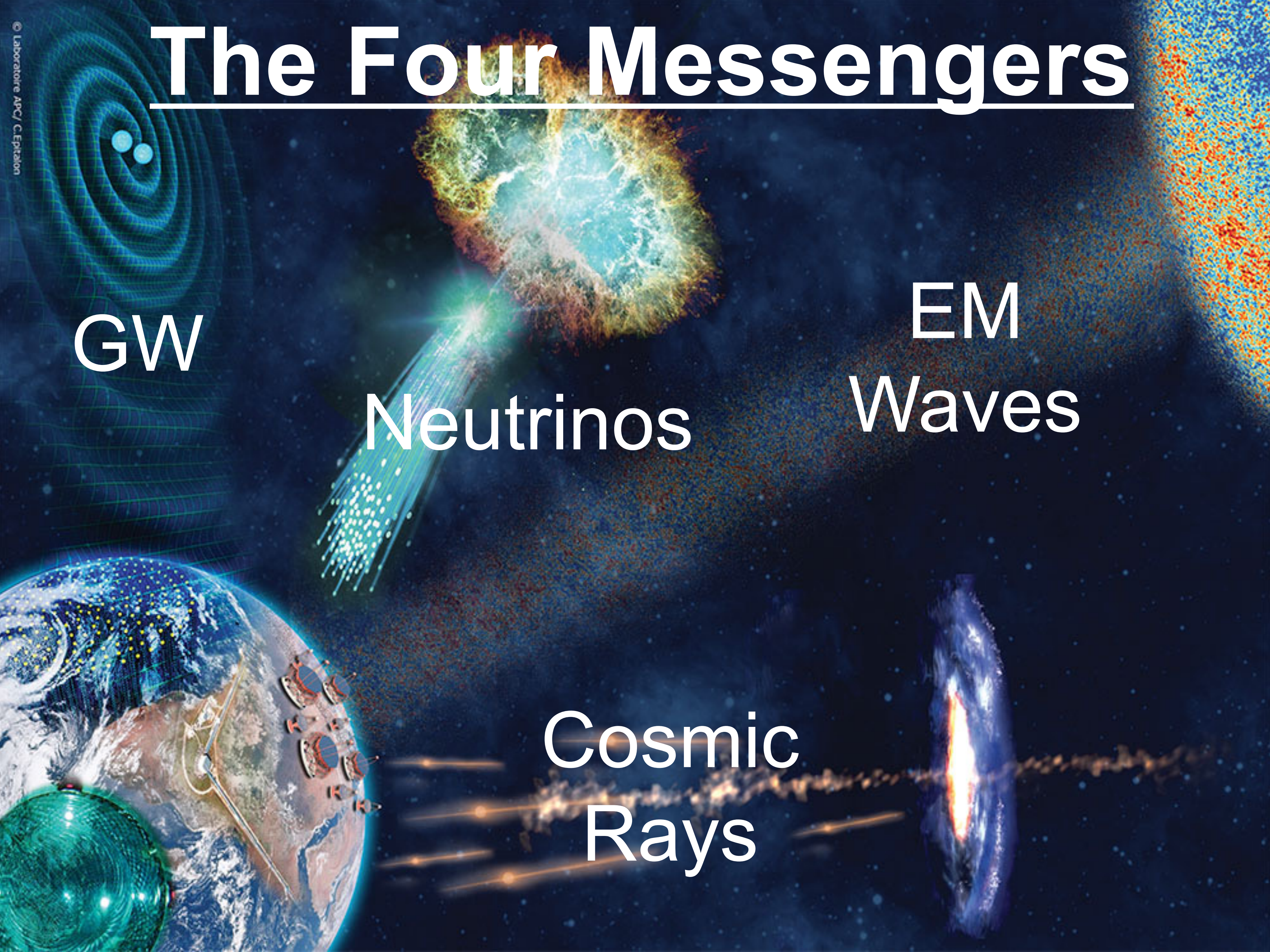
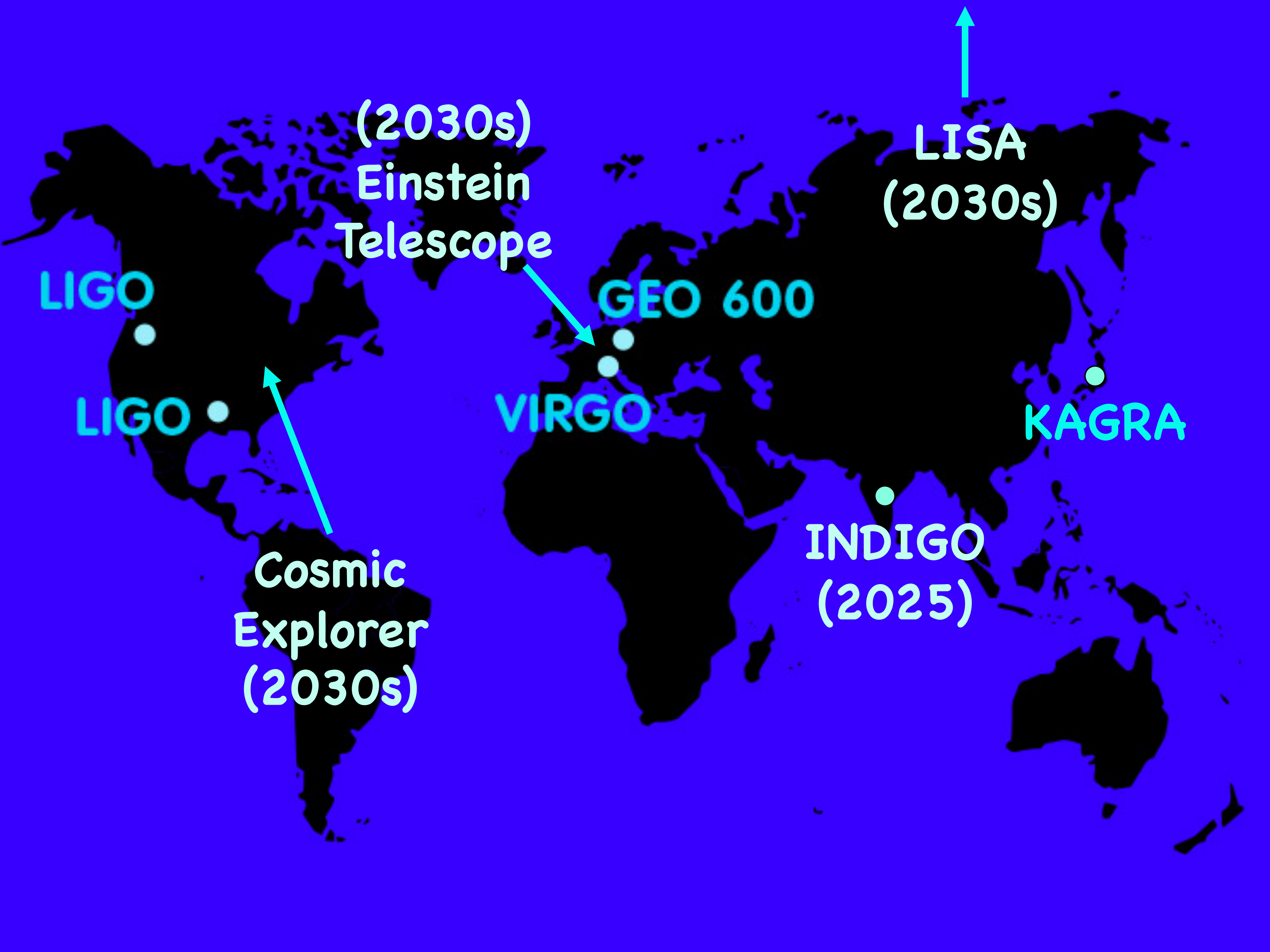
IFT-Madrid, 1st December 2022

[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 Autónoma de Madrid

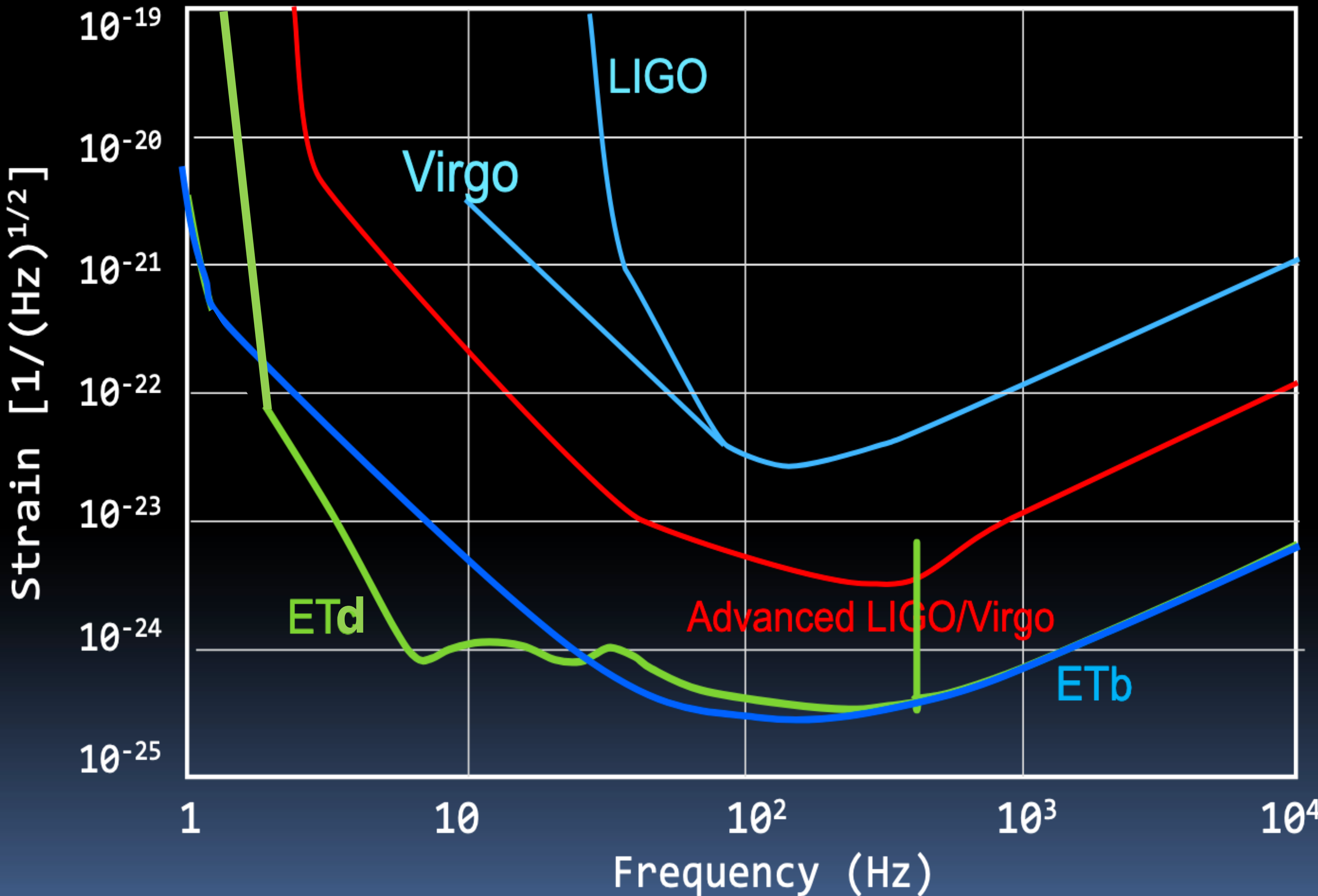
The Four Messengers



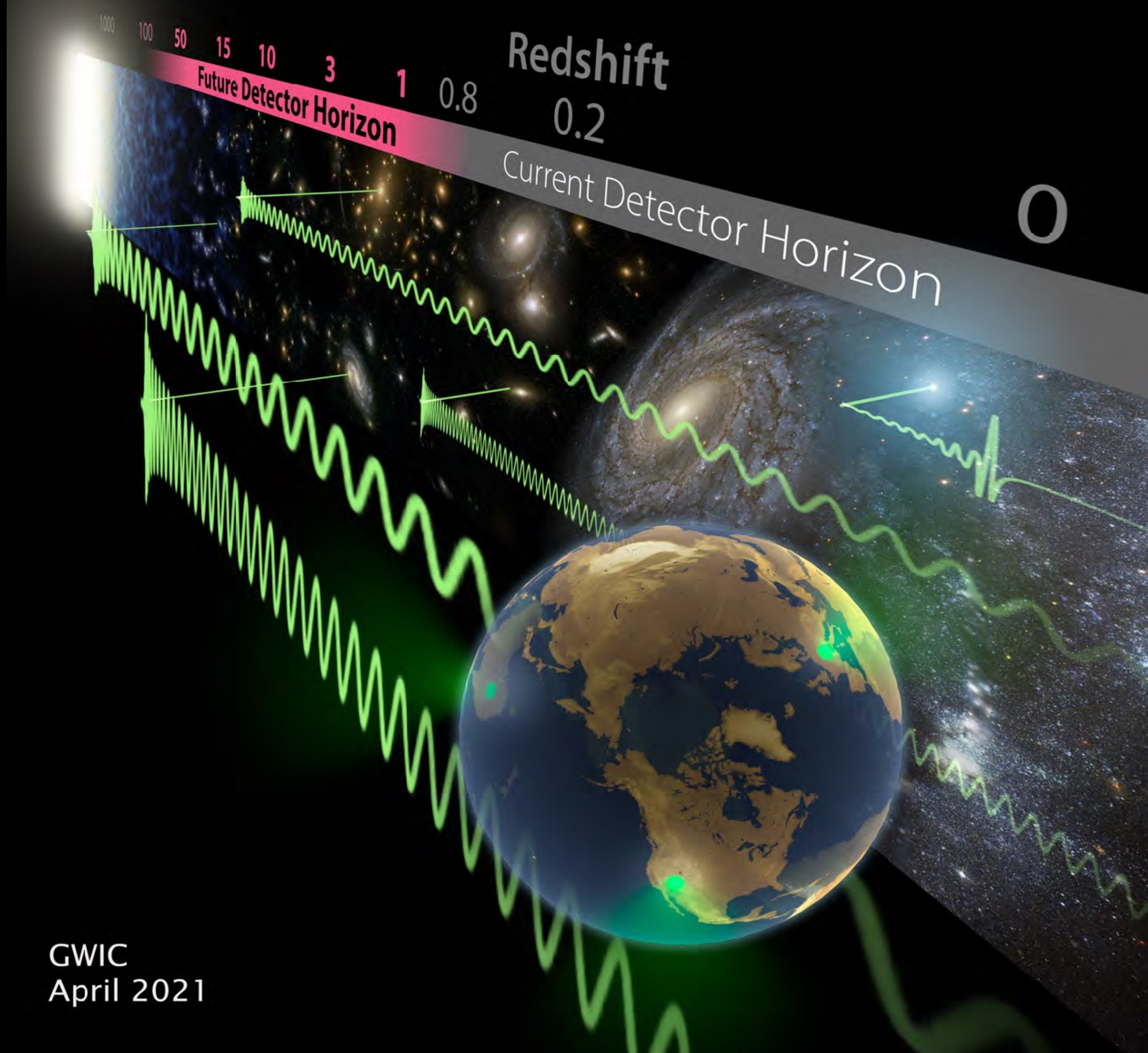


(2030s)
Einstein
Telescope
LISA
(2030s)
LIGO
GEO 600
LIGO
VIRGO
KAGRA
INDIGO
(2025)
Cosmic
Explorer
(2030s)

Sensitivity ET vs LIGO



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



GWIC
April 2021

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

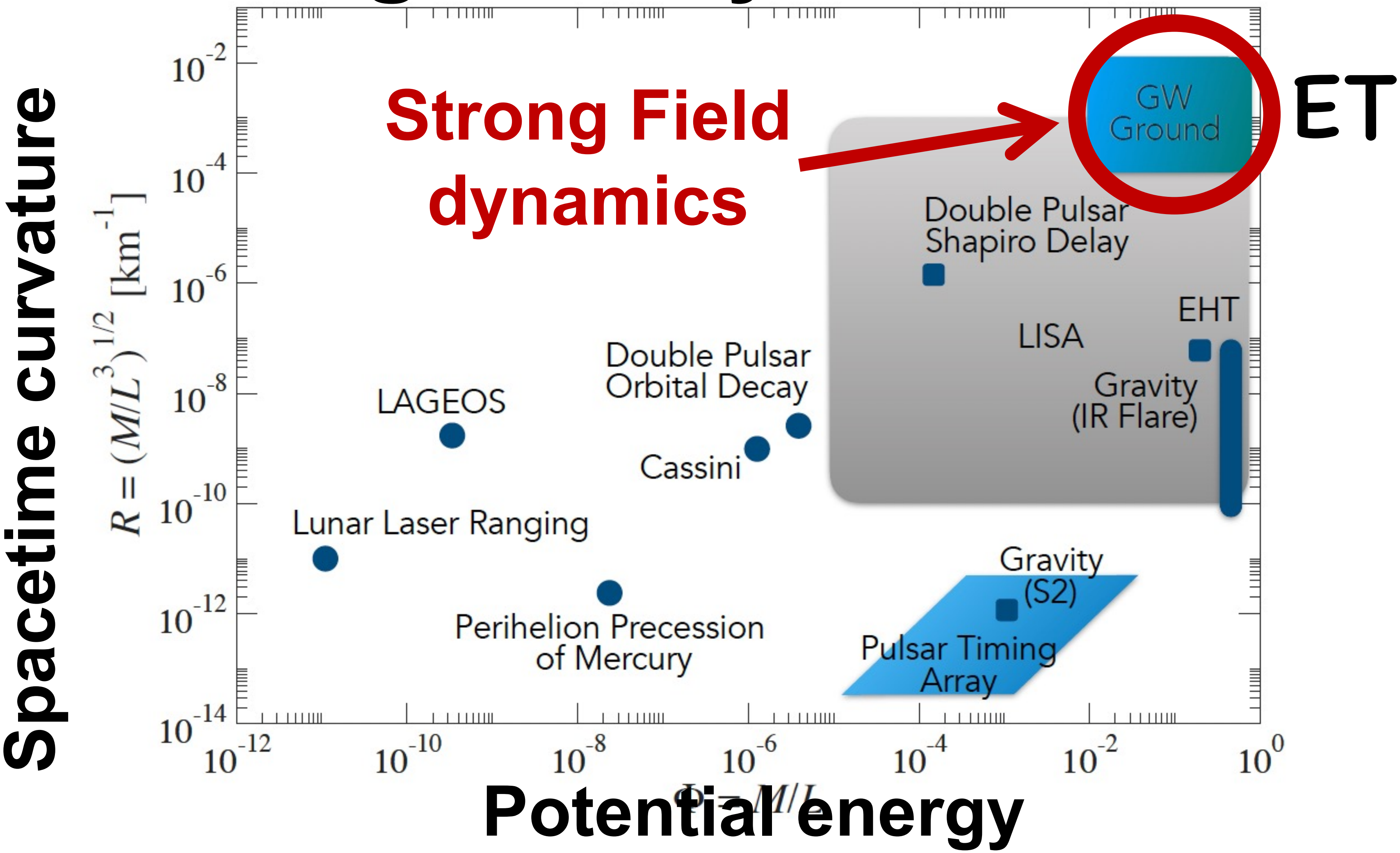
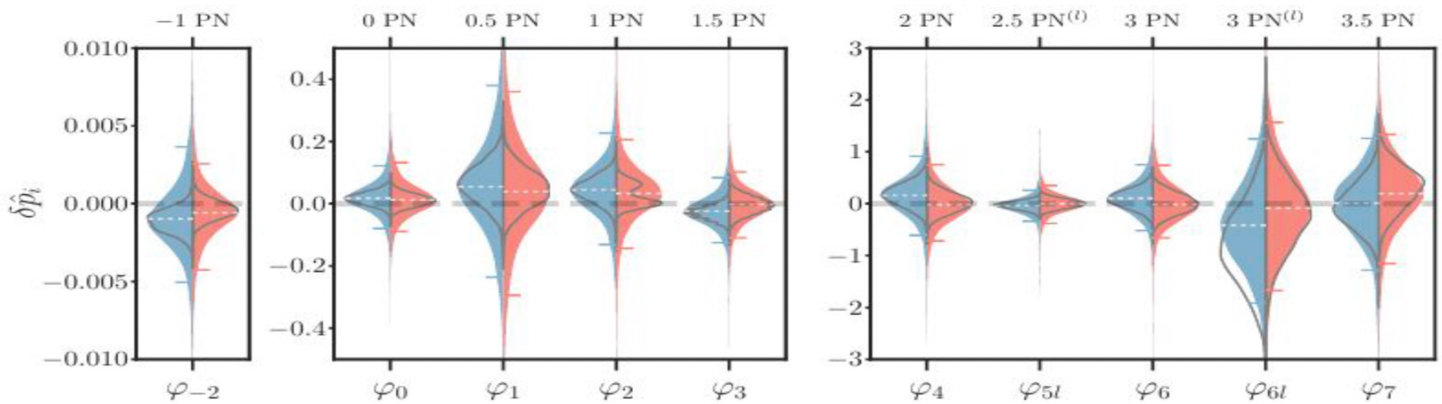
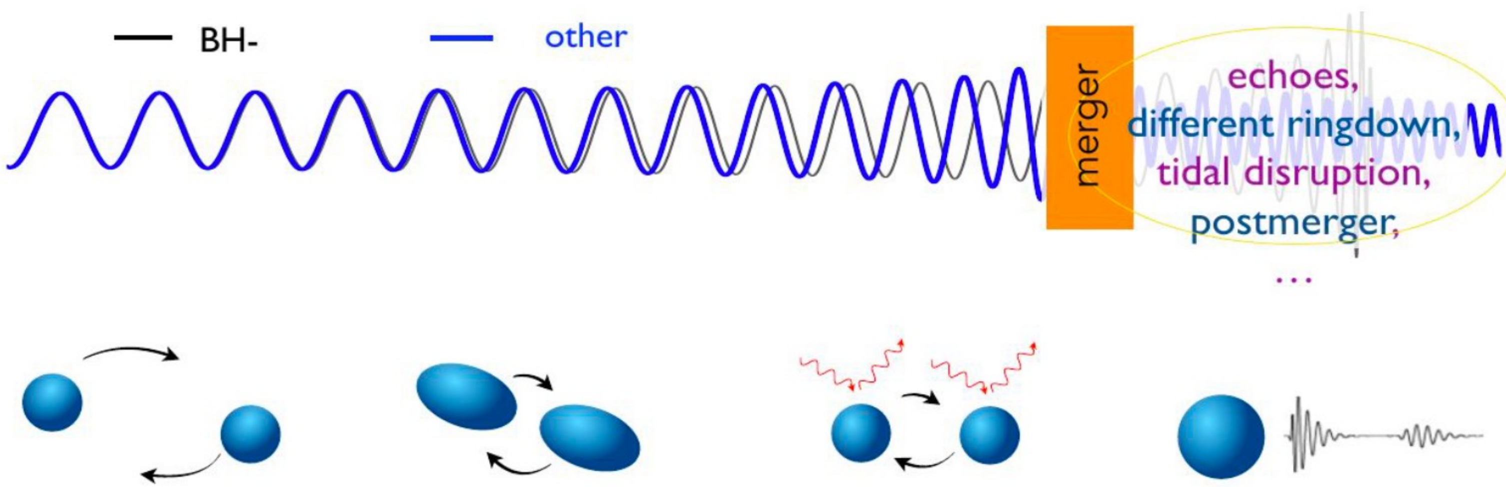


Figure 8. Probing gravity at all scales: illustration of the reach in spacetime curvature versus potential energy targeted by different kinds of observations. M and L are the characteristic mass and length involved in the system or process being observed. The genuinely strong-field dynamics of spacetime 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



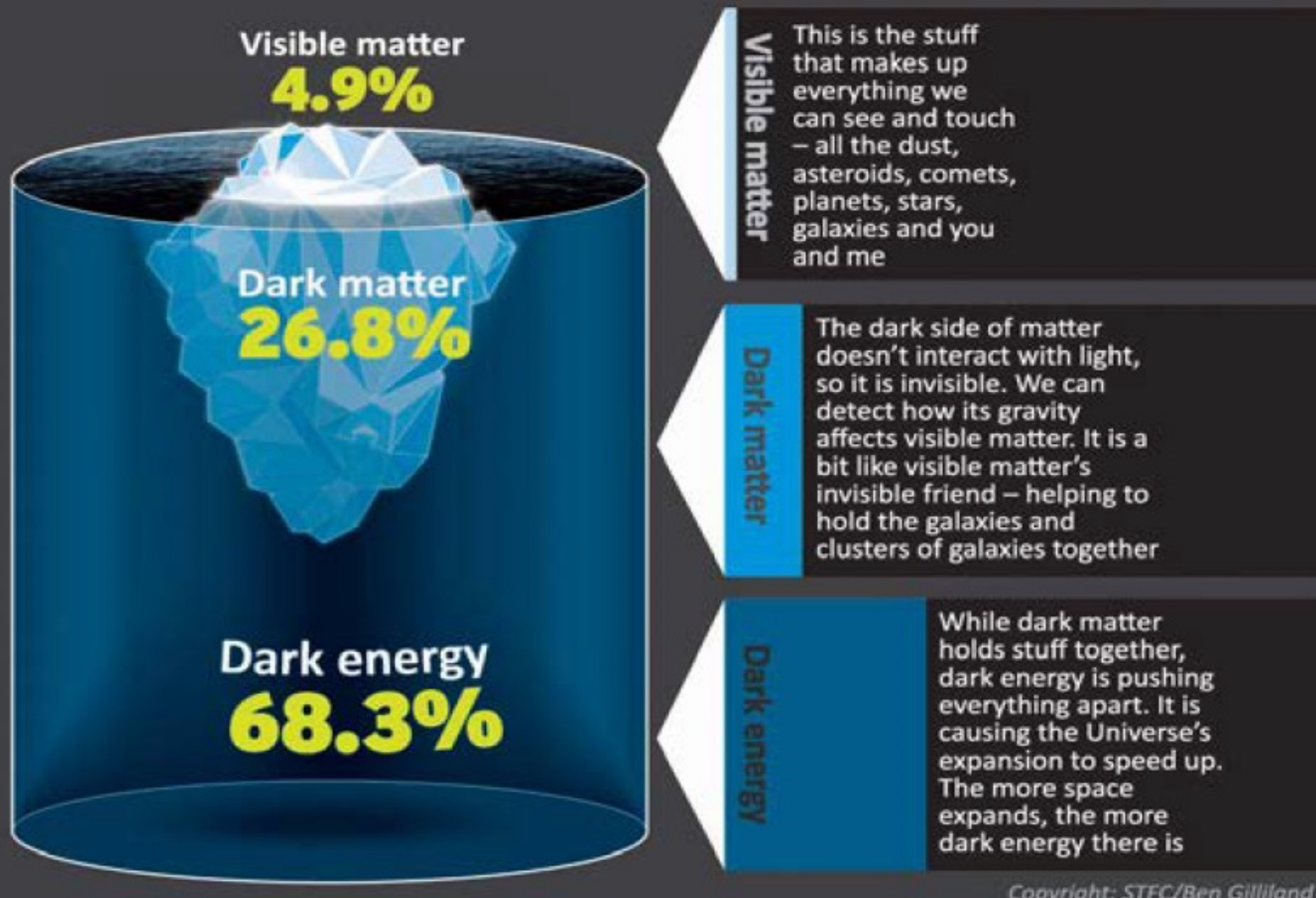


~point masses: same signal for all objects

tidal effects* + *multipolar structure

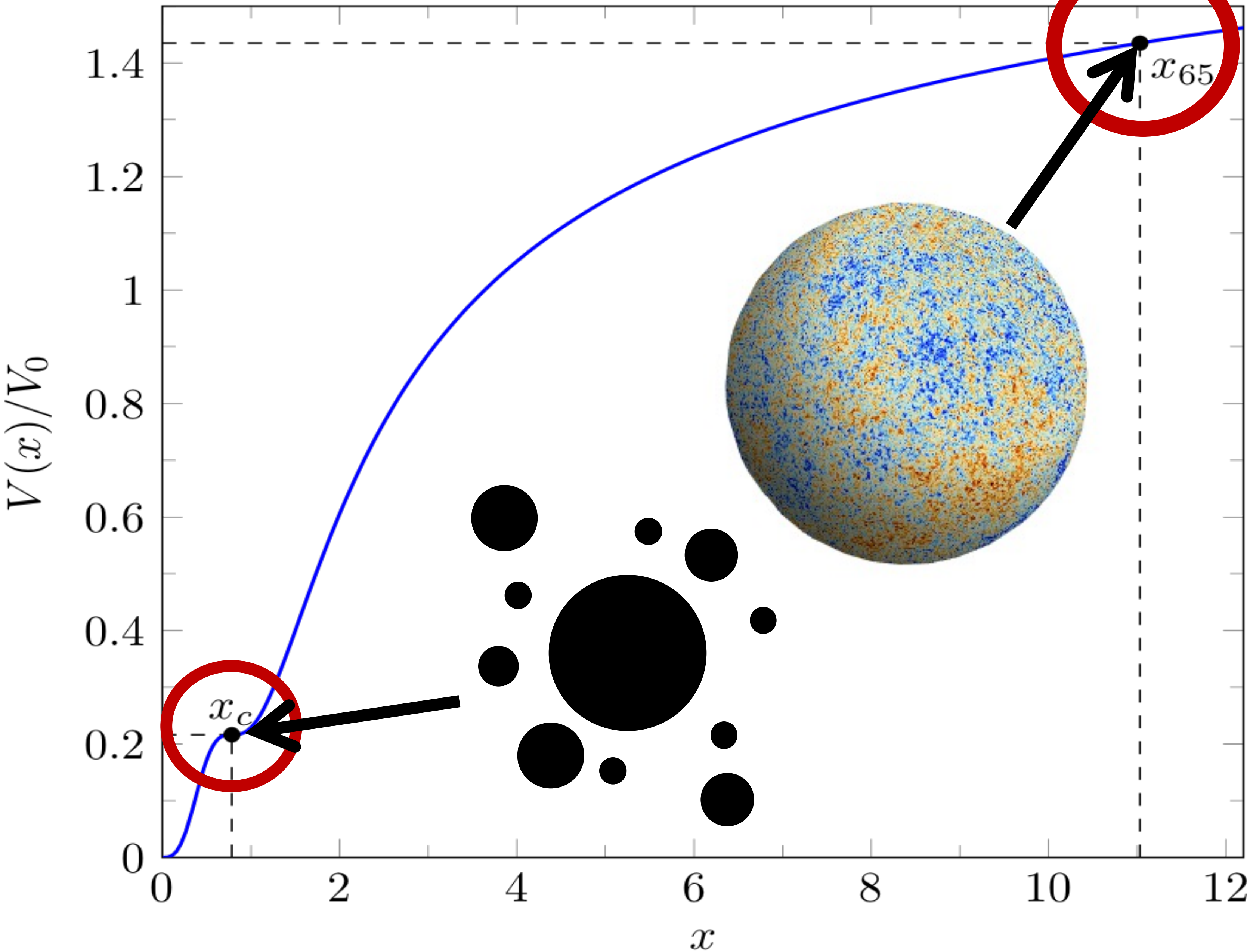
absence of horizon ***absorption effects***

echoes

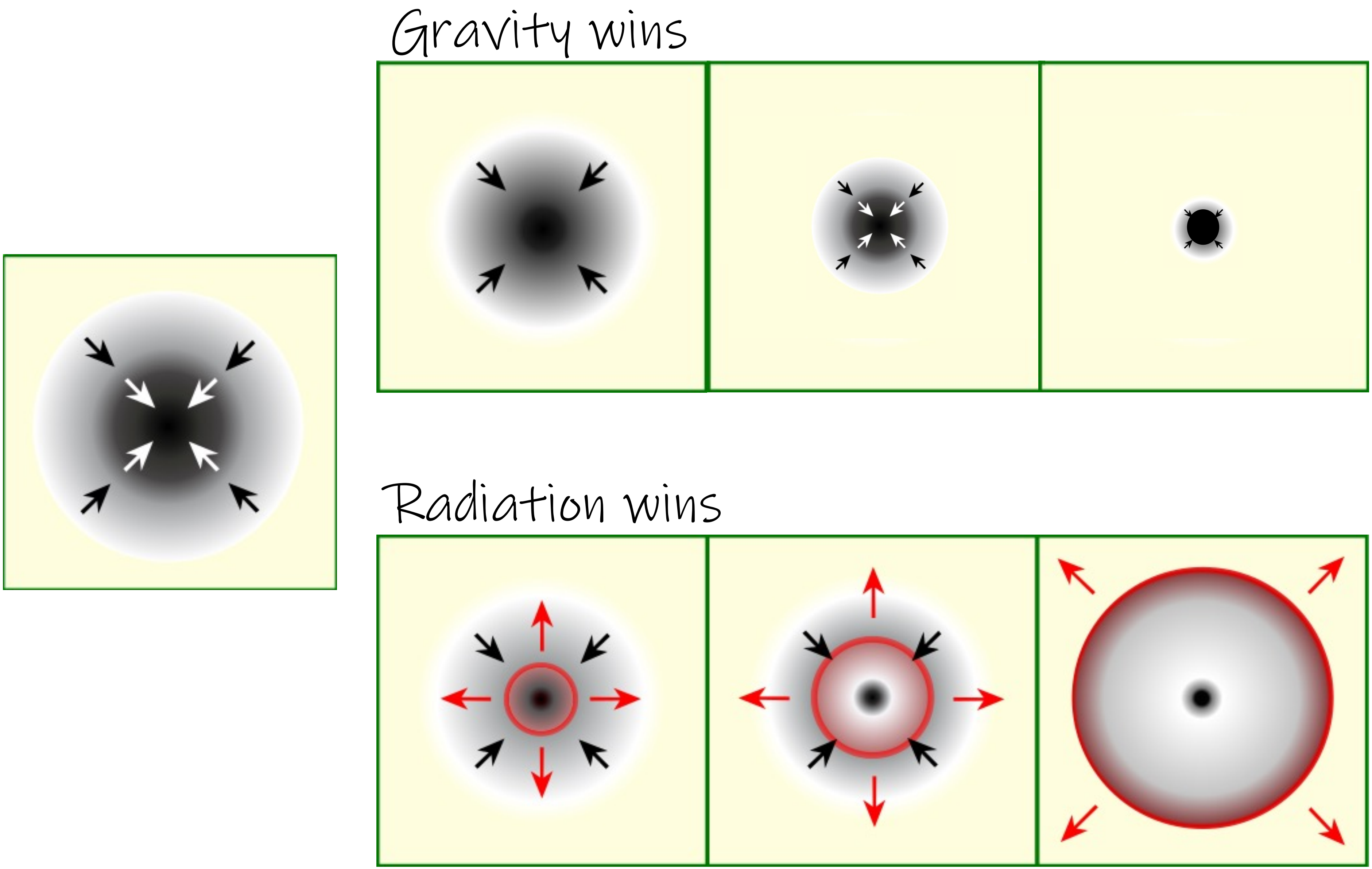


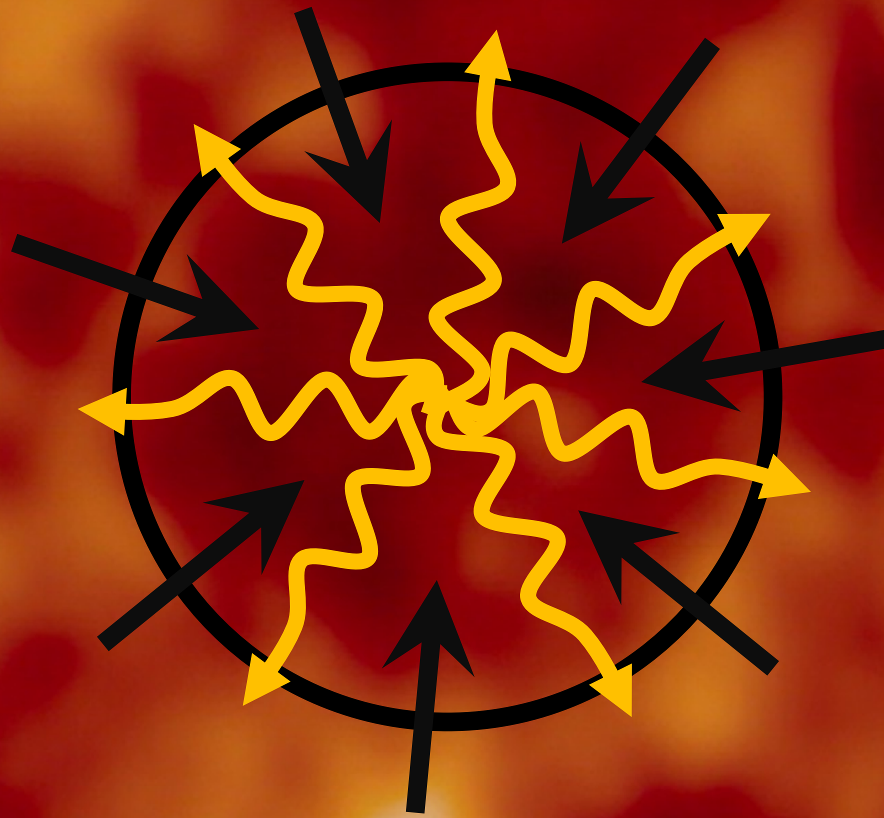
Universe Components

Primordial Black Holes = DM



Gravitational Collapse

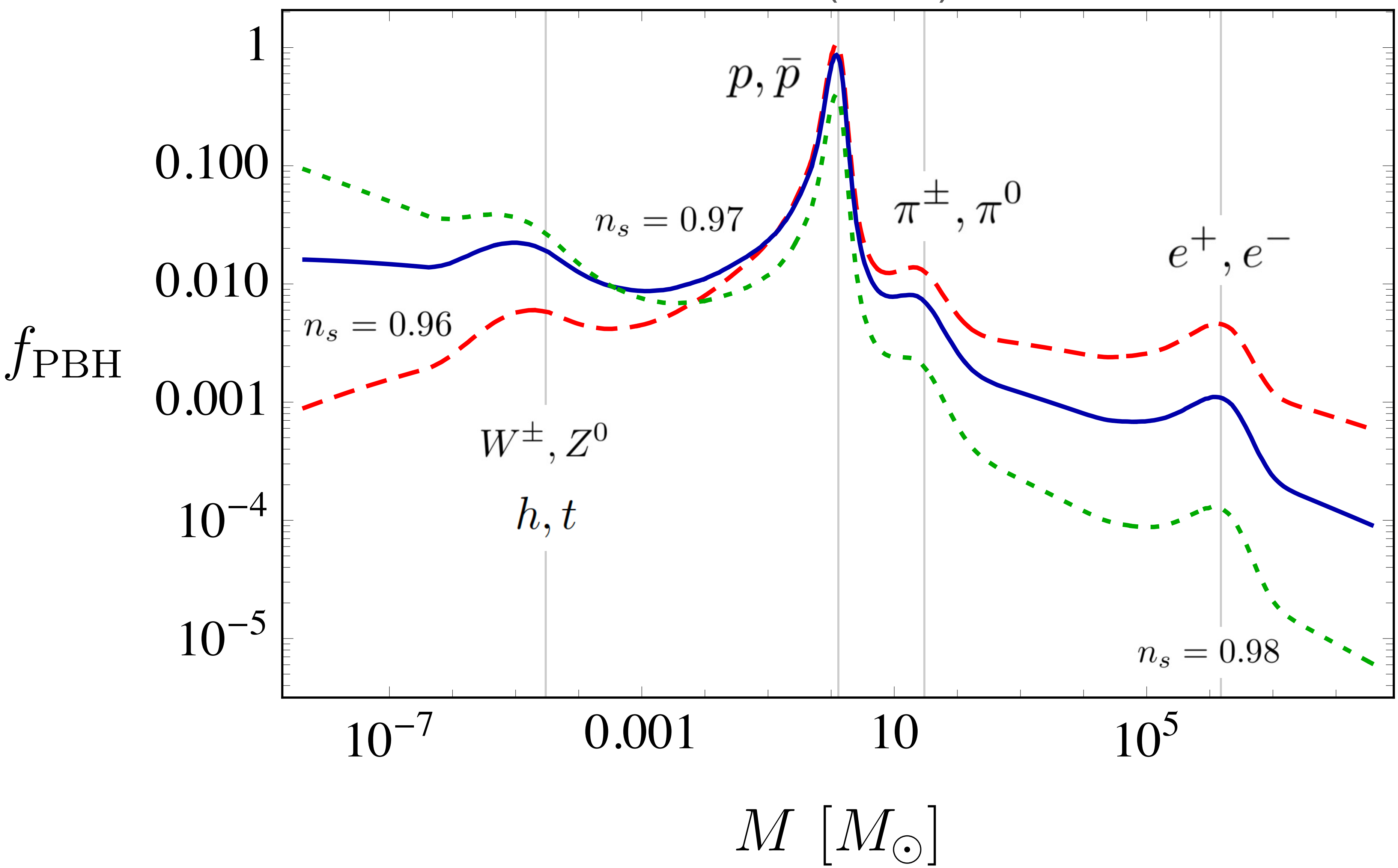




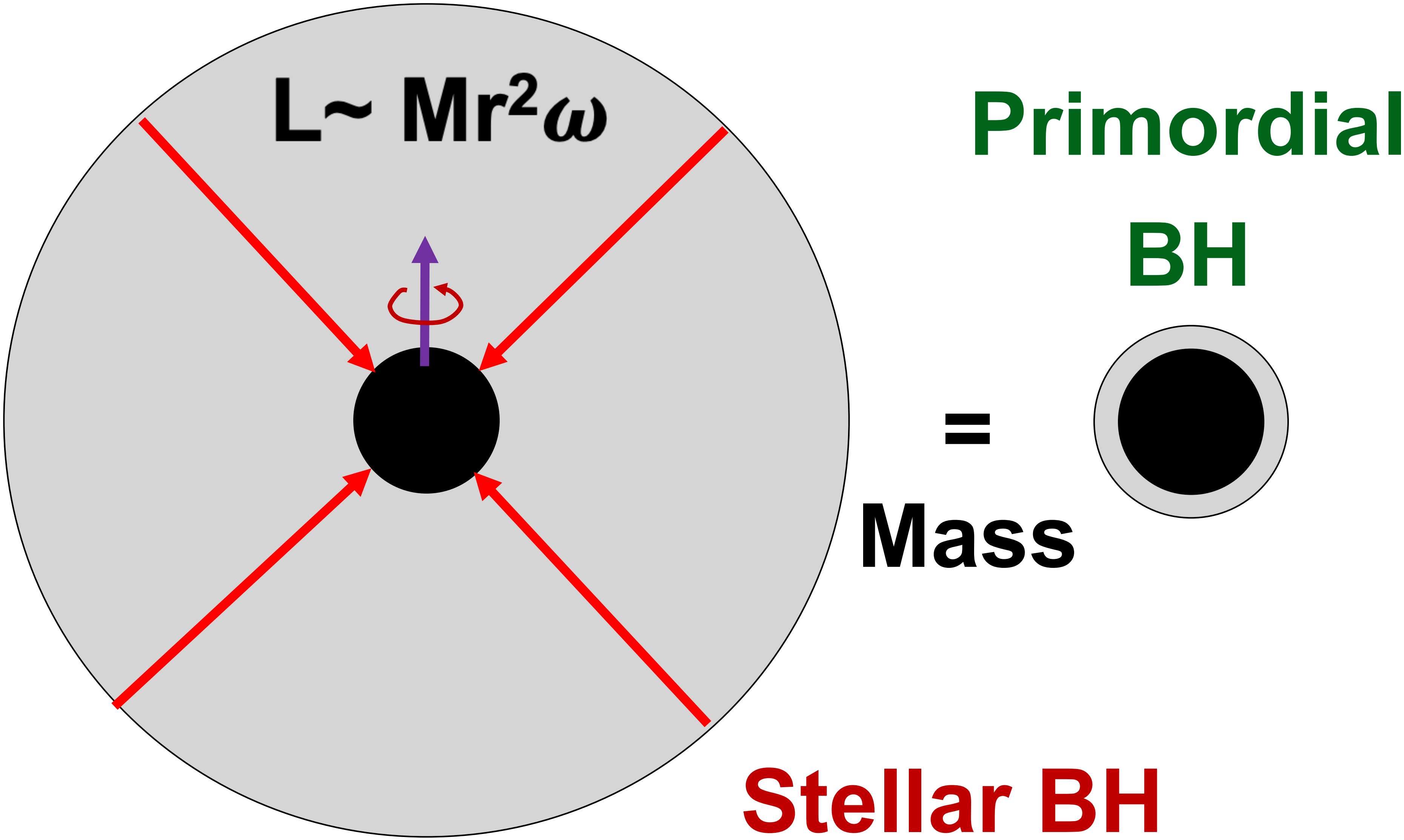
Primordial plasma

PBH mass spectrum

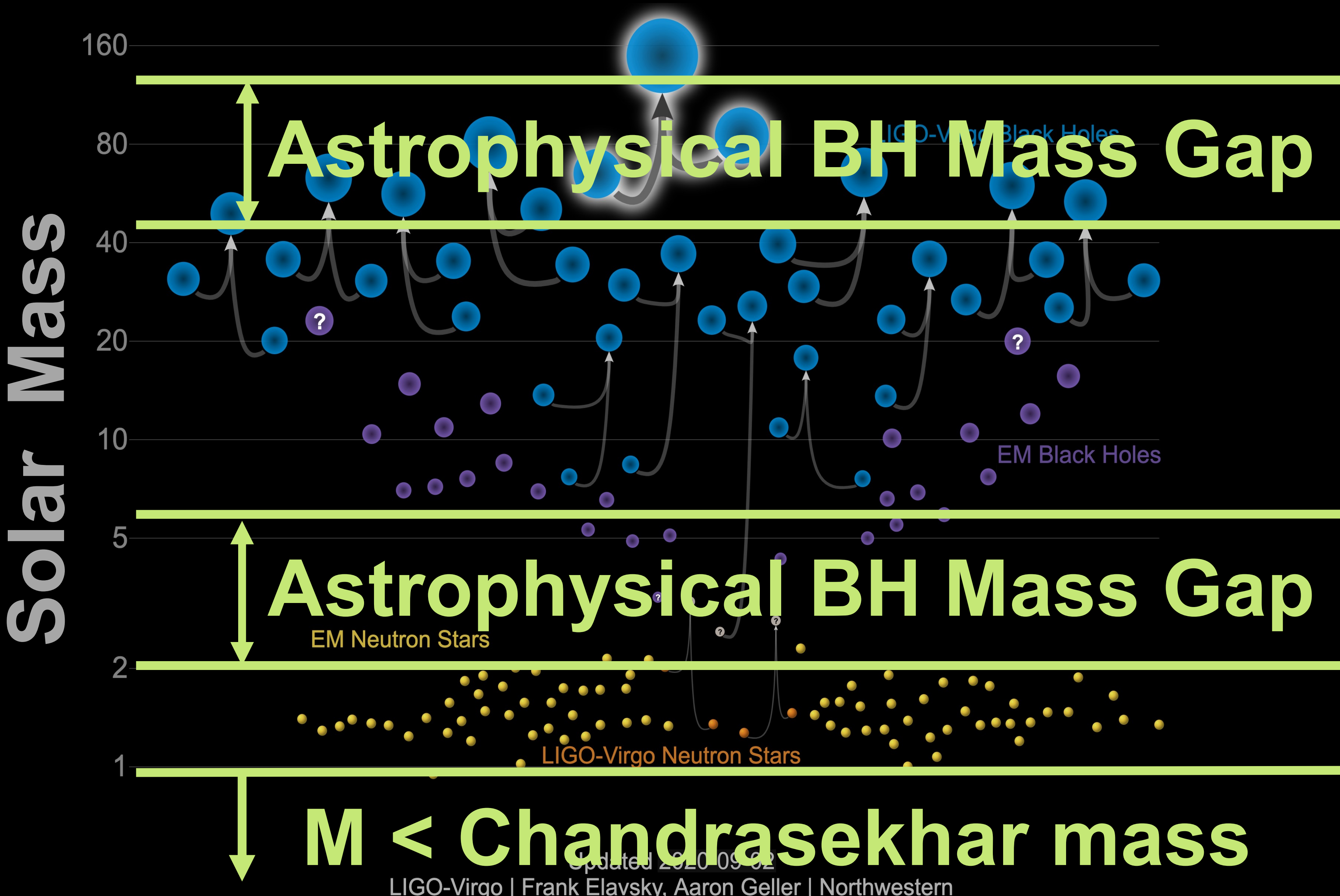
Carr, Clesse, JGB, Kühnel (2019)



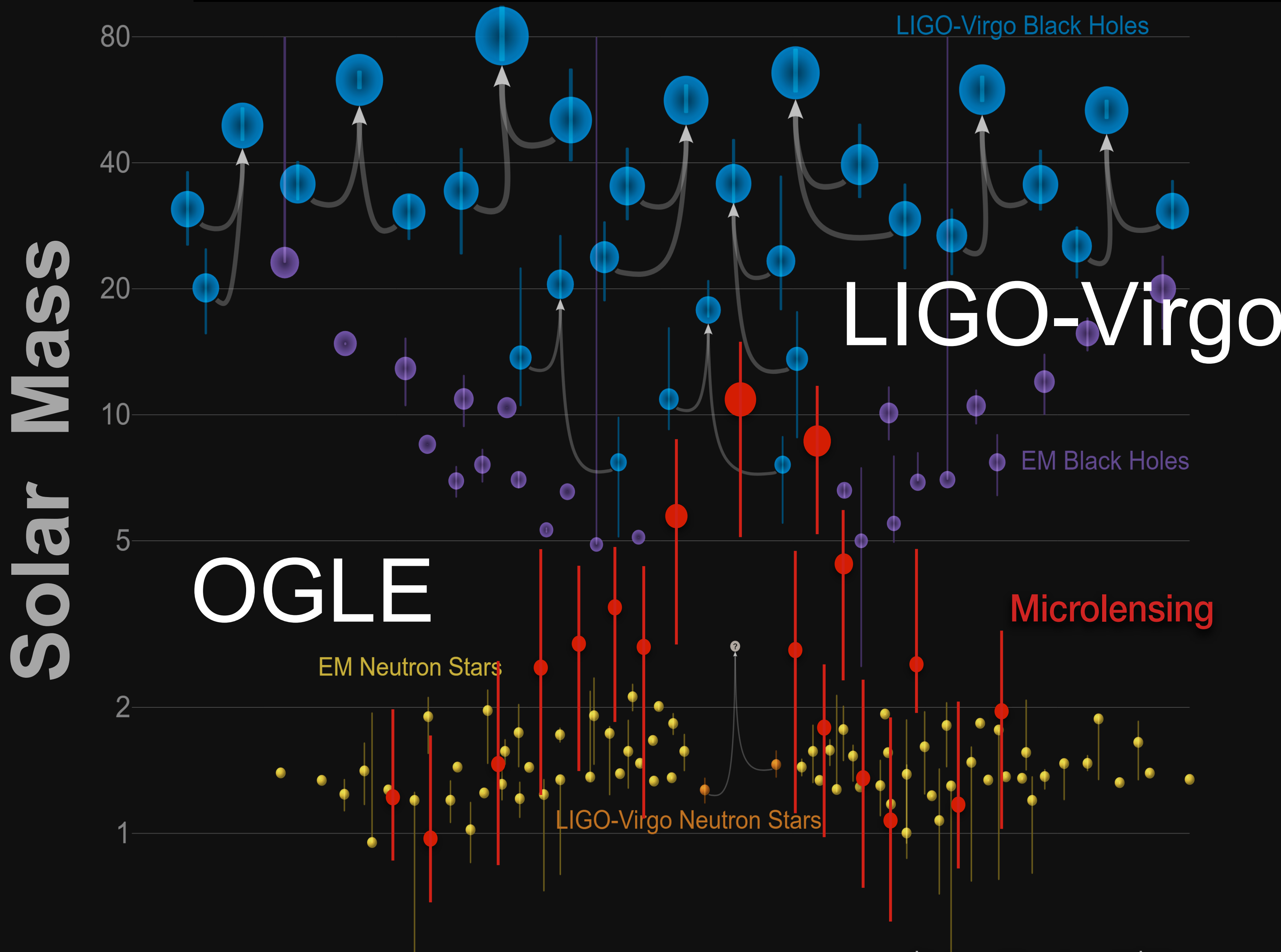
PBH are ~ spinless



Black Holes and Neutron Stars

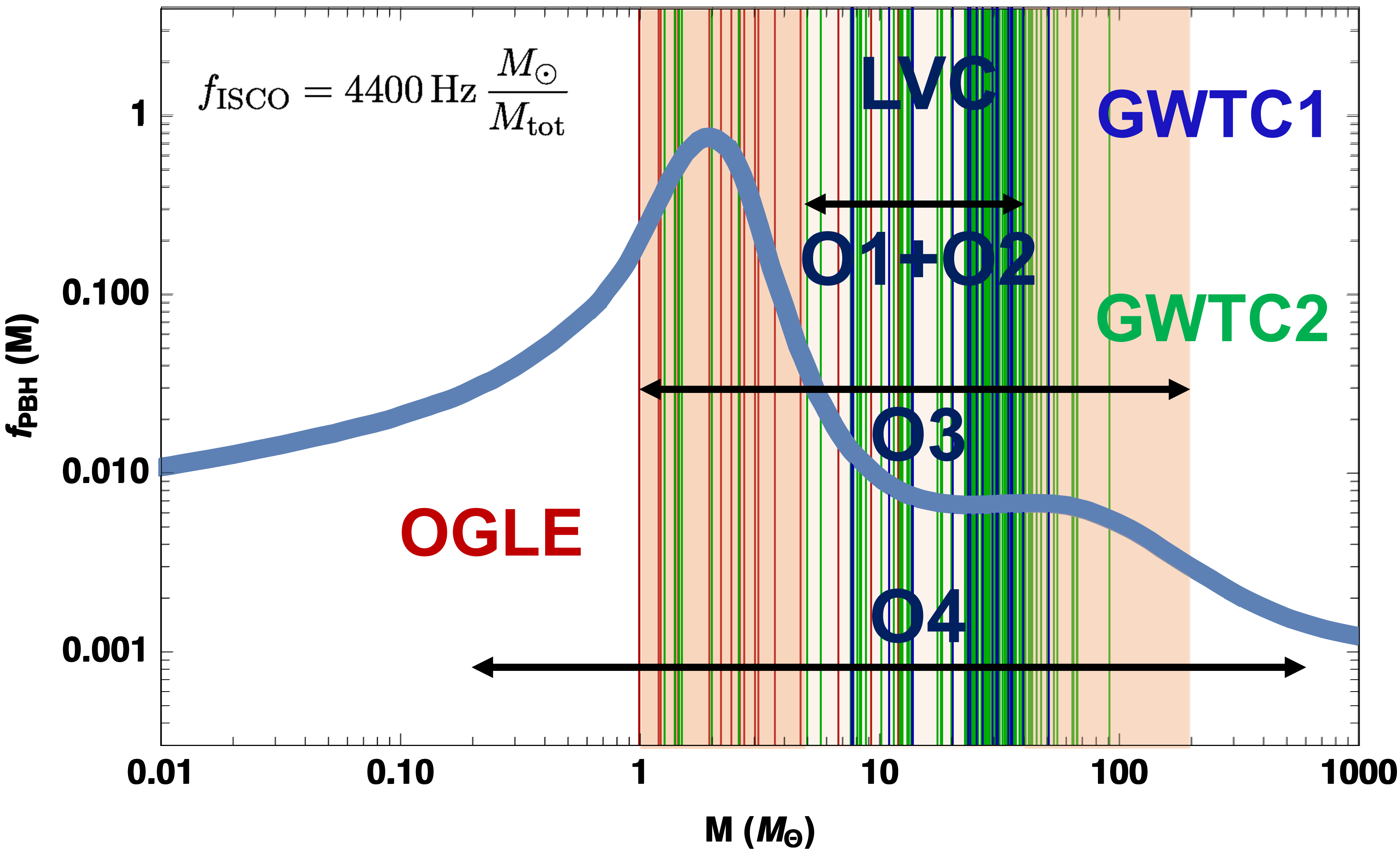


Black Holes and Neutron Stars

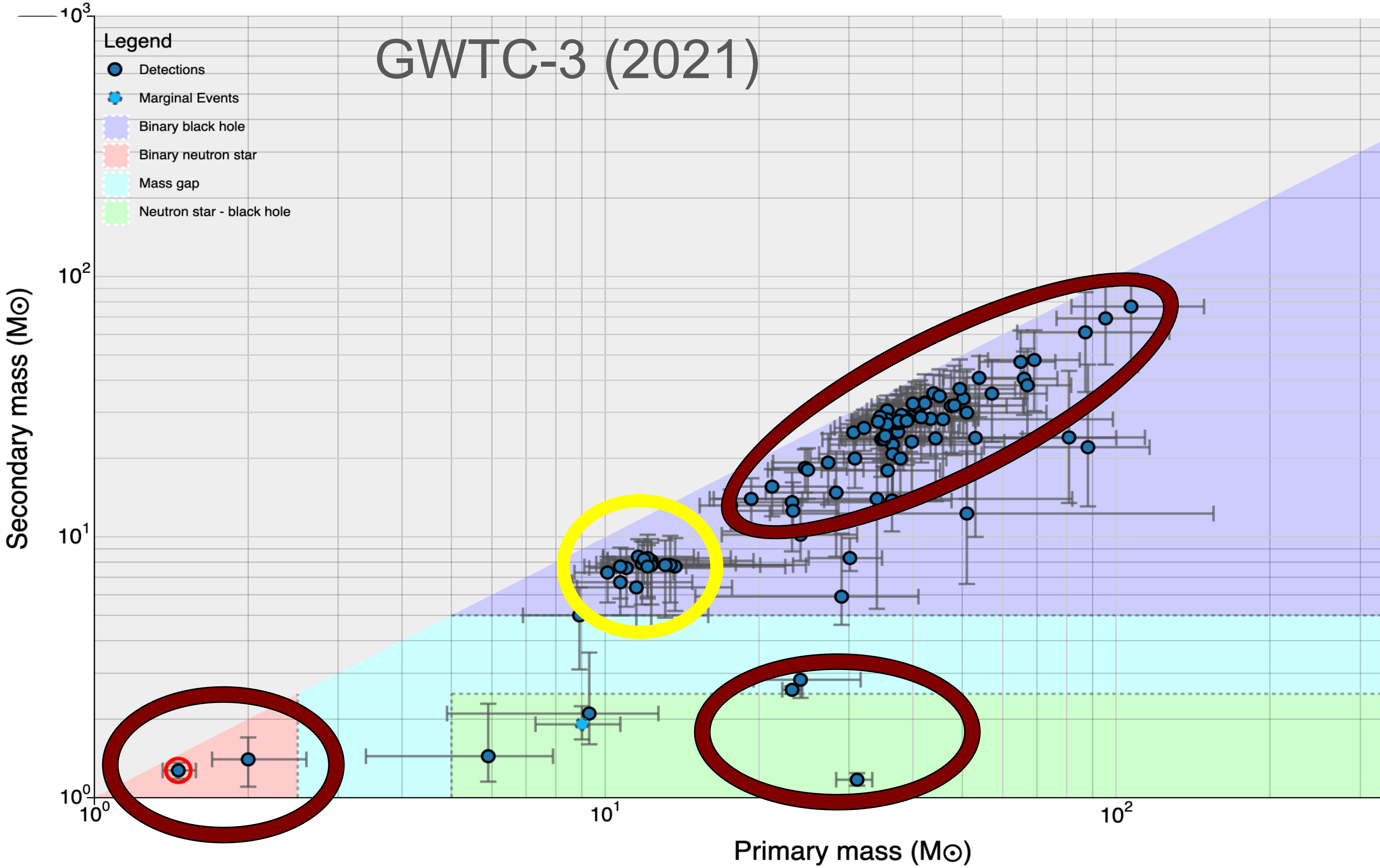


Model prediction: mass spectrum

JGB, Clesse (2020)



Primary and secondary masses



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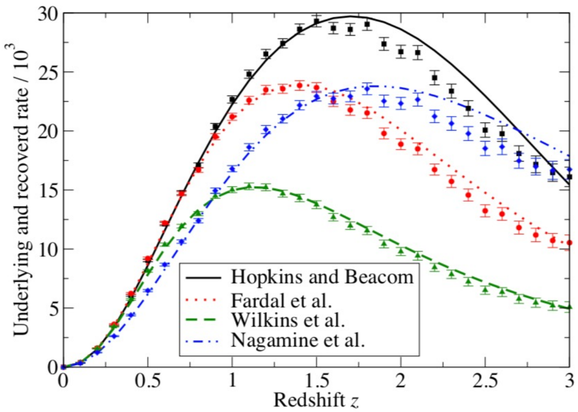
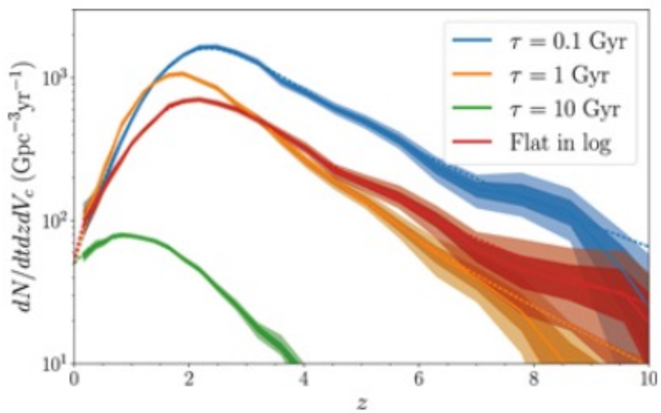
Tracking Star Formation & Multiple BBH Populations

✧ Distinguish star formation models up to z~10

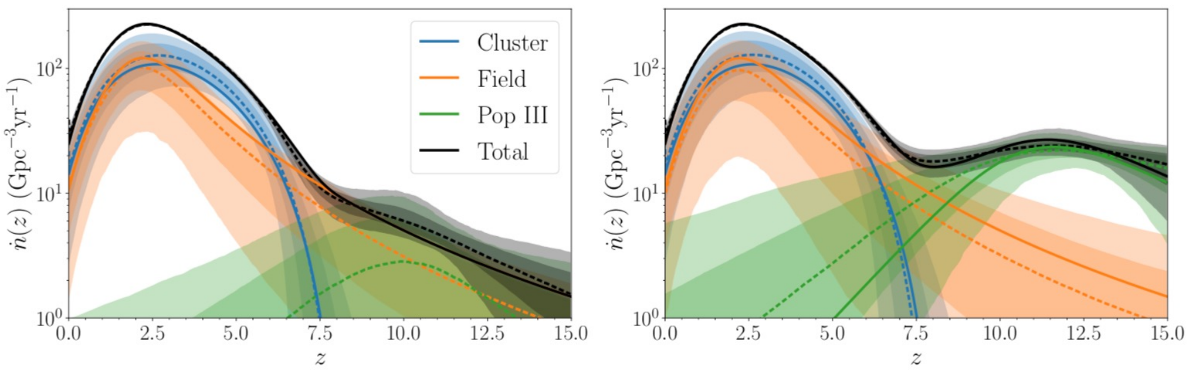


ET Design Study (2011)



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

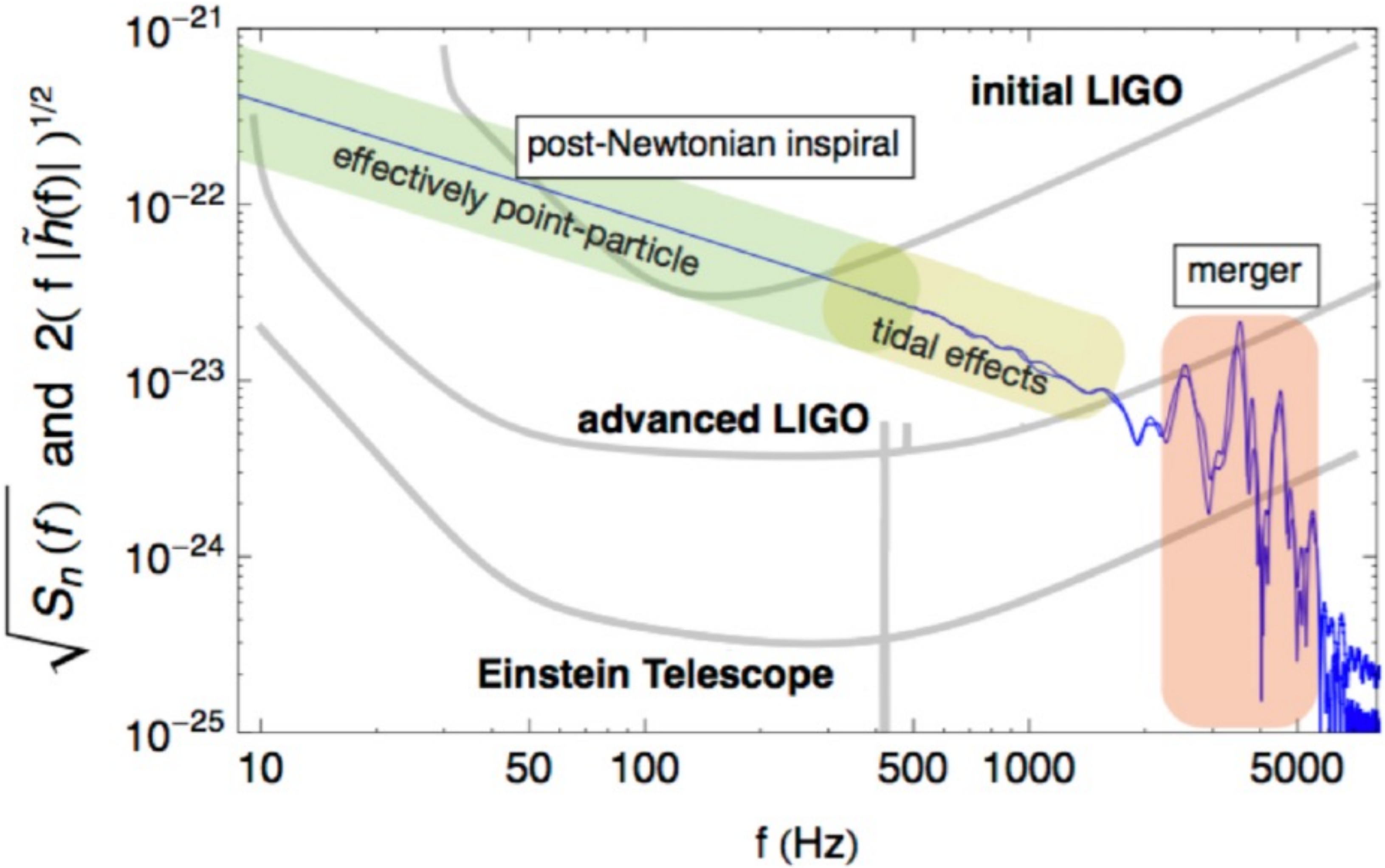


Figure 4. Gravitational wave signal from a NS-NS merger at a distance 100 Mpc, as it sweeps across the detector-accessible frequency range. Figure from [37] (adapted from an original figure by J. Read, based on data from [38]).

Neutron Stars and QCD phases

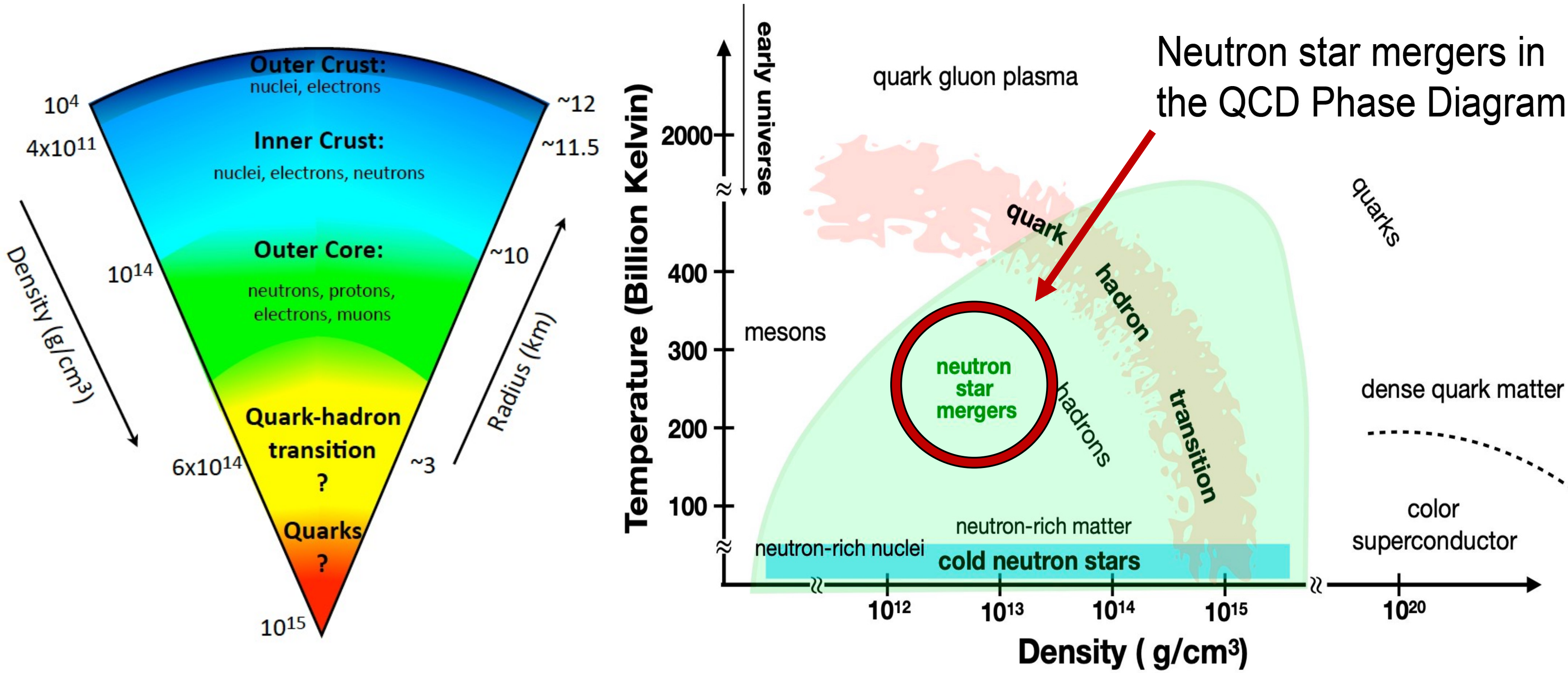
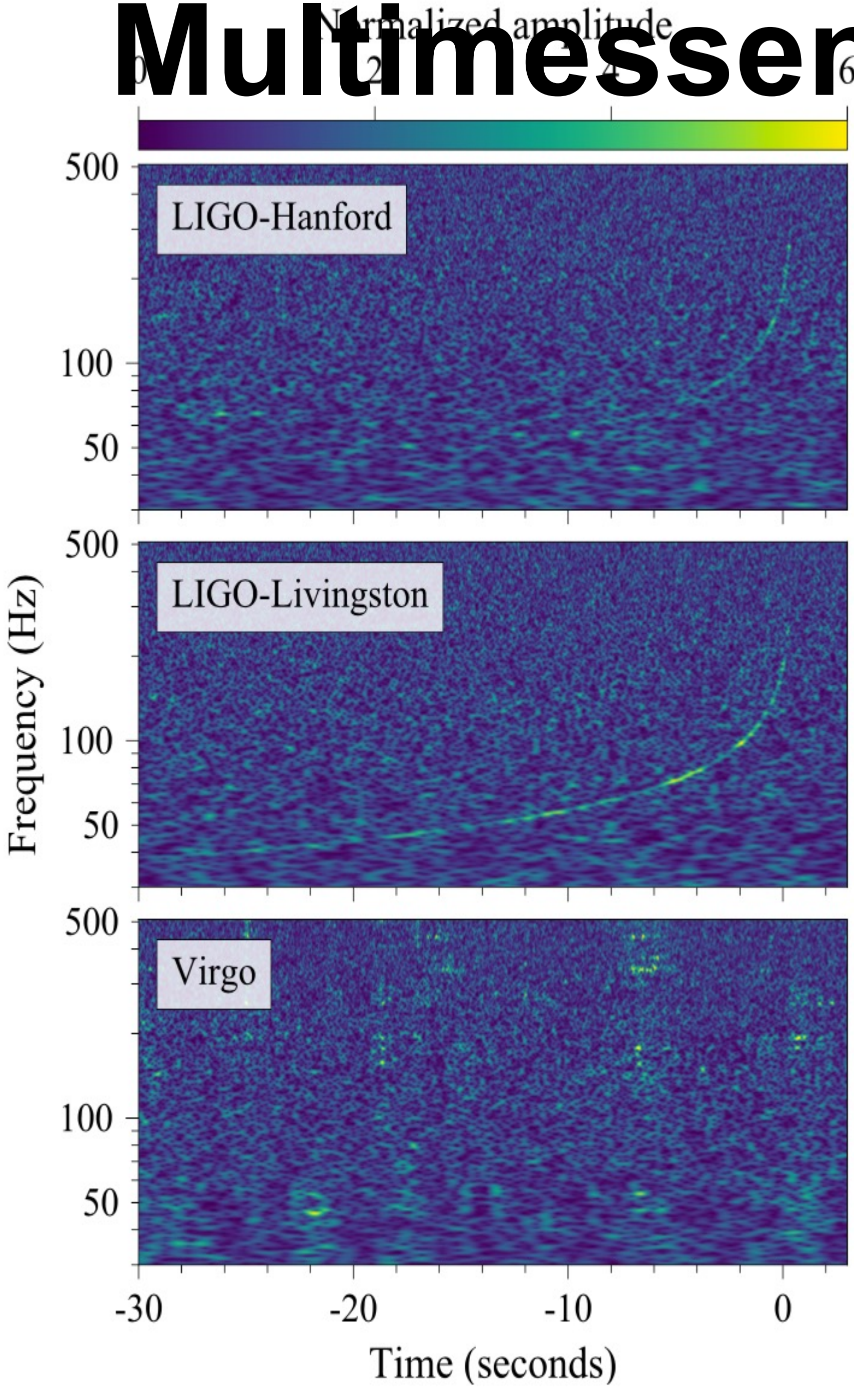
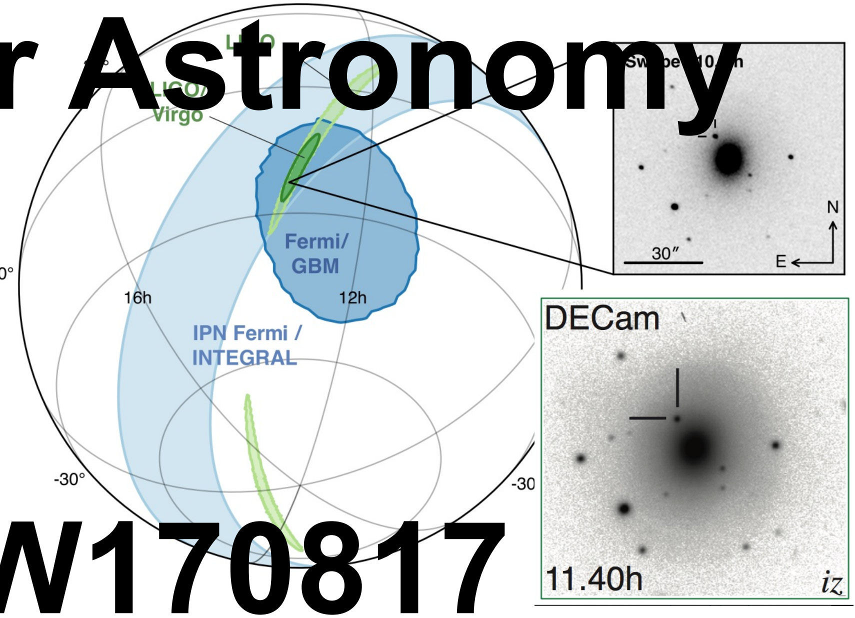


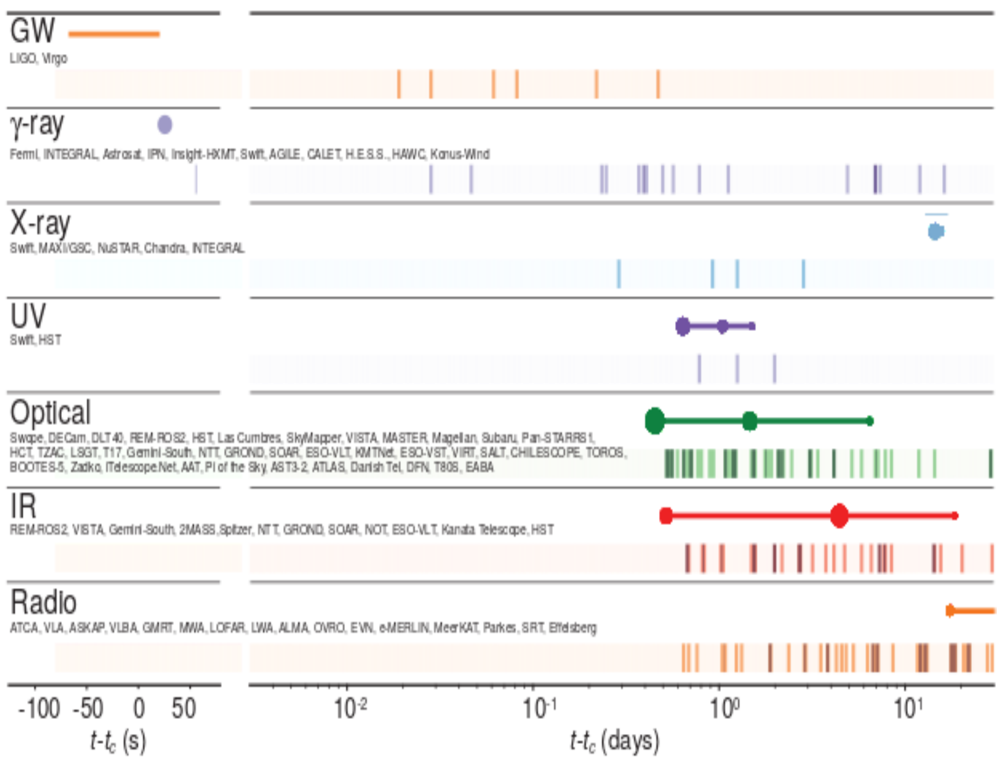
Figure 3. Left: Conjectured interior structure of a neutron star. Right: Matter encountered in neutron stars and binary mergers explores a large part of the QCD phase diagram in regimes that are inaccessible to terrestrial collider experiments.

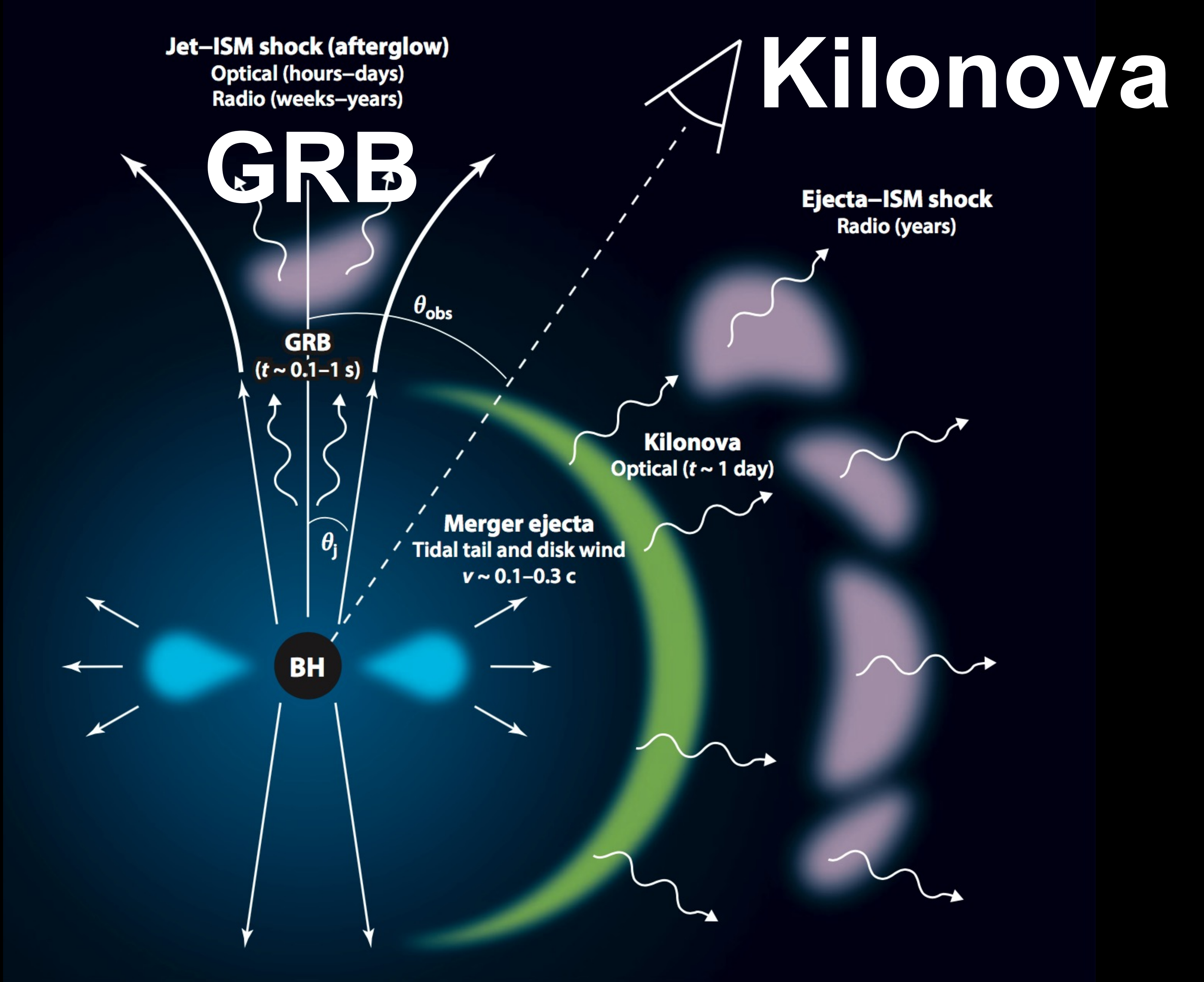
Multimessenger Astronomy

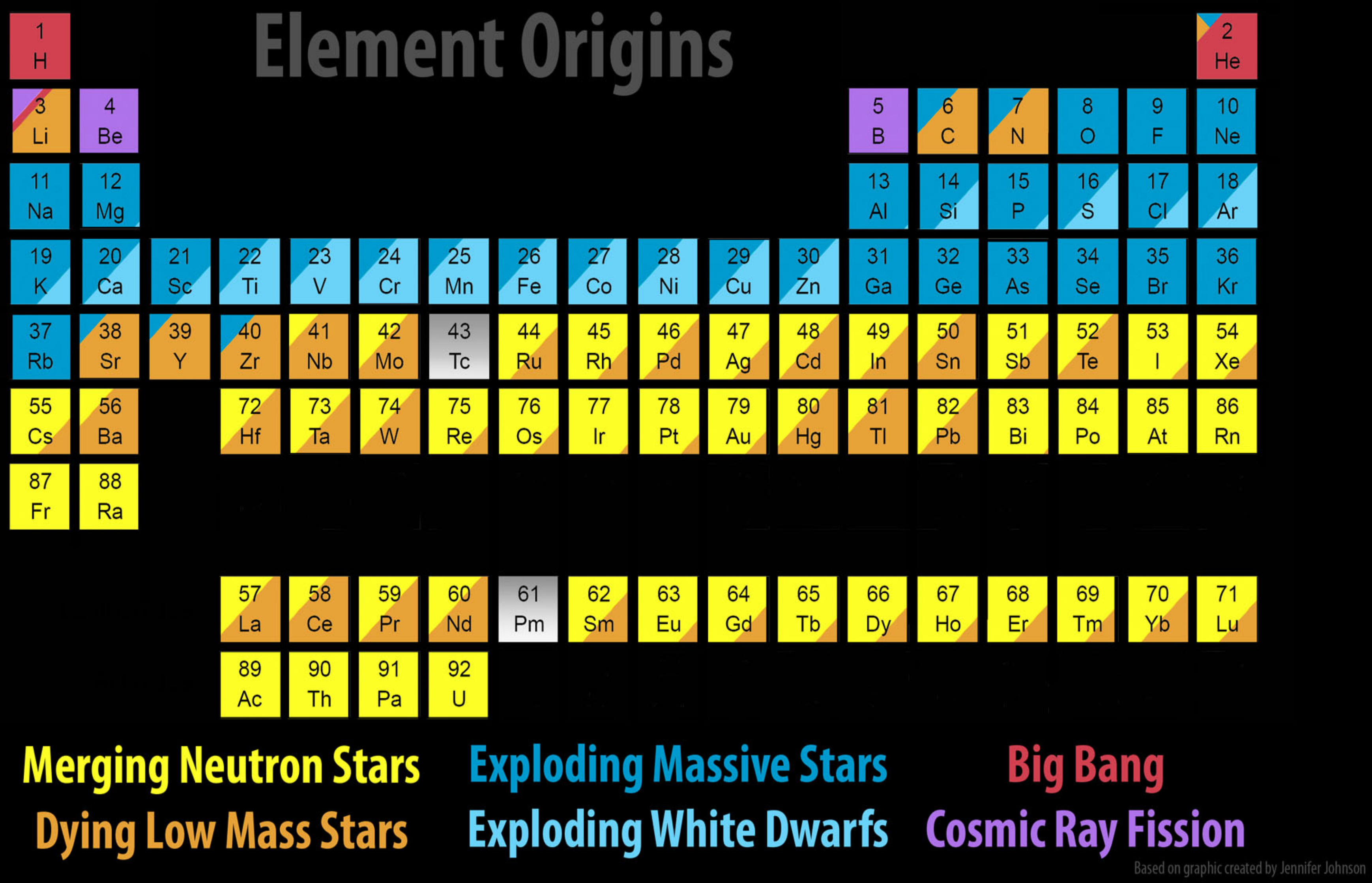




GW170817




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

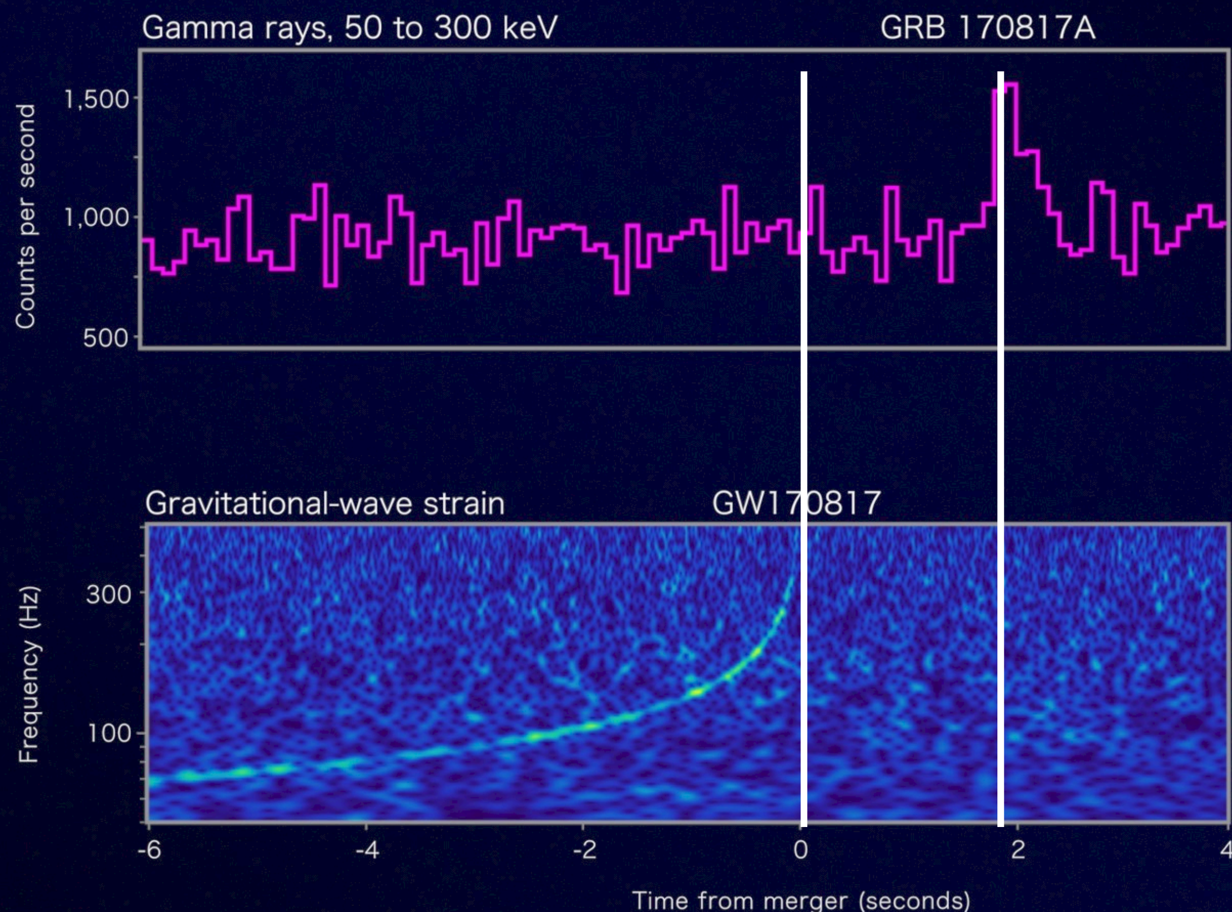

Element Origins
1 H
2 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe
55 Cs
56 Ba
72 Hf
73 Ta
74 W
75 Re
76 Os
77 Ir
78 Pt
79 Au
80 Hg
81 Tl
82 Pb
83 Bi
84 Po
85 At
86 Rn
87 Fr
88 Ra
57 La
58 Ce
59 Pr
60 Nd
61 Pm
62 Sm
63 Eu
64 Gd
65 Tb
66 Dy
67 Ho
68 Er
69 Tm
70 Yb
71 Lu
89 Ac
90 Th
91 Pa
92 U
Merging Neutron Stars
Exploding Massive Stars
Big Bang
Dying Low Mass Stars
Exploding White Dwarfs
Cosmic Ray Fission
Based on graphic created by Jennifer Johnson

$c_{gw} = c_{em}$

(1.7 s in 144 Myrs)

Fermi

LIGO



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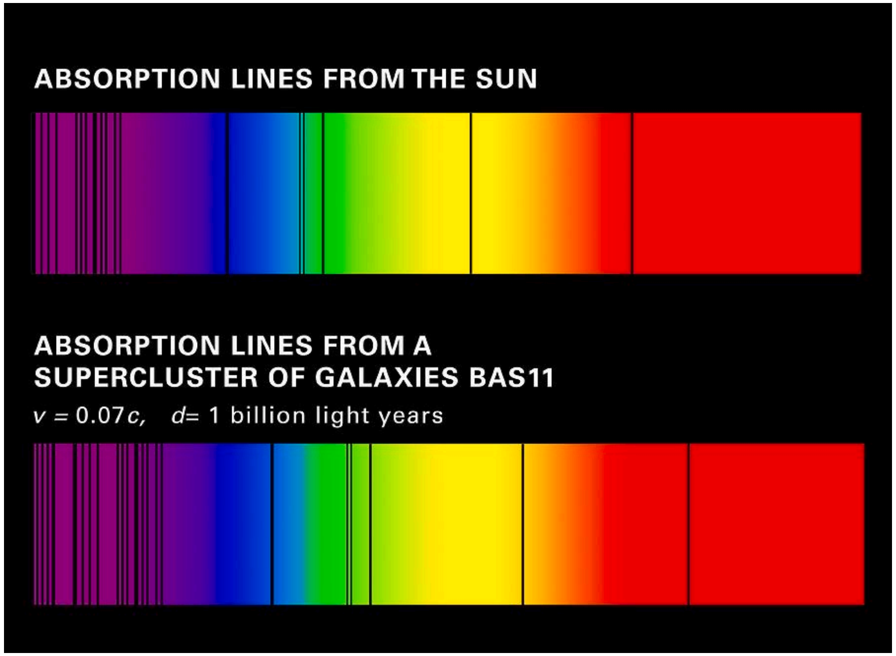
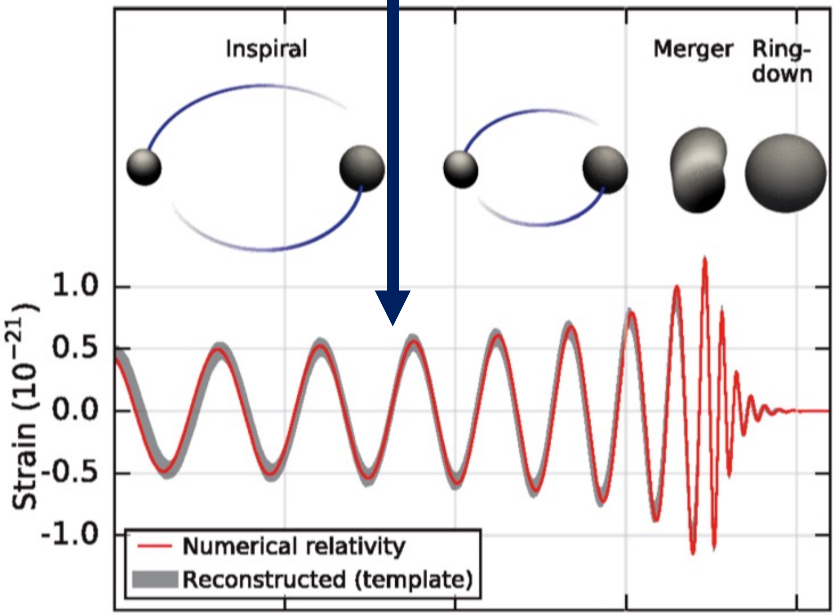
Universe Expansion

Hubble Law

$$H_0 d_L = z$$

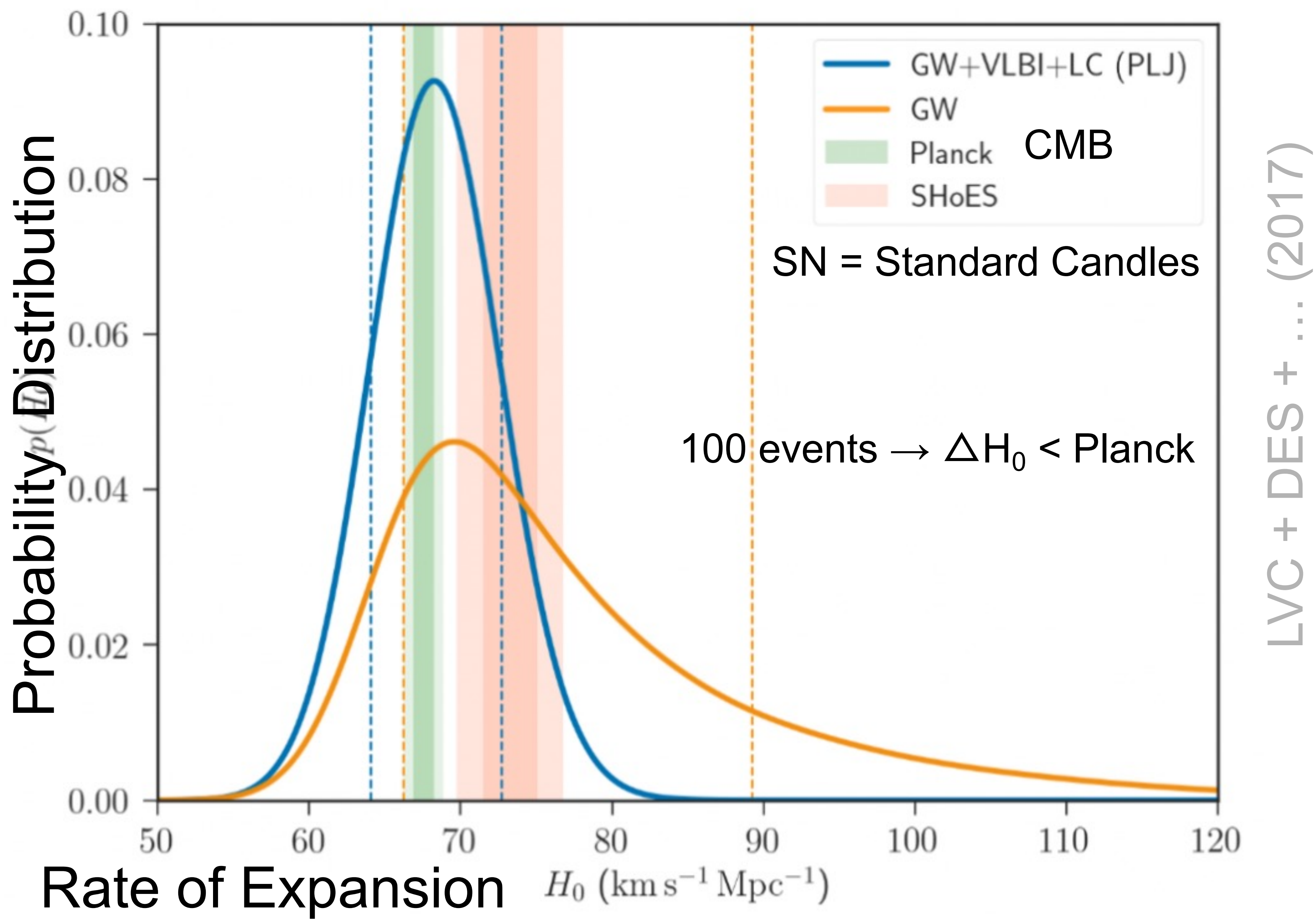




NGC4993

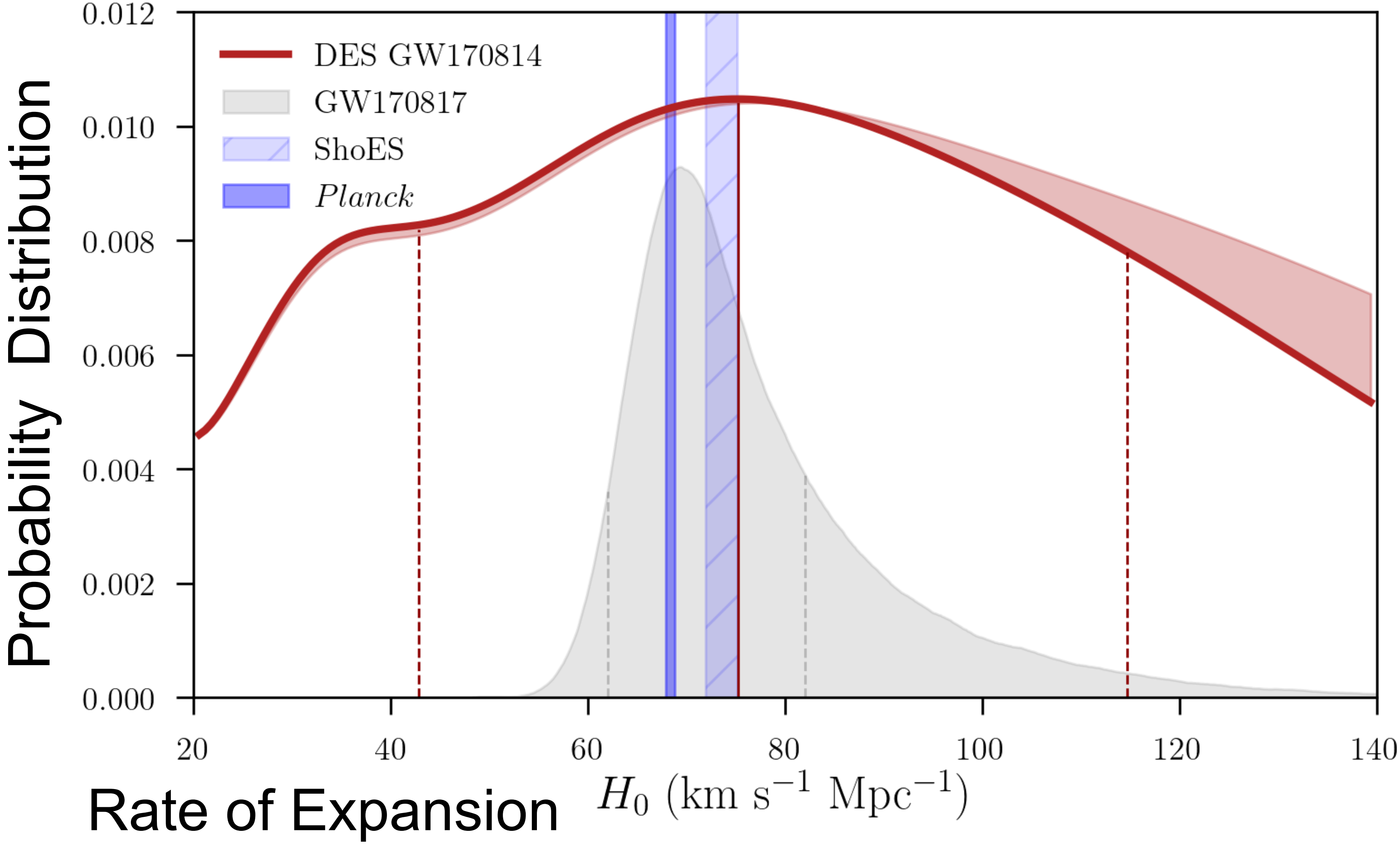
$z = 0.009727$

GW = Standard Sirens



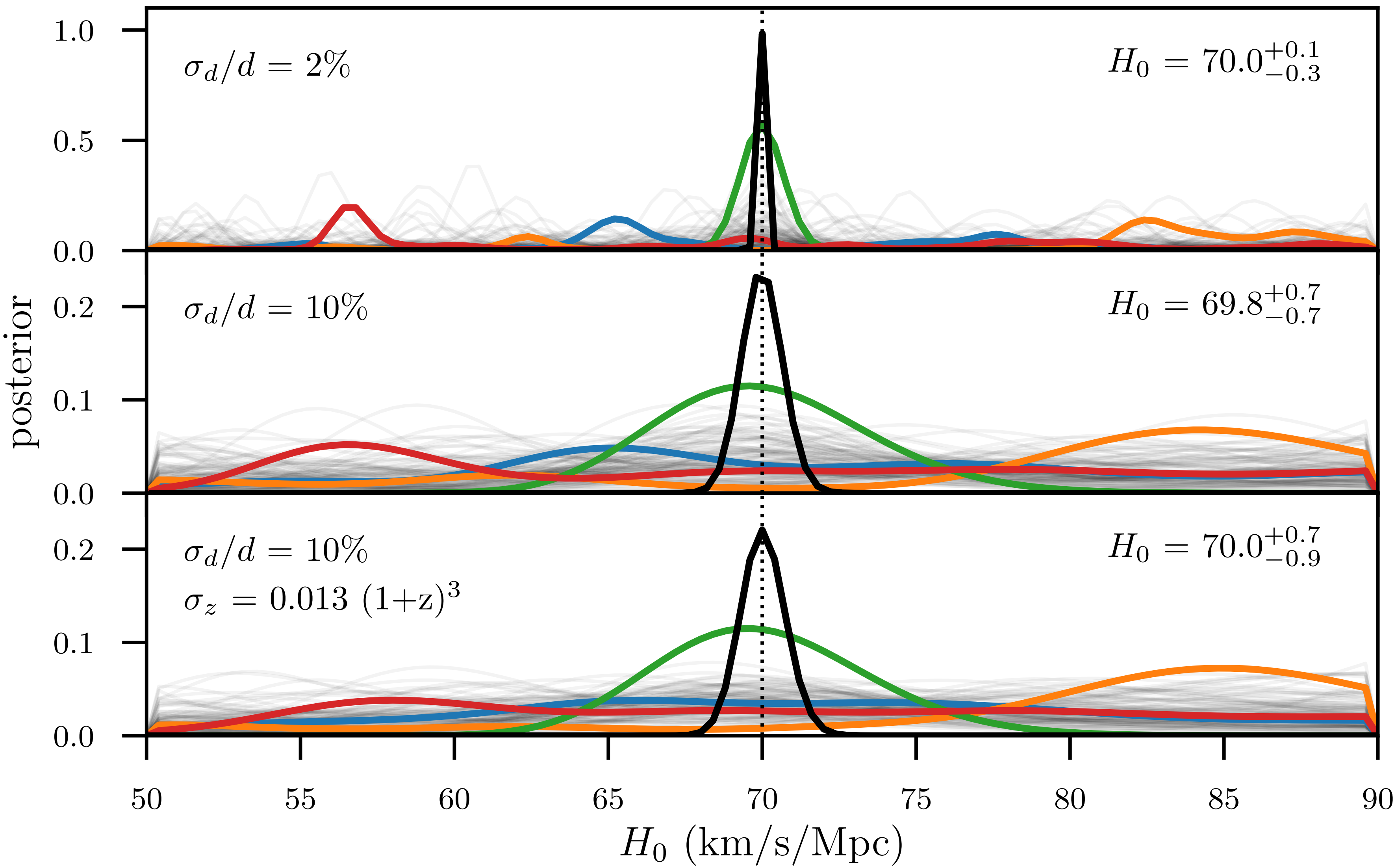
GW = Dark Sirens

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

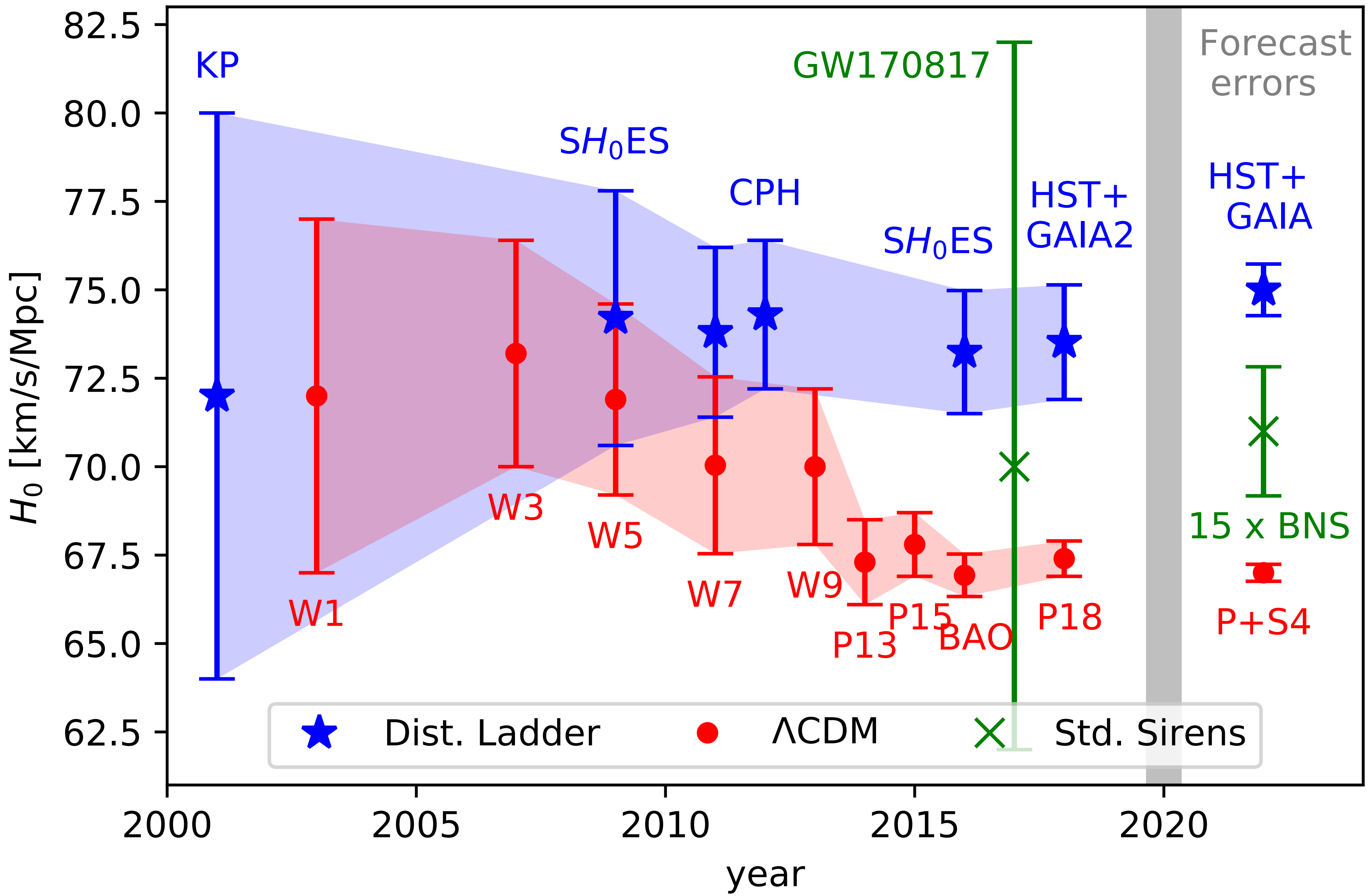


GW = Dark Sirens

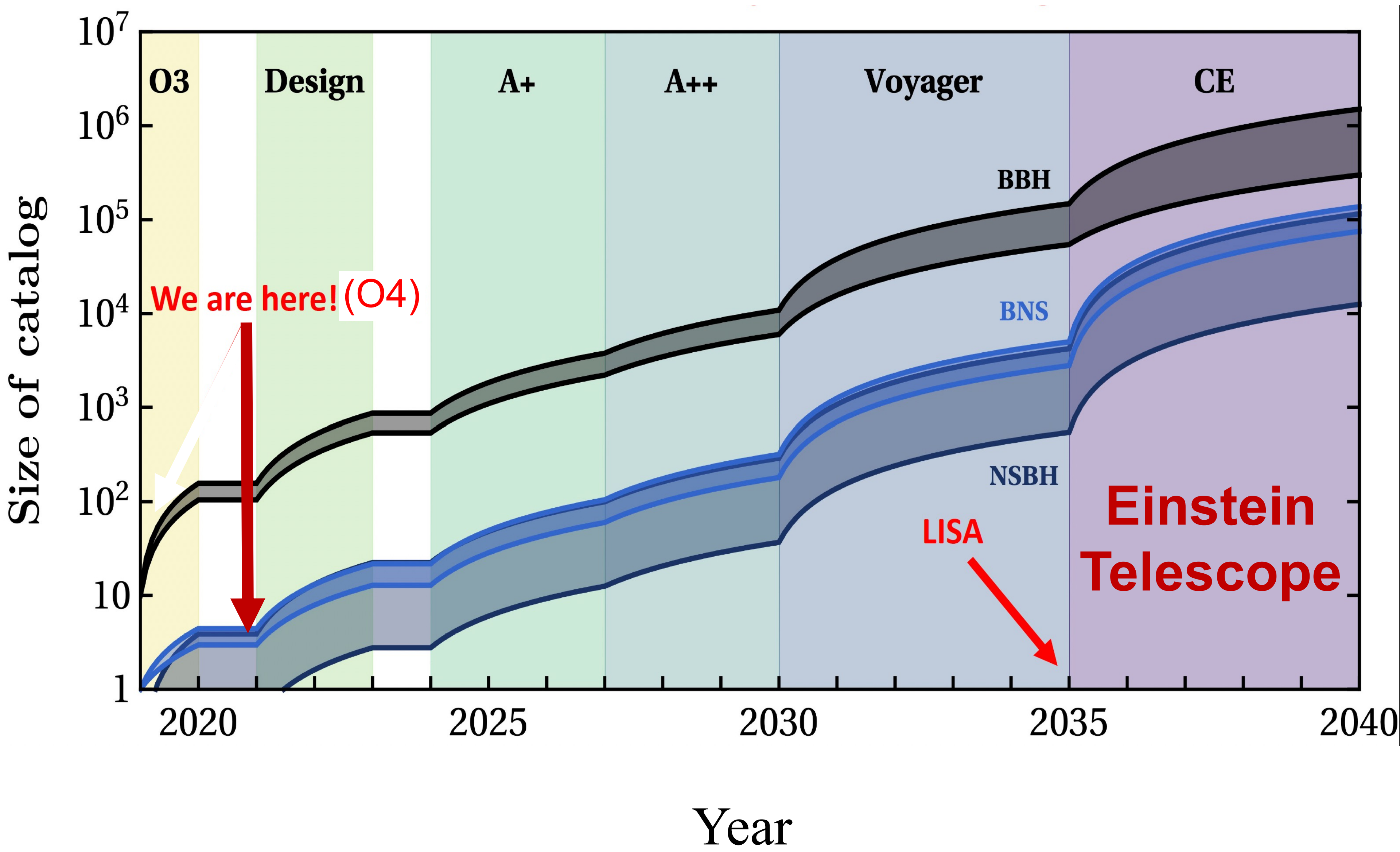
Soares-Santos, Palmese, JGB et al. (2019)



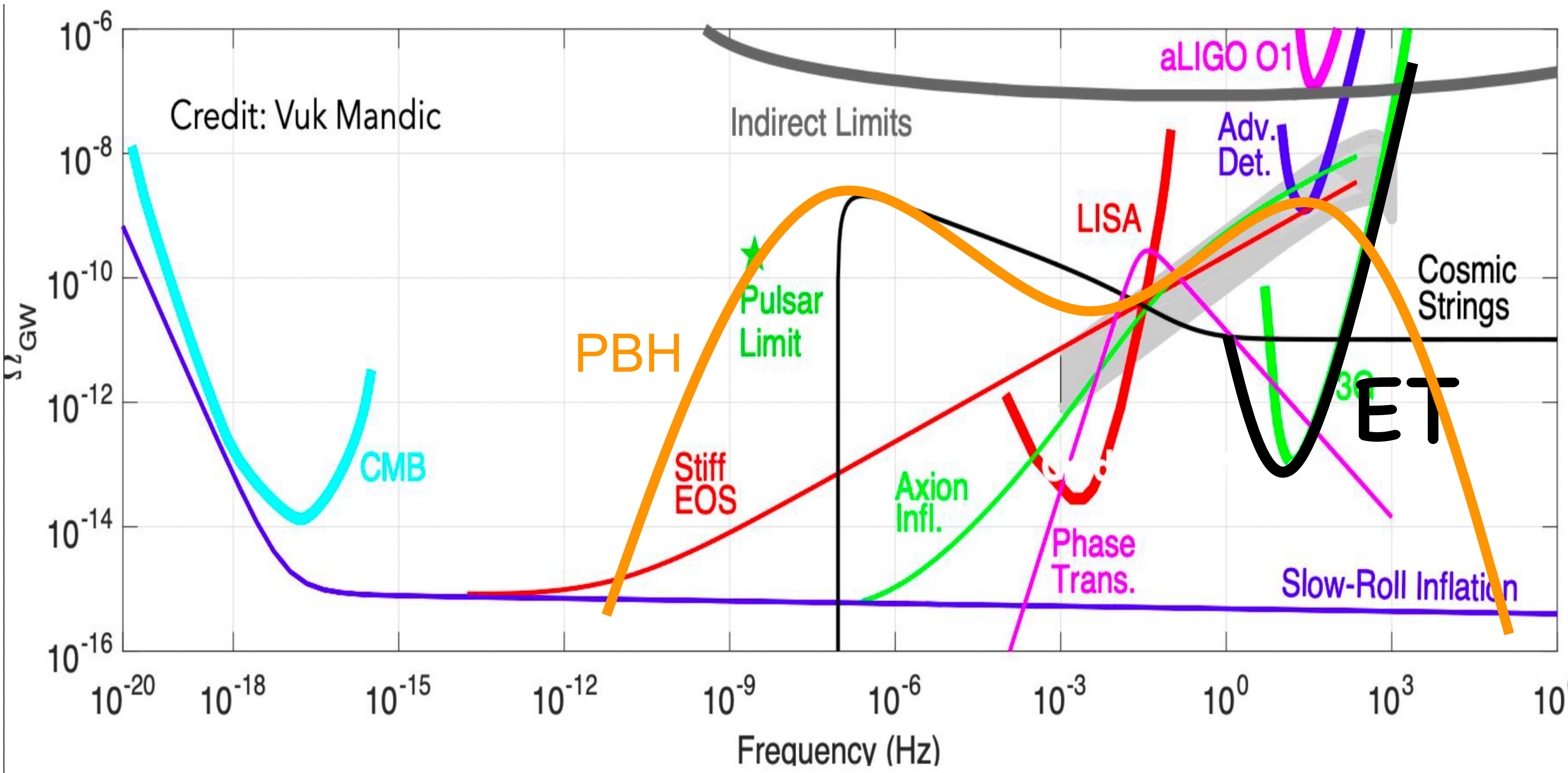
H_0 tension: Future prospects



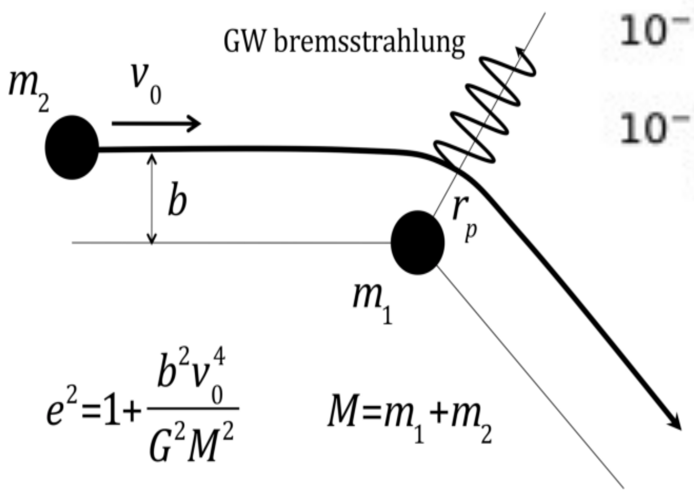
Expected BBH, BNS, NSBH

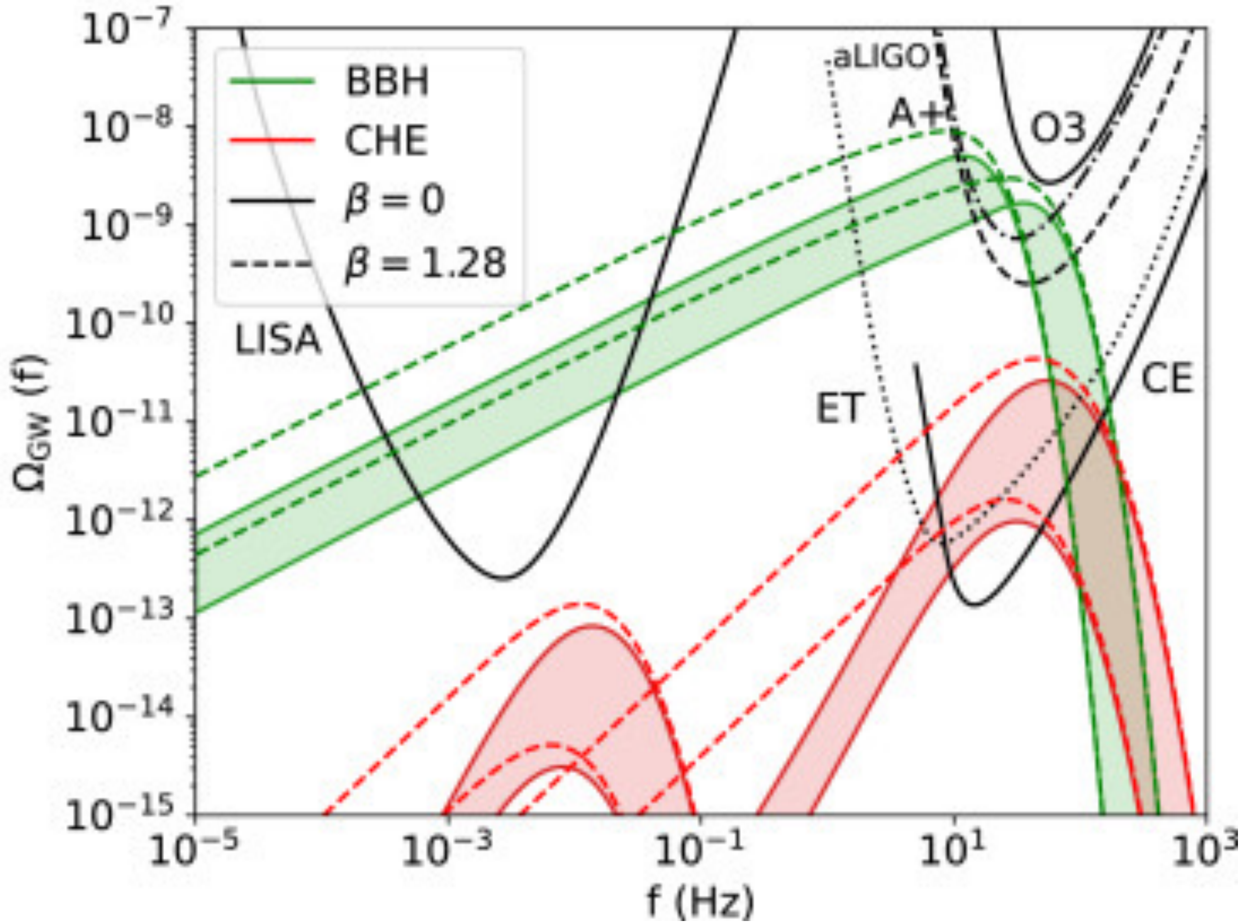


Stochastic GW Background



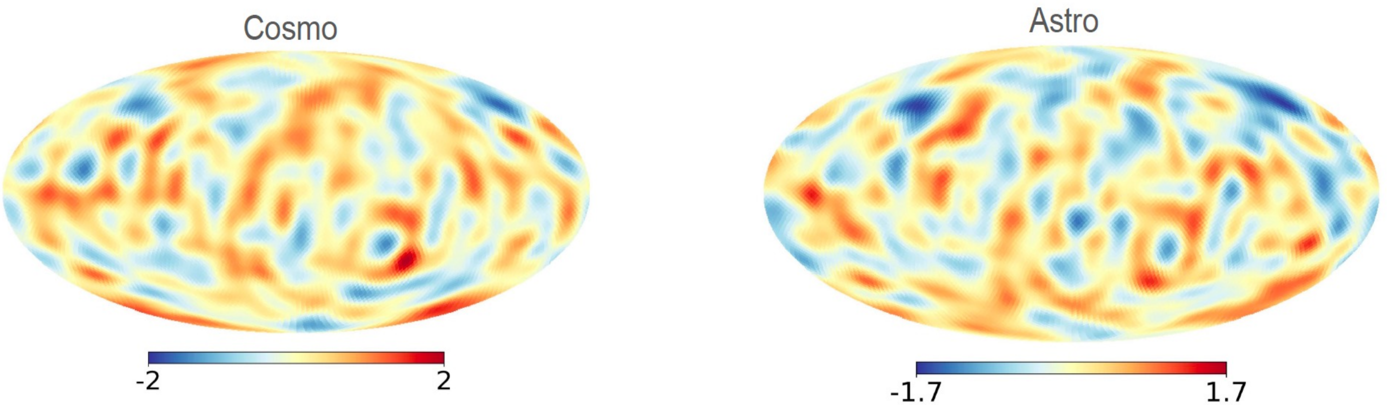
Stochastic GW Background





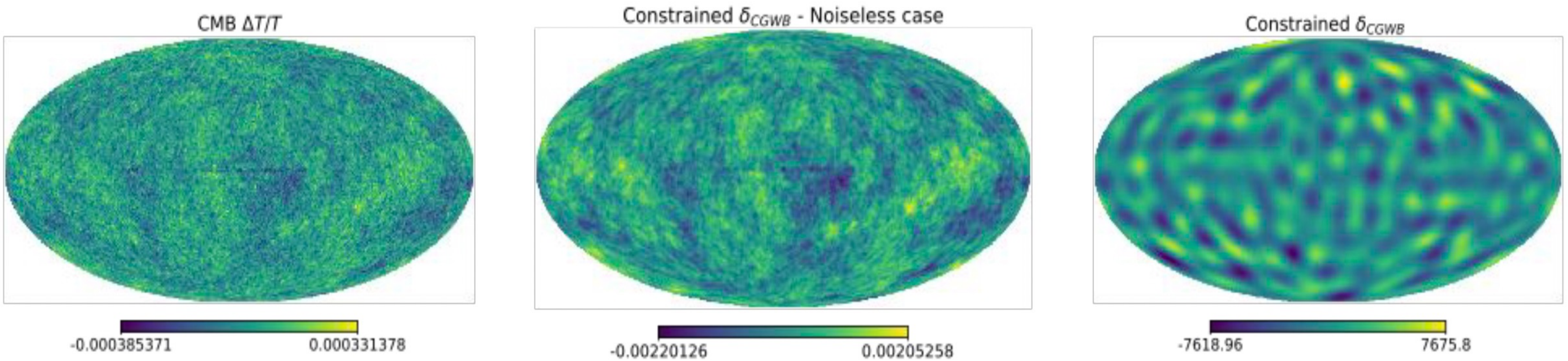
Mapping the SGWB

O4 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

- Second Generation GW interferometers are still an essential step towards the future.

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

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