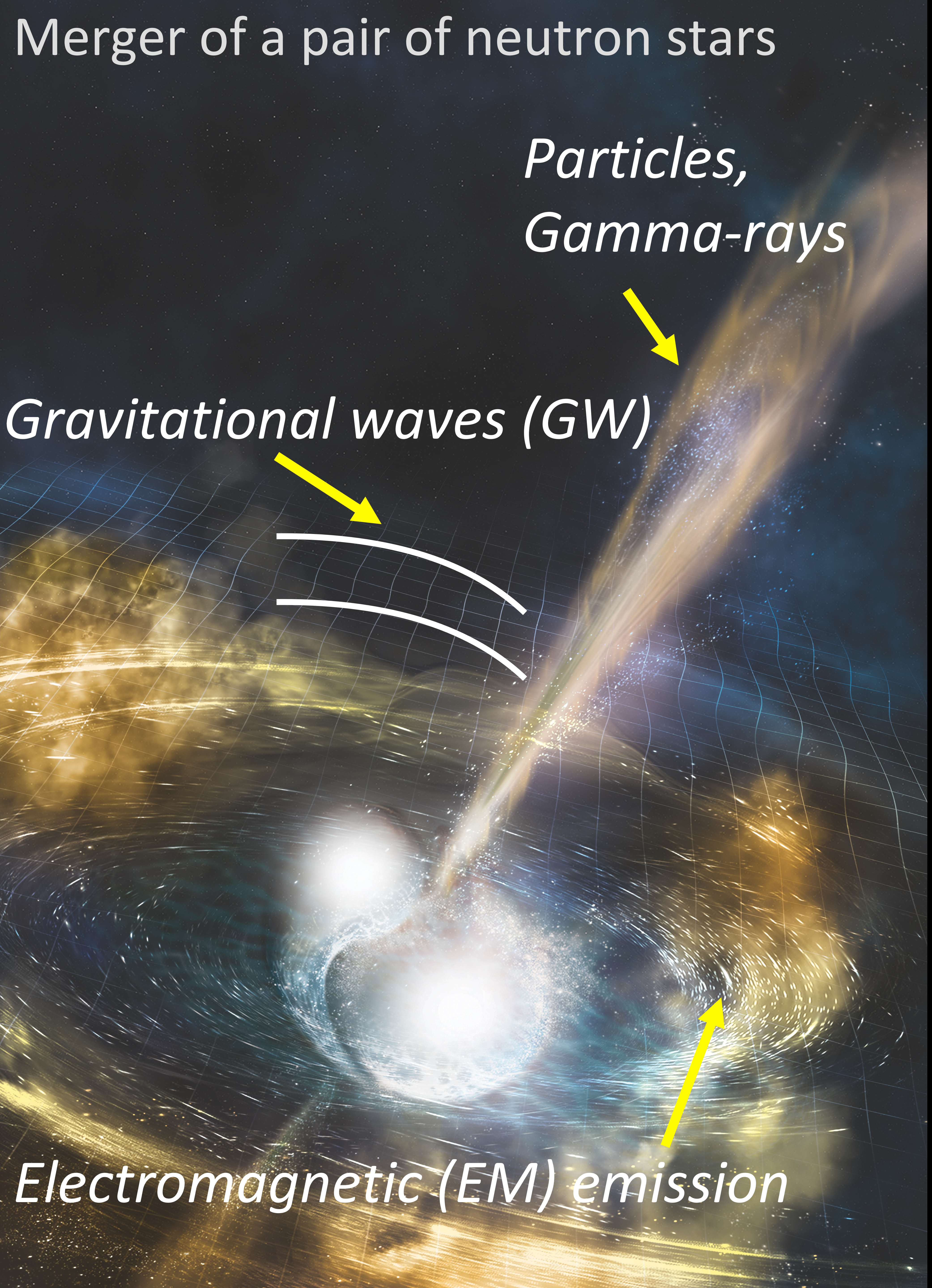


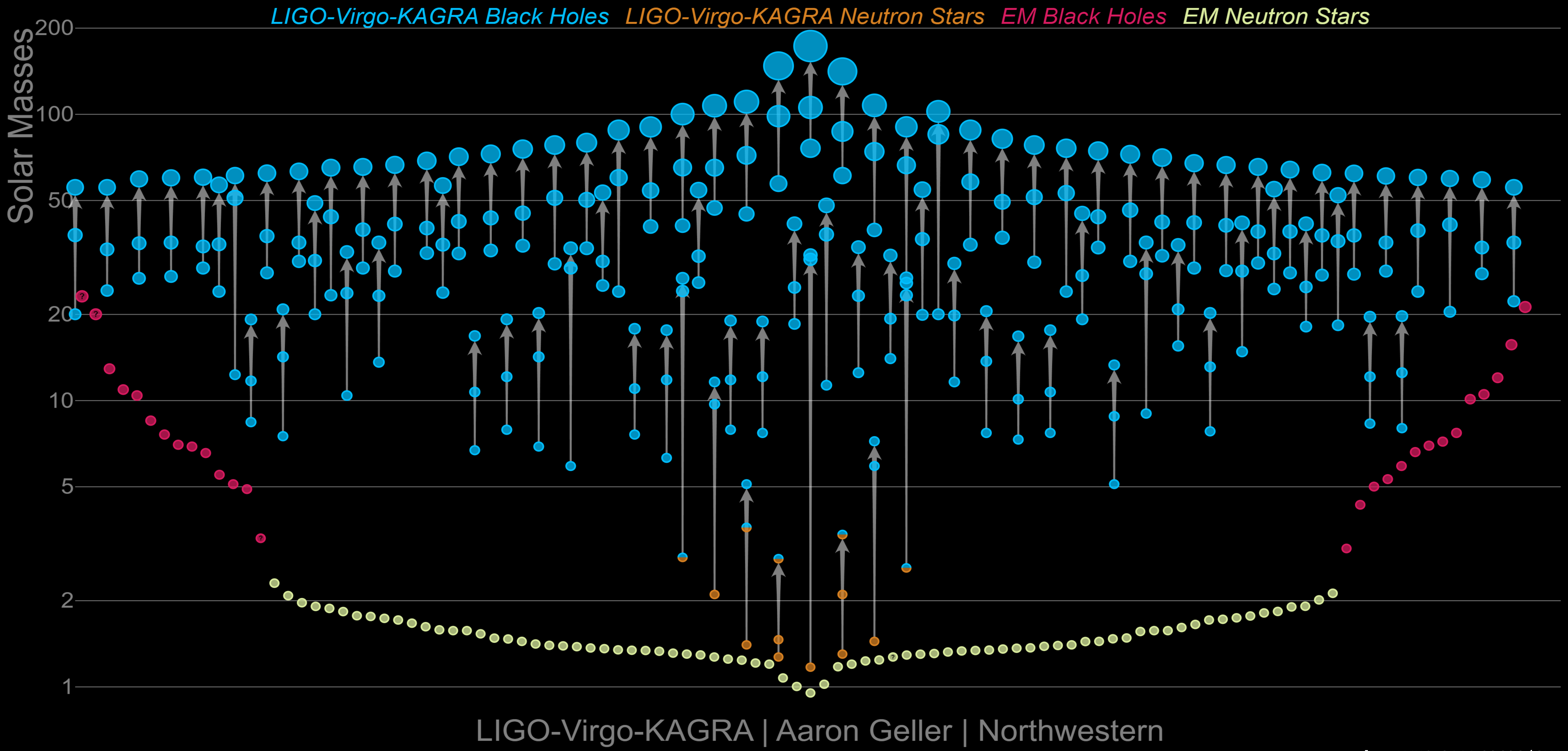
New perspectives onto the Universe in the era of Gravitational Wave (GW) Physics

Samaya Nissanke

GRAPPA, University of Amsterdam and Nikhef, the Netherlands;
Frankfurt Institute for Advanced Studies,
Kavli IPMU Tokyo

42nd International Conference on High Energy Physics,
Praha, 23rd July 2024

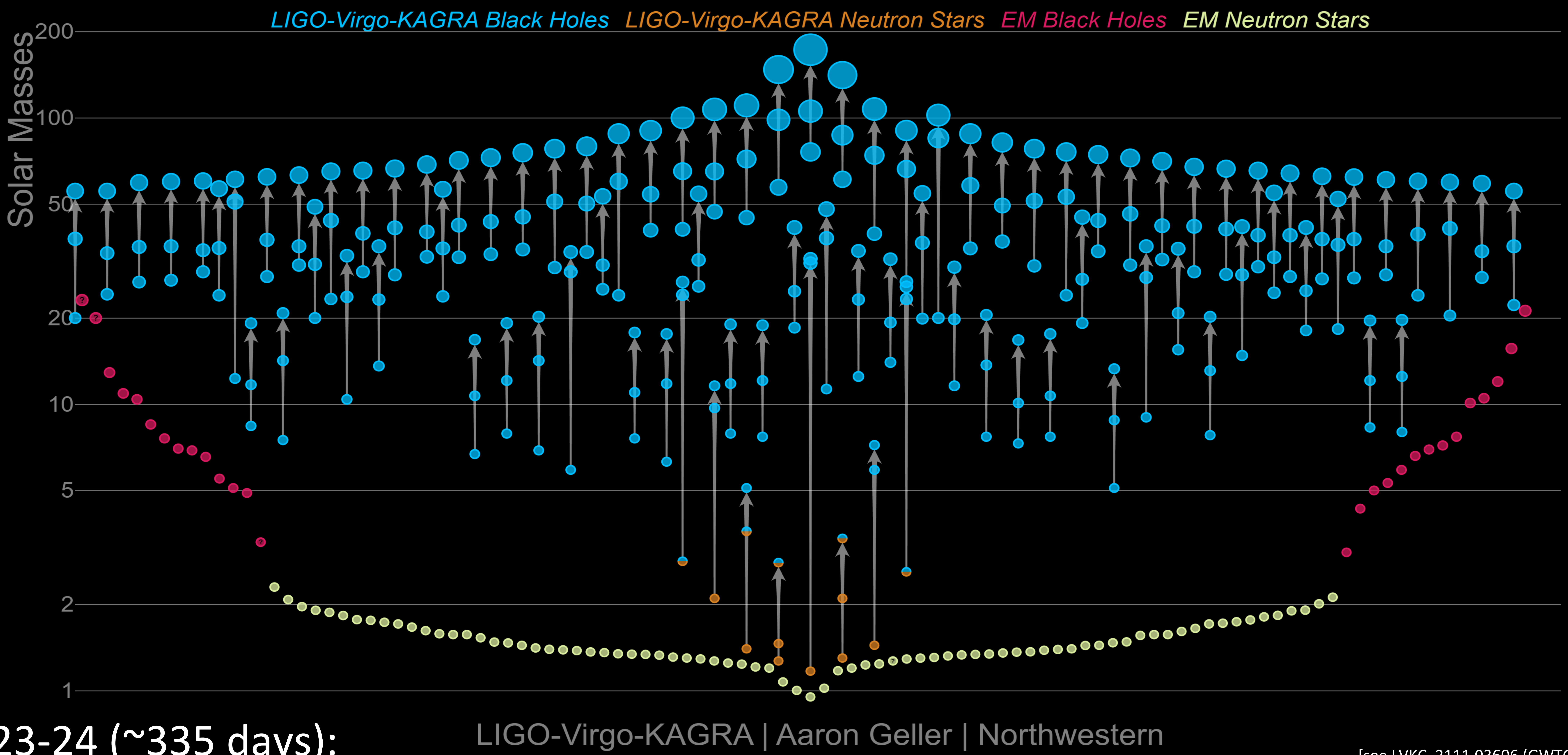
The Compact Object Zoo Today



2015-2020, O1-O3: 477 days

[see LVKC, 2111.03606 (GWTC3), arXiv 2010.14527 (GWTC 2; LVC, arXiv 1811.15007 (GWTC-1) see also Venumadhav, Zackay, Dai, …2019; Zackay et al. 2019a,b, Magee et al 2019, Nitz, + 2019, 2020, 2021]

The Compact Object Zoo Today

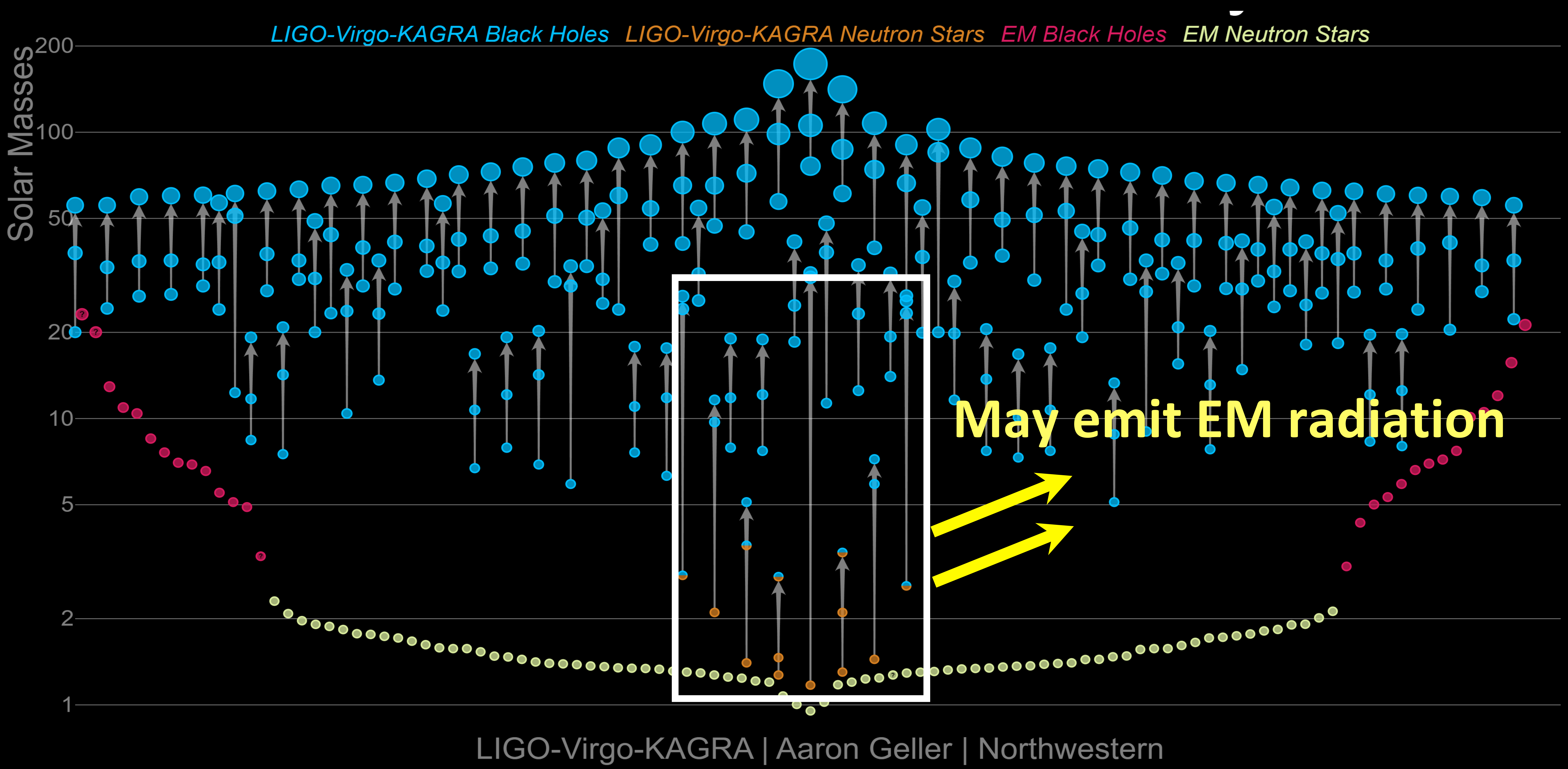


O4, 2023-24 (~335 days):
118 significant candidates (inc. GW230529)

https://gracedb.ligo.org/superevents/public/O4/?page=1&showall=0

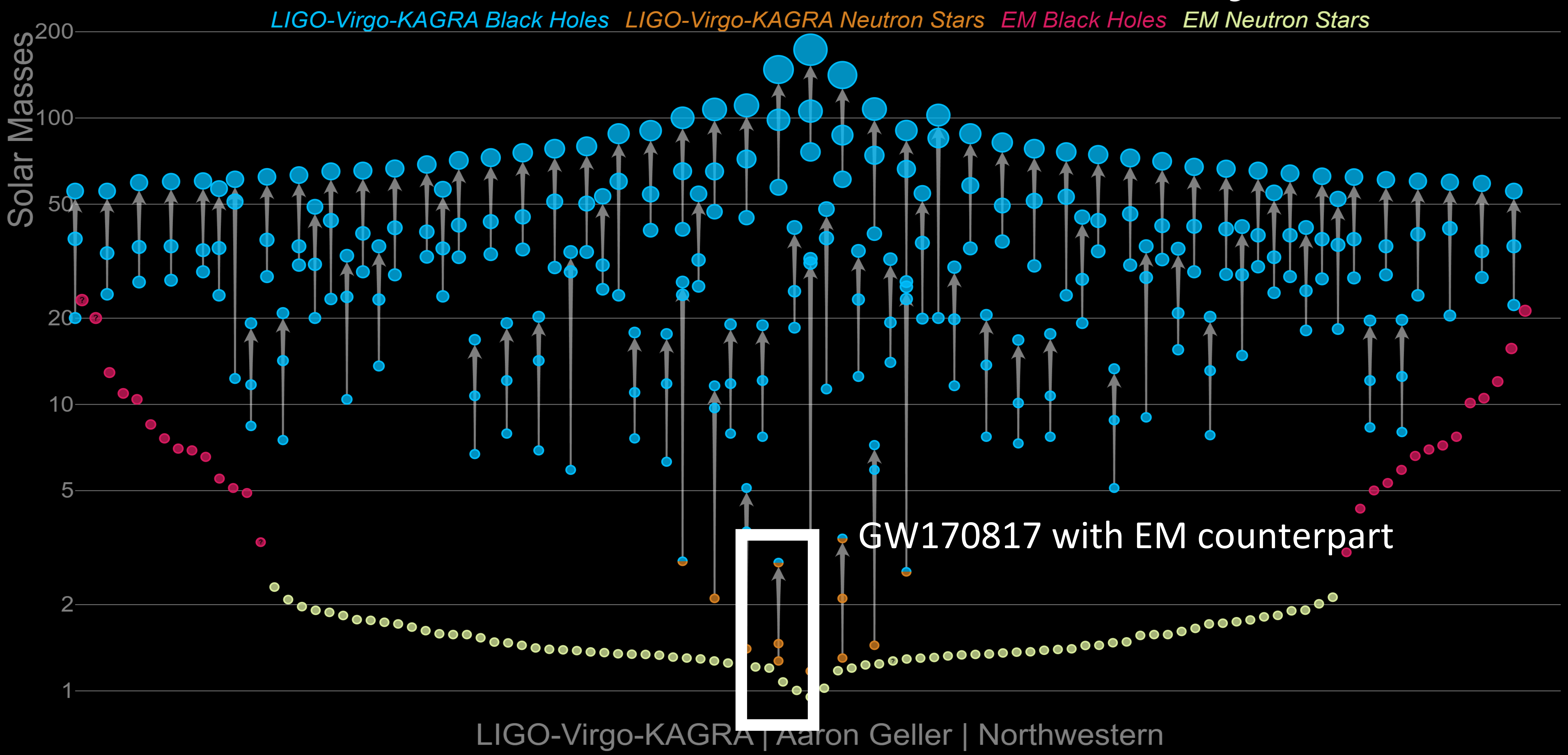
[see LVKC, 2111.03606 (GWTC3), arXiv 2010.14527 (GWTC 2; LVC, arXiv 1811.15007 (GWTC-1) see also Venumadhav, Zackay, Dai, …2019; Zackay et al. 2019a,b, Magee et al 2019, Nitz, + 2019, 2020, 2021]

Neutron Star Binary Mergers



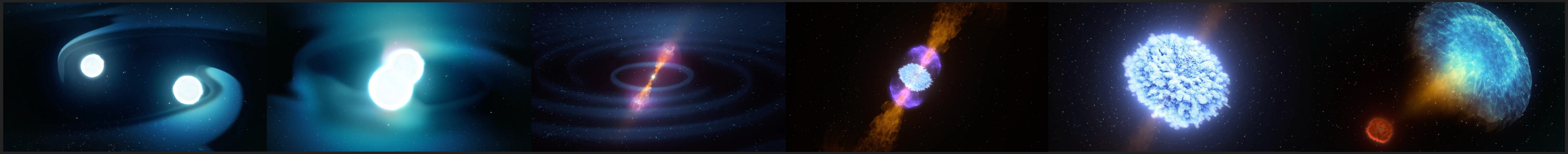
2 Binary Neutron Star & 4 Neutron Star-Black Hole Mergers

Neutron Star Binary Mergers



The first binary neutron star merger

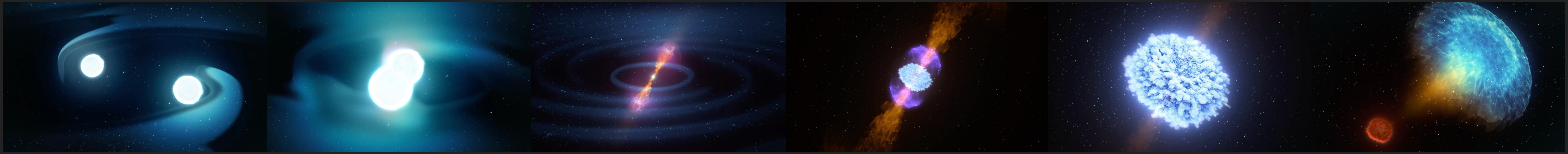
GW170817



- minute ***time = 0*** ***Seconds*** ***hours-days*** ***months-years***

The first binary neutron star merger

GW170817



First Gravitational Wave Standard Siren Hubble Constant Constraint

First Short Gamma Ray Burst - Binary Neutron Star Merger Association

First kilonova discovery and astrophysical site of r-process heavy elements

First tests of the speed of light and gravity with a GW+EM event …

Gravitational Wave Mergers: the source of many discoveries

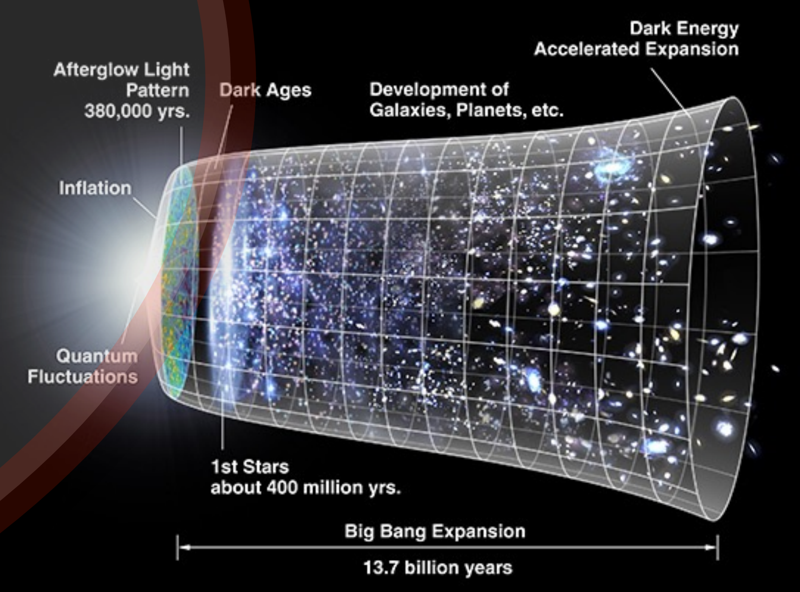
Chemical enrichment in the Universe

Binary stellar evolution & the fate of massive stars

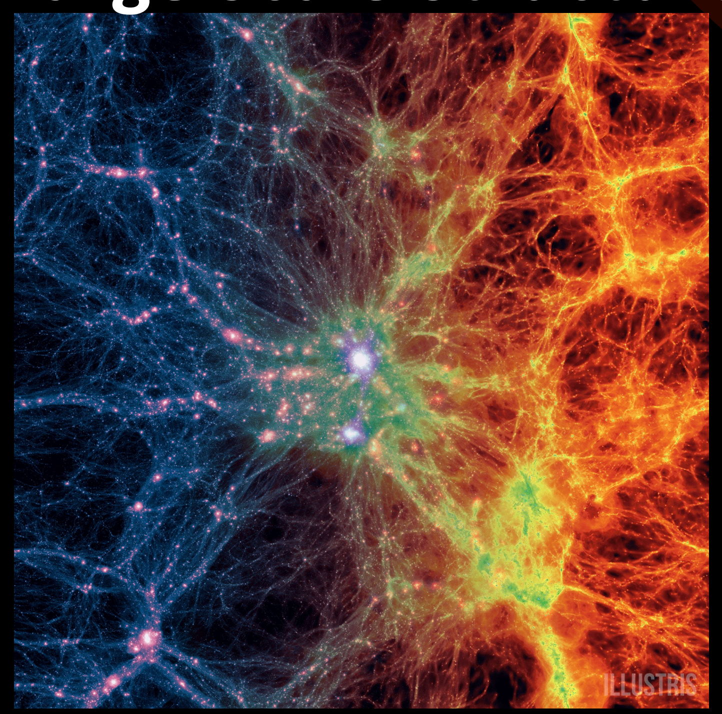
High energy astrophysics

GW Mergers (including multi-messenger GW170817)

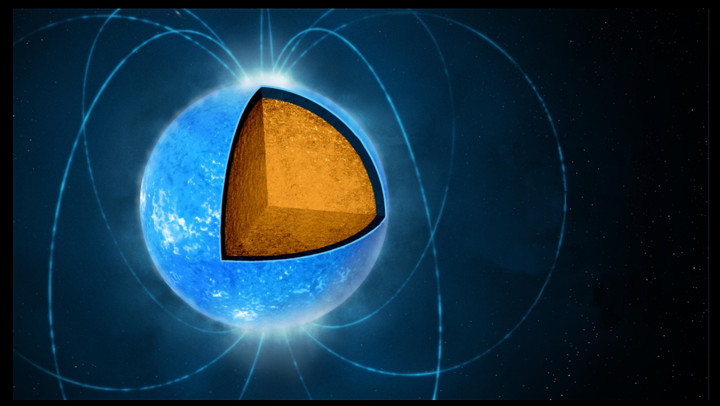
Cosmology



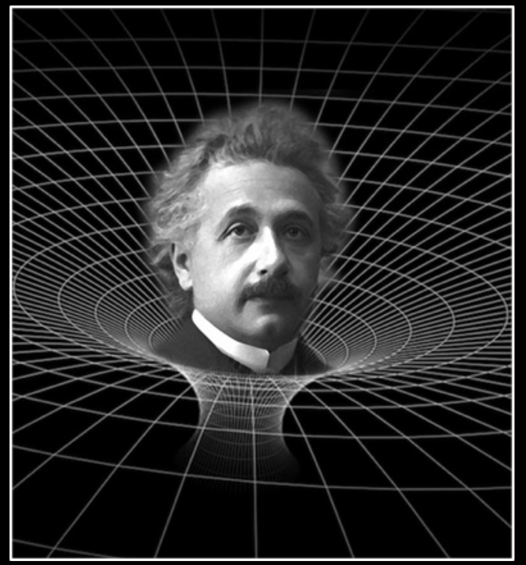
Large Scale Structure



Nuclear Physics



General Relativity and Beyond the Standard Model Physics



Gravitational Wave Mergers: the source of many discoveries

Chemical enrichment in the Universe

Binary stellar evolution & the fate of massive stars

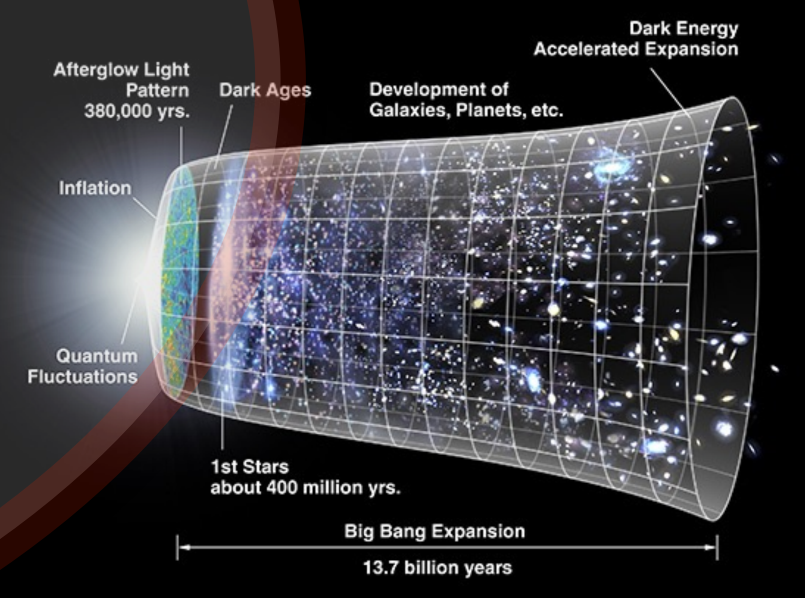
High energy astrophysics

GW detectors

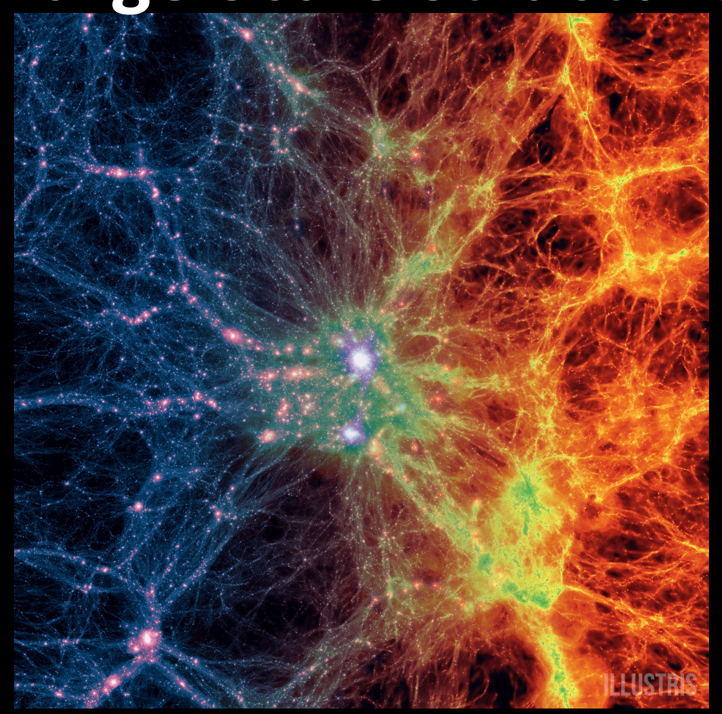
Data theory, big data and machine learning

Time-domain Astronomy

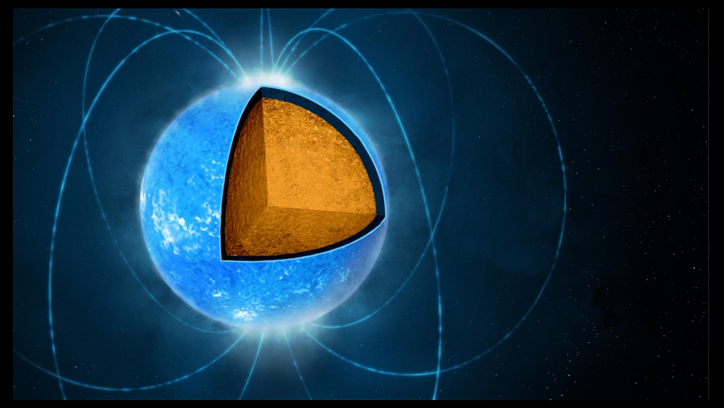
Cosmology



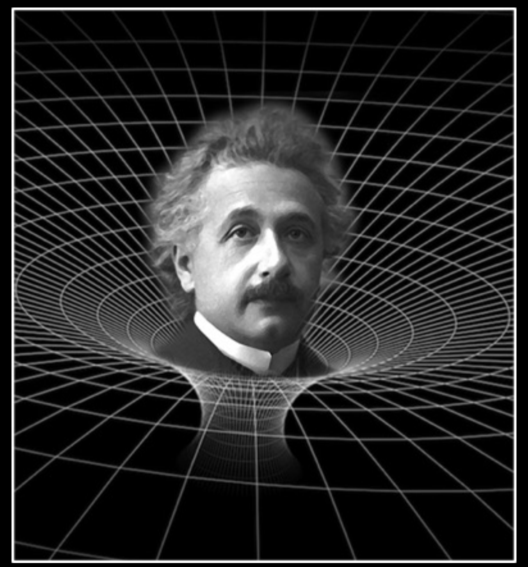
Large Scale Structure



Nuclear Physics



General Relativity and Beyond the Standard Model Physics



Talk Outline

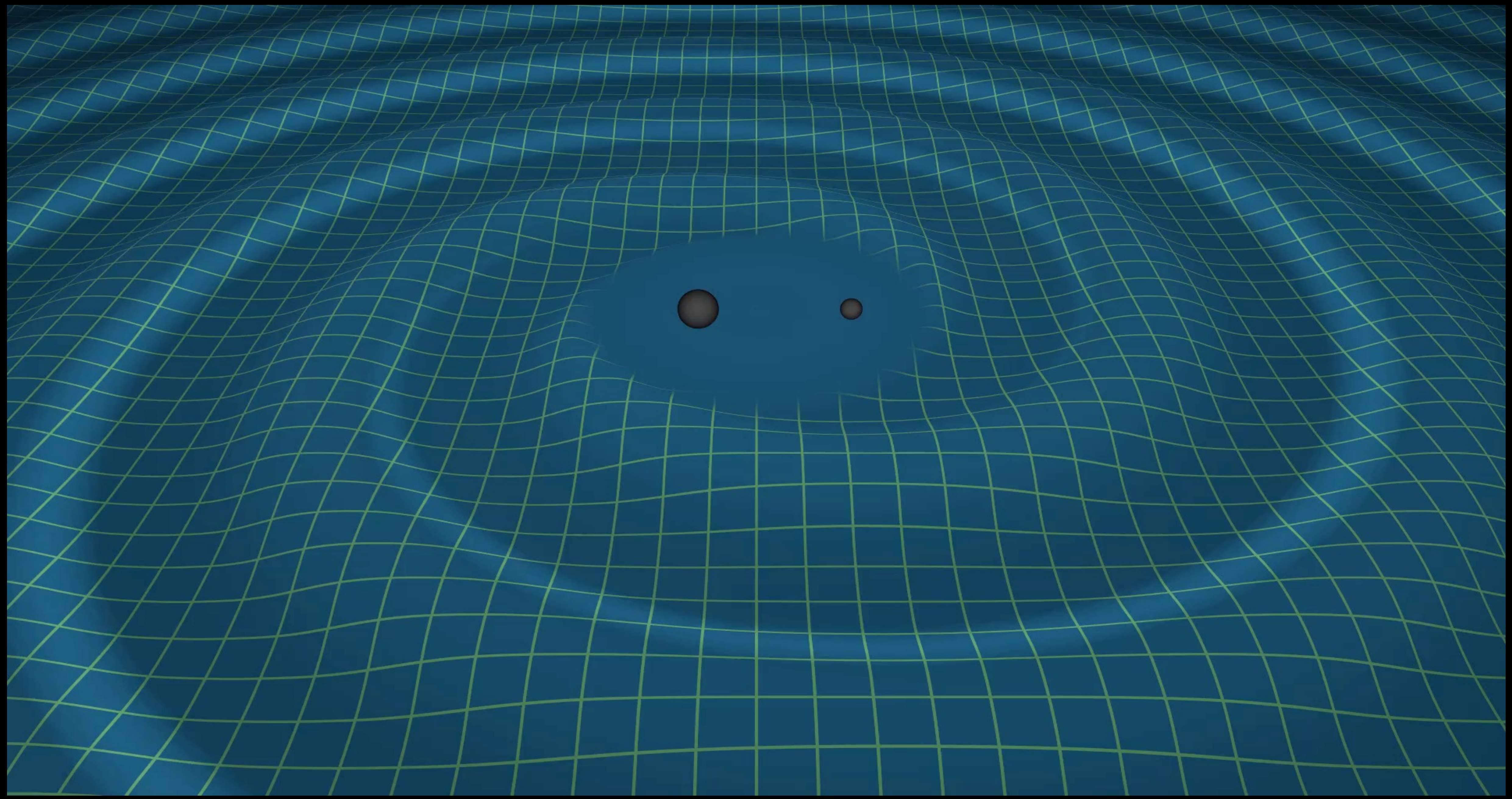
1. Gravitational Wave Observations with ground-based detectors: what we have learnt and open questions?

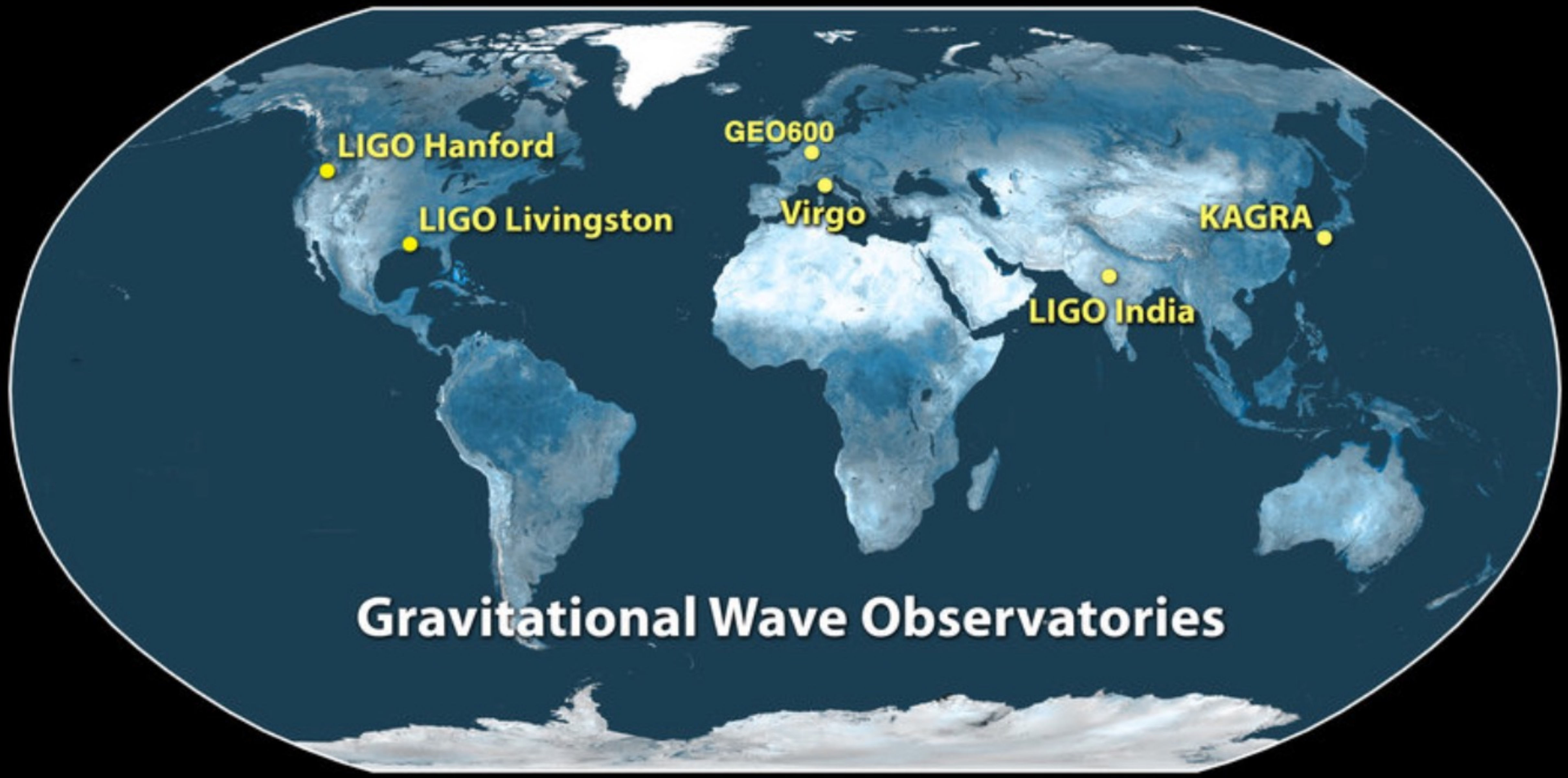
2. Perspectives and future ground based GW detectors

Collaborations: Virgo Collaboration (LIGO-Virgo-KAGRA), Einstein Telescope Collaboration, LISA Consortium, Zwicky Transient Facility, UVEX, JAGAWR etc.

Disclaimer: O(1000s) references on GW1701817 alone, LRR reviews in progress

GWs are perturbations in spacetime curvature measurable by a network of detectors



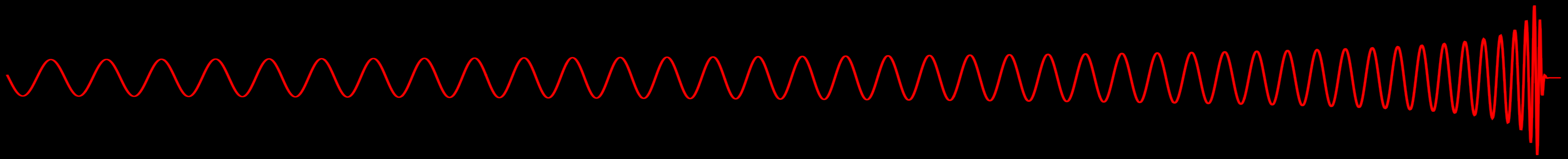


Measurable: GW strain h (t) ~ 1/distance
two polarizations h_+ and $h_\times$

24 - 2048 Hz

Dr Samaya Nissanke

What do we learn from **GWs?**



h(t): 9-17 parameters

- Redshifted Masses
- Spins
- Tidal deformability
- Eccentricity
- Geometric properties:
  - Inclination angle
  - Source Position
  - Luminosity distance

Task 1: input more physics & environment into waveforms

h(t): 9-17 parameters

- Redshifted Masses
- Spins
- Tidal deformability
- Eccentricity
- Geometric properties:
  - Inclination angle
  - Source Position
  - Luminosity distance

Task 2 : we require faster analysis

e.g., machine learning: speed up the analysis by three orders of magnitude

[Delaunay, .. including SN 2021, **DINGO;** Dax et al. 2021. 2022, **PEREGRINE:** Bhardwaj, Alvey, Miller, SN, Weniger, ‘23a, Alvey, Bhardwaj, SN, Weniger, ‘23b]

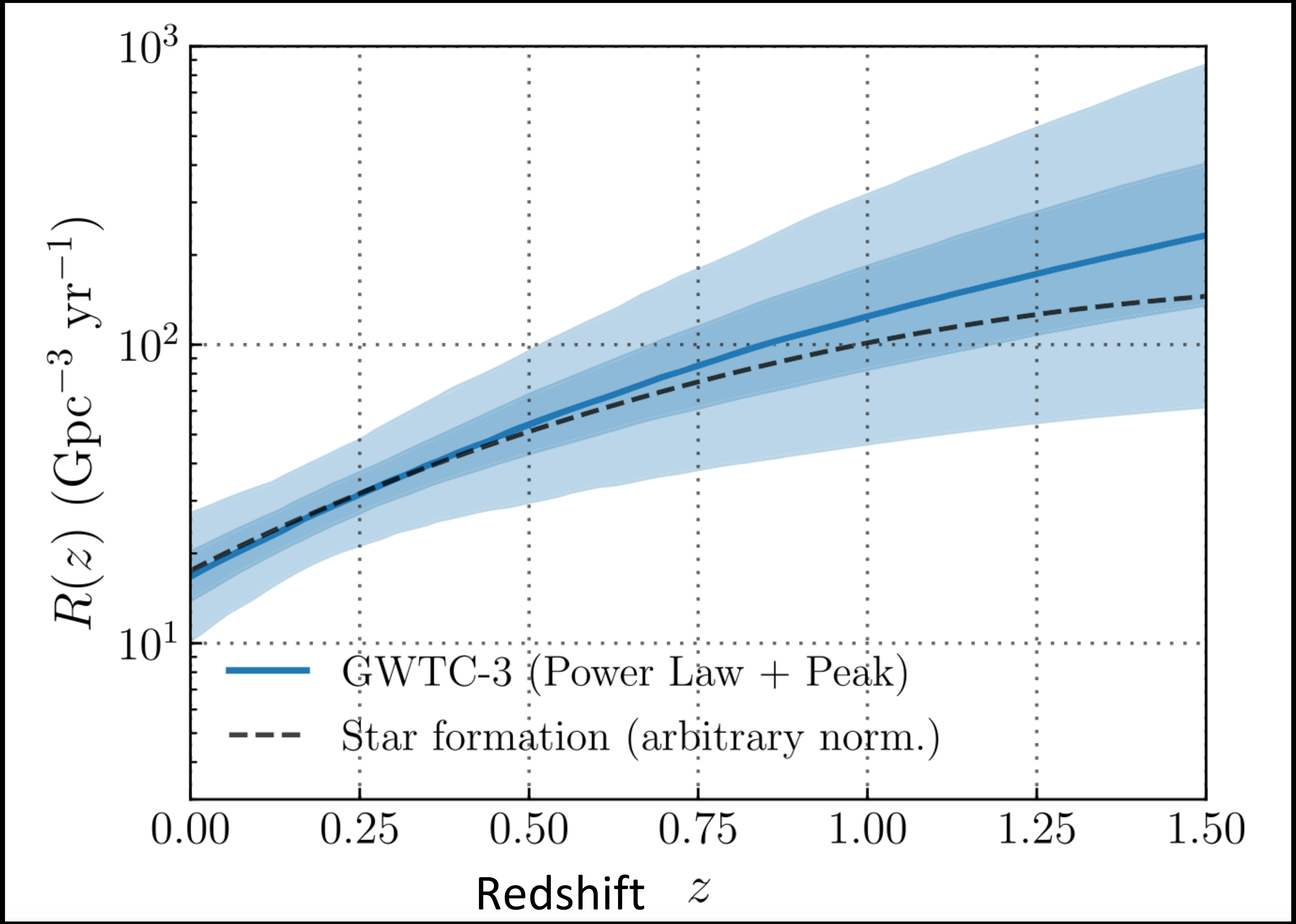
h(t): 9-17 parameters

+ Redshifted Masses
+ Spins
+ Tidal deformability
+ Eccentricity
+ Geometric properties:
  - Inclination angle
  - Source Position
  - Luminosity distance

[See talks by N. Arnaud and F. Di Renzo in astroparticle physics & cosmology session]

What have we learnt so far ?

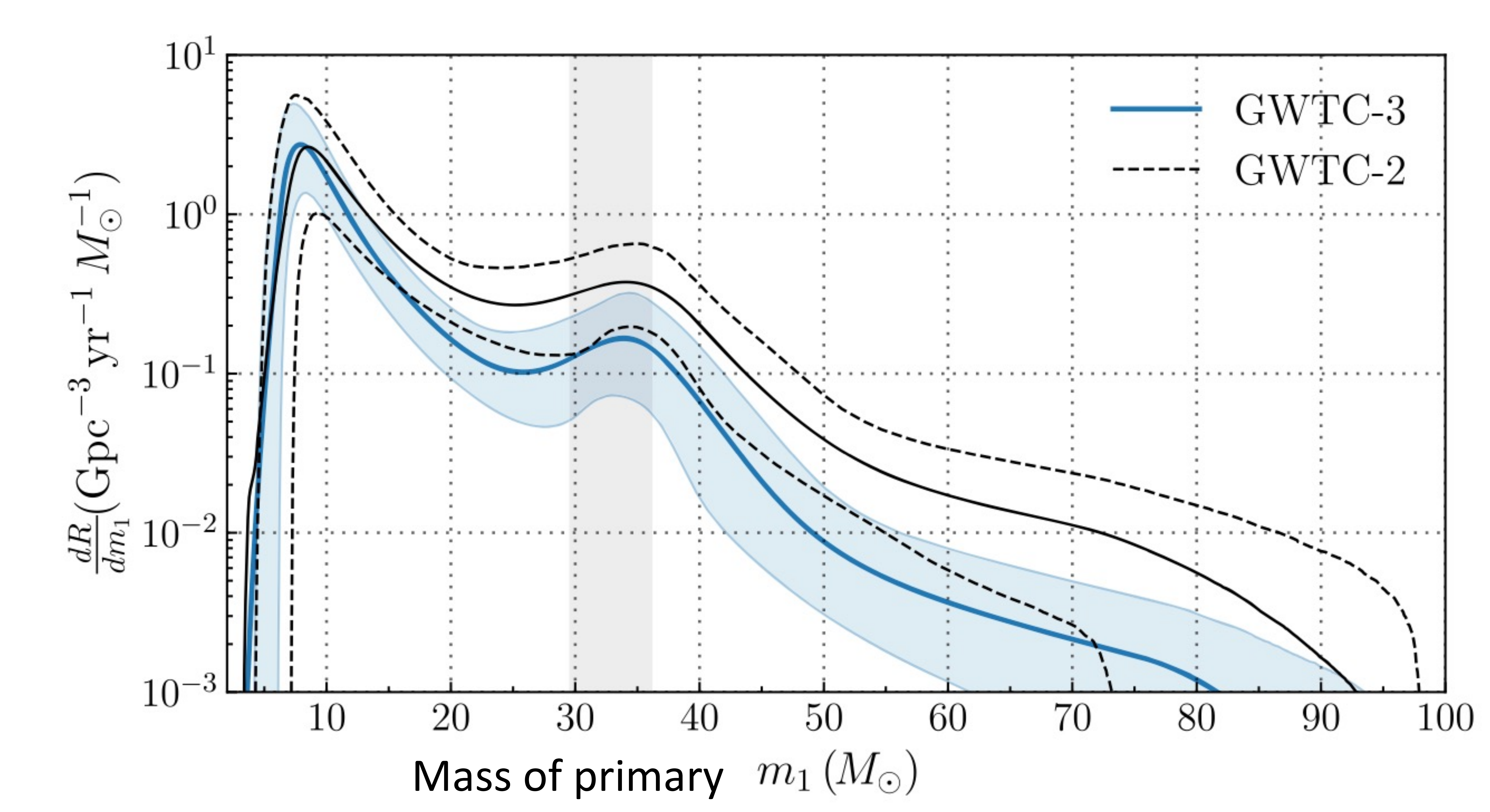
2. The rate of Binary Black Hole Mergers Evolves



[LVKC, Phys. Rev. X **13**, 011048, 2023]

What have we learnt so far ?

3. Structure in the Mass Distribution

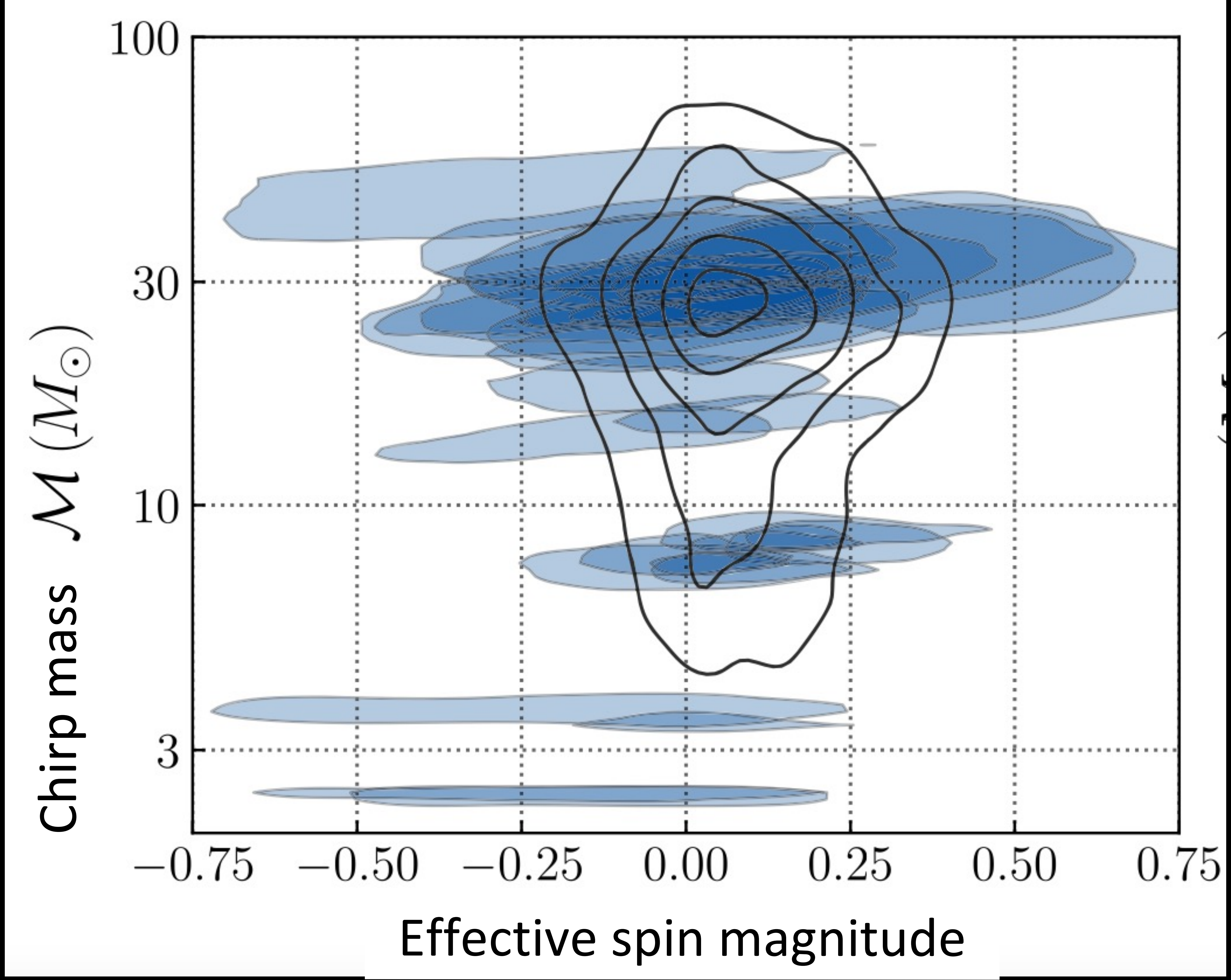


[LVKC, Phys. Rev. X **13**, 011048, 2023]

What have we learnt so far ?

4. Spins of compact objects are measured poorly and are small.

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

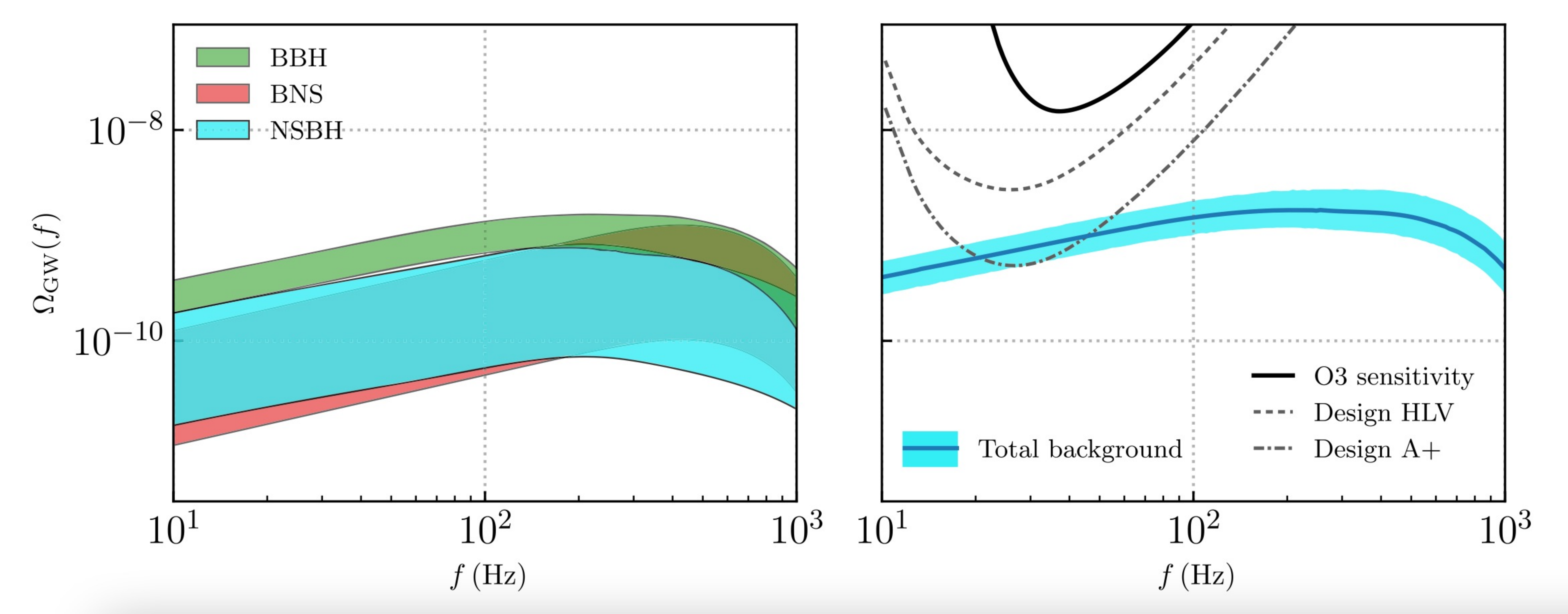


[LVKC, Phys. Rev. X **13**, 011048, 2023]

What have we learnt so far ?

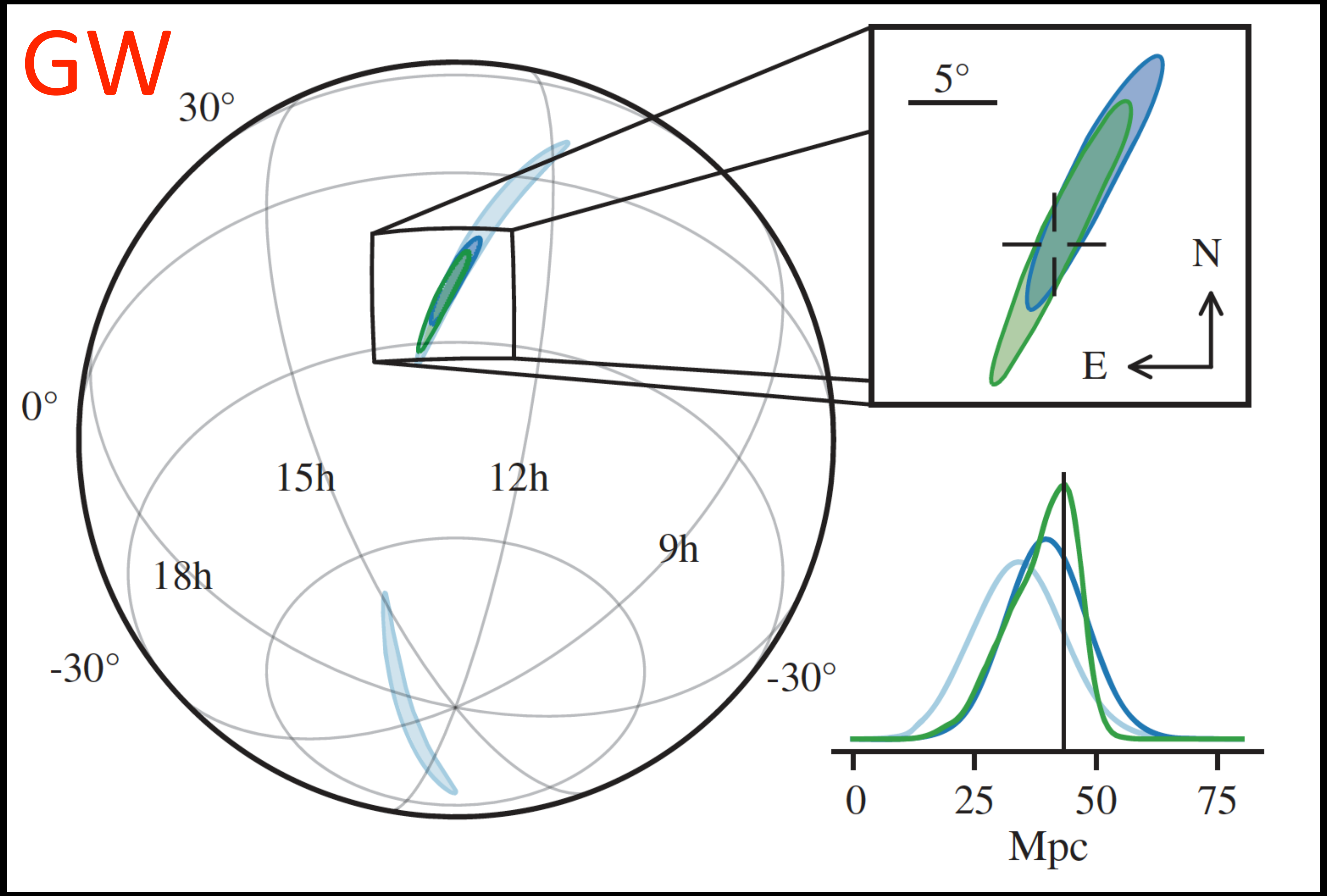
5. The fraction of the ***total energy density*** *of the universe contributed by GWs is $\Omega_{GW} < 5.8 \times 10^{-9}$(95.c.r.)*

[LVKC, Phys. Rev. D **104**, 022004, 2021]

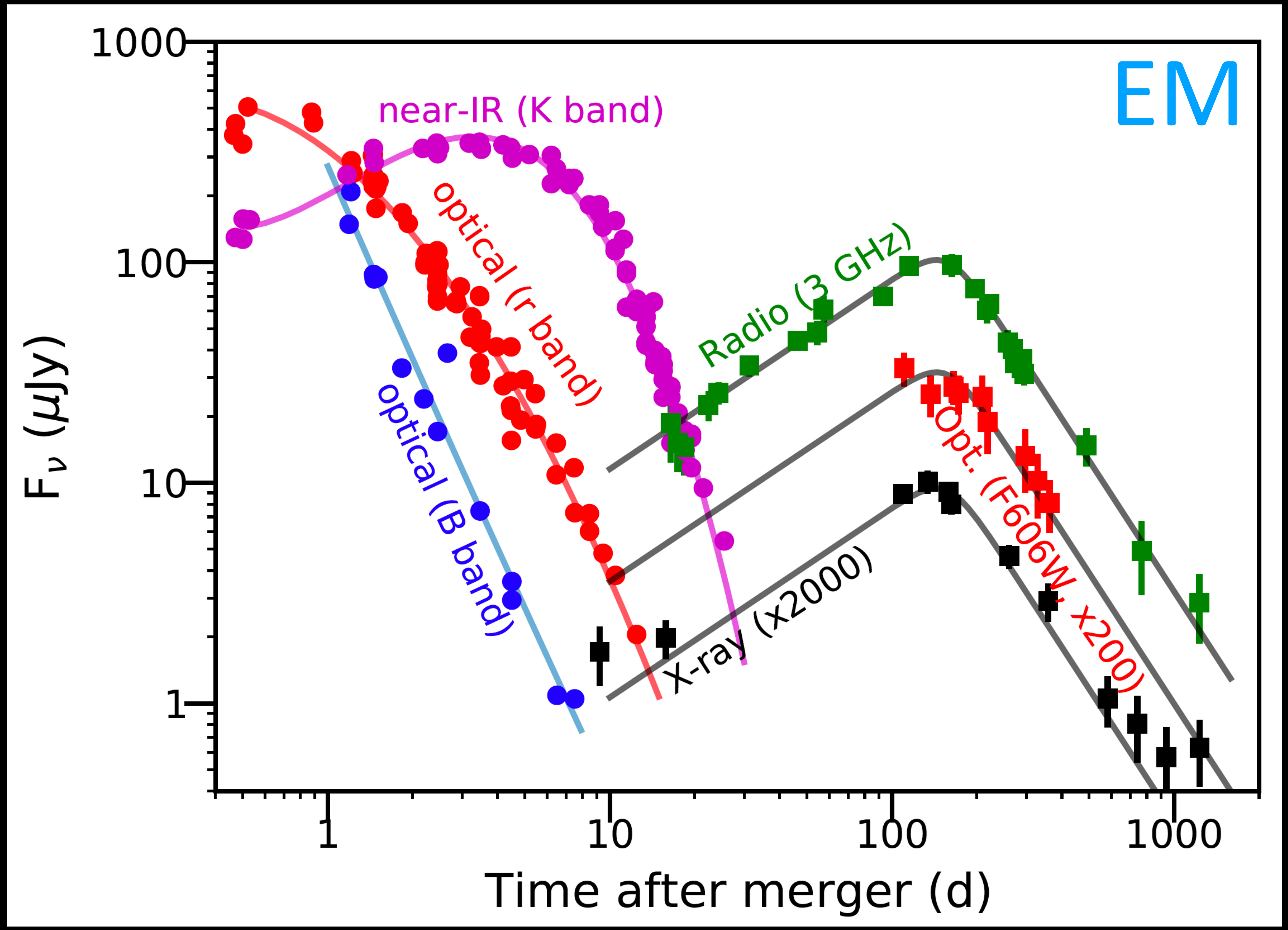


[LVKC, Phys. Rev. X **13**, 011048, 2023]

Multi-Messenger Campaign for GW170817



[LVC, PRL, 119, 161101 (2017),
LIGO, Virgo, EM partners +, ApJLetters **848** L12 (2017)]



[1 Jansky is 10^{-26} W/m^2/Hz]

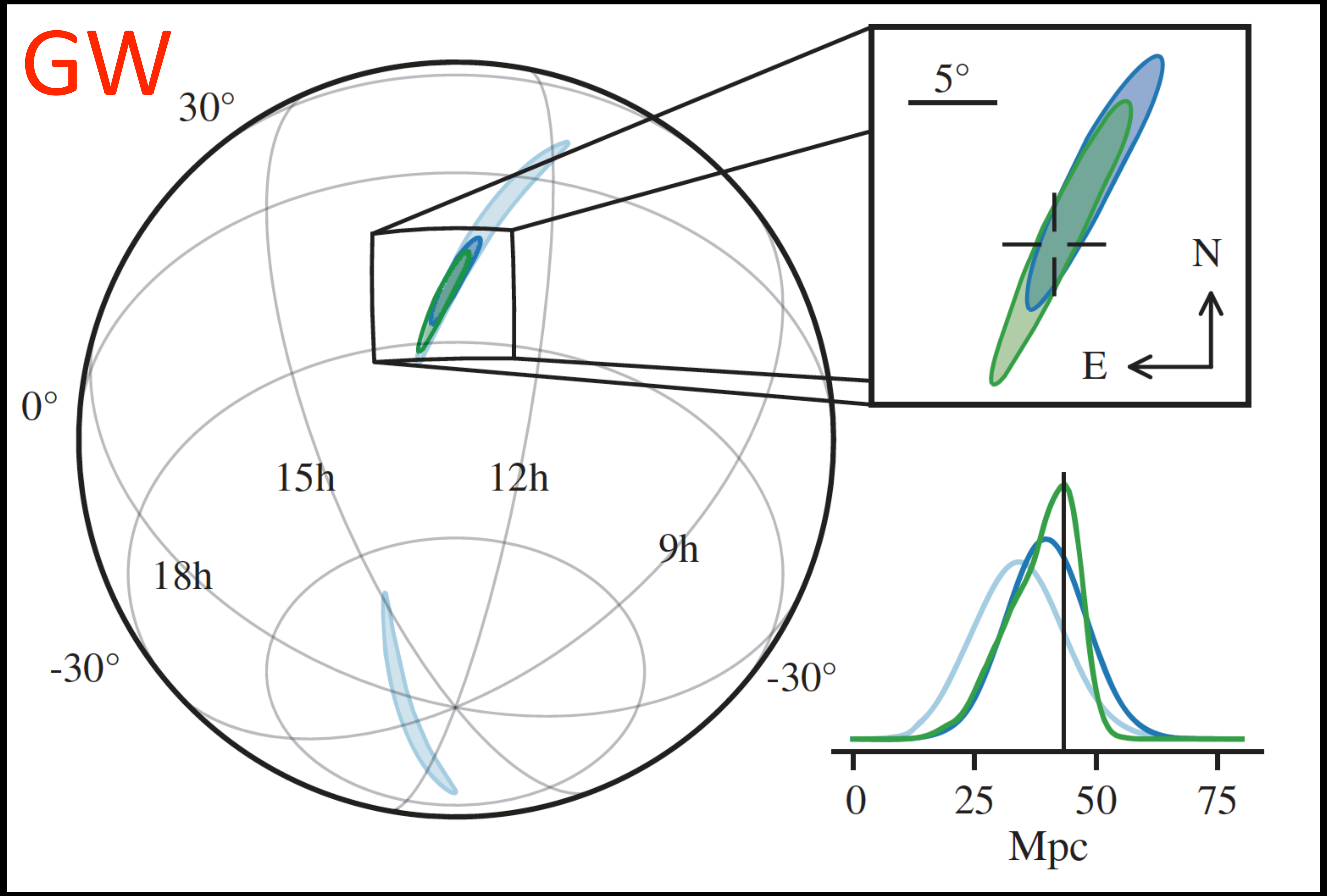
[credit: Kunal Mooley]

Global ground and space-based effort:

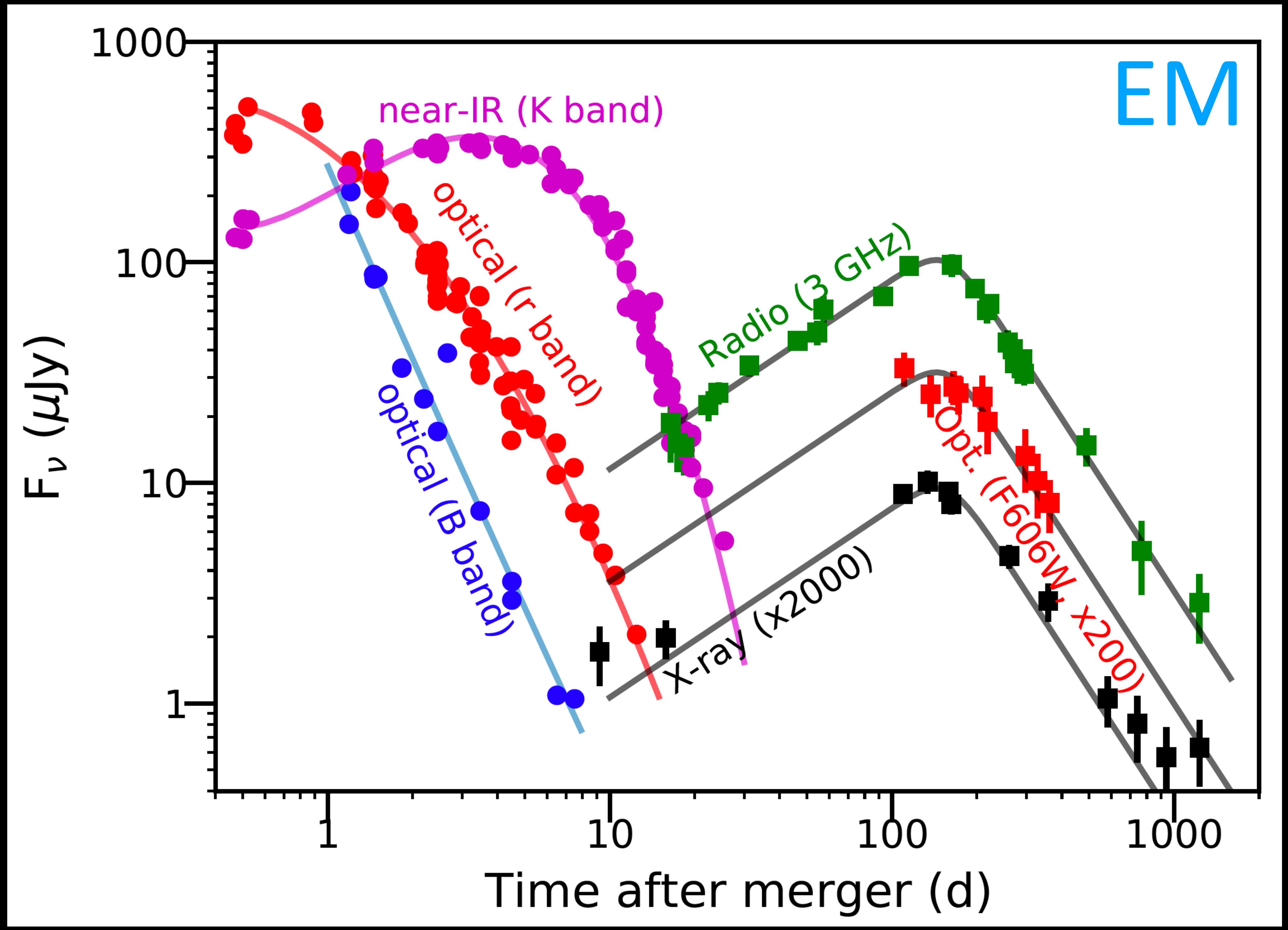
70+ teams, 100+ instruments, over 3200 co-authors

[LIGO, Virgo, EM partners +, ApJLetters **848** L12 (2017); see SN et al. 2011,2013, Kasliwal and SN 2013]

Task 3: characterising other astrophysical transients



[LVC, PRL, 119, 161101 (2017),
LIGO, Virgo, EM partners +, ApJLetters **848** L12 (2017)]



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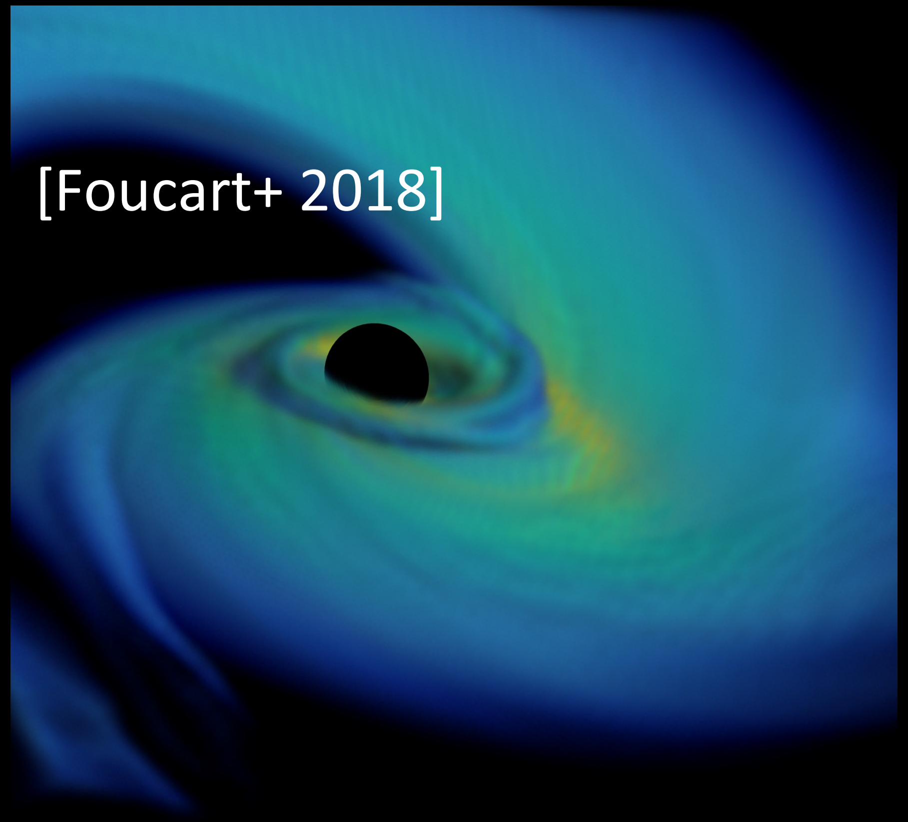
Dr Samaya Nissanke

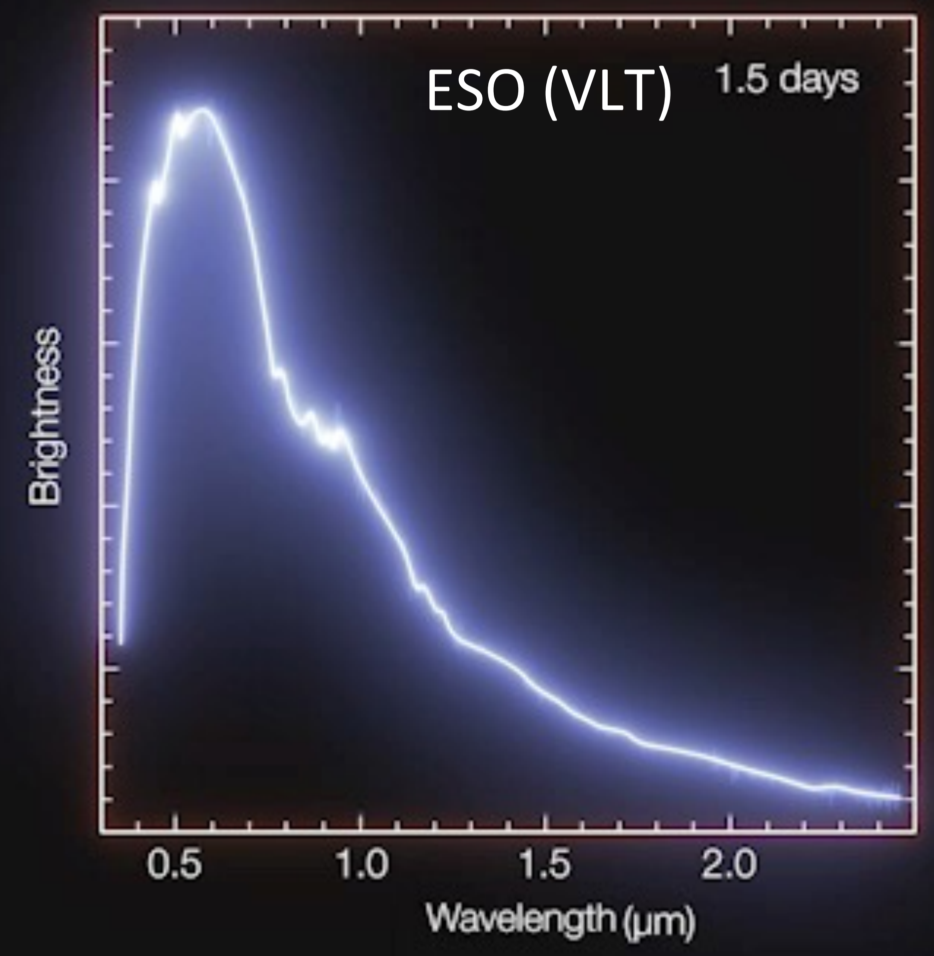
A tale of two outflows => EM counterparts

Kilonova: site of heavy elements

$M_{ej} \approx 0.01\text{-}0.05\ M_\odot$
$v \approx 0.1\text{-}0.3c$



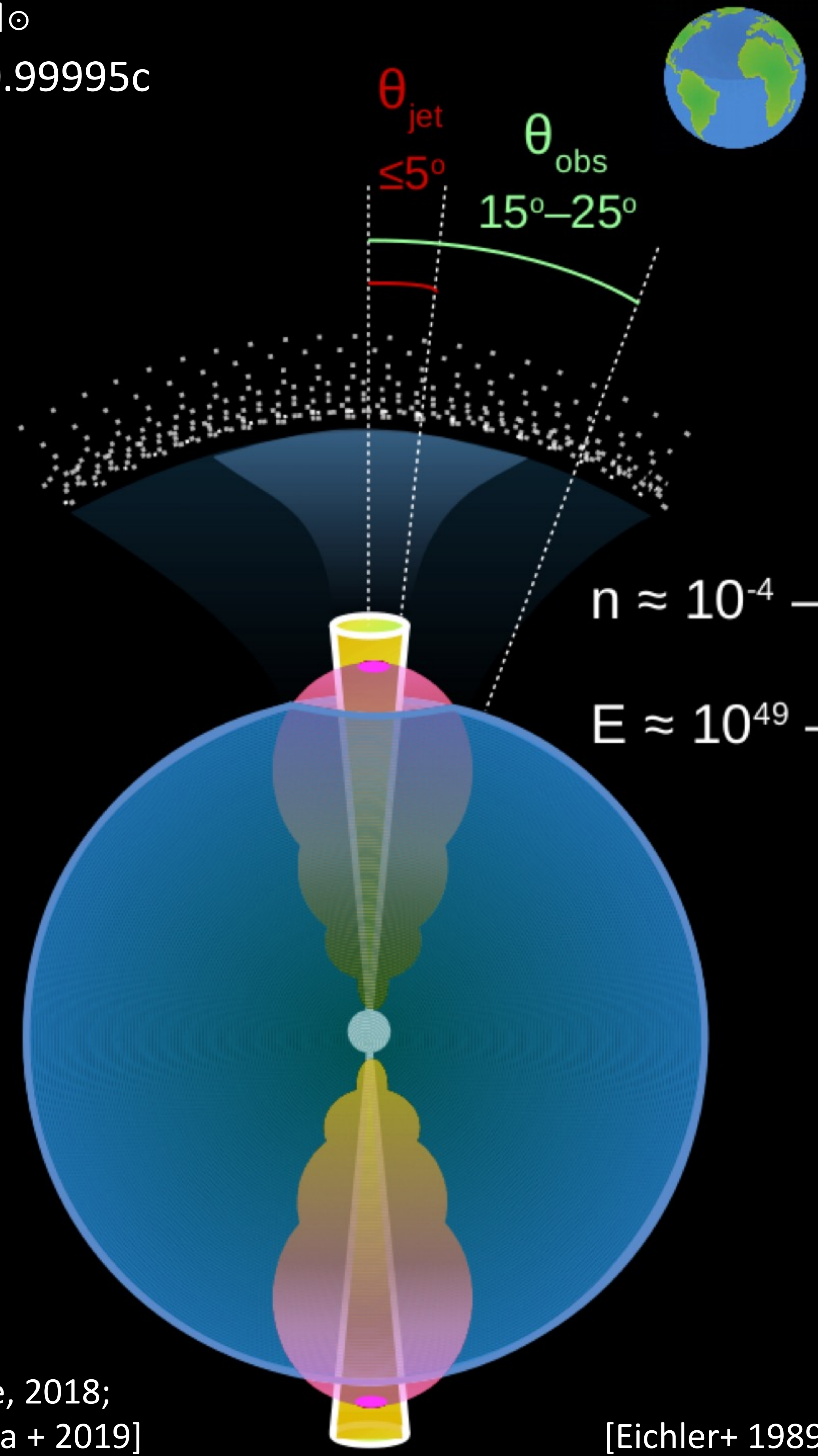
[Lattimer and Schramm 1974, Li and Paczynski 1998, Rosswog 1999, Kulkarni 2005, Metzger +.. 2010, Kasen + 2013 ...]



[see e.g., Pian et al. 17, Smartt et al. 2017 .... Watson et al. 2019]

Short Gamma Ray Burst: relativistic jet

$M_{ej} \approx 10^{-6}\ M_\odot$
$v \approx 0.99c - 0.99995c$



$n \approx 10^{-4} - 5\text{x}10^{-3}\ cm^{-3}$

$E \approx 10^{49} - 10^{50}$ erg

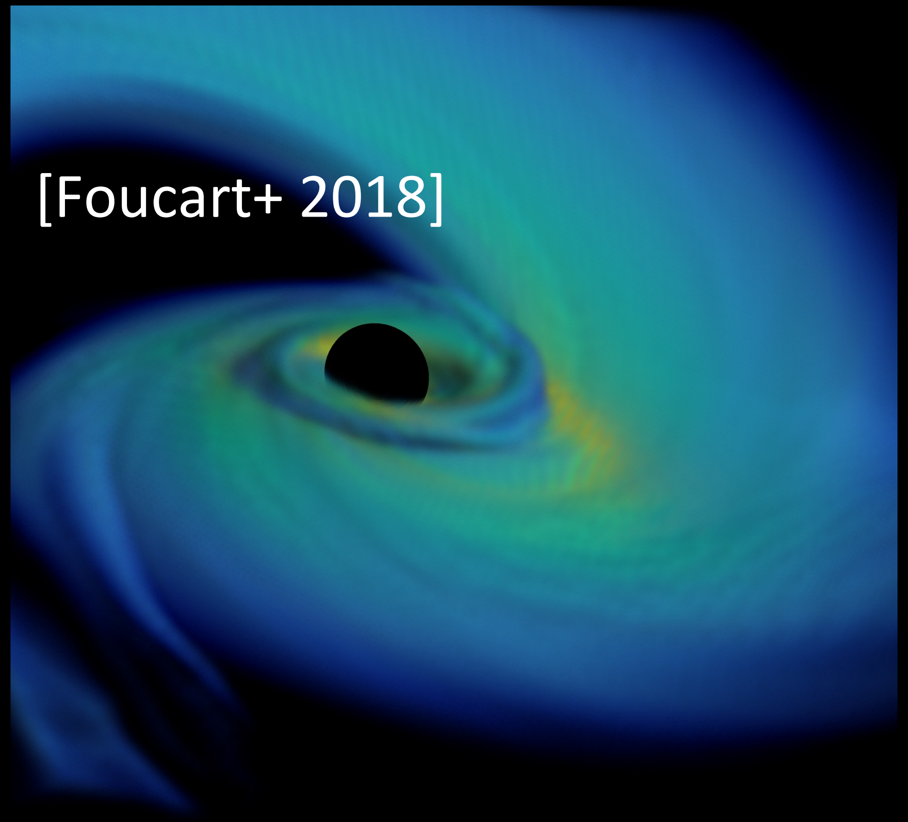
[Mooley+, Nature, 2018; See also Ghirlanda + 2019]

[Eichler+ 1989, Paczynski 1989,...]

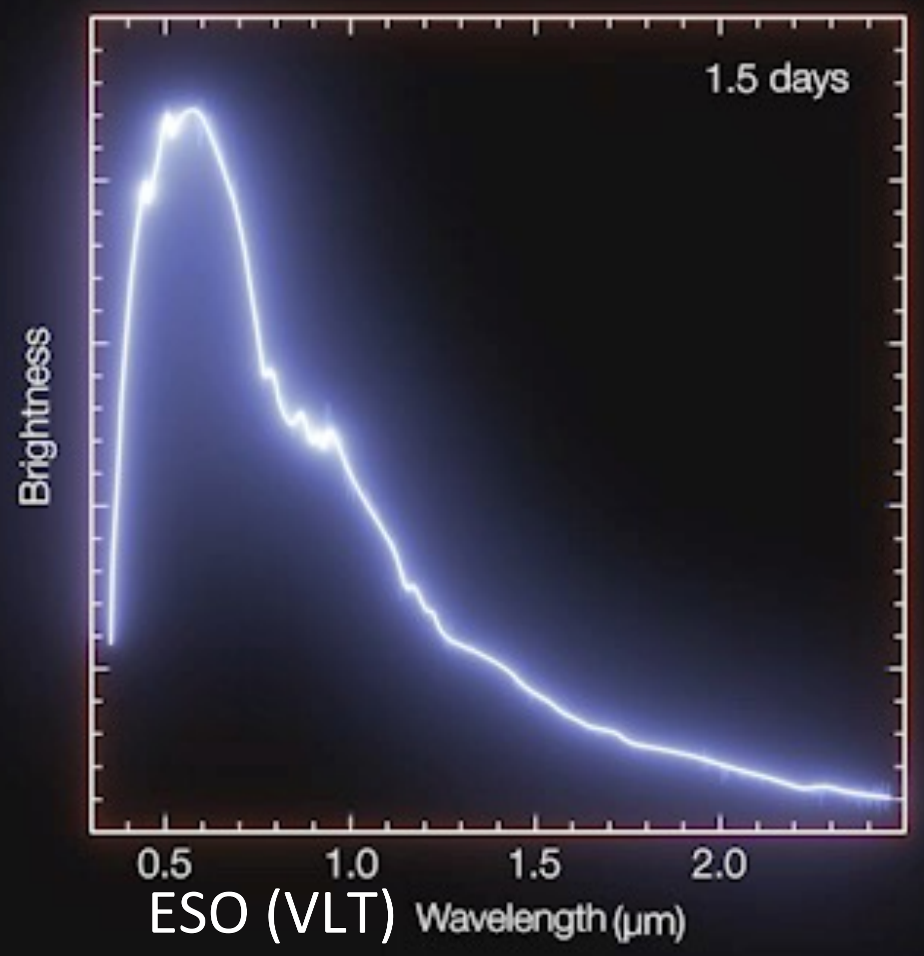
Task 4: modelling of outflows' microphysics

Kilonova: site of heavy elements

$M_{ej} \approx 0.01\text{-}0.05\ M_\odot$
$v \approx 0.1\text{-}0.3c$



[Lattimer and Schramm 1974, Li and Paczynski 1998, Rosswog 1999, Kulkarni 2005, Metzger +.. 2010, Kasen + 2013 ...]



ESO (VLT)

[see e.g., Pian et al. 17, Smartt et al. 2017 .... Watson et al. 2019]

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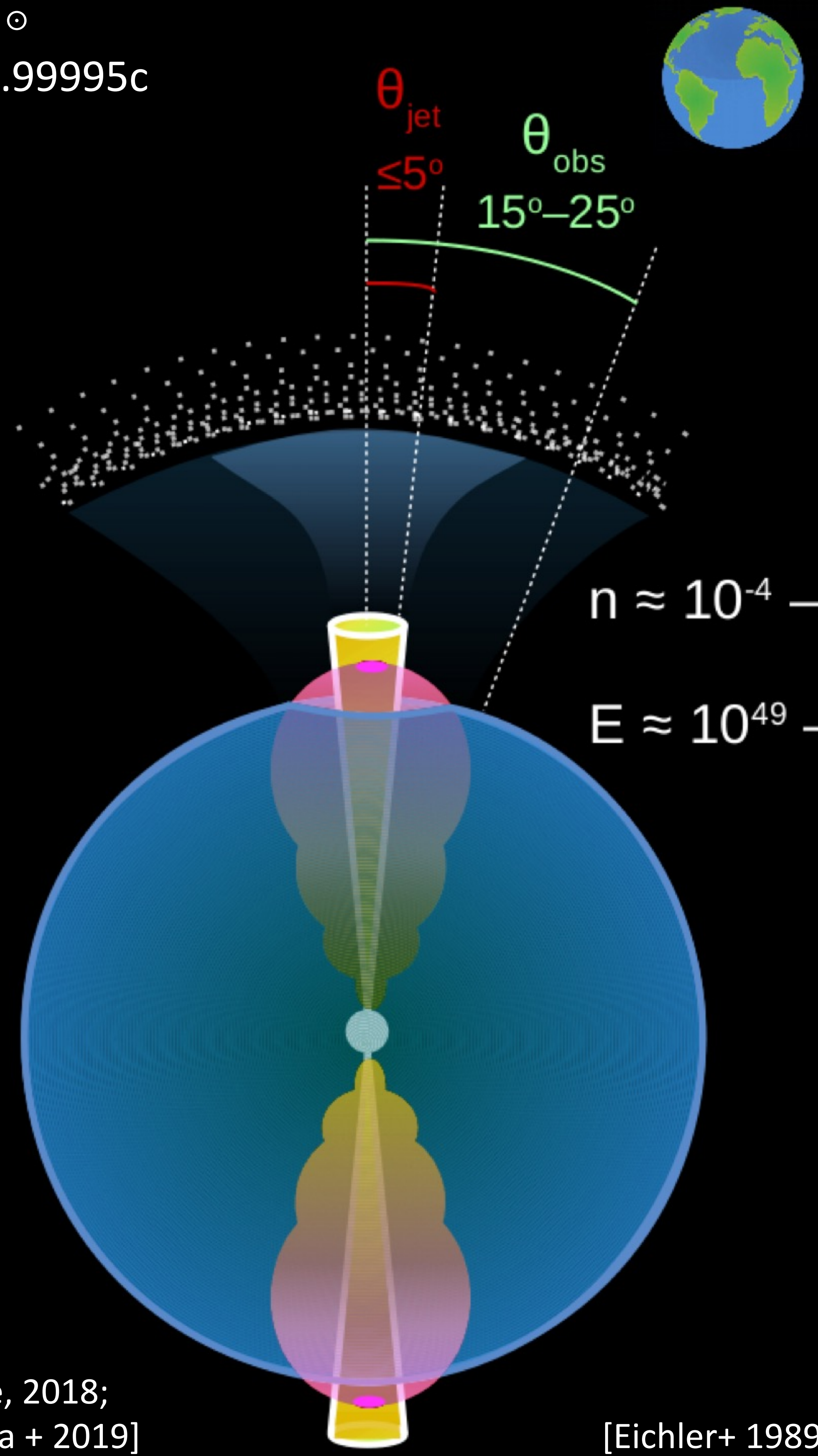

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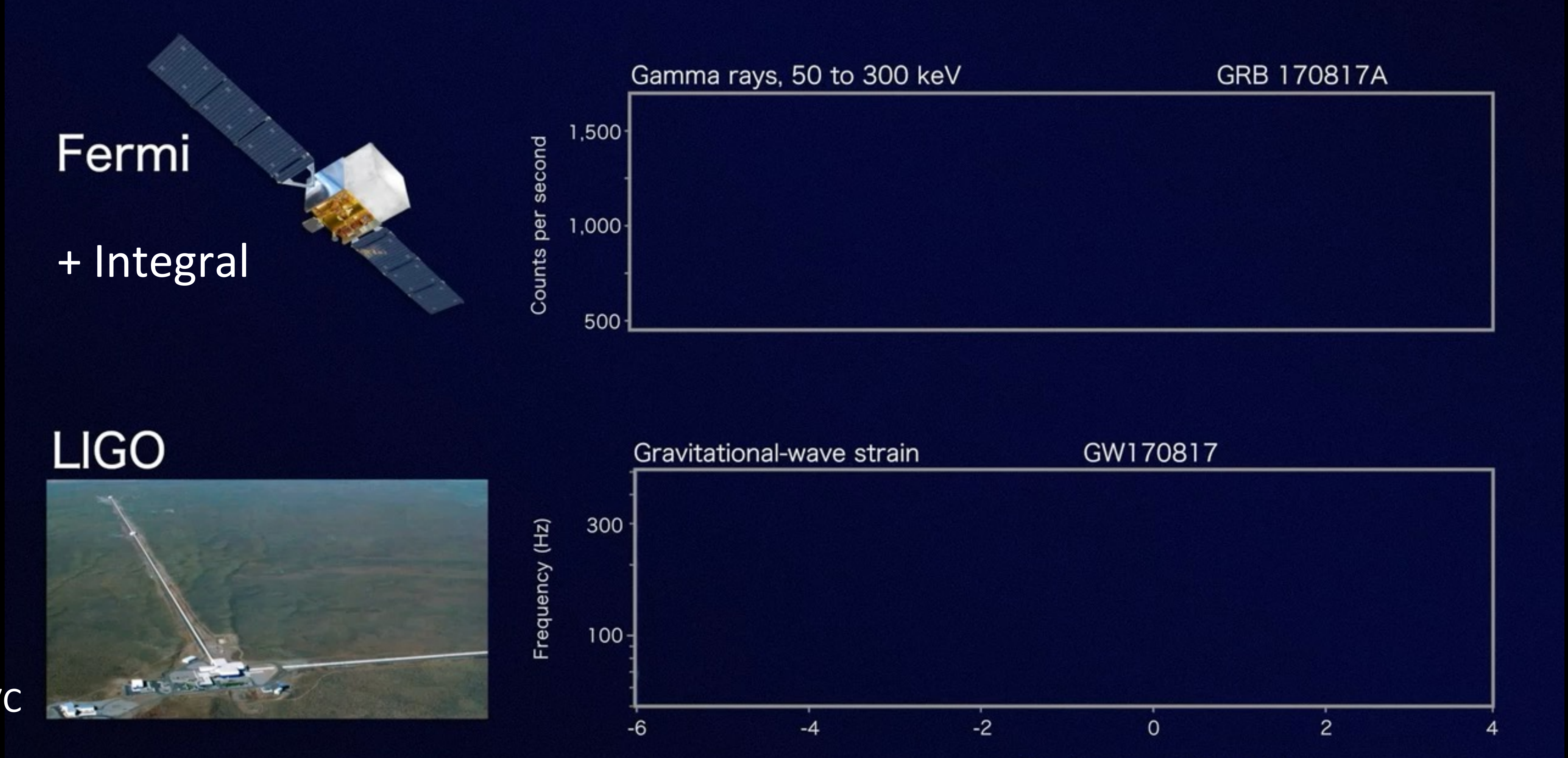
[Mooley+, Nature, 2018; See also Ghirlanda + 2019]

[Eichler+ 1989, Paczynski 1989,...]

1. GW+EM: GW170817 & GRB170817A

[LVC+Fermi+Integral, ApJ Lett, 848:L13, 2017; LVC, PRL., 119, 161101 (2017)]

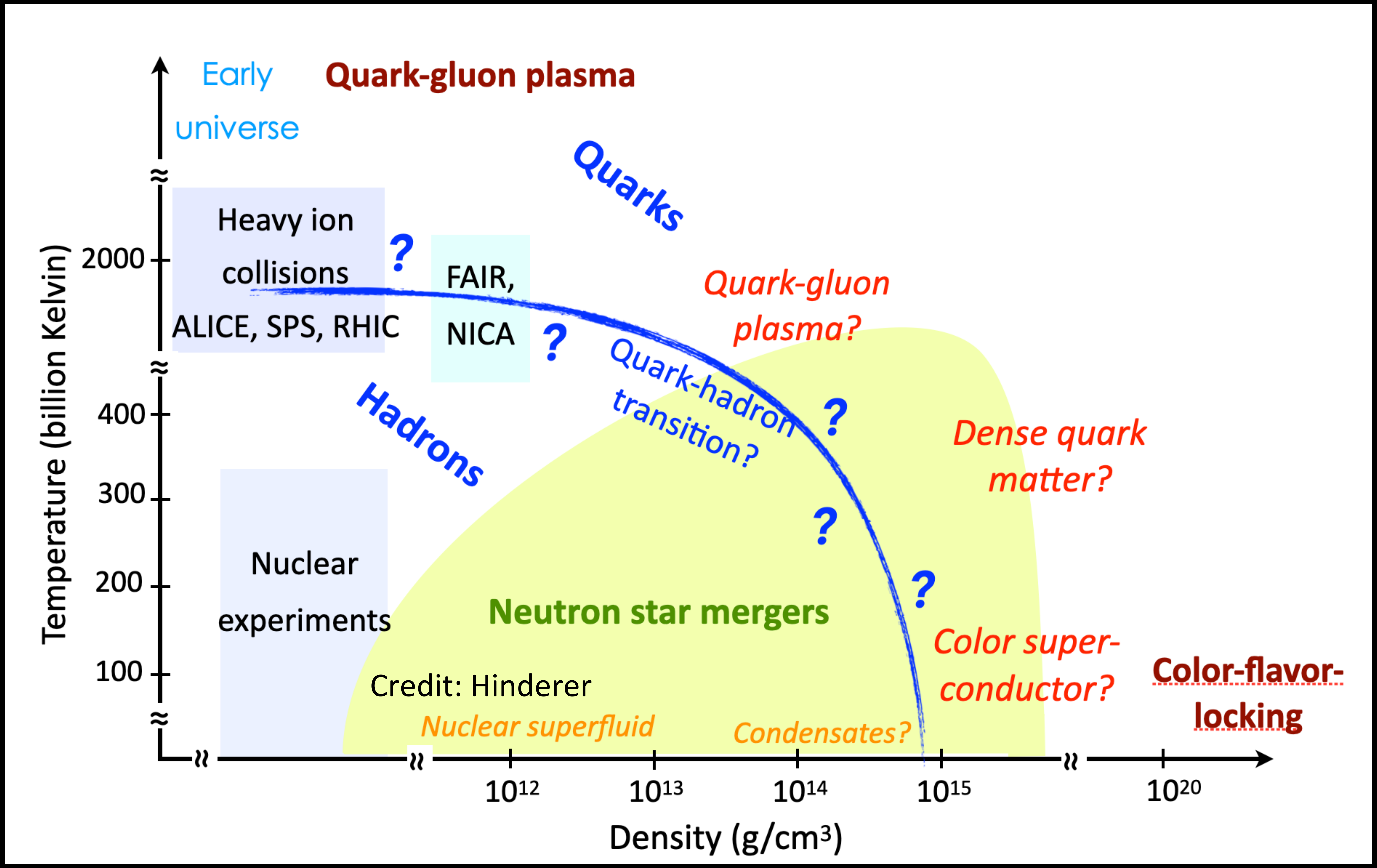


Credit: NASA/LVC

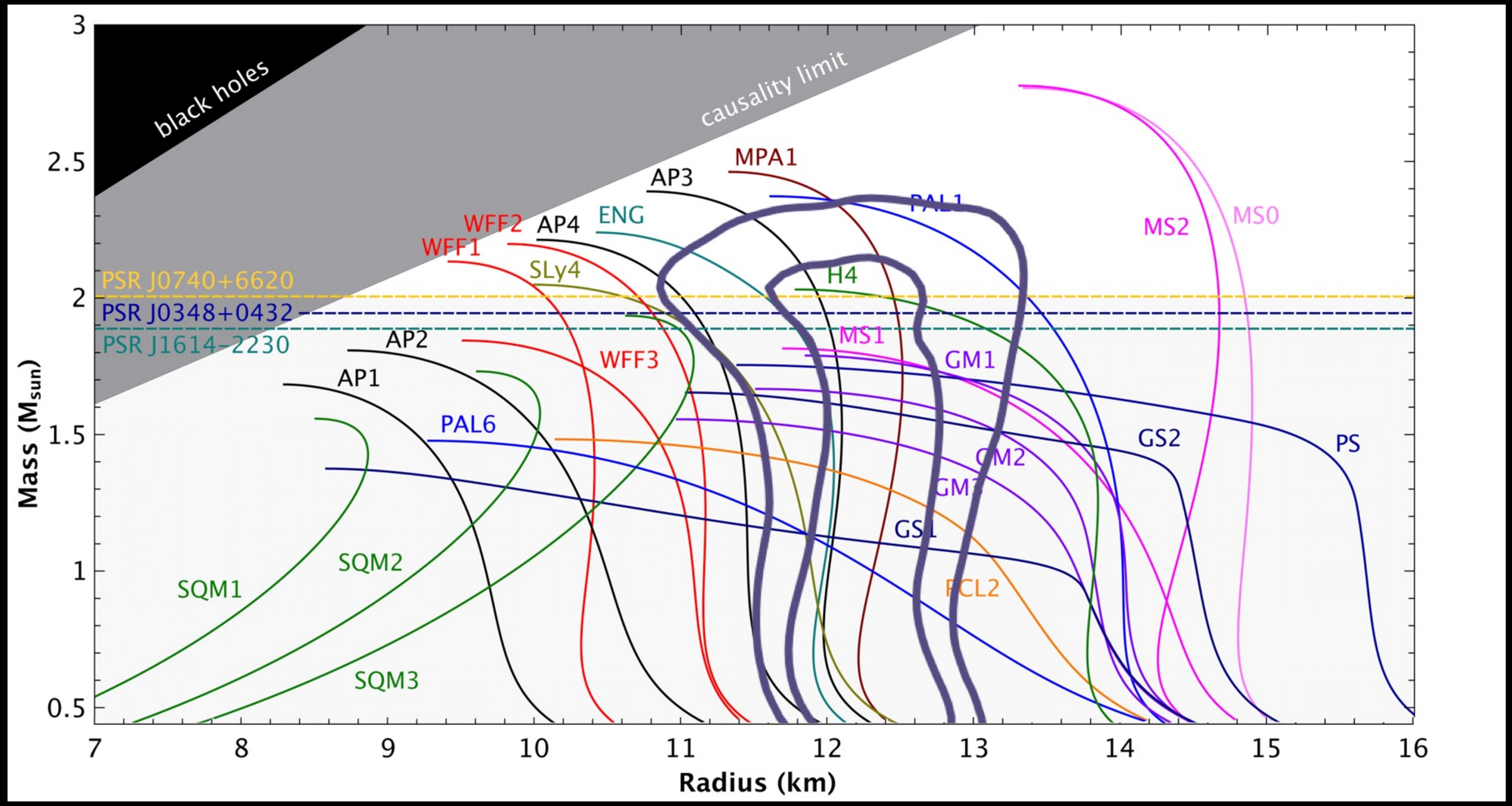
Test of speed of gravity and light and equivalence principle

$$-3 \times 10^{-15} \leq \frac{v_{gw}}{v_{em}} - 1 \leq 7 \times 10^{-16}$$

2. GW+EM: Neutron Star Equation of State



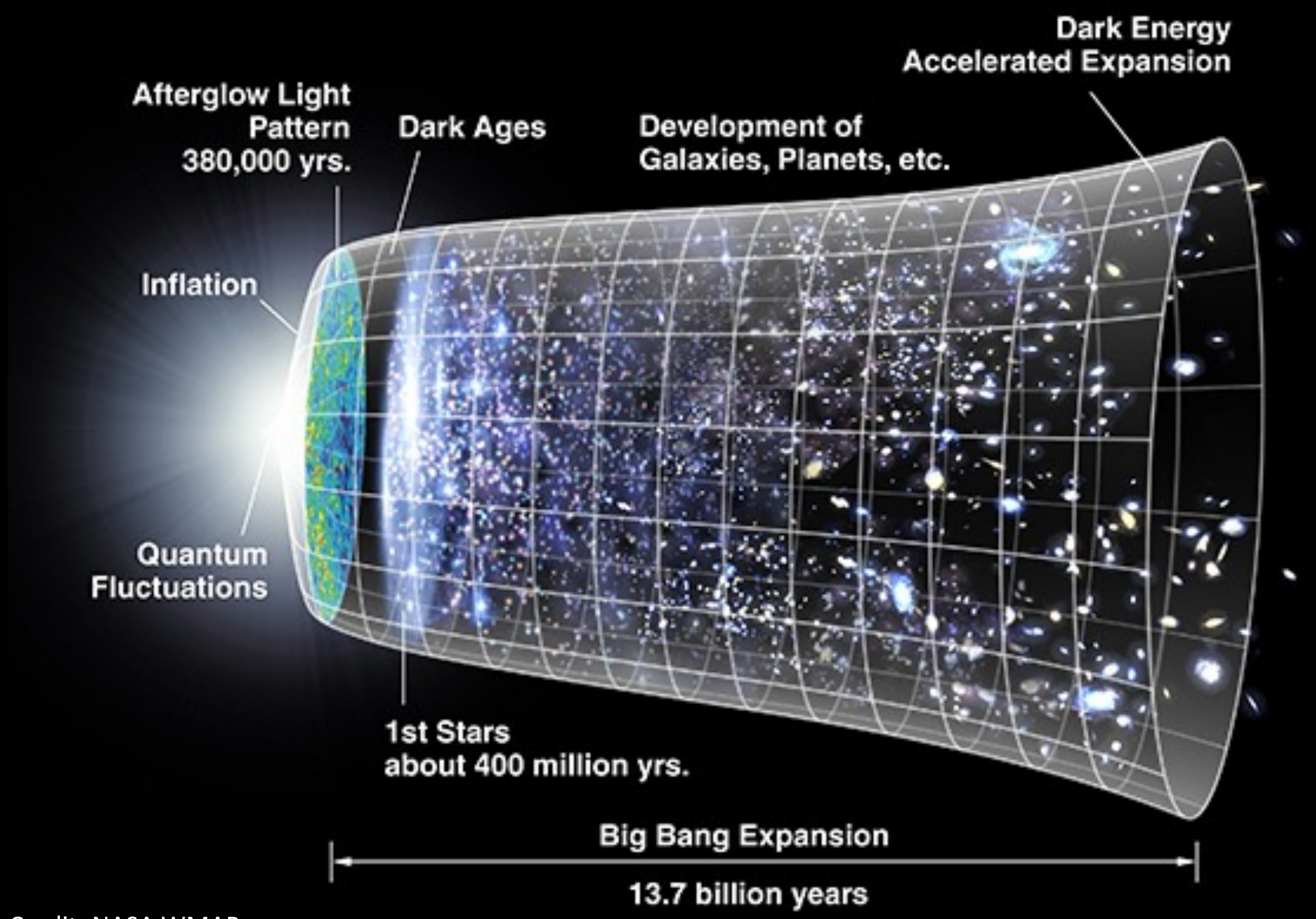
[Raaijmakers, .. Nissanke + 2019, 20, 21a, b]



[see also e.g., Agathos+2015, Coughlin et al. 2019a; Dietrich et al. 2020, 22; Huth et al. 2022, Sarin ..SN 2023]

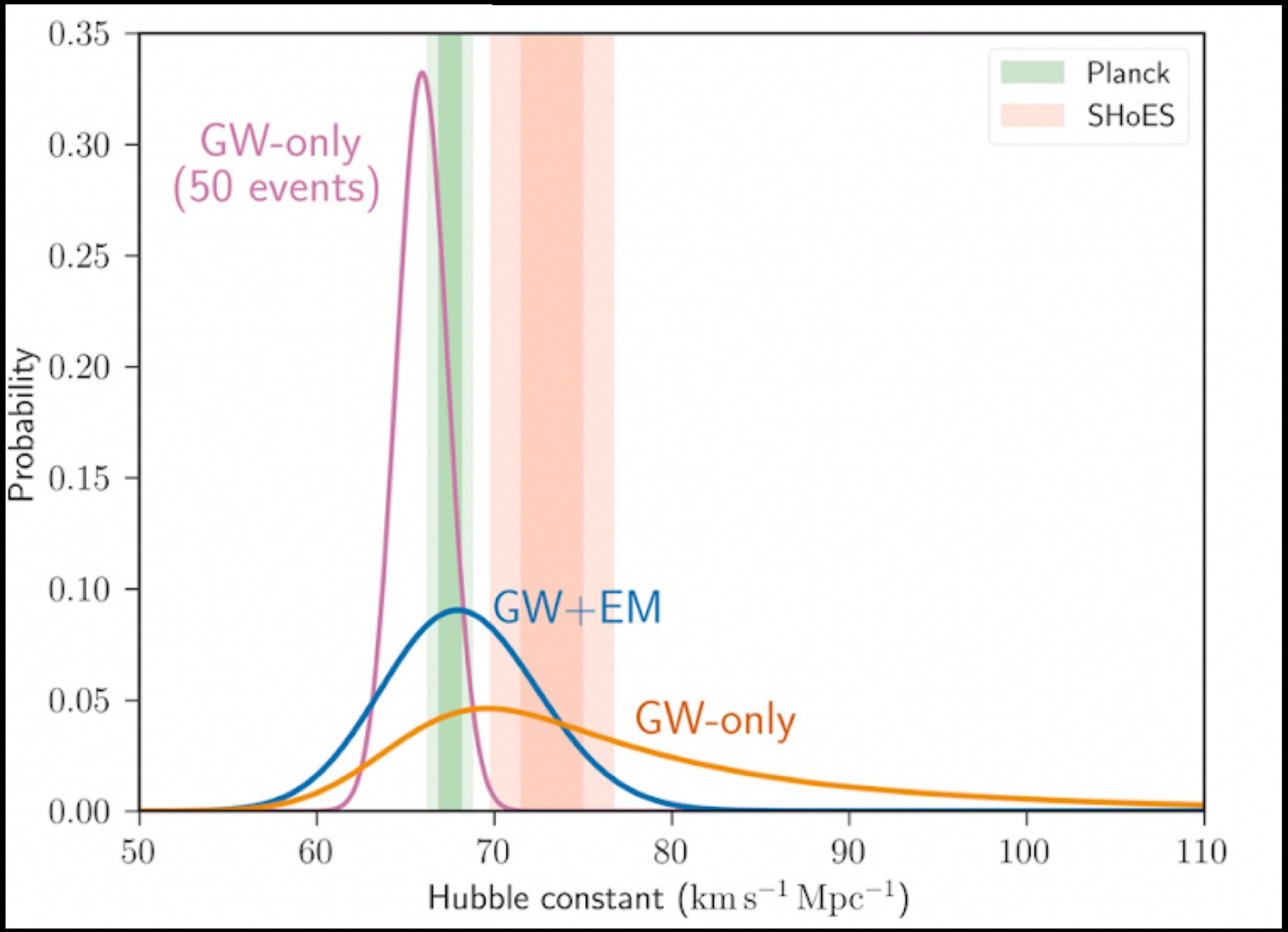
~ O(50) strong (S/N ~50) multi-messenger events

3: GW+EM: Universe's expansion history – Hubble constant



Credit: NASA WMAP

[Schutz 1986, Dalal et al. 2006, Nissanke et al. 2010, 13, …]



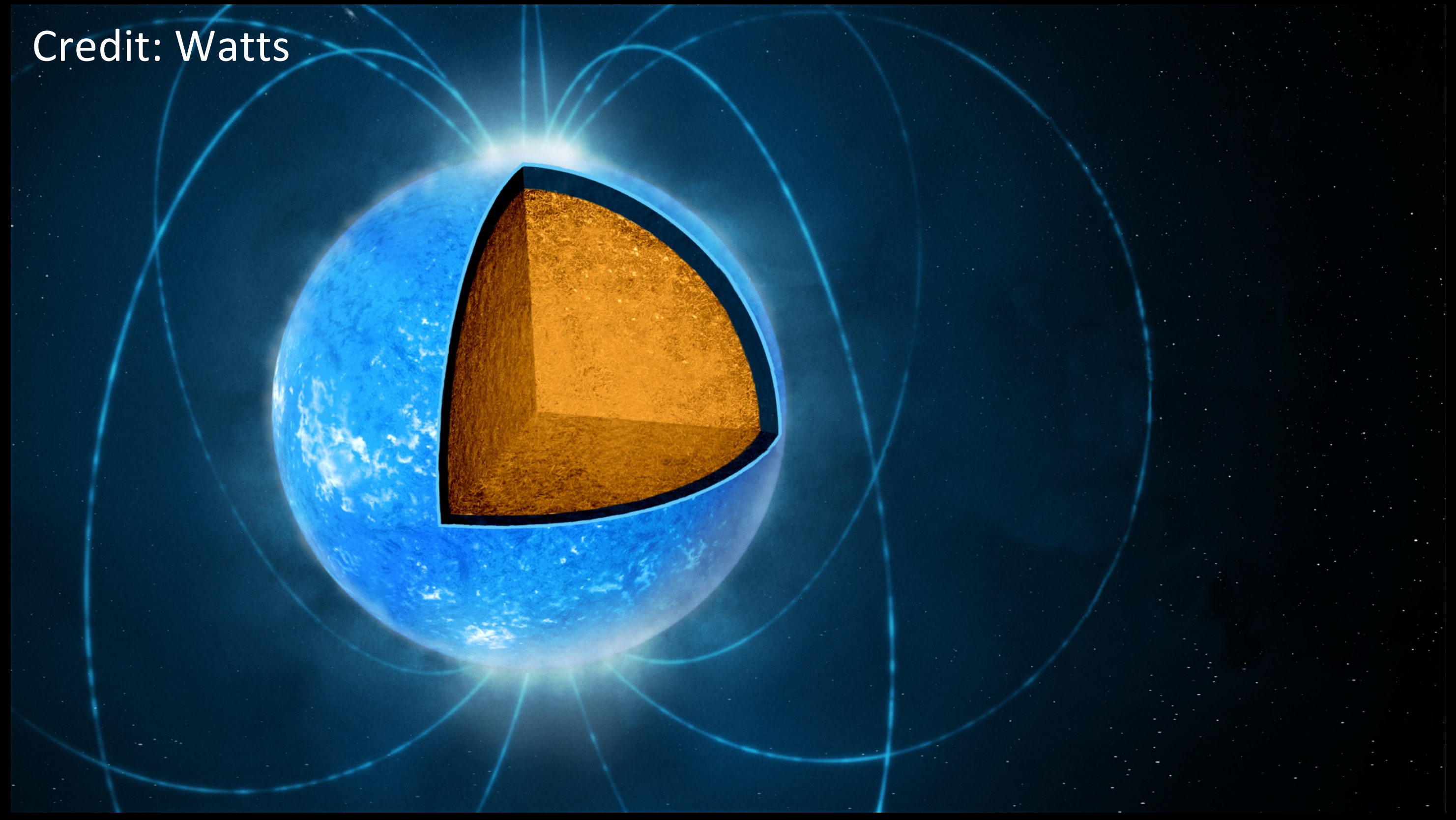
LVC +6 OIR, Nature, *551*, 2017, Feeney.. Nissanke + 2019; Hotokezaka .. Nissanke + 2019; see also e.g.,Chen+ 2018, Vitale+ 2018 …, Huang +2022]]

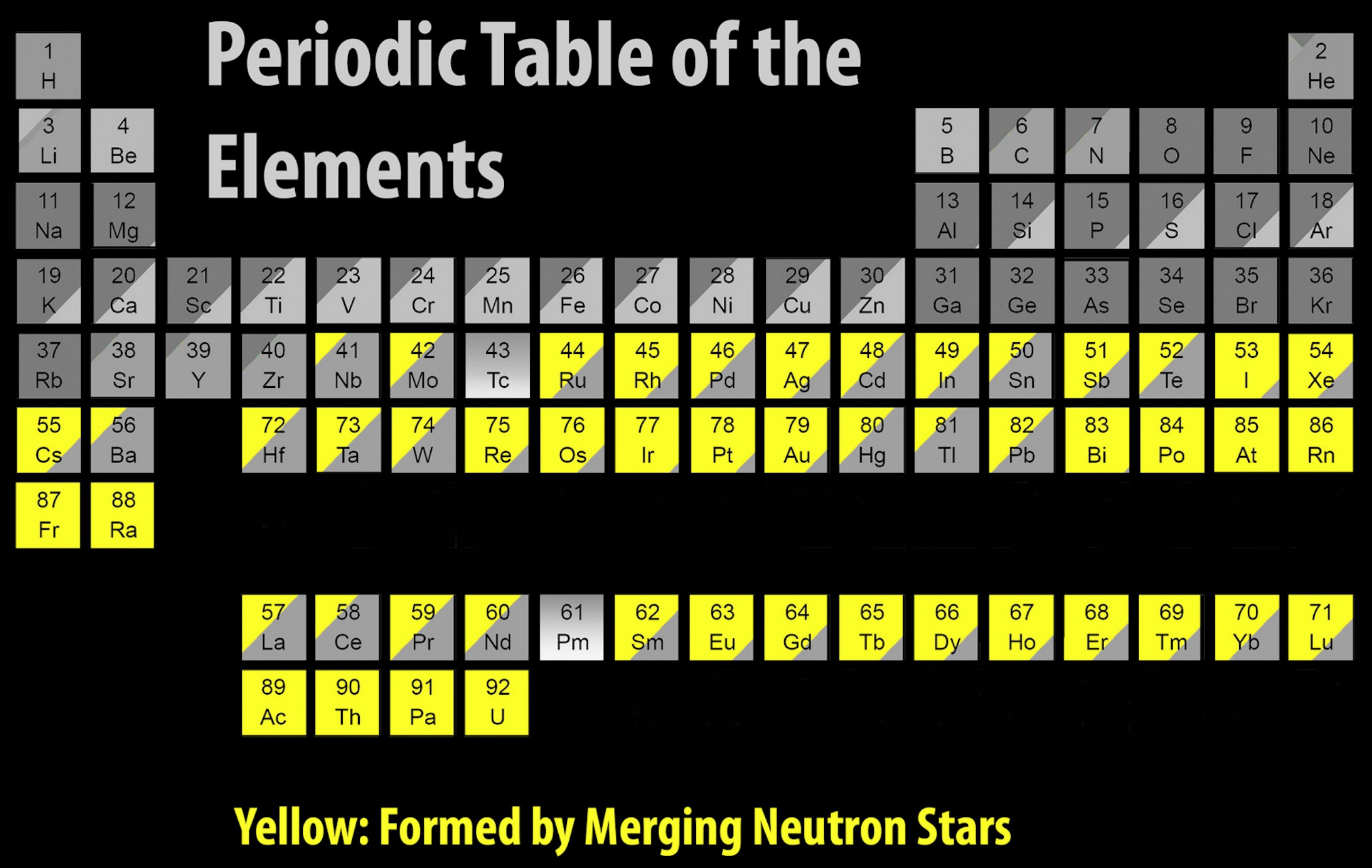
~ O(50) GW + redshift events to 2%

~ O(15) GW+redshift+inc. angle (GW170817-like) to 2%

What would we like to learn?

1. *What is the nature of the remnant?*
2. *What is the NS Equation of State?*
3. *What is the maximum NS mass & how rapidly can they spin?*
4. *Are neutron star mergers the astrophysical site of heavy elements?*
5. *How do BNS form and evolve?*

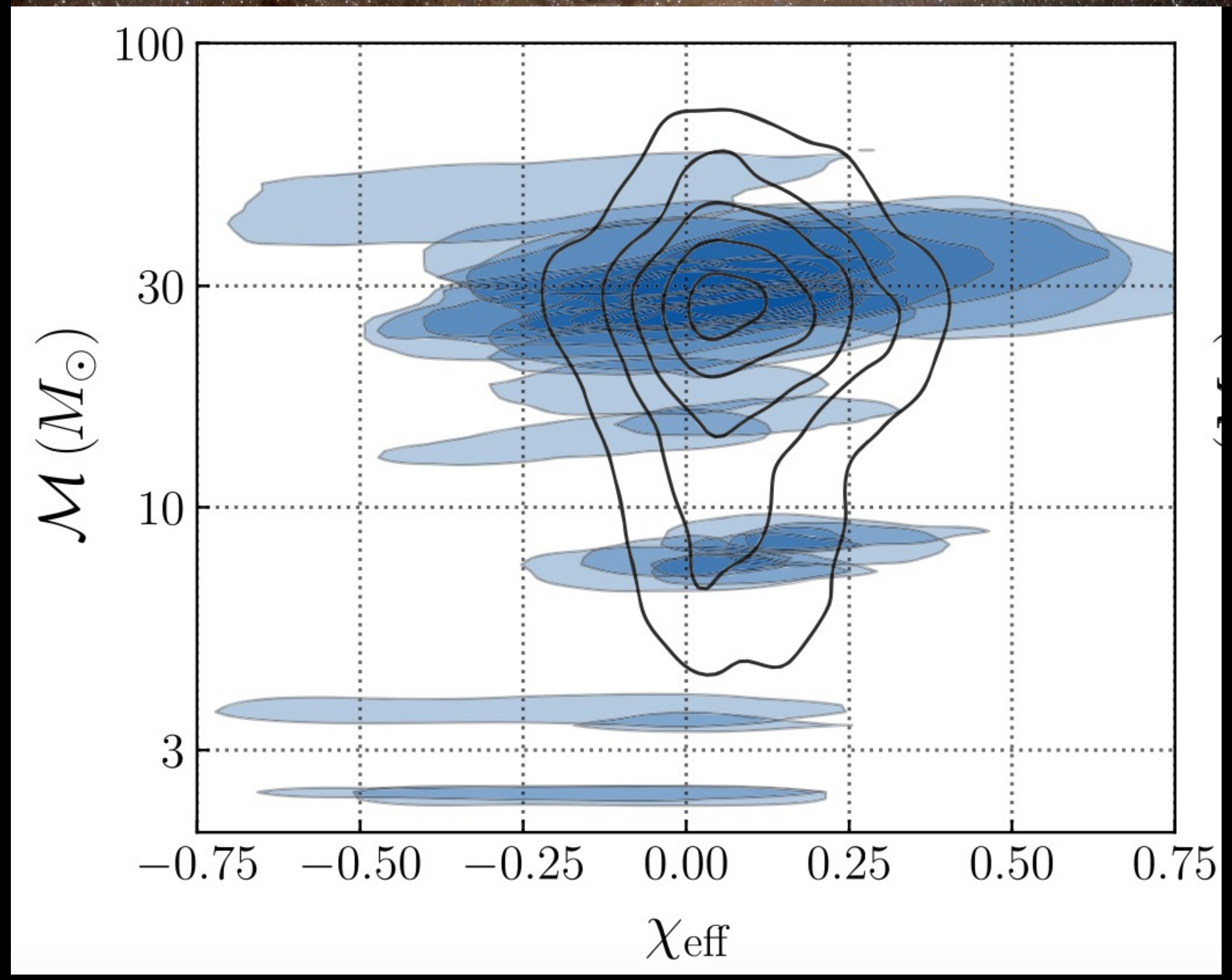




Credit: Johnson/ LIGO Labs

Credit: Bangalore Sathyaprakash

What would we like to learn?



[LVKC, Phys. Rev. X **13**, 011048, 2023]

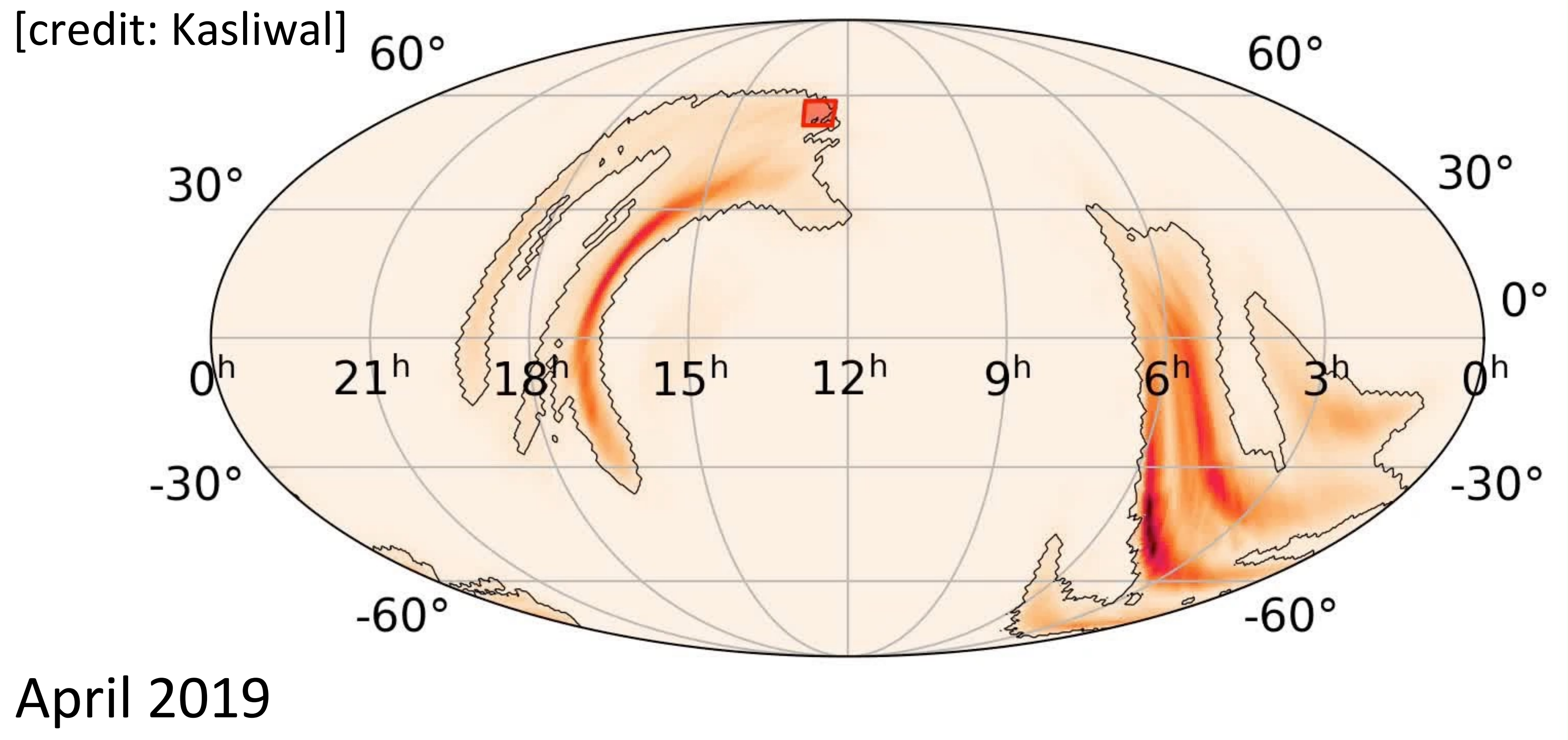
1. *How do BBH mergers form and evolve? Formation channels?*
2. *Are BH spins close to zero & if so, why?*
3. *Are GW BBHs primordial in origin?*
4. *Are there EM counterparts to BBH mergers?*
5. *Do we need BH formation to power a relativistic jet?*

Credit: Bangalore Sathyaprakash

Perspectives with future GW detectors

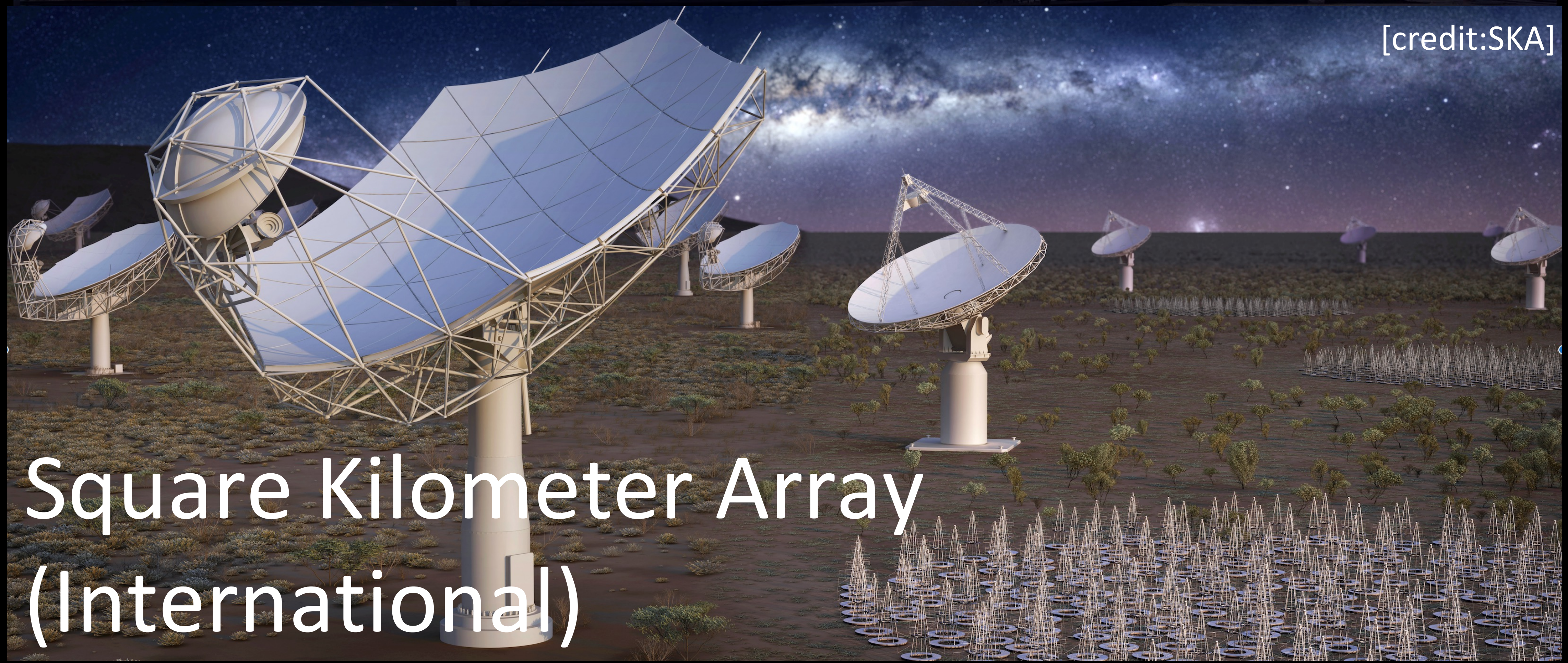
New EM facilities enable a multicoloured movie of the dynamic Universe

Today

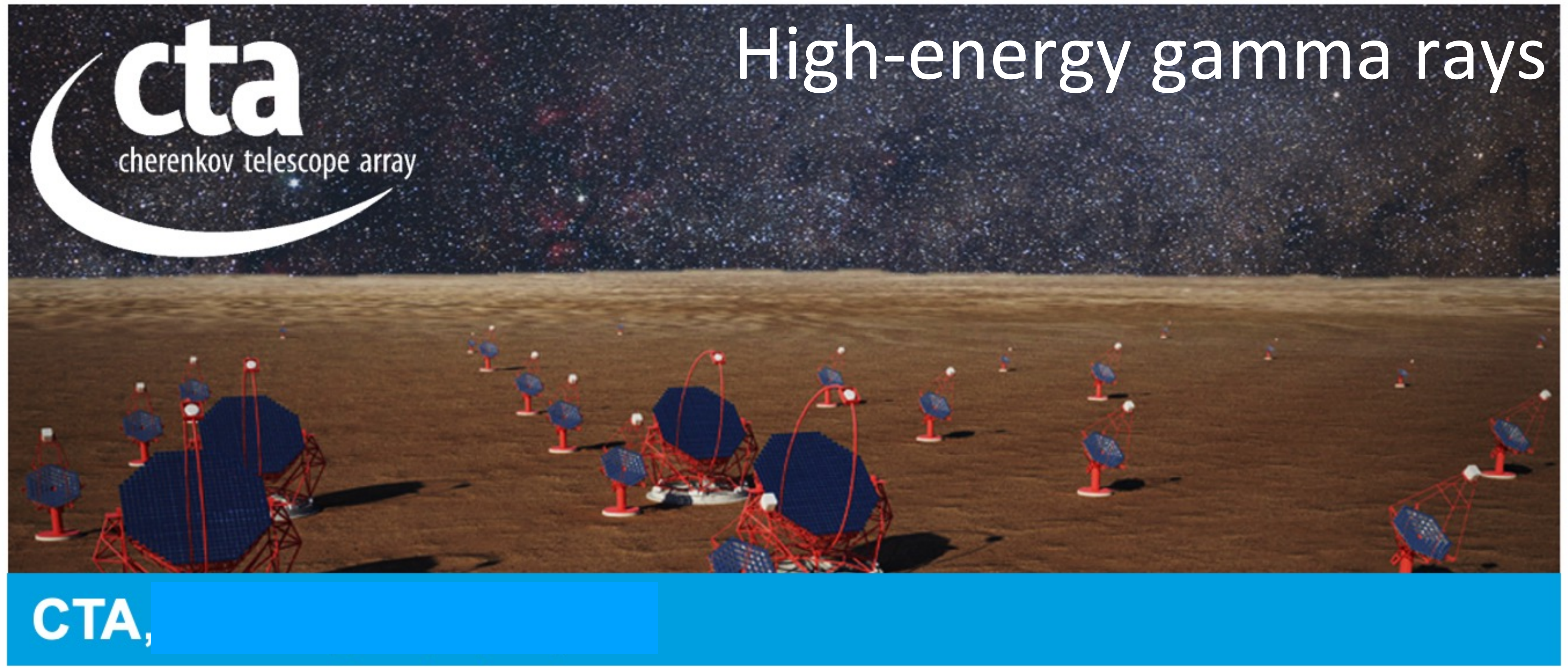


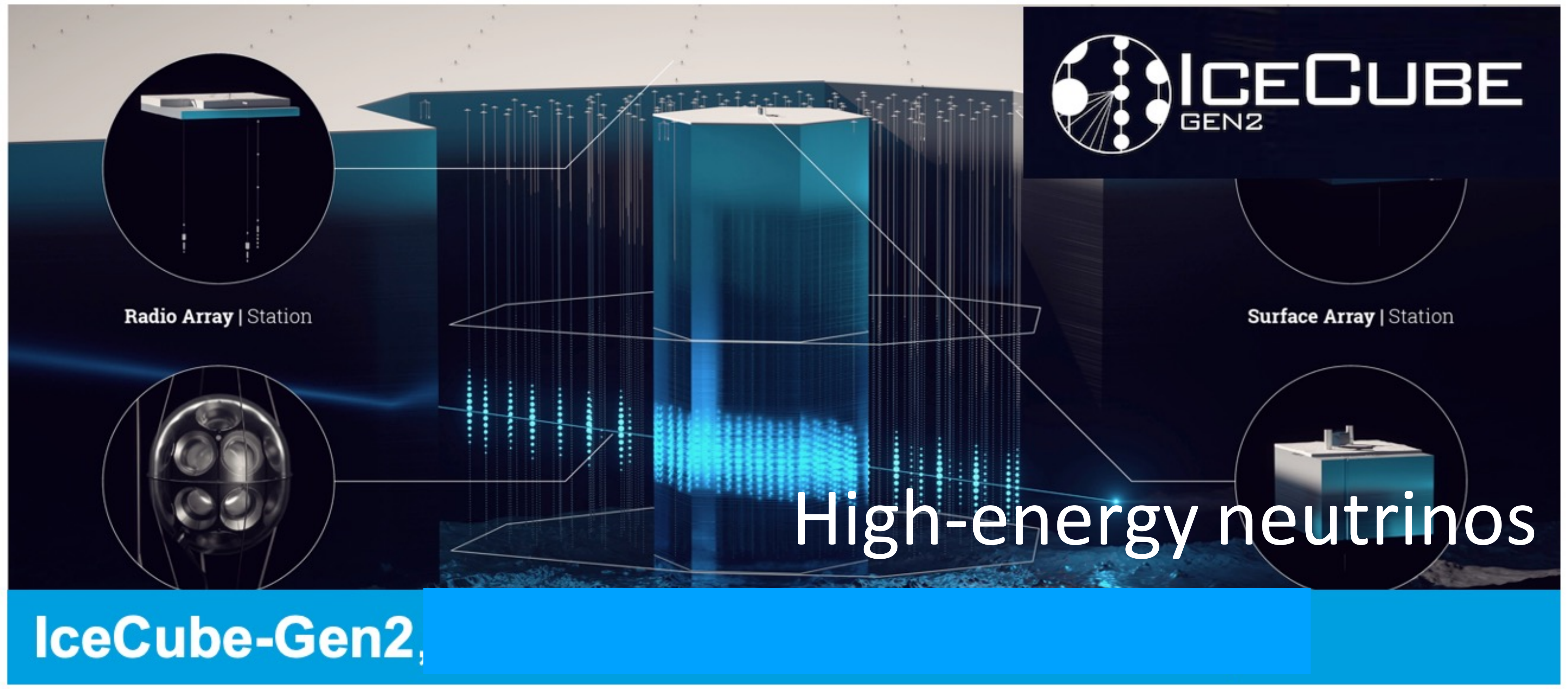
Zwicky Transient Facility)

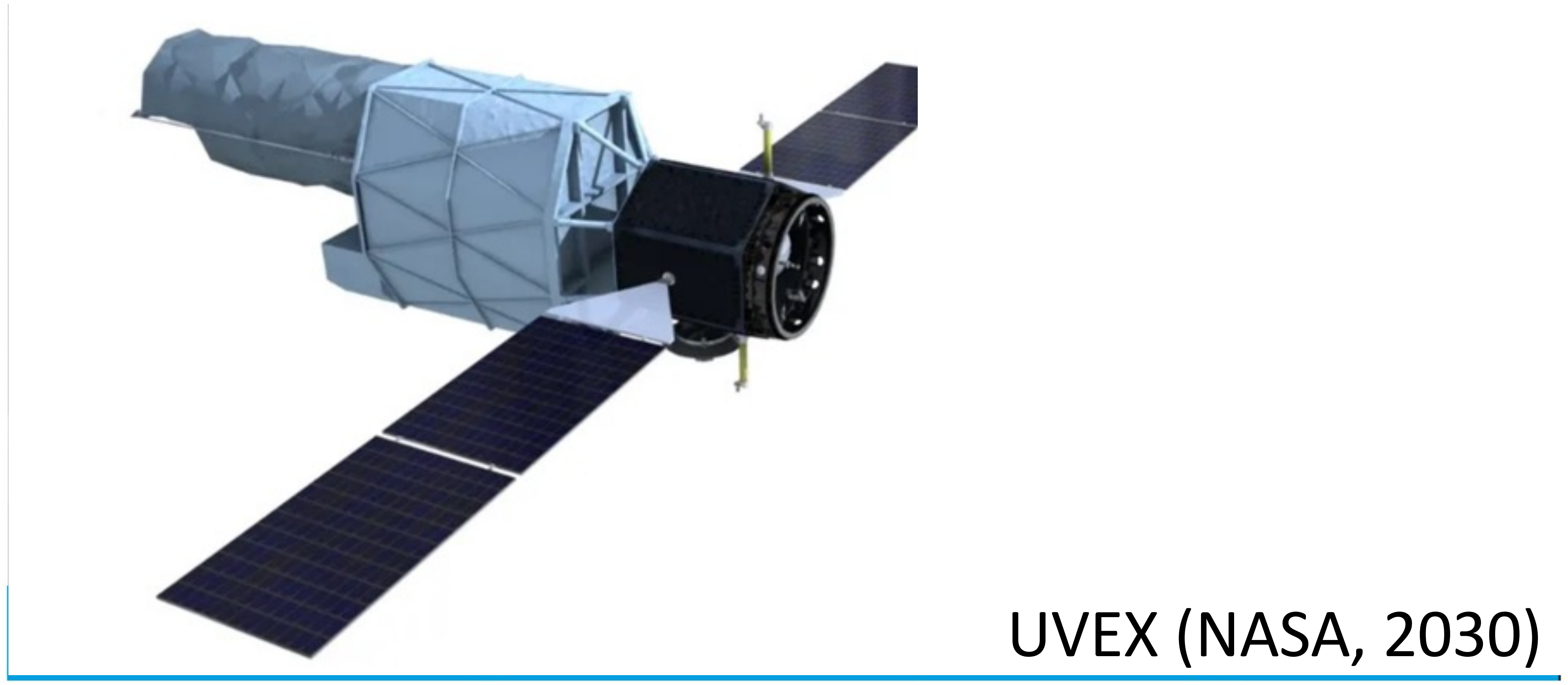
Mid-2020s



New facilities enable a multimessenger movie of the dynamic Universe



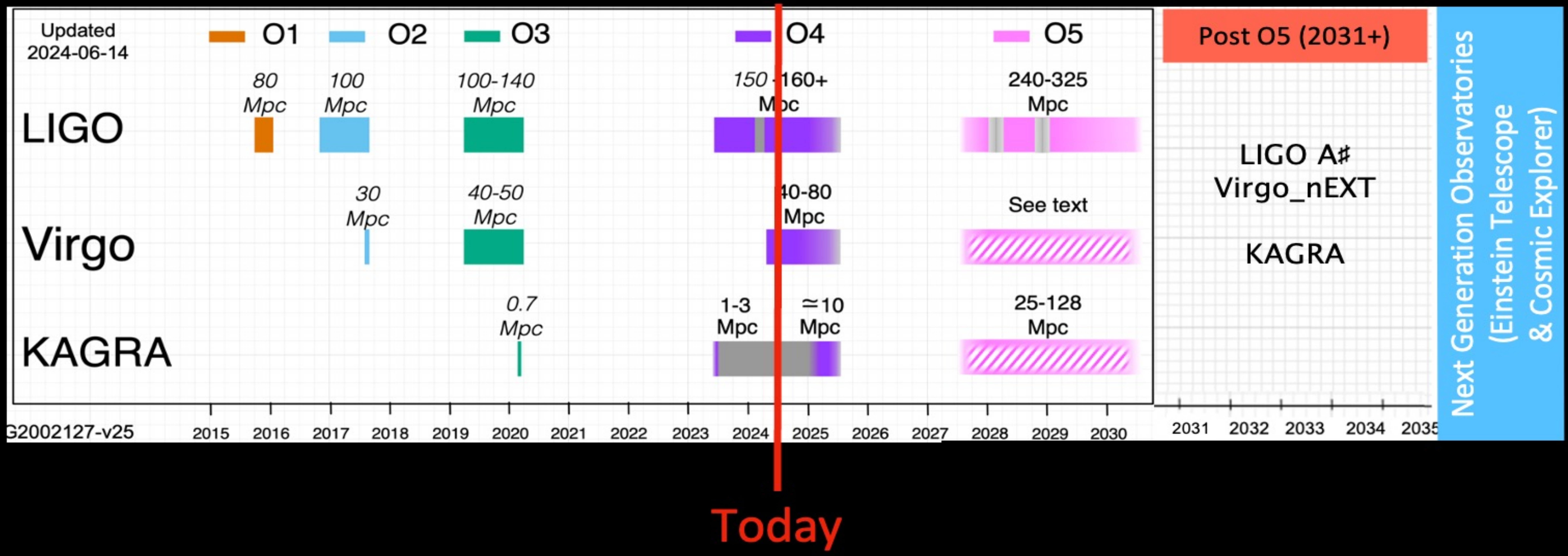




[slide courtesy of C. Stegmann, adapted]

Current Status of GW Detectors: from individual objects to statistics

[LVC, Living Reviews in Relativity 19, 1, 2018; https://dcc.ligo.org/public/0172/G2002127/022/ObsScen_timeline.pdf]



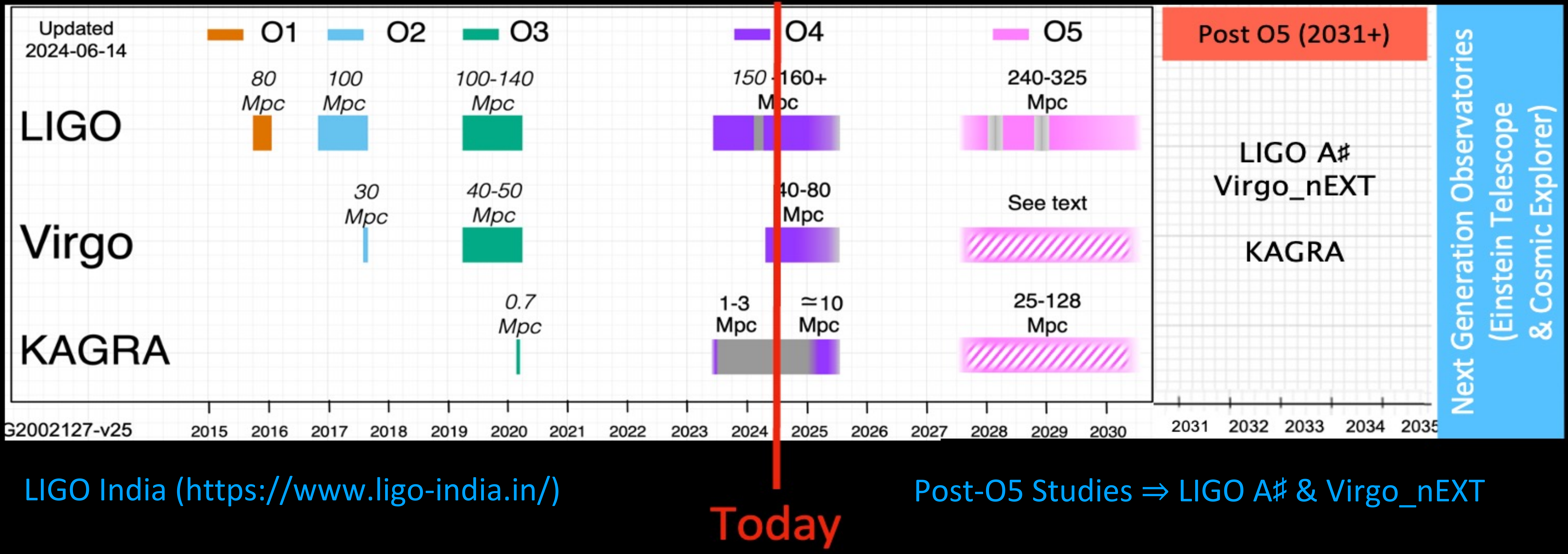
2023-2024: NS-NS: 10^{+52}_{-10} year^{-1}

NS-BH: 1^{+91}_{-1} year^{-1}

Dr Samaya Nissanke

Current Status of GW Detectors: from individual objects to statistics

[LVC, Living Reviews in Relativity 19, 1, 2018; https://dcc.ligo.org/public/0172/G2002127/022/ObsScen_timeline.pdf]



LIGO India (https://www.ligo-india.in/)

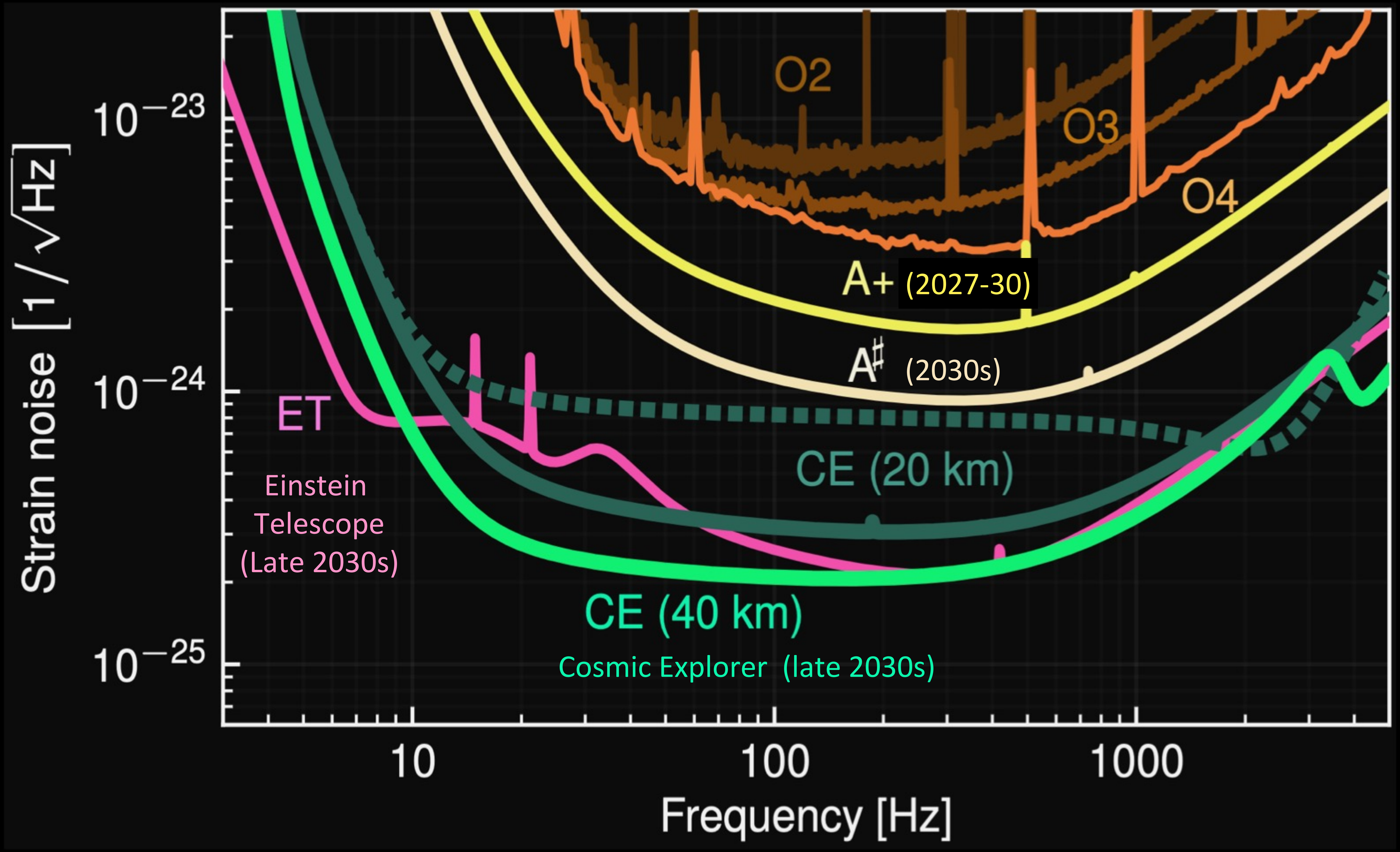
Envisioned to start as an A+ detector
Capable of A♯ hardware

Post-O5 Studies ⇒ LIGO A♯ & Virgo_nEXT

Factor of ~2 increase in sensitivity compared to O5

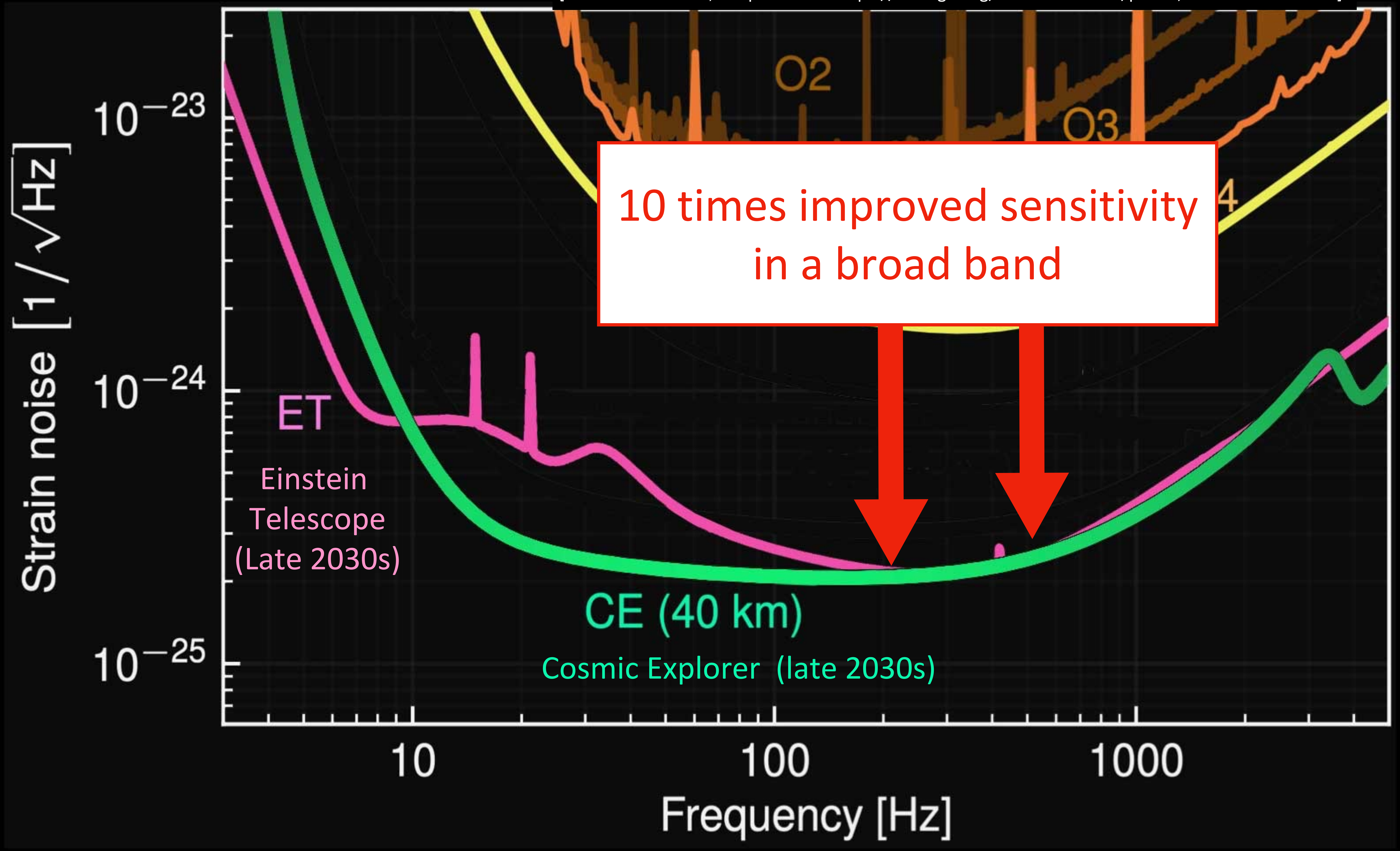
Ground-based GW detectors in the 2030s

[credit: Kevin Kuns; adapted from https://dcc.ligo.org/LIGO-T2200287/public, arXiv: 2109.09882]



ngGW observatories: “precise, wide, deep”

[credit: Kevin Kuns; adapted from https://dcc.ligo.org/LIGO-T2200287/public, arXiv: 2109.09882]



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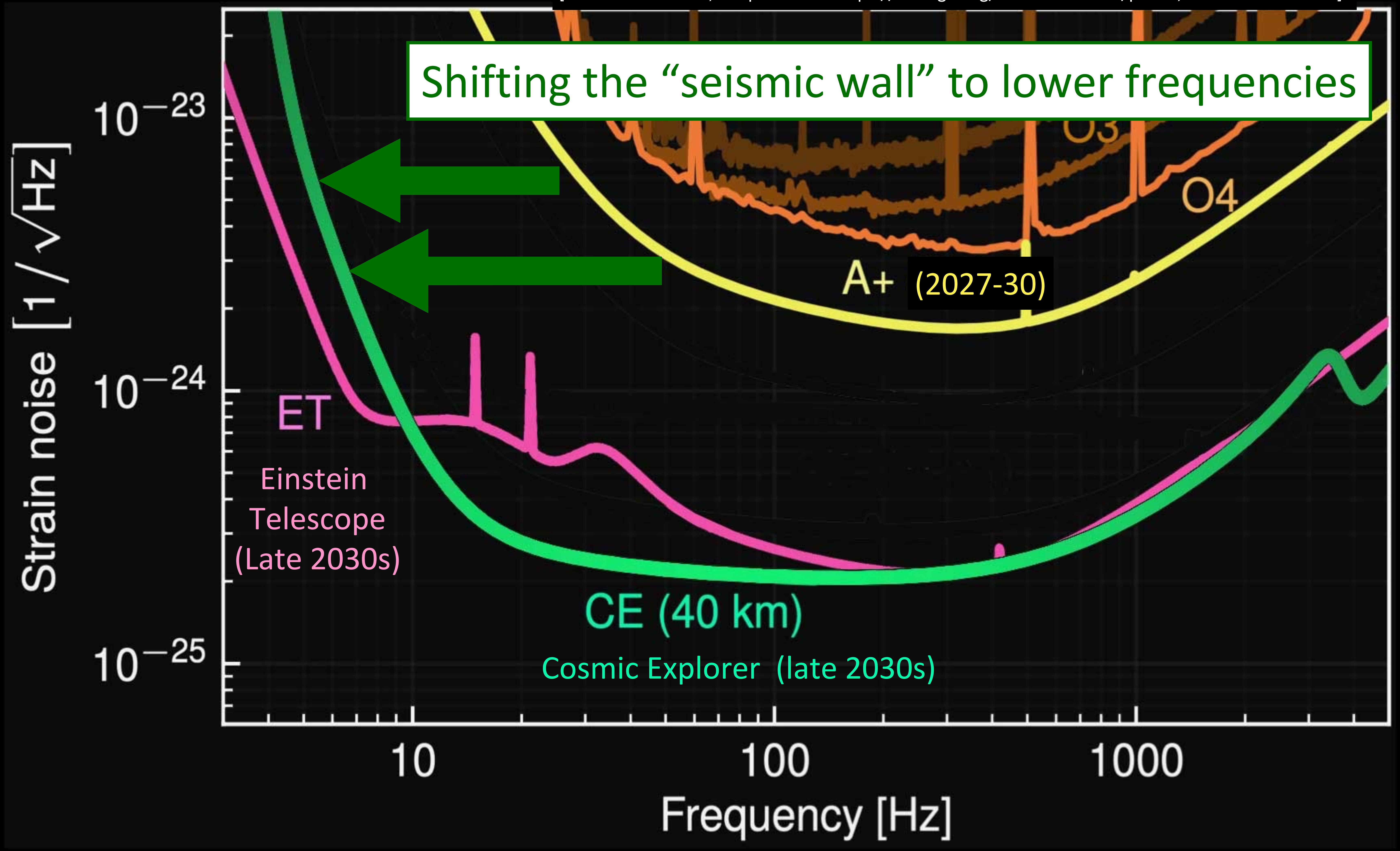

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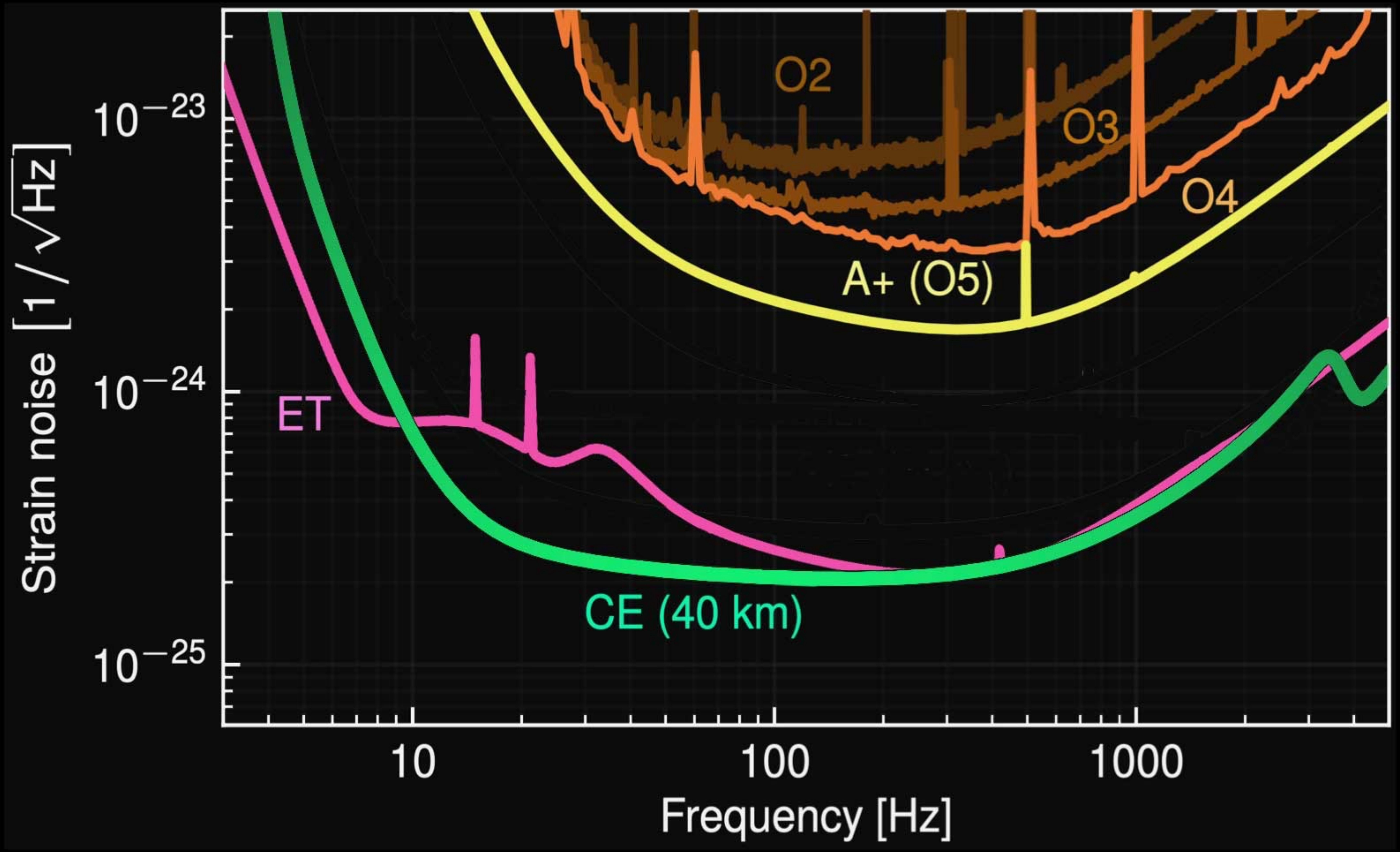
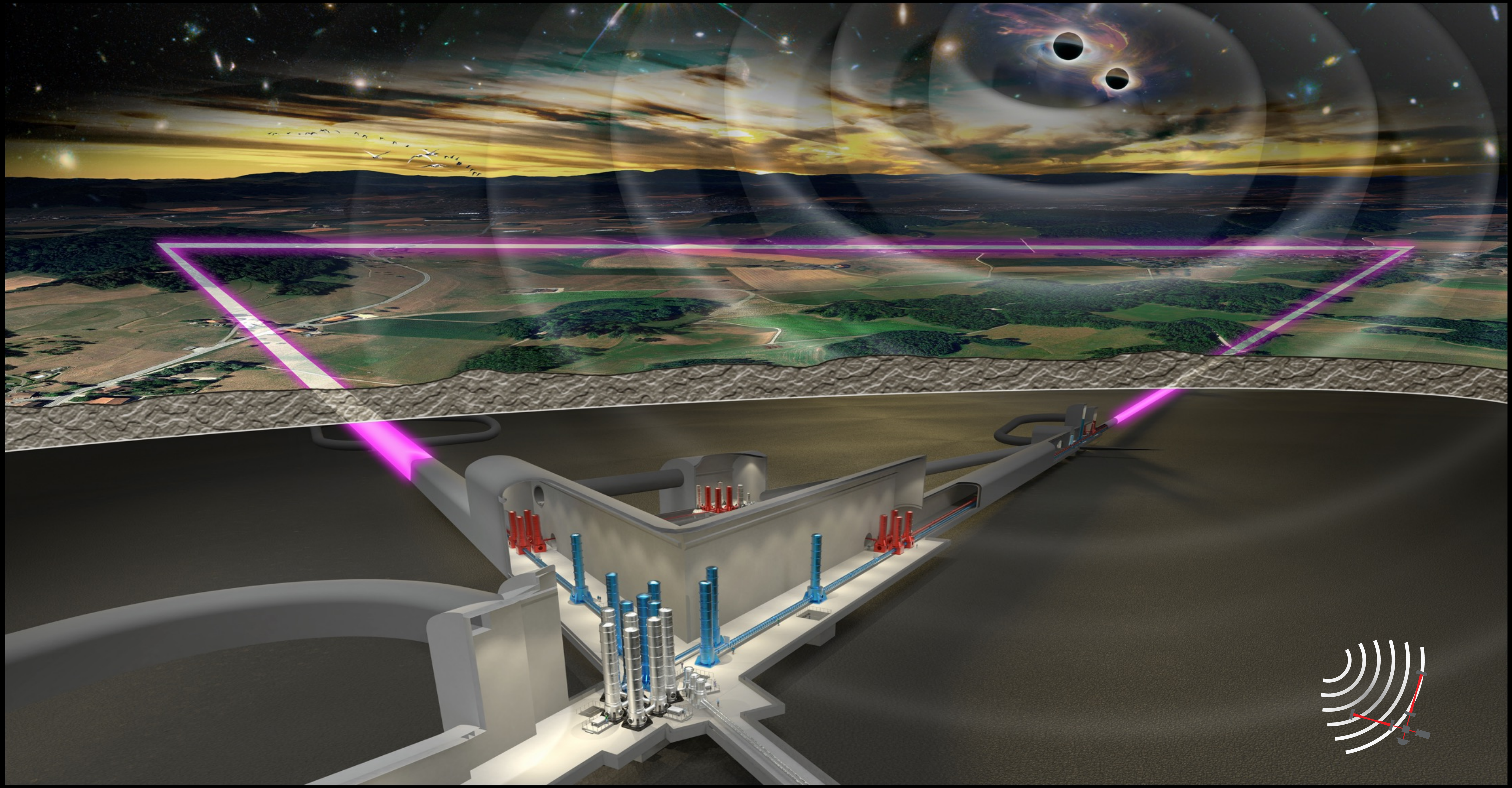


Equivalent to an order of magnitude increase in the diameter of a telescope

Einstein Telescope: the next generation



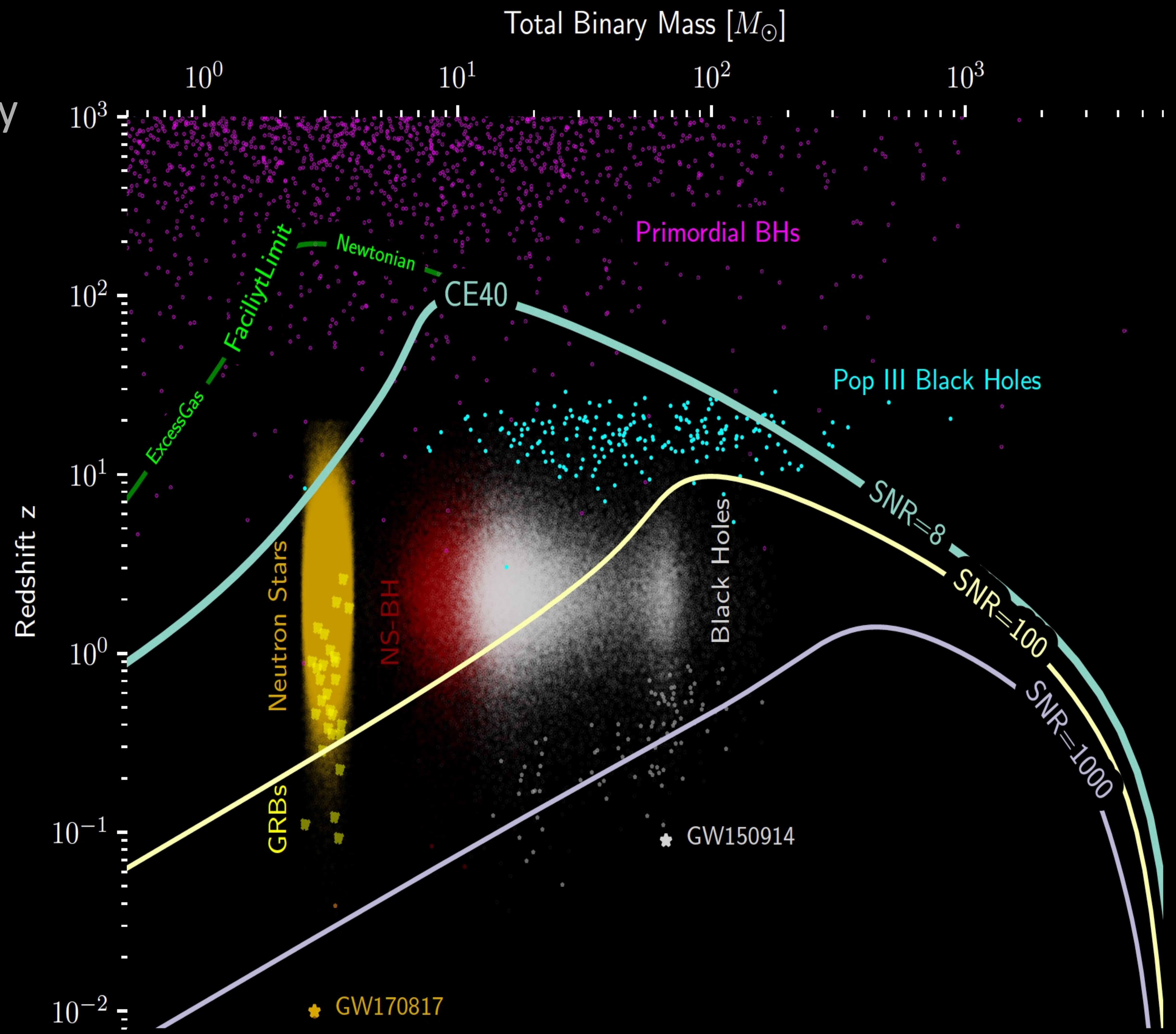
Large laboratories and three 10 km long tunnels, more than 200m underground.
10 times better than design sensitivity of current detectors,
providing GW data for at least 50 years.
ESFRI (2020): ET Observatory and Collaboration formed.

[slide courtesy of A. Friese]

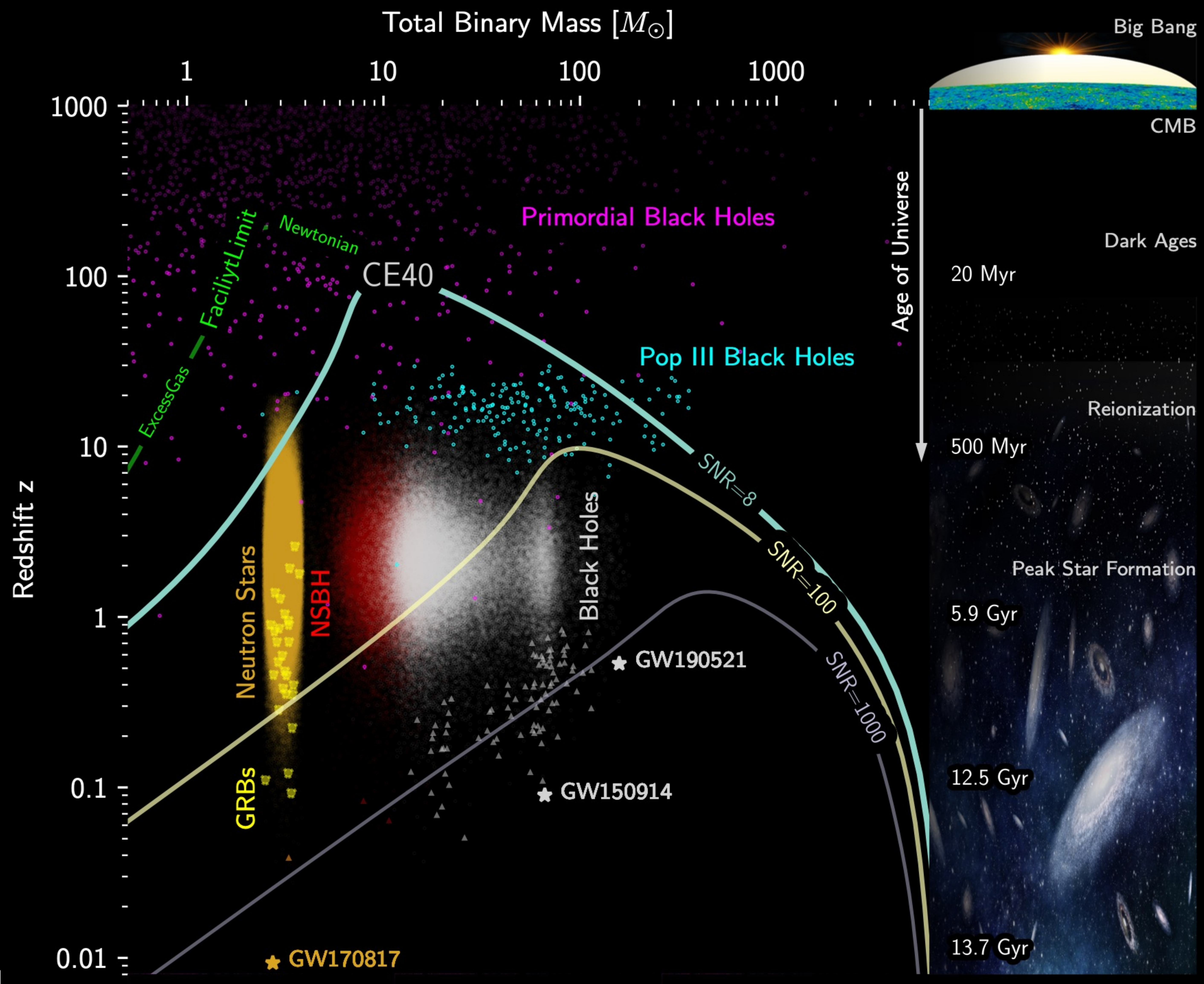
Cosmic Explorer

The US Vision for Gravitational-Wave Astrophysics

- Next-Generation Gravitational-Wave Observatory
  - 40 km and 20 km L-shaped surface observatories
  - 10x sensitivity of today's observatories
  - Global network together with European Einstein Telescope
- Enables access to
  - Stellar to intermediate mass mergers throughout Cosmic Time
  - Dynamics of Dense Matter
  - Extreme Gravity
- Endorsed by Snowmass & Astro2020 Decadal

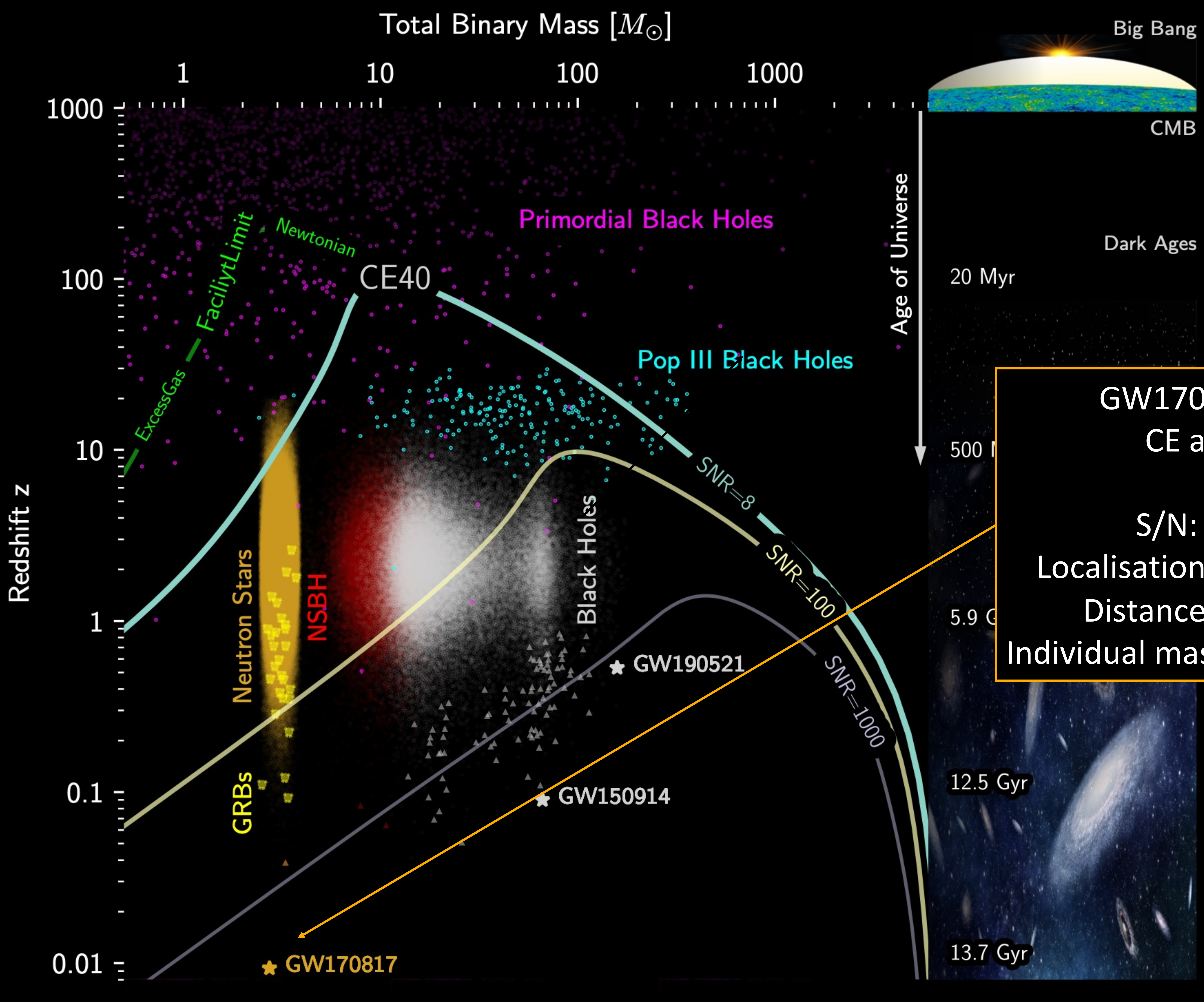


ET and CE’s cosmic reach and sheer number



[arXiv:2307.10421]

ET and CE's cosmic reach and sheer number



GW170817 with
CE and ET

S/N: ~1700
Localisation: 0.0029 deg^2
Distance error: 1%
Individual mass errors: 10^{-3} %

[arXiv:2307.10421]

The Science Case for Einstein Telescope

ASTROPHYSICS

Black hole properties
origin (stellar vs. primordial) evolution, demography

Neutron star properties
interior structure (QCD at ultra-high densities, exotic states of matter)
demography

Multi-band and -messenger astronomy
joint GW/EM observations (GRB, kilonova,...)
multiband GW detection (with LISA)
neutrinos

Detection of new astrophysical sources
core collapse supernovae
isolated neutron stars
stochastic background of astrophysical origin

FUNDAMENTAL PHYSICS AND COSMOLOGY

The nature of compact objects
near-horizon physics
tests of no-hair theorem
exotic compact objects

Tests of General Relativity
post-Newtonian expansion
strong field regime

Dark matter
primordial BHs
axion clouds, dark matter on compact objects

Dark energy and modifications of gravity
dark energy equation of state
modified GW propagation

Stochastic backgrounds of cosmological origin
inflation, phase transitions, cosmic strings

[see Maggiore et al.; 1912.02622],
also https://www.einsteintelescope.nl/
and https://www.et-gw.eu/]

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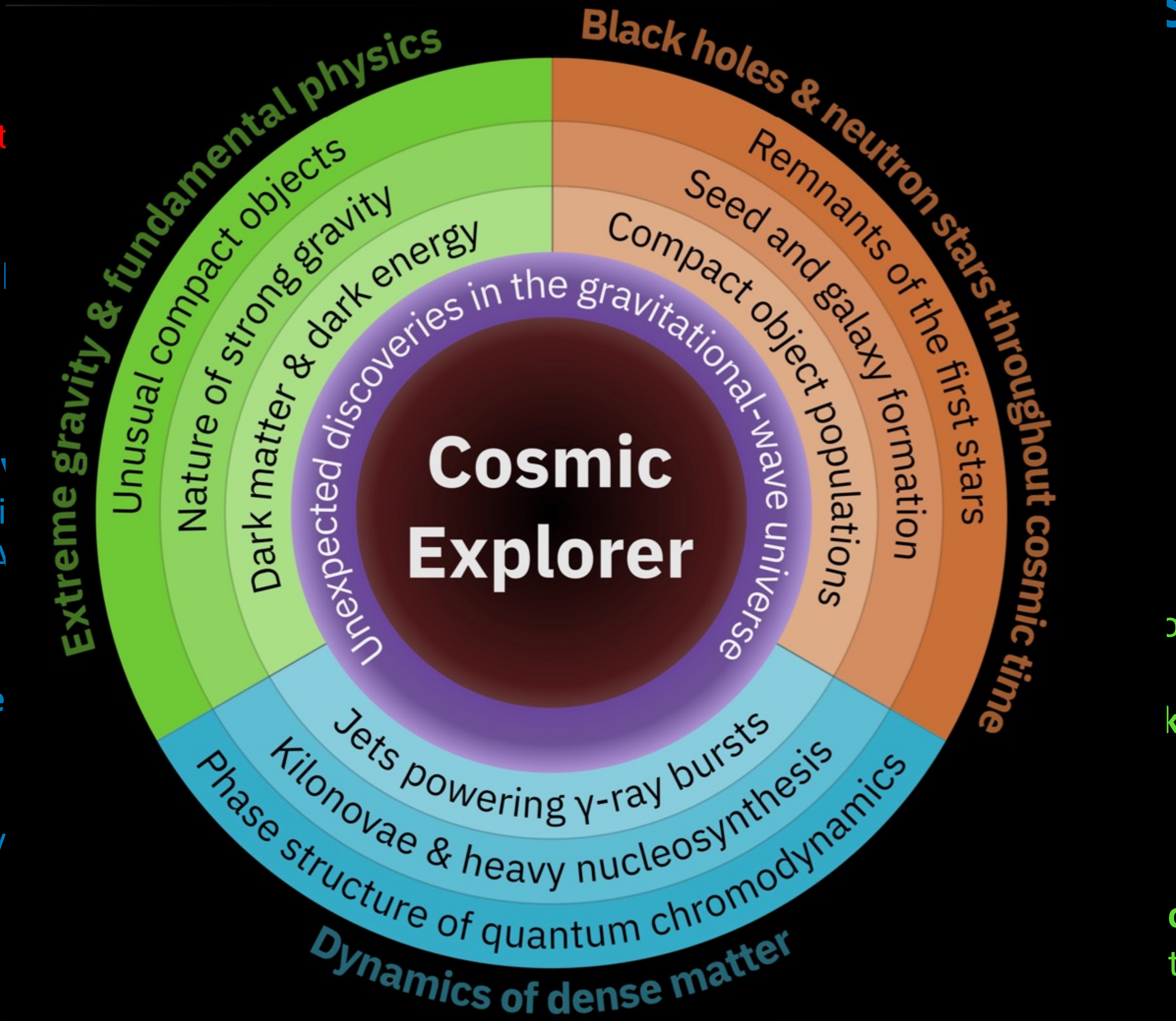

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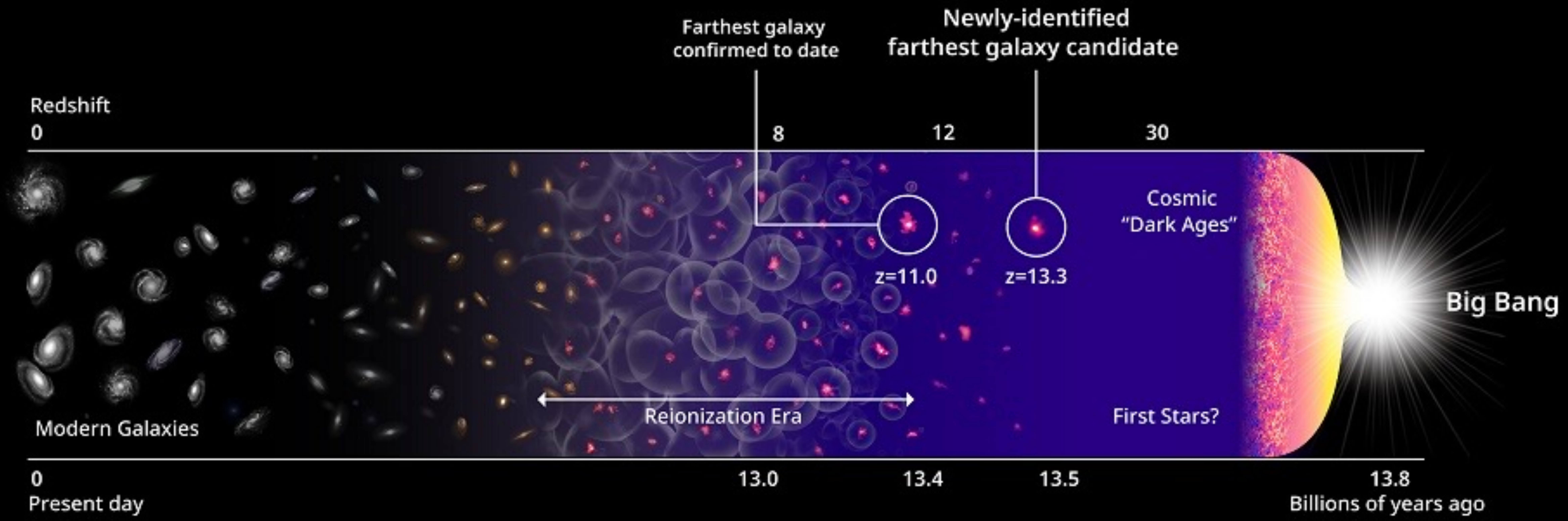
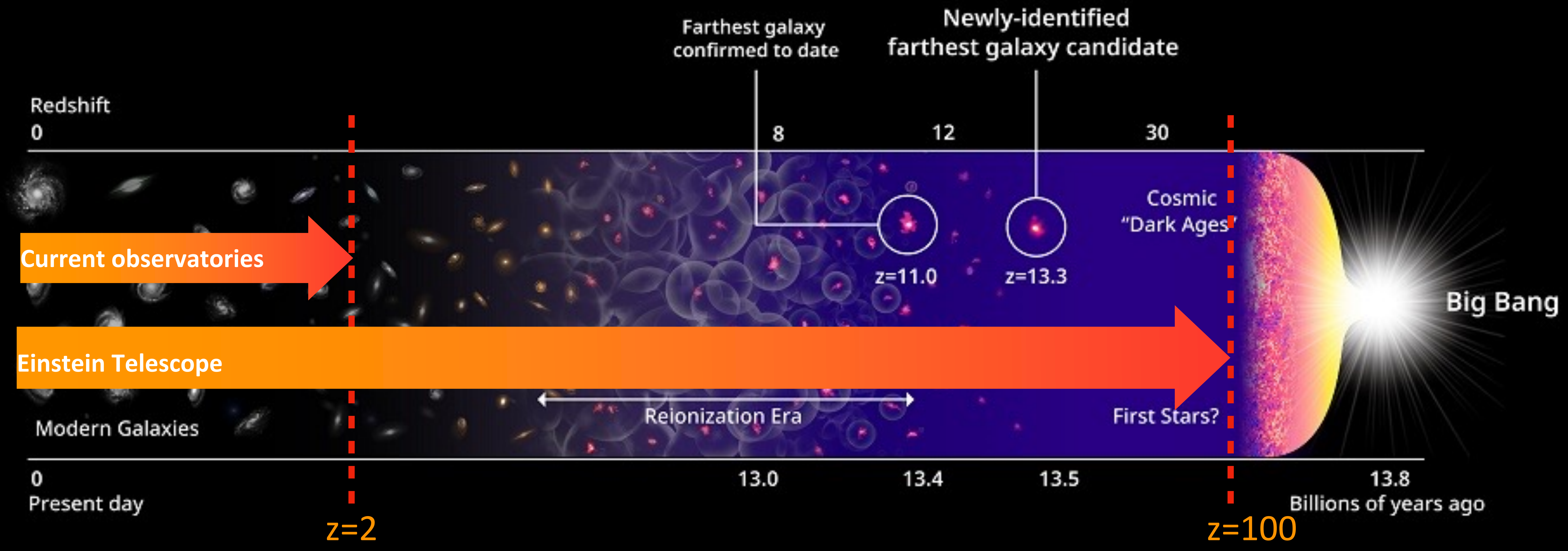
Cosmic Reach of Einstein Telescope



Cosmic Reach of Einstein Telescope



How many?

DETECTION CAPABILITY OF 2G AND 3G NETWORKS

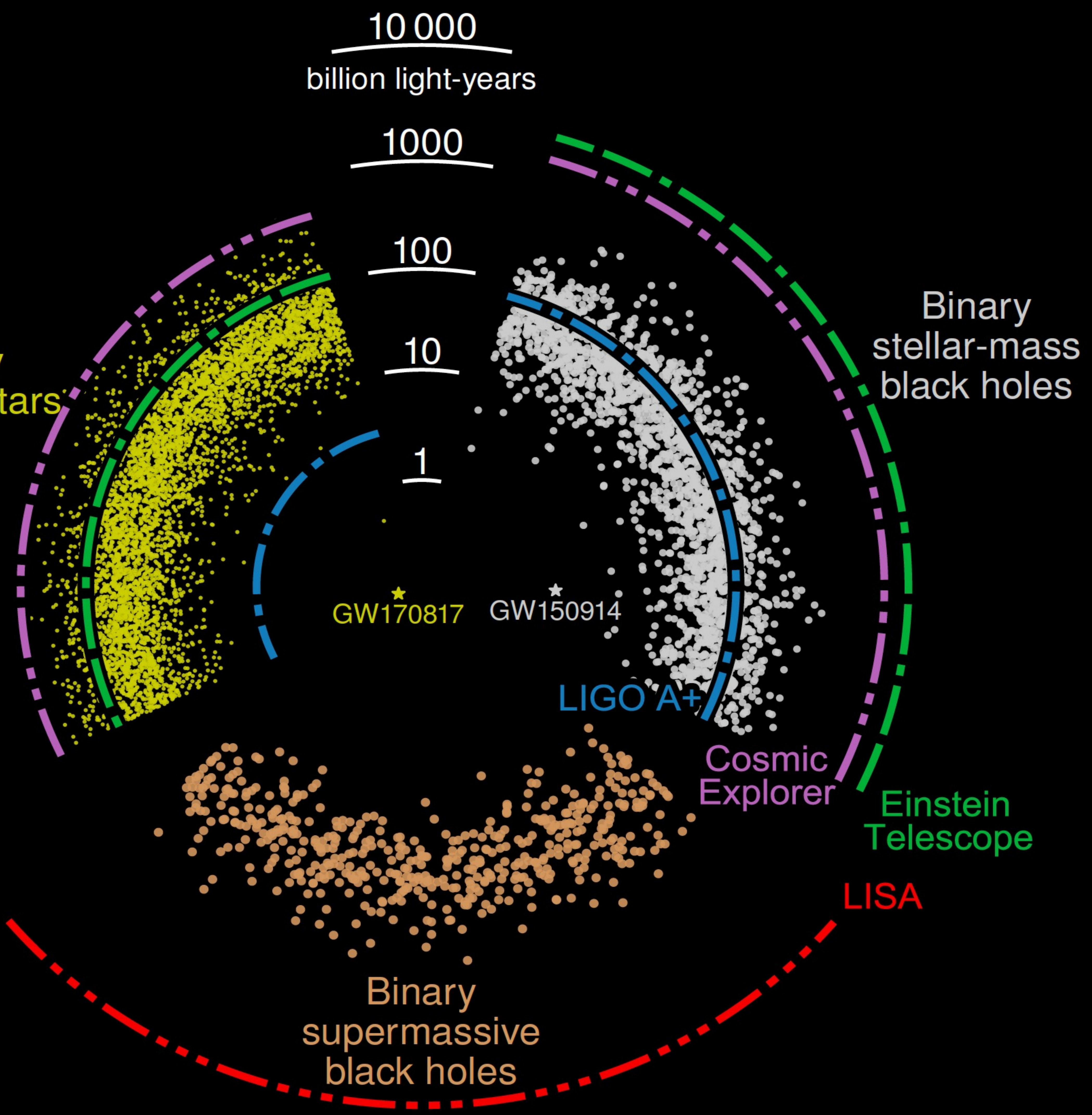
Table 2.1: Expected number of binary NS detections per year N; localized with a resolution of < 1, < 10 and < 100 square degrees, N_1, N_{10} and N_{100}, respectively, and median localization error M, in a network consisting of LIGO-Hanford, LIGO-Livingston and Virgo (HLV), HLV, KAGRA and LIGO-India (HLVKI) and 1 Einstein Telescope and 2 Cosmic Explorer detectors (1ET+2CE).

Network	N	N_1	N_{10}	N_{100}	M
HLV	48	0	16	48	19
HLVKI	48	0	48	48	7
1ET+2CE	990k	14k	410k	970k	12

[Astro 2020 White Paper arXiv:1903.09277:
from GWIC MMA working gp, Co-chairs Bailes, Kasliwal, Nissanke]

The necessity of ET and CE combined

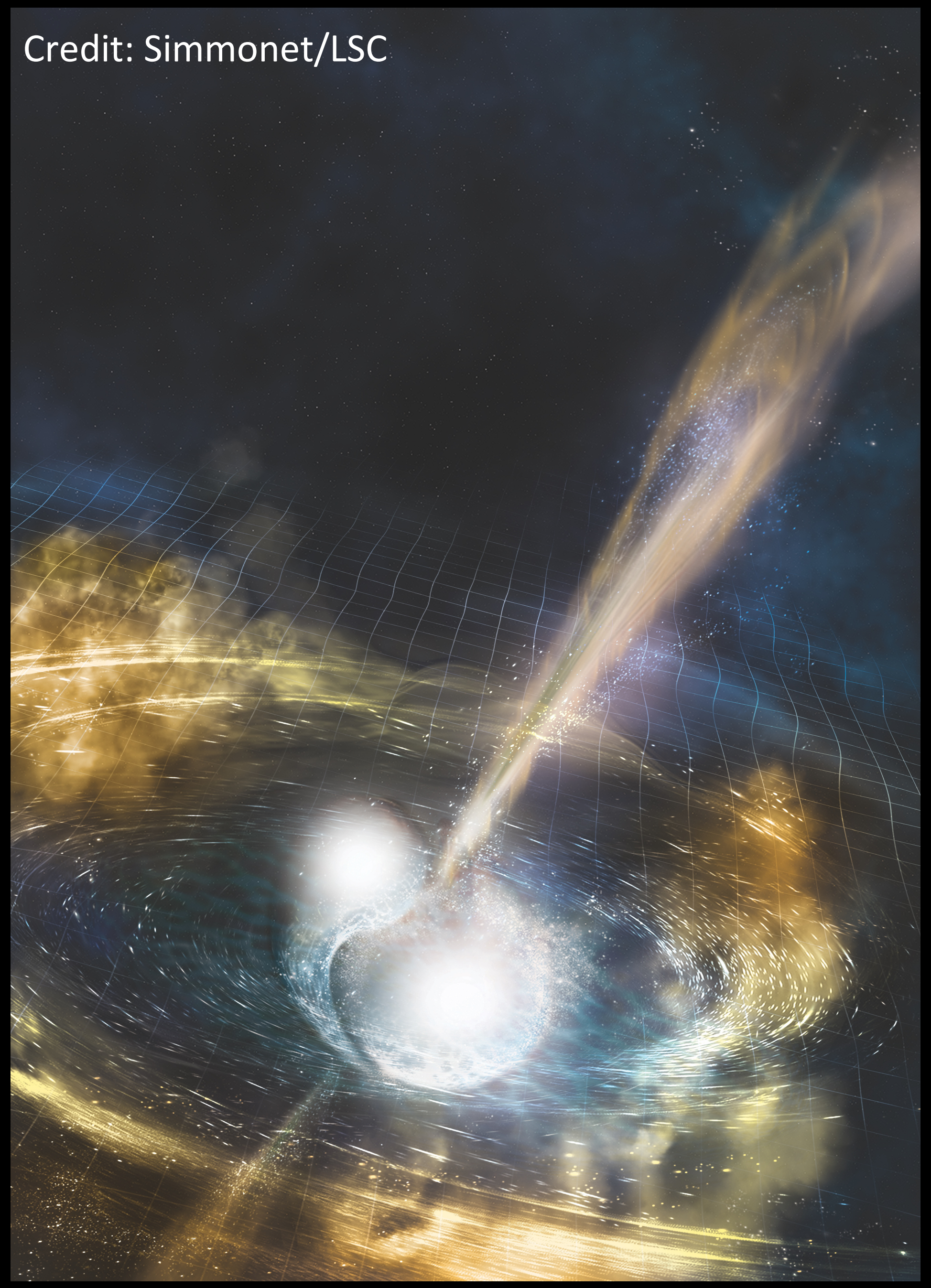
2030s: Ten thousand to a hundred thousand neutron star and black hole mergers per year detected in GW!



Credit: Evan Hall

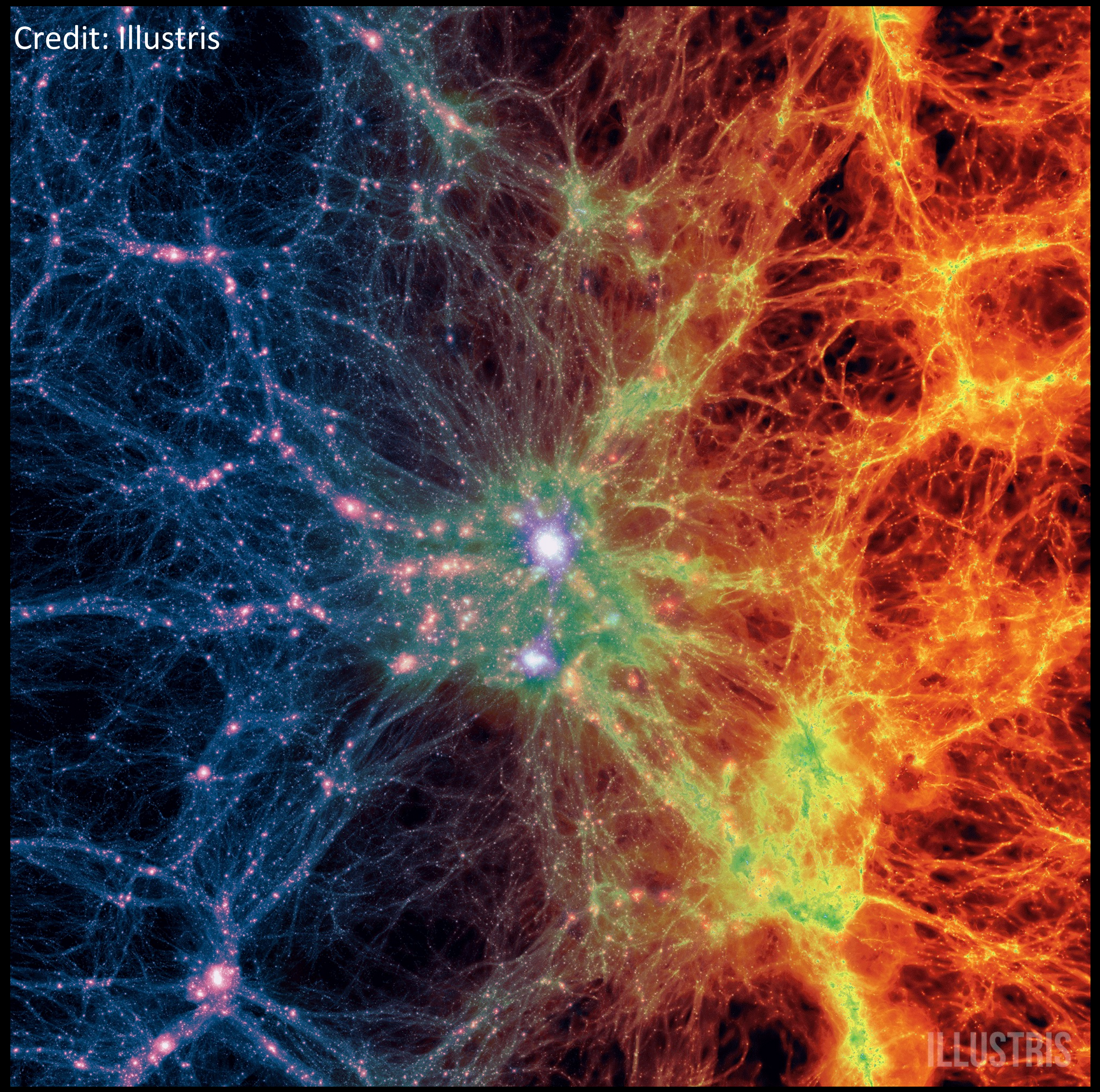
GW+EM requires radical transformation today

EM follow up of single sources



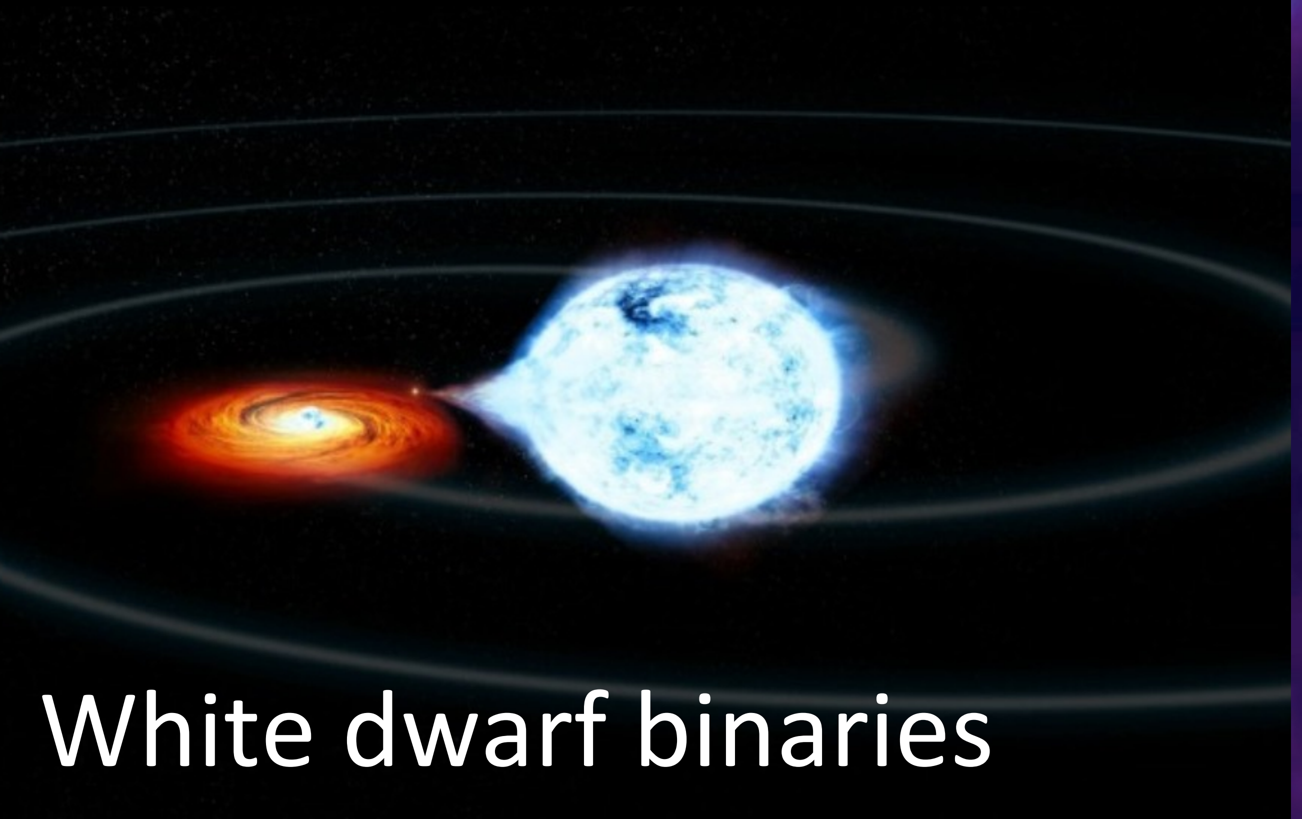
Cherry Pick Loud events - golden for GW+EM

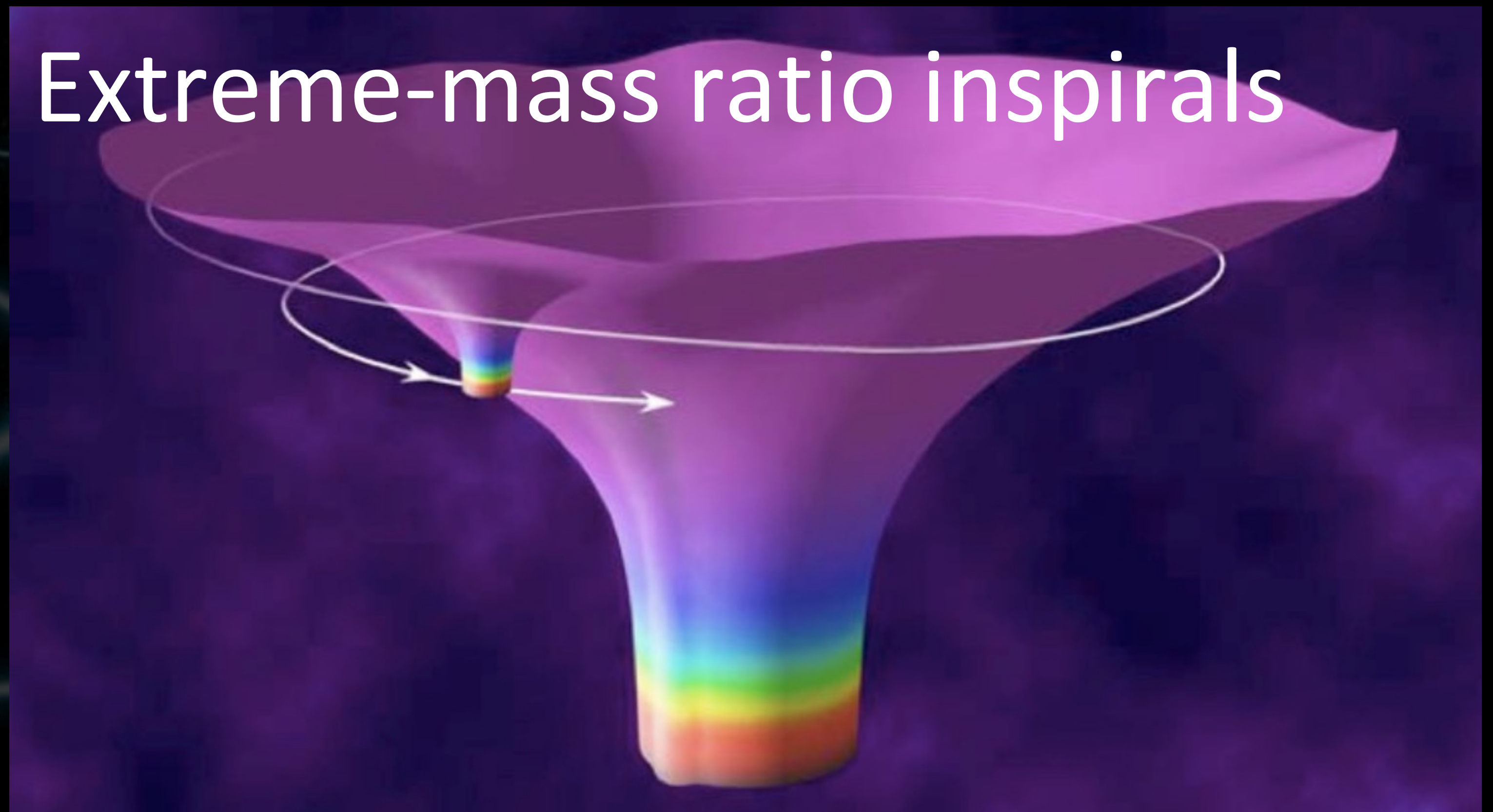
Cross correlating GW and EM source catalogs

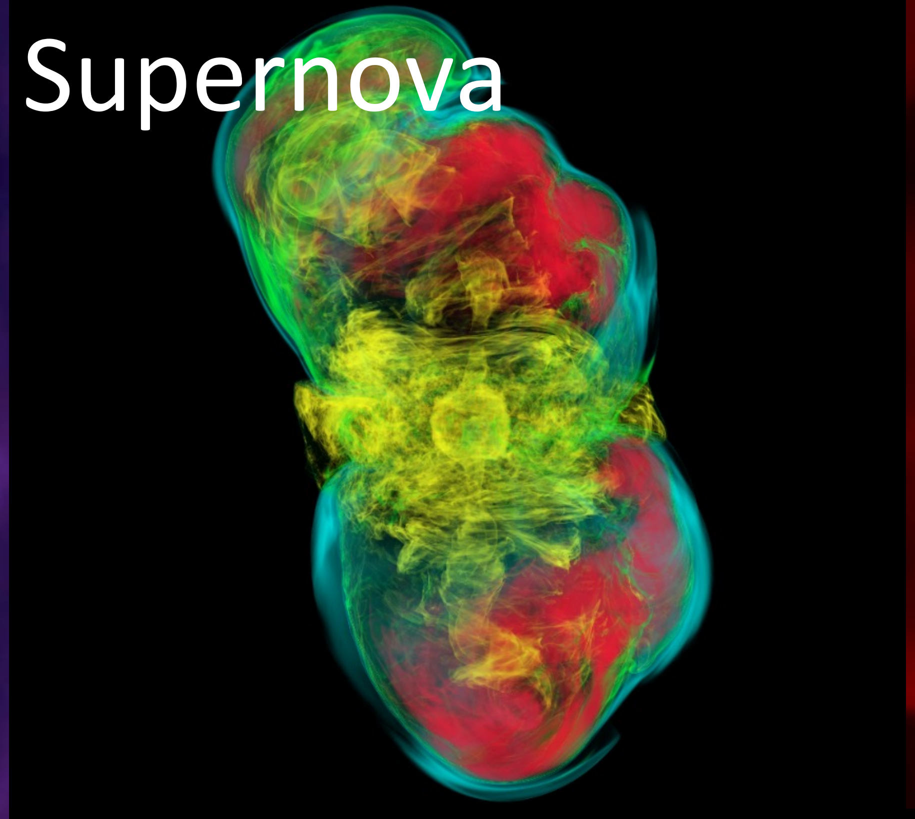


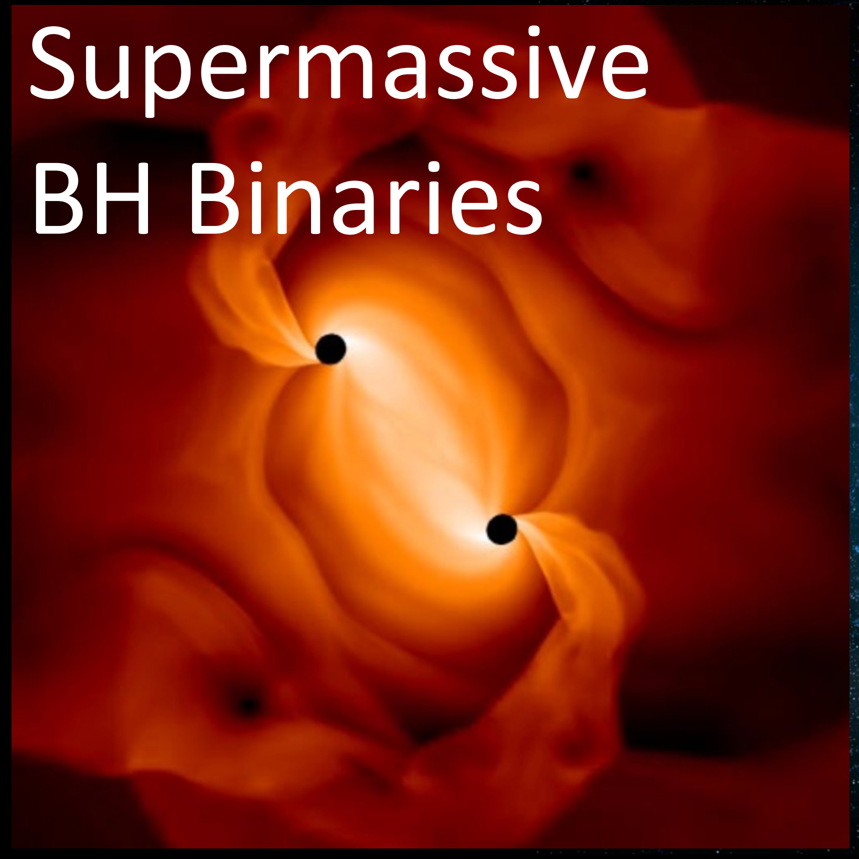
Large Scale Structure; Extragalactic Astronomy

Gravitational wave & multi-messenger astronomy: the future is both loud and bright!









Conclusions

Gravitational wave physics has had a momentous decade with new discoveries, exceptional events as well as progress into population studies.

ngGW detectors are transformational 50 year facilities : wide, precise and deep —> facilities for both astronomy and high energy physics.

Address theory and computational challenges for gravitational waveforms and for electromagnetic counterpart modelling.

Leverage AI and machine learning for data analysis as well as source modelling both in GWs and EM: accuracy, precision and speed are critical.

Necessary to ensure pre-existing detector networks remain for training of next generation of gravitational wave and multi-messenger scientists .