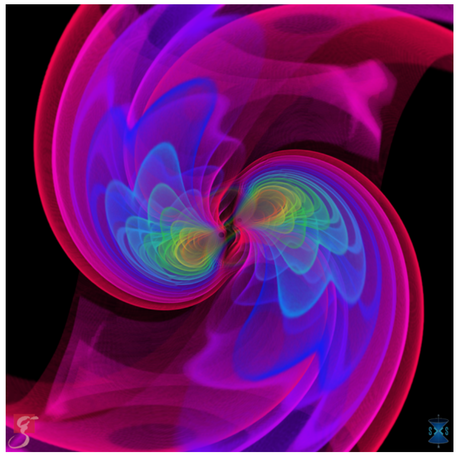
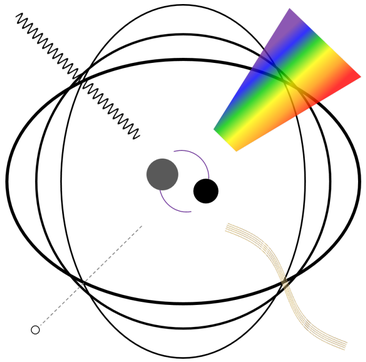
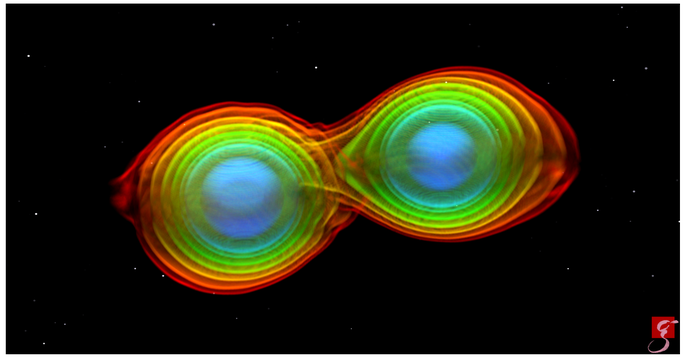






The Gravitational-Wave Universe

Alessandra Buonanno

Max Planck Institute for Gravitational Physics

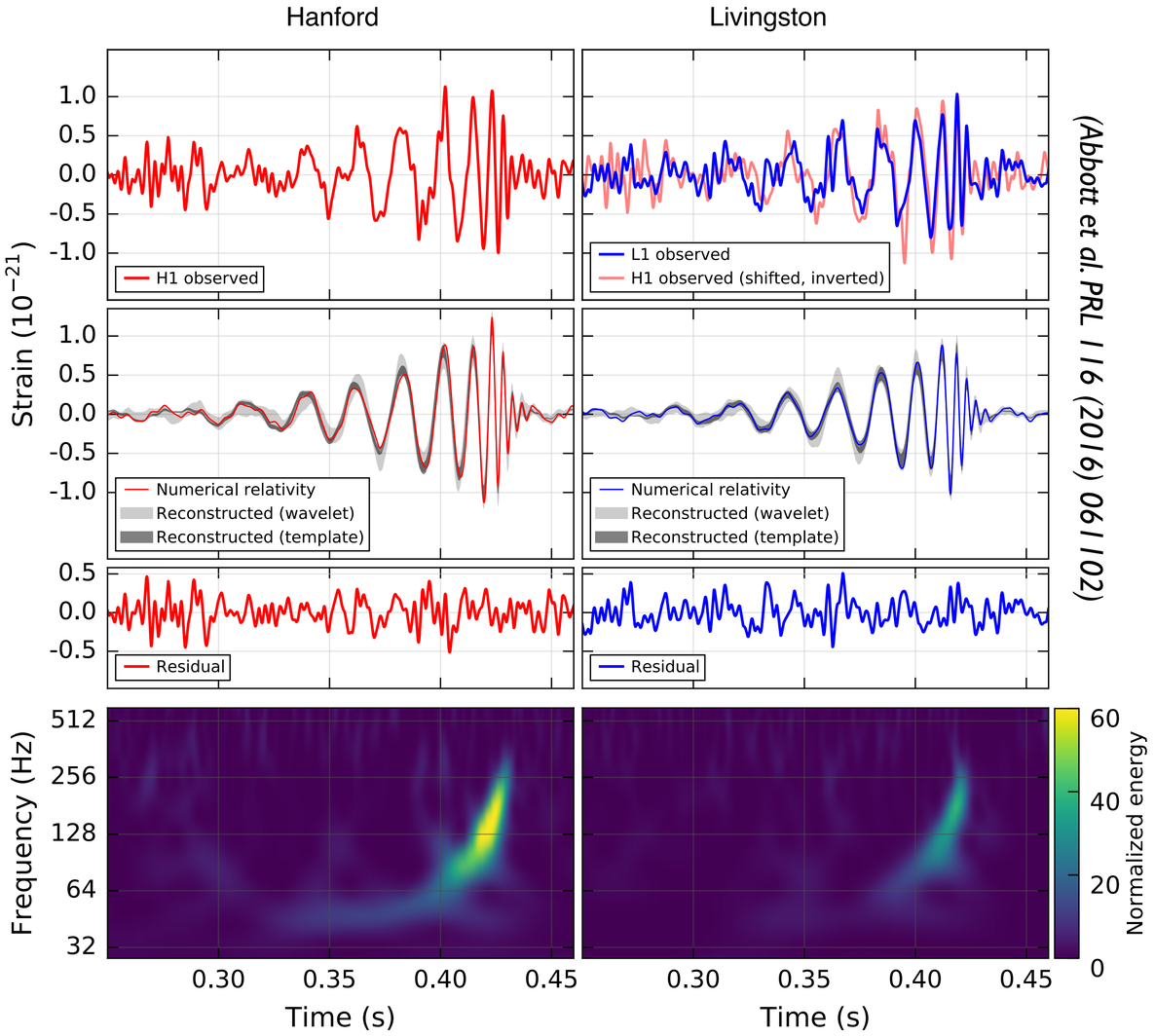
(Albert Einstein Institute)

Department of Physics, University of Maryland

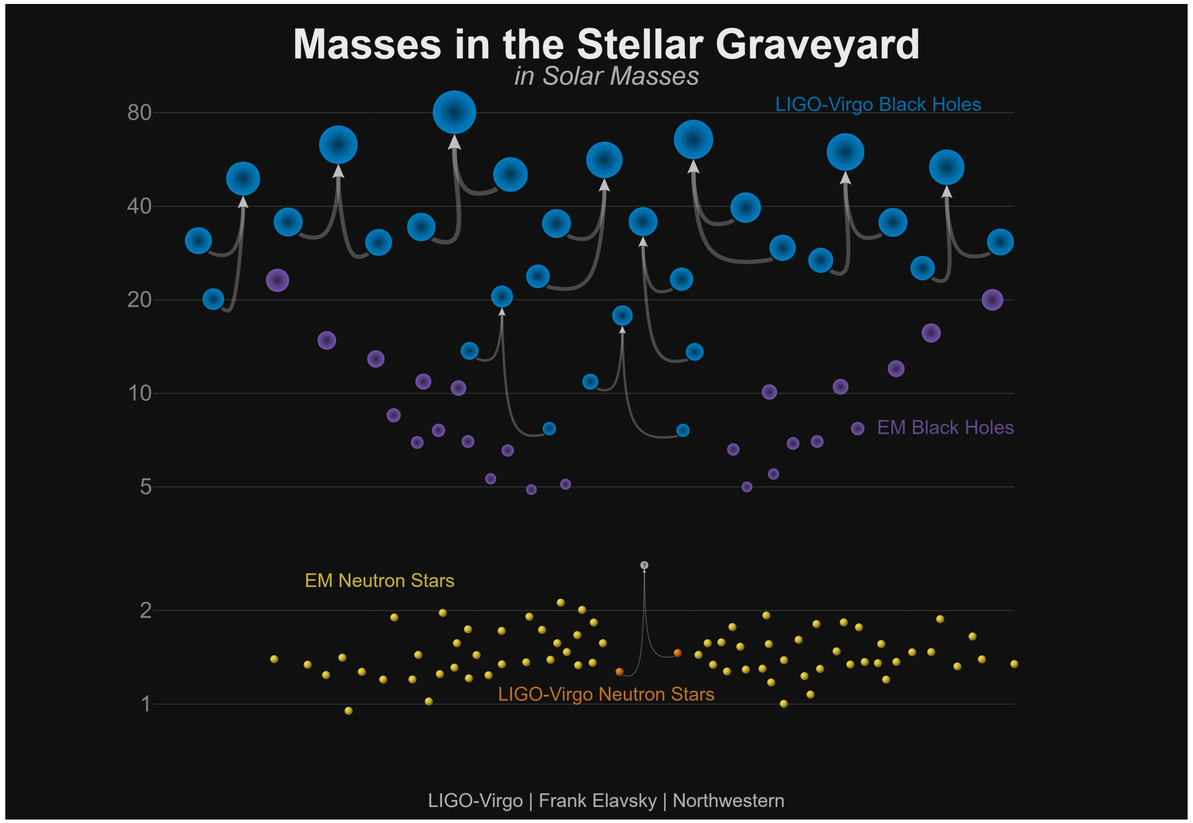
"Shaping the ESA's Space Science Plan for 2035-2050", Madrid October 29-31, 2019

Gravitational Waves Ushered in New Era of Astrophysics

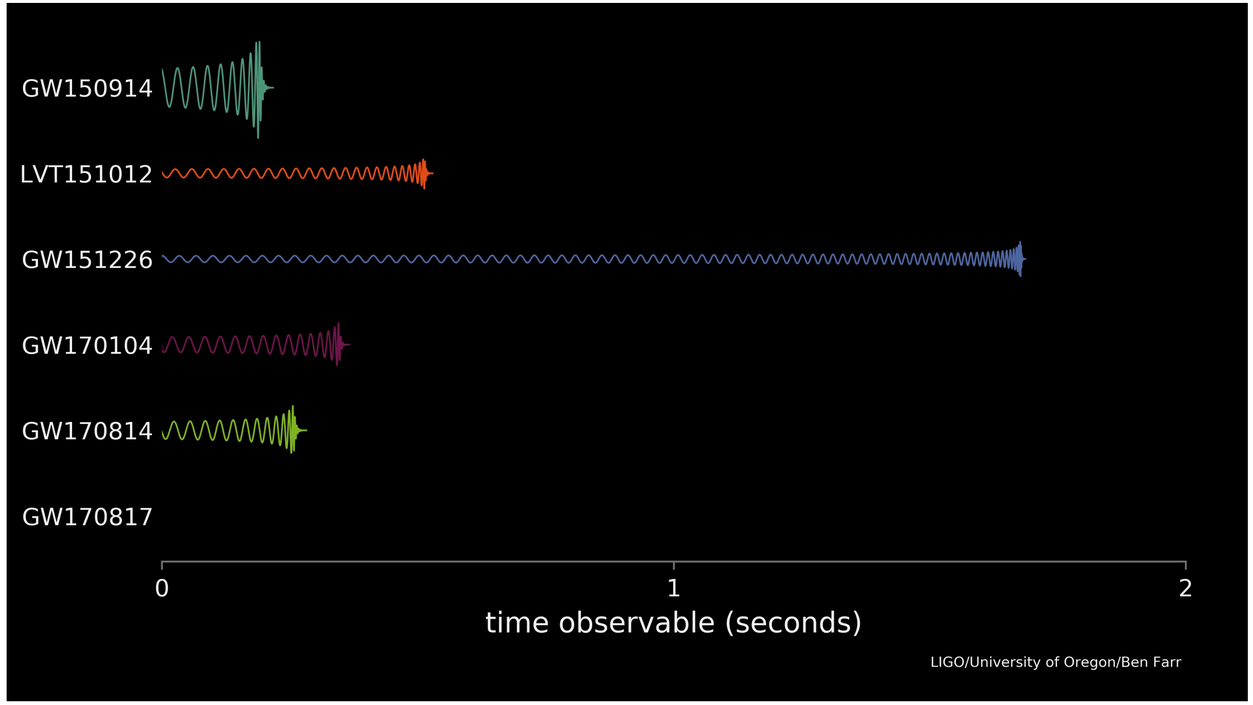
- **Discovery** of **GW** from **a binary black-hole merger** by LIGO



- **Since GW150914** was observed, **many more black hole binaries (BHBs) discovered** by LIGO/Virgo.



Which BH's masses can detectors probe? How do we infer source's properties?

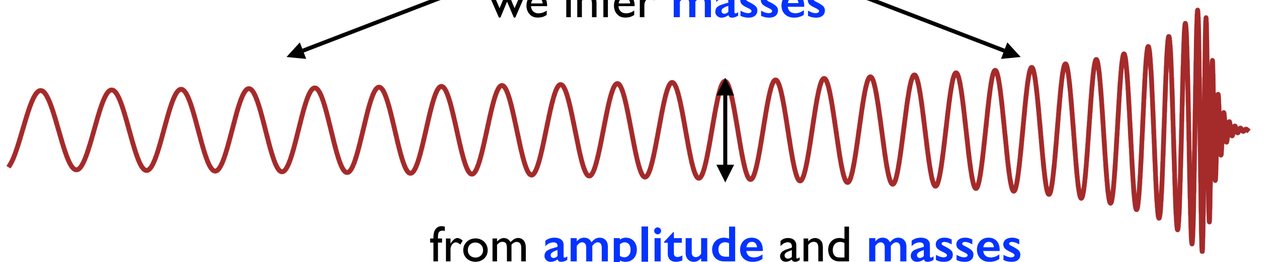


- Compact-object binaries **merge** at $f_{\rm merger} \sim 4400/(M/M_\odot)$Hz

- At fixed binary's mass, the **lower** the **GW frequency,** the **earlier** the **inspiral stage**

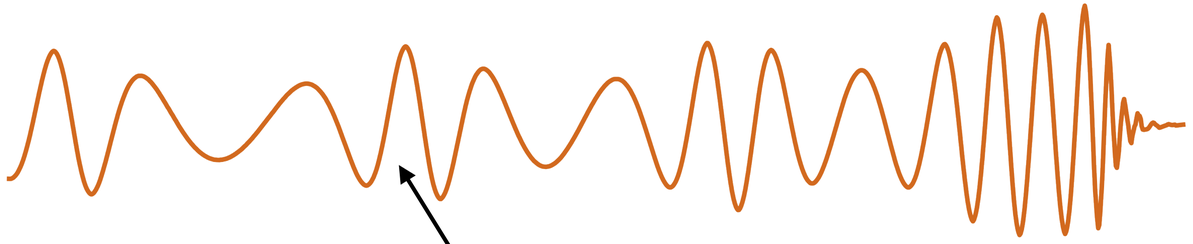
$$f = \omega/\pi \quad \omega^2 r^2 = GM/r$$

from **frequency evolution** we infer **masses**



from **amplitude** and **masses** we infer **distance**

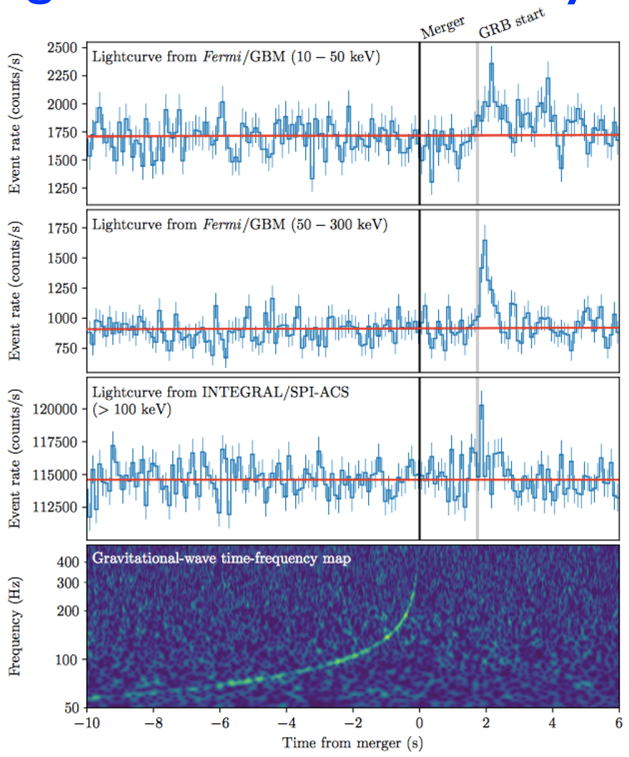
from **time of arrival**, **amplitude and phase** at detectors we infer **sky location**



from **modulations** of **amplitude and phase** we infer **spins and eccentricity**

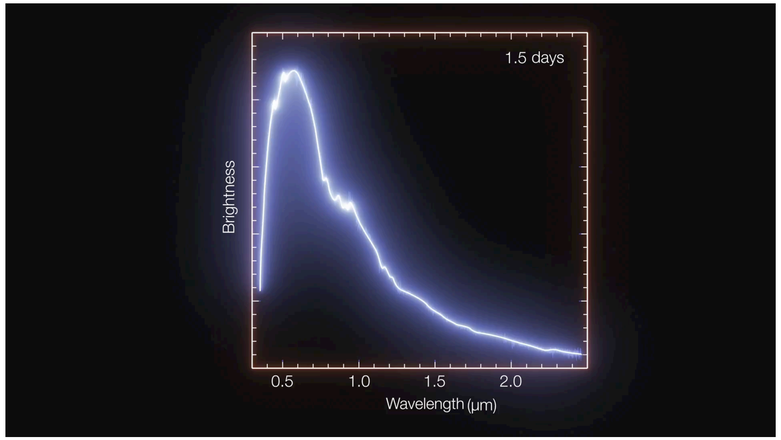
Gravitational Waves Ushered in Multi-Messenger Astronomy

- **GW170817** has shed light on the **origin** of **short Gamma Ray Bursts.**



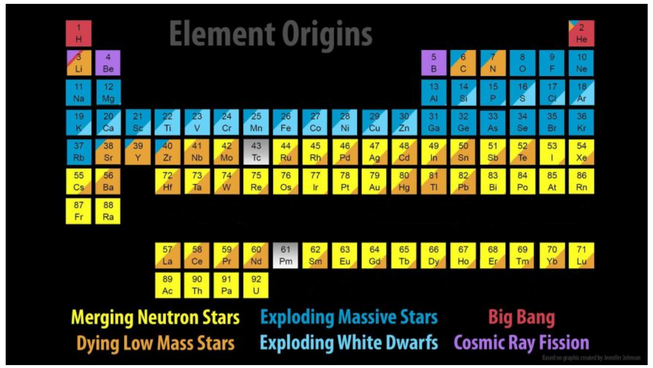
(Abbott et al. APJ 848 (2017) L12)

- GW170817 produced **EM emission from Gamma to Radio**.

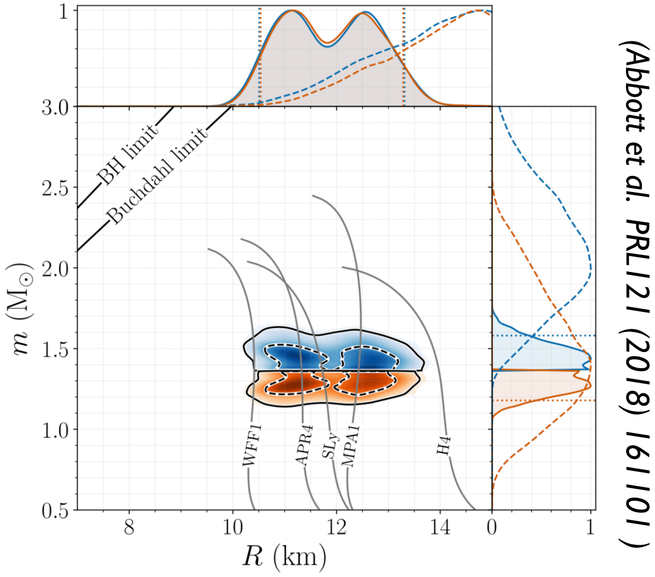


(ESO: spectra of kilonova in NGC4993)

- GW170817 and the **origin** of **heavy elements**.

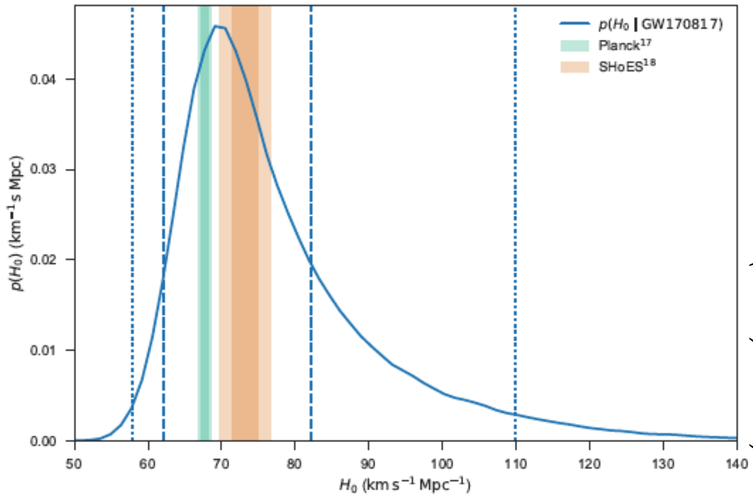


- Setting constraints on **radius/equation of state** of **neutron stars**.



(Abbott et al. PRL121 (2018) 161101)

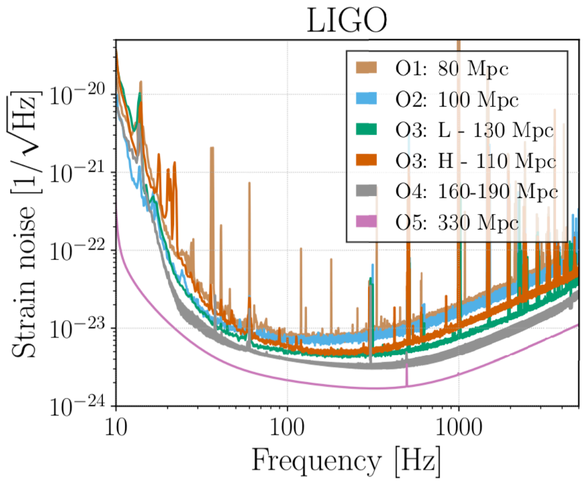
- Independent **measurement** of **Hubble parameter.**

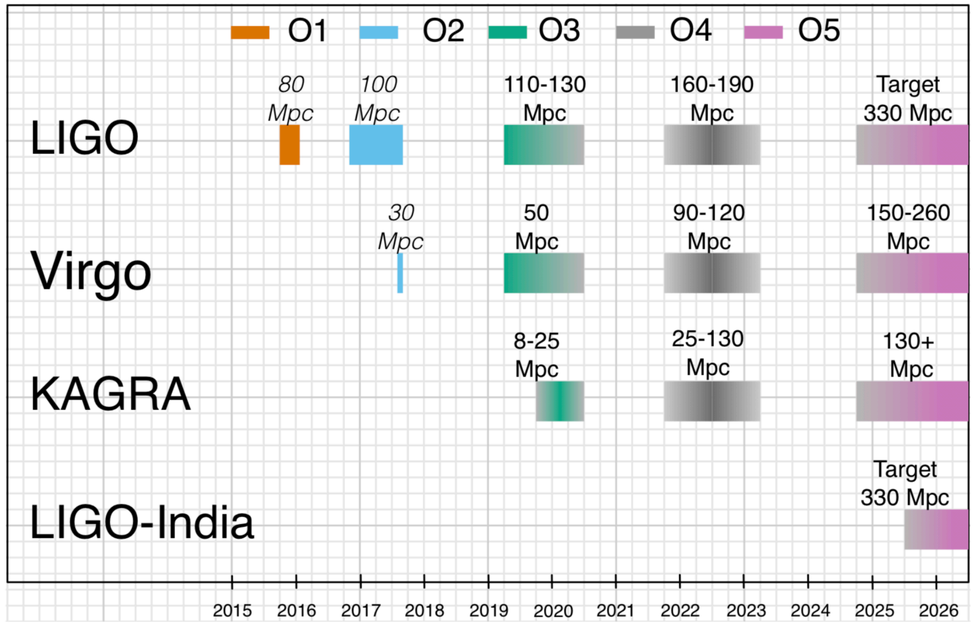


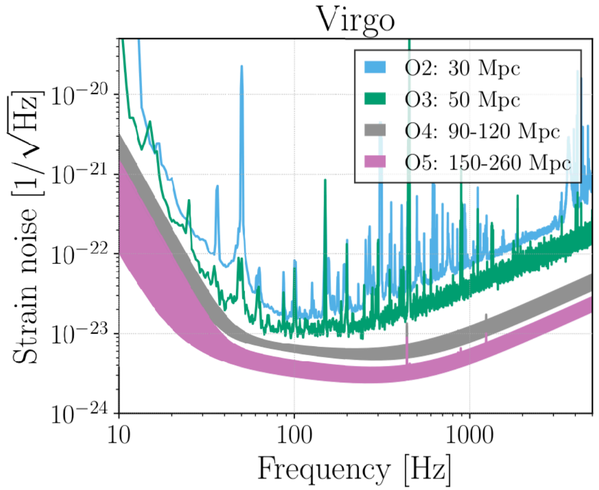
(Abbott et al. Nature (2017) 24471)

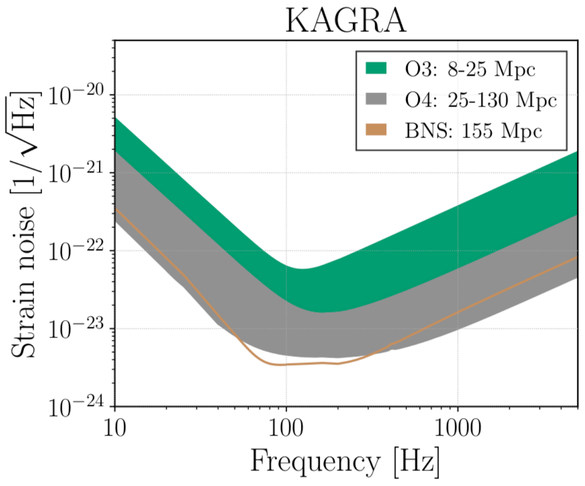
Gravitational-Wave Landscape until ~2030

(Aasi et al. Living Rev. Rel. 21, 2019)









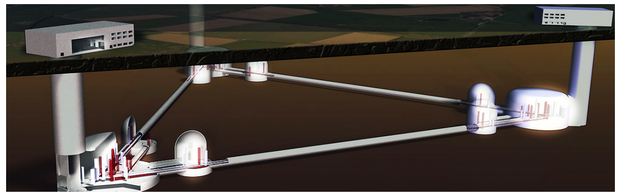
- From **several tens to hundreds** of binary detections per year
- Inference of **astrophysical properties** of BHBs, NSBHs and BNSs **in local Universe**

(Aasi et al. Living Rev. Rel. 21, 2019)

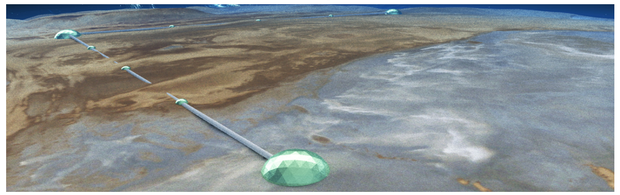
Observation Run	Network	Expected BNS Detections	Expected NSBH Detections	Expected BBH Detections
O3	HLV	2^{+8}_{-2}	0^{+19}_{-0}	15^{+19}_{-10}
O4	HLVK	8^{+42}_{-7}	2^{+94}_{-2}	68^{+81}_{-38}
		Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.
O3	HLV	250 – 310	310 – 390	250 – 340
O4	HLVK	29 – 48	48 – 69	33 – 47
		Comoving Volume (10^3 Mpc^3) 90% c.r.	Comoving Volume (10^3 Mpc^3) 90% c.r.	Comoving Volume (10^3 Mpc^3) 90% c.r.
O3	HLV	90 – 130	590 – 1000	11000 – 19000
O4	HLVK	43 – 71	400 – 560	6400 – 10000

Gravitational-Wave Landscape after ~2030 on the ground

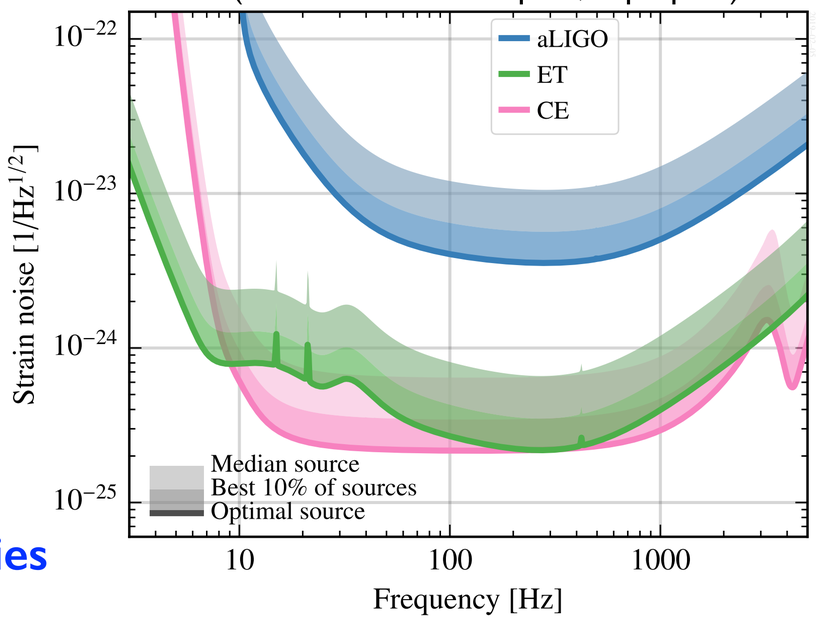
Einstein Telescope

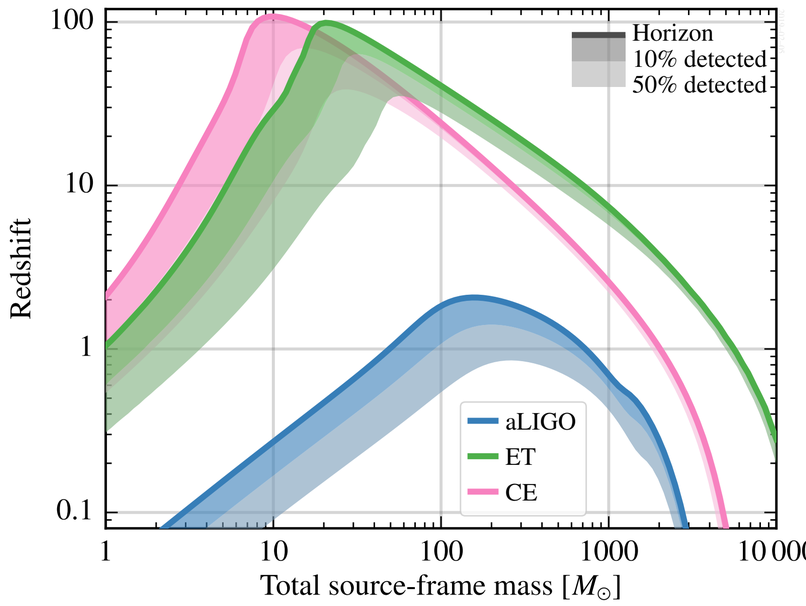


Cosmic Explorer

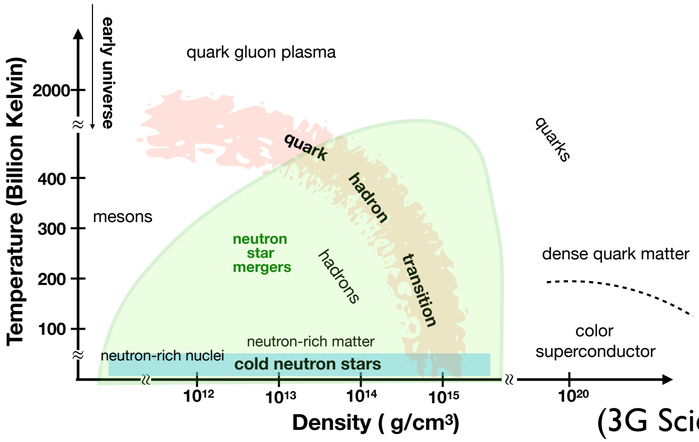


(3G Science-Case Report, in prep 19)



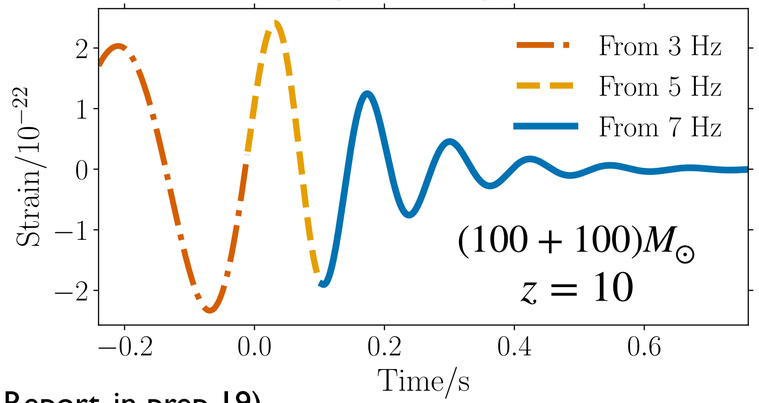


- **Understanding fundamental properties** of matter in **unexplored regimes** of **density** and **temperatures** with ET/CE and EM facilities.

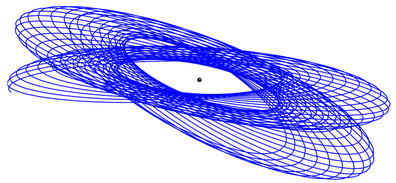


(3G Science-Case Report, in prep 19)

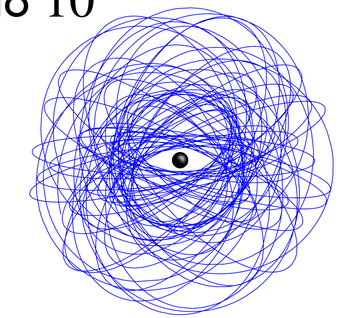
- Merger and ringdown of **Intermediate Black Holes (IMBHs)**



- **Intermediate Mass-Ratio Inspirals (IMRIs),** with mass ratio 10^3

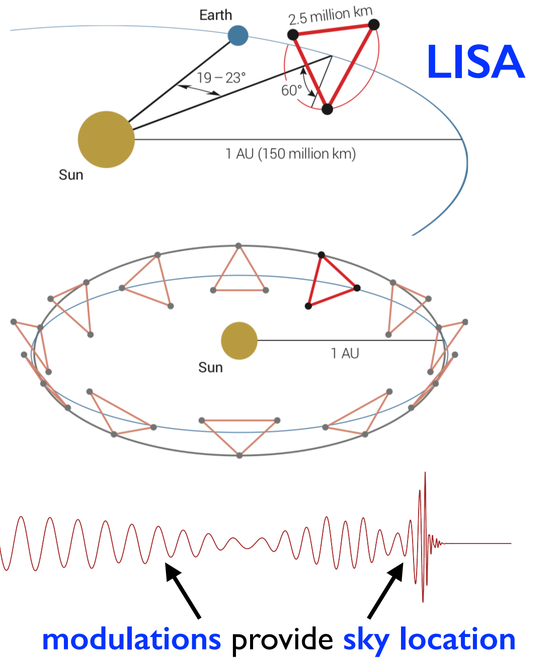


at GW frequency ~1Hz



at GW frequency ~10 Hz

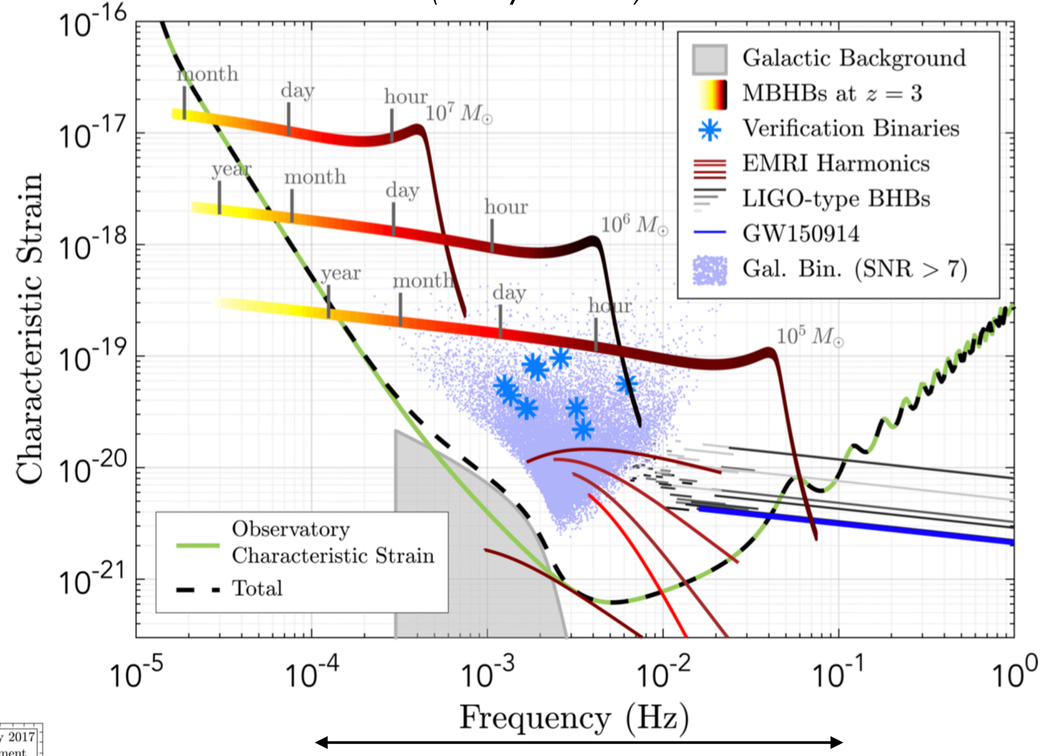
Gravitational-Wave Landscape after ~2030 in space



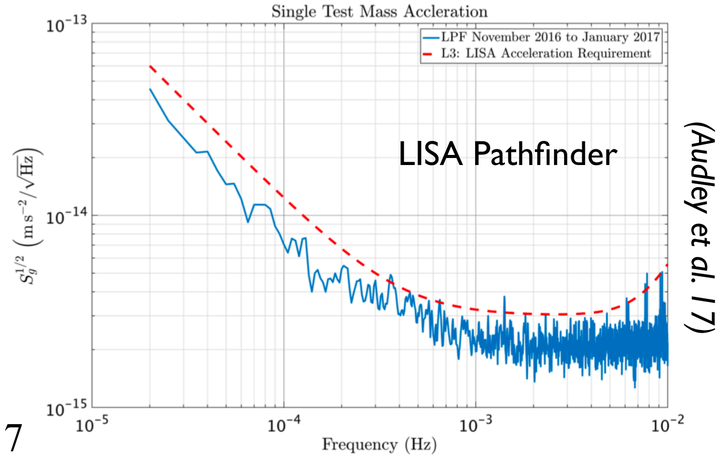
LISA

modulations provide **sky location**

(Audley et al. 17)



opening **three decades** of GW spectrum

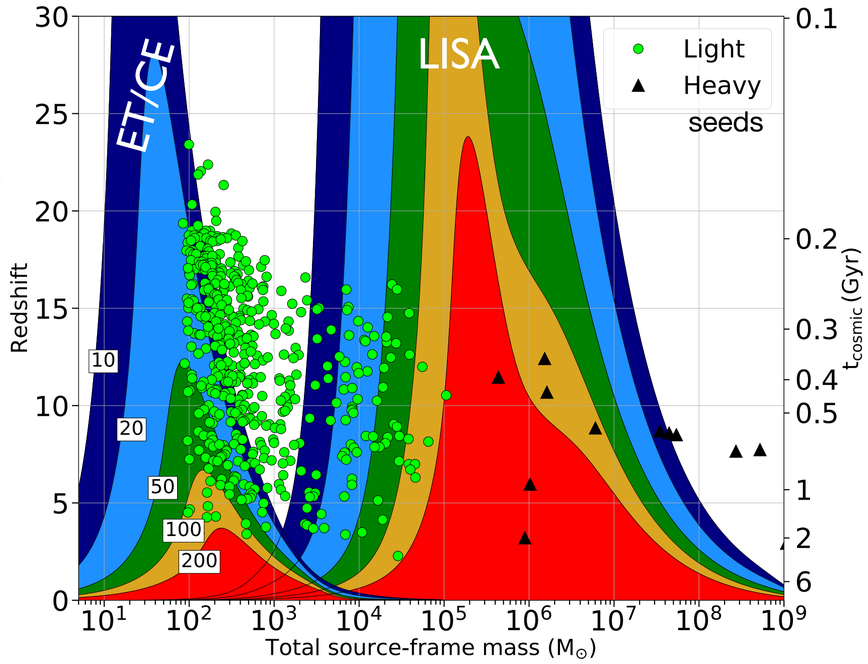


(Audley et al. 17)

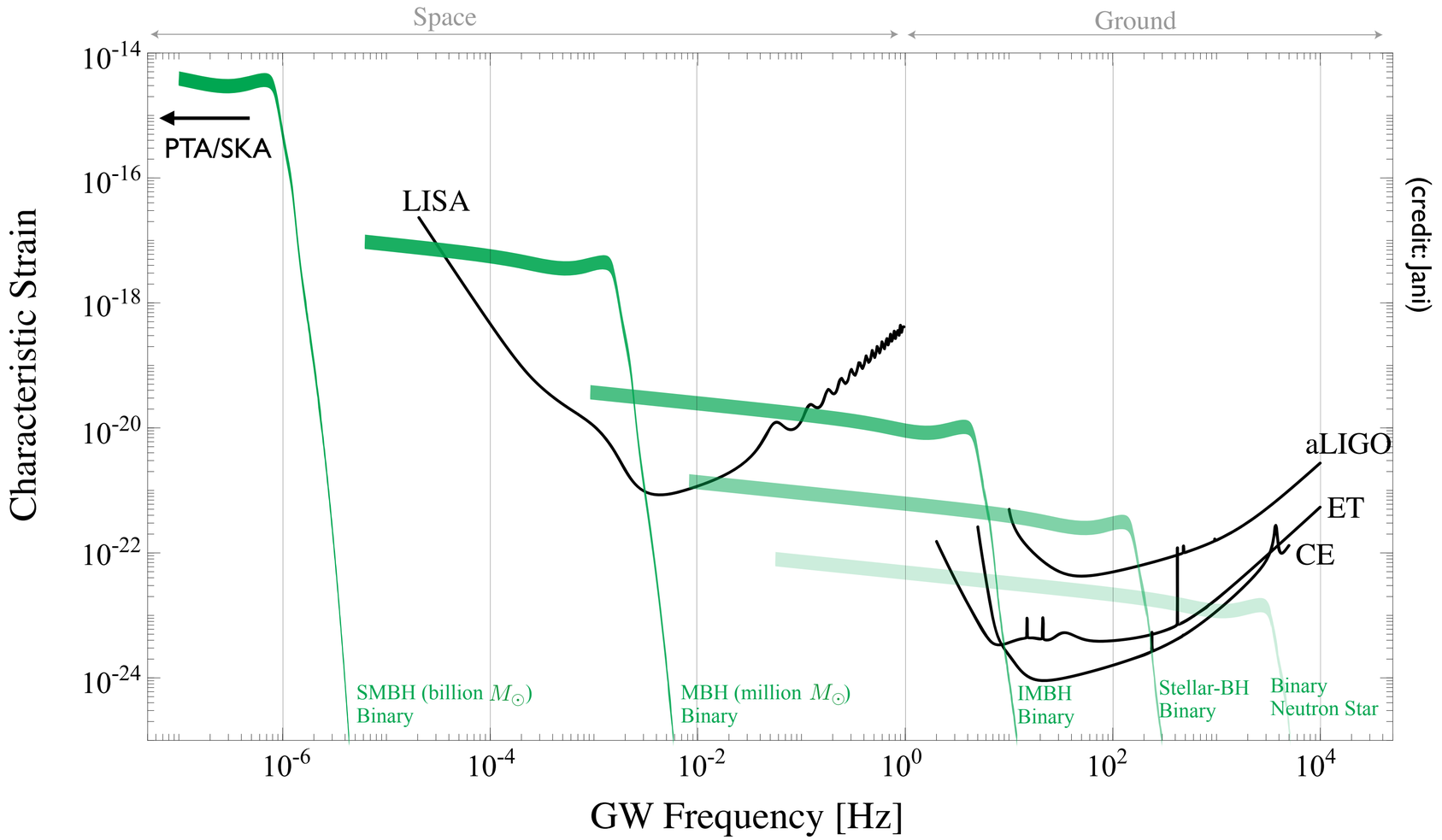
- **New** GW **sources**:
  - extreme mass-ratio inspirals (**EMRIs**)
  - massive BHs (**MBHs**)
  - WD binaries

ESA leading mission with
NASA junior partner

(3G Science-Case Report, in prep 19)

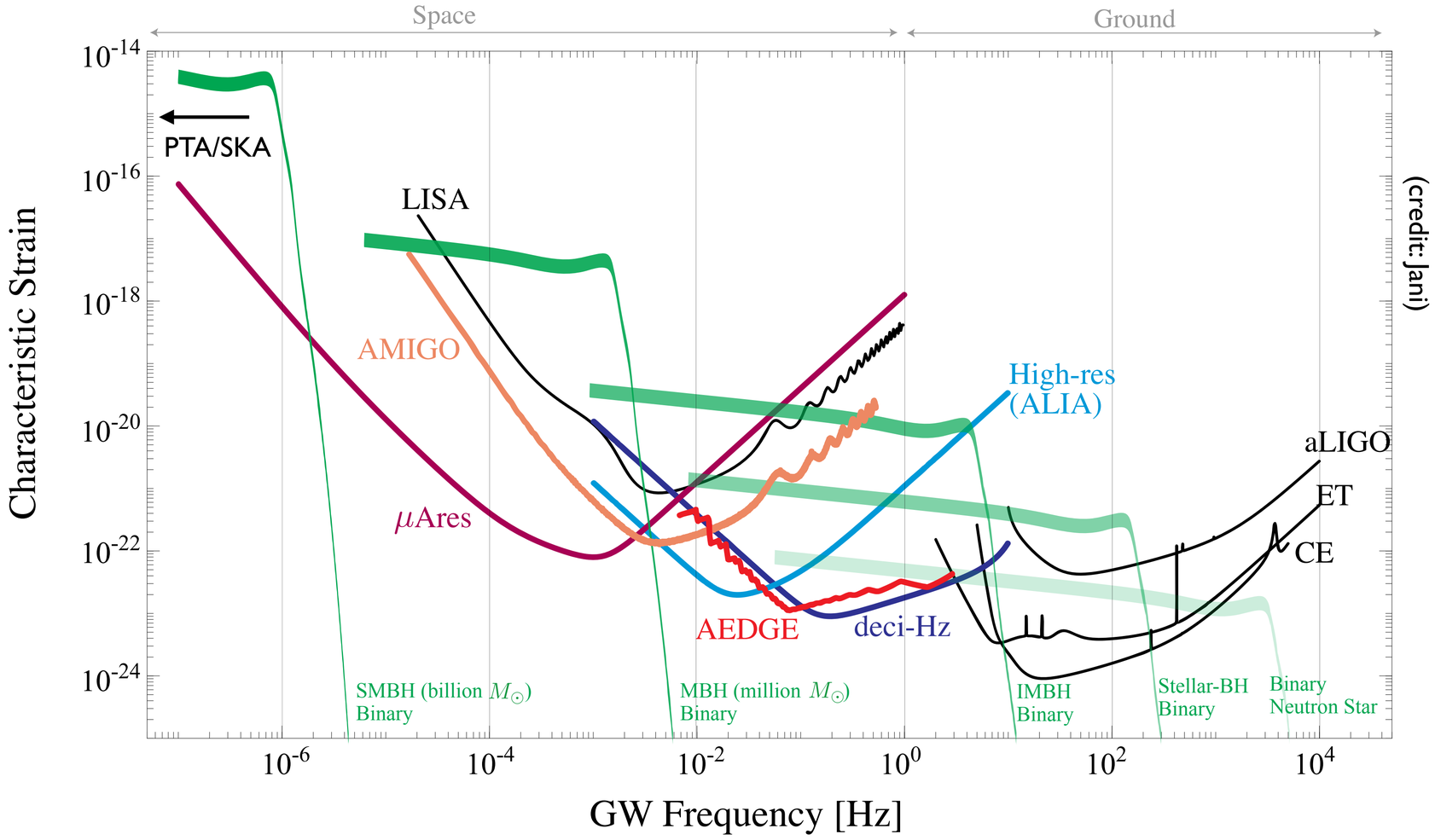


The GW Lanscape before Voyage 2050



The GW Landscape with Voyage 2050

- Opening **new GW frequency bands** will likely enable **discoveries of new sources**, as proven by EM astronomy, and also pursue **unprecedented science**



The Missing Link in GW Astronomy: Discoveries waiting in the decihertz range *(Berry)*

AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration in Space *(Buchmüller)*

High Angular-Resolution GW Astronomy *(Dvorkin)*

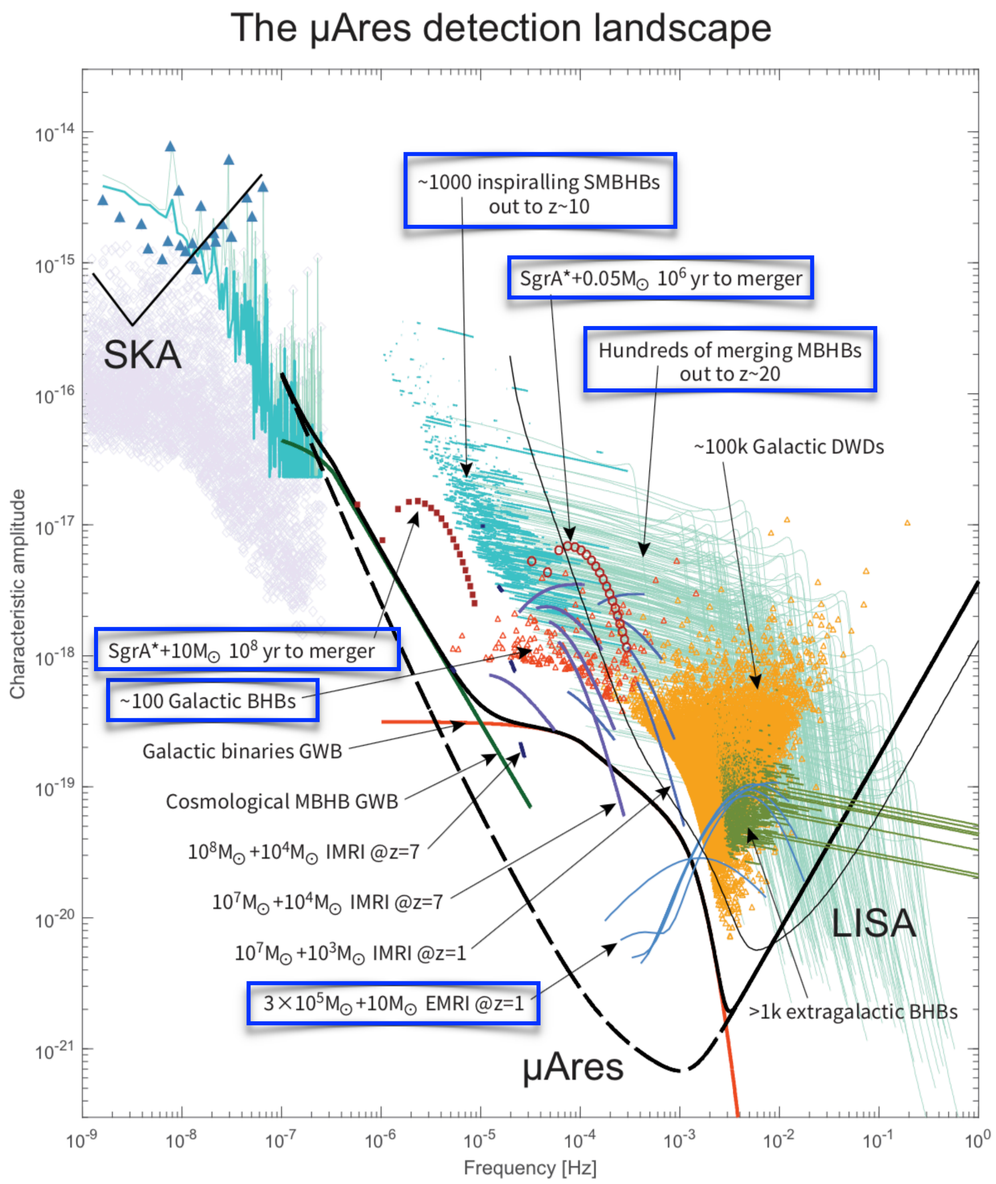
Probing the Nature of BHs: Deep in the mHz GW Sky *(Cardoso, Witzany)*

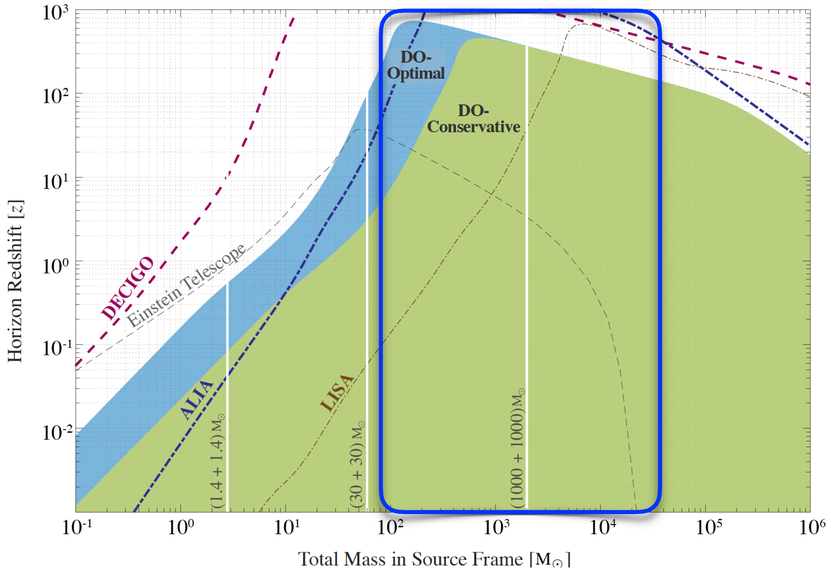
Unveiling the Gravitational Universe at μ-Hz Frequencies *(Sesana, Korsakova)*

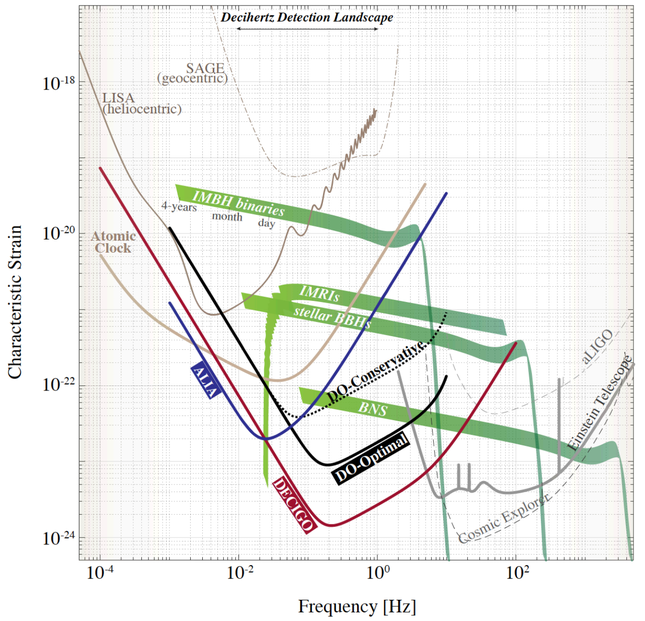
Theme 1. Physics and Astrophysics of Black Holes

- How **high-redshift quasars emerged**? How **mass assembly of first MBHs occurred**: accretion (EM observations) or merger (GW observations)?
- Nail down the **physics of MBHB dynamics** (or pairing), e.g., stellar hardening, gaseous drag, triplets
- Probe **formation and dynamics of IMBHs** in star clusters, galactic nuclei and nuclear-star clusters
- **Multi-band astronomy** (with ground-based detectors) with **stellar mass BHs** from cosmic down to the early Universe, measuring how **BH's properties change with redshift**
- Understanding **relativistic dynamics in dense nuclei** with **EMRIs**, and mapping MBH **spacetime with exquisite precision**
- Investigate **dynamics** of stars and **compact-objects** around **Sgr A*** in Milky Way
- Unveil **nature** of **compact objects**, **nature** of **gravity, BH spectroscopy** with **unprecedented precision**

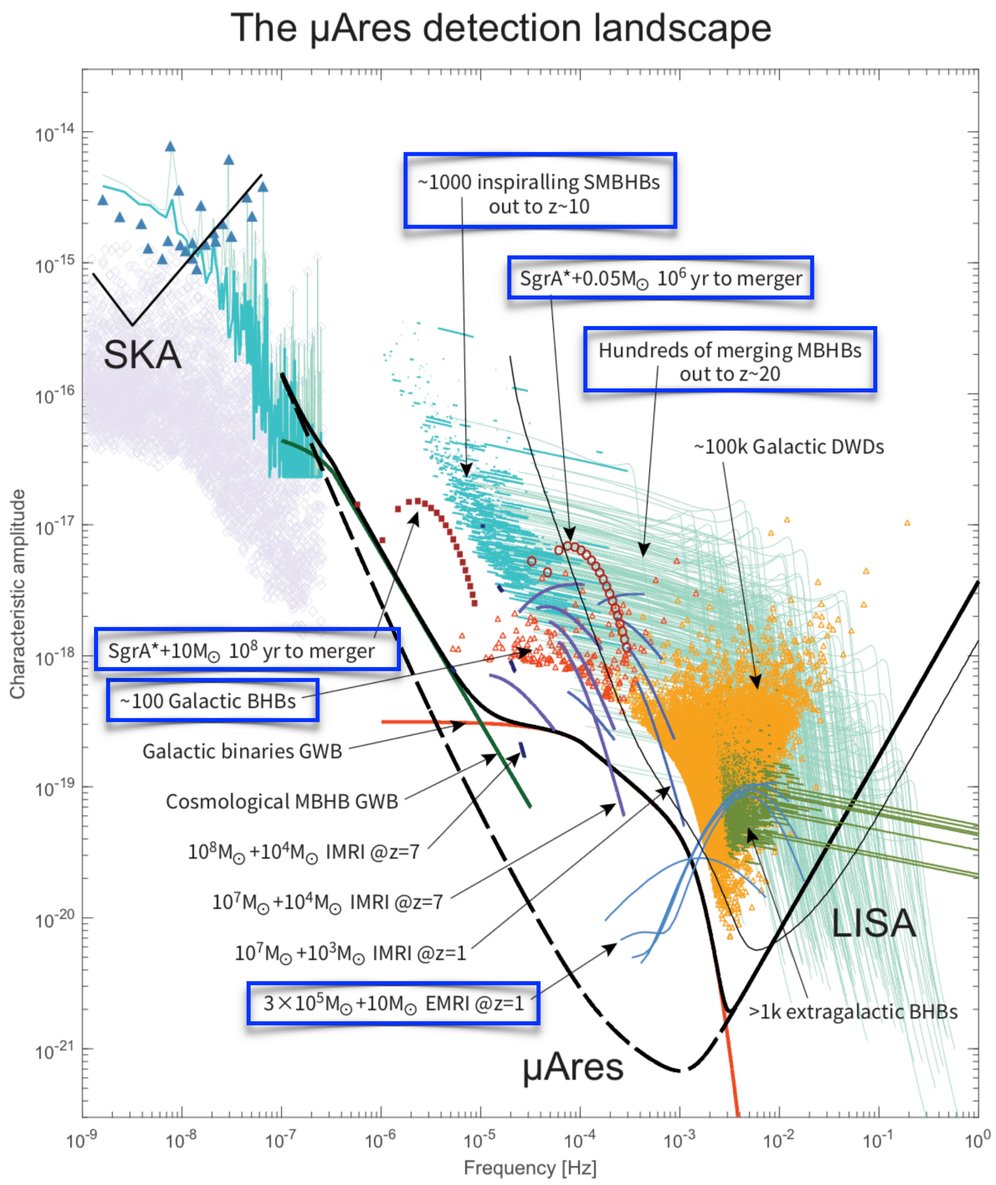
Theme I. Physics and Astrophysics of Black Holes (contd.)

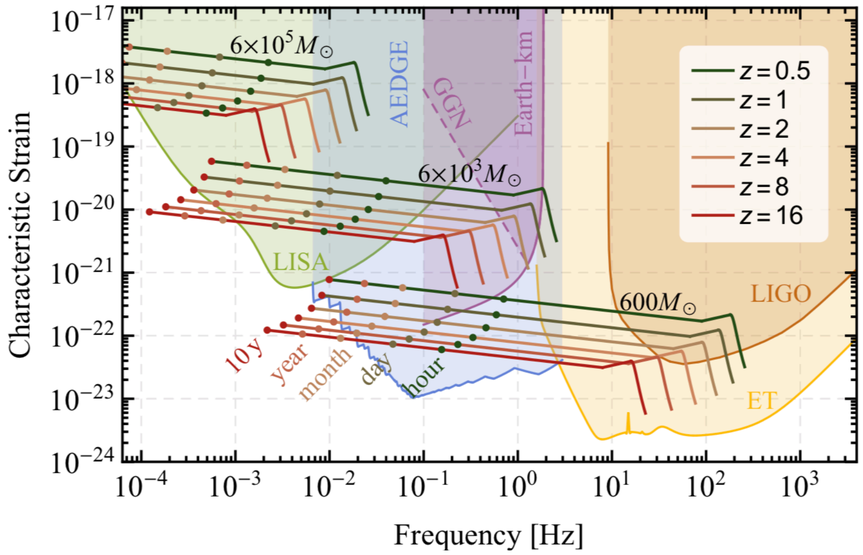


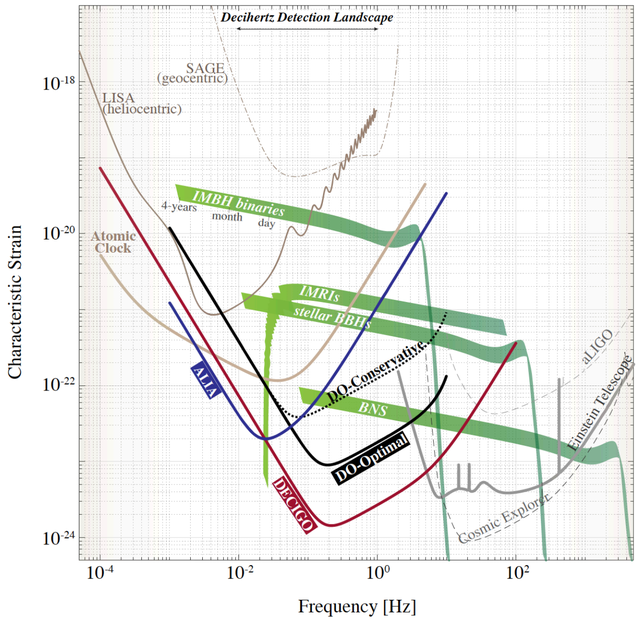




Theme I. Physics and Astrophysics of Black Holes (contd.)







Theme 2. Multi-Messenger Astronomy (GW, EM, Neutrinos, Cosmic Rays)

- Observe in **multiband** (with ground-based detectors) **BNS** and **NSBH binaries**: alert EM telescopes **months to years in advance** to identify and study the host galaxy

- Observe **double WD systems close to** their **point of initial contact**, allowing the observation of **GW signal** followed by a **type Ia supernova**

- Identify **EM signatures of inspiraling** (and **accreting**) **MBHBs** for all mission timescale, and identify **the *key* to search** for them in **AGN** spectra and lightcurves

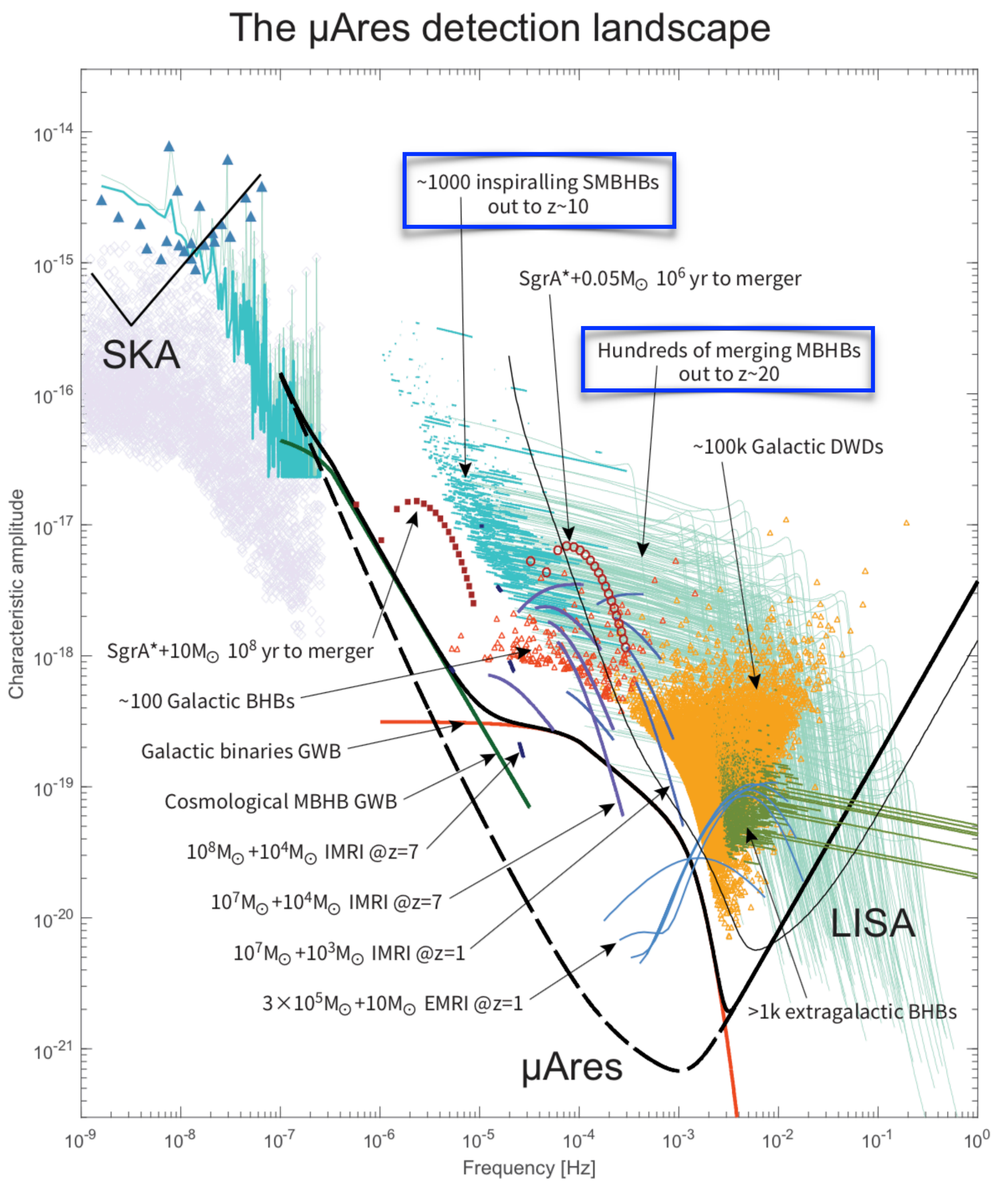
- Build large sample of MBHB **standard sirens out to** $z \sim 5$.

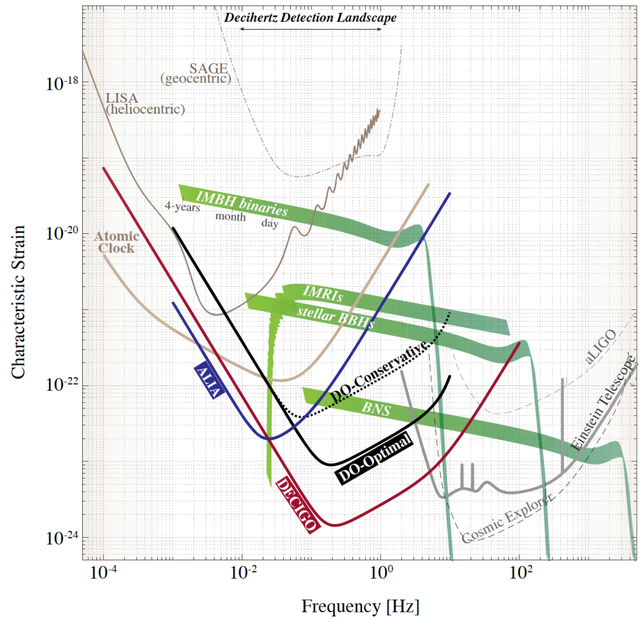
- With **arcmin angular resolution**, identify host galaxy and achieve **exquisite cosmography** with **BBHs and BNSs**

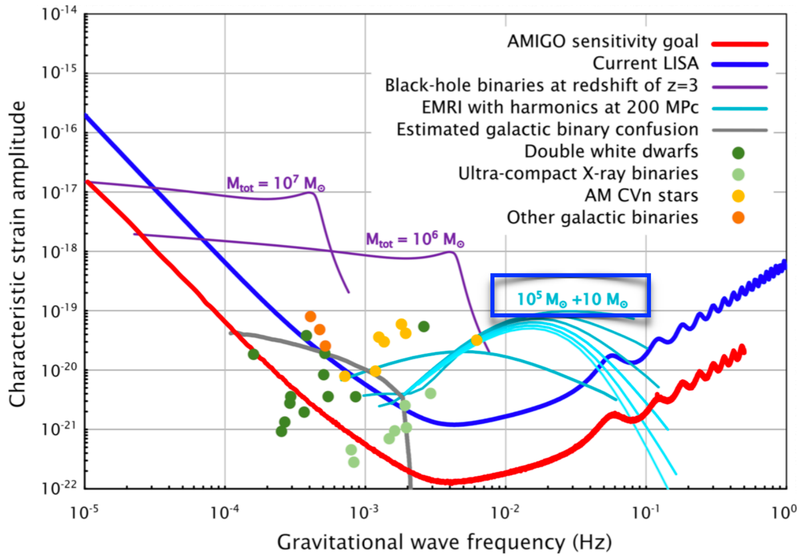
- Study **anisotropies** of **astrophysical stochastic GW backgrounds**, and then **correlate with EM backgrounds**

- **Correlate GW signals** with **cosmic rays** and **cosmic neutrinos** and shed light on **their origin**

Theme 2. Multi-Messenger Astronomy (GW, EM, Neutrinos, Cosmic Rays) (contd.)

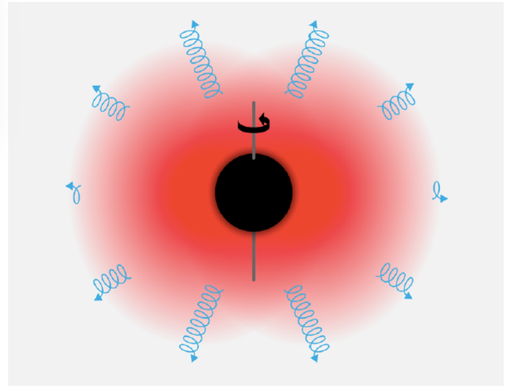






Theme 3. Physics Beyond Standard Model/General Relativity and Beyond

- Discover **ultralight particles, axions** forming ***clouds* around MBHBs** if their Compton wavelength is comparable to BH's size



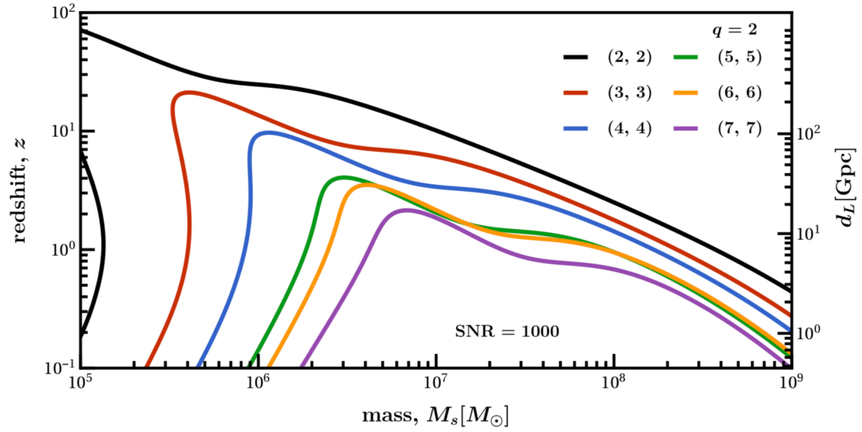
- Probe **dark-matter substructures** and the Universe expansion via **strong GW lensing**

- Observe **imprints of dark-matter** environment **on GW waveforms** from inspiriling MBHBs

- Probe **strong equivalence principle** with stellar-mass BHs, NSs and MBHs when **specific fields/couplings** are present in **gravity theories**

- Probe the Universe and gravity through **cosmological propagation of GWs** (speed, dispersion, diffraction)

- **Gravitational spectroscopy** with BBH collisions



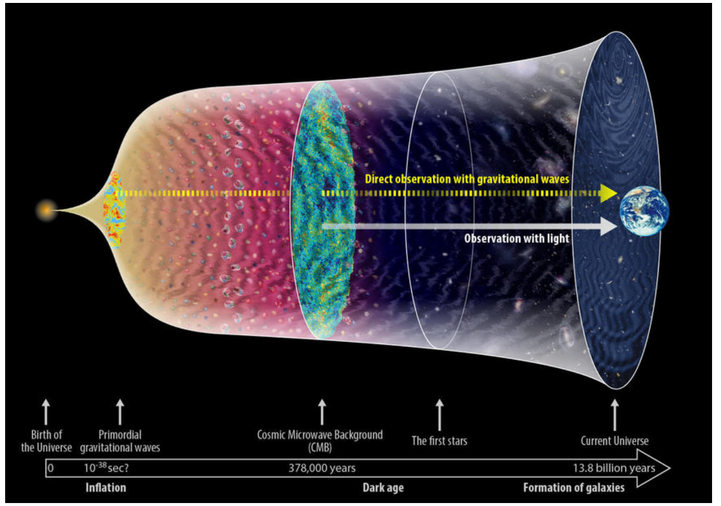
- Discover **particles/fields dominating** physical processes in **very early Universe**

Theme 4. Gravitational Waves and the Early Universe

- Open a **new window** into the Universe

- Probe **energies beyond accelerators** on the Earth

- Disclose **dark Universe beyond** the time **CMB** was produced



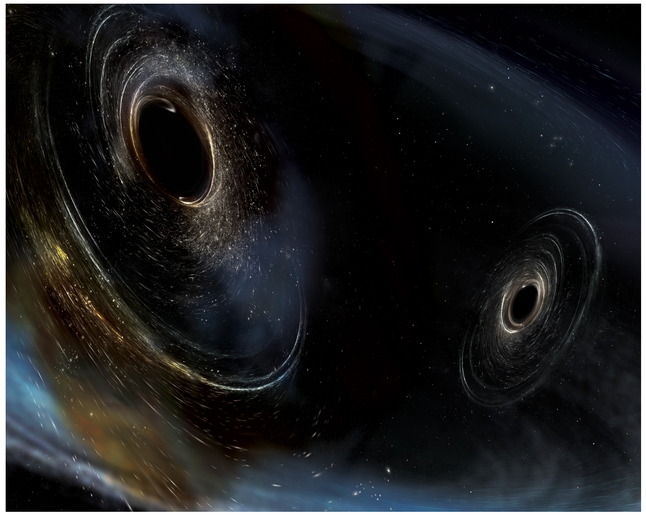
- Observe **stochastic GW background** from **inflation** (depending on **spectral tilt**), first-order **phase transitions** with **physics beyond standard model**, preheating, and **cosmic strings**.

- Discover **epochs, from end of inflation to BBN,** in which Universe was **dominated neither by vacuum energy nor** by **radiation** or **matter**

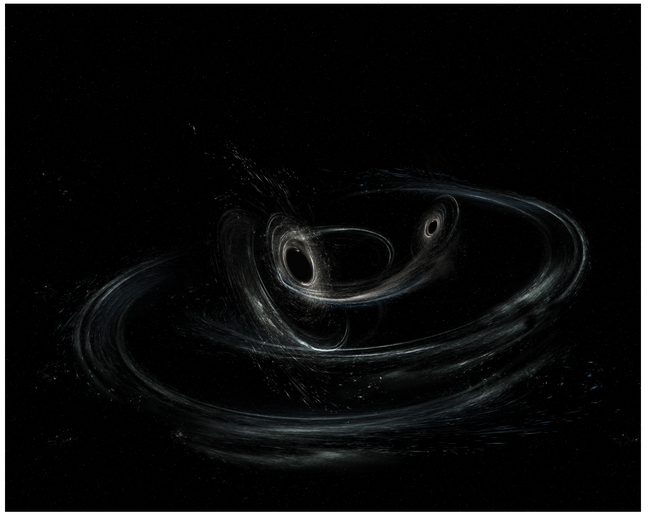
- Need to detect and remove ***all*** **BNSs, NSBHs** and **BBHs in our Universe** to achieve sensitivity to observe slow-roll inflation background

Final Remarks on the GW Universe and Voyage 2050

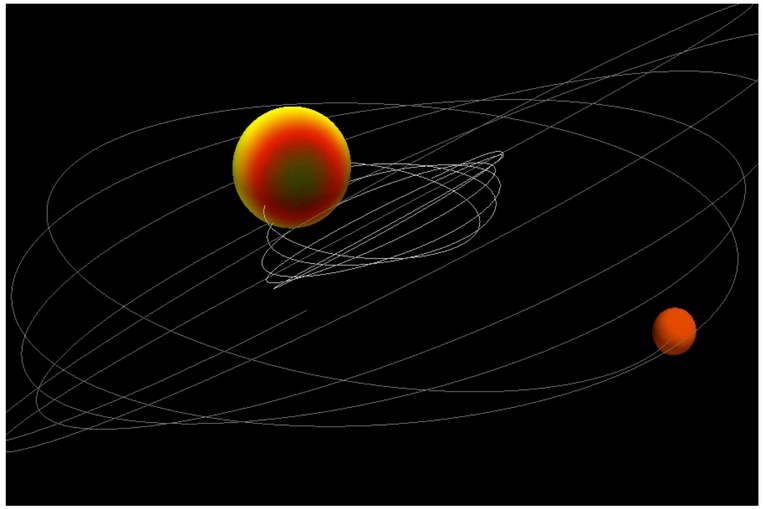
- The **GW tool** is **as essential as** the **EM tool.** Main question: which **outstanding science** do we want to address **after LISA?**
- The **GW Universe** spans sources **from** the **very early Universe to** the **Milky Way**, and a variety of **astrophysical**, **cosmological** and **fundamental physics phenomena**. It is also **the key player** in **multi-messenger astronomy**
- The **opening of new** frequency **bands** has always led to **remarkable, radical discoveries**, as witnessed in EM astronomy



(credit: Simonnet, Sonoma State U)



(credit: Simonnet, Sonoma State U)



(credit: Fraser/Pfeiffer, CITA)