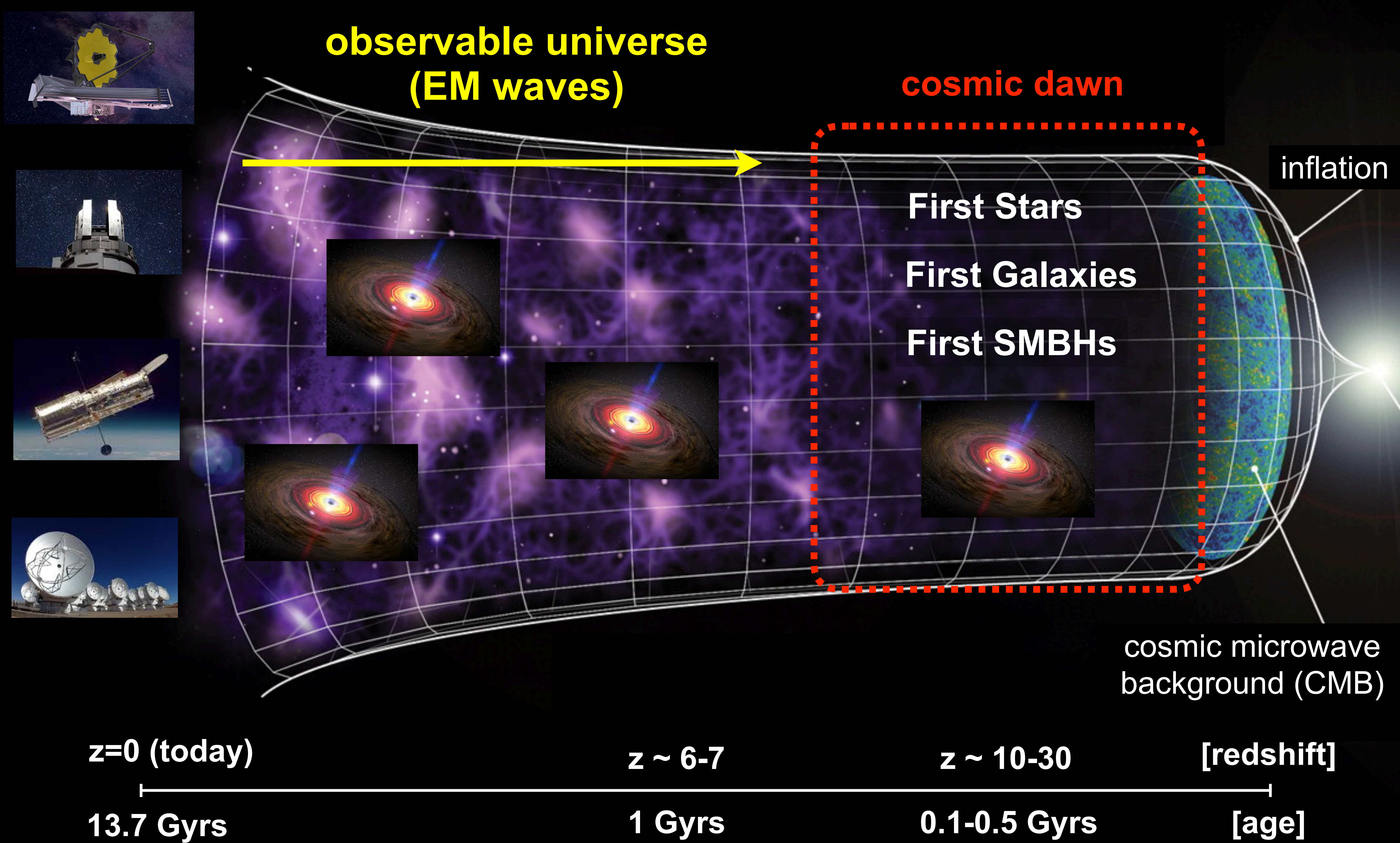
電磁波・重力波観測で探る
ブラックホール天文学

稲吉恒平 (北京大, KIAA)

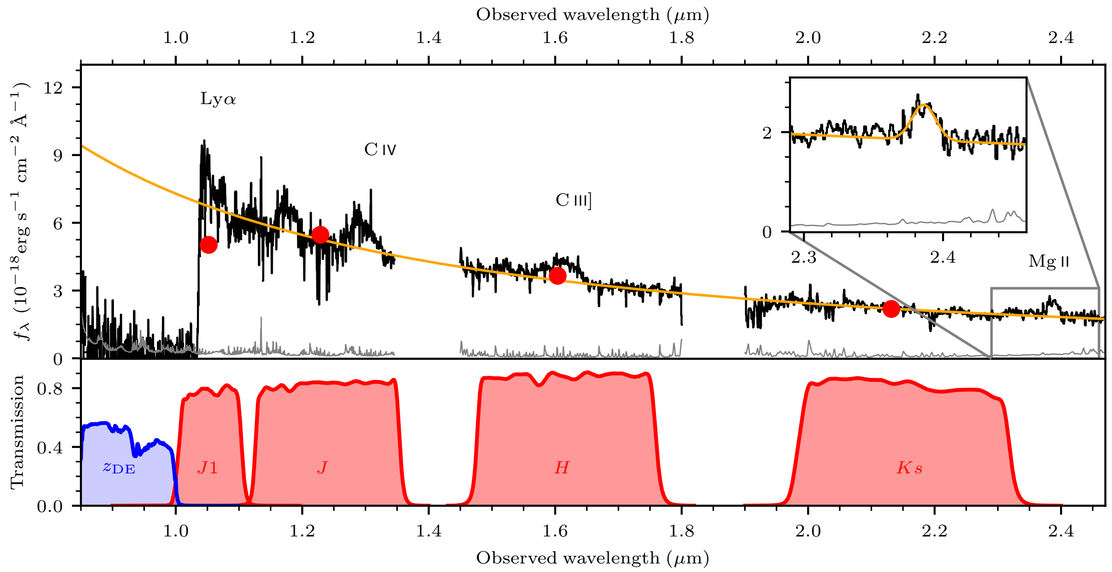
14-15th November 2022 @2040年代のスペース天文学研究会

Exploration of the early universe (~2020s)

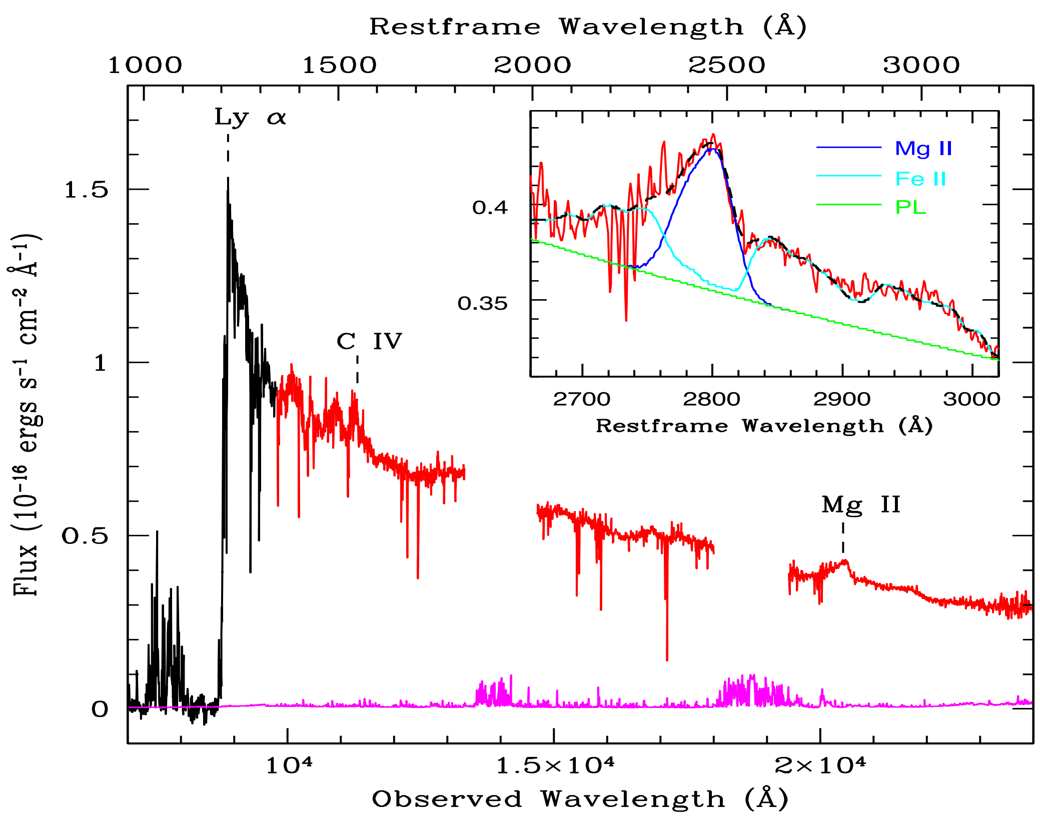


High-z monsters

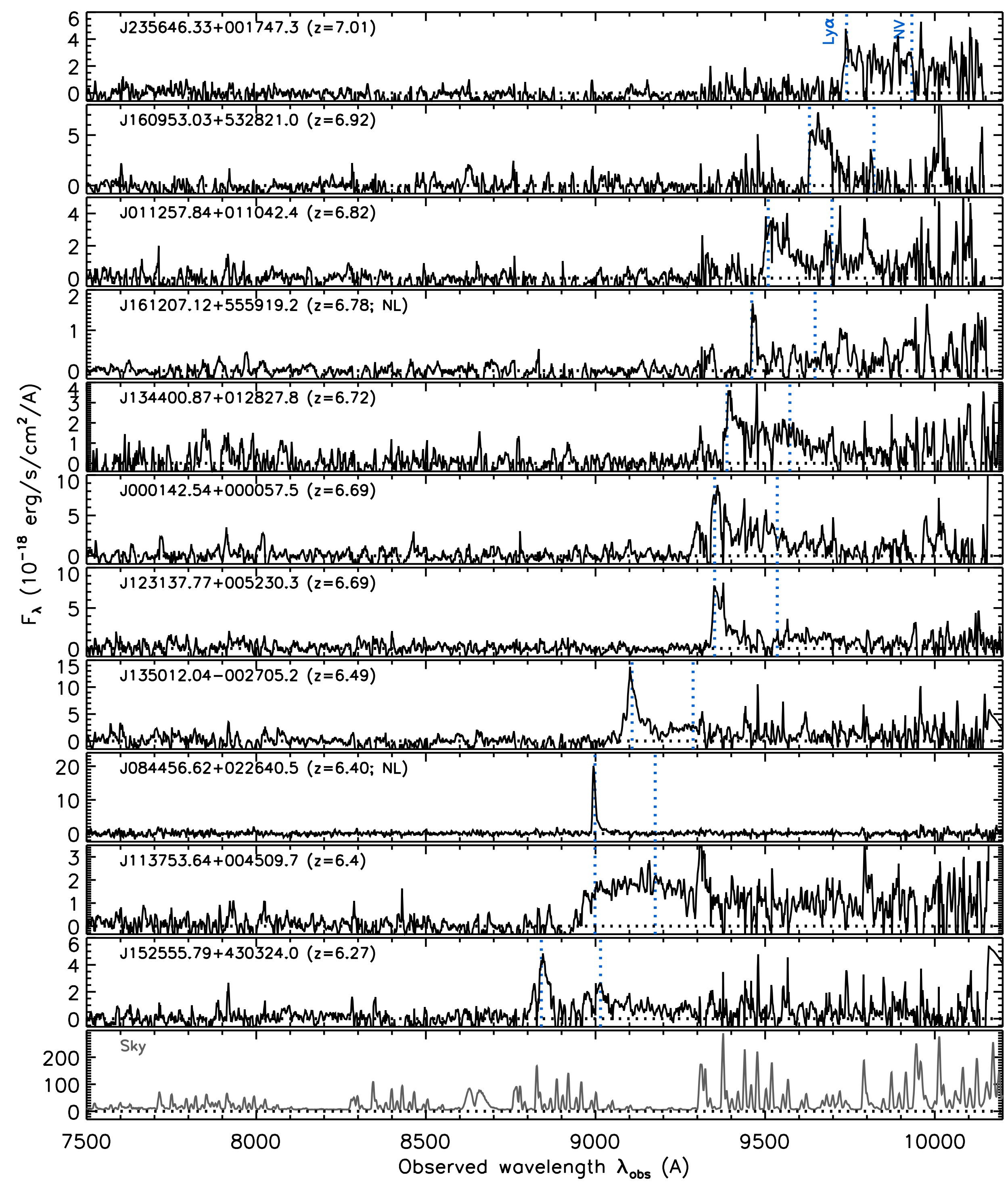
Most distant z=7.54 Banados et al. (2017)



Most massive $M=10^{10}M_{sun}$ Wu et al. (2015)

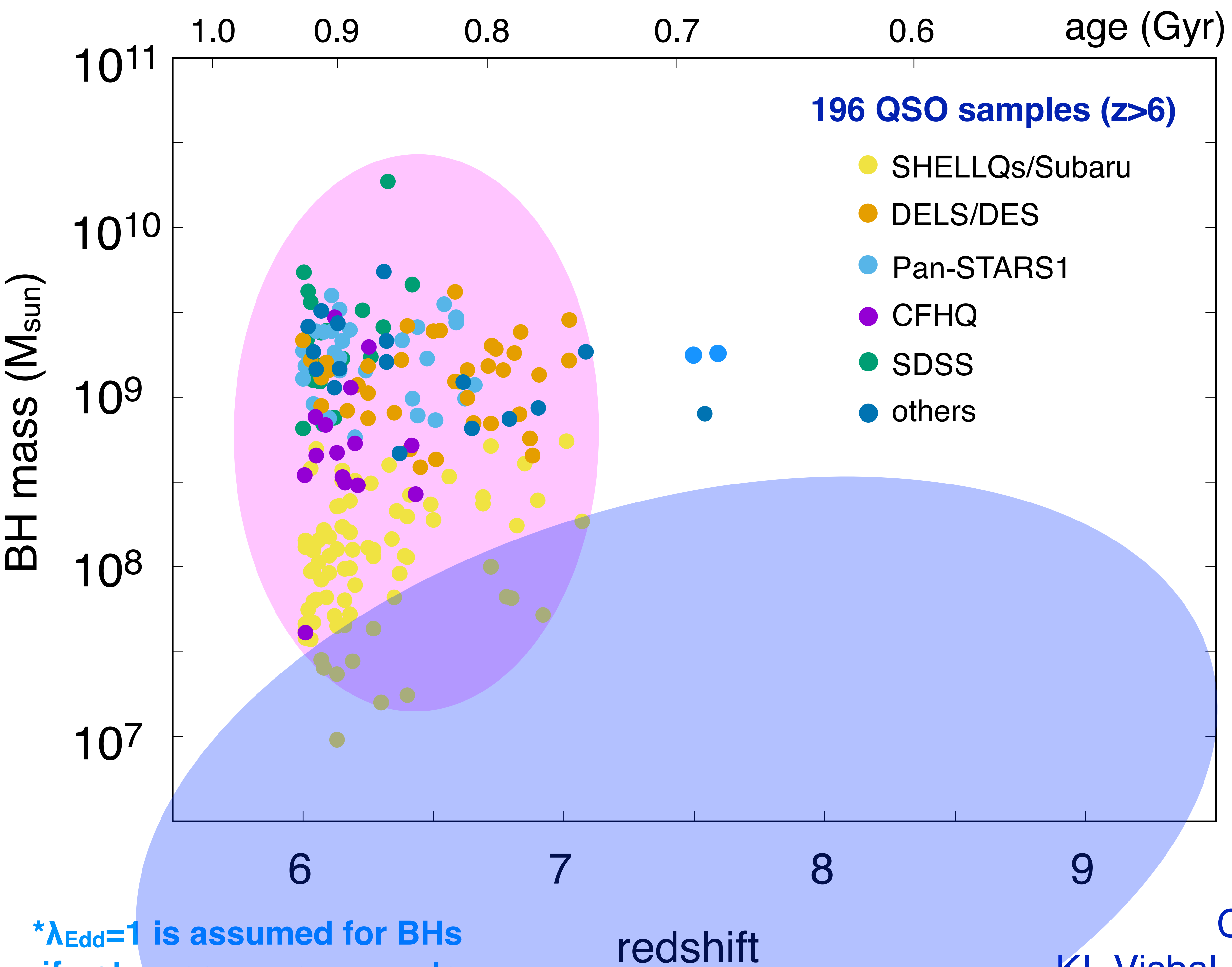


Subaru HSC, SHELLQs (Matsuoka et al. 2019)

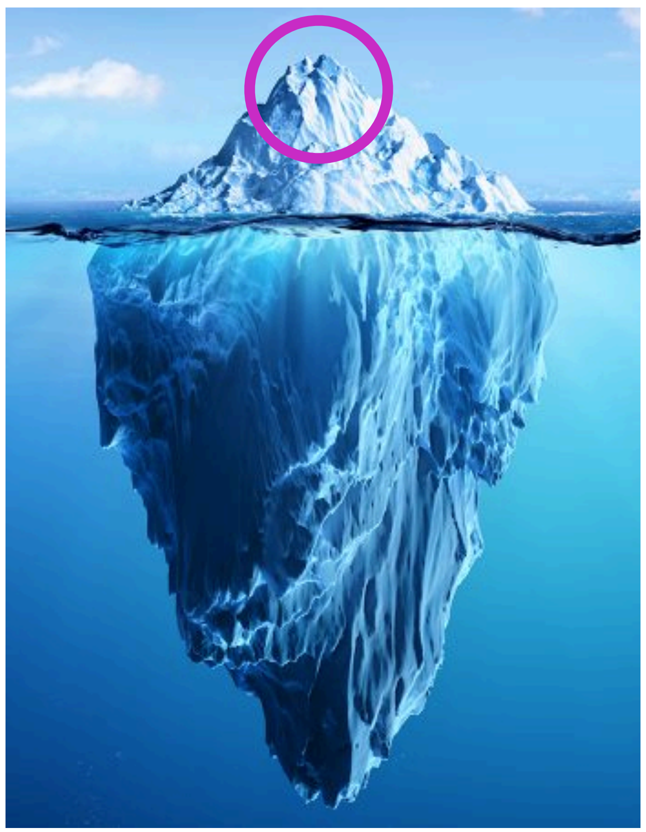


High-z SMBH populations

Note: 9 QSOs were found at z>6 before 2006… (X.Fan)



Tips of iceberg

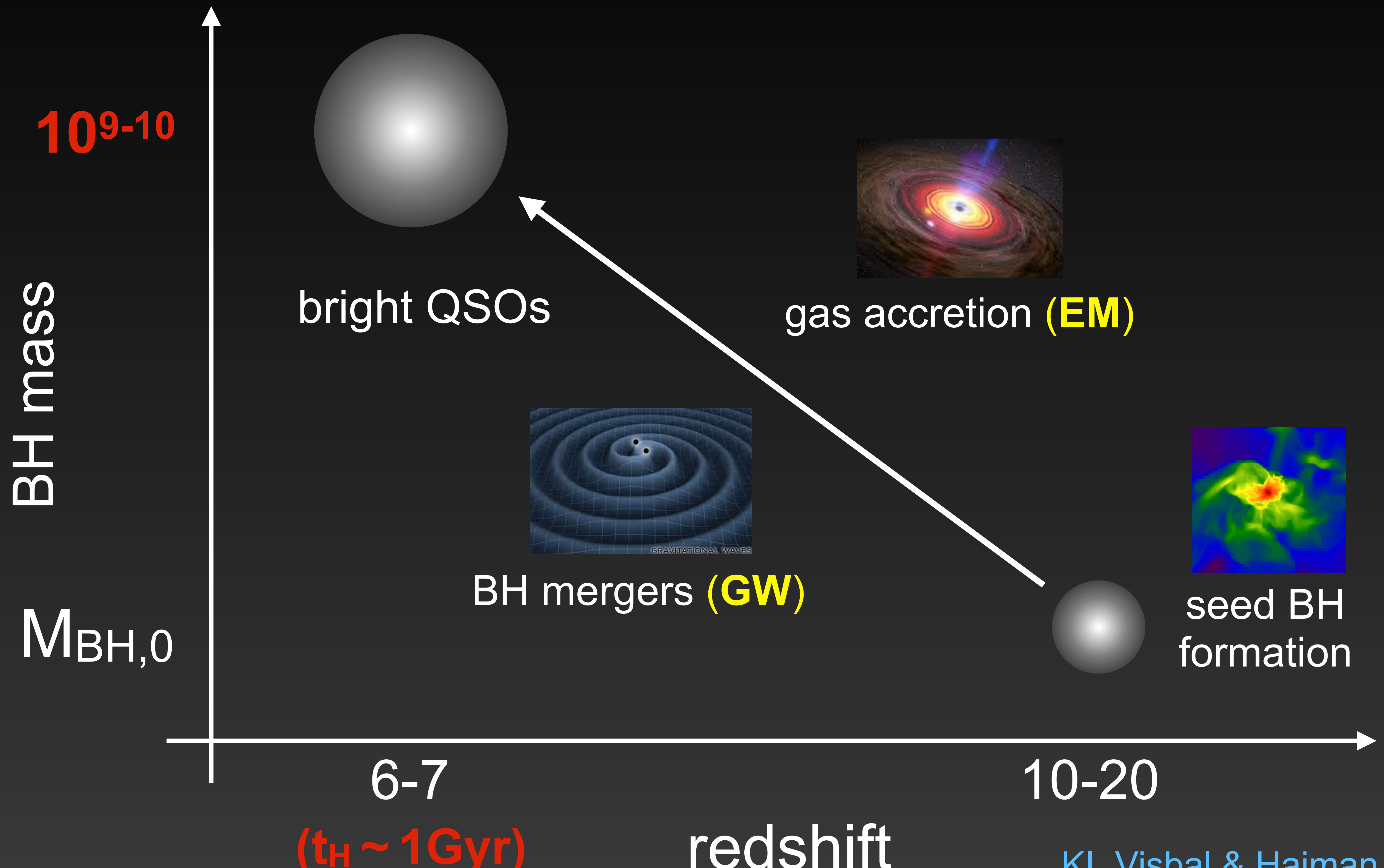


Underlying / dominant BH population

*$\lambda_{Edd}=1$ is assumed for BHs if not mass measurements

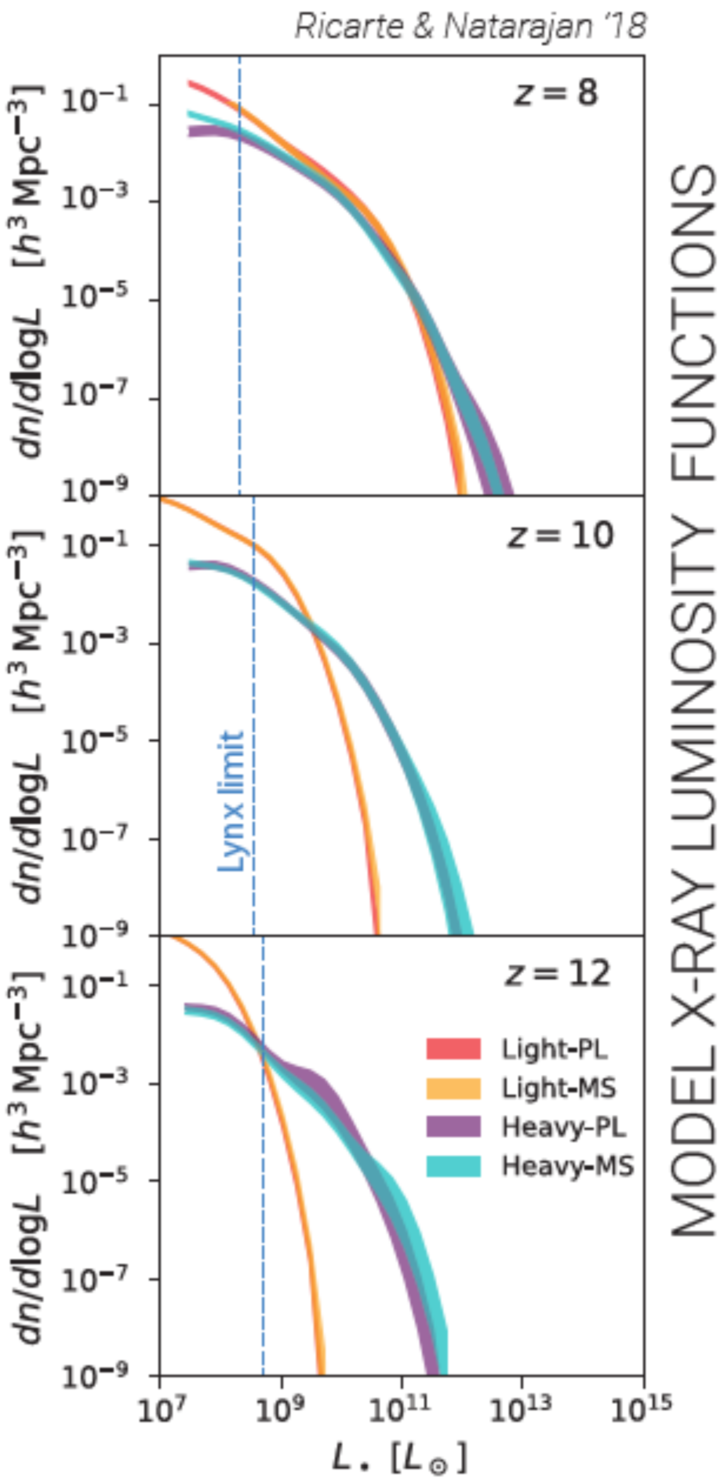
Compilation from KI, Visbal & Haiman (2020), ARA&A

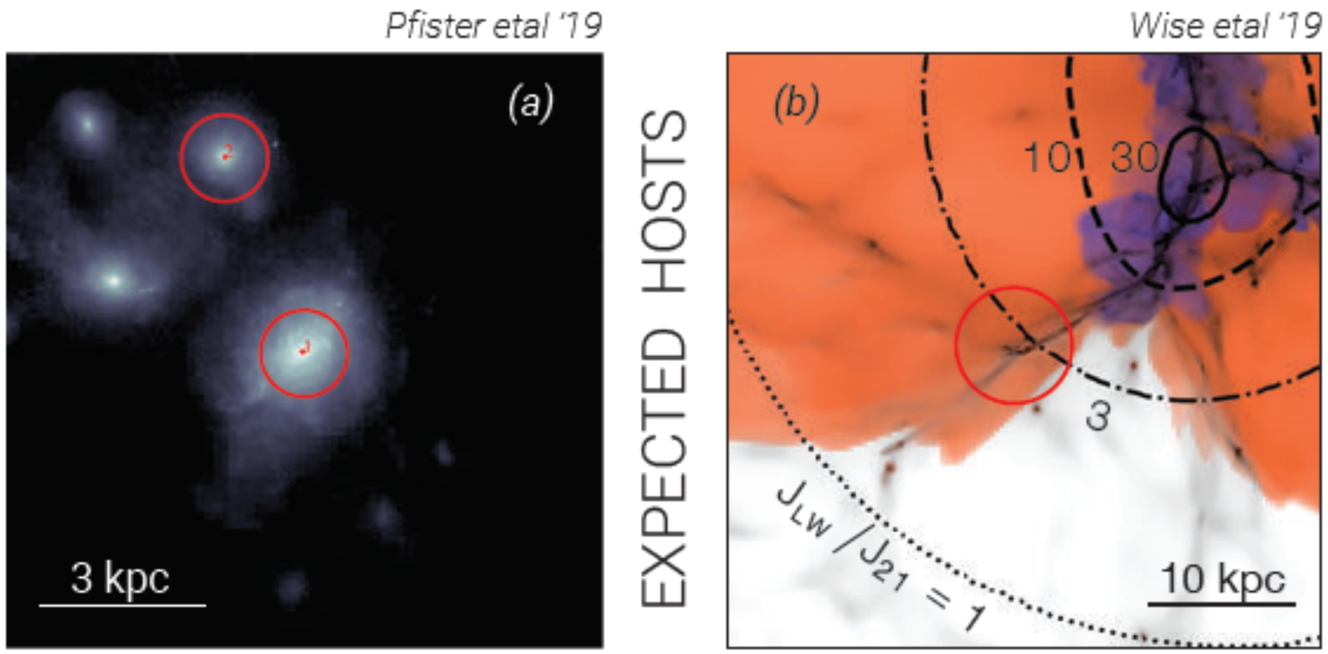
Assembly of massive BHs



KI, Visbal & Haiman, 2020, ARA&A, 58, 27

EM windows into the early BHs



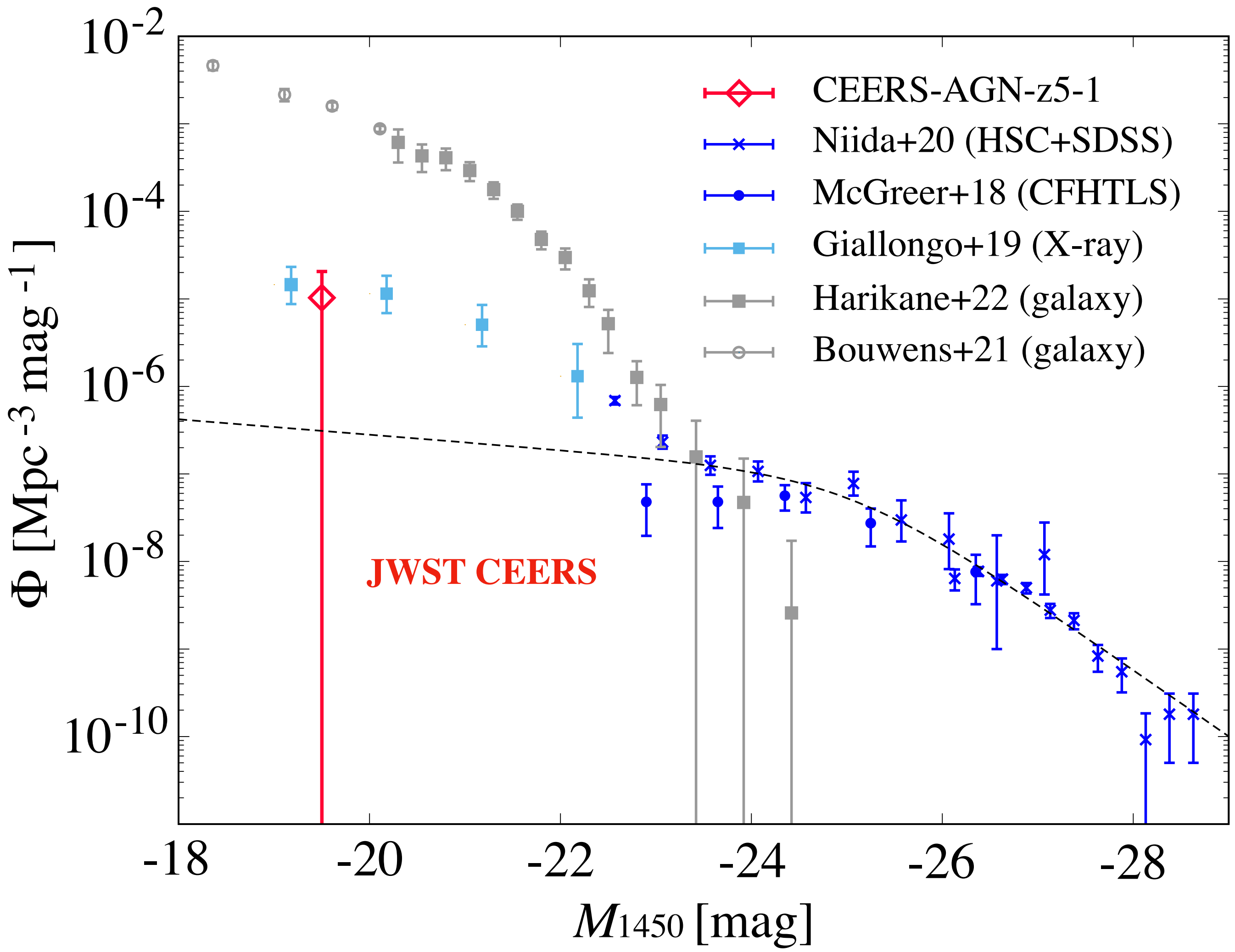


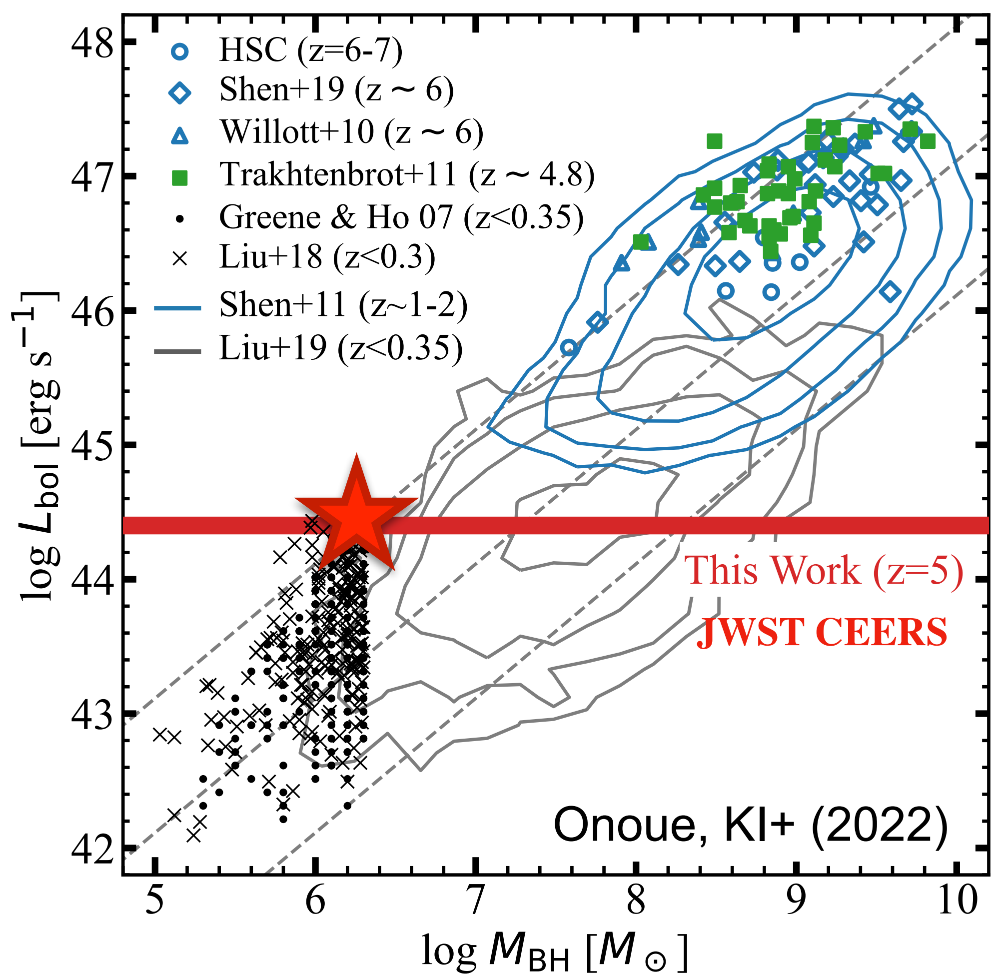
Key questions :

1. Origins of SMBHs (seed model)
2. Early coevolution of SMBH with galaxies
3. Synergy between deep X-ray and IR/opt imaging surveys and spectroscopy

Haiman+ KI (2021), Astro 2020

Demographics of SMBH populations

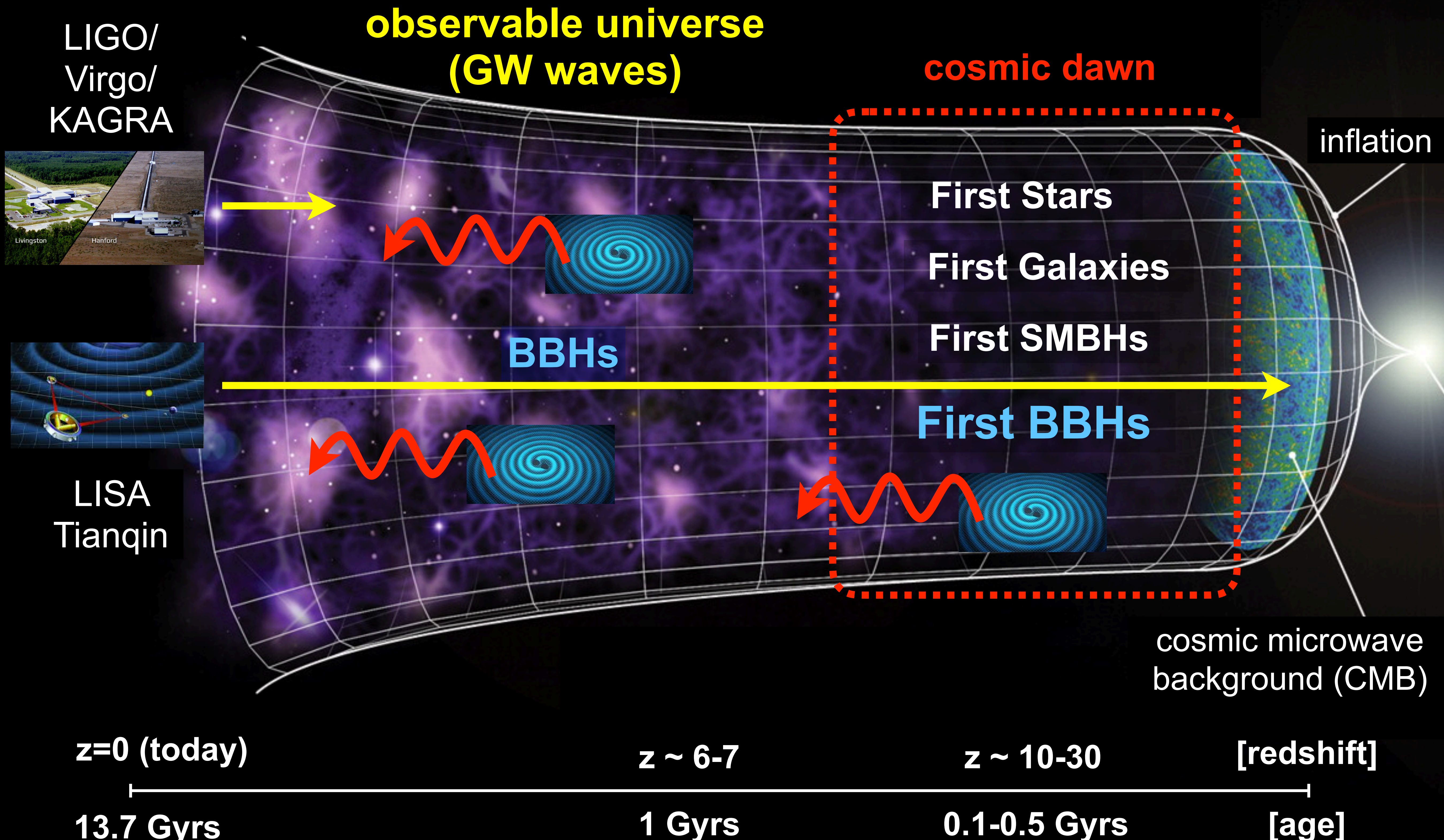




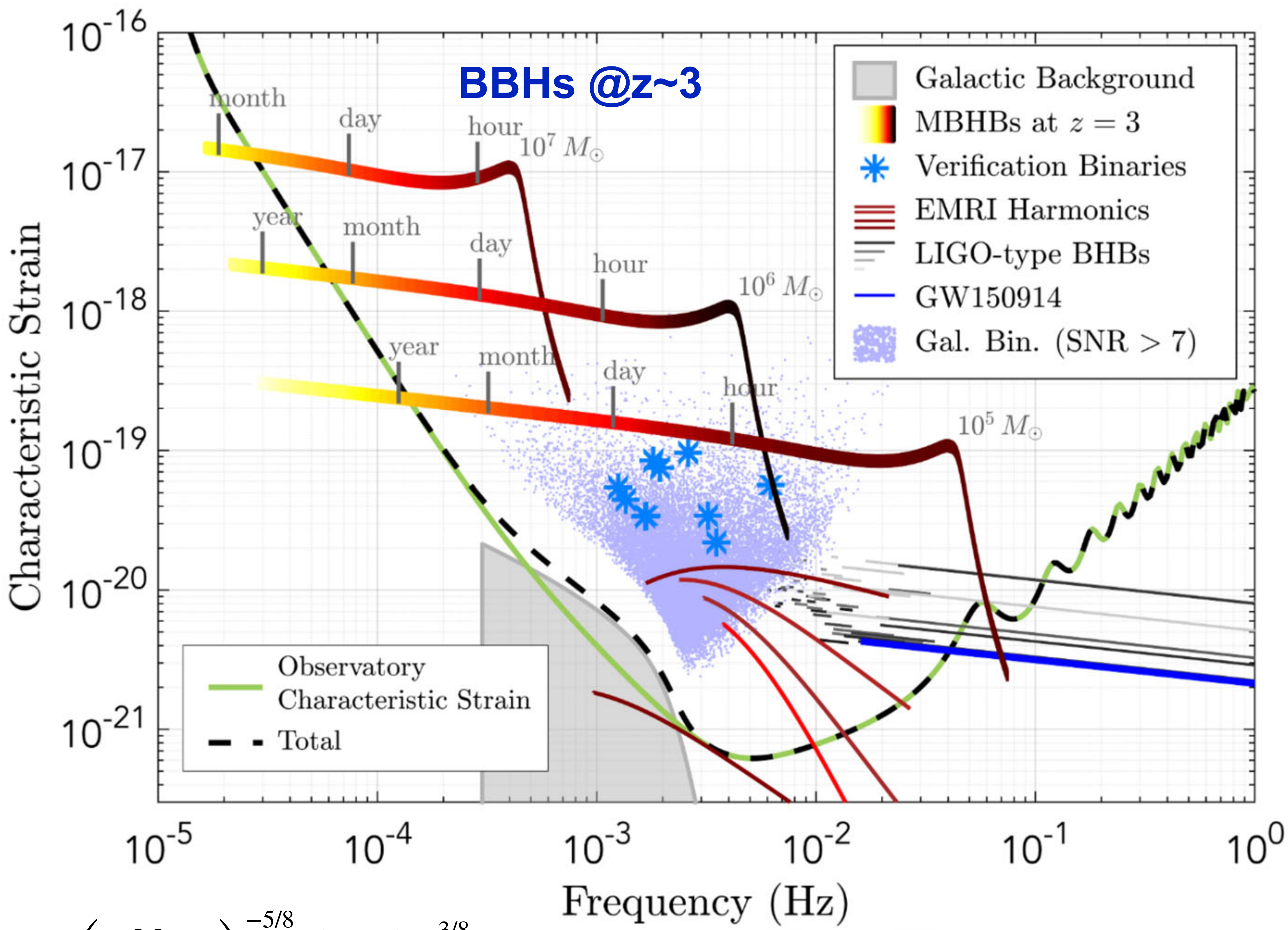
Key prospects :

1. More discoveries (wide-field surveys): LSST, Euclid, RST, Lynx, etc.
2. More identification & BH mass estimate: JWST-like, NIR-spec
3. Host galaxies & environments: JWST, LUVOIR, ALMA, ngVLA, etc.

Exploration of the early universe (~2040s)



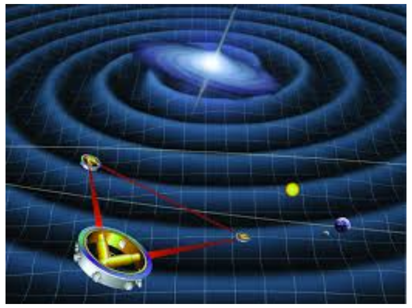
Low-frequency GWs from IMBHs

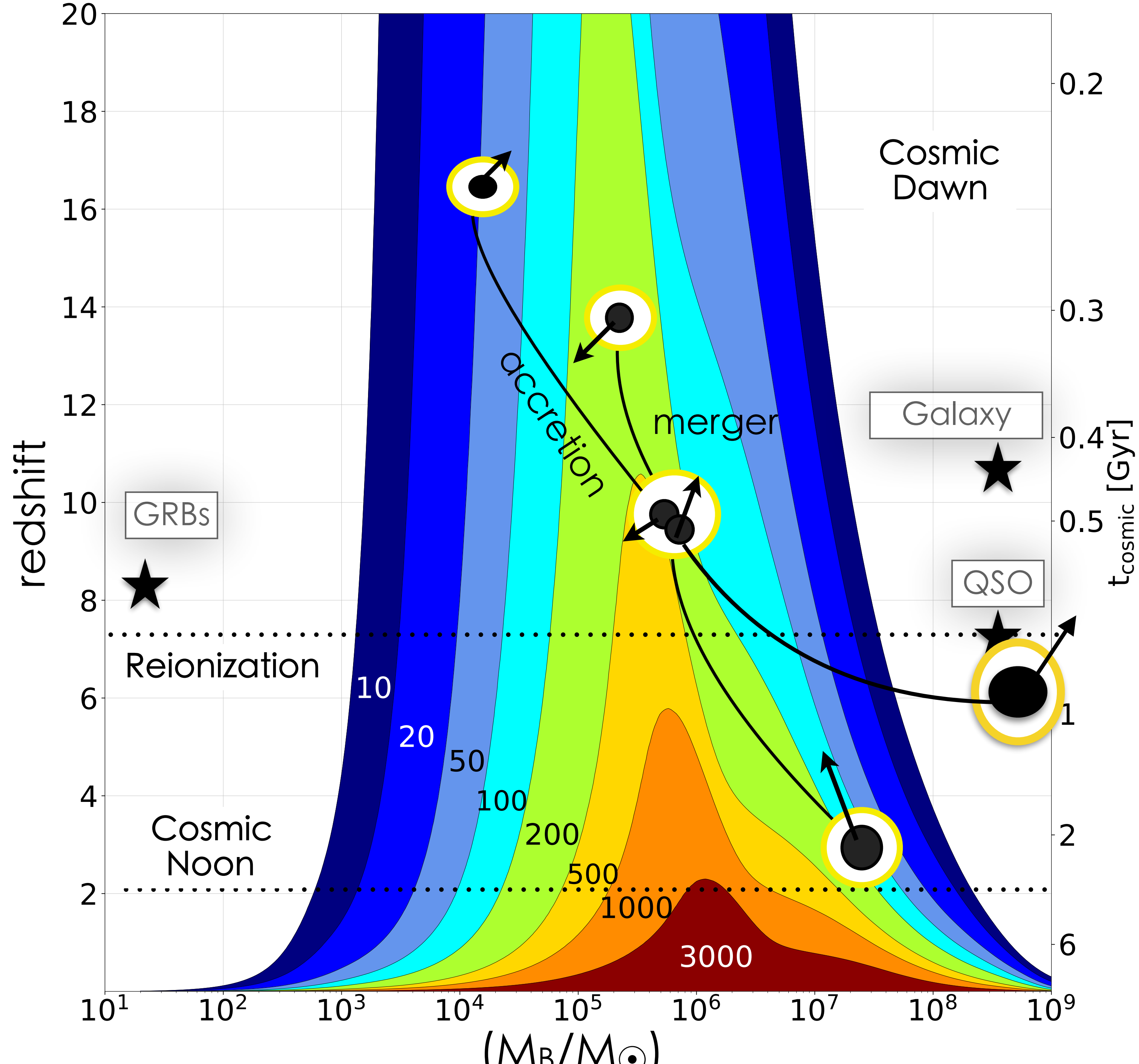


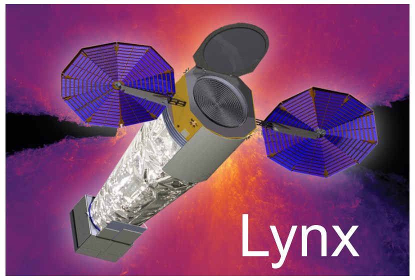
$$f_{\rm gw} \simeq 0.02\ {\rm mHz} \left(\frac{M_{\rm c,z}}{10^6\ M_\odot}\right)^{-5/8} \left(\frac{\tau}{5\ {\rm yr}}\right)^{-3/8}$$

Amaro-Seoane et al. (2017)

Synergy btw EM & GW observations


LISA/Tianqin

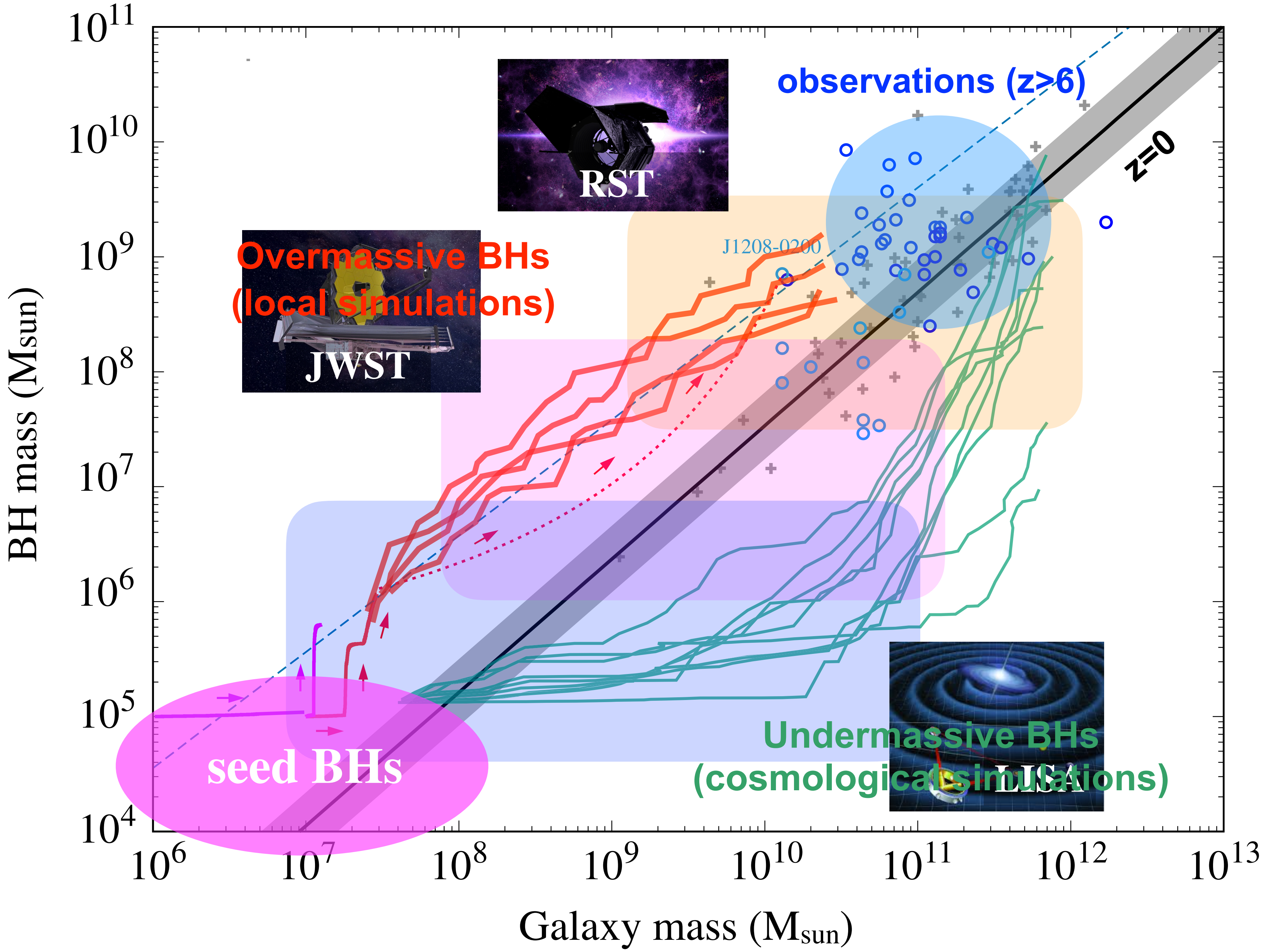




and more…

Colpi et al. (2021), Astro2020

Overmassive vs. undermassive scenarios

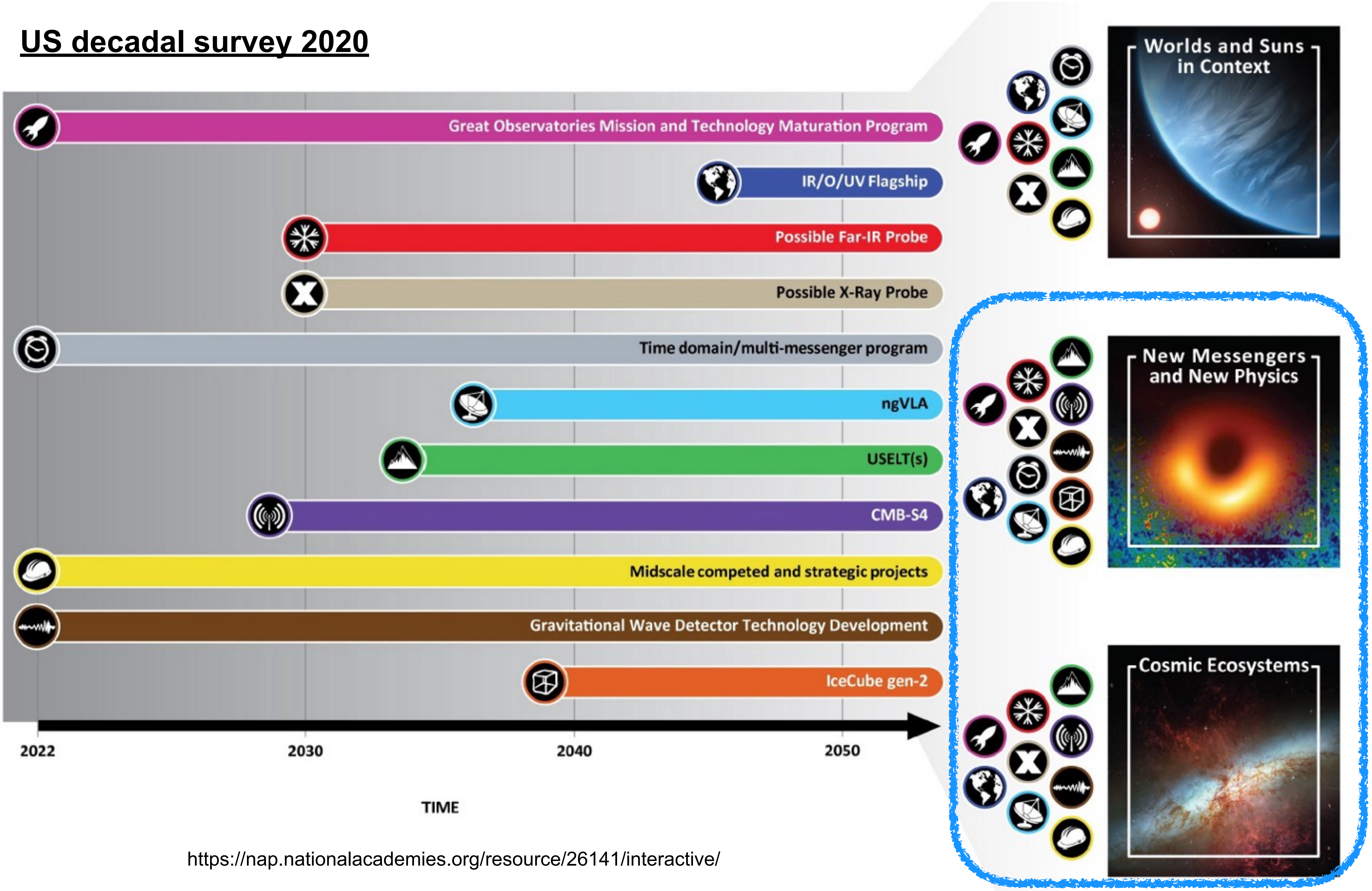


Observations: Wang+ (2010, 2013), Pensabene+ (2020), Izumi+ (2019, 2021)

Simulations: Valentini+(2021), Inayoshi+ (2022a), Hu+ (2022b), Habouzit+ (2022), Zhu+ (2022)

Timeline toward 2040s

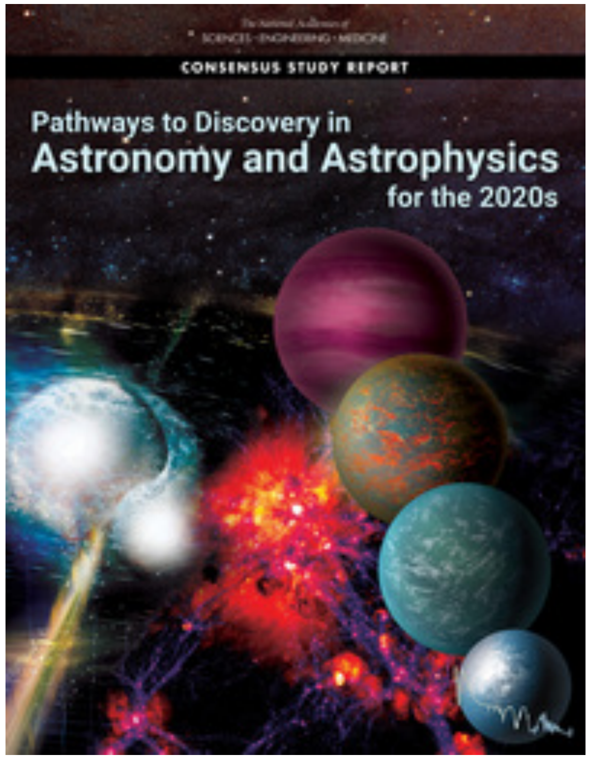
US decadal survey 2020



https://nap.nationalacademies.org/resource/26141/interactive/

High-z: Scientific goals in 2030-2040s

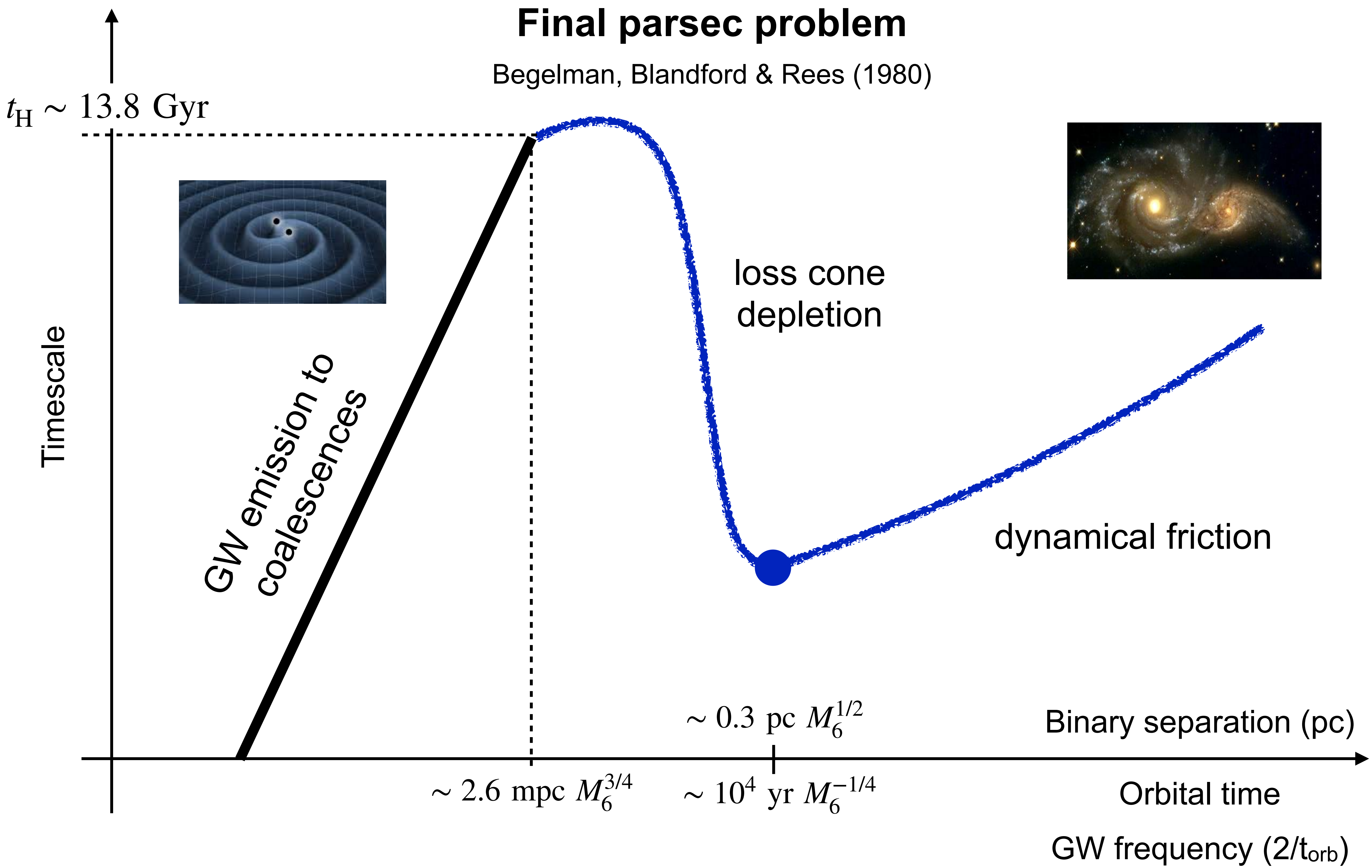
- Unveiling the Drivers of Galaxy Growth
  - discoveries of the first stars / galaxies / BHs
  - origin of SMBHs (seed) & QLF + BHMF
  - early coevolution of BHs with galaxies
  - cosmic dawn / reionization



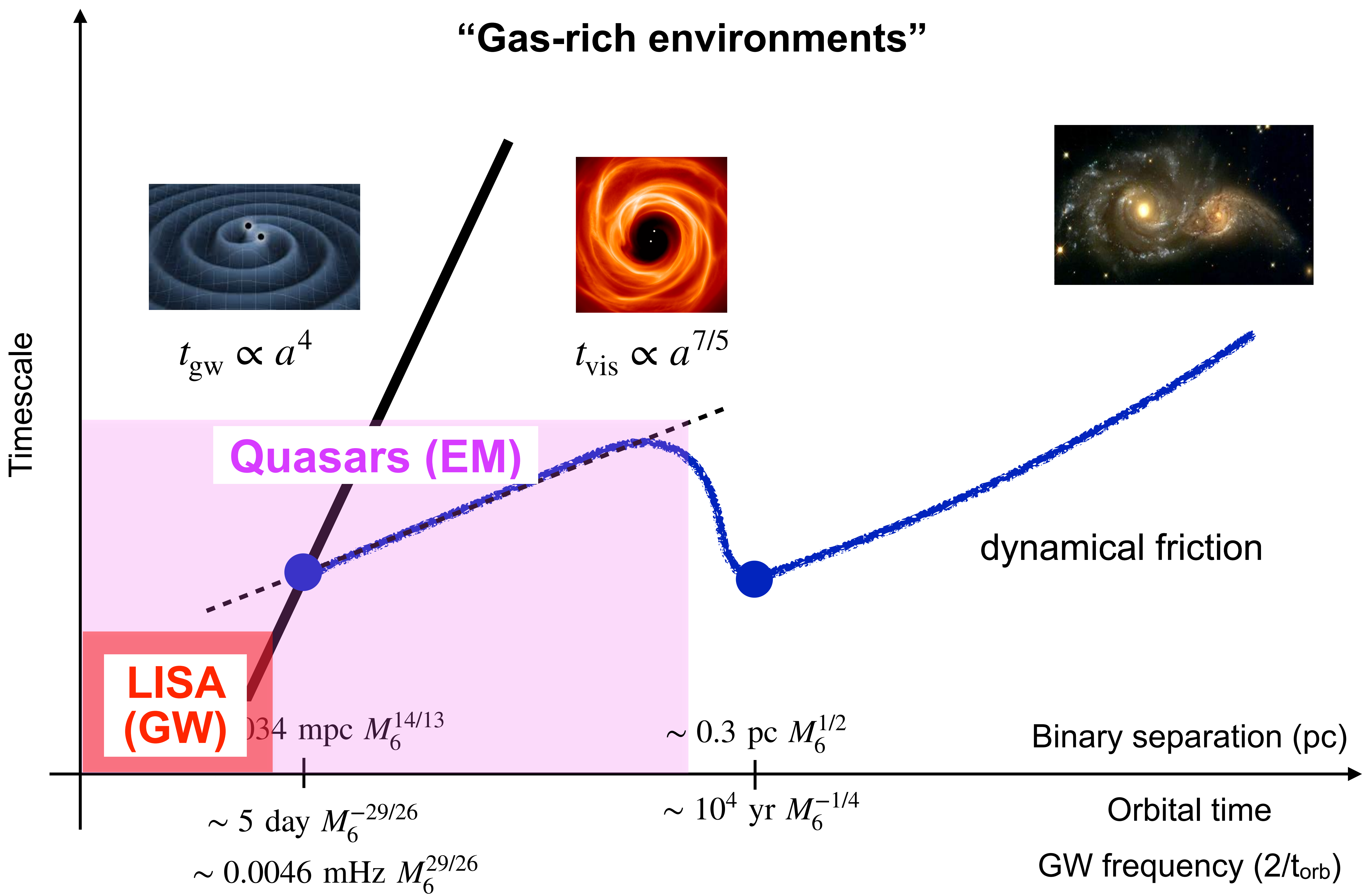
- New Windows on the Dynamic Universe
  - "true" multi-messenger astronomy
  - dynamical and radiative processes of astrophysical objects (binary BHs) in strong gravity

Good & fun research topics for young researchers

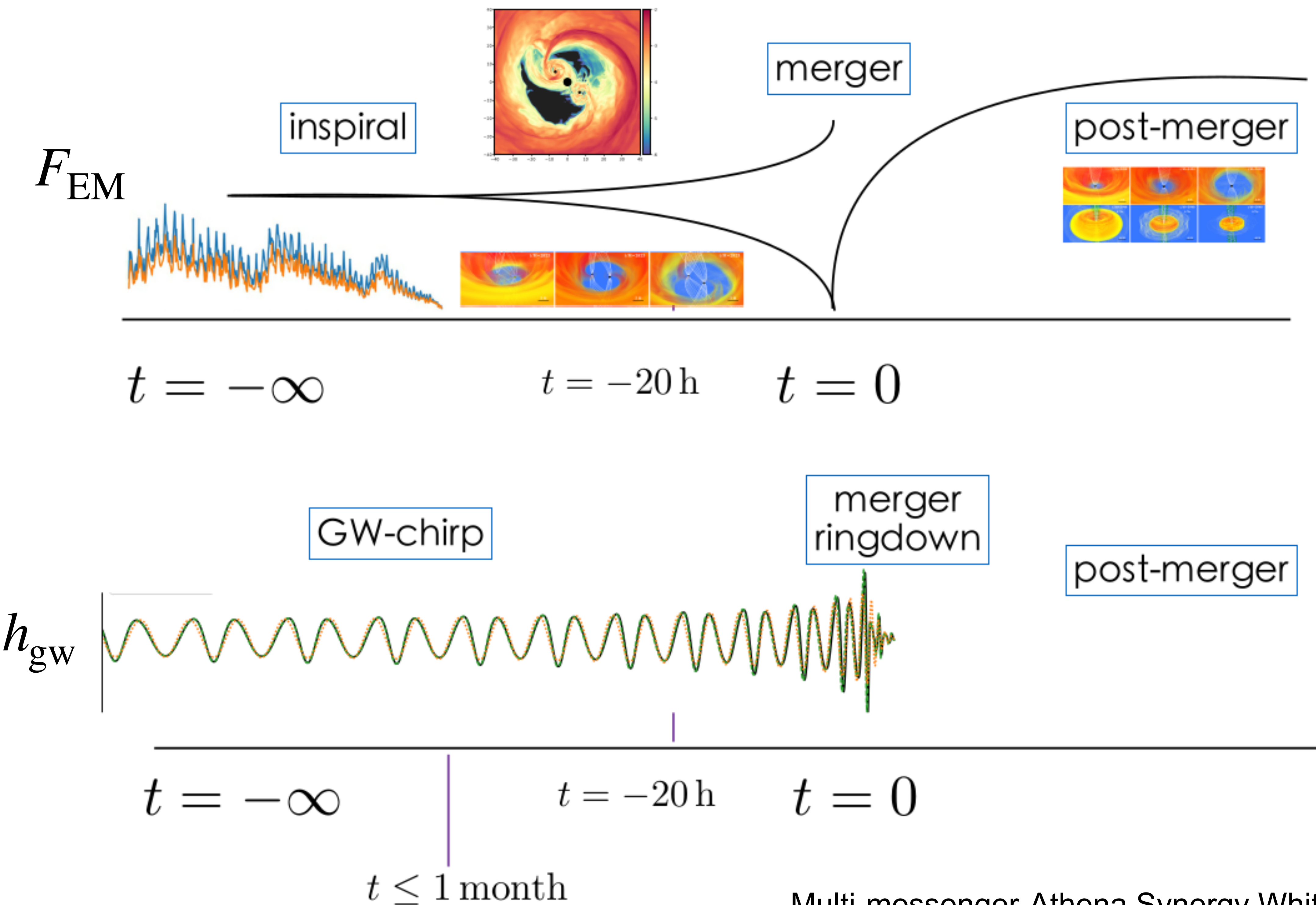
A long way to BH coalescences

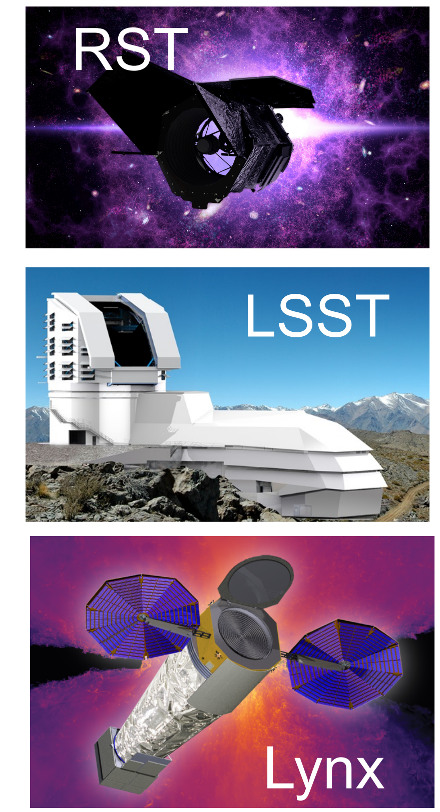


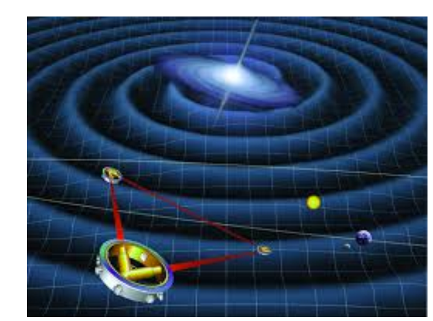
A long way to BH coalescences



Coincident detections of EM & GWs







LISA/Tianqin

Multi-messenger-Athena Synergy White Paper
arXiv: 2110.15677

Conditions for coincident EM+GW

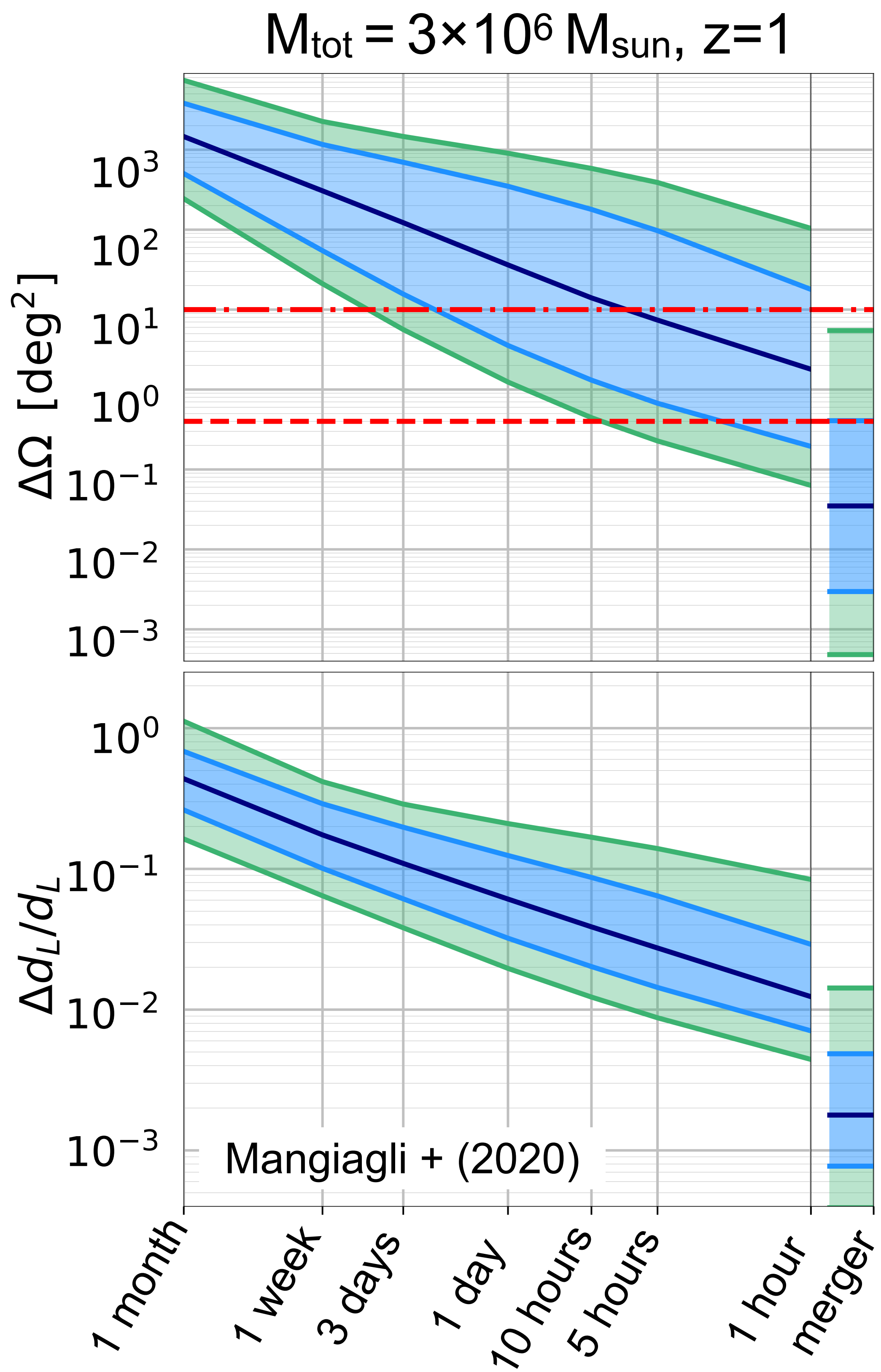
1. Massive BBHs at ~O(mpc) separations have t_{orb} ~O(yrs), making associated EM variability accessible on human time

2. Ultra-compact BBHs ~O(100 R_g) separations are going to merge within the operation time of LISA/Tianqin ~O(yrs)

3. Sky localization of the sources with GW observations should be done with a good accuracy (~10 deg^2 or better) prior to their coalescences / in post-merger phases

* NOTE: LVK GW sources would be generally followed up via EM telescopes in the post-merger stages. However, LISA sources would be found via EM observations ~ months - hours before their mergers.

Sky localization of GWs



For a BBH with $M_{tot} = 3\times10^6\ M_{sun}$

$\Delta\Omega$ = 10 deg^2 (LSST):

T_{gw} < 3 days (z=1)

T_{gw} < 5 hours (z=3)

$\Delta\Omega$ = 0.3-0.4 deg^2 (RST/Lynx):

T_{gw} < 3 hours (z=1)

post-merger (z=3)

* the accuracy of advanced localization depends on the orientation of the orbital plane, mass ratio, spin magnitude and direction, and sky position

QSO numbers

- chance to find ultra-compact BBHs: $f_{\rm duty} \sim 10 \text{ yr}/10 \text{ Myr} \sim O(10^{-6})$

better sky localization

i	0.5	1.5	2.5	3.5	4.5	5.5	6.5	Total
16	666	597	254	36	0	0	0	1550
17	4140	4630	1850	400	54	0	0	11100
18	19600	28600	10700	1980	321	19	0	61200
19	68200	131000	53600	8760	1230	115	0	263000
20	162000	372000	194000	35000	4290	441	1	767000
21	275000	693000	453000	113000	14000	1380	34	1550000
22	336000	1040000	756000	269000	41200	3990	157	2450000
23	193000	1440000	1060000	476000	103000	10900	527	3280000
24	0	1370000	1360000	687000	205000	27400	1520	3660000
25	0	314000	1540000	888000	331000	60800	4100	3140000
26	0	0	279000	760000	358000	86800	7460	1490000
Total	1060000	5390000	5720000	3240000	1060000	192000	13800	16700000

Table 10.2: Predicted Number of AGN in 20,000 deg^2 over $15.7 < i < 26.3$ and $0.3 < z < 6.7$ with $M_i \leq -20$. The ranges in each bin are $\Delta i = 1$ and $\Delta z_{em} = 1$, except in the first and last bins where they are 0.8 and 0.7, respectively.

LSST Science Collaboration (arXiv: 0912.0201)

EM signatures

This is an open question, but periodicity would be a key…

See Bogdanović et al. (2022) LRR, 25, 3

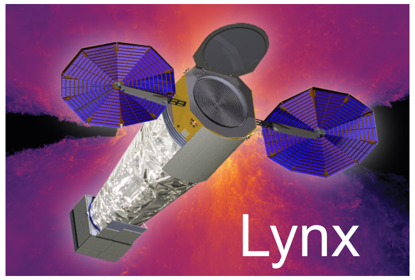
EM signatures (e.g., X-ray)

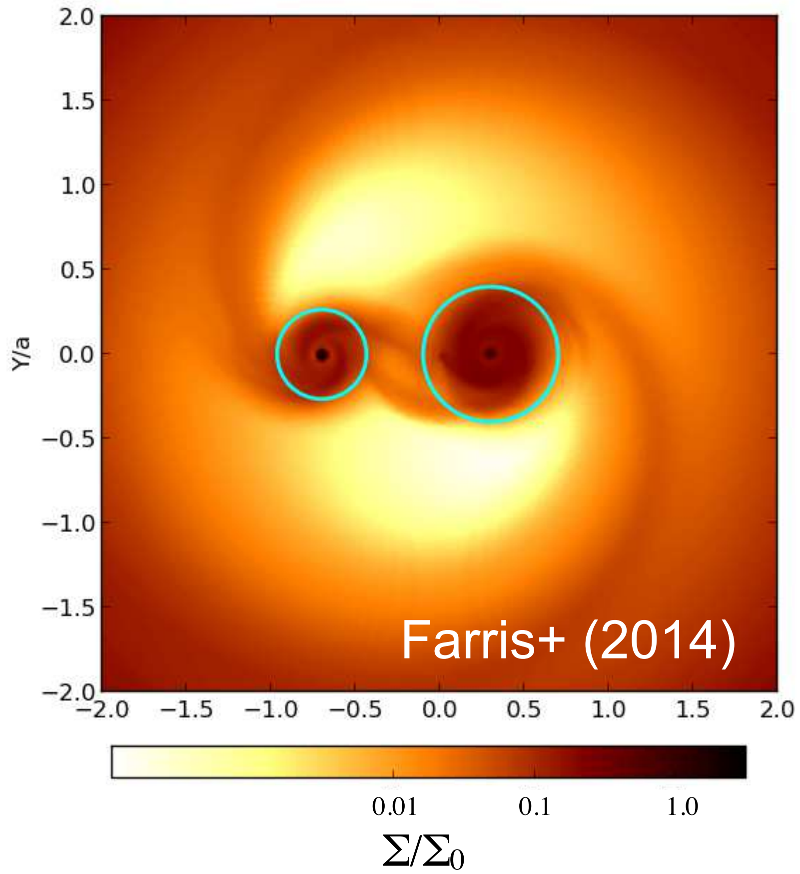
- X-rays ; mini-disks around individual BHs, sizes of <~100 R_g

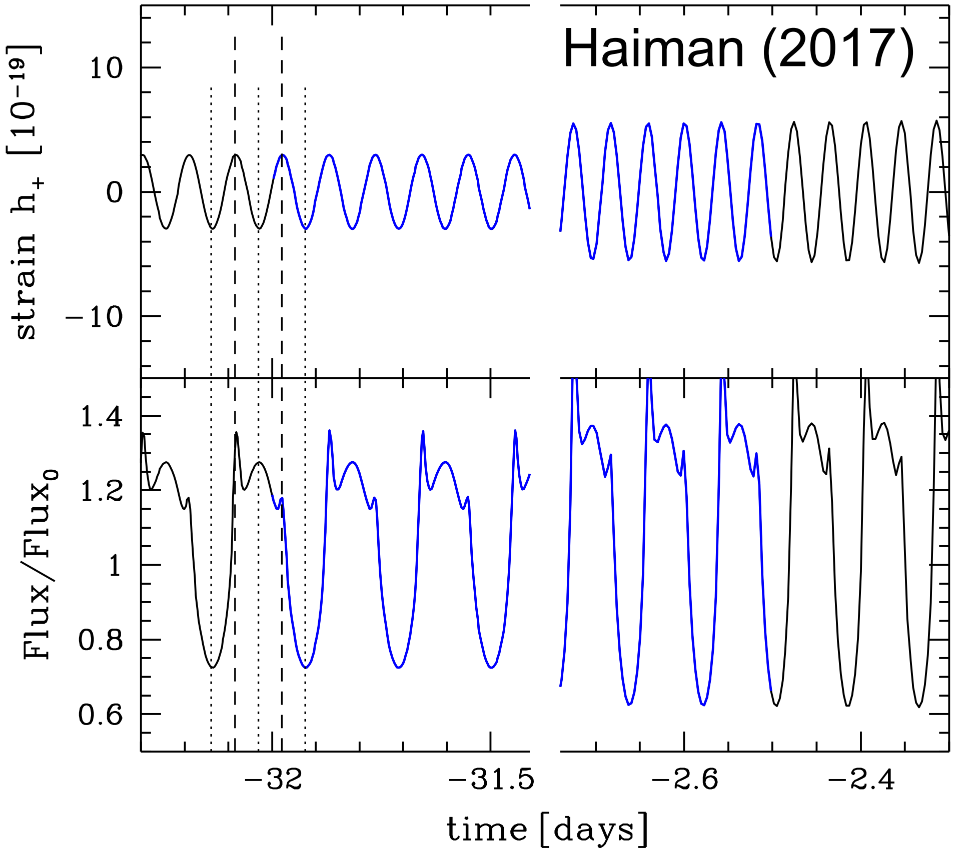
  i) Modulating accretion through the mini-disks

  ii) Doppler-boosting of the mini-disk emission (v~0.1c)

  iii) Self-lensing of the mini-disk emission

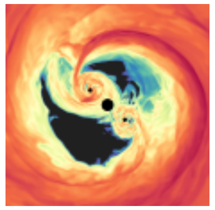






EM signatures

Which ones would be interesting?

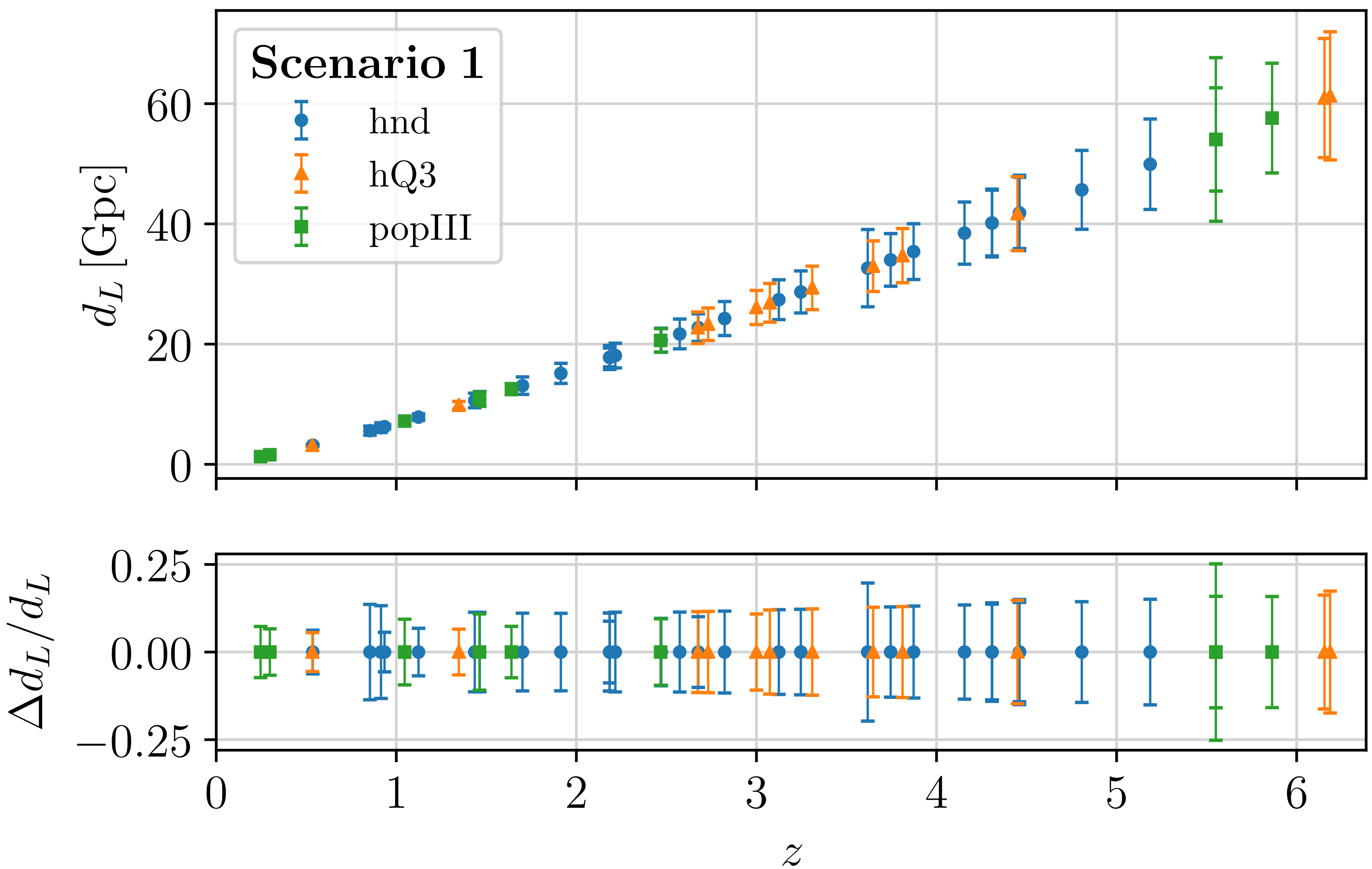


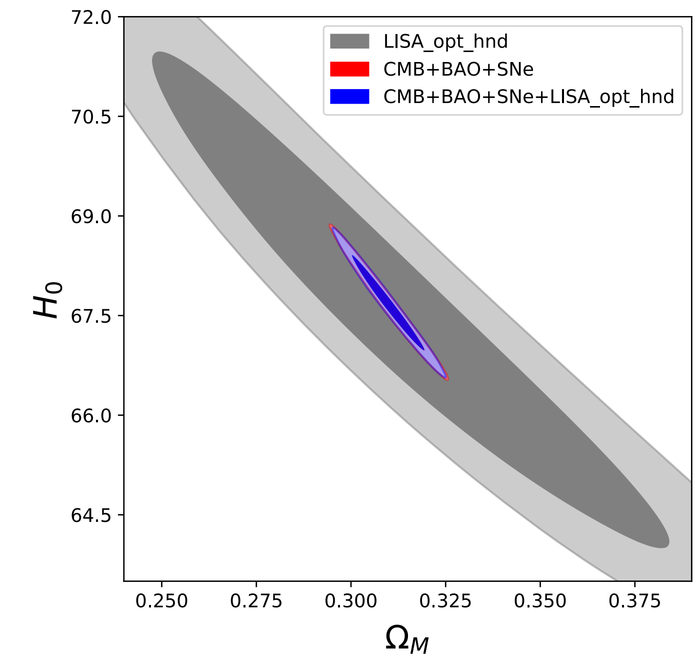
Wavelength band	Signature	Origin of emission	*Coincident GW+EM observations?*
Radio/ sub-mm	Flare and possibly periodicity	Radiatively inefficient binary accretion flows	Unlikely…
		Jets in magnetized accretion flows	
IR,opt, UV	Periodicity	Overdense "lump" in the circumbinary disk	Maybe, but likely in post-mergers
	Spectral inflection ("notch")	Low density cavity in the circumbinary disk	
X-ray	Periodicity	Modulating accretion through the mini-disks	Yes, but please find it as early as possible
		Sloshing of gas between the mini-disks	
		Doppler-boosting of the mini-disk emission	
		Self-lensing of the mini-disk emission	
	Relativistic Fe Kα emission lines	Mini-disk reflection spectrum	
	Dimming	Retreat of the circumbinary disk at merger	

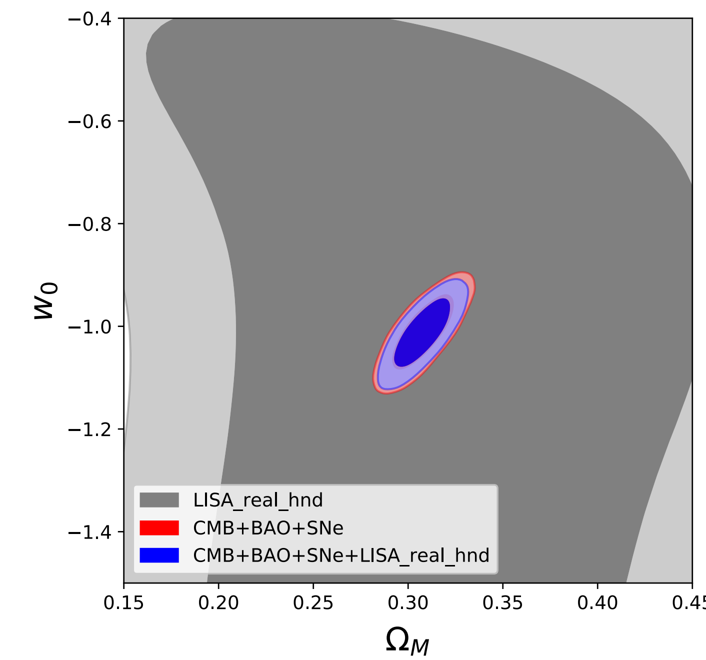
See Bogdanović et al. (2022) LRR, 25, 3

Constraints on cosmology

Belgacem+(2019); see also Schutz (1986), Holz & Hughes (2005)







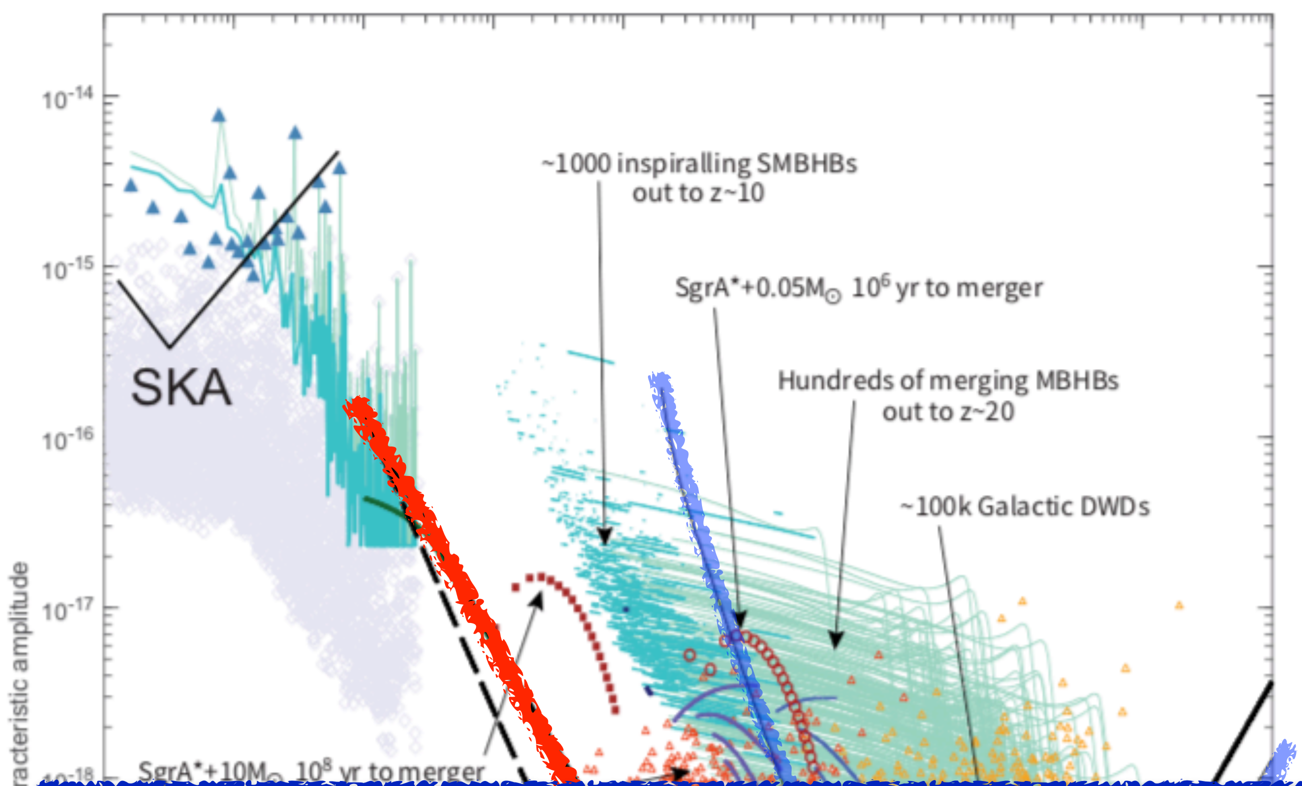
GW observations: $D_{\rm L}$, $M_{\rm c,z}$

EM observations: z

Constraints on cosmological expansion (time-dep. DE)

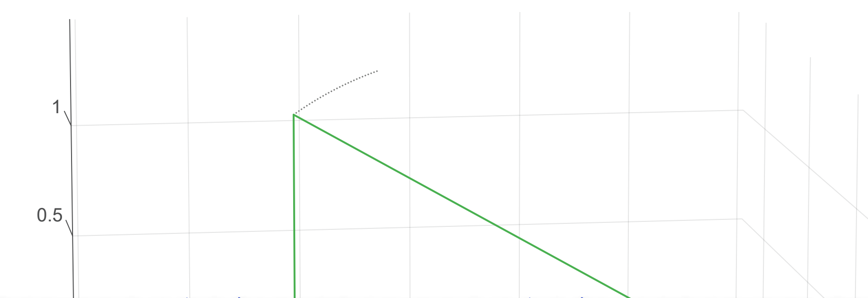
μHz GW astronomy?

The μAres detection landscape



Sesana+ (2019) arXiv:1908.11391

Average orbit radius	0.7 AU	1.0 AU	1.5 AU
Average arm length	187 million km	259 million km	395 million km
Total arm length variations (in plane constellation)	185,000 km	105,000 km	492,000 km
Total arm length variations (out of plane constellation)	176,000 km	217,000 km	65,700 km
Maximum line-of-sight velocities	6 m/s	4 m/s	12 m/s
Doppler frequencies at 1064 nm	5.5 MHz	4.0 MHz	11.0 MHz



Abstract

We propose a space-based interferometer surveying the gravitational wave (GW) sky in the milli-Hz to μ-Hz frequency range. By the 2040s', the μ-Hz frequency band, bracketed in between the Laser Interferometer Space Antenna (LISA) and pulsar timing arrays, will constitute the largest gap in the coverage of the astrophysically relevant GW spectrum. Yet many outstanding questions related to astrophysics and cosmology are best answered by GW observations in this band. We show that a μ-Hz GW detector will be a truly overarching observatory for the scientific community at large, greatly extending the potential of LISA. Conceived to detect massive black hole binaries from their early inspiral with high signal-to-noise ratio, and low-frequency stellar binaries in the Galaxy, this instrument will be a cornerstone for multimessenger astronomy from the solar neighbourhood to the high-redshift Universe.

Summary

- In 2040s, multi-messenger astronomy will allow us to explore the hidden nature of massive BHs both at low & high redshifts
- Coincident GW+EM observations of merging binary BHs will be achievable only when space-based GW detectors and X-ray/IR space telescopes (or 30m-class telescopes) are available
- The strategies to maximize the synergy crossing the fields are still under debate (even in ideal situations, not clear…)
- A big fraction of the above questions would also be solved by detection of GW sources in ~μHz (between LISA and PTAs)