Electromagnetic Counterparts II

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What is an electromagnetic counterpart?

- Source of gravitational waves ✓
- Source of electromagnetic waves ✓
  - Coincident in time (Events)
    - Mergers
    - Supernovae

Tuesday

  - Coincident in space (Continuous)
    - Compact Binaries
    - Pulsars
  - Statistically correlated (Long Delay)
    - Binary SMBH
    - Tidal Disruptions

Today

- Supermassive Black Hole Binaries
- Reside in centers of galaxies
- M-σ relation implies relationship between galaxy growth and black hole growth
- Galaxies merge
- SMBH merge

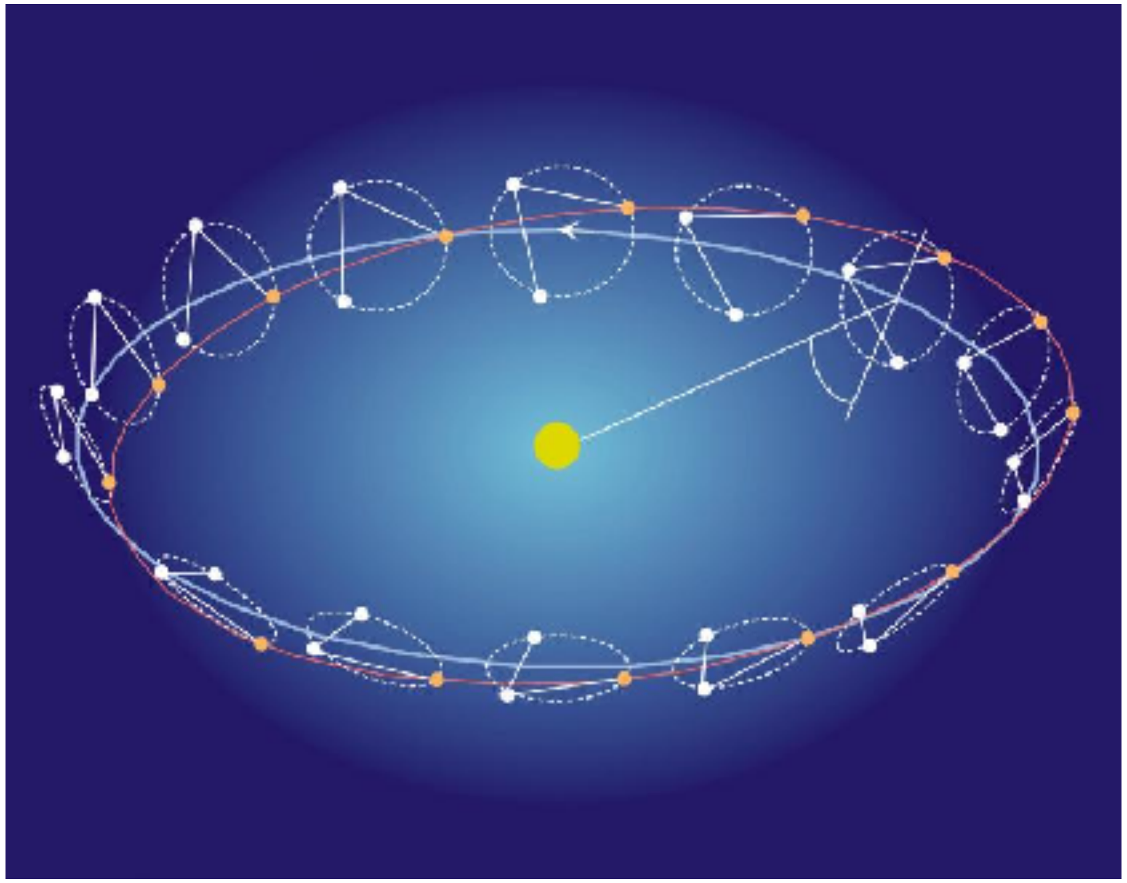
Merger frequency is related to the "Innermost Stable Circular Orbit" ISCO

$$r_{\mathrm{ISCO}} \sim 3R_s = \frac{6GM}{c^2}$$

$$GM = r^2\omega^3 \qquad \Longrightarrow \qquad f_{\mathrm{ISCO}} \sim 3 \times 10^4 \ \mathrm{Hz} \left(\frac{M_\odot}{M}\right)$$

So SMBH binaries merge in the mHz band: LISA

LISA Digression

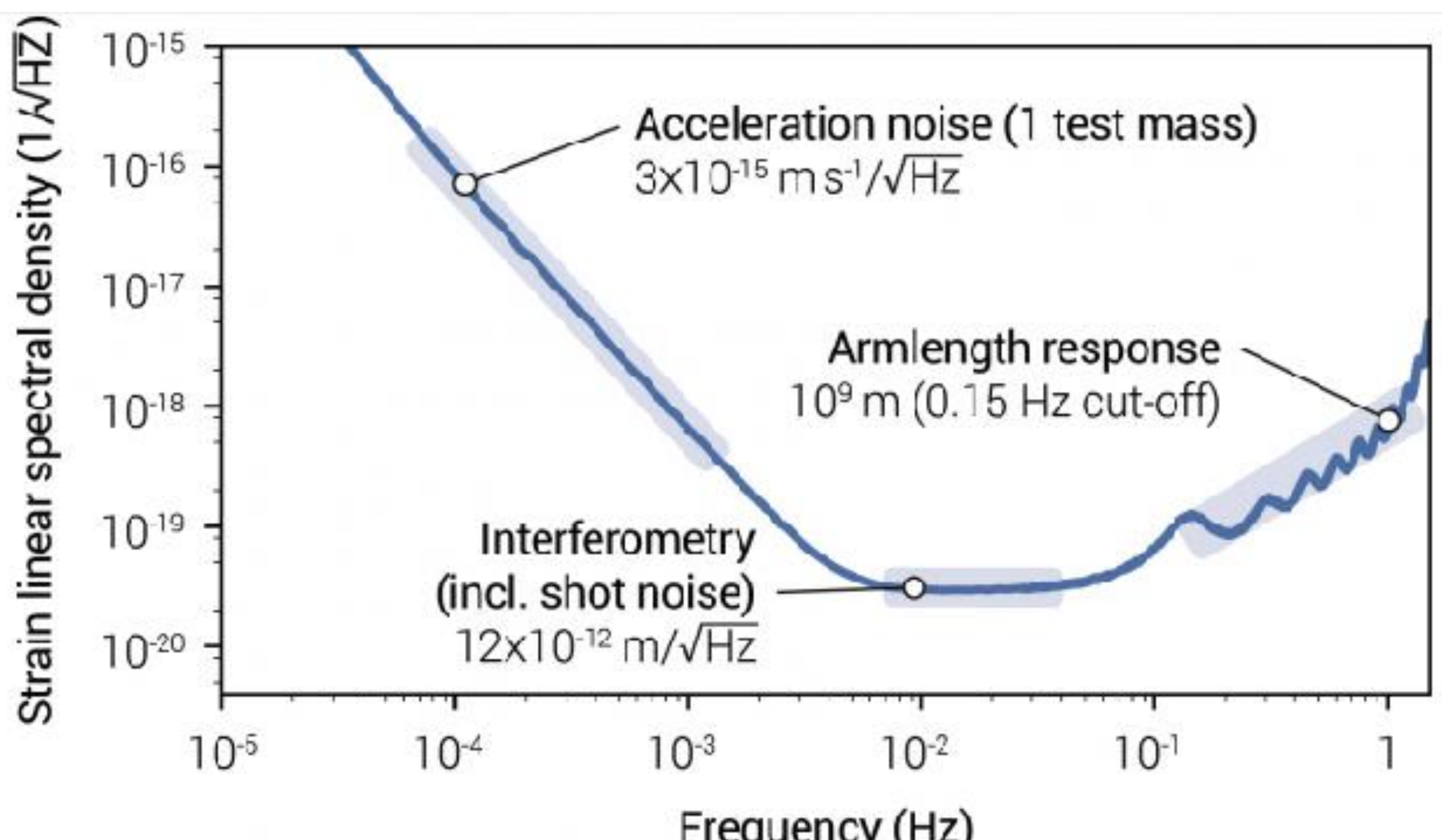


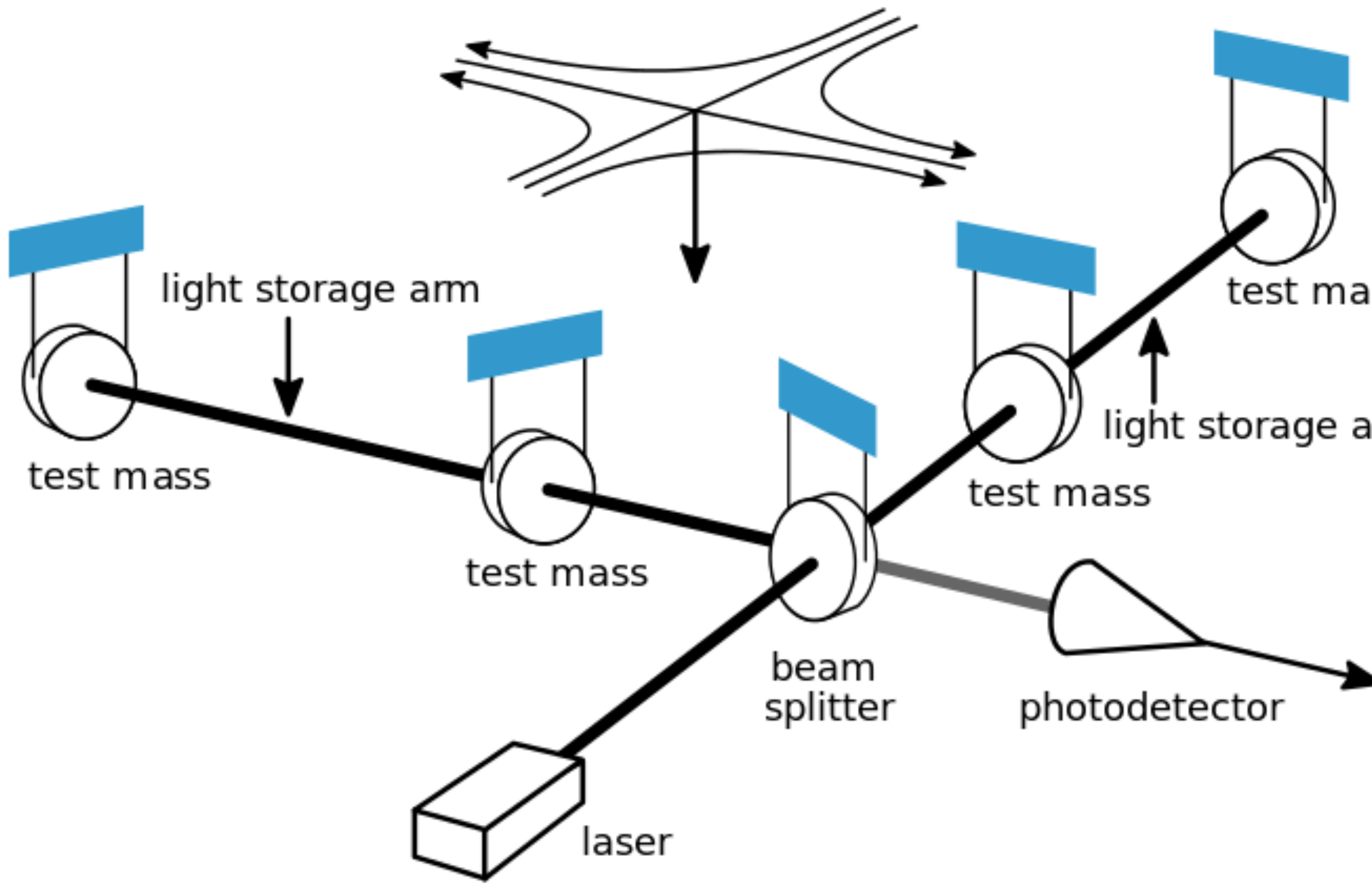
Quick Summary of eLISA

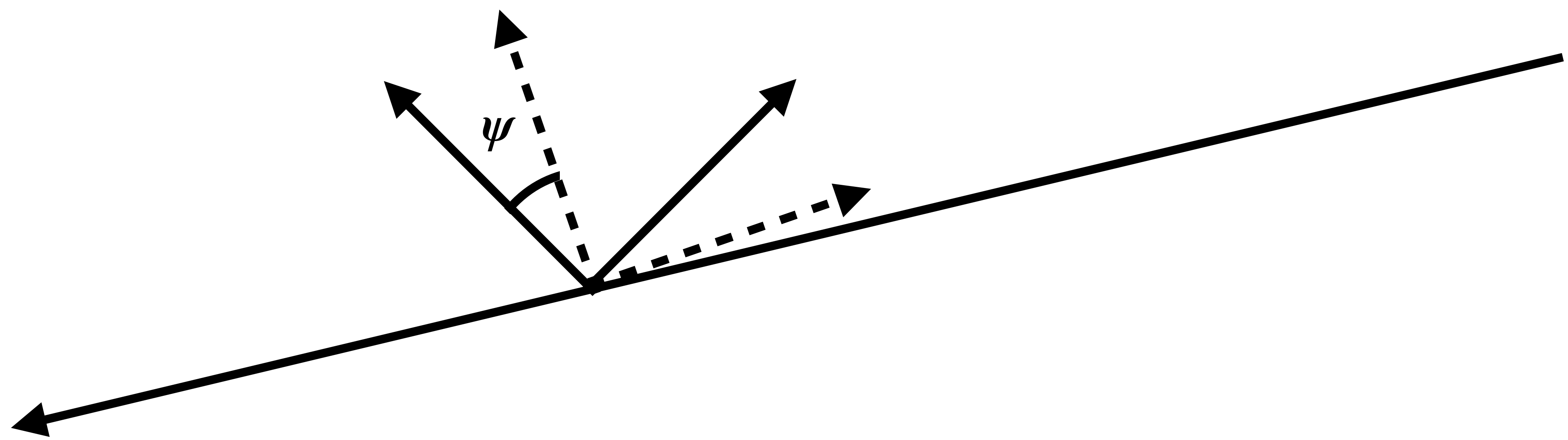
- Three spacecraft in solar orbit
- Laser links between two pairs
- 2.5 x 10^6 km armlengths

ESA L3 Mission

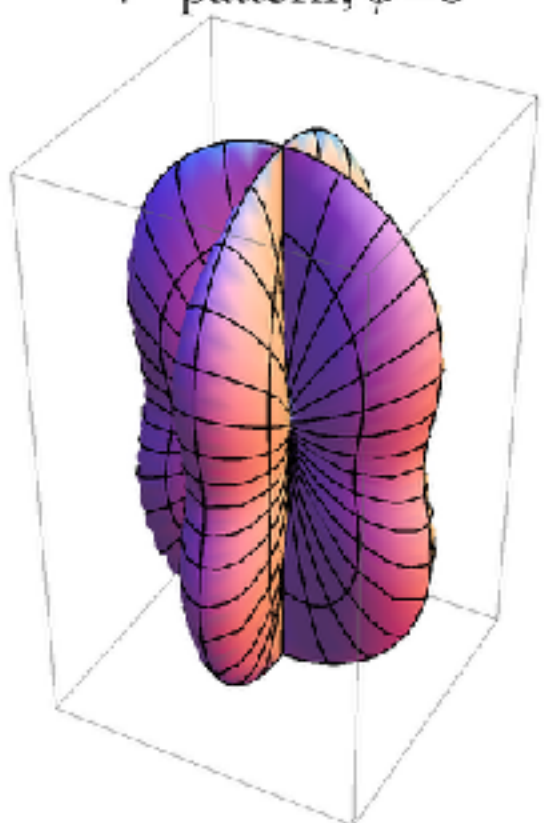
Scheduled launch: 2034



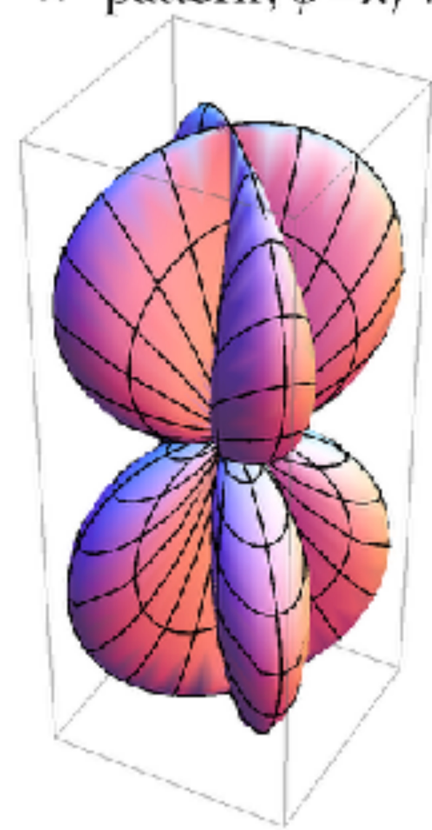

light storage arm
test mass
test mass
beam
splitter
test mass
light storage arm
test mass
photodetector
laser



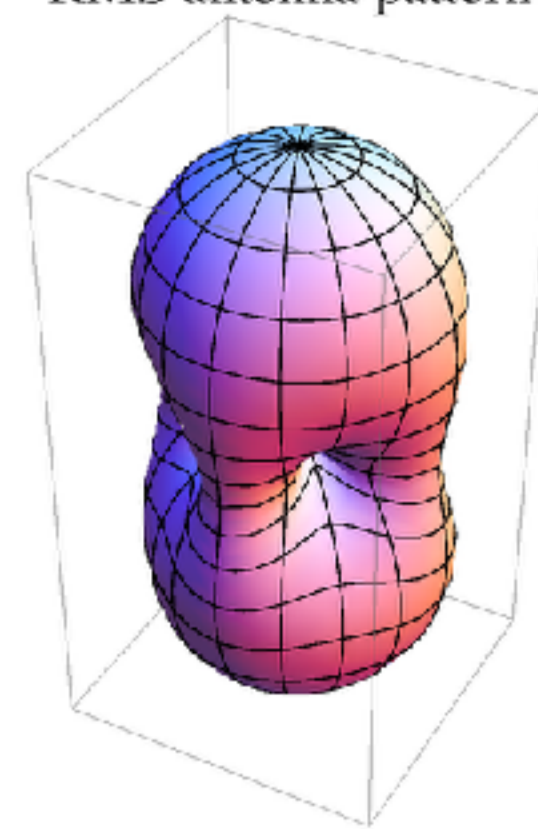
"+" pattern, $\psi=0$

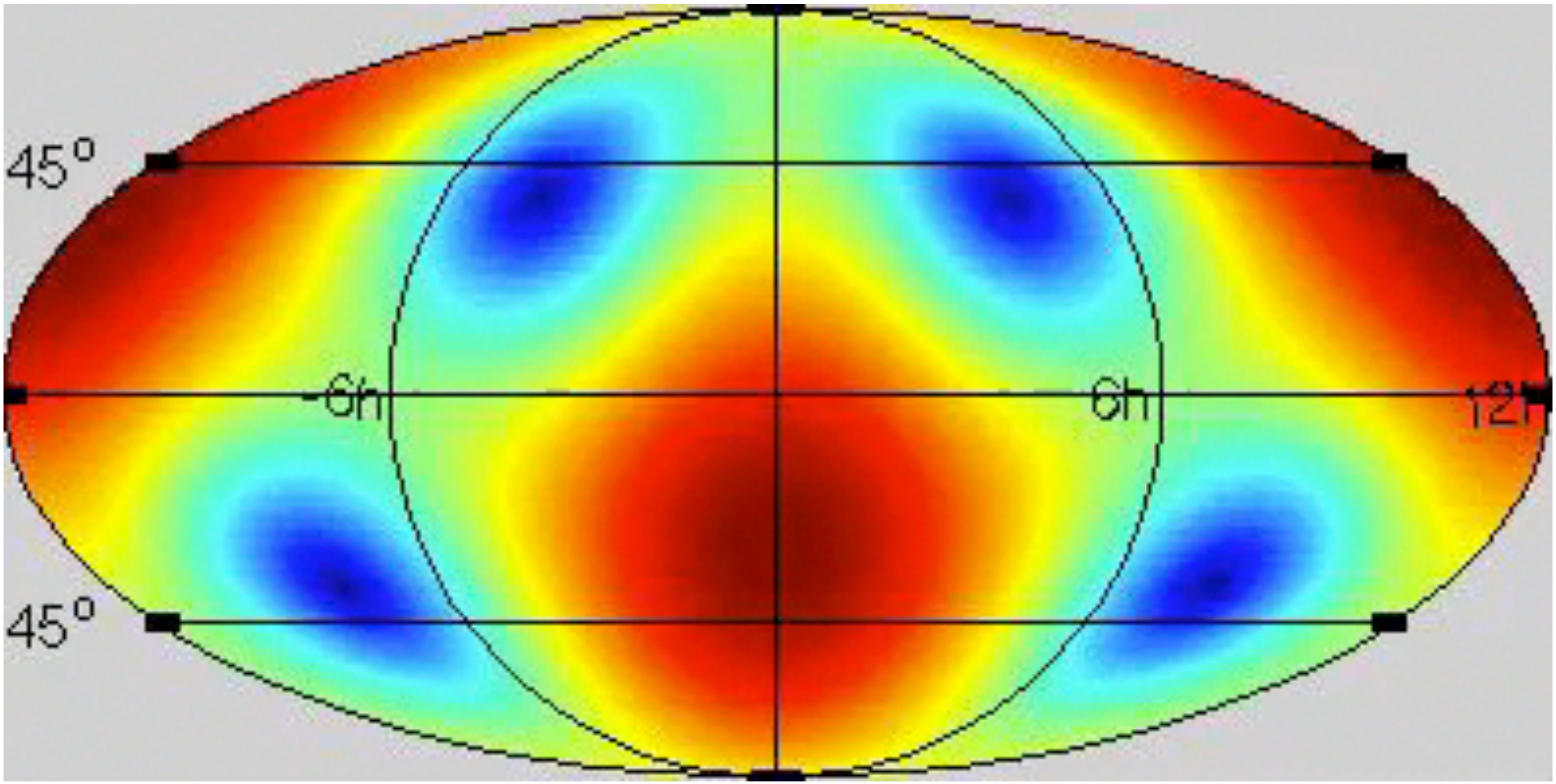


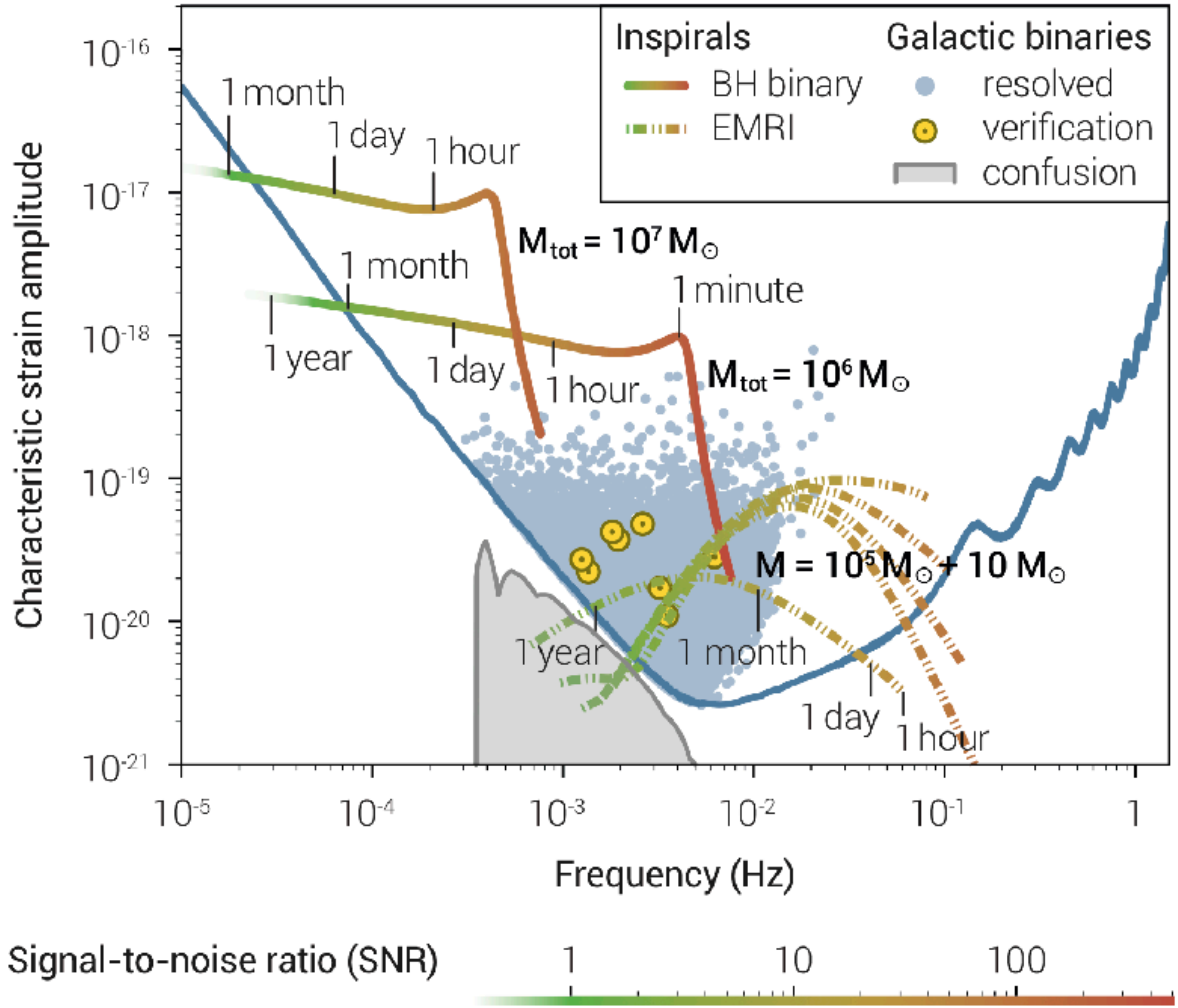
"×" pattern, $\psi=\pi/4$



RMS antenna pattern

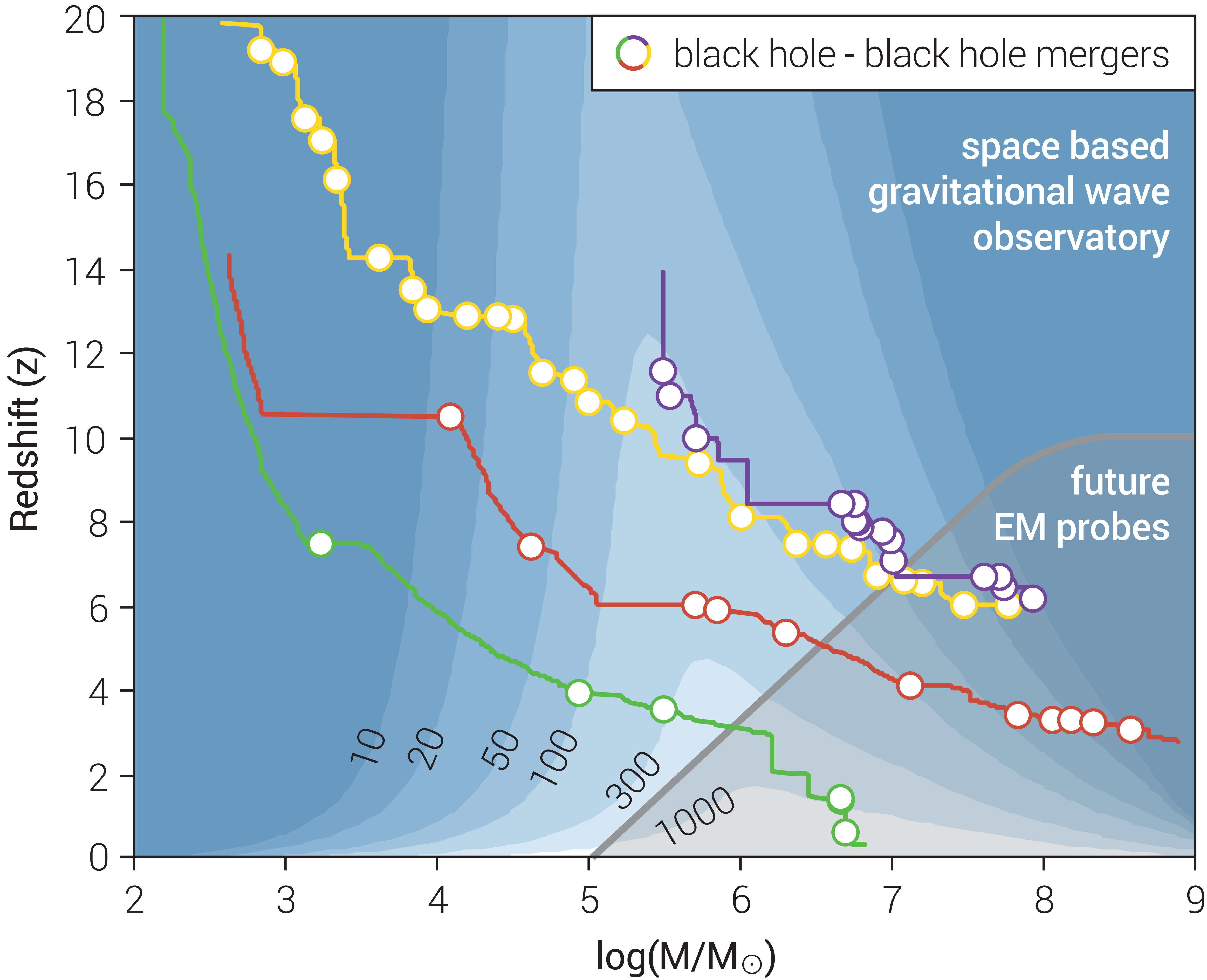



45°
-6h
6h
12h
45°



Inspirals
BH binary
EMRI
Galactic binaries
resolved
verification
confusion
Characteristic strain amplitude
Frequency (Hz)
1 month
1 day
1 hour
1 month
1 year
1 day
1 hour
1 minute
$M_{tot} = 10^7 M_\odot$
$M_{tot} = 10^6 M_\odot$
$M = 10^5 M_\odot + 10 M_\odot$
1 year
1 month
1 day
1 hour
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
Signal-to-noise ratio (SNR)
1
10
100

Show Eris Movie


black hole - black hole mergers
space based
gravitational wave
observatory
future
EM probes
10
20
50
100
300
1000
Redshift (z)
0
2
4
6
8
10
12
14
16
18
20
2
3
4
5
6
7
8
9
log(M/M⊙)

Motivation

- LISA should be able to detect SMBH binary mergers
- LISA should be able to localize them to less than a square degree (possibly much less).
- We will know the properties (masses, spins, distance, location) in exquisite detail (less than 1 %)
- If we could identify the host galaxy, we could skip the distance ladder and go straight to redshift/distance out to z=10 (or more).

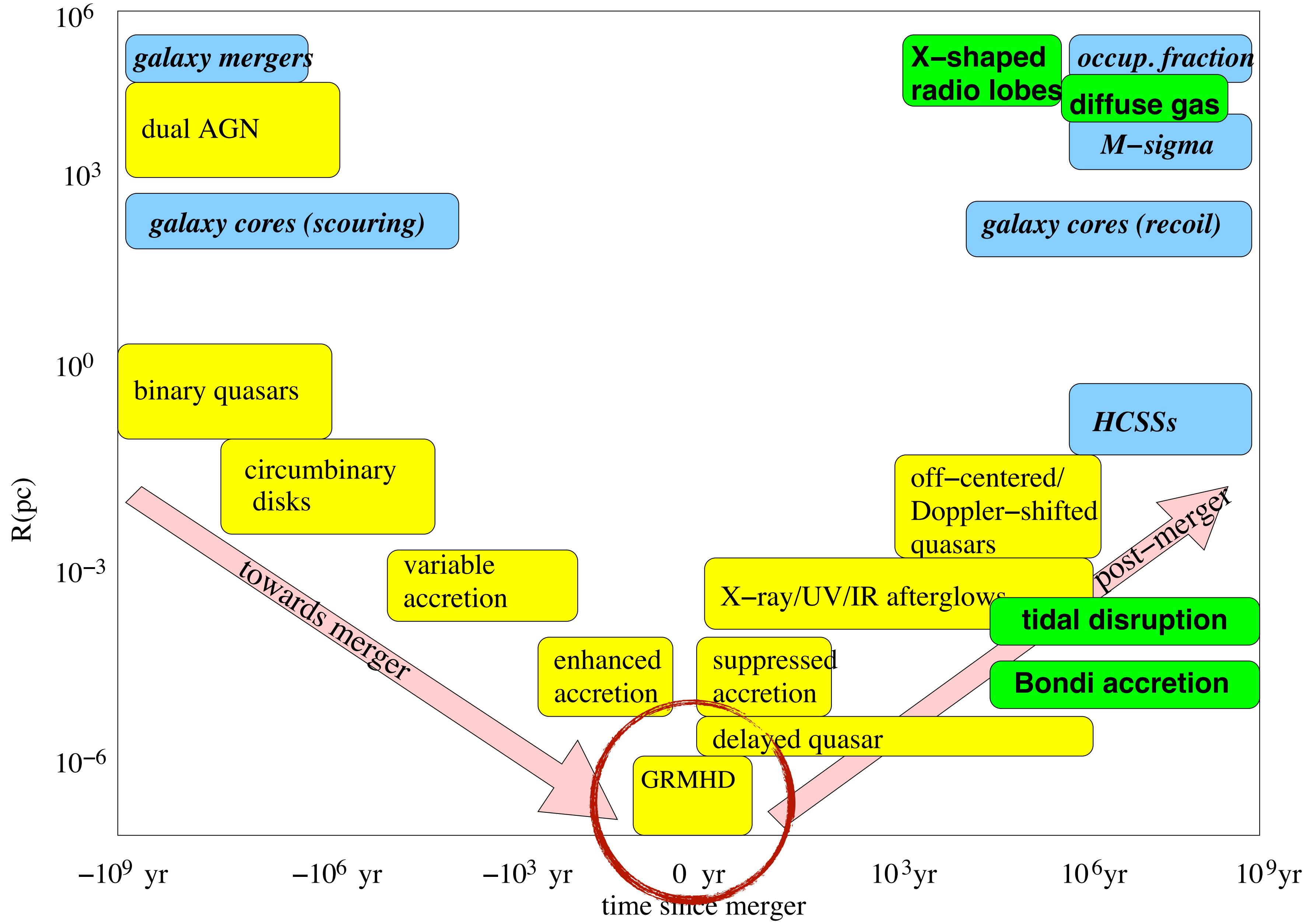
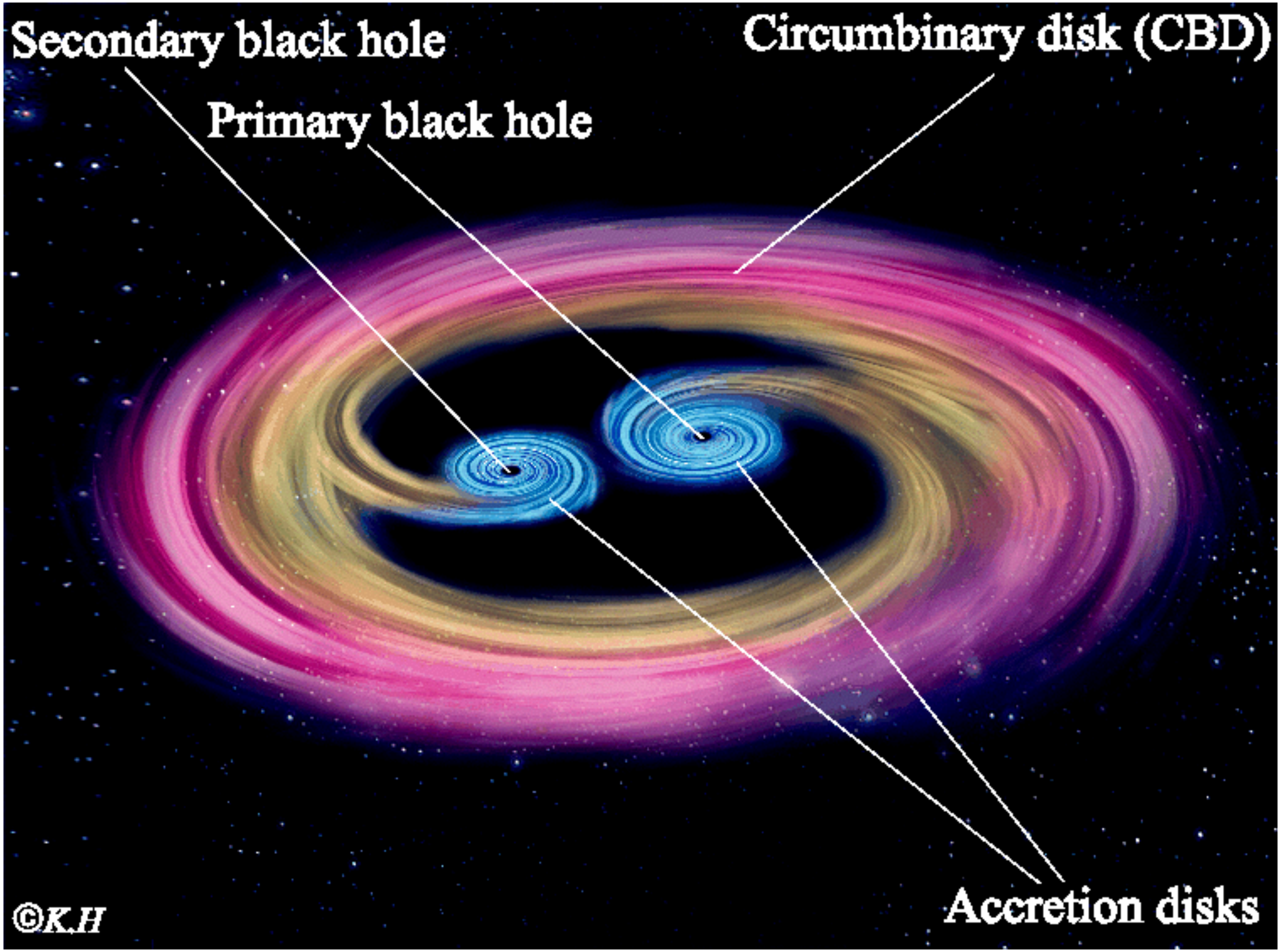


Figure 4. Selection of potential EM sources, sorted by timescale, typical size of emission region, and physical mechanism (blue/*italic* = stellar; yellow/Times-Roman = accretion disk; green/**bold** = diffuse gas/miscellaneous). The evolution of the merger proceeds from the upper-left through the lower-center, to the upper-right.

Schnittman, 2013

Candidate EM counterpart SMBH binary



Hayasaki, 2009

- Many properties of black hole binary mergers are independent of mass (or scale with mass).
- Numerical simulations of black hole binary mergers indicate roughly 5% of the initial mass is converted to gravitational wave energy.
- A pair of million solar mass black holes will radiate 100,000 solar masses of energy at merger.
- The circumbinary disk will no longer be in equilibrium.

Analytical Model

Prior to merger, disk particles are in circular orbits

Keplerian velocity : $v_{\mathrm{K}} = \sqrt{\dfrac{GM}{R}}$

Specific angular momentum : $j = v_{\mathrm{K}} R = \sqrt{GMR}$

Orbital Radius : $R = \dfrac{j^2}{GM}$

After merger, disk particles are in perturbed orbits

$$M \longrightarrow M\,(1 - \varepsilon)$$

$$R'_{\mathrm{circ}} = \frac{j^2}{GM\,(1 - \varepsilon)} = R\,(1 + \varepsilon)$$

After the mass loss, the particles find themselves in elliptical orbits with periapsis at *R* and apapsis at *R*'.

Epicycles!

$$R_{\rm new}\,(R,t) = R'_{\rm circ}(R) + A\sin\left(\Omega t + \phi_0\right)$$

Require $R = R'$ at $t=0$, *so*

$$\phi_0 = 3\pi/2 \qquad \text{and} \qquad A = R'_{\rm circ} - R = \varepsilon R$$

$$\Omega = \quad \text{orbital frequency} \quad = \sqrt{\frac{GM\,(1-\varepsilon)}{R'^3_{\rm circ}}}$$

Nearby particles will go to different orbits and eventually be 180° out of phase, leading to density peaks

Time scales

Phase difference

$$\Delta\phi = t_{\rm dp}\left[\Omega(R) - \Omega(R + 2\varepsilon R\right] = \frac{3t_{\rm dp}\varepsilon}{t_{\rm dyn}}$$

So the time scale for density peak formation is:

$$t_{\rm dp} \simeq \frac{t_{\rm dyn}}{\varepsilon} \qquad \text{with} \qquad t_{\rm dyn} = \frac{1}{\Omega}$$

For SMBH, this is more than 3 days assuming in inner disk radius of about 2 AU.

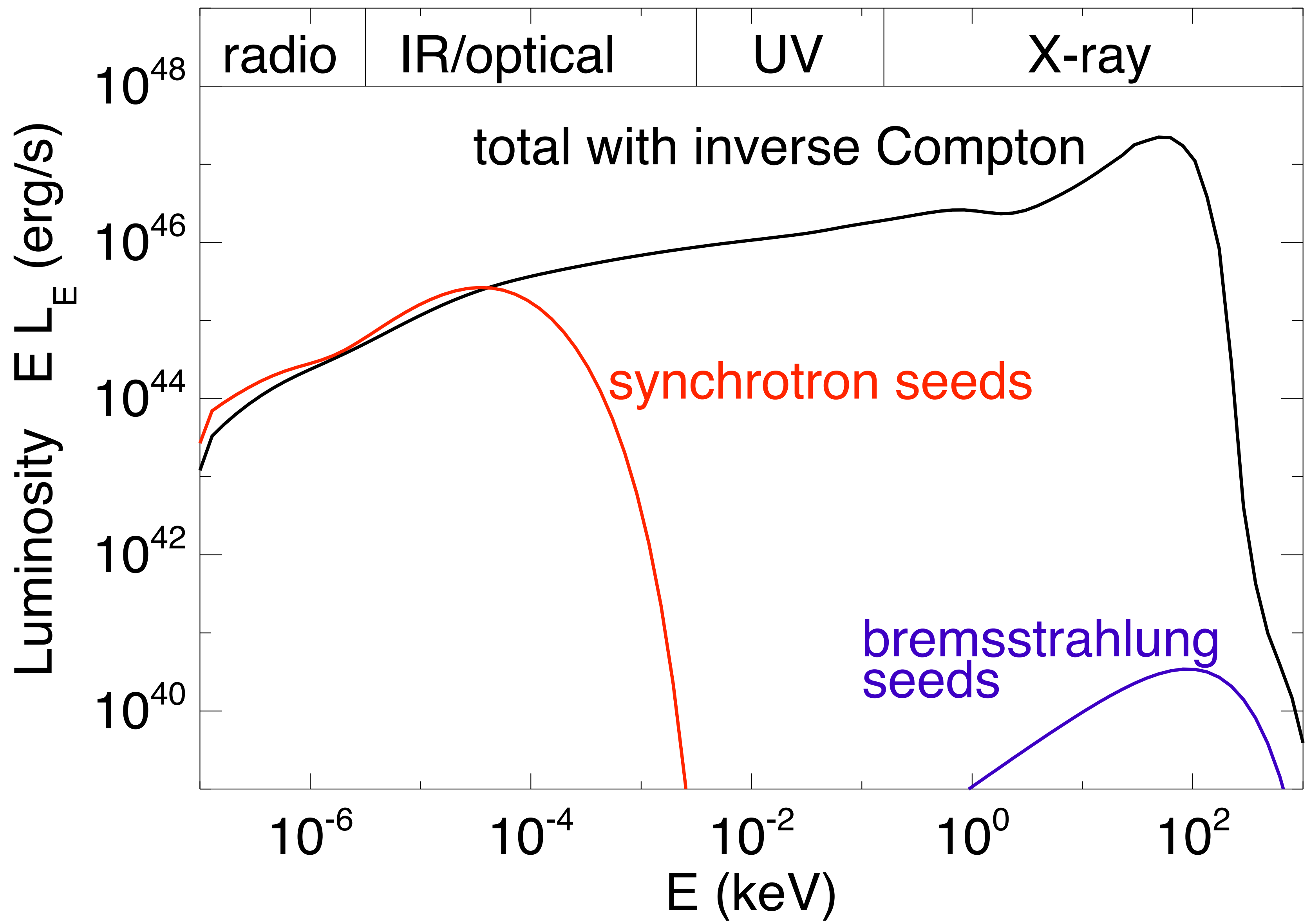
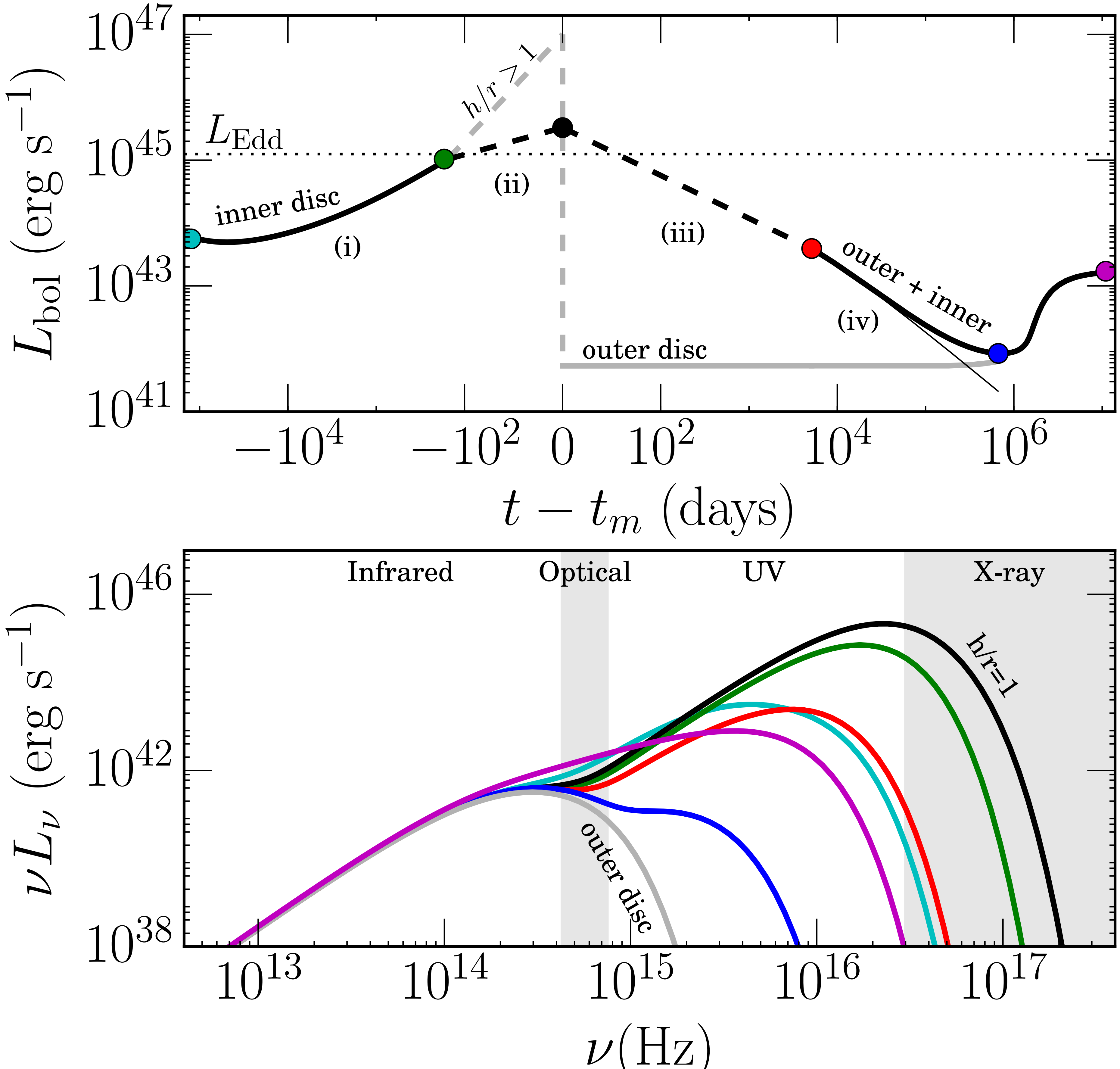
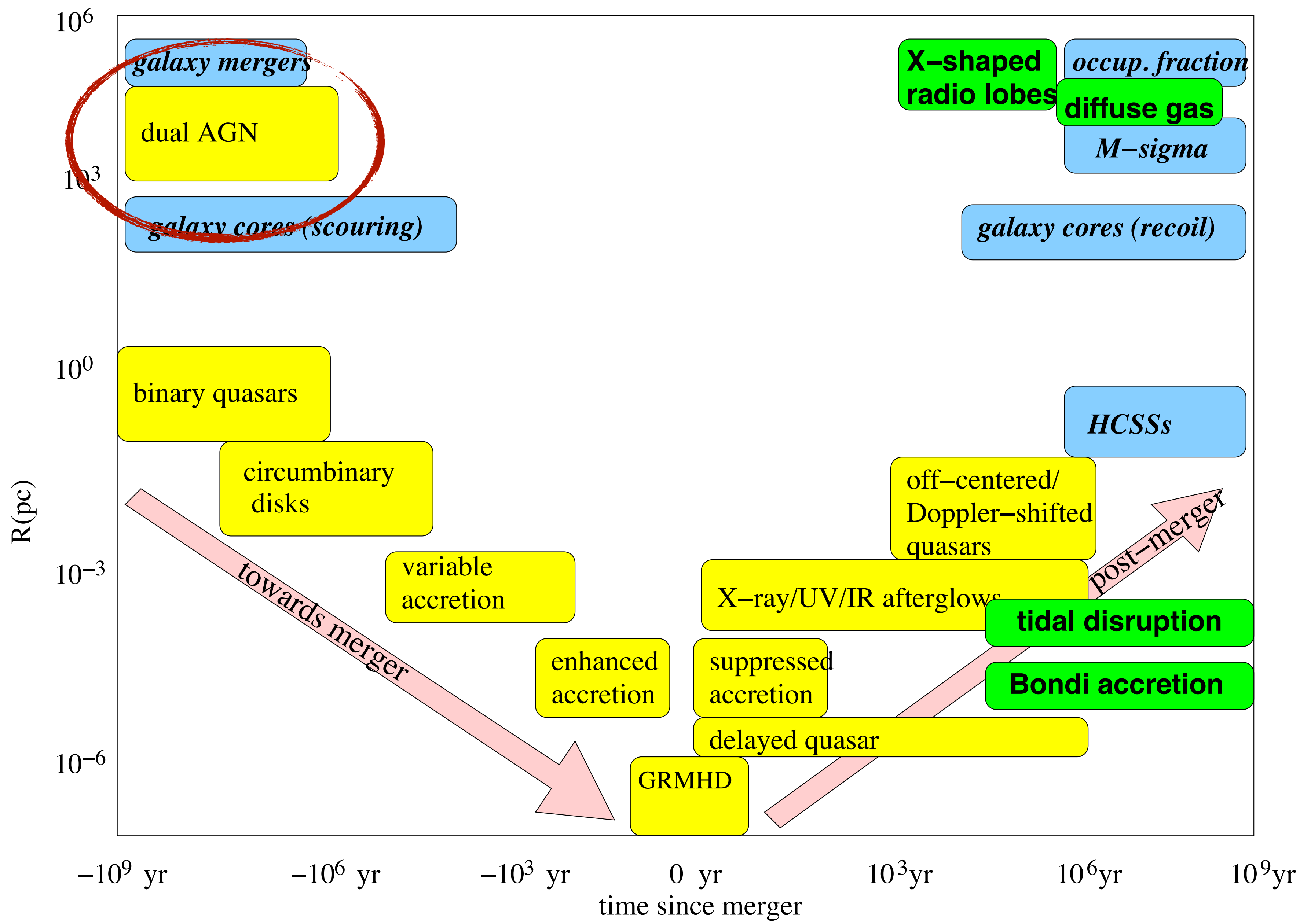


Figure 3. A preliminary calculation of the broad-band spectrum produced by the GRMHD merger of [88], sampled near the peak of gravitational wave emission. Synchrotron and bremsstrahlung seeds from the magnetized plasma are ray-traced with `Pandurata` [224]. Inverse-Compton scattering off hot electrons in a diffuse corona gives a power-law spectrum with cut-off around kT_e. The total mass is $10^7 M_\odot$ and the gas has $T_e = 100$ keV and optical depth of order unity.



Fontecillo et al. 2016



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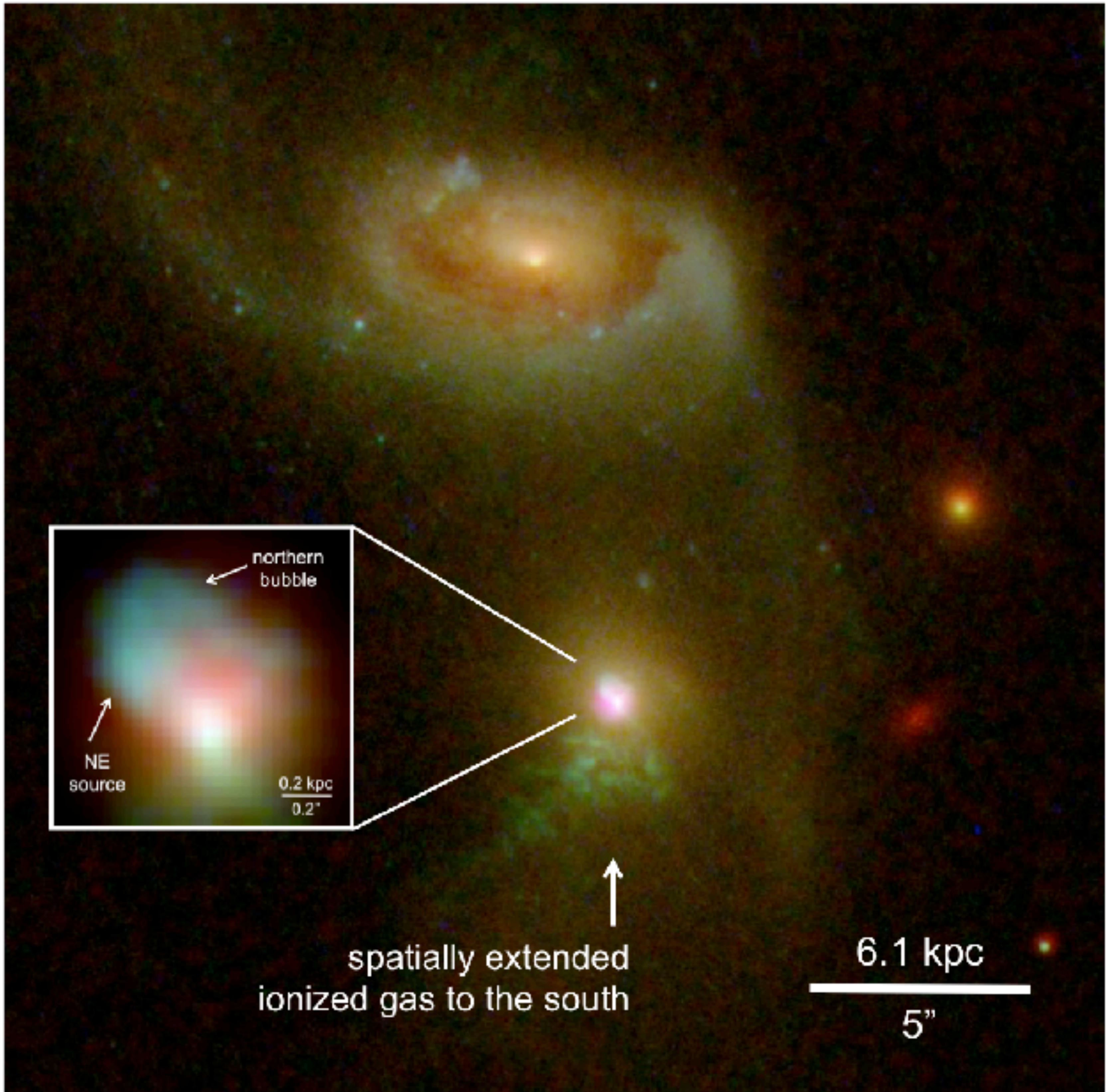
northern bubble
NE source
0.2 kpc
0.2"
spatially extended
ionized gas to the south
6.1 kpc
5"

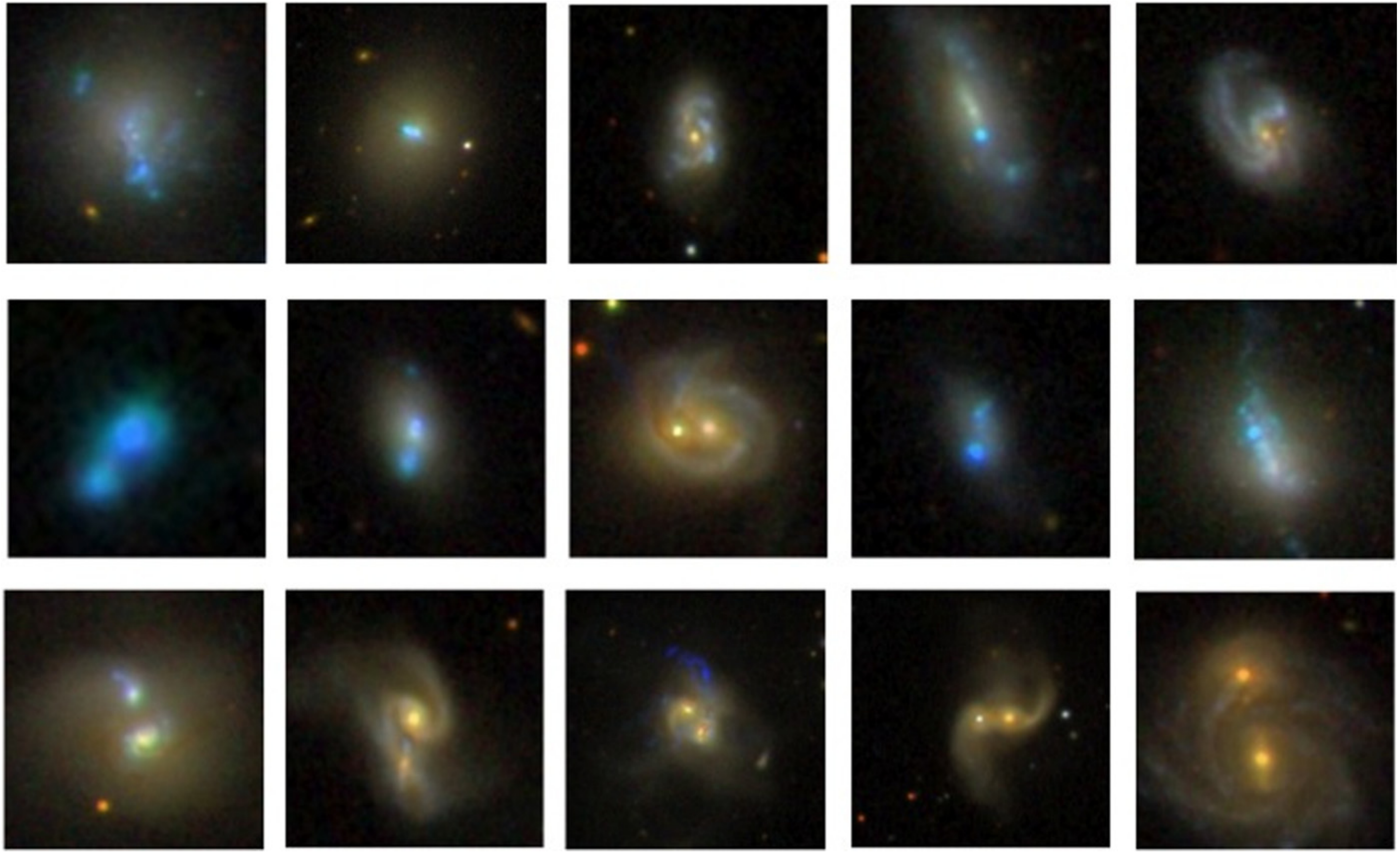

Figure 1. From top to bottom, left to right: color *gri* SDSS DR8 images of the sources NGC 5058, NGC 3773, Mrk 1114, Mrk 712, Mrk 721, Mrk 116, Mrk 104, NGC 3758, Mrk 1263, NGC 7468, NGC 5860, Mrk 423, NGC 5256, Mrk 212, and MCG +00-12-073. Sources are ordered in ascending nuclear separation. The field of view is different for each object (i.e., 25 arcsec × 25 arcsec, 51 arcsec × 51 arcsec, and 100 arcsec × 100 arcsec) so that the morphological type of the host galaxy can be appreciated.

Prospects for SMBH counterparts

- Long time delays — of order years.
- Low luminosities for the distances involved.
- Unlikely to connect counterpart with GW observation.
- Look for characteristic brightening of galaxy merger remnants
- Correlate rate densities of EM events with rate densities of observed GR events.