TDAMM

“Transient” from (Super)Massive Black Hole Mergers

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SMBH binary merger: a multi messenger event

1. SMBH binaries ultimately merge by **emitting gravitational** waves ($< 10^{-2}$ pc)
2. In order to merger, a complex interplay of interactions between SMBHs and the gas and stars in their host galaxies is required, which provide ample opportunities for **multi-wavelengh EM counterparts** to this process
3. In gas rich mergers, EM signals are produced by the presence of accretion discs and jets both before and after merger. Jets may be source of **accelerated particles** (cosmic rays and neutrinos)

SMBH binary merger: a multi messenger event

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Gravitational Waves (GW) emitter

GW Power:

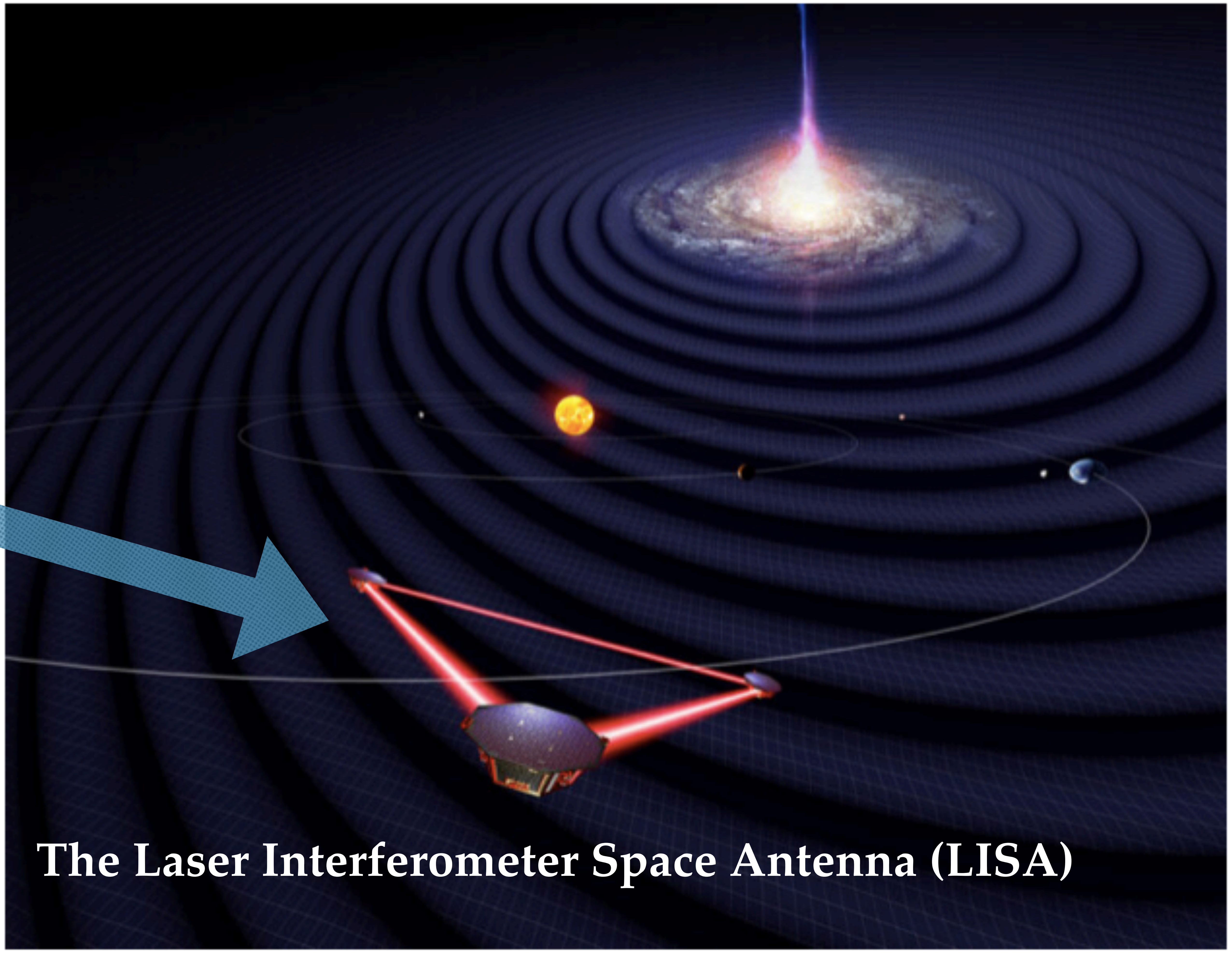
$$P_{GW} \sim \left(\frac{c^5}{G}\right)\left(\frac{GM}{c^5 a}\right)^5 \leq 3.6 \times 10^{59}\ \frac{\mathrm{erg}}{\mathrm{s}}$$

GW frequency at ISCO:

$$f_{\mathrm{GW}} = \frac{1}{6\sqrt{6}\pi}\frac{c^3}{GM(1+z)} \approx \frac{4}{1+z}\ mHz \left(\frac{10^6 M_\odot}{M}\right)$$

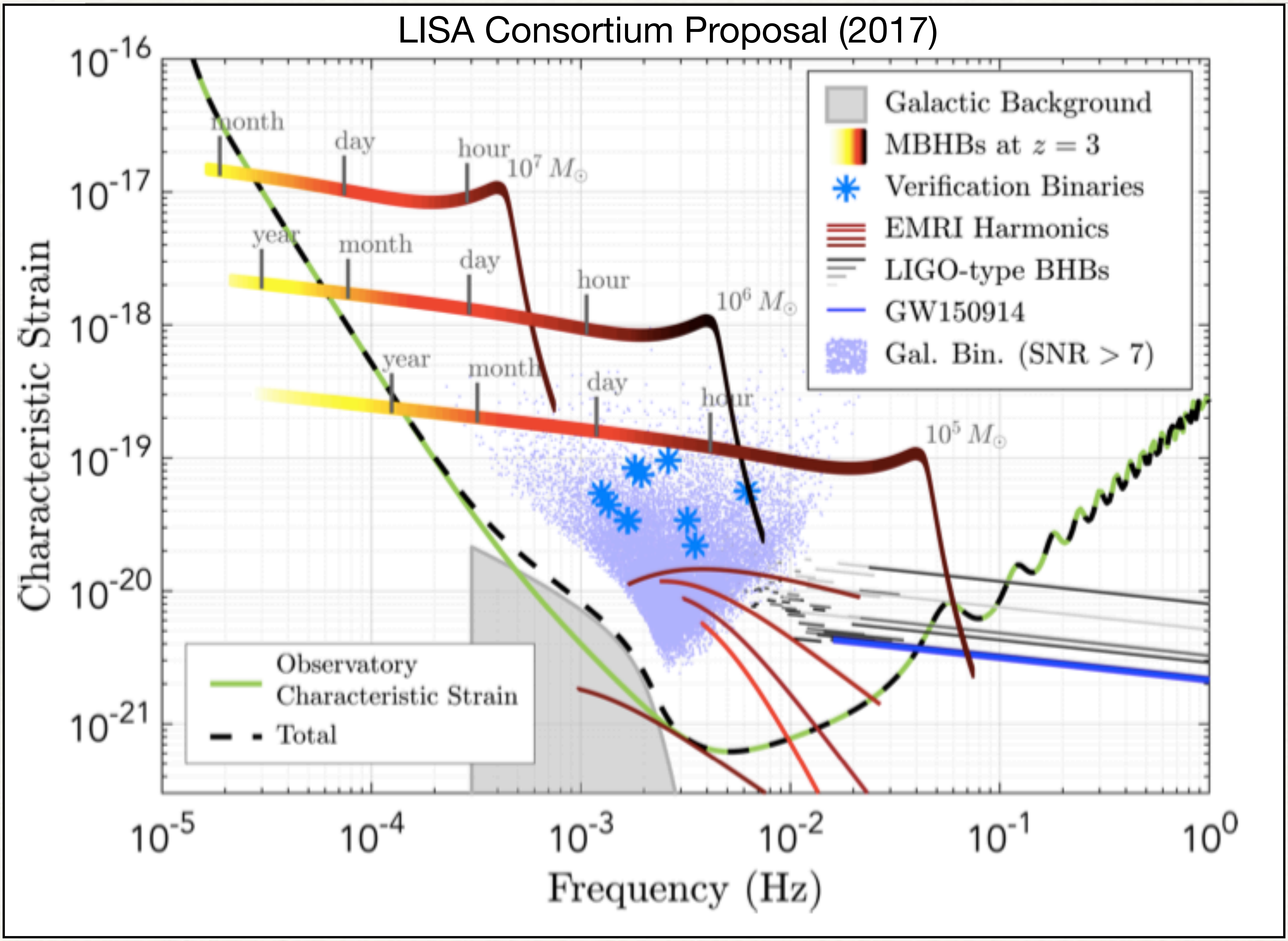
Merger Timescale in the LISA band:

$$t_{\mathrm{P}} \approx 0.32 \frac{(1+q)^2}{q f(e)} \left(\frac{a}{\mathrm{AU}}\right)^4 \left(\frac{M}{10^6 \mathrm{M}_\odot}\right)^{-3} \mathrm{yr}\,.$$



LISA constellation within our solar system in front of gravitational waves emitted by an active galaxy / © University of Florida / Simon Barke (CC-BY 4.0)

SMBH binaries in the LISA Band



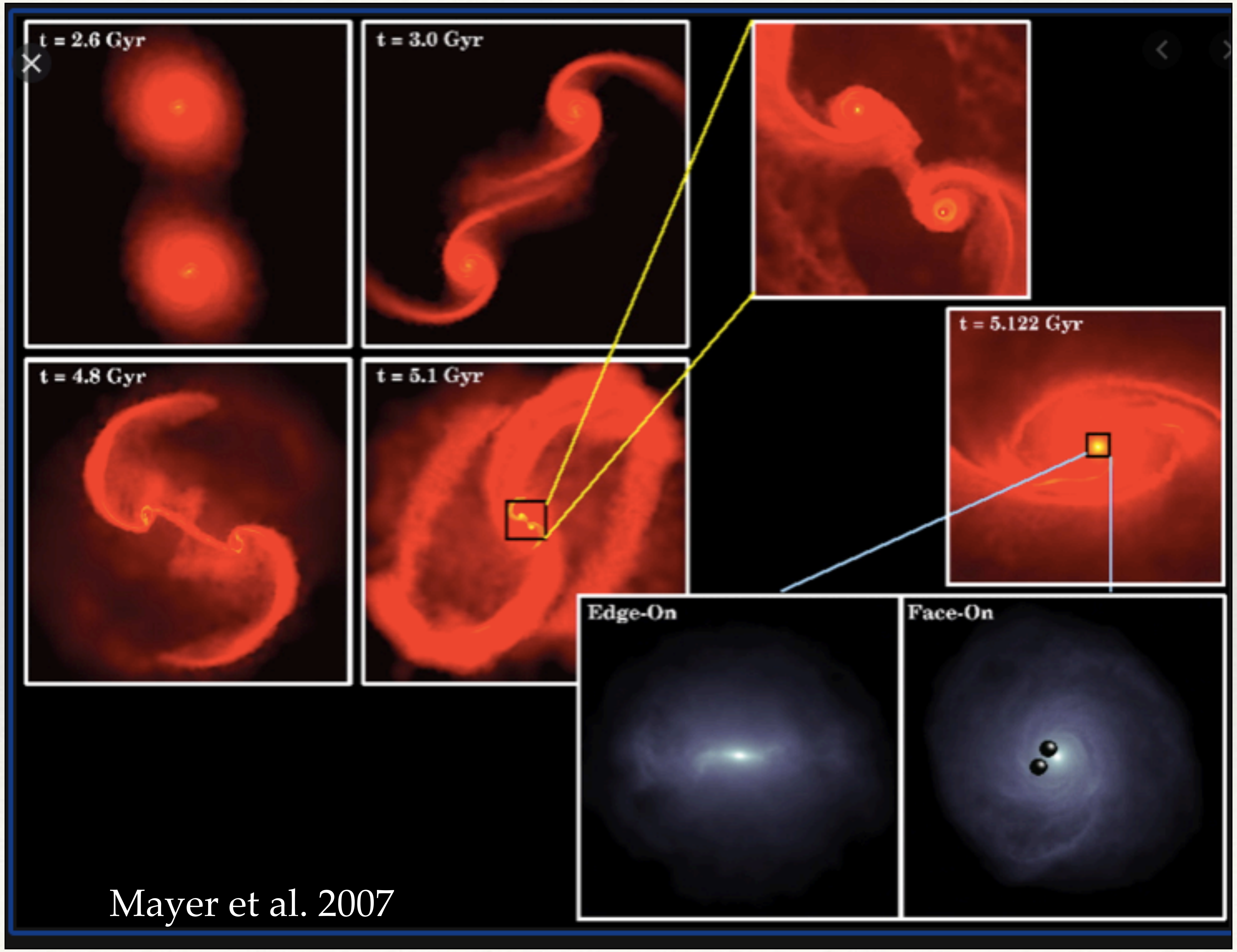
- Merging binaries in LISA
- Week to months in band
- High mass/high redshift —> low f

$$f_{\mathrm{GW}} \approx \frac{4}{1+z}\, mHz \left(\frac{10^6 M_\odot}{M} \right)$$

SMBH binary merger: a multi messenger event

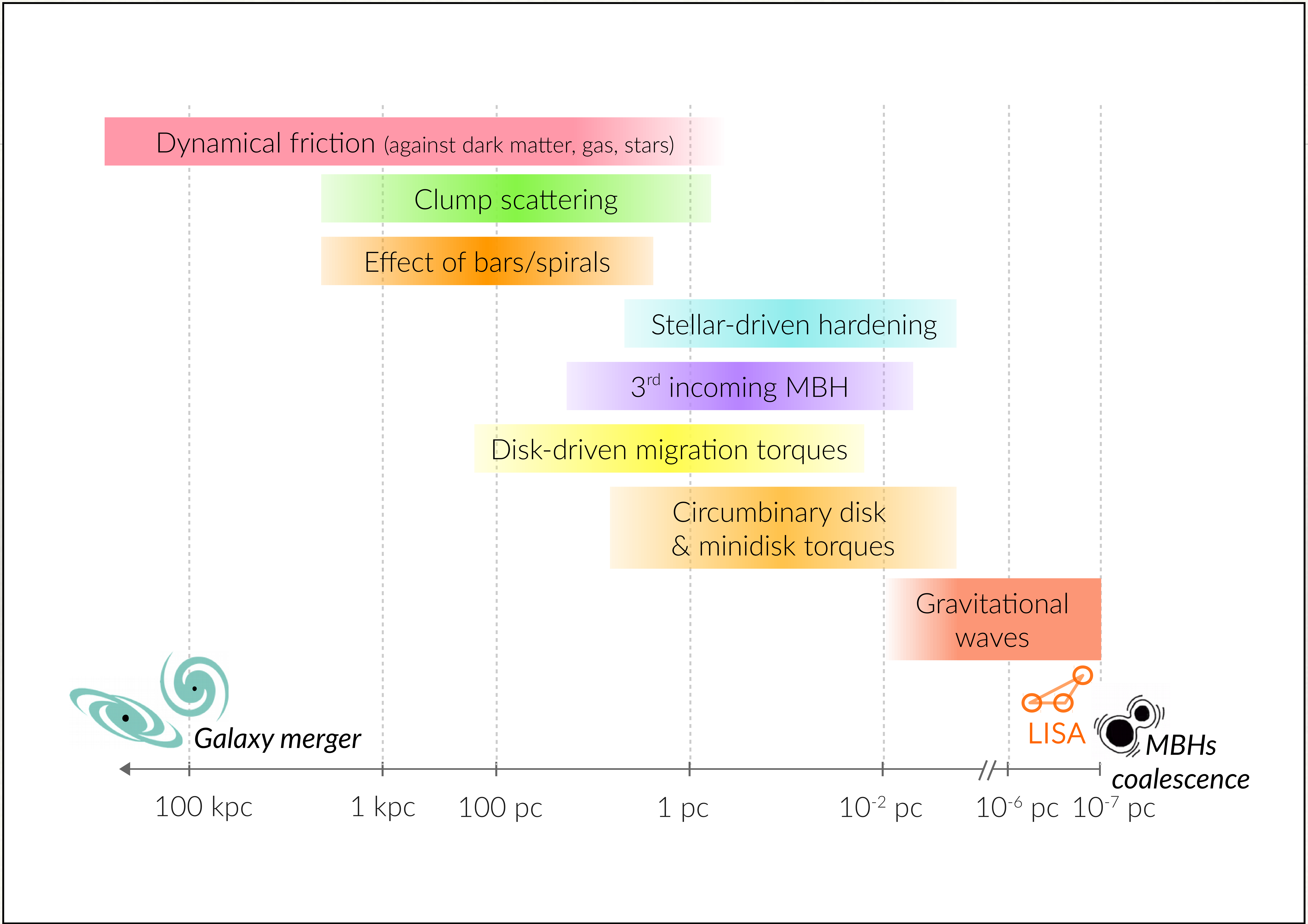
2. In order to merger, a complex interplay of interactions between SMBHs and the gas and stars in their host galaxies is required, which provide ample opportunities for **multi-wavelength EM counterparts** to this process

The articulated process of merging



Mayer et al. 2007

Figure: LISA Astrophysics Working Group White Paper (LRR); made by Elisa Bortolas



SMBH binary merger: a multi messenger event

3. In gas rich mergers, EM signals are produced by the presence of **accretion discs and jets** both *before* and *after* merger. Jets may be source of **accelerated particles** (cosmic rays and neutrinos)

Electromagnetic counterparts to GWs: Type 1

Large scale EM emission *related* to the process of merger
in conceptual and statistical relation with GW events

- Merging galaxies

Covered by Tingting Liu yesterday

- Dual AGNs
- *Binary* AGNs (not yet detected)*
- Pre and Post merger emission searched in wide-field surveys
- Wandering black holes

* Very Large Array (ngVLA) may resolve MBHB pairs down to sub-10 pc separations and track binary orbits through changing pc-scale jet morphology (Burke-Spolaor et al., 2018).

Electromagnetic counterparts to GWs: Type 2

EM observations of a given merger event, where LISA is a trigger

- Detections by EM observatories (e.g. SKA, ngVLA, Roman, Rubin, Athena, LynX, AXIS) of "transients" driven by LISA localisation capability
- Detections of host galaxies of LISA events

Up to a few tens in 4 years (e.g. Mangiagli+2022)

What do we learn from combining multimessenger info?

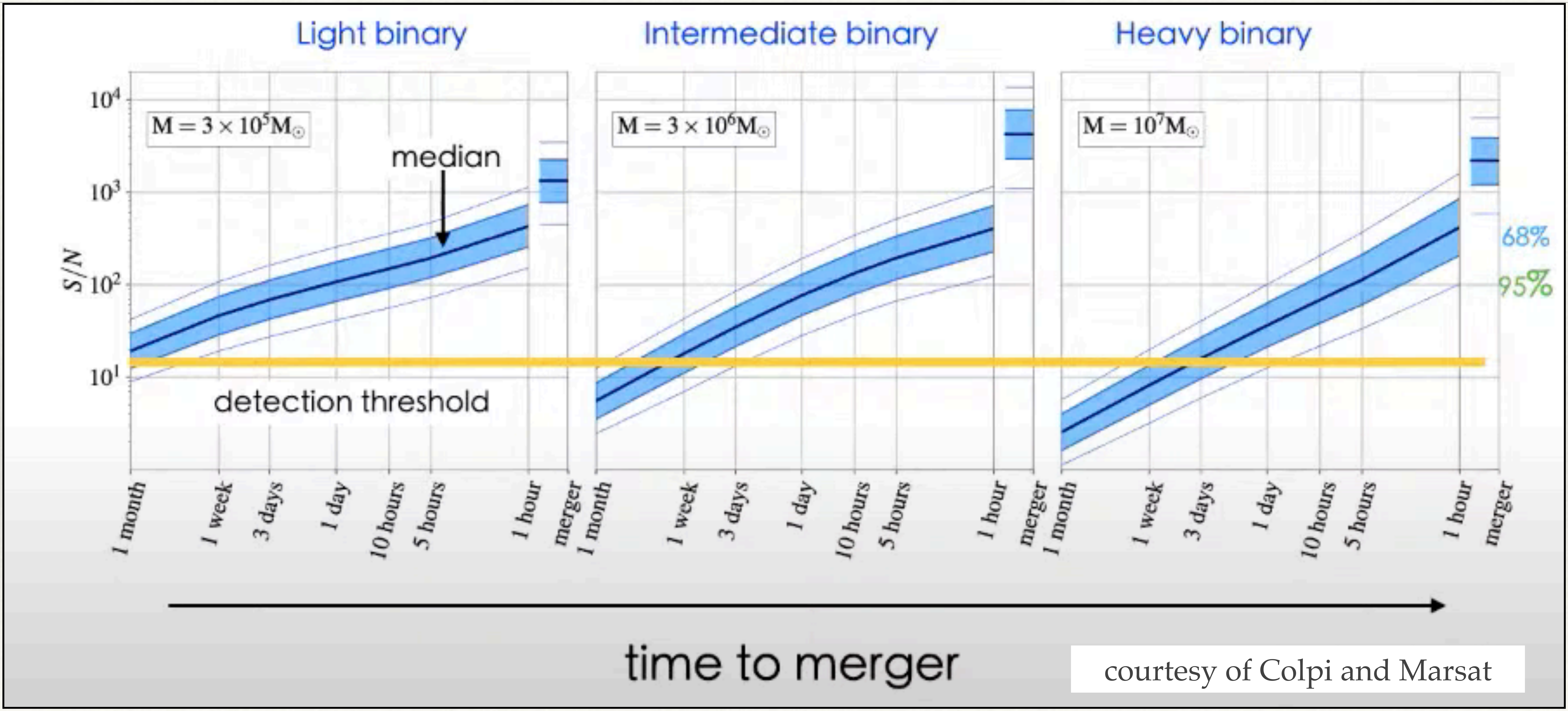
- **Astrophysics:**
  - The process of galaxy/SMBH merger, fundamental ingredient in the cosmological hierarchical process of structure formation
  - Physics of accretion discs and jets in (violently) changing spacetime
- **Physics:** test of GR comparing speed of light and gravity
- **Cosmology:** testing cosmological parameter with standard sirens out to z~5

LISA's detection and localisation capability

On-the-fly detection

Piro et al. (incl. EMR) in prep.

all events at z=1

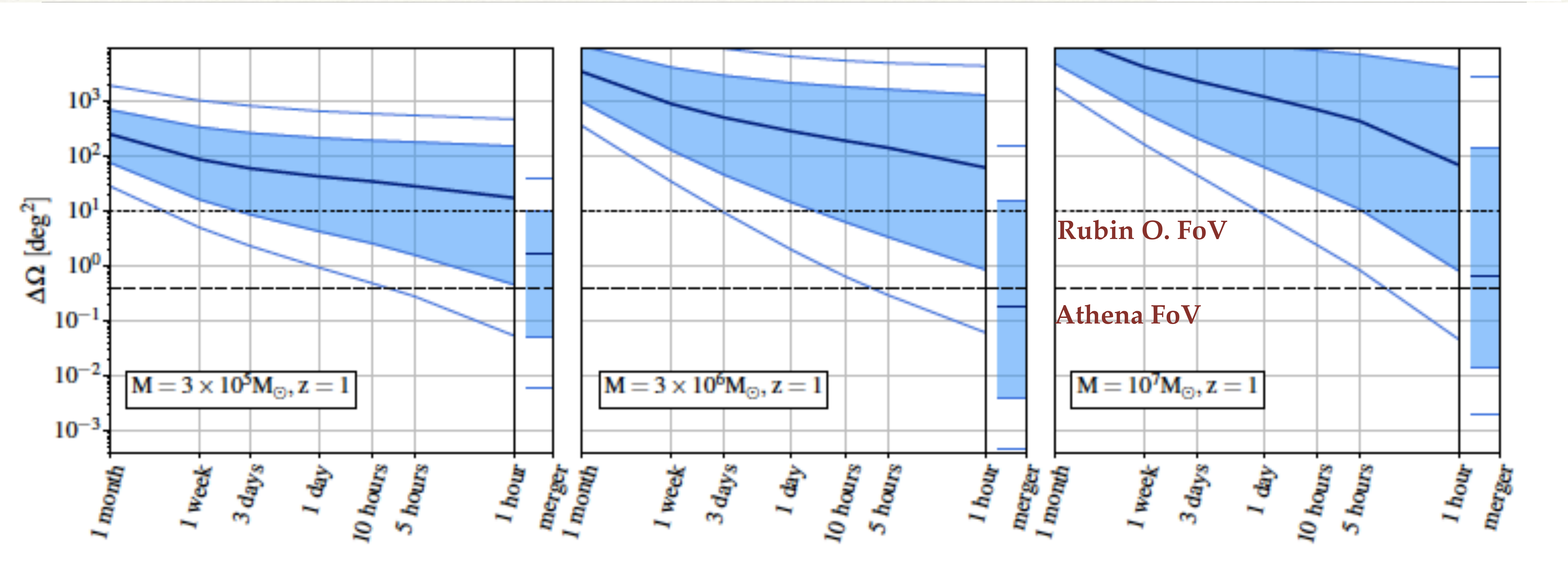


courtesy of Colpi and Marsat

see also Mangiagli+2020

On-the-fly localisation

Piro et al. (incl. EMR) in prep.



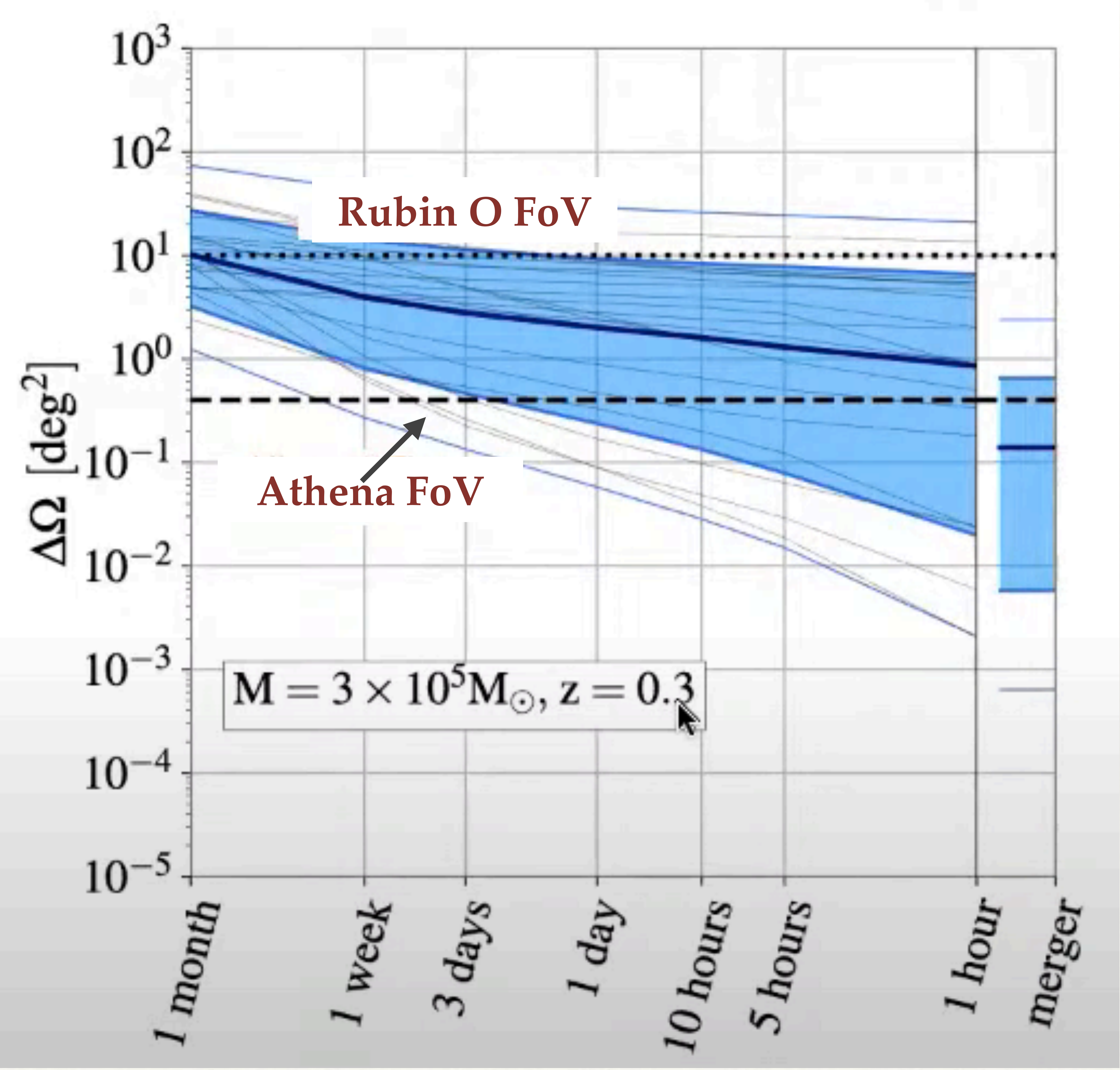
Localisation at *after* merger is far more likely than in the pre-merger phase

Pre-merger localisation only for nearby light binaries

- Rubin Observatory FoV can be covered by Athena in 3 days with a scanning pattern of 23 observations f 9KS each

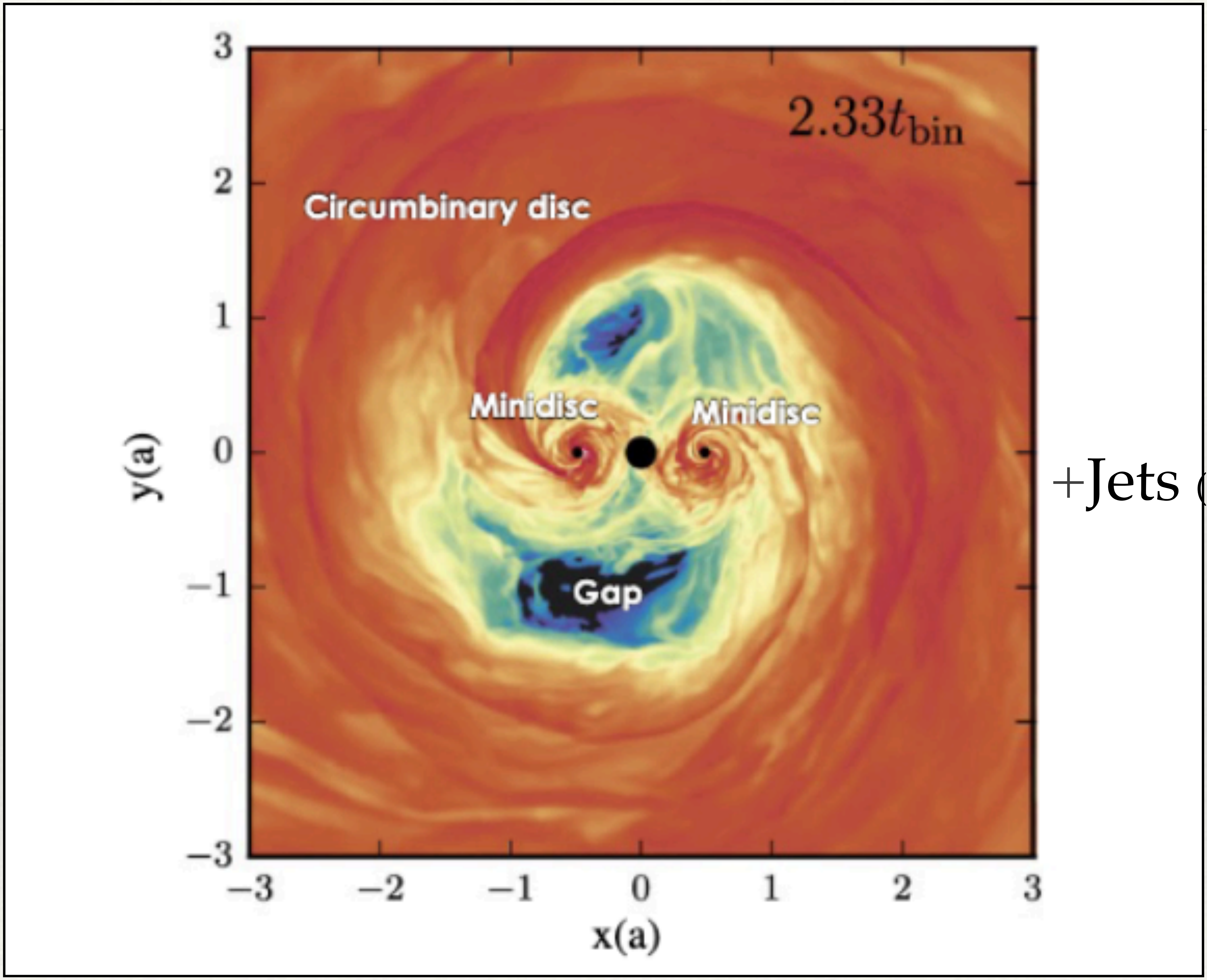
- Chirp mass and mass ratio can be determined with 1% precision one week before coalescence

- Luminosity distance can be measure with 10% precision one week before merger



Expected counterparts to LISA events

Pre-merger phase

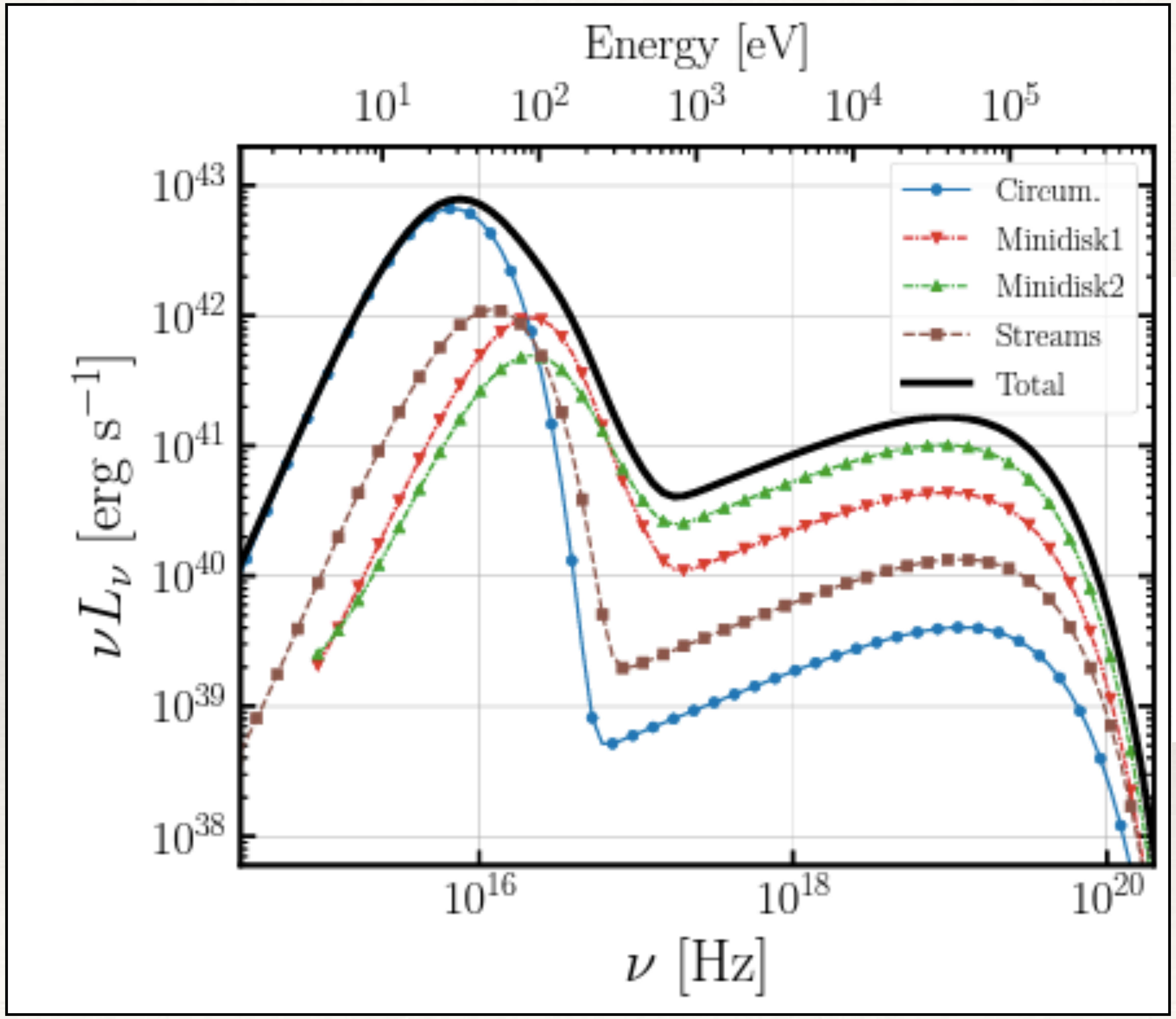


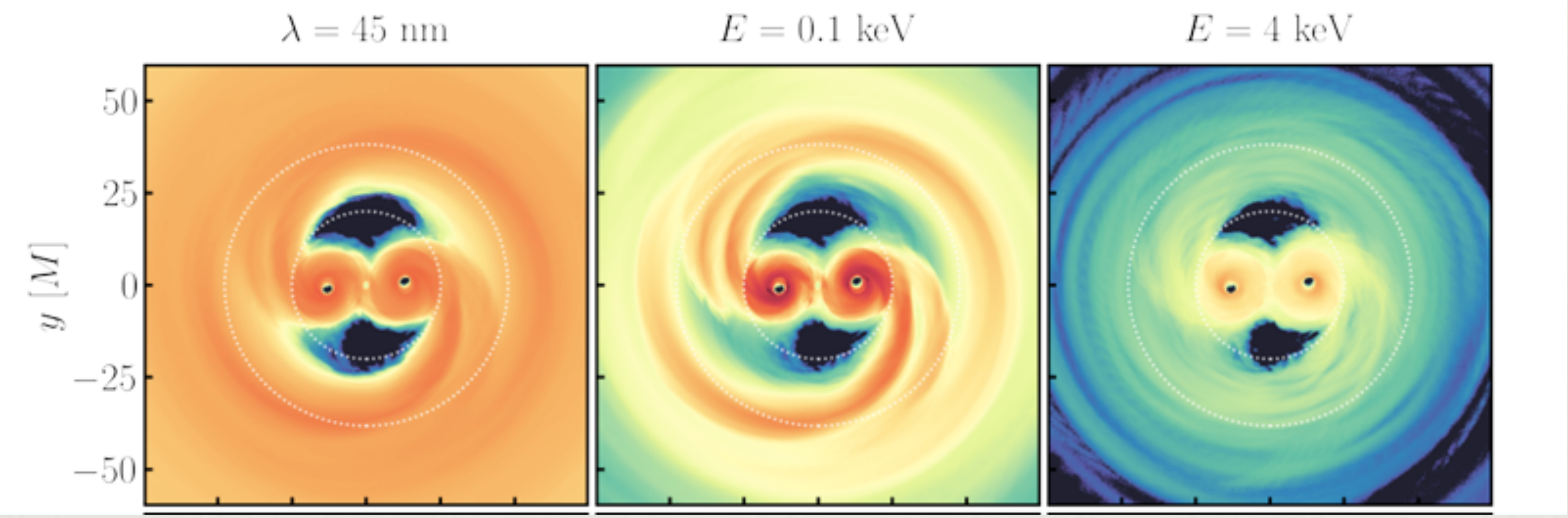
+Jets (Palenzuel+10; Moesta+2012)

Astro WG White Paper;
Figure adapted from Bowen+ 18 Credits: Volonteri, Krolik

See also: Sgi+21;Gold+14; Farris+14;Roedig14;Tang+18;Haiman 17; Bowen+17; Pascalidis+21; Armengol +21; Combi+22

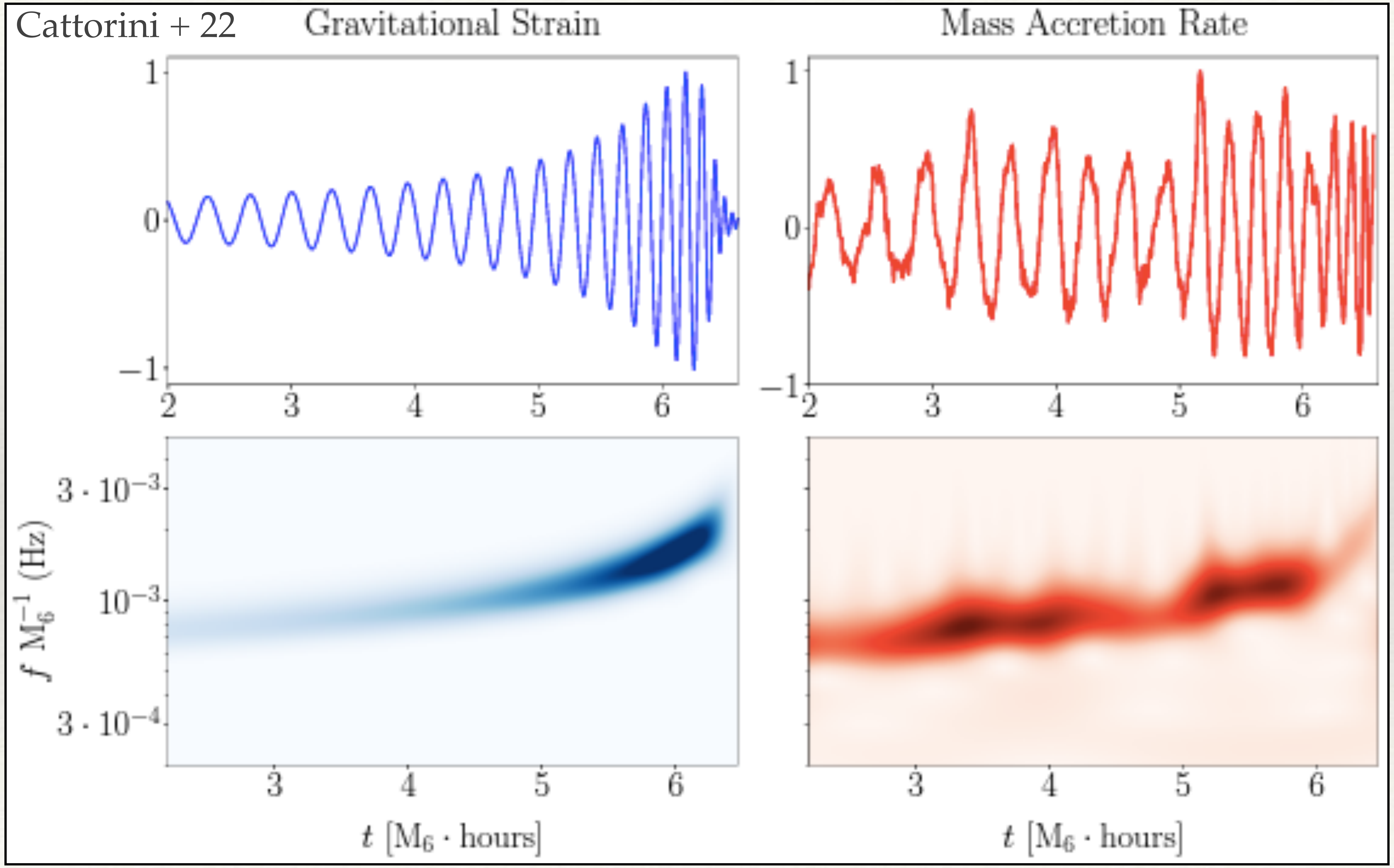
Accretion discs' multiwavelength emission





Gutierrez et al. 2022

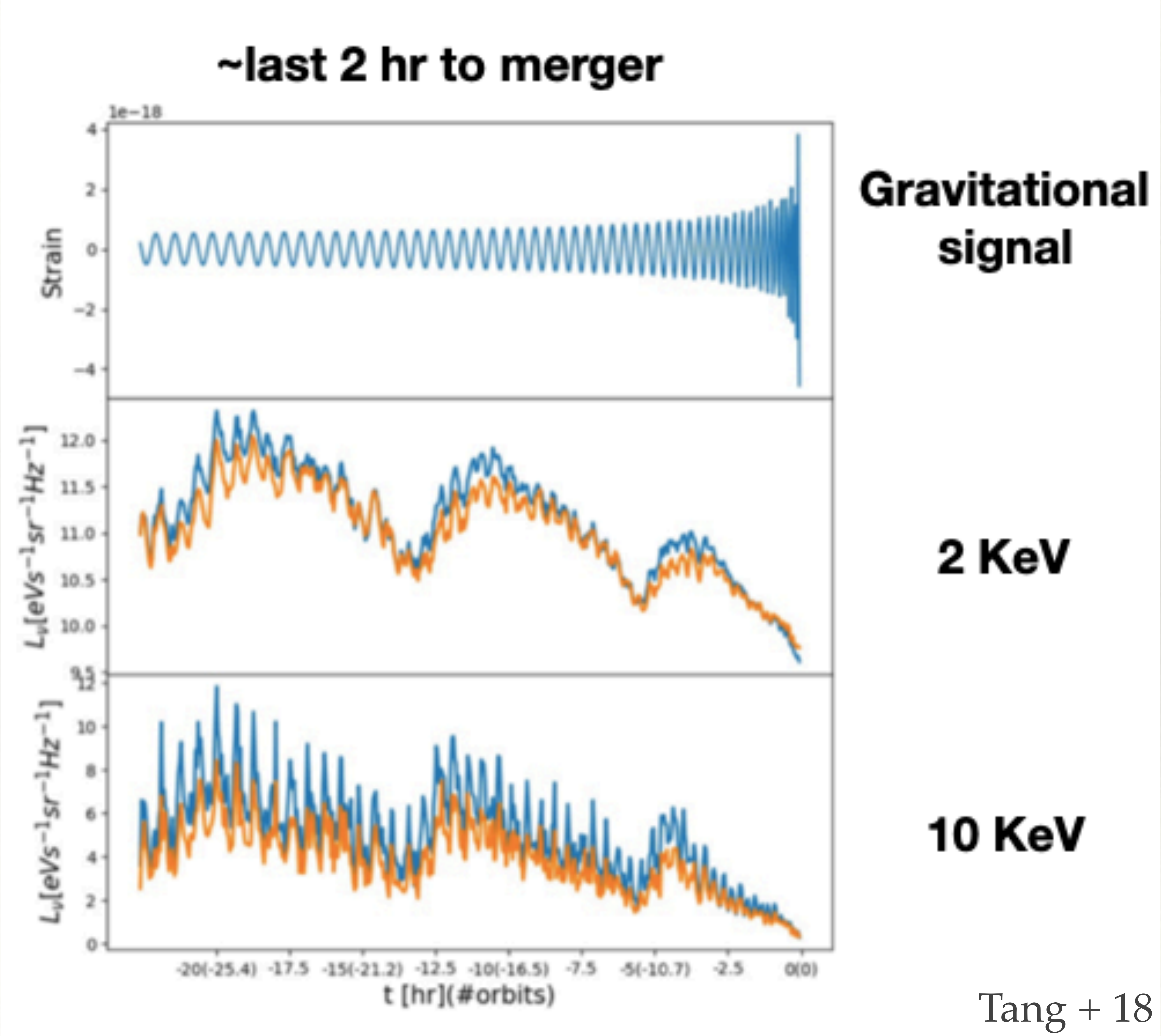
Multimessenger variability



see also: Roedig+14; Farris+ 2014; Tang + 18; Bowen + 17,18, Yike+18; D'Ascoli+18; Kelley+19

Multimessenger variability

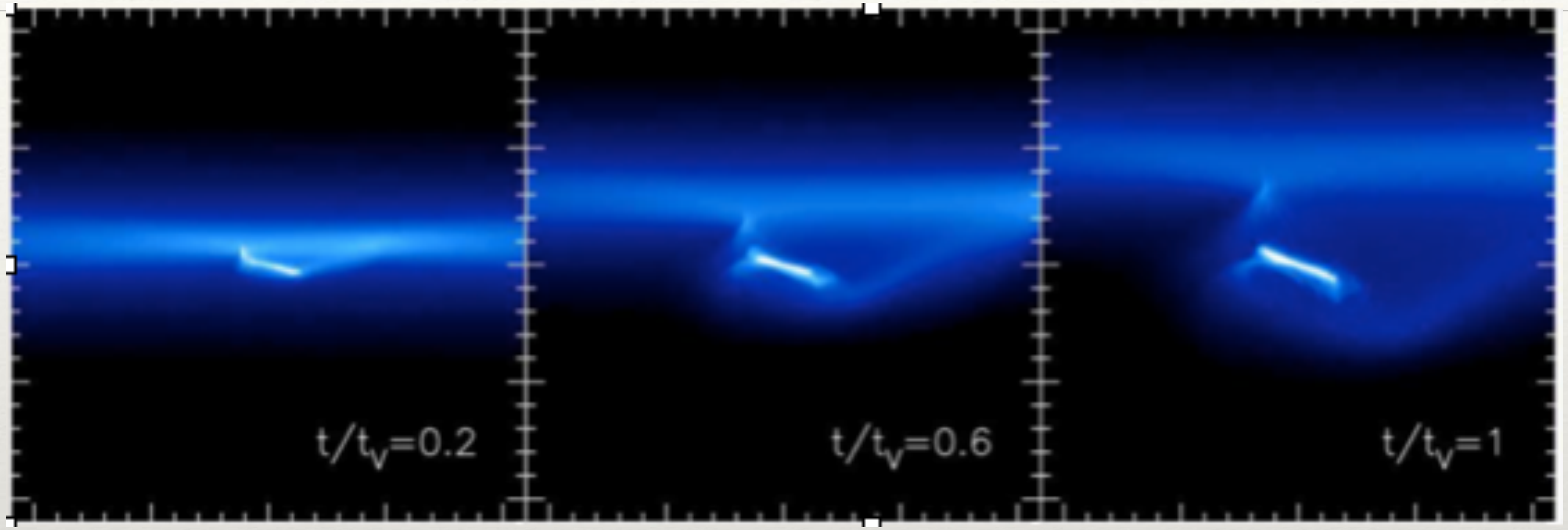
X-ray emission may be modulated in time with characteristic frequencies linked to orbital motion and/or surrounding fluid patterns



Tang + 18

Accretion disc related emission: *post*-merger phase

GW recoil driven shocks



Rossi + 2010

- SMBH spins parallel ==> recoil in the disc plane with the highest luminosity: what is the spectral shape?

- Recoils with velocity > 1000 km/s create the so called "wandering black holes"

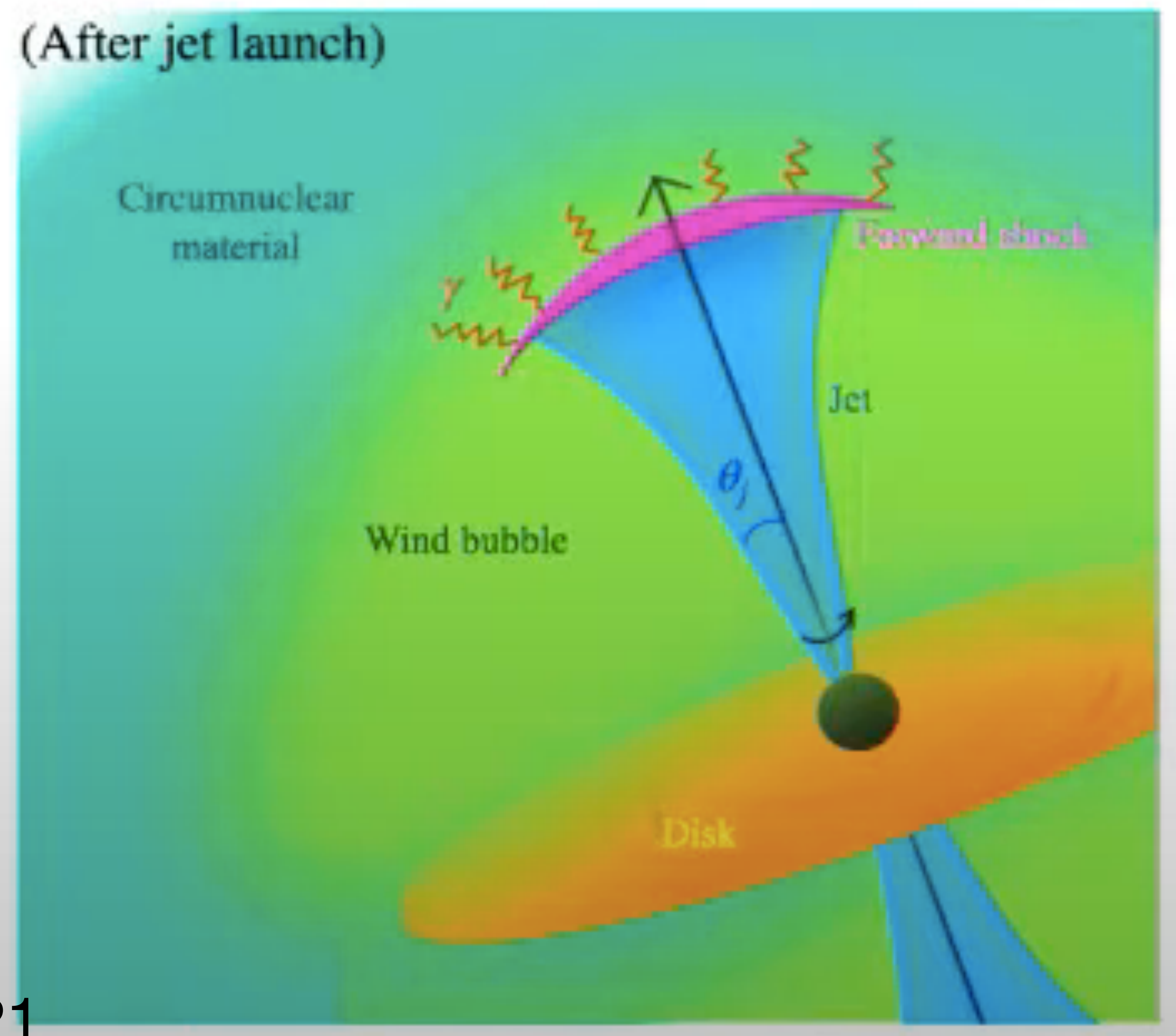
See also: Lippai+ 08; Shields & Bonning 08; Schnittman & Krolik 08; Megevand+ 09;

AGN-type accretion resumed after merger

Additional post merger emission from:

- Turned-on AGN as accretion resumes (Milosavljević and Phinney 05)
- Re-formation of X-ray corona and jet: non-thermal X-rays and gamma-rays

Yuan+21, Gold + 2014, and Khan +2018



Yuan+2021

post-merger: not your fast transient!

- Timescales for post-merger accretion emissions are likely to be $\sim$**months to years.**

- Timescale for jet to be visible: days to months

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What is needed for realise the potential of the multi-messenger detections?

Focusing on Type 1 EM Counterparts

- **Theory**: more robust predictions with radiative transfer to make predictions of EM light-curves and spectra of coalescing MBHBs <u>under a variety of conditions</u>

  Challenges: Dynamical range (resolution!); physics (3D, GR, MHD, radiative transfer, feedback); wide parameter surveys to simulate wide range of events.

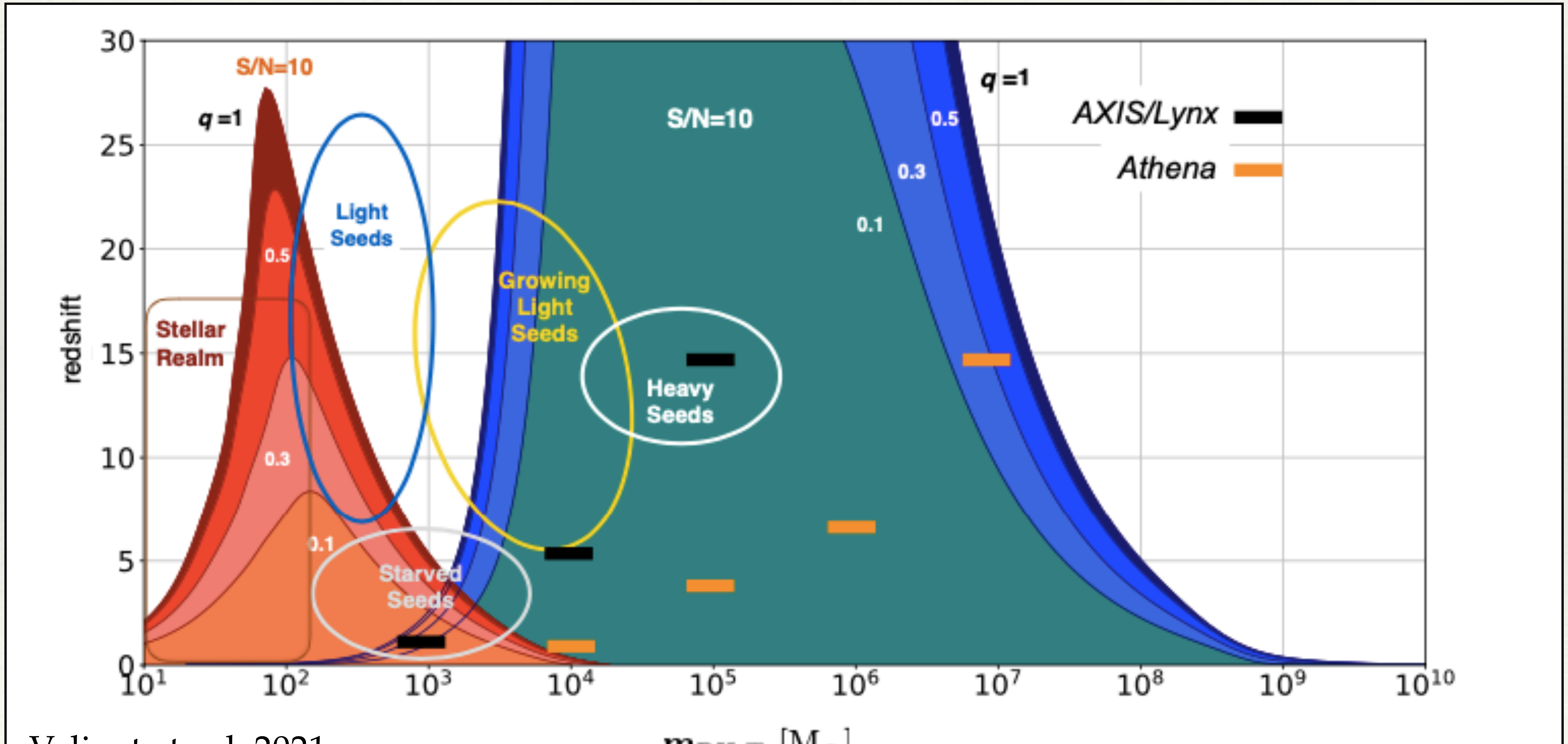
  Finally, simulate mock observations !

What is needed for realise the potential of the multi-messenger detections?

- **Accretion:** Better characterisation of *low mass* AGN (level of obscuration, bolometric correction, intrinsic variability, spectra), between $10^5 - 10^7 M_{\odot}$. A multi wavelength descriptions.

What is needed for realise the potential of the multi-messenger detections?

- **Accretion, LISA triggered detections:** X-rays.



Valiante te al. 2021

What is needed for realise the potential of the multi-messenger detections?

- **Jets:** Radio facilities to detect Jet emission (SKA, ngVLA).
- **Optical survey instruments** (such as Rubin Observatory, Roman Te) for localisation and accretion/jet characterisation
- **Directly imaging** MBHB orbits radio, via advances in Very Long Base Interferometer at mm-wavelengths. EHT has the ability and angular resolution to astrometrically track the orbits of MBHB with 0.01 pc separation at Gpc distances.
- **Host galaxies**: Increasingly complete catalogues of *dwarf* galaxies
- **Multi-band observations: GW observatories in space/on earth** together with LISA to improve localisation and/or increase Massive ($> 10^2 M_\odot$) Black Hole mass range covered