Radiation from Supermassive Black Hole Binaries Approaching Merger

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Credit Image: NASA's GSFC, Scott Noble; simulation data, d'Ascoli et al. 2018
Despite most GW detections were BH mergers, no clear EM counterpart was detected. This is not surprising; stellar-mass BHs suffer 'dry' mergers.
And what about binary systems of **Supermassive Black Holes**?

How do supermassive black hole binaries form and evolve?

- **kpc**: Galaxy Mergers. Relaxation
- **pc**: Lose angular momentum
- **sub-pc**: Inspiralling (GW emission)
- **\( r_g \)**: BH merger

*The study of SMBBHs is fundamental to understand the formation and accretion history of SMBHs across cosmic ages.*

Adapted from L. Combi’s slides.
The NANOGrav 15 yr Data Set: Evidence for a Gravitational-wave Background

Consistent with astrophysical expectations for a signal from a population of supermassive black hole binaries!
Contrary to stellar-mass BH binaries, supermassive black hole binaries would be located in **gas-rich environments**

$$L \sim \dot{M}_B \propto M_{BH}^2$$

EM emission?

Accretion structure may be quite different from what we know of single BH accretion disks

$$a_{cav} \sim 2r_{12}$$
THE PROBLEM: Identifying SMBHBs before/during/after merger -> theoretical and observational problem

- How is the accretion system? How much matter falls into the cavity and forms a disk?

- How much matter is close to the black holes at the merger? When does the decoupling occur? -> EM bright merger?

- Do SMBHBs produce dual Jets? EM signatures associated?

- Post-merger -> Kicks? Reborn accretion disk and rebrighting?

- Other messengers? Neutrinos or CRs?
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Proposed EM signatures: 

**PG 1302-102**  
(Graham+ 2015, D’Orazio+ 2015, Jun+2015) 

Not confirmed. It could be statistical red-noise. Need many cycles. 

**Self-lensing?**  
(D’Orazio+ 2017, Ingram+ 2021, Davelaar+ 2022, Gutierrez+ in prep) 

Adapted from S. Noble’s slides 

**OJ 287** 

**PKS 2131–021**  
(O’Neill+ 2021)
Simulating SMBHB is a multi-scale and highly non-linear problem

Different numerical strategies and techniques are applied!

Matter + Gravity

Viscous Hydro. + Newtonian

MHD + Newtonian

GR-MHD + Numerical Relativity

Adapted from S. Noble’s slides
GRMHD simulations of SMBBHs approaching merger

- For cold disks and $q \sim 1$, the accretion system has an overdensity at the inner cavity, called the ‘lump’
- Formation of minidisks

Modulated accretion onto cavity at the **beat frequency** between the lump and the disks

From R. Mignon-Risse’s slides

Consistently found in several simulations (hydro 2D -> 3DGRMHD)

\[
f_{\text{lump}} \sim 0.28f_{\text{bin}}
\]

\[
f_{\text{beat}} \sim f_{\text{bin}} - f_{\text{lump}} \sim 0.72f_{\text{bin}}
\]

*(Bowen+ 2019)*
How massive are minidisks?

- Interplay between ISCO and Hill Sphere
  - Hill sphere increases with separation
  - ISCO decreases with spin

\[ r_{tr} \sim 0.35r_{12}(t) \]

(Combi+ 2022)
How massive are minidisks?

- Interplay between ISCO and Hill Sphere

<table>
<thead>
<tr>
<th>High spin</th>
<th>Low spin</th>
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\[ r_{\text{tr}} \sim 0.35 r_{12}(t) \]

Bright & Paschalidis (2022)
Calculation of EM emission

Camera-to-source approach

\[ \frac{d^2 x^\mu}{d\lambda^2} + \Gamma^\mu_{\alpha\beta} \frac{dx^\alpha}{d\lambda} \frac{dx^\beta}{d\lambda} = 0 \]

Geodesic equation

\[ \frac{\partial I}{\partial \lambda} = j - \alpha I \]

Radiative transport equation

High-accretion rate systems

Opt. thick

Low-accretion rate systems

Opt. thin

(Noble+ 2007, dAscoli+ 2018, Gutierrez+ 2022)
Different components dominant at different frequencies

(Gutiérrez et al. 2022)
How do circumbinary disks and mini-disks compare with standard single black hole accretion disks? A `notch`?

- Circumbinary disk very similar to a truncated Shakura-Sunyaev disk.
- Mini-disks are less bright due to low radiative efficiency. Most of the matter falls into the hole directly.
- ‘Notch’ absent due to
  - Less bright minidisks
  - Stream emission
Spinning 
\((a=0.6)\)

Data from 
Combi+ (2022)

Optically thin plasma: Kinematic effects are important; Self-lensing produce strong flares!

Gutiérrez et al. (2023b, in prep.)
Highly dependent on the line-of-sight inclination

Gutiérrez et al. (2023b, in prep.)
What about jets?

- Possibility of **dual** jets -> EM signatures?
- Important questions: how do they compare with single AGN jets? Are they equally bright? How do the emission change during merger? -> MM merger

- Individual jets? Unique jet?
- Simulations show a jet efficiency of ~ 10% for spinning black holes
- Dual jet interaction? $L_j \sim \eta_{\text{eff}} \dot{M} c^2$

Paschalidis et al. (2021)

Combi et al. (2022)
Jet-jet interaction: *non thermal radiation*?

Magnetic reconnection

Semenov et al. (2004)

Bright & Paschalidis (2022)

Gutierrez et al. (2023, submitted)
Radiation from dual jet interaction

Dissipation at a height

\[ z_{\text{diss}} \sim \left(\frac{r_{12}}{2}\right)/\theta \]

\[ B' \approx 1.5 \times 10^3 \eta^{-1/2} \dot{m}^{1/2} M_f^{-1/2} \left(\frac{\Gamma_j}{3}\right)^{-1} \left(\frac{r_{12}}{30 R_g}\right)^{-1} \text{ G} \]

Particle acceleration

\[ \frac{d}{d\gamma''} \left[ \dot{\gamma''} |_{\text{loss}} N''(\gamma''; \xi) \right] + \frac{N''(\gamma''; \xi)}{t'_{\text{esc}}} = Q''(\gamma''; \xi), \]

\[ v_{\text{obs}} F_{v_{\text{obs}}} (t_{\text{obs}}) = \left( \frac{3\mu (\tau'')}{\tau''} \right) \frac{D_p A V''}{d_L^2} v'' j''_{v''}(t_{\text{em}}) \]

Periodicities? Flaring behavior?
Takeaways

SMBH binaries are very likely **multimessenger** sources, we need **good-precise-predictions** to identify them:

- **before**, during, and after merger
- **very hard problem** (need complex and expensive simulations)
- possible signatures: periodic modulations (Doppler boosting, **variable accretion rate**, BL shifting, jet precession), **periodic flares** (self-lensing, jet-jet interaction?), unique SED features?
Background slides
Different observational strategies needed for different systems: masses, separations, mass ratios

For a SMBHB of $M = 10^9 M_\odot$ short observations every $\sim 5$ days and catch the variabilities.

Self-lensing for $q=0.1$

Porter, EG, + in prep.