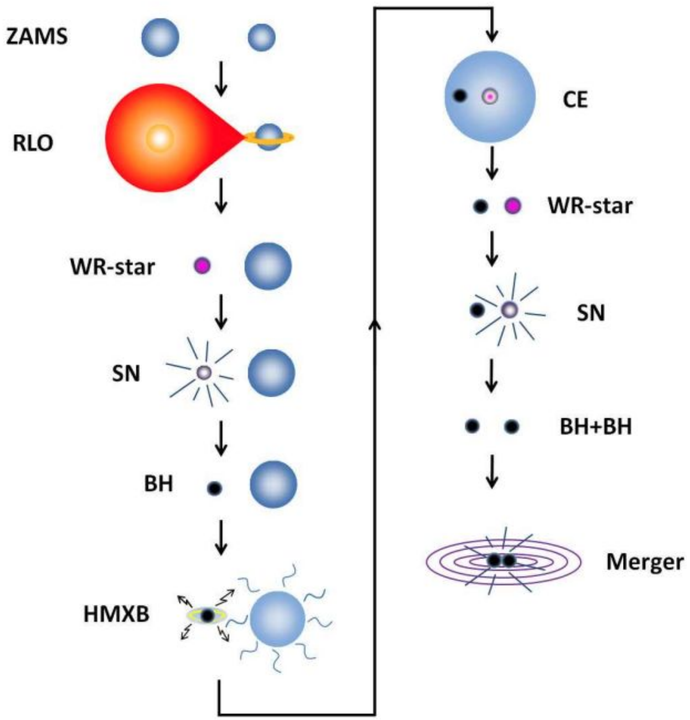
Candidate Electromagnetic Counterpart to the Binary Black Hole Merger S190521g

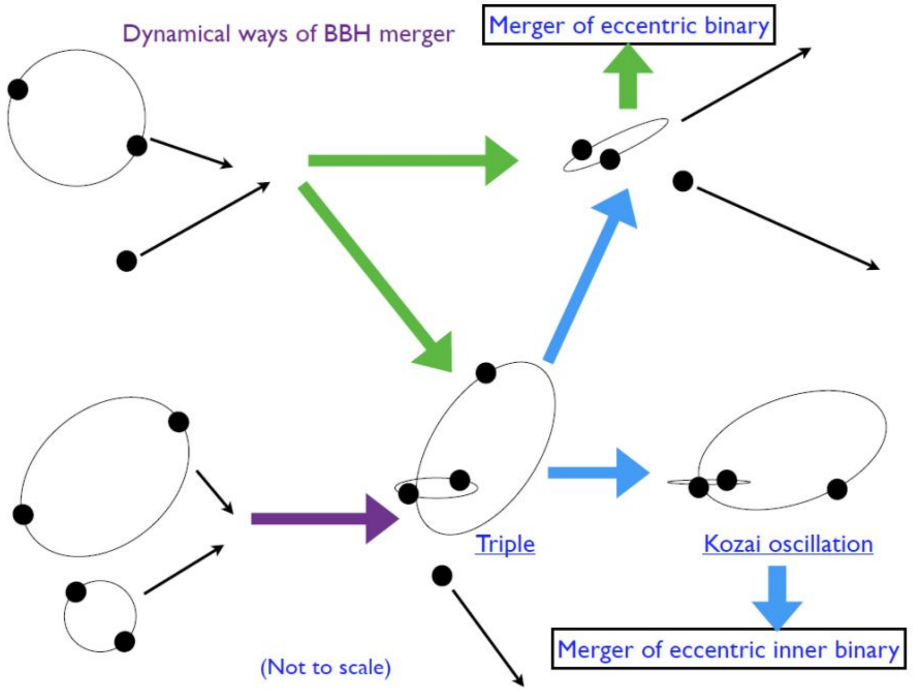
M.J. Graham, K.E.S. Ford, B. McKerman et al. 2020
Phys. Rev. Lett. 124, 251102

Stellar binary black hole formation scenarios

Isolated Field Binary Mergers

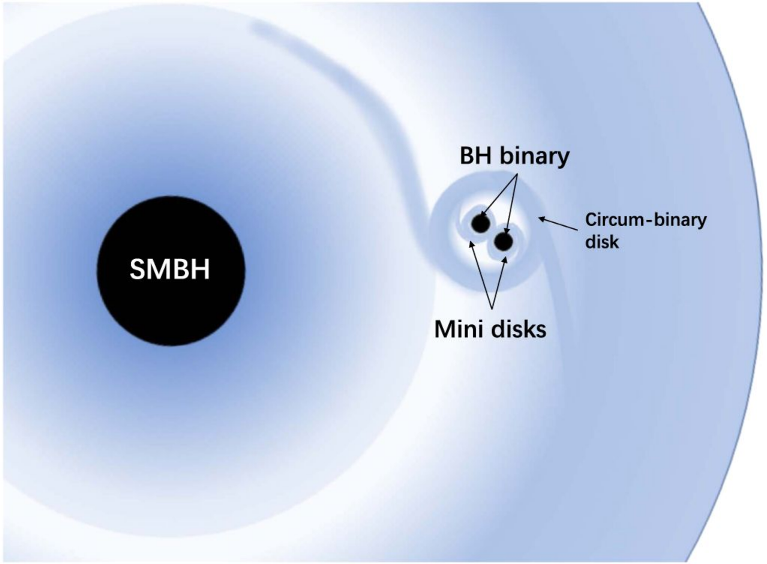


Dynamical Mergers



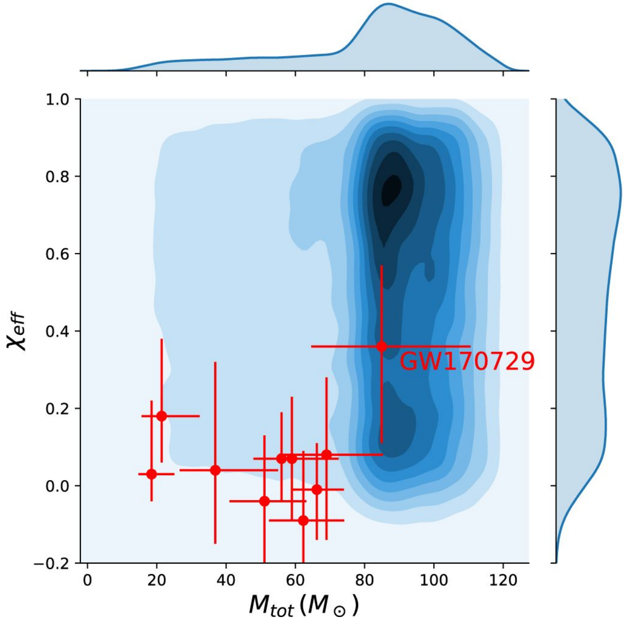
Banerjee et al. 2016

EM counterparts from stellar BBH mergers?



- Merger of two BHs in gaseous AGN disk can generate EM counterpart
- Dynamical formation scenario

- Other LIGO massive BBHs: GW170817A and GW170729
- Simulated probability density of BBH mergers in AGN disks



Yi & Cheng 2019, ApJ, 884, 1

Searching for candidate counterparts to S190521g with the Zwicky Transient Facility

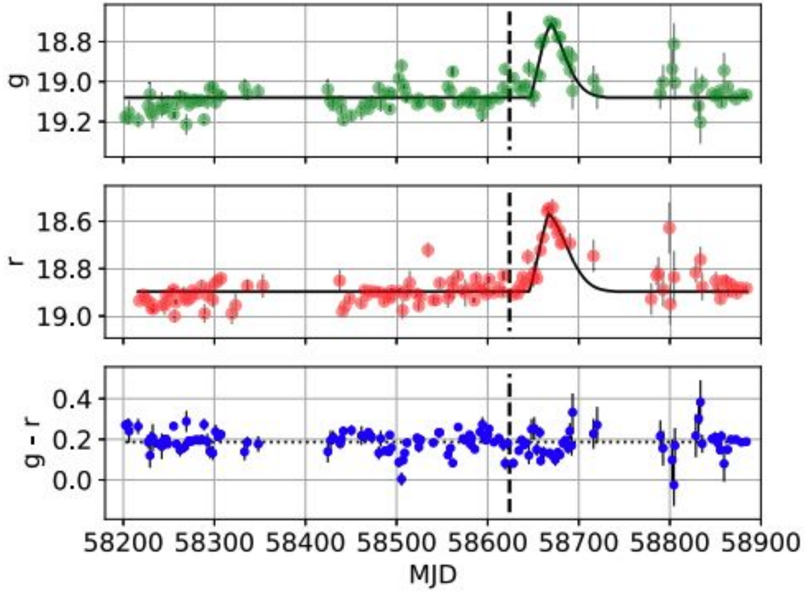
Zwicky Transient Facility (ZTF)
optical survey on Samuel Oschin 48in telescope
Site: Palomar, CA, USA
FOV: 47 sq. deg.
3750 sq. deg. / hour to 20.5 r-mag

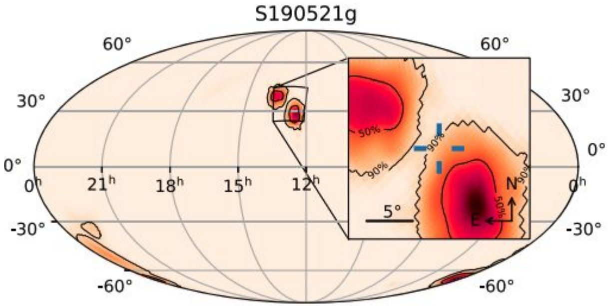
Image credit: astro.caltech.edu

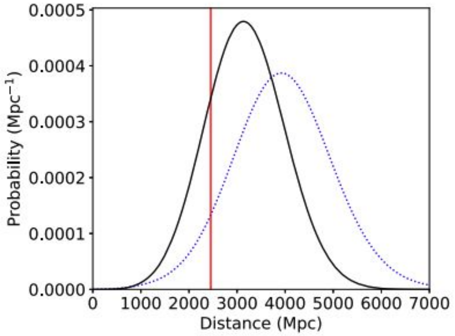
- General Search
  - Total of 21 BBH triggers in O3a
  - Positional consistency: within 90% confidence region, and 3sigma distance
  - AGN identified with Million Quasar Catalog
  - Search for flaring AGN activity within 60 days post-LIGO trigger in ZTF alert stream
- S190521g event properties
  - FAR = 3.8 * 10^(-9) Hz
  - dL = 3931 +/- 953 Mpc (updated: 5.3 Gpc)

(Graham et al. 2020)

ZTF19abanrhr: a candidate EM counterpart



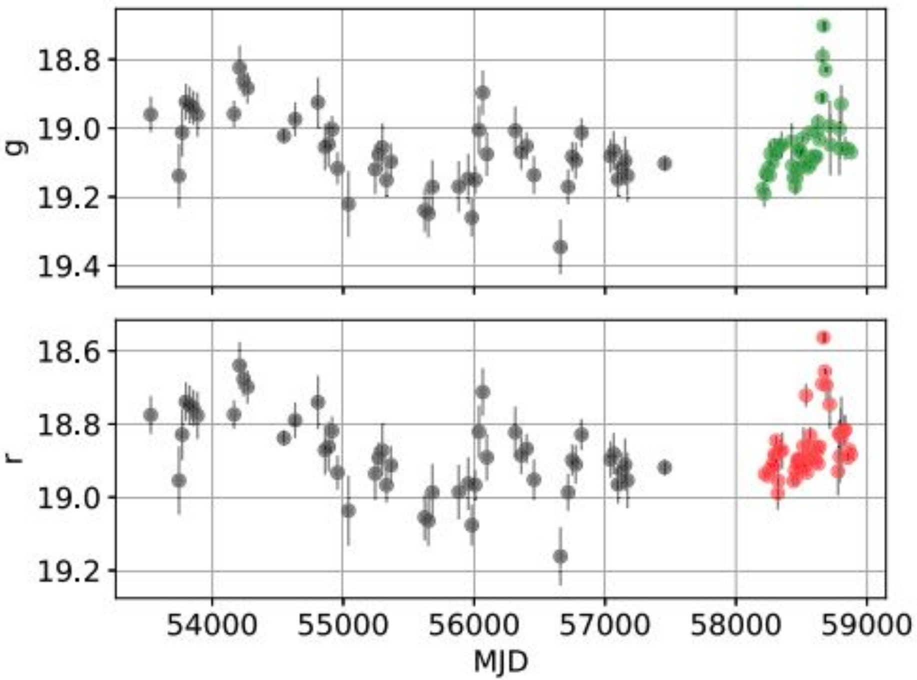


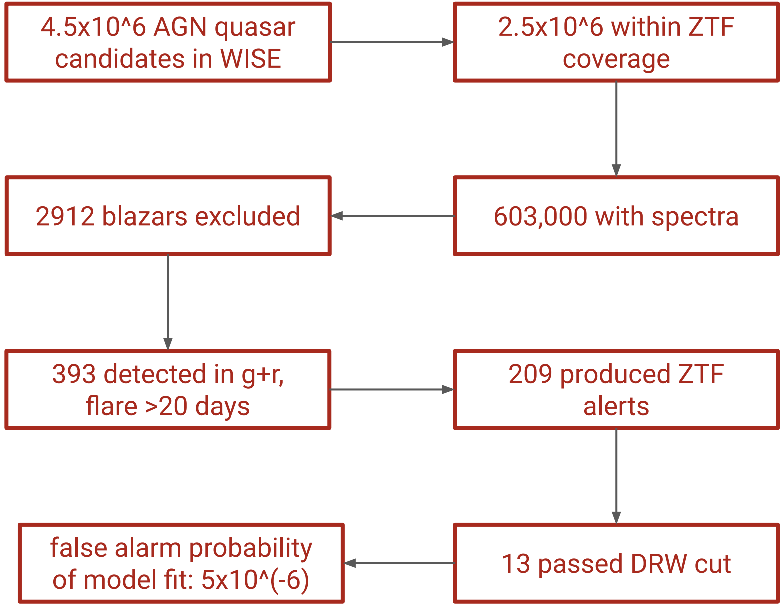


(Graham et al. 2020)

- Announced ~34 d after GW trigger
- associated with AGN J1249+3449 at z=0.438
- 78% contour (2D)
- 1.6 sigma from marginal luminosity distance
- M~10^8 Msun (line profile)
- rate: 10^(-5) events in area and time considered
- flare: 10^(45) erg/s increase over 50 days → 10^(50) erg released!

False Positives I: AGN variability





From damped random walk (DRW) model fits, an equivalent flare is found in 4 out of 250,000 simulations of the lightcurve: 0.002% probability of ZTF19abanrhr arising from an AGN flare (Graham et al. 2020).

False Positives II, III and IV: SNe, Microlensing and TDEs

II. Supernovae

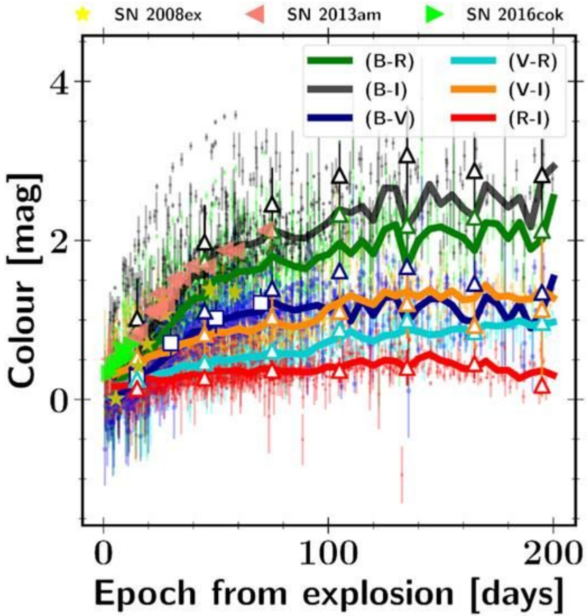
- Rate: occur in AGN disks at ~2 x 10^(-7) / AGN / yr
- Timescale: rise time 20-50 days, decay time 100-200 days
- Color: evolves over time (typically reddens)

III. Microlensing

- Rate: 10^(-4)/AGN
- Timescale: ~years
- Color: Uniform, at rest-frame UV/optical

IV. Tidal Disruption Events

- Occur around central SMBH in galaxy for M < 10^8 Msun
- Rate of BH-NS TDEs: 4-113 (f_AGN/0.1) / yr
- Total energy: 10^(52) erg (BH-NS); 10^(49) - 10^(51) erg (Type Ia SN from BH-WD)

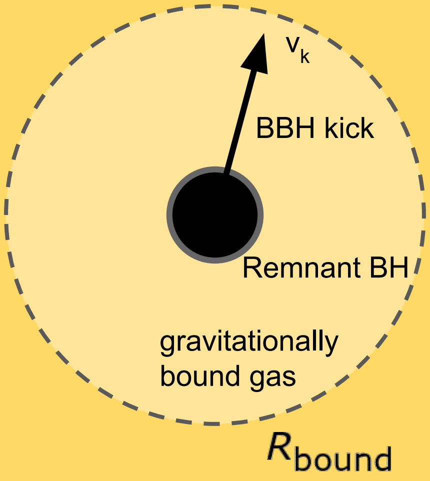


Jaeger et al. 2019, MNRAS, 490, 2

Mass estimation

$$A_{90} \propto \mathrm{SNR}^{-2} \longrightarrow$$ SNR ~ 8.6

$$\mathrm{SNR} \propto \frac{M_c^{5/6}}{d_L} \longrightarrow$$ BBH total mass ~ 150 M_sun



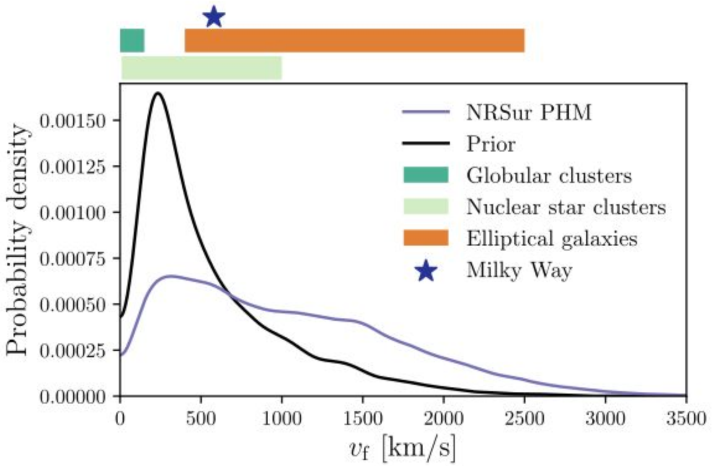
- Gravitationally bound region

$$R_{\rm bound} < \frac{GM_{\rm BBH}}{v_k^2}$$

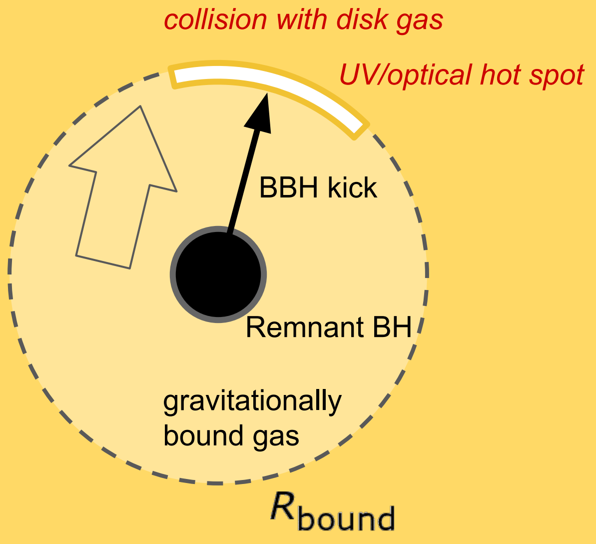
$$\frac{R_{\rm bound}}{R_H} = 0.34 \left(\frac{q}{10^{-6}}\right)^{2/3} \left(\frac{a}{10^3\, r_g}\right)^{-1} \left(\frac{v_k}{200\,\mathrm{km/s}}\right)^{-2}$$

v_k : kick velocity
$q = M_{\rm BBH}/M_{\rm SMBH}$

a : semimajor axis of BH orbit around SMBH
$r_g = GM_{\rm SMBH}/c^2$



Post-merger kick posterior from Abbott et al. 2020 (GW190521 paper)



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v_k : kick velocity a : semimajor axis of BH orbit around SMBH

$q = M_{\rm BBH}/M_{\rm SMBH}$ $r_g = GM_{\rm SMBH}/c^2$

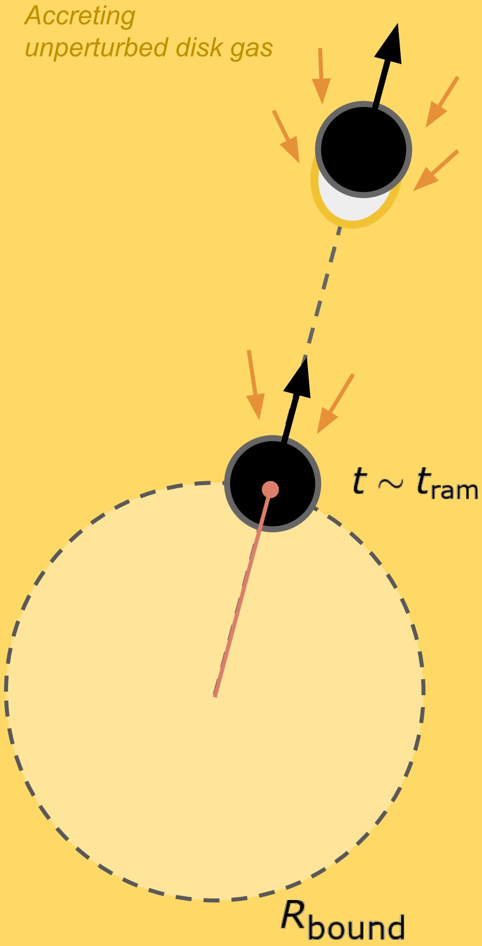
- Total energy delivered to the bound gas

$$E = \frac{1}{2} M_b v_k^2$$

$$= 3\times 10^{45}\,{\rm erg} \left(\frac{\rho}{10^{-10}\,{\rm g\,cm^{-3}}}\right) \left(\frac{M_{\rm BBH}}{100\,M_\odot}\right)^3 \left(\frac{v_k}{200\,{\rm km\,s^{-1}}}\right)^{-4}$$

inadequate to explain ZTF19abanrhr

* total energy ~ $O(10^{51}$ erg$)$



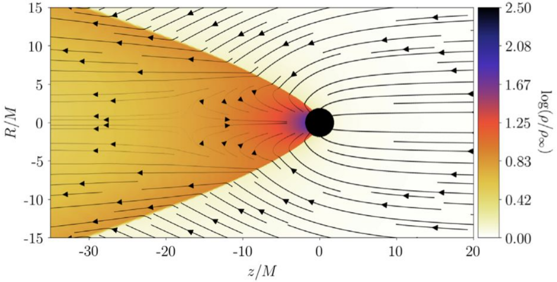
$$t_{ram} = \frac{R_{bound}}{v_k}$$

$$\sim 20\,\mathrm{days} \left(\frac{M_{BBH}}{100\,M_\odot}\right)\left(\frac{v_k}{200\,\mathrm{km\,s^{-1}}}\right)^{-3}$$

~ 29 days in observed frame

- BH enters unperturbed disk gas at t > t_{ram}

$$\dot{M}_{BHL} = \frac{4\pi G^2 M_{BBH}^2 \rho}{(v_k + c_s)^3}$$

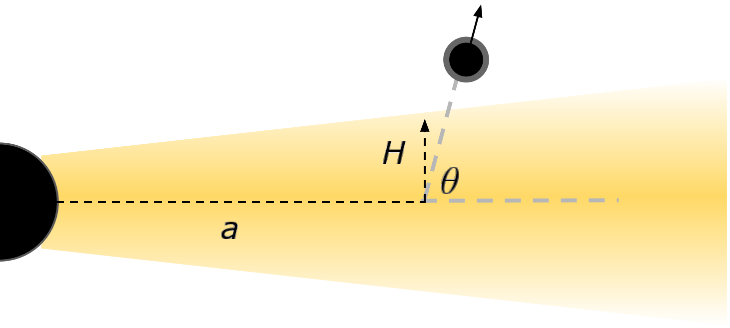


Tejeda and Aguayo-Ortiz 2019

$$L_{BHL} \approx 2.5 \times 10^{45}\,\mathrm{erg\,s^{-1}} \times \left(\frac{\eta}{0.1}\right)\left(\frac{\rho}{10^{-10}\,\mathrm{g\,cm^{-3}}}\right)\left(\frac{M_{BBH}}{100 M_\odot}\right)^2\left(\frac{v_k}{200\,\mathrm{km\,s^{-1}}}\right)^{-3}$$

- Slowing down timescale

$$t_{dec} = 224\,\mathrm{yr}\left(\frac{\rho}{10^{-10}\,\mathrm{g\,cm^{-3}}}\right)^{-1}\left(\frac{M_{BBH}}{100 M_\odot}\right)^{-1}\left(\frac{v_k}{200\,\mathrm{km\,s^{-1}}}\right)^{3}$$



- EM signal ends if BH exits the disk

$$t_{\rm end} = 67\,{\rm days}\ \frac{1}{\sin(\theta/60^\circ)}\left(\frac{a}{700r_g}\right)\left(\frac{H/a}{0.01}\right) \times \left(\frac{v_k}{200\,{\rm km\,s^{-1}}}\right)^{-1}\left(\frac{M_{\rm SMBH}}{10^8\,{\rm M_\odot}}\right)$$

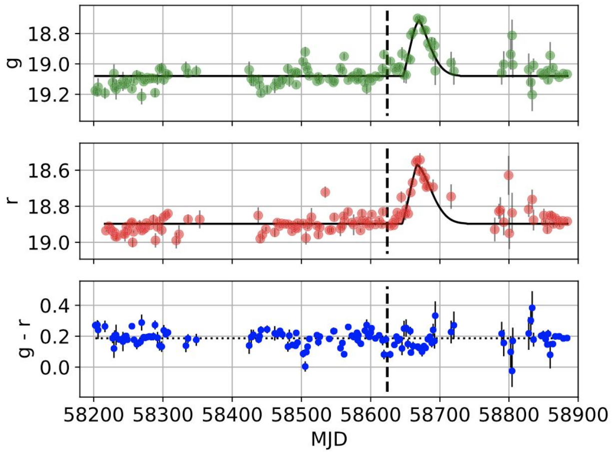


Fig 2 from the paper

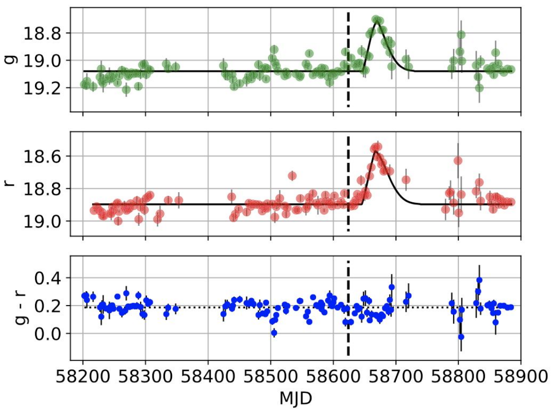
- Photon diffusion timescale

$$t_{\rm diff} = 8\,{\rm days}\ \left(\frac{\tau}{100}\right)\left(\frac{H/a}{0.01}\right)\left(\frac{a}{700r_g}\right)\left(\frac{M_{\rm SMBH}}{10^8\,{\rm M_\odot}}\right)$$

smearing out lightcurve emergent from the disk surface

Parameter estimation

Convolve shock lightcurve with M-B distribution:



From fitting the EM data:

$t_{\rm diff} = 38^{+2}_{-1}$ days $\quad t_{\rm delay} = 23^{+1}_{-1}$ days $\quad t_{\rm end} = 80$ days

And total energy ~ 10^{57} erg.

From g-r color: low temperature, so kick velocity not too high

Brief duration (~40 days in observed frame, ~28 in source frame) -> remnant exit the disk

Assuming M_{BBH}~100 Msun and t_{ram} ~ t_{delay} they recover the other parameters:

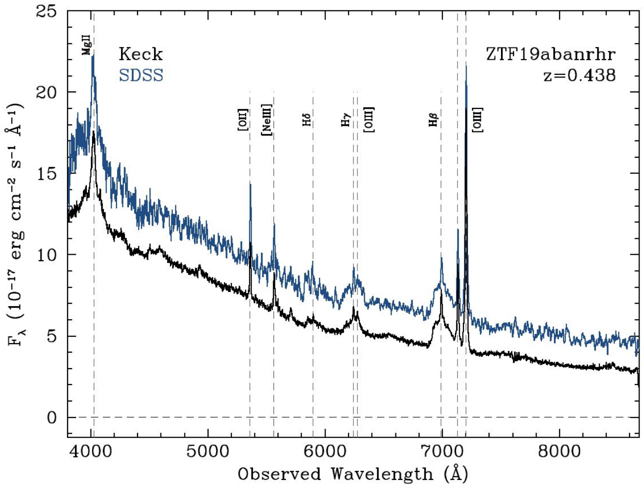
$v_k \sim 200\ \mathrm{km\,s^{-1}}$ scales with t_{ram} and M_{BBH}

E_{tot} ~ t_{flare} L_{BHL} -> L_{BHL} ~ 10^{45} erg/s

Assuming the event happens in the migration trap (a~700 r_G):

$H/a \sim 0.01 \qquad \theta \sim 60°$

Other tests of association



- From the spectrum: the flare is off-center and produces an asymmetric illumination of the broad-line region clouds -> asymmetric broad line profile that decays on the same timescale of the flare. Unfortunately spectrum taken too late.
- The kick velocity is not high enough to escape the disk: the remnant must come back (another Bondi-accretion flare) in a timescale

$$1.6 \text{ yr}(M_{\rm SMBH}/10^8\ M_\odot)(a/10^3 r_g)^{3/2}.$$

- Hierarchical origin: significant spin and moderate kick

Future observations

- Delay between GW and EM depends on density and height of the disk
- Strength of the the signal depends on BBH mass squared, recoil kick velocity to the negative three power, and the AGN disk gas density

  -> brightest will be massive, small kicks, dense disks

- Timescale of the second flares depends on the mass of the SMBH