Neutrino Emission during Supermassive and Stellar Mass Binary Black Hole Mergers

NASA.gov

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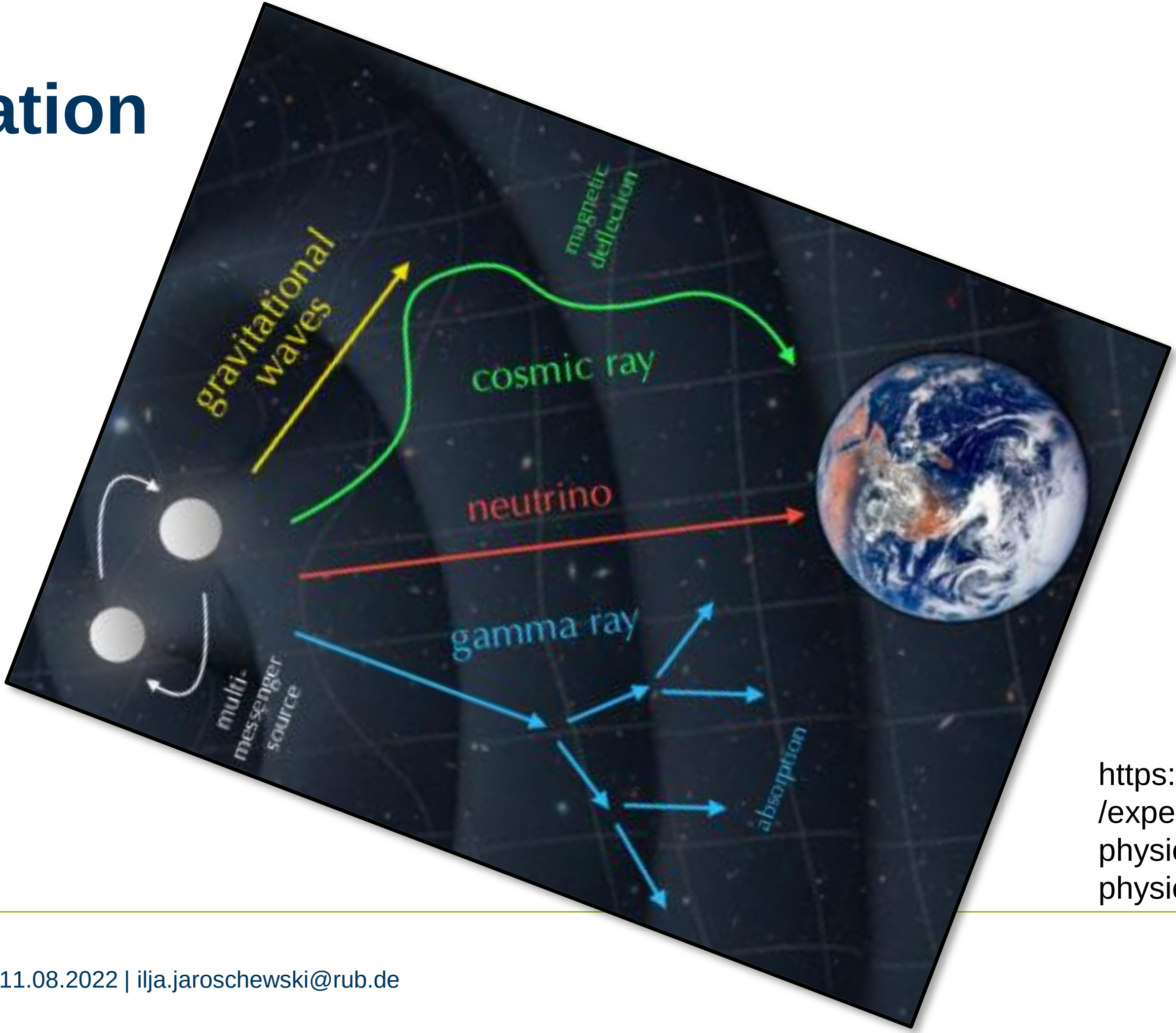
Motivation



https://nbi.ku.dk/english/research/experimental-particle-physics/icecube/astroparticle-physics/

Motivation

- **Diffuse astrophysical neutrino flux measured at IceCube:**

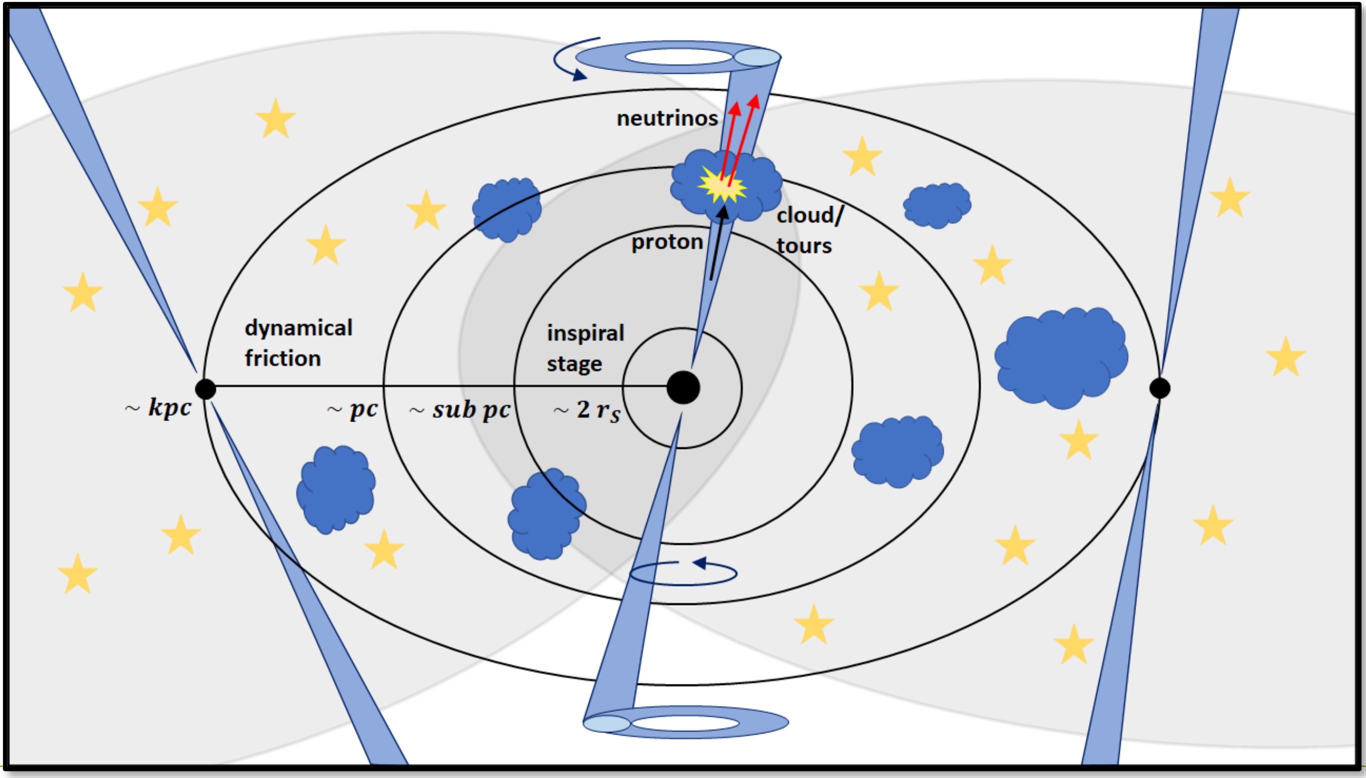
Question: What are the sources?

- **Possible correlation of a high-energy neutrino with a gamma-ray flare from the blazar TXS 0506+056 in 2017 (Aartsen+ 2018)**
- **2014/2015 long-duration TeV neutrinos flare without gamma-ray flare from TXS 0506+056 (Aartsen+ 2018)**
- **Idea by Gergely & Biermann (2009):**

→ SMBBH merger accompanied with a spin-flip of the jet

How can a merger produce neutrinos?

1. SMBBH mergers



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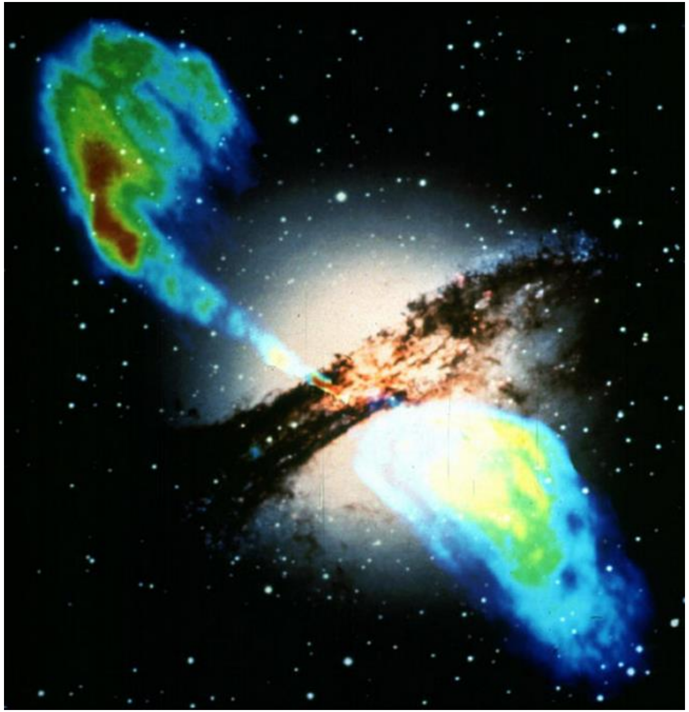
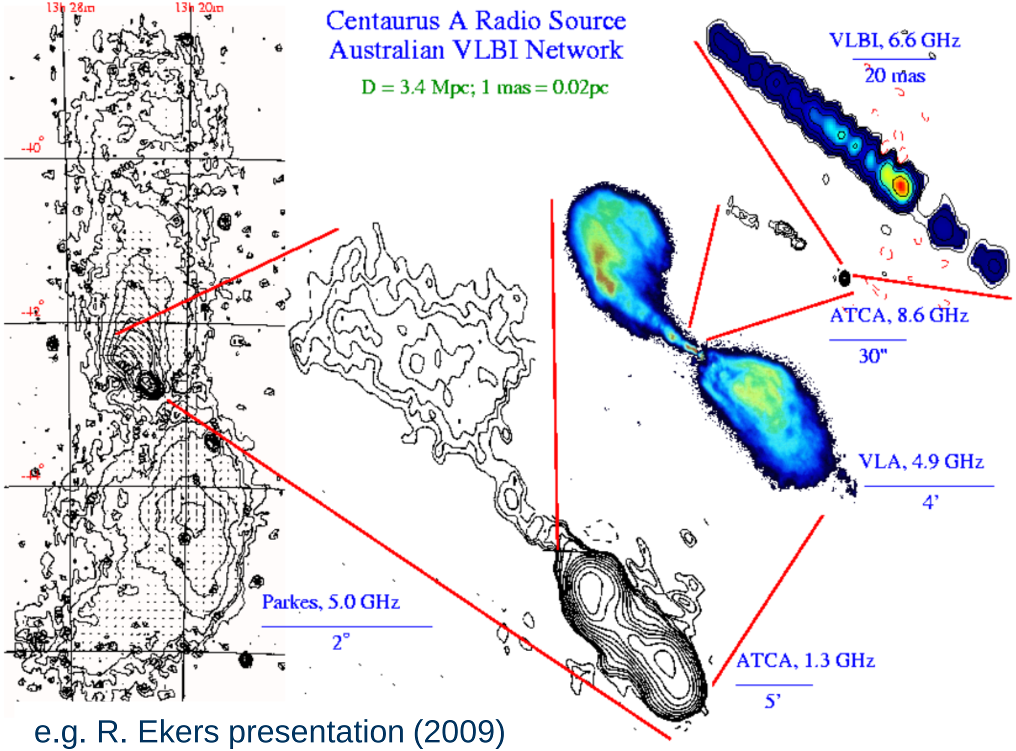
Cen A – a recent SMBBH merger?



ESA/Hubble



e.g. R. Ekers presentation (2009)

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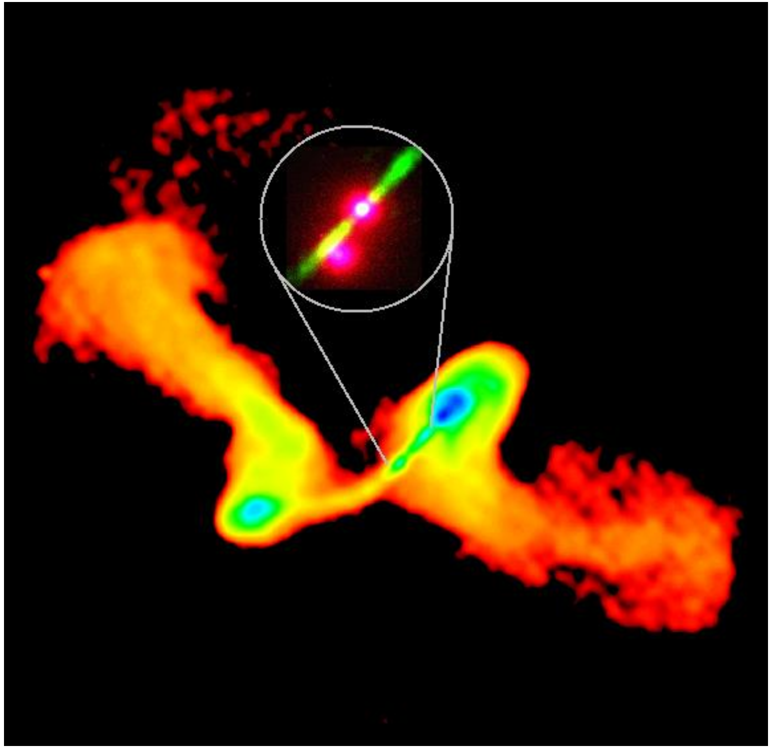
Radio Galaxie NGC326



National Radio Astronomy Observatory / AUI, observers Murgia et al. STScI (inset)

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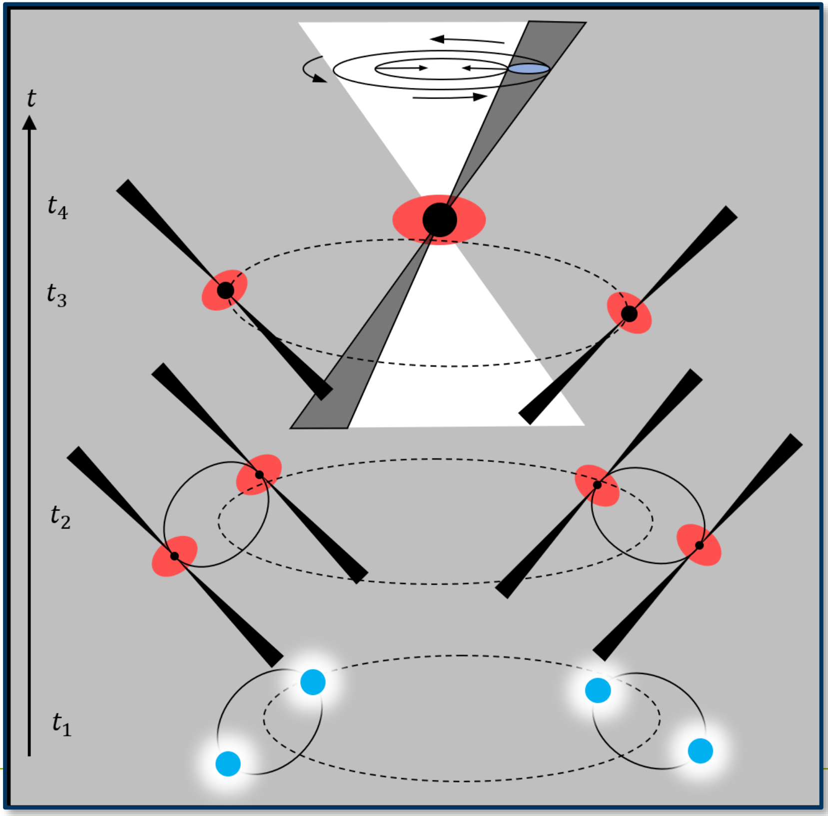
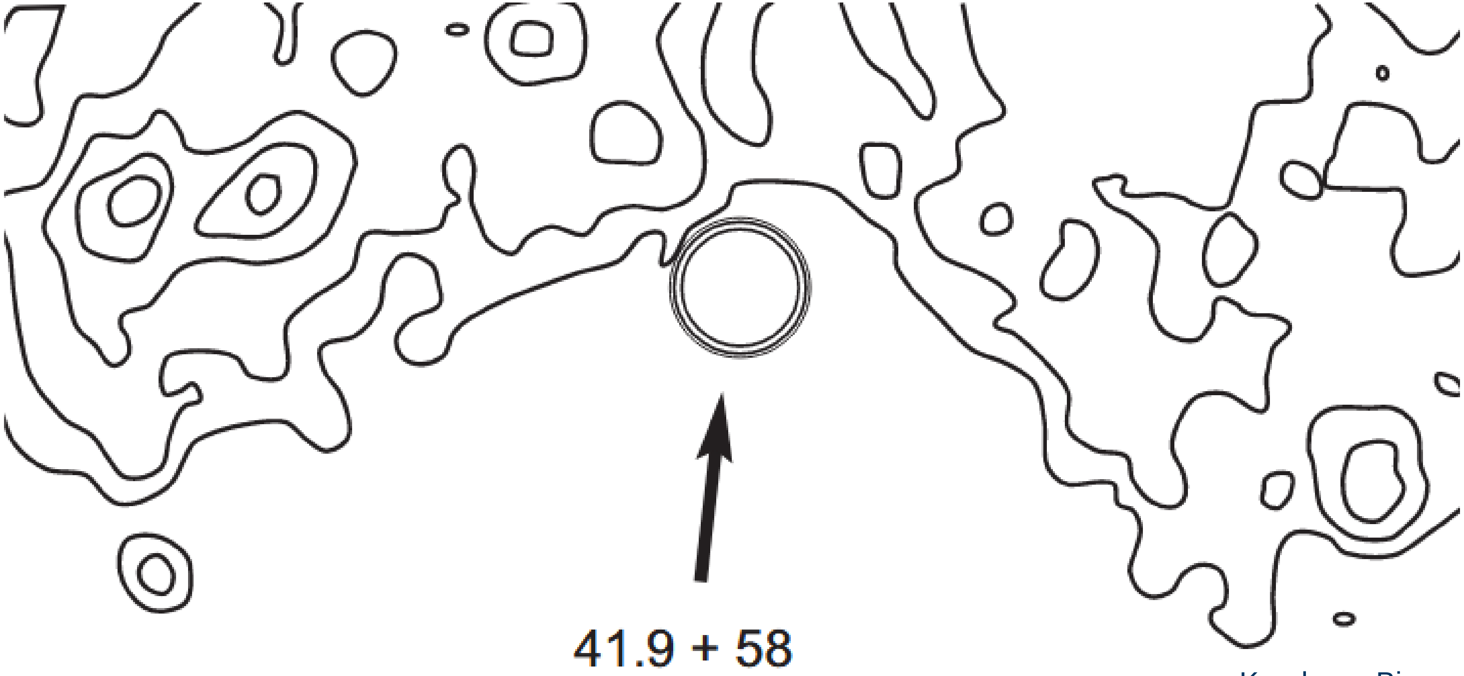
2. Stellar mass BBH mergers



M82: radio source 41.9+58 – a recent BBH merger?



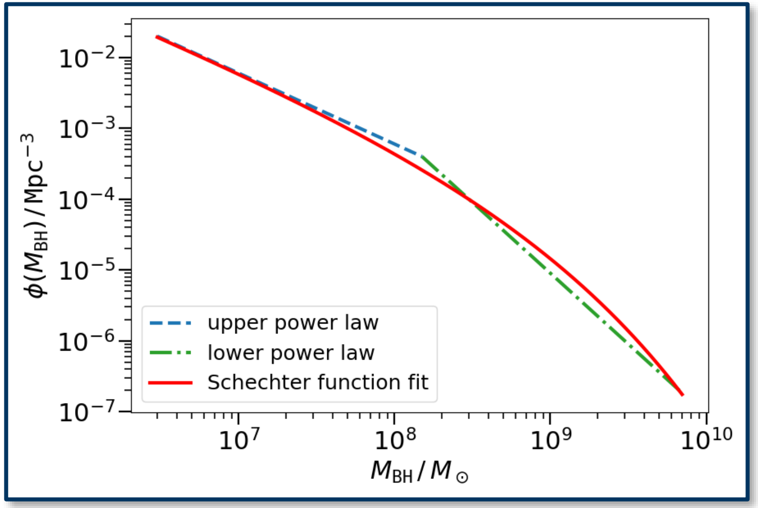
Kronberg, Biermann & Schwab 1985

Biermann et al. 2018

Neutrino – GW – Connection

$$E_\nu^{\text{total}} = f_{\text{SMBBH}}^{\nu} \cdot E_{\text{GW}}$$

$$E_\nu^p \, \Phi(E_\nu)\Big|_{obs} \propto \kappa_p \cdot \xi_z \cdot f_{\text{SMBBH}}^{\nu} \cdot \int_M \frac{\mathrm{d}\,E_{\text{GW}}}{\mathrm{d}t} \cdot \frac{n(M)}{M} \, \mathrm{d}M$$



Caramete & Biermann 2010

Fraction of total mass emitted in GWs: $E_{\text{GW}} = h(q) \cdot Mc^2$

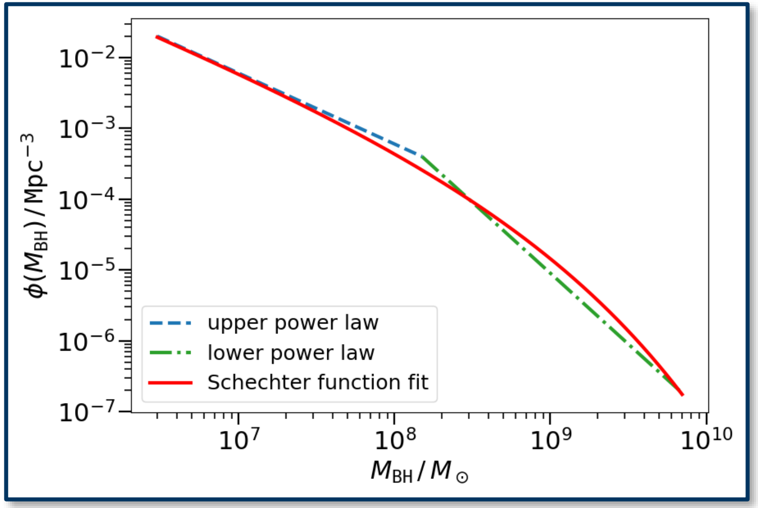
$$\mathbf{q} \in [1/3, 1/30] \quad \rightarrow \quad h(q):\ 1.3\,\% - 3.8\,\%$$

$$\int_M \frac{\mathrm{d}\big(\,h(q) \cdot Mc^2\,\big)}{\mathrm{d}t} \cdot \frac{n(M)}{M} \, \mathrm{d}M = h(q) \cdot \langle M \rangle c^2 \cdot \frac{n_{\text{SMBBH}}}{\bar{t}_{total}} = h(q) \cdot \langle M \rangle c^2 \cdot R$$

Neutrino – GW – Connection

$$E_\nu^{\text{total}} = f^\nu_{\text{SMBBH}} \cdot E_{\text{GW}}$$

$$E_\nu^p \, \Phi(E_\nu)\Big|_{obs} \propto \kappa_p \cdot \xi_z \cdot f^\nu_{\text{SMBBH}} \int_M \frac{\mathrm{d}\,E_{\text{GW}}}{\mathrm{d}t} \cdot \frac{n(M)}{M} \,\mathrm{d}M$$



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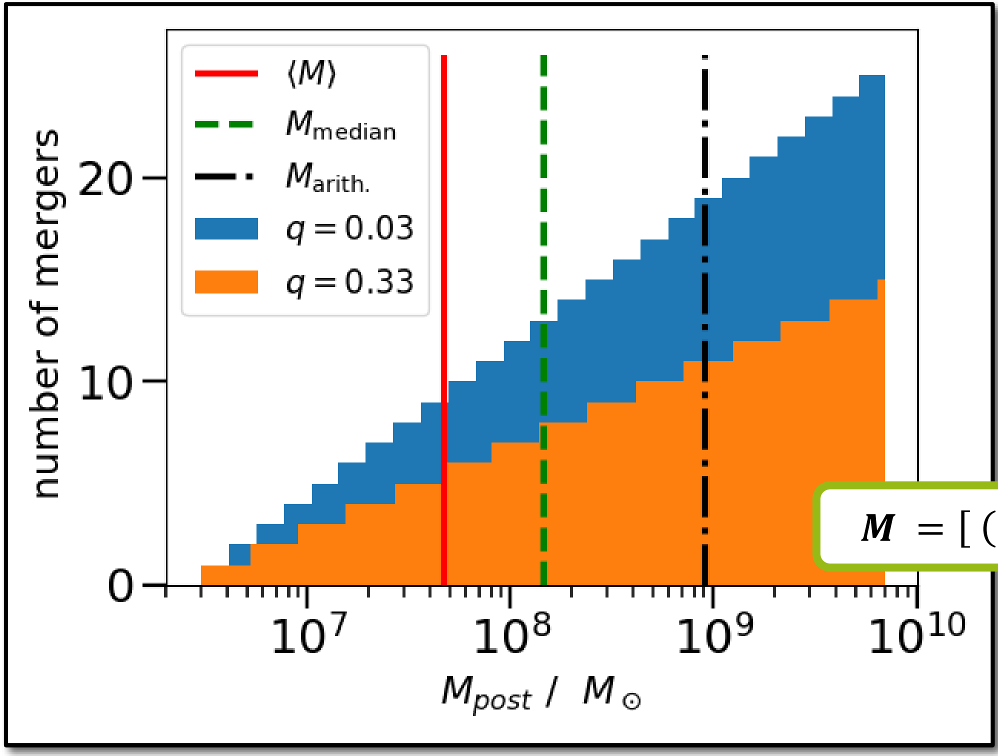
Required number of SMBH mergers



M in $M_\odot$	number of mergers n	$\bar{t}_{total}$ in Gyr
$q = 1/3$		
$\langle M \rangle$	6	2.47
M_{median}	8	1.86
$q = 1/30$		
$\langle M \rangle$	10	1.48
M_{median}	13	1.14

$$\boldsymbol{M = [\,(\,1 + \eta_{acc} - k(q)\,) \cdot (1 + q)\,]^n \cdot m_1}$$

$\eta_{acc} \approx 33\ \%$

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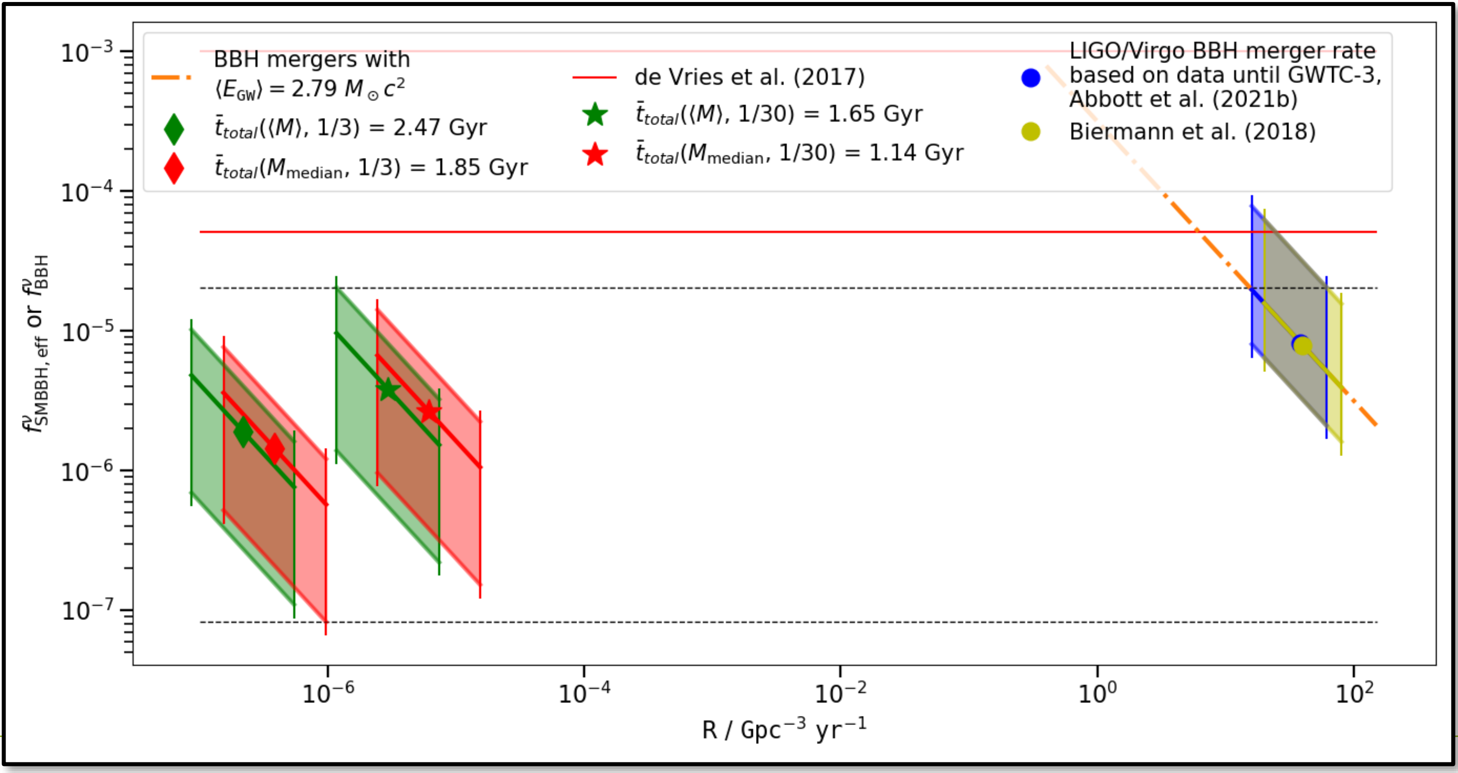
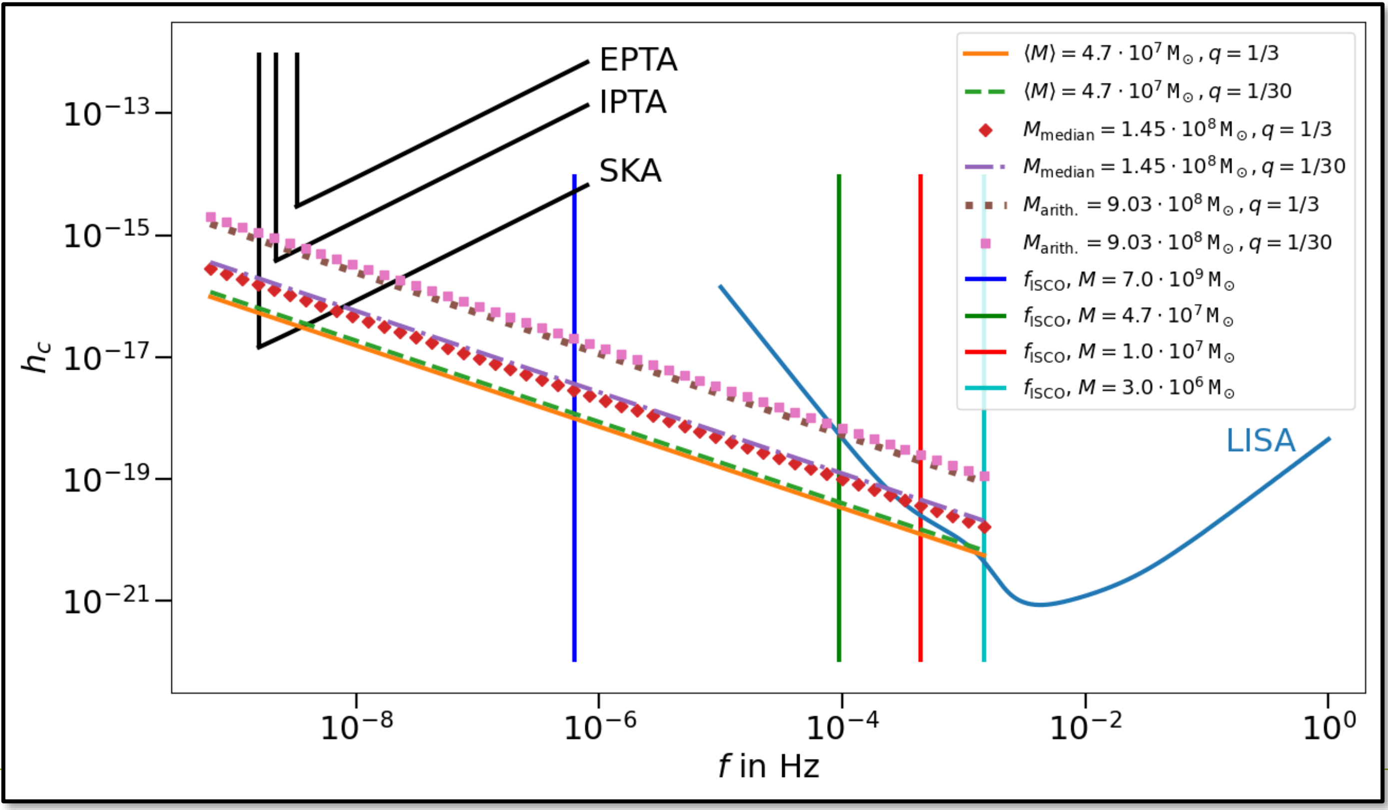
$\nu_\mu + \bar{\nu}_\mu$ flux with 10 years of data

$$n_{\text{SMBBH}} = \frac{\overline{t_{insp}}}{\overline{t_{total}}} \cdot n_{\text{SMBH}}$$



Characteristic strain



Summary and Outlook

- If 90% of the diffuse astrophysical neutrino flux that is detected by IceCube comes from SMBBH mergers and the rest from stellar mass BBH mergers in Starburst galaxies, it is explainable, if only $\sim \mathbf{10^{-5}}$ **to** $\sim \mathbf{10^{-6}}$ of the emitted gravitational wave energy goes into neutrinos
→ **same accelerator physics?**

- Gravitational wave detectors such as LISA or SKA will put a constrain on the **SMBH mass distribution** and **SMBBH merging rate** → improve this model

- **Future work:**
connection neutrinos – injection rate of CR:

$$E^2 \frac{d\dot{N}}{dE_p}\bigg|_{\rm inj} = E_{\rm CR} \cdot R_{\rm SMBH}$$

Thank you!

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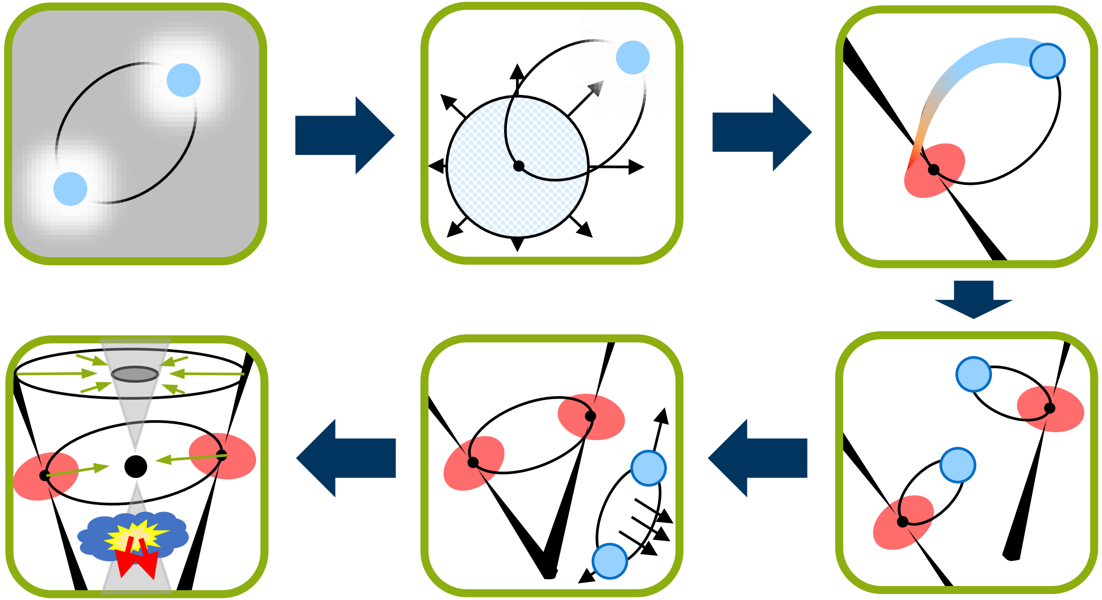
Appendix

2. BBH mergers in Starburst Galaxies - alternative

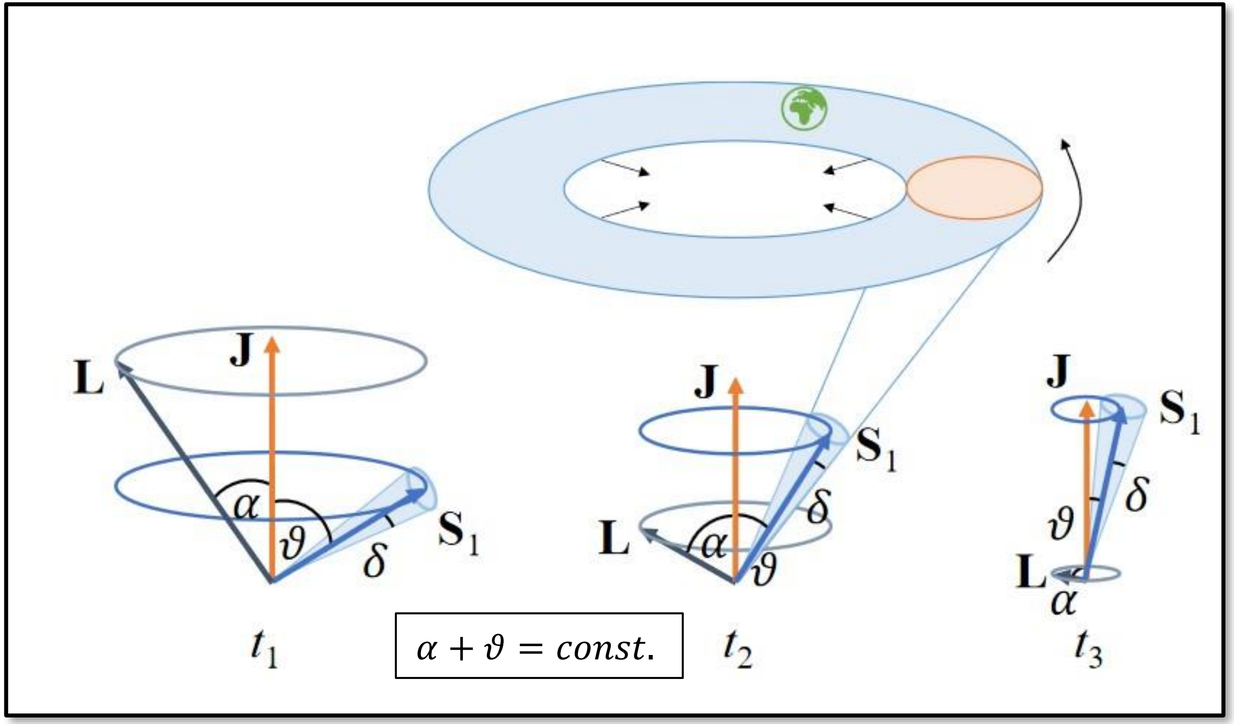


SMBBH mergers – common occurrences

- Every radio galaxy with a central black hole $\gtrsim 3 \cdot 10^6 M_\odot$ underwent at least one supermassive black hole merger with a spin-flip of the jet
- Time scale of neutrino production is the same as the time scale for gravitational wave radiation → inspiral stage at sub-pc separation
- Inspiral time for mass ratio $q = \frac{1}{3}: 4 \cdot 10^5 - \sim 10^9$ yr with increasing total mass
- Smaller mass ratio $q = \frac{1}{30}$: about factor 5 larger

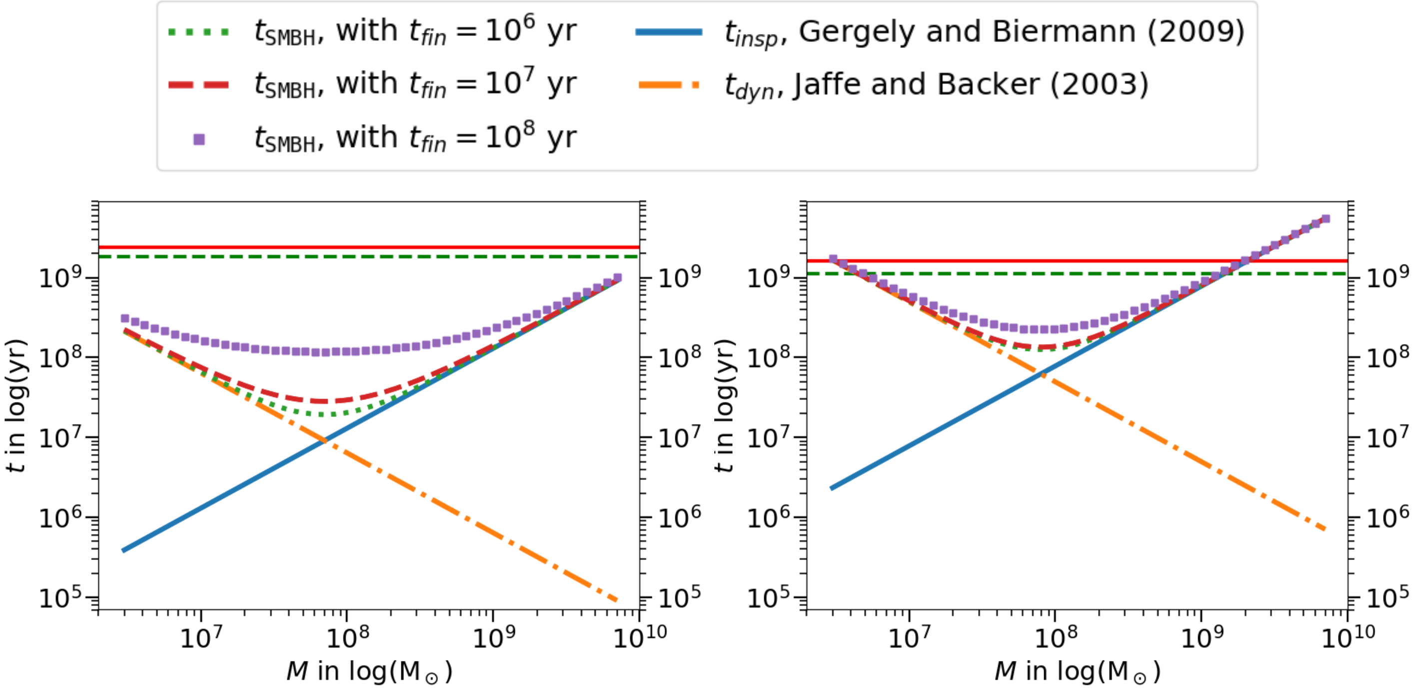
→ heaviest SMBHs must have formed at $q > \frac{1}{30}$

Spin-flip of the Jet – in more Detail



De Bruijn et al. 2020

Total SMBH Merger time



a) $q = 1/3$ b) $q = 1/30$

Current SMBBH density

Duration of the inspiral time for 4 different models

model	$\zeta_M/h(q)/10^{\pm0.4}$ in $M_\odot\ \mathrm{Mpc}^{-3}\ \mathrm{yr}^{-1}$		$\bar{t}_{insp}$ in yr	
	$q = 1/3$	$q = 1/30$	$q = 1/3$	$q = 1/30$
Gergely and Biermann (2009)	$1.44 \cdot 10^{-3}$	$2.40 \cdot 10^{-4}$	$1.86 \cdot 10^{6}$	$1.12 \cdot 10^{7}$
Sesana et al. (2012)	$4.60 \cdot 10^{-3}$	$5.11 \cdot 10^{-4}$	$5.84 \cdot 10^{5}$	$5.26 \cdot 10^{6}$
Cavaliere et al. (2019)	$9.34 \cdot 10^{-3}$	$2.01 \cdot 10^{-3}$	$2.88 \cdot 10^{5}$	$1.34 \cdot 10^{6}$
Peters (1964)	$1.16 \cdot 10^{-2}$	$1.92 \cdot 10^{-3}$	$2.33 \cdot 10^{5}$	$1.40 \cdot 10^{6}$

Total time between two SMBBH mergers including an accompanying galaxy merger for different mean masses.

mass ratio q	mass in $M_\odot$	number of mergers	$\bar{t}_{total}$ in yr
1/3	$4.7 \cdot 10^{7}$	6	$2.47 \cdot 10^{9}$
	$1.45 \cdot 10^{8}$	8	$1.86 \cdot 10^{9}$
	$9.03 \cdot 10^{8}$	11	$1.35 \cdot 10^{9}$
1/30	$4.7 \cdot 10^{7}$	9	$1.65 \cdot 10^{9}$
	$1.45 \cdot 10^{8}$	13	$1.14 \cdot 10^{9}$
	$9.03 \cdot 10^{8}$	19	$7.81 \cdot 10^{8}$

$$n_{\mathrm{SMBH}} \approx 5.73 \cdot 10^{6}\ \mathrm{Gpc}^{-3}$$

$$n_{\mathrm{SMBBH}} = \frac{\overline{t_{insp}}}{\overline{t_{total}}} \cdot n_{\mathrm{SMBH}}$$

Results for SMBBHs

Table 3. Overview over the estimated mean number of SMBBH mergers in the Hubble time. The mean merger times, resulting SMBBH merger rates as multiple of $\bar{t}_{insp}/\bar{t}_{total}$ and effective fraction of neutrino from GW energy during a SMBBH merger $f^{\nu}_{\mathrm{SMBBH,eff}}$ are shown as well. All values are separated in mass ratios 1/3 and 1/30.

mass ratio q	mass in $M_\odot$	number of mergers	$\bar{t}_{total}$ in yr	$R_{\mathrm{tot}} \cdot \frac{\bar{t}_{total}}{\bar{t}_{insp}}$ in $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$	$f^{\nu}_{\mathrm{SMBBH,eff}}$
1/3	$4.7 \cdot 10^7$	6	$2.47 \cdot 10^9$	$2.32 \cdot 10^{-3\pm0.4}$	$1.92^{+8.31}_{-1.10} \cdot 10^{-6}$
	$1.45 \cdot 10^8$	8	$1.85 \cdot 10^9$	$3.09 \cdot 10^{-3\pm0.4}$	$1.44^{+6.23}_{-0.83} \cdot 10^{-6}$
	$9.03 \cdot 10^8$	11	$1.35 \cdot 10^9$	$4.25 \cdot 10^{-3\pm0.4}$	$1.05^{+4.53}_{-0.60} \cdot 10^{-6}$
1/30	$4.7 \cdot 10^7$	9	$1.65 \cdot 10^9$	$3.47 \cdot 10^{-3\pm0.4}$	$3.85^{+16.65}_{-2.21} \cdot 10^{-6}$
	$1.45 \cdot 10^8$	13	$1.14 \cdot 10^9$	$5.02 \cdot 10^{-3\pm0.4}$	$2.66^{+11.53}_{-1.24} \cdot 10^{-6}$
	$9.03 \cdot 10^8$	19	$7.81 \cdot 10^8$	$7.33 \cdot 10^{-3\pm0.4}$	$1.82^{+7.89}_{-1.05} \cdot 10^{-6}$

Table 4. Values for the fraction of the mean inspiral time from the mean SMBBH merger time for the four inspiral time models used, separated in mass ratios 1/3 and 1/30. Values for $\bar{t}_{total}$ are taken from Table 3.

inspiral time model	$\frac{\bar{t}_{insp}}{\bar{t}_{total}}$					
	$q = 1/3$			$q = 1/30$		
	$\bar{t}_{total} = 2.47$ Gyr	$\bar{t}_{total} = 1.85$ Gyr	$\bar{t}_{total} = 1.35$ Gyr	$\bar{t}_{total} = 1.65$ Gyr	$\bar{t}_{total} = 1.14$ Gyr	$\bar{t}_{total} = 0.78$ Gyr
Gergely and Biermann (2009)	$7.53 \cdot 10^{-4}$	$1.00 \cdot 10^{-3}$	$1.38 \cdot 10^{-3}$	$6.79 \cdot 10^{-3}$	$9.82 \cdot 10^{-3}$	$1.43 \cdot 10^{-2}$
Sesana et al. (2012)	$2.36 \cdot 10^{-4}$	$3.14 \cdot 10^{-4}$	$4.33 \cdot 10^{-4}$	$3.19 \cdot 10^{-3}$	$4.61 \cdot 10^{-3}$	$6.73 \cdot 10^{-3}$
Cavaliere et al. (2019)	$1.17 \cdot 10^{-4}$	$1.55 \cdot 10^{-4}$	$2.13 \cdot 10^{-4}$	$8.12 \cdot 10^{-4}$	$1.18 \cdot 10^{-3}$	$1.72 \cdot 10^{-3}$
Peters (1964)	$9.43 \cdot 10^{-5}$	$1.25 \cdot 10^{-4}$	$1.73 \cdot 10^{-4}$	$8.48 \cdot 10^{-4}$	$1.23 \cdot 10^{-3}$	$1.79 \cdot 10^{-3}$

H.E.S.E flux with 7.5 years of data

$$n_{\mathrm{SMBBH}} = \frac{\overline{t_{insp}}}{\overline{t_{total}}} \cdot n_{\mathrm{SMBH}}$$