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A two-step strategy to identify episodic sources of gravitational waves and high-energy neutrinos in starburst galaxies

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Supermassive black hole (BH) mergers with spin-flips accelerate energetic particles through their relativistic precessing jets, producing high-energy neutrinos and finally gravitational waves (GWs). In star formation, massive stars form in pairs, triplets, and quadruplets, allowing second-generation mergers of the remnants with discrepant spin directions. The GW data support such a scenario. Earlier, we suggested that stellar mass BH mergers (visible in M82) with an associated spin-flip analogously allow the acceleration of energetic particles, with ensuing high-energy neutrinos and high-energy photons, and finally produce GWs. At cosmic distances, only the GWs and the neutrinos remain detectable. In this study, we generalize the argument to starburst and normal galaxies throughout their cosmic evolution and show that these galaxies may dominate over active galactic nuclei (AGN) in the flux of ultra-high-energy particles observed at Earth. All these sources contribute to the cosmic neutrino background, as well as the GW background (they detected lower frequencies). We outline a search strategy to find such episodic sources, which requires including both luminosity and flux density.

KEYWORDS

neutrinos, starburst, galaxies, black hole mergers, gravitational waves, particle acceleration

1 Introduction

Searches for identifying the source of a given high-energy neutrino or gravitational wave (GW) event usually try to find both coincidences in direction on the sky and some temporal coincidence, like excess emission at the same time. One of the best candidates for very high-energy particle acceleration is the effect of relativistic precessing jets during the merger of two black holes (BHs). Such an event has been proposed to be identified in the starburst galaxy M82, due to the action of the precession of a pair of powerful jets emanating from two stellar mass BHs prior to their merger (Kronberg et al., 1985; Allen and Kronberg, 1998; Biermann et al., 2018). As we will show, these jets match in their power the observed minimum of jet power of active galactic nuclei (Punsly and Zhang (2011)), and so they can be quite efficient in producing ultra-high-energy cosmic ray (UHECR) particles, and as a consequence high-energy neutrinos. In such a discussion, it is important to note that energetic neutrinos might be highly boosted in the direction of the jet at the time of emission, and so additional selection effects operate Kun et al. (2021) and Becker Tjus et al. (2022).

1.1 Binary star orbital angular momentum evolution

An important question is regarding the possibility of most or all stellar mass BHs being born with near maximal rotation. There are two obvious mechanisms to get them to rotate fast:

The first mechanism acts when the newly formed massive star has a rapidly rotating core, which remains in sufficiently high rotation until the star blows up as a supernova (SN), and the BH is formed (Chieffi and Limongi, 2013; Limongi and Chieffi, 2018; Limongi et al., 2020). This requires that angular momentum transport is small throughout the star and also that the wind does not remove a significant quantity of rotational angular momentum throughout the life of the star.

The second mechanism is plausible via tidal locking since most massive stars reside in binaries, triples, or even quadruple systems. In the following, we will work through the requirements for this path. This implies that during their evolution, binary stars get close enough to actually achieve tidal locking (Chini et al., 2012; Chini et al., 2013a; Chini et al., 2013b).

We will show that the removal of orbital angular momentum by the winds of the two stars is a key aspect.

For didactic simplicity, we consider two stars of equal mass M at a distance of $2r$ from each other orbiting in a circle with period P. Then, the total orbital angular momentum is given by

$$J_{orb} = \pi^{-1/3} M^{5/3} G_N^{2/3} P^{1/3}, \qquad (1)$$

where G_N is Newton's constant of gravitation and the radial scale r can be connected to the other measures of the system by

$$r = \frac{1}{2\pi^{2/3}} M^{1/3} G_N^{1/3} P^{2/3}. \qquad (2)$$

It follows that the time changes are given by

$$\frac{\dot{J}_{orb}}{J_{orb}} = \left(\frac{5}{3}\frac{\dot{M}}{M} + \frac{1}{3}\frac{\dot{P}}{P}\right), \qquad (3)$$

and

$$\frac{\dot{r}}{r} = \left(\frac{1}{3}\frac{\dot{M}}{M} + \frac{2}{3}\frac{\dot{P}}{P}\right). \qquad (4)$$

The loss of orbital angular momentum by a wind is given by

$$\dot{J}_{orb} = 2\dot{M}\, r\, v_\phi \left(1 + \varepsilon_{W,B}\right), \qquad (5)$$

where the term $\varepsilon_{W,B}$ describes the loss by the torque of the magnetic field (Weber and Davis, 1967), their Eq. 9), and v_ϕ is the rotational velocity of the flow. In this study, we assume that the orbital radius acts as a lever arm. It follows that the temporal evolution of the orbital radius is given by

$$\frac{\dot{r}}{r} = 2\frac{\dot{M}}{M}\left(\varepsilon_{W,B} - \frac{1}{2}\right). \qquad (6)$$

Next, we need to put this into context: the angular momentum transport from both stars is given by Weber and Davis (1967) in their Eqs. 8, 9

$$\dot{J}_{orb} = 2\left(4\pi r^2 \rho\, v_r v_\phi r + B_r B_\phi r^3\right), \qquad (7)$$

where v_r is the radial velocity and the ratio of the second term and the first term gives $\varepsilon_{W,B}$. The first term corresponds to $2\dot{M}\, r\, v_\phi$ above.

It follows that for mass loss, and so for $\frac{\dot{M}}{M} < 0$, the orbital separation will increase for the case of no magnetic fields. However, for $\varepsilon_{W,B} > 1/2$, the orbital separation will decrease. For equipartition in the wind, $\varepsilon_{W,B} \simeq 1$. If magnetic fields were really strong, it would allow a lever arm even larger than the orbital radius $\varepsilon_{W,B} > 1$.

We conclude here that magnetic winds are the key for driving massive binary stars together, allowing locked-in rotation. This gives rotation with the speed close to what had been assumed in the simulations of Limongi and Chieffi (2018) and Limongi et al. (2020).

The ratio of the magnetic term to the flow term can be written as the inverse of two Alfvén–Mach numbers:

$$M_{A,r} = \frac{v_r(r_*)\sqrt{4\pi\rho(r_*)}}{B_r(r_*)}, \qquad (8)$$

and

$$M_{A,\phi} = \frac{v_\phi(r_*)\sqrt{4\pi\rho(r_*)}}{B_\phi(r_*)}, \qquad (9)$$

where r_* is the radius, density ρ, rotational velocity v_ϕ, and tangential magnetic field B_ϕ are evaluated. In the long distance limit, here v_r goes to a constant, ρ as $1/r^2$, v_ϕ as $1/r$, B_r as $1/r^2$, and B_ϕ as $1/r$. It follows that $M_{A,r} \sim r$, and $M_{A,\phi} \sim 1/r$ so that the product $M_{A,r}M_{A,\phi} \sim 1$. Then,

$$\varepsilon_{W,B} = \frac{1}{M_{A,r}M_{A,\phi}} \sim 1. \qquad (10)$$

In a number of OB stars compiled by Chini et al. from Chini et al. (2012), Chini et al. (2013a), and Chini et al. (2013b), a typical orbital period is approximately 4 days, with quite a spread. The initial typical radius of these stars is approximately $10^{12.2}$ cm, which is almost independent of mass (Chieffi and Limongi, 2013), and so the inferred typical initial surface velocity is approximately 300 km/s, just the high velocity used in these calculations (Limongi and Chieffi, 2018). Surface magnetic fields are of order 10^3 G

(Walder et al., 2012); however, the observational evidence suggests that some massive stars rotate more slowly with age rather than faster, as argued here. That could happen, if the local angular momentum is maintained so that the core rotates faster with time, and the outer parts of a star rotate more slowly with time. To obtain a quantitative estimate for $\epsilon_{W,B}$, we have to adopt some further numbers: $v_r \simeq 2000$ km/s, and for the magnetic field near the surface, we adopt a low estimate of $B_r \simeq B_\phi \simeq 100$ G. For the mass loss, we take $10^{-5}\,M_\odot\,\mathrm{yr}^{-1}$. This gives an estimate of $\epsilon_{W,B} \simeq 1$. If the magnetic fields were any stronger, $\epsilon_{W,B}$ would be larger, and then the orbital angular momentum loss would be yet stronger, allowing the two stars to get closer even faster. However, if the magnetic fields were significantly weaker, this preponderance of the magnetic fields in removing orbital angular momentum would disappear, the two stars in a binary system would move apart, rotate ever more slowly, and the spin of the resulting BH might be far below maximal. The scant data (Walder et al., 2012) suggest that of the massive stars, not all end up producing a rotating BH, rotating near maximum; only some do. The fraction of massive stars in binaries that do produce a rotating BH is unknown at present.

However, there is the other option, mentioned at first above, that the cores of all massive stars are rotating fast right from the formation, allowing the surface to rotate much more slowly, and hence deceiving any observer. This will be relevant also for all massive stars in binary systems that do not tighten their orbit over time.

We will focus here on those stars that do produce a BH rotating near the maximum allowed. All well-observed radio supernovae (RSNe) seem to share a common property that the product of the magnetic field and the radius ($B \times r$) has the same value in the wind (Biermann et al., 2018; Biermann et al., 2019), comparing different radial scales r and different RSNe in one galaxy, M82, as well as in different galaxies. Furthermore, we note that this value is consistent with what has been observed around the SMBH in the galaxy M87 EHT-Coll. et al. (2019). Furthermore, the wind/jet power derived is consistent with the minimum jet power for radio-loud optically selected quasars (Punsly and Zhang, 2011). In many of the cases, the central SMBH is believed to be near maximum rotation (Daly, 2019), EHT-Coll. et al. (2019). In this study, we explain this property also in stellar mass BHs as a result of the central BH rotating near maximum at the beginning (Chieffi and Limongi, 2013; Limongi and Chieffi, 2018; Limongi et al., 2020), possibly reducing its angular momentum quite rapidly.

1.2 Angular momentum of the black hole

For all models, the final predicted BH angular momentum is approximately

$$J_{BH*} \geq 10^{51.1} \left(\frac{M_{BH*}}{10\,M_\odot}\right)^2 \mathrm{erg\,s} \simeq 10^{50.9} \left(\frac{M_{BH*}}{10\,M_\odot}\right)^2 \mathrm{erg\,s} = J_{BH,max}. \tag{11}$$

If there is excess of angular momentum, it has to be dissipated before a BH can even form, even if near maximal rotation. There are several possibilities:

- First option: A small initial BH mass near its spin limit grows and sheds all excess angular momentum during growth through tidal gravitational torque or through magnetic torque. As massive star explosions are very clumpy, this might produce GWs. No such waves have yet been detected.
- Second option: The collapse first forms a binary BH (BBH) or a binary of a BH and a neutron star. At each radius, the angular momentum contained matches the limiting number allowed for that mass. This implies that we have maximal differential rotation, for BBHs near maximal individual spins are plausible—individual spin-down has been shown to be slow (King et al., 1999). This option would produce a high-frequency GW event, and none has been seen as yet, that could be attributed to such a scenario for certain. On the other hand, three events have been seen with low mass partners LIGO/VIRGO-Coll. et al. (2021), which could be neutron stars or BHs. The sum of the two partners is consistent with the lowest mass BHs known. The aligned spin before the merger is consistent with 0 in all three cases, which is expected in such a scenario. A bright SN showing the explosion of a very massive star is implied to accompany the final merger of the two fragments turned BH or neutron star.
- Third option: There is a burst of ejected excess angular momentum and energy via magnetic fields: this is akin to a proposal by Bisnovatyi-Kogan (1970), and in many papers later, such as Bisnovatyi-Kogan and Moiseenko (2008). He proposed that this is the mechanism involved in explosion of massive stars to make a SN.
- Fourth option: A collapse into a Kerr geometry, with $(J_{BH}\,c)/(M_{BH}^2\,G_N) > 1$, is allowed (Joshi et al., 2020). This is still an astrophysical BH (i.e., lot of mass compacted in small volume, with no event horizon). There are powerful mechanisms as to how such (a naked singularity) configuration very rapidly gives away angular momentum and settles to a rotating BH with a horizon. Here, one gets the required burst-like energy also from high angular momentum decay.

All options listed here lead to formation of a BH in near maximal rotation, a state which may last only a short time. So we will assume near maximal rotation for now, and revisit these arguments later again. If there is no excess to start with, the angular momentum can still be very close to maximal according to the simulations of Limongi et al. (2020).

2 Black hole mergers, supernovae, and other episodic events

In this study, we focus on stellar mass BH mergers, as one example of a short injection of energetic particles, recognizable via the cone of precessing jets, that clean out the interstellar medium (ISM) (e.g., source 41.9 + 58 in the starburst galaxy M82, Kronberg et al. (1985); Allen and Kronberg (1998); Biermann et al. (2018)).

2.1 Source 41.9 + 58, a second-generation stellar mass black hole merger?

The compact radio source 41.9 + 58 sits at the apex of a triangular region without radio emission opening south, with a less regular region without radio emission to the north (Kronberg et al., 1985); a detailed image is shown in Biermann et al. (2018). The difference can be understood as the result of projection effects since the disk of M82 is slightly tilted relative to the line of sight. This can be interpreted as the action of a pair of two-sided precessing jets emanating from two coalescing active rotating BHs of stellar mass (Kronberg et al., 1985; Biermann et al., 2018). As most massive stars sit in stellar binary systems, triples, and often even quadruples, each close binary system will interact such that their spins can be expected to align, while distant binaries resulting from two first-generation mergers of two stars or BHs each can be expected to yield very different spin directions. Magnetic winds help bring two stars or two BHs together by removing orbital angular momentum. The large cone of precession results in the case that the two BHs initially have vastly different spin directions and the BHs slowly align their spin directions before their actual merger (Gergely and Biermann, 2009). This topology is inconsistent with an explosion in a stratified atmosphere since that always leads to a stem-like outflow (extensive literature is given in Biermann et al. (2018)). Such stem-like outflows are in fact seen as filaments above and below the disk of M82 (Biermann et al., 2018).

Could there be other such features hidden in the radio map of the inner region of M82 (Kronberg et al., 1985)? If a large proper motion were to be allowed, then there are a number of possibilities that allow an interpretation of another such double-cone feature, with source 44.0 + 59.5 a speculative option.

So the detection of one such source out of 43 yields a very uncertain estimate of their rate of 1 per 2,500 years in the starburst galaxy M82 (Biermann et al., 2018). M82 has a far infra-red (FIR) dominated luminosity of approximately $10^{10.6}\,L_\odot$ (Kronberg et al., 1985), and so that rate can be estimated to be correspondingly higher for a higher FIR luminosity.

2.2 Fraction of mergers among massive stars

In M82, we observe 43 compact sources (Kronberg et al., 1985), probably all of which are explosions of blue super giant (BSG) stars since the winds of red super giant (RSG) stars do not provide enough ram pressure to allow the quick formation of RSNe of the size as observed, of a few parsec (Kronberg et al., 1985; Allen and Kronberg, 1998; Allen, 1999; Biermann et al., 2018; Biermann et al., 2019). We find a single source, 41.9 + 58, which appears to be fully consistent with a second-generation BH merger. The FIR luminosity of M82 can be interpreted as a measure of the star formation rate. The SN rate for massive stars (i.e., all above a zero age main sequence (ZAMS) mass of approximately $10\,M_\odot$) can be estimated to be within the range of 1 per 1.5 years and 1 per 5 years (Kronberg et al., 1985; Biermann et al., 2018), and so the rate of such second-generation mergers can be very crudely estimated to 1 in 1,000 of massive stars, with an error range of probably at least an order of magnitude.

2.3 Rate of mergers

Using a scaling with FIR luminosity yields a maximal rate of $10^{12}/10^{10.6} \times 1/2$, 500 per year, so approximately 1 in approximately 100 years at most. This is again an order of magnitude estimate only.

What is exactly the scenario of energetic particle injection? Powerful plasma jets precess and therefore continuously encounter new material to accelerate to ultra-high energies. This new material is fed to the central region of the starburst galaxy by friction in the interstellar medium (Toomre and Toomre, 1972; Wang and Biermann, 2000), in the model to consider any gaseous galaxy akin to an accretion disk Lüst (1952). Starburst galaxies often involve the merger of two galaxies, stirring up their ISM (Toomre and Toomre, 1972).

Then, the next question is the length of time of the active episode: for that, we use column 2 of Table 2 in Gergely and Biermann (2009), so the initial inspiral rate, scaling the expression in the last line, for the angle change, to $10\,M_\odot$ and an equal mass binary, gives a time scale of 5 years, still a small fraction of 100 years. This implies that in our model, the injection of energetic particles due to the inspiral motion of active BHs is taken to last of order 5 years (this time scale scales linearly with mass). Therefore, the precessing motion makes the injection of new particles much more efficient for acceleration than in a non-moving jet. Thereafter, when the merged BH drives another pair of jets, injection of energetic particles continues, but at a much lower rate since the precessing motion has ceased, so the encounter with the new material is reduced.

This time scale is based on the initial stage, when GW emission becomes the dominant means to remove orbital angular momentum (Gergely and Biermann, 2009). We have proposed above that magnetic stellar winds, using the angular momentum lever arm of the orbital radius, remove sufficient orbital angular momentum to get the system to this point.

This time scale is short compared with the time scale between such events, as estimated above at order 100 years for the most luminous starburst galaxies and longer for starburst galaxies of lower FIR luminosity. Therefore, it appears possible, but fairly unlikely, that any starburst galaxy will experience many such activity episodes at the same time.

2.4 Episodic activity and corresponding energies

Therefore, for a starburst galaxy of an FIR luminosity L_{FIR} other than the maximum of $10^{12}\,L_\odot$, the time-scale between such episodes of injection is then correspondingly longer than 100 years, and hence is of order 100 years $\{10^{12}\,L_\odot/L_{FIR}\}$.

This implies that in any given flux density interval of a sample, those galaxies that have the highest FIR luminosity contribute the most, and therefore, are at the highest redshift. They have the highest probability to be in an active stage right now (in the observer frame), as compared to other galaxies at the same flux density, but at lower redshift. This is a key step in the argument proposed.

If BH spin energy drives powerful jets, it implies that the rotational energy is available, implying that for a final mass of $10\,M_\odot$, we have $\{\sqrt{2}-1\}\,M_{BH}\,c^2$ maximally available to drive a magnetic jet, replete with energetic particles. For a $10\,M_\odot$ final mass, this is some fraction of $10^{54.9}$ $M_{BH,1}$ erg times an inefficiency factor that estimates what fraction of this energy goes into energetic particles. Allowing 1/3, this gives $10^{54.4}$ $M_{BH,1}$ erg. Counting at first only the second-generation mergers happening every 2,500 years (note the uncertainty in this number), it implies that potentially we have a power input of $10^{43.8}$ $M_{BH,1}$ erg/s, noting that this involves two such BHs. The minimum power required in M82 to clean out the ISM (Biermann et al., 2018) can be estimated as follows: first of all, the $P\,dV$ work can be estimated by using the numbers in Kronberg et al. (1985): The volume is a cone of approximately 50 pc baseline radius and approximately 30 pc height, giving a volume of approximately 10^5 pc^3; the pressure can be estimated also from Kronberg et al. (1985) as approximately four times the magnetic field pressure (magnetic field, energetic particles, and thermal particles giving a pressure equal or larger than magnetic fields and energetic particles combined), so using a magnetic field strength of $10^{-3.7}$ G gives a pressure of $10^{-8.8}$ dyn. The total $P\,dV$ work is then $10^{51.7}$ erg. Since we are referring to the sweeping action of the precession cone, the time scale has to be that for changing the angle: as derived above, this yields 5 years for this time scale, assuming for reference again 10 $M_{\odot}$, and so the associated power flow has to be of order $10^{43.5}$ erg/s for two jets, so $10^{43.2}$ erg/s for one jet. This is in fact consistent with the power flow derived from the quantity $(B \times r)$ = $10^{16.0\pm0.12}$ G × cm observed for the common magnetic field in young RSN (Biermann et al., 2018; Biermann et al., 2019); based on Kronberg et al. (1985), Allen and Kronberg (1998), and Allen (1999)), using the approach of Falcke and Biermann (1995)). This yields $10^{42.8}$ erg/s, easily within the errors of such a comparison. This derivation is independent of BH mass, as the consistency with the minimum power in radio quasars (Punsly and Zhang, 2011), and with the magnetic field in the M87 radio core EHT-Coll. et al. (2019). This is a consistency check on the power flow in the precessing jets. At this point, we can derive the time scale of angular momentum loss and energy loss: this can be determined by dividing the maximally available energy of $10^{54.9}$ $M_{BH,1}$by this luminosity derived here of $10^{42.8}$ erg/s, which gives $10^{12.1}$ s $M_{BH,1}$; here, $M_{BH,1}$is the mass of the BH in units of 10 solar masses. On this time scale, a maximally rotating BH loses angular momentum and energy, at the minimum. This shows that for a BH mass of $10^{6.6}$ $M_{\odot}$, we reach the lifetime of the Universe. Curiously, this happens to be the mass of the SMBH in our Galactic Center, for which its rotation state is not yet known EHT-Coll. et al. (2022). The power derived here is slightly lower than the power output derived at the beginning, of $10^{43.5}$ erg/s for one BH; a simple interpretation may be that there are channels other than the magnetic jet itself to use up the rotational energy of the BH, e.g., via the Penrose process (Penrose and Floyd, 1971), or even simpler that the life time of the high spin of the BHs is just longer than the merging time scale; since many BHs get a kick at formation, they leave the galaxy, and the detections of RSNe in M82 may be limited by these objects just flying out. If this is the correct understanding, then all these rotating BHs are flying through the region around galaxies like M82 and lose most of the rotational energy out there.

If this rotational energy of a rotating BH is ejected via magnetic fields and energetic particles, in a relativistic wind or jet, could their contribution to energetic particles in intergalactic space surpass the contribution from super massive BHs (SMBHs)? The combined usable rotational energy of all these stellar mass BHs can be estimated for our galaxy, following the summary of the data in Biermann et al. (2018), based on Diehl et al. (2006), using 10 $M_{\odot}$ again as a reference for simplicity, as approximately $10^{62.4}$ erg, to be compared with the maximal useable rotation energy of our Galactic Center BH, assuming that it ever achieved this, as $10^{60.5}$ erg. This all depends on interpreting these stellar mass BHs beginning with a near maximal rotation state, as suggested by the commonality of the magnetic field in RSNe, and the simulations by Chieffi and Limongi (2013) and Limongi and Chieffi (2018); the argument has been given above in detail. If these stellar mass BHs also produce relativistic jets, the maximum energy particles may reach well beyond the ankle in the CR spectrum. By these same magnetic fields, they lose their rotation quite fast, in approximately $10^{4.2}$ yrs for a 10 $M_{\odot}$ BH (above we derived a similar number, $10^{4.6}$ yrs, using energy output). Summed over the lifetime of our Galaxy, this corresponds to a power input of $10^{44.7}$ erg/s outside our Galaxy; today it is a factor of order 2 less and hence approximately $10^{44.4}$ erg/s. The Galactic CRs require an input of order $10^{41.0}$ erg/s (Gaisser et al., 2013), which gives an efficiency of approximately $10^{-3.5}$ for CR injection inside the CR disk. As the typical galaxy density is of order 10^{-2} Mpc^{-3} (Lagache et al., 2003), and an order of magnitude lower at the FIR luminosity of our Galaxy, using this efficiency, it yields a crude estimate of $10^{39.0}$ erg/s Mpc^{-3}. This can also be checked directly with the density of SMBHs (e.g., Caramete and Biermann, 2010) of $10^{5.5\pm0.4}$ M$_{\odot}$ Mpc^{-3}, which corresponds to a maximally usable CR energy flow of $10^{38.2}$ erg/s Mpc^{-3}, which is slightly less than the possible contribution from massive star BHs, but consistent within the uncertainties. On the other hand, SMBHs can accrete and power outflows also at the Eddington limit, yielding very much higher possible power inputs for a short time: using the same densities of SMBHs (Caramete and Biermann, 2010) and a time fraction of order 10^{-2} for high activity yields then approximately $10^{41.6}$ erg/s Mpc^{-3}, still below the purely spin-down-based stellar mass BH power input, derived above, of $10^{44.4}$ erg/s. This can be compared with the average UHECR energy input worked out by, e.g., Waxman (1995) of $10^{37.1}$ Mpc^{-3} erg/s. The possible contribution from massive stars exceeds the AGN UHECR contribution, so massive star BHs may make a substantial contribution to UHECRs, in the case of initially high rotation, and relativistic jets, as implied by the M82 observations. This is fully consistent with new Auger results from Auger-Coll. (2024).

Finally, there is another consequence of this minimum loss time for angular momentum. In a star cluster of massive stars, these stars also lose orbital angular momentum via their magnetic winds, setting up a merger of massive stars to form a supermassive star (Spitzer (1969); Sanders (1970); Wang and Biermann (2000), which in turn may quickly form an SMBH of a mass close to that of the GC SMBH (Appenzeller and Fricke, 1972) focus on the explosion only). *A fortiori,* this also works for the merger of stellar mass BHs. This process can speed along the early formation of SMBHs, as observed by JWST (Übler et al., 2023).

2.5 Other sources of episodic activity

The classical episodic events that inject energetic particles are primarily SN explosions (e.g., Cox, 1972). However, normal SN explosions running through a former stellar wind give a maximal particle energy of approximately $10^{17.5}$ Z eV, reaching the ankle but certainly do not go beyond (Biermann et al.,2018). The reason is that in such RSNe, the magnetic field in terms of $B \times r$ is observed to be always close to the measure $10^{16.0\pm0.12}$ G × cm (Biermann et al., 2018; Biermann et al., 2019), as extensively discussed above. In the well-observed sources, there is not clearly a large tail of this quantity on either side of this specific number. However, the selection effects could be large in such a tally. However, if these rotating BHs were to initiate a relativistic jet (Mirabel and Rodríguez, 1999), the particle energies accelerated could go much higher.

Other episodic sources are binary star systems with one BH, pulsars and pulsar winds, white dwarf SNe (SN I a), active neutron stars in binary systems, and neutron star mergers.

It is important to add that a further source of episodic acceleration can be due to electric discharges (Gopal-Krishna and Biermann, 2024): winds and jets patterned after the Parker wind (Parker, 1958) carry an electric current. When the power varies with time, the electric current changes. This change builds up electric charges and fields following Maxwell's equations (Gopal-Krishna and Biermann, 2024), here the equation of continuity for electric currents which is contained in Maxwell's equations. These electric fields can discharge violently and produce acceleration of particles (see for the possibility of an electric discharge close to the central BH Aleksić et al. (2014)); in the limit of strong electric fields, this discharge acceleration produces a 1D momentum p spectrum of p^{-2}, quickly scattered to a 3D p^{-4} spectrum. This spectrum has been recognized in radio emission in radio filaments that may have undergone an electric discharge (Gopal-Krishna and Biermann, 2024), both galactic and extra-galactic. The magnetic irregularity spectrum excited by this steep particle spectrum also contributes to a good fit to the newest AMS data for Fe energetic particles (Allen et al., 2024), and presumably also for other primary elements like He, C, and O, with the difference that He, C, and O have spallation additions from higher elements and not only spallation losses like Fe.

2.6 Probability

The probability that a given starburst galaxy is ejecting, for instance, high-energy neutrinos right now (in the observer frame) runs with the FIR luminosity in our proposed model. Therefore, comparing all sources at some given flux density, those at the highest luminosity, therefore highest redshift, have the highest probability to contribute. As shown above, there is probably no case where multiple activity contributors are relevant at the same time.

To go beyond identifying most probable sources, say by working out the total neutrino background, we go one step further: once the sources are summed weighted by probability, we follow by adding all different flux density levels (*cf.* Caramete, 2016).

Clearly, a merger of two stellar mass BHs with the associate precession of jets aligning each with the spin of a BH is likely to accelerate particles to high energies so that interaction takes place, and neutrinos are emitted. At the very end of this stage, the two BHs will merge and emit a burst of GWs. It is important to note that due to boosting, the selection effects governing the detection of neutrinos and a burst of GWs are very different. So the detection of both due to the same episode of a source at about the same time is unlikely.

The main aspect in the analysis is that at any given flux density, the sources with the highest intrinsic luminosity, so highest redshift, have the highest probability to contribute. This would be the same conclusion for the other possibilities of episodic injection of energetic particles, such as SNe. However, if the energetic particles are stored and not ejected via the open precession cone, then the line of reasoning is valid only if most of the interaction happens right at the start, as has been argued already (Stanev et al., 1993; Biermann et al., 2001; Biermann et al., 2018; Allen et al., 2024).

2.7 Analogy of supermassive black hole mergers

This approach may be useful as well for AGN with central SMBHs since their activity is also episodic. Assuming that relativistic boosting is not stronger for minimum power AGN-BHs at near maximal rotation, then looking for the highest luminosity within a given flux density interval should also give a higher probability for the source to give either neutrinos or GWs. For many AGN, the FIR range has the highest probability to actually be strongly influenced by thermal dust emission (e.g., Chini et al., 1989a; Chini et al., 1989b), powered by the activity of the central SMBH. The flat spectrum AGN S5 1803 + 784 is a famous counter-example, with its FIR emission in line with a flat spectrum extrapolation from 5 GHz.

So we tentatively propose for AGN-BHs a similar observing strategy as for starburst galaxies, with a focus on the FIR: take spectra of all sources in the plausible search window on the sky, including the FIR continuum. Then, select a flux density interval and pick a sample of the highest luminosity sources among them. Try to verify whether any of them could be the source; if unsuccessful, pick another flux density interval, and repeat the exercise.

So a similar approach might be useful to test to select at any given flux density the highest luminosity sources, with two approaches; first, to go for the FIR dust emission, and second for the FIR flat spectrum extension.

2.8 An observational strategy

Consider the detection of a GW event, or alternatively the detection of a high-energy neutrino event, likely to be of astronomical origin. Then, first an area needs to be identified that may contain the galaxy with the source. Thereafter, take a spectral map of this area, which shows the approximate redshift for all sources.

Proceed as follows:

i) Rank all candidate sources in FIR flux density.
ii) Start with the galaxy at the highest flux density, and then define the (index j, here $j = 1$), the first sample (index i) by

$$\Sigma L_{FIR,j,i} > L_{FIR,M82} \frac{\tau_{3.4}}{\tau_{ep}}, \tag{12}$$

where $\tau_{3.4}$, the repetition time scale is, in our BH merger approach, 2, 500 years, and τ_{ep}, the length of the UHECR injection is, in our approach, the length of the time, during which the jets precess, 5 years. Thus, in this sample, there is a ≃ 100 percent expectation that some galaxy is in an active phase of an episode. The size of the sample is one parameter. The chosen flux density interval needs to be large enough so that subsequent intervals do not overlap in combined probability of identification.

iii) Then, rank within the sample all sources by FIR luminosity. The galaxy with the highest luminosity has the highest probability to be the real source.
iv) Repeat, using the next group of galaxies (index *j*), and use the same size of the sample, by adjusting the next flux density boundary; for a Euclidean Universe, one choice could be stepping flux densities by a factor of $2^{-2/3}$ so that we get equal and large numbers at each step.

Check the candidates in the set for any sign of activity that may relate to the event chosen, like visible variability. Considering the observations of M82, a sign would be if a compact source changes structure or spectrum as 41.9 + 58 did. If there is no such sign, pick the next set of lower flux density, and repeat the exercise. Iterate the procedure, until successful, or until the observations run out of sensitivity.

Clearly, this needs a learning experience, different for every class of sources identified. We chose this model to emphasize the possibility for the maximal energy to go beyond the ankle, near 10^{18} eV, and do so with a high rate of injection into the acceleration process. Our model as proposed can be justified only for starburst galaxies, and it remains to be tested whether an analogous approach might also be helpful also for AGN.

3 Conclusion

We propose a model and a two-step strategy to identify sources for either high-energy neutrinos or GWs based on the concept that their production and emission from starburst galaxies are episodic, with the probability that the galaxy contains an emitter currently active in the observer frame running with the FIR luminosity, and the probability that we actually detect the emission running with the flux density. An analogous approach for AGN might be similar, but remains to be developed, justified, and tested.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

MA: writing–review and editing. PB: writing–original draft. AC: writing–review and editing. RC: writing–review and editing. DF: writing–review and editing. LG: writing–review and editing. BH: writing–review and editing. IJ: writing–review and editing. PJ: writing–review and editing. PK: writing–review and editing. EK: writing–review and editing. AM: writing–review and editing. E-SS: writing–review and editing. TS: writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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