# Massive star explosions: A Pandora's box for Cosmic Ray particles and maximally rotating black holes?

**Peter L. Biermann**[1,2,3,4] **and**

UMD, College Park, Mar 30, 2020 - now Sep 14, 2020

[1]MPIfR, Bonn, Germany; [2]K.I.T., Karlsruhe; [3]UA Tuscaloosa, USA; [4]Univ. Bonn: **AUGER; JEM-EUSO**, **B. Harms** (UA Tuscaloosa), **M. Allen** (WSU Pullman, WA), **A. Chieffi** (INAF Rome), **P.P. Kronberg** (U. Toronto), **E. Kun** (Konkoly Obs. Budapest), **E-S. Seo**, (**AMS, ISS-CREAM**; U. MD), and also with help by **J. Becker Tjus** (**IceCube, H.E.S.S.**; U. Bochum), **R. Casadio** (INFN Bologna), **L.Á. Gergely** (**LIGO**; U. Szeged, Hungary), **P.S. Joshi** (ICC, Charusat U., Anand, GUJ, India), **B.B. Nath** (RRI, Bangalore), **T. Stanev** (**IceCube, Sybill**; Bartol, U. DE), ... .

# Cosmic ray spectrum, knee at $\simeq 3 \cdot 10^{15}$ eV and ankle at $\simeq 3 \cdot 10^{18}$ eV, believed to be transition to extragalactic CRs

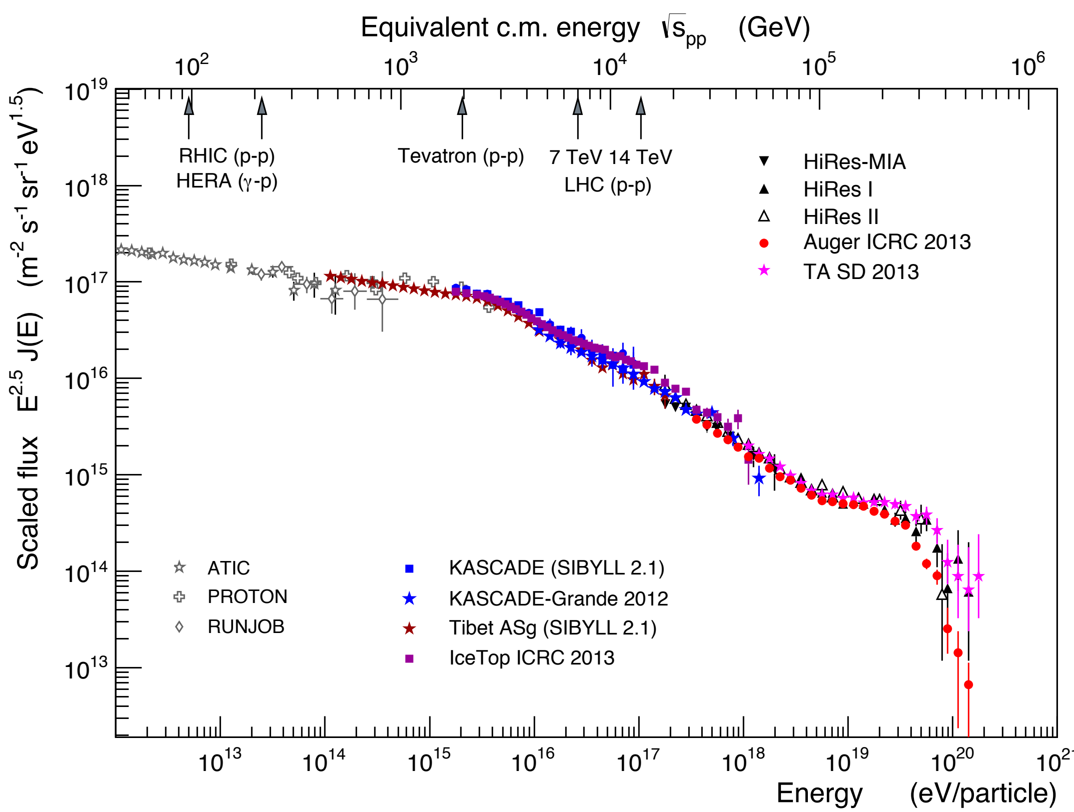


Figure 1 Overall spectrum of cosmic rays, the classical High Energy Particles (HEP). **We have reason to suspect that many SN-explosions contribute flux at the features; by Hillas' (1984 ARAA 22, 425) argument their value of $B \times r$ must be the same or nearly the same.** Source R. Engel 2016.

# Stellar mass black hole (BH) spins consistent with zero before merging

Table 1 $\chi_{\rm eff}$ **is weighted combined individual spin parallel to the orbital spin, dimensionless; error bars not shown here. In a binary BH spin-flip (Gergely + PLB 2009 ApJ) spins remain the same magnitude, but align with orbital spin at the merger. Following a tight probable previous merger the spin could be large for large disorientation, as GW190521 shows**. The possibly largest individual pre-merger spin goes with the largest BH mass; after the merger the BH spin is about 0.7 every time. The full table with all error bars is shown at the end of the lecture. Source LIGO/VIRGO 2019 PRX 9, 031040

| ID | $M_1/M_\odot$ | $M_2/M_\odot$ | $\chi_{eff}$ | $M_{fin}/M_\odot$ |
|---|---|---|---|---|
| GW150914 | 35.6 | 30.6 | **−0.01** | 63.1 |
| GW151012 | 23.3 | 13.6 | **+0.04** | 35.7 |
| GW151226 | 13.7 | 7.7 | **+0.18** | 20.5 |
| GW170104 | 31.0 | 20.1 | **−0.04** | 49.1 |
| GW170608 | 10.9 | 7.6 | **+0.03** | 17.8 |
| GW170729 | 50.6 | 34.3 | **+0.36** | 80.3 |
| GW170809 | 35.2 | 23.8 | **+0.07** | 56.4 |
| GW170814 | 30.7 | 25.3 | **+0.07** | 53.4 |
| GW170818 | 35.5 | 26.8 | **−0.09** | 59.8 |
| GW170823 | 39.6 | 29.4 | **+0.08** | 65.6 |

# M82 radio map 1981: RSN 41.9+58, youngest

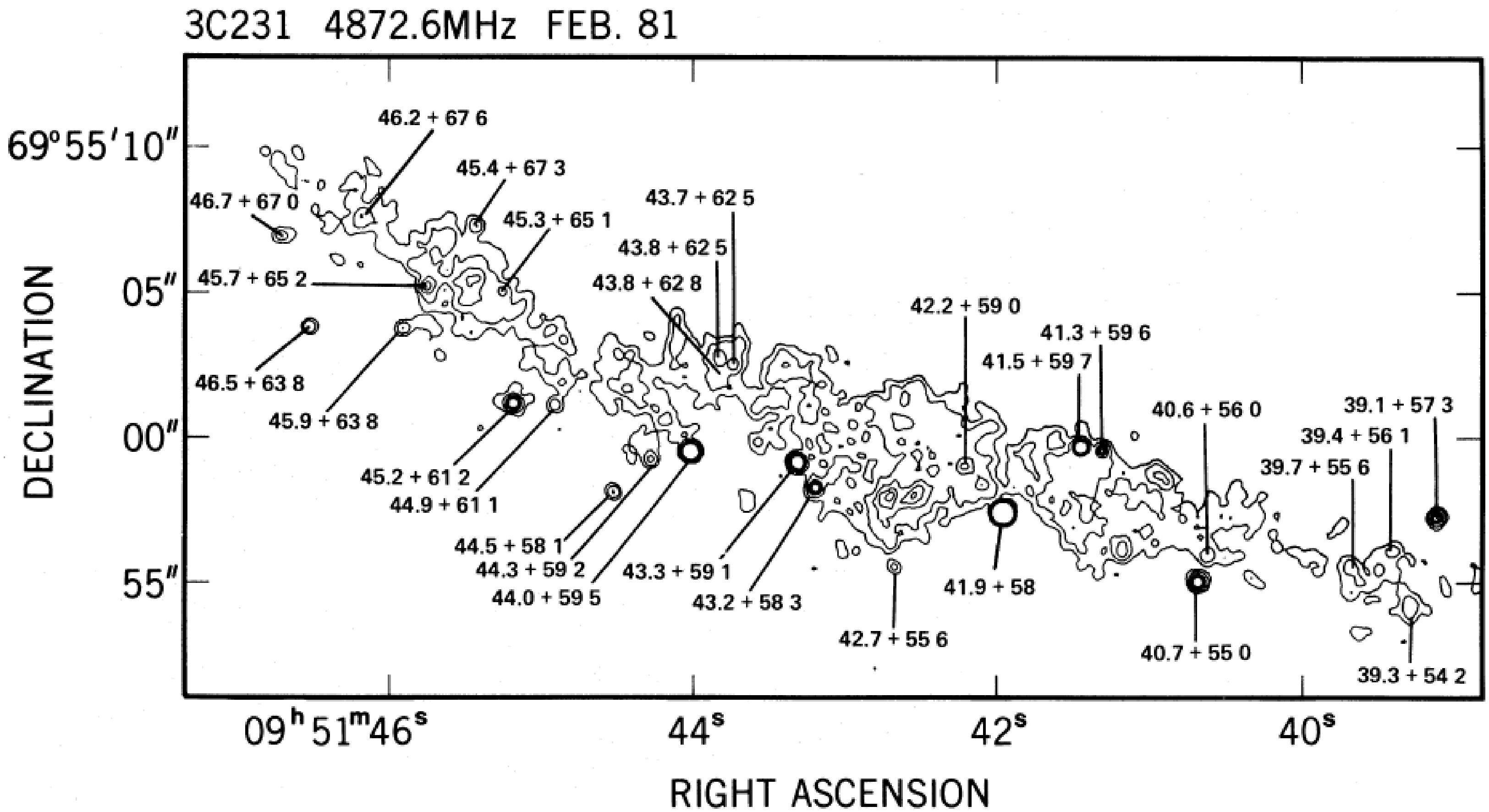


Figure 2 A detailed sub-arcsecond resolution, 5 GHz VLA image of the inner $\sim$ 600 pc of M82. (Kronberg, PLB & Schwab 1985 ApJ 291, 693). It is the first of a series of subsequent images at similar resolution, which span widely different variability rates, spectrum, and radio luminosity. Other related HEP and gravitational physics issues are discussed below (IR, X-ray, gamma ray, and CR observations), and elsewhere. **Each compact radio source here is understood to be due to a blue super giant star explosion into its wind, with 41.9+58 possibly a GRB.**

# M82 41.9+58: Merging black holes (BHs):
# Conical clean-out by jets in spin-flip and kick

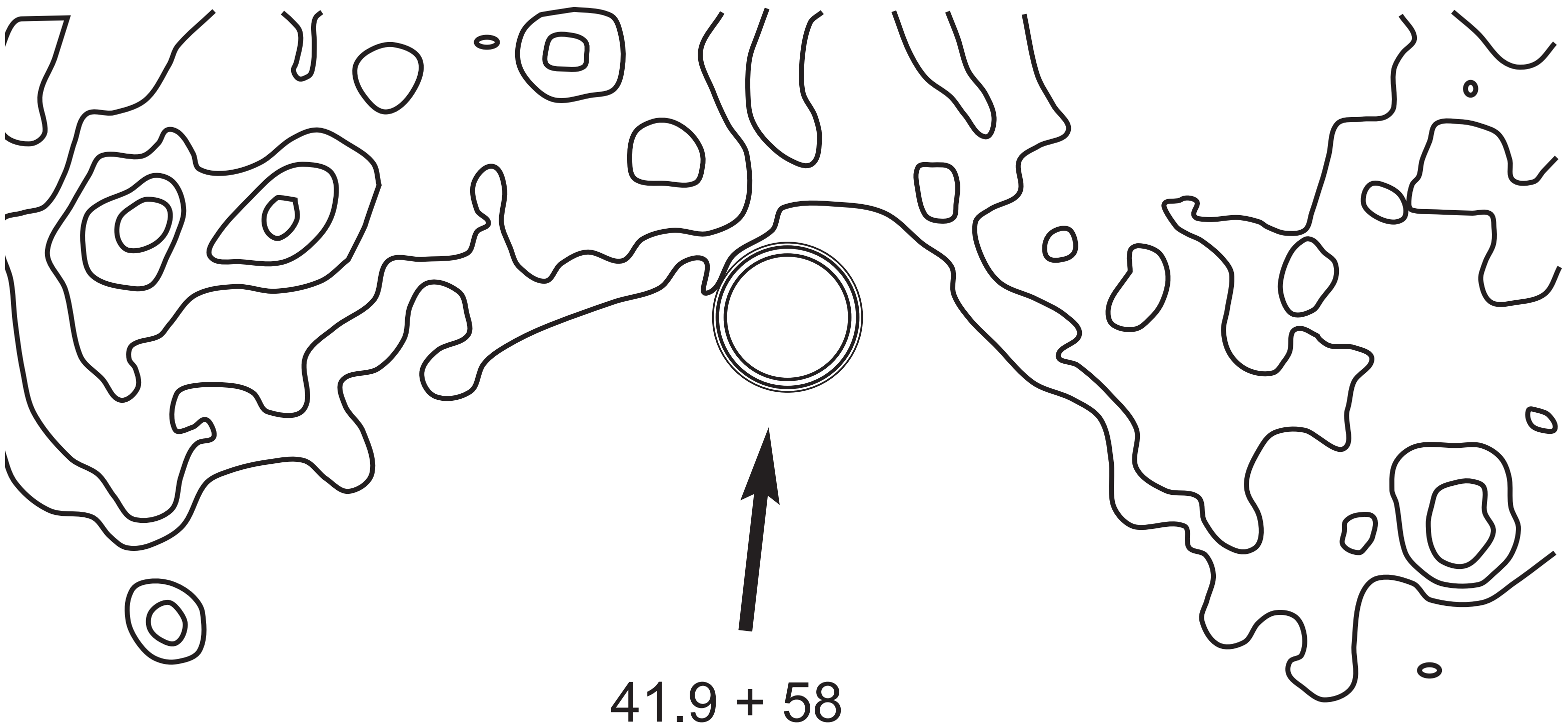


Figure 3 Picture not all to scale. Source Kronberg, PLB, & Schwab 1985 ApJ 291, 693: excerpt of Fig. 2, produced by P.P. Kronberg 2017.

# M82 41.9+58: Conical clean-out and kick from merging black holes (BHs) −> GRB?

• Point-source explosion in stratified atmosphere yields chimney-like structure, never cone (Kompaneets, 1960 Sov. Phys. Dokl., +). Chimneys in many disk galaxies, also M82.

• Double conical clean-out (Gergely & PLB 2009 ApJ: in spinflip in BH merger) by jets and counter-jets suggested by patchy emission, shadowed by foreground in slight tilt. BH kick!

• Requires maximal jet-powers from $P\,dV$ −> maximal spin of both BHs? Spin-down slow!

• Source 41.9+58 GRB ?: Muxlow et al. (2005)

• BH merger rate derived from M82 consistent with LIGO/VIRGO.

# M82 sample: Massive star wind-SN-explosions

Table 2 Supernova remnants (SNRs) in starburst galaxy M82, based on Allen & Kronberg (their Table 5; 1998 ApJ 502, 218), in turn based on Allen (1999 Ph.D. thesis); Source PLB + 2019 Galaxies 7, 48

| Coordinate name | size $2\,r$ in pc | flux density in mJy | sp. index | est. magnetic field $B$ in mGauss | $\log(B \times r)$ in Gauss $\times$ cm |
|---|---|---|---|---|---|
| 40.68 + 550 | 3.72 | 17.9 | −0.52 | 1.80 | **16.0** |
| 41.31 + 596 | 2.17 | 8.59 | −0.54 | 2.32 | **15.9** |
| 41.96 + 574 | 0.33 | 122.8 | −0.72 | 26.4 | **16.1** |
| 42.53 + 619 | 1.71 | 30.9 | $-1.84^{*}$ | 11.7 | **16.5** |
| 42.67 + 556 | 3.02 | 4.44 | −0.61 | 1.46 | **15.8** |
| 43.19 + 583 | 1.16 | 15.3 | −0.67 | 4.79 | **15.9** |
| 43.31 + 591 | 3.02 | 30.3 | −0.64 | 2.54 | **16.1** |
| 44.01 + 595 | 0.78 | 62.0 | −0.51 | 9.83 | **16.1** |
| 44.52 + 581 | 3.72 | 7.2 | −0.61 | 1.40 | **15.9** |
| 45.18 + 612 | 3.49 | 24.1 | −0.68 | 2.13 | **16.1** |
| 45.86 + 640 | 1.09 | 4.10 | −0.53 | 3.39 | **15.8** |
| 46.52 + 638 | 3.88 | 9.71 | −0.73 | 1.53 | **16.0** |
| 46.70 + 670 | 3.41 | 5.22 | −0.57 | 1.37 | **15.9** |
| **Mean and** | **stand.dev.** | | | | **16.0 ± 0.12** |
| Source | 42.53 + 619 | not used | due | to steep spectrum | |

Galaxies sample + M82 sample: 23 RSNe, $\boldsymbol{< \log(B \times r) >}$ **same,** $\mathbf{10^3}$ **in** $\boldsymbol{r}$; MERLIN sample larger errors.

# Massive star can collapse to final BH with maximal rotation I

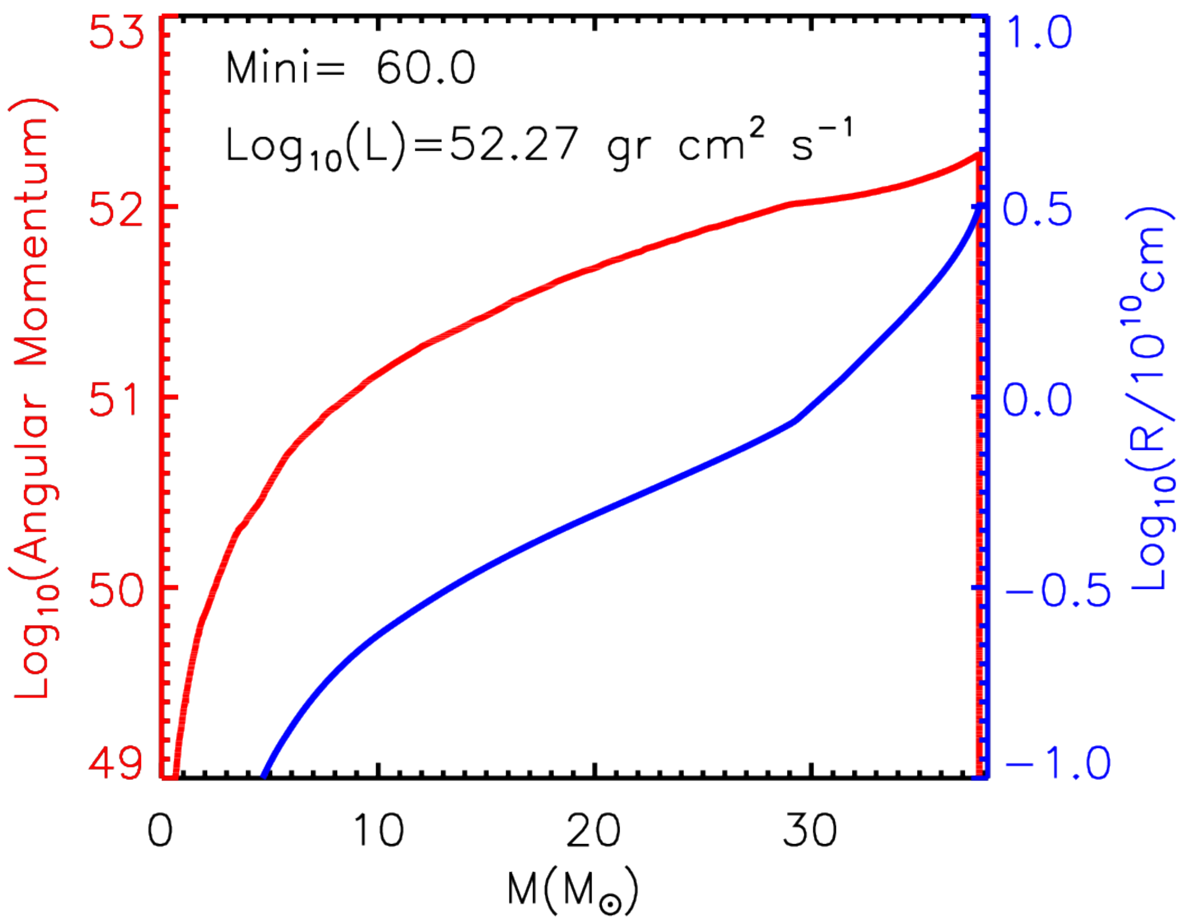


Figure 4 Internal structure of 60 $M_\odot$ star just before making black hole of 38 $M_\odot$. Source: Chieffi 2019 priv.comm., Limongi & Chieffi 2018 ApJS 237, 13. **Spin $10^{52.27}$ erg s factor of $\sim$ $10^{0.21}$ over limit at 38 $M_\odot$, excess; similar for other masses. Maximal differential rotation.**

## Massive star can collapse to final BH with maximal rotation II

A black hole formed would be near maximum spin $J_{BH,max} = 10^{50.9}(M_{BH}/\{10 M_\odot\})^2$ erg s,

BH spin of $10^{52.27}$ erg s excess factor of $\sim 10^{0.21}$ over limit at 38 $M_\odot$; same other masses.

1st option: Growth from small initial BH mass near spin limit.

2nd option: first form a binary BH (BBH).

Maximal differential rotation, for BBHs maximal individual spin each plausible - individual spin-down slow (King & Kolb 1999 MNRAS)

# Massive star can collapse to final BH with maximal rotation III

**3rd option, P.S. Joshi:** Collapse into Kerr geometry, with $(J_{BH}\, c)/(M_{BH}^2\, G_N) > 1$ allowed. Still astrophysical black hole (i.e. lot of mass compacted in small volume, no event horizon). There are powerful mechanisms, how such **naked singularity** very rapidly gives away angular momentum, and settles to a black hole with horizon. We get required burst-like energy also from high angular momentum decay.

**4th option:** Burst of ejected excess angular momentum and energy via magnetic fields: akin to proposal by G. Bisnovatyi-Kogan 1970 +

**All options** $->$ maximally rotating BH.

## Observed SN-wind magnetic fields match requirements for CR knee/ankle energies

- Mean (cgs) + stand.dev. (PLB et al. 2018, 2019, here) $\langle \log(B_{sh} \times r \, \{U_{sh}/c\}^2) \rangle = 14.3 \pm 0.72$.
- $\langle \log(B_{sh} \times r) \rangle = 16.0 \pm 0.12$.
- $E_{ankle} = \{\frac{1}{8}\} \, e \, Z \, B \times r = Z \, 10^{17.55 \pm 0.12}$ **eV**. $E_{knee} = E_{ankle}\{U_{sh}/c\}^2 = Z \, 10^{15.9 \pm 0.72}$ **eV**. $Z$ **is charge**. $B \times r$ **constant with radius.**

11

- BSG star SN-shock races through stellar wind. **Radio SNe (RSNe) in M82**: shock in free expansion (Kronberg et al. 1985 ApJ), **–> piston mass $\simeq 0.1 \, M_{\odot}$ - shown by $\gamma$-ray line emission.**
- Test of CR model: Interactions in molecular clouds via **$\gamma$-spectrum of Galaxy !** (de Boer et al., 2017).

# The shadow of the black hole in M87

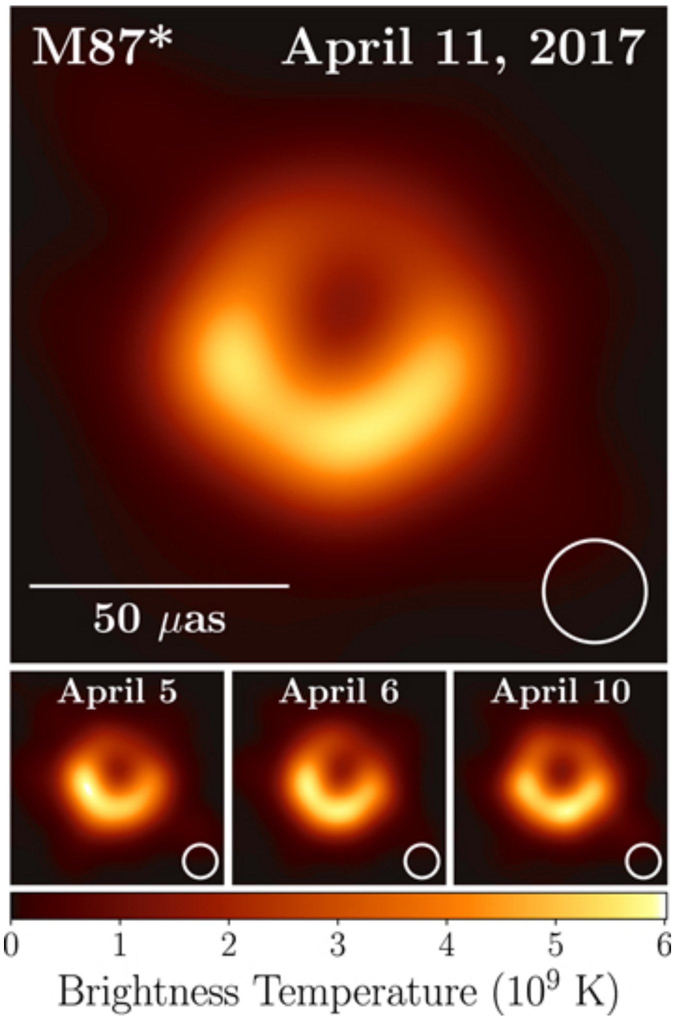


Figure 5 The picture of the black hole shadow. Source EHT-Coll. 2019 ApJL 875, L1

## M87 Black Hole (BH) magnetic fields and luminosity

- **Radius of ring $r = 2.6 \cdot 10^{15}$ cm**
- **$= 2.8$ gravitational radii ($r_G = G_N M_{BH}/c^2$)**
- **Magnetic field of ring $B = 4.9$ Gauss**
- So **$B \times r = 10^{16.1}$ Gauss cm**
- Luminosity observed **Blandford-Znajek power $L = 10^{43.3}$ erg/s** (Blandford & Znajek 1977 MNRAS)
- **Spin estimate 0.94 of maximum**, i.e. close to maximum
- **Uncertainties and error bars** discussed in the six original papers, here paper L5 (ApJL 875, L5, 2019)

# Magnetic field properties around probably maximally rotating black holes

- 12 RSNe from 12 galaxies (PLB et al. 2018 ASR) $\boldsymbol{B \times r = 10^{15.9 \pm 0.47}}$ **Gauss cm**, $\sim$ **CR** $\boldsymbol{E_{ankle}}$ **BH mass** $\sim$ **7.5 to** $\sim$ **50** $\boldsymbol{M_\odot}$ (LIGO/VIRGO sample: 2019 PRX 9, 031040): $\boldsymbol{r \simeq 10^{16}}$ **cm**

- 12 RSNe in M82 (PLB et al. 2019 Galaxies) $\boldsymbol{B \times r = 10^{16.0 \pm 0.12}}$ **Gauss cm**, $\sim$ **CR** $\boldsymbol{E_{ankle}}$ **BH mass** $\sim$ **7.5 to** $\sim$ **50** $\boldsymbol{M_\odot}$ (LIGO/VIRGO sample: 2019 PRX 9, 031040): $\boldsymbol{r \simeq 10^{17.7 \ldots 18.8}}$ **cm**

- M87 shadow (EHT 2019 ApJL 875, L5) $\boldsymbol{B \times r = 10^{16.1}}$ **Gauss cm**, $\sim$ **CR** $\boldsymbol{E_{ankle}}$ **BH mass about** $\boldsymbol{6.5 \cdot 10^9 M_\odot : r \simeq 10^{15.4}}$ **cm**

- $\boldsymbol{e\, B_{sh} \times r = 10^{18.45 \pm 0.12}}$ **eV** $\boldsymbol{= (m_X\, m_{Pl})^{1/2}\, c^2}$; **any significance for** $\boldsymbol{m_X\, c^2}$, **order GeV?**

## Magnetic field around rotating black hole in Galactic Center (GC)

Ref Gravity Coll. 2018 AA: $r_g \simeq 10^{11.8}$ cm. Magnetic field $B \simeq 20$ Gauss, radial scale $\simeq 8\, r_g \simeq 10^{12.7}$. Therefore $\boldsymbol{B \times r \simeq 10^{14}}$ **Gauss cm.**

Ref Bower et al. 2019 ApJL: Radial scale $\simeq 4\, r_g \simeq 10^{12.4}$ cm. Magnetic field $B \simeq 20$ to $50$ Gauss. **Therefore** $\boldsymbol{B \times r \simeq 10^{13.9 \pm 0.2}}$ **Gauss cm.**

**Assume simply, that for small spin**

$$(B_\phi \times r) \sim (J_{BH}\, c)/(G_N\, M_{BH}^2)$$

**then predicted spin** $\sim \boldsymbol{10^{-2.1 \pm 0.2}}$ of maximum. Spin-down luminosity scales as $J_{BH}^3\, \varepsilon_B/4$: Predicts pure spin-down luminosity, $\boldsymbol{10^{37.0 \pm 0.6}\, \varepsilon_B/4}$ **erg/s, inferred from data** $\boldsymbol{10^{37.2}}$ **erg/s, using Falcke + 1995 AA.**

# General Relativity for rotating black holes

Metric tensor elements for Kerr metric in Boyer - Lindquist coordinates (simplified nomenclature, $a$ normalized angular momentum, $M$ normalized mass)

$$ds^2 = \frac{d\phi^2 \sin^2(\theta)\left(\left(a^2+r^2\right)^2 - a^2 \sin^2(\theta)\Delta(r)\right)}{\rho(r,\theta)^2}$$

$$-\frac{(dtd\phi + dtd\phi)\left(2aMr\sin^2(\theta)\right)}{\rho(r,\theta)^2}$$

$$+d\theta^2\rho(r,\theta)^2 + \frac{dr^2\rho(r,\theta)^2}{\Delta(r)} + dt^2\left(-\left(1-\frac{2\,Mr}{\rho(r,\theta)^2}\right)\right).$$

**gravitational constant set to unity, $M$ BH mass**

$$\rho(r,\theta)^2 \;=\; r^2 + a^2\,\cos^2(\theta)\,,$$
$$\Delta(r) \;=\; r^2 - 2\,M\,r + a^2\,.$$

## E and B fields for maximally rotating BHs

$$\mathbf{E}_{\boldsymbol{\theta}}(\mathbf{r}, \boldsymbol{\theta}) = \frac{\mathbf{E}_0}{\boldsymbol{\rho}(\boldsymbol{r}, \boldsymbol{\theta})}, \quad \mathbf{E}_0 \text{ constant},$$

$$\boldsymbol{B}^{\boldsymbol{r}}(\boldsymbol{r}, \boldsymbol{\theta}) = \frac{\mathbf{B}_0}{\sqrt{\boldsymbol{g}_{\boldsymbol{rr}}\, \boldsymbol{g}_{\boldsymbol{\theta\theta}}\, \boldsymbol{g}_{\boldsymbol{\phi\phi}}}}, \quad \mathbf{B}_0 \text{ constant},$$

Based on observational data, we assume that

$$\sqrt{\boldsymbol{g}_{\boldsymbol{rr}}\, \boldsymbol{g}_{\boldsymbol{\theta\theta}}}\, \boldsymbol{B}^{\boldsymbol{\phi}}(\boldsymbol{r}, \boldsymbol{\theta}) = \text{constant} = \mathbf{B}_{\boldsymbol{p}0}\,.$$



ignoring here any possible $\theta$-dependence. **The key point this constant $\mathbf{B}_{p0}$ independent of BH mass $M$, likely dependent on BH angular momentum.** We assume below, proportional to normalized angular momentum, here $\sim a/M$, elsewhere $(J_{BH}\, c)/(M_{BH}^2\, G_N)$.

## Energy and angular momentum extraction

For observer at infinity rate is

$$\dot{E}_{rad} = \frac{4\pi \mathrm{B}_{p0}\,\mathrm{E}_0\,\left(a^2 + r(r-2M)\right)}{r^2\sqrt{a^2+r^2}}$$

$$\dot{L}_{rad} = \frac{4\pi \mathrm{B}_0\,\mathrm{B}_{p0}\,\left(a^2 + r(r-2M)\right)^{3/2}}{r^2\sqrt{a^2+r^2}}.$$

Comparison with large distance yields: **Luminosity here maximal at $\simeq\ 3\,r_G$ for maximal rotation, as observed for M87. $->\ 2\,\varepsilon_B\ \simeq\ 3$.**

**Angular momentum transport asymptotically constant with $r$. Via magnetic fields, as most in Weber & Davis 1967.**

**Boundary condition at BH and particle flow replaced here with electric current flow. Properties of BH determine the boundaries.**

## Spin-down of maximally rotating BHs I
## (Parker 1958 ApJ; Weber & Davis 1967 ApJ)

$$J_{BH,max} \,=\, \hbar \, \{M_{BH}/m_{Pl}\}^2 \,=\, 10^{50.9} \, M_{BH,1}^2 \, \mathrm{erg\,s}$$

$$\frac{\hbar}{\tau_J} \left(\frac{M_{BH}}{m_{Pl}}\right)^2 \,=\, B_r \, r^2 \, B_\phi r \,=\, (B_\phi \, r)^2 \, l_{Pl} \left(\frac{M_{BH}}{m_{Pl}}\right) 2 \, \varepsilon_B$$

**Here $B_r \,=\, B_\phi$ at $2 \, \varepsilon_B \, r_G$; $r_G \,=\, l_{Pl} \, (M_{BH}/m_{Pl})$; assumption that this radius exists.**

$$\mathbf{CRs:} \;\; E_{ankle} \sim e \, B_\phi \, r \,=\, (m_X \, m_{Pl})^{1/2} \, c^2$$

Allen: $m_X \,=\, m_p \, 10^{-0.16 \pm 0.24}$. **$m_X$ stand-in for observed energy, why $\sim$ GeV?** $2 \, \varepsilon_B$ **and** $1/\varepsilon_{PN}$ distance rel. to gravit. radius of total mass.

# Spin-down of maximally rotating BHs II

$$\frac{1}{\tau_J} = \frac{\hbar\, c}{e^2} \left(\frac{M_{BH}}{m_{Pl}}\right)^{-1} \frac{m_X}{m_{Pl}} \frac{1}{\tau_{Pl}} 2\, f_N\, \varepsilon_B \sim E^2_{ankle}$$

**Time ($10^{4.7}\, M_{BH,1}\, f_N^{-1}\, \varepsilon_B^{-1}$ yr) $\sim$ BH mass.**

$$\frac{E_{rot,max}}{\tau_J} = \frac{\hbar\, c}{e^2} \frac{m_X\, c^2}{\tau_{Pl}} 2\, f_N\, \varepsilon_B = 10^{42.86}\, f_N\, \varepsilon_B\, \mathrm{erg\, s^{-1}}$$



**independent of BH mass**. $2 < 2\, \varepsilon_B = \varepsilon_{PN}^{-1}$.
$f_N$ **non-EM allowed for here** during formation. See Komissarov 2004 MNRAS, Gergely & PLB 2009 ApJ.

**Maximal energy flux observed for $\lesssim 10^3$ years, so about $10^{53.1}$ erg $\varepsilon_B$, plenty to explode star!**

## Spin-down of maximally rotating BHs III

**Energy $m_X\, c^2$ observed quantity, speculation on why near GeV. Value of $f_N$ very uncertain!**

**(1) Magnetic field $B_{\phi}$, since observed $B_{\phi}\, r\ =$ *const* follows Parker's (1958 ApJ) law**

**(2) In Parker wind there is angular momentum transport (Weber & Davis 1967 ApJ)**

**(3) Since value of $(B\, r)$ for M87 matches that for many RSNe; M87 BH may be near maximal spin, we adopt view that BHs from SNe are also near maximal spin: low spin GC BH consistent**

**(4) Magnetic field of (i) wind spin-down given by RSNe and of (ii) CRs: match quantitatively!**

**(5) Magnetic spin-down, $\nu$ or GW spin-down - successive or in parallel? Or slow, $f_N\ =\ 1$?**

## Spin-down of maximally rotating BHs IV

Using M87, $\varepsilon_B \sim 3/2$, above. $f_N = 1$ in steady BH

**Then implied spin-down luminosity $10^{43.04}$ erg s$^{-1}$. The observed M87 BZ equivalent luminosity $L_{BZ} = 10^{43.3}$ erg/s (EHT 2019 ApJL). Match?!**

**Spin down luminosity $\sim E_{ankle}^2 \sim m_X$.**



Allows interpretation all **power due to spin-down**; no extra accretion necessary (see Blandford & Znajek 1977 MNRAS 179, 433). **Energy max $(\sqrt{2}-1)\, M_{BH,irr}\, c^2$**

**Spin-down luminosity independent of BH mass, and spin-down time scales linearly with BH mass. Numbers from RSNe, M87 and CRs.**

## Spin-down of maximally rotating BHs V

Spin-down energy for **$10\,M_\odot$ BH at end of spin-down**, so $M_{BH,irr} = 10\,M_\odot$, which implies initially $M_{BH} = \sqrt{2} \times 10\,M_\odot = 14.2...\,M_\odot$.

$$2\,M_{BH,irr}^2 = M_{BH}^2 \left(1 + \left(1 - \left(\frac{J\,c}{M_{BH}^2\,G_N}\right)^2\right)^{1/2}\right)$$



Available $c^2\,(M_{BH} - M_{BH,irr}) \simeq 10^{54.9}\,\mathrm{erg}$.
**Where is all that energy? Cosmic background?**
Spin-down $\lesssim 10^{53.1}$ **erg from** $\lesssim 10^3$ **yrs**. SN-explosion $\sim\ 10^{52}$ **erg**. Kinetic energy $\sim\ 10^{51}$ **erg**. Magnetic fields and CRs $\sim\ 10^{50.7}$ **erg** at 3 pc. Sum $\sim\ 10^{53.1}$ **erg, order of $10^{-1.8}$ of available energy**?
**Successive or parallel? (1) Slow magnetic wind spin-down, and/or (2) GW or $\nu$ spin-down?**

# Spin-down of maximally rotating BHs VI

**Gravitational waves emitted in merger same property: Planck luminosity scale independent of BH mass (several factors of order unity, pre-factor $10^{-3.0}$). Spin-down luminosity independent of BH mass, time-scale $\sim$ BH mass. $L_{Pl}$:**

$$L_{Pl} = \frac{m_{Pl}\, c^2}{\tau_{Pl}} = \frac{c^5}{G_N} = 10^{59.56}\, \mathrm{erg\, s^{-1}}$$



**Planck luminosity independent of $\hbar$, spin-down luminosity contains $\hbar$, combination of quantum physics and gravitational theory?**
**This analogy is consistent with speculative interpretation of magnetic spin-down, based on the numbers from M87, RSNe and CRs.**

## Spin-down of maximally rotating BHs VII

**Life-time estimate of RSNe allows upper limit to $f_N$ non-EM via time-scale of total emission.**

Allen & Kronberg 1998 ApJ, and Kronberg & Allen 2000 ApJ give plenty of data:
**Among 22 sources (non-GRB and non-HII) there are three that vary, one that has steep spectrum.** Those that vary can be interpreted as young, since variability runs inverse with age. One with steep spectrum probably old.

**Observing time 12 years**, so either 3 of 22 started, or 1 in 22 dies. Range of probable age is from about $(22/3)*12 = 88$ to $22*12 = 264$ yrs. **Safe $< 1,000$ yrs**

## Spin-down of maximally rotating BHs VIII

Interpretation: **free expansion through wind $\sim$ 30 yrs followed by slow-down or stalling phase, during which $\boldsymbol{B \times r}$ does not change much**. Hypothesis central feeding keeps everything alive. Piston?

Upper limit to lifetime at const. $r \times B$ about 1,000 years. Condition $\mathbf{10^{4.7}}\, \boldsymbol{M_{BH,1}\, f_N^{-1}\, \varepsilon_B^{-1}}\, \mathbf{yr} \;<\; \mathbf{10^{3.0}\, yrs.}$ Lower limit from free expansion phase, **safe $>$ 30 yrs.** Median BH mass 2019 data $\sim$ $30\, M_{\odot}$; $\varepsilon_B$ from M87 $\sim 3/2$. So: $\mathbf{10^{3.5}} > \boldsymbol{f_N} > \mathbf{10^{2.0}}$.

**Limits $10^{51.7}$erg $< \boldsymbol{E_{SN,EM}} < 10^{54.9-2.0} = 10^{52.9}$ erg in EM channels**, implies **non-EM channel yield most of $10^{54.9}$ erg in $<$ 1,000 years**. Just for fresh BH formation. **Above $10^{53.4}$ erg max.**

## Pandora's box questions: Ergosphere maximal pair creation cauldron?

- Particles in ergosphere (for maximal rotation at equator between $G_N \, M_{BH}/c^2$ and twice this radius) accelerated, collide with each other to make $p \; \bar{p}$ pairs ($e^-$ and $e^+$ secondaries with lots of neutrinos).

- Power source spin-down via rotation and magnetic fields: numbers from RSNe and CRs

- Once pair created, one out, one in, taking angular momentum from the BH, so Penrose mechanism (1971 Nature). Out- and in-side driven by magnetic fields.

- Spin-down luminosity, spin-down flux - both $\sim \; E^2_{ankle} \; \sim \; m_X \, c^2$ - give maximal rate of particles accepted by BH in pure spin-down.

## Pandora's box questions: Quantum mechanical theory of BHs ?

- Casadio et al. (2013, 2014, 2017), Dvali et al. (2013, 2014): **BH pictured as Bose-Einstein condensate of weakly interacting soft gravitons with occupation number $N = (M_{BH}\, r_+\, c)/(\hbar)$, graviton energy $(m_{Pl}\, c^2)/\sqrt{N}$, wavelength $\sqrt{N}\, l_{Pl}$, and maximal angular momentum $\hbar\, N$. One fluctuation $\sqrt{N}$ corresponds to mass $m_{Pl}$.**



- **Factor $(\hbar\, c)/(e^2)$ from electric potential limit? Factor of $m_p/m_{Pl}$ from angular momentum transport taking charged particles $p\,\bar{p}$ of mass $m_p$ relative to fluctuation mass scale? Data:**

$$\frac{E_{rot,max}}{\tau_J} \simeq \left(\frac{\hbar\, c}{e^2}\right)\left(\frac{m_p}{m_{Pl}}\right)\left(\frac{m_{Pl}\, c^2}{\tau_{Pl}}\right)$$

## Pandora's box questions: CRs and BHs:

- BH merger vs. max. rotating BH spin-down
- Both luminosities independent of BH mass
- Both time scales linear with BH mass
- GW luminosity does not depend on $\hbar$
- Magnetic field spin-down depends on $\hbar$
- QM BE-model of BHs (Casadio et al. 2017)?
- Explains CR knee and CR ankle energies
- $p\ \bar{p}$ pair creation in ergosphere?
- SN analogous to Bisnovatyi-Kogan 1970 +
- Covers $7.5\,M_{\odot}$ to $6.5\,10^{9}\,M_{\odot}$ in BH mass
- Test with GW190521 nonthermal emission

• Hope is still in Pandora's box •

## Energy budget questions:

- (1) Energy $m_X \sim E^2_{ankle}$, order of GeV? (2) energy fraction in EM vs available, $\lesssim 10^{-1.5}$?
- $->$ if non-EM ($\sim$ 100 vs 1) all GWs or $\nu$'s, then strong cosmic background! Or slow?
- Or, spin not low in merger, spin stays high? Then no GW and no $\nu$ background!
- Briefly BBH or naked singularity first?
- Prediction: If BBH then we should observe many lower mass BH mergers, that always just follow a SN explosion - none seen yet
- BHs in a BBH system high spin? Yes, GW190521. A 2nd generation merger (ApJL 2020)? If so, no strong spin-down since previous merger

## Stellar mass BH and CR questions:

- **Structure of pair creation cauldron? visible?**
- **Anti-proton production for CRs?**
- **Or electron/positron pairs?**
- **Massive star SN-explosion mechanism? Bisnovatyi-Kogan 1970 ... 2018: $\Omega + B$**
- **Why usually $V_{SN} \simeq 0.1\,c$? Why usually $10^{-5}\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$? Why usually $0.1\,\mathrm{M}_{\odot}$, piston? Piston mass caling with $M_{BH}$?**
- **Spin-down gives readily $\gtrsim 10^{52.4\,...\,53.4}$ erg!**
- **$B \times r \sim (J_{BH}\,c)/(G_N\,M_{BH}^2)$? True?**
- **How fast can stellar mass BHs merge? Can they have maximal spin at their merger ?**

# Caveats:

- Could $f_N$ have compensating factor $\hbar^{-1/2}$?
- Then spin-down luminosity independent of $\hbar$
- Could $f_N$ be $(\hbar c)/(e^2) = 10^{2.136,791,...}$?
- Spin-down very fast via kHz GWs?
- Spin-down very fast via $\gtrsim$ 200 MeV $\nu$s?
- M82 RSN 41.9+58 suggests not.
- Questions have come out of Pandora's box - hope for answers from more data is left!

**THANK YOU**

# Lower spin BHs and Sgr A$^*$, the GC BH: I

**Assume the simplest, that for small spin**

$$(B_\phi \, r) \sim (J_{BH} \, c)/(G_N \, M_{BH}^2)$$

The spin-down time can be rewritten as

$$\frac{1}{\tau_J} = \frac{1}{\tau_{Pl}} \frac{\hbar \, c}{e^2} \left( \frac{m_X}{m_{Pl}} \right) \left( \frac{m_{Pl}}{M_{BH}} \right) \left( \frac{J_{BH} \, c}{M_{BH}^2 \, G_N} \right) 2 \, \varepsilon_B$$



For small spin, the difference between the actual BH mass and the irreducible BH mass can be written as

$$M_{BH} - M_{BH,irr} -> \frac{M_{BH}}{8} \left( \frac{J_{BH} \, c}{M_{BH}^2 \, G_N} \right)^2$$

## Lower spin BHs and Sgr A$^*$, the GC BH: II

Assuming only EM on this long time-scale multiplying this with $c^2$ and dividing this by $\tau_J$ gives a luminosity of

$$\frac{E_{rot}}{\tau_J} = \frac{1}{\tau_{Pl}} \frac{\hbar\, c}{e^2} m_X\, c^2 \left( \frac{J_{BH}\, c}{M_{BH}^2\, G_N} \right)^3 (\varepsilon_B/4)$$



**Assume that GC BH is powered by magnetic wind spin-down**, then we can derive the spin from the factor between $10^{43.3}\, erg/s$ and the observed $10^{37.2}\, erg/s$. The spin then indicated is $(J_{BH}\, c)/(M_{BH}^2\, G_N) \simeq 10^{-2}$. **Consistent with estimate from observed low $B \times r$** (see above). **EHT data may test this.**

# Consequences

The angular momentum loss can be written as

$$(B_\phi \, r)^2 \, c \, \frac{l_{Pl}}{c} \, \frac{M_{BH}}{m_{Pl}} \simeq$$

$$\simeq \frac{m_p \, m_{Pl} \, c^5}{e^2} \left( \frac{J_{BH} \, c}{G_N \, M_{BH}^2} \right)^2 \frac{l_{Pl}}{c} \, \frac{M_{BH}}{m_{Pl}} =$$

$$\simeq \frac{\hbar \, c}{e^2} \, \frac{m_p \, c^2}{\tau_{Pl}} \left( \frac{J_{BH} \, c}{G_N \, M_{BH}^2} \right)^2 \frac{l_{Pl}}{c} \, \frac{M_{BH}}{m_{Pl}}$$

## Binary BH possibility?

**If SN always followed by BBH merger.**

**Prediction: BBH mergers in the low mass range! These are massive star SNe and may include BBH formation and BBH merger.**

From available angular momentum $\varepsilon_{BBH} = 10^{1.05}$, for maximum spin each. Putting $2\,\varepsilon_{BBH} = 1/\varepsilon_{PN}$ third regime in Table 2 of Gergely & PLB 2009.

**Delay between SN explosion and BBH merger:**

$\boldsymbol{\tau_{delay} = 10^{0.8}\,\mathrm{s}\,M_{BH,1}}$,

a few seconds for maximal individual spin. **For minimal individual spin time delay $\mathbf{10^{2.2}}$ s, a few minutes**. The difference may only be recognizable in a time delay between **neutrino emission and GW emission**.

## $\bar{p}$ CR contribution from pair creation cauldron

If a cauldron exists then pair-creation particle spectrum likely to be $E^{-2}$, so irregularity spectrum in magnetic fields $k^{-5/3}$ (Kolmogorov by excitation across all energies: PLB + 2001 AA)?

Therefor anti-proton/proton secondary source spectrum $E^{-7/3}$?



Upon escape from pair-creation cauldron transport in Galaxy adds another factor of $E^{-1/3}$, so that spectrum fits observed $4\,\pi$ CR-component from Red Super Giant (RSG) stars in CR-protons?

Therefore ratio of $\bar{p}/p$ constant with energy possible - numerical value of $\sim\ 10^{-3.7}$?

## Cosmic background? I

Numbers for M82: massive star SN-rate (i.e. all above 10 $M_\odot$) order 1/year, and so BSG SNe (i.e. all above 33 $M_\odot$) order 1/7 years

FIR luminosity observed of M82: $10^{10.6}\,L_\odot$

Galaxy massive star SN-rate 1/75 years, so BSG SNe 1/600 years, with source attributed (i.e. non-diffuse) FIR luminosity $10^{9.3}\,L_\odot$

Translation of FIR luminosity to BSG SNe not same for Galaxy, starburst galaxies like M82

Lagache et al. (2003) show FIR LF: starburst galaxies may dominate cosmic BSG SNe rate, with galaxies somewhat stronger than M82 contributing most

A BSG SN $10^{54.9}\,M_{BH,1}$ ergs $->$ non-EM bg

# Cosmic background? II

Dust emission of M82 might be optically thick, from converted UV, so anisotropic (Savage & Mathis 1979 ARAA, Lagache et al. 2005 ARAA, Salak et al. 2013 PASJ) due to its very large column density.

Evidence that starburst galaxies have optically thick spectra bluewards of 100 $\mu$ is found in ALMA data, Faisst et al., 2020, arXiv 2005.07716

This suggests again, that starbursts mostly form massive stars, Kronberg et al. 1985 ApJ.

## Cosmic background? III

ZAMS mass vs. BH mass from models (A. Chieffi): **ZAMS mass $\simeq 25\,M_{\odot}$ produces BH of $\simeq 10\,M_{\odot}$.**

Massive stars approach Eddington luminosity up main sequence, lifetime of a few million years: **Lifetime output $\simeq 10^{39.+14+0.4} = 10^{53.4}\,\mathrm{erg}\,M_{BH,1}$; is most of this translated into FIR emission?** Integrating luminosity over lifetime gives net factor of $\simeq 10^{-0.4}$ less, using stars from 20 to 60 $M_{\odot}$.



**GW output $10^{54.9}\,\mathrm{erg}\,M_{BH,1}$, far above 300 Hz (LIGO/VIRGO 2019 PRD) in merger**

**GW or $\nu$ background about $80 \times$ FIR bg**

Going down to $5\,M_{\odot}$, factor increases by $\simeq 10$, increasing expected NEM background by 10. **Ratio independent of history; early phases with low heavy element abundance could be different (Mirabel et al. 2011 AA; Chieffi & Limongi 2013 ApJ).**

# Cosmic background? IV

In starburst galaxies ($10^7$ to $10^8$ yrs) top-heavy IMF: 10 million years lifetime of $\simeq\ 20\,M_{\odot}$ star, 100 million years lifetime of $\simeq\ 5\,M_{\odot}$.

---

Planck 2018. VI. Cosmological parameters:

$\Omega_{\Lambda}\ =\ 0.6889 \pm 0.0056$

$\Omega_{dm}\ =\ 0.2607 \pm 0.0048 \quad \Omega_{b}\ =\ 0.04897 \pm 0.00091$

$H_0\ =\ 67.66 \pm 0.42\,\mathrm{km/s/Mpc}$

Thomson depth: $\tau_T\ =\ 0.0561 \pm 0.0071$

Age of universe: $t_0\ =\ (13.787 \pm 0.020) \cdot 10^9\,\mathrm{yr}$

---

$\Omega_{MWBG}\ =\ 10^{-4.1}$

$\Omega_{FIR}\ \simeq\ 10^{-6.7}$, so here

$\Omega_{NEM}\ \simeq\ 10^{-4.8}$, possibly higher

or all hidden in high spin that decays slowly?

# Structure of ergosphere?

Rate of new particles entering BH, leaving ergosphere to go outside of order $10^{46}\,s^{-1}$ $p/\bar{p}$ and (more) $e^-e^+$, all produced by collisions, that make pairs - independent of BH mass. Collisions make secondaries $e^-e^+$ and $\nu$s.

There could be many more collisions:
BH takes particles $\lesssim$ acceptance limit. Any excess used up in other collisions $->$ neutrinos.

Particles $->$ electric current by gradient/ curvature drift. Currents in $\theta, r$ $->$ $B_\phi$, observed. Electric currents peak near inner edge of the ergosphere, outer event horizon.

# BHs of minium spin I

For low spin and assuming simplicity we worked out above

$$\frac{E_{rot}}{\tau_J} \simeq \frac{1}{\tau_{Pl}} \frac{\hbar\, c}{e^2} m_X\, c^2 \left( \frac{J_{BH}\, c}{M_{BH}^2\, G_N} \right)^3$$

**Just using statistical fluctuations mininum spin**

$$J_{BH,min} = \hbar \sqrt{N} \simeq \hbar \frac{M_{BH}}{m_{Pl}}$$



inserting above yields

$$L_{rot,min} \simeq \frac{\hbar\, c}{e^2} \frac{m_X\, c^2}{\tau_{Pl}} \left( \frac{m_{Pl}}{M_{BH}} \right)^3$$

which is far lower than Hawking radiation.

# BHs of minium spin II

Next we can ask at which spin Hawking radiation and this luminosity are equal in order of magnitude, and that is at

$$J_{BH,equiv} = J_{BH,max} \left( \frac{e^2}{\hbar\, c} \frac{m_{Pl}}{m_X} \left( \frac{m_{Pl}}{M_{BH}} \right)^2 \right)^{1/3}$$



For $10\, M_{\odot}$ and $10^8\, M_{\odot}$ BHs this is $10^{-20.3}$ and $10^{-25}$, respectively, of maximum spin, so in many cases larger than the Hawking radiation.

# Galaxies sample: Massive stars: wind-SN-CRs

Table 3 Some radio supernova (RSN) data and results: Source PLB + 2018 ASR 62, 2773

| Name | type | progen. | $\log\left(\frac{\dot{M}_{\star}}{M_{\odot} yr^{-1}}\right)$ | $\log\left(\frac{B_{sh} \times r_{sh}}{\text{Gauss cm}}\right)$ | $\log\left(\frac{B_{sh} \times r_{sh} \{U_{sh}/c\}^2}{\text{Gauss cm}}\right)$ |
|---|---|---|---|---|---|
| 1993J | IIb | RSG | -5.0 | **16.8** | 14.4 |
| 2003L | Ibc | BSG | -5.1 | **16.3** | 14.9 |
| 2003bg | Ic/Ibc | BSG | -3.5 | **16.4** | 15.2 |
| 2007gr | Ic | BSG | -6.2 | **15.3** | 13.9 |
| 2008D | Ibc | BSG | -5.1 | **15.9** | 15.5 |
| 2008iz | II | RSG | -4.4 | **16.0** | 13.8 |
| 2011dh | IIb | BSG | -4.5 | **15.7** | 13.7 |
| 2011ei | IIb/Ib | BSG | -4.9 | **15.3** | 13.5 |
| 2012au | Ib | BSG | -5.4 | **15.8** | 14.4 |
| 2013df | IIb | RSG | -4.1 | **15.9** | 13.5 |
| 1998bw | rel. | BSG | -6.6 | **16.4** | ... |
| 2012ap | rel.(i) | BSG | -5.2 | **16.0** | 15.4 |
| 2012ap | rel.(ii) | BSG | -5.2 | **16.** | 16. |
| Mean | and | stand.dev. | $-5.1 \pm 0.8$ | **$15.9 \pm 0.47$** | $14.3 \pm 0.72$ |
| mean | = | stand.dev. | | 2008D vel. | no rel. |
| error | | $/\sqrt{N}$ | | limit used; | case used |

# Detailed BH properties with error bars before and after merging

| Event | $m_1/\mathrm{M}_\odot$ | $m_2/\mathrm{M}_\odot$ | $\mathcal{M}/\mathrm{M}_\odot$ | $\chi_{\mathrm{eff}}$ | $M_{\mathrm{f}}/\mathrm{M}_\odot$ | $a_{\mathrm{f}}$ | $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$ | $\ell_{\mathrm{peak}}/(\mathrm{erg\,s}^{-1})$ | $d_L/\mathrm{Mpc}$ | $z$ | $\Delta\Omega/\mathrm{deg}^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| GW150914 | $35.6^{+4.8}_{-3.0}$ | $30.6^{+3.0}_{-4.4}$ | $28.6^{+1.6}_{-1.5}$ | $-0.01^{+0.12}_{-0.13}$ | $63.1^{+3.3}_{-3.0}$ | $0.69^{+0.05}_{-0.04}$ | $3.1^{+0.4}_{-0.4}$ | $3.6^{+0.4}_{-0.4} \times 10^{56}$ | $430^{+150}_{-170}$ | $0.09^{+0.03}_{-0.03}$ | 180 |
| GW151012 | $23.3^{+14.0}_{-5.5}$ | $13.6^{+4.1}_{-4.8}$ | $15.2^{+2.0}_{-1.1}$ | $0.04^{+0.28}_{-0.19}$ | $35.7^{+9.9}_{-3.8}$ | $0.67^{+0.13}_{-0.11}$ | $1.5^{+0.5}_{-0.5}$ | $3.2^{+0.8}_{-1.7} \times 10^{56}$ | $1060^{+540}_{-480}$ | $0.21^{+0.09}_{-0.09}$ | 1555 |
| GW151226 | $13.7^{+8.8}_{-3.2}$ | $7.7^{+2.2}_{-2.6}$ | $8.9^{+0.3}_{-0.3}$ | $0.18^{+0.20}_{-0.12}$ | $20.5^{+6.4}_{-1.5}$ | $0.74^{+0.07}_{-0.05}$ | $1.0^{+0.1}_{-0.2}$ | $3.4^{+0.7}_{-1.7} \times 10^{56}$ | $440^{+180}_{-190}$ | $0.09^{+0.04}_{-0.04}$ | 1033 |
| GW170104 | $31.0^{+7.2}_{-5.6}$ | $20.1^{+4.9}_{-4.5}$ | $21.5^{+2.1}_{-1.7}$ | $-0.04^{+0.17}_{-0.20}$ | $49.1^{+5.2}_{-3.9}$ | $0.66^{+0.08}_{-0.10}$ | $2.2^{+0.5}_{-0.5}$ | $3.3^{+0.6}_{-0.9} \times 10^{56}$ | $960^{+430}_{-410}$ | $0.19^{+0.07}_{-0.08}$ | 924 |
| GW170608 | $10.9^{+5.3}_{-1.7}$ | $7.6^{+1.3}_{-2.1}$ | $7.9^{+0.2}_{-0.2}$ | $0.03^{+0.19}_{-0.07}$ | $17.8^{+3.2}_{-0.7}$ | $0.69^{+0.04}_{-0.04}$ | $0.9^{+0.05}_{-0.1}$ | $3.5^{+0.4}_{-1.3} \times 10^{56}$ | $320^{+120}_{-110}$ | $0.07^{+0.02}_{-0.02}$ | 396 |
| GW170729 | $50.6^{+16.6}_{-10.2}$ | $34.3^{+9.1}_{-10.1}$ | $35.7^{+6.5}_{-4.7}$ | $0.36^{+0.21}_{-0.25}$ | $80.3^{+14.6}_{-10.2}$ | $0.81^{+0.07}_{-0.13}$ | $4.8^{+1.7}_{-1.7}$ | $4.2^{+0.9}_{-1.5} \times 10^{56}$ | $2750^{+1350}_{-1320}$ | $0.48^{+0.19}_{-0.20}$ | 1033 |
| GW170809 | $35.2^{+8.3}_{-6.0}$ | $23.8^{+5.2}_{-5.1}$ | $25.0^{+2.1}_{-1.6}$ | $0.07^{+0.16}_{-0.16}$ | $56.4^{+5.2}_{-3.7}$ | $0.70^{+0.08}_{-0.09}$ | $2.7^{+0.6}_{-0.6}$ | $3.5^{+0.6}_{-0.9} \times 10^{56}$ | $990^{+320}_{-380}$ | $0.20^{+0.05}_{-0.07}$ | 340 |
| GW170814 | $30.7^{+5.7}_{-3.0}$ | $25.3^{+2.9}_{-4.1}$ | $24.2^{+1.4}_{-1.1}$ | $0.07^{+0.12}_{-0.11}$ | $53.4^{+3.2}_{-2.4}$ | $0.72^{+0.07}_{-0.05}$ | $2.7^{+0.4}_{-0.3}$ | $3.7^{+0.4}_{-0.5} \times 10^{56}$ | $580^{+160}_{-210}$ | $0.12^{+0.03}_{-0.04}$ | 87 |
| GW170817 | $1.46^{+0.12}_{-0.10}$ | $1.27^{+0.09}_{-0.09}$ | $1.186^{+0.001}_{-0.001}$ | $0.00^{+0.02}_{-0.01}$ | $\leq 2.8$ | $\leq 0.89$ | $\geq 0.04$ | $\geq 0.1 \times 10^{56}$ | $40^{+10}_{-10}$ | $0.01^{+0.00}_{-0.00}$ | 16 |
| GW170818 | $35.5^{+7.5}_{-4.7}$ | $26.8^{+4.3}_{-5.2}$ | $26.7^{+2.1}_{-1.7}$ | $-0.09^{+0.18}_{-0.21}$ | $59.8^{+4.8}_{-3.8}$ | $0.67^{+0.07}_{-0.08}$ | $2.7^{+0.5}_{-0.5}$ | $3.4^{+0.5}_{-0.7} \times 10^{56}$ | $1020^{+430}_{-360}$ | $0.20^{+0.07}_{-0.07}$ | 39 |
| GW170823 | $39.6^{+10.0}_{-6.6}$ | $29.4^{+6.3}_{-7.1}$ | $29.3^{+4.2}_{-3.2}$ | $0.08^{+0.20}_{-0.22}$ | $65.6^{+9.4}_{-6.6}$ | $0.71^{+0.08}_{-0.10}$ | $3.3^{+0.9}_{-0.8}$ | $3.6^{+0.6}_{-0.9} \times 10^{56}$ | $1850^{+840}_{-840}$ | $0.34^{+0.13}_{-0.14}$ | 1651 |



TABLE III. Selected source parameters of the eleven confident detections. We report median values with 90% credible intervals that include statistical errors, and systematic errors from averaging the results of two waveform models for BBHs. For GW170817 credible intervals and statistical errors are shown for IMRPhenomPv2NRT with low spin prior, while the sky area was computed from TaylorF2 samples. The redshift for NGC 4993 from [92] and its associated uncertainties were used to calculate source frame masses for GW170817. For BBH events the redshift was calculated from the luminosity distance and assumed cosmology as discussed in Appendix B. The columns show source frame component masses $m_i$ and chirp mass $\mathcal{M}$, dimensionless effective aligned spin $\chi_{\mathrm{eff}}$, final source frame mass $M_f$, final spin $a_f$, radiated energy $E_{\mathrm{rad}}$, peak luminosity $l_{\mathrm{peak}}$, luminosity distance $d_L$, redshift $z$ and sky localization $\Delta\Omega$. The sky localization is the area of the 90% credible region. For GW170817 we give conservative bounds on parameters of the final remnant discussed in Sec. V E.

Figure 6 Twenty black hole spins. **$\chi_{\mathrm{eff}}$ is weighted combined individual spins parallel to the orbital spin. The possibly largest value of $\chi_{\mathrm{eff}}$ is for the largest BH mass.** Source LIGO/VIRGO 2019 PRX 9, 031040

# High mass and high spin of merger GW190521, 2nd gen?

**Table 1.** Source properties for GW190521: median values with 90% credible intervals that include statistical errors.

| Waveform Model | NRSur PHM | Phenom PHM | SEOBNR PHM |
|---|---|---|---|
| Primary BH mass $m_1$ ($M_\odot$) | $85^{+21}_{-14}$ | $90^{+23}_{-16}$ | $99^{+42}_{-19}$ |
| Secondary BH mass $m_2$ ($M_\odot$) | $66^{+17}_{-18}$ | $65^{+16}_{-18}$ | $71^{+21}_{-28}$ |
| Total BBH mass $M$ ($M_\odot$) | $150^{+29}_{-17}$ | $154^{+25}_{-16}$ | $170^{+36}_{-23}$ |
| Binary chirp mass $\mathcal{M}$ ($M_\odot$) | $64^{+13}_{-8}$ | $65^{+11}_{-7}$ | $71^{+15}_{-10}$ |
| Mass-ratio $q = m_2/m_1$ | $0.79^{+0.19}_{-0.29}$ | $0.73^{+0.24}_{-0.29}$ | $0.74^{+0.23}_{-0.42}$ |
| Primary BH spin $\chi_1$ | $0.69^{+0.27}_{-0.62}$ | $0.65^{+0.32}_{-0.57}$ | $0.80^{+0.18}_{-0.58}$ |
| Secondary BH spin $\chi_2$ | $0.73^{+0.24}_{-0.64}$ | $0.53^{+0.42}_{-0.48}$ | $0.54^{+0.41}_{-0.48}$ |
| Primary BH spin tilt angle $\theta_{LS_1}$ (deg) | $81^{+64}_{-53}$ | $80^{+64}_{-49}$ | $81^{+49}_{-45}$ |
| Secondary BH spin tilt angle $\theta_{LS_2}$ (deg) | $85^{+57}_{-55}$ | $88^{+63}_{-58}$ | $93^{+61}_{-60}$ |
| Effective inspiral spin parameter $\chi_{\rm eff}$ | $0.08^{+0.27}_{-0.36}$ | $0.06^{+0.31}_{-0.39}$ | $0.06^{+0.34}_{-0.35}$ |
| Effective precession spin parameter $\chi_{\rm p}$ | $0.68^{+0.25}_{-0.37}$ | $0.60^{+0.33}_{-0.44}$ | $0.74^{+0.21}_{-0.40}$ |
| Remnant BH mass $M_{\rm f}$ ($M_\odot$) | $142^{+28}_{-16}$ | $147^{+23}_{-15}$ | $162^{+35}_{-22}$ |
| Remnant BH spin $\chi_{\rm f}$ | $0.72^{+0.09}_{-0.12}$ | $0.72^{+0.11}_{-0.15}$ | $0.74^{+0.12}_{-0.14}$ |
| Radiated energy $E_{\rm rad}$ ($M_\odot c^2$) | $7.6^{+2.2}_{-1.9}$ | $7.2^{+2.7}_{-2.2}$ | $7.8^{+2.8}_{-2.3}$ |
| Peak Luminosity $\ell_{\rm peak}$ (erg s$^{-1}$) | $3.7^{+0.7}_{-0.9} \times 10^{56}$ | $3.5^{+0.7}_{-1.1} \times 10^{56}$ | $3.5^{+0.8}_{-1.4} \times 10^{56}$ |
| Luminosity distance $D_{\rm L}$ (Gpc) | $5.3^{+2.4}_{-2.6}$ | $4.6^{+1.6}_{-1.6}$ | $4.0^{+2.0}_{-1.8}$ |
| Source redshift $z$ | $0.82^{+0.28}_{-0.34}$ | $0.73^{+0.20}_{-0.22}$ | $0.64^{+0.25}_{-0.26}$ |
| Sky localization $\Delta\Omega$ (deg$^2$) | 774 | 862 | 1069 |

Figure 7 Massive BH merger with high spins, probably 2nd generation merger. Source LIGO/VIRGO 2020 ApJL arXiv 2009.01190

# Anti-Protons in CRs (RSG stars ? Or pair creation cauldron ?)

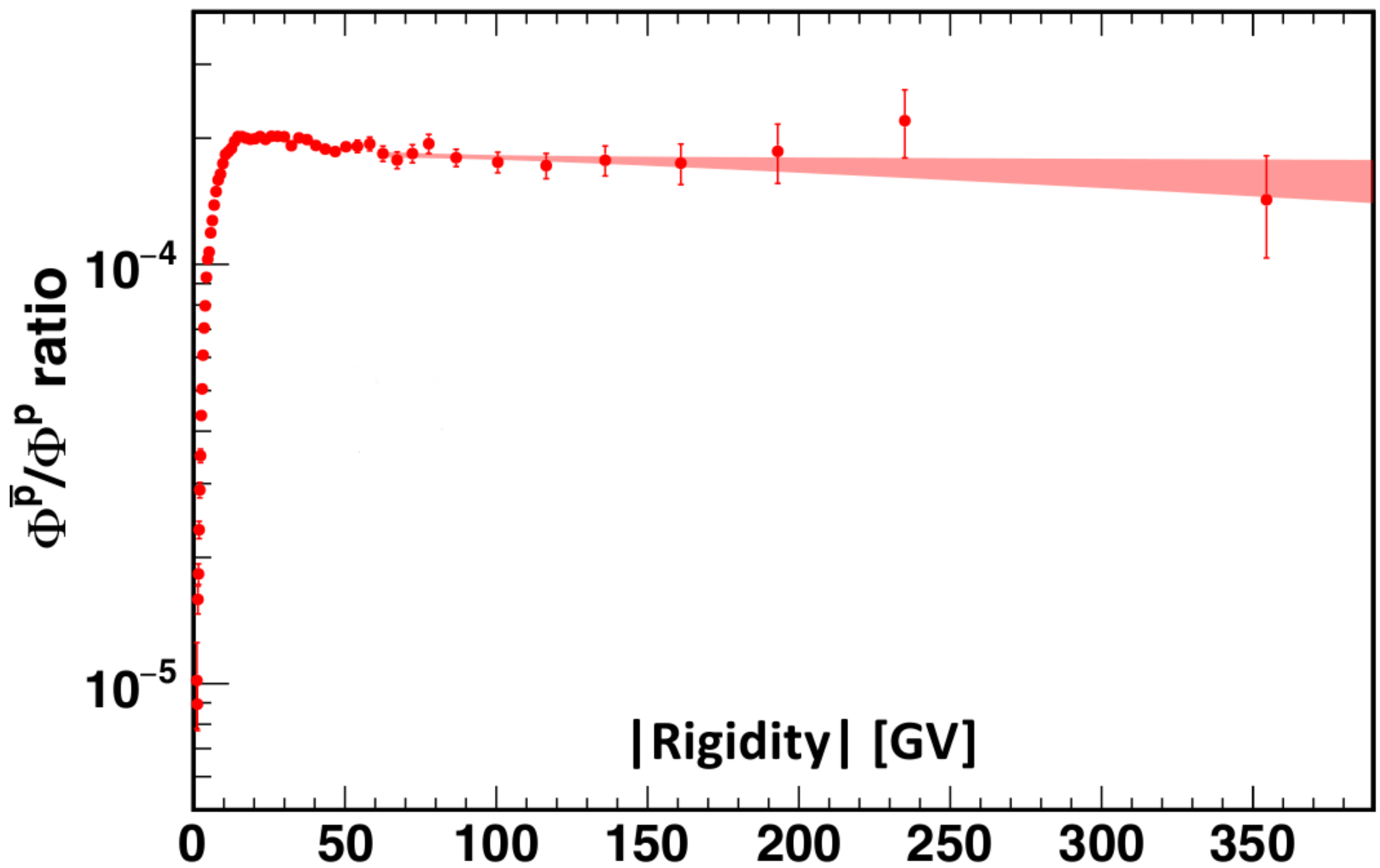


Figure 8 The AMS antiproton fraction. Can be fitted with proton interaction, **protons from massive RSG star explosions?** Source: Aguilar et al. (AMS-Coll.) 2016a, modified by I. Gebauer; cited from paper ASR 2018.

# General Relativity for rotating black holes I

Metric tensor elements for Kerr metric in Boyer - Lindquist coordinates (simplified nomenclature, $a$ normalized angular momentum, $r$ normalized radius)

$$\boldsymbol{ds^2 = \frac{d\phi^2 \sin^2(\theta)\left(\left(a^2+r^2\right)^2 - a^2 \sin^2(\theta)\Delta(r)\right)}{\rho(r,\theta)^2}}$$

$$\boldsymbol{-\frac{(dtd\phi + dtd\phi)\left(2aMr\sin^2(\theta)\right)}{\rho(r,\theta)^2}}$$

$$\boldsymbol{+d\theta^2\rho(r,\theta)^2 + \frac{dr^2\rho(r,\theta)^2}{\Delta(r)} + dt^2\left(-\left(1-\frac{2\,Mr}{\rho(r,\theta)^2}\right)\right).}$$

**gravitational constant set to unity, $M$ mass of black hole**

$$\boldsymbol{\begin{aligned} \rho(r,\theta)^2 &= r^2 + a^2\cos^2(\theta)\,, \\ \Delta(r) &= r^2 - 2\,M\,r + a^2\,. \end{aligned}}$$

# The Electromagnetic tensor I

$$F_{\mu\nu} = \begin{pmatrix} 0 & 0 & \tilde{E}_\theta(r,\theta) & 0 \\ 0 & 0 & \tilde{B}_\phi(r,\theta) & -\tilde{B}_\theta(r,\theta) \\ -E_\theta(r,\theta) & -\tilde{B}_\phi(r,\theta) & 0 & \tilde{B}_r(r,\theta) \\ 0 & \tilde{B}_\theta(r,\theta) & -\tilde{B}_r(r,\theta) & 0 \end{pmatrix},$$

components determined from vector potential $A_\mu$



$$F_{\mu\nu} = \partial_\mu \left(\sqrt{g_{\nu\nu}}\, A_\nu(r,\theta)\right) - \partial_\nu \left(\sqrt{g_{\mu\mu}}\, A_\mu(r,\theta)\right) .$$

Measured components of electric and magnetic fields related to tilde components in $F_{\mu\nu}$ by

$$\begin{aligned} \tilde{E}_\theta(r,\theta) &= E_\theta(r,\theta) \\ \tilde{B}_r(r,\theta) &= \sqrt{g_{\theta\theta}\, g_{\phi\phi}}\, B^r(r,\theta) \\ \tilde{B}_\theta(r,\theta) &= -\sqrt{g_{rr}\, g_{\phi\phi}}\, B^\theta(r,\theta) \\ \tilde{B}_\phi(r,\theta) &= \sqrt{g_{rr}\, g_{\theta\theta}}\, B^\phi(r,\theta) \end{aligned}$$

# The Electromagnetic tensor II

These expressions are based on the definitions of the electric and magnetic fields given in Komissarov (2004 MNRAS). They have the asymptotic forms given in Weber and Davis (1967 ApJ), but differ from Parker (1958 ApJ) in the choice of the $\theta$-dependence for convenience; adjusting this would just change the numerical coefficients at the end. Assume $r-$ and $\phi$-components of electric field zero.

# E and B fields I

$E_\theta(r,\theta)$ component of electric field can be determined for case of static magnetic field, $\partial\,\vec{B}/\partial\,t\;=\;0$, from

$$\left(\nabla\times\vec{E}\right)_\phi\;=\;0\,.$$

**This requires**

$$\mathrm{E}_\theta(\mathrm{r},\theta)\;=\;\frac{\mathrm{E}_0}{\rho(r,\theta)}\,,$$

**where $E_0$ constant. $B^r(r,\theta)$ component of B from $\nabla$**

$$\nabla\;\cdot\;\vec{B}(r,\theta)\;=\;0\,.$$

$\mathrm{B}_0$ constant. Other components of **B** undetermined.

## E and B fields II

For $B^{\theta}(r,\theta) = 0$ (Weber & Davis 1967 ApJ) requires

$$\boldsymbol{B^{r}(r,\theta) = \frac{\mathbf{B_0}}{\sqrt{g_{rr}\, g_{\theta\theta}\, g_{\phi\phi}}}},$$

Based on observational data, we assume that

$$\boldsymbol{\sqrt{g_{rr}\, g_{\theta\theta}}\, B^{\phi}(r,\theta) = \textbf{constant} = \mathbf{B}_{p0}}\,.$$

ignoring here any possible $\theta$-dependence. The key point is that this constant is independent of BH mass $M$, but likely to be dependent on the angular momentum; we assume below that it is proportional to the normalized angular momentum, so in the language used here $\sim\; a/M$, below this is $(J_{BH}\, c)/(M_{BH}^2\, G_N)$.

## The energy and angular momentum fluxes I

$$\boldsymbol{\mathcal{E}^r = \frac{\mathrm{B}_0\,\mathrm{E}_0\,\Delta(r)}{\rho(r,\theta)^5}} \qquad\qquad \boldsymbol{\mathcal{E}^\theta = 0}$$

$$\boldsymbol{\mathcal{L}^r = \frac{\mathrm{B}_0\,\mathrm{B}_{p0}\,\Delta(r)^{3/2}}{\rho(r,\theta)^5}} \qquad\qquad \boldsymbol{\mathcal{L}^\theta = 0.}$$

**Energy flux and angular momentum flux are related via**

$$\boldsymbol{\mathcal{E}^r = \omega(r,\theta)\,\mathcal{L}^r\,,}$$

**where**

$$\boldsymbol{\omega = \frac{\tilde{E}_\theta}{\tilde{B}_r} = \frac{E_0}{B_0\sqrt{\Delta}}\,.}$$

Same relation as in Eq.(4.4) of Blandford and Znajek (1977 MNRAS). The location of the horizon is determined by the condition $\Delta(r) = 0$.

## The energy and angular momentum fluxes II

So flux components components $\mathcal{E}^r$ and $\mathcal{L}^r$ vanish on the horizon. On equator of black hole ($\theta = \pi/2$) radial component of angular momentum flux reaches maximum at radius of slightly less than three horizon radii. Expressions are similar to ones obtained by Blandford and Znajek (1977 MNRAS), but there are significant differences due to the differences between our model and theirs. In BZ model both of poloidal components of the energy flux are non-zero, while in our model both of the fluxes in the $\theta$-direction (polar direction) are zero. The vanishing of $\theta$-component of energy flux in our model due to setting $r$- and $\phi$-components of electric field equal to zero, and vanishing of the $\theta$-component of angular momentum flux is due to setting $\theta$-component of magnetic field equal to zero, following Weber and Davis (1967 ApJ).

## Energy extraction and angular momentum extraction

For observer at infinity rate of energy extraction is

$$\dot{E}_{rad} = \int \mathcal{E}^r \rho(r,\theta)^2 \, d\Omega \,,$$

**rate of angular momentum extraction is**

$$\dot{L}_{rad} = \int \mathcal{L}^r \rho(r,\theta)^2 \, d\Omega \,,$$

**where $d\Omega$ is the infinitesimal solid angle. The evaluation of these integrals gives**

$$\dot{E}_{rad} = \frac{4\pi \mathrm{B}_{p0} \, \mathrm{E}_0 \, \left(a^2 + r(r-2M)\right)}{r^2\sqrt{a^2+r^2}}$$

$$\dot{L}_{rad} = \frac{4\pi \mathrm{B}_0 \, \mathrm{B}_{p0} \, \left(a^2 + r(r-2M)\right)^{3/2}}{r^2\sqrt{a^2+r^2}} .$$

## Calculation of the current

The current can be calculated from the covariant divergence of the electromagnetic field tensor

$$\nabla_\mu F^{\mu\nu} = J^\nu$$

For the radial and theta components of the current this calculation gives

$$J^r = -\frac{4\,a^2\,\mathrm{Bp0}\sin(\theta)\cos(\theta)\left(a^2 + r\,(r - 2\,GM)\right)}{\left(a^2\cos^2(\theta) + r^2\right)^3}$$

$$J^\theta = -\frac{2\,\mathrm{Bp0}\left(a^2\cos^2(\theta)(GM - r) + r\left(2\,a^2 + r\,(r - 3\,GM)\right)\right)}{\left(a^2\cos^2(\theta) + r^2\right)^3}$$

The $J^t$ and $J^\phi$ components are non-zero, but their expressions are much longer. The latter two components decrease much more rapidly with $r$ than either $J^r$ or $J^\theta$.

## Charge density

The expression for the charge density as obtained from the covariant divergence relation is given by

$$J^0 = \frac{2\sqrt{2}\,a^2\,\sin(2\,\theta)}{\left(a^2 + r\,(r - 2\,M)\right)\left(a^2\cos(2\theta) + a^2 + 2\,r^2\right)^{7/2}}$$

$$[6a^4\,\mathrm{E}_0\,\cos^2(\theta) - 20\,a\,\mathrm{B}_0\,M\,r\,\sqrt{a^2 + r\,(r - 2\,M)} +$$

$$2\,\mathrm{E}_0\,r^3\,(4\,M + 3\,r)$$

$$+(a^2\,\mathrm{E}_0\,r)\,(14\,M + 9\,r + 3\,(-2\,M + r)\,\cos(2\theta))]$$

Title: Massive star explosions: A Pandora's box for Cosmic Ray particles and maximally rotating black holes?

Peter L. Biermann (MPIfR Bonn, KIT Karlsruhe, UA Tuscaloosa, Un. Bonn), Benjamin C. Harms (Un. AL), Michael L. Allen (WA St.Un.), Alessandro Chieffi (INFN Rome), Philipp P. Kronberg (Un. Toronto), Emma Kun (Konkoly Obs. Budapest), Eun-Suk Seo (Un. MD), also with help by Julia Becker Tjus (Un. Bochum), Roberto Casadio (INFN Bologna), László Á. Gergely (Un. Szeged), Pankaj S. Joshi (ICC, Charusat U., Anand, GUJ, India), Biman B. Nath (RRI, Bangalore), and Todor Stanev (Bartol, Un. DE)

What is the physical process that gives the same Cosmic Ray knee and Cosmic Ray ankle energy for all Super-Nova (SN) explosions that contribute strongly to particles in that energy range, PeV to EeV? Why do the observed stellar mass black holes (BHs) show negligible spin before merging? There are two typical energies in the spectrum of cosmic rays, the *knee* energy $E_{CR,knee}$, where the spectrum turns down, and the *ankle* energy $E_{CR,ankle}$, with $E_{CR,knee} \simeq E_{CR,ankle} \, (V_{SN}/c)^2$: Both energies are proportional to $e\,B\,r$, observed in wind-SNe and the numbers match. That energy squared is proportional to the angular momentum transport in an observed Parker type wind of a wind-SN (Parker 1958, Weber & Davis 1967). So our proposal to interpret these observations is: A freshly formed stellar mass BH of maximal rotation rapidly loses its spin (A. Chieffi). The observations suggest $(e\,B\,r)^2 = m_X \, m_{Pl} \, c^4$ with $m_X$ of order GeV; with an error of $10^{\pm 0.24}$ (M. Allen, P.P. Kronberg). This expression can be interpreted as a maximal Penrose process using p $\bar{\text{p}}$ or $e^+e^-$ pairs. Spin-down gives a luminosity scale: $L_{rot} = (\hbar\, c)/(e^2)\, (m_X\, c^2)/(\tau_{Pl})$. This is analogous to the luminosity scale for BH mergers, called the Planck luminosity: $L_{GW} = (m_{Pl}\, c^2)/(\tau_{Pl})$. In this latter expression the quantity $\hbar$ scales out, as it is equal to $c^5/G_N$. In the spin-down expression $\hbar$ does not scale out, so we can ask speculatively: might this be the signature of a combination of General Relativity with Quantum Mechanics based on observations? Both times, the characteristic time scales with the BH mass, while the luminosity scale is independent of BH mass. The EHT observations of the super-massive black hole in the galaxy M87 are consistent with the values for the product $B\,r$ of massive star SNe as well as the observed luminosity. The quantum mechanical model of BHs (R. Casadio) may allow to let us understand these observations.