The correlation between magnetic flux and jet power
(or between electromagnetic losses power and total power)

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Half a Century of Blazars and Beyond

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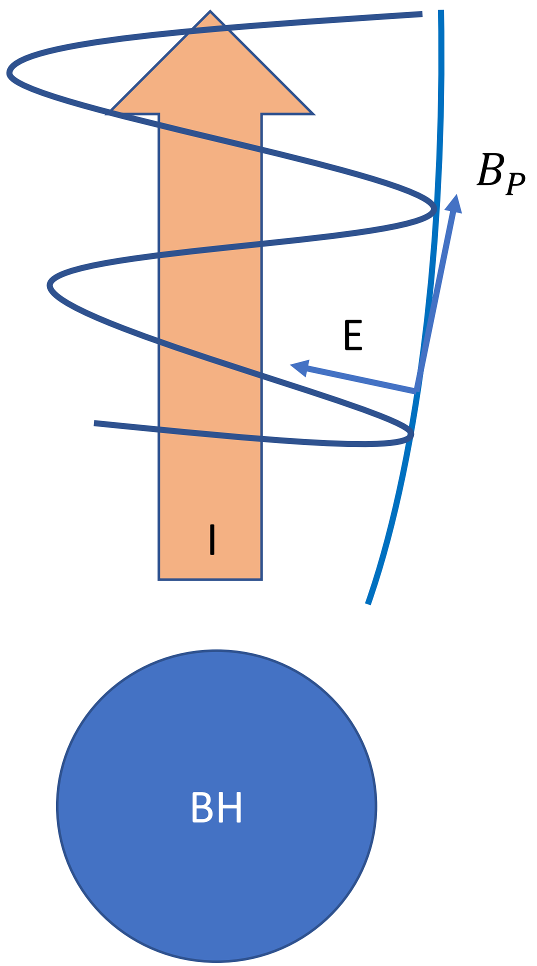
Outline

- The electromagnetic losses
- Non uniform source – magnetic fields and flux
- Magnetic field measurements: core shift & brightness temperature measurements
- Power vs. magnetic flux – results

The electromagnetic losses



The electromagnetic losses can be estimated through the following MHD outflow properties

$$P_{tot} \sim I \cdot \delta U$$

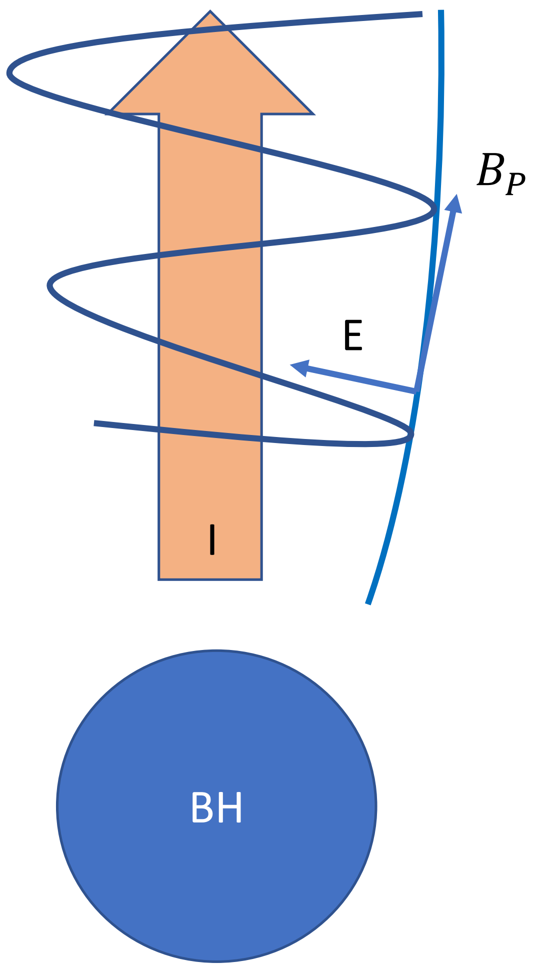
- The electric potential drop

$$\delta U = ER = \frac{\Omega_F R}{c} BR$$

- The current in a magnetosphere is carried by the Goldreich-Julian particle number density

$$\rho_{GJ} = -\frac{\Omega_F B}{2\pi c}$$

The electromagnetic losses



- And the corresponding current

$$I = \frac{\Omega_F B R^2}{2}$$

The electromagnetic losses estimate

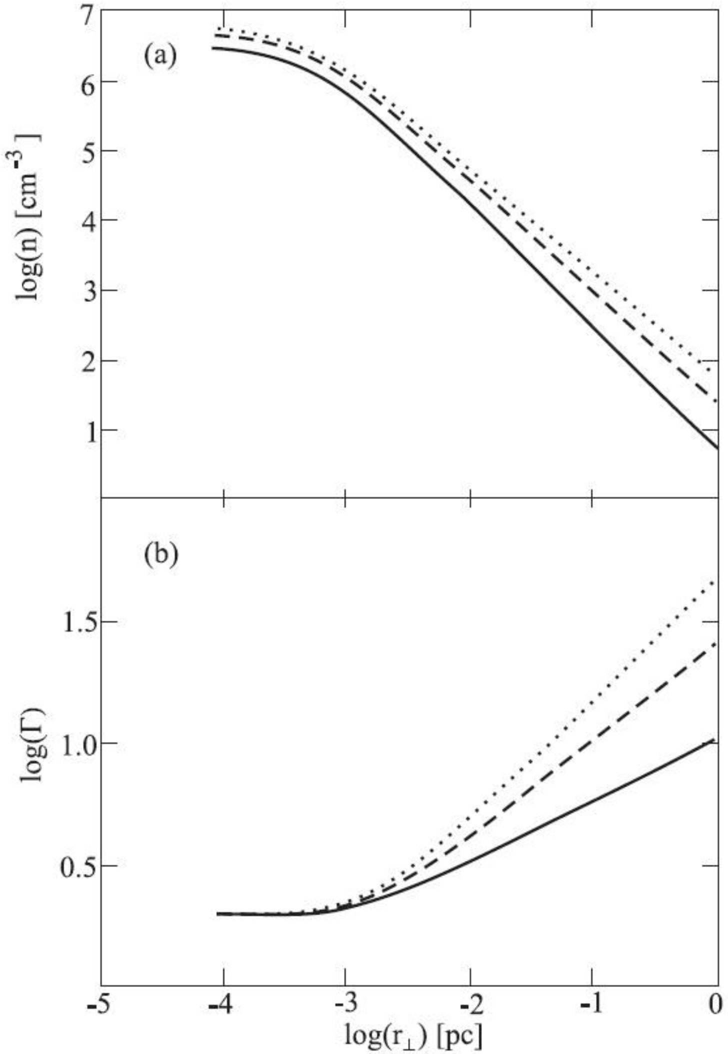
$$P_{tot} = \frac{c}{2}\left(\frac{\Psi a}{\pi r_g}\right)^2$$

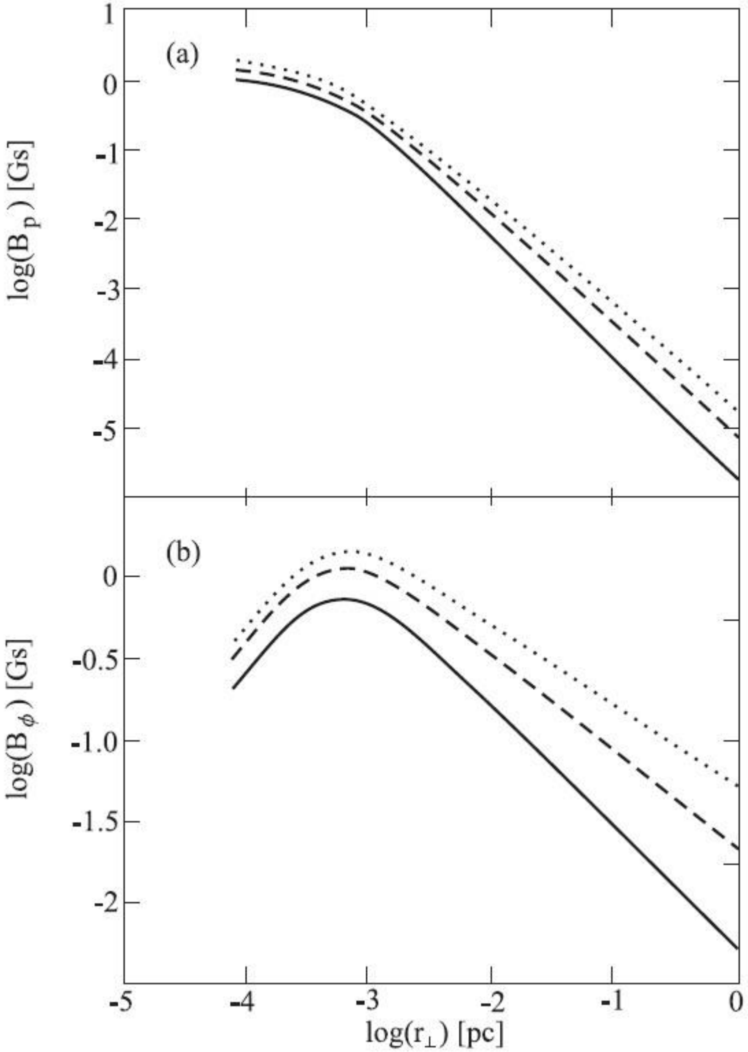
More thorough MHD calculation

$$P_{tot} = \frac{c}{8}\left(\frac{\Psi a}{\pi r_g}\right)^2$$

Here $a = r_g / R_L$

Non uniform source – magnetic fields and flux

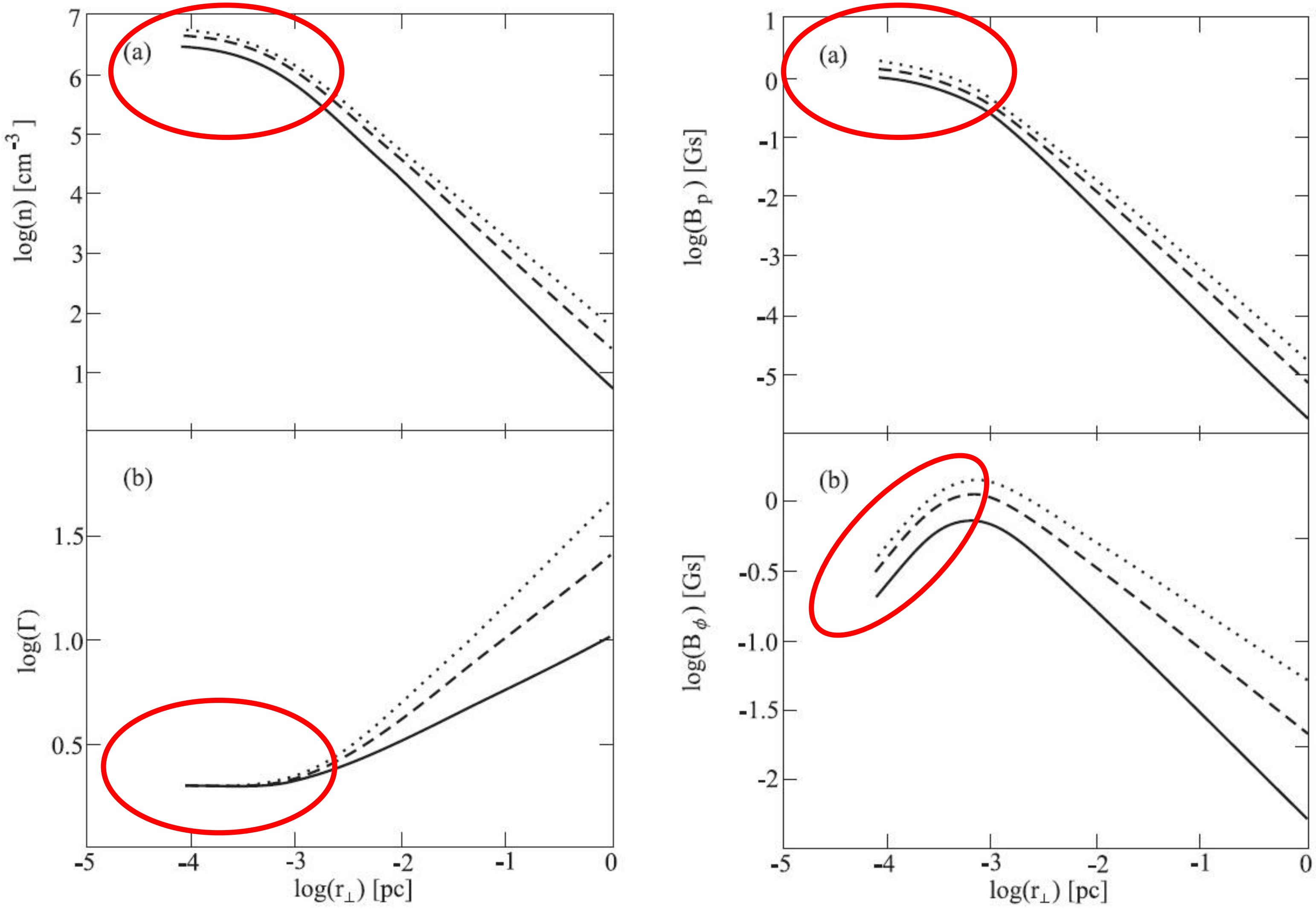




The principal behavior of *B* and *n* is obtained in many analytical, semi-analytical, and numerical works: Lyubarsky 2009, Tchekhovskoy & Bromberg 2016, and many others

Nokhrina+ 2015

Non uniform source – magnetic fields and flux



The central core:

$n \approx const$

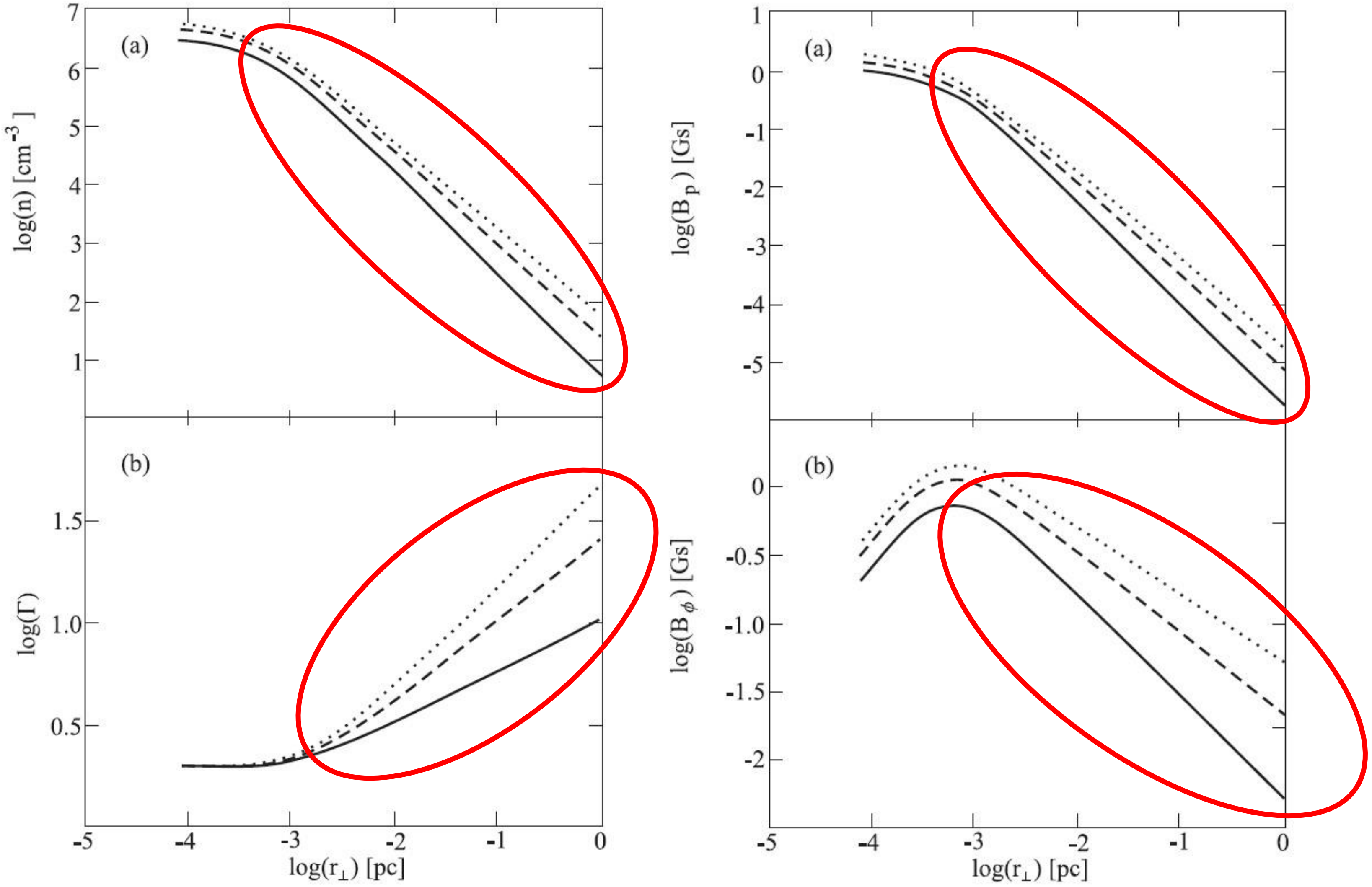
$B_P \approx const$

$B_\varphi \propto r$

$\Gamma \approx const$

Nokhrina+ 2015

Non uniform source – magnetic fields and flux



The central core:

$n \propto r^{-2}$

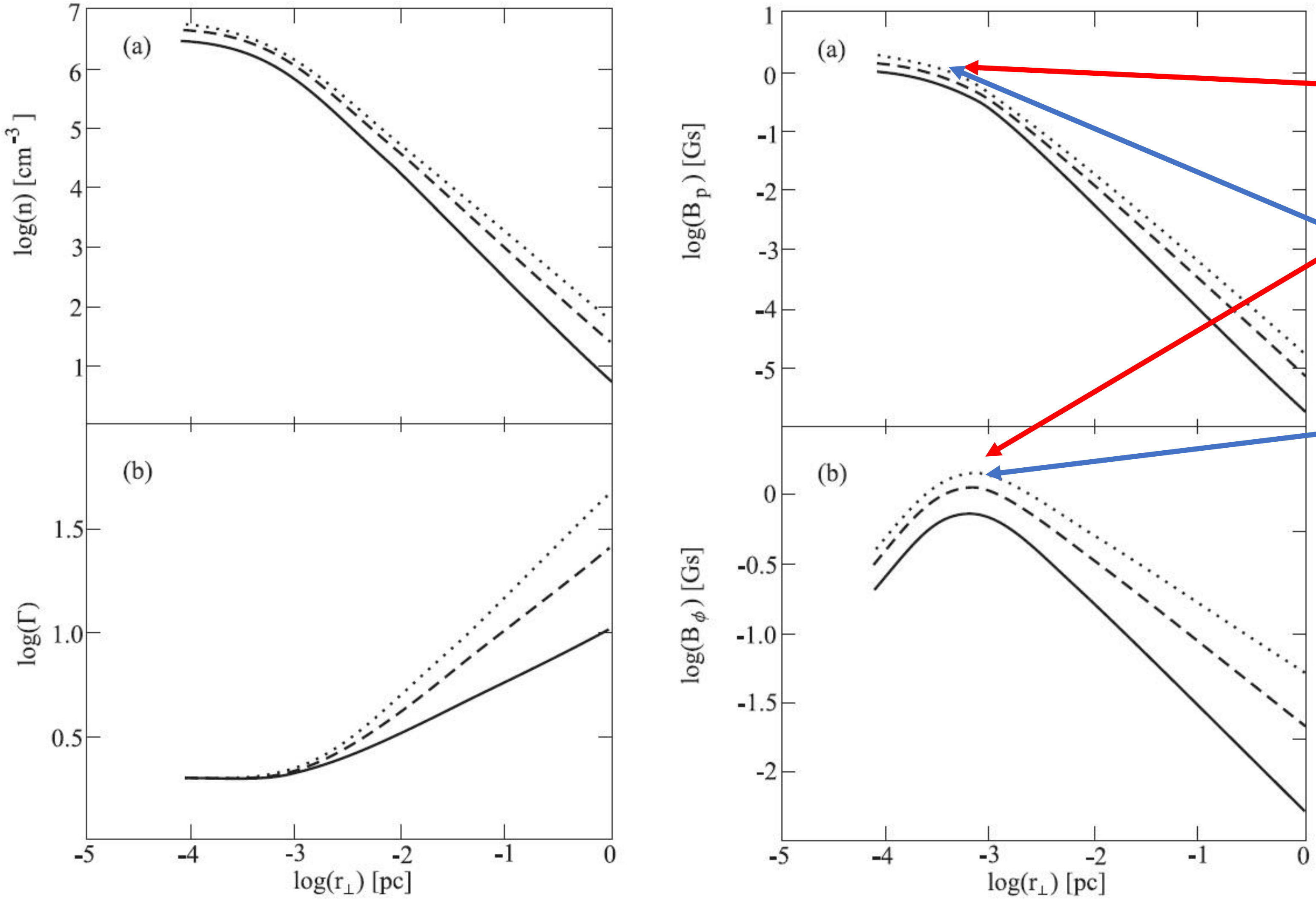
$B_P \propto r^{-2}$

$B_\varphi \propto r^{-1}$

$\Gamma \propto r$

Nokhrina+ 2015

Non-uniform model: analytical results



The central core size

$R_0 \approx R_L$

The magnetic field amplitude

B_0

Nokhrina+ 2015

Non uniform source – magnetic fields and flux

- We can calculate the total magnetic flux Ψ;
- We can relate the total flux Ψ to both toroidal and poloidal field amplitude B_0;
- The natural scale for MHD models is $R_L = \frac{c}{\Omega_F}$, and it is through introducing a that we relate it with r_g by $R_L = \frac{r_g}{a}$.

Magnetic field measurements

By core shift effect (Lobanov 1998, O'Sullivan & Gabuzda 2009, …)

- Uniform synchrotron self-absorbed sphere
- Magnetic field and particles are in equipartition
- The amplitudes of n and B following Blandford-Königl scalings

By brightness temperature measurements (Zdziarski+ 2015, N17)

- Applicable for the sources suspected to be in non-equipartition regime (extreme brightness temperatures)
- Allows for easy account for a non-uniform structure

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In both cases we measure the toroidal dominant component

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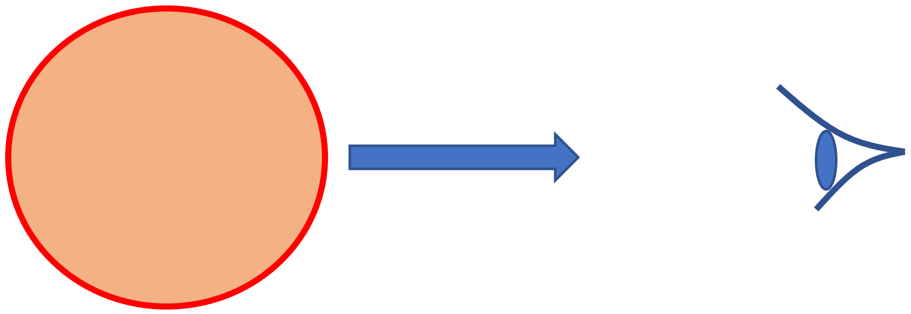
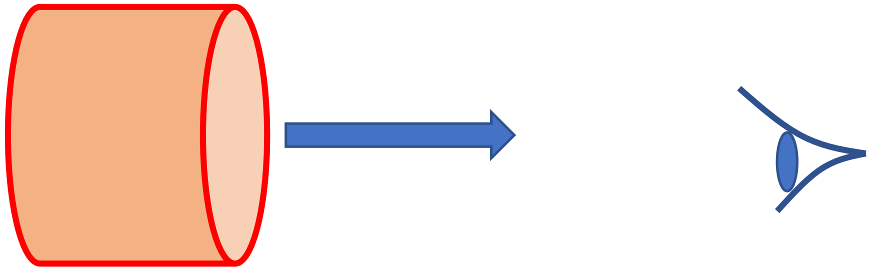
Magnetic field measurements



$B_{uni} = 3.3 \times 10^{-2}\ G$

Same S_ν



$B_0 = 3\ G$

(for BL Lac, from Nokhrina 2017, MNRAS, 468, 2372)

$$\left(\frac{B_0}{\mathrm{G}}\right) = 6.4 \times 10^{-4} \frac{R_\mathrm{j}}{R_\mathrm{L}} \frac{\Gamma\delta}{1+z} \left(\frac{\nu_\mathrm{obs}}{\mathrm{GHz}}\right) \left(\frac{T_{\mathrm{b,\,obs}}}{10^{12}\,\mathrm{K}}\right)^{-2}$$

$$\left(\frac{B_\mathrm{uni}}{\mathrm{G}}\right) = 7.4 \cdot 10^{-4} \frac{\Gamma\delta}{1+z} \left(\frac{\nu_\mathrm{obs}}{\mathrm{GHz}}\right) \left(\frac{T_{\mathrm{b,\,obs}}}{10^{12}\mathrm{K}}\right)^{-2}$$

We may use uniform-model measured magnetic field, substituting it in the flux formula with the obtained factor B_0/B_{uni}

Power vs. magnetic flux – results

- The magnetic flux may be calculated by

$$\boxed{\Psi = 2.7 B_{\mathrm{uni,\,cs}} R_{\mathrm{j}} \frac{r_{\mathrm{g}}}{a} \left[1 + 2 \ln \frac{R_{\mathrm{j}}\, a}{r_{\mathrm{g}}} \right] = \frac{\Psi_a}{a}}$$

- But the total power for electromagnetic losses has a term Ψa, so it depends on a logarithmically weakly, and can be checked against the observations:

$$P_{em} = \frac{c}{8}\left(\frac{\Psi a}{\pi r_g}\right)^2 = \frac{c}{8}\left(\frac{2.7}{\pi} B_{uni,cs} R_j \left(1 + 2\log\frac{R_j a}{r_g}\right)\right)^2$$

Power vs. magnetic flux – results

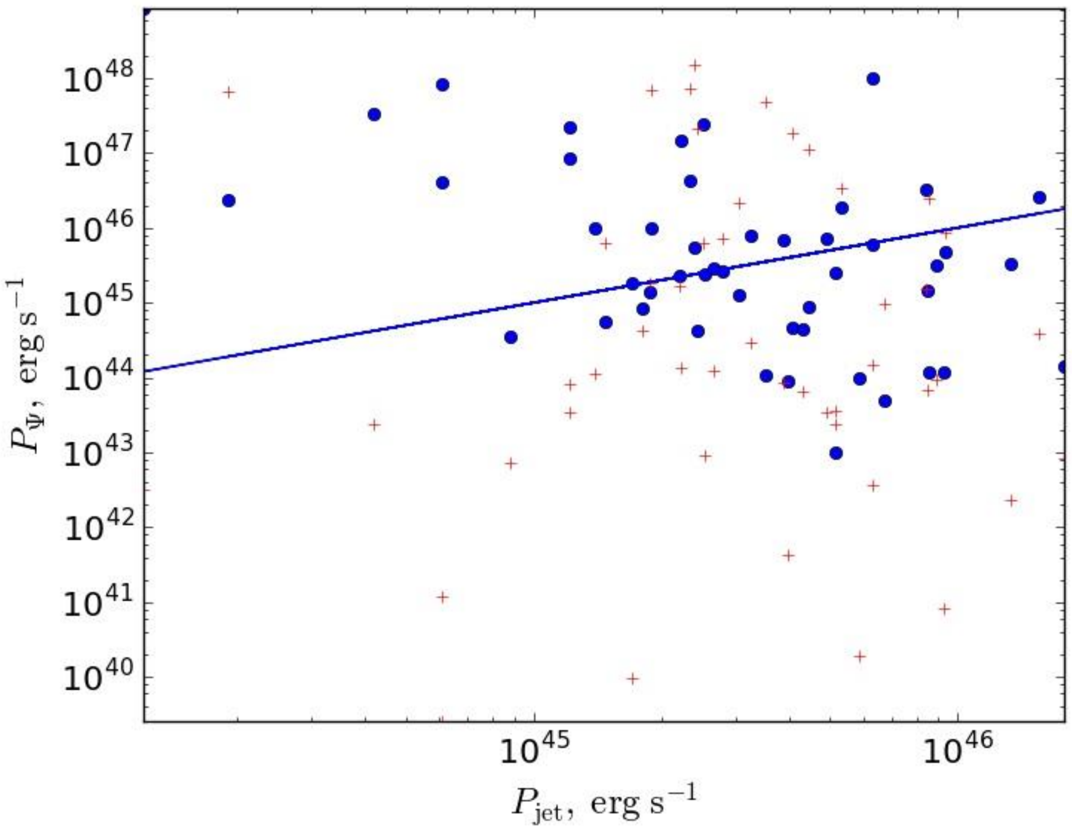
- We use 48 sources with small viewing angles and measured core shift and opening angles
- For the jet power estimate we use the correlation between P_{jet} and the jet luminosities in 200 – 400 MHz band (Cavagnolo+ 2010):

$$\left(\frac{P_{\rm jet}}{10^{43}\,{\rm erg\,s^{-1}}}\right) = 3.5\left(\frac{P_{200-400}}{10^{40}\,{\rm erg\,s^{-1}}}\right)^{0.64}$$

Power vs. magnetic flux – results

Source (1)	z (2)	Ψ_{MAD} G cm^2 (3)	Ψ_{br} G cm^2 (4)	Ψ_{cs} G cm^2 (5)	P_{Ψ} [erg s^{-1}] (6)	P_{jet} [erg s^{-1}] (7)
0133+476	0.859	5.51×10^{33}	1.17×10^{31}	5.34×10^{32}	1.92×10^{46}	2.54×10^{45}
0212+735	2.367	5.77×10^{35}	5.97×10^{32}	8.93×10^{32}	8.10×10^{43}	5.17×10^{45}
0234+285	1.206	5.71×10^{34}	1.24×10^{34}	5.31×10^{32}	8.65×10^{44}	3.52×10^{45}
0333+321	1.259	9.36×10^{34}	6.00×10^{32}	3.81×10^{32}	3.88×10^{44}	6.72×10^{45}
0336−019	0.852	1.55×10^{34}	1.45×10^{32}	2.12×10^{33}	6.31×10^{46}	3.26×10^{45}
0403−132	0.571	3.00×10^{34}	4.34×10^{33}	1.09×10^{33}	6.89×10^{45}	4.45×10^{45}
0528+134	2.070	6.05×10^{34}	1.61×10^{30}	3.24×10^{32}	7.75×10^{44}	5.85×10^{45}
0605−085	0.870	1.68×10^{34}	9.94×10^{33}	1.70×10^{33}	4.45×10^{46}	2.39×10^{45}
0736+017	0.189	6.94×10^{32}	3.86×10^{30}	1.29×10^{33}	2.68×10^{48}	4.20×10^{44}
0738+313	0.631	1.48×10^{35}	3.22×10^{33}	2.71×10^{33}	4.51×10^{45}	1.48×10^{45}
0748+126	0.889	4.33×10^{34}	1.39×10^{32}	1.90×10^{33}	2.31×10^{46}	2.65×10^{45}
0827+243	0.943	1.81×10^{34}	1.72×10^{32}	6.87×10^{32}	6.62×10^{45}	1.80×10^{45}
0836+710	2.218	1.78×10^{35}	7.19×10^{31}	8.30×10^{32}	1.11×10^{45}	1.78×10^{46}
0906+015	1.026	9.81×10^{33}	5.66×10^{32}	3.90×10^{32}	1.02×10^{46}	3.05×10^{45}

Power vs. magnetic flux – results

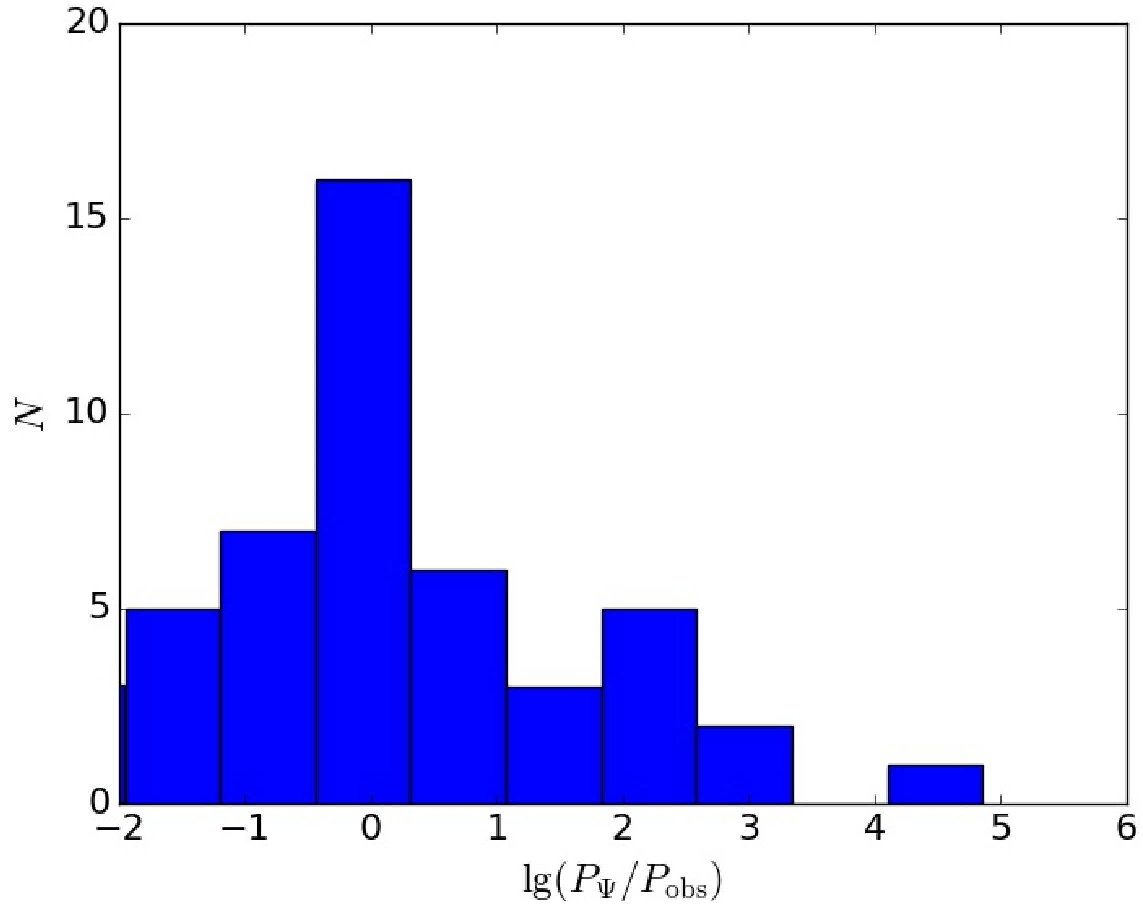


The dispersion may be due to

- uncertainty in measurements of the observed parameters (core shift, opening angle, etc.);
- the power estimate – the method implies the averaged over period of time power;
- the caveats in a model – a presence of a disk wind, a current closure in a jet.

Left upper sources – the flux with assumed $a = 0.5$ *is in agreement with MAD model;*

Power vs. magnetic flux – results



- The sources distribution is peaked at the power predicted by electromagnetic losses mechanism.
- One third of the sources do have the power that can be attributed to purely electromagnetic losses mechanism.
- 60% of sources have jet power that may be associated with EM losses.

Further prospective – to use the short-term power estimate (Ghisellini+2014, Pjanka+2017).

Conclusions

- We may estimate the total magnetic flux from the magnetic field measurements (differently for different models) if given the rotation parameter $a = r_g/R_L$.
- The power of electromagnetic losses by a BH depend on a logarithmically, other values may be estimated from the observations.
- For the chosen 48 sources the distribution of electromagnetic power to total power is peaked at 1, with 60% of sources having the total power that is consistent with purely EM losses.

Psi	P_obs	P	B1_csh	R1_j, cm	Psi_csh	P_csh	Pmad
1,16699E+31	2,54E+45	9,14318E+42	4,326921773	3,81994E+16	5,34903E+32	2,40115E+45	2,04155E+48
5,97054E+32	5,17E+45	3,62232E+43	0,274130116	6,76958E+16	8,92615E+32	1,01204E+43	3,38814E+49
1,23635E+34	3,52E+45	4,69074E+47	2,101686781	2,43461E+16	5,31071E+32	1,08187E+44	9,9991E+48
6,00219E+32	6,72E+45	9,62896E+44	2,310551523	1,65501E+16	3,80769E+32	4,84386E+43	2,34402E+49
1,44995E+32	3,26E+45	2,94892E+44	12,07908482	2,96377E+16	2,12028E+33	7,88237E+45	3,38814E+48
4,33761E+33	4,45E+45	1,10017E+47	6,490289693	2,13191E+16	1,08574E+33	8,61631E+44	5,2476E+48
1,60927E+30	5,85E+45	1,90642E+40	1,741265172	2,51053E+16	3,2449E+32	9,68887E+43	2,69129E+49
9,94388E+33	2,39E+45	1,5208E+48	16,36342301	1,97261E+16	1,70144E+33	5,56546E+45	4,36476E+48
3,85831E+30	4,20E+44	2,39747E+43	44,97141955	3,50975E+16	1,2903E+33	3,3516E+47	7,76177E+47
3,22153E+33	1,48E+45	6,35453E+45	3,060202706	4,08606E+16	2,71291E+33	5,63301E+44	1,34884E+49
1,3909E+32	2,65E+45	1,24036E+44	7,773119717	3,00431E+16	1,90004E+33	2,8933E+45	1,20216E+49
1,71816E+32	1,80E+45	4,14084E+44	6,293286526	1,99277E+16	6,8718E+32	8,27962E+44	4,57047E+48
7,19304E+31	1,78E+46	8,33266E+42	4,400692268	1,59052E+16	8,30267E+32	1,38773E+44	5,12815E+49
5,66434E+32	3,05E+45	2,15406E+46	6,183048991	2,14303E+16	3,89727E+32	1,27465E+45	6,45596E+48
3,93079E+33	4,07E+45	1,80268E+47	2,38769561	3,56185E+16	5,61843E+32	4,60362E+44	5,8879E+48
1,29428E+32	6,30E+45	1,48256E+44	19,05348997	1,87398E+16	2,31665E+33	5,93733E+45	4,57047E+48
1,1581E+32	4,32E+45	6,52309E+43	6,269469512	1,69466E+16	8,49327E+32	4,3855E+44	9,11928E+48
2,10428E+32	8,94E+45	9,40082E+43	9,461010541	2,92361E+16	3,45061E+33	3,1598E+45	1,17479E+49
3,47988E+31	3,89E+45	8,51312E+43	17,26758116	1,83631E+16	8,90612E+32	6,97022E+45	2,81813E+48
4,34054E+33	1,90E+44	6,63814E+47	12,94680501	4,12098E+16	2,29078E+33	2,31119E+46	2,81813E+45
6,70808E+33	1,90E+45	6,9208E+47	44,7528545	1,09782E+16	2,28271E+33	1,00177E+46	3,46705E+48
3,928E+30	6,31E+45	3,59173E+42	179,787964	1,89193E+16	5,83615E+33	9,91112E+47	1,77812E+48

Difference with Zamaninasab+ 2014

Z+15:

$$\Gamma \sim \frac{1}{\theta_j}$$

With typical $\theta_j \sim 0.01$

N17:

$$\Gamma \sim \sigma_M$$

where we estimated σ_M in N+15, with typical σ_M~10

=> Discrepancy in Ψ of the order of 10, in power – 100.

The core shift magnetic field measurement

- + (specific) equipartition = the bulk flow has a magnetization ~ 1 and about 1% of particles have the relativistic temperatures (Sironi, Spitkovsky, Arons 2013)

$$B^2 = \sigma_\xi 4\pi m c^2 n_e \Gamma$$

=>

$$\boxed{\left(\frac{B_{cs}}{G}\right) = 0.17\left(\frac{\eta_{cs}}{\text{mas GHz}}\right)^{0.75}\left(\frac{D_L}{\text{Gpc}}\right)^{0.75}\frac{\Gamma}{\chi^{0.25}(1+z)^{0.75}\sin^{0.5}\varphi\,\delta^{0.5}}}$$

NB: the toroidal magnetic field dominates the jet, so it is the toroidal field we measure

The brightness temperature magnetic field

- The brightness temperature definition

$$S_\nu = \frac{2\pi\nu^2\theta^2}{c^2} k_\mathrm{B} T_\mathrm{b}$$

- The spectral flux for the self-absorbed spherically symmetric source (Gould 1979)

$$S_\nu = \pi\hbar\nu \frac{\rho_\nu}{æ_\nu} \frac{R^2}{d^2} u(2Ræ_\nu)$$

- =>

$$\boxed{\left(\frac{B_\mathrm{uni}}{\mathrm{G}}\right) = 7.4 \cdot 10^{-4} \frac{\Gamma\delta}{1+z} \left(\frac{\nu_\mathrm{obs}}{\mathrm{GHz}}\right) \left(\frac{T_\mathrm{b,\,obs}}{10^{12}\mathrm{K}}\right)^{-2}}$$

(Zdziarski+2015, N17)

Zdziarski, Sikora, Pjanka & Tchekhovskoy, 2015: the distribution of ratio of magnetic field is peaked around its equipartition value: