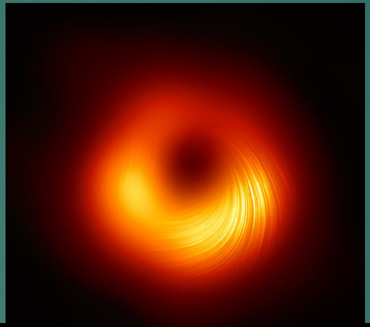
GRMHD Positron Applications from the Present and Primordial Universe



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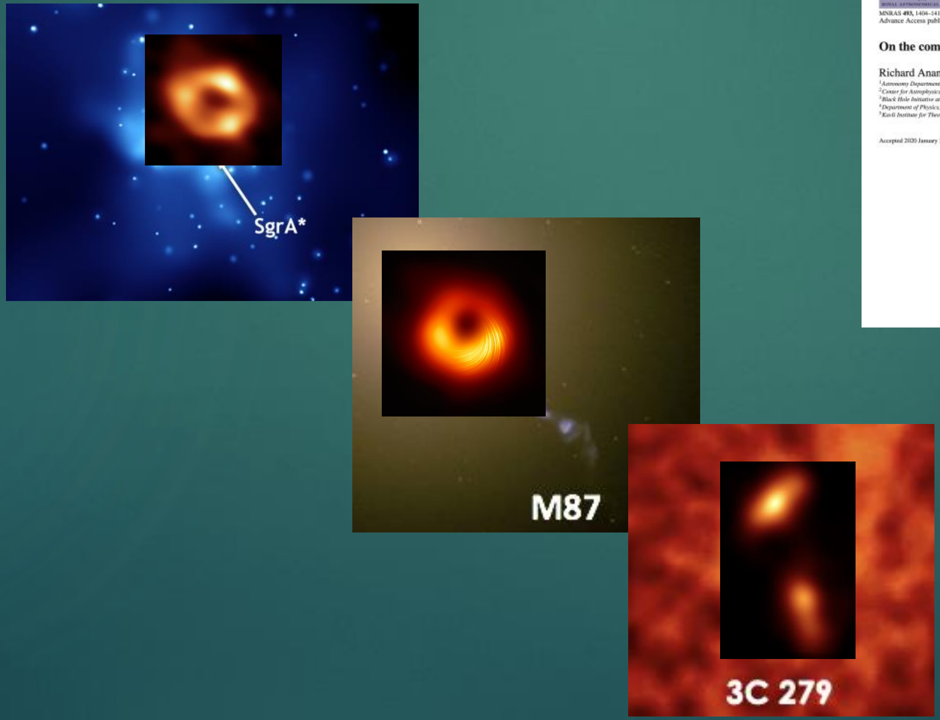
"Observing" JAB Systems

1. Start with general relativistic magnetohydrodynamic (GRMHD) simulation or semi-analytic model of jet (or outflow)/accretion flow/black hole (JAB) system
2. Convert GRMHD variables to radiation prescriptions for emission, absorption, polarization, particle acceleration and/or dissipation to emulate sources
3. Add "observer" viewing sources, e.g., Event Horizon Telescope (EHT) targets:

   I. Sgr A*

   II. M87

   III. 3C 279



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On the comparison of AGN with GRMHD simulations: I. Sgr A*

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ABSTRACT
We present models of Galactic Centre emission in the vicinity of Sagittarius A* that use parametrizations of the electron temperature or energy density. These models include those inspired by two-temperature general relativistic magnetohydrodynamic (GRMHD) simulations as well as jet-motivated prescriptions generalizing equipartition of particle and magnetic energies. From these models, we calculate spectra and images and classify them according to their distinct observational features. Some models produce morphological and spectral features, e.g. image sizes, the sub-mm bump, and low-frequency spectral slope compatible with observations. Models with spectra consistent with observations produce the most compact images, with the most prominent, asymmetric photon rings. Limb-brightened outflows are also visible in many models. Of all the models we consider, that which represents the current data the best is one in which electrons are relativist
is larger than the thermal pressure, but cold (i.e. negligib
otherwise. This work is part of a series also applying the 'obs
to near-horizon regions of supermassive black holes in M87

Key words: black hole physics – accretion, accretion discs

On the Comparison of AGN with GRMHD Simulations: II. M87

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arXiv:2309.05602v1 [astro-ph.HE] 11 Sep 2023

ABSTRACT
Horizon-scale observations of the jetted active galactic nucleus M87 are compared with simulations spanning a broad range of dissipation mechanisms and plasma content in three-dimensional general relativistic flows around spinning black holes. Observations of synchrotron radiation from radio to X-ray frequencies can be compared with simulations by adding prescriptions specifying the relativistic electron-plus-positron distribution function and associated radiative transfer coefficients. A suite of time-varying simulations with various spins and plasma magnetizations is chosen to represent distinct possibilities for the M87 jet/accretion flow/black hole (JAB) system. We then input turbulent heating and equipartition-based emission prescriptions (and piecewise combinations thereof) in the time-dependent 3D simulations, in which jet morphology, polarization and variation are "observed" and compared with real observations so as to try to infer the rules that govern the polarized emissivity. The models in this paper support a magnetically arrested disk (MAD) with several possible spin/emission model combinations supplying the jet in M87, whose inner jet and black hole shadow have been observed down to the photon ring at 230 GHz by the Event Horizon Telescope (EHT). We also show that some MAD cases that are dominated by intrinsic circular polarization have near-linear V/I dependence on unpaired electron or positron content while SANE polarization exhibits markedly greater positron-dependent Faraday effects – future probes of the SANE/MAD dichotomy and plasma content with the EHT. This is the second work in a series also applying the "observing" simulations methodology to near-horizon regions of supermassive black holes in Sgr A* and 3C 279.

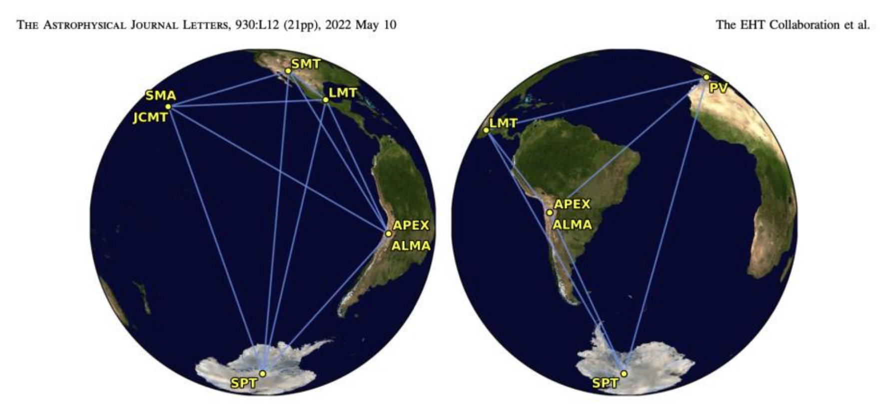
Key words: active galactic nucleus (AGN), general relativistic magnetohydrodynamic (GRMHD) simulation, relativistic jet, very long baseline interferometry (VLBI)

Paper I: Anantua et al (2020)b MNRAS **493**, 1404

Paper II: Anantua et al (2023)b ArXiv:2309.05602

Application I.

Positron Modeling of M87*



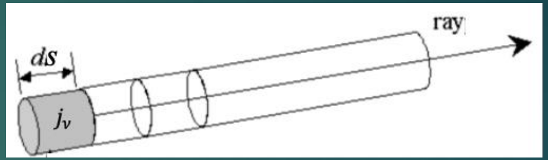
Zooming towards M87’s Jet and Central Black Hole

Courtesy of European Southern Observatory (ESO)

Radiative Transfer

- Radiative transfer links source properties such as emissivity j_ν to observed radiation

$$\frac{dI_\nu}{ds} = j_\nu \Rightarrow I_\nu = \int_0^s j_\nu ds'$$



- Polarized radiative transfer equations w./absorption and Faraday effects (Dexter 2016):

$$\frac{d}{ds}\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} j_I \\ j_Q \\ j_U \\ j_V \end{bmatrix} - \begin{bmatrix} \chi_I & \chi_Q & \chi_U & \chi_V \\ \chi_Q & \chi_I & \rho_V & \rho_U \\ \chi_U & -\rho_V & \chi_I & \rho_Q \\ \chi_V & -\rho_U & -\rho_Q & \chi_I \end{bmatrix} \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}$$

For synchrotron radiation

$$j_I \rightarrow j_\nu \sim P_e F(\vec{B}, \nu), \qquad P_e \sim \int \gamma N(\gamma) d\gamma$$

- Emitting particle distribution functions $N(\gamma)$:
  - Thermal

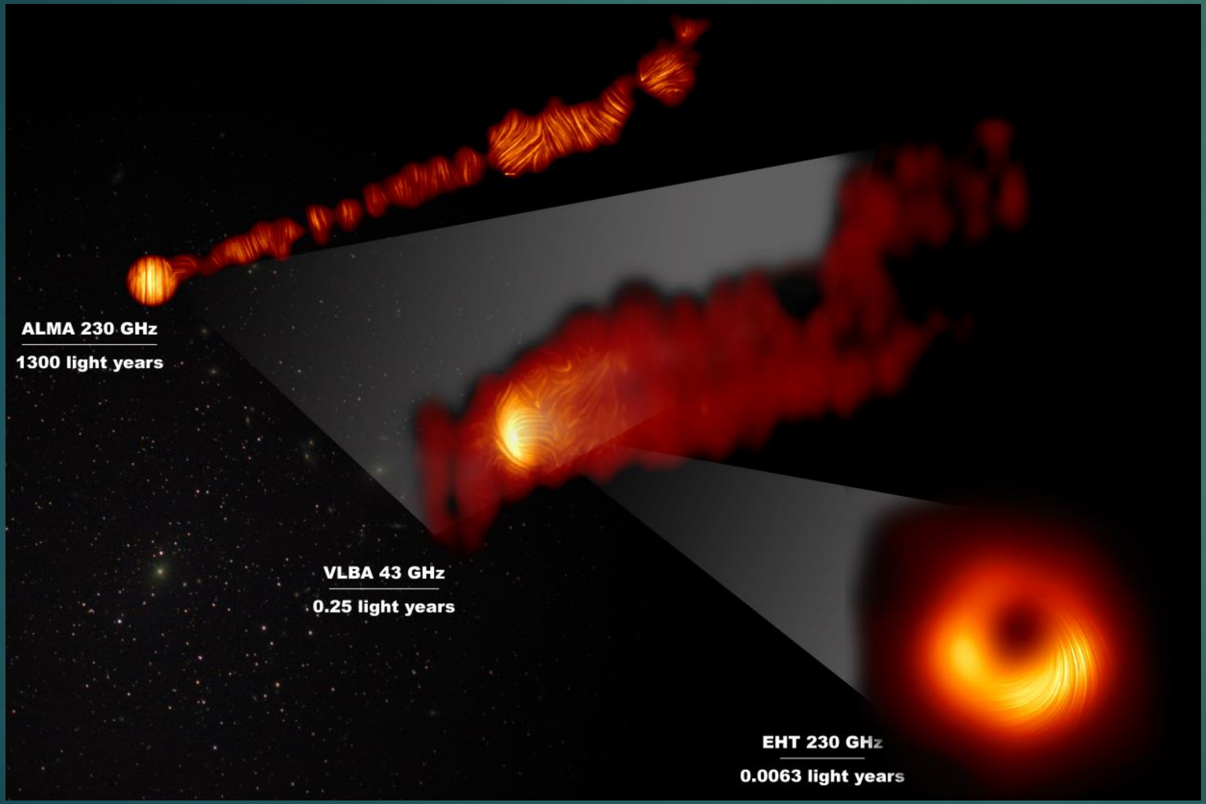
$$N(\gamma) \sim \exp(-\gamma/\theta_e)$$

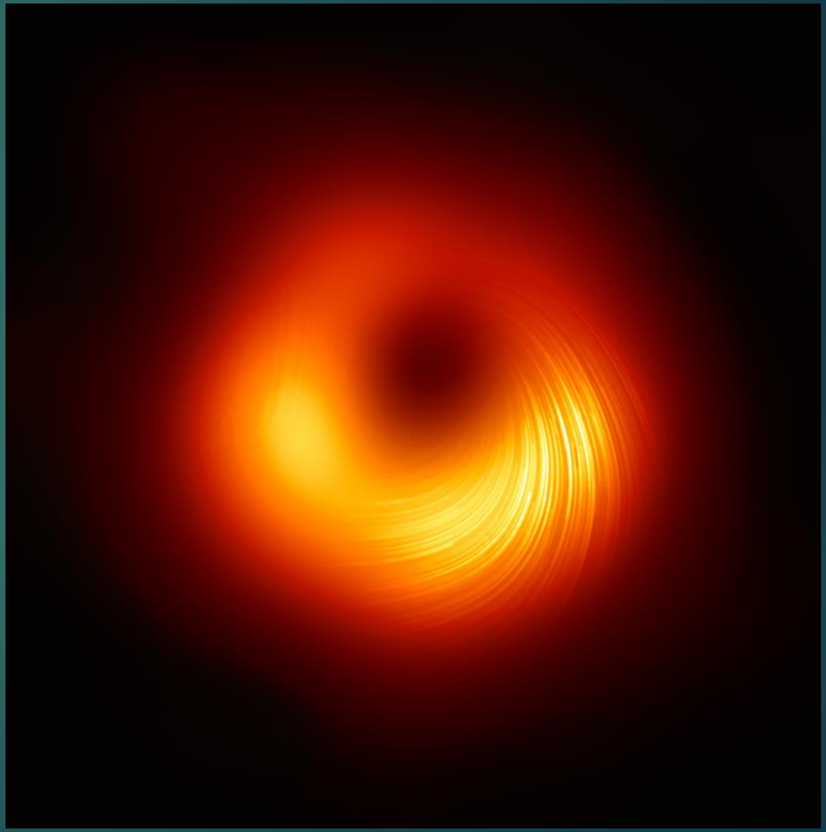
  - Power law

$$N(\gamma) \sim \gamma^{-p}$$

Polarized M87 Observations

- M87 polarization has been observed by ALMA, VLBA and EHT





EHT M87 Simulation Library

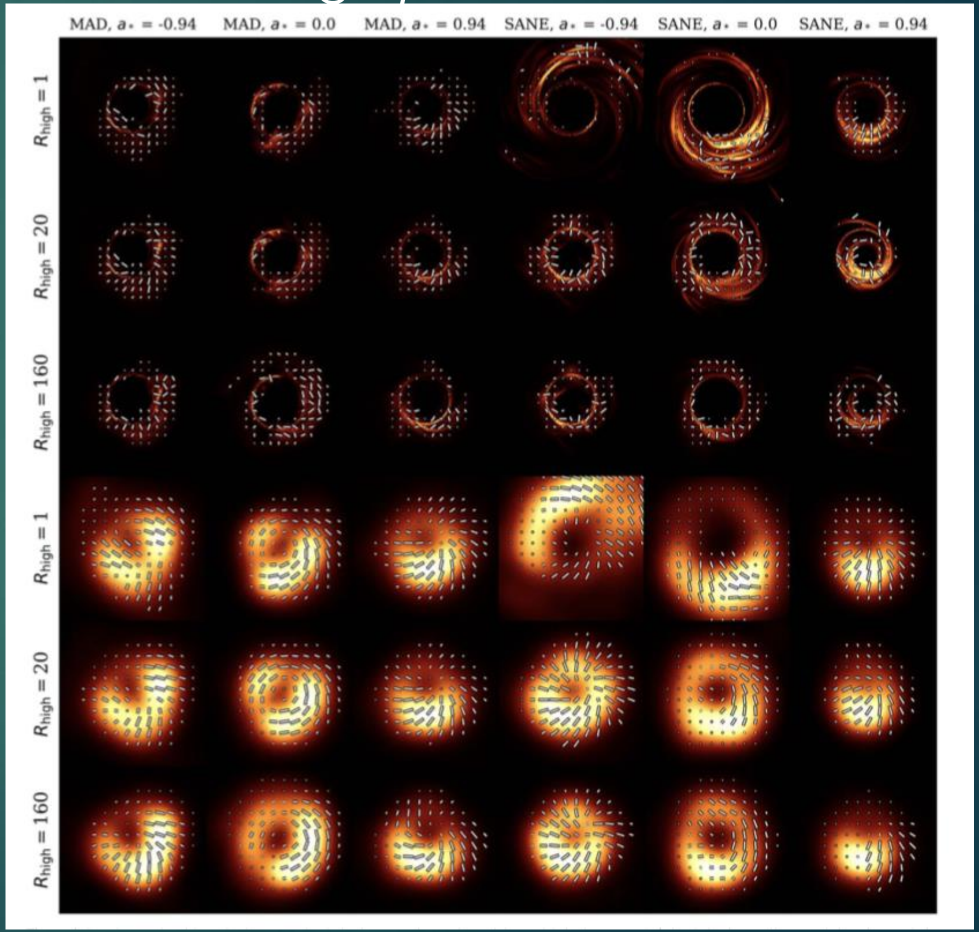
- Turbulent heating physics (Howes 2010): Relativistic electrons preferentially heated at low $\beta = \frac{P_g}{P_B}$; protons and other ions at high β, relativistically cold plasma
- R-Beta Model (EHTC Papers I-VIII)

$$R = \frac{T_i}{T_e} = \frac{1}{1+\beta^2} R_{\text{low}} + \frac{\beta^2}{1+\beta^2} R_{\text{high}}$$

- Using the R-Beta Model (w./$R_{\text{low}} = 1$) and

SANE and MAD simulations (w./ $\frac{a}{M} = -0.94, 0, 0.94$):

  - Increasing spin magnitude increases asymmetry
  - MAD has mostly spiral EVPA/vertical implied B-field
  - SANE has mostly radial EVPA/toroidal implied B-field



EHTC Paper VIII

Emission Prescriptions with Magnetic Energy Conversion

- Constant Electron Beta (β_e) Model – Magnetic-to-Particle Energy Conversion:

$$\beta_e = \frac{P_e}{P_B} = \frac{(\gamma_e - 1)u_e}{B^2/2} \Longrightarrow u_e = \rho T_e = \frac{1}{(\gamma_e - 1)}\beta_e \frac{B^2}{2}$$

Equipartition for $P_e \sim P_B$

- Magnetic Bias Model

$$P_e = K_n \left(\frac{b}{\sqrt{2}}\right)^{2n}, \qquad K_n = K_1 \frac{\langle \frac{b^2}{2} \rangle}{\langle \left(\frac{b}{\sqrt{2}}\right)^{2n} \rangle}, K_1 = 1$$

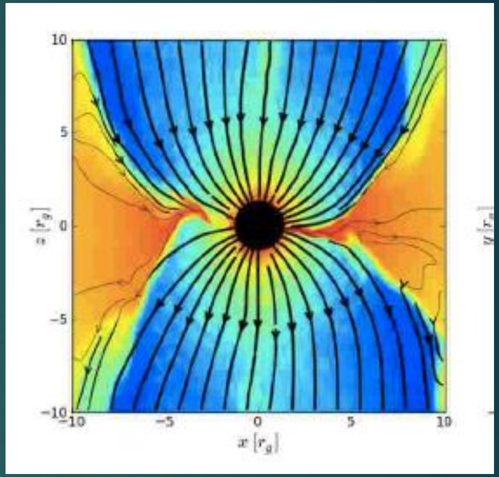
M87 Simulation Assumptions and Fluid Equations

- Start with a HARM GRMHD simulation assuming:
  - Geometrically thick disk
  - Magnetically arrested disk
  - Jet power derived from flux threading black hole of mass M and spin a/M=0.92
- Mass conservation $\nabla_\mu(\rho u^\mu) = 0$
- Energy-momentum conservation

$$\nabla_\mu T^{\mu\nu} = 0$$

$$T^\mu_\nu = \left(\rho + u_g + P_g + b^2\right)u^\mu u_\nu + (P_g + b^2/2)\delta^\mu_\nu - b^\mu b_\nu$$

- Assume power law coefficients for radiative transfer in jet models



McKinney, Tchekhovskoy and Blandford MNRAS **423** 3083 (2012)

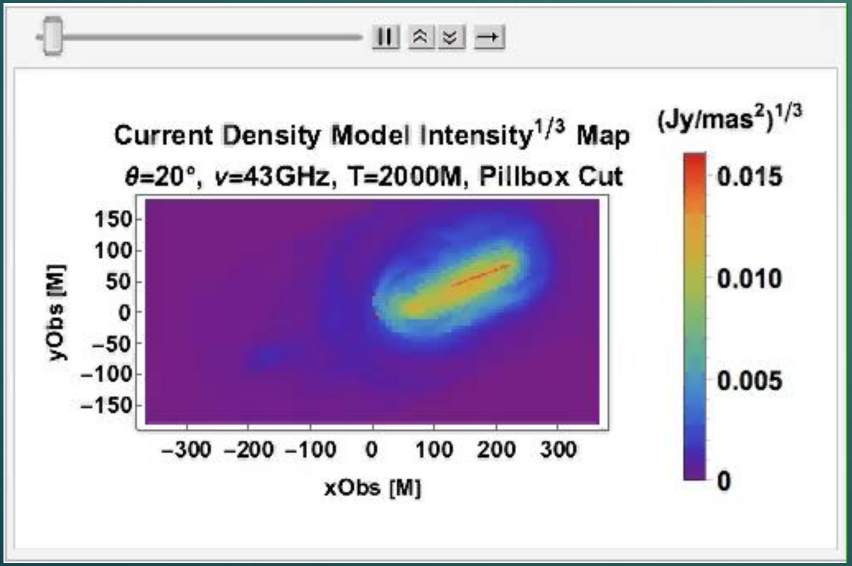
$$r_g = M = \frac{GM_{\mathrm{BH}}}{c^2} = 5.0 \times 10^{12}\mathrm{m}$$

Connecting with Observations: M87 43 GHz Radio Map Time Series vs. Current Density Model

- Current density (*j*) model based on having particles accelerated at current layers

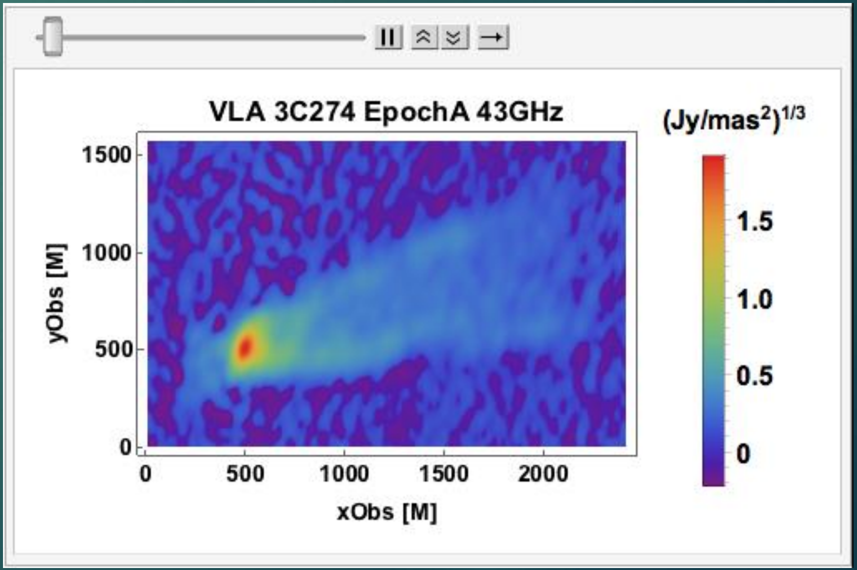
$$j_\nu \propto \widetilde{P}_e \propto j^2$$

(θ_{Obs},Φ_{Obs})=(20°,0°), T_{Obs}=2000M,2056M,…,2560M
Emissivity: Current Density Model
Disk subtraction: |z|>35M
L_{JSq}=1e4 M



Anantua, Blandford and Tchekhovskoy (2018) Galaxies, 6, 31

M87 43GHz (7mm) VLA maps
21-Day frame rate, Epochs A,B,D-L



Courtesy of Craig Walker (NRAO), Chun Ly (UCLA), Bill Junor (Los Alamos), and Phil Hardee (U. Alabama)

Stationary Axisymmetric Self-Similar Semi-Analytic Jet Model

- Assume stationary (d/dt=0), axisymmetric (d/dϕ =0) parabolic jet with self-similarity parameter $\xi = s^2/z$
- Use force-free $\rho\vec{E} + \vec{j} \times \vec{B} = \vec{0}$ jet region of a HARM simulation
  - Relate GRMHD variables to fieldline angular speed $\Omega_B(\xi)$ and flux $\Phi_B(\xi)$ connected to horizon

$$I = -2\Omega_B \xi \Phi'$$

$$\begin{pmatrix} B_s \\ B_\phi \\ B_z \end{pmatrix} = \begin{pmatrix} -\frac{1}{2\pi s}\frac{\partial \Phi}{\partial z} \\ \frac{I}{2\pi s} \\ \frac{1}{2\pi s}\frac{\partial \Phi}{\partial s} \end{pmatrix}$$

$$\begin{pmatrix} v_s \\ v_\phi \\ v_z \end{pmatrix} = \begin{pmatrix} \frac{s}{2z} v_z \\ s\Omega_B(1 - v_z) \\ v_{z0} e^{-0.001 s^8/z^4} \end{pmatrix}$$

$$\vec{E} = \vec{B} \times (\hat{\Omega}_B \times \vec{r})$$

and at z=50M, derive fitting forms for flux threading the horizon

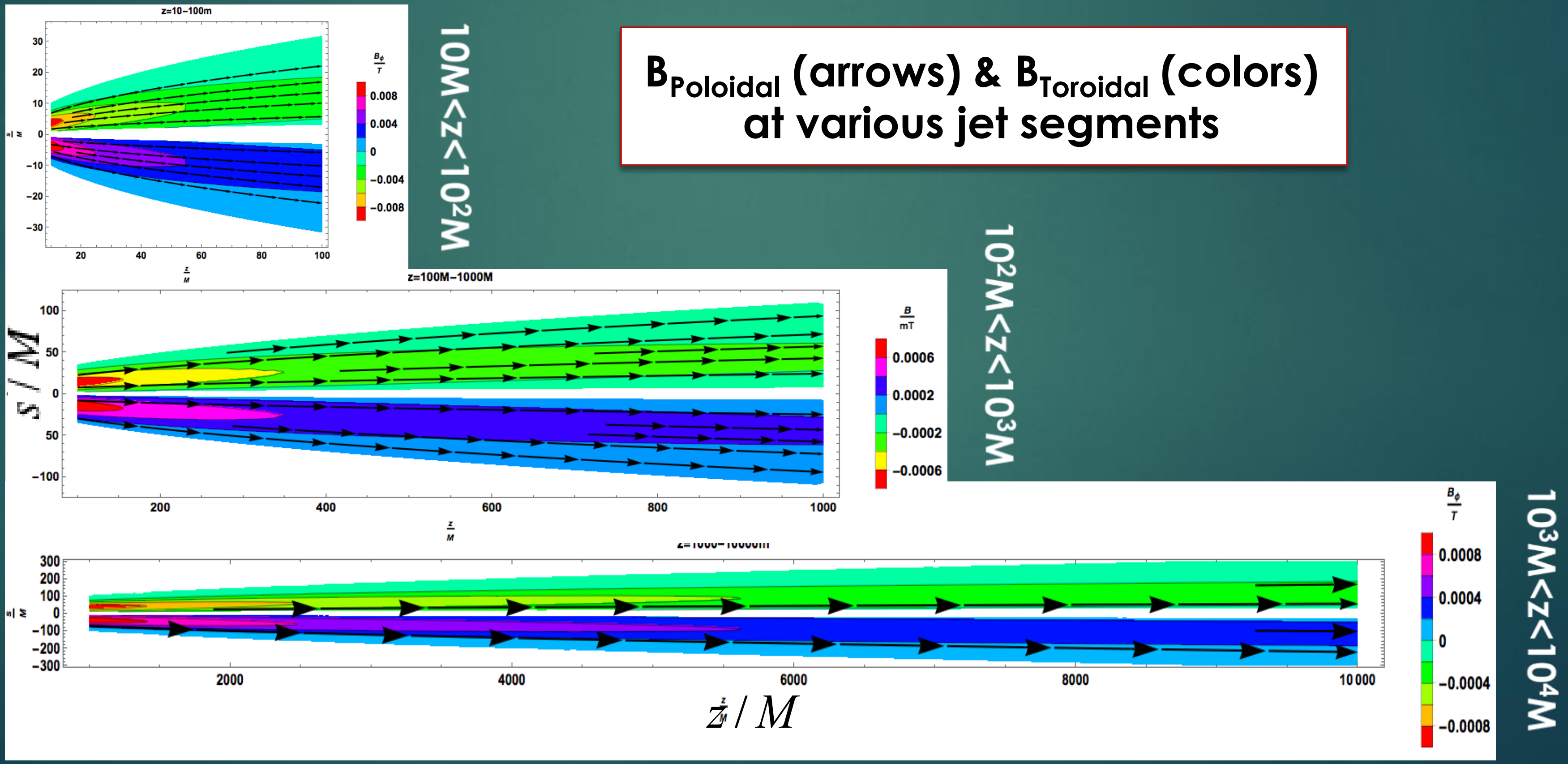
$$\Phi_B(\xi) = \tanh[-0.3\xi]$$

and fieldline angular speed

$$\Omega_B(\xi) = 0.15 \exp[-0.3\xi^2]$$

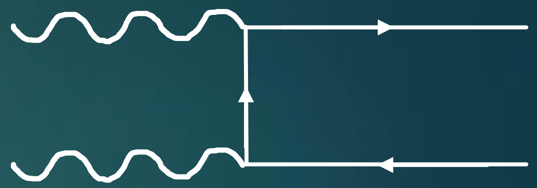
Semi-Analytic Jet Model

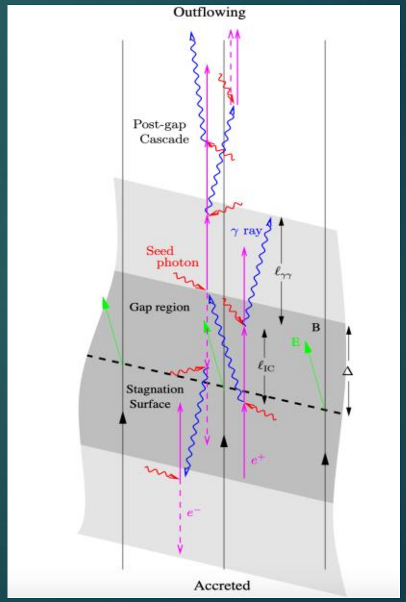
- Assume stationary (d/dt=0), axisymmetric (d/dϕ =0) parabolic jet with self-similarity based on force-free $\rho\vec{E}+\vec{j}\times\vec{B}=\vec{0}$ region of HARM jet simulation
- Use self-similarity to obtain GRMHD flow on different scales



Positron Physics in JAB Systems

- Positrons can be created in AGN jet/accretion flow/black hole (JAB) systems via:
  - Photon-photon interactions: $\gamma\gamma \rightarrow e^- e^+$ (Breit-Wheeler Pair Production):
    - Electrons in Compton clouds of disk photons may scatter soft photons to MeV energies, which photons undergo photon-photon interactions resulting in e-e+ pairs (Laurent & Titarchuk 2018) in jet funnel walls
    - Funnel wall positron number densities predicted for Sgr A* ($n_\pm = 10^{-8}$ cm^{-3}) and M87 ($n_\pm = 10$ cm^{-3}) walls (Moscibrodzka et al. 2011)
  - Spark gap processes
    - Jets in AGN generically host a spark gap in which plasma moves away from the black hole beyond the outer light cylinder but must fall toward the central black hole within a stagnation surface at smaller radii from the hole (Levinson & Segev 2017)





Broderick and Tchekhovskoy (2015) ApJ, **801**, 1

- Positron effects can be included by in GRMHD postprocessors by generalizing:
  - Particle number density $n = n_i + n_{e+} + n_{e-}$ (Anantua et al. 2020a) and:

$$j_{I,Q,U} \rightarrow j_{I,Q,U}\left(1 + \frac{n_{e+}}{n_{e-}}\right), \quad j_V \rightarrow j_V\left(1 - \frac{n_{e+}}{n_{e-}}\right)$$

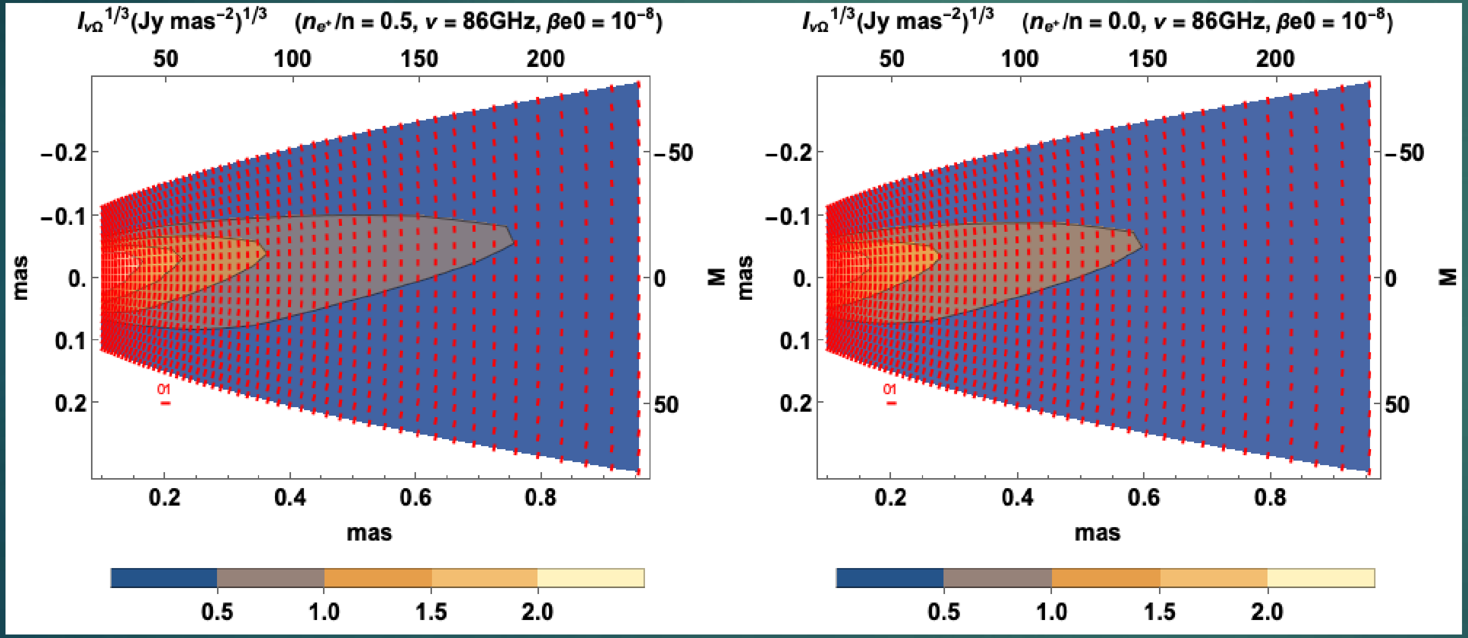
$$\chi_{I,Q,U} \rightarrow \chi_{I,Q,U}\left(1 + \frac{n_{e+}}{n_{e-}}\right), \quad \chi_V \rightarrow \chi_V\left(1 - \frac{n_{e+}}{n_{e-}}\right)$$

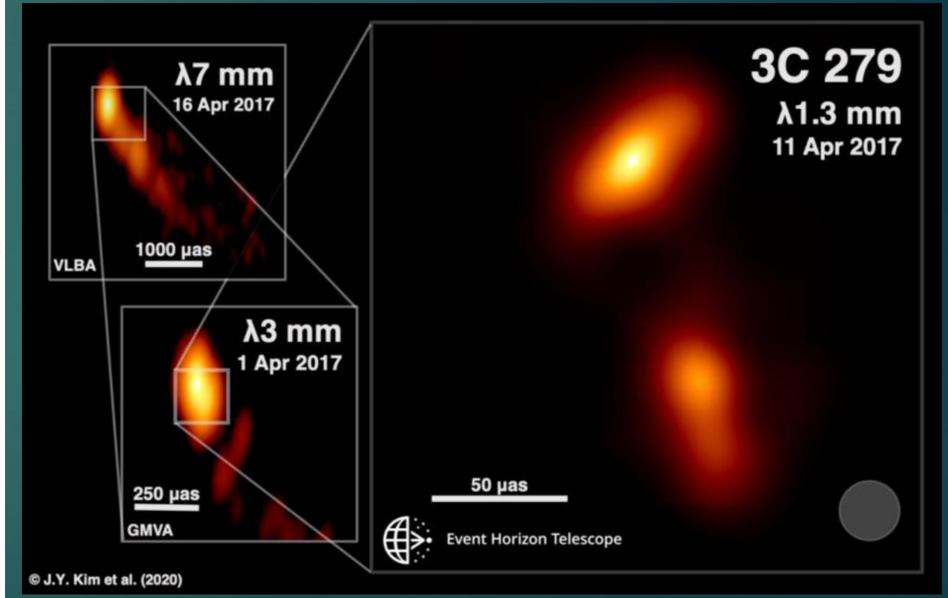
$$\rho_{Q,U} \rightarrow \rho_{Q,U}\left(1 + \frac{n_{e+}}{n_{e-}}\right), \quad \rho_V \rightarrow \rho_V\left(1 - \frac{n_{e+}}{n_{e-}}\right)$$

Synchrotron Intensity Asymmetry with Positrons

- In the $\beta_{e0} = 10^{-8}$ Constant Electron Beta model $\left(j_\nu \propto P_e P_B^{\frac{1+\alpha}{2}} \nu^{-\alpha} \propto \beta_{e0} P_B^{\frac{3+\alpha}{2}} \nu^{-\alpha}\right)$ with positrons, at 86 GHz, as ion content increases from 0% to 100% of positive charge carriers (or n_{e^+}/n goes from 0.5->0), the intensity map
  - Becomes inwardly core shifted
  - Remains bilaterally asymmetric

Anantua, Emami, Loeb and Chael
ApJ **896** 30 (2020)





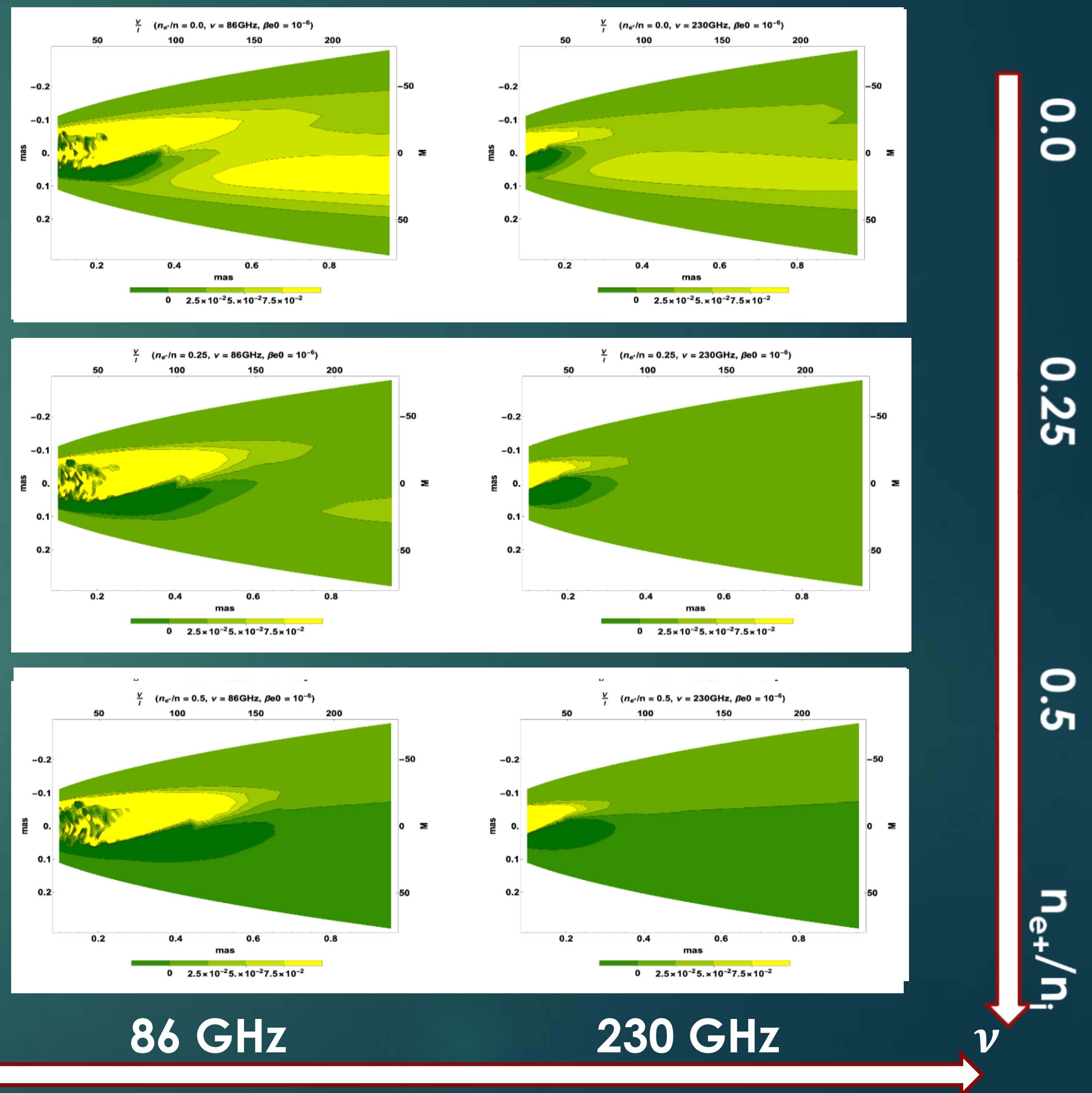
- Our fiducial $\gamma_{\min}$ =10 and $\gamma_{\max} = \infty$

Degree of Circular Polarization

$\beta_{e0} = 10^{-6}$

- For the parameter space 86GHz ≤ ν ≤ 230 GHz, 0 ≤ n_{e+}/n ≤ 0.5, $10^{-10} \le \beta_{e0} \le 10^{-6}$, circular polarization degree V/I
  - Tends to increase for ionic plasma at lower frequencies and higher β_{e0}
  - Ranges from 0 to O(10^{-3})
  - Is maximized near the black hole and along the jet axis, as seen for $\beta_{e0} = 10^{-8}$, except for the most leptonic plasma
- Symmetric e^-e^+ plasma virtually destroys V/I, despite minor Faraday conversion

Anantua, Emami, Loeb and Chael
ApJ **896** 30 (2020)

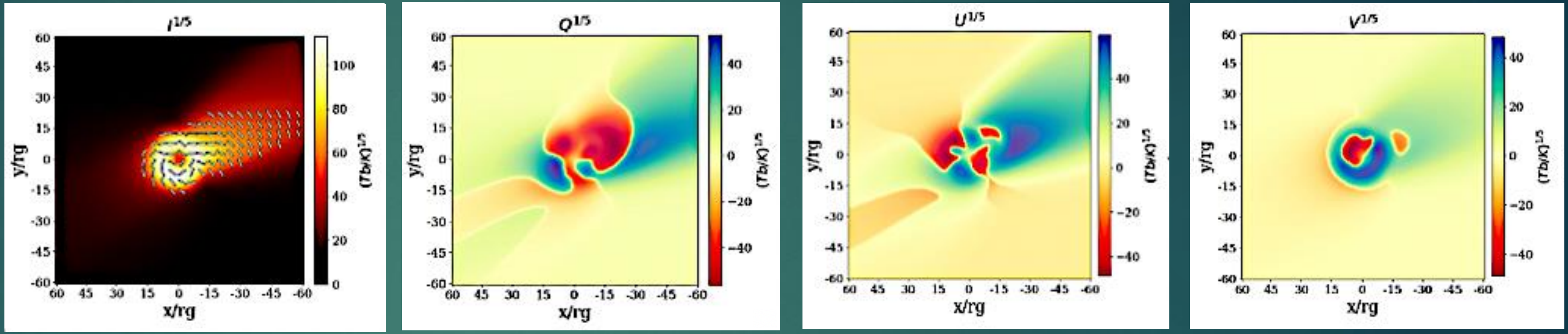


Near-Horizon Jet Model Stokes Maps: M87

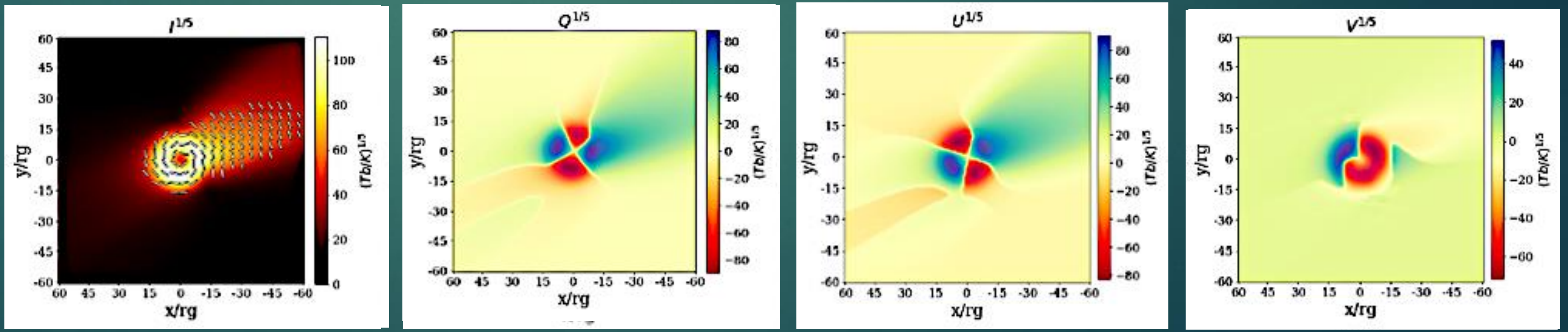
- Constant Electron Beta Model $\left(j_\nu \propto P_e P_B^{\frac{1+\alpha}{2}}\right)$, ν =230 GHz

$(P_e)_{\mathrm{Beta}} = \beta_{e0} P_B$,
$\beta_{e0} = 10^{-4}, 10^{-2}, \ldots$

$0 \le f_{\mathrm{Pos}} = \frac{n_{e+}}{n_{e-}} \le 1$



$\beta_{e0} = 10^{-4}, f_{\mathrm{Pos}} = 0$

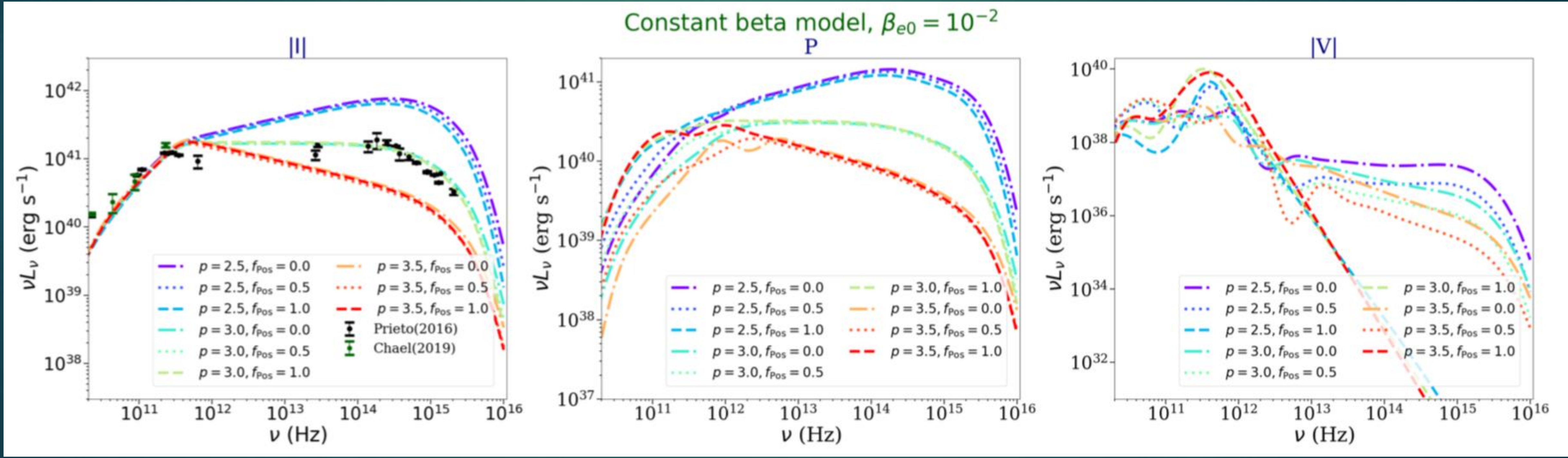


$\beta_{e0} = 10^{-4}, f_{\mathrm{Pos}} = 1$

Emami, Anantua, Chael & Loeb 2021
ArXiv: 2101.05327

Near-Horizon Jet Model Polarized Spectra: M87

- Constant Electron Beta Model polarized spectral decomposition
  - I insensitive to f_{pos}
  - P sensitive to f_{pos} at low ν
  - V sensitive to f_{pos} since $j_V, \rho_V \propto (1 - f_{\rm Pos}), \rho_{Q,U} \propto (1 + f_{\rm Pos})$

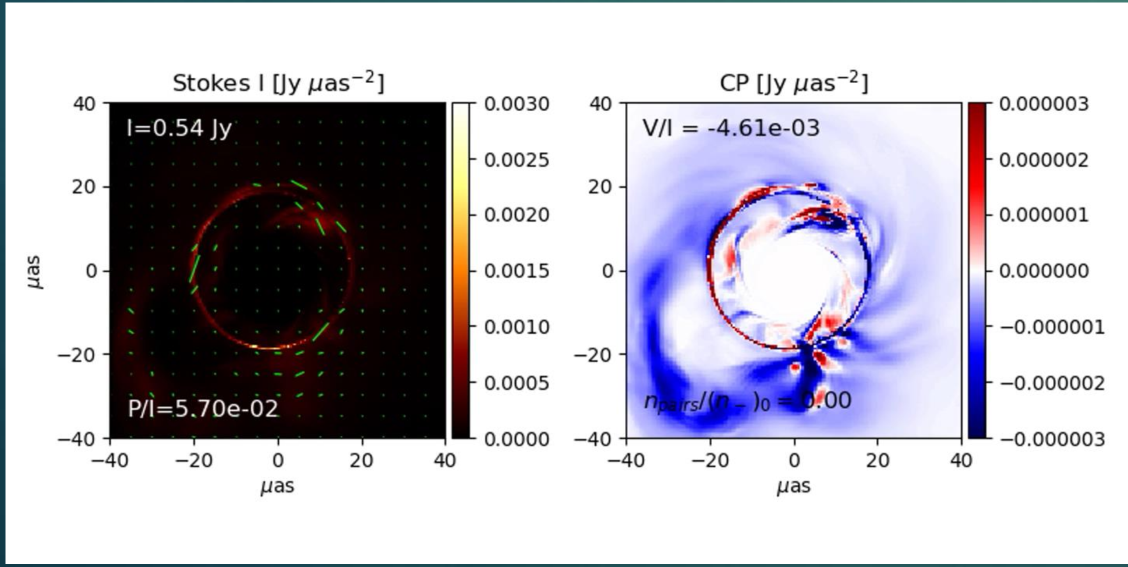


Emami, Anantua, Chael & Loeb 2021
ArXiv: 2101.05327

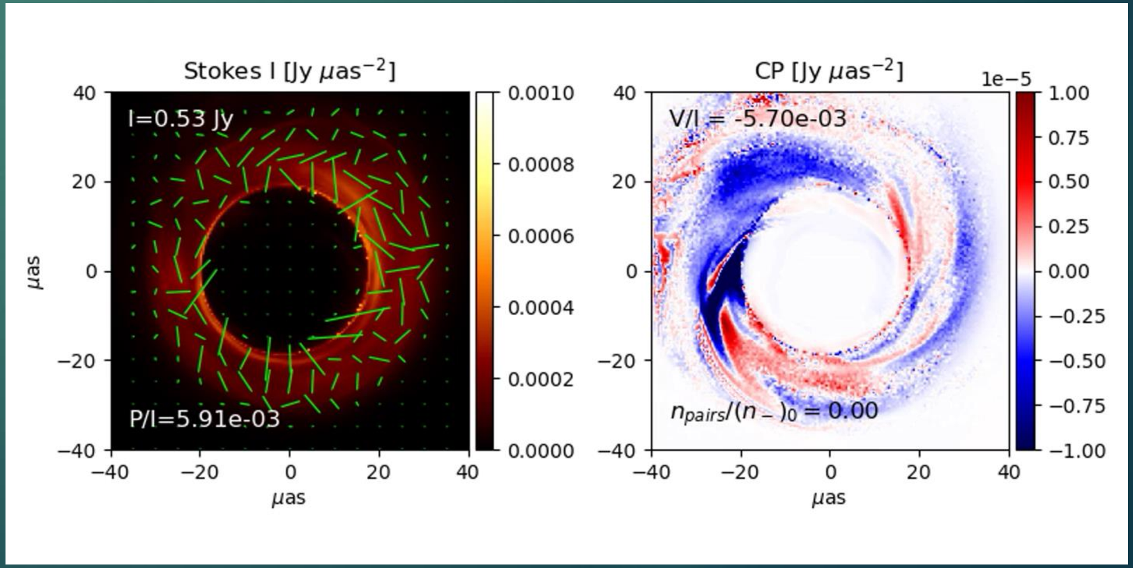
Positron Effects on "Observing" GRMHD Simulations: MAD vs. SANE

- Using a HARM GRMHD simulation and adding e+/e- pairs so $n = n_p + (n_{e-})_0 + n_{\mathrm{Pairs}}$ in ray tracing at 230 GHz results in
  - Magnetically Arrested Disk (MAD) simulations with decreasing V/I with increasing $n_{e+} = \frac{n_{\mathrm{pairs}}}{2}$ due to positrons cancelling intrinsic circular polarization
  - MAD simulation models have lower Faraday depth than Standard and Normal Evolution (SANE), resulting in slower rates of EVPA rotation

MAD R_{high}=20, a/M= -0.5



SANE R_{high}=20, a/M= -0.5

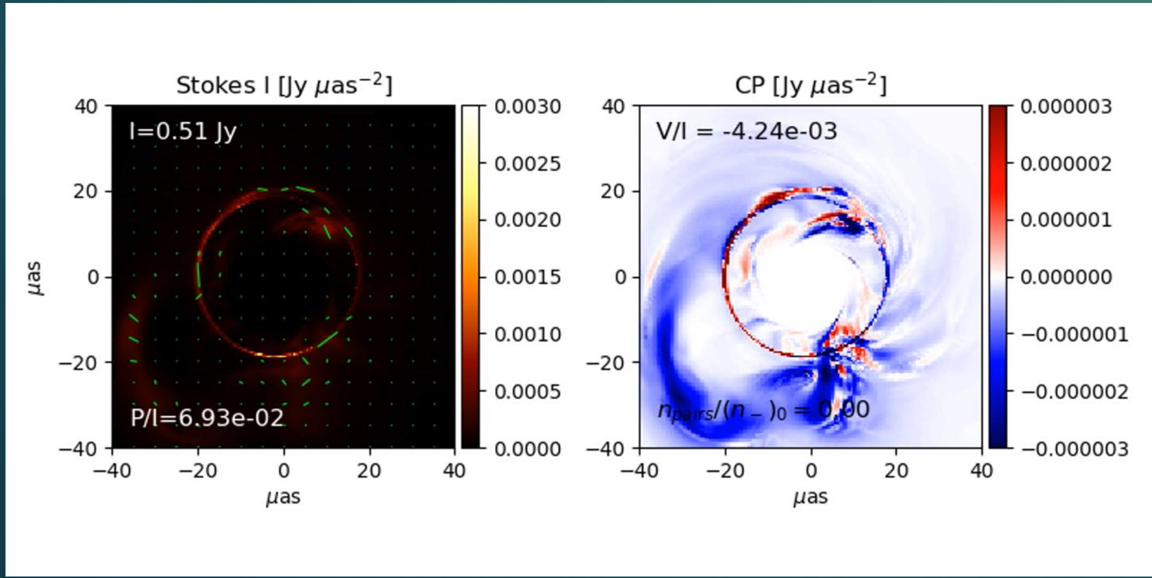


Anantua et al.
et al. 2023b)
https://arxiv.org/abs/2309.05602

Positron Effects on "Observing" GRMHD Simulations: Critical Beta Model

- Using a HARM GRMHD simulation and adding e+/e- pairs so $n = n_p + (n_{e-})_0 + n_{\mathrm{Pairs}}$ in ray tracing at 230 GHz with Critical Beta Model $\frac{T_e}{T_p + T_e} = f\ \mathrm{Exp}[-\beta/\beta_c]$ results in
  - Magnetically Arrested Disk (MAD) simulations with decreasing V/I with increasing $n_{e+} = \frac{n_{\mathrm{pairs}}}{2}$ due to positrons cancelling intrinsic circular polarization
  - MAD simulation models have lower Faraday depth than Standard and Normal Evolution (SANE), resulting in slower rates of EVPA rotation

MAD $f = 0.5, \beta_{\mathrm{crit}}$=1, a/M= -0.5



Comparison of AGN with GRMHD Simulations. II: M87 15

Table 3. Linear polarization $|m|_{\mathrm{net}}$ and $<|m|>$ for fiducial models at $T = 25{,}000M$. The observational constraints from EHT M87 Paper VII take the form of the polarization ranges $0.01 \leqslant |m|_{\mathrm{net}} \leqslant 0.037$ and $0.057 << |m| >< 0.107$. Note that the bold values refer to fiducial models which satisfy the net linear polarization constraints.

	SANE R−Beta	SANE R−Beta w./ Jet	SANE ($a=-0.5$) Crit. Beta	SANE Crit. Beta w./ Jet	MAD R−Beta	MAD R−Beta w./ Jet	MAD ($a=-0.5$) Crit. Beta	MAD Crit. Beta w./ Jet
$\lvert m\rvert_{\mathrm{net}}(f_{\mathrm{pos,min}})$	$3.93 \cdot 10^{-3}$	$3.97 \cdot 10^{-3}$	$8.51 \cdot 10^{-3}$	$2.26 \cdot 10^{-3}$	$5.51 \cdot 10^{-2}$	$4.07 \cdot 10^{-2}$	$6.93 \cdot 10^{-2}$	$4.86 \cdot 10^{-2}$
$\lvert m\rvert_{\mathrm{net}}(f_{\mathrm{pos,max}})$	$1.62 \cdot 10^{-3}$	$2.88 \cdot 10^{-3}$	$2.73 \cdot 10^{-3}$	$2.50 \cdot 10^{-3}$	$\mathbf{3.67 \cdot 10^{-2}}$	$\mathbf{3.10 \cdot 10^{-2}}$	$5.21 \cdot 10^{-2}$	$\mathbf{3.55 \cdot 10^{-2}}$
$<\lvert m\rvert>(f_{\mathrm{pos,min}})$	$1.29 \cdot 10^{-1}$	$1.38 \cdot 10^{-1}$	$1.35 \cdot 10^{-1}$	$1.44 \cdot 10^{-1}$	$3.49 \cdot 10^{-1}$	$3.30 \cdot 10^{-1}$	$2.71 \cdot 10^{-1}$	$2.53 \cdot 10^{-1}$
$<\lvert m\rvert>(f_{\mathrm{pos,max}})$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
					MAD R−Beta	MAD R−Beta w./ Jet	MAD ($a=+0.94$) Crit. Beta	MAD Crit. Beta w./ Jet
$\lvert m\rvert_{\mathrm{net}}(f_{\mathrm{pos,min}})$					$4.91 \cdot 10^{-2}$	$4.56 \cdot 10^{-2}$	$\mathbf{3.35 \cdot 10^{-2}}$	$\mathbf{3.67 \cdot 10^{-2}}$
$\lvert m\rvert_{\mathrm{net}}(f_{\mathrm{pos,max}})$					$5.17 \cdot 10^{-2}$	$5.06 \cdot 10^{-2}$	$4.59 \cdot 10^{-2}$	$4.82 \cdot 10^{-2}$
$<\lvert m\rvert>(f_{\mathrm{pos,min}})$					$5.76 \cdot 10^{-1}$	$5.18 \cdot 10^{-1}$	$5.18 \cdot 10^{-1}$	$4.81 \cdot 10^{-1}$
$<\lvert m\rvert>(f_{\mathrm{pos,max}})$					$5.86 \cdot 10^{-1}$	$5.25 \cdot 10^{-1}$	$5.81 \cdot 10^{-1}$	$5.26 \cdot 10^{-1}$

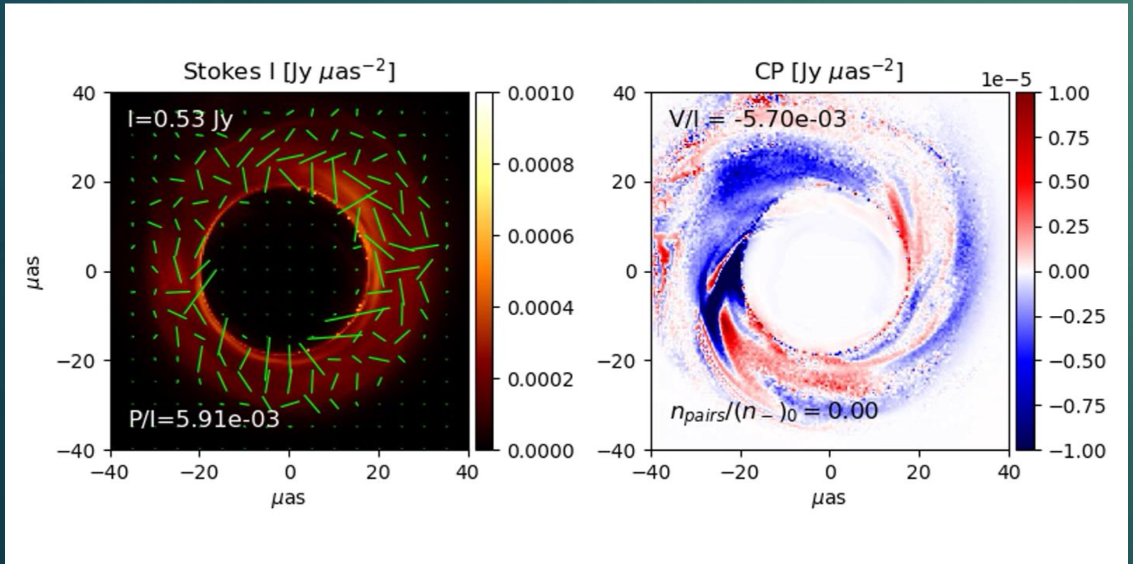
MAD Observationally Preferred!

Paper II

Positron Effects on "Observing" GRMHD Simulations: Hybrid Models

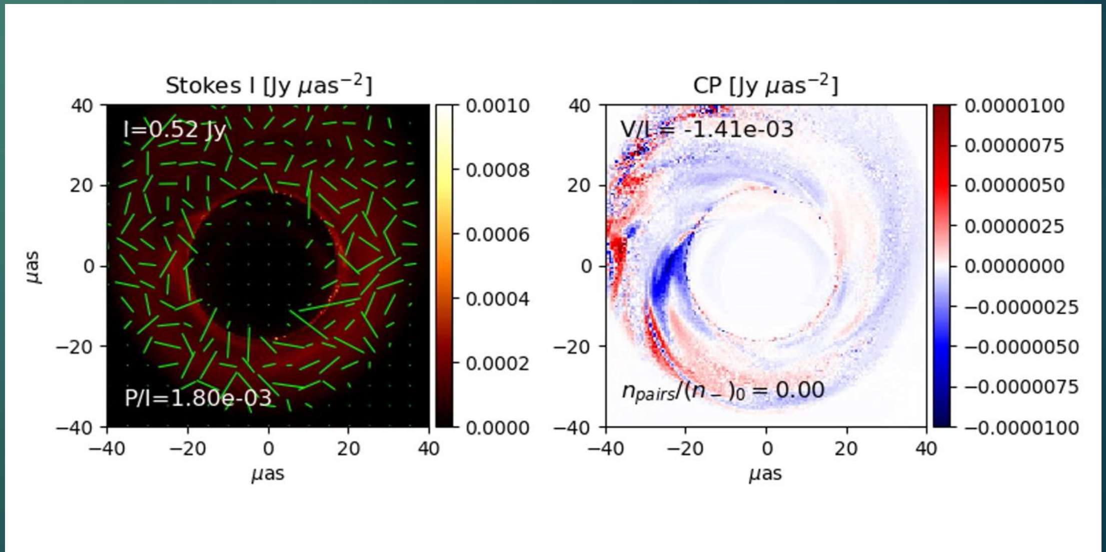
- Using a HARM GRMHD simulation and adding e+/e- pairs so $n = n_p + (n_{e-})_0 + n_{\text{Pairs}}$ in ray tracing at 230 GHz
  - Hybrid models can be constructed with different emission in the high σ (electromagnetic-to-particle flux density ratio) jet funnel by setting $P_e = \beta_{e0} P_B$ between a disk-jet transition sigma and a sigma cut above which the simulation becomes numerically unstable

SANE R_{high}=20, a/M= -0.5



SANE R_{high}=20, a/M= -0.5

$\beta_e = 10^{-2}$ for $\sigma_{\text{trans}} < \sigma < \sigma_{\text{cut}}$



Anantua et al.
et al. 2023b)
https://arxiv.org/abs/2309.05602

Application II.

Positronium Accretion of Primordial Black Holes

The Primordial Universe: First 14 Seconds

- Wienberg (1977) "The First 3 Minutes"
  - For $t_{\text{Uni}} \gtrsim 10^{-2}\text{s}$, $T_{\text{Uni}} \lesssim 10^{11}K$, energetic photons regularly created particle-antiparticle pairs
  - For $10^{-2}\text{s} \lesssim t_{\text{Uni}} \lesssim 14\text{s}$ there were around 10^{9} electron-positron pairs for every proton
- Fowler and Anantua (2023) https://arxiv.org/abs/2303.09341
  - Primordial black hole (PBH) accretion of positronium plasma under magnetorotational instability (MRI) can result in
    - A PBH population with masses $10^{15}\text{g} \lesssim M \lesssim 10^{17}\text{g}$ contributing to dark matter
    - Hawking radiation PBH supplying the present gamma ray background
- Curd, Fowler and Anantua (in prep)
  - General Relativistic Magnetohydrodynamic (GRMHD) simulations with PBH accretion of positronium

PBH Bondi Accretion

- Under Bondi (spherical) accretion around 1s after the Big Bang, primordial black holes grow rapidly accreting the ambient medium around the horizon
- Under Bondi accretion, $\frac{M}{t} \approx \frac{dM}{dt} \approx 4\pi {R_g}^2 \mathrm{v} \rho_{\mathrm{Amb}}, \quad \mathrm{v} \approx c$ near horizon
- Using ambient density $\rho_{\mathrm{Amb}} \approx \frac{10^5}{t^2} \mathrm{s}^2 \frac{\mathrm{g}}{\mathrm{cm}^3}$
  - The black hole mass after 1s is $M_{\mathrm{PBH,Bondi}} \approx 4 \cdot 10^{39} \mathrm{g}$

PBH Accretion Under MRI

- Magnetorotational instability -

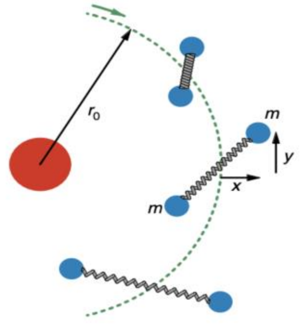


Figure 1: Conventional MRI schematic from Hung et al. (2019) https://www.nature.com/articles/s42005-018-0103-7 Fig. 1.

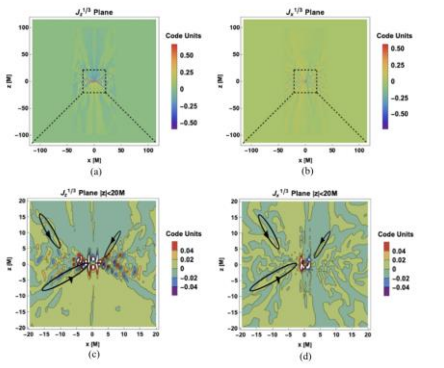


Figure 1: Volume current patterns in vertical GRMHD simulation slices showing disk MRI turbulence near the equatorial plane leading to the development of short-circuit currents preventing the buildup of magnetic tower jet dynamo current

Fowler, Li and Anantua
ApJ **885** 4 (2019)

- Our model including MRI in the primordial plasma slowly accretes from a long range R_0:

$$\frac{dM}{dt} \approx \frac{M}{t} \approx 4\pi {R_0}^2 \rho_{\text{Amb}} C^* \text{v}_k, \qquad \text{v}_k = \sqrt{\frac{GM}{R_0}}$$

$$\rho_{\text{Amb}} \approx \frac{10^5}{t^2} \text{s}^2 \frac{\text{g}}{\text{cm}^3}$$

$$R_0 = \frac{0.02\left(\frac{\text{cm}^3}{\text{g}}\right)^{1/3}}{\left(\frac{\xi}{R}\right)^{4/3}} M(t)^{1/3} t^{2/3} \propto M(t)^{\frac{1}{3}} t^{\frac{2}{3}}, \qquad \text{Accretion Radius} - \text{Time Relation}$$

$$\left(\frac{\xi}{R}\right)_{\text{MRI}} \approx 0.01$$

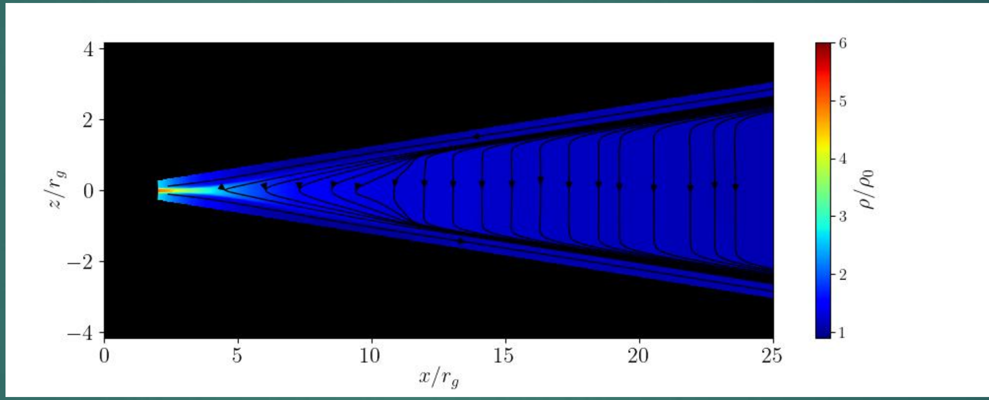
Leading to identity

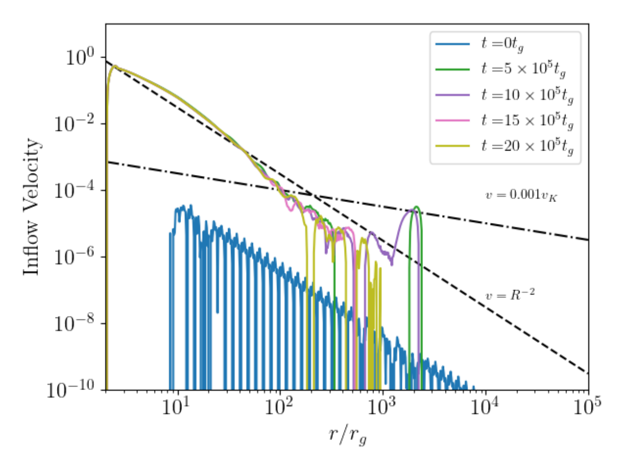
$$\frac{M}{t} \approx 4\pi \frac{10^5}{t^2} \text{s}^2 \frac{\text{g}}{\text{cm}^3} \sqrt{G} C^* \left(\frac{0.02\left(\frac{\text{cm}^3}{\text{g}}\right)^{1/3}}{\left(\frac{\xi}{R}\right)^{4/3}}\right)^{3/2} \frac{M}{t}$$

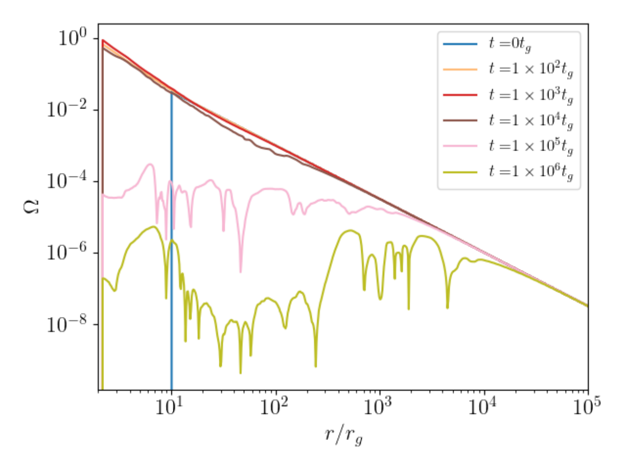
(in our model, t determines R_0)

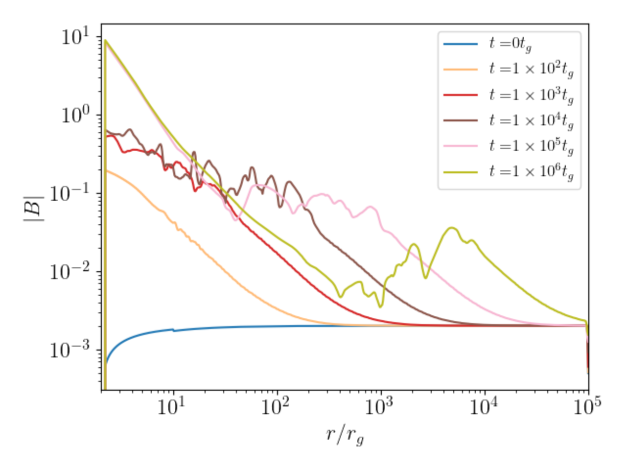
GRMHD PBH Simulation

- In KORAL simulations in Curd et al. (in prep), the inflow velocity and magnetic field under magnetorotational instability yield percent-level PBH contributions to current dark matter density









Conclusions

- Observing Jet/Accretion Flow/Black Hole (JAB) Systems is a methodology that links intuitive e-/e+ emission models of phenomenological processes such as turbulent heating and conversion of magnetic to particle energy with discrete near-horizon AGN observations
- M87
  - Using polarized emission modeling between 43 GHz and 230 GHz
    - Observations favor Blandford-Znajek jet sourced by dynamically strong, spiral magnetic fields on the ring surrounding the black hole
    - GRMHD simulations accentuate MAD/SANE dichotomy by positron effects. e.g., rotating EVPA, altered V/I
- The accretion of positronium under magentorotational instability may result in $10^{15}\mathrm{g} \lesssim M \lesssim 10^{17}\mathrm{g}$ primordial black holes associated with percent-level present dark matter contributions and a gamma ray background