High Energy Radiation from Black Holes

Gamma Rays, Cosmic Rays, and Neutrinos

Chuck Dermer

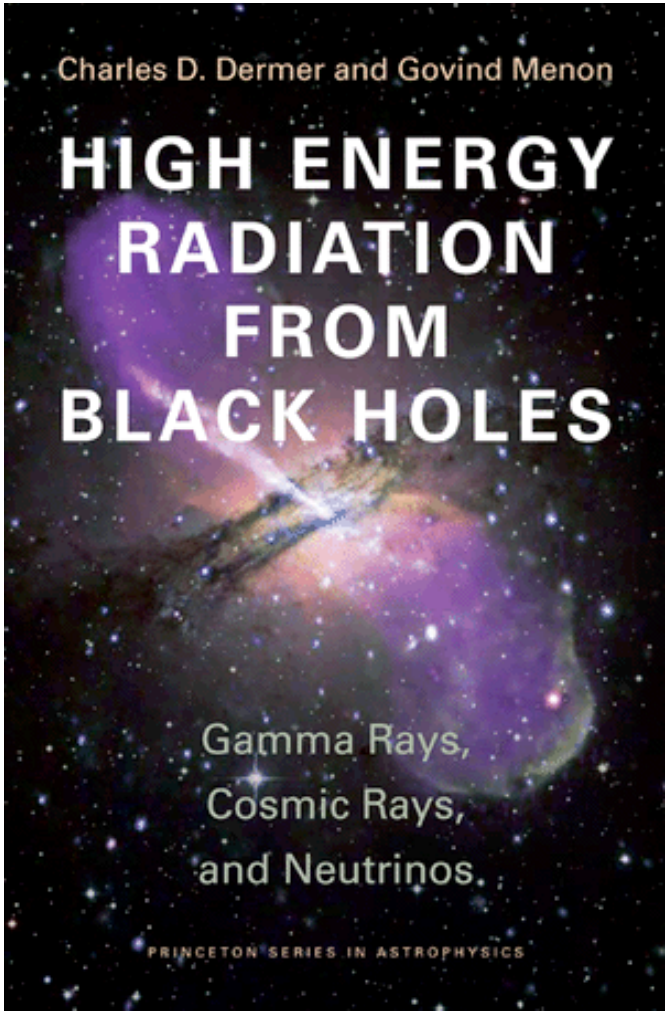
Naval Research Laboratory

charles.dermer@nrl.navy.mil

Govind Menon

Troy University

gmenon@troy.edu



Scientific Hypothesis

1. Highest energy and most powerful radiations made from black-hole engines

   Synchrotron/Compton theory, $\gamma\gamma$ compactness arguments, theory of relativistic flows

2. Ultra-high energy cosmic rays made in radio and gamma-ray loud blazars and GRBs

   Hadronic vs. leptonic γ-ray and neutrino emission signatures in these sources

3. Turbulence or shocks accelerate particles to high energies

   First and second-order Fermi acceleration; binary collision processes; blast wave physics

4. Energy source is the black-hole rotation and accretion

   Extraction of energy through the Blandford/Znajek process

Press Restatement

BLACK HOLES ARE RESPONSIBLE FOR THE MOST ENERGETIC COSMIC PARTICLES AND RADIATION

Blasts of radiation brighter than a trillion suns. Charged particles with the energy of a well-thrown baseball. Jets of magnetized plasma streaming across intergalactic space. What do these have in common? Their energy is derived from black holes.

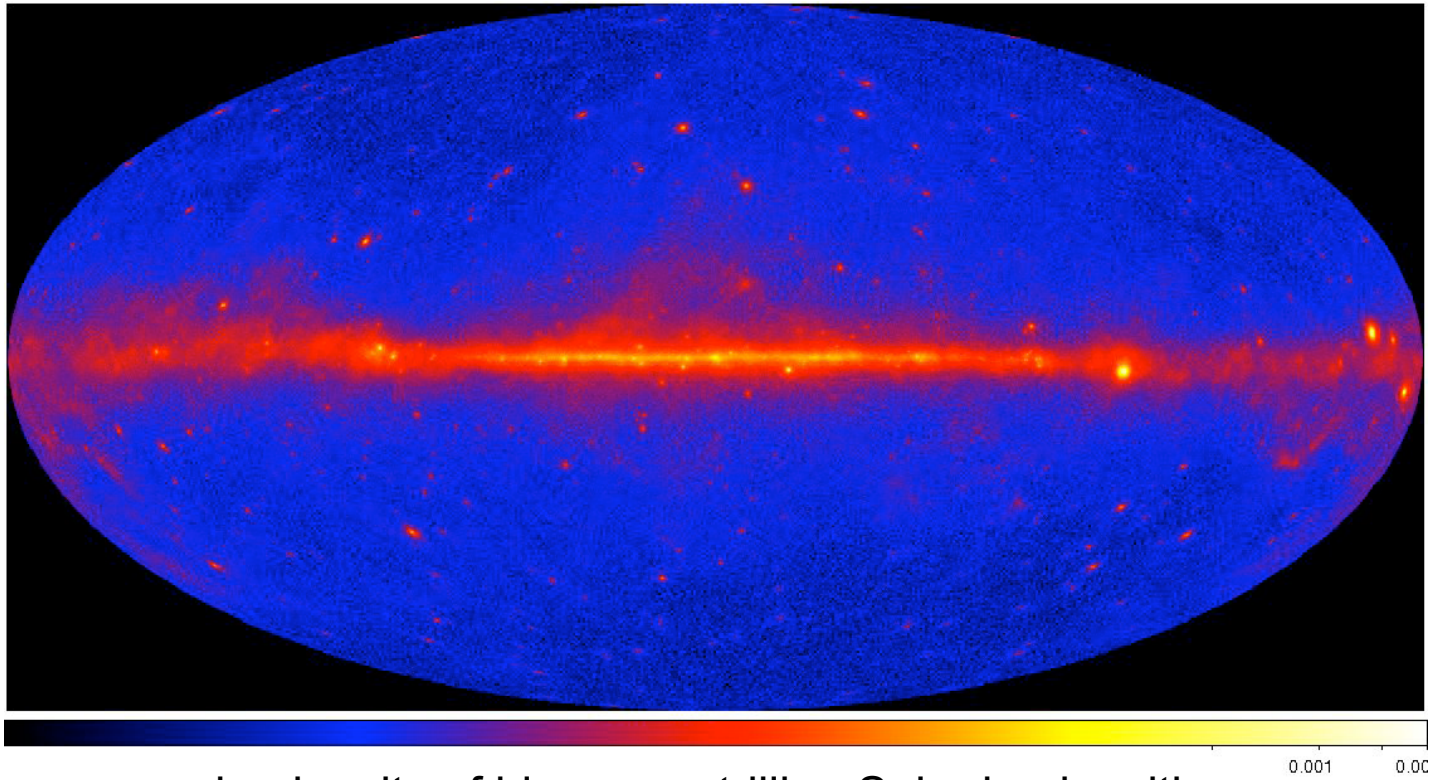
Gamma Ray Galaxies: Black-Hole Powered

Two classes:

1. **Active galaxies: Nearly 700 GeV,[1] 30 TeV; including 10 GeV and TeV radio galaxies/SSRS/RLNLS1s**
2. Star-forming galaxies: Milky Way, LMC, NGC 253, M82,…M31(?)

LAT 1 year sky image[2]

[1]talk, B. Lott
[2]Fermi talks



Gamma-ray luminosity of blazars: > trillion Solar luminosities

Gamma Ray Galaxies: Cosmic-ray/supernova powered

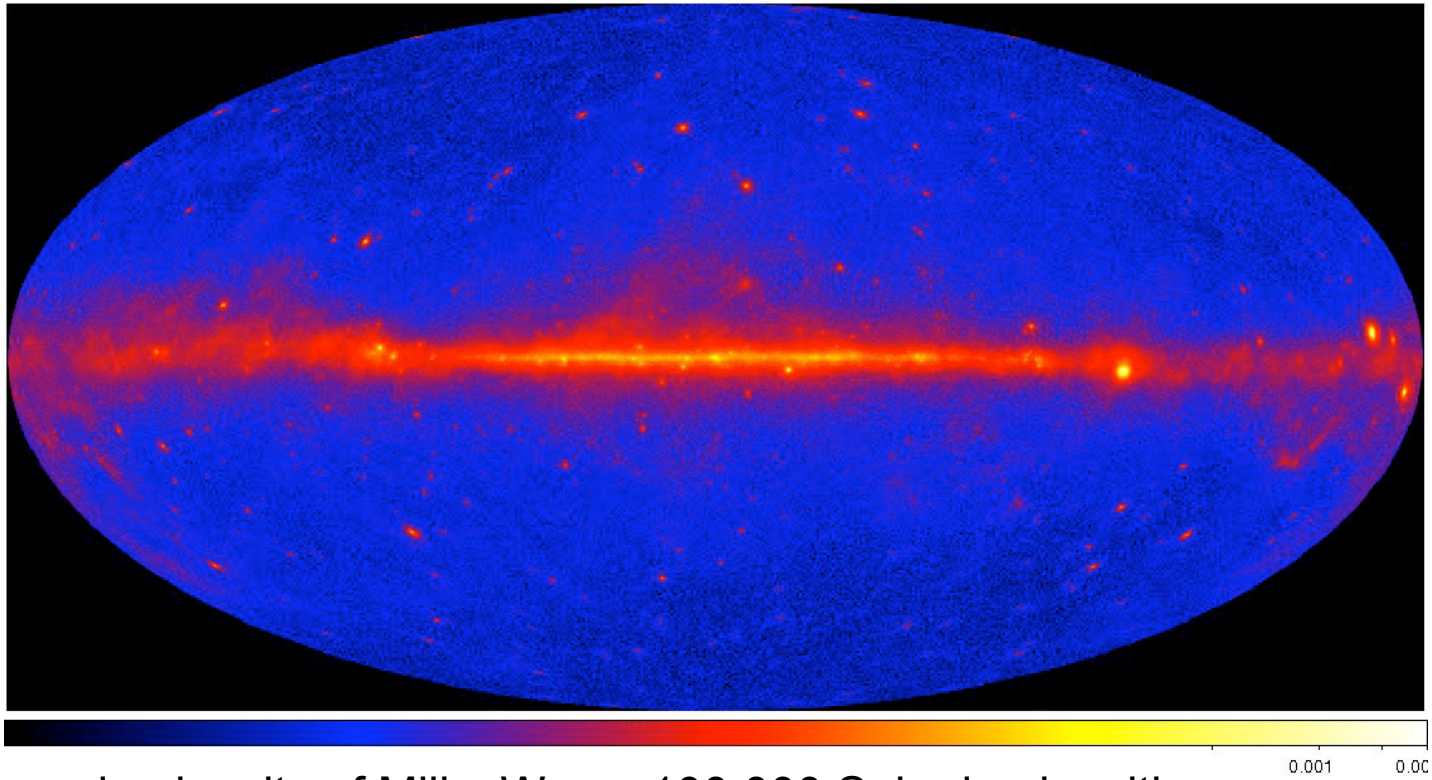
Two classes:

1. Active galaxies: Nearly 700 GeV,[1] 30 TeV; including 10 GeV/TeV radio galaxies
2. **Star-forming galaxies: Milky Way, LMC, NGC 253, M82,…M31(?)**

galactic cosmic-ray Induced γ rays

LAT 1 year sky image[2]

[1]talk, B. Lott
[2]Fermi talks



Gamma-ray luminosity of Milky Way: ~100,000 Solar luminosities

The γ-ray/cosmic-ray connection

Why so many detected black-hole powered gamma-ray galaxies (distant and therefore very luminous), and so few detected star-forming gamma-ray galaxies (nearby and therefore weak)?

Nearby, low luminosity *star-forming* gamma-ray galaxies (***millions*** x Solar luminosity) **:**

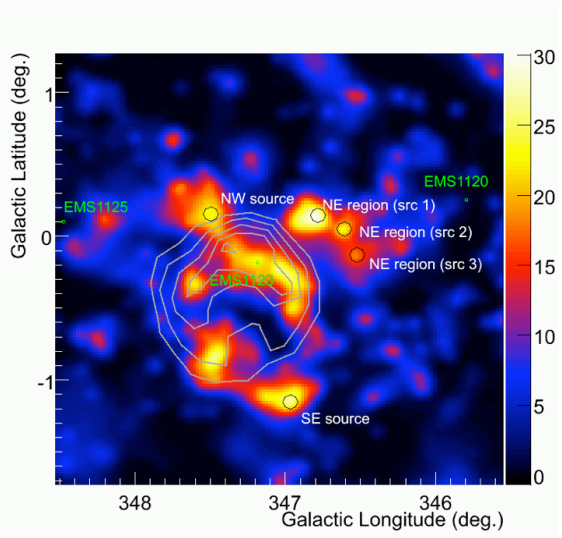
*powered by supernovae explosions and collapse to neutron stars***?**

Distant, highly luminous *active* gamma-ray galaxies (*trillions* x Solar luminosity) **:**

*powered by black holes**?***

Fermi mechanism predicts that highest energy particles made by sources with largest compactness = luminosity/size

Large compactness found in stellar core collapse to a neutron star forming supernovae and supernova remnants



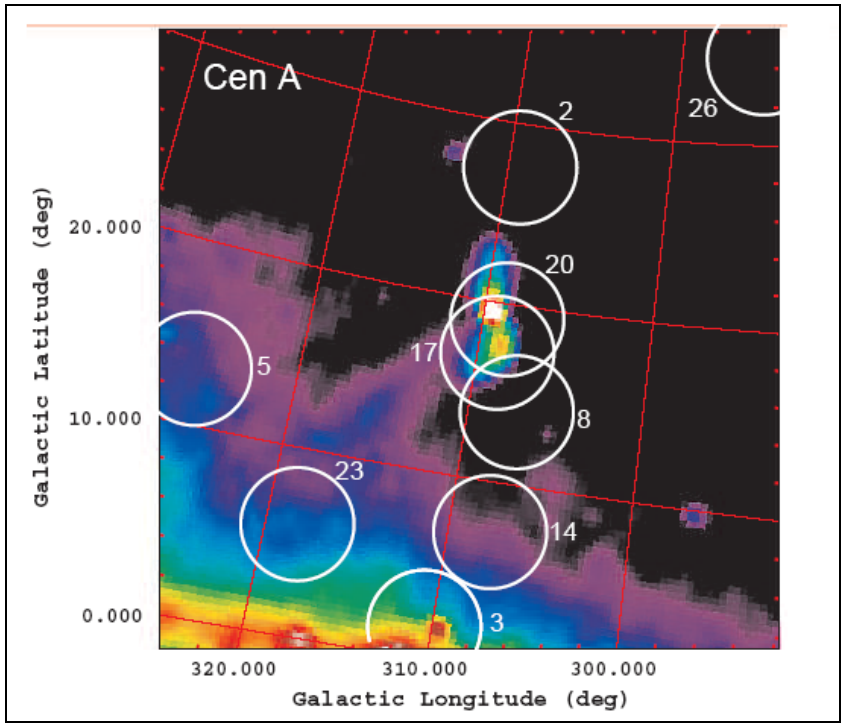
Fermi map of SNR RX J1713.7−3946

Sources of the highest energy radiations

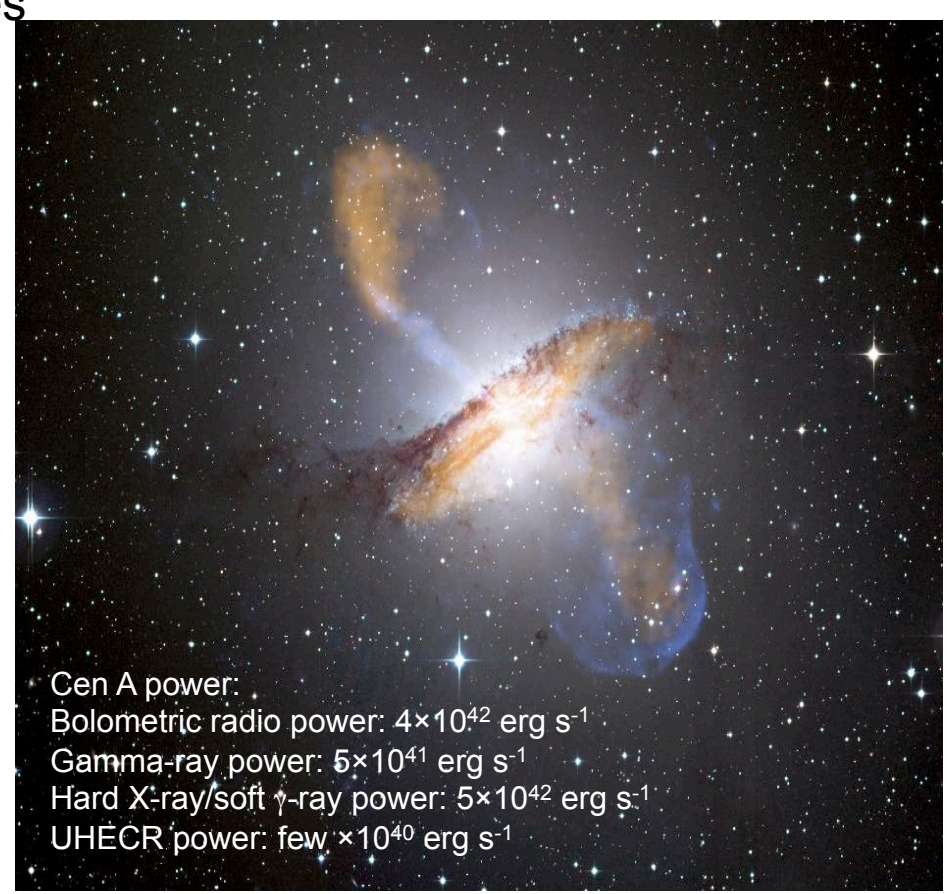
Huge compactness found near accreting black holes, especially if rotating

Very highest energy radiations, including *ultra-high energy cosmic rays*, made by black holes

1. stellar core collapse to a black hole (gamma ray burst)
2. rotating supermassive black holes
3. microquasars in galaxies



Moskalenko, et al. 2008



Ultra-high energy cosmic rays from Centaurus A?

Black Hole Electrodynamics and Energy Extraction

Govind Menon

Troy University

&

Charles Dermer

U.S. Naval Research Laboratory

E&B fields in Flat Space-time

The Maxwell Tensor in Special Relativity

$$F = \begin{bmatrix} 0 & -E_1 & -E_2 & -E_3 \\ E_1 & 0 & B_3 & -B_2 \\ E_2 & -B_3 & 0 & B_1 \\ E_3 & B_2 & -B_1 & 0 \end{bmatrix}$$

$$\vec{E} = \vec{D}$$

$$\vec{B} = \vec{H}$$

$$g = -dt^2 + dx^2 + dy^2 + dz^2$$

How do we define E&B fields?

- The Maxwell Tensor in General Relativity

$$F = \begin{bmatrix} 0 & D^1/\alpha & D^2/\alpha & D^3/\alpha \\ -D^1/\alpha & 0 & H_3/\sqrt{-g} & -H_2/\sqrt{-g} \\ -D^2/\alpha & -H_3/\sqrt{-g} & 0 & H_1/\sqrt{-g} \\ -D^3/\alpha & H_2/\sqrt{-g} & -H_1/\sqrt{-g} & 0 \end{bmatrix}$$

$$\left(\beta^2 - \alpha^2\right)dt^2 + 2\beta_\varphi \, d\varphi \, dt + \gamma_{ij} \, dx^i dx^j$$

$$\sqrt{-g} \equiv \sqrt{-\det\left(g_{ij}\right)} = \alpha\sqrt{\det\left(\gamma_{ij}\right)}$$

$$\left(\vec{D},\vec{H}\right)\rightarrow\left(\vec{E},\vec{B}\right)$$

even in "vacuum"

$$\vec{E}=\alpha\vec{D}+\vec{\beta}\times\vec{B}$$

$$\vec{H}=\alpha\vec{B}-\vec{\beta}\times\vec{D}$$

where

$$\beta=\left(0,0,\beta_{\varphi}\right)$$

(E,B) & (D,H) then satisfy

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \cdot \vec{D} = \rho$$

$$\partial_t \vec{B} + \nabla \times \vec{E} = 0$$

$$-\partial_t \vec{D} + \nabla \times \vec{H} = \vec{J}$$

$$\Omega_- = \frac{a}{2Mr_+ - \rho_+^2}$$

$$B^r = \frac{2}{a}\Lambda\frac{\cos\theta}{\sin^4\theta}\sqrt{\frac{\Delta}{\rho^2\Sigma}}$$

$$\Delta = r^2 - 2Mr + a^2$$

$$E_\theta = \frac{-2}{a^2}\Lambda\frac{\cos\theta}{\sin^5\theta}$$

$$\rho^2 = r^2 + a^2\cos^2\theta$$

$$B_\varphi = \frac{2}{a^2}\Lambda\frac{\cos\theta}{\sin^4\theta}\sqrt{\frac{\Sigma}{\rho^2\Delta}}$$

$$\Sigma = \left(r^2 + a^2\right)^2 - a^2\Delta\sin^2\theta$$

Lambda is any function of theta.

Energy and Angular Momentum Extraction

$$\frac{d\varepsilon}{dt} = -\int H_{\varphi}\Omega B^{r}\sqrt{\gamma_{rr}}\,dA = \frac{-8\pi}{a^{4}}\int_{0}^{\pi}\frac{\Lambda^{2}Cos^{2}\theta}{Sin^{9}\theta}\,d\theta \le 0$$

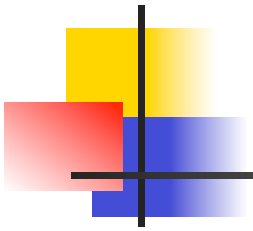
$$\frac{dl}{dt} = -\int H_{\varphi}B^{r}\sqrt{\gamma_{rr}}\,dA = \frac{-8\pi}{a^{3}}\int_{0}^{\pi}\frac{\Lambda^{2}Cos^{2}\theta}{Sin^{7}\theta}\,d\theta \le 0$$

The current vector

$$J^{\nu} = -\frac{2}{a^2}\frac{1}{\sqrt{\gamma}}\partial_{\theta}\left[\frac{\Lambda\cos\theta}{\sin^4\theta}\right] n^{\nu}$$

$$n = \frac{1}{\Delta}\left(r^2 + a^2,\ -\Delta,\ 0,\ a\right)$$

Note: n is the inward pointing principal null vector field in the Kerr Geometry.



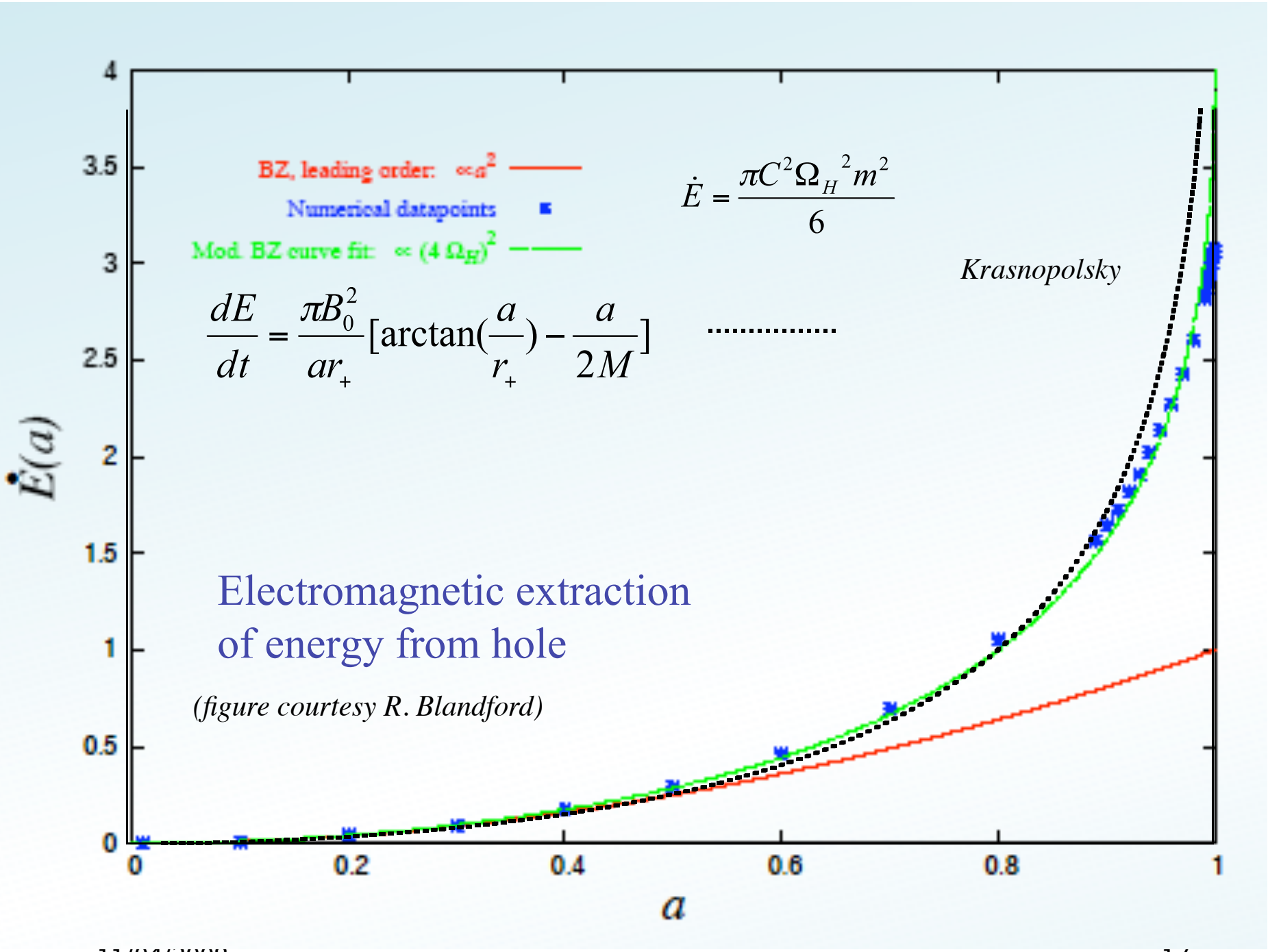
Ω_+ Solution

$$\Omega_+ = \frac{a}{2Mr_+ + \rho_+^2}$$

$$B^r = \frac{1}{\sqrt{\gamma}} \frac{Q_0 \sin\theta}{2\rho_+} \frac{\sqrt{a\Omega_H}}{\Omega_+}$$

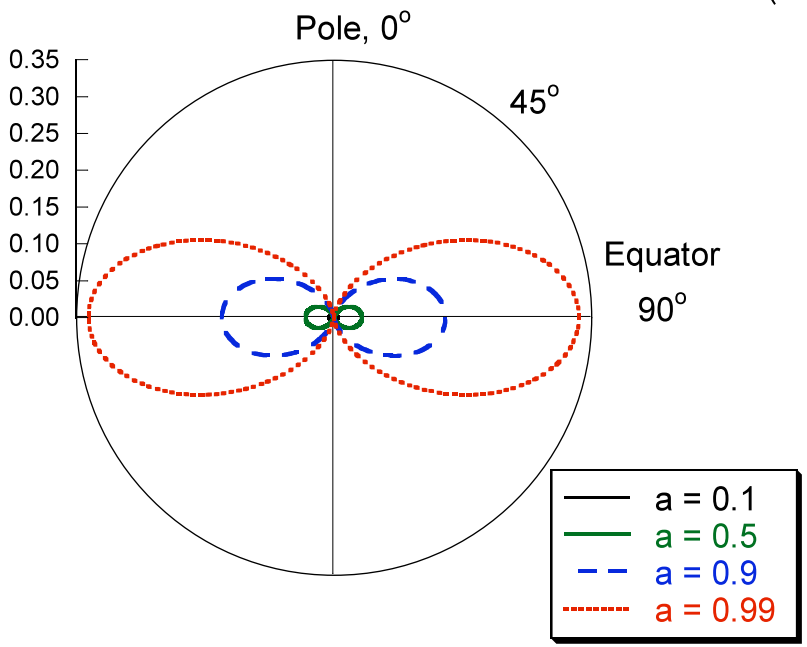
$$E_\theta = -\sqrt{\gamma}\Omega_+ B^r$$

$$H_\varphi = -\sqrt{\gamma}\Omega_+ B^r \sin\theta$$


BZ, leading order: $\propto a^2$
Numerical datapoints
Mod. BZ curve fit: $\propto (4\,\Omega_H)^2$
$\dot{E} = \frac{\pi C^2 \Omega_H{}^2 m^2}{6}$
Krasnopolsky
$\frac{dE}{dt} = \frac{\pi B_0^2}{a r_+}[\arctan(\frac{a}{r_+}) - \frac{a}{2M}]$ .....
Electromagnetic extraction of energy from hole
(figure courtesy R. Blandford)
$\dot{E}(a)$
a
0
0.5
1
1.5
2
2.5
3
3.5
4
0
0.2
0.4
0.6
0.8
1

Angular Dependence of Energy Extraction

Energy Flux $$\frac{d^2E}{dAdt} \approx \frac{a\Omega_H}{r^2}\left(\frac{B_0 \sin\theta}{2\rho_+}\right)^2$$



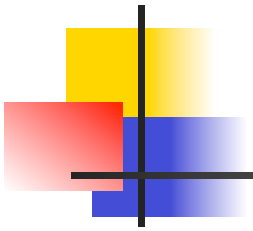
i.e., most of the energy extraction takes place along the equatorial plane

BZ extraction of Power

$$P_{\Omega_+} = \frac{\pi Q_0^2}{a r_+}\left[\arctan\frac{a}{r_+} - \frac{a}{2M}\right]$$

$$P_{\Omega_+} \approx 2\times 10^{47}\, l_{EDD}\, M_9 \ \mathrm{ergs\ s^{-1}}$$

$$M = 10^i\, M_\odot\, M_i$$



- The results presented here are used to argue that rotating black holes are the sources of the highest energy radiations

- For details, see

High Energy Radiation from Black Holes

(Princeton Univ. Press 2009)

Charles Dermer and Govind Menon

and our poster

Resurrection of the Ω_+ solution

- Thus far we only looked at energy extraction resulting from Electromagnetic Poynting Flux.

- The particle jet vanishes along the equatorial plane. It may well peak close to the polar axis of the Kerr Geometry

Resurrection of the Ω_- solution

- It is possible construct an exact solution where the current flows through the out flowing null geodesic of the Kerr geometry.

- The out flowing null geodesic can be decomposed to two timelike curves (corresponding to matter sources).