UCI University of California, Irvine

Plasma Astrophysics Term Project: **Explanations and Predictions of UHECRs and UHE Gamma Rays in Intergalactic and Extragalactic objects**

Greg Huxtable, Noor Eltawil, Wei-Xiang Feng, Gabe Player, Wenhao Wang, Toshikazu Ebisuzaki, Toshi Tajima

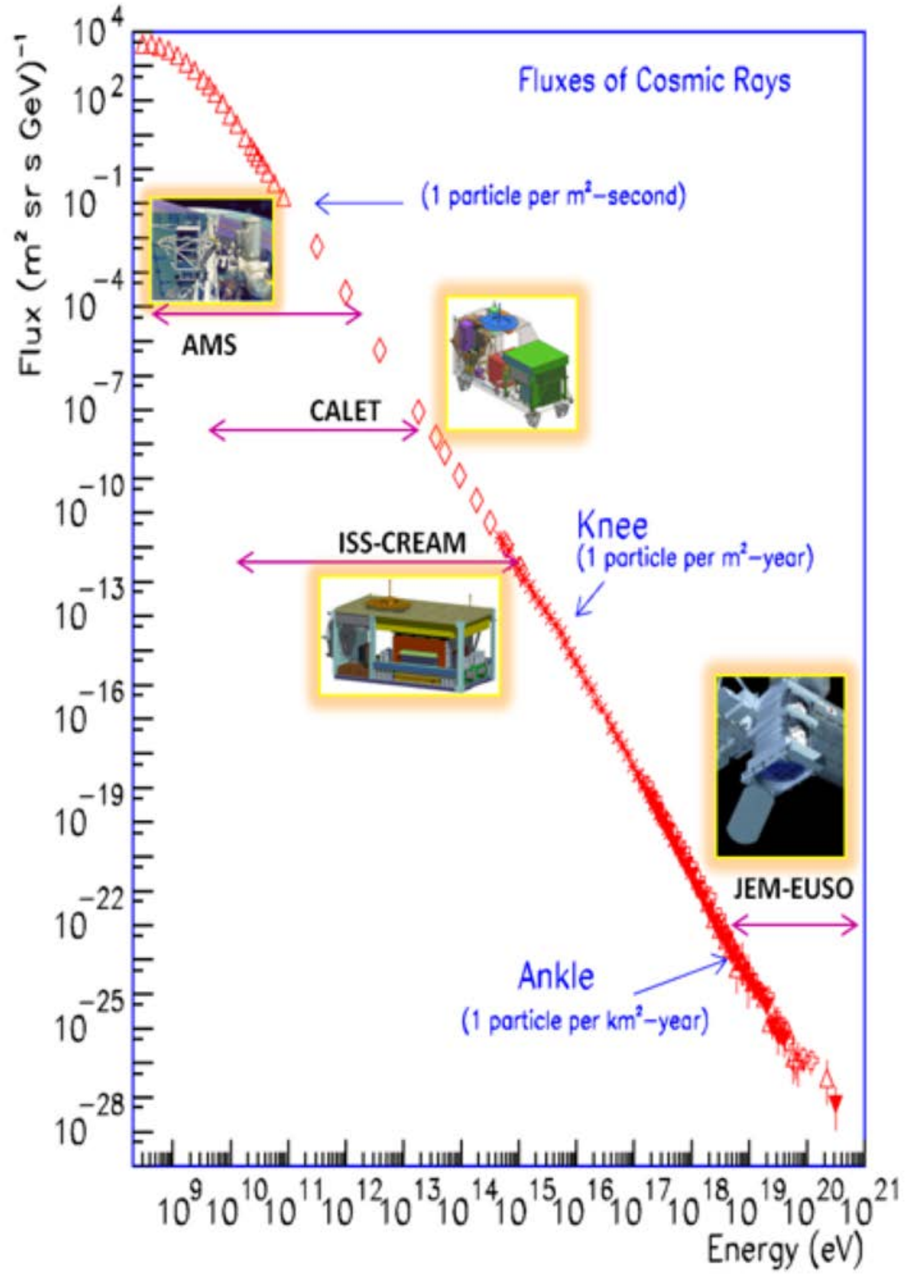
- Team effort between members from UCI and UCR, and Prof. Ebisuzaki (RIKEN, Japan)
- With Toshi's and Ebisuzaki's guidance were able to put together a nice paper (soon to be submitted to ApJ 🤞)

Term Project

- Surveyed 5 different astronomical objects
  - Each has been observed to emit UHECRs, or is a good candidate (T. Ebisuzaki, T. Tajima 2014)
  - Each has a different central object mass
- Gathered existing data on each object
  - Showed WFA theoretical values are in agreement
  - Predicted sources of UHECRs, UHE gamma rays, neutrinos

UHECRs

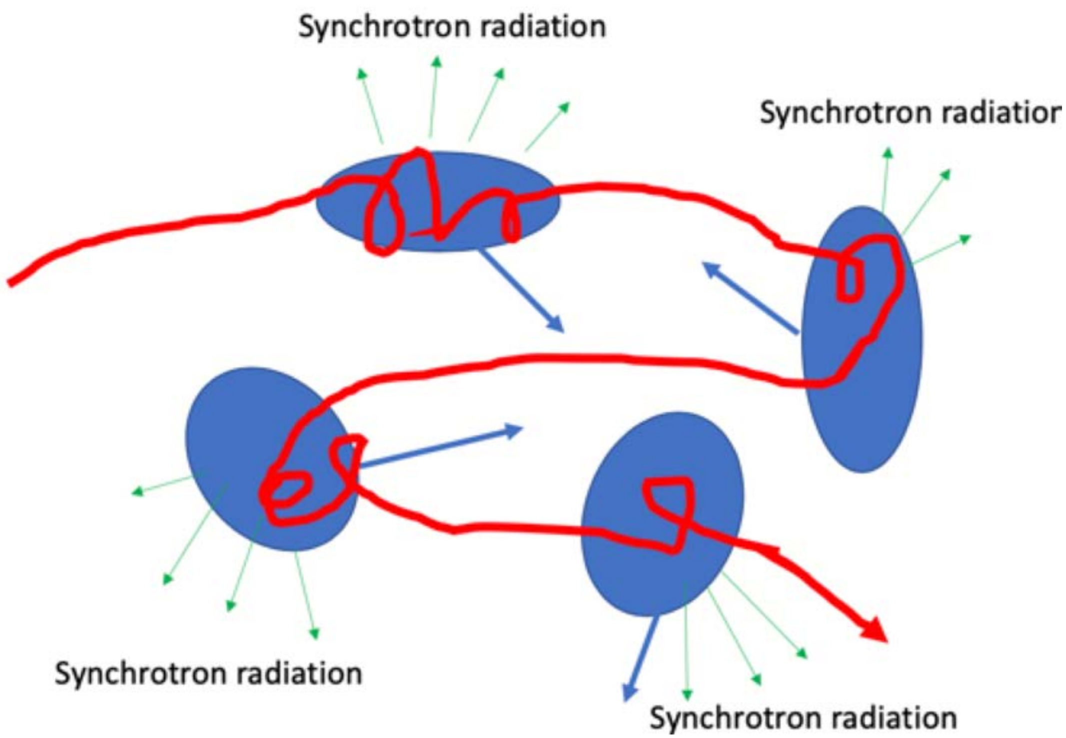
- Ultra high energy cosmic rays (UHECRs) $> 10^{19}$ GeV insufficiently understood by Physics & Astronomy community
- Similarly, UHE gamma rays $\gg$ 10 GeV are somewhat of a mystery
- WFA can easily generate these signals
  - Fermi acceleration cannot



Fermi Acceleration

Explains the creation of low E gamma rays, x-rays, microwaves, etc, but fails to explain dynamics in the UHE regime

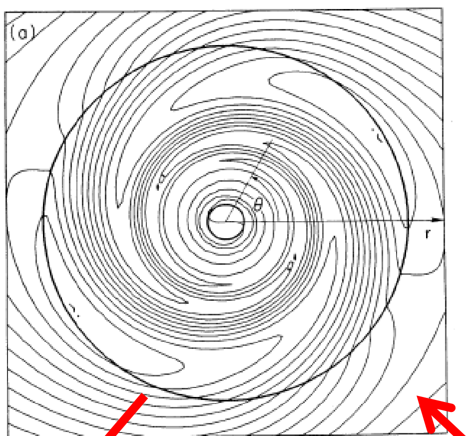
- Stochastic
- Incoherent
- No time or spatial structure; steady state
- Suffers from large synchrotron loss ($< 10^{19}$ eV)
  - Very difficult for e^- to reach > 10 GeV



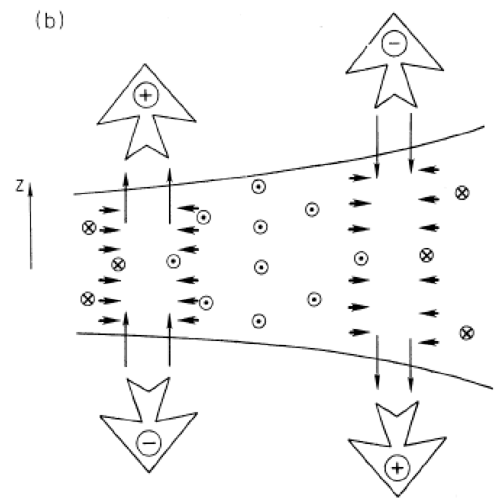
Power radiated from bending relativistic charge (J. D. Jackson, 1975)

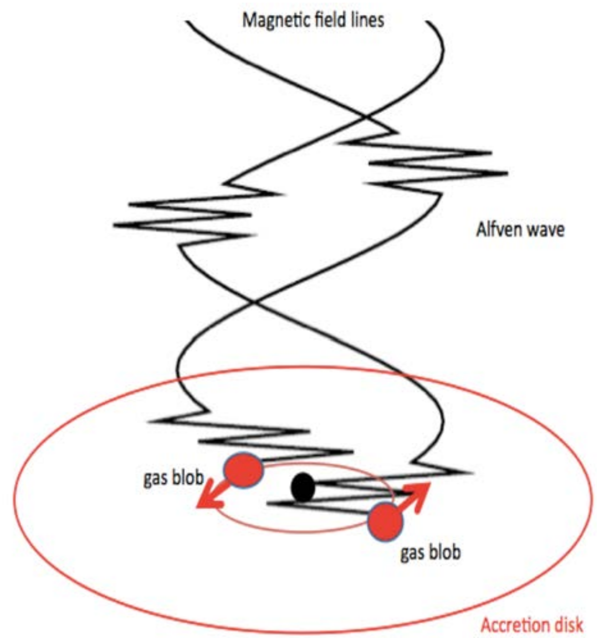
$$P(t') = \frac{2}{3}\frac{e^2|\dot{\boldsymbol{v}}|^2}{c^3}\gamma^4$$

Magneto-Rotational Instability (MRI)

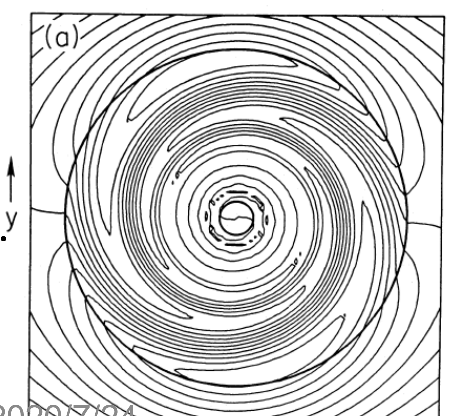


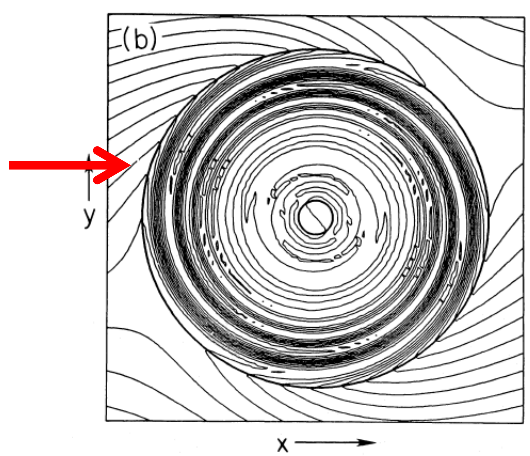
low





growing



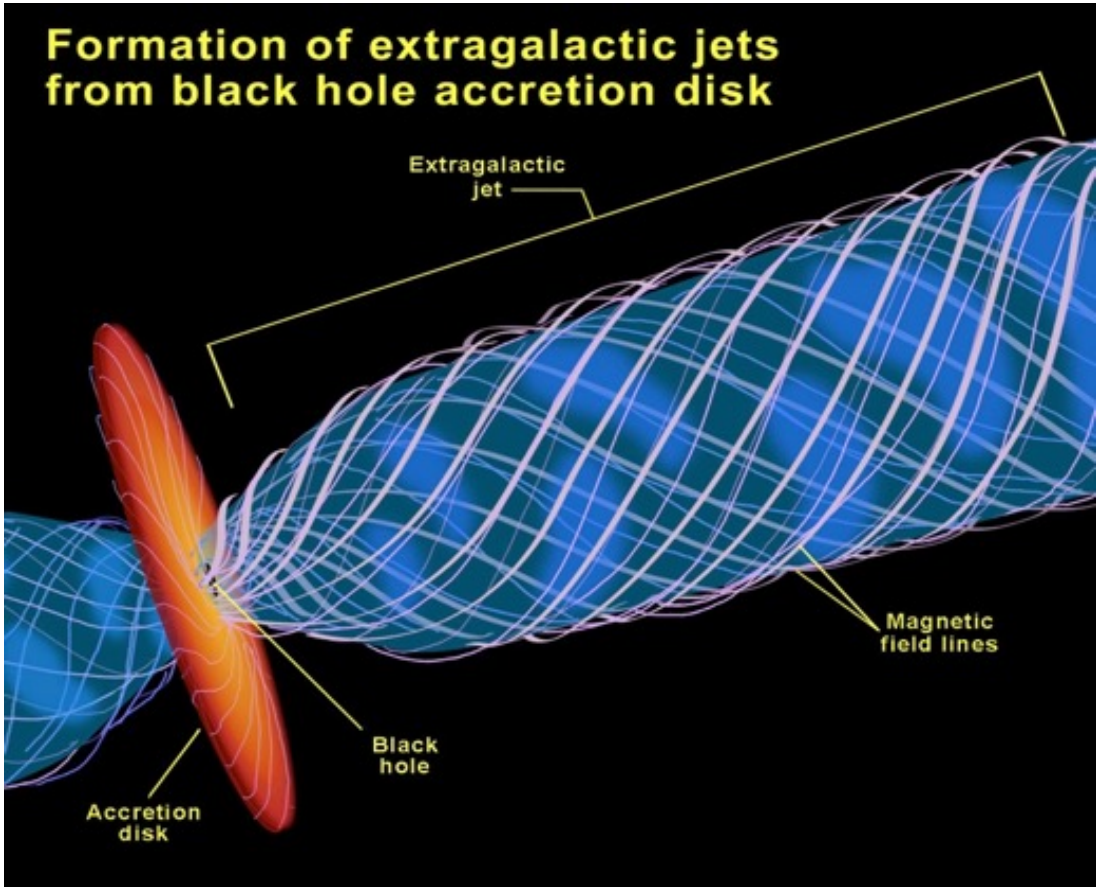


high

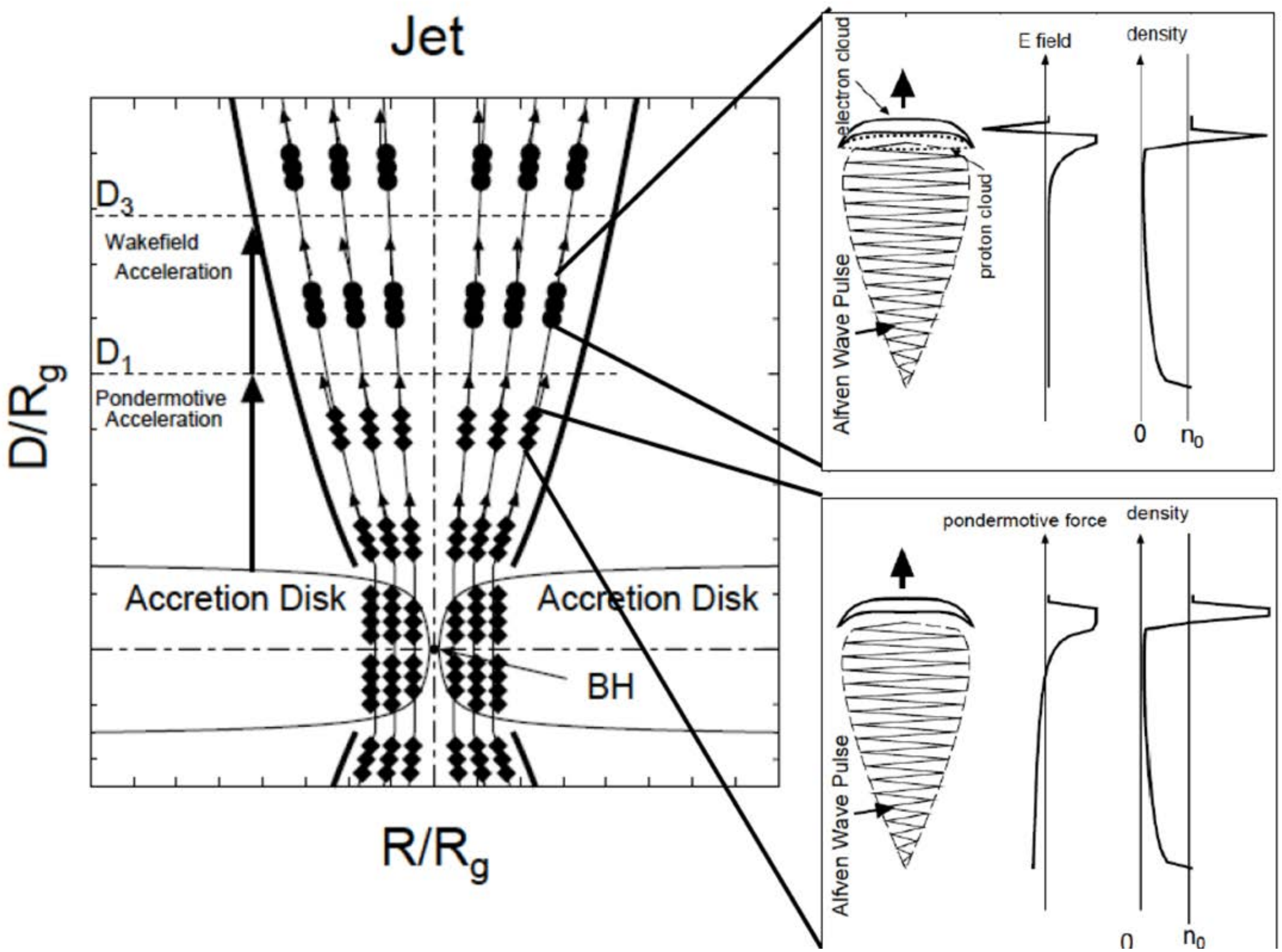
Differential rotation twists magnetic field, increasing resistivity, allowing gravity to overcome centrifugal force, "eruption".
Explains change in index

WFA in the Universe

- MRI gives rise to massive accretion and Alfvén shock
- Alfvén shock eventually mode converts to an EM wave and drives WFA



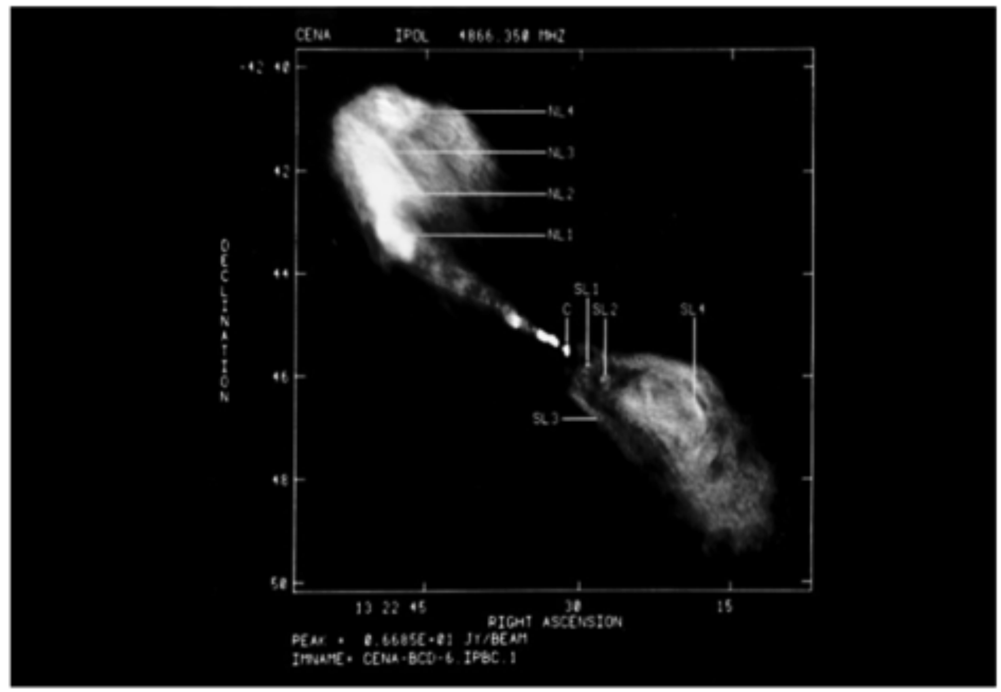
- $a_0 \approx 10^{6-10}$ (extremely high compared to laboratory plasmas)
- $n_e \approx 10^4$ (near BH); $10^1\ \text{cm}^{-3}$ (along jet, away from BH)
- $D_3 \approx 10^{11-19}\ cm$ (acceleration length)



Particles reach velocities $\sim c$

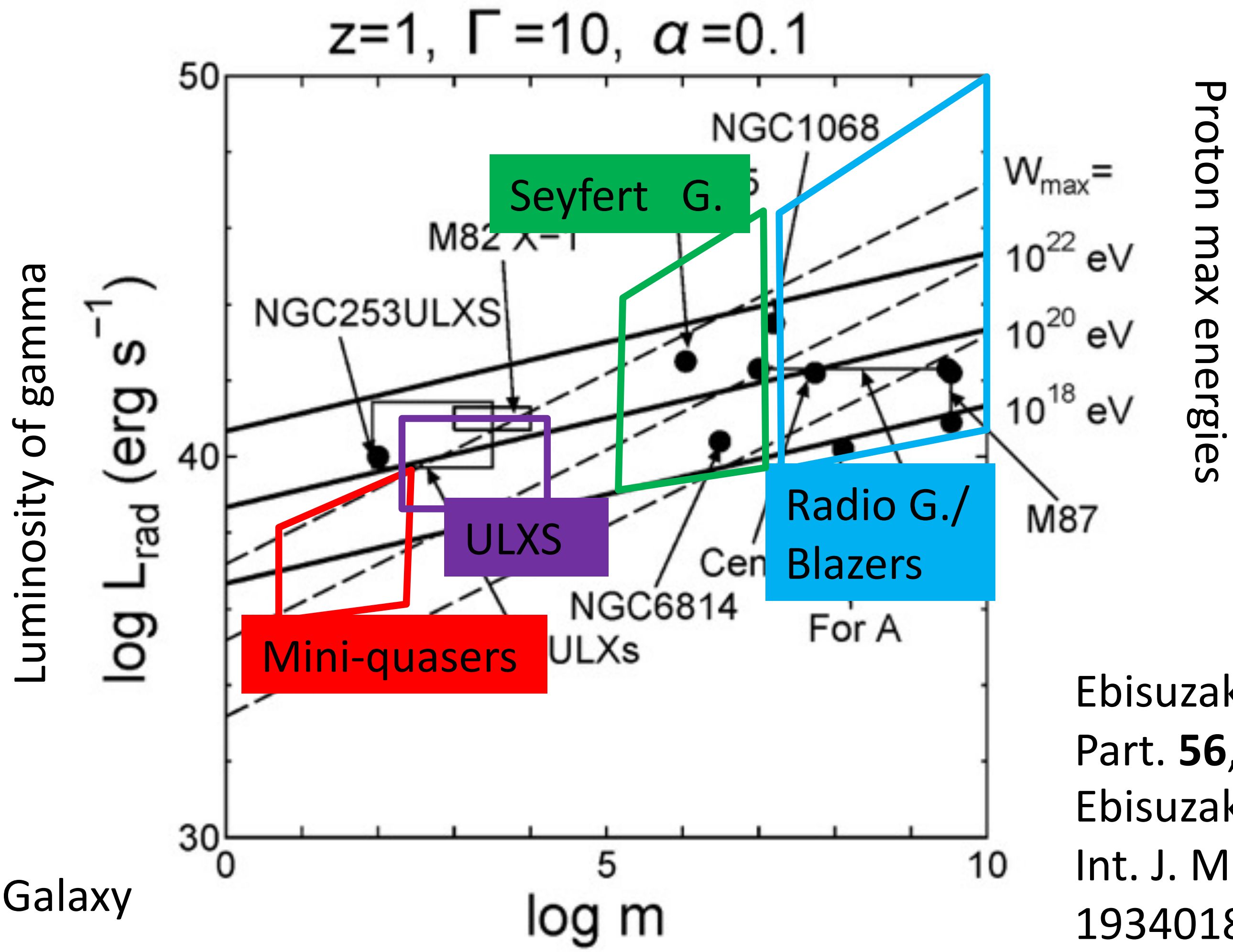
UHE Gamma Ray Production; UHECR Path

- Upon reaching the end of the jet, UHE electrons collide with decelerated matter in the “lobes” to produce UHE gamma rays
- Neutrino’s created by collisions of UHE protons/nuclei in the lobes, follow a path parallel to the jet axis since that is the direction of momentum for the collision
  - Leading to gamma ray burst and neutrino burst temporal correlations
- UHECRs may be bent by magnetic fields, however, the most energetic ones are bent less



$$W_{max} = \frac{1}{9}\left(\frac{e^4 c^2 R_0^2}{2m_e c^4 \kappa_T^2}\right)^{1/3} z\Gamma\alpha^{2/3}\dot{m}^{4/3}m^{2/3}$$

Max Proton (UHECR) Energy Given Mass and Luminosity

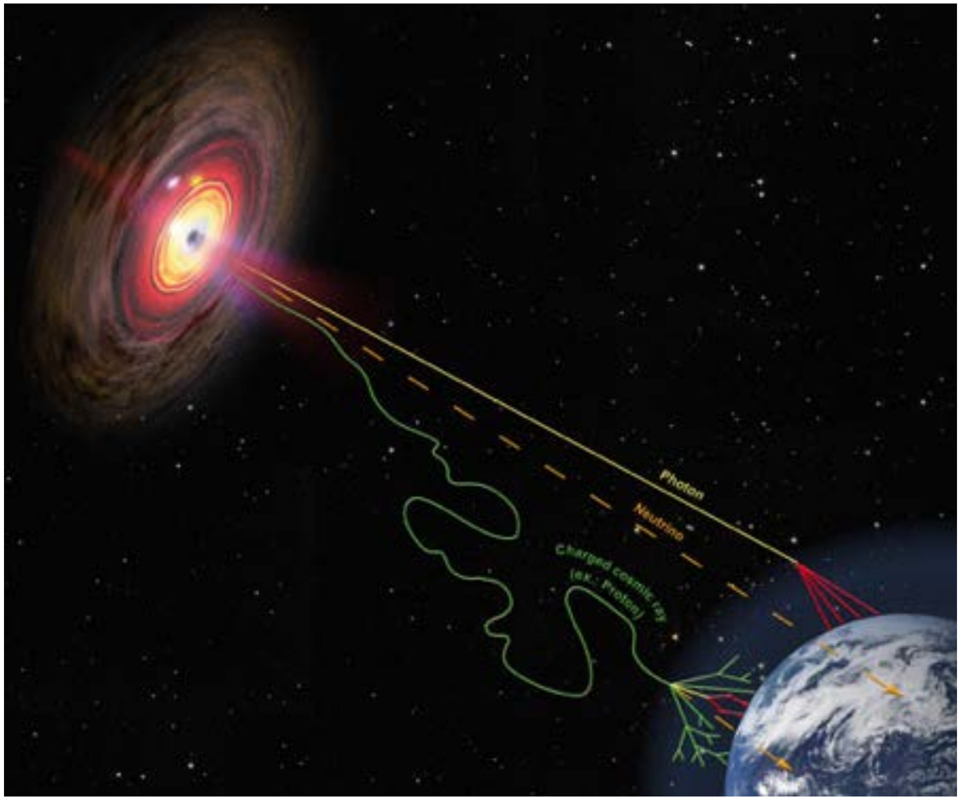


Microquasars:
can be in our Galaxy

Ebisuzaki, Tajima Astro. Part. **56**, 9 (2014) ; Ebisuzaki and Tajima, Int. J. Mod. Phys. A**34,** 1934018 (2019).

Blazars; TXS 0506+056

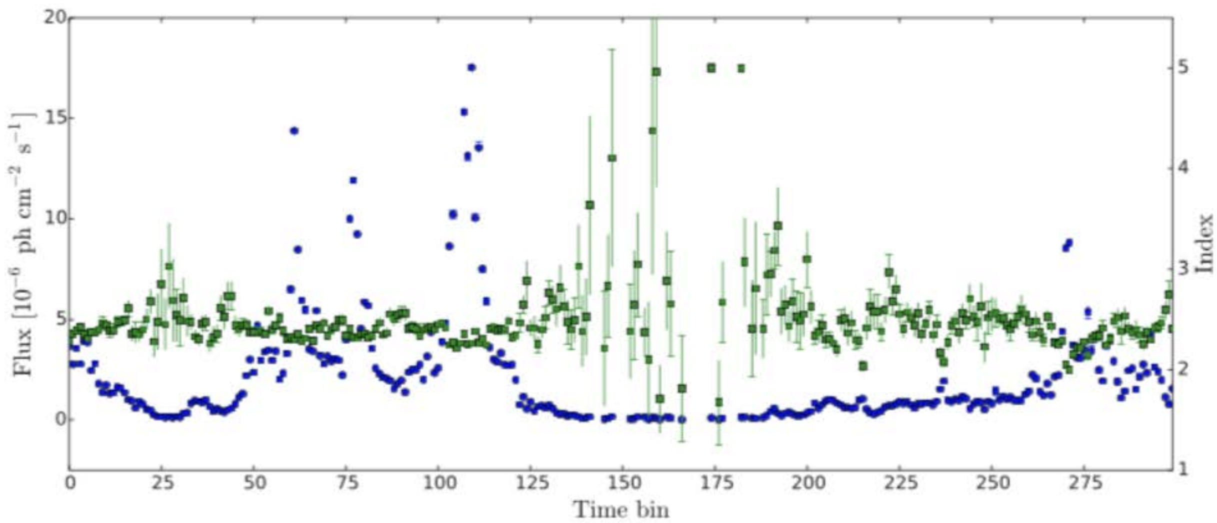
$$M \approx 10^8\ M_\odot$$



Anti-correlation b/w Flux & Index

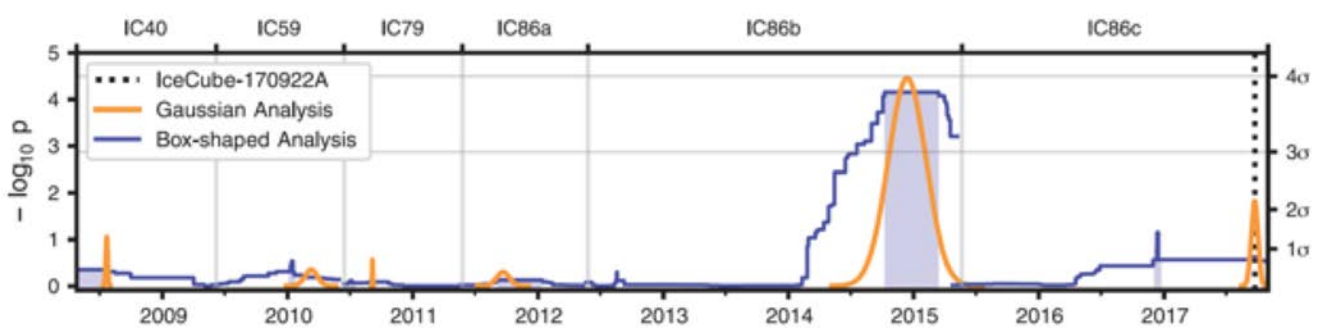
- Anti-correlation b/w flux and index
  - After sudden accretions (increase in flux), the accretion disk "relaxes" back to the low beta state (low index ~2)
  - Then the magnetic field begins to amplify again, high beta state (index >2), and the flux drops off until MRI takes over again
- WFA explains corresponding increases in luminosity and decreases in spectral index.
- How do we explain corresponding values of small flux and small index?

IceCube Collaboration. Science 361.6398 (2018)



Simultaneous Signals

- Time structure: simultaneous arrival of neutrino with other signal
  - Chance coincidence of the neutrino with the flare of TXS 0506+056 is disfavored at the 3σ level in any scenario where neutrino production is linearly correlated with g-ray production or with g-ray flux variations.
- Coincidence of neutrino location with blazar
- Periodic observation of neutrino burst (fig. ref. [2])
- Good candidate for UHECRs

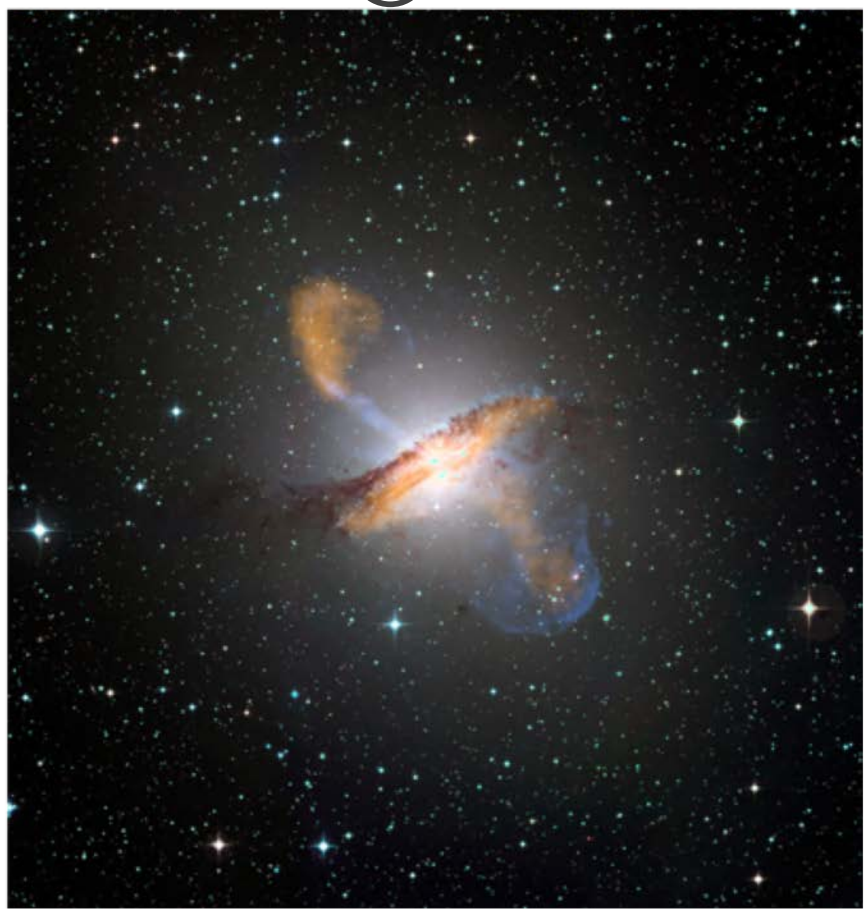


[1]. Telescope, Liverpool, IceCube Collaboration. Science 361.6398, 2018
[2]. IceCube Collaboration. Science 361.6398 (2018)

object	Mass $[M_\odot]$	Accretion rate $[\dot{M}_{Edd}]$	L_γ $[erg\ s^{-1}]$	$L_\gamma^{(10^\circ)}$ $[erg\ s^{-1}]$	$L_\gamma^{(data)}$ $[erg\ s^{-1}]$	L_{tot} $[erg\ s^{-1}]$	T_A	W_{max} $[eV]$
TXS	5e8	0.1	8.0e41	2.1e44	2.8e46	6.5e44	57.9 day	8.48e22
[redacted]								

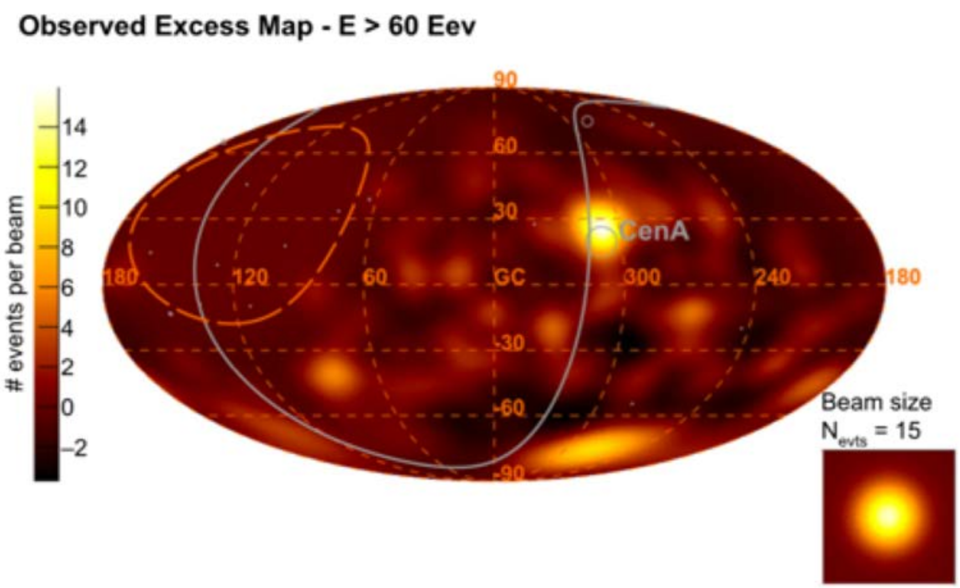
Centaurus A; Radio galaxy

$M \approx 10^7 M_\odot$

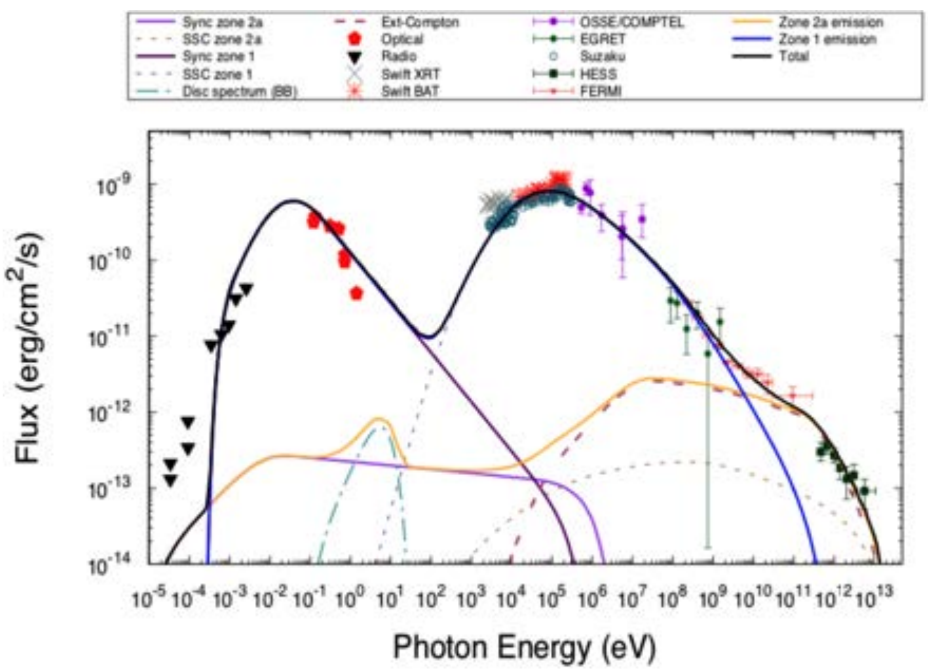


Observed UHECRs, UHE gamma rays

- Gamma ray emission > 100 GeV
  - Spectral index: 2.7 ± 0.7 (Astrophysical Journal 695:L40-L44, 2009 April 10))
- > 55 EeV UHECRs



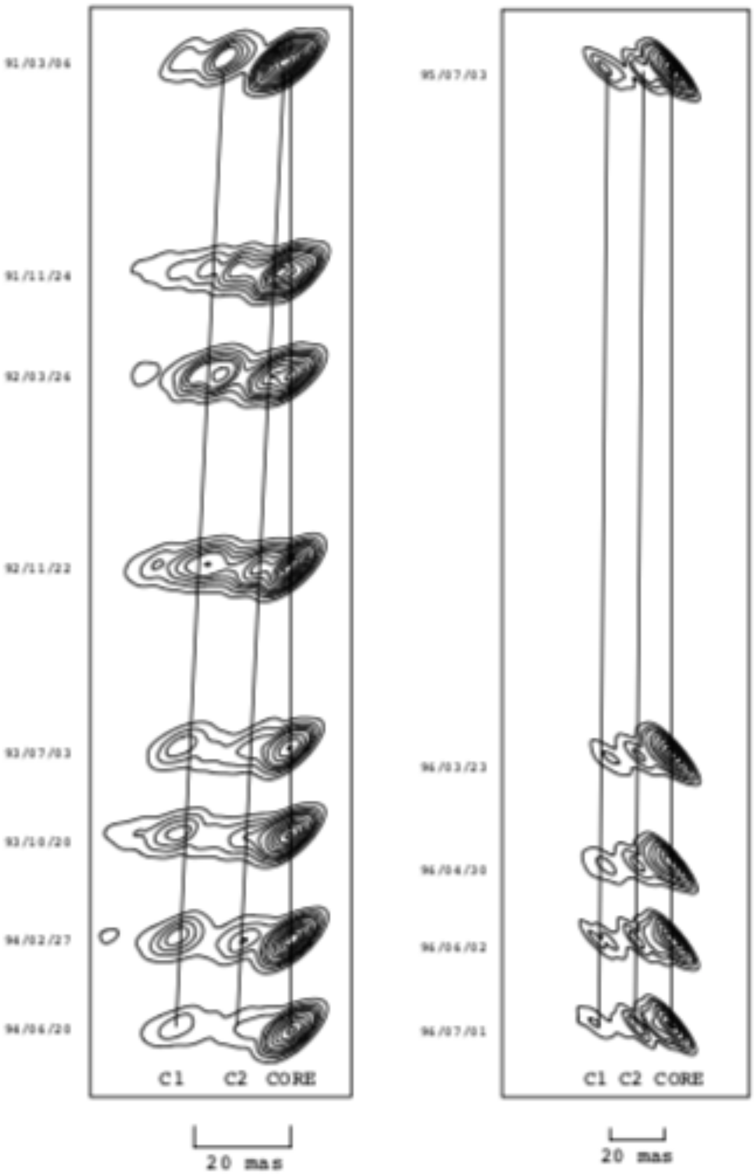
(Astrophysical Journal Letters, 853:L29 (10pp), 2018)



MNRAS 478, L1-L6 (2018)

Observed	Mass	L_rad	UHECRs Energy Level (Max Proton Energy Level)	X-Ray Luminosity	X-Ray Energy Level	Gamma Ray Energy Level	Gamma Ray Luminosity
	5.5×10^{7} M_⊙	1.6×10^{41} erg/s	$10^{19\text{-}20}$ eV (PAO)	10^{38} erg/s; 10^{39} erg/s (inner jet);	0.4-4.5 keV (inner jet structure: knots)	10^{12}- 10^{13} eV	10^{40} erg/s
Derived		8.1 x 10^{45} erg/s Discrepancy likely due to 50 degree offset from line of sight	$10^{19\text{-}20}$ eV	2.4 Ms/yr	4.5 x 10^{4} $(3R_g/D)$ cm^{-3}	1.65 x 10^{13} cm	1.58 x 10^{19} $(\dot{m}/0.1)^{5/3}$ cm
				Critical Accretion rate	Jet Density	Gravitational Radius of BH (R_g)	Acceleration Length (D_3)

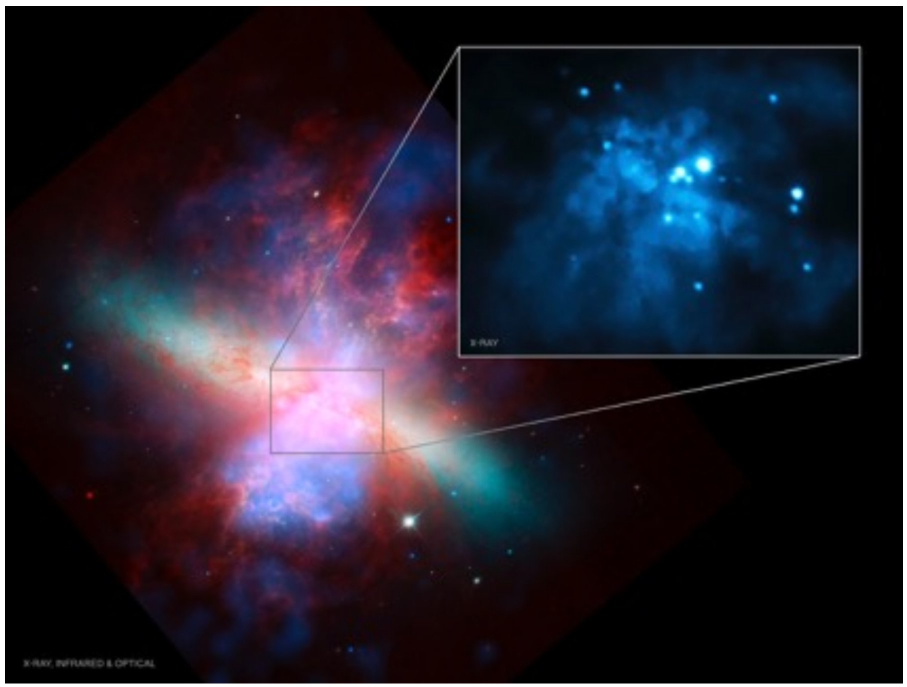
Time Evolution of Jets



- Inexplainable by steady-state Fermi acceleration
- Jets extending >100 kpc
  - Knots emanating from supermassive BH with velocity near “c”

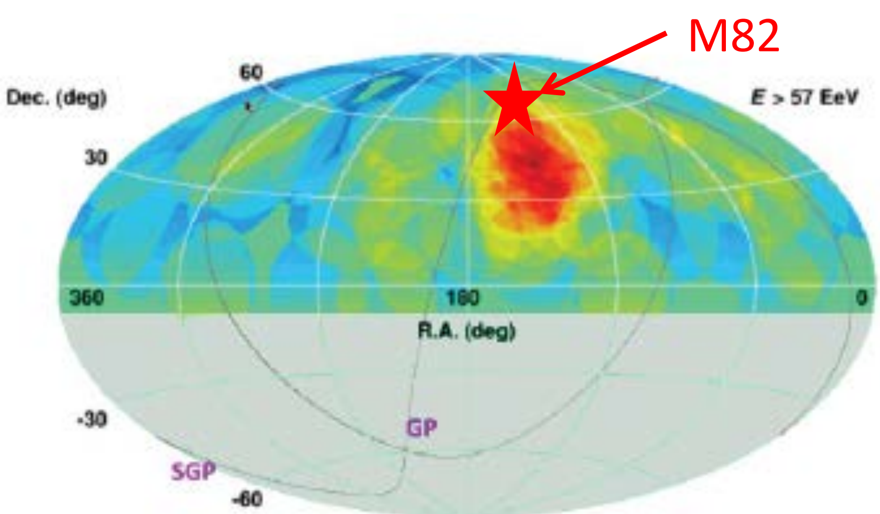
M82; Seyfert Galaxy

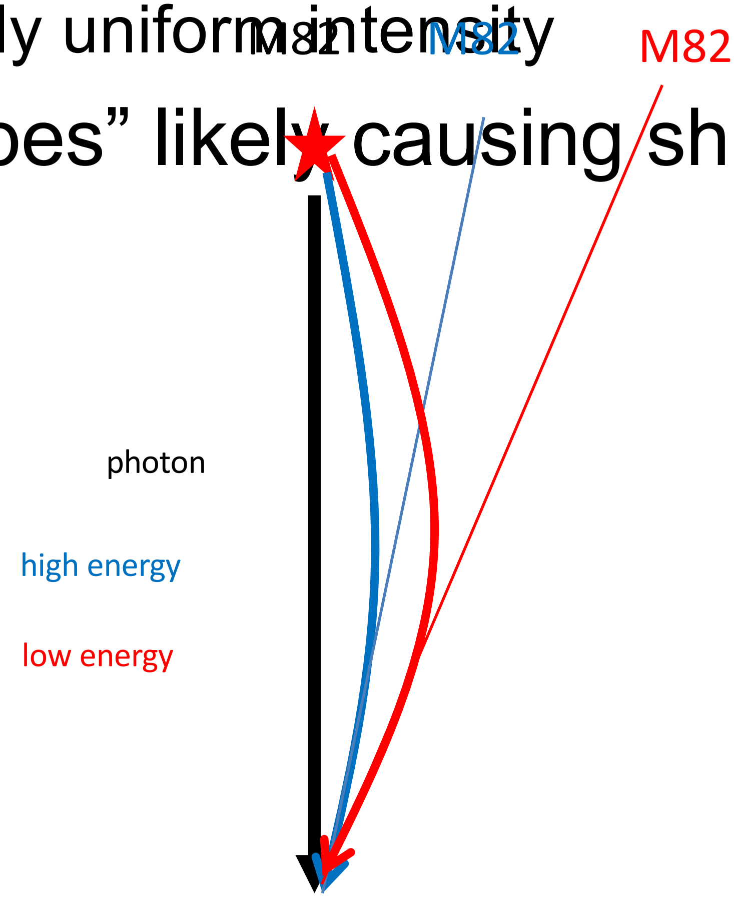
$$\text{M} \approx 10^{3-4}\ M_{\odot}$$



Most Likely Source for UHECR "Hot Spot"

- Anisotropy in the skymap
  - Fermi would predict nearly uniform intensity
- Bending of B field at "lobes" likely causing shift in bright spot

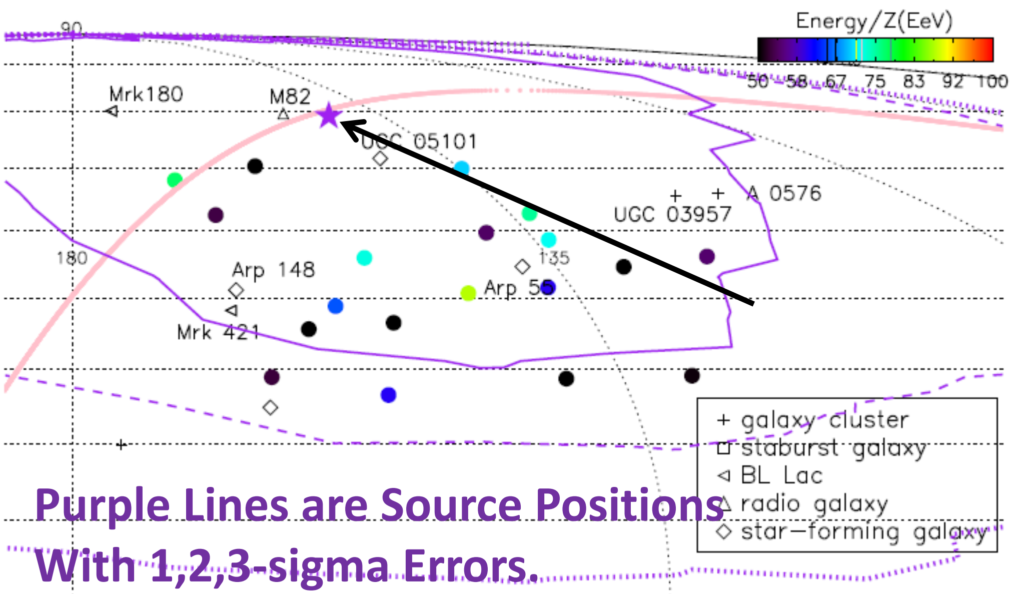




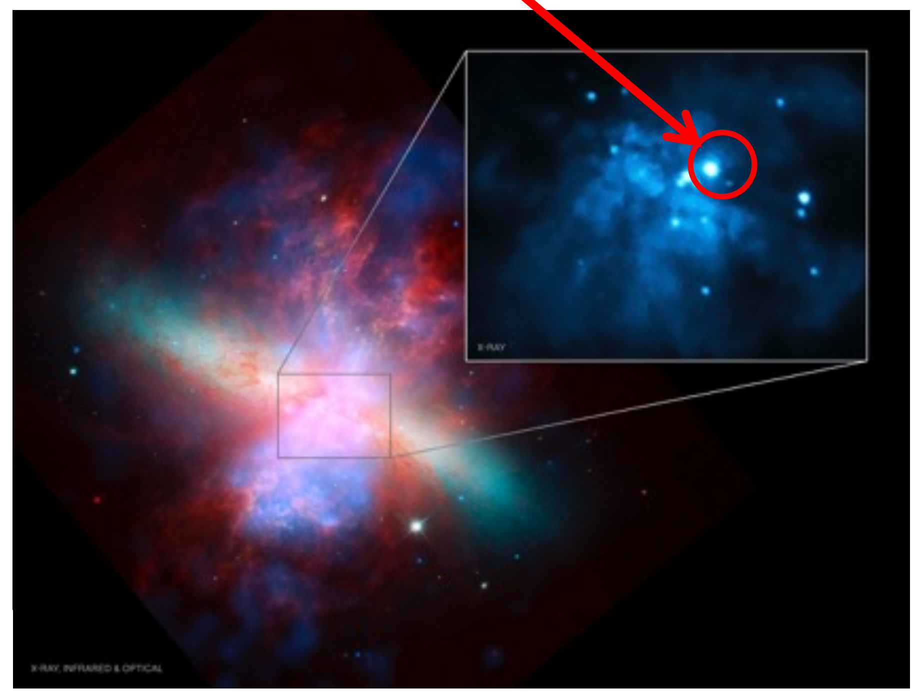
Magnetic bending of charged particles

M82 X-1: 1000-10000 Ms BH

- We suspect M82 emits, and is an ideal source for UHECRs ~ 10^{23} eV due to close proximity to Earth



Purple Lines are Source Positions With 1,2,3-sigma Errors.



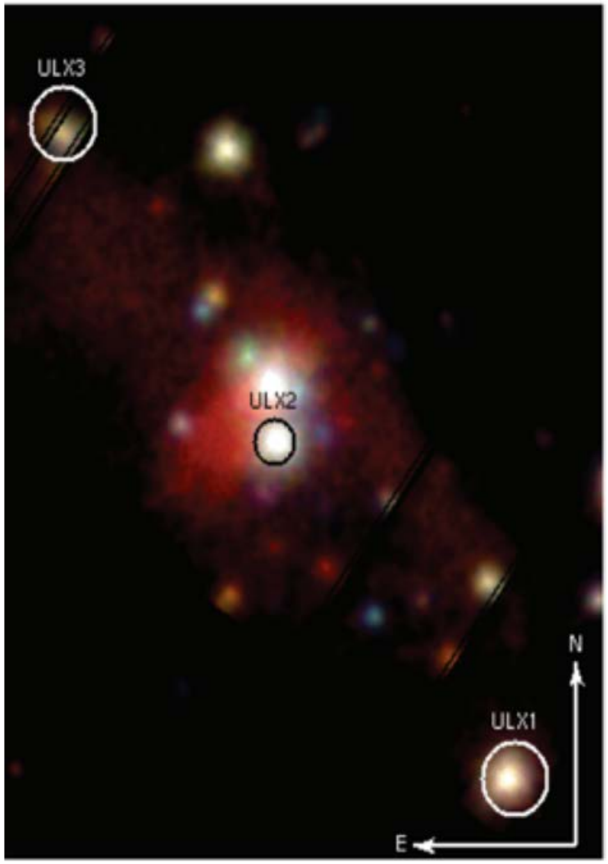
Composite of X-ray, IR, and optical emissions

NASA / CXC / JHU / D. Strickland; optical: NASA / ESA / STScI / AURA/ Hubble Heritage Team; IR: NASA / JPL-Caltech /Univ. of AZ / C. Engelbracht; inset – NASA / CXC / Tsinghua University / H. Feng et al.

The **most likely Source Position** As a Result of Our Analysis.

NGC 0253; Starburst Galaxy

$M \approx 10^{2-3}\ M_{\odot}$



NGC 253 Near "Hot Spot"

UHECRs energy ~ 39 EeV

[Aab et al., ApJL, 853:L29 (2018); Armando et al., EPJConf. 210, 01007 (2019)]

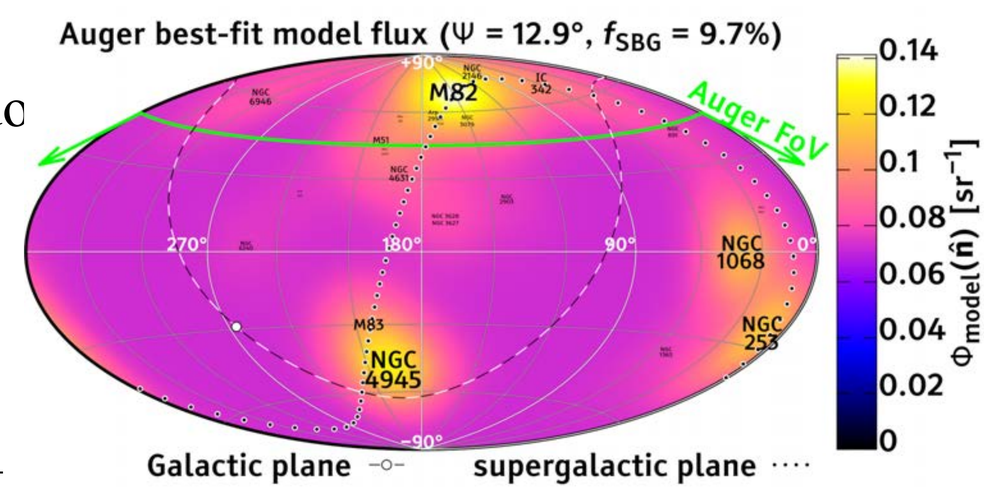
Deviation from isotropy: Auger warm spot near NGC253 is not statistically significant compared to TA hot spot

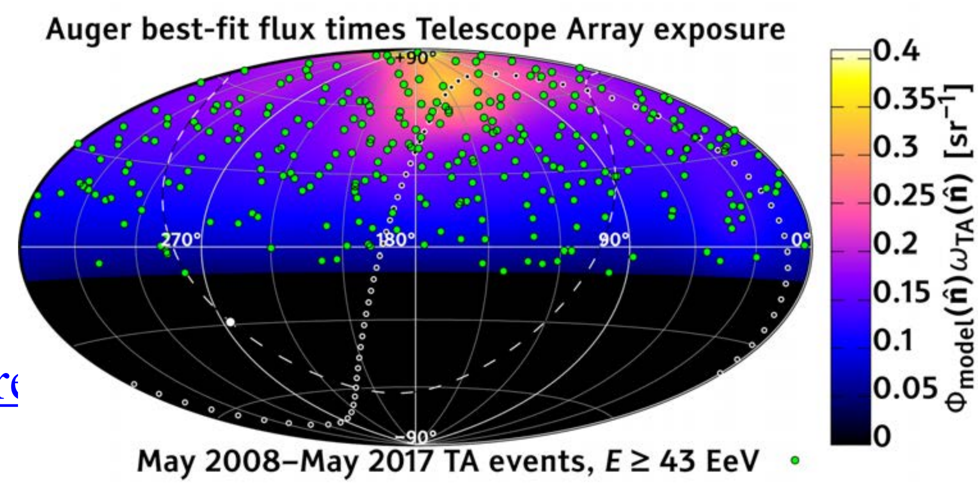
[Attallah & Bouchachi, MNRAS 478, 800–806 (2018)]

The time correlation of UHECRs with ultra-high energy γ-ray will support Wakefield theory's explanation

Researchers suggested a SMBM~(5*10^6)M⊙

(https://www.jpl.nasa.gov/news/news.php?release=2013-198)





SS 433; Microquasar
M ≈ 30-24 $M_\odot$

SS 433 Emits UHE Gamma Rays and likely UHECRs

- Inside our Milky Way galaxy
- Binary star, with precessing jet
- Observed to emit UHE gamma rays
- May be a good candidate for UHECRs, albeit low in flux

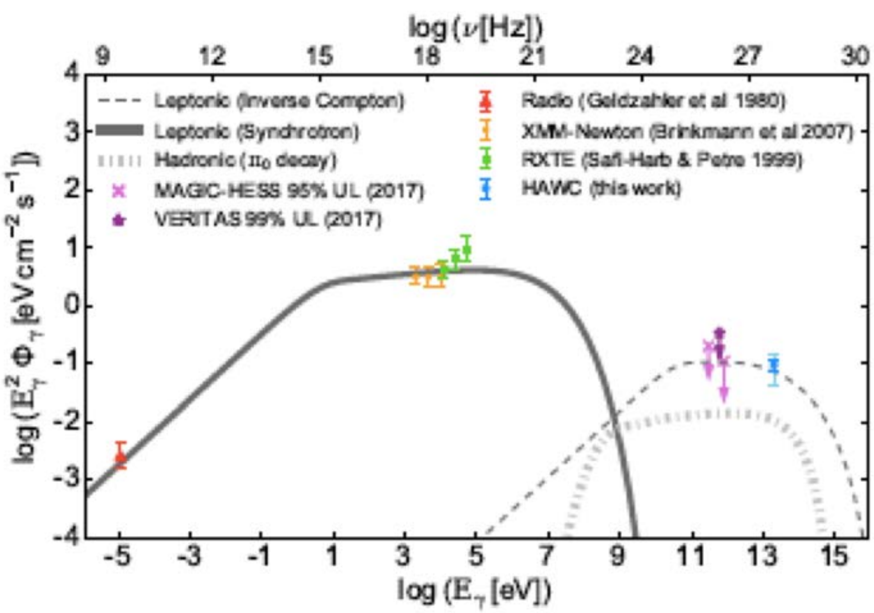
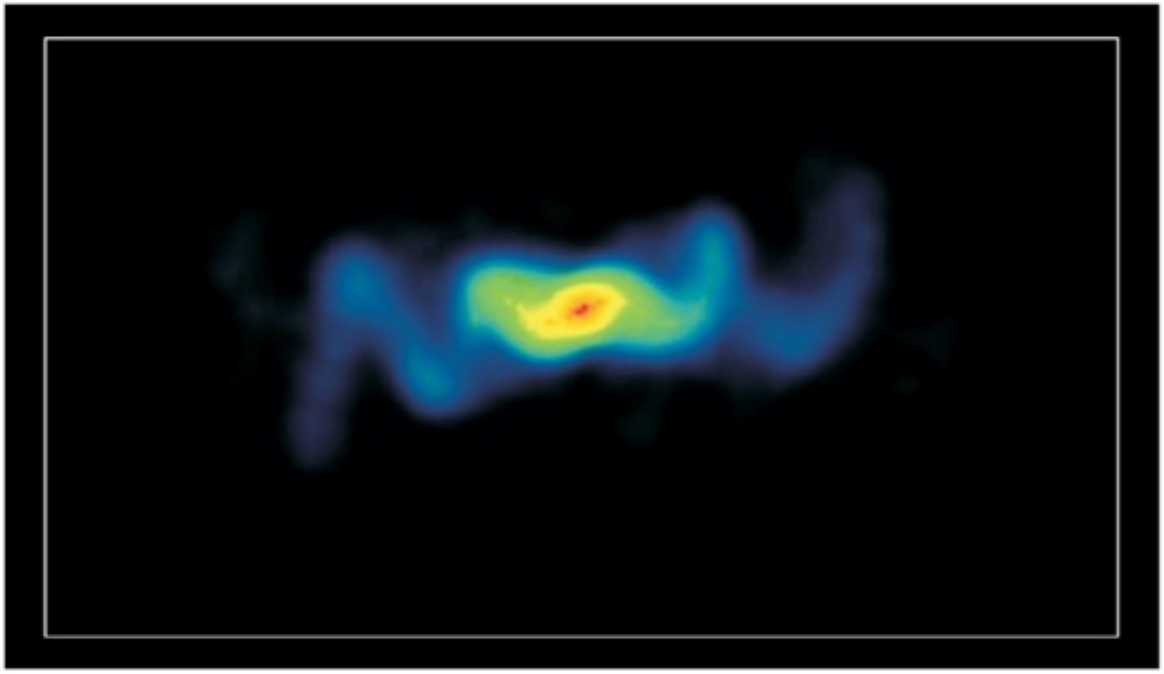


Figure 2: **Broadband spectral energy distribution of the eastern emission region.** The data include radio, soft X-ray, hard X-ray, and VHE γ-ray upper limits, and HAWC observations of e1. Error bars indicate 1σ uncertainties, with the thick (thin) errors on the HAWC flux indicating statistical (systematic) uncertainties and arrows indicating flux upper limits. The multiwavelength spectrum produced by electrons assumes a single electron



object	Mass $[M_\odot]$	Accretion rate $[\dot{M}_{Edd}]$	L_γ $[erg\ s^{-1}]$	$L_\gamma^{(10^\circ)}$ $[erg\ s^{-1}]$	$L_\gamma^{(data)}$ $[erg\ s^{-1}]$	L_{tot} $[erg\ s^{-1}]$	T_A	W_{max} $[eV]$
[redacted]								
SS 433	12	2.25e2	4.32e37	7.62e37	1e40	3.51e41	0.12 sec	2.08e22

Summary

- Fermi acceleration is very unlikely the cause of these UHE signals
  - Suffers from synchrotron loss; cannot generate UHECRs $> 10^{19}$ eV, UHE gamma rays > 10 GeV
  - Cannot explain simultaneity of bursts, and their time sequences
  - Cannot explain anisotropy
  - Cannot explain evolution of jets
- WFA together with MRI explains all of this