Plasma Astrophysics

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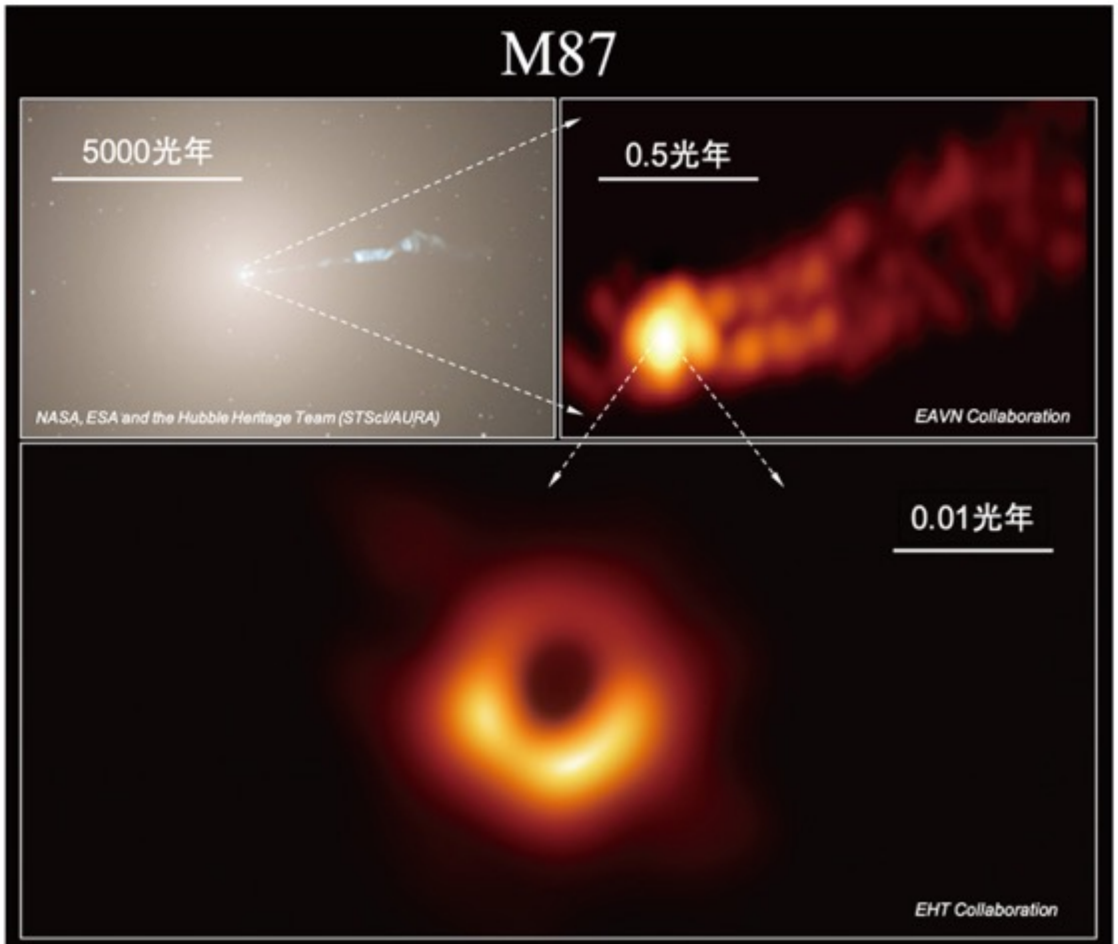
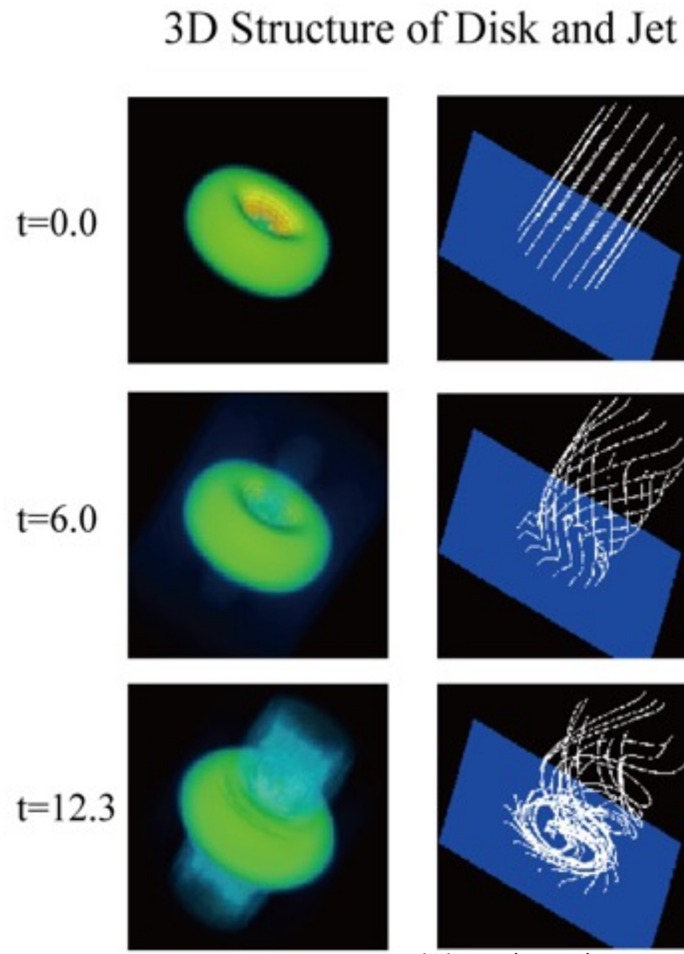
Class 9:PHY249 (2020Spring)



Event Horizon Telescope (2020)



Tajima Shibata (1997) p. 387

Plasma Astrophysics (Tajima, 2020)

- Class 9: Checking the observations and interpretations / predictions
- -**Do we have (or will have) localized UHECRs?** ←

  -**What properties do they have?** ←

such as

high energies? (such as ~ or > 10^{19} eV?)

spatial localization?

time structures?

accompaniment of other waves (γ, X, radio, light)?

cosmic rays other than protons (such as neutrinos)?

-**Are they explainable by the new theory?**

- Are there some concerns or questions?

Are facts doubled checked?

Can we write a short report on each astrophysical object?

Preparatory writing on the possibilities of Localized UHECRs and associated phenomena related to wakefields

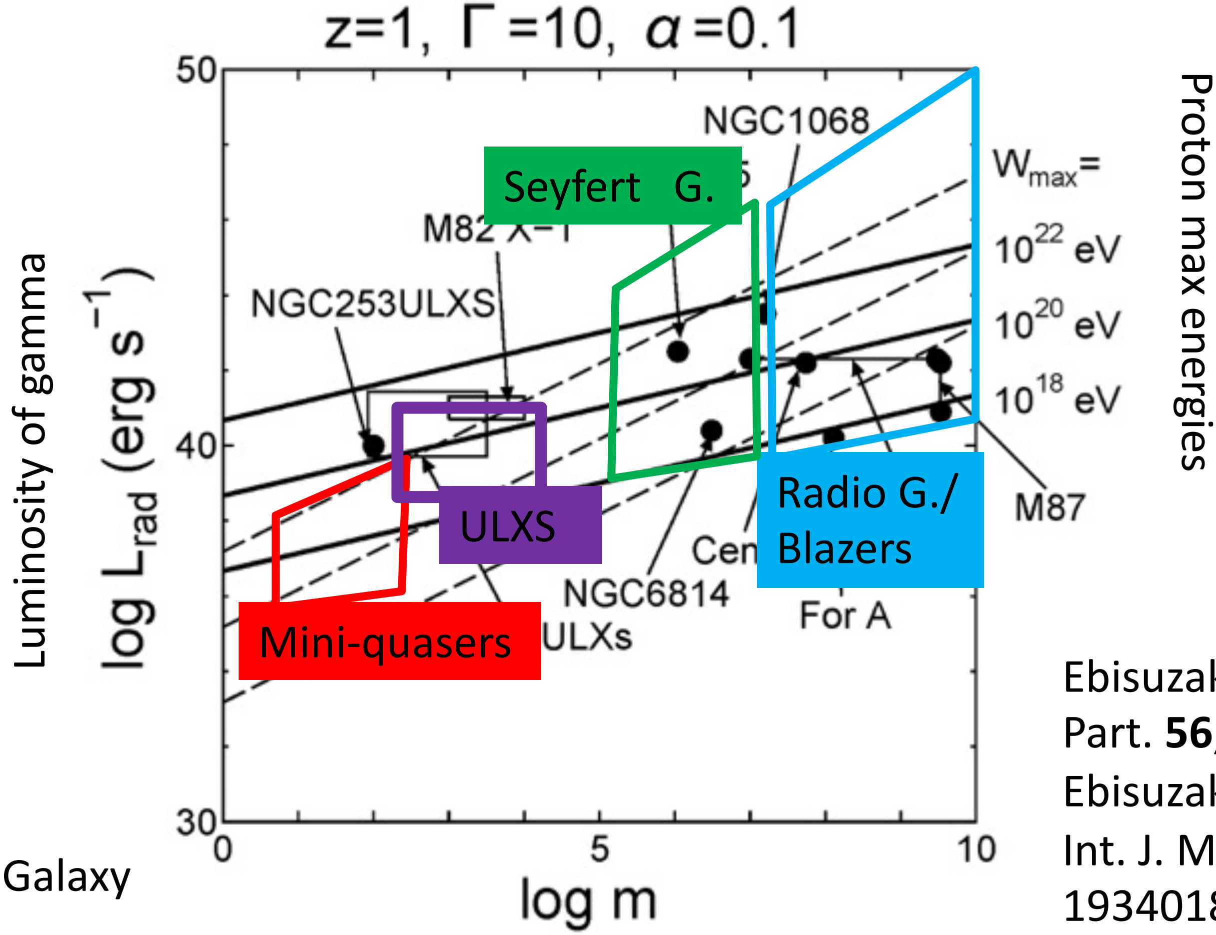
Each object name (and the team names):

- Category of the astrophysical object
- Chief characteristics of observed phenomena (or emissions)
- Typical energy or other numbers (such as gammas, radio,…)
- Observed (or lack of) localized UHECRs
- Other detailed characteristics, such as the time structures, coincidence (or lack) of other obsrevations
- Other comments, reservations, special significances, etc.

Our teams

Assigned Example					
	Greg	Wenhao	Gabe	Michael	Noor
Blazar	**X**	**X**			
M82			**X**	**X**	
Cen A	**X**				**X**
NGC 0253				**X**	**X**
SS 433		**X**	**X**		

cosmic ray acceleration and gamma-ray emission



Microquasars:
can be in our Galaxy

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

BH Astronomy with Ultra High Energy CRs

Background theory formulas

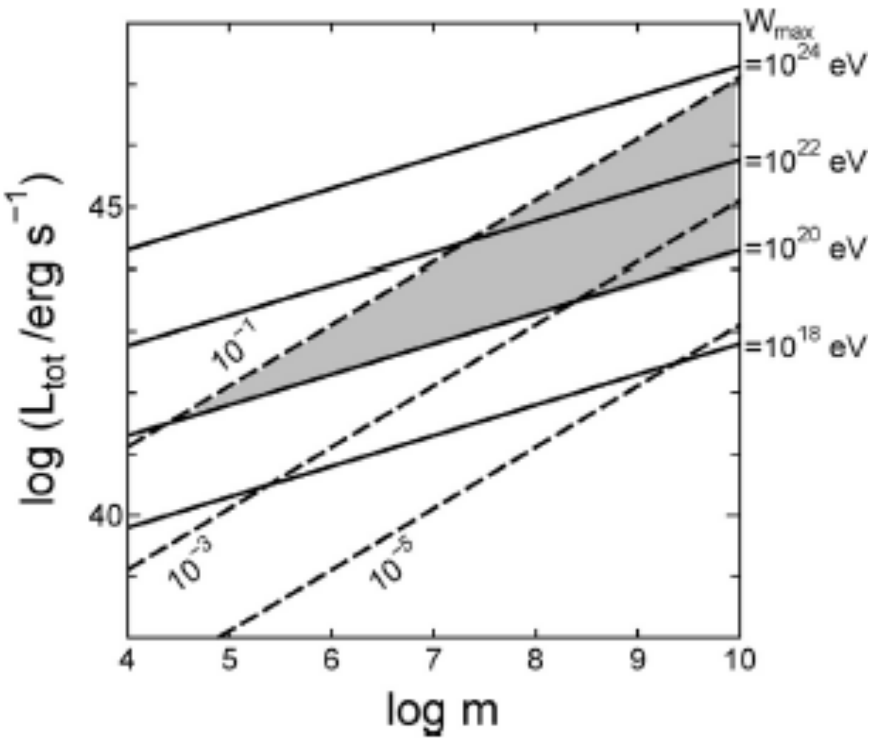


Fig. 4 The total luminosities of accreting blackholes are plotted against the blackhole mass (in the unit of solar mass) for various maximum attainable energy W_{max} (solid lines) for the case of $\Gamma = 20$ and $\xi = 10^{-2}$. Dashed lines are drawn for the values $\dot{m} = 10^{-5}, 10^{-3}$, and 10^{-1}. The grey triangle represents the parameter sets which allow the acceleration of UHECRs ($\gtrsim 10^{20}$ eV). We set the upper limit of $\dot{m}$ to be around 0.1 for the pondermotive/wakefield acceleration to work, since the accretion disk becomes radiation dominant as $\dot{m}$ approaches unity, and the Alfven wave pulse becomes weaker than the estimate in the present paper.

Table 1
Major features of pondermotive acceleration in an accreting supermassive blackhole.

	Values	Units
$2\pi/\omega_A$	$2.0 \times 10^2(\dot{m}/0.1)(m/10^8)$	s
$1/\nu_A$	$1.0 \times 10^6\eta^{-1}(m/10^8)$	s
D_3/c	$1.2 \times 10^9(\dot{m}/0.1)^{5/3}(m/10^8)^{4/3}$	s
W_{max}	$2.9 \times 10^{22} z(\Gamma/20)(\dot{m}/0.1)^{4/3}(m/10^8)^{2/3}$	eV
L_{tot}	$1.2 \times 10^{45}(\dot{m}/0.1)(m/10^8)$	erg s^{-1}
L_A	$1.2 \times 10^{42}\eta(\dot{m}/0.1)(m/10^8)$	erg s^{-1}
L_γ	$1.2 \times 10^{41}(\eta\kappa/0.1)(\dot{m}/0.1)(m/10^8)$	erg s^{-1}
L_{UHECR}	$1.2 \times 10^{40}(\eta\kappa\zeta/10^{-2})(\dot{m}/0.1)(m/10^8)$	erg s^{-1}
L_{UHECR}/L_{tot}	$1.0 \times 10^{-5}(\eta\kappa\zeta/10^{-2})$	–
L_{UHECR}/L_γ	$1.0 \times 10^{-1}(\zeta/0.1)$	–

$\xi = L_j/L_{tot}$, $\eta = v_A Z_D/V_A$, $\kappa = E_{CR}/E_A$, and $\zeta = \ln(W_{max}/(10^{20} eV))/\ln(W_{max}/W_{min})$.

$$W_{max} = z\int_0^{D_3} F_{pm} dD \quad (24)$$

$$= 4.6 \times 10^{19}\, z(\Gamma/20)(\dot{m}/0.1)^{1/2}(m/10^8)^{1/2}(D_3/3R_g)^{1/2} \text{ eV}$$

$$= 2.9 \times 10^{22}\, z(\Gamma/20)(\dot{m}/0.1)^{4/3}(m/10^8)^{2/3} \text{ eV}, \quad (25)$$

where

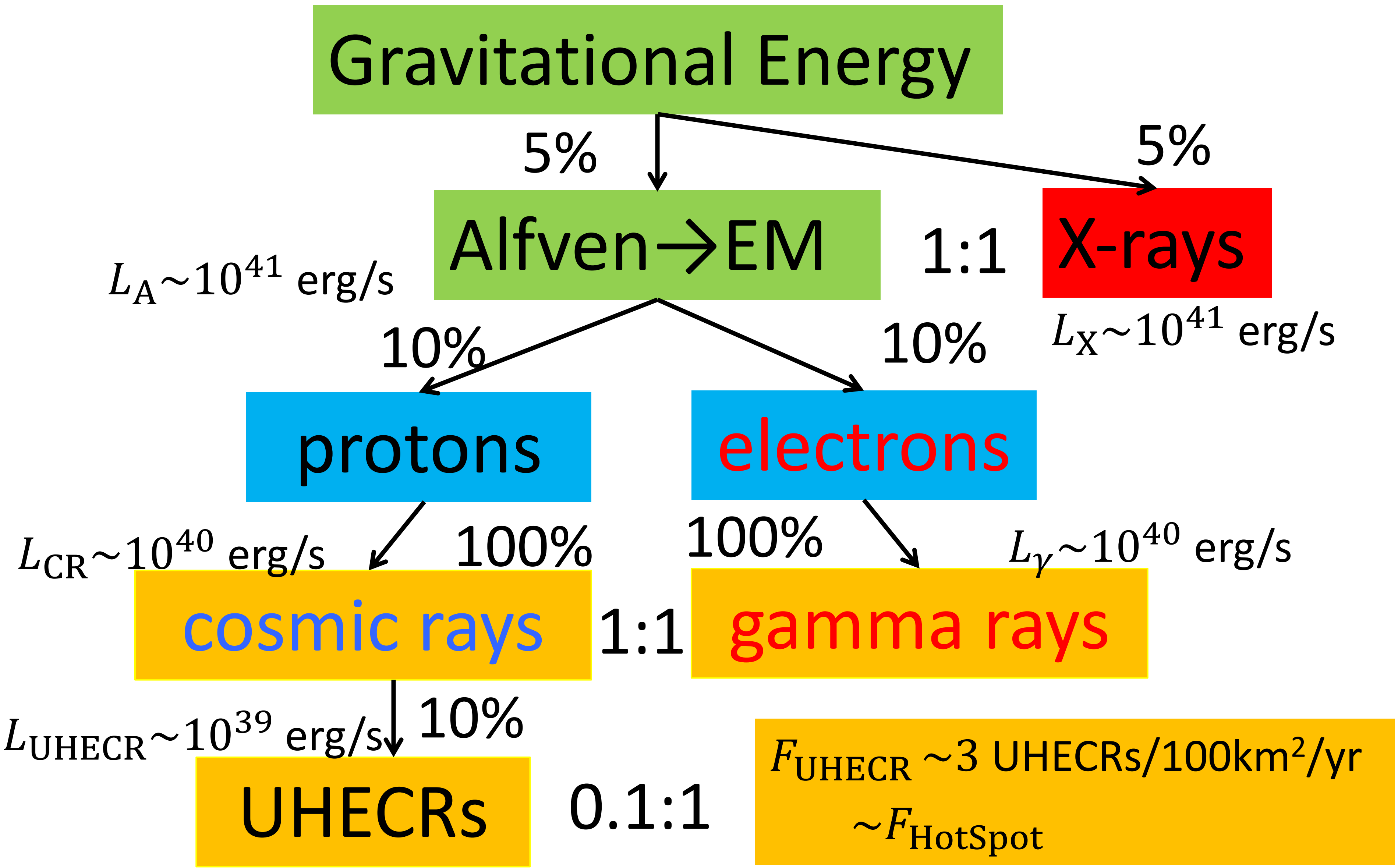
$$F_{pm} = \Gamma m_e c a \omega_A \quad (26)$$

luminosity is, therefore, found to be as:

$$L_\gamma \sim \kappa E_B \nu_A = 1.6 \times 10^{34}(\kappa/0.1)\eta \dot{m} m \text{ erg s}^{-1}. \quad (33)$$

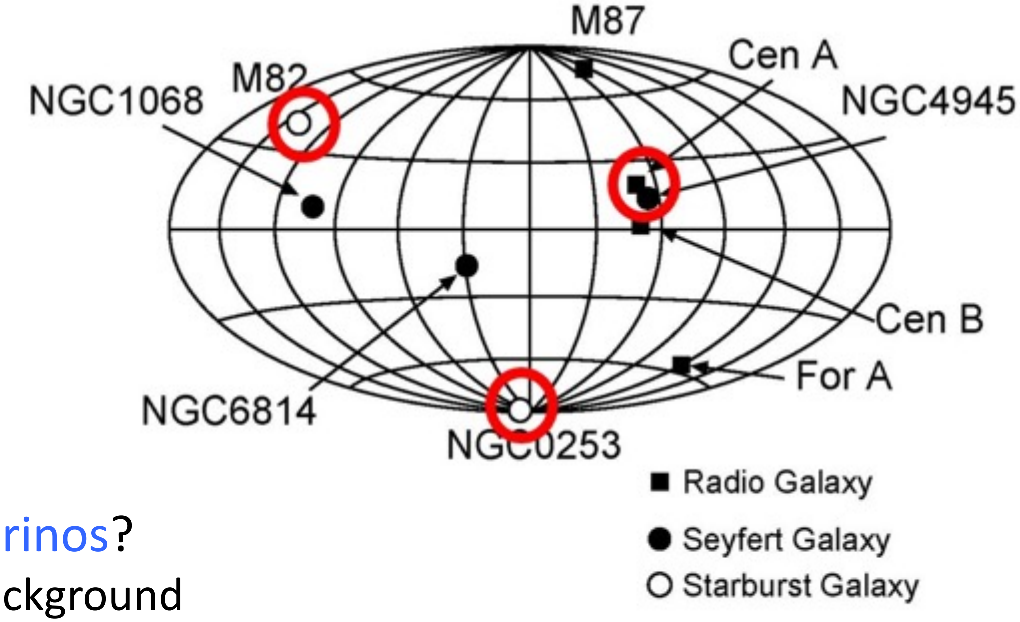
Ebisuzaki, Tajima Astro. Part. **56**, 9 (2014).

Energy release by Wakefield (e.g.M82 X-1)



Localizable Brightest cosmic rays by wakefields ?

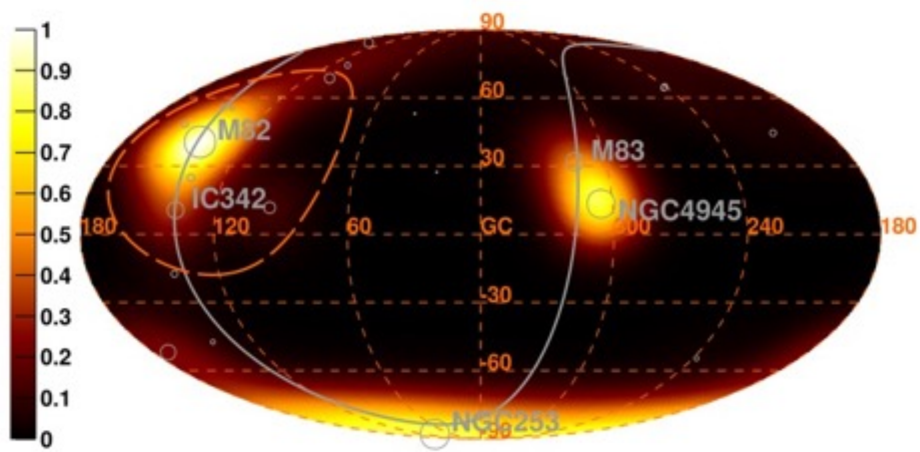
(A)



Localized UHECR?
thus Localized neutrinos?
not as a spread background

(B)

Model Flux Map - Starburst galaxies - E > 39 EeV



II. Specific examples ← our theory

0. Blackhole (BH) as an engine of AGN [textbook p.387]

1. **Blazar** γ-emmission → protons (UHECR); time-structured, coincidental with γ, neutrino

[Canac, et al. 2020;IceCube, Science, 2020]

2. **Cen A** (radio galaxy) [see refs. inside]
3. **M82** (starburst galaxy) [see refs. inside]
4. **NGC 0253** (starburst galaxy) [see refs. inside]
5. **SS 433** (microquasar) [Abeysakara et al., 2018]

[other refs. are also inside of these slides]

Astrophysical plasma (and lab) parameters

	objects	B(G)	L(cm)	n(cm^{-3})	T(K)
(A)	Earth	0.31	6.4×10^8		
	Solar Wind at 1AU	6×10^{-5}	1.5×10^{13}	1	10^6
	Jupiter	4	7×10^9		
	Pulsar (Neutron Star)	10^8-10^{12}	10^6		
(B)	Solar center	?		10^{26}	10^7
	– conv. zone	10^4(?)	10^{10}	10^{23}	10^6
	– photosphere (spots)	2×10^3	10^9	10^{17}	10^4
	– corona	10	10^{10}	10^8	10^6
	Magnetic stars	10^3-10^4	10^{11}		d
	Galactic disks	5×10^{-6}	$10^{20}-10^{22}$	1	10^4
	– halos	10^{-6}	10^{23}	10^{-3}	10^6
(C)	Molecular cloud	$10^{-5}-10^{-4}$	10^{19}	10^3	10
	– core	$10^{-4}-10^{-3}$	10^{18}	10^7	10
	Bipolar flows	10^{-4}	10^{18}	10^3	10
	AGN nucleus	$10^{-1}-10^{-3}$	10^{18}		
	– jets	$10^{-3}-10^{-5}$	$10^{18}-10^{24}$		
	– lobes	$10^{-6}-10^{-7}$	10^{23}		
	Intergalactic (in cluster)	$10^{-6}-10^{-8}$	10^{25}	$10^{-3}-10^{-6}$	(10^6-10^7)
	– (intercluster)	$<10^{-9}$		$(10^{-6}-10^{-9})$	

TABLE 1.4 Typical Fundamental Quantities in some Celestial Objects
B: magnetic field strengths
L: characteristic scale
n: particle number density
T: temperature
ref: Asseo and Sol (1987).

objects	magnetic	thermal	kinetic	rotation	grav.
(A) Solar Wind at 1AU	10^{-10}	10^{-10}	10^{-9}		10^{-11}
(B) Solar convection zone	10^7	10^{13}	10^{6*}	10^9	10^{14}
– photosphere	10^5	10^5	10^3		10^8
– corona	4	0.01	10^{-4}		0.1
Galactic disks	10^{-12}	10^{-12}	10^{-12}	10^{-9}	10^{-9}
(C) Molecular Cloud	4×10^{-10}	10^{-12}	10^{-11}	10^{-11}	10^{-11}

TABLE 1.5 Various Energies in Some Celestial Objects in erg cm^{-3}
*turbulent velocity $v = 0.03$ km/s: Parker (1979) p. 145
magnetic energy $= B^2/8\pi$
thermal energy $= \frac{3}{2}nkT$
kinetic energy $= \frac{1}{2}\rho v^2$
rotational energy $= \frac{1}{2}\rho v_{rot}^2$
gravitational energy $= GM\rho/r$

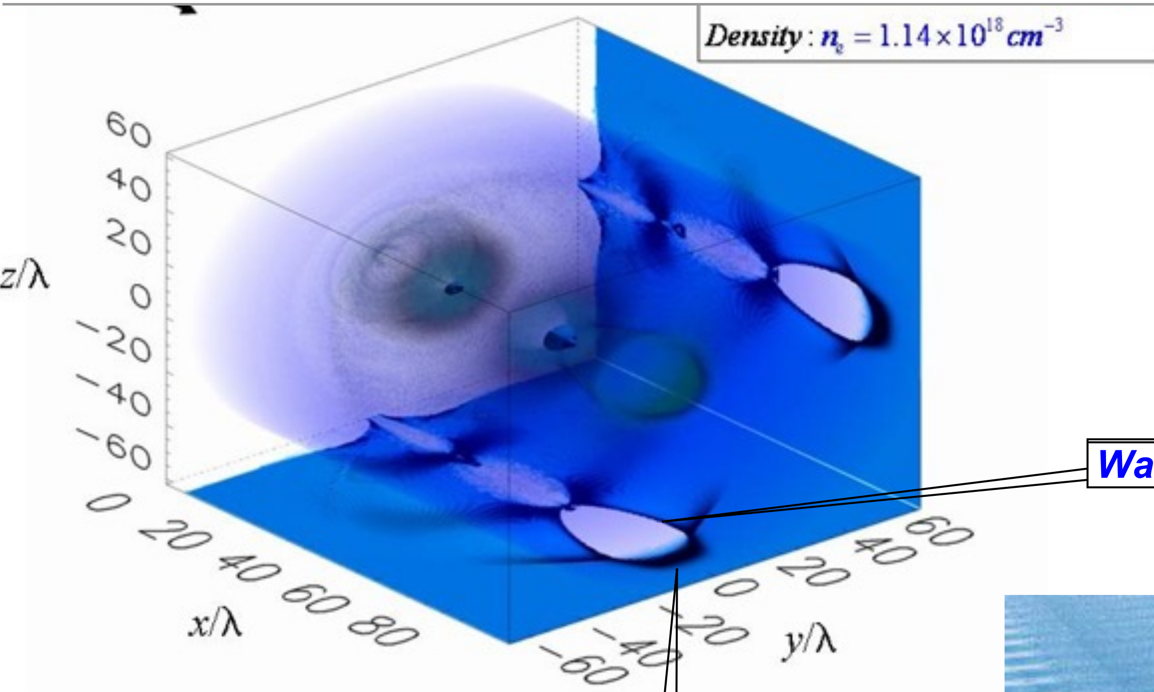
Debye length	$\lambda_D \equiv \left(\frac{kT}{4\pi n e^2}\right)^{1/2} \simeq 2\left(\frac{T}{10^6\,\mathrm{K}}\right)^{1/2}\left(\frac{n}{10^9\,\mathrm{cm^{-3}}}\right)^{-1/2}$ cm
electron Larmor radius	$r_{Le} \equiv \frac{v_{th,e}}{\Omega_e} = \frac{c}{eB}(m_e kT)^{1/2} \simeq 2\left(\frac{B}{10\,\mathrm{G}}\right)^{-1}\left(\frac{T}{10^6\,\mathrm{K}}\right)^{1/2}$ cm
ion Larmor radius	$r_{Li} \equiv \frac{v_{th,i}}{\Omega_i} = \frac{c}{eB}(m_i kT)^{1/2} \simeq 10^2\left(\frac{B}{10\,\mathrm{G}}\right)^{-1}\left(\frac{T}{10^6\,\mathrm{K}}\right)^{1/2}$ cm
(electron) collisionless skin depth	$\lambda_e \equiv \frac{c}{\omega_{pe}} \simeq 30\left(\frac{n}{10^9\,\mathrm{cm^{-3}}}\right)^{-1/2}$ cm
electron mean free path	$\lambda_{mfp} = \frac{v_{th,e}}{\nu_{ei}} = \frac{m_e^2 v_{th,e}^4}{n e^4 \ln\Lambda} \simeq 10^7\left(\frac{n}{10^9\,\mathrm{cm^{-3}}}\right)^{-1}\left(\frac{T}{10^6\,\mathrm{K}}\right)^2$ cm
pressure scale height	$H \equiv \frac{C_s^2}{\gamma g} = \frac{R_g T}{\mu g} \simeq 6\times10^9\left(\frac{T}{10^6\,\mathrm{K}}\right)\left(\frac{g}{g_\odot}\right)^{-1}\left(\frac{\mu}{0.5}\right)^{-1}$ cm
Schwarzschild radius	$r_g \equiv \frac{2GM}{c^2} \simeq 3\times10^5\left(\frac{M}{M_\odot}\right)$ cm

TABLE 1.6 Fundamental Length Scales in Plasmas
$g_\odot = GM_\odot/R_\odot^2 \simeq 2.74\times10^4$ cm^2/s, $R_\odot \simeq 7\times10^{10}$ cm

34

Textbook pp.33-36

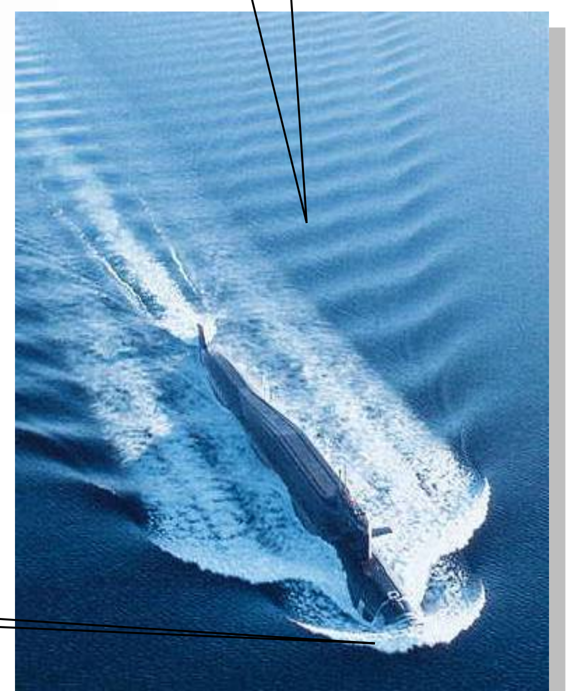
Wakefields: Bow and Wake



(Bulanov, Esirkepov)

Wakefield acceleration

Wake Wave



Coherent, collective,
robust, huge amplitude

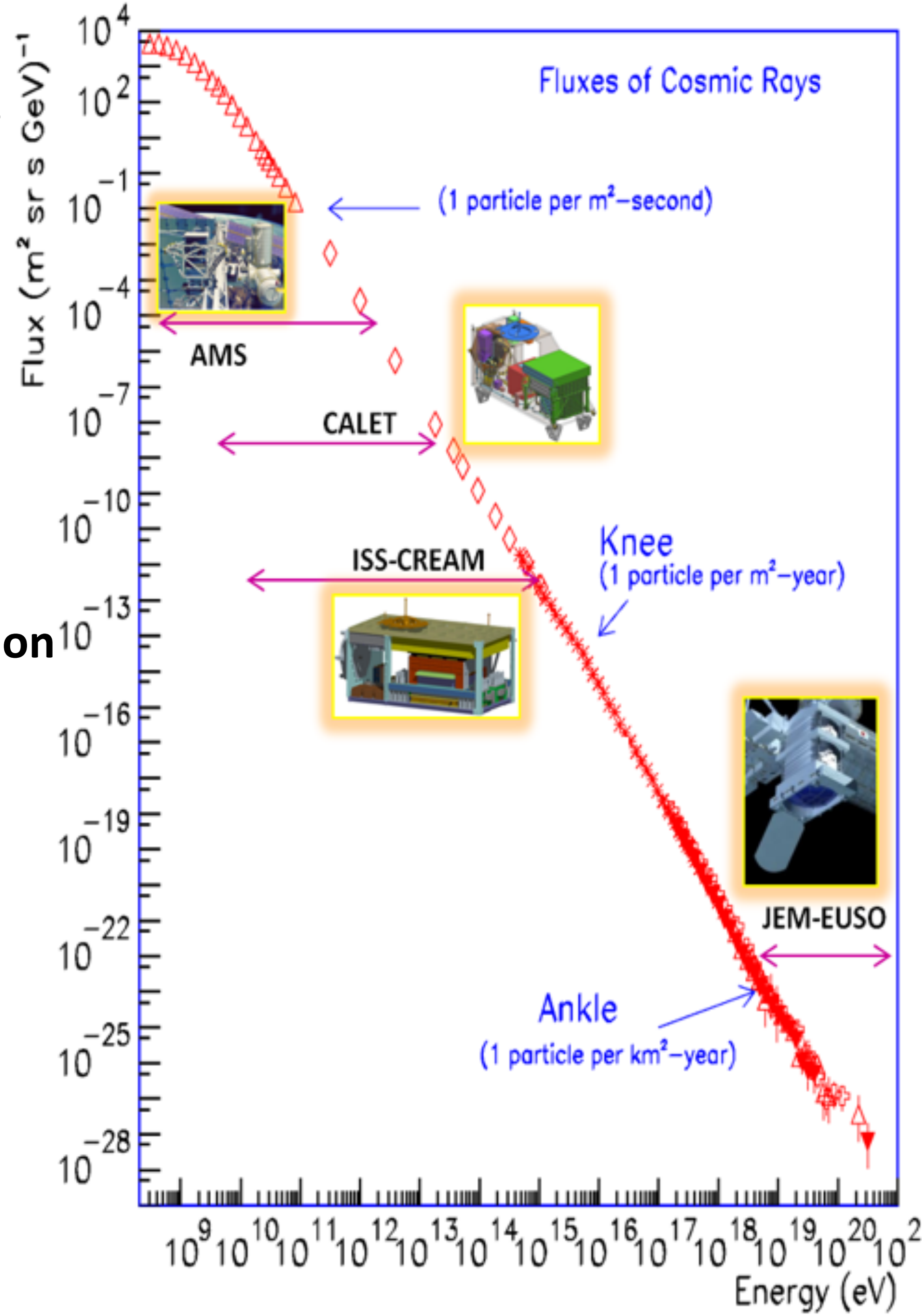
Bow Wave

Ponderomotive acceleration

Ultrahigh Energy Cosmic Rays (UHECR)

Fermi mechanism runs out of steam
- beyond 10^{19} eV
- due to synchrotron radiation

Wakefield acceleration
- comes in rescue
- prompt, intense, linear acceleration
- small synchrotron radiation
- radiation damping effects?

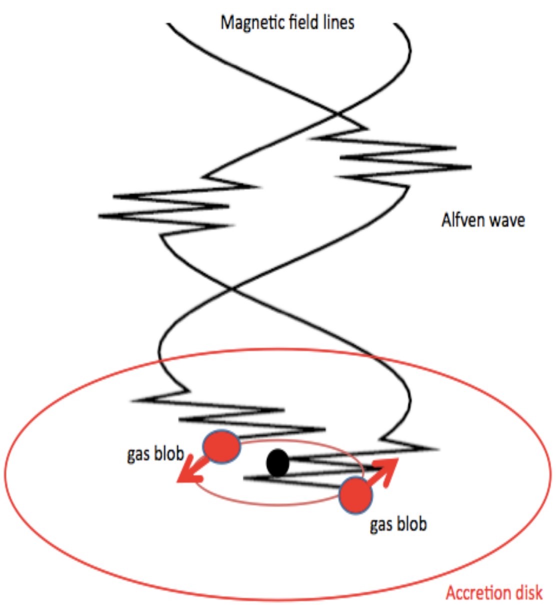


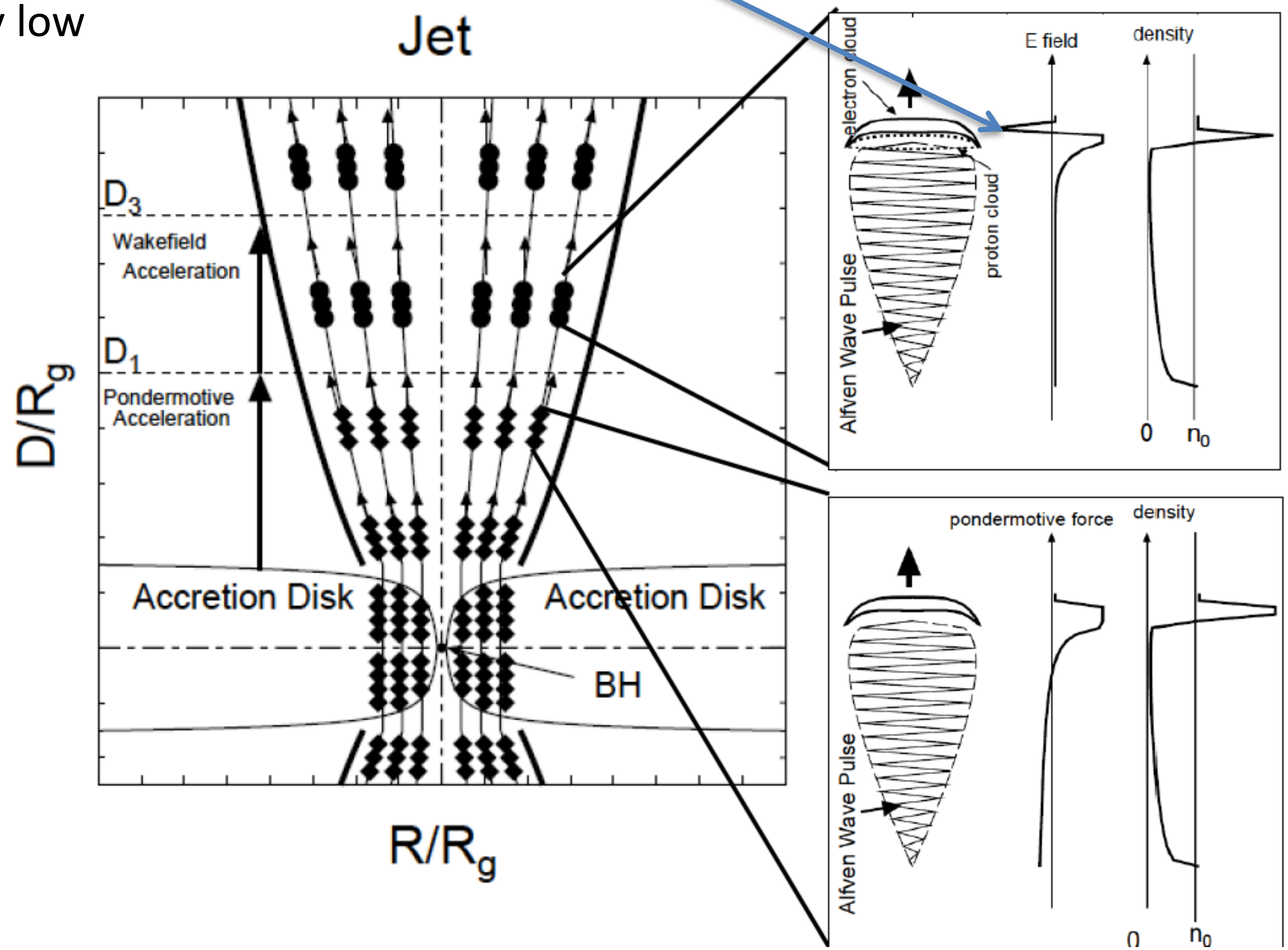
Astrophysical wakefield acceleration: Superintense Alfven Shock in the Blackhole Accretion Disk toward ZeV Cosmic Rays (a_0 ~ 10^6 -10^{10}, large spatial scale)

$a_0 = eE_0 / mc\omega_0 >> 1$: normalized EM wave amplitude

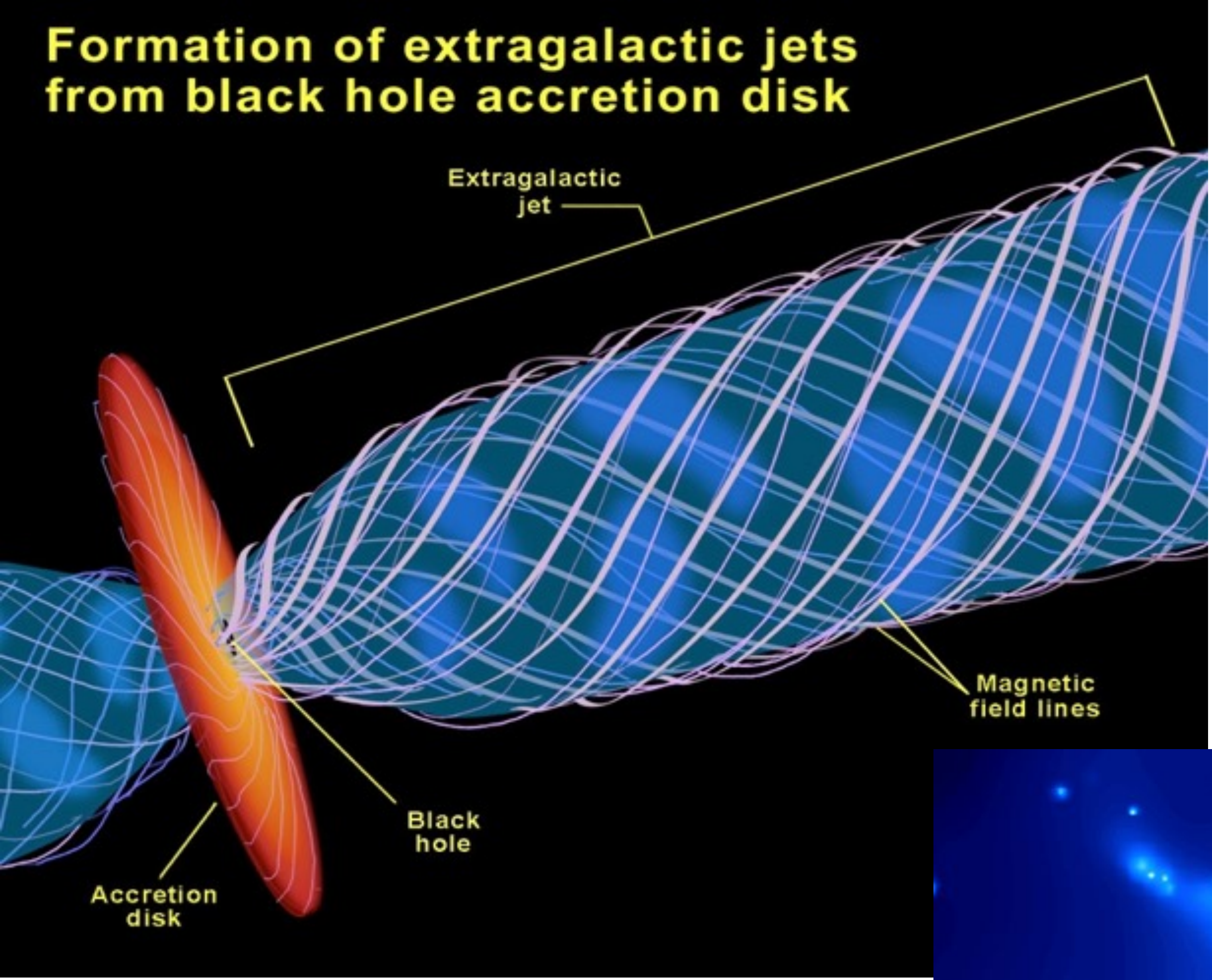
E_0: modest

$\omega_0 = 2\pi c / \lambda$: extremely low





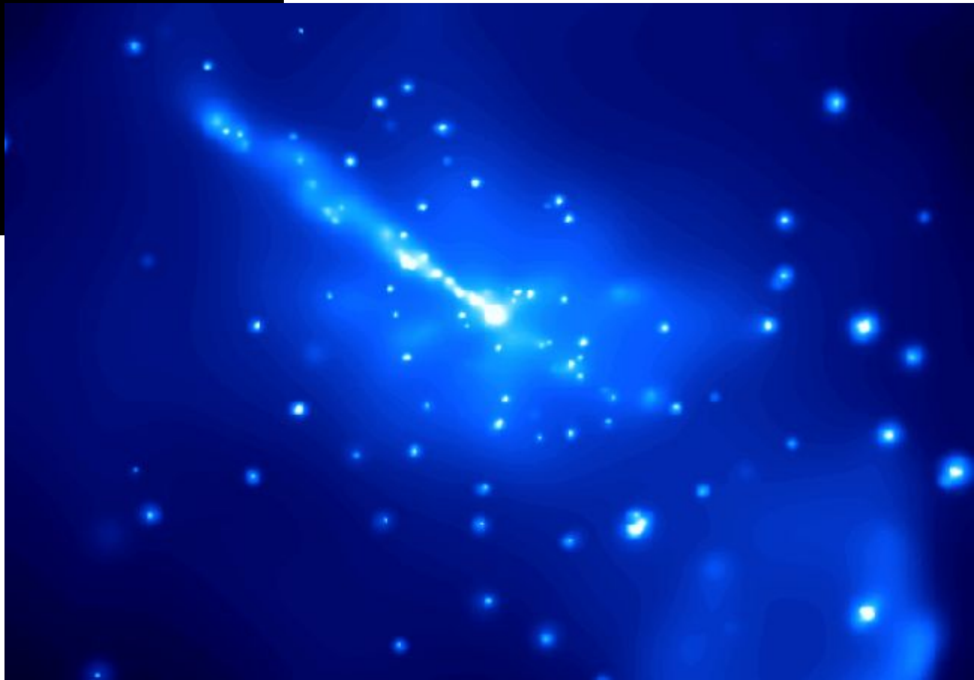
Ebisuzaki and Tajima, Astropart. Phys.(2014)



Fermi's **'Stochastic Acceleration'**
(large synchrotron radiation loss)

↓

Coherent wakefield acceleration
(no limitation of the energy)



Nature's LWFA : Blazar jets

extreme high energy cosmic rays (~10^{21} eV)

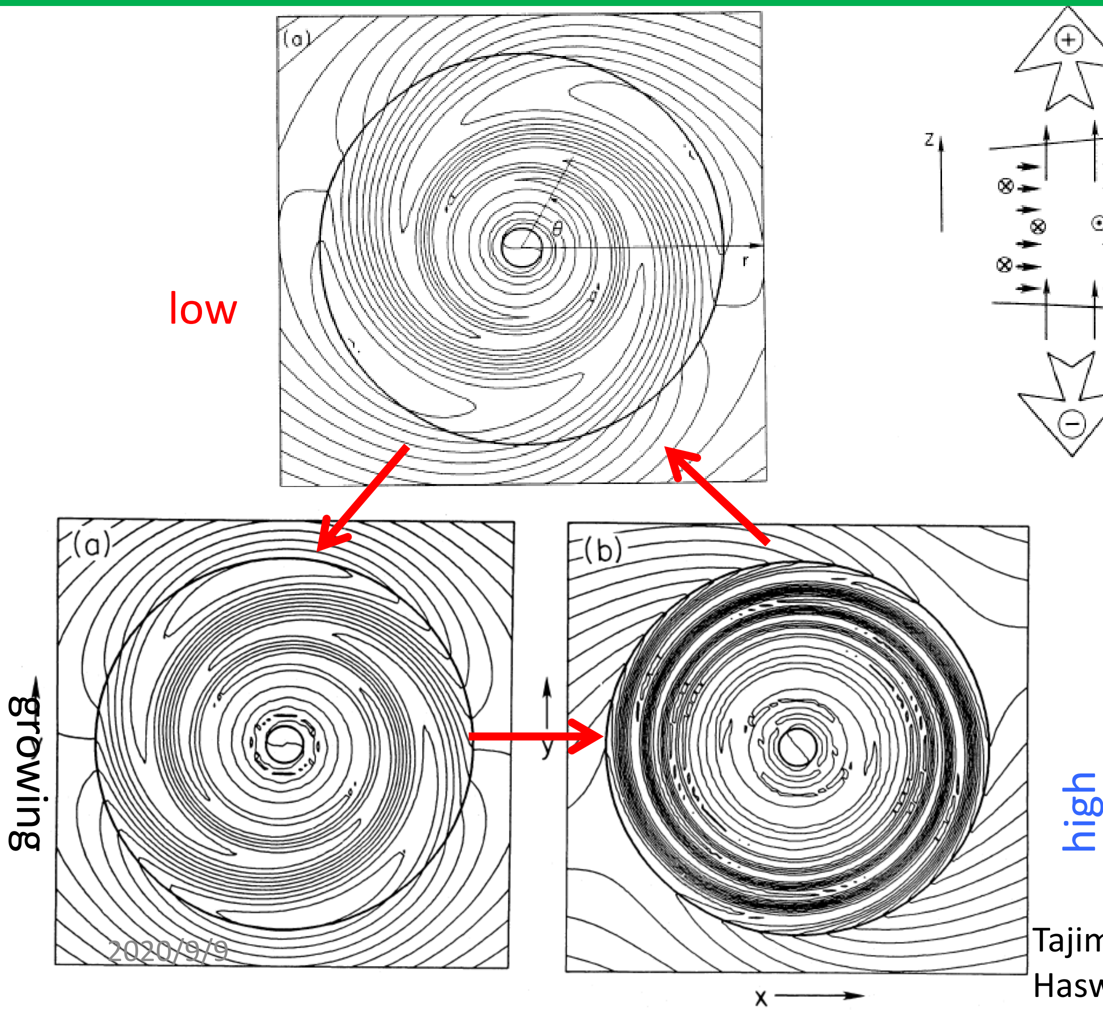
episodic γ-ray bursts observed

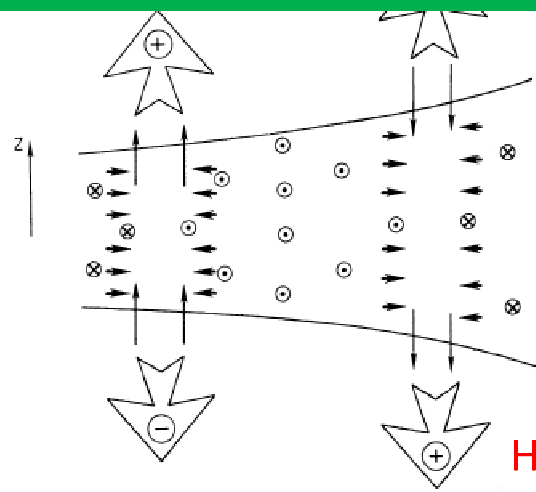
consistent with LWFA theory

Ebisuzaki-Tajima (2014)

Halo and jet acceleration in an accretion disk

A Burst of Electromagnetic Disturbance





Halo heating and acceleration
→ low energy X, γ, ν

Tajima and Gilden 1987, ApJ 320, 741-745
Haswell, Tajima, and Sakai, 1992, ApJ, 401, 495-507