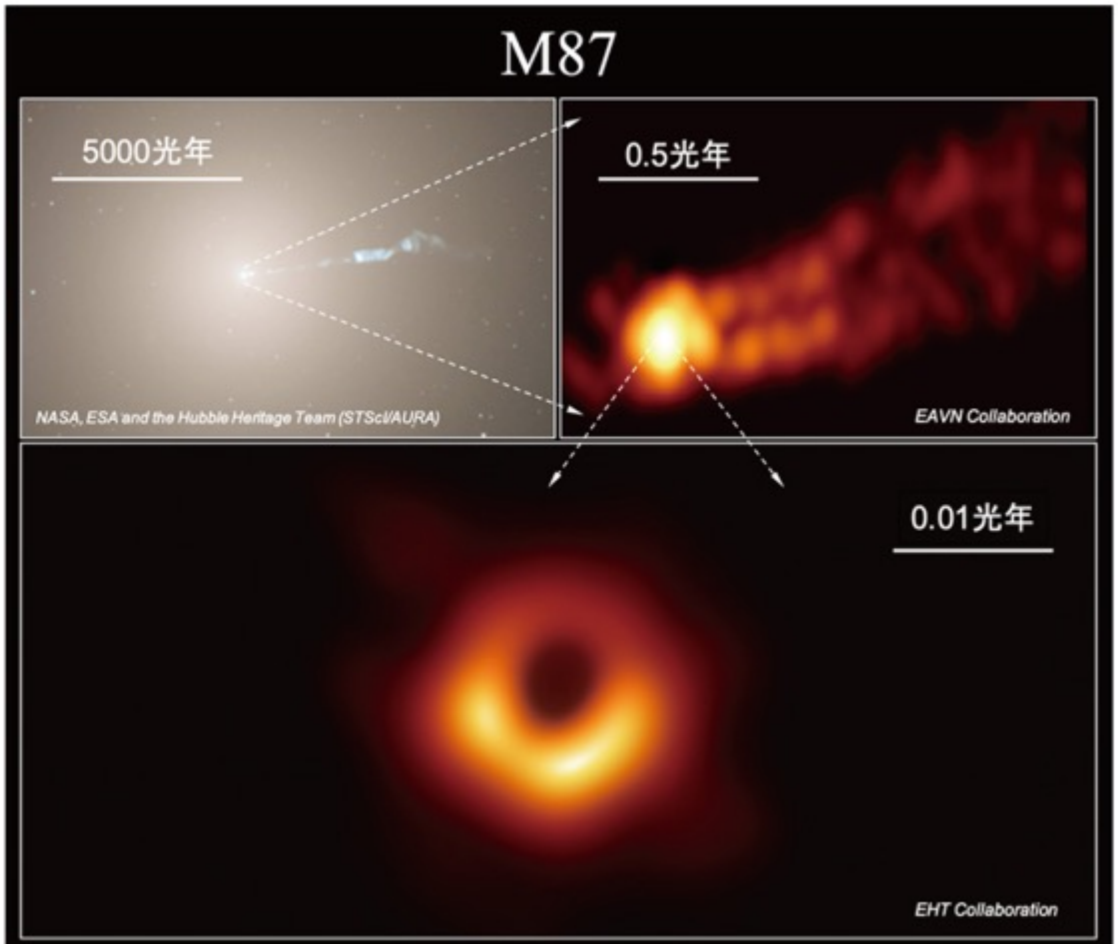
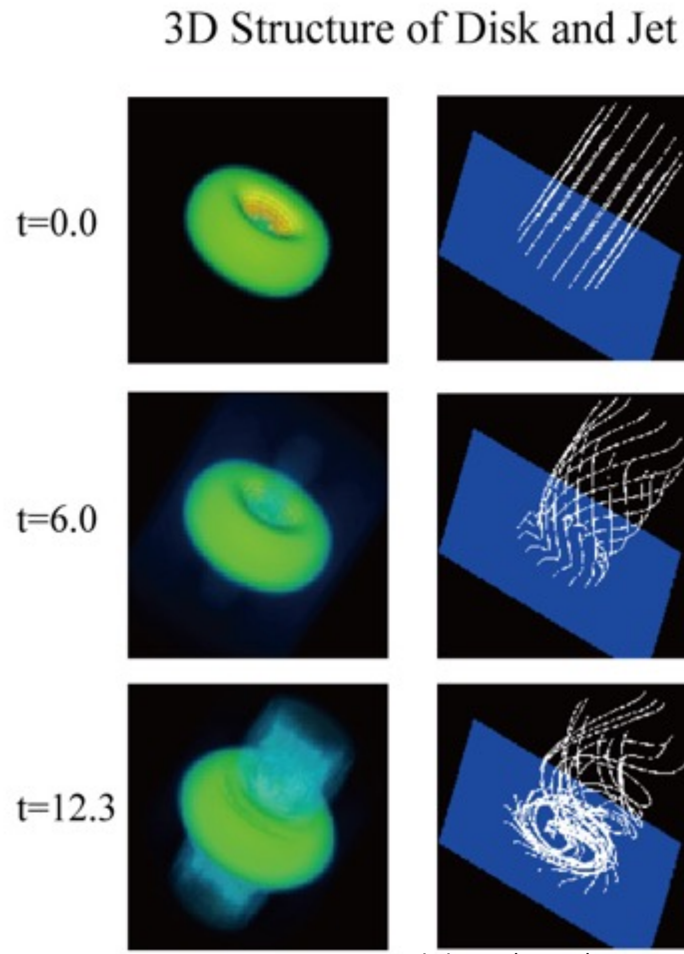
Plasma Astrophysics

Toshiki Tajima, UCI

Class 6:PHY249 (2020Spring)



Event Horizon Telescope (2020)



Tajima Shibata (1997) p. 387

Plasma Astrophysics (Tajima, 2020)

----- ------ ------ ------ ------ ------- general overview

- Class 1: Introduction to "plasma astrophysics"

  instabilities vs. structure formation of plasma

  exemplary processes in plasma astrophysics, plasma β

- Class 2: Gravity + Plasma + B

  magnetic Buoyancy, magneto-rotational instability (MRI)

  explosive evolution of flux tubes, filamentary Universe

- Class 3: Accretion disk and jets

  MRI on accretion disk, anomalous viscosity, jet formation

  Stimulus to evolution of the Universe

-------- ------- -------- ------- -------- now specific realizations

- Class 4: Neutron star-neutron star collision

  gravitational wave and γ-bursts

- Class 5: "Physiology" of accretion disks

  Mother Nature's accelerator (from Fermi → new paradigm)

- Class 6: **Ultra High Energy Cosmic Rays (UHECRs)**

  Can we see localized UHECRs?

Localizable UHECRs (?)

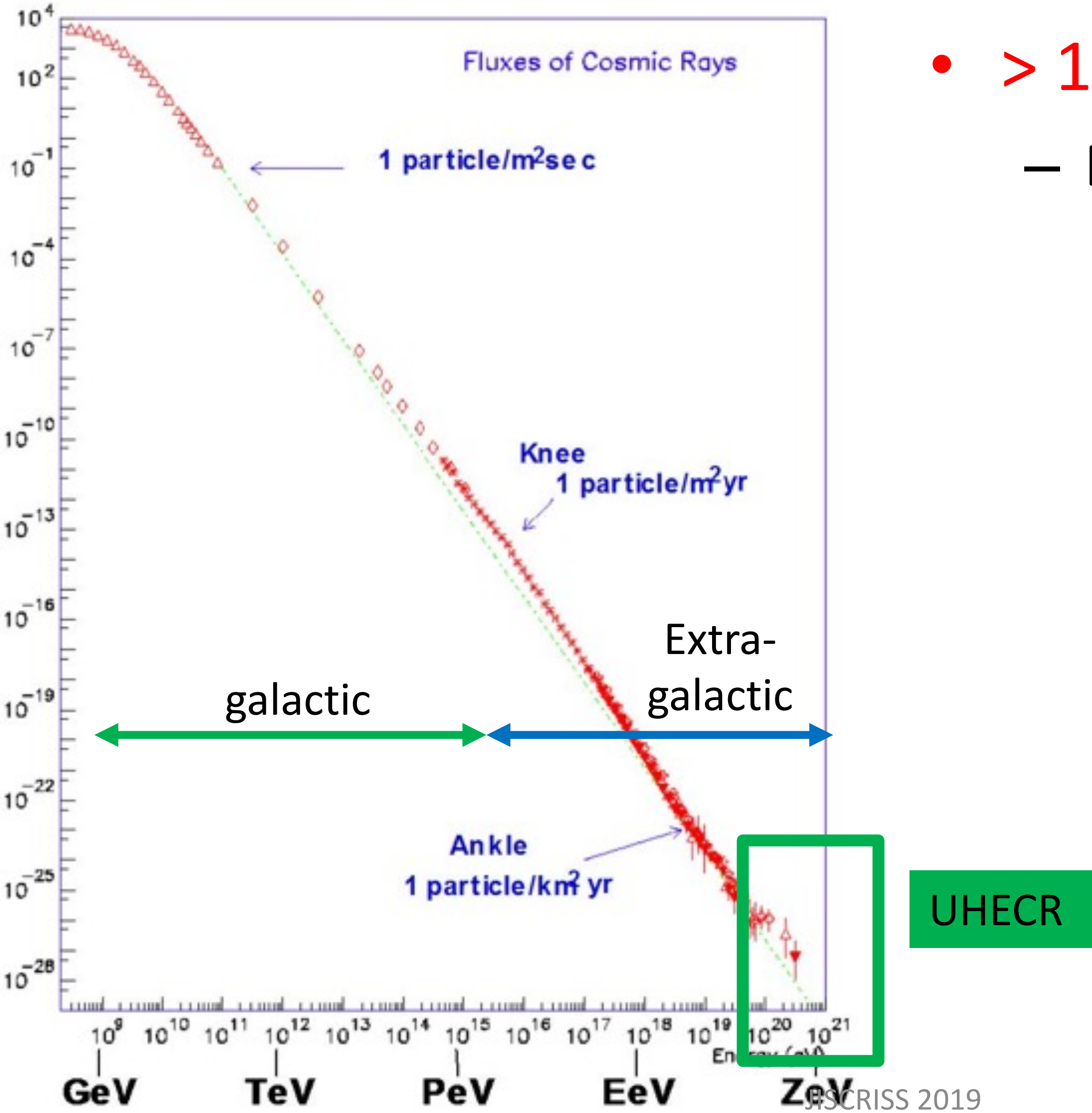
- Ultra High Energy Cosmic Rays (UHECR) beyond 10^{19} eV:
  conventional theory (Fermi, 1954) cannot explain

- Conventional theory (1954) predicts
  (1) isotropic detection of UHECRs
  (2) no short time structure
  (3) no correlations with other signals such as γ emissions

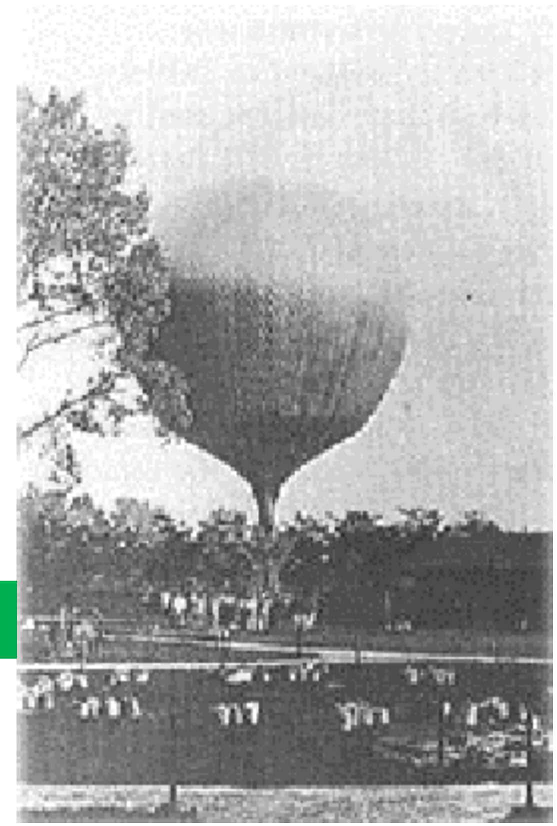
We will see why the above is the case.

- Can we have observations of **UHECRs** with such:?
  (1) beyond $10^{18\text{-}19}$ eV
  (2) localized
  (3) time structured
  (4) correlated with other signals (s.a. γ emissions, radiowaves,)
  (5) non-protons (s.a. neutrinos,)
  (6) Can we predict? Can you do so in your Term Project?

Origin of **Cosmic rays**



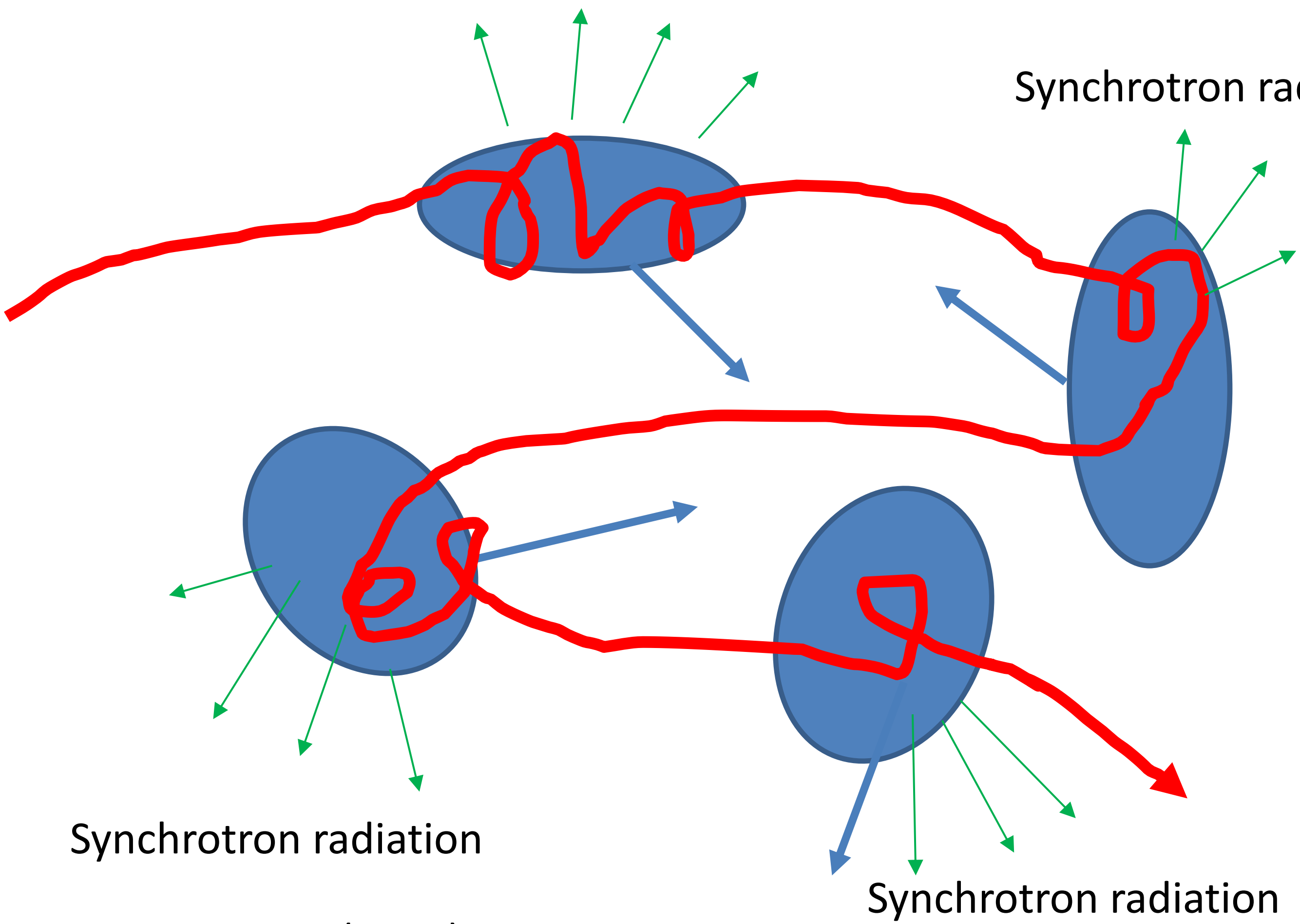
- > 100 years enigma
  - Discovered in **1912** by Victor Hess

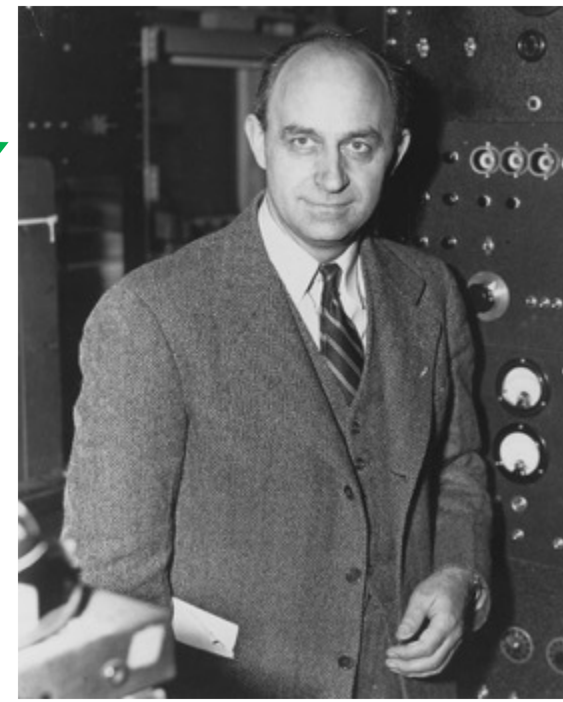


Fermi stochastic acceleration

Incoherent stochastic process requires bending→synchrotron loss

Synchrotron radiation (even protons begin losing energy ≥ 10^{19} eV)





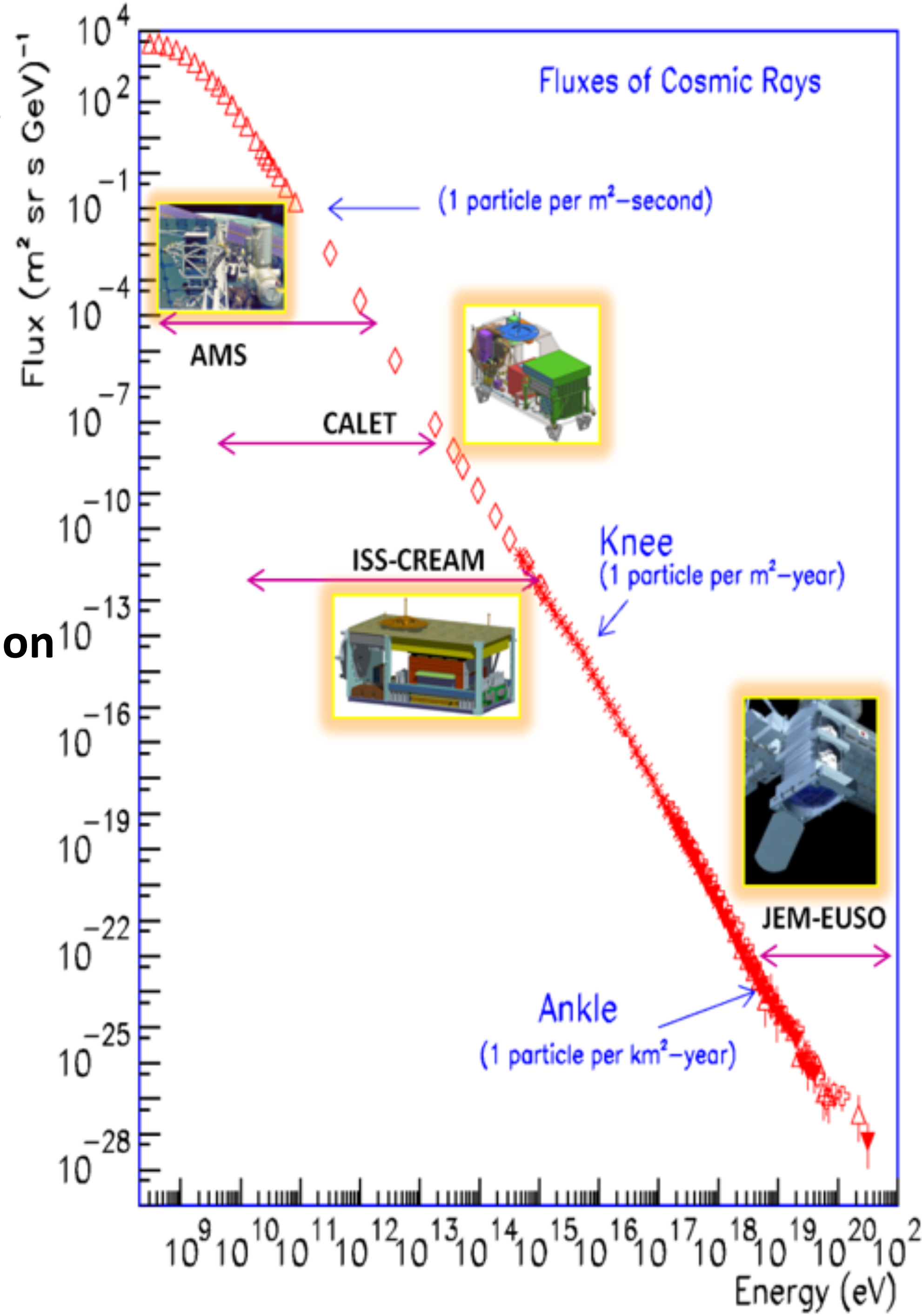
Enrico Fermi
By Department of Energy. Office of Public Affairs

E. Fermi, ApJ **119** (1954) 1.

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?



Plasma's Collective Force / Modes

(vs. single-particle force)

<u>Collective</u> force ~$\boldsymbol{N^2}$ (nonlinear ← linear force ~N)

<u>Coherent and smooth</u> structure (not stochastic)

<u>enhancement</u> by $10^3 – 10^4$ (even by $\mathbf{10^{6-12}}$) >> interaction of one particle x one particle

Collective mode delivery (EM x plasma x B)←→ long-ranged force (gravity, EM)

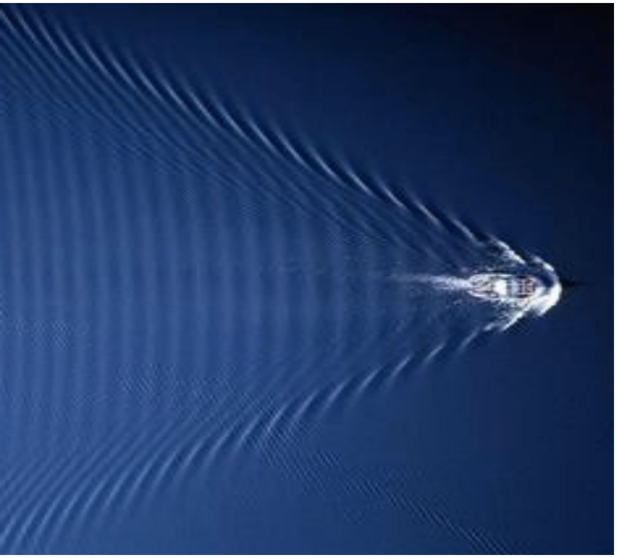
what difference?

e.g. jet   e.g. galaxy-galaxy interaction

Laser Wakefield (LWFA):

Wake phase velocity >> water movement speed, maintains **coherent** and **smooth** structure

Tsunami phase velocity becomes ~0, causes **wavebreak** and **turbulence**

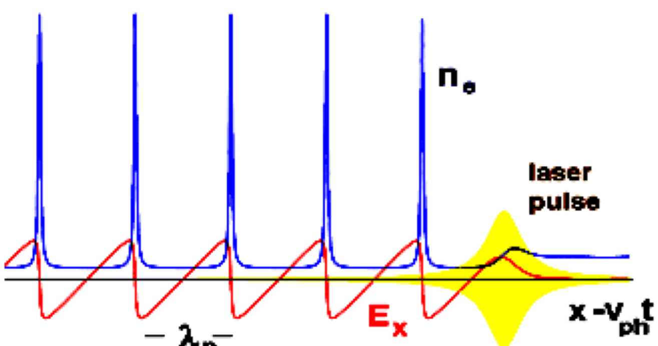


vs

Strong beam (of laser / particles) drives plasma waves to saturation amplitude: $E = m\omega v_{ph} /e$

No wave breaks and wake **peaks** at v≈c

Wave **breaks** at $v < c$

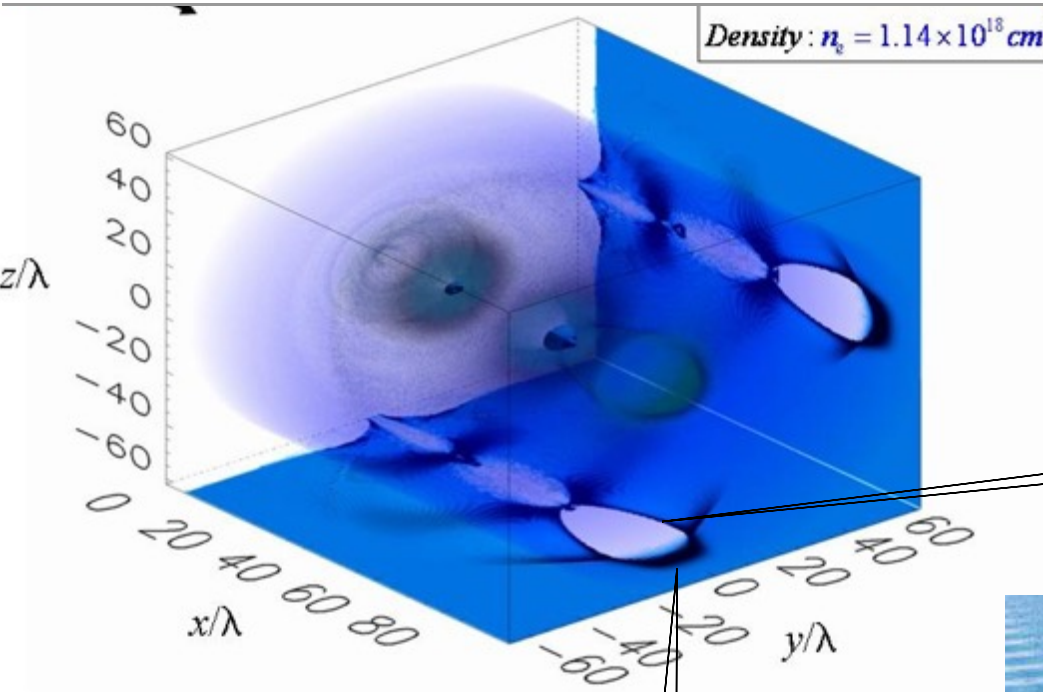


← relativity regularizes (*relativistic coherence*)

$a_0 \sim 10 >> 1$ (relativistic wave)

Relativistic coherence enhances beyond the Tajima-Dawson field $E = m\omega_p c /e$ (~ GeV/cm)

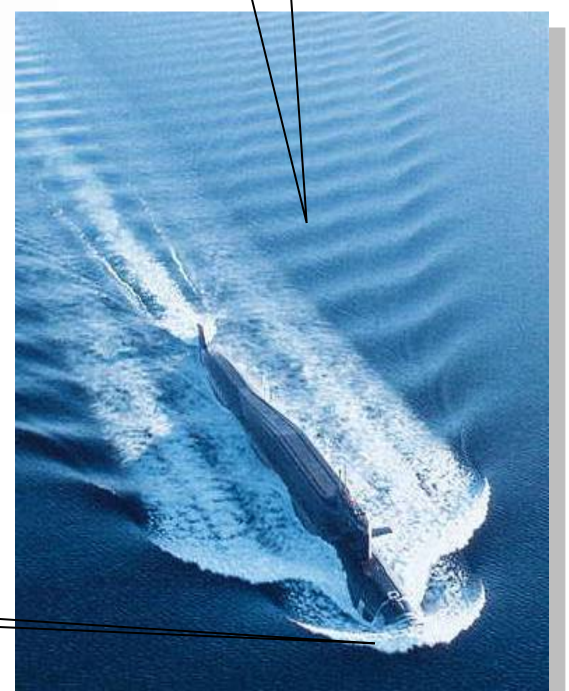
Laser-driven Bow and Wake



(Bulanov, Esirkepov)

Wakefield acceleration

Wake Wave

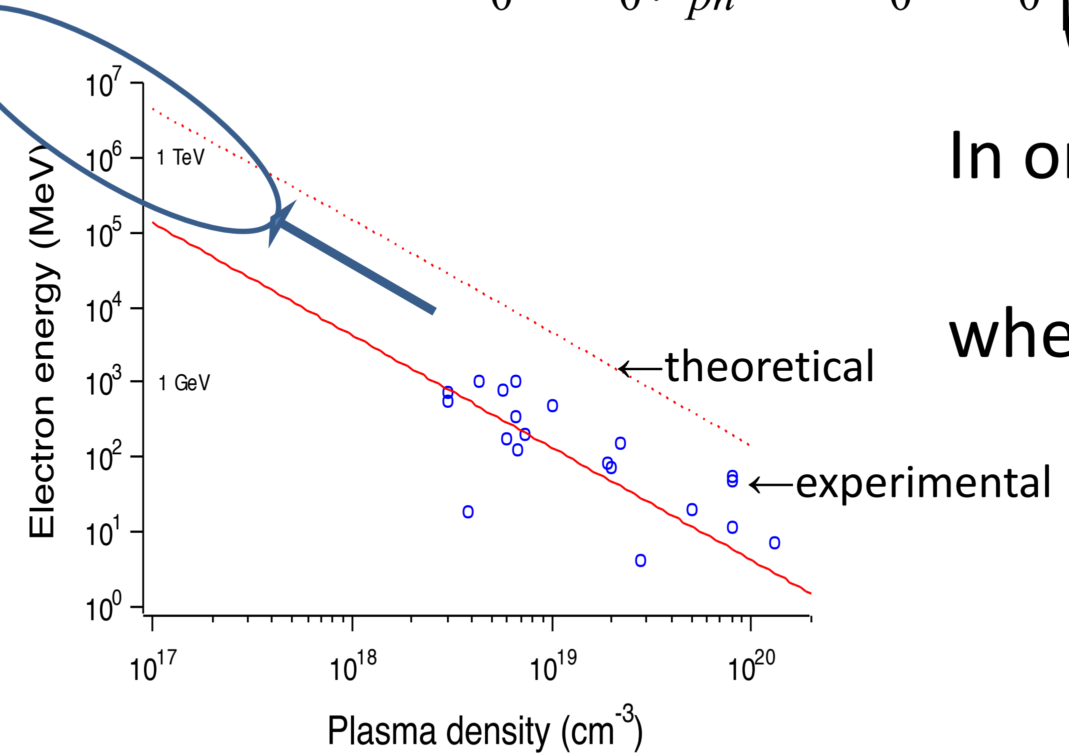


Bow Wave

Ponderomotive acceleration

Universal Theory of Wakefield toward extreme energy

$$\Delta E \approx 2m_0c^2a_0^2\gamma_{ph}^2 = 2m_0c^2a_0^2\left(\frac{n_{cr}}{n_e}\right),$$ (when 1D theory applies)



In order to avoid wavebreak,

$$a_0 < \gamma_{ph}^{1/2},$$

where

$$\gamma_{ph} = (n_{cr}/n_e)^{1/2}$$

n_{cr} =10^{21} (fs photon (laser))

= 10 (10^3 s wave in disk)

n_e = 10^{18} (gas)

= 10^{-2} (gas in the jet)

$$L_d = \frac{2}{\pi}\lambda_p a_0^2\left(\frac{n_{cr}}{n_e}\right),$$

dephasing length

$$L_p = \frac{1}{3\pi}\lambda_p a_0\left(\frac{n_{cr}}{n_e}\right),$$

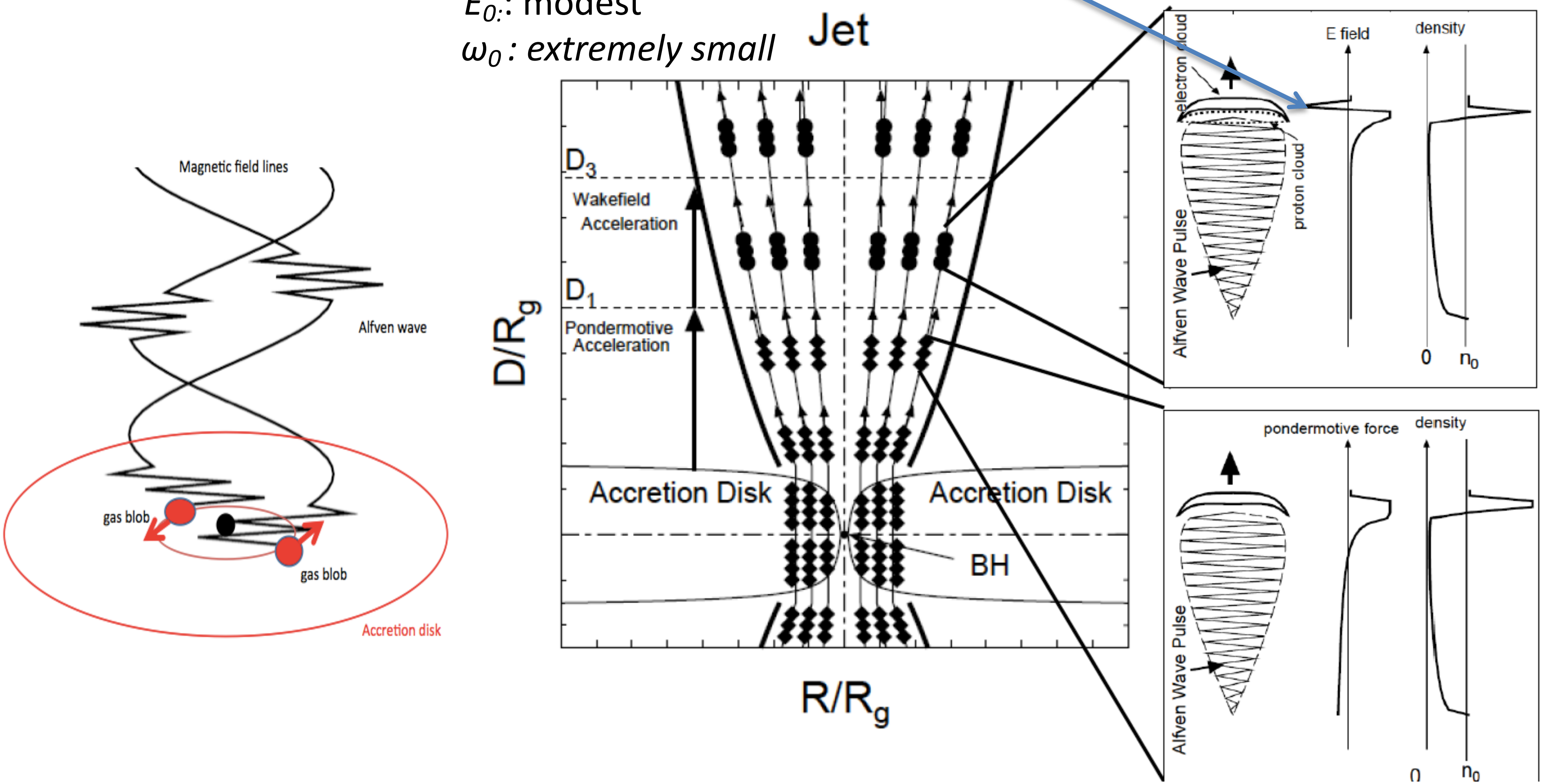
pump depletion length

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

$a_0 = eE_0 / mc\omega_0 >> 1$

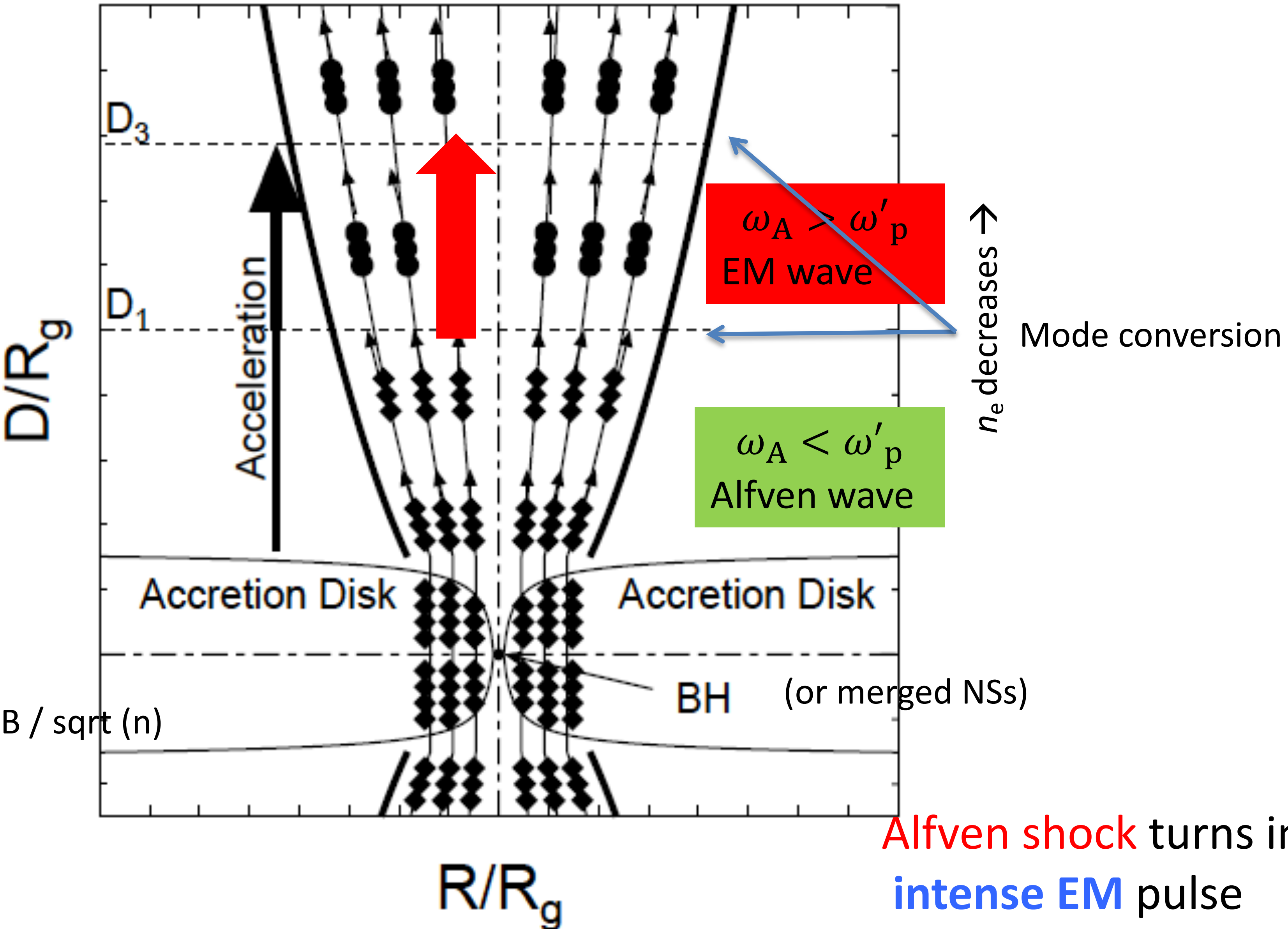
E_0: modest

ω_0 : extremely small



Ebisuzaki and Tajima, Astropart. Phys.(2014)

Wakefield in Jet



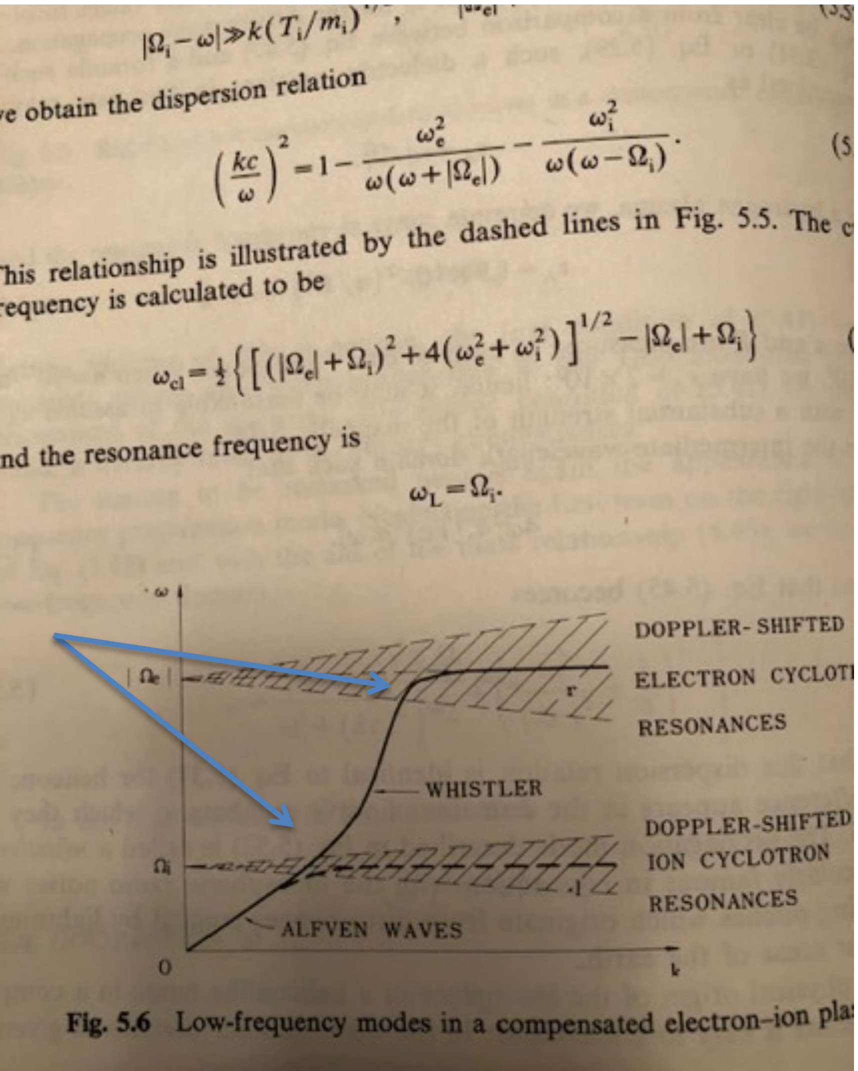
V_A ~ B / sqrt (n)

Alfven shock turns into intense EM pulse

T. Ebisuzaki and T. Tajima, Astropart. Phys. (2014)

Mode conversion along the jet

As Alfven shock propagates along jet, $\omega = kv_A$ kept const. while $v_A \sim B / \sqrt{n}$, $\Omega \sim B$, $\omega_p \sim \sqrt{n}$
See what happens in the dispersion curves below:



$|\Omega_i - \omega| \gg k(T_i/m_i)^{1/2}$,

we obtain the dispersion relation

$$\left(\frac{kc}{\omega}\right)^2 = 1 - \frac{\omega_e^2}{\omega(\omega+|\Omega_e|)} - \frac{\omega_i^2}{\omega(\omega-\Omega_i)}.$$

This relationship is illustrated by the dashed lines in Fig. 5.5. The c
requency is calculated to be

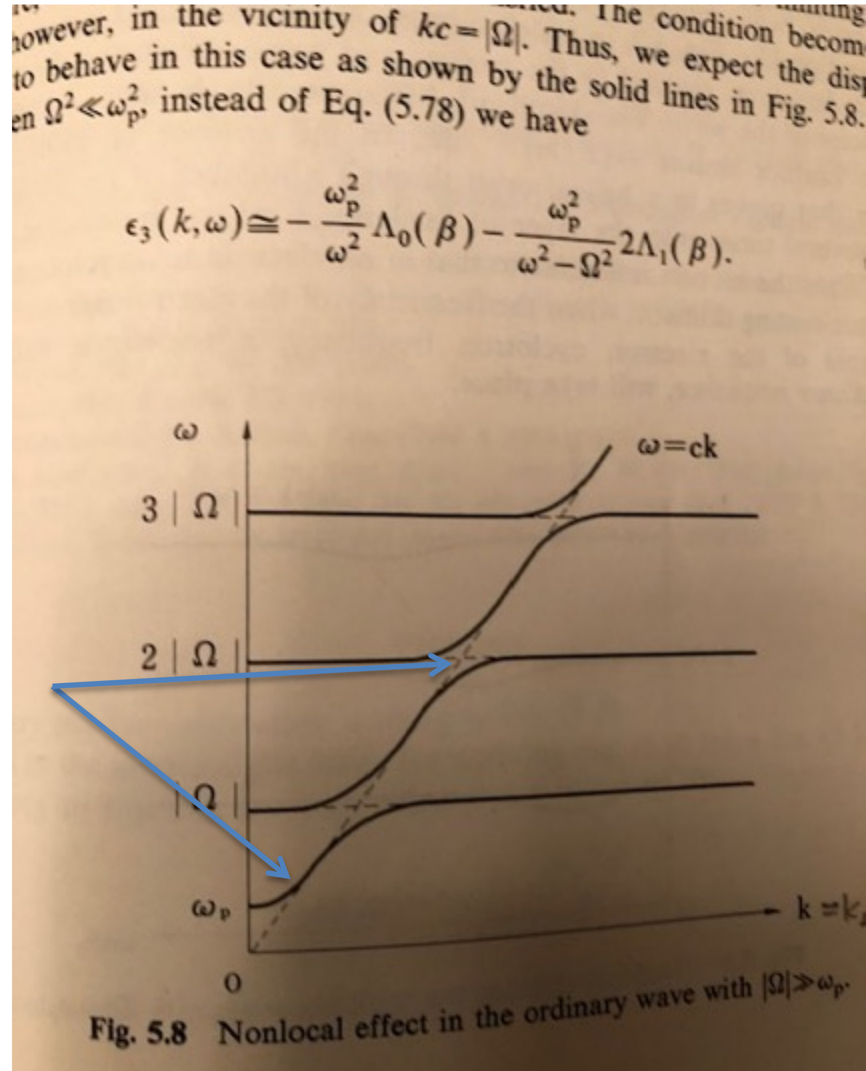
$$\omega_{cl} = \tfrac{1}{2}\left\{\left[(|\Omega_e|+\Omega_i)^2 + 4(\omega_e^2+\omega_i^2)\right]^{1/2} - |\Omega_e| + \Omega_i\right\}$$

and the resonance frequency is

$$\omega_L = \Omega_i.$$

Fig. 5.6 Low-frequency modes in a compensated electron–ion pla

S. Ichimaru (1973)

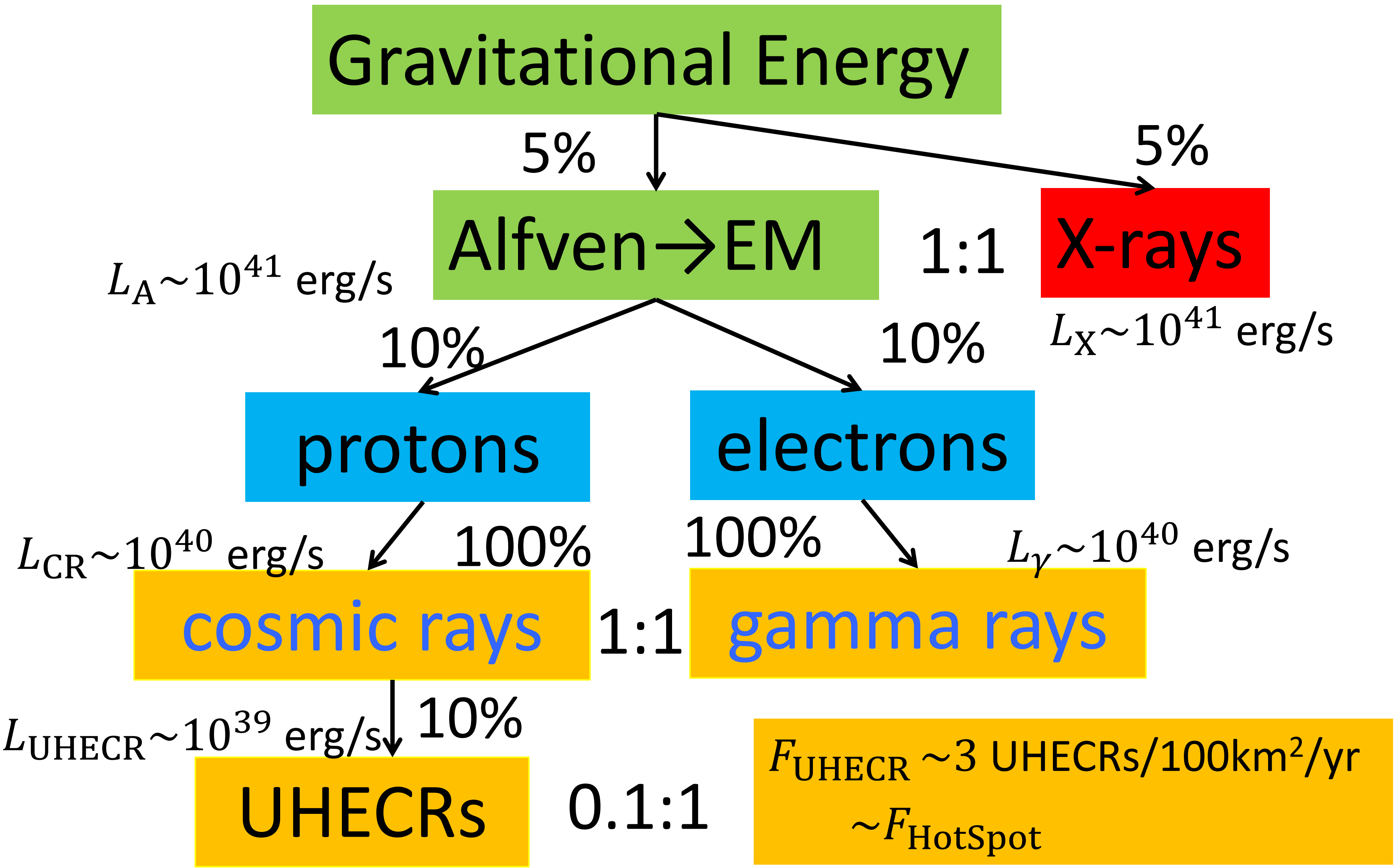


however, in the vicinity of $kc = |\Omega|$. Thus, we expect the disp
to behave in this case as shown by the solid lines in Fig. 5.8.
en $\Omega^2 \ll \omega_p^2$, instead of Eq. (5.78) we have

$$\epsilon_3(k,\omega) \simeq -\frac{\omega_p^2}{\omega^2}\Lambda_0(\beta) - \frac{\omega_p^2}{\omega^2-\Omega^2}2\Lambda_1(\beta).$$

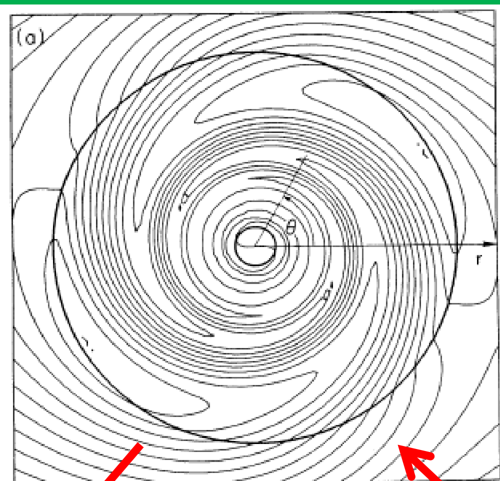
Fig. 5.8 Nonlocal effect in the ordinary wave with $|\Omega| \gg \omega_p$.

Energy release by wakefield

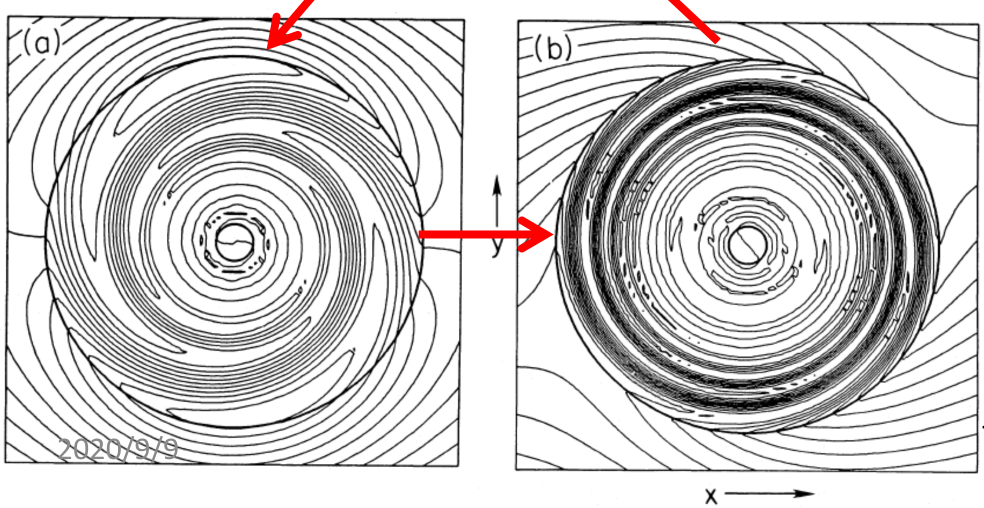


Halo and jet acceleration in an accretion disk

A Burst of Electromagnetic Disturbance

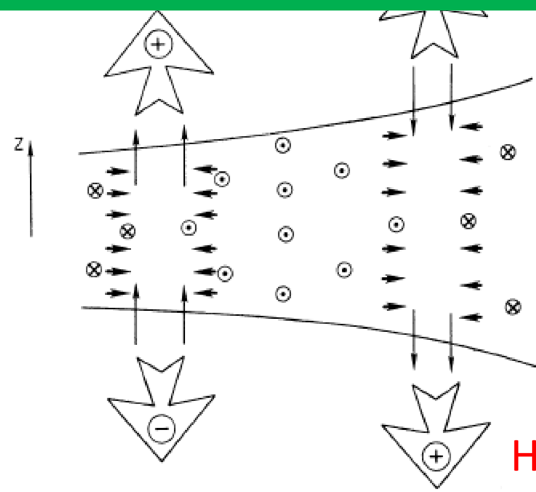


low



growing

high



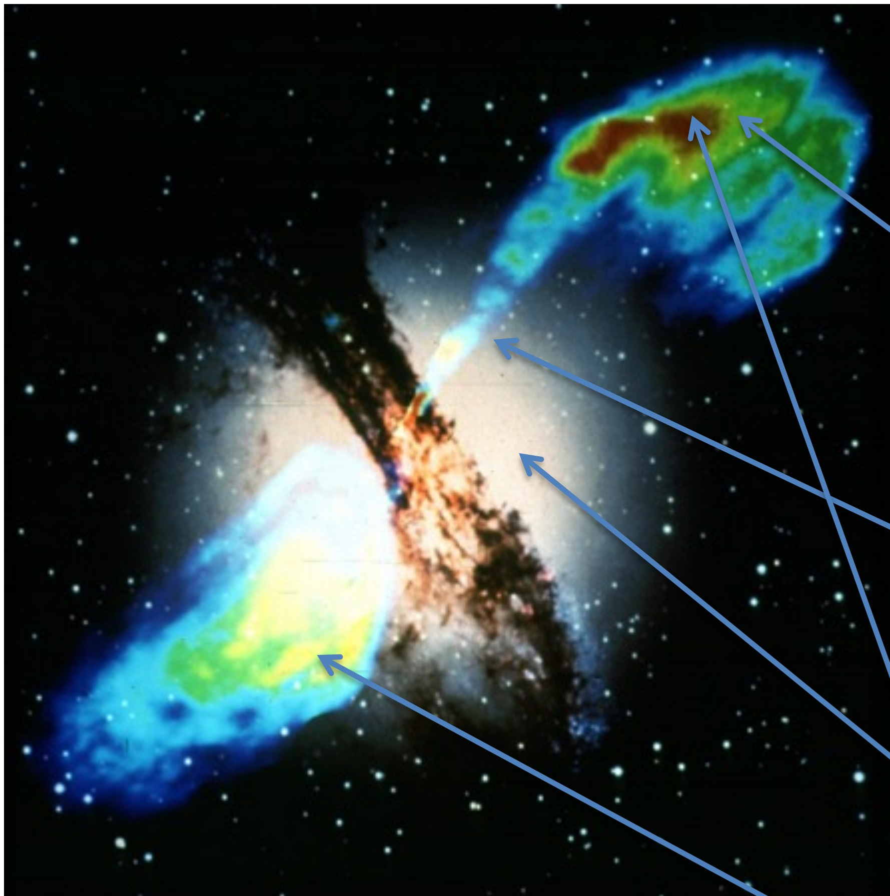
Halo heating and acceleration

→ low energy X and γ

Tajima and Gilden 1987, ApJ 320, 741-745

Haswell, Tajima, and Sakai, 1992, ApJ, 401, 495-507

"Physiology" of AGN energy releases



Cen A

- Distance : 3.4Mpc
- Radio Galaxy
  - Nearest
  - Brightest radio source
- Elliptical Galaxy
- Black hole at the center w/ relativistic **jets**, high energy acceleration

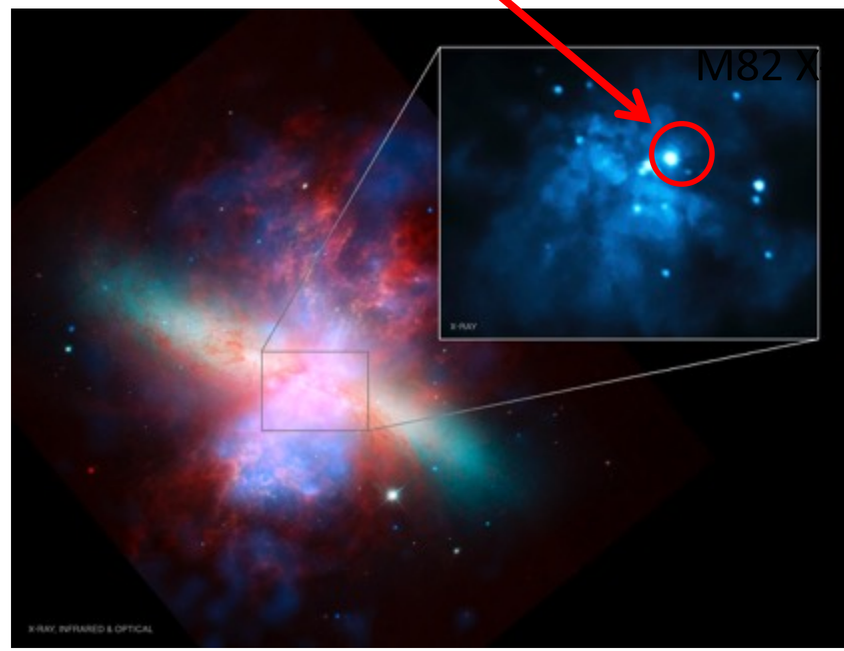
Halo emissions

Lobe deceleration of jets

M82: Nearest Starburst Galaxy

M82 X-1: 1000-10000 Ms BH

Just after the collision with M81

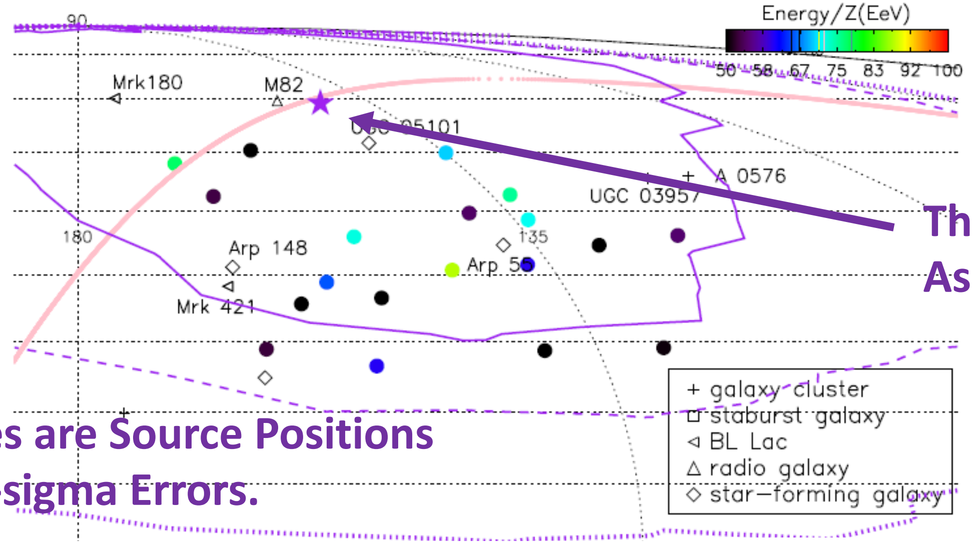


Composite of X-ray, IR, and optical emissions

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.

TA Hot Spot: UHECRs from M82?

He, Kusenko, Nagataki + PRD 2016.



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

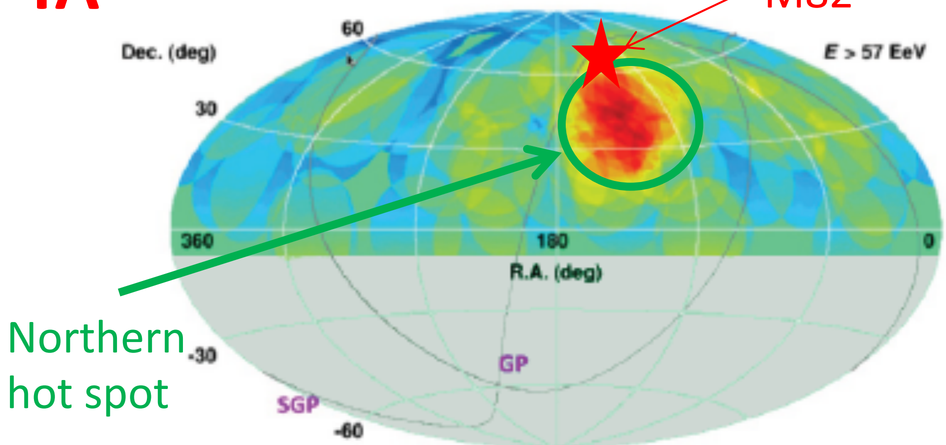
M82 is very Close from the most likely Source Position!

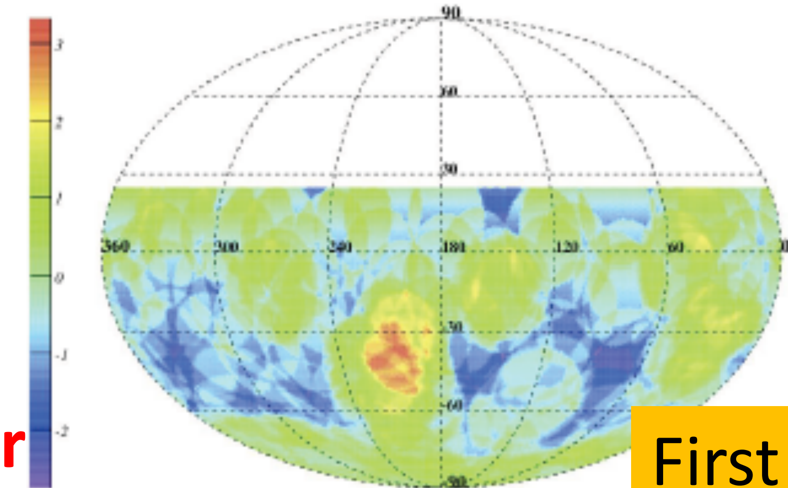
Purple Lines are Source Positions With 1,2,3-sigma Errors.

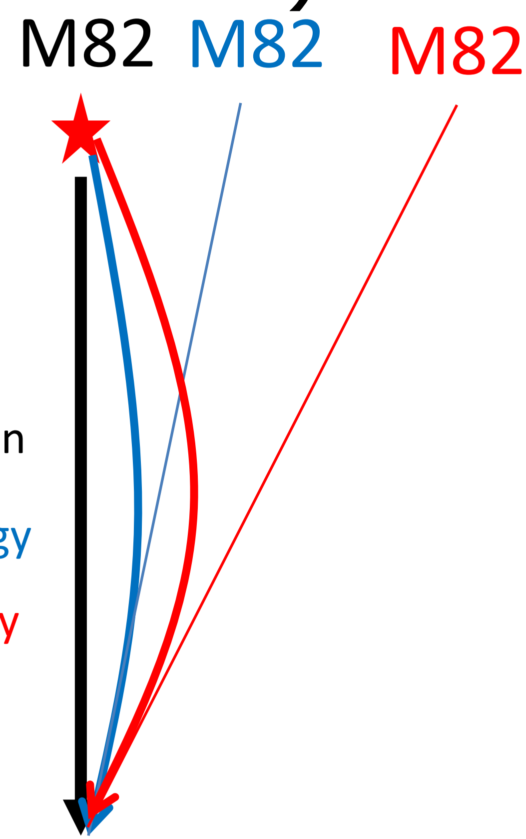
Source Name	Source Type	Distance (Mpc)	A_1 (°)	A_2 (°)	$P/P_{\rm bes-fit}$ (%)
best-fit	-	-	$17.4^{+17.0}_{-11.0}$	$9.4^{+3.7}_{-0.3}$	100
M82	starburst galaxy	3.4	17.6	9.6	99.8
UGC 05101	star-forming galaxy	160.2	11.6	9.2	96.9
Mrk 180	blazar	185	19.9	9.3	91.3
UGC 03957	galaxy cluster	150.3	14.9	9.5	67.4
A 0576	galaxy cluster	169.0	17.0	9.4	63.4
Arp 55	star-forming Galaxy	162.7	1.9	9.7	55.3
Arp 148	star-forming Galaxy	143.3	10.5	10.0	41.8
Mrk 421	blazar	134	11.2	9.9	35.6

Arrival Direction Map
(cosmic rays>5×10^{19} eV)

TA







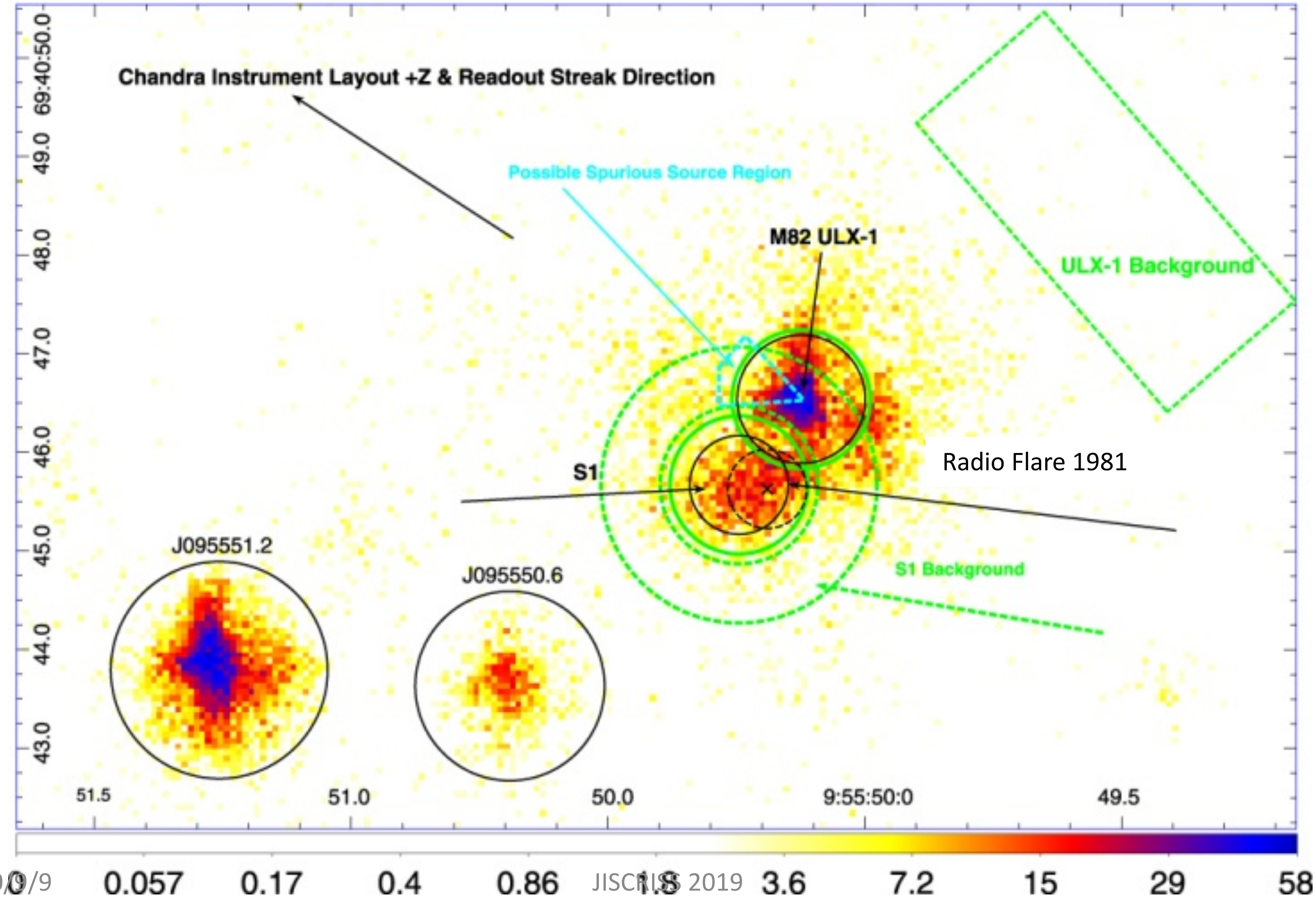
Magnetic bending of charged particles

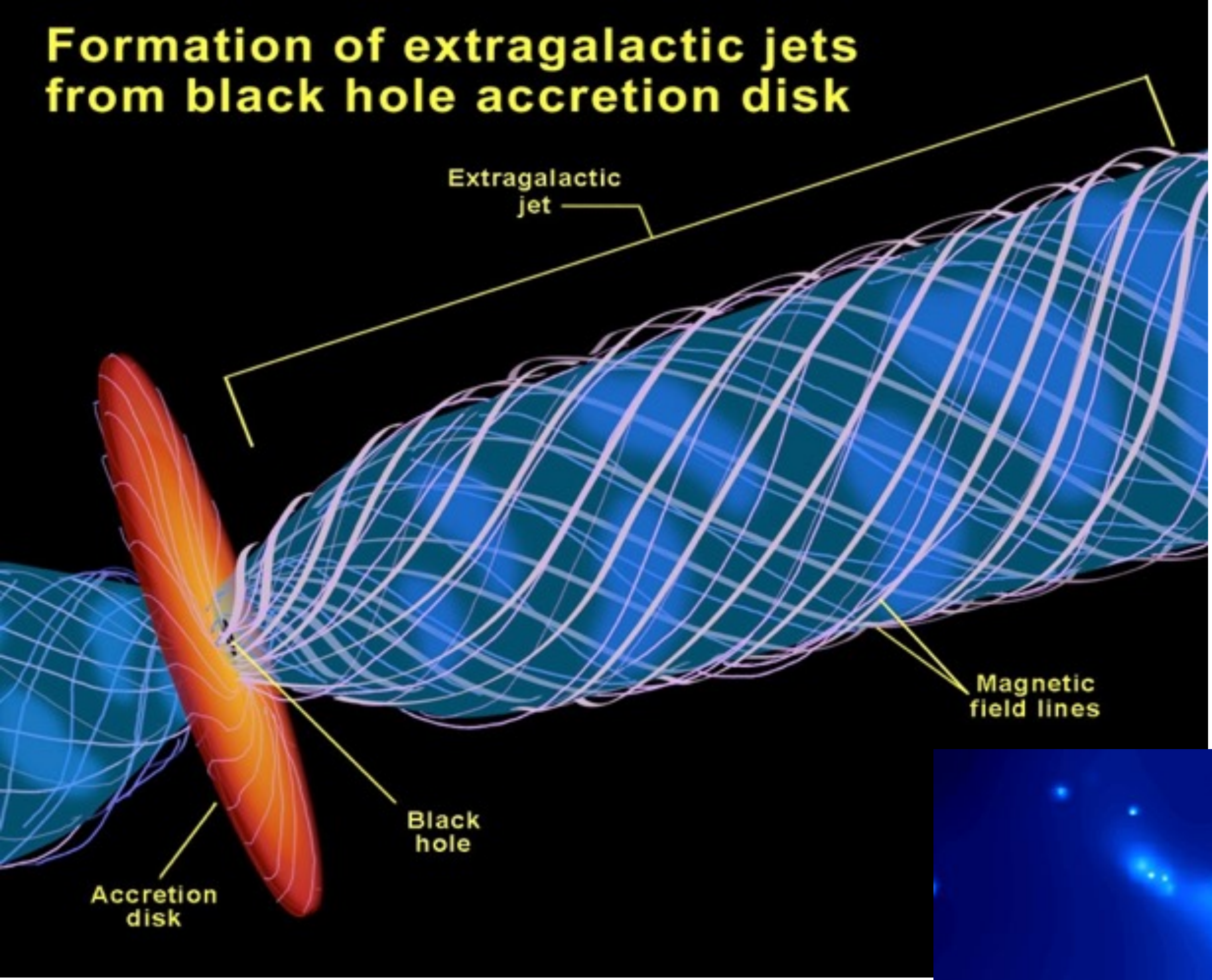
First Identification of CR sources?

First sign of anisotropy in charged particles

An AGN-like Jet in M82?
X-ray/Radio (flare in 1981)

Xu et al. 2015 ApJ Letters 799, L28

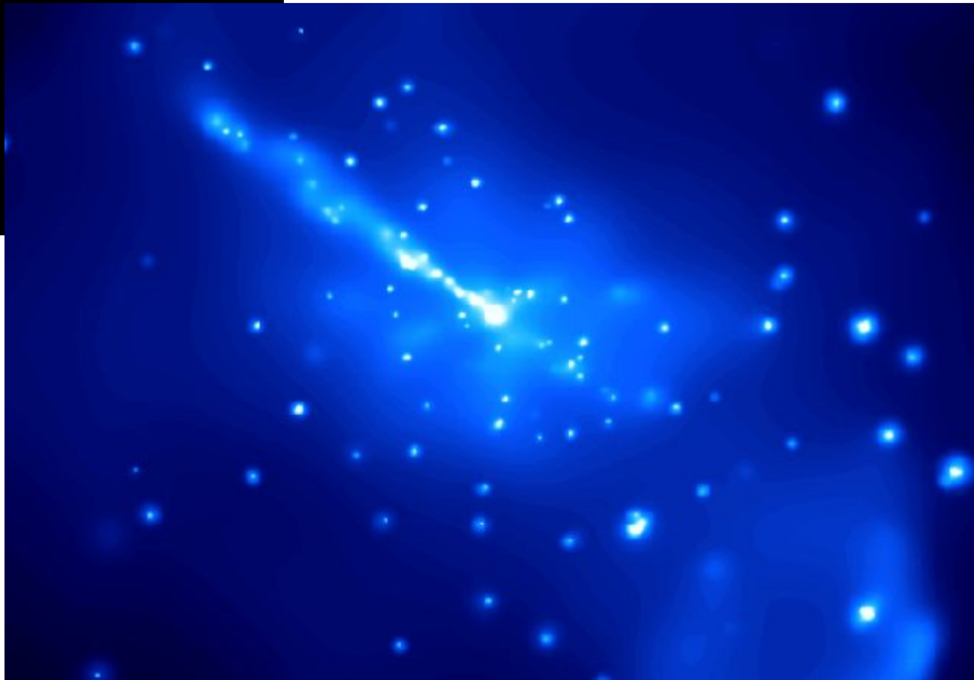




Fermi's '**Stochastic Acceleration**'
(large synchrotron radiation loss)

🡻

Coherent wakefield **acceleration**
(no limitation of the energy)

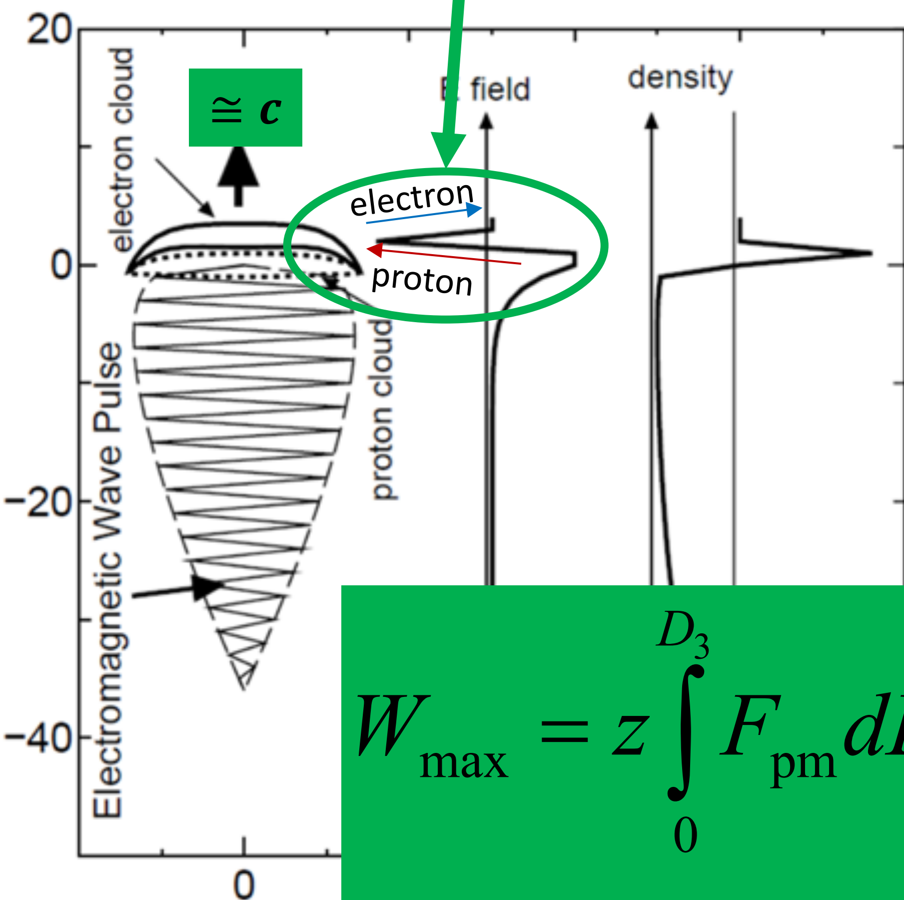


Nature's LWFA **: Blazar** jets
extreme high energy cosmic rays (~10^{21} eV)
episodic γ-ray bursts observed
consistent with LWFA theory

Ebisuzaki-Tajima (2014)

Wakefield Acceleration

Co-linear acceleration by electrostatic field

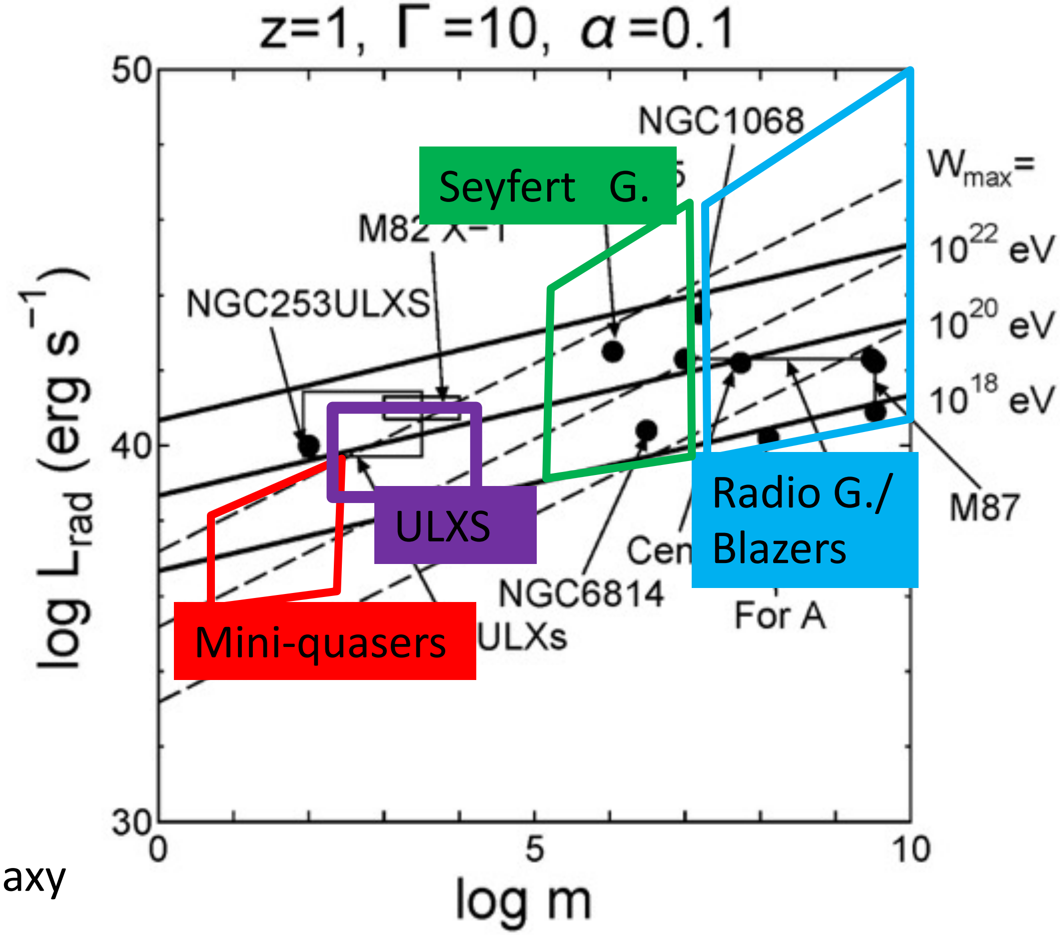


$$W_{\max} = z \int_0^{D_3} F_{\mathrm{pm}} \, dD$$

$$F_{\mathrm{pm}} = \Gamma m_e c a_0 \omega_A$$

- **Stable acceleration structure**
  - Coherent and Strong Field
  - Moving in $\cong c$
  - Colinear acceleration
  - across a long length
  - Built in deep in the theory
- **All the messenger channels**
  - Electrons→photons (HE, radio)
  - Protons→CRs→neutrinos
  - Gravitational waves (NS mergers)
- **Variabilities**
  - Caused by disk instability
  - In all messenger channels
  - Violent and simultaneous

cosmic ray acceleration and gamma-ray emission



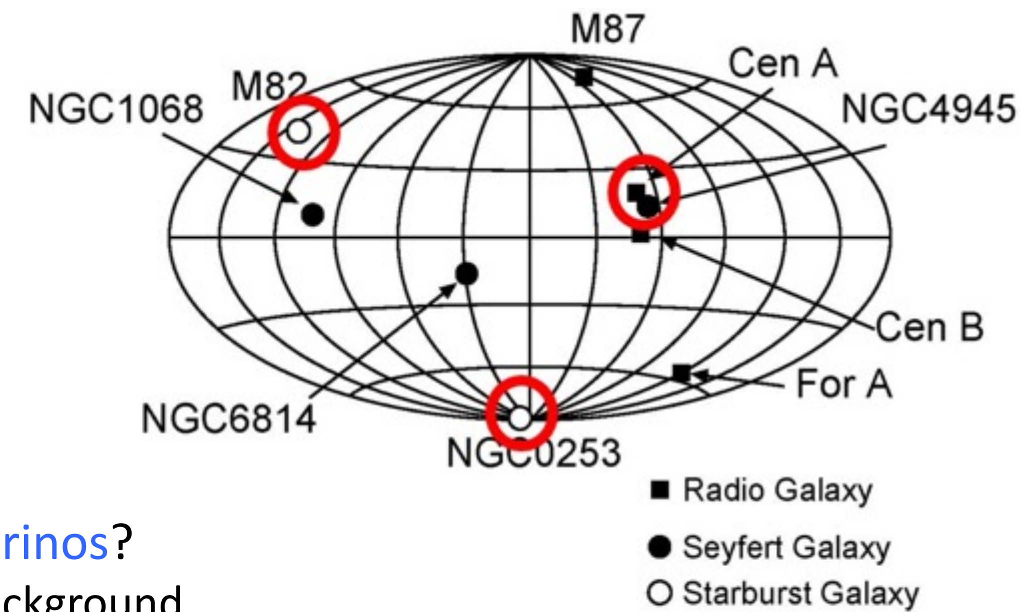
Miniquasars:
can be in our Galaxy

Ebisuzaki, Tajima
EPJ **223**, 1113(2014);
(2020)

BH Astronomy with Ultra High Energy CRs

Brightest cosmic rays by wakefields

(A)



Localized UHECR?

thus Localized neutrinos?

not as a spread background

(B)