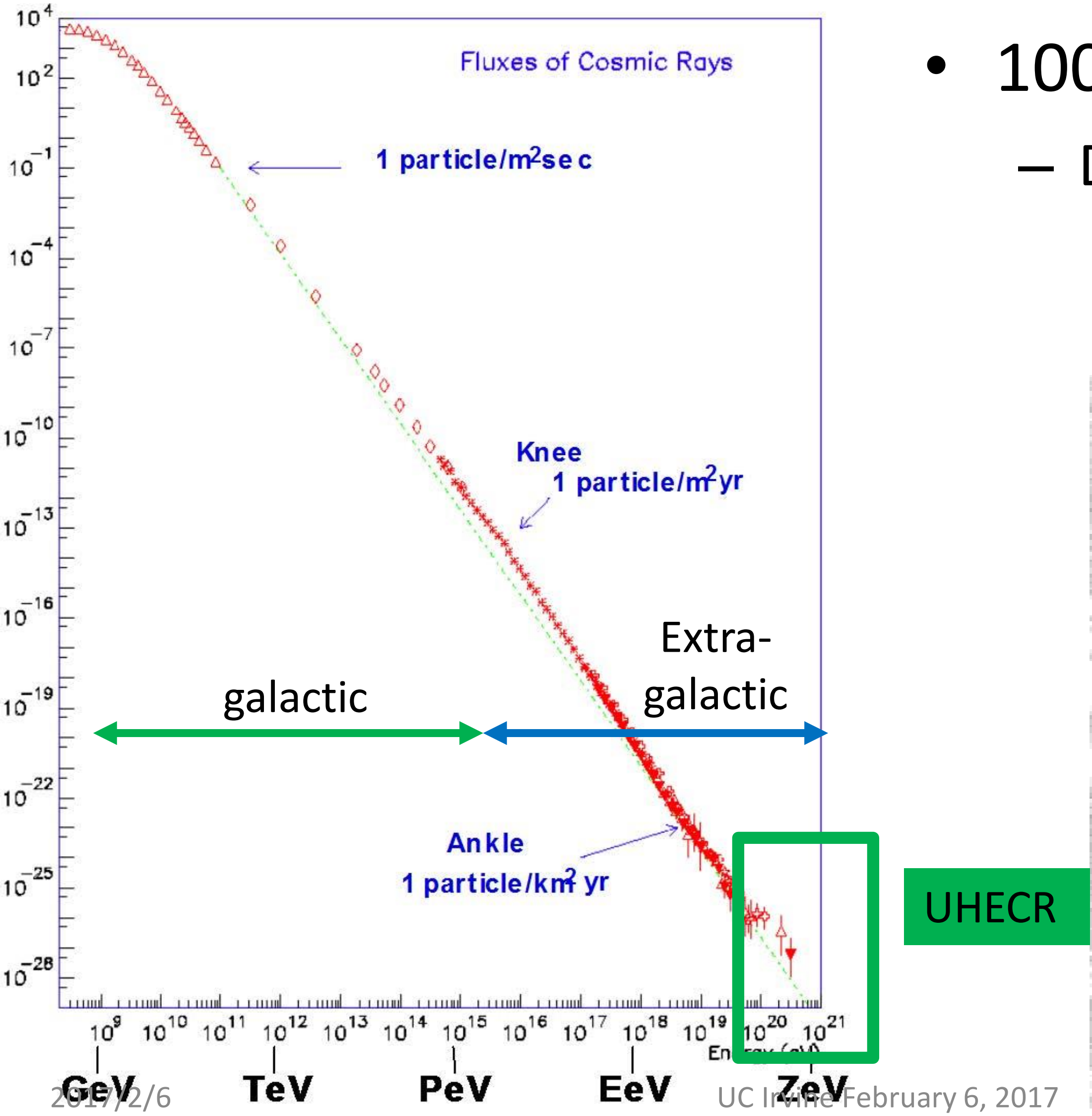
Astronomical ZeV Acceleration in the relativistic jet from an accreting supermassive blackholes

Toshikazu Ebisuzaki and Akira Mizuta
(RIKEN)

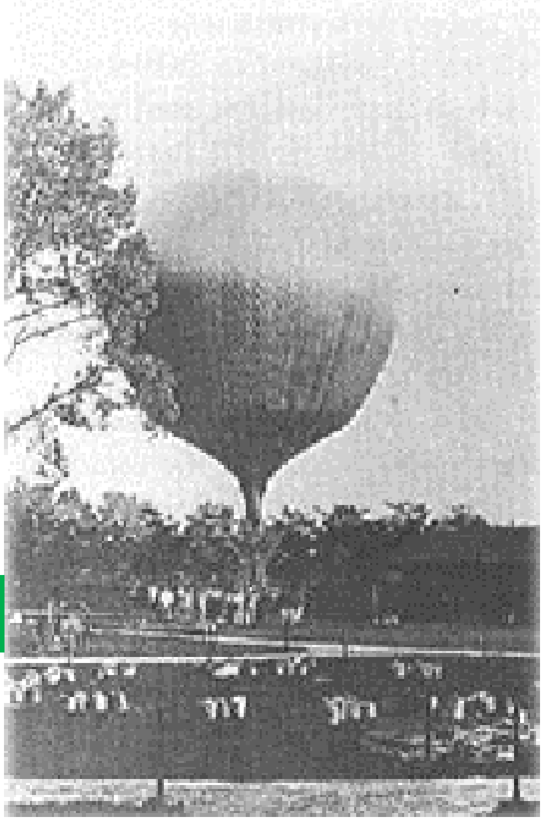
Toshiki Tajima (UC Irvine)

Origin of Cosmic rays

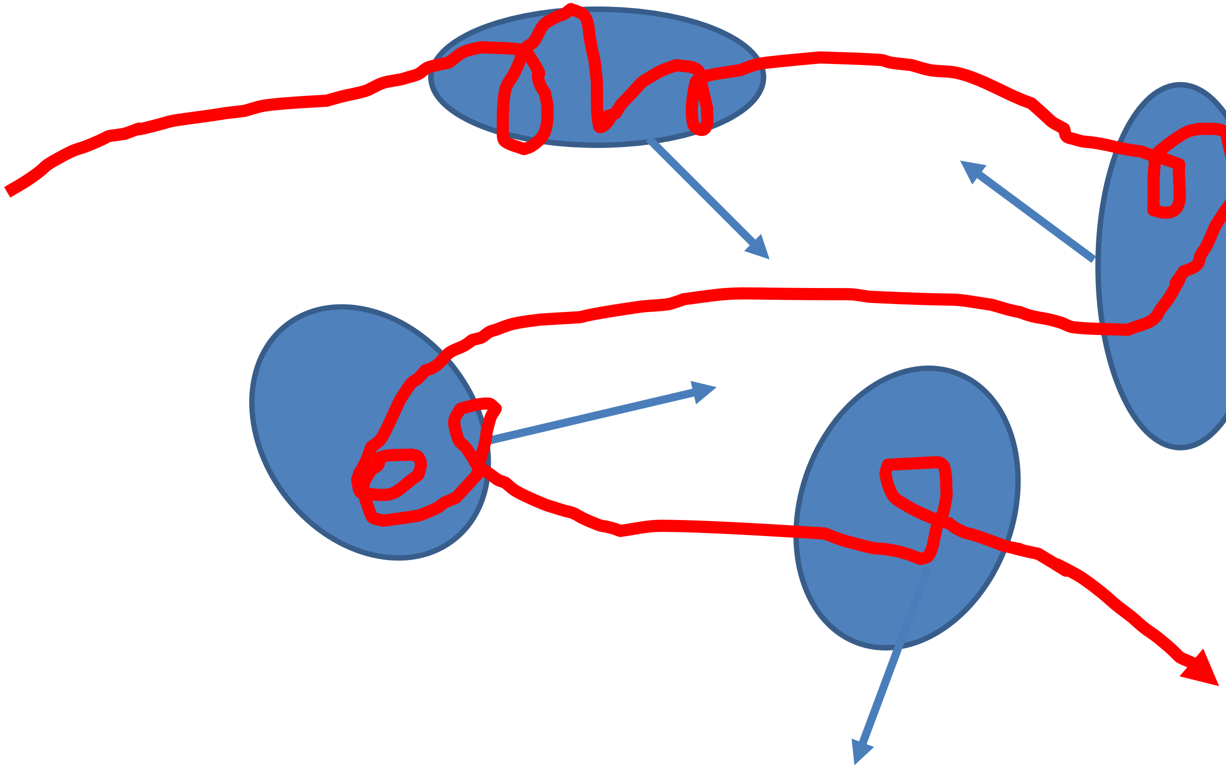


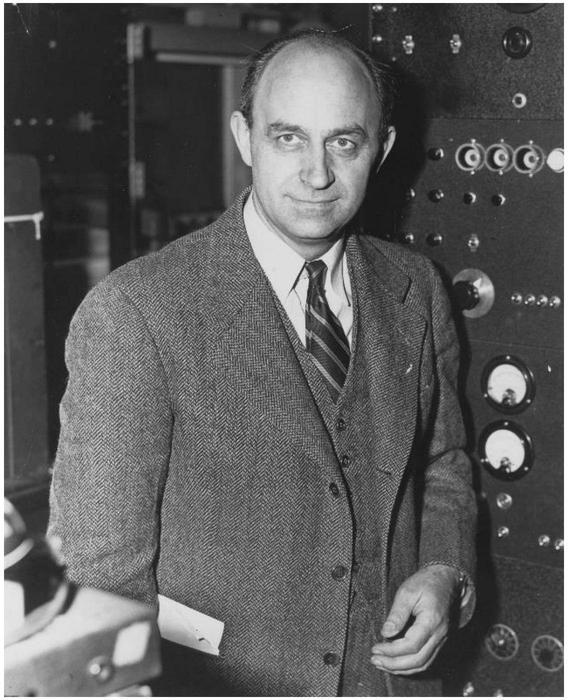
- 100 years enigma
  - Discovered in 1912

    by Victor Hess



Conventional theory:
Fermi mechanism





By Department of Energy. Office of Public Affairs

E. Fermi, ApJ 119 (1954) 1.

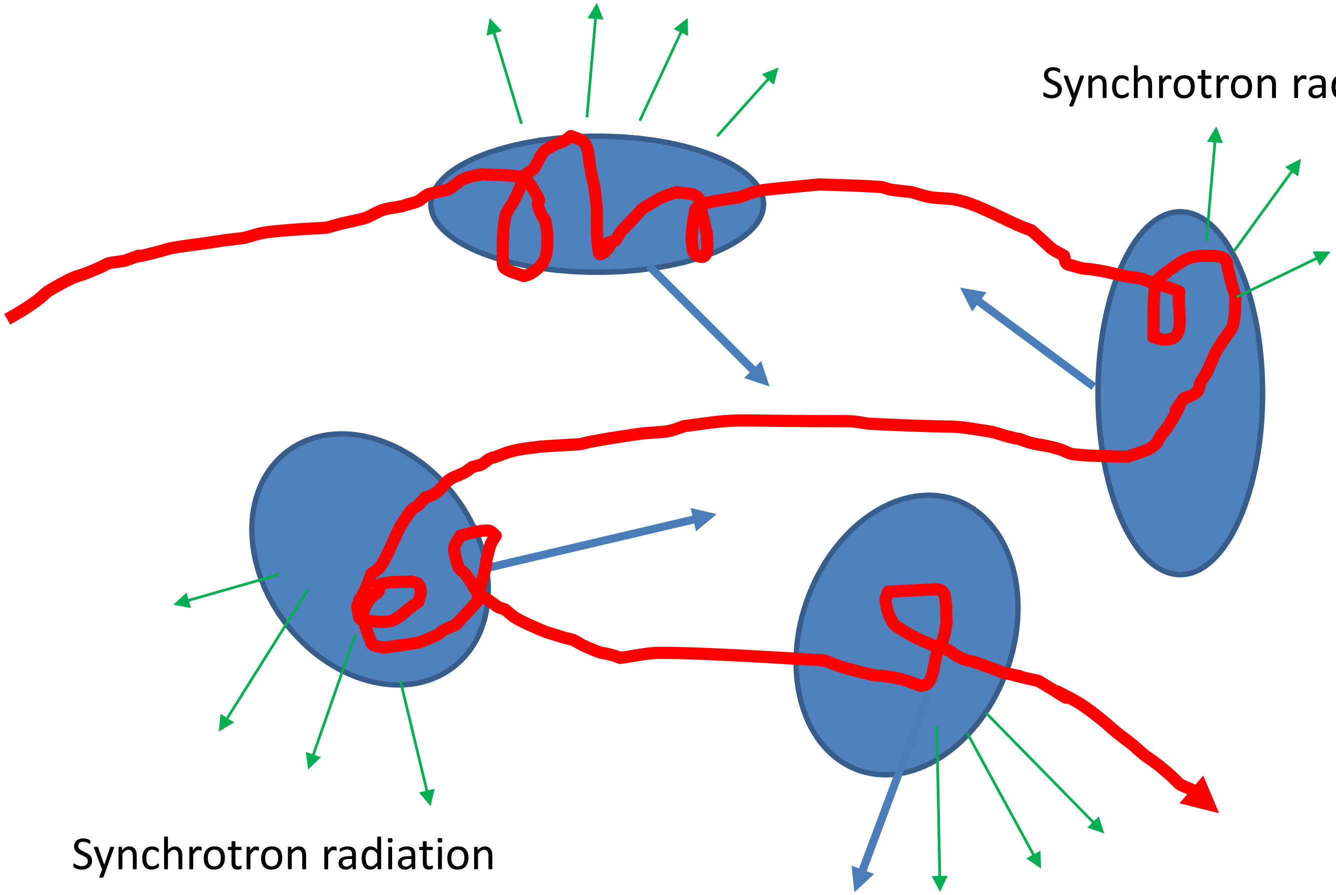
Difficulties of Fermi acceleration in UHECR~10^{20} eV

1. Bending is inevitable

    →synchrotron loss

Fermi mechanism

requires bending→synchrotron loss

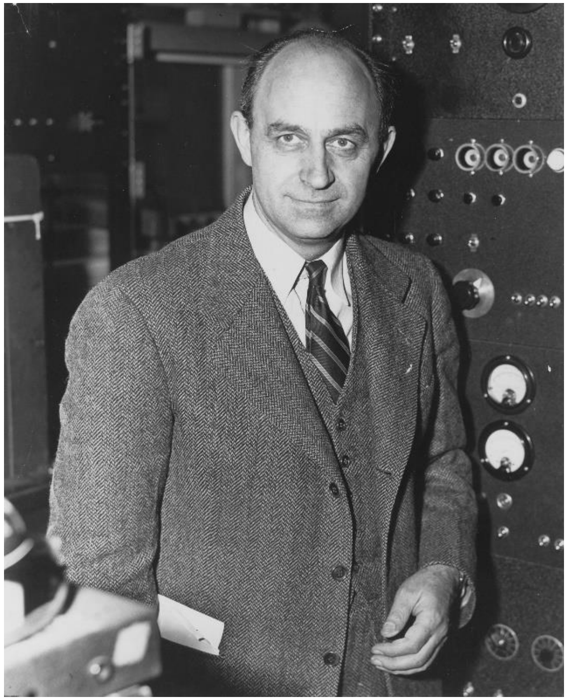


Synchrotron radiation

Synchrotron radiation

Synchrotron radiation

Synchrotron radiation



By Department of Energy. Office of Public Affairs

E. Fermi, ApJ 119 (1954) 1.

Difficulties of Fermi acceleration in UHECR

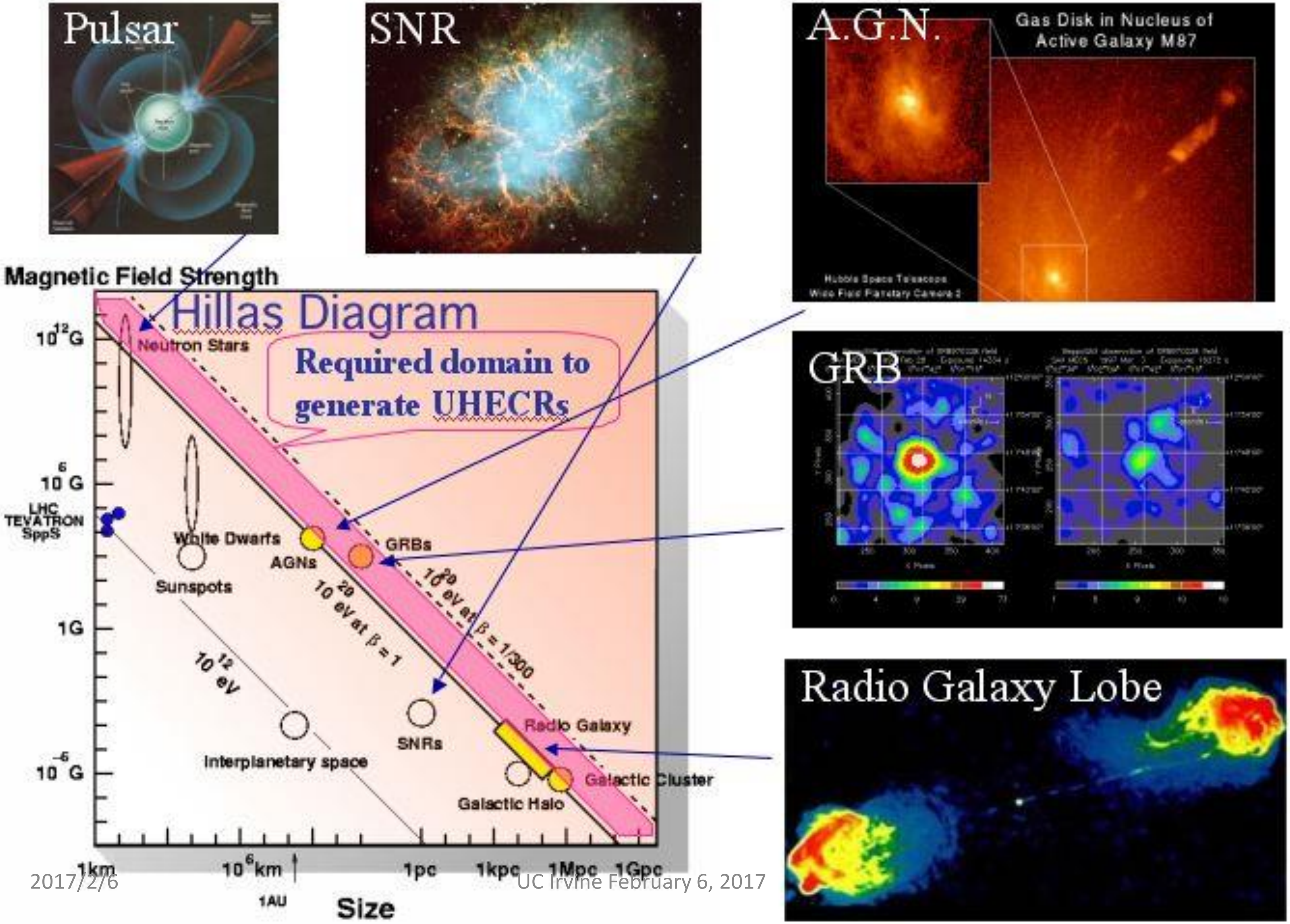
1. Bending is inevitable

   →synchrotron loss

2. Confinement is difficult

   →no acceleration

Theoretical Upper limit of Fermi mech.< 10^{20} eV



Difficulties of Fermi acceleration in UHECR

1. Bending is inevitable

   →synchrotron loss

2. Confinement is difficult

   →no acceleration

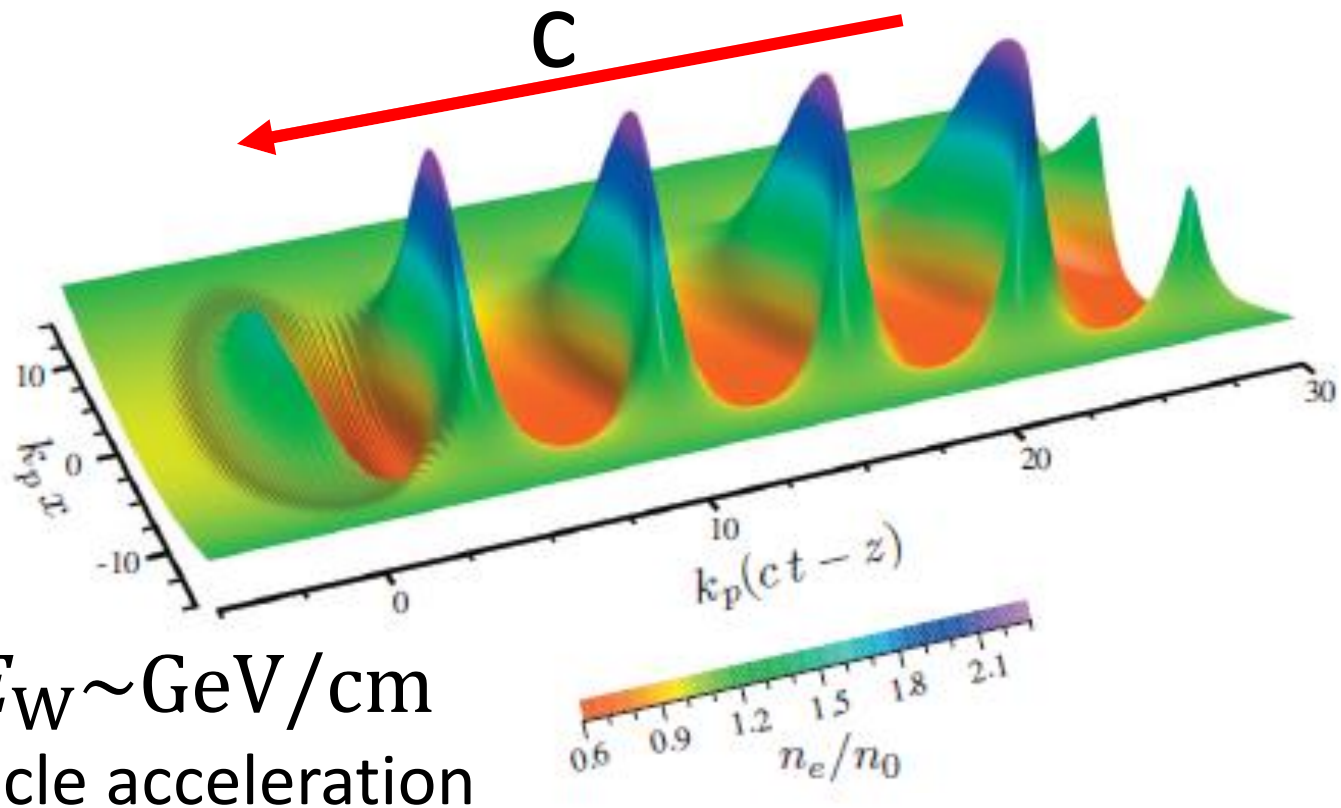
3. Escape problem

   →magnetic field does not disappear without adiabatic loss

Wakefield acceleration

Wake of a ship

Laser Wakefield



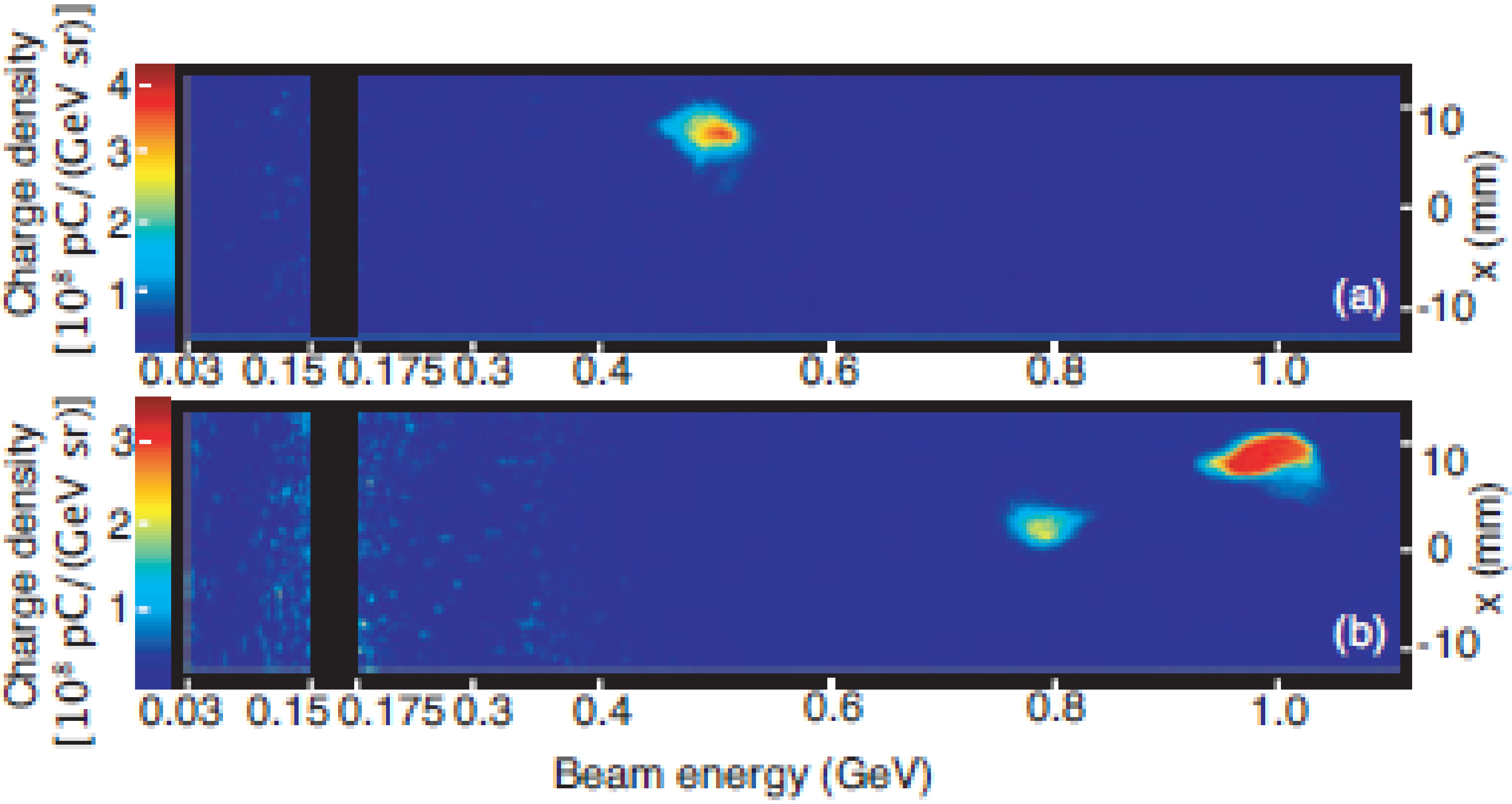
$E_W \sim \mathrm{GeV/cm}$

Particle acceleration

T. Tajima and J. M. Dawson (1979)

FIG. 2. (Color) Plasma density perturbation excited by Gaussian laser pulse with $a_0=1.5$, $k_0/k_p=20$, $k_pL_{\mathrm{rms}}=1$, and $k_pr_0=8$. Laser pulse is traveling to the left.

Electron bunch by a single shot of laser beam



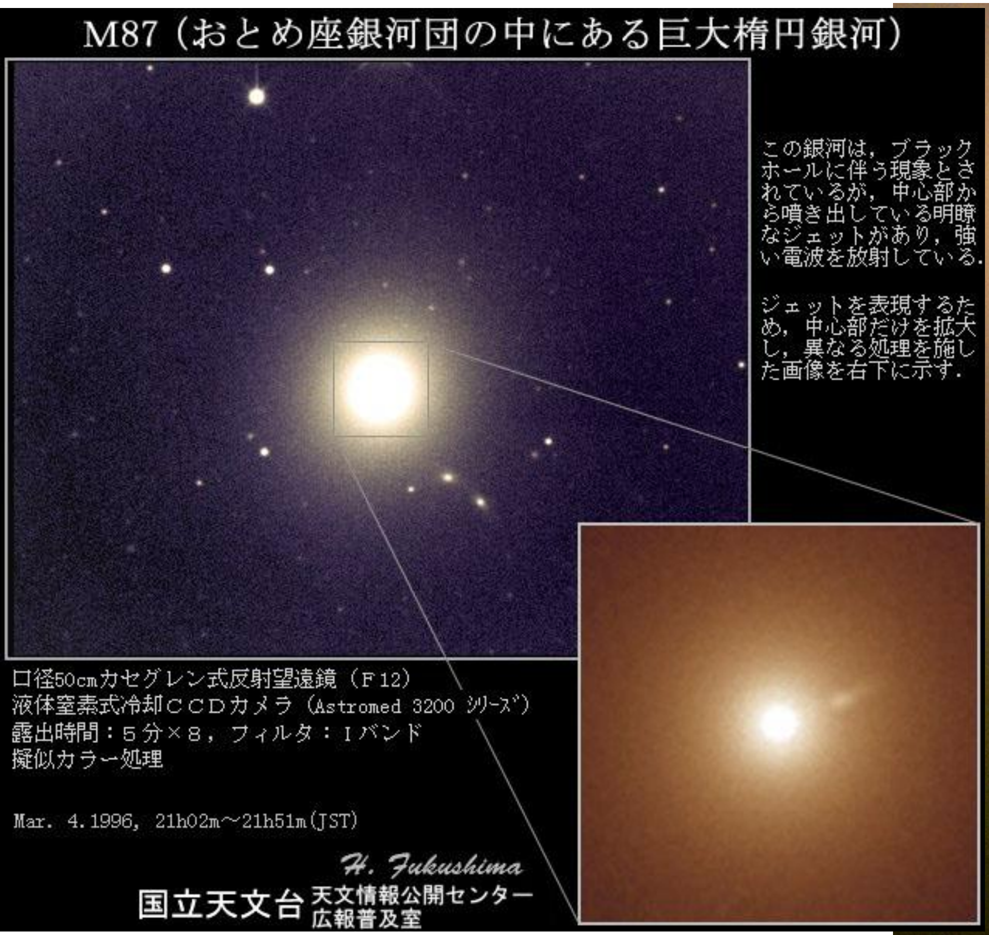
Leemans et al. (2006) Nature Physics, 2, 696.

Nakamura et al. (2007) Phys. Plasma, 14, 056078

Linear Acceleration with an Accreting Blackhole

- (Super-) massive blackholes
  - Central Engines of Active Galactic Nuclei:
    - Radio Galaxies/Blazars: 10^8-10^9 solar mass
    - Seyfert Galaxies: ~10^6 solar mass
      - Center of Milky Way G.: 4×10^6 solar mass BH
    - Starburst Galaxies:
      - ~$10^{2\text{-}5}$ solar mass=Intermediate mass BH in young clusters
      - Ultra Luminous X-ray Sources
- Accretion disk:
  - Strong Alfven wave emitter
- Jet:
  - Relativistic Flow Γ=10-30

Vir A=M87



M87（おとめ座銀河団の中にある巨大楕円銀河）

この銀河は，ブラックホールに伴う現象とされているが，中心部から噴き出している明瞭なジェットがあり，強い電波を放射している．

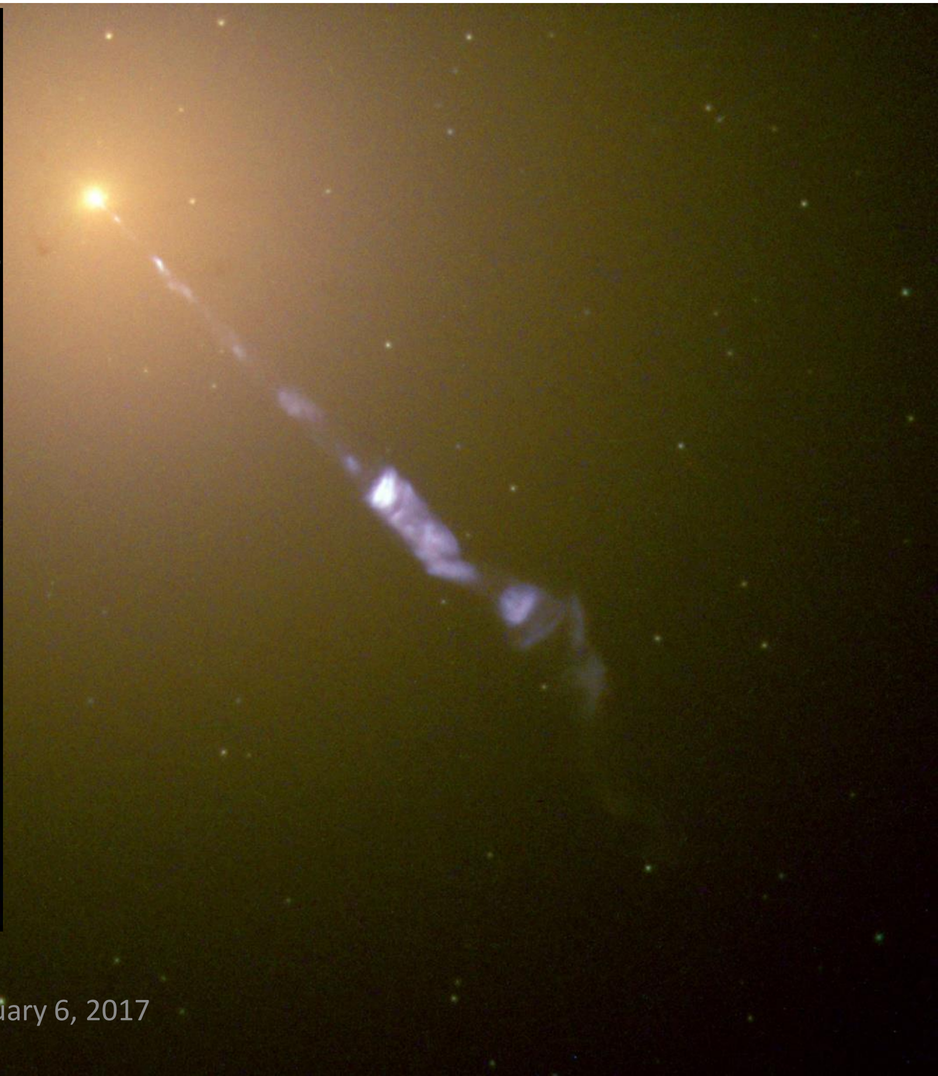
ジェットを表現するため，中心部だけを拡大し，異なる処理を施した画像を右下に示す．

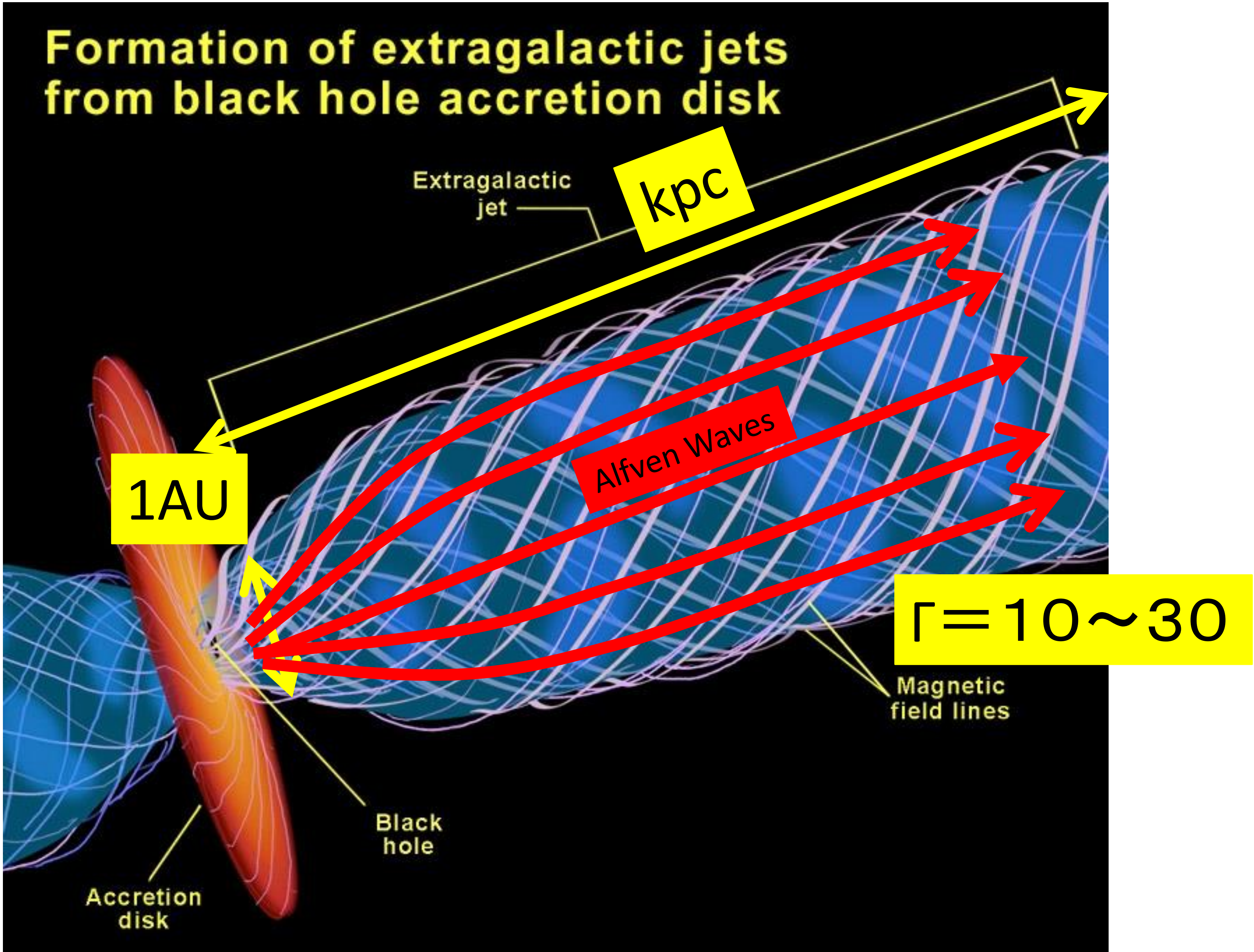
口径50cmカセグレン式反射望遠鏡（Ｆ12）
液体窒素式冷却ＣＣＤカメラ（Astromed 3200 ｼﾘｰｽﾞ）
露出時間：５分×８，フィルタ：Ｉバンド
擬似カラー処理

Mar. 4.1996, 21h02m〜21h51m(JST)

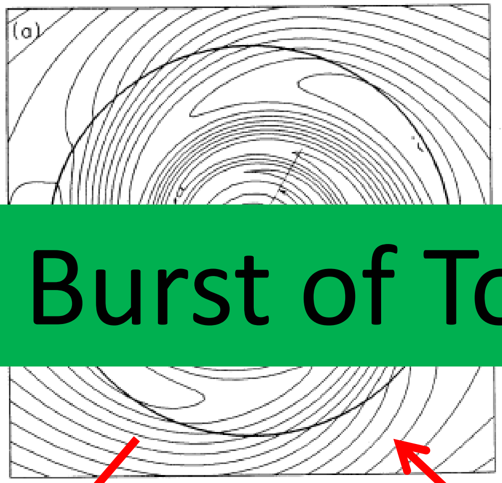
H. Fukushima

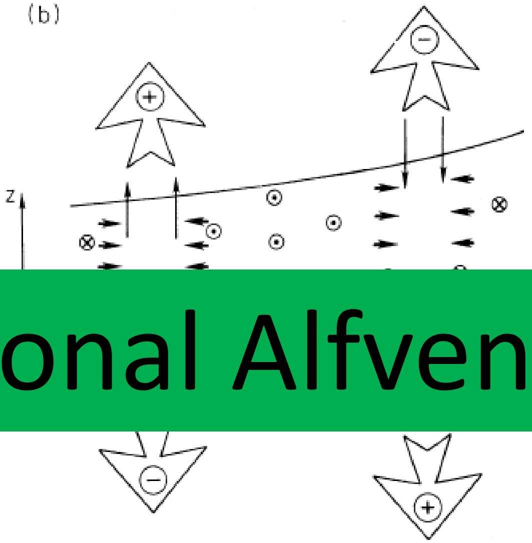
国立天文台 天文情報公開センター 広報普及室



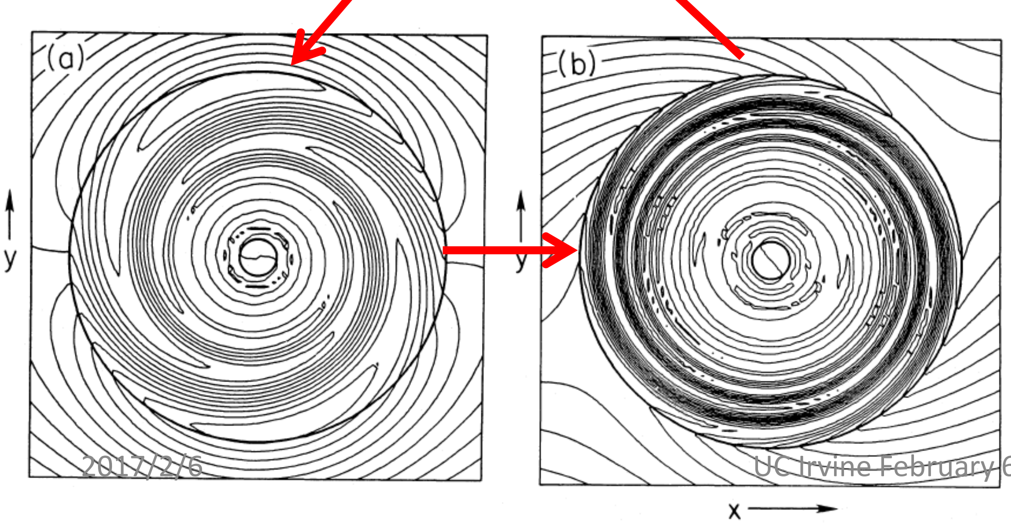

Formation of extragalactic jets from black hole accretion disk
Extragalactic jet
kpc
Alfven Waves
1AU
Γ＝10～30
Magnetic field lines
Black hole
Accretion disk

Eruption of magnetic field in an accretion disk





A Burst of Torsional Alfven Waves



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

Alfven Burst

Estimated at $10R_\mathrm{g}$

- Rise time

$$\tau_\mathrm{A} = (Z_\mathrm{D}/C_\mathrm{sD})(\Omega/A)$$

- Recurrence time

$$1/\nu_\mathrm{A} = Z_\mathrm{D}/(\eta V_\mathrm{AD})$$

- Energy Flux in a burst

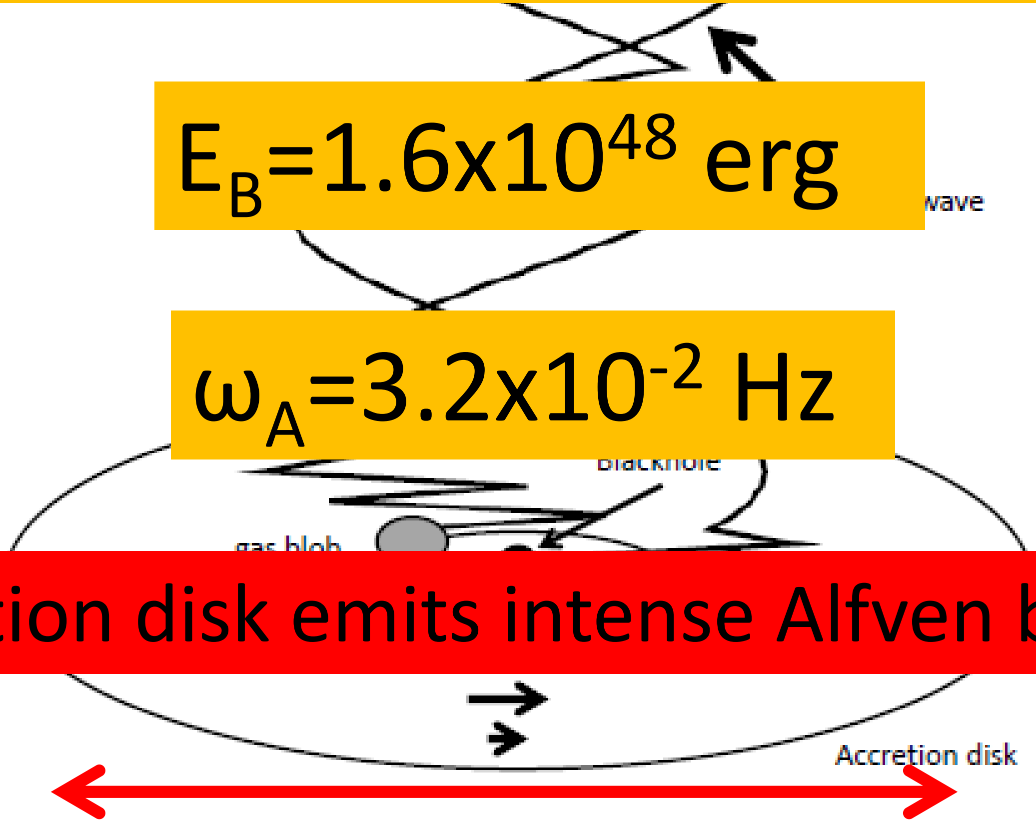
$$\Phi_\mathrm{AJ} = \Phi_\mathrm{AD} = V_\mathrm{AD}{B_\mathrm{D}}^2/4\pi$$

- Total energy of a burst

$$E_\mathrm{B} = ({B_\mathrm{D}}^2/4\pi)\pi(10R_\mathrm{g})^2$$

Accretion Disk around a BH

$m=10^8$



$a_0=eE/mc\omega_A=9.7\times10^{10}$

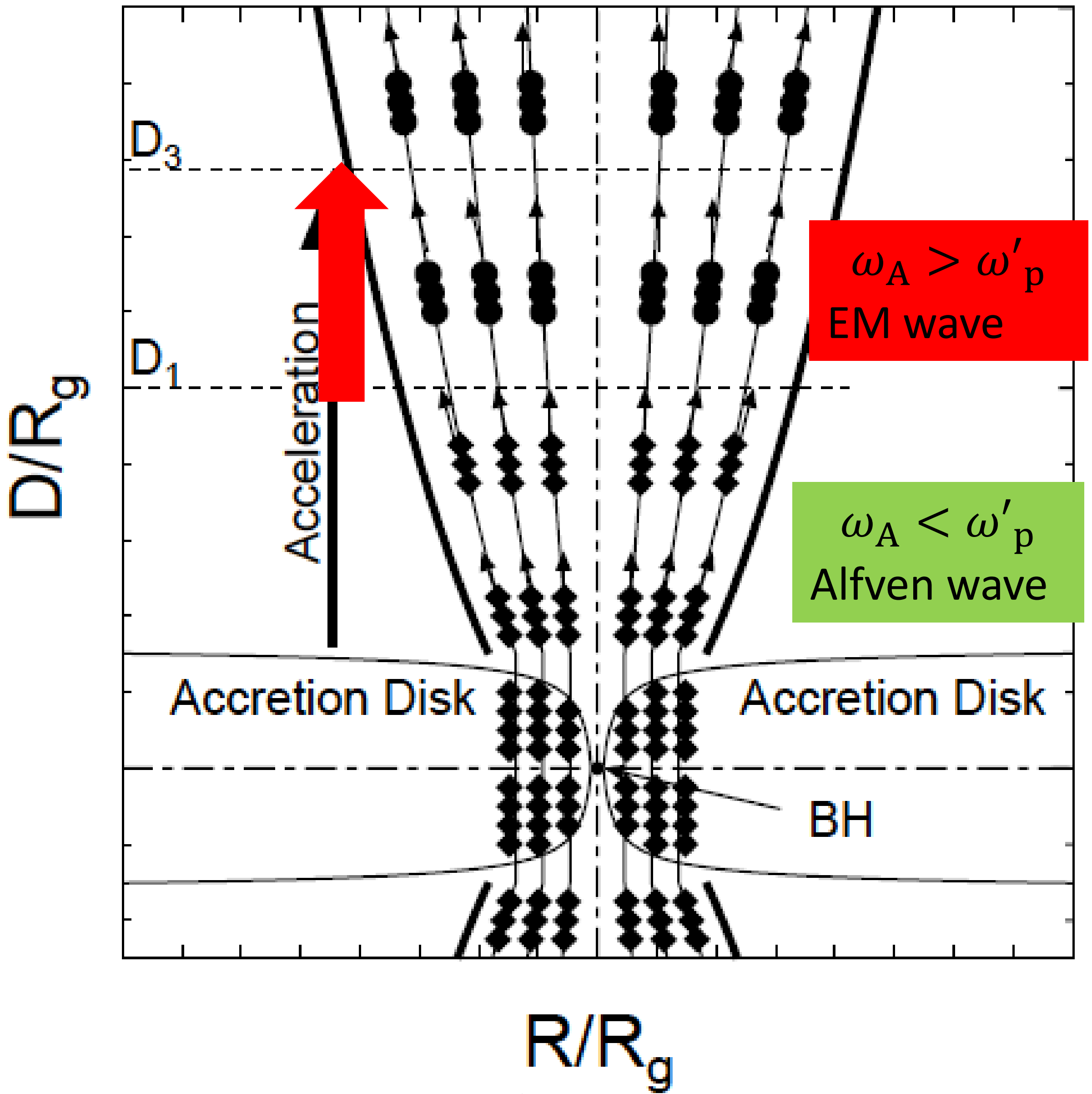
$E_B=1.6\times10^{48}$ erg

$\omega_A=3.2\times10^{-2}$ Hz

Accretion disk emits intense Alfven bursts

~AU

Jet

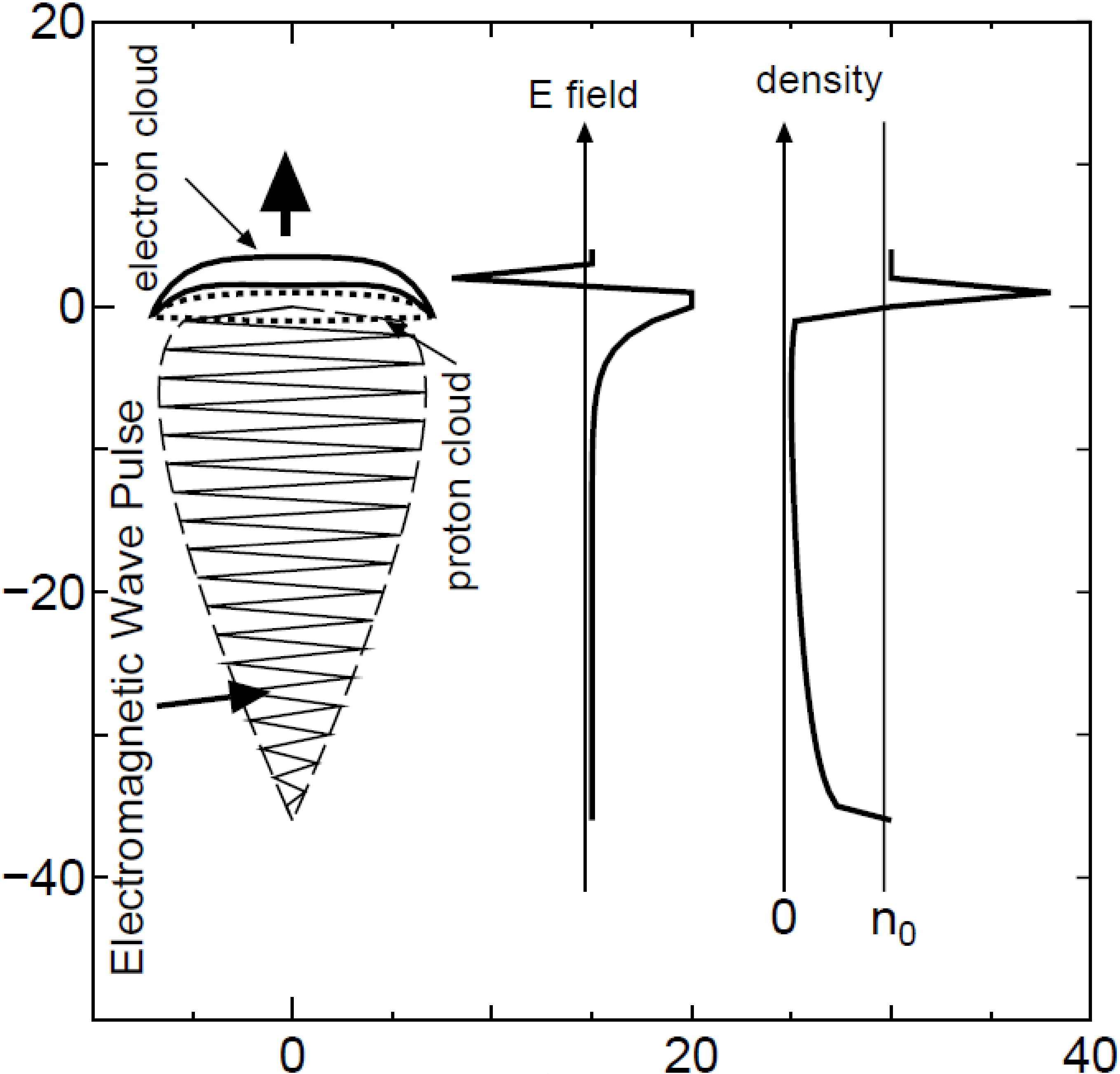


$\omega_\mathrm{A} > \omega'_\mathrm{p}$

EM wave

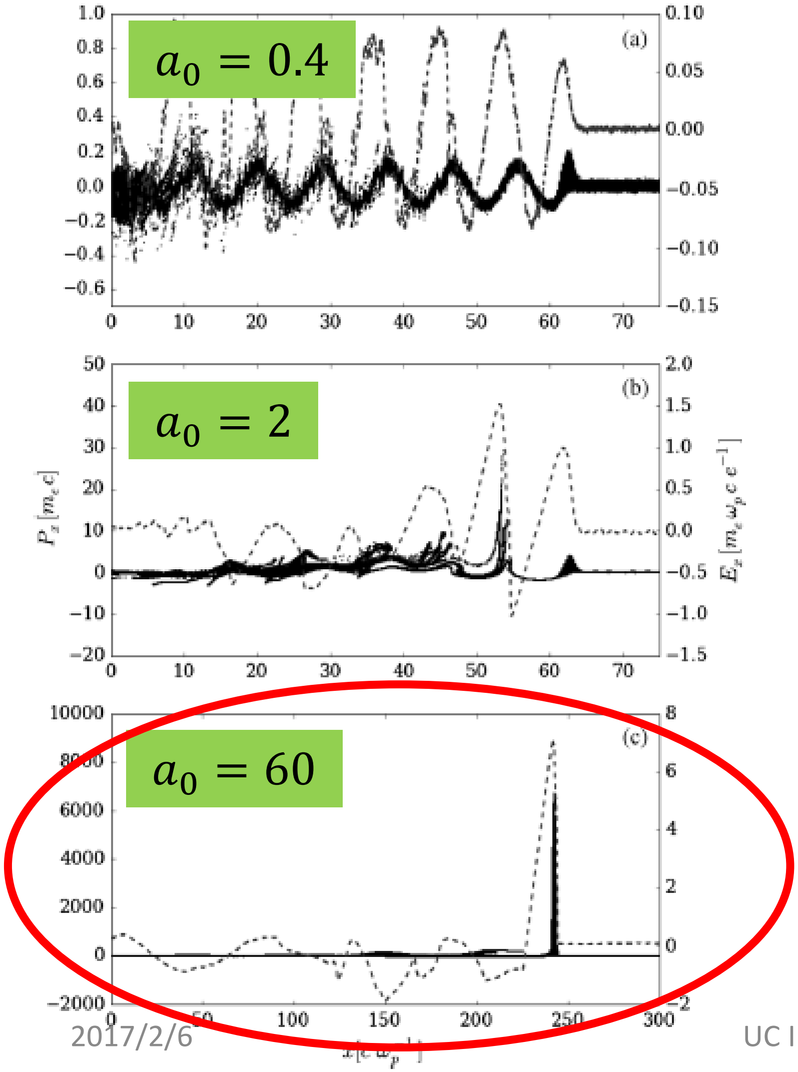
$\omega_\mathrm{A} < \omega'_\mathrm{p}$

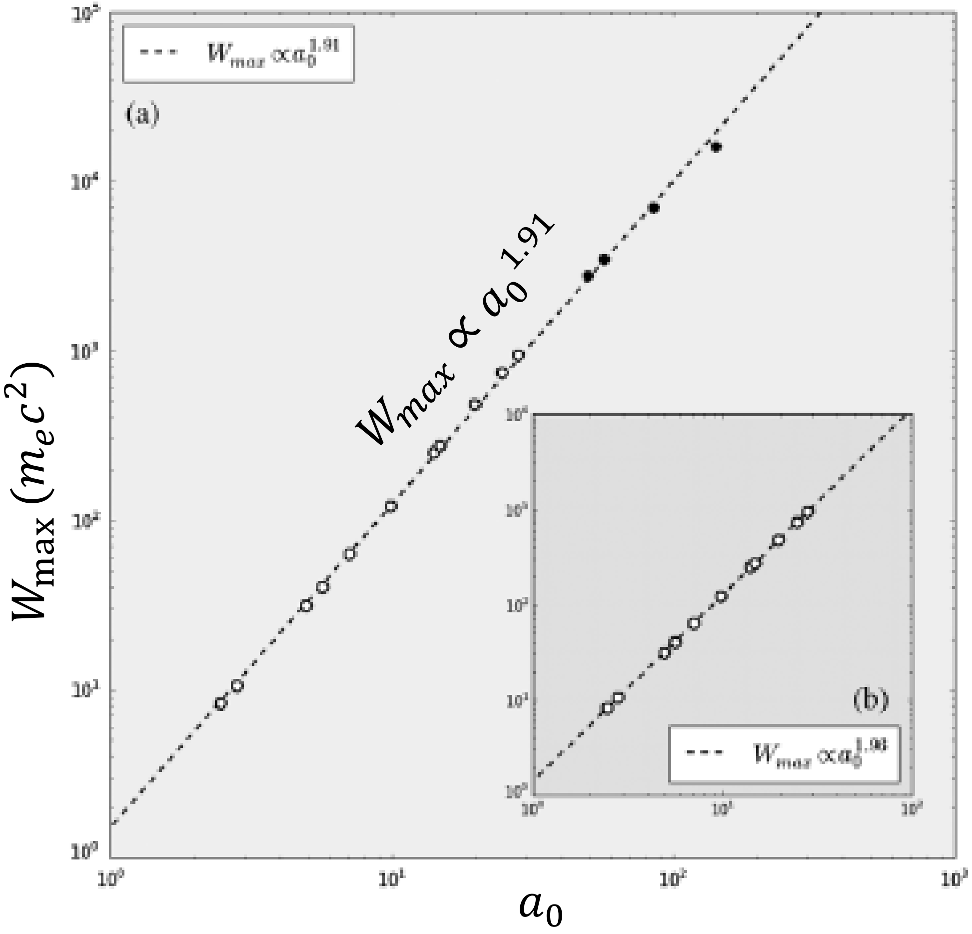
Alfven wave


20
0
−20
−40
0
20
40
electron cloud
proton cloud
Electromagnetic Wave Pulse
E field
density
0
n_0

1D Particle-in-Cell simulation

with the code by Nagata2008





Lau et al. 2015, Phys. Rev. 18, 024401

Acceleration by pondermotive force

$$W_{\mathrm{max}} = z \int_{0}^{D_3} F_{\mathrm{pm}} dD$$

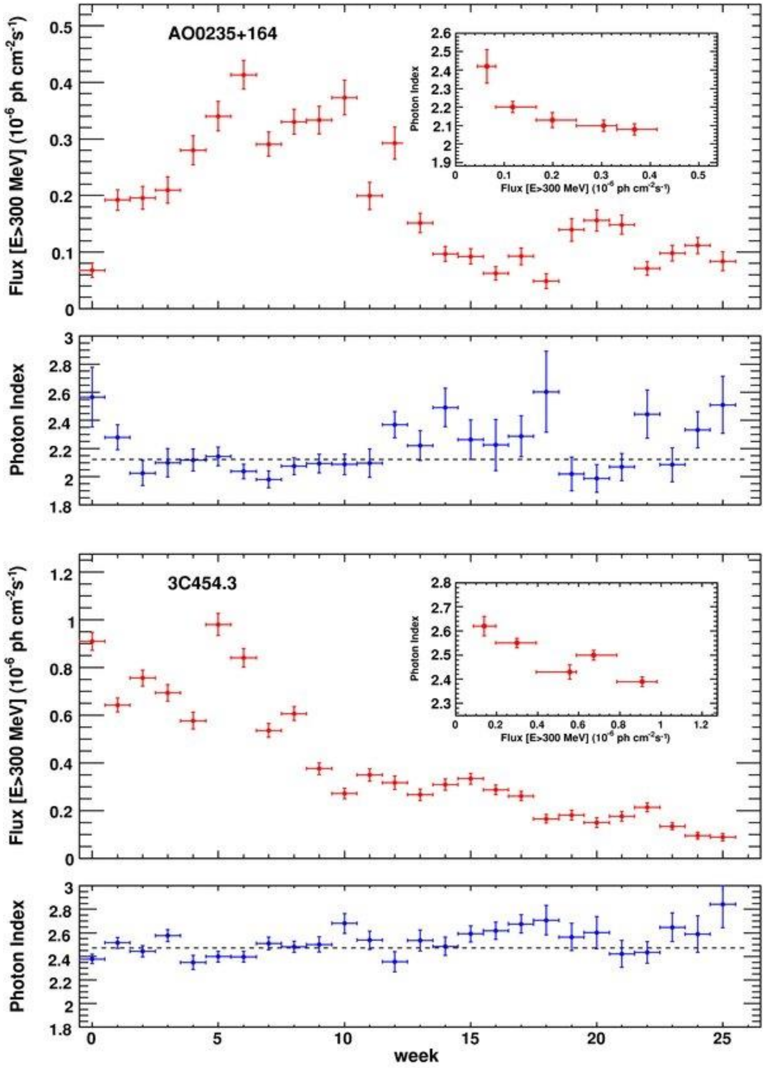
$$F_{\mathrm{pm}} = \Gamma m_{\mathrm{e}} c a \omega_A$$

ZeV Accelerator

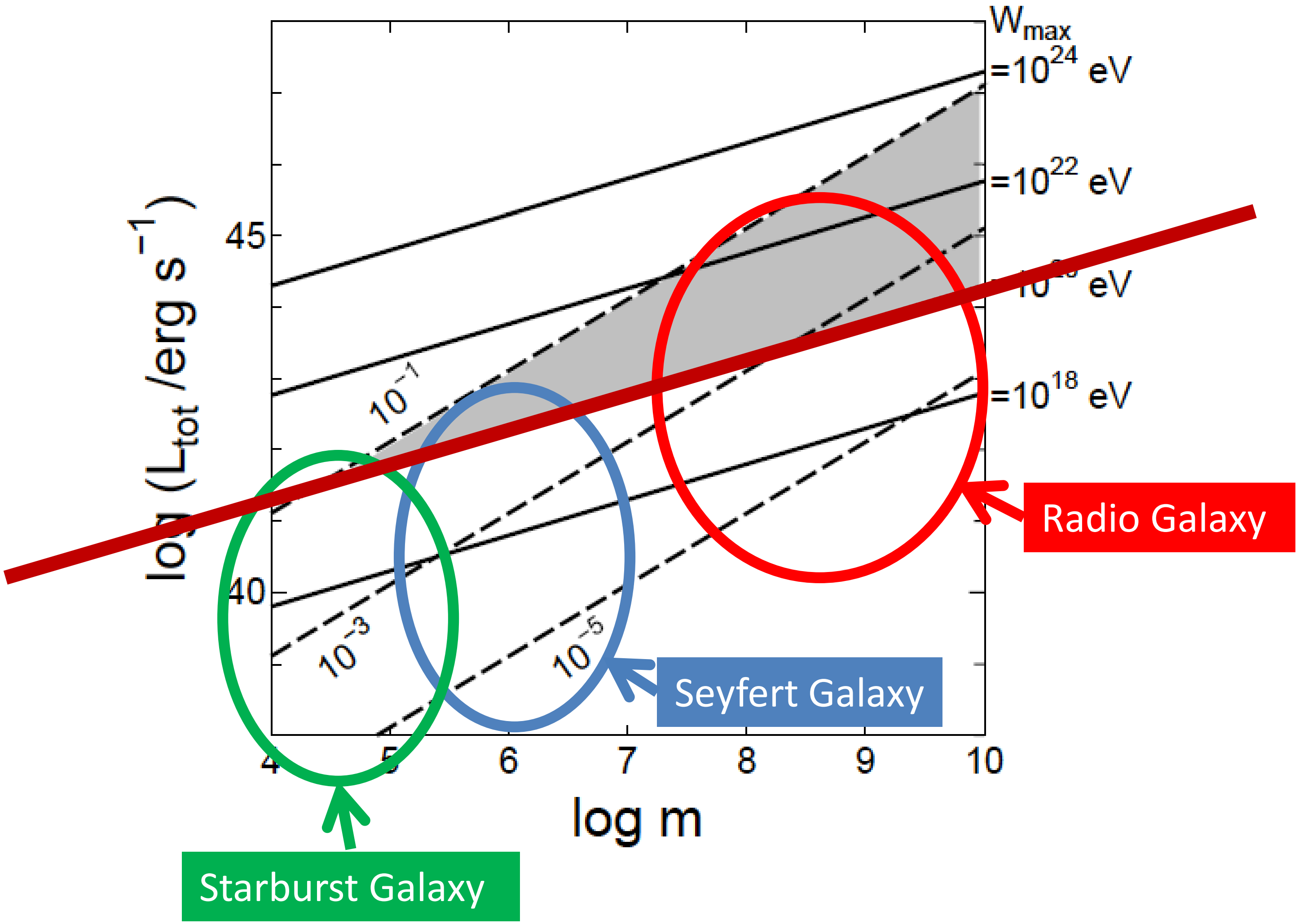
$$m = 10^8, \dot{m} = 0.1, \alpha = 0.1$$

$2\pi/\omega_\mathrm{A}$	$2.0 \times 10^2\ \mathrm{s}$
$1/\nu_\mathrm{A}$	$1.0 \times 10^6\ \mathrm{s}$
D_3/c	$1.2 \times 10^9\ \mathrm{s}$
W_max	$2.9 \times 10^{22}\ \mathrm{eV}$
L_tot	$1.2 \times 10^{45}\ \mathrm{erg\ s^{-1}}$
L_A	$1.2 \times 10^{42}\ \mathrm{erg\ s^{-1}}$
L_γ	$1.2 \times 10^{41}\ \mathrm{erg\ s^{-1}}$
L_UHECR	$1.2 \times 10^{40}\ \mathrm{erg\ s^{-1}}$
$L_\mathrm{UHECR}/L_\mathrm{tot}$	1.0×10^{-5}
$L_\mathrm{UHECR}/L_\gamma$	1.0×10^{-1}

Figure 3 from Spectral Properties of Bright Fermi-Detected Blazars in the Gamma-Ray Band
A. A. Abdo et al. 2010 ApJ 710 1271 doi:10.1088/0004-637X/710/2/1271



Conditions for UHECRs



Radio Galaxy

Seyfert Galaxy

Starburst Galaxy

$$L_{\mathrm{tot}} = 1.3 \times 10^{38} m\dot{m}\ \mathrm{erg\,s^{-1}}$$

Wakefield/pondermotive acceleration

1. No bending: linear acceleration

    →No synchrotron loss

2. No Confinement is necessary

    →just push

3. No escape problem

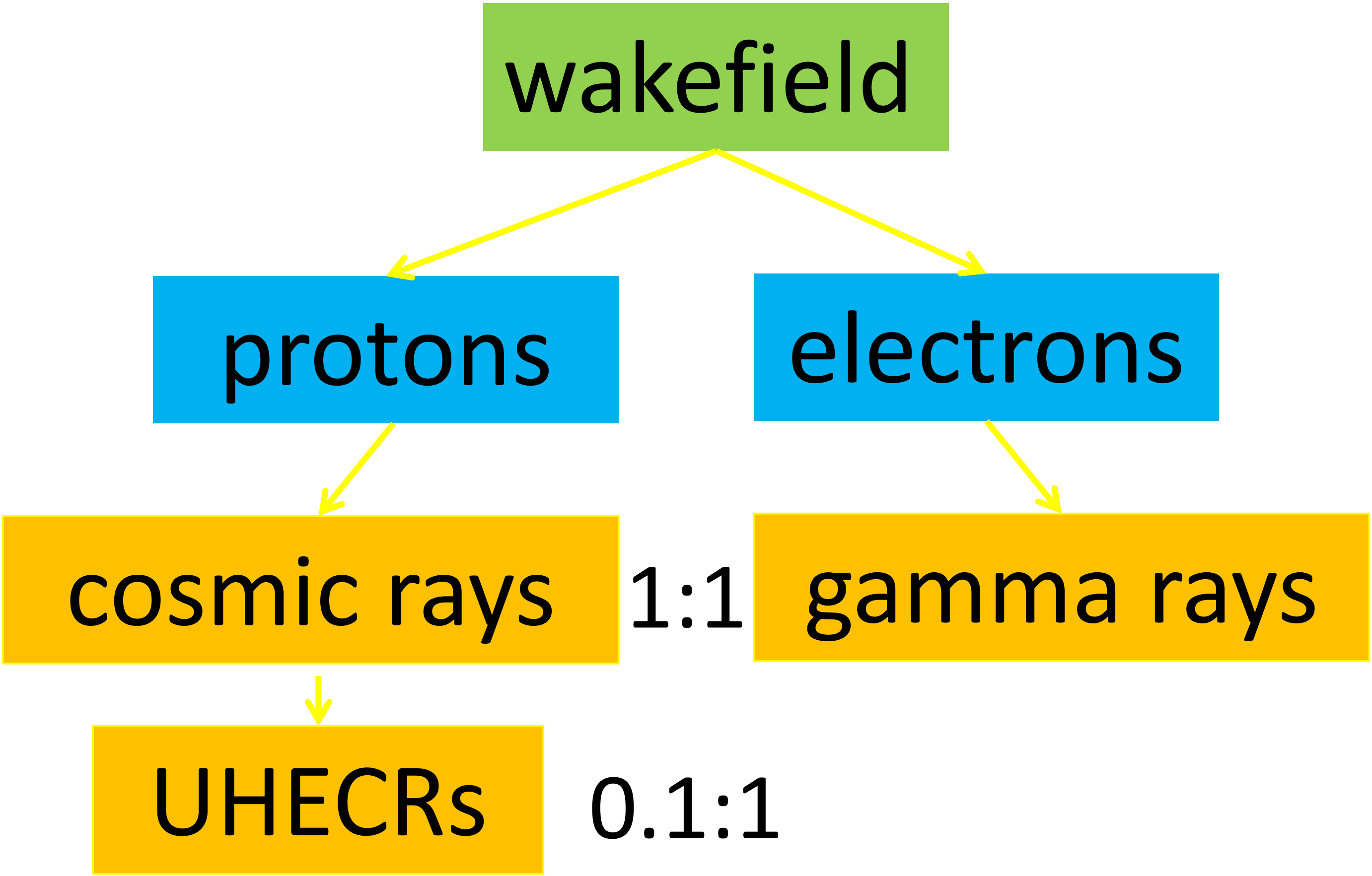
    →Wake will naturally disappear

4. Prediction: it must be gamma-ray sources

Energy budget

Total accretion energy	1.0
Gravitational wave	0.01
Radiation total	0.09
Alfven wave	0.001
Gamma-rays (electrons)	0.0001
Cosmic rays total	0.0001
UHECRs	0.00001

Energy Flow and Spectra



wakefield

protons

electrons

cosmic rays

1:1

gamma rays

UHECRs

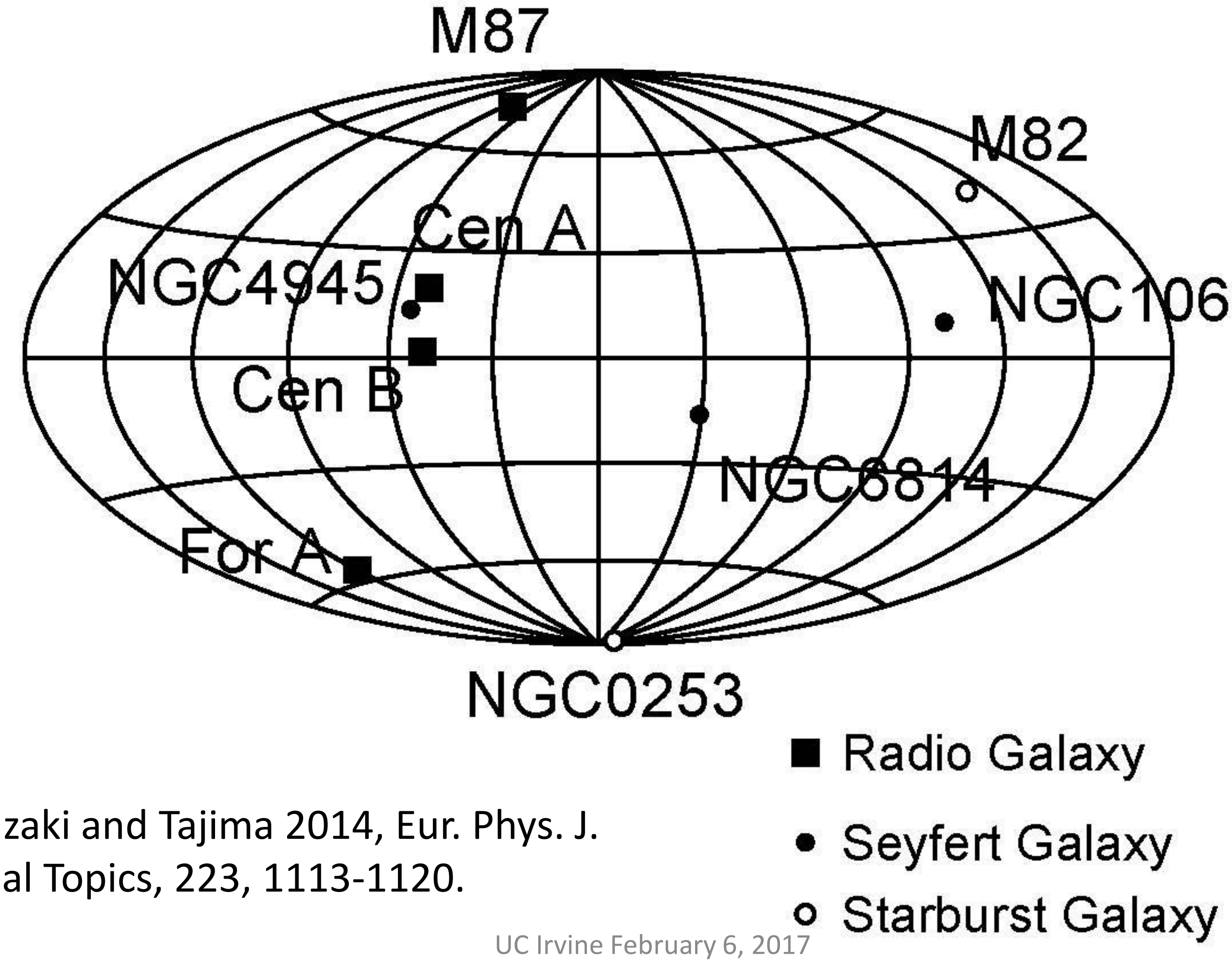
0.1:1

$F(W) \propto W^{-2}$

Nine nearby Fermi AGNs

Counterpart name	LII	BII	Class	Redshift	Flux1GeV-100 GeV (erg cm^{-2} s^{-1})	Spectral index	Radio flux(mJy)	X Flux (erg cm^{-2} s^{-1})
NGC 0253	97.39	-87.97	Starburst galaxy	0.001	(6.2+/-1.2) e-10	2.313	2994	6.02E-12
NGC 1068	172.1	-51.94	Seyfert galaxy	0.00419	(5.1+/-1.1) e-10	2.146	4849	4.55E-11
For A	240.15	-56.7	Radio Galaxy	0.005	(5.3+/-1.2) e-10	2.158	255	2.38E-12
M 82	141.41	40.56	Starburst galaxy	0.001236	(10.2+/-1.3) e-10	2.28	6205	2.29E-11
M 87	283.78	74.48	Radio Galaxy	0.0036	(17.3+/-1.8) e-10	2.174	138488	6.30E-11
Cen A Core	309.51	19.41	Radio Galaxy	0.00183	(30.3+/-2.4) e-10	2.763	42000	9.00E-12
NGC 4945	305.27	13.33	Seyfert galaxy	0.002	(7.5+/-1.7) e-10	2.103	5776	2.36E-12
Cen B	309.72	1.72	Radio Galaxy	0.012916	(18.6+/-3.5) e-10	2.325	8890	8.83E-12
NGC 6814	29.35	-16.02	Seyfert galaxy	0.0052	(6.8+/-1.6) e-10	2.544	52	1.56E-11

Fermi gamma-ray galaxies (Nearby)

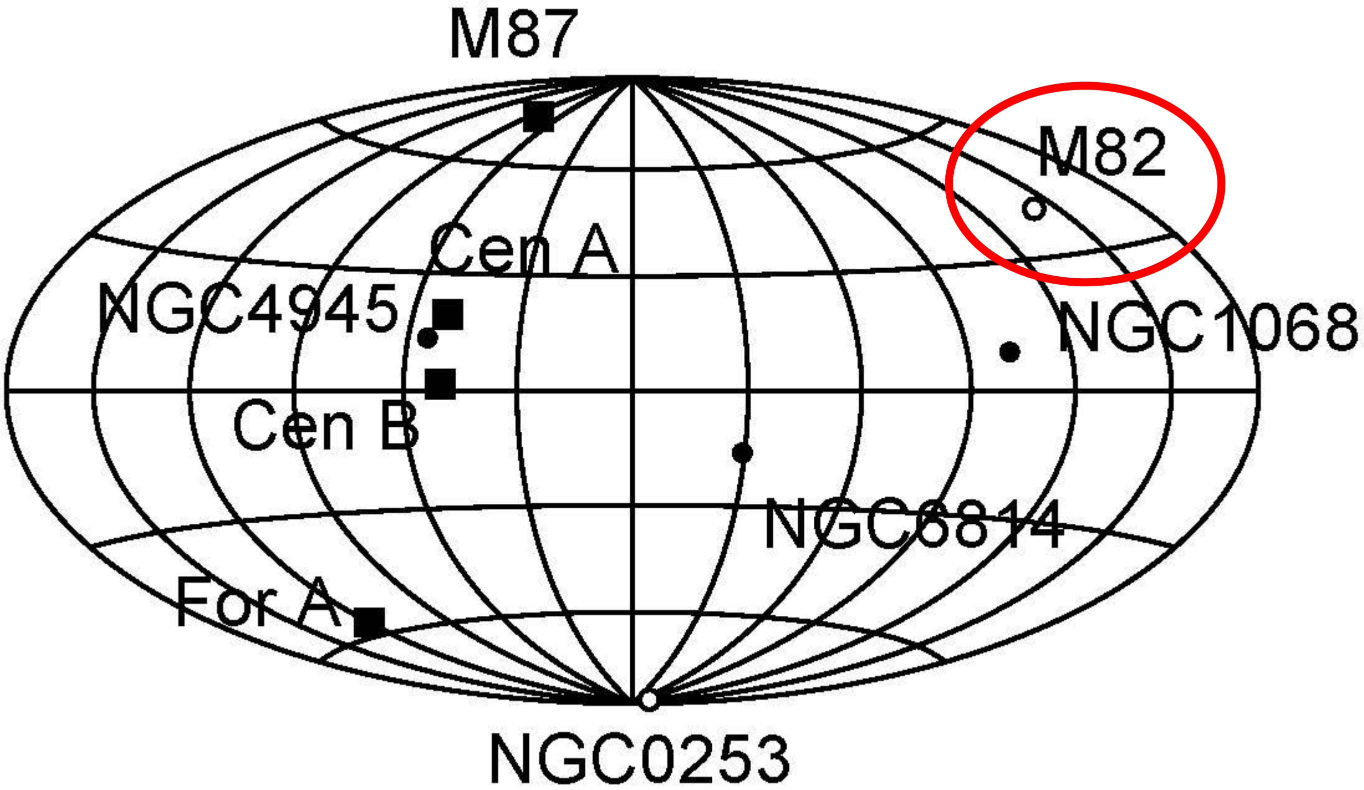


Ebisuzaki and Tajima 2014, Eur. Phys. J. Special Topics, 223, 1113-1120.

Wakefield/pondermotive acceleration

1. No bending: linear accerelation
   →No synchrotron loss
2. No Confinement is necessary
   →just push
3. No escape problem
   →Wake will naturally disappear
4. Prediction: it must be gamma-ray source YES
5. How about coherence?

Fermi gamma-ray galaxies (Nearby)

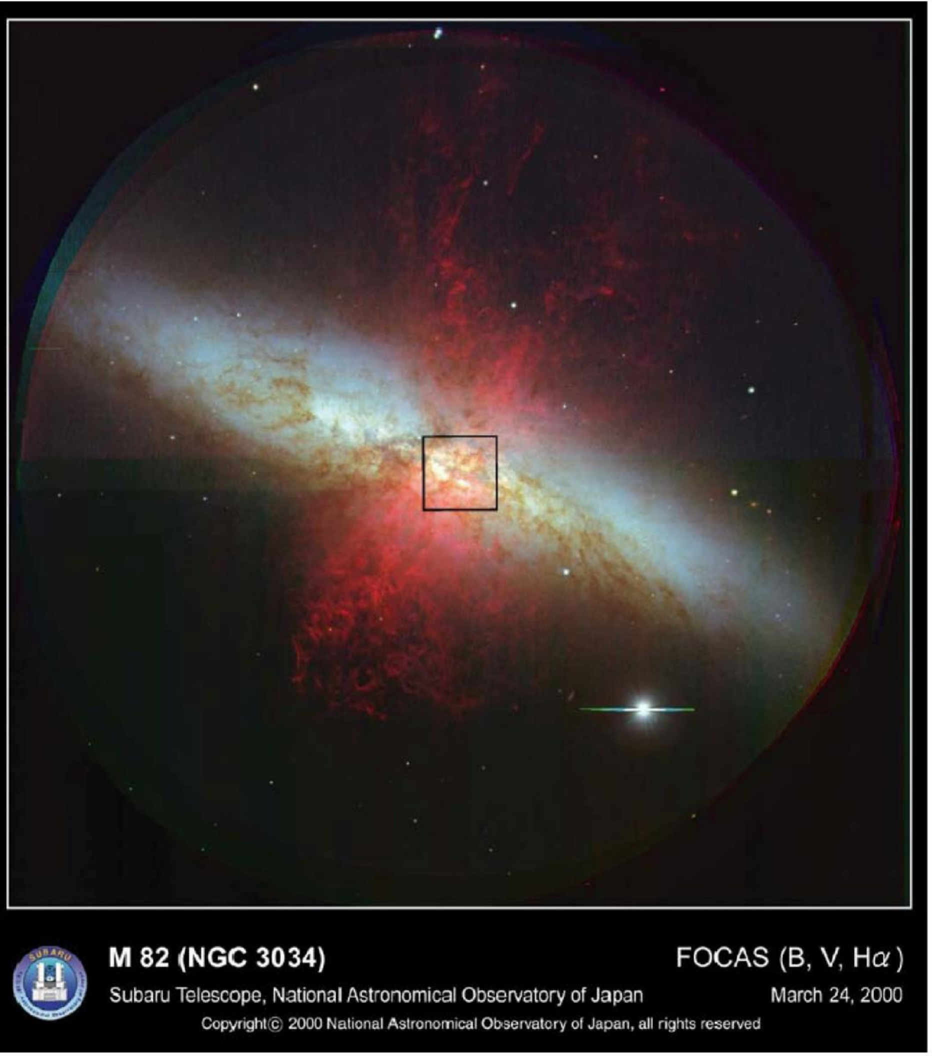


■ Radio Galaxy

● Seyfert Galaxy

○ Starburst Galaxy

Ebisuzaki and Tajima 2014, Eur. Phys. J. Special Topics, 223, 1113-1120.



M 82 (NGC 3034) FOCAS (B, V, Hα)

Subaru Telescope, National Astronomical Observatory of Japan March 24, 2000

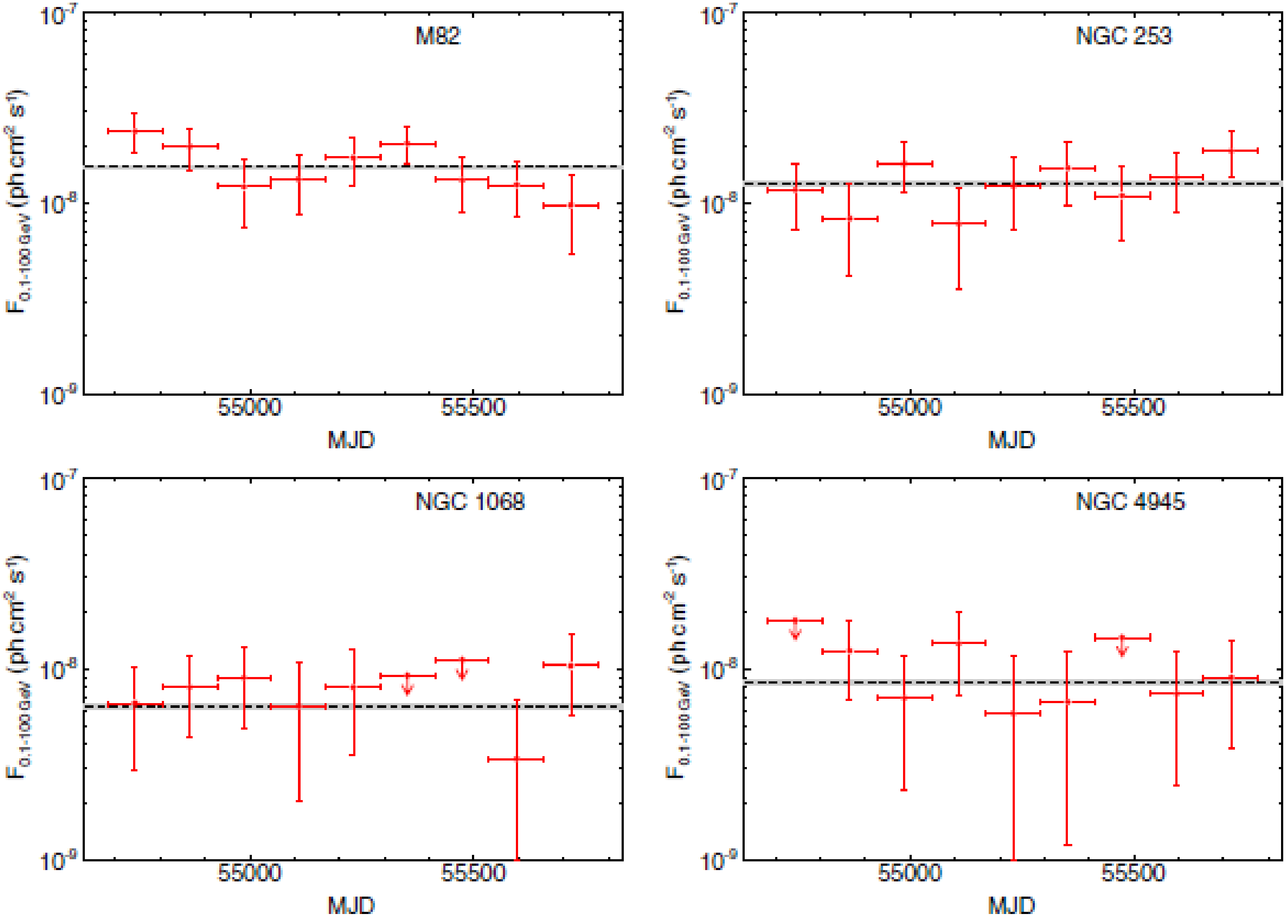
すばる望遠鏡に取りつけた微光天体分光撮像装置FOCASで得られたおおぐま座の不規則銀河M82の写真（国立天文台提供）。スターバースト現象に伴う大量の超新星爆発によって高温に電離されたガスが、銀河から放出されている様子がHα輝線として観測されている（写真の赤い部分）。四角で囲んだ領域は、右図に対応する部分である。

M82 (NGC3034)
HRC, Chandra X-ray Observatory
Cosmic Ray Group, Kyoto University, September 13, 2000

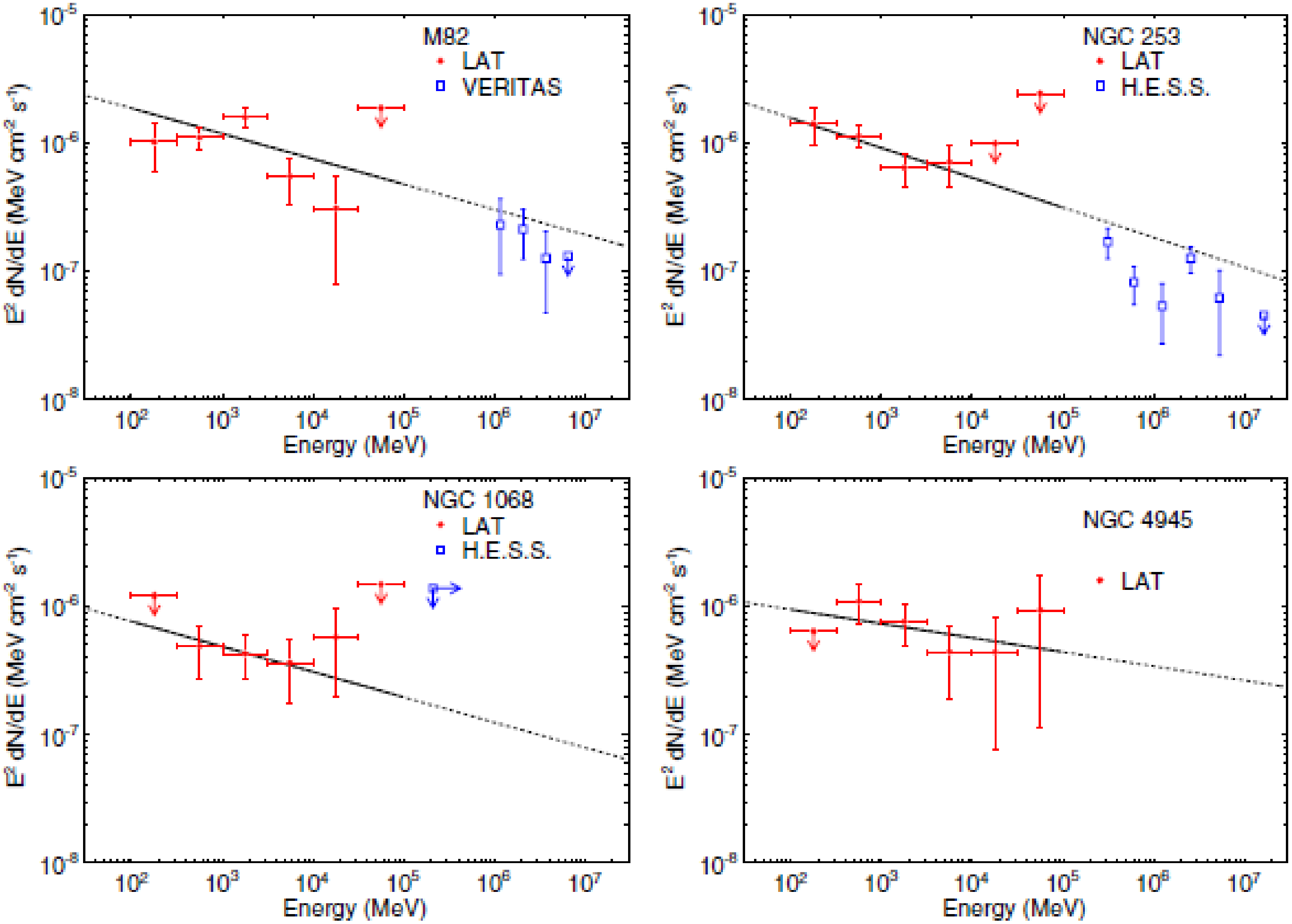
アメリカのX線天文衛星チャンドラを用いて私達が撮影したM82の中心領域（左図の四角で囲まれた領域）のX線写真。最も明るく光っているX線星が、今回新たに発見した中質量ブラックホールである。矢印は同時に発見したやや小型のブラックホールを示している。M82の中心はX線で非常に暗いこと、中質量ブラックホールはM82の中心から外れていることに注意。M82の中心から中質量ブラックホールまでの距離は約500光年である。

図4:爆発的形成銀河M82の可視光画像とX線画像

Light Curves



Energy Spectra



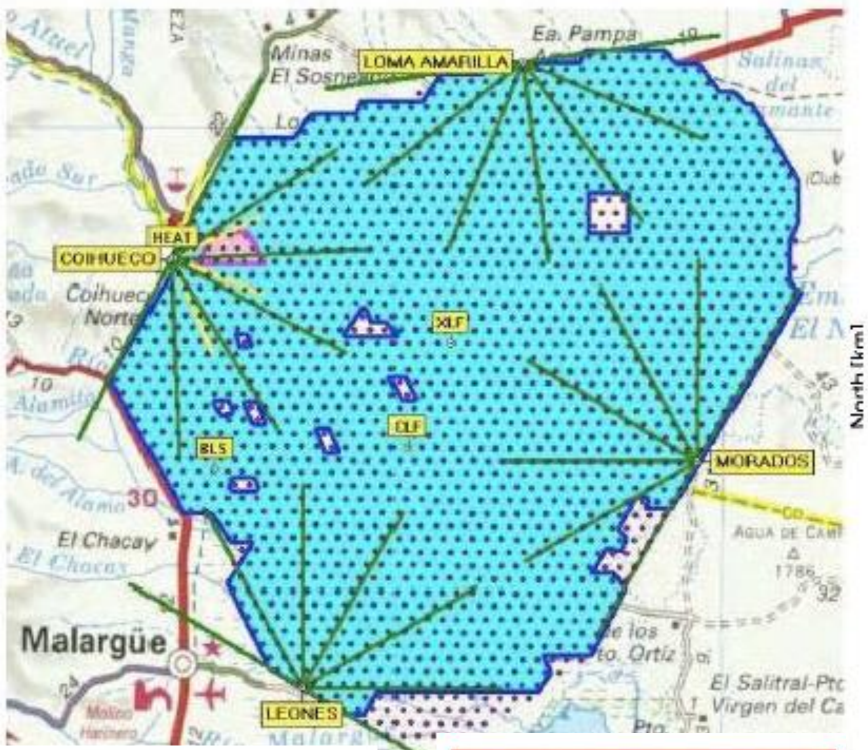
Ground Based Observatories

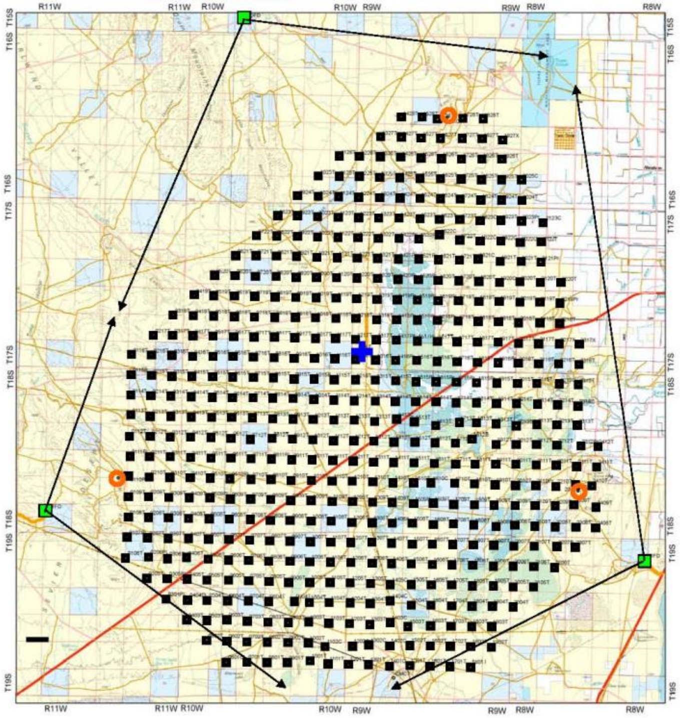
Auger

1600 surface detectors
3000 km^2

TA

507 surface detectors
700 km^2






Water tank SD

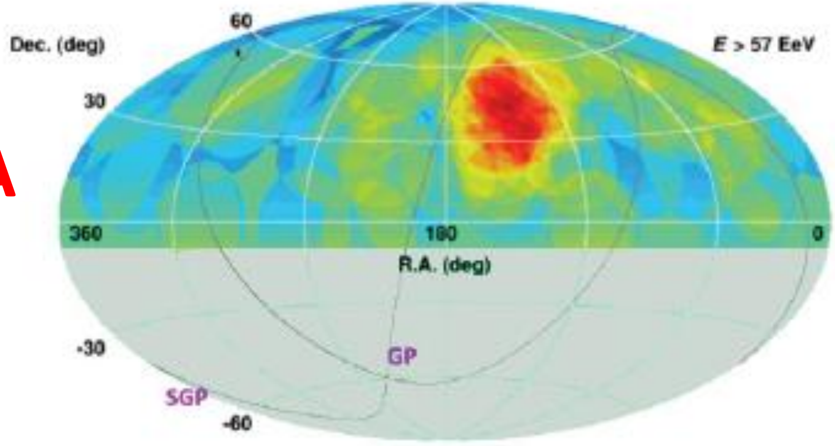

FD telescope

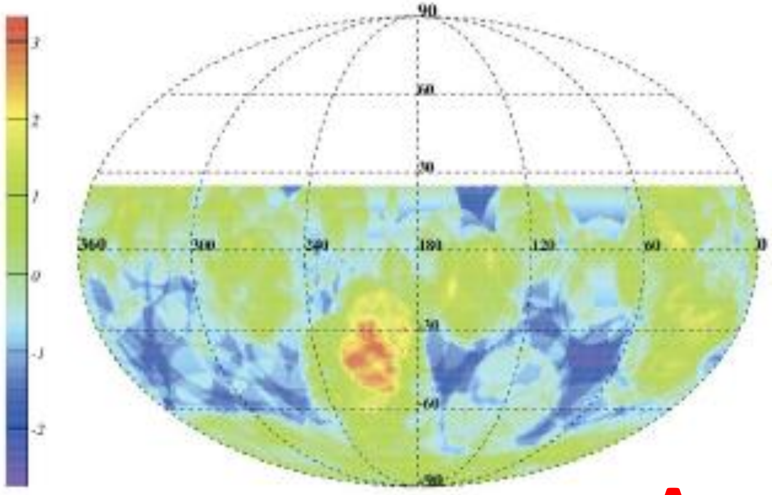

Scintillator SD


FD telescope

Arrival Direction Map (Auger/TA)

TA

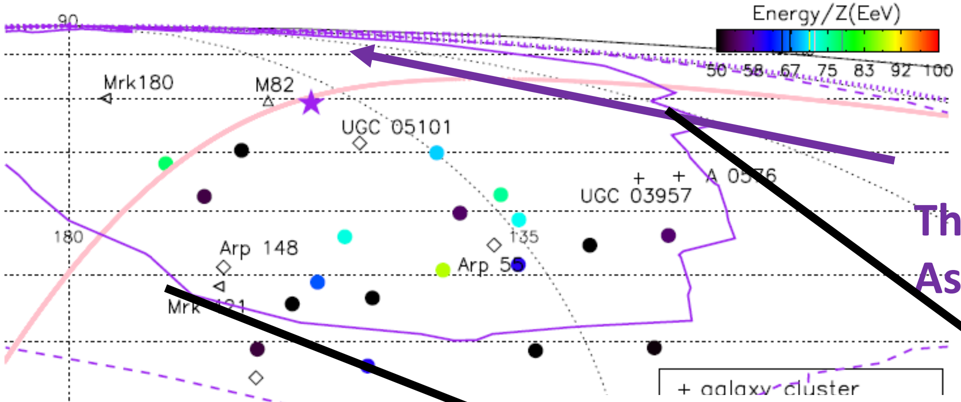




Auger

TA Hot Spot: UHECRs from M82?

He, Kusenko, Nagataki + PRD 2016.

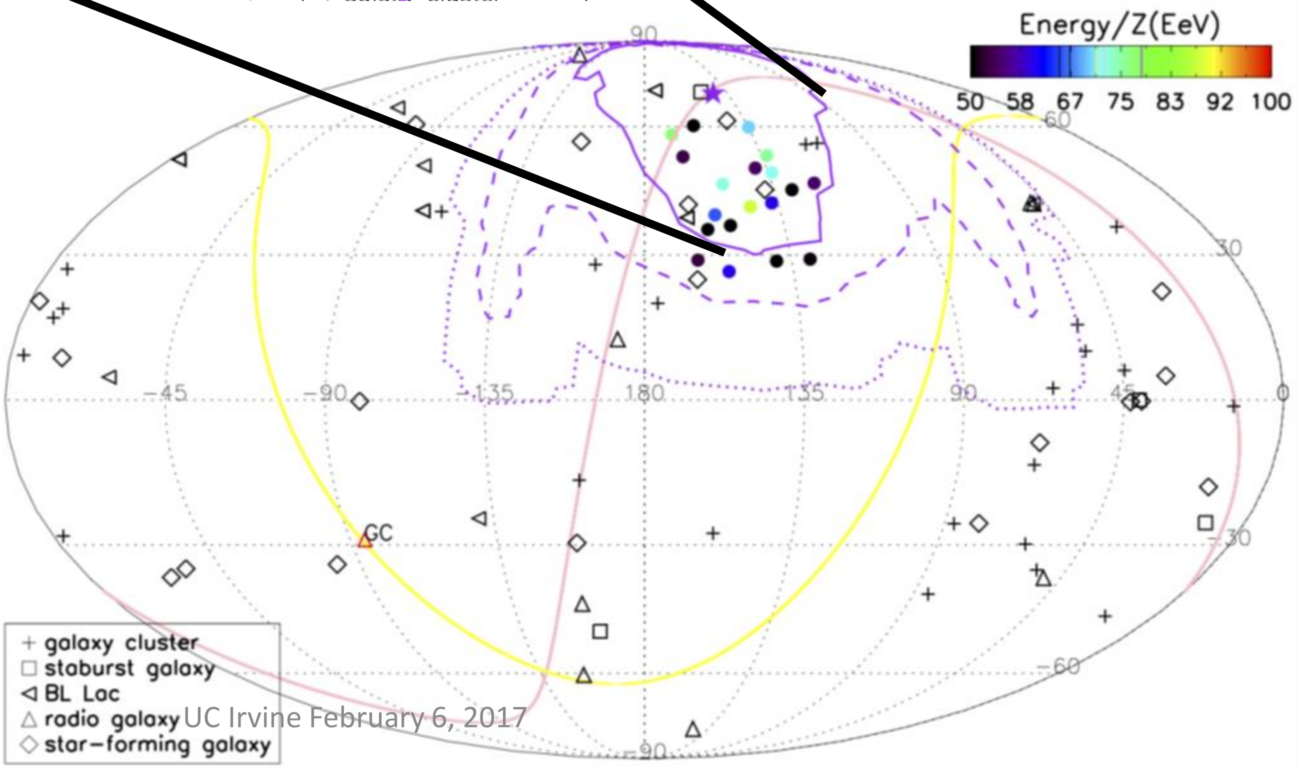


The most likely Source Position As a Result of Our Analysis.

M82 is very Close

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

Source Name	Source Ty
best-fit	-
M82	starburst gal
UGC 05101	star-forming g
Mrk 180	blazar
UGC 03957	galaxy clus
A 0576	galaxy clus
Arp 55	star-forming G
Arp 148	star-forming G
Mrk 421	blazar



M82 X-1 is promising

- $F_{\gamma \mathrm{M82}} = 10.2 \times 10^{-10}$erg s^{-1} cm^{-2} →

  $L_{\gamma \mathrm{M82X-1}} = 1.3 \times 10^{34}$ W

  ←10% of M82 total, d=3.2 Mpc

  $L_{\mathrm{UHECR\ M82X-1}} = 1.3 \times 10^{33}$W

  $\leftarrow \frac{L_{\mathrm{UHECR}}}{L_{\gamma}} = 0.1$

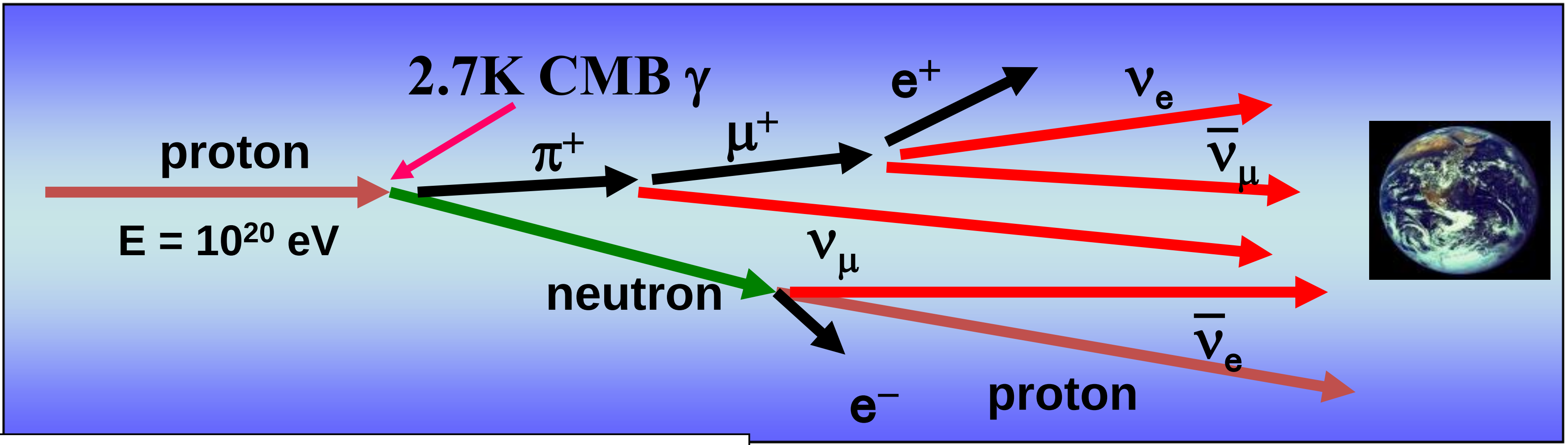
  $F_{\mathrm{UHECR\ M82X-1}} \sim$2 UHECRs/100km^2/yr

  $\sim F_{\mathrm{HotSpot}}$

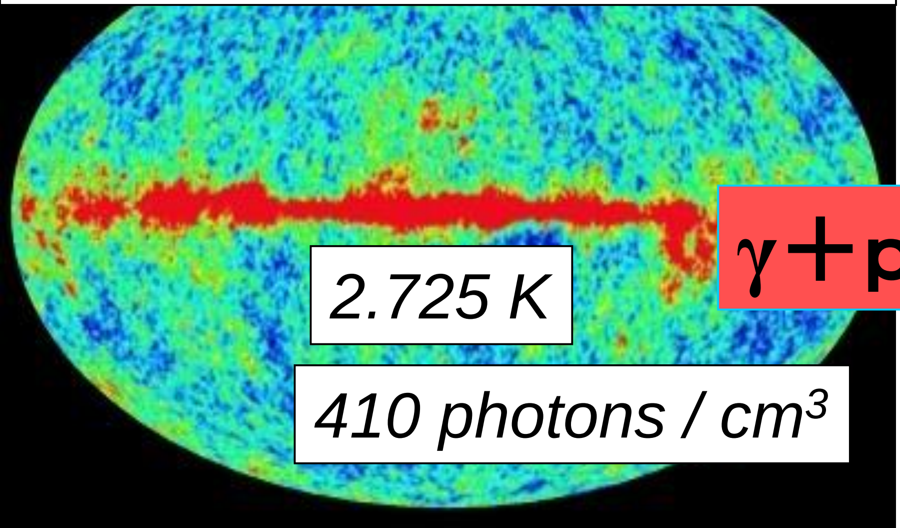
How about neutrinos?

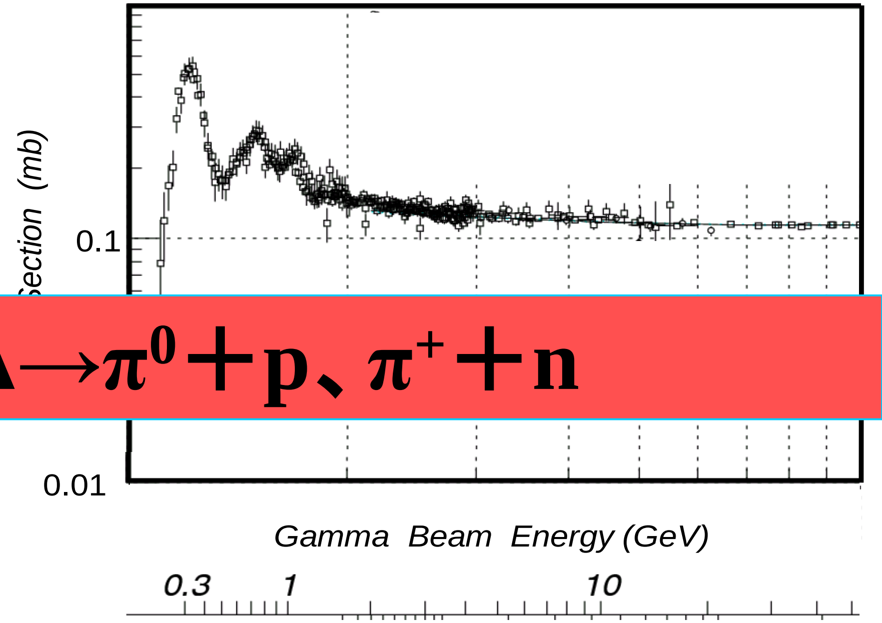
Greisen-Zatsepin-Kuz'min Process

Greisen1966; Zatsepin and Kuz'min1966



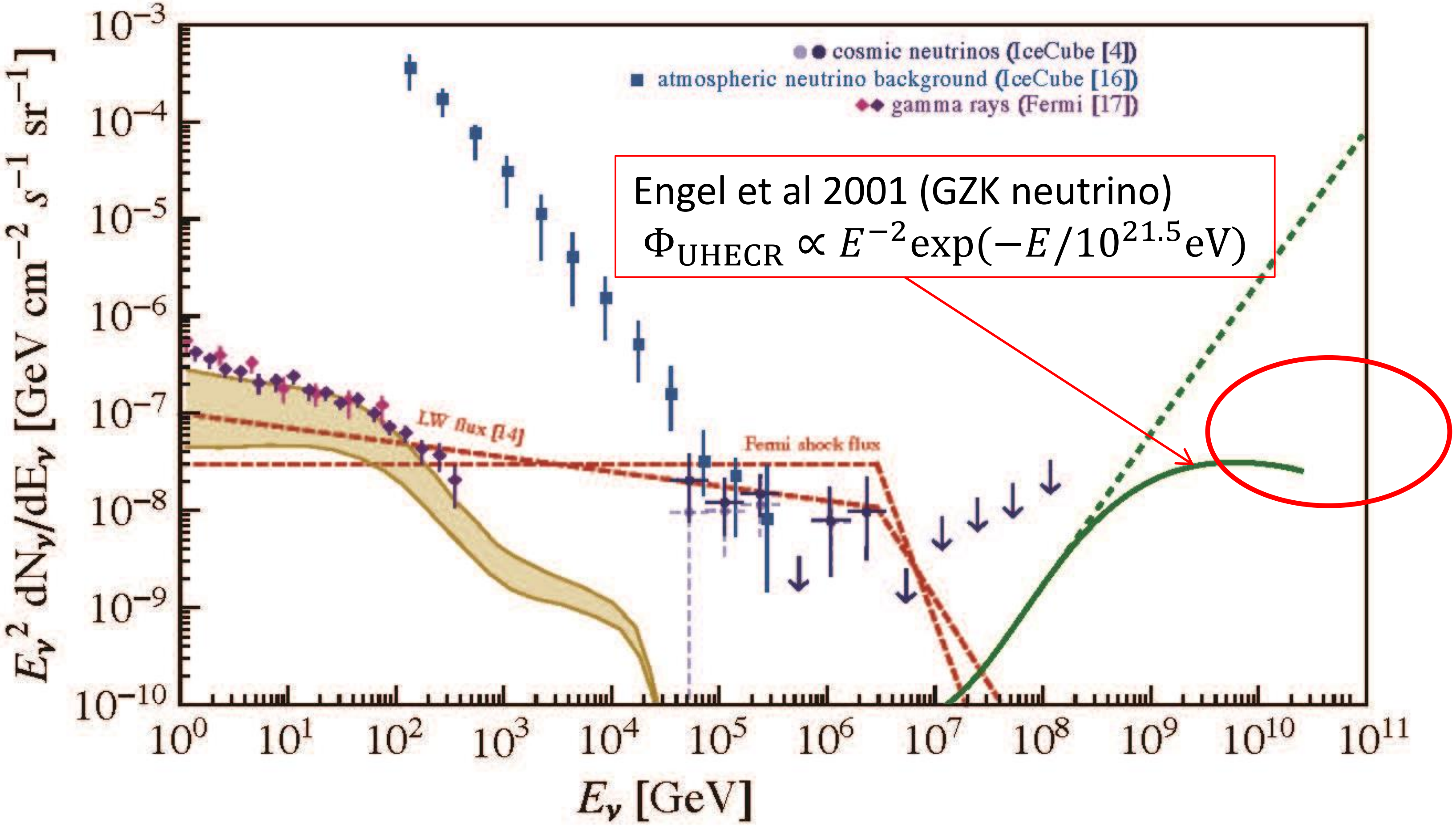
Microwave Cosmic Background Radiation





$$\gamma + p \rightarrow \Delta \rightarrow \pi^0 + p、\pi^+ + n$$

Neutrino and gamma ray flux



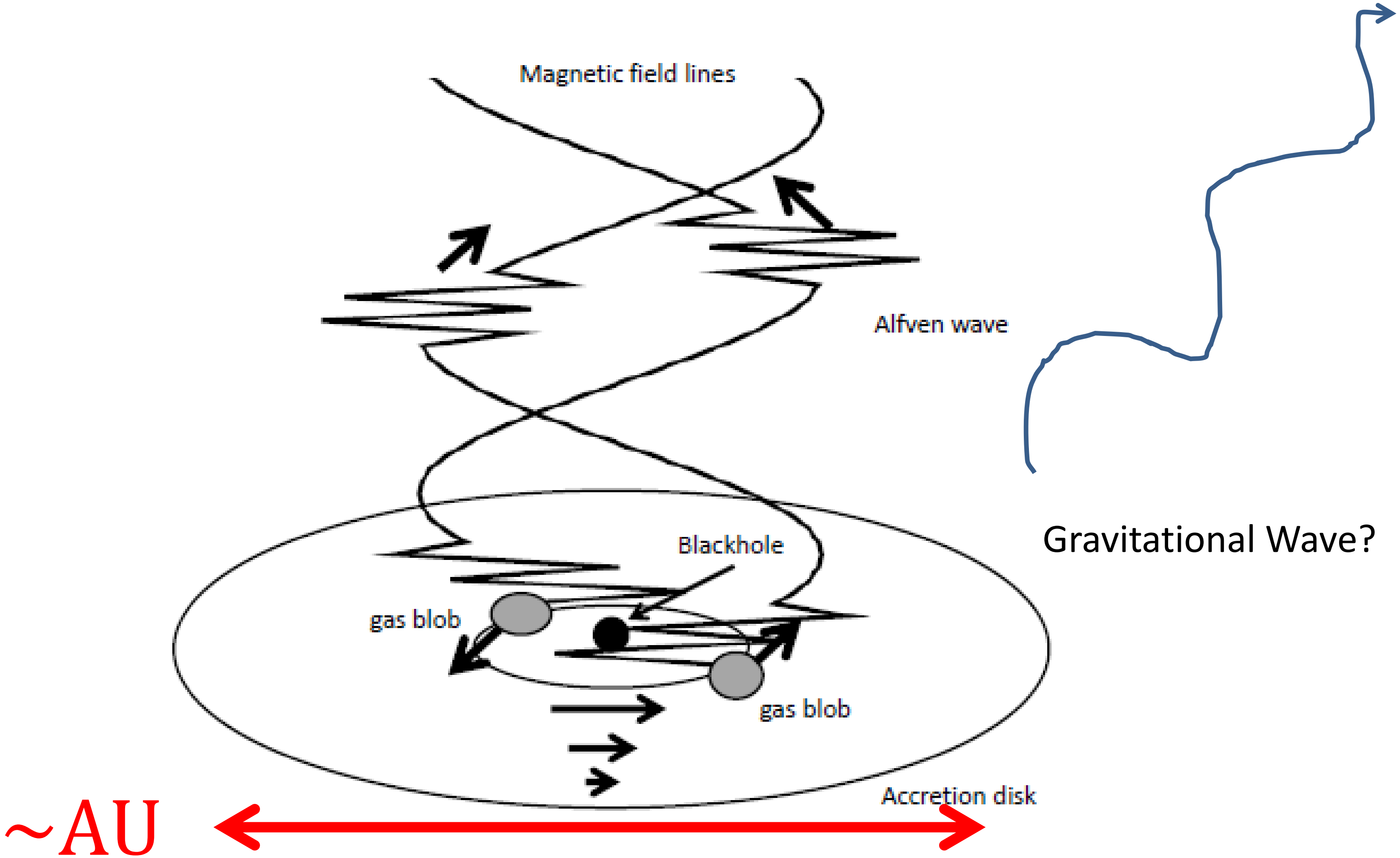
Engel et al 2001 (GZK neutrino)

$\Phi_{\mathrm{UHECR}} \propto E^{-2}\exp(-E/10^{21.5}\mathrm{eV})$

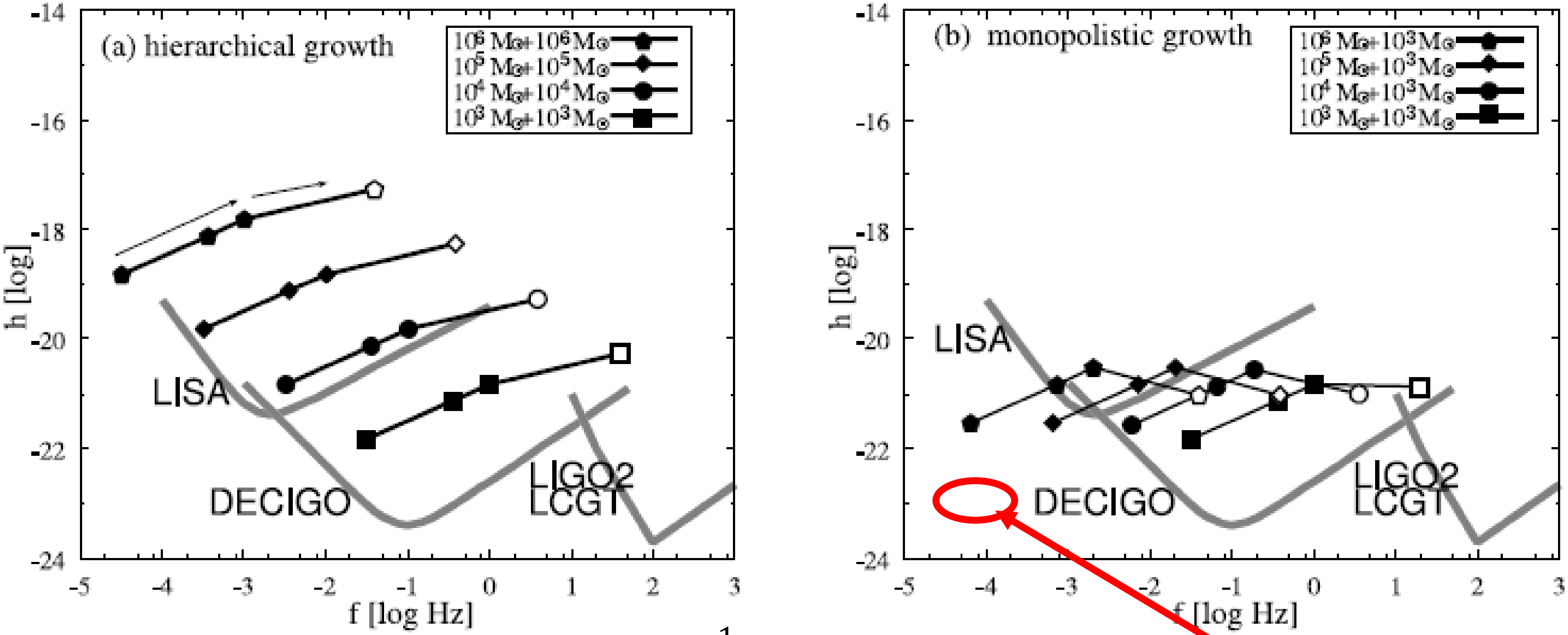
Taken from Anchordoqui et al. 2014, Phys. Rev. D., 89, 127304
and Yacobi et al. 2016, Ap. J., 823, 89, modified by TE

Accretion Disk around a BH

m=10^8



How about Gravitational wave ?



$$h \sim 5.5 \times 10^{-21} \left(\frac{\epsilon}{0.01}\right) \left(\frac{R}{4\mathrm{Gpc}}\right)^{-1} \left(\frac{m}{\sqrt{2 \times 10^{3}\, M_\odot}}\right)$$

$$m < 7.0 \times 10^{-10} \left(\frac{M_{\mathrm{BH}}}{10^{6}\, M_\odot}\right)^{2}$$

M87
D=16.4 Mpc
$M_{\mathrm{BH}} = 6.6 \times 10^{9}\, M_\odot$

Matsubayashi, Shinkai, and Ebisuzaki 2004, Ap. J, 614, 864-868

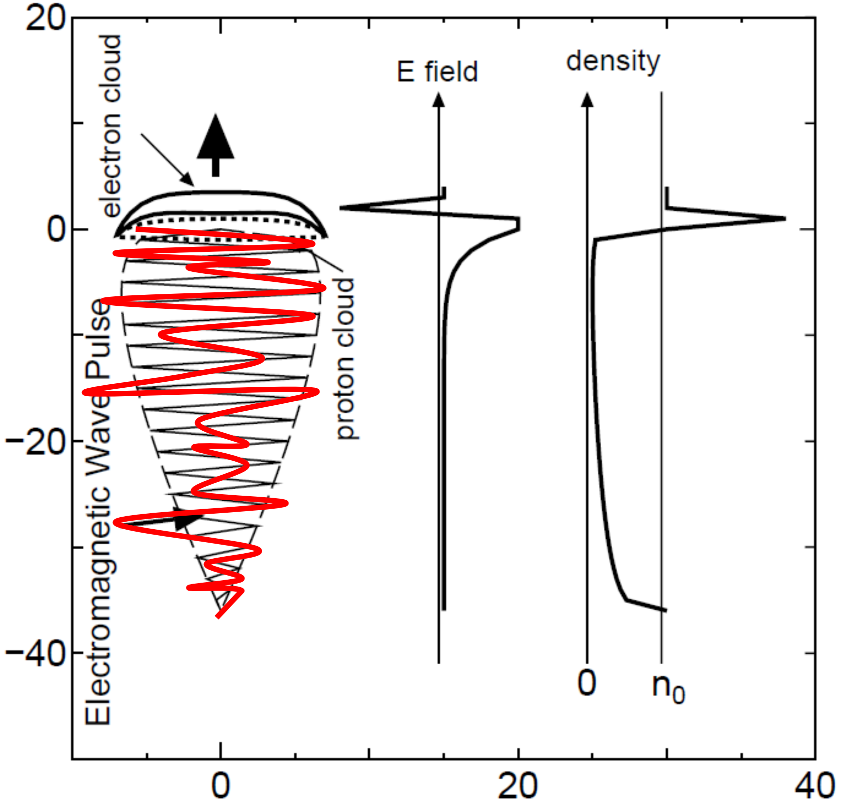
Conclusions

- Accreting BH+disk+jet = Astronomical Linear accelerator
  - Bursts of Intense Alfven waves (highly relativistic)←Laser
  - Jet ←wave guide
- Active Galactic Nuclei
  - Nearby gamma emitting AGNs

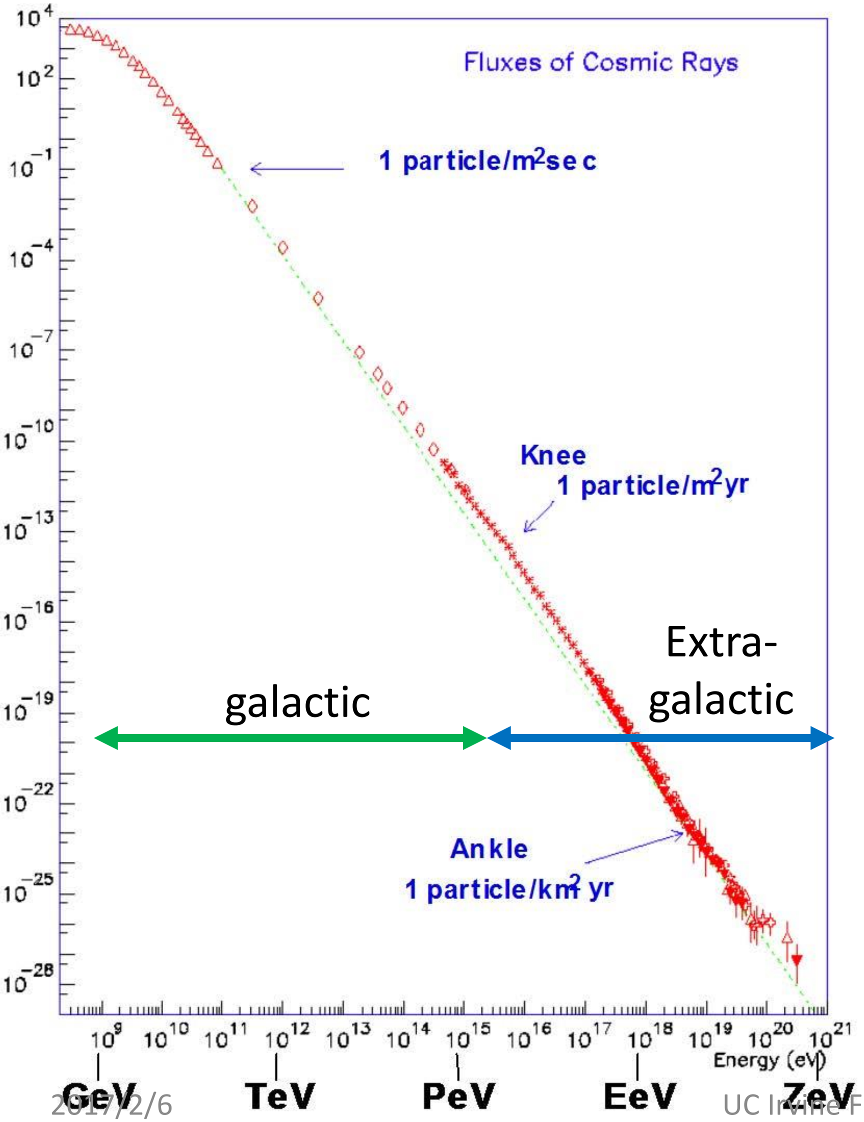
    =ZeV acceleration of particles: UHECRs~10^{20} eV
- Intermediate Mass Blackholes (IMBH: 10^3-10^5 Ms) in M82
  - Possible origin of the Northern Hotspot by TA Group
- EeV-ZeV neutrinos: GZK process
- GW detection needs a large space antenna >>LISA

Relativistic coherence

- Extremely relativistic
  →freezing-out

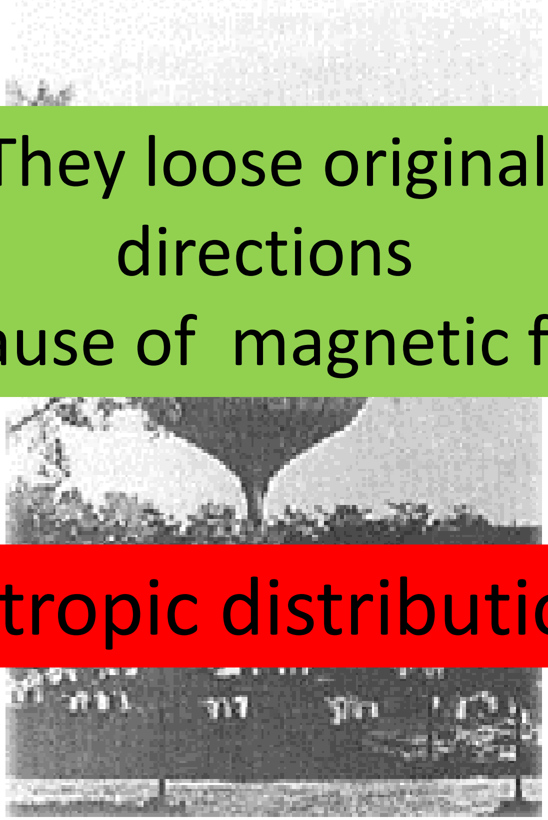


Origin of Cosmic rays



- 100 years enigma
  - Discovered in 1912

    by Victor Hess



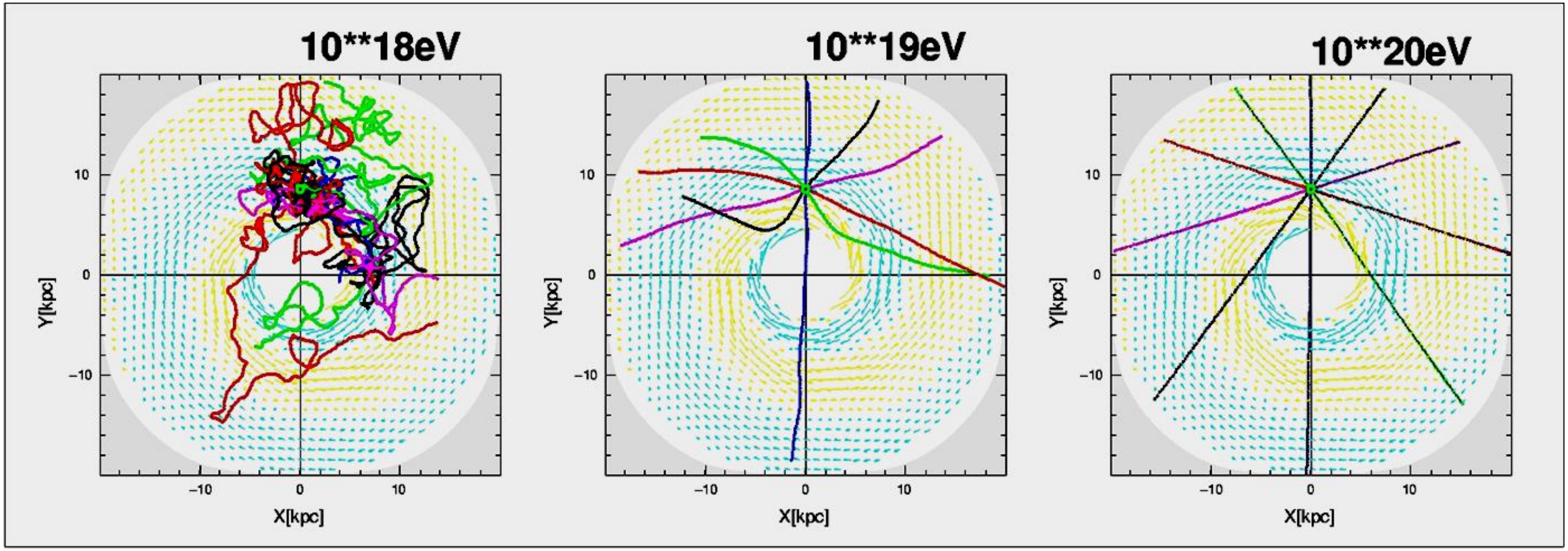
They loose original directions because of magnetic field

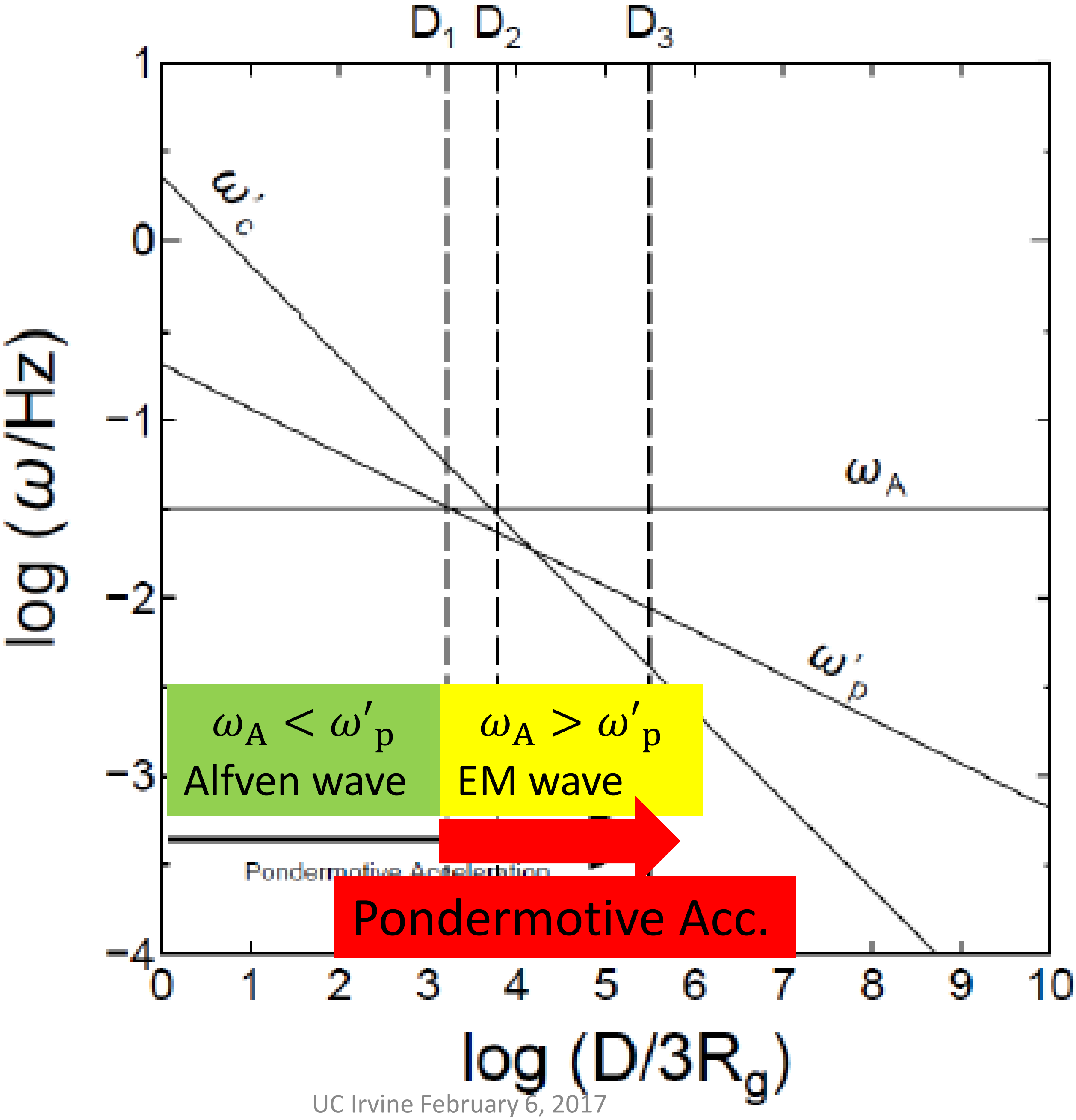
Isotropic distribution

Why CR>10^{20} eV？

Straight Line Astronomy

No bending vs bending





$\omega_A < \omega'_p$

Alfven wave

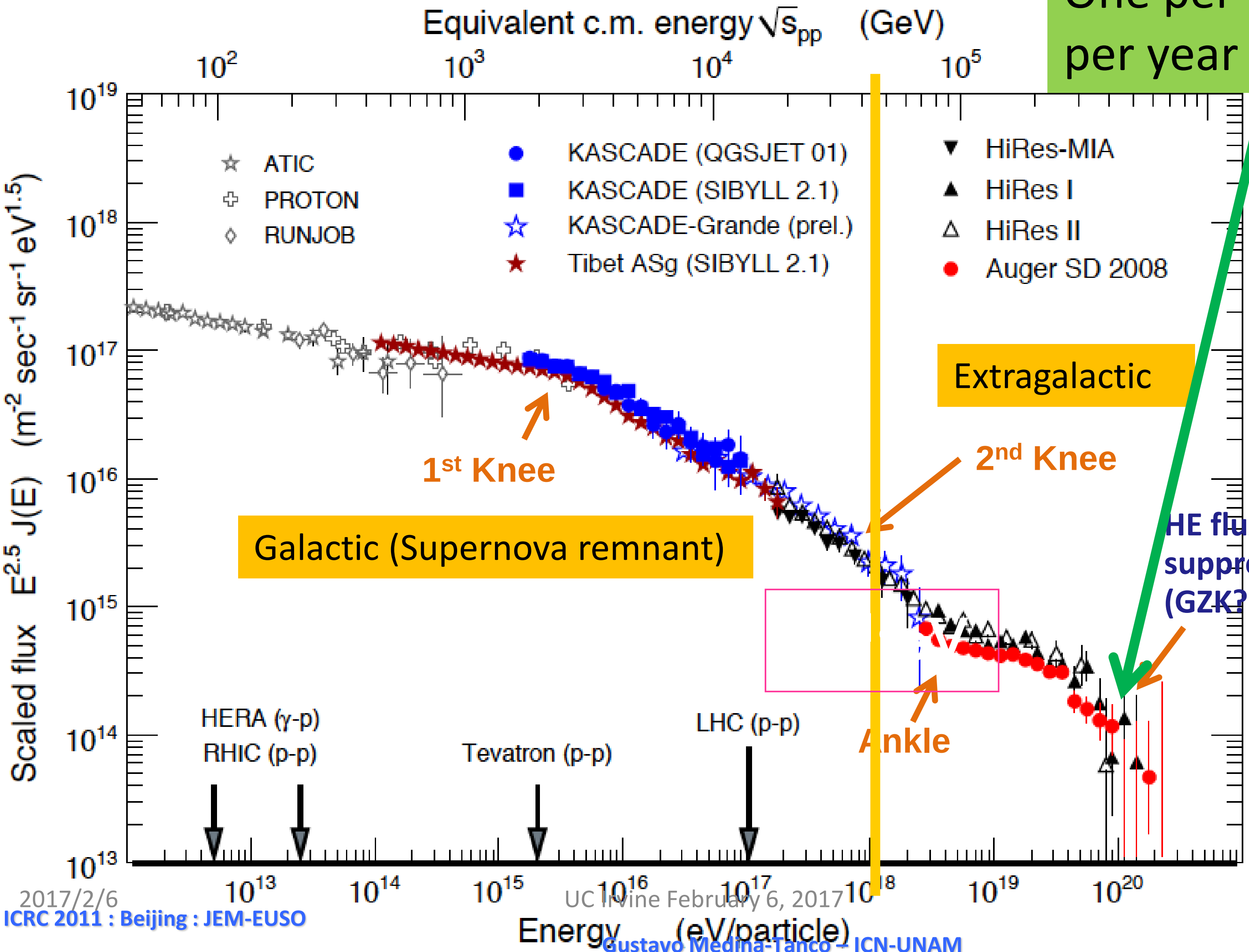
$\omega_A > \omega'_p$

EM wave

Pondermotive Acc.

Energy Spectrum

One per 100km^2
per year



Extragalactic

1st Knee

2nd Knee

Galactic (Supernova remnant)

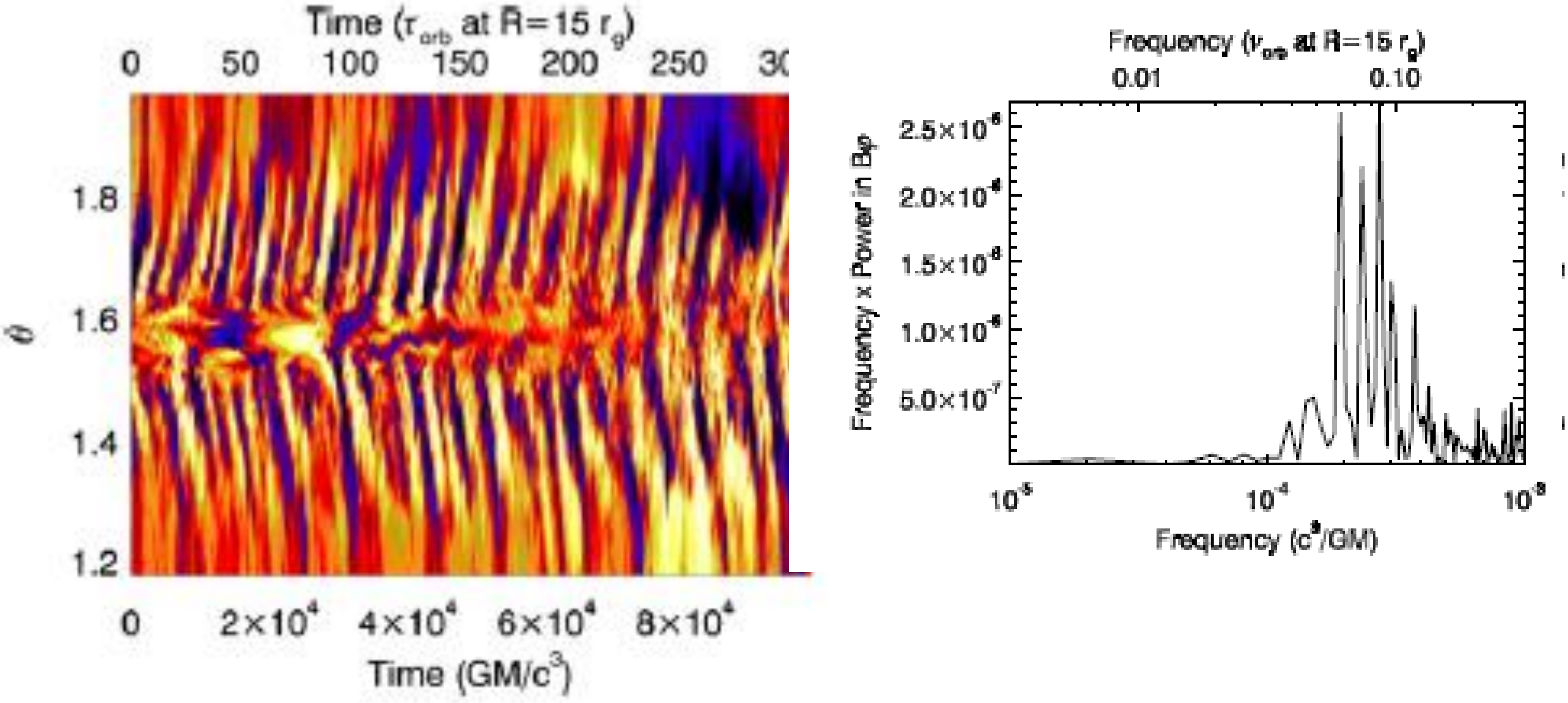
HE flux suppression (GZK?)

Ankle

ICRC 2011 : Beijing : JEM-EUSO

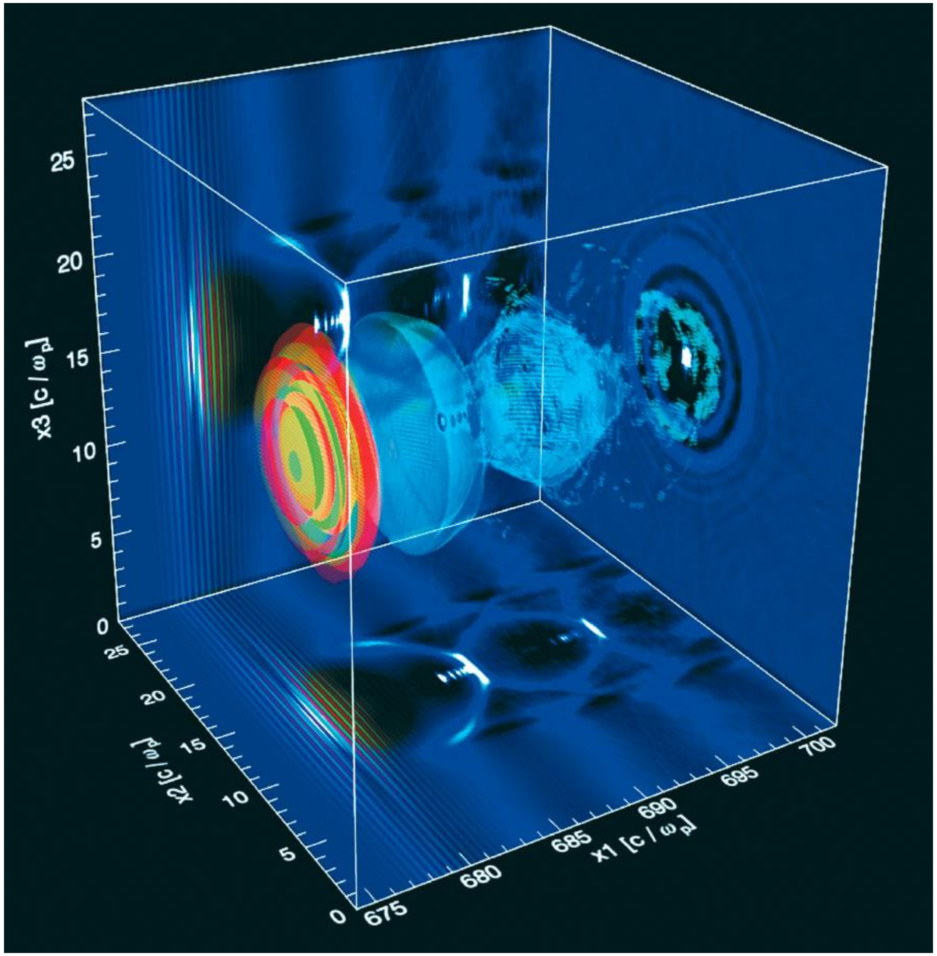
Gustavo Medina-Tanco – ICN-UNAM

Low Frequency
Quasi Periodic Oscillation



3D Numerical Simulation of Accretion disk
by O'Neil et al 2008

Wakefield


x3 [c / ω_p]
0
5
10
15
20
25
x2 [c / ω_p]
0
5
10
15
20
25
x1 [c / ω_p]
675
680
685
690
695
700

M82 (NGC3034)
HRC, Chandra X-ray Observatory
Cosmic Ray Group, Kyoto University, September 13, 2000

アメリカのX線天文衛星チャンドラを用いて私達が撮影したM82の中心領域（図4の左図の四角で囲まれた領域）のX線写真（京都大学　鶴　剛助手提供）。最も明るく光っているX線星が、今回新たに発見した中質量ブラックホールである。矢印は同時に発見したやや小型のブラックホールを示している。M82の中心はX線で非常に暗いこと、中質量ブラックホールはM82の中心から外れていることに注意。M82の中心から中質量ブラックホールまでの距離は約500光年である。

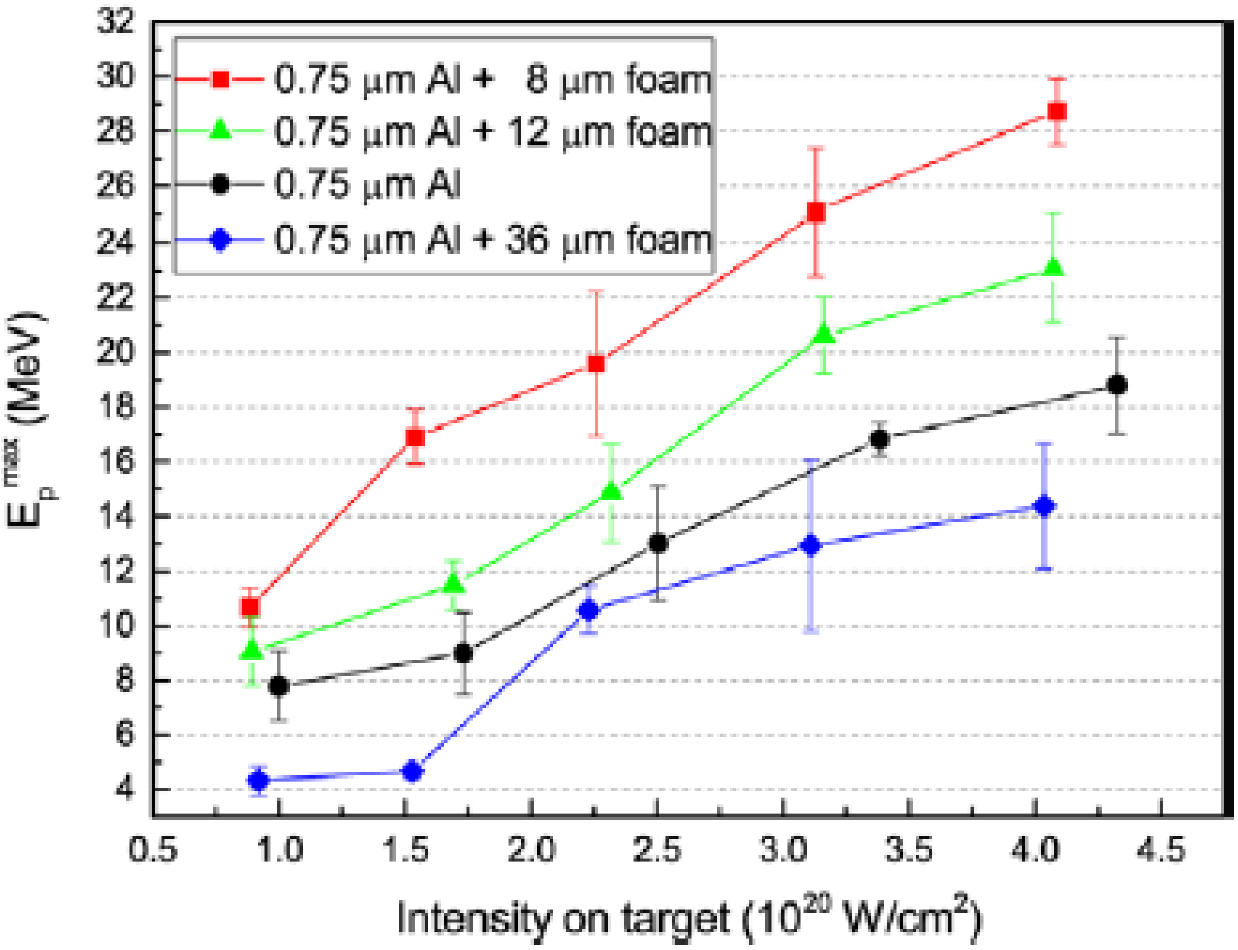
M82 (NGC3034) SUBARU Telesope, CISCO (K')
Cosmic Ray Group, Kyoto University, Japan
National Astronomical Observatory of Japan

国立天文台すばる望遠鏡とCISCO観測装置を用いて私達のグループが撮影したM82の赤外線写真（京都大学　岩室史英　助手提供）。＋字はM82の中心であり、丸はこの観測によって検出された星団を示している。この観測より中質量ブラックホールが存在していると考えられる星団が検出された。

図5：中質量ブラックホールが星団に属してることがわかった

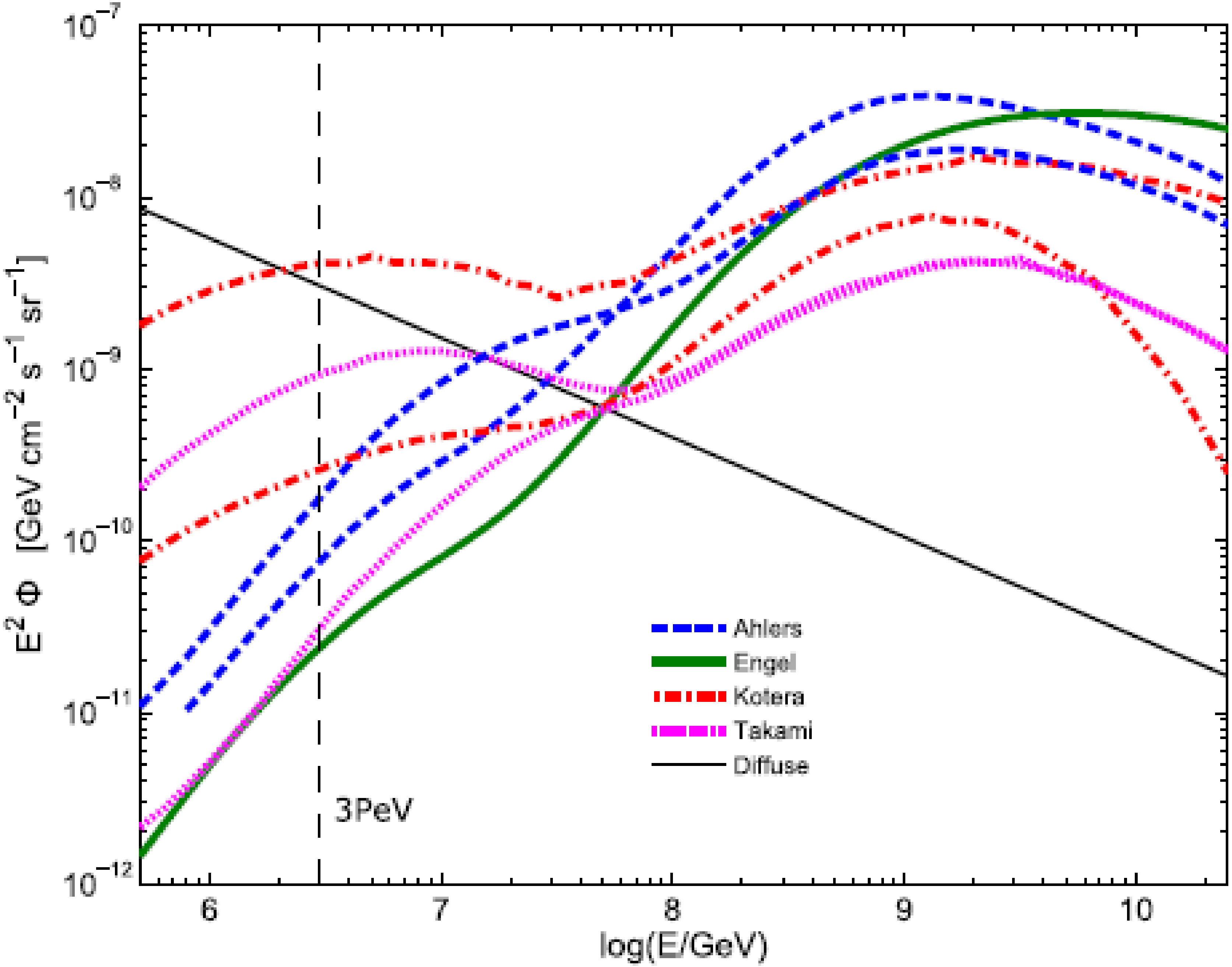
Proton acceleration

Prencipe et al. (2016) Plasma Phys. Control. Fusion, 58, 034019



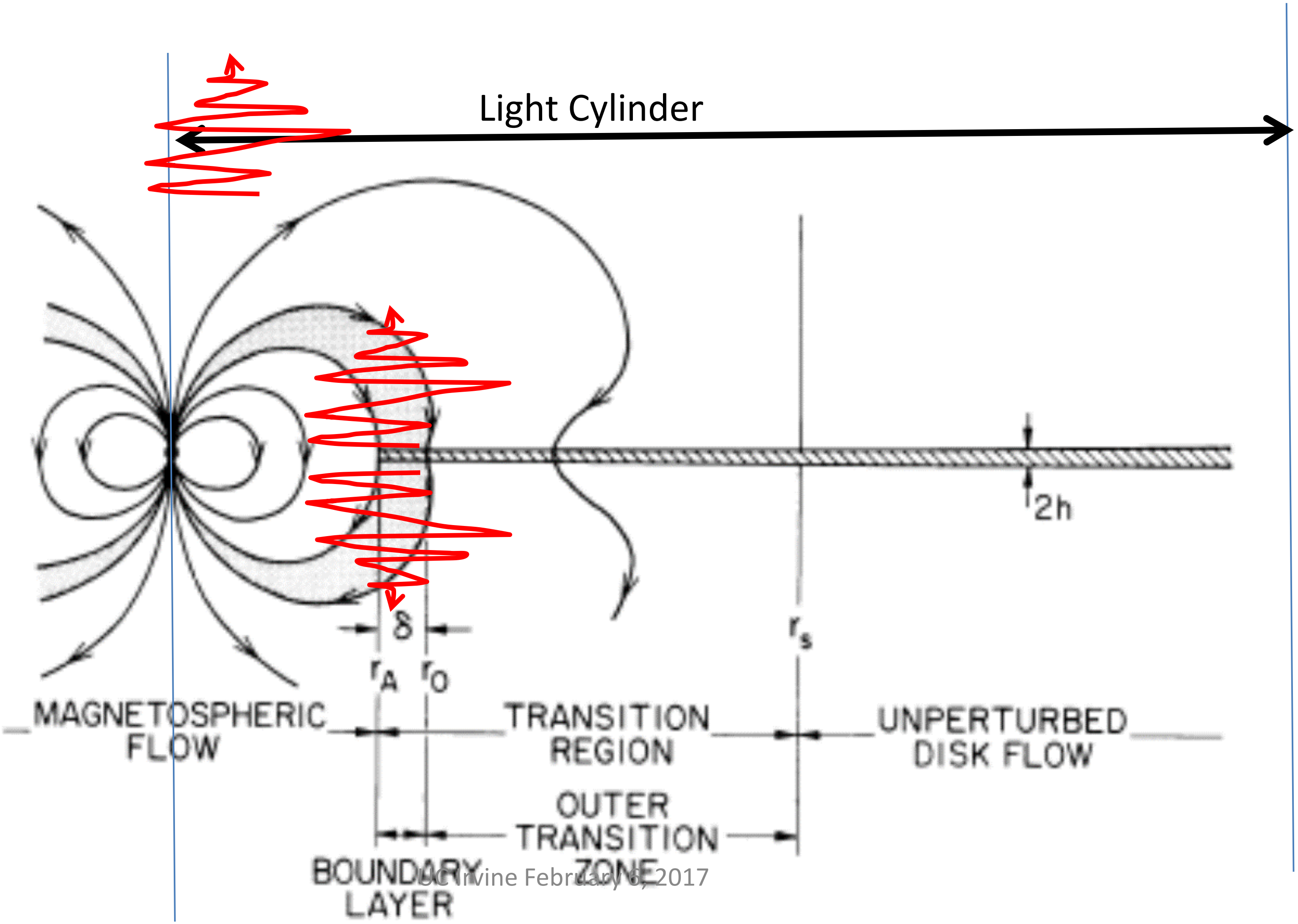
Intermedeate Mass Blackholes in M82

- Ultra Luminous X-ray Sources
  - Mass>1000 solar mass
- Near the center (not a just a center) of M82
  - Star bursting galaxy
- Located in the young Star Cluster MGG11

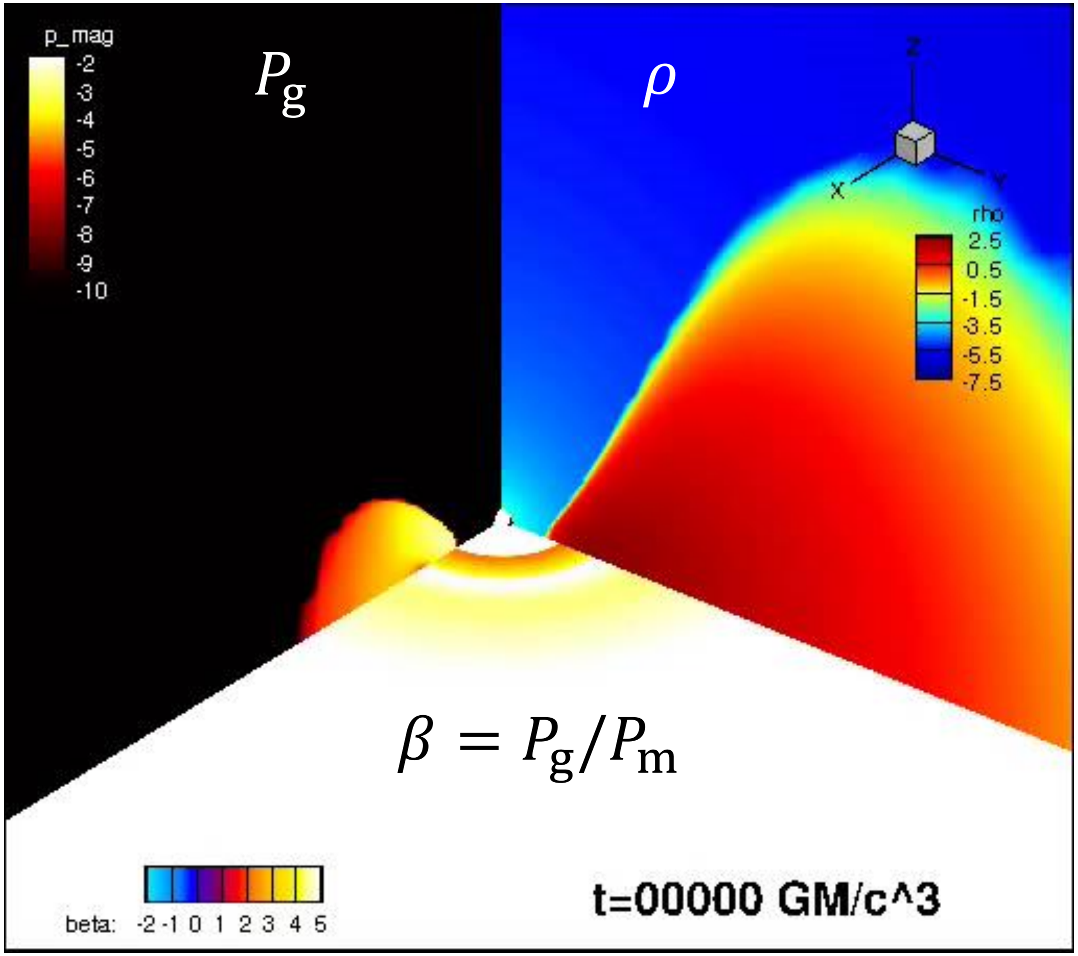


$E^2\,\Phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
6
7
8
9
10
log(E/GeV)
3PeV
Ahlers
Engel
Kotera
Takami
Diffuse

Magnetar with accretion

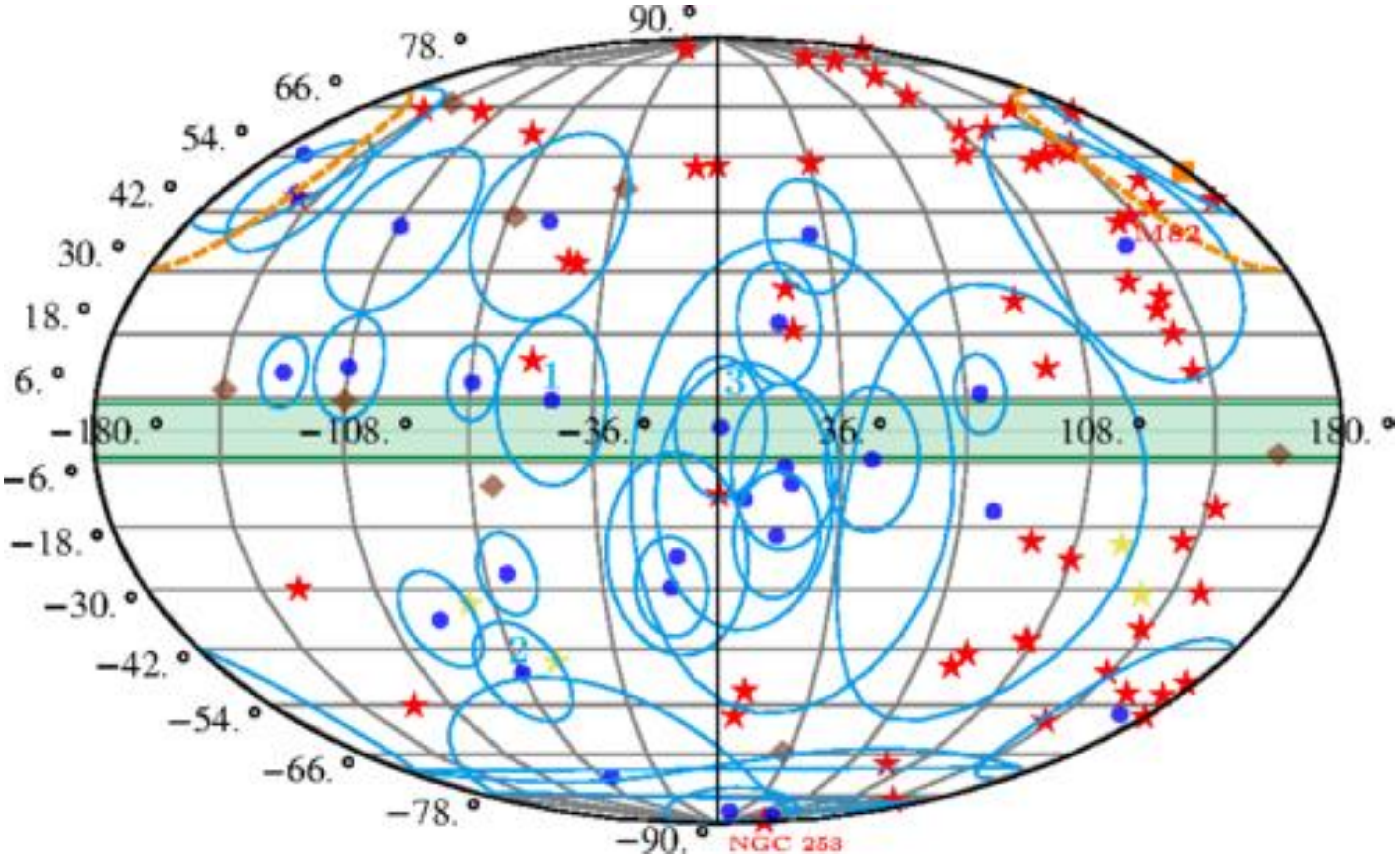


3-D relativistic MHD simulation



A. Mizuta et al. 2016

Comparison of IceCube event locations [4] with star-forming galaxies [21] and the ultrahigh energy cosmic ray hot spot reported by the TA Collaboration



Anchordoqui et al. 2014, Phys. Rev. D., 89, 127304